

# MEGATRON: the environments of Population III stars at Cosmic Dawn and their connection to present-day galaxies

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## ABSTRACT

We present results of Population III (Pop III) formation in the MEGATRON suite of simulations, which self-consistently follows radiation and non-equilibrium chemistry, and resolves gas at near-pc resolution in a Milky Way-mass progenitor at Cosmic Dawn. While the very first Pop III stars form in haloes with masses well below the atomic cooling limit, the majority of Pop III stars form in more massive systems above the  $10^4$  K atomic cooling threshold as a Lyman–Werner (LW) background of  $10^{-21}$  erg s<sup>-1</sup> cm<sup>-2</sup> Hz<sup>-1</sup> sr<sup>-1</sup> is rapidly established. We find that the global Pop III star formation rate stabilizes to a value of  $10^{-3}$  M<sub>⊙</sub> yr<sup>-1</sup> at  $z = 20$ . Among the three processes that quench Pop III star formation in minihaloes, the LW background, gas starvation, and external chemical enrichment, the LW background is most important. A small fraction of haloes undergo multiple episodes of Pop III star formation when the earlier forming stars all directly collapse to black holes. If the haloes become massive enough, they can form up to  $\sim 100$  Pop III stars in a single burst, which may be observable by *James Webb Space Telescope* with moderate gravitational lensing. Pop III stars form at a wide range of distances from UV-bright galaxies, with only 0.06 per cent of Pop III stars forming within the virial radius of galaxies with  $M_{UV} < -17$ . Finally, by tracking Pop III star remnants down to  $z = 0$ , we find that 75 – 80 per cent reside in the stellar halo of our simulated Milky Way analogue, while the remainder are gravitationally bound to lower mass systems, including satellite haloes.

**Key words:** stars: Population III – galaxies: high-redshift.

## 1 INTRODUCTION

Big bang nucleosynthesis (BBN) predicts that gas in our Universe was initially composed of hydrogen, helium, and trace amounts of lithium. This metal-free ‘pristine’ or ‘primordial’ gas adiabatically cooled and began to gravitationally collapse in overdensities following its decoupling from the radiation field at  $z \sim 1100$ , and was slowly funnelled into the first dark matter haloes. The first stars in our Universe formed from this primordial gas in small and molecular hydrogen-cooling dark matter haloes ( $\sim 10^5 - 10^6$  M<sub>⊙</sub>; minihaloes) around  $z \sim 30$  (R. Barkana & A. Loeb 2001; T. H. Greif 2015). Such metal-free, Population III (Pop III) stars, synthesized the first metals in their cores and began the process of enriching the Universe with heavy elements (V. Bromm & A.

Loeb 2003). The ionizing photons from Pop III stars began cosmic Reionization and brought about an end to the cosmic Dark Ages (J. Miralda-Escudé 2003). Most haloes in the early Universe once hosted Pop III stars, playing a critical role in the initial evolution of galaxies (J. L. Johnson, T. H. Greif & V. Bromm 2008; V. Bromm et al. 2009). Consequently, Pop III stars are a crucial component for our understanding of the Universe at Cosmic Dawn.

Pop III stars have theoretically different structures than later-time stellar populations. Their atmospheres are not subject to metal-driven cooling instabilities, which produce stellar winds (J. S. Vink, A. de Koter & H. J. G. L. M. Lamers 2000), unless metals cycle throughout via mixing in fast rotators (S. Ekström et al. 2008), and their cores do not have enough carbon to ignite the CNO cycle in the initial hydrogen-burning stage (main sequence, MS). Observationally, little is known about them, and theoretically, simulations still disagree on their properties. The masses of Pop III stars are notoriously uncertain, with estimates for the Pop

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III initial mass function (IMF) differing by orders of magnitude in characteristic mass, and profiles ranging from uniform to log-normal (e.g. S. Hirano et al. 2014; K. M. J. Wollenberg et al. 2020; O. Jaura et al. 2022). Constraining the Pop III IMF is crucial for understanding the dominant feedback mechanisms of the first stars, whose metals brought forth a new generation of enriched, Pop II stars, and regulated the growth of the earliest galaxies (B. D. Smith et al. 2015; J. Jaacks et al. 2018). Although estimates of the mass distribution of Pop III stars vary, it is generally accepted that the Pop III IMF is top-heavy compared to present-day stellar populations. The best constraints come from the non-detection of Pop III stars in the stellar halo of the Milky Way (MW, e.g. with the Sloan Digital Sky Survey, SDSS; B. Yanny et al. 2009), and from the chemical signatures of local metal-poor stars (M. N. Ishigaki et al. 2018; R. Jiang et al. 2024).

The majority of Pop III stars likely form in isolation or within small ( $\leq 10^4 M_\odot$ ) stellar clusters at high redshift (V. Bromm & N. Yoshida 2011), making them extremely difficult to observe directly even with our most sensitive detectors. As a consequence, there has not yet been a galaxy observed with a confirmed detection of a Pop III star at high- $z$ , although many Pop III galaxy candidates have been proposed (E. Vanzella et al. 2023, 2026; R. Maiolino et al. 2024; X. Wang et al. 2024; S. Cai et al. 2025; S. Fujimoto et al. 2025; K. Nakajima et al. 2025). Gravitational lensing would help resolve individual Pop III stars if the magnification is large enough. Although the probability of such a configuration is low, we are already finding metal-poor stars/clusters in highly magnified ( $\mu \sim 1000$ ) caustics (B. Welch et al. 2022). If Pop III stars can form with masses down to  $\sim 0.8 M_\odot$ , they may survive to the present day (A. Maeder & G. Meynet 2012), and be identified in our local group of galaxies from their chemical signatures (S. J. Tanaka et al. 2017). So far, no Pop III stars have been found in archaeological surveys of the MW or local dwarfs, which places a constraint on the lower bound of the Pop III IMF to be  $\sim 0.7 - 0.8 M_\odot$  (S. Salvadori et al. 2010; T. Hartwig et al. 2015).

The study of Pop III stars has remained primarily theoretical due to the difficulties of directly observing them or their remnants. With more sensitive telescopes, there is a need for numerical simulations and semi-analytical models to make predictions of galaxies hosting Pop III systems, such as predictions of their unique spectral features (e.g. H. Katz et al. 2023; J. A. A. Trussler et al. 2023), how long the Pop III phase lasts (e.g. H. Xu et al. 2016; S. Hegde & S. R. Furlanetto 2025), and the types of environments which stimulate/prevent Pop III formation (e.g. J. Park, M. Ricotti & K. Sugimura 2021; S. Nishijima, S. Hirano & H. Umeda 2024). Upcoming spectral surveys of local stars (e.g. the 4-metre Multi-Object Spectroscopic Telescope, 4MOST; N. Christlieb et al. 2019 and the William Herschel Telescope Enhanced Area Velocity Explorer, WEAVE; S. Jin et al. 2024) also need better constraints on where Pop III stars end up at present day to aid in targeted searches of these metal-free relics.

The wide range of spatial scales required to understand the Pop III formation phase forces simulations of Pop III stars to typically either focus on the small-scale clouds forming hydrostatic cores to predict the Pop III IMF (e.g. P. C. Clark et al. 2011; S. Hirano et al. 2014; T. Hosokawa et al. 2016), or on the large-scale galactic context in which they form to produce statistical studies of Pop III birth sites and their subsequent impact on galaxy formation (e.g. J. H. Wise et al. 2012; H. Xu, J. H. Wise & M. L. Norman 2013; T. Kimm et al. 2017; H. Katz et al. 2023; K. Brauer et al. 2025). Environmental studies have been typically limited to small

( $\sim 2 \text{ cMpc } h^{-1}$ ) cosmological boxes that sample a limited number of haloes and environmental configurations (although see e.g. the Renaissance simulations; H. Xu et al. 2013, for an overdense  $\sim 40 \text{ cMpc}^3 h^{-3}$  volume).

The  $\text{H}_2$  content in haloes is a critical component in determining whether haloes will eventually form a Pop III star, with the lower bound on halo mass for Pop III formation, called  $M_{\text{crit}}$  or  $M_{\text{min}}$ , being highly dependent on the production/destruction rate of  $\text{H}_2$ . A key regulator in the production of  $\text{H}_2$  in pristine halo cores is Lyman–Werner (LW) radiation, which travels far from young galaxies and across the intergalactic medium (IGM), photodissociating the molecular hydrogen and preventing cooling (Z. Haiman, T. Abel & M. J. Rees 2000) up to densities where  $\text{H}_2$  shielding can become effective. Results from the Renaissance simulations (H. Xu et al. 2013, 2016) show that the Pop III formation phase can continue past the late stages of reionization (see also e.g. O. Zier et al. 2025), extended from the delay of star formation by LW radiation in haloes below the atomic cooling limit (see also e.g. B. W. O’Shea & M. L. Norman 2008). It is still unclear how this LW background, which is expected to be anisotropic and environment-dependent, affects potential Pop III birth sites in a system like our MW.

To address these scientific questions, we utilize the MEGATRON simulations. MEGATRON is a suite of high-resolution zoom simulations at Cosmic Dawn of the Lagrange region of a halo that has approximately MW mass by  $z = 0$ . The volume of the zoom region is  $20 \text{ cMpc}^3 h^{-3}$ , which allows for a comprehensive statistical study of Pop III stars in the context of an MW-like environment. MEGATRON forms individual Pop III stars, and models the transition to Pop II stars, which will increasingly contribute to the LW background radiation as the Pop II star formation rate (SFR) begins to dominate the total SFR. With its near-pc resolution for gas at  $z \sim 30$ , radiative transfer coupled to a complex non-equilibrium chemistry network including  $\text{H}_2$ , MEGATRON is ideal for studying the formation sites of the first stars in our Universe. MEGATRON includes a dark-matter-only (DMO) simulation run to  $z = 0$ , which we utilize to trace where the remnants of Pop III stars end up at present day.

This paper is structured as follows. We introduce the MEGATRON suite of simulations in Section 2, including our treatment of Pop III star formation. We then present our results in Section 3, and conclusions in Section 4.

## 2 METHOD

MEGATRON is a suite of cosmological radiation hydrodynamic simulations run with the RAMSES-RTZ code (H. Katz 2022) and the PRISM ISM model (H. Katz et al. 2022), extended from RAMSES-RT (J. Rosdahl et al. 2013; J. Rosdahl & R. Teyssier 2015) and RAMSES (R. Teyssier 2002). The simulations model gravity, hydrodynamics coupled to multifrequency radiative transfer, and a non-equilibrium chemistry network of over 80 species to accurately model heating and cooling processes. In this section, we give a brief overview of the four high- $z$  simulations used in our analysis, which have been run down to  $z = 8.5$ , focusing on the details which are important in the context of Pop III star formation. For details on how we treat particle dynamics, gas dynamics, and radiative transfer, see H. Katz et al. (2025a).

## 2.1 Initial conditions and resolution

Initial conditions (ICs) are generated with GENETIC (S. Stopyra et al. 2021; A. Pontzen et al. 2022) using cosmological parameters from the *Planck* data release (Planck Collaboration XIII 2016;  $\Omega_m = 0.3139$ ,  $\Omega_\Lambda = 0.6861$ ,  $\sigma_8 = 0.8440$ ,  $n_s = 0.9645$ , and  $h = 0.6727$ ) in a  $(50 \text{ cMpc } h^{-1})^3$  box. The ICs are originally taken from M. P. Rey & T. K. Starkenburg (2022) and modified following the procedure in A. Pontzen et al. (2021) to mitigate gas advection errors. We apply quadratic modifications (M. P. Rey & A. Pontzen 2018) to the density field, producing an early-forming scenario for an MW progenitor and yielding a large number of haloes at high- $z$  that are bright enough to be observed by *James Webb Space Telescope* (*JWST*). Baryon-dark matter streaming velocities are not included in the ICs.

As with most zoom simulations, an initial large volume DMO simulation is run to identify an MW-mass ( $\sim 10^{12} M_\odot$ ) halo at  $z = 0$ . All particles within  $3 r_{\text{vir}}$  are then traced back to the ICs, defining the Lagrangian patch. The simulation is then re-centred on the  $z = 0$  position of the halo of interest, and a zoom region is constructed as a set of nested grids covering the Lagrangian patch, reaching a maximum mass resolution of  $2.48 \times 10^4 M_\odot h^{-1}$  for the dark matter (an effective resolution of  $8196^3$  in a  $50 \text{ cMpc } h^{-1}$  box). The zoom region encompasses a volume of  $(2.7 \text{ cMpc } h^{-1})^3 \approx 20 \text{ cMpc}^3 h^{-3}$ .

Refinements of the grid are performed according to the local fluid properties (total mass in the cell and jeans length) down to  $48 \text{ pc } h^{-1}$ . Since the refinement criteria is in comoving coordinates, the physical resolution is initially much smaller than  $48 \text{ pc } h^{-1}$ , reaching  $1.5 \text{ pc } h^{-1}$  resolution at the onset of Pop III formation ( $z \sim 30$ ). This high resolution combined with our top-heavy Pop III IMF (described later on), means that almost all Pop III stars have resolved Strömgren spheres in the initial stages of Pop III formation.

