MEASURING COSMOLOGICAL PARAMETERS WITH TYPE Ia SUPERNOVAE IN REDMAGIC GALAXIES

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ABSTRACT

Current and future cosmological analyses with Type Ia Supernovae (SNe Ia) face three critical challenges: i) measuring redshifts from the supernova or its host galaxy; ii) classifying SNe without spectra; and iii) accounting for correlations between the properties of SNe Ia and their host galaxies. We present here a novel approach that addresses each challenge. In the context of the Dark Energy Survey (DES), we analyze a SNIa sample with host galaxies in the redMaGiC galaxy catalog, a selection of Luminous Red Galaxies. Photo-z estimates for these galaxies are expected to be accurate to \( \sigma_{\Delta z/(1+z)} \approx 0.02 \). The DES-5YR photometrically classified SNIa sample contains approximately 1600 SNe and 125 of these SNe are in redMaGiC galaxies. We demonstrate that redMaGiC galaxies almost exclusively host SNe Ia, reducing concerns with classification uncertainties. With this subsample, we find similar Hubble scatter (to within \( \sim 0.01 \) mag) using photometric redshifts in place of spectroscopic redshifts. With detailed simulations, we show the bias due to using photo-zs from redMaGiC host galaxies on the measurement of the dark energy equation-of-state \( w \) is up to \( \Delta w \sim 0.01 \) – 0.02. With real data, we measure a difference in \( w \) when using redMaGiC photometric redshifts versus spectroscopic redshifts of \( \Delta w = 0.005 \). Finally, we discuss how SNe in redMaGiC galaxies appear to be a more standardizable population due to a weaker relation between color and luminosity \( (\beta) \) compared to the DES-3YR population by \( \sim 5\sigma \); this finding is consistent with predictions that redMaGiC galaxies exhibit lower reddening ratios \( (R_v) \) than the general population of SN host galaxies. These results establish the feasibility of performing redMaGiC SN cosmology with photometric survey data in the absence of spectroscopic data.

1. INTRODUCTION

Type Ia Supernovae (SNe Ia) remain a critical tool as standardizable candles to measure cosmological parameters and constrain models for dark energy. In the next decade, multiple surveys such as the Vera Rubin Observatory Legacy Survey of Space and Time (LSST; Ivezić et al. 2019) and the Nancy Grace Roman Space Telescope (Roman; Honsell et al. 2018) will discover more than a million SNe which will be leveraged to constrain models for dark energy. In the next decade, multiple surveys such as the Vera Rubin Observatory Legacy Survey of Space and Time (LSST; Ivezić et al. 2019) and the Nancy Grace Roman Space Telescope (Roman; Honsell et al. 2018) will discover more than a million SNe which will be leveraged to constrain models for dark energy. In the next decade, multiple surveys such as the Vera Rubin Observatory Legacy Survey of Space and Time (LSST; Ivezić et al. 2019) and the Nancy Grace Roman Space Telescope (Roman; Honsell et al. 2018) will discover more than a million SNe which will be leveraged to constrain models for dark energy. In the next decade, multiple surveys such as the Vera Rubin Observatory Legacy Survey of Space and Time (LSST; Ivezić et al. 2019) and the Nancy Grace Roman Space Telescope (Roman; Honsell et al. 2018) will discover more than a million SNe which will be leveraged to constrain models for dark energy.
ever, this approach to obtaining redshifts requires large amounts of dedicated telescope time and additional modeling of spectroscopic efficiency due to biases toward brighter host galaxies (Vincenzi et al. 2021b).

So far, there have been limited studies on using photometric redshift estimates (photo-z) in a cosmological study with SNe Ia. Kessler et al. (2010) produced LSST simulations and showed that a light-curve fit using a host-galaxy photo-z prior yields comparable redshift precision to spectroscopic redshifts. However, Sako et al. (2011) found that using SN-only photo-zs with real SDSS data resulted in pathologies that propagated to biases in the distances and therefore the measurement of cosmological parameters. Other studies (Wojtak et al. 2015; Davis et al. 2019) have found that systematic redshift errors as small as $10^{-4}$ can mimic a 1% perturbation in $w$ but also illustrate that the impact of redshift biases diminishes with increasing redshift.

For SNIa samples with diverse host-galaxy types, the issue of preferentially targeting brighter galaxies is particularly problematic because there is a correlation between the mass and rest-frame U-R color of the galaxies and the luminosity of the SNe (Sullivan et al. 2010; Kelly et al. 2010; Kelsey et al. 2021). There have also been observed correlations between other global host-galaxy properties such as metallicity and morphological type (Hamuy et al. 2000; Kelly et al. 2010; Smith et al. 2020), as well as local host-galaxy environments (Rigault et al. 2013, 2015, 2020; Roman et al. 2018; Kelsey et al. 2021). These correlations are not well understood and are the subject of ongoing efforts to implement better bias corrections and modeling (Smith et al. 2020; Rigault et al. 2020; Brout & Scollnic 2021; Popovic et al. 2021). Since the measurement of $w$ is based on a relative measurement between distances of SNe at high- and low-redshift, a redshift dependent selection of galaxy type may cause a significant systematic in measurements of $w$. Here we investigate a solution to the above problems by exploiting SNe located in Luminous Red Galaxies (LRGs), which are a well known homogeneous population consisting of so called “red and dead” elliptical galaxies. LRGs are expected to contain very low rates of core-collapse SNe, as core-collapse progenitors are massive and largely present in active star forming galaxies such as spiral galaxies. Foley & Mandel (2013) found that 98% of all SNe with elliptical host galaxies in the Lick Observatory Supernova Search sample (Leaman et al. 2011) are SNe Ia, implying that host-galaxy information alone can reduce photometric contamination from core-collapse SNe, and Irani et al. (2021) conclude that only 0.3% of all core-collapse SNe have elliptical hosts. Secondly, LRG spectra contain a prominent 4000 Å break, which enables precise and accurate photo-z estimates that have traditionally been utilized in large-scale structure studies. The photo-z bias of these galaxies can be further constrained with the use of red galaxies selected using the redMaGiC algorithm described in (Rozo et al. 2016), which utilizes a modified photo-z estimator based on a full red-sequence model. Lastly, limiting the host-galaxy type allows for a more consistent sample across redshifts that is less sensitive to complicated correlations between SN light-curve properties and host-galaxy properties. While in the future there will be enough low-redshift SNe observed in LRGs to have a SN sample solely in one host-galaxy type, this study instead combines SNe in LRGs at $z > 0.05$ with the traditional spectroscopic low-redshift sample to provide a SN sample large enough for Ia cosmological analysis.

Less than 10% of SN host galaxies are expected to be LRGs (Foley & Mandel 2013). For DES, which has 3,627 SNe Ia before light-curve quality cuts and 1,606 after quality cuts, this LRG selection yields 227 SNe before cuts and 125 after cuts (6.26% and 7.78% respectively). For the LSST sample of ~2 million SNe, we expect ~10^5 SNe in LRGs.

