

# Measuring Cosmological Parameters with Type Ia Supernovae in redMaGiC Galaxies

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DES SN WG (in prep.)

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# Outline

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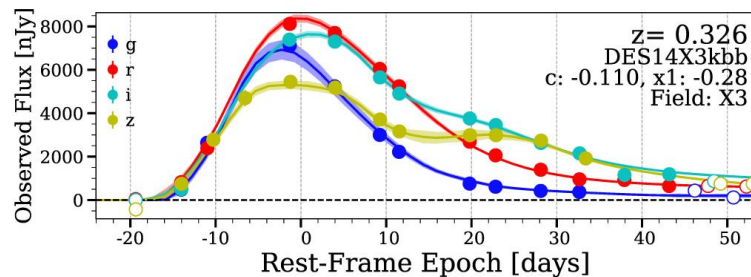
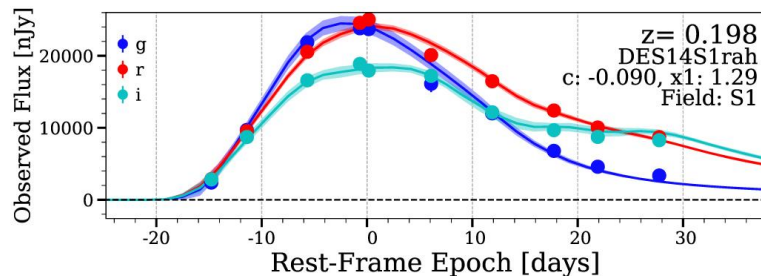
1. Motivations and Challenges in Current SNIa Cosmology
2. Data, Sims, and Methods
3. Results
4. Future Work



# Motivations and Challenges in Current SNIa Cosmology

# SN Ia Cosmology Review

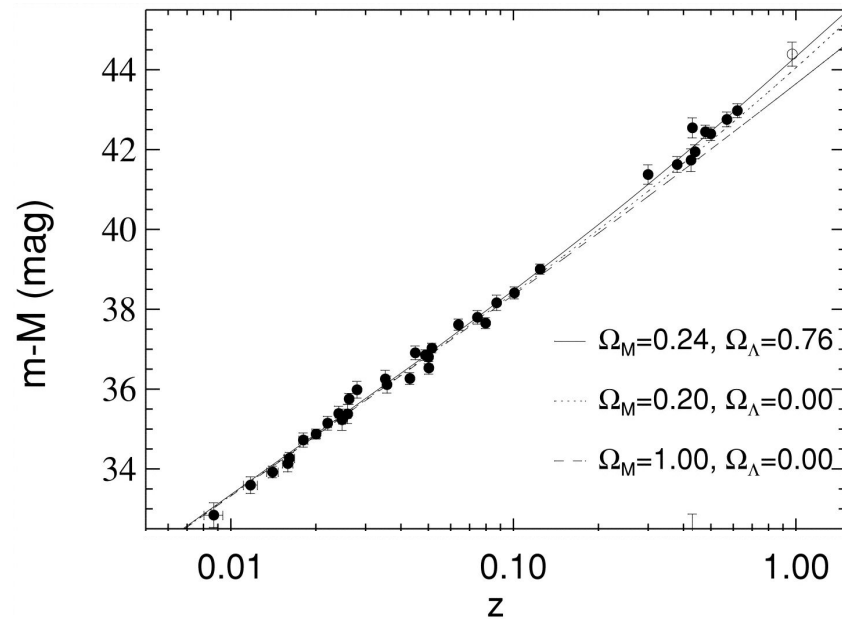
- Type Ia SNe are **standardizable candles**
- Fit light-curve parameters
  - color ( $c$ ) and stretch ( $x_1$ )
- After standardization, scatter can be reduced to  $\sim 0.1$  mag



Brout et al. 2019

# SN Ia Cosmology Review

- Measure distance-redshift relation (Hubble Diagram)
- Constrain dark energy equation-of-state  $w$



Riess et al. 1998

# Redshifts and Classification

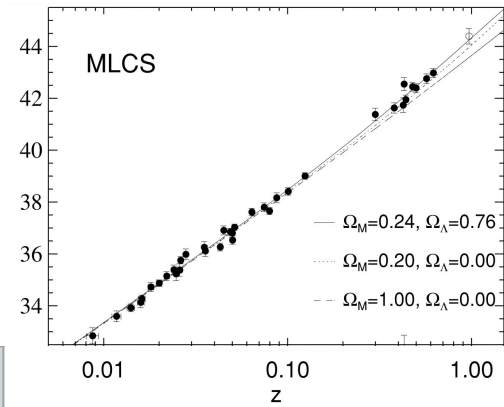
Redshifts

Classification

	Spectroscopic classification of SN	Photometric classification of SN
Spectroscopic redshift from host galaxy	Spectroscopic SN Sample	Photometric SN Sample
Spectroscopic redshift from SN		<b>Not Used</b>
Photometric redshift from host galaxy	<b>Not Used</b>	<b>Not Used</b>

$\mu$

m-M (mag)



Riess et al.  
1998

# Motivations: 3 top challenges for future SNIa surveys

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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

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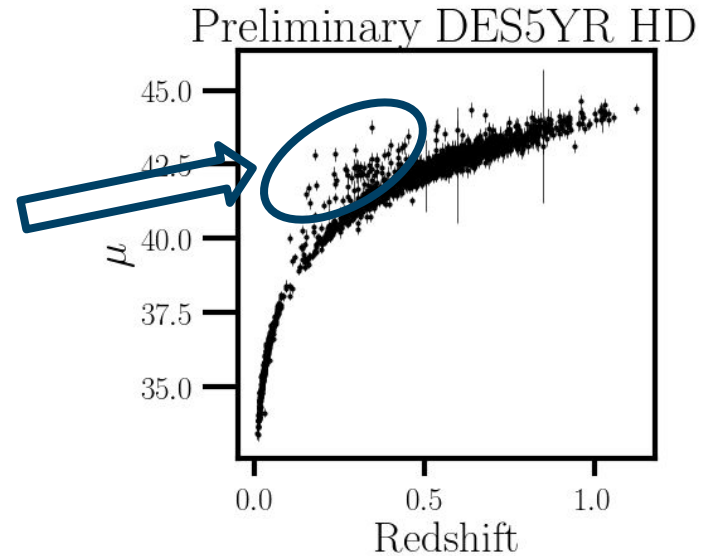
- Typically rely on spec- $z$  from SN or its host-galaxy
- Host-galaxy spectroscopic follow-ups to photometric surveys
  - Need to model spectroscopic efficiency
  - Large amounts of dedicated telescope time
- Resource limited and time consuming



## 2. Core-collapse SNe contamination

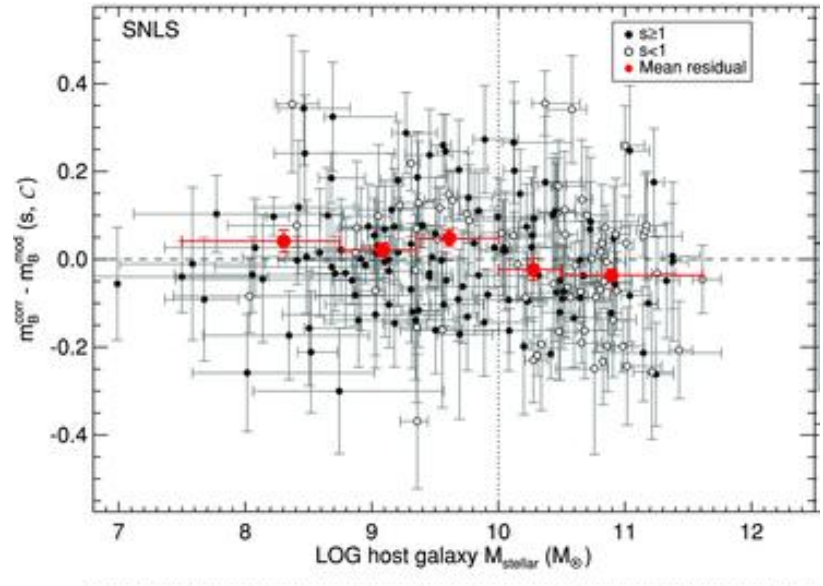
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- Core-collapse SNe (Type Ib, Ic, II, etc) "contaminate" the Hubble Diagram
- Photometric classification is a large area of research and effort for SN analyses



