THE DARK ENERGY SURVEY

Spectroscopic SNeIa 3-Year Cosmology Results

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On behalf of the DES Supernova Working Group

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Penn UNIVERSITY of PENNSYLVANIA

DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

Fermilab

THE DARK ENERGY SURVEY

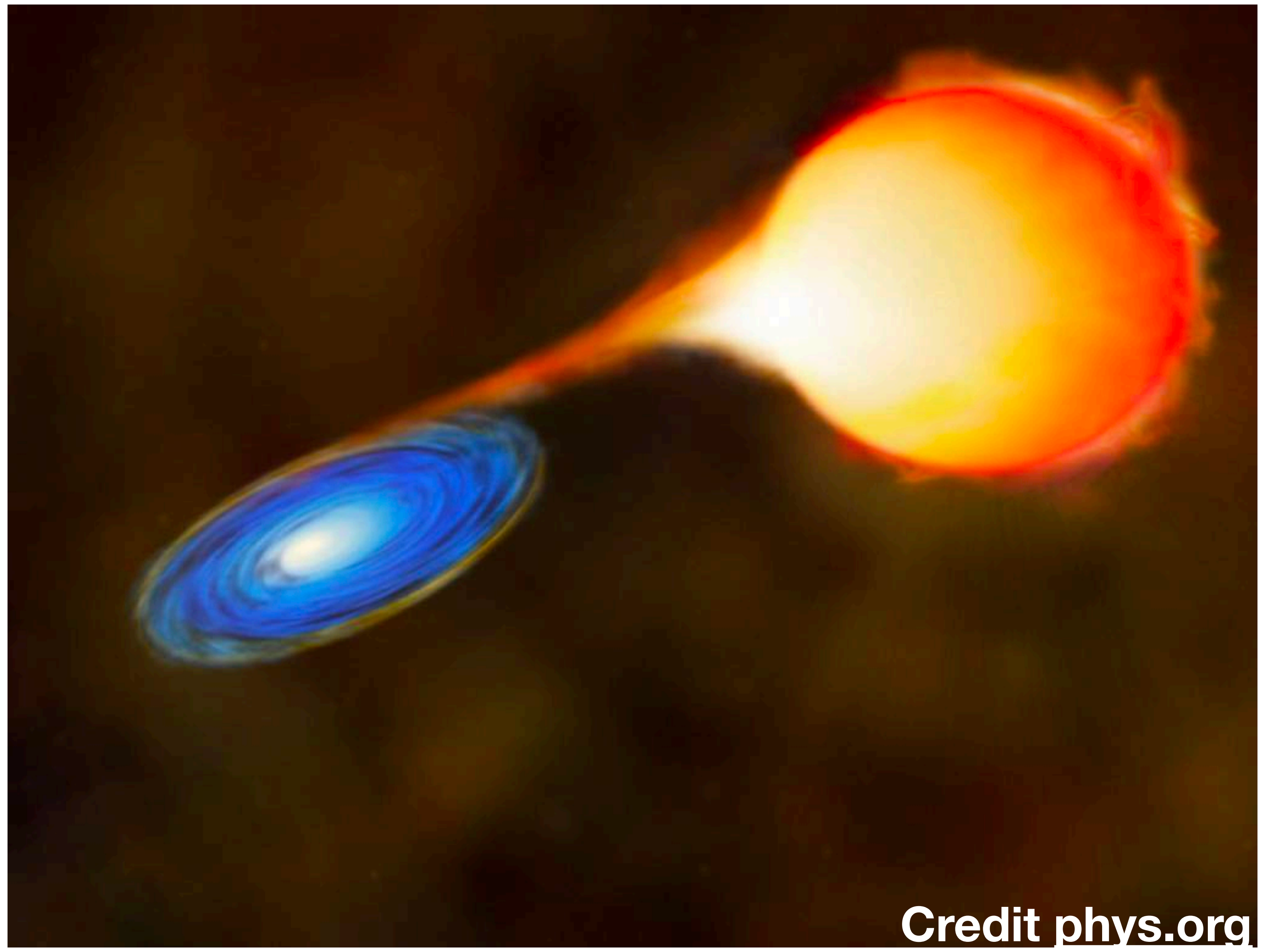
Motivation

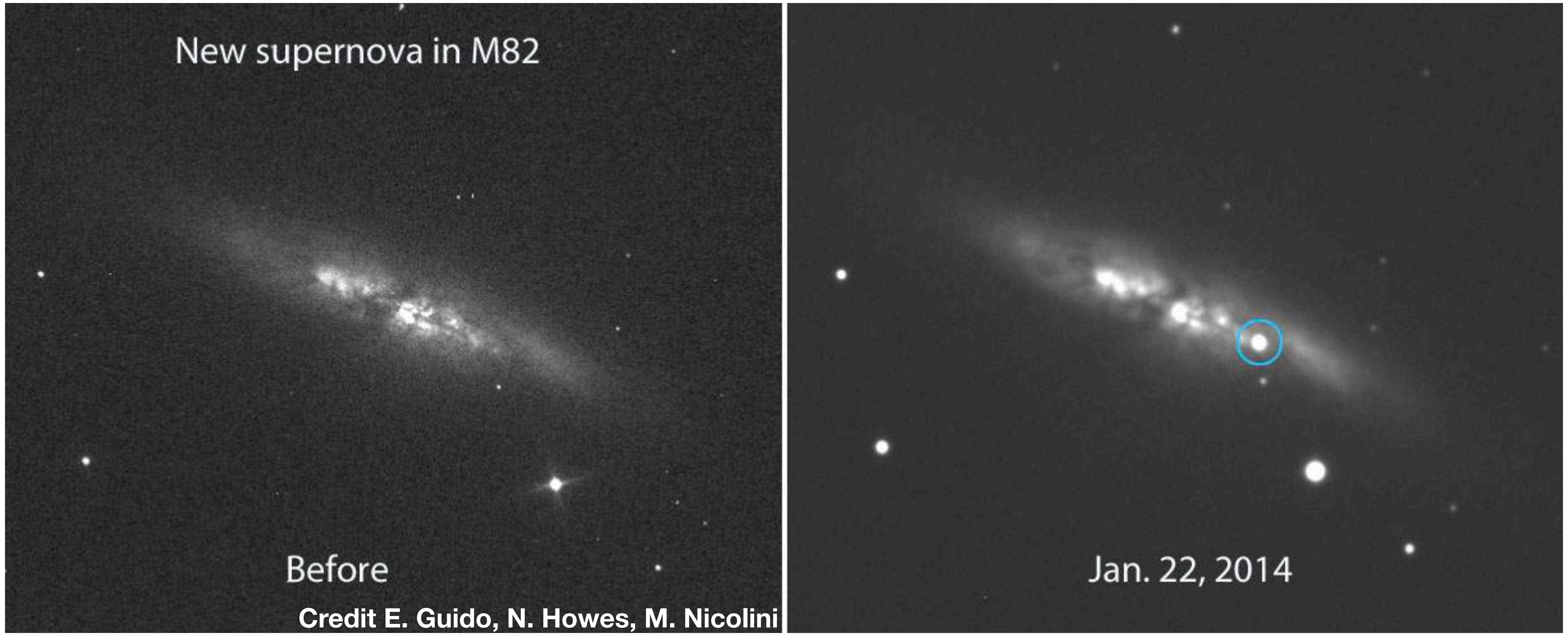
Ingredients for SN Ia Cosmology

Results from the First 3 Years

The Future of DES-SN

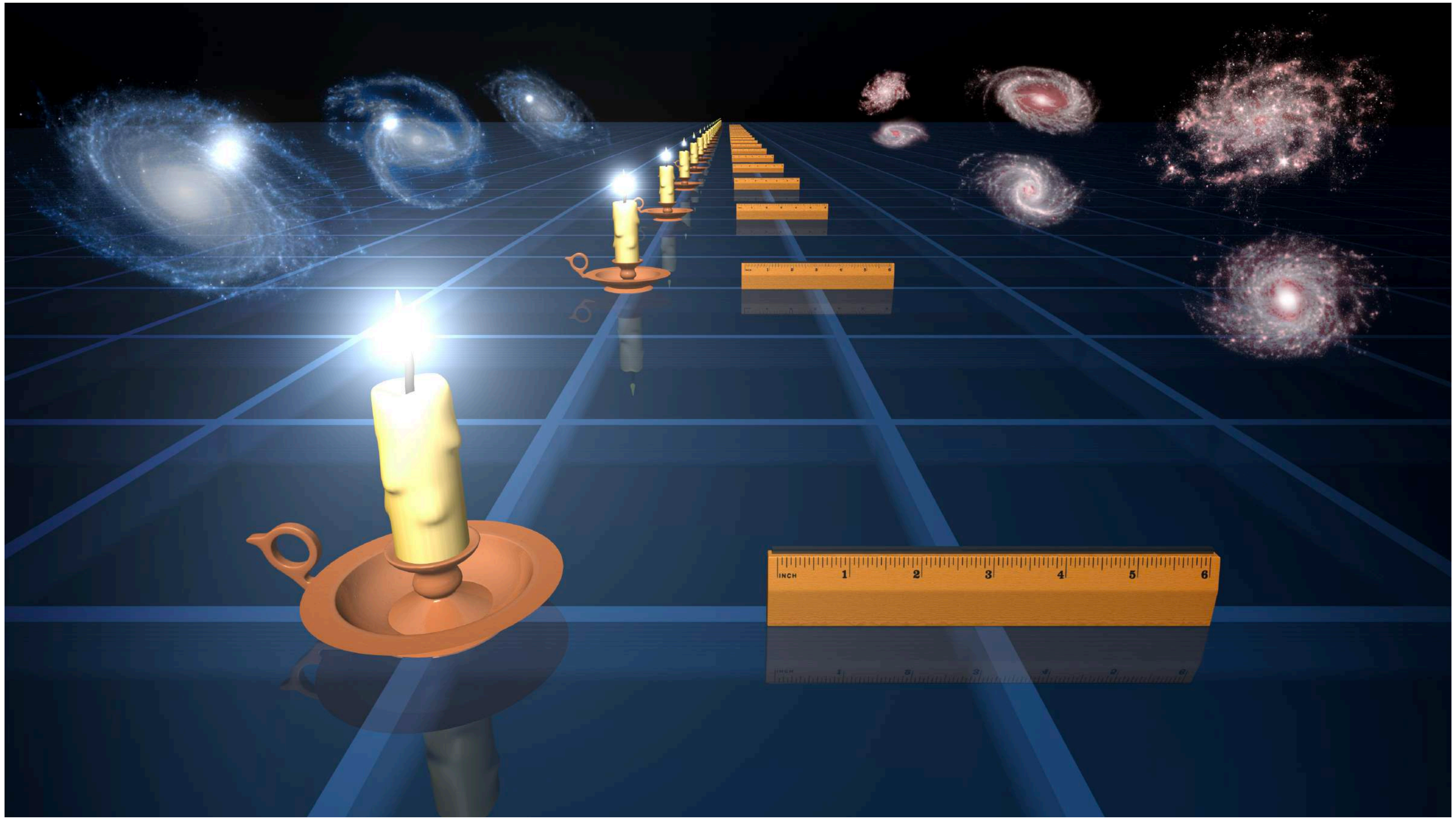
What are Type Ia Supernovae?





1 SN per galaxy per century

Why Type Ia Supernovae?



Luminosity Distance

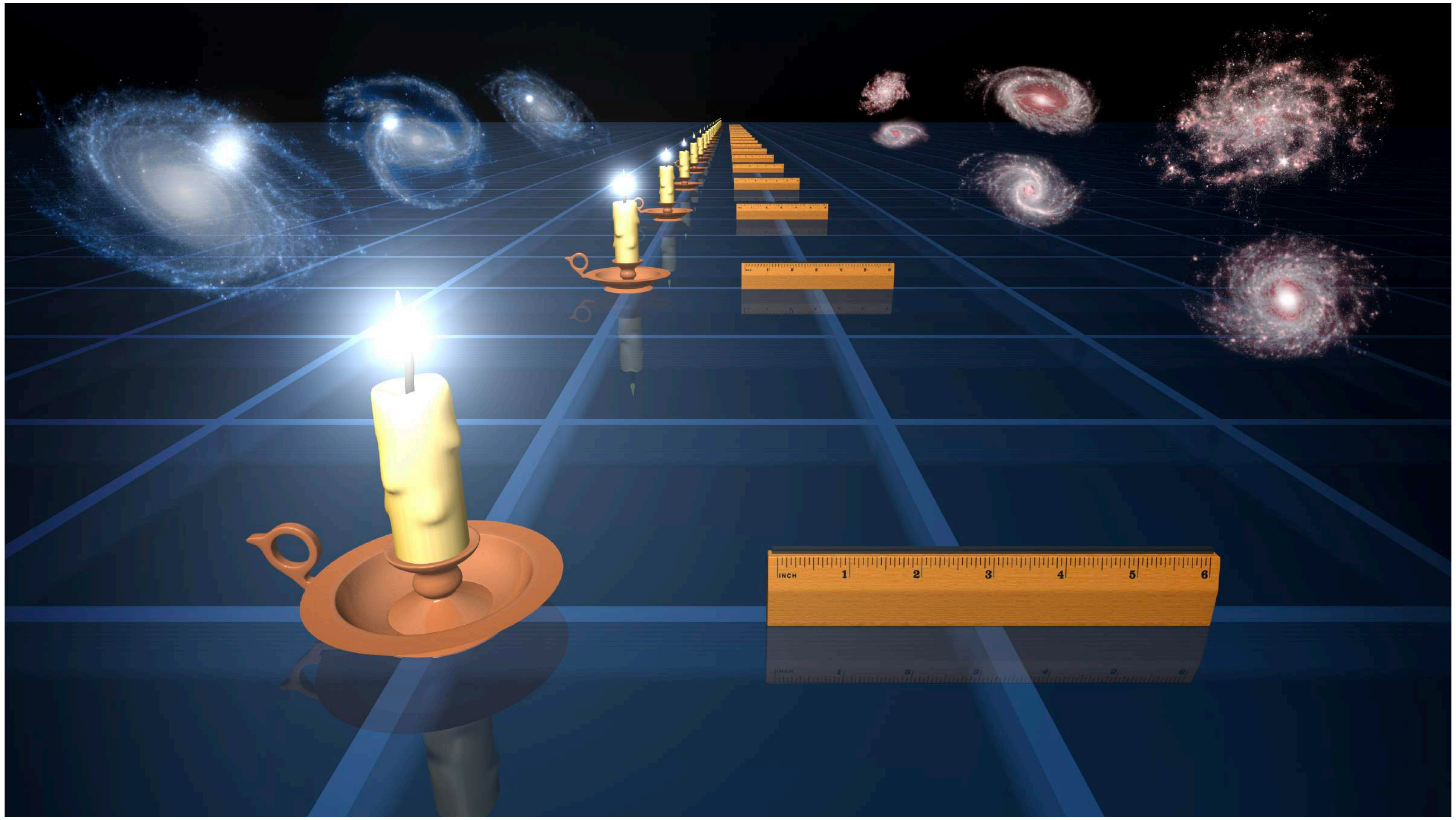
$$F = \frac{L}{4\pi D_L^2}$$

Distance Modulus

$$\mu(D_L) = m - M$$

Apparent **Intrinsic**

Why Type Ia Supernovae?



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Intuition → $\Delta\mu \sim \%$

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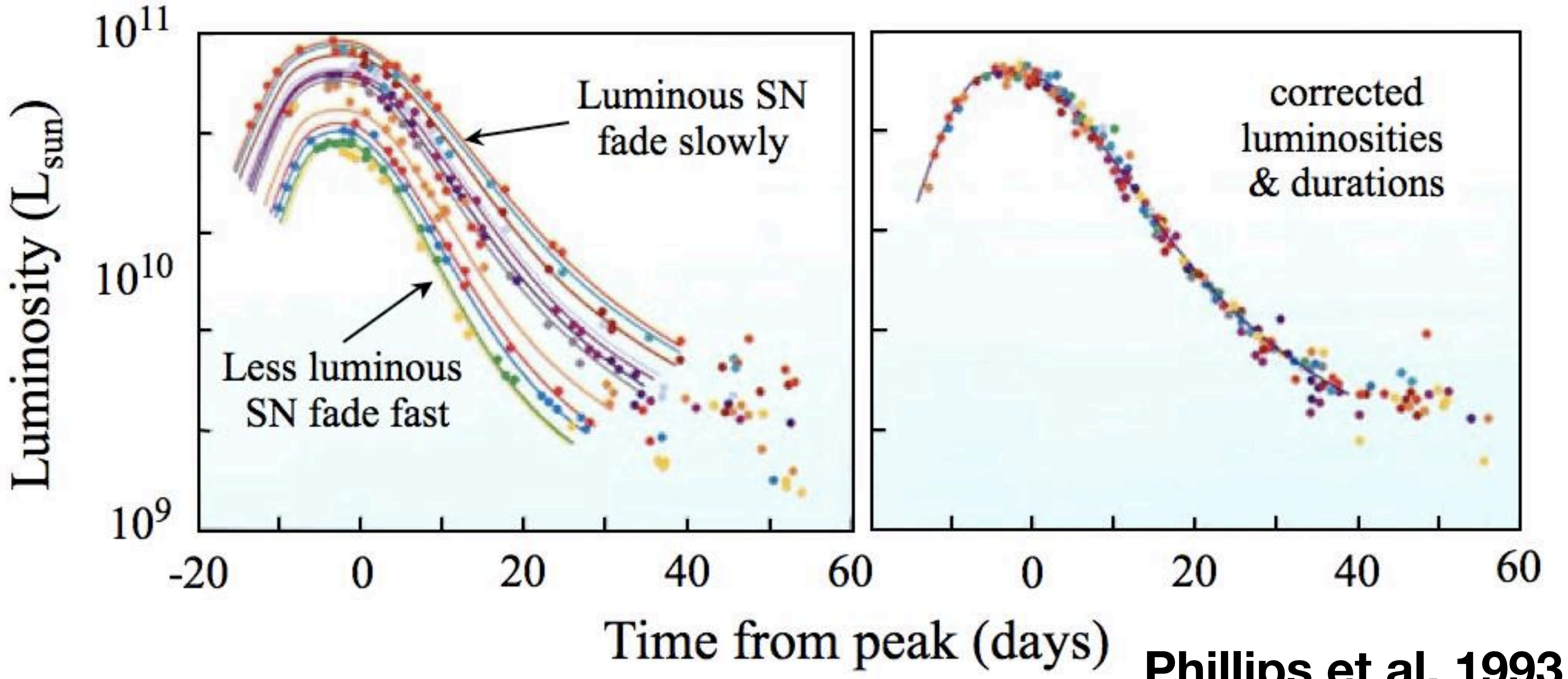

Phillips et al. 1993

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

- *Standardizable* Candles
- Intrinsic luminosity is known to ~10%
- We measure the redshift of the SN or the Host galaxy

20 year anniversary

March 1998 - acceleration of the Universe - nonzero cosmological constant discovery by the SCP and HZT.

20 year anniversary

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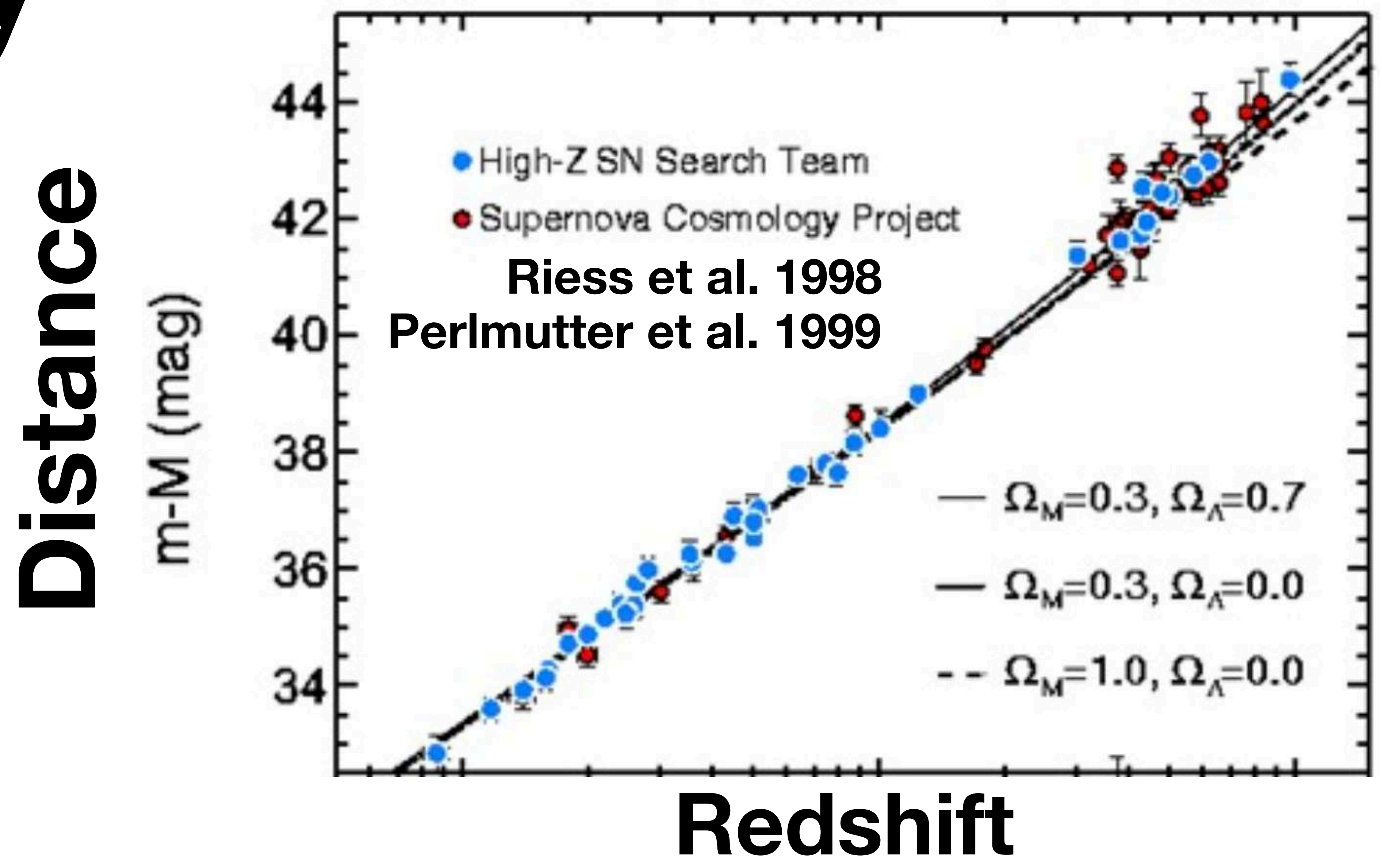
Nobel Prize Datasets



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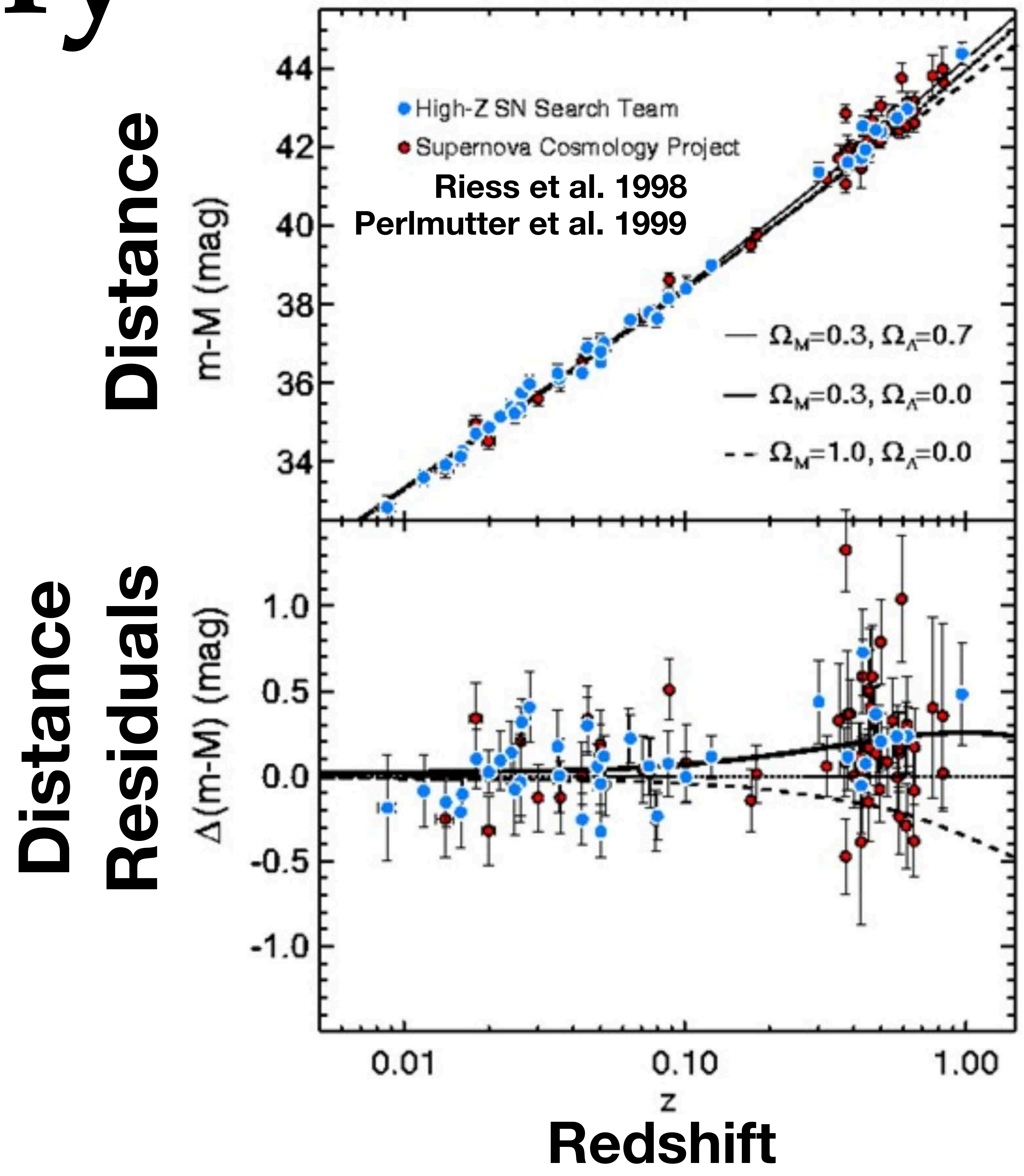

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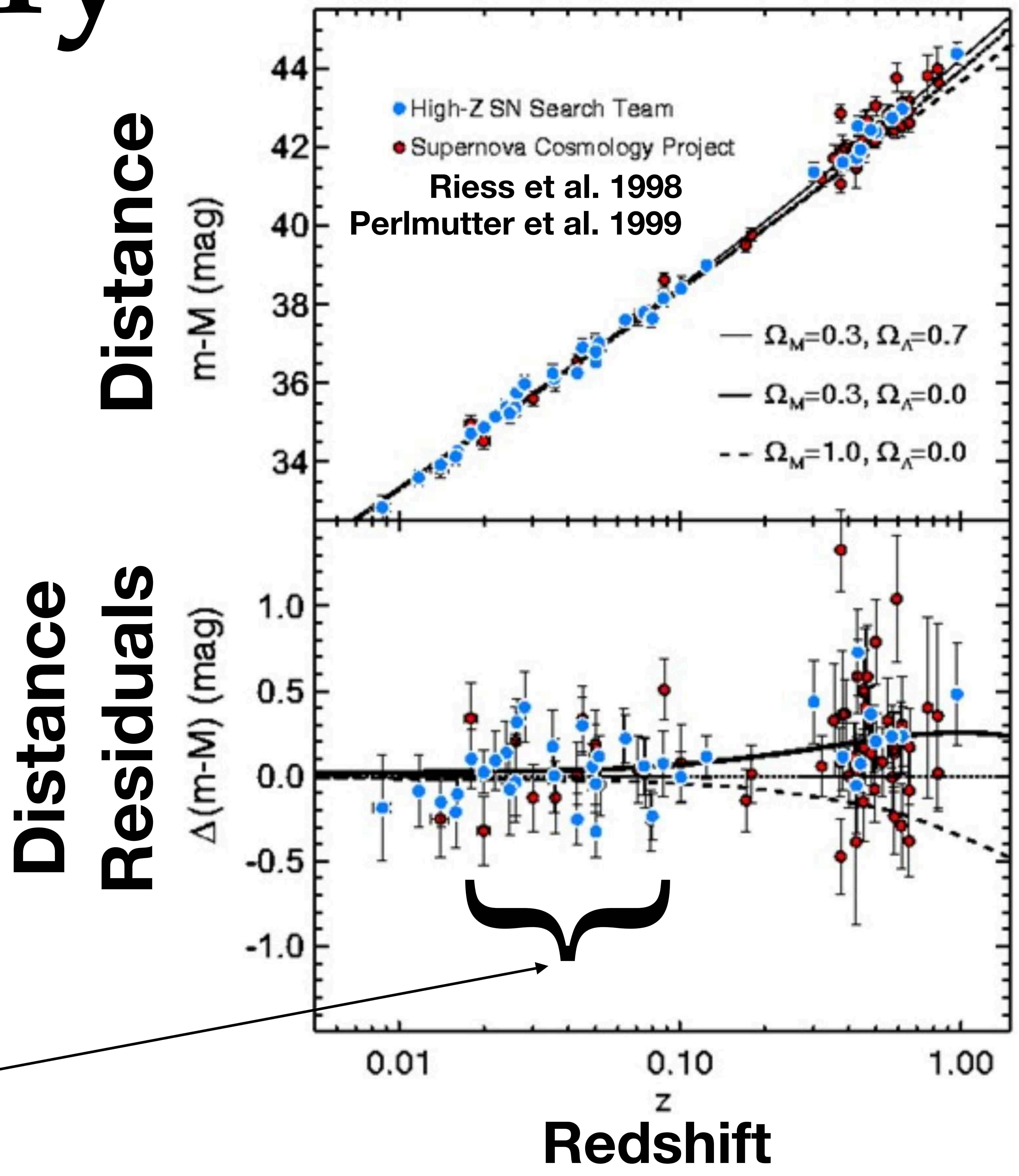

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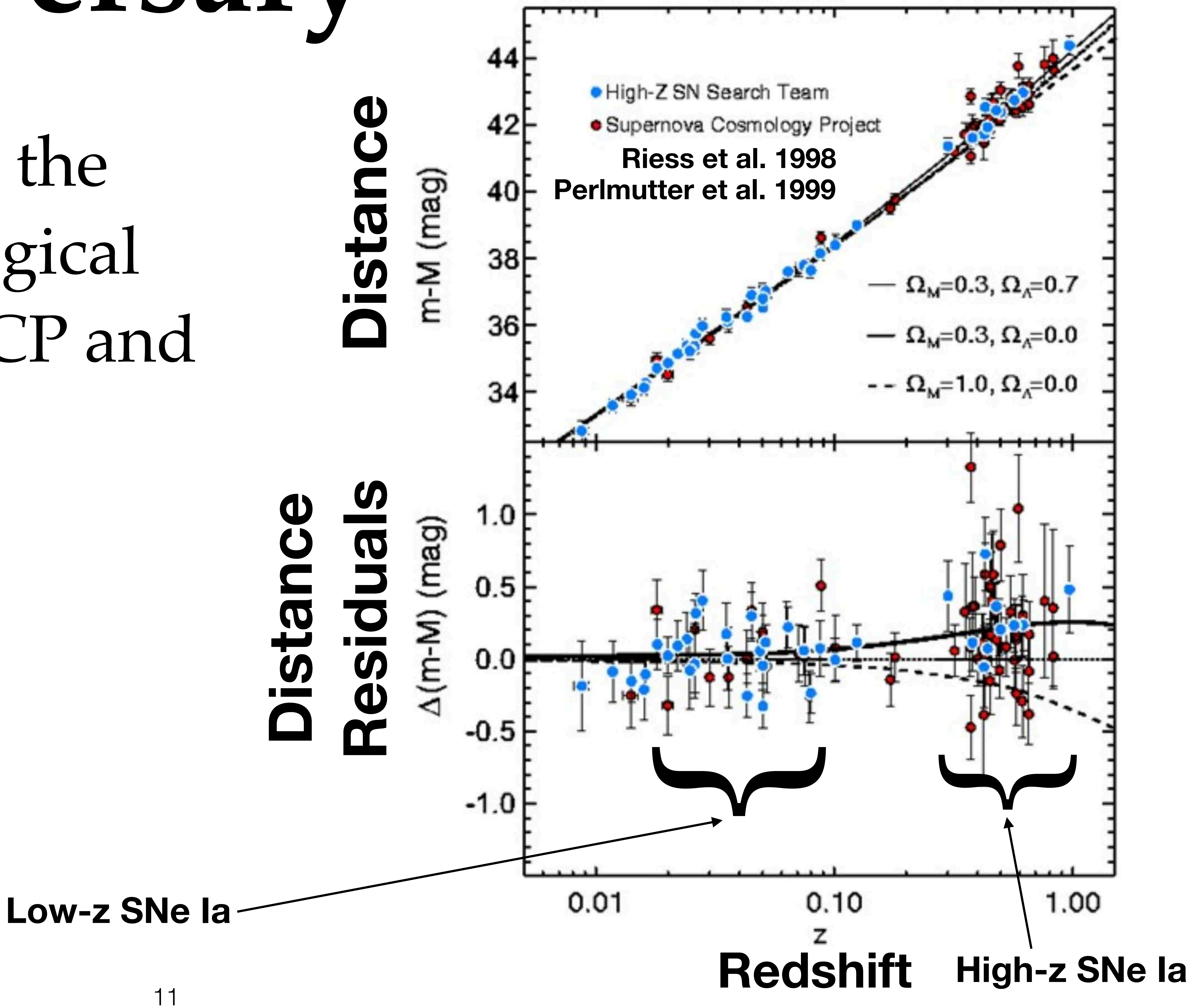


Name of the game…

Luminosity distance

Redshift

→

Measure the effective scale of the universe over time

Search for departures from the standard cosmological model

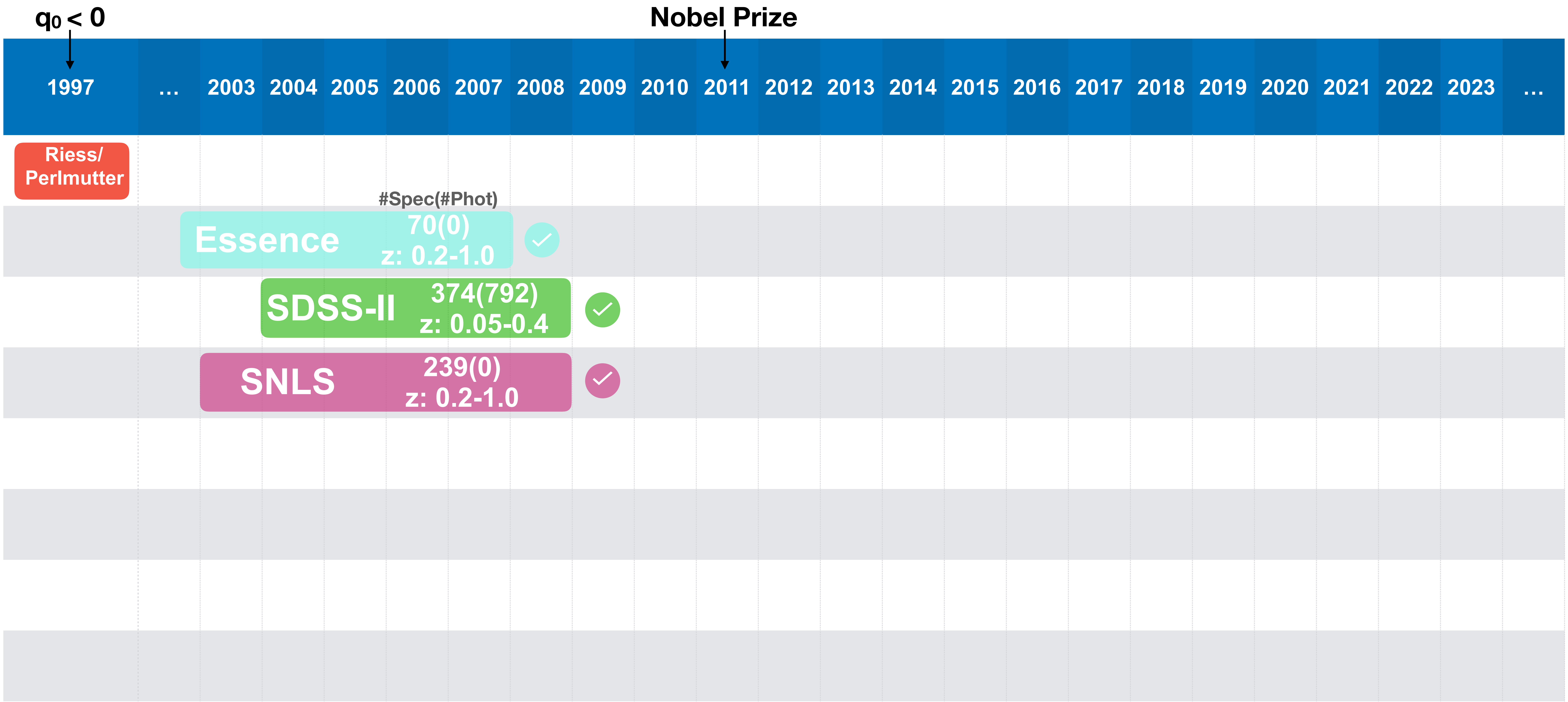
ΛCDM

Landscape of High Redshift Rolling SN Surveys

$q_0 < 0$ (↓ 1997) — Nobel Prize (↓ 2011)

1997	…	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	…
Riess/ Perlmutter																							

Landscape of High Redshift Rolling SN Surveys



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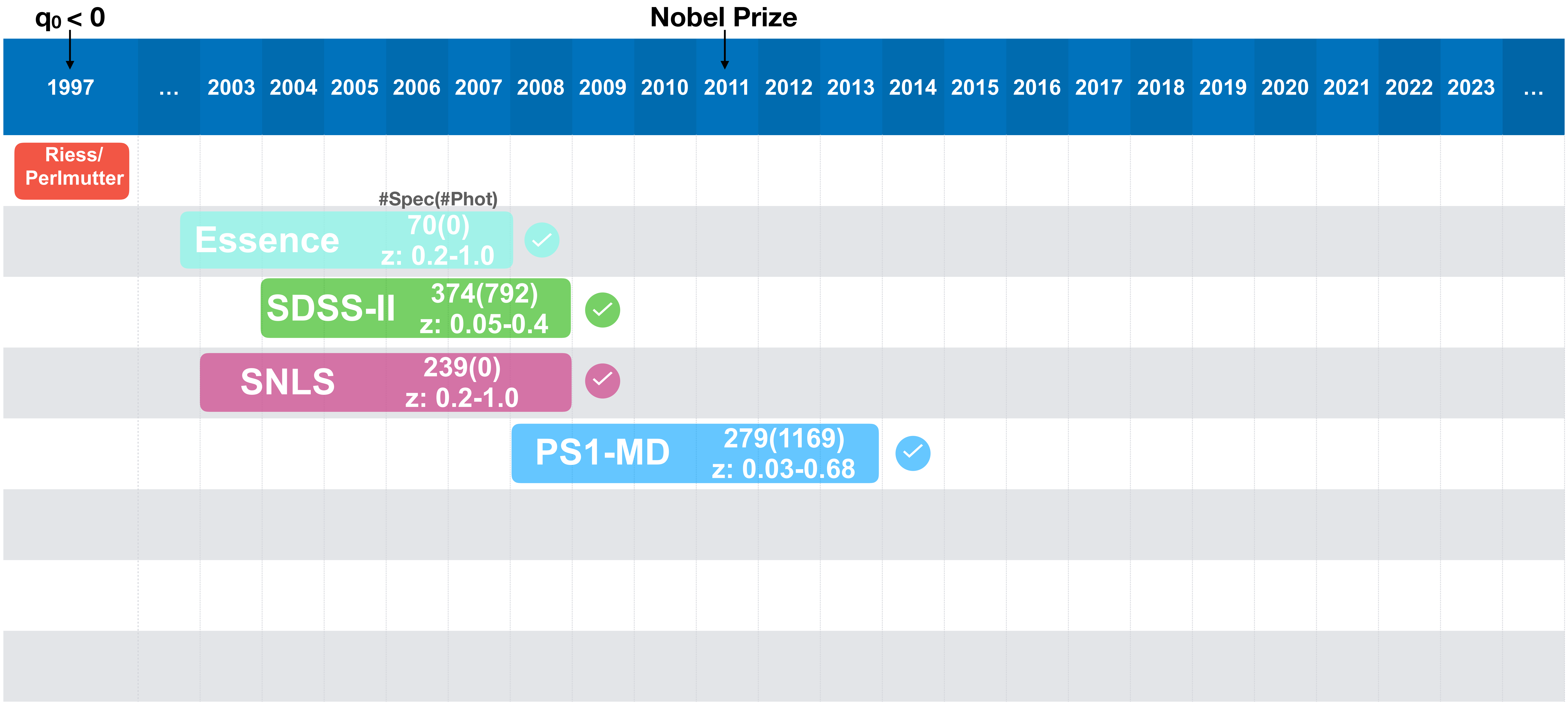

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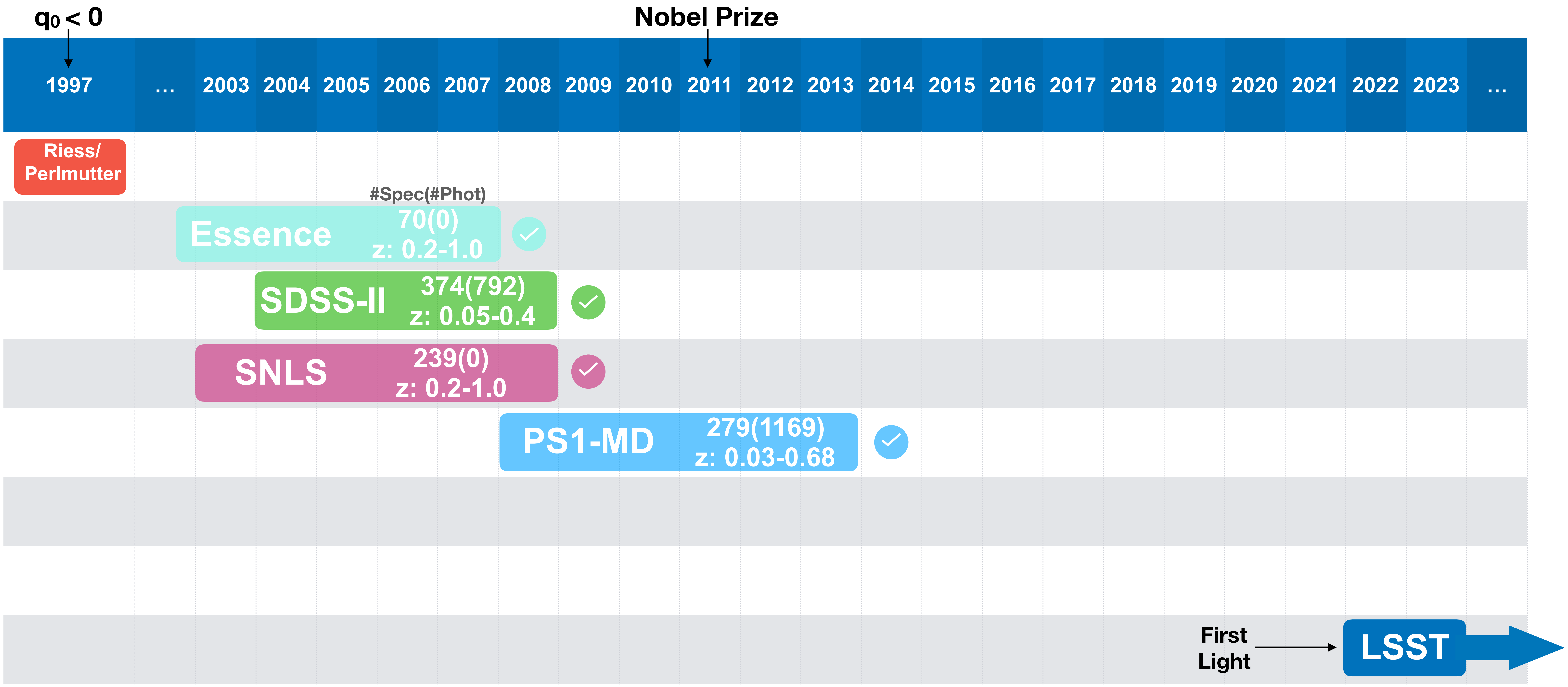

