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Still accelerating: type Ia supernova cosmology is robust to host galaxy age evolution

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ABSTRACT

Type Ia supernovae are a cornerstone of modern cosmology, providing first evidence for cosmic acceleration and new tests of dark energy. Son et al. (S25) claim a strong redshift evolution in standardized supernova luminosities driven by supernova progenitor age, with dramatic cosmological implications: rapidly evolving dark energy, decelerating expansion, and a 9σ tension with ΛCDM. We show that the underpinning evidence required for this conclusion – the supernova progenitor-age dependence, the redshift-dependent age difference, and their combined impact – is either negligible or relies on effects already corrected for in modern supernova analyses. First, the S25 analysis omits the standard host-galaxy stellar mass correction that captures known environmental dependencies that also correlate with stellar age. Applying this correction to the S25 sample, we find no dependence of standardized supernova brightness on host age. Independent data also show no significant difference at low-redshift in standardized brightness between star-forming galaxies and several Gyr older quiescent galaxies of the same stellar mass. Secondly, the S25 scenario predicts strong redshift evolution of the host-mass effect. Data from the Dark Energy Survey supernova survey measure evolution of -0.028 ± 0.034 mag z^{-1}, consistent with zero and altering the dark-energy equation-of-state measurement (w) by <0.01 if included. Thirdly, we demonstrate that the claimed ~ 5 Gyr progenitor age difference between nearby and distant supernovae is overstated by factors of three to five largely due to a conflation of host galaxy age with supernova progenitor age. We conclude that type Ia supernova cosmology remains robust for current measurements of dark energy.

Key words: galaxies: evolution – dark energy – distance scale – transients: supernovae.

1 INTRODUCTION

Type Ia supernovae (SNe Ia) are one of the best standardizable candles and most powerful probes of cosmology. Measurements of SN Ia distances and redshifts provide direct observational evidence of cosmic acceleration and the inference of dark energy (A. G. Riess et al. 1998; S. Perlmutter et al. 1999). Using SNe Ia alone, the evidence for acceleration is now very strong, and precise constraints on the dark energy equation-of-state parameter w are routinely obtained using SNe Ia in combination with complementary probes (D. Brout et al. 2022; DES Collaboration

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2024; D. Rubin et al. 2025; B. Popovic et al. 2026), while evidence for dark energy also remains strong without using SNe (DESI Collaboration 2025; DES Collaboration 2026). SNe also remain an important component in measurements of the Hubble constant (A. G. Riess et al. 2022; L. Galbany et al. 2023; L. Breuval et al. 2024; W. L. Freedman et al. 2025; H0DN Collaboration 2026).

The use of SNe Ia as distance indicators relies, broadly, on the ability to standardize their luminosities and that the standardized luminosity does not change significantly with cosmic time (i.e. redshift). The standardization itself typically exploits two empirical relations: the 'faster–fainter' relation between the SN Ia peak brightness and the width of its light curve (M. M. Phillips 1993), and the 'bluer–brighter' relationship between the SN Ia peak brightness and its colour (A. G. Riess, W. H. Press & R. P. Kirshner 1996; R. Tripp 1998). With modern data sets and analysis techniques, the post-standardization scatter on the inferred distances to SNe Ia unexplained by model or measurement uncertainties is ~ 0.1 mag in distance modulus, or ~5 per cent in distance.

This standardization process leaves a residual dependence of the SN Ia distances on the properties of the galaxies in which they exploded: the post-standardization peak brightness of SNe Ia in 'low stellar mass' [$\log(M_\star/\mathrm{M}_\odot) \leq 10$] galaxies is, on average, $\sim 0.05 - 0.1$ mag fainter than in their higher stellar mass counterparts regardless of survey, redshift, or analysis approach (P. L. Kelly et al. 2010; M. Sullivan et al. 2010; H. Lampeitl et al. 2010; M. Childress et al. 2013; S. A. Uddin et al. 2017; S. Ramaiya et al. 2025). As a result, the inclusion of observed SN–host relationships in the estimation of SN distances, in some form, is now well-established in SN Ia cosmology (A. Conley et al. 2011; M. Betoule et al. 2014; D. Brout et al. 2022; M. Vincenzi et al. 2024; D. Rubin et al. 2025).

It is widely acknowledged that stellar mass is unlikely to be the driving cause of this effect, but the actual underpinning physical cause remains unclear. Empirically, there are well-known relationships between galaxy stellar mass and many other galaxy properties (e.g. C. A. Tremonti et al. 2004; A. Gallazzi et al. 2005; F. Mannucci et al. 2010; T. Garn & P. N. Best 2010) making the isolation of the causal variable difficult. Dependencies between standardized SN Ia luminosity and other host galaxy properties are observed, including gas-phase metallicity (J. S. Gallagher et al. 2005; C. B. D'Andrea et al. 2011; M. Childress et al. 2013; Y.-C. Pan et al. 2014; M. E. Moreno-Raya et al. 2016; I. Millán-Irigoyen et al. 2022), stellar metallicity (J. S. Gallagher et al. 2008), star-formation activity (M. Sullivan et al. 2010; M. Rigault et al. 2013, 2020), rest-frame galaxy colour (M. Childress et al. 2013; M. Roman et al. 2018; L. Kelsey et al. 2021, 2023; M. Ginolin et al. 2025a), and the equivalent width of the [O II] emission line (M. Dixon et al. 2022; B. Martin et al. 2024).

Many of these observations have indirect links to stellar age, and this has motivated significant research on the link between SN Ia progenitor ages, host galaxy stellar ages, and SN Ia standardization (M. Rigault et al. 2013; M. Childress et al. 2013; B. M. Rose, P. M. Garnavich & M. A. Berg 2019; P. Wiseman et al. 2022, 2023). There are two signficant challenges. The first is that galaxy ages are notoriously difficult to measure without very high-S/N galaxy spectroscopy, and fits to broad-band optical photometry only estimate luminosity-weighted ages of the stellar population. This is only the same as the SN progenitor age in a coeval simple stellar population, i.e. a group of stars formed at the same time; galaxies universally have more complex star-formation histories (SFHs). The second challenge is the function describing the probability of a stellar population producing a SN Ia as a function of time: the delay-time distribution (DTD; see review of D. Maoz, F. Mannucci & G. Nelemans 2014). The rate of supernovae in a galaxy is a convolution of the SN Ia DTD and the galaxy's SFH, making the interpretation of galaxy ages in the context of SN progenitors extremely complex: a typical massive galaxy can produce SNe Ia from both young and old progenitor systems. Reflecting this uncertainty, SN cosmology analyses apply standardization corrections based on stellar mass as a simple empirical variable, and SN progenitor and galaxy age models can then be included as systematic tests; see, for example, the Dark Energy Survey (DES) 5-yr SN cosmology analysis (DES-SN5YR; M. Vincenzi et al. 2024; B. Popovic et al. 2026).

