

# Comparing the DES-SN5YR and Pantheon+ SN cosmology analyses: investigation based on ‘evolving dark energy or supernovae systematics’?

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## ABSTRACT

Recent cosmological analyses measuring distances of type Ia supernovae (SNe Ia) and baryon acoustic oscillations (BAO) have all given similar hints at time-evolving dark energy. To examine whether underestimated SN Ia systematics might be driving these results, Efstathiou (2025) compared overlapping SN events between Pantheon+ and DES-SN5YR (20 per cent SNe are in common), and reported evidence for an  $\sim 0.04$  mag offset between the low- and high-redshift distance measurements of this subsample of events. If this offset is arbitrarily subtracted from the entire DES-SN5YR sample, the preference for evolving dark energy is reduced. In this paper, we show that this offset is mostly due to different corrections for Malmquist bias between the two samples; therefore, an object-to-object comparison can be misleading. Malmquist bias corrections differ between the two analyses for several reasons. First, DES-SN5YR used an improved model of SN Ia luminosity scatter compared to Pantheon+ but the associated scatter-model uncertainties are included in the error budget. Secondly, improvements in host mass estimates in DES-SN5YR also affected SN standardized magnitudes and their bias corrections. Thirdly, and most importantly, the selection functions of the two compilations are significantly different, hence the inferred Malmquist bias corrections. Even if the original scatter model and host properties from Pantheon+ are used instead, the evidence for evolving dark energy from CMB, DESI BAO Year 1 and DES-SN5YR is only reduced from  $3.9\sigma$  to  $3.3\sigma$ , consistent with the error budget. Finally, in this investigation, we identify an underestimated systematic uncertainty related to host galaxy property uncertainties, which could increase the final DES-SN5YR error budget by 3 per cent. In conclusion, we confirm the validity of the published DES-SN5YR results.

**Key words:** dark energy – transients: supernovae.

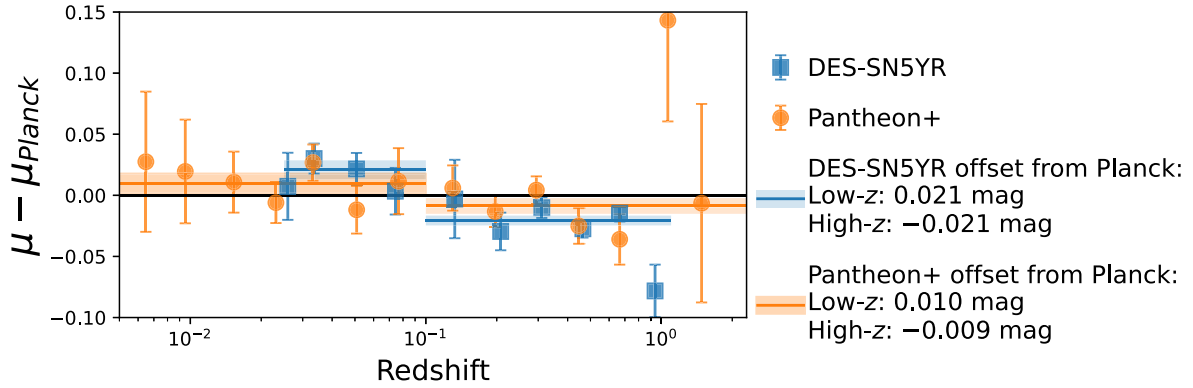
## 1 CONTEXT

The cosmological results from the Dark Energy Survey Supernova Program (DES-SN) have been published in two stages: (1) a small *spectroscopically classified* subset of  $\sim 200$  events combined with  $\sim 100$  previously released low- $z$  events from the community (DES-SN3YR: Abbott et al. 2019; Brout et al. 2019b), and (2) a more complete *photometrically classified* sample of 1600 events, combined with  $\sim 190$  low- $z$  events from the community (DES-SN5YR:

DES Collaboration 2024; Vincenzi et al. 2024). In between these two efforts, a much larger *spectroscopically confirmed* sample of 1701 publicly released light curves was used to publish cosmology constraints (Pantheon+: Brout et al. 2022a; Scolnic et al. 2022). While Pantheon+ is technically not a DES-SN result, the Pantheon+ and DES-SN5YR analyses included a significant overlap of software (Kessler et al. 2009; Zuntz et al. 2015; Hinton & Brout 2020), people and development, particularly for the intrinsic scatter modelling based on dust (Brout & Scolnic 2021; Popovic et al. 2023) and Beams with Bias Corrections (BBC: Kessler & Scolnic 2017).

At low redshifts ( $z < 0.1$ ), there is significant sample overlap between Pantheon+ and DES-SN5YR. More than 90 per cent of the

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**Figure 1.** Pantheon+ and DES-SN5YR binned Hubble residuals calculated w.r.t. a Flat  $\Lambda$ CDM cosmology assuming  $\Omega_M = 0.315$  from *Planck*. In each redshift bin, we show the weighted mean of the Hubble residual and statistical-only uncertainties. The horizontal bands show the weighted mean of the Hubble residuals (and associated uncertainties) above and below redshift 0.1 for both Pantheon+ and DES-SN5YR.

low- $z$  SNe in DES-SN5YR are also included in Pantheon+ (184 low- $z$  overlapping events in total, 118 from the Foundation SN sample, 59 from CfA SN programs, and 7 from the Carnegie Supernova Project; Hicken et al. 2009, 2012; Foley et al. 2017; Krisciunas et al. 2017). Pantheon+ includes  $\sim 500$  additional low- $z$  events that were not included in DES-SN5YR to minimize low- $z$  related systematics (in particular, calibration uncertainties). At high redshifts ( $z > 0.1$ ), sample overlap between Pantheon+ and DES-SN5YR includes 145 common DES SN events, which is  $\sim 8$  per cent of the DES-SN5YR high- $z$  sample and  $\sim 14$  per cent of the Pantheon+ high- $z$  sample.

