A Step-by-Step Guide to Measure Cosmological Parameters from DES SNIa

Dan Scolnic

1 Supernova per galaxy every 100 Years

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What we know about SNIa:

-Carbon-Oxygen white dwarf accretes matter from companion, reaches near Chandrasekhar limit, explodes

-Type Ia SNe luminosities can be standardized to ~10% by correct brightness for decline-rate and color

-1 SN per galaxy per century

-Enough to make pretty movies..

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What we know about SNIa:

-Carbon-Oxygen white dwarf accretes matter from companion, reaches near Chandrasekhar limit, explodes

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What we don't know about SNIa:

-What is companion star to white dwarf (double degenerate or single degenerate)?

-What's the remaining 10% due to?

-Why is there a correlation between galaxy type and luminosity?

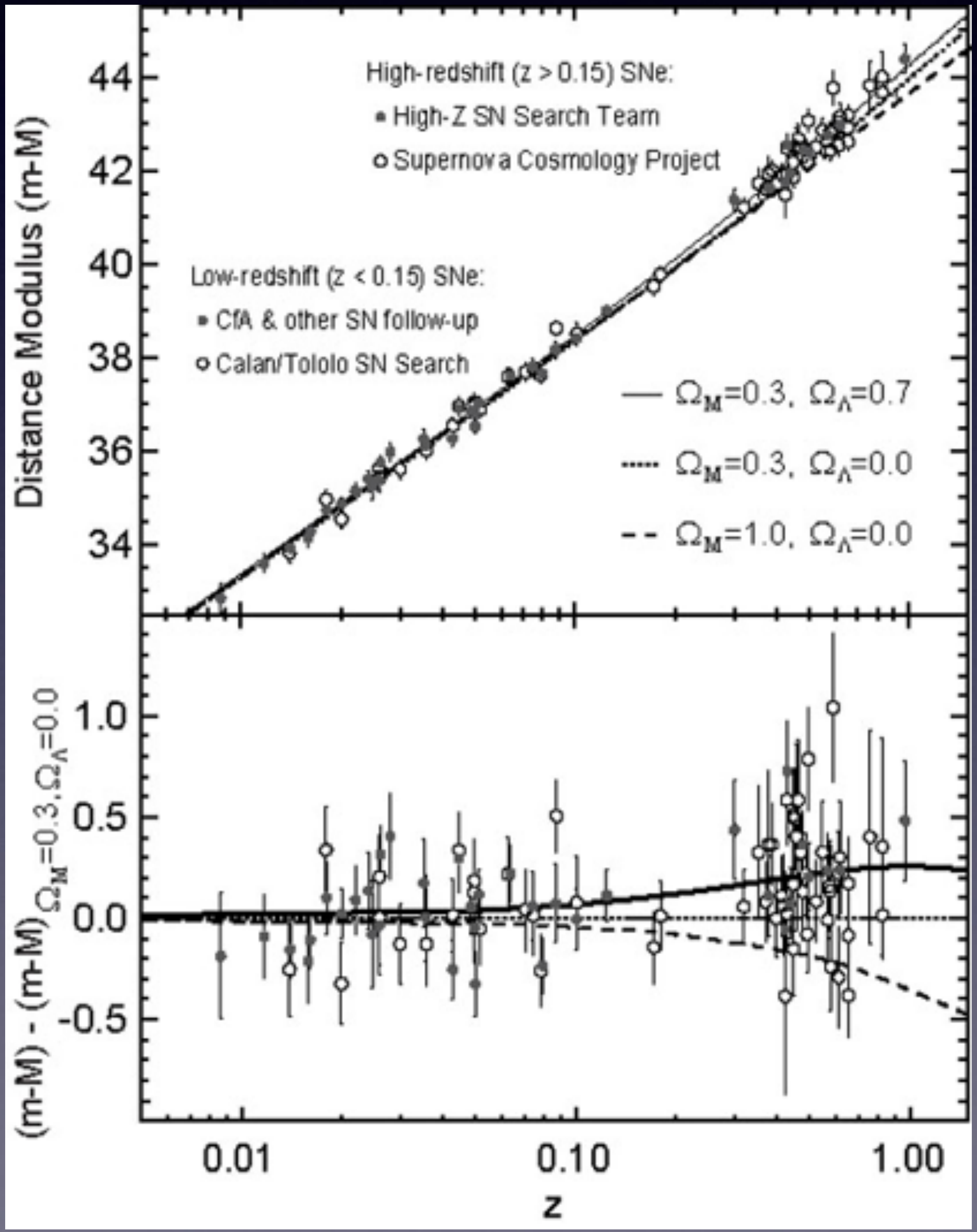
How measurements of SNIa are used

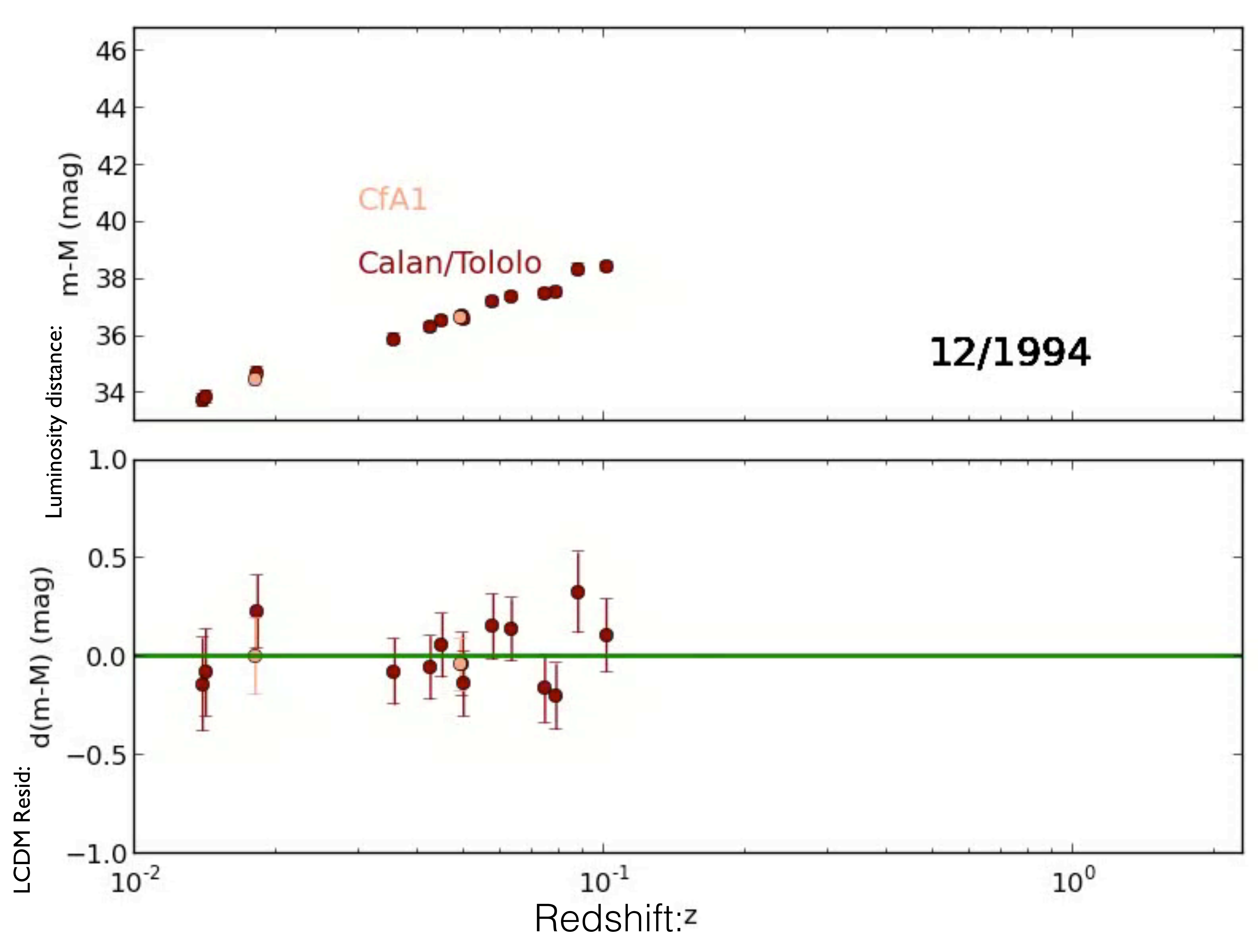
—SNIa intrinsic luminosity is known (to 10%) and apparent luminosity can be measured

