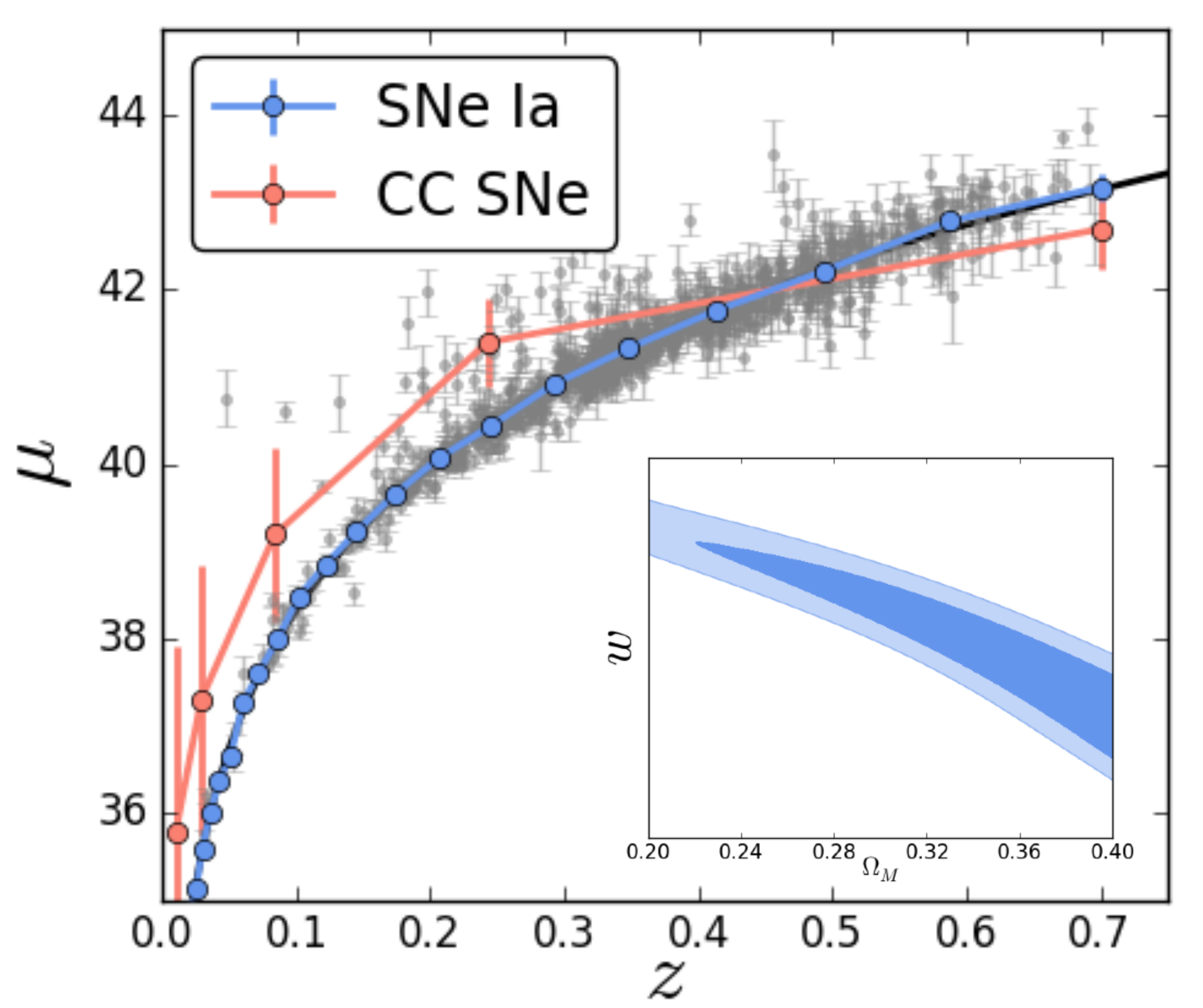


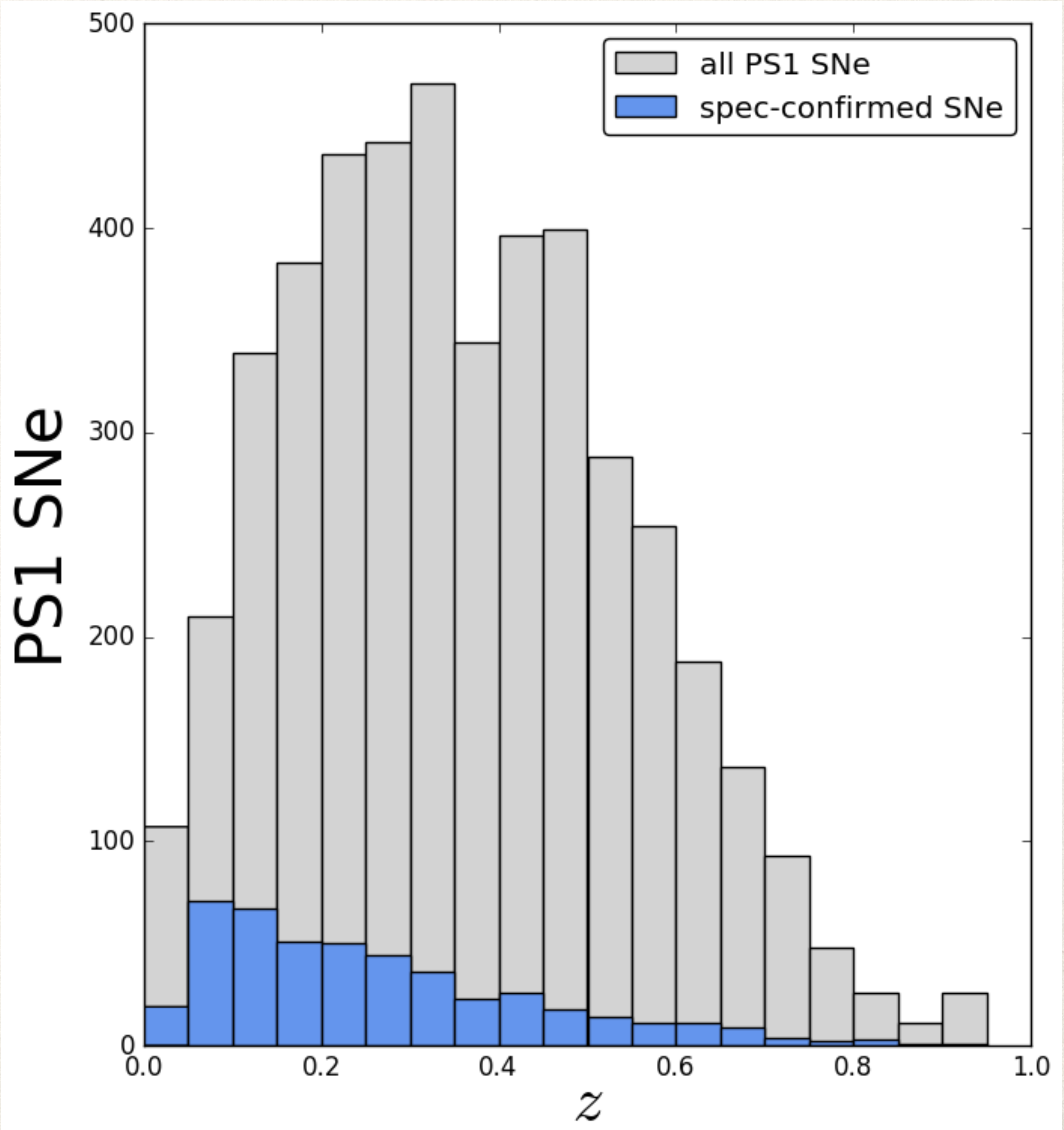
Contaminated Cosmology: Measuring w with Photometrically Classified Supernovae from Pan-STARRS

David Jones

with Dan Scolnic, Adam Riess, Richard Kessler, Armin Rest, Bob Kirshner, Carolyn Ortega, and many others

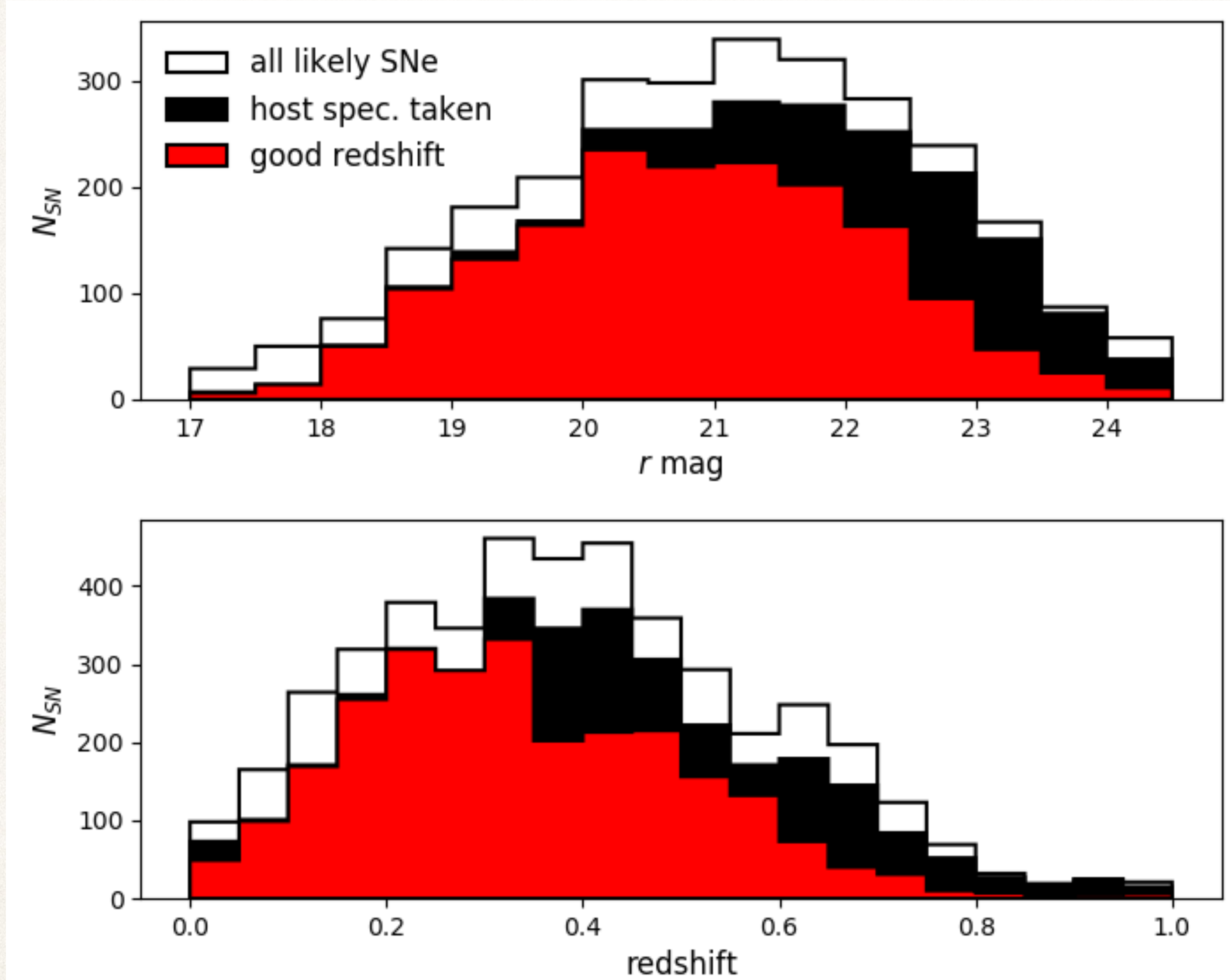
Dark Energy with Pan-STARRS

- 1.8 meter telescope diameter
- 1.4 gigapixel camera
- 3 degree field of view
- Observed 70 square degree patch ~nightly for 4 years
- Transient science goals:
  - Supernovae (core-collapse and thermonuclear)
  - AGN
  - Stellar flares
  - Gamma ray burst afterglows
- But most transients do not have spectra!

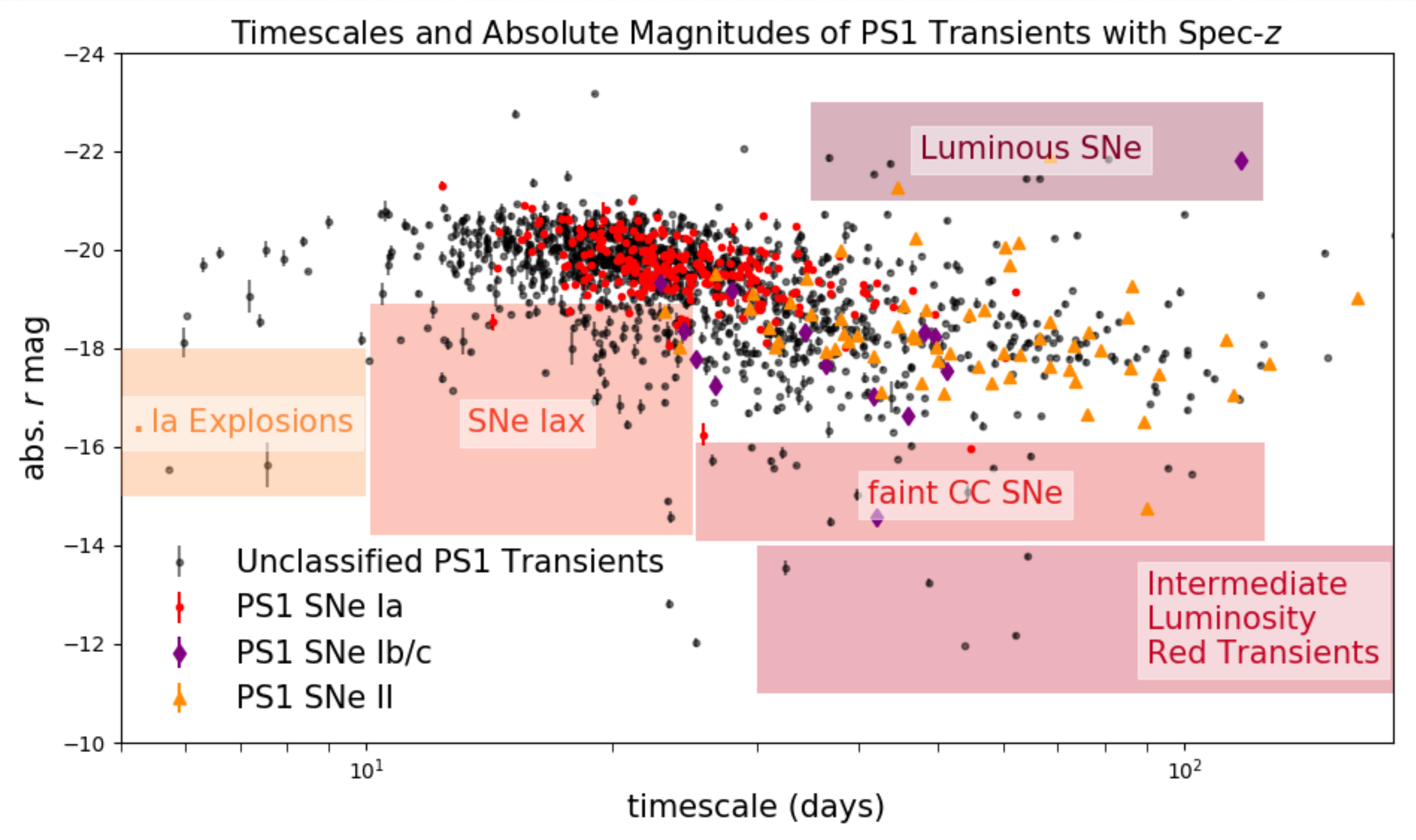


Photometric SNe from Pan-STARRS

- Obtaining SN spectra during the survey is hard; getting host galaxy spectra after the survey has ended is easy.
- Measured redshifts for 60% of the 5,000 likely SNe in Pan-STARRS with MMT, WIYN, AAT.
- Our survey will finish after a few more nights on MMT this fall.



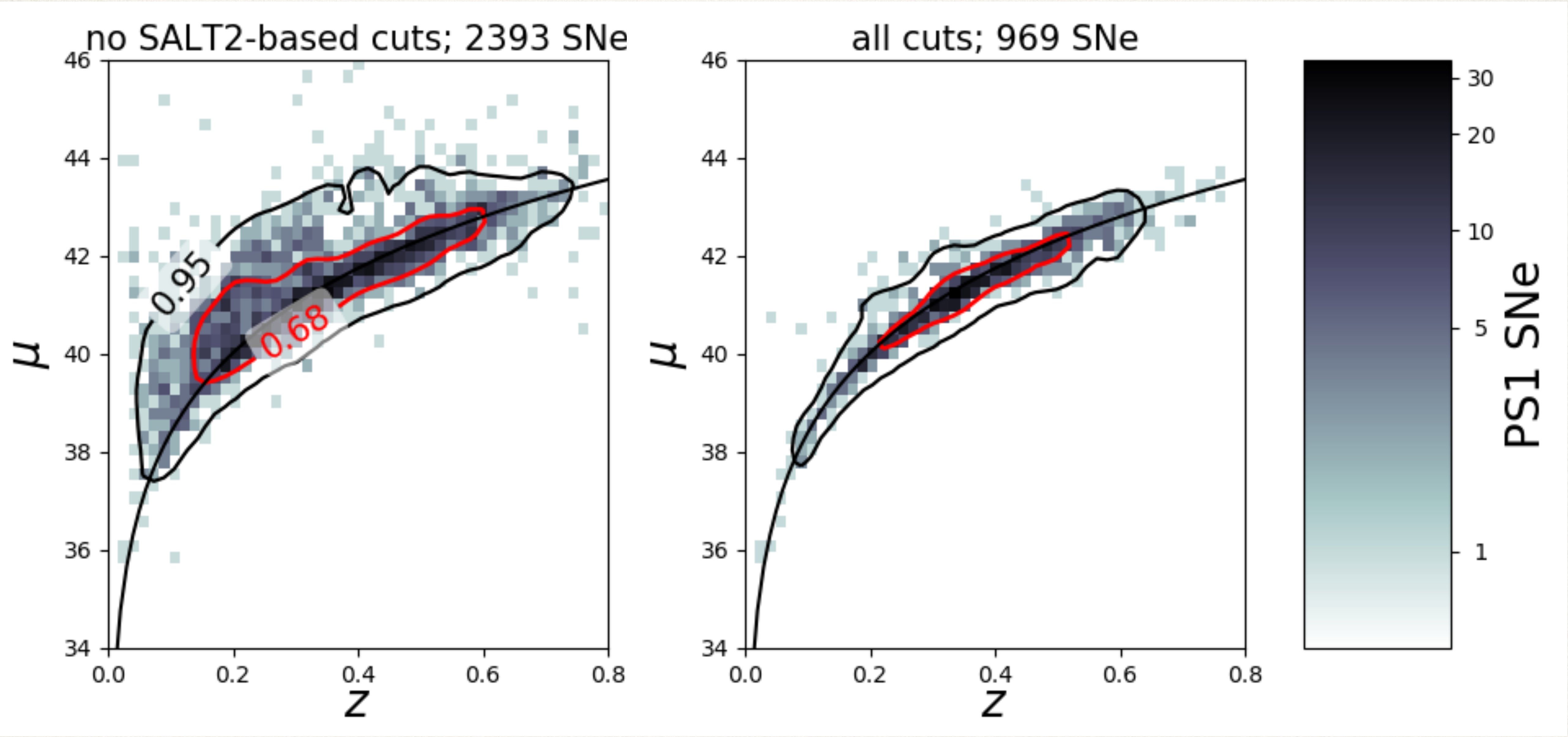
Not Just SNe Ia…



Approx. regions of parameter space for different transients (boxes) from Kulkarni+07, Nugent+15, Foley+13

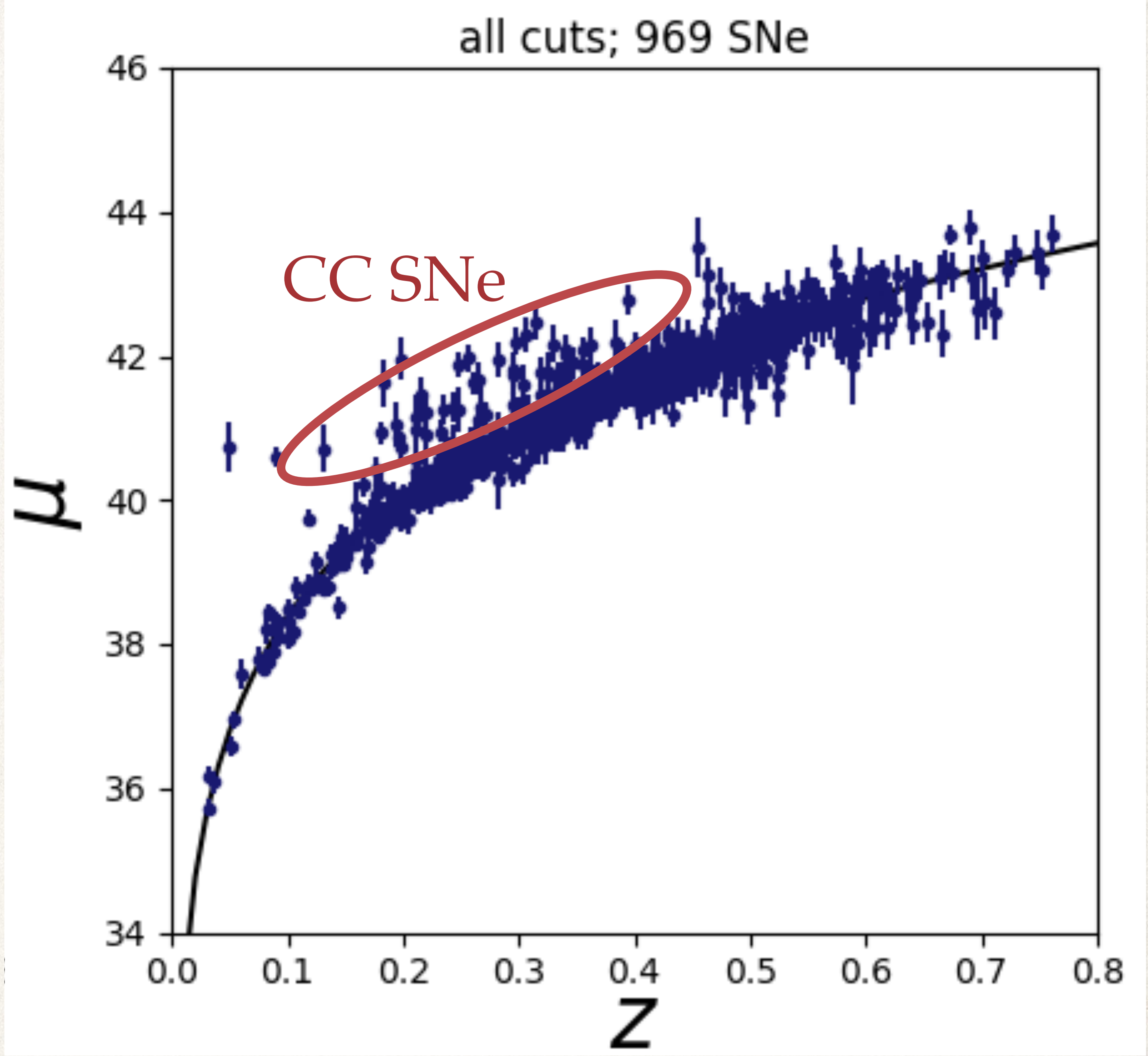
Photometric SNe from Pan-STARRS

- Our Hubble (density) diagram, with and without shape, color, and uncertainty cuts.



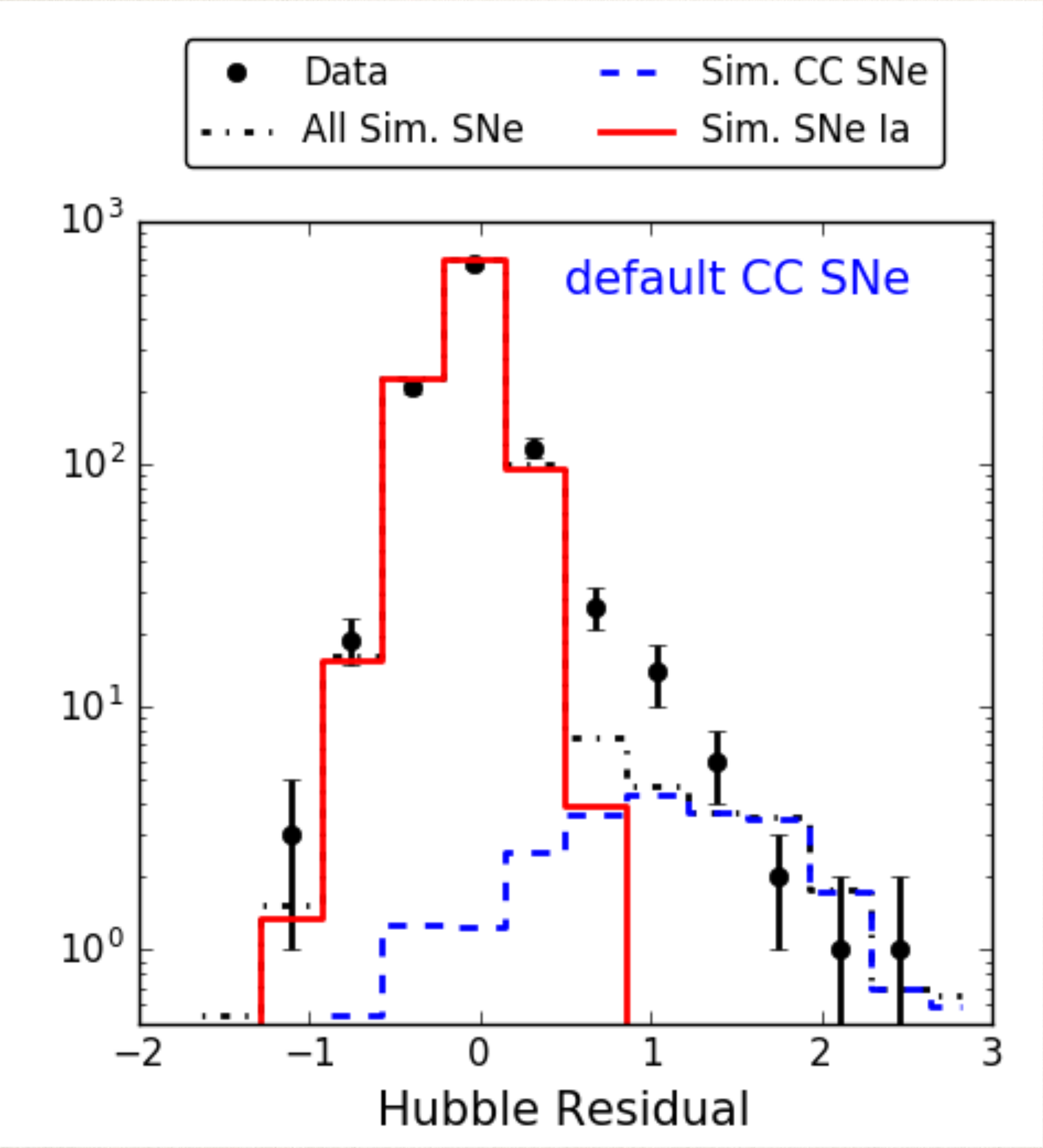
A Contaminated Hubble Diagram

- How important is understanding CC SN contamination?
  - change in w of 5% corresponds to a difference of 0.02 mag from $0 < z < 0.5$
  - Assume SN Ia scatter = 0.15 mag and contaminating CC SNe are 1 mag fainter than SNe Ia. Then, 5% error in w = 2% contamination at low z.
  - That's just 20 PS1 SNe
  - If CC SNe are even fainter than SNe Ia, the problem is worse!



