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# First cosmology results using type Ia supernovae from the Dark Energy Survey: the effect of host galaxy properties on supernova luminosity

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## ABSTRACT

We present improved photometric measurements for the host galaxies of 206 spectroscopically confirmed type Ia supernovae discovered by the Dark Energy Survey Supernova Program (DES-SN) and used in the first DES-SN cosmological analysis. For the DES-SN sample, when considering a 5D ( $z, x_1, c, \alpha, \beta$ ) bias correction, we find evidence of a Hubble residual ‘mass step’, where SNe Ia in high-mass galaxies ( $> 10^{10} M_{\odot}$ ) are intrinsically more luminous (after correction) than their low-mass counterparts by  $\gamma = 0.040 \pm 0.019$  mag. This value is larger by 0.031 mag than the value found in the first DES-SN cosmological analysis. This difference is due to a combination of updated photometric measurements and improved star formation histories and is not from host-galaxy misidentification. When using a 1D (redshift-only) bias correction the inferred mass step is larger, with  $\gamma = 0.066 \pm 0.020$  mag. The 1D–5D  $\gamma$  difference for DES-SN is  $0.026 \pm 0.009$  mag. We show that this difference is due to a strong correlation between host galaxy stellar mass and the  $x_1$  component of the 5D distance-bias correction. Including an intrinsic correlation between the observed properties of

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SNe Ia, stretch and colour, and stellar mass in simulated SN Ia samples, we show that a 5D fit recovers  $\gamma$  with  $-9$  mmag bias compared to a  $+2$  mmag bias for a 1D fit. This difference can explain part of the discrepancy seen in the data. Improvements in modelling correlations between galaxy properties and SN is necessary to ensure unbiased precision estimates of the dark energy equation of state as we enter the era of LSST.

**Key words:** surveys – supernovae: general – distance scale – cosmology: observations – transients: supernovae.

## 1 INTRODUCTION

As standardizable candles, type Ia supernovae (SNe Ia), are a geometric probe of the expansion history of the Universe (Riess et al. 1998; Perlmutter et al. 1999) and provide a mature, robust measure of its accelerated expansion (Betoule et al. 2014; Riess et al. 2018; Scolnic et al. 2018; DES Collaboration 2019). SNe Ia are not perfect standard candles: empirical ‘corrections’ based on light-curve shape (Phillips 1993) and colour (Riess, Press & Kirshner 1996; Tripp 1998) are required to standardize their peak luminosity, reducing the observed scatter in their peak magnitudes from  $\sim 0.35$  to  $\sim 0.14$  mag, or  $\sim 7$  per cent in distance. With around 1000 spectroscopically confirmed SNe Ia currently published for cosmological analyses (Scolnic et al. 2018), and with the size of photometrically classified samples ever-increasing (Jones et al. 2018a; LSST Dark Energy Science Collaboration 2012), understanding the origin and optimal treatment of these empirical correlations is key to maximizing their constraining power. Enhancing the standardization of SNe Ia beyond corrections for light-curve shape and colour may improve measurements of the evolution of dark energy with redshift.

The local environment in which SNe Ia explode can provide insights into the physical mechanisms governing these events and their observed diversity. Global properties of SN Ia host galaxies, such as the stellar mass, star formation rate (SFR), metallicity and mean age of the stellar populations, have been observed to correlate with various properties of SNe Ia. SNe Ia are  $\sim 25$  times more common (per unit stellar mass) in highly star-forming galaxies than passive systems (Mannucci et al. 2005; Sullivan et al. 2006; Smith et al. 2012), and such star-forming galaxies also host intrinsically slower-declining and observationally brighter SNe Ia (Hamuy et al. 1995, 2000; Sullivan et al. 2006; Johansson et al. 2013; Wolf et al. 2016; Moreno-Raya et al. 2018). The origin of these differences is unknown, but may arise from multiple progenitor configurations capable of producing SNe Ia (Scannapieco & Bildsten 2005; Mannucci, Della Valle & Panagia 2006).

Correlations between the luminosity of SNe Ia (after correction for light-curve width and colour) and the stellar mass of their host galaxies have motivated a third empirical correction (Kelly et al. 2010; Lampeitl et al. 2010; Sullivan et al. 2010). This is commonly parametrized as a ‘mass step’, with two absolute magnitudes for SNe Ia in the cosmological fits, depending on whether an event is located in a high stellar-mass ( $M_{\text{stellar}} > 10^{10} M_{\odot}$ ) or low stellar-mass ( $M_{\text{stellar}} < 10^{10} M_{\odot}$ ) host galaxy. This correction has been observed at  $3\text{--}6\sigma$  confidence in multiple samples, spanning low- and high-redshift, and using different light curve fitters and distance estimation techniques. It is now ubiquitous in most cosmological analyses using SNe Ia (Sullivan et al. 2011; Betoule et al. 2014; Scolnic et al. 2018), but lacks a firm physical motivation. There has been speculation that the mass step may be driven by the age of the stellar population (Childress, Wolf & Zahid 2014) or metallicity (Sullivan et al. 2010), and similar luminosity effects have also been observed using variables beyond stellar mass, such as metallicity,

stellar age (Gupta et al. 2011; D’Andrea et al. 2011; Hayden et al. 2013), and star-formation rate (Sullivan et al. 2010). As stellar populations evolve with redshift, and evolve differently for age and metallicity, uncovering and modelling the source of the mass step is a key challenge when using cosmological samples of  $> 1000$  SNe Ia over an extended phase of cosmic history.

While the majority of early studies used SN Ia samples at cosmological distances, and thus focused on a galaxy’s *global* photometric properties, more recent studies have highlighted a link between the intrinsic brightness of SNe Ia and the characteristics of their *local* environment. Rigault et al. (2013), using (for example)  $H\alpha$  nebular emission as a proxy for local SFR, have shown that locally passive environments preferentially host redder, low-stretch SNe, which appear to be intrinsically brighter than their locally star-forming counterparts after correction. The size of this local effect remains surprisingly controversial: using statistically significant data sets, Roman et al. (2018), Kim et al. (2018), Rigault et al. (2018), and Kelsey et al. (in preparation) find results consistent with Rigault et al. (2013), while Jones, Riess & Scolnic (2015) and Jones et al. (2018b) find no evidence of a correlation between SN Ia luminosity and local environment.

The Dark Energy Survey (DES) ‘three-year’ (DES3YR) cosmological analysis (DES Collaboration 2019) combines data for 251 spectroscopically confirmed SNe Ia (206 after applying light-curve quality cuts) from the DES-SN programme, with a low-redshift sample of 122 SNe Ia to constrain the equation of state of dark energy ( $w$ ). Using data on the global properties of its SNe Ia, the DES3YR cosmology analysis (Brout et al. 2019b, hereafter B19), using a ‘BEAMS with Bias Corrections’ (BBC; Kessler & Scolnic 2017) framework, found no significant correlations between SN Ia luminosity and stellar mass for the DES-SN subsample. It was unclear whether this was due to the relatively small DES-SN Ia sample size, or whether some novel aspects of the DES analysis pipeline had (perhaps inadvertently) removed or corrected for the mass-step effect. In this paper, we present new host galaxy data for the 251 spectroscopically confirmed SNe Ia from DES-SN. Using stacked DES imaging from all 5 yr of DES-SN, excluding dates around the SN explosion, we measure the host galaxy fluxes and estimate their stellar masses and star-formation rates, and compare them to the light-curve properties of the SNe Ia they host, finding a strong correlation between  $M_{\text{stellar}}$ , SN Ia light-curve width and the bias correction used to correct for survey selection effects. Using simulated samples of the DES-SN survey that include intrinsic correlations between SN parameters and host galaxy  $M_{\text{stellar}}$  we show that this correlation inadvertently leads to reduction in the ‘mass step’ measured by DES. This result is consistent across a wide range of systematic tests.

This paper is organized as follows. In Section 2, we introduce the photometric measurements and derived galaxy parameters for the DES-SN sample and examine the sensitivity of these measurements to alternative photometric measurements and assumptions on the template galaxy spectral energy distributions (SEDs) used to

determine stellar masses. Section 3 considers correlations between the light-curve parameters of SNe Ia and the derived parameters of their host galaxies. Section 4 introduces and measures the mass step for DES3YR and studies how systematic uncertainties affect the inferred mass step. In Section 5, we use simulated samples to show that estimates of the mass step in a BBC framework are dependent on the underlying assumptions of the galaxy population and their correlation with the SNe that they host. We conclude in Section 6. Throughout this paper, we use AB magnitudes (Oke & Gunn 1983) and where relevant assume a reference cosmological model that is a spatially-flat  $\Lambda$ CDM model, with a matter density  $\Omega_m = 0.3$  and a Hubble constant  $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ .

## 2 SN AND HOST GALAXY DATA

The DES-SN Program was a 5 yr rolling search using the 570 Megapixel Dark Energy Camera (DECam; Flaugher et al. 2015) on the 4-m Blanco telescope at the Cerro Tololo Inter-American Observatory (CTIO), giving a  $2.7 \text{ deg}^2$  field of view. DES-SN observed two ‘deep’ fields and eight ‘shallow’ fields in *griz* filters approximately every 7 d, to single-visit depths of  $\sim 24.5$  and  $\sim 23.5$  mag, respectively.

Transient events were detected using a difference-imaging pipeline (Kessler et al. 2015), with machine-learning algorithms used to remove spurious candidates (Goldstein et al. 2015). During the first 3 yr, 251 SNe Ia were spectroscopically classified (D’Andrea et al. 2018). The SN Ia light-curve fluxes were measured using a ‘Scene Model Photometry’ (SMP) technique (Brout et al. 2019a), and the photometric calibration is described in Burke et al. (2018) and Lasker et al. (2019). The light curves were fit with the SALT2 SED template (Guy et al. 2007, 2010), trained using the Joint Lightcurve Analysis (JLA; Betoule et al. 2014) SN compilation, and implemented in the SNANA software package (Kessler et al. 2009). The light-curve fitting provides estimates of the rest-frame amplitude ( $m_B$ ), stretch ( $x_1$ ), and colour ( $c$ ) for each SN. Quality cuts, based on the light-curve coverage, are applied to the sample (see Brout et al. 2019b for details), which removes 45 SNe Ia. This leaves 206 SNe Ia in the fiducial DES sample. Due to an updated estimate of the time of maximum light in the SNANA package, one event (SNID=1279500) is lost compared to the analysis of DES Collaboration (2019) and B19. This does not impact our conclusions.

In the DES analysis (B19), the DES-SN sample is combined with 122 ‘low-redshift’ ( $z < 0.1$ ) SNe Ia from the literature to form the DES3YR sample. In this paper, we also consider other SN Ia samples from the literature: the JLA sample (Betoule et al. 2014) (740 SNe Ia) and the ‘Pantheon’ sample (Scolnic et al. 2018). The latter combines SNe Ia discovered by the Pan-STARRS1 (PS1) Medium Deep Survey with the JLA sample, as well as events from the *Hubble Space Telescope* (Suzuki et al. 2012; Riess et al. 2018) to form a sample of 1048 SNe Ia.

### 2.1 SN Ia distance estimation

The observed distance modulus for each SN,  $\mu_{\text{obs}}$ , is given by

$$\mu_{\text{obs}} = m_B + \alpha x_1 - \beta c + M_0 + \gamma G_{\text{host}} + \mu_{\text{bias}}, \quad (1)$$

where

$$G_{\text{host}} = \begin{cases} +1/2 & \text{if } \log M_{\text{stellar}}/M_{\odot} > M_{\text{step}} \\ -1/2 & \text{otherwise.} \end{cases} \quad (2)$$

$M_{\text{stellar}}$  is the SN host-galaxy stellar mass, and  $\gamma$  is commonly referred to as the ‘mass step’. The value of  $M_{\text{step}}$  is often fixed to some fiducial value, typically 10.  $\alpha$ ,  $\beta$ ,  $\gamma$ , and  $M_0$  are nuisance parameters that describe the global SN Ia population, and are usually determined simultaneously with the distances of with the cosmological parameters.

A correction,  $\mu_{\text{bias}}$ , determined from simulations, is also made to each SN Ia to account for various survey selection effects, such as Malmquist bias and spectroscopic targeting algorithms. In previous analyses (e.g. Conley et al. 2011; Betoule et al. 2014),  $\mu_{\text{bias}}$  is a function of redshift (a ‘1D correction’), and is estimated from either image-level simulations (Perrett et al. 2010) or catalogue-level simulations (Betoule et al. 2014). More recent analyses (Scolnic et al. 2018; Brout et al. 2019b) have determined  $\mu_{\text{bias}}$  as a 5D function of ( $z$ ,  $x_1$ ,  $c$ ,  $\alpha$ ,  $\beta$ ) using the BBC framework, splitting  $\mu_{\text{bias}}$  into three terms:  $m_{B\text{bias}}$ ,  $x_{1\text{bias}}$ , and  $c_{\text{bias}}$ . The fiducial DES3YR analysis (B19) uses the BBC formalism, which relies upon large, accurate simulations of the underlying SN Ia population determined using the SNANA package (Kessler et al. 2019) combined with a model for intrinsic brightness variations, or ‘intrinsic scatter’. The DES3YR analysis (B19) uses two intrinsic scatter models from Kessler et al. (2013): (Guy et al. 2010, hereafter G10) and (Chotard et al. 2011, hereafter C11). For simplicity, we restrict our analysis to the G10 model, which recovers consistent values of  $\gamma$  for the DES-SN sample compared to the C11 model (B19). The residuals from a cosmological model (often termed ‘Hubble residuals’) are given by

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

where  $\mu_{\text{theory}}$  is the theoretical distance modulus, which is dependent on the cosmological parameters.

A mass step has been detected in nearly all large SN Ia surveys at all redshifts (Sullivan et al. 2010; Lampeitl et al. 2010), with SNe Ia in galaxies with  $\log M_{\text{stellar}}/M_{\odot} > 10$  brighter on average (after standardization) than those in lower mass galaxies. Typical values for  $\gamma$  using a 1D  $\mu_{\text{bias}}$  correction ( $\gamma_{\text{1D}}$ ) include  $\gamma_{\text{1D}} = 0.070 \pm 0.023 \text{ mag}$  ( $3.0\sigma$ ; Betoule et al. 2014) for the sample of 740 JLA SNe Ia and  $\gamma_{\text{1D}} = 0.070 \pm 0.013 \text{ mag}$  ( $5.5\sigma$ ; Roman et al. 2018) for the 882 SNLS5 SNe Ia while (Scolnic et al. 2018) using a 5D  $\mu_{\text{bias}}$  correction ( $\gamma_{\text{5D}}$ ) found  $\gamma_{\text{5D}} = 0.053 \pm 0.009 \text{ mag}$  ( $5.5\sigma$ ) for the 1048 SNe Ia that comprise the Pantheon data set and  $\gamma_{\text{5D}} = 0.039 \pm 0.016 \text{ mag}$  ( $2.4\sigma$ ) for the 365 SNe Ia spectroscopically confirmed by PS1. Conversely, B19 found  $\gamma_{\text{5D}} = 0.009 \pm 0.018 \text{ mag}$  ( $0.5\sigma$ ) for the DES-SN sample when using a G10 scatter model and  $\gamma_{\text{5D}} = 0.004 \pm 0.017 \text{ mag}$  ( $0.2\sigma$ ) when using a C11 model for intrinsic scatter.

## 2.2 SN Ia host galaxy data

### 2.2.1 Host galaxy photometry

Photometric data for the host galaxies of the DES3YR cosmology analysis (Brout et al. 2019b; DES Collaboration 2019) were determined from the DES SVA1-GOLD catalogue. This catalogue has  $10\sigma$  limiting magnitudes of  $(g, r, i, z) = (24.0, 23.8, 23.0, 22.3)$ , as described in Rykoff et al. (2016) and Bonnett et al. (2016). It was constructed from DES Science Verification (SV) data collected prior to the DES-SN data used in the DES3YR sample. In this paper, we upgrade from the DES SVA1-GOLD catalogue and instead determine photometric properties of the DES SNe Ia host galaxies from DES deep stack photometry (Wiseman et al. 2020, hereafter W20) utilizing images from all 5 yr of DES-SN.



In summary, for each transient, the images used to create the deep stack photometry are selected from the 5 yr of the DES-SN survey, excluding the season where the transient was first detected. Defining  $\tau_{\text{obs}}$  as the ratio between the effective exposure time of an individual observation given the atmospheric conditions, and the true exposure time (Morganson et al. 2018), we select images with  $\tau_{\text{obs}} > X$ , with  $0.2 < X < 0.5$ , optimized for each field/combination to produce final images with the greatest possible depth (W20). We combine these images using SCAMP (Bertin 2006) and SWARP (Bertin et al. 2002), and create catalogues using Source Extractor (SEXTRACTOR Bertin & Arnouts 1996; Bertin 2011). These coadded images have limiting magnitudes of  $(griz) = (25.6, 25.8, 26.0, 26.0)$  in the eight shallow fields and  $(griz) = (26.1, 26.3, 26.5, 26.4)$  in the two deep fields. We use SEXTRACTOR *griz* ‘FLUX\_AUTO’ measurements, and correct for foreground extinction using the Milky Way (MW) dust maps of Schlegel, Finkbeiner & Davis (1998).

The photometric catalogue of W20 considers each DECam CCD individually when constructing deep stacked images. To ensure that host galaxies are not lost due to CCD gaps, which comprise 10 per cent of the DECam field of view (Flaugher et al. 2015), we supplement this catalogue with data from the DES SVA1-GOLD catalogue. Only 1 of our 206 SNe Ia has host galaxy measurements determined from the SVA1-GOLD catalogue, which has consistent ‘FLUX\_AUTO’ values with those of W20 for galaxies common to both catalogues.