The binned Pantheon+ and DES-SN5YR Hubble diagram residuals are compared in Fig. 1 with respect to (w.r.t.) a flat  $\Lambda$ CDM cosmology model assuming the *Planck* best-fitting dark matter energy density  $\Omega_M = 0.315$  (Planck Collaboration VI 2020b). The binned Hubble residuals are consistent within  $1\sigma$  in every bin between Pantheon+ and DES-SN5YR, and both data sets show a discrepancy w.r.t. *Planck*. Discrepancies are in the same direction (positive residuals at low- $z$  and negative residuals at high- $z$ ) but for DES-SN5YR the effect is larger ( $\pm \sim 0.02$  mag discrepancies for DES-SN5YR compared to  $\pm \sim 0.01$  mag discrepancies for Pantheon+) and uncertainties are smaller due to improved light-curve modelling and larger high- $z$  statistics. Using flat priors on cosmology parameters the ‘SN-only’ Pantheon+ and DES-SN5YR analyses found consistent results in Flat  $\Lambda$ CDM ( $\Omega_M = 0.334 \pm 0.018$  and  $\Omega_M = 0.352 \pm 0.017$ , respectively) and Flat  $w$ CDM ( $w = -0.90 \pm 0.14$  and  $w = -0.80^{+0.14}_{-0.16}$ , respectively, see also fig. 12 in DES Collaboration 2024). In Flat  $w_0w_a$ CDM,<sup>1</sup> the results are consistent to  $\sim 2\sigma$ ,

$$\begin{aligned} \text{Pantheon+}: w_0 &= -0.93 \pm 0.15, w_a = -0.1^{+0.9}_{-2.0}, \\ \text{DES SN5YR}: w_0 &= -0.36^{+0.36}_{-0.30}, w_a = -8.8^{+3.7}_{-4.5}. \end{aligned}$$

While the Pantheon+ distance uncertainties are larger compared to DES-SN5YR, the Pantheon+ cosmology uncertainties are smaller because of the (i) larger redshift range (0.001–2.26) compared to the DES-SN5YR redshift range (0.025–1.13), and (ii) additional systematic uncertainties included in DES-SN5YR.

Shortly after the DES-SN5YR constraints were published, the Dark Energy Spectroscopic Instrument (DESI) Collaboration released cosmological results from the measurement of BAO in galaxy, quasar and Lyman  $\alpha$  forest tracers from the first year of observations (DESI-BAO-Y1; DESI Collaboration 2025). When combining DESI

with CMB measurements (CMB anisotropies from *Planck* and CMB lensing data from *Planck* and ACT, Planck Collaboration I 2020a; Carron, Mirmelstein & Lewis 2022), a  $2.6\sigma$  evidence for time-varying dark energy equation of state is found. This evidence is unchanged when the Pantheon+ SN constraints are added ( $2.5\sigma$  evidence), but grows to  $3.9\sigma$  when DES-SN5YR constraints are used instead of Pantheon+. These tantalizing hints for dynamical dark energy have motivated further scrutiny of these cosmological results, and re-analyses have focused on public data releases from Pantheon+ and DES-SN5YR.

Other than DES-SN and Pantheon+, there was another cosmological analysis using more than 2000 spectroscopically confirmed SNe Ia from public data releases: the UNION3 compilation (Rubin et al. 2025). For the Flat  $\Lambda$ CDM model, they found results consistent with DES-SN5YR and Pantheon+ (best-fitting  $\Omega_M = 0.356^{+0.028}_{-0.026}$ ). For the Flat  $w$ CDM model, they found  $w = -0.74^{+0.17}_{-0.19}$ , a slightly larger deviation from a cosmological constant compared to DES-SN5YR and Pantheon+. They do not publish SN-only results for the Flat  $w_0w_a$ CDM model. When UNION3 is combined with DESI BAO and CMB, there is a  $3.1\sigma$  evidence for time-evolving dark energy. The UNION3 sample has a large overlap of supernova light curves with Pantheon+. However, the UNION3 analysis used a Bayesian hierarchical framework ‘Unity’ (Rubin et al. 2015), which is very different from the methodology used in Pantheon+ and DES-SN5YR. UNION3 has not released a Hubble diagram, and therefore we do not include UNION3 comparisons in this investigation.

## 2 RECENT ANALYSIS BY EFSTATHIOU (2024)

Efstathiou (2025) examined publicly released Hubble diagrams from Pantheon+ and DES-SN5YR, and performed a distance comparison with the overlapping SNe that are used in both samples. Efstathiou (2025) notes an  $\sim 0.04$  mag discrepancy in standardized brightnesses between the low- $z$  and high- $z$  overlapping events in Pantheon+ and DES-SN5YR. He suggests that this discrepancy is the reason why the DES-SN5YR sample provides more significant evidence for evolving dark energy compared to Pantheon+ and, in Flat  $\Lambda$ CDM, a larger  $\Omega_M$  compared to CMB measurements from *Planck*. The discrepancy highlighted by Efstathiou (2025) is measured using a very limited subsample of the data included in the two compilations ( $< 20$  per cent of the data, corresponding to only bright events at high- $z$ ). Comparing the entire samples, however, the discrepancies are at the 0.01 mag level, at both high and low redshifts (Fig. 1).

<sup>1</sup>Following the dark energy equation of state parametrization  $w(a) = w_0 + w_a(1 - a)$ .

In this paper, we do not address DESI results or discrepancies from *Planck*, and in the spirit of blind analyses we do not comment on the [dis]agreement with respect to a cosmological constant. Our response addresses the 0.04 mag discrepancy observed by Efstathiou (2025) between the DES-SN5YR and Pantheon+ and we explain the reasons for this mismatch. We focus on the 118 low- $z$  Foundation events and 145 high- $z$  DES events that overlap in Pantheon+ and DES-SN5YR and consider the distance modulus offset:

$$\Delta\mu_{\text{offset}} = \langle \mu_{\text{Pantheon+}} - \mu_{\text{DES-SN5YR}} \rangle_{\text{Foundation}} - \times \langle \mu_{\text{Pantheon+}} - \mu_{\text{DES-SN5YR}} \rangle_{\text{DES}} \quad (1)$$

where  $\langle \mu_{\text{Pantheon+}} - \mu_{\text{DES-SN5YR}} \rangle$  is the mean difference between Pantheon+ and DES-SN5YR distance moduli ( $\mu_{\text{Pantheon+}}$  and  $\mu_{\text{DES-SN5YR}}$ , respectively) computed from the inverse-variance weighted average over the overlapping Foundation or DES SNe. Since we only use SNe Ia to measure *relative* distances, any constant offset between the two data sets would be absorbed by a combination of the Hubble constant  $H_0$  and SN Ia absolute magnitude  $M_0$ , and not the cosmological parameters of interest here. In other words, if the distance moduli from Pantheon+ and DES-SN5YR differed by the same amount at both low and high redshifts, this would not affect the inferred cosmology.