—Ratio of two provides the luminosity-distance (d_L) of the supernova

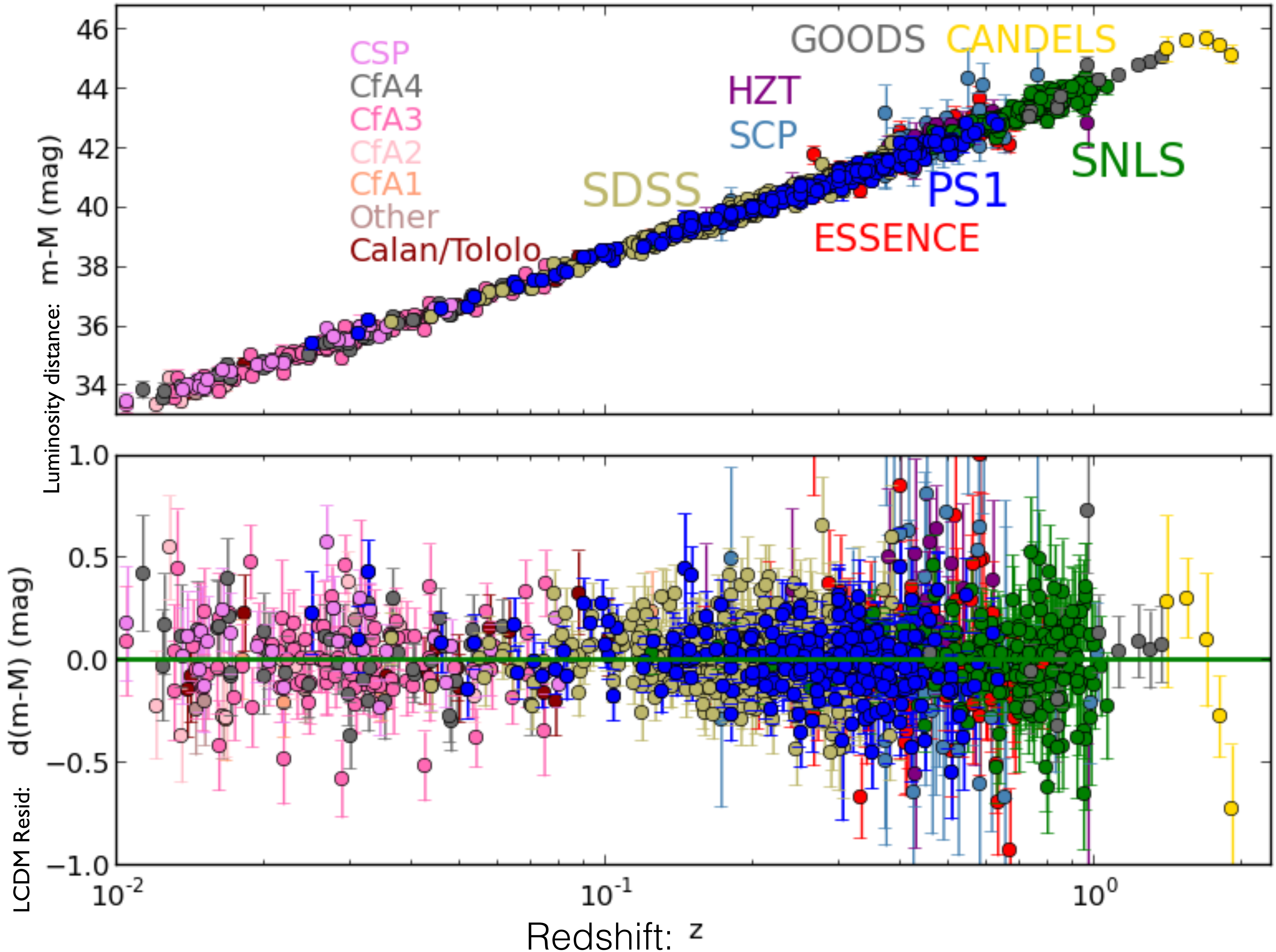
—Redshift measured independently from spectroscopy

—Each SNIa can be used for a single d_L (z) on a Hubble diagram

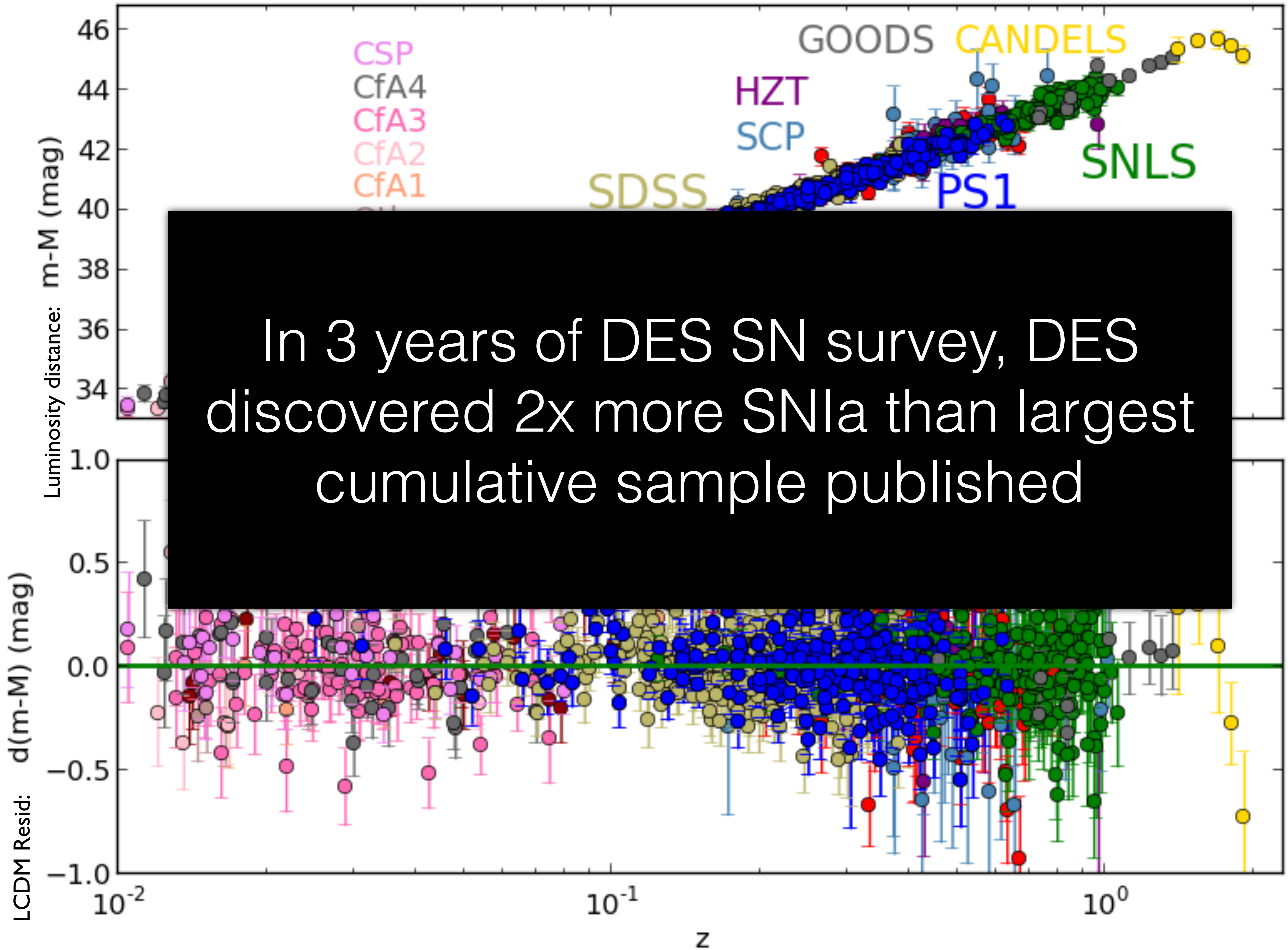




Luminosity distance:
m-M (mag)
CfA1
Calan/Tololo
12/1994
LCDM Resid:
d(m-M) (mag)
Redshift:z



CSP
CfA4
CfA3
CfA2
CfA1
Other
Calan/Tololo
SDSS
HZT
SCP
GOODS
CANDELS
SNLS
PS1
ESSENCE
Luminosity distance: m-M (mag)
LCDM Resid: d(m-M) (mag)
Redshift: z
46
44
42
40
38
36
34
1.0
0.5
0.0
−0.5
−1.0
10^{-2}
10^{-1}
10^{0}