## 2.2 Chemistry and radiation

The high- $z$  suite of MEGATRON simulations are initialized with the primordial composition predicted from BBN, allowing the metallicity to grow naturally from pollution by Pop III and Pop II stars. Metallic species are followed in non-equilibrium if they contribute at least 1 per cent to the equilibrium cooling curve derived from CLOUDY (G. J. Ferland et al. 2017) across the temperature range  $10^1 - 10^8 \text{ K}$ . We track primordial species:  $e^-$ , H I–II, He I–III; molecules:  $\text{H}_2$  and CO; and the following metallic ions: O I–VIII, C I–VI, N I–VII, Fe I–XI, Si I–XI, Ne I–X, and Mg I–X. Specifically, ions can be created or destroyed through ionization, recombination, and charge exchange processes following H. Katz et al. (2022), or by forming molecules. See H. Katz et al. (2025a) for how dust is modelled.

The net cooling rate  $\Lambda_{\text{net}}$  is computed from primordial species,  $\text{H}_2$ , CO, dust processes, and metallic transitions. If a specific metallic ion is not directly tracked, its contribution to the cooling curve is still considered under the assumption of collisional ionization equilibrium. The net heating rate  $\Gamma_{\text{net}}$  is computed from photoheating from stellar spectral energys densities (SED), photoelectric heating from dust, and  $\text{H}_2$  heating (formation, dissociation, and pumping).

The radiation from stars is propagated in eight frequency bins covering the infrared (IR) to the extreme ultraviolet (EUV), transferring energy by photoionization (EUV-Opt) and photoheating

(FUV) of the gas, photodissociation of molecular hydrogen (LW), and momentum through radiation pressure (RP; optical-IR). Further details on the method of radiative transfer can be found in H. Katz et al. (2025a). The LW background from sources outside the zoom region is considered to be subdominant compared to the background generated by our early collapsing region, and the ionization flux from the included UV background (F. Haardt & P. Madau 2012) is negligible at the redshifts we consider.

## 2.3 Star formation in the fiducial model

The high- $z$  suite of MEGATRON simulations have various models for star formation (SF). In this section, we describe the fiducial model which we call the efficient SF model, and describe star formation in alternative models in the next section. Star formation proceeds according to the turbulent properties of the gas, and is similar to the SF model used in the SPHINX (J. Rosdahl et al. 2018) simulation. A gas cell is able to form stars if its gas density is  $> 10 m_p \text{ cm}^{-3}$  and  $> 200 \times \rho_{\text{crit}}$  with  $\rho_{\text{crit}}$  the critical density, the turbulent Jeans length is smaller than the cell size, the gas flow is convergent across the adjacent cells, and the gas density field is at a local maxima. The efficiency of star formation  $\epsilon_{\text{ff}}$  is computed from the local turbulence (P. Padoan & A. Nordlund 2011; C. Federrath & R. S. Klessen 2012, see H. Katz et al. 2024). For Pop III star formation each star particle represents an individual star, while Pop II stars are sampled as simple stellar populations.

### 2.3.1 Pop II model

At metallicity  $Z > 2 \times 10^{-8}$  (the transition metallicity between Pop II and Pop III stars, where gas cloud fragmentation becomes more efficient; K. Omukai et al. 2005), we probabilistically sample the formation of star particles in integer multiples of  $500 M_\odot$  based on a Poisson distribution. Stellar SEDs are computed based on the metallicity and age of star particles using BPASS v2.2.1 (J. J. Eldridge, R. G. Izzard & C. A. Tout 2008; J. J. Eldridge et al. 2017; E. R. Stanway & J. J. Eldridge 2018), and scaled by mass of the star particle. Similarly, core-collapse supernovae (CCSNe) are stochastically sampled at each time-step using the BPASS v2.2.1 IMF, where CCSN progenitors are stars with initial masses ranging from  $8 - 25 M_\odot$ . They release  $10^{51}$  erg of energy at the time of the explosion. For details on metal yields and stellar winds of Pop II stars in MEGATRON, see H. Katz et al. (2025a).

### 2.3.2 Pop III model

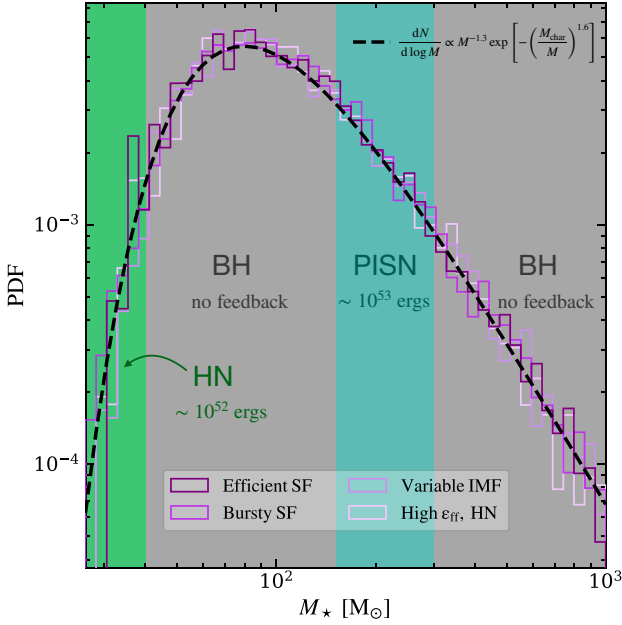
Below metallicity  $Z = 2 \times 10^{-8}$ , individual Pop III stars form from the following the IMF

$$\frac{dN}{d \log M} \propto M^{-1.3} \exp \left[ - \left( \frac{M_{\text{char}}}{M} \right)^{1.6} \right], \quad (1)$$

with a characteristic mass  $M_{\text{char}} = 100 M_\odot$  (J. H. Wise et al. 2012).

We assume that once a Pop III star is formed, it remains on the main sequence with no change to its luminosity or mass until hydrogen burning ends. Stellar SEDs for Pop III stars are interpolated in age and mass following tabulated values from D. Schaerer (2002).

At the end of their lives, Pop III stars follow four different mass-dependent phases, three of which we show in Fig 1. Stars between



**Figure 1.** The IMF of Pop III stars used in the MEGATRON suite of simulations. Histograms of Pop III masses for each run are included to show they all sample the lognormal IMF. Regions in the background are coloured according to the feedback channels a star of particular initial mass will follow, starting with HN and moving to BH formation with a narrow-mass regime where the star can undergo PISN. The Pop III model also includes CCSN at lower masses. They are however probabilistically unlikely to be sampled due to the chosen characteristic mass of  $\sim 100 M_{\odot}$ .

$10 - 20 M_{\odot}$  undergo normal CCSN releasing  $10^{51}$  erg.<sup>1</sup> At slightly higher masses, stars between  $20 - 40 M_{\odot}$  explode as hypernova (HN) injecting energies of  $10 - 40 \times 10^{51}$  erg depending on mass (K. Nomoto et al. 2006). From  $40 - 140 M_{\odot}$ , and above  $300 M_{\odot}$ , we assume direct collapse to a black hole (BH) with no supernova explosion. In the intermediate-mass range, stars between  $140 - 300 M_{\odot}$  explode as pair-instability supernovae (PISNe), releasing energy depending on the remaining He core mass (A. Heger & S. E. Woosley 2002). The above feedback mechanisms from Pop III stars will enrich the surrounding medium with metals, with differing chemical yields depending on the type of supernova. We adopt chemical yields for the various feedback processes from H. Umeda & K. Nomoto (2002); K. Nomoto et al. (2006), and K. Nomoto, C. Kobayashi & N. Tominaga (2013).

#### 2.4 Star formation in alternative models

We introduce here three additional simulations which have varying physics for Pop II star formation, to explore the robustness of our results to changes in galaxy formation physics. The bursty SF model increases the energy of Pop II supernovae from  $10^{51}$  to  $5 \times 10^{51}$  erg. The variable IMF model allows for a Pop II IMF which is dependent on the local gas density and metallicity computed using STARBURST99 (C. Leitherer et al. 1999), along with adding HN for Pop II stars. Finally, the HN + High  $\epsilon_{\text{ff}}$  model combines Pop II HN feedback with a stricter jeans length criterion of four times the grid resolution, and uses a constant  $\epsilon_{\text{ff}} = 100$  per cent.

<sup>1</sup>Due to the low sampling probability, our simulations contain no stars with low enough masses for CCSN.

HNe in the last two models occur for Pop II stars above  $25 M_{\odot}$ . The Pop III model is identical in all runs with the only difference being the Jeans criteria for star formation in the HN + High  $\epsilon_{\text{ff}}$  model.

#### 2.5 Generating spectra

Galaxy spectra are generated from gas cells and star particles, located within  $0.25 r_{\text{vir}}$  of the halo centre, by summing the stellar SEDs from both Pop II and Pop III stars, the nebular emission, and the nebular continuum. Nebular emission of recombination and collisionally excited lines are computed using PYNEB (V. Luridiana, C. Morisset & R. A. Shaw 2015) and the CHIANTI database (K. P. Dere et al. 2019), where we build up emissivity grids in temperature and electron density for each line. We correct for emission lines from cells with unresolved Strömgren spheres using CLOUDY (G. J. Ferland et al. 2017, see H. Katz et al. 2025a for details), and the nebular continuum is computed using PYNEB. When processing the Pop III SEDs for observability, we use mass-dependent SEDs derived from Pop III atmospheric modelling (M. M. Larkin, R. Gerasimov & A. J. Burgasser 2023). To compare with observational instruments such as *JWST*, we convert the spectra from our computed luminosities  $L$  to AB magnitudes:

$$m_{\text{AB}} = -2.5 \log_{10} \left( \frac{L_{\nu}}{4\pi D_L^2} (1+z)^{-1} \frac{\text{s cm}^2 \text{ Hz}}{\text{erg}} \right) - 48.6, \quad (2)$$

where the luminosity is per frequency unit and  $D_L$  is the luminosity distance. We convolve the spectra with selected filters from *JWST*'s Near Infrared Camera (NIRCam) and Mid-Infrared Instrument (MIRI) using SEDPY (B. D. Johnson 2019). UV magnitudes of galaxies are computed following J. B. Oke & J. E. Gunn (1983) as

$$M_{\text{UV}} = 51.595 - 2.5 \log_{10} \left( \frac{L_{1500 \text{ \AA}}}{\text{erg s}^{-1} \text{ Hz}^{-1}} \right). \quad (3)$$

#### 2.6 Structure finding

For the purpose of this work, we use a different halo catalogue from that used in the main simulation paper (which also includes an analysis of Pop III systems; H. Katz et al. 2025a). We identify dark matter haloes and subhaloes using the ROCKSTAR-GALAXIES structure finder (P. S. Behroozi, R. H. Wechsler & H.-Y. Wu 2013), retaining all haloes with more than 30 particles ( $\gtrsim 10^6 M_{\odot}$ ) to ensure completeness on haloes forming Pop III stars, down to halo masses of  $7 \times 10^5 M_{\odot}$ . Halo merger trees are constructed using the YT (M. J. Turk et al. 2011) and TANGOS (A. Pontzen & M. Tremmel 2018; A. Pontzen et al. 2023) packages. We make use of the `crosslink` command from TANGOS to link the same DM structures across the different MEGATRON simulations if they are initialized with the same ICs, allowing us to track the same haloes across different runs.

#### 2.7 Tracing Pop III stars

Running the simulations to  $z = 0$  is too computationally expensive. To find where Pop III stars reside at  $z = 0$ , we trace the positions of Pop III stars in the simulations at the last available snapshot ( $z \sim 8.5$ ) to  $z = 0$  using a DMO simulation run with the same ICs and the same DM mass resolution. The large-scale formation of structures is driven by the dark matter field, and should proceed to form the same haloes, at least in the regime

of the Pop III formation phase. While non-linear coupling from baryonic feedback will cause the matter-power spectrum to deviate from that of a pure DM result at low- $z$ , we expect mergers and tidal stripping between haloes in the DMO run to follow closely that of a hydro run.

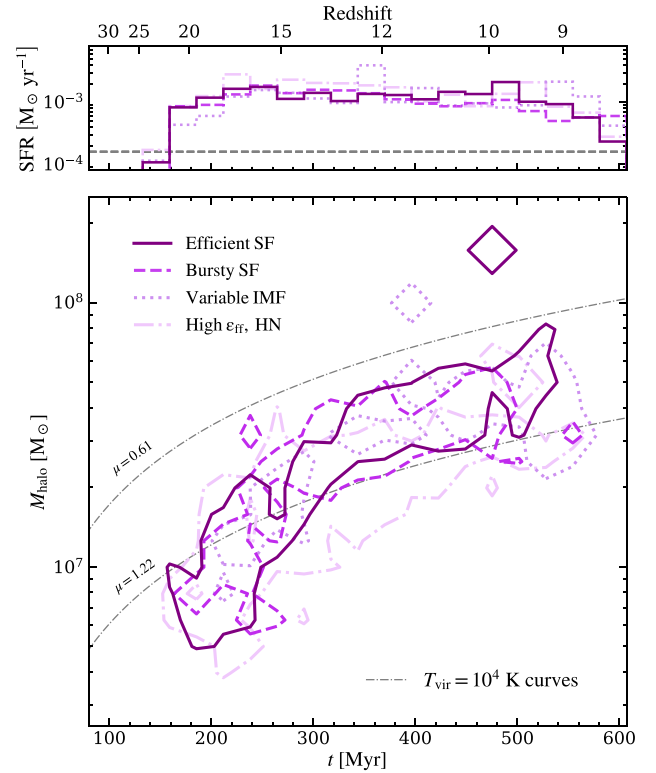
We match the IDs of DM particles that are near Pop III remnants at  $z = 8.5$  with their positions in the DMO simulations at  $z = 0$ . In our analysis, we trace groups of DM particles using a physical distance criteria from the Pop III star. For the purpose of this work, we choose to track the 25 DM particles which are closest physically to each Pop III star at  $z \sim 8.5$ . We find them at  $z = 0$  in the DMO simulation and assign them to the main halo or subhaloes according to the halo catalogue.