We note that Efstathiou (2025) did not use SN distance moduli  $\mu$ , but instead defined SN magnitudes as  $m = \mu - M_0$ , with  $M_0$  fixed to  $-19.33$ . Using this definition, Efstathiou (2025) found that,

$$\langle m_{\text{Pantheon+}} - m_{\text{DES-SN5YR}} \rangle_{\text{Foundation}} \sim -0.05, \quad (2)$$

$$\langle m_{\text{Pantheon+}} - m_{\text{DES-SN5YR}} \rangle_{\text{DES}} \sim -0.01, \quad (3)$$

suggesting that the most significant discrepancies between Pantheon+ and DES-SN5YR are in the analyses of the Foundation SN sample. However, this approach implicitly assumes that  $M_0$  is the same for Pantheon+ and DES-SN5YR, which is not true because  $M_0$  depends on the light-curve model training and analysis, which differ between these two analyses. We therefore focus on the quantity  $\Delta\mu_{\text{offset}}$  (equation 1) as it eliminates any confusion in the definition of  $M_0$ .

We provide a brief analysis recap in Section 3. The main reasons for the observed discrepancy are given in Sections 4 and 5, and some concluding remarks are in Section 6.

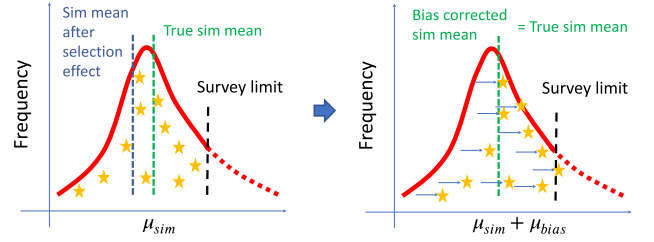
### 3 SNE IA STANDARDIZATION AND THE ROLE OF BIAS CORRECTIONS

Here, we briefly summarize the main steps necessary to standardize SNe Ia brightnesses and correct for selection biases. The first step to standardize SN brightnesses is to fit each SN light curve for the parameters  $\{m_x, x_1, c\}$ , which are the amplitude, stretch, and colour of an SN, respectively (Guy et al. 2007; Betoule et al. 2014). For each SN, these parameters are used to measure its standardized apparent magnitude,  $m_x$  (Tripp 1998)

$$m_x^{\text{std}} = m_x + \alpha x_1 - \beta c + \gamma G_{M_*}, \quad (4)$$

where  $\alpha$ ,  $\beta$ , and  $\gamma$  are globally fitted nuisance parameters modelling the stretch-, colour-, and host-luminosity dependencies, respectively.  $G_{M_*}$  is a  $\pm 1/2$  step function that describes the magnitude offset observed between SNe found in high stellar mass ( $M_* > 10^{10}M_\odot$ ) and low stellar mass ( $M_* < 10^{10}M_\odot$ ) galaxies (the so-called ‘mass step’). SN standardized apparent brightnesses are used to measure SN distance moduli  $\mu$ , defined as

$$\mu = m_x^{\text{std}} - \mu_{\text{bias}} - M_0 \quad (5)$$



**Figure 2.** *Left panel:* Derived distances from simulated SN events  $\mu_{\text{sim}}$  for SNe in a given 4D bin of  $z, x_1, c, M_*$ . The derived mean of the simulated data (blue vertical dashed line) is biased compared to the true simulated mean (green vertical dashed line). *Right panel:* Simulation-derived bias corrections ( $\mu_{\text{bias}}$ ) are added to every SN Ia in the bin (horizontal arrows) such that the derived mean aligns with the true mean. The correction depends on the SN Ia light-curve model, scatter model, and instrumental noise.

where  $M_0$  is the SN absolute brightness (fully degenerate with  $H_0$ ). The term  $\mu_{\text{bias}}$  corrects each SN distance for selection effects and analysis biases.  $\mu_{\text{bias}}$  are determined from large simulations on a 4D grid of redshift, stretch, colour, host mass bins. These corrections are defined as an average in each 4D bin,  $\mu_{\text{bias}} = \langle \mu_{\text{sim}} - \mu_{\text{true}} \rangle$ , where  $\mu_{\text{sim}} = m_x^{\text{std}} - M_0$  are the derived SN distances for simulated SN events and  $\mu_{\text{true}}$  are the true simulated SN distances. We discuss  $\mu_{\text{bias}}$  in more detail below.

Most SN surveys are magnitude-limited. SNe Ia are intrinsically variable objects, with bluer ( $c < 0$ ) and longer duration ( $x_1 > 0$ ) explosions being brighter than redder ( $c > 0$ ) and shorter duration ( $x_1 < 0$ ) explosions. While the standardization process (equation 4) results in nearly uniform brightness, the pre-standardized brightness variation is more than 1 mag. This variation would not lead to a bias in the magnitudes  $m_x^{\text{std}}$  in the hypothetical case that all SN Ia have exactly the same brightness after standardization, without error. However, an  $\sim 15$  per cent variation in brightness remains after standardization, composed of remaining intrinsic variation in the explosions, measurement noise, and modelling error. Detected SNe Ia have a selection bias that preferentially includes intrinsically brighter events near the magnitude limit of the survey (as defined by a selection function). This selection effect results in a distance bias that  $\mu_{\text{bias}}$  in equation (4) corrects for; without this bias correction, the cosmology results would be significantly altered.

We illustrate this bias in Fig. 2. The left panel represents the  $\mu_{\text{sim}}$  distribution of simulated SNe Ia in a given 4D bin of redshift, stretch, colour, and host stellar mass and only events brighter than the detection limit are observed. The bias correction ( $\mu_{\text{bias}}$ ) adjusts all of the simulated SNe in the given bin such that the derived mean of  $\mu_{\text{sim}}$  matches the true mean,  $\mu_{\text{true}}$ , that would be measured without selection bias.