The host galaxies of the DES SNe Ia were identified using the ‘Directional Light Radius’ (DLR) methodology described in Sullivan et al. (2006), Smith et al. (2012), Gupta et al. (2016), Sako et al. (2018) and below in Appendix A. Following Gupta et al. (2016) and Sako et al. (2018), we only consider galaxies with  $d_{\text{DLR}} < 7$  to be candidates for the true host, and also require that the potential host be classified as a galaxy based on the CLASS\_STAR SEXTRACTOR output (Soumagnac et al. 2015). SNe with no galaxy matching this criteria are denoted hostless. 201 of 206 (98 per cent) of the DES-SN sample have an associated host galaxy. This fraction of hostless SN, 2 per cent, is less than that found for the Supernova Legacy Survey (6 per cent; Sullivan et al. 2006) and SDSS-SN (4 per cent; Sako et al. 2018), highlighting the depth of the deep-stacks relative to the redshift range probed by DES-SN. When using the shallower SVA1-GOLD catalogue, as used in B19, 18 events are denoted hostless, while 5 events are associated with different galaxies, either due the detection of new sources located in close proximity to the SN or due to changes in the measured light-profile of the nearby hosts. AB magnitudes, corrected for MW extinction, for each identified host in DES-SN are given in Table B1.

### 2.2.2 Host galaxy physical parameters

To estimate the stellar mass ( $M_{\text{stellar}}$ ) and star-formation rate (SFR) for each host galaxy in our sample, we use a methodology similar to that used in Sullivan et al. (2010) and Kim et al. (2018). We use the PÉGASE.2 spectral synthesis code (Fioc & Rocca-Volmerange 1997; Le Borgne & Rocca-Volmerange 2002) to calculate the SED of a galaxy as a function of time, using 9 smooth, exponentially declining star formation histories (SFHs), with  $\text{SFR}(t) = \exp^{-t/\tau}$ , where  $t$  is the age of the galaxy and  $\tau$  is the e-folding time; each SFH is therefore normalized to produce  $1 M_{\odot}$ . The SED of each SFH is calculated at 102 time-steps from 0 to 14 Gyr, and we include the

standard PÉGASE.2 prescription for nebular emission. Each SFH has an initial metallicity ( $Z$ ) of 0.004 that evolves consistently, with new stars formed with the metallicity of the ISM. We use a Kroupa (2001, hereafter K01) initial mass function (IMF). (In Sections 2.2.3 and 4.2, we investigate potential systematic uncertainties associated with this IMF choice.) At each time-step, PÉGASE.2 provides the total mass in stars, and following Sullivan et al. (2006), we calculate the average SFR over the previous 250 Myr of the SFH. For each SED, we also use seven foreground dust screens with a colour excess,  $E(B - V)$ , ranging from 0.0 to 0.30 mag in steps of 0.05 mag. This grid effectively creates 63 unique host-galaxy models, each with 102 time-steps (i.e. 6426 unique SEDs). We note that the rest-frame wavelength range probed by the DES filters, limits our ability to accurately constrain the dust content of galaxies, which can impact the estimates of  $M_{\text{stellar}}$  and SFR by 0.1dex (Mitchell et al. 2013; Laigle et al. 2019), although Palmese et al. (2020) show that this effect is negligible for early type galaxies.

For each host galaxy, the fluxes of each model SED at the redshift of the SN in the DES  $g, r, i, z$  filters are calculated (giving 6426 sets of model fluxes,  $F_{\text{model}}$ ), and for each  $F_{\text{model}}$  we minimize the  $\chi^2$  as

$$\chi^2 = \sum_{x \in \text{griz}} \left( \frac{A F_{\text{model};x} - F_{\text{obs};x}}{\sigma_{\text{obs};x}} \right)^2, \quad (4)$$

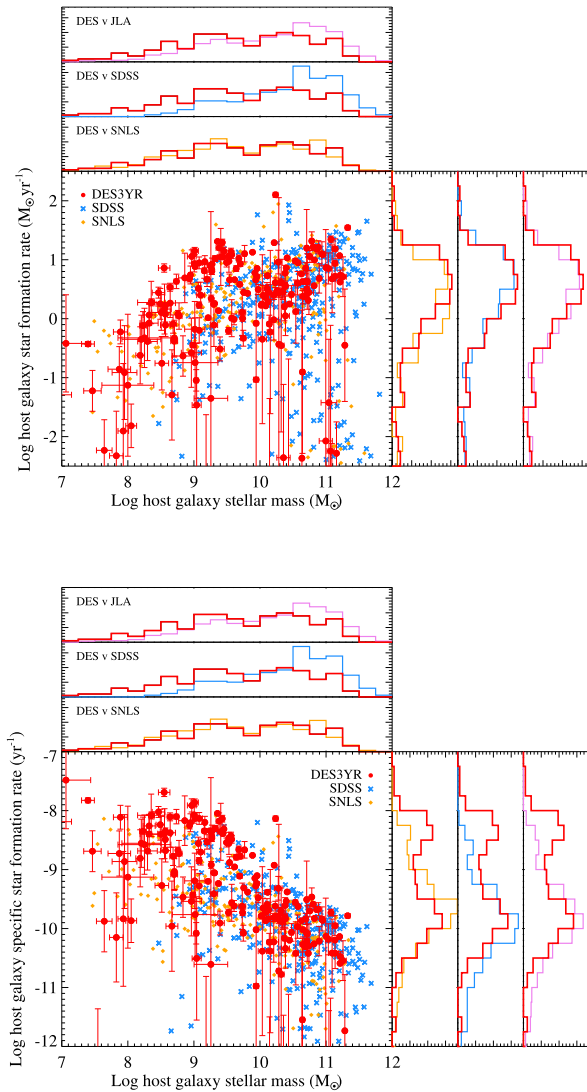
where  $A$  is a scale factor determined from a global  $\chi^2$  minimization. To ensure consistency with our assumed cosmological model, we enforce that the age of the best-fitting template must be less than the age of the Universe at the redshift of the SN.  $M_{\text{stellar}}$  and SFR are calculated from  $A$  and the best-fitting SED. From these, we calculate the specific SFR (sSFR) as  $\text{sSFR} = \text{SFR}/M_{\text{stellar}}$ .

We use a Monte Carlo approach to estimate the statistical uncertainties in our derived parameters. For each galaxy, we perform 1000 random realizations of  $F_{\text{obs}}$ , drawing a new  $F'_{\text{obs}}$  randomly from a normal distribution with a mean  $F_{\text{obs}}$  and  $\sigma = \sigma_{\text{obs}}$ , and repeating the minimization procedure described above. The quoted uncertainties on the best-fitting parameters are the standard deviation of the best-fitting parameters overall realizations. Derived values for  $M_{\text{stellar}}$  and sSFR for each identified host in DES-SN is given in Table B1.

For comparison, the DES3YR analysis in B19 used a PÉGASE.2 template library comprised of 9 spectral types, described in Smith et al. (2012), evaluated at 200 age steps and a K01 IMF. The best-fitting SED, stellar mass, and star formation rate were determined with the code ZPEG (Le Borgne & Rocca-Volmerange 2002) using  $\chi^2$  minimization. In Section 4.2.1, we investigate how the mass estimates for this study compare to those determined in our fiducial analysis. Further, while the DES-SN estimates of  $M_{\text{stellar}}$  and sSFR are based only on 4 band photometry, with no information on the rest-frame infrared contribution, Palmese et al. (2016), for cluster galaxies with a known redshift, found no evidence of an offset in  $\log M_{\text{stellar}}/M_{\odot}$  estimated from 5 band DES-SV photometry compared to that estimated from 17 band photometry. This suggests that while the inclusion of near-infrared data would improve constraints on the underlying galaxy SED, our best-fitting models are likely unlikely unbiased.

For our DES host galaxies, the relationships between  $M_{\text{stellar}}$  and SFR, and  $M_{\text{stellar}}$  and sSFR, are shown in Fig. 1, together with the distributions of  $M_{\text{stellar}}$ , SFR, and sSFR. For comparison, we also show the values for SN Ia hosts discovered by the SDSS (Sako et al. 2018) and SNLS (Conley et al. 2011) surveys; for consistency, we have re-fitted the host galaxy data from Sullivan et al. (2010) and Sako et al. (2018) using the above framework. As anticipated, there

<sup>1</sup>Where  $\tau = 100, 200, 300, 400, 500, 750, 1000, 1500, 2000$  Myr.



**Figure 1.** Top: The relationship between  $M_{\text{stellar}}$  and SFR for the DES-SN sample (red circles). Overplotted are the values for the SDSS (blue crosses) and SNLS (orange diamonds) samples, combined as the JLA sample (violet) and analysed in a consistent manner. Bottom: As left, showing the relationship between  $M_{\text{stellar}}$  and sSFR. The parameter distributions are normalized to contain an equal area.

is a strong correlation between host galaxy  $M_{\text{stellar}}$ , SFR, and sSFR (defined in part by our underlying SFHs). The most massive galaxies typically have a lower sSFR, while lower mass galaxies consistently have a higher sSFR. The correlation between  $M_{\text{stellar}}$ , SFR and sSFR for the DES hosts are consistent with those found for the SDSS and SNLS samples.

The  $M_{\text{stellar}}$  distribution for the DES sample is consistent with the SNLS sample, which also probes a wide redshift range. The SDSS sample tends to have more massive host galaxies. The SDSS sample probes lower redshifts (with a mean of 0.20) compared DES-SN (a with mean redshift of 0.39) and SNLS (0.64). The increased contribution from high-mass galaxies for the SDSS sample may be a consequence of this, as galaxies at lower redshifts tend to be more massive, or a selection effect reflecting the fact that SNe Ia in bright host galaxies are harder to spectroscopically confirm at higher redshift. The SFR distributions for the DES sample are consistent with the SDSS and SNLS samples, while for sSFR,

there is an overdensity of high sSFR ( $\log \text{sSFR} > -9$ ) hosts in the DES sample compared to the SDSS and SNLS samples. The hosts of these events are preferentially low mass, with mean  $\log M_{\text{stellar}}/M_{\odot} = 8.86 \pm 0.09$ , and moderately star forming, with mean  $\log \text{SFR}/M_{\odot} \text{ yr}^{-1} = 0.46 \pm 0.08$ .

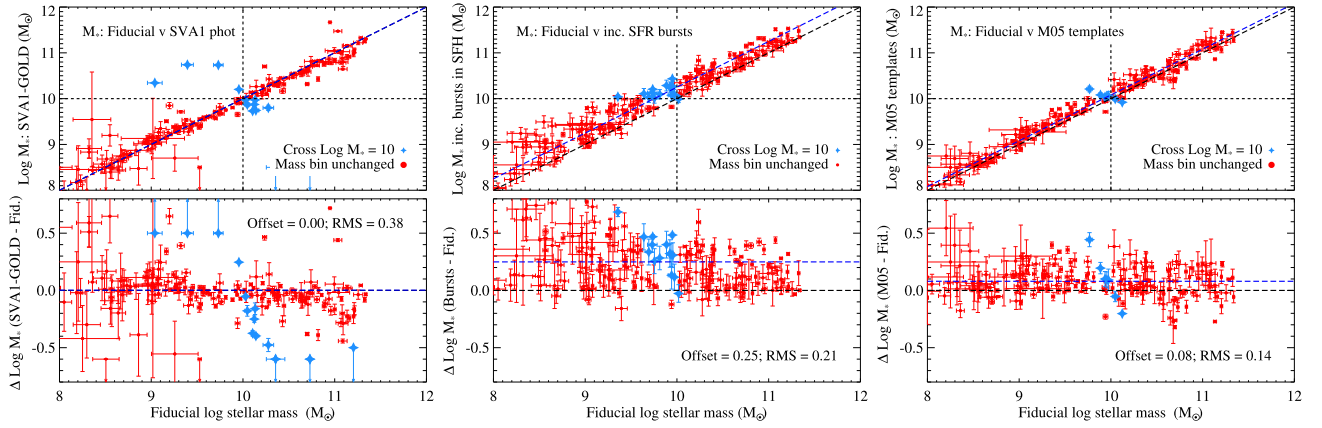
### 2.2.3 Systematic uncertainties of the stellar mass estimates

Our  $M_{\text{stellar}}$  estimates depend on the photometric catalogue considered and assumptions on the SFH, IMF, and SED templates used to describe the galaxy population, all of which are of debate in the literature. We here test the sensitivity of our  $M_{\text{stellar}}$  estimates to these assumptions. The results are shown in Fig. 2 and Table 1.

The left-hand panel of Fig. 2 and row 10 of Table 1 show the correlation between our fiducial  $M_{\text{stellar}}$ , derived using photometry determined from deep stacks, compared to those obtained from the SVA1-GOLD catalogue as described in Section 2.2.1. There is no evidence of a systematic offset between the two measurements, and the best-fitting linear fit has a slope of  $0.98 \pm 0.03$ . There is a mean difference in  $\log M_{\text{stellar}}$  of  $0.002 \pm 0.016$  dex between the two measurements, and an rms scatter of 0.38 dex. An increased scatter is observed for galaxies with  $\log M_{\text{stellar}}/M_{\odot} < 9.5$  due to the increased scatter in the fluxes for the faintest objects in our sample, but no systematic trend as a function of stellar mass is observed. The blue crosses in Fig. 2 correspond to galaxies that cross the threshold of  $\log M_{\text{stellar}}/M_{\odot} = 10$  between the two analysis; i.e. those that have  $\log M_{\text{stellar}}/M_{\odot} > 10$  in one mass estimate, but have  $\log M_{\text{stellar}}/M_{\odot} < 10$  in the other. These objects have implications for the inferred mass step (see Section 4 for details), where  $\log M_{\text{stellar}}/M_{\odot} = 10$  is used to differentiate between two classes of SNe Ia with differing absolute magnitudes. 4 of 188 SN hosts (two per cent) are classified as high mass when considering the SVA1-GOLD catalogue, but are considered low-mass hosts in our fiducial analysis using deep co-adds. Ten objects (5 per cent) satisfy the reverse criteria.

Our fiducial analysis uses ‘FLUX\_AUTO’ measurements derived from deep stack images. These flux estimates are determined from model fits where each passband is treated independently. An alternative approach is to use a fixed apertures across all filters. These, ‘FLUX\_DETMODEL’ measurements will better represent the colour of each galaxy, but as a consequence, can underestimate the total flux. Row 11 of Table 1 shows the consequence of using ‘FLUX\_DETMODEL’ measurements instead of ‘FLUX\_AUTO’ from the SVA1-GOLD catalogue. Consistent with the estimates using ‘FLUX\_AUTO’ measurements, no residual offset with stellar mass is observed.

The central panel of Fig. 2 and row 3 of Table 1 show the correlation between our fiducial  $M_{\text{stellar}}$  estimates and those derived when using SFHs that contain bursts of star formation. In this analysis, we use the same nine exponentially declining SFHs, but superimpose a burst of star-formation on each underlying SFH. These bursts occur randomly between 1 and 10 Gyr into the smooth, exponentially declining, SFH, and can form between 0.05 and 25 per cent of the total stellar mass in the SFH. Each burst also has an exponentially declining SFH, with  $\tau = 10, 50, \text{ or } 100 \text{ Myr}$  (selected with equal probability; Childress et al. 2013a). We generate 4000 such SFHs, with an increased time resolution around the time of the bursts, calculate a new set of  $F_{\text{model}}$  with the same foreground dust screens as before, and repeat the  $\chi^2$  minimization, retaining the original nine SFHs for consideration. With differing age profiles, these burst models break the degeneracy between age and metallicity in the SFHs.



**Figure 2.** Testing the robustness of  $M_{\text{stellar}}$  estimates. Left-hand panel: Fiducial  $M_{\text{stellar}}$  estimates compared to those estimated using *griz* galaxy magnitudes taken from the DES SVA1-GOLD catalogue (Rykoff et al. 2016). The lower panel shows the difference in  $M_{\text{stellar}}$  as a function of stellar mass. No linear trend as a function of stellar mass is observed. Centre panel: As left-hand panel, but considering the effect of extra bursts of star formation in the template SEDs used to determine derived galaxy parameters. Including additional bursts of star-formation increases the inferred  $\log M_{\text{stellar}}/M_{\odot}$  by  $0.25 \pm 0.02$ . Right-hand panel: As left-hand panel, but showing the inferred stellar masses when alternative templates (Maraston 2005) are used in the fit. These templates decrease the inferred  $\log M_{\text{stellar}}/M_{\odot}$  by  $0.11 \pm 0.01$ , but no trend is observed. In all panels, DES-SN objects are plotted in red, with galaxies that have inferred  $\log M_{\text{stellar}}/M_{\odot} > 10$  in one axis but  $\log M_{\text{stellar}}/M_{\odot} < 10$  in another (i.e. those that would cross the  $M_{\text{step}}$  in equation 2) plotted as blue diamonds. The mean offset between the two values is highlighted by a blue dashed line.

**Table 1.** Comparison between  $M_{\text{stellar}}$  derived for the host galaxies of the 206 spectroscopically confirmed SNe Ia that comprise the DES-SN sample and those derived with different assumptions.