In this paper, we provide a first investigation into the feasibility of using photometric redshifts from the redMaGiC galaxy catalog in a Type Ia Supernova cosmology analysis. The outline of the paper is as follows. In Section 2, we summarize the DES SN and host-galaxy data used for this work. In Section 3, we discuss the simulations used to validate the method and for estimating bias corrections. In Section 4, we discuss the application of the method to DES-5YR data. In Section 5, we discuss the implications and results of our study. In Section 6, we present our conclusions.

2. DATA

2.1. redMaGiC Galaxies

Luminous Red Galaxies occupy a very narrow range in color and intrinsic luminosity, and they contain old, red stellar populations. LRGs are a useful probe for large-scale structure studies (Stoughton et al. 2002), as they are intrinsically luminous and therefore can be observed out to high redshift, and they are relatively massive and therefore tend to cluster strongly. LRG spectral energy distributions (SEDs) have a prominent 4000 Å feature caused by absorption lines from metals in stellar atmospheres that make LRGs ideal candidates for photo-z estimations.

The red galaxies and photo-z data used in this study were obtained using the red-sequence Matched-filter Galaxy (redMaGiC) algorithm (Rozo et al. 2016) run on six seasons of DES data with preliminary photometry. The algorithm is based on the infrastructure of redMaP-Per (Rykoff et al. 2014), a red sequence cluster finder designed for large photometric surveys. The algorithm selects red galaxies based on a chosen comoving space density and luminosity threshold. First, redMaGiC fits every red sequence galaxy with the redMaPPer red sequence template and computes its best fit photo-z. Using this photo-z, it computes the galaxy luminosity. Lastly, it applies selection requirements (cuts) on the luminosity and $\chi^2$ of the template fit, with the cuts tuned to select a desired comoving space density.

After applying redMaGiC cuts, a subset of galaxies with spectroscopic redshifts that are members of redMaPPer clusters is used to further train and validate a photo-z afterburner. To avoid biased selection from using galaxies with spectroscopic follow-up, the redshift calibration uses redMaPPer photometric cluster redshifts ($z_{\text{cluster}}$) where each $z_{\text{cluster}}$ is fit simultaneously with all cluster members and is therefore more accurate than any individual galaxy redshift. The training sample’s median redshift offset $\Delta z_{\text{cluster}} = z_{\text{red}} - z_{\text{cluster}}$ is calculated in bins of $z_{\text{red}}$, where $z_{\text{cluster}}$ is the cluster redshift and $z_{\text{red}}$ is the initial
photometric redshift. This median offset is added to $z_{\text{red}}$ using spline interpolation to give the final photometric redshift, $z_{\text{redmagic}}$.

The redshift range of the sample is $z_{\text{redmagic}} \in [0.05, 0.95]$ and is shown in Figure 1 along with the $z$ band magnitude ($m_z$) distribution. The redshift distribution peaks around $z = 0.7$ and the magnitude distribution peaks around $m_z = 21.0$. The redMaGiC algorithm is typically run to produce two sets of catalogs: "high-luminosity" and "high-density." The high-luminosity catalog restricts selection to galaxies with luminosity greater than $1 \, L_\odot$ and is defined as the median of offsets $\Delta z = z_{\text{spec}} - z_{\text{redmagic}}$, and the photo-$z$ scatter $\sigma_{\Delta z/(1+z)}$ is defined as $1.4826 \times \text{MAD}$, where MAD is the median absolute deviation $| \Delta z - \overline{\Delta z} | / (1 + z_{\text{spec}})$. Figure 2 shows the photo-$z$ performance of the combined high-density and high-luminosity Year 6 redMaGiC sample. To compare the performance of spectroscopic redshifts ($z_{\text{spec}}$) and $z_{\text{redmagic}}$, we select galaxies with an available spectroscopic redshift, which reduces the number of galaxies from 4,162,865 to 55,735.

To quantify the performance of photometric redshifts, the photo-$z$ bias $\overline{\Delta z}$ is defined as the median of offsets $\Delta z = z_{\text{spec}} - z_{\text{redmagic}}$, and the photo-$z$ scatter $\sigma_{\Delta z/(1+z)}$ is defined as $1.4826 \times \text{MAD}$, where MAD is the median absolute deviation $| \Delta z - \overline{\Delta z} | / (1 + z_{\text{spec}})$. Figure 2 shows the photo-$z$ performance of the combined high-density and high-luminosity Year 6 redMaGiC sample. A comparison to a one-to-one relation between spec-$z$ and photo-$z$ can be seen in the upper halves of the plots. The bottom halves of the plots show the bias and scatter plotted as a function of $z_{\text{redmagic}}$. In the left plot, the full redMaGiC sample has a scatter of less than 0.02 and bias less than 0.01 over the entire redshift interval.

2.2. DES SN data

In this analysis, we use data from the DES Supernova program (DES-SN) obtained with the Dark Energy Camera (DECam; Flaugher et al. 2015) mounted on the 4 meter Blanco telescope at the Cerro Tololo Inter-American Observatory (CTIO). DES-SN operated over five seasons, taking observations in the optical griz filters in ten 3 square degree fields at a cadence of ~ 7 days. These images were preprocessed by the DES Data Management team (DESDM; Morgan et al. 2018). Next, transients were detected in these images using the Difference Imaging pipeline (DIFFIMG; Kessler et al. 2015) by subtracting reference images from new observations. While scene modeling photometry (SM; Holtzman et al. 2008; Astier et al. 2013; Brout et al. 2019) is planned for the entire DES-5YR photometric sample, we utilize DIFFIMG photometry that is calibrated at the 2% level. This precision is sufficient for the purposes of this redMaGiC analysis, as calibration errors have the same effect on distances for spec-$z$ and photo-$z$, and here we only report differences between these two analyses. The transient sample is defined after restricting candidates to those with at least two detections at the same location on two separate nights in any band and that pass an automated artifact rejection algorithm (AUTOSCAN; Goldstein et al. 2015). From these criteria, approximately 30,000 transients are identified, which include SNe, AGNs, and other transients and artefacts.

For each transient, a host galaxy is assigned using the directional light radius (DLR) method (Sullivan et al. 2006; Gupta et al. 2016; Popovic et al. 2020). This host matching is performed with the depth-optimized coadds from Wiseman et al. (2020). The Photometric Supernova Identification software (PSNID; Sako et al. 2011) was run during survey operations on every active candidate, which fit the transient light-curve and provided preliminary classifications. This information informed the targeting for the host-galaxy follow-up spectroscopic program (Smith et al. 2020).

