Type Ia Supernova Cosmology without Spectroscopic Redshifts

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Preliminary Exam
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Outline

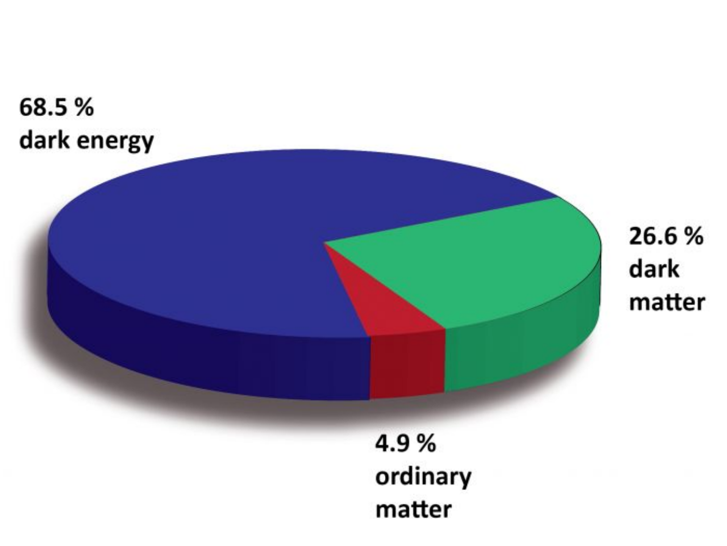
1. Cosmological Context
2. Cosmology with Type Ia Supernovae
3. Modern Challenges
4. redMaGiC SN Cosmology
5. Future Work

1

Cosmological Context

Cosmology is the study of the origins, history, and evolution of our universe

- Flat-ΛCDM is our current best model
- Λ = cosmological constant
- CDM = Cold Dark Matter



NIST

What is Dark Energy?

- **Cause of accelerated expansion of the universe**
- Can characterize as a perfect fluid with equation-of-state w
  - $w = P/\rho$ (Pressure/density)
- If dark energy is a cosmological constant (i.e. Λ), then $w = -1$
- Does $w = -1$?
  - **We are interested in improving our measurements of w** and other cosmological parameters to constrain cosmological models

Type Ia Supernovae (SNe Ia) are one cosmological probe among many others

- Different observational probes are sensitive to different parameters and regions of cosmic time
- **SNe Ia are particularly sensitive to the expansion history of the universe**
- Use a combination of probes to make strong final constraints, but SN analyses have typically been fairly isolated

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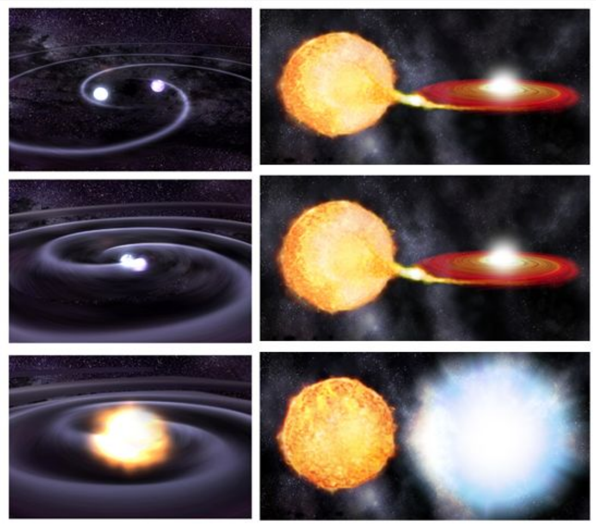
Cosmology with Type Ia Supernovae

To measure expansion history, we need to measure distances to faraway objects

- **Standard candle method**
  - If we know the intrinsic brightness of an object and measure its apparent brightness, we can infer a distance
- Supernovae are very luminous (observable to high redshift)
- **Type Ia Supernovae** are **standardizable candles**

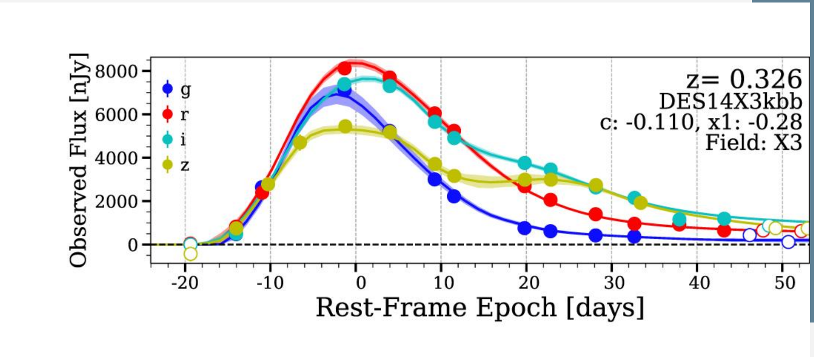
SNIa Explosion Mechanisms

- Single degenerate model
  - Giant accretes mass onto white dwarf until it reaches Chandrasekhar limit, it explodes as a supernova
- Double degenerate model
  - Two orbiting white dwarfs merge and combined mass exceeds the Chandrasekhar limit
- **Explode at consistent mass-> have fairly consistent luminosity**

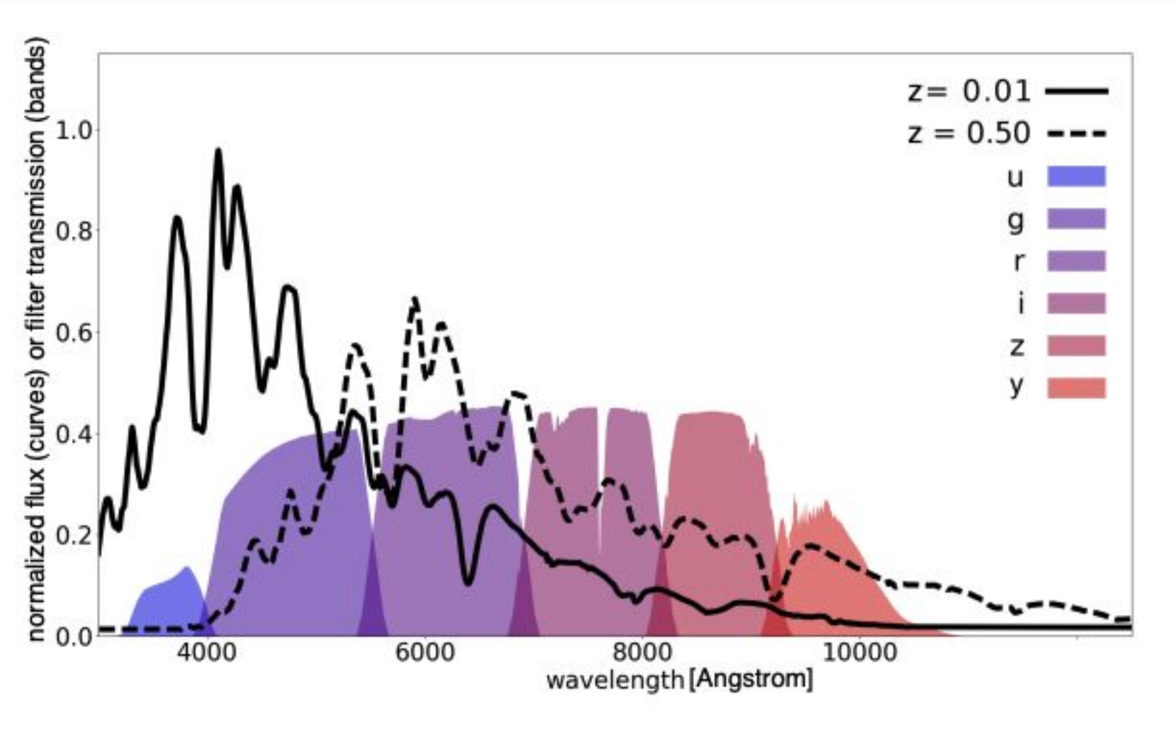


How do we observe supernovae?

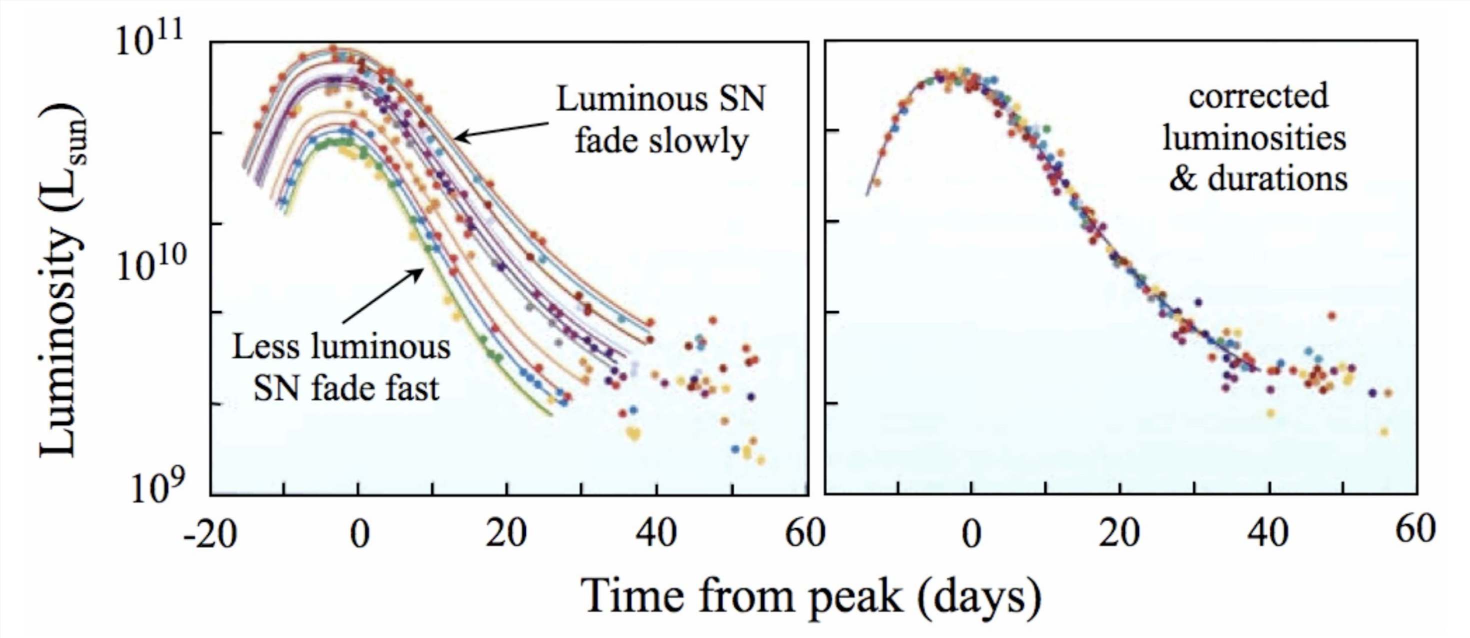
- Detection pipeline using reference images
- SNe reside in a host galaxy
- Observe regions of the sky repeatedly over a period of time
- Different methods for observing astronomical objects
  - Photometry
  - Spectroscopy



Photometry vs. Spectroscopy

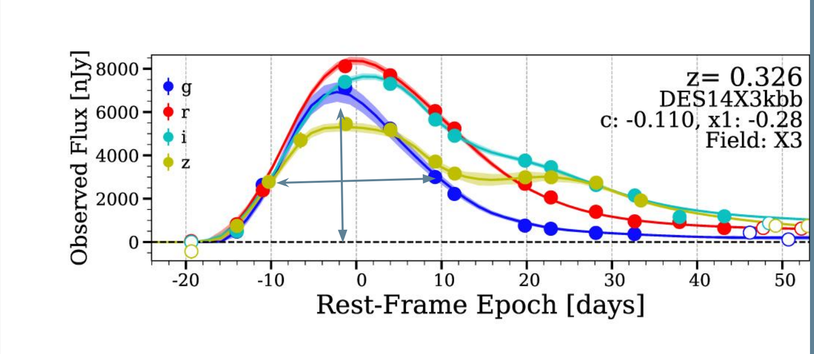


What do we mean by "standardizable"?