Row #	Photometric catalogue	Templates <sup>a</sup>	IMF <sup>a</sup>	$\langle \Delta \log M_{\text{stellar}}/M_{\odot} \rangle^b$ (rms)	# Hosts moving class	
					High mass <sup>c</sup>	Low mass <sup>d</sup>
1; Fiducial result	W20	PÉGASE	K01	–	–	–
2; B19	SVA1-GOLD: mag_detmodel	ZPEG	K01	$0.12 \pm 0.02$ (0.38)	8 (4.3%)	11 (5.9%)
3	W20	PÉGASE:bursts	K01	$0.25 \pm 0.02$ (0.21)	14 (7.0%)	1 (0.5%)
4	W20	PÉGASE	S55	$0.17 \pm 0.01$ (0.09)	11 (5.5%)	0 (0.0%)
5	W20	PÉGASE:bursts	S55	$0.43 \pm 0.02$ (0.24)	25 (12.4%)	0 (0.0%)
6	W20	M05	K01	$-0.11 \pm 0.01$ (0.15)	0 (0.0%)	8 (4.0%)
7	W20	M05	S55	$0.08 \pm 0.01$ (0.14)	5 (2.5%)	2 (1.0%)
8	W20	BC03	S55	$0.18 \pm 0.01$ (0.09)	10 (5.0%)	0 (0.0%)
9	W20	ZPEG	K01	$0.08 \pm 0.02$ (0.20)	8 (4.0%)	3 (1.5%)
10	SVA1-GOLD: mag_auto	PÉGASE	K01	$0.00 \pm 0.02$ (0.38)	10 (5.3%)	4 (2.1%)
11	SVA1-GOLD: mag_detmodel	PÉGASE	K01	$0.03 \pm 0.02$ (0.37)	9 (4.8%)	4 (2.1%)

<sup>a</sup>Galaxy templates, assumptions of the SFH and IMF used. See Section 2.2.3 for details.

<sup>b</sup> $\langle \Delta(\log M_{\text{stellar}} - \log M_{\text{stellar, fid}}) \rangle$ , where  $\log M_{\text{stellar, fid}}$  is derived from the PEGASE templates with a K01 IMF.

<sup>c</sup>Number of hosts with  $\log M_{\text{stellar, estimate}}/M_{\odot} > 10$  and  $\log M_{\text{stellar, fid}}/M_{\odot} < 10$ .

<sup>d</sup>Number of hosts with  $\log M_{\text{stellar, estimate}}/M_{\odot} < 10$  and  $\log M_{\text{stellar, fid}}/M_{\odot} > 10$ .

From Fig. 2, the inclusion of additional bursts of star-formation typically increases the inferred  $M_{\text{stellar}}$  estimate, with a mean offset of  $0.25 \pm 0.02$  dex and an rms = 0.21 dex. 189 (94 per cent) of the host galaxies in our sample ‘prefer’ (i.e. have a smaller minimum  $\chi^2$  for) SFHs with a recent burst of star-formation in the last 10 Gyr. We find strong evidence (at  $4.4\sigma$ ) that our fiducial stellar mass estimates are not one to one correlated with those determined when recent bursts of star formation are allowed in the galaxy SED. The increase in stellar mass for lower mass galaxies is proportionally higher than that observed in high-mass systems. 14 of 201 (seven per cent) of the SN Ia hosts move from the low-mass to high-mass class when recent bursts of star-formation are allowed, with one galaxy (one per cent) moving into the low-mass class. To further test the effect of our choice of SED modelling parameters, in Table 1, row 4, we show how assuming a K01 IMF affects the estimated values of  $M_{\text{stellar}}$ . Repeating our fiducial analysis (with no additional bursts of star formation) with a Salpeter IMF (Salpeter 1955, hereafter S55)

results in a systematic offset of  $0.17 \pm 0.01$  dex (with the masses derived from a S55 IMF being more massive), and rms of 0.09 dex. There are 11 additional high-mass hosts (six per cent) when a S55 IMF is used, while no hosts move from the high-mass to low-mass class.

Our final test of the robustness of our  $M_{\text{stellar}}$  estimates concerns the population model considered. The Maraston (2005) population synthesis models include contributions from the thermally pulsing asymptotic giant branch (TP-AGB) phase of stellar evolution. We use 19 exponentially declining SFHs based on these models, each evaluated at 61 time-steps. Generating SFHs using a K01 IMF, the right-hand panel of Fig. 2 and row 6 of Table 1, shows the correlation between  $M_{\text{stellar}}$  derived by our fiducial technique compared to those derived using the templates of Maraston (2005). A strong correlation is observed between the two mass estimates, with a systematic offset of  $0.11 \pm 0.01$  dex (with our fiducial  $M_{\text{stellar}}$  values being more massive) and an rms of 0.15 dex. No evidence of a residual



correlation between the two mass estimates and our fiducial stellar masses is observed, with a best-fitting linear relationship having a slope of  $0.99 \pm 0.01$ . There are 8 additional low-mass hosts (4 per cent) when using the  $M_{\text{stellar}}$  estimates from M05, with no objects moving into the high-mass bin. Table 1, row 7, also shows the effect of using a S55 IMF in this analysis, with a mean offset of  $0.08 \pm 0.01$  dex (with the S55 IMF masses being more massive) and an rms of 0.14. In this case, only 7 galaxies move across the  $\log M_{\text{stellar}}/M_{\odot} = 10$  division: 5 (3 per cent) listed as high mass when a Salpeter IMF is considered compared to 2 (1 per cent) which are better fit as being low mass.

To further test the effect of our choice of template SFH, in Table 1, row 8, we show the results when using the Bruzual & Charlot (2003) single stellar populations (SSPs) with a Salpeter IMF. A mean offset of  $0.18 \pm 0.01$  dex, with an rms of 0.20 dex is seen with the  $M_{\text{stellar}}$  values being more massive for the Bruzual & Charlot models. As a result, 10 galaxies (5 per cent) move into the high-mass class, while no extra events are identified as low-mass hosts. This result is consistent with the result when using the PÉGASE templates with a S55 IMF (Table 1, row 7), suggesting that this difference is driven solely by the choice of IMF.

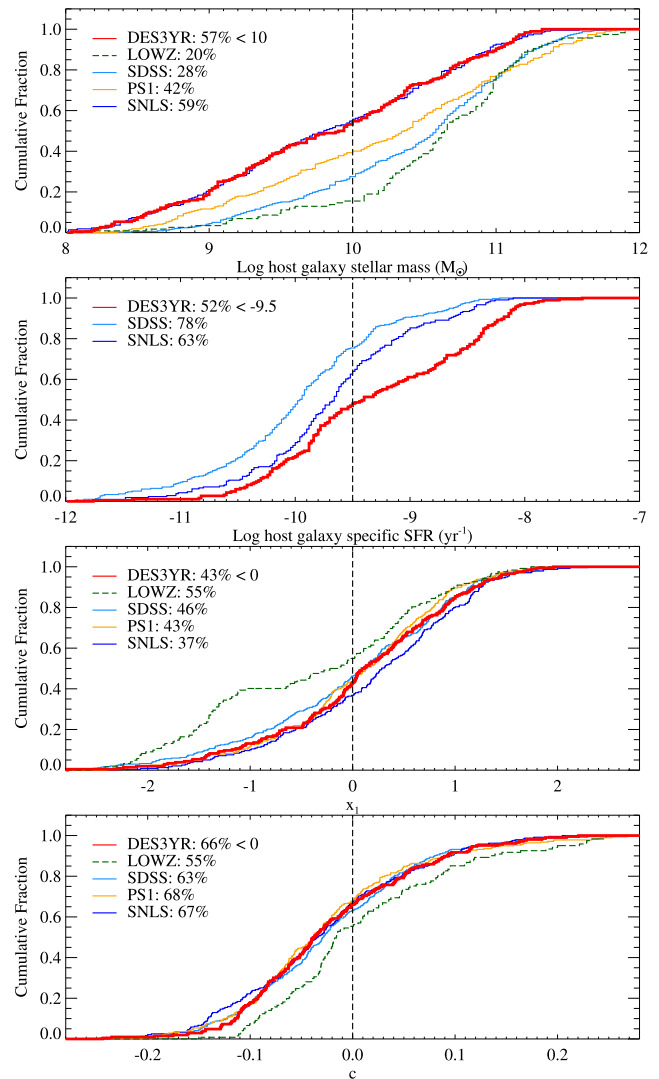
These tests show that our estimates of  $M_{\text{stellar}}$  are robust to the choice of photometric catalogue and the SED models used in our fiducial analysis. Considering all systematic tests a mean of 13.3 (6.8 per cent) galaxies move across the  $\log M_{\text{stellar}}/M_{\odot} = 10$  boundary, with a maximum of 25 (12.4 per cent). For comparison, for our fiducial analysis, 7 (3.4 per cent) galaxies could be classified as both high and low mass when the  $1\sigma$  statistical uncertainty on  $\log M_{\text{stellar}}/M_{\odot}$  is considered. This suggests that, for our deep stack photometry, photon counting statistics are subdominant to uncertainties in our assumptions on the parameters used to describe the galaxy population when estimating  $M_{\text{stellar}}$ .

### 3 SN IA PROPERTIES AS A FUNCTION OF HOST GALAXY PROPERTIES

Here, we examine the demographics of the SN Ia host galaxies, and correlations between the SN Ia host galaxy properties and the SNe Ia they host. Of particular importance is identifying and understanding differences between the host galaxies of the DES SN Ia sample and other SN Ia samples at a similar redshifts, as these differences can result in discrepancies between measured mass steps.

Fig. 3 shows the cumulative distribution of  $M_{\text{stellar}}$ , sSFR,  $x_1$  and  $c$  for the DES-SN sample compared to literature data sets, with the mean sample properties given in Table 2. The distribution of  $M_{\text{stellar}}$  for the DES-SN sample is consistent with that of the SNLS sample, with a Kolmogorov–Smirnov (KS) probability 0.78. These two high-redshift samples are both untargeted searches probing a wide redshift range, able to locate SNe Ia in all but the most extreme host galaxy environments. By contrast, the DES  $M_{\text{stellar}}$  distribution is different to that found for the low-redshift sample (with KS test probability  $1.2 \times 10^{-8}$ ), where the SNe Ia are predominately found in high-mass ( $\log M_{\text{stellar}}/M_{\odot} > 10$ ) host galaxies. This is expected and is due in part to selection effects in low-redshift galaxy-targeted transient surveys, and in part to evolution in the galaxy population (see discussion in Pan et al. 2014).

At intermediate redshift, the distribution of  $M_{\text{stellar}}$  for the PS1 and SDSS samples are consistent, with KS probability 0.11. We find a KS probability of 0.037 (0.0001) between the DES and PS1 (SDSS) samples, with 57 per cent of SNe Ia found in low-mass ( $M_{\text{stellar}} < 10$ ) hosts for the DES-SN sample, compared to 42 per cent and 28 per cent for PS1 and SDSS, respectively. This



**Figure 3.** Cumulative distributions of  $M_{\text{stellar}}$ , sSFR,  $x_1$ , and  $c$  for the DES-SN sample (shown in red) compared to literature data sets (SDSS, light-blue; SNLS, dark blue; PS1, yellow; low-z, green). The fraction of SNe Ia with  $\log M_{\text{stellar}}/M_{\odot} < 10$ ,  $\text{sSFR} < -9.5$ ,  $x_1 < 0$ , and  $c < 0$  is also shown.

is likely a selection effect of the DES-SN sample. SNe in faint (and thus lower mass) hosts are preferentially targeted for real-time spectroscopic follow-up in DES (D’Andrea et al. 2018) as these host galaxies are more challenging to measure redshifts for once the SN light has faded, potentially biasing the DES-SN sample to lower-mass hosts compared to those determined by other surveys.

sSFR measurements are available for the DES-SN, SDSS, and SNLS samples (Kim et al. 2018). Galaxies with lower sSFR have smaller amounts of star formation relative to their stellar mass, and are thus dominated by an older stellar population. As shown in Fig. 1, there is an excess of high-sSFR ( $\text{sSFR} > -9.5$ ) hosts in the DES-SN sample compared to the SDSS and SNLS samples, with KS probabilities of 0.00002 (0.008) between the DES and SDSS (SNLS) samples, indicating that the DES-SN sample is dominated by a younger stellar population. This again can be attributed to the spectroscopic targeting algorithm utilized by DES-SN (D’Andrea et al. 2018), which focused on SNe in faint, low-mass hosts. These, younger stellar environments, typically exhibit higher star-



**Table 2.** The mean properties of samples used in this analysis.

Survey	$N_{\text{SN}}$	$\bar{z}$	$\bar{x}_1$	$\bar{c}$	$\overline{\log M_{\text{stellar}}/M_{\odot}}$	Percentage of low-mass hosts <sup>b</sup>
DES-SN <sup>a</sup>	206	0.364	0.115	−0.0367	9.70	57.3
SDSS (Betoule et al. 2014)	374	0.198	0.152	−0.0307	10.23	40.9
SDSS (Scolnic et al. 2018)	335	0.202	0.170	−0.0277	10.40	37.6
SNLS (Betoule et al. 2014)	239	0.640	0.285	−0.0339	9.64	59.0
SNLS (Scolnic et al. 2018)	236	0.642	0.306	−0.0318	9.64	59.3
PS1	279	0.292	0.138	−0.0377	10.32	41.6
low- $z$	124	0.0288	−0.132	−0.0172	10.64	19.4

<sup>a</sup>Passing selection criteria in B19.

<sup>b</sup>Percentage of hosts with  $\log M_{\text{stellar}}/M_{\odot} < 10$ .

formation rates potentially biasing the DES-SN sample to galaxies with higher sSFR compared to literature samples.

The SN Ia properties ( $x_1$ ,  $c$ ) of the cosmological samples (DES-SN, SNLS, SDSS, PS1) are consistent, indicating little evolution in the population parameters, and little evidence of SN specific selection techniques. The only inconsistency is with the low-redshift sample, which is over-represented with redder ( $c > 0.1$ ), faster-declining ( $x_1 < 0.0$ ) SNe Ia. These differences have been seen previously (Scolnic & Kessler 2016; Scolnic et al. 2018), but again are expected as the low-redshift sample is primarily SNe Ia obtained from targeted surveys, and hence in high-mass galaxies. These galaxies preferentially host fainter (lower  $x_1$ ), redder SNe Ia (Sullivan et al. 2010; Smith et al. 2012).

### 3.1 Correlating SN and host galaxy properties

Correlations between the light-curve shape ( $x_1$ ) and host galaxy properties have been observed in many previous studies (e.g. Sullivan et al. 2010; Lampeitl et al. 2010; Gupta et al. 2011; Childress et al. 2013b; Wolf et al. 2016): low-mass, high star-forming, low-metallicity, young stellar populations preferentially host broader (high  $x_1$ ), brighter SNe Ia.

The DES-SN data set recovers these trends (Fig. 4). At  $2.5\sigma$  significance, we find evidence that higher stellar-mass ( $\log M_{\text{stellar}}/M_{\odot} > 10$ ) galaxies host redder SNe Ia than those found in lower mass galaxies, with a mean difference of  $\Delta c = 0.027 \pm 0.011$ . This is consistent with a difference of  $0.022 \pm 0.005$  measured by B19 and  $0.012 \pm 0.004$  found by Scolnic et al. (2018). For the DES-SN sample, there is no evidence of a difference in dispersion in  $c$  as a function of  $M_{\text{stellar}}$ . The SNe Ia colour distribution in high-mass galaxies has an rms of 0.086 compared to 0.081 for those in low-mass hosts.

As expected, there is a strong correlation between light-curve width ( $x_1$ ) and galaxy properties, with high  $x_1$  SNe Ia preferentially found in low  $M_{\text{stellar}}$  ( $\log M_{\text{stellar}}/M_{\odot} < 10$ ), high sSFR (sSFR  $> -9.5$ ) galaxies: the mean  $x_1$  differs between high and low  $M_{\text{stellar}}$  galaxies at  $7.6\sigma$ , and at  $5.3\sigma$  between low and high sSFR galaxies. The  $x_1$  distribution is also narrower for SNe Ia found in low stellar mass galaxies compared to high stellar mass galaxies, with an rms of 0.73 compared to 0.95; consistent results are found as a function of sSFR.

## 4 THE MASS STEP IN DES3YR

Correlations between  $M_{\text{stellar}}$  and SN Ia Hubble residuals have been reported in the literature. For example, the JLA analysis (Betoule et al. 2014) found  $\gamma = 0.070 \pm 0.023$  mag, a detection at  $3.04\sigma$ , while the Roman et al. (2018) analysis measured  $\gamma =$

$0.070 \pm 0.013$  mag, a detection at  $5.4\sigma$ . The DES3YR cosmology analysis (B19), using galaxy photometry from DES-SVA1, found no significant correlation, with  $\gamma = 0.021 \pm 0.018$  mag for the DES3YR (DES-SN and low- $z$  combined) sample and  $\gamma = 0.009 \pm 0.018$  mag for the DES-SN subsample alone.