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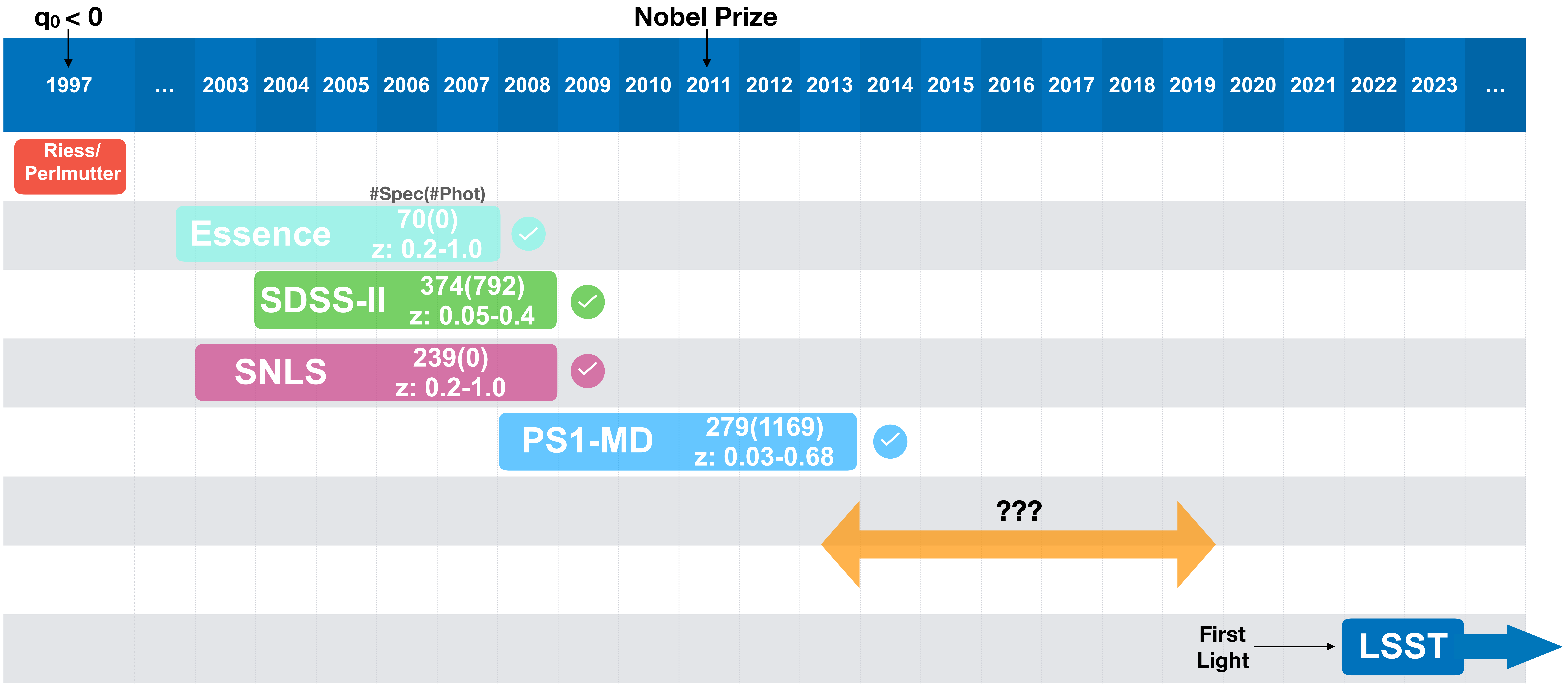

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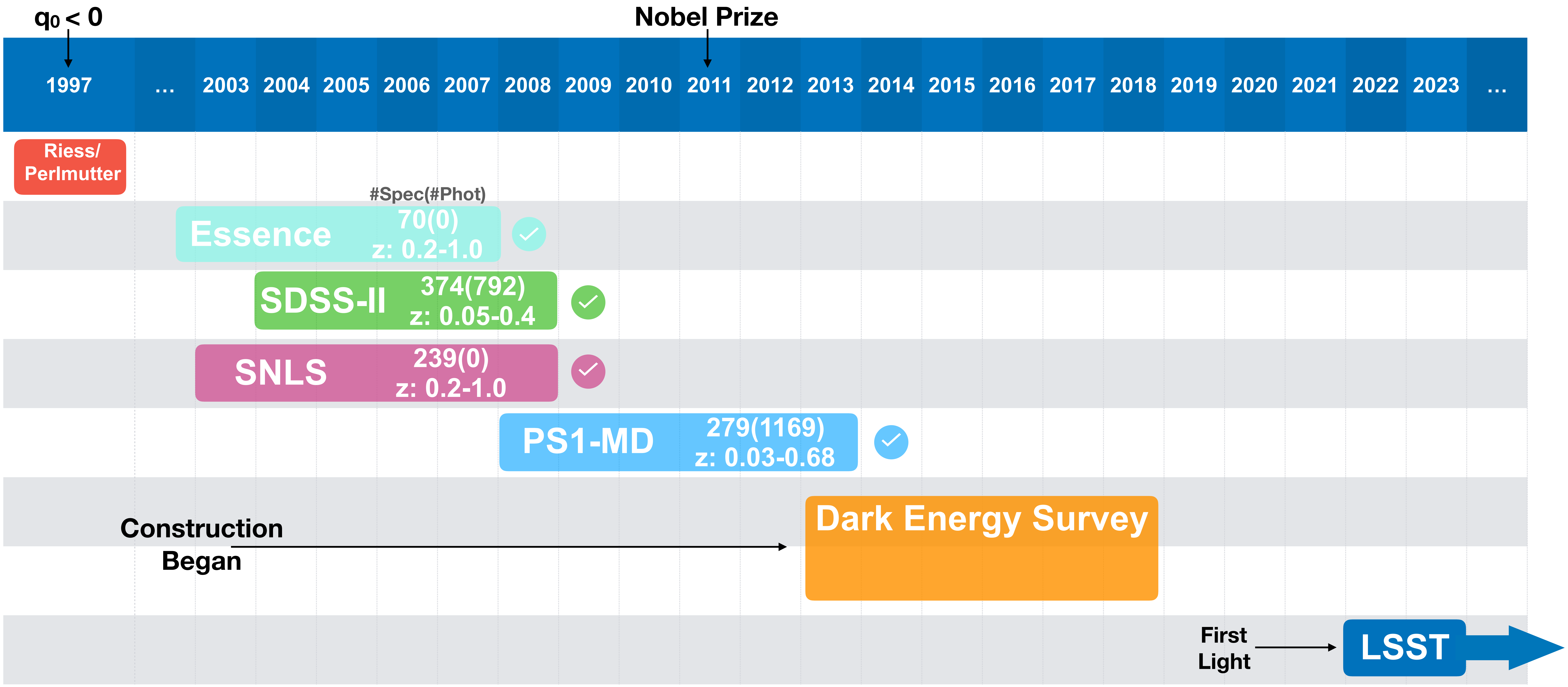


THE DARK ENERGY SURVEY

4 Main Probes

- Supernovae
- Weak Lensing
- Baryon Acoustic Oscillations
- Cluster counting

THE DARK ENERGY SURVEY

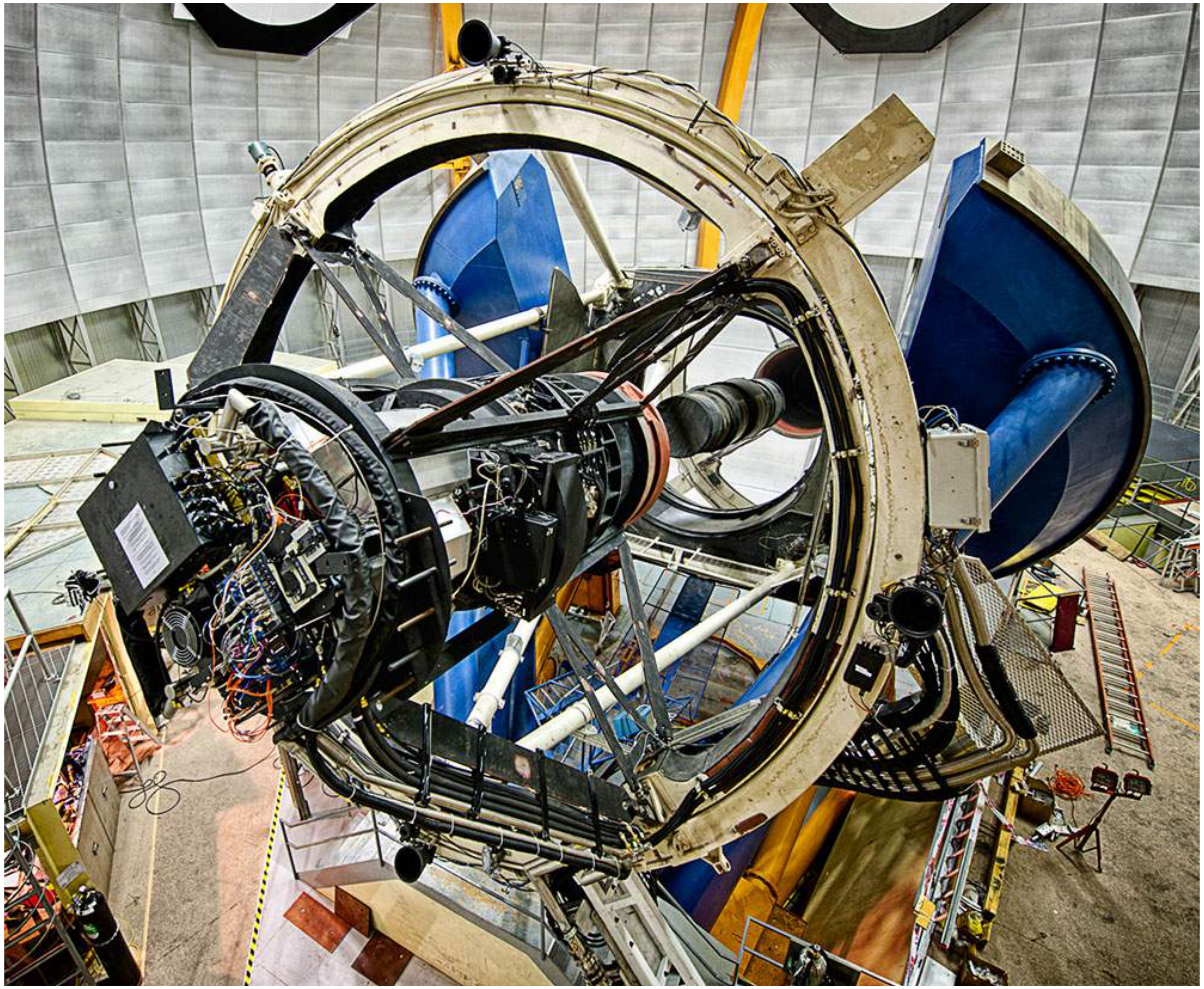
570 Megapixels

2.2 degree diameter FOV camera on the Blanco 4m telescope

Facility instrument for astronomy community (DES 30% time)

DES 2013-2018 (525 nights)

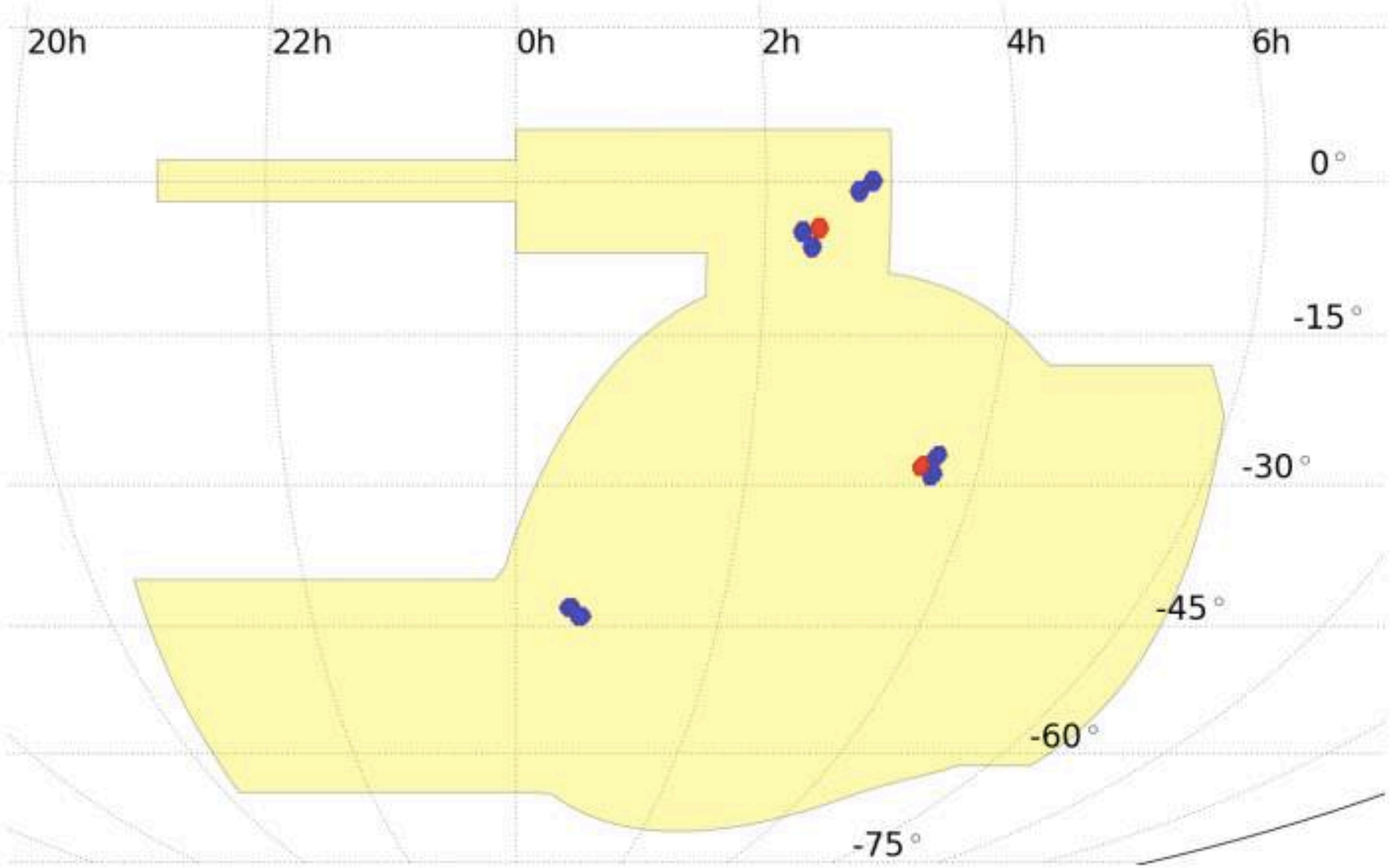
Mean cadence of 7nights. Cadence monitor



www.darkenergysurvey.org

THE DARK ENERGY SURVEY

Two multi-band imaging surveys

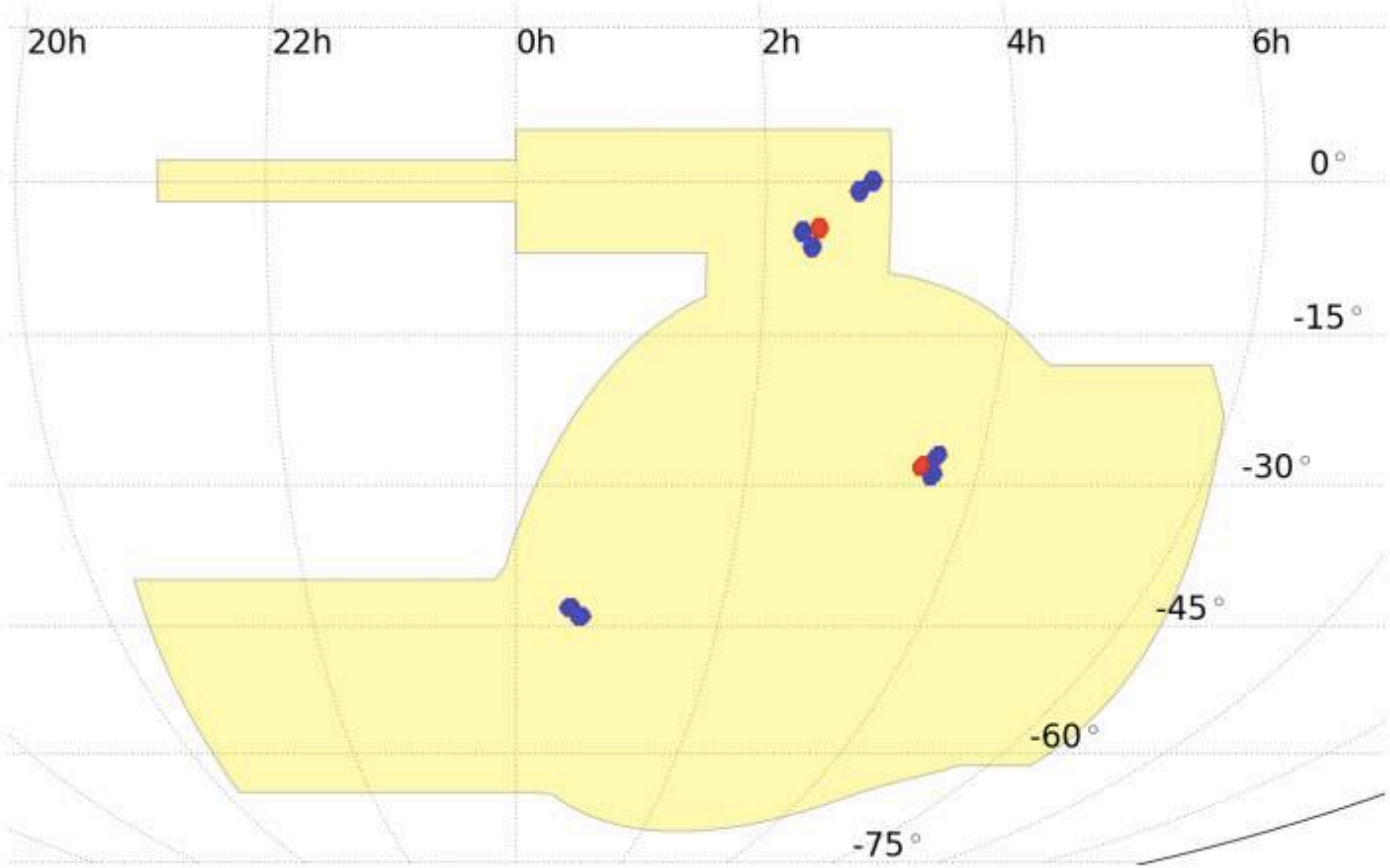


D'Andrea et al. 2018

THE DARK ENERGY SURVEY

Two multi-band imaging surveys

5000 deg^2 *grizY*



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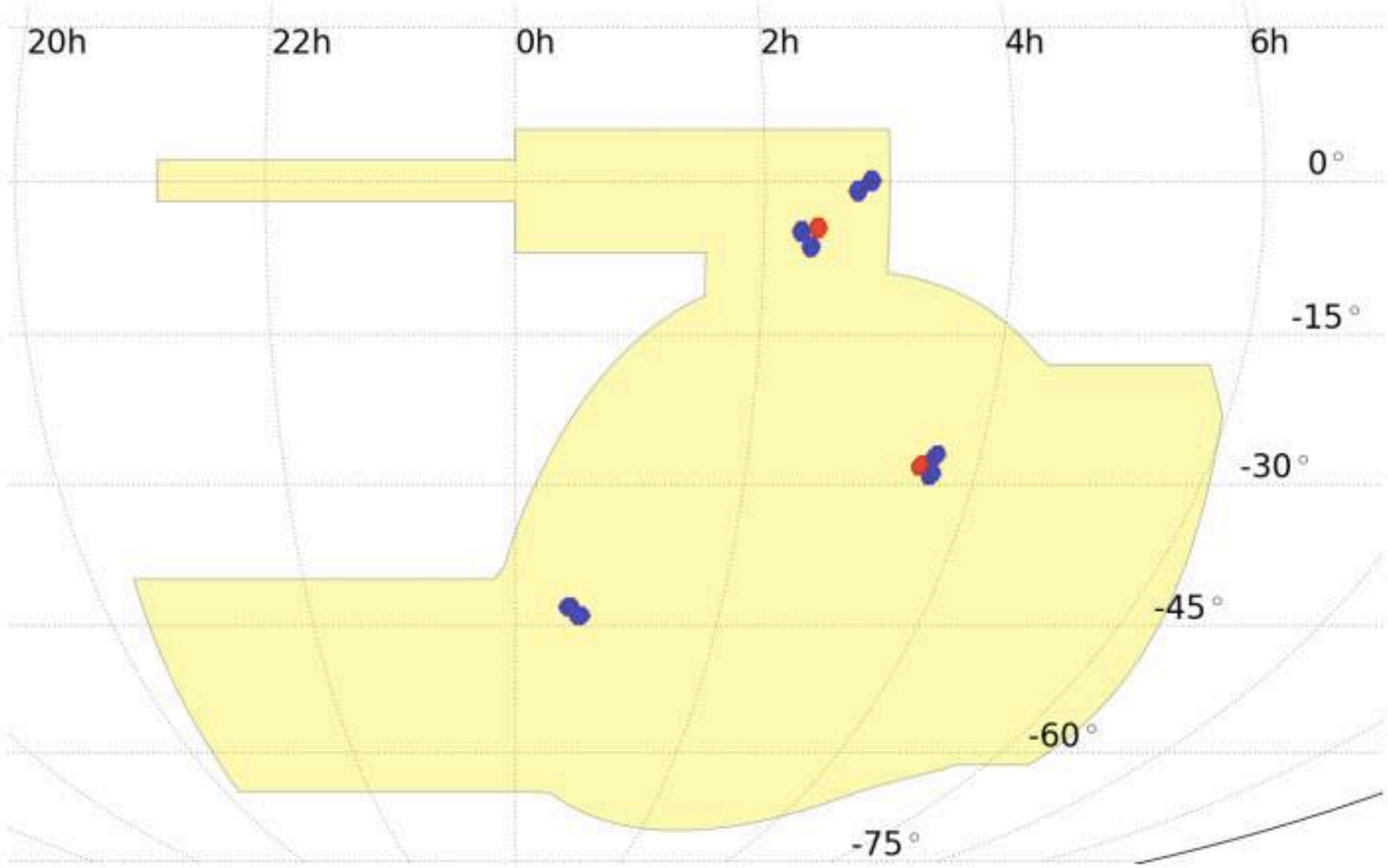
Two multi-band imaging surveys

5000 deg² *grizY*

30 deg² repeat *griz*
10 pointings (SNe)



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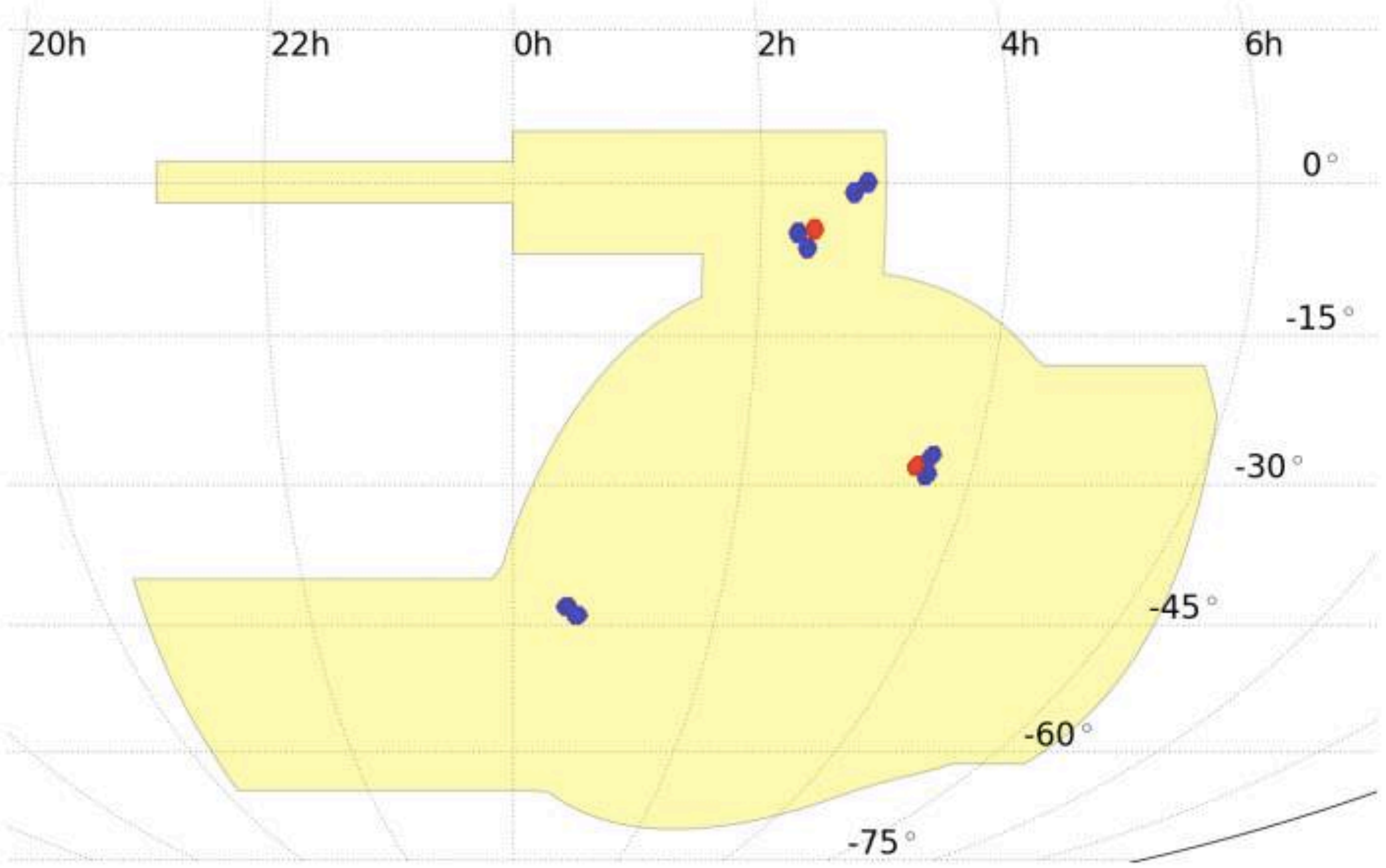

	area (deg²)	visits (per filter)	filters	exposure time in sec (per visit)	Depth
SN shallow	22	125	*griz*	175/150/200/400	23.5
SN deep	5	125	*griz*	600/1200/1800/3630	24.5

D'Andrea et al. 2018

THE DARK ENERGY SURVEY

Two multi-band imaging surveys

5000 deg² *grizY*

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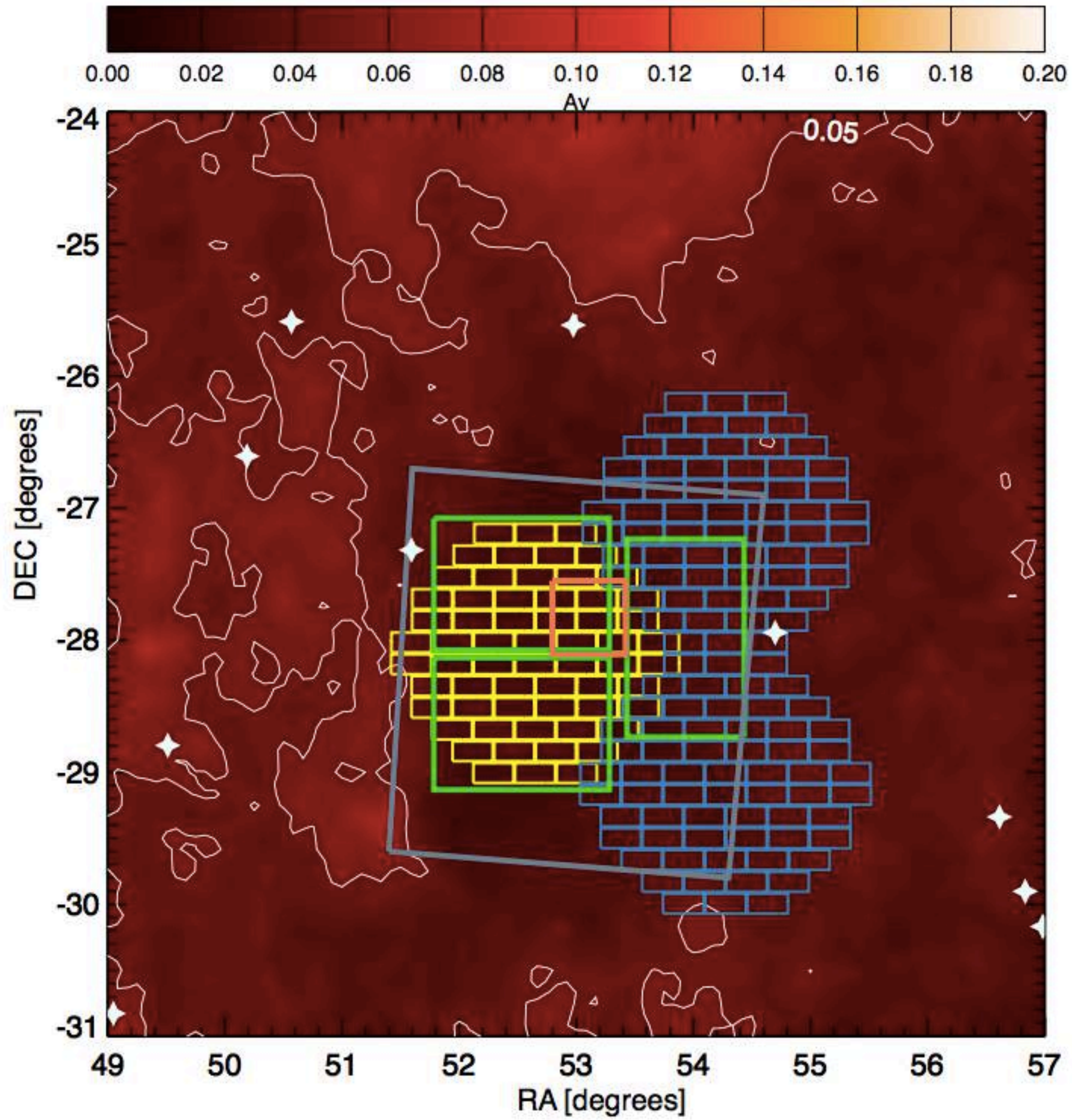
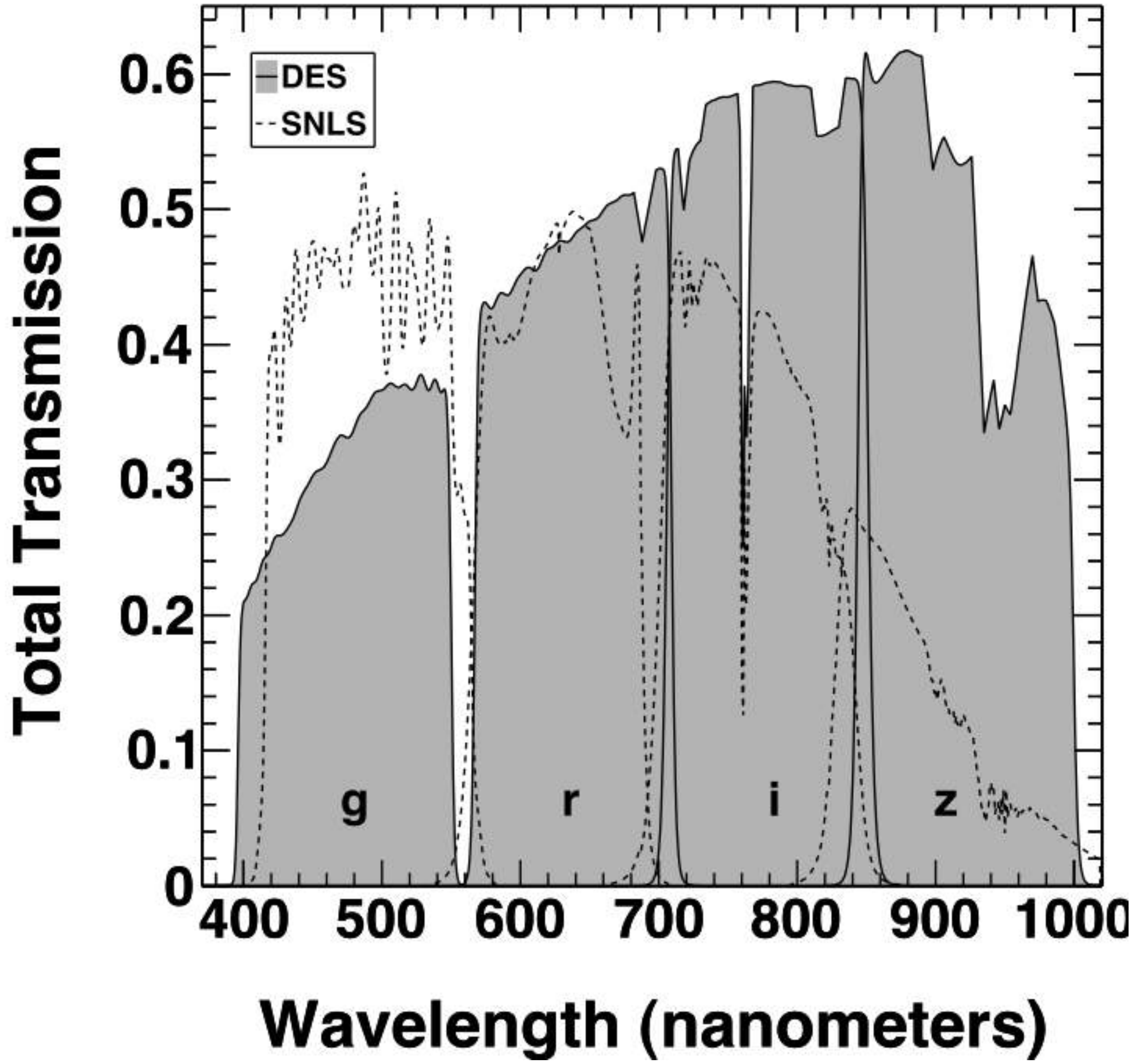
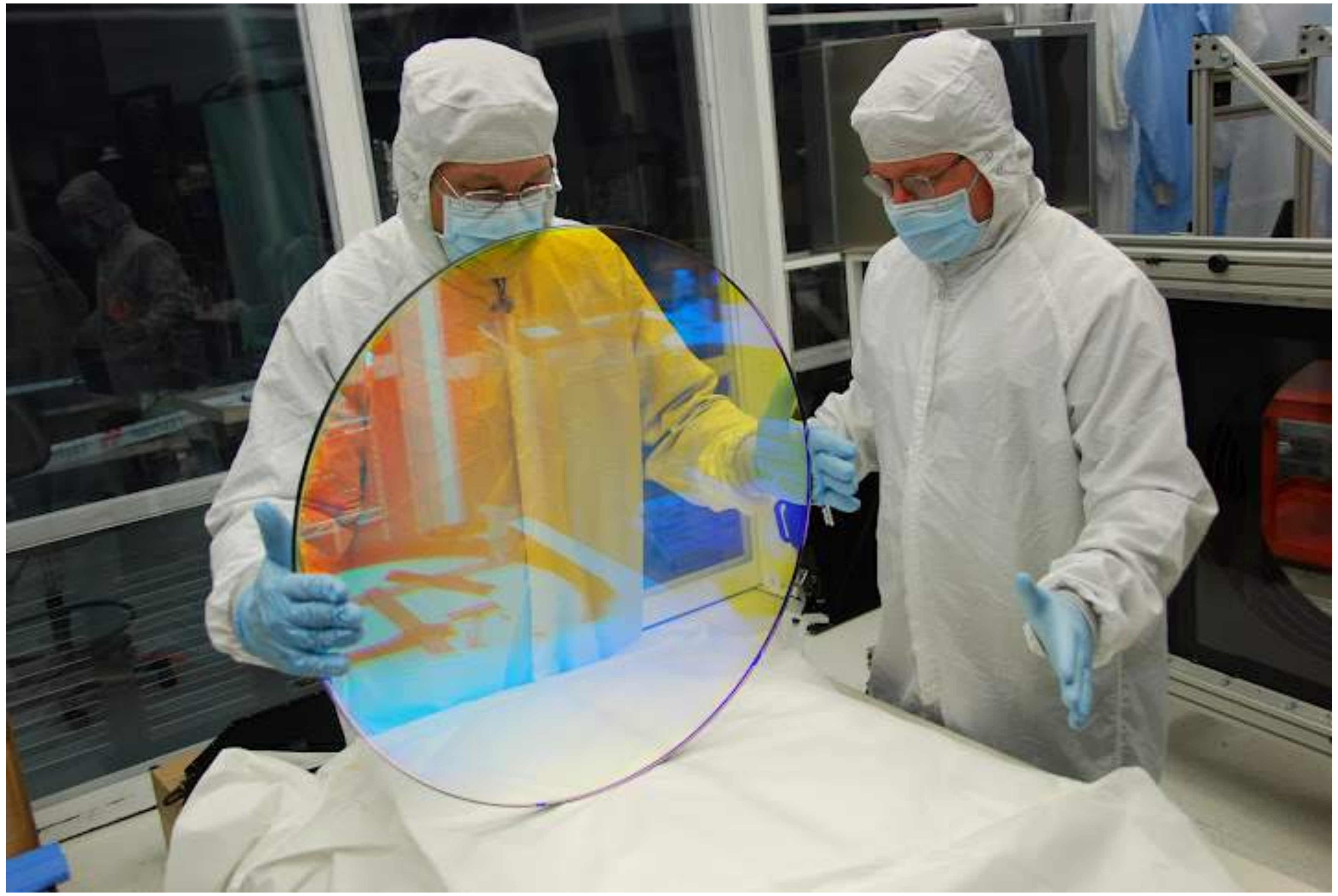


D'Andrea et al. 2018

THE DARK ENERGY SURVEY

New red-sensitive camera (DECAM) on CTIO 4m





Classification of the Supernova to be used for cosmology

- DES "discovered" ~15,000 Likely Supernovae
- ~2500 Type Ia for all 5 years

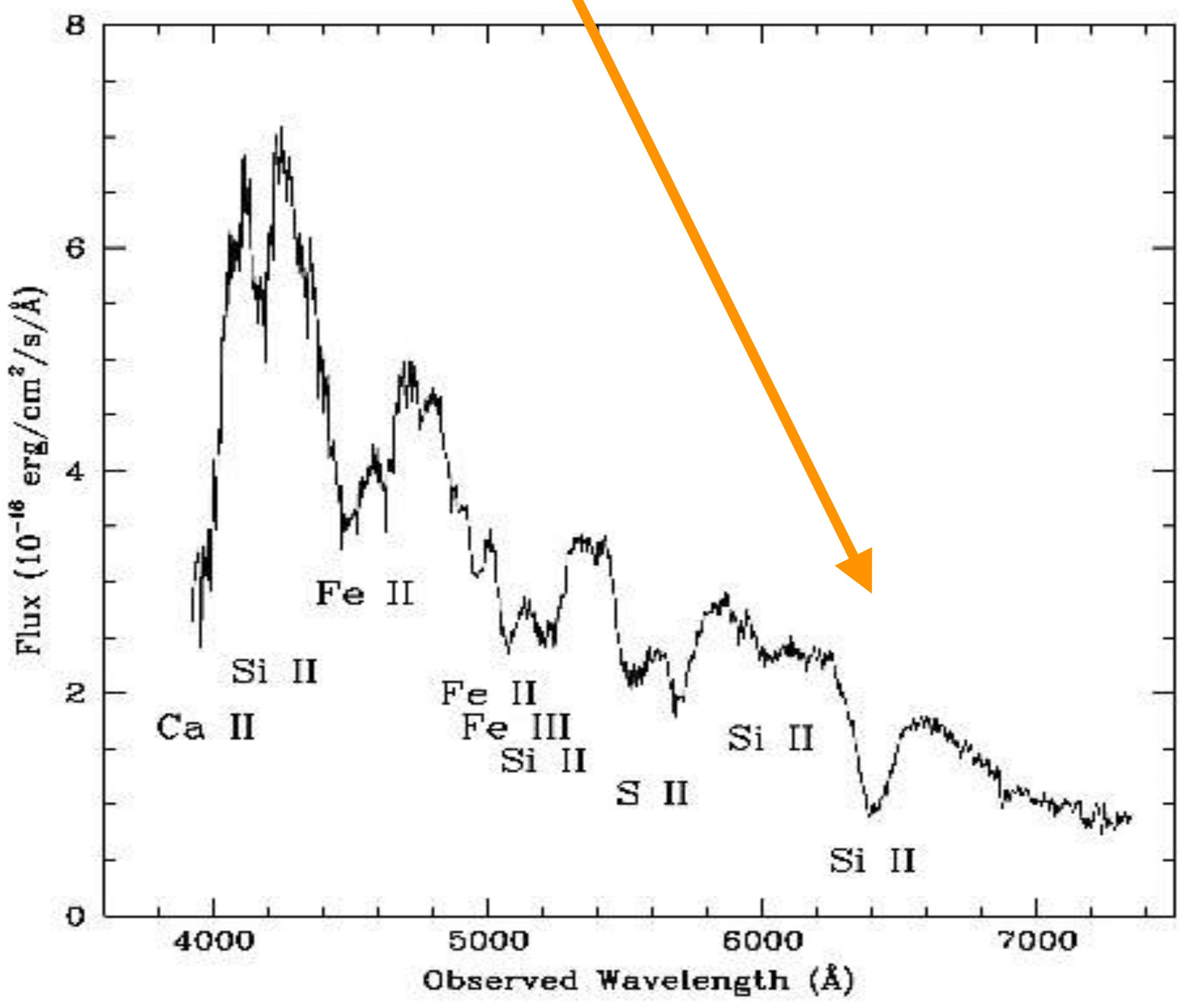
With 4 filters **Or** Spectrum of SN

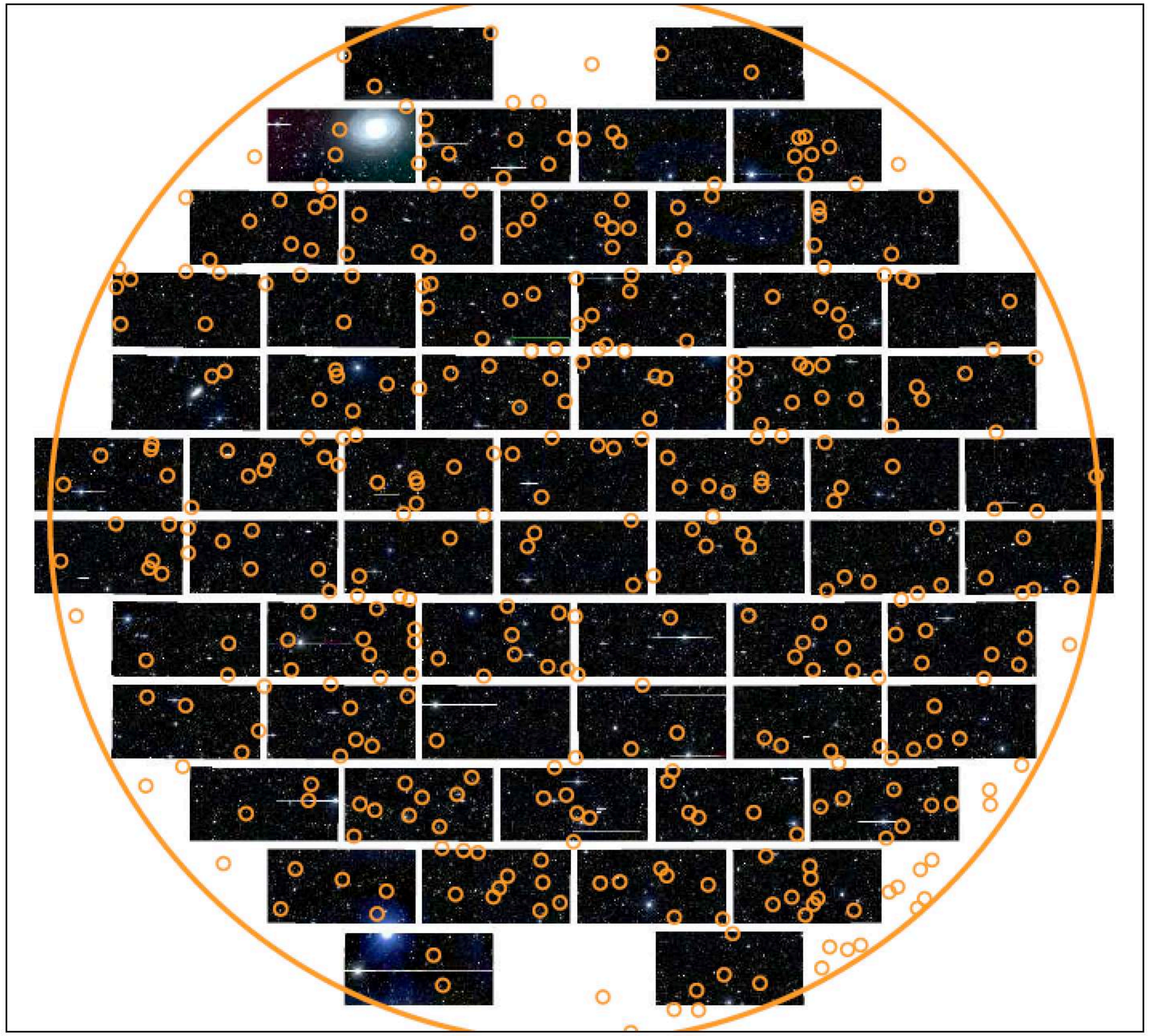
Spectra of SNe

Spectroscopically confirmed 251 SNe from the first three years of data.