We have validated this method by using the full hydrodynamic simulation, tracing early-forming Pop III stars ( $z > 20$ ) to the end of the simulation ( $z = 8.5$ ) using their neighbouring dark matter and comparing to the true position. The majority of stars are traced to within 200 pc of their true position. Furthermore, in the DMO simulation, we find that for haloes which survive to  $z = 0$ , the most bound particles at  $z = 8.5$  remain bound to the halo at  $z = 0$  (see Appendix A). Pop III stars typically form close to the gravitational centres of their host haloes. If the stars reside in subhaloes that remain bound and relatively undisturbed, we expect our method to be robust in identifying their  $z = 0$  hosts. However, if the stars initially reside in haloes that merge into the main halo, we expect the stars to have virialized with the main halo by  $z = 0$ .

### 3 RESULTS

In this section, we present our results on the formation of Pop III stars in the MEGATRON suite of simulations. The simulations form [2655, 2392, 2721, 3217] Pop III stars by  $z = 8.5$  for the efficient SF, bursty SF, variable IMF, and HN + High  $\epsilon_{\text{ff}}$  runs, respectively. As we will discuss later, there can be many repeated events of Pop III formation in the same halo, so we also consider the number of unique birth sites which produce Pop III stars. The simulations contain [882, 858, 863, 1180] unique haloes hosting Pop III formation. In comparison, B. F. Griffen et al. (2018) found  $\sim 550$  Pop III-forming sites for an MW progenitor (when also accounting for radiative feedback), although their semi-analytic model does not self-consistently follow the LW background.

We plot the evolution of the Pop III halo mass regime as a function of time in Fig. 2. The initial formation of Pop III stars at around  $z = 30$  is facilitated by molecular hydrogen cooling in  $\sim 3 \times 10^6 M_{\odot}$  haloes, which is quickly shut down by LW (11.2–13.6 eV) radiation from the first stars. While not reflective of the average, some Pop III stars are able to form in haloes slightly below  $10^6 M_{\odot}$ . Pop III formation transitions to occurring in more massive haloes, above the atomic cooling limit, as the background radiation field increases. Atomic cooling, primarily facilitated by the Lyman- $\alpha$  transition, enables haloes to reach high enough densities for  $\text{H}_2$  self-shielding against LW to become effective. Although the formation rate of Pop III stars in minihaloes is already small compared to those in atomic cooling haloes, our results could overestimate the number of Pop III stars forming in minihaloes as we do not explicitly model the effect of baryon-dark matter streaming velocities (D. Tseliakhovich & C. Hirata 2010; A. Stacy, V. Bromm & A. Loeb 2011; A. Fialkov et al. 2012; A. T. P. Schauer et al. 2021). Indeed, a large enough local streaming veloc-



**Figure 2.** Top: SFR of Pop III stars as a function of time from the start of the simulations. The SFR quickly rises to  $10^{-3} M_{\odot} \text{yr}^{-1}$  and remains mostly constant for all simulations until the end of the simulation at  $z = 8.5$ . The grey dashed line at  $\sim 1.7 \times 10^{-4} M_{\odot} \text{yr}^{-1}$  is the level for the contour in the lower panel. Bottom: contours in halo mass and time of haloes hosting Pop III stars weighed by the SFR of Pop III stars, for each simulation. The mass–time tracks for haloes with a virial temperature of  $10^4$  K (R. Barkana & A. Loeb 2001) are shown as the grey dash–dotted lines, labelled by mean molecular weight ( $\mu = 1.22$ : neutral gas; and  $\mu = 0.61$ : ionized gas). For all simulations, Pop III formation migrates from minihaloes to atomic cooling haloes on a short time-scale. Pop III starbursts in  $10^8 M_{\odot}$  haloes are visible for the efficient SF and variable IMF runs.

ity<sup>2</sup> acts against gravitational collapse and delays star formation, increasing the critical mass  $M_{\text{crit}}$  at a given redshift.

The global Pop III SFR quickly rises to  $10^{-3} M_{\odot} \text{yr}^{-1}$  and remains approximately constant until the end of the simulation. A constant Pop III SFR down to the late stages of reionization is also observed in other simulations (e.g. J. H. Wise et al. 2012; H. Xu et al. 2016). If we divide the Pop III SFR by the volume of the Lagrangian patch, our constant global Pop III SFR translates to a Pop III SFR density (SFRD) of  $\sim 7 \times 10^{-5} M_{\odot} \text{yr}^{-1} \text{Mpc}^{-3} h^3$ . As our environment is overdense and biased towards building up large haloes at high redshift, we expect our SFRD to be large compared to an underdense environment. Many other works predict similar values for the Pop III SFRD (T. Hartwig et al. 2022), although most exhibit a continuous increase of the SFRD in time until  $z \sim 10$  (E. Visbal, G. L. Bryan & Z. Haiman 2020; B. Liu & V. Bromm 2021; E. M. Ventura et al. 2025), with some reaching an order of magnitude higher SFRD than our work by

<sup>2</sup>The formation of the MW may have been subject to a particularly high streaming velocity ( $v_{\text{SV}} = 1.75\sigma_{\text{SV}}$ ; B. Uysal & T. Hartwig 2023).

that time (R. S. de Souza et al. 2014; J. Jaacks et al. 2018). While our SFR hints at a slow decline near  $z = 8.5$ , such behaviour may not necessarily continue down to lower redshift. For example, S. Hegde & S. R. Furlanetto (2025) find a decreasing Pop III SFRD from its peak at  $z = 15$  until  $z = 8$  due to the increasing scarcity of Pop III-forming haloes below the atomic cooling limit, at which point the SFRD continuously increases to  $z = 5$  as atomic cooling haloes take over. In our simulations, we find the transition of Pop III formation from minihaloes to atomic cooling haloes occurs almost immediately after the first stars form.

In MEGATRON, we follow the dominant  $H_2$  formation channel facilitated by  $H^-$  (equation 4) and do not consider other, subdominant mechanisms such as the formation of  $H_2$  through  $H^+$  or  $H_2^+$ . Our chemistry network also does not explicitly follow the formation of HD, which allows for cooling below 100 K in metal-free gas (T. Nagakura & K. Omukai 2005). Some studies which include a more comprehensive 11/12-species primordial chemistry network (R. Lenoble, B. Commerçon & J. Rosdahl 2024) recover a similar lower mass threshold for Pop III formation, and higher resolution (both in gas cells and DM particles, J. H. Wise et al. 2012; T. Kimm et al. 2017) recover a similar mass range of haloes forming Pop III stars. Whether we cool exclusively through  $H_2$  or also HD, the halo will eventually form Pop III star(s). HD cooling can lead to lower core temperatures in atomic cooling haloes, which could affect the Pop III IMF through further cloud fragmentation (V. Bromm et al. 2009).

### 3.1 The environments of Pop III systems

#### 3.1.1 Before the Pop III star forms

The initial state of gas in a halo at the onset of Pop III formation is pristine, with cooling driven by  $H_2$  in the inner regions down to 300 K. An example of  $H_2$  cooling gas in a pristine halo core is shown in Fig. 3, where the hydrogen number density reaches  $10^3 \text{ cm}^{-3}$  with a temperature of  $\sim 300$  K for the efficient SF run. The HN + High  $\epsilon_{\text{ff}}$  forms Pop III stars in generally less dense environments than the other runs, leading to a decrease in Pop III-forming halo masses at later times, as the requirements for cooling efficiency are less strict to achieve star formation densities (see Fig. 2).

LW radiation from neighbouring star-forming regions dissociates  $H_2$  in low-mass haloes, as LW has little opacity in neutral H/He and can penetrate deeply into dense atomic gas residing in pristine halo cores. In our work, we find cooling reduction from LW radiation is the dominant player in halting Pop III formation in  $\sim 4 \times 10^6 M_\odot$  haloes. Within 200 Myr after the big bang, Pop III formation transitions to more massive haloes (see Fig. 2), whose virial temperatures are  $\sim 10^4$  K. This critical time ( $z \approx 20$ ) corresponds to the LW background reaching  $J_{\text{LW}} = J_{21} \equiv 10^{-21} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1} \text{ sr}^{-1}$ , as measured at the virial radii of every starless halo in the simulations (see the bottom plot in Fig. 5, where we show the strength of the LW field as a function of time for bins of halo masses). The LW intensity from local sources in our region is expected to dominate over any a cosmic LW background originating from more distant galaxies, as our zoom-in region is overdense and biased towards early galaxy formation.

We show in Fig. 4, the  $H_2$  fraction in Pop III-forming halo cores (gas weighted by density in the inner 10 per cent of the virial radius) as a function of  $J_{\text{LW}}$ , haloes are coloured by the electron fraction  $f_{e^-} \equiv n_{e^-}/n_{\text{H}}$  in the dense core. Across all simulations, two distinct populations emerge: haloes subject to low

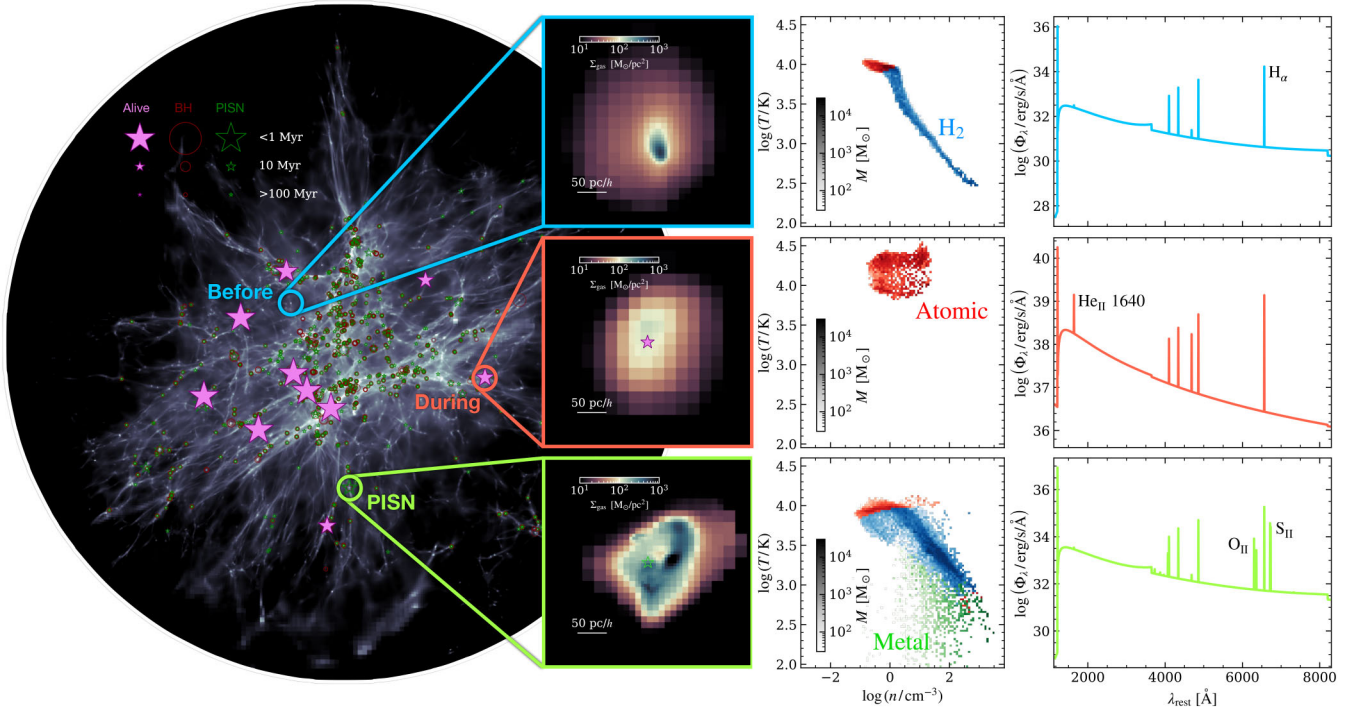
levels of LW radiation (with low  $f_{e^-} \lesssim 10^{-4}$ , the residual electron fraction following recombination, D. Galli & F. Palla 1998) at early times and haloes able to withstand higher amounts of LW radiation (with high  $f_{e^-} > 10^{-4}$ ) at later times. Haloes subject to small amounts of LW radiation are around  $\sim 3 \times 10^6 M_\odot$  at  $z \sim 25$ , while more ionized haloes are an order of magnitude more massive and form later on. These two populations arise in the Pop III.1 and Pop III.2 formation scenarios, respectively (V. Bromm et al. 2009; R. S. Klessen & S. C. O. Glover 2023).