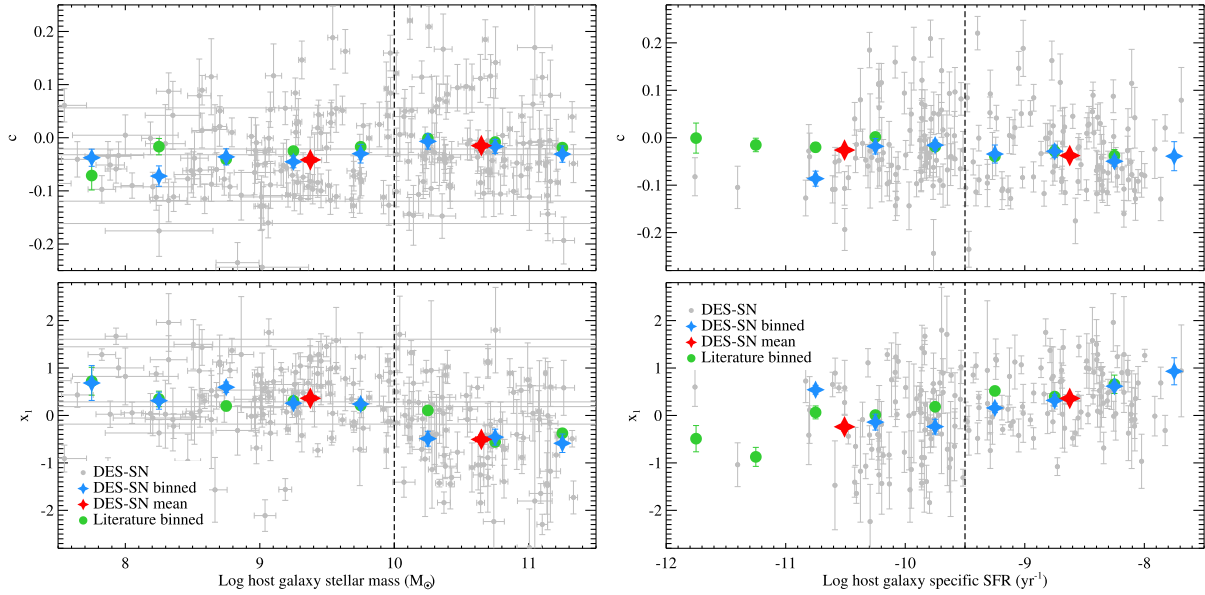
Fig. 5 shows the correlation between  $M_{\text{stellar}}$  and SN Ia Hubble residuals ( $\Delta\mu = \mu_{\text{obs}} - \mu_{\text{theory}}$ ) for the DES-SN sample. In this analysis, to calculate  $\mu_{\text{theory}}$ , we fix the cosmological parameters ( $\Omega_m, \Omega_\Lambda$ )=(0.30, 0.70). To calculate  $\mu_{\text{obs}}$  we set the SN Ia nuisance parameters to the best-fitting values determined from fitting the DES3YR sample assuming no correction for stellar mass such that  $(\alpha, \beta, \gamma)$ =(0.142, 3.03, 0.0) in equation (2). The top panel of Fig. 5 shows the results with a 5D  $\mu_{\text{bias}}$  correction (see Section 2.1), as used in B19, with the bottom panel showing the results when a 1D  $\mu_{\text{bias}}$  correction is applied. The implications of this choice are discussed in detail in Section 4.3.

Table 3 shows the best-fitting value of  $\gamma$  from this analysis compared to values determined in the literature. For the DES-SN sample, no significant correlation with  $M_{\text{stellar}}$  is observed: fitting only for  $\gamma$  and keeping the location of the mass step at  $M_{\text{step}} = 10$ , we find  $\gamma = 0.030 \pm 0.017$  mag (inconsistent with zero at  $1.8\sigma$ ). When  $\alpha$ ,  $\beta$  and  $\gamma$  are all floated in the fit, we recover  $\gamma = 0.040 \pm 0.019$  mag ( $2.1\sigma$ ) for the DES-SN sample,  $\gamma = 0.043 \pm 0.018$  mag ( $2.4\sigma$ ) for the DES3YR sample and  $\gamma = 0.068 \pm 0.038$  mag ( $1.8\sigma$ ) for the low- $z$  subsample alone. The value for the DES-SN sample is higher, at  $1.3\sigma$ , than the value found in the previous DES3YR analysis (B19). The value found here for the DES-SN sample is consistent with  $\gamma$  derived from the JLA analysis at  $< 1\sigma$  and with  $\gamma = 0$  at  $2.1\sigma$ .

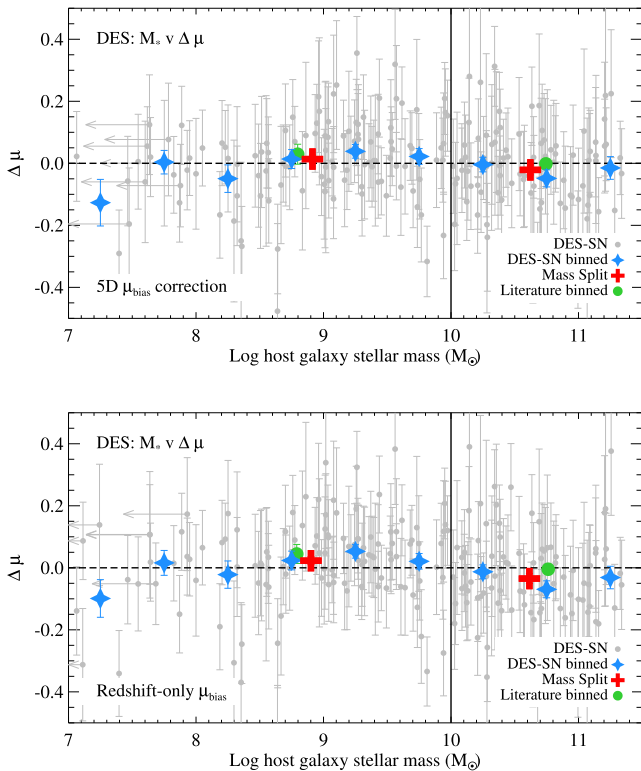
### 4.1 Comparison to Brout et al. (2019b)

For this analysis of the DES-SN sample, we find  $\gamma = 0.040 \pm 0.019$  mag, compared to  $\gamma = 0.009 \pm 0.018$  mag as determined by B19, a difference of  $\Delta\gamma_{\text{sys}} = \gamma_{\text{sys}} - \gamma_{\text{fid}} = -0.031$  mag. While statistically consistent at  $1.3\sigma$ , these two measurements use the same sample of 206 SNe Ia, each with identical SMP light curves, analysed consistently with the BBC framework (using a G10 intrinsic scatter model), suggesting a larger tension. These two analyses differ in two distinct ways: here, we use deep stack photometry (W20) and improved SFHs in the determination of  $M_{\text{stellar}}$ .

To probe the sensitivity of our results to these effects, Fig. 6 shows the difference between our fiducial  $M_{\text{stellar}}$  estimates and those used in the analysis of B19. No evidence of a correlation with stellar mass is observed, with a mean offset of  $\Delta M_{\text{stellar}} = 0.10 \pm 0.02$  dex and an rms of 0.24 for galaxies present in both catalogues, with the estimates from B19 being marginally higher. This difference is consistent with our analysis of the sensitivity



**Figure 4.** Left: The relationship between  $M_{\text{stellar}}$  and  $c$  (top panel) and  $x_1$  (lower panel) for the DES-SN sample. Data points are shown in grey, with the mean value in bins of stellar mass are shown as blue diamonds. The overall mean values for high and low mass galaxies are shown as red diamonds. Means for the literature sample are plotted as closed green circles. Right: Same as left-hand panels, only as a function of host galaxy specific star formation rate.



**Figure 5.** The DES3YR mass step: Hubble residuals as a function of host galaxy stellar mass ( $M_{\text{stellar}}$ ) for the DES-SN sample. Residuals are calculated using the best-fitting nuisance parameters determined from the combined DES3YR and low-redshift sample. DES-SN data points are shown in grey. Mean values in bins of stellar mass are plotted as blue diamonds, with the overall values for high mass ( $\log M_{\text{stellar}}/M_{\odot} > 10$ ) and low-mass galaxies plotted as large red crosses for the DES-SN sample and green diamonds for the low-redshift data. The *top* panel shows the results when a 5D  $\mu_{\text{bias}}$  correction is used as described in (B19), while the *lower* panel shows the results for a 1D  $\mu_{\text{bias}}$  correction as discussed in Section 4.3.

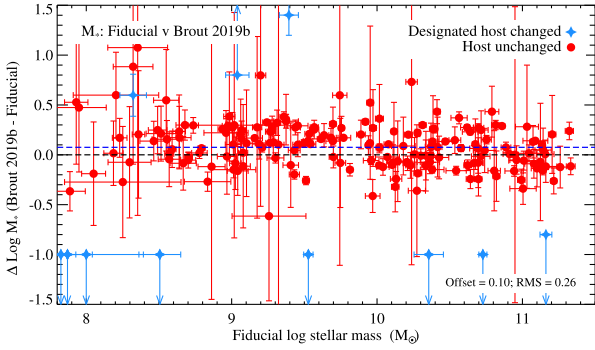
of our mass estimates, as discussed in Section 2.2.3. Compared to the B19 sample, 11 previously high-mass hosts ( $\log M_{\text{stellar}}/M_{\odot} > 10$ ) are reclassified as low-mass ( $\log M_{\text{stellar}}/M_{\odot} < 10$ ) in our analysis, with 8 galaxies moving in the reverse direction. The 11 reclassified low-mass hosts have smaller uncertainties on distance, with a mean uncertainty on  $\mu$  of 0.11 compared to 0.15 for the 8, now high-mass hosts. Of the 18 SNe Ia that were designated as hostless in B19, 13 are matched with a galaxy in the W20 catalogue, of which only 2 have  $\log M_{\text{stellar}}/M_{\odot} > 10$ , potentially impacting the value of  $\gamma$ , as all hostless objects were designated ‘low-mass’ in the B19 analysis. Due to the increased depth and updated galaxy profile information provided by the deep stacked images, 5 SNe Ia are associated to different galaxies in the W20 catalogue compared to the SVA1-GOLD catalogue. Of these, three cross the  $\log M_{\text{stellar}}/M_{\odot} = 10$  boundary, with two designated as high-mass based on the photometry of W20. Galaxies associated as host galaxies in the deep stacks that differ from those of SVA1-GOLD catalogue are highlighted as blue diamonds on Fig. 6.

To test how host galaxy misidentification affects our results we remove the 5 events with differing associated host galaxies that cross the  $\log M_{\text{stellar}}/M_{\odot} = 10$  boundary and reanalyse the DES-SN sample. For the 201 events that pass this criteria we measure  $\gamma = 0.044 \pm 0.019$  mag, while removing these events from the B19 sample we recover  $\gamma = 0.009 \pm 0.019$  mag. These values are consistent with results for the full sample, suggesting that host galaxy association is not the cause of  $\Delta\gamma_{\text{sys}} = -0.031$  mag between this analysis and that of B19.

Table 4, row 6, shows the effect of varying our host galaxy template library. Using the deep-stack photometry of W20 combined with the methodology used in B19 to estimate  $\log M_{\text{stellar}}/M_{\odot}$ , we find  $\gamma = 0.036 \pm 0.018$  mag, consistent with our fiducial result. Conversely, Table 4, row 11 shows the results using photometric measurements from the SVA1-GOLD catalogue, as used by B19, but the methodology used here, and described in Section 2.2.2 to estimate  $M_{\text{stellar}}$ . In this case, we recover  $\gamma = 0.031 \pm 0.020$  mag. This value is also consistent, if marginally smaller than our fiducial result. These tests suggest that no single cause explains the  $\Delta\gamma_{\text{sys}} =$

**Table 3.** Best-fitting  $\gamma$  determined from various samples as a function of the parameters varied. For a 5D  $\mu_{\text{bias}}$  correction, all subsamples recover a positive  $\gamma$  at a consistent value, with the exception of B19, as discussed in Section 4.1. For a 1D  $\mu_{\text{bias}}$  correction, a higher value of  $\gamma$  is found, as discussed in Section 4.3.

Sample	Biascor	Fixed parameters	Fitted parameters	Best-fitting $\gamma$ (mag)	Significance	Reference
DES-SN	5D	$\alpha, \beta, M_{\text{step}}$	$\gamma$	$0.030 \pm 0.017$	$1.8\sigma$	This work
DES-SN	5D	$M_{\text{step}}$	$\alpha, \beta, \gamma$	$0.040 \pm 0.019$	$2.1\sigma$	This work
DES-SN (B19)	5D	$M_{\text{step}}$	$\alpha, \beta, \gamma$	$0.009 \pm 0.018$	$0.5\sigma$	Brout et al. (2019b)
DES3YR	5D	$M_{\text{step}}$	$\alpha, \beta, \gamma$	$0.043 \pm 0.018$	$2.4\sigma$	This work
low- $z$	5D	$M_{\text{step}}$	$\alpha, \beta, \gamma$	$0.068 \pm 0.038$	$1.8\sigma$	This work
Pantheon	5D	$M_{\text{step}}$	$\alpha, \beta, \gamma$	$0.053 \pm 0.009$	$5.5\sigma$	Scolnic et al. (2018)
PS1	5D	–	$\alpha, \beta, \gamma, M_{\text{step}}$	$0.039 \pm 0.016$	$2.4\sigma$	Scolnic et al. (2018)
DES-SN	1D	$M_{\text{step}}$	$\alpha, \beta, \gamma$	$0.066 \pm 0.020$	$3.3\sigma$	This work
DES3YR	1D	$M_{\text{step}}$	$\alpha, \beta, \gamma$	$0.064 \pm 0.019$	$3.4\sigma$	This work
SNLS5YR	1D	$M_{\text{step}}$	$\alpha, \beta, \gamma$	$0.070 \pm 0.013$	$5.5\sigma$	Roman et al. (2018)
JLA	1D	$M_{\text{step}}$	$\alpha, \beta, \gamma$	$0.070 \pm 0.023$	$3.0\sigma$	Betoule et al. (2014)
Pantheon	1D	–	$\alpha, \beta, \gamma, M_{\text{step}}$	$0.072 \pm 0.010$	$7.2\sigma$	Scolnic et al. (2018)
PS1	1D	–	$\alpha, \beta, \gamma, M_{\text{step}}$	$0.064 \pm 0.018$	$3.6\sigma$	Scolnic et al. (2018)



**Figure 6.** Fiducial  $M_{\text{stellar}}$  estimates compared to those determined by B19, using *griz* galaxy magnitudes taken from the DES SVA1-GOLD catalogue and estimated using the PÉGASE.2 template library combined with the ZPEG code. No trend as a function of stellar mass is observed, with a mean offset of  $0.10 \pm 0.02$  and an r.m.s of 0.24 for galaxies present in both catalogues. The mean offset between the two values is highlighted by a blue dashed line. Galaxies associated as host galaxies in the deep stacks that differ from those of SVA1-GOLD catalogue, either due to the detection of galaxies below the SVA1-GOLD detection limit or due to differing DLR ratios, are plotted as blue diamonds.

$-0.031$  mag observed between this analysis and that of B19, and therefore the reduced value of  $\gamma$  found by B19 is likely caused by a combination of the photometric catalogue and template library.

#### 4.1.1 Cosmological Implications

To study how our  $M_{\text{stellar}}$  estimates affect the cosmological parameters, we replicate the analysis of B19, and combine the DES3YR sample with a CMB prior from Planck Collaboration XIII (2016). Considering a statistical-only covariance matrix, we find a shift in the dark energy equation of state of  $\Delta w = 0.011$  when using a G10 intrinsic model ( $\Delta w = 0.015$  for the C11 model) when using our  $M_{\text{stellar}}$  estimates compared to those used in B19. This shift, while non-negligible, is subdominant to the astrophysical systematic uncertainty of  $\sigma_w = 0.026$  determined for the DES3YR cosmological analysis (B19, Table 8).

## 4.2 Systematic tests of the mass step

We next study the sensitivity of our  $\gamma$  estimate to various assumptions in our analysis. Determining  $\gamma$  depends on two measurements: the host galaxy mass estimates and the estimated distance to each event. We discuss each in turn.

### 4.2.1 Sensitivity of the mass step to stellar mass estimates

In Section 2.2.3, we showed that our stellar mass estimates have a small sensitivity to choices in our analysis (e.g. galaxy photometry, stellar libraries used, SFHs) with at most 15 per cent of SNe moving between the high and low stellar mass bins as we vary these choices (Table 1). In Table 4 we show the implications these choices have on the best-fitting value of  $\gamma$ . In all cases, we vary  $\alpha$ ,  $\beta$  and  $\gamma$  simultaneously in the BBC fit, and find no statistically significant variation in  $\alpha$  or  $\beta$ . We consider two samples: the DES-SN sample alone, and then combined with the low-redshift SN Ia data: the DES3YR sample.

For the DES-SN sample,  $\gamma$  is maximally inconsistent from  $\gamma = 0$  at  $2.3\sigma$  (Table 4, row 4). There is no significant difference from our fiducial result for any of the systematic tests considered. Averaged overall systematic tests considered in Table 4, we recover  $\langle \gamma \rangle = 0.030$  mag with a mean uncertainty of  $\langle \sigma \rangle = 0.019$  mag and rms of 0.009 mag. These results confirm that our assumptions on the underlying SFHs and photometric catalogue used to estimate the DES-SN host stellar masses do not significantly impact the best-fitting value of  $\gamma$ .

When the low-redshift sample is included in this analysis,  $\gamma$  is maximally inconsistent from zero at  $2.6\sigma$  (Table 4, row 14). Combining all estimates of  $\gamma$ , we recover  $\langle \gamma \rangle = 0.037$  mag with  $\langle \sigma \rangle = 0.018$  mag and an rms of 0.008 mag, again consistent with our fiducial value.

To test the sensitivity of  $\gamma$  to the statistical uncertainties on  $\log M_{\text{stellar}}/M_{\odot}$ , we produce 1000 realizations of the DES-SN sample, where each realization is generated by randomly sampling the  $M_{\text{stellar}}$  probability distribution function for each event. Determining the best-fitting values of  $\alpha$ ,  $\beta$ ,  $\gamma$  using a 5D  $\mu_{\text{bias}}$  correction for each sample we find a mean value of  $\gamma = 0.040$  mag with standard deviation 0.003 mag. This value is consistent with our fiducial analysis, and suggests that the statistical uncertainty on the measured value of  $\log M_{\text{stellar}}/M_{\odot}$  is subdominant to the uncertainty

**Table 4.** Comparison between  $\gamma$  determined using various photometric catalogues and SFHs to estimate  $M_{\text{stellar}}$ .