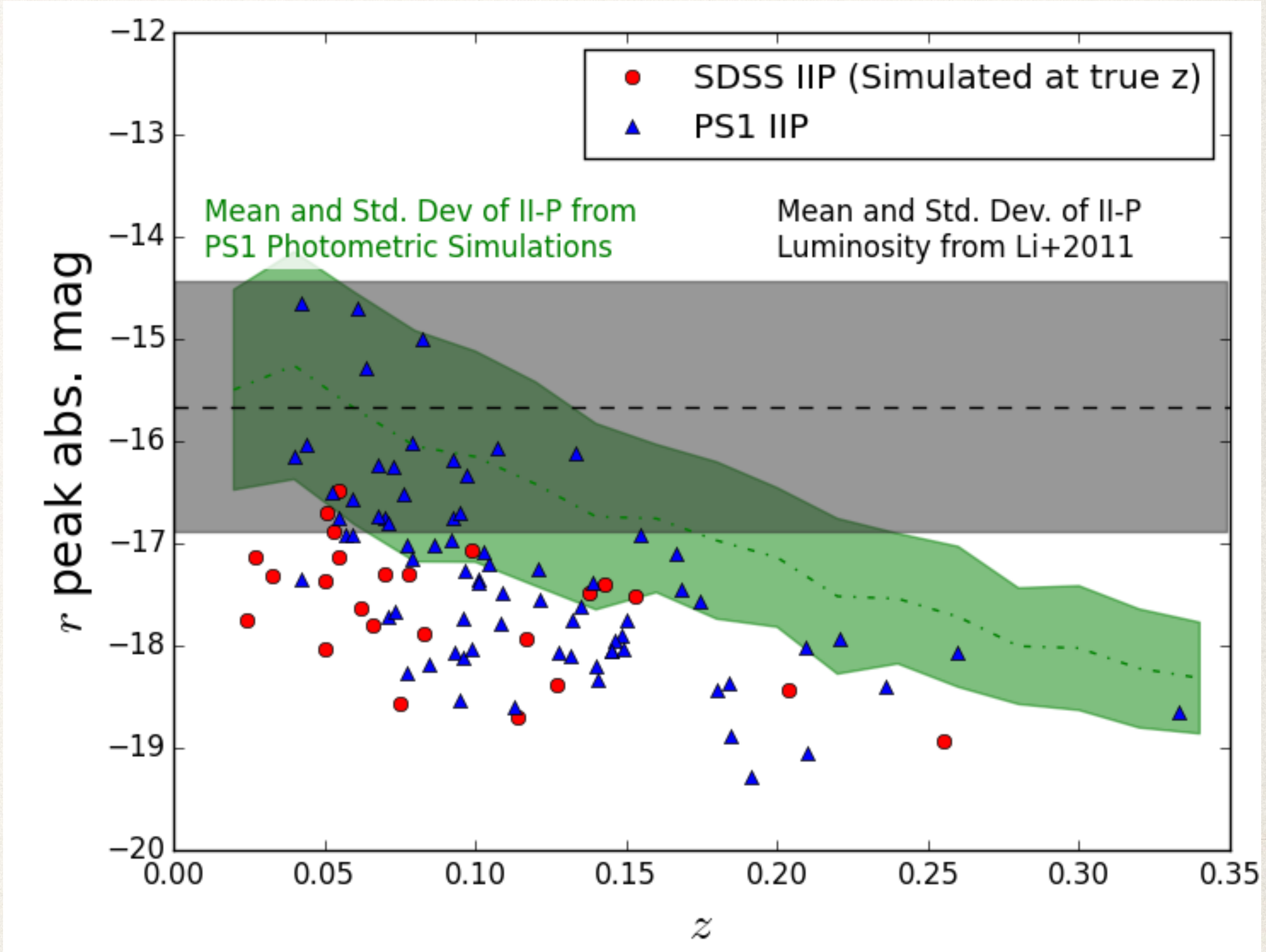
Do we understand CC SN Contamination?

- Simulations from SNANA disagree with our data!



Templates could be biased or incomplete

Li+11 LF in grey, Pan-STARRS simulations in green, SNANA templates from SDSS in red



Overcoming CC SN Contamination with BEAMS

- We can use Bayesian Estimation Applied to Multiple Species (BEAMS; Kunz, Bassett & Hlozek 2007) to fit CC SNe and SNe Ia simultaneously.

- The BEAMS posterior is proportional to the product of individual SN likelihoods and priors on free parameters:

$$P(\theta|D) \propto P(\theta) \times \prod_{i=1}^{N} \mathcal{L}_i.$$

- Likelihood uses a Gaussian distribution for SNe Ia and CC SNe

Prior Probabilities

$$\mathcal{L}_i = \mathrm{P_i(Ia)} \times \frac{1}{\sqrt{2\pi(\sigma_{i,Ia}^2 + \sigma_{Ia}^2)}} \exp\left(-\frac{(\mu_{i,Ia} - \mu_{Ia}(z_i))^2}{2(\sigma_{i,Ia}^2 + \sigma_{Ia}^2)}\right)$$ SN Ia Gaussian

$$+ \mathrm{P_i(CC)} \times \frac{1}{\sqrt{2\pi(\sigma_{i,CC}^2 + \sigma_{CC}(z_i)^2)}} \exp\left(-\frac{(\mu_{i,CC} - \mu_{CC}(z_i))^2}{2(\sigma_{i,CC}^2 + \sigma_{CC}(z_i)^2)}\right).$$ CC SN Gaussian

- Uses prior probabilities from the Nearest Neighbor (NN) classifier (Sako+14)

BEAMS Applied to Simulations

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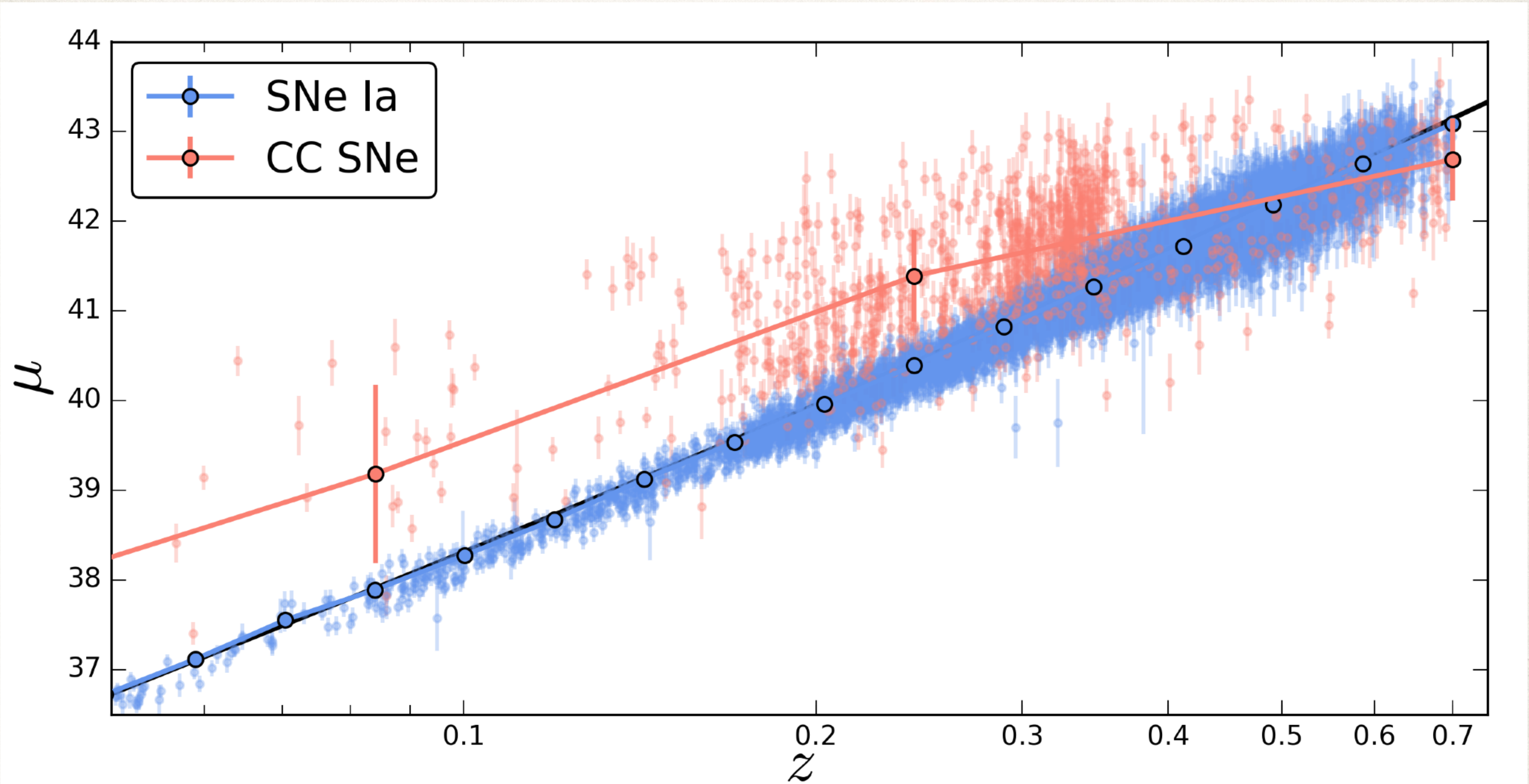
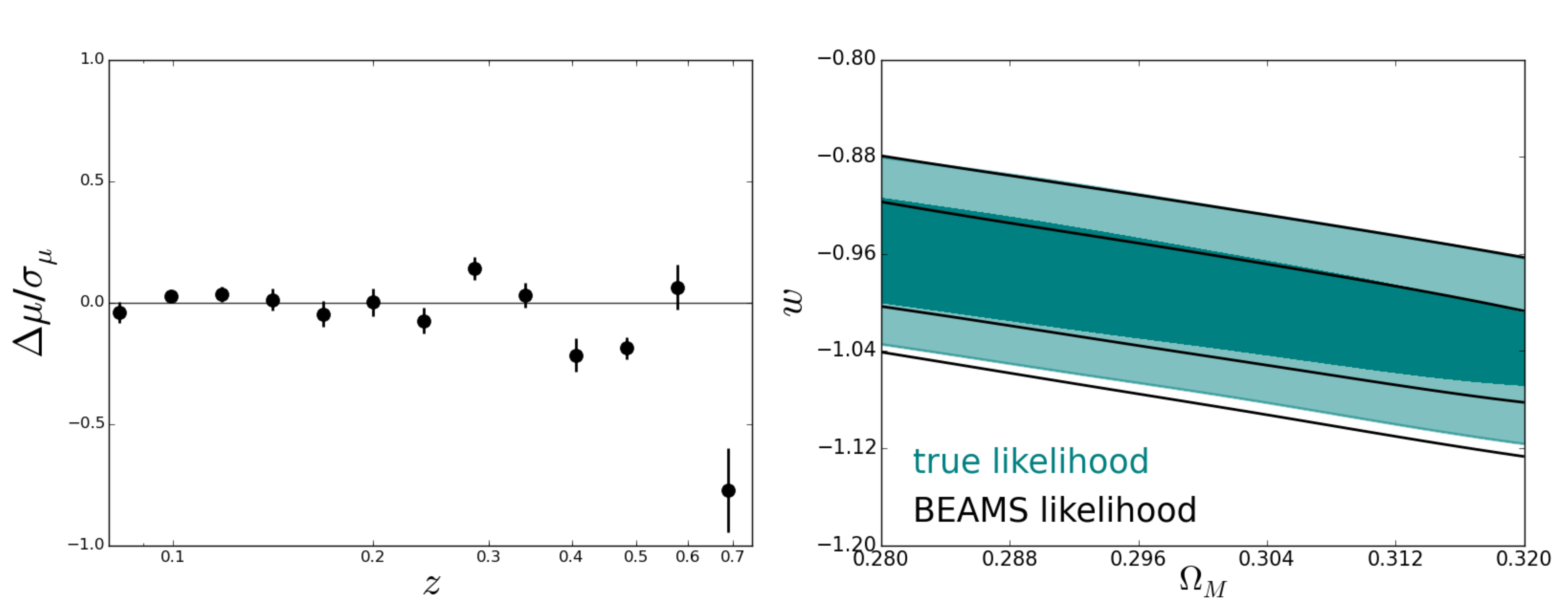


PS1 Cosmology with BEAMS

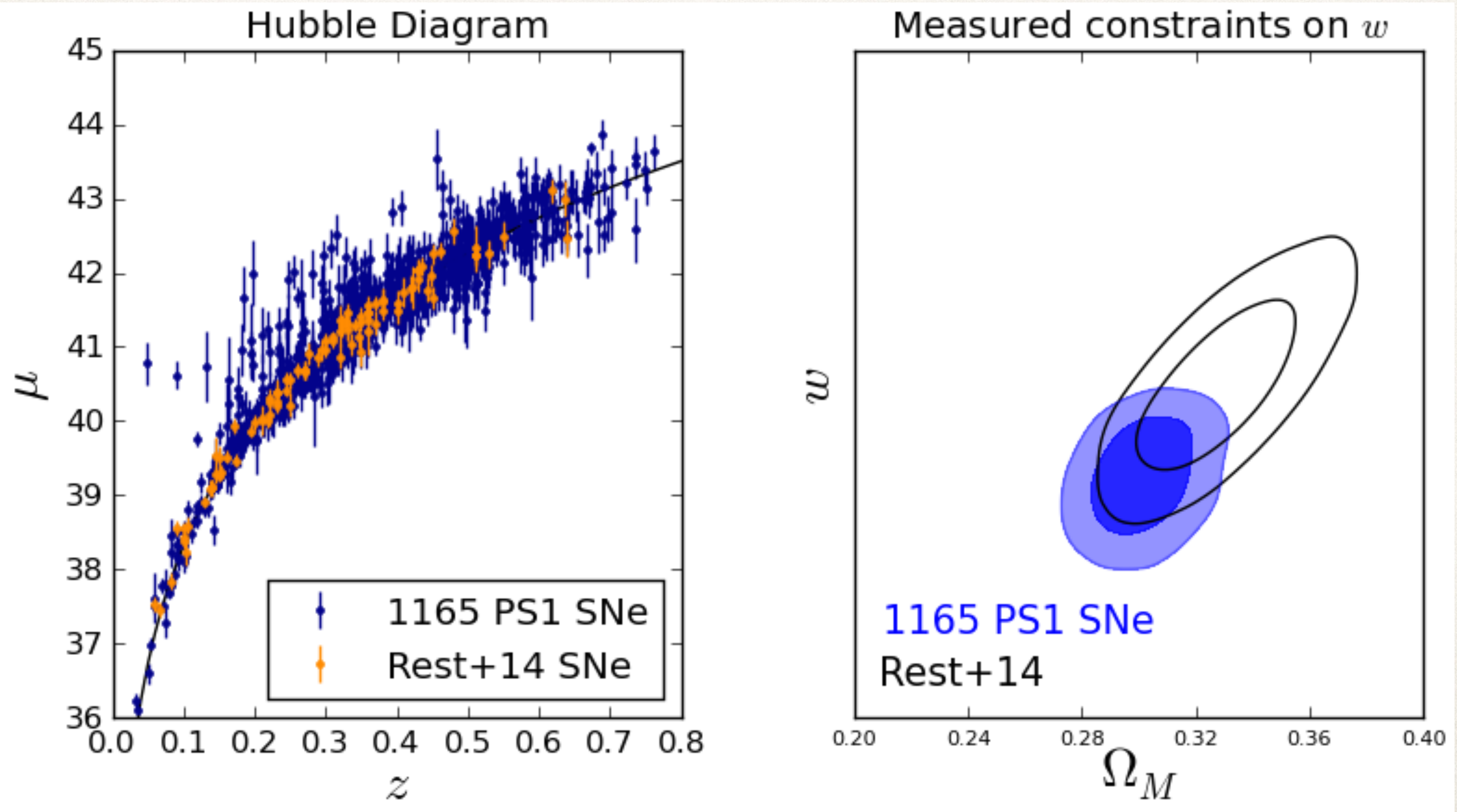
- We tested BEAMS on 25 simulations of 1,000 SNe

BEAMS Applied to Simulations - Δw = 0.003 +/- 0.002



Conclusions

- Pan-STARRS can measure dark energy with nearly 1,100 cosmologically useful SNe. This is the largest current SN Ia sample.
- We see more bright CC SNe than expected.
- BEAMS can measure *w* with bias of just 0.003 with only a small increase in uncertainty relative to a pure SN Ia sample.
- An early look at the real data:



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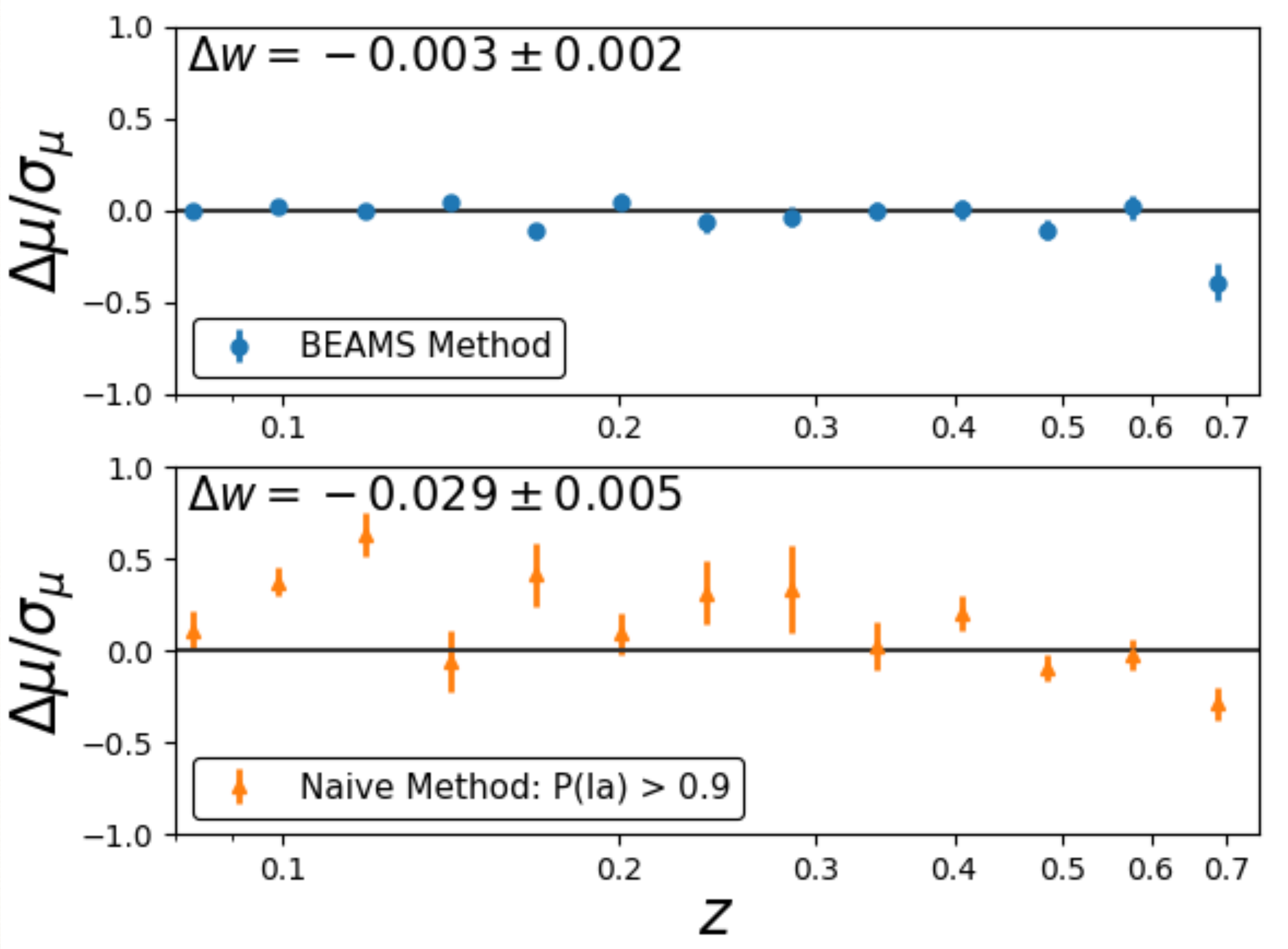
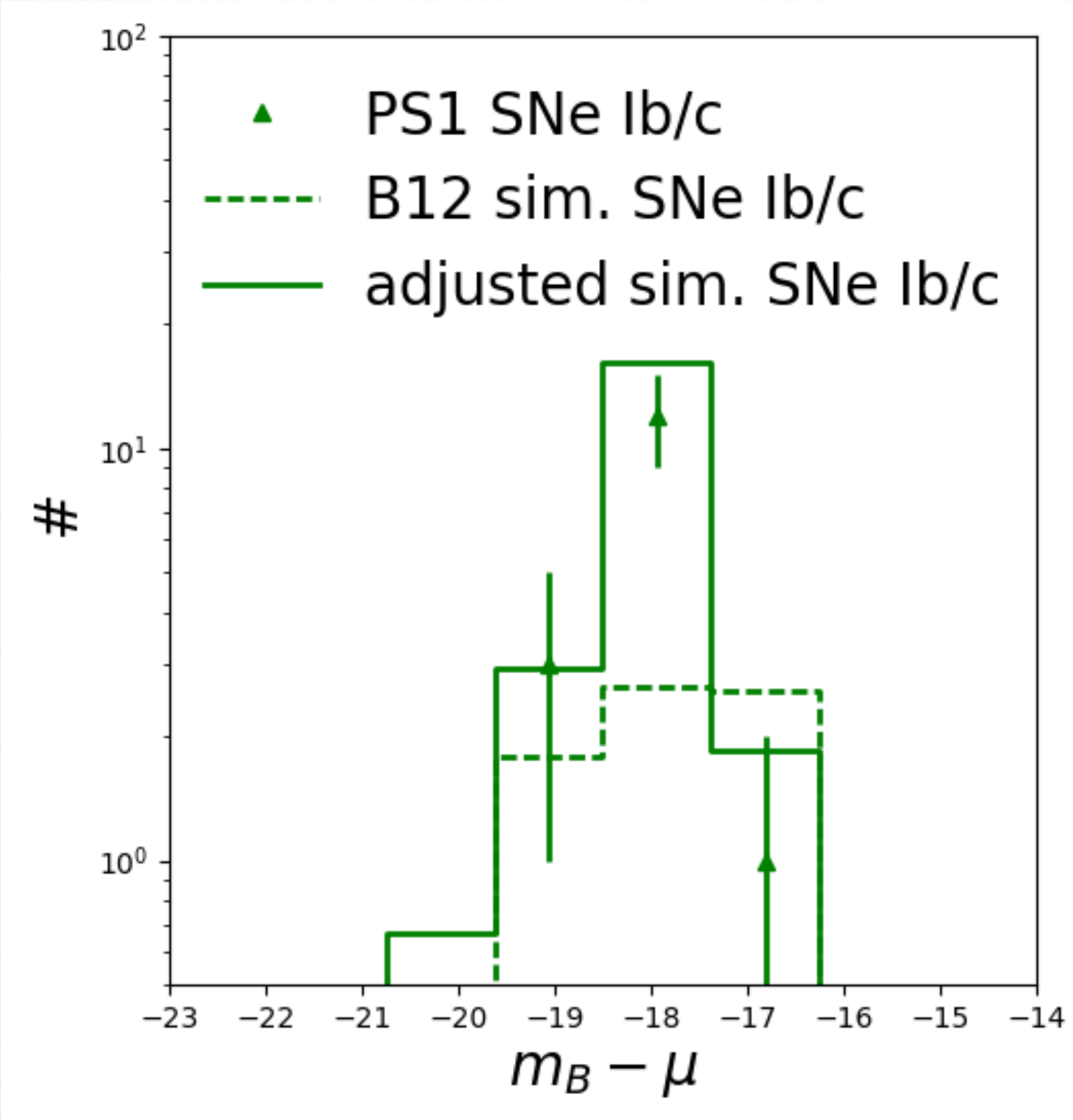
BEAMS Method

Making a cut of P(Ia) > 0.9



Do we understand CC SN Contamination?