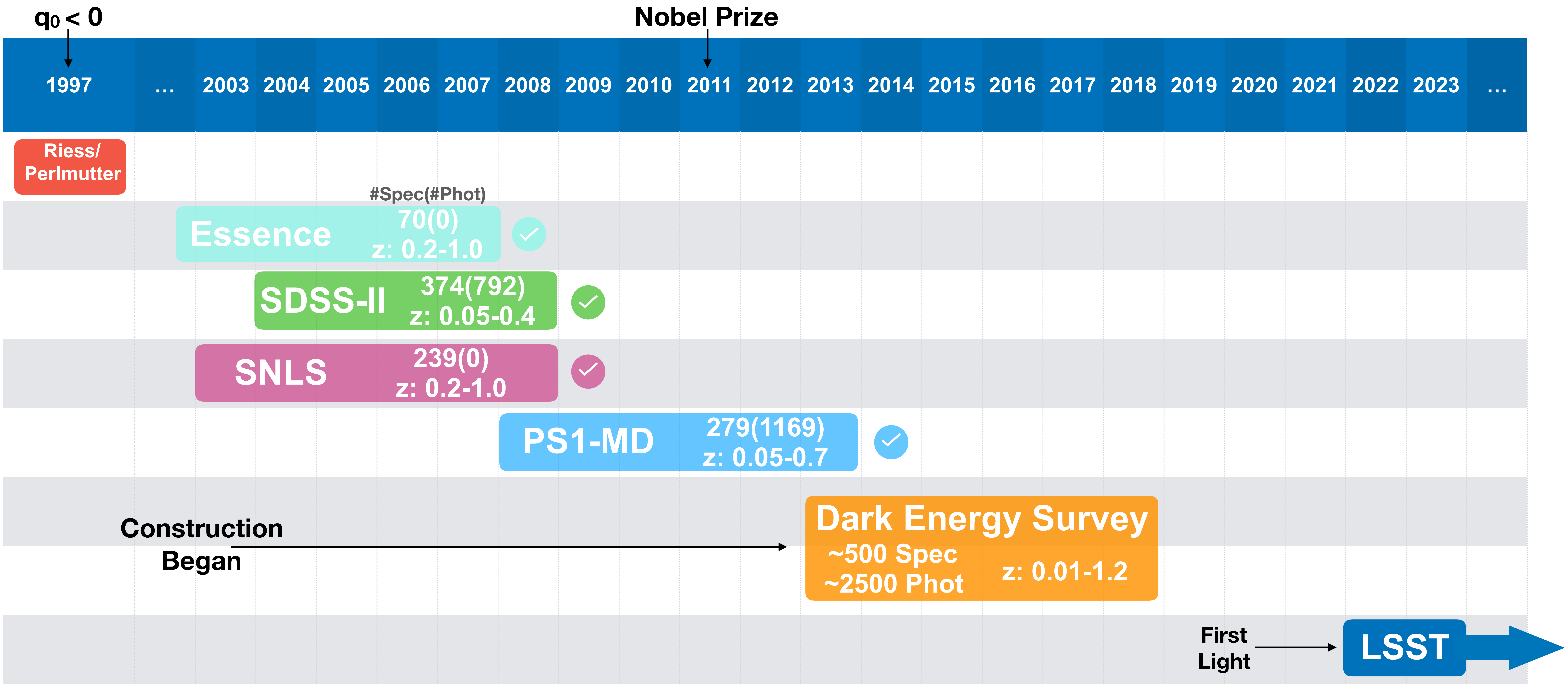
Majority from OzDES Collaboration

Identify via Si II feature in spectrum





Landscape of High Redshift Rolling SN Surveys



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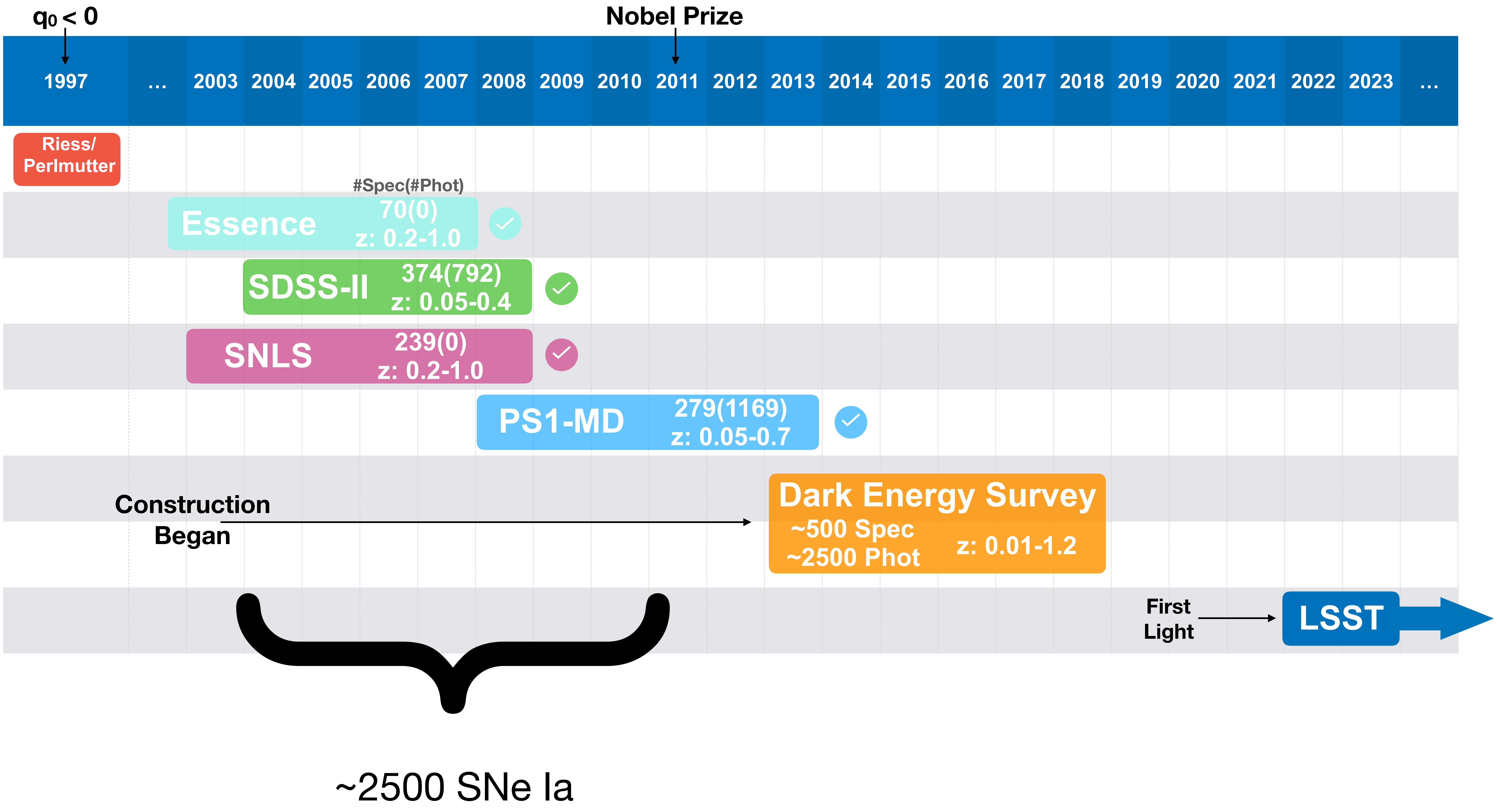

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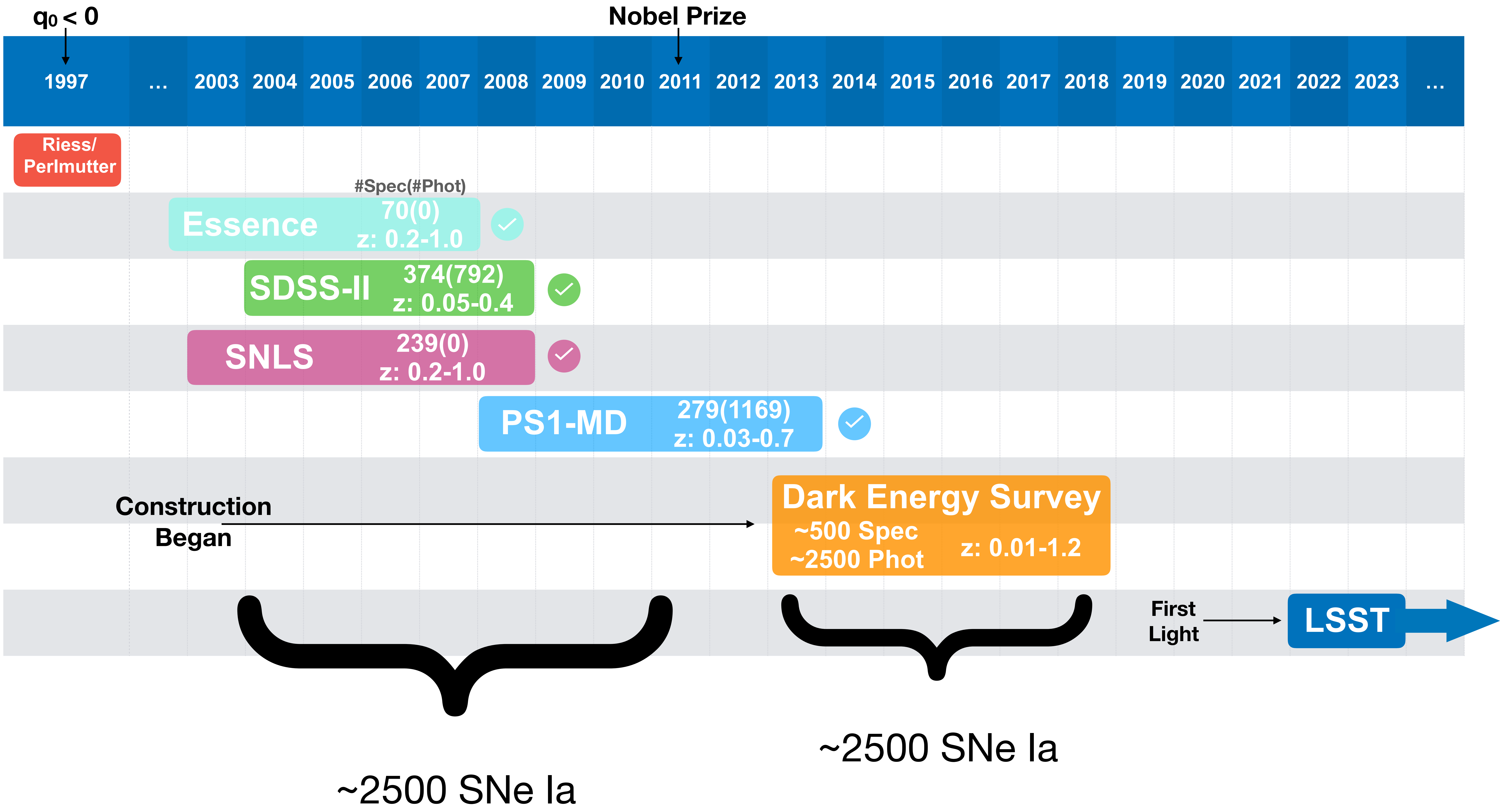
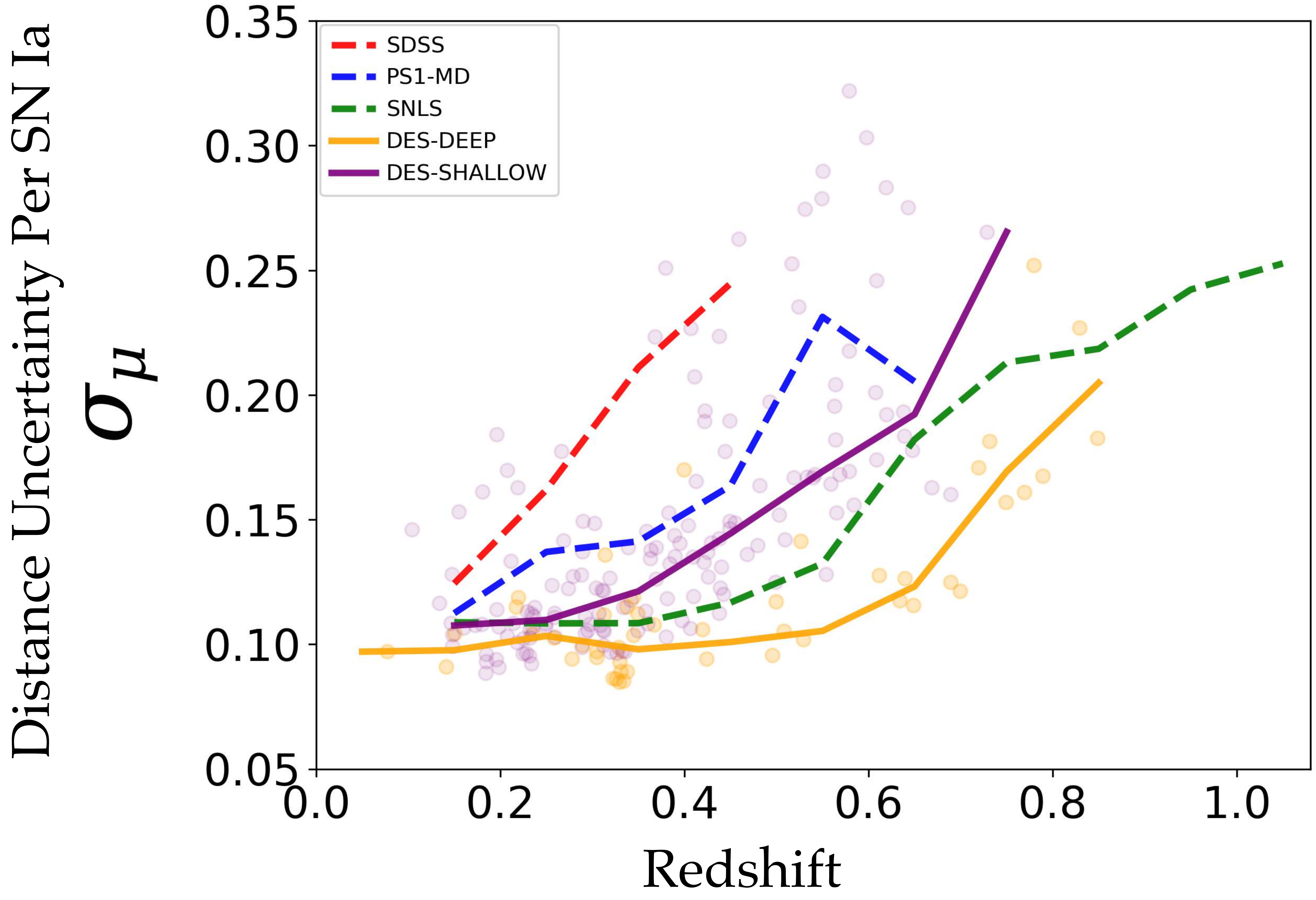


How Do DES SNe Stack Up?



How Does DES-SN3YR Stack Up?

σ_w (stat+syst)	#SNe Ia	Spec Analyses
0.054	740	Joint Lightcurve Analysis (2014)
0.040	1050	Pantheon (2018)
0.063	453	Pan-STARRS1 (2018)
???	329	DESSN-3YR (2018)

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0.059*	329	DESSN-3YR (2018)

*Including accounting for previously unforeseen systematic uncertainties

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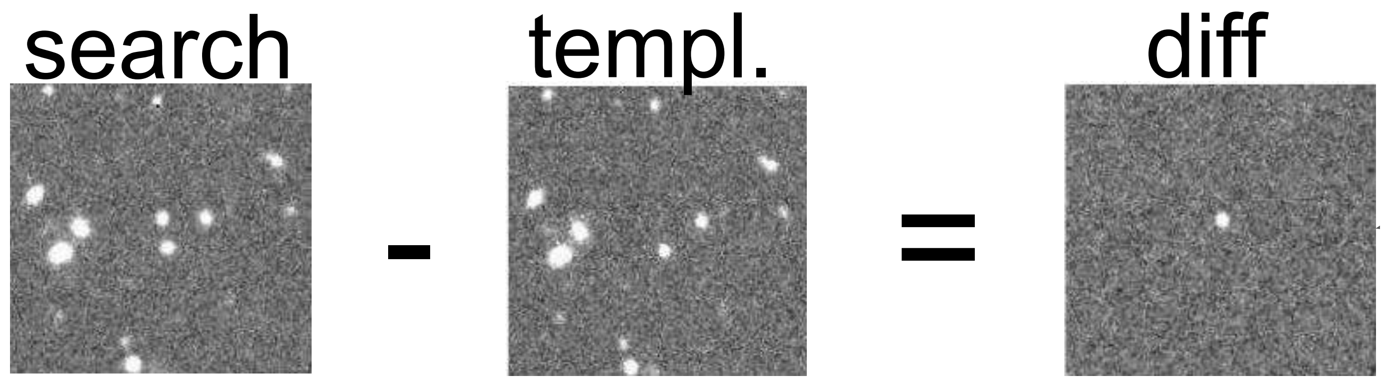
Ingredients for Supernova Cosmology

Difference Imaging

→ SNe Candidates



Ingredients for Supernova Cosmology

Difference Imaging

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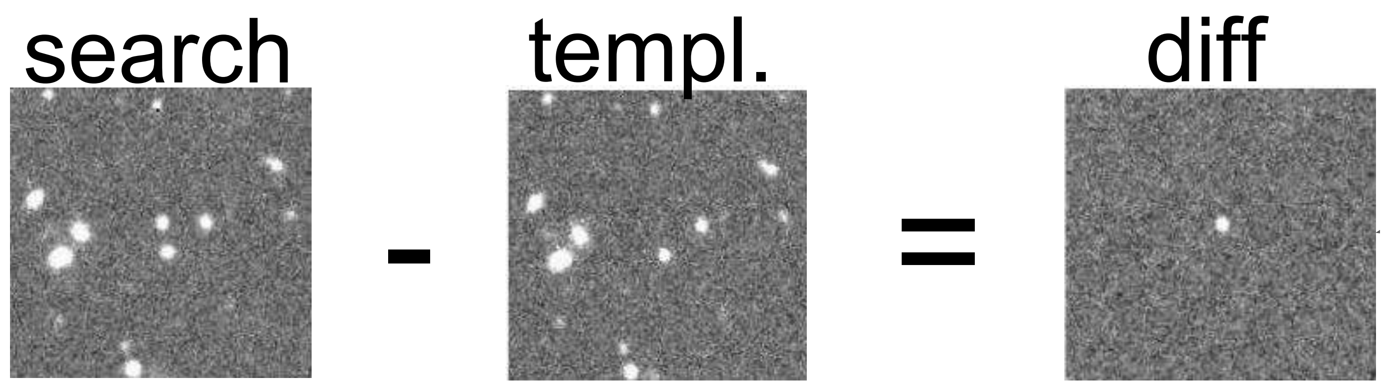
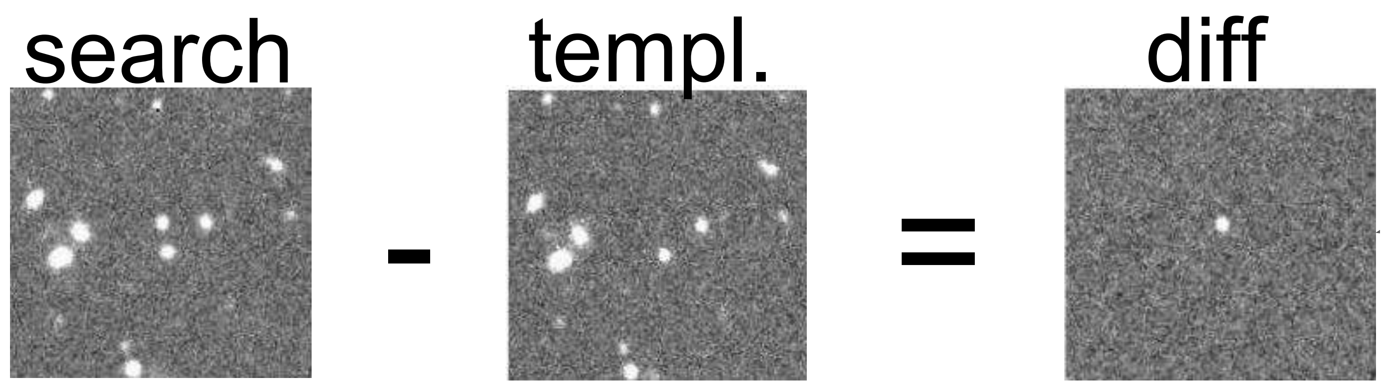


Spectra → Type & redshift

Ingredients for Supernova Cosmology

Difference Imaging

→ SNe Candidates



Spectra → Type & redshift

Photometry → “Standardizable Candles”

Ingredients for Supernova Cosmology

Difference Imaging

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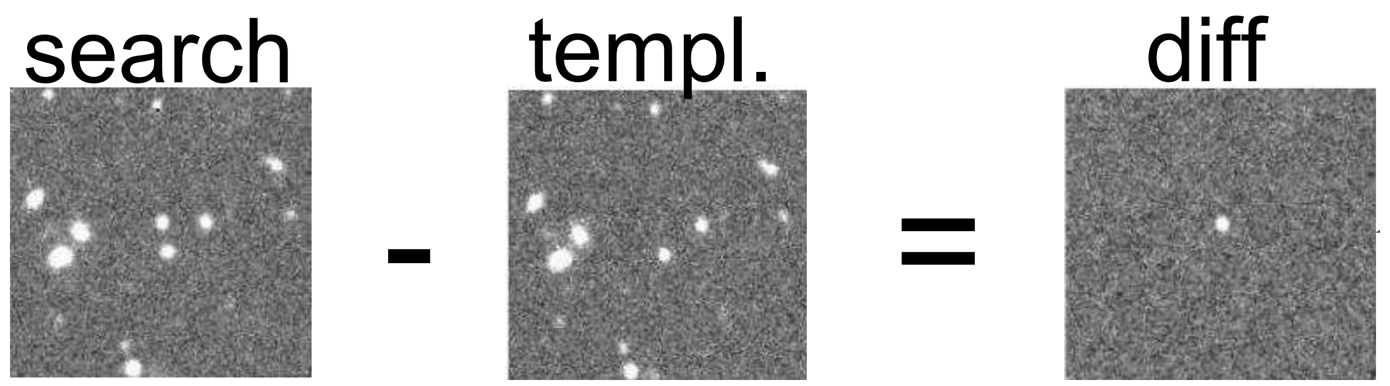

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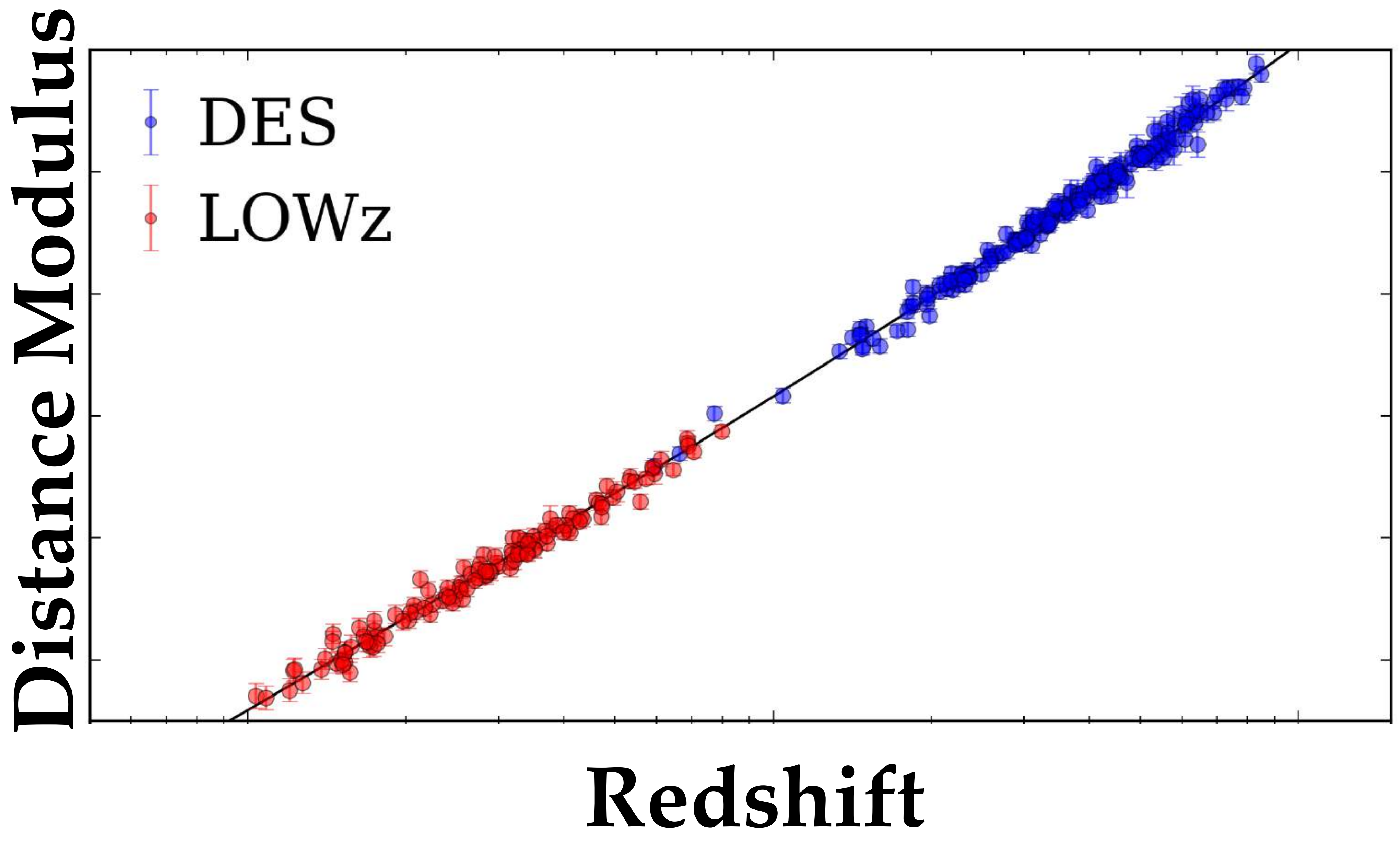

Ingredients for Supernova Cosmology

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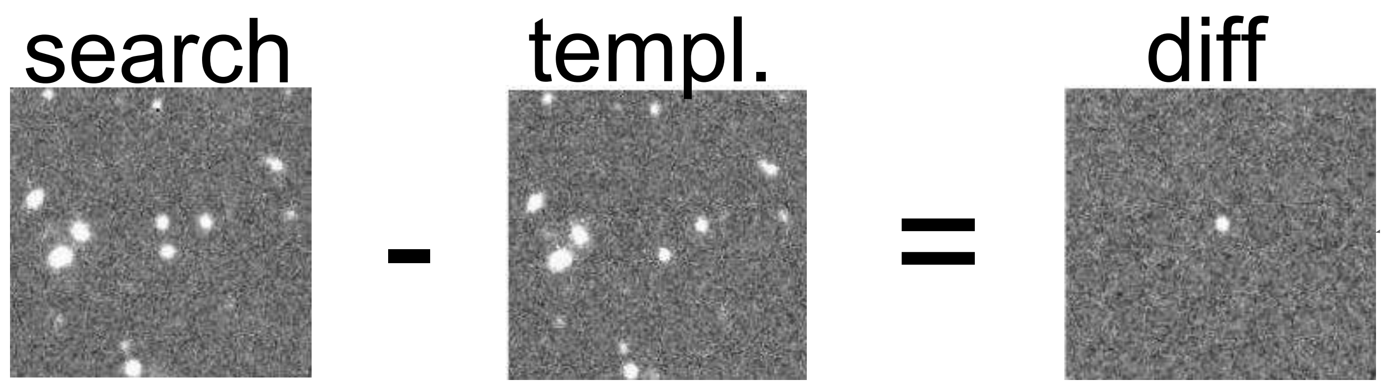
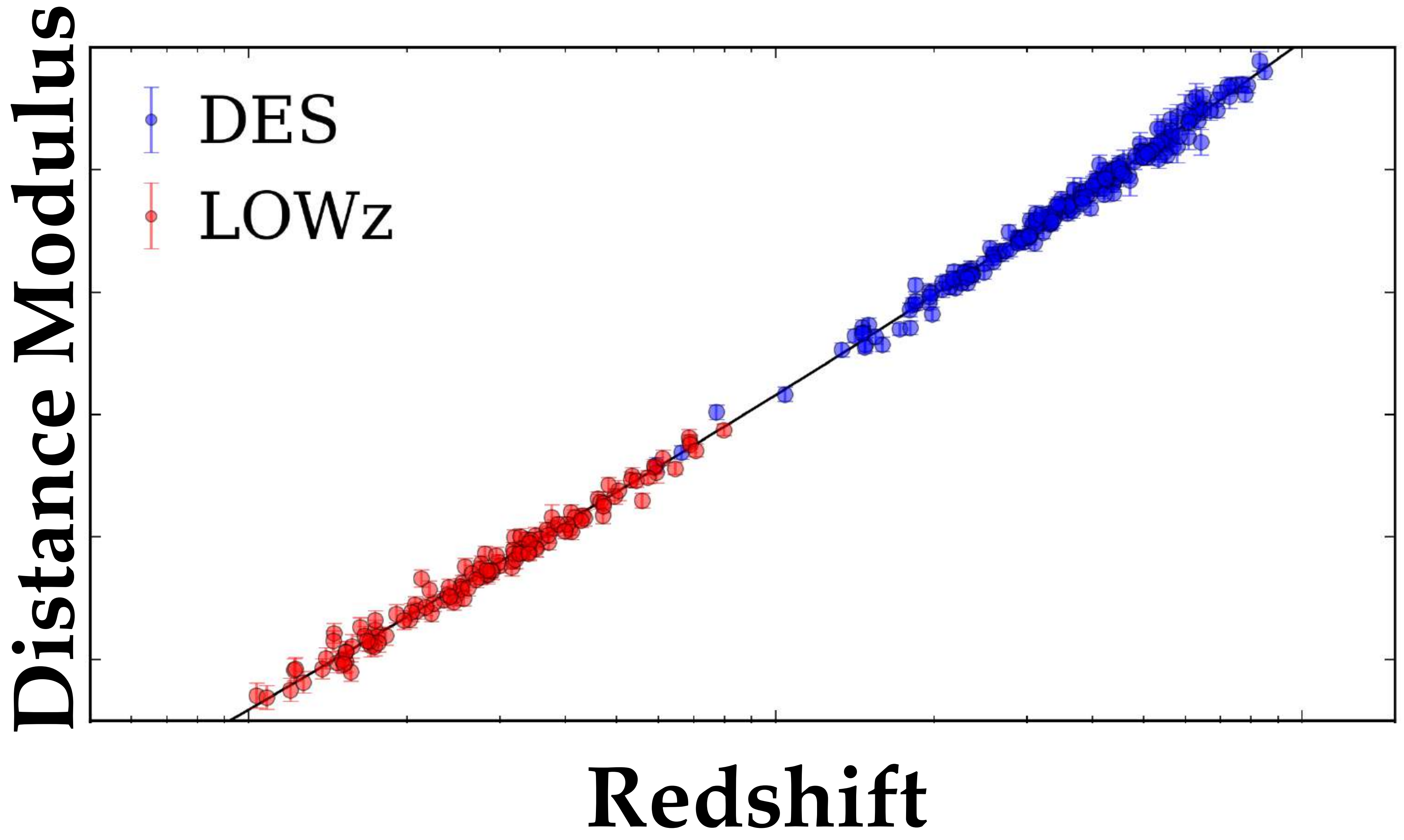


→ SNe Candidates

Spectra → Type & redshift

Photometry → “Standardizable Candles”

Calibration → Rel. Dist. btwn. All SNe



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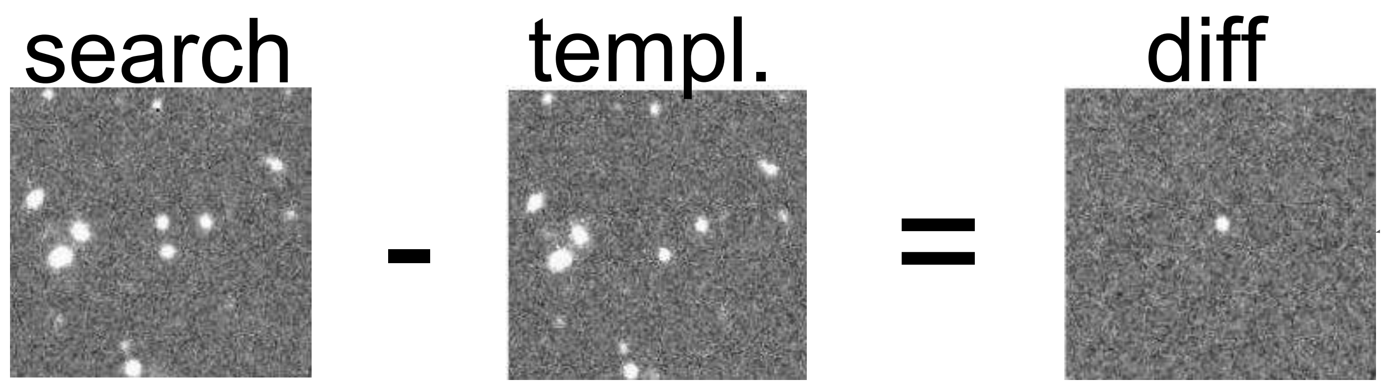

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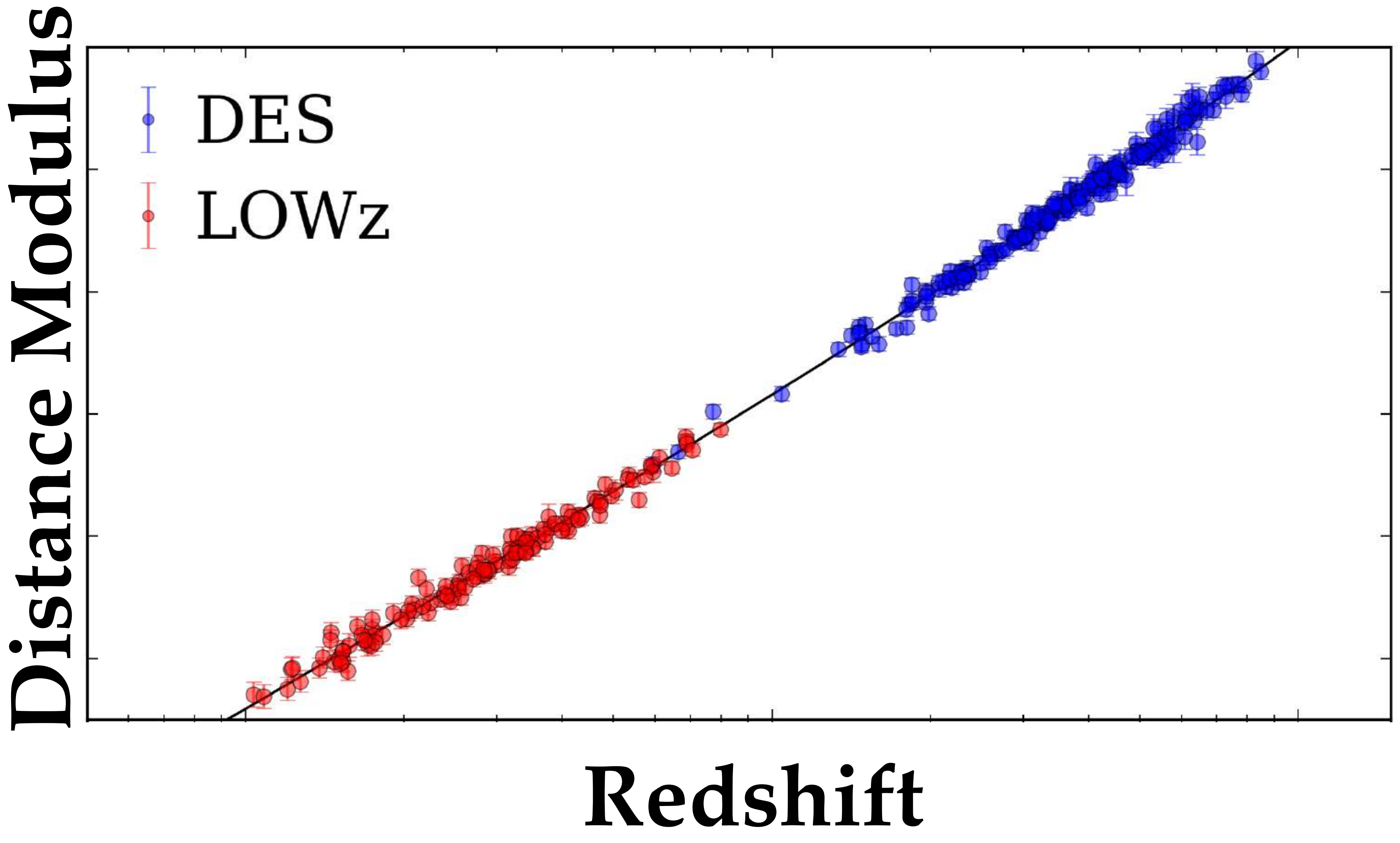

Ingredients for Supernova Cosmology

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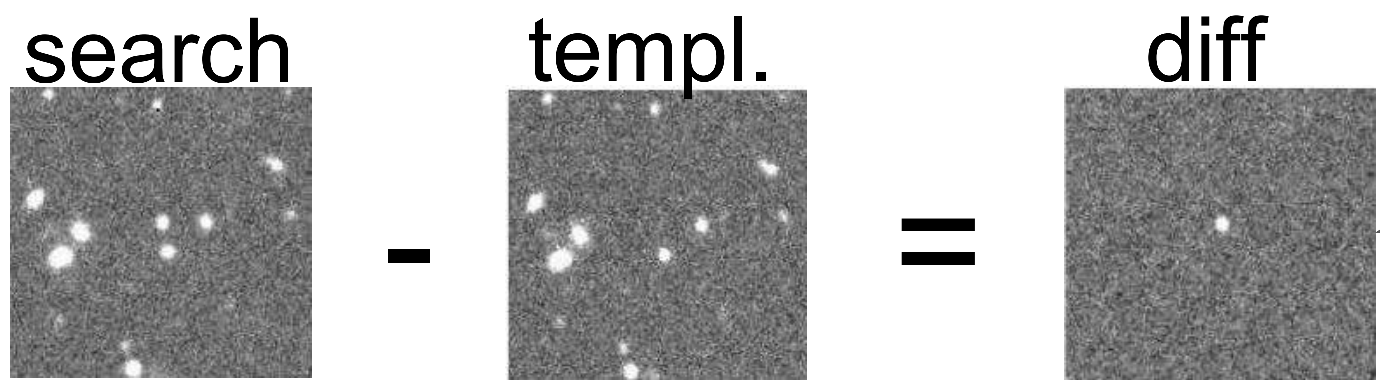

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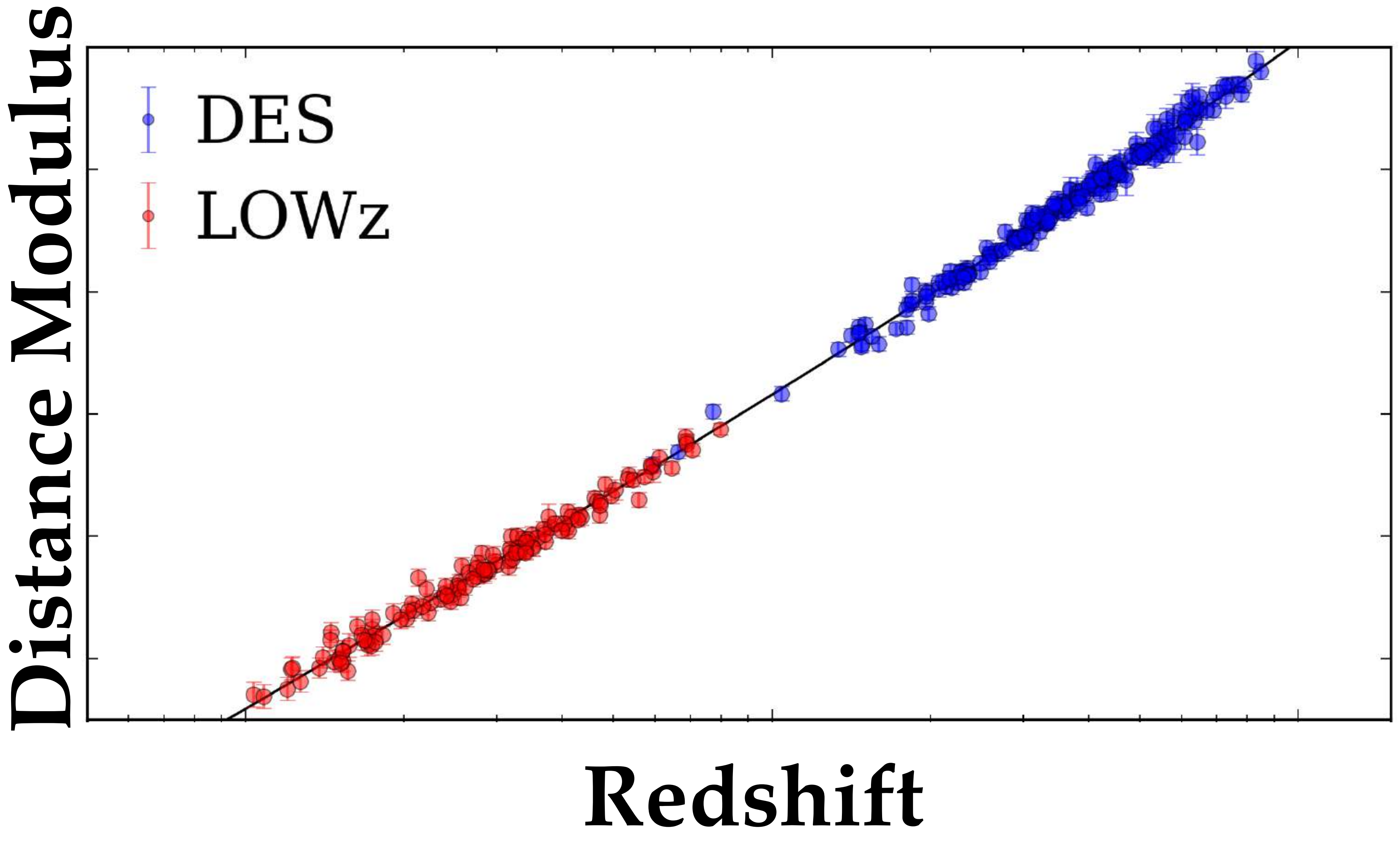

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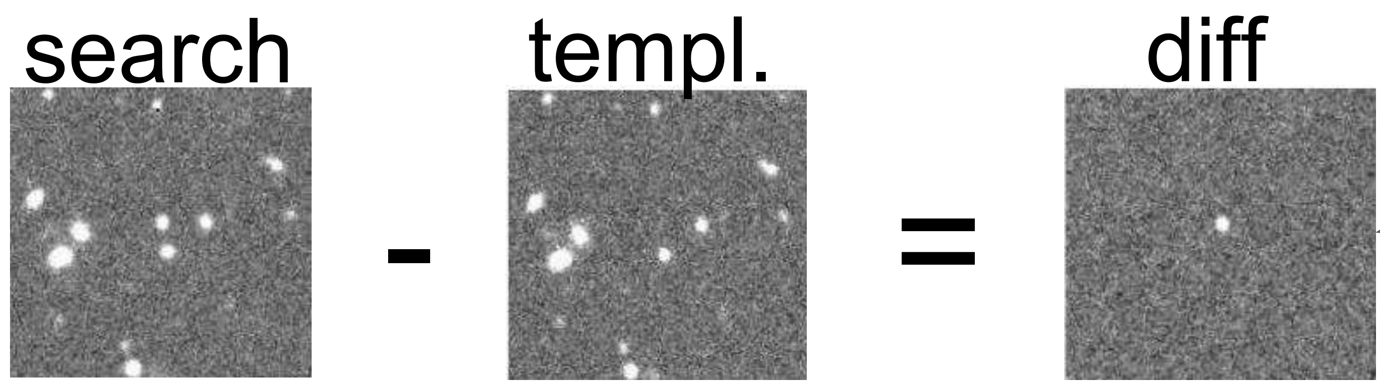

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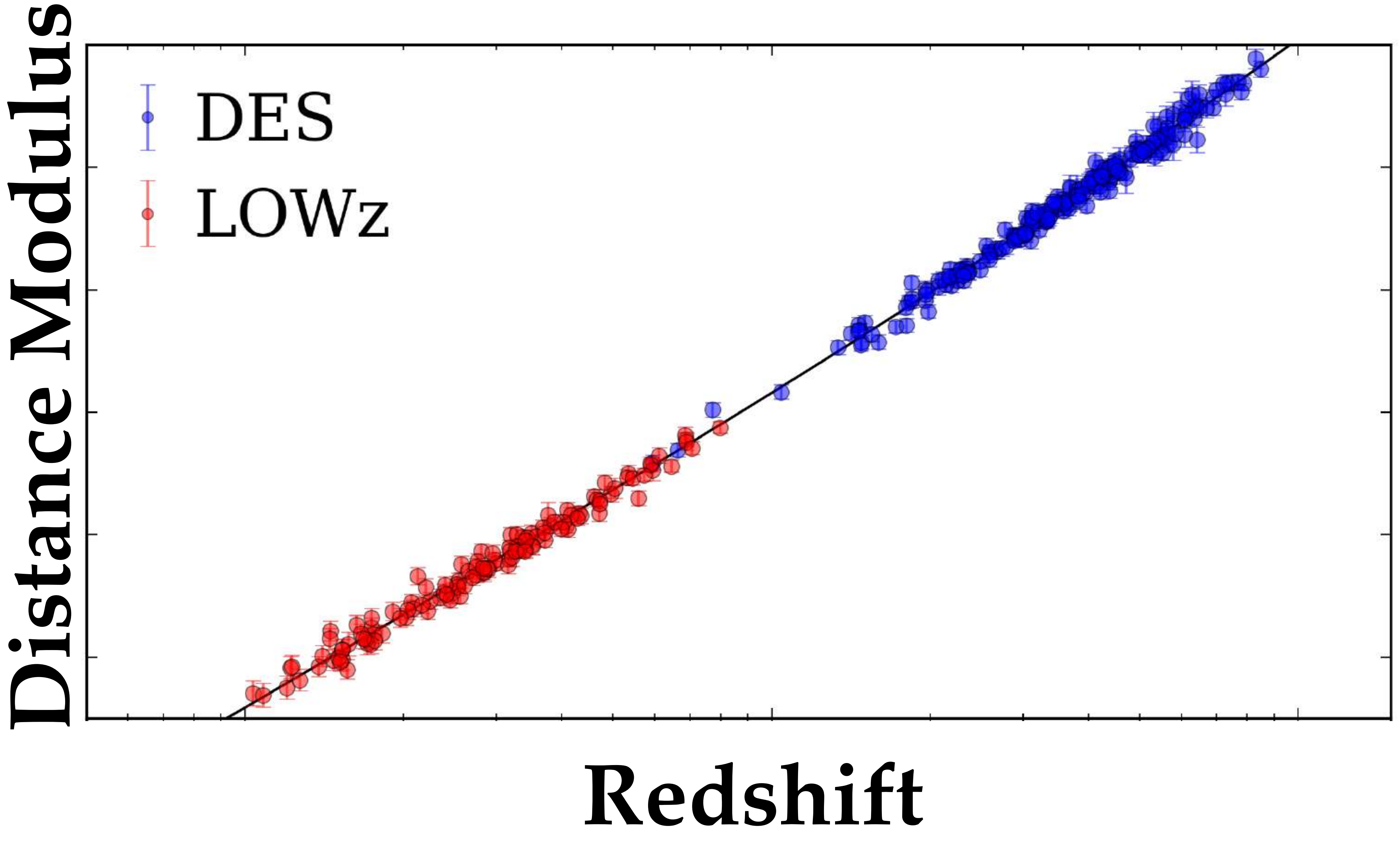
CosmoMC → wCDM fit with SNeIa + Planck 2015