We find that minihaloes with incoming LW radiation fluxes  $J_{\text{LW}}/J_{21} \geq 1$  do not form Pop III stars efficiently. Indeed, a strong enough LW field will dissociate  $H_2$  and prevent the gas from cooling, and haloes early on are not massive enough to atomically cool. These minihaloes continue to accrete gas, and begin to efficiently cool through atomic hydrogen transitions once their virial temperatures reach  $\sim 10^4$  K (see the relation to halo mass in Fig. 2). Pop III stars can form in atomic cooling systems that are irradiated by fluxes up to  $10^2 J_{21}$ . This is due to the extra electrons available in a warmer and more ionized medium, facilitating the formation of  $H_2$  through the following pathway (S. C. O. Glover et al. 2010):



Pop III.2 stars in our simulations mostly form under LW strengths of  $0.3 - 30 J_{21}$ , which is a similar range to that seen for Pop III-forming galaxies in the Renaissance simulations at  $z = 7.6$  (H. Xu et al. 2016). Furthermore, for a given LW strength, more massive haloes have consistently larger  $f_{\text{H}_2}$ , as  $H_2$  self-shielding becomes more effective due to increased gas masses. Stars in the HN + High  $\epsilon_{\text{ff}}$  simulation form in less dense gas than the other runs, leading to higher electron fractions from the lack of effective self-shielding. If the incident LW flux becomes too large, pristine atomic cooling haloes could instead proceed to form a direct collapse black hole (E. Visbal, Z. Haiman & G. L. Bryan 2014), with the spectral shape of the incoming radiation being potentially important to set the  $H_2$  and  $H^-$  destruction rates (B. Agarwal et al. 2016).

Most of the Pop III-forming haloes across all runs have  $10^{-5} < f_{\text{H}_2} < 10^{-3}$ , but there is also a significant population (13–25 per cent depending on the simulation) with  $f_{\text{H}_2} < 10^{-8}$  and  $J_{21} > 2$ . These haloes are not shown in Fig. 4 as they are already hosting Pop III stars, and although the LW intensity at their virial radii is  $\sim 10 J_{21}$ , it can reach upwards of  $10^5 J_{21}$  in the inner regions of the halo. Such systems have elevated levels of free electrons ( $f_e > 2 \times 10^{-3}$ ), and are hence able to form  $H_2$  on very short time-scales after the hosted Pop III star leaves the main sequence, leading to rapid cooling and the formation of another Pop III star. This process occurs if RP is unable to blow out the gas, and implies the former Pop III star has not undergone an SN, which would enrich and disrupt the gas in the galaxy. We do not model  $\text{Ly}\alpha$ RP, which is an important process that impacts the ISM and would impact efficacy of subsequent SF events or supernova (O. Nebrin et al. 2025), as the resonant scattering of  $\text{Ly}\alpha$  photons could drive significant momentum transfer in dense, dust-free gas (T. Kimm et al. 2018). We have run calibration simulations for MEGATRON (H. Katz et al. 2024), including Pop III stars and  $\text{Ly}\alpha$  RP, which does indeed lower the total stellar mass by disrupting star-forming regions in low-metallicity gas. We discuss in Section 3.2 how repeated episodes of Pop III star formation in the same



**Figure 3.** Left: projection of the gas density of the Lagrangian volume in the efficient SF simulation at  $z = 8.5$ . All Pop III stars which have formed by that redshift are overlotted on the projection, with symbol sizes corresponding to their age, and colours/markers indicating if the star is still alive or a remnant. Most of the stars older than 5 Myr are now remnants, either a BH or PISN, and are mostly concentrated in the high-density filamentary structure, compared to young Pop III stars which live on the outskirts. In the insets of the figure, we highlight three different haloes displaying the three stages of Pop III formation: before the star forms, while the star is alive, and the resulting PISN if the star meets the initial mass requirement ( $140 < M_{\star} < 300$ ). Right: each row is for a particular stage of Pop III evolution. The first column is the gas density projection in the inner part of the halo, the second column is the halo’s phase diagram weighed by mass and coloured by dominant cooling process (blue:  $H_2$ , red: atomic, and green: metal cooling), and the third column is the halo’s intrinsic spectrum built up from nebular emission and continuum (and for the middle row, the Pop III SED).

halo (chained one after another) can lead to Pop III starbursts in  $10^8 M_{\odot}$  haloes.

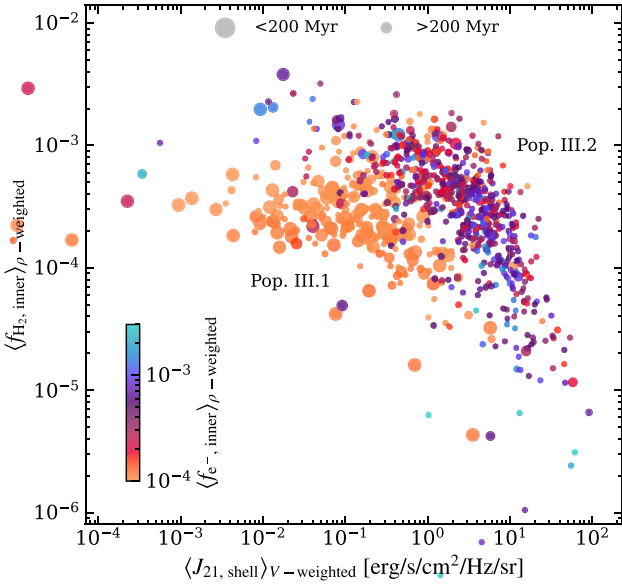
To some extent, the Pop III formation phase can be bypassed if haloes are externally enriched with metals from nearby galaxies (B. D. Smith et al. 2015; K. Brauer et al. 2025). In the upper panel of Fig. 5, we plot the fraction of metal enriched haloes hosting no stars as a function of time in the bursty SF simulation. We find at the latest stages of the simulations,  $\sim 20 - 30$  per cent of starless haloes in the mass range of  $3 \times 10^6 - 3 \times 10^7 M_{\odot}$  (the masses of haloes which predominantly form Pop III stars) have elevated density-weighted metallicities of  $Z > 10^{-8}$ , which is the critical metallicity threshold for Pop. II formation. As most haloes in this mass range are not significantly enriched, we determine Pop III suppression from metal-enriched outflows of nearby galaxies to be subdominant compared to radiative suppression. The number of externally enriched haloes in the bursty SF simulation is an upper bound, as it features the most external metal enrichment of all four simulations, due to the increased supernova energy of Pop. II stars blowing out more metal mass beyond  $r_{\text{vir}}$  of their host halo.

The decreased possibility for haloes to form Pop III stars could also be linked to the lowering of gas fractions in haloes. As FUV radiation increasingly permeates the simulation volume, it photoheats gas in the IGM, pressurizing it and smoothing out small-scale fluctuations in its structure. As a result, the funnelling of gas from filaments into DM haloes becomes increasingly inefficient

as the global SFR increases (M. Dijkstra et al. 2004; H. Katz et al. 2020). In an MW-like environment, this process should occur much faster than in an average patch of the IGM (P. Ocvirk et al. 2016).

In addition, the IGM could be significantly heated (and ionized) by X-ray sources (S. Hegde & S. R. Furlanetto 2023). Such heating would further suppress gas accretion onto low-mass haloes. Conversely, a higher electron fraction would increase the  $H_2$  production rate, so it is unclear whether an X-ray background would help or prevent Pop III formation. We do not explicitly follow X-ray photons, and the uncertainties in the abundance of high- $z$  X-ray sources and their accretion luminosities makes quantifying this effect difficult.

In the middle panel of Fig. 5, we plot the average gas mass in haloes containing no stars as a function of time, divided by the maximum average value reached (typically reached in the first several time bins, as the trends are almost monotonous.) We do this for both the total amount of gas in haloes (in red), and for the amount of gas within  $0.1 r_{\text{vir}}$  (in blue). We find that  $\sim 10^6 M_{\odot}$  haloes forming at 600 Myr have on average a factor of 3–10 (depending on the simulation) times less total gas mass than haloes of the same mass forming at 100 Myr. Comparatively, the inner gas reservoirs in the lowest mass haloes see an order of magnitude drop over 100 Myr at early times, which is attributed to the photodissociation of  $H_2$  by LW radiation discussed earlier. The suppression of Pop III formation at early times is therefore



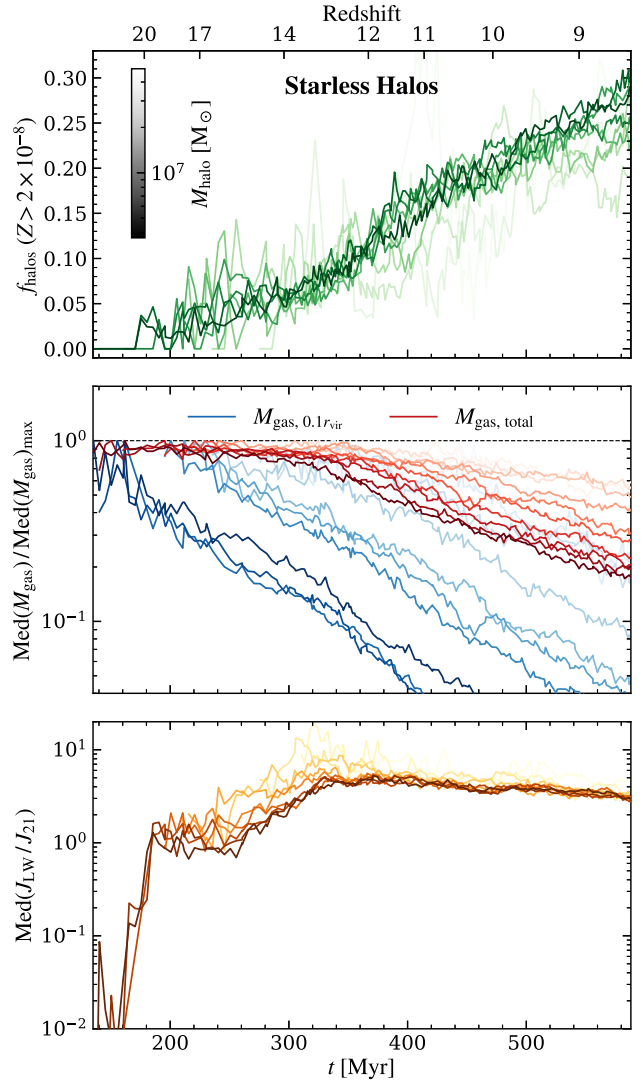
**Figure 4.** The fraction of molecular hydrogen  $f_{\text{H}_2}$  in the inner  $0.1r_{\text{vir}}$  of haloes undergoing their first Pop III formation (within  $\sim 5$  Myr), as a function of LW intensity (parametrized as  $J_{21}$ ) in a thin shell at the virial radius of the halo, for the efficient SF simulation. haloes are coloured by the electron fraction  $f_e$  in the inner  $0.1r_{\text{vir}}$ , and the sizes of points correspond to the age of Universe at that time. Quantities which are computed in the inner halo are density weighted, while quantities computed in the shell are volume weighted. Two distinct populations emerge: haloes with low electron fractions ( $f_e \sim 10^{-4}$ , the Pop III.1 case) forming at early times, and haloes with elevated electron fractions ( $f_e > 10^{-4}$ , the Pop III.2 case) forming at later times, across a wide range of LW strengths.

completely dominated by the inability of haloes to condense gas into their cores.

Although we capture the diversity of Pop III environments which would influence their formation properties (Pop III.1 versus Pop III.2, see Fig. 4), we do not differentiate between the two populations in our star formation prescription, and instead use a single IMF for both formation scenarios. Pop III.2 stars could span a lower mass range from effective HD cooling (S. Nishijima et al. 2024) leading to higher degrees of freedom for gas fragmentation. We also do not consider the Pop III.1 theory for supermassive BH-progenitor stars ( $\sim 10^5 M_{\odot}$ ), driven by dark matter annihilation heating from weakly interacting massive particles (see J. C. Tan et al. 2024).

### 3.1.2 During the Pop III main sequence

For haloes where the gas does cool well below the virial temperature, star formation proceeds as described in Section 2.3.2. Pop III stars generally have higher luminosities and very hard spectra compared to Pop. II counterparts of similar mass (D. Schaerer 2002). The top-heavy nature of our Pop III IMF means Pop III stars in MEGATRON primarily produce ionizing photons. The radiation from Pop III SEDs quickly dissociates the surrounding  $\text{H}_2$  and photoheats the dense gas to  $10^4$  K, as seen in the middle row of Fig. 3. For the most massive ( $> 300 M_{\odot}$ ) Pop III stars, photoheating and RP can completely blow the gas away. As expected for a hard ionizing source, the spectra feature prominent He II recombination lines which are likely to be unique spectroscopic signatures of Pop III systems (H. Katz et al. 2023; J. A. A. Trussler

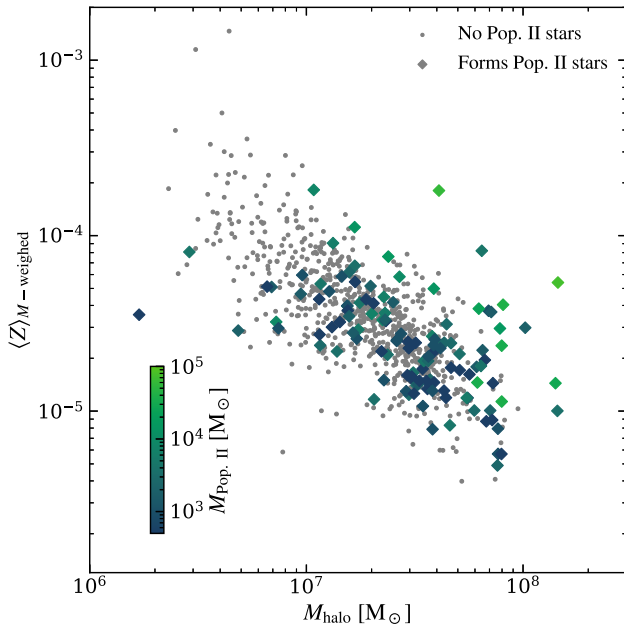


**Figure 5.** Top: the fraction of haloes containing no stars within their virial radii in the bursty SF simulation which have density-weighted metallicities  $Z > 2 \times 10^{-8}$  (the threshold for Pop. II formation) as a function of time. Lines are coloured by halo mass. Starless and metal enriched haloes become more common over time, and make up  $\sim 20 - 30$  per cent of all starless haloes at 600 Myr. Middle: the median gas mass of starless haloes at a given time divided by the maximum value reached at any time. Red represents the total gas mass in haloes out to the virial radius, and in blue indicates the inner gas mass out to  $0.1 r_{\text{vir}}$ . Bottom: the median LW intensity across starless haloes, as measured at the virial radius, as a function of time. The LW intensity increases rapidly after the first stars form, reaching  $J_{21}$  at 200 Myr, which suppresses Pop III formation in minihaloes.

et al. 2023). During the Pop III MS, gas in the inner halo is irradiated by LW radiation with intensity in the range  $10^3 - 10^6 J_{21}$  which maintains the  $\text{H}_2$  fraction below  $10^{-7}$ . As expected, the local LW intensity is positively correlated with Pop III stellar mass and negatively correlated with  $\text{H}_2$  fraction.