The DES-5YR SN-like photometric sample is restricted to SNe with associated host-galaxy spectroscopic redshifts. These redshifts are obtained from the spectroscopic follow-up (Smith et al. 2020) program, primarily from the OzDES survey (Yuan et al. 2015; Childress et al. 2017; Lidman et al. 2020). OzDES is a 100-night program using the 2dF+AAOmega spectrograph on the 3.9 meter Anglo-Australian Telescope. External redshift catalogues from the literature (as cited in Table 1 of


![Graphs showing redshift comparison between photometric and spectroscopic for redMaGiC galaxies.](image)

**Fig. 2.—** Top Left: Photometric redshifts vs. spectroscopic redshifts of redMaGiC galaxies. The dashed line has a slope of 1 for visual comparison. Bottom Left: Bias (binned $\Delta z$) in dash-dotted pink and scatter in dotted yellow for redMaGiC photo-z. Only galaxies with a spectroscopic redshift are included in the bias and scatter calculation. Right: Same as left, but for the subset of redMaGiC galaxies with a SN match. A bias of 0.006z is shown in grey in the bottom panel.

We use the SALT2 light-curve model (Guy et al. 2007; 2010) to fit SN light-curves and standardize the SNIa brightnesses. This fitting is implemented in the Supernova ANAlysis software (SNANA; Kessler et al. 2009b) framework, based on the MINUIT $\chi^2$ minimization algorithm to obtain best fit parameters and uncertainties. The fitted parameters are color, stretch $x_1$, epoch of SN peak brightness $t_0$, and the overall amplitude $x_0$, with $m_B = -2.5 \log_{10}(x_0)$. The distance modulus, $\mu$, is estimated using the Tripp estimator (Tripp 1998; Astier et al. 2006):

$$\mu = m_B + \alpha x_1 - \beta c - M_z + \delta \mu_{bias}$$

(1)

where $M_z$ is the distance offset in redshift bins $z_i$, $\alpha$, $\beta$ are coefficients parametrizing the relationship between stretch, color, and luminosity, and $\delta \mu_{bias}$ is the distance bias correction, which is described below. Rather than fitting for nuisance parameters ($\alpha$, $\beta$) in a global fit, we use values measured by the Dark Energy Survey (Brout et al. 2019a): $\alpha = 0.145$, $\beta = 3.1$.

Before fitting with SALT2, the data is further restricted to transients that have at least two bands with data satisfying max SNR > 4. After fitting with SALT2, we apply the following selection requirements that are typical for a cosmology analysis, along with an additional color uncertainty requirement:

- fitted color $|c| < 0.3$
- fitted color uncertainty $\sigma_c < 0.2$
- fitted stretch $|x_1| < 3.0$
- fitted stretch uncertainty $\sigma_{x_1} < 1.0$
- fitted $t_0$ uncertainty $\sigma_{t_0} < 2.0$ days
- Milky Way color excess $E(B - V) < 0.3$

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Vincenzi et al. (2021b) are used to supplement and optimize this redshift information. Following OzDES selection cuts and host associations, we have 5,049 galaxies with secure redshifts.

We further restrict the DES-5YR photometric sample (with no classifier applied) to SNe that have redMaGiC host galaxies. To associate host galaxies, we find all SNe with DLR-assigned host galaxy RA/Dec coordinates matching within one arcsecond to a redMaGiC galaxy from the Y6 run. 227 SNe, approximately 6% of the ~3700 SNe fit by SALT2 in the 5YR sample, have redMaGiC host galaxies. The right side of Figure 2 shows the redshift performance for the subset of redMaGiC galaxies with a SN match. The median redshift bias for the redMaGiC SNe is $\Delta z = 0.008$, and we find a redshift-dependent trend of $\sim 0.006 z$, which we show in Figure 2. We average the bias measured across 100 random samples of 227 galaxies drawn from the full redMaGiC distribution to obtain a mean bias of 0.001 with a scatter of 0.001, implying that the mean bias for the redMaGiC SNe is a $\sim 3\sigma$ fluctuation from the full redMaGiC sample bias. As it is possible that the subpopulation of redMaGiC SNe has an unmodeled selection effect, we propagate the $\sim 0.006 z$ bias as a systematic in Section 4.2.2. The mean scatter for the subsample is 0.015, compared to 0.012 for the full sample, and 0.015 from the averaged same-size samples.

In addition to the DES-SN sample, we include an external spectroscopically confirmed low-redshift sample to anchor the Hubble Diagram. We use 182 SNe Ia from the Foundation Supernova Survey (Foley et al. 2018; Jones et al. 2018). We note that this low-redshift sample contains SNe from a range of host-galaxy types.

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### 2.3. Light-curve Fits, Distance Estimation, and Cosmological Parameter Recovery

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Using the Beams with Bias Corrections (BBC; Kessler & Scolnic 2017) formalism, we bias correct our distance modulus values. The simulations used to determine bias corrections (biascor) are detailed in Section 3. Typical cosmological Ia analyses use higher dimensional bias corrections (BBC5D/BBC7D/BBC-B820; Popovic et al. 2021), with biases binned along SN properties, and use simulations with a 2 × 2 grid of α and β (to interpolate for each fitted α, β). However, to simplify this first redMaGic analysis we use redshift-dependent (1D) bias corrections with no dependence on other parameters, and our simulations have fixed α and β. The BBC fit determines an intrinsic scatter term (σ_int) and M_v, in N_2 BBC redshift bins. From the SALT2- and BBC-fitted parameters, we compute a bias-corrected distance (Eq. 1) for each SN to use in the cosmology fit.

The uncertainty in μ is given by:

\[ σ^2 = σ_{int}^2 + σ_{vpec}^2 + (σ_μ^vpec)^2 \]  

where σ_int is the intrinsic scatter needed to achieve reduced χ^2 = 1 for the BBC fit, σ_vpec describes the uncertainty computed from fitted light-curve parameters and their covariances, σ_μ^vpec is the contribution from peculiar velocity uncertainty σ_vpec with:

\[ σ_μ^vpec = \left( \frac{5}{\ln(10)} \right) \frac{1 + z}{z(1 + z/2)} \left( \frac{σ_vpec}{c} \right) \]  

and σ_vpec is the contribution from redshift uncertainty σ_z.

In Appendix A1, we explain why the redshift uncertainty (σ_z) is not included in Equation 3 as it has been previously in Kessler & Scolnic (2017). Instead, an empirical method is used to account for the contribution of photo-z uncertainties to the uncertainty in μ (σ_μ^z) as explained in Section 4.2.1.