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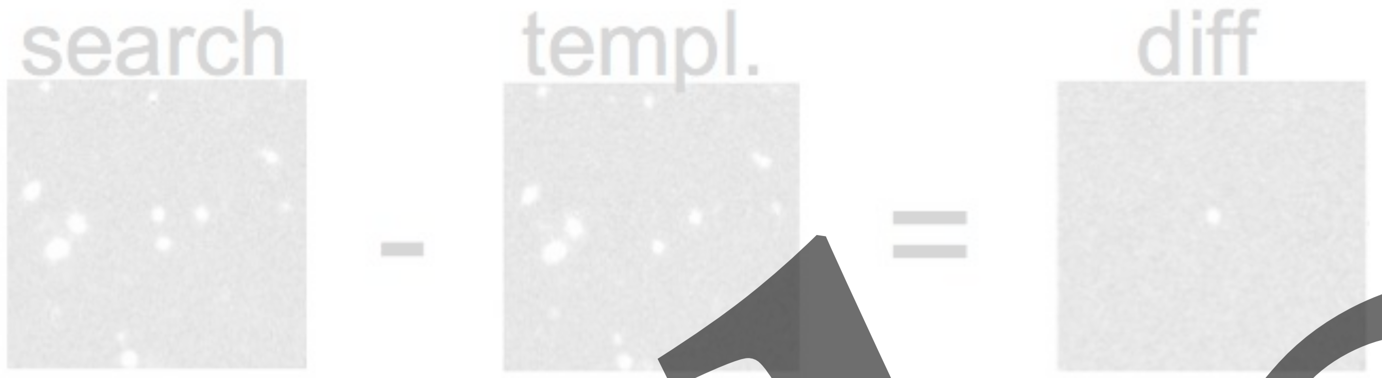

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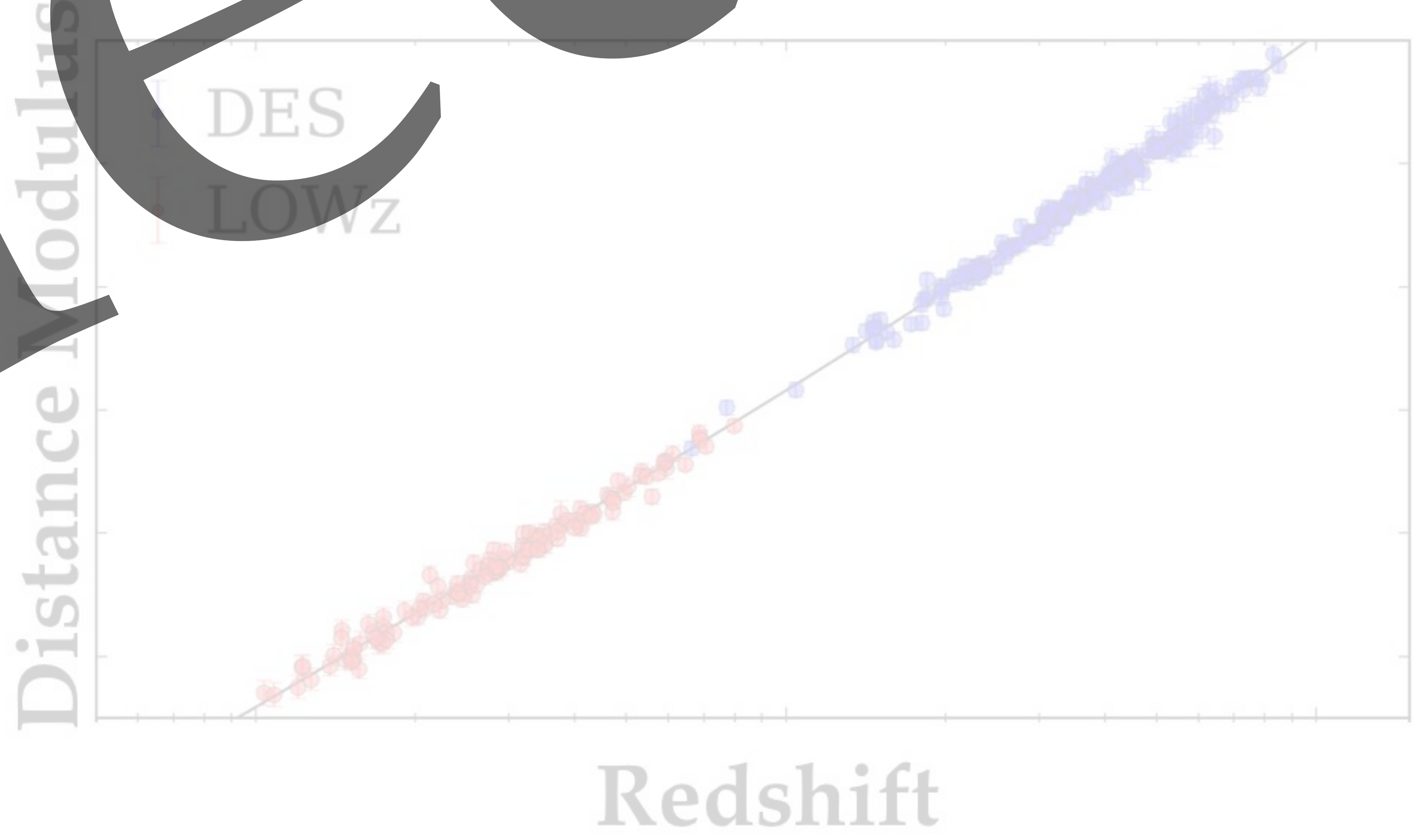
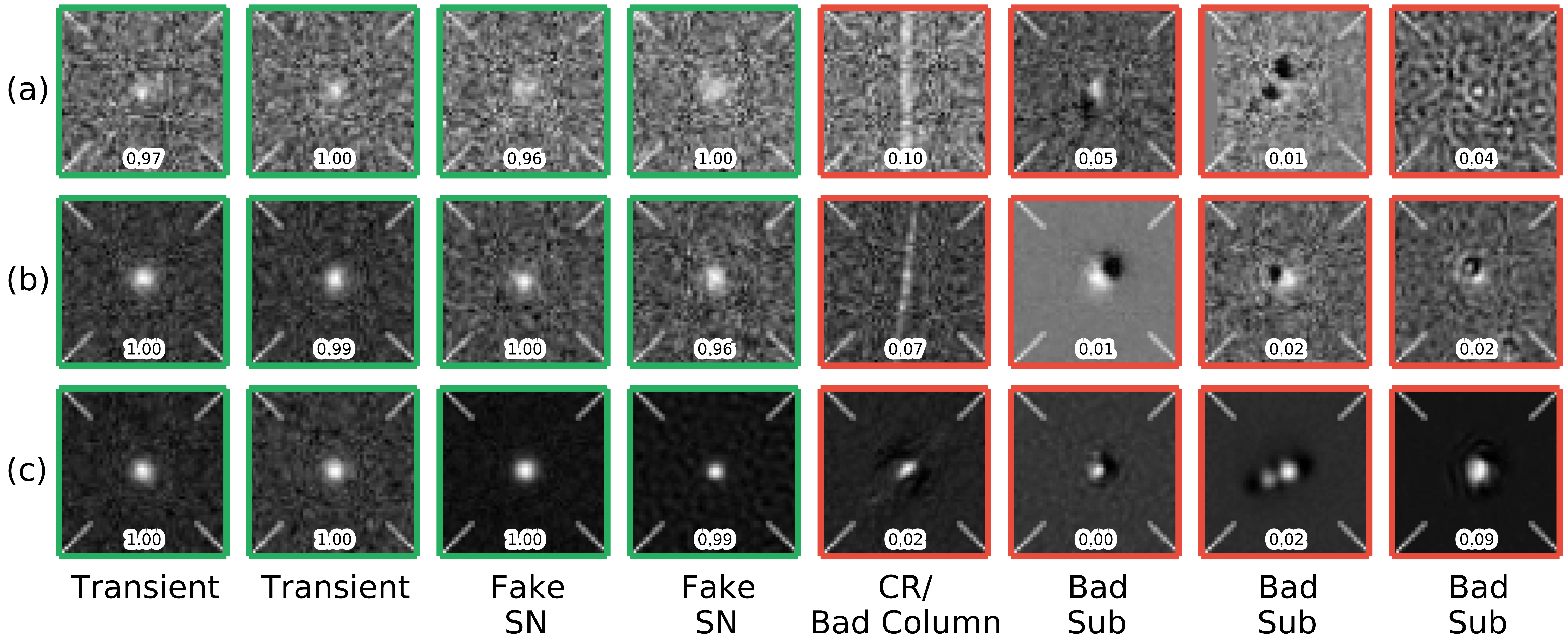


Blinded

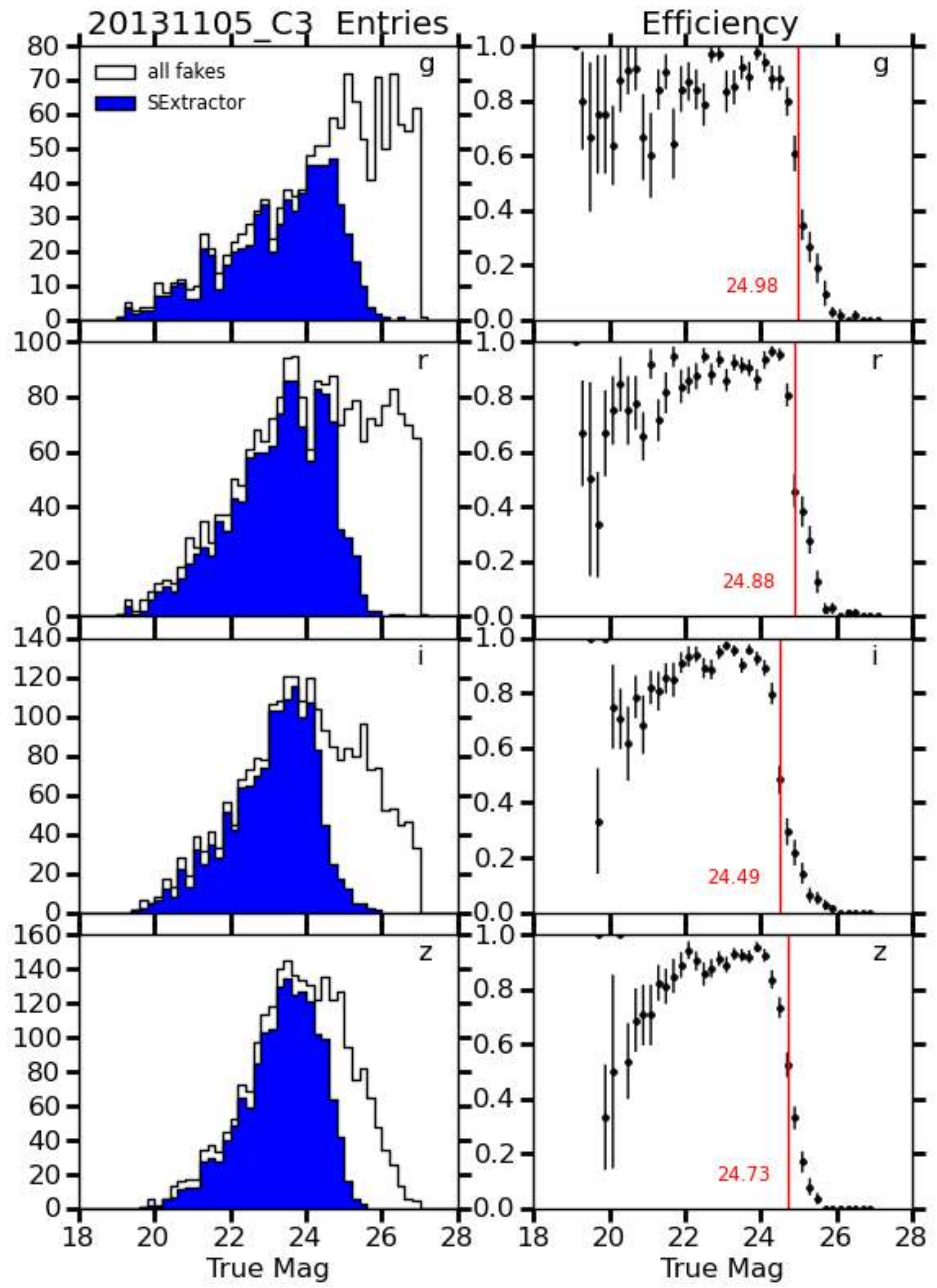
Automated Supernova Survey Monitoring

Machine learning to filter junk detections.
~200-500 detections per visit; only ~4% artifacts!



Goldstein et al. (2015)

Realtime monitoring system with fake sources



Kessler et al. (2015)

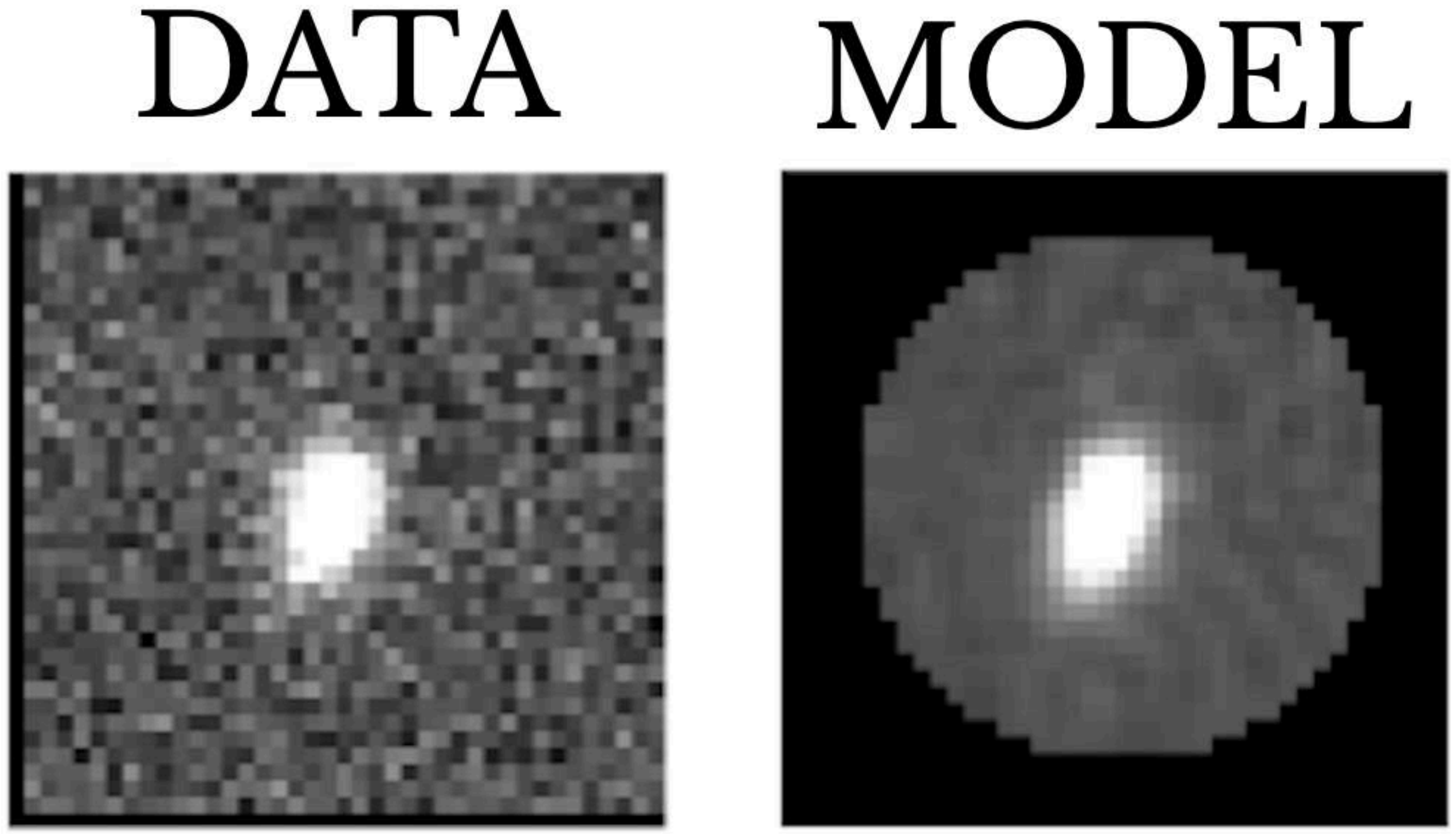
Precision Flux Measurements For Precision Distances

We forward model THE SCENE:

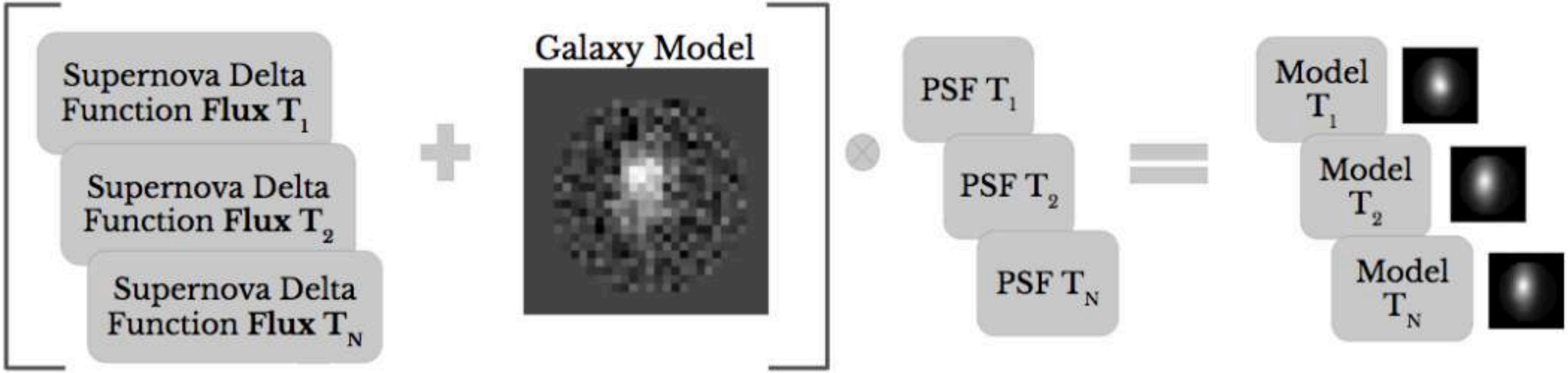
Environment

Supernova

Telescope + **Atmosphere**

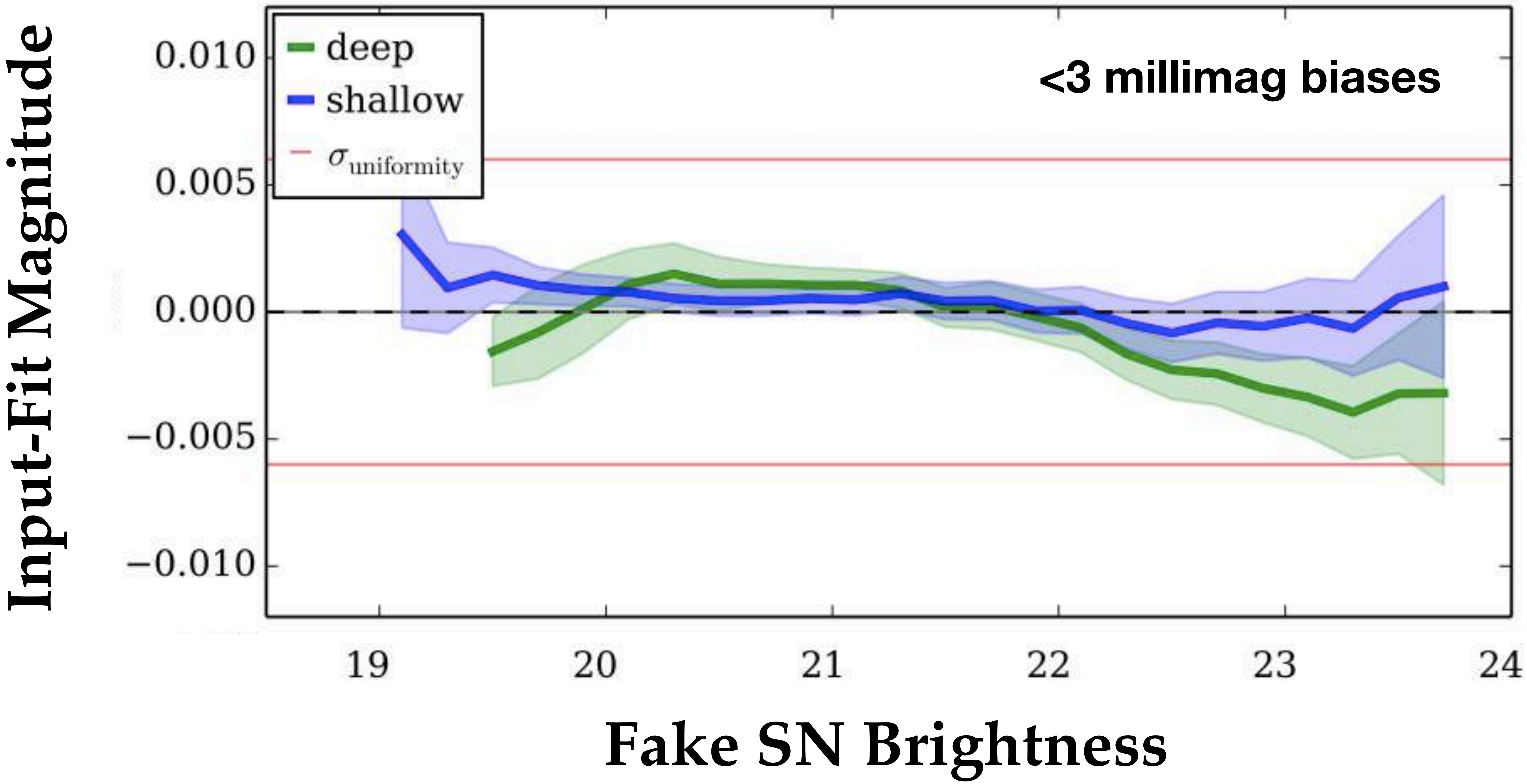


SMP Model Visual Representation



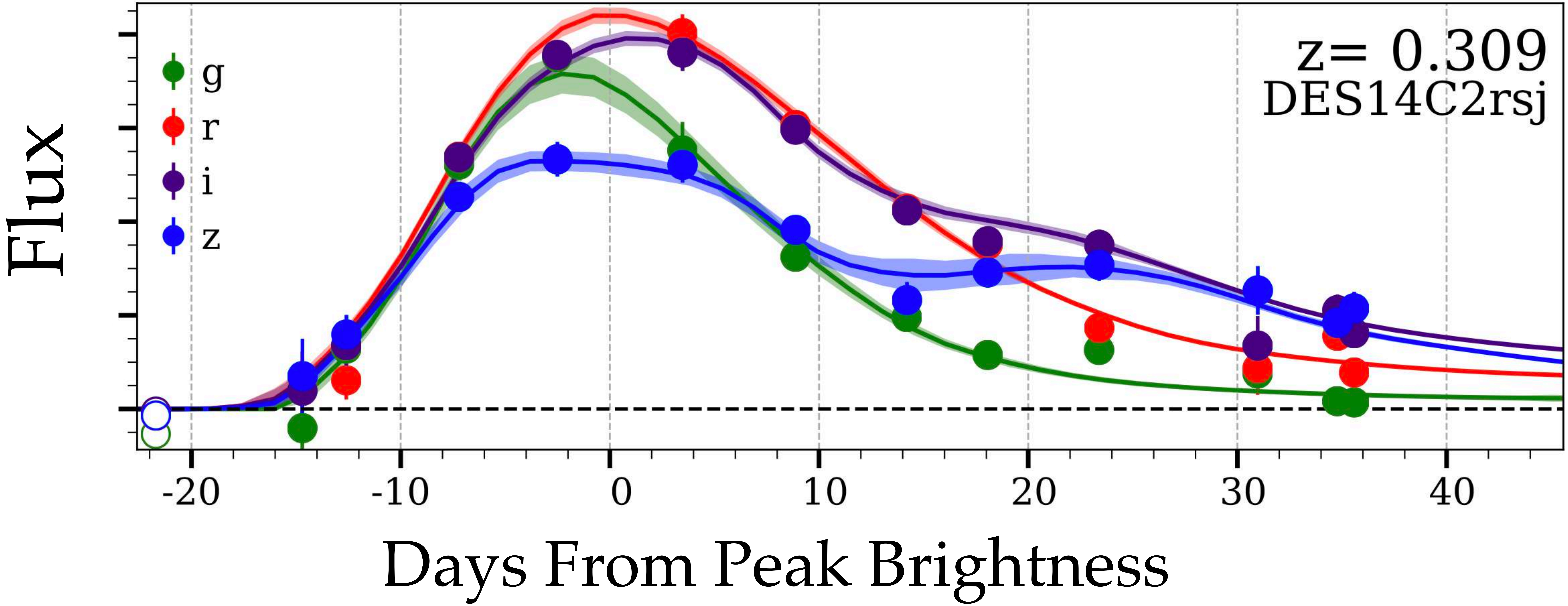
Fake Supernovae Overlaid on Images

Brout et al. 2018-SMP



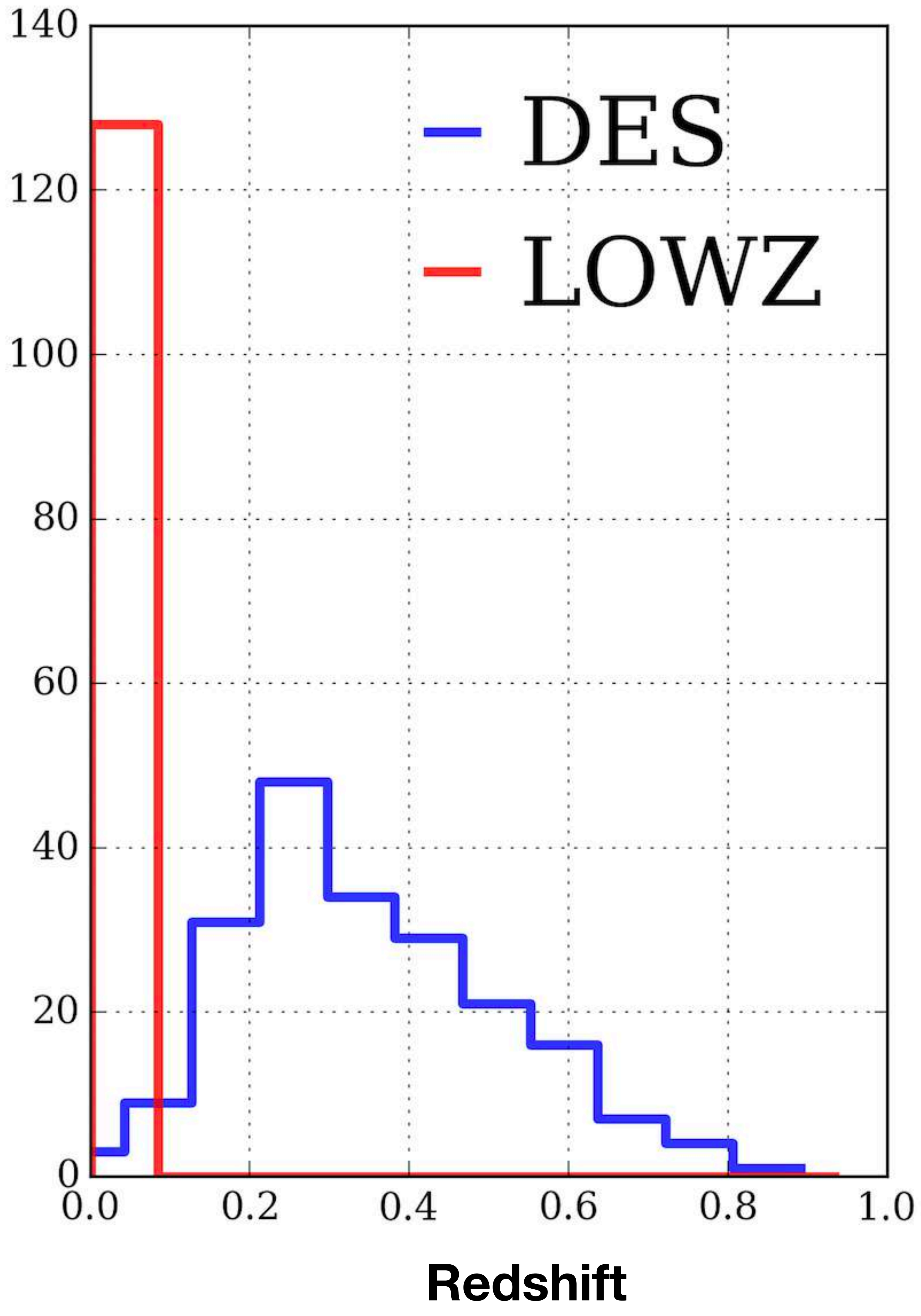
DES Light curve Photometry

Brout et al. 2018-SMP

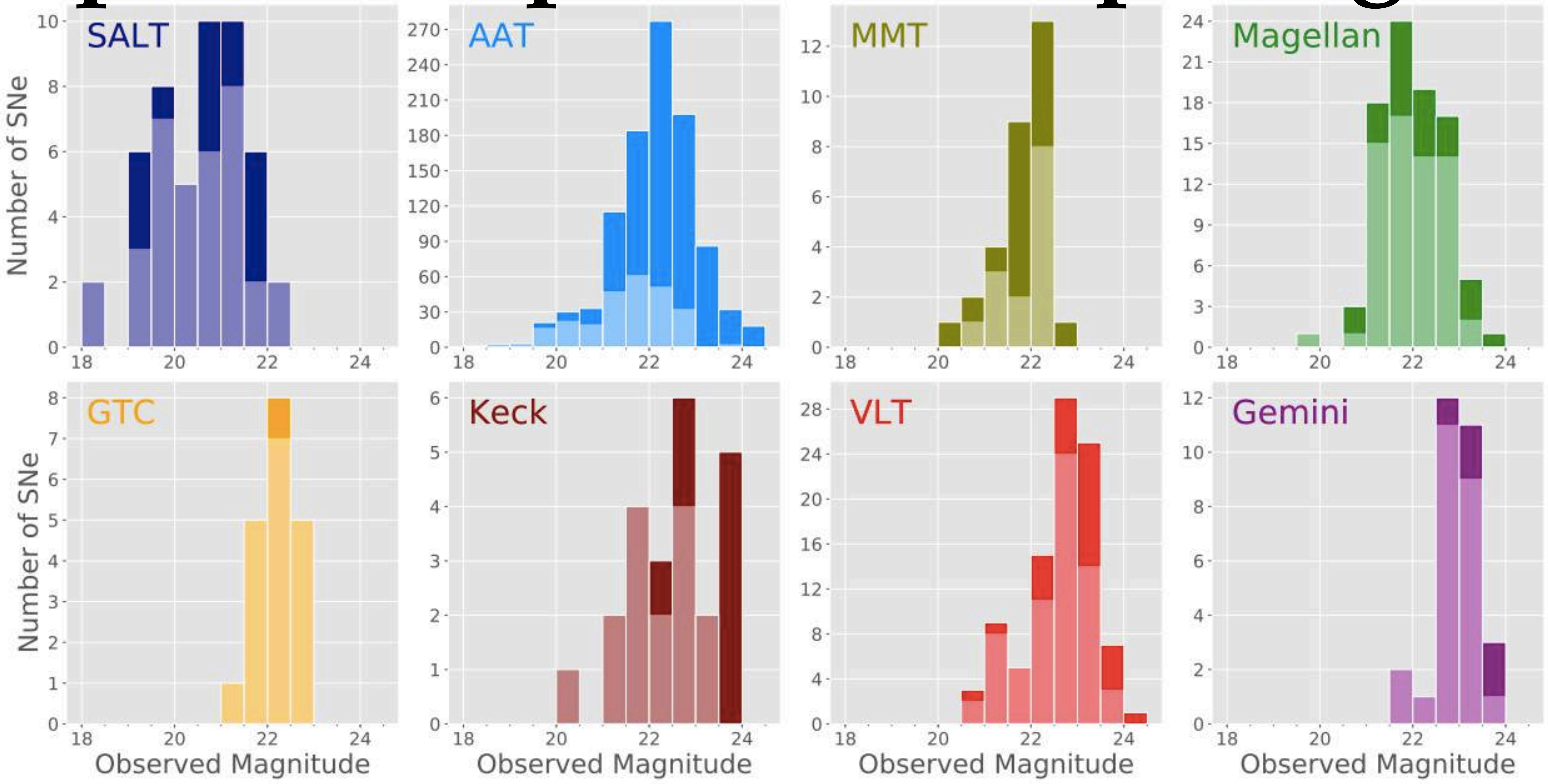


The DES-SN3YR Spec Ia Dataset

Source	Spec. Redshifts	#Spec SNe Ia
DES-SN (3yr spec sample)	0.02 < z < 0.85	207
External Low-z (CfA3-4, CSP)	0.01 < z < 0.10	122

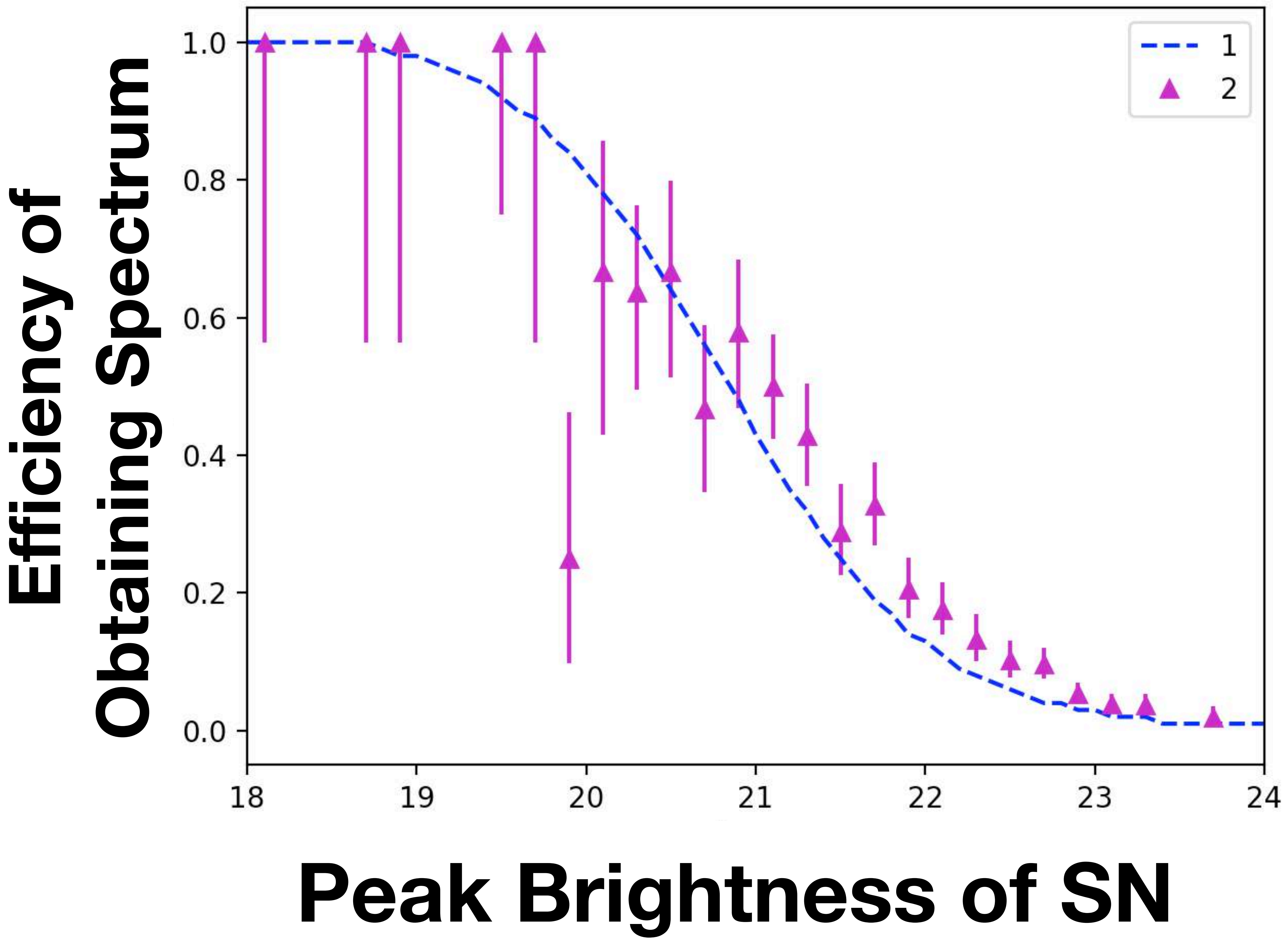


Spectroscopic Followup Program



D'Andrea et al. 2018

Selection Effects Result in Biased Distances



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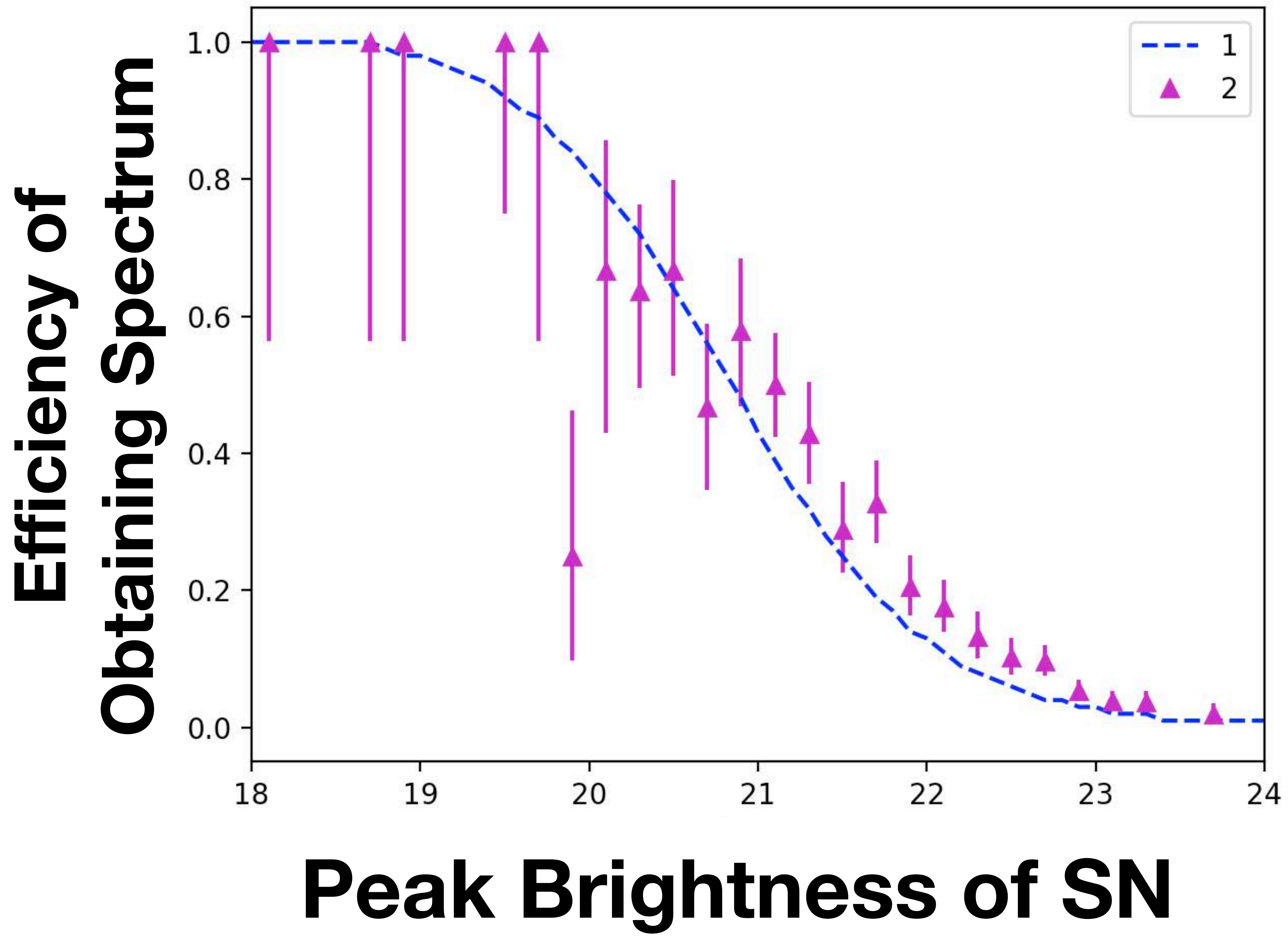
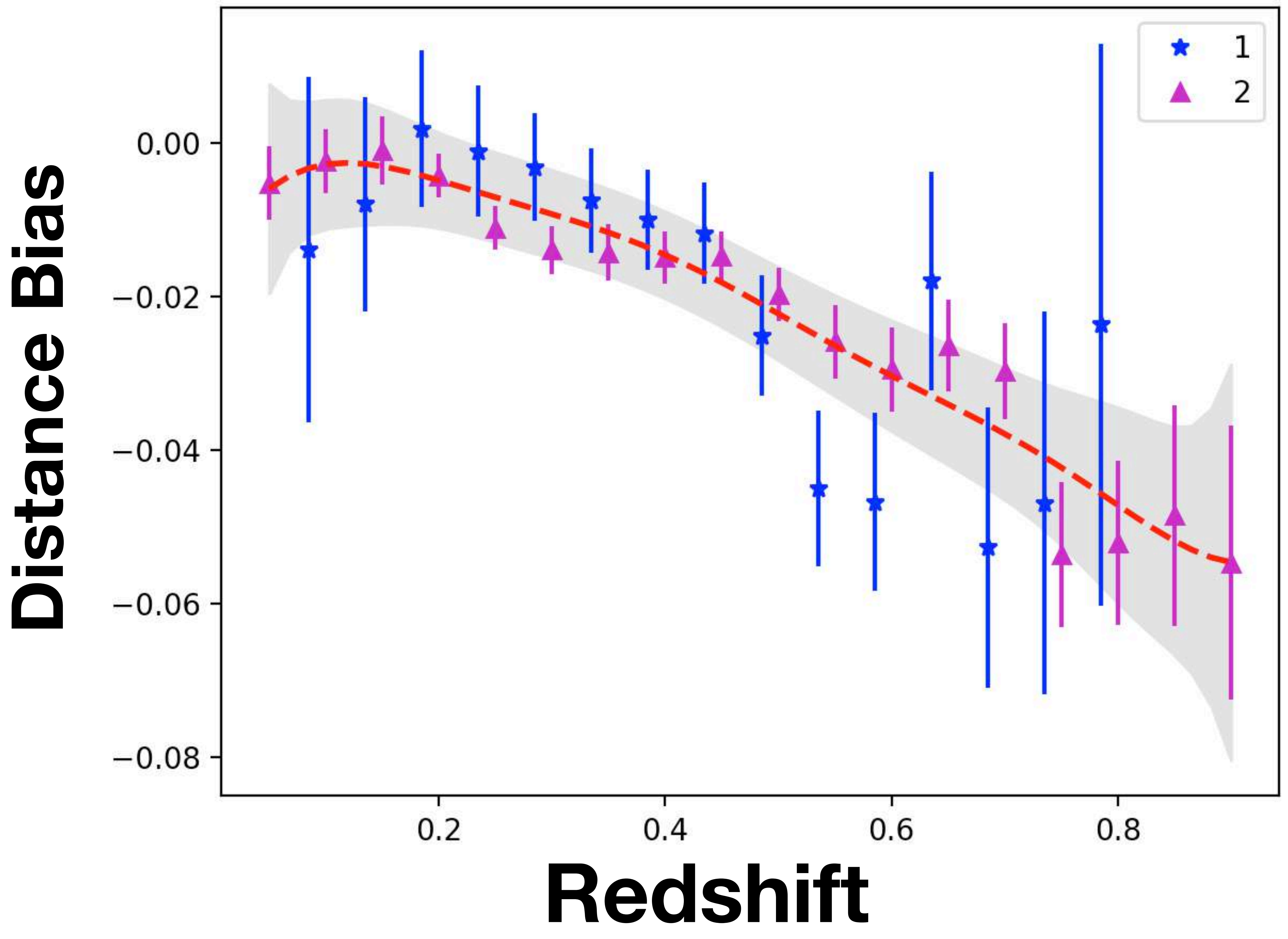
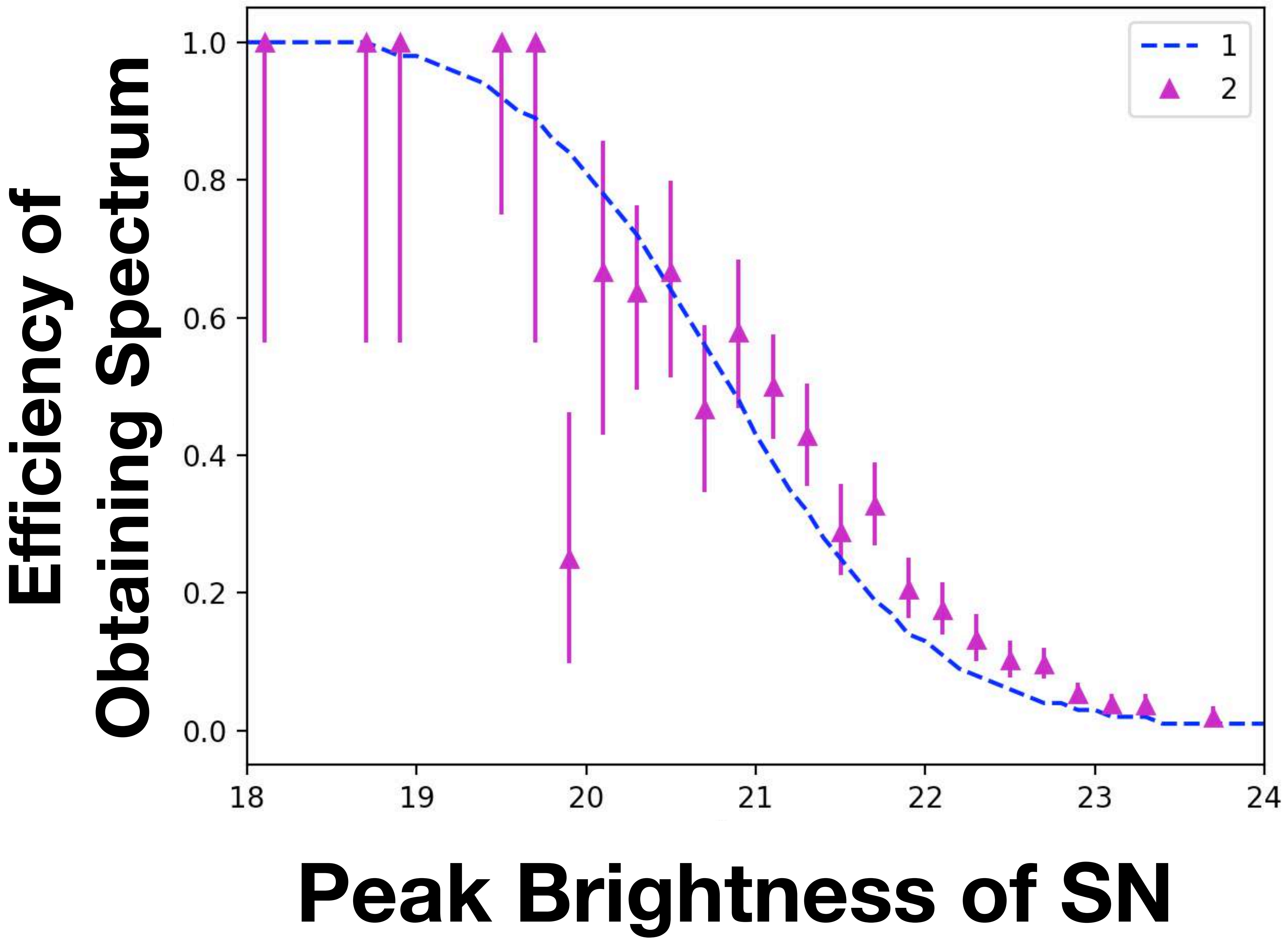
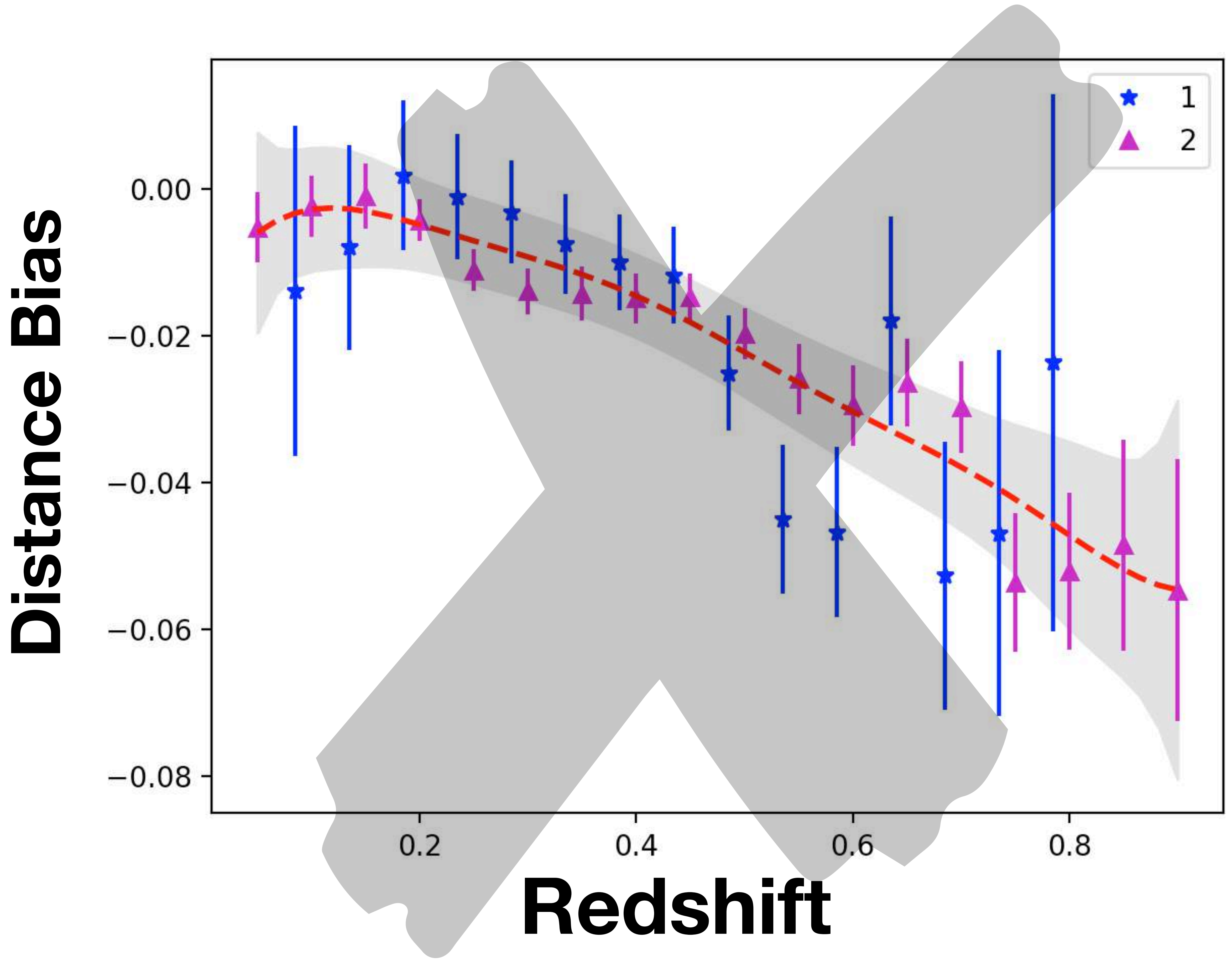




