Underdetermination in Dark Energy and Inflationary Cosmology

William J. Wolf

University of Oxford

A thesis submitted for the degree of

Doctor of Philosophy

April 2025

Abstract

This thesis investigates a number of topics in cosmology.

Part II presents physics results that provide a novel perspective concerning the underdetermination issues facing model building within both inflation and dark energy research. Here, I focus on a number of scalar field models, and illustrate the extent to which they can saturate the parameter spaces that describe both early and late-time cosmological observables in an essentially arbitrary manner, as well as approximate the predictions of other distinct models with arbitrarily close precision.

Parts III and IV examine a number of philosophical issues relevant to this state of affairs. Among other topics, I explore whether deploying particular non-empirical arguments or explanatory considerations might allow for promising discrimination strategies when faced with competing cosmological theories. Finally, I consider the possibility that the present situations regarding inflation and dark energy might reflect novel cases of the permanent underdetermination of theory by evidence and explore the epistemic strategies that may be available to us. I argue that resorting to effective field theories is promising under certain conditions and can be seen as analogous to the overarching and common core strategies that have previously been deployed in cases of strong underdetermination.

Acknowledgements

There are so many individuals without whom I would not have been able to undertake the work that went into this thesis. I fear that it is impossible to give due acknowledgment to everyone that contributed to my ability to work towards this project and/or enriched my life during this period. However, I will attempt to do so within a reasonable length of space.

To begin, I would like to thank:

- The British Society for the Philosophy of Science (BSPS), the St Cross Centre for the History and Philosophy of Physics (HAPP), and the Oxford University faculty of philosophy, for generous financial support throughout the duration of my studies here.

- My family; my brothers, Stephen, Peter, Paul, Antonio, and Alexander Wolf; my sister and brother in law, Angel and Gregory Morrison; my nephew and niece, Nicola and Ave-Maria Morrison; and my grandparents, Bill and Mary Wolf, and Steve and Linda Kish, for an endless supply of love and joyful support.

- My friends from home and all over the world; there are so many of you and there is no way I can list everyone. But I would like to thank Michael, Ryan, Dave, Brooke, Selma, Liv, and Merri for being particularly amazing friends, especially during these years.

- Lili Tavlan, for your constant enthusiastic support in everything, and especially for attentively reading my writing and always challenging me to be a clearer thinker, writer, and communicator (no matter what the topic is!).

- My academic friends, colleagues, and collaborators; Carlos García-García, Karim Thébault, Eleanor March, Ruward Mulder, Kiki Timmermans, Gen Ye, Nicolas Teh, and Patrick Duerr. I have learned so much from all of you through discussion, feedback, and/or collaboration, and you have all contributed greatly to my intellectual development. Special thanks to Carlos for your patience and for taking the time to teach me how to use `hi_class` (as well as many other computational tools), which has been invaluable to me in so much of the research I have done.

- My academic mentors before Oxford; at the University of Notre Dame during my undergraduate degree, Antonio Delgado, for encouraging me to follow my interests and pursue physics, and Katherine Brading, for introducing me to the incredible world of philosophy of physics and philosophy of science, and likewise for encouraging me to continue pursuing them; at the University of Chicago during my masters degree, Macarena Lagos, for mentoring me throughout my first cosmology research projects.

And finally, there are four individuals to whom I am in the greatest debt for my ability to produce this work.

- My father and mother; Ronald and Julie Wolf. There are so many ways in which none of this would be possible without you. But I especially want to thank you both for instilling in me a love of learning, fostering my intellectual curiosity from the very beginning, and always pushing me to reach my potential in everything I do. You were my first teachers, in academics and in life, and there are no words that can adequately express my gratitude for everything you have done for me.

- My DPhil supervisors; James Read and Pedro Ferreira. Both of you have been so incredibly generous with your time, and have gone above and beyond in your dedication as mentors. I could not imagine a more supportive, stimulating, and exciting environment for my DPhil. It is absolutely the case that I would not be here now without James going out of his way to encourage me to apply and without his exceptional support in helping me to obtain funding for the DPhil. I also want to thank Pedro for bringing me into the cosmology group at Oxford and investing so much time in my development even before officially coming on board as my supervisor. I have had a wonderfully unique experience as a graduate student being trained as both a philosopher and physicist and seamlessly inhabiting both worlds, and I am so grateful to both of you for everything you have done to make this happen. It has truly been an honor to be colleagues, friends, and collaborators during this time.

Publication Information

Part II of this thesis is based on the following publications:

- William J. Wolf and Pedro G. Ferreira (2023). "Underdetermination of dark energy". *Phys. Rev. D* 108.10, p. 103519. DOI: 10.1103/PhysRevD.108.103519. arXiv: 2310.07482 [astro-ph.CO]

- William J. Wolf (2024b). "Minimizing the tensor-to-scalar ratio in single-field inflation models". *Phys. Rev. D* 110.4, p. 043521. DOI: 10.1103/PhysRevD.110.043521. arXiv: 2407.00358 [astro-ph.CO]

Part III of this thesis is based on the following publications:

- William J. Wolf (2024a). "Cosmological Inflation and Meta-Empirical Theory Assessment". *Stud. Hist. Phil. Sci.* 103, pp. 146–158. DOI: 10.1016/j.shpsa.2023.12.006. arXiv: 2309.02283 [physics.hist-ph]

- William J. Wolf and Karim P. Y. Thébault (2023). "Explanatory Depth in Primordial Cosmology: A Comparative Study of Inflationary and Bouncing Paradigms". *British Journal for the Philosophy of Science*. DOI: 10.1086/725096. arXiv: 2210.14625 [physics.hist-ph]

- William J. Wolf and Patrick M. Duerr (2023). "The Virtues of Pursuit-Worthy Speculation: The Promises of Cosmic Inflation". *British Journal for the Philosophy of Science*. DOI: 10.1086/728263. arXiv: 2309.16266 [physics.hist-ph]

Part IV of this thesis is based on the following publication:

- William J. Wolf and James Read (2025). "Navigating permanent underdetermination in dark energy and inflationary cosmology". arXiv: 2501.13521 [physics.hist-ph]

I am the sole author of two of the publications on this list, the lead author on the other four, and the sole author of this thesis. Permission to include material based upon jointly-authored work has been obtained from the Faculty of Philosophy, University of Oxford, as well as from all co-authors. This thesis is approximately 63,000 words.

During my time here at Oxford, I also completed the following list of physics and philosophy publications in addition to those that form the basis of my thesis:

Physics Publications:

- William J. Wolf, Carlos García-García, Deaglan J. Bartlett, et al. (2024). "Scant evidence for thawing quintessence". *Phys. Rev. D* 110.8, p. 083528. DOI: 10.1103/PhysRevD.110.083528. arXiv: 2408.17318 [astro-ph.CO]

- William J. Wolf, Pedro G. Ferreira, and Carlos García-García (2025b). "Matching current observational constraints with nonminimally coupled dark energy". *Phys. Rev. D* 111.4, p. L041303. DOI: 10.1103/PhysRevD.111.L041303. arXiv: 2409.17019 [astro-ph.CO]

- William J. Wolf, Carlos García-García, and Pedro G. Ferreira (2025). "Robustness of dark energy phenomenology across different parameterizations". *JCAP* 05, p. 034. DOI: 10.1088/1475-7516/2025/05/034. arXiv: 2502.04929 [astro-ph.CO]

- William J. Wolf, Carlos García-García, Theodore Anton, et al. (2025). "Assessing Cosmological Evidence for Nonminimal Coupling". *Phys. Rev. Lett.* 135.8, p. 081001. DOI: 10.1103/jysf-k72m. arXiv: 2504.07679 [astro-ph.CO]

- William J. Wolf (2025). "Inflationary attractors and radiative corrections in light of ACT". arXiv: 2506.12436 [astro-ph.CO]

- William J. Wolf, Pedro G. Ferreira, and Carlos García-García (2025a). "Cosmological constraints on Galileon dark energy with broken shift symmetry". arXiv: 2509.17586 [astro-ph.CO]

- William J. Wolf, James Read, and Nicholas J. Teh (2023). "Edge Modes and Dressing Fields for the Newton–Cartan Quantum Hall Effect". *Found. Phys.* 53.1, p. 3. DOI: 10.1007/s10701-022-00615-4. arXiv: 2111.08052 [cond-mat.mes-hall]

- William J. Wolf, James Read, and Quentin Vigneron (2024). "The non-relativistic geometric trinity of gravity". *Gen. Rel. Grav.* 56.10, p. 126. DOI: 10.1007/s10714-024-03308-7. arXiv: 2308.07100 [gr-qc]

Philosophy Publications:

- William J. Wolf and James Read (2023). "Respecting boundaries: theoretical equivalence and structure beyond dynamics". *Eur. J. Phil. Sci.* 13.4, p. 47. DOI: 10.1007/s13194-

023-00545-6. arXiv: 2302.07180 [physics.hist-ph]

- William J. Wolf, Marco Sanchioni, and James Read (2024). "Underdetermination in classic and modern tests of general relativity". *Eur. J. Phil. Sci.* 14.4, p. 57. DOI: 10.1007/s13194-024-00617-1. arXiv: 2307.10074 [physics.hist-ph]
- William J. Wolf and Patrick M. Duerr (2024). "Promising stabs in the Dark: theory virtues and pursuit-worthiness in the Dark Energy problem". *Synthese* 204.6, p. 155. DOI: 10.1007/s11229-024-04796-5. arXiv: 2403.04364 [physics.hist-ph]
- Patrick M. Duerr and William J. Wolf (2023). "Methodological Reflections on the MOND/Dark Matter Debate". *Stud. Hist. Phil. Sci.* 101, pp. 1–23. DOI: 10.1016/j.shpsa.2023.07.001. arXiv: 2306.13026 [physics.hist-ph]
- Pedro G. Ferreira, William J. Wolf, and James Read (2025). "The Spectre of Underdetermination in Modern Cosmology". arXiv: 2501.06095 [physics.hist-ph]
- Eleanor March, William J. Wolf, and James Read (2024). "On the geometric trinity of gravity, non-relativistic limits, and Maxwell gravitation". *Philosophy of Physics* 02, p. 15. DOI: 10.31389/pop.80. arXiv: 2309.06889 [physics.hist-ph]

Table of Contents

Part I

Introduction

1 | A brief overview of modern cosmology

This thesis addresses physics, philosophical, and foundational issues pertinent to model building in modern cosmology.

Chapters (2) and (3) present physics results that provide a novel perspective on the extent of the underdetermination issues facing model building within both inflation and dark energy research. This has to do with the reality that cosmological observables are limited in the extent of the information that they provide us. Consequently, the evidence available to us dramatically underdetermines the model-building possibilities within both dark energy and inflation physics. These chapters illustrate this underdetermination with respect to arguably the most straight-forward model building constructs within these strands of research: a single, minimally coupled, canonical scalar field.

The subsequent chapters (4), (5), and (6) explore various philosophical responses to this state of affairs. These include situating this underdetermination with respect to cosmological evidence within the context of the broader philosophical discussion on underdetermination and exploring whether there are any available strategies to break the underdetermination, as well as analyzing both the role of explanatory reasoning and the possibility of non-empirical arguments providing a decisive verdict on theory choice.

Each chapter is self-contained and can be read on its own, but this introduction aims to give a basic primer on all the cosmological physics that will be relevant in the thesis. The material reviewing the fundamentals of cosmology is drawn from Baumann (2022), Mukhanov (2005), and Weinberg (2008a), but follows Baumann (2022) most closely.

1.1 FLRW cosmological background

Cosmology studies the entire universe from mere fractions of a second after its birth to the present over length scales on the order of megaparsecs and gigaparsecs. Over such length scales, gravity is the primary actor as a long range force that is always attractive. Consequently, the birth of physical cosmology as a proper scientific discipline only occurred following Einstein's discovery of the theory of *General Relativity* (GR) (Einstein 1915, 1916). GR proposes that gravity is a manifestation of spacetime curvature, where this spacetime curvature is determined by the distribution of mass-energy content within it.[1] The fundamental equations of GR that capture this

[1] Although one need not necessarily interpret gravity as a manifestation of spacetime curvature; other geometric descriptions that are torsion or non-metricity based are available. See, e.g., Bahamonde et al. (2023), Jiménez, Heisen-

relationship are known as the *Einstein Field Equations* (EFEs) which are given by,

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = \kappa T_{\mu\nu}, \tag{1.1}$$

Where $R_{\mu\nu}$ is the Ricci curvature tensor, R is the Ricci scalar, $g_{\mu\nu}$ is the metric tensor, Λ is what is known as the *Cosmological Constant* (CC), $T_{\mu\nu}$ is the energy-momentum stress tensor, and $\kappa = 8\pi G/c^4$.

GR generalizes Einstein's earlier spacetime theory of *Special Relativity* (SR) (Einstein 1905), which has a flat spacetime metric,

$$\eta_{\mu\nu} = \begin{pmatrix} -c^2 & 0 \\ 0 & \delta_{ij} \end{pmatrix}, \tag{1.2}$$

and line element:

$$ds^2 = dx^\nu \eta_{\nu\mu} dx^\mu = -c^2dt^2 + dx^2 + dy^2 + dz^2, \tag{1.3}$$

where c refers to the speed of light and will be set to $c = 1$ for the length of this thesis. SR unifies space and time in a four dimensional manifold, but does not include gravity. Once gravity is included in the more general theory, the geometric possibilities for spacetime expand considerably. GR is, in some senses, fundamentally about solving for the spacetime metric $g_{\mu\nu}$ given a particular configuration for the relevant matter-energy content given by the stress tensor $T_{\mu\nu}$. However, Eq. (1.1) encodes a set of 10 non-linear, coupled, partial differential equations that are notoriously complicated and only solvable for a small number of scenarios. These are dramatically simplified when one introduces symmetries that may be relevant for particular systems.

In cosmology, the so-called *Cosmological Principle* (CP), which holds that the distribution of matter and energy in the universe is homogeneous and isotropic on large scales (i.e., invariant under translations and rotations), has been near universally adopted.[2] The reasons for this are philosophical and pragmatic in the sense that it both seems reasonable and has proven to be

berg, and Koivisto (2018), Mulder and Read (2023), Wolf and Read (2023), Wolf, Read, and Vigneron (2024), and Wolf, Sanchioni, and Read (2024) for some physics and philosophical discussion.

[2]A minority of cosmologists have also pursued isotropic, but inhomogeneous, cosmological models known as Lemaître–Tolman–Bondi (LTB) models. Similarly, one can also consider Bianchi models which are homogeneous, but not necessarily isotropic. These will not be discussed in the present thesis because they are only pursued by a very small number of physicists as they are generally much harder to work with and observationally disfavored. That is, if the universe had significant anisotropies or inhomogeneities, there are telltale empirical signatures that one would expect to see that have not been observed. While they are certainly interesting and worth investigating both intrinsically and as a foil/contrast to the standard FLRW model, they represent a more niche corner of the cosmological literature. See, e.g., Amendola and Tsujikawa (2015) and Ellis, Maartens, and MacCallum (2012) for some general discussion and Ade et al. (2014), Bull, Clifton, and Ferreira (2012), Jaffe et al. (2006), and Pontzen and Challinor (2007) for some comments on the viability of such scenarios.

incredibly powerful to assume that the universe should be the same everywhere. Furthermore, without making some assumptions about the relevant symmetries, it is not at all clear how one would even attempt to begin studying the cosmos using GR.

However, as Mukhanov (2005, p. 3) puts it, this "wild, intuitive" guess that has been taken as a starting assumption ever since Einstein (1917a) introduced the first model of relativistic cosmology now has a firm empirical basis and is believed to hold over scales $\simeq 100$ megaparsecs and larger. Solving Eq. (1.1) given a homogeneous and isotropic distribution of matter-energy content leads to the *Friedmann-Lemaître-Robertson-Walker* (FLRW) metric:

$$g_{\mu\nu} = \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & \frac{a^2(t)}{1-kr^2} & 0 & 0 \\ 0 & 0 & a^2(t)r^2 & 0 \\ 0 & 0 & 0 & a^2(t)r^2\sin^2\theta \end{pmatrix}, \tag{1.4}$$

with a line element,

$$ds^2 = -dt^2 + a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2\left(d\theta^2 + \sin^2\theta d\phi^2\right)\right], \tag{1.5}$$

where the metric has been written in spherical coordinates. This metric is characterized by the scale factor $a(t)$, which scales the spatial part of the metric as space dynamically evolves (expands or contracts) in time, and the curvature k, which determines whether or not we are in a geometrically flat ($k = 0$), open ($k < 0$), or closed ($k > 0$) universe. While the curious absence of spatial curvature will play a role in our discussion of cosmic inflation, there is a wealth of data that indicates that we live in a spatially flat universe with vanishing curvature (Aghanim et al. 2020b); consequently, we will set $k = 0$ in all that follows. This FLRW metric captures the spacetime structure of a universe obeying the CP that evolves according to the dynamical laws of GR.

Given that we now have the form of the metric, we are in a position to write down the dynamical laws that govern the evolution of the universe. That is, one can compute the left hand side of Eq. (1.1) using the FLRW metric given in Eq. (1.4), and then further supplement the right hand side of Eq. (1.1) with the assumption that the matter stress energy behaves as a perfect fluid[3],

$$T_{\mu\nu} = (\rho + p)U_\mu U_\nu + pg_{\mu\nu}, \tag{1.6}$$

[3]This is another foundational assumption in cosmology that flows from the assumptions of homogeneity and isotropy on large scales—this form of the stress-energy tensor is forced by the symmetries of the FLRW metric. See, e.g., Weinberg (2008a, Ch. 1) or Baumann (2022, Ch. 2).

with energy density ρ and pressure p. This leads to the first and second Friedmann equations which describe the dynamics of the universe,

$$\frac{\dot{a}^2}{a^2} = \frac{8\pi G}{3}\rho + \frac{\Lambda}{3}, \tag{1.7}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p) + \frac{\Lambda}{3}. \tag{1.8}$$

The ratio $\dot{a}/a$ will appear frequently and is known as the Hubble rate, $H \equiv \dot{a}/a$, which quantifies the universe's rate of expansion and whether it is expanding $(H > 0)$ or contracting $(H < 0)$. As can be seen from examining these equations, the evolution of H will be determined by the properties of the different types and quantities of energy density and pressure that are input into the Friedmann equations.

Given the central importance of the quantities p and ρ in characterizing different types of matter-energy content, it is convenient to define the so-called *equation of state* w as the ratio of

$$w \equiv \frac{p}{\rho}. \tag{1.9}$$

Using the so-called continuity equation, one can solve for how a particular kind of energy density will evolve as $a(t)$ evolves in time. The continuity equation,

$$\dot{\rho} + 3H\rho(1 + w) = 0, \tag{1.10}$$

follows from the conservation of energy, $\nabla^{\mu}T_{\mu\nu} = 0$. One can then re-write the continuity equation as a differential equation in a and solve it to find that,

$$\rho \propto a^{-3(1+w)}. \tag{1.11}$$

Given this information, one can then determine the evolution of H depending on how the various matter-energy components within the universe evolve with the scale factor.

The current Λ-Cold Dark Matter (Λ)CDM model of the universe is the standard model of cosmology. It consists of $\lesssim 1\%$ radiation, $\sim 5\%$ baryonic matter (corresponding to that matter described by the standard model of particle physics), $\sim 25\%$ dark matter (a mysterious form of matter that interacts gravitationally but only very weakly with electromagnetism), and $\sim 70\%$ dark energy (a mysterious form of energy with a negative pressure). Radiation has an equation of state $w = 1/3$, corresponding to

$$\rho_r(t) = \rho_{r0} a^{-4}. \tag{1.12}$$

Matter (both dark and baryonic) has an equation of state $w = 0$, corresponding to

$$\rho_m(t) = \rho_{m0} a^{-3}. \tag{1.13}$$

And finally Λ, which is the simplest proposal for dark energy (there will be much more on this and other proposals for dark energy later), has an equation of state $w = -1$, corresponding to

$$\rho_\Lambda(t) = \rho_{\Lambda 0} a^0, \tag{1.14}$$

meaning that its energy density does not dilute with the increase in scale factor unlike the other components. Here and elsewhere, the subscript 0 corresponds to the present day value. For example, $\rho_{\Lambda 0}$ would be the present day value of the energy density of Λ.

Given this information, we can now write down the Friedmann equation corresponding to the standard model of cosmology:

$$H(a) = H_0 \sqrt{\Omega_{\mathrm{m},0} a^{-3} + \Omega_{\mathrm{r},0} a^{-4} + \Omega_{\Lambda,0}}, \tag{1.15}$$

where H_0 is the value of the Hubble parameter today and we have written the energy densities in terms of the factional energy densities today that correspond to a flat universe. In other words, $1 = \Omega_{\mathrm{m},0} + \Omega_{\mathrm{r},0} + \Omega_{\Lambda,0}$, where, e.g., $\Omega_{\mathrm{m},0} = \rho_{\mathrm{m},0}/\rho_{\mathrm{c}}$ and $\rho_{\mathrm{c}} = 3H^2/8\pi G$.

1.2 Dark energy and expansion history data

How have we made the determination that our universe is composed of the mass-energy distribution outlined above? While there are a number of lines of evidence pointing to this conclusion, the most crucial evidence (and the most relevant to this thesis) consists of distance measurements that map out the expansion history of the universe. As such, this requires an understanding of distances in an FLRW cosmology.

In cosmology, it is common to move between scale factor and redshift because most of these measurements involve observing the redshift of whatever light the source has emitted. The relationship between these two is given by,

$$1 + z = \frac{1}{a}. \tag{1.16}$$

In order to calculate distances, we must account for the universe's evolution as light travels towards us. Thus, the co-moving distance $\chi(z)$[4] is expressed as an integral:

$$\chi(z) = \int_0^z \frac{dz'}{H(z')}. \tag{1.17}$$

The two most important types of distance measurements that are probed in cosmology are luminosity distance and angular diameter distance. Both of these distances are observer dependent, but related to the co-moving distance. The luminosity distance relates the intrinsic luminosity of an object to its observed brightness, while angular diameter distance refers to the ratio between an object's physical size and its observed size.

To understand luminosity distance, we note that in static Euclidean space, the absolute luminosity L from a source is distributed uniformly over the area $4\pi\chi^2$ of a sphere:

$$F = \frac{L}{4\pi\chi^2}, \tag{1.18}$$

where F is the observed flux. However, in an expanding universe, the observed flux will decrease both as a result of the photons losing energy through their redshift and as a result of the universe's expansion decreasing the rate of arrival for the photons. This contributes two factors of $(1+z)$ to the equation for flux,

$$F = \frac{L}{4\pi\chi^2(1+z)^2} = \frac{L}{4\pi d_L^2}. \tag{1.19}$$

Consequently, the luminosity distance d_L is,

$$d_L = (1+z)\chi_c. \tag{1.20}$$

For angular diameter distance, we note that the angular size of an object in static Euclidean space would be,

$$\delta\theta = \frac{D}{\chi}, \tag{1.21}$$

where D is its transverse physical size. However, in an expanding universe the size scales with a which introduces another factor of $(1+z)$,

$$\delta\theta = \frac{D}{\chi a(t)} = \frac{D(1+z)}{\chi} = \frac{D}{d_A}. \tag{1.22}$$

[4]I.e., the distance in coordinates that remains fixed over time with the universe's expansion as opposed to the proper distance which changes as the universe expands given by $\chi = d_p(t)/a(t)$.

Consequently, the angular diameter distance d_A is given by,

$$d_A = \chi/(1+z). \tag{1.23}$$

There are several kinds of data that allow us to map out the expansion history of the universe. These include data from Type Ia supernovae (SNe), baryonic acoustic oscillations (BAO), and the Cosmic Microwave Background (CMB) (Abbott et al. 2024; Adame et al. 2024; Ade et al. 2016; Akrami et al. 2020; Scolnic et al. 2022). SNe measurements are of course sensitive to luminosity distance. Given that SNe Ia have known luminosity profiles, they serve as valuable standard candles for calibrating distances. BAOs are periodic fluctuations in the density of baryonic matter in the early universe, which leave an imprint on CMB and the distribution of galaxies observed today. These measurements are sensitive to the angular diameter distance. The CMB is oldest light in the universe, coming from the time immediately after the universe cooled enough to allow photons to stream freely. This radiation provides an incredibly valuable wealth of data that tells about the primordial density perturbations, the geometry of the universe, the ratio of baryonic to cold dark matter, among many other things. Most important for us right now is that it provides us information about the angular diameter distance at the epoch of recombination (when free electrons combined with protons to form neutral hydrogen to allow photons to stream freely).

As we know from Eq. (1.17), such distance measurements provide direct access to $H(z)$, and through mapping out $H(z)$ across the expansion history of the universe, we can infer the mass-energy composition of the universe. This is what has allowed cosmologists to infer the ΛCDM model and the relative fractions of the energy densities of the various components in Eq. (1.15). More precisely, these observations give us measurements and their associated errors that provide $H(z)_{obs}$. Then, we *fit* theoretical models of $H(z)_{theory}$ to $H(z)_{obs}$ in order to determine the kinds of mass energy species present and their fractional contributions to the energy density. For example, some of the clearest evidence for dark energy emerged in studying Type Ia SNe in the late 1990s (Perlmutter et al. 1998; Riess et al. 1998). This is because, when one assumes that the universe contains only matter and radiation, the SNe are much dimmer (i.e., their observed $d_L(z)$ are much larger) than a cosmological model with only matter and radiation would predict. However, one can introduce another energy density component $\Omega_{\rm x}$ with $w_{\rm x}$ into $H(z)$,

$$H^2(a) = H_0^2 \left[\Omega_{\rm r} a^{-4} + \Omega_{\rm m} a^{-3} + \Omega_{\rm x} e^{3\int_a^1 (1+w_{\rm x})\mathrm{d}\ln \mathrm{a}}\right], \tag{1.24}$$

where it is found that a dark energy component $\Omega_{\rm DE}$ with $w_{\rm DE} \simeq -1$ brings the predicted $d_L(z)$

into alignment with the observed $d_L(z)$ if $\Omega_{\rm DE} \simeq 0.7$ and $\Omega_{\rm m} \simeq 0.3$.

A cosmological constant Λ is the simplest possible component with that behavior as it has $w_\Lambda = -1$. This equation of state can be thought of as a kind of repulsive gravity as it exerts negative pressure, meaning that this energy density drives an accelerating expansion of the universe. Furthermore, because it will never dilute with the expansion of the scale factor, Λ will eventually totally dominate the energy density of the universe, leading to an exponential expansion of the scale factor $a(t) \propto e^{H(t)}$. While there are a great number of possible candidates for dark energy, until now all available data has been consistent with Λ which has been the favored option. However, recent evidence from Dark Energy Spectroscopic Instrument (DESI) BAO measurements (Adame et al. 2024), in conjunction with CMB and SNe data (Abbott et al. 2024; Akrami et al. 2020; Qu et al. 2024; Scolnic et al. 2022), has detected the first statistically significant ($\sim 3\sigma$) evidence that dark energy may be evolving ($w_{\rm DE} \neq -1$).

In order to study whether dark energy is dynamical or not, cosmologists have adopted various ways of parameterizing dark energy. This is a necessary process as it is crucial for both visualizing and interpreting data in a way that allows us to compare various dark energy models in terms of their ability to fit the data. The standard way of parametrising time-varying dark energy is given by the Chevallier-Polarski-Linder (CPL) form (Chevallier and Polarski 2001; Linder 2003),

$$w(a) = w_0 + w_a\,(1-a)\,, \tag{1.25}$$

where w_0 is the value of the equation of state now and w_a captures the time variation of the equation of state. The parameterization is essentially conceived of as a Taylor expansion of the equation of state at recent times ($a \simeq 1$), with the linear term capturing the leading order temporal variation of the equation of state.

$$\frac{dw}{da} = -w_a. \tag{1.26}$$

Upon adopting this parameterization, once can then determine which parameters (w_0, w_a) best describe the data. For example, one then uses

$$H^2(a) = H_0^2\left[\Omega_{\rm m} a^{-3} + (1-\Omega_{\rm m})\, e^{3w_a(a-1)} a^{-3(1+w_0+w_a)}\right], \tag{1.27}$$

and can then generate constraints on (w_0, w_a). What has been found is that $(-1, 0)$, which corresponds to Λ, is disfavored in a statistically significant manner with respect to dynamical possibilities ($w_a \neq 0$). To see this, we can adopt the dark energy parameterization in Eq. (1.26) and obtain the constraints on the equation of state variables (w_0, w_a) using the expansion history data

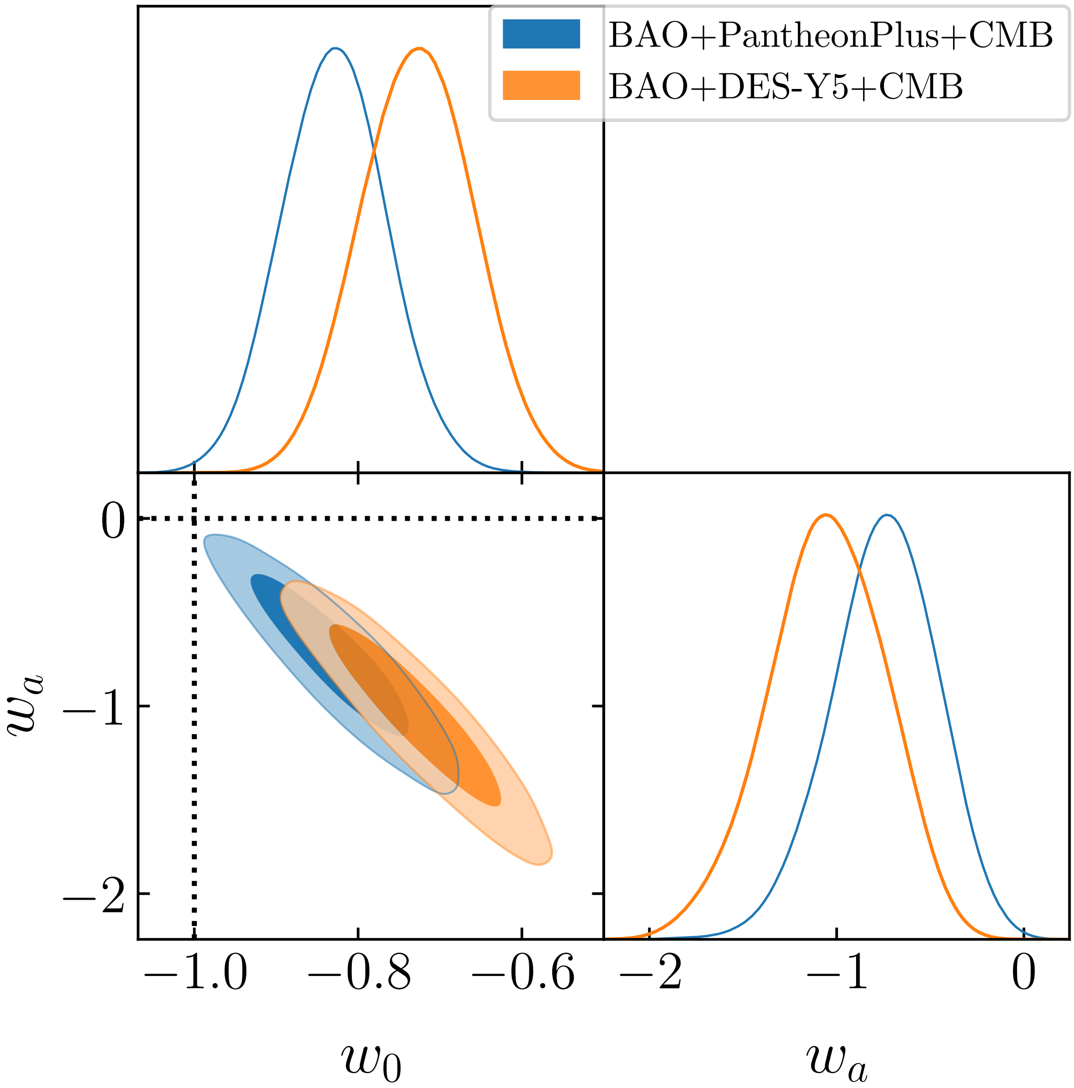


Figure 1.1: Constraints on CPL (w_0, w_a) parameter space (68% and 95% C.L.) using the combined DESI BAO data (Adame et al. 2024), CMB (Planck and ACT lensing) data (Aghanim et al. 2020a,b; Madhavacheril et al. 2024; Qu et al. 2024), and both Pantheon+ SNe data (Scolnic et al. 2022) and DES-Y5 SNe data (Abbott et al. 2024).

coming from the BAO, SNe, and CMB (more details on this later). The constraints are given in Fig. (1.1) and show that the evidence pulls away from the ΛCDM model.

What are we to make of this? These results are of course preliminary and we must await further data and analysis to see if they hold up. If this tension remains and/or strengthens, it will potentially kill Einstein's cosmological constant Λ as a viable explanation for dark energy. What then causes dark energy? There are many possibilities, but arguably the next most straightforward candidate is what is known as *quintessence*. First introduced by Caldwell, Dave, and Steinhardt (1998) and Ratra and Peebles (1988), quintessence proposes that dark energy is in fact driven by a scalar field φ with a canonical kinetic term and a potential $V(\varphi)$. The theory is described by the action,

$$S = \int d^4x\sqrt{-g}\left[\frac{1}{2}M_{\rm P}^2 R - \frac{1}{2}g^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi - V(\varphi)\right] + S_m, \tag{1.28}$$

where $M_{\rm P}$ is the reduced Planck mass, g is the determinant of the metric $g_{\mu\nu}$, R is the Ricci curvature scalar, and S_m is the action for matter. The scalar field minimally couples to gravity through the metric determinant and is assumed to have no direct coupling to matter fields. The equation of state for such a field is,

$$w_\varphi \equiv \frac{P_\varphi}{\rho_\varphi} = \frac{\dot{\varphi}^2/2 - V(\varphi)}{\dot{\varphi}^2/2 + V(\varphi)}, \tag{1.29}$$

meaning that when its energy is potential dominated it approximates the behavior of Λ with $w_\varphi \simeq -1$, but when the field begins to roll it can change from this value and of particular interest to us will be so-called *thawing* models, which evolve in such that the equation of state increases in value $(dw/da > 0)$. At first glance, this seems to be exactly the kind of behavior that is being uncovered by the latest data constraints. The question then becomes, what can we say about microphysical dynamical dark energy models such as those described by quintessence based on our understanding of (w_0, w_a) parameters?

1.3 Inflation and primordial perturbations

While the current universe is believed to be composed of matter (baryonic and dark), radiation, and dark energy, the standard ΛCDM model also includes something known as the *inflaton*, or a scalar field responsible for generating a period of quasi-exponential expansion (i.e., *cosmic inflation*) in the very early universe before the CMB. More properly understood, the 'ΛCDM' model is actually the 'ΛCDM + inflation' model.

Why do cosmologists feel so strongly that there was this inflationary period in the very early universe? After all, such an energy component is not something whose effects can be directly observed today (or in the relatively recent past) in the same way that the effects of matter, radiation, and dark energy can be. Methodologically, the status of inflation is a much thornier and nuanced business, with arguments for its inclusion in the standard model of cosmology relying on a complicated cocktail of explanatory, non-empirical, and empirical reasoning.

The two most important factors here are (1) certain 'fine-tuning' coincidences related to the initial conditions of the universe that inflation purports to explain or resolve (at least partially) and (2) inflation's remarkable ability to generate density perturbations with the properties necessary to seed later cosmic structures.

Beginning with (1), we have the *horizon problem* and the *flatness problem*. The ΛCDM model without inflation is a particular version of the *Hot Big Bang* (HBB) model. Certain structural aspects of the HBB model sans inflation create some extraordinary, if not downright shocking, coincidences in light of cosmological data which indicates that the universe is indeed homogeneous, isotropic, and flat over the enormous scales for which this holds.

Consider that the maximum distance that light (and hence any kind of causal information) can travel is given by the co-moving particle horizon:

$$d_h = \int_{t_i}^{t} \frac{dt}{a(t)} = \int_{\log a_i}^{\log a} (aH)^{-1} \, d \log a, \tag{1.30}$$

where $(aH)^{-1}$ is the co-moving Hubble radius which intuitively represents the fraction of the universe that is in causal contact at a given time. Given that the universe was first dominated by radiation and then spent most of its history dominated by dark matter, one can show the the co-moving Hubble radius is a monotonically increasing function given these mass-energy inputs; i.e., the fraction of the universe in causal contact increases with time. One can then calculate that, of our current horizon, only points within $\sim 2^\circ$ of separation on the night sky were in causal contact at the time that CMB radiation was released. Yet, the entire CMB displays remarkable homogeneity and isotropy, with temperature variations only on the order of $\sim 10^{-6}$ across the *entire* sky. How could the early universe be nearly perfectly homogeneous and isotropic without any causal processes to produce such precise uniformity and given that so much of the present horizon seemingly was never in prior causal contact? This is the horizon problem.

In addition to this bizarre coincidence, it also happens to be the case that the universe has been measured to be remarkably flat today at sub-percent levels of precision. Given standard HBB model dynamics though, this also seems puzzling. A flat universe corresponds to $\Omega_k \simeq 0$, but one can show that this is an unstable fixed point given typical FLRW dynamics. That is, one can write Ω_k in the following suggestive way:

$$\Omega_k = 1 - \Omega = \frac{-k}{a^2 H^2}. \tag{1.31}$$

As before, the co-moving Hubble radius $(aH)^{-1}$ is increasing when the universe is matter or radiation dominated, so the factor $(aH)^{-2}$ will be increasing as well. Even if the initial HHB state had $k \simeq 0$, FLRW dynamics for familiar mass-energy inputs will drive the universe away from flatness and the universe should develop significant curvature rather quickly. The only way to avoid this in the HBB model is to fine-tune the initial curvature to be so arbitrarily small that even today we still observe a flat universe to sub-percent level precision. One can quantify the degree of fine-tuning needed to ensure compatibility with current constraints on the spatial curvature, finding that (Baumann 2011),

$$\begin{aligned} |\Omega\left(a_{\mathrm{BBN}}\right)-1| &\leq \mathcal{O}\left(10^{-16}\right) \\ |\Omega\left(a_{\mathrm{GUT}}\right)-1| &\leq \mathcal{O}\left(10^{-55}\right) \\ |\Omega\left(a_{\mathrm{pl}}\right)-1| &\leq \mathcal{O}\left(10^{-61}\right). \end{aligned} \tag{1.32}$$

This means that at these various epochs of big bang nucleosynthesis, GUT scales, and Planck scales, the value of the curvature parameter needs to be fine-tuned to those extraordinary precisions, otherwise we could not account for the observed vanishing of spatial curvature in the present epoch. This is the flatness problem.

Introducing an inflationary epoch into the early universe can go a long way towards alleviating these problems. Inflation proposes that at early times, the universe's mass-energy was dominated by a scalar field φ with a potential $V(\varphi)$, corresponding to the action we saw earlier in Eq. (1.28). The difference is that this inflationary epoch would have had to occur at much higher energies than dark energy (i.e., at approximately GUT scale energies) and this inflation scalar field, rather than having only recently begun to evolve as with quintessence, would have needed to reach the end of its evolution to end the inflationary epoch and enter the radiation and matter dominated expansion observed after the CMB. As we have already seen, such a scalar field dominated by its potential energy will have $w_\varphi \simeq -1$, which will correspond to quasi-exponential expansion in the scale factor $a(t) \simeq e^{H(t)}$. A sufficiently long period cosmic inflation[5] can resolve the horizon and flatness problems because it will shrink the co-moving Hubble sphere. That is, rather than $(aH)^{-1}$ increasing as in matter or radiation domination, during exponential expansion H is approximately constant while $a(t) \simeq e^{H(t)}$. The co-moving Hubble sphere will shrink dramatically. This resolves the horizon problem because it allows the distant points in our Hubble horizon to have actually been in causal contact in the past, despite appearing to be causally disconnected in the past when naively extrapolating backwards. Then, causal processes can produce the observed uniformity. This resolves the flatness problem because it exponentially drives the curvature parameter in Eq. (1.31) to zero. That is, rather than typical HBB dynamics driving the universe away from flatness, inflationary dynamics drive the universe towards flatness.

Even though the standard HBB can accomodate these facts with sufficient fine-tuning of the initial conditions, inflation is widely believed to offer a satisfying explanation to these extraordi-

[5]We require approximately 60 e-foldings to resolve the horizon and flatness problems, where an e-fold N corresponds to $N = \log(a_f/a_i)$. That is, 60 e-folds corresponds to a final a_f that is e^{60} larger than the initial a_i.

nary coincidences that would otherwise be relegated to seemingly inexplicable brute facts (much more on this later). While technically not being the first to propose cosmic inflation (Starobinsky 1980), Guth (1981) was the first to connect the idea of an inflationary epoch to the resolution of these perceived fine-tuning difficulties which is largely credited with why inflation was so quickly adopted by the wider community. However, there was another development shortly after the inital papers. Several cosmologists independently showed that inflationary perturbations would naturally produce density fluctuations that could plausibly explain the origin of cosmic structure (Bardeen, Steinhardt, and Turner 1983; Guth and Pi 1982; Hawking 1982; Mukhanov and Chibisov 1981). Here, we give a brief modern discussion of this calculation as inflation's ability to produce appropriate density fluctuations in the early universe is by far the most important reason underlying its broad acceptance in the cosmology community.

All discussion has so far been at the level of the background, i.e., the leading order dynamics for an FLRW spacetime populated with various matter-energy species. However, it is obviously the case that the universe is not perfectly homogeneous and isotropic, otherwise there would no clusters, galaxies, stars, planets, or any other kinds of cosmic structure, just a smooth featureless expanse. Studying these features thus requires understanding cosmological perturbation theory, where perturbations can be treated as small departures from the background metric and energy distribution.

One can expand the metric tensor as:

$$g_{\mu\nu} = g_{\mu\nu}^{(0)} + \delta g_{\mu\nu}, \tag{1.33}$$

where $g_{\mu\nu}^{(0)}$ is the background FLRW metric and $\delta g_{\mu\nu}$ represents small perturbations. The most general perturbed metric tensor, including scalar, vector, and tensor perturbations, is:

$$ds^2 = -(1+2\Phi)dt^2 + 2aB_i dx^i dt + a^2(t)\left[(1-2\Psi)\delta_{ij} + h_{ij}\right] dx^i dx^j, \tag{1.34}$$

where:

- $\Phi(x,t)$ is a scalar perturbation related to the gravitational potential.
- $\Psi(x,t)$ is another scalar perturbation related to spatial curvature.
- $B_i(x,t)$ represents vector perturbations, which describe rotational vorticity modes.
- $h_{ij}(x,t)$ is the tensor perturbation, corresponding to gravitational waves.

However, the perturbed metric given by Eq. (1.34) is not uniquely defined and depends on particular choices of coordinates. When working with cosmological perturbations, one typically either picks a particular gauge choice for convenience or otherwise works in gauge-invariant variables. Similarly, the inflaton field can be expanded as:

$$\varphi(x,t) = \varphi_0(t) + \delta\varphi(x,t), \tag{1.35}$$

where $\varphi_0(t)$ is the homogeneous background field, and $\delta\varphi(x,t)$ is the perturbation representing small variations in the value of the inflation field. Given the perturbed metric and the perturbed field, and then deciding on a strategy to handle the residual gauge freedom, one can substitute these into the scalar field equation of motion to solve for the evolution of scalar inflationary perturbations $\delta\varphi$. After some (very) lengthy and tedious calculations, one finds the famous Mukhanov-Sasaki equation:

$$f'' + \left(k^2 - \frac{z''}{z}\right) f = 0, \tag{1.36}$$

where $f \equiv a\delta\varphi$, $z \equiv a\varphi_0'/\mathcal{H}$, and derivatives marked with prime represent derivatives with respect to conformal time $d\eta = dt/a$. This gives the equation of motion for cosmological perturbations of the inflation field. And finally, this is related to an important gauge invariant quantity known as the comoving curvature perturbation $\mathcal{R}$,

$$\mathcal{R} = \frac{\mathcal{H}}{\varphi_0}\delta\varphi, \tag{1.37}$$

where $\mathcal{R}$ describes spatial curvature perturbations on co-moving hypersurfaces and intuitively can be thought of as a spatially varying time delay for the end of inflation. This quantity is very important because it remains nearly constant on superhorizon scales (assuming the perturbations are sufficiently adiabatic), meaning that even when perturbation modes exit the horizon as they do with inflation, we can still reliably track their behavior and connect them to observables once they re-enter the horizon.

The final ingredient to consider is that inflation is conceived of as a field in the tradition of particle physics, and thus we must use the tools of quantum field theory to quantize these perturbations. For simplicity, we adopt the slow-roll approximation which will be important later on when we discuss observables.

As we know, inflation is driven by a scalar field φ rolling down a potential $V(\varphi)$. The evolution of this field is governed by the Klein-Gordon equation in an expanding universe which gives us the background dynamics:

$$\ddot{\varphi} + 3H\dot{\varphi} + V'(\varphi) = 0, \tag{1.38}$$

where $\ddot{\varphi}$ is the acceleration of the field, H is the Hubble parameter, $V'(\varphi) = dV/d\varphi$ is the slope of the potential. In order to produce the necessary cosmic inflation, the potential must dominate the dynamics for a considerable amount of time. This means that $\dot{\varphi}^2 \ll V$ which implies that both $\ddot{\varphi}$ and $\dot{\varphi}^2$ can be safely neglected, simplifying the equation of motion to:

$$3H\dot{\varphi} \approx -V'(\varphi). \tag{1.39}$$

This can be captured in terms of two slow-roll parameters,

$$\epsilon = \frac{1}{2}\left(\frac{V'(\phi)}{V(\phi)}\right)^2, \quad \eta = \frac{V''(\phi)}{V(\phi)}, \tag{1.40}$$

where these have been written in terms of the potential. These parameters remain small when the universe is undergoing inflation ($\epsilon, \eta \ll 1$) and inflation ends when $\epsilon \simeq 1$.

In the slow-roll approximation, Eq. (1.36) becomes:

$$f_k'' + \left(k^2 - \frac{2}{\eta}\right) f_k = 0, \tag{1.41}$$

where then the standard quantization procedure applies. That is, the field and its conjugate momentum are promoted to quantum operators $\hat{f}(\eta, x)$ and $\hat{\pi}(\eta, x)$ with the commutation relations imposed,

$$[\hat{f}(\eta, x), \hat{\pi}(\eta, x')] = i\delta(x - x'). \tag{1.42}$$

One can write in terms of creation and annihilation operators $\hat{f}(\eta, x) = f_k(\eta)\hat{a}_k + f_k^*(\eta)\hat{a}_{-k}^\dagger$, where in Fourier space $[\hat{a}_k, \hat{a}_{k'}^\dagger] = (2\pi)^3\delta(k - k')$. Solving Eq. (1.41) for an appropriate choice of vacuum state gives the *Bunch-Davies mode function*:

$$f_k(\eta) = \frac{e^{-ik\eta}}{\sqrt{2k}}\left(1 - \frac{i}{k\eta}\right). \tag{1.43}$$

This choice of vacuum ensures that when the modes are deep inside the horizon ($k >> aH$), spacetime looks flat as these solutions correspond to standard Klein-Gordon plane waves in Minkowski spacetime.

One can then compute the variance of the inflationary fluctuations,

$$\langle \left|\hat{f}\right|^2 \rangle = \int \mathrm{d}\ln k \, \frac{k^3}{2\pi^2} \left|f_k(\eta)\right|^2 , \tag{1.44}$$

where we can now write the dimensionless power spectrum in terms of $\delta\varphi$ rather than the variable f, leading to the following result in the superhorizon limit,

$$\Delta^2_{\delta\phi}(k) \approx \left(\frac{H(t)}{2\pi}\right)^2 \bigg|_{k=aH(t)} , \tag{1.45}$$

evaluated at the horizon crossing $k = aH$. Using this result with Eq. (1.37), one can write the power spectrum for these primordial perturbations from the inflation field as,

$$\mathcal{P}_s = \Delta^2_{\mathcal{R}}(k) = A_\mathrm{s} \left(\frac{k}{k_*}\right)^{n_\mathrm{s}-1} , \tag{1.46}$$

where

$$A_s = \frac{1}{8\pi^2} \frac{1}{\epsilon} \frac{H^2}{M_\mathrm{P}^2}, \tag{1.47}$$

gives the amplitude and,

$$n_s(k) - 1 = \frac{d\log\mathcal{P}_s}{d\log k} \approx -6\epsilon + 2\eta, \tag{1.48}$$

gives the spectral index which quantifies the scale dependence of the power spectrum, and on the right hand side it is shown how this quantity can be calculated directly from the slow-roll parameters. The power spectra of these scalar fluctuations has been measured, with the Planck satellite finding that $A_s \approx 10^{-9}$ and that they are approximately but not exactly scale-invariant with $n_s \simeq 0.965$ (in addition to being adiabatic and Gaussian) (Aghanim et al. 2020b; Akrami et al. 2020). As we shall later discuss, the fact that n_s is nearly but not exactly equal to one is crucial evidence for inflation as inflationary dynamics (approximated by the slow-roll parameters) will necessarily drive this value away from perfect scale-invariance. It is these fluctuations that produce density perturbations that show up as tiny variations in the power spectrum of radiation in the CMB and that later grow to seed cosmic structure in the later universe. Taking a second to appreciate this remarkable insight, if the universe did undergo an inflationary epoch in its early history, this means that the galaxies we observe today originated as tiny, quantum mechanical variations in the value of the inflaton field at different points in space.

In addition to scalar perturbations, inflation also generically produces tensor perturbations which lead to the production of a stochastic background of primordial gravitational waves (GWs).

The equation of motion for tensor perturbations is:

$$h''_{ij} + 2\mathcal{H}h'_{ij} - \nabla^2 h_{ij} = 0. \tag{1.49}$$

Following similar procedures as with the scalar fluctuations, one can show,

$$\Delta_h^2(k) = A_{\mathrm{t}} \left(\frac{k}{k_*}\right)^{n_{\mathrm{t}}}, \tag{1.50}$$

with the amplitude and tensor spectral index then given by,

$$A_{\mathrm{t}} \equiv \frac{2}{\pi^2}\frac{H^2}{M_{\mathrm{P}}^2}. \tag{1.51}$$

Given that we have already measured scalar fluctuations, models of inflation will give a prediction for the ratio of the tensor and scalar perturbations,

$$r \equiv \frac{A_{\mathrm{t}}}{A_{\mathrm{s}}} = 16\epsilon. \tag{1.52}$$

However, primordial gravitational waves have not yet been measured, meaning that we only have upper bounds on this quantity.

In order to compare inflationary models with data, their predictions for (r, n_s) are the primary tool used to assess viability. For example, it is common to produce so-called “inflationary zoo plots”, which compare predictions for various inflation models with data constraints in the (r, n_s) plane. Fig. 1.2 is one example taken from Akrami et al. (2020). As indicated on the figure, one can get an idea of the viability of these selected models, with some being disfavored while others are still viable. The hope is that a clear detection of r will allow us to single out a unique model of inflation, but underdetermination worries are already present as parts of this parameter space can evidently be occupied by distinct models.

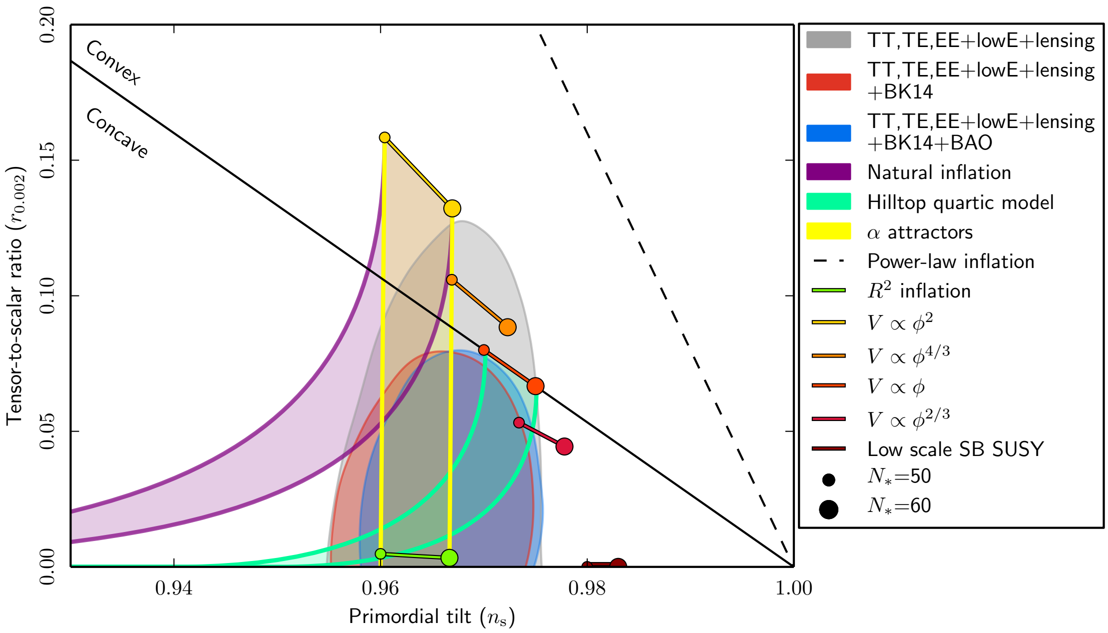


Figure 1.2: Inflation zoo plot comparing selected inflation models with Planck and Bicep constraints on (r, n_s) taken from Akrami et al. (2020).

1.4 Roadmap

We are now in position to provide a more detailed roadmap of this thesis.

Chapter (2) is based on Wolf and Ferreira (2023) and explores what we can infer about the microphysics of quintessence (and dark energy more generally) when cosmological data is interpreted in terms of Eq. (1.26). To this end, it will explore aspects of how microphysical models of dark energy get mapped into (w_0, w_a) parameters that describe the equation of state and some unavoidable ambiguities and limitations that ensue. The ultimate goal would be to determine the unique action for the theory of dark energy, bringing dark energy onto the same level as the standard model of particle physics where we can write down a fundamental action that details the field's dynamics and interactions. However, I will argue that microphysical theories of dark energy are underdetermined because they can easily be constructed to saturate large swaths of the observable parameter space in an essentially arbitrary manner.

Chapter (3) is based on Wolf (2024b) and explores what we can infer about the microphysics of inflation from obtaining constraints on (r, n_s). It shows how, by adopting an effective field theory perspective on so-called 'hilltop' models of single field inflation, one can easily saturate the (r, n_s) parameter space, which provides another perspective on the underdetermination of microphysical models of inflation in addition to other recent research which has shed light on the extent of the flexibility and unconstrained nature of the inflation paradigm.

Chapter (4) is based on Wolf (2024a), where I assess arguments that have been made that the theory of inflation may already have significant non-empirical confirmation. I argue that, based on the most prominent account of non-empirical assessment that has been developed to date, the current non-empirical confirmation case for inflation is weak. This does not in any way diminish the explanatory accomplishments of inflation or even suggest that cosmologists should not accept inflation as the best available description of the early universe. Rather, the focus here is the context of confirmation and compares inflation with prior examples where one could make a strong case for non-empirical confirmation (the Higgs mechanism and gravitational waves).

Chapter (5) is based on both Wolf and Thébault (2023) and Wolf and Duerr (2023). Here, I closely examine the explanatory virtues of inflation, arguing that one way to cash out the explanatory merits of inflation is through the concept of *explanatory depth*, where this is understood as an explanation's performance in the face of counterfactual scenarios. Furthermore, a novel notion of explanatory depth is developed that facilitates a direct comparison between the explanatory virtues of the inflation paradigm and a competitor paradigm known as *ekpyrotic cyclic cosmology*. Finally, the chapter closes with an assessment of the *predictive novelty* of various inflationary predictions, arguing that this provides the best epistemic case for the pursuit (and acceptance) of inflation in the standard model of cosmology.

Chapter (6) is based on Wolf and Read (2025), where I contextualize the underdetermination present in dark energy and inflation in terms of the broader philosophical literature on the underdetermination of theory by evidence. After reviewing the philosophical literature on underdetermination, I argue that these reflect instances of *permanent underdetermination*. However, I repurpose strategies that have been developed in response to instances of *strong underdetermination* to argue that, under some circumstances, there may be compelling resolutions to break the permanent underdetermination identified in the case of dark energy and inflation.

Part II

Dark energy and inflation

2 | On the degeneracy of thawing models of dark energy

2.1 Introduction

Evidence for the accelerating expansion of the universe has been steadily accumulating since its discovery in 1998 (Abbott et al. 2019; Ade et al. 2016; Aghanim et al. 2020b; Alam et al. 2017; Hinshaw et al. 2013; Perlmutter et al. 1999; Riess et al. 1998). These observations have all been consistent with a cosmological constant up until the latest results from DESI (Adame et al. 2024), which has detected the first significant evidence for deviation from a cosmological constant when used in combination with CMB and SNe data. Of course, these results are preliminary and it remains to be seen if the evidence strengthens or goes away with more data and further analysis. See, e.g., Carloni, Luongo, and Muccino (2024), Dinda and Maartens (2025), Lodha et al. (2024), Shlivko and Steinhardt (2024), Tada and Terada (2024), Wolf, Ferreira, and García-García (2025b), Wolf, García-García, Anton, et al. (2025), Wolf, García-García, Bartlett, et al. (2024), Wolf, García-García, and Ferreira (2025), and Ye et al. (2024) for just a small sample of this literature focused on interpreting the implications of these results for dark energy. At the very least, this has provided strong motivations to exploring other proposals that seek to account for this accelerating expansion by postulating the existence of dark energy (Amendola and Tsujikawa 2015). Dark energy typically refers to an exotic form of matter, represented by additional fundamental field(s) that dynamically evolve over time and may (or may not) modify gravity on cosmological scales (Clifton et al. 2012), depending on the exact nature of the field.

Characterizing this accelerating expansion usually begins by defining the equation of state.

$$w \equiv \frac{P}{\rho}, \tag{2.1}$$

where P is the pressure and ρ is the energy density of whatever is sourcing the accelerating expansion. If expansion is driven by a cosmological constant, the equation of state is locked in at the value $w = -1$. If, on the other hand, expansion is driven by a dynamical field, it will evolve over time and the equation of state can then be described as a function of a, the scale factor of the universe, so that $w = w(a)$.

Ultimately, one would like to be able to extract the detailed time dependence of the equation of state in the form of $w(a)$ or $w(z)$ where z is the redshift, $1 + z \equiv a^{-1}$ and, indeed, there have been attempts at doing so (Raveri, Pogosian, et al. 2023; Said et al. 2013). In practice there is limited information that one can extract about the evolution of $w(a)$ and, as a result, this has led to the wide-spread adoption of a very natural and popular parameterization known as the Chevallier-Polarski-Linder (CPL) parameterization (Chevallier and Polarski 2001; Linder 2003), given by:

$$w(a) = w_0 + w_a(1 - a). \tag{2.2}$$

This parameterization approximates the dark energy equation of state close to today ($a \sim 1$); where w_0 gives the value of the equation of state now and w_a characterizes the temporal evolution of dark energy. This allows for a very useful description of dark energy models in terms of the parameters (w_0, w_a). Fig. (2.1) shows the current constraints on these parameters. These constraints were determined by implementing the parameterized model in `hi_class` (Bellini, Sawicki, and Zumalacárregui 2020; Blas, Lesgourgues, and Tram 2011; Zumalacárregui et al. 2017) and using `Cobaya` (Torrado and Lewis 2021) to interface between the theory code and data. We then obtain constraints on (w_0, w_a) by comparing it directly with the combined DESI BAO DR1 data (Adame et al. 2024), CMB (Planck and ACT lensing) data (Aghanim et al. 2020a,b; Madhavacheril et al. 2024; Qu et al. 2024), and both Pantheon+ SNe data (Scolnic et al. 2022) and DES-Y5 SNe data (Abbott et al. 2024) using a Metropolis-Hasting algorithm (Hastings 1970; Lewis 2013; Lewis and Bridle 2002; Metropolis et al. 1953) to sample the cosmological and dark energy parameters in Table 2.1 while imposing uniform priors. Additionally, we use the Gelman-Rubin criterion (Gelman and Rubin 1992) to impose that $R - 1 < 0.02$ in the diagonalized parameter space. A cosmological constant, Λ, is of course given by $w_a = 0$ and $w_0 = -1$, while various dynamically driven dark energy possibilities occupy the rest of the parameter space. The constraints clearly show that the evidence pulls away from the ΛCDM model at the $\simeq 2\sigma - 3\sigma$ level of significant.

There is a tremendous amount of open parameter space and future work that must be done in order to measure (w_0, w_a) more accurately. This invites the following question: what can pinning down the values of (w_0, w_a) teach us about the microphysical nature of dark energy? As others have noted (Caldwell and Linder 2005), constraining down to $w_a \sim 0$ and $w_0 \sim -1$ would strongly points towards a cosmological constant, but can never fully eliminate dynamically driven dark energy as a possibility because it may simply not yet have entered a stage of temporal evolution that is observable to us. There is of course another possibility. What if future surveys continue to indicate that $w_0 \neq -1$ and that there is significant temporal evolution captured in w_a with sufficient statistical significance as the latest evidence has begun to suggest?

Clearly, observing $w_a \neq 0$ with statistical significance would rule out the basic cosmological constant scenario and point towards the existence of dark energy driven expansion. However, would such observations allow us to definitively say anything more specific about dark energy, other than inferring its dynamical nature? Most obviously, we would like to gain an understanding of the fundamental microphysics responsible of dark energy (Caldwell and Linder 2005; Escamilla et al. 2023; García-García, Bellini, et al. 2020; Huterer and Peiris 2007; Linder 2023; Marsh, Bull, et al. 2014; Park, Raveri, and Jain 2021; Peirone et al. 2017; Raveri, Bull, et al. 2017; Scherrer 2015; Traykova et al. 2021). This presumably (in keeping with the field theoretic paradigm of modern physics) would be captured in a Lagrangian expression; one that includes structural information concerning the relevant types of dynamical field(s), the couplings to gravity and other material fields, and the forms of the respective kinetic and potential terms. To this end, the shear volume of dark energy models that have been explored is extensive: a by no means exhaustive list includes canonical quintessence, k-essence, α-attractors, f(R) gravity, Horndeski scalar-tensor gravity, DHOST theories, Einstein-Aether theories, bi-metric theories, and many more (Amendola and Tsujikawa 2015; Charmousis et al. 2012; Clifton et al. 2012; Copeland, Sami, and Tsujikawa 2006; García-García, Linder, et al. 2018; Horndeski 1974; Joyce, Lombriser, and Schmidt 2016; Kase and Tsujikawa 2019; Kobayashi 2019; Sotiriou and Faraoni 2010; Tsujikawa 2013). Furthermore, many of these theories have a large number of specific realizations.

It is hard to overstate the value of gaining such access to the fundamental microphysics of dark energy. For example, if dark energy is caused by some exotic field, this could allow us to situate dark energy within the standard model of particle physics. Such information might give us crucial information regarding persistent conundrums such the Hierarchy problem or what further symmetry principles are at play in particle physics (Carroll 1998; Martin 2008). If modifications to gravity are at play, this could give us information regarding gravity's renormalizability (Sotiriou and Faraoni 2010). Cosmologically speaking, it could indicate the ultimate fate of the universe itself: will the universe continue in an accelerating expansion forever (as in the cosmological constant scenario or particular "freezing" realizations of dark energy) or will the universe stop accelerating (as in "thawing" realizations of dark energy) (Caldwell and Linder 2005); or could it even potentially begin contracting (Andrei, Ijjas, and Steinhardt 2022; Steinhardt and Turok 2002b)?

In this chapter, we will attempt to shed some further light concerning the degree to which constraining and determining the values of the parameters w_0 and w_a will inform us about the fundamental microphysics driving dark energy. Our verdict is largely pessimistic: it is unlikely that constraining the (w_0, w_a) plane will ever allow us to single out a specific theory of dark energy, even if we were to detect clear evidence of dynamical behavior ($w_0 \neq -1$ and $w_a \neq 0$).

We support our argument in two primary ways: (i) we demonstrate that there is significant underdetermination in the (w_0, w_a) plane in the sense that there is a complete degeneracy between multiple realizations of dark energy and their mapping over vast swaths of this parameter space; (ii) we highlight some shortcomings of using (w_0, w_a) by demonstrating that this parameterization is remarkably sensitive to the properties of the data used to constrain it, introducing additional confounding factors.

On (i), it has been previously suggested in many places in the literature that typical realizations of "freezing" and "thawing" models of dark energy occupy small, well-defined regions in the (w_0, w_a) plane; and that measurements of these parameters would clearly indicate whether or not dark energy was described by a simple realization (e.g., single field, minimally coupled, canonical, etc.) of one of these classes (Barger, Guarnaccia, and Marfatia 2006; Caldwell and Linder 2005; Clemson and Liddle 2009; Linder 2006, 2008). Furthermore, the typical understanding holds that finding values for w_0 and w_a outside these narrow regions would indicate more complicated dynamics, exotic physics, or highly unnatural fine-tuning.

We challenge this orthodoxy specifically regarding thawing dark energy. We do so by exploring arguably the simplest model of dark energy, a minimally coupled scalar field with a quadratic potential. We analytically demonstrate, using exact solutions in a matter-dominated background, that this model can arbitrarily sweep across huge sections of the (w_0, w_a) plane depending on simple choices of model parameters. Furthermore, this model is of particular interest because it can be understood as an effective field theory approximation of a significant number of other distinct models (Burgess 2020); this means that it provides a map between any space on the (w_0, w_a) plane that it sweeps and many distinct models. We then show that these conclusions hold more generally where we numerically integrate the equations for a mixed dark matter/dark energy universe thought to describe the actual universe we live in. Indeed, the difficulty of constructing a unique potential from observational data has been noted in other places (see, e.g., Park, Raveri, and Jain (2021)). Here we analytically and numerically illustrate that determining a unique dark energy is almost certainly impossible by using this simple model (and the many models that it approximates) to cover significant portions of the parameter space.

Regarding (ii), we demonstrate that the w_0, w_a parameterization is very sensitive to the range of redshifts one fits over. That is, we show that this parameterization captures some $w(a)$ evolutions for the quadratic model reasonably well, but fairs far less successfully with others; making the mapping between theoretical dark energy models and the (w_0, w_a) phase space sensitively

Cosmological Parameters	
ω_b	$\mathcal{U}[0.005, 0.1]$
Ω_m	$\mathcal{U}[0.01, 0.99]$
H_0 [km/s/Mpc]	$\mathcal{U}[20, 100]$
n_s	$\mathcal{U}[0.8, 1.2]$
$\ln 10^{10} A_s$	$\mathcal{U}[1.61, 3.91]$
τ	$\mathcal{U}[0.01, 0.8]$
Dark Energy Parameters	
w_0	$\mathcal{U}[-3.0, 1.0]$
w_a	$\mathcal{U}[-3.0, 2.0]$

Table 2.1: Prior distributions used in the cosmological parameter inference. $\mathcal{U}(a, b)$ stands for an uniform distribution in the range $[a, b]$.

dependent on arbitrary choices regarding the range of redshifts one fits over. We illustrate this effect with a few different choices of survey parameters.