In both the DES-SN5YR and Pantheon+ analyses, BBC models selection biases using large simulations and interpolates  $\mu_{\text{bias}}$  in the 4D space mentioned above. In these large simulations, we model the survey cadence, instrument characteristics, survey selection effects, and the true distribution of SN Ia magnitudes. The latter includes SN Ia populations of stretch and colour to define a mean brightness model, as well as an ‘intrinsic scatter’ model to account for brightness variations about the mean model.

The intrinsic distribution of SN Ia magnitudes is described by a physically motivated model that captures features such as intrinsic colour variation and host galaxy dust. This model is calibrated and fitted using data to reproduce the observed distributions and correlations of SN Ia parameters. As more data have been collected, the scatter model has continuously improved. The first attempt at a

**Table 1.** Distance modulus offsets between Foundation (low- $z$ ) and DES (high- $z$ ) SNe common to DES-SN5YR and Pantheon+ compilations. The ‘contribution to  $\Delta\mu_{\text{offset}}$ ’ column shows the size of the change in  $\Delta\mu_{\text{offset}}$  due to each effect. The ‘remaining  $\mu_{\text{offset}}$ ’ column shows the offset remaining after that effect has been reverted or removed.

Analysis changes applied to DES-SN5YR	Contribution to $\Delta\mu_{\text{offset}}$ [mag]	Remaining $\Delta\mu_{\text{offset}}$ [mag]
None		<b>−0.042</b>
Revert to Pantheon+ intrinsic scatter model <sup>a</sup>	<b>0.008</b>	<b>−0.034</b>
Revert to Pantheon+ host stellar mass estimations	<b>0.010</b>	<b>−0.024</b>
Remove offset due to different selection functions <sup>b</sup>	<b>0.016</b>	<b>−0.008</b>

<sup>a</sup>Pantheon+ used the original BS21 intrinsic scatter model. DES-SN5YR included this model in the systematic error budget, but used an improved version of the BS21 model for the nominal analysis.

<sup>b</sup>This offset arises because the different DES subsamples have different corrections for selection functions. See Section 5.

model beyond a coherent mag shift at all epochs and wavelengths was a simple spectral-energy-distribution (SED) intrinsic scatter model (Kessler et al. 2013, based on Guy et al. 2010; Chotard et al. 2011), and it was used in the original Pantheon analysis (Scolnic et al. 2018) and DES-SN3YR (Brout et al. 2019b). Next, a significant update based on the properties of dust in SN host galaxies (Brout & Scolnic 2021) was used in Pantheon+. Finally, an updated version of the dust model (Popovic et al. 2023) was used in DES-SN5YR (see Section 4). The final bias correction applied to each SN Ia depends on the convolution of sample selection and the simulation of instrumental noise and intrinsic scatter.

#### 4 MAJOR ANALYSIS IMPROVEMENTS BETWEEN PANTHEON+ AND DES-SN5YR

The DES-SN5YR analysis introduced several improvements compared to the Pantheon+ analysis, in terms of the light-curve fitting model (upgrading from SALT2 to SALT3), intrinsic scatter model used in bias corrections, estimates of host galaxy stellar masses, and photometric calibration (using the latest DES internal calibration). A comprehensive list of these improvements is presented and discussed in Appendix A. In this section, we discuss the two analysis updates that have a significant impact on  $\Delta\mu_{\text{offset}}$  and summarize our results in Table 1.

(1) This model is essential to simulate and estimate accurate bias corrections on measured SN distances (equation 5 and Section 3). Both Pantheon+ and DES-SN5YR use a model for scatter in which the colour of SN Ia is a combination of intrinsic variation and reddening by host-galaxy dust, which itself depends on host galaxy properties (Brout & Scolnic 2021). This model is described by a set of 12 free parameters: 4 parameters characterizing intrinsic SN colour variations (mean and standard deviations of intrinsic colour and intrinsic  $\beta$ ) + 8 parameters characterizing dust properties and their dependency on the host galaxy (mean and standard deviations of  $R_V$  and dust extinction exponential coefficient  $\tau$  in high- and low-mass galaxies).

Pantheon+ used the dust parameters originally presented in Brout & Scolnic (2021), which were manually tuned such that the SNANA simulation reproduces the trends observed in data. In DES-SN5YR, we improved the measurement of these 12 parameters using the forward-modelling fitting method in Popovic et al. (2023). The differences between the colour/dust parameters used in Pantheon+ and DES-SN5YR are presented in table 3 of Vincenzi et al. (2024). Despite its overly simplistic approach to evaluating dust parameters, the original Pantheon+ modelling approach was still considered

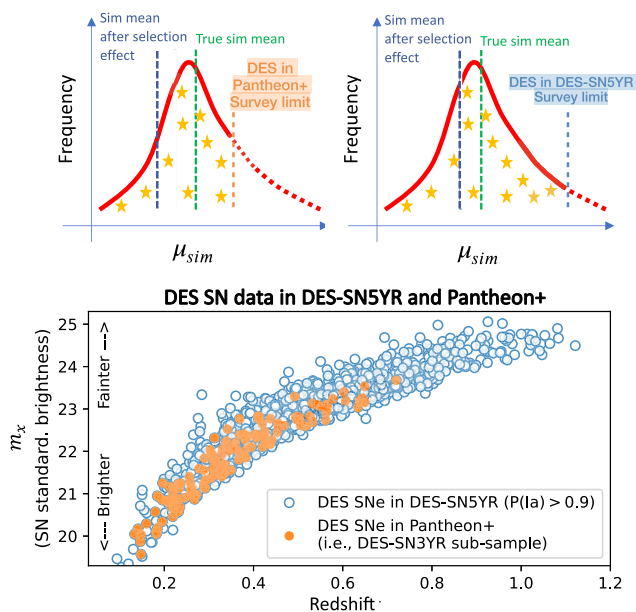
plausible, and therefore included in the DES-SN5YR analysis as a potential source of systematic uncertainty. In figs. 13–15 and table 8 in Vincenzi et al. (2024), we present the effects of this source of systematic (labelled as ‘BS21’) and show that using the BS21 intrinsic scatter model (instead of the nominal model from Popovic et al. 2023) introduces an offset of  $\sim 0.010$  mag between the low- and high-redshift samples of the DES-SN5YR Hubble diagram.