Following recent studies of systematic biases in SNIa cosmological analyses (Brout et al. 2021; Popovic et al. 2021), we fit for w using a Gaussian prior on ΩM of mean 0.311 and σ = 0.01. We use the “wfit” χ^2 minimization program implemented in SNANA.

| Post-SALT2 fit cut              | Number remaining | Number rejected |
|--------------------------------|------------------|-----------------|
| SNe in redMaGic galaxies fit by SALT2 | 224              |                 |
| SN color |c| < 0.3                        | 185              | 39               |
| SN color uncertainty σ_c < 0.2      | 184              | 1               |
| SN stretch |x| < 3.0                        | 147              | 37               |
| SN stretch uncertainty σ_x < 1.0     | 125              | 22              |
| SN to uncertainty σ_t < 2.0         | 125              | 0               |
| Milky Way color excess E(B − V) < 0.3 | 125              | 0               |

### TABLE 1
Summary Table of Post-SALT2 fit cuts

3. SIMULATIONS
To quantify the cosmological biases from using photometric redshifts, we use SNANA catalog level simulations to realistically represent the DES-5YR photometric SN sample and to analyze alongside the real data. We exclude core-collapse SN contamination from our simulations, as significant contamination is not expected, as discussed in Section 4.1. In addition, we generate large samples used by BBC for determining bias corrections (Kessler & Scolnic 2017) to correct for known selection effects in our analysis.

3.1. Baseline DES Simulation

We use the SNANA software with the Pippin pipeline (Hinton & Brout 2020) to produce our simulations. Following the detailed simulations developed in Kessler et al. (2019), we generate realistic transient light-curves with several modifications. Briefly, the simulation consists of three major steps. First, a source SED is generated, and various astrophysical effects such as cosmological dimming, galactic extinction, lensing, and redshift effects are applied. The SED model is then integrated over the DES filters and observational noise is added using the DES observing conditions (PSF, sky noise, photometric zeropoints). Lastly, the detection efficiency and spectroscopic selection function of DES are implemented to select simulated events. To describe the SNIa brightness variation, we vary the SALT2 SED using the G10 intrinsic scatter model from Kessler et al. (2013).

Vincenzi et al. (2021b), hereafter V21, makes several improvements to the DES-3YR simulations to replicate the DES-5YR photometric SN sample, which contains both core-collapse SNe and SNe Ia, but not other transients. We provide an overview of the important features utilized in our simulations. First, V21 uses a model of the host-galaxy spectroscopic redshift efficiency which is parametrized as a function of host-galaxy brightness, color, and year of discovery. V21 also improves on the host-galaxy library from Smith et al. (2020) by compiling galaxy masses and Star Formation Rates (SFR) and accounting for differing SN rates in different types of galaxies. Simulating SN host galaxies based on published SN rates ensures that host-galaxy property dependencies are appropriately accounted for and that selection effects are modeled accurately across different galaxy types.

3.2. Modifications to Baseline DES-5YR Simulation

To properly simulate SNIa samples, the underlying distributions of SALT2 parameters x1 and c must accurately reproduce our observations. Previous analyses Scolnic et al. (2018) & Abbott et al. (2019) have used the method in Scolnic & Kessler (2010) to determine a migration matrix describing the impact of selection effects, noise, and intrinsic scatter on the underlying distributions. We use this methodology as implemented in the parent population fitting program from Popovic et al. (2021) to account for the host-galaxy stellar mass relationship. These parent populations are described by an asymmetric Gaussian. In comparison to the population fits for the full DES-3YR spectroscopic sample, we find that the redMaGic population parameters differ in color and stretch. When averaged over host-galaxy mass bins, the subset redMaGic population is described by parameters as given in Table 2. We provide the full parent population parameters for both the subset redMaGic population and the full DES-3YR spectroscopic sample in Appendix A2. We highlight that the lower
value of mean $x_1$ for the redMaGiC subsample is consistent with previous studies that show higher mass galaxies and lower specific star formation rates (sSFR) are correlated with lower $x_1$ values (Childress et al. 2014; Rigault et al. 2020; Nicolas et al. 2021).

We modify the V21 host-galaxy library and select only passive, bright galaxies to mimic the selection of redMaGiC galaxies. Selecting only passive galaxies as determined by log(sSFR) $< -11.5$ yr$^{-1}$ (Sullivan et al. 2006; Vincenzi et al. 2021b), we apply a cut on $r$ band magnitude in the host-galaxy redshift efficiency map, $m_r < 23.3$, and a cut on host-galaxy mass, logMass $> 10.5$, based on the distributions for the entire redMaGiC galaxy sample.

To accurately simulate the photo-$z$ biases and scatter in using photometric redshifts, we include a photo-$z$ for each galaxy in the host-galaxy library based on the bias and scatter from the redMaGiC catalog. For each galaxy in the modified V21 host-galaxy library, we find its closest match in redshift to the redMaGiC catalog, evaluate the bias $z_{\text{redmagic}} - z_{\text{spec}}$ for the redMaGiC galaxy, and add this bias to the host-galaxy true redshift value to determine the photo-$z$. While this galaxy matching would ideally be weighted by mass to prevent preferentially selecting lower mass galaxies, we find that the range of masses for redMaGiC host galaxies is narrow (further discussed in Section 5), circumventing this concern. Figure 3 shows that the photo-$z$ redshift bias and scatter are well reproduced with respect to the data. These photometric redshifts are propagated into the simulated data.

As discussed in Section 5 we measure the color-luminosity relation $\beta$ of 2.0 from the data and therefore simulate our redMaGiC-hosted SN sample with $\beta$ of 2.0 as well. A summary of the SN and host galaxy simulation properties is given in Table 3.

3.3. Comparison with Data

To validate the simulation, we normalize the total number of simulated SNe to the total number of observed SNe and find that our simulations reproduce the redshift distributions from the data well, as seen in Figure 4. We find that the light-curve parameter $(c, x_1, m_B)$ distributions are also well reproduced. For redshift, we find reduced $\chi^2 = 103/30$. For light-curve parameters $c, x_1$, and $m_B$, we find $\chi^2 = 60/30, 42/30,$ and $55/30$ respectively. While the $\chi^2$ value for redshift is somewhat high due to the discrepant bins around $0.3 < z < 0.5$, the current DES-5YR analysis (Fig. 7 in V21) reports a comparable reduced $\chi^2$ value for the shallow fields of 65/22. There are likely some unmodeled selection and noise effects. We note that the redshift agreement could be improved if the redMaGiC algorithm is applied to the host-galaxy library, rather than the rough cuts utilized here, but this is beyond the scope of this work. Notably, the general shape agreement at higher redshift ($z > 0.55$) is of the greatest relevance, as it is where the distance bias correction impact is largest. For $c, x_1,$ and $m_B,$ our $\chi^2$ values are also comparable to V21, which finds values of 62/22, 29/21, and 37/19 respectively.