Selection Effects Result in Biased Distances



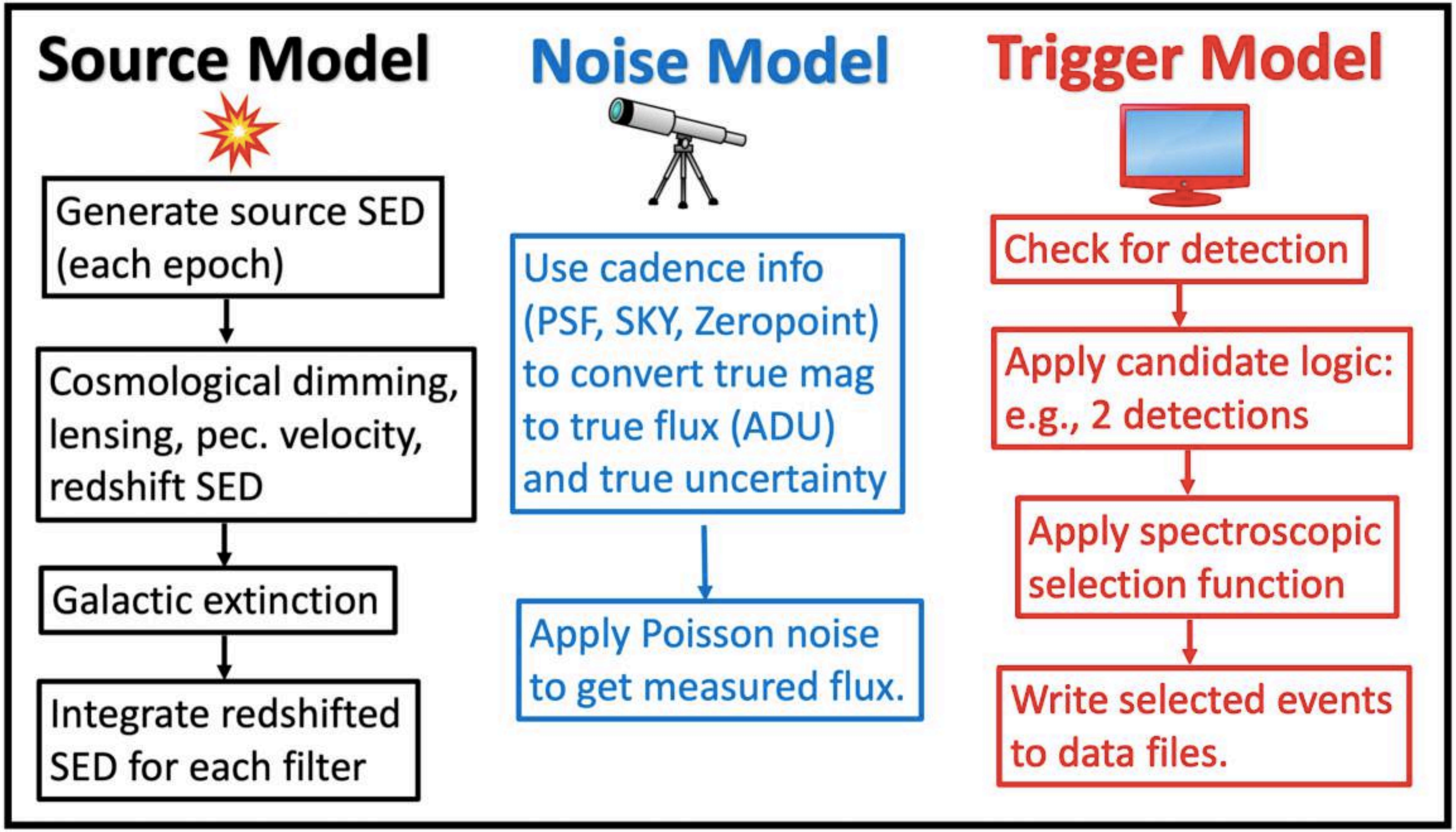


To predict observed biases, we use accurate simulations

SNANA

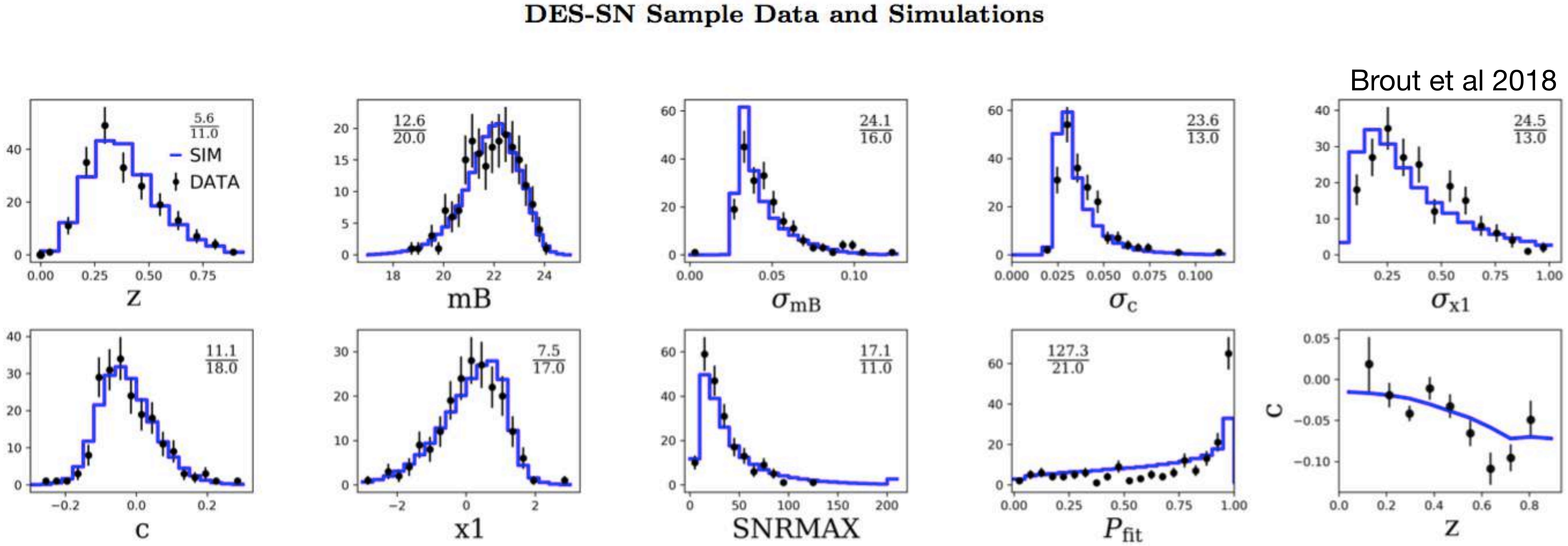
Simulations are able to capture nearly every aspect of DES-SN survey.

Large sims (1 million SNe) are used to predict and correct for distance biases in the DES-SN3YR dataset.



Kessler et al. 2018

To predict biases, we need accurate simulations



Compute Distance Bias Corrections

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

We compute bias corrections in 5D

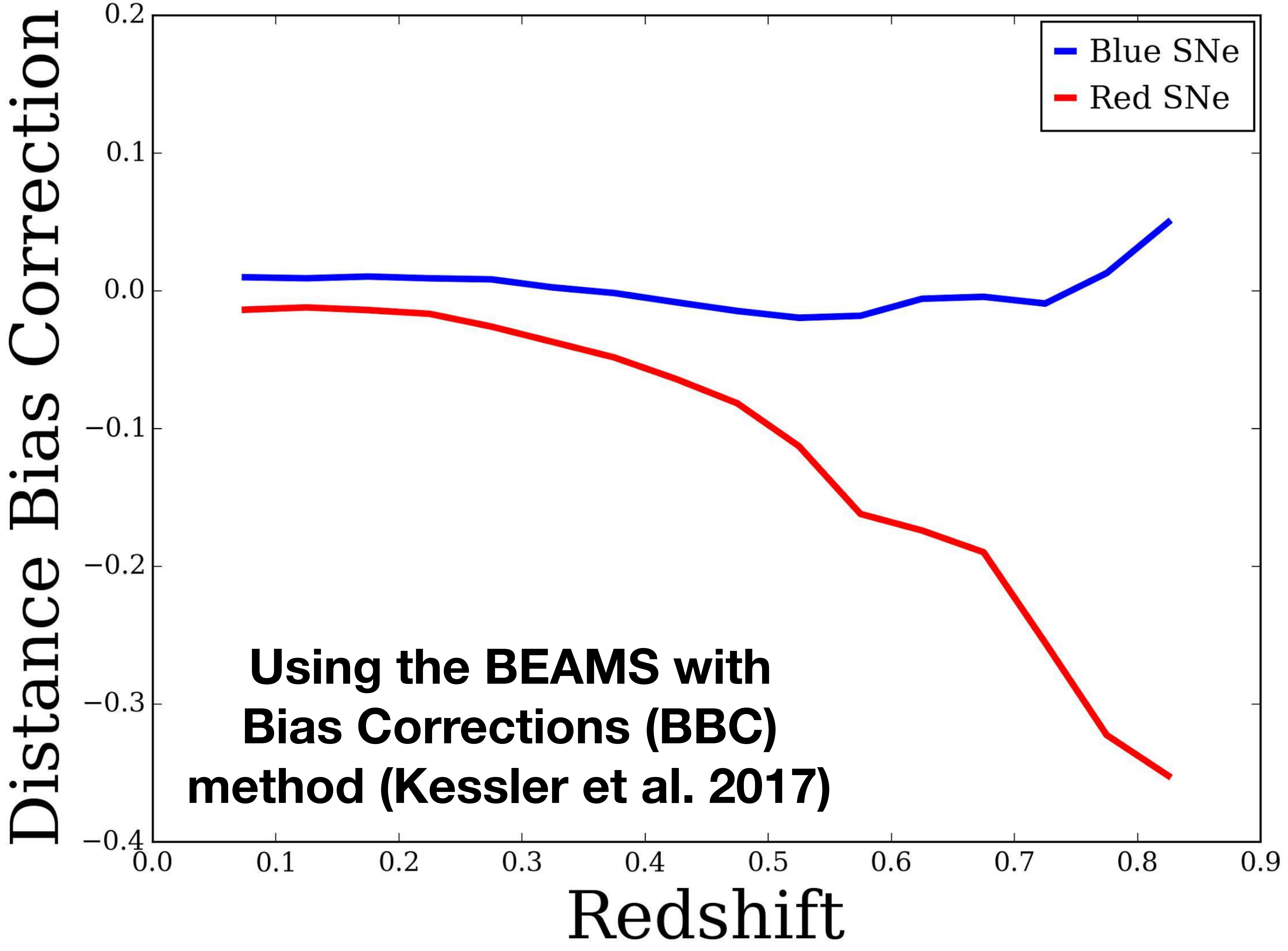
1. SN color

2. SN Light curve stretch

3. Redshift

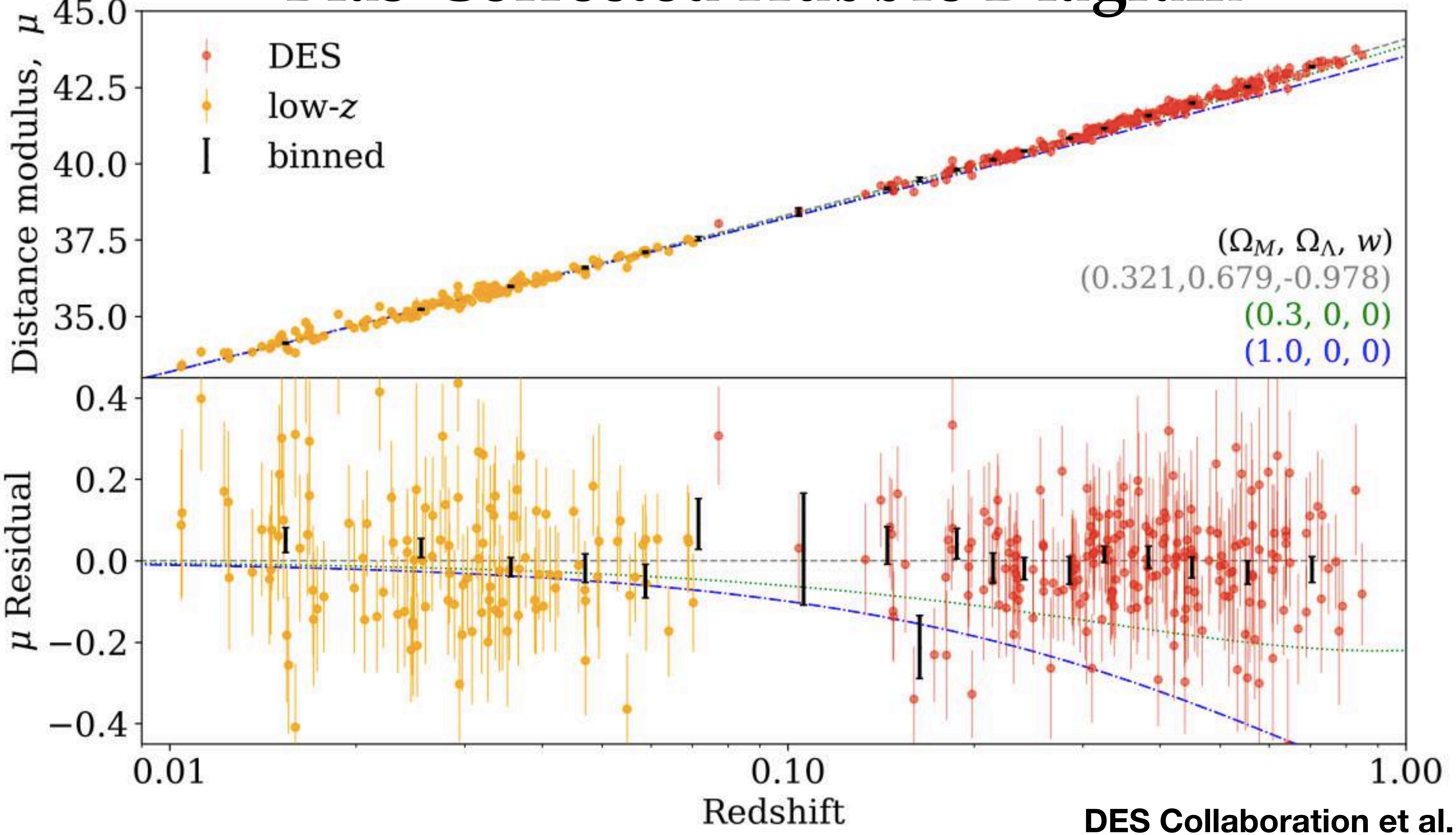
4. Standardization nuisance parameter for SN color (beta)

5. Standardization nuisance Parameter for SN light curve stretch (alpha)



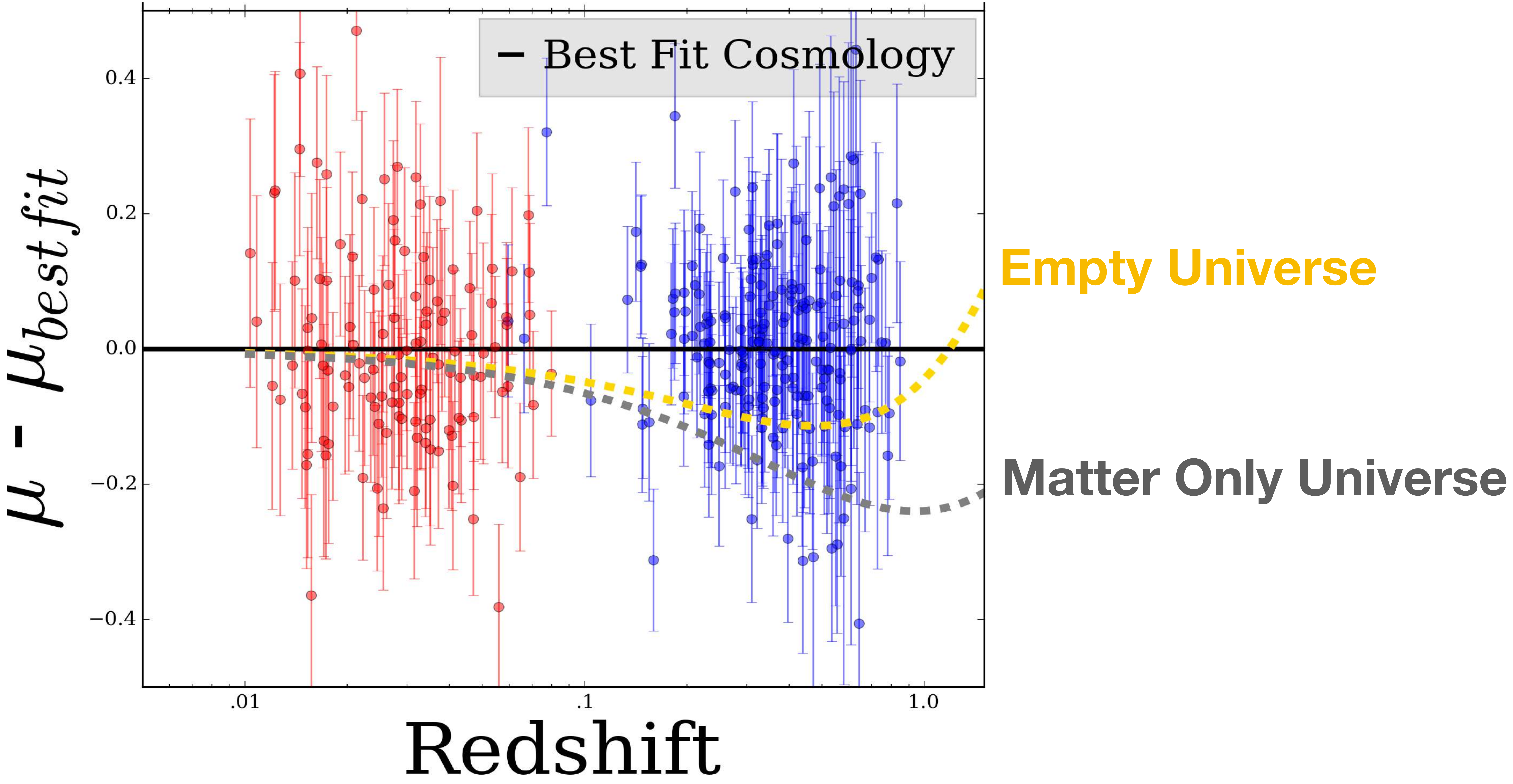
THE DARK ENERGY SURVEY

Bias-Corrected Hubble Diagram

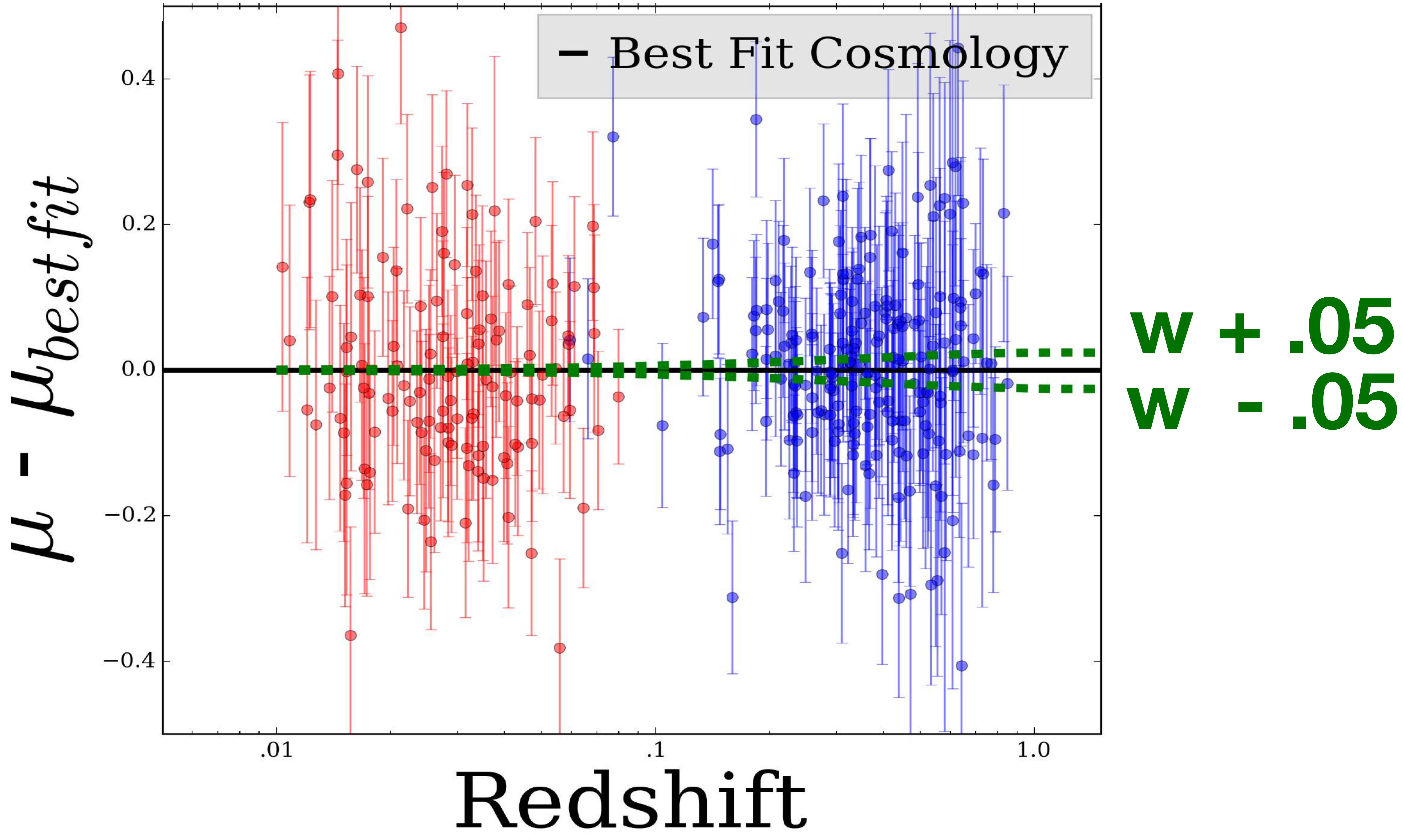


DES Collaboration et al. 2018

Measuring acceleration is “easy” now…



Precision cosmology however, is difficult



https://www.darkenergysurvey.org/des-year-3-supernova-cosmology-results/

THE DARK ENERGY SURVEY

Cosmological Parameter Constraints
DES Collaboration et al.

DES Y1 Combined Probes
DES Collaboration et al.

H_0 Measurement
Macaulay et al.

Analysis, Systematics, & Validation
Brout et al.

Photometric Pipeline
Brout et al.

Spectroscopic Followup
D'Andrea et al.

Simulations to Correct Distance Biases
Kessler et al.

Effect of Chromatic Corrections
Lasker et al.

Bayesian Heirarchical Method
Hinton et al.

Our systematics fall in the following categories

TABLE 4
SOURCES OF UNCERTAINTY

Size[a]	Description	Reference
	SN Photometry	
1 mmag	From astrometry	Bernstein et al. (2017)
1 mmag	Non-linearity of the CCD.	Bernstein et al. (2017)
1-2 mmag	Photometric zero pointing.	B18-SMP
3 mmag	Photometric bias determined by fakes.	B18-SMP
	Calibration	
$6/\sqrt{3}$ mmag	DECam $\sigma_{\rm uniformity}$	Burke et al. (2018)
0.6 nm	DECam filter curves uncertainty.	Abbott et al. (2018)
$[-2,-2,-1,5]$ mmag	Modeling of C26202 implemented as coherent shift $[g,r,i,z]$	Figure 4
5mmag/700 nm	HST Calspec spectrum modeling uncertainty	Bohlin et al. (2014)
1/3 No SuperCal	SuperCal process	S18, Scolnic et al. (2015)
Following S18	Low-z samples photometric calibration.	S18, CfA3-4, CSP-1
Following S18	Low-z samples filter curve measurement.	S18, CfA3-4, CSP-1
Following B14	SALT2 light curve model calibration.	B14
	Bias Corrections (Astrophysical)	
Table 3	c, x_1 Parent populations resulting in $\Delta\chi^2 = 2.3$	§ 4.3
1/2 (G10 − C11)	Model of intrinsic scatter variations	§ 4.2
Two $\sigma_{\rm int}$	Separate fit $\sigma_{\rm int}$ for each subset	§ 4.2
0.05 in w	[†]Cosmology in which the bias correction sample is simulated.	§ 4.5
4% Scaling	MW Extinction maps	§ 4.9, Schlafly & Finkbeiner (2011b)
	Bias Corrections (Survey)	
$3.5\sigma \rightarrow 3\sigma$ outlier cut	[†]Low-z Hubble diagram outlier cut.	§ 4.7
$1\sigma_{\rm stat}$ Fluctuation	Spectroscopic selection function statistical fluctuations.	§ 4.4, Figure 8
Low-z Selection	Low-z subset magnitude → volume limited survey.	§ 4.3
5% $\sigma_{\rm phot}$ Underestimation	[†]Incorrect SN photometric uncertainties.	§ 4.8
	Redshifts	
4×10^{-5} in z	[†]Coherent z-shift.	§ 4.6, Calcino & Davis (2017)
$0.9 \times \beta_{\rm bias}$	Peculiar velocity modeling	§ 4.6, Zhang et al. (2017)

[a] Size adopted for each source of systematic uncertainty.
[†] Sources of systematic uncertainty that have not been included in previous analyses.

Brout et al. 2018

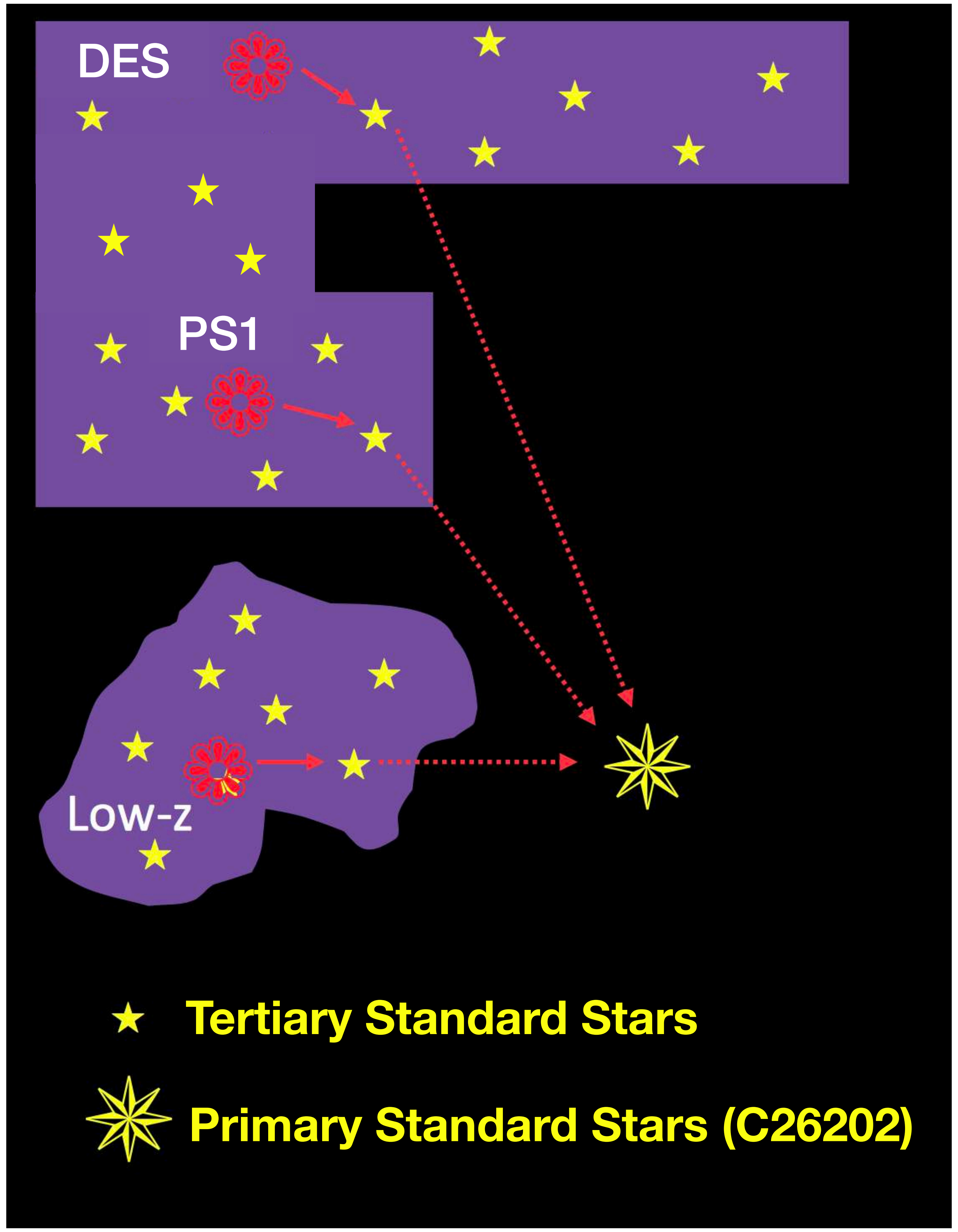
1. Photometry + Calibration
   (20 low-z bands + 4 DES bands)
2. Astrophysics Modeling
3. Survey Modeling
4. Redshifts

→ Total 74 Sources of Systematic Uncertainty

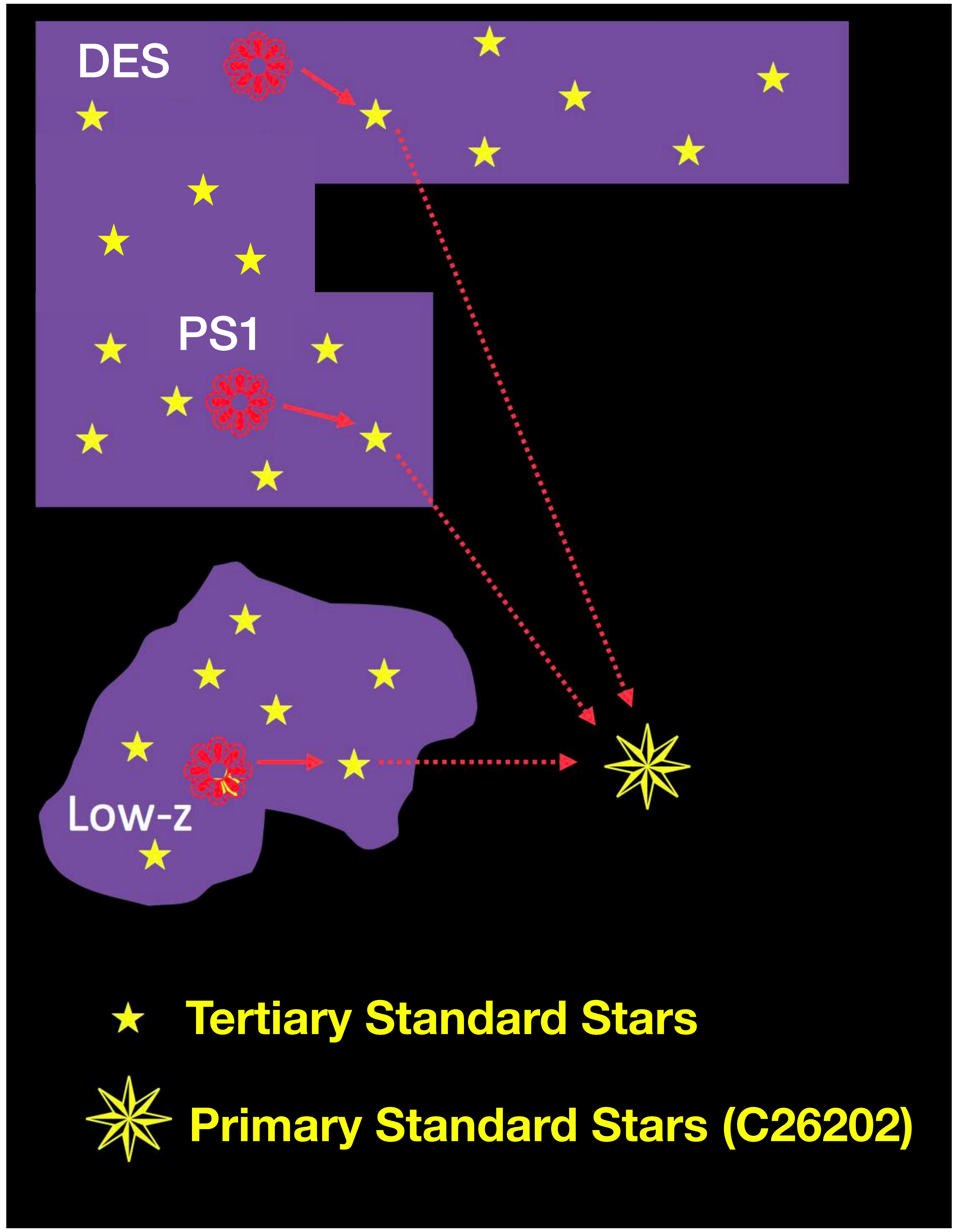
Calibration historically has been the largest systematic uncertainty

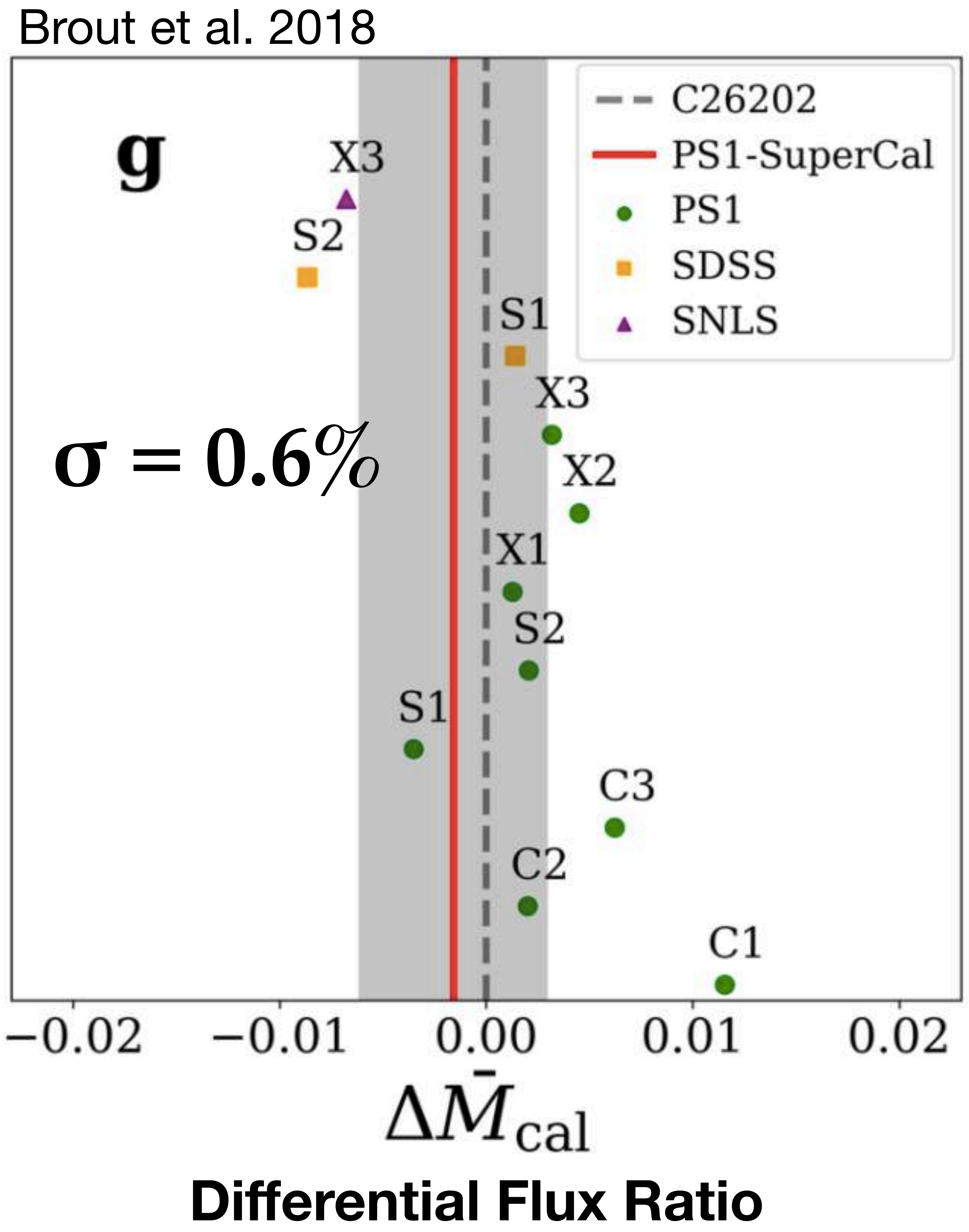
- Every image needs to be internally calibrated.
- And each supernova sample needs to be calibrated to each other