(2) In DES-SN5YR, host-galaxy stellar masses have been updated for DES using deeper coadd photometry (Wiseman et al. 2020), and also updated for the low- $z$  samples (Foundation, CfA, and CSP) to ensure that the same galaxy SED fitting method was used for both the high- $z$  and low- $z$  samples (section 2.5 in Vincenzi et al. 2024). For the Foundation subset of DES-SN5YR, the host masses of 10 SNe Ia (out of 118 total common between DES-SN5YR and Pantheon+) were changed from low-mass galaxies to high-mass galaxies ( $> 10^{10} M_{\odot}$ ), and vice versa 3 were changed from a high-mass to low-mass galaxy ( $< 10^{10} M_{\odot}$ ). For the DES subset, the host masses of 10 (out of 145 common between DES-SN5YR and Pantheon+) were changed to low-mass galaxies, and 2 were changed to high-mass galaxies. Comparing the common SNe, the average difference in host stellar mass between Pantheon+ and DES-SN5YR is  $-0.16$  dex for Foundation SN hosts and  $+0.07$  dex for DES SN hosts. Neither analysis explicitly accounted for the host mass uncertainties, which results in a modest underestimate of systematics uncertainties.

Both analysis improvements contribute to the discrepancies highlighted by Efstathiou (2025). To quantify the impact that the analysis improvements in DES-SN5YR would have on Pantheon+, one would ideally re-analyze Pantheon+ sample using current codes and methods. However, such a re-analysis on a 3-yr old sample is technically challenging on a short time-scale. Instead, it is sufficient to take the more practical approach of re-analyzing DES-SN5YR by substituting Pantheon+ modelling choices.

In Table 1, we show changes in  $\Delta\mu_{\text{offset}}$  when reverting the DES-SN5YR intrinsic scatter model and host mass values to match what was used in Pantheon+. The observed  $\Delta\mu_{\text{offset}}$  is reduced from  $-0.042$  mag to  $-0.024$  mag (43 per cent reduction). The DES-SN5YR error budget adequately accounts for systematics related to the choice of intrinsic scatter model, but both Pantheon+ and DES-SN5YR underestimated uncertainties due to host stellar masses. We have estimated the missing systematic uncertainty related to host stellar mass: the total DES-SN5YR systematic error on  $w$  (assuming Flat $w$ CDM) and  $w_0$  or  $w_a$  (assuming Flat $w_0w_a$ CDM) increase by less than 3 per cent.

Finally, we estimate how DES-SN5YR cosmological results would change when reverting to the older (less accurate) scatter model and



**Figure 3.** Illustration of the different selection functions characterizing the DES sub-samples in DES-SN5YR and Pantheon+. The *upper-left* panel illustrates the DES SNe included in Pantheon+ which are intentionally selected to be the brightest and highest signal-to-noise DES SNe, whereas the *upper-right* panel shows DES-SN5YR with a significantly more complete sample. In the lower panel, we show SALT3-fitted  $m_x$  vs redshift for the real DES data in DES-SN5YR (empty circles) and in Pantheon+ (filled circles). For DES-SN5YR, we only plot SNe with high (> 90 per cent) probability of being type Ia. Even at lower redshifts ( $z < 0.4$ ), the sample of DES SNe in Pantheon+ is not complete and clearly biased towards the brightest events.

host properties from Pantheon+. The evidence for evolving dark energy from CMB, DESI BAO Year 1, and DES-SN5YR is mildly reduced from  $3.9\sigma$  to  $3.3\sigma$ .

#### 4.1 A note on bias-corrected distances in Pantheon+ and DES-SN5YR

The updated light curve and intrinsic scatter models resulted in a constant shift of 0.04 mag between bias-corrections in Pantheon+ and DES-SN5YR. While this 0.04 mag offset may confuse the interpretation of distances in the two analyses, this offset *has no effect on the cosmological results of DES-SN5YR or Pantheon+* because SN dark energy constraints are insensitive to global offsets in the distances.

### 5 MODELLING SELECTION EFFECTS

In Section 4, we show the impact of explicit analysis changes between Pantheon+ and DES-SN5YR. However, even if both analyses were identical in their methods and assumptions, we still expect to see a non-zero  $\Delta\mu_{\text{offset}}$  when performing a direct object-to-object comparison between the Pantheon+ and DES-SN5YR data compilations. The reason for this expectation is that the selection of the overlapping DES sub-sample embedded in Pantheon+ and DES-SN5YR is very different. As noted in the previous two Sections, changes to the selection function also change the bias corrections.

The effects of bias corrections on Pantheon+ and DES-SN5YR are illustrated in Fig. 3. The Pantheon+ analysis included the DES-SN3YR sub-sample, i.e. a sample of the *brightest* DES SNe for which

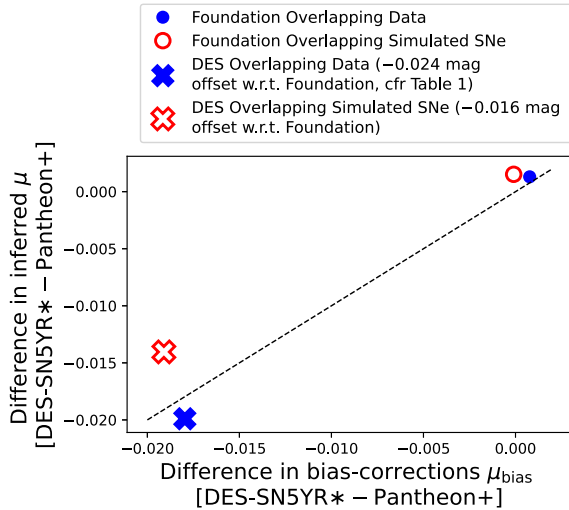
spectroscopic follow-up of the live transient was available (207 SNe). Therefore, this sample is characterized by *strong selection biases* and requires *large bias corrections*. In sharp contrast to this earlier analysis, the DES-SN5YR analysis used photometric classification (Möller & de Boissière 2020; Qu et al. 2021; Möller et al. 2022) and selected all DES SNe for which the host spectroscopic redshifts was available. This sub-sample is significantly deeper in redshift and more complete, and it includes a significantly larger number of SNe (1635 SNe).