The chapter proceeds as follows. Sect. (2.2) provides an overview of quintessence: we introduce two flavours of the quadratic potential ("slow-roll" and "hilltop" variations), derive their analytic solutions, and discuss how this model can effectively approximate a huge variety of models with distinct potentials. Sect. (2.3) derives analytic expressions relating the quadratic potential to the (w_0, w_a) parameter space and demonstrates that this model can sweep huge portions of the (w_0, w_a) plane. We then numerically solve the equations of motion and show that this conclusion holds in a realistic universe with both dark matter and dark energy. Sect. (2.4) discusses these results in light of current surveys aimed at constraining w_0 and w_a. Sect. (2.5) concludes.

2.2 Quintessence

Quintessence is perhaps the simplest theoretical proposal for dark energy (see, e.g., Caldwell, Dave, and Steinhardt (1998), Peebles and Ratra (1988), and Ratra and Peebles (1988) for early papers on the subject), and is characterized by a dynamical scalar field φ with a canonical kinetic term and a potential $V(\varphi)$. The theory is given by an action of the following form:

$$S = \int d^4x\sqrt{-g}\left[\frac{1}{2}M_{\rm P}^2 R - \frac{1}{2}g^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi - V(\varphi)\right] + S_m, \tag{2.3}$$

where $M_{\rm P}$ is the reduced Planck mass, g is the determinant of the metric $g_{\mu\nu}$, R is the Ricci curvature scalar, and S_m is the action for matter. The scalar field minimally couples to gravity through the metric determinant and is assumed to have no direct coupling to matter fields.

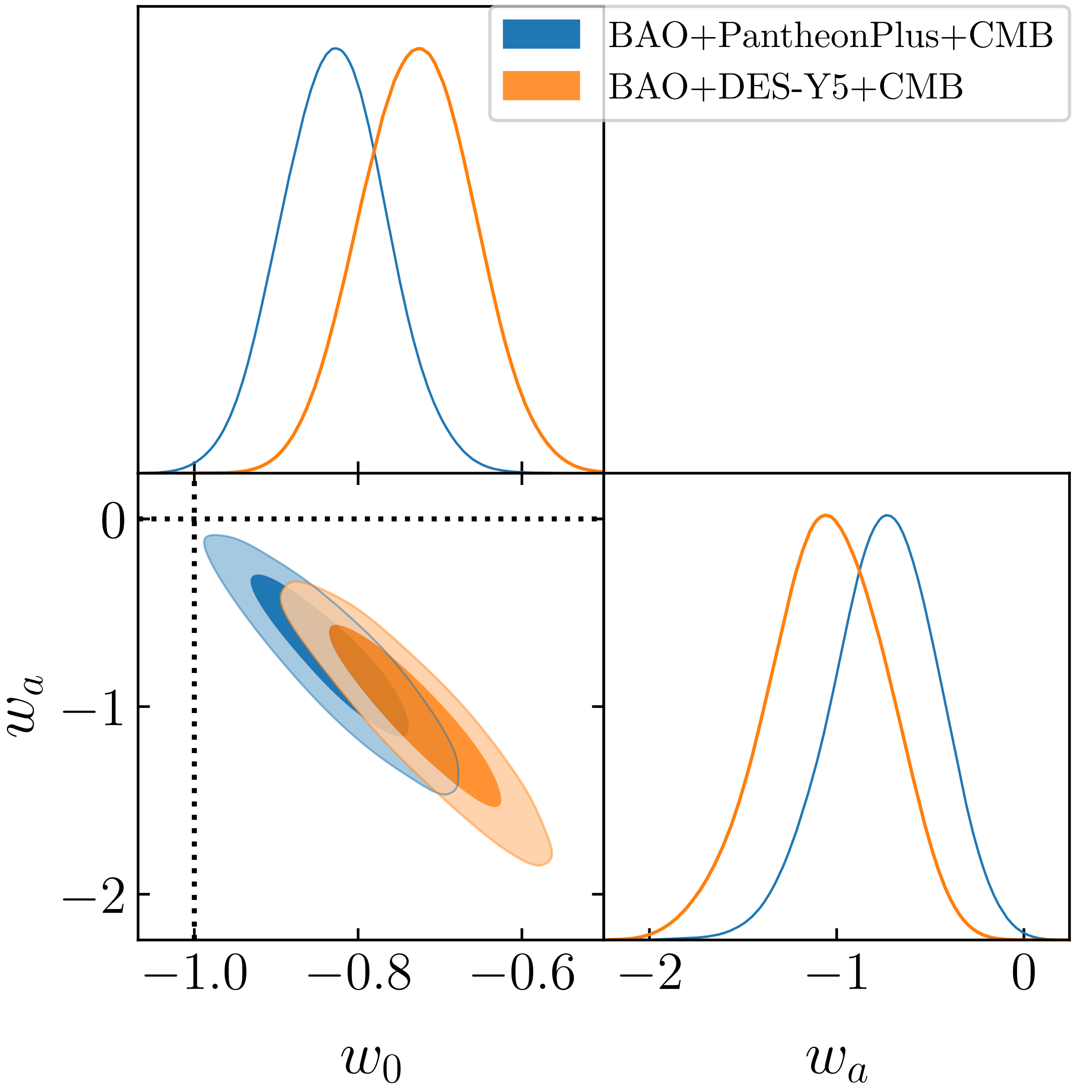


Figure 2.1: Constraints on CPL (w_0, w_a) parameter space (68% and 95% C.L.) using the combined DESI BAO data (Adame et al. 2024), CMB (Planck and ACT lensing) data (Aghanim et al. 2020a,b; Madhavacheril et al. 2024; Qu et al. 2024), and both Pantheon+ SNe data (Scolnic et al. 2022) and DES-Y5 SNe data (Abbott et al. 2024). Broadly speaking, this parameter space can be divided up into a few regions. "Freezing" quintessence corresponds to the region of the parameter space where $w_a > 0$ and refers to models where the dark energy equation of state is evolving asymptotically towards $w_{\rm DE} \simeq -1$, while "thawing" quintessence corresponds to the region where $w_a < 0$ and refers to models where the dark energy equation of state is evolving away from $w_{\rm DE} \simeq -1$ to less negative values. The region given by $w < -1$ is known as the phantom region. It requires more exotic physics to describe and will not be a focus of this study. As we can see, the favored region of parameter space is all located in the thawing region.

The equation of state for dark energy $w_{\rm DE}$ driven by such a field is given by:

$$w_{\rm DE} \equiv \frac{P_\varphi}{\rho_\varphi} = \frac{\dot{\varphi}^2/2 - V(\varphi)}{\dot{\varphi}^2/2 + V(\varphi)}, \tag{2.4}$$

where P_φ is the pressure and ρ_φ is the energy density of the scalar field φ. Here, we can see that $w_{\rm DE}$ will dynamically evolve in time with the evolution of the scalar field.

The evolution of the scalar field is given by the scalar field equation of motion:

$$\ddot{\varphi} + 3H\dot{\varphi} + V'(\varphi) = 0, \tag{2.5}$$

where $V'(\varphi) = dV/d\varphi$ and H gives the expansion rate of the universe through the first Friedmann equation:

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{1}{3M_{pl}^2}(\rho + \rho_\varphi), \tag{2.6}$$

where a is the scale factor of the universe and ρ is the density of matter and radiation. Together, these equations completely determine the dynamics of quintessence. Solving for the dynamics of φ allows one to then determine the evolution of $w_{\rm DE}$ through Eq. (2.4).

The most extensively studied quintessence models fall into two broad categories: *freezing* quintessence or *thawing* quintessence. As the names suggest, freezing quintessence describes dark energy evolution $w_{\rm DE}$ which was different from $w_{\rm DE} \simeq -1$ in the past, but is now evolving asymptotically towards this value as the universe expands (i.e., "freezing in") and broadly speaking falls in the $w_a > 0$ part of the parameter space; thawing quintessence describes dark energy evolution where $w_{\rm DE}$ has been close to $w_{\rm DE} \simeq -1$ in the past, but is now beginning to evolve towards larger values as the universe expands (i.e., "thawing out") and broadly speaking falls in the $w_a < 0$ region of the parameter space. Here, we will be particularly concerned with thawing models as this corresponds to the most viable part of the parameter space.

So far everything has been completely general. One must then specify a form of the potential function $V(\varphi)$, which will enable us to solve the equations of motion, as well as give a particular realization of the relevant microphysics driving dark energy and allow for a direct investigation of any observables associated with the specific model(s). Mirroring a similar situation with inflation (Martin, Ringeval, and Vennin 2014; Sousa et al. 2024), the number of distinct models that are distinguished by their potential function is large. The possible forms of the potential include all imaginable varieties and combinations of power laws, inverse power laws, exponentials, axions, trigonometric functions, and many more. See, e.g., Amendola and Tsujikawa (2015), Martin

(2008), and Tsujikawa (2013) for reviews on quintessence which mention many of these potentials and Martin, Ringeval, and Vennin (2014) for an exhaustive review on inflationary potentials, many of which can be similarly adapted to quintessence. Furthermore, the exact form of the potential holds important information regarding the microphysics responsible for dark energy, the overarching structure and integration of such a field into the standard model of particle physics, and the ultimate fate of the universe's evolutionary trajectory.

However, in this chapter, we will only consider arguably the simplest model of quintessence: dark energy driven by a quadratic $m^2\varphi^2$ potential. The reason for this is that this model can be understood from an effective field theory perspective as the leading order expansion of many other distinct models. In other words, an arbitrary (analytic) single-field model can be represented by an expansion:

$$V = V_0 + \left.\frac{dV}{d\varphi}\right|_{\varphi=0} \varphi + \left.\frac{1}{2}\frac{d^2V}{d\varphi^2}\right|_{\varphi=0} \varphi^2 + \left.\frac{1}{6}\frac{d^3V}{d\varphi^3}\right|_{\varphi=0} \varphi^3 + \cdots . \tag{2.7}$$

However, this can often be cast in a form that resembles the quadratic potential. For example, consider another well-studied model described by an exponential potential $V(\varphi) = V_0 e^{-\lambda\varphi}$ (Barreiro, Copeland, and Nunes 2000; Caldwell, Dave, and Steinhardt 1998; Copeland, Liddle, and Wands 1998; Ferreira and Joyce 1998; Rubano and Scudellaro 2002). Expanding, we have that,

$$V(\varphi) = V_0 \left(1 - \lambda\varphi + \frac{\lambda^2}{2}\varphi^2 ...\right). \tag{2.8}$$

However, a simple field re-definition $\varphi \to \varphi - \varphi_0$ where φ_0 is constant allows us to cast this in a quadratic form resembling the m^2 potential. That is,

$$V(\varphi - \varphi_0) = V_0 \left(1 + \frac{\lambda^2}{2}(\varphi^2) - \varphi(\lambda + \lambda^2\varphi_0) + ...\right), \tag{2.9}$$

where φ_0 can be chosen such that $\varphi_0 = -1/\lambda$ and the linear term vanishes, and any constant terms can be absorbed into the definition of V_0. Thus, we see that an exponential potential can, under certain circumstances, be well-approximated as a quadratic potential of the form $V(\varphi) \simeq V_0 + \frac{1}{2}m^2\varphi^2$, where in this case the "effective mass" is given by $\lambda^2 V_0 = V''$. Similarly, one could consider the potential of pseudo Nambu-Goldstone boson given by $V(\varphi) = V_0[\cos(\varphi/f) + 1]$ (Abrahamse et al. 2008; Dutta and Scherrer 2008; Frieman, Hill, et al. 1995) or the supergravity motivated potential $V(\varphi) = V_0(2 - \cosh\sqrt{2}\varphi)$ (Kallosh and Linde 2003), and find that under this expansion these models are also approximated by a quadratic potential with a negative sign in front of the mass term $V(\varphi) \simeq V_0 - \frac{1}{2}m^2\varphi^2$ (the expansion for these potentials begins near a maximum so the linear term automatically vanishes). Given that this is an effective parameterization in a local region of the potential, we do not need to concern ourselves with the fact that $V(\varphi)$ may be unbounded from below.

Before proceeding to analyzing quintessence as a massive scalar field (with a positive or negative mass term), it may be helpful to explicitly prove that this approximation is highly effective in the regime of interest. To do so, we will consider two examples of well-motivated quintessence models, and examine the evolutions of their equations of state, which as we have seen is the primary driver of their observable predictions as it determines cosmological dynamics through its influence on the Hubble rate.

$$V_{\rm exp}(\varphi) = V_0 e^{-\lambda\varphi} \tag{2.10}$$

$$V_{\rm ax}(\varphi) = m_a^2 f_a^2 \left[1 + \cos\left(\frac{\phi}{f_a}\right)\right] \tag{2.11}$$

The first potential is for the exponential model that we have already seen above, while the second potential corresponds to that of an axion, which is closely related to the pseudo-Nambu Goldstone model. Axions are of significant interest to physicists in the many contexts–including dark matter, inflation, dark energy, beyond standard model particle physics, and string theory–as they possess a shift symmetry that makes them stable to radiative corrections (Arvanitaki et al. 2010; Marsh 2016). This makes them especially intriguing "natural" candidates for all kinds of exotic or unknown physics.

In order to do this, we will numerically solve Eq. (2.5) for a cosmology with a matter density $\Omega_{\rm m} = .31$ and a Hubble rate today $H_0 = 67\ {\rm km\,s^{-1}\,Mpc^{-1}}$ for both of the potentials listed above. We will then compute the Taylor expansion of each model out to quadratic order to determine the "effective" V_0 and m^2 parameters, and solve for the same cosmology with the effective potential, comparing the resulting equations of state $w(a)$. Working briefly in units where $M_{\rm P} = 1$ and the effective V_0 is in units of $M_{\rm P}^2(H_0/h)^2$ and the effective m^2 is in units of $(H_0/h)^2$, we have for the exponential potential that $(V_0, \lambda) = (1.075, 0.8)$ corresponds to an effective $(V_0, m^2) = (0.538, 0.344)$, and for the axion potential that $(m_a^2, f_a) = (14, 0.187)$ corresponds to an effective $(V_0, m^2) = (0.979, -7.0)$. In both cases, the evolution of the equation of state for the exponential/axion potential compared to its quadratic counterpart agree to sub-percent levels of precision throughout the entire evolution even up to today ($a = 1$). This is depicted in Fig. (2.2). Fig. (2.3) depicts the axion potential and its quadratic approximation throughout its entire field excursion. They are essentially indistinguishable.

If the $m^2\varphi^2$ model can cover large swaths of the parameter space in dark energy observables,

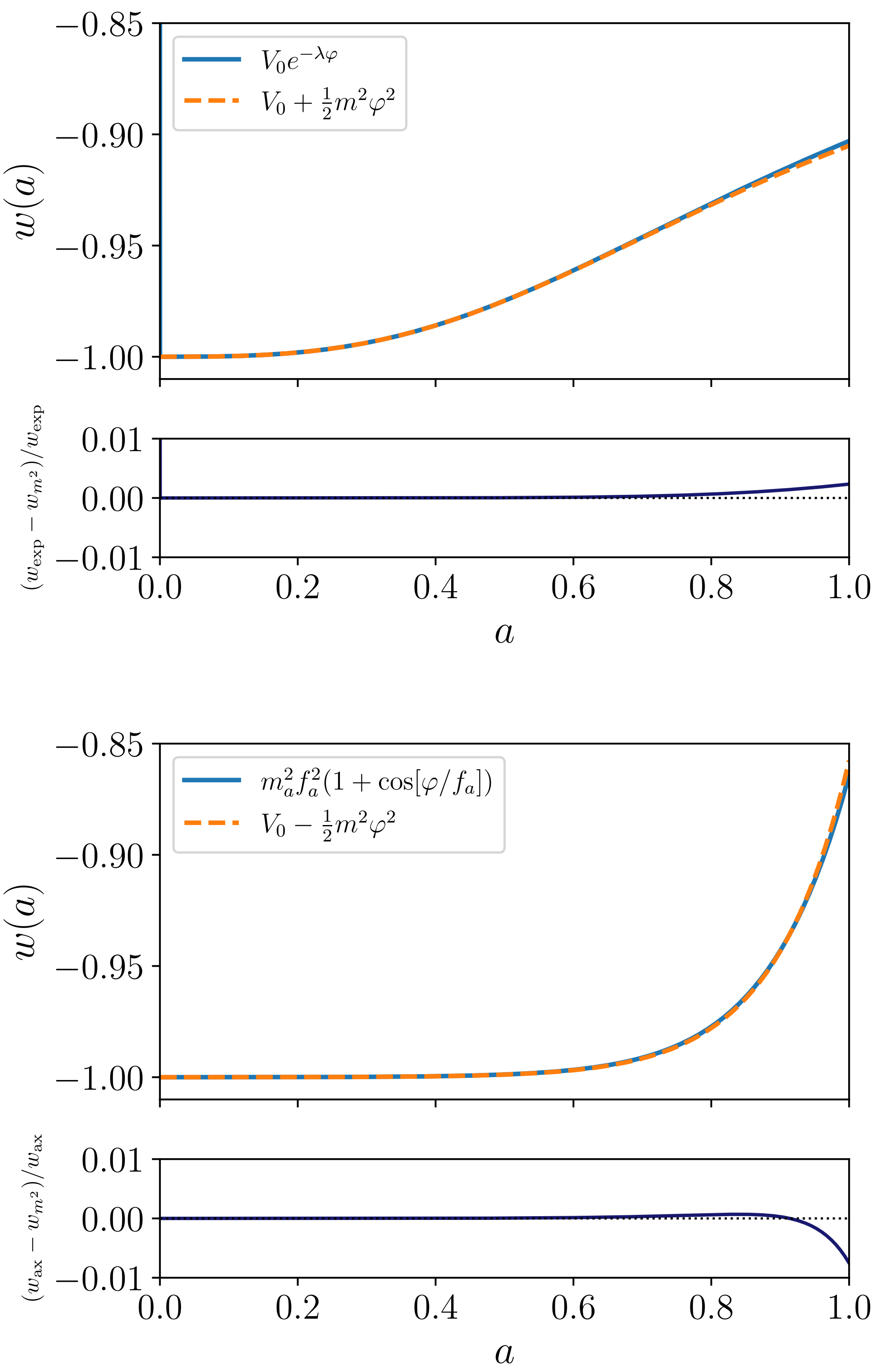


Figure 2.2: Representative models of the exponential and axion potentials compared with the massive quadratic potential for parameters corresponding to their Taylor expansions. In both cases, the evolution of the equation of state for the exponential/axion potential compared to its quadratic counterpart agree to sub-percent levels of precision throughout the entire evolution.

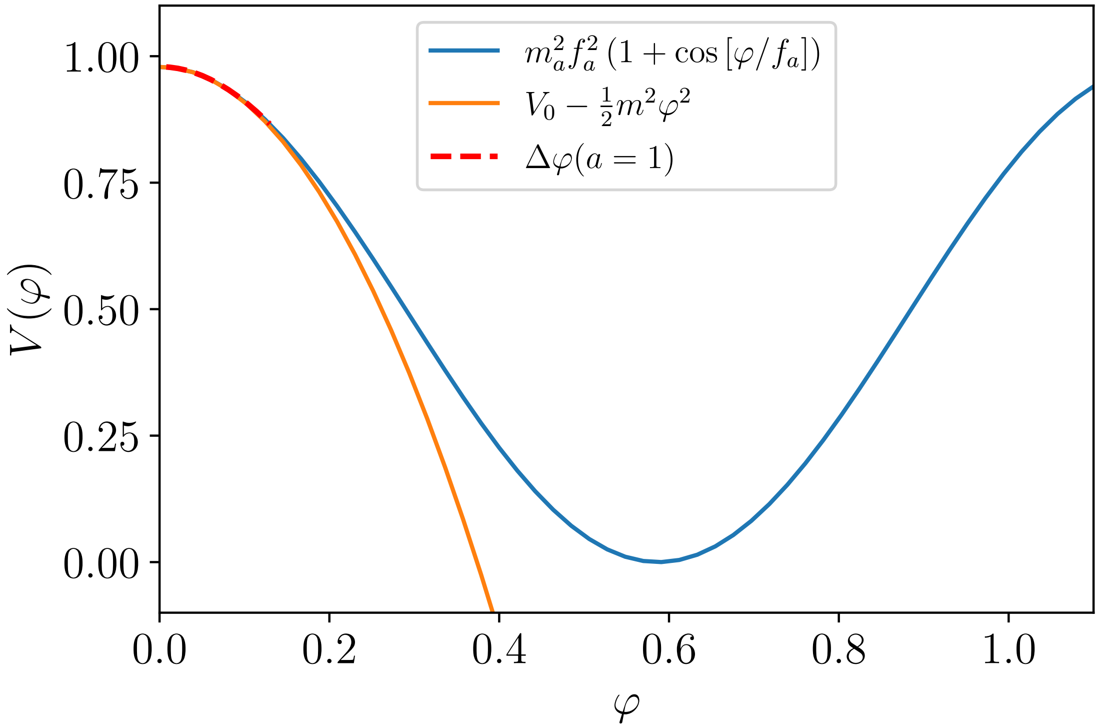


Figure 2.3: Axion potential vs. its quadratic approximation throughout its entire field excursion $\Delta\varphi$.

this also implies a significant underdetermination in the form of the potential and the underlying microphysics driving dark energy. That is, any dark energy trajectories that can be obtained by an $m^2\varphi^2$ model can also trivially be recast as any number of other dark energy models (admitting such an expansion of course) with distinct functional forms of their potentials and different fundamental microphysics. As indicated above, in the following we will consider two variations of the quadratic model: (i) the positive $m^2\varphi^2$ model, which is representative of the standard slow-roll thawing quintessence models and (ii) the negative $m^2\varphi^2$ model, which is representative of so-called "hilltop" quintessence models. Let us now flesh out our understanding of these two branches of the quadratic potential.

2.2.1 $V_0 + \frac{1}{2}m^2\varphi^2$

We begin with the positive quadratic model as this is representative of the most standard kind of thawing quintessence. Standard thawing models are characterized by a set of "slow-roll" conditions (not to be confused with the inflationary slow-roll conditions) (Scherrer and Sen 2008). They are:

$$\left(\frac{1}{V}\frac{dV}{d\varphi}\right)^2 \ll 1, \tag{2.12}$$

$$\frac{1}{V}\frac{d^2V}{d\varphi^2} \ll 1. \tag{2.13}$$

These conditions are important because they ensure that the potential is flat enough to yield $w_{\rm DE} \simeq -1$ at early times, before the field starts slowly rolling, driving $w_{\rm DE}$ to larger values at late time.

As mentioned earlier, our representative of standard, slowly rolling thawing models will be given by the quadratic potential:

$$V(\varphi) = V_0 + \frac{1}{2}m^2\varphi^2. \tag{2.14}$$

Another benefit of this particular model is that, depending on the dominant background energy component, Eqs. (2.5-2.6) can be solved exactly (Liddle and Scherrer 1999; Marsh and Ferreira 2010; Scherrer 2022). Here and throughout the rest of this chapter, we work in dimensionless variables $t \to H_0 t$, $H \to H/H_0, \varphi \to \varphi/m_{pl}, m \to m/H_0$, where H_0 is the Hubble constant today. We also take the ansatz $a(t) \propto t^p$ which is true in both radiation and matter domination, leading to exact analytic expressions for φ:

$$\varphi(t) = a(t)^{-3/2}(mt)^{1/2}\left(AJ_n(mt) + BY_n(mt)\right), \tag{2.15}$$

where J_n and Y_n are Bessel functions of the first and second kinds respectively and $n = (1/2)\sqrt{9p^2 - 6p + 1}$. To simplify, we work in a matter dominated background ($p = 2/3, n = 1/2$). As we will show later though, our results are generalisable to the accelerated expansion era. The general solution for $\varphi(t)$ is of the form:

$$\varphi(t) = \frac{A}{t}\sin(mt) + \frac{B}{t}\cos(mt). \tag{2.16}$$

The particular solution $\varphi(t)$ for the initial value problem with an initial value φ_i, an initial velocity $\dot{\varphi}_i$, at some early initial time t_i (where we have written this using the small parameter $\xi = mt_i \ll 1$) is:

$$\varphi(t) = \frac{\varphi_i}{mt}\left[\sin(mt-\xi) + \xi\cos(mt-\xi)\right] + \frac{\dot{\varphi}_i\xi}{m^2 t}\sin(mt-\xi), \tag{2.17}$$

Expanding in ξ, to leading order we find $\varphi(t)$:

$$\begin{aligned} \varphi(t) &\simeq \frac{\varphi_i}{mt}\sin(mt), \\ \varphi(t) &\simeq \varphi_i\left(1 - \frac{(mt)^2}{6}\right), \end{aligned} \tag{2.18}$$

where in the last line we have expanded again (this time in mt) as we have used that $mt < 1$ so that the scalar field has not entered the oscillatory regime (in this region of the potential will not produce $w_{\rm DE} \sim -1$). Eq. (2.18) will allow us to write down an analytic expression for Eq. (2.4) for this quintessence model.

2.2.2 $V_0 - \frac{1}{2}m^2\varphi^2$

While the slow-roll conditions given in Eqs. (2.12-2.13) are sufficient to generate a typical thawing quintessence model, they are not both strictly necessary. As described first in Dutta and Scherrer (2008), one can relax the condition given in Eq. (2.13) and still maintain the qualitative features of thawing quintessence, but with some notable differences. In this scenario, the scalar field rolls down a local maximum of the potential. Here, the model is such that the field remains close enough to the local maximum that Eq. (2.12) is still valid, but not necessarily Eq. (2.13). This has been dubbed *hilltop* quintessence (Chiba 2009; Dutta and Scherrer 2008) in analogy with similar hilltop models of inflation (see, e.g., Boubekeur and Lyth (2005) and Stein and Kinney (2023)).

We will examine a hilltop quintessence model given by a quadratic potential both because (as before) there are simple analytic expressions for the scalar field dynamics and this model approximates a tremendous variety of distinct dark energy models as their leading order expansion. The potential is given by:

$$V(\varphi) = V_0 - \frac{1}{2}m^2\varphi^2. \tag{2.19}$$

Eqs. (2.5-2.6) can again be solved exactly for matter and radiation dominated backgrounds (Alam, Sahni, and Starobinsky 2003). The only difference is the presence of the minus sign in front of m^2; resulting in similar analytic solutions this time given by

$$\varphi(t) = a(t)^{-3/2}(mt)^{1/2}\left(AI_n(mt) + BK_n(mt)\right), \tag{2.20}$$

where I_n and K_n are modified Bessel functions of the first and second kinds respectively. In the matter dominated era, the general solution for φ is:

$$\varphi(t) = \frac{A}{t}\sinh(mt) + \frac{B}{t}\cosh(mt). \tag{2.21}$$

The particular solution $\varphi(t)$ for the initial value problem with an initial value φ_i, an initial velocity $\dot{\varphi}_i$, at some early initial time t_i (where we have written this using the small parameter $\xi = mt_i \ll$

1) is:

$$\varphi(t) = \frac{\varphi_i}{mt}\left[\sinh(mt-\xi) + \xi\cosh(mt-\xi)\right] + \frac{\dot{\varphi}_i\xi}{m^2 t}\sinh(mt-\xi), \tag{2.22}$$

Expanding in ξ, to leading order we find:

$$\varphi(t) \simeq \frac{\varphi_i}{mt}\sinh(mt) \tag{2.23}$$

Notice that these are hyperbolic functions so we do not need to demand that $mt < 1$ to avoid the oscillatory regime. Similarly, Eqs. (2.23) will allow us to write down an analytic expression for Eq. (2.4) for this hilltop model. Having obtained solutions for the scalar field, we will now proceed to analyzing the evolution of the dark energy equation of state in these respective models.

2.3 Dark energy in the (w_0, w_a) plane

2.3.1 The w_0-w_a parameterization revisited

As mentioned earlier, the favoured parameterization for dark energy is given by:

$$w(a) = w_0 + w_a(1-a).$$

Before we proceed, we need to be clear about how w_0 and w_a are actually determined. In practice, a given choice of w_0 and w_a will determine the time evolution of the dark energy density, ρ_{DE} or, in the case of quintessence, ρ_φ. This density, via the Friedmann equations, will determine the expansion rate of the universe as a function of time. Given a set of observations – typically measurements of standards candles over a redshift range – one can pin down values of the expansion rate at different times, or redshift. One then finds the w_0 and w_a (and their associated uncertainties) that best fit the observations. In other words, in practice, w_0 and w_a arise from fitting the data over a range of redshifts.

We can consider another parametrization of the equations of state,

$$w(a) = \tilde{w}_0 + \tilde{w}_a(1-a),$$

where

$$\begin{aligned}\tilde{w}_0 &\equiv w(a=1),\\ \tilde{w}_a &\equiv -\frac{dw}{da}(a=1).\end{aligned}$$

One can then calculate the values of $(\tilde{w}_0, \tilde{w}_a)$ for different choices of potentials, background expansions and initial conditions. This can give us a useful, often analytic, understanding of their features and how they relate to the underlying theory, and indeed in the literature it is common to think about dark energy models directly in terms of how the equation of state behaves in a similar way to what we have discussed above (see, e.g., Caldwell and Linder (2005) and Linder (2006, 2008)). But it should be clear from the outset that the values obtained in this way, while indicative, will not be the values one obtains through the fitting procedure described above. We will bear this in mind as we proceed in what follows and we will be particularly careful, by using this notation, to distinguish between the two different "types" of (w_0, w_a).

Let us now explore how the dynamics for different dark energy models (as well as their mapping into the $(\tilde{w}_0, \tilde{w}_a)$ parameters) can be straightforwardly understood from the scalar field equation of motion,

$$\ddot{\varphi} + 3H\dot{\varphi} + V_{,\varphi} = 0,$$

where we have an "acceleration" term, a "friction" term, and a "potential" term.

These terms will be important at different epochs depending on the classification of dark energy model. For example, in freezing models at early times the evolution of the potential term is significant as $w_{\rm DE} \neq -1$. Yet, as a freezing model approaches $w_{\rm DE} \simeq -1$, the potential becomes very flat and the dynamics are dominated by the friction term. The situation is different with thawing models as at early times the equation of state is locked in at $w_{\rm DE} \simeq -1$ and the friction term is dominant. As a thawing model evolves away from $w_{\rm DE} \simeq -1$, the potential term becomes more important as it is the field's evolution through its potential that causes dark energy to thaw.

This leads to well-defined bounds that typical (i.e., slow-roll) freezing and thawing models respectively are thought to live in throughout the course of their evolution, where these bounds only span a tiny subset of the broader freezing ($w_a > 0$) or thawing ($w_a < 0$) regions. In particular, the thawing bounds are given by $-1 \lesssim \tilde{w}_a/(1+\tilde{w}_0) \lesssim -3$ and it is commonly accepted in the literature that thawing quintessence models are constrained to live within this range (e.g., Barger, Guarnaccia, and Marfatia (2006), Caldwell and Linder (2005), Clemson and Liddle (2009), and

Linder (2006, 2008)); which clearly represents only a tiny fraction of the broader thawing region depicted in Fig. (2.1). These bounds are largely determined by the background in which the scalar field evolves in. Essentially, one can examine the ratios between the friction and acceleration terms and the potential and acceleration terms, and conclude that a slow-roll thawing model will be one for which this lower bound obtains when in a radiation dominated background and this upper bound obtains when in a matter dominated background (again see Caldwell and Linder (2005) and Linder (2006, 2008) for further discussion). Thus, a thawing quintessence model in a matter-dominated universe will evolve along a narrow line given by $\tilde{w}_a/(1+\tilde{w}_0) \sim -3$.

However, most of the available parameter space in the $(\tilde{w}_0, \tilde{w}_a)$ plane clearly lies outside of this given range. The question is, can we find a way to use the $V_0 \pm m^2\varphi^2$ models to fill in any of the remaining parameter space outside of the typically quoted thawing bounds? The answer, as we shall see below, is yes. This is because hilltop models of the type considered above have notably different evolutionary trajectories than the more standard slow-roll thawing models (Dutta and Scherrer 2008).

2.3.2 Analytic expressions for $w(a)$

2.3.2.1 $V_0 + \frac{1}{2}m^2\varphi^2$

In order to determine the evolution of $w(a)$ for the positive quadratic model, we utilize Eqs. (2.14, 2.18) and replace them in Eq. (2.4) to get,

$$w(t) \simeq -1 + \frac{m^2\varphi_i^2}{9V_0}(mt)^2. \tag{2.24}$$

In order to determine the expression as a function of the scale factor, we recall that during matter domination $t = t_0 a^{3/2}$ with respect to some reference time t_0.

To determine $(\tilde{w}_0, \tilde{w}_a)$ we need,

$$w(a) = -1 + X(mt_0)^2 a^3, \tag{2.25}$$

$$\frac{dw}{da}(a) = 3X(mt_0)^2 a^2, \tag{2.26}$$

where $X = \frac{m^2\varphi_i^2}{9V_0}$. At $a = 1$ and using Eq. (2.2), we find that,

$$\frac{\tilde{w}_a}{1+\tilde{w}_0} = -3. \tag{2.27}$$

As expected, the slow-roll $m^2\varphi^2$ model evolves along this previously quoted line in the $(\tilde{w}_0, \tilde{w}_a)$

plane with a slope of -3.

2.3.2.2 $V_0 - \frac{1}{2}m^2\varphi^2$

Similarly, we use Eqs. (2.19, 2.23, 2.4) to determine $w(a)$ for the hilltop model.

$$w(t) \simeq -1 + \frac{(m\varphi_i)^2}{V_0(mt)^4}\left(\sinh(mt) - mt\cosh(mt)\right)^2 \tag{2.28}$$

Also utilizing $t = t_0 a^{3/2}$ and defining $\epsilon = \frac{(m\varphi_i)^2}{2V_0}$, we now have that[1],

$$w(a) = -1 + \frac{2\epsilon}{a^6(mt_0)^4}\left[\sinh(mt_0a^{3/2}) - mt_0a^{3/2}\cosh(mt_0a^{3/2})\right]^2 \tag{2.29}$$

and that,

$$\begin{aligned}\frac{dw}{da}(a) = &\frac{-6\epsilon}{a^4(mt_0)^4}\sinh\left(mt_0a^{3/2}\right)\left[\sinh\left(mt_0a^{3/2}\right) - mt_0a^{3/2}\cosh\left(mt_0a^{3/2}\right)\right] \\ &+ \frac{-12\epsilon}{a^7(mt_0)^4}\left[\sinh(mt_0a^{3/2}) - mt_0a^{3/2}\cosh(mt_0a^{3/2})\right]^2.\end{aligned} \tag{2.30}$$

At $a = 1$ and using Eq. (2.2), the expression simplifies considerably, giving:

$$\frac{\tilde{w}_a}{\tilde{w}_0 + 1} = 6 + \frac{3\,(mt_0)^2\sinh\left(mt_0\right)}{\sinh\left(mt_0\right) - \left(mt_0\right)\cosh\left(mt_0\right)}. \tag{2.31}$$

The behavior of the hilltop model will be notably different than that of the slow-roll model. For example, the behavior for small m (or equivalently $V'' \ll 1$) approaches $\tilde{w}_a \approx -3(1 + \tilde{w}_0)$. This is not surprising as this is the regime in which the hilltop model approximates the slow-roll conditions in the previous model. However, as one violates these conditions with larger m, the trajectory of $w(a)$ can change substantially.

A consequence of this is that these models can now look significantly different in the $(\tilde{w}_0, \tilde{w}_a)$ plane and one can quite easily tune the slope to be steeper depending on the choice of m. For example, Eq. (2.31) indicates that the slope would span between $-3 \lesssim \tilde{w}_a/(\tilde{w}_0 + 1) \lesssim -15.5$ for $.01 \leq mt_0 \leq 6$. The slope's dependence on the mass parameter is depicted in Fig. (2.4).

This (i) indicates that we can use the quadratic hilltop model to essentially find any value we want in the $(\tilde{w}_0, \tilde{w}_a)$ plane simply by selecting appropriate mass/V'' and V_0 parameters. Furthermore, due to this model's ability to approximate any other model that admits a Taylor expansion

[1] See Chiba (2009) and Dutta and Scherrer (2008) for derivations of related, but more complicated expressions for $w(a)$ in hilltop models. The expressions derived there represent approximate analytic solutions for $w(a)$ assuming that the universe evolves in a dark energy dominated background. In this paper, we will focus on the exact analytic solution in a matter dominated background and the full numerical solution for a mixed dark matter/dark energy universe.

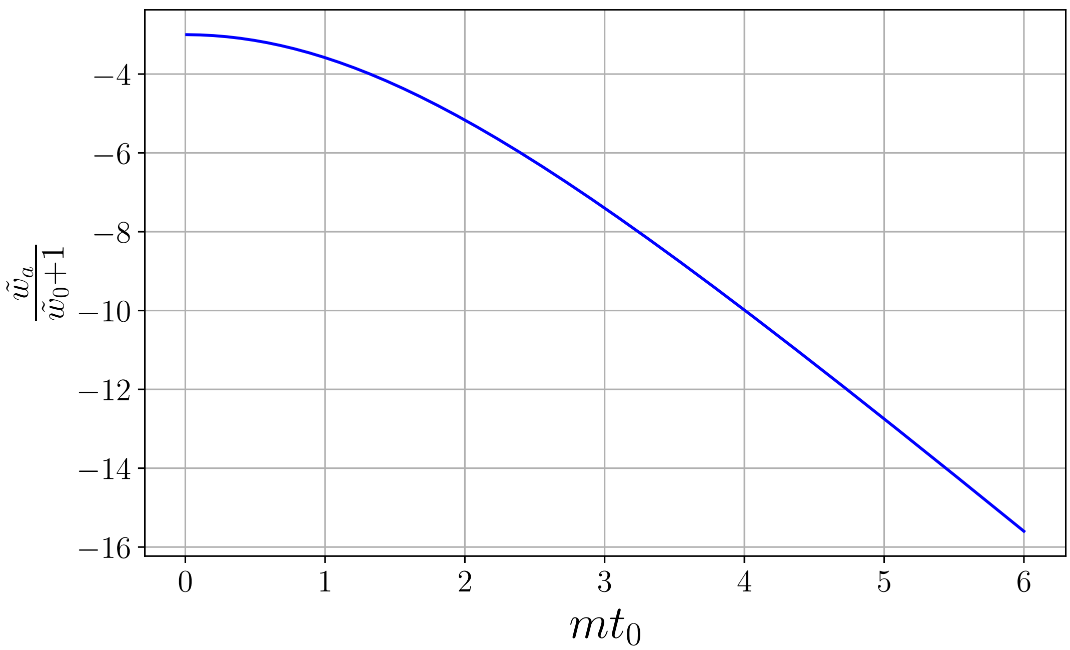
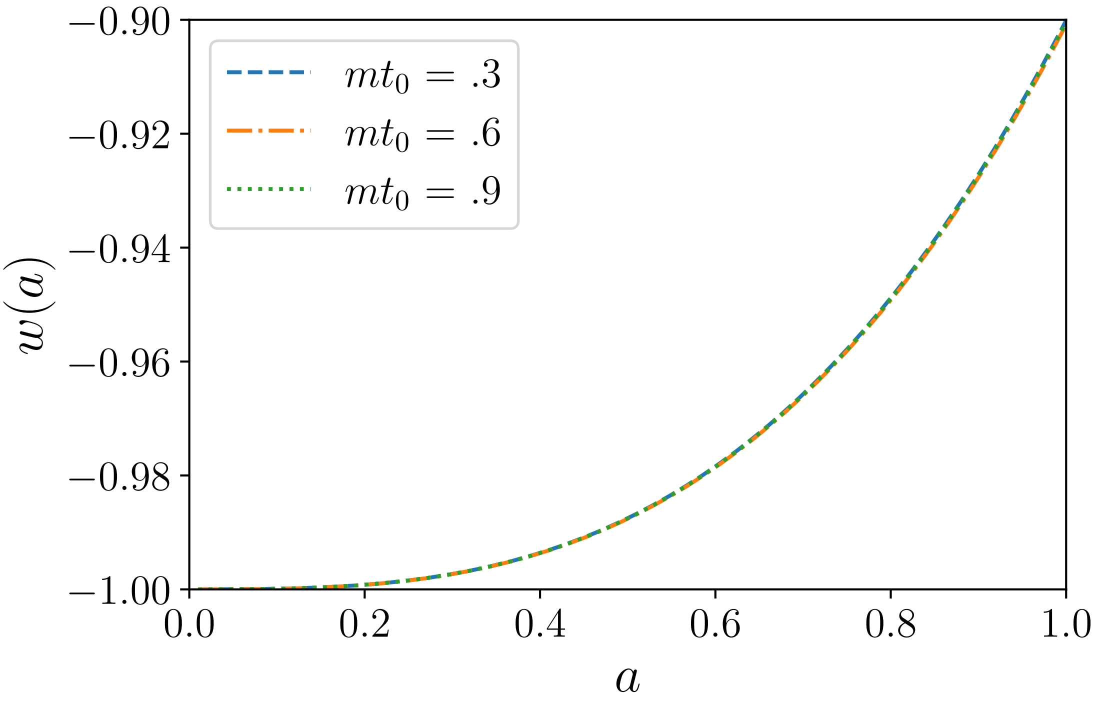


Figure 2.4: The dependence of the slope $\tilde{w}_a/(\tilde{w}_0 + 1)$ in the $(\tilde{w}_0, \tilde{w}_a)$ plane on the scalar field mass parameter in the hilltop branch of the quadratic model.

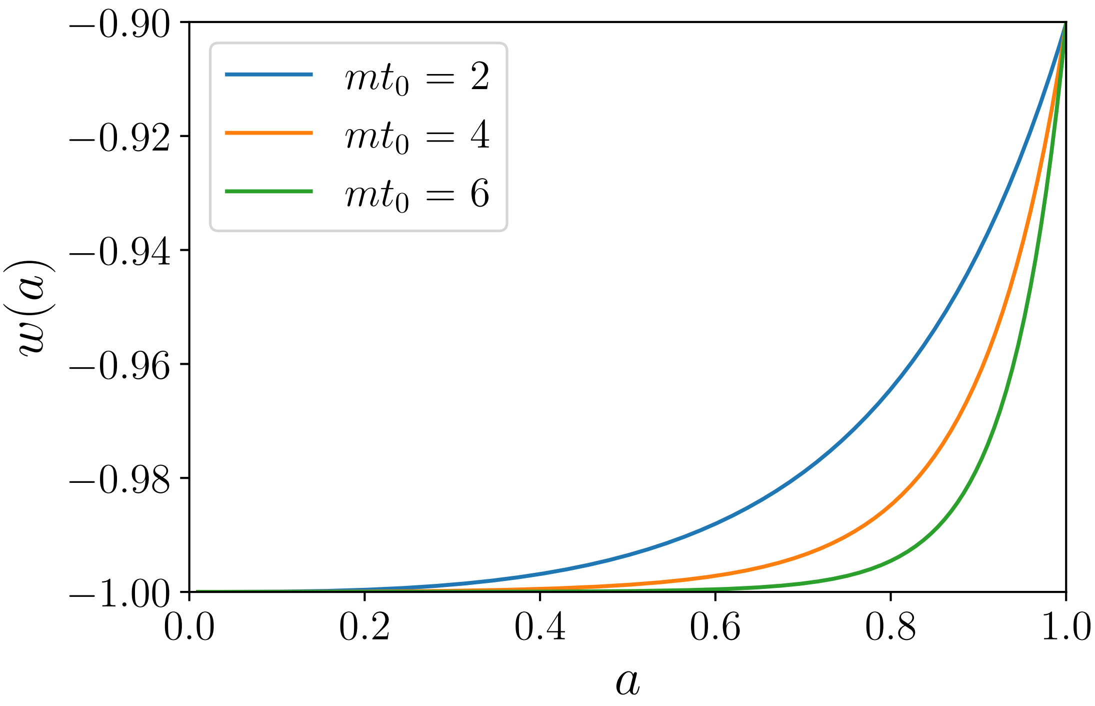
of the type considered in Eq. (2.7), this (ii) similarly indicates that we can map any distinct dark energy model within this family (quadratic, exponentials, axions, etc) to any point in the $(\tilde{w}_0, \tilde{w}_a)$ plane that the quadratic model can reach through any one of these models' "effective" mass and V_0 terms. Taken together, these point to a potentially serious underdetermination in the microphysics of dark energy with respect to our observable parameterization of $w(a)$. It seems like no matter where we end up in the $(\tilde{w}_0, \tilde{w}_a)$ plane within the broader thawing region, there are always a multitude of models that can be easily mapped to any point with a simple choice of parameters.

2.3.3 Covering the $(\tilde{w}_0, \tilde{w}_a)$ plane

Let us now see more concretely how these models map into the $(\tilde{w}_0, \tilde{w}_a)$ plane. To begin with, it is instructive to plot $w(a)$ for different choices of parameters. If we first consider the models with a positive quadratic term (depicted in Fig. (2.5a)), we see that, for a fixed $\tilde{w}_0$, the evolution of the different solutions all converge to a single trajectory and seem to have the same slope as a decreases. This is qualitatively different for what happens for models with a negative quadratic term; in Fig. (2.5b), we plot a few models with the same $\tilde{w}_0$ but with a range of different slopes, as a decreases (see also Dutta and Scherrer (2008) for further excellent discussion on the $w(a)$ evolutionary trajectories of hilltop models). This is a strong indication of what one should expect when mapping each of these theories onto the $(\tilde{w}_0, \tilde{w}_a)$ plane. The positive quadratic model will be



(a) Slow-roll thawing quintessence trajectories.



(b) Hilltop thawing quintessence trajectories.

Figure 2.5: $w(a)$ evolution for different choices of model parameters for the slow-roll/positive quadratic model and the hilltop/negative quadratic model. The parameter mt_0 was varied and X was chosen so that $\tilde{w}_0 \simeq .90$. For the slow-roll models, all converge on the same evolutionary track and will have the same slope in the $(\tilde{w}_0, \tilde{w}_a)$ plane. All the hilltop models have very different evolutions and the trajectories become steeper as mt_0 is increased. Consequently, they will be represented differently in the $(\tilde{w}_0, \tilde{w}_a)$ plane.

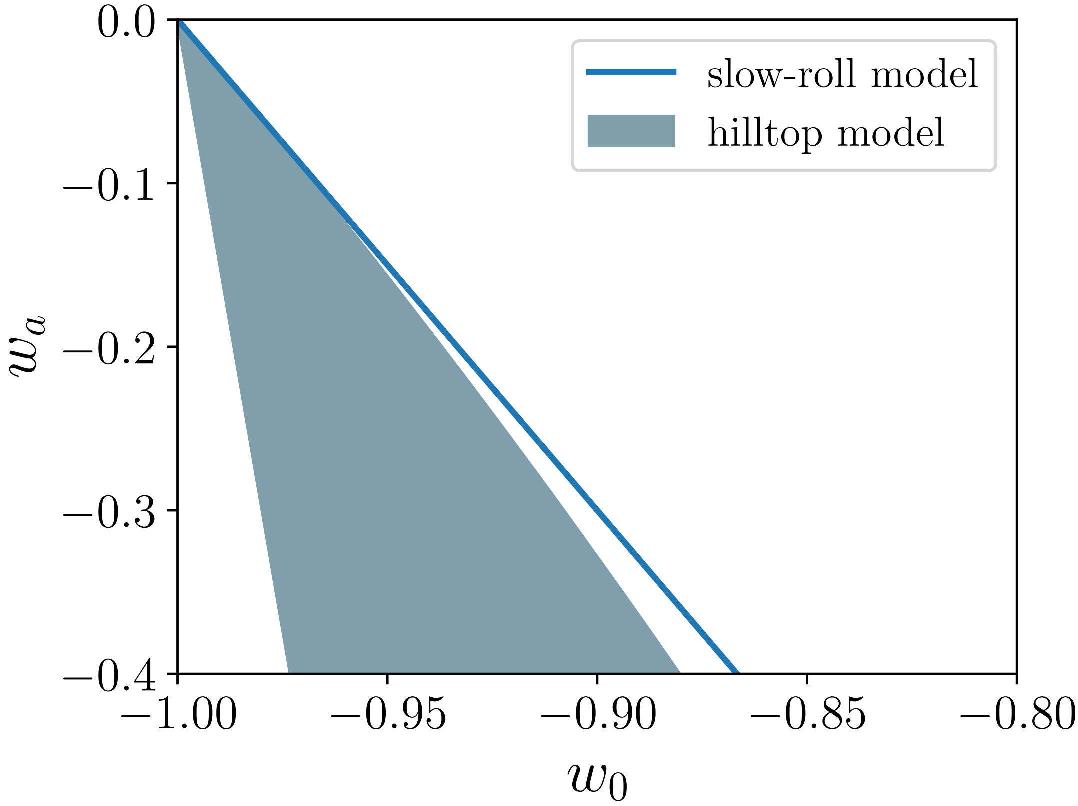


Figure 2.6: $\tilde{w}_0 \equiv w(a=1)$ and $\tilde{w}_a \equiv -dw/da(a=1)$ assuming matter domination for both the slow-roll/positive quadratic model and the hilltop/negative quadratic model. The slow-roll model was randomly sampled for parameters $mt_0 \in [.01, 1]$ and $X \in [.1, 2]$ and the hilltop model was randomly sampled for parameters $mt_0 \in [.01, 6]$ and $\epsilon \in [.0002, 2]$. The hilltop model can arbitrarily sweep across huge swaths of the broader thawing ($\tilde{w}_a < 0$) region when compared to more standard slow-roll models that only live along a narrow strip of this region given by $\tilde{w}_a \sim -3(\tilde{w}_0 + 1)$.

locked in a narrow line along this plane as its parameters are varied, while the negative quadratic model will sweep out across the plane as its parameters are varied because these variations will create substantially different $w(a)$ trajectories.

In order to explore the $(\tilde{w}_0, \tilde{w}_a)$ plane, we first use the analytic expressions we have derived, and sample over a range of different parameter values to fill in the $(\tilde{w}_0, \tilde{w}_a)$ plane. As expected, the slow-roll model lies on the line with a slope -3, depicted in Fig. (2.6). This model (and any others that it approximates) are locked in this narrow region of the $\tilde{w}_0, \tilde{w}_a$ parameter space.

The hilltop version of the quadratic model, on the other hand, picks up where the slow-roll model leaves off and sweeps over the steeper ranges of the $(\tilde{w}_0, \tilde{w}_a)$ plane as Fig. (2.6) shows. This model (and similarly any of the other many models that it approximates) can occupy large swathes of parameter space and in principle can sweep up to the "phantom" line ($\tilde{w}_0 < -1$), at which point more exotic physics would clearly be required.

Our analytic results for a matter dominated universe are already a clear indication that we can obtain almost any value of $(\tilde{w}_0, \tilde{w}_a)$ with this simple model. Given that, under general conditions for many models of thawing quintessence, one can express the Taylor expansions of their potentials as the potential described by this simple model, this is confirmation that these models are underdetermined. In other words, many models will lead to the same observational results.

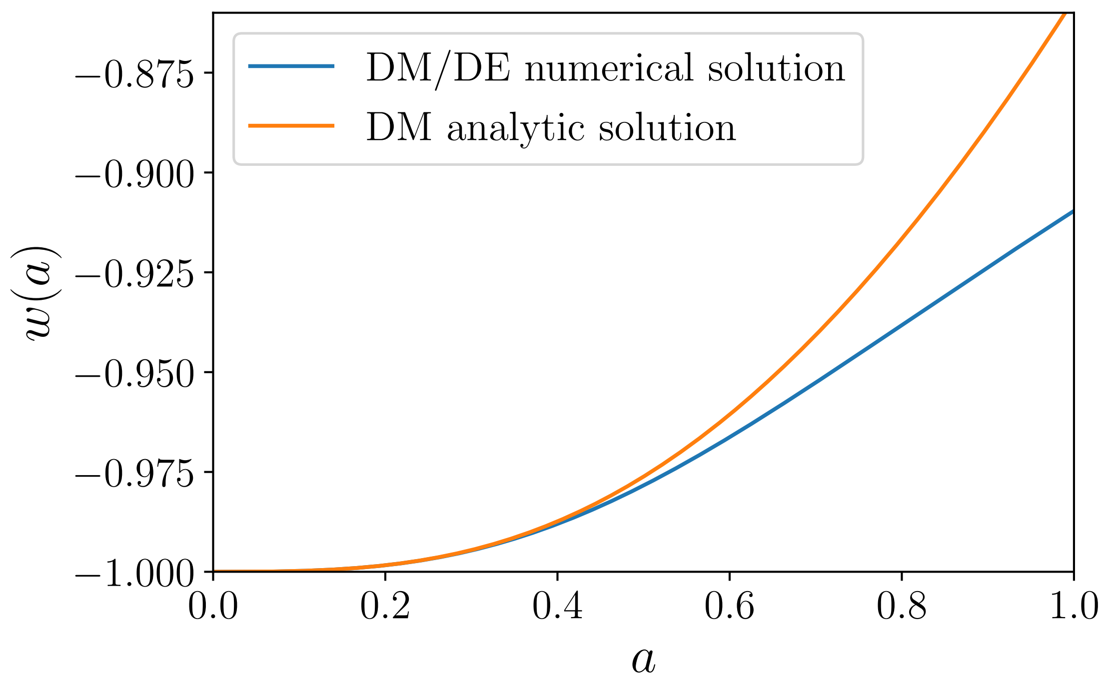
Until now we have based our reasoning on analytic expressions for the Taylor expansion of $w(a)$ in the matter era; they tell us exactly what drives the changes in slope in terms of the parameters of the microphysics theory. But, of course, the universe is no longer matter dominated so it will be important to make sure that these conclusions hold up under a more realistic scenario. To check that is the case, we numerically integrate Eq. (2.5) for a mixed dark matter/dark energy universe. Instead of assuming a pre-determined evolution for a, we solve the Friedman equation in the presence of the scalar field so that

$$H^2(a) = \frac{1}{3}\left(\rho_{\mathrm{m}0}a^{-3} + \frac{1}{2}\dot{\varphi}^2 + V(\varphi)\right). \tag{2.32}$$

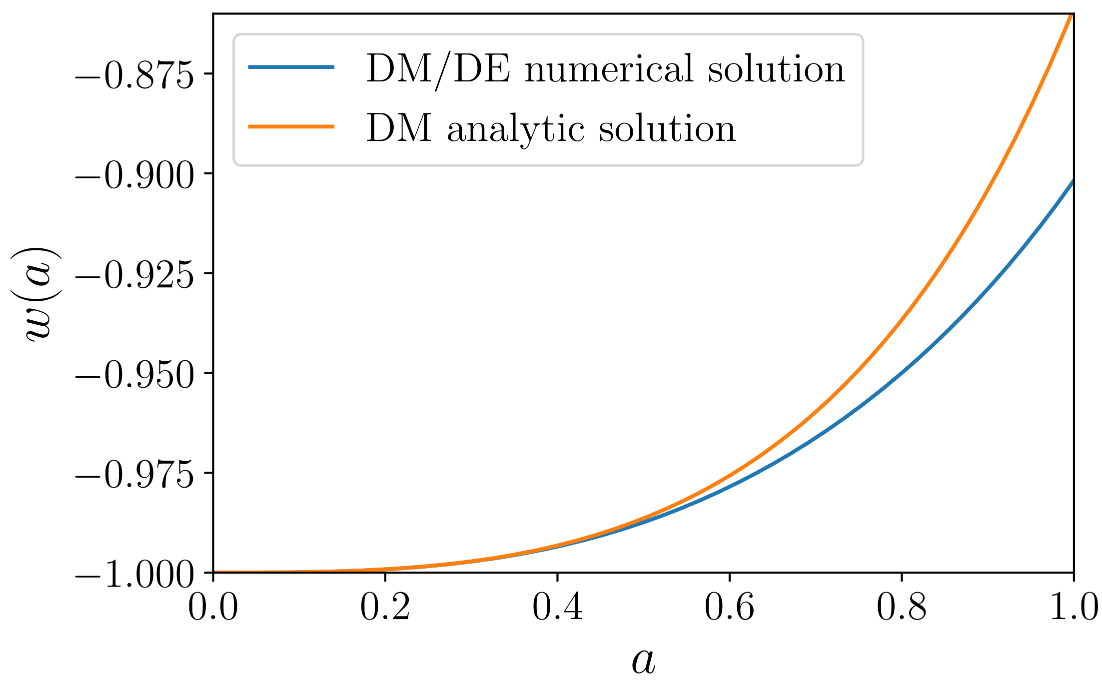
We choose initial conditions (at some suitably early time) such that $\dot{\varphi} \simeq 0$, and a value of φ_i that leads to $\Omega_{\mathrm{DE}} \simeq .7$ and $H = 1$ at the end of the integration (at $a = 1$). We then generate $w(a)$ numerically for a wide variety of parameters and find $(\tilde{w}_0, \tilde{w}_a)$ for both models.

The numerical integration for the positive quadratic, slow-roll model yields a similar result: this model lives on a very thin strip of parameter space. However, the line it traces out is $\tilde{w}_a/(\tilde{w}_0 + 1) \sim -1.5$ (again at $a = 1$), rather than $\tilde{w}_a/(\tilde{w}_0 + 1) \sim -3$ as in the matter dominated case. This is because in a universe with a substantial dark energy component, the Hubble friction term will be enhanced; meaning that the evolution of $w(a)$ will be suppressed when compared to the matter dominated case for the same choice of parameters (see Fig. (2.7a)). Notice also, that this numerical integration shows that for a mixed dark matter/dark energy universe, the evolution of $w(a)$ for the positive quadratic model is far more linear than the matter dominated universe. Thus, the resulting line behavior in the $(\tilde{w}_0, \tilde{w}_a)$ plane will be less than the matter dominated value. This $\tilde{w}_a/(\tilde{w}_0+1) \sim -1.5$ result for thawing quintessence in a mixed dark matter/dark energy universe is consistent with what was found in García-García, Bellini, et al. (2020), Linder (2015), Scherrer (2015), and Scherrer and Sen (2008) for similar kinds of models that can be said to represent more typical realizations of thawing quintessence.

The numerical integration for the negative quadratic, hilltop model in a mixed dark matter/dark energy universe also yields a similar result when compared with the analytic solution for



(a) Slow-roll thawing quintessence trajectories.



(b) Hilltop thawing quintessence trajectories.

Figure 2.7: $w(a)$ numerical integration for both the slow-roll/positive quadratic model and the hilltop/negative quadratic model in a mixed dark matter/dark energy universe compared to their respective matter dominated analytic solution for the same choice of parameters. In both cases, we see that the numerical solution does not evolve quite as much. This is because the Hubble friction term is enhanced when dark energy becomes a significant part of the scalar field equation of motion when compared with the matter dominated solution.

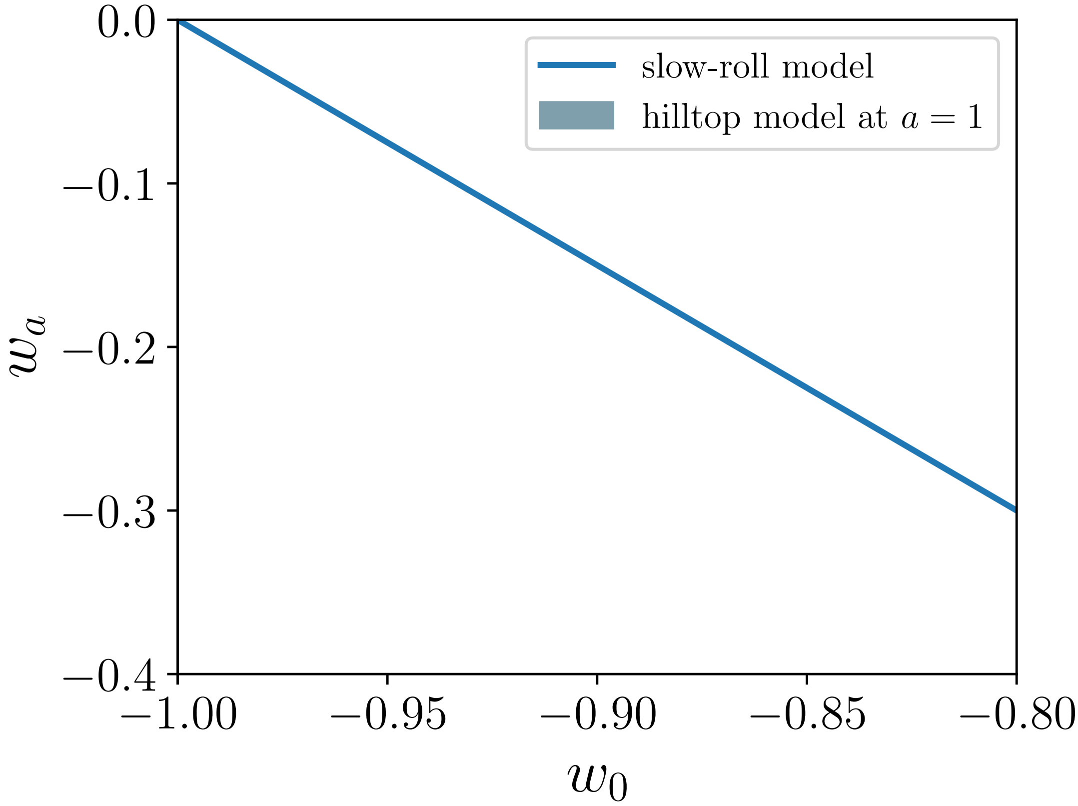


Figure 2.8: This is the result for $\tilde{w}_0 \equiv w(a = 1)$ and $\tilde{w}_a \equiv -dw/da(a = 1)$ determined after numerically integrating Eq. (2.32) for a universe with $\Omega_{\rm DE} \simeq .7$ for both the slow-roll/positive quadratic model and the hilltop/negative quadratic model. Both models are qualitatively similar in their behavior, with the slow-roll model now living on $\tilde{w}_a \sim -1.5(\tilde{w}_0 + 1)$ while the hilltop model takes values roughly between $-1.5(\tilde{w}_0 + 1) \lesssim \tilde{w}_a \lesssim -10(\tilde{w}_0 + 1)$ and sweeps across the parameter space.

a matter dominated universe: this model sweeps out a wide swath of the $(\tilde{w}_0, \tilde{w}_a)$ plane. As with the positive quadratic model, the friction term is enhanced meaning that the evolution of $w(a)$ is suppressed when compared with the matter dominated case for the same choice of parameters (see Fig. (2.7b)). Here, the evolution of $w(a)$ for the negative quadratic model is still non-linear, but the evolution is not quite as steep. Thus, we expect the resulting area that the model sweeps in the $(\tilde{w}_0, \tilde{w}_a)$ to be somewhat smaller to the matter dominated case. Here, we find, for this numerical evolution and $mt_0 \in [.01, 6]$, $-1.5 \lesssim \tilde{w}_a/(\tilde{w}_0 + 1) \lesssim -10$ (Fig. (2.8)).

Thus we have shown, both analytically and with numerical solutions, that we can generate an incredibly broad family of possible behaviours for the equation of state, $w(a)$. Specifically, we have shown that we can get nearly any arbitrary value of $\tilde{w}_0$ and $\tilde{w}_a$ with a quadratic model for the dark energy potential, both analytically in a matter dominated universe and numerically in a mixed dark matter/dark energy universe thought to be a good description of our current universe. This means that our conclusions implying a significant underdetermination of the microphysics underlying dark energy with respect to the observables $\tilde{w}_0$ and $\tilde{w}_a$ also hold in a realistic description of the universe, as these numerical solutions for the quadratic model will similarly map many distinct dark energy models onto the exact same regions of the $(\tilde{w}_0, \tilde{w}_a)$ plane just as well as the analytic solutions in a matter dominated universe. Furthermore, it is also worth emphasizing that these results can be understood as being broadly consistent with some other studies in the literature that have considered the $(\tilde{w}_0, \tilde{w}_a)$ parameterization from different perspectives than the one we have adopted here. For example, Scherrer (2015) takes the CPL parameterization as a starting point in order to determine which scalar field models can reasonably correspond to it and finds that a number of potentials $V(\varphi)$ are consistent with $\tilde{w}_a \sim -1.5(\tilde{w}_0 + 1)$ because many potentials will exhibit sufficiently linear behavior when φ only rolls over a small enough region of the potential. Another interesting study (Huterer and Peiris 2007) adapts the flow equation formalism from inflation to a very generic description of quintessence and also concludes that quintessence models can be found in many regions in the $(\tilde{w}_0, \tilde{w}_a)$ plane outside the typical freezing and thawing bounds; where they calculate $(\tilde{w}_0, \tilde{w}_a)$ from the best-measured principal components (PCs) (see Huterer and Starkman (2003)) of the $w(a)$ trajectory.

2.4 Fitting w_0 and w_a

We do not directly measure $\tilde{w}_0$ and $\tilde{w}_a$. In practice, as discussed above, we *fit* w_0 and w_a over a range of redshifts. The parameter space depicted in Fig. (2.1) is determined in this way. Typically one has a range of distance measurements – such as the angular diameter distance or luminosity distance of structures or objects – which are integrals of the expansion rate and which, in turn, are a function of the energy density of dark energy. One then infers the properties of the dark energy component from how well a given model fits the distance measurements.

There are a number of Stage IV surveys that have been proposed to further our understanding of dark energy (Abate et al. 2012; Bacon et al. 2020; Laureijs et al. 2011). To simplify, we emulate a typical stage IV survey and assume that the results are measurements of the Hubble parameter as a function of redshift. Our conclusions would be no-different if we had used distance measurements themselves. As an example, we take the redshift range and forecast uncertainties in Font-Ribera et al. (2014).

The model we need to fit is the the Friedman equation in the form

$$H^2(a) = H_0^2 \left[\Omega_{\rm m} a^{-3} + (1 - \Omega_{\rm m})\, e^{3w_a(a-1)} a^{-3(1+w_0+w_a)} \right]. \tag{2.33}$$

And we approximate the negative logarithm of the likelihood as

$$-2\ln\mathcal{L} \simeq \sum_i \frac{(H_{obs}(z_i) - H(z_i))^2}{\sigma_i^2}, \tag{2.34}$$

where $H_{obs}(z)$ is the observed H, $H(z)$ is the computed H from Eq. (2.33) as a function of the w_0 and w_a parameters, and σ_i refers to the uncertainty at the redshift bin i.

Assume now that the observed $H(a)$ corresponds to a particular model of thawing quintessence for which we have full numerical solutions. Let us then generate numerical evolutions for $w(a)$ (and the resulting $H(a)$) and determine the best w_0, w_a fit using Eqs. (2.2, 2.33, 2.34) for redshifts $z \in [.15, 1.85]$ (corresponding to the redshift bins from Font-Ribera et al. (2014)). We begin with the positive quadratic model first and then proceed to the negative quadratic model.

For the positive quadratic model, this fitting procedure produces results that are very similar to what we found earlier: the w_0, w_a values for the quadratic model lie on a very narrow strip of the (w_0, w_a) plane right around $w_a/(w_0+1) \sim -1.5$ (again consistent with other studies such as García-García, Bellini, et al. (2020), Linder (2015), Scherrer (2015), and Scherrer and Sen (2008)). Upon reflection, this should not be terribly surprising. After all, as we have seen in Fig. (2.7a), the numerical solution $w(a)$ for the positive quadratic model in a mixed dark matter/dark energy dominated universe like our own is highly linear. Thus, its mapping into the (w_0, w_a) plane will not change substantially between only taking these values at $a = 1$ or fitting them over a quite significant range of redshifts.