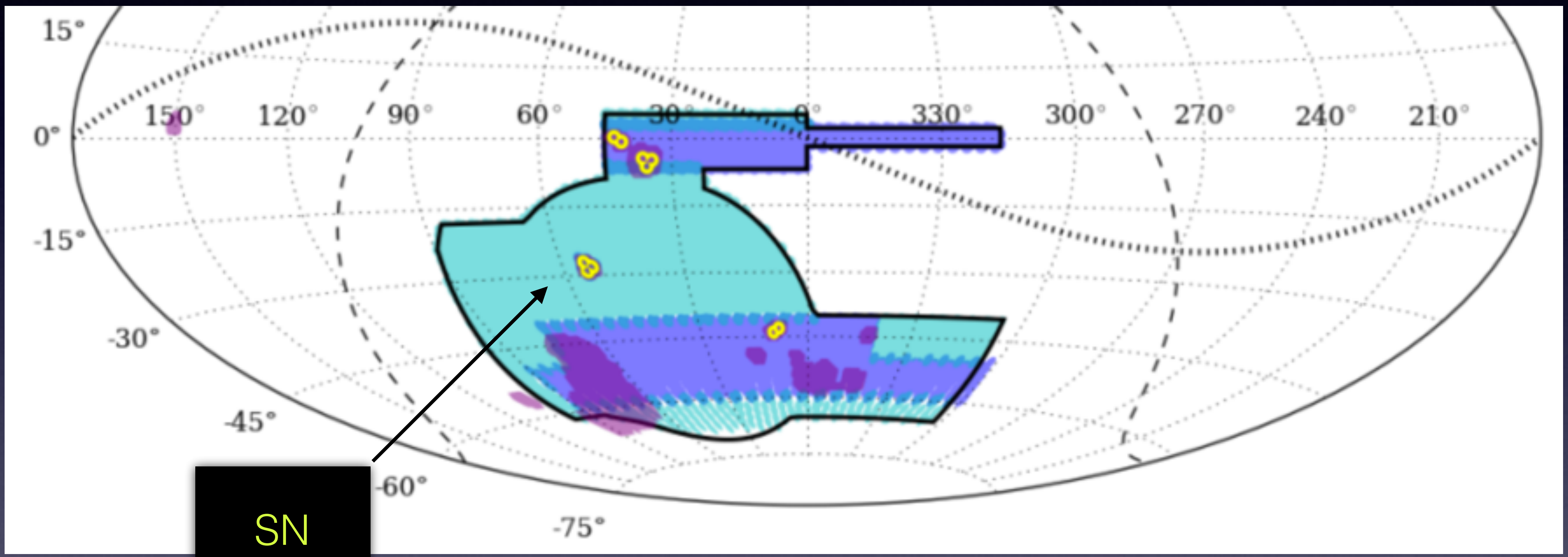


In 3 years of DES SN survey, DES discovered 2x more SNIa than largest cumulative sample published

This is the past/current/future status of SNIa surveys

	Past/Current	Current/Future	More Future
Low-z: z<0.1	CfA1-4, SNF, CSP	CSP,PTF, Foundation	LSST?
Mid-z: 0.1<z<1.0	SDSS,SNLS, ESSENCE	PS1,DES	LSST
High-z: 1.0<z	HST	HST-CANDELs/ Frontier	Euclid/ WFIRST
#s:	~1000	~10,000	>100,000

The basics of the DES SN survey



SN Fields

- 5 observing seasons of 5 months, ~7 day cadence.
- 3 sq. degree FOV, 2.7 sq. degree active
- 8 shallow fields (r~23.5 mag) 2 deep fields (r~24.5 mag)
- Red sensitive CCDs to probe higher redshifts
- OzDES follow-up with AAT for host galaxy redshifts
- SN fields overlap with existing deep imaging

SN Analysis Basics

- Discovery
- Follow-up
- Photometry
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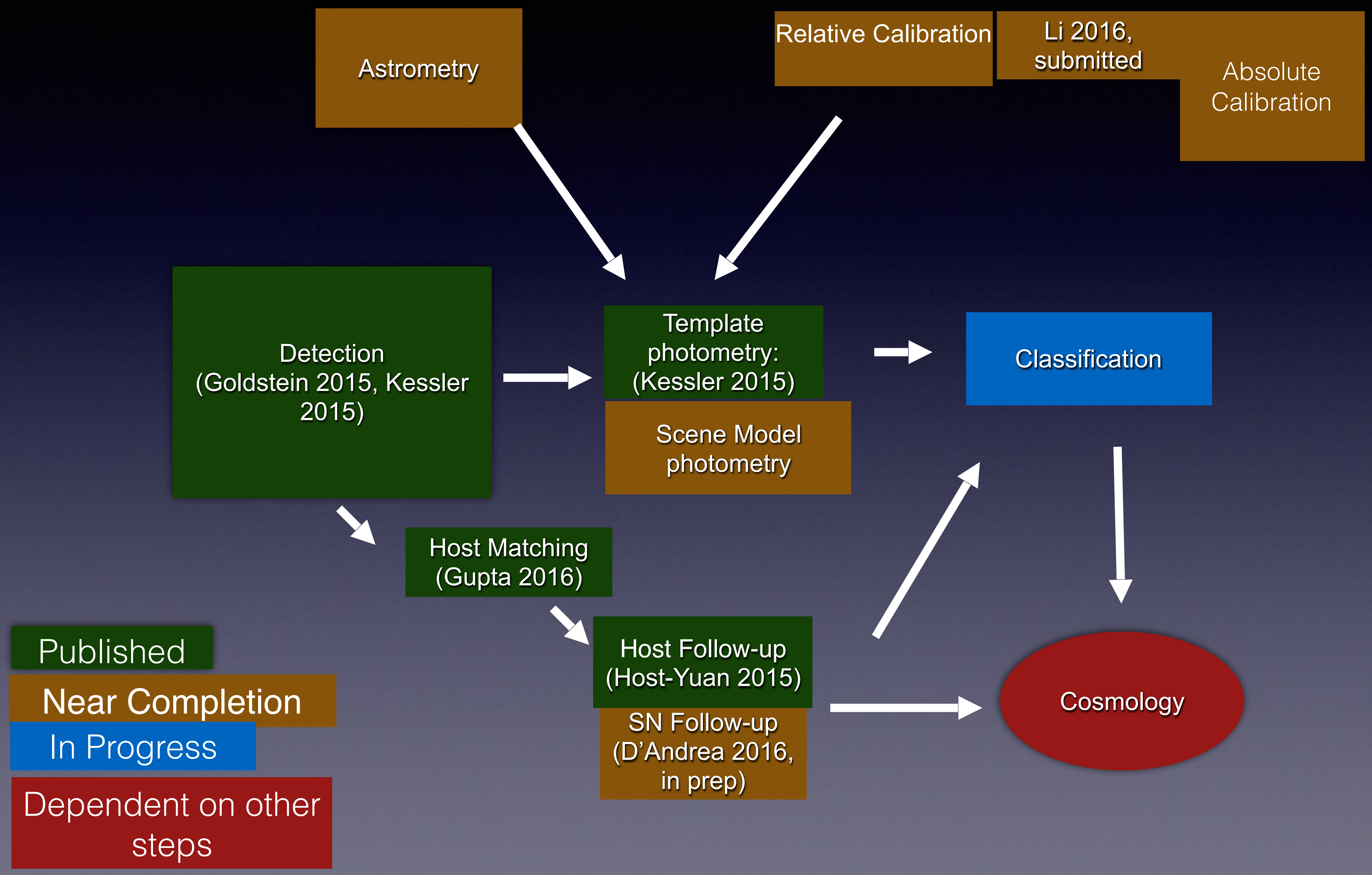
- Light-curve fitting
- Systematics
- Classification
- Cosmology

Roadmap to Cosmology



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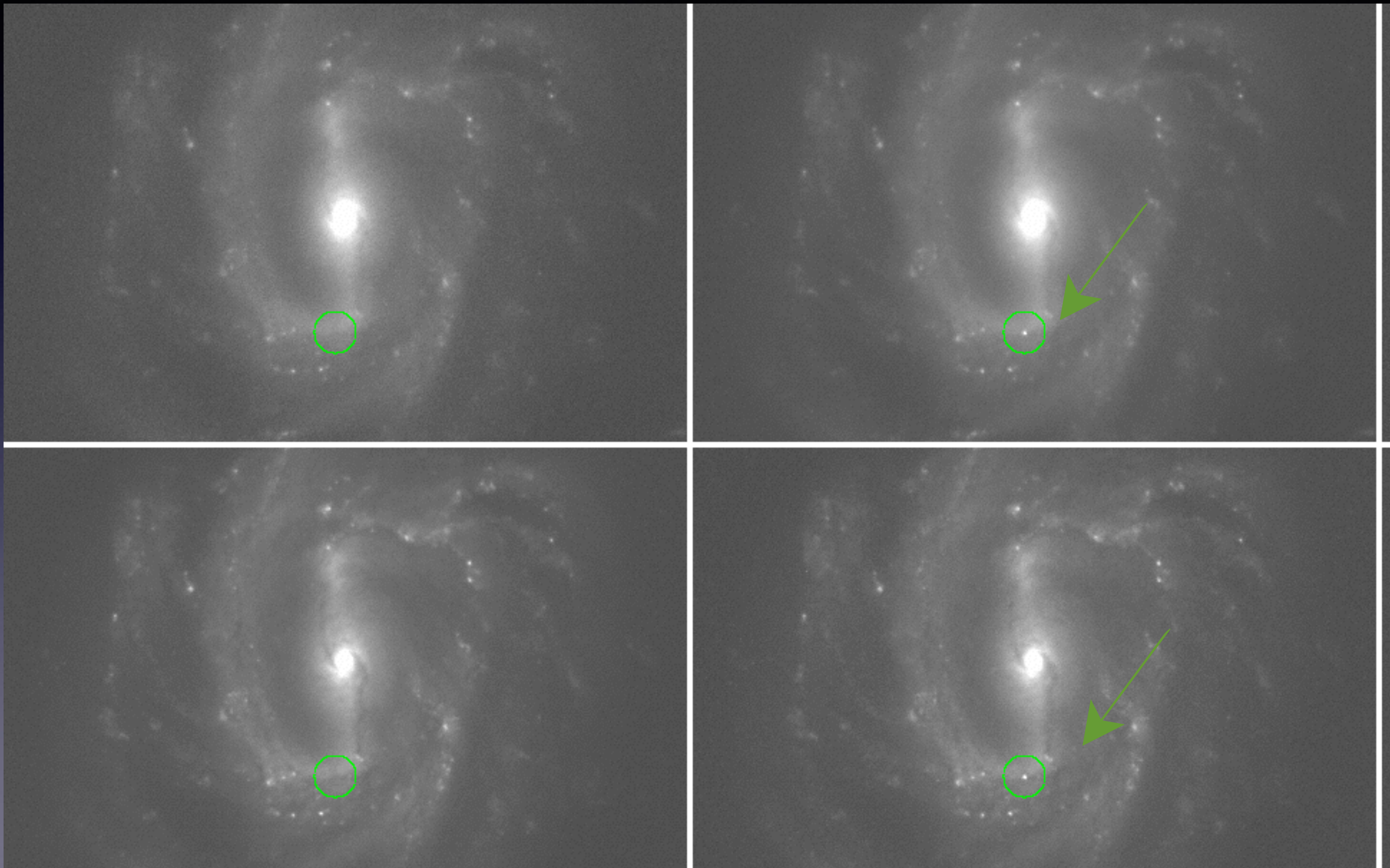
DES is considered a rolling survey that with repeated observations and high depth, finds hundreds of SN a year