These fundamental differences in selection functions result in different bias corrections between the Pantheon+ and DES-SN5YR analyses<sup>2</sup> and make it difficult to compare the overlapping events as proposed in Efstathiou (2025). Since we can accurately model the selection functions of the DES subsample included in Pantheon+ and the DES-SN5YR sample, we can reproduce this effect using simulations. We generate a large ( $\times 10$ ) DES-like simulation and apply the Pantheon+ DES selection function and the DES-SN5YR selection function to obtain two samples that reflect the DES sub-samples included in Pantheon+ and DES-SN5YR. We identify the overlapping simulated events between the two samples and compare their bias-corrections.

In Fig. 4, we compare differences in bias corrections,  $\mu_{\text{bias}}(\text{DES-SN5YR}^*) - \mu_{\text{bias}}(\text{Pantheon}^+)$  with differences in distance moduli  $\mu(\text{DES-SN5YR}^*) - \mu(\text{Pantheon}^+)$ . For this comparison, DES-SN5YR\* is analyzed using Pantheon+ modelling choices as described in Section 4 and Table 1. Using a consistent analysis avoids conflating multiple effects and more clearly shows the effect of bias corrections described in this section. As shown in Fig. 4, for the low- $z$  samples ( $z < 0.1$ ), the difference in  $\mu_{\text{bias}}$  is negligible because the sample selection is nearly the same for the two analyses. At higher redshifts ( $z > 0.1$ ), the data show large differences in  $\mu_{\text{bias}}$  ( $\sim 0.02$ ) that are directly reflected into differences in  $\mu$ . These differences are reproduced by our simulations at the 5 millimag level. Our simulations show that differences in  $\mu_{\text{bias}}$  are expected when analysing the two subsamples in the context of the (more biased towards brighter events) Pantheon+ analysis or in the context of the (significantly more complete) DES-SN5YR analysis. In particular, both in data and simulations we find that Pantheon+ bias corrections differ by approximately  $\sim -0.02$  mag.

From our simulations, we estimate that this bias-correction effect contributes  $\sim 0.016$  mag to the  $\Delta\mu_{\text{offset}}$  observed by Efstathiou (2025). However, we highlight that this effect is only important when performing an object-to-object comparison like the one presented by Efstathiou (2025). This effect is not relevant for the *full-sample* Hubble diagram comparison shown in Fig. 1 because each full sample is corrected for their specific sample biases. In other words, in Fig. 1 we compare the bias-corrected ‘Data mean’ at each redshift bin (following the terminology of Fig. 2) rather than individual objects removed from their original context.

<sup>2</sup>This problem can be compared to an analogy in which an individual’s height is measured in two different contexts – among a group of basketball players (analogous to ‘the brightest SNe’) and again in a supermarket (analogous to ‘complete and representative group of SNe’). A larger *average height correction* is needed for individuals among basketball players than among people in a supermarket. While it may seem paradoxical that the same individual leads to different corrections, the context in which they are selected fundamentally influences the inferred statistics. This phenomenon is analogous to the Monty Hall problem, wherein the method of selection affects the probability distribution of results.



**Figure 4.** For the DES and Foundation sub-samples of overlapping SNe between DES-SN5YR\* and Pantheon+, we compare the difference in bias corrections  $\mu_{\text{bias}}$  with the difference in distance moduli,  $\mu$ . Differences relative to the Foundation (DES) sub-sample of overlapping data are marked with circles (crosses). Filled symbols correspond to differences in the real data, while empty symbols correspond to differences estimated from simulations. Instead of using the original DES-SN5YR distance moduli, we use distances from DES-SN5YR\*, i.e. from the re-analysis of DES-SN5YR using the Pantheon+ modelling as described in Section 4. For this reason, differences in measured distance moduli from the data are  $-0.024$  (and not  $-0.042$ , see Table 1). To avoid confusion with different  $M_0$ , we subtract  $0.04$  mag from all the DES-SN5YR\* bias-corrections. Using simulations, we quantify the expected differences in  $\mu$  between the DES sub-samples in Pantheon+ and DES-SN5YR to be  $-0.016$ .

## 6 CONCLUSION

Efstathiou (2025) noted a  $0.04$  mag low-versus-high redshift distance offset (equation 1) between overlapping Pantheon+ and DES-SN5YR events. We have investigated this offset and find that it is explained as follow.

(i) **Two analysis improvements since Pantheon+:** These improvements are related to the intrinsic scatter model and host stellar mass estimates, and account for  $0.018$  mag discrepancy between Pantheon+ and DES-SN5YR (from  $-0.042$  to  $-0.024$ , see Table 1);

(ii) **Selection differences between Pantheon+ and DES-SN5YR:** Larger distance bias corrections are required for the more heavily biased Pantheon+ sample of spectroscopically identified events, compared to smaller bias corrections for the more complete sample of photometrically classified events in DES-SN5YR (Fig. 4). This difference in selection functions does not affect cosmology results, but leads to misleading conclusions in an object-to-object comparison like the one presented by Efstathiou (2025), where only 20 per cent of the brightest SNe are selected from both analyses. This effect account for an additional  $0.016$  mag discrepancy between Pantheon+ and DES-SN5YR (from  $-0.024$  to  $-0.008$ , see Table 1). This biased comparison can be avoided by comparing the binned Pantheon+ and DES-SN5YR Hubble diagrams as shown in Fig. 1.

Near the completion of our response to Efstathiou (2025), Notari, Redi & Tesi (2025) performed a re-analysis of Pantheon+ and DES-SN5YR in which common SNe are excluded from one sample in order to perform a combined analysis of the two-independent samples. We have not performed a detailed investigation of their

analysis or claims, but we note a few qualitative issues with their analysis. First, removing or adding events changes the selection criteria and hence requires updated bias corrections. Secondly, while the  $0.04$  mag  $M_0$  offset between Pantheon+ and DES-SN5YR distances does not impact cosmology results from each separate analysis, this offset can bias results from combining distances without a re-analysis using consistent SN Ia modelling and bias corrections.