The negative quadratic model, on the other hand, maps quite differently into the (w_0, w_a) plane when this fitting procedure is employed. Qualitatively, we still see that various parameter choices for this model will produce a 'cloud' in the parameter space (rather than a narrow line as with the positive quadratic model). However, this cloud is significantly more narrow than we saw in the $a = 1$ case as it very roughly lies between $-1.5 \lesssim w_a/(w_0+1) \lesssim -2.5$. Fig. (2.9) depicts the (w_0, w_a) plane for the same numerical evolution as Fig. (2.8), except that w_0 and w_a have been determined by fitting $H(z)$ over $z \in [.15, 1.85]$ rather than by determining the values $\tilde{w}_0$ and $\tilde{w}_a$ from $w(a)$ at $a = 1$; whereas we saw this choice of parameters previously swept across $-1.5 \lesssim \tilde{w}_a/(\tilde{w}_0+1) \lesssim -10$. Fig. (2.10) depicts how the $\tilde{w}_0$, $\tilde{w}_a$ values map onto the fitted parameters w_0 and w_a; and there we can clearly see how this fitting procedure 'squeezes' the (w_0, w_a) phase space that these hilltop models live in.

While this does not change the broader conclusion – that there is a significant amount of

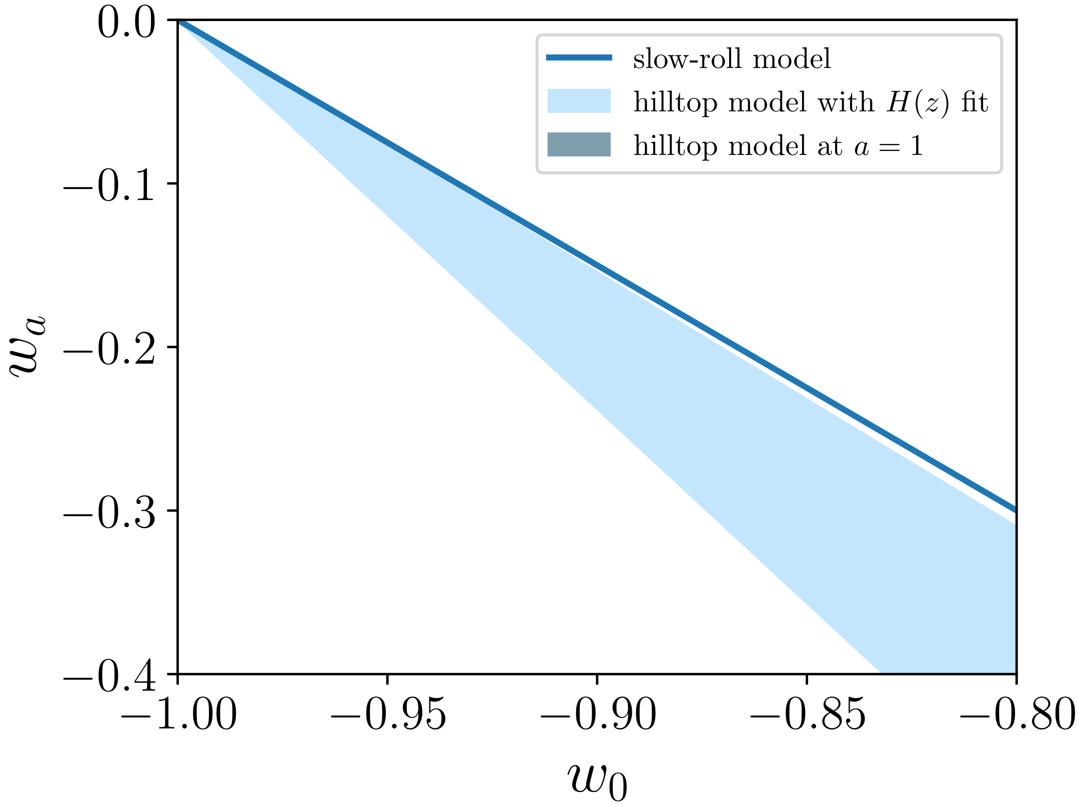


Figure 2.9: The light blue shaded region depicts the result for w_0 and w_a determined by numerically integrating $w(a)$ for the hilltop model in a universe with $\Omega_{\rm DE} \simeq .7$ and finding the best fit for Eqs. (2.33-2.34) over $z \in [.15, 1.85]$. This is overplotted against the $\tilde{w}_0 \equiv w(a = 1)$, $\tilde{w}_a \equiv -dw/da(a = 1)$ result (dark gray shaded region) for the same hilltop model and choice of parameters depicted in Fig. (2.8). This indicates that there is an ambiguity in how these hilltop models are represented in the (w_0, w_a) plane as the exact size of the swept region (for the same choice of parameters) will sensitively depend on the range of redshifts that one fits over due to the highly non-linear evolution of $w(a)$ in these hilltop models. Fitting over a more restricted range of more recent redshifts would cause the fitted results to more closely resemble the $a = 1$ results. By contrast, the slow-roll models (dark blue line) still lie in the same narrow strip as their location is insensitive to the choice of fitting procedure as their evolution is highly linear.

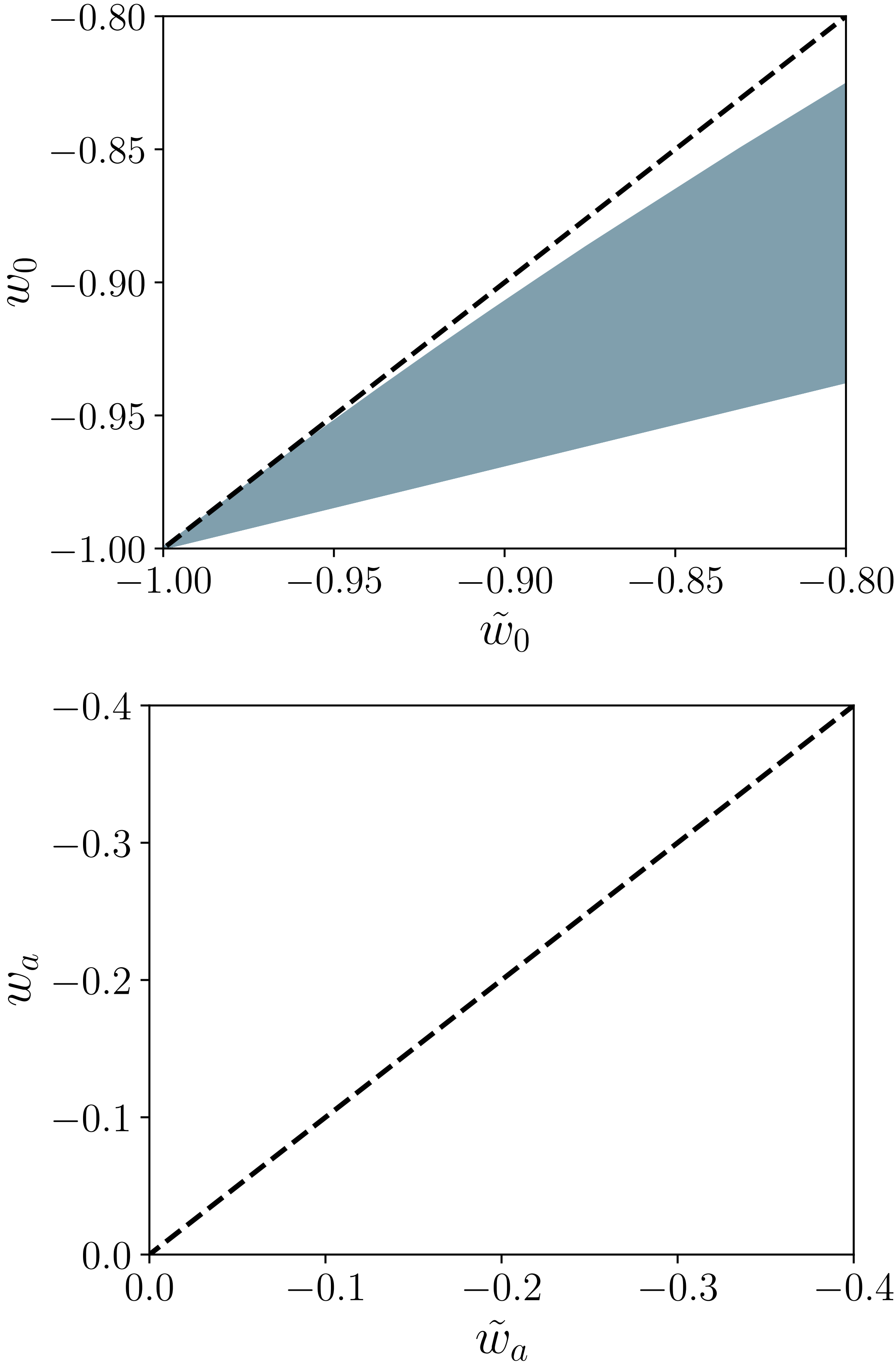


Figure 2.10: Comparison between the w_a and w_0 values depicted in the (w_0, w_a) plane of Fig. (2.9). This shows how the values determined by fitting $H(z)$ through Eqs. (2.33-2.34) and those determined by $\tilde{w}_0$ and $\tilde{w}_a$ map onto each other. In other words, this fitting procedure squeezes the representation of the hilltop model in the (w_0, w_a) plane. The exact degree to which the swept region is squeezed depends on the range of redshifts included in the fit.

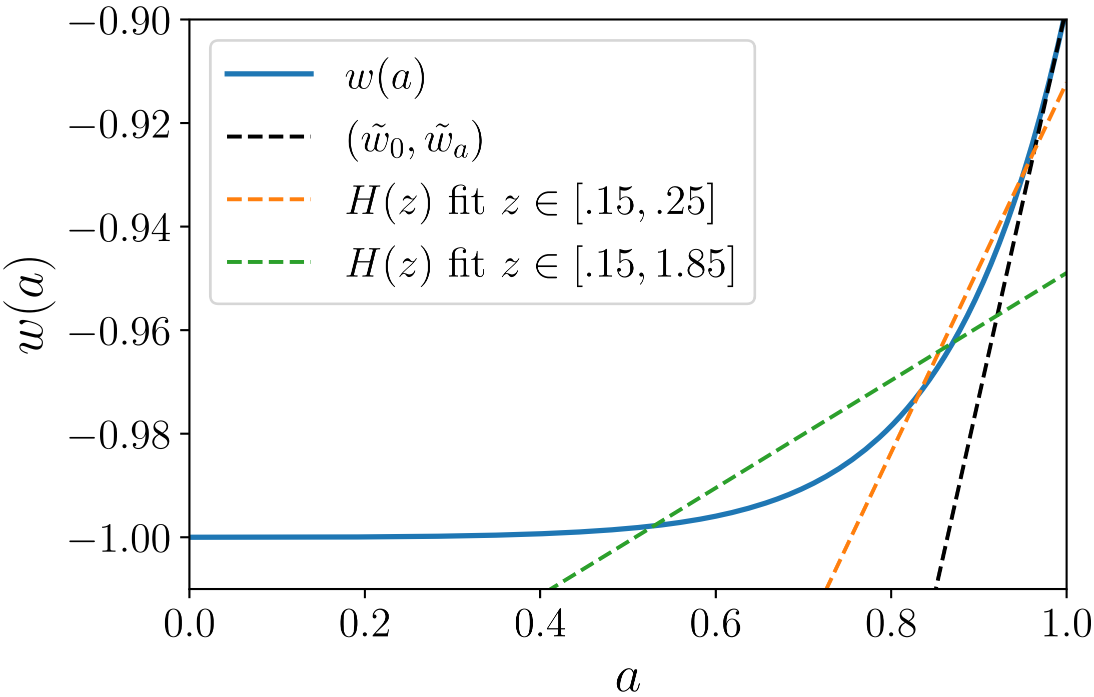


Figure 2.11: Evolution of $w(a)$ compared with two different fits for the $w(a) = w_0 + w_a(1-a)$ parameterization (solid blue line). The dashed green line was determined by fitting $H(z)$ through Eqs. (2.33-2.34) for $z \in [.15, 1.85]$. The dashed yellow line was determined by fitting from $z \in [0.15, 0.25]$. The dashed black line was determined at $a = 1$. We can see that fitting over the more recent range of redshifts better captures the $w(a)$ evolution for the steeper hilltop models considered here. Consequently, we can understand why the swept area of Fig. (2.9) is squeezed when fit over a large range of redshifts: the fit for w_0 and w_a in that case does not fully capture the steeper part of the $w(a)$ trajectory that occurs at the more recent redshifts and consequently maps these models into a less steep part of the (w_0, w_a) plane. The smaller and more recent the range of redshifts included in the fit, the closer that the fitted (w_0, w_a) values will be to the $(\tilde{w}_0, \tilde{w}_a)$ values determined at $a = 1$.

parameter space for which the microphysics of dark energy is severely underdetermined because many distinct microphysical models can sweep significant parts of this parameter space – this does reveal that exactly how a model of dark energy maps into the (w_0, w_a) plane can potentially be sensitively dependent on somewhat arbitrary choices for fitting procedure. This surprising sensitivity can be traced to the fact that the $w(a)$ evolution in the hilltop model has significant non-linearities. Consequently, as a linear parameterization, w_0 and w_a may not necessarily provide a good description of a dark energy model that does not feature a fairly linear evolutionary trajectory $w(a)$ (see also Dutta and Scherrer (2008) and Scherrer (2015)). This immediately allows us to understand that the w_0, w_a parameterization will not provide a good description over that range of redshifts for the hilltop model, because the vast majority of $w(a)$'s evolution is weighted at very recent redshifts (e.g., recall Figs. (2.7b, 2.5b)).

Clearly the redshift range of the data plays a significant role in the range of w_0, w_a one obtains from thawing quintessence. Paradoxically, but not surprisingly, Fig. (2.11) shows that, if one narrows the range of redshifts (in this case from $z \in [.15, 1.85]$ to $z \in [0.15, 0.25]$) we can see that we get a closer approximation with the $\tilde{w}_0, \tilde{w}_a$ parameterization to the full $w(a)$ evolution. Consequently, one can repeat the procedure we have done in this section, but fit over a smaller range of redshifts. One then finds that doing so will result in a wider sweeping of the (w_0, w_a) plane that much more closely resembles $(\tilde{w}_0, \tilde{w}_a)$ the more one restricts the range of redshifts to those where the most significant $w(a)$ evolution occurs as the fit now "sees" the steeper part of the trajectory. The reason one might want to do this is that, as Fig. (2.11) clearly shows, this is a far better parameterization of the actual $w(a)$ trajectory. However, in practice, the attendant costs of doing so would require utilizing less survey data and significantly increasing the uncertainties of the observations. With all these considerations though, it is clear that there is some ambiguity in how hilltop models of the type considered here will map into the (w_0, w_a) plane as different fitting procedures will result in the models sweeping different areas of the plane. Consequently, we should seek alternative parameterizations for the microphysics of dark energy that are not so dependent on such a choice of fitting procedure.

2.5 Conclusion

One of the goals of modern cosmology is to determine the microphysical model that underpins the accelerated expansion of the universe. The most popular proposal is that it is driven by some form of dark energy which can be characterized by an equation of state. The guiding principle has been that, with current and future cosmological observations, we will be able make accurate measurements of the equation of state and, as a result, pin down the right microphysical model of dark energy. In this chapter, we have focused on a very broad class of models of dark energy – thawing quintessence – and showed that future observations will inevitably underdetermine the microphsyics of dark energy.

By focusing on a widely used parametrization of the cosmological dark energy – w_0 and w_a – we have shown that we can get almost any value of these parameters with a simple quadratic model for the potential. Thus, contrary to what has often been claimed in the literature, simple realizations of thawing quintessence are *not* confined to a small region of the (w_0, w_a) phase space. Furthermore, this does not require any highly exotic physics, unusual fine-tuning, or inordinately complicated dynamics. Essentially, one just needs a simple single field model of canonical quintessence with a quadratic potential, and in particular the hilltop flavour of this model which was first investigated in detail by Dutta and Scherrer (2008). As we have seen, this model can find nearly any spot in the thawing region of the (w_0, w_a) plane with a judicious choice of basic model parameters. We showed this using exact solutions for φ in the matter dominated universe as well as numerically integrating the scalar field equations of motion for a mixed dark matter/dark energy universe.

This indicates that there is a significant underdetermination with respect to this model and any other model that can be placed anywhere within the (w_0, w_a) plane that this quadratic model can sweep. As we demonstrated earlier, we already know of several distinct microphysical models of dark energy that can be mapped into this exact same region of the parameter space because the quadratic model approximates all of the many models that admit of a Taylor expansion of the form Eq. (2.7) where the potential is expanded to quadratic order. Thus, these models will be indistinguishable from the quadratic model considered here from the point of view of observables in the (w_0, w_a) plane.

Given that we can fill out the parameter space with the quadratic model and map between that model's predictions for the parameter space and many other models, this deflates some of the motivation for investigating models with different potentials. There could certainly be interesting or even compelling theoretical reasons or non-empirical motivations for pursuing specific models (coherence, explanatory power, aesthetics, problem-solving capabilities etc; see, e.g., Dawid (2013), Duerr and Wolf (2023), Kuhn (1977), Laudan (1977), Nyrup (2015), Schindler (2018b), Wolf (2024a), Wolf and Duerr (2023), and Wolf and Thébault (2023)). For example, there are specific potentials that are pursued for their ability to resolve outstanding fine-tuning problems (Zlatev, Wang, and Steinhardt 1999) or that possess particularly attractive theoretical qualities such as having radiative stability due to their symmetries (Frieman, Hill, et al. 1995). However, it is unlikely that strictly empirical methods will single out a unique potential.

Our work does not rule out the possibility of structure formation (Alonso et al. 2017; Ferreira 2019; Ruiz and Huterer 2015; Sharma and Sur 2022; Wen, Nguyen, and Huterer 2023), gravitational waves (Baker et al. 2017; Barausse et al. 2020; Belgacem et al. 2019; Dalang, Fleury, and Lombriser 2020; Ezquiaga and Zumalacárregui 2017, 2018; Wolf and Lagos 2020), fifth force tests (Burrage and Sakstein 2018; Joyce, Jain, et al. 2015; Will 2014) etc. pointing us towards more specific microphysical realizations of dark energy. For example, non-minimal couplings could conceivably show up in any of these different types of measurements and could be used to narrow down the possible microphysical models one might consider (Linder 2023).

Finally, many of these ideas explored here have been expanded upon and studied in much more physical detail following the completion of this chapter. First, the procedure used here for fitting $H(z)$ using forecasted errors is best thought of as a reasonable proxy for how (w_0, w_a) is determined from the data. However, while $H(z)$ is much closer to what we actually measure than $w(z)$, in truth we actually measure distance quantities that are sensitive to $H(z)$ through an integral. Wolf, García-García, Bartlett, et al. (2024) then developed a procedure for compressing the actual data used in the latest DESI analysis that shows a preference for dynamical dark energy and determining a scalar field model's best fit representation in (w_0, w_a) parameters by fitting the parameterized dark energy model to the scalar field models' predictions for the *exact* observables probed in cosmological surveys using the known errors and uncertainties of those particular measurements. It was then found that quintessence does not actually look that favorable with respect to what expansion history data seems to be saying through the posterior constraints on (w_0, w_a) displayed in Fig. (2.1). This work also obtained constraints on (V_0, m^2), finding a strong preference for the hilltop branch over the positive mass branch and that, while quintessence can improve the fit to the data over Λ, when one accounts for the introduction of new parameters using various information theoretic criteria, the evidence is not particularly compelling.

This strongly motivates investigating other possibilities that might explain the preference for dynamical dark energy seen in the data. As mentioned here, this $m^2\varphi^2$ model of quintessence is conceived of as an effective field theory that universally captures the phenomenology of a well-behaved, single, minimal coupled scalar field description of dark energy. One can be more general though and consider a broader effective field theory for scalar field driven dark energy

(Park, Zurek, and Watson 2010):

$$S = \int d^4x\sqrt{-g}\left[\frac{M_{\rm P}^2}{2}F(\varphi)R - G(\varphi)X - V(\varphi) - J(\varphi)X^2 + \mathcal{L}_M\left(g_{\alpha\beta}, \psi_M\right)\right], \qquad (2.35)$$

where $g_{\alpha\beta}$ is the metric and R its Ricci tensor, φ is the quintessence field, and $X = \partial_\mu\varphi\partial^\mu\varphi/2$, $\mathcal{L}_M$ is action for matter fields ψ_M. F, G, J and V are arbitrary functions of φ allowed by effective field theory. The model we have studied here is given by the choie $F = 1$, $G = 1$, $J = 0$, and $V(\varphi) = V_0 \pm \frac{1}{2}m^2\varphi^2$. Following up on this, Wolf, Ferreira, and García-García (2025b) found that introducing a non-minimal coupling into similar types of hilltop models aligns far better with the posterior constraints on (w_0, w_a) as these models can experience a recent phantom crossing and thaw very rapidly, corresponding to evolution that favors the lower left hand part of the thawing plane (again when fitting the (w_0, w_a) representation to the model's predictions using the data directly). A phantom crossing happens when $w(a)$ begins with $w < -1$ in the past, but then with subsequent evolution has evolved to $w > -1$ today. Additionally, this type of model can offer a more notable improvement in fit to the data over ΛCDM, suggesting that there may be emerging cosmological evidence for non-minimal coupling in the gravitational sector. This of course creates a number of theoretical difficulties as a field that enters the phantom regime violates the null energy condition which is known to be problematic for a number of reasons. However, whether one uses model agnostic methods, various parametric dark energy models, or even particular microphysical models, the data seems to be displaying a robust preference for dark energy that was at some point phantom in the past. The particular choice here corresponded to $F(\varphi) = (1 - \xi\varphi^2)$, $G = 1$, $J = 0$, and $V(\varphi) = V_0(1 - \beta e^{-\lambda\varphi})$ as this had a recognizable hilltop form, but this can also be just as easily expressed as $V(\varphi) = V_0 + \beta\varphi + \frac{1}{2}m^2\varphi^2$, which of course leads us right back to the conclusion of this chapter: if dark energy is dynamically driven by a scalar field, we will almost certainly never nail down its potential function because the leading order terms of the Taylor expansion saturate the cosmological phenomenology we have access to. Wolf, García-García, Anton, et al. (2025) performed a full Bayesian analysis of the non-minimally coupled dark energy model with the Taylor expanded potential, finding strong evidence for this model over Λ (with a Bayes factor $\simeq 7$). However, this analysis also reveals that the cosmological data has a strong preference for a large non-minimal coupling ξ and a negative mass/concave down potential $m^2 = d^2V/d\varphi^2 < 0$. In particular, the large non-minimal coupling indicates that, if the cosmological data is correct (this is still very much an open question), new physics must come into play on non-cosmological scales to screen fifth forces that otherwise should have shown up in solar system and astrophysical probes.

Additionally, Wolf, García-García, and Ferreira (2025) investigated alternative ways of parameterizing dark energy that differ from Eq. (2.2), finding that all of the other most common two parameter models of (w_0, w_a) show a similar preference for dynamical dark energy, successfully reproduce the phenomenology of minimal and non-minimal thawing quintessence, and yield similar conclusions regarding the viability of these dark energy proposals when they are used to interpret expansion history data.

And finally, Eq. (2.35) is not the only scalar field description of dark energy that provides a theory of cosmic acceleration that aligns well with current cosmological data. Rather than modifying the gravitational sector with a non-minimal coupling, one can modify the kinetic sector.

$$S = \int d^4x\sqrt{-g}\left[\frac{M_{\rm P}^2}{2}R - K(\varphi, X) - G(\varphi, X)\Box\varphi\right]. \tag{2.36}$$

These theories would generally belong to the so-called "kinetic braiding" class of gravitational theories (Deffayet et al. 2010). Unfortunately, these theories are generically phantom throughout their evolution and approach de Sitter expansion from below the phantom divide, meaning that they will be very poor descriptions of the current cosmological data. However, one can also introduce a potential $V(\varphi)$ into this construction so that:

$$S = \int d^4x\sqrt{-g}\left[\frac{M_{\rm P}^2}{2}R - K(\varphi, X) - G(\varphi, X)\Box\phi - V(\varphi)\right]. \tag{2.37}$$

Preliminary investigations indicated that a potential of the familiar quadratic form $V(\varphi) = V_0 + \frac{1}{2}m^2\varphi^2$ can cause the field to accelerate across the phantom divide and provide a good description of current cosmological data, similar to Eq. (2.35), but with some differences in terms of other ancillary gravitational consequences. These theories were then more fully investigated in Wolf, Ferreira, and García-García (2025a), with the finding that they perform similarly well to the non-minimally coupled model in terms of their ability to describe the cosmological data related to the expansion history of the universe.

3 | Minimizing the tensor-to-scalar ratio in single-field inflation models

3.1 Introduction

Inflation is currently the best theory we have to explain and describe the initial state of the early universe (Albrecht and Steinhardt 1982; Bardeen, Steinhardt, and Turner 1983; Guth 1981; Hawking 1982; Linde 1982; Mukhanov and Chibisov 1981; Starobinsky 1980). The theory of inflation proposes that the early universe experienced a period of accelerated, quasi-exponential expansion. During this period, inflationary dynamics produced a nearly flat and homogeneous universe, while quantum fluctuations in the inflaton field itself imprinted the universe with a characteristic spectrum of scalar density fluctuations/inhomogeneities that would seed the large-scale structure of the late-time universe. The statistical features of this spectrum, observed in the Cosmic Microwave Background (CMB), align with generic inflationary predictions that suggest that these fluctuations should be adiabatic, Gaussian, and nearly scale-invariant (Ade et al. 2022; Aghanim et al. 2020b; Akrami et al. 2020).

While the inflationary paradigm has been a spectacular success, seen a number of novel predictions confirmed, and justifiably become the dominant paradigm for modeling the early universe (Chowdhury et al. 2019; Guth, Kaiser, and Nomura 2014; Martin, Ringeval, and Vennin 2014, 2024; Wolf 2024a; Wolf and Duerr 2023), the enthusiasm for inflation has been moderately tempered in recent years. This is no doubt partially due to the failure to detect observable B-modes, which have long hailed as a "smoking-gun" for inflation (e.g., Baumann et al. (2009) and Baumann (2009); c.f. Brandenberger (2019)) because they would inform us about another key prediction of inflation models: the tensor/scalar ratio r. This observable has been one of the primary parameters used to constrain inflationary models because it gives us direct information concerning the microphysics of inflation; i.e., its energy scale and the form of its potential. Furthermore, it has traditionally been held that standard, "simple" single-field inflationary models typically produce large, or at least observable, tensor/scalar ratios (Easther, Bahr-Kalus, and Parkinson 2022). Consequently, the null results have eliminated many of the simplest inflation models and inspired some to explore alternative approaches with renewed attention such as bouncing and string gas cosmologies (although inflation remains the dominant paradigm) (Brandenberger and Peter 2017; Brandenberger 2011b; Cai, Easson, and Brandenberger 2012; Cai, Wan, et al. 2017; Chowdhury et al. 2019; Easson, Sawicki, and Vikman 2011; Guth, Kaiser, and Nomura 2014; Ijjas and Steinhardt 2016b; Ijjas, Steinhardt, and Loeb 2013; Khoury et al. 2001; Martin, Ringeval, and Vennin 2024; Martin, Ringeval, Trotta, et al. 2014; Steinhardt and Turok 2002b; Wolf and Thébault 2023).

However, the answer to the question of what we can infer about the status of simple inflation models based on the detection or non-detection of r is a subtle business. This of course depends upon one's definition of "simple", which, similarly to Stein and Kinney (2023), we take to roughly be that the model consists of a single, canonical scalar field with a potential that can be approximated by an effective operator expansion (c.f., Boyle, Steinhardt, and Turok (2006) and Sousa et al. (2024) for further discussions on possible definitions of "simple" in this context). To this point, Stein and Kinney (2023) provide a straightforward counter example to the claim that simple single-field inflation models cannot produce a small tensor/scalar ratio: they construct a hilltop model with a potential described by a leading order quadratic term, and show that subleading order operators in the potential can induce an earlier end to inflation, and in doing so, lower r "arbitrarily".

This result intersects with some more general observations, especially emphasized by Kallosh and Linde (2019) and further explored in Hoffmann and Sloan (2021, 2023), that:

1. There are a number of inflation models in the literature with unregularized potentials that are unbounded from below.
2. Producing a physically viable inflation model depends upon stabilizing, or "correcting", the potential. Otherwise, the universe would immediately re-collapse.
3. The observable predictions of inflation models can depend *sensitively* on the nature of the correction terms that ensure inflation ends smoothly.

In light of these observations, it remains to be seen whether and to what extent an arbitrarily small tensor/scalar ratio can be realized within the construction of Stein and Kinney (2023).

In this paper, we answer this question by explicitly constructing models of inflation that can realize a vanishingly small r. To do so, we explore corrections to the quadratic hilltop model as suggested by Stein and Kinney (2023) to show how a small r can be realized within this construction. Furthermore, while we find that these models can easily produce values for r well below even the most optimistic observational sensitivities, we also find that r can essentially be lowered arbitrarily, at least until its value begins to asymptote around $r \sim 10^{-11}$.

This chapter proceeds as follows. Sec. (3.2) describes the theory of inflation, slow-roll dynamics, and the observables associated with inflation models. Sec. (3.3) discusses the necessity of correcting, or regularizing, unbounded inflationary potentials, and explores some of the ways that this has been done in the literature. This section also shows how the standard quadratic hilltop model can be corrected by considering the behavior of terms in the generic Taylor expansion of the potential. Sec. (3.4) explores the observational predictions for r and n_s for this general model, and shows how r can be lowered in a nearly arbitrary way before hitting a lower bound. Sec. (3.5) concludes.

3.2 Inflationary slow-roll dynamics

We begin with a discussion of the basic inflation scenario: a single, canonical scalar field ϕ minimally coupled to gravity in a homogeneous and isotropic FLRW background. The scale factor of the universe $a(t)$ evolves according to the Friedmann equations

$$H^2 = \frac{1}{3M_{\rm P}^2}\left(\frac{1}{2}\dot{\phi}^2 + V(\phi)\right), \tag{3.1}$$

$$\dot{H} = \frac{1}{2}\frac{\dot{\phi}^2}{M_{\rm P}^2}, \tag{3.2}$$

where $H = \dot{a}/a$ and $M_{\rm P}$ is the Planck mass; and the scalar field ϕ evolves according to the Klein-Gordon equation in a Friedmann background

$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0, \tag{3.3}$$

where $V' = dV/d\phi$.

While these are the full dynamics, in order to produce the needed accelerated expansion, inflation occurs when the potential $V(\phi)$ is the primary driver of the dynamics. This permits us to work in the *slow-roll* approximation. In this approximation, the kinetic term and the field acceleration are both vanishingly small $\dot{\phi}^2 = \ddot{\phi} \simeq 0$. This leads to the following system of simpler equations:

$$H^2 \simeq \frac{V(\phi)}{3M_{\rm P}^2}, \tag{3.4}$$

$$3H\dot{\phi} \simeq -V'(\phi). \tag{3.5}$$

The slow-roll approximation can be conveniently parameterized in terms of the *slow-roll param-*

eters ϵ and η.

$$\epsilon \equiv \frac{M_\mathrm{P}^2}{2}\left(\frac{V'}{V}\right)^2, \tag{3.6}$$

$$\eta \equiv M_\mathrm{P}^2 \frac{V''}{V}. \tag{3.7}$$

The accelerated expansion that inflation induces can only be sustained when these parameters are small, i.e., $\epsilon \ll 1$ and $\eta \ll 1$, and inflation ends when $\epsilon(\phi_E) \simeq 1$.

We can also use this to calculate the number of *e-folds* $N(\phi)$ between the end of inflation E and some earlier initial time I when the fluctuations exit the horizon and freeze.

$$N(\phi) = \log\left(\frac{a_E}{a_I}\right) = \int_{\phi_\mathrm{I}}^{\phi_\mathrm{E}} \frac{d\phi}{M_\mathrm{P}} \frac{1}{\sqrt{2\epsilon(\phi)}}. \tag{3.8}$$

Inflation generally needs $N \simeq 60$ e-folds to successfully resolve the aforementioned fine-tuning puzzles as well as to be compatible with observations.

This theory provides an explanatorily satisfying solution to the fine-tuning puzzles that inspired its development and elegantly produces a flat, homogenized universe. Where inflation really shines; however, is that the theory also explains and predicts how the universe generates the tiny inhomogeneities observed in the CMB that would later grow into the large-scale cosmic structure that we see today. Tiny quantum fluctuations in the inflaton field itself $\delta\phi$ produce density perturbations in the metric that inflationary dynamics then stretch and amplify over cosmological scales. Scalar density perturbations are produced with a power spectrum

$$\mathcal{P}_\phi = \left\langle |\delta\phi(k)|^2 \right\rangle \propto A_s(k)^{n_s - 1}, \tag{3.9}$$

and amplitude

$$A_s = \frac{1}{8\pi^2}\frac{1}{\epsilon}\frac{H^2}{M_\mathrm{P}^2}, \tag{3.10}$$

where k refers to the scale/wavenumber of the mode and n_s is the so-called scalar spectrum index—a key observable that characterizes the scale-dependence of the fluctuation power spectrum which is defined as

$$n_s(k) - 1 = \frac{d\ln\mathcal{P}_\phi}{d\ln k}. \tag{3.11}$$

Additionally, inflation produces primordial gravitational waves, which are tensor perturbations that produce a distinctive B-mode polarization pattern. The amplitude of tensor perturbations is given by

$$A_t = \frac{2}{\pi^2}\frac{H^2}{M_{\rm P}^2}, \tag{3.12}$$

which allows us to define the scalar/tensor ratio r as

$$r = \frac{A_t}{A_s}. \tag{3.13}$$

The quantities r and n_s are the two primary observables used to constrain inflationary models. Furthermore, they can be directly calculated from the slow-roll parameters, leading to

$$n_s - 1 = -6\epsilon\left(\phi_I\right) + 2\eta\left(\phi_I\right), \tag{3.14}$$

$$r = 16\epsilon\left(\phi_I\right), \tag{3.15}$$

where quantities are evaluated when the modes exit the horizon at ϕ_I.

3.3 Unregularized inflation models and stabilising corrections

3.3.1 Observables are sensitive to corrections

There are many models of inflation that have been considered which have potentials that are unbounded from below. Hilltop models are among these and will be the primary focus of this paper. This class of models has been investigated in a wide variety of contexts including inflation and dark energy (see, e.g., Bostan, Güleryüz, and Şenoğuz (2018), Boubekeur and Lyth (2005), Dimopoulos (2020), Dutta and Scherrer (2008), German (2021), Hoffmann and Sloan (2021), Kinney et al. (2006), Kohri, Lin, and Lyth (2007), Lillepalu and Racioppi (2023), Rashidi, Heidarzadeh, and Nozari (2022), Stein and Kinney (2023), Tzirakis and Kinney (2007), and Wolf and Ferreira (2023)), and is described by a potential of the following form,

$$V(\phi) = V_0\left[1 - \left(\frac{\phi}{\mu}\right)^n\right], \tag{3.16}$$

where V_0 is the energy scale at the height of the potential, μ is a mass scale, and n is an integer. While the region near the top of the potential clearly satisfies the basic criteria for a successful inflationary model, one can also easily see from Fig. (3.1) that such potentials are unbounded from below. This is problematic because once $V < 0$, the universe will stop expanding, eventually begin to collapse, and fail to produce a viable cosmology (Felder et al. 2002; Kallosh and Linde 2019). Other potentials with this feature include D-brane inflation, radiatively corrected

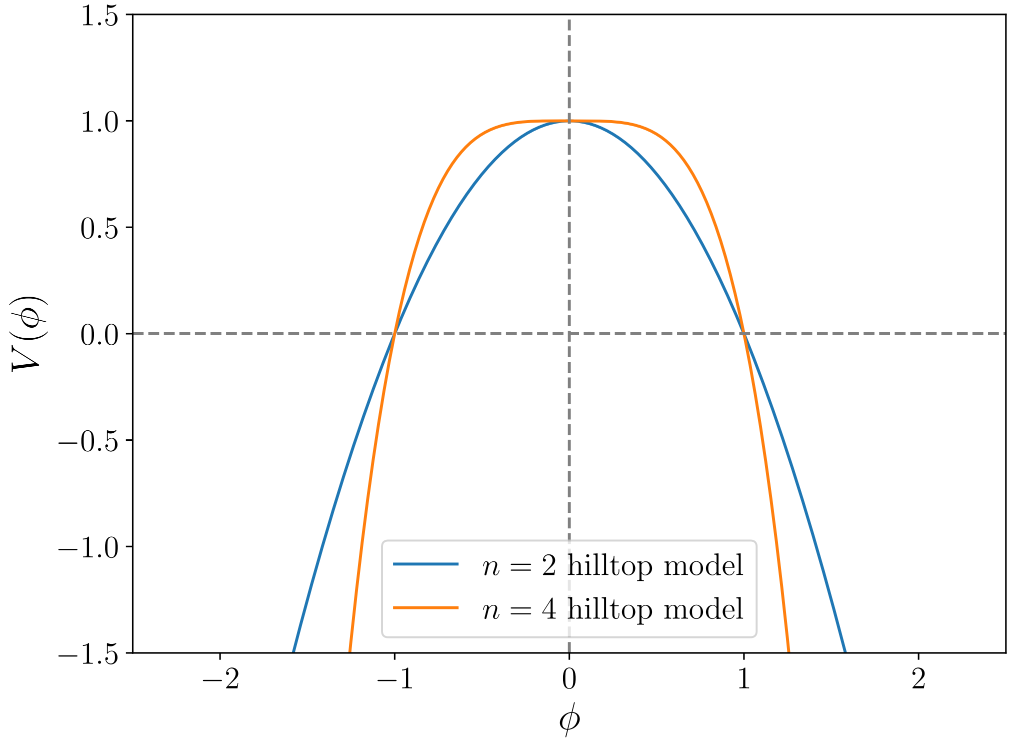


Figure 3.1: Potentials $V(\phi)$ for quadratic ($n = 2$) and quartic ($n = 4$) hilltop models normalized to $V(0) = V_0 = 1$ with $\mu = 1$. While the top of the hill is suitable for inflation, these potentials eventually become negative. These results are unphysical and would lead the post inflationary universe to immediately recollapse (Felder et al. 2002; Kallosh and Linde 2019).

Higgs inflation, and exponential SUSY inflation (e.g., Martin, Ringeval, and Vennin (2014)). Due to these considerations, Kallosh and Linde (2019) persuasively argues that *any* model with this feature cannot be considered as a viable inflationary model; and furthermore, that for any of them to be valid they must be corrected such that they form stable minima that can secure a smooth exit from inflation.

As it turns out, the nature of this stabilisation at the minima can dramatically affect observable predictions for r and n_s (Hoffmann and Sloan 2023; Kallosh and Linde 2019; Martin, Ringeval, and Vennin 2014). Thus, we cannot not naively assume the oft-cited (r, n_s) predictions derived from from Eq. (3.16) or others like it are representative of the predictions for viable versions of these models; rather, we need to actually construct stable models and compute the predictions.

3.3.2 Stabilising the quadratic hilltop model

Inspired by the results of Stein and Kinney (2023), we would like to explore constructing a stable version of the quadratic hilltop model ($n = 2$), with the goal of seeing what freedom lies in higher order terms to lower r "arbitrarily".

How do we go about doing this? There are a few options. As Kallosh and Linde (2019) notes, one can somewhat trivially stabilise the potential by introducing a finely-tuned correction term that very close approximates the form of Eq. (3.16) for $\phi < \phi_{min}$, but then at ϕ_{min} becomes constant and turns sharply upwards for $\phi > \phi_{min}$. This preserves the predictions of Eq. (3.16), but in an obviously ad-hoc and unsatisfying manner. However, we want to explore how to *lower* r while remaining viable in n_s, rather than merely retain the same predictions.

An arguably more natural option would be to square Eq. (3.16). This has been pursued for the $n = 2$ quadratic hilltop squared inflation (also known as double-well inflation) (Chowdhury et al. 2019; Martin, Ringeval, and Vennin 2014) and $n = 4$ quartic hilltop inflation (Hoffmann and Sloan 2021). Yet, in both cases, squaring the potential has the effect of *raising*, rather than lowering, r. For double well inflation, r lies almost entirely outside data constraints, while quartic hilltop squared inflation remains viable, although its predictions for r are pushed up notably.

Yet another option, which has been pursued in Hoffmann and Sloan (2023) for the quartic hilltop model, is to add a polynomial term to stabilise the potential. For instance, one could stabilise the quadratic hilltop potential in the following way

$$V(\phi) = V_0 \left[1 - \left(\frac{\phi}{\mu}\right)^2 + \alpha_p \left(\frac{\phi}{\mu}\right)^p\right], \quad p > 2, \tag{3.17}$$

where one can analytically work out the value of α_p to ensure that the potential reaches its minimum at zero. That is,

$$\phi_{vev} = \mu \left(\frac{2}{p\alpha_p}\right)^{\frac{1}{p-2}}, \tag{3.18}$$

and requiring that $V(\phi_{vev}) = 0$ allows us to solve for,

$$\alpha_p = \left(\frac{p}{2} - 1\right)^{\left(\frac{p}{2}-1\right)} \left(\frac{p}{2}\right)^{-\frac{p}{2}}. \tag{3.19}$$

However, just as Hoffmann and Sloan (2023) found in the case of the quartic hilltop model, this has the effect of raising the predictions for r and generally shifts curves in the (r, n_s) plane up and towards the left, rather than down and towards the right. The higher order the single polynomial correction is, the closer that the inflationary observables will match the uncorrected model because the correction term will have less of an effect on the potential during the stages at which inflation is occurring; consequently though, adding a single polynomial stabilising term will not lower r. This is partially because simply adding adding a single correcting term will have the effect of making inflation end *later*, whereas the results of Stein and Kinney (2023) indicate that the freedom to lower r is at least somewhat tied to the ability to reduce ϕ_E. See Fig. (3.2) where this potential is depicted for $p = 4$.

How then do we lower r? Taking our cue from the suggestive results in Stein and Kinney (2023), we will need to construct higher order terms that induce an earlier end to inflation. Let's briefly consider an ad-hoc example to explicitly see how one of such potential could produce a lower r:

$$V(\phi) = V_0 \left[1 - \beta_2 \left(\frac{\phi}{\mu}\right)^2 - \beta_4 \left(\frac{\phi}{\mu}\right)^4 + \beta_6 \left(\frac{\phi}{\mu}\right)^6\right], \tag{3.20}$$

with $\phi_{vev} = \mu/\sqrt{3}$ and the coefficients $\beta_2 = 3$, $\beta_4 = 9$, and $\beta_6 = 27$ chosen to ensure $V(\phi_{vev}) = 0$. As one can see in Fig. (3.2), the introduction of an additional negative term causes the potential to dip more steeply and end inflation before either the quadratic hilltop model of Eq. (3.16) or the potential with the polynomial correction at $p = 4$ in Eq. (3.17). However, the final correction term is positive and successfully provides a smooth end to inflation. See Fig. (3.3) for the (r, n_s) curves resulting from these different hilltop potentials.

3.4 Results

While the above are options are straightforward ways one could think of to stabilise the potential, they are all somewhat ad-hoc. As any analytic potential admits of a Taylor expansion,

$$V = V_0 + \left.\frac{dV}{d\phi}\right|_{\phi=0} \phi + \frac{1}{2}\left.\frac{d^2V}{d\phi^2}\right|_{\phi=0} \phi^2 + \frac{1}{6}\left.\frac{d^3V}{d\phi^3}\right|_{\phi=0} \phi^3 + \cdots, \tag{3.21}$$

there are a huge number of possibilities that could show up at higher orders. Thinking of this as an effective field theory (Burgess 2020), the relevant symmetries and energy scale cut-off will determine which of the terms show up and at what order the expansion terminates. There are many potentials whose leading order terms are quadratic and thus would be well represented at leading order by the quadratic hilltop model, but with a number of higher order terms that could perhaps serve our purposes to both stabilise the potential, as well as modify observable predictions for r or n_s.

Thus, given our ignorance regarding inflationary energy scales and a lack of any especially compelling theoretical motivations to consider stabilising correction terms of any particular type,

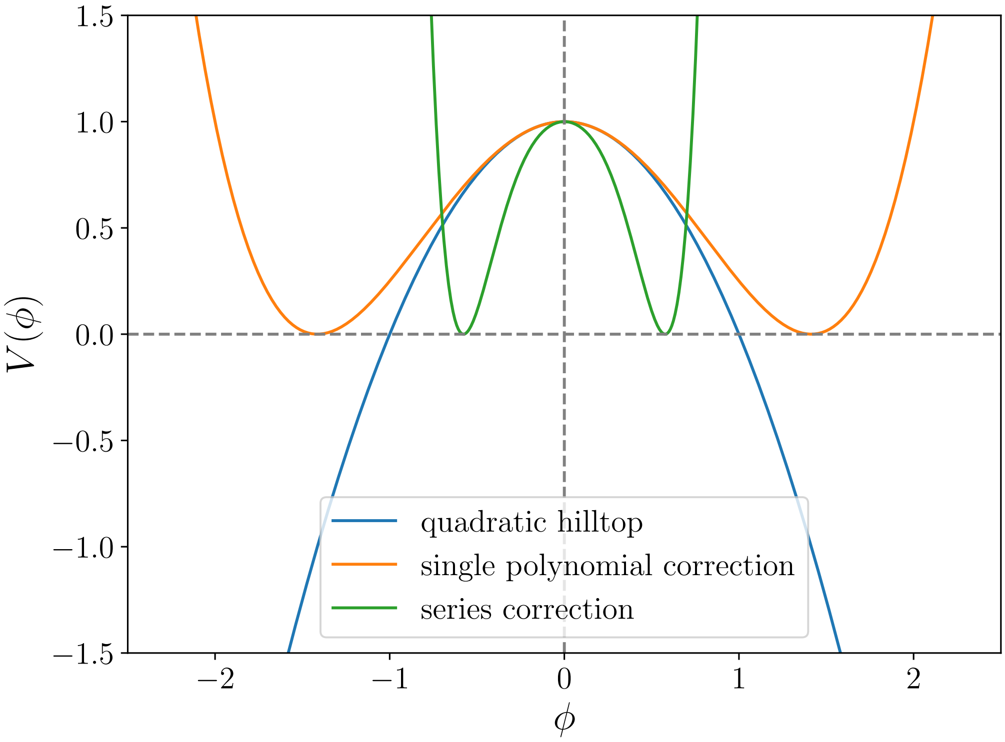


Figure 3.2: The potentials $V(\phi)$ for the quadratic hilltop model (Eq. (3.16) for $n = 2$), a polynomial correction to the hilltop quadratic model (Eq. (3.17) for $p = 4$), and a more involved potential involving a series of multiple polynomial terms (given by Eq. (3.20)). For visualization purposes, all potentials have been normalized to $V(0) = V_0 = 1$ and the mass scale chosen as $\mu = 1$. One can easily see from these potentials that the nature of the correction terms involved will have an impact on when inflation ends and the resulting observable predictions.

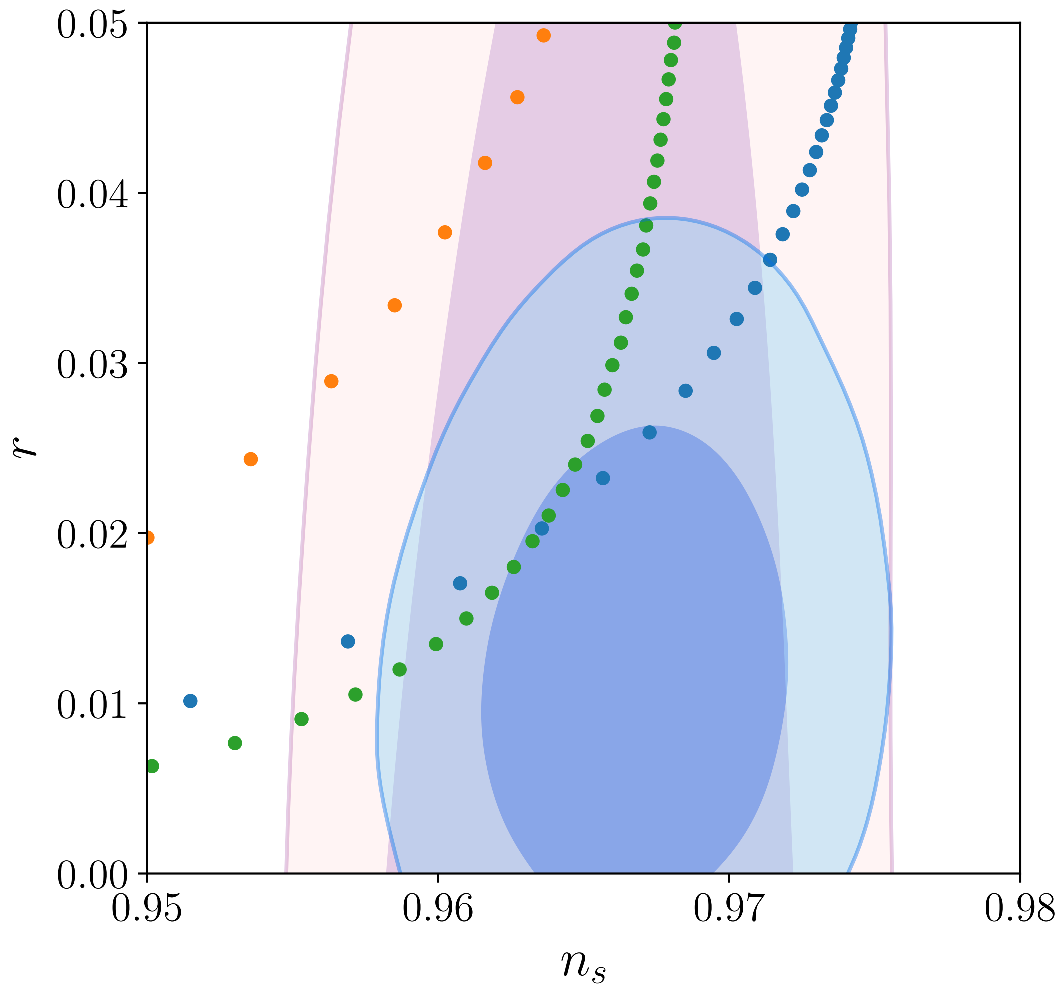


Figure 3.3: Observable predictions in the (r, n_s) plane for the potentials depicted in Fig. (3.2) at $N = 60$ efolds of inflation. The contours are from Planck 2018 (Aghanim et al. 2020b) and the improved Bicep/Keck 2018 constraints (Ade et al. 2021). The blue dotted line corresponds to the uncorrected quadratic hilltop model (c.f., Fig. 1 in Stein and Kinney (2023) or Fig. (3.4) here for the same predictions plotted on a log scale), while the yellow line corresponds to the potential with a single polynomial correction and the green lines corresponds to the potential with a series of polynomial corrections. We can see that with the potential that received a single polynomial correction the predictions for r are raised, while for the potential that received a series of polynomial corrections the predictions for r are lowered in part of the plane before turning sharply upwards. There is a tremendous amount of freedom in higher order terms to affect inflationary observables.

we will work very generally and consider models given by a polynomial expansion

$$V(\phi) = V_0 + \sum_{n=2}^{n=q} \frac{a_n}{n!} \left(\frac{\phi}{\mu}\right)^n , \tag{3.22}$$

where the various a_n's represent expansion coefficients of approximately $\mathcal{O}(1)$, and from now on we choose $\mu = M_\mathrm{P}$ so that ϕ is scaled as $\phi \to \phi/M_\mathrm{P}$. As depicted in Eq. (3.23), we restrict $a_2 < 0$ in order to ensure that our leading order term is described by the quadratic hilltop model, while a_n, where $2 < n < q$, can take positive or negative values, and a_q is the order at which the expansion terminates and must be positive to ensure that the potential stabilises.

coefficient	range
a_2	$\in [-1.0, -.01]$
$a_{2<n<q}$	$\in [-1.0, 1.0]$
a_q	$\in [.01, 1.0]$

(3.23)

So, for example, going out to $q = 6$ would be given by the following:

$$V(\phi) = V_0 + \frac{a_2}{2!}\phi^2 + \frac{a_3}{3!}\phi^3 + \frac{a_4}{4!}\phi^4 + \frac{a_5}{5!}\phi^5 + \frac{a_6}{6!}\phi^6, \tag{3.24}$$

where a_6 is required to be positive, a_2 is required to be negative, and all the a_n's in between are bounded as indicated above in Eq. (3.23). Of course, there is a tremendous amount of freedom in an expansion of this type, and the resulting potentials can take on a number of shapes, possibly having multiple minima. Thus, when we generate a potential, we then span a wide range of ϕ to find the global minimum and adjust V_0 such that $V(\phi_{vev}) = 0$ at this point (see Abel et al. (2023) for a similar set-up with more general polynomials that include linear terms). Here we choose to span from $\phi \in [0, 20M_\mathrm{P}]$ in search of stabilising minima.

Given the high dimensionality of the parameter space and potential degeneracies between the parameters, we will pursue two strategies to explore it and assess the observational predictions of a single-field model given by an expansion of the form Eqs. (3.22-3.23). In Sect. 3.4.1, we will pursue a Markov chain Monte Carlo (MCMC) strategy to sample values from the parameter space to ascertain some generic features of this model. In Sect. 3.4.2, we will pursue minimization strategies to see how far we truly can push r with this general set up.

3.4.1 Covering the (r, n_s) plane

We begin by exploring MCMC simulations to sample the parameter space described in Eq. (3.23) for the potential given Eq. (3.22). There are a number of ways to go about this, but here we found that sampling the parameters from Eq. (3.23) in a Latin hypercube while uniformly sampling efold values in the range $N \in [50, 70]$ was effective for probing the observable parameter space. Furthermore, we restricted ourselves to viable models that have a scalar spectral index within the Planck allowed regions, which is approximately $.955 \geq n_s \leq .975$. While we could extend out to any order in the expansion given by Eq. (3.22), we found that that the (r, n_s) plane rapidly becomes saturated well beyond sensitivity forecasts for future CMB experiments by the time we get to $q = 6$. So, in this section, we focus on orders $q = 4, 5, 6$.

Beginning with $q = 4$, we sampled until we had obtained $\sim 10,000$ viable models; finding that at this order the observable predictions for this model have a relatively tight structure that, for the most part, predict *higher* r values than the uncorrected quadratic hilltop model. In light of the discussion of Sec. (3.3.2) and the results of Hoffmann and Sloan (2023), this is not terribly surprising. The stabilising correction term occurs at a_4 (a relatively high order), meaning that it will have a more significant impact on the on the potential trajectory during inflation than it would if it were a higher order term. Meanwhile, there is not that much freedom in a_2 or a_3 to induce an earlier end to inflation.

Moving to orders $q = 5$ and $q = 6$, we sampled in a Latin hypercube until we obtained $\sim 50,000$ viable models for both $q = 5$ and $q = 6$ because the parameter space is significantly larger and more varied than in the $q = 4$ case. We find that the predictions begin to rapidly saturate the (r, n_s) plane, and that the r values can be pushed significantly lower.[1] Again, considering the results of Hoffmann and Sloan (2023), this more varied behavior makes sense. The fact that the stabilising correction term is higher order means that it has less of an impact on the actual period of inflation, only coming into play at the very end where it sharply corrects and stabilises the potential. At the same time, there is more freedom in the other orders to carve out an inflationary history that lowers r.

These results are also significant for another reason. Sensitivity forecasts for the next generation CMB-S4 experiment project a sensitivity of $r \sim 10^{-3}$ (Abazajian et al. 2016). Here, the observable predictions for the model given by the expansion we are considering covers essentially the entire viable n_s range and many orders of magnitude below the sensitivity forecasts in r. This

[1] See Wolf and Ferreira (2023) for similar results and discussions in the context of quintessence driven dark energy, where the quadratic hilltop model can be shown to sweep the $w_0 - w_a$ plane that parameterises dark energy phenomenology.

is yet another suggestion, in alignment with both Stein and Kinney (2023) and Kallosh and Linde (2019), that "simple" single-field inflationary models can never be ruled out with a non-detection of r.[2] These results are explored and summarized in Figs. (3.4-3.5).

3.4.2 Optimizing a minimum value for r

While it is clear that models described by the expansion in Eq. (3.22) can cover the observable parameter space in the (r, n_s) plane arbitrarily as far as foreseeable experimental sensitivity is concerned, there is still the question of how low r can possibly go. In order to explore an answer to this question, we will go order by order Eq. (3.22), and optimize the potential $V(\phi)$ given the parameter space described by Eq. (3.23) in order to minimize the value of r.

There are a variety of tools one could utilize here. One of the more obvious strategies to pursue is to deploy something like SciPy's minimize function. This tool takes an "objective function" that can receive a number of variables as an input and outputs a scalar value, and then finds a minimum value for the objective function. In our case, the objective function takes the potential in Eq. (3.22) and parameter bounds in Eq. (3.23) as inputs, and then outputs the calculated values of r and n_s. While this minimization tool has a number of methods available, including both gradient-based and derivative-free methods, we found that utilising this approach tended to frequently get stuck in local minima that would not always produce r values as low as some of the ones we would find in the MCMC simulations. We attribute this to the inherent structural complexity of the function and the vast size of the parameter space. Gradient-based methods would quite naturally get stuck because they are based on first derivatives and this function clearly has a vast landscape of local minima. However, even the derivative-free methods would also seem to find themselves eventually getting stuck in local minima.

After exploring this option, we then deployed more sophisticated optimization techniques, settling on SciPy's differential evolution algorithm, which is specifically designed to find the global minima of non-convex functions with possibly many local minima. Like minimize, it optimizes some object function with input variables and a scalar output; however, it is also a population-based approach that maintains a number of candidate solutions which iteratively evolve through population crossover, mutation, and selection. This allows the optimization to more effectively explore the parameter space even if the objective function contains many local minima. Here, we found that population sizes of around $25 - 50$ (initialized from a Latin hypercube) along with relatively high mutation ($\sim 1 - 2$) and recombination/crossover rates (~ 1) was effective for

[2] See Kallosh and Linde (2019) and Kallosh, Linde, and Yamada (2019) for discussions of single-field α-attractor and modified D-brane models which the authors show can also cover huge swaths of the (r, n_s) plane.

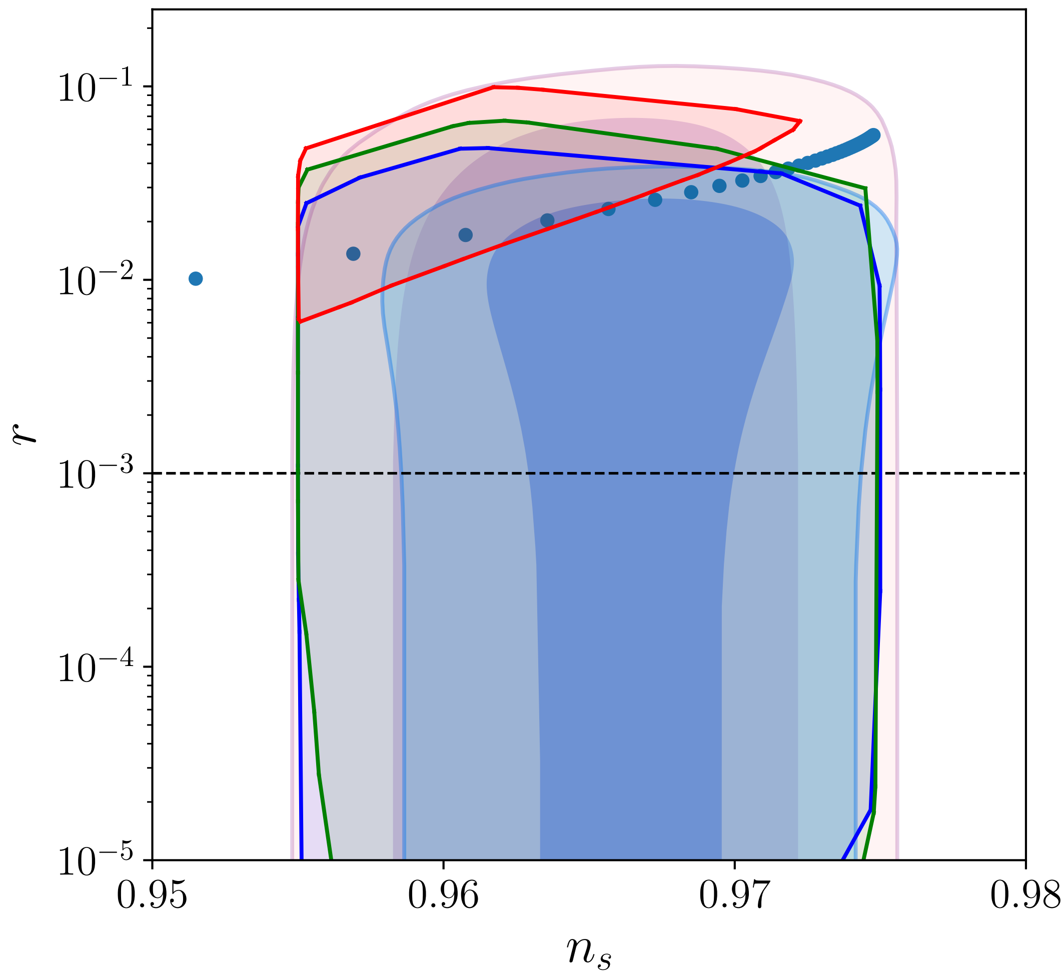


Figure 3.4: Results of MCMC sampling the inflation model described by the expansion and parameters in Eqs. (3.22-3.23). The red outline contains the results for $q = 4$, the green outline contains the results for $q = 5$, the blue outline contains the results for $q = 6$, the blue dotted line represents the predictions for the uncorrected quadratic hilltop model at $N = 60$ efolds of inflation (c.f., Fig. 1 in Stein and Kinney (2023) or Fig. (3.3) here), the black dashed line represents the observational forecasts for the next generation CMB-S4 experiment which project a sensitivity of $r \sim 10^{-3}$ (Abazajian et al. 2016), and the contours representing the allowed regions of parameter space are from Planck and Bicep/Keck respectively (Ade et al. 2021; Aghanim et al. 2020b). While the sampled space for the $q = 4$ model is relatively tight, we see in going to orders $q = 5$ and $q = 6$ that these models rapidly begin to saturate the (r, n_s) plane all the way down to $r \sim 10^{-5}$ (and below)—roughly two orders of magnitude below the projected sensitivity of CMB-S4.

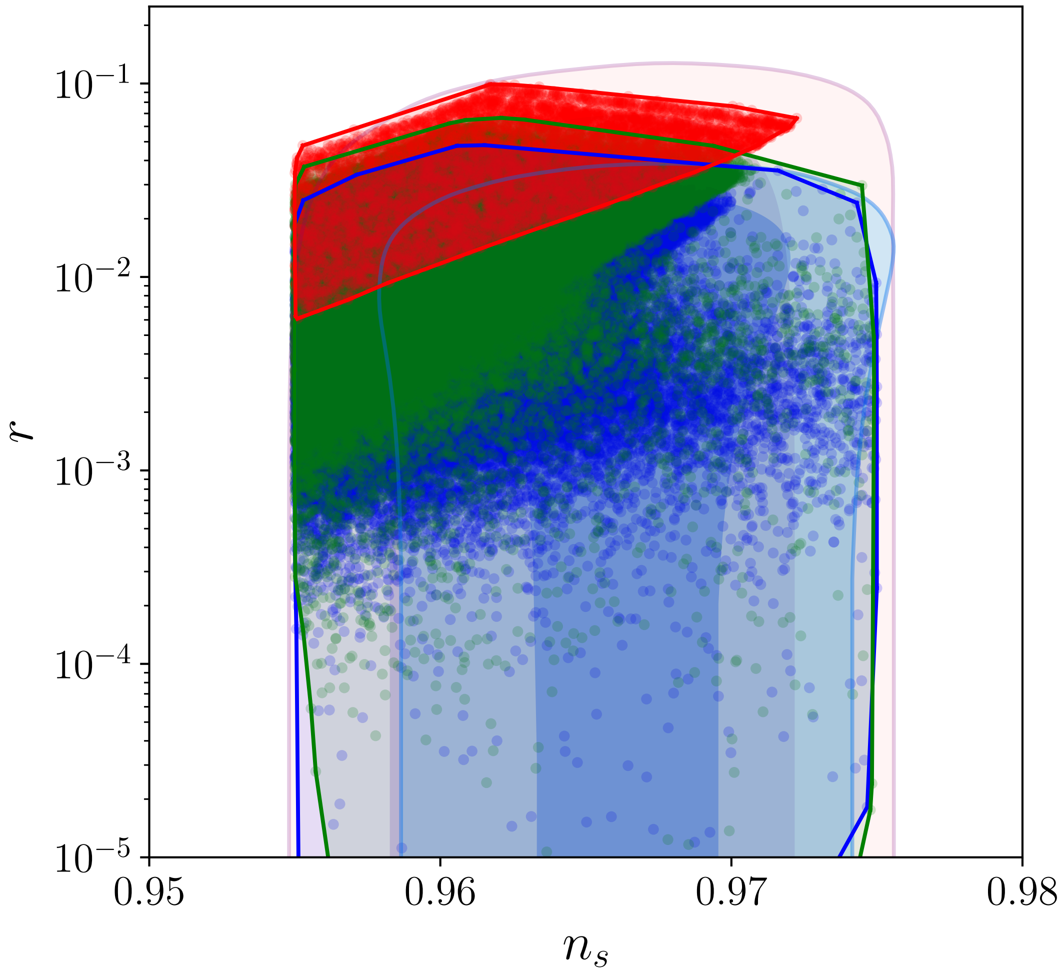


Figure 3.5: Scatter plot results of MCMC sampling the inflation model described by the expansion and parameters in Eqs. (3.22-3.23). As before the red represents $q = 4$, the green represents $q = 5$, and the blue represents $q = 6$. While Fig. (3.4) only depicted the regions that encompassed the parameter space for the various q orders in the expansion that were explored, this figure gives some insight into how the points are distributed. We see that while both $q = 5$ and $q = 6$ span similar areas in n_s and seem to reach arbitrarily low values of r, $q = 6$ distributes the points more evenly across the (r, n_s) plane and contains more very small values of r. This is not surprising considering that having the stabilising term at a higher order will make for a sharper correction at the end that has less of an effect on the dynamics throughout the range of the potential, while also allowing for more freedom in the other parameters to lower r.