- Simulations from SNANA disagree with our data!
- Simulated SN Ib/c and II are not bright enough



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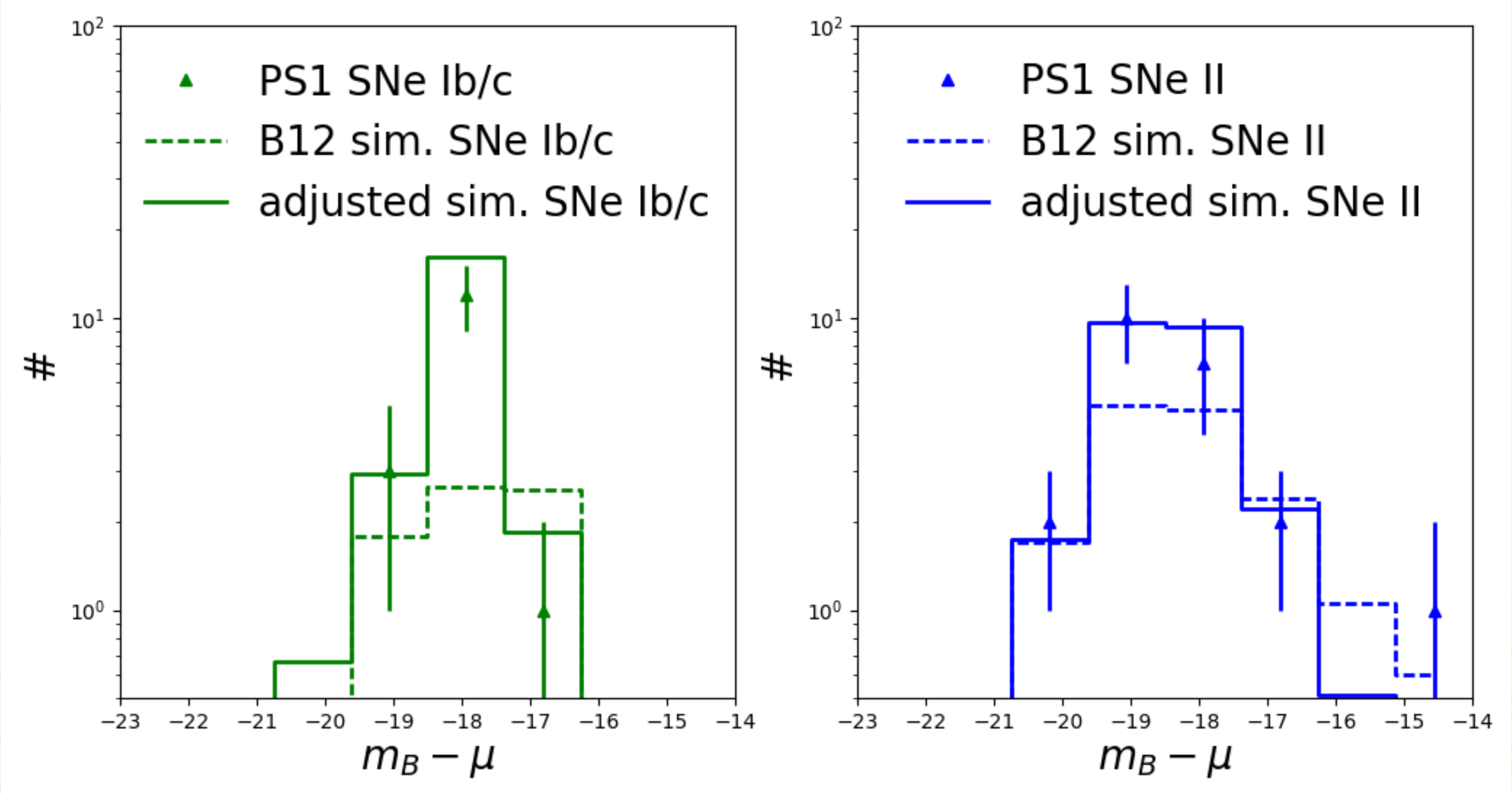

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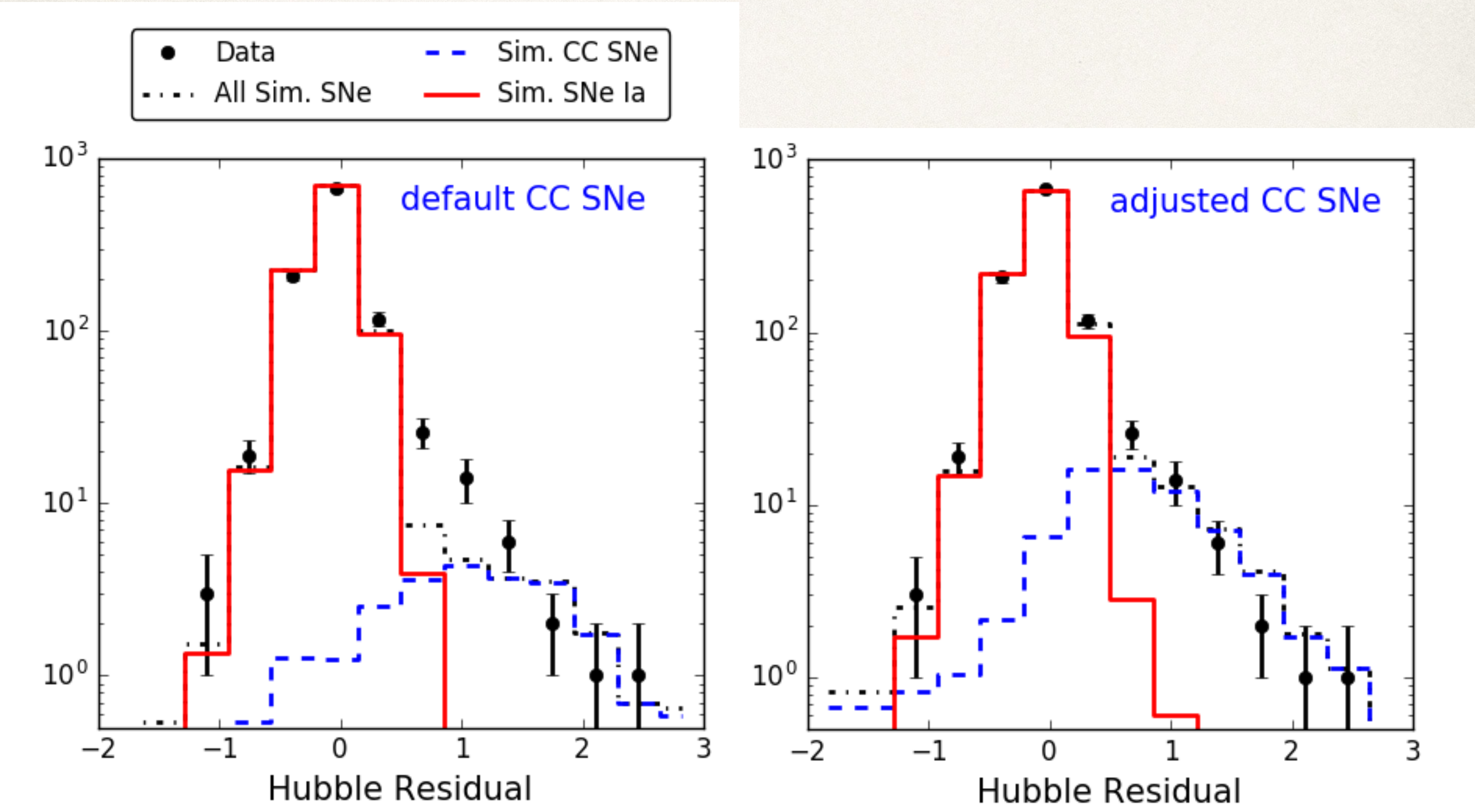
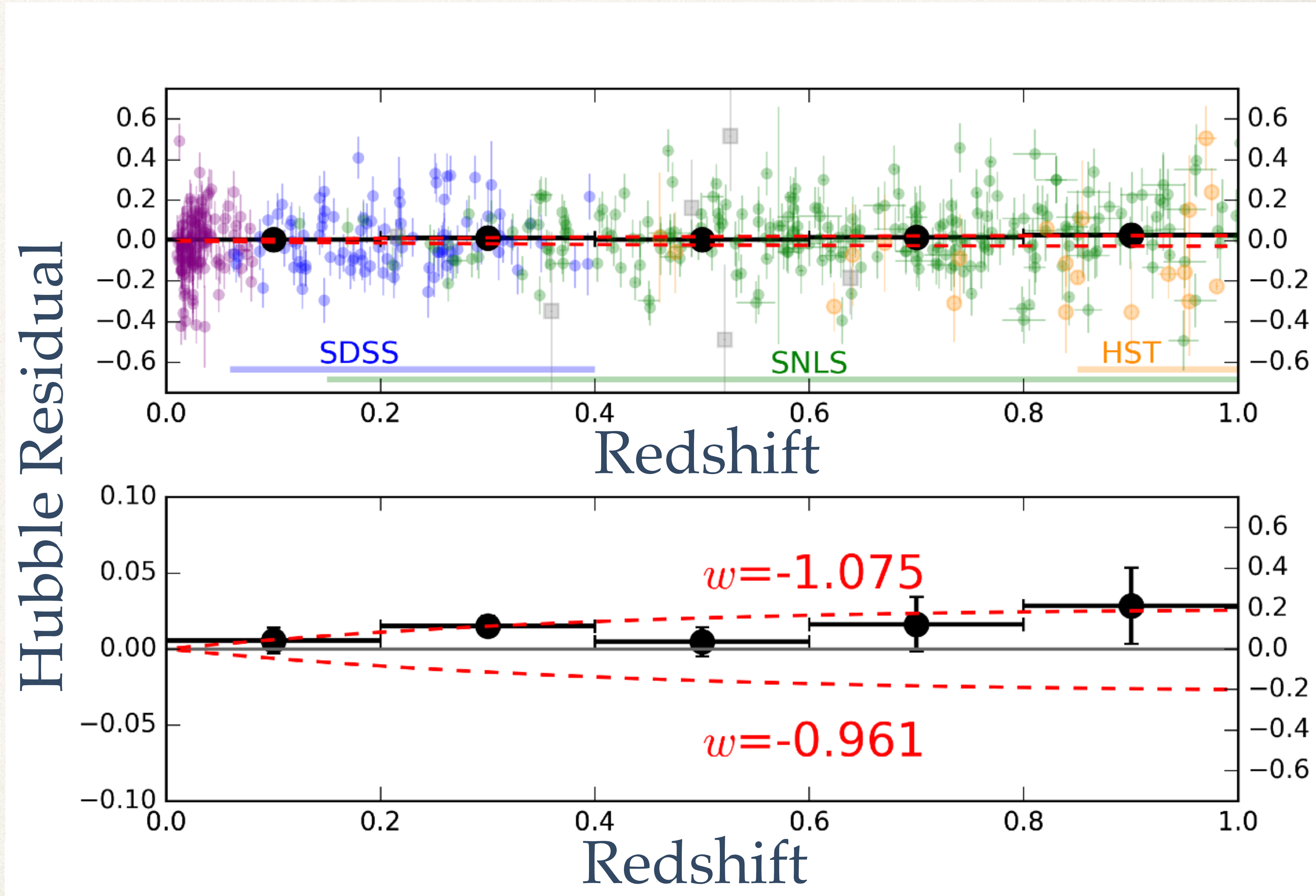


The Current State of SN Ia Cosmology

- Three reasons we need to measure w better:
  - A w that varies from -1 to -2 is still w/i 95% confidence interval.
  - H_0 measurements could favor phantom dark energy ($w < -1$)
  - Do we understand the systematics?
- We can improve statistics and systematics with SNe from Pan-STARRS!



Allowed parameters from Betoule et al. (2014)

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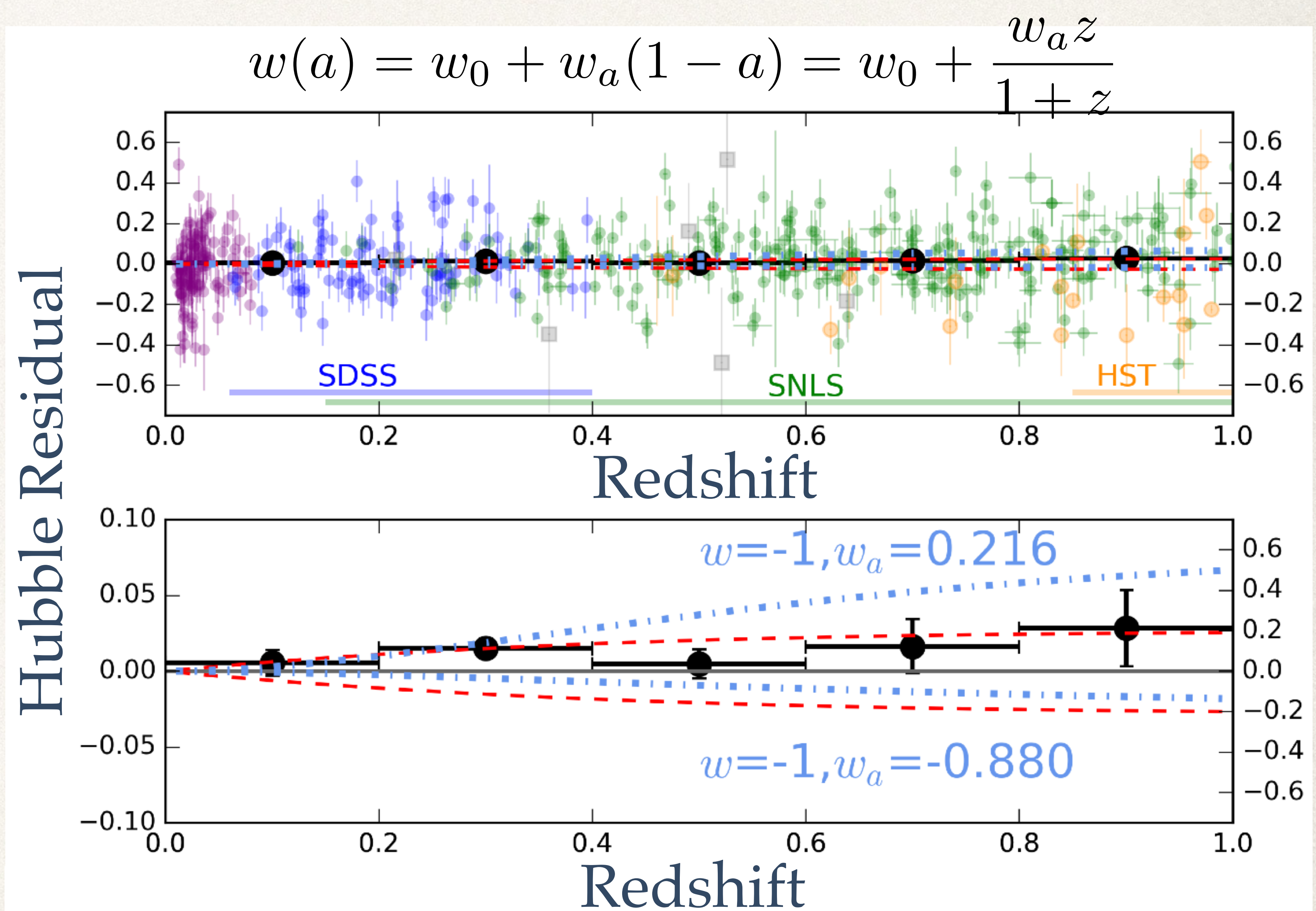

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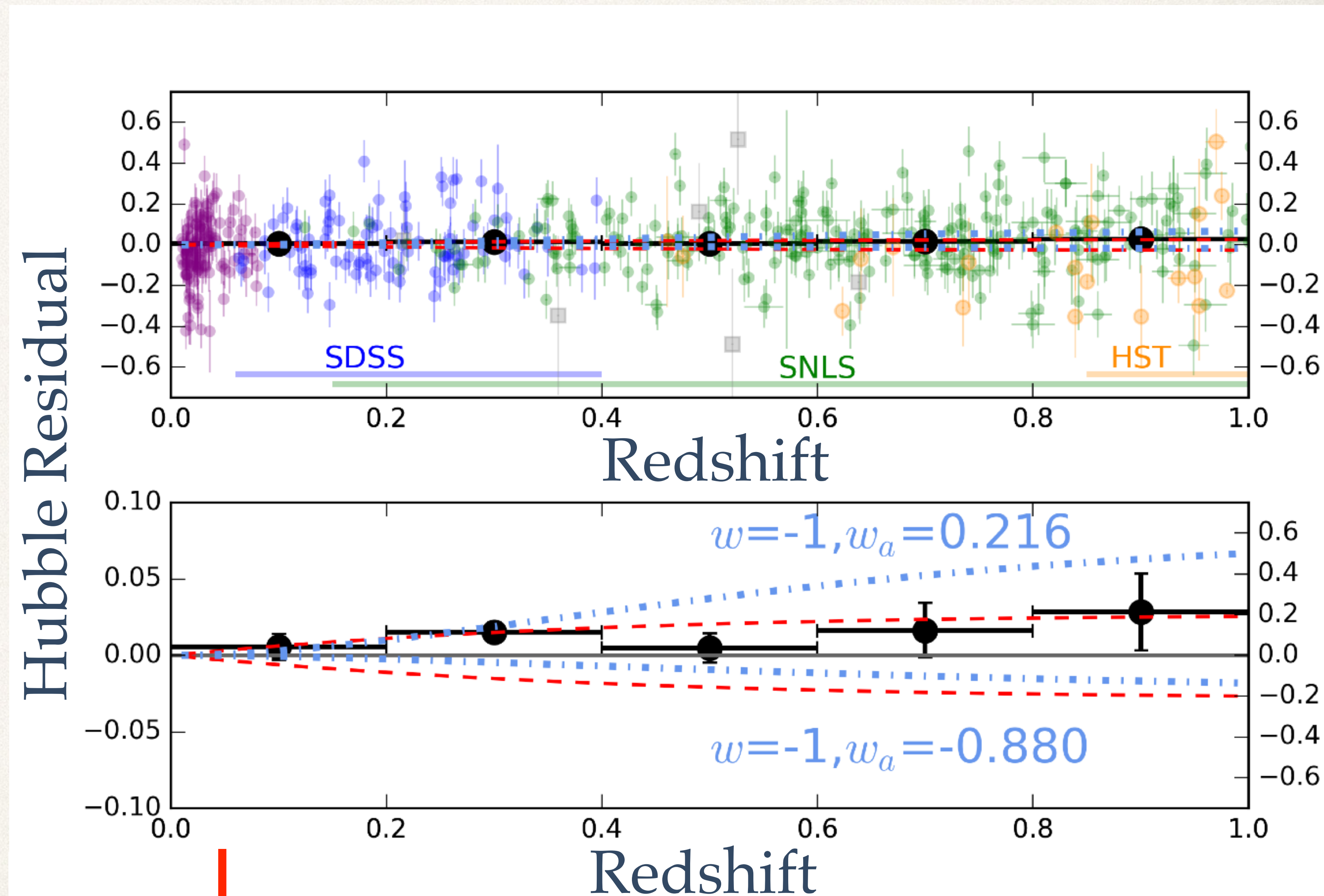

local H_0 vs. Planck (-0.18±0.05 mag)

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Riess+2016

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- Likelihood uses a Gaussian distribution for SNe Ia and CC SNe

$$\mathcal{L}_i = \mathrm{P_i(Ia)} \times \frac{1}{\sqrt{2\pi(\sigma^2_{i,Ia} + \sigma^2_{Ia})}} \exp(-\frac{(\mu_{i,Ia} - \mu_{Ia}(z_i))^2}{2(\sigma^2_{i,Ia} + \sigma^2_{Ia})})$$ SN Ia Gaussian

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See also: Falck et al. (2010), Hlozek et al. (2012), Rubin et al. (2015)

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measurements from the data

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SN Ia Gaussian

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- Uses prior probabilities from the Nearest Neighbor (NN) classifier (Sako+14)
- BEAMS estimates free (redshift dependent) parameters

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free parameters

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- Uses prior probabilities from the Nearest Neighbor (NN) classifier (Sako+14)

- BEAMS estimates free (redshift dependent) parameters

Intro to Dark Energy

- Responsible for the accelerated expansion of the universe (Riess+98, Perlmutter+99)
- Makes up 70% of the universe
- From the expansion history of the universe, can measure the equation of state, w
- If dark energy is a cosmological constant, $w = -1$
- Betoule et al. (2014) used SN Ia+CMB+BAO to measure w to <6% uncertainty.

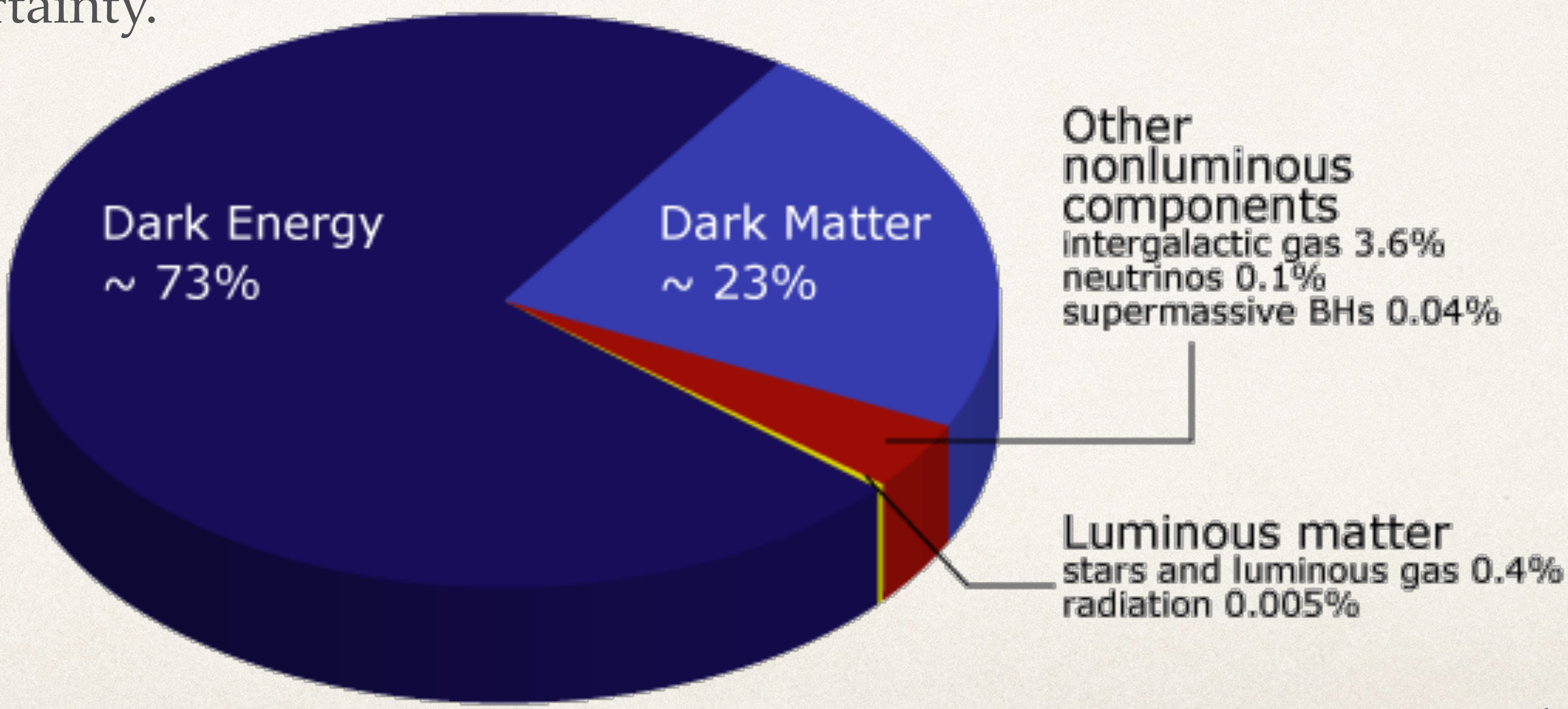

Image source: Annenberg Learner

BEAMS Applied to Simulations

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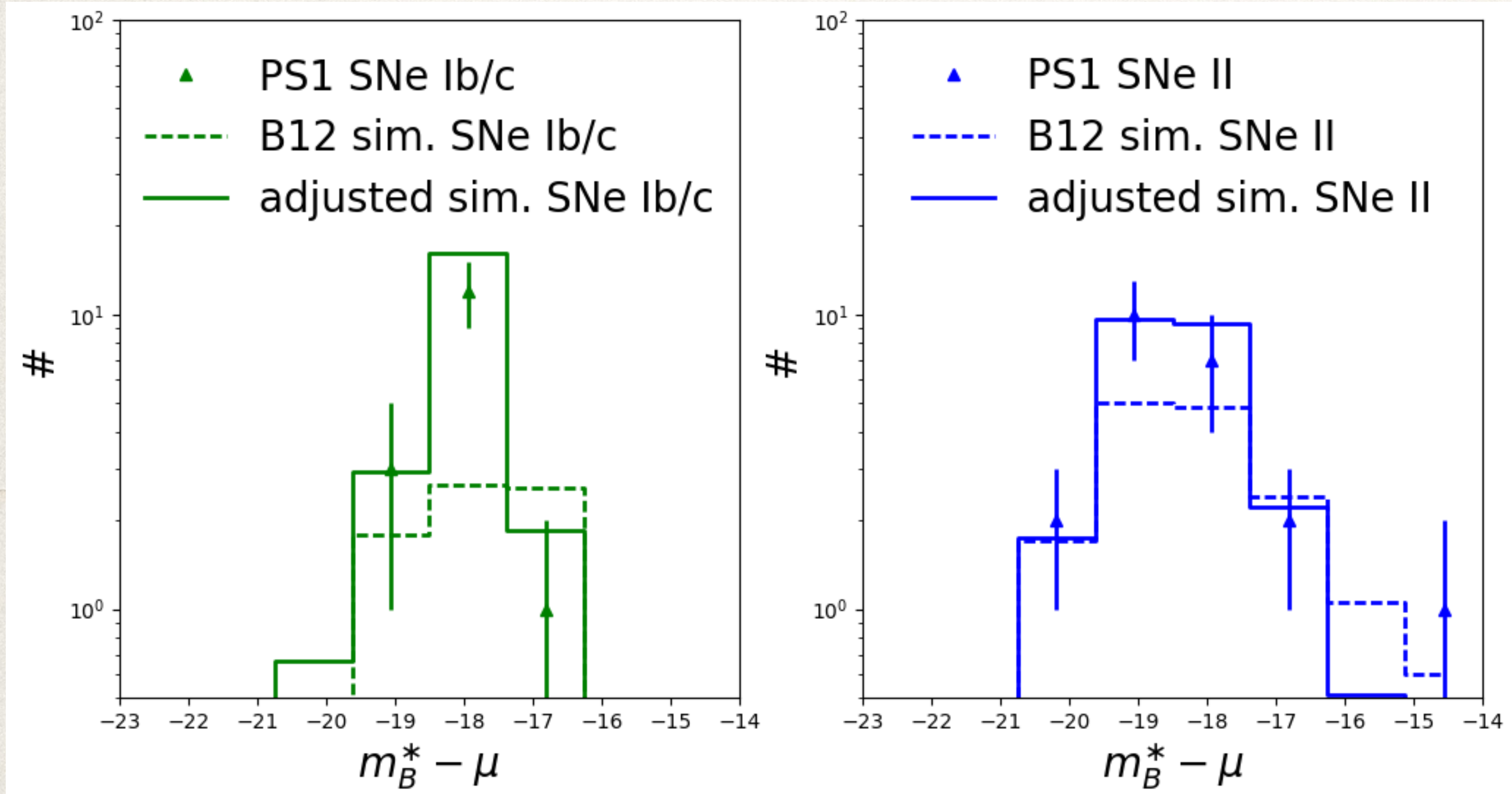

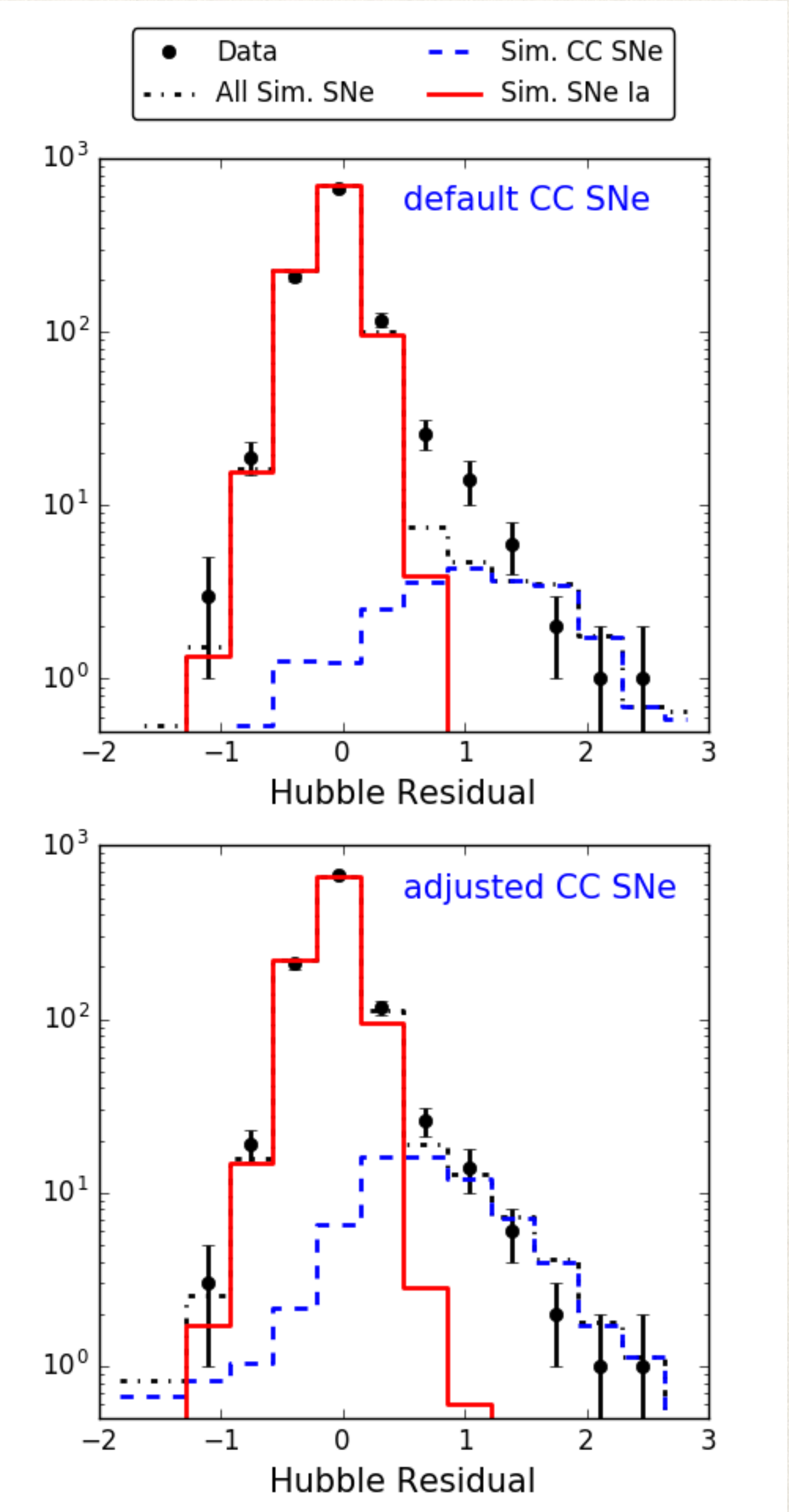

PS1 Cosmology with BEAMS

- We tested BEAMS on 25 simulations of 1,000 SNe

	Simulations		
	bias	bias/$\sigma_{\rm stat}$	$\Delta\sigma_{\rm stat}$
w	**-0.004±0.002**	-0.1	0.001 (1%)