Row #	SN sample	Photometric catalogue	Templates	IMF	$\gamma$ (mag)	$\Delta\gamma$ (mag) <sup>a</sup>
1 Fiducial result	DES-SN	W20	PÉGASE	K01	$0.040 \pm 0.019$	0.0
2 B19 <sup>b,c,d</sup>	DES-SN	SVA1-GOLD:mag_detmodel	ZPEG	K01	$0.009 \pm 0.019$	-0.031
3	DES-SN	W20	PÉGASE:bursts	K01	$0.030 \pm 0.018$	-0.010
4	DES-SN	W20	PÉGASE	S55	$0.042 \pm 0.019$	+0.002
5	DES-SN	W20	PÉGASE:bursts	S55	$0.019 \pm 0.018$	-0.021
6 <sup>b</sup>	DES-SN	W20	ZPEG	K01	$0.036 \pm 0.018$	-0.004
7	DES-SN	W20	M05	K01	$0.032 \pm 0.019$	-0.008
8	DES-SN	W20	M05	S55	$0.030 \pm 0.019$	-0.010
9	DES-SN	W20	BC03	S55	$0.030 \pm 0.019$	-0.010
10	DES-SN	SVA1-GOLD:mag_auto	PÉGASE	K01	$0.032 \pm 0.020$	-0.008
11 <sup>c</sup>	DES-SN	SVA1-GOLD:mag_detmodel	PÉGASE	K01	$0.031 \pm 0.020$	-0.009
12 Fiducial result	DES3YR	W20	PÉGASE	K01	$0.043 \pm 0.018$	0.0
13 B19 <sup>b,c,d</sup>	DES3YR	SVA1-GOLD:mag_detmodel	ZPEG	K01	$0.024 \pm 0.018$	-0.020
14	DES3YR	W20	PÉGASE:bursts	K01	$0.037 \pm 0.018$	-0.006
15	DES3YR	W20	PÉGASE	S55	$0.045 \pm 0.018$	+0.002
16	DES3YR	W20	PÉGASE:bursts	S55	$0.029 \pm 0.017$	-0.015
17 <sup>b</sup>	DES3YR	W20	ZPEG	K01	$0.042 \pm 0.018$	-0.001
18	DES3YR	W20	M05	K01	$0.038 \pm 0.018$	-0.005
19	DES3YR	W20	M05	S55	$0.037 \pm 0.018$	-0.006
20	DES3YR	W20	BC03	S55	$0.038 \pm 0.018$	-0.006
21	DES3YR	SVA1-GOLD:mag_auto	PÉGASE	K01	$0.038 \pm 0.018$	-0.006
22 <sup>c</sup>	DES3YR	SVA1-GOLD:mag_detmodel	PÉGASE	K01	$0.038 \pm 0.018$	-0.006

<sup>a</sup> $\gamma - \gamma_{\text{fid}}$  where  $\gamma_{\text{fid}}$  is given in row 1 or 12 depending upon sample.

<sup>b</sup>Matches the methodology used in Betoule et al. (2014) and Scolnic et al. (2018).

<sup>c</sup>Matches the photometry used in the analysis of B19.

<sup>d</sup>The value of  $\gamma$  matches that in Table 5 of B19 (considering the G10 intrinsic scatter model) for the DES3YR analysis, but differs by 0.001 for the DES-SN sample due to the loss of CID=1279500. See the text for details.

on the assumptions made when estimating the SFH of a given galaxy when estimating  $\gamma$ .

#### 4.2.2 Sensitivity of the mass step to light-curve systematics

There are four major sources of uncertainty from the light curves that could impact the value of  $\gamma$ : (1) the photometric technique used to estimate light-curve fluxes, (2) the light-curve cuts used to generate the DES3YR sample, (3) the parametrization of the mass step, and (4) the methodology used to estimate distances and nuisance parameters. Table 5 shows the best-fitting value of  $\gamma$  for each systematic test considered.

**4.2.2.1 Photometry** The DES SN Ia analysis uses a SMP technique (Brout et al. 2019a) to measure light-curve fluxes and uncertainties. This technique forward models a time-dependent flux from the transient with an underlying constant host galaxy component, and compares to the DES images. This method differs from traditional ‘difference imaging’, where a deep reference image is subtracted from each SN observation. As a crosscheck of  $\gamma$  to SMP photometry, we consider flux estimates using the DES real-time difference-imaging pipeline (DIFFIMG; Kessler et al. 2015). Propagating these light curves through the DES3YR cosmology pipeline, we find  $\gamma = 0.019 \pm 0.021$  mag for the DES-SN SNe, and  $0.030 \pm 0.019$  mag when combined with the low-redshift sample (Table 5, rows 3 and 16). These values differ from our fiducial values of  $\gamma$  by  $-0.021$  and  $-0.013$  mag, respectively. Analysing the DES-SN sample with the DES real-time difference-imaging pipeline reduces the number of SN that pass the light-curve coverage criteria defined in B19 by 6 and increases the rms dispersion of our sample from 0.126 to 0.134 mag.

Considering only the 193 DES-SN common to both data sets we measure  $\gamma = 0.028 \pm 0.020$  mag when using DIFFIMG photometry compared to  $0.030 \pm 0.019$  mag for the SMP photometry. These values are consistent, suggesting that the value of  $\gamma$  determined using DIFFIMG photometry, smaller than our fiducial analysis, is driven by the complement of the two data sets, not the photometric measurements themselves. The 7 SNe Ia in the DIFFIMG sample that do not pass the SMP criteria have mean  $M_{\text{stellar}} = 9.94 \pm 0.20$ , consistent with the DES-SN sample (Table 2), and mean  $\Delta\mu = 0.142 \pm 0.070$ , indicating that these events are responsible for the additional scatter in this sample. The three events with  $M_{\text{stellar}} > 10.0$  have mean  $\Delta\mu = 0.285 \pm 0.111$ , compared to  $0.036 \pm 0.045$  for SNe Ia in low-mass hosts, suggesting that these outlying events, excluded from the SMP analysis, are responsible for the reduced value of  $\gamma$  when analysing the DES-SN sample with DIFFIMG photometry.

**4.2.2.2 SN selection cuts** Our analysis requires all SNe Ia to have well-observed light curves to reliably constrain the light-curve fit parameters, and we require  $-3 < x_1 < 3$  and  $-0.3 < c < 0.3$  matching the range over which the SALT2 model has been trained (Guy et al. 2010).

To test the effect that our selection criteria has on  $\gamma$ , in rows 4–7 of Table 5, we split the DES-SN sample into subsamples of  $x_1$  and  $c$ . For SNe Ia with  $x_1 < 0$ , we recover  $\gamma = 0.000 \pm 0.029$  mag for the DES sample alone, compared to  $\gamma = 0.026 \pm 0.028$  mag for those with  $x_1 > 0$ , different at  $1.2\sigma$ . From Fig. 4, SNe Ia with  $x_1 < 0$  are preferentially found in high-mass galaxies, while those with  $x_1 > 0$  are dominated by low-mass galaxies. For the analogous test with  $c$  we find  $\gamma = -0.001 \pm 0.021$  mag for events with  $c < 0$  and  $\gamma = 0.106 \pm 0.039$  mag for those with  $c > 0$ , different



**Table 5.** The best-fitting value of  $\gamma$  considering systematic uncertainties in the light-curve fitting procedure. The fiducial results from this study are highlighted in bold.

Row #	SN Sample	Phot.	Cuts <sup>a</sup>	$M_{\text{step}}^b$	$\gamma_{\tau}^b$	BiasCor	N <sub>SN</sub>	$\gamma$ (mag)	$\Delta\gamma$ (mag) <sup>c</sup>	rms <sup>d</sup>
1	DES-SN	SMP	None	Fixed	Fixed	5D	206	0.040 ± 0.019	0.0	0.126
2	DES-SN	SMP	None	Fixed	Fixed	1D	208	0.066 ± 0.020	+0.026	0.153
3	DES-SN	DIFFIMG	None	Fixed	Fixed	5D	200	0.019 ± 0.021	−0.021	0.134
4	DES-SN	SMP	C<0.0	Fixed	Fixed	5D	136	−0.001 ± 0.021	−0.041	0.108
5	DES-SN	SMP	C>0.0	Fixed	Fixed	5D	70	0.106 ± 0.039	+0.066	0.154
6	DES-SN	SMP	$x_1 < 0.0$	Fixed	Fixed	5D	88	0.000 ± 0.029	−0.040	0.136
7	DES-SN	SMP	$x_1 > 0.0$	Fixed	Fixed	5D	118	0.046 ± 0.026	+0.006	0.117
8	DES-SN	SMP	None	9.68 ± 0.06	Fixed	5D	206	0.046 ± 0.018	+0.006	0.126
9	DES-SN	SMP	None	10.17 ± 0.13	Fixed	1D	208	0.064 ± 0.022	+0.024	0.153
10	DES-SN	SMP	None	Fixed	0.003 ± 0.016	5D	206	0.040 ± 0.019	+0.000	0.126
11	DES-SN	SMP	None	Fixed	0.003 ± 0.143	1D	208	0.066 ± 0.020	+0.026	0.153
12	DES-SN	SMP	None	9.70 ± 0.01	0.001 ± 0.019	5D	206	0.047 ± 0.018	+0.007	0.127
13	DES-SN	SMP	None	9.70 ± 0.01	0.001 ± 0.006	1D	208	0.076 ± 0.020	+0.035	0.154
14	DES3YR	SMP	None	Fixed	Fixed	5D	328	0.043 ± 0.018	0.0	0.144
15	DES3YR	SMP	None	Fixed	Fixed	1D	336	0.064 ± 0.019	+0.021	0.157
16	DES3YR	DIFFIMG	None	Fixed	Fixed	5D	322	0.030 ± 0.019	−0.013	0.151
17	DES3YR	SMP	C<0.0	Fixed	Fixed	5D	203	−0.012 ± 0.021	−0.055	0.126
18	DES3YR	SMP	C>0.0	Fixed	Fixed	5D	125	0.128 ± 0.034	+0.084	0.170
19	DES3YR	SMP	$x_1 < 0.0$	Fixed	Fixed	5D	155	0.026 ± 0.028	−0.017	0.140
20	DES3YR	SMP	$x_1 > 0.0$	Fixed	Fixed	5D	173	0.046 ± 0.024	+0.003	0.141
21	DES3YR	SMP	None	10.89 ± 0.04	Fixed	5D	328	0.052 ± 0.021	+0.009	0.145
22	DES3YR	SMP	None	10.89 ± 0.03	Fixed	1D	336	0.065 ± 0.022	+0.022	0.157
23	DES3YR	SMP	None	Fixed	0.151 ± 0.083	5D	328	0.049 ± 0.021	+0.006	0.145
24	DES3YR	SMP	None	Fixed	0.164 ± 0.122	1D	336	0.077 ± 0.023	+0.034	0.158
25	DES3YR	SMP	None	10.15 ± 0.02	0.001 ± 0.021	5D	328	0.050 ± 0.018	+0.007	0.145
26	DES3YR	SMP	None	10.15 ± 0.00	0.001 ± 0.000	1D	336	0.073 ± 0.019	+0.030	0.158

<sup>a</sup>The fiducial analysis includes cuts of  $-3.0 < x_1 < 3.0$  and  $-0.3 < c < 0.3$ .

<sup>b</sup>Fixed to  $M_{\text{step}} = 10.0$  and  $\gamma_{\tau} = 0.01$  in the fiducial analysis.

<sup>c</sup> $\gamma - \gamma_{\text{fid}}$  where  $\gamma_{\text{fid}}$  is given in row 1 or 2 depending upon sample.

<sup>d</sup>rms of Hubble diagram residuals from LCDM model after correction ( $\Delta\mu$  in equation 3).

at  $2.4\sigma$ . We find consistent results when combining the DES-SN sample with the low-redshift sample (Table 5, rows 17–20). From Fig. 4, there is some evidence that high-mass hosts preferentially host redder ( $c > 0$ ) SNe Ia. Averaging overall mass estimates derived from deep stack photometry we find a mean difference of 1.2 and  $1.7\sigma$  between the value of  $\gamma$  determined for high and low  $x_1$  and  $c$ , respectively.

**4.2.2.3 Parametrizing the mass step** Our fiducial analysis considers the mass step to be parametrized by equation (2) with  $M_{\text{step}} = 10$ . To test how this assumption affects the value of  $\gamma$ , in row 8 of Table 5, we simultaneously fit for  $\gamma$  and  $M_{\text{step}}$ , finding  $M_{\text{step}} = 9.68 \pm 0.06$  and  $\gamma = 0.046 \pm 0.018$  mag ( $\Delta\gamma_{\text{sys}} = +0.006$  mag) for the DES sample alone. These values are consistent with those found when combining with the low-redshift sample and with our fiducial result.

In equation (2), the mass step is parametrized as a step function at  $M_{\text{stellar}} = M_{\text{step}}$ . To test the sensitivity of our results on this assumption, we re-parametrize  $G_{\text{host}}$  in equation (1) as a smooth function around a transition mass (Childress et al. 2014) such that

$$G_{\text{host}} = \left[ \frac{1}{1 + \exp\left(\frac{-(M_{\text{stellar}} - M_{\text{step}})}{\gamma_{\tau}}\right)} - 0.5 \right], \quad (5)$$

where  $\gamma_{\tau}$  parametrizes the  $M_{\text{stellar}}$  scale of the mass step. Fitting for  $\gamma_{\tau}$  and  $\gamma$  simultaneously (while holding  $M_{\text{step}}$  fixed at  $M_{\text{step}} = 10$ ), we recover  $\gamma_{\tau} = 0.003 \pm 0.016$  and  $\gamma = 0.040 \pm 0.019$  mag, while fitting for  $\gamma_{\tau}$ ,  $M_{\text{step}}$ , and  $\gamma$  simultaneously, we recover  $\gamma = 0.047 \pm 0.018$  mag,  $\gamma_{\tau} = 0.001 \pm 0.019$ , and  $M_{\text{step}} = 9.70 \pm 0.00$

(Table 5, rows 10–12). The fits including the low-redshift sample are consistent with these values. For these systematic tests, we recover  $\Delta\gamma_{\text{sys}} = +0.000$ ,  $+0.006$ ,  $+0.007$ , and  $+0.007$  mag, indicating that there is no evidence that a different mass step parametrization affects  $\gamma$ .

In Section 2.2.3, we showed that while our fiducial estimates of  $M_{\text{stellar}}$  are one to one correlated with those determined when using alternative SFHs, IMFs, and photometric catalogues, the recovered values of  $M_{\text{stellar}}$  can be offset by up to 0.25 dex. To test the sensitivity of  $M_{\text{step}}$  and  $\gamma$  to these offsets, we vary our assumptions on the underlying SFHs and photometric catalogue, as described in Section 2.2.3, and fit  $M_{\text{step}}$  and  $\gamma$ . Averaged overall systematic tests considered in Table 1, we find  $\langle\gamma\rangle = 0.043$  with an rms of 0.005 and  $\langle M_{\text{step}} \rangle = 10.26$  with rms 0.38. The value of  $\gamma$  is uncorrelated with  $M_{\text{step}}$ . These results are consistent with those found in Section 4.2.1, suggesting that our assumptions of the underlying SFHs and photometric catalogue used to estimate  $M_{\text{stellar}}$  do not significantly impact the value of  $\gamma$ .

**4.2.2.4 Distance estimates** The DES3YR cosmological analysis uses the BBC framework (Kessler & Scolnic 2017; Brout et al. 2019b) that differs from earlier analyses (such as JLA) by implementing 5D bias-corrections determined from large simulations of the DES survey (Kessler et al. 2019). In the BBC framework,  $\mu_{\text{bias}}$  ‘corrects’ the observed values of  $m_B$ ,  $x_1$  and  $c$  for each SN Ia and includes a correction for the distance uncertainty.

When we use a 1D  $\mu_{\text{bias}}$  correction dependent only on  $z$  (e.g. Betoule et al. 2014); we recover  $\gamma = 0.066 \pm 0.020$  mag ( $\Delta\gamma_{\text{sys}} = +0.026$  mag) for the DES-SN sample, and  $\gamma = 0.064 \pm 0.019$  mag ( $\Delta\gamma_{\text{sys}} = +0.021$  mag) when including the low-redshift SNe. These are the highest values of  $\gamma$  measured for the DES-SN sample, and are consistent with the values found by Betoule et al. (2014) and Roman et al. (2018). To test this further, Table 5 (rows 9, 11, and 13) shows the results when a 1D bias correction is used and various combinations of  $M_{\text{step}}$  and  $\gamma_{\tau}$  are varied. In all cases, the best-fitting value of  $\gamma$  is larger than that found in the fiducial analysis and the corresponding systematic test using a 5D  $\mu_{\text{bias}}$  correction.

Fig. 7 shows the effect that the 5D bias correction has overall systematic tests considered. The top panel shows the results for the DES3YR sample, while the bottom panel highlights the results for the DES-SN subset. This figure shows the best-fitting value of  $\gamma$  for both 5D and 1D bias corrections, when alternative estimates of  $M_{\text{stellar}}$  are used along with different photometric estimates and light-curve cuts. In all cases, the 1D bias correction produces a higher value of  $\gamma$ . Overall 42 systematic tests, a 1D bias correction recovers a larger value of  $\gamma$  compared to a 5D bias correction with offsets between 0.012 and 0.082 mag, with a mean of 0.028 mag and standard deviation 0.013 mag.

To estimate an uncertainty on this measurement, we simulate 100 realizations of the DES-SN sample (using the prescription described in Section 5). For each simulated sample, we determine the best-fitting values of  $\alpha$ ,  $\beta$ ,  $\gamma$  using both a 5D and 1D  $\mu_{\text{bias}}$  correction. Averaging overall samples, we find a mean value of  $\Delta\gamma = 0.014$  mag (see Section 5.3.2 for details) with a standard deviation of 0.009 mag. Our results are unaffected if we further require that the 5D and 1D samples comprise exactly the same SNe after cuts.