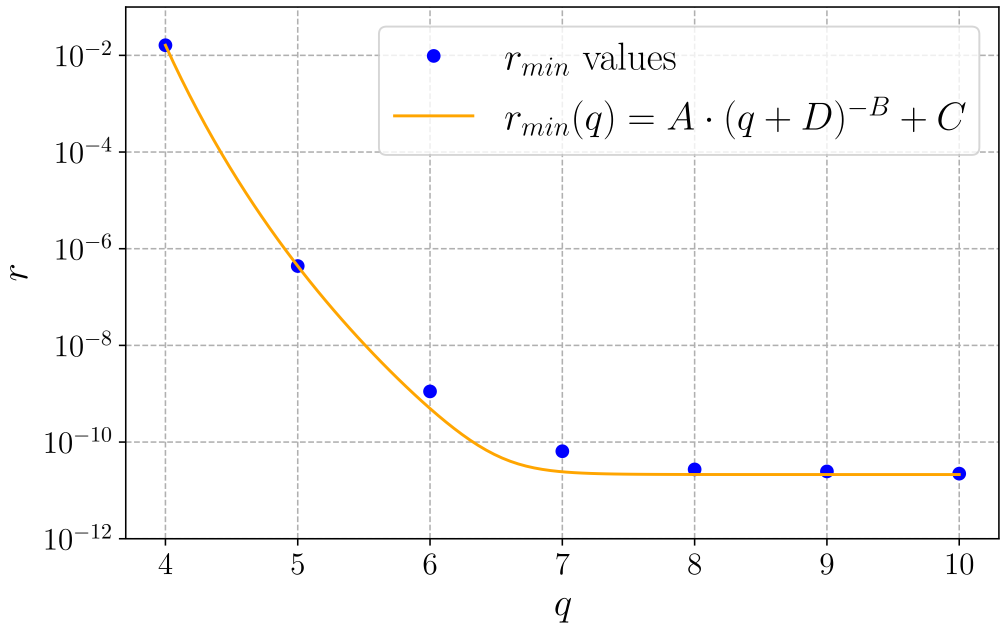


Figure 3.6: Results of the optimization procedure to minimize r order by order in q. As one can see by inspection or by Eq. (3.25), the relationship is well-described by a power law that asymptotes at $r \sim 10^{-11}$. See Table. (3.1) for exact r_{min} values.

exploring the parameter space.

In the following results, for reasons that will soon become apparent, we went even further out in terms of the order of the potential's expansion than we did in the MCMC sampling. We found that the higher order one caries out the expansion in Eq. (3.22) to, the lower the mininum r, but that by $q = 8$ the r values seem to asymptote. We then carried out the expansion all the way out to order $q = 10$ to confirm that this is the case. As one can see from examining Fig. (3.6) or Table. (3.1), the optimization procedure we employed produces a smooth curve that shows the minimum tensor/scalar ration r_{min} obtained from the potential $V(\phi)$ as a function of the order q at which the expansion in Eq. (3.22) was carried out to. The functional relationship is well-described by a power law $r_{min} \propto q^{-B}$, before it asymptotes at a lower bound of $r_{min} \sim 10^{-11}$. The exact functional form is given by:

$$r_{min}(q) = A \cdot (q + D)^{-B} + C, \tag{3.25}$$

where $A \approx 17.77$, $B \approx 19.78$, $C \approx 2.13 \times 10^{-11}$, $D \approx -2.58$. Taken together, it does indeed seem that for all intents and purposes, higher order terms in the expansion given by Eq. (3.22) effectively have the freedom to lower r arbitrarily as suggested by Stein and Kinney (2023).

q	r	n_s
4	1.62×10^{-2}	0.9550
5	4.378×10^{-7}	0.9552
6	1.116×10^{-9}	0.9606
7	6.456×10^{-11}	0.9675
8	2.718×10^{-11}	0.9551
9	2.469×10^{-11}	0.9555
10	2.222×10^{-11}	0.9570

Table 3.1: Table of q, r, and n_s values corresponding the to results depicted in Fig. (3.6).

3.5 Conclusion

Throughout the literature on inflation there has been much discussion concerning what the inflationary paradigm generically predicts for crucial observables such as r and n_s. While many of the simplest and most commonly explored models do predict a relatively high r (and some have been eliminated as a result), there are now a number of counter examples that show that single-field inflation can also produce an undetectably negligible tensor/scalar ratio (Kallosh and Linde 2019; Kallosh, Linde, and Yamada 2019; Stein and Kinney 2023). Even going beyond our most optimistic scenarios for observational sensitivities though, studies such as this one which suggests that single-field inflation can produce tensor/scalar ratios as low as $r \sim 10^{-11}$, Lorenzoni, Kaiser, and McDonough (2024) which investigates a two-field model of natural inflation that can produce tensor/scalar ratios as low as $r \sim 10^{-15}$, or Braglia et al. (2020) which studies the mechanisms by which additional fields can suppress r, underscore the almost infinite flexibility of the inflation paradigm.

Here, we explored modifications to the quadratic hilltop model and explicitly showed that introducing possible correction terms can radically alter the observable predictions, where the form of the correction terms we considered was motivated by a widely applicable effective field theory operator expansion. Such higher order correction terms are both necessary to stabilise the potential in order to ensure a smooth end to inflation, and also represent additional degrees of freedom that can lower r significantly. We showed this to be the case both by randomly sampling many possible viable models described by such an expansion, as well as by optimizing to find the minimum allowed values of r.

Where does this leave us? A null detection of r seemingly will never totally rule out single-field inflation. Yet, as these examples suggest, the further down r goes the more structurally complicated the mathematical form of the potential need to become (Boyle, Steinhardt, and Turok 2006; Sousa et al. 2024). While such models may indeed be simple in the sense that they can be described by a single canonical scalar field minimally coupled to gravity, pushing r lower does indeed seem to require more structural complexity. Like dark energy (Wolf and Ferreira 2023), early universe models suffer from surprisingly stubborn underdetermination problems; however, future observations will no doubt continue to offer valuable information concerning the physical processes underlying cosmological phenomena.

Part III

Non-empirical assessment and explanation in cosmic inflation

4 | Cosmological inflation and meta-empirical theory assessment

4.1 Introduction

Developing methodological tools for the evaluation of scientific theories has long been a central theme in the philosophy of science. This particular area of the literature largely springs from Popper's famous analysis of the demarcation problem, where he proposed empirical "falsification" as the criteria that drove scientific progress (Popper 1935). Other such programmes developed, including Kuhn's model of science as alternating between periods of "normal" science and revolutionary paradigm changes (Kuhn 1962), Lakatos' analysis of progressive and degenerating research programmes (Lakatos 1970), and Laudan's emphasis on problem solving and pursuit-worthiness within research traditions (Laudan 1977). These programmes largely focused on direct empirical verification in their assessments of scientific theories. However, due in part to fundamental theoretical physics outpacing the technological capacities of experimental science, there has been a recent emphasis on non-empirical considerations in scientific evaluation.

Meta-Empirical Assessment (MEA), a methodological programme initially developed by Dawid (2013), stands in contrast to the older classic methodologies that more closely focused on empirical assessment. MEA does not deny the primacy of empirical assessment and its ultimate necessity, but rather highlights the role of non-empirical considerations in theory assessment. To be more specific, empirical evidence "consists of data of a kind that can be predicted by the theory assessed on its basis", whereas non-empirical evidence is the kind of evidence that "supports a theory even though the theory does not predict the evidence" (Dawid 2013, p.36). For example, the standard model of particle physics cannot itself predict that no successful alternative to it will be found; however, the fact that no other compelling theoretical framework has emerged to challenge it, after nearly a century and vast cognitive resources being devoted to this problem, should increase our confidence in its efficacy. This is especially valuable in situations where we currently do not have adequate avenues to fully adjudicate the empirical merits of the theory or theories in question. The MEA programme's criteria for the non-empirical assessment of theories are primarily built on three arguments (to be discussed in more detail in the next section): the *No Alternatives Argument* (NAA), the *Unexpected Explanatory Coherence Argument* (UEA), and the *Meta-Inductive Argument* (MIA).

Cosmological inflation is a popular and promising theory that has emerged as an extension to the standard hot big bang model of cosmology. This theory proposes that the universe underwent a period of dramatic, near exponential, expansion very early on in its history. While its advocates highlight inflation's ability to cleanly and efficaciously account for long-standing puzzles in cosmology, as well as tout some empirically successful predictions, direct empirical confirmation of the theory has proven to be somewhat elusive despite expectations to the contrary from some members of the physics community. Inflation is thus an ideal candidate for Dawid's MEA programme.

In this chapter, I will evaluate the meta-empirical assessment prospects for the theory of cosmological inflation. I will argue that the theory has the potential to sustain an impressive UEA argument, but that it is somewhat premature to firmly assess it on the basis of an NAA argument as assessing the viability of alternatives has yet to fully play out within the physics community; which for the most part largely concurs with Dawid and McCoy (2023) (see also McCoy (2021)). However, I will disagree with Dawid and McCoy's assessment of the MIA argument as applied to inflation. In particular, I will closely examine arguably successful instances of MIA, including prominent examples from particle physics and cosmology, and demonstrate that inflation lacks the ingredients that makes these other MIA applications so compelling. In short, MIA-type reasoning for an unconfirmed scientific theory is most compelling when such a theory is strongly implicated by consistency arguments coming from the empirical evidence and the other well-confirmed scientific theories that it is drawing meta-empirical support from. Inflation, as I shall argue, does not quite fall into this category. While the theory has genuinely impressive achievements, its relationship to the theories that it seeks to draw MIA support from (the standard models of particle physics and cosmology) is driven primarily by explanatory considerations rather than by consistency arguments. This is significant because non-empirical confirmation of the type that the MEA programme envisions requires support from at least two (and preferably all three) arguments in order to get inference to the best explanation (IBE) or Bayesian reasoning off the ground so as to place non-trivial limitations on scientific underdetermination. Thus, I take the difficulties inflation has in multiple MEA dimensions to indicate that there is not (yet) a compelling non-empirical case for the confirmation of the theory.

This chapter proceeds as follows. In section §4.2, I recall the basics of the MEA programme and its original application to string theory. In section §4.3, I draw particular attention to the MIA argument by exploring arguably successful examples of this reasoning playing out in both particle physics and cosmology. In section §4.4, I apply MEA to inflationary cosmology, arguing that while it is premature to make an NAA-style argument for inflation due to currently viable alternatives, inflation does have an impressive UEA case. Furthermore, I argue that inflation has serious deficiencies with an MIA-tpye argument that is applied in its favor because in this context inflation succeeds primarily on its explanatory benefits, rather than through consistency-driven, empirically based inferences. In §4.5, I argue that while applying Dawid's programme to inflationary cosmology does not offer compelling meta-empirical confirmation of inflation, future developments could conceivably make the case for meta-empirical confirmation significantly stronger. I conclude in §4.6.

4.2 Meta-empirical assessment

MEA is comprised of three main arguments that work together to offer non-empirical confirmation to the theory under consideration. These are the *No Alternatives Argument* (NAA), the *Unexpected Explanatory Coherence Argument* (UEA), and the *Meta-Inductive Argument* (MIA) (Dawid 2013). In this section, I will review these arguments and how they collectively place limits on scientific udertermination, as well as examine how they are applied to string theory, the scientific theory that has been most often discussed in the context of this methodological programme.

4.2.1 Meta-empirical assessment basics

1. *No Alternatives Argument:* This argument holds that, when assessing a scientific theory, it is instructive to consider the number of potential alternatives that can offer satisfying accounts of the same phenomena, while also remaining coherent and consistent with other theories and general background knowledge. That is, one conjectures "a connection between the spectrum of theories the scientists came up with and the spectrum of all possible scientific theories that fit the available data [...] if a viable scientific theory exists and only very few scientific theories can be built in agreement with the available data, the chances are good that the theory actually developed by scientists is viable" (Dawid 2013, p. 51). If, after a long, exhaustive search, no other alternatives have emerged, this can indicate that there simply may not be viable alternatives that account for the phenomena in an equally satisfying manner.

   The obvious vulnerability with this line of reasoning is the prospect of unconceived alternatives. The human capacity for imagination, reasoning, and technical skill is certainly not infinite, leaving open the possibility that we are simply overlooking viable or even superior alternatives. In order for NAA to be a convincing argument, it needs to be supplemented with additional arguments in favor of the particular theory in question.

2. *Unexpected Explanatory Coherence Argument:* This argument points to instances where the theory in question provides additional explanatory power or enhances overall coherence with other theories and background knowledge, over and above what the theory was introduced to account for. This is a powerful argument in a theory's favor because it "mirrors the canonical reasoning for a theory's viability based on novel empirical confirmation" (Dawid 2013, p. 52) in that it provides novel explanatory power and coherence at the conceptual level and integrates the theory in question more fully with other phenomena and theories in our scientific background knowledge. An example of this would be the introduction of gauge symmetry into the standard model of particle physics. Gauge symmetries were introduced initially to solve the renormalization problem, but then also happened to provide a framework from which the entire spectrum of elementary particles could be explained and derived from purely theoretical arguments (Dawid 2013, p. 81).

3. *Meta-Inductive Argument:* This argument most closely resembles traditional models of empirical assessment. Here, one uses the empirically confirmed successes of other theories, models, or principles within the more general research programme or the empirically confirmed successes of particular components of the theory itself to infer that a theory is on the right track. There is a long history within the physical sciences of applying specific physical principles, problem solving techniques, and patterns of reasoning, and the empirical successes of these strategies speak to their viability even if a direct empirical test is not immediately available. "The empirical observations that provide the basis for MIA thereby increase the trust in so far empirically unconfirmed scientific theories which are supported by the given strategies" (Dawid 2013, p. 53). This amounts to making a "meta-inductive inference that regular predictive success in a research field justifies the assumption that future predictions of a similar kind will be correct as well. To be applicable the inference must rely on a reasonable understanding as to what can count as a prediction of a similar kind" (Dawid 2013, p. 55).

It is clear that these arguments are all mutually re-enforcing and become far more compelling when they are stacked together. Yet, it is important to stress that none of them is significant in complete isolation from the others. Indeed, history is replete with examples of theories that seemed either to be the only game in town, or offered impressive explanatory power, or were similar to previously successful strategies, but later turned out to be wrong. Crucially, "meta-empirical assessment needs to be based on at least two if not all three arguments in conjunction" in order to generate significant meta-empirical confirmation (De Baerdemaeker and Dawid 2022,

p. 344).

Individually, we can understand all of these arguments as placing some constraints on scientific underdetermination, or the landscape of possible theories that can adequately account for our observations. NAA explicitly limits scientific underdetermination by arguing that there is no viable alternative that can adequately account for the same phenomena. UEA and MIA can as well, but in a more restricted sense. For example, instances of UEA can indicate limits on scientific underdetermination within the theory's regime of applicability (i.e., the landscape of possible theories within that regime is limited to those that retain certain explanatory features), but does not necessarily rule out a more fundamental theory from retaining these merits. Similarly, MIA puts limits on scientific underdetermination because the number of theories that are potentially compatible with successfully established empirical or theoretical knowledge will necessarily be restricted in some ways as every further instance of confirmation rules out the potential theories that are not compatible with each subsequent empirical confirmation. Taking instances where these arguments are all present forces the scientist to question the plausibility that a particular theory, one that seems to have no viable alternatives that account for the phenomena in a satisfactory manner, and that offers remarkable unexpected explanations, and that benefits from empirical support at the meta-level, could actually turn out to be mistaken. We can intuitively understand that this will begin to strain credulity at some point after enough of this kind of "non-empirical" evidence has accumulated.

When at least two (and better yet, all three) of these arguments are present, Dawid argues that they collectively provide compelling instances of non-empirical theory confirmation. He argues that we can understand such confirmation as either *inference to the best explanation* (IBE) or *Bayesian confirmation*. IBE infers the viability of statements based on the criteria that they offer the best explanation for the observations in question (Bird 2007a; Lipton 2007). This applies to non-empirical theory assessment because placing significant limitations on scientific underdetermination through NAA, UEA, and MIA dramatically increases the likelihood of the theory in question providing the best explanation for the phenomena (Dawid 2013, p. 65). Typical Bayesian reasoning holds that empirical data that supports the theory in question raises the probability of the theory's viability. This process proceeds iteratively and is continually updated as more evidence comes in. As has been argued by Dawid, Hartmann, and Sprenger (2015), the core components of Bayesian reasoning function even if the evidence is not of the empirical kind. We can thus understand the limitations that NAA, UEA, and MIA place of scientific underdetermination to constitute the kind of evidence that causes us to update our probabilities regarding a theory's viability.[1]

4.2.2 MEA and string theory

Dawid initially developed MEA to account for both the strong degree of confidence that string theory has within the particle physics community and the comparatively cautious (to put it generously) attitude that other communities within the physical sciences have towards it. His analysis argues that the particle physics community had long been successfully using this kind of reasoning in developing the standard model of particle physics, which explains their relative confidence in the ultimate viability of string theory. As much of the literature surrounding this programme has been developed in the context of this string theory application, it will be helpful to briefly recall how these arguments are applied to argue for the viability of string theory as a way of seeing the programme in practice.

As with any discussion of string theory, perspectives are highly divergent. Dawid, as well as the string community more generally, maintain that string theory convincingly sustains a uniquely strong NAA argument. It aspires to a universal description of all known interactions in terms of the contemporary particle physics research programme. As is well-known, gravity is a non-renormalizable interaction, but upon dropping the idea of point particles and positing the extendness of elementary particles (strings), one can use the traditional methods of particle physics to universally describe all known interactions down to the Planck scale; furthermore, there seems to be no other viable way to accomplish this. Rovelli (2016) notes though, the strength of this NAA argument and the idea that string theory is the only game in town is very dependent on the set of assumptions a theorist is working under. As a researcher in such an alternative programme, he points out that "an alternative to string theory is loop quantum gravity, considered the "only game in town" by those who embrace it, under their set of assumptions" (Rovelli 2016, p. 2). What are the assumptions that give string theory the most plausible NAA claim? Crucially, there are good reasons to believe that moving from point particles to strings is the only way of extending the enormously successful quantum field theory principles and techniques to a theory that unifies and encompasses all four known interactions, while respecting fundamental principles such as causality and unitarity (Polchinski 2007a,b). That is, if one assumes that the universe and all of its interactions down to the most fundamental levels are correctly described by the gauge-symmetric, quantum theoretic principles used in construction of the standard model of

[1]Menon (2019) has argued that this Bayesian reasoning does not apply in the case of the NAA due to worries that obtaining significant, or "non-negligible confirmation", requires an implausible fine-tuning of the theory's priors. Dawid (2020) has responded by arguing that the "priors needed for making a no-alternatives argument significant are in line with what can be plausibly assumed in a successful research field".

particle physics, string theory does seem have an interesting NAA case. However, this assumes that none of the above principles need adjusting and that there are not further, as of yet unknown fundamental principles that become relevant at these scales.

Moving on to UEA, string theory is noted for producing a significant number of instances of unforeseen explanations and generating coherence with other areas of physics. For example, string theory not only makes gravity renormalizable, but also implies that the graviton, along with other fundamental particles, naturally emerges in a unified framework as different oscillation modes of the string (Dawid 2013, p. 33). As another example, black hole entropy can be understood within the string framework by counting the microstates in the string theoretic description of certain black holes, thus generating coherence with thermodynamic principles that have always been puzzling when applied to black holes and gravitational phenomena (Strominger and Vafa 1996).

The MIA argument for string theory is somewhat similar to the NAA argument because it follows from trusting the gauge and quantum field theory principles that are weaved into the standard model of particle physics. String theory emerged out of applying principles from quantum field theory to the study of fundamental interactions; these quantum field theory techniques and principles have seen spectacular success in the empirical confirmations of all the major components of the standard model. The empirical success of this programme in its totality provides non-empirical evidence for the viability of extending this programme to further interactions and higher energies, even if direct empirical tests of these extensions are not immediately available. However, it should also be pointed out that string theory has run into some difficulties in recent years. While not fatal blows, the failure to observe supersymmetric particles and the theory's (seemingly) generic prediction of a *negative* cosmological constant have put pressure on the theory (Rovelli 2016).[2]

Furthermore, that the standard model can provide meta-inductive support to string theory at all has been disputed by Chall (2018), who argues that MIA should not apply to successor theories because the empirical confirmation of the predecessor has already been accounted for as any successor theory *must* retain the successes of its predecessor. It should not double count as meta-empirical support. Thus, in the case of string theory, the success of the standard model would not offer MIA support to a successor theory such as string theory. In a response, Dawid (2020) points out that meta-level evidence is qualitatively different than empirical results that are

[2]The issue surrounding whether or not string theory allows for the construction of metastable de Sitter vacua, in contrast to the anti de Sitter vacua that lead to a negative cosmological constant, is contentiously debated within the string theory community to this day. See Cicoli et al. (2019) and Danielsson and Van Riet (2018) for reviews from both sides of this debate.

predicted by a predecessor theory because this meta-level evidence represents contingents facts that about the success of the research programme and underlying principles, facts that cannot be predicted by the either predecessor or successor theory.

Unsurprisingly, there is not a consensus regarding the degree to which string theory succeeds in its non-empirical (and empirical) merits. However, this discussion illustrates how these meta-empirical arguments function in the case of non-empirical theory assessment. As the MIA will feature particularly in this paper, we now turn to examine it a little more closely.

4.3 Exploring the meta-inductive argument

Recall that MIA is an *empirical* argument. That is, there must be a non-trivial, consequential connection between the hypothesis or theory that one would like to infer support for on the meta-level and the actual empirical evidence that one is citing in this inference. Crucially, "the inference must rely on a reasonable understanding as to what can count as a prediction of a similar kind" (Dawid 2013, p. 55). As the MIA case for string theory extrapolates from a predecessor theory to a successor theory at a completely different scale of fundamentality, this is not the most useful example of this kind of inference for the theory we are going to assess because inflation is not a more fundamental theory, but rather an extension of the current standard model of cosmology. In this section, we will explore examples of this inference that are more readily comparable to cosmological inflation, including the Higgs mechanism and prior instances of MIA within the field of cosmology itself. As we shall see, these examples cash out this inference between empirical evidence and meta-level support for an unconfirmed theory in particularly compelling fashion. More specifically, the empirical evidence is of such a nature that the unconfirmed hypothesis we infer meta-level support for is naturally implicated by a consistent application of the confirmed parts of the theory.

4.3.1 MIA example 1: the Higgs mechanism

The so-called Higgs mechanism was independently proposed by a number of researchers (Englert and Brout 1964; Guralnik, Hagen, and Kibble 1964; Higgs 1964) and performs a critical role in the standard model of particle physics as it does nothing less than account for the observed mass spectrum of the elementary particles.

In brief, the concept of gauge symmetry is fundamental to the standard model of particle physics as these symmetries are crucial for constructing renormalizable quantum field theories that allow us to make empirical predictions concerning particle interactions. Additionally, it provides a framework from which the spectrum of existing particles can be derived from the group representations attached to these gauge symmetries. Gauge symmetries (on a standard physics interpretation of the concept) are local symmetries, or symmetries that can vary from spacetime point to spacetime point such as the U(1) symmetry of electromagnetism.[3] When constructing the Lagrangian of the standard model, it turns out that introducing typical mass terms for elementary particles like electrons or W bosons spoils these gauge symmetries. This is incredibly inconvenient when all of these particles turn out to, in fact, possess mass.

This problem was solved with the addition of the Higgs field, a spin-zero scalar field, that couples to these particles. It preserves the important gauge symmetries present in the theory because this addition does not directly involve adding a mass term for any of the other fields in the theory's Lagrangian. However, it is energetically favorable for the potential of the Higgs field to rest at its minimum. When the field is at its minimum, it acquires a vacuum expectation value that, when realized in the theory, is an instance of spontaneous symmetry breaking. This vacuum expectation value of the Higgs field, through its coupling to the other fields in the theory, confers mass to the elementary particles. In particular, the way this mechanism is implemented preserves a massless photon (as expected), while providing a realistic mass spectrum to fermions and the rest of the bosons.

As this theory percolated within the particle physics community, physicists developed an extraordinary degree of confidence, or even certainty, in the viability of the Higgs mechanism, to the point that they invested billions of dollars and decades of effort in the Large Hadron Collider (LHC) to discovery the Higgs boson and explore its properties. Failure to find the Higgs boson would have been a full-blown catastrophe for the particle physics community.

Dawid argues that their confidence in the eventual confirmation of the Higgs mechanism comes about precisely through the types of non-empirical arguments used in his MEA methodology (Dawid 2013, p. 113). According to Dawid, the reasoning proceeds along the following lines. (i) Physicists needed quantum field theory to describe relativistic phenomena on the atomic and sub-atomic scales. (ii) Calculating particle interactions required renormalizable theories. (iii) Renormalizable theories necessarily possess a gauge symmetric structure. (iv) Gauge symmetric quantum field theories together with the existence of massive particles, require spontaneous symmetry breaking via the Higgs mechanism. Every one of these preceding steps (i-iii) involved spectacular empirical confirmations and the particles involved were known to possess mass. In

[3]This is in contrast to global symmetries, such as a rigid Galilean transformation, which act identically on each spacetime point. See Murgueitio Ramírez and Teh (forthcoming), Wallace and Greaves (2014), and Wolf, Read, and Teh (2023) for some discussions in the philosophical literature concerning the interpretation and empirical significance of local and global symmetries.

the absence of any viable alternatives, it was clearly epistemically warranted to extrapolate from these empirical successes of the standard model and have a high degree of confidence in the viability of the Higgs mechanism even before obtaining direct empirical verification of the Higgs itself. As we all know, the Higgs was recently confirmed and this event signaled the triumph of the standard model of particle physics (Aad et al. 2012)[4]. This serves as the paradigmatic example of Dawid's MEA programme at its best and the MIA argument in particular.

What is the exact nature of this inference and what relationship do the prior empirical successes of the standard model have towards the unconfirmed Higgs theory? Consider Dawid (2013, p. 112-113, my emphasis):

> "*The standard model just could not account for the occurrence of massive objects in the observed world if the Higgs sector was simply left out. Thus, the Higgs mechanism was an essential part of the standard model* and did not constitute an independent new theory in its own right...Nevertheless, it was based on a separable set of theoretical posits and its predictions could be distinguished from those based on other segments or principles of the standard model: it predicted at least one new particle and a certain structure of that particle's interactions with itself and with matter. The Higgs sector therefore constituted a separable "module" of the standard model, a kind of sub-theory whose viability could be discussed separately from the other parts of the standard model."

The part of the quote that I have emphasized identifies that the introduction of the Higgs mechanism was a matter of *empirical adequacy* for the standard model of particle physics. In other words, there was an *inconsistency* between the empirical success of the gauge symmetric quantum field theories of the standard model and the empirically observed mass spectrum of elementary particles that could only be reconciled with the Higgs mechanism. The standard model without the Higgs mechanism is not empirically adequate because it cannot account for the mass spectrum observed in fermions and bosons. Without the Higgs mechanism, the standard model describes these particles as massless, which plainly contradicts reality. It is not an exaggeration to say that the standard model would need to be abandoned without this modification. The mere fact that many of the most important predictions derived from the standard model can be aligned with the empirical data coming from particle physics experiments at all is inextricably dependent on the role that the Higgs field plays in the structure of the standard model.

[4]See Dawid (2015) for a discussion on some issues concerning the theoretical reasoning at play in interpreting the data that was used in this confirmation.

To be even more explicit regarding how this MIA inference works, the standard model of particle physics with the Higgs mechanism SMP_H (standard model with the Higgs boson) is constructed using all of the insight, principles, and strategies used in gauge symmetric quantum field theory. The empirical data O_{BH} (observations before the discovery of the Higgs boson) represents all the rich phenomenology explored in our particle accelerators before the Higgs boson was directly detected. In a traditional empirical methodology, SMP_H is understood to predict O_{BH} and the observations O_{BH} are taken to offer confirmation to the particular modules of SMP_H that are directly responsible for them (for example, discovering a particle based on observing its tracks and decay products in a scattering experiment would be seen as evidence for that particular component of the standard model). MIA holds that empirical observations O_{BH} are also understood to offer non-empirical confirmation to the general research programme as a whole because they validate the principles and components used in the whole construction, including the modules of SMP_H that did not yet have direct empirical confirmation O_H until the 2012 discovery. What is the connection between O_{BH} and H that justifies such an inference? This particular MIA inference between the empirical evidence O_{BH} and the unconfirmed module H is underwritten by the following: the fact that the predictions of SMP_H and the observations O_{BH} coincide is necessarily contingent on H. In other words, SMP does *not* predict a significant portion of O_{BH} without the addition of H. Drawing on O_{BH} to make a meta-inductive inference for H is thereby justified because H is required for the empirical adequacy of the standard model that explains and predicts O_{BH}. There is no consistent, empirically adequate standard model of particle physics without the Higgs mechanism. Even if direct observations of the Higgs mechanism took decades to produce, a significant portion of the empirical observations made in testing the standard model up to that point necessarily implicated the Higgs mechanism because it was the only way that those particular facets of the standard model could consistently be reconciled with the existence of the relevant mass spectrum of observed particles.

4.3.2 MIA example 2: applying general relativity to cosmology

Jim Peebles, a recent Nobel laureate and one of the preeminent figures in modern cosmology, has identified that non-empirical assessment played a major role in the history of cosmology both before and during his time in the field. Primarily, these meta-empirical inferences have involved trusting General Relativity (GR) over distance scales and in scenarios that were many orders of magnitude separated from the regimes that it was well-established in (Peebles 2020b, Ch. 1). Essentially, cosmology has taken a theory that was tested over solar system and terrestrial-type scales and extrapolated it more than 15 orders of magnitutde to describe the dynamics and evolution of the known universe. For the purpose of exploring how such inferences have worked in cosmology, I have identified two of many potential instances where non-empirical, meta-level support has been inferred from an empirically well-confirmed theory: the realization that the universe evolves dynamically and the existence of gravitational waves.[5]

4.3.2.1 The dynamical universe

Modern cosmology developed out of the theory of General Relativity, where Einstein (1917b) proposed the first relativistic model of the universe in 1917.[6] This was his static model of the universe, (in)famous for featuring his supposed "biggest blunder", the cosmological constant. Yet, dynamically evolving models of the universe were soon independently suggested by Friedmann (1922, 1924) and Lemaître (1927). In deciding between these two hypotheses, that of a static universe (the received view) and that of a dynamic universe, we can see evidence of MIA-type reasoning. The key realization, arguably obvious in Lemaitre's work, but first explicitly stated by Eddington (1930), was that Einstein's static universe is perturbatively unstable. This insight immediately renders the static universe a phenomenologically unviable description of the universe.

The reasoning proceeds as follows. GR had received impressive confirmation in a number of the classical tests of the theory, including the explanation of Mercury's perihelion and the prediction of the deflection of light rays observed in the 1919 total solar eclipse. This of course instills confidence in the general relativistic research programme and in its applicability to other, as of then untested, regimes. In applying GR to cosmological solutions, it becomes clear that static solutions are unstable and thus cannot represent an empirically viable description of the universe. Thus, we are confronted with two ideas: (i) GR's empirical confirmations within the solar system justify our confidence in extending the theory towards applications in other regimes, despite the fact that it had then not been tested at all within other regimes and (ii) a consistent application of GR to cosmological descriptions of the universe necessarily implies that the universe must evolve dynamically.

[5]It should be noted here that MIA was initially intended to apply to inferences involving the non-empirically confirmed theories and *other* empirically confirmed theories. However, I am grouping these novel applications of GR under MIA because the operative concept that is most important here is the *inductive risk* taken in extrapolating these theories across so many orders of magnitude, where the idea is that this inductive risk mirrors the inductive risk present when making an inference from the empirical successes of another theory or model in the research programme that utilizes similar strategies or concepts. It is this inductive risk that Peebles is referring to when he discusses the meta-empirical considerations used in cosmological research. Furthermore, if we think of GR as a research programme rather than just a theory, these novel applications to such different phenomena over vast orders of magnitudes are plausibly imagined as sub-modules of the overall relativistic research programme. Once confirmed though, these instances would count as examples of novel confirmation and could thus be categorized under the UEA argument. Before confirmation though, I would argue that they bear most resemblance to MIA due to the inductive risk present in this kind of reasoning.

[6]See O'Raifeartaigh, O'Keeffe, et al. (2017) for a historical review.

Einstein (1931) eventually proposed his own dynamical model of the universe, but also noted that the demonstration that his previous static model was unstable was sufficient grounds to reject it entirely independent of any other considerations; saying that "on these grounds alone, I am no longer inclined to ascribe a physical meaning to my former solution, quite apart from Hubble's observations" (translation from O'Raifeartaigh and McCann (2014)). The reference to the famous Hubble (1929) results concerning the apparent recession of spiral nebulae might make it seem as if Einstein is using a more tradition kind of empirical reasoning here. But, as Eddington (1930, p. 677) pointed out, "the proof of the instability of Einstein's model greatly strengthens our grounds for interpreting the recession of the spiral nebulae as an indication of world curvature" because at the time it was not clear if these nebulae observations were "local peculiarities" or "genuine expansion".

While it is certainly true that the empirical results helped turn the tide against the static universe, it is also true that the results were by no means conclusive at the time. Indeed, O'Raifeartaigh (2019) has argued that it was precisely this lack of conclusive, robust astronomical data that caused Lemaître's work to be initially overlooked, contrary to the usual assertion that his work was too obscure to be taken seriously. In this case, we can see evidence of MIA-type reasoning that led Einstein and Eddington to reject the static universe. They clearly extrapolated the prior empirical successes of GR to cosmological phenomena that did not yet have robust empirical results. Furthermore, they recognized that GR did not admit physically reasonable static possibilities. Applying GR on cosmological scales in an internally and externally consistent manner necessarily demanded a dynamically evolving universe. As we have seen, this reasoning actually influenced their interpretation of the limited empirical results available at the time.

This is slightly different from the Higgs example because the dynamical universe is a robust and unavoidable prediction of GR. It is not a separate module of the theory in the same way that the Higgs was a separable module that was later introduced for reasons of theoretical and empirical consistency. The connection between early empirical confirmations of GR and the theory or model of a dynamically evolving universe that warrants the inference of non-empirical support comes about from the fact that a dynamically evolving universe can be directly derived from GR itself. That is, a dynamically evolving universe naturally follows from a straightforward, consistent application of GR to regimes beyond where it had been tested.

4.3.2.2 The existence of gravitational waves

The history of gravitational waves (GWs) offers another example of MIA-type reasoning. Initially, Einstein doubted that they could exist at all given the non-existence of a gravitational dipole moment. However, the research community wavered back and forth on this question over the decades. Episodes include Einstein eventually deriving three types of GWs, Eddington demonstrating that two of them were pure coordinate artifacts and casting doubt of the existence of the third type, Einstein and Rosen concluding, but not publishing a paper that argued that GWs did not exist, and subsequent discussions between Einstein, Robertson, and Infeld that resulted in the opposite conclusion. Finally work from Pirani and Feymann provided more convincing theoretical justifications for the existence of GWs that inspired concrete interest in searching for them at the famous 1957 Chapel Hill relativity conference (Cervantes-Cota, Galindo-Uribarri, and Smoot 2016).

In their 1972 annual review, Press and Thorne (1972, p. 336) noted that it was regrettable that physicists spent decades doubting the existence of GWs, but that it was now understood that GR "predicts, unequivocally, that gravitational waves must exist; that they must be generated by any nonspherical, dynamically changing system; that they must produce radiation-reaction forces in their source; that those radiation-reaction forces must always extract energy from the source; that the waves must carry off energy at the same rate as they extract it; and that the energy in the waves can be redeposited in matter...".

Similar to cosmological solutions of GR indicating that the universe need be dynamical, GW were then understood as a robust prediction of GR and physicists had a high degree of confidence in eventually detecting them. The first two decades of such efforts were met with failure, but the discovery of the Hulse-Taylor binary, along with subsequent analysis of the orbital period decay, pointed to strong indirect evidence for the existence of GWs (Hulse and Taylor 1975; Taylor, Fowler, and McCulloch 1979). This paved the way for LIGO and VIRGO, the next generation of laser-interferometry based GW detectors, which culminated in the first direct detection of GWs in 2016 as these instruments detected a binary black hole merger (Abbott et al. 2016).

Discovering GWs required truly enormous investments of time, money, and resources, and in this regard, is similar to the Higgs discovery. However, as was the case with the dynamical universe, GWs are not a later supplemental module of the theory, but can be understood as a straightforward consequence of GR because they are directly derivable from the theory. That is, a consistent application of GR's theoretical and programmatic resources necessarily implies the existence of GWs. GR's tremendous empirical merits again legitimized inferring non-empirical support for other areas of the research programme that had not yet been verified, including to phenomena and regimes that had not yet been experimentally probed. The MIA argument justifies the enormous investment (monetary and temporal) and confidence from the community, despite not having any direct (or indirect) empirical evidence for GWs over multiple decades of somewhat frustrating failures.[7]

4.4 MEA programme and cosmological inflation

The theory of cosmological inflation was initially proposed by Guth (1981) and Starobinsky (1980). In its modern presentation, the basic idea is that very early in the universe's history, the matter-energy content of the universe was dominated by a scalar field. This scalar field has certain properties (i.e., its potential energy is the dominant contribution to the energy density and the potential has a functional form that is relatively flat) that effectively lead to an equation of state that generates a significant repulsive force in the form of negative pressure. This causes a rapid, exponential expansion of the universe's scale factor.

Inflation initially gained traction due to its ability to help resolve perceived explanatory problems in the standard hot big bang model and to provide a causal mechanism for generating density perturbations in the early universe (more on these issues in §4.4.2). Furthermore, as evidence from successive cosmological probes accumulated, these observations painted a picture of the universe that looks very much like the universe we would expect to see if inflation had occurred. Among other predictions, an inflationary epoch suggests that the universe should have the following properties (Guth 2004):

1. Geometrically flatness
2. Approximate uniformity in the distribution of its mass-energy content
3. Possess density perturbations with very particular statistical properties: nearly scale-invariant (i.e., approximately independent of length scale), Gaussian (i.e., normal distribution), and adiabatic (i.e., independent of matter-energy species).

Briefly, we can understand that these predictions naturally follow from inflation because a period of rapid spatial expansion will dynamically flatten the universe and smooth out inhomogeneities. The properties of density perturbations are a bit more involved, but they follow from treating the

[7] Indeed, this has paid off tremendously as we are only in the very beginning of what promises to be a long and fruitful era of gravitational wave astronomy. Gravitational waves have been and will continue to be used to explore the strong gravity regime, alternative theories of gravity, structure formation in the early universe, astronomical processes via multi-messenger signals, etc. See, e.g., Bailes et al. (2021), Baker et al. (2017), Barausse et al. (2020), and Wolf and Lagos (2020) for some discussions and applications.

scalar field responsible for inflation quantum mechanically (as discussed in Chapter (1)). These density perturbations are crucial to our description of the universe because they generate cosmic structure (i.e., clusters, galaxies, stars etc). Measurements from WMAP and Planck indicate that the universe we observe in the Cosmic Microwave Background (CMB) is in very close agreement with these 'generic predictions' (Aghanim et al. 2020b; Guth, Kaiser, and Nomura 2014; Spergel et al. 2003).

While this is certainly a nice story so far, it is no surprise that things get a bit more complicated. One complication is that there is a truly enormous variety of inflation models, many with wildly diverging physical motivations, implications for cosmology and particle physics, and empirical predictions. One of the most comprehensive surveys in the literature counts 74 different models of "simple" single-field inflation (Martin, Ringeval, and Vennin 2014), *not* including many other more complicated scenarios such as multi-field inflation. In other words, inflation is more of a framework or paradigm than an actual theory. In practice, actually confirming one of these models will prove to be difficult. While the predictions listed above are very generic within the inflationary paradigm, there is significant variety in other predictions that come from different inflationary models. Most importantly, in addition to density perturbations, inflation also produces tensor perturbations in the form of primordial gravitational waves. The crucial observational signature for these tensor perturbations is the so called 'tensor-to-scalar ratio' r (Baumann 2009, Sect. 3), which measures the ratio of amplitudes between tensor perturbations (i.e., primordial gravitational waves) and scalar perturbations (i.e., density perturbations of matter). Measuring this quantity (as well as others such as the 'spectral index' n_s, which quantifies the exact scale dependence of the scalar perturbations) ideally would provide an excellent opportunity to discriminate between distinct models and potentially provide further evidence for inflation, but as mentioned earlier in this thesis, there are quite significant challenges in any attempt to do this.

Unfortunately, despite significant efforts to detect this quantity (which included a prominent false positive (Cowen 2015)), primordial gravitational waves have not been detected, with Planck placing upper bounds on r, disfavoring many of the simplest inflationary models. While there are many surviving models and the paradigm is still considered to be on very strong footing by the majority of the physics community (Chowdhury et al. 2019; Guth, Kaiser, and Nomura 2014), the class of models favored following these results are known as "plateau inflation" (Martin, Ringeval, Trotta, et al. 2014). Such models have been criticized by skeptics of inflation as being somewhat less appealing considering that they require more parameters to generate the relevant observables and require more finely-tuned initial conditions to get the inflation off the ground

(Ijjas, Steinhardt, and Loeb 2013).

While not yet a full-blown crisis, the somewhat unexpected, persistent difficulty in nailing down direct empirical support for a particular inflation model and the trend towards seemingly more complicated models based on the constraints we do have, has caused a minority of physicists to question the status of the inflationary paradigm. Furthermore, it seems like truly *conclusive* empirical tests of inflation are currently beyond our experimental capabilities, which has led Dawid to the conclusion that "assessments of the status of inflationary cosmology will most probably have to rely heavily on assessments of scientific underdetermination for a long period of time" (Dawid 2013, p. 91). In a more recent article that attempts to adjudicate some of the recent debates between members of the physics community who favor inflation and those who have wavered, Dawid and McCoy (2023) more explicitly argue that we should turn to MEA to assess inflation given the current status of the empirical picture. Following this suggestion, I will engage with the MEA assessments offered by Dawid and McCoy as well as provide my own MEA assessment for inflation, beginning first with NAA and UEA, before proceeding to MIA.

4.4.1 No alternatives argument

Inflation is the dominant paradigm in early universe cosmology and is generally considered to be the best theory for providing robust, convincing explanations for the various problems encountered earlier. Yet, recent difficulties with the paradigm have caused some notable members of the community to approach alternatives with renewed energy. The most prominent alternatives in the literature at present are bouncing cosmologies, with a particular emphasis on "ekpyrotic" bouncing cosmologies (Ijjas and Steinhardt 2018, 2019; Steinhardt and Turok 2002a,b). Other bouncing alternatives include the Matter Bounce, String Gas cosmology, and the Pre-Big-Bang scenario (Brandenberger and Peter 2017).

All of these alternatives *can* solve the problems that inflation addresses, the question rather becomes at what cost do these models solve these problems and do they represent reasonably adequate, viable alternatives? Here we appeal to Kuhn (1977) and his model of theory choice, whereby scientists weigh objective theory virtues such as empirical accuracy, scope, and simplicity/parsimony according to their own subjective preferences.

Briefly, consider how an ekpyrotic model handles issues we have seen like homogeneity, flatness, and scalar density perturbations. An ekpyrotic model induces contraction within the universe through a scalar field with a steep, negative exponential potential (rather than a flat, positive potential). It turns out that slowly contracting universes lead to remarkably similar outcomes as those expected from rapidly expanding universes, as the slow contraction dynamically flattens the universe and produces uniformity in the matter-energy distribution.[8] However, when contraction reverses and the universe enters an expansion phase similar to the one we are currently experiencing, these models often encounter catastrophic "ghost instabilities". These particularly nasty pathologies result from an unbounded Hamiltonian that both renders the theory perturbatively ill-defined and allows for the infinite production of particle states at arbitrarily high energies (Rubakov 2014; Wolf and Lagos 2019). As cosmological models with such pathologies are not considered to be phenomenologically viable, proponents of bouncing models have found ways to avoid them by introducing more complicated dynamics by modifying gravity (Cai and Piao 2017; Easson, Sawicki, and Vikman 2011; Ijjas and Steinhardt 2017). Additionally, ekpyrotic models can produce the observed, nearly scale-invariant spectrum of scalar density perturbations, but it turns out that an additional scalar field is needed to realize this (Brandenberger and Peter 2017). Proponents of inflation have argued that these are serious problems, and if they can be overcome at all, require inordinately difficult and poorly motivated modifications to evade them (Kallosh, Kang, et al. 2008; Linde, Mukhanov, and Vikman 2010; Linde 2015). Wolf and Thébault (2023) have identified this kind of "dynamical fine-tuning" as a major reason why physicists' tend to have a general distaste for such bouncing models (more on this in Chapter (5)).

Despite these complications that call into question the parsimony of such models, bouncing models do have some advantages over their inflation competitors. For example, Hollands and Wald (2002) and Penrose (1989) have forcefully argued that the inflationary paradigm encounters a significant conceptual problem. Any universe emerging out of an initial singularity would naturally be expected to possess a very high entropy. Furthermore, a state with entropy this high would be incompatible with the occurrence of inflation while the possible initial states that could be compatible with inflation seem to be vanishingly small in comparison. On the contrary, these ekpyrotic models are constructed to be non-singular and thus evade this specific issue concerning the entropy. Another advantage comes about from the fact that these kinds of bouncing models predict that there should not be significant production of primordial gravitational waves (Ijjas and Steinhardt 2018), meaning that they are very easily made consistent with the aforementioned Planck results.

The significance of all these issues for both paradigms is an open issue and actively debated in the physics community. Furthermore, the philosophy literature has waded into this debate as well, with Dawid and McCoy (2023) providing a philosophical analysis of the ongoing debate and Wolf

[8]See Ijjas and Steinhardt (2018) for explanation on contraction dynamics and a comparison with inflationary dynamics.

and Thébault (2023) offering a philosophical analysis comparing the explanatory merits of both approaches. Ultimately though, resolution will come from the technical results and subjective judgment of individuals within the theoretical physics community. In other words, the ultimate outcome of the NAA for inflation "must play out largely among the physicists involved in the corresponding research programs" (Dawid and McCoy 2023, p. 28). The takeaway though, is that at present there are actively pursued alternatives that are empirically adequate, viable options, even if the judgment of the community as a whole still (understandably) finds inflation to be more desirable according to their theory choice preferences. With the current status quo, it does not seem like one can draw any firm conclusions regarding the status of an NAA argument in the context of early universe cosmology. Chapter (5) will further explore these issues from the perspective of examining the various explanatory merits of these approaches.

4.4.2 Unexpected explanatory coherence argument

On the other hand, the UEA argument for inflation is particularly strong. Indeed, all of the generic predictions listed in the beginning of §4.4 can be plausibly understood as contributing to this argument. The original proposals for inflation emerged from exploring the consequences of ideas in high energy particle physics and applying them to a cosmological context. For example, Guth (1981) was investigating the cosmological consequences of phase transitions in grand unified theories, while Starobinsky (1980) was investigating potential contributions from quantum mechanical corrections to GR in the form of higher order curvature terms that could be relevant in the high energy density environments of the early universe. They found that their investigations pointed to the conclusion that the universe might have undergone an inflationary period of exponential ('quasi-de Sitter') expansion.

However, it was Guth who quickly realized that the dynamics resulting from the phase transitions he was investigating could offer a resolution to the classic puzzles of standard hot big bang cosmology. As mentioned earlier, the *horizon problem* and the *flatness problem* stand out.[9] The *horizon problem* refers to the fact that the universe is remarkably uniform over large scales, to the point that CMB measurements have revealed that the universe has a uniform temperature of 2.73 K, with average variations of 1 part in 100,000 across the sky. The scales that homogeneity holds over are so large that the vast majority of the universe is not within a common causal horizon, leaving the question of how distant points, points that do not share a causal past, could display such remarkable uniformity. The *flatness problem* refers to measurements that indicate

[9]Again, following standard presentations of the subject found in Baumann (2009, 2022), Mukhanov (2005), and Weinberg (2008a).

that the universe is nearly spatially flat today. This is surprising because an exactly flat universe corresponds to a very particular critical density value for the matter-energy content in the early universe, with any deviation from this value being an unstable fixed point that would lead the universe to rapidly diverge from spatial flatness. The fact that the universe is still so remarkably close to flatness today indicates that this critical density value needed to be extraordinarily special.

Inflation, despite not being specifically designed to solve these problems, immediately provides compelling explanations for these observations. Inflation resolves the horizon problem and explains large scale uniformity. It indicates that the universe actually did have a common causal past; such extreme expansion makes it only *appear* today as if very distant points are outside each other's past light cones. Furthermore, exponential expansion smooths out any inhomogeneities and produces uniformity. The flatness of the universe is also no longer a mystery because this extreme stretching of space will naturally flatten the universe, almost regardless of what its initial curvature or matter-energy density was.

Perhaps inflation's most important accomplishment, if its turns out to be correct, is providing a theory that explains the origin of density perturbations. Before inflation, cosmologists could provide a purely phenomenological account of cosmic structure, but there was no predictive theory of its origin or properties (Smeenk 2018). However, it was also quickly realized that inflation provides a compelling origin story for these density perturbations in the form of a causal mechanism that generates them (i.e., tiny quantum mechanical variations in the inflation field) (Bardeen, Steinhardt, and Turner 1983; Guth and Pi 1982; Hawking 1982; Mukhanov and Chibisov 1981). Inflation remarkably connects the observed large-scale structure of the universe to tiny quantum fluctuations during this period of inflation. As the theory was not engineered to produce this result, inflation unexpectedly provided a powerful, causal, and remarkably coherent explanation of the observed large-scale structure of the universe. "Rather than pulling the initial spectrum out of a hat, as one might suspect of the earlier proposals, the inflationary theorist can pull a [nearly scale-invariant] spectrum [...] out of the vacuum fluctuations of a quantum field" (Smeenk 2018, p. 9).

Another potential instance of UEA, pointed out by Dawid and McCoy (2023), concerns the potential for inflation to provide an explanation for the value of the cosmological constant. As the inflation paradigm strongly implies a multiverse framework known as 'eternal inflation' (see Aguirre (2007) and Guth (2007) for a physics review of eternal inflation and its implications), it can be argued that this framework, in conjunction with anthropic reasoning, provides the most reasonable explanation for the particular value of the cosmological constant. While the merits of this instance of UEA will no doubt depend on one's thoughts regarding the multiverse issue and the validity of anthropic reasoning, this serves as another potential example of UEA for the inflationary paradigm.

4.4.3 MIA argument and cosmological inflation

As mentioned before, MIA is an empirical argument that relies upon connecting the hypothesis or theory that one would like to infer meta-level support for to the actual empirical evidence that one is citing in this inference. And in doing so, we need "a reasonable understanding as to what can count as a prediction of a similar kind". The theory of cosmological inflation is a natural outgrowth of both particle physics and general relativity, so it makes sense to consider if the inference made in support of inflation is of a similar kind to other successful inferences within these research programmes. For the Higgs mechanism, this inference between empirical support and theory relied upon the role that the Higgs mechanism played resolving an important inconsistency between observations and the standard model in a manner that was integral to achieving empirical adequacy. For the examples from cosmology, the inferences relied upon consistently applying GR (an empirically successful theory) to regimes and phenomena that had yet to be tested.

At first glance, the introduction of inflation into the standard model of cosmology seems most similar to the introduction of the Higgs mechanism into the standard model of particle physics. The inflaton field and the Higgs field are both scalar fields built using standard quantum field theory machinery, and they were both attached to their respective theories in order to solve outstanding problems and provide explanations for observations that were puzzling given the theoretical frameworks the respective communities were operating within. Furthermore, there is not a sense in which a field that serves the specific role or has the particular properties that we expect of the inflaton is directly derivable from established knowledge in either the standard model of particle physics or the standard model of cosmology.[10] For example, trusting in the merits of GR following significant empirical confirmations necessarily entails that the universe evolves dynamically and that GWs exist because these are straightforward consequences of the theory. Inflation does not follow this pattern in any sense when viewed from either the particle physics or cosmology angle. Like the Higgs mechanism, the inflation hypothesis is an addition to the standard model of cosmology. Thus, it is most natural to compare the MIA argument for inflation to the MIA argument for the Higgs mechanism.

[10]There is one possible exception to this statement that will be discussed in Chapter (6). This exception relates to the possibility of the Higgs field itself being responsible for inflation; however, the Higgs inflation scenario requires a further modification to the standard model of particle physics.

Dawid and McCoy (2023) briefly sketch an MIA argument for cosmological inflation by arguing that MIA support for inflation can be identified in both of the particle physics and cosmology research traditions. On the particle physics side, they argue that the predictive success of particle physics and its underlying principles instills trust in our abilities to construct successful scalar potentials within the framework of quantum field theory. This presumably refers to the historically successful example of the Higgs field (an empirically verified scalar field) and to the fact that fully nailing down any serious candidate for the inflaton will involve probing this field's interactions with established particle physics knowledge. From cosmology, they point to Peebles' identification of previous instances of successful non-empirical assessment in cosmology, instances that involved trusting GR on far larger distance scales than had ever been empirically probed before (Peebles 2020b). They argue that this licenses inflation theorists to trust the conjunction of GR and particle physics inspired inflatons at the energy scales relevant to inflation and the very early universe.

Unfortunately for inflation, these general arguments do not quite work because there is an important disanalogy between a theoretical extension like inflation and a theoretical extension like the Higgs mechanism. As we have seen, the Higgs mechanism is not merely an important component of the standard model of particle physics, but rather it is *essential* for the empirical adequacy and consistency of the whole model. Can the same be said about inflation and its relationship to the standard model of cosmology? In other words, do the demands of empirical adequacy and consistency *necessitate* the introduction of inflation to the standard model of cosmology?

The answer, which may be surprising to some given the amount of attention that inflation receives, is most certainly not, and this is readily acknowledged by both physicists and philosophers. As Baumann (2009, p. 25) notes, "the flatness and horizon problems are *not* strict inconsistencies in the standard cosmological model" and that with the right initial conditions for the density parameter and inhomogeneities the big bang model certainly accounts for the present observational picture (see also Guth (1997, p. 184)). Earman and Mosterin (1999, p. 13), in an early philosophical assessment of inflation, likewise conclude that "the basic motivation for the inflationary paradigm comes from alleged inadequacies with the standard big bang model. It is far from clear to us that these are indeed genuine difficulties since they have to do not with empirical adequacy but with styles of explanation".

Earman and Mosterin point out that the explanations afforded by the big bang model are not obviously deficient according to the standard accounts of explanation. Additionally, they argue that these explanations are perfectly coherent with the most influential account of explanation in the literature: the deductive-nomological (D-N) model (Hempel and Oppenheim 1948). This model holds that for a given explanandum, a sufficient explanans results from the combination of appropriate initial conditions and dynamical laws. We can use both the currently observed conditions in the universe and the dynamical Einstein field equations to retrace the evolution of the universe and determine the unique initial conditions immediately after $t_i = 0$. We can then demonstrate how these initial conditions produce the universe we see today by rolling them forward to t_f again by applying the dynamical Einstein equations. This is a perfectly acceptable explanation in virtually any other dynamical problem in the physical sciences.[11] Why should standard applications of initial conditions and dynamical laws be so egregiously problematic in cosmology?

Before proceeding, it is important to emphasize that just because a theory or model is empirically adequate or can be understood to satisfy some philosophical model of explanation, this does not mean that it is not deficient in some way. Physicists are clearly dissatisfied with the big bang model because of the *fine-tuning* of initial conditions needed to make it work. Indeed, fine-tuning can amount to an empirical problem that rises to the level of an inconsistency that demands a resolution. However, there are many different types of fine-tuning and it is important to distinguish examples of fine-tuning that simply are contingent facts about the way things are as opposed to those that demand some kind of important explanatory resolution. As Hossenfelder (2019) has emphasized, there are many assumptions within our theories, ranging from the particular values certain dimensionless parameters take (among all possible values) to the particularly sets of mathematically consistent axioms we use (among an infinite number of choices), that are there simply because they adequately describe nature. No one denies that it is appealing to find explanations for these sorts of things and that it is worth searching for them, but they do not necessarily "scream for explanation" in the same manner that the most egregious instances of fine-tuning do.

When exactly does fine-tuning "scream for explanation"? Hossenfelder (2019) argues that fine-tuning screams for an explanation precisely when we have a well-defined probability distribution that allows us to clearly quantify the unlikeliness of what we are observing. For example, if we observed a significant deviation from the predictions of thermodynamics, a standard D-N explanation that the combination of initial conditions and dynamics just happened to produce an unlikely state would obviously be deficient. Observing gross violations of the Born rule would be

[11] Of course, the D-N model is known to have many problems and the model as initially conceived cannot be the full story on scientific explanation for many reasons that have been discussed ad nauseam in the philosophical literature. However, it is a good starting point that seems to reasonably capture the essence of scientific explanation in at least some cases; typical dynamical explanations included. Thus, it serves as a nice illustrative example. We will explore explanation further in Chapter (5).

similarly shocking. These instances would demand some further explanation because this kind of fine-tuning becomes an *empirical problem* that can be cashed out in terms of careful probabilistic reasoning that empirically predicts what we should (and should not) be observing.

Does the big bang model exhibit this kind of fine-tuning? McCoy (2015, 2018) has explored this question in some detail, and argued that the physics literature largely lacks substantive justification for its interpretation of these initial conditions as "improbable". Additionally, arguments that these conditions are truly unlikely or egregiously problematic must rely on defining a suitable probability measure. Such probability measures in cosmology cannot be defined without introducing arbitrary cut-offs to regularize for divergent integrals and furthermore, the resulting verdict is very sensitive to such arbitrary choices (Schiffrin and Wald 2012b). These problems are intimately related to the infinite dimensional phase space of GR (even in the case of the "minisuperspace" that, roughly speaking, restricts itself to FLRW spacetimes). It is not clear that a probability measure can be chosen in any physically meaningful way (Curiel 2015).

Given that this clear line of probabilistic reasoning is blocked, one can appeal to more qualitative analyses of fine-tuning. For example, Baras (n.d.) argues that fine-tuning calls for an explanation when it instantiates an *extraordinary* type, which can be understood as a fact that is contrary to what we would expect given our background knowledge. One can easily argue that this characterization applies to the problems in the big bang model given its issues with dynamical instability and causality, as these immediately strike us as deeply puzzling, if not unsettling. However, this certainly does not rise to the level of an inconsistency that impinges upon the empirical adequacy of the model as we saw in the example of the Higgs mechanism. This does not deny that inflation offers significant gains in coherence and explanatory power (see, e.g., Wolf and Duerr (2023, Sect. 4); Wolf and Thébault (2023, Sect. 3&4), and Chapter (5))[12]; however, such merits (as tremendous as they are) are arguably more plausibly viewed as being indicators of reasons to *pursue* a theory (Laudan 1977; Nyrup 2015; Šešelja and Straßer 2014), rather than offering some type of *confirmation*.

Despite inflation being a natural extension of both standard models of particle physics and cosmology, making an MIA-style argument for inflation would require inferring support for inflation primarily on the basis of our explanatory preferences, rather than on the empirical success of and consistency with well-established theories that would be cited in such support. This does not mean that MIA arguments cannot work in instances of fine-tuning, but rather that it is important

[12]Coherence and explanatory power also play a significant role in other debates within contemporary cosmology. See Duerr and Wolf (2023) for an analysis of the MOND/Dark Matter debate with a particular focus on the coherence (and ad-hocness) of these proposals.

to consider whether the fine-tuning present represents something that can be reasonably characterized as a contingent fact or represents some kind of empirical failure or inconsistency in the current standard model.

The empirically observed state of the universe does not warrant as significant of an MIA inference in favor of inflation as it did in the Higgs example precisely because this observed state cannot be understood to represent an *inconsistency* with the current standard model that bears upon the empirical adequacy of the framework; without such an inconsistency, an MIA-type inference to inflation lacks the bite that the inference to the Higgs mechanism so clearly has. Furthermore, the empirical and theoretical evidence one needs to cite in such an inference simply does not *demand* a resolution with the same urgency or point to a unique solution with the same force. Nor can inflation be understood to be a directly derivable consequence from an empirically well-established theory as we saw in the examples of the dynamically evolving universe and the existence of gravitational waves. In these previous examples of MIA, consistency arguments directly tied to the empirical evidence itself necessarily implicated the unconfirmed theories we inferred MIA support for. The same cannot be said for inflation. Inflation's explanations are indeed far better and more satisfying, but the aesthetic appeal of inflation's explanatory merits is more properly understood as a (very compelling!) reason to enthusiastically pursue the theory further (Wolf and Duerr 2023).[13]

Applying MIA to inflation is not very convincing despite offering significant explanatory advantages over the standard model without inflation. Along with an inconclusive NAA argument, there is not a convincing case for ascribing significant non-empirical confirmation to the theory of cosmological inflation because two of the three arguments needed to generate significant limitations to scientific underdetermination are fairly weak.

4.5 Future meta-empirical prospects for inflation

To this point, we have seen that successful examples of MIA-type reasoning for a particular hypothesis in cosmological and particle physics contexts have followed two patterns. (i) The hypothesis is inextricably tethered to both the empirical adequacy and consistency of the larger research programme. (ii) The hypothesis is a directly derivable consequence of an underlying theory or framework that has robust empirical support. As I have argued, inflation is a poor fit for (i) because inflation is not required for the consistency or empirical adequacy of the rest of

[13]Cabrera (2021) has argued that MEA should be reworked as a programme that belongs to the context of pursuit rather than justification or confirmation. I am sympathetic to this argument. As indicated in this section, I think that the MEA case for inflation would be significantly stronger if the MEA arguments were construed as arguments for pursuit.

the cosmological research programme, in marked contrast to the role that the Higgs mechanism plays in the particle physics research programme. Additionally, (ii) does not work either because neither of the standard models can be understood to necessarily entail inflation, as inflation is rather a separable extension of these programmes.

However, this does not mean that future developments do not have the potential to make an MIA-style argument for cosmological inflation more compelling. Indeed, there are conceivable future scenarios that could bring inflation into closer alignment with either (i) or (ii), and in doing so render inflation “a prediction of a similar kind”, where the empirical considerations more directly warrant an inference for an inflationary epoch. For example, there is arguably a scenario where further empirical observations would make the relationship that inflation has to the standard model of cosmology more analogous to the relationship between the Higgs and the standard model of particle physics. This involves the aforementioned tensor-scalar ratio r and a positive detection of primordial gravitational waves.

Detecting these primordial gravitational waves, or tensor perturbations, is considered to be a holy grail for cosmology because measuring their properties has the potential to put powerful constraints on early universe theories. One reason for this is that such gravitational waves would be measured through detecting a so-called ‘B-mode’ pattern of polarization, which is significant because it can be proven that *only* tensor perturbations produce B-mode polarization, whereas scalar perturbations *only* produce E-mode polarization (Kamionkowski, Kosowsky, and Stebbins 1997; Zaldarriaga and Seljak 1997). The upshot is that there are only a few known processes that could produce such signals, and the processes that could produce these signals are clearly delineated from those that create the scalar perturbations we have already measured.

While a positive detection would clearly point towards one of these processes, the mere detection of primordial gravitational waves would not uniquely single out inflation as is commonly believed. Indeed, Brandenberger (2011a) notes that such signals can be produced both in some versions of bouncing cosmologies (depending on details of the contraction phase before the bounce) and even in standard big bang cosmology (through global phase transitions known as cosmic strings). However, the particular properties of these gravitational waves very well could eliminate these candidates. For example, bouncing models that produce significant amounts of gravitational waves also would induce particular non-Gausianities in the statistics of the signal (Brandenberger 2011a), while gravitational waves sourced by cosmic strings in standard big bang cosmology would vanish over superhorizon scales due to causality constraints (Baumann and Zaldarriaga 2009). Thus, a positive detection of primordial gravitational waves, combined with the right properties in the gravitational wave spectrum, could very well point to an inflationary epoch and even indicate the energy scale of such a period, as well as constrain the shape of the inflaton potential (Baumann 2009).

In this scenario, there would be a much stronger case that the standard model of cosmology *must* invoke cosmological inflation to maintain its empirical adequacy (see also Smeenk (2017) for philosophical analysis along similar lines). After all, the presence of empirical signatures that cannot be produced in any known way in standard big bang cosmology would seemingly render the standard model empirically inadequate in its account of the observations, and indicate that an extension such as inflation is necessary. Such a scenario would arguably resemble the kinds of consistency arguments we have already seen much more closely. Furthermore, this would also likely eliminate alternative theories and create a much stronger NAA argument as well.

Some might even be tempted to say that this would constitute direct proof for the inflaton. Yet, the inflaton is most often viewed as an additional matter field that falls within the purview of standard quantum field theory and particle physics, and this should inform our standards of direct proof. Traditionally, most other fields in particle physics have been probed with deep inelastic scattering experiments, whereby they are directly 'observed' via particle traces extracted from the detectors and inferred through the decay products resulting from such collisions. However, as is detailed by Dawid (2015), the actual process of confirming the Higgs boson involved many interesting complications due to the fact that it is electrically neutral and consequently does not produce a trace in the detector. This meant that subsequent decay events could not be uniquely attributed to a single vertex in a scattering event as observations allowed for multiple possible explanations for the observed decay products. This required the existence of the Higgs boson to be established statistically based on examining the number of events observed vs. what would be expected in a background without the Higgs. Confirming the inflaton via traditional particle physics experimentation would not merely be far more challenging than these complications with the Higgs, but is actually considered by most to simply not be within the realm of possibility due to the $\sim 10^{15}$ GeV energies inflation is believed to have occurred at; energy scales that lie far outside the realm of terrestrial collider experiments.

If r could be measured and the inflaton potential and energy scale could be meaningfully constrained, this may force a re-assessment of what it means for a particle or field to be confirmed experimentally. However, even if it is not realistic to confirm the inflaton in the *exact* same manner as we did the Higgs or other standard model particles, there are proposals within the field of cosmology that would offer something fairly analogous.

For example, exploring the physics of reheating would be a significant step towards this goal. Reheating refers to the epoch immediately after inflation, where the inflaton field oscillates around the minimum of its potential, decays and transfers its energy into the creation of other particles, and thereby produces the matter-energy content that populates the universe during the early radiation dominated stage (Martin, Ringeval, and Vennin 2015). Thus, we may gain information regarding how the standard model fields we know couple to and interact with the inflaton, and how these interactions and byproducts of reheating inform our expectations for early universe observables. Another possibility known as "cosmological collider physics" has recently emerged, with the idea being that the inflationary epoch might have excited entirely new fields and created particles we are not familiar with that have masses comparable to the Hubble scale (Arkani-Hamed and Maldacena 2015). The idea is that these interactions and subsequent decays would leave statistical imprints on the scalar perturbations in the CMB, in analogy with how collider experiments leave statistical imprints and patterns that can be measured on detectors. While the details of all of these proposals are somewhat speculative and have yet to be fully ironed out, it is not inconceivable to think that they could offer something more analogous to the way in which other fields and particles are understood to have received direct empirical verification. (Although, keep in mind that this does *not* mean that any of these would uniquely single out inflationary microphysics. As discussed in Chapter (2) and Chapter (6), the observable parameter space is so unconstrained that this is very hard to envision.)

Before more direct proof could be obtained though, inflation could plausibly be understood to have a much stronger argument for non-empirical confirmation under the scenario explored at the beginning of this section, where the detection of primordial gravitational waves indicates, as a matter of necessity, that such an inflationary epoch must be grafted onto the standard ΛCDM model to resolve an important empirical inconsistency.

4.6 Conclusion

Meta-empirical assessment and confirmation is an interesting new methodological tool in the philosophy of science. There is evidence that this type of reasoning has played a significant role in developing the standard models of both particle physics and cosmology; however, meta-empirical considerations will become even more important in the future as theorizing becomes ever more detached from timely empirical exploration. The theory of cosmological inflation is a fascinating addition to the standard model of cosmology that has the potential to unify phenomena at large and small scales, as well as provide compelling explanations for the observed state of the universe.

However, as of now, inflation does have viable alternatives, limiting the appeal of an NAA-type argument. Additionally, inflation fails to support a compelling MIA-type argument (judging from the standards of other more compelling instances of MIA) because the current state of empirical observations does not implicate inflation to the same degree seen in other relevant successful instances of MIA. Future observations could very well pave the way for a more compelling non-empirical confirmation case for inflation. For the time being though, lacking two of the three main pillars of the MEA programme, it is premature to ascribe a strong degree of non-empirical confirmation to inflation.