In conclusion, we hope that this post-publication investigation offers the community valuable insights into the DES-SN5YR and Pantheon+ analyses, and it reinforces one of the main conclusions drawn from the DES-SN5YR analysis (Vincenzi et al. 2024): the limiting factor and largest source of systematics in current SN Ia cosmology analysis is the modelling of intrinsic scatter and SN-host correlations in bias corrections. Nevertheless, these uncertainties are usually included in the error budget of the current data sets, and thus accounted for in the uncertainties on cosmological parameters. In particular, the DES-SN5YR analysis accounted for several additional sources of systematic uncertainties related to intrinsic scatter and SN-host correlations that have not been included in any previous analysis (including Pantheon+). Here, we identified one untracked systematic uncertainty due to host galaxy measurement uncertainties, which increases the previously reported uncertainties by about 3 per cent.

Upcoming data from the Zwicky Transient Factory (Rigault et al. 2025), the Vera C. Rubin Observatory, and the Roman Space Telescope will improve our understanding and control of these sources of systematics.

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MV led the primary analysis and drafted the manuscript; RK and PS contributed substantially to the analysis, manuscript preparation, and figure curation. JL contributed to the analysis and provided comments on the manuscript. DS and TMD advised on the analysis, provided detailed feedback on the manuscript, and served as internal reviewers. AM, BR, BP, CL, DB, MSa, MSm, MSu, PW, LG, RC, and JMu provided comments on the manuscript. The remaining authors have made contributions to this paper that include, but are not limited to, the construction of DECam and other aspects of collecting the data; data processing and calibration; developing broadly used methods, codes, and simulations; running the pipelines and validation tests; and promoting the science analysis. This paper has gone through internal review by the DES collaboration.

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the Eidgenössische Technische Hochschule (ETH) Zürich, Fermi National Accelerator Laboratory, the University of Illinois at Urbana-Champaign, the Institut de Ciències de l’Espai (IEEC/CSIC), the Institut de Física d’Altes Energies, Lawrence Berkeley National Laboratory, the Ludwig-Maximilians Universität München and the associated Excellence Cluster Universe, the University of Michigan, NSF’s NOIRLab, the University of Nottingham, The Ohio State University, the University of Pennsylvania, the University of Portsmouth, SLAC National Accelerator Laboratory, Stanford University, the University of Sussex, Texas A&M University, and the OzDES Membership Consortium.

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## DATA AVAILABILITY

All data used in this analysis are publicly available at <https://github.com/PantheonPlusSH0ES/DataRelease> and <https://github.com/des-science/DES-SN5YR>.

## REFERENCES

- Abbott T. M. C. et al., 2019, *ApJ*, 872, L30  
 Betoule M. et al., 2014, *A&A*, 568, A22  
 Brout D., Scolnic D., 2021, *ApJ*, 909, 26  
 Brout D. et al., 2019a, *ApJ*, 874, 106  
 Brout D. et al., 2019b, *ApJ*, 874, 150  
 Brout D. et al., 2022a, *ApJ*, 938, 110  
 Brout D. et al., 2022b, *ApJ*, 938, 111  
 Burke D. L. et al., 2018, *AJ*, 155, 41  
 Carron J., Mirmelstein M., Lewis A., 2022, *J. Cosmol. Astropart. Phys.*, 2022, 039  
 Chotard N. et al., 2011, *A&A*, 529, L4  
 DES Collaboration, 2024, *ApJL*, 973, L14  
 DESI Collaboration, 2025, *JCAP*, 2025, 021  
 Efstathiou G., 2025, *MNRAS*, 538, 875  
 Foley R. J. et al., 2017, *MNRAS*, 475, 193  
 Guy J. et al., 2007, *A&A*, 466, 11  
 Guy J. et al., 2010, *A&A*, 523, A7  
 Hicken M. et al., 2009, *ApJ*, 700, 331  
 Hicken M. et al., 2012, *ApJS*, 200, 12  
 Hinton S., Brout D., 2020, *J. Open Source Softw.*, 5, 2122  
 Kenworthy W. D. et al., 2021, *ApJ*, 923, 265  
 Kessler R., Scolnic D., 2017, *ApJ*, 836, 56  
 Kessler R. et al., 2009, *PASP*, 121, 1028  
 Kessler R. et al., 2013, *ApJ*, 764, 48  
 Krisciunas K. et al., 2017, *AJ*, 154, 211  
 Möller A., de Boissière T., 2020, *MNRAS*, 491, 4277  
 Möller A. et al., 2022, *MNRAS*, 514, 5159  
 Notari A., Redi M., Tesi A., 2025, *JCAP*, 2025, 048  
 Planck Collaboration I, 2020a, *A&A*, 641, A1  
 Planck Collaboration VI, 2020b, *A&A*, 641, A6  
 Popovic B., Brout D., Kessler R., Scolnic D., 2023, *ApJ*, 945, 84  
 Qu H., Sako M., Möller A., Doux C., 2021, *AJ*, 162, 67  
 Rigault M. et al., 2025, *AAP*, 694, A1  
 Rubin D. et al., 2015, *ApJ*, 813, 137  
 Rubin D. et al. *ApJ*, 2025, 986, 231  
 Sánchez B. O. et al., 2024, *ApJ*, 975, 5  
 Scolnic D. M. et al., 2018, *ApJ*, 859, 101  
 Scolnic D. et al., 2022, *ApJ*, 938, 113  
 Sevilla-Noarbe I. et al., 2021, *ApJS*, 254, 24  
 Taylor G. et al., 2023, *MNRAS*, 520, 5209  
 Tripp R., 1998, *A&A*, 331, 815  
 Vincenzi M. et al., 2024, *ApJ*, 975, 86  
 Wiseman P. et al., 2020, *MNRAS*, 495, 4040  
 Zuntz J. et al., 2015, *Astron. Comput.*, 12, 45

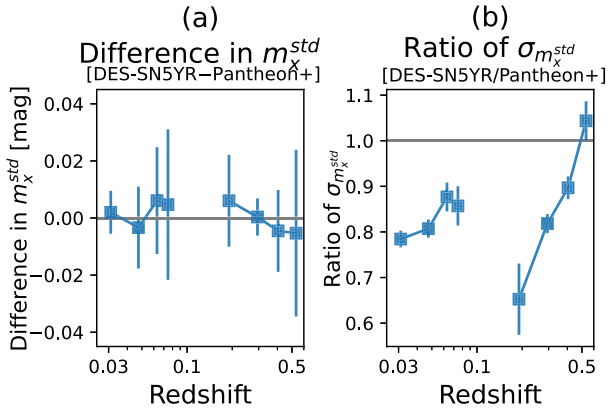
## APPENDIX A: ADDITIONAL ANALYSIS IMPROVEMENTS IN DES-SN5YR FROM PANTHEON+

In this Appendix, we list the additional analysis changes introduced in DES-SN5YR compared to Pantheon+. In contrast to the analysis updates discussed in Section 4, the updates discussed here have a negligible effect on the  $\Delta\mu_{\text{offset}}$  discussed by Efstathiou (2025).