However, a series of studies by the same group (Y. Kang et al. 2020; Y.-W. Lee et al. 2022; C. Chung et al. 2023, 2025), have claimed that there is a linear trend whereby SNe Ia in older stellar populations (older host galaxies) are brighter post-standardization compared to those in younger host galaxies, and more critically that this trend is unaccounted for in cosmological analyses. Since stellar populations evolve with redshift, if this correlation is intrinsic to the SNe then it could induce an apparent redshift evolution in the post-standardization SN Ia brightnesses, biasing cosmological measurements (see e.g. D. Sarkar et al. 2008; M. Rigault et al. 2013; M. J. Childress, C. Wolf & H. J. Zahid 2014; M. Rigault et al. 2020). Y.-W. Lee et al. (2022) argued that applying a redshift-dependent correction for this effect could eliminate the evidence for dark energy. More recently, J. Son et al. (2025, hereafter S25) report a strongly evolving dark energy based on a correction derived from data from C. Chung et al. (2025), with the dark energy equation-of-state parameter w showing significant redshift evolution.

These claims are important and warrant a thorough examination and testing. This serves as the motivation for this paper and we examine the claims in S25 in two contexts. First, in Section 2 we describe the established tools that are used in cosmological SN Ia analyses and that are designed to mitigate for host-galaxy biases. Since galaxy stellar mass and galaxy age are highly correlated, it is not surprising, and we show, that the mass-standardization already included in modern SN Ia analyses largely accounts for all SN–host correlations, leaving no substantial leftover correlation with host galaxy ages. Secondly, in Section 3 we review the complex relationships between SN Ia progenitors and their host galaxies and show several subtle but critical issues with the method involved in applying a redshift-dependent correction to SN Ia luminosities based on the host galaxy age measurements. We summarize with a conclusion in Section 4.

2 ROBUSTNESS OF SN IA COSMOLOGY TO HOST GALAXY CORRELATIONS

In this section we review the procedures underpinning SN Ia cosmology, and highlight how modern cosmology analyses with SNe Ia detect and mitigate the host-galaxy driven biases discussed in S25. We show that these analyses find no significant evidence for redshift evolution in SN Ia standardization.

2.1 SN Ia distance measurements

SNe Ia can be standardized by applying adjustments based on the 'faster–fainter' and 'bluer–brighter' relationships to their measured peak brightnesses m_B. There are different frameworks to implement this. In this paper we infer distance moduli, $\mu_{\rm obs}$, via an adapted version of the relation presented by R. Tripp (1998), i.e.

$$\mu_{{\rm obs},i} = m_{B,i} - M_0 + \alpha x_{1,i} - \beta c_i + \gamma G_{{\rm host},i} + \mu_{{\rm bias},i}\,, \quad (1)$$

where $x_{1,i}$ and c_i are the light-curve 'stretch' and colour[1] of the ith SN, α, β parametrize the global standardization relationships, and M_0 is the global intrinsic SN Ia absolute magnitude for $x_1 = 0$ and $c = 0$. $G_{{\rm host},i}$ represents some property P of the ith SN's host galaxy, often stellar mass, and γ represents the size of the correction based on that host property, typically applied as a step function at some threshold $P_{\rm step}$, i.e.

$$\gamma G_{\rm host} = \begin{cases} +\gamma/2 & \text{if } G_{\rm host} > P_{\rm step}, \\ -\gamma/2 & \text{otherwise,} \end{cases} \quad (2)$$

with the correction often colloquially referred to as the 'mass step'. The $\mu_{{\rm bias},i}$ term is a bias correction made to each SN to correct for both Malmquist-like selection effects (e.g. M. Hamuy & P. A. Pinto 1999; J. Marriner et al. 2011) and astrophysical effects that include relationships between SNe Ia and their hosts and dust extinction (D. Brout & D. Scolnic 2021; B. Popovic et al. 2021), and is calculated from simulations (R. Kessler et al. 2009; R. Kessler & D. Scolnic 2017).

The 'Hubble residuals', $\Delta\mu$, are then defined as the difference between $\mu_{\rm obs}$ and the distance modulus calculated from a cosmological model, $\mu_{\rm theory}$, defined as

$$\Delta\mu = \mu_{\rm obs} - \mu_{\rm theory}(\mathcal{C}, z)\,, \quad (3)$$

where $\mathcal{C}$ is a set of cosmological parameters. The dispersion or scatter of $\Delta\mu$ around the best cosmological fit is caused by a combination of observational noise and a remaining inherent dispersion of the SNe, often termed 'intrinsic scatter'. The magnitude of intrinsic scatter and its relationship to SN and their host galaxy parameters is well studied and accounted for in cosmological measurements (e.g. J. Guy et al. 2010; N. Chotard et al. 2011; D. Brout & D. Scolnic 2021; B. Popovic et al. 2023).

2.2 Overview of the S25 argument

S25 assemble a heterogeneous sample of SNe Ia, taking SNe and their host galaxy photometry from two samples of SNe discovered by the Sloan Digital Sky Survey (SDSS) SN Survey: R. R. Gupta et al. (2011) and B. M. Rose et al. (2019). The Hubble residuals of these SNe were compiled for an analysis by C. Chung et al. (2025), that in turn were originally published by R. R. Gupta et al. (2011) and H. Campbell et al. (2013), the latter using an early implementation of SN Ia photometric classification methods. Neither of those studies included any host galaxy (stellar mass) correction term or the bias correction term in equation (1). Instead, C. Chung et al. (2025) use a single ad hoc corrective term as a function of redshift in an attempt to account for an expected astrophysical bias from progenitor-redshift evolution. The Hubble residuals are then compared to estimates of host-galaxy stellar population ages derived from spectral energy distribution (SED) template fitting to broad-band optical (SDSS) host galaxy photometry (C. Chung et al. 2025).

S25 show that their Hubble residuals correlate with the estimated ages of the host galaxies. S25 then argue that evolution in the mean age of the host population with redshift will result in incorrect distance measurements for the SNe, and biased cosmological parameters. S25 estimate the magnitude of this bias by assuming that the Hubble residual–galaxy age relation translates directly to a Hubble residual–SN Ia progenitor age relation, and then derive a 'correction' based on a model of SN Ia progenitor age redshift evolution. This methodology is inaccurate, as the SN progenitor age will always be younger than the age of its host galaxy, and the relation between them will itself vary with redshift and depends on modelling assumptions. We return to this topic in Section 3.

2.3 Testing the existing framework for host galaxy–SN standardization relationships

In modern SN Ia analyses distance estimates account for host galaxy dependencies in two ways, both neglected by S25. The first is the straightforward application of the $G_{\rm host}$ term in equation (1). The second is the modelling of selection biases ($\mu_{\rm bias}$ in equation 1) in different SN samples, which are calculated from the relationships between SN properties (stretch, colour, and brightness), dust extinction, host galaxies, and survey characteristics. Most SN Ia cosmology analyses use the host galaxy stellar mass as $G_{\rm host}$, primarily for its reliability and simplicity of measurement with the limited host galaxy photometric coverage typically available at high redshift (E. F. Bell & R. S. de Jong 2001; E. N. Taylor et al. 2010; S. Salim et al. 2016; S. Ramaiya et al. 2025). We discuss two tests of this existing standardization framework.