### 3.1.3 After the Pop III star dies

The two primary channels of post main-sequence evolution of Pop III stars in our simulations are either direct collapse into a



**Figure 6.** The gas-phase metallicity in haloes as a function of halo mass,  $\sim 10$  Myr following a PISN from a Pop III star in the HN + High  $\epsilon_{\text{ff}}$  simulation. Grey circles are haloes that have not yet formed new stars and diamonds represent haloes undergoing Pop. II formation, coloured by their current Pop. II stellar mass. In general, the metallicity decreases for increasing halo gas mass, as metals are diluted in larger gas reservoirs. Haloes with the highest gas masses can grow over  $10^5 M_{\odot}$  in stellar mass in a short period of time following the PISN.

BH ( $\sim 63$  per cent) or a PISN explosion ( $\sim 36$  per cent). If the star forms a BH, it releases no energy or metals,<sup>3</sup> allowing the gas to remain pristine. As stated previously, since the gas is no longer subject to a strong radiation field, it quickly reforms  $\text{H}_2$  and cools again to form another Pop III star. This process can repeat several times in the same halo core before, statistically, a Pop III star forms within the mass range for PISN. If the star undergoes a PISN, upwards of  $10^{53}$  erg of energy is released into the surrounding dense gas, transferring momentum which can push significant amounts of gas out of the core. Along with energy, a PISN also releases metals into the gas, which allows the gas to quickly cool (as seen in Fig. 3) and begin forming the next generation of stars (the Pop. II phase<sup>4</sup>). The spectra of such systems show prominent [O II] and [S II] collisional lines, and [O III] if the gas is still hot enough, but are extremely faint due to the lack of stellar radiation. We do find a very small subset of PISN systems which are still hosting a shining Pop III star.

We find that for all but the smallest haloes ( $M_{\text{halo}} \leq 4 \times 10^6 M_{\odot}$ ) forming Pop III stars in the PISN mass range, the resulting supernova does not eject most of the gas (including metals) from the halo virial radius, checking the gas phase metallicity content both within 5 and 10 Myr after the supernova. We show in Fig. 6 the mass-weighted metallicity as a function of halo mass following a PISN event. In general, larger haloes contain more gas. As a result, the metallicity decreases with increasing gas

mass as metals are diluted in larger gas reservoirs. The scatter in metallicity for a given halo mass in Fig. 6 is partly driven by the mass range of Pop III stars undergoing PISN, which span a factor of a few in metal yields depending on the initial mass of the star. The gas phase metallicity in haloes are all greater than  $10^{-6}$ , which is enough enrichment to begin the Pop. II formation phase. After  $\sim 10$  Myr, we find that 45 per cent of haloes that hosted a PISN are now forming Pop. II stars in the efficient SF simulation, compared to only 10 per cent in the HN + High  $\epsilon_{\text{ff}}$  where environments are typically over an order of magnitude less dense. Although metals and gas are retained by haloes, we may not be fully resolving the complex mixing of metals following a PISN, as we find the majority of metals to efficiently mix into the cold phase of the ISM on a  $\sim 10$  Myr time-scale, quickly cooling the enriched gas and driving the beginning of the Pop. II star formation phase.

Our results differ from J. Mead et al. (2025), who find the majority of minihaloes to expel all metals following supernovae, and their Pop III stars are much smaller and only include CCSNe with  $10^{51}$  erg. Since haloes forming Pop III stars in the AEOS simulations are an order of magnitude less massive than those in MEGATRON, metals and indeed the rest of the gas is retained by the steeper gravitational potential (T. Kitayama & N. Yoshida 2005; D. Whalen et al. 2008; R. J. Cooke & P. Madau 2014). In fact, haloes with the lowest gas masses ( $M_{\text{gas}} \approx 10^5 M_{\odot}$ ) can reach metallicities of  $6 \times 10^{-3}$  following a PISN, as metals are diluted less. As a result of PISN enrichment, there exists an iron metallicity plateau at  $[\text{Fe}/\text{H}] \approx -2.5$  in the gas phase of small dwarf galaxies (see M. P. Rey et al. 2025, for more details).

### 3.2 Pop III starbursts in massive galaxies

We find in all simulations a few Pop III starbursts occurring in haloes up to  $3 \times 10^8 M_{\odot}$ . The starbursts are comprised of around 20–130 Pop III stars forming in rapid succession, with some visible as outliers in Fig. 2. As these systems have the largest amount of Pop III stars shining at the same time, they represent the brightest Pop III galaxies in our simulations. The total gas masses in Pop III starburst haloes range from  $2 \times 10^7 - 4 \times 10^7 M_{\odot}$ , and are found to have been the sites of previous Pop III formation.

H. Xu et al. (2016) are also able to form Pop III starbursts in their haloes, although in their simulation they form in haloes with lower gas masses of  $6 \times 10^6$  to  $10^7 M_{\odot}$ . While they attribute this growth to external LW radiation preventing collapse in the vicinity of bright galaxies, we find our haloes to self-quench cooling through the repeated formation of Pop III stars in the BH mass range. This allows for the host halo to continue growing while keeping the gas pristine, until a critical gas mass is reached to trigger a Pop III starburst. Since the halo has built up a large reservoir of dense gas, Pop III stars can keep forming even under the strong LW radiation and photoheating sourced from the stars.

Our results for Pop III starburst galaxies could change significantly if assuming a different Pop III IMF, or if the thermochemistry was better calibrated for the Pop III.2 formation case. As Pop III.2 stars could be potentially formed from a less top-heavy IMF, a lower mass range would yield fewer BHs and therefore a smaller probability for Pop III starbursts. The rapid star formation process could also be halted sooner if  $\text{Ly}\alpha$  RP was included in our simulations (see the calibration simulations including  $\text{Ly}\alpha$  RP in H. Katz et al. 2024). In metal-poor gas, with stars that produce many ionizing photons,  $\text{Ly}\alpha$  becomes a dominant source of pressure (O. Nebrin et al. 2025). Such pressure would potentially drive gas

<sup>3</sup>We do not model subsequent feedback, including RT from BHs which may be accreting.

<sup>4</sup>See N. Choustikov et al. (2025) for details on the ISM of Pop. II galaxies in the MEGATRON high- $z$  suite.

out of the collapsing cloud and prevent further star formation, although the detailed structure of the ionized region needs to be resolved to properly quantify this effect.

While our simulations are able to produce Pop III starbursts, we stress that they are extremely rare events (1–3 per simulation) and not representative of the larger population of Pop III systems. Nevertheless, they are fundamentally interesting objects as they are the easiest to observe.

### 3.3 The observability of Pop III galaxies

#### 3.3.1 Spectra of a bright Pop III galaxy

The spectra of Pop III systems in MEGATRON are diverse, with UV slopes in the range  $-2 < \beta < -1.5$  (redder than those of typical Pop. II galaxies, see H. Katz et al. 2025a). Equivalent widths of the He II lines depend strongly on the mass of the Pop III stars, and typically range from 10–200 Å. Equivalent widths of the H $\alpha$  line also vary, with values between 3000–5000 Å. The top-heavy nature of our Pop III IMF used in the simulations means that these stars have very efficient production of ionizing photons, leading to nebular emission brighter than the stellar spectra itself (A. J. Cameron et al. 2024; H. Katz et al. 2025c). Here, we focus on the spectra of the brightest Pop III galaxy produced in the MEGATRON simulations, which we show in Fig. 7 as  $m_{\text{AB}}$  against observed wavelength  $\lambda_{\text{obs}}$ . We convolve the spectra with *JWST* NIRCcam and MIRI filters as they represent the deepest existing observations.

The strongest emission lines in the spectra are Ly $\alpha$  and H $\alpha$ , the first spectral lines in the Lyman and Balmer series, respectively. Whilst a booming H $\alpha$  line (with equivalent widths greater than 3000) is an indicator of Pop III systems, the Ly $\alpha$  line is likely to be heavily attenuated by the neutral IGM in the epoch of reionization (A. K. Inoue et al. 2014). However, since galaxies both make and reside in ionized bubbles, the Ly $\alpha$  emission from Pop III galaxies might be detectable, as we have already observed the Ly $\alpha$  transition in objects beyond redshift 10 (A. J. Bunker et al. 2023; J. Witstok et al. 2025). The size of the bubble depends on redshift, neutral fraction of the IGM, and EW of the Ly $\alpha$  line. It is unclear whether such a galaxy would have enough ionizing flux to carve out an ionized bubble out to a few pMpc, required to redshift Ly $\alpha$  out of the resonance wavelength (A. Saxena et al. 2023), and would probably need neighbouring systems to help re-ionize the IGM. The equivalent width of H $\alpha$  of our brightest Pop III galaxy is measured at  $\text{EW}(\text{H}\alpha) = 3870$  Å, and both He II lines have equivalent widths of  $\text{EW}(\text{He}_{\text{II}, 1640}; \text{He}_{\text{II}, 4686}) = 66$  Å. The recently discovered system LAP2-b (E. Vanzella et al. 2026) has a derived stellar mass of at most  $2 \times 10^4 M_{\odot}$  which is comparable to our brightest Pop III galaxy, but has a measured  $\text{EW}(\text{H}\alpha) = 647$  Å which is 6–8 times weaker than our Pop III galaxies.

The burden of proof for Pop III systems is incredibly high, as it involves proving the absence of metals. Photometric and spectroscopic observations only yield upper limits on metal lines, and we would need to measure the nebular continuum in exquisite detail to confirm the absence of carbon lines and rule out a high enough carbon abundance for the CNO cycle to operate. As the [O III] 5007 Å line is the most prominent metal line accessible at high redshift, a potentially important diagnostic for constraining spectra into the Pop III regime is the [O III]/H $\beta$  ratio (H. Katz et al. 2023). For almost all Pop III galaxies in MEGATRON, the spectra are nebular-dominated and only feature recombination

lines of H and He. We do however find rare cases where multiple Pop III stars forming at the same time, with one star going PISN while the others remain on the MS, leading to bright [O III], [O II], and [S II] emission.

The physical resolution at the onset of Pop III formation (1.5 pc), combined with the top-heavy IMF, means that almost all Strömgren spheres are resolved at  $z = 30$ . As the simulation proceeds to lower redshift, the expanding Universe coarsens the resolution of our grid. By the end of the simulation ( $z = 8.5$ ), most Pop III stars no longer have resolved Strömgren spheres except for the most massive ones, leading to a less accurate processing of ionizing photons and potentially biasing emission line/nebular continuum predictions (although we apply CLOUDY corrections to cells with unresolved Strömgren spheres,<sup>5</sup> see H. Katz et al. 2025a for details.)