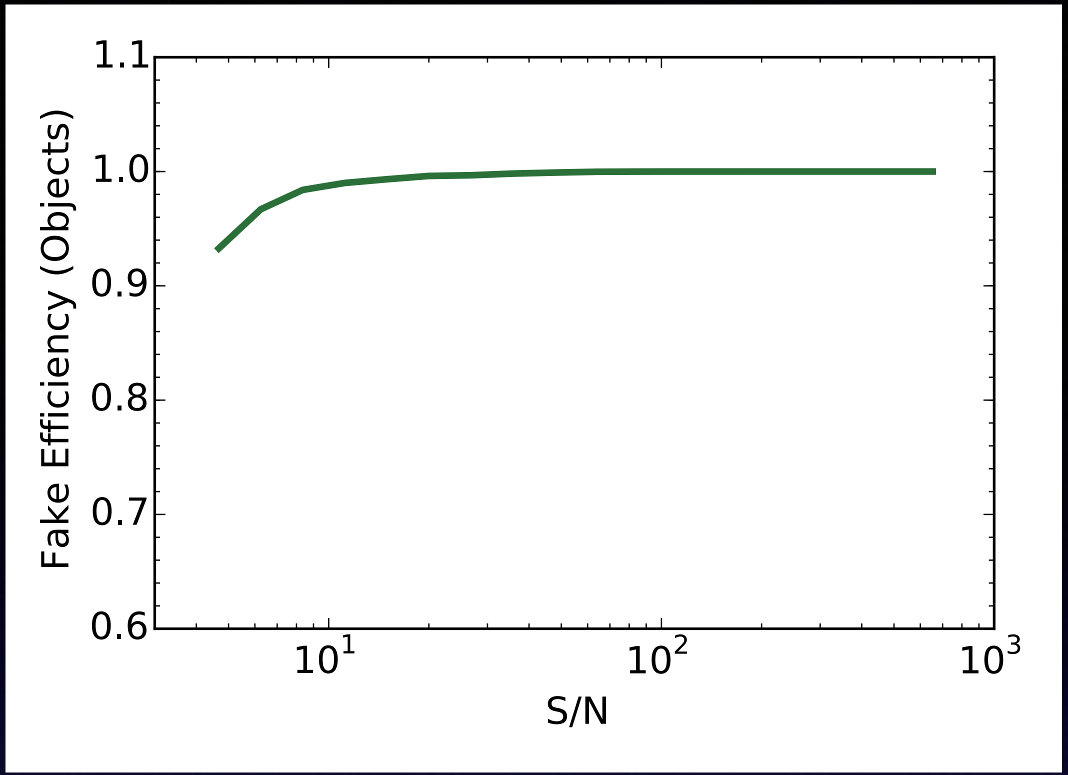
Supernovae are found by subtracting observations separated by time

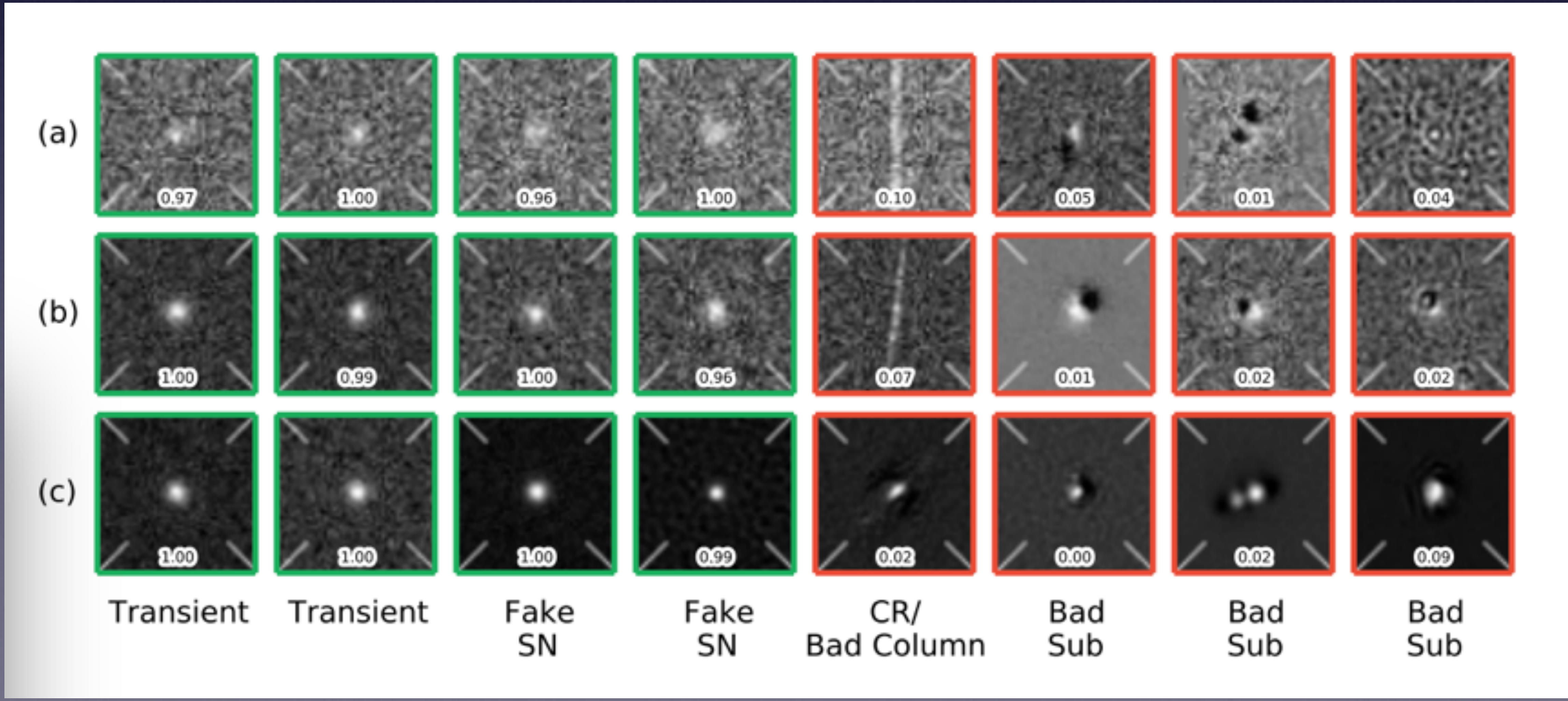


Automated Scanning
(Goldstein et al 2015)