2.3.1 *Tests using stellar mass as the standardization parameter*

Due to the nature of galaxy growth, there is a long-established, strong correlation between the stellar mass of a galaxy and the mean age of its stellar population: more massive galaxies are, on average, older. This relationship holds for SN Ia host galaxies and is shown in the left panel of Fig. 1 for the SN sample used by C. Chung et al. (2025), where we find a correlation at 8.8σ significance using the LINMIX fitting method (B. C. Kelly 2007).

While stellar age and stellar mass are clearly distinct host galaxy properties, the mass standardization and bias-correction terms remove any significant relation between Hubble residuals and host galaxy age for the SN sample used by S25. For this sample we compare the galaxy ages as measured by C. Chung et al. (2025) against more recent Hubble residuals published in the Pantheon + SN Ia compilation for the same SNe (D. Scolnic et al. 2022) and which, crucially, provides host (stellar mass) standardization and bias corrections for each event (D. Brout et al. 2022).[2] We use the Pantheon + data as it contains Hubble residuals for the SDSS SNe used by C. Chung et al. (2025), unlike the more recent DES-SN5YR compilation.

To show the effect of these corrections, in Fig. 1 we show the $\Delta\mu$–host age relationship for the C. Chung et al. (2025) samples both before (centre) and after (right) stellar mass standardization and bias correction. Before correction,

[1]Here we present the Tripp formula in the framework of fitting SNe Ia with the Supernova Adaptive Light Curve Template (SALT2; J. Guy et al. 2007, 2010; W. D. Kenworthy et al. 2021), but the principle is the same regardless of the fitting technique and exact definitions of the SN parameters.

[2]https://github.com/PantheonPlusSH0ES/DataRelease, commit 7fc6805.

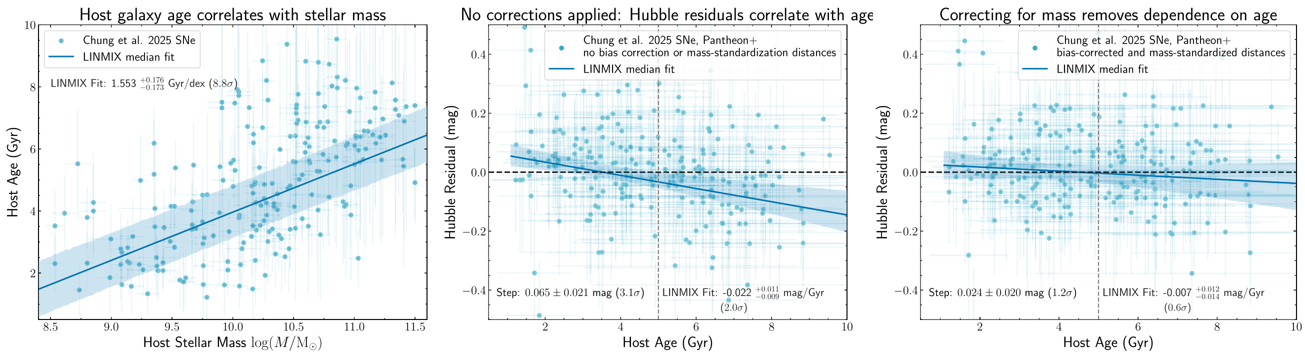

Figure 1. *Left:* Host galaxy stellar mass versus galaxy age for the sample used by S25. Galaxy ages are taken from C. Chung et al. (2025) and are strongly correlated with host galaxy stellar mass. *Centre:* Hubble residual before bias correction and mass standardization, versus galaxy age. Hubble residuals are taken from the Pantheon + analysis. We recover a somewhat smaller slope than C. Chung et al. (2025), and with lower significance; *Right:* Hubble residuals after a bias correction and standardization for stellar mass. The relationship between Hubble residual and host galaxy age is smaller, and not significant.

we find a slope ∼25 per cent smaller than that used in S25 (-0.022 mag Gyr^{-1} compared to -0.030). After corrections, the slope $-0.007^{+0.012}_{-0.014}$ mag Gyr^{-1} is more than four times weaker than that measured by S25 and is not statistically significant ($<1\sigma$).

Similar results have been found for the DES-SN5YR sample (L. Kelsey et al. 2023) who use host galaxy rest-frame colour, a proxy for host age. They also find a small and not significant relationship between $\Delta\mu$ and host galaxy colour after correcting the $\Delta\mu$ for stellar mass, as well as vice-versa.

2.3.2 Tests using SNe with different host galaxy morphologies

A second simple test for a significant age bias in published SN Ia distances can be conducted by comparing the $\Delta\mu$ for SNe Ia in passive and star-forming galaxies in the local Universe. Galaxy morphology is not a perfect tracer of galaxy age (M. Briday et al. 2022), but early-type galaxies are known to contain older stellar populations than later-types at all stellar masses (T. Parikh et al. 2021). In the model of S25 the difference in the mean age of their stellar populations (∼3–6 Gyr) should be reflected in an age difference between SN progenitors: their models imply a ∼0.09–0.18 mag difference in average $\Delta\mu$. Indeed, the lack of a difference in $\Delta\mu$ for local SNe Ia in early (old) and late (young) type hosts was one of the tests for evolution employed (and passed) in both A. G. Riess et al. (1998) and S. Perlmutter et al. (1999) for the initial evidence for cosmic acceleration: Riess et al., for example, measured a mean difference of 0.04 ± 0.07 mag, smaller than expected by S25.