# 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

# Introducing: SN cosmology in red, dead galaxies

Addresses top SN challenges:

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

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

1. **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
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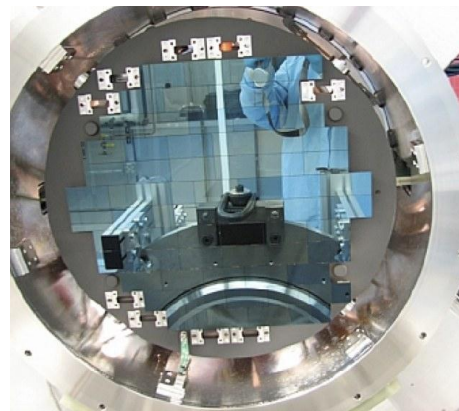
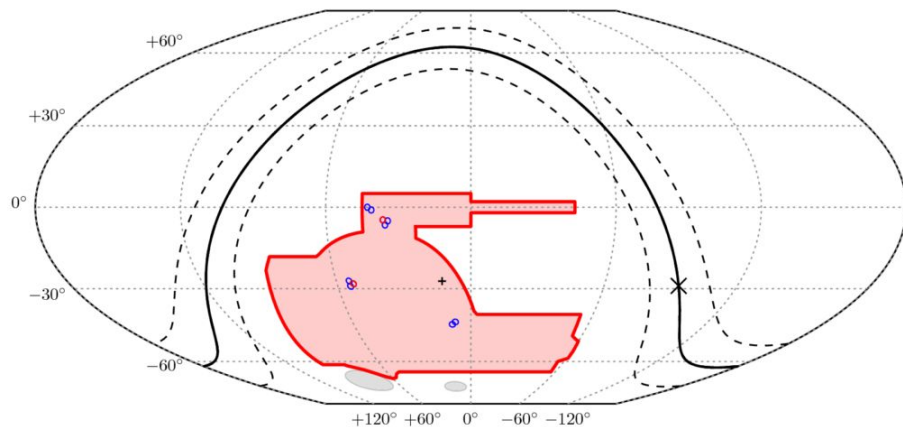


# Data, Sims, and Methods

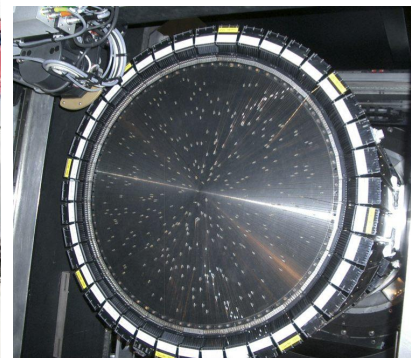
# Dark Energy Survey

- 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

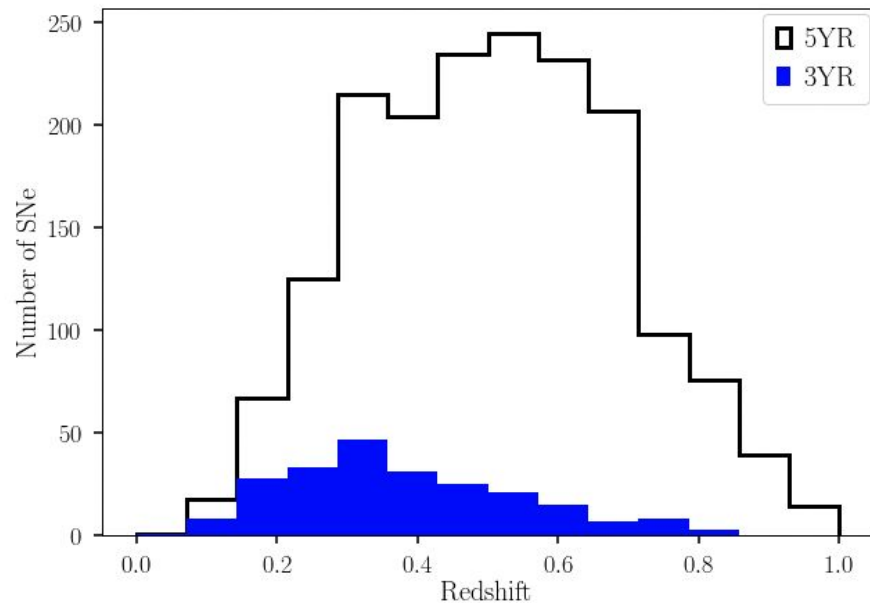


2dF

# DES-SN samples

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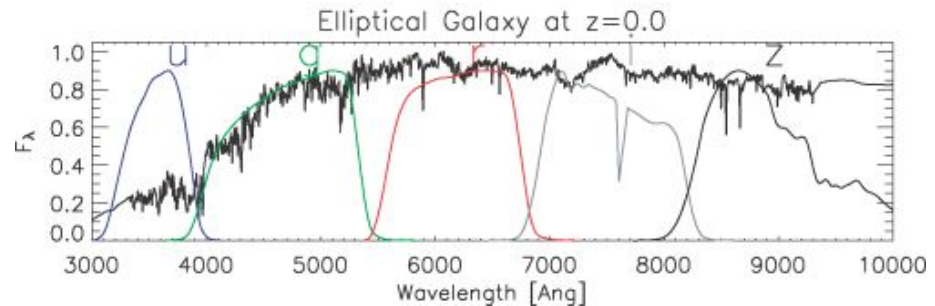
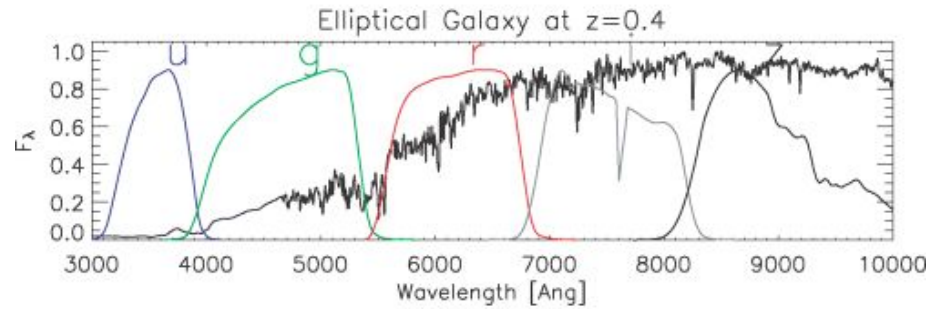
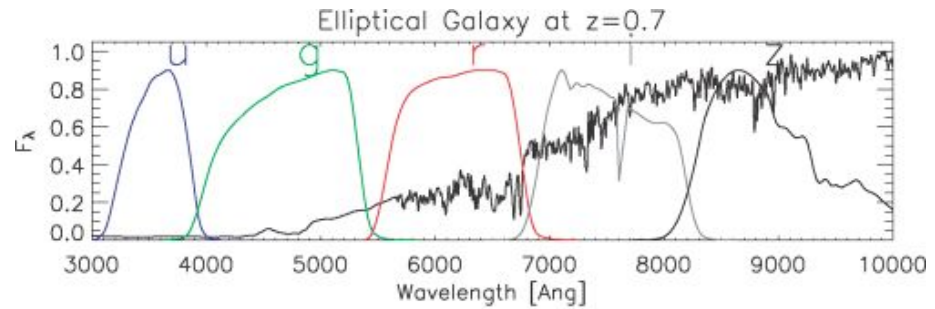
	3YR	5YR
Classification	Spec	Phot
Redshifts	Spec	Spec
Sample size	~200 + ~120 low-z	~1600 + ~300 low-z