Calibration systematic uncertainty

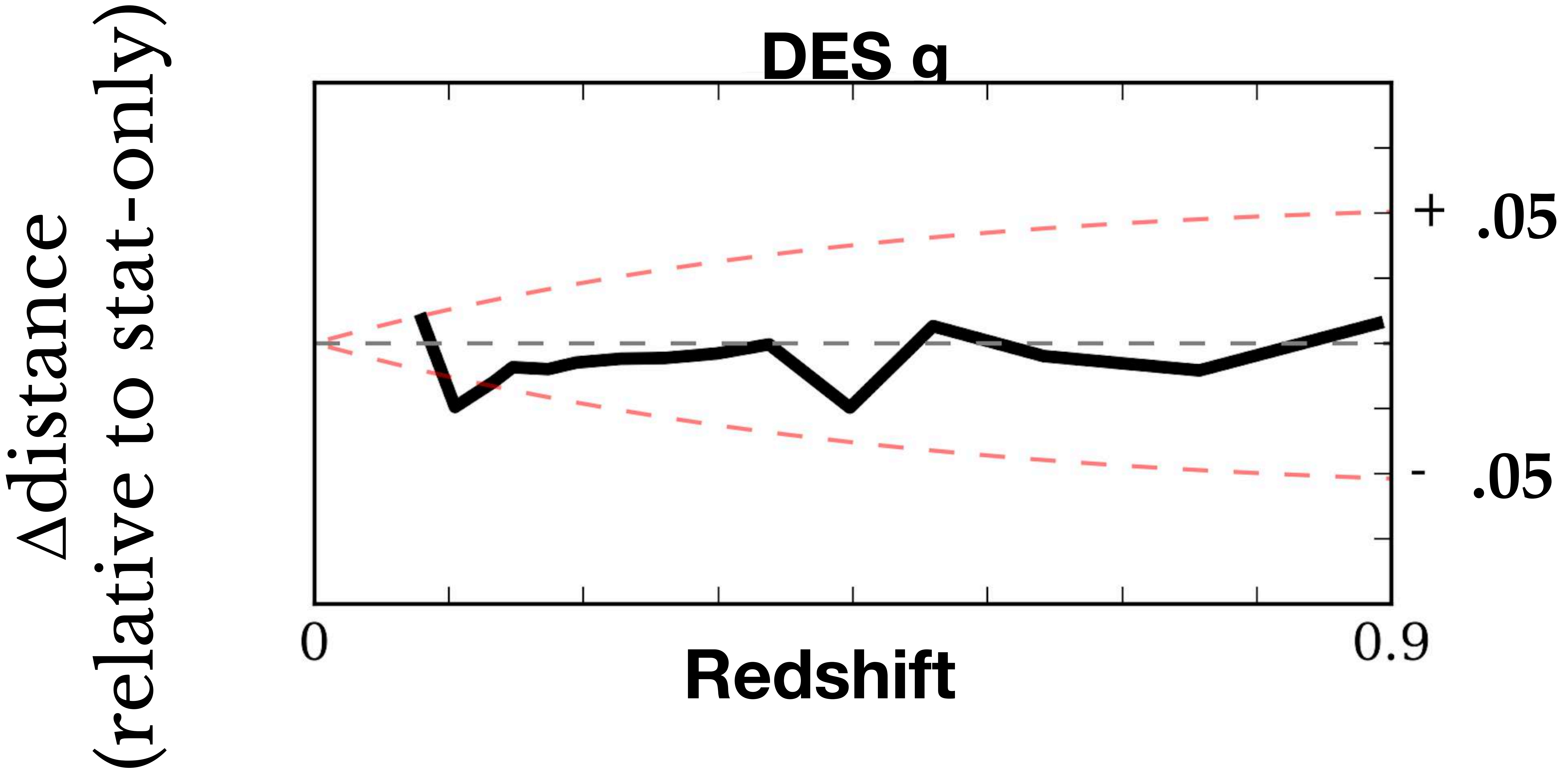


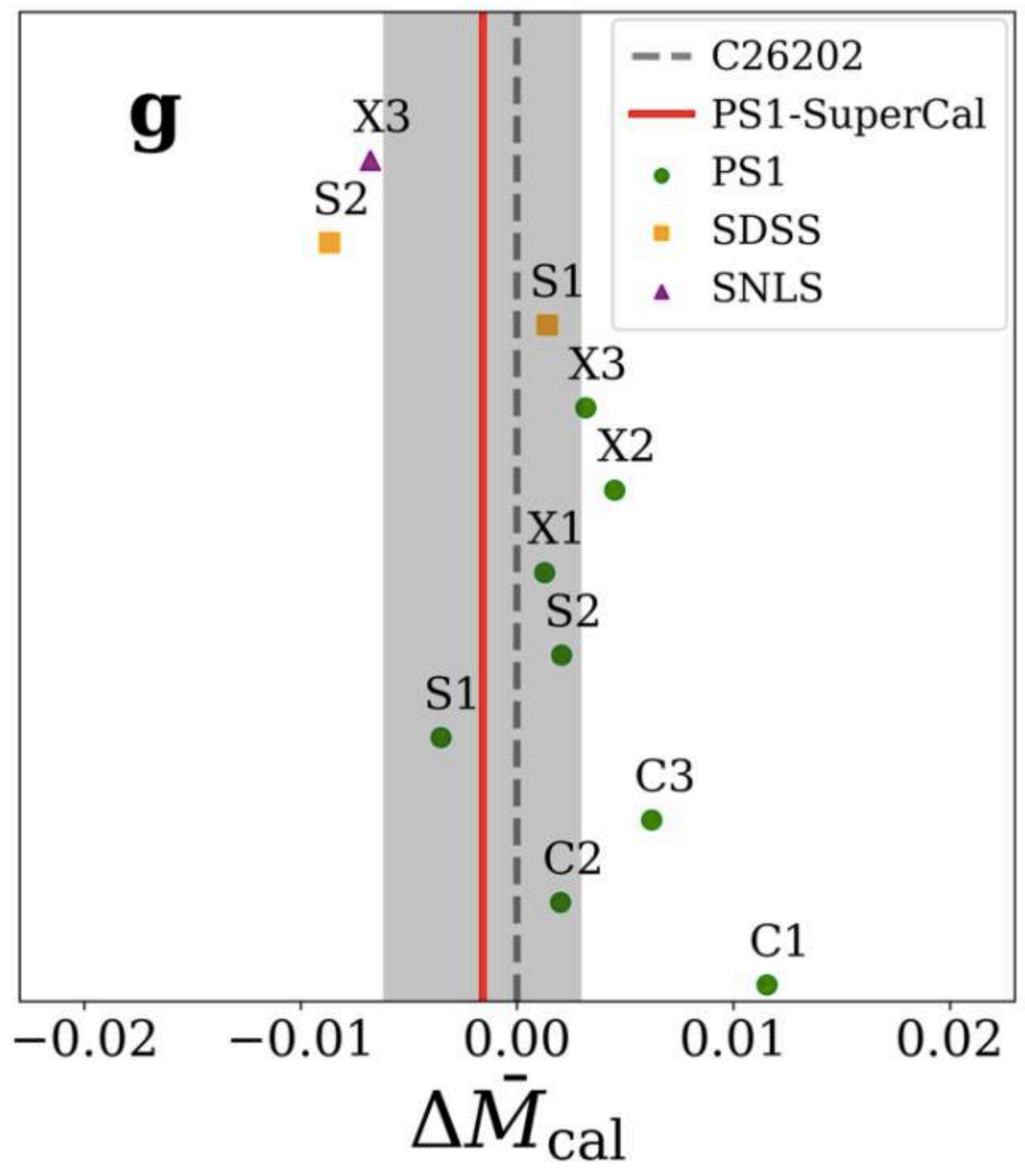
Calibration systematic uncertainty





The change in distance after varying each systematic





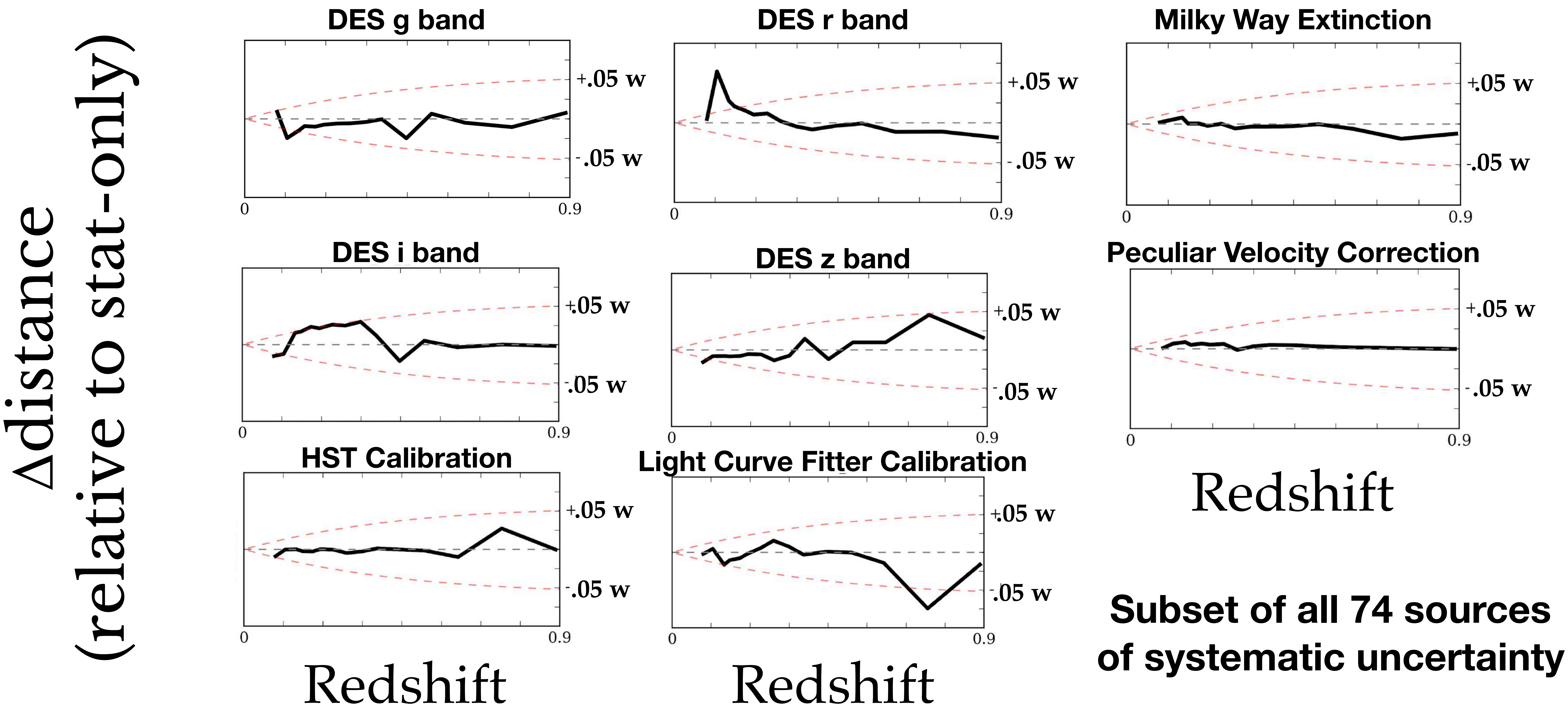
The change in distance after varying each systematic

We build our redshift-binned 20×20 systematic covariance matrix $C_{\rm syst}$ for all sources (SYS_k),

$$C_{\mathcal{Z}_i \mathcal{Z}_j,\mathrm{syst}} = \sum_{k=1}^{K=74} \frac{\partial \Delta \langle \mu_{\mathrm{SYS}} \rangle_{\mathcal{Z}_i}}{\partial \mathrm{SYS}_k} \frac{\partial \Delta \langle \mu_{\mathrm{SYS}} \rangle_{\mathcal{Z}_j}}{\partial \mathrm{SYS}_k} \sigma_k^2,$$

which denotes the covariance between the $\mathcal{Z}_i^{th}$ and $\mathcal{Z}_j^{th}$ redshift bin summed over the K different sources of systematic uncertainty ($K = 74$) with magnitude σ_k.

The change in distance after varying each systematic



Subset of all 74 sources of systematic uncertainty

Fitting for Cosmology

$$\chi^2 = \Delta\mu C^{-1} \Delta\mu$$

$$C = C_{stat} + C_{syst}$$

CosmoMC + Planck 2015 CMB Priors

We need to be careful about confirmation bias

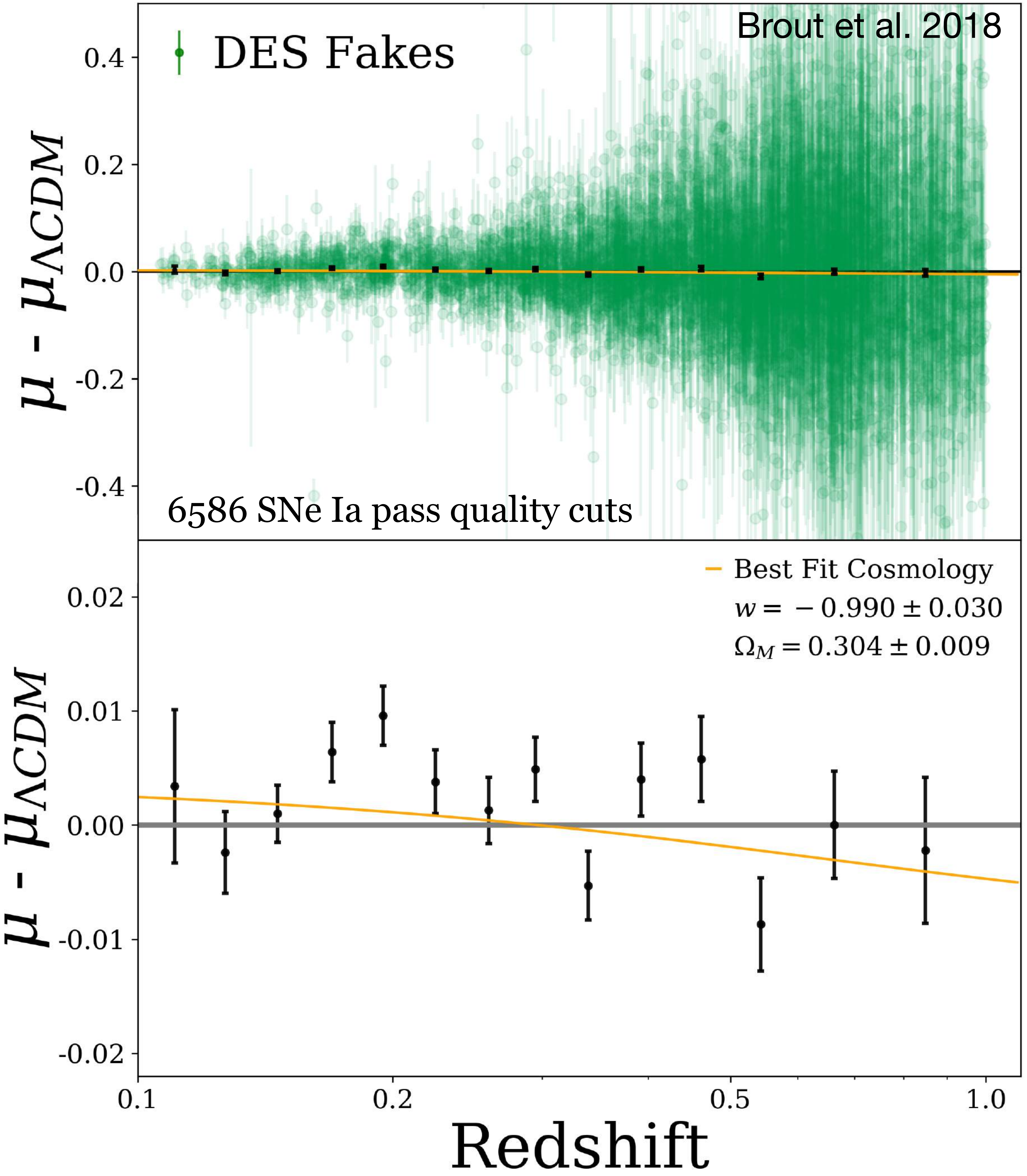
We implemented **blinding** and we **validated** more rigorously than any previous supernova survey.

Validation

First large scale, end to end validation of the DES-SN pipelines using 10,000 Fake SN Ia light curves inserted into real DECam images.

These fake light curves are analyzed by:

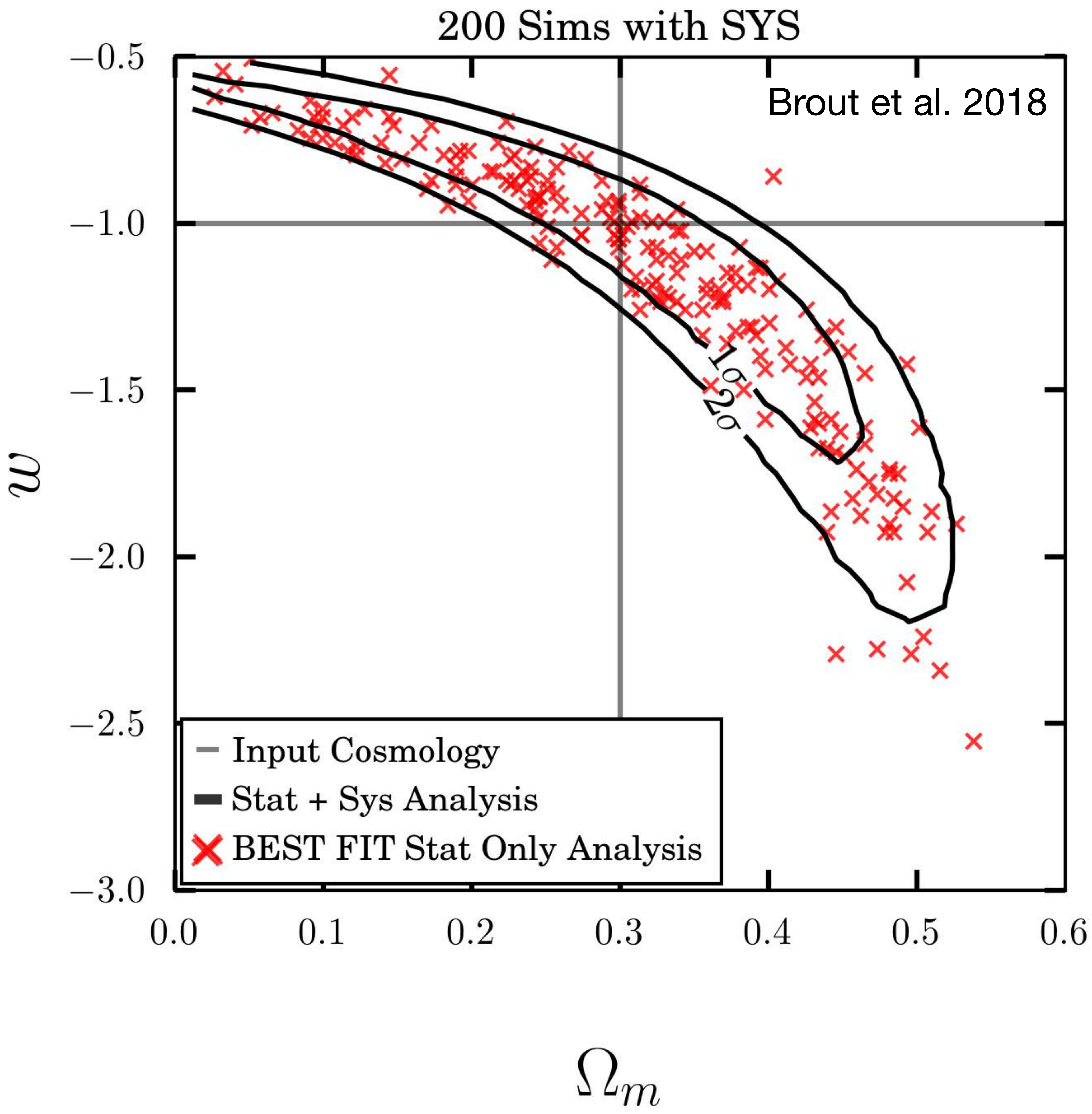
Difference imaging
+
Scene Modeling Photometry
+
Bias Corrections
+
Cosmology Analysis



Validation

We validate the cosmological analysis pipeline (BBC) best fit cosmology and uncertainties:

using 400 simulated datasets with simulated sources of systematic uncertainty.



How did we know we were ready to unblind?

400 “DES Like" Catalog level simulations with simulated systematic uncertainties are use to check for

w BIAS	**-0.002 +- 0.003**
UNCERTAINTY CROSSCHECK	**< 8%**

THE DARK ENERGY SURVEY

Motivation

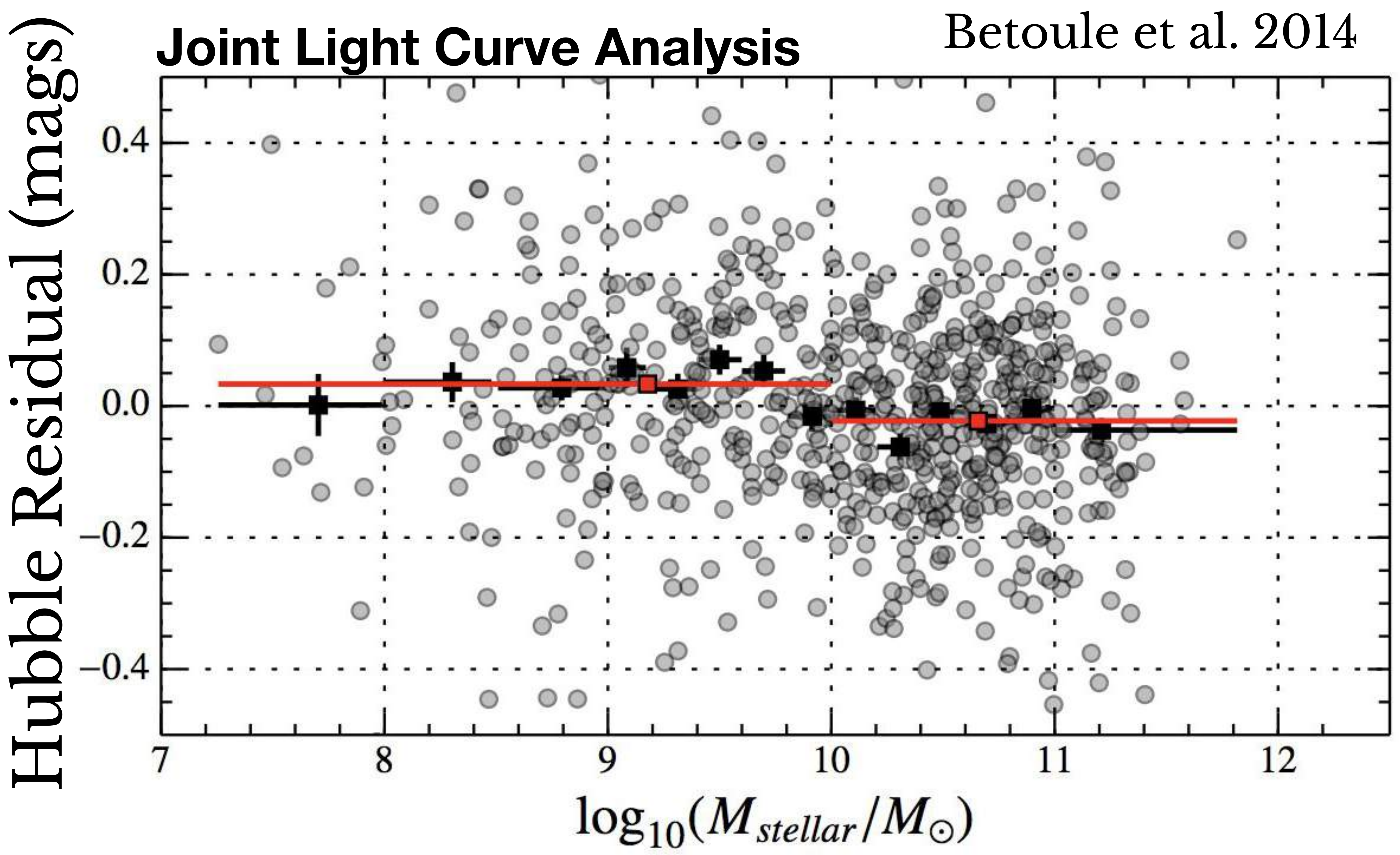
Ingredients for SN Ia Cosmology

Results from the First 3 Years

The Future of DES-SN

Results

Fitted Hubble residual step across M_{host}

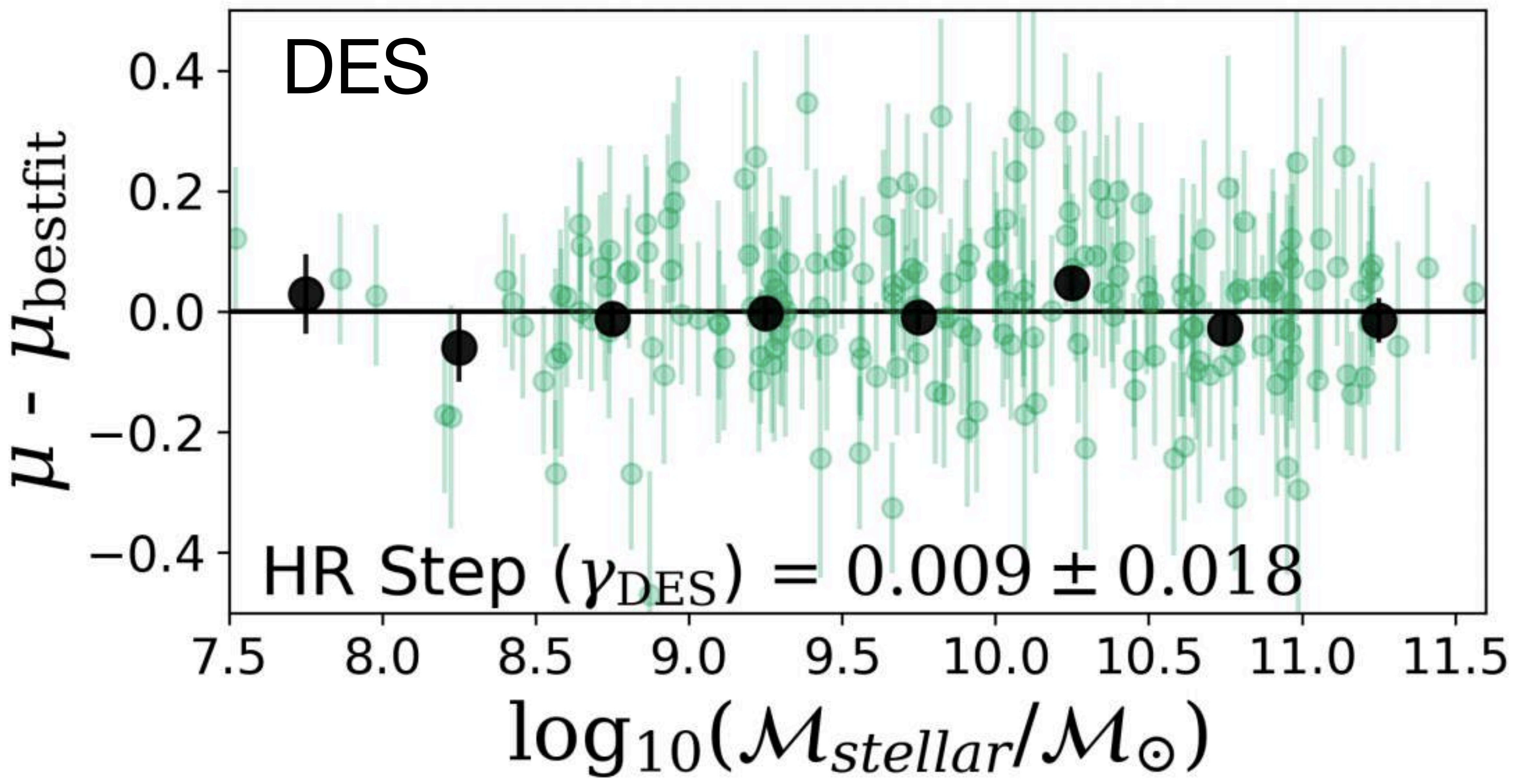


First found by (Hicken et al. 2009, Sullivan et al. 2010, Lampeitl et al. 2010)

Results

Fitted Hubble residual step across M_{host}

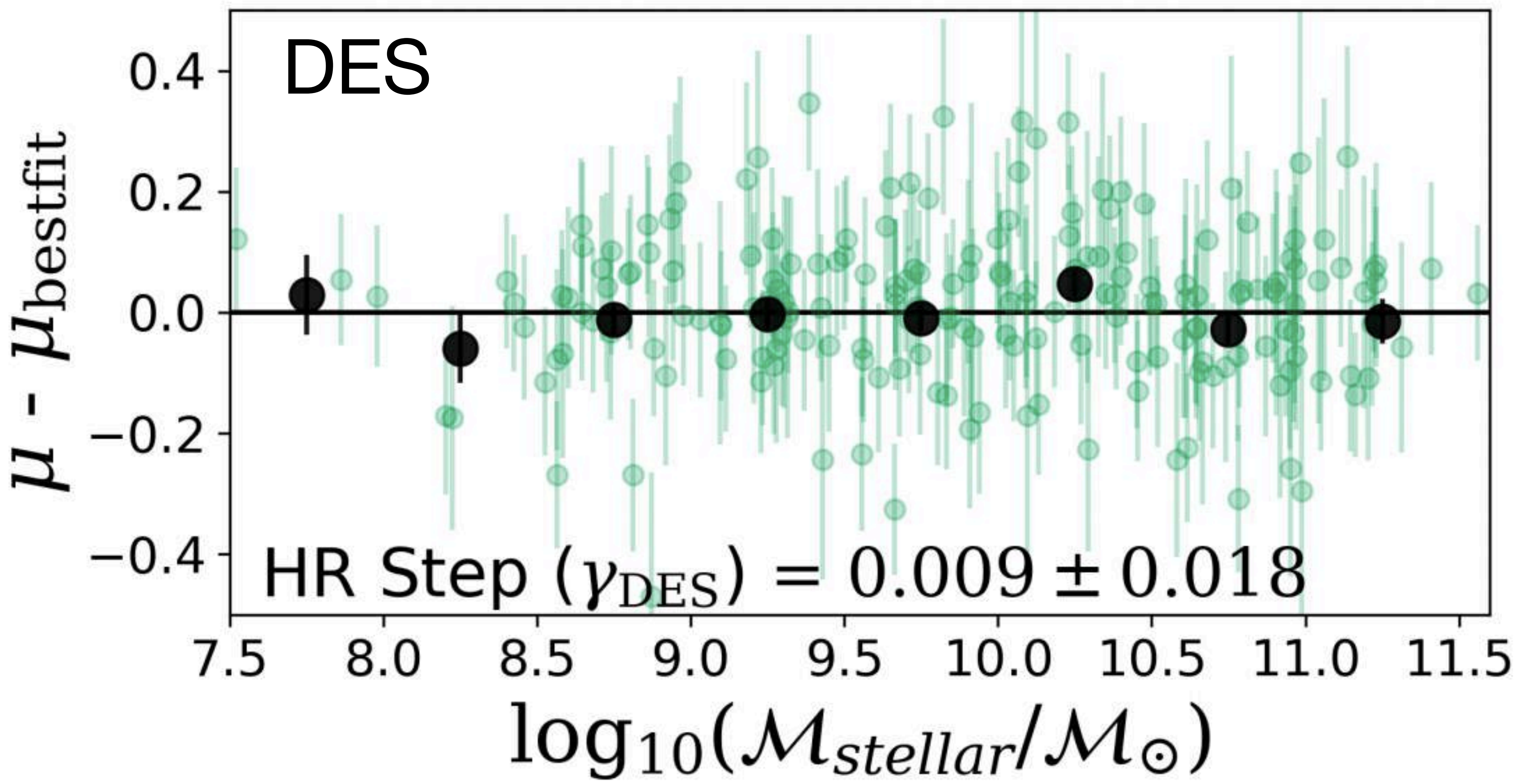
We see no correlation…



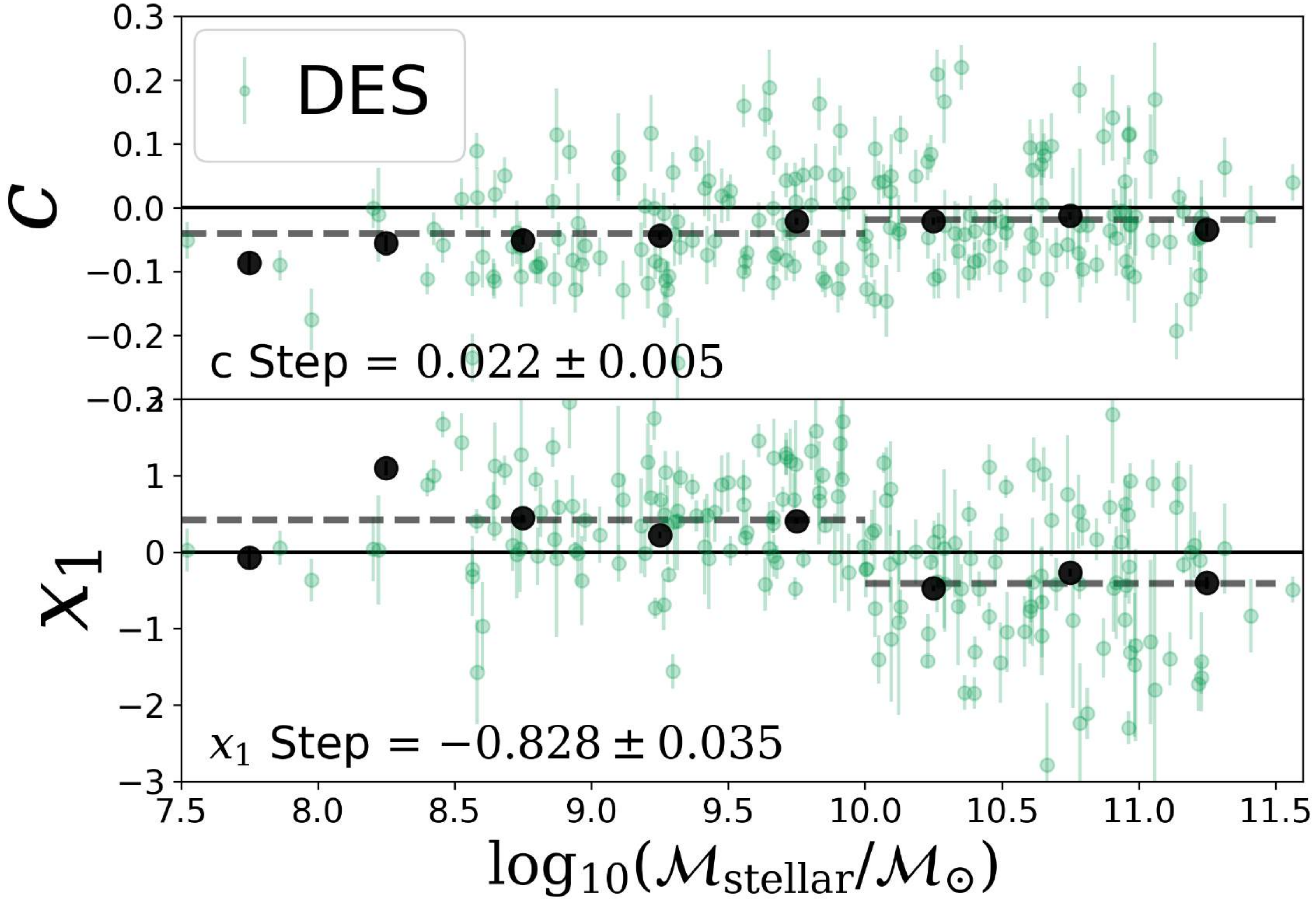
Results

Fitted Hubble residual step across M_{host}

We see no correlation…



We do see correlations with c, x_1



Brout et al. 2018

Results

Fitted Hubble residual step across M_{host}

We see no correlation...

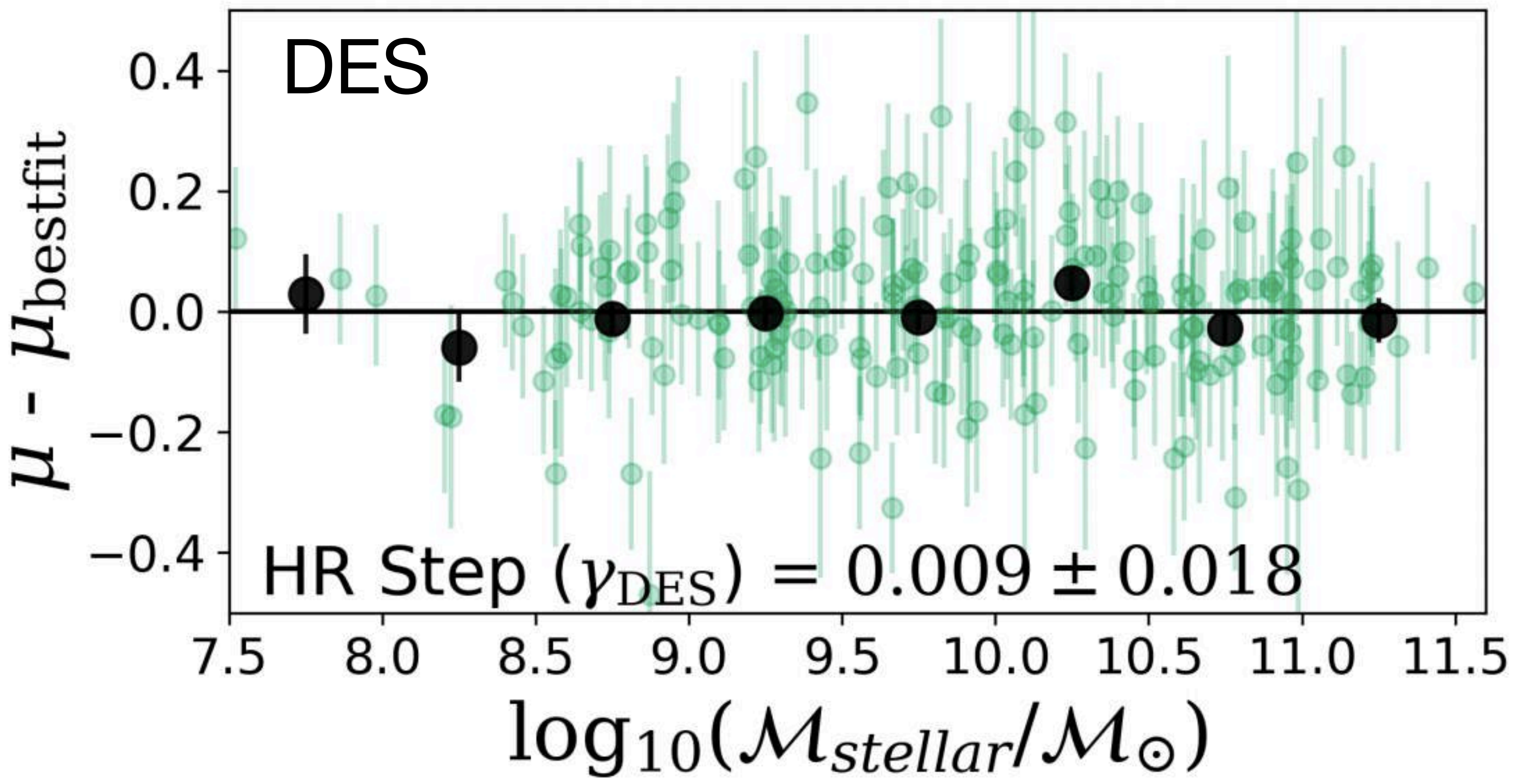


TABLE 7
SYSTEMATIC VARIATIONS FOR γ_{DES}

Variation	γ [mag]	# SNe Ia
Nominal	0.009 ± 0.018	207
$c > 0$	0.069 ± 0.039	70
$c < 0$	-0.005 ± 0.020	137
$x_1 > 0$	0.018 ± 0.025	119
$x_1 < 0$	-0.013 ± 0.029	88
no z band	0.000 ± 0.021	202
1D BiasCorr.	0.041 ± 0.021	207
`DiffImg` Photometry	0.001 ± 0.020	207
$\mathcal{M}_{\rm stellar} \neq$ null	0.010 ± 0.020	207
$\mathcal{R}_{\rm step} = 10.1$	0.021 ± 0.019	207
10 z-bins	0.015 ± 0.018	207
Le Phare	0.008 ± 0.020	207

NOTE. — Changes in γ for the DES subset after perturbations to analysis. Parameter values are shown for the G10 model of intrinsic scatter only.

Brout et al. 2018

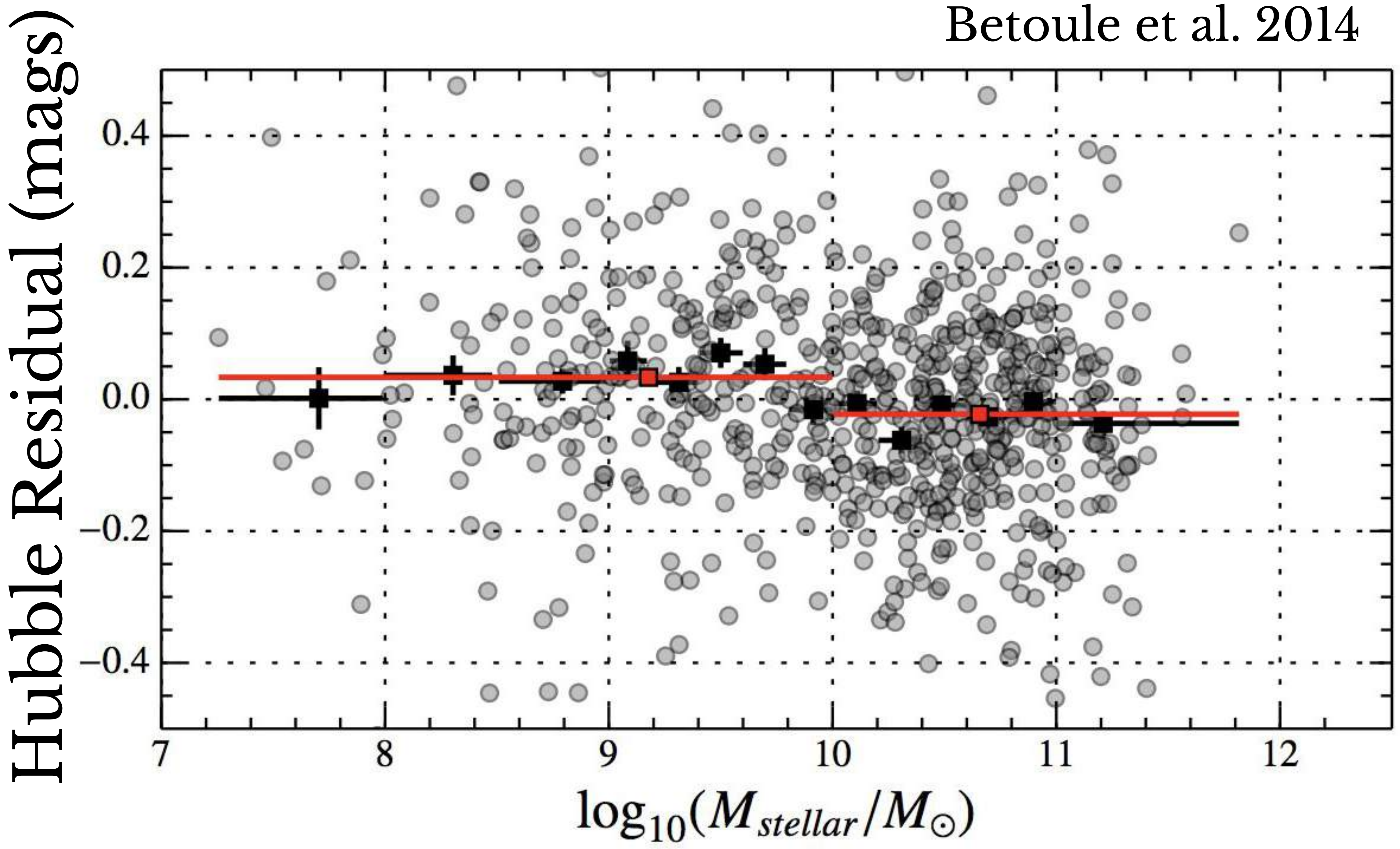
Results

Fitted Hubble residual step across M_{host}

vs.

Intrinsic Scatter

Betoule et al. 2014



Results

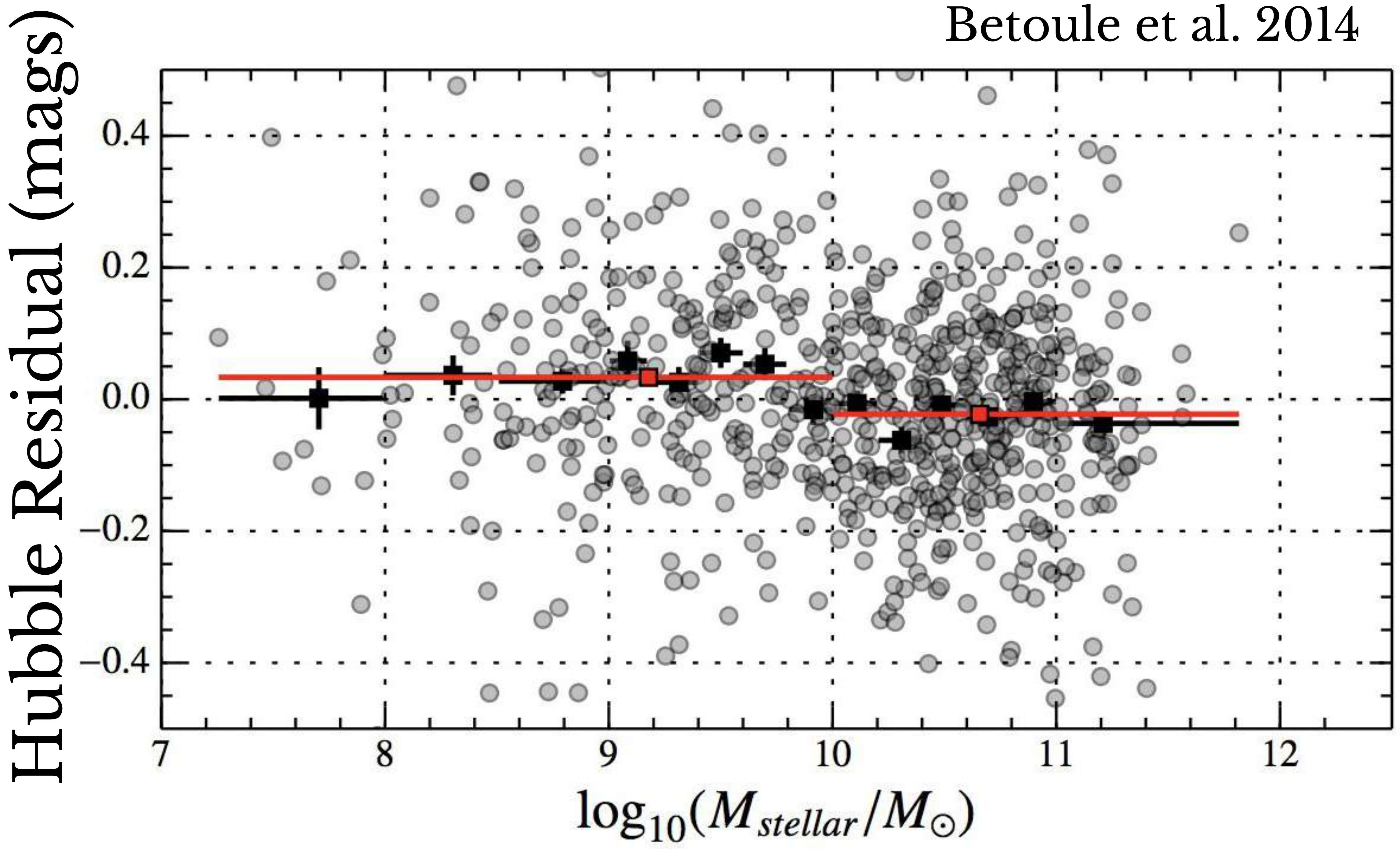
Fitted Hubble residual step across M_{host}

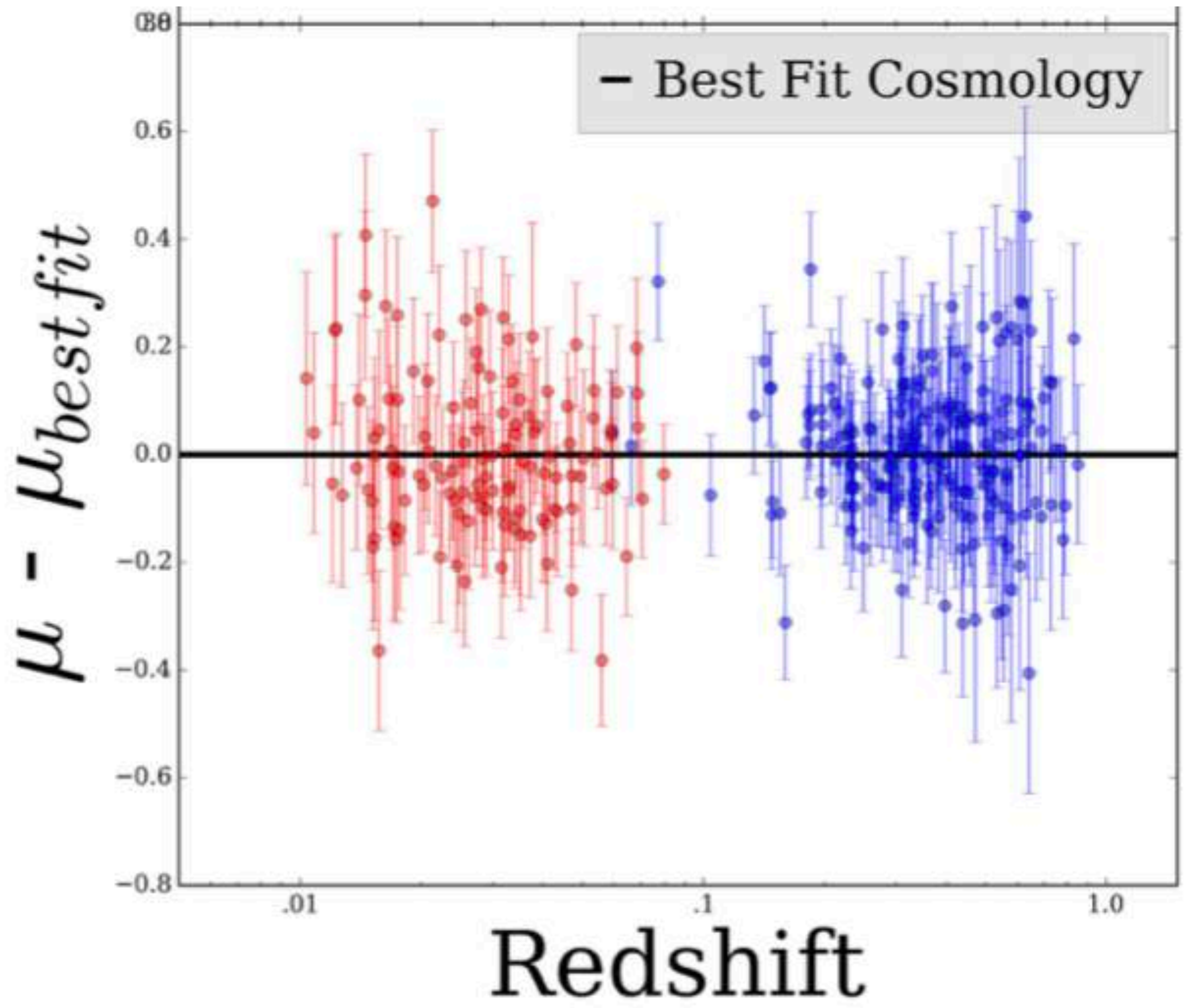
vs.