Fitting light-curves

- Fit light-curve parameters using e.g. the SALT2 model
- Parametrized by overall flux normalization (x0), "stretch" (x1), and color (c)
- **Stretch** is related to shape
- **Color** is related to difference in luminosity between two filters



We use the Tripp Equation to standardize and estimate the SN distance

- Define the distance modulus $\mu = m - M = 5 \times log(d/10)$

Distance modulus

Related to overall amplitude

stretch

color

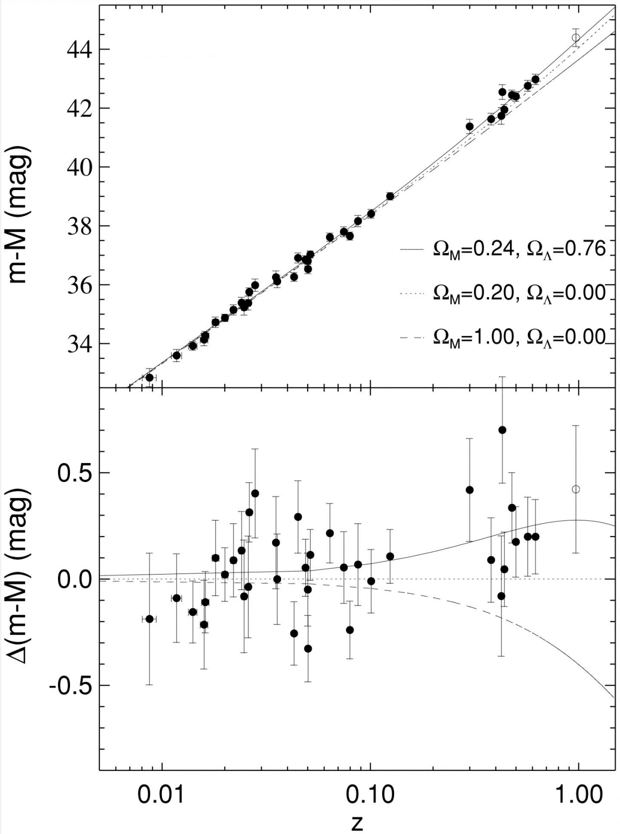
$$\mu = m_B + \alpha x_1 - \beta c - M_B$$

Absolute magnitude of a standard Ia

Nuisance parameters

Hubble Diagram

- Measure **distance-redshift relation** (Hubble Diagram)
- Compare estimated and theoretical distance moduli
- Difference is called Hubble residual (△μ) -> use in χ^2 fit to determine best fit parameters



Riess et al. 1998

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Modern Challenges

3 top challenges for future SNIa surveys

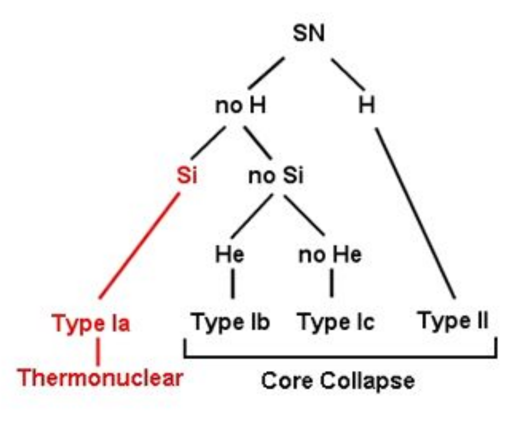
1. Impossible to acquire **redshifts** for all SNe
2. Lack of SN spectroscopy forces us to rely on photometric **SN classification**
3. Accounting for correlations between SN properties and host galaxy properties

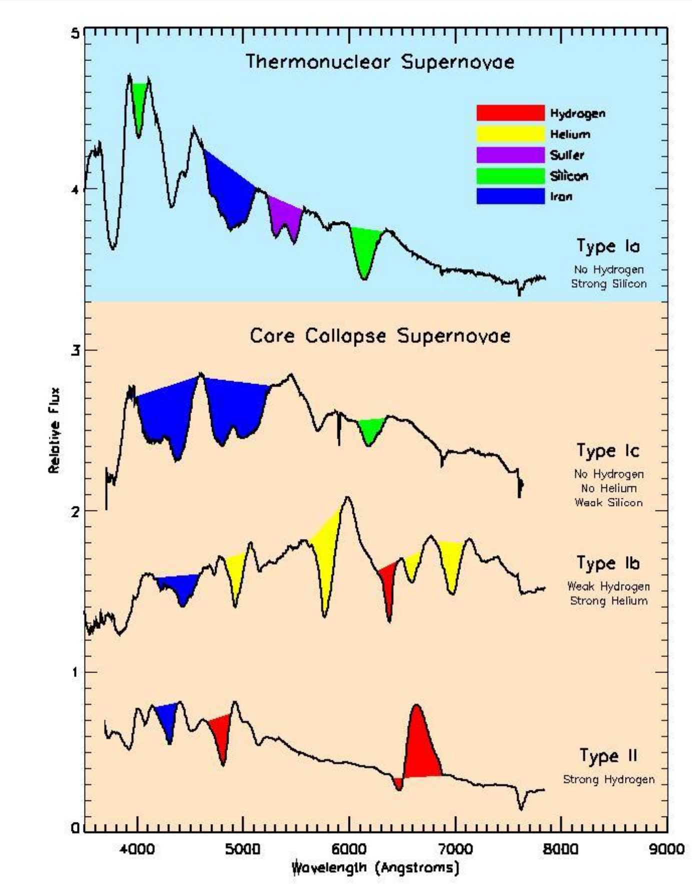
1. Obtaining redshifts for large numbers of SNe

- **Typically rely on spectroscopic redshift** from SN or its host-galaxy using spectroscopic follow-ups to photometric surveys
  - Need to model spectroscopic efficiency
  - Large amounts of dedicated telescope time
- **Resource limited** and time consuming

2. Classifying Supernovae

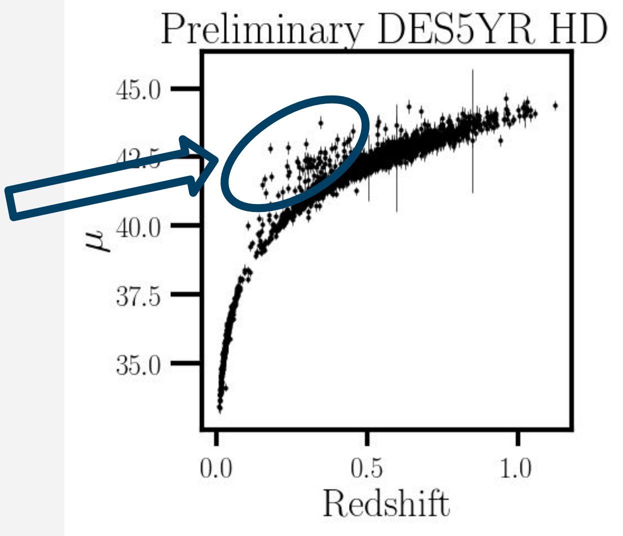
- Easy with spectroscopy, harder with just photometry
  - Type Ia (thermonuclear)
  - Core-collapse (Types Ib, Ic, II)





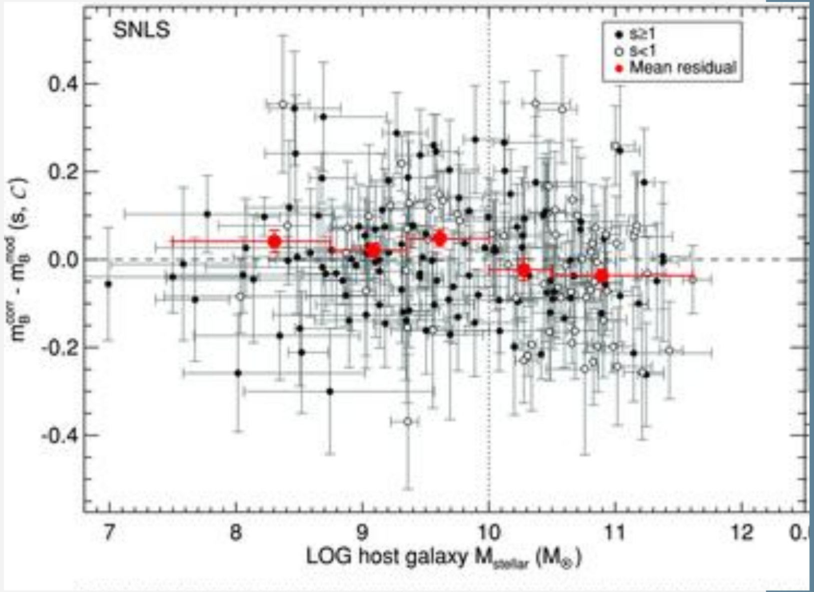
Core-collapse SN contamination

- Core-collapse SNe "contaminate" the Hubble Diagram
- Photometric classification has been a large area of research and effort for SN analyses



3. Host-galaxy/SN property correlations

- Observed correlations between host-galaxy properties and SN standardized brightness
  - E.g. mass step
  - **Incomplete understanding of physical explanation**
- Rely on empirical corrections



Sullivan et al. 2010

Samples used for current SNIa analyses

Classification

Redshifts

	Spectroscopic classification of SN	Photometric classification of SN
Spectroscopic redshift from host galaxy	*Spectroscopic SN Sample*	*Photometric SN Sample*
Spectroscopic redshift from SN		**Not Currently Used**
Photometric redshift from host galaxy	**Not Currently Used**	**Not Currently Used**

My research focus

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redMaGiC SN Cosmology

New method: SN cosmology in red, dead galaxies
Chen et al. (2022)

Idea: Use SNe in redMaGiC galaxy catalog: algorithm selects Luminous Red Galaxies, "red and dead"

Addresses top SN challenges:

1. Redshifts
2. Classification
3. Host galaxy/SN property correlations

1. redMaGiC galaxies have accurate and precise photometric redshifts
2. Expect low rates of core-collapse SNe
3. By restricting analysis to a single type of galaxy, we are less sensitive to unknown host galaxy/SN relations

Measuring Cosmological Parameters with Type Ia Supernovae in redMaGiC galaxies

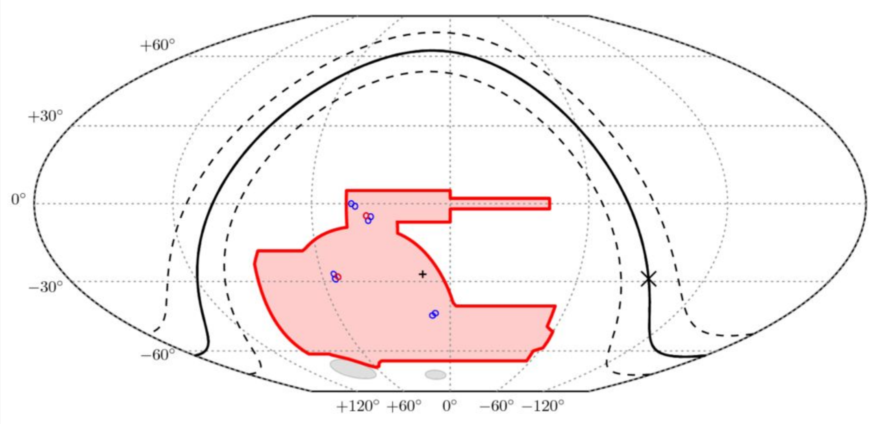
R. Chen, D. Scolnic, E. Rozo, E. S. Rykoff, B. Popovic, R. Kessler, M. Vincenzi, T. M. Davis, P. Armstrong, D. Brout, L. Galbany, L. Kelsey, C. Lidman, A. Möller, B. Rose, M. Sako, M. Sullivan, G. Taylor, P. Wiseman, J. Asorey, A. Carr, C. Conselice, K. Kuehn, G. F. Lewis, E. Macaulay, M. Rodriguez-Monroy, B. E. Tucker, T. M. C. Abbott, M. Aguena, S. Allam, F. Andrade-Oliveira, J. Annis, D. Bacon, E. Bertin, S. Bocquet, D. Brooks, D. L. Burke, A. Carnero Rosell, M. Carrasco Kind, J. Carretero, R. Cawthon, M. Costanzi, L. N. da Costa, M. E. S. Pereira, S. Desai, H. T. Diehl, P. Doel, S. Everett, I. Ferrero, B. Flaugher, D. Friedel, J. Frieman, J. García-Bellido, M. Gatti, E. Gaztanaga, D. Gruen, S. R. Hinton, D. L. Hollowood, K. Honscheid, D. J. James, O. Lahav, M. Lima, M. March, F. Menanteau, R. Miquel, R. Morgan, A. Palmese, F. Paz-Chinchón, A. Pieres, A. A. Plazas Malagón, J. Prat, A. K. Romer, A. Roodman, E. Sanchez, M. Schubnell, S. Serrano, I. Sevilla-Noarbe, M. Smith, M. Soares-Santos, E. Suchyta, G. Tarle, D. Thomas, C. To, D. L. Tucker, T. N. Varga

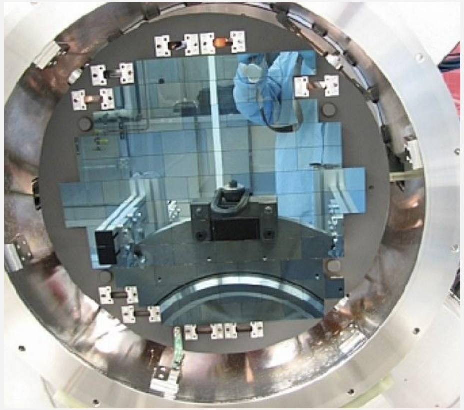
Current and future cosmological analyses with Type Ia Supernovae (SNe Ia) face three critical challenges: i) measuring redshifts from the supernova or its host galaxy; ii) classifying SNe without spectra; and iii) accounting for correlations between the properties of SNe Ia and their host galaxies. We 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 $\sigma_{\Delta z/(1+z)} \sim 0.02$. 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 ~ 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 (β) compared to the DES-3YR population by $\sim 5\sigma$; this finding is consistent with predictions that redMaGiC galaxies exhibit lower reddening ratios ($\mathrm{R_V}$) 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.