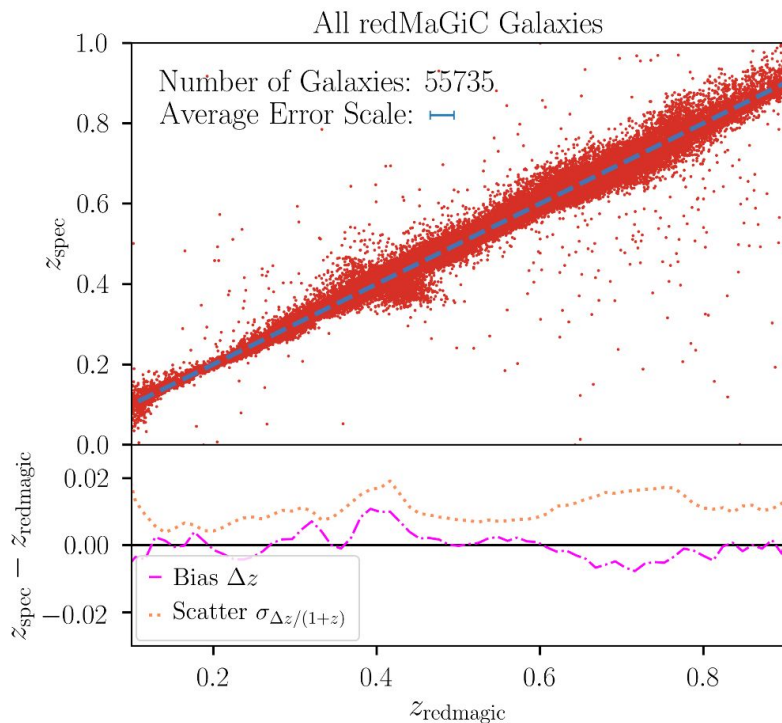
# redMaGiC galaxies

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- 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 $\sigma_z \sim 0.015$ and selected to have minimal uncertainties



## Typical redshift uncertainties:

- Host spec-z:  $\sigma_z \sim 0.0001$
- SN spec-z:  $\sigma_z \sim 0.005-0.01$
- Regular photo-z:  
 $\sigma_z \sim 0.03-0.04$

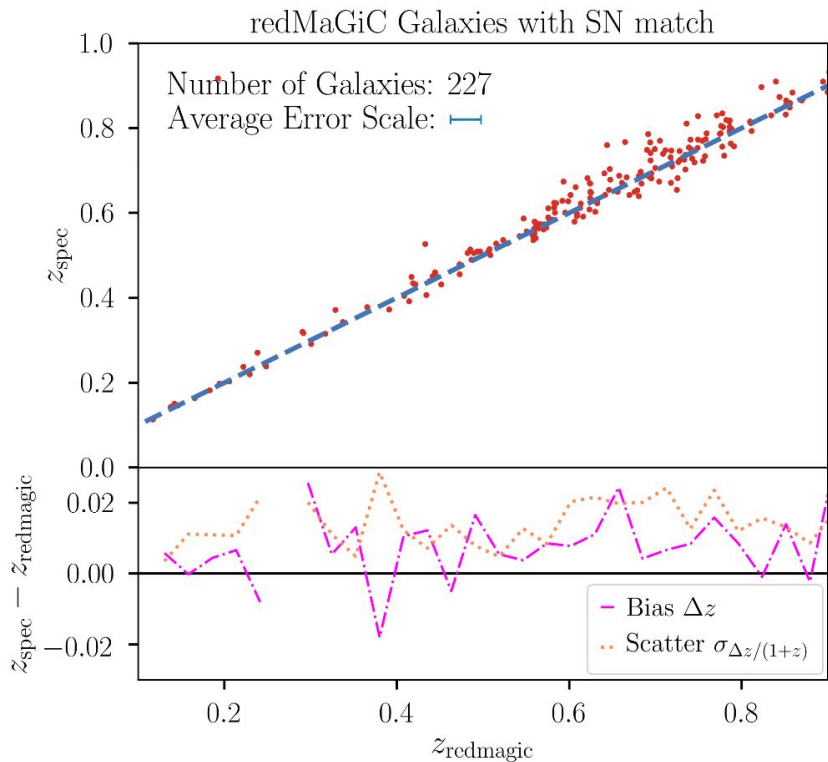
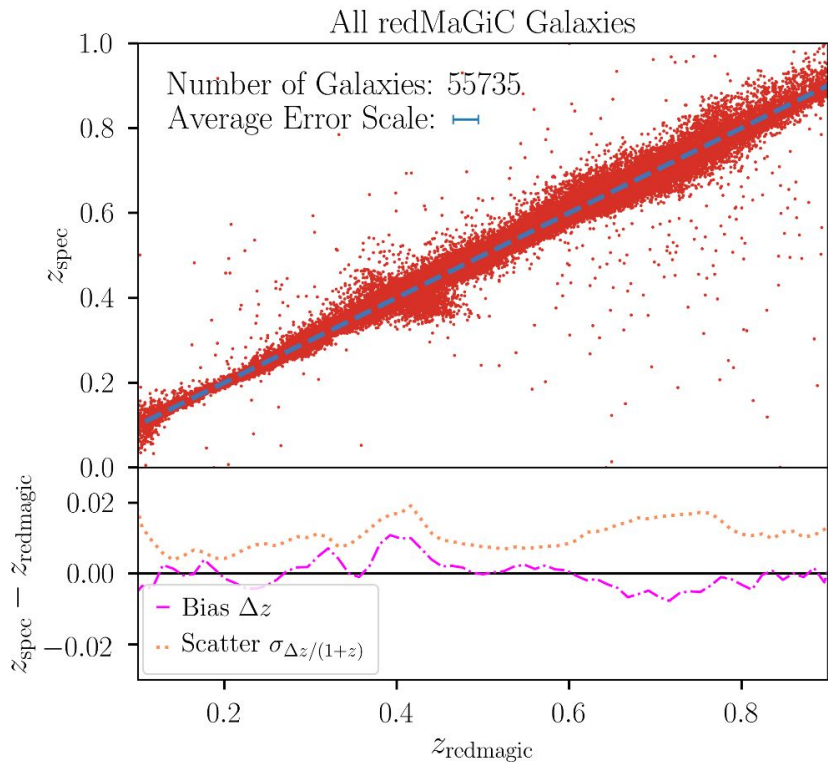


# SNe in redMaGiC galaxies

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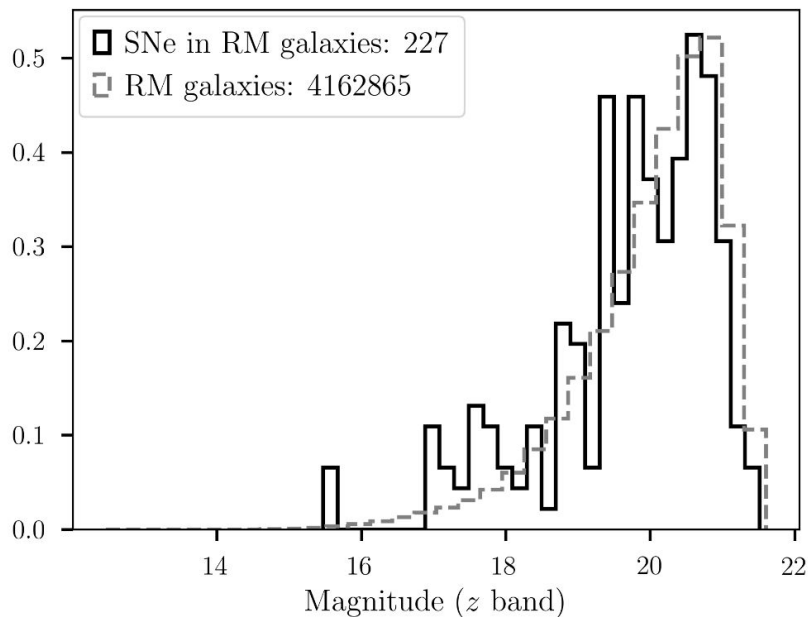
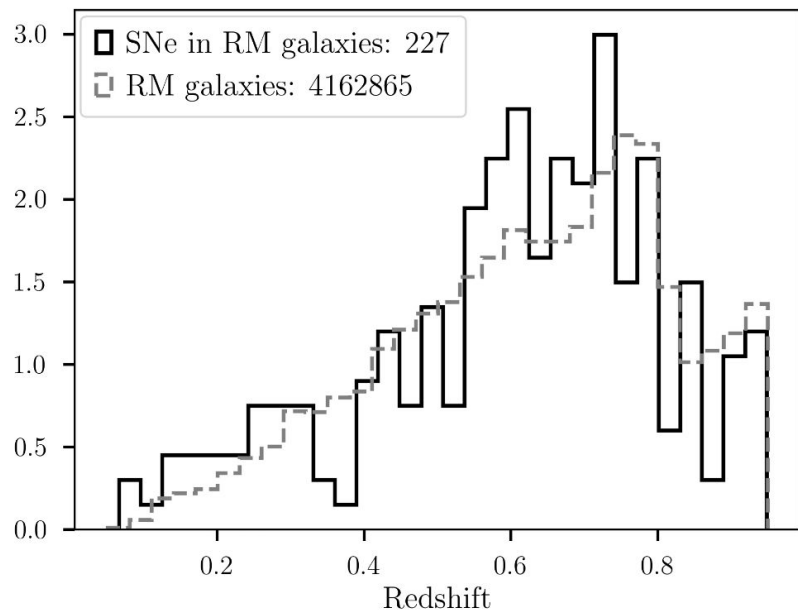
- 5YR photometric SN sample, Y6 redMaGiC
- Match coordinates of redMaGiC galaxies to SN host galaxies (requiring spectroscopic redshift)
- ~6% (125/1600) of DES5YR photometric SN sample are found in redMaGiC galaxies (after cuts)

# redMaGiC photo- $z$ are precise to $\sigma_z \sim 0.015$ and selected to have minimal uncertainties



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

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# Are there really only SNIa in redMaGiC galaxies?