	Data		
	bias	bias/$\sigma_{\rm stat}$	$\Delta\sigma_{\rm stat}$
w	**-0.047±0.013**	0.5	0.015 (17%)

PS1 Cosmology with BEAMS

- We tested BEAMS on 25 simulations of 1,000 SNe
- We tested BEAMS on 25 samples of 100 SNe drawn from our data, comparing to PS1 cosmological results from Rest+14

	Simulations		
	bias	bias/$\sigma_{\mathtt{stat}}$	$\Delta\sigma_{\mathtt{stat}}$
μ	-0.008$\pm$0.003	-0.1	0.002 (3%)

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	Simulations		
	bias	bias/σ_{stat}	$\Delta\sigma_{\mathrm{stat}}$
μ	-0.008±0.003	-0.1	0.002 (3%)
α	0.005±0.000	1.0	0.000 (3%)
β	0.096±0.006	1.5	0.008 (12%)

Two more BEAMS free parameters

$$\mu_i = m^*_{B,i} + \alpha \times X_{1,i} - \beta \times C_i - M$$

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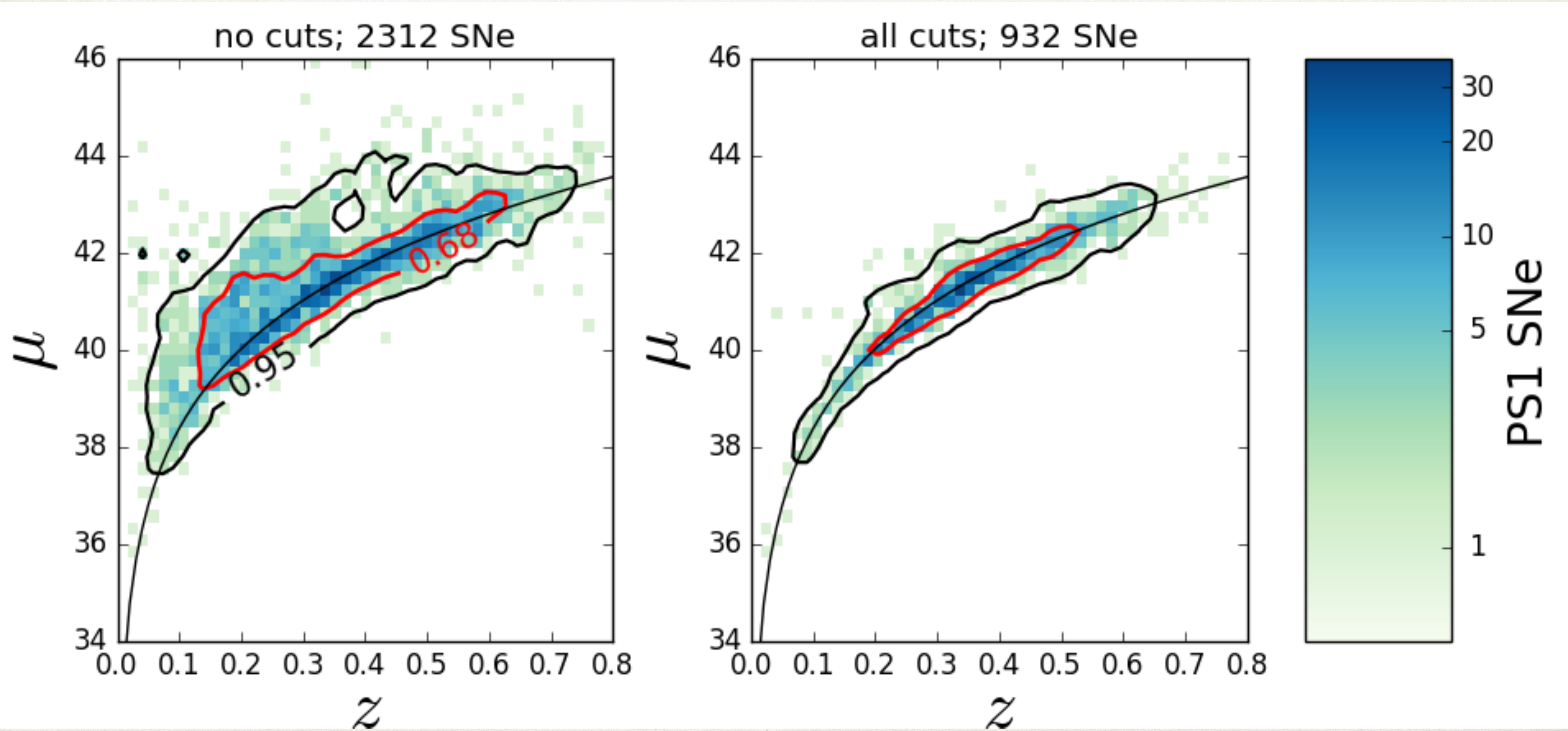
Real data: difference between BEAMS and Rest+14

	Data		
	bias	bias/σ_{stat}	$\Delta\sigma_{\mathrm{stat}}$
μ	-0.023±0.021	-0.4	0.025 (29%)
α	-0.006±0.001	-0.6	0.002 (17%)
β	0.108±0.019	0.9	0.045 (37%)
w	**-0.047±0.013**	0.5	0.015 (17%)

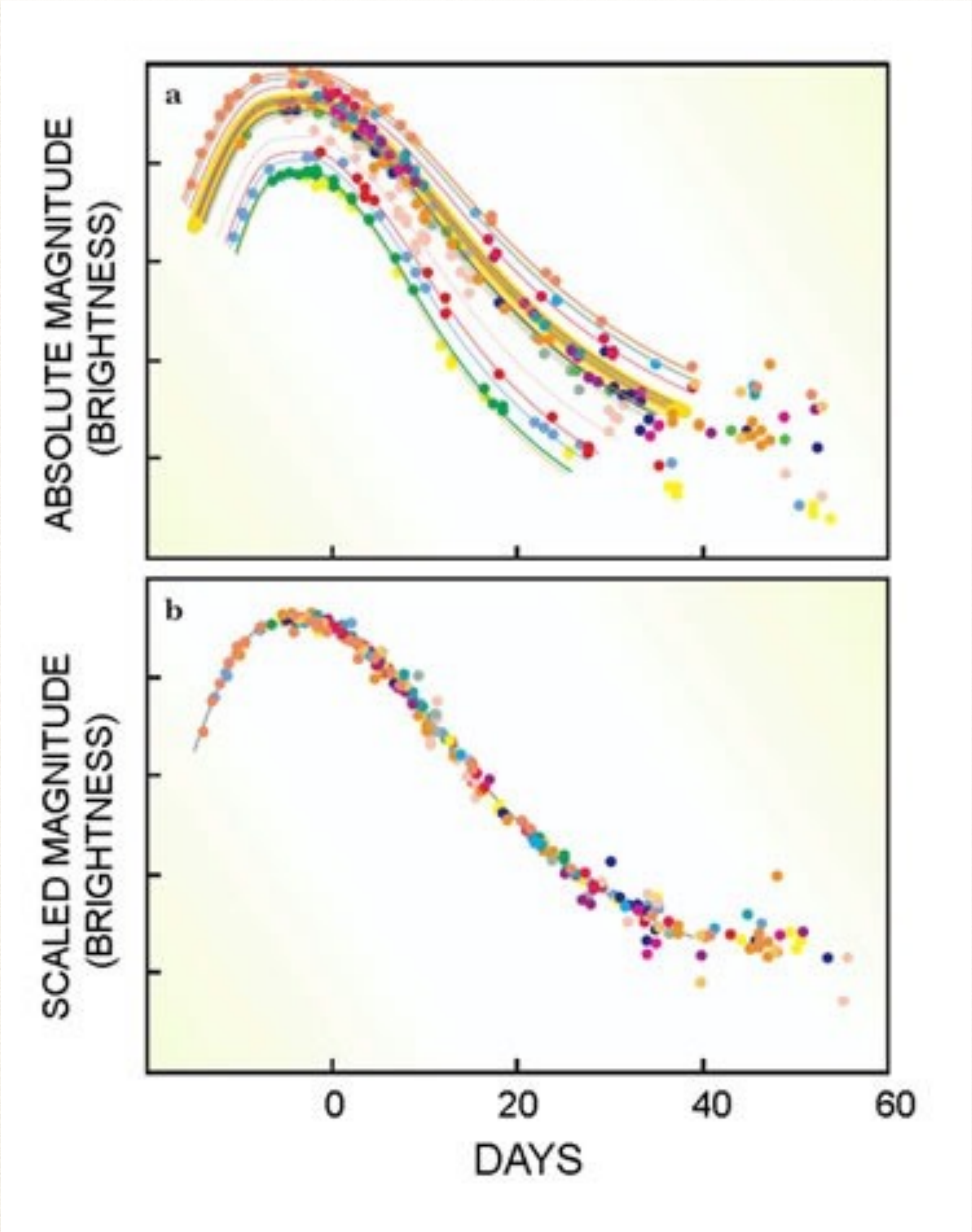
Photometric SNe from Pan-STARRS

- Our Hubble (density) diagram, with and without shape, color, and uncertainty cuts.



Type Ia SNe as Cosmological Probes

- Type Ia Supernovae are formed by the detonation of a white dwarf when it reaches the Chandrasekhar mass.
- Intrinsically brighter SN Ia have broader light curves and can measure distances to ~6% accuracy.
- Betoule et al. (2014) used SN Ia+CMB+BAO to measure *w* to <6% uncertainty.



The Supernova Cosmology Project

The Current State of SN Ia Cosmology

Three reasons we need to measure *w* better:

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- Do we understand the systematics?

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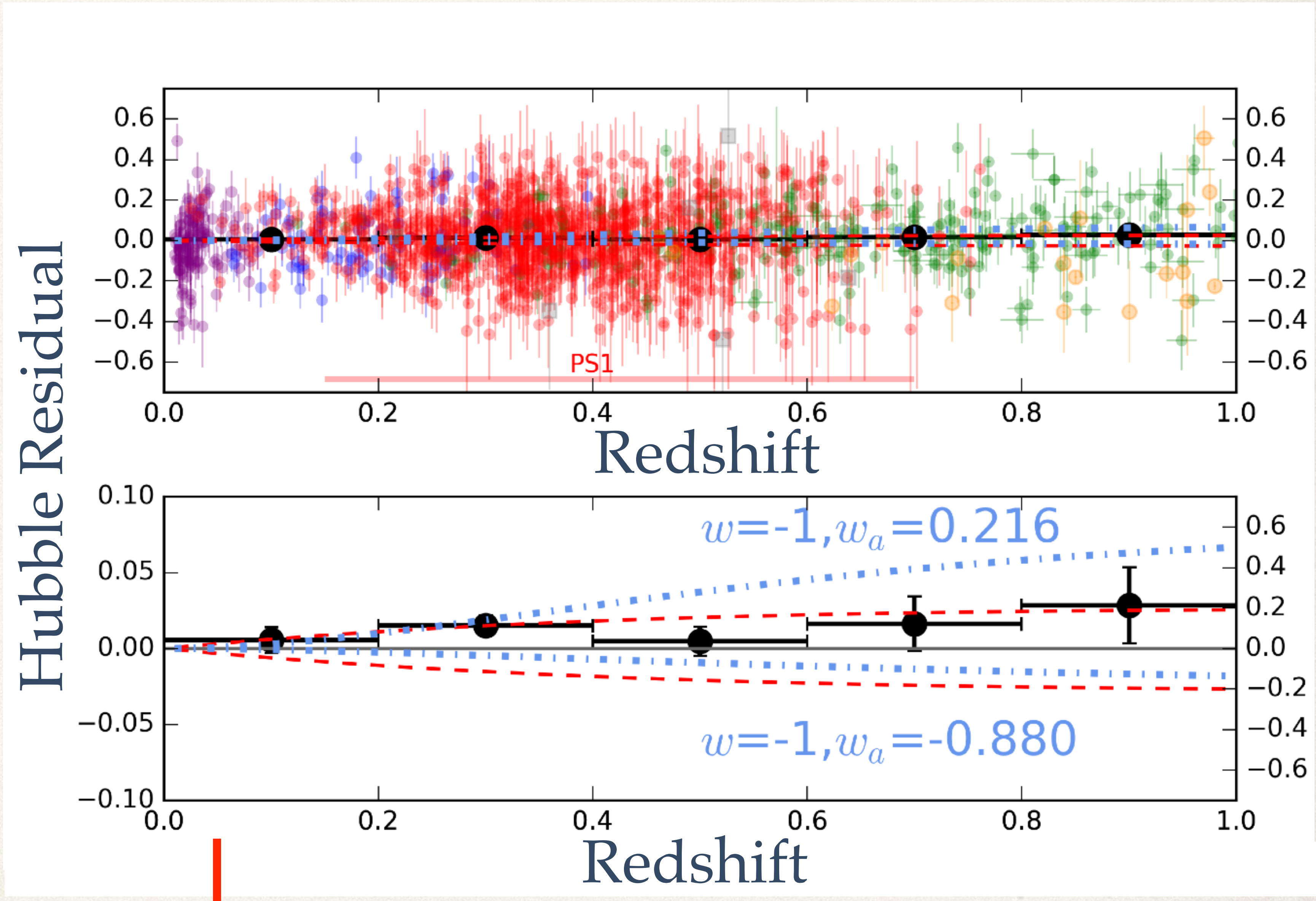

local H_0 vs. Planck (-0.18±0.05 mag)

Allowed parameters from Betoule et al. (2014)

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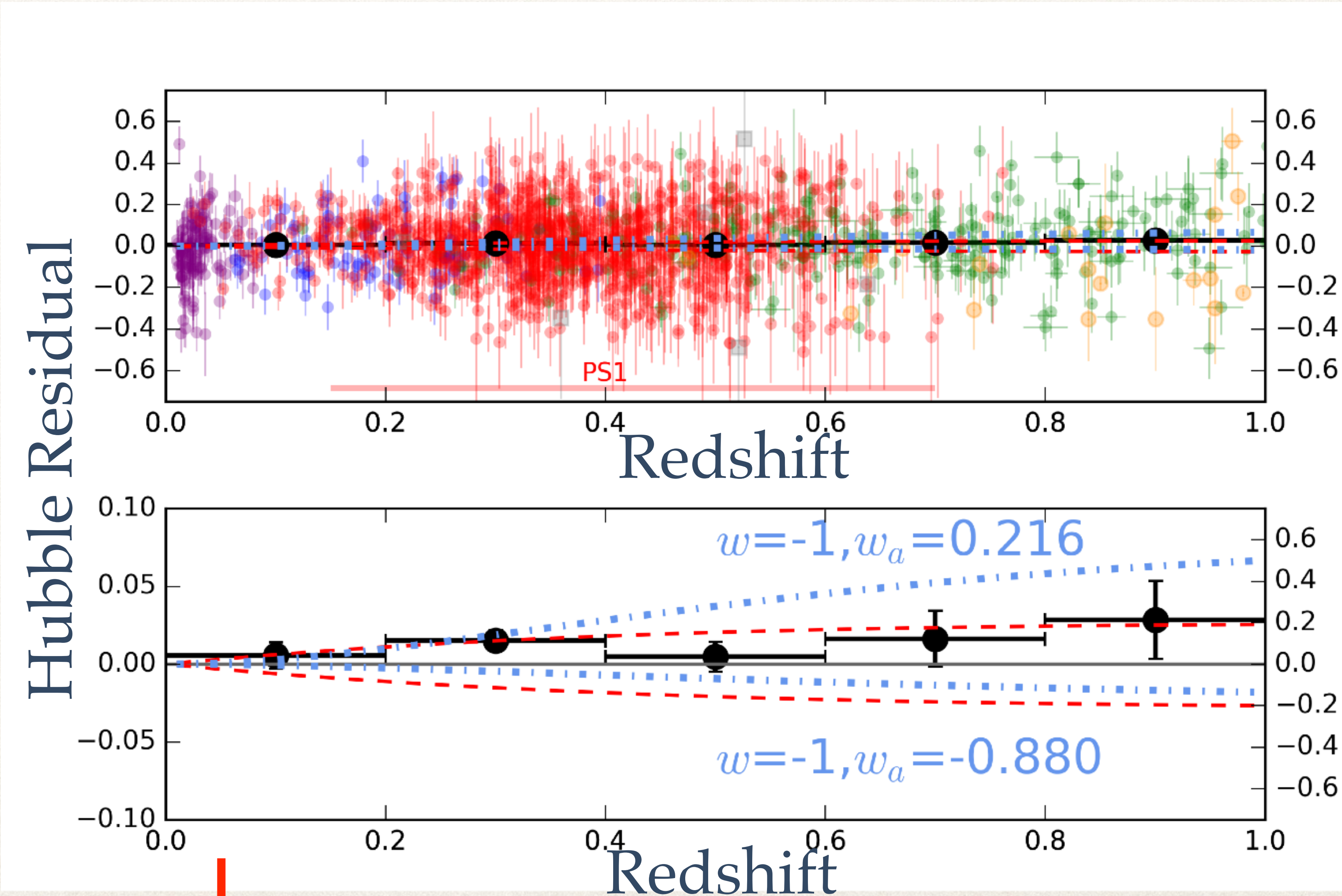

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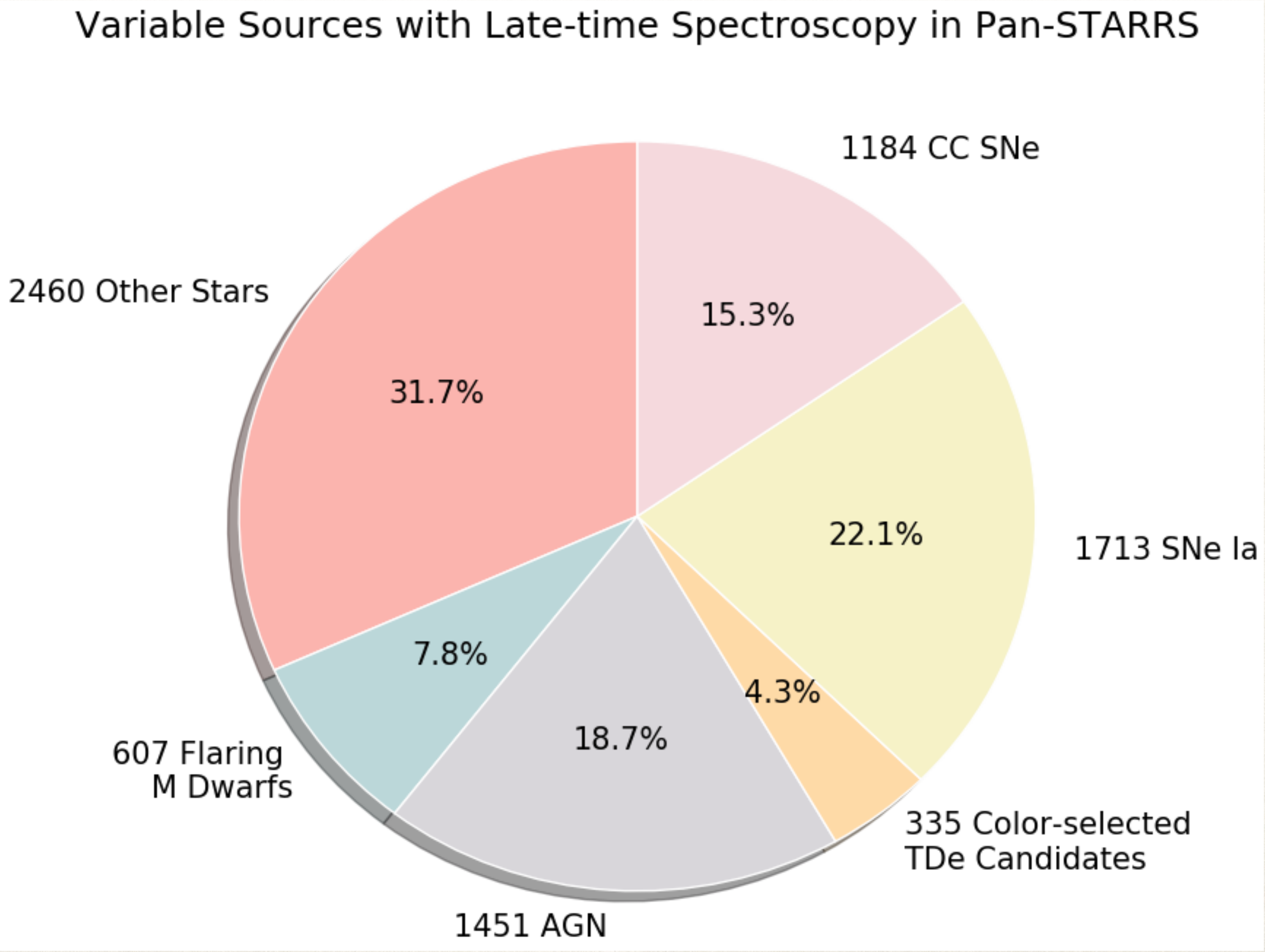
local H_0 vs. Planck (-0.18±0.05 mag)

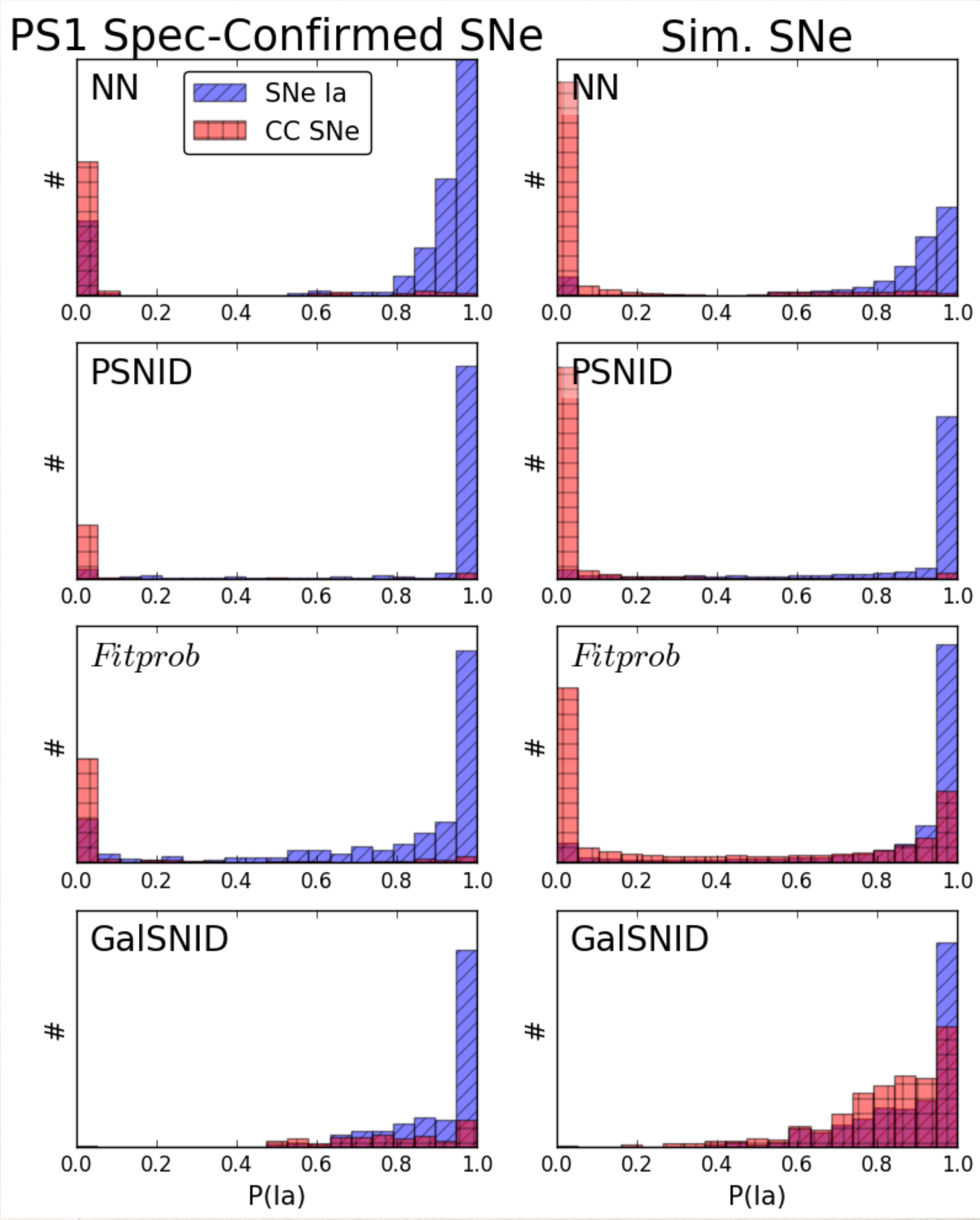
Photometric SNe from Pan-STARRS

- A rough estimate of objects with late time spectroscopy from Pan-STARRS:



Are these results robust?

- Let's try a few different P(Ia) priors:
  - SALT2 Fit Prob.
  - PSNID (Sako+11)
  - GalSNID (Foley & Mandel 2013; Jones+16 in prep.)