Dark Energy Survey

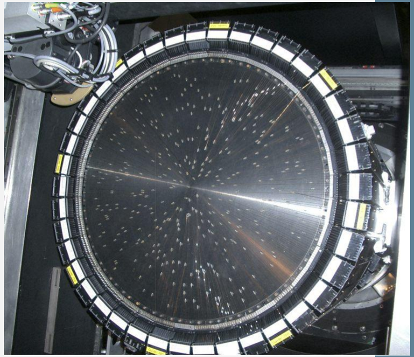
- DES-SN program: 5 seasons, *griz* filters, 10 3 sq-deg fields, cadence of 7 days
- Relied on OzDES for SN and host galaxy spectroscopic follow-up

DES footprint





DECam



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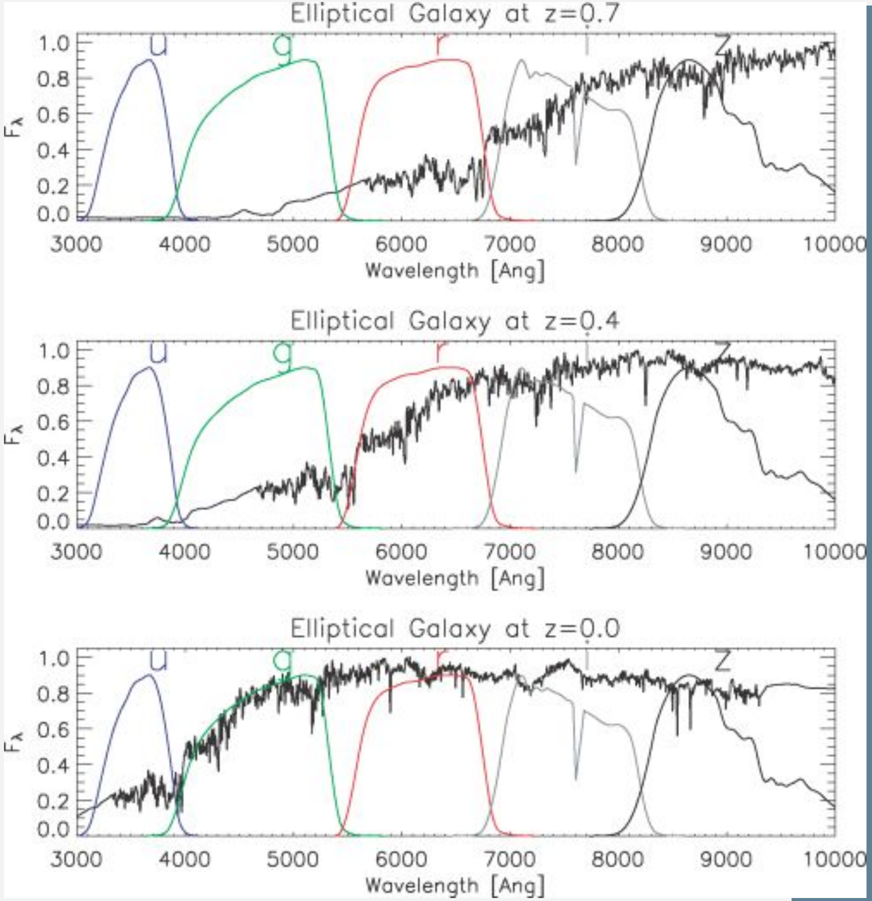
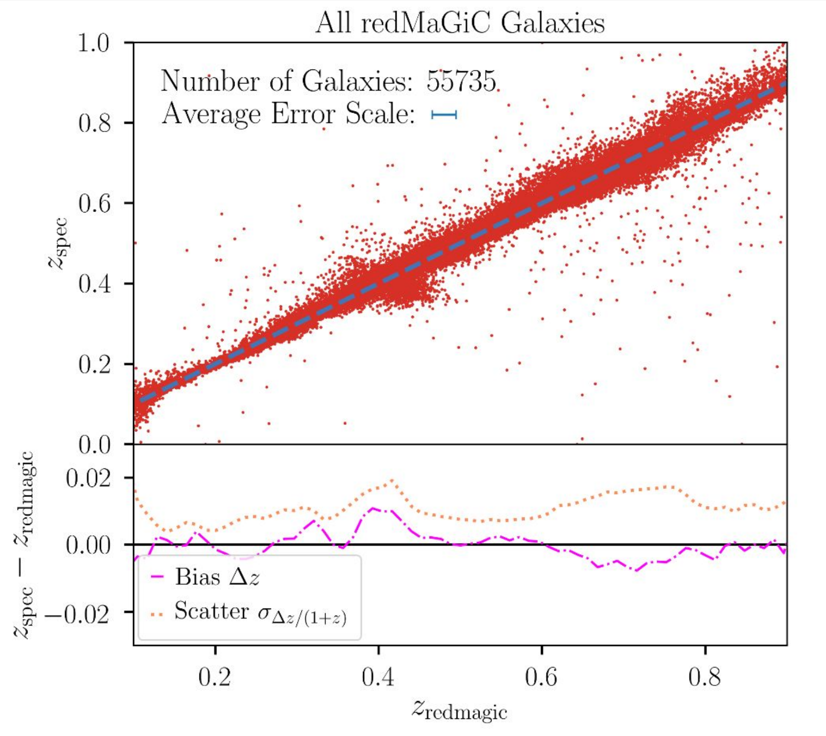
redMaGiC galaxies

- Luminous Red Galaxies (LRGs)-- "red and dead"
  - Prominent 4000 Å break in SED = **good for photo-*z***
- redMaGiC algorithm selects red galaxies, photo-*z* afterburner to reduce biases



redMaGiC photo-*z* are precise to σ_z ~0.015 and selected to have minimal uncertainties



Typical redshift uncertainties:

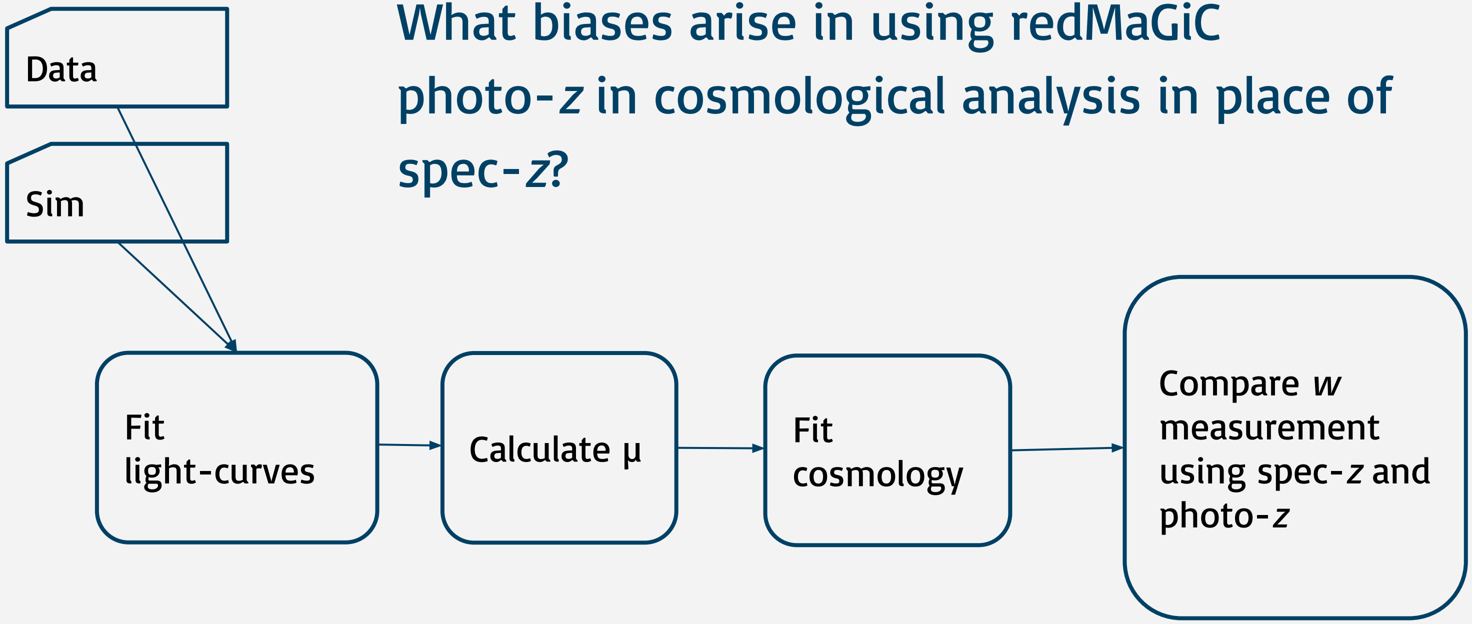
- Host spec-*z* : σ_z ~ 0.00001
- SN spec-*z* : σ_z ~ 0.005-0.01
- Regular photo-*z* : σ_z ~ 0.03-0.04

SNe in redMaGiC galaxies

- DES5YR photometric SN sample
- Check which SN host galaxies have matching coordinates with redMaGiC galaxies (requiring spectroscopic redshift)
- **~6% (125/1600) of DES5YR photometric SN sample are found in redMaGiC galaxies** (after cuts)

Method overview

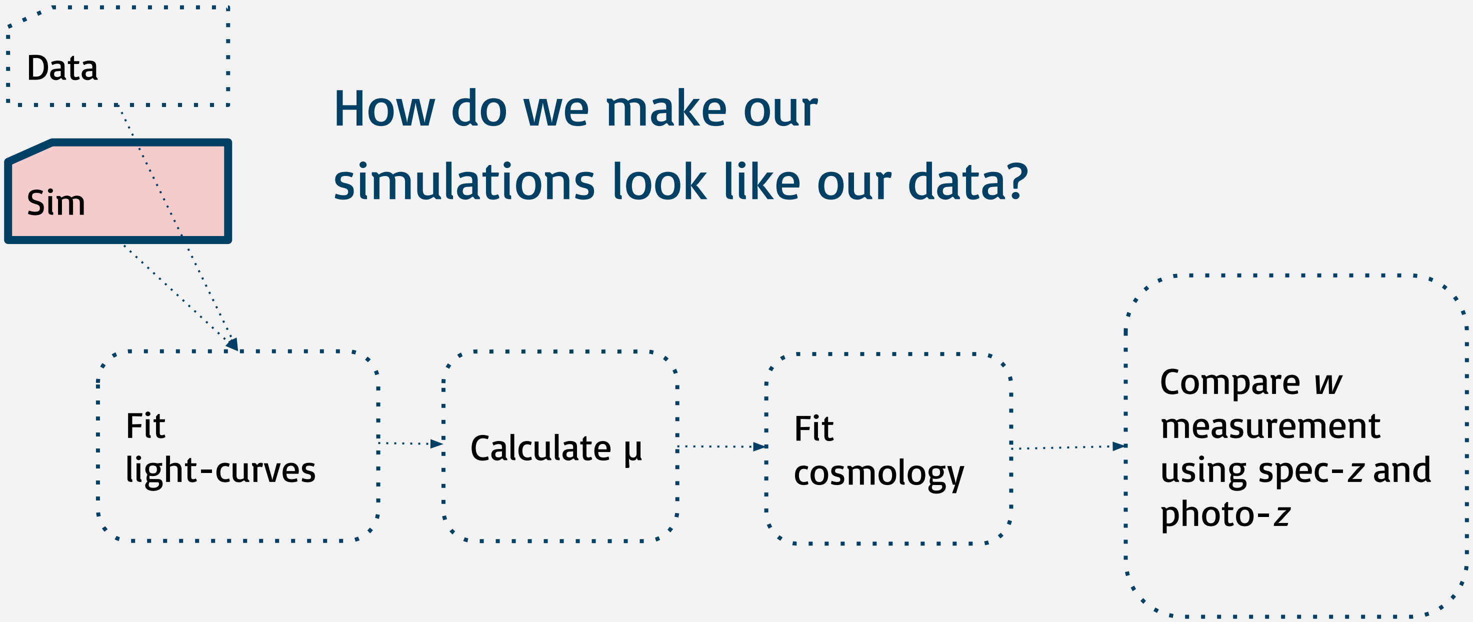
What biases arise in using redMaGiC photo-z in cosmological analysis in place of spec-z?