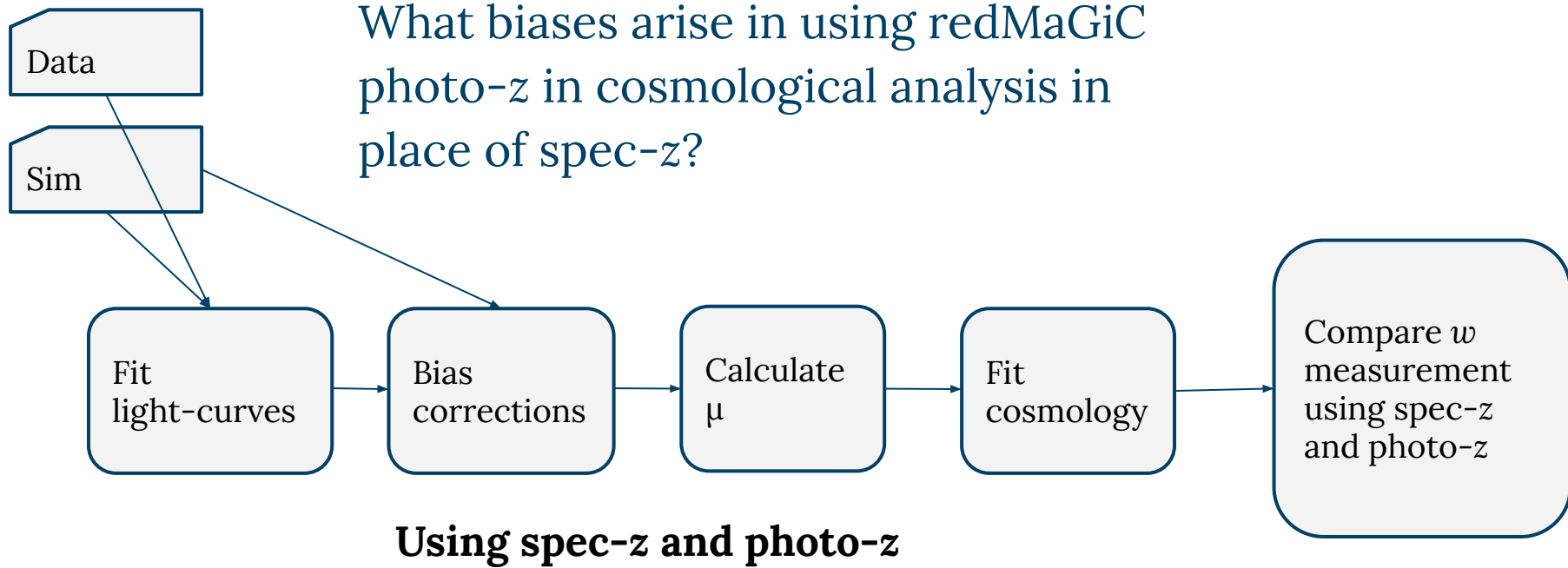
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- Photometric classifier run on full DES5YR sample
- 4 out of 125 classified as CC with 0.5 PIa cut
- ~3% contamination (although there is uncertainty in the classifier itself)

	Fraction (%) of SNe classified by SNN as unlikely-Ia
Baseline DES-5YR Photometric Sample	– (8.2%)
SNe in redMaGiC galaxies	4/125 (~ 3%)
DES-5YR Spectroscopically-classified Sample	3/401 (~ 1%)

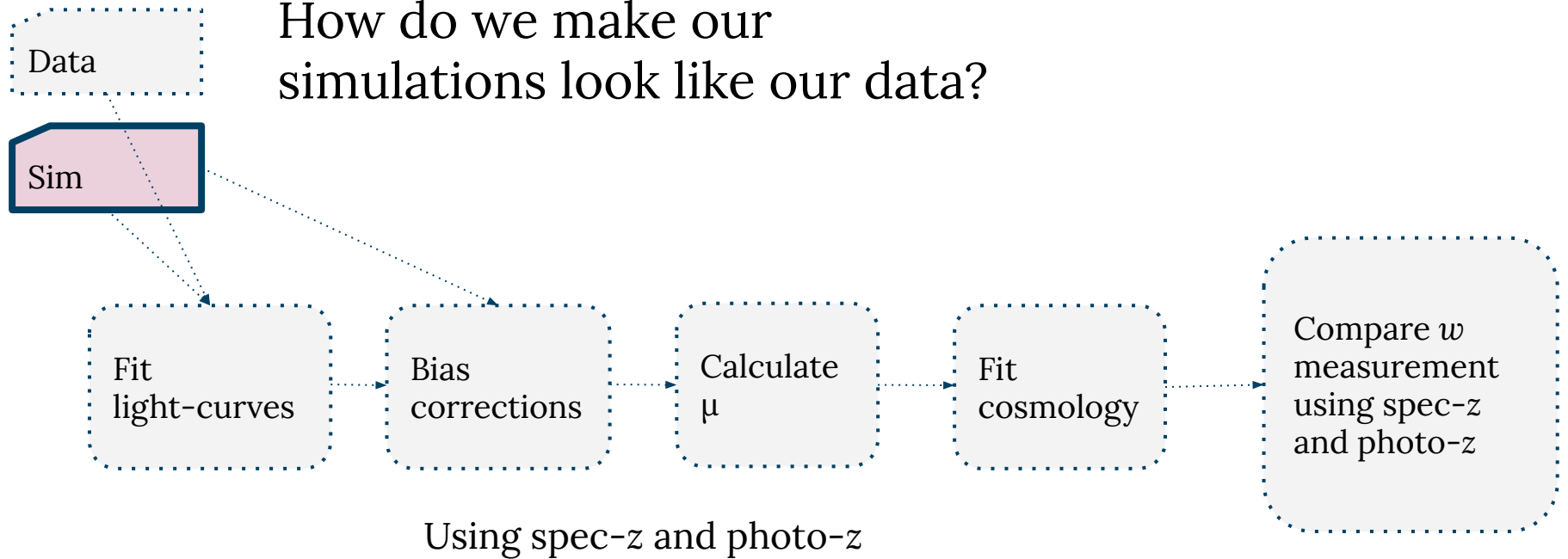
# Method Overview

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



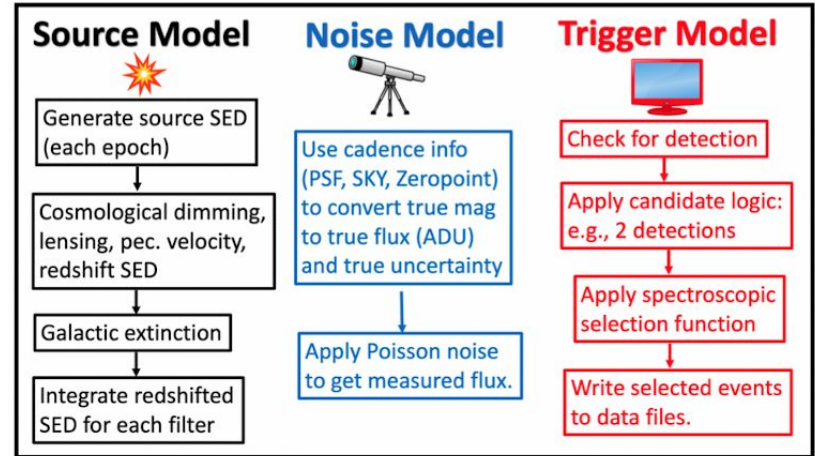
# Simulations

How do we make our simulations look like our data?