Simulating the Pan-STARRS Sample

- SNANA software (Kessler+2010):
  - Data-based Monte Carlo simulations (not pixel level detail)
- We simulated:
  - Sky noise
  - Zeropoints
  - Detection efficiency
  - Host galaxy noise
  - Incorrect Redshifts (~2.5%)
  - CC SNe from 43 II-P, II-L, IIn, Ib and Ic templates

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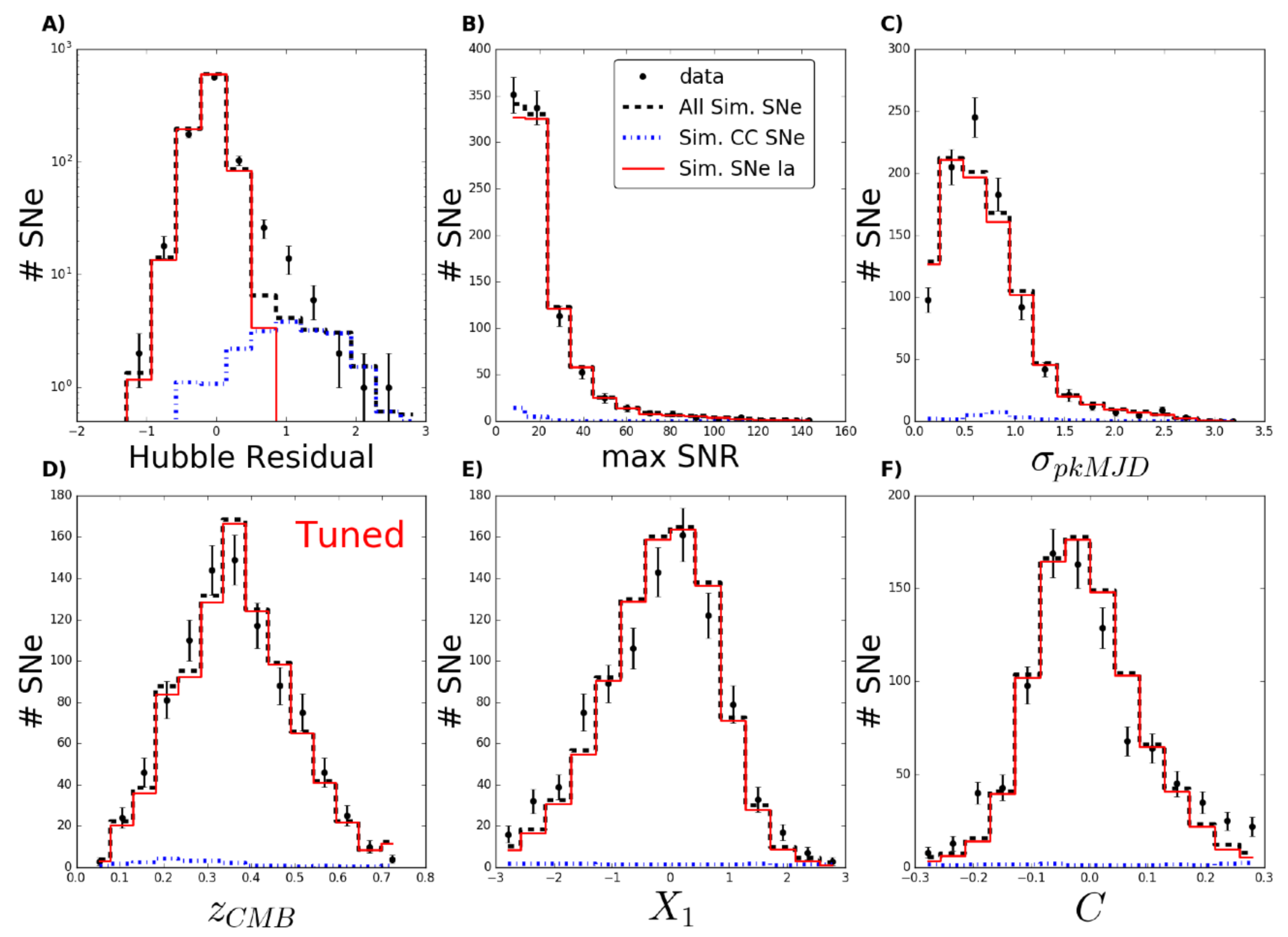

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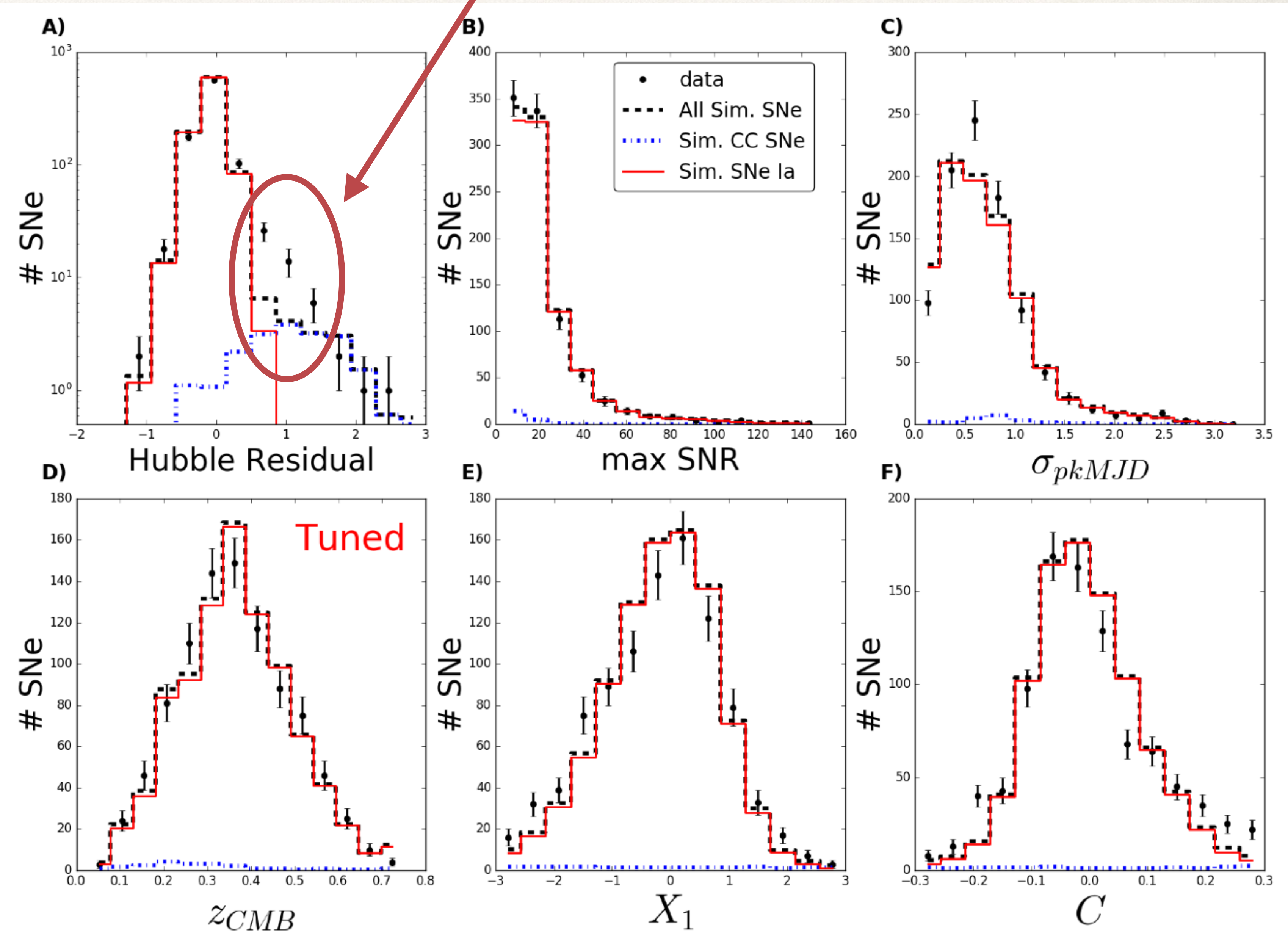
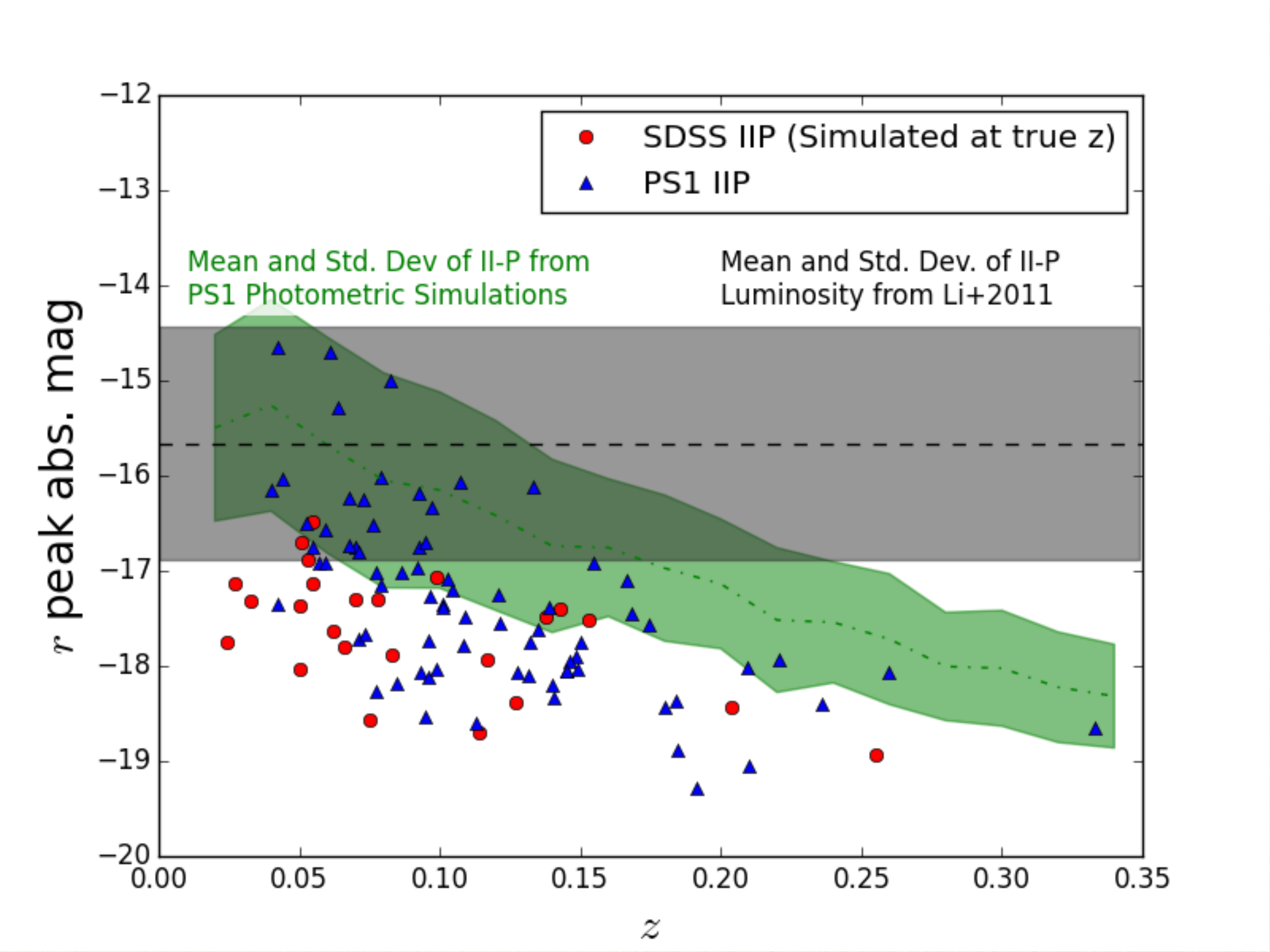
How well do we really understand CC SNe?



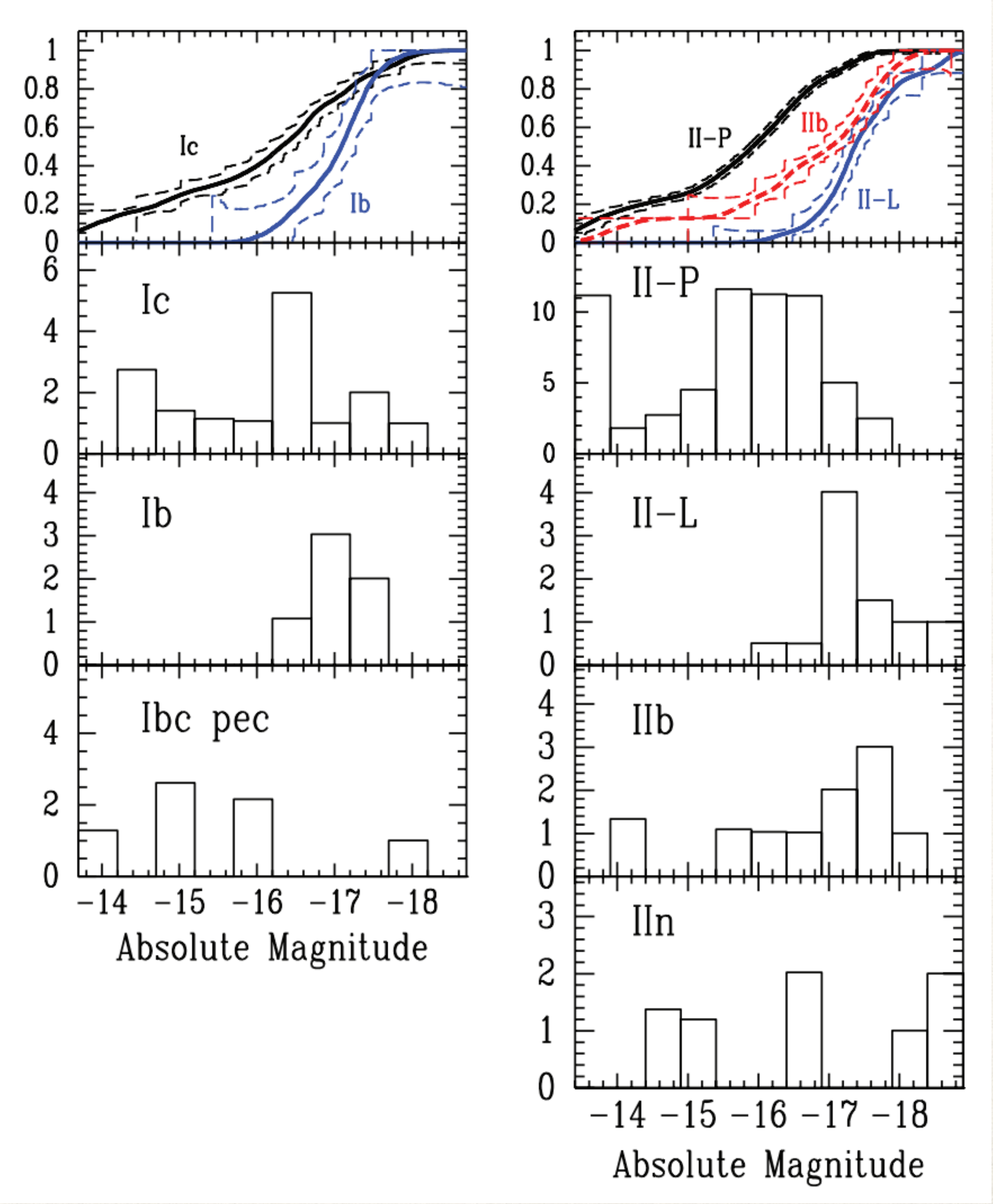
Core-Collapse SNe: Two Flawed Assumptions

Do our templates represent the population?



Core-Collapse SNe: Two Flawed Assumptions

Are CC SN luminosity Functions Gaussian?

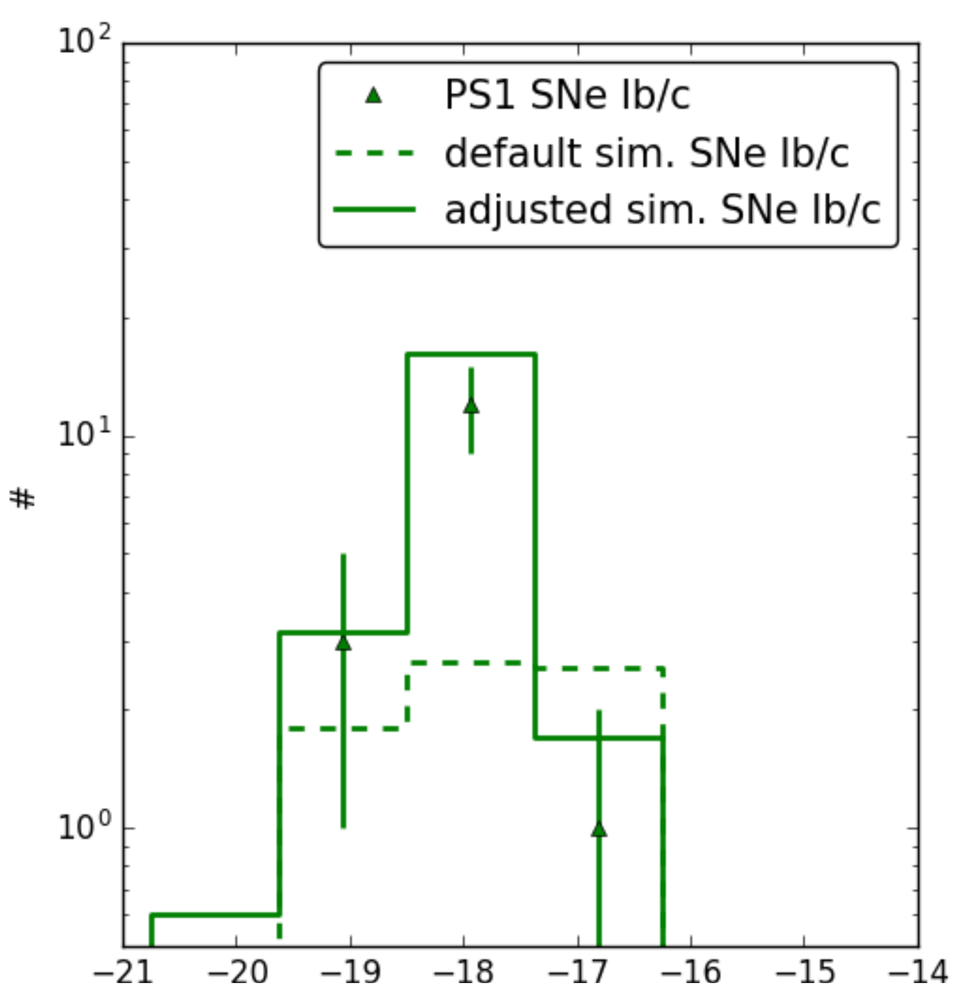


From Li+2011

"Empirical" Distributions of CC SNe

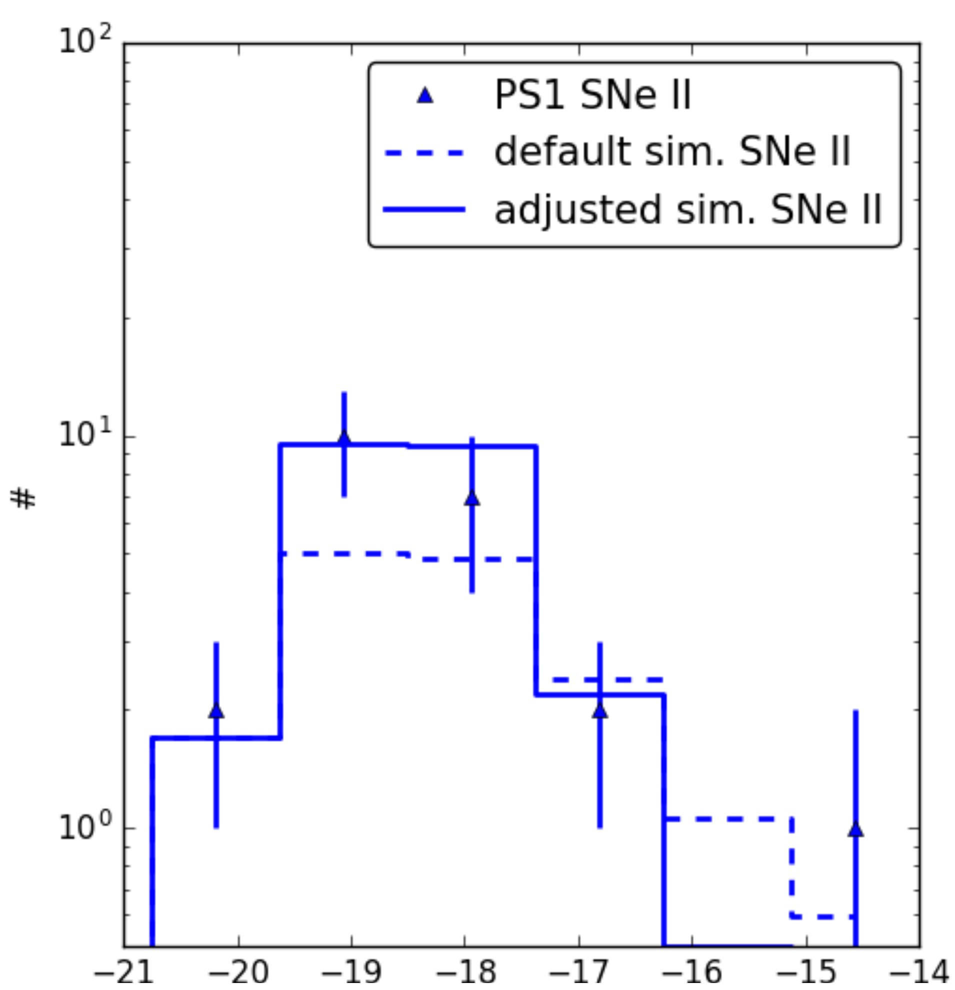
- We ran PSNID on our real and simulated data to see if the distributions of likely Type II and Type Ib/c SNe lined up - they didn't.
- CC SNe must be ~1 mag brighter with ~30-50% less dispersion to match our data.

SNe Ib/c (green)



Abs. B Mag

SNe II (blue)



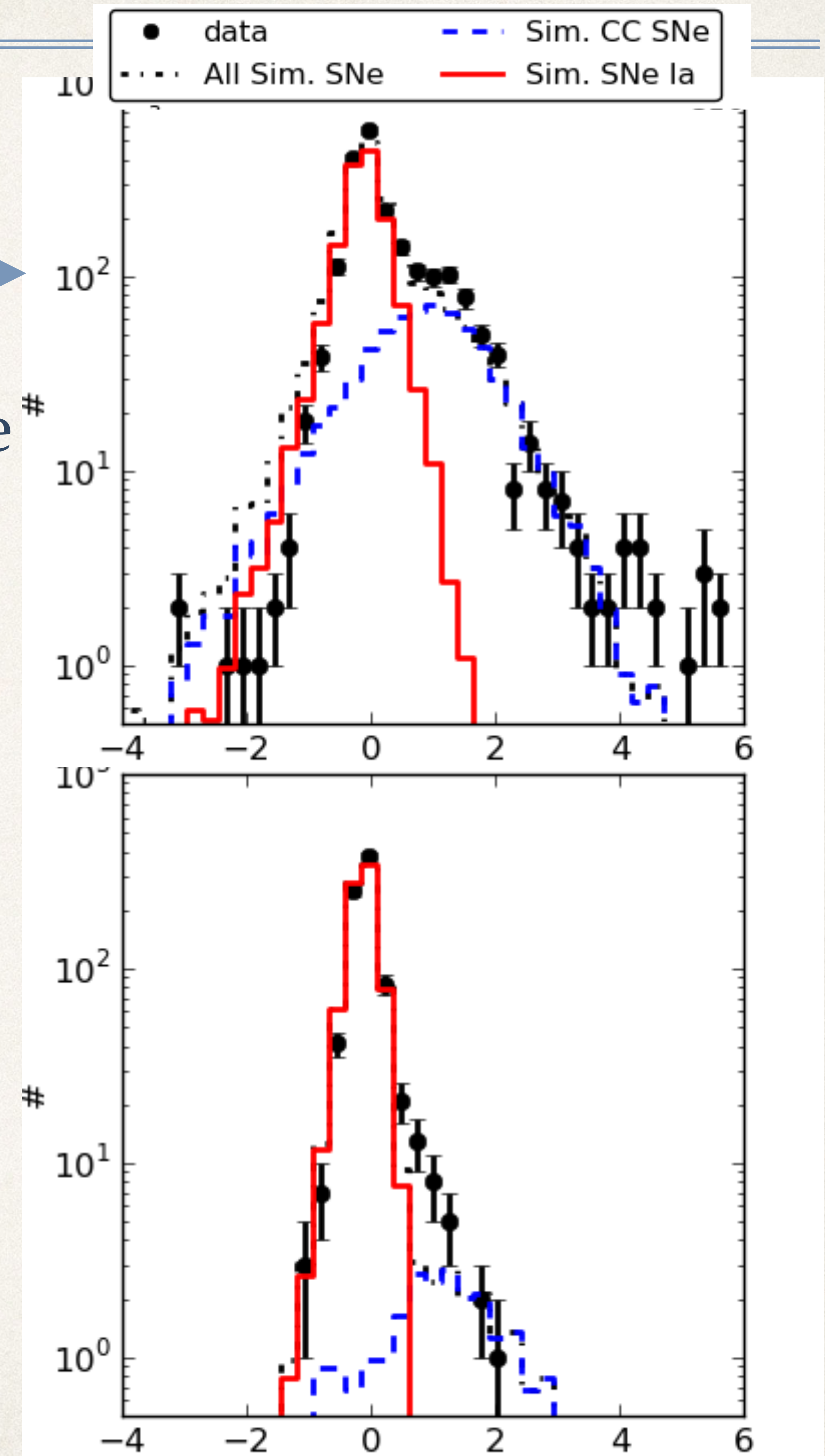
Abs. B Mag

“Empirical” Distributions of CC SNe

- A few thoughts/ideas:
  - Simulated CC SNe agree pretty well with our data before cuts but not after.
  - We have a relatively sparse sampling of CC SNe - do CC SNe with a smaller range of shapes and colors have lower scatter?
  - Are Ia-like CC SNe intrinsically brighter?
  - We know II-P SNe with shorter plateau phases (likely smaller SALT2 X_1) are brighter. Could something similar be happening for SN Ib/c?

No cuts; these agree better?

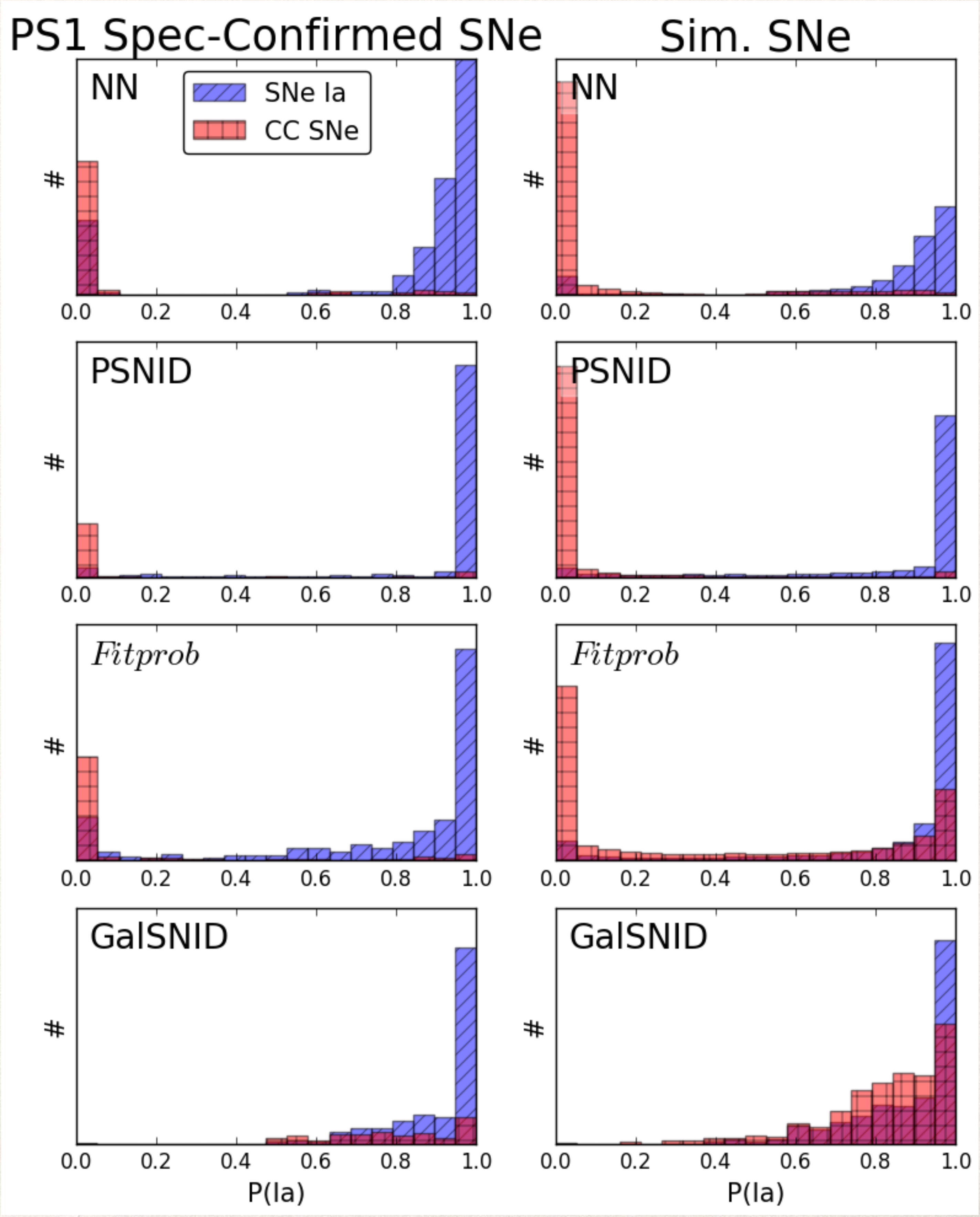
cuts



Hubble residual

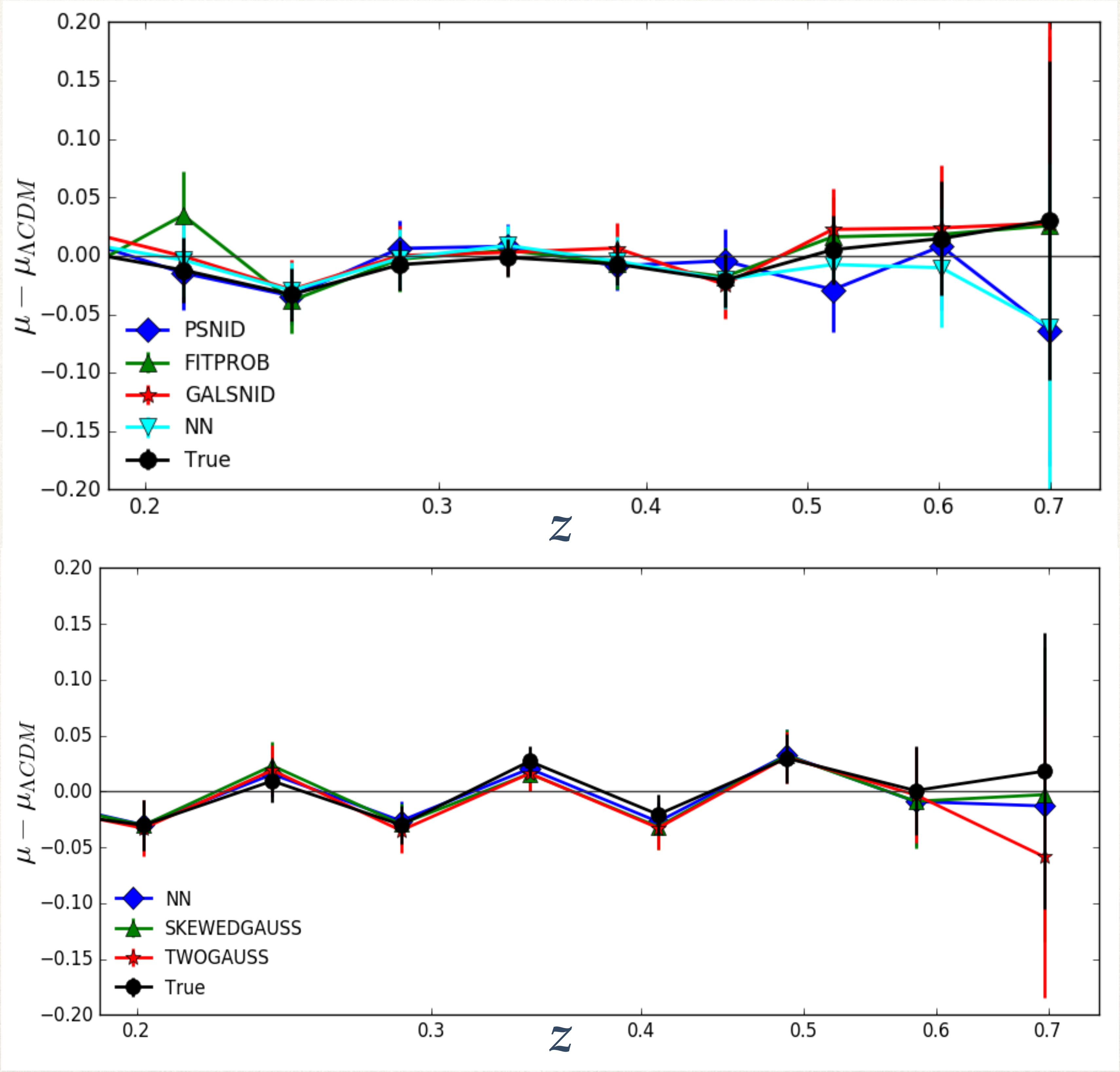
Are these results robust?