Using spec-*z* and photo-*z*

Simulations

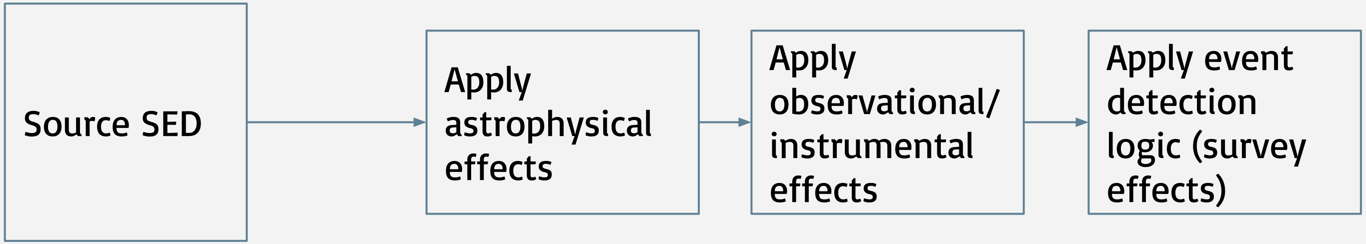
How do we make our simulations look like our data?



Using spec-*z* and photo-*z*

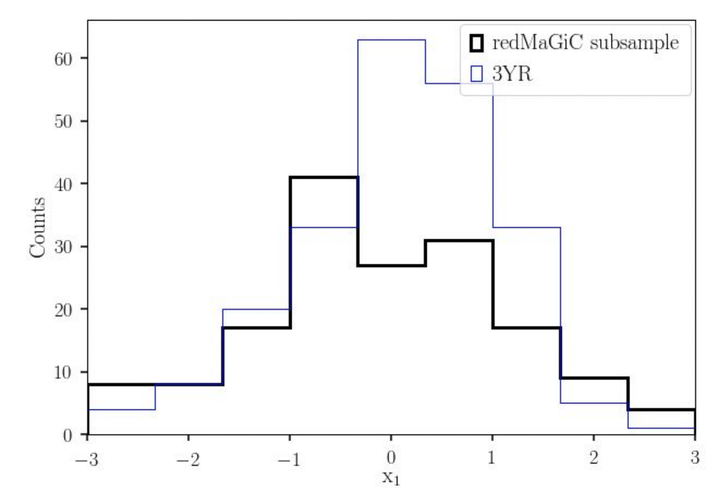
Simulations

- **Forward model SNe Ia** with catalog level simulations using the SNANA (SN analysis) software
- Use simulations to validate our analysis



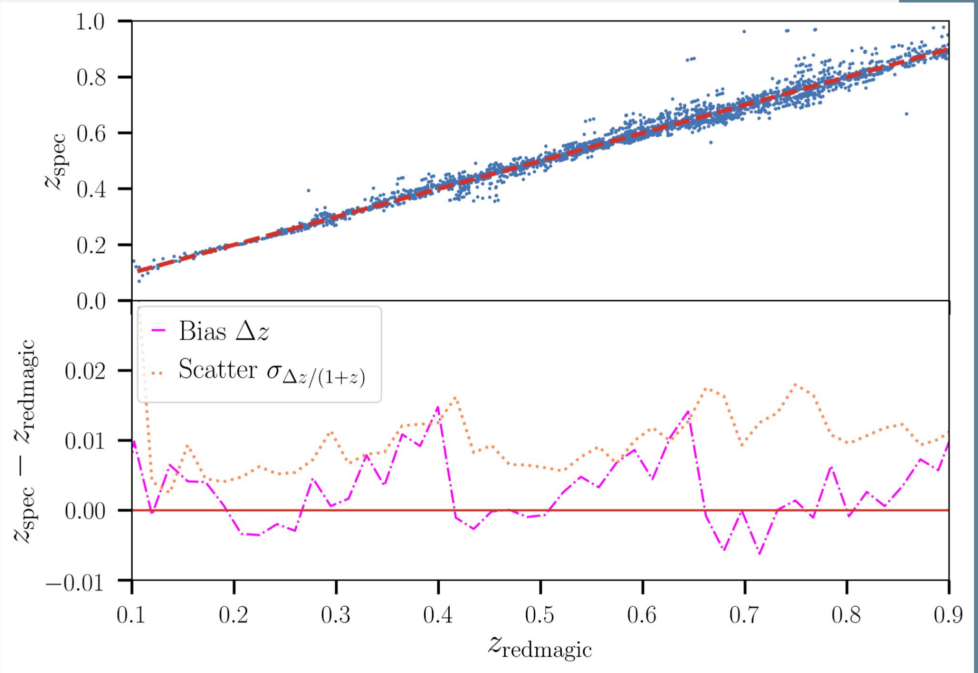
We make modifications to the baseline DES5YR photometric sample simulations

- Baseline simulation inputs to SNANA from Vincenzi et al. 2021a
- Host galaxies are assigned from a realistic host galaxy library
  - **Make cuts to mimic selection of redMaGiC** (bright, red, dead)
- Parent populations (Popovic et al. 2021)
  - Fit underlying stretch and color population parameters
  - Lower mean x1 than DES3YR

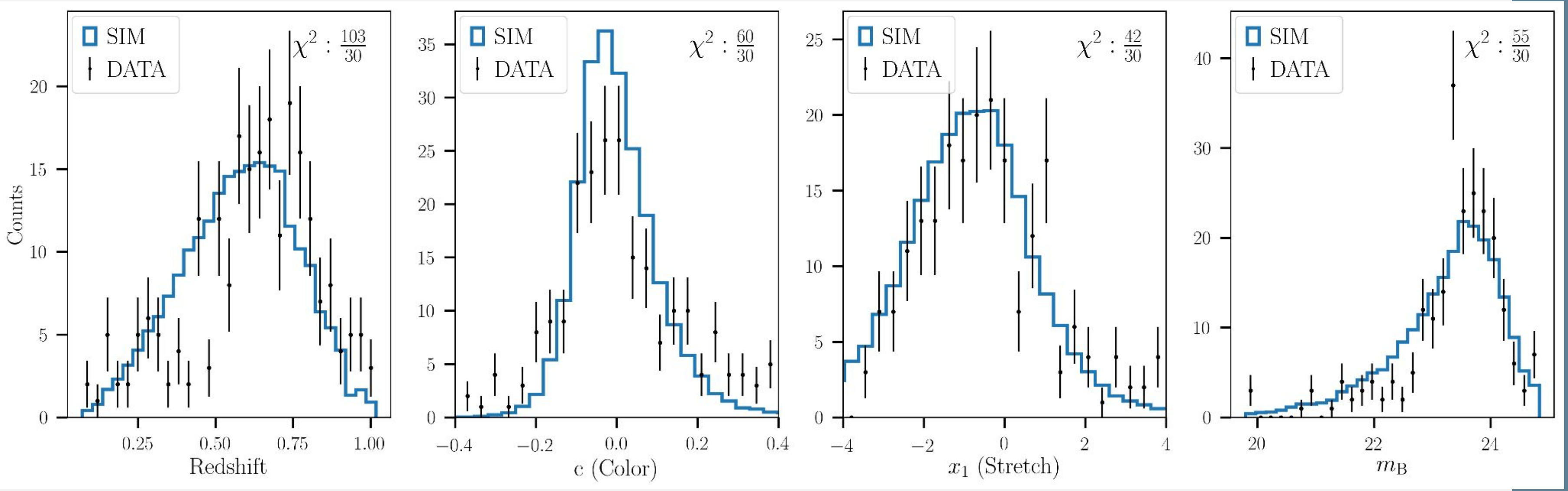


How do we simulate the photo-z?

- Start with **DES5YR library of host galaxies**
- Find closest match in redshift in redMaGiC catalog for each host galaxy
- **Evaluate bias from redMaGiC galaxy** and add to host true redshift = simulated photo-*z*