-Removes factor of 13 of junk, only 1% lost

-Efficiency monitored with extensive `fake' pipeline





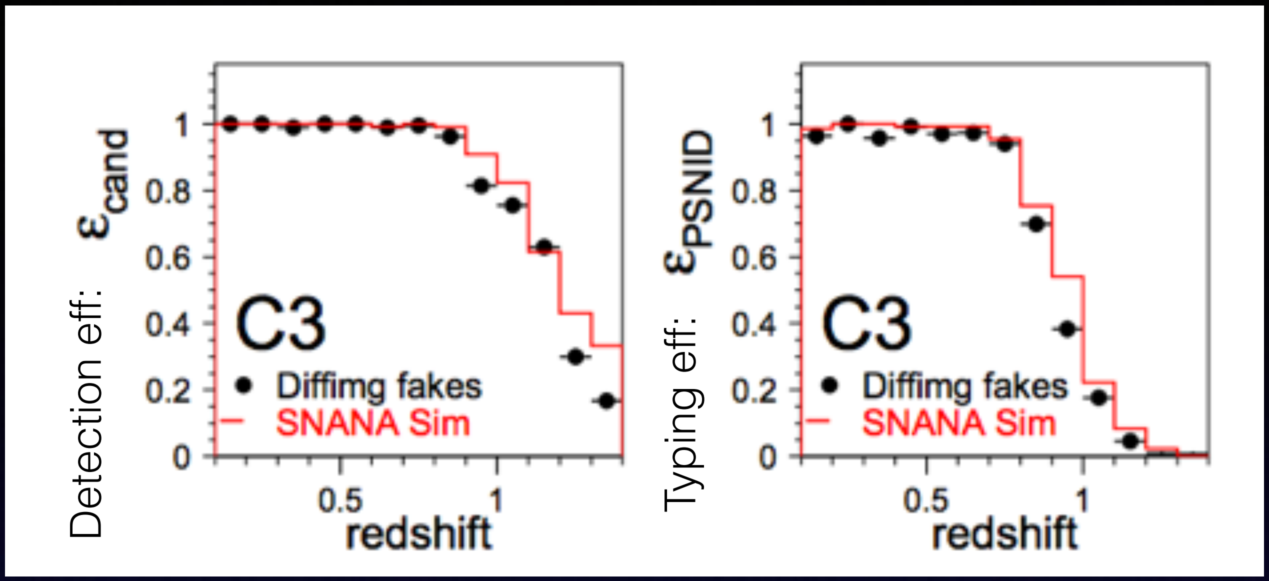
Difference Imaging Pipeline

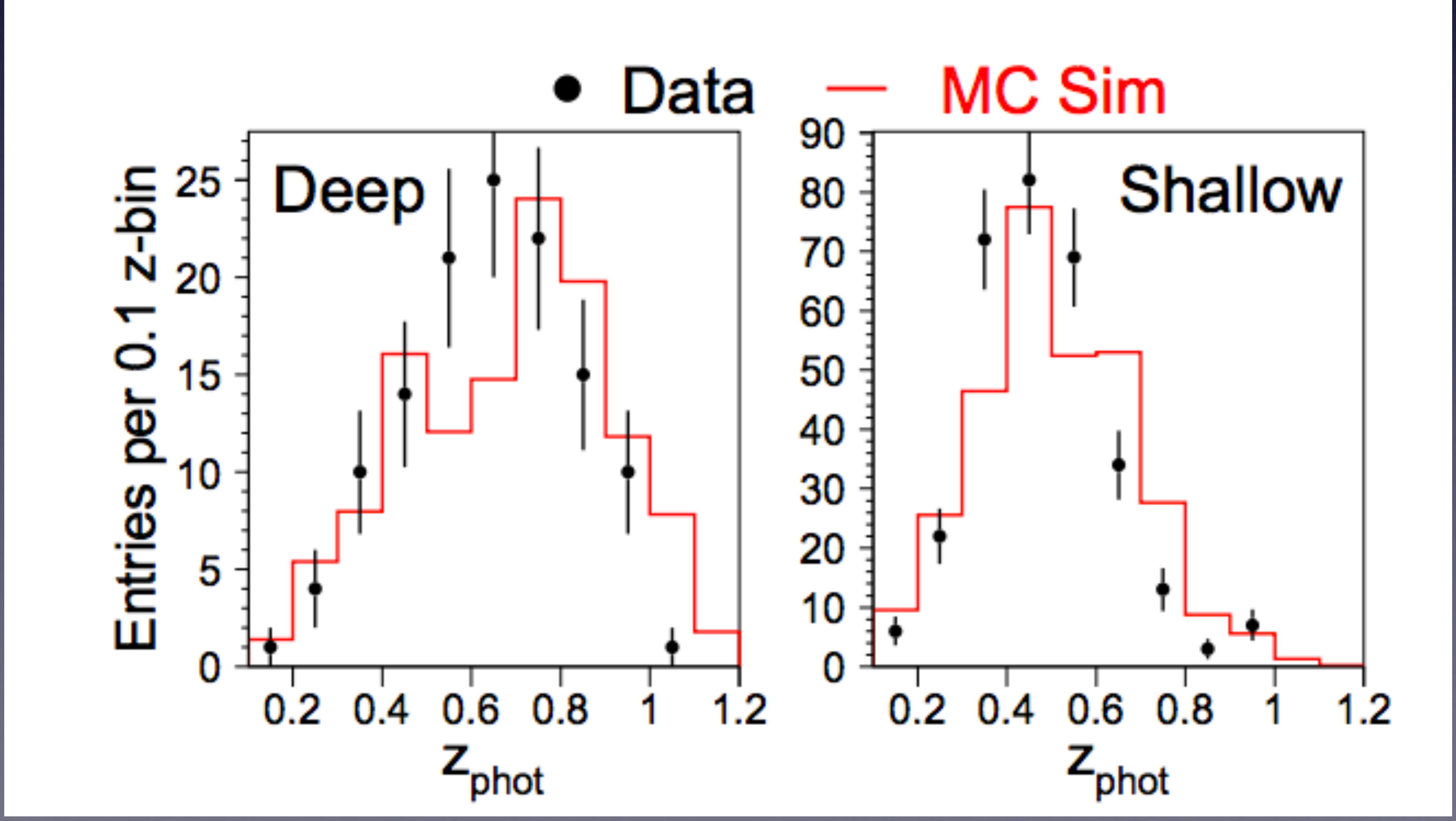
(Kessler et al 2015)

-Injects full fake light curves through entire discovery/photometry pipeline

-Simulations are excellent match to data

-Can trace all the way to distance measurements, cosmology biases





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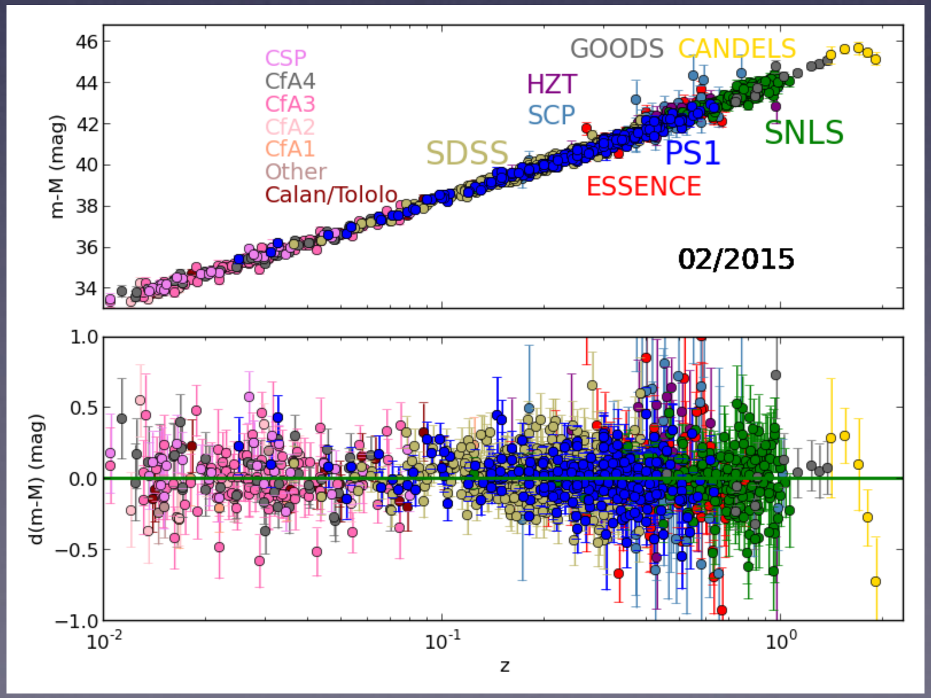
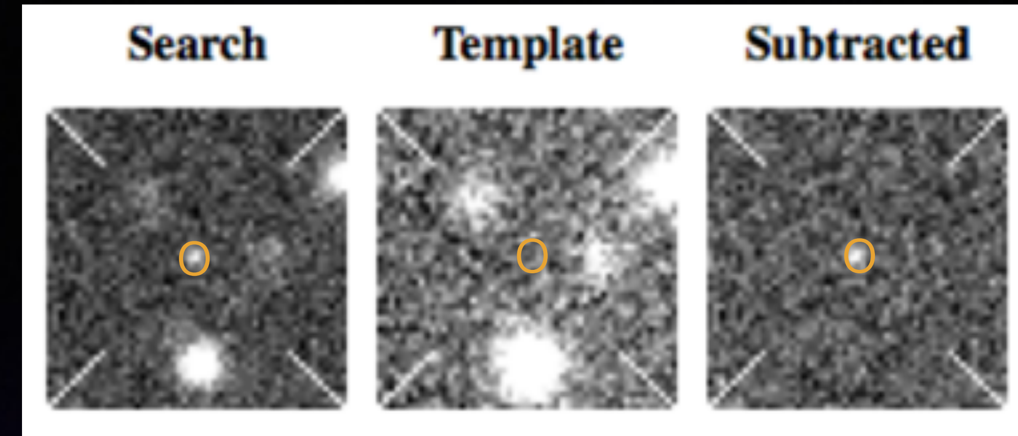
For DES, follow-up is necessarily primarily to get a redshift for the SN. The light curve gives a distance (y-axis on Hubble diagram), the redshift is the x-axis point.