- Let's try a few different P(Ia) priors:
  - SALT2 Fit Prob.
  - PSNID (Sako+11)
  - GalSNID (Foley & Mandel 2013; Jones+16 in prep.)
- And a two different CC SN models:
  - Two Gaussians
  - Skewed Gaussian



PS1 Cosmology with BEAMS

- Some results from simulations:



PS1 Cosmology with BEAMS

- Does BEAMS bias w?

Cosmological Parameters from 1,000 Sim. SNe

Different CC SN Models

	Δw	$\Delta \sigma_w$
one Gaussian*	-0.005 (-0.1σ)	**0.001 (1%)**
two Gaussians*	-0.003 (-0.1σ)	0.003 (6%)
skewed Gaussian*	**-0.001 (-0.0σ)**	0.002 (3%)

Different P(Ia) Priors

	Δw	$\Delta \sigma_w$
NN	-0.005 (-0.1σ)	**0.001 (1%)**
PSNID	**0.004 (0.1σ)**	0.001 (2%)
SALT2 Fit Prob.	-0.017 (-0.4σ)	0.002 (4%)
GalSNID	-0.022 (-0.5σ)	0.003 (6%)
Half[c]	-0.024 (-0.5σ)	0.003 (5%)

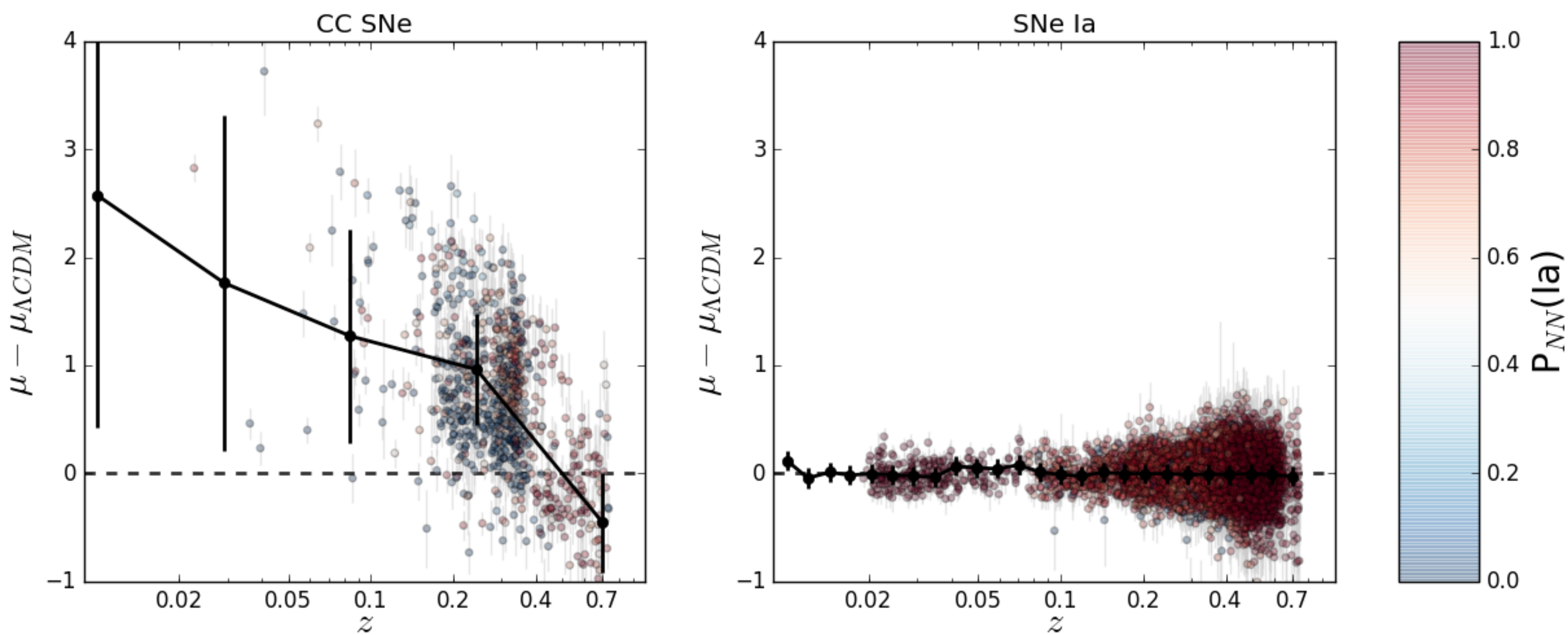
Baseline Model

Very small bias in w, negligible increase in uncertainty

PS1 Cosmology with BEAMS

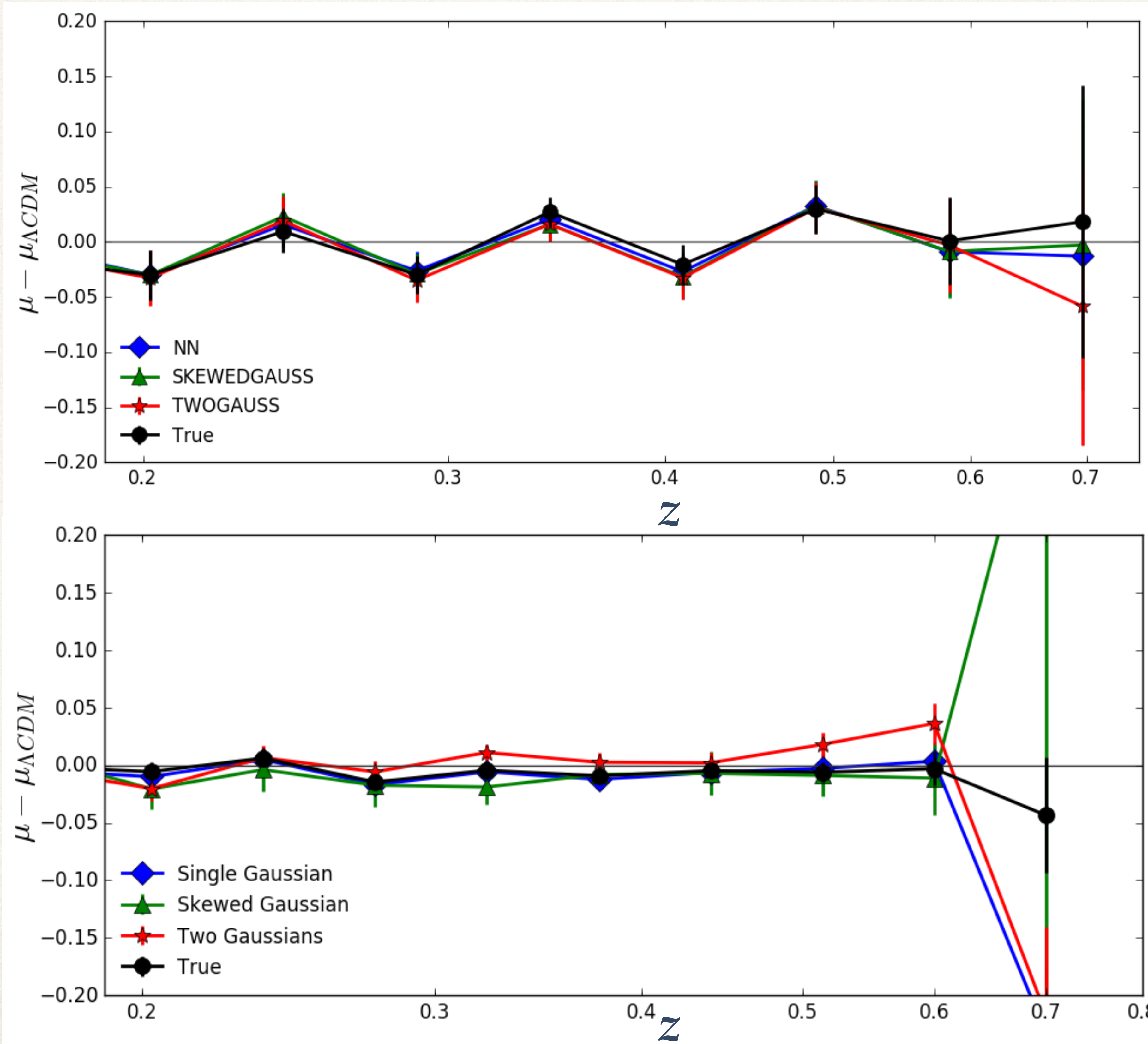
- We can use Bayesian Estimation Applied to Multiple Species (BEAMS; Kunz, Bassett & Hlozek 2007) to fit CC SNe and SNe Ia simultaneously.

BEAMS Applied to Simulations



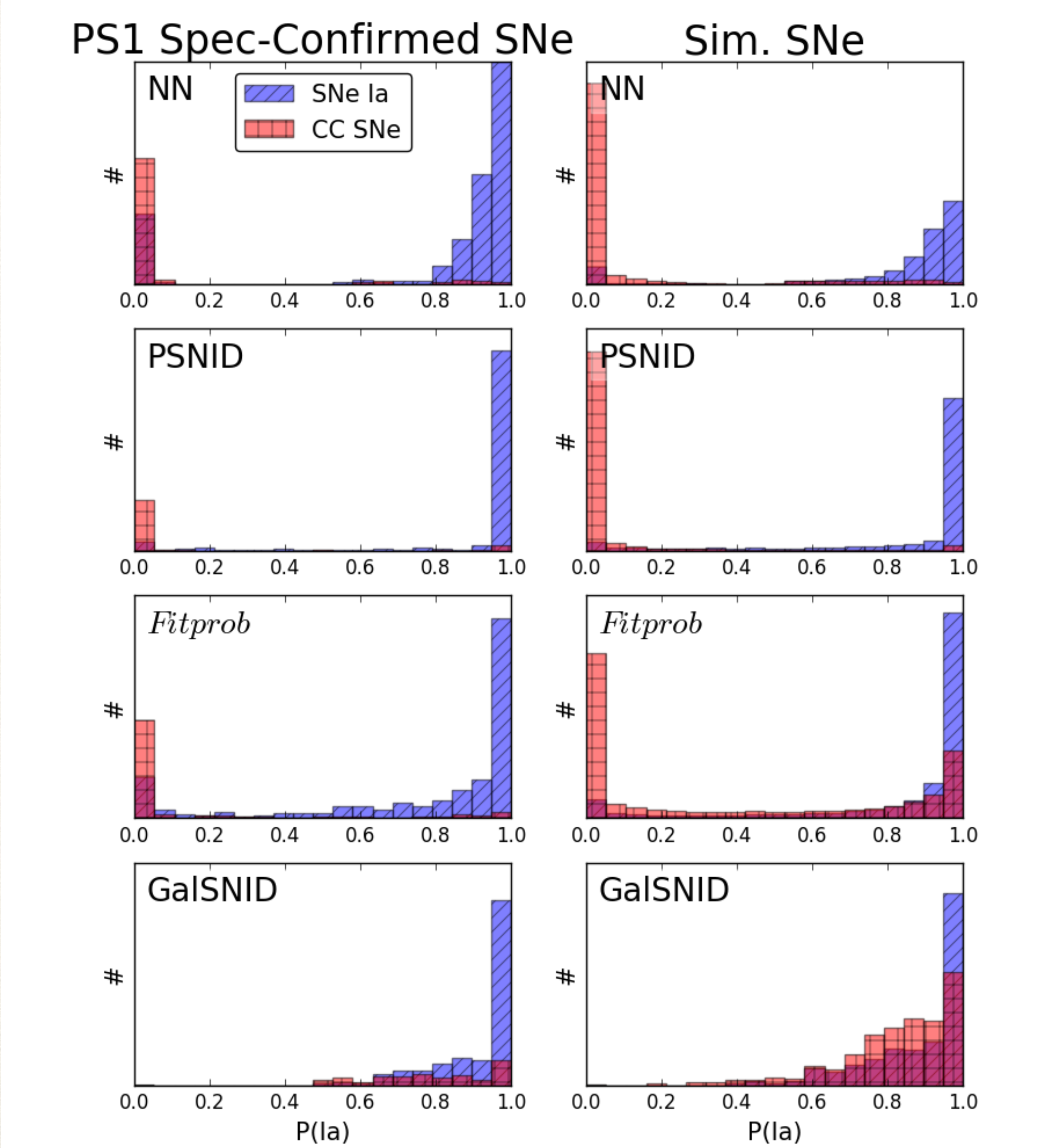
PS1 Cosmology with BEAMS

- The effect of different CC SN models:



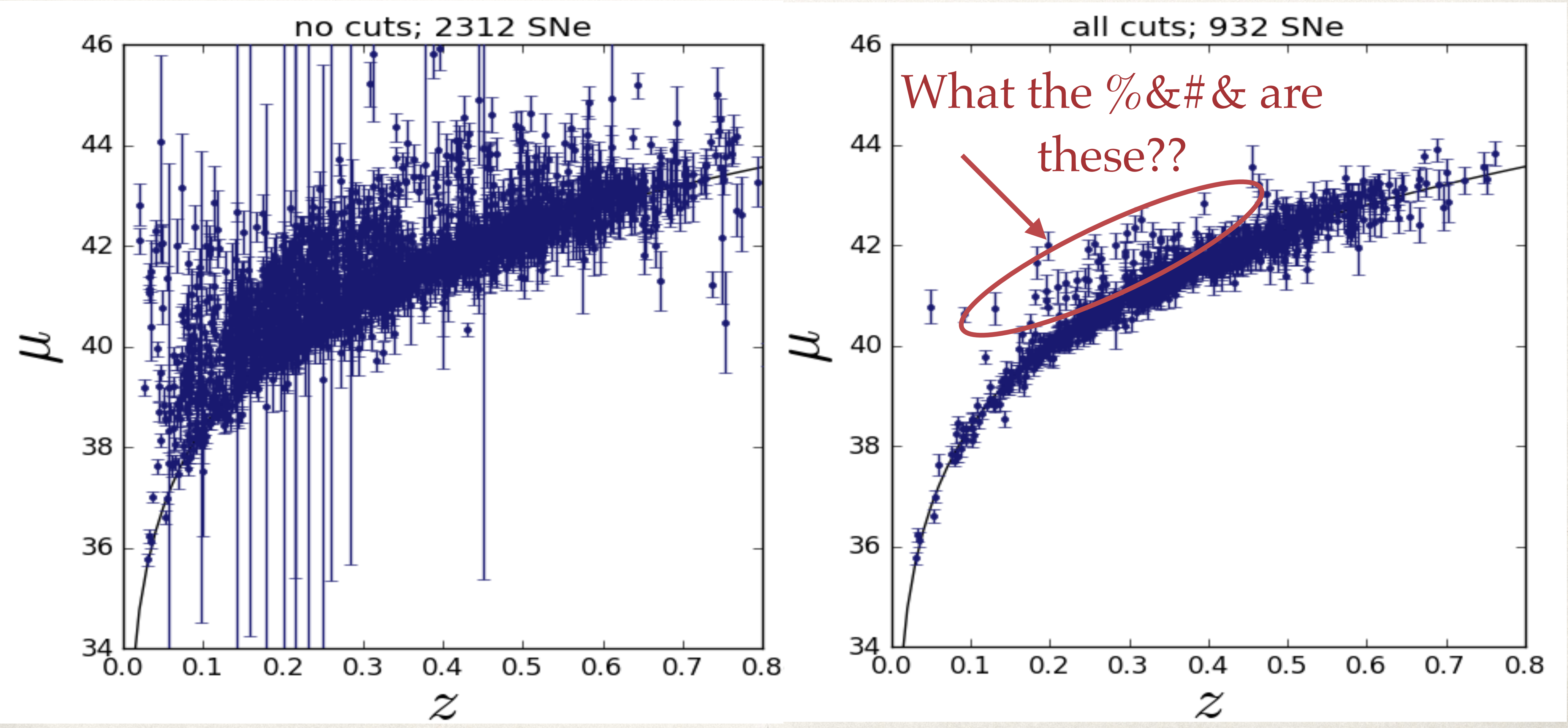
PS1 Cosmology with BEAMS

- We can use Bayesian Estimation Applied to Multiple Species (BEAMS; Kunz, Bassett & Hlozek 2007) to fit CC SNe and SNe Ia simultaneously.
- Let's try a few P(Ia) priors:
  - SALT2 Fit Prob.
  - PSNID (Sako+11)
  - GalSNID (Foley & Mandel 2013; Jones+16 in prep.)
  - Nearest Neighbor (Sako+14)



Photometric SNe from Pan-STARRS

- Our Hubble diagram, with and without shape, color, and uncertainty cuts.



The Next Step: Moving to a Photometric Sample

- We can lower calibration systematics *and* improve statistics by using a large number of SNe from as few surveys as possible
- If we don't need to get a spectrum for every SN, that makes this easier…

Uncertainty:	Err. on w
Calibration:	0.045
SN Color Model:	0.023
Host Galaxy Dependence:	0.015
MW Extinction:	0.013
Selection Bias:	0.012
Coherent Flows:	0.007
Photometric:	?????
Total:	**0.056**

PS1 systematic uncertainties on w from Scolnic et al. (2014)

PS1 Cosmology with BEAMS

- Does BEAMS bias w?

BEAMS Cosmological Parameters using Different Priors; 1000 Simulated PS1 SNe

	SNe alone			Planck Ω_M prior			SNe alone		
P(Ia) Method	w	Δw	$\Delta\sigma_w$	w	Δw	$\Delta\sigma_w$	Ω_M	$\Delta\Omega_M$	$\Delta\sigma_{\Omega_M}$
No CC SNe	-0.980±0.111	···	···	-1.042±0.050	···	···	0.265±0.047	···	···
Fit Prob.	-0.983±0.121	-0.003 (0.0σ)	0.010 (9%)	-1.029±0.052	0.013 (0.1σ)	0.002 (4%)	0.273±0.051	0.008 (0.2σ)	0.004 (9%)
GalSNID	-1.070±0.146	-0.090 (0.8σ)	0.035 (32%)	-1.052±0.054	-0.010 (0.1σ)	0.004 (8%)	0.301±0.056	0.036 (0.8σ)	0.009 (19%)
Toy Model	-0.974±0.115	0.006 (0.1σ)	0.004 (4%)	-1.017±0.049	0.025 (0.2σ)	-0.001 (2%)	0.272±0.050	0.007 (0.2σ)	0.003 (6%)
PSNID	-1.055±0.137	-0.075 (0.7σ)	0.026 (23%)	-1.025±0.053	0.017 (0.3σ)	0.003 (6%)	0.308±0.055	0.043 (0.9σ)	0.01 (22%)

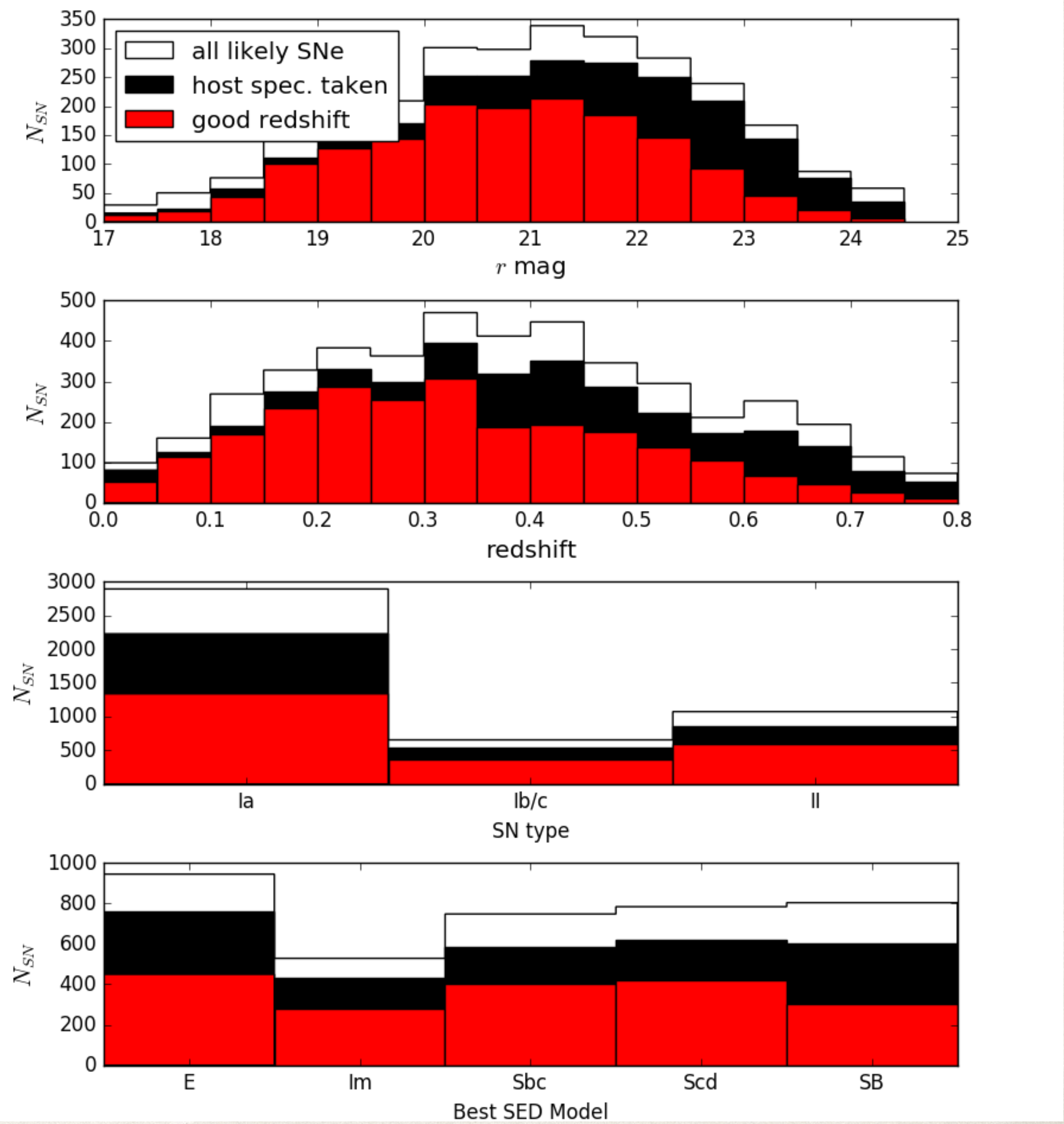
We don't see any bias

Using mass prior, only small increase in uncertainty on w

When we look with 10,000 sim. SNe, we still don't see any bias

Photometric SNe from Pan-STARRS

- Obtaining SN spectra during the survey is hard, but getting host galaxy spectra after the survey has ended is easy!
- We got redshifts for 60% of the 5,000 likely SNe in Pan-STARRS with multi-object spectroscopy from MMT, WIYN and the AAT.