Intrinsic Scatter

$$\sigma_\mu^2 = C_{m_B,m_B} + \alpha^2 C_{x_1,x_1} + \beta^2 C_{c,c} + 2\alpha C_{m_B,x_1} - 2\beta C_{m_B,c} - 2\alpha\beta C_{x_1,c} + \sigma^2_{\text{vpec}} + \sigma^2_z + \sigma^2_{\text{lens}} + \sigma^2_{\text{int}}$$

Betoule et al. 2014





Results

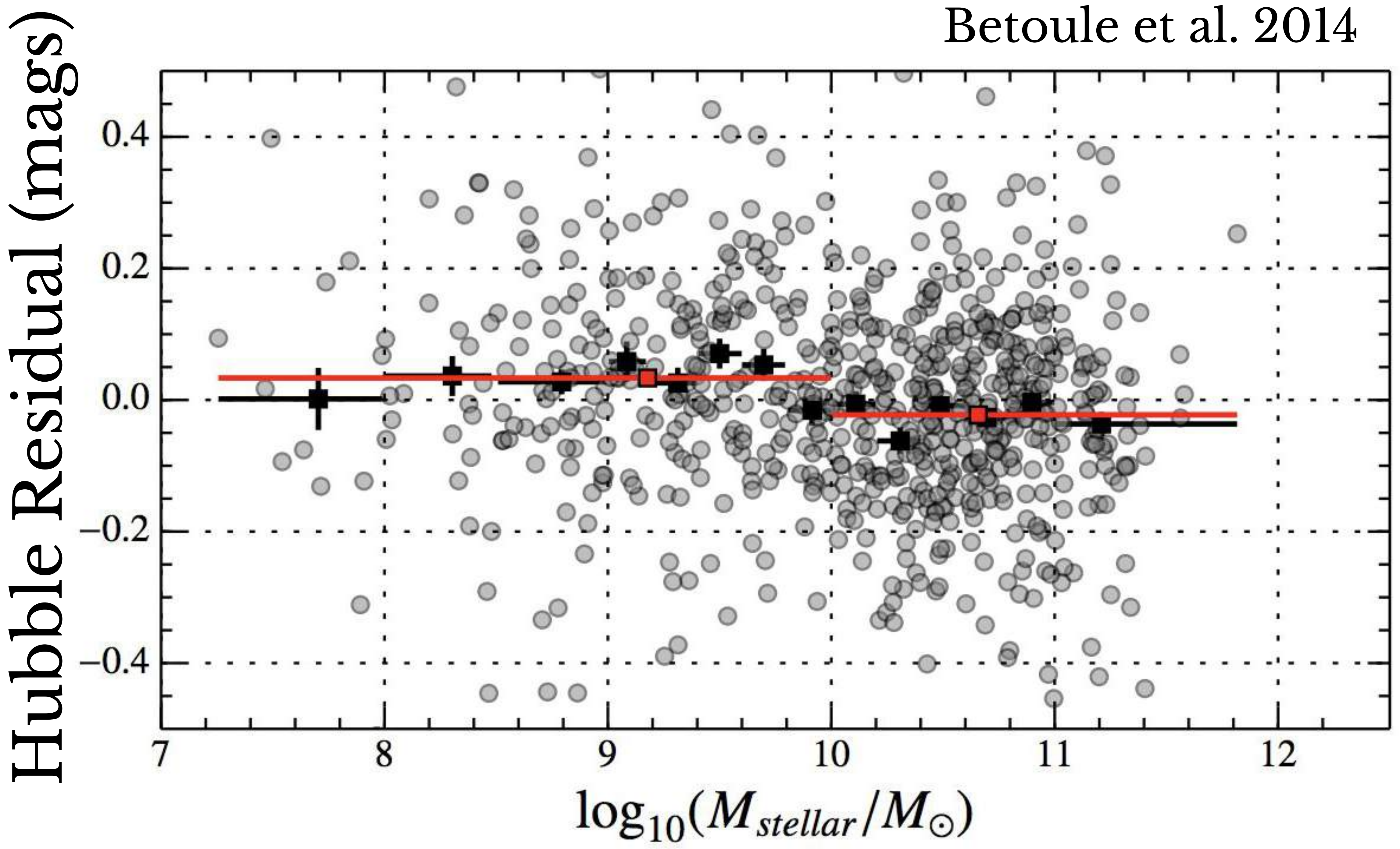
Fitted Hubble residual step across M_{host}

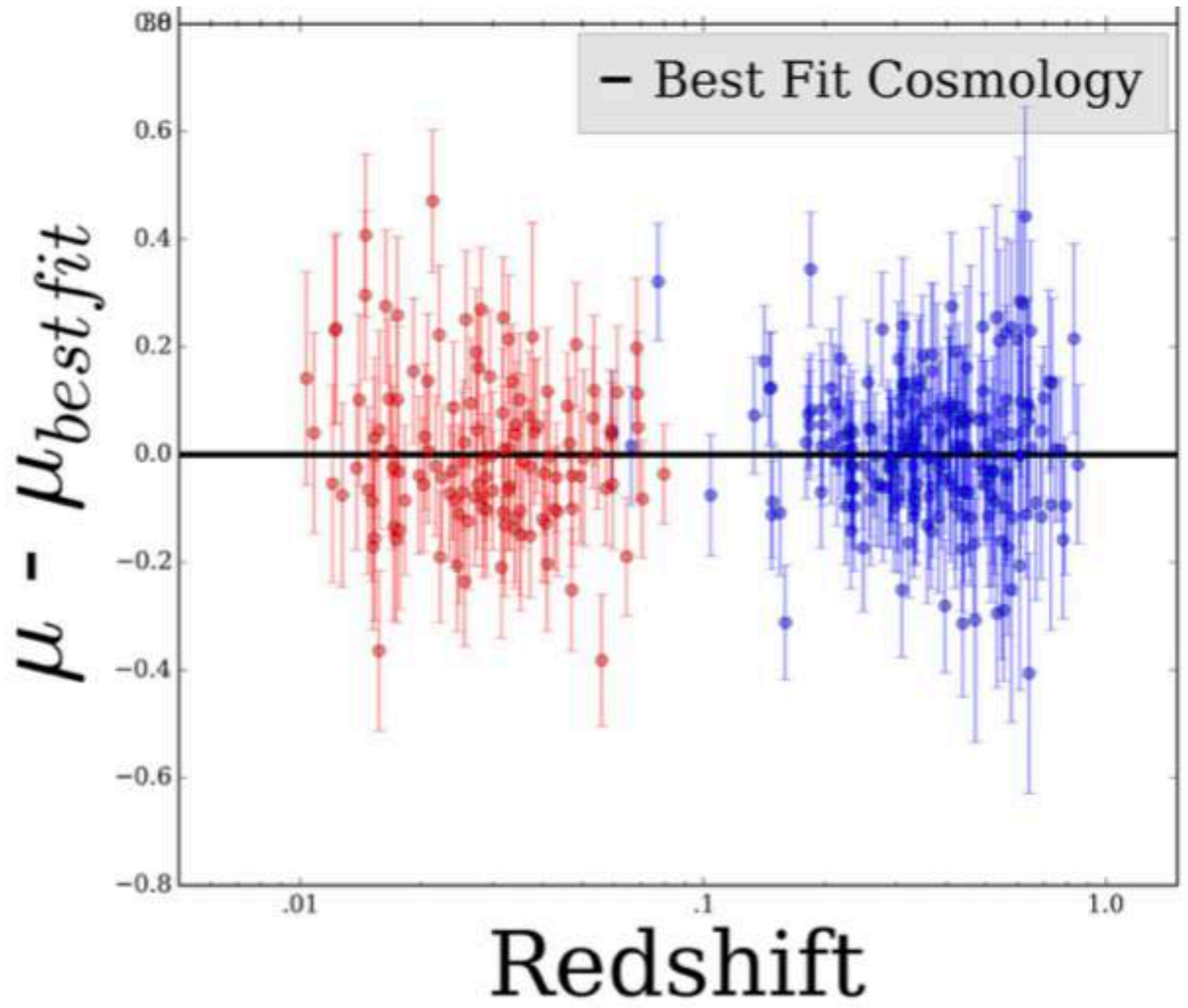
vs.

Intrinsic Scatter

$$\sigma_\mu^2 = C_{m_B,m_B} + \alpha^2 C_{x_1,x_1} + \beta^2 C_{c,c} + 2\alpha C_{m_B,x_1} - 2\beta C_{m_B,c} - 2\alpha\beta C_{x_1,c} + \sigma^2_{\text{vpec}} + \sigma^2_z + \sigma^2_{\text{lens}} + \sigma^2_{\text{int}}$$

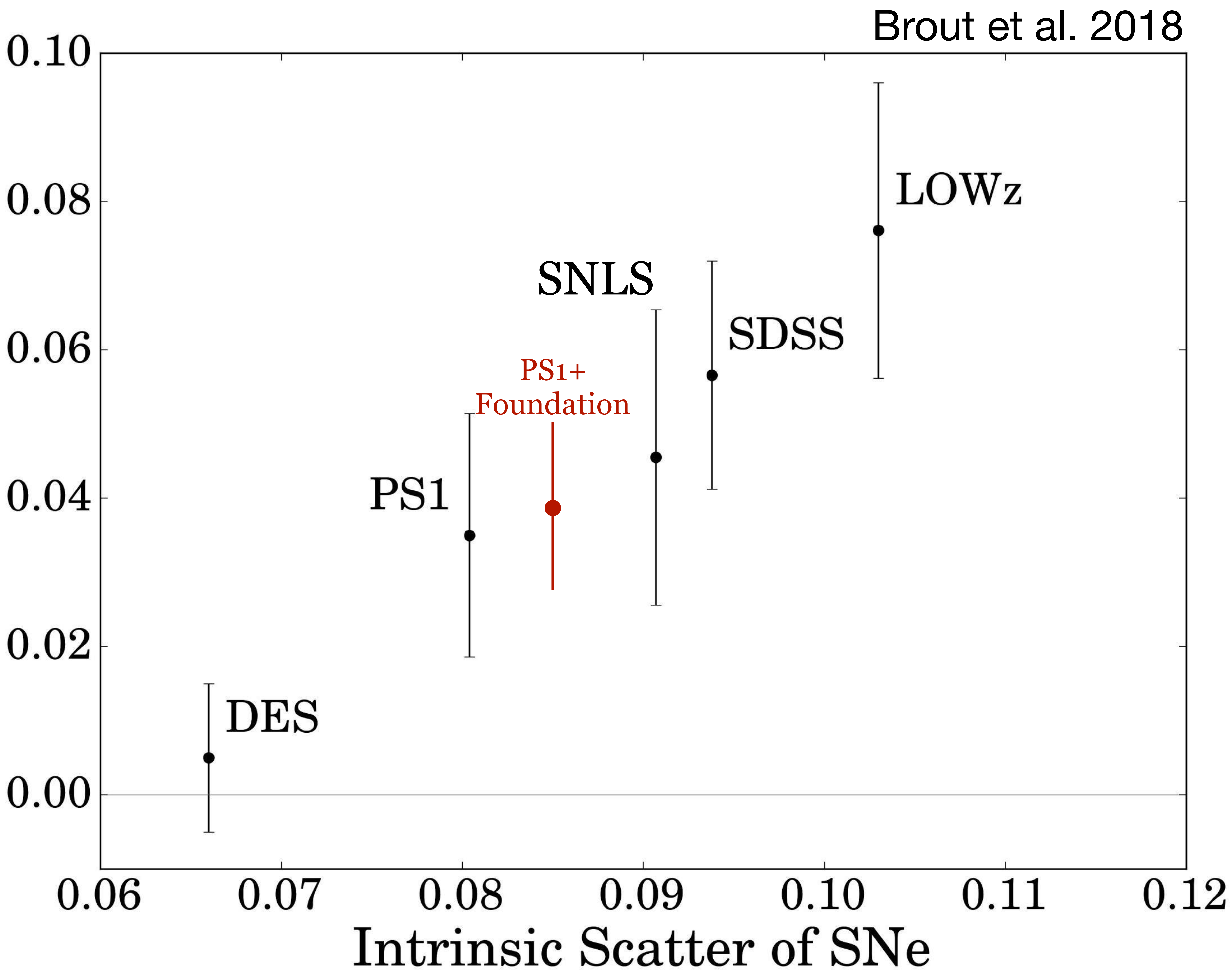
Betoule et al. 2014





Results

Fitted Hubble residual step across M_{host}



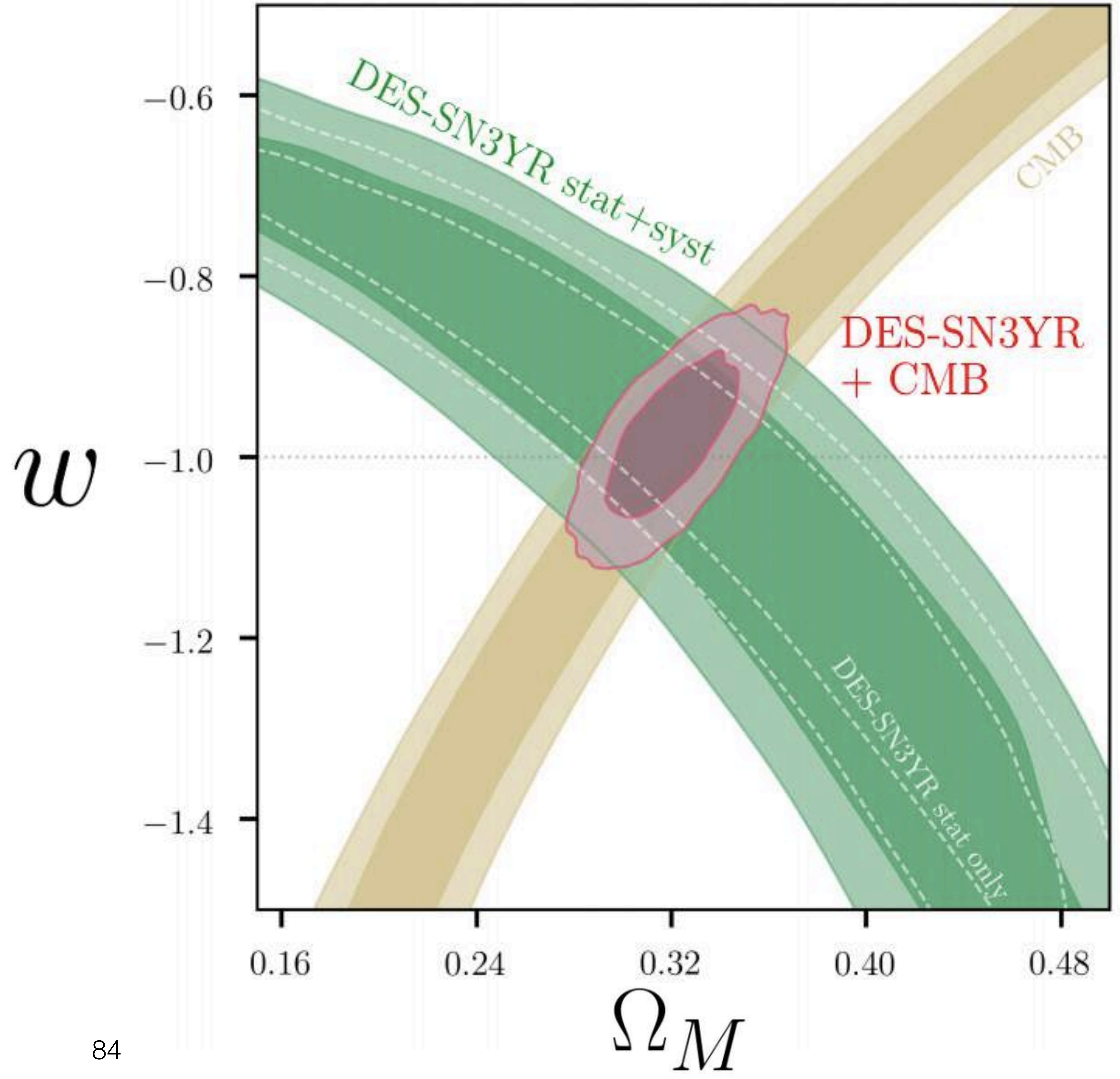
DES has lowest intrinsic scatter and doesn't see HR effect. Not understood, but interesting clue...

DES-SN3YR Results!

DES-SN3YR Results!

Flat wCDM

DES Collaboration et al. 2018

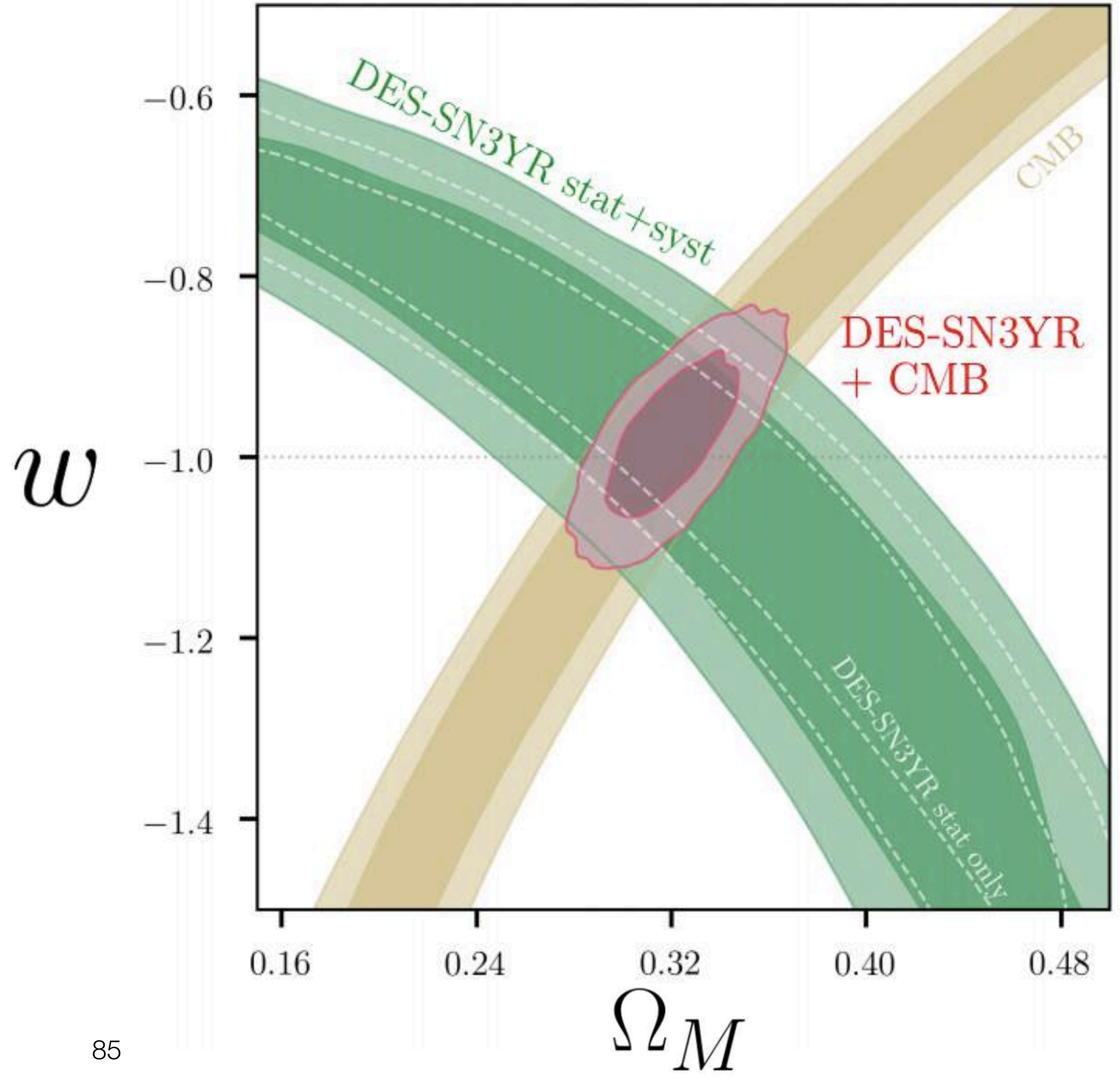


DES-SN3YR Results!

$$w = -0.978 \pm 0.059$$

Flat wCDM

DES Collaboration et al. 2018



DES-SN3YR Results!

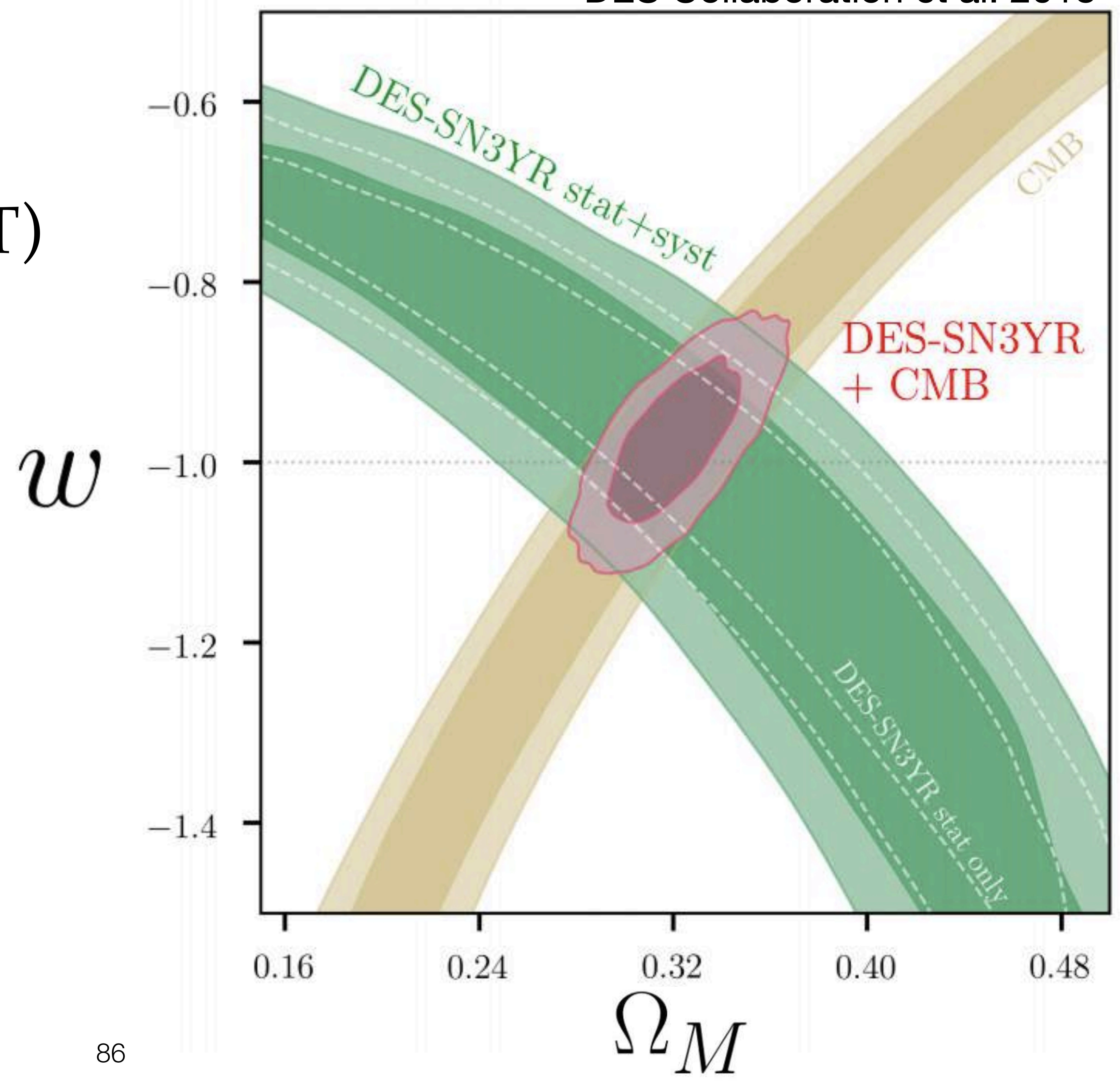
Flat wCDM

$$w = -0.978 \pm 0.059$$

$\sigma_w =$ 0.042 (STAT), 0.042 (SYST)

The beginning of an era dominated by systematic uncertainties

DES Collaboration et al. 2018



DES-SN3YR Results!

Flat wCDM

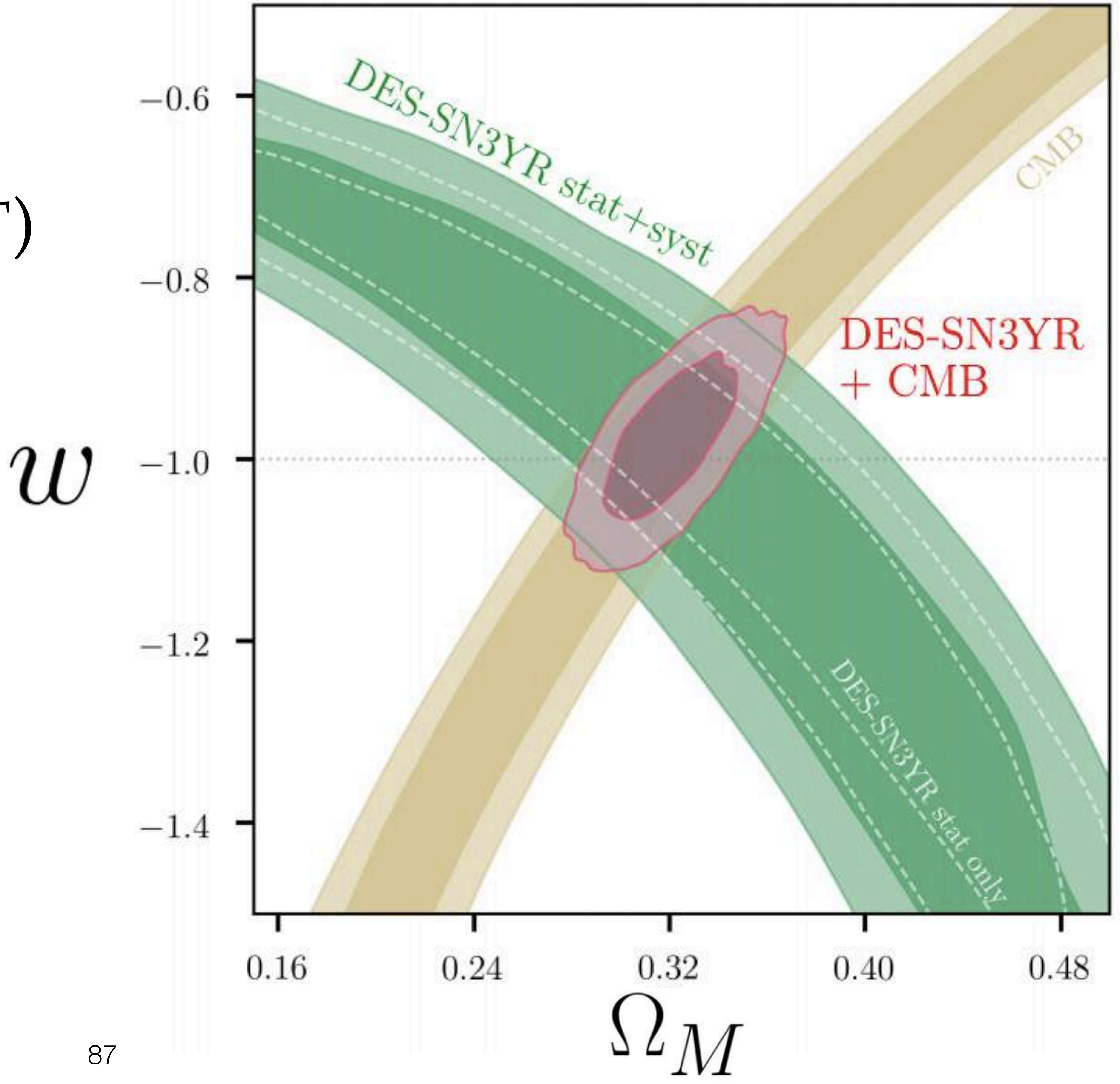
$$w = -0.978 \pm 0.059$$

$$\sigma_w = \quad 0.042\ (\text{STAT}),\ 0.042\ (\text{SYST})$$

The beginning of an era dominated by systematic uncertainties

All hope is not lost! With higher statistics we can improve our understanding of SN astrophysics and survey modeling

DES Collaboration et al. 2018

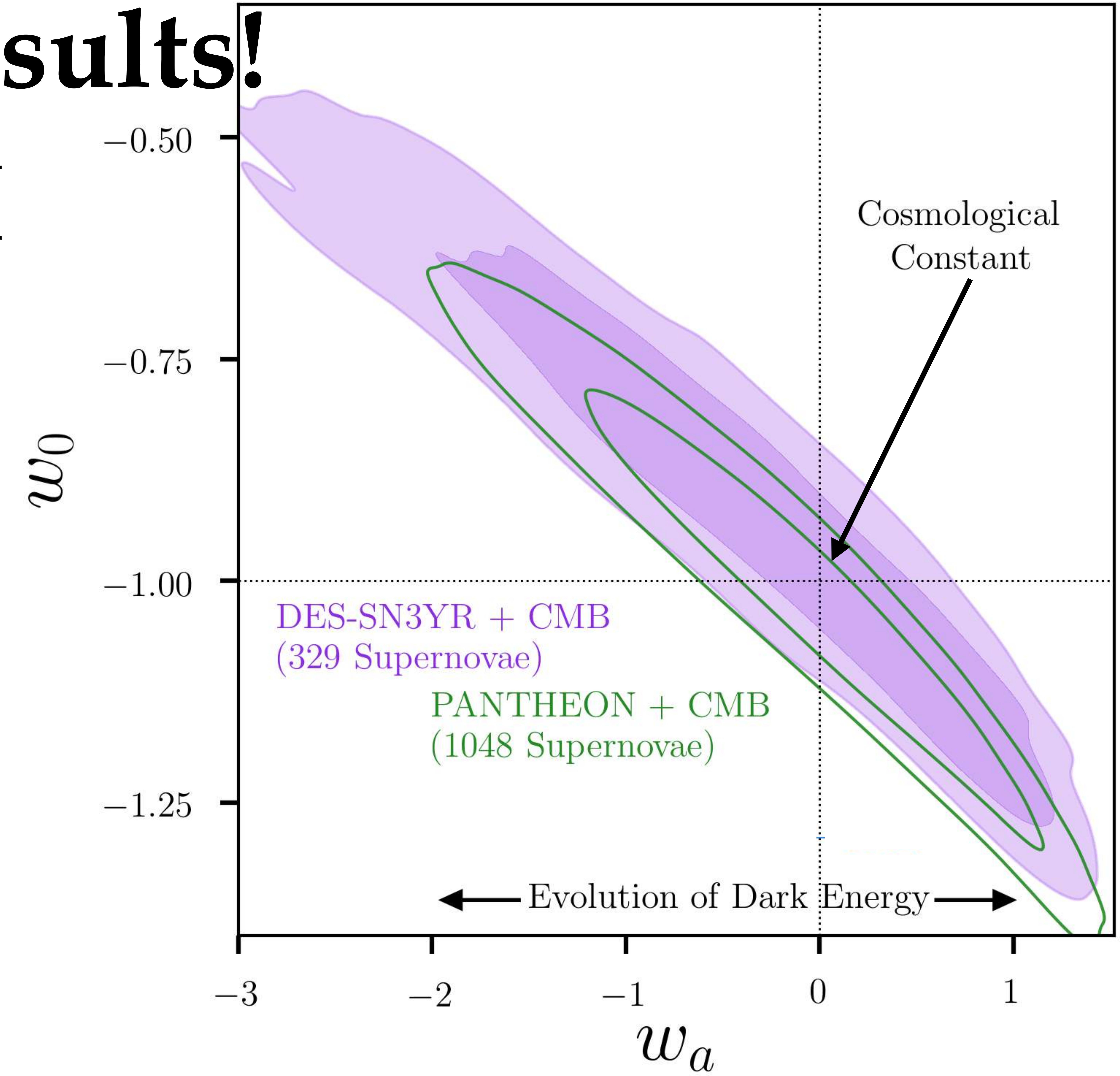


DES-SN3YR Results!

Flat w_0w_aCDM

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

$$w_a = -0.387 \pm 0.430$$



w UNCERTAINTY CONTRIBUTIONS FOR wCDM MODEL[a]

Description[b]	σ'_w
Total Stat ($\sigma_w^{\rm stat}$)	0.042
Total Syst[c] ($\sigma_w^{\rm total\ syst}$)	0.042
[Photometry & Calibration]	**[0.021]**
[μ-Bias Corrections: Survey]	**[0.023]**
[μ-Bias Corrections: Astrophysical]	**[0.026]**

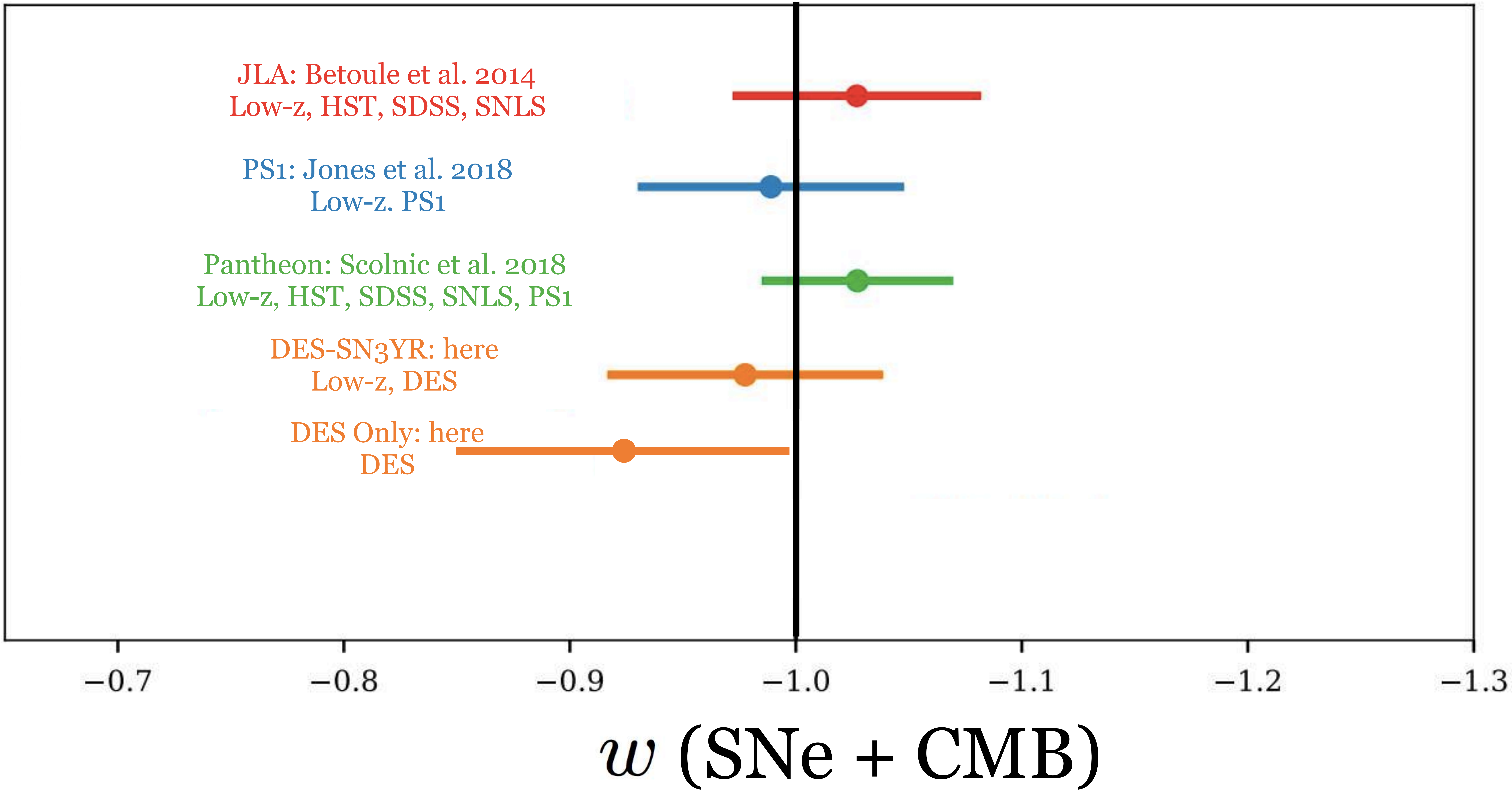
Previously Unforeseen Systematics

- Low-z outlier cuts*
- A non-constant value for the intrinsic scatter scaling. (one for each SN sample)
- The cosmology of the simulated samples used for bias corrections.
- A z+0.00004 redshift systematic

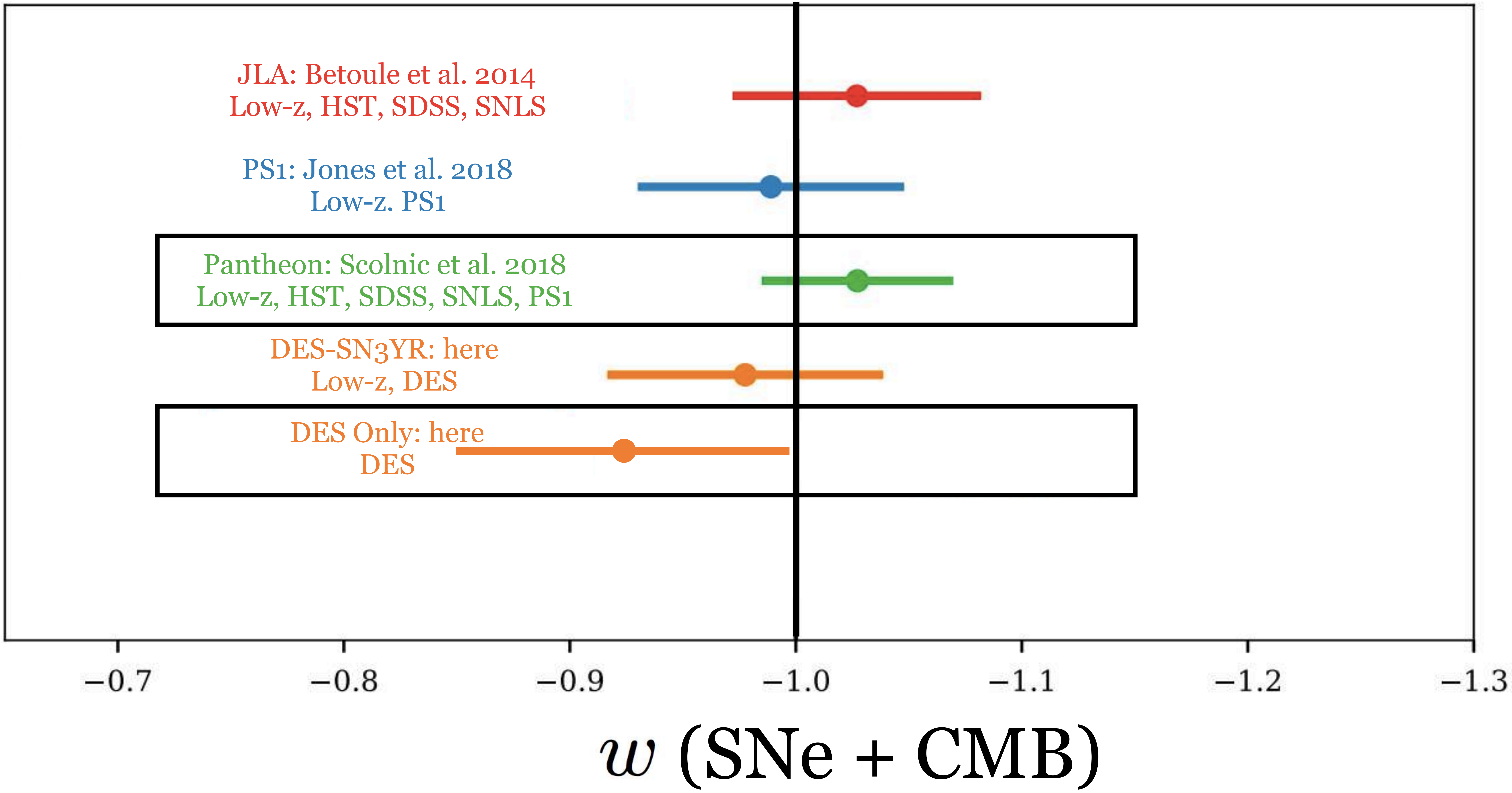
These new systematics combine to $\sigma_w = 0.02$ which is comparable to previously listed groupings.

*the single largest systematic
In the entire DES-SN3YR analysis

Cosmological Results for Recent Analyses



Cosmological Results for Recent Analyses



DES Only Results From Combined Probes

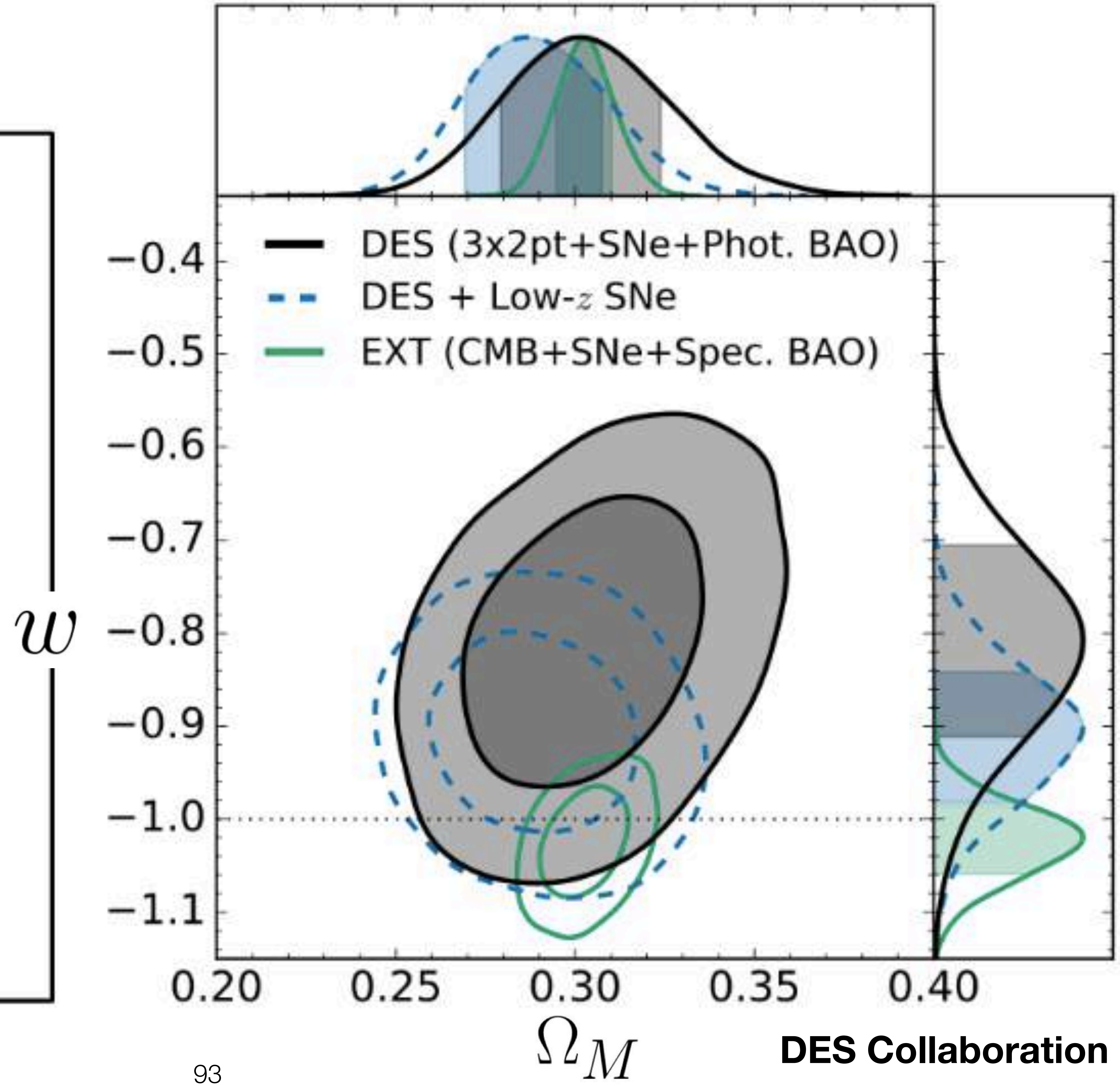
First single photometric probe to independently rule out a no dark energy universe.