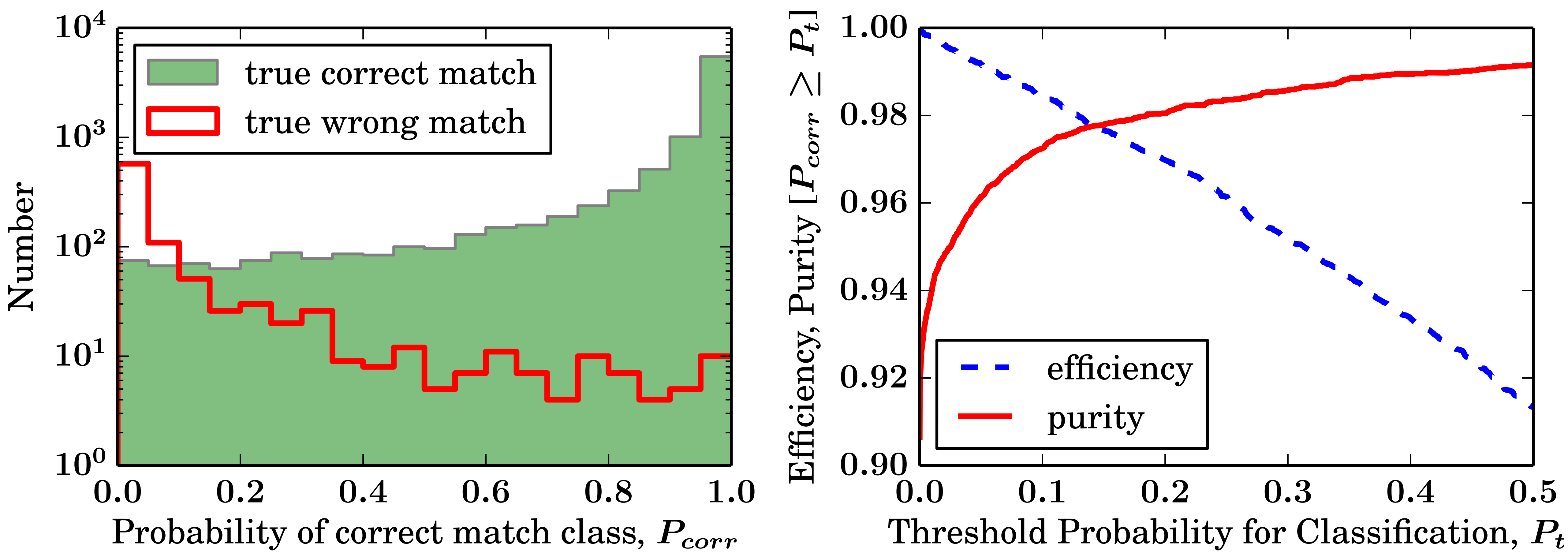
Host Galaxy Matching

(Gupta et al. 2016)

-Host galaxy matching critical for galaxy follow-up
-Inaccurate matching leads to systematic biases
-New methods reach 98% purity (old - 92%)



Preliminary:



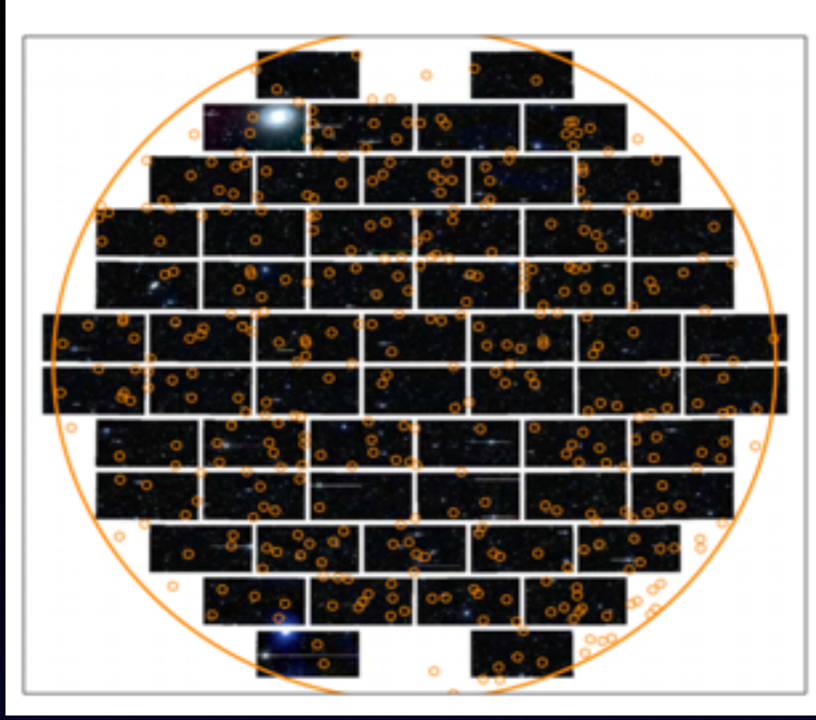
Host Galaxy Follow-up

(Yuan et al 2015)

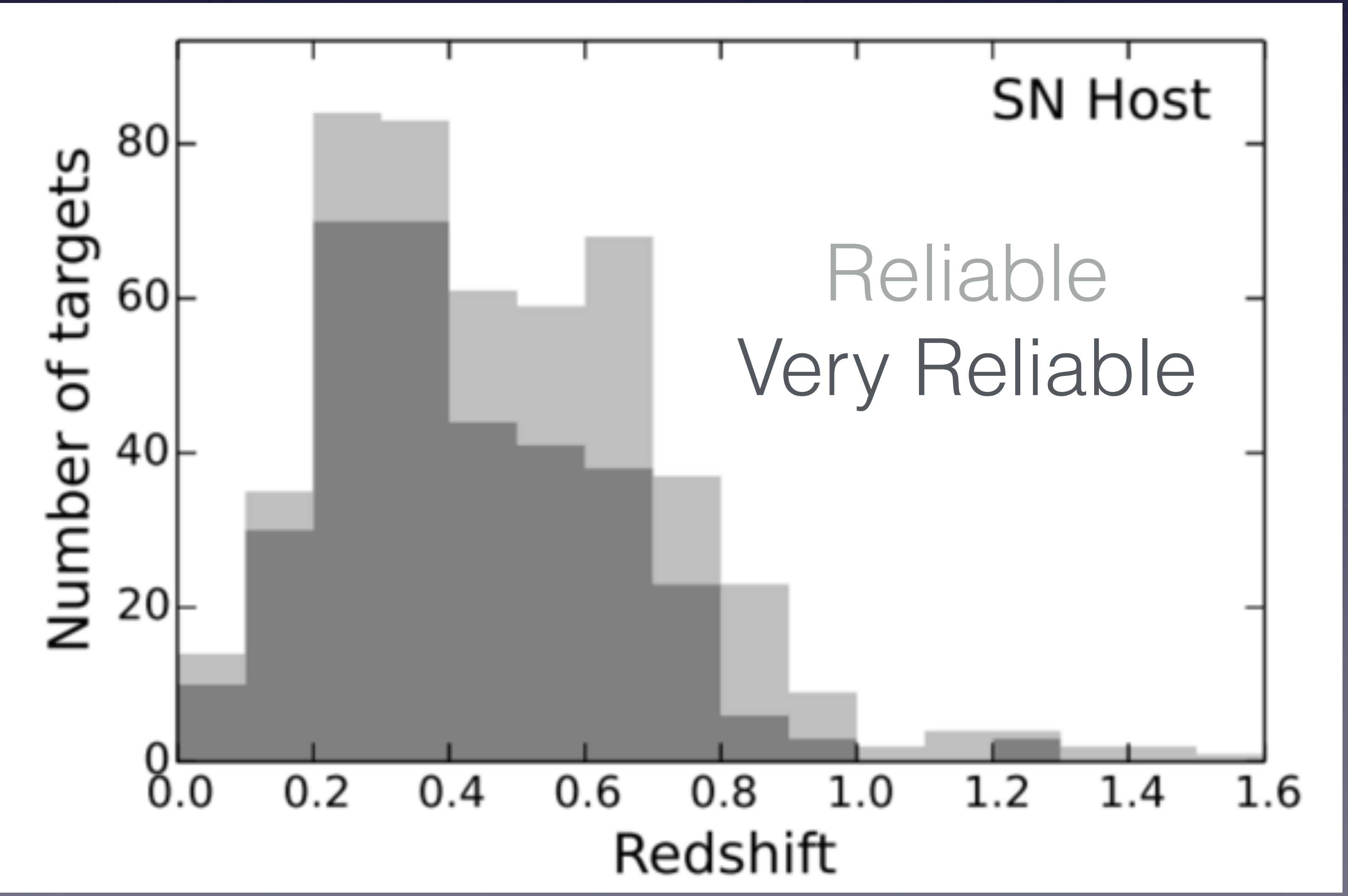
-AAT field-of-view same as DECam field-of-view