PS1 Cosmology with BEAMS

- Methodology from Kunz, Bassett & Hlozek (2007), Rubin et al. (2015)

- Can model SNe Ia and a contaminating distribution using two gaussians with the likelihood function:

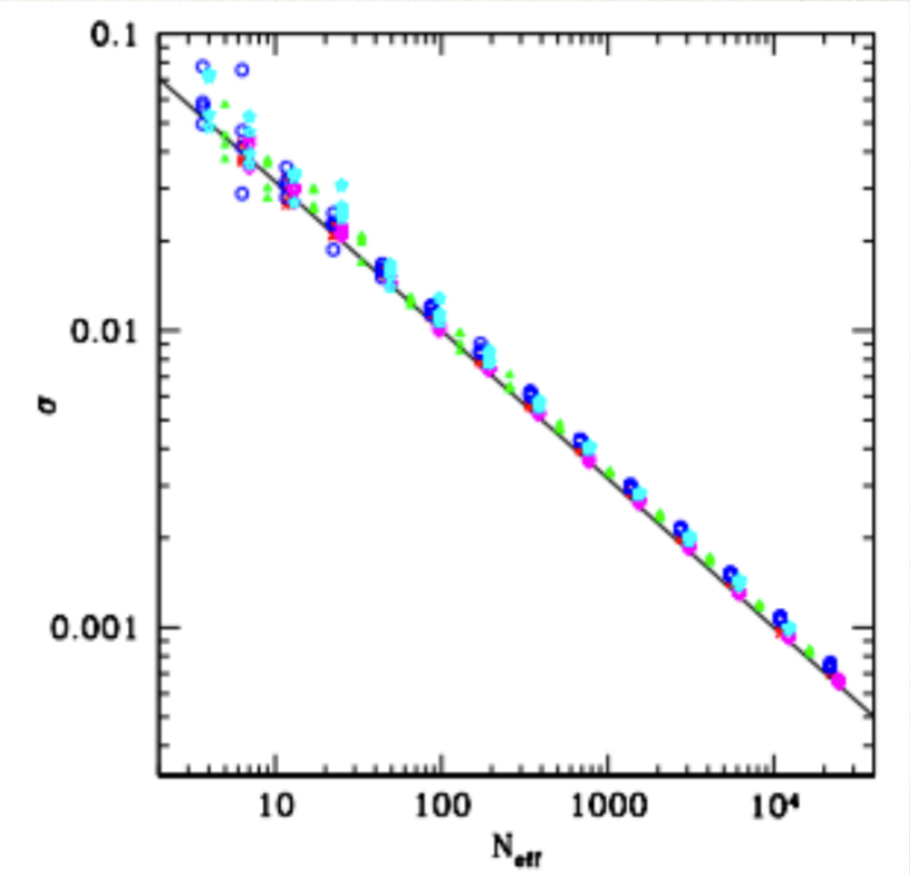
$$P(D_j|\theta, b, \Sigma, \tau_j = B) = \mathcal{L}_{B,j}(\theta, b, \Sigma)$$
$$= \frac{1}{\sqrt{2\pi}\Sigma} e^{-((\mu_j - m(\theta) - b)^2/2\Sigma^2)}$$

- Giving the posterior:

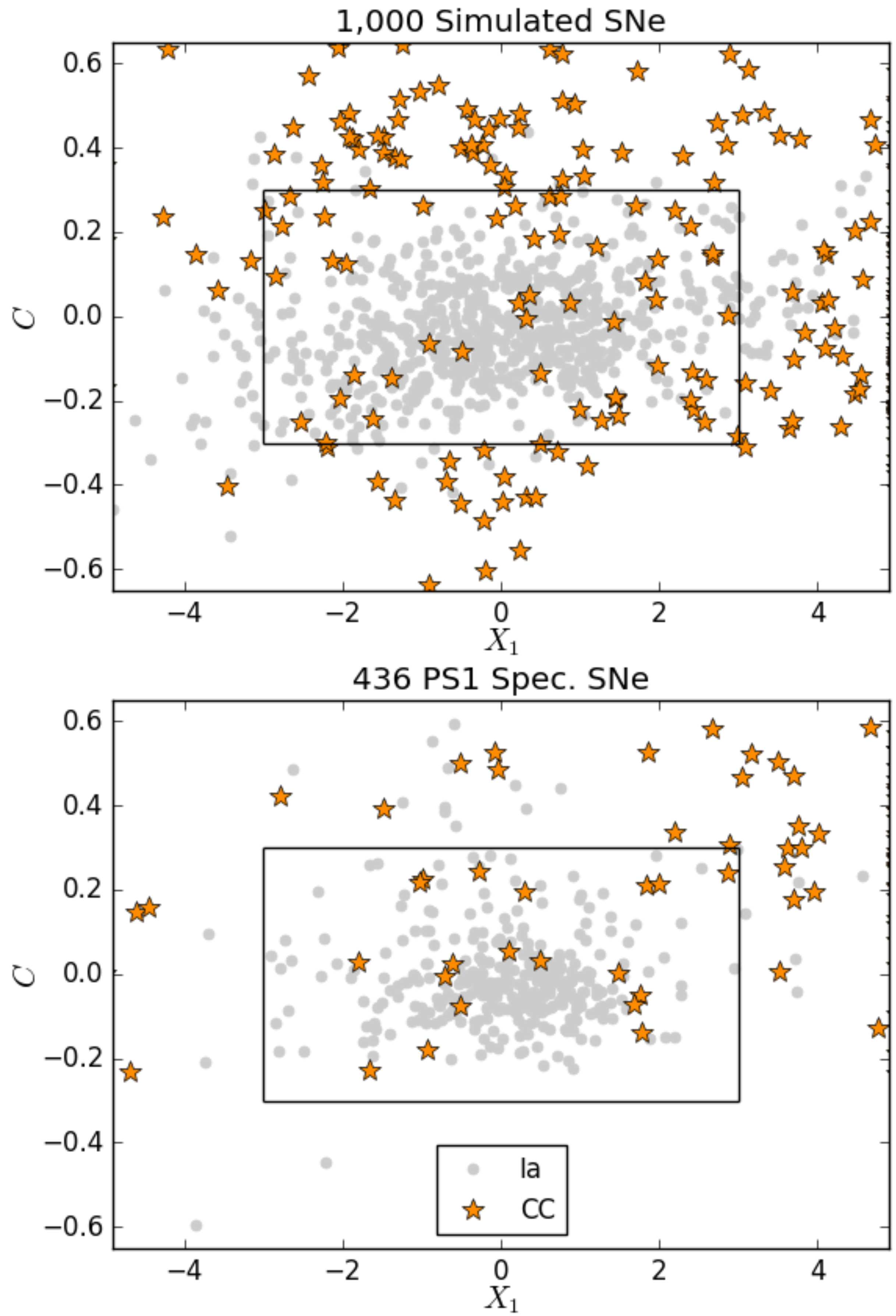
$$P(\theta|D) \propto \sum_{b,\Sigma} P(\theta)P(b)P(\Sigma) \prod_{j=1}^{N} \{\mathcal{L}_{A,j}(\theta)P_j + \mathcal{L}_{B,j}(\theta, b, \Sigma)$$
$$\times (1 - P_j)\}.$$

These prior probabilities are from SN classification

- How well does it work? Very well in theory. In practice we're not sure yet…



Optimal (black line) vs simulated uncertainties (colored points) from Kunz, Bassett & Hlozek (2007)


1,000 Simulated SNe
C
X1
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
−4
−2
0
2
4
436 PS1 Spec. SNe
Ia
CC

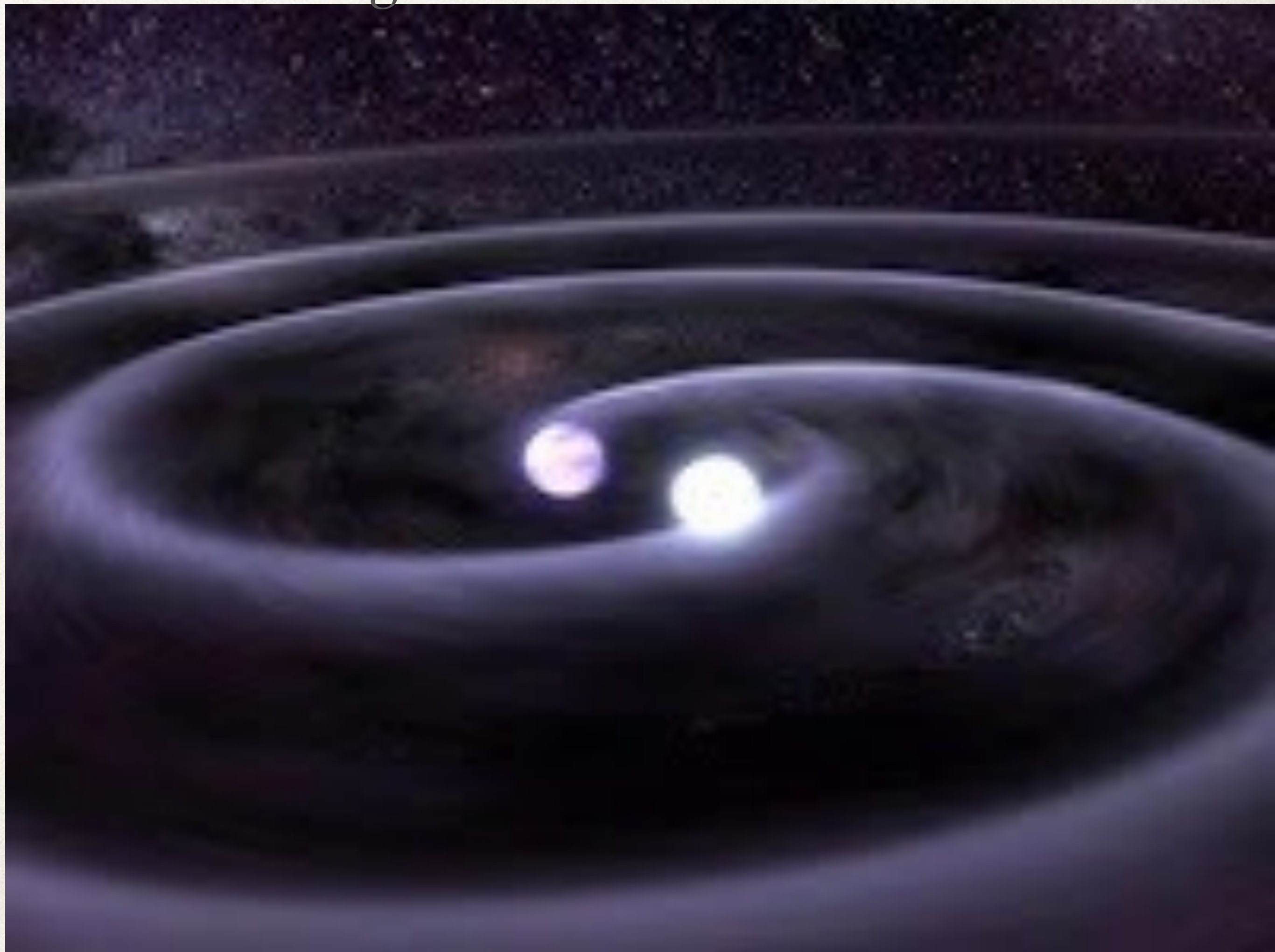
Bin	$P(D_i\|\mathrm{Ia})$	$P(D_i\|\mathrm{Ibc})$	$P(D_i\|\mathrm{II})$
Cross-Correlation Template			
absorption	$0.502^{+0.047}_{-0.048}$	$0.256^{+0.061}_{-0.061}$	$0.286^{+0.034}_{-0.034}$
ellipt+A stars	$0.431^{+0.043}_{-0.043}$	$0.598^{+0.086}_{-0.085}$	$0.609^{+0.049}_{-0.049}$
late-type	$0.029^{+0.010}_{-0.009}$	$0.037^{+0.025}_{-0.024}$	$0.030^{+0.011}_{-0.011}$
emission	$0.029^{+0.010}_{-0.009}$	$0.098^{+0.037}_{-0.036}$	$0.071^{+0.015}_{-0.015}$
Host Galaxy R			
0.0 – 1.0	$0.232^{+0.022}_{-0.021}$	$0.148^{+0.037}_{-0.037}$	$0.186^{+0.026}_{-0.026}$
1.0 – 2.0	$0.261^{+0.021}_{-0.022}$	$0.457^{+0.074}_{-0.074}$	$0.378^{+0.035}_{-0.035}$
2.0 – 3.0	$0.194^{+0.020}_{-0.020}$	$0.173^{+0.050}_{-0.049}$	$0.189^{+0.026}_{-0.026}$
3.0 – 4.0	$0.094^{+0.014}_{-0.014}$	$0.099^{+0.037}_{-0.037}$	$0.103^{+0.020}_{-0.019}$
4.0 – 5.0	$0.054^{+0.010}_{-0.010}$	$0.049^{+0.024}_{-0.025}$	$0.064^{+0.013}_{-0.013}$
Hα Equivalent Width			
<-5.0	$0.040^{+0.009}_{-0.009}$	$0.000^{+0.000}_{-0.000}$	$0.006^{+0.003}_{-0.003}$
-5.0 – 0.0	$0.217^{+0.022}_{-0.022}$	$0.072^{+0.031}_{-0.031}$	$0.088^{+0.017}_{-0.017}$
0.0 – 5.0	$0.159^{+0.017}_{-0.018}$	$0.237^{+0.051}_{-0.052}$	$0.202^{+0.023}_{-0.022}$
5.0 – 10.0	$0.097^{+0.015}_{-0.016}$	$0.124^{+0.031}_{-0.031}$	$0.153^{+0.019}_{-0.020}$
>10.0	$0.356^{+0.029}_{-0.029}$	$0.557^{+0.072}_{-0.072}$	$0.528^{+0.039}_{-0.040}$
Hβ Equivalent Width			
<-5.0	$0.078^{+0.014}_{-0.013}$	$0.010^{+0.010}_{-0.011}$	$0.009^{+0.006}_{-0.005}$
-5.0 – 0.0	$0.419^{+0.031}_{-0.031}$	$0.299^{+0.052}_{-0.052}$	$0.310^{+0.029}_{-0.028}$
0.0 – 5.0	$0.341^{+0.026}_{-0.027}$	$0.423^{+0.062}_{-0.062}$	$0.432^{+0.034}_{-0.034}$
5.0 – 10.0	$0.078^{+0.014}_{-0.013}$	$0.113^{+0.031}_{-0.031}$	$0.139^{+0.020}_{-0.020}$
>10.0	$0.084^{+0.013}_{-0.014}$	$0.155^{+0.042}_{-0.041}$	$0.108^{+0.017}_{-0.017}$
OIII Equivalent Width			
<-5.0	$0.073^{+0.013}_{-0.013}$	$0.031^{+0.021}_{-0.021}$	$0.014^{+0.005}_{-0.006}$
-5.0 – 0.0	$0.195^{+0.020}_{-0.020}$	$0.155^{+0.042}_{-0.041}$	$0.102^{+0.017}_{-0.017}$
0.0 – 5.0	$0.525^{+0.033}_{-0.034}$	$0.608^{+0.082}_{-0.083}$	$0.631^{+0.043}_{-0.042}$
5.0 – 10.0	$0.086^{+0.013}_{-0.014}$	$0.093^{+0.031}_{-0.031}$	$0.082^{+0.014}_{-0.015}$
>10.0	$0.115^{+0.015}_{-0.016}$	$0.113^{+0.031}_{-0.031}$	$0.168^{+0.023}_{-0.022}$
OII Equivalent Width			
<-5.0	$0.162^{+0.023}_{-0.022}$	$0.107^{+0.036}_{-0.036}$	$0.143^{+0.027}_{-0.027}$
-5.0 – 0.0	$0.103^{+0.017}_{-0.017}$	$0.036^{+0.018}_{-0.018}$	$0.062^{+0.017}_{-0.018}$
0.0 – 5.0	$0.290^{+0.028}_{-0.028}$	$0.125^{+0.054}_{-0.054}$	$0.179^{+0.027}_{-0.026}$
5.0 – 10.0	$0.114^{+0.017}_{-0.017}$	$0.125^{+0.054}_{-0.054}$	$0.062^{+0.017}_{-0.018}$
>10.0	$0.242^{+0.025}_{-0.025}$	$0.250^{+0.071}_{-0.071}$	$0.272^{+0.035}_{-0.036}$

Type Ia SNe as Cosmological Probes

- Type Ia Supernovae are formed by the detonation of a white dwarf when it reaches the Chandrasekhar mass.

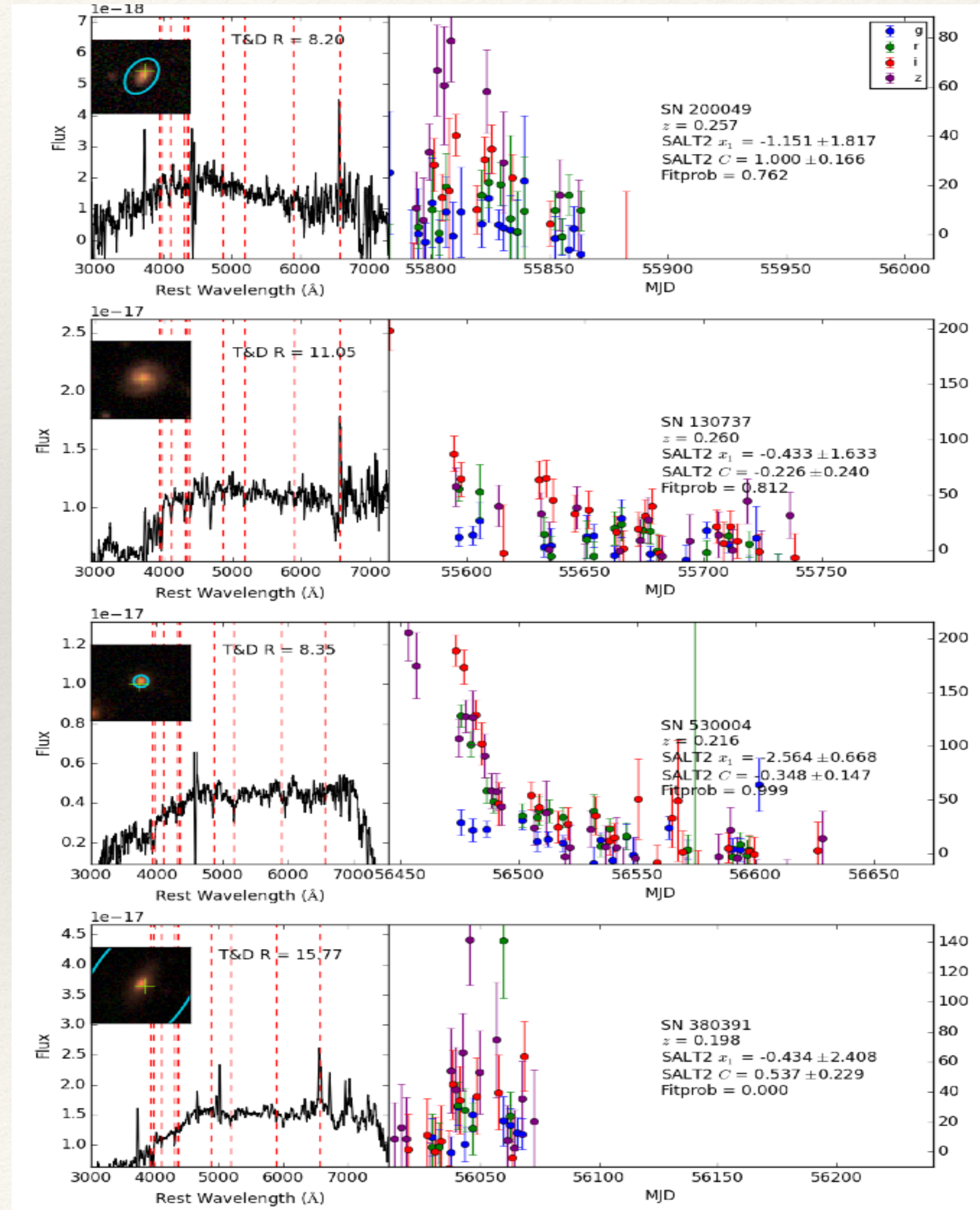
A white dwarf accretes mass from a giant star

Two white dwarfs merge through the emission of gravitational radiation



1. Basic Error Cuts: Shape and Time of Max.

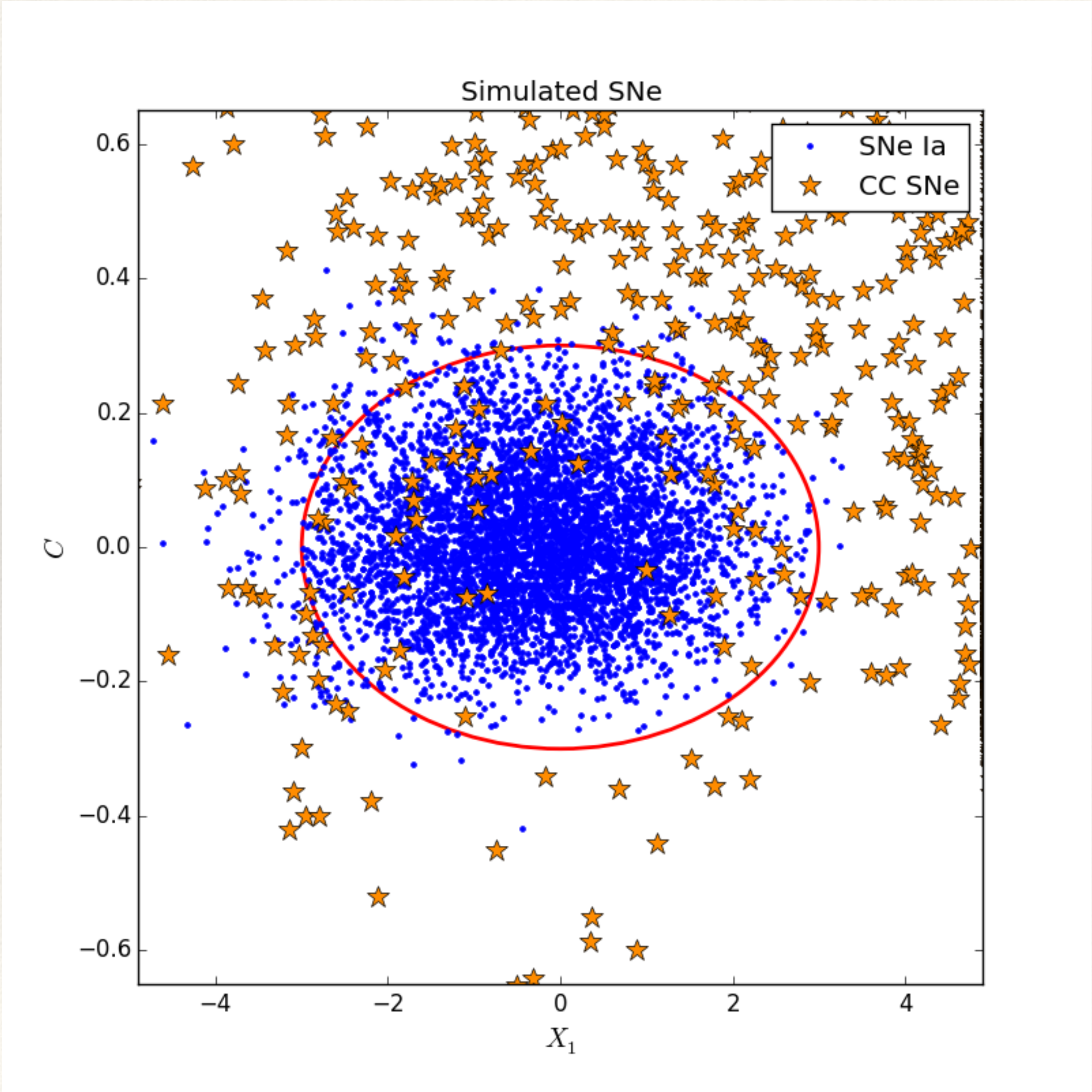
Light curves that have been cut



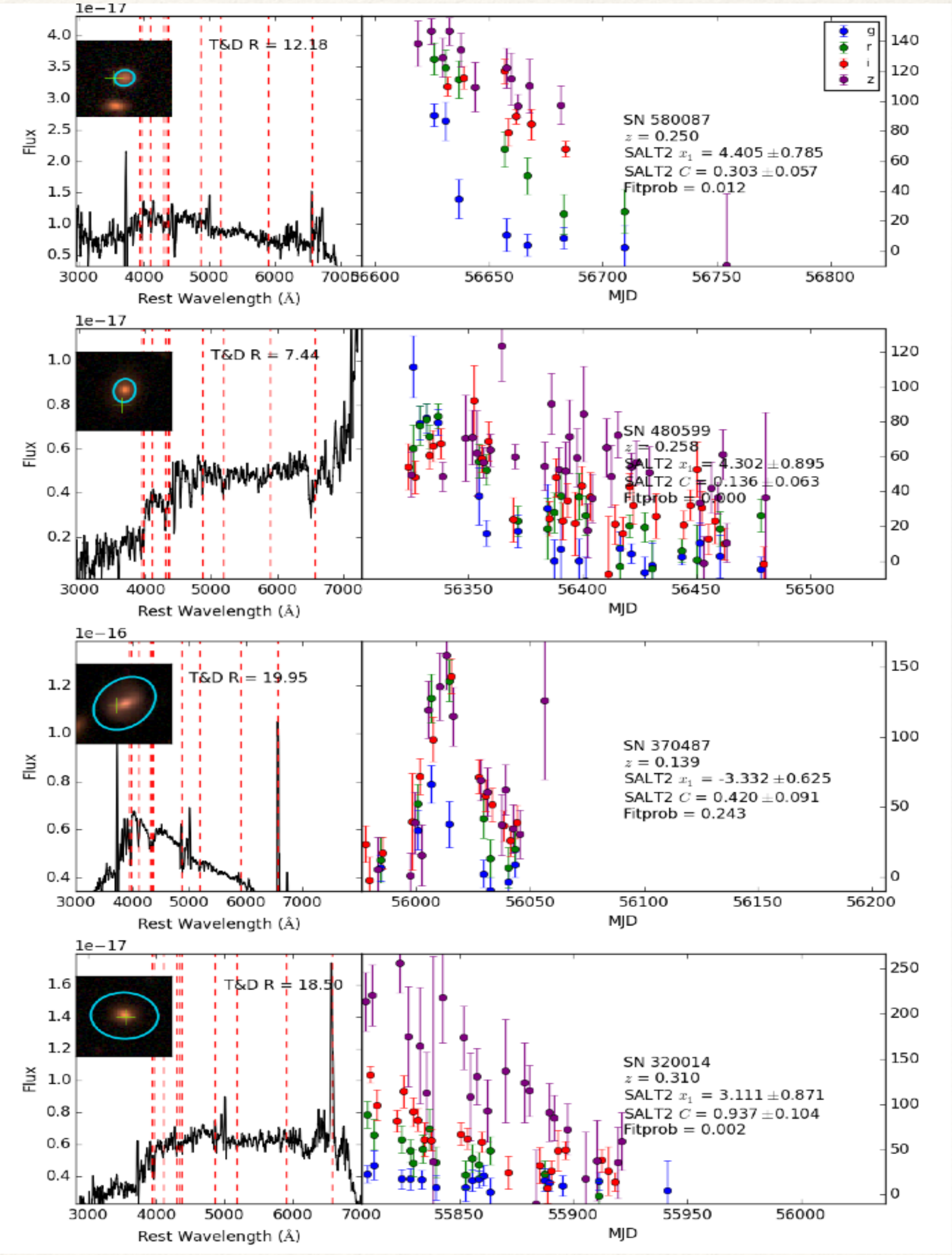
Sample cuts

	All SNe	Rest+14
Total	3135	147
Final	1068	103
− Not Fit by SALT2 (minimal cuts)	753	6
− $\sigma(pkMJD) > 2$	266	1
− $\sigma(X_1) > 1$	529	3
− $\|X_1\| > 3.0$	100	2
− $\|C\| > 0.3$	226	2
− $X_1^2/3^2 + C^2/0.3^2 < 1$	46	1
− Fit prob. < 0.001	118	0