Overall, for the DES-SN sample, we find an offset of

$$\Delta\gamma = [\gamma_{1D} - \gamma_{5D}]_{\text{data}} = 0.026 \pm 0.009 \text{ mag.} \quad (6)$$

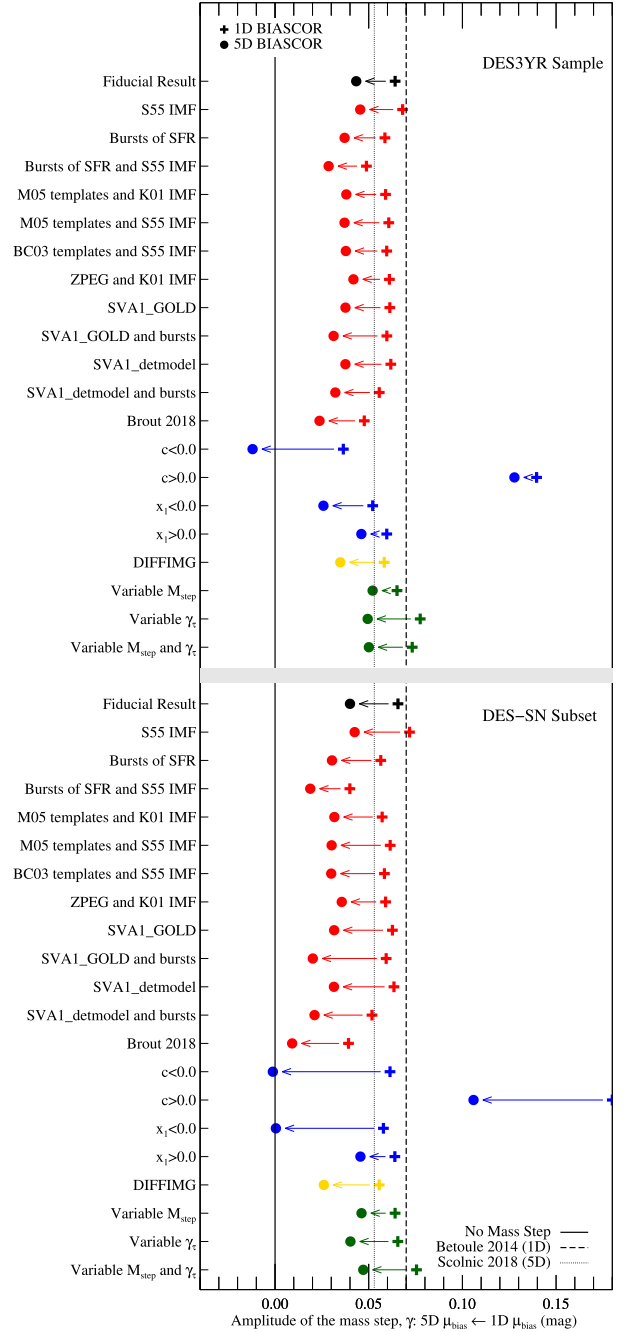
This value consistent with a difference of  $\Delta\gamma = 0.025$  mag observed for the PS1 sample (Scolnic et al. 2018, section 3.7). The cause of this offset is explored in Section 4.3.

### 4.3 The dependence of the mass step on the bias correction

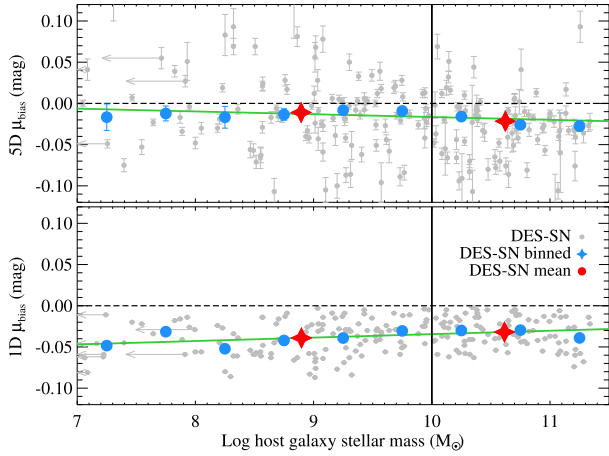
Systematic offsets between the value of  $\gamma$  when using 1D and 5D bias corrections implies a difference in  $\mu_{\text{bias}}$  between SNe Ia found in high-mass galaxies compared to their low-mass counterparts. Fig. 8 shows the correlation between the SN host stellar mass and the bias correction applied to that SN distance,  $\mu_{\text{bias}}$ , for both the 1D and 5D bias corrections. For the 5D bias correction, there is a correlation between  $M_{\text{stellar}}$  and  $\mu_{\text{bias}}$  with a slope  $-0.004 \pm 0.001$ . There is a difference in the mean value of  $\mu_{\text{bias}}$  between high- and low-mass galaxies of  $\Delta\mu_{\text{bias}} = 0.011 \pm 0.004$  mag. The 1D bias correction shows the opposite correlation, with a mean difference of  $\Delta\mu_{\text{bias}} = -0.007 \pm 0.003$  mag.

Fig. 9 shows the origin of the 5D  $\mu_{\text{bias}}$  correlation: the correction to the observed values of  $m_B$ ,  $x_1$ , and  $c$  for each event, denoted  $m_{B\text{bias}}$ ,  $x_{1\text{bias}}$ , and  $c_{\text{bias}}$ . No evidence of a relationship between  $M_{\text{stellar}}$  and  $m_{B\text{bias}}$  or  $c_{\text{bias}}$  is observed, but we find a correlation between  $M_{\text{stellar}}$  and  $x_{1\text{bias}}$  with a difference of  $\Delta x_{1\text{bias}}$  of  $0.064 \pm 0.028$  mag ( $2.3\sigma$ ) between SNe in high- and low-mass galaxies for the DES-SN sample. Fixing  $\alpha = 0.150$  (the value derived for the DES3YR sample), this corresponds to  $\Delta\mu_{\text{bias}} = \alpha \times \Delta x_{1\text{bias}} = 0.010 \pm 0.004$  mag, consistent with the offset of  $\Delta\mu_{\text{bias}} = 0.011$  mag determined above.

This result is consistent with Fig. 4, where high-mass galaxies predominately host low- $x_1$  SNe Ia. These events require a different



**Figure 7.** The best-fitting values of  $\gamma$  considering different systematic uncertainties. For each entry, the right-hand value (plotted as a plus symbol) indicates the value when a 1D bias correction is used, while the left-hand entry (plotted as a filled circle) is for the 5D correction. Red entries denote alternative mass estimates (see Section 2.2.3), blue denote systematics in the sample selection, yellow the results when DIFFIMG photometry is used in the light-curve fitting, and green when various assumptions about the mass step parametrization are considered. The dashed and dotted lines show the values of  $\gamma$  determined by Betoule et al. (2014) (assuming a 1D bias correction) and Scolnic et al. (2018), assuming a 5D bias correction, while the solid line indicates the case where  $\gamma = 0$ . The top panel shows the results for the DES3YR sample, while the bottom panel presents results for the DES-SN subset.



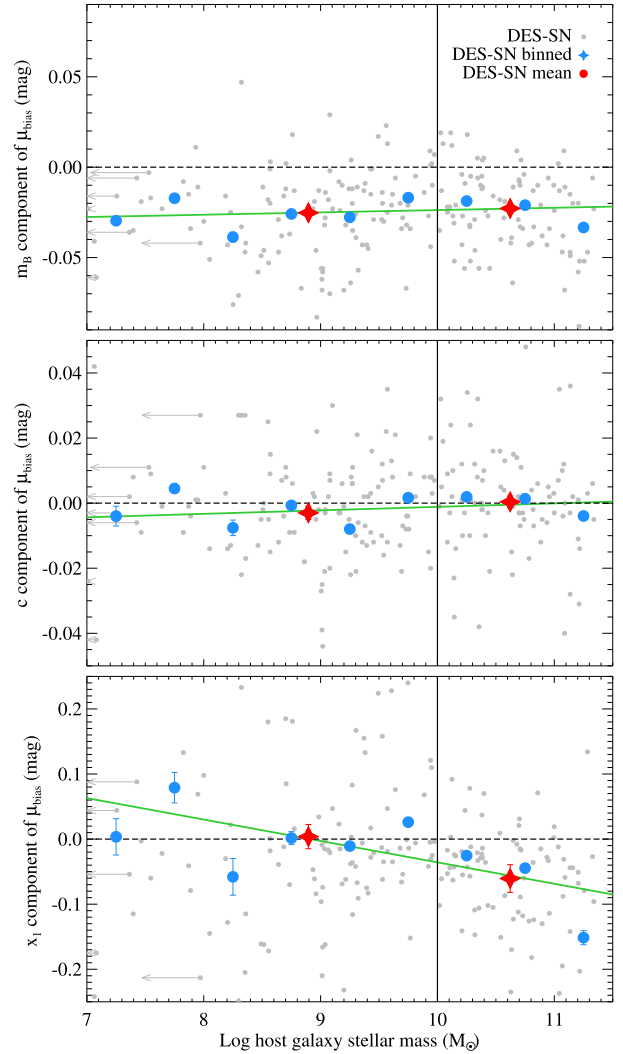
**Figure 8.** The relationship between  $M_{\text{stellar}}$  and  $\mu_{\text{bias}}$  for the DES-SN sample. The top panel shows the results for a 5D  $\mu_{\text{bias}}$  correction, with the lower panel showing the results for a 1D  $\mu_{\text{bias}}$  correction. Data points are shown in grey. The mean value in bins of stellar mass are shown as blue filled circles, with the value for high- and low-mass samples shown as red diamonds. The best-fitting linear relationship is shown in green.

bias correction compared to the higher- $x_1$  SNe Ia in low-mass hosts (Fig. 9). This comparison suggests that, in the BBC framework, a fraction of  $M_{\text{step}}$  as measured by a 1D  $\mu_{\text{bias}}$  correction, is not an independent offset in SN Ia luminosity related to  $M_{\text{stellar}}$ , but an uncorrected contribution related to  $x_1$ , as deduced by a 5D  $\mu_{\text{bias}}$  correction. In Section 5, we test this inference by imprinting realistic correlations between SN and  $M_{\text{stellar}}$  into simulations of DES-SN, independent on  $M_{\text{step}}$ , and test for potential biases in the recovered value of  $\gamma$  for both 5D and 1D  $\mu_{\text{bias}}$  corrections.

## 5 SIMULATING THE MASS STEP

The low  $\gamma$ -value observed for the DES3YR and DES-SN samples when using a 5D  $\mu_{\text{bias}}$  correction compared to a 1D  $\mu_{\text{bias}}$  correction is a result of a correlation between  $x_1$  and  $M_{\text{stellar}}$ . This correlation is likely inferred from the correlation between  $x_1$  and  $M_{\text{stellar}}$  (Fig. 4). The simulated  $\mu_{\text{bias}}$  corrections used in existing cosmological analyses, e.g. B19, do not include correlations between SN and host, so we now turn to simulating DES-SN with correlations between  $M_{\text{stellar}}$  and  $(x_1, c)$  to see if we can predict a correlation between  $x_1$  and  $M_{\text{stellar}}$  and to evaluate the impact this has on the measured value of  $\gamma$ .

In Section 5.1, we outline the SNANA methodology used to simulate DES-SN, while in Section 5.2.1 we describe the procedure used to generate galaxy libraries that match the characteristics of the DES-SN sample. In Section 5.2.2, we use a near complete sample of cosmological SNe Ia drawn from the SDSS and SNLS samples to produce simulated SNe with intrinsic correlations between SN and  $M_{\text{stellar}}$ . Having simulated large realistic representations of the DES-SN sample we show the consistency in light-curve properties between our simulated samples and DES-SN in Section 5.3.1. Finally, in Section 5.4 we discuss the effect that correlations between  $M_{\text{stellar}}$  and  $(x_1, c)$  have on the inferred mass step for simulated samples and compare these results to those observed in the DES3YR dataset. From analysing our simulated samples, we find  $\Delta\gamma = 0.011$  mag and a systematic offset of  $-0.009$  mag for a 5D  $\mu_{\text{bias}}$  correction relative to the simulated value.



**Figure 9.** The relationship between  $M_{\text{stellar}}$  and the individual components of the 5D  $\mu_{\text{bias}}$  ( $m_B$ ,  $c$ , and  $x_1$ ) correction for the DES-SN sample. Data points are shown in grey. The mean value in bins of stellar mass are shown as blue filled circles, with the value for high- and low-mass samples shown as red diamonds. The best-fitting linear relationship is shown in green. A correlation coefficient of 0.152, inconsistent from 0 at  $2.2\sigma$  is seen between  $M_{\text{stellar}}$  and  $x_1$ .

### 5.1 Simulations of DES-SN

Simulations of the DES-SN sample are performed using the ‘Super-Nova ANALYSIS’ (SNANA) software package (Kessler et al. 2009). The simulation inputs include a rest-frame SALT-II SED model (Guy et al. 2010; Betoule et al. 2014), an intrinsic scatter model (Guy et al. 2010; Kessler et al. 2013), SN Ia population parameters (Scolnic & Kessler 2016), the volumetric rate of SN Ia and its evolution with redshift (Perrett et al. 2010), a library of survey observations with measured observing parameters (sky noise, PSF, zero-point), DECam filter transmission curves and a model of the DES detection and spectroscopic follow-up efficiency (fig. 4 of Kessler et al. 2019). The application of the SNANA methodology to simulating the DES3YR sample is described in detail in Kessler et al. (2019), while a detailed analysis of the effect that systematic uncertainties have on the resulting cosmological constraints is given

in B19. To achieve statistical uncertainties of  $<0.001$  mag on  $\gamma$ , we simulated samples of  $\sim 250\,000$  events after light-curve cuts.

## 5.2 Producing realistic simulations

### 5.2.1 Estimates of stellar mass

Host galaxy information is imprinted in SNANA simulations using a host galaxy library (HOSTLIB) where each simulated SN is associated with a random galaxy with consistent redshift. The HOSTLIB for DES-SN subset is generated from a catalogue of 380 000 galaxies derived from the DES-SV data as described in Gupta et al. (2016). Each HOSTLIB galaxy contains information on the coordinates, heliocentric redshift, observer-frame magnitudes, and Sérsic profile components. To include the effect of a mass step and host galaxy correlations in our DES-SN simulations, we estimate the mass for each HOSTLIB galaxy using the methodology described in Section 2.2.2. To test the effect that our galaxy sample has on our conclusions, we also use a HOSTLIB generated from the DES SVA1-GOLD catalogue (Rykoff et al. 2016). This catalogue only includes objects with spectroscopic redshifts, and thus is significantly smaller (14 000 entries compared to 380 000).

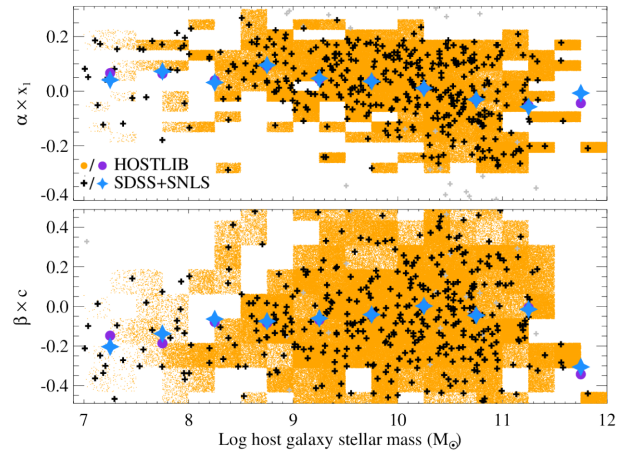
The HOSTLIBs described above represent a complete sample of galaxies as determined from DES data. As SNe Ia preferentially occur in low  $M_{\text{stellar}}$  galaxies compared to the overall galaxy population (Smith et al. 2012), we weight our HOSTLIB galaxies to match the distribution of  $M_{\text{stellar}}$  observed for SN Ia hosts. To generate this mass function we require an unbiased, near complete sample of SN Ia hosts.

As part of the real-time survey operations, DES preferentially targeted SN-like events in low luminosity environments (D’Andrea et al. 2018), potentially biasing the DES-SN sample with respect to host galaxy properties. In contrast, the SDSS and SNLS surveys spectroscopically confirmed SNe Ia using targeting programs principally agnostic to local environment. Therefore, to compile a near complete sample of SNe Ia hosts we combine the SDSS and SNLS samples (Betoule et al. 2014), with redshift limits of  $z = 0.25$  for the SDSS sample and  $z = 0.70$  for the SNLS sample to ensure that each subsample of SNe Ia is spectroscopically complete (Perrett et al. 2010; Sullivan et al. 2010; Sako et al. 2018). As anticipated, this sample of 417 SN Ia hosts (denoted ‘SDSS+SNLS’) closely resembles the DES-SN sample for high-mass events, but shows fewer events in low  $M_{\text{stellar}}$  environments, with a mean stellar mass of 9.74 compared to 9.70 for DES-SN. To generate a galaxy mass function representative of SN Ia hosts, we determine the cumulative distribution function (CDF) of the ‘SDSS+SNLS’ host masses in bins of  $\log M_{\text{stellar}}/M_{\odot}$  with width 0.25, and draw galaxies from our HOSTLIB to match this.

### 5.2.2 Including intrinsic correlations between SN and host

As shown in Section 3.1 and Fig. 4, the light-curve width of an SN Ia is correlated with the  $M_{\text{stellar}}$  of its host galaxy, and from Section 4.2, this correlation affects the inferred  $\mu_{\text{bias}}$  correction that drives the low best-fitting value of  $\gamma$  for the DES-SN sample. Here, we attempt to predict this effect in simulations by introducing a correlation between  $M_{\text{stellar}}$  and  $(x_1, c)$  in our host galaxy library.