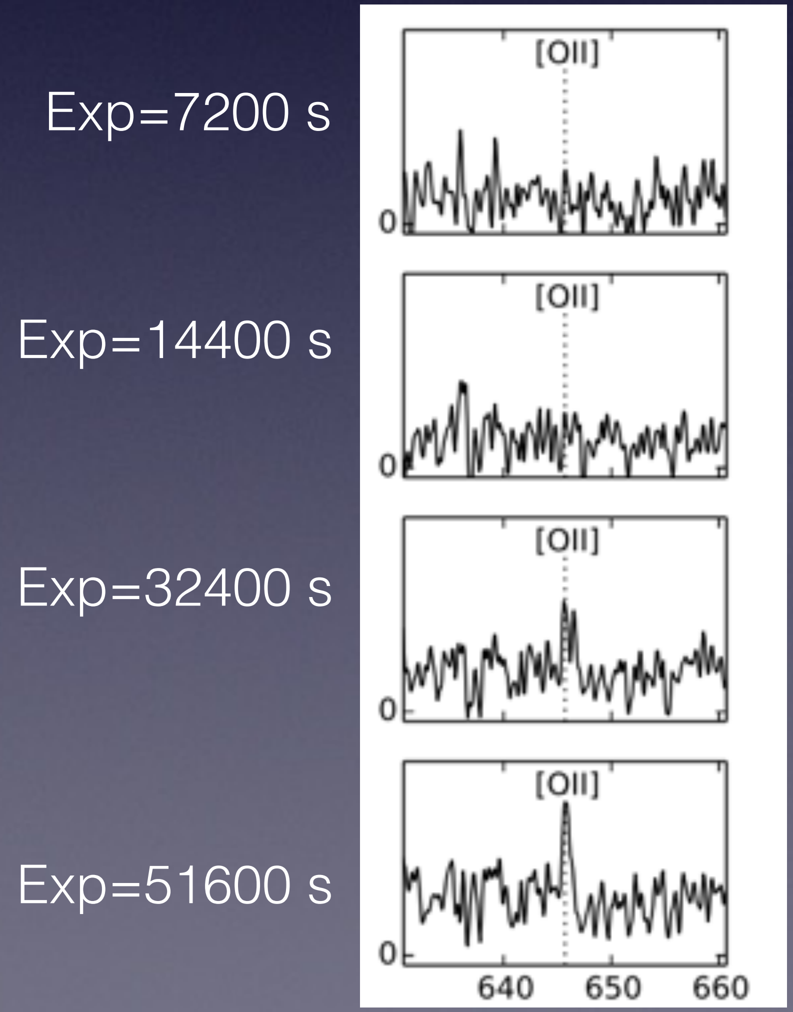
-6000 redshifts measured over AAT-OzDES follow-up

-Improved efficiency with stacking



AAT FOV on DECam FOV





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Photometry is critical because it gives the measurements of the light curve itself.

The most difficult step in SN photometry is how to make the galaxy templates and do image subtraction

- Two main approaches:
  - Stacking -- convolution -- subtraction
  - Scene modeling

Image convolution and subtraction

The crux of the difference imaging problem is to find a convolution kernel K that matches the PSFs of two astronomical images, I (referred to as the image) and T (referred to as the template). These images in general are taken under different conditions, including atmospheric transparency, atmospheric seeing, or exposure times. One may even difference data taken from different sites and equipment entirely. However, this technique does **not** work well for differencing data taken in different filters - to the extent that instrumental response as a function of wavelength is different on different equipment, differencing data taken from different sites does require some care.

Mathematically, the equation you want to solve is the minimization of the function

$$\sum \left([T \otimes K](x,y) - I(x,y) \right)^2$$

by solving for the kernel K. If K can be decomposed onto basis functions, then this is a linear least-squares problem, and can be solved uniquely by matrix inversion. In this method, the kernel is decomposed into basis functions

$$K(u,v) = \sum_n A_n \, K_n(u,v)$$

$$K_n(u,v) = e^{-(u^2+v^2)/2\sigma_k^2} \, u^i \, v^j.$$

By default in HOTPANTS, $n = 3$ and

$$\sigma_{k1} = 0.7 \text{ pixels}; \; i+j \leq 6$$

$$\sigma_{k2} = 1.5 \text{ pixels}; \; i+j \leq 4$$

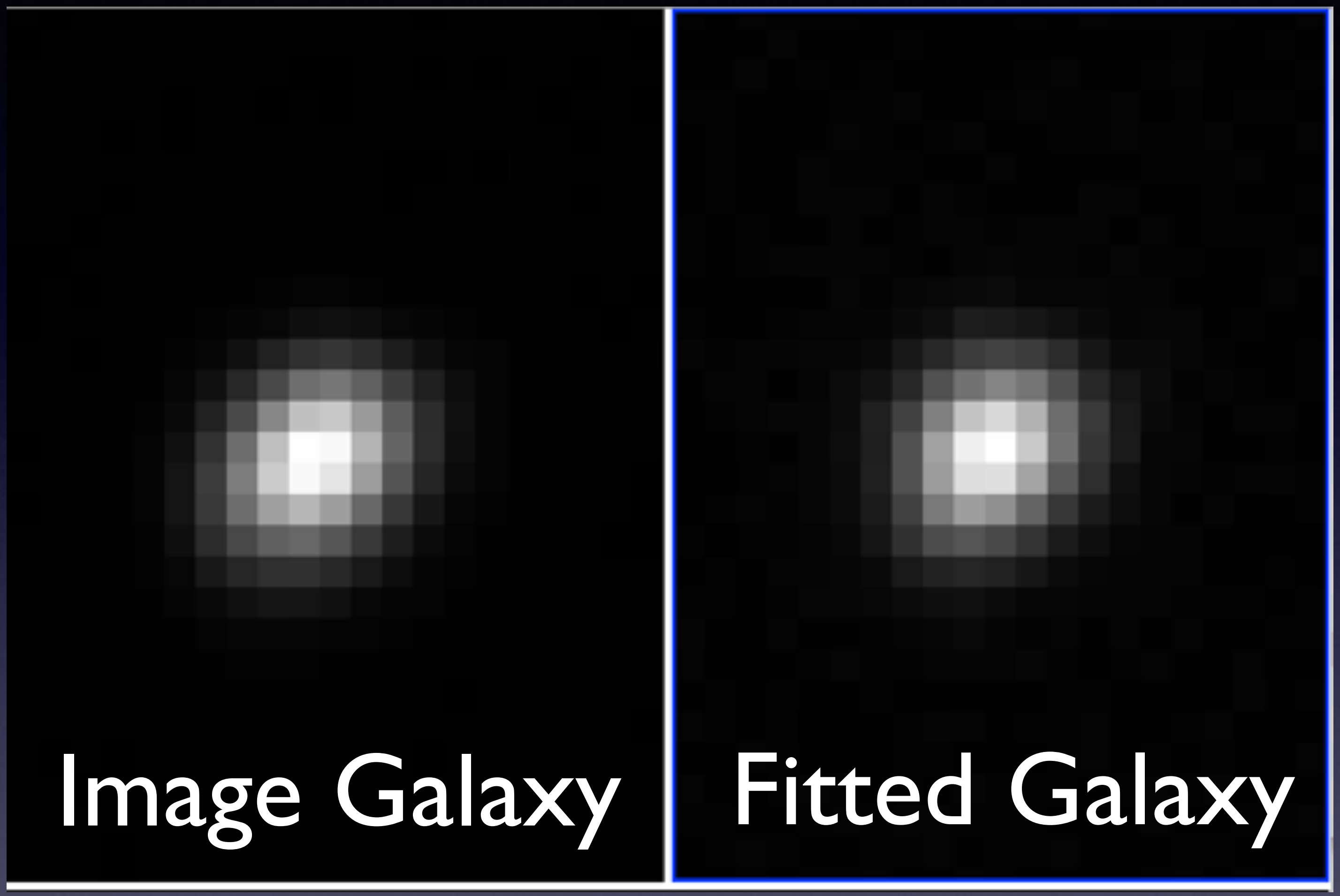
$$\sigma_{k3} = 3.0 \text{ pixels}; \; i+j \leq 2$$