To compare the simulated host-galaxy photometric redshifts to data, we examine the mean redshift bias and scatter in the redshift range 0.1-0.9 as illustrated in Figures 2 and 3. The combined high-density and high-luminosity redMaGiC catalog has mean redshift bias of 0.0005 and mean redshift-binned scatter of 0.0106 without any outlier cut. A random selection of 3,000 simulated host-galaxy redshifts has mean bias of 0.0003 and RMS scatter of 0.0099. Across redshift bins, the simulated redshifts have sub-percent bias and scatter of less than 0.02, accurately reproducing the data.

Table 2 Parent Population Parameters, Averaged Over Host-Galaxy Mass Bins

| SNIA Property | mean $\sigma_{\text{mean}}$ | $\sigma_{\text{per}}$ |
|---------------|-----------------------------|---------------------|
| SNe with redMaGiC hosts | $c$ | -0.04 | 0.04 | 0.13 |
| DES-3YR sample | $x_1$ | -0.86 | 1.69 | 1.35 |

Table 3 Simulation Inputs and SN Properties

| HOSTLIB (V21) | |
|----------------|-----------------------------|
| Host logMass | $> 10.5$ |
| Host $r$ mag | $< 23.3$ |
| Host log(sSFR) | $< -11.5$ (passive) |

4. Analysis and Results

We next discuss the results from our use of redMaGiC photometric redshifts for SNIA cosmology. In Section 4.1 we quantify and discuss the SNIA purity for supernovae in redMaGiC galaxies. In Section 4.2 we describe the performance of photo-$z$s in comparison to spec-$z$s for our simulations and the effects on cosmological parameters. In Section 4.3 we apply our methods to data and compare the results with our simulations.
4.1. Potential Core-collapse Contamination

Large elliptical galaxies such as LRGs are expected to contain mostly SNe Ia (Hakobyan et al. 2020), with very low rates of core-collapse SNe. We quantify the potential core-collapse contamination in our redMaGiC subsample by examining photometric light-curve classification probabilities. The classification probabilities are obtained with the SuperNNova (SNN; Möller & de Boissière 2020) photometric SN classifier trained on the “baseline” DES-like simulation presented in Vincenzi et al. (2021a) which is generated from SEDs that include SALT2 and V19 core-collapse templates (Vincenzi et al. 2019). SNN gives a probability ranging from 0 to 1.0, with 1.0 being most-likely-Ia. To consider potential contaminants, we define an unlikely-Ia SN as having probability of being a Type Ia (PIa) of < 0.5. With conventional SALT2 cosmology cuts (Betoule et al. 2014), color uncertainty cut as included in this analysis, and no classifier, the simulated DES-5YR photometric SN sample includes 8% contamination (Vincenzi et al. 2021b; Möller et al. 2022). Of the 125 SNe in redMaGiC galaxies that pass post-SALT2 cuts, 4 are classified by SNN as unlikely-Ia (\sim 3%).

For comparison, we consider the SNN classification probabilities for the DES-5YR spectroscopically-confirmed SNIa sample, which serves as a “truth” set of SNe Ia. Of the 401 “true” SNe Ia, 3 are classified by SNN as non-Ia (\sim 1%). These fractions and percentages are shown in Table 4. We also consider the sample of DES-5YR spectroscopically-confirmed non-Ia SNe and find that there is no overlap with the redMaGiC SN sample.

| Simulated DES-5YR photometric SN sample with no classifier | Fraction (%) of SNe classified by SNN as unlikely-Ia |
|----------------------------------------------------------|--------------------------------------------------|
| SNe in redMaGiC galaxies                                 | 135/1680 (8%)                                    |
| DES-5YR spectroscopically-confirmed SNIa sample         | 4/125 (~ 3%)                                      |
|                                                          | 3/401 (~ 1%)                                      |

Of the four events in the redMaGiC subsample classified as non-Ia by SNN, one is a spectroscopically-confirmed Type Ia, and two are classified as Ia when SNN is trained instead on J17 templates (Jones et al. 2017). The baseline SNN model for DES in Möller et al. (2022) also classifies one of the events as Ia. In particular, we note that in the Difference Imaging pipeline, the misclassified spectroscopically confirmed SNIa has inaccurately subtracted template images in the g band. Notably, photometric classifiers do not have 100% efficiency and can miss true SNe Ia. We confirm the claim that redMaGiC galaxies have very low rates of core-collapse SNe.

4.2. Results from Simulations

We utilize our simulations as described in Section 3 to characterize the systematic effects of using photometric redshifts to measure \( \Delta w \). Within the SNANA framework, we measure cosmological parameters using both the spectroscopic redshift and the redMaGiC host-galaxy photo-\( z \) as described in Section 5.2.

With the resulting light-curves, we perform the analysis detailed in Section 4.2 and obtain \( \mu \) for each event. The true distance in each biascor is computed from the measured redshift, either the spectroscopic redshift or the redMaGiC host-galaxy photo-\( z \). While the dispersion of the Hubble residuals will be larger as a result of using 1D (redshift) bias corrections instead of 5D (\( z, x_1, c, \alpha, \beta \)), we clarify that there are no additional biases introduced, because our simulations accurately model the data for each redshift case and therefore produce the appropriate bias correction. We study the impact of using incorrect bias corrections due to potential mismodeling of redshift bias and scatter in Section 4.2.2. The bias corrections for the anchoring low-redshift sample are computed separately. Although we simulate the DES sample with \( \beta = 2.0 \), for this study in the BBC step we fix \( \beta = 3.1 \) as described in Section 2.3 due to the inclusion of the low-\( z \) anchor. We again clarify that any biases introduced due to the use of samples with different \( \beta \) will be the same when using spectroscopic and photometric redshifts and therefore will not contribute to the \( \Delta w \) values reported here.

4.2.1. Redshift Contribution to Distance Modulus Uncertainty

To estimate the contribution to the distance modulus uncertainty from the photometric redshift uncertainty,
we examine the difference in Hubble residual scatter between spec-zs and photo-zs using simulations. To avoid statistical limitations from the redMaGiC sample size, we enlarge the host galaxy library by applying the same photo-z bias as described in Section 3.2 to the V21 host-galaxy library without the redMaGiC-like galaxy cuts. As a crosscheck, we also simulate a second set of photo-zs using a simple RMS map where the host-galaxy photo-z scatter is described as a function of redshift (as seen in Figure 2). We find that for the DES redshift range in both sets of simulations the distance modulus uncertainty contribution from the use of photo-zs is ~ 0.06 mag, which is small compared to the RMS from the distance measurement uncertainty (using the spec-z) of ~ 0.18 mag or higher. For this work, we therefore neglect this contribution to the uncertainty in µ and note future methods for treating redshift uncertainties in Section 4.