# Simulations

- SNANA = SN analysis software
- Forward model SNe Ia with catalog level simulations
- Source SED + astrophysical effects and observational effects + detection efficiency



Kessler et al. 2019

# Simulations

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- Baseline simulation inputs to SNANA from Vincenzi et al. 2021
  - Improves DES3YR sims to replicate photometric sample
  - Improved model of spectroscopic redshift efficiency
  - Improved host galaxy library, accounts for different SN rates in different types of galaxies



# Simulations: Host-galaxy library

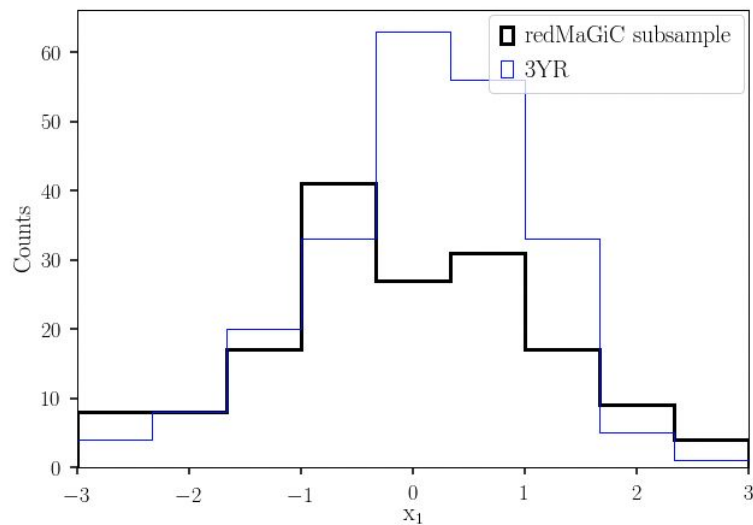
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- Host galaxies are assigned from realistic library
- Make cut on sSFR, r mag, and galaxy mass to **mimic selection of redMaGiC** (bright, red, and dead)
  - $\log\text{Mass} > 10.5$
  - $r \text{ mag} < 23.3$
  - $\log(\text{sSFR}) < -11.5$  (passive)

# Simulations: Parent Populations

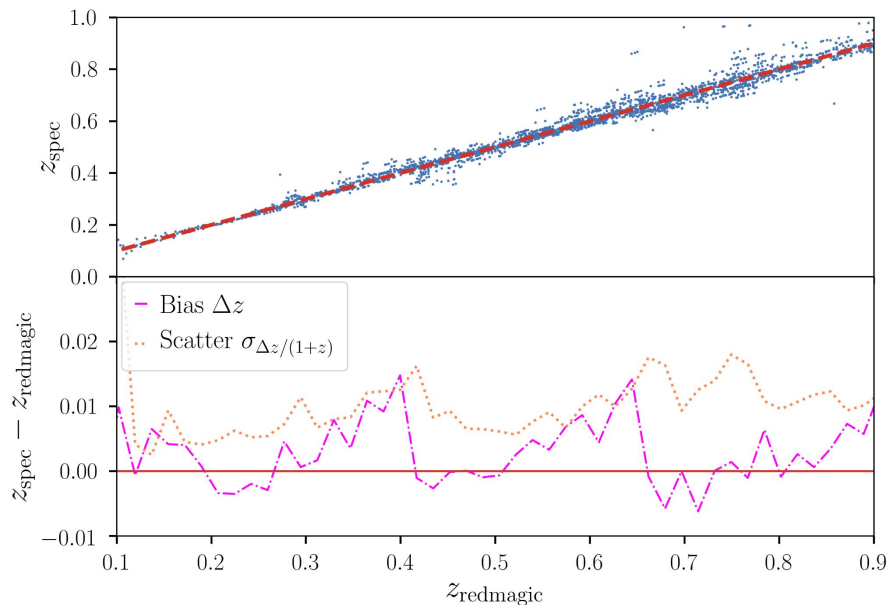
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- Parent populations from Popovic et al. 2021a fitter
- Comparing stretch ( $x_1$ ) and color (c) population parameters with DES3YR
  - Consistent findings with previous works that high mass/low sSFR galaxies are correlated with lower  $x_1$  values



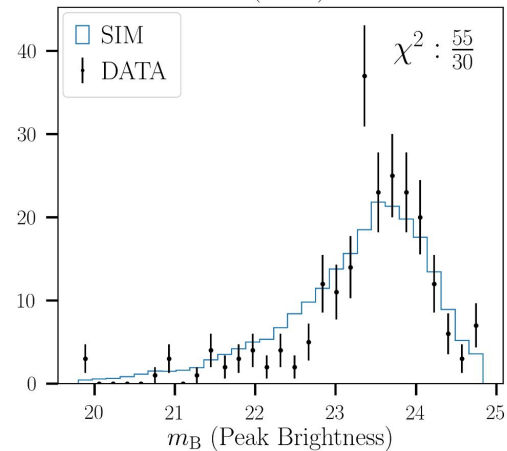
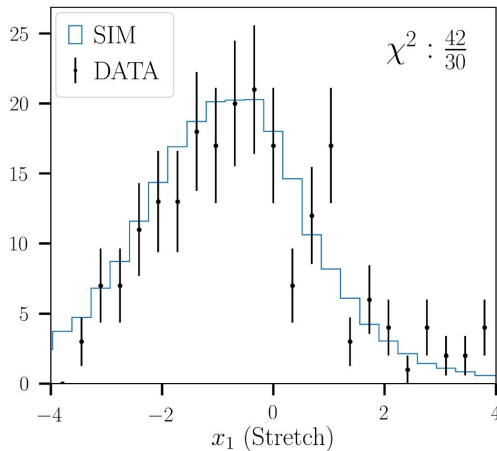
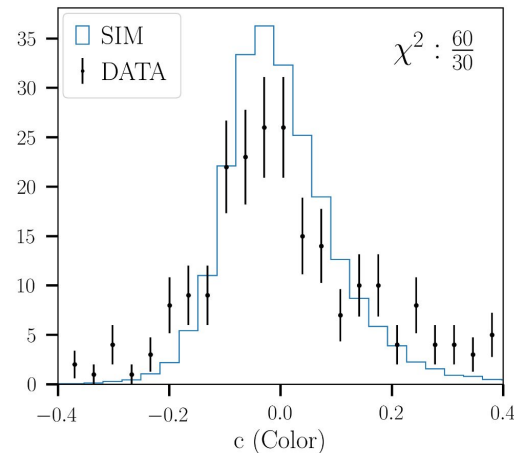
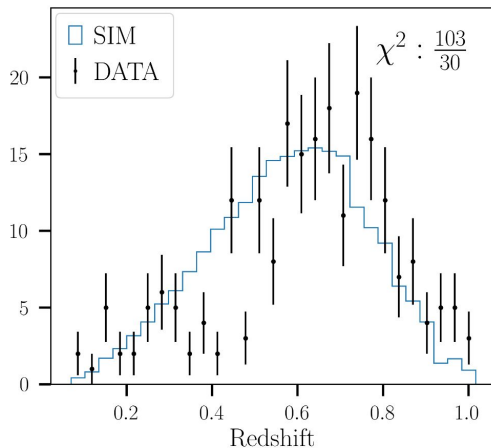
# Simulations: photo-z