With the DES-SN sample likely biased with respect to  $M_{\text{stellar}}$  (D’Andrea et al. 2018), to do this, we use instead the near-complete SDSS+SNLS sample of SN Ia hosts (as described in Section 5.2.1). For each galaxy in the HOSTLIB, with given stellar mass, we draw a random value of  $x_1$  and  $c$  from the corresponding



**Figure 10.** Simulation Input: Top:  $M_{\text{stellar}}$  versus  $\alpha \times x_1$  (light-curve width) for our HOSTLIB (shown in orange) compared to a combined SDSS+SNLS sample (shown in black). For a given  $M_{\text{stellar}}$ , the corresponding  $x_1$  is determined from the distribution of the SDSS+SNLS sample in that mass bin. The mean value of  $x_1$  in bins of  $M_{\text{stellar}}$  for the HOSTLIB and SDSS+SNLS samples are plotted as violet circles and blue diamonds, respectively. Bottom: Same as above, only for as a function of light-curve colour ( $\beta \times c$ ).

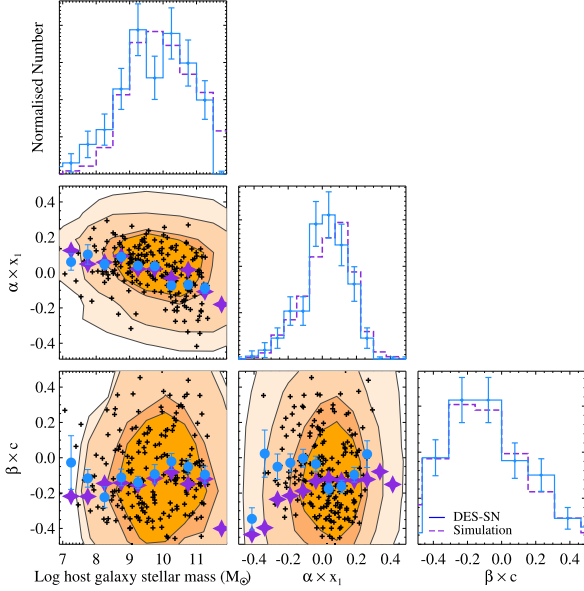
CDF in bins of  $\log M_{\text{stellar}}/M_{\odot}$  with width 0.25. To account for our use of measured values of  $x_1, c$ , which probe the underlying distribution of  $x_1, c$  only after the inclusion of intrinsic scatter and measurement uncertainty (March et al. 2011), we exclude events that lie in regions that contribute less than 10 per cent of the total probability. This cut predominantly removes SNe Ia with  $x_1 < -2.0$  and  $x_1 > 2.0$ . The resulting correlation between  $M_{\text{stellar}}$  and  $x_1, c$  for our HOSTLIB is shown in Fig. 10 (plotted as  $M_{\text{stellar}}$  versus the standardized contribution to  $\mu$ :  $\alpha \times x_1$  and  $\beta \times c$ ), where each shaded region is scaled based on the number of events contained within it. The SDSS+SNLS sample itself is overplotted for comparison. As anticipated, a correlation between  $M_{\text{stellar}}$  and  $x_1$  is observed, with SNe Ia with  $x_1 < 0$  preferentially found in high-mass hosts. There is some evidence of a reduced scatter in  $c$  for low-mass galaxies ( $M_{\text{stellar}} < 9$ ), which preferentially host SN with  $c < 0$ .

Each galaxy in our HOSTLIB now has an estimate of  $M_{\text{stellar}}, x_1$  and  $c$ , with  $M_{\text{stellar}}$  correlated with  $(x_1, c)$  based on the SDSS+SNLS SN Ia sample. To simulate DES-SN, we use the HOSTLIB  $x_1$  and  $c$  values instead of generating values for each simulated event from a parent population (see Scolnic & Kessler 2016, for details).

To determine how the value of  $\gamma$  is affected when correlations between  $M_{\text{stellar}}$  and  $(x_1, c)$  are introduced, for comparison we also simulate DES-SN with no underlying correlations. Here, we draw a value of  $x_1$  and  $c$  from the distributions described in the high- $z$  row from table 1 of Scolnic & Kessler (2016), matching the analysis of B19 and  $M_{\text{stellar}}$  from our fiducial HOSTLIB.

To ensure consistency between the underlying distributions of  $x_1$  and  $c$  between our simulated samples and the simulations used to calculate  $\mu_{\text{bias}}$ , denoted ‘BIASCOR’ samples, we generate our own BIASCOR simulations of 300 000 SNe Ia self-consistently from each HOSTLIB to ensure that  $\mu_{\text{bias}}$  is determined correctly. Finally, we include a mass step in our analysis, by enforcing an absolute magnitude shift of  $\gamma_{\text{sim}} = 0.05$  mag between SN in high ( $\log M_{\text{stellar}}/M_{\odot} > 10$ ) and low ( $\log M_{\text{stellar}}/M_{\odot} < 10$ ) mass galaxies in both of our simulations with intrinsic correlations and correlation-free simulations. To test the consistency of our results to the value





**Figure 11.** Simulation output: Corner plot showing the distributions of  $M_{\text{stellar}}$ ,  $x_1$ , and  $c$  for the DES-SN sample (in blue) compared to our simulated sample that includes correlations between  $M_{\text{stellar}}$  and  $(x_1, c)$  (shown as violet dashed histograms). The mean value of  $x_1$  and  $c$  as a function of  $M_{\text{stellar}}$  for the simulated sample is shown as violet crosses with the DES-SN sample shown as blue closed circles. Contours highlighting the area enclosed by 99.7, 95.5, 68.2, and 50 per cent of the simulated sample are shown in orange.

of  $\gamma_{\text{sim}}$ , we also produce both correlated and uncorrelated simulated samples with no mass step, i.e.  $\gamma_{\text{sim}} = 0$  mag.

In summary, we have simulated two samples, with a mass step of  $\gamma = 0.05$  mag. One ‘correlated’ sample includes a correlation between  $M_{\text{stellar}}$  and  $(x_1, c)$ , while for our other ‘uncorrelated’ sample  $M_{\text{stellar}}$  and  $(x_1, c)$  are independent. Two more simulations, with and without correlations but with  $\gamma_{\text{sim}} = 0$  mag, completes our simulation set. In all cases, the mass step is independent of the underlying correlation between  $M_{\text{stellar}}$  and  $(x_1, c)$ , and thus an unbiased estimator of distance should recover the simulated value of  $\gamma$  for all simulated samples.

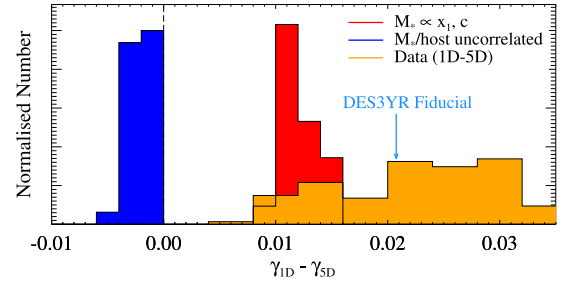
### 5.3 Comparison to data

#### 5.3.1 Population parameters

After applying selection requirements and light-curve fitting to the simulated DES-SN sample, Fig. 11 shows the distributions of  $M_{\text{stellar}}$ ,  $x_1$  and  $c$  for our DES-SN simulation, with intrinsic correlations, of 250 000 SN Ia compared to the DES-SN data set. As anticipated, we observe a strong dependence between  $M_{\text{stellar}}$  and  $x_1$  matching that observed from the data (Fig. 10) and that from the SDSS+SNLS sample input into the simulation (Fig. 4). The dispersion in  $\beta \times c$  is larger than that observed for  $\alpha \times x_1$ , but with limited evidence of a correlation between  $M_{\text{stellar}}$  and  $c$ , consistent with that observed for DES-SN (Fig. 4). With the simulated values of  $x_1$  and  $c$  being independently drawn from the SDSS+SNLS sample (see Section 5.2.2), no significant correlation is observed between these two parameters. The resulting distributions of  $M_{\text{stellar}}$ ,  $x_1$ , and  $c$  are closely matched to the DES-SN sample, with the simulated sample marginally favouring SNe Ia in lower mass galaxies compared to the DES-SN sample. This is driven

**Table 6.** The difference between  $\gamma_{1D}$  and  $\gamma_{5D}$  for our simulated samples when intrinsic correlations between  $M_{\text{stellar}}$  and  $(x_1, c)$  are and are not considered in our simulated samples. Also shown is the result for DES-SN.

Sample	SN/host correlations	$\gamma_{1D} - \gamma_{5D}$ (mag)
DES-SN	—	$0.026 \pm 0.009$
Correlated simulation	$x_1, c$	$0.011 \pm 0.001$
Uncorrelated simulation	None	$-0.002 \pm 0.001$



**Figure 12.** Histograms showing the difference in the best-fitting value of  $\gamma$  for simulated samples when a 5D  $\mu_{\text{bias}}$  correction is used compared to the results assuming a 1D  $\mu_{\text{bias}}$  correction for differing assumptions on the relationship between  $M_{\text{stellar}}$  and  $(x_1, c)$ . The results assuming no correlation between  $M_{\text{stellar}}$  and  $(x_1, c)$  are shown in blue, while those where a correlation is enforced using the prescription described in Section 5.2.2 are shown in red. Each histogram shows the results of all systematic tests (input HOSTLIB, BIASCOR simulation used to estimate  $\mu_{\text{bias}}$ , sample weighting and mass step parametrization) as outlined in Table 8. An input correlation between  $M_{\text{stellar}}$  and  $(x_1, c)$  suppresses the value of  $\gamma$  for the 5D  $\mu_{\text{bias}}$  by 0.012 mag compared to a 1D  $\mu_{\text{bias}}$  correction, while considering no correlation increases the value by 0.002 mag. Also shown in yellow is the difference between  $\gamma$  when assuming a 5D  $\mu_{\text{bias}}$  correction compared to a 1D  $\mu_{\text{bias}}$  correction for the DES-SN sample when various systematic tests (as highlighted in Section 4.2) are considered. This distribution has a mean of 0.028 mag. The fiducial result for the DES3YR analysis is highlighted with a blue arrow.

by the lack of high-mass galaxies in our HOSTLIB as described in Section 5.2.1. As shown in Fig. 10, SN found in these environments preferentially exhibit low values of  $x_1$  and marginally higher values of  $c$ .

#### 5.3.2 The inferred distances: $\mu_{\text{bias}}$

Table 6 shows the difference between  $\gamma_{1D}$  and  $\gamma_{5D}$  for our simulated samples of DES-SN. When a correlation between  $M_{\text{stellar}}$  and  $(x_1, c)$  is included in our simulated samples (as described in Section 5.2.2) we find  $\gamma_{1D} - \gamma_{5D} = 0.012 \pm 0.001$  mag, with  $\gamma_{1D} - \gamma_{5D} = -0.001 \pm 0.001$  mag for the case of no intrinsic correlations.

Fig. 12 and Table 6 compare these results to DES-SN. To test the robustness of our results, Fig. 12 shows the distribution of  $\gamma_{1D} - \gamma_{5D}$  from varying our assumptions on the underlying  $M_{\text{stellar}}$  distribution, including outlying values of  $(x_1, c)$ , and using different parameterisations of the mass step. For a simulated sample without correlations between SN and host, averaging overall systematic tests, we find  $\gamma_{1D} - \gamma_{5D} = -0.002 \pm 0.001$  mag. When a correlation between  $M_{\text{stellar}}$ ,  $x_1$ , and  $c$  is included in our simulated sample, averaging overall systematic tests, we find a mean offset of  $0.011 \pm 0.001$  mag. Given uncertainties on the true relationship

between SN and host, this is well matched with the offset found in Section 4.2 for DES-SN of  $0.026 \pm 0.009$  mag (equation 6), suggesting that the correlation between  $M_{\text{stellar}}$  and  $(x_1, c)$  is a significant source of the low  $\gamma$ -value measured for DES-SN using a 5D  $\mu_{\text{bias}}$  correction.

#### 5.4 Biases in the recovered value of $\gamma$

In Section 5.3.2, we found a difference between  $\gamma_{5D}$  and  $\gamma_{1D}$  of 0.012 mag for our simulated samples when intrinsic correlations between  $M_{\text{stellar}}$  and  $(x_1, c)$  are included in our simulations. Given that our simulated samples include a mass step that is independent of this correlation, this points to a bias in the recovered value of  $\gamma$  for either, or both, analyses.

Table 7 shows how the fitted value of  $\gamma$  for our DES-SN simulations compares to the simulated value, for both 1D and 5D  $\mu_{\text{bias}}$  corrections. When an intrinsic correlation between  $M_{\text{stellar}}$  and  $(x_1, c)$  is included in our simulated samples, the value of  $\gamma$  assuming a 5D  $\mu_{\text{bias}}$  correction is reduced relative to the simulated value of  $\gamma$ , with an offset of  $\Delta\gamma_{5D} = \gamma_{5D; \text{fit}} - \gamma_{\text{sim}} = -0.012 \pm 0.001$  mag, compared to  $\Delta\gamma_{1D} = \gamma_{1D; \text{fit}} - \gamma_{\text{sim}} = 0.000 \pm 0.001$  mag.

Table 8 and Fig. 13 show the robustness of this result by varying our assumptions on the source and underlying  $M_{\text{stellar}}$  distribution, varying the input value of  $\gamma_{\text{sim}}$ , including outlying values of  $(x_1, c)$ , and using different parametrizations of the mass step. We find an average offset of  $\Delta\gamma_{5D} = -0.0093 \pm 0.0013$  mag (where the uncertainty is derived from the scatter of the results) inconsistent with zero at  $6.9\sigma$ , compared to  $\Delta\gamma_{1D} = 0.0019 \pm 0.0011$  mag ( $1.8\sigma$ ). When we include no mass step in our simulations (i.e.  $\gamma_{\text{sim}} = 0.0$  mag), but leave  $\gamma$  as a free parameter in the fit, we find a best-fitting value of  $\gamma_{5D} = -0.008 \pm 0.001$  mag, and  $\gamma_{1D} = 0.003 \pm 0.001$  mag, indicating that the offset in  $\gamma_{5D}$  is independent of the value of  $\gamma_{\text{sim}}$ .

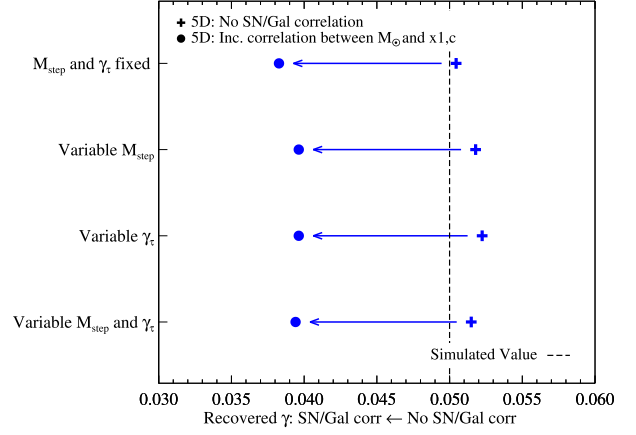
When we consider the case without intrinsic correlations between  $M_{\text{stellar}}$  and  $(x_1, c)$ , the measured value of  $\gamma$  is consistent with the simulated value for both 5D and 1D  $\mu_{\text{bias}}$  corrections. For our fiducial analysis, we find best-fitting values of  $\Delta\gamma_{5D} = 0.000 \pm 0.001$  mag and  $\Delta\gamma_{1D} = -0.001 \pm 0.001$  mag (Table 7). Averaged overall systematic tests, we recover  $\Delta\gamma_{5D} = 0.0024 \pm 0.0012$  mag and  $\Delta\gamma_{1D} = 0.0004 \pm 0.0007$  mag. The 5D  $\mu_{\text{bias}}$  correction is inconsistent with the simulated value of  $\gamma$  at  $2.0\sigma$ , compared to  $0.6\sigma$  for the 1D  $\mu_{\text{bias}}$  correction. For our simulations with no mass step (i.e.  $\gamma_{\text{sim}} = 0.0$  mag), we find a best-fitting value of  $\gamma_{5D} = 0.003 \pm 0.001$  mag and  $\gamma_{1D} = 0.001 \pm 0.001$  mag, showing that our results are consistent independent of the input value of  $\gamma_{\text{sim}}$ .

**Table 7.** Measured nuisance parameters from simulations for the DES-SN sample when intrinsic correlations between  $x_1, c$  and  $M_{\text{stellar}}$  are and are not included. The fiducial results from this study are highlighted in bold.

SN/host <sup>a</sup> correlations	BiasCor	$\sigma_{\text{int}}$	$\Delta\alpha^b$	$\Delta\beta^b$	$\Delta\gamma^b$ (mag)
<b><math>x_1, c</math></b>	5D	0.100	-0.001	0.009	-0.012
<b><math>x_1, c</math></b>	1D	0.098	0.001	0.032	0.000
None	5D	0.099	0.001	0.006	0.000
None	1D	0.098	0.002	0.040	-0.001

<sup>a</sup>For each simulated event, the SN parameters are either linked to  $M_{\text{stellar}}$  through the SDSS+SNLS sample or drawn from a parent population following the methodology of Scolnic & Kessler (2016). See Section 5.2.2 for details.

<sup>b</sup> $\Delta x = x_{\text{fit}} - x_{\text{sim}}$  where  $(\alpha_{\text{sim}}, \beta_{\text{sim}}, \gamma_{\text{sim}}) = (0.15, 3.1, 0.05)$ .



**Figure 13.** Simulation output: The best-fitting value of  $\gamma_{\text{fit}}$  for our simulated DES-SN samples considering different systematic uncertainties when assuming a 5D  $\mu_{\text{bias}}$  correction. For each entry, the right-hand value (plotted as a plus symbol) indicates the value when our simulated sample does not contain a correlation between  $M_{\text{stellar}}$  and  $(x_1, c)$ , while the left-hand entry (plotted as a filled circle) is the result when a correlation is enforced using the prescription described in Section 5.2.2. The simulated value of  $\gamma_{\text{sim}} = 0.05$  is shown as dashed vertical line. Entries are for our fiducial HOSTLIB, derived from DES-SV data, matched to the mass distribution. Four results with differing assumptions about the mass step parametrization are shown. In all cases,  $\gamma_{\text{fit}}$  is reduced by  $\sim 0.10$  mag when correlations between  $M_{\text{stellar}}$  and  $x_1, c$  are included. As shown in Tables 7 and 8, using alternative galaxy catalogues and weighting schemes results in consistent results.