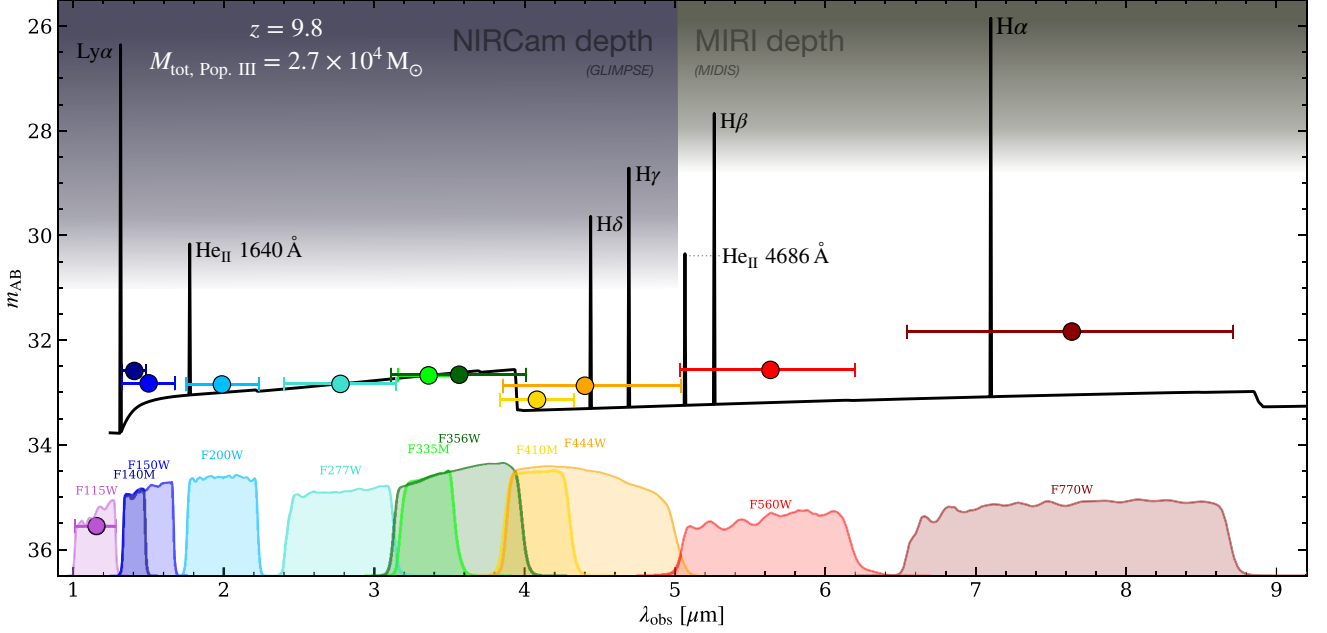
#### 3.3.2 UV magnitudes

We compute the UV magnitudes of every halo hosting an actively shining Pop III star in the MEGATRON simulations using the method described in Section 2.5. We plot in Fig. 8 the UV magnitudes of our simulated Pop III galaxies as a function of redshift, and compare them to some of the faintest galaxies detected by *JWST*. The vast majority of Pop III galaxies have  $-6 > M_{\text{UV}} > -12$ , with the distribution peaking around  $M_{\text{UV}} \sim -9$ . The brightest Pop III galaxy in our simulations reaches  $M_{\text{UV}} \sim -14.5$  at  $z = 9.8$ , and is around two orders of magnitude fainter than the faintest galaxies detected by *JWST* beyond  $z = 8$  (M. Castellano et al. 2023; E. Merlin et al. 2024; G. Roberts-Borsani et al. 2025; V. Kokorev et al. 2025). A gravitational lens with magnification  $\mu > 10$  would allow the Pop III galaxy spectrum to be detectable by deep NIRCcam imaging if considering integration times similar to those of the GLIMPSE survey. While such a scenario might seem unlikely (A. Vikaeus et al. 2022; E. Zackrisson et al. 2024), there are potentially pristine and star-forming systems already being observed at  $z \sim 4$  under a strong ( $\mu \sim 50$ ) magnifying lens (E. Vanzella et al. 2026).

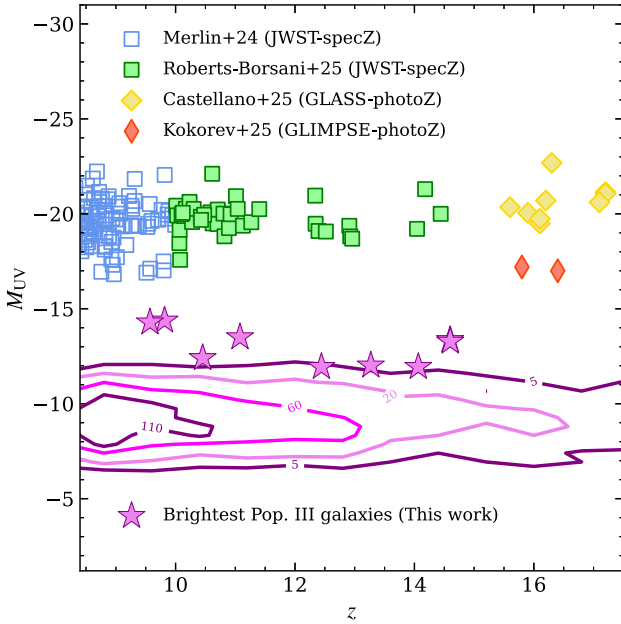
#### 3.3.3 Proximity to UV-bright galaxies

Current searches for Pop III stars using *JWST* either focus on gravitational caustics, where lensing of a background galaxy can boost the observed flux of individual star-forming regions by an order of magnitude, or look at the surrounding environments of UV-bright galaxies. Some of the faintest objects *JWST* is currently detecting beyond  $z = 8$  have  $M_{\text{UV}} \sim -17$  (see Fig. 8), so we adopt this value as our lower limit for UV-bright galaxies. In Fig. 9, we show the closest distance between newly formed Pop III stars and galaxies as a function of  $M_{\text{UV}}$ . In general, the minimum distance between Pop III stars and UV-bright galaxies decreases with increasing  $M_{\text{UV}}$ . The efficient SF run consistently has Pop III stars closest to bright galaxies, with some Pop III stars forming within the virial radius of galaxies with  $-17.5 < M_{\text{UV}} < -17$ . This simulation produces many more UV-bright galaxies than the other three simulations due to it having the weakest feedback. The large number of bright galaxies occupy more of the volume which increases the probability of having nearby Pop III stars.

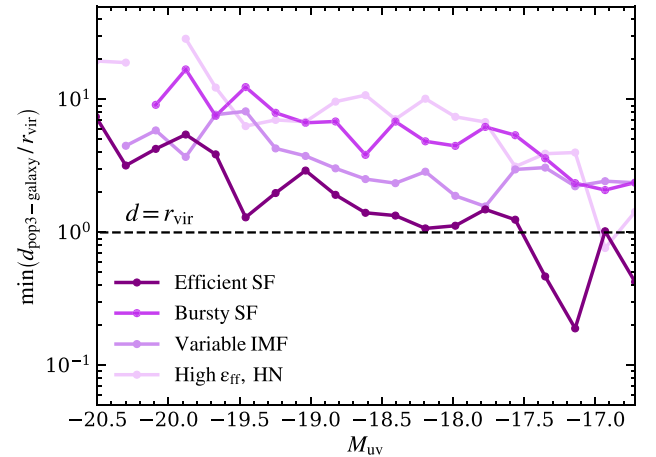
<sup>5</sup>RAMSES-RTZ has been shown to be within 10 per cent of CLOUDY for idealized tests (H. Katz et al. 2024).



**Figure 7.** AB magnitude of the brightest Pop III galaxy spectra in our simulations as a function of observed wavelength. The galaxy contains 136 shining Pop III stars at  $z = 9.8$  for a combined stellar mass of  $2.7 \times 10^4 M_{\odot}$ . We include mock photometric measurements from the *JWST* NIRCcam and MIRI instruments, with the coloured circles corresponding to a select number of filters. The transmission and range of each filter are shown at the bottom of the figure. The NIRCcam and MIRI depths are illustrated as gradients terminating at  $m_{AB} \sim 31$  (Galactic Legacy Infrared Mid-Plane Survey Extraordinaire, GLIMPSE; V. Kokorev et al. 2025) and  $m_{AB} = 28.75$  (MIRI Deep Imaging Survey, MIDIS; G. Östlin et al. 2025), respectively, representing the deepest integration depths reached by those instruments. The spectra feature strong H I and He II recombination lines with equivalent widths  $EW(H\alpha) = 3870 \text{ \AA}$  and  $EW(He II, 1640; He II, 4686) = 66 \text{ \AA}$ .



**Figure 8.** The UV magnitudes of the 10 brightest Pop III galaxies in MEGATRON as a function of redshift across all the simulations. All other Pop III galaxies are represented by density isocontours with the count thresholds as inline labels. We include the highest redshift galaxies observed by *JWST*, whose redshift has either been spectroscopically confirmed (E. Merlin et al. 2024; G. Roberts-Borsani et al. 2025), or inferred from NIRCcam photometry (M. Castellano et al. 2023; V. Kokorev et al. 2025). Pop III galaxies generally have  $-7 > M_{UV} > -12$ , and the brightest galaxy reaches  $M_{UV} = -14.5$  which is still 2 dex below that of the faintest *JWST* galaxy observed.



**Figure 9.** The minimum distance between a recently formed Pop III star and UV-bright galaxies, divided by those galaxies' virial radii, as a function of  $M_{UV}$ . The coloured lines are for the four different MEGATRON simulations. Pop III stars are able to form closer to UV-bright galaxies for increasing  $M_{UV}$ , with the efficient SF run forming Pop III stars within  $r_{vir}$  of *JWST*-observable galaxies beyond  $z = 8$ .

Out of the four MEGATRON runs, only the efficient SF and HN + High  $\epsilon_{ff}$  simulations are able to produce Pop III stars within the virial radius of bright galaxies. Consistent across all runs, the vast majority of Pop III stars form at least  $10 r_{vir}$  away from bright galaxies, with only  $6 / \sim 10^4$  Pop III stars forming within the virial radius of UV-bright galaxies, challenging the feasibility of detecting Pop III stars in this manner. As we find a general trend

of Pop III stars forming closer to increasingly dimmer galaxies, and if *JWST* is able to detect galaxies further down to  $M_{\text{UV}} = -15$  (perhaps even down to  $M_{\text{UV}} = -12$ , see I. Chemerynska et al. 2026), then the prospects of finding Pop III stars in the vicinity of UV-bright galaxies could improve. Whether through proximity of UV-bright galaxies or behind strong gravitational lenses, detecting Pop III stars at high- $z$  remains an onerous enterprise, and it very well could be that the current approaches of observational surveys are the most optimal.

### 3.4 Pop III distribution at $z = 0$

An interesting open question regarding Pop III stars concerns where they end up at the present day. Many surveys have looked for very metal-poor stars (A. Frebel & J. E. Norris 2015), whose chemical abundances are the result of individual Pop III supernova (e.g. A. P. Ji et al. 2020). If Pop III stars are able to form below  $0.8 M_{\odot}$ , then they could potentially survive to  $z = 0$  (A. Maeder & G. Meynet 2012), and have unique spectroscopic signatures (specifically the lack of metal lines, both in emission and absorption) detectable by upcoming archaeological surveys like 4MOST (N. Christlieb et al. 2019) and WEAVE (S. Jin et al. 2024). As our IMF of choice is very top-heavy, none of the Pop III stars in MEGATRON have main-sequence lifetimes long enough to live to the present day, they instead become BHs or explode as SN. However since the Pop III stars in our simulations are relics of pristine and dense star-forming gas clouds, regardless of the specific details of the uncertain Pop III IMF, our Pop III stars trace the sites of metal-free star formation. Nevertheless, given the uncertainties in the Pop III IMF, if we temporarily assume that some low-mass Pop III stars can form at these sites, we can ask where these stars might be at the present day.

We track the positions of Pop III stars to  $z = 0$  following the method described in Section 2.7, and plot their spatial distribution in Fig. 10, coloured by whether they reside in main haloes or subhaloes. We include the number of Pop III stars per halo as a function of halo mass, and the cumulative distribution function of Pop III stars as a function of distance from the main halo centre. We find the majority of Pop III stars reside in the main halo, with 70 per cent of main halo stars found further than 10 kpc ( $> 0.02 r_{\text{vir}}$ ) from the halo centre. E. Starkenburg et al. (2017) also find a dominant fraction of Pop III stars reside in the stellar haloes of the APOSTLE simulations. Furthermore, we find 20–25 per cent of Pop III stars are in subhaloes that have not undergone major tidal disruption. Our results are in close agreement with those of H. Yang et al. (2025), who analyse haloes from the Auriga project and find a similar 80–20 split between their first stellar population<sup>6</sup> in the main halo and in subhaloes, respectively.

Individual subhaloes can host upwards of 100 Pop III remnants, even down to halo masses of  $2 \times 10^6 M_{\odot}$ . While one might expect to find more Pop III stars in systematically larger subhaloes, the relation is not as clear. The trend remains relatively flat in  $N_{\text{pop3}}$  for haloes with masses  $< 10^9 M_{\odot}$ , with a steep increase in  $N_{\text{pop3}}$  for haloes more massive than  $10^9 M_{\odot}$ . While we cannot make a determination on the final stellar masses of the subhaloes in the DMO simulation, we can assume they are comparable to local dwarf galaxies of similar halo mass. When con-

sidering the derived stellar masses of the MW and surrounding satellites, the best regions to search for Pop III stars may well be in small dwarfs whose  $M_{\star, \text{Pop III}}/M_{\star, \text{total}}$  ratios are highest (M. Magg et al. 2018; R. S. Klessen & S. C. O. Glover 2023).

## 4 CONCLUSIONS

We have analysed the MEGATRON suite of simulations of an MW progenitor, run with the RAMSES-RTZ code (H. Katz 2022), to understand the formation of Pop III stars in the early Universe, focusing on the environments in which they form, their observational properties, and where their remnants end up at the present day. MEGATRON is well suited to study the formation of the first stars because:

- (i) it encompasses the large-scale environment of an MW-mass progenitor;
- (ii) it follows a non-equilibrium thermochemical network, including the formation of  $\text{H}_2$ ;
- (iii) it includes on-the-fly and multifrequency radiative transfer from star particles, including the LW band which is a crucial component for studying Pop III environments;
- (iv) it has high resolution ( $\lesssim 1.5 \text{pc } h^{-1}$ ) at the onset of the formation of Pop III stars, resolving the individual Strömgren spheres of the earliest stars;
- (v) it includes a DMO version run to  $z = 0$ , allowing us to connect the remnants of Pop III stars to their spatial distributions at the present day.