Have to build a template from multiple images first to make T

The second approach is to do scene modeling

Forward modeling of a galaxy on a pixel-by-pixel grid

- Does a n_pix x n_pix + n_image fit over SN brightness and galaxy intensity



$$M(x,y) = sky(x,y) + S\left(\sum_{stars} I_{star}PSF(x - x_{star}, y - y_{star}) + I_{SN}PSF(x - x_{SN}, y - y_{SN}) + \sum_{x_g,y_g} \mathcal{G}(x_g,y_g)PSF(x - x_g, y - y_g)\right)$$

Holtzman 2008

I=Intensity, G=Galaxy, M=Model

$$\chi^2 = \sum_{xy} \frac{(O(x,y) - M(x,y))^2}{(M(x,y)/G + (\frac{\sigma_{rn}^2}{G^2}))}$$

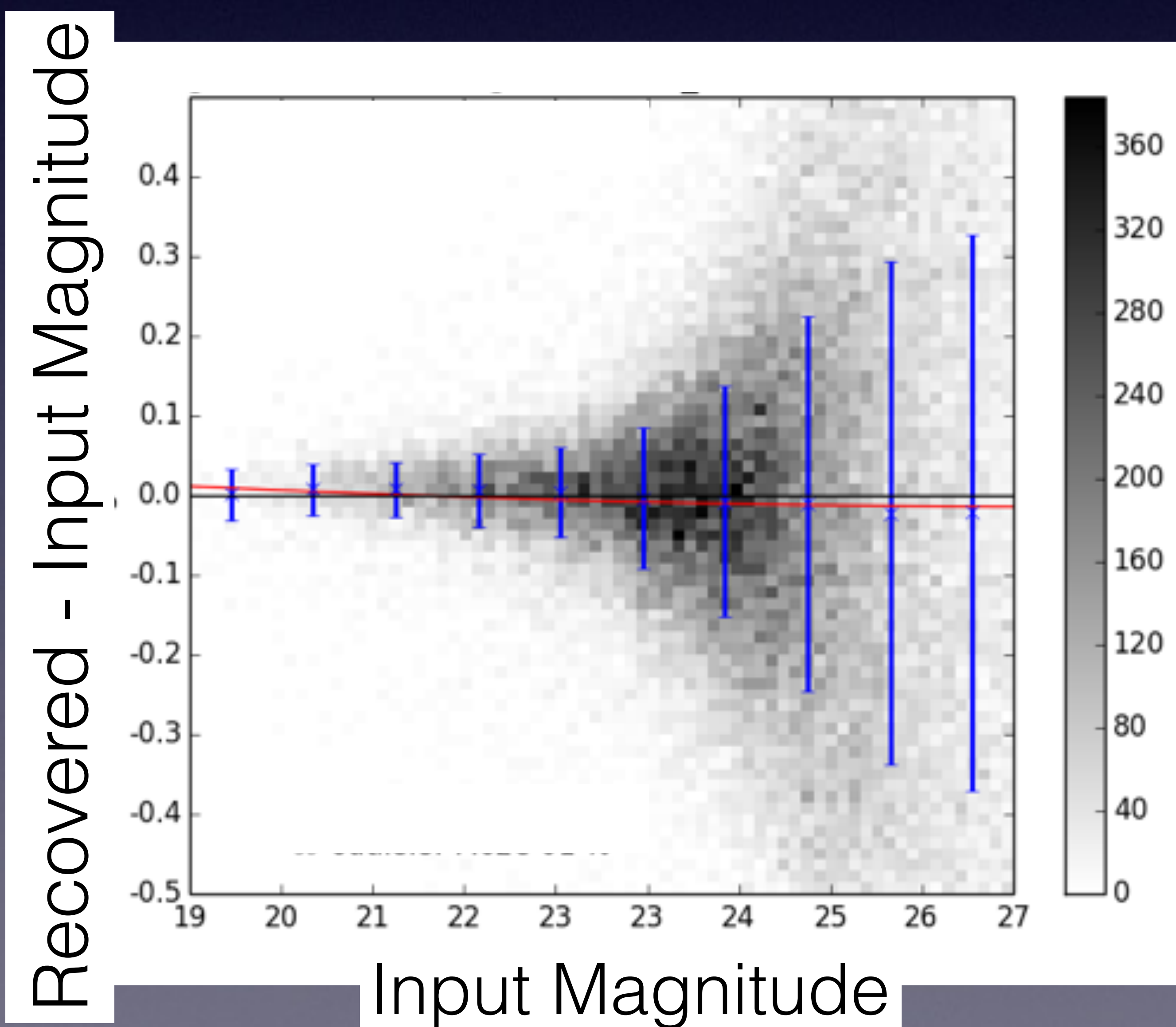
O=Image

Photometry

Two independent pipelines

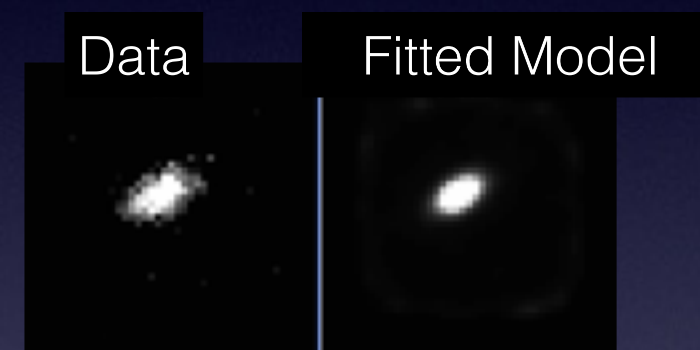
+Image Subtraction

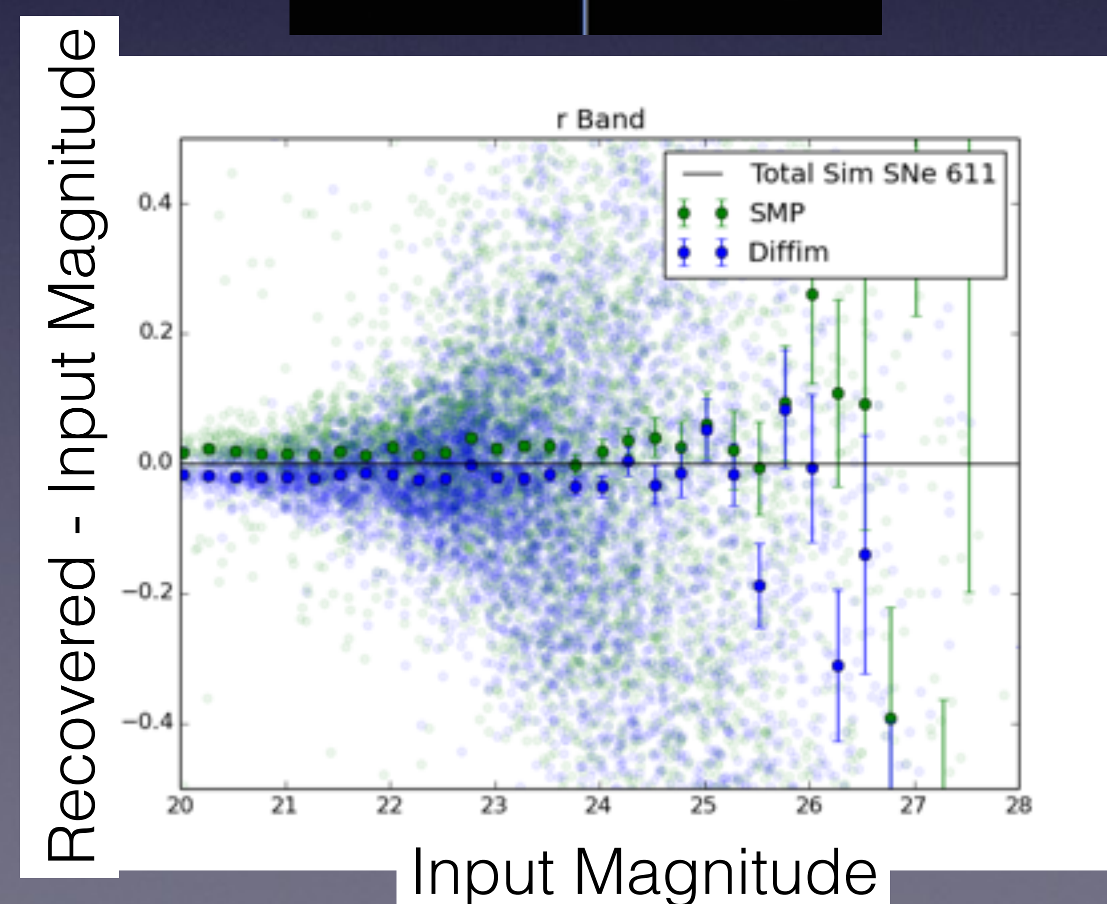
-Sub 1% biases, more scatter with increasing galaxy brightness



+Scene Modeling

-Forward modeling of galaxies by solving for temporally constant galaxy and fluctuating SN flux





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