4.2.2. Hubble Diagrams and Cosmological Parameters

Using the spectroscopic and photometric host-galaxy redshifts, we analyze the simulated data to produce Hubble diagrams with ~ 120 simulated SNe, shown in Figure 5. The redshift scatter for spectroscopic redshift is by definition 0.00. We obtain a scatter of 0.009 for the redMaGiC photo-z and compute the Hubble scatter (i.e., the scatter of the Hubble residuals) using a robust measure of the standard deviation, defined as 1.48 × MAD. The Hubble scatter for the spec-z case is 0.193 mag, while for the redMaGiC photo-z, the Hubble scatter is 0.201 mag. As expected, both redshift and Hubble scatter are larger for redMaGiC photo-z than spec-z (summarized in Table 5).

In Table 7, we show ∆w, the difference in w between using the spectroscopic redshift and the photo-z method. This difference is averaged over 150 statistically independent simulations to obtain an average ∆w. We find

$$\Delta w = -0.0011 \pm 0.0020$$

with standard deviation 0.0249.

Next, we examine systematic variations in which the simulated photo-z bias or scatter does not match the data. To improve our w-bias estimate from systematics, we first evaluate the effect of an exaggerated shift and then assume a linear scale for a more realistic shift. For the photo-z scatter systematic test, a biascor is generated with an analytic description of the host photo-z, where $z_{\text{ph}} - z_{\text{spec}}$ is drawn from a Gaussian of width $\sigma = 0.03(1+z)$. We measure $\frac{d(\Delta w)}{d(\Delta z/\text{scatter})} = 0.0107 \pm 0.003$ and estimate a realistic systematic of 0.0054 given scatter of 0.015. For the photo-z bias systematic test as mentioned in Section 2, we measure the change in w with respect to change in bias. A biascor is generated with the host photo-z containing an additional bias of 0.006 z. Applying the bias correction on the data, we measure $\frac{d(\Delta w)}{d(\Delta z)} = 0.0171$, and therefore a potential systematic bias of 0.0171.

Without utilizing the actual spectroscopic redshifts of our sample of 227 SNe to ascertain a potential systematic bias, we also consider a realistic test of potential calibration shifts of the photometric redshifts as used in current large-scale structure cosmological analyses. We generate a biascor with z-dependent bias as determined in the 2-parameter fit calibration of the redMaGiC galaxy sample using clustering redshifts, or ‘cross-correlation redshifts,’ as used for DES weak lensing and galaxy clustering studies. Cawthon et al. (2020) present the best fit shift and stretch parameters that are applied to the redMaGiC photometric redshift distributions to better match the redshifts determined via angular cross-correlation of the redMaGiC sample with spectroscopic galaxy samples. We parameterize this shift (given as $\Delta z$ in Cawthon et al. 2020 Table 7) as a function of redshift using cubic spline interpolation and add it to the photo-z biascor simulated as described in Section 3.2. We find $\Delta w = -0.0050 \pm 0.0024$ with standard deviation 0.0294. These $\Delta w$ values are also shown in Table 7. While each of these biascor tests results in larger $\Delta w$, they remain consistent within the standard deviations. This indicates that the use of redMaGiC photo-z is robust to potential mismodeling in our biascor simulations.

We also test the impact of having removed the $\sigma_z$ term from Equation 3 as described in Section 2.3 and Appendix A1. We find $\Delta w = 0.0098 \pm 0.0029$ with standard deviation 0.0361. The mean value of $\Delta w$ is not strongly impacted, but the uncertainties are increased as expected due to the overestimated redshift error when $\sigma_z$ is included.

### 4.3. Results from Data

The same methods used on simulations are applied to our data. For bias corrections, we generate biascor simulations as described in Section 3. Notably, the measured Hubble scatter when using the null redshift range is larger than predicted from the simulations (0.271 mag vs. 0.192 mag). This discrepancy is due to scatter at $z > 0.8$, which is 0.451 mag for data and 0.238 mag for simulations. This indicates that are not adequately modeling the SN light-curves at higher redshifts. Therefore, we limit the redshift range of our data and simulation samples to $z < 0.8$, the upper limit of the redshift range for the DES-3YR spectroscopic sample. We obtain the Hubble diagrams shown in Figure 6 and the $\Delta w$ for data shown in Table 7. For redMaGiC photo-z, we obtain red-

| Methods | Redshift Scatter | Hubble Scatter | Redshift Scatter | Hubble Scatter |
|---------|----------------|---------------|----------------|---------------|
| spec-z  | 0.0000 | 0.193 mag | 0.0000 | 0.196 mag |
| redMaGiC photo-z | 0.009 | 0.201 mag | 0.014 | 0.193 mag |

**Table 5** Redshift and Hubble Scatter for simulations and data

| Methods | $\alpha$ | $\beta$ | $\sigma_{\text{int}}$ | $\alpha$ | $\beta$ | $\sigma_{\text{int}}$ |
|---------|---------|---------|-----------------|---------|---------|-----------------|
| spec-z  | 0.14    | 3.1     | 0.106           | 0.14    | 3.1     | 0.138           |
| redMaGiC photo-z | 0.14 | 3.1 | 0.111 | 0.14 | 3.1 | 0.145 |

**Table 6** BBC nuisance parameters for simulations and data. $\alpha$ and $\beta$ are fixed, while $\sigma_{\text{int}}$ is floated.
shift scatter of 0.014 and Hubble scatter of 0.193 mag. These figures are summarized in Table 5. We measure intrinsic scatter \( \sigma_{\text{int}} = 0.138 \) for the data in comparison to 0.106 for our simulations. Similarly, we measure \( \sigma_{\text{int}} = 0.145 \) in comparison to 0.111 for the photo-z case. These floated BBC parameters, along with the fixed values for \( \alpha \) and \( \beta \) are provided in Table 6.

When using redMaGiC photo-z, we obtain

\[
\Delta w = 0.0049
\]  

compared to the spectroscopic case. This result is consistent with our expectations from simulations (\(-0.0011 \pm 0.0020\) with standard deviation 0.0249) and is significantly smaller than the data \( w \) uncertainty using spec-z (0.0432), indicating that systematic uncertainties from using redMaGiC photo-z are subdominant to our overall \( w \) uncertainty. In summary, and as expected from simulations, replacing spectroscopic redshifts with photometric redshifts has a negligible impact on the width of the cosmological posteriors. Moreover, the systematic

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**TABLE 7**

| Methods                      | \( \Delta w \) | \( \Delta w \) Error | \( \Delta w \) STD | \( \Delta w \) | \( w \) Uncertainty |
|------------------------------|----------------|-----------------------|---------------------|----------------|---------------------|
| spec-z                       | 0.00           | 0.00                  | 0.00                | 0.00           | 0.0432              |
| redMaGiC photo-z             | -0.0011        | 0.0020                | 0.0249              | 0.0049         | 0.0458              |
| RM photo-z with additional z-dependent bias biascor | -0.0050        | 0.0024                | 0.0294              | -0.0146        | 0.0641              |

**Fig. 5.**—Hubble diagram from analyzing simulation for: spec-z from host galaxy (left), redMaGiC photo-z from the host galaxy (right). The number of high-z SNe is shown on each panel, as well as the redshift scatter \( \sigma_{\Delta z/(1+z)} \) and Hubble scatter.