We are not the first to model Pop III formation, nor do we have the best resolution, but we have all five points above. Particularly, the environments of Pop III stars in a proto-MW has not yet been studied with such prescriptions (although see B. F. Griffen et al. 2018 in the context of semi-analytic models). The main findings from our analysis are that:

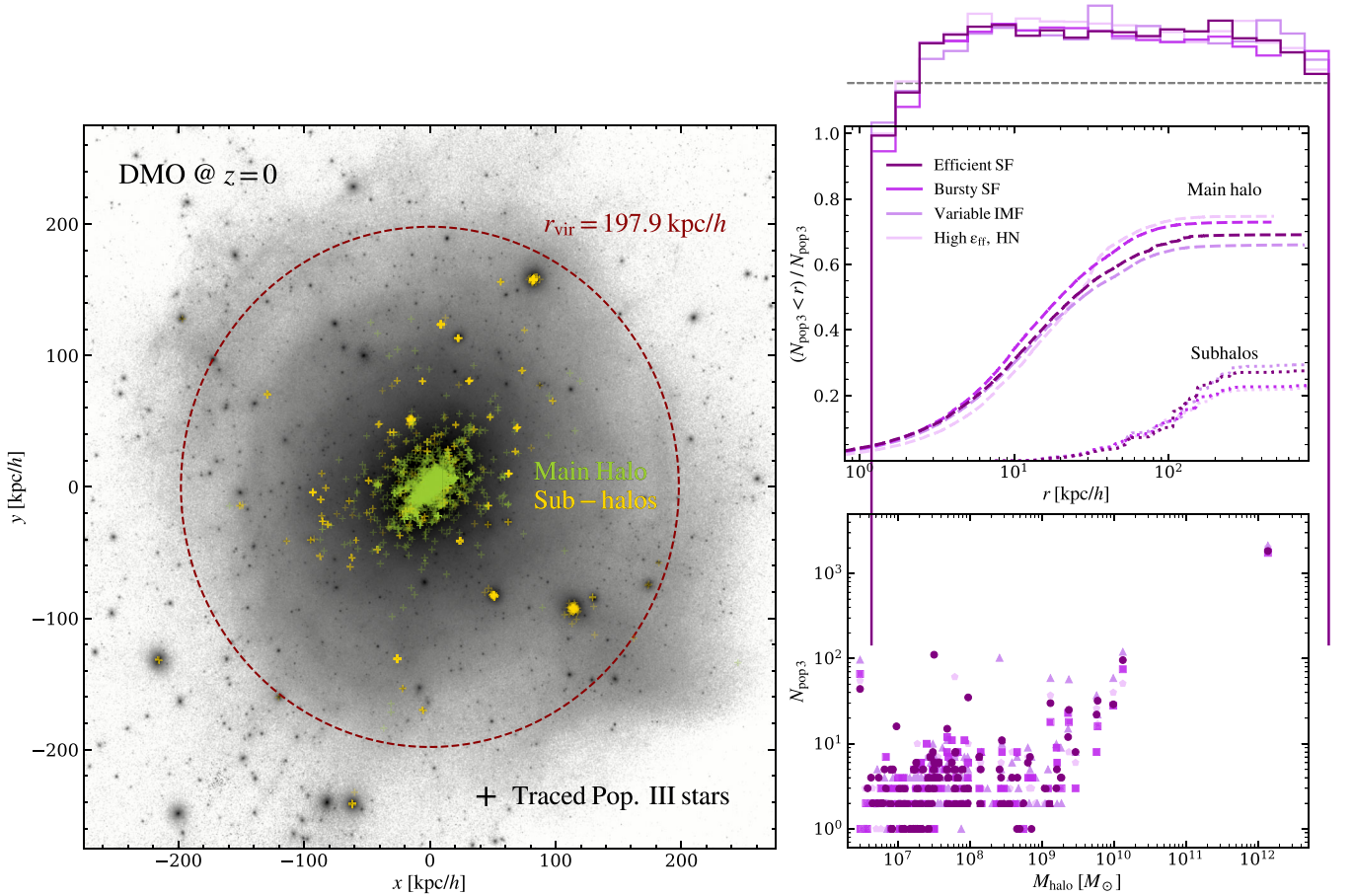
(i) Pop III stars preferentially form in haloes in the mass range  $\sim 10^6 - 10^8 M_{\odot}$  with a constant SFR of  $10^{-3} M_{\odot} \text{yr}^{-1}$  up to the end of the simulations ( $z \approx 8.5$ ). The presence of LW radiation from nearby star-forming regions can dissociate  $\text{H}_2$  and prevent Pop III formation in  $10^6 M_{\odot}$  haloes, pushing Pop III star formation to more massive haloes ( $\sim 10^7 - 10^8 M_{\odot}$ ). Although we find an increase in starless but metal-enriched haloes over time, the majority of starless haloes remain pristine down to  $z \sim 8.5$ .

(ii) On extremely rare occasions, the order of a few per simulation, a halo can host the formation of many Pop III stars. If the repeated Pop III star formation events all conclude with direct collapse to a BH, the host halo will continue to grow and remain metal-free, until a critical gas mass of  $\sim 10^8 M_{\odot}$  is reached to trigger a Pop III starburst. These starbursts can form up to 100 Pop III stars in rapid succession in haloes up to  $2 \times 10^8 M_{\odot}$ . If haloes in the Universe are able to form such starbursts, they would be the most likely to be directly observable.

(iii) Although there is a clear trend of Pop III stars forming closer to galaxies as a function of increasing  $M_{\text{UV}}$ , Pop III stars typically form far away from UV-bright galaxies, with only  $\sim 6$  out of  $10^4$  Pop III stars forming within the virial radius of galaxies with  $M_{\text{UV}} < -17$ . This suggests that detecting Pop III stars as a consequence of their proximity to bright galaxies is unlikely, but is probably the most optimal approach compared to a random search.

(iv) Finally, we trace the positions of Pop III stars to  $z = 0$  using a DMO version of our simulations and find that most of them

<sup>6</sup>These simulations do not explicitly form Pop III stars, and instead call their first stellar population ‘earliest star relic’.



**Figure 10.** Left: particle projection of the dark matter structure in the DMO simulation at  $z = 0$ , centred on the main halo. The virial radius of the halo is indicated by the circle drawn with a dark red dashed line. Crosses represent a Pop III star traced down to  $z = 0$  by following the closest 25 dark matter particles in the last output of the efficient SF simulation. We pick a random dark matter particle from the list of 25, plot a cross at its position at  $z = 0$ , and colour the cross in green if it is in the main halo, or in yellow if it is in a subhalo. Upper right: the CDF of the distances between the Pop III stars and the centre of the main halo at  $z = 0$ , for both main halo and subhalo stars. Lower right: the number of Pop III stars in each halo as a function of halo mass, coloured by which simulation do the Pop III stars originate from.

(>70 per cent) reside in the main halo, with a significant fraction (20–25 per cent) in subhaloes. Our conclusions are similar to those of previous studies (E. Starck et al. 2017; H. Yang et al. 2025), which also found that Pop III stars are predominantly located in the diffuse stellar haloes of their host galaxies. Additionally, there are tidally undisturbed haloes down to masses of  $10^6 M_{\odot}$  which can host up to  $\sim 100$  Pop III stellar remnants

In recent years, we have become increasingly reliant on numerical simulations to self-consistently model the environments of Pop III stars (H. Xu et al. 2013; T. Kimm et al. 2017; H. Katz et al. 2023; K. Brauer et al. 2025), particularly the inhomogeneous nature of the LW background and its dependence on the overdensity structure sourced in the ICs. Our work is the first to self-consistently follow the LW background in the progenitor of an MW-like environment along with modelling the formation of individual Pop III stars. Although simulating such environments with a high enough resolution to resolve the Pop III phase remains computationally difficult, the MEGATRON simulations highlight the importance of following the radiation field in such an environment.

The distribution of Pop III stars in an MW environment at present day have not yet been derived from self-consistent mod-

elling of Pop III formation. With MEGATRON, we are able to connect the formation of Pop III stars to the halo–subhalo structure at  $z = 0$ . Our results therefore provide a key theoretical baseline for the search of Pop III stars in near-field cosmology. There are many current efforts to find Pop III stars, with an ever increasing catalogue of metal-poor stars in the MW stellar halo (N. Christlieb et al. 2019) and nearby dwarf galaxies (A. Skúladóttir et al. 2023). Simulations such as MEGATRON will be key to interpret results for many of the upcoming surveys, allowing to constrain the early evolution of galaxies like our MW.

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## DATA AVAILABILITY

The data used in this paper can be obtained on reasonable request to the corresponding author.

## REFERENCES

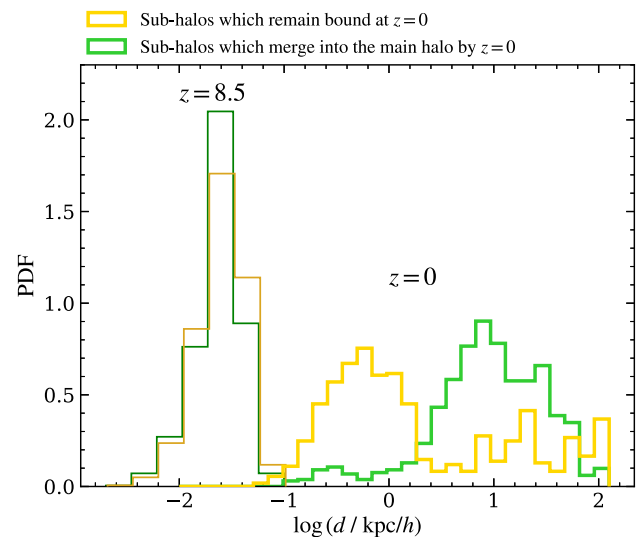
- Agarwal B., Smith B., Glover S., Natarajan P., Khochfar S., 2016, *MNRAS*, 459, 4209
- Astropy Collaboration, 2022, *ApJ*, 935, 167
- Barkana R., Loeb A., 2001, *Phys. Rep.*, 349, 125
- Behroozi P. S., Wechsler R. H., Wu H.-Y., 2013, *ApJ*, 762, 109
- Brauer K. et al., 2025, *ApJ*, 980, 41
- Bromm V., Loeb A., 2003, *Nature*, 425, 812
- Bromm V., Yoshida N., 2011, *ARA&A*, 49, 373
- Bromm V., Yoshida N., Hernquist L., McKee C. F., 2009, *Nature*, 459, 49
- Bunker A. J. et al., 2023, *A&A*, 677, A88
- Cai S. et al., 2025, *ApJ*, 993, L52
- Cameron A. J., Katz H., Witten C., Saxena A., Laporte N., Bunker A. J., 2024, *MNRAS*, 534, 523
- Castellano M. et al., 2023, *ApJ*, 948, L14
- Chemerynska I. et al., 2026, *MNRAS*, 546, 23
- Choustikov N. et al. 2026, *Open J. Astrophys.*, 9
- Christlieb N. et al., 2019, *The Messenger*, 175, 26
- Clark P. C., Glover S. C. O., Klessen R. S., Bromm V., 2011, *ApJ*, 727, 110
- Cooke R. J., Madau P., 2014, *ApJ*, 791, 116
- Dere K. P., Del Zanna G., Young P. R., Landi E., Sutherland R. S., 2019, *ApJS*, 241, 22
- de Souza R. S., Ishida E. E. O., Whalen D. J., Johnson J. L., Ferrara A., 2014, *MNRAS*, 442, 1640
- Dijkstra M., Haiman Z., Rees M. J., Weinberg D. H., 2004, *ApJ*, 601, 666
- Ekström S., Meynet G., Chiappini C., Hirschi R., Maeder A., 2008, *A&A*, 489, 685
- Eldridge J. J., Izzard R. G., Tout C. A., 2008, *MNRAS*, 384, 1109
- Eldridge J. J., Stanway E. R., Xiao L., McClelland L. A. S., Taylor G., Ng M., Greis S. M. L., Bray J. C., 2017, *Publ. Astron. Soc. Aust.*, 34, e058
- Federrath C., Klessen R. S., 2012, *ApJ*, 761, 156
- Ferland G. J. et al., 2017, *Rev. Mex. Astron. Astrofis.*, 53, 385
- Fialkov A., Barkana R., Tselikhovich D., Hirata C. M., 2012, *MNRAS*, 424, 1335
- Frebel A., Norris J. E., 2015, *ARA&A*, 53, 631
- Fujimoto S. et al., 2025, *ApJ*, 989, 46
- Galli D., Palla F., 1998, *A&A*, 335, 403
- Glover S. C. O., Federrath C., Mac Low M. M., Klessen R. S., 2010, *MNRAS*, 404, 2
- Greif T. H., 2015, *Comput. Astrophys. Cosmol.*, 2, 3
- Griffen B. F., Dooley G. A., Ji A. P., O'Shea B. W., Gómez F. A., Frebel A., 2018, *MNRAS*, 474, 443
- Haardt F., Madau P., 2012, *ApJ*, 746, 125
- Haiman Z., Abel T., Rees M. J., 2000, *ApJ*, 534, 11
- Harris C. R. et al., 2020, *Nature*, 585, 357
- Hartwig T., Bromm V., Klessen R. S., Glover S. C. O., 2015, *MNRAS*, 447, 3892
- Hartwig T. et al., 2022, *ApJ*, 936, 45
- Hegde S., Furlanetto S. R., 2023, *MNRAS*, 525, 428
- Hegde S., Furlanetto S. R., 2025, *Open J. Astrophys.*, 8, 147
- Heger A., Woosley S. E., 2002, *ApJ*, 567, 532
- Hirano S., Hosokawa T., Yoshida N., Umeda H., Omukai K., Chiaki G., Yorke H. W., 2014, *ApJ*, 781, 60
- Hosokawa T., Hirano S., Kuiper R., Yorke H. W., Omukai K., Yoshida N., 2016, *ApJ*, 824, 119
- Hunter J. D., 2007, *Comput. Sci. Eng.*, 9, 90
- Inoue A. K., Shimizu I., Iwata I., Tanaka M., 2014, *MNRAS*, 442, 1805
- Ishigaki M. N., Tominaga N., Kobayashi C., Nomoto K., 2018, *ApJ*, 857, 46
- Jaacks J., Thompson R., Finkelstein S. L., Bromm V., 2018, *MNRAS*, 475, 4396
- Jaura O., Glover S. C. O., Wollenberg K. M. J., Klessen R. S., Geen S., Haemmerle L., 2022, *MNRAS*, 512, 116
- Ji A. P. et al., 2020, *ApJ*, 889, 27
- Jiang R., Zhao G., Li H., Xing Q., 2024, *ApJ*, 976, 68
- Jin S. et al., 2024, *MNRAS*, 530, 2688
- Johnson B. D., 2019, *Astrophysics Source Code Library*, record ascl:1905.026
- Johnson J. L., Greif T. H., Bromm V., 2008, *MNRAS*, 388, 26
- Katz H., 2022, *MNRAS*, 512, 348
- Katz H. et al., 2020, *MNRAS*, 494, 2200
- Katz H. et al., 2022, PRISM: A Non-Equilibrium, Multiphase Interstellar Medium Model for Radiation Hydrodynamics Simulations of Galaxies, <https://ui.adsabs.harvard.edu/abs/2022arXiv221104626K>
- Katz H., Kimm T., Ellis R. S., Devriendt J., Slyz A., 2023, *MNRAS*, 524, 351
- Katz H., Rey M. P., Cadiou C., Kimm T., Agertz O., 2026, *Open J. Astrophys.*, 9
- Katz H. et al., 2025a, Meg P1. preprint (arXiv:2510.05201), <https://arxiv.org/abs/2510.05201>
- Katz H. et al., 2025c, *Open J. Astrophys.*, 8, 104
- Kimm T., Katz H., Haehnelt M., Rosdahl J., Devriendt J., Slyz A., 2017, *MNRAS*, 466, 4826
- Kimm T., Haehnelt M., Blaizot J., Katz H., Michel-Dansac L., Garel T., Rosdahl J., Teyssier R., 2018, *MNRAS*, 475, 4617
- Kitayama T., Yoshida N., 2005, *ApJ*, 630, 675