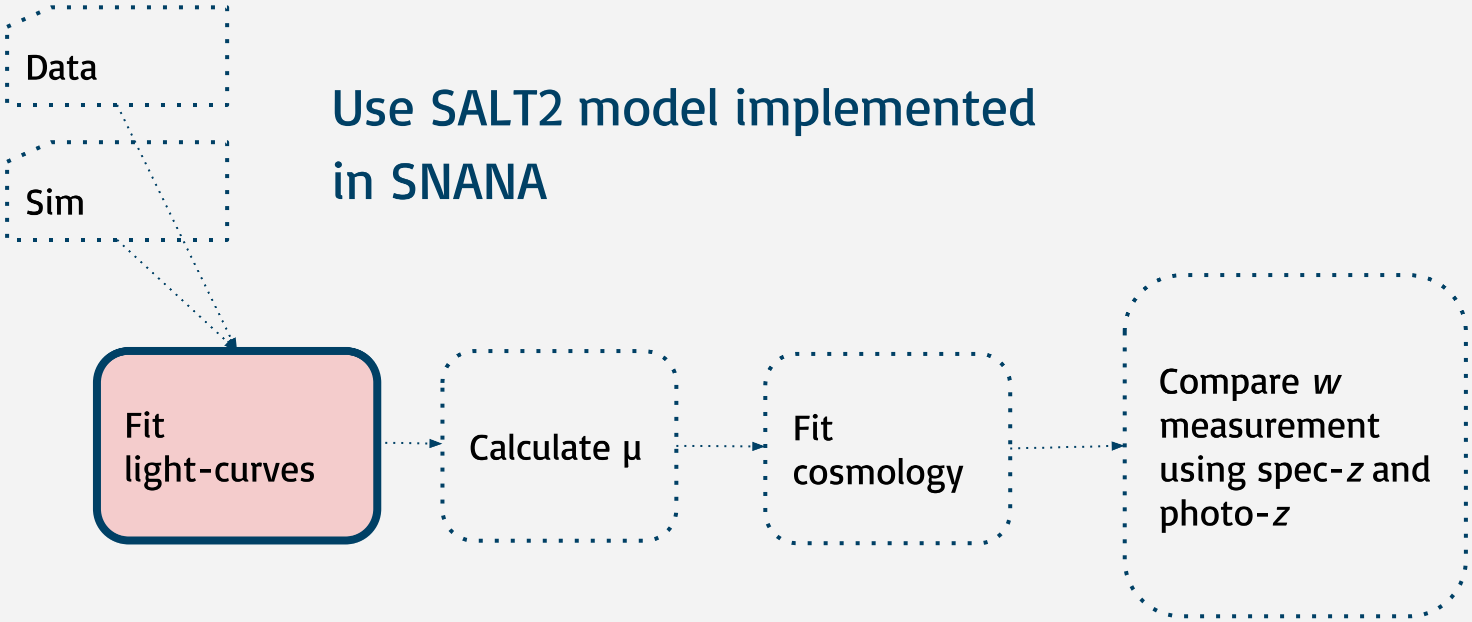


Comparing simulations and data



Light-curve fitting

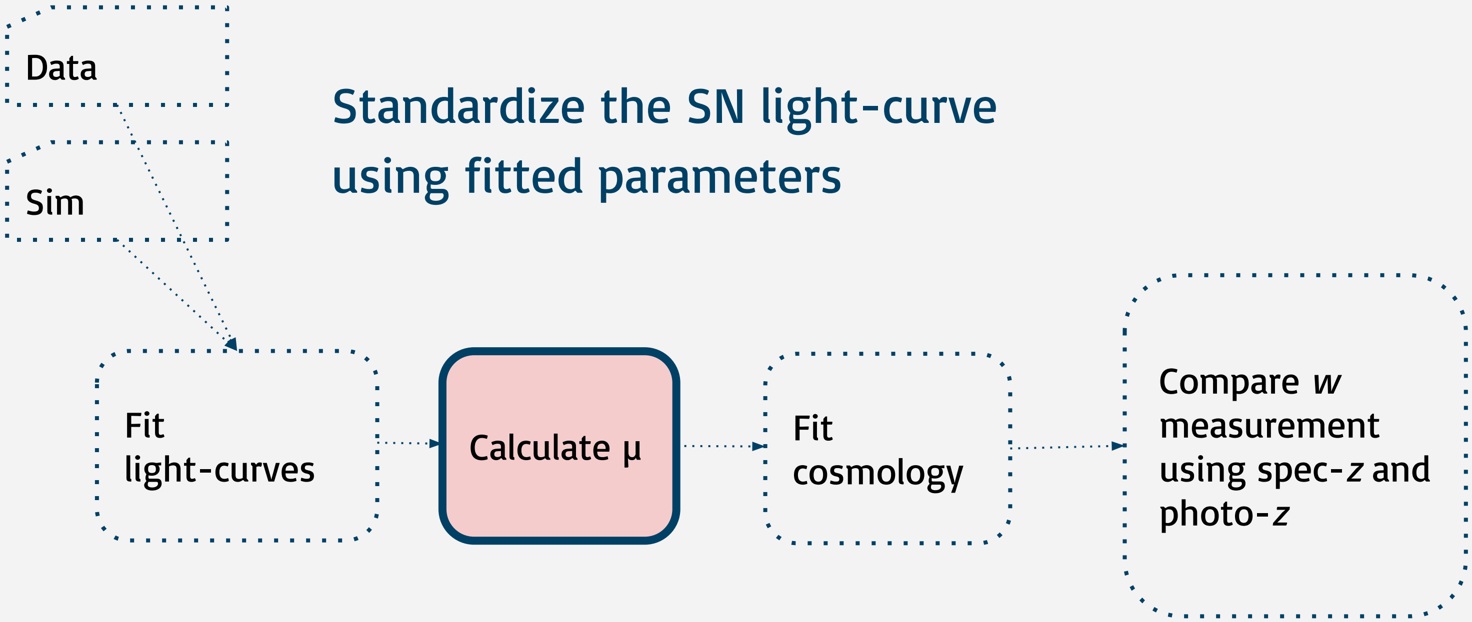
Use SALT2 model implemented in SNANA



Using spec-*z* and photo-*z*

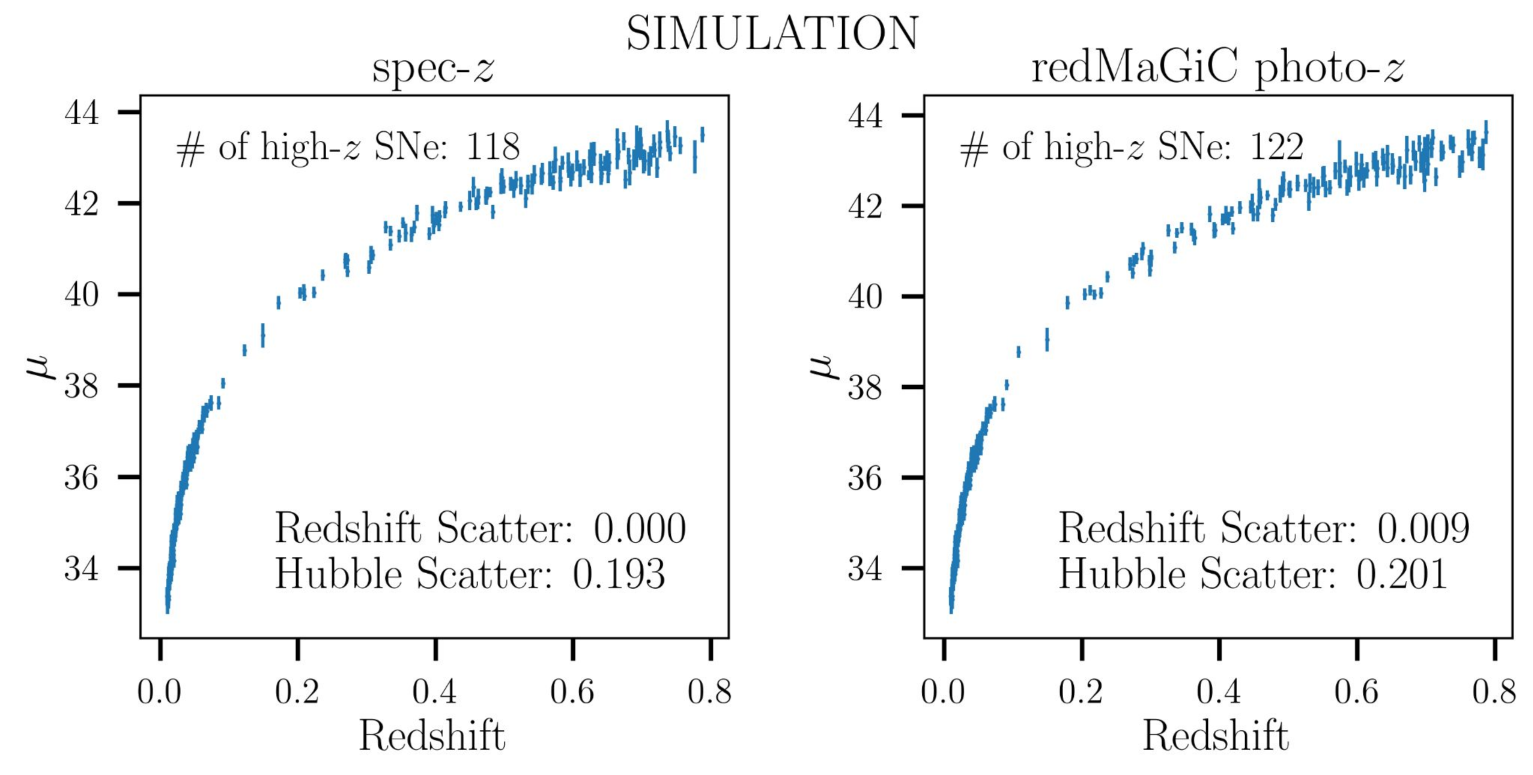
Calculating μ

Standardize the SN light-curve using fitted parameters

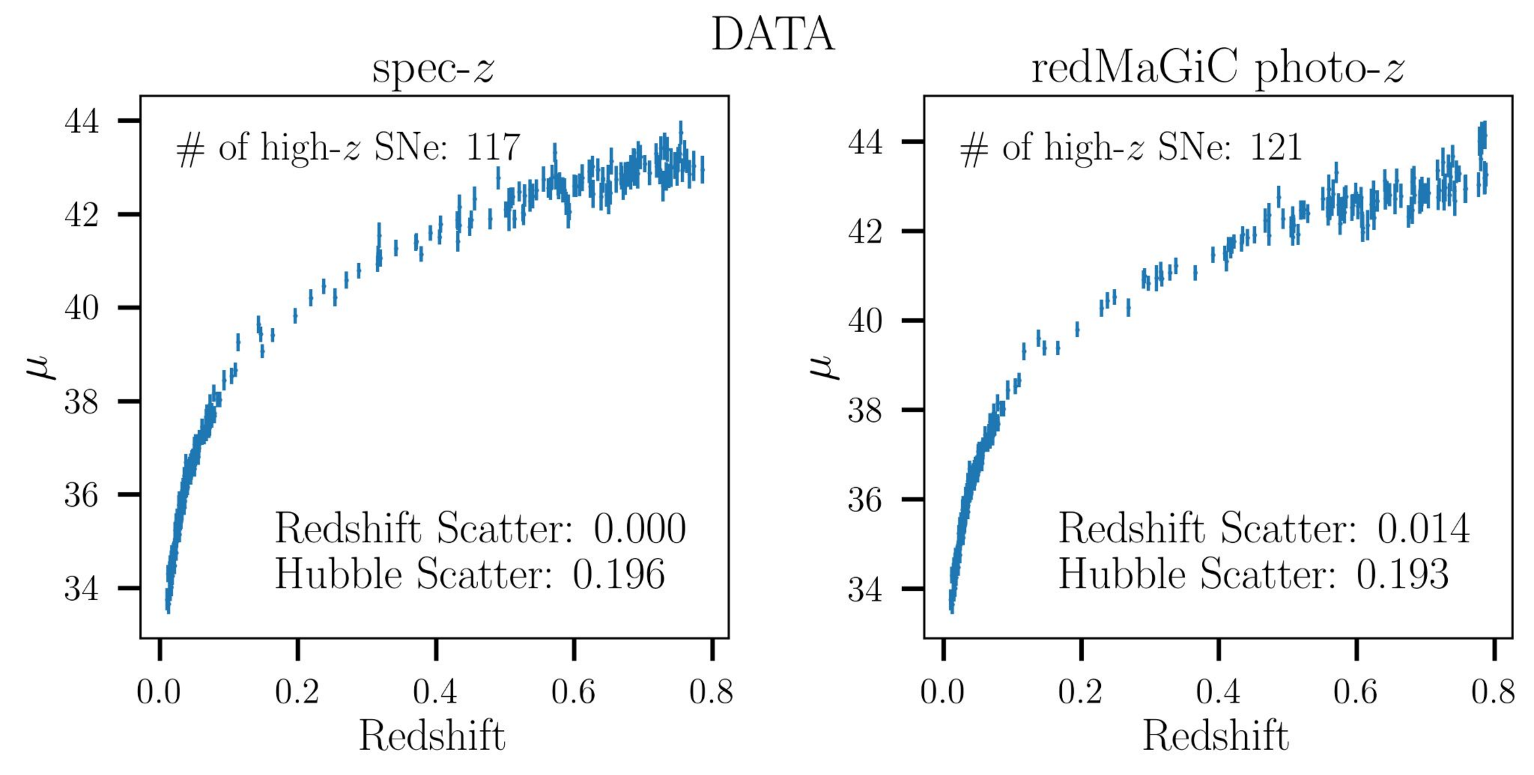


Using spec-*z* and photo-*z*

Simulation Hubble Diagrams

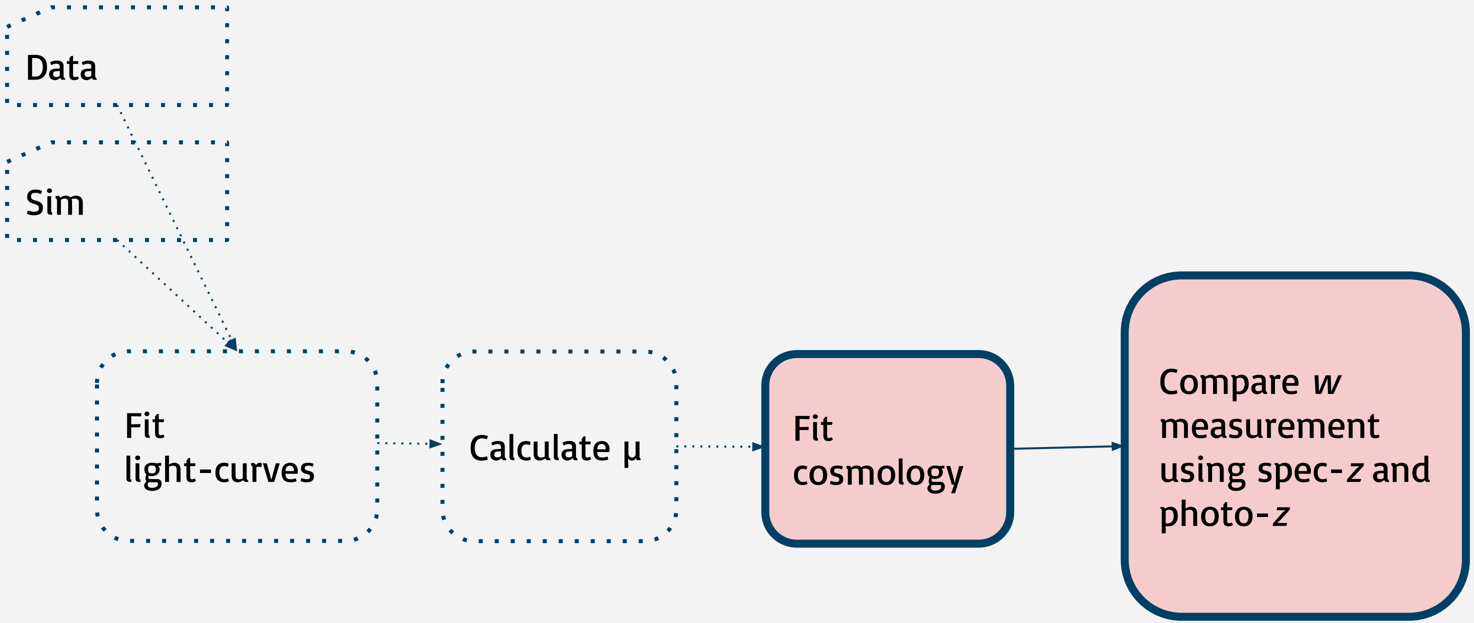


Data Hubble Diagrams



Results

Fitting for cosmology



Using spec-*z* and photo-*z*

Taking simulations to cosmology, we expect that cosmological biases may be as small as 0.01 in *w*

- Average over 150 instances of data-like sims
- Fit *w* and look at differences with spec-*z* case
- **redMaGiC photo-*z* result in a comparable, unbiased *w* measurement**

	Simulation		
Methods	Δw	Δw Error	Δw STD
spec-z	0.00	0.00	0.00
redMaGiC photo-z	-0.0011	0.0020	0.0249

$$\Delta w = w_{\text{spec}} - w_{\text{redMaGiC}}$$

Using redMaGiC photo-z as host galaxy photo-z for SNIa cosmology is promisingly unbiased!