- 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



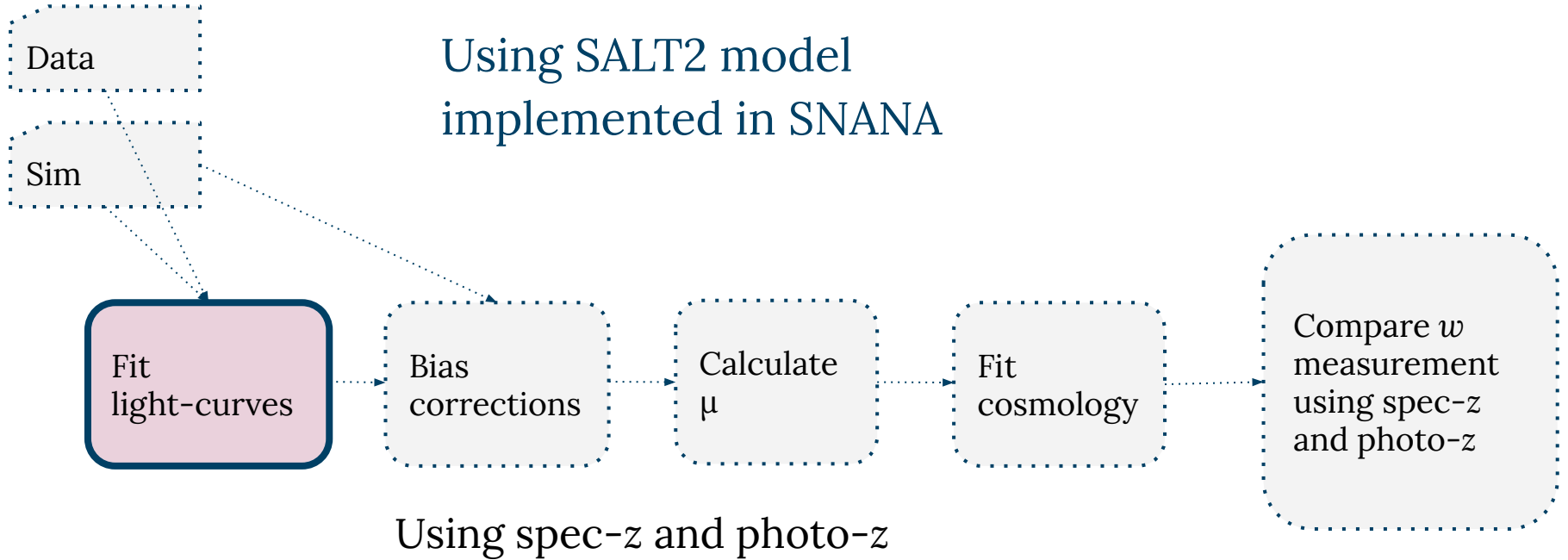
# Sims vs. Data

- General agreement between simulations/data for redshift and light-curve parameters



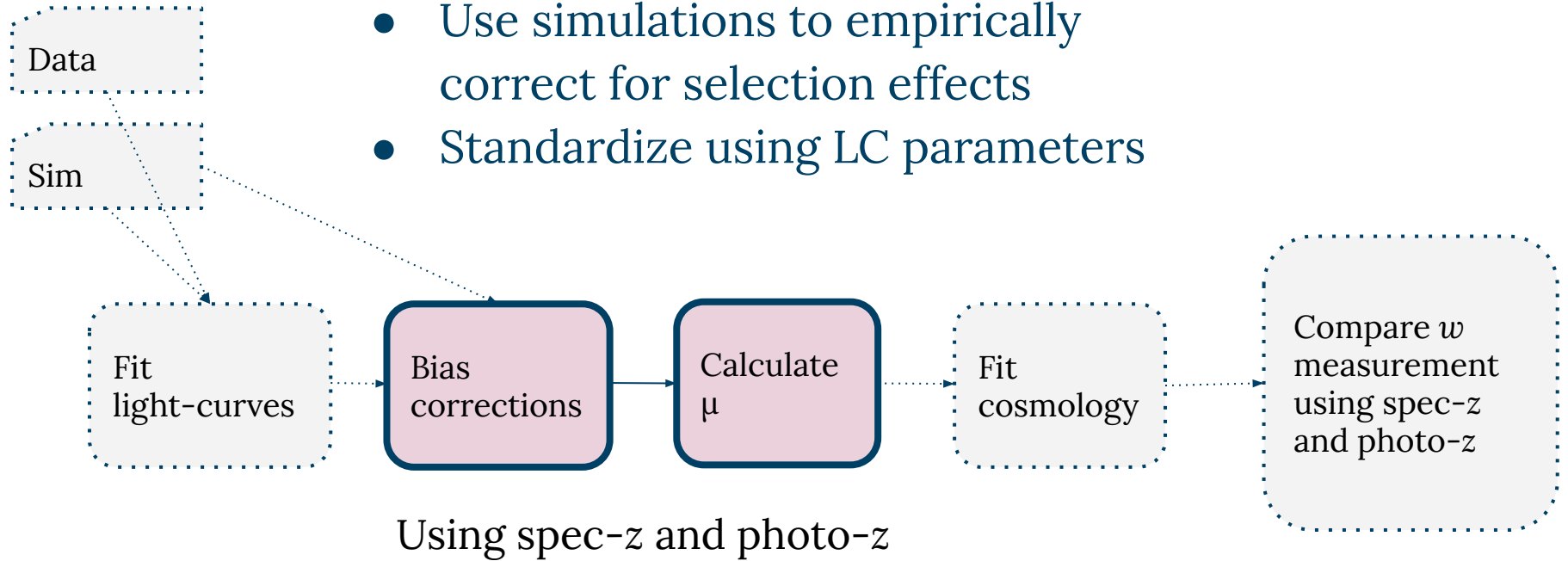
# Light-curve fitting

Using SALT2 model  
implemented in SNANA



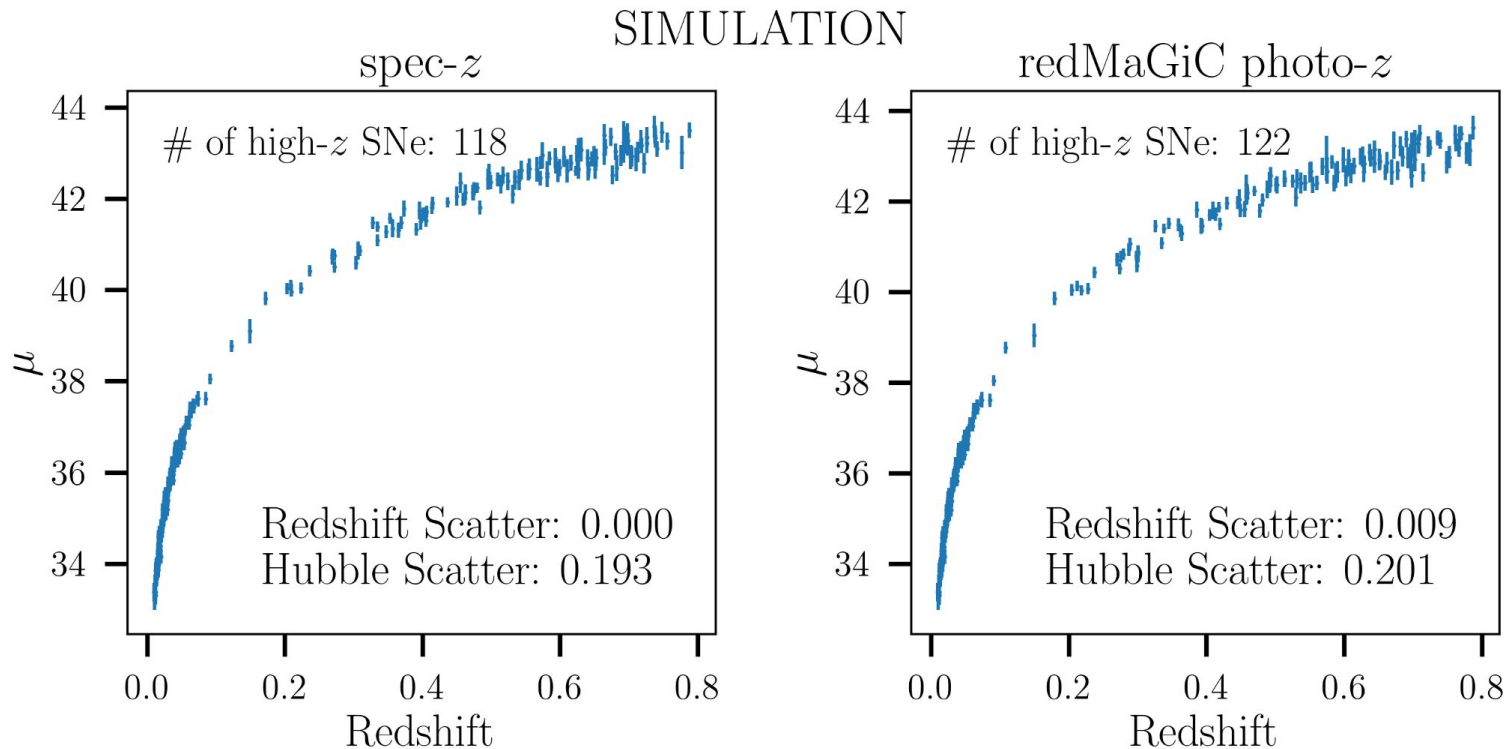
# Bias corrections and $\mu$

- Use simulations to empirically correct for selection effects
- Standardize using LC parameters