DES: SN + 3x2pt + Phot. BAO

$$w = -0.80^{+0.09}_{-0.11}$$

DES-SN + Planck16

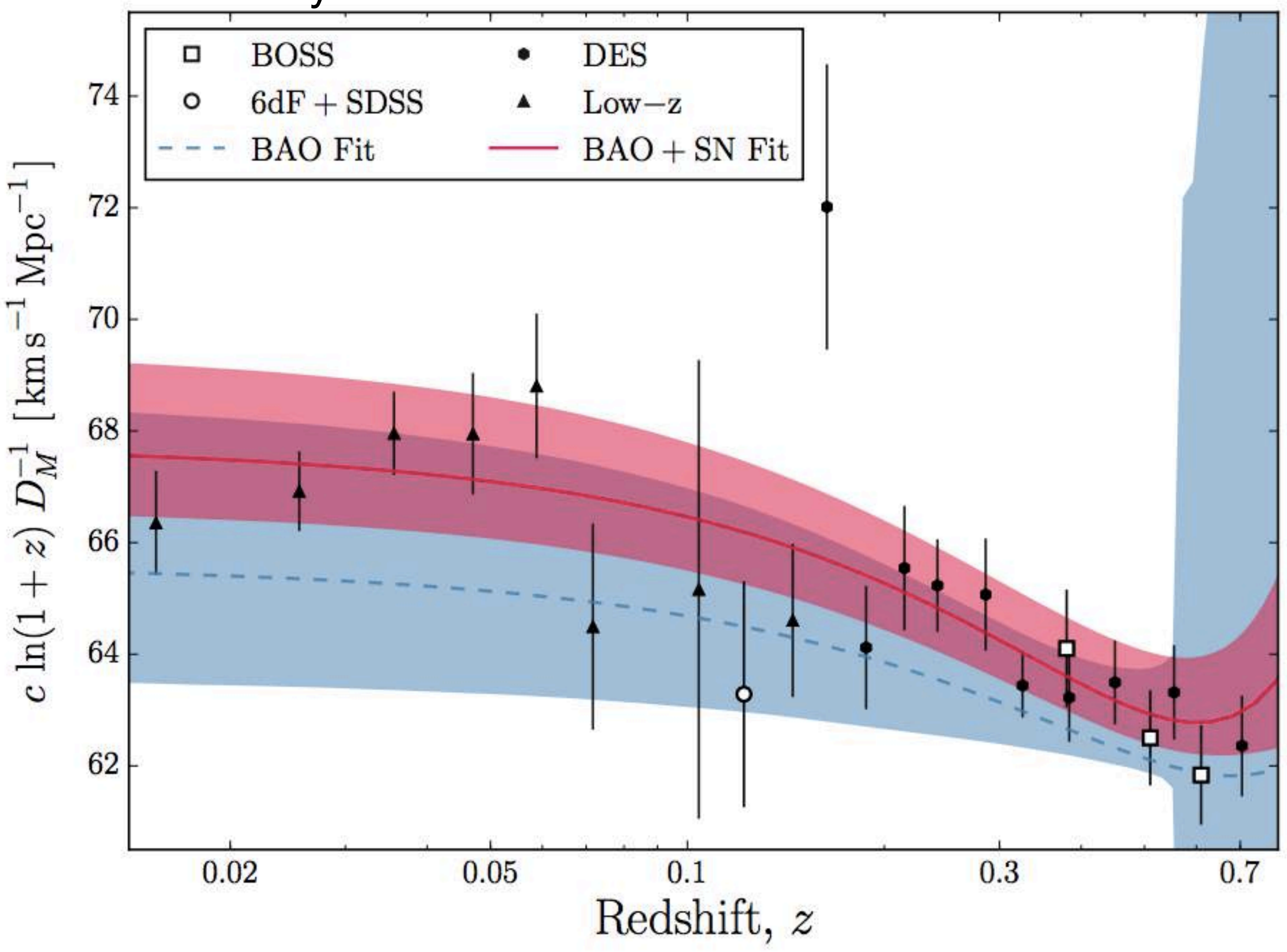
$$w = -0.911 \pm 0.087$$



DES Collaboration et al. 2018

Inverse Distance Ladder H0 Technique

Macaulay et al. 2018



Breaks degeneracy with peak intrinsic and H_o

Minimal assumptions about the underlying cosmological model.

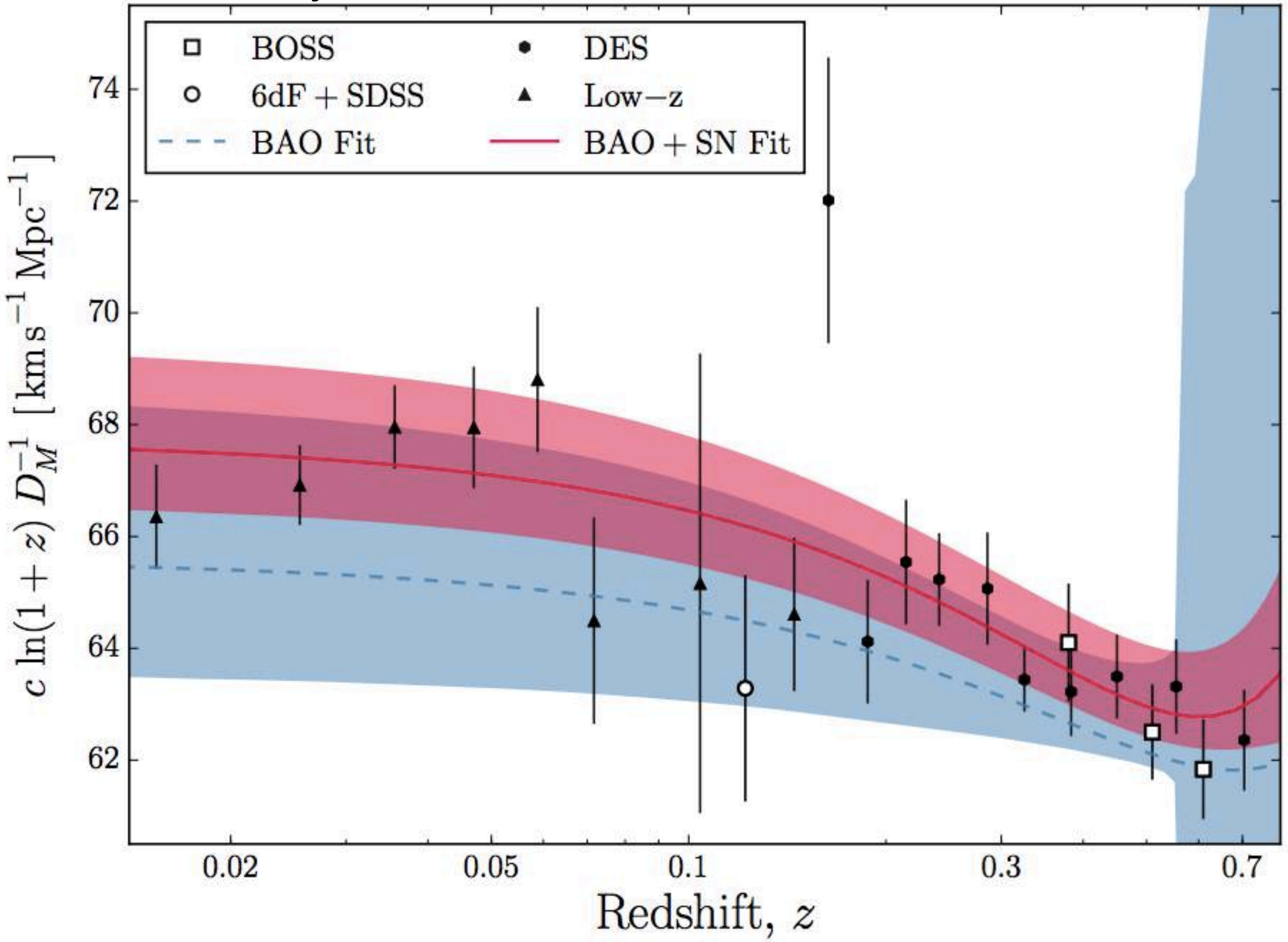
Polynomial cosmographic model.

Gaussian prior on r_s = 147 +- 1

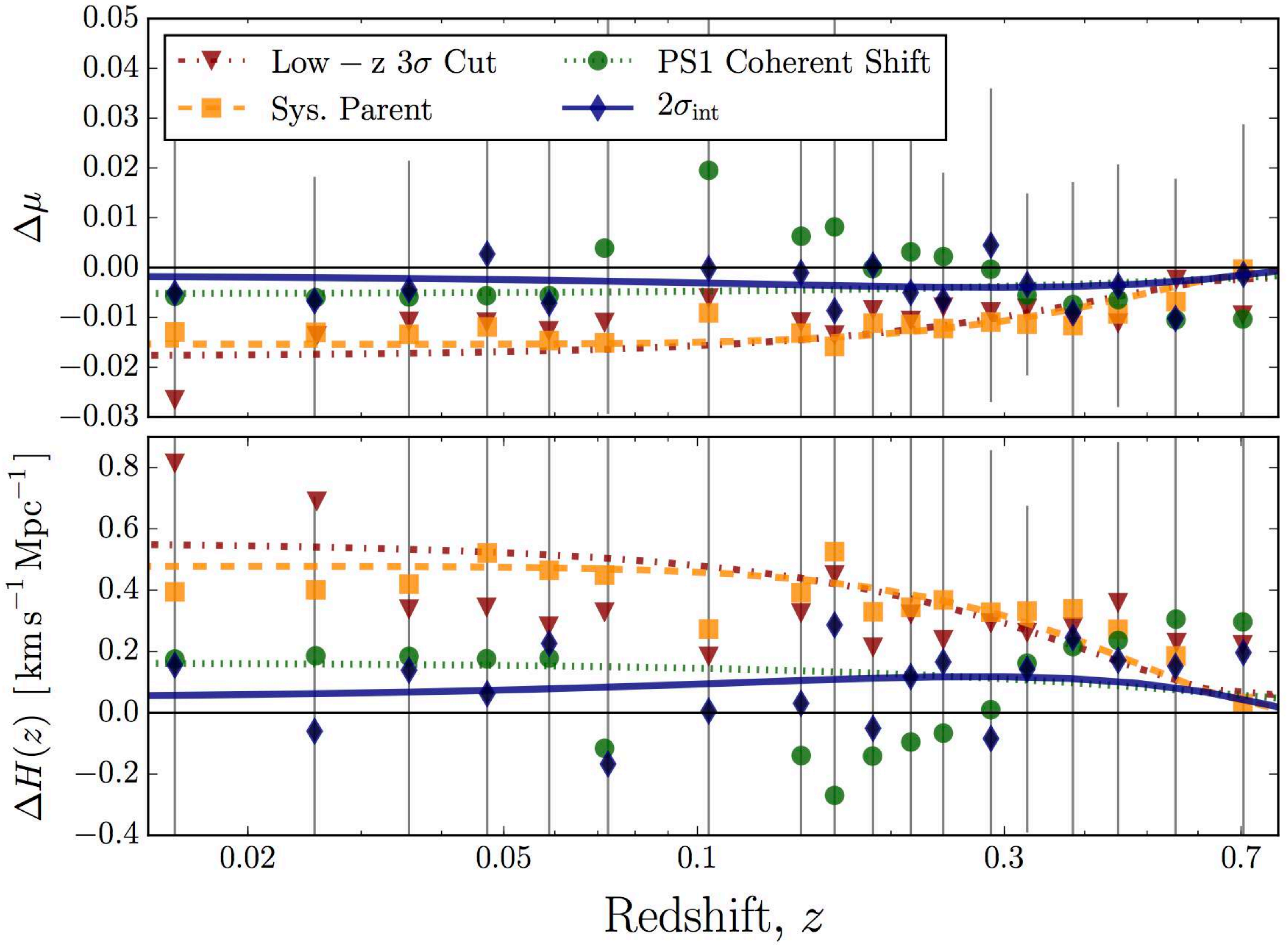
H0 = 67.77+- 1.30 km/s/Mpc

Inverse Distance Ladder H0 Technique

Macaulay et al. 2018

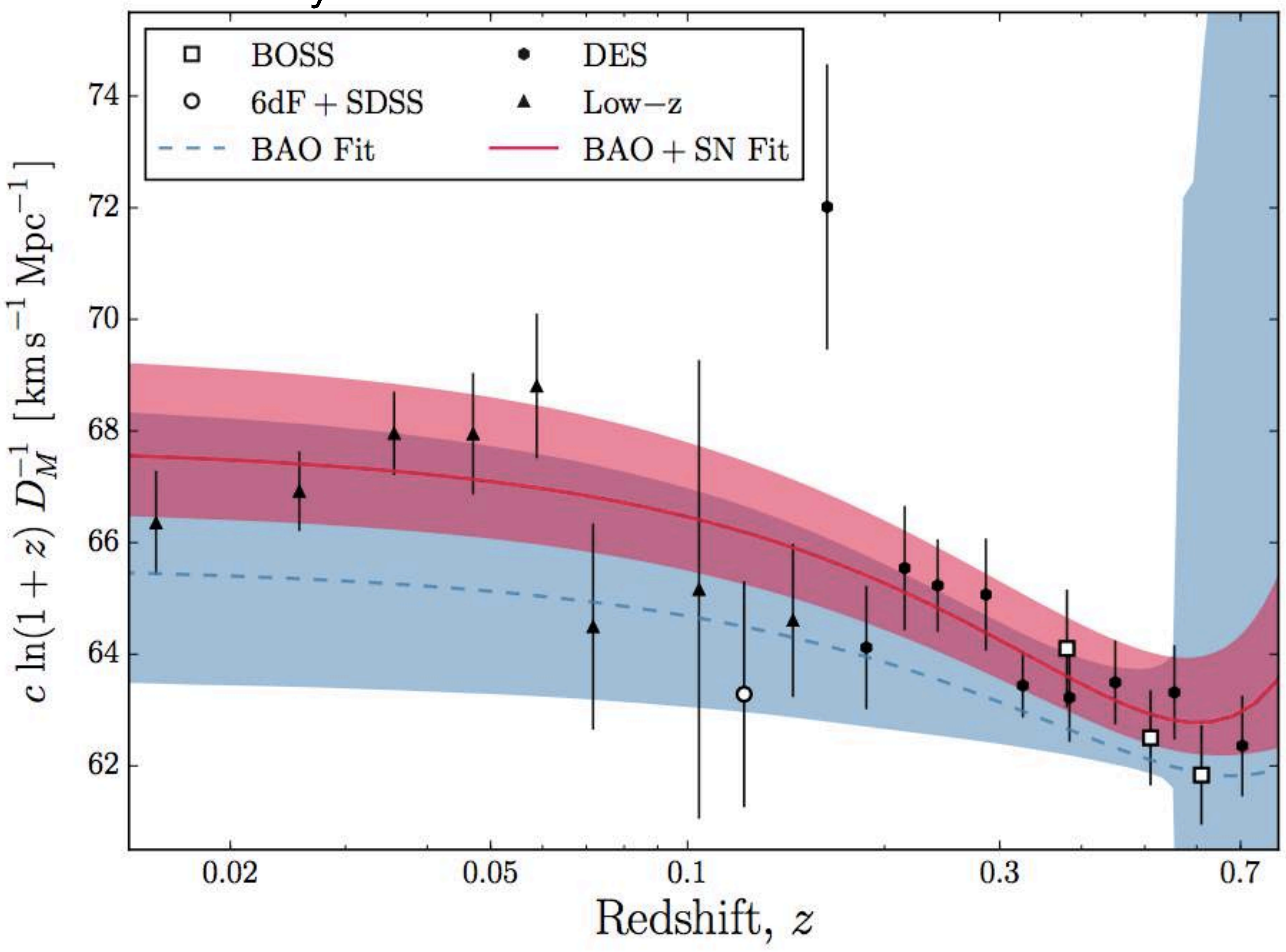


First H0 inverse distance ladder systematic error budget.



Inverse Distance Ladder H0 Technique

Macaulay et al. 2018



Description	H_0 shift	σ_{syst}	σ_{syst} / σ_{stat}
Total Stat.	0.000	1.048	1.00
Total Sys.	0.162	0.760	0.72
ALL Calibration	-0.078	0.375	0.36
DES Cal.	-0.016	0.276	0.26
Low-z Cal	-0.026	0.254	0.24
SALT	0.053	0.217	0.21
ALL Other	0.004	0.661	0.63
Intrinsic Scatter	0.129	0.330	0.31
$z + 0.00004$	0.036	0.083	0.08
c, x_1 Parent Pop.	-0.031	0.249	0.24
Low-z Vol. Lim.	-0.081	0.124	0.12
Flux Err.	-0.004	0.179	0.17
Spec. Eff	-0.091	0.125	0.12
Ref. Cosmo.	-0.065	0.134	0.13
Low-z 3σ Cut	0.498	0.193	0.18
Sys. Parent	0.370	0.222	0.21
PS1 Coherent Shift	0.064	0.246	0.23
$2\ \sigma_{int}$	-0.068	0.231	0.22

DES-SN3YR Data Release

https://des.ncsa.illinois.edu/releases/sn

- Filter+atmosphere transmission curves
- Redshifts
- Photometry
- Fit light curve parameters, distances, bias corrections
- Large simulated bias correction sample
- Binned Hubble Diagram, Full Systematics Covariance Matrix, and CosmoMC inputs and chains.

THE DARK ENERGY SURVEY

Motivation

Ingredients for SN Ia Cosmology

Results from the First 3 Years

The Future of DES-SN

Challenges of High-z Analyses

- **<u>Photometric classification:</u>** Addition of new systematic —> core collapse SNe contamination. This seems to be under control now. The difficulty remains in modeling the contamination sample.

w Uncertainty Contributions for wCDM model

Description[b]	σ'_w
Total Stat (σ_w^{stat})	0.042
Total Syst[c] ($\sigma_w^{\text{total syst}}$)	0.042
[Photometry & Calibration]	**[0.021]**
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[μ-Bias Corrections: Survey]	**[0.023]**
[μ-Bias Corrections: Astrophysical]	**[0.026]**
[CC contamination]	[0.???]

w UNCERTAINTY CONTRIBUTIONS FOR wCDM MODEL

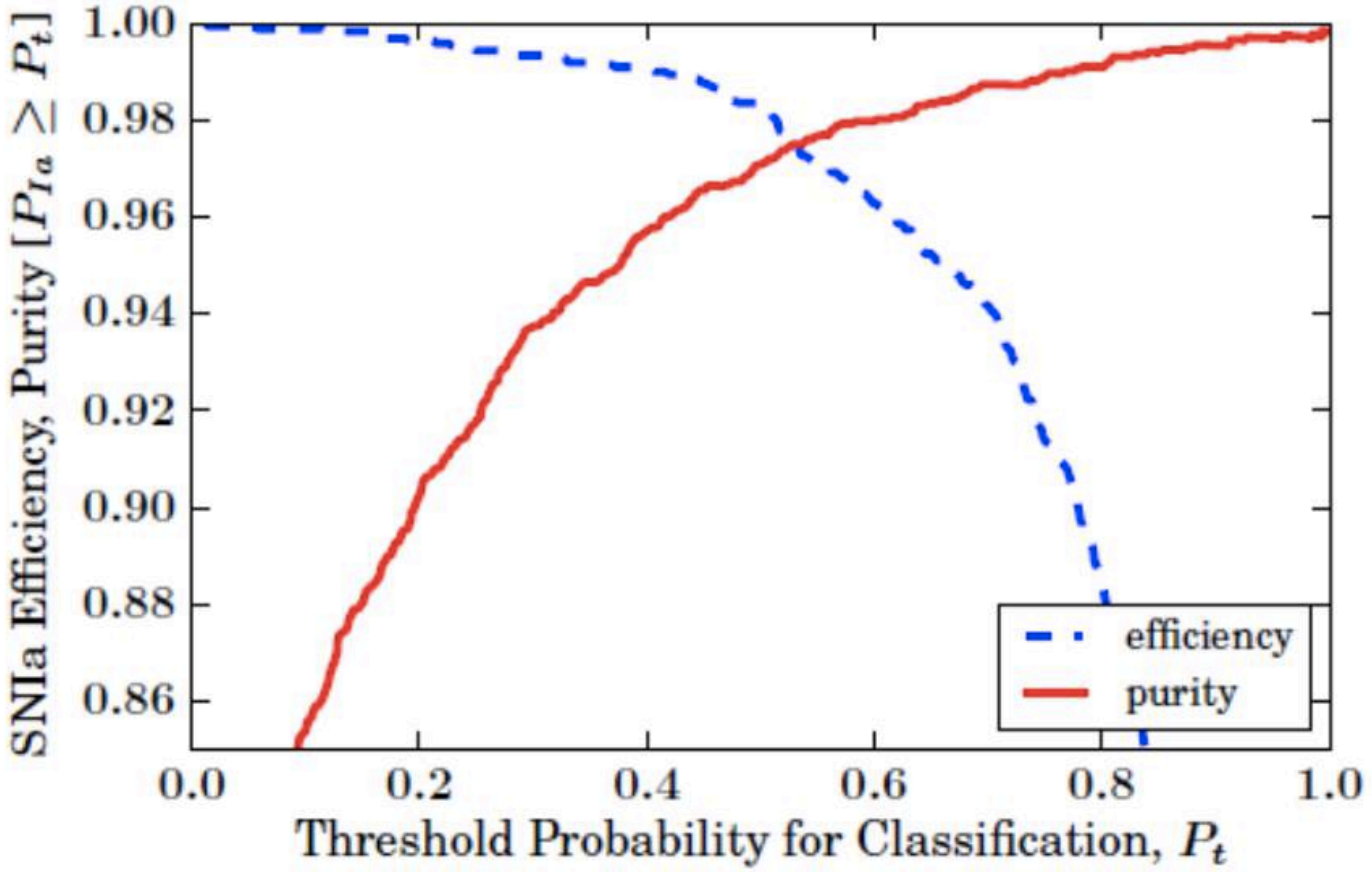
Description[b]	σ'_w
Total Stat (σ_w^{stat})	0.042
Total Syst[c] ($\sigma_w^{\text{total syst}}$)	0.042
[Photometry & Calibration]	**[0.021]**
[μ-Bias Corrections: Survey]	**[0.023]**
[μ-Bias Corrections: Astrophysical]	**[0.026]**
[CC contamination]	[0.???]

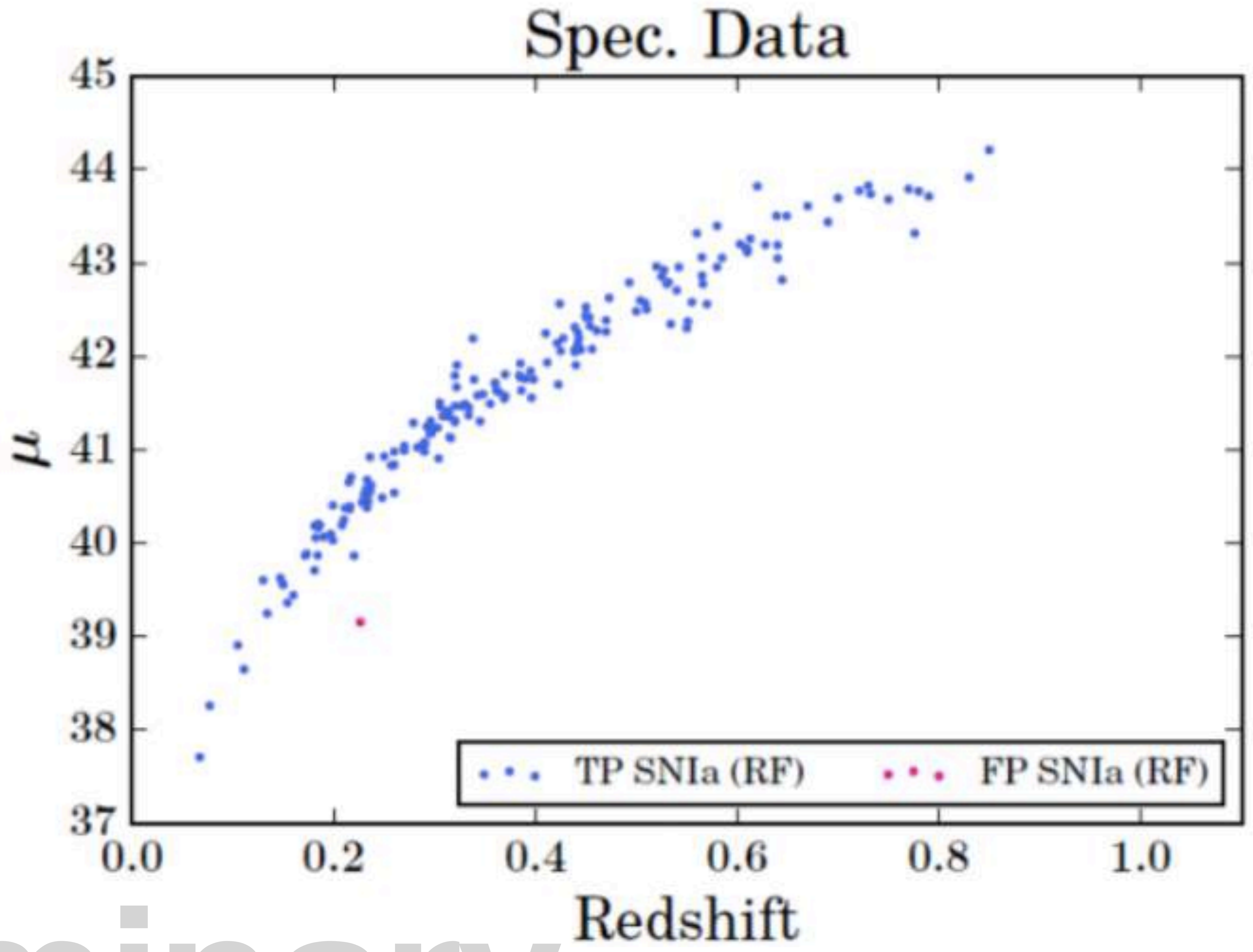
PS1: Jones et al. 2018
Find 0.013 due to CC contamination

Random Forest Phot. Classification

87% MLcut efficiency

1 False positive (using spec data type) is SNIc





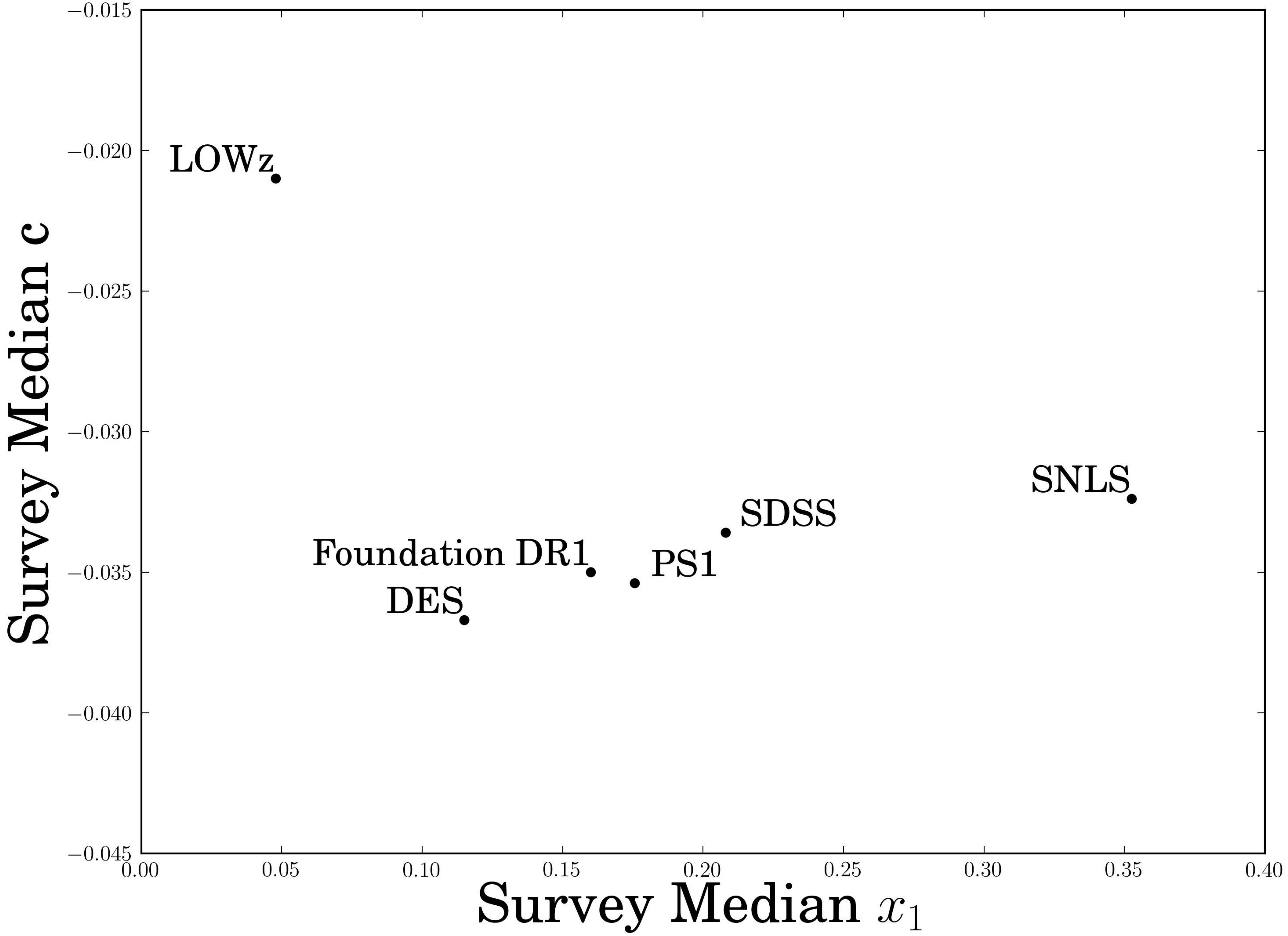
Preliminary

Credit: S. Kuhlman

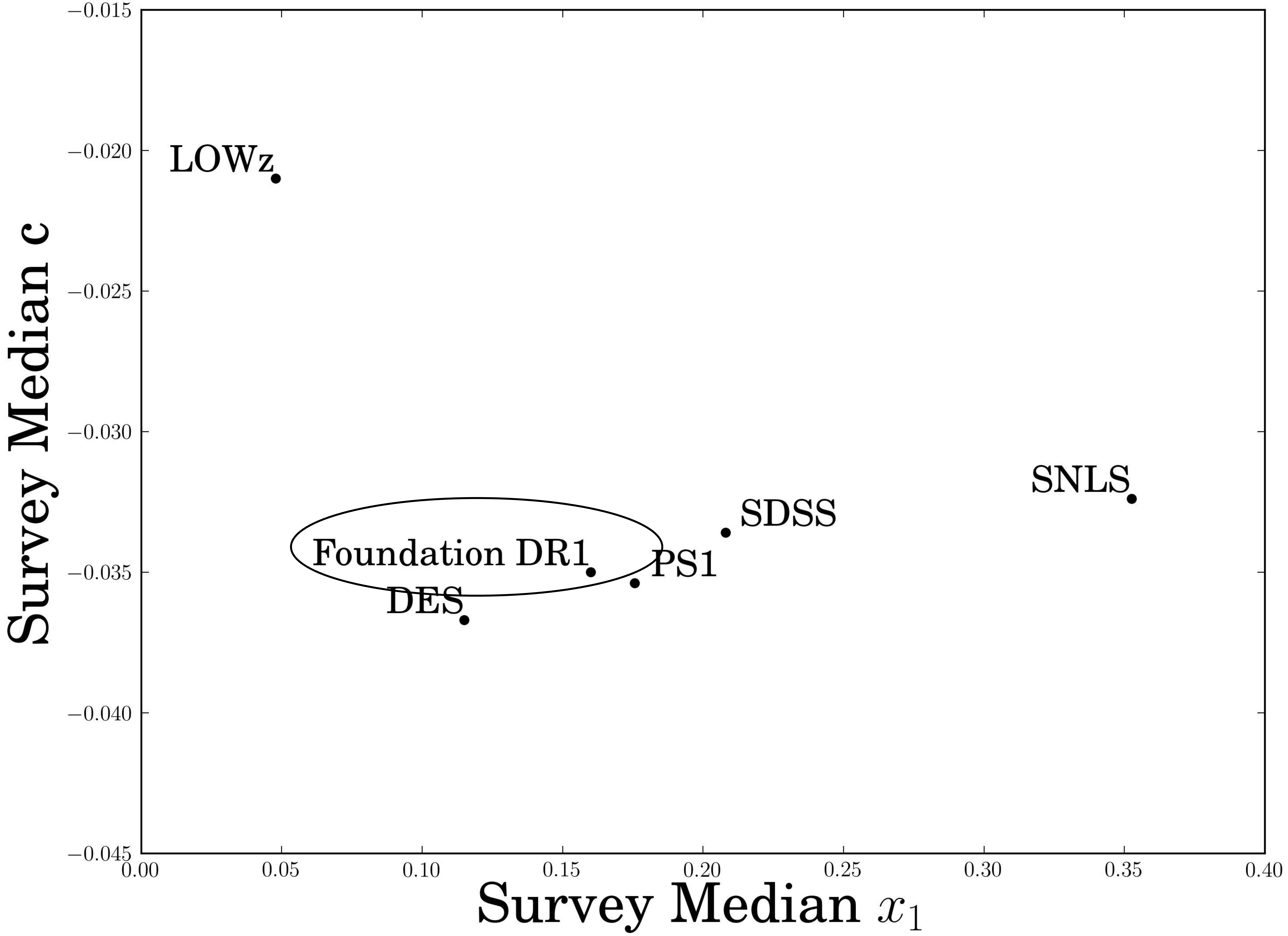
Challenges of High-z Analyses

- **Photometric classification:** Addition of new systematic —> core collapse SNe contamination. This seems to be under control now. The difficulty remains in modeling the contamination sample.

- **The Low-z Anchor:** We are currently poorly able to model the selection function of the low-z sample. This will hopefully be remedied by rolling (easily modelable) low-z surveys such as Foundation (Foley et al 2017).



Survey Median c
−0.015
−0.020
−0.025
−0.030
−0.035
−0.040
−0.045
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
LOWz
SNLS
SDSS
Foundation DR1
PS1
DES
Survey Median x_1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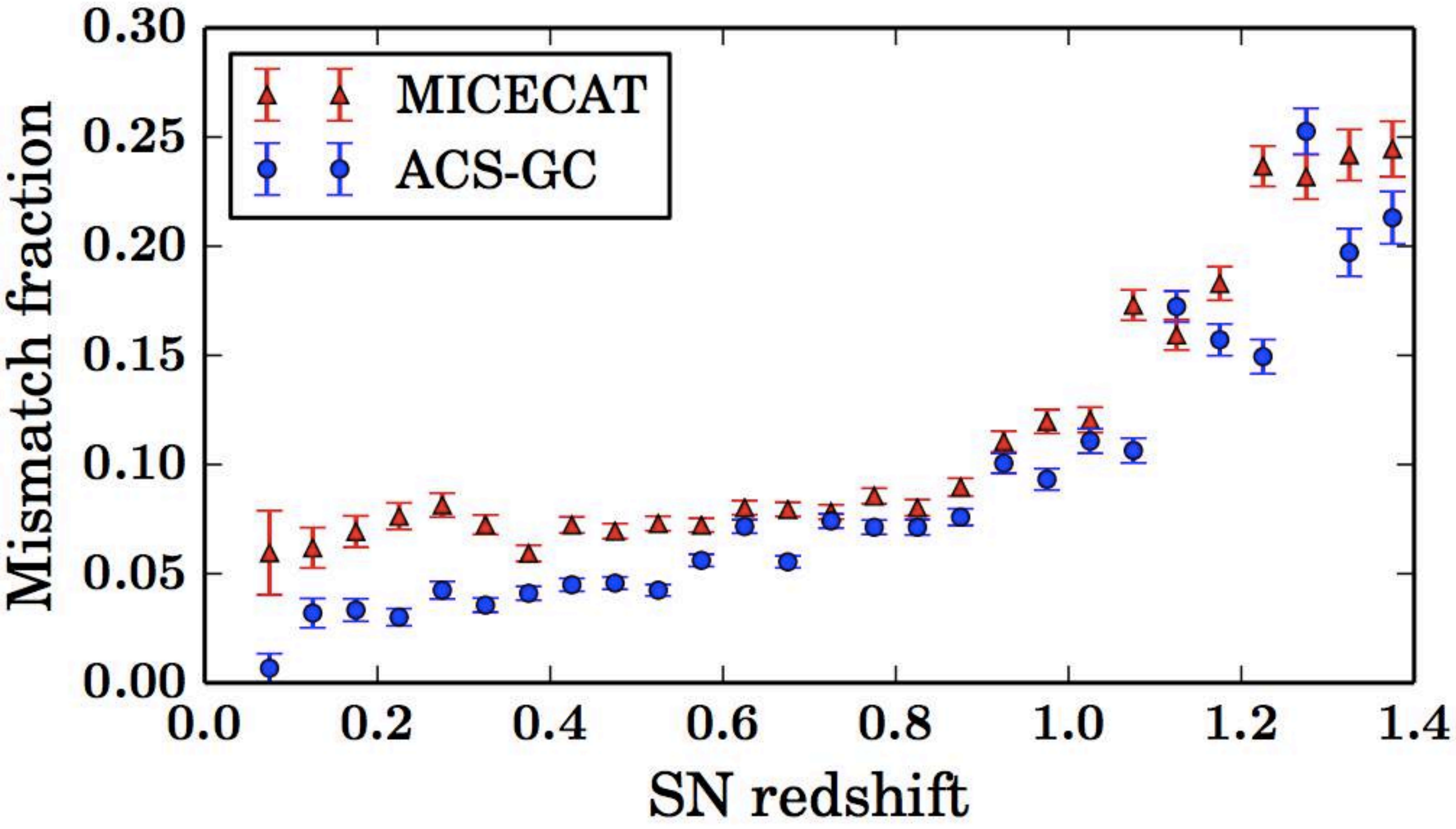
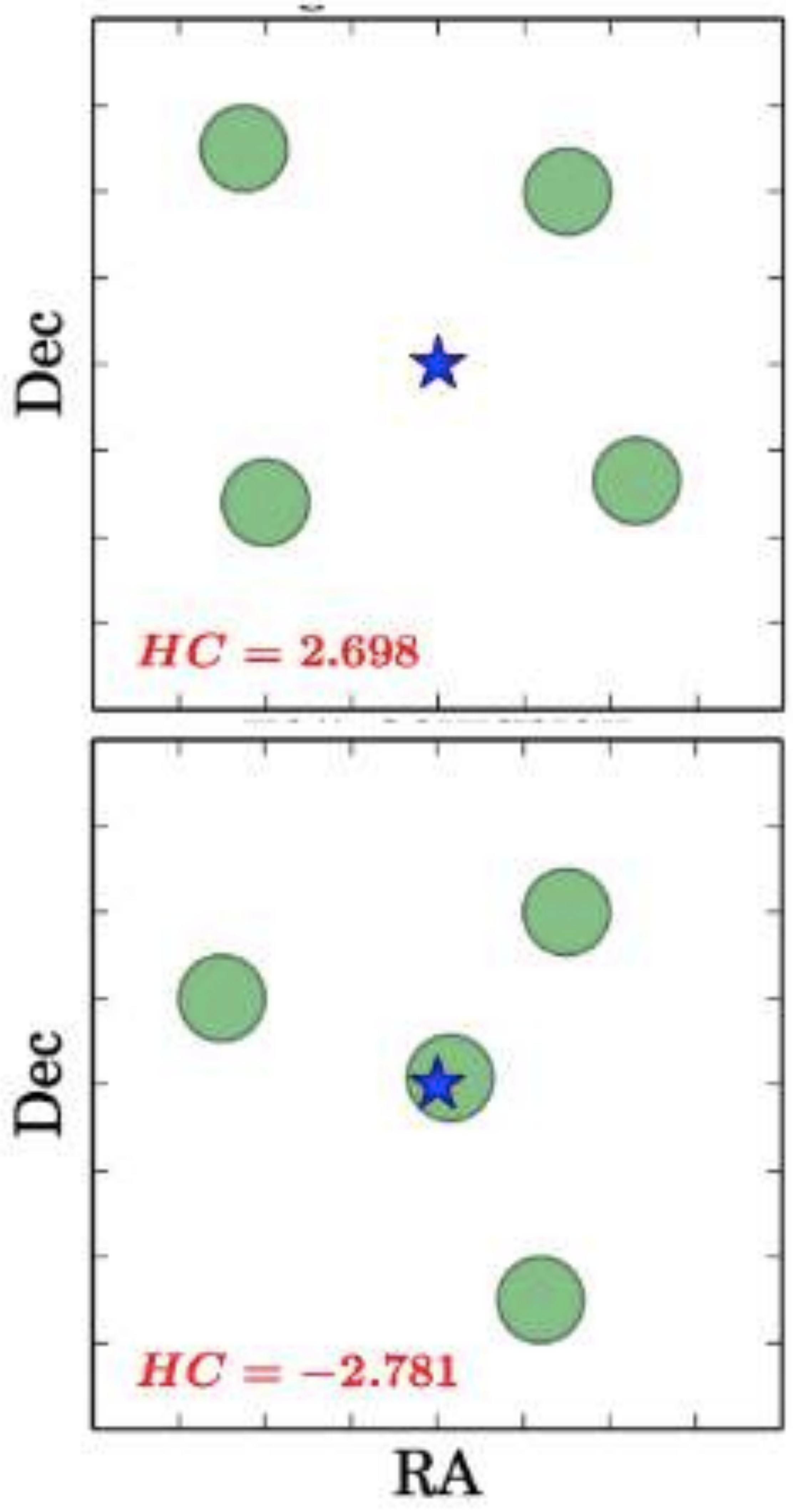
- **Host Galaxy Confusion:** stronger at higher redshifts.

Host galaxy confusion

Credit:
Gupta et al. 2016



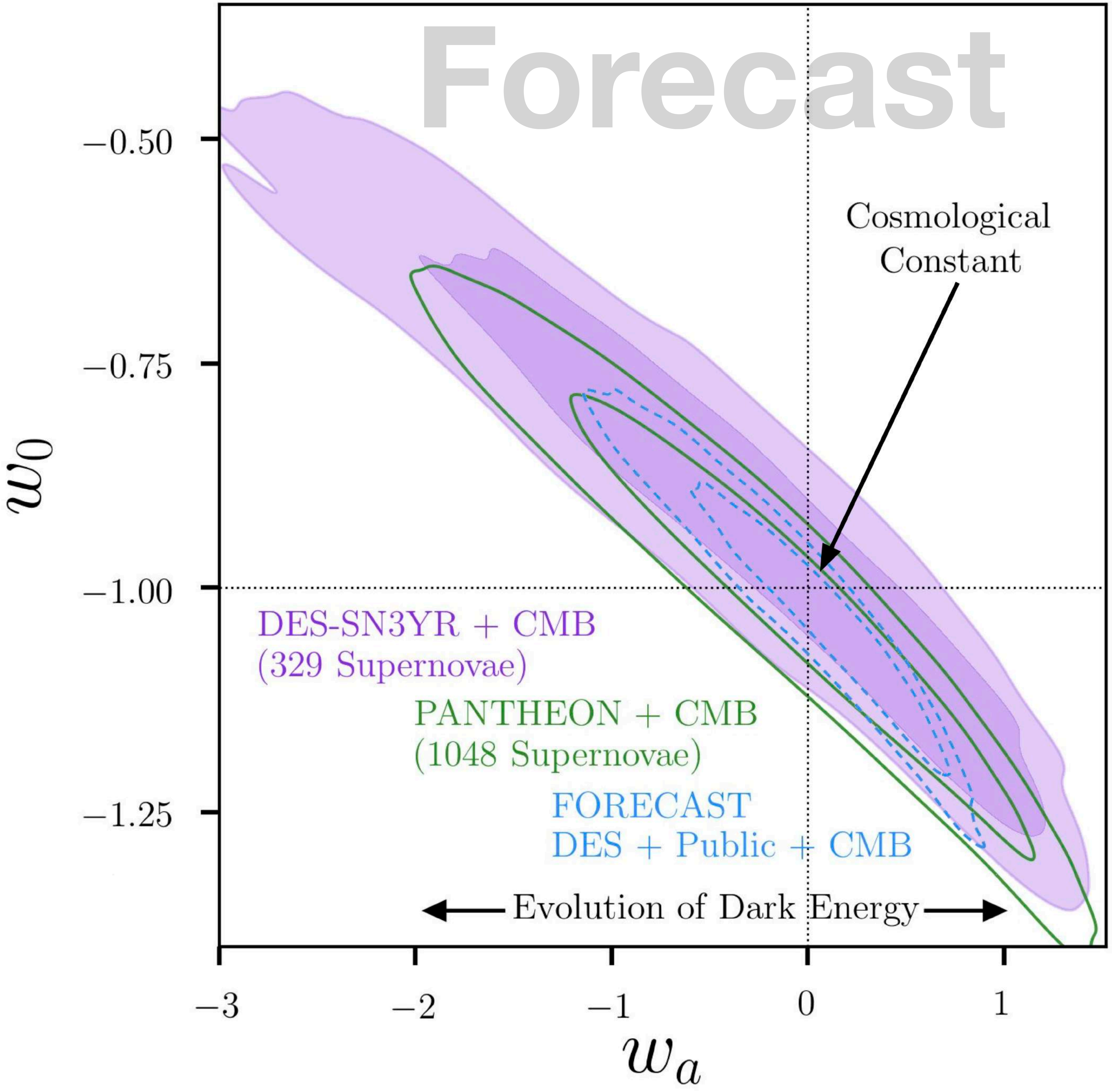


Future of DES

DES 5 Year Photometrically Classified Data ~2500 Type Ia SNe will double currently available statistics.

There is much more work to do to analyze the full dataset and set the stage for future surveys (LSST and WFIRST)

Caveat: No assumptions in improvements of systematics.



THE DARK ENERGY SURVEY

Thank You