	Simulation			Data	
Methods	Δw	Δw Error	Δw STD	Δw	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

$$\Delta w = w_{\rm spec} - w_{\rm redMaGiC}$$

Differences in *w* are consistent with simulations

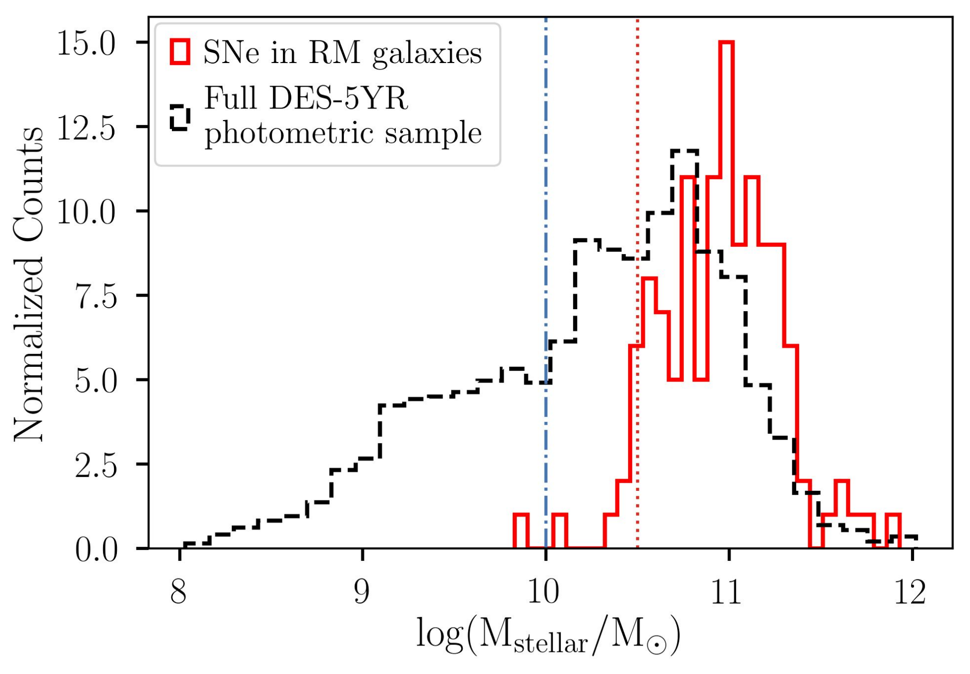
Are there really only SNIa in redMaGiC galaxies?

- Run photometric classifier on full DES5YR sample
- 4 out of 125 (~3%) are classified as CC
- From a sample that should be entirely Ia, ~1% are classified as CC
- 1 of the 4 is a spec-confirmed Ia, 2 are classified as Ia with different templates

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

SN host-galaxy relations

- redMaGiC galaxies: 10.5 < logMass < 11.9
- DES full sample: 8 < logMass < 12
- **Mass step cannot be measured**
- Expect redMaGiC subsample to be more robust to host-galaxy relations



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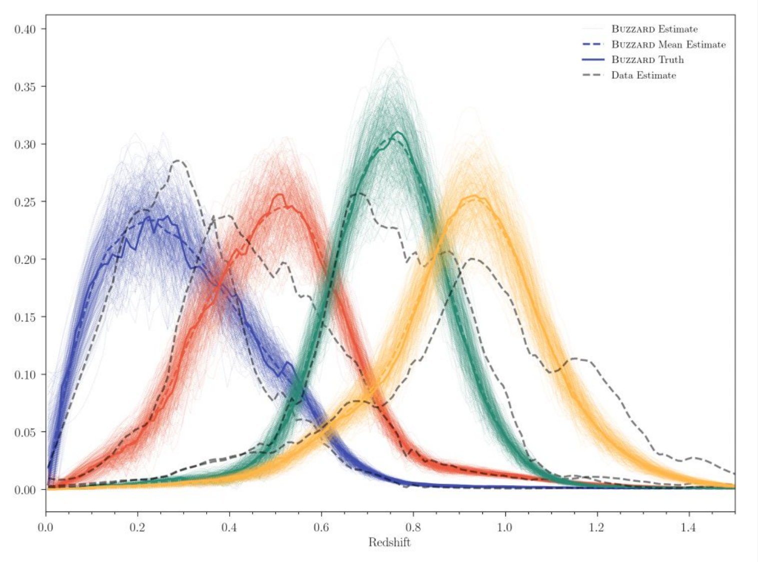
Future Work

SN light-curve redshift fit

- Can **fit redshift simultaneously with LC parameters**
  - Correct method to account for redshift uncertainties
- Can include **host-galaxy photo-*z* as prior**
- Pathologies at high redshift
  - Likely due to SALT2 model range

Redshift distributions

- Could we include information about the **distribution of redshifts** like 3x2 pt does?
- Bayesian approach?



Myles et al. 2021

Future Photometric Surveys

- LSST and Roman are upcoming next generation surveys
- Using TiDES forecast (Frohmaier et al. in prep)
    - 2.4 million projected LSST SNe, **6% of this is 144,000 SNe!**
    - Assuming 2400 low-*z* SNe, recover **uncertainty on *w* of 0.0124** (compared to current constraints which are on 3-4% level for statistical uncertainty)

Summary

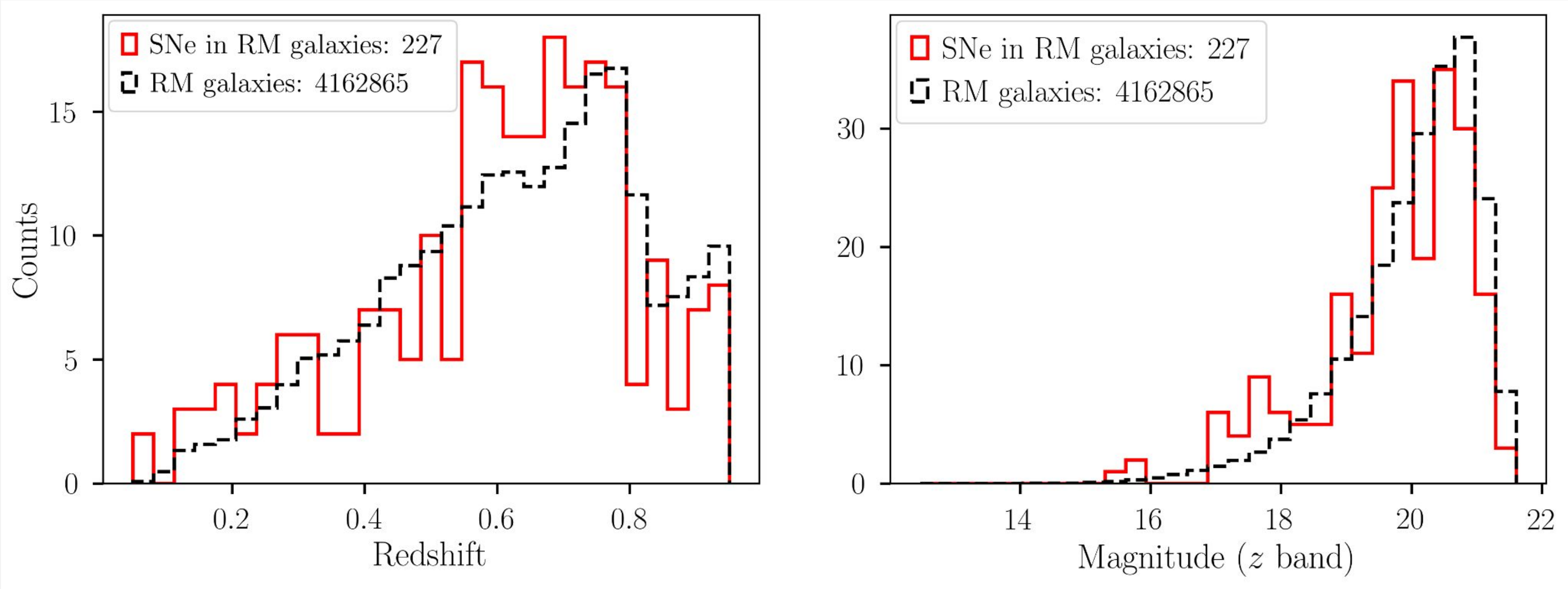
- **redMaGiC SN cosmology** is a proof of concept for the use of **photometric redshifts for SNIa samples** that addresses multiple big concerns simultaneously
- Using host redMaGiC photo-z results in w biases up to ~ 0.01-0.02
- A lot of information to be used from different sources of photometric and **host-galaxy redshift info**

Backup Slides

Paper Details

https://arxiv.org/abs/2202.10480

Distributions for SN in redMaGiC galaxies are similar to distributions for all redMaGiC galaxies



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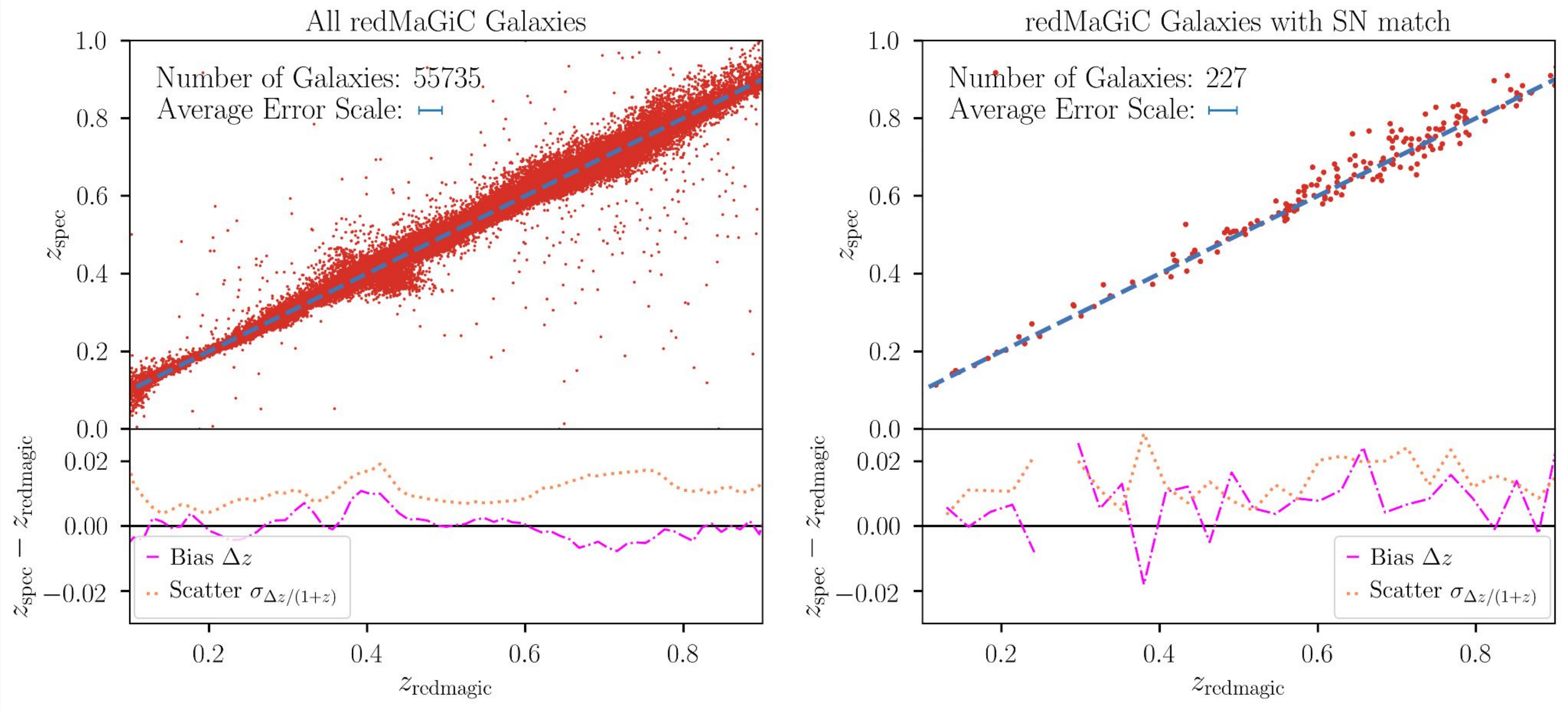
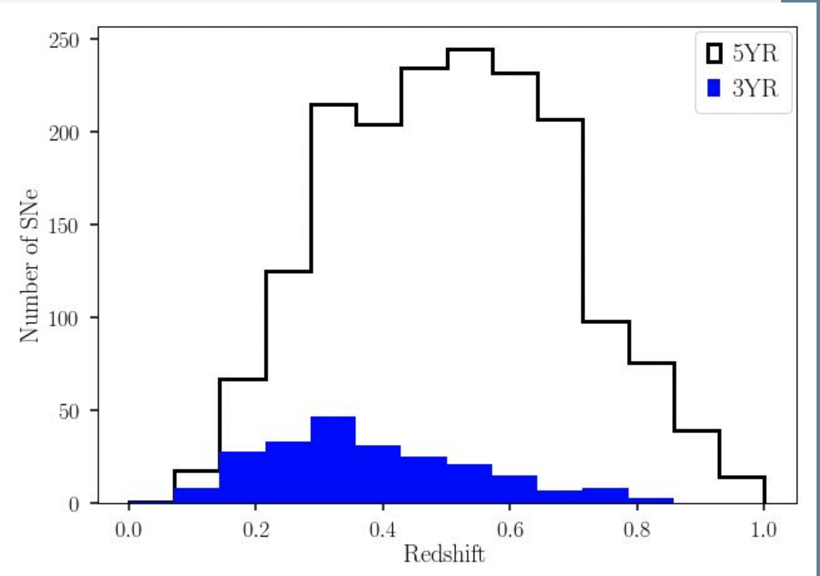