We use the DES-SN5YR SN sample (B. O. Sánchez et al. 2024)[3] over $z = 0.025 - 0.15$ and those SNe with host morphology visually classified (A. G. Riess et al. 2022) and passing standard cosmological quality cuts (e.g. M. Betoule et al. 2014). In Fig. 2 we show the Hubble residuals, after applying mass standardization and bias corrections, as a function of host stellar mass and split by morphological classification. On average, the $\Delta\mu$ difference between late-type hosted SNe ($N = 149$ events) and early-type hosted SNe ($N = 48$ events) is

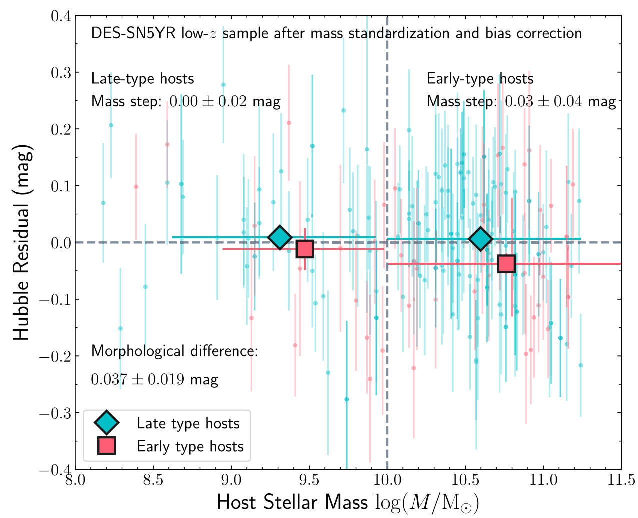

Figure 2. Hubble residuals of low-redshift SNe Ia as a function of stellar mass, split by the morphology of the host galaxies. Hubble residuals are from the DES-SN5YR compilation and have had both the stellar mass standardization and bias correction applied. The mean difference in age of the two morphology categories is several Gyr, which based on the S25 scenario of 0.03 mag Gyr^{-1} would predict a ∼0.09–0.18 mag difference between the two populations, which is not seen in the mean of the data.

0.037 ± 0.020 mag, in the sense that SNe Ia hosted by early-type galaxies are brighter. The difference is almost identical (0.036 ± 0.021 mag) without applying mass standardization or bias correction. For a realistic ∼3–6 Gyr difference in mean age for these host types (T. Parikh et al. 2021; D. Mattolini et al. 2025) and the 0.03 mag Gyr^{-1} host-age – $\Delta\mu$ gradient from S25, the difference is predicted to be ∼0.09–0.18 mag. The DES-SN5YR data do not show evidence for the host galaxy age dependence at the level used by S25 to infer, from those same data, their cosmological result.

These two tests demonstrate that the existing SN Ia cosmological framework appears to adequately correct for the claimed effects by S25, simply by accounting for known correlations between SNe Ia and their host galaxy stellar mass.

[3]from the main branch of https://github.com/des-science/DES-SN5YR using commit c9a4fca.

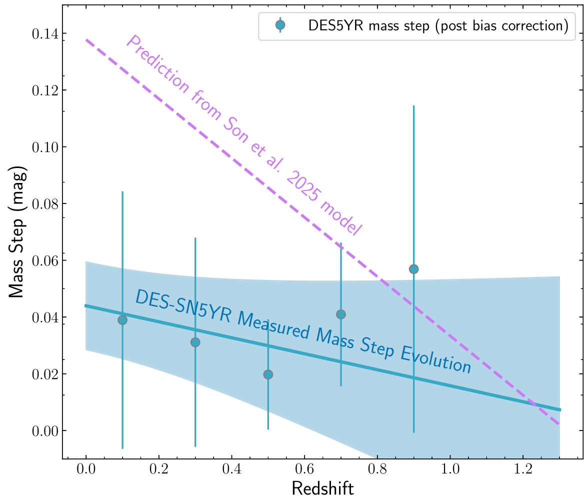

Figure 3. The size of the redshift-evolving γ ('mass step') correction measured with DES-SN5YR data (blue points). The blue line is the best fit to the DES data of the form $\gamma(z) = \gamma_0 + \gamma_1 z$ and the blue shaded area the range of evolution allowed based on the uncertainty from this fit. This is compared to the predicted redshift evolution from the age-bias model of S25 (purple dashed line). The important difference occurs at low-redshift where the observed γ is much smaller than the prediction and little changed from high redshift.

2.4 Robustness to an evolving host galaxy correction

We can further search for evidence of the failure of the current approach used in SN Ia cosmology by measuring the size of γ in equation (1) in bins of redshift. This is an established test when inferring cosmological constraints from SN Ia data sets (e.g. M. Betoule et al. 2014; D. Rubin et al. 2025), and here we show data from the recent DES-SN5YR analyses (M. Vincenzi et al. 2024; B. Popovic et al. 2026) (Fig. 3). If the primary driver of the relationship between host galaxy environment and SN standardization is the age of the SN progenitor or of the galaxy, then the size of γ will decrease with increasing redshift. This is because both SN progenitor and galaxy ages are younger at higher redshifts compared to $z = 0$ (M. Rigault et al. 2013; M. J. Childress et al. 2014): at low-redshift the mean 'high mass' galaxy is old (or hosts old SNe) but at high-redshift the high mass hosts are younger (Fig. A2). Thus, at high-redshift, hosts are younger at all stellar masses which should result in a reduced standardization difference in the S25 model (see also M. Rigault et al. 2020).

Fig. 3 shows the measured γ in DES-SN5YR data as a function of redshift. This is measured from the difference between $\Delta\mu$ in low- and high-mass galaxies in each redshift bin without applying the $\gamma G_{\rm host}$ term (equation 2). There is no evidence for any redshift evolution in γ.

The DES-SN5YR analyses fit these data via a simple, linear parametrization of

$$\gamma(z) = \gamma_0 + \gamma_1 z, \tag{4}$$

where γ_0 is the value of γ at $z = 0$ and γ_1 is a linear coefficient of any redshift evolution. DES-SN5YR find $\gamma_0 = 0.044 \pm 0.015$ and $\gamma_1 = -0.028 \pm 0.034$ (B. Popovic et al. 2026). We show the range of evolution allowed by the $\gamma(z)$ fit (i.e. the full uncertainty range on γ_0 and γ_1) in Fig. 3. We find no significant evolution in γ ($< 1\sigma$) and thus no evidence that host galaxy stellar mass does not provide a sufficient standardization. Furthermore, when including the measured redshift evolution of γ, DES-SN5YR find a shift in the measurement of w of < 0.01.[4]

To estimate the predicted γ evolution from the alternative, age-bias model, we take the $\Delta\mu$–age relationship used by S25 and apply it to SNe simulated with a simple galaxy evolution model following the method of P. Wiseman et al. (2022, hereafter W22), outlined in more detail in Section 3 and in Appendix A2. As expected, the S25 model predicts a strongly evolving γ, inconsistent with that observed in the DES-SN5YR data. Most notably, the age-bias model predicts a low-redshift mass step of ~ 0.14 mag, $\sim 6\,\sigma$ larger than that measured by DES5YR (0.044 ± 0.015). The reason, as we show in the next section, is that the progenitors of SNe Ia observed in low-redshift surveys are not much older on average (∼1–2 Gyr) than the progenitors of SNe Ia in high-redshift surveys due to the shape of the SN Ia DTD.

3 MODELLING SUPERNOVA–HOST-GALAXY RELATIONSHIPS AS A FUNCTION OF REDSHIFT

In the previous section we showed how modern SN Ia cosmology analyses incorporate host galaxy environmental dependencies in SN Ia standardization. When these are included, we find no empirical evidence for any signatures of the effects proposed by S25. In this section we use a complementary approach using a detailed, empirically calibrated model of the redshift evolution of SN Ia host galaxy properties to show what redshift-dependent changes in host age, SN progenitor age, or stellar mass, are allowed by observations. We show that these are far weaker than those suggested by S25.