5 | Explanatory depth in primordial cosmology: a comparative study of inflationary and bouncing paradigms

5.1 Introduction

A heated debate has raged in contemporary cosmology regarding the scientific merits of the dominant inflationary paradigm. A small, but influential, minority of cosmologists have both questioned the justificatory basis for the predominate position of inflation and argued for an alternative paradigm based upon bouncing cosmological models. One axis of this debate relates to the comparison between the two approaches with regard to empirical support both in terms of the *prediction* and *accommodation* of evidence. Most vividly, dispute along this axis has played out in exchanges between Ijjas, Steinhardt, and Loeb (2013, 2014) and Guth, Kaiser, Linde, et al. (2017) and Guth, Kaiser, and Nomura (2014). This aspect has recently received a detailed philosophical analysis from Dawid and McCoy (2023).

Another axis of this debate concerns the relative *explanatory* merits of the two approaches, taken both in comparison to each other and to the traditional hot big bang paradigm. In this context, it is worth noting that even the seemingly straightforward explanatory comparison between inflationary explanations and the hot big bang model proves controversial. Inflation was originally motivated by the observation that the hot big bang model involved *implausible coincidences* which cried out for explanation (Azhar and Butterfield 2016; Smeenk 2005). However, explication of the basis for the superiority of the inflationary explanation in comparison to the 'fine-tuned' hot big bang model is non-trivial. In particular, as persuasively argued by McCoy (2015), a simple probabilistic framing of the explanatory virtues of inflation in comparison to the fine-tuned hot big bang model suffers from chronic ambiguities in defining probabilistic structure within a modern cosmological context.

In this chapter, we will provide a *multi-dimensional* analysis of the explanatory virtues of inflation in comparison to bouncing cosmologies. Our approach to explanatory depth in modern cosmology is founded on identifying *initial conditions fine-tuning*, *dynamical fine-tuning*, and *autonomy* as relevant dimensions of depth. We take this to be a descriptively valid approach in this context since informal articulations of precisely these concepts are regularly invoked in the cosmology literature. In particular, with regard to dynamical fine-tuning and autonomy, we will demonstrate the particular relevance of these dimensions to the inflation vs. bouncing cosmology comparison in the context of dynamical instabilities and the so-called trans-Planckian problem.

Furthermore, we take there to be a good normative basis for treating depth along each of our three dimensions as an epistemic virtue since each of our three dimensions of explanatory depth are indicative of a form of *explanatory modal robustness*. That is, in each of the dimensions a deeper explanation is such that, all else being equal, explanatory connections between explanans and explanandum will persist in a wider range of counterfactual scenarios, whether in terms of different initial conditions, different dynamical maps, or different realisations of phenomena at physical scales far away from the explanandum.

Our analysis will not lead us to a conclusive verdict with regard to the explanatory superiority of these two rival approaches to cosmology. Rather, we will seek to clarify the relevant terms of the debate, and in doing so, better understand the basis upon which scientists are in fact disagreeing. Furthermore, we will suggest that the different choices with regard to explanatory strategy have direct implications for the heuristics of model building in contemporary cosmology. The nature of the dispute can thus in part be understood in terms of a disagreement over different strategies regarding how best to constrain theoretical practice. Given the heavily unconstrained empirical environment of modern cosmology, such methodological diversity is well justified. Finally, towards the end, we will explore another aspect of this debate and highlight important instances of successful predictive novel coming from inflation, arguing that this is the best epistemic justification for inflation whether one adopts attitudes of confirmation, pursuit, or acceptance.

5.2 Primordial paradigms: bangs, bounces, and inflation

Here, we review cosmological dynamics, in particular drawing a contrast between expanding FLRW dynamics with familiar matter content or an inflationary scalar field and contracting FLRW dynamics following from an ekpyrotic scalar field.

5.2.1 Hot big bang model

The Hot Big Bang (HBB) model has been the standard paradigm for model building in cosmology for the better part of a century.[1] Its modern ΛCDM incarnation (sans inflation) describes an expanding universe evolving according to the FLRW (Friedmann-Lemaître-Robertson-Walker) solution of General Relativity, that is composed of $\sim 5\%$ baryonic matter, $\sim 25\%$ non-baryonic cold dark matter, CDM, and $\sim 70\%$ dark energy, Λ. This universe is both extraordinarily flat and homogeneous, with departures in homogeneity restricted to tiny density fluctuations of order

[1]For a more detailed overview of modern cosmology together with attendant philosophical issues see Azhar and Butterfield (2016), Chamcham et al. (2017), Ellis (2014), and Smeenk and Ellis (2017).

$\sim 10^{-5}$ and precisely characterized by a nearly scale-invariant power spectrum.[2]

The dynamics of any FLRW universe are generically captured by the two Freidmann equations:

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{1}{3}\rho - \frac{k^2}{a^2} + \frac{\Lambda}{3}, \tag{5.1}$$

$$\dot{H} + H^2 \equiv \frac{\ddot{a}}{a} = -\frac{1}{6}(\rho + 3p), \tag{5.2}$$

where a is the scale factor, ρ is matter energy density, p is pressure, k is the spatial curvature, Λ is the cosmological constant, and H is the Hubble parameter. The HBB model takes the observed conditions and material constituents of the universe, and projects the evolution of the universe forward through these equations, as well as backwards towards an initial cosmic singularity.

5.2.2 Inflating and bouncing models

Despite its successes, physicists believe that the HBB model ought to be modified and the most popular proposals for doing so fall into two main categories: inflationary models (the dominant paradigm) and bouncing models (a distant secondary option).[3] Such extensions primarily operate through the particular mass-energy content (i.e., the energy density and pressure) that these models place into the Friedmann equations, which then determines the subsequent evolution of the universe in terms of the velocity and acceleration of the scale factor.

Inflation is a paradigm for building models within which the universe underwent a period of very rapid expansion at early times. There are, however, an extraordinary number of ways of implementing this paradigm. Physicists have cataloged and categorized *at least* 74 different models of single-field inflation, not to mention more complicated multi-field models (Martin, Ringeval, and Vennin 2014). Here we will restrict our attention to single-field models as these represent the most common way of realizing the paradigm. Similarly, bouncing cosmology is not so much a single theory, but rather a paradigm of related models that implements the idea that the universe can transition from expansion to contraction and vice-versa from contraction to expansion. There are likewise many ways of modelling contracting and expanding scenarios. We will restrict our attention to models that pair ultra-slow contraction ('ekpyrotic contraction') with a non-singular bounce since these models are of current interest and distinguish themselves from

[2]These findings have been confirmed by main cosmology probes such as COBE, WMAP, and Planck (Aghanim et al. 2020b; Bennett et al. 2013; Smoot 1999), and received strong independent support from measurements of supernovae (Perlmutter et al. 1999), baryonic acoustic oscillations (BAO) (Aubourg et al. 2015), galaxy rotation curves (Sofue and Rubin 2001), gravitational lensing (Ellis 2010), Lyman-alpha forest (Weinberg et al. 2003), galaxy clusters (Allen, Evrard, and Mantz 2011).

[3]There are even more options than this, including string gas cosmology (Brandenberger 2008) and emergent universe models (Ellis and Maartens 2004). However, we will not address these in this chapter.

inflation by avoiding singularities (Ijjas and Steinhardt 2018).[4]

Inflation and bouncing models are primarily driven by a dynamical scalar field, ϕ, with an associated potential, $V(\phi)$, which is coupled to gravity and dominates the mass-energy content of the universe during particular stages of evolution. For example, consider an action of the form:

$$S = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{1}{2}R + \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V(\phi)\right]. \tag{5.3}$$

The dynamics of such models can be understood schematically by tracking the equation of state that results from the particular scalar fields and potentials that describe such scenarios. Generically, the equation of state for a scalar field is given by:

$$w = \frac{p}{\rho} = \frac{\frac{1}{2}\dot{\phi}^2 - V(\phi)}{\frac{1}{2}\dot{\phi}^2 + V(\phi)}, \tag{5.4}$$

where $\dot{\phi}^2$ represents the kinetic energy of the scalar field.

5.2.2.1 Inflation models

1. *Inflation*: Inflation is driven by a scalar field (the 'inflaton') with a *positive* potential and these potentials are usually constructed so that there is a range of values for which the potential is relatively flat. When the potential is flat, the kinetic term $\dot{\phi}^2$ will be small as the field ϕ rolls down the potential function ('slow-roll inflation'). Under these circumstances, $V \gg \dot{\phi}^2$ and $w \approx -1$.

2. *Dynamics from inflation*: This corresponds to a period of accelerating expansion (i.e., $\ddot{a} \gg 0$ and $\dot{a} \gg 0$) as long as the potential dominates the equation of state. This leads to an exponential expansion of space where $a(t) \propto e^{Ht}$, which mimics the current epoch of dark energy dominated expansion (Baumann 2011).

5.2.2.2 Bouncing models

1. *Bouncing models*: Bouncing models aim to construct a universe where expansion transitions to contraction, and vice versa. For instance, we are currently in a period of dark energy dominated expansion, which very well could be driven by a scalar field in a flat, positive range of its potential function (i.e., $w \approx -1$). Consider what happens if a relatively flat, positive potential V evolves to become steep and *negative*. Here, ρ cannot be

[4] Alternative ways of constructing bouncing cosmologies include singular bouncing cosmologies and non-singular matter bounce cosmologies, amongst others (Battefeld and Peter 2015; Brandenberger and Peter 2017).

negative because it represents the energy density of the universe. The kinetic term $\dot{\phi}^2$ becomes large and is approximately equal to V, which leads to a small positive number in the denominator of w. Yet, for negative V, the pressure p is also positive, which leads to a large positive number in the numerator of w. The result is that $w \gg 1$.

2. *Dynamics from bouncing models*: When the scalar field begins rolling to negative values, the sign of the acceleration equation changes from $\ddot{a} > 0$ to $\ddot{a} < 0$ because $\frac{\ddot{a}}{a} = -\frac{8\pi G}{3}\left(\dot{\phi}^2 - V(\phi)\right)$, contrary to the inflationary case where V is positive and dominates the equation. This decelerates the universe and eventually reverses expansion entirely. We can see this from recalling the first Friedmann equation $H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\left(\frac{1}{2}\dot{\phi}^2 + V(\phi)\right)$ and recognizing that a large, negative V offsets $\dot{\phi}$. Eventually, the negative acceleration will flip the sign of H to negative, taking $\dot{a} > 0$ to $\dot{a} < 0$. Following this period of contraction, an appropriate modification of gravity (via the dynamics of the scalar field) leads to a non-singular bounce well before the Planck scale and the potential rolls back to a positive value, causing the universe to revert back to expansion (Andrei, Ijjas, and Steinhardt 2022; Ijjas and Steinhardt 2018; Steinhardt and Turok 2002a,b).

5.3 Explanatory depth as a theoretician's virtue

An adequate account of the dominant theoretical standpoint regarding model building in primordial cosmology requires consideration of the concept of scientific explanation. At first sight this observation may appear somewhat surprising since the HBB model provides a valid explanans for the relevant cosmological explananda under virtually any extant account of explanation (Earman and Mosterin 1999; McCoy 2015). If the strong theoretical preference for modifications of the HBB model is to be understood in explanatory terms, we are thus required to take a more nuanced approach to role of explanation in the context of primodial cosmology. The most obvious approach would be to understand the explanatory weakness of HBB model, and strength of its rivals, in probabilistic terms. The HBB model may explain flatness, but, by contrast, inflation both explains flatness *and makes it overwhelmingly likely*. The problems with this style of argument have been carefully discussed in both the scientific and philosophical literature (Curiel 2015; Gryb 2021; McCoy 2015, 2017; Schiffrin and Wald 2012a; Smeenk 2014). The key conclusion is that there exist chronic ambiguities in the non-arbitrary definition of probabilistic structure in a modern cosmological context. Depending on a judicious choice of formalisation one can justify both the statement that inflation is overwhelmingly likely and its negation.

The failure of a probabilistic explanatory approach might plausibly be taken to point away from explanatory considerations altogether, or at the very least, downgrade their relevance (McCoy 2015). From an experimentally driven 'empiricist standpoint', such a view appears to be well-justified. An alternative 'theoretician's standpoint', by contrast, is that the inflationary explanation is indeed superior on account of having greater 'depth'. The theoretician's search for an alternative explanation to that provided by the HBB model is then a search for *deeper explanation*. How might we characterise the notion of explanatory depth more precisely? And what motivates theoretical cosmologists to be interested in deeper explanations?

The first key observation, noted en passant by Maudlin (2007, Ch. 1), is that what cosmologists are really looking for is a *dynamical explanation*; an explanation that shifts the explanatory burden of the relevant observed facts from the initial conditions (i.e., brute stipulations of contingent facts and random processes) to the dynamical laws (i.e., nomic regularities that render the phenomena expected and substantially less contingent). Following Baumann (2011, p. 544), we can accept that the big bang model is perfectly adequate if we assume initial conditions that are extraordinarily flat and homogeneous (with tiny inhomogeneities possessing *just* the right amplitude and features for structure formation), but "a theory that explains these initial conditions dynamically seems very attractive". Guth and Steinhardt (1984, p. 116) voiced a similar motivation in the initial development of inflation, noting that the dynamics that govern the period of inflation have a very attractive feature: "from almost any set of initial conditions the universe evolves to precisely the situation that had to be postulated as the initial state in the standard model".

5.3.1 Explanation and explanatory depth

The aim of deploying the idea of explanatory depth in the context of modern cosmology is to make more precise the intuition behind such statements. Before developing the promised multi-dimensional account of explanatory depth in the context of this cosmological debate, it is worth pausing to briefly inspect the concept of scientific explanation and explanatory depth more generally. Determining "satisfactory explanations of whatever strikes us as being in need of explanation" (Popper 1983, p. 132) is nigh universally considered to be one of the foremost aims of science. Explanation gives us insight into "why things are one way rather than some other way" (Ylikoski and Kuorikoski 2010, p. 204), where "some other way" refers to other conceivable possibilities in the explanatory contrast class (van Fraassen 1980, Ch. 5) or "foils" that are distinct from the outcome we observe. The concept of explanatory depth is one way of cashing out the quality of an explanation and was formulated by Hitchcock and Woodward (2003) in the context of a counterfactual theory of explanation. Here, explanations are conceived of as answers to "what-if-things-had-been-different-questions" (w-questions). One explanation is thus deeper than another when it can answer more of these w-questions. In doing so, a deeper explanation remains intact under a greater range of "explanatory generalisations", where these explanatory generalisations broadly represent various counterfactual conditions that can be applied to the explanans (more on this and the different kinds of explanatory generalisations we will consider later). In other words, explanatory depth is indicative of a form of *explanatory modal robustness*. That is, there are a greater number of ways in which the world could be for which the (deep) explanation will still obtain. Generally speaking, such explanatory reasoning can be highly valuable in a number of ways.

One benefit of deep and modally robust explanations that will be particularly relevant to us is their capacity to enhance our understanding of the phenomena we are interested in. Understanding and explanation are tied at the hip: explanation facilitates our understanding (Friedman 1974; Grimm 2010; Ylikoski and Kuorikoski 2010). Consequently, understanding is undeniably an important epistemic aim of science (see, e.g., Bangu (2017), Dellsén (2016), McCoy (2023), Regt (2009), Riggs (2003), and Šešelja and Straßer (2014)).[5] We can thus consider the modal robustness of an explanans to be an *epistemic* virtue in so far as it enhances our understanding of explananda.

Understanding, very broadly, refers to our cognitive grasp of the phenomena. The concept of understanding can be cashed out in a way that is naturally complementary to our account of explanatory depth; that is, in terms of the ability to make counterfactual evaluations (Grimm 2006). In making counterfactual evaluations, we further grasp "why things are one way rather than some other way" because we develop insight into and gain cognitive control over the explanatorily relevant factors upon which the explanandum depends and further grasp how they hang together within our broader web of background knowledge and beliefs. However, understanding can also be pluralistically construed in a number of other ways depending on the context, including unification (Kitcher 1989), causality (Craver and Tabery 2019), intelligibility (deRegt and Dieks 2005), and coherence (Bartelborth 1999). As we shall see, explanations with depth also have the potential to enhance understanding as construed in these other ways directly as a result of insights gained from these counterfactual evaluations.

[5]The philosophy of science literature has traditionally focused on the acquisition of factual knowledge and truths as the primary epistemic aim of science (see, e.g., Bird (2007b), Hempel (1965), and Trout (2002)). While it is certainly unobjectionable to any scientist (or *reasonable* philosopher of science) to state that science is concerned with the acquisition of knowledge, it is also self-evidently true that science is concerned with more than *only* the raw accumulation of facts. Science also seeks to *understand* the phenomena it purports to describe; indeed, developing understanding is crucial to gaining insights, utilizing existing theories, solving new problems, making predictions, drawing connections between disparate phenomena, and developing the comprehensive cognitive control necessary to facilitate the remarkable scientific progress we have witnessed over the last few centuries. The more recent philosophy of science literature has provided an important corrective to the traditional literature and justifiably given appropriate attention to the epistemic value and role of understanding in science.

Epistemic virtues are not the only pertinent concerns to the practicing scientist. There are also a number of more *pragmatic* considerations that influence which explanations are seen as more appealing or worthy of further pursuit. Pragmatic virtues, while not completely disconnected from the more epistemic virtues, are more directly concerned with practical matters (Douglas 2013; van Fraassen 1980, Ch. 4). How effective or useful is the explanation as part of the working scientists' toolkit for making sense of the world? For example, simplicity is evidently an important pragmatic theory virtue because simpler theories are easier to utilize and deduce empirical consequences from, making them more straightforward to assess when confronted with empirical data.[6]

Of special import to us will be how an explanation handles uncertainties. Various uncertainties crop up in any scientific endeavor. We regularly make approximations, build idealised models, encounter systematic uncertainties in our measurements, work around error-contaminated data, filter out noise, etc. These are all inextricably entangled with the scientific process. With approximations and idealisations, in most (if not all) even semi-realistic examples it is unclear how one would gain *any* computational tractability without eliding certain complexities that we know to be present. When it comes to the practicalities of making measurements and interpreting data, uncertainties and errors will always infect our conclusions. What aspects of a good explanation allow us to mitigate the risks associated with these ever-present uncertainties?

Ylikoski and Kuorikoski (2010) highlight the role of *stability* or *robustness* in an explanation with respect to the values that its parameters can take. The operating intuition here has it that the more *sensitive* an explanation is to changes in its parameters, the less powerful it is. Robustness, or insensitivity, implies that an explanation is at least somewhat independent of those parameter-specific details; this is supposed to capture the intuition that "good explanations make their explananda necessary or at least less contingent" (Ylikoski and Kuorikoski 2010, p. 208); necessary, that is, with respect to the relevant contrast class.

Modal robustness in this sense offers a double benefit. On one hand, such explanations are more secure in the sense that they are still reliable "in situations in which there are changes in factors that are not explicitly accounted for or when the case is extrapolated to unforeseen extremes" (Ylikoski and Kuorikoski 2010, p. 209). That is, they achieve the epistemic and prag-

[6]There is also an epistemic dimension to many pragmatic virtues. For example, one can make a good argument that a simpler theory (when compared to a more complicated one) contributes to the epistemic goal of understanding because it is easier to understand the various parameters and their dependencies and/or relationships to the explanandum. One can also go further and argue that a simpler theory may be less likely to overfit data and may even better capture empirical relationships in a predictively accurate way than a comparatively more complex theory (Forster and Sober 1994). However, when discussing pragmatic elements of theory or explanatory assessment, it is the more practical benefits that are in focus.

matic goals of maintaining their "key functions of explaining and helping us to understand the world", even under conditions of uncertainty (Šešelja and Straßer 2014, p. 3112). They permit us, as we inevitably must, to work with approximations, uncertainty, error-contaminated data models, and idealisations—without having to fret over potentially momentous and epistemically uncontrollable consequences. On the other hand, modally robust explanations also allow us to avoid making potentially hazardous commitments in our analyses. That is, the lack of sensitivity means that we are no longer forced to wed our explanatory analyses to highly specific parameter choices; which, in many cases are often unverifiable in practice or even in principle.

5.3.2 A multi-dimensional account of explanatory depth in primoridal cosmology

In order to frame a comparative study of inflation and bouncing paradigms, we will adopt a multi-dimensional account of explanatory depth. Following the discussion of Ylikoski and Kuorikoski (2010) and Weslake (2010), we take explanatory depth to be a non-unitary concept with different dimensions relevant to different domains. We further take cosmology to be a domain in which there are at least three relevant dimensions of explanatory depth: initial conditions fine-tuning, dynamical fine-tuning, and autonomy.

Some valuable work has already been done in a recent paper by Azhar and Loeb (2021). Their analysis focuses on explanatory depth, or counterfactual invariance, with respect to the initial conditions of the parameters that are fed into the explanans. Under their account, one explanation is deeper than another when, for a fixed number of parameters and a single observable, there is a greater range of parameter values that do not yield significant changes to the observable. For example, an equilibrium explanation (Sober 1983) provides a deep explanation in the sense that it completely avoids initial conditions fine-tuning, precisely because the explanandum of a final equilibrium state is suitably invariant under counterfactual values of the initial conditions part of the explanans. Stated another way, the less sensitive (and more robust) the explanatory relationship is to counterfactual values of parameters within the explanans, the deeper the explanation is.

Briefly dwelling on a simple example will help elucidate both pragmatic and epistemic benefits of a modally robust explanation. It is of course the case that there are multiple ways of explaining the final equilibrium state of say, a box filled with monotonic gas particles given some appropriate length of time. One could, in principle (even if extremely impractical), track the initial trajectories and interactions of every particle in box until the final state is reached. This would constitute a sensible D-N explanation in which the conjunction of initial conditions and dynamical laws explain the outcome we are interested in (Hempel 1965; Hempel and Oppenheim 1948). While this explanation allows us to understand the phenomena in a sense, the modally robust/explanatorily deep explanation offers an explanation (and understanding) that is far more powerful.

The second law of thermodynamics and statistical mechanics tells us that given a sufficient period of time we should expect to the find the particles in an equilibrium state, irrespective of the initial conditions. This has the epistemic benefit of enhancing our cognitive insight into and control over entropy as the most important explanatorily relevant factor over which the explanandum depends. For example, it can be shown that the equilibrium macrostate is the state that maximizes the entropy of the system (i.e., the number of microstates corresponding to a particular macrostate). Additionally, it can be shown that any fluctuations or deviations from the maximum entropy state will be supressed exponentially, ensuring that the system stays in equilibrium. There is furthermore a tremendously important pragmatic benefit whereby this explanation allows us to abstract away from the essentially impossible task of tracking the evolution of the system's specific microstates (which can only practically be done in the most trivial and simple versions of such a system), and instead immediately jump to the macrostate that corresponds to the highest entropy—the equilibrium state. What would be a computationally impossible task can be done in a few lines in a notebook. For every system like this, there is of course *some* story about what microstate the system is in at any one time, but these are not the explanatorily relevant factors that the phenomena (a robust, final equilibrium state) depends on. It is the modally robust explanation that allows us to both develop a deep understanding of this and pragmatically abstract away from less relevant, distracting details like the initial conditions and microstate dynamics.

To unpack this a little bit more, while here we are operating mostly within a contrastive/counterfactual account of scientific explanation, there is also the concept of *nomic expectability* which has been emphasized in many accounts of scientific explanation, including the D-N model and unification models. The basic idea is that what it means to explain phenomena is to show that it should be an expected outcome that follows from established scientific laws (Salmon 1989, p. 57).[7] While a microphysical accounting of all the particle interactions and trajectories does satisfy this concept (i.e., the final state can be understood as an outcome of the dynamical laws), it does leave something to be desired. For example, while finding the equilibrium state is the overwhelmingly most likely outcome to observe, it is also possible (though almost unfathomably unlikely) to observe a state far away from equilibrium. However, one could

[7] As has been much discussed in the literature, nomic expectability clearly can't be the whole story in many contexts. See, e.g., Woodward and Ross (2021) and references therein.

just as well explain this by selecting a suitable initial state that leads to this configuration. From this vantage point the microphysical explanation does not by itself provide any means of differentiating between what we should expect with respect to these two technically possible outcomes because they are both equivalent in the sense that a suitable initial configuration can be found to produce both outcomes (they can both be understood as nomically expected). That is, all possible final state outcomes in the contrast class are reduced to brute fact stipulations about initial configurations combined with dynamical laws. However, the explanation coming from thermodynamics and statistical mechanics immediately equips us to understand that it is the equilibrium configuration that we should expect to observe over any others (again given an appropriate length of time). While both outcomes can be said to satisfy a very basic notion of "nomic expectability" under the microphysical explanatory framework, it is clear that the modally robust explanation coming from statistical mechanics and thermodynamics confers nomic expectability to the explanandum in a far more powerful sense as it is singled out as nomically privileged. The modally robust explanation allows us to understand both why the equilibrium state obtains and why it is almost impossible for any other state to obtain. The explanandum, understood in this way, is now rendered "necessary or at least less contingent" when compared to the basic microphysical account which by construction emphasizes contingent facts about the initial configuration as crucial difference making explanatory details. In other words, this explanation enables us to automatically and efficiently understand the spectrum of counterfactual possibilities and situate the phenomena as privileged with respect to its contrast class in a way that the pure microphysical explanation does not. Explanatory depth with respect to initial conditions in this case is a clear marker of this epistemic virtue.

The second aspect of our proposal is the suggestion that the absence of *dynamical* fine-tuning is a relevant dimension of depth in the cosmological context. This involves a moderate modification of depth in terms of fine-tuning of the *initial conditions* to fine-tuning of the *dynamical maps*. Whereas the former are understood as points in state space that specify the state of the system at some initial time, the latter are one parameter groups of transformations that map the state of the system at one time onto the state of the system at some other time.[8] In analogy with the previous definition of initial conditions fine-tuning, dynamical fine-tuning is defined such that one explanation is deeper than another when, for a fixed number of parameters and a single observable, there is a greater range of appropriately similar dynamical maps that do not yield significant changes in the observable. The articulation of the normative basis for depth qua lack of dynami-

[8]The concept of a dynamical map is drawn from the widely applicable framework of Dynamical Systems (Broer and Takens 2011).

cal fine-tuning to be treated as an epistemic virtue parallels that we just gave for initial conditions fine-tuning. An explanation with less dynamical fine-tuning will be one in which, all else being equal, the explanatory connection between explanans and explanandum will persist in a range of counterfactual scenarios with different dynamical maps. Thus, once more, one may understand the epistemic virtue of an explanation that is deep in the relevant sense of lacking dynamical fine-tuning in terms of its modal robustness.

To give a brief (and simplified example), a renormalization group explanation provides a deep explanation in the sense of not requiring dynamical fine-tuning, precisely because the explanandum of critical behaviour is suitably invariant under a variety of counterfactual forms of the fundamental Hamiltonian that enters into the explanans (Batterman 2000, 2002; Franklin 2018; Reutlinger 2014). As in the previous example, there are of course many valid explanations for critical phenomena that can coexist together. However, the more modally robust explanation offers both epistemic and pragmatic benefits that are not obviously available in other avenues of explanation. For example, the renormalization group explanation offers a power unification of critical phenomena as it reveals critical phenomena seen in all different kinds of (seemingly) completely unrelated systems to be manifestations of the same underlying physical considerations. The rationale for treating this kind of unification as an epistemic virtue is straightforward. In the words of Kitcher (1989, p. 432), science advances "our understanding of nature by showing us how to derive descriptions of many phenomena, using the same patterns of derivation again and again, and, in demonstrating this, it teaches us how to reduce the number of types of facts we have to accept as ultimate (or brute)". Here again, an explanation's modal robustness, this time with respect to dynamical considerations, is a clear indicator of an epistemic virtue. In what follows we will argue that the key explanatory weakness of bouncing models is lack of depth along the dimension of dynamical fine-tuning when compared with inflation's depth along this dimension.

The third aspect of our proposal involves characterisation of a further dimension of depth. Here we are drawing partial inspiration from the idea of Weslake (2010) that *autonomy* is a significant dimension of explanatory depth. In our characterisation, one dynamical explanation is deeper than another when the explanatory connection between the explanans and explanandum is insensitive to the breakdown of our dynamical modelling frameworks or laws in regimes at very different scales from that of the explanandum.[9] Paradigmatically, an explanation will be deep in the sense of autonomy when the scale of the explanans and explanandum are closely matched and

[9]Scale here might refer to spatial scale, energy scale, temporal scale, or numerical competent scale. Autonomy is in our sense is closely connected to the conception of scale-relativity discussed by Ladyman and Wiesner (2020) and Creţu (2022).

an explanation will be shallow in the sense of autonomy when the explanans make reference to a much smaller spatial scale than the explanandum, and the relevant explanatory connection is highly sensitive to assumptions regarding this scale.[10]

The most vivid illustration of dynamical explanations that are deeper in the sense of autonomy are the explanations provided in continuum fluid mechanics, c.f., Batterman (2018) and Darrigol (2013). Such explanations are successful precisely because their objects are macro-scale explananda for which they provide macro-scale explanans. As such, they avoid reference to many-body molecular scales which are outside the validity of the relevant continuous fluid dynamical laws (since they are at a smaller spatial scale) and outside the tractability regime of the more fundamental molecular dynamics (since fluids have numbers of components of the order of the Avogadro number).

The articulation of the normative basis for depth qua autonomy to be treated as an epistemic and/or pragmatic virtue again draws upon the idea of modal robustness. An explanation which is more autonomous will be one in which, all else being equal, the explanatory connection between explanans and explanandum will persist in a range of counterfactual scenarios where the realisation of phenomena at physical scales far away from the explanandum is very different. This idea can be clearly illustrated by the aforementioned example of continuum fluid mechanics where the explanations provided are autonomous because they are insensitive to a huge variety of possible micro-physical realisations of the underlying molecular-hydrodynamics.

It is important to note that our conception of autonomy as a dimension of explanatory depth does not make reductive explanations *necessarily* shallow in the sense of autonomy. Rather, our approach cautions against a form of reductive explanation that proceeds by connecting explananda at one scale, to explanans that require highly specific approaches to modelling at very different scales. In general, we have good reasons to expect such explanations to be less modally robust precisely because they require specific modelling assumptions to hold across multiple scales. It is certainly possible in principle for explanations to be both deep in the sense of autonomy and reductive in the sense of having the explananda and explanans defined at different scales.[11] More-

[10]For Westlake autonomy is the view that it is possible for non-fundamental sciences to provide deeper explanations than fundamental science on the basis of a greater degree of abstraction, where abstraction is applicability to a greater range of types of physical systems. Our conceptualisation of autonomy, by contrast, is inspired by the idea of applicability to a greater range of realisations of the mico-physical structure underlying one type of physical system. The distinction is thus broadly equivalent to that between universality and robustness (Batterman 2000, 2002; Gryb, Palacios, and Thébault 2021; Palacios 2022).

[11]In particular, there can be circumstances where the relevant cross-scale explanatory connection does not display a high level sensitivity to model assumptions regarding the scale of the explanans. We will consider an example of such an explanation in the context of explanations of Hawking radiation based upon modified dispersion relations in Section 5.6.1. Arguably, this is also precisely what reductive accounts of renormalization group explanations aim to demonstrate (Castellani and Margoni 2022; Franklin 2018; Reutlinger 2017; Saatsi and Reutlinger 2018).

over, there are situations in science where it turns out to be unavoidable to connect phenomena at one scale to models and theories at a very different scale, even when the theory at that scale is not well established, and the robustness of the explanatory connection is not yet understood. A particularly good historical example of such a situation is the requirement for early twentieth century physicists to move beyond classical physics into the then highly speculative domain of quantum physics in order to account for the thermal properties of solids (Darrigol 2009). We take there to be good reasons to expect that, all else being equal, autonomous explanations will more reliable. This does not, however, rule out there being situations where all else is not equal, and only a non-autonomous explanation is in fact available.

Bringing this all together, in the initial conditions and dynamical dimensions of depth, it seems that there is a clear cut case to be made that an explanation exhibiting depth/modal robustness along one of these dimensions is a clear indicator of both epistemic and pragmatic virtues. With the dimension of autonomy, it is less clear because in some situations autonomy seems to be a virtue whereas in others the lack of autonomy can be a very powerful feature that connects phenomena at very different scales in unexpected and fruitful ways. We will explore this further later on, but it turns out that cosmologists actually strongly disagree about whether autonomy should be construed as a virtue or not in their modeling practices.

In the cosmological context, the explananda are tied to the scale of the CMB and the relevant dynamical modelling framework is the perturbed Friedmann equations together with quantum field theory. An explanation that is deep in the sense of autonomy will, in this context, be one in which the explanatory connection between the relevant explanans and explanandum does not require highly specific approaches to modelling scales far away from the CMB scale. In what follows we will argue that inflationary models generically lose out to bouncing models in the autonomy dimension of explanatory depth due to the so-called trans-Planckian problem, which requires reference to scales far beyond the the CMB scale. However, while the very reason some cosmologists pursue bouncing models is because they place a premium value on autonomy; in contrast, other cosmologists, seeing this as potentially remarkable virtue, view inflation's lack of autonomy as a valuable opportunity to learn about Planck scale physics. Interestingly, we will also argue that the subset of inflationary models that are autonomous, those that satisfy the so-called trans-Planckian censorship conjecture (TCC), are found to sacrifice explanatory depth along the dimension of dynamical fine-tuning. Autonomy and dynamical fine-tuning, as dimensions of explanatory depth, are thus precisely those required to elucidate the structure of the relevant debates since the different putative cosmological explanations prove to excel along the different dimensions defined within our account of explanatory depth.

This brings us to the fourth aspect of our account, which is drawn from the problem of comparing rival explanations that excel along different dimensions of explanatory depth. On our view, the choice for theoretical cosmologists implied by such comparisons is best understood in terms of differing attitudes with regard to heuristics for future model building. That is, a choice between explanations with different forms of *heuristic fecundity*. Most straightforwardly, the reason why explanations that lack depth qua initial conditions fine-tuning are so unsatisfactory is, at least in part, due to the heuristic sterility of explanations of phenomena that appeal to special initial conditions. A more complex choice, that we will argue to be relevant to our particular context, is between explanations that are deeper along the dimensions of autonomy and dynamical fine-tuning. The heuristic value of an autonomous but dynamically fine-tuned explanation can be understood in terms of the positive heuristics provided for theoretical model building in a constrained space within limitations on both the realm of relevant empirical phenomena and the possible dynamical structures that can be implements. By contrast, the value of an explanatory approach that is deep in virtue of not being dynamically fine-tuned, but shallower in virtue of lack of autonomy, might be understood in broadly empiricist terms. We will return to these issues in the final section.

In conclusion, our approach to explanatory depth in modern cosmology is founded on identifying initial conditions fine-tuning, dynamical fine-tuning, and autonomy as the relevant dimensions of depth. We take this to be a descriptively valid approach in this context since informal articulations of precisely these concepts are regularly invoked in the cosmology literature. Furthermore, we take there to be a good normative basis for treating depth along each of these dimensions as an epistemic virtue since each of our three dimensions of explanatory depth are indicative of a form of *explanatory modal robustness*. That is, in each of the dimensions a deeper explanation is such that, all else being equal, explanatory connections between explanans and explanandum will persist in a wider range of counterfactual scenarios, be these in terms of different initial conditions, different dynamical maps, or different realisations of phenomena at physical scales far away from the explanandum. Finally, while we do not take there to be epistemic norms that dictate the choice between explanations that excel along different dimensions of depth, we think that there is a good basis to draw connections between such choices and differing pragmatic attitudes of theorists with regard to heuristics for future model building.

5.4 Initial conditions and explanatory depth

Here, we offer a brief recap of the flatness and horizon problems which have already shown up in a few places in this thesis in order to illustrate how bouncing models resolve them when compared to their inflationary rivals.

Additionally, in light of our previous discussions which have emphasized the surprising difficulty the literature has faced when it comes to *precisely* nailing down exactly why these fine-tuning issues are so problematic (despite widely held intuitions that they are indeed serious problems), it is worth providing a brief justification as these problems can't be straightforwardly construed as obvious explanatory failures or in probabilistic terms.

Carroll (2014, p. 4) captures the basic intuition: "(a)ny fine-tuning is necessarily a statement about one's expectations about what would seem natural or non-tuned." Construing fine-tuning in terms of instantiations of *extraordinary types*—types that, given our background knowledge, we don't expect as Baras (n.d.) and Baras and Shenker (2020) does provides a nice philosophical framework with which to analyze this intuition. When do certain facts or phenomena "call" for an explanation? In other words, which facts are sufficiently "suggestive" or "peculiar" so as to make an explanation *desirable* (but neither compulsory nor guaranteed to exist)?

According to Baras, a particular fact or phenomenon x calls for an explanation if it instantiates an extraordinary type. A type is unusual or striking in light of what we know, or even have reason (not) to expect. Our background knowledge about the pertinent domain determines the definition/individuation of those types, as well as their classification as *extraordinary*. The occurrence of ordinary/non-striking types of entities *coheres* well (has strong and plentiful "inferential links") with background knowledge (including the natural resources of the theory "in charge" of the pertinent domain): our background knowledge provides good reasons to expect those types—rather than others (see Schindler (2018a) and Schindler (2018b, Ch. 5)).[12] As coherence is an important theory virtue, we'll adopt the perspective that theories which alleviate fine-tuning issues are pursuit-worthy because they promise to enhance the coherence of our knowledge. Additionally, naturally defined measures allow a categorisation of extraordinary types. Thanks to the appeal to coherence, however—an explanatory relation that admits of different strengths and kinds—typicality or probability measures *aren't necessary* for the classification of types as extraordinary. Extraordinariness is commonly, and can be, adjudicated on qualitative grounds.

[12]Following Schindler (2018a) and Duerr and Wolf (2023), one may conversely take the instantiation of extraordinary/striking types to signal a theory's ad-hocness. Recall also the traditional link between explanation and expectation stressed by, e.g., Hempel or Salmon (see Woodward and Ross (2021, Sect. 4)).

We thus arrive at the following proposal for a modest interpretation of fine-tuning issues as *tentative* indicators for pursuit-worthy theories:

- **FT-1**: A fact (e.g., initial conditions) is fine-tuned, iff it instantiates what, given our background knowledge, counts as an extraordinary type—a type not optimally cohering with our warranted expectations.

- **FT-2**: Ceteris paribus—in the absence of more glaring empirical or theoretical anomalies—a theory that explains a fine-tuned fact deserves pursuit more than one that doesn't explain it.

This account vindicates the hunch that, without inflation (or some other early universe extension like bouncing cosmologies), the HBB-model faces two principal fine-tuning feature that call for an explanation:

- *Flatness problem:* Suppose that we pare down the types of universes to those with a homogeneous and isotropic large-scale structure. They are naturally classified geometrically, i.e., according to their spatial curvature—describing either an open, closed or flat universe. Flat universes, such as ours are extraordinary in light of GR's dynamics: they are unstable/fragile (McCoy 2020, Sect. 3). That is, GR's dynamics governing the universe's evolution rapidly amplifies ever-so-slight initial deviations from flatness at any point in time; the universe would be driven towards either openness or closedness.

- *Horizon problem:* Types of universes that are uniform (homogeneous and isotropic) such as ours are extraordinary given that most of the visible universe hasn't been in causal contact, if we adopt the HBB-model's dynamics. Our background knowledge leads us to *not* expect causally disconnected regions to share the same properties to such precise detail (Baumann 2011, p. 23). Furthermore, the universe isn't only flat and homogeneous. But the density fluctuations—the statistical *deviations* from perfect homogeneity—that fill the universe "are correlated over apparently acausal distances. This [...] begs for a dynamical explanation" (Baumann 2022, p. 138).

Inflation and bouncing cosmologies answer these "calls for explanation". As we shall see shortly, both of these frameworks are able to demote the above facts to tokens of *ordinary* types, rather than *extraordinary* types. Given inflation or bouncing cosmologies, uniformity, spatial flatness, and the observed statistical properties of density fluctuations are to be *expected* in our universe; these features become "generic predictions". We now turn to discussing how this comes about in more detail.

5.4.1 Flatness problem

The *flatness problem* can be characterized as the realization that, for the universe to possess its observed flatness today, the initial value of the density ρ had to be extraordinarily close to what is known as its critical value. The critical value for density ρ_c is the unique value for which $k = 0$ according to the first Friedmann equation and can be written as the ratio $\Omega = \rho/\rho_c$. This allows one to write the so-called curvature parameter Ω_k in the following suggestive way:

$$\Omega_k = 1 - \Omega = \frac{k}{a^2 H^2} \tag{5.5}$$

The scale factor, a, is proportional to the actual size of the universe and the Hubble parameter, H, is inversely proportional to how far an observer can actually see (i.e., in units where $c = 1$, the Hubble horizon is simply H^{-1}). Thus, this parameter can be roughly understood as being proportional to the ratio of the apparent size of the universe to its actual size. If $\Omega = 1$, $\Omega_k = 0$ and $k = 0$, and the universe is flat. However, this is an unstable fixed point for energy inputs like radiation or matter in the HBB model. Thus, the curvature parameter Ω_k will diverge over time *regardless* of what its initial value was as a and H evolve in the HBB model. A universe that is observed to be essentially spatially flat today requires a density that was extraordinarily close to the critical value at earlier times (within 10^{-55} of the critical value when extrapolating back to GUT scale energies (Baumann 2011)).

The preceding discussion on inflationary dynamics immediately equips us to see how an inflationary epoch will offer a significant increase in explanatory depth when compared to the HBB model. Recall that $H = \dot{a}/a$ and that during inflation, $a(t) \propto e^{Ht}$. Thus, H is approximately constant while a grows exponentially, and consequently, Ω_k is driven towards zero. This is analogous to how curved spaces can appear flat when the space we are considering is sufficiently small compared to the actual radius of curvature. Inflationary dynamics completely turn the tables. Rather than requiring a finely-tuned, specially chosen density value to explain why the universe we see today is flat, seemingly any initial density value will correspond to a flat universe. The HBB drives the universe away from flatness while inflation drives the universe towards flatness. When compared to the HBB model, inflation offers a deeper explanation because it allows for significantly more variation in the values of the initial conditions without dissolving the explanatory relationship with the explanandum.

Does this analysis carry over to bouncing models? At first glance, it might seem surprising that it does. After all, a contracting universe is seemingly the opposite of an expanding universe.

If exponential expansion flattens the universe, how could slow contraction accomplish the same? Furthermore, as a gets smaller during contraction shouldn't that amplify the curvature parameter rather than suppress it? The key insight is that during a slow contraction the behavior of H changes as well. A simple manipulation of the Friedmann equations shows that, when the equation of state $w \neq -1$, $H^{-1} \propto a^{\epsilon}$, where $\epsilon = \frac{3}{2}(1+w)$. For a contracting universe with an equation of state $w >> 1$, this means that the curvature parameter can be written as $\Omega_k \propto a^{2\epsilon}/a^2$ (Ijjas and Steinhardt 2018). While a^2 decreasing in the denominator would seemingly blow up the curvature parameter, Ω_k is actually suppressed because the numerator $a^{2\epsilon}$ decreases faster. That is, the universe visible to an observer shrinks faster than the universe itself. Thus, a period of slow contraction mimics the effects of an inflationary period and likewise drives the universe towards flatness. Furthermore, this mechanism's effectiveness has been confirmed with detailed numerical simulations (Ijjas, Cook, et al. 2020). Bouncing models which utilize this contraction mechanism offer an account of explanatory depth that is similarly compelling to their inflationary competitors.

5.4.2 Horizon problem

The universe is also remarkably homogeneous, with departures from homogeneity showing up only at the level of $\sim 10^{-5}$. Homogeneity by itself is not a problem. It would not be surprising for a system of particles in causal contact to attain conditions and properties that are nearly homogeneous, but the fact that the vast majority of the universe exists in causally disconnected patches makes observing such homogeneity a genuinely striking puzzle. This is known as the *horizon problem*. The Hubble horizon forms a causal past light cone for each observer. Many of the points in the universe that we see today lie outside outside each other's present Hubble horizons, while displaying the same remarkable homogeneity. It has been estimated that at the time of recombination when the CMB photons first started streaming, the universe consisted of $\sim 10^{83}$ causally disconnected regions (Mukhanov 2005).

Inflating and bouncing cosmologies approach this problem similarly. Rather than simply asserting that the initial conditions of the universe were such that causally disconnected regions happen to be homogeneous, they provide a mechanism such that these regions of the universe share a causal past, before then explaining why these regions *appear* to be causally disconnected now.

Prior to an inflationary phase, distant points in the universe share a causal past. During inflation, the rapid exponential expansion of space shrinks the so-called co-moving Hubble horizon

$(aH)^{-1}$. Intuitively the co-moving Hubble horizon represents the fraction of the universe that is observable. Following exponential expansion, this co-moving Hubble horizon shrinks significantly, meaning that regions that were in prior causal contact now appear to be outside each other's past light cones. Inflation needs approximately 60 e-folds (i.e., the time interval in which the exponentially growing scale factor grows by a factor of e) to solve the horizon problem (Baumann 2011).

Coming to bouncing models, we find again that inducing a period of slow contraction produces similar behavior. Slow contraction causes the co-moving Hubble radius to shrink. Rather than shrinking via the exponential expansion of a as with inflation, the co-moving Hubble radius shrinks because a^{ϵ} declines faster than a. This is again due to the very different behavior of H given matter-energy content with an equation of state $w >> 1$. Upon transitioning to a subsequent expanding phase, the co-moving Hubble horizon proceeds to grow again, which results in regions that were previously in causal contact re-entering the horizon, while appearing as if they were never in causal contact (Ijjas and Steinhardt 2018).

Both of these accounts allow the universe we observe today to share a common causal past, yet as Ijjas and Steinhardt (2018, p. 10) explain, "removing the causal impediment is necessary but not sufficient to explain why the energy density distribution was so smooth at the time of last scattering". The aforementioned dynamical mechanisms responsible for resolving the horizon problem manage to explain this as well. Rather than postulating what would need to be very finely-tuned initial conditions within causally disconnected regions of the universe, both paradigms allow for a far larger variance in initial parameter values that eventually lead to the same observable state of interest. Even if there were somewhat significant inhomogeneities in these causally connected regions, the dynamics of inflation models inflate them away (Brandenberger 2016; East et al. 2016), whereas conversely the dynamics of bouncing models dramatically shrink them (Ijjas and Steinhardt 2018), with the end result being that the universe is homogenized.[13] Here again, dynamics drive the explanatory power and depth of the respective models, and there is a significant reduction in the fine-tuning of initial conditions needed to account for the observed state of the universe.

[13]Of course, these cosmological models are not compatible with *any* conceivable initial conditions. However, in both cases, the acceptable range of initial conditions that produce the universe we observe is dramatically enlarged by orders of magnitude.

5.4.3 Scale-invariant density perturbations

The inhomogeneities in the CMB are extremely important to cosmology because it is these density perturbations that ultimately seed the large-scale structure in the universe. It had long been argued that primordial density perturbations should be scale-invariant ($n_s = 1$) (Harrison 1970; Peebles and Yu 1970; Zeldovich 1972).[14] However, within the HBB model it is not at all clear where these density perturbations come from. Of course, you can put finely-tuned inhomogeneities in the initial conditions, but this would add yet another implausible degree of fine-tuning.

The prediction of a nearly scale-invariant spectrum of density perturbations is counted as one of the most important successes of the inflationary paradigm. Within a few years of the theory first appearing, it became clear that inflation could source these perturbations and several researchers had independently derived a nearly scale-invariant spectrum of fluctuations (Bardeen, Steinhardt, and Turner 1983; Guth and Pi 1982; Hawking 1982; Mukhanov and Chibisov 1981; Press 1980). Intuitively, these perturbations represent tiny quantum mechanical variations in the field values of the inflaton itself. We can use standard quantum field theory to quantize these perturbations and compute their quantum statistics, resulting in the power spectrum (Baumann 2011):

$$\Delta^2_{\mathcal{R}}(k) = A_{\mathrm{s}} \left(k/k_*\right)^{n_{\mathrm{s}}-1} , \tag{5.6}$$

where $\Delta^2_{\mathcal{R}}$ is the power spectrum of density fluctuations $\mathcal{R}$, A_s is the amplitude, k is the fluctuation mode, k_* is a reference length scale usually taken to be the horizon crossing, and n_s is the scalar spectral index. n_{s} can be computed for any inflation model from analyzing its dynamics and $n_s \simeq 1$ is a generic feature of single-field inflation models that satisfy the typical constraints in the inflationary paradigm (such as having a relatively flat potential with a valid slow-roll approximation).

Bouncing paradigms predict a nearly scale-invariant spectrum as well through a similar procedure (with some important differences, as we shall see later). Similar to the flatness and horizon problems, both inflating and bouncing paradigms invoke dynamics that drive the values of important features of the universe towards those that are actually observed, and both offer similar increases in explanatory depth over the standard HBB model by shifting the burden of explanation from finely-tuned initial conditions to dynamics.

[14]This property has been measured and is frequently discussed as the scalar-spectral index n_s. Planck has measured this to be $n_s = 0.9649 \pm 0.0042$, with perfect scale-invariance corresponding to $n_s = 1$ (Aghanim et al. 2020b).

5.4.4 Summary

The explanations for the initial state of the universe offered by inflationary and bouncing cosmologies are deep in that both theories provide dynamics that produce a universe like the one we observe in a manner that displays a remarkable insensitivity to initial conditions. The epistemic and pragmatic benefits of this style of explanation are numerous. With the HBB, the essential feature of the model (i.e., the dynamics) play very little role in actually explaining what we observe. The explanatory burden relies almost exclusively on heuristically sterile, brute fact stipulations about the initial state of the universe, and these say nothing about the relevant contrast class other than that they are not realized given this extraordinarily special configuration. With an inflating or bouncing scalar field, the essential dynamical features of the model take front and center in the explanation. These dynamical explanations not only explain why the universe has the properties that it does, but also allow us to understand why the universe almost certainly couldn't be any other way: the dynamics of an inflating universe or an ekpyrotically contracting universe make it so that a universe like ours is an expected outcome that is far less sensitive to the exact choice of initial state. The dynamics actually drive the universe towards then one we observe in the CMB and away from the other possibilities in the relevant contrast class! That is, what we observe has now been transformed into an ordinary type that is rendered "necessary or at least less contingent" when compared with the HBB model.

Additionally, these explanations allow us to model the universe in the midst of significant uncertainty: we do not and will never have empirical access to the true initial state at the very beginning of the universe. Consequently, there is significant pragmatic value in being able to model the universe in a way that does not sensitively depend on information concerning parameters that we can never have access to. We no longer have to feature these particular assumptions, which are highly suspect and precarious due to in part to their unverifiable nature, as the primary driving factor in producing the universe we observe today.

5.5 Dynamics and explanatory depth

Dynamics, like initial conditions, can be varied within the explanans. This may seem strange at first since we are used to working with fixed dynamical laws while varying parameters such as initial conditions. However, inflation and bouncing cosmologies are not themselves specific theories with fixed dynamical laws, but rather paradigms with many different dynamical realizations. In other words, we are interested in how effective these research programmes are at providing a greater range of dynamical maps appropriately suited to describing the observable universe, for a given set of parameters and observables. In this context, we can examine the space of dynamical realizations within the paradigms and evaluate these competing paradigms on the sensitivity of their explanatory relationships to different dynamical implements. We will show that this is one manner in which these paradigms start to diverge in their explanatory depth, with inflation emerging as the deeper explanation in terms of this dimension of dynamical fine-tuning. Furthermore, as we shall see, cosmologists who favour inflation have long pointed to this as a significant virtue of the inflation paradigm.

5.5.1 Primordial gravitational waves

A positive detection of primordial gravitational waves, or tensor perturbations is a major goal in observational cosmology. Two of the primary reasons these perturbations are so significant are as follows: (i) they produce a distinctive B-mode polarization that cannot be mimicked by the types of scalar perturbations we have already detected (Zaldarriaga and Seljak 1997) and (ii) such a distinctive signature would be seen by many cosmologists as strong evidence for inflation because inflation generally predicts significant production of primordial gravitational waves (Baumann and Zaldarriaga 2009). It is important to note that such a detection does not uniquely single out inflation. As Brandenberger (2019) emphasizes, primordial gravitational waves can be produced both by topological defects in standard HBB cosmology or in particular realizations of other early universe paradigms. Thus, if tensor perturbations were detected, one would have to carefully examine additional data points such as the tensor spectral tilt to differentiate competing theories.

Such tensor perturbations can be directly related to the energy scale of an inflating or contracting mechanism because the ratio between tensor and scalar perturbations r can be manipulated to directly constrain V and the energy scale of such a mechanism (Baumann 2011). Inflation is generally expected to occur at near GUT-scale energies, leading to a relatively high production of tensor perturbations and tensor-scalar ratio r. On the other hand, the slow contraction mechanism employed by the kinds of ekpyrotic bouncing models we are considering[15] occurs at lower energies that are much further away from the Planck scale, leading to significantly lower expectations for tensor perturbations, which would make r unobservably small (Ijjas and Steinhardt 2019).

The most recent Planck constraints indicate that $r < .10$ (Aghanim et al. 2020b). Clearly, this is not a problem for bouncing models. However, these recent constraints actually rule out many of the simplest and most studied inflation models that broadly fall under the a category known as 'power-law inflation'. Following the Planck results, detailed assessments of the paradigm have

[15]It should be noted that some other kinds of bouncing models that, such as a pure matter bounce scenario, can lead to significant production of primordial gravitational waves (Brandenberger 2019).

found that ‘plateau inflation’ models are now strongly favoured by the data (Akrami et al. 2020; Chowdhury et al. 2019; Martin 2016). While these models are not prima facie unreasonable[16], this episode illustrates that the inflation paradigm has had to invoke some non-trivial degree of dynamical fine-tuning to account for present observational constraints on the tensor-scalar ratio.

5.5.2 Scale-invariant density perturbations

While generically predicting unobservable tensor perturbations and a low r value is certainly a point for the bouncing paradigm, things get a little more complicated when coming back to the scalar perturbations. While both inflation and bouncing paradigms can produce results consistent with the scale-invariant spectrum of density perturbations seen in cosmological probes, inflation does so in a more natural way.

In an expanding, inflating universe the growing scalar modes that are understood to be the all-important seeds of structure formation are actually decaying modes in the corresponding time-reversed, contracting universe. Similarly, the growing modes in a contracting universe map onto the decaying modes in the corresponding expanding universe (Creminelli, Nicolis, and Zaldarriaga 2005; Lehners et al. 2007). The dynamics responsible for inflation naturally source scale-invariant density perturbations through the typical growing modes. However, a bouncing cosmology needs to reckon with the fact that the growing modes during the contraction phase become decaying modes during subsequent expansion, but the decaying modes that would naturally grow in the subsequent expansion have already decayed away.

One way to solve this problem is to introduce an additional, ‘spectator’ scalar field that couples to the ekpyrotic scalar field (Lehners et al. 2007; Levy, Ijjas, and Steinhardt 2015). While the details are beyond the scope of this paper, the coupling of the spectator and ekpyrotic fields can generate a scale-invariant spectrum of density fluctuations. Other solutions include choosing particular matching conditions to match growing modes in the contracting phase to growing modes in the expanding phase, but this is arguably less desirable as it requires very specific choices of matching conditions (Brandenberger and Peter 2017).

There is thus is a sense in which the bouncing cosmology paradigm requires dynamical fine-tuning in a way that the inflation paradigm does not. Inflation and its many dynamical realizations generically predict density perturbations with the features we observe, whereas the basic dynamical realizations of bouncing cosmologies require supplementation in the form of additional dynamical variables to produce the same results.

[16]Although, they have been criticised for requiring more parameters and fine-tuning than power-law models in order to achieve the same desired outcomes Ijjas, Steinhardt, and Loeb (2013).

5.5.3 Avoiding instabilities

Perhaps the biggest hurdle that bouncing models have to overcome is the existence of instabilities. Within physics, 'instability' can have a few different meanings. It could refer to an unstable fixed point, such as we saw in the example of the flatness problem. This is not in and of itself disqualifying as it just means that we don't expect the system to remain in its state for very long. Instabilities can manifest in far more concerning ways though, in the form of an unbounded Hamiltonian. These instabilities are frequently called 'ghost' or 'gradient' instabilities and are considered to be so problematic because they are both perturbatively ill-defined and can lead to the infinite production of non-physical, negative energy states (Rubakov 2014; Wolf and Lagos 2019). These frequently manifest themselves in the form of 'wrong-signed' terms in a theory's Lagrangian, such as a minus sign in front of the kinetic term. Theories with such instabilities are not generally considered to be physically viable.

This pathological behavior can be traced to the fact that bouncing cosmologies violate the *null energy condition* (NEC). The NEC holds that for any form of material content, $p + \rho \geq 0$. Inflation does not violate this constraint as this condition holds during an expansion phase with $w \approx -1$; however, bouncing cosmologies necessarily violate this condition when they transition from contraction to expansion. That is, $\dot{H} \propto -(p + \rho) \leq 0$ during contraction, and flipping $\dot{H}$ from $\dot{H} < 0$ to $\dot{H} > 0$ when contraction reverses to expansion requires violating this energy condition (Ijjas and Steinhardt 2018).

This problem is typically approached by introducing non-standard kinetic terms into the relevant scalar fields and/or introducing modifications to gravity that become relevant during the bounce phase (Cai, Easson, and Brandenberger 2012; Easson, Sawicki, and Vikman 2011; Ijjas and Steinhardt 2016a, 2017).[17] This usually takes inspiration from Horndeski gravity, which is the most general form of a scalar-tensor theory of gravity leading to second order equations of motion (Horndeski 1974). In particular, one way of doing this makes use of the so-called $\mathcal{L}_4$ interaction, which includes a non-minimal coupling between the scalar field and the Ricci scalar as well as non-standard kinetic terms. This particular variant of modified gravity within non-singular bouncing models allows for a stable violation of the NEC before, during, and after the bounce phase, free of pathologies.

This reflects an interesting way in which the dynamical realizations of the bouncing paradigm need to be dynamically fine-tuned (i.e., introduce highly specific modified gravity dynamics). Not

[17] This problem of constructing stable solutions in bouncing cosmologies is subtle. See also Cai, Li, et al. (2017), Cai and Piao (2017), Cai, Wan, et al. (2017), Creminelli, Pirtskhalava, et al. (2016), Kobayashi (2016), and Libanov, Mironov, and Rubakov (2016) for various approaches and developments in solving this problem.

all dynamical fine-tuning is bad. When examining the space of dynamical realizations of these paradigms, it is not at all problematic for *empirically motivated* dynamical fine-tuning to enter the picture as new observations further constrain models. Indeed, this can actually be desirable as it narrows the space of acceptable theories and helps theorists and experimentalists focus on those models which are more likely to be successful. However, dynamical realizations of the bouncing paradigm need not only be fine-tuned to accord with some observations, as does inflation, they must also be dynamically fine-tuned to be viable in principle.

Inflation possesses more explanatory depth in the dimension of dynamical fine-tuning because the paradigm itself can sustain the explanatory relationship with the observable universe in a way that is far less sensitive to specific choices with regard to the structure that dictates the relevant dynamical maps. This relative insensitivity to dynamical structure was in fact understood quite early on in the theory's development. In particular, Linde (1983, p. 180) argued in a seminal paper that our conclusions regarding inflation's ability to produce a universe like the one we observe is "almost model-independent" and that "inflation occurs for all reasonable potentials V(ϕ)", with the only real conditions being that the potential must be reasonably flat and operate at sufficient energy scales. This reasoning was also echoed in Guth, Kaiser, and Nomura (2014, p. 112) in their response to Ijjas, Steinhardt, and Loeb (2013) as they noted that inflation generates "generic predictions" that correspond to our observed universe and that these generic predictions "are consequences of simple inflationary models" and depend only on "the energy scale of the final stage of inflation". Bouncing models and their relevant dynamical structures, on the other hand, necessarily need to be wedded to very specific modified gravity dynamics, along with any associated baggage, to maintain their physical and explanatory viability. Indeed, leading proponents of inflation have critically noted that that the kinds of modifications utilized in these efforts seem to be inordinately complicated and fraught with difficulties (Linde 2015). The bouncing paradigm thus requires more dynamical fine-tuning than the inflationary paradigm and this reflects the reality that it is simply a much more difficult and non-trivial task to construct physically viable models within the bouncing paradigm.

5.5.4 Summary

Comparing the epistemic value of a deep explanation to one that is shallow in that it requires significant dynamical fine-tuning can be cashed out in terms of coherence and the resulting implications for our understanding of early universe physics. Inflation displays a remarkable coherence with other ideas in particle physics and quantum gravity; suitable scalar fields and potentials are ubiquitous in many promising ideas for extending the standard model. The first inflationary models investigated were motivated by spontaneous symmetry breaking in grand unified theories. Two of the most promising inflationary models today, non-minimal Higgs inflation and Starobinksy inflation, both have clear theoretical motivations given that their functional forms can be seen as naturally arising from the next to leading order terms that we would expect at high energies when extending either the standard model of particle physics or general relativity (see Martin, Ringeval, and Vennin (2014, Sec. 4)). By contrast, bouncing cosmologies are much harder to understand using basic expectations from high energy physics. Furthermore, the dynamical fine-tuning necessary to formulate a bouncing model that satisfies the most basic viability criteria requires introducing and meticulously fine-tuning several new parameters whose primary role is to prevent the formation of catastrophic instabilities. The explanatory deficiency here can be understood in terms of ad-hocness and incoherence that such constructs generate (see, e.g., Duerr and Wolf (2023) and Schindler (2018a) for related discussion).

Of course, one must be careful to not overstate inflation's coherence with respect to particle physics background knowledge: inflation and its various models/iterations remain speculative. Smeenk (2003, p. 251, fn. 6) rightly warns against doing so: "(o)ne important disanalogy between [inflation and (speculative) GUT-scale physics] is that no fundamental principles guide inflationary model-building in the same sense that gauge invariance and renormalizability guide the unification program", despite the fact that certain models might display coherence with these principles. Rather, the empirically adequate models for inflationary dynamics—which include some of the *simplest* ones (as Linde (2015) rightly underlines)!—instantiate fairly generic types of dynamics—dynamics/potentials that our particle-physics background knowledge gives us reason to deem plausible. On the other hand, there are no such (convincing) justifications for the kinds of dynamics that need to be deployed to ensure the viability of bouncing models.

Pragmatically speaking, both the deep and shallow explanation have their merits and deficiencies. The inflationary explanation is more secure in the sense that it performs far better under the highly uncertain conditions of these energy scales due to the lack of required dynamical fine-tuning. On the other hand, the dynamical fine-tuning required to construct viable bouncing models provide tight theoretical constraints on the types of models theorists can consider, allowing researchers to narrow their focus.

5.6 Autonomy and explanatory depth

Recall that one dynamical explanation is deeper than another along the dimension of autonomy when the explanatory connection between the explanans and explanandum is less sensitive to the breakdown of the relevant dynamical modelling frameworks or laws in regimes at very different scales from that of the explanandum. The trans-Planckian problem in cosmology can be understood as a threat to the autonomy of the explanations for key cosmic phenomena, such as the scale-invariance of the density fluctuations, based upon a breakdown in separation of scales. In this section we will consider the particular relevance of the problem to our explanatory comparison between inflationary and bouncing models. We will find that the problem gives us give reason to believe that the explanations offered by inflationary models are in general terms less deep than those offered by bouncing cosmology along the dimension of autonomy. We will also find that in the context of the so-called Trans-Planckian Censorship Conjecture (TCC), the sub-set of compatible inflationary models are such that they have greater depth in the dimension of autonomy; however, this comes at the expense of depth in the dimension of dynamical fine-tuning.

5.6.1 Inflation and Planck scale physics

The trans-Planckian problem for inflationary cosmology can be stated as follows. First, we observe that scalar perturbations result from tiny fluctuations in the fields driving cosmological dynamics. For an inflating space-time, the exponential expansion present in any such scenario stretches these fluctuations exponentially. Second, we note that inflation needs to last for a minimum length of time in order to solve the horizon and flatness problems. Third, we can then reason that if inflation lasts for a sufficient duration of time, fluctuation modes that originated as trans-Planckian modes (i.e., modes that are smaller than the Planck length) can be stretched such that they exit the Hubble radius and 'freeze'. These frozen modes undergo a quantum to classical transition, re-enter the horizon, and seed the scale-invariant density perturbations that form large scale structure, a cosmological explanandum of considerable importance. Thus, at least some of these *classical* fluctuations originated as *quantum* fluctuations smaller than the Planck length. In other words, this means that we are modeling these trans-Planckian modes using the cosmological framework comprised of the perturbed Friedmann equations and quantum field theory, when it is clear that this lies well outside this framework's domain of validity. The problem can then be stated qualitatively in terms of a *sensitive dependence* between the prediction of a scale-invariant spectrum in inflationary cosmology and *hidden assumptions* about super-Planck scale physics (Martin and Brandenberger 2001b).

Before providing a more detailed description of the problem in terms of a concrete cosmological model, let us briefly set out the implications of the problem for the explanatory depth of inflation. First, and most obviously, the trans-Planckian problem implies that for the inflationary explanation of the scale-invariant spectrum to obtain, one needs to add supplementary conditions relating to the relevant hidden assumptions regarding the super-Planck scale physics. Most prominently, as we shall discuss shortly, this seemingly requires some assumption regarding the adiabaticity within the Planck scale initial conditions or dynamics. This explicitly sacrifices at least some degree of explanatory depth along either the initial conditions or dynamical fine-tuning dimensions. Even more problematically, such a modification to the explanation has dire consequences for the explanatory depth along the dimension of autonomy. The physical scale of the explanans makes specific reference to details of the physics at the Planck scale, which is well beyond the domain of applicability for the explanans' dynamical laws. The mismatch with the physical scale of the explanandum is then around thirty orders magnitude (using a comparison between the Planck temperature and the CMB temperature). We can thus see why the trans-Planckian problem means that the inflationary explanation for the scale-invariant spectrum is rendered shallow along the dimension of autonomy and at least somewhat shallower along the dimensions of fine-tuning (either initial conditions or dynamical depending on the formulation of the problem).

To give a more concrete explanation of the problem we can build upon the analogy with the trans-Planckian problem in black hole thermodynamics.[18] Soon after Hawking's famous prediction that black holes produce thermal radiation (Hawking 1975), it was noted that the derivation of Hawking radiation makes essential use of a breakdown in the separation between micro- and macro-scales (Gibbons 1977). Following the formulation of Helfer (2003), it can be demonstrated that modes measured as energies lower than the Planck scale by stationary observers near future time-like infinity must have originated as trans-Planckian modes from the point of view of free-falling observers less than a Planck unit of proper time before falling through the horizon. The Hawking radiation incident on a finite, stationary detector far away from the black hole can therefore be traced back to what are, for free-falling observers, trans-Planckian energies at the horizon.[19] Significantly, as noted by Jacobson (2005, p. 79), the trans-Planckian problem amounts to "a breakdown in the usual separation of scales invoked in the application of effective field theory".[20] The black hole trans-Planckian problem presents a serious challenge to the prospect of a deep explanation for Hawking radiation in precisely the sense of autonomy that we have articulated. The original Hawking-style derivation connects explanans and explananda across hugely different scales in such a manner that the radiative effect to be explained is highly sensitive to

[18]This problem is subject to a detailed philosophical treatment in Gryb, Palacios, and Thébault (2021) and in what follows we build on that discussion, in particular §2.3 and §4.3

[19]For more on the trans-Planckian problem for Hawking radiation see (Brout et al. 1995; Jacobson 1993; Jacobson 1991; Unruh 1981, 1995). Accessible introductions are (Jacobson 2005, §7) and (Harlow 2016, pp.36-8).