**Fig. 6.**—Hubble diagrams for redshift methods as described in Figure 5, but with data. The number of high-z SNe, as well as the redshift scatter \( \sigma_{\Delta z/(1+z)} \) and Hubble scatter are given for each redshift method.
shift in the posterior is negligible compared to the width of the posterior.

5. DISCUSSION

There are three advantages to a redMaGiC-only SN analysis: i) lower probability of of having non-Ia SNe, ii) ability to use host-galaxy photo-z, and iii) robustness to SN host-galaxy correlations. The first two of these have been covered extensively in this paper, so we here address the third. We note that of our redMaGiC SN subsample, only 1 out of 125 SNe has logMass < 10. In Figure [7] we show the logMass distributions for the full DES-5YR photometric sample and for the redMaGiC SN subsample (Smith et al. 2020; Wiseman et al. 2020). About 90% of our redMaGiC sample has 10.5 < logMass < 11.9, a much narrower range compared to the full DES5YR photometric sample that spans 8 < logMass < 12. Due to the range of host-galaxy masses for the redMaGiC subsample, it is impossible to measure the mass step, which is defined as the difference in intrinsic luminosity (after correction) between high mass galaxies (logMass > 10) and low mass galaxies (Smith et al. 2020). We expect that cosmological analyses using this subset of SNe Ia will be more robust to host-galaxy stellar mass dependencies, where we use stellar mass as a proxy for other host-galaxy properties. Future studies may also find it worthwhile to consider the homogeneity of other host-galaxy properties such as star formation rate or metallicity.

When β is floated in the BBC fit, we find β = 2.068 ± 0.210 for the redMaGiC sample, which is significantly smaller than β = 3.178 ± 0.139 for the DES-5YR spectroscopic sample (where β or R_B = R_v + 1). Interestingly, Meldorf et al. (in prep) find that the R_v distribution for redMaGiC galaxies is at the lower end of R_v range for the DES host-galaxy distribution (R_v = 1.54 ± 0.02), whereas for the full distribution it is R_v = 2.61 ± 0.07. This finding supports the prediction from Brout & Scolnic (2021) that the Hubble scatter vs. color relation can be explained by differing dust properties from different host-galaxy populations, as it shows a direct link between the low β found for a particular subset of galaxies and a low R_v predicted for this same set. Sullivan et al. (2010) found that SNe with low-sSFR host galaxies have lower β than SNe with high-sSFR hosts, and consistently, Kelsey et al. (2021) found lower β in high mass/redder rest-frame U-R galaxies than in low mass/bluer U-R galaxies. This finding indicates that our redMaGiC subsample of SNe is less sensitive to color.

5.1. Future Prospects

As described in Kessler et al. (2010), it is possible to use the SALT2 framework to fit a photometric redshift from the light-curve simultaneously with z_1, c, m_B, l_0. To improve photo-z precision and reduce outliers, the host-galaxy photo-z can be used as a prior for this SN light-curve fit. This 5-parameter fit is the technically correct method to account for redshift uncertainties so that they can be propagated to other SALT2 fitted parameters and covariances. However, our attempts to implement these methods presented problems at high-redshift, because only two passbands (i and z) are within the SALT2 model range, which poorly constrains the SN color and redshift. In addition, the SALT2 model requires interpolations that result in occasional discontinuities in the model derivatives with respect to redshift, which can lead to pathological behavior in MINUIT. Further investigation and resolution of these issues is beyond the scope of this paper, but should be considered for future work in photometric SN cosmology. An alternative method is to measure the redshift contribution to the distance modulus uncertainty empirically, as detailed in Section 4.2.1. A further area of follow-up that will be required is improved modeling and better understanding of the Hubble scatter discrepancy between data and simulations at high redshifts (z > 0.8) as explained in Section 4.3.

SN Ia cosmology with next generation surveys in the era of LSST and Roman will require methods such as the one presented here to make full use of the photometric data without the constraints imposed by the limits of spectroscopy. To make a simple forecast for LSST, we follow the simulations from the TIDES Collaboration (Swann et al. 2019; Frohmaier et al. in prep) using the Baseline 1.7 OpSim run. We assume that 6% of the LSST SNe Ia discovered are in LRGs and that the redMaGiC photo-z resolution is σ_z = 0.02. In total, there are ~2.4 million SNe Ia with two points of SNR > 5 that pass light-curve quality cuts, of which 6% is 144 thousand SNe. Assuming a low-z sample of 2400 SNe to anchor the Hubble Diagram (LSST-DESC Science Requirements Document; The LSST Dark Energy Science Collaboration et al. 2018) and a prior on Ω_M of 0.311 ± 0.01, we recover an uncertainty on w of 0.014. This is 2x smaller than the statistical constraint from the current sample of Pantheon SNe (Scolnic et al. 2018). Mitra & Linder (2021) provide a quantitative requirement on photo-z systematics for LSST and Roman and conclude that the redshift systematic from LSST color matched nearest neighbors (CMNN) photo-z estimates must be reduced by an order of magnitude for unbiased SNIa cosmology. However, they do not propagate photo-z biases through the light-curve fits, resulting in more stringent redshift requirements, as they do not account
for the redshift-color correction noted in Appendix A1. Further studies and deeper understanding of the systematic uncertainties associated with photometric redshifts will be required to fully utilize the statistical power of such datasets. Appropriate treatment of photometric redshifts will require the inclusion of redshift in bias corrections (5D or 7D), rather than the 1D corrections used in this study. An alternative method is also presented in the zBEAMS hierarchical Bayesian formalism by Roberts et al. (2017). A Bayesian approach may improve the treatment of redshift errors and properly account for the redshift-color self-correction in data discussed in Appendix A1.

With increasing numbers of SN observations, it will be possible to use a low redshift sample that also contains only SNe in LRGs, providing us with a full sample of SNe Ia exclusively in red galaxies. However, the impacts of systematic redshift errors are much stronger at low redshift (Wojtak et al. 2015; Davis et al. 2019), and the color-redshift relation that reduces the impact of biases in the DES redshift range may not be sufficient for unbiased use of photometric redshifts at low-z. Further studies will also be required to determine the effects of redshift biases on constraining a time-varying equation-of-state. In the nearer future, with the Year 6 (Y6) analysis from DES and redMaGiC run on the deep fields, the number of SNe found to be hosted in red galaxies will increase. It may also be possible to investigate alternative methods of selecting LRGs in order to create a larger host-galaxy sample. Another extension that will require further investigation would be whether other galaxy types besides LRGs can be similarly used to restrict the host-galaxy type and reduce the photometric redshift bias. Lastly, it may be possible to include information about the distribution of redshifts beyond individual redshifts as is standard practice in other cosmology analyses such as the 3×2 pt probes. The application of information traditionally used for other cosmology probes, such as the redMaGiC catalogs, to SNIa cosmology is a largely unexplored area with tremendous potential.