3.1 Modelling framework for SN Ia host galaxy masses and ages

To demonstrate the relationships between redshift, SN Ia progenitors, and the ages and masses of the galaxies that host SNe Ia, we employ the simulations of P. Wiseman et al. (2022). These in turn build upon the work of M. J. Childress et al. (2014) who presented an empirical model of the evolution of individual simulated galaxies and their stellar age distributions over cosmic time. We describe the models briefly in Appendix A.

To calculate the SN Ia progenitor age distribution in a galaxy, the SFH of the galaxy is convolved with the SN Ia DTD, the function describing the probability of a given stellar population producing a SN Ia as a function of time since the stars were formed. The DTD is difficult both to predict from theoretical models and to measure, but can be inferred by measuring how the volumetric rate of SNe Ia changes with redshift (e.g. A. Gal-Yam & D. Maoz 2004; O. Graur et al. 2011; C. Frohmaier et al. 2019) or how the specific SN rate varies among galaxies with different SFHs (T. Totani et al. 2008; O. Graur, F. B. Bianco & M. Modjaz 2015; P. Wiseman et al. 2021; A. Castrillo et al. 2021). Generally, these techniques find a DTD, $\Phi(t)$, consistent with a power law of the form

$$\Phi(t) = \begin{cases} 0 & t < t_p \\ A\, t^{\beta_{\rm DTD}} & t \geq t_p, \end{cases} \tag{5}$$

[4] This shift is measured using SNe only to constrain w. The shift is smaller when combining with other probes.

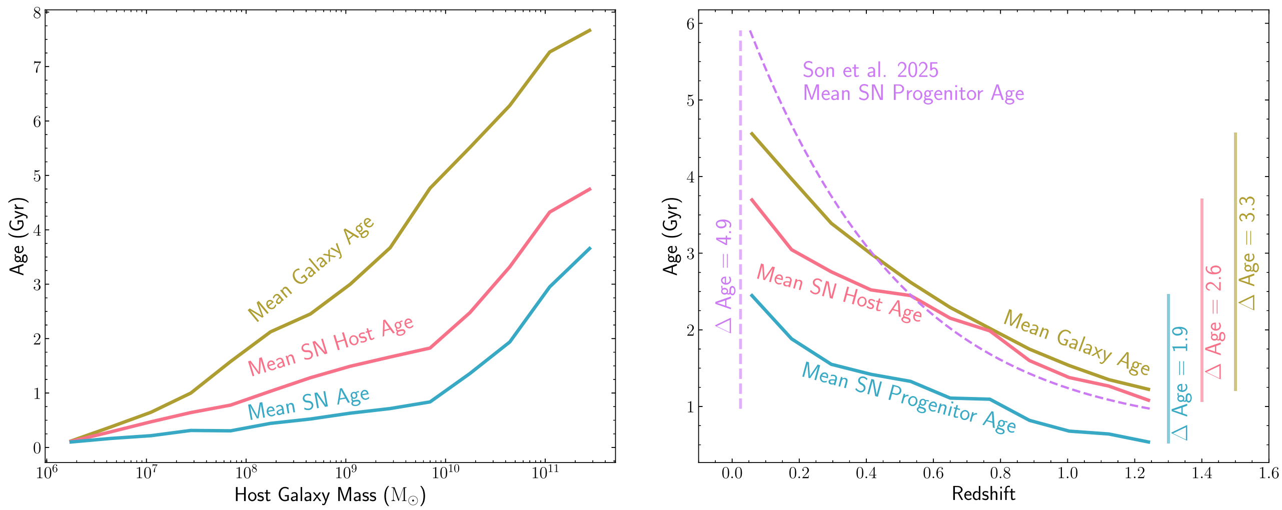

Figure 4. Relationships between galaxy stellar masses, stellar and SN Ia progenitor ages, and redshifts, according to the physically motivated models from W22. *Left*: Mean galaxy age (gold), mean SN Ia host galaxy age (pink), and mean SN Ia progenitor age (blue) as a function of galaxy stellar mass at $z = 0$. The age of galaxies, as well as the SN Ia progenitors, is clearly correlated with the stellar mass; *Right*: Mean galaxy age (gold), mean SN Ia host age (pink), and mean SN Ia progenitor age (blue) as a function of redshift. Due to the SN Ia delay time distribution (DTD), the SN age difference across the redshift range is half the galaxy age difference and 50 per cent smaller than the SN host age–redshift difference. The purple dashed line is the prediction from the DTD and cosmic SFH assumed by S25.

where t is the time since a stellar population formed, A is a normalization factor (the SN Ia 'production efficiency'), $\beta_{\rm DTD}$ the slope of the power law, and $t_{\rm p}$ is the age of the stellar population before which SN Ia progenitor carbon–oxygen white dwarfs have not had sufficient time to form, and thus the probability of an SN Ia explosion is zero.

Observations suggest that $\beta_{\rm DTD}$ is around -1, and stellar evolution time-scales set a lower limit for $t_{\rm p}$ of 30–40 Myr. Such a power-law DTD has a key property that is important in this paper: it results in most SNe Ia originating from 'young' (< 1 Gyr old) progenitors at all redshifts and, per unit stellar mass, galaxies with star formation therefore produce more SNe Ia than passive galaxies (see A. Oemler & B. M. Tinsley 1979; F. Mannucci et al. 2005; M. Sullivan et al. 2006, for relevant supporting observations). This means that at any redshift and at any stellar mass, SN Ia host galaxy samples are dominated by galaxies with some star formation. However, the exact choice of the $\beta_{\rm DTD}$ and $t_{\rm p}$ parameters affect the distribution of SN Ia progenitor ages in a galaxy, which we discuss in further detail in Appendix A2.

3.2 Issues with direct application of a redshift-dependent correction

Our modelling of SN Ia and their host galaxies then reveals two key problems with the redshift-dependent standardization correction estimated by and used in S25. We discuss these in turn.

3.2.1 *Host galaxy age and SN Ia progenitor age are not interchangeable*

In the left panel of Fig. 4, we show how our model galaxy ages, model SN host galaxy ages, and model SN progenitor ages correlate with host stellar mass at $z = 0$. The relationship is strong as expected from data (see Fig. 1). The mean SN host galaxy age is younger than the mean galaxy age at all stellar masses, and that SN progenitor ages are younger still: estimates of galaxy age are not interchangeable with the SN progenitor age (see also M. J. Childress et al. 2014). The effect of redshift on these relationships can be found in the Appendix (Fig. A2).

This is because the age of a SN progenitor is not directly related to the age of the galaxy at the time of explosion due to the DTD: the DTD is dominated by short delay times, so SN samples are dominated by galaxies with some star formation. Galaxy age does not deterministically predict SN Ia progenitor age. (The only way in which this could be the case would be if the DTD was a delta function). S25 therefore incorrectly assume that it is valid to apply their measured $\Delta\mu$–host-galaxy-age relationship to an estimate of redshift evolution of the SN progenitor ages.