[20]For discussion of the general connection between various senses of autonomy and EFTs see Crowther (2018) and Franklin (2020).

assumptions regarding Planck scale physics. This renders the explanation less modally robust in the sense that it is sensitively dependent upon the detailed physics of a very different scale.

There are many responses to the black hole trans-Plackian problem.[21] Here, we will focus our attention on approaches that appeal to modified dispersion relations (Barcelo, Garay, and Jannes 2009; Himemoto and Tanaka 2000; Unruh and Schützhold 2005). Essentially, this means that we model quantum gravity corrections to the Hawking spectrum by modifying the dispersion relation of the high-energy Hawking modes. We then use this modified dispersion relation, following a generalisation of Hawking's original derivation, to compute the late-time flux of Hawking modes. Assuming that these modifications to the dispersion relation satisfy a number of plausible criteria, the Hawking spectrum turns out to be insensitive to the modifications. The thermal spectrum of radiation is thus robust against a wide variety of potential modifications to the dispersion relation and even if the modes responsible for black hole radiation do originate from the trans-Planckian regime, the thermal properties of such radiation will very likely be insensitive to such Planck scale physics. The virtue of explanations of Hawking radiation based upon modified dispersion relations is thus precisely their explanatory depth in the sense of autonomy: the explanations provided are such that the explanatory connection between the explanans and explanandum is insensitive to the breakdown of our dynamical modelling frameworks or laws in regimes at very different scales from that of the explanandum. The relevant cross-scale explanatory connection does not display a high-level sensitivity to assumptions regarding the scale of the explanans and thus the explanation provided is deep in the sense of autonomy despite connecting very different scales.

The contrast with the cosmological trans-Planckian problem can then be explicitly made by applying a similar modified dispersion relation approach in the context of inflationary models. The key idea is to consider non-trivial relation between the physical frequency and comoving momentum of fluctuation modes (Brandenberger and Martin 2013; Martin and Brandenberger 2003; Martin and Brandenberger 2001b). For example, we can consider scalar metric fluctuations and modify the standard linear dispersion relation such that:

$$\omega^2 = k^2 \;\rightarrow\; \omega = F(k),$$

[21] Of particular interest are arguments based upon respectively: i) the Unruh effect and equivalence principle (Agullo et al. 2009); ii) horizon symmetries (Banerjee and Kulkarni 2008; Birmingham, Gupta, and Sen 2001; Iso, Umetsu, and Wilczek 2006); iii) the adiabatic theorem and particular 'nice slice' representation Polchinski (1995); and iv) connections between non-thermal vacuum states and violation of the semi-classical Einstein equations (Candelas 1980; Sciama, Candelas, and Deutsch 1981). See Gryb, Palacios, and Thébault (2021), Harlow (2016), and Wallace (2018) for further discussion.

where $k \equiv \frac{n^2}{a^2}$, n and k are the comoving and physical wave-numbers respectively, and F is assumed to be a non-linear function.

The modifications to the dispersion relation can then be fed into the dynamics of simple inflationary models and the quantitative effects on the resulting power-spectrum studied. In contrast with the example of Hawking radiation above, it turns out that the scale-invariance of the power spectrum depends sensitively on the form of modification. In particular, it can be shown that it is only if the modified dispersion relation satisfies an adiabaticity constraint in the UV sector that we can avoid the spectrum of cosmological perturbations acquiring a blue tilt whose spectral slope can well exceed current limits. This amounts to a specific choice of quantum gravity dynamics that is compatible with adiabaticity. The modified dispersion relation approach thus directly implies that inflationary explanations for the scale-invariant spectrum are required to sacrifice explanatory depth in terms of both autonomy and the dynamical fine-tuning dimensions.[22]

An alternative approach is to *not* evolve the fluctuation modes during the time period in which their wavelength is smaller than the length scale of new physics. This corresponds to introducing a time-like 'new physics hypersurface' on which special initial conditions are imposed. As noted by Brandenberger and Martin (2013), under such an approach the trans-Planckian problem has simply been shifted to the problem of choosing initial conditions on the new physics hypersurface. Furthermore, one version of this approach consists in explicitly starting modes off in their local adiabatic vacuum. Some physicists have argued that this is indeed a plausible approach to the problem and developed analogies in support of this argument with more familiar systems and their EFT descriptions (Burgess, Alwis, and Quevedo 2021). Even here though, this converts the dynamical fine-tuning at the trans-Planckian scales needed in the modified dispersion relation approach to a form of initial conditions fine-tuning. Moreover, once more, such an approach will inevitably sacrifice explanatory depth along the dimension of autonomy.

Part of the reason why this form of shallowness is particularly concerning is not only that the explanation depends on specific modelling choices at different energy scales, but also that our present knowledge of this particular energy scale is almost entirely speculative. The optimistic way of viewing the situation is that employing either of the above approaches could give us powerful hints and empirical constraints on Planck scale physics, while the pessimistic view worries that these approaches require a concerning reliance on speculation.

[22] We should note here that the modified dispersion relation based arguments towards this conclusion are not entirely without controversy. See discussions of Kaloper, Kleban, Lawrence, and Shenker (2002) and Kaloper, Kleban, Lawrence, Shenker, and Susskind (2003) and Brandenberger and Martin (2002) and Burgess, Cline, et al. (2003).

5.6.2 Bouncing cosmologies and Planck scale physics

The relationship between various proposals for bouncing cosmology and the physics of the Planck scale is a key factor in evaluating the models. One of the primary motivations for the introduction of a bounce is 'resolution' of the initial singularity.[23] A generic feature of bouncing cosmologies is that an initially contracting phase connects us to the currently expanding one via a bounce that takes place at some minimal value of the scale factor, hence avoiding the blow-up in scalar curvature invariants generically associated with the cosmic big bang singularity (Ellis and Schmidt 1977; Hawking and Penrose 1970; Thorpe 1977).[24] There is thus a quite general sense in which the bouncing cosmology paradigm can be expected to provide explanations which are autonomous from the Planck scale.

At a more specific level, in the context of the trans-Planckian problem, we can find good reasons to expect that explanatory depth along the dimension of autonomy will obtain for explananda such as the scale-invariance of the spectrum of density fluctuations. In particular, while fluctuations will shrink somewhat during a contraction phase, as long as the bounce remains far from the Planck regime, the fluctuations of interest never come close to approaching the trans-Planckian regime (Brandenberger 2021; Cai 2014). According to Brandenberger and Peter (2017), if the energy scale of the bounce corresponds to the same energy scale as in typical inflation models, then the wavelengths of scales corresponding to observed cosmic microwave background anisotropies were always larger than 1 mm. This means that the relevant explanations can be provided in a manner such that they are autonomous from the Planck scale without requiring further dynamical or initial conditions fine-tuning.[25] Indeed, proponents of such bouncing models argue that models in which all stages of the universe's evolution are dominated classically are advantageous in this sense because "there is no quantum-to-classical transition to be explained" (Ijjas and Steinhardt 2018, p. 9), a significant contrast to the trans-Planckian problem in inflation.

Another potential benefit of non-singular approaches that avoid the Planck scale is that they can offer a resolution of the *entropy problem*. Penrose (1989) and Penrose (1979) has argued that any universe that emerges from a gravitational singularity would naturally be expected to be maximally entropic as all degrees of freedom should be excited (matter, radiation, gravitational, etc.).

[23] For discussion of criteria for singularity resolution in quantum cosmology see (Thébault 2023).

[24] It is worth noting here the contrast with inflation where it has been shown that the Penrose-Hawking singularity theorems can be extended to show that a broad range of 'physically reasonable' eternal inflationary universes are necessarily inextenable and geodesically past incomplete, and therefore singular in the relevant sense (Borde, Guth, and Vilenkin 2003).

[25] A similar argument can run for the autonomy of the bouncing cosmological explanation of the smoothness of the universe from potential destabilisation effects of chaotic evolution in the asymptotic BKL regime. See Ijjas and Steinhardt (2018) and Battefeld and Peter (2015) for detailed discussion.

In particular, the gravitational entropy associated with tidal effects and inhomogeneities should dominate this early state and contribute an enormous amount of entropy to the universe. Furthermore, these inhomogeneities should be so significant that even inflation would seemingly be precluded from beginning at all. Yet, the universe we observe in the CMB is nearly maximal in its thermal entropy and completely negligible in its gravitational entropy, which already corresponds to a very low initial entropy state. This implies that there must have been an even more special initial state in the preceding inflationary epoch. A non-singular bouncing model seemingly avoids these entropy puzzles because its autonomy naturally protects it from the singularities that lead to such large expectations for the initial entropy of the universe.

While researchers within the bouncing paradigm consider resolving this problem to be a major advantage over inflation, the explanatory comparison is a little more difficult to frame in the terms we have introduced. In part, this is because the aforementioned issues regarding probability measures mean that arguments based upon appeal to relative typicality are not well-defined (Schiffrin and Wald 2012a). Furthermore, the inflation community has also pointed out that a full resolution of questions surrounding singularities will likely only come with a theory of quantum gravity that describes Planck scale physics (Guth, Kaiser, and Nomura 2014). If one has every expectation that we can develop a theory that will address these questions, combined with the understanding that these various cosmological paradigms are effective field theories, we can see why inflation theorists are less concerned by the entropy problem and singularity avoidance. In this way, the discussion somewhat mirrors that for trans-Planckian modes, where bouncing cosmologists see an important explanatory advantage and inflationary cosmologists instead see hints about physics at higher energy scales. The difference is that quantum gravity is an appropriate and natural arena in which to investigate questions surrounding gravitational singularities, whereas there seems to be something genuinely perplexing, if not problematic, about mixing Planck scale physics with descriptions of essentially classical density perturbations associated with the large-scale structure of the universe.

5.6.3 Inflation and the trans-Planckian censorship conjecture

Let us now return our discussion to inflationary models and consider a third potential response to inflation's trans-Planckian problem: the recently formulated *Trans-Planckian Censorship Conjecture (TCC)* (Bedroya, Brandenberger, et al. 2020; Bedroya and Vafa 2020; Brandenberger 2021). The TCC holds that observers such as us are necessarily screened from trans-Planckian modes, in analogy with the Cosmic Censorship Conjecture (CCC), which, in its weak form, can be plausibly interpreted to assert that for 'physically reasonable' spacetimes, there can be no singularities visible for observers at 'late' times (i.e., near future null infinity) (Penrose 1969, 1973). In both cases the idea is that there is a physical constraint that prevents observers from being exposed to radiative modes which have in their past probed arbitrarily high frequencies.

In qualitative terms, the TCC amounts to an assertion that the trans-Planckian problem can be circumvented *by fiat* such that structure formation in the early universe is autonomous with regard to the physics of the Planck regime. In more quantitative terms, the TCC consists in the specification of a condition which enforces the autonomy of inflationary models from the Planckian scale. This condition can be expressed explicitly via the relation (Brandenberger 2021):

$$\frac{a_f}{a_i}\ell_p < \frac{1}{H_f}, \tag{5.7}$$

where inflation begins at scale factor a_i and ends at scale factor a_f. This equation implies that a fluctuation the size of the Planck length ℓ_p cannot be amplified such that it is greater than the Hubble radius at end of inflation. In other words, such trans-Planckian modes are not allowed to exit the horizon and 'freeze', only to re-enter the horizon as classical modes later. As long as this inequality holds, observers are protected from trans-Planckian modes.[26]

Assuming the truth of the TCC, an inflation model will necessarily be autonomous from Planck scale physics: the explanations offered for the relevant cosmic explananda are stipulated to be such that the relevant physical scales are closely matched. We do not need to speculate about initial conditions on trans-Planckian scales in order to offer an explanation for classical large scale structure formation. Inflationary explanations with the TCC in hand are deep in the explanatory dimension of autonomy since the explanans, explananda, and domain of applicability of the relevant dynamical laws are all within the same broad arena.

However, this success along the autonomy dimension of explanatory depth comes with an attendant cost. The inequality (5.7) represents an upper bound on the amount of inflation that can occur without violating the TCC; however, there is also a lower bound if inflation's dynamical, causal explanations are to function properly. The lower bound is given by the following (Brandenberger 2021):

$$\frac{a_i}{a_0}\frac{1}{H_0} < \frac{1}{H_i}, \tag{5.8}$$

where a_0 denotes the current scale factor and H_0^{-1} denotes the current Hubble radius, while i denotes the beginning of inflation. The inequality (5.8) implies that modes that are within the horizon now must have been in causal contact (i.e., within the Hubble radius H_i^{-1}) at the

[26]In this context, there is a connection between the TCC and the Swampland Conjectures in string theory (Bedroya and Vafa 2020).

beginning of inflation. This is necessary for inflationary dynamics to offer a causal explanation of structure formation.

The two bounds given by (5.7) and (5.8) can be combined to constrain the energy scale of inflation, such that inflation would have had to occur at $\sim 10^8$GeV, or several orders of magnitude lower than the GUT scale ($\sim 10^{15}$GeV) that inflation has traditionally been believed to operate within. This has significant implications for inflationary dynamics. Among other things, it implies that the inflaton potential must be dynamically fine-tuned in order to match the observed amplitude of scalar fluctuations, while also operating within these constraints on the energy scale (Bedroya, Brandenberger, et al. 2020; Brandenberger 2021). It should also be noted, as Brandenberger (2021) acknowledges, that TCC constraints on inflation are weaker in more complicated multi-field inflation models. As these types of models are beyond the scope of this paper, we will not address them in detail here. However, this is relevant because some cosmologists who favour inflation believe that more realistic models of inflation could plausibly feature multiple fields and multiple stages of inflation. As Guth, Kaiser, and Nomura (2014) emphasize, recent developments in high energy physics and our current understanding of string vacua point towards the idea that realistic models of inflation may indeed be significantly more intricate than the standard single-field picture. Our analysis also applies in this case, just with the caveat that constraints coming from the TCC, along with the fine-tuning needed to operate within them, would need to be revised accordingly.

The implication, within our account for evaluating depth of explanations, is that inflation with the TCC trades explanatory shallowness in terms of autonomy for explanatory shallowness in terms of dynamical fine-tuning. The problem of choosing between inflationary explanations with and without the TCC, like that of choosing between inflation and bouncing explanations, then becomes one of *weighting* dimensions of depth. We will consider this issue and its broader implications for both cosmology and the nature of scientific methodology in the final section.

5.7 Dimensions of depth and heuristics

In this chapter, we have understood explanatory depth as a non-unitary concept with different dimensions relevant to different domains. The domain of primordial cosmology is one in which the three most relevant dimensions can be understood as i) initial conditions fine-tuning; ii) dynamical fine-tuning; and iii) autonomy. Following the insightful analysis of Azhar and Loeb (2021), we diagnosed the explanatory preference of contemporary cosmologists for the inflationary paradigm over the HBB paradigm as being based upon the greater explanatory depth along the dimension of initial conditions fine-tuning. This observation encodes a primarily descriptive rational reconstruction of the preference of cosmologist for inflation over the HBB.

Where things become more complex, and our account starts to blend the normative and descriptive, is in the explanatory comparison between inflationary and bouncing paradigms. In that context, we have isolated what we take to be the principal factor motivating the explanatory preference of most, although not all, cosmologists for the inflationary approach. Both paradigms successfully provide explanations that avoid initial conditions fine-tuning and offer far more depth than the HBB model which preceded them. However, the paradigms can be differentiated along the dimension of dynamical fine-tuning. Due to the need to avoid unphysical instabilities, models within the bouncing paradigm can be understood to display a form of dynamical fine-tuning which renders the relevant explanations lacking in depth along this dimension. That is, the explanatory relationship between explanans and explanandum is highly sensitive to variations in the dynamical structures *because* the physical viability of such models requires a significant degree of dynamical fine-tuning.

Taken on its own, dynamical fine-tuning allows us to appreciate why most theorists favour an inflationary account of the early universe. However, things become more controversial when we consider the explanatory dimension of autonomy. In this context, the trans-Planckian problem afflicts inflationary models, but not bouncing models, and represents a severe challenge to the autonomy of the relevant explanations, particularly with regard to the scale-invariance of the power spectrum. This bifurcates the explanatory merits of inflation into two different routes.

One possibility is that we accept that inflation's explanatory merits are shallow along this dimension of autonomy. In this case, inflation could potentially provide invaluable access to trans-Planckian physics and quantum gravity. This reflects an exciting opportunity where "unobservable physics might unexpectedly come within observational reach" (Burgess, Alwis, and Quevedo 2021, p. 1). However, in this scenario, inflation ends up being a bridesmaid rather than *the* bride, in that it stands adjacent to the trans-Planckian physics that is also responsible for the salient features of the observable universe. This is of course a trade-off that many physicists are happy to make, but in this case we must acknowledge that inflation does not carry the same explanatory weight most often attributed to it as some of this explanatory burden is then shifted to the relevant trans-Planckian details.

The other possibility is to make a move to restore the autonomy of inflation's explanatory power. The trans-Planckian problem can be ameliorated by appeal to the trans-Planckian Censorship Conjecture. Such a move, in turn, then requires inflationary models to be themselves

Dimension of Depth	Inflation (no TCC)	Inflation (with TCC)	Big Bounce
Initial conditions fine-tuning	✓/✗	✓	✓
Dynamical fine-tuning	✗/✓	✗	✗
Autonomy	✗	✓	✓

Table 5.1: Deeper explanations are marked by a ✓ and correspond to *less* fine-tuning. The ✗/✓ in Inflation (no TCC) reflects a choice with regard to how to avoid the trans-Planckian problem.

dynamically fine-tuned in a non-trivial way so as to avoid violating the conjecture. The result of this move is that both inflationary and bouncing models display a lack of explanatory depth in terms of dynamical fine-tuning. The main source of the difference between the paradigms is then that bouncing models need to be dynamically fine-tuned to be viable in principle, whereas inflation models need to be dynamically fine-tuned in order for the desired explanatory relationships to hold. Descriptively, it does seem like the dynamical fine-tuning evident in bouncing models is judged more harshly because it concerns the physical viability of the model, rather than the dynamical fine-tuning invoked to match observational constraints. The full situation can be concisely represented in Table 5.1.

Where does this leave us? One the one hand, our analysis provides a degree of clarity with regard to the reasons why cosmologists so strongly disagree with regard to the extra-empirical merits of the various paradigms: on our account they may simply be arguing at cross purposes by relying upon comparisons along incommensurable dimensions of depth. On the other hand, the result of this explanatory incommensurability is to blunt the normative utility of our analysis so far as we would like to provide a means through which to recommend scientists towards the deepest explanation available. On our analysis, there is no fact of the matter with regard to whether the explanations provided by inflationary or bouncing paradigms are deeper because there are multiple relevant dimensions of depth without a common measure of comparison.

What we would like to propose, on a more constructive note, is that the explanatory preference with regard to the different dimensions of depth can be understood in terms of differing attitudes with regard to heuristics for future model building. In particular, the reason why explanations that lack depth qua initial conditions fine-tuning are so unsatisfactory is, at least in part, due to the heuristic sterility of explanations of phenomena that appeal to special initial conditions.[27]

The choice between explanations that are deeper along the dimensions of autonomy and dynamical fine-tuning might be similarly framed in terms of their respective forms of heuristic fe-

[27] Here we would similarly categorise explanations for temporal asymmetry that rely on the so-called past hypothesis Earman (2006) and Gryb (2021).

cundity. The heuristic value of an autonomous but dynamically fine-tuned explanation can be understood in terms of the positive heuristics provided for theoretical model building in a constrained space within limitations on both the realm of relevant empirical phenomena and the possible dynamical structures that can be implements. By contrast, the value of an explanatory approach that is deep in virtue of not being dynamically fine-tuned, but shallower in virtue of lack of autonomy, might be understood in broadly empiricist terms: the failure of autonomy opens a window for plausible empirical constraints connecting vastly different energy scales. In this sense, trade-offs between dimensions of explanatory depth might be interpreted as encoding differing methodological stances rather than a choice between strictly incommensurable alternatives.

5.8 Acceptance *vs.* pursuit

Through this part of the thesis, we have encountered two primary cognitive stances that one can adopt towards theories of the early universe: acceptance/confirmation and pursuit-worthiness. This distinction between acceptance and pursuit-worthiness was most prominently made by Laudan (1977, 1996), where he proposed that we should distinguish sharply between the rules of appraisal governing acceptance and the much weaker and more permissive rules that should govern pursuit. Each prompts a different epistemological agenda, i.e., normative evaluations of rational warrant. Within the "context of *pursuit*", one inquires into whether a theory deserves further development: "(t)o consider a theory worthy of pursuit amounts to believing that it is reasonable to work on its elaboration, on applying it to other relevant phenomena, on reformulating some of its tenets" (Barseghyan and Shaw 2017, p. 3). By contrast, acceptance concerns the more traditional objective of epistemology: evidential warrant for, or confirmation of, a theory.

With regard to most of the literature on inflation, the scientific literature understandably does not overly concern itself with such philosophical distinctions, while most of the philosophical literature has tentatively operated within the framework of confirmation as it focuses on the evidentiary criteria that either has already been reached or must yet be attained to justify the acceptance of inflation (e.g., Dawid and McCoy (2023), Earman and Mosterin (1999), McCoy (2019), and Smeenk (2017)). Furthermore, it has been argued that various disputes within both philosophy and science often come down to the participants not properly clarifying the terms of the debate, i.e., whether they are arguing in the context of pursuit or acceptance (Barseghyan and Shaw 2017). However, given the current state of early universe cosmology, it is certainly the case that inflation has not yet achieved the level of empirical/evidentiary support needed to achieve a *convincing* case for confirmation, despite the fact that it is well supported by the data. And indeed, as argued in Wolf and Duerr (2023), even many of the strongest proponents of inflation can be read as adopting a stance of (enthusiastic) pursuit towards inflation while the evidentiary case sorts itself out (as opposed to accusations from some that they have been too quick to “accept” inflation). Similarly, opponents of inflation and proponents for other early universe programmes can be read as advocating for re-allocating pursuit towards alternatives given some of the problems with inflation and the simple fact that the evidentiary case is still open despite the expectation of many that we would have observed primordial gravitational waves by this juncture.

What justifies pursuit? This question, of course, has been widely explored in the philosophy literature (see, e.g., Fleisher (2022), Lichtenstein (2021), Šešelja and Straßer (2014), and Shaw (2022)). For our purposes, following Nyrup (2015) (and more specifically in this context Wolf and Duerr (2023, 2024)): we’ll adopt the perspective that “theory virtues” (Ivanova 2024; Keas 2018; Kuhn 1977; McMullin 2013) are indicators of promise and strong reasons to further pursue a theory.[28] The guiding thought is analogous to a cost-benefit analysis, where the potential benefit is an empirically successful and cognitively highly valuable theory, while the potential costs correspond to the resources (e.g., energy and time) invested into the theory should the theory have to be jettisoned in the end. Theories exhibiting virtues, such as explanatory power, unification, simplicity, coherence, etc contribute to the primary aim of science, which as before, we take to be finding “satisfactory explanations of whatever strikes us as being in need of explanation” (Popper 1983, p. 132). Note that some theory virtues—those typically regarded as pragmatic (rather than truth-tracking)—may not only indicate potential cognitive gain; they may also lower cognitive costs (e.g., making an approach easier to handle). In other words, justifying pursuit is “a decision theoretic problem of how to optimize the epistemic output of science” (Nyrup 2015, p. 753).

So far this chapter has undertaken a careful analysis of the explanatory dimensions at play in debates concerning early universe cosmology, concluding from this perspective that the various candidates perform well along incommensurable dimensions of explanatory depth. This does not stop one from having an opinion about how we should value their relative explanatory merits, but the normative force of any such pronouncement will be limited (notwithstanding the heuristic insight into approaches that perform well in different dimensions of explanatory depth). Explanatory power is one among many virtues though. Might something else decisively militate in favor one of these paradigms? At first blush, one may have doubts. For example, inflation and bouncing cosmologies both display similar unificatory power when it comes to, e.g., unifying large scale structure in the cosmos with quantum field theory or offer comparably similar gains

[28] We set aside questions here of whether and to what extent theory virtues can serve as a guide to truth (e.g., explanatory “loveliness” (Lipton 1991)).

in understanding when it comes to, e.g., understanding the fine-tuning issues surrounding initial conditions. Similarly, they both have their own strengths and weaknesses when it comes to the coherence (or incoherence) they generate with respect to external background knowledge.

However, next we will argue that there is one theory virtue that generates a significant asymmetry between the epistemic and pragmatic merits of inflation when compared to any other framework that purports to model the early universe: fruitfulness/fertility/predictive novelty.

5.9 Predictive novelty and inflation

Inflation makes certain generic predictions about the early universe that have been empirically confirmed, and as we shall argue, these predictions are novel in (at least) three important senses. This demarcates inflation from alternative proposals, which have all been, as a matter of historical fact, constructed after the fact in order to reproduce inflation's successes.

Thinking in terms of pursuit-worthiness, predictions fulfill two functions. First, predictive power allows physicists to ascertain whether inflation is on the right track. Predictions—either already performed or on the horizon—serve as preliminary reality or plausibility checks: they act as pro tem touchstones for adjudicating whether inflation's promises warrant a modicum of trust. Secondly, such plausibility checks seem especially compelling for *novel* predictions.

5.9.1 Predictions

It is not too much to ask that our scientific theories be put up against empirical tests, usually in the form of predictions. One of the rationales behind that demand is that the passing of such tests is supposed to redound to a theory's credibility; the theory thereby receives some special kind of confirmation. While here we focuses on the pursuit-worthiness of inflation—rather than the evidential credentials for its acceptance—it seems reasonable to demand that a pursuit-worthy theory pass *some* evidential threshold (either already or in the near future): for a theory to be pursuit-worthy one ought to be able to plausibly make some progress in ascertaining if it *might* qualify as acceptable. In other words, a pursuit-worthy theory should make at least some rough predictions that can be checked.

Inflation makes a handful of generic predictions (Guth, Kaiser, and Nomura 2014; Linde 2015); some of them can be—and in fact *have been*—tested. We have encountered two[29] of those

[29] Another prediction that has come up repeatedly in this thesis is inflation's predicts the existence of tensor perturbations in the form of primordial gravitational waves. Although the predicted amplitude of such signals is model-dependent, the (hopeful) detection of these signals is a major target of future surveys and these results (whether positive or null) will give us important information about the early universe.

predictions already:

1. The near-perfect geometric flatness of the universe, with curvature deviating from flatness at a quantifiable (micro-percentage) level.
2. The near, but not exact, scale invariance of the density perturbation power spectrum.

After briefly introducing various philosophical conceptions of predictive novelty, we will argue that these are indeed successful novel predictions of the inflationary paradigm.

5.9.2 Predictive novelty

A theory's predictive novelty, its ability to make novel predictions, is widely prized as the most important theoretical virtue (Kuhn 1977; Kuhn 1962; Lakatos 1978; Popper 1935). Typically, it's invoked as support for a theory in the context of confirmation. For our purposes given that inflation does not meet the evidentiary standards for complete confirmation, a weaker and intuitively plausible claim will do. Consider a situation where a theory has non-trivial predictive novelty, but falls short of the customary standards for confirmation. Under these circumstances, a theory's predictive novelty still signals greater promise than one lacking it. Predictive novelty, among other benefits, provides epistemic assurances, facilitates the creation of new evidence and new evidence/theory relations, guards against overfitting, and provides independent evidence for the theory in question (see Douglas and Magnus (2013) for an excellent overview). Collectively, these all boost a theory's pursuit-worthiness.

Various proposals exist for cashing out predictive novelty (see, e.g., Carrier (1988), Musgrave (1974), and Schindler (2018a)).[30] For our purposes, three are particularly germane. Without adopting a partisan attitude towards them, we'll briefly consider how inflation fares *vis-à-vis temporal* novelty, *heuristic* novelty, *problem* novelty.

5.9.2.1 *Temporal* novelty

Traditionally, as championed by Popper (1963, p. 36) or Lakatos (1978, p. 5), novelty has been construed in temporal terms: a prediction only counts as novel, on this view, if the forecast fact or phenomenon hasn't been *known beforehand* (or has even been expected *not* to occur).

When inflation was developed, the value of the universe's spatial curvature was only weakly constrained. Guth (1981, p. 347) noted at the time that "one can safely assume" that $0.01 < \Omega < 10$. Until the early 2000s, an open universe still remained very much an empirical possibility;

[30]They include *temporal* novelty, *heuristic/use*-novelty, *problem* novelty, *theoretical* novelty, and *non-adhoc* novelty. We believe that inflation scores highly on *all* of these accounts.

many prominent cosmologists in fact favoured it (Coles and Ellis 1997; Peebles 1986). Inflation not merely explains why the universe is somewhat flat to within a couple orders of magnitude (i.e., solve the flatness problem as it was understood in the 1980s); it gives a specific prediction that the present value of Ω in our universe is $\Omega \simeq 1$. This observation was first partially confirmed when the Boomerang mission detected a peak in the angular power spectrum of the CMB, giving $0.88 < \Omega < 1.12$ (Bernardis et al. 2000). Subsequent CMB experiments WMAP and PLANCK further refined this value, to currrently $1 - \Omega = 0.0007 \pm 0.0019$ (Aghanim et al. 2020b; Bennett et al. 2013). Inflation's prediction of a geometrically flat universe anticipated these measurements by approximately two decades (Guth 1981).

Proceeding to cosmic structure, "the most remarkable feature of inflation, widely recognized shortly after Guth's paper, was its ability to generate a nearly scale-invariant spectrum of density perturbations with correlations on length scales larger than the Hubble radius" (Smeenk 2017, p. 216). Inflation gave a clear prediction that the power spectrum of these density perturbations should be *nearly*, but *not exactly*, scale-invariant (as well as adiabatic and Gaussian) because inflationary dynamics necessarily push n_s away from unity as the field evolves, before the primordial density perturbations themselves had even been detected.[31] The first confirmation of inflation's predictions for the power spectrum of the density fluctuations came from the WMAP satellite; it ruled out a perfectly scale-invariant spectrum (Bennett et al. 2013). PLANCK further corroborated the finding by measuring $n_s = 0.9649 \pm 0.0042$—in excellent agreement with what one would expect if an inflationary epoch sourced these perturbations (Aghanim et al. 2020b). As with flatness, inflation's successful prediction preceded the observations by decades (Bardeen, Steinhardt, and Turner (1983), Guth and Pi (1982), Hawking (1982), and Mukhanov and Chibisov (1981), see Smeenk (2018) for historical details).

5.9.2.2 *Heuristic/use* novelty

According to the heuristic/use conception of novelty, one draws a distinction between predictions and accommodations (Worrall 1985, 2014). On this understanding, predictions are achievements of a theory that account for facts in a manner that flows from the theory's natural resources; accommodations, by contrast, occurs when data itself is used to determine parameters (or free functions) in the theory. This is relevant because some physicists (e.g., Bucher, Goldhaber, and Turok (1995)) and philosophers (e.g., Earman and Mosterin (1999)) have questioned whether spatial flatness is genuinely a robust prediction of inflation. Remarkably, it turns out that it is actually possible to construct open models of inflation, which allow for non-flat, open universes (Bucher,

[31] The first measurements came from the COBE satellite (Smoot et al. 1992).

Goldhaber, and Turok 1995). Nonetheless, a flat universe can be said to be a generic prediction of inflation, whereas an open universe can only be *accommodated*. In this sense, inflation can accommodate an open universe by using the observed curvature in an open universe as input data to reverse engineer/fix appropriate field values during the inflationary stage (see Bucher, Goldhaber, and Turok (1995)). By contradistinction, the basic structure and dynamics of inflation quite *generically* imply a flat universe; such a particular data point is *not* harnessed for specifying any parameters/free functions within the theory.

5.9.2.3 *Problem* novelty

Gardner (1982, p. 2) delineates a distinct nuance of predictive use-novelty. It pivots on what he dubs "*problem*-novelty": problem-novel phenomena "don't belong to the problem-situation which governed the construction of the hypothesis". That is, problem-novel phenomena don't belong to the *class of problems* that the theory's inventor considered their theory responsible to solve. For a theory's prediction to exhibit this type of novelty, the theory must not be "specifically designed to deal with the facts" or "cleverly engineered" to reproduce them (Zahar 1973, p. 102).

A glance at the earliest papers on inflation verifies that inflation wasn't specifically designed to predict the geometric flatness of the universe, or to source cosmic structure. Rather, both Guth (1981) and Starobinsky (1980) used ideas from particle physics to investigate how cosmological models might behave at the higher energy-scales in the early universe. While Guth initially investigated phase transitions in GUT models and later had a "spectacular realization" regarding the resolution of fine-tuning issues (Guth 1997, p. 179), Starobinsky developed models of inflation from a different perspective. He argued that we should expect quantum-mechanical corrections to GR in the high-curvature, high-energy regimes of the early universe. Consequently, he pursued the cosmological consequences that would result from these corrections and similarly found that we should expect a de Sitter-type exponential expansion in the early universe. Unlike Guth, Starobinsky in fact didn't notice any connection between this behaviour and the resolution of the HBB-model's fine-tuning problems. Regarding cosmic structure formation, as we already commented on, it was only *after* inflation's invention that it was realised that the theory provided a mechanism to explain it. As Baumann (2022, p. 336) emphasises, "[...] the theory was not engineered to produce these fluctuations [...] their origin is instead a natural consequence of treating inflation quantum mechanically."

Both of these predictions are problem-novel: the theorists who originally developed inflation weren't striving for a theory that resolves the fine-tuning problems or that accounts for cosmic structure formation; rather they *later* noticed that applying well-motivated ideas in high-energy particle physics to cosmology naturally offered compelling answers to those questions.

In sum: Irrespective of whether one construes predictive novelty in temporal, heuristic, or problem-novel terms, inflation has a significant leg up on its competitors. More recent alternatives obviously cannot compete with inflation in terms of temporal novelty. Furthermore, they were developed in a context in which the problems that inflation unexpectedly solved were more fully integrated into the problem situation; hence they can't be said to be problem-novel either. From this perspective, inflation is the most epistemically warranted and pursuit-worthy approach to early universe cosmology.

Part IV

Permanent underdetermination in cosmology

6 | Navigating permanent underdetermination in dark energy and inflationary cosmology

6.1 Introduction

The standard 'ΛCDM + inflation' model of modern cosmology is remarkably successful in accurately describing the evolution of the universe from mere fractions of a second after its birth until the present day (Aghanim et al. 2020b). Notwithstanding a few anomalies which are being actively investigated, all the available evidence indicates that this model offers an excellent description of reality. Yet, there remains a persistent sense of dissatisfaction due to the glaring absence of adequate explanations for much of the model's structure, which stems from the fact that it is largely phenomenological in nature. The basic ingredients of the model include:

Friedmann–Lemaître–Robertson–Walker (FLRW) metric: The universe is described on large scales by the FLRW geometry, which is characterized by its homogeneity and isotropy. Deviations from homogeneity and isotropy are treated as small perturbations.

Inflation: An early period of accelerated expansion that smoothed and flattened the universe, and produced tiny density perturbations that seeded future large-scale structure, driven by a field called the 'inflaton'.

Baryonic matter and radiation: Matter-energy content represented by the familiar standard model of particle physics.

Dark matter: A non-baryonic 'dark' matter that is crucial for accounting for empirical observations of galaxy rotation curves, the matter power spectrum, gravitational lensing, etc.

Dark energy: A late period of accelerated expansion that the universe is only just entering driven by a form of 'dark' energy.

The reasons for dissatisfaction are obvious. The only component of the model over which we have any kind of firm epistemic control are the fields in the standard model of particle physics, and these represent only a tiny fraction of the universe's energy budget at $\sim 5\%$ (compared with $\sim 25\%$ for dark matter and $\sim 70\%$ for dark energy). In the words of Peebles (2020a, p. 340), the model consists of placeholders that represent the "simplest ideas that would allow a fit to the observations", as is evident in the name: 'Λ' refers to a cosmological constant, 'CDM' refers to cold dark matter, and 'inflation' refers to a dynamical scalar field; all being the simplest possible physical realizations that satisfy the required empirical constraints.

One of the goals of modern cosmology is to determine the ‘underlying physical theory’ (Di Valentino et al. 2021, p. 3) behind this effective description of the universe. However, recent developments in cosmology indicate that this goal—already recognized as exceptionally challenging—might be even more daunting than cosmologists had expected. In particular, Ferreira, Wolf, and Read (2025) consider seriously the possibility that cosmological observations will permanently underdetermine the microphysical models underlying the phenomena behind inflation, dark matter, and dark energy due to the limited amount and type of empirical information that can be extracted from them. The variety of model-building constructs that exist within current cosmology are *very* broad for all of these three exotic energy components; here, we will zoom in on this claim with respect to certain classes of inflation and dark energy models, illustrating in detail how the simplest classes of inflation and dark energy models (i.e., canonical, single scalar field models) are permanently underdetermined with respect to the primary cosmological observables in their respective contexts. We then investigate and apply a philosophical taxonomy of possible responses (that was previously developed in the context of strong underdetermination) to these instances of permanent underdetermination, arguing that some of these theories' effective field theory (EFT) formulations map onto these philosophical responses and finding that under some circumstances the underdetermination within these restricted classes of theories can arguably be broken.

The structure of the chapter is as follows. §6.2 reviews recent developments in inflationary and dark energy model building, and how cosmologists map between these theories and cosmological observables. §6.3 argues that model building in both dark energy and inflation reflect instances of what Pitts (2010) has called ‘permanent underdetermination’, in the sense that there will always be distinct microphysical theories that attribute fundamentally different structures to nature, but which give empirical predictions that are *arbitrarily close* to each other; meaning that the underdetermination can never be broken empirically. This section also reviews some strategies that have been deployed in the context of strong underdetermination and argues that they can also be applied in cases of permanent underdetermination. §6.4 introduces effective field theories (EFTs), as in fact these will feature prominently in analyzing the strategies that have been pursued in response to permanent underdetermination. §6.5 explores and assesses applications of the discrimination, overarching, and common core approaches (in the terminology of Le Bihan and Read (2018)) in response to permanent underdetermination in dark energy and inflationary cosmology, and argues that there are some viable strategies that can break the underdetermination.

6.2 State of play in modern cosmology

In this chapter, we will study certain classes of theories that are commonly used to model both inflation and dark energy. We will consider only the simplest versions of these theories, which are both given by a single, canonical scalar field on an FLRW metric:

$$S = \int d^4x\sqrt{-g}\left[\frac{1}{2}M_{\mathrm{P}}^2R - \frac{1}{2}g^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi - V(\varphi)\right] + S_m, \tag{6.1}$$

where g is the metric, R is the Ricci scalar, M_{P} is the Planck mass, φ is the scalar field, $V(\varphi)$ is the potential of the scalar field, and S_m represents the action for matter fields.

When modeling the early universe, this theory is referred to as 'inflation' and the scalar field is taken to dominate the mass-energy budget of the universe. When modeling dark energy in the late time universe, this theory is referred to as 'quintessence' and the scalar field and matter are both dynamically relevant as they have comparable energy densities in the present epoch. While the action above is written with a minimal coupling between the scalar field and the Ricci scalar, in the single field inflation paradigm it is common to also consider non-minimal couplings between the scalar field and gravity as there are plausible arguments that they are to be expected at these energies (see Martin, Ringeval, and Vennin (2014) for a comprehensive review). Such non-minimal couplings can also be considered in quintessence, but since this is less common than in inflation we will follow the main physics literature here and confine ourselves to minimally coupled quintessence models (see Tsujikawa (2013) for a comprehensive review).

6.2.1 Inflation

Inflation initially gained traction due to its ability to offer satisfying explanations for various fine-tuning problems within the Hot Big Bang model (Guth 1981; Starobinsky 1980),[1] such as its ability to answer the question, 'why is the universe so precisely flat and homogeneous?' Inflation offers a compelling dynamical resolution to those problems by introducing a scalar field φ with a potential $V(\varphi)$ that dominates the matter-energy content of the universe at early times. While many different functional forms of the potential have been considered, all giving distinct microphysical models of inflation (e.g., the interaction responsible for inflation could be given by massive fields, exponentials, axions, Nambu-Goldstone bosons, the Higgs or Higgs-like fields, etc.), as long as the potential is sufficiently flat it can alleviate these fine-tuning concerns. Briefly,

[1] The very brief characterization here glosses over some details. See, e.g., McCoy (2015, 2019), Smeenk (2005), and Wolf and Duerr (2023) for further discussion on the nature and severity of these fine-tuning problems, inflation's achievements in explanatory power and predictive novelty, and various other theoretical motivations at play in the context of inflation's development.

the dynamics of an FLRW universe are described by the Friedmann equation,

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{k^2}{a^2}, \tag{6.2}$$

which relates the evolution of the scale factor of the universe a to the energy density ρ and k is the curvature of the geometry. A crucial quantity here is the so-called 'equation of state', defined by $w \equiv p/\rho$, which is the ratio of pressure p and energy density ρ of a perfect fluid. The forms of the equations of state of the various energy density components within the universe will determine the dynamical trajectory of spacetime. When the universe is dominated by a scalar field with a flat potential, this generates an equation of state $w(a) \simeq -1$, which effectively acts as a repulsive form of gravity and causes the universe's scale factor a to expand quasi-exponentially in time, $a \simeq e^{Ht}$. This both flattens the geometry of the universe (i.e., k^2/a^2 becomes negligible) and explains how large sections of the universe, that now appear to be outside each other's past light cones, actually share a common causal past that produces the observed uniformity in the distribution of matter and energy (see, e.g., Baumann (2022, Ch. 4) for details).

Yet, where inflation truly shines is its account of cosmic structure. Inflation generically predicts that quantum fluctuations in the scalar field should produce slight deviations from uniformity, and that these scalar perturbations should be approximately adiabatic, Gaussian, and scale-invariant. Primordial perturbations matching this description have been confirmed by the *Planck* satellite, and it is these perturbations that source the large-scale structure seen today in the late-time universe (Aghanim et al. 2020b; Akrami et al. 2020).

In addition to these scalar perturbations, inflation is also expected to produce tensor perturbations, with their amplitudes and power spectra being denoted, A_s and A_t, and $\mathcal{P}_s$ and $\mathcal{P}_t$, respectively. As mentioned above, the amplitude and power spectra of the scalar fluctuations have been measured; however, the tensor fluctuations (i.e., primordial gravitational waves) still elude detection and are one of the primary targets of ongoing and future cosmological probes. Crucially, the dynamics of individual inflationary models generally give predictions for the ratio of the amplitudes of scalar and tensor perturbations, as well as for the scale-dependence of the scalar fluctuations. Thus, inflation is characterized primarily by two observables, the tensor-to-scalar ratio r and the scalar spectral index n_s:

$$r = \frac{A_t}{A_s}, \qquad n_s(k) - 1 = \frac{d \log \mathcal{P}_s}{d \ln k}. \tag{6.3}$$

Furthermore, predictions for these quantities can usually be derived directly from analyzing the dynamics of individual inflation models in the so-called 'slow-roll' approximation (when the scalar inflaton field 'rolls' down its potential energy hill slowly compared to the expansion of the universe), which allows for the creation of a convenient map between these cosmological observables and the inflationary model space in terms of the pairs (r, n_s).

While many models of inflation do map onto distinct regions of the (r, n_s) parameter space (see Akrami et al. (2020, Fig. 8) for the inflationary 'zoo plot' of models) and there was initially the general expectation that inflation should produce an observable r (Boyle, Steinhardt, and Turok 2006; Tegmark 2005), as the upper bound on r has been pushed lower and as theorists have further explored the inflationary landscape, these initial expectations have proved to be too naïve.

To list just a few examples, Kallosh, Linde, and Yamada (2019) demonstrated how one can cover the entire viable region of (r, n_s) plane with 'α-attractor' and 'KKLT' models. Stein and Kinney (2023) and Wolf (2024b) showed that, within 'hilltop' models, higher order terms in the potential, which were often neglected in computing their predictions, in fact can have a significant effect on the end of inflation and can reduce predictions for r arbitrarily while still remaining within the viable n_s region. Sousa et al. (2024) used machine learning techniques to identify inflationary potentials and found several largely unexplored functional forms with predictions below observational thresholds in the (r, n_s) plane. All of these constructions can be understood within the simplest version of the single-field inflationary paradigm and so do not generate any egregious added complexity or *ad hocness* in order to produce such predictions. Yet, they are distinctly different microphysical accounts in terms of the fundamental interactions which they take to underlie inflation. Furthermore, the constructs mentioned here all have the ability to push (r, n_s) many orders of magnitude below projected experimental sensitivities for next generation CMB probes (Abazajian et al. 2016) in addition to covering much of, if not all, of the remaining viable parameter space that will remain within experimental reach.

6.2.2 Dark energy

The presence of dark energy is inferred primarily through distance measurements (Frieman, Turner, and Huterer 2008). That is, we have an abundance of data that informs us about cosmological observables such as angular diameter distances or luminosity distances to particular objects at specific epochs in the expansion history of the universe. These distance measurements are sensitive to the Hubble rate $H(a)$, which relates the universe's rate of expansion in terms of its scale factor a to its energy density through the Friedmann equation. Until a few decades ago, cosmologists assumed that radiation and matter were the only stress-energy species relevant to the dynamics of the universe. However, if we assume they are the *only* sources of energy density in our cosmological modelling, there are large discrepancies between the cosmological distances observed and those predicted under those modeling assumptions.[2] These observations indicate that there is a missing component in the universe's energy density.

In other words, $H(a)$ can be rewritten in the following way to show how it is sensitive to how various types of energy density scale with respect to the expansion of the universe's scale factor:

$$H^2(a) = H_0^2 \left[\Omega_{\mathrm{r}} a^{-4} + \Omega_{\mathrm{m}} a^{-3} + \Omega_{\mathrm{x}} e^{3\int_a^1 (1+w_{\mathrm{x}})\mathrm{d}\ln \mathrm{a}} \right], \tag{6.4}$$

where Ω_x represents the energy density and w_x represents the equation of state for some unspecified additional component. Taking $w_x \equiv w_{\mathrm{DE}} \simeq -1$ brings the predicted and observed distance measurements into alignment. This indicates that the universe is dominated by a form of 'dark' energy that is (approximately) not diluting with the increase of the scale factor; thus entering another period of accelerated, quasi-exponential expansion, in close analogy with the inflationary account of the early universe.

How do we map between the data/observational side and the theory space of dark energy? As the effects of dark energy models are primarily driven by the behavior of their equation of state, physicists have largely adopted a well-known parameterization of the dark energy equation of state known as the Chevallier-Polarski-Linder (CPL) parameterization (Chevallier and Polarski 2001; Linder 2003):

$$w(a) = w_0 + w_a(1-a), \tag{6.5}$$

where w_0 is the value of the equation of state today and w_a characterizes the temporal variation of the equation of state. This allows us to characterize various dark energy models in terms of the pairs (w_0, w_a). For example, Λ would be given by $(-1,\ 0)$, while any dynamical models would have $w_a \neq 0$. If dark energy is dynamical (i.e., not driven by Λ), the next most simple and obvious way to model it is to adapt the single scalar field machinery of inflation to the dark energy problem, as was most notably done by Caldwell, Dave, and Steinhardt (1998) and Ratra and Peebles (1988), which is known as 'quintessence'. While the observational picture here is still far from settled, recent results from the DESI collaboration (Adame et al. 2024) (discussed earlier in this thesis) have provided the first substantial evidence for deviations from a cosmological constant and for a dynamically evolving equation of state. At the very least, these results motivate considering a dynamical framework that goes beyond the base cosmological constant scenario.

[2] See Durrer (2011) for a good discussion.

Similarly to the inflation case, there was some hope that cosmologists would be able to pin down a precise microphysical model of dark energy by its predictions for (w_0, w_a) (Caldwell and Linder 2005). Yet, these hopes have likewise not materialized. More specifically, current constraints highly favour the 'thawing' regime of dark energy.[3] As has been explored by Dutta and Scherrer (2008), Shlivko and Steinhardt (2024), and Wolf and Ferreira (2023), 'hilltop' models of quintessence have dynamical features that enable them to describe the equation of state $w(a)$ as evolving in a slow, approximately linear manner, or in a very rapid, highly non-linear manner, and everything in between. Consequently, these models can arbitrarily saturate huge swathes of the (w_0, w_a) parameter space because they can effectively generate a slow dynamical evolution, in which case they approximate the universal behavior of the many familiar models found in Scherrer and Sen (2008), or an arbitrarily rapid dynamical evolution (described by w_a) for any value of the equation of state today w_0, in which case they approximate a number of other distinct models with similar features in their potentials.[4]

As discussed in Wolf and Ferreira (2023), within the region of field space for which a quintessence field can serve as dark energy, the predictions between many distinct microphysical models are, both in principle and in practice, indistinguishable from each other in terms of their predictions for the equation of state and its resulting observables. For a brief concrete example, the typical hilltop model and the axion/pseudo-Nambu-Goldstone Boson (pNGB) model can arbitrarily approach each other's predictions in (w_0, w_a) because, when their potentials are Taylor expanded, their leading order terms are identical. Further, it is these terms that describe the regime of field space responsible for the observed dark energy in the current epoch because dark energy given by an equation of state close to the cosmological constant value can only have undergone a fairly limited amount of evolution. Yet, for time-scales on the order of the life-span of the universe, their differences in microphysics would lead to either an abrupt recollapse of the universe in the case of the standard hilltop model because the potential eventually becomes negative (Felder et al. 2002), or merely a peaceful end to further acceleration in the case of the PNGB model because this potential eventually stabilizes and oscillates around its minimum (Frieman,

[3]This means that the equation of state becomes less negative as it evolves, corresponding to $dw/da > 0$.

[4]There is an additional nuance here. While from a theoretical perspective this parameterization of $w(a)$ is frequently interpreted as a Taylor expansion of $w(a)$ around recent cosmological times, from a data perspective these are 'fitting parameters'. This means a particular dark energy model does not have a unique representation in terms of (w_0, w_a) parameters (as opposed to inflation where those models do have unique representations in (r, n_s) parameters because the observables calculated directly from the theory). Rather, a dark energy model's representation in this parameter space will depend on which data sets are used and which redshift epochs the said data sets probed because (w_0, w_a) is properly determined by finding the best fitting parameters for Eq. (6.4) for the data considered (as the true raw observables are sensitive to $H(z)$). Regardless, the models considered here will still sweep huge regions of the parameter space, this footnote is just to highlight that the exact representation of it is somewhat data dependent. See Shlivko and Steinhardt (2024), Wolf and Ferreira (2023), Wolf, García-García, Bartlett, et al. (2024), and Wolf, García-García, and Ferreira (2025) for further discussion and different approaches for doing so.

Hill, et al. 1995). Nothing less than our knowledge of the future fate of the universe is at stake here!

Furthermore, in analogy with the single-field inflation paradigm, the theories of dark energy described above by the quintessence paradigm all fall within a common but simple framework: that is, they are all described by a single, minimally coupled scalar field with a canonical kinetic term and a potential function. Consequently, the ability for all of these distinct models to saturate the same observable parameter space is not artificially generated by engineering unrealistically complex or *ad hoc* constructs. They are all on a relatively level playing field, described by the simplest imaginable way to build scalar field theories within general relativity on an FLRW cosmological background.

6.3 Underdetermination

6.3.1 Types of underdetermination

The underdetermination of theory by evidence is undoubtedly a central pillar in the realism debates of contemporary philosophy of science (Duhem 1954). The familiar distinction between 'transient'/'weak' underdetermination and 'strong' underdetermination delineates the boundaries of our epistemic misgivings (Quine 1975; Sklar 1975). As the familiar story goes, there might be a number of theories competing to explain the available data; yet, they differ in their empirical predictions, which suggests that such underdetermination is transient and will be broken once further empirical data can be gathered. Far more epistemically worrying *prima facie* is the possibility that there exist a number empirically equivalent theories that could never be distinguished from each other by any empirical data, but which also present distinct and conflicting ontological visions of the world. Here, we take empirical equivalence between theories T and T' to mean the *exact* equivalence between the empirical substructures of every model M of T and M' of T' (van Fraassen 1980). This strong underdetermination represents a serious challenge to those with realist predilections because it seems to undermine any firm basis for using science to identify our ontological commitments.

However, the debate concerning the degree of epistemic threat posed by strong underdetermination has largely hinged on whether there are any truly compelling examples of such underdetermination. On the one hand, some philosophers have taken the threat seriously (e.g., Acuña (2021), Earman (1993), Hoefer (2020), Jones (1991), Kukla (1993), Mulder and Read (2023), Mulder (2024), Quine (1975), and Wolf, Sanchioni, and Read (2024)) and pointed to, among other examples, alternative formulations of quantum mechanics, Newtonian mechanics, and general relativity to argue that there may be genuine instances of strong underdetermination. On the other hand, these examples have all generated a fair amount of skepticism, with skeptics dismissing such examples as artificial, and, for example, arguing that the theories in question are either notational variants of one and the same theory, or that the proposed ‘alternatives’ are deficient in some obvious way (e.g., Laudan and Leplin (1991), Musgrave (1992), Norton (2008), and Stanford (2001)). Norton (2008, p. 20), in this context, has prominently argued that, in any case where we can tractably demonstrate empirical equivalence between two theories, “we cannot preclude the possibility that the theories are merely variant formulations of the same theory”, and that this suggests that we should view purported instances of strong underdetermination with suspicion.

More recently, Pitts (2010) has identified a third form of underdetermination, dubbed ‘permanent underdetermination’. Rather than models sharing exactly equivalent empirical substructures as in the case of strong underdetermination, here the idea is that the models are technically empirically inequivalent, but nevertheless arbitrarily close in their empirical substructures. As an example, Pitts considers the approximate empirical equivalence of various massless theories in modern particle physics and gravitation research alongside their massive counterparts. That is, consider that $\{(\forall m)T_m\}$ is a family of related theories parameterized by mass m, whereas T_0 is the corresponding massless theory. T_0 and $\{(\forall m)T_m\}$ approximate each other arbitrarily closely in the limit $m \to 0$. So while T_0 may in principle be transiently underdetermined with certain members T_i of the family, as long as T_0 remains viable it can *never* be empirically distinguished from the larger family $\{(\forall m)T_m\}$. Crucially, “the empirical equivalence is not merely approximate, and hence perhaps temporary; rather, the empirical equivalence is *arbitrarily close and hence permanent*” (Pitts 2010, p. 271, my emphasis).

This novel type of underdetermination is arguably far more interesting and compelling than strong underdetermination, if only for the reason that this type of underdetermination is immediately immune from the common charge that the theories in question are merely notational variants of each other. They plainly cannot be ‘one and the same’ because they are empirically inequivalent and make different ontological claims; yet, there is also a precise sense in which they can never be distinguished from one another empirically.

6.3.2 Permanent underdetermination in cosmology

Up to this point, philosophical attention regarding underdetermination in cosmology has focused largely on allegedly strong underdetermination in large-scale spacetime geometry and topology

(Belot 2023; Butterfield 2014; Ellis 2006; Manchak 2009), or stayed closer to transient underdetermination (implicitly and/or explicitly) and explored how various extra-empirical or methodological considerations might in the meantime influence matters of interpretation, theory-choice, or theory-pursuit given the (quite challenged) observational *status quo* in the early universe or dark matter/energy (Antoniou forthcoming; Azhar and Butterfield 2016; Dawid and McCoy 2023; Duerr and Wolf 2023; Koberinski, Falck, and Smeenk 2023; Martens and Lehmkuhl 2020; Massimi 2021; Smeenk 2017; Wolf and Duerr 2023; Wolf and Thébault 2023). However, this chapter confronts the possibility that cosmology might well be plagued with *permanent* underdetermination in the above sense, and indeed that this more pernicious underdetermination applies to distinct models within the *same* theories/frameworks. The upshot is that cosmological modeling might already be hopelessly undetermined even before departing from the simplest ways of describing concrete cosmological observables in an expanding, perturbed FLRW spacetime.

To be a little more specific, the issue of permanent underdetermination in cosmology is the following. In the dark energy case, one can always find multiple distinct microphysical models which come arbitrarily close in their predictions of the parameters (w_0, w_a).[5] Likewise, in the inflation case, one can always find multiple distinct microphysical models which come arbitrarily close in their predictions of the parameters (r, n_s). So, in both cases we have an apparent case of permanent underdetermination, and it is incumbent upon us to attempt to overcome this if we are to identify a specific cosmological model which is best apt to describe our universe.

Before proceeding, it is worth pausing briefly to say just a few more words concerning the observational status quo and the diagnosis of permanent underdetermination. Typically, when analyzing potential instances strong or permanent underdetermination, the implication is that the underdetermination holds with respect to all possible observations. Here we have identified and focused on the primary observables relevant to testing and constraining dark energy and inflation models. Is it possible that there are other empirical factors that could come into play that might lead to the conclusion that these are not examples of permanent underdetermination?

In our view, the answer is almost certainly 'no'. The first thing to be said is that our empirical access within cosmology as a whole, and to the early and late-time universe physics that we attempt to model with inflation and dark energy in particular, is incredibly limited. With inflation,

[5]To be clear, this applies regardless of whether or not the most recent indications from the data that dark energy might be dynamical hold up. If the data pulls back towards a cosmological constant, all the options are still on the table as all of the models discussed here (and many more) are all perfectly capable of mimicking a cosmological constant to produce $(w_0, w_a) \simeq (-1, 0)$. If the data continues to pull away from a cosmological constant, we may be able to eliminate Λ as a viable candidate (an example of eliminative reasoning in this content Koberinski, Falck, and Smeenk (2023)), but that would still leave a multitude of completely distinct dynamical possibilities on the table.

the actual physics occurs at an epoch and at energy scales to which we have no direct empirical access. We are limited to gathering relic statistical imprints produced by the actual physical process—well after the fact and only once the universe has cooled enough to allow photons to stream freely. While we have some small measure of direct empirical access to dark energy because we are living through this epoch at present, this empirical access is limited to just a few basic kinds of measurements that chart out the expansion history or growth of cosmic structure on the largest scales in the universe. As discussed in detail by Ferreira, Wolf, and Read (2025), these data points are useful (but blunt) instruments that give us some insight into the bulk properties of these energy components' fluid-like descriptions, but leave details of their microstructure massively unconstrained. This is similar to how measuring the viscosity of a fluid might give us some insight into its properties, but utilizing only this information, there is very little we could say about its detailed molecular or atomic structure. Given this state of affairs, it is almost certain that observables like those identified here will forever remain the only relevant observables that one can use to make any substantive statements about the physics of inflation or dark energy, and these observables only give (at best) a limited glimpse at what the underlying microphysical structure might be.

The second thing to say is that, while there are some other observational parameters that can be constrained beyond (w_0, w_a) and (r, n_s) that, under some very particular circumstances, might come into play to tell us something about dark energy or inflation that the primary observables are not themselves able to, there are very good reasons to believe that such observables will not affect this diagnosis of permanent underdetermination.

Two reasons for this are as follows. First, as discussed by Ferreira, Wolf, and Read (2025), most other potential observables discussed in these contexts as possibilities would necessarily be far fainter and more poorly constrained when compared with the primary observables as they have not yet been detected. Second, both the single-field inflation and quintessence paradigms represent essentially the simplest way of building scalar field theories relevant to cosmology, and they both happen to offer empirically adequate and viable descriptions of the regimes which they purport to describe. These other possible observables represent telltale signs of highly exotic physics that go beyond these simple frameworks. For example, cosmologists also consider the possibility of finding non-Gaussian signatures in the primordial density perturbations. However, it is known that simple inflation models such as the ones discussed here produce unobservably small non-Gaussianities (Martin, Ringeval, and Vennin 2014). Observations of primordial non-Gaussianity would necessitate a move to more complicated models, such as those with non-canonical kinetic terms or with sharp features in their potential functions (Chen 2010). Similarly, cosmologists have been looking for evidence of fifth forces that could conceivably show up in solar system tests or in the growth of cosmic structure. If evidence revealing such effects was confirmed, it would necessitate moving away from the simple quintessence framework and towards true modified gravity theories such as scalar-tensor theories with a non-minimal coupling to the Ricci scalar (Joyce, Lombriser, and Schmidt 2016).[6] In either case, further observational signatures beyond the main observables described here point us towards substantially more exotic physics that *requires* the introduction of more parameters and more complicated interactions. Given that we have permanent underdetermination at the simplest level of empirically adequate description, we have every reason to expect that the underdetermination problem would be even worse if observations required that we adopt more complicated frameworks with larger parameter spaces.

To sum up: barring some as-yet unconceived revolution that would fundamentally change the kind of empirical access we have to cosmological phenomena, it is very likely that both inflation and dark energy are permanently underdetermined (Ferreira, Wolf, and Read 2025). Due both to the inherent empirical limitations and access within cosmology, it is almost certainly the case that these will remain the primary observations for making any substantive empirical statements about inflation or dark energy. While some other possible observational signatures beyond these are conceivable if inflation and/or dark energy are significantly more exotic than conceived here, detecting such signatures would likely make the problems of permanent underdetermination even worse for the reasons mentioned above.

Ultimately, we want to get as close as we can to the underlying physical theory that describes the evolution of the universe. While this is of course a tremendously ambitious goal, finding ways to break or lessen the underdetermination certainly has the potential to make a positive contribute in this direction. Currently, physics is inundated with hundreds (if not thousands) of 'toy' models and variegated theoretical proposals for inflation and dark energy. A strong justification for pursuing strategies to break or weaken this underdetermination is to single out privileged descriptions of the relevant physics, and thereby identify redundancies, enhance understanding, and sharpen the heuristics used for investigating cosmological phenomena in the hopes of moving closer to this goal.

[6] See, e.g., Wolf, Ferreira, and García-García (2025b), Wolf, García-García, Anton, et al. (2025), Ye (2024), and Ye et al. (2024) for some recent discussion of how non-minimally couple scalar-tensor theories might alleviate some perplexing aspects of current cosmological data.

6.3.3 Responses to underdetermination

What responses are available when presented with cases of permanent underdetermination? To explore an answer to this question, we can avail ourselves of a (suitably modified) taxonomy of possible responses to strong underdetermination given by Le Bihan and Read (2018). Of these, three strategies stand out as potentially having relevance for permanent underdetermination:

Discrimination: Preferentially discriminate in favor the ontological claims of one theory amongst the underdetermined alternatives.[7]

Common Core: Break the underdetermination by moving to a new interpretive framework. The new framework is obtained by isolating the 'common core' that is shared among the underdetermined alternatives and then interpreting this shared common core as a distinct, ontologically viable theory of its own.[8]

Overarching: Break the underdetermination by developing a new (potentially richer) theoretical structure which subsumes the original underdetermined theories.[9]

While these strategies have all frequently been pursued in the context of strong underdetermination, they might also be applied profitably in response to cases of permanent underdetermination. Of the three, the discrimination approach is fit for purpose as is and requires no modification. There evidently can be reasons to prefer one theory over another in cases of permanent underdetermination, including (but not limited to) super-empirical virtues (e.g., simplicity, coherence, predictive novelty, etc.), explanatory power, and the lack (or presence) of theoretical structures deemed pathological.

On the other hand, applying the common core and overarching approaches to permanently (as opposed to strongly) underdetermined theories requires a little more thought. Begin with the common core strategy: here, one is guided by the need to construct some weaker (i.e., structurally more impoverished) theory which is nevertheless empirically equivalent to the original underdetermined theories. As such, it is not so obvious how to identify the common core when empirical equivalence fails, as is indeed the case in instances of permanent underdetermination. One strategy here would be to focus only on empirical equivalence *in some domain*, and proceed from

[7]E.g., consider that one might break the underdetermination between various different formulations of electromagnetism in favour of the fibre bundle formulation both of grounds of (a) ontological parsimony and (b) expressive power (since this formulation still admits a variational principle etc.).

[8]E.g., see Haro and Butterfield (2021) and March, Wolf, and Read (2024) for applications of the common core approach in response to Newtonian-themed instances of strong underdetermination, where Maxwell gravitation/spacetime could be argued to be the common core.

[9]E.g., see Muller (1997a,b) for discussion on how matrix and wave mechanics were synthesized into the now-standard formulation of quantum mechanics based upon Hilbert spaces.

there.

When it comes to the strategy of building an overarching theory, the situation is this. Overarching theories, such as M-theory subsuming various superstring theories or quantum mechanics subsuming matrix and wave mechanics, exhibit a richer solution space than the theories they encompass, which is not terribly surprising considering that such a framework by necessity must be more general in some sense. Of course in the case of permanent underdetermination, the new ontological framework stemming from the common core or overarching strategies will necessarily not be precisely equivalent to the underdetermined theories as they are not precisely equivalent to each other. Yet, that notwithstanding, nothing would seem to preclude one from following the 'overarching' strategy when faced with permanent underdetermination.

Now, when considering both the common core and overarching approaches, a point made by Le Bihan and Read (2018) in the context of strong underdetermination bears stressing: simply constructing a new theory (whether a common core theory or an overarching theory) does not *per se* ameliorate philosophical problems of underdetermination—in fact, there is a clear sense in which developing some new theory makes the situation worse! As such, these strategies must be supplemented with further philosophical reasoning (e.g., reasoning in terms of parsimony or explanation or unification) in order to justify treating the newly-developed theory as preferred, and thereby to overcome the case of underdetermination under consideration.[10] This point continues to stand when these strategies are brought to bear on cases of permanent underdetermination, which is our concern here.

6.4 Effective field theories

6.4.1 The EFT paradigm in physics

Effective field theories (EFTs) are ubiquitous in modern physics. The essence of the EFT paradigm is this: we take some target system which is in some sense and to some degree isolated from external influences, and we are interested in providing a description of this target system up to a level of precision which makes sense relative to the physics of the system as compared with that of the environment and of the relevant measuring devices (this could involve a comparison of energy scales, or of length scales, or of something else, depending upon context). So, there is a scale-relativity built into the EFT paradigm. Often, this scale-relativity is indeed built into the model explicitly: one defines a power counting parameter δ such that quantities can be calculated

[10]Note that the common core approach places weight upon ontological parsiomony, whereas 'overarching' strategies seem in general to place more weight upon unification.

to some order in δ; relative to a given modelling context, terms sufficiently high order in δ will be negligible.

It is by now well-recognised that both the Standard Model of particle physics and general relativity can be understood as EFTs. As Burgess (2020, p. 241) writes on the latter:

> From this point of view the Einstein–Hilbert action should not be regarded as being carved by Ancient Heroes into tablets of stone; one should instead seek the most general action built from the spacetime metric, $g_{\mu\nu}$, that is invariant under the symmetries of the problem [...] organised in a derivative expansion.

As we'll explore later, the actions which have been offered in inflation and dark energy models are also highly plausibly understood as being those associated with EFTs—and, indeed, this offers some novel possibilities for tackling underdetermination in cosmology in general. Before we get to that, though, a little more on the connections between the EFT paradigm on the one hand and underdetermination of theory by evidence in the other.

6.4.2 EFTs and underdetermination

Suppose now, following Polchinski (2017), that one has some high-energy theory which admits of multiple distinct perturbative expansions—expansions, indeed, which might agree up to some order (in the power counting parameter δ) but diverge thereafter.[11] Then, associated with the high-energy theory will be multiple distinct low-energy theories—theories which, indeed, might be approximately (but not exactly) empirically adequate in some domain. In a specific situation in which there is a large number—perhaps even an infinity—of such theories (a situation illustrated by Polchinski (2017, §2.5) in the context of the Montonen–Olive duality), this plurality might even give rise to a case of permanent underdetermination!