6. CONCLUSION

Using the DES-5YR photometric sample, we present a first proof-of-concept that SNe Ia in redMaGiC hosts are a promising new avenue for SN cosmology. We show that restricting SNe to those with redMaGiC host galaxies serves as a useful cross-check for photometric classification, as they preferentially host only Type Ia SNe: ~3% of redMaGiC SNe are photometrically classified as non-Ia, compared to 8% of a simulated DES-5YR photometric SN sample with no classifier.

We further present our cosmological parameter results and biases from using redMaGiC host-galaxy photo-z. Using redMaGiC photo-z results in biases in $w$ of ~0.01 when run on data, which is consistent with expectations from simulations. The Hubble scatter from data is 0.193 mag for redMaGiC photo-z, which is consistent with 0.201 mag obtained from simulations. Our findings indicate that redMaGiC photo-z can be used in a relatively unbiased manner with respect to spectroscopic redshifts. Lastly, we describe related extensions and potential future work using other sources of host-galaxy redshift information. This work lays the essential groundwork for future development of the use of photometric redshifts for SNIa cosmology in time-domain surveys, particularly for LSST and surveys with the Roman Space Telescope.

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APPENDIX

A1. Redshift Uncertainties and Redshift Color Dependencies

The formalism for uncertainty in $\mu$ is typically described as given in Kessler et al. (2009a). However, in using host-galaxy photo-z for this study, when naively including a $\sigma^2_z$ term in Equation 3, we find that the predicted uncertainty is overestimated compared to the true measured RMS for $\mu$ residuals. We show the cause of this overestimated uncertainty in Figure 8. When using the photo-z, the dominant effect on the recovered distance is due to a change in recovered color (following Equation 1). While $m_B$ and $z_1$ are uncorrelated with redshift bias, the top right of Figure 8 shows that for simulations, the color parameter and redshift bias are correlated. As shown on the bottom part of Figure 8, we find that the change in distance modulus $\mu$ calculated from the fiducial $\Lambda$CDM model is roughly equal to the difference in color $c$ multiplied by $\beta$, denoted as $\beta \times \delta c$. The left two plots in Figure 8 are made using the DES-5YR data, while the right two are made using our simulations. In practice, we can see on the Hubble Diagram that mis-estimated redshifts correspond to a one-to-one self correction in $\mu$ along the $\Lambda$CDM curve. This trend is also observed in the data, with a redshift bias corresponding to a corrective bias in $\mu$.

We find that including the $\sigma^2_z$ term is in general incorrect, as $\mu$ and $z$ are strongly correlated via the SALT2 color
term. This change has a negligible effect on previous analyses performed with spectroscopic redshifts, as the redshift uncertainty for spec-z is very close to zero. When the photometric redshift is misestimated, the light-curve fit returns a shifted color to compensate, which reduces the resulting scatter in the Hubble Diagram.

We note that for peculiar velocities ($v_{pec}$), the measured distance and redshift are independent, and therefore including the $\sigma_{spec}$ term as has previously been done is appropriate. While this correction empirically works for the DES redshift range, we also note it does not necessarily apply to low-z SNe, which deviate further from a one-to-one correction. We further note that the relation may not be strictly linear; as the magnitude of the $z_{redmagic} - z_{spec}$ bias increases past 0.05 or more, the deviation from a strict one-to-one relation does as well.

### A2. Parent Population Parameters

Here we present the parent population parameters for both the redMaGiC subset SNe and the full DES-3YR spectroscopic sample as a function of mass and parametrized as described in Popovic et al. (2021). A summary of the average population parameters (described by a mean, left-sided $\sigma_-$ and right-sided $\sigma_+$) is given in Table 2.

#### TABLE 9

| Parent Populations for DES-3YR Spectroscopic Sample |
|---|---|---|---|
| logMass | $c$ | $x_1$ |
|---|---|---|
| 10.2 | -0.084 ± 0.053 | 0.044 ± 0.038 | 0.194 ± 0.075 |
| 10.4 | -0.033 ± 0.03 | 0.041 ± 0.02 | 0.03 ± 0.024 |
| 10.6 | -0.078 ± 0.026 | 0.024 ± 0.018 | 0.157 ± 0.064 |
| 10.8 | -0.07 ± 0.018 | 0.016 ± 0.012 | 0.134 ± 0.026 |
| 11.0 | -0.067 ± 0.018 | 0.015 ± 0.012 | 0.13 ± 0.025 |
| 11.2 | -0.064 ± 0.022 | 0.019 ± 0.015 | 0.134 ± 0.025 |
| 11.4 | -0.051 ± 0.022 | 0.018 ± 0.014 | 0.105 ± 0.023 |
| 11.6 | -0.021 ± 0.004 | 0.029 ± 0.023 | 0.105 ± 0.037 |
| 11.8 | 0.09 ± 0.098 | 0.139 ± 0.071 | 0.19 ± 0.076 |

#### TABLE 8

Parent Populations for redMaGiC SN Sample

| logMass | $c$ | $x_1$ |
|---|---|---|
| 8.8 | -0.087 ± 0.033 | 0.028 ± 0.025 | 0.145 ± 0.043 |
| 9.0 | -0.091 ± 0.025 | 0.021 ± 0.018 | 0.139 ± 0.035 |
| 9.2 | -0.094 ± 0.018 | 0.015 ± 0.013 | 0.137 ± 0.033 |
| 9.4 | -0.1 ± 0.02 | 0.017 ± 0.014 | 0.169 ± 0.035 |
| 9.6 | -0.097 ± 0.025 | 0.022 ± 0.017 | 0.166 ± 0.037 |
| 9.8 | -0.089 ± 0.022 | 0.02 ± 0.015 | 0.158 ± 0.033 |
| 10.0 | -0.09 ± 0.021 | 0.019 ± 0.014 | 0.165 ± 0.037 |
| 10.2 | -0.099 ± 0.021 | 0.019 ± 0.014 | 0.204 ± 0.037 |
| 10.4 | -0.091 ± 0.024 | 0.021 ± 0.016 | 0.179 ± 0.035 |
| 10.6 | -0.075 ± 0.028 | 0.026 ± 0.019 | 0.147 ± 0.033 |
| 10.8 | -0.087 ± 0.016 | 0.012 ± 0.01 | 0.128 ± 0.04 |
| 11.0 | -0.077 ± 0.021 | 0.018 ± 0.014 | 0.133 ± 0.041 |
| 11.2 | -0.062 ± 0.034 | 0.031 ± 0.025 | 0.153 ± 0.049 |

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