From Tables 7 and 8, there is some evidence that the reduced value of  $\gamma_{5D}$  is offset by an increase in the value of  $\beta$ , but averaging overall possible combinations, we find no evidence of an offset in the value of  $\beta$ , with  $\Delta\beta_{5D} = 0.010 \pm 0.004$  ( $2.6\sigma$ ) and  $\Delta\beta_{1D} = 0.034 \pm 0.018$  ( $1.9\sigma$ ) when intrinsic correlations between  $M_{\text{stellar}}$ ,  $x_1$  and  $c$  are included in our simulated samples.

##### 5.4.1 Implications for 5D $\mu_{\text{bias}}$ corrections

From our simulated samples, when intrinsic correlations between  $M_{\text{stellar}}$  and  $(x_1, c)$  are included, a 5D  $\mu_{\text{bias}}$  correction recovers a reduced value of  $\gamma$  relative to the simulated value, with an offset of 0.009 mag. To test for the source of this bias, we search for correlations between  $M_{\text{stellar}}$  and  $(m_{B\text{bias}}, \Delta x_{1\text{bias}}, c_{\text{bias}})$ . We find strong evidence of correlation between  $M_{\text{stellar}}$  and  $x_{1\text{bias}}$ , with a difference of  $\Delta x_{1\text{bias}}$  of  $0.052 \pm 0.001$  mag between SNe in low- and high-mass galaxies. This is consistent with  $0.062 \pm 0.028$  mag measured for DES-SN in Section 4.3. We find offsets of  $0.0005 \pm 0.0001$  mag and  $-0.0009 \pm 0.0001$  mag between SNe in low- and high-mass galaxies for  $m_{B\text{bias}}$  and  $c_{\text{bias}}$ , respectively. These values are consistent with those observed for DES-SN. When correlations between  $M_{\text{stellar}}$  and  $(x_1, c)$  are not included in our simulations, we find no evidence of a correlation between  $M_{\text{stellar}}$  and  $x_{1\text{bias}}, m_{B\text{bias}}$  or  $c_{\text{bias}}$ , as expected.

For our simulated samples,  $\gamma$  is independent of  $(x_1, c)$ . However, when intrinsic correlations between  $M_{\text{stellar}}$  and  $(x_1, c)$  are included in our simulations, a 5D  $\mu_{\text{bias}}$  correction misinterprets  $\gamma$  as being caused by these correlations, summing 0.009 mag of  $\gamma$  into  $x_{1\text{bias}}$ . This result suggests that a fraction of the decrease in  $\gamma$  seen for the DES-SN sample, when using a 5D  $\mu_{\text{bias}}$  correction compared to a 1D  $\mu_{\text{bias}}$  correction has been incorrectly attributed to be an uncorrected contribution to  $x_1$ . This is further confirmed by the DES-SN sample,

**Table 8.** Systematic tests on the best-fitting value of  $\gamma$  from simulated samples.

HOSTLIB	SN/host correlations <sup>a</sup>	BiasCor	$\gamma_{\text{sim}}$	Mass distribution <sup>b</sup>	Outlier Removal <sup>c</sup>	$\sigma_{\text{int}}$	$M_{\text{step}}^d$	$\gamma_{\tau}^d$	$\Delta\alpha^e$	$\Delta\beta^e$	$\Delta\gamma^e$ (mag)
DES-SV	$x_1, c$	5D	0.05	SDSS+SNLS	Trimmed	0.100	Fixed	Fixed	-0.001	0.009	-0.012
DES-SV	$x_1, c$	5D	0.05	Unweighted	Trimmed	0.100	Fixed	Fixed	-0.001	0.011	-0.009
DES-SV	$x_1, c$	5D	0.05	SDSS+SNLS	Full	0.100	Fixed	Fixed	-0.001	0.016	-0.009
DES-SV	$x_1, c$	5D	0.05	SDSS+SNLS	Trimmed	0.100	9.998	Fixed	-0.001	0.011	-0.010
DES-SV	$x_1, c$	5D	0.05	SDSS+SNLS	Trimmed	0.100	Fixed	0.03	-0.001	0.009	-0.010
DES-SV	$x_1, c$	5D	0.00	SDSS+SNLS	Trimmed	0.100	Fixed	Fixed	-0.001	0.010	-0.008
SVA1-GOLD	$x_1, c$	5D	0.05	SDSS+SNLS	Trimmed	0.101	Fixed	Fixed	-0.001	0.002	-0.010

<sup>a</sup>For each simulated event, the SN parameters are either linked to  $M_{\text{stellar}}$ , through the SDSS+SNLS sample or drawn from a parent population following the methodology of Scolnic & Kessler (2016). See Section 5.2.2 for details.

<sup>b</sup>For each simulated event, whether or not the value of  $M_{\text{stellar}}$  is chosen randomly from the HOSTLIB file or from a weighted distribution determined from the pseudo complete SDSS+SNLS sample. See Section 5.2.1 for details.

<sup>c</sup>For each HOSTLIB, whether or not events in the SDSS+SNLS sample with  $x_1 < -2$  and  $x_1 > 2$  are included when determining the correlation between  $M_{\text{stellar}}$  and  $(x_1, c)$ . See Section 5.2.1 for details.

<sup>d</sup>Fixed to  $M_{\text{step}} = 10.0$  and  $\gamma_{\tau} = 0.01$  in the fiducial analysis.

<sup>e</sup> $\Delta x = x_{\text{fit}} - x_{\text{sim}}$  where  $(\alpha_{\text{sim}}, \beta_{\text{sim}}, \gamma_{\text{sim}}) = (0.15, 3.1, 0.05)$ .

where there is no evidence of differing nuisance parameters for high stretch SNe Ia compared to their low stretch counterparts. Fixing  $\gamma = 0$  and splitting the DES-SN sample in to high and low bins of  $x_1$ , we measure

$$x_1 > 0 : \alpha, \beta, M_0 = 0.140 \pm 0.028, 3.11 \pm 0.18, \\ -19.348 \pm 0.014$$

and

$$x_1 < 0 : \alpha, \beta, M_0 = 0.155 \pm 0.023, 2.88 \pm 0.19, \\ -19.369 \pm 0.016.$$

These values are consistent at  $< 1\sigma$ , suggesting that high stretch SNe Ia follow the same correction as low stretch SNe Ia, when no correction for  $M_{\text{stellar}}$  is allowed. We find some evidence of a difference in the distribution of  $c$  for SNe Ia with  $x_1 < 0$  compared to  $x_1 > 0$ , with mean  $c = -0.010 \pm 0.009$  mag for SNe Ia with  $x_1 < 0$  compared to  $c = -0.046 \pm 0.006$  mag for those with  $x_1 > 0$ . For our simulated sample, we find  $c = -0.0425 \pm 0.0003$  mag for SNe Ia with  $x_1 < 0$  and  $c = -0.0358 \pm 0.0002$  mag  $x_1 > 0$ , consistent for low-stretch SNe Ia, but inconsistent for high-stretch events at  $2.97\sigma$ , suggesting that this is likely an uncorrected for selection effect. From this test, there is little evidence from the DES-SN sample that high and low-stretch SNe Ia follow different standardization relationships. As a consequence, there is no evidence that an additional  $x_1$  dependent correction, beyond  $\alpha$ , is required for the DES-SN sample, as inferred by the 5D  $\mu_{\text{bias}}$ , which considers a fraction of the mass step to be an uncorrected contribution to  $x_1$ . Overall, we find that the value of  $\gamma$  found using a 5D  $\mu_{\text{bias}}$  correction is reduced relative to the true, underlying value by  $\sim 0.01$  mag.

Offsets in  $\Delta\gamma$  have been found for all cosmological analyses that use a 5D  $\mu_{\text{bias}}$  correction, with  $\Delta\gamma = 0.026 \pm 0.009$  mag for DES-SN and  $\Delta\gamma = 0.025$  mag for the PS1 sample (Scolnic et al. 2018). With this offset likely caused by the correlation between SN and host galaxy parameters, this suggests the need for a 7D  $\mu_{\text{bias}}$  correction, with additional terms linked to  $\gamma$  and  $M_{\text{stellar}}$ . The cosmological implications of this offset, while subdominant to the current statistical and systematic error budget from SNe Ia, will likely be important for future experiments, such as the Large Synoptic Survey Telescope (LSST). The ramifications of this offset on the equation-of-state of dark energy will be explored in an upcoming analysis of the DES5YR sample of  $\sim 2,000$  SNe Ia.

## 6 SUMMARY AND CONCLUSIONS

In this paper we have presented photometric measurements and derived physical parameters for the host galaxies of the 206 SNe Ia discovered by the Dark Energy Survey (DES) Supernova Program (DES-SN) and used in the first DES-SN cosmological analysis (DES3YR). While host properties for the DES3YR analysis (Brout et al. 2019b) were based on a relatively shallow catalogue (SVA1-GOLD), here we obtain host properties from deep stack photometry, based on all 5 yr of DES-SN, fit to a library of SEDs to infer stellar masses and star-formation rates, we have shown the following:

(i) The distribution of  $M_{\text{stellar}}$  and sSFR for the DES-SN sample is consistent with that derived from the SNLS survey, which spans a similar redshift range. The DES-SN sample has a higher fraction of low  $M_{\text{stellar}}$  galaxies than that determined by the intermediate redshift, SDSS and PS1 samples. The values derived for  $M_{\text{stellar}}$  are robust to the templates, IMF and photometric catalogue used.

(ii) We observe a correlation between  $M_{\text{stellar}}$  and SN Ia light-curve width ( $x_1$ ), as found previously for literature samples, but there is no evidence of a correlation with SN colour ( $c$ ).

(iii) The correlation between  $M_{\text{stellar}}$  and Hubble residuals ( $\Delta\mu$ ), parameterised as a ‘mass step’ ( $M_{\text{step}}$ ) is observed at 2.4 and  $2.1\sigma$  for the DES3YR and DES-SN samples, respectively. The best-fitting value of the strength of the mass step,  $\gamma = 0.040 \pm 0.019$  mag is consistent with results derived for the Pantheon and PS1 analyses and robust to the methodology and underlying assumptions used to derive  $M_{\text{stellar}}$ . The value found here is larger than  $\gamma = 0.009 \pm 0.018$  mag found by B19. This difference is not due to host galaxy misassociation, but a combination of improved photometric measurements and an updated SED library.

(iv) We find a dependence on the value of  $\gamma$  based upon the methodology used to determine distances to each event. Within the BBC framework, we find that  $\gamma$  is reduced by 0.026 mag when using a 5D ( $z, x_1, c, \alpha, \beta$ )  $\mu_{\text{bias}}$  correction compared to a 1D ( $z$ -only) correction. This conclusion is consistent across all other systematics considered.

(v) We find a strong correlation between  $M_{\text{stellar}}$  and the BBC  $x_1$  component of the  $\mu_{\text{bias}}$  correction, suggesting that the BBC framework infers that some fraction of the mass step is not due to  $M_{\text{stellar}}$ , but is an uncorrected contribution due to  $x_1$ .

(vi) To test this, and search for biases in the recovered value of  $\gamma$ , we simulate the DES-SN sample, introducing realistic correlations between  $M_{\text{stellar}}$  and  $(x_1, c)$ . These input correlations are independent



of the mass step. When  $M_{\text{stellar}}$  is independent of  $x_1$ ,  $c$  both 1D and 5D  $\mu_{\text{bias}}$  corrections successfully recover the input value of  $\gamma$ . When correlations between  $M_{\text{stellar}}$  and  $x_1$ ,  $c$  are introduced, we recover:

$$[\gamma_{1D} - \gamma_{5D}]_{\text{sim}} = 0.012 \pm 0.002 \text{ mag}$$

$$[\gamma_{1D} - \gamma_{5D}]_{\text{data}} = 0.026 \pm 0.009 \text{ mag.}$$

(vii) For our simulated samples including intrinsic correlations, we find that the value of  $\gamma_{5D}$  is reduced relative to the simulated value by 0.0093 mag. There is no evidence of a bias in  $\alpha$  or  $\beta$  for either a 1D or 5D  $\mu_{\text{bias}}$  correction. This indicates that the value of  $\gamma$  found for DES-SN using a 5D  $\mu_{\text{bias}}$  correction is systematically underestimated by  $\sim 0.01$  mag.

While significant attention has been given to the methodology used to determine  $M_{\text{stellar}}$  for SN Ia hosts, it is clear that the methodology used to determine distances to SNe Ia plays an important role in the inferred mass step. Given the strong dependence between  $M_{\text{stellar}}$  and  $x_1$  for SNe Ia, the use of a 5D  $\mu_{\text{bias}}$  correction dependent on  $z$ ,  $x_1$ ,  $c$ ,  $\alpha$ , and  $\beta$  can result in a systematic under-estimation of the relationship between SN Ia luminosity and host galaxy properties. This may potentially result in biases when estimating the cosmological parameters, subdominant to the current statistical and systematic error budget from SNe Ia, but likely be important for future experiments, such as the LSST. The underlying correlation between  $M_{\text{stellar}}$  and  $(x_1, c)$  also suggests the need for additional terms in the  $\mu_{\text{bias}}$  correction, with linked to  $M_{\text{stellar}}$  and  $\gamma$  to fully encapsulate SN Ia selection effects.

Given the potential evolution in the distribution of  $M_{\text{stellar}}$  with redshift (Rigault et al. 2013), it is critical to consider the underlying relationship between SN Ia luminosity and local environment when estimating the distance to individual SN Ia. Upcoming samples of thousands of SNe Ia, both in the local Universe with IFU spectroscopy (Galbany et al. 2016) and at high redshift from samples such as DES, LSST, and the Wide Field InfraRed Survey Telescope (*WFIRST*; Hounsell et al. 2018), will allow us to constrain the intrinsic correlation between host and SN, and probe its evolution with redshift. This is key to understanding the source of  $M_{\text{step}}$  and ensuring the inferred cosmological parameters from SNe Ia surveys are unbiased in the era of precision cosmology.

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## SUPPORTING INFORMATION

Supplementary data are available at *MNRAS* online.

## DES3YR\_hostgalprop\_table\_2020mar18\_plain.tex

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## APPENDIX A: HOST GALAXY ASSOCIATION

The DLR methodology (Sullivan et al. 2006; Smith et al. 2012; Gupta et al. 2016; Sako et al. 2018) used to define the host galaxy of each DES SN Ia defines the distance from an SN event (at  $x_{\text{SN}}$ ,  $y_{\text{SN}}$ ) to the centre of a potential host galaxy (at  $x_{\text{gal}}$ ,  $y_{\text{gal}}$ ) according to

$$d_{\text{DLR}} = \frac{\text{separation from SN to galaxy}}{\text{DLR}}, \quad (\text{A1})$$

where DLR is the elliptical radius of a galaxy in the direction of the SN. This is based on the elliptical shape determined by SEXTRACTOR, defined by semimajor ( $r_A$ ) and semiminor ( $r_B$ ) axes together with a position angle ( $\theta$ ). The DLR is then given by

$$\text{DLR}^2 = C_{xx}x_r^2 + C_{yy}y_r^2 + C_{xy}x_r y_r, \quad (\text{A2})$$

where  $x_r = x_{\text{SN}} - x_{\text{gal}}$ ,  $y_r = y_{\text{SN}} - y_{\text{gal}}$ ,  $C_{xx} = \cos^2(\theta)/r_A^2 + \sin^2(\theta)/r_B^2$ ,  $C_{yy} = \sin^2(\theta)/r_A^2 + \cos^2(\theta)/r_B^2$ , and  $C_{xy} = 2 \cos(\theta) \sin(\theta)(1/r_A^2 - 1/r_B^2)$ .

In short, the DLR method normalizes the separation between a SN and a candidate host galaxy by the size of that galaxy in the direction of the SN, and then selects the galaxy with the smallest  $d_{\text{DLR}}$  as the true host. Following Gupta et al. (2016) and Sako et al. (2018), we only consider galaxies with  $d_{\text{DLR}} < 7$  to be candidates for the true host.

## APPENDIX B: HOST GALAXY MAGNITUDES AND DERIVED PROPERTIES

**Table B1.** Host galaxy photometric measurements and derived properties for the DES-SN sample.

DES name	SNID	Redshift	<i>g</i>	<i>r</i>	<i>i</i>	<i>z</i>	$\log(M_{\text{stellar}})$	$\log(\text{sSFR})$	Catalogue
DES13C3dgs	1248677	0.3502	21.80 ± 0.01	21.04 ± 0.01	20.81 ± 0.01	20.59 ± 0.01	9.57 ± 0.03	− 8.48	W19
DES13S1qv	1250017	0.1817	22.17 ± 0.01	21.60 ± 0.01	21.37 ± 0.01	21.25 ± 0.01	8.78 ± 0.05	− 8.69	W19
DES13C1hwx	1253039	0.4535	24.01 ± 0.04	23.04 ± 0.02	22.56 ± 0.03	22.36 ± 0.03	9.39 ± 0.07	− 9.91	W19
DES13E1goh	1253101	0.4596	25.48 ± 0.11	24.32 ± 0.05	24.22 ± 0.07	23.81 ± 0.06	8.57 ± 0.08	− 8.68	W19
DES13C1juw	1253920	0.1956	22.18 ± 0.01	21.13 ± 0.01	20.68 ± 0.01	20.53 ± 0.01	9.43 ± 0.04	− 14.40	W19

<sup>a</sup>Redshift quoted to 4 decimal places (d.p.) when determined from galaxy emission/absorption features or 2 d.p. when determined from SN template matches.

<sup>b</sup>This table is available in full online as part of the supplementary material.

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