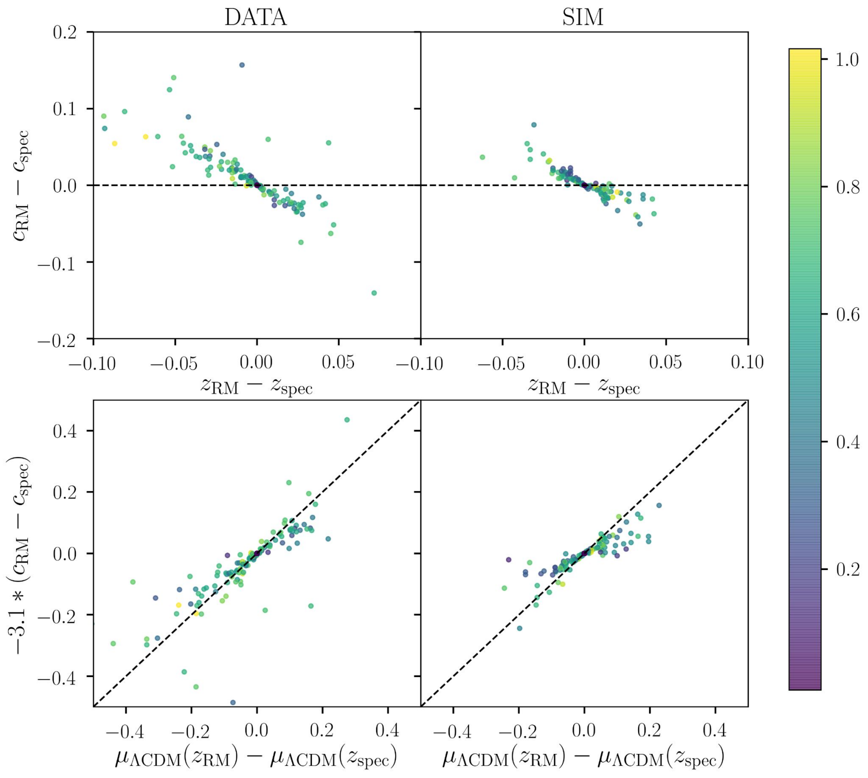
DES-SN samples

	3YR	5YR
Classification	Spec	Phot
Redshifts	Spec	Spec
Sample size	~200 + ~120 low-z	~1600 + ~300 low-z



Redshift-color relation

- μ uncertainty was previously overestimated compared to true measured RMS for μ residuals
- Redshift and color bias are correlated
- Fortunate cancelation along LCDM

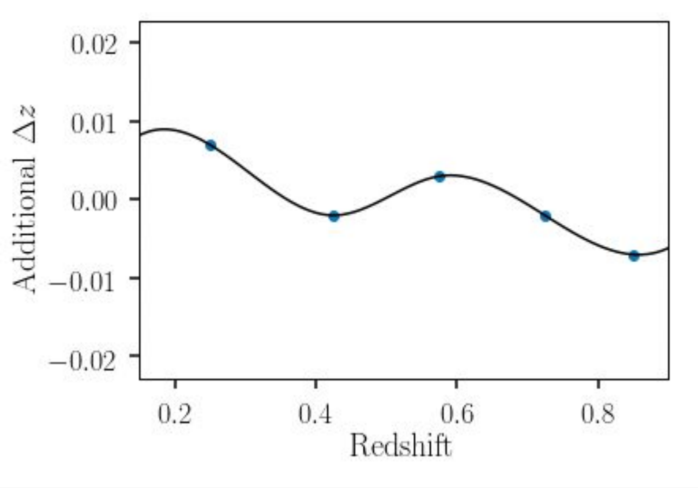


Redshift contribution to mu uncertainty

- Enlarge host galaxy library without RM-like cuts, also simulate photo-z using RMS map
- Subtract in quad as function of redshift $\sqrt{{\sigma_{\mu_{phot}}}^2 - {\sigma_{\mu_{spec}}}^2}$
- ~0.06 mag in both sets of simulations
- Small compared to RMS from mu uncertainty using spec-z (~0.18 mag or higher)
- Neglect this contribution for this analysis

Systematics Tests

- Simulate host-galaxy photo-*z* with exaggerated scatter and scale linearly
  - Measure change in $\triangle w$ with respect to change in scatter
  - Expect systematics of 0.0086
- 0.015 for bias of 0.006z
- Test realistic bias with redMaGiC 2 parameter fit calibration bias from clustering redshifts, from cross-correlation of redMaGiC with spec galaxy samples (Cawthon et al. 2020)



$$\Delta w = -0.005 \pm 0.0024$$

Increasing the SN sample size

- Consistent host-galaxy type across redshifts requires **redMaGiC low-*z* galaxies**
  - But... requires extra work, bright galaxies are unusual at low-*z*, require special photometry
  - And redshift biases have higher impact at low-*z*
- Other methods of restricting host galaxy type?

Color-luminosity relation (β)

- redMaGiC subsample has fitted β~2 compared to β~3 for DES3YR
- Meldorf et al. in prep measure R_V (reddening ratio) for redMaGiC galaxies is (1.54) vs full sample (2.61)
- Supports BS21 explanation
  - Direct link between low β for a subset of galaxies and low R_V predicted for the same set

Why only CC in LRGs?

- CC progenitors are massive (> 8 Msun) and explode in gas-rich, star forming galaxies
- In terms of galaxy age– CC explode first, then prompt Ia, then there's a long tail for accretion (thermonuclear)
- Foley & Mandel 2013 (98% of SNIa with elliptical hosts are Ia), Irani et al. 2021 (0.3%+0.3-0.1 of all CC SNe have elliptical hosts)

cont'd

- CC explode in late-type galaxies, associated with spiral arms and H II regions
- More luminous galaxies tend to be elliptical, gas poor, lack recent star formation
- Can separate star forming and passive with color-magnitude diagram
- Ia are more frequently found in galaxies w properties consistent with older populations
    - Fraction is larger in early-type, red, luminous hosts (probIa is higher if host is luminous, red, early-type)
    - Also with properties consistent with older populations

Astronomy

Magnitudes

- Smaller number = brighter
- One mag = brightness factor of 2.5

$$m_x = -2.5 \log_{10}\left(\frac{F_x}{F_{x,0}}\right)$$

$$m = -2.5 \log_{10} F(d)$$
$$M = -2.5 \log_{10} F(d = 10)$$

$$m - M = 2.5 \log_{10}(d/10)^2 = 5 (\log_{10} d - 1) = 5 \log_{10}\left(\frac{d}{10\,\mathrm{pc}}\right)$$

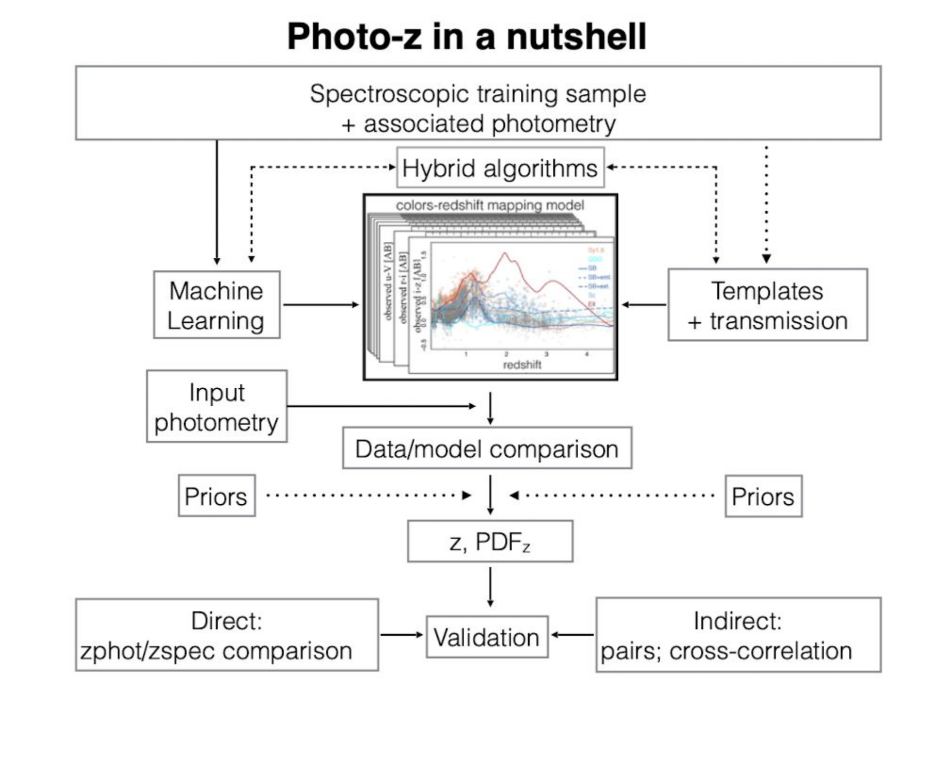
Chandrasekhar limit

- ~1.4 M_sun
- Set degeneracy pressure = gravitational pressure, solve for mass

$$M_{\text{limit}} = \frac{\omega_3^0 \sqrt{3\pi}}{2} \left(\frac{\hbar c}{G} \right)^{\frac{3}{2}} \frac{1}{(\mu_e m_H)^2}$$

Photo-z

Photometric redshifts



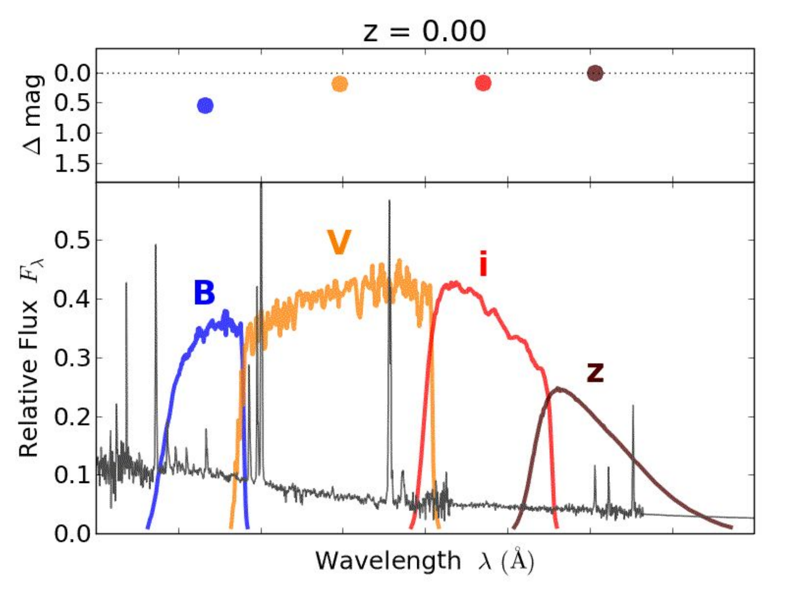


Photo-z bias and scatter defn

- Bias Δz = zspec −zredmagic
- Photo-z scatter $\sigma\Delta z/(1+z)$ is defined as 1.4826 × MAD, where MAD is the median absolute deviation $| \Delta z - \Delta z | /(1 + zspec)$

redMaGiC algorithm details

- Red-sequence matched-filter galaxy
- Selects red galaxies based on chosen comoving space density and luminosity threshold
- First fits every red sequence galaxy with red sequence template and computes best fit photo-z
- Then compute galaxy luminosity
- Then applies cuts on luminosity and chi-sq of template fit, with cuts tuned to select desire comoving space density