We also note the sharp increase in the slope of the galaxy and SN progenitor age correlations at 10^{10} M$_\odot$. This shows why, even if the environmental dependencies of SN luminosities were driven primarily by age, a mass standardization split at that mass effectively serves to standardize their luminosities.

3.2.2 *SN Ia progenitor ages show only modest redshift evolution*

In the right panel of Fig. 4, we show the redshift evolution of the average mass-weighted age of the global galaxy population and of SN Ia host galaxies calculated from our models. Again, SN hosts are, on average, younger than the overall galaxy population and they also evolve less with redshift. The SN progenitor ages evolve even less than the SN host galaxy ages. SN progenitor ages, SN host ages, and galaxy ages have substantially different evolution with redshift and, again, should not be conflated.

This means that the average SN Ia progenitor age difference between $z = 0$ and $z = 1$ predicted by S25 is exaggerated at 5.3 Gyr: the difference in SN Ia progenitor age in our models between $z = 0$ and $z = 1.2$ is only 1.9 Gyr (Fig. 4). This overestimation likely stems from the DTD employed by S25, with a prompt time-scale of $t_p = 0.3$ Gyr and a power-law slope of $\beta_{\rm DTD} = -1.0$, as per M. J. Childress et al. (2014), rather than 30–40 Myr prompt time set primarily by stellar and binary evolution (I. Hachisu, M. Kato & K. Nomoto 2008b, a), and steeper value (~ -1.13) of the power-law slope indicated by recent DTD measurements. Appendix A2 discusses the choices of DTD parameters in more detail.

3.3 Why a host-age driven effect predicts a redshift-evolving mass step

The mass step is calculated at a fixed stellar mass ($P_{\rm step}$ in equation 2), but because of the correlations between galaxy age, redshift, and stellar mass, the mean age of galaxies on either side of that threshold changes as a function of redshift. At low redshift, there is a large difference in mean age between low- and high-mass galaxies, but at high redshift this difference is smaller (Fig. A3). The S25 hypothesis, that galaxy age drives the mass step, results in a strong mass step in low-redshift samples because of the strong galaxy age–mass correlation and the large difference between the ages of the low- and high-mass galaxies. However, at high redshift, because the host ages are more uniform regardless of their stellar mass, there is minimal standardization difference between the SNe in low- and high-mass galaxies, resulting in no mass step. In Appendix A3 we show how this effect is produced as an outcome of the overall change in the age of SN hosts as a function of redshift.

To predict the scale of redshift evolution of the mass step predicted by the S25 hypothesis (the line in Fig. 3), we draw SNe from galaxies in our simulation following the SFH and DTD. We then ascribe a 'luminosity offset' based on the mass-weighted age of the host according to the 0.03 mag Gyr^{-1} slope used by S25. As a function of redshift, we then measure the average offset in low and high mass galaxies (i.e. the mass step), which we plot against the measured redshift evolution. As is apparent, a strong evolution in the mass step expected by a strong change in SN progenitor age is not seen in the DES-SN5YR data.

3.4 Fraction of SNe in high mass host galaxies

A full explanation of the lack of redshift evolution of Hubble residuals and the mass step in observations, compared to that claimed by S25, is a combination of the effects described thus far in this section: host galaxy and SN Ia progenitor ages are not interchangeable, and host galaxy and SN Ia progenitor ages do not evolve as strongly with redshift as claimed. A final check of the S25 prediction versus the data can be made by considering the fraction of SNe Ia that are observed in high-mass hosts as a function of redshift.

If SN Ia host ages vary as strongly with redshift as predicted by S25 then the fraction occurring in low and high-mass hosts will also vary with redshift. The evolution of this high-mass fraction is directly predictable by the W22 model as individual galaxies are treated independently; however, using the DTD convolved with cosmic SFH model as in S25 does not allow for the comparison of host stellar mass, since the cosmic SFH integrates over stellar mass. To estimate the evolution of the high-mass fraction in the DTD$\times$cosmic-SFH model, we take galaxies in the W22 model at a fixed redshift $z = 0.5$ and compute the fraction of high-mass galaxies as a function of SN Ia progenitor age. We then take the predicted SN Ia ages as a function of redshift from the S25 DTD$\times$cosmic-SFH model and interpolate from the W22 SN Ia age distribution to estimate a high mass fraction.

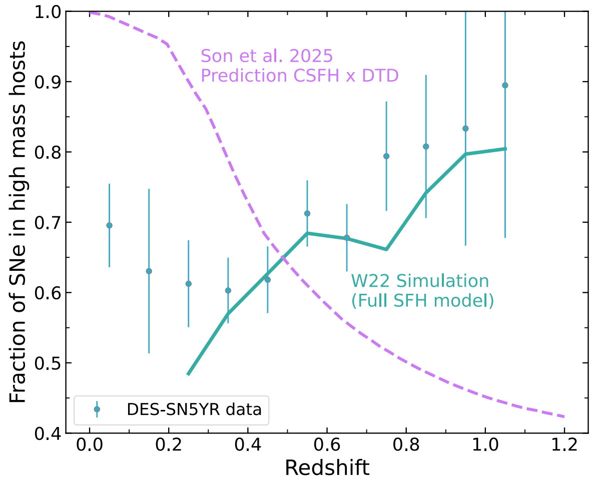

Figure 5. Evolution of the fraction of SNe Ia in high stellar mass galaxies as a function of redshift. Data are taken from the full DES-SN5YR data set, including low-redshift surveys. The solid line is the prediction from a simulation with full treatment of galaxy quenching, starbursts, dust, and SN and galaxy selection effects from W22. The dashed line is a prediction based on estimating how the fraction of SNe Ia in high mass galaxies would evolve with redshift given the large difference in SN Ia ages predicted by the DTD and cosmic SFH model used by S25.

The fraction of SNe in galaxies above the mass-step threshold $\log(M_*/{\rm M}_\odot) = 10$ is shown in Fig. 5, again using the DES-SN5YR data set. The W22 model, which takes into account stochastic galaxy processes and survey selection effects, reproduces the evolution of the high-mass fraction well from $z > 0.3$ with no tuning. This simulation was designed to reproduce the DES-SN5YR data so does not extend to low redshifts where survey selection effects are different.

The estimated evolution of the high-mass fraction using the S25 DTD and cosmic SFH with no selection effects is a very different shape to the observations. We have tested how this prediction is affected by the choice of redshift with which to estimate the SN age–mass-fraction function, and the overall trend is always the same. Although this figure does not directly explain the lack of evolution in the mass step in observations, it exemplifies the nuance and care required in predicting the evolution of SN host galaxy properties, in particular the treatment of individual galaxies rather than using universal functions, and the importance of including survey selection effects.