Klessen R. S., Glover S. C. O., 2023, *ARA&A*, 61, 65  
 Kokorev V. et al., 2025, *ApJ*, 983, L22  
 Larkin M. M., Gerasimov R., Burgasser A. J., 2023, *AJ*, 165, 2  
 Leitherer C. et al., 1999, *ApJS*, 123, 3  
 Lenoble R., Commerçon B., Rosdahl J., 2024, *A&A*, 685, A7  
 Liu B., Bromm V., 2021, *MNRAS*, 506, 5451  
 Luridiana V., Morisset C., Shaw R. A., 2015, *A&A*, 573, A42  
 Maeder A., Meynet G., 2012, *Rev. Mod. Phys.*, 84, 25  
 Magg M., Hartwig T., Agarwal B., Frebel A., Glover S. C. O., Griffen B. F., Klessen R. S., 2018, *MNRAS*, 473, 5308  
 Maiolino R. et al., 2024, *A&A*, 687, A67  
 Mead J. et al., 2025, *ApJ*, 980, 62  
 Merlin E. et al., 2024, *A&A*, 691, A240  
 Miralda-Escudé J., 2003, *ApJ*, 597, 66  
 Nagakura T., Omukai K., 2005, *MNRAS*, 364, 1378  
 Nakajima K. et al., 2025, preprint (arXiv:2506.11846)  
 Nebrin O., Smith A., Lorinc K., Hornquist J., Larson a., Mellema G., Giri S. K., 2025, *MNRAS*, 537, 1646  
 Nishijima S., Hirano S., Umeda H., 2024, *ApJ*, 965, 141  
 Nomoto K., Tominaga N., Umeda H., Kobayashi C., Maeda K., 2006, *Nucl. Phys. A*, 777, 424  
 Nomoto K., Kobayashi C., Tominaga N., 2013, *Annu. Rev.*, 51, 457  
 O’Shea B. W., Norman M. L., 2008, *ApJ*, 673, 14  
 Ocvirk P. et al., 2016, *MNRAS*, 463, 1462  
 Oke J. B., Gunn J. E., 1983, *ApJ*, 266, 713  
 Omukai K., Tsuribe T., Schneider R., Ferrara A., 2005, *ApJ*, 626, 627  
 Östlin G. et al., 2025, *A&A*, 696, A57  
 Padoan P., Nordlund A., 2011, *ApJ*, 730, 40  
 Park J., Ricotti M., Sugimura K., 2021, *MNRAS*, 508, 6176  
 Planck Collaboration XIII, 2016, *A&A*, 594, A13  
 Pontzen A., Tremmel M., 2018, *ApJS*, 237, 23  
 Pontzen A., Rey M. P., Cadiou C., Agertz O., Teyssier R., Read J., Orkney M. D. A., 2021, *MNRAS*, 501, 1755  
 Pontzen A., Cadiou C., Stopyra S., Roth N., Rey M. P., 2022, *pynbody/genetIC: Version 1.3.5*. <https://doi.org/10.5281/zenodo.6327377>  
 Pontzen A., Tremmel M., Cadiou C., Rey M. P., Wright A., Davies J., philosoph Quinn T., 2023, *Pynbody/Tangos: Version 1.9.1*. Zenodo  
 Rey M. P., Pontzen A., 2018, *MNRAS*, 474, 45  
 Rey M. P., Starkenburg T. K., 2022, *MNRAS*, 510, 4208  
 Rey M. P. et al., 2025, Meg P2. preprint (arXiv:2510.05232), <https://arxiv.org/abs/2510.05232>  
 Roberts-Borsani G. et al., 2025, preprint (arXiv:2508.21708)  
 Rosdahl J., Teyssier R., 2015, *MNRAS*, 449, 4380  
 Rosdahl J., Blaizot J., Aubert D., Stranex T., Teyssier R., 2013, *MNRAS*, 436, 2188  
 Rosdahl J. et al., 2018, *MNRAS*, 479, 994  
 Salvadori S., Ferrara A., Schneider R., Scannapieco E., Kawata D., 2010, *MNRAS*, 401, L5  
 Saxena A. et al., 2023, *A&A*, 678, A68  
 Schaerer D., 2002, *A&A*, 382, 28  
 Schauer A. T. P., Glover S. C. O., Klessen R. S., Clark P., 2021, *MNRAS*, 507, 1775  
 Skúladóttir A. et al., 2023, *The Messenger*, 190, 19  
 Smith B. D., Wise J. H., O’Shea B. W., Norman M. L., Khochfar S., 2015, *MNRAS*, 452, 2822  
 Stacy A., Bromm V., Loeb A., 2011, *ApJ*, 730, L1  
 Starkey E. R., Eldridge J. J., 2018, *MNRAS*, 479, 75  
 Starkenburg E., Oman K. A., Navarro J. F., Crain R. A., Fattahi A., Frenk C. S., Sawala T., Schaye J., 2017, *MNRAS*, 465, 2212  
 Stopyra S., Pontzen A., Peiris H., Roth N., Rey M. P., 2021, *ApJS*, 252, 28  
 Tan J. C., Singh J., Cammelli V., Sanati M., Petkova M., Nandal D., Monaco P., 2024, preprint (arXiv:2412.01828)  
 Tanaka S. J., Chiaki G., Tominaga N., Susa H., 2017, *ApJ*, 844, 137  
 Teyssier R., 2002, *A&A*, 385, 337  
 The pandas development team, 2020, *pandas-dev/pandas: Pandas*. <https://doi.org/10.5281/zenodo.3509134>

Trussler J. A. A. et al., 2023, *MNRAS*, 525, 5328  
 Tseliakhovich D., Hirata C., 2010, *Phys. Rev. D*, 82, 083520  
 Turk M. J., Smith B. D., Oishi J. S., Skory S., Skillman S. W., Abel T., Norman M. L., 2011, *ApJS*, 192, 9  
 Umeda H., Nomoto K., 2002, *ApJ*, 565, 385  
 Uysal B., Hartwig T., 2023, *MNRAS*, 520, 3229  
 Vanzella E. et al., 2023, *A&A*, 678, A173  
 Vanzella E. et al., 2026, *A&A*, 705, L12  
 Ventura E. M., Qin Y., Balu S., Wyithe J. S. B., 2025, *MNRAS*, 540, 483  
 Vikaeus A., Zackrisson E., Schaerer D., Visbal E., Fransson E., Malhotra S., Rhoads J., Sahlén M., 2022, *MNRAS*, 512, 3030  
 Vink J. S., de Koter A., Lamers H. J. G. L. M., 2000, *A&A*, 362, 295  
 Virtanen P. et al., 2020, *Nat. Methods*, 17, 261  
 Visbal E., Haiman Z., Bryan G. L., 2014, *MNRAS*, 445, 1056  
 Visbal E., Bryan G. L., Haiman Z., 2020, *ApJ*, 897, 95  
 Wang X. et al., 2024, *ApJ*, 967, L42  
 Welch B. et al., 2022, *ApJ*, 940, L1  
 Whalen D., van Veelen B., O’Shea B. W., Norman M. L., 2008, *ApJ*, 682, 49  
 Wise J. H., Turk M. J., Norman M. L., Abel T., 2012, *ApJ*, 745, 50  
 Witstok J. et al., 2025, *Nature*, 639, 897  
 Wollenberg K. M. J., Glover S. C. O., Clark P. C., Klessen R. S., 2020, *MNRAS*, 494, 1871  
 Xu H., Wise J. H., Norman M. L., 2013, *ApJ*, 773, 83  
 Xu H., Norman M. L., O’Shea B. W., Wise J. H., 2016, *ApJ*, 823, 140  
 Yang H., Gao L., Guo Q., Li H., Shao S., Zhao G., 2025, *ApJ*, 994, 271  
 Yanny B. et al., 2009, *AJ*, 137, 4377  
 Zackrisson E. et al., 2024, *MNRAS*, 533, 2727  
 Zier O. et al., 2025, *MNRAS*, 544, 410

## APPENDIX A: TRACING DM PARTICLES

We show in Fig. A1, a validation of our particle traceback method using haloes and their constituent DM particles from the DMO simulation. We select the 25 particles which are most bound to



**Figure A1.** Distribution of particle distances to the most bound particle in their halo at  $z = 8.5$  (thin lines), and the distribution of particle distances to the same particle at  $z = 0$  (thick lines). We differentiate between subhaloes which survive to  $z = 0$  (yellow), and those which merge into the central halo (green). The distributions are done for 50 haloes and stacked. Subhaloes which remain bounded at  $z = 0$  have their particles remain more clustered together, while those which merge see their particles spread out over a larger volume (as the main halo virializes).

subhaloes with masses  $M_{\text{halo}} > 2 \times 10^7 M_{\odot}$  at  $z = 8.5$ , and compute the distribution of distances from those particles to the most bound particle (proximity to halo centre) at that redshift (thin lines). We then track those same particles to  $z = 0$  and compute the distribution of distances to the same particle again (thick lines). The yellow lines correspond to subhaloes which survive as distinct structures until  $z = 0$ , while the green lines correspond to subhaloes which merge into the central halo by  $z = 0$ .

We find that particles in haloes which merge into the central halo have average distances on the order of  $\sim 10$  kpc at  $z = 0$ , as the particles follow random orbits in the virialized main halo. In contrast, we see that particles which belong to subhaloes that survive to  $z = 0$  remain relatively clustered together, with a minority of particles being stripped away to larger distances. This validates our approach of tracing Pop III star particles to  $z = 0$  by following the dark matter particles which were most bound to their host haloes at the time of formation.

#### A1 Minimizing phase space instead of distance

Instead of choosing the 25 DM particles physically closest to the Pop III star, we also explored using the 25 DM particles

which minimized the phase-space criteria  $d_{\text{phase}}$ . Following the approach of P. S. Behroozi et al. (2013), we define our phase space criteria  $d_{\text{phase}}$  between two particles  $p_1$  and  $p_2$  in an ensemble of many points as

$$d_{\text{phase}}(p_1, p_2) = \left( \frac{|\mathbf{x}_1 - \mathbf{x}_2|^2}{\sigma_x^2} + \frac{|\mathbf{v}_1 - \mathbf{v}_2|^2}{\sigma_v^2} \right)^{1/2}, \quad (\text{A1})$$

where  $\mathbf{x}$  and  $\mathbf{v}$  are the position and velocity of the particles, and  $\sigma$  is the standard deviation on those quantities across all particles in the system. We found that for a small subset of dark matter particles ( $\sim 10$ ) near a Pop III star, choosing them based upon the phase-space criteria was not significantly better at tracking the star from  $z = 20$  to 8.5, compared to choosing the physically closest particles to the star. We also found that simply increasing the amount of particles sampled around the Pop III star improved the tracking of the star, more-so than attempting to cleverly choose a subset which matched more closely the kinematics of the star. Furthermore, the  $z = 0$  distributions in Fig. A1 do not meaningfully change when switching to a phase-space criteria for particle selection.

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