Photo-z afterburner

- Subset of galaxies with spec-z that are members of redmapper clusters (but actually use photometric cluster redshifts instead to avoid biased spectroscopic follow-up selection)
- Median redshift offset for training sample is calculated in zred bins, then added via spline interpolation to initial estimate

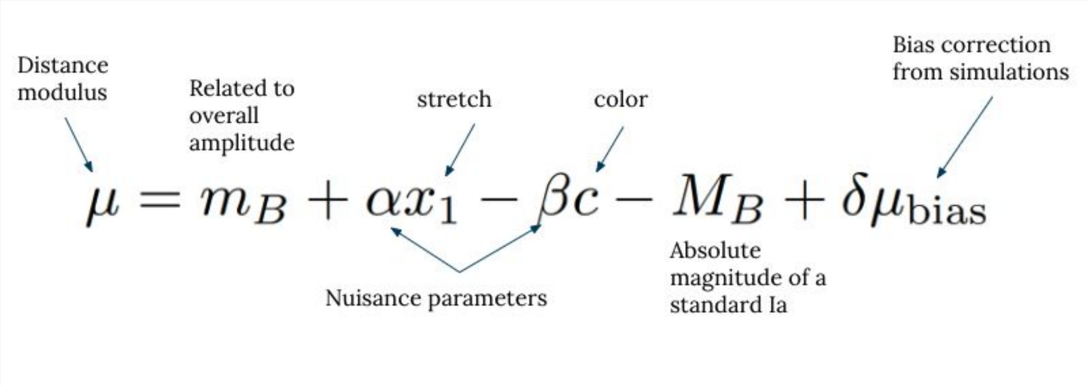
redMaGiC outliers

- Brighter = easier to distinguish red sequence galaxies
- Looking at spectra of outliers at low redshift: spectra are consistent except at shorter wavelength theres an excess of blue light + Halpha and OII lines (indicative of star formation)
- Photo-z biased high: outlier galaxies have steeper continuum consistent with dust-reddening from galaxy

SN Analysis Details

Bias corrections

- Use large simulations to determine bias for empirical correction for known selection effects ($\delta\mu_{bias}$ from the Tripp eq.)
- Calculate migration from simulated truth values to correct distances



Fitting cosmology

- Output of BBC is bias corrected Hubble Diagram + covariance matrix
- Wfit: simple chi2 minimization between estimated mu and reference cosmology over grid of Omega M, w, M_B (M_B then marginalized over, prior from Planck)
- For full analyses, use software like CosmoMC to combine full likelihoods

$$\Delta D_i = \mu_i - \mu_{\mathrm{model}}(z_i)$$

$$\mu_{\mathrm{model}}(z_i) = 5\log(d_L(z_i)/10\mathrm{pc})$$

$$2\ln(\mathcal{L}) = \chi^2 = \Delta\vec{D}^T\, C^{-1}_{\mathrm{stat+syst}}\, \Delta\vec{D}$$

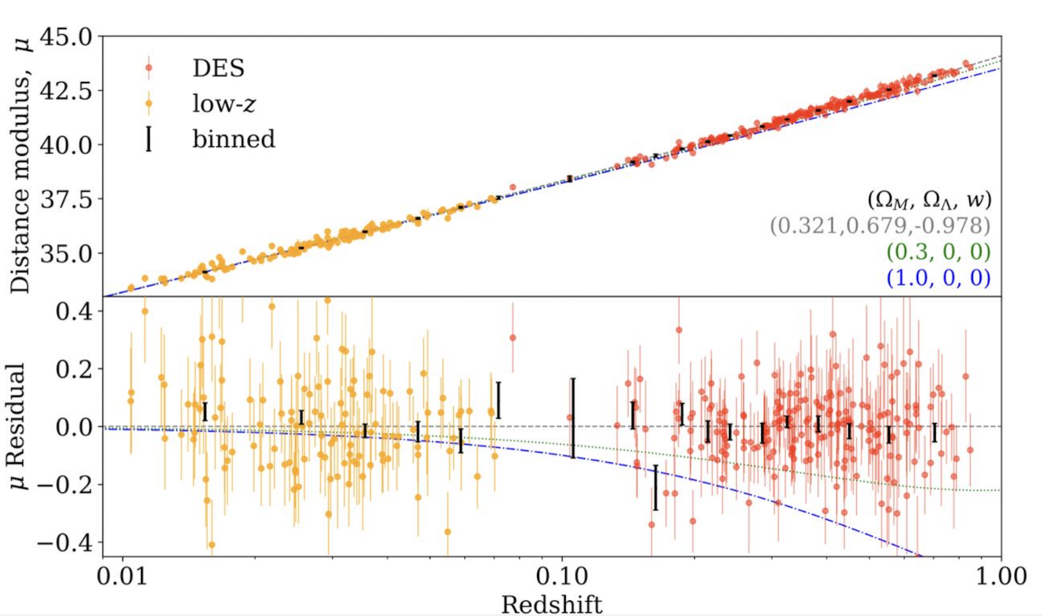
$$d_L(z) = (1+z)c\int_0^z \frac{dz'}{H(z')},$$

$$H(z) = H_0\sqrt{\Omega_M(1+z)^3 + \Omega_\Lambda(1+z)^{3(1+w)}}.$$

Other top SN systematics

- Photometry and calibration
- LC modeling
- Bias corrections
- MW extinction
- PV and redshift shifts
- Contamination

DES 3YR results



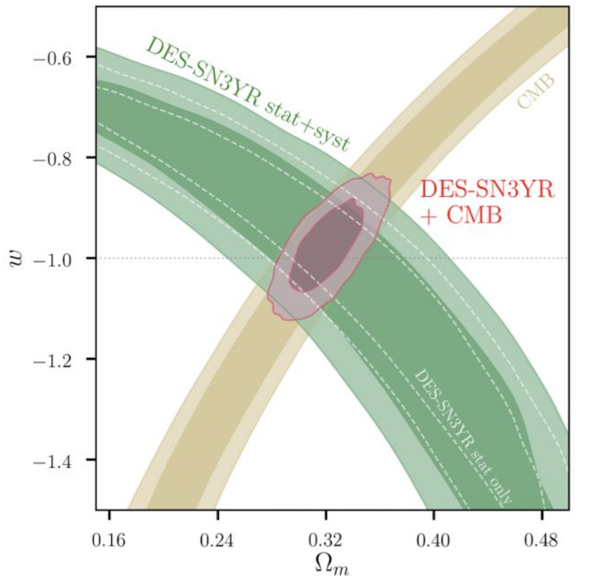


FIG. 3.— Constraints on Ω_m-w for the flat wCDM model (68% and 95% confidence intervals). SN contours are shown with only statistical uncertainty (white-dashed) and with total uncertainty (green-shaded). Constraints from CMB (brown) and DES-SN3YR+CMB combined (red) are also shown.

Pantheon+ results

Table 3. Results for Cosmological Models

	Ω_M	Ω_Λ	H_0	w_0	w_a
Pantheon+ & SH0ES - *All Models*					
FlatΛCDM	0.338 ± 0.018	0.662 ± 0.018	73.4 ± 1.1	-	-
ΛCDM	0.277 ± 0.054	0.570 ± 0.080	73.3 ± 1.1	-	-
Flat$w$CDM	$0.307^{+0.058}_{-0.063}$	$0.693^{+0.063}_{-0.058}$	$72.86^{+0.94}_{-1.06}$	-0.89 ± 0.13	-
Flatw_0w_aCDM	$0.386^{+0.056}_{-0.070}$	$0.614^{+0.070}_{-0.056}$	$73.40^{+0.99}_{-1.22}$	$-1.81^{+1.71}_{-0.60}$	$-0.4^{+1.0}_{-1.8}$
External Probes (No SH0ES) - *Flat$w$CDM*					
Planck & Pantheon+	$0.325^{+0.010}_{-0.008}$	$0.675^{+0.008}_{-0.010}$	$66.49^{+0.50}_{-0.83}$	$-0.982^{+0.022}_{-0.038}$	-
Planck & galaxyBAO & Pantheon+	$0.319^{+0.006}_{-0.007}$	$0.681^{+0.007}_{-0.006}$	$66.78^{+0.76}_{-0.50}$	$-0.974^{+0.025}_{-0.031}$	-
Planck & allBAO & Pantheon+	$0.316^{+0.005}_{-0.008}$	$0.684^{+0.008}_{-0.005}$	$66.87^{+1.00}_{-0.32}$	$-0.978^{+0.024}_{-0.031}$	-
External Probes (No SH0ES) - *Flatw_0w_aCDM*					
Planck & Pantheon+	$0.318^{+0.012}_{-0.014}$	$0.682^{+0.014}_{-0.012}$	$67.4^{+1.1}_{-1.2}$	$-0.851^{+0.092}_{-0.099}$	$-0.70^{+0.49}_{-0.51}$
Planck & galaxyBAO & Pantheon+	$0.318^{+0.009}_{-0.006}$	$0.682^{+0.006}_{-0.008}$	$67.12^{+0.71}_{-0.69}$	$-0.878^{+0.063}_{-0.069}$	$-0.45^{+0.29}_{-0.32}$
Planck & allBAO & Pantheon+	$0.316^{+0.009}_{-0.005}$	$0.684^{+0.005}_{-0.009}$	$67.41^{+0.52}_{-0.82}$	$-0.841^{+0.066}_{-0.061}$	$-0.65^{+0.28}_{-0.32}$

Notes: Summary of marginalized parameter constraints for Pantheon+ and other external probes. The mean and 68% confidence limit are provided for each cosmological parameter. A blank value indicates a parameter not used in the cosmological fit.

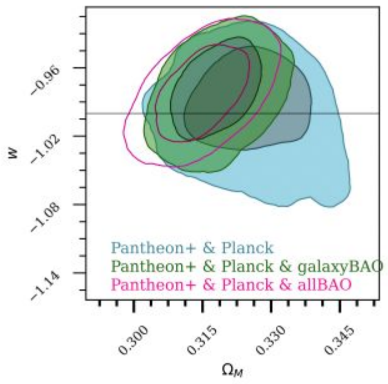


Figure 11. Constraints for Flatw_0CDM from the Pantheon+ dataset in combination with Planck & galaxyBAO or Planck & allBAO.

Cosmology Details

Definition of redshift

- Relativistic/Doppler: objects moving apart
- Gravitational: radiation travels toward weaker gravitational potential
- Cosmological: expanding space

$$a(t) = \frac{1}{1+z}$$

Calculation of redshift, z

Based on wavelength	Based on frequency
$z = \frac{\lambda_{obsv} - \lambda_{emit}}{\lambda_{emit}}$	$z = \frac{f_{emit} - f_{obsv}}{f_{obsv}}$
$1 + z = \frac{\lambda_{obsv}}{\lambda_{emit}}$	$1 + z = \frac{f_{emit}}{f_{obsv}}$

Cosmology equations

- FLRW metric = solution of Einstein field equations->together give Friedmann equations
- a = scale factor (~size of universe, 1 at present day)

$$H = \frac{\dot{a}}{a}$$

$$H^2 = \Omega_{r,0}a^{-4} + \Omega_{m,0}a^{-3} + \Omega_{k,0}a^{-2} + \Omega_{\Lambda,0}$$

$$\rho_c = \frac{3H^2}{8\pi G}$$

$$H(z) = H_0\sqrt{\Omega_M(1+z)^3 + \Omega_\Lambda(1+z)^{3(1+w)}}.$$

Equations of state

- w=0 for nonrelativistic matter "matter"
- w=⅓ for photons "radiation"
- W < -⅓ provides positive acceleration
- w=-1 means pressure=-density, constant density and constant pressure
- density(a) proportional to a^-3(1+w)

DE Models

$$w = w_0 + w_a(1 - a)$$

- wCDM = constant dark energy, fit for w
- w0waCDM = time-varying w, dependent on scale factor
    - Poorly constrained currently

- FlatΛCDM: Ω_M is floated, $w = -1$, and $\Omega_M + \Omega_\Lambda = 1$.
- ΛCDM: $w = -1$, Ω_M and Ω_Λ are floated.
- Flat$w$CDM: w and Ω_M are floated, $\Omega_M + \Omega_\Lambda = 1$.
- Flatw_0w_aCDM: $w = w_0 + w_a \times (1 + z)$, Ω_M, w_0, w_a are floated and $\Omega_M + \Omega_\Lambda = 1$.

Measures of Distance in Cosmology

- For flat cosmology,

$$d_L(z) = (1+z)c\int_0^z \frac{dz'}{H(z')},$$

- Comoving distance = observers are both moving with Hubble flow, does not change with time, accounts for expansion of universe
- Comoving distance = proper distance at present time

Cosmological probes