So, the EFT paradigm can (at least in some cases) afford a means of understanding the *origins* of cases of permanent underdetermination such as those encountered in modern cosmology. But as we'll discuss in the next section, it also affords a novel way of thinking about various ways in which such cases of underdetermination might be resolved.

One last word on this: a precondition for deploying the EFT paradigm in order to overcome apparent cases of permanent underdetermination in cosmology is that one can be a scientific realist about EFTs at all—given that (by definition!) EFTs are effective only in some domain, and might break down thereafter, one might worry about such an approach. For an engagement

[11] For Polchinski (2017), such a situation is definitional of a 'duality' in physics.

with authors who voice such concerns, and for a compelling corrective that EFTs can and should be interpreted realistically, we refer the reader to the work of Williams (2019), which we endorse wholeheartedly going forward, and which is quite naturally understood as being part of a broader recent movement in the philosophy of science towards regarding ontology as being 'scale-relative' (see, e.g., Ladyman and Ross (2007)), and towards thinking in particular that one's ontological commitments in a given physical context should be given by the mathematics which best describes the physical goings-on in that context (see, in particular, the 'mathematics-first structural realism' of Wallace (2022)). Our discussions in this chapter are properly situated within this school of thought.

6.5 Addressing permanent underdetermination in cosmology

6.5.1 Responses to permanent undetermination in inflationary models

The situation *vis-à-vis* permanent underdetermination and inflation is as follows. It seems to be the case that given a pair $(r,\ n_s)$, which represents the primary cosmological observables relevant to an inflationary epoch in the early universe, there will always be a plethora of distinct microphysical models that can generate predictions for $(r,\ n_s)$ that are arbitrarily close to each other. Thus, we have an instance of permanent underdetermination. As we will be interested in exploring the extent to which we can successfully break this underdetermination, whether by identifying a privileged ontology of one of the theories or by finding some new ontology in which to embed the underdetermined theories, it is worth briefly reflecting on the ontological posits of the standard inflationary paradigm.

Standard inflation can be described succinctly as being given by models of the form $\langle M, g_{\text{FLRW}}, \Phi_i, \varphi\rangle$, where M is a four-dimensional differentiable manifold, g_{FLRW} is the FLRW metric on M, Φ_i represent other matter fields (e.g., standard models fields, dark matter, etc), and φ represents the inflaton field. As there are many distinct microphysical models, these will all pick out distinct dynamical possibilities from amongst this set. These dynamically possible models will then be given by $\langle M, g_{\text{FLRW}}, \Phi_i, \varphi_V\rangle$, where φ_V denotes a specific microphysical model of inflation determined by the particular potential function $V(\varphi)$ that describes it. Furthermore, these dynamical possibilities all obey dynamics given by the Klein-Gordon equation in an FLRW background,

$$\ddot{\varphi} + 3H\dot{\varphi} + V'(\varphi) = 0, \tag{6.6}$$

with $V'(\varphi) = dV/d\varphi$. The solutions for φ will of course depend upon the particular inflation model as the functional form of V will dictate the model-specific dynamics of the scalar field. These dynamics then get fed into H, which determines the dynamical trajectory of the universe itself through its impact on the scale factor a. With this in mind, we identify two plausible strategies that can be deployed in response to permanent underdetermination in inflation: the discrimination approach and the overarching approach.

Discriminating would involve favoring the ontological claims of some particular model out of all those considered. Given our background knowledge from the Standard Model of particle physics, it turns out that there is a uniquely privileged candidate: Higgs inflation, denoted by $\langle M, g_{\text{FLRW}}, \Phi_i, \varphi_H \rangle$. As the only fundamental scalar field that has been empirically verified, at first glance the Higgs seems to have the properties we are after: it is scalar field that that permeates all of space in order to contribute to the universe's energy density and it has a flat region in its potential. If it were concluded that the standard model Higgs, before it reached the minimum of its potential that it now occupies, produced an inflationary epoch consistent with observations, there would be an open-and-shut case for discriminating in favor of φ_H. The resulting consilience, coherence, and parsimony with respect to the most precise, empirically verified, and fundamental theory that physics is in possession of would be so overwhelming that it is hard to imagine there would be any desire for physicists to investigate the other many hundreds (literally) of 'toy' models that have been considered. However, this tantalizing scenario ultimately does not work; there are excellent constraints on the parameters of the standard model Higgs, and the observed value of the self-coupling constant and the Higgs mass produce amplitudes for density perturbations many orders of magnitude larger than those which are actually observed (Bezrukov and Shaposhnikov 2008).

While the Higgs field, understood exactly according to the Standard Model of particle physics, is not a viable inflation candidate, there does perhaps remain a way in which to salvage a discrimination-type argument in its favor. As discussed in Bezrukov and Shaposhnikov (2008) and Martin, Ringeval, and Vennin (2014), at very high energies, renormalizing a scalar field generally creates a non-minimal coupling between the scalar field and the Ricci scalar of gravity because quantum corrections typically introduce such terms in the effective action. With these considerations in mind, it has been shown that Higgs inflation with a non-minimal coupling can produce inflation in excellent agreement with observations with a nearly scale-invariant spectrum and $r \sim 10^{-2}$. If future observations were to indicate strong agreement with these predictions, then there would be a very strong argument for discriminating in favor of Higgs inflation as similar reasoning to that detailed above would still apply. Higgs inflation with a non-minimal coupling would be strikingly cohesive with the Standard Model of particle physics, and the only new physics required by such a scenario would be that which is already expected as a natural consequence of renormalizing scalar fields in a curved spacetime background.[12] At that point, it would be difficult to argue that other inflationary models should be taken as serious competitors. This scenario would also be ideal for pursuing further questions in cosmology or high energy particle physics given that many of the various couplings and interactions with other particles are already known quantities.

Of course, there is no guarantee that this scenario will play out. Observations might instead favour another region of parameter space, or the upper bounds on r might get pushed below observational sensitivities. Another clear approach that can be distilled from the literature is strongly analogous to the overarching approach and is explicitly due to some physicists' stated desires to work in an 'agnostic' or 'model independent' way given the lack privileged microphysical model. The strategy is then to embed the inflation paradigm in an EFT.[13] There are a few approaches (e.g., Azhar and Kaiser (2018), Burgess (2017), Cheung et al. (2008), and Weinberg (2008b)), but that of Cheung et al. (2008) is arguably the most well-known.

Here, the authors apply the EFT-building philosophy to the problem of inflation. That is, given that the main observable constraints are directly sensitive to scalar fluctuations, they construct the effective action at the perturbative level for these inflationary scalar fluctuations with "the lowest dimension operators compatible with the underlying symmetries" (Cheung et al. 2008, p. 1). That is, the physical situation in which we are interested is the description of scalar fluctuations around a quasi-de Sitter background. Here, the relevant symmetries are spatial diffeomorphisms and time diffeomorphisms, but the scalar field acts as a 'clock' that breaks the time-translation symmetry which the de Sitter background would otherwise have had (hence, 'quasi'-de Sitter). Schematically, such a theory can be written in the following way (Burgess 2017, Eq. 3.32):

$$\mathcal{L} = \frac{M_p^2}{2}R - \alpha(t) - \beta(t)g^{00} + \frac{1}{2}M_2^4(t)\left(g^{00}+1\right)^2 + \frac{1}{3!}M_3^4(t)\left(g^{00}+1\right)^3 + \cdots . \quad (6.7)$$

Here, the theory has been written in the so-called 'unitary gauge' where the scalar degree of free-

[12] While this argument can be made in compelling fashion at the level of theory virtues (e.g. simplicity, coherence, predictive novelty, etc.) (Kuhn 1977; Schindler 2018b), one can also imagine making such an argument from the perspective of the meta-empirical arguments given in Dawid (2013).

[13] There are numerous conceptual issues with applying the EFT framework to inflation and cosmology more generally. Briefly, the usual separation of scales that is present in other EFT applications does not seem to hold in the same way in cosmology. Here, we set aside these issues and take for granted that these methods can be applied. See Koberinski and Smeenk (forthcoming[a],[b]) for deflationary views from the philosophy literature and Martin and Brandenberger (2001a) for a physics formulation of the so-called Trans-Planckian problem which looms large in these discussions. See Burgess, Alwis, and Quevedo (2021) for a rebuttal from the physics literature and Wolf and Thébault (2023) for a philosophical analysis of the heuristic value of biting the bullet and accepting this breakdown of scales.

dom is absorbed into the metric g. The first term represents gravity through the Einstein-Hilbert term, while the next two terms encode the unperturbed dynamics of the background spacetime and scalar field. The higher-order terms can be built out of the temporal part of the metric g^{00}, the extrinsic curvature $K_{\mu\nu}$, the Riemann tensor $R_{\mu\nu\rho\sigma}$, etc. (see Cheung et al. 2008, Appendix A for details). While in principle the coefficients in front of the various terms represent arbitrary functions of time, specific choices for these functions will correspond to familiar inflationary models. For example, the phenomenology of the simplest inflation models discussed here can all be understood to be contained within the first three terms here, whereas the higher order terms describe the phenomenology that results from deviations from this paradigm (e.g. the action for standard slow-roll inflation is given by the choice $\alpha = V(\varphi)$, $\beta = \frac{1}{2}\dot{\varphi}^2$, and all other functions parameterizaing the higher order terms are set to zero). The higher order terms might capture higher-order effects such as non-Gaussianities which we would expect to derive from non-standard or higher order kinetic terms.

What we have here represents a clear-cut case of applying the overarching approach. As an analogy, consider well-known examples that have been identified in the literature as exemplifying this strategy, which include (to repeat from above) embedding the various superstring theories within the framework of M-theory, or embedding matrix and wave mechanics into what is now consider to be 'orthodox' quantum mechanics (Le Bihan and Read 2018). The distinctive feature of this strategy is that the underdetermined theories have been unified such that they can be understood as different facets of the overarching theory that subsumes them. This is exactly what has been done here. That is, the above inflationary EFT represents the most general framework compatible with the most basic physical assumptions of inflation (quasi-de Sitter expansion in a perturbed FLRW background), and the various microphysical inflationary proposals correspond to particular choices for α, β, and the functions parameterizing the higher order terms. However, it is also important to emphasize that this framework is far more general than the simplest versions of the inflation paradigm, and can accommodate much more exotic physics as particular realizations of the various EFT parameters.

What is the fundamental ontology posited by this framework? The ontology still consists of a scalar field, but the scalar field is now frequently denoted π to distinguish it from the standard inflaton field φ. The inflationary EFT can be described by models of the form $\langle M, g_{\text{FLRW}}, \Phi_i, \pi\rangle$ and the dynamics for π come from the very long and cumbersome EFT action schematically introduced above. While we are still working with a scalar field, there are some changes in its interpretation. π is now interpreted as a Goldstone boson that results from the spontaneous breaking of time-translation symmetry, which generates some level of analogy with other dynamical systems in particle or condensed matter physics that exhibit spontaneous symmetry breaking.

However, as noted in §6.3, the existence of an overarching theory does not by itself break the underdetermination. There is a further interpretive move that has to be made to justify the overarching framework over its various constituents. While what such a justification looks like will obviously be context dependent, as discussed earlier, what we are really looking for is an argument that would uniquely privilege one of these theories, with the ultimate goal being to develop the best theoretical description that can predictively account for cosmological phenomena and provide good explanations for (or even resolve) the scientific questions that we are interested in.

Unfortunately, in contrast with Higgs inflation, such a justification for the overarching theory is lacking. The EFT of inflation is *only* valid for the period of inflation itself (Cheung et al. 2008, p. 17). If there was an inflationary period in the early universe, we know that inflation had to end at some point and that a subsequent period of reheating is needed to describe how the inflaton decayed and the universe was populated with the mass-energy content observed today (i.e., the matter fields Φ_i). The specific microphysics that dictates the nature of these particle interactions is relevant to these processes. In other words, the φ_V component of $\langle M, g_{\text{FLRW}}, \Phi_i, \varphi_V \rangle$ is relevant for understanding the Φ_i component once inflation has ended. And working with π obscures these links. Consequently, the totality of the physics relevant to the problem ensures that this overarching theory does not remove the need to explore and refine specific microphysical models. Furthermore, this particular EFT approach offers only limited epistemic value for understanding the microphysics of inflation. This is because it essentially offers a very general parameterization of possible physical effects that can result from a scalar degree of freedom. This is not to deny that there is significant pragmatic value in the overarching theory in that it "allows a relatively model-independent survey of what kind of observables are possible at low energies, without having to go through all possible microscopic models beforehand" (Burgess 2017, p. 86). This can give us some insight into the general classes of inflationary models that might fit well with the data, but will not by itself offer any kind of perspicuous interpretation in terms of a particular microphysical model of inflation. That is, actual candidate microphysical theories will occupy different parts of the parameter space that this EFT defines, but the EFT itself does not present itself as a viable microphysical structure which could be the source of inflation, which is ultimately what we are after. While this EFT approach is no doubt valuable for describing the inflationary epoch, it remains necessary to investigate microphysical models alongside it. Rather than truly breaking the underdetermination, this EFT approach provides a very useful and informative tool that can help to constrain future model building efforts.

6.5.2 Responses to permanent underdetermination in dark energy models

The situation for dark energy can be set up in much the same way as for inflation. We have a plethora of microphysical models of the form $\langle M, g_{\text{FLRW}}, \Phi_i, \varphi \rangle$. The dynamical possibilities, which are a subset of these models, then correspond to $\langle M, g_{\text{FLRW}}, \Phi_i, \varphi_V \rangle$, where φ_V denotes a specific microphysical model of quintessence that obeys the dynamics that follow from its potential function V and the solutions to Eq. (6.6). In this case though, the scalar field φ is not totally dominant but rather competes with the already-existing matter fields Φ_i for influence over the dynamics of the universe, which generally makes these dynamics more complicated. Yet, there are many distinct microphysical models which give arbitrarily close predictions for (w_0, w_a) and are thus indistinguishable from each other. Similarly, one response to this situation mirrors the inflationary case. There is an almost identical EFT approach to dark energy that has been developed and applied over the years (Gubitosi, Piazza, and Vernizzi 2013) (i.e., write down all the terms in the action that the symmetries of the problem allow and constrain the free functions that parameterize those terms); however, this is not the only option as one can motivate a different kind of effective field approach. Below we will argue that there is a straightforward application of the common core strategy available in response to permanent underdetermination in dark energy.

Depending on the problem of interest, it is often the case that physicists consider a Taylor expansion of the potential V to some order in φ when working with scalar field cosmological models (e.g., Boyle, Steinhardt, and Turok (2006), Chiba (2009), Dutta and Scherrer (2008), Kallosh and Linde (2003), Wolf (2024b), and Wolf and Ferreira (2023)). In other words, any arbitrary, analytic potential can be represented by a series expansion:

$$V(\varphi) = V_0 + \left.\frac{dV}{d\varphi}\right|_{\varphi=0} \varphi + \frac{1}{2}\left.\frac{d^2V}{d\varphi^2}\right|_{\varphi=0} \varphi^2 + \frac{1}{6}\left.\frac{d^3V}{d\varphi^3}\right|_{\varphi=0} \varphi^3 + \cdots . \tag{6.8}$$

While this is not exactly the same as the EFT philosophy pursued in the inflation case where the authors used symmetries to write down the most general theory under the given physical assumptions, it is still an EFT in the sense that it is focusing on the scale-relative effects of a general scalar field potential. This is particularly interesting in the context of the dark energy problem due to the material facts with which we are confronted. The universe has only recently entered a period of accelerated expansion that has been found to be either indistinguishable from, or incredibly close to, a cosmological constant depending on the data considered. All of the empirical facts on the ground are telling us that $w_{\rm DE} \simeq -1$ over the period of comic history to which we have robust empirical access. If dark energy is indeed driven by some of scalar field within this general framework, this indicates that the field excursion will be small and that the dominant contribution will come from the constant part of Eq. (6.8), whereas the (small) deviations from the value predicted by a cosmological constant will necessarily be encoded in and dominated by the next-to-leading order term in the expansion.

What does this term look like? For a large number of scalar field potentials, such as those whose functional forms are even or which have a critical point about the point at which the expansion is taken, the linear term in Eq. (6.8) automatically vanishes because the first derivative V' is zero, leaving the quadratic term as the next-to-leading order contribution. This includes several well-known potentials such as hilltop potentials, the quadratic potential, axions, pseudo-Nambu-Goldstone bosons, Gaussians, various supergravity-motivated potentials, etc., all of which look identical in this regime and can be described accurately by an energy scale V_0 and a quadratic term $V'' = m^2$ (Dutta and Scherrer 2008; Kallosh and Linde 2003; Wolf and Ferreira 2023), where we have now identified the second derivative of the scalar field potential as a mass term (more on this soon). What about potentials for which the linear term does not automatically vanish such as the frequently deployed exponential potential (which is often motivated by string theory considerations)? It turns out that even here, one can perform a field redefinition for the scalar field in order to eliminate the linear term and provide an equivalent description given by the rescaled field with a next-to-leading order quadratic term (Wolf and Ferreira 2023). The upshot is that, in the regime of field space where scalar field physics can describe dark energy, a tremendous number of the most widely used and theoretically well-motivated potentials can all be characterized to an excellent approximation with the same functional form given by

$$V(\varphi) = V_0 \pm \frac{1}{2}m^2\varphi^2. \tag{6.9}$$

Furthermore, this functional form happens to have the dynamical freedom mentioned earlier that allows it to saturate large areas of the observable (w_0, w_a) parameter space. One the one hand, when $V'' > 0$ the dark energy equation of state has been found to evolve according to highly universal behavior characterized by slow, linear evolution (Scherrer and Sen 2008; Wolf and Ferreira 2023). While, on the other hand, when $V'' < 0$ the dark energy equation of state can evolve incredibly rapidly in a sharp, highly non-linearly manner depending on the choice of model parameters and initial conditions; this allows it to sweep over the observable parameter space (Dutta and Scherrer 2008; Shlivko and Steinhardt 2024; Wolf and Ferreira 2023). This is due to the resulting effects on the parameter w_a, which captures the time variation of the equation of state. And finally, when $V'' \to 0$, the model recovers the cosmological constant.

In other words, this single functional form can account for the phenomenology associated with all dark energy models that fall under the umbrella of a single, canonical, minimally-coupled scalar field. The relevant scales and phenomena themselves seem to single out this kind of effective description for the physics. Furthermore, the fact that all of these distinct models can be understood to agree on this effective description of the physics makes this analogous to the common core strategy described in §6.3. That is, for every distinct microphysical dark energy model of the form $\langle M, g_{\text{FLRW}}, \Phi_i, \varphi_V \rangle$, there is an equivalent description (to arbitrarily close empirical precision) given by a model of the form $\langle M, g_{\text{FLRW}}, \Phi_i, \varphi_{(V_0, m^2)} \rangle$. The common core approach would then implore us to adopt this description, given in terms of an effective mass and energy scale, as it has been isolated by determining which aspects of the ontology are mutually agree upon by all of the underdetermined models.

As before, however, the mere existence of a viable common core does not by itself break the underdetermination. Further argumentation or interpretation is needed in order to justify the common core theory as successfully breaking the underdetermination. One clear justification takes the form of a 'robustness argument' in favour of the common core of the underdetermined models: since the common core features in the plurality of underdetermined models (and is robust in that sense), we have some heightened degree of confidence that this common core offers explanatory value within the problem context of dark energy physics beyond the individual merits of each specific quintessence proposal viewed in isolation. In other words, the common core is a robust feature of this family of dark energy proposals in the sense that it offers a unique description which all of these models flow to within the regime of interest. This robustness establishes the potential explanatory viability of the common core in a highly reliable manner, which by itself confers additional pursuit-worthiness to it on explanatory grounds. For discussion of such arguments in the context of a search for a quantum theory of gravity, see Linnemann (2020).

Another flavor of justification that often shows up in the context of adopting a common core theory over its rival description involves appeals to parsimony: if there is excess, idle structure in our ontology, then it is well-advised not to take such structure seriously when articulating one's roster of ontological commitments. In the case of the permanent underdetermination of dark energy models, a justification exactly identical to the above isn't available because all of these theories share roughly the same basic ontological structure; i.e., there is some spacetime metric, matter fields, and a dark energy scalar and it's not obvious that there is any dramatic Occamist gain which results from moving to $\langle M, g_{\text{FLRW}}, \Phi_i, \varphi_{(V_0,m^2)}\rangle$ if parsimony is construed as ontological parsimony (the sheer quantity of entities or kinds of a particular entity). Yet, parsimony need not be exclusively construed in this way. In addition to ontological parsimony, there is also syntactic parsimony, which refers to the parsimony of the theory's structure, particularly in terms of the number and complexity of its assumptions, variables, or formal/mathematical elements (Schindler 2018b).

Here, the effective description really shines. The familiar mass/quadratic term leads to linear equations of motion which are formally equivalent to those of a damped harmonic oscillator when $m^2 > 0$, or a system exhibiting an exponential instability within this regime when $m^2 < 0$ (which also has many classical analogues). This means that, contra most scalar field potentials considered in the literature, the theory given by $\langle M, g_{\text{FLRW}}, \Phi_i, \varphi_{(V_0,m^2)}\rangle$ leads to Eq. (6.6) having either shockingly simple analytic solutions or very manageable numerical solutions depending on the exact context. Of course, this generates insight into parameter dependencies, increases computational speed and tractability, and facilitates further predictive power (see, e.g., Dutta and Scherrer (2008) and Wolf and Ferreira (2023) for specific examples where this has been leveraged in this problem-context). There is also arguably a significant gain in understanding to be had as this theory allows us to import our pre-existing insights (both quantitative and qualitative) into a new application. We are just dealing with a field that possesses the property of mass, which is arguably the kind of physics that we have most epistemic control over at both the classical and quantum level as mass is simply a known intrinsic property of fields that quantifies their resistance to motion. This theory then lends itself to a familiar, perspicuous interpretation of the ontology that isn't always available if one is working with some highly exotic field that may have been introduced with dubious or speculative physical motivations in mind. Despite all of these dark energy theories being similar in terms of ontological parsimony, $\langle M, g_{\text{FLRW}}, \Phi_i, \varphi_{(V_0,m^2)}\rangle$ is clearly privileged in terms of its syntactic parsimony, for both pragmatic and epistemic reasons.

Another factor which speaks in favour of the common core theory in this case has to do with its unification of all the various alternative microphysical models. Rather than painstakingly investigating each model individually, one can now investigate the whole family of models under their effective description in one go. This has been exploited to great effect in Wolf, García-García, Bartlett, et al. (2024), where constraints were obtained on the entire family of models through utilizing the effective description in terms of V_0 and m^2. Among other things, this allows one to directly glean information concerning the likelihood of the common core model parameters (that again captures the whole family of theories) when confronted directly with cosmological data. There it was shown that in light of the recent DESI data which favors a time evolving dark energy equation of state, models with $m^2 < 0$ are favored in terms of their likelihood over models with $m^2 \simeq 0$ or $m^2 > 0$, which provides some small measure of evidence for the detection of a 'negative' cosmological scalar field mass (there are several important nuances to this statement that we are eliding over—see Wolf, García-García, Bartlett, et al. (2024) for more details).

This reflects a model-agnostic approach to this general class of dark energy theories that allows one to evade the difficult and time-consuming task of investigating each and every distinct potential that can be dreamt up. Yet, if one, for some reason (maybe due to some more fundamental interest in a particular model(s)), did not want to be model-agnostic, this is useful here too. Such a unified description facilitates a like-to-like comparison of different theories which are known to occupy certain regions of the (V_0, m^2) parameter space using a common language in terms of the same parameters (e.g., the typical exponential model which has $m^2 > 0$ as opposed to, say, an axion model with $m^2 < 0$). Furthermore, one can always map between the parameters described by the microphysical model and those described by the common core theory in terms of an effective energy scale and an effective mass, if there is any need to do so.

Given that the physics of the problem dictates that all of these various field theory proposals can be effectively described with a massive scalar field, there are real pragmatic and epistemic gains that can be made by leveraging this common core model for the simplest versions of dark energy. In contrast with the overarching approach of inflation, here we think there is a good argument to be made that in many contexts it is not necessary to continue to model-build or to use specific microphysical models within the quintessence paradigm as the common core theory offers a perspicuous interpretation of quintessence physics in terms of the microphysics of a massive scalar field.

Of course, this by no means offers a full resolution to the underdetermination problems afflicting dark energy research and still leaves many questions about dark energy unanswered and/or sidelined for further pursuit. In other words, we still have to reckon with the permanent underdetermination between dark energy models described by the theory above and all of the other distinct dark energy proposals that do not fall within this remit (such as more exotic scalar field models, modified gravity models, or even more heterodox proposals (Wolf and Duerr 2024; Wolf, García-García, Anton, et al. 2025)). However, within this local sub-region of dark energy research described by a single, canonical scalar field with an analytic potential, the scale-specific physics and cosmological phenomena we are engaging with here does seem to have a privileged microphysical description. Thus, upon assuming quintessence is driving dark energy, the underdetermination can arguably be broken locally within this framework by adopting the common core theory. The common core theory represents a unique description of dark energy physics that is robust in the sense that all of these various dark energy proposals flow into it within the cosmological regime of interest, has a number of pragmatic and epistemic benefits considering that it is given in terms of the perspicuous microphysics of a massive scalar field, and unifies the various other microphysical proposals in addition to providing a convenient map back to the microphysical models if there are any specific contexts that would warrant such attention; in sum, the common core theory arguably goes some way towards ameliorating the underdetermination problems in dark energy research.

6.6 Conclusions

In this chapter, we have considered the underdetermination present in modern day cosmological modelling of both inflation and dark energy. We have identified this in both cases as an instance of permanent underdetermination in the sense of Pitts (2010), and have built upon the analysis of Ferreira, Wolf, and Read (2025) by illustrating in detail how the simplest classes of inflation and dark energy models are underdetermined with respect to their primary observables and situating this problem within the broader underdetermination literature. Furthermore, noting also that both inflation and dark energy modelling can be understood (and, indeed, often *are* understood by practicing cosmologists) via the framework of EFTs, we have exploited this framework in order to explore how certain philosophical responses to underdetermination might be brought to bear on each case.

Our conclusions offer both good and bad news. The good news is that, in the case of dark energy models, the common core strategy can be applied locally to the quintessence paradigm once one notices that the phenomenology of the distinct microphysical models within it is captured by just the first couple of terms in the expansion of the potential $V(\varphi)$—so, there is little (if anything) to be lost in committing to just such terms in one's ongoing physical reasoning—these terms of course constituting the 'common core' of the dark energy models under consideration. Similarly, there might be a viable discrimination strategy for inflation if the observational predictions fall within what we expect for Higgs inflation. On the other hand, the more deflationary news is that the 'overarching' strategy which is sometimes adopted in response to the permanent underdetermination of inflationary models seems insufficient to constitute a plausible resolution to this underdetermination, since it is little more than the combination of all such inflationary models into one ‘larger’ model in which some parameters are left unfixed.[14] While undeniably useful to the practicing cosmologist, this approach is unable to make a substantive dent in the underdetermination issues highlighted here. And finally, the analysis here of course applies only ‘locally’ within the classes of theories considered here, and does not, for example, address how underdetermination might be dealt with when the theories considered are compared to other approaches to modeling the phenomena that inflation and dark energy are taken to represent.

Stepping back somewhat, in our view this works represents a fruitful interaction between modern cosmology and philosophy of science. On the one hand, cosmology illustrates live and serious cases of underdetermination that can be leveraged by philosophers in order to better understand scientific methodology as it is applied by practitioners in real time. On the other hand, philosophy can perhaps provide an illuminating perspective on the epistemic value and pursuit-worthiness of certain approaches given the unique epistemic challenges faced by modern cosmology. For example, one conclusion of our work would be that there is little obviously to be gained at the present moment from further detailed dark energy model-building, or utilizing models other than the common core theory, at least at the level of investigating cosmological phenomena within the quintessence paradigm. Another would be that there perhaps *is* more to be gained from model-building in the inflationary cases, especially with regard to, e.g., non-minimally-coupled Higgs models, in whose favour various arguments (e.g., consilience) would certainly speak.

[14]Cf., Maudlin (1996) on unification. According to Maudlin, we have unification in a merely unphysical sense if the unification combines multiple physical models without giving some physical account of the common origin of the structures involved in those models, physical interactions between them, etc.

References

Aad, Georges et al. (2012). “Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC”. *Phys. Lett. B* 716, pp. 1–29. DOI: 10.1016/j.physletb.2012.08.020. arXiv: 1207.7214 [hep-ex].

Abate, Alexandra et al. (2012). “Large Synoptic Survey Telescope: Dark Energy Science Collaboration”. arXiv: 1211.0310 [astro-ph.CO].

Abazajian, Kevork N. et al. (2016). “CMB-S4 Science Book, First Edition”. arXiv: 1610.02743 [astro-ph.CO].

Abbott, B. P. et al. (2016). “Observation of Gravitational Waves from a Binary Black Hole Merger”. *Phys. Rev. Lett.* 116.6, p. 061102. DOI: 10.1103/PhysRevLett.116.061102. arXiv: 1602.03837 [gr-qc].

Abbott, T. M. C. et al. (2019). “First Cosmology Results using Type Ia Supernovae from the Dark Energy Survey: Constraints on Cosmological Parameters”. *Astrophys. J. Lett.* 872.2, p. L30. DOI: 10.3847/2041-8213/ab04fa. arXiv: 1811.02374 [astro-ph.CO].

— (2024). “The Dark Energy Survey: Cosmology Results with ∼1500 New High-redshift Type Ia Supernovae Using the Full 5 yr Data Set”. *Astrophys. J. Lett.* 973.1, p. L14. DOI: 10.3847/2041-8213/ad6f9f. arXiv: 2401.02929 [astro-ph.CO].

Abel, Steve A., Andrei Constantin, Thomas R. Harvey, and Andre Lukas (2023). “Cosmic Inflation and Genetic Algorithms”. *Fortsch. Phys.* 71.1, p. 2200161. DOI: 10.1002/prop.202200161. arXiv: 2208.13804 [hep-th].

Abrahamse, Augusta, Andreas Albrecht, Michael Barnard, and Brandon Bozek (2008). “Exploring parameter constraints on quintessential dark energy: The pseudo-Nambu-Goldstone-boson model”. *Phys. Rev. D* 77, p. 103503. DOI: 10.1103/PhysRevD.77.103503. arXiv: 0712.2879 [astro-ph].

Acuña, Pablo (2021). “Charting the landscape of interpretation, theory rivalry, and underdetermination in quantum mechanics”. *Synthese* 198.2, pp. 1711–1740.

Adame, A. G. et al. (2024). “DESI 2024 VI: Cosmological Constraints from the Measurements of Baryon Acoustic Oscillations”. arXiv: 2404.03002 [astro-ph.CO].

Ade, P. A. R. et al. (2014). “Planck 2013 results. XXVI. Background geometry and topology of the Universe”. *Astron. Astrophys.* 571, A26. DOI: 10.1051/0004-6361/201321546. arXiv: 1303.5086 [astro-ph.CO].

Ade, P. A. R. et al. (2016). "Planck 2015 results. XIV. Dark energy and modified gravity". *Astron. Astrophys.* 594, A14. DOI: 10.1051/0004-6361/201525814. arXiv: 1502.01590 [astro-ph.CO].

— (2021). "Improved Constraints on Primordial Gravitational Waves using Planck, WMAP, and BICEP/Keck Observations through the 2018 Observing Season". *Phys. Rev. Lett.* 127.15, p. 151301. DOI: 10.1103/PhysRevLett.127.151301. arXiv: 2110.00483 [astro-ph.CO].

— (2022). "The Latest Constraints on Inflationary B-modes from the BICEP/Keck Telescopes". In: *56th Rencontres de Moriond on Cosmology*. arXiv: 2203.16556 [astro-ph.CO].

Aghanim, N. et al. (2020a). "Planck 2018 results. V. CMB power spectra and likelihoods". *Astron. Astrophys.* 641, A5. DOI: 10.1051/0004-6361/201936386. arXiv: 1907.12875 [astro-ph.CO].

— (2020b). "Planck 2018 results. VI. Cosmological parameters". *Astron. Astrophys.* 641. [Erratum: Astron.Astrophys. 652, C4 (2021)], A6. DOI: 10.1051/0004-6361/201833910. arXiv: 1807.06209 [astro-ph.CO].

Aguirre, Anthony (2007). "Eternal Inflation, past and future". arXiv: 0712.0571 [hep-th].

Agullo, Ivan, Jose Navarro-Salas, Gonzalo J. Olmo, and Leonard Parker (2009). "Insensitivity of Hawking radiation to an invariant Planck-scale cutoff". *Phys. Rev.* D80, p. 047503. DOI: 10.1103/PhysRevD.80.047503. arXiv: 0906.5315 [gr-qc].

Akrami, Y. et al. (2020). "Planck 2018 results. X. Constraints on inflation". *Astron. Astrophys.* 641, A10. DOI: 10.1051/0004-6361/201833887. arXiv: 1807.06211 [astro-ph.CO].

Alam, Shadab et al. (2017). "The clustering of galaxies in the completed SDSS-III Baryon Oscillation Spectroscopic Survey: cosmological analysis of the DR12 galaxy sample". *Mon. Not. Roy. Astron. Soc.* 470.3, pp. 2617–2652. DOI: 10.1093/mnras/stx721. arXiv: 1607.03155 [astro-ph.CO].

Alam, Ujjaini, Varun Sahni, and A. A. Starobinsky (2003). "Is dark energy decaying?" *JCAP* 04, p. 002. DOI: 10.1088/1475-7516/2003/04/002. arXiv: astro-ph/0302302.

Albrecht, Andreas and Paul J. Steinhardt (1982). "Cosmology for Grand Unified Theories with Radiatively Induced Symmetry Breaking". *Phys. Rev. Lett.* 48. Ed. by Li-Zhi Fang and R. Ruffini, pp. 1220–1223. DOI: 10.1103/PhysRevLett.48.1220.

Allen, Steven W., August E. Evrard, and Adam B. Mantz (2011). "Cosmological Parameters from Observations of Galaxy Clusters". *Annual Review of Astronomy and Astrophysics* 49.1, pp. 409–470. DOI: 10.1146/annurev-astro-081710-102514.

Alonso, David, Emilio Bellini, Pedro G. Ferreira, and Miguel Zumalacárregui (2017). "Observational future of cosmological scalar-tensor theories". *Phys. Rev. D* 95.6, p. 063502. DOI: 10.1103/PhysRevD.95.063502. arXiv: 1610.09290 [astro-ph.CO].

Amendola, Luca and Shinji Tsujikawa (2015). *Dark Energy: Theory and Observations*. Cambridge University Press. ISBN: 978-1-107-45398-2.

Andrei, Cosmin, Anna Ijjas, and Paul J. Steinhardt (2022). "Rapidly descending dark energy and the end of cosmic expansion". *Proc. Nat. Acad. Sci.* 119.15, e2200539119. DOI: 10.1073/pnas.2200539119. arXiv: 2201.07704 [astro-ph.CO].

Antoniou, Antonis (forthcoming). "Robustness and Dark Matter Observation". *Philosophy of Science*, pp. 1–36. DOI: 10.1017/psa.2023.50.

Arkani-Hamed, Nima and Juan Maldacena (2015). "Cosmological Collider Physics". arXiv: 1503.08043 [hep-th].

Arvanitaki, Asimina et al. (2010). "String Axiverse". *Phys. Rev. D* 81, p. 123530. DOI: 10.1103/PhysRevD.81.123530. arXiv: 0905.4720 [hep-th].

Aubourg, Éric et al. (2015). "Cosmological implications of baryon acoustic oscillation measurements". *Physical Review D* 92.12, p. 123516.

Azhar, Feraz and Jeremy Butterfield (2016). "Scientific Realism and Primordial Cosmology". arXiv: 1606.04071 [physics.hist-ph].

Azhar, Feraz and David I. Kaiser (2018). "Flows into inflation: An effective field theory approach". *Phys. Rev. D* 98.6, p. 063515. DOI: 10.1103/PhysRevD.98.063515. arXiv: 1807.02088 [astro-ph.CO].

Azhar, Feraz and Abraham Loeb (2021). "Finely tuned models sacrifice explanatory depth". *Foundations of Physics* 51.5, pp. 1–36.

Bacon, David J. et al. (2020). "Cosmology with Phase 1 of the Square Kilometre Array: Red Book 2018: Technical specifications and performance forecasts". *Publ. Astron. Soc. Austral.* 37, e007. DOI: 10.1017/pasa.2019.51. arXiv: 1811.02743 [astro-ph.CO].

Bahamonde, Sebastian et al. (2023). "Teleparallel gravity: from theory to cosmology". *Rept. Prog. Phys.* 86.2, p. 026901. DOI: 10.1088/1361-6633/ac9cef. arXiv: 2106.13793 [gr-qc].

Bailes, M. et al. (2021). "Gravitational-wave physics and astronomy in the 2020s and 2030s". *Nature Rev. Phys.* 3.5, pp. 344–366. DOI: 10.1038/s42254-021-00303-8.

Baker, T. et al. (2017). "Strong constraints on cosmological gravity from GW170817 and GRB 170817A". *Phys. Rev. Lett.* 119.25, p. 251301. DOI: 10.1103/PhysRevLett.119.251301. arXiv: 1710.06394 [astro-ph.CO].

Banerjee, Rabin and Shailesh Kulkarni (2008). "Hawking radiation and covariant anomalies". *Phys. Rev. D* 77 (2), p. 024018. DOI: 10.1103/PhysRevD.77.024018. URL: https://link.aps.org/doi/10.1103/PhysRevD.77.024018.

Bangu, Sorin (2017). "Scientific Explanation and Understanding: Unificationism Reconsidered". *European Journal for Philosophy of Science* 7.1, pp. 103–126. DOI: 10.1007/s13194-016-0148-y.

Baras, Dan (n.d.). "Calling for Explanation: An Extraordinary Account". Unpublished manuscript. URL: https://danbaras.com/wp-content/uploads/2020/07/Extraordinary-Types.pdf.

Baras, Dan and Orly Shenker (2020). "Calling for Explanation: The Case of the Thermodynamic Past State". *European Journal for Philosophy of Science* 10.3, pp. 1–20. DOI: 10.1007/s13194-020-00297-7.

Barausse, Enrico et al. (2020). "Prospects for Fundamental Physics with LISA". *Gen. Rel. Grav.* 52.8, p. 81. DOI: 10.1007/s10714-020-02691-1. arXiv: 2001.09793 [gr-qc].

Barcelo, C., L. J. Garay, and G. Jannes (2009). "Sensitivity of Hawking radiation to superluminal dispersion relations". *Phys. Rev.* D79, p. 024016. DOI: 10.1103/PhysRevD.79.024016. arXiv: 0807.4147 [gr-qc].

Bardeen, James M., Paul J. Steinhardt, and Michael S. Turner (1983). "Spontaneous Creation of Almost Scale - Free Density Perturbations in an Inflationary Universe". *Phys. Rev. D* 28, p. 679. DOI: 10.1103/PhysRevD.28.679.

Barger, V., E. Guarnaccia, and D. Marfatia (2006). "Classification of dark energy models in the (w(0), w(a)) plane". *Phys. Lett. B* 635, pp. 61–65. DOI: 10.1016/j.physletb.2006.02.018. arXiv: hep-ph/0512320.

Barreiro, T., Edmund J. Copeland, and N. J. Nunes (2000). "Quintessence arising from exponential potentials". *Phys. Rev. D* 61, p. 127301. DOI: 10.1103/PhysRevD.61.127301. arXiv: astro-ph/9910214.

Barseghyan, Hakob and Jamie Shaw (2017). "How Can a Taxonomy of Stances Help Clarify Classical Debates on Scientific Change?" *Philosophies* 2.4, p. 24. DOI: 10.3390/philosophies2040024.

Bartelborth, Thomas (1999). "Coherence and Explanations". *Erkenntnis* 50.2-3, pp. 209–224. DOI: 10.1023/a:1005594409663.

Battefeld, D. and Patrick Peter (2015). "A Critical Review of Classical Bouncing Cosmologies". *Phys. Rept.* 571, pp. 1–66. DOI: 10.1016/j.physrep.2014.12.004. arXiv: 1406.2790 [astro-ph.CO].

Batterman, Robert W (2000). “Multiple realizability and universality”. *The British Journal for the Philosophy of Science* **51**.1, pp. 115–45.

— (2002). *The devil in the details: Asymptotic reasoning in explanation, reduction, and emergence*. Oxford: Oxford University Press.

— (2018). “Autonomy of theories: An explanatory problem”. *Noûs* 52.4, pp. 858–873.

Baumann, Daniel et al. (2009). “CMBPol Mission Concept Study: Probing Inflation with CMB Polarization”. *AIP Conf. Proc.* 1141.1. Ed. by Scott Dodelson et al., pp. 10–120. DOI: 10.1063/1.3160885. arXiv: 0811.3919 [astro-ph].

Baumann, Daniel (2009). “TASI Lectures on Inflation”. arXiv: 0907.5424 [hep-th].

— (2011). “Inflation”. In: *Theoretical Advanced Study Institute in Elementary Particle Physics: Physics of the Large and the Small*, pp. 523–686. DOI: 10.1142/9789814327183_0010. arXiv: 0907.5424 [hep-th].

— (2022). *Cosmology*. Cambridge University Press. DOI: 10.1017/9781108937092.

Baumann, Daniel and Matias Zaldarriaga (2009). “Causality and Primordial Tensor Modes”. *JCAP* 06, p. 013. DOI: 10.1088/1475-7516/2009/06/013. arXiv: 0901.0958 [astro-ph.CO].

Bedroya, Alek, Robert Brandenberger, Marilena Loverde, and Cumrun Vafa (2020). “Trans-Planckian Censorship and Inflationary Cosmology”. *Phys. Rev. D* 101.10, p. 103502. DOI: 10.1103/PhysRevD.101.103502. arXiv: 1909.11106 [hep-th].

Bedroya, Alek and Cumrun Vafa (2020). “Trans-Planckian Censorship and the Swampland”. *JHEP* 09, p. 123. DOI: 10.1007/JHEP09(2020)123. arXiv: 1909.11063 [hep-th].

Belgacem, Enis et al. (2019). “Testing modified gravity at cosmological distances with LISA standard sirens”. *JCAP* 07, p. 024. DOI: 10.1088/1475-7516/2019/07/024. arXiv: 1906.01593 [astro-ph.CO].

Bellini, Emilio, Ignacy Sawicki, and Miguel Zumalacárregui (2020). “hi_class: Background Evolution, Initial Conditions and Approximation Schemes”. *JCAP* 02, p. 008. DOI: 10.1088/1475-7516/2020/02/008. arXiv: 1909.01828 [astro-ph.CO].

Belot, Gordon (2023). *Accelerating Expansion: Philosophy and Physics with a Positive Cosmological Constant*. New York: Oxford University Press.

Bennett, Charles L et al. (2013). “Nine-year Wilkinson Microwave Anisotropy Probe (WMAP) observations: final maps and results”. *The Astrophysical Journal Supplement Series* 208.2, p. 20.

Bernardis, P. de et al. (2000). "A Flat universe from high resolution maps of the cosmic microwave background radiation". *Nature* 404, pp. 955–959. DOI: 10.1038/35010035. arXiv: astro-ph/0004404.

Bezrukov, Fedor L. and Mikhail Shaposhnikov (2008). "The Standard Model Higgs boson as the inflaton". *Phys. Lett. B* 659, pp. 703–706. DOI: 10.1016/j.physletb.2007.11.072. arXiv: 0710.3755 [hep-th].

Bird, Alexander (2007a). "Inference to the Best Explanation". *Philosophy and Phenomenological Research* 74.2, pp. 424–432. DOI: 10.1111/j.1933-1592.2007.00028.x.

— (2007b). "What is Scientific Progress?" *Noûs* 41.1, pp. 64–89. DOI: 10.1111/j.1468-0068.2007.00638.x.

Birmingham, Danny, Kumar S. Gupta, and Siddhartha Sen (2001). "Near horizon conformal structure of black holes". *Phys. Lett.* B505, pp. 191–196. DOI: 10.1016/S0370-2693(01)00354-9. arXiv: hep-th/0102051 [hep-th].

Blas, Diego, Julien Lesgourgues, and Thomas Tram (2011). "The Cosmic Linear Anisotropy Solving System (CLASS) II: Approximation schemes". *JCAP* 07, p. 034. DOI: 10.1088/1475-7516/2011/07/034. arXiv: 1104.2933 [astro-ph.CO].

Borde, Arvind, Alan H. Guth, and Alexander Vilenkin (2003). "Inflationary space-times are incomplete in past directions". *Phys. Rev. Lett.* 90, p. 151301. DOI: 10.1103/PhysRevLett.90.151301. arXiv: gr-qc/0110012.

Bostan, Nilay, Ömer Güleryüz, and Vedat Nefer Şenoğuz (2018). "Inflationary predictions of double-well, Coleman-Weinberg, and hilltop potentials with non-minimal coupling". *JCAP* 05, p. 046. DOI: 10.1088/1475-7516/2018/05/046. arXiv: 1802.04160 [astro-ph.CO].

Boubekeur, Lotfi and David. H. Lyth (2005). "Hilltop inflation". *JCAP* 07, p. 010. DOI: 10.1088/1475-7516/2005/07/010. arXiv: hep-ph/0502047.

Boyle, Latham A., Paul J. Steinhardt, and Neil Turok (2006). "Inflationary predictions reconsidered". *Phys. Rev. Lett.* 96, p. 111301. DOI: 10.1103/PhysRevLett.96.111301. arXiv: astro-ph/0507455.

Braglia, Matteo, Dhiraj Kumar Hazra, L. Sriramkumar, and Fabio Finelli (2020). "Generating primordial features at large scales in two field models of inflation". *JCAP* 08, p. 025. DOI: 10.1088/1475-7516/2020/08/025. arXiv: 2004.00672 [astro-ph.CO].

Brandenberger, Robert (2016). "Initial conditions for inflation — A short review". *Int. J. Mod. Phys. D* 26.01, p. 1740002. DOI: 10.1142/S0218271817400028. arXiv: 1601.01918 [hep-th].

Brandenberger, Robert (2021). "Trans-Planckian Censorship Conjecture and Early Universe Cosmology". *LHEP* 2021, p. 198. DOI: 10.31526/lhep.2021.198. arXiv: 2102.09641 [hep-th].

Brandenberger, Robert and Patrick Peter (2017). "Bouncing Cosmologies: Progress and Problems". *Found. Phys.* 47.6, pp. 797–850. DOI: 10.1007/s10701-016-0057-0. arXiv: 1603.05834 [hep-th].

Brandenberger, Robert H and Jerome Martin (2002). "On signatures of short distance physics in the cosmic microwave background". *International Journal of Modern Physics A* 17.25, pp. 3663–3680.

Brandenberger, Robert H. (2008). "String Gas Cosmology". arXiv: 0808.0746 [hep-th].

— (2011a). "Is the Spectrum of Gravitational Waves the "Holy Grail" of Inflation?" arXiv: 1104.3581 [astro-ph.CO].

— (2011b). "String Gas Cosmology: Progress and Problems". *Class. Quant. Grav.* 28, p. 204005. DOI: 10.1088/0264-9381/28/20/204005. arXiv: 1105.3247 [hep-th].

— (2019). "Is the spectrum of gravitational waves the "Holy Grail" of inflation?" *Eur. Phys. J. C* 79.5, p. 387. DOI: 10.1140/epjc/s10052-019-6883-4. arXiv: 1104.3581 [astro-ph.CO].

Brandenberger, Robert H. and Jerome Martin (2013). "Trans-Planckian Issues for Inflationary Cosmology". *Class. Quant. Grav.* 30, p. 113001. DOI: 10.1088/0264-9381/30/11/113001. arXiv: 1211.6753 [astro-ph.CO].

Broer, Hendrik Wolter and Floris Takens (2011). *Dynamical systems and chaos*. Vol. 172. Springer.

Brout, R., S. Massar, R. Parentani, and Ph. Spindel (1995). "Hawking radiation without trans-Planckian frequencies". *Phys. Rev. D* 52 (8), pp. 4559–4568. DOI: 10.1103/PhysRevD.52.4559. URL: https://link.aps.org/doi/10.1103/PhysRevD.52.4559.

Bucher, Martin, Alfred S. Goldhaber, and Neil Turok (1995). "An open universe from inflation". *Phys. Rev. D* 52, pp. 3314–3337. DOI: 10.1103/PhysRevD.52.3314. arXiv: hep-ph/9411206.

Bull, Philip, Timothy Clifton, and Pedro G. Ferreira (2012). "The kSZ effect as a test of general radial inhomogeneity in LTB cosmology". *Phys. Rev. D* 85, p. 024002. DOI: 10.1103/PhysRevD.85.024002. arXiv: 1108.2222 [astro-ph.CO].

Burgess, C. P. (2017). "Intro to Effective Field Theories and Inflation". arXiv: 1711.10592 [hep-th].

Burgess, C. P. (2020). *Introduction to Effective Field Theory*. Cambridge University Press. ISBN: 978-1-139-04804-0, 978-0-521-19547-8. DOI: 10.1017/9781139048040.

Burgess, C. P., S. P. de Alwis, and F. Quevedo (2021). "Cosmological Trans-Planckian Conjectures are not Effective". *JCAP* 05, p. 037. DOI: 10.1088/1475-7516/2021/05/037. arXiv: 2011.03069 [hep-th].

Burgess, Clifford P, James M Cline, François Lemieux, and Richard Holman (2003). "Are inflationary predictions sensitive to very high energy physics?" *Journal of High Energy Physics* 2003.02, p. 048.

Burrage, Clare and Jeremy Sakstein (2018). "Tests of Chameleon Gravity". *Living Rev. Rel.* 21.1, p. 1. DOI: 10.1007/s41114-018-0011-x. arXiv: 1709.09071 [astro-ph.CO].

Butterfield, Jeremy (2014). "On Under-determination in cosmology". *Stud. Hist. Phil. Sci. B* 46, pp. 57–69. DOI: 10.1016/j.shpsb.2013.06.003. arXiv: 1406.4747 [physics.hist-ph].

Cabrera, Frank (2021). "String Theory, Non-Empirical Theory Assessment, and the Context of Pursuit". *Synthese* 198, pp. 3671–3699. DOI: 10.1007/s11229-018-01987-9.

Cai, Yi-Fu (2014). "Exploring Bouncing Cosmologies with Cosmological Surveys". *Sci. China Phys. Mech. Astron.* 57, pp. 1414–1430. DOI: 10.1007/s11433-014-5512-3. arXiv: 1405.1369 [hep-th].

Cai, Yi-Fu, Damien A. Easson, and Robert Brandenberger (2012). "Towards a Nonsingular Bouncing Cosmology". *JCAP* 08, p. 020. DOI: 10.1088/1475-7516/2012/08/020. arXiv: 1206.2382 [hep-th].

Cai, Yong, Hai-Guang Li, Taotao Qiu, and Yun-Song Piao (2017). "The Effective Field Theory of nonsingular cosmology: II". *Eur. Phys. J. C* 77.6, p. 369. DOI: 10.1140/epjc/s10052-017-4938-y. arXiv: 1701.04330 [gr-qc].

Cai, Yong and Yun-Song Piao (2017). "A covariant Lagrangian for stable nonsingular bounce". *JHEP* 09, p. 027. DOI: 10.1007/JHEP09(2017)027. arXiv: 1705.03401 [gr-qc].

Cai, Yong, Youping Wan, et al. (2017). "The Effective Field Theory of nonsingular cosmology". *JHEP* 01, p. 090. DOI: 10.1007/JHEP01(2017)090. arXiv: 1610.03400 [gr-qc].

Caldwell, R. R., Rahul Dave, and Paul J. Steinhardt (1998). "Cosmological imprint of an energy component with general equation of state". *Phys. Rev. Lett.* 80, pp. 1582–1585. DOI: 10.1103/PhysRevLett.80.1582. arXiv: astro-ph/9708069.

Caldwell, R. R. and Eric V. Linder (2005). "The Limits of quintessence". *Phys. Rev. Lett.* 95, p. 141301. DOI: 10.1103/PhysRevLett.95.141301. arXiv: astro-ph/0505494.

Candelas, Philip (1980). “Vacuum polarization in Schwarzschild spacetime”. *Physical Review D* 21.8, p. 2185.

Carloni, Youri, Orlando Luongo, and Marco Muccino (2024). “Does dark energy really revive using DESI 2024 data?” arXiv: 2404.12068 [astro-ph.CO].

Carrier, Martin (1988). “On Novel Facts”. *Zeitschrift Für Allgemeine Wissenschaftstheorie* 19.2, pp. 205–231. DOI: 10.1007/bf01801335.

Carroll, Sean M. (1998). “Quintessence and the rest of the world”. *Phys. Rev. Lett.* 81, pp. 3067–3070. DOI: 10.1103/PhysRevLett.81.3067. arXiv: astro-ph/9806099.

— (2014). “In What Sense Is the Early Universe Fine-Tuned?” In: arXiv: 1406.3057 [astro-ph.CO].

Castellani, Elena and Emilia Margoni (2022). “Renormalization group methods: Which kind of explanation?” *Studies in History and Philosophy of Science* 95, pp. 158–166.

Cervantes-Cota, Jorge L., S. Galindo-Uribarri, and G-F. Smoot (2016). “A Brief History of Gravitational Waves”. *Universe* 2.3, p. 22. DOI: 10.3390/universe2030022. arXiv: 1609.09400 [physics.hist-ph].

Chall, Cristin (2018). “Doubts for Dawid’s Non-Empirical Theory Assessment”. *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics* 63, pp. 128–135. DOI: 10.1016/j.shpsb.2018.01.004.

Chamcham, Khalil, Joseph Silk, John D Barrow, and Simon Saunders (2017). *The Philosophy of Cosmology*. Cambridge University Press.

Charmousis, Christos, Edmund J. Copeland, Antonio Padilla, and Paul M. Saffin (2012). “General second order scalar-tensor theory, self tuning, and the Fab Four”. *Phys. Rev. Lett.* 108, p. 051101. DOI: 10.1103/PhysRevLett.108.051101. arXiv: 1106.2000 [hep-th].

Chen, Xingang (2010). “Primordial Non-Gaussianities from Inflation Models”. *Adv. Astron.* 2010, p. 638979. DOI: 10.1155/2010/638979. arXiv: 1002.1416 [astro-ph.CO].

Cheung, Clifford et al. (2008). “The Effective Field Theory of Inflation”. *JHEP* 03, p. 014. DOI: 10.1088/1126-6708/2008/03/014. arXiv: 0709.0293 [hep-th].

Chevallier, Michel and David Polarski (2001). “Accelerating universes with scaling dark matter”. *Int. J. Mod. Phys. D* 10, pp. 213–224. DOI: 10.1142/S0218271801000822. arXiv: gr-qc/0009008.

Chiba, Takeshi (2009). “Slow-Roll Thawing Quintessence”. *Phys. Rev. D* 79. [Erratum: Phys.Rev.D 80, 109902 (2009)], p. 083517. DOI: 10.1103/PhysRevD.80.109902. arXiv: 0902.4037 [astro-ph.CO].

Chowdhury, Debika, Jérôme Martin, Christophe Ringeval, and Vincent Vennin (2019). "Assessing the scientific status of inflation after Planck". *Phys. Rev. D* 100.8, p. 083537. DOI: 10.1103/PhysRevD.100.083537. arXiv: 1902.03951 [astro-ph.CO].

Cicoli, Michele et al. (2019). "De Sitter vs Quintessence in String Theory". *Fortsch. Phys.* 67.1-2, p. 1800079. DOI: 10.1002/prop.201800079. arXiv: 1808.08967 [hep-th].

Clemson, Timothy G and Andrew R Liddle (2009). "Observational constraints on thawing quintessence models". *Mon. Not. Roy. Astron. Soc.* 395, pp. 1585–1590. DOI: 10.1111/j.1365-2966.2009.14641.x. arXiv: 0811.4676 [astro-ph].

Clifton, Timothy, Pedro G. Ferreira, Antonio Padilla, and Constantinos Skordis (2012). "Modified Gravity and Cosmology". *Phys. Rept.* 513, pp. 1–189. DOI: 10.1016/j.physrep.2012.01.001. arXiv: 1106.2476 [astro-ph.CO].

Coles, Peter and George FR Ellis (1997). "The case for an open Universe". *Nature* 380.6576, pp. 6–7.

Copeland, Edmund J., Andrew R Liddle, and David Wands (1998). "Exponential potentials and cosmological scaling solutions". *Phys. Rev. D* 57, pp. 4686–4690. DOI: 10.1103/PhysRevD.57.4686. arXiv: gr-qc/9711068.

Copeland, Edmund J., M. Sami, and Shinji Tsujikawa (2006). "Dynamics of dark energy". *Int. J. Mod. Phys. D* 15, pp. 1753–1936. DOI: 10.1142/S021827180600942X. arXiv: hep-th/0603057.

Cowen, Ron (2015). "Gravitational waves discovery now officially dead". *Nature*.

Craver, Carl and James Tabery (2019). "Mechanisms in Science". In: *The Stanford Encyclopedia of Philosophy*. Ed. by Edward N. Zalta. Summer 2019. Metaphysics Research Lab, Stanford University.

Creminelli, Paolo, Alberto Nicolis, and Matias Zaldarriaga (2005). "Perturbations in bouncing cosmologies: Dynamical attractor versus scale invariance". *Phys. Rev. D* 71, p. 063505. DOI: 10.1103/PhysRevD.71.063505. arXiv: hep-th/0411270.

Creminelli, Paolo, David Pirtskhalava, Luca Santoni, and Enrico Trincherini (2016). "Stability of Geodesically Complete Cosmologies". *JCAP* 11, p. 047. DOI: 10.1088/1475-7516/2016/11/047. arXiv: 1610.04207 [hep-th].

Creţu, Ana-Maria (2022). "Authentication, scale-relativity, and relational kindhood". *Synthese* 200.1, pp. 1–21.

Crowther, Karen (2018). *Effective spacetime*. Springer.

Curiel, Erik (2015). "Measure, Topology and Probabilistic Reasoning in Cosmology". arXiv: 1509.01878 [gr-qc].

Dalang, Charles, Pierre Fleury, and Lucas Lombriser (2020). "Horndeski gravity and standard sirens". *Phys. Rev. D* 102.4, p. 044036. DOI: 10.1103/PhysRevD.102.044036. arXiv: 1912.06117 [gr-qc].

Danielsson, Ulf H. and Thomas Van Riet (2018). "What if string theory has no de Sitter vacua?" *Int. J. Mod. Phys. D* 27.12, p. 1830007. DOI: 10.1142/S0218271818300070. arXiv: 1804.01120 [hep-th].

Darrigol, Olivier (2009). "A simplified genesis of quantum mechanics". *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics* 40.2, pp. 151–166.

— (2013). "For a Philosophy of Hydrodynamics". In: *The Oxford Handbook of Philosophy of Physics*. Oxford University Press. ISBN: 9780195392043. DOI: 10.1093/oxfordhb/9780195392043.013.0002.

Dawid, Richard (2013). *String theory and the scientific method*. Cambridge, UK: Cambridge University Press. ISBN: 978-1-107-02971-2, 978-1-139-34251-3. DOI: 10.1017/CBO9781139342513.

— (2015). "Higgs Discovery and the Look Elsewhere Effect". *Philosophy of Science* 82.1, pp. 76–96. DOI: 10.1086/679179.

— (2020). *Meta-Empirical Confirmation: Addressing Three Points of Criticism*. URL: https://philsci-archive.pitt.edu/18818/.

Dawid, Richard, Stephan Hartmann, and Jan Sprenger (2015). "The No Alternatives Argument". *British Journal for the Philosophy of Science* 66.1, pp. 213–234. DOI: 10.1093/bjps/axt045.

Dawid, Richard and Casey McCoy (2023). "Testability and viability: is inflationary cosmology "Scientific"?" *Eur. J. Phil. Sci.* 13.4, p. 51. DOI: 10.1007/s13194-023-00556-3.

De Baerdemaeker, Siska and Richard Dawid (2022). "MOND and meta-empirical theory assessment". *Synthese* 200.5, p. 344. DOI: 10.1007/s11229-022-03830-8.

Deffayet, Cedric, Oriol Pujolas, Ignacy Sawicki, and Alexander Vikman (2010). "Imperfect Dark Energy from Kinetic Gravity Braiding". *JCAP* 10, p. 026. DOI: 10.1088/1475-7516/2010/10/026. arXiv: 1008.0048 [hep-th].

Dellsén, Finnur (2016). "Scientific Progress: Knowledge Versus Understanding". *Studies in History and Philosophy of Science Part A* 56.C, pp. 72–83. DOI: 10.1016/j.shpsa.2016.01.003.

deRegt, Henk W. and Dennis Dieks (2005). "A Contextual Approach to Scientific Understanding". *Synthese* 144.1, pp. 137–170. DOI: 10.1007/s11229-005-5000-4.

Di Valentino, Eleonora et al. (2021). “In the realm of the Hubble tension—a review of solutions”. *Class. Quant. Grav.* 38.15, p. 153001. DOI: 10.1088/1361-6382/ac086d. arXiv: 2103.01183 [astro-ph.CO].

Dimopoulos, Konstantinos (2020). “An analytic treatment of quartic hilltop inflation”. *Phys. Lett. B* 809, p. 135688. DOI: 10.1016/j.physletb.2020.135688. arXiv: 2006.06029 [hep-ph].

Dinda, Bikash R. and Roy Maartens (2025). “Model-agnostic assessment of dark energy after DESI DR1 BAO”. *JCAP* 01, p. 120. DOI: 10.1088/1475-7516/2025/01/120. arXiv: 2407.17252 [astro-ph.CO].

Douglas, Heather (2013). “The Value of Cognitive Values”. *Philosophy of Science* 80.5, pp. 796–806. DOI: 10.1086/673716.

Douglas, Heather and P. D. Magnus (2013). “State of the Field: Why Novel Prediction Matters”. *Studies in History and Philosophy of Science Part A* 44.4, pp. 580–589. DOI: 10.1016/j.shpsa.2013.04.001.

Duerr, Patrick M. and William J. Wolf (2023). “Methodological Reflections on the MOND/Dark Matter Debate”. *Stud. Hist. Phil. Sci.* 101, pp. 1–23. DOI: 10.1016/j.shpsa.2023.07.001. arXiv: 2306.13026 [physics.hist-ph].

Duhem, Pierre Maurice Marie (1954). *The Aim and Structure of Physical Theory*. Princeton, Princeton University Press.

Durrer, Ruth (2011). “What do we really know about Dark Energy?” *Phil. Trans. Roy. Soc. Lond. A* 369, pp. 5102–5114. arXiv: 1103.5331 [astro-ph.CO].

Dutta, Sourish and Robert J. Scherrer (2008). “Hilltop Quintessence”. *Phys. Rev. D* 78, p. 123525. DOI: 10.1103/PhysRevD.78.123525. arXiv: 0809.4441 [astro-ph].

Earman, John (1993). “Underdetermination, Realism, and Reason”. *Midwest Studies in Philosophy* 18.1, pp. 19–38. DOI: 10.1111/j.1475-4975.1993.tb00255.x.

— (2006). “The “past hypothesis”: Not even false”. *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics* 37.3, pp. 399–430.

Earman, John and Jesus Mosterin (1999). “A Critical Look at Inflationary Cosmology”. *Philosophy of Science* 66.1, pp. 1–49. DOI: 10.1086/392675.

Easson, Damien A., Ignacy Sawicki, and Alexander Vikman (2011). “G-Bounce”. *JCAP* 11, p. 021. DOI: 10.1088/1475-7516/2011/11/021. arXiv: 1109.1047 [hep-th].

East, William E., Matthew Kleban, Andrei Linde, and Leonardo Senatore (2016). “Beginning inflation in an inhomogeneous universe”. *JCAP* 09, p. 010. DOI: 10.1088/1475-7516/2016/09/010. arXiv: 1511.05143 [hep-th].

Easther, Richard, Benedict Bahr-Kalus, and David Parkinson (2022). “Running primordial perturbations: Inflationary dynamics and observational constraints”. *Phys. Rev. D* 106.6, p. L061301. DOI: 10.1103/PhysRevD.106.L061301. arXiv: 2112.10922 [astro-ph.CO].

Eddington, A. S. (1930). “On the Instability of Einstein’s Spherical World”. *Mon. Not. Roy. Astron. Soc.* 90, pp. 668–678.

Einstein, Albert (1905). “On the electrodynamics of moving bodies”. *Annalen Phys.* 17, pp. 891–921. DOI: 10.1002/andp.200590006.

— (1915). “The Field Equations of Gravitation”. *Sitzungsber. Preuss. Akad. Wiss. Berlin (Math. Phys.)* 1915, pp. 844–847.

— (1916). “The Foundation of the General Theory of Relativity”. *Annalen Phys.* 49.7. Ed. by Jong-Ping Hsu and D. Fine, pp. 769–822. DOI: 10.1002/andp.19163540702.

— (1917a). “Cosmological Considerations in the General Theory of Relativity”. *Sitzungsber. Preuss. Akad. Wiss. Berlin (Math. Phys.)* 1917, pp. 142–152.

— (1917b). “Kosmologische Betrachtungen zur allgemeinen Relativitätstheorie”. *Sitzungsberichte der Königlich Preußischen Akademie der Wissenschaften (Berlin)*, pp. 142–152.

— (1931). “Zum kosmologischen Problem der allgemeinen Relativitätstheorie”. *Sitzungsb. König. Preuss. Akad.:* pp. 235–237.

Ellis, George F. R. (2006). “Issues in the philosophy of cosmology”. In: *Philosophy of physics*. Ed. by Jeremy Butterfield and John Earman, pp. 1183–1285. DOI: 10.1016/B978-044451560-5/50014-2. arXiv: astro-ph/0602280.

Ellis, George F. R. and Roy Maartens (2004). “The emergent universe: Inflationary cosmology with no singularity”. *Class. Quant. Grav.* 21, pp. 223–232. DOI: 10.1088/0264-9381/21/1/015. arXiv: gr-qc/0211082.

Ellis, George F. R., Roy Maartens, and Malcolm A. H. MacCallum (2012). *Relativistic Cosmology*. Cambridge University Press.

Ellis, George FR and Bernd G Schmidt (1977). “Singular space-times”. *General Relativity and Gravitation* 8.11, pp. 915–953.

Ellis, George Francis Rayner (2014). “On the philosophy of cosmology”. *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics* 46, pp. 5–23.

Ellis, Richard (2010). “Gravitational lensing: A unique probe of dark matter and dark energy”. *Philosophical transactions. Series A, Mathematical, physical, and engineering sciences* 368, pp. 967–87. DOI: 10.1098/rsta.2009.0209.

Englert, F. and R. Brout (1964). "Broken Symmetry and the Mass of Gauge Vector Mesons". *Phys. Rev. Lett.* 13. Ed. by J. C. Taylor, pp. 321–323. DOI: 10.1103/PhysRevLett.13.321.

Escamilla, Luis A. et al. (2023). "The state of the dark energy equation of state circa 2023". arXiv: 2307.14802 [astro-ph.CO].

Ezquiaga, Jose María and Miguel Zumalacárregui (2017). "Dark Energy After GW170817: Dead Ends and the Road Ahead". *Phys. Rev. Lett.* 119.25, p. 251304. DOI: 10.1103/PhysRevLett.119.251304. arXiv: 1710.05901 [astro-ph.CO].