3.5 Correlation versus causation

The assumption underpinning the claim of S25 is that the host galaxy age *drives* the luminosity variation of SNe Ia. While the above analysis shows that other assumptions they make exaggerate the strength of any redshift evolution, one would expect no such evolution at all if the observed Hubble-residual–age relationship is driven by an underlying effect that evolves less, or not at all, with redshift. There is a subtle but critical difference between the causation and correlation of Hubble residual relationships: Hubble residuals before mass-standardization correlate with host galaxy age (Fig. 1), but they may not be caused by it; Hubble residuals correlate with many other host galaxy parameters.

The physics of the explosions, or the way we observe them, are not directly influenced by the age of the galaxy (or, for that matter, its stellar mass). Rather, there are unknown parameters, which correlate with the host galaxy age and the SN physics, or the way we observe the SNe. The true driving cause of the relationship is uncertain, and if it does not evolve with redshift or evolves less with redshift than host galaxy age, then applying a correction based on the host age is incorrect.

There may also be other systematic effects. For example, possible deficiencies in the linear standardization of SNe Ia from equation (1) are beginning to emerge with new high-fidelity low-redshift data sets, particularly non-linearities in the αx_1 term in low-x_1 SNe Ia (P. Garnavich et al. 2023; C. Larison et al. 2024; M. Newsome et al. 2024; M. Ginolin et al. 2025b). Such low-x_1 SNe Ia preferentially occur in massive and passive host galaxies (M. Hamuy et al. 2000; M. Sullivan et al. 2010), reinforcing the incorrectness in assuming that any effects observed in such SN Ia populations can be attributed to age alone.

4 CONCLUSIONS

We have tested whether the correlation between SN Ia Hubble residuals and host galaxy ages claimed by S25 can induce an apparent redshift evolution in SN Ia standardization that biases cosmological inferences. While Y.-W. Lee et al. (2022) and S25 suggested that such an effect could remove the need for dark energy or otherwise significantly modify cosmological inferences, our analysis shows that these effects are both already accounted for, and exaggerated. We find:

(i) Applying mass-standardization and bias-corrections in line with state-of-the-art cosmological analyses reduces the strength of the Hubble-residual–age relationship and renders it insignificant;

(ii) An effect driven by galaxy age predicts a redshift evolution in the size of the mass step; we show that measurements of the evolving mass step are inconsistent with the S25 prediction at $\sim 6\,\sigma$;

(iii) We identify a number of inaccurate assumptions present in the S25 analysis, namely the direct application of a galaxy-age measurement to an SN-age redshift evolution, and an overestimation of the redshift evolution of SN ages due to assumptions about the SN Ia delay-time distribution;

(iv) We reiterate the need for careful modelling of galaxy star-formation histories and survey selection effects when predicting the evolution of SN Ia luminosities and host galaxy parameters.

SN Ia cosmology is a mature field in which great care is taken to address complex and often hidden systematic effects. Testing for the robustness of the methods is a critical undertaking, but one that requires equal measures of care. We look forward to the future of SN Ia cosmology as we enter the era of extreme data sets from the Zwicky Transient Facility (E. C. Bellm et al. 2019; M. Rigault et al. 2025), the Vera C. Rubin Observatory (Z. Ivezic et al. 2019; M. Lochner et al. 2022; P. Gris et al. 2023), the TiDES survey on the 4-m Multi-Object Spectroscopic Telescope (C. Frohmaier et al. 2025), and the *Nancy Grace Roman Space Telescope* (R. Kessler et al. 2025), where such care will be of more importance than ever before.

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DATA AVAILABILITY

No new original data are presented in this paper, and all data used are publicly available in the references given.

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APPENDIX A: SIMULATIONS

We base our simulations on the framework developed in P. Wiseman et al. (2021, 2022), itself derived from the concepts laid out in M. J. Childress et al. (2014): see these papers for a full description. Here we provide a brief overview of the simulations, which are produced in several stages:

(i) a semi-empirical model of galaxies evolving with cosmic time;
(ii) a reconstruction of galaxy observables from star-formation histories;
(iii) the generation of SNe Ia within galaxies according to the SFH and DTD allowing for the tracing of SN Ia progenitor and galaxy ages;
(iv) the generation of SN Ia light-curve parameters according to the SN progenitor and galaxy properties.

A1 Galaxies

Galaxy simulations are described in full in P. Wiseman et al. (2021), and are based on the original prescription in M. J. Childress et al. (2014). Each galaxy is seeded at $10^6\,\mathrm{M}_\odot$ at some formation time and grows according to empirical relationships between star-formation rate, stellar mass, and redshift. A basic quenching 'penalty' is applied such that star-formation shuts off as galaxies grow more massive. Stellar mass-loss to SNe (of all types) and compact objects is accounted for. This model was updated in P. Wiseman et al. (2022) to include a stochastic prescription for quenching, and is able to reproduce both the overall cosmic SFH (P. S. Behroozi, R. H. Wechsler & C. Conroy 2013; P. Madau & M. Dickinson 2014), the star-forming main sequence, and a population of passive galaxies. For each galaxy, the stellar age distribution is known with a granularity of 0.5 Myr. These SFHs are combined with stellar population synthesis codes to provide estimates for galaxy spectra and global galaxy broad-band colours, and reproduce the bimodal distribution of red and blue galaxies. The simulations reproduce the overall mass assembly of galaxies with cosmic time.

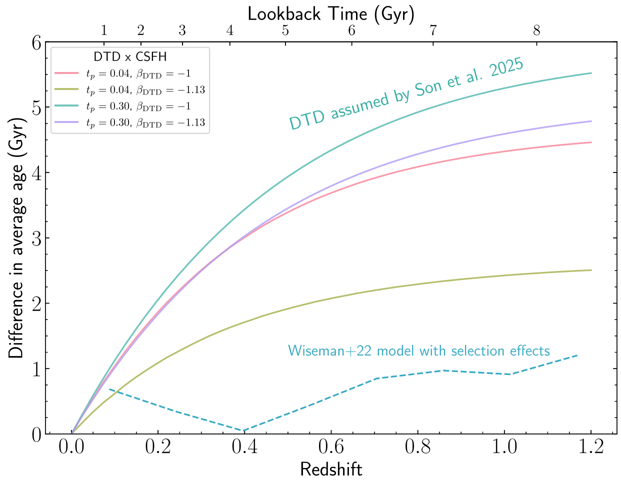

Figure A1. Differences in the median SN Ia progenitor age as a function of redshift (lookback time) under different DTD assumptions. With $\beta_{\rm DTD} = -1$, $t_p = 300$ Myr the difference in median progenitor age (or median delay time) between SN populations at $z = 0$ and $z = 1$ is 4.5 Gyr. In contrast, with $\beta_{\rm DTD} = -1.13$, $t_p = 40$ Myr the difference is closer to 1.5 Gyr. The dashed line is the median progenitor age of SNe in a simulation with full treatment of galaxy quenching, starbursts, dust, and SN and galaxy survey selection effects.