# Simulation Hubble Diagrams

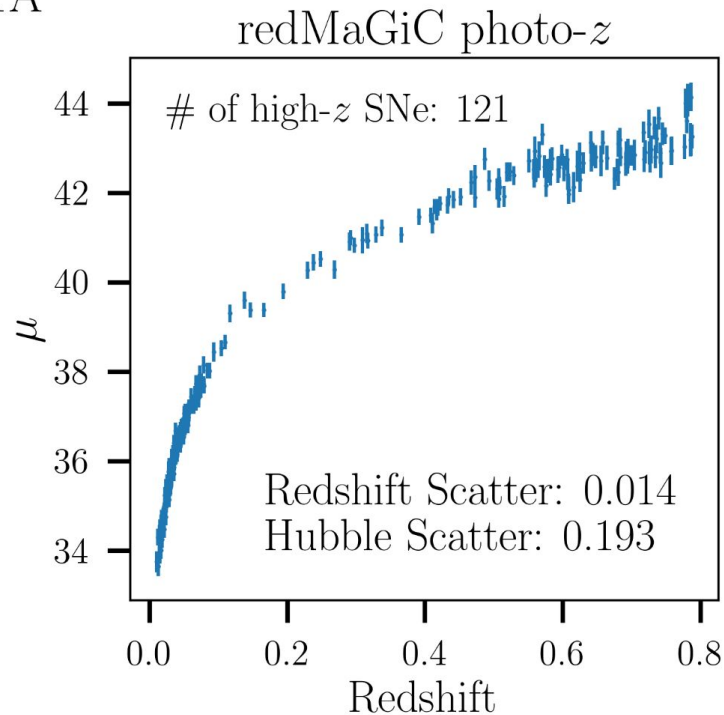
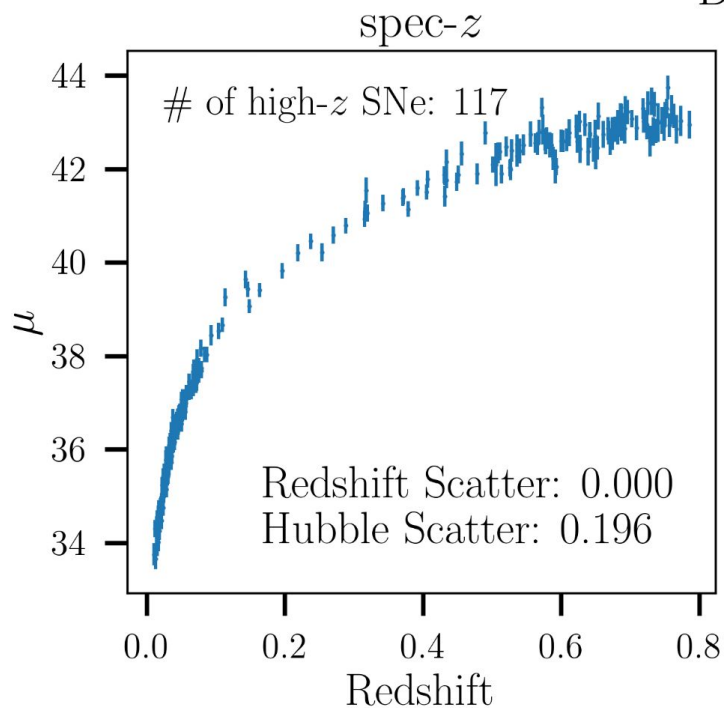
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# Data Hubble Diagrams

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DATA

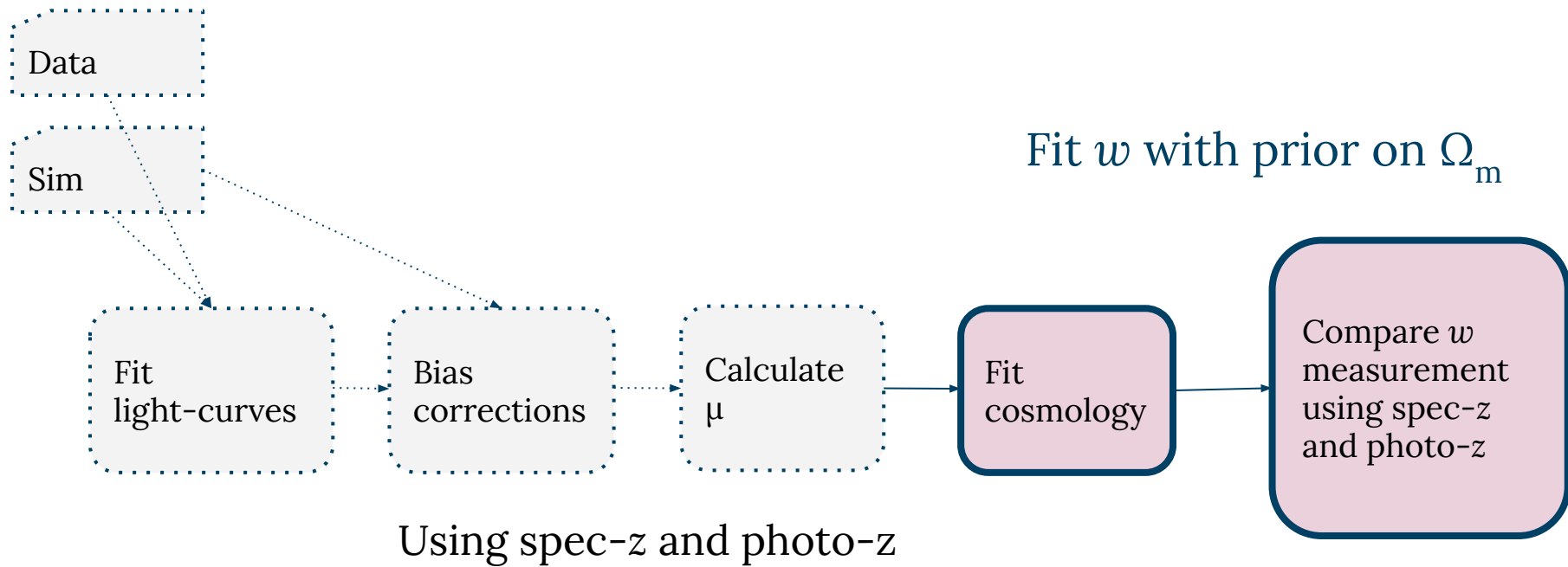






# Results

# Cosmology fit



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

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

Methods	Simulation		
	$\Delta w$	$\Delta w$ Error	$\Delta w$ 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!

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Methods	Simulation				Data
	$\Delta w$	$\Delta w$ Error	$\Delta w$ STD		$w$ 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

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

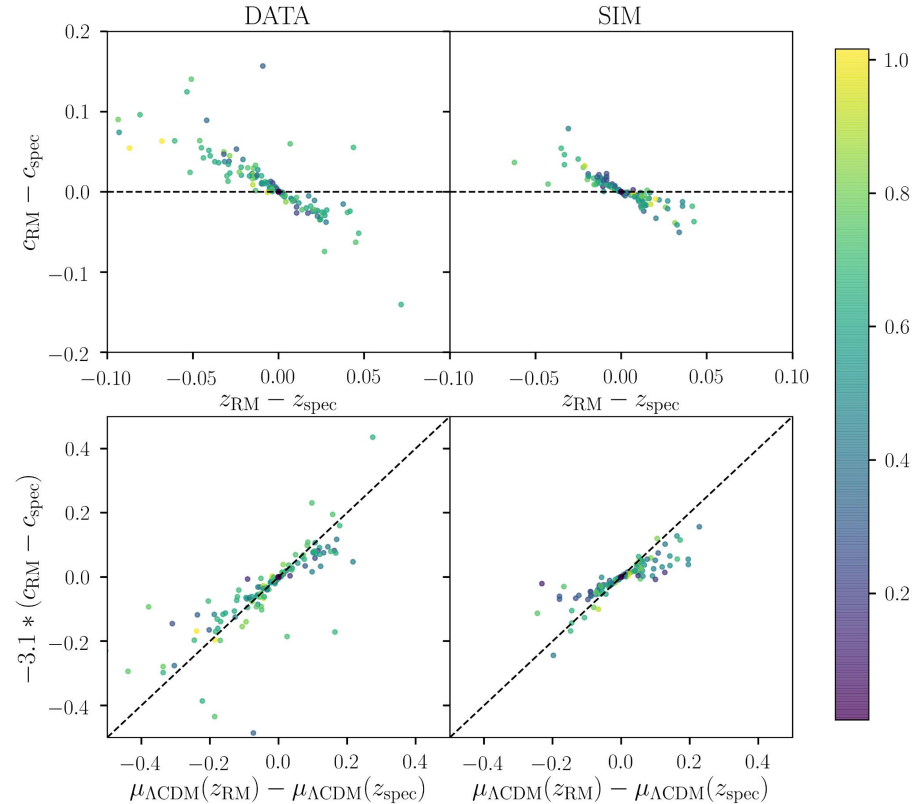
Differences in  $w$  are consistent with simulations