2. Shape, Color, and Fit Prob. Cuts

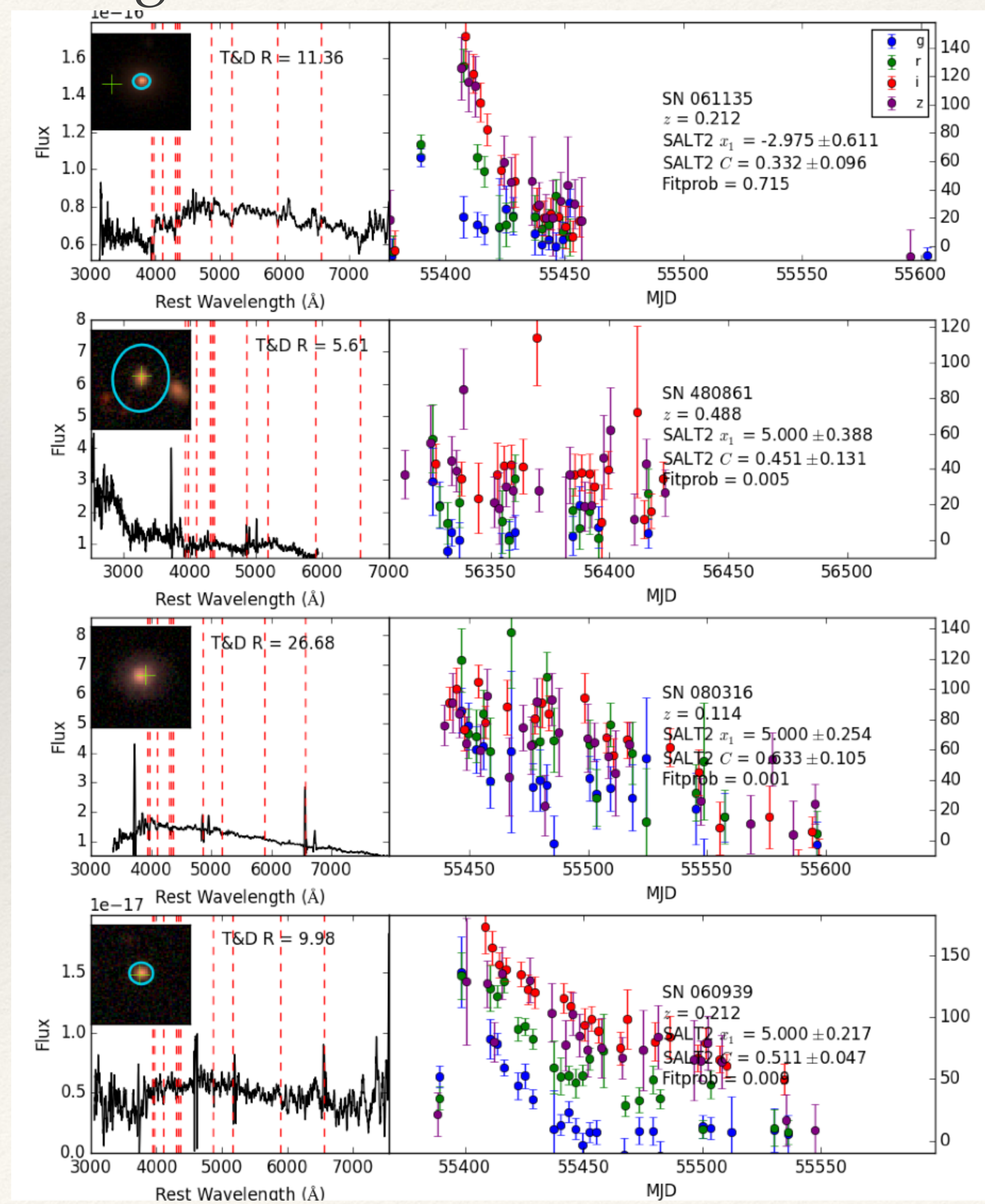


Light curves that have been cut



2. Shape, Color, and Fit Prob. Cuts

Light curves that have been cut



Sample cuts

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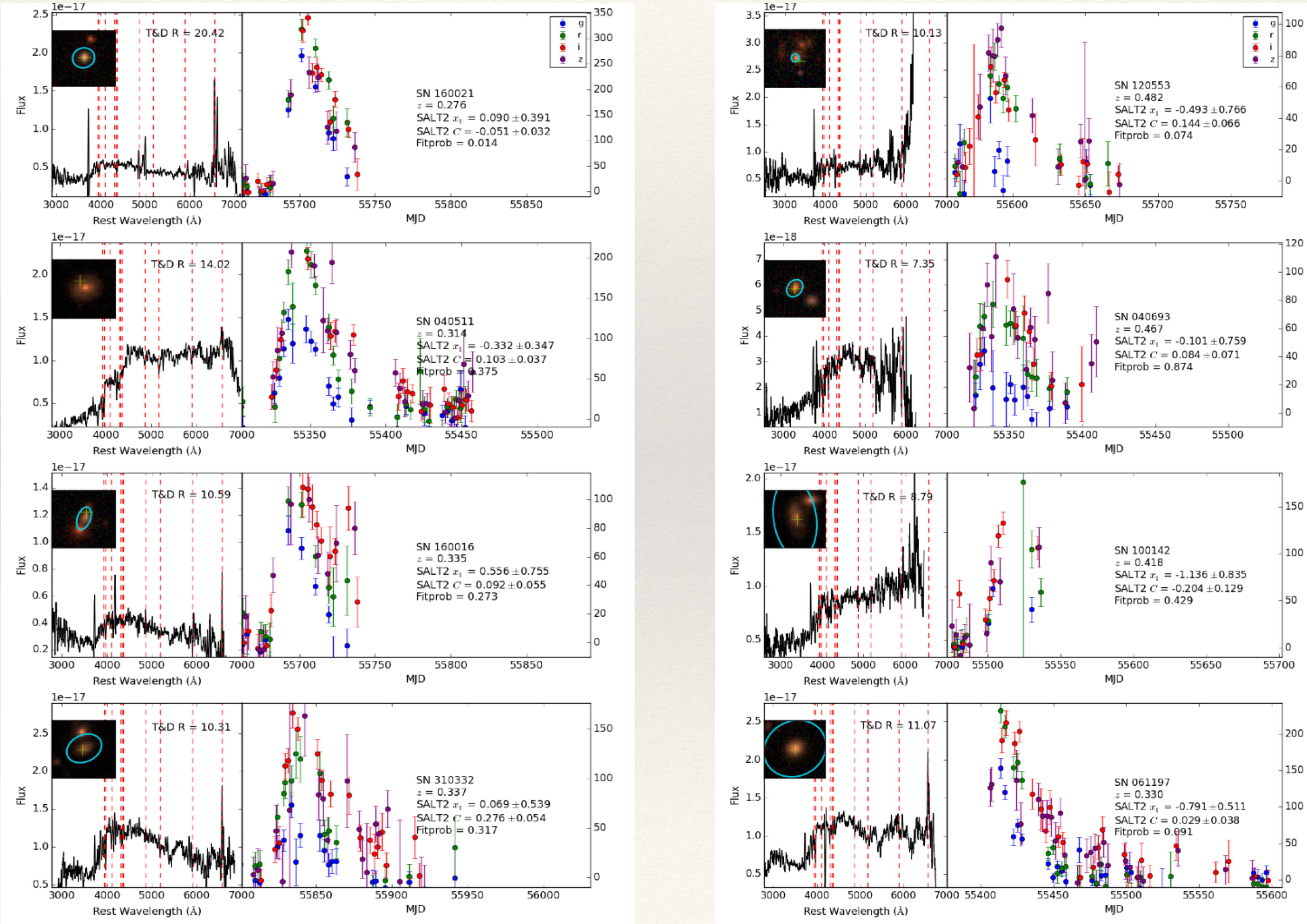
− $\|C\| > 0.3$	226	2
− $X_1^2/3^2 + C^2/0.3^2 < 1$	46	1
− Fit prob. < 0.001	118	0

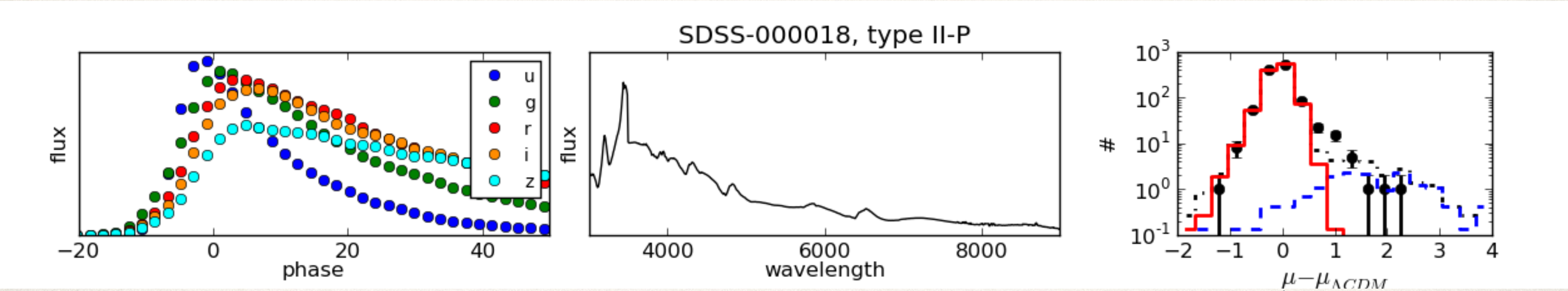
2. Shape, Color, and Fit Prob. Cuts

Light curves that remain after cuts



Simulating the Pan-STARRS Sample

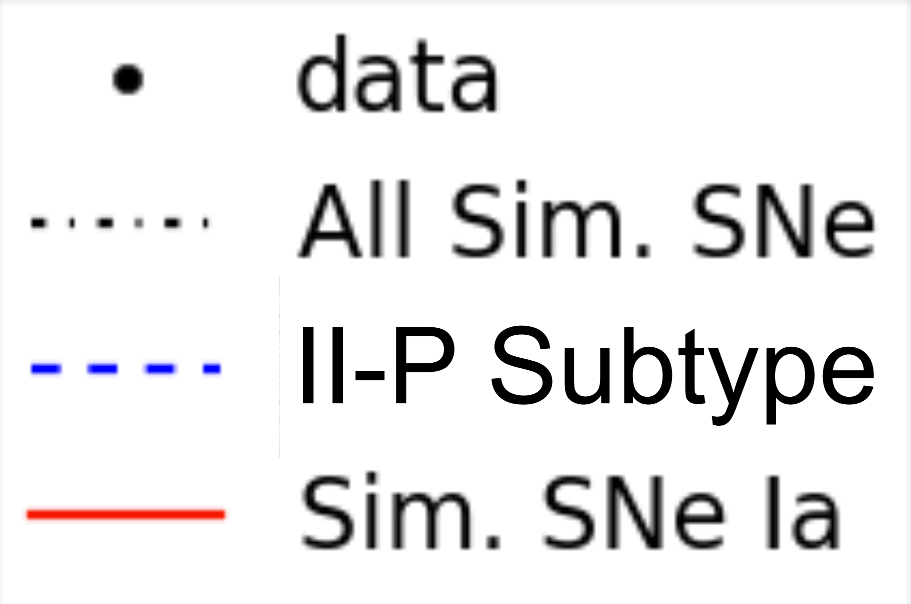
- Which SN types could resolve the data/simulation discrepancy? Let's try a few:



Example LC

Example Spectrum

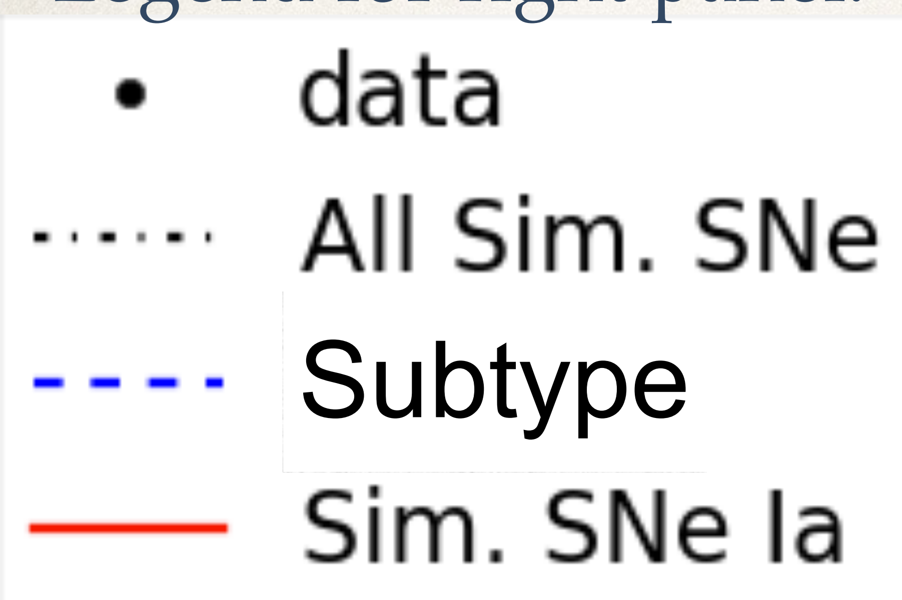
Subtype Distance Modulus (blue)

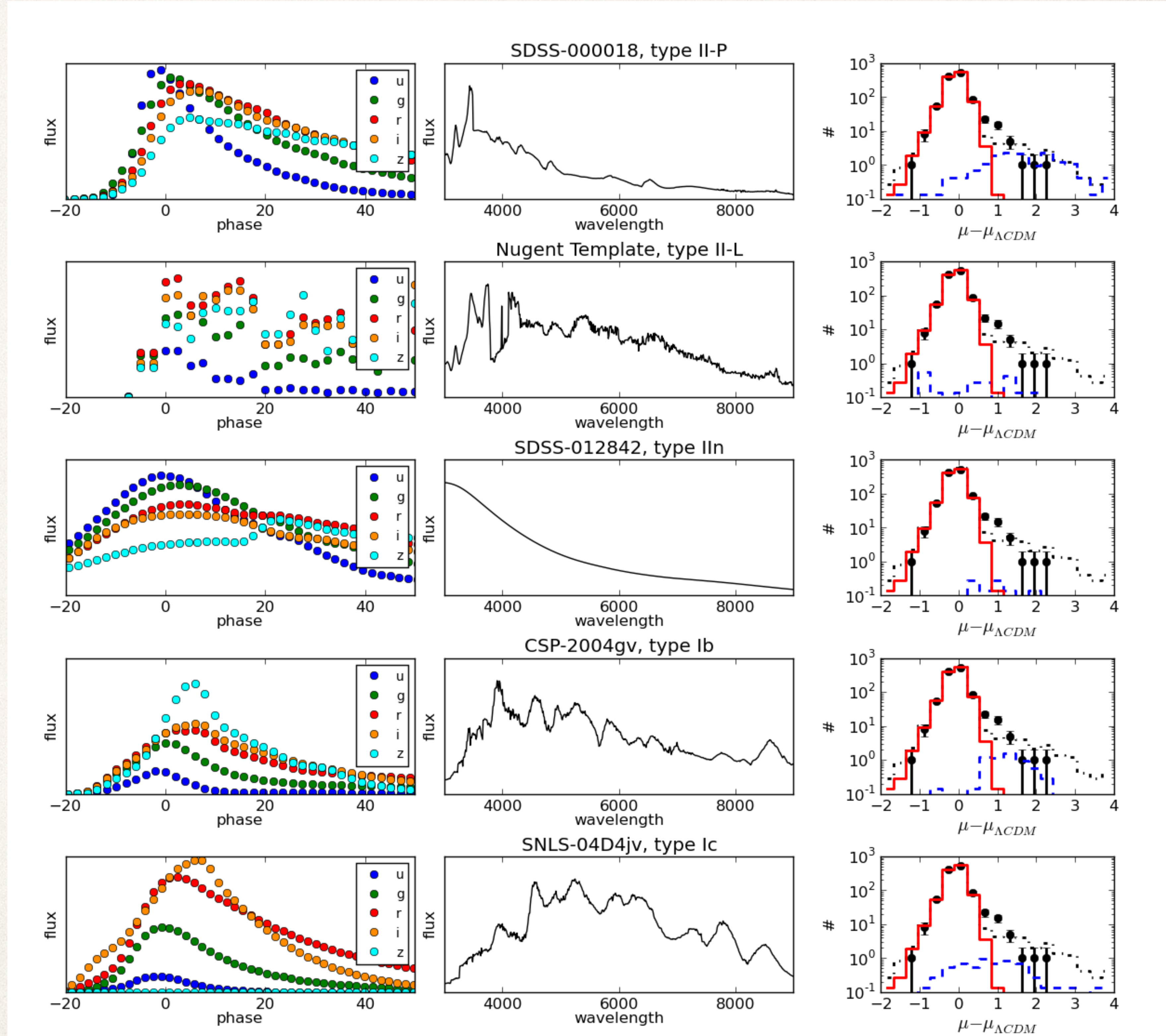


Simulating the Pan-STARRS Sample

- Which SN types could resolve the data/simulation discrepancy?

Legend for right panel:



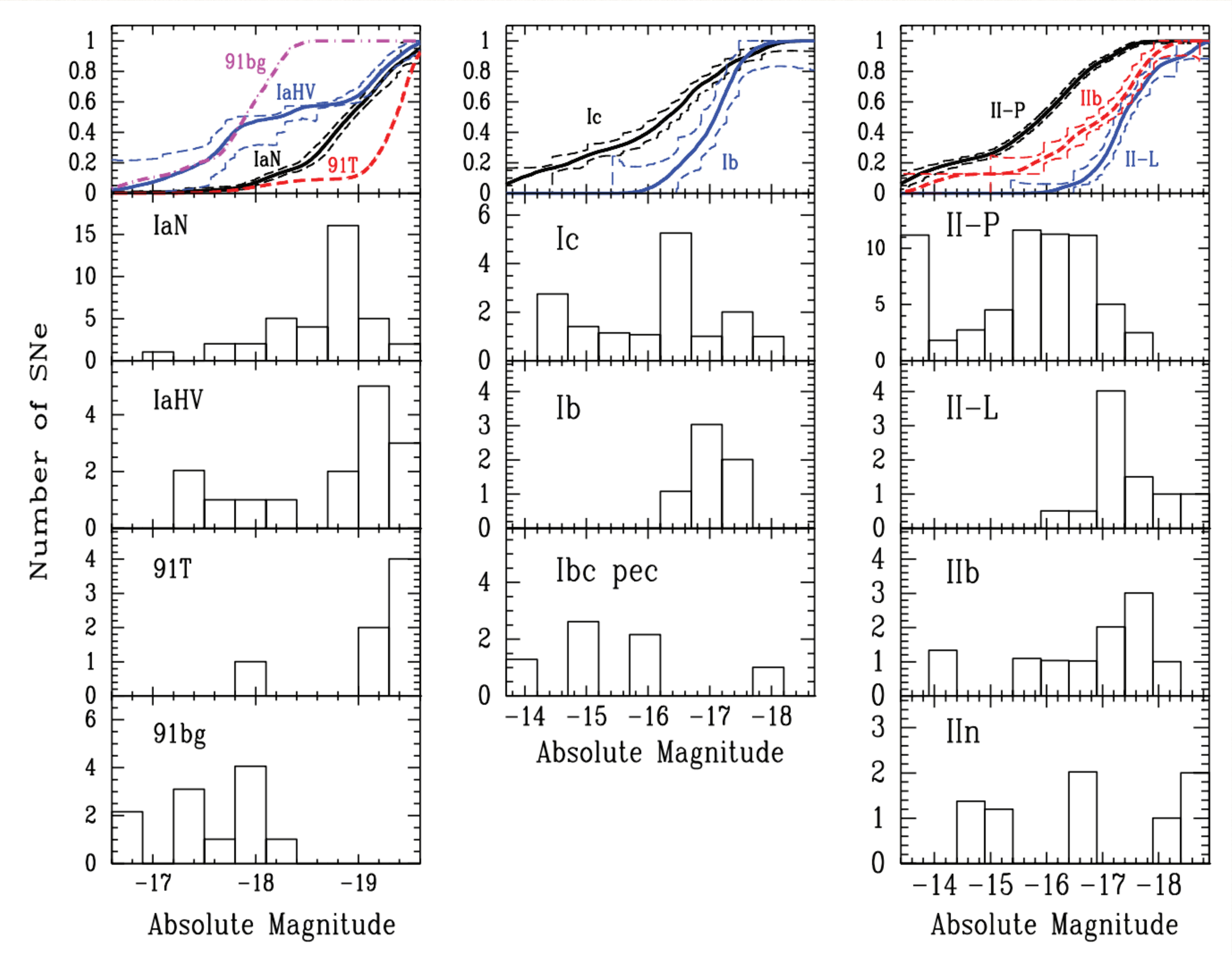


Example LC

Example Spectrum

Subtype Distance Modulus (blue)

Li et al. (2011)

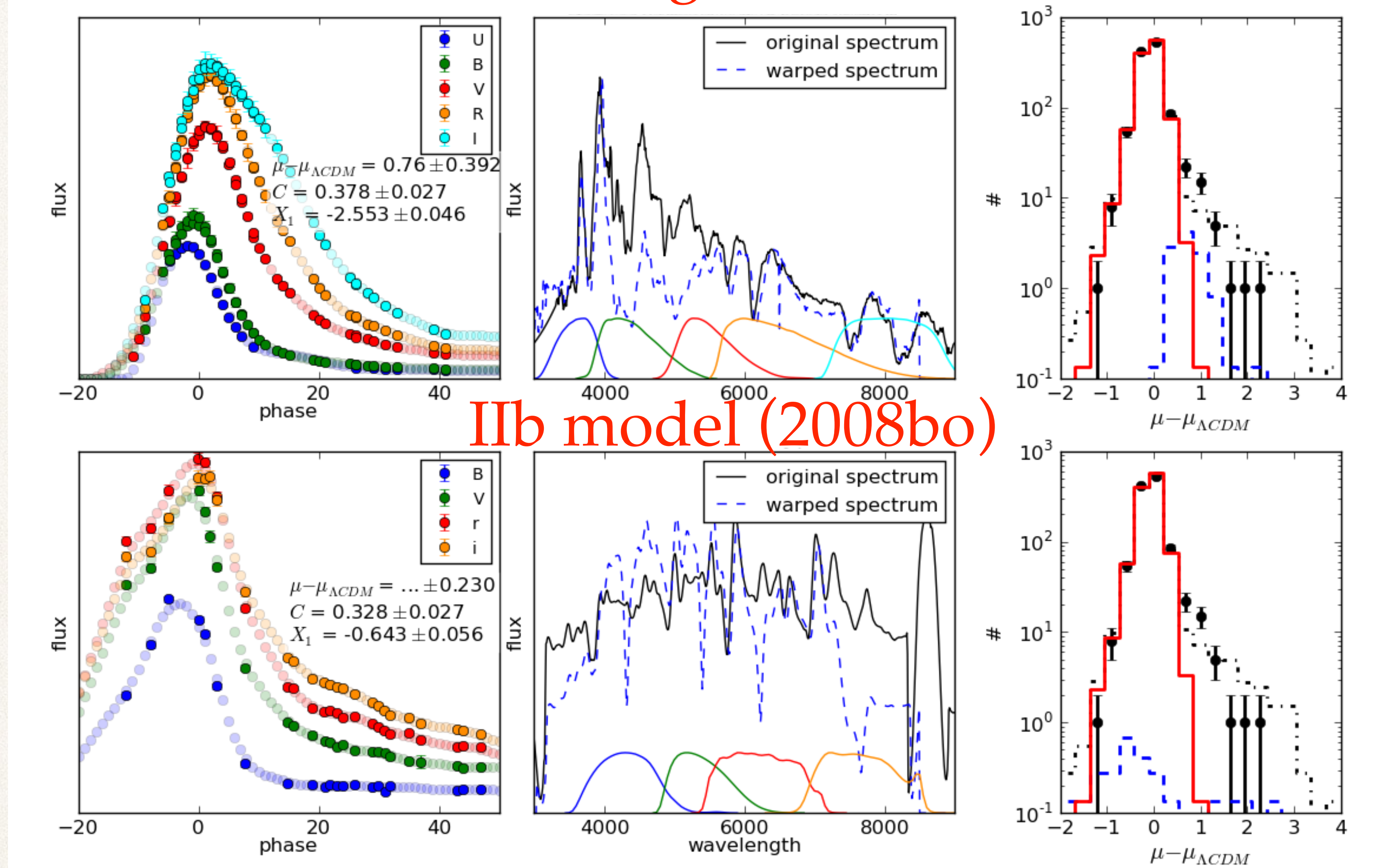


91bg
IaHV
IaN
91T
Ic
Ib
II-P
IIb
II-L
Ibc pec
IIn
Number of SNe
-17
-18
-19
-14
-15
-16
Absolute Magnitude

Simulating the Pan-STARRS Sample

- What about SN types that aren't included in SNANA:
  - Iax - likely too faint, fast decliners
  - SLSNe - rare, bright, and with faint hosts
  - Ibc-pec - likely too faint as well
  - Ia-91T - already included in SALT2 model
  - IIb?
  - Ia-91bg?
- We need more spectral templates!

91bg model



IIb model (2008bo)

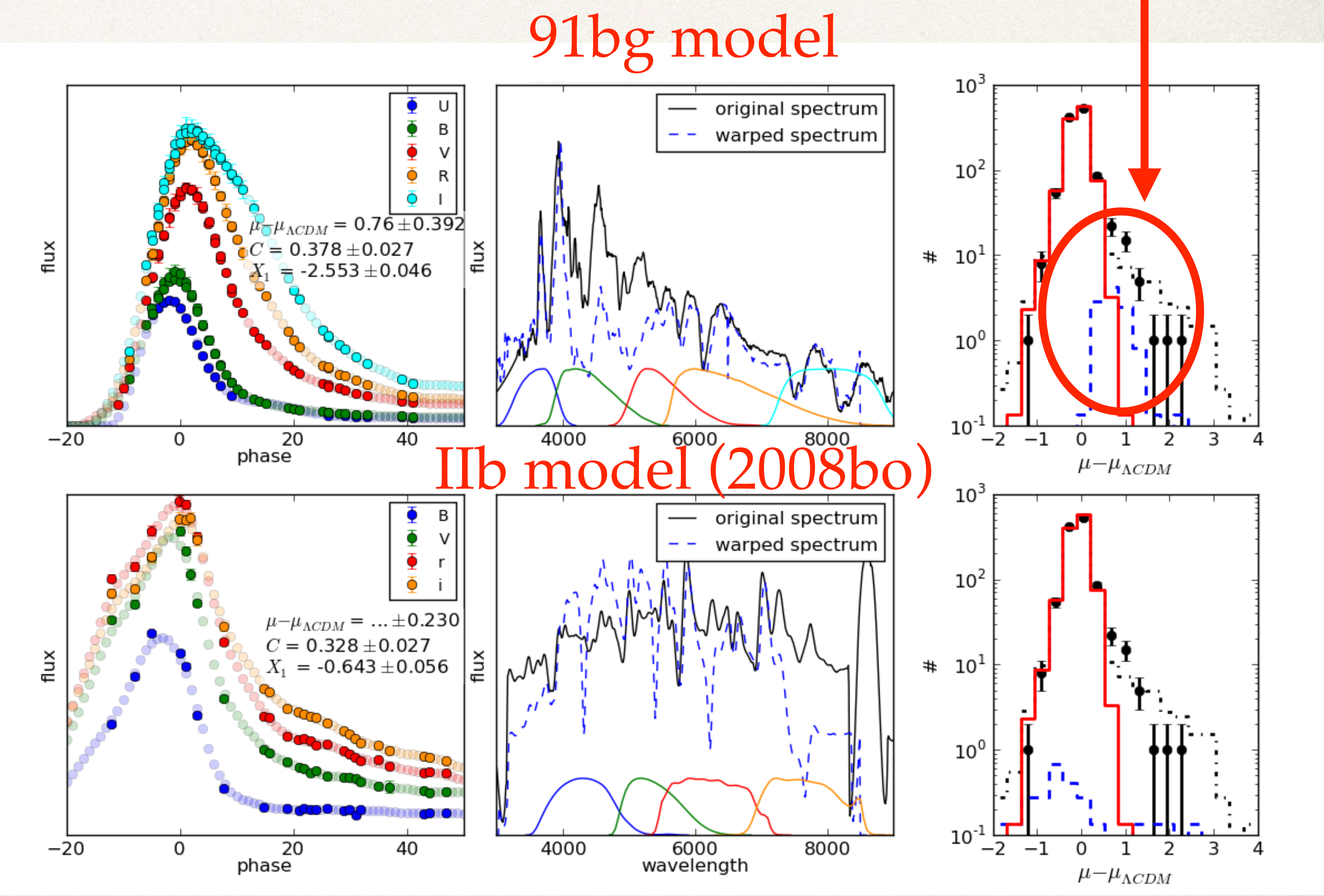
Ia-91bg and IIb models we've added to SNANA

SN 2008bo spectrum from Modjaz+14

Simulating the Pan-STARRS Sample

- What about SN types that aren't included in SNANA:
  - Iax - likely too faint, fast decliners
  - SLSNe - rare, bright, and with faint hosts
  - Ibc-pec - likely too faint as well
  - Ia-91T - already included in SALT2 model
  - IIb?
  - Ia-91bg?
- We need more spectral templates!

These could be important?



Ia-91bg and IIb models we've added to SNANA

SN 2008bo spectrum from Modjaz+14