A2 Type Ia supernovae

To choose galaxies in the simulation to become SN Ia hosts, the relative rate of SNe Ia in each host is derived from the sum of the convolution of the SFH and the SN Ia DTD (i.e. integrating the SN progenitor age distribution with respect to age). We use the $\beta_{\rm DTD} = -1.13$ and $t_p = 0.04$ Gyr. The total number at a given stellar mass is this summed convolution multiplied by the stellar mass function, for which we use the redshift-dependent ZFOURGE functions (A. R. Tomczak et al. 2014). This step constructs the true *intrinsic* SN Ia host distribution. The progenitor age of each of these SNe is determined by drawing at random from the SN Ia progenitor age distribution.

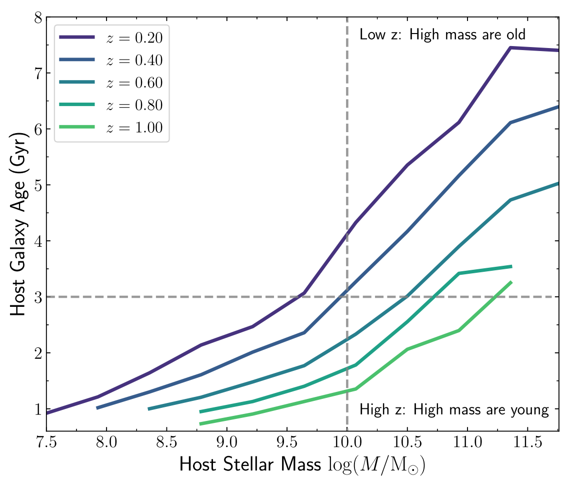

Figure A2. SN Ia host galaxy ages as a function of their stellar mass for different redshifts. At fixed stellar mass, hosts are younger at higher redshift.

The choice of the parameters defining the DTD can have a significant impact on the details of the simulations. Recent measurements using a variety of complementary methods tend to $\beta_{\rm DTD} < -1$ (E. Heringer, C. Pritchet & M. H. v. Kerkwijk 2019; A. Castrillo et al. 2021; J. Freundlich & D. Maoz 2021; P. Wiseman et al. 2021; X. Chen, L. Hu & L. Wang 2021). The prompt time is challenging to measure, and is expected to lie between 0.04 and 0.3 Gyr with most measurements preferring the lower end of that range: E. Aubourg et al. (2008) found an upper limit of 180 Myr; P. Wiseman et al. (2021) found $t_{\rm p}$ to be consistent with 0.04 Gyr; X. Chen et al. (2021) found $t_p = 0.12^{+0.14}_{-0.08}$ Gyr; A. Castrillo et al. (2021) found $t_p = 0.05^{+0.10}_{-0.03}$ Gyr. P. Wiseman et al. (2021) used the canonical 40 Myr in subsequent simulations that accurately reproduce SN Ia host galaxy populations (P. Wiseman et al. 2022).

Fig. A1 illustrates the difference between the evolution in average age given the DTD parameters assumed by S25 and those inferred by P. Wiseman et al. (2021). Each line has been produced by convolving a P. S. Behroozi et al. (2013) cosmic SFH (as adopted by S25) with a DTD, and implies that the magnitude of any putative standardization evolution with redshift is highly sensitive to the adopted DTD. Overestimating the prompt time-scale and underestimating the strength of the power-law slope exaggerates the expected age difference across redshift, overpredicts the number of low-redshift SNe Ia in quiescent galaxies, and exaggerates the inferred impact on cosmology of an age-dependent bias. We refer back to the right-hand panel of Fig. 4 where we have plotted the progenitor age evolution predicted by S25, which is clearly overestimated by several Gyr compared to our detailed modelling, to the extent that S25 predict that SN progenitors evolve more than the average age of all galaxies in our model.

The use of the cosmic SFH to approximate the evolution of galaxy ages with cosmic time is also problematic. While in principle convolving the DTD with the cosmic SFH should result in the same SN progenitor age distribution as producing individual SFHs and convolving each with the DTD and the galaxy stellar mass function, in practice, SN surveys are subject to selection effects. Individual galaxies experience quenching and starbursts, are obscured by dust, and require identification and measurements in order to be included in SN host samples. The dashed line in Fig. A1 shows the recovered SN progenitor age evolution in a simulation that includes realistic modelling of evolutionary processes as well as selection effects. The difference in median progenitor age observed between low and high redshift is minimal (~1 Gyr).

A3 Age and mass fraction evolution with redshift

Here we show how the redshift evolution of average SN Ia host age naturally predicts an evolving stellar mass step, if the step were to be entirely driven by the host age.

Fig. A2 is similar to Fig. 4 except we now show the average SN Ia host age at five different redshifts. At low redshift, low-mass galaxies are young while high-mass galaxies are old. At high redshift, even the most massive galaxies are comparatively young. The fraction of galaxies either side of the canonical $10^{10}\,{\rm M}_{\odot}$ host mass split is shown in Fig. A3. At low redshift, even if the step is driven by host age, the old galaxies are massive and young galaxies are low mass, meaning the step will be evident when traced by mass. At high redshift, since all the high mass galaxies are also young, there would be little luminosity difference between SNe Ia in low and high-mass hosts.

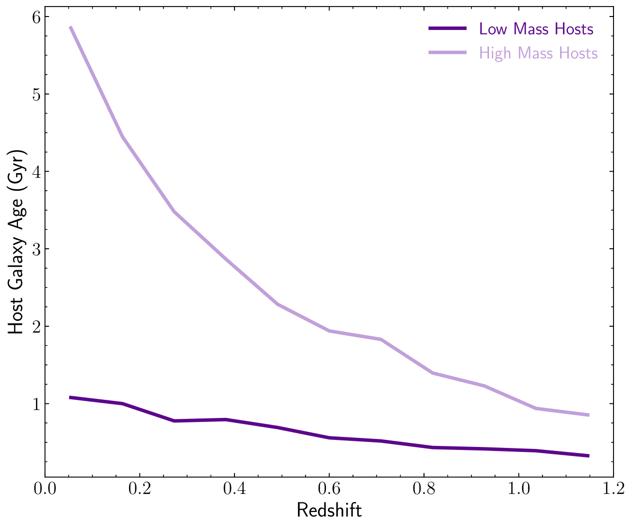

Figure A3. The average age of SN Ia host galaxies on either side of the mass step (10^{10} $M_{\odot}$), as a function of redshift. At high redshift, the average high-mass galaxy is still relatively young. Thus, if the SN Ia luminosity differences are caused by gradients in luminosity across a large range of galaxy ages, high-redshift hosts will show very little difference between the low and high-mass bins, resulting in a smaller mass step.

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