— (2018). "Dark Energy in light of Multi-Messenger Gravitational-Wave astronomy". *Front. Astron. Space Sci.* 5, p. 44. DOI: 10.3389/fspas.2018.00044. arXiv: 1807.09241 [astro-ph.CO].

Felder, Gary N., Andrei V. Frolov, Lev Kofman, and Andrei D. Linde (2002). "Cosmology with negative potentials". *Phys. Rev. D* 66, p. 023507. DOI: 10.1103/PhysRevD.66.023507. arXiv: hep-th/0202017.

Ferreira, Pedro G. (2019). "Cosmological Tests of Gravity". *Ann. Rev. Astron. Astrophys.* 57, pp. 335–374. DOI: 10.1146/annurev-astro-091918-104423. arXiv: 1902.10503 [astro-ph.CO].

Ferreira, Pedro G. and Michael Joyce (1998). "Cosmology with a primordial scaling field". *Phys. Rev. D* 58, p. 023503. DOI: 10.1103/PhysRevD.58.023503. arXiv: astro-ph/9711102.

Ferreira, Pedro G., William J. Wolf, and James Read (2025). "The Spectre of Underdetermination in Modern Cosmology". arXiv: 2501.06095 [physics.hist-ph].

Fleisher, Will (2022). "Pursuit and Inquisitive Reasons". *Studies in History and Philosophy of Science Part A* 94.C, pp. 17–30. DOI: 10.1016/j.shpsa.2022.04.009.

Font-Ribera, Andreu et al. (2014). "DESI and other dark energy experiments in the era of neutrino mass measurements". *JCAP* 05, p. 023. DOI: 10.1088/1475-7516/2014/05/023. arXiv: 1308.4164 [astro-ph.CO].

Forster, Malcolm R. and Elliott Sober (1994). "How to Tell When Simpler, More Unified, or Less a D Hoc Theories Will Provide More Accurate Predictions". *British Journal for the Philosophy of Science* 45.1, pp. 1–35. DOI: 10.1093/bjps/45.1.1.

Franklin, Alexander (2018). "On the renormalization group explanation of universality". *Philosophy of Science* 85.2, pp. 225–248.

— (2020). "Whence the effectiveness of effective field theories?" *The British Journal for the Philosophy of Science*.

Friedman, Michael (1974). “Explanation and Scientific Understanding”. *Journal of Philosophy* 71.1, pp. 5–19. DOI: 10.2307/2024924.

Friedmann, A. (1922). “Über die Krümmung des Raumes”. *Zeitschrift fur Physik* 10, pp. 377–386. DOI: 10.1007/BF01332580.

— (1924). “Über die Möglichkeit einer Welt mit konstanter negativer Krümmung des Raumes”. *Zeitschrift fur Physik* 21.1, pp. 326–332. DOI: 10.1007/BF01328280.

Frieman, Joshua, Michael Turner, and Dragan Huterer (2008). “Dark Energy and the Accelerating Universe”. *Ann. Rev. Astron. Astrophys.* 46, pp. 385–432. DOI: 10.1146/annurev.astro.46.060407.145243. arXiv: 0803.0982 [astro-ph].

Frieman, Joshua A., Christopher T. Hill, Albert Stebbins, and Ioav Waga (1995). “Cosmology with ultralight pseudo Nambu-Goldstone bosons”. *Phys. Rev. Lett.* 75, pp. 2077–2080. DOI: 10.1103/PhysRevLett.75.2077. arXiv: astro-ph/9505060.

García-García, Carlos, Emilio Bellini, et al. (2020). “Theoretical priors in scalar-tensor cosmologies: Thawing quintessence”. *Phys. Rev. D* 101.6, p. 063508. DOI: 10.1103/PhysRevD.101.063508. arXiv: 1911.02868 [astro-ph.CO].

García-García, Carlos, Eric V. Linder, Pilar Ruíz-Lapuente, and Miguel Zumalacárregui (2018). “Dark energy from α-attractors: phenomenology and observational constraints”. *JCAP* 08, p. 022. DOI: 10.1088/1475-7516/2018/08/022. arXiv: 1803.00661 [astro-ph.CO].

Gardner, Michael R. (1982). “Predicting Novel Facts”. *British Journal for the Philosophy of Science* 33.1, pp. 1–15. DOI: 10.1093/bjps/33.1.1.

Gelman, Andrew and Donald B. Rubin (1992). “Inference from Iterative Simulation Using Multiple Sequences”. *Statistical Science* 7.4, pp. 457–472. DOI: 10.1214/ss/1177011136. URL: https://doi.org/10.1214/ss/1177011136.

German, Gabriel (2021). “Quartic hilltop inflation revisited”. *JCAP* 02, p. 034. DOI: 10.1088/1475-7516/2021/02/034. arXiv: 2011.12804 [astro-ph.CO].

Gibbons, GW (1977). “Quantum Processing Near Black Holes”. In: *Proceedings of the First Marcel Grossmann Meeting on General Relativity*. Ed. by R Ruffini. North-Holland, Amsterdam, pp 449–58.

Grimm, Stephen R. (2006). “Is Understanding a Species of Knowledge?” *British Journal for the Philosophy of Science* 57.3, pp. 515–535. DOI: 10.1093/bjps/axl015.

— (2010). “The Goal of Explanation”. *Studies in History and Philosophy of Science Part A* 41.4, pp. 337–344. DOI: 10.1016/j.shpsa.2010.10.006.

Gryb, Sean (2021). “New difficulties for the past hypothesis”. *Philosophy of Science* 88.3, pp. 511–532.

Gryb, Sean, Patricia Palacios, and Karim P. Y. Thébault (2021). “On the Universality of Hawking Radiation”. *Brit. J. Phil. Sci.* 72.3, pp. 809–837. DOI: 10.1093/bjps/axz025. arXiv: 1812.07078 [physics.hist-ph].

Gubitosi, Giulia, Federico Piazza, and Filippo Vernizzi (2013). “The Effective Field Theory of Dark Energy”. *JCAP* 02, p. 032. DOI: 10.1088/1475-7516/2013/02/032. arXiv: 1210.0201 [hep-th].

Guralnik, G. S., C. R. Hagen, and T. W. B. Kibble (1964). “Global Conservation Laws and Massless Particles”. *Phys. Rev. Lett.* 13 (20), pp. 585–587. DOI: 10.1103/PhysRevLett.13.585.

Guth, Alan H, David I Kaiser, Andrei D Linde, et al. (2017). “A cosmic controversy”. *Scientific American* 317.1, pp. 5–7.

Guth, Alan H. (1981). “The Inflationary Universe: A Possible Solution to the Horizon and Flatness Problems”. *Phys. Rev. D* 23. Ed. by Li-Zhi Fang and R. Ruffini, pp. 347–356. DOI: 10.1103/PhysRevD.23.347.

— (1997). *The Inflationary Universe*. Addison-Wesley.

— (2004). “Inflation”. In: *Carnegie Observatories Centennial Symposium. 2. Measuring and Modeling the Universe*, pp. 31–52. arXiv: astro-ph/0404546.

— (2007). “Eternal inflation and its implications”. *J. Phys. A* 40. Ed. by Joan Sola, pp. 6811–6826. DOI: 10.1088/1751-8113/40/25/S25. arXiv: hep-th/0702178.

Guth, Alan H., David I. Kaiser, and Yasunori Nomura (2014). “Inflationary paradigm after Planck 2013”. *Phys. Lett. B* 733, pp. 112–119. DOI: 10.1016/j.physletb.2014.03.020. arXiv: 1312.7619 [astro-ph.CO].

Guth, Alan H. and S. Y. Pi (1982). “Fluctuations in the New Inflationary Universe”. *Phys. Rev. Lett.* 49, pp. 1110–1113. DOI: 10.1103/PhysRevLett.49.1110.

Guth, Alan H. and Paul J. Steinhardt (1984). “The Inflationary Universe”. *Scientific American* 250.5, pp. 116–129. ISSN: 00368733, 19467087. URL: http://www.jstor.org/stable/24969372 (visited on 06/22/2022).

Harlow, Daniel (2016). “Jerusalem lectures on black holes and quantum information”. *Reviews of Modern Physics* 88.1, p. 015002.

Haro, Sebastian De and Jeremy Butterfield (2021). “On Symmetry and Duality”. *Synthese* 198.4, pp. 2973–3013. DOI: 10.1007/s11229-019-02258-x.

Harrison, E. R. (1970). “Fluctuations at the Threshold of Classical Cosmology”. *Phys. Rev. D* 1 (10), pp. 2726–2730. DOI: 10.1103/PhysRevD.1.2726. URL: https://link.aps.org/doi/10.1103/PhysRevD.1.2726.

Hastings, W. K. (1970). “Monte Carlo sampling methods using Markov chains and their applications”. *Biometrika* 57.1, pp. 97–109. ISSN: 0006-3444. DOI: 10.1093/biomet/57.1.97. eprint: https://academic.oup.com/biomet/article-pdf/57/1/97/23940249/57-1-97.pdf. URL: https://doi.org/10.1093/biomet/57.1.97.

Hawking, S. W. (1982). “The Development of Irregularities in a Single Bubble Inflationary Universe”. *Phys. Lett. B* 115, p. 295. DOI: 10.1016/0370-2693(82)90373-2.

Hawking, Stephen W (1975). “Particle creation by black holes”. *Communications in mathematical physics* 43.3, pp. 199–220.

Hawking, Stephen William and Roger Penrose (1970). “The singularities of gravitational collapse and cosmology”. *Proceedings of the Royal Society of London. A. Mathematical and Physical Sciences* 314.1519, pp. 529–548.

Helfer, Adam D (2003). “Do black holes radiate?” *Reports on Progress in Physics* 66.6, p. 943.

Hempel, Carl G (1965). *Aspects of Scientific Explanation and other Essays in the Philosophy of Science*. New York: Free Press.

Hempel, Carl Gustav and Paul Oppenheim (1948). “Studies in the Logic of Explanation”. *Philosophy of Science* 15.2, pp. 135–175. DOI: 10.1086/286983.

Higgs, Peter W. (1964). “Broken Symmetries and the Masses of Gauge Bosons”. *Phys. Rev. Lett.* 13. Ed. by J. C. Taylor, pp. 508–509. DOI: 10.1103/PhysRevLett.13.508.

Himemoto, Yoshiaki and Takahiro Tanaka (2000). “Generalization of the model of Hawking radiation with modified high frequency dispersion relation”. *Physical Review D* **61**.6, p. 064004.

Hinshaw, G. et al. (2013). “Nine-year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Cosmological Parameter Results”. *Astrophys. J. Supp.* 208.2, 19, p. 19. DOI: 10.1088/0067-0049/208/2/19. arXiv: 1212.5226 [astro-ph.CO].

Hitchcock, Christopher and James Woodward (2003). “Explanatory generalizations, part II: Plumbing explanatory depth”. *Noûs* 37.2, pp. 181–199.

Hoefer, Carl (2020). “Scientific Realism Without the Quantum”. In: *Scientific Realism and the Quantum*. Ed. by Steven French and Juha Saatsi. Oxford University Press.

Hoffmann, Josh and David Sloan (2021). “Squared quartic hilltop inflation”. *Phys. Rev. D* 104.12, p. 123542. DOI: 10.1103/PhysRevD.104.123542. arXiv: 2108.13316 [gr-qc].

Hoffmann, Josh and David Sloan (2023). “Regularization of single field inflation models”. *Phys. Rev. D* 107.2, p. 023502. DOI: 10.1103/PhysRevD.107.023502. arXiv: 2208.09390 [astro-ph.CO].

Hollands, Stefan and Robert M. Wald (2002). “An Alternative to inflation”. *Gen. Rel. Grav.* 34, pp. 2043–2055. DOI: 10.1023/A:1021175216055. arXiv: gr-qc/0205058.

Horndeski, Gregory Walter (1974). “Second-order scalar-tensor field equations in a four-dimensional space”. *Int. J. Theor. Phys.* 10, pp. 363–384. DOI: 10.1007/BF01807638.

Hossenfelder, Sabine (2019). “Screams for Explanation: Finetuning and Naturalness in the Foundations of Physics”. *Synthese* 198.Suppl 16, pp. 3727–3745. DOI: 10.1007/s11229-019-02377-5.

Hubble, Edwin (1929). “A relation between distance and radial velocity among extra-galactic nebulae”. *Proceedings of the National Academy of Sciences* 15.3, pp. 168–173. DOI: 10.1073/pnas.15.3.168. eprint: https://www.pnas.org/doi/pdf/10.1073/pnas.15.3.168. URL: https://www.pnas.org/doi/abs/10.1073/pnas.15.3.168.

Hulse, R. A. and J. H. Taylor (1975). “Discovery of a pulsar in a binary system.” *Astrophys. J. Lett.* 195, pp. L51–L53. DOI: 10.1086/181708.

Huterer, Dragan and Hiranya V. Peiris (2007). “Dynamical behavior of generic quintessence potentials: Constraints on key dark energy observables”. *Phys. Rev. D* 75, p. 083503. DOI: 10.1103/PhysRevD.75.083503. arXiv: astro-ph/0610427.

Huterer, Dragan and Glenn Starkman (2003). “Parameterization of dark-energy properties: A Principal-component approach”. *Phys. Rev. Lett.* 90, p. 031301. DOI: 10.1103/PhysRevLett.90.031301. arXiv: astro-ph/0207517.

Ijjas, Anna, William G Cook, et al. (2020). “Robustness of slow contraction to cosmic initial conditions”. *Journal of Cosmology and Astroparticle Physics* 2020.08, p. 030.

Ijjas, Anna and Paul J. Steinhardt (2016a). “Classically stable nonsingular cosmological bounces”. *Phys. Rev. Lett.* 117.12, p. 121304. DOI: 10.1103/PhysRevLett.117.121304. arXiv: 1606.08880 [gr-qc].

— (2016b). “Implications of Planck2015 for inflationary, ekpyrotic and anamorphic bouncing cosmologies”. *Class. Quant. Grav.* 33.4, p. 044001. DOI: 10.1088/0264-9381/33/4/044001. arXiv: 1512.09010 [astro-ph.CO].

— (2017). “Fully stable cosmological solutions with a non-singular classical bounce”. *Phys. Lett. B* 764, pp. 289–294. DOI: 10.1016/j.physletb.2016.11.047. arXiv: 1609.01253 [gr-qc].

Ijjas, Anna and Paul J. Steinhardt (2018). “Bouncing Cosmology made simple”. *Class. Quant. Grav.* 35.13, p. 135004. DOI: 10.1088/1361-6382/aac482. arXiv: 1803.01961 [astro-ph.CO].

— (2019). “A new kind of cyclic universe”. *Phys. Lett. B* 795, pp. 666–672. DOI: 10.1016/j.physletb.2019.06.056. arXiv: 1904.08022 [gr-qc].

Ijjas, Anna, Paul J. Steinhardt, and Abraham Loeb (2013). “Inflationary paradigm in trouble after Planck2013”. *Phys. Lett. B* 723, pp. 261–266. DOI: 10.1016/j.physletb.2013.05.023. arXiv: 1304.2785 [astro-ph.CO].

— (2014). “Inflationary schism”. *Phys. Lett. B* 736, pp. 142–146. DOI: 10.1016/j.physletb.2014.07.012. arXiv: 1402.6980 [astro-ph.CO].

Iso, Satoshi, Hiroshi Umetsu, and Frank Wilczek (2006). “Hawking radiation from charged black holes via gauge and gravitational anomalies”. *Phys. Rev. Lett.* 96, p. 151302. DOI: 10.1103/PhysRevLett.96.151302. arXiv: hep-th/0602146 [hep-th].

Ivanova, Milena (2024). “Aesthetic Virtues and Theory Acceptance”. In: *Scientific Theories and Philosophical Stances: Themes from van Fraassen*. Ed. by Claus Beisbart and Michael Frauchiger. De Gruyter, pp. 147–164.

Jacobson, Ted (1993). “Black hole radiation in the presence of a short distance cutoff”. *Physical Review D* 48.2, pp. 728–41. DOI: 10.1103/PhysRevD.48.728.

— (2005). “Introduction to quantum fields in curved spacetime and the Hawking effect”. In: *Lectures on Quantum Gravity*. New York: Springer, pp. 39–89.

Jacobson, Theodore (1991). “Black-hole evaporation and ultrashort distances”. *Physical Review D* 44.6, p. 1731.

Jaffe, T. R., S. Hervik, A. J. Banday, and K. M. Gorski (2006). “On the viability of Bianchi type viih models with dark energy”. *Astrophys. J.* 644, pp. 701–708. DOI: 10.1086/503893. arXiv: astro-ph/0512433.

Jiménez, Jose Beltrán, Lavinia Heisenberg, and Tomi Koivisto (2018). “Coincident General Relativity”. *Phys. Rev. D* 98.4, p. 044048. DOI: 10.1103/PhysRevD.98.044048. arXiv: 1710.03116 [gr-qc].

Jones, Roger (1991). “Realism About What?” *Philosophy of Science* 58.2, pp. 185–202. DOI: 10.1086/289611.

Joyce, Austin, Bhuvnesh Jain, Justin Khoury, and Mark Trodden (2015). “Beyond the Cosmological Standard Model”. *Phys. Rept.* 568, pp. 1–98. DOI: 10.1016/j.physrep.2014.12.002. arXiv: 1407.0059 [astro-ph.CO].

Joyce, Austin, Lucas Lombriser, and Fabian Schmidt (2016). “Dark Energy Versus Modified Gravity”. *Ann. Rev. Nucl. Part. Sci.* 66, pp. 95–122. DOI: 10.1146/annurev-nucl-102115-044553. arXiv: 1601.06133 [astro-ph.CO].

Kallosh, Renata, Jin U Kang, Andrei D. Linde, and Viatcheslav Mukhanov (2008). “The New ekpyrotic ghost”. *JCAP* 04, p. 018. DOI: 10.1088/1475-7516/2008/04/018. arXiv: 0712.2040 [hep-th].

Kallosh, Renata and Andrei Linde (2019). “On hilltop and brane inflation after Planck”. *JCAP* 09, p. 030. DOI: 10.1088/1475-7516/2019/09/030. arXiv: 1906.02156 [hep-th].

Kallosh, Renata, Andrei Linde, and Yusuke Yamada (2019). “Planck 2018 and Brane Inflation Revisited”. *JHEP* 01, p. 008. DOI: 10.1007/JHEP01(2019)008. arXiv: 1811.01023 [hep-th].

Kallosh, Renata and Andrei D. Linde (2003). “M theory, cosmological constant and anthropic principle”. *Phys. Rev. D* 67, p. 023510. DOI: 10.1103/PhysRevD.67.023510. arXiv: hep-th/0208157.

Kaloper, Nemanja, Matthew Kleban, Albion Lawrence, and Stephen Shenker (2002). “Signatures of short distance physics in the cosmic microwave background”. *Physical Review D* 66.12, p. 123510.

Kaloper, Nemanja, Matthew Kleban, Albion Lawrence, Stephen Shenker, and Leonard Susskind (2003). “Initial conditions for inflation”. *Journal of High Energy Physics* 2002.11, p. 037.

Kamionkowski, Marc, Arthur Kosowsky, and Albert Stebbins (1997). “Statistics of cosmic microwave background polarization”. *Phys. Rev. D* 55 (12), pp. 7368–7388. DOI: 10.1103/PhysRevD.55.7368. URL: https://link.aps.org/doi/10.1103/PhysRevD.55.7368.

Kase, Ryotaro and Shinji Tsujikawa (2019). “Dark energy in Horndeski theories after GW170817: A review”. *Int. J. Mod. Phys. D* 28.05, p. 1942005. DOI: 10.1142/S0218271819420057. arXiv: 1809.08735 [gr-qc].

Keas, Michael N. (2018). “Systematizing the Theoretical Virtues”. *Synthese* 195.6, pp. 2761–2793. DOI: 10.1007/s11229-017-1355-6.

Khoury, Justin, Burt A. Ovrut, Paul J. Steinhardt, and Neil Turok (2001). “The Ekpyrotic universe: Colliding branes and the origin of the hot big bang”. *Phys. Rev. D* 64, p. 123522. DOI: 10.1103/PhysRevD.64.123522. arXiv: hep-th/0103239.

Kinney, William H., Edward W. Kolb, Alessandro Melchiorri, and Antonio Riotto (2006). “Inflation model constraints from the Wilkinson Microwave Anisotropy Probe three-year data”.

Phys. Rev. D 74, p. 023502. DOI: 10.1103/PhysRevD.74.023502. arXiv: astro-ph/0605338.

Kitcher, Philip (1989). "Explanatory Unification and the Causal Structure of the World". In: *Scientific Explanation*. Ed. by Philip Kitcher and Wesley Salmon. Minneapolis: University of Minnesota Press, pp. 410–505.

Kobayashi, Tsutomu (2016). "Generic instabilities of nonsingular cosmologies in Horndeski theory: A no-go theorem". *Phys. Rev. D* 94.4, p. 043511. DOI: 10.1103/PhysRevD.94.043511. arXiv: 1606.05831 [hep-th].

— (2019). "Horndeski theory and beyond: a review". *Rept. Prog. Phys.* 82.8, p. 086901. DOI: 10.1088/1361-6633/ab2429. arXiv: 1901.07183 [gr-qc].

Koberinski, Adam, Bridget Falck, and Chris Smeenk (2023). "Contemporary Philosophical Perspectives on the Cosmological Constant". *Universe* 9.3, p. 134. DOI: 10.3390/universe9030134. arXiv: 2212.04335 [physics.hist-ph].

Koberinski, Adam and Chris Smeenk (forthcoming[a]). "Λ and the Limits of Effective Field Theory". *Philosophy of Science*. DOI: 10.1017/psa.2022.16.

— (forthcoming[b]). "Establishing a Theory of Inflationary Cosmology". *British Journal for the Philosophy of Science*. DOI: 10.1086/733886.

Kohri, Kazunori, Chia-Min Lin, and David H. Lyth (2007). "More hilltop inflation models". *JCAP* 12, p. 004. DOI: 10.1088/1475-7516/2007/12/004. arXiv: 0707.3826 [hep-ph].

Kuhn, Thomas S. (1977). "Objectivity, Value Judgment, and Theory Choice". In: *The Essential Tension: Selected Studies in Scientific Tradition and Change*. University of Chicago Press, pp. 320–39.

Kuhn, Thomas Samuel (1962). *The Structure of Scientific Revolutions*. Ed. by Otto Neurath. Chicago: University of Chicago Press.

Kukla, André (1993). "Laudan, Leplin, Empirical Equivalence and Underdetermination". *Analysis* 53.1, pp. 1–7. DOI: 10.1093/analys/53.1.1.

Ladyman, James and Don Ross (2007). *Every Thing Must Go: Metaphysics Naturalized*. New York: Oxford University Press.

Ladyman, James and Karoline Wiesner (2020). *What is a complex system?* Yale University Press.

Lakatos, Imre (1970). "Falsification and the Methodology of Scientific Research Programmes". In: *Criticism and the Growth of Knowledge*. Ed. by Imre Lakatos and Alan Musgrave. Cambridge University Press, pp. 91–196.

Lakatos, Imre (1978). *The Methodology of Scientific Research Programmes: Volume 1: Philosophical Papers*. Cambridge University Press.

Laudan, Larry (1977). *Progress and its Problems: Toward a Theory of Scientific Growth*. University of California Press.

— (1996). *Beyond Positivism and Relativism: Theory, Method, and Evidence*. Westview Press.

Laudan, Larry and Jarrett Leplin (1991). "Empirical Equivalence and Underdetermination". *Journal of Philosophy* 88.9, pp. 449–472.

Laureijs, R. et al. (2011). "Euclid Definition Study Report". arXiv: 1110.3193 [astro-ph.CO].

Le Bihan, Baptiste and James Read (2018). "Duality and Ontology". *Philosophy Compass* 13.12, e12555. DOI: 10.1111/phc3.12555.

Lehners, Jean-Luc, Paul McFadden, Neil Turok, and Paul J. Steinhardt (2007). "Generating ekpyrotic curvature perturbations before the big bang". *Phys. Rev. D* 76, p. 103501. DOI: 10.1103/PhysRevD.76.103501. arXiv: hep-th/0702153.

Lemaître, G. (1927). "Un Univers homogène de masse constante et de rayon croissant rendant compte de la vitesse radiale des nébuleuses extra-galactiques". *Annales de la Société Scientifique de Bruxelles* 47, pp. 49–59.

Levy, Aaron M., Anna Ijjas, and Paul J. Steinhardt (2015). "Scale-invariant perturbations in ekpyrotic cosmologies without fine-tuning of initial conditions". *Phys. Rev. D* 92.6, p. 063524. DOI: 10.1103/PhysRevD.92.063524. arXiv: 1506.01011 [astro-ph.CO].

Lewis, Antony (2013). "Efficient sampling of fast and slow cosmological parameters". *Phys. Rev.* D87.10, p. 103529. DOI: 10.1103/PhysRevD.87.103529. arXiv: 1304.4473 [astro-ph.CO]. URL: https://arxiv.org/abs/1304.4473.

Lewis, Antony and Sarah Bridle (2002). "Cosmological parameters from CMB and other data: A Monte Carlo approach". *Phys. Rev.* D66, p. 103511. DOI: 10.1103/PhysRevD.66.103511. arXiv: astro-ph/0205436 [astro-ph]. URL: https://arxiv.org/abs/astro-ph/0205436.

Libanov, M., S. Mironov, and V. Rubakov (2016). "Generalized Galileons: instabilities of bouncing and Genesis cosmologies and modified Genesis". *JCAP* 08, p. 037. DOI: 10.1088/1475-7516/2016/08/037. arXiv: 1605.05992 [hep-th].

Lichtenstein, Eli I. (2021). "(Mis)Understanding Scientific Disagreement: Success Versus Pursuit-Worthiness in Theory Choice". *Studies in History and Philosophy of Science Part A* 85, pp. 166–175. DOI: 10.1016/j.shpsa.2020.10.005.

Liddle, Andrew R. and Robert J. Scherrer (1999). "A Classification of scalar field potentials with cosmological scaling solutions". *Phys. Rev. D* 59, p. 023509. DOI: 10.1103/PhysRevD.59.023509. arXiv: astro-ph/9809272.

Lillepalu, Helena Grete and Antonio Racioppi (2023). "Generalized hilltop inflation". *Eur. Phys. J. Plus* 138.10, p. 894. DOI: 10.1140/epjp/s13360-023-04512-1. arXiv: 2211.02426 [astro-ph.CO].

Linde, A., V. Mukhanov, and A. Vikman (2010). "On adiabatic perturbations in the ekpyrotic scenario". *JCAP* 02, p. 006. DOI: 10.1088/1475-7516/2010/02/006. arXiv: 0912.0944 [hep-th].

Linde, Andrei (2015). "Inflationary Cosmology after Planck 2013". In: *100e Ecole d'Ete de Physique: Post-Planck Cosmology*, pp. 231–316. DOI: 10.1093/acprof:oso/9780198728856.003.0006. arXiv: 1402.0526 [hep-th].

Linde, Andrei D. (1982). "A New Inflationary Universe Scenario: A Possible Solution of the Horizon, Flatness, Homogeneity, Isotropy and Primordial Monopole Problems". *Phys. Lett. B* 108. Ed. by Li-Zhi Fang and R. Ruffini, pp. 389–393. DOI: 10.1016/0370-2693(82)91219-9.

— (1983). "Chaotic Inflation". *Phys. Lett. B* 129, pp. 177–181. DOI: 10.1016/0370-2693(83)90837-7.

Linder, Eric V. (2003). "Exploring the expansion history of the universe". *Phys. Rev. Lett.* 90, p. 091301. DOI: 10.1103/PhysRevLett.90.091301. arXiv: astro-ph/0208512.

— (2006). "The paths of quintessence". *Phys. Rev. D* 73, p. 063010. DOI: 10.1103/PhysRevD.73.063010. arXiv: astro-ph/0601052.

— (2008). "The Dynamics of Quintessence, The Quintessence of Dynamics". *Gen. Rel. Grav.* 40, pp. 329–356. DOI: 10.1007/s10714-007-0550-z. arXiv: 0704.2064 [astro-ph].

— (2015). "Quintessence's last stand?" *Phys. Rev. D* 91, p. 063006. DOI: 10.1103/PhysRevD.91.063006. arXiv: 1501.01634 [astro-ph.CO].

— (2023). "Benchmarks of Dark Energy". arXiv: 2304.04803 [astro-ph.CO].

Linnemann, Niels S. (2020). "Non-Empirical Robustness Arguments in Quantum Gravity". *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics* 72, pp. 70–86. DOI: 10.1016/j.shpsb.2020.06.001.

Lipton, Peter (1991). *Inference to the Best Explanation*. London, New York: Routledge/Taylor, and Francis Group.

Lipton, Peter (2007). "Inference to the Best Explanation". *Philosophy and Phenomenological Research* 74.2, pp. 421–423. DOI: 10.1111/j.1933-1592.2007.00027.x.

Lodha, K. et al. (2024). "DESI 2024: Constraints on Physics-Focused Aspects of Dark Energy using DESI DR1 BAO Data". arXiv: 2405.13588 [astro-ph.CO].

Lorenzoni, Dario L., David I. Kaiser, and Evan McDonough (2024). "Natural Inflation with Exponentially Small Tensor-To-Scalar Ratio". arXiv: 2405.13881 [astro-ph.CO].

Madhavacheril, Mathew S. et al. (2024). "The Atacama Cosmology Telescope: DR6 Gravitational Lensing Map and Cosmological Parameters". *Astrophys. J.* 962.2, p. 113. DOI: 10.3847/1538-4357/acff5f. arXiv: 2304.05203 [astro-ph.CO].

Manchak, John Byron (2009). "Can We Know the Global Structure of Spacetime?" *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics* 40.1, pp. 53–56. DOI: 10.1016/j.shpsb.2008.07.004.

March, Eleanor, William J. Wolf, and James Read (2024). "On the geometric trinity of gravity, non-relativistic limits, and Maxwell gravitation". *Philosophy of Physics* 02, p. 15. DOI: 10.31389/pop.80. arXiv: 2309.06889 [physics.hist-ph].

Marsh, David J. E. (2016). "Axion Cosmology". *Phys. Rept.* 643, pp. 1–79. DOI: 10.1016/j.physrep.2016.06.005. arXiv: 1510.07633 [astro-ph.CO].

Marsh, David J. E., Philip Bull, Pedro G. Ferreira, and Andrew Pontzen (2014). "Quintessence in a quandary: Prior dependence in dark energy models". *Phys. Rev. D* 90.10, p. 105023. DOI: 10.1103/PhysRevD.90.105023. arXiv: 1406.2301 [astro-ph.CO].

Marsh, David J. E. and Pedro G. Ferreira (2010). "Ultra-Light Scalar Fields and the Growth of Structure in the Universe". *Phys. Rev. D* 82, p. 103528. DOI: 10.1103/PhysRevD.82.103528. arXiv: 1009.3501 [hep-ph].

Martens, Niels C. M. and Dennis Lehmkuhl (2020). "Dark matter = modified gravity? Scrutinising the spacetime–matter distinction through the modified gravity/ dark matter lens". *Stud. Hist. Phil. Sci. B* 72, pp. 237–250. DOI: 10.1016/j.shpsb.2020.08.003. arXiv: 2009.03890 [physics.hist-ph].

Martin, Jerome (2008). "Quintessence: a mini-review". *Mod. Phys. Lett. A* 23. Ed. by Pauchy W. Y. Hwang, Xiao-Gang He, and Kin-Wang Ng, pp. 1252–1265. DOI: 10.1142/S0217732308027631. arXiv: 0803.4076 [astro-ph].

— (2016). "The Observational Status of Cosmic Inflation after Planck". *Astrophys. Space Sci. Proc.* 45. Ed. by Júlio C. Fabris et al., pp. 41–134. DOI: 10.1007/978-3-319-44769-8_2. arXiv: 1502.05733 [astro-ph.CO].

Martin, Jerome and Robert Brandenberger (2003). "On the dependence of the spectra of fluctuations in inflationary cosmology on transPlanckian physics". *Phys. Rev. D* 68, p. 063513. DOI: 10.1103/PhysRevD.68.063513. arXiv: hep-th/0305161.

Martin, Jerome and Robert H. Brandenberger (2001a). "The TransPlanckian problem of inflationary cosmology". *Phys. Rev. D* 63, p. 123501. DOI: 10.1103/PhysRevD.63.123501. arXiv: hep-th/0005209.

Martin, Jerome, Christophe Ringeval, and Vincent Vennin (2014). "Encyclopædia Inflationaris". *Phys. Dark Univ.* 5-6, pp. 75–235. DOI: 10.1016/j.dark.2014.01.003. arXiv: 1303.3787 [astro-ph.CO].

— (2015). "Observing Inflationary Reheating". *Phys. Rev. Lett.* 114.8, p. 081303. DOI: 10.1103/PhysRevLett.114.081303. arXiv: 1410.7958 [astro-ph.CO].

— (2024). "Cosmic Inflation at the Crossroads". arXiv: 2404.10647 [astro-ph.CO].

Martin, Jérôme and Robert H. Brandenberger (2001b). "Trans-Planckian problem of inflationary cosmology". *Physical Review D* 63.12. DOI: 10.1103/PhysRevD.63.123501.

Martin, Jérôme, Christophe Ringeval, Roberto Trotta, and Vincent Vennin (2014). "The Best Inflationary Models After Planck". *JCAP* 03, p. 039. DOI: 10.1088/1475-7516/2014/03/039. arXiv: 1312.3529 [astro-ph.CO].

Massimi, Michela (2021). "Cosmic Bayes. Datasets and Priors in the Hunt for Dark Energy". *European Journal for Philosophy of Science* 11.1, pp. 1–21. DOI: 10.1007/s13194-020-00338-1.

Maudlin, Tim (1996). "On the Unification of Physics". *Journal of Philosophy* 93.3, pp. 129–144.

— (2007). *The Metaphysics Within Physics*. Oxford University Press.

McCoy, C. D. (2015). "Does Inflation Solve the Hot Big Bang Model's Fine-Tuning Problems?" *Studies in History and Philosophy of Modern Physics* 51, pp. 23–36. DOI: 10.1016/j.shpsb.2015.06.002.

— (2018). "The Implementation, Interpretation, and Justification of Likelihoods in Cosmology". *Studies in History and Philosophy of Modern Physics* 62, pp. 19–35. DOI: 10.1016/j.shpsb.2017.05.002.

— (2019). "Epistemic Justification and Methodological Luck in Inflationary Cosmology". *British Journal for the Philosophy of Science* 70.4, pp. 1003–1028. DOI: 10.1093/bjps/axy014.

— (2020). "Stability in Cosmology, From Einstein to Inflation". In: *Thinking About Space and Time*. Ed. by Claus Beisbart, Tilman Sauer, and Christian Wüthrich. Cham: Birkhäuser, pp. 71–89.

McCoy, C. D. (2021). “Meta-Empirical Support for Eliminative Reasoning”. *Studies in History and Philosophy of Science Part A* 90, pp. 15–29.

— (2023). “Understanding the Progress of Science”. In: *Scientific Understanding and Representation: Modeling in the Physical Sciences*. Ed. by Kareem Khalifa, Insa Lawler, and Elay Shech. Routledge, pp. 353–369.

— (2017). “Can typicality arguments dissolve cosmology’s flatness problem?” *Philosophy of Science* 84.5, pp. 1239–1252.

McMullin, Ernan (2013). “The virtues of a good theory”. In: *The Routledge Companion to Philosophy of Science*. Ed. by Martin Curd and Stathis Psillos. New York: Routledge.

Menon, Tushar (2019). “On the Viability of the No Alternatives Argument”. *Studies in History and Philosophy of Science Part A* 76, pp. 69–75. DOI: 10.1016/j.shpsa.2018.10.005.

Metropolis, Nicholas et al. (1953). “Equation of State Calculations by Fast Computing Machines”. *The Journal of Chemical Physics* 21.6, pp. 1087–1092. DOI: 10.1063/1.1699114. eprint: https://doi.org/10.1063/1.1699114. URL: https://doi.org/10.1063/1.1699114.

Mukhanov, V. (2005). *Physical Foundations of Cosmology*. Oxford: Cambridge University Press. ISBN: 978-0-521-56398-7. DOI: 10.1017/CBO9780511790553.

Mukhanov, Viatcheslav F. and G. V. Chibisov (1981). “Quantum Fluctuations and a Nonsingular Universe”. *JETP Lett.* 33, pp. 532–535.

Mulder, Ruward A. and James Read (2023). *Is spacetime curved? Assessing the underdetermination of general relativity and teleparallel gravity*. URL: https://philsci-archive.pitt.edu/22897/.

Mulder, Ruward Arthur (2024). “Real commitment: a coarse-grained approach to reality via alternative theories in physics”. PhD thesis. Apollo - University of Cambridge Repository. DOI: 10.17863/CAM.116676. URL: https://www.repository.cam.ac.uk/handle/1810/381526.

Muller, F. A. (1997a). “The Equivalence Myth of Quantum Mechanics –Part I”. *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics* 28.1, pp. 35–61. DOI: 10.1016/s1355-2198(96)00022-6.

— (1997b). “The Equivalence Myth of Quantum Mechanics–Part II”. *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics* 28.2, pp. 219–247. DOI: 10.1016/s1355-2198(97)00001-4.

Murgueitio Ramírez, Sebastián and Nicholas Teh (forthcoming). "Abandoning Galileo's Ship: The Quest for Non-Relational Empirical Significance". *British Journal for the Philosophy of Science*.

Musgrave, Alan (1974). "Logical Versus Historical Theories of Confirmation". *British Journal for the Philosophy of Science* 25.1, pp. 1–23. DOI: 10.1093/bjps/25.1.1.

— (1992). "Realism About What?" *Philosophy of Science* 59.4, pp. 691–697. DOI: 10.1086/289702.

Norton, John D. (2008). "Must Evidence Underdetermine Theory". *The Challenge of the Social and the Pressure of Practice*, pp. 17–44.

Nyrup, Rune (2015). "How Explanatory Reasoning Justifies Pursuit: A Peircean View of Ibe". *Philosophy of Science* 82.5, pp. 749–760. DOI: 10.1086/683262.

O'Raifeartaigh, C. and B. McCann (2014). "Einstein's cosmic model of 1931 revisited: an analysis and translation of a forgotten model of the universe". *Eur. Phys. J. H* 39. [Erratum: Eur.Phys.J.H 47, 8 (2022)], pp. 63–85. DOI: 10.1140/epjh/e2013-40038-x. arXiv: 1312.2192 [physics.hist-ph].

O'Raifeartaigh, Cormac (2019). "Eddington, Lemaitre and the hypothesis of cosmic expansion". In: arXiv: 1907.12297 [physics.hist-ph].

O'Raifeartaigh, Cormac, Michael O'Keeffe, Werner Nahm, and Simon Mitton (2017). "Einstein's 1917 static model of the universe: a centennial review". *Eur. Phys. J. H* 42.3, pp. 431–474. DOI: 10.1140/epjh/e2017-80002-5. arXiv: 1701.07261 [physics.hist-ph].

Palacios, Patricia (2022). *Emergence and Reduction in Physics*. Cambridge University Press.

Park, Minjoon, Kathryn M. Zurek, and Scott Watson (2010). "A Unified Approach to Cosmic Acceleration". *Phys. Rev. D* 81, p. 124008. DOI: 10.1103/PhysRevD.81.124008. arXiv: 1003.1722 [hep-th].

Park, Minsu, Marco Raveri, and Bhuvnesh Jain (2021). "Reconstructing Quintessence". *Phys. Rev. D* 103.10, p. 103530. DOI: 10.1103/PhysRevD.103.103530. arXiv: 2101.04666 [astro-ph.CO].

Peebles, James (2020a). *Cosmic Century. An Inside History of our Modern Understanding of the Universe*. Cambridge, UK: Cambridge University Press.

Peebles, James and Bharat Ratra (1988). "Cosmology with a Time Variable Cosmological Constant". *Astrophys. J. Lett.* 325, p. L17. DOI: 10.1086/185100.

Peebles, P. J. E. (1986). "The mean mass density of the universe". *Nature* 321.6072, pp. 27–32.

Peebles, P. J. E. (2020b). *Cosmology's Century: An Inside History of Our Modern Understanding of the Universe*. Princeton University Press. DOI: doi:10.1515/9780691201665. URL: https://doi.org/10.1515/9780691201665.

Peebles, P. J. E. and J. T. Yu (1970). "Primeval Adiabatic Perturbation in an Expanding Universe". *apj* 162, p. 815. DOI: 10.1086/150713.

Peirone, Simone, Matteo Martinelli, Marco Raveri, and Alessandra Silvestri (2017). "Impact of theoretical priors in cosmological analyses: the case of single field quintessence". *Phys. Rev. D* 96.6, p. 063524. DOI: 10.1103/PhysRevD.96.063524. arXiv: 1702.06526 [astro-ph.CO].

Penrose, R. (1989). "Difficulties with inflationary cosmology". *Annals N. Y. Acad. Sci.* 571. Ed. by E. J. Fenyves, pp. 249–264. DOI: 10.1111/j.1749-6632.1989.tb50513.x.

Penrose, Roger (1969). "Gravitational collapse: The role of general relativity". *Nuovo Cimento Rivista Serie* 1, p. 252.

— (1973). "Naked singularities". *Annals of the New York Academy of Sciences* 224.1, pp. 125–134.

— (1979). "Singularities and time-asymmetry." In: *General Relativity: An Einstein centenary survey*. Ed. by S. W. Hawking and W. Israel, pp. 581–638.

Perlmutter, S. et al. (1998). "Discovery of a supernova explosion at half the age of the Universe and its cosmological implications". *Nature* 391, pp. 51–54. DOI: 10.1038/34124. arXiv: astro-ph/9712212.

— (1999). "Measurements of Ω and Λ from 42 high redshift supernovae". *Astrophys. J.* 517, pp. 565–586. DOI: 10.1086/307221. arXiv: astro-ph/9812133.

Pitts, J. Brian (2010). "Permanent Underdetermination From Approximate Empirical Equivalence in Field Theory: Massless and Massive Scalar Gravity, Neutrino, Electromagnetic, Yang-Mills and Gravitational Theories". *British Journal for the Philosophy of Science* 62.2, pp. 259–299. DOI: 10.1093/bjps/axq014.

Polchinski, J. (2007a). *String theory. Vol. 1: An introduction to the bosonic string*. Cambridge Monographs on Mathematical Physics. Cambridge University Press. DOI: 10.1017/CBO9780511816079.

— (2007b). *String theory. Vol. 2: Superstring theory and beyond*. Cambridge Monographs on Mathematical Physics. Cambridge University Press. DOI: 10.1017/CBO9780511618123.

Polchinski, Joseph (1995). "String theory and black hole complementarity". In: *STRINGS 95: Future Perspectives in String Theory*, pp. 417–426. arXiv: hep-th/9507094.

Polchinski, Joseph (2017). “Dualities of Fields and Strings”. *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics* 59.C, pp. 6–20. DOI: 10.1016/j.shpsb.2015.08.011.

Pontzen, Andrew and Anthony Challinor (2007). “Bianchi Model CMB Polarization and its Implications for CMB Anomalies”. *Mon. Not. Roy. Astron. Soc.* 380, pp. 1387–1398. DOI: 10.1111/j.1365-2966.2007.12221.x. arXiv: 0706.2075 [astro-ph].

Popper, Karl R. (1935). *The Logic of Scientific Discovery*. London, England: Routledge.

— (1963). *Conjectures and Refutations: The Growth of Scientific Knowledge*. New York: Routledge.

— (1983). *Realism and the Aim of Science*. Ed. by William Warren Bartley. New York: Routledge.

Press, William H (1980). “Spontaneous Production of the Zel'dovich Spectrum of Cosmological Fluctuations”. *Physica Scripta* 21.5, pp. 702–707. DOI: 10.1088/0031-8949/21/5/021. URL: https://doi.org/10.1088/0031-8949/21/5/021.

Press, William H. and Kip S. Thorne (1972). “Gravitational-Wave Astronomy”. *Ann. Rev. Astron. Astrophys.* 10, p. 335. DOI: 10.1146/annurev.aa.10.090172.002003.

Qu, Frank J. et al. (2024). “The Atacama Cosmology Telescope: A Measurement of the DR6 CMB Lensing Power Spectrum and Its Implications for Structure Growth”. *Astrophys. J.* 962.2, p. 112. DOI: 10.3847/1538-4357/acfe06. arXiv: 2304.05202 [astro-ph.CO].

Quine, Willard (1975). “On Empirically Equivalent Systems of the World”. *Erkenntnis* 9.3, pp. 313–28. DOI: 10.1007/bf00178004.

Rashidi, Narges, Mohaddeseh Heidarzadeh, and Kourosh Nozari (2022). “Constant-roll inflation with hilltop potential”. *Eur. Phys. J. Plus* 137.4, p. 514. DOI: 10.1140/epjp/s13360-022-02740-5.

Ratra, Bharat and P. J. E. Peebles (1988). “Cosmological Consequences of a Rolling Homogeneous Scalar Field”. *Phys. Rev. D* 37, p. 3406. DOI: 10.1103/PhysRevD.37.3406.

Raveri, Marco, Philip Bull, Alessandra Silvestri, and Levon Pogosian (2017). “Priors on the effective Dark Energy equation of state in scalar-tensor theories”. *Phys. Rev. D* 96.8, p. 083509. DOI: 10.1103/PhysRevD.96.083509. arXiv: 1703.05297 [astro-ph.CO].

Raveri, Marco, Levon Pogosian, et al. (2023). “Principal reconstructed modes of dark energy and gravity”. *JCAP* 02, p. 061. DOI: 10.1088/1475-7516/2023/02/061. arXiv: 2107.12990 [astro-ph.CO].

Regt, Henk W. de (2009). “The Epistemic Value of Understanding”. *Philosophy of Science* 76.5, pp. 585–597. DOI: 10.1086/605795.

Reutlinger, Alexander (2014). “Why Is There Universal Macrobehavior? Renormalization Group Explanation as Noncausal Explanation”. *Philosophy of Science* 81.5, pp. 1157–1170. DOI: 10.1086/677887.

— (2017). “Are causal facts really explanatorily emergent? Ladyman and Ross on higher-level causal facts and renormalization group explanation”. *Synthese* 194.7, pp. 2291–2305.

Riess, Adam G. et al. (1998). “Observational evidence from supernovae for an accelerating universe and a cosmological constant”. *Astron. J.* 116, pp. 1009–1038. DOI: 10.1086/300499. arXiv: astro-ph/9805201.

Riggs, Wayne D. (2003). “Understanding ’Virtue’ and the Virtue of Understanding”. In: *Intellectual Virtue: Perspectives From Ethics and Epistemology*. Ed. by Michael DePaul and Linda Zagzebski. Oxford University Press, pp. 203–226.

Rovelli, Carlo (2016). “The dangers of non-empirical confirmation”. In: arXiv: 1609.01966 [physics.hist-ph].

Rubakov, V. A. (2014). “The Null Energy Condition and its violation”. *Phys. Usp.* 57, pp. 128–142. DOI: 10.3367/UFNe.0184.201402b.0137. arXiv: 1401.4024 [hep-th].

Rubano, Claudio and Paolo Scudellaro (2002). “On some exponential potentials for a cosmological scalar field as quintessence”. *Gen. Rel. Grav.* 34, pp. 307–328. DOI: 10.1023/A:1015395512123. arXiv: astro-ph/0103335.

Ruiz, Eduardo J. and Dragan Huterer (2015). “Testing the dark energy consistency with geometry and growth”. *Phys. Rev. D* 91, p. 063009. DOI: 10.1103/PhysRevD.91.063009. arXiv: 1410.5832 [astro-ph.CO].

Saatsi, Juha and Alexander Reutlinger (2018). “Taking Reductionism to the Limit: How to Rebut the Antireductionist Argument from Infinite Limits”. *Philosophy of Science* 85.3, pp. 455–482.

Said, Najla et al. (2013). “New Constraints On The Dark Energy Equation of State”. *Phys. Rev. D* 88, p. 043515. DOI: 10.1103/PhysRevD.88.043515. arXiv: 1303.4353 [astro-ph.CO].

Salmon, Wesley C. (1989). *Four Decades of Scientific Explanation*. Minneapolis, MN: University of Minnesota Press.

Scherrer, Robert J. (2015). “Mapping the Chevallier-Polarski-Linder parametrization onto Physical Dark Energy Models”. *Phys. Rev. D* 92.4, p. 043001. DOI: 10.1103/PhysRevD.92.043001. arXiv: 1505.05781 [astro-ph.CO].

Scherrer, Robert J. (2022). “Exact general solutions for cosmological scalar field evolution in a background-dominated expansion”. *Phys. Rev. D* 105.10, p. 103502. DOI: 10.1103/PhysRevD.105.103502. arXiv: 2202.01132 [gr-qc].

Scherrer, Robert J. and A. A. Sen (2008). “Thawing quintessence with a nearly flat potential”. *Phys. Rev. D* 77, p. 083515. DOI: 10.1103/PhysRevD.77.083515. arXiv: 0712.3450 [astro-ph].

Schiffrin, Joshua S and Robert M Wald (2012a). “Measure and probability in cosmology”. *Physical Review D* 86.2, p. 023521.

— (2012b). “Measure and Probability in Cosmology”. *Phys. Rev. D* 86, p. 023521. DOI: 10.1103/PhysRevD.86.023521. arXiv: 1202.1818 [gr-qc].

Schindler, Samuel (2018a). “A Coherentist Conception of Ad Hoc Hypotheses”. *Studies in History and Philosophy of Science Part A* 67, pp. 54–64. DOI: 10.1016/j.shpsa.2017.11.011.

— (2018b). *Theoretical Virtues in Science: Uncovering Reality Through Theory*. Cambridge: Cambridge University Press.

Sciama, Dennis W, P Candelas, and D Deutsch (1981). “Quantum field theory, horizons and thermodynamics”. *Advances in Physics* 30.3, pp. 327–366.

Scolnic, Dan et al. (2022). “The Pantheon+ Analysis: The Full Data Set and Light-curve Release”. *Astrophys. J.* 938.2, p. 113. DOI: 10.3847/1538-4357/ac8b7a. arXiv: 2112.03863 [astro-ph.CO].

Šešelja, Dunja and Christian Straßer (2014). “Epistemic Justification in the Context of Pursuit: A Coherentist Approach”. *Synthese* 191.13, pp. 3111–3141. DOI: 10.1007/s11229-014-0476-4.

Sharma, Mohit Kumar and Sourav Sur (2022). “Imprints of interacting dark energy on cosmological perturbations”. *Int. J. Mod. Phys. D* 31.03, p. 2250017. DOI: 10.1142/S0218271822500171. arXiv: 2112.08477 [astro-ph.CO].

Shaw, Jamie (2022). “On the Very Idea of Pursuitworthiness”. *Studies in History and Philosophy of Science Part A* 91.C, pp. 103–112. DOI: 10.1016/j.shpsa.2021.11.016.

Shlivko, David and Paul J. Steinhardt (2024). “Assessing observational constraints on dark energy”. *Phys. Lett. B* 855, p. 138826. DOI: 10.1016/j.physletb.2024.138826. arXiv: 2405.03933 [astro-ph.CO].

Sklar, Lawrence (1975). “Methodological Conservatism”. *Philosophical Review* 84.3, pp. 374–400. DOI: 10.2307/2184118.

Smeenk, C and G Ellis (2017). “Philosophy of Cosmology”. *Stanford Encyclopedia of Philosophy*.

Smeenk, Chris (2003). “Approaching the Absolute Zero of Time: Theory Development in Early Universe Cosmology”. Available at https://publish.uwo.ca/~csmeenk2/files/SmeenkDiss.pdf. PhD thesis.

— (2005). “False vacuum: Early universe cosmology and the development of inflation”. In: *The universe of general relativity*. Springer, pp. 223–257.

— (2014). “Predictability crisis in early universe cosmology”. *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics* 46, pp. 122–133.

— (2017). “Testing Inflation”. In: *The Philosophy of Cosmology*. Ed. by Simon Saunders, Joseph Silk, John D. Barrow, and Khalil Chamcham, pp. 206–227. DOI: 10.1017/9781316535783.011.

— (2018). “Inflation and the Origins of Structure”. *Einstein Stud.* 14, pp. 205–241. DOI: 10.1007/978-1-4939-7708-6_9.

Smoot, George F et al. (1992). “Scientific results from the Cosmic Background Explorer (COBE)”. *Science* 258.5086, pp. 192–197.

Smoot, George F. (1999). “COBE observations and results”. *AIP Conference Proceedings* 476.1, pp. 1–10. DOI: 10.1063/1.59326.

Sober, Elliott (1983). “Equilibrium Explanation”. *Philosophical Studies* 43.2, pp. 201–210. DOI: 10.1007/bf00372383.

Sofue, Yoshiaki and Vera Rubin (2001). “Rotation Curves of Spiral Galaxies”. *Annual Review of Astronomy and Astrophysics* 39.1, pp. 137–174. DOI: 10.1146/annurev.astro.39.1.137.

Sotiriou, Thomas P. and Valerio Faraoni (2010). “f(R) Theories Of Gravity”. *Rev. Mod. Phys.* 82, pp. 451–497. DOI: 10.1103/RevModPhys.82.451. arXiv: 0805.1726 [gr-qc].

Sousa, Tomás, Deaglan J. Bartlett, Harry Desmond, and Pedro G. Ferreira (2024). “Optimal inflationary potentials”. *Phys. Rev. D* 109.8, p. 083524. DOI: 10.1103/PhysRevD.109.083524. arXiv: 2310.16786 [astro-ph.CO].

Spergel, D. N. et al. (2003). “First year Wilkinson Microwave Anisotropy Probe (WMAP) observations: Determination of cosmological parameters”. *Astrophys. J. Suppl.* 148, pp. 175–194. DOI: 10.1086/377226. arXiv: astro-ph/0302209.

Stanford, P. Kyle (2001). “Refusing the Devil’s Bargain: What Kind of Underdetermination Should We Take Seriously?” *Philosophy of Science* 68.S3, pp. 1–12. DOI: 10.1086/392893.

Starobinsky, Alexei A. (1980). "A New Type of Isotropic Cosmological Models Without Singularity". *Phys. Lett. B* 91. Ed. by I. M. Khalatnikov and V. P. Mineev, pp. 99–102. DOI: 10.1016/0370-2693(80)90670-X.

Stein, Nina K. and William H. Kinney (2023). "Simple single-field inflation models with arbitrarily small tensor/scalar ratio". *JCAP* 03, p. 027. DOI: 10.1088/1475-7516/2023/03/027. arXiv: 2210.05757 [astro-ph.CO].

Steinhardt, Paul J. and Neil Turok (2002a). "A Cyclic model of the universe". *Science* 296, pp. 1436–1439. DOI: 10.1126/science.1070462. arXiv: hep-th/0111030.

— (2002b). "Cosmic evolution in a cyclic universe". *Phys. Rev. D* 65, p. 126003. DOI: 10.1103/PhysRevD.65.126003. arXiv: hep-th/0111098.

Strominger, Andrew and Cumrun Vafa (1996). "Microscopic origin of the Bekenstein-Hawking entropy". *Phys. Lett. B* 379, pp. 99–104. DOI: 10.1016/0370-2693(96)00345-0. arXiv: hep-th/9601029.

Tada, Yuichiro and Takahiro Terada (2024). "Quintessential interpretation of the evolving dark energy in light of DESI observations". *Phys. Rev. D* 109.12, p. L121305. DOI: 10.1103/PhysRevD.109.L121305. arXiv: 2404.05722 [astro-ph.CO].

Taylor, J. H., L. A. Fowler, and P. M. McCulloch (1979). "Measurements of general relativistic effects in the binary pulsar PSR1913 + 16". *Nature* 277.5696, pp. 437–440. DOI: 10.1038/277437a0.

Tegmark, Max (2005). "What does inflation really predict?" *JCAP* 04, p. 001. DOI: 10.1088/1475-7516/2005/04/001. arXiv: astro-ph/0410281.

Thébault, Karim P Y (2023). "Big bang singularity resolution in quantum cosmology". *Classical and Quantum Gravity* 40.5, p. 055007.

Thorpe, John A (1977). "Curvature invariants and space–time singularities". *Journal of Mathematical Physics* 18.5, pp. 960–964.

Torrado, Jesus and Antony Lewis (2021). "Cobaya: Code for Bayesian Analysis of hierarchical physical models". *JCAP* 05, p. 057. DOI: 10.1088/1475-7516/2021/05/057. arXiv: 2005.05290 [astro-ph.IM].

Traykova, Dina et al. (2021). "Theoretical priors in scalar-tensor cosmologies: Shift-symmetric Horndeski models". *Phys. Rev. D* 104.8, p. 083502. DOI: 10.1103/PhysRevD.104.083502. arXiv: 2103.11195 [astro-ph.CO].

Trout, J. D. (2002). "Scientific Explanation and the Sense of Understanding". *Philosophy of Science* 69.2, pp. 212–233. DOI: 10.1086/341050.

Tsujikawa, Shinji (2013). "Quintessence: A Review". *Class. Quant. Grav.* 30, p. 214003. DOI: 10.1088/0264-9381/30/21/214003. arXiv: 1304.1961 [gr-qc].

Tzirakis, Konstantinos and William H. Kinney (2007). "Inflation over the hill". *Phys. Rev. D* 75, p. 123510. DOI: 10.1103/PhysRevD.75.123510. arXiv: astro-ph/0701432.

Unruh, WG (1981). "Experimental black-hole evaporation?" *Physical Review Letters* 46.21, pp. 1351–53.

— (1995). "Sonic analogue of black holes and the effects of high frequencies on black hole evaporation". *Physical Review D* **51**.6, p. 2827.

Unruh, William G and Ralf Schützhold (2005). "Universality of the Hawking effect". *Physical Review D* 71.2, p. 024028.

van Fraassen, Bas C. (1980). *The Scientific Image*. Oxford, England: Oxford University Press.

Wallace, D. and Hilary Greaves (2014). "Empirical Consequences of Symmetries". *British Journal for the Philosophy of Science* 65.1, pp. 59–89. DOI: 10.1093/bjps/axt005.

Wallace, David (2018). "The case for black hole thermodynamics part I: Phenomenological thermodynamics". *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics* 64, pp. 52–67.

— (2022). "Stating Structural Realism: Mathematics-First Approaches to Physics and Metaphysics". *Philosophical Perspectives* 36.1, pp. 345–378. DOI: 10.1111/phpe.12172.

Weinberg, David H., Romeel Davé, Neal Katz, and Juna A. Kollmeier (2003). "The Lyman-α Forest as a Cosmological Tool". *AIP Conference Proceedings* 666.1, pp. 157–169. DOI: 10.1063/1.1581786.

Weinberg, Steven (2008a). *Cosmology*. ISBN: 978-0-19-852682-7.

— (2008b). "Effective Field Theory for Inflation". *Phys. Rev. D* 77, p. 123541. DOI: 10.1103/PhysRevD.77.123541. arXiv: 0804.4291 [hep-th].

Wen, Yuewei, Nhat-Minh Nguyen, and Dragan Huterer (2023). "Sweeping Horndeski canvas: new growth-rate parameterization for modified-gravity theories". *JCAP* 09, p. 028. DOI: 10.1088/1475-7516/2023/09/028. arXiv: 2304.07281 [astro-ph.CO].

Weslake, Brad (2010). "Explanatory depth". *Philosophy of Science* 77.2, pp. 273–294.

Will, Clifford M. (2014). "The Confrontation between General Relativity and Experiment". *Living Rev. Rel.* 17, p. 4. DOI: 10.12942/lrr-2014-4. arXiv: 1403.7377 [gr-qc].

Williams, Porter (2019). "Scientific Realism Made Effective". *British Journal for the Philosophy of Science* 70.1, pp. 209–237. DOI: 10.1093/bjps/axx043.

Wolf, William J. (2024a). “Cosmological Inflation and Meta-Empirical Theory Assessment”. *Stud. Hist. Phil. Sci.* 103, pp. 146–158. DOI: 10.1016/j.shpsa.2023.12.006. arXiv: 2309.02283 [physics.hist-ph].

— (2024b). “Minimizing the tensor-to-scalar ratio in single-field inflation models”. *Phys. Rev. D* 110.4, p. 043521. DOI: 10.1103/PhysRevD.110.043521. arXiv: 2407.00358 [astro-ph.CO].

— (2025). “Inflationary attractors and radiative corrections in light of ACT”. arXiv: 2506.12436 [astro-ph.CO].

Wolf, William J. and Patrick M. Duerr (2023). “The Virtues of Pursuit-Worthy Speculation: The Promises of Cosmic Inflation”. *British Journal for the Philosophy of Science*. DOI: 10.1086/728263. arXiv: 2309.16266 [physics.hist-ph].

— (2024). “Promising stabs in the Dark: theory virtues and pursuit-worthiness in the Dark Energy problem”. *Synthese* 204.6, p. 155. DOI: 10.1007/s11229-024-04796-5. arXiv: 2403.04364 [physics.hist-ph].

Wolf, William J. and Pedro G. Ferreira (2023). “Underdetermination of dark energy”. *Phys. Rev. D* 108.10, p. 103519. DOI: 10.1103/PhysRevD.108.103519. arXiv: 2310.07482 [astro-ph.CO].

Wolf, William J., Pedro G. Ferreira, and Carlos García-García (2025a). “Cosmological constraints on Galileon dark energy with broken shift symmetry”. arXiv: 2509.17586 [astro-ph.CO].

— (2025b). “Matching current observational constraints with nonminimally coupled dark energy”. *Phys. Rev. D* 111.4, p. L041303. DOI: 10.1103/PhysRevD.111.L041303. arXiv: 2409.17019 [astro-ph.CO].

Wolf, William J., Carlos García-García, Theodore Anton, and Pedro G. Ferreira (2025). “Assessing Cosmological Evidence for Nonminimal Coupling”. *Phys. Rev. Lett.* 135.8, p. 081001. DOI: 10.1103/jysf-k72m. arXiv: 2504.07679 [astro-ph.CO].

Wolf, William J., Carlos García-García, Deaglan J. Bartlett, and Pedro G. Ferreira (2024). “Scant evidence for thawing quintessence”. *Phys. Rev. D* 110.8, p. 083528. DOI: 10.1103/PhysRevD.110.083528. arXiv: 2408.17318 [astro-ph.CO].

Wolf, William J., Carlos García-García, and Pedro G. Ferreira (2025). “Robustness of dark energy phenomenology across different parameterizations”. *JCAP* 05, p. 034. DOI: 10.1088/1475-7516/2025/05/034. arXiv: 2502.04929 [astro-ph.CO].

Wolf, William J. and Macarena Lagos (2019). "Cosmological Instabilities and the Role of Matter Interactions in Dynamical Dark Energy Models". *Phys. Rev. D* 100.8, p. 084035. DOI: 10.1103/PhysRevD.100.084035. arXiv: 1908.03212 [gr-qc].

— (2020). "Standard Sirens as a Novel Probe of Dark Energy". *Phys. Rev. Lett.* 124.6, p. 061101. DOI: 10.1103/PhysRevLett.124.061101. arXiv: 1910.10580 [gr-qc].

Wolf, William J. and James Read (2023). "Respecting boundaries: theoretical equivalence and structure beyond dynamics". *Eur. J. Phil. Sci.* 13.4, p. 47. DOI: 10.1007/s13194-023-00545-6. arXiv: 2302.07180 [physics.hist-ph].

— (2025). "Navigating permanent underdetermination in dark energy and inflationary cosmology". arXiv: 2501.13521 [physics.hist-ph].

Wolf, William J., James Read, and Nicholas J. Teh (2023). "Edge Modes and Dressing Fields for the Newton–Cartan Quantum Hall Effect". *Found. Phys.* 53.1, p. 3. DOI: 10.1007/s10701-022-00615-4. arXiv: 2111.08052 [cond-mat.mes-hall].

Wolf, William J., James Read, and Quentin Vigneron (2024). "The non-relativistic geometric trinity of gravity". *Gen. Rel. Grav.* 56.10, p. 126. DOI: 10.1007/s10714-024-03308-7. arXiv: 2308.07100 [gr-qc].

Wolf, William J., Marco Sanchioni, and James Read (2024). "Underdetermination in classic and modern tests of general relativity". *Eur. J. Phil. Sci.* 14.4, p. 57. DOI: 10.1007/s13194-024-00617-1. arXiv: 2307.10074 [physics.hist-ph].

Wolf, William J. and Karim P. Y. Thébault (2023). "Explanatory Depth in Primordial Cosmology: A Comparative Study of Inflationary and Bouncing Paradigms". *British Journal for the Philosophy of Science*. DOI: 10.1086/725096. arXiv: 2210.14625 [physics.hist-ph].

Woodward, James and Lauren Ross (2021). "Scientific Explanation". In: *The Stanford Encyclopedia of Philosophy*. Ed. by Edward N. Zalta. Summer 2021. Metaphysics Research Lab, Stanford University.

Worrall, John (1985). "Scientific Discovery and Theory-Confirmation". In: *Change and Progress in Modern Science: Papers related to and arising from the Fourth International Conference on History and Philosophy of Science, Blacksburg, Virginia, November 1982*. Ed. by Joseph C. Pitt. Dordrecht: Springer Netherlands, pp. 301–331. ISBN: 978-94-009-6525-6. DOI: 10.1007/978-94-009-6525-6_11. URL: https://doi.org/10.1007/978-94-009-6525-6_11.

— (2014). "Prediction and Accommodation Revisited". *Studies in History and Philosophy of Science Part A* 45.1, pp. 54–61. DOI: 10.1016/j.shpsa.2013.10.001.

Ye, Gen (2024). “Bridge the Cosmological Tensions with Thawing Gravity”. arXiv: 2411.11743 [astro-ph.CO].

Ye, Gen, Matteo Martinelli, Bin Hu, and Alessandra Silvestri (2024). “Non-minimally coupled gravity as a physically viable fit to DESI 2024 BAO”. arXiv: 2407.15832 [astro-ph.CO].

Ylikoski, Petri and Jaakko Kuorikoski (2010). “Dissecting explanatory power”. *Philosophical studies* 148.2, pp. 201–219.

Zahar, Elie (1973). “Why Did Einstein’s Programme Supersede Lorentz’s? (II)”. *British Journal for the Philosophy of Science* 24.3, pp. 223–262. DOI: 10.1093/bjps/24.3.223.

Zaldarriaga, Matias and Uros Seljak (1997). “An all sky analysis of polarization in the microwave background”. *Phys. Rev. D* 55, pp. 1830–1840. DOI: 10.1103/PhysRevD.55.1830. arXiv: astro-ph/9609170.

Zeldovich, Yaa B. (1972). “A hypothesis, unifying the structure and the entropy of the Universe”. *mnras* 160, 1P. DOI: 10.1093/mnras/160.1.1P.

Zlatev, Ivaylo, Li-Min Wang, and Paul J. Steinhardt (1999). “Quintessence, cosmic coincidence, and the cosmological constant”. *Phys. Rev. Lett.* 82, pp. 896–899. DOI: 10.1103/PhysRevLett.82.896. arXiv: astro-ph/9807002.

Zumalacárregui, Miguel et al. (2017). “hi_class: Horndeski in the Cosmic Linear Anisotropy Solving System”. *JCAP* 08, p. 019. DOI: 10.1088/1475-7516/2017/08/019. arXiv: 1605.06102 [astro-ph.CO].