# Additional Findings

# Redshift-color relation

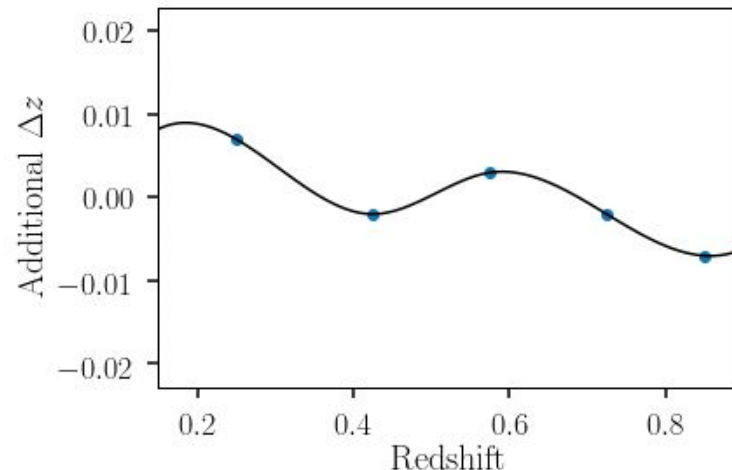
- $\mu$  uncertainty was previously overestimated
- Redshift and color bias are correlated
- Fortunate cancelation along LCDM



# Systematics tests

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- Simulate host-galaxy photo-z with exaggerated bias and scatter and scale linearly
  - Measure change in  $\Delta w$  with respect to change in scatter and bias
  - Expect systematics of 0.0086, 0.015
- Test realistic bias with redMaGiC calibration bias (Cawthon et al. 2020)

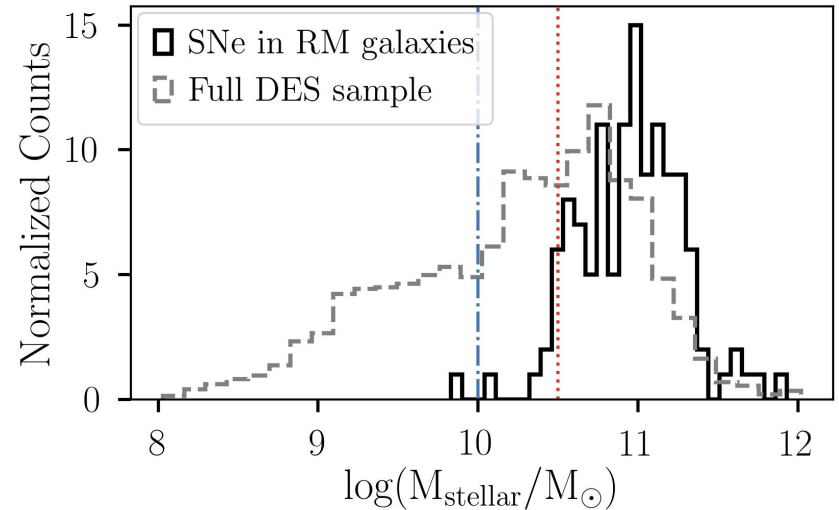


$$\Delta w = -0.005 \pm 0.0024$$

# SN-host galaxy relations

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- redMaGiC galaxies:  $10.5 < \log\text{Mass} < 11.9$
- DES full sample:  $8 < \log\text{Mass} < 12$
- Mass step cannot be measured
- Expect redMaGiC subsample to be more robust to host-galaxy relations





# Color-luminosity relation ( $\beta$ )

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- redMaGiC subsample (recall: massive, red, low SFR) has fitted  $\beta \sim 2$ 
  - Compared to  $\beta \sim 3$  for DES3YR
- Meldorf et al. in prep  $R_V$  measurement for redMaGiC galaxies is (1.54) vs full (2.61)
- Supports BS21 explanation
  - Direct link between low  $\beta$  for a subset of galaxies and low  $R_V$  predicted for the same set



# Future Work

# SN light-curve redshift fit

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- 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
  - SALT2 model range
  - May be improved with SALT3

# Increasing the SN sample

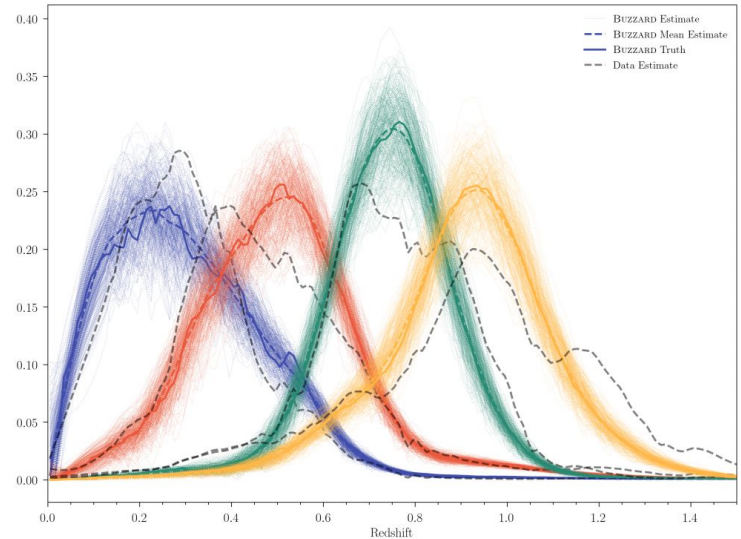
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- Consistent host-galaxy type across redshifts requires **redMaGiC low-z galaxies**
  - But... requires extra work, bright galaxies are unusual at low-z, require special photometry
  - And color-redshift relation may not be sufficient at low-z
- redMaGiC run on deep fields -> more potential host galaxies
- Other methods of restricting host galaxy type?

# Redshift distributions

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- Could we include information about the **distribution of redshifts** like 3x2 pt does?
- Bayesian approach? (better treatment of redshift uncertainties)



# Future Photometric Surveys

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- LSST and Rubin are upcoming
  - LSST (18,000 sq deg) vs DES (30 sq deg)
- Using TiDES forecast (Frohmaier et al. in prep)
  - Assume 6% of SNe Ia discovered are in LRGs and photo-z resolution of 0.02
  - 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** (2x smaller than statistical constraint from Pantheon)

# Summary

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- Proof of concept for exciting and promising new method for photometric SNIa samples that addresses multiple big concerns simultaneously
- Using host redMaGiC photo- $z$  results in  $w$  biases  $\sim 0.01$
- A lot of information to be used from different sources of host-galaxy redshift info

# Backup Slides



# Tripp equation

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Distance modulus

Related to overall amplitude

stretch

color

Bias correction from simulations

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

Nuisance parameters

Absolute magnitude of a standard Ia

# Redshift contribution to mu uncertainty

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

$$\sqrt{\sigma_{\mu_{\text{phot}}}^2 - \sigma_{\mu_{\text{spec}}}^2}$$

# Why only CC in LRGs?

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- CC progenitors are massive ( $> 8 M$ ) and explode in gas-rich, star forming galaxies
- In terms of galaxy age– CC first, then prompt Ia, then long tail for accretion
- Foley & Mandel 2013, Irani et al. 2021

# redMaGiC algorithm details

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- 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 desired comoving space density