**Light-curve fitting model:** Pantheon+ used the SALT2 light-curve model from Betoule et al. (2014) to fit each event for the standardization parameters  $\{m_x, x_1, c\}$ . In DES-SN5YR, we upgraded to the recently published SALT3 model (Kenworthy et al. 2021), after carefully testing the SALT2 and SALT3 models on published cosmological samples (Taylor et al. 2023).

We compare the SALT2 and SALT3 standardized  $m_x^{\text{std}}$  in Fig. A1 and find that differences are negligible. Therefore, we do not expect the differences between SALT2 and SALT3 models to explain any of the trends highlighted by Efstathiou (2025).

While the  $m_x^{\text{std}}$  differences are small, its uncertainty is significantly reduced in DES-SN5YR (see Fig. A1b). This reduction is due to the broader wavelength range covered by the SALT3 model. The SALT3 mean rest-frame wavelength per band extends 1000 Å farther into the near-infrared compared to SALT2 (from 7000 to 8000 Å), enabling the use of Foundation and DES  $z$ -band data at low redshifts (where observed  $z$ -band corresponds to  $\sim 8000$  Å in the rest frame). The



**Figure A1.** *Left panel:* Median  $m_x^{\text{std}}$  difference versus redshift (and error on the median) for common SNe in DES-SN5YR and Pantheon+. Across all redshifts, differences in  $m_x^{\text{std}}$  are consistent with zero. *Right panel:* ratio of  $m_x^{\text{std}}$  uncertainties between DES-SN5YR and Pantheon+. For a more direct comparison, we measure  $m_x^{\text{std}}$  and its uncertainty using the same nuisance parameters for both DES-SN5YR and Pantheon+:  $\alpha = 0.15$ ,  $\beta = 3.1$ , and  $\gamma = 0$ .

SALT3 model therefore results in larger weight given to low- $z$  SNe in DES-SN5YR compared to Pantheon+.

**Calibration:** Photometric calibration for both Pantheon+ and DES-SN5YR is presented by Brout et al. (2022b) using a cross-calibration approach. For the Foundation SN sample, the same calibration was used for both Pantheon+ and DES-SN5YR. However, the DES subsets in Pantheon+ and DES-SN5YR are treated independently because each sample was reprocessed independently. The same Scene Modelling Photometry code (Brout et al. 2019a; Sánchez et al. 2024) was used to produce light curves for both sub-samples, but the DES survey calibration was updated towards the end of the survey (compare Burke et al. 2018; Sevilla-Noarbe et al. 2021) and therefore DES-SN5YR required slightly different AB calibration offsets ( $-0.004$  to  $0.009$  mag) compared to the earlier DES-SN3YR data release included in Pantheon+. The final AB calibration offsets used in Pantheon+ and DES-SN5YR are presented in table 3 of Brout et al. (2022b) and their uncertainties propagated in our systematic error budget. These calibration offsets are significantly smaller than the observed  $\Delta\mu_{\text{offset}}$  (equation 1) and are therefore unlikely to have much impact on it.

**Nuisance parameters:** Pantheon+ and DES-SN5YR each used their BBC-fitted nuisance parameters for SN standardization and distance estimates: Pantheon+ found  $\alpha=0.148$ ,  $\beta=3.09$ , and  $\gamma=0$ , while DES-SN5YR found  $\alpha=0.161$ ,  $\beta=3.12$ , and  $\gamma=0.038$ . Therefore, when comparing distances for the same events across the two analyses, differences are expected.

**Beams with bias corrections:** the BBC framework was used both in Pantheon+ and DES-SN5YR, and there have been several code updates<sup>3</sup> between the publication of Pantheon+ and DES-SN5YR. One of the most significant code updates was related to the treatment of the parameter  $\beta$  in the calculation of the bias-corrections. In Pantheon+, the (wrong) *intrinsic*  $\beta$  parameter ( $\beta_{\text{intr}} \sim 2$ ) was used in equation (4) to estimate bias corrections, instead of the effective  $\beta$  ( $\beta_{\text{eff}} \sim 3$ ), which is a combination of intrinsic  $\beta$  and extrinsic dust law.

<sup>3</sup><https://github.com/RickKessler/SNANA/blob/master/src/SALT2mu.c>

We do not test this by reverting the entire DES-SN5YR to use the same SALT2 model as Pantheon+ because Fig. A1 shows that discrepancies are negligible. We also do not recompute the DES-SN5YR calibration because differences between calibration offsets applied to the DES sub-samples in Pantheon+ and DES-SN5YR are also significantly smaller than  $\Delta\mu_{\text{offset}}$ .

Updating the DES-SN5YR analysis using the (obsolete) Pantheon+ version of the BBC code does not have a significant effect on  $\Delta\mu_{\text{offset}}$ . However, using the current BBC code in the original Pantheon+ analysis results in an average distance change of  $\sim +0.005$  mag at low- $z$  ( $z < 0.1$ ) and  $\sim -0.005$  mag at high- $z$  ( $z > 0.1$ ). Therefore, BBC code updates impact the overall Pantheon+ Hubble diagram.

As a final test, we reprocessed the DES-SN5YR analysis (which was frozen nearly 1.5 yr ago) with the current BBC code and found a distance change of  $\sim 0.001$  mag between low- $z$  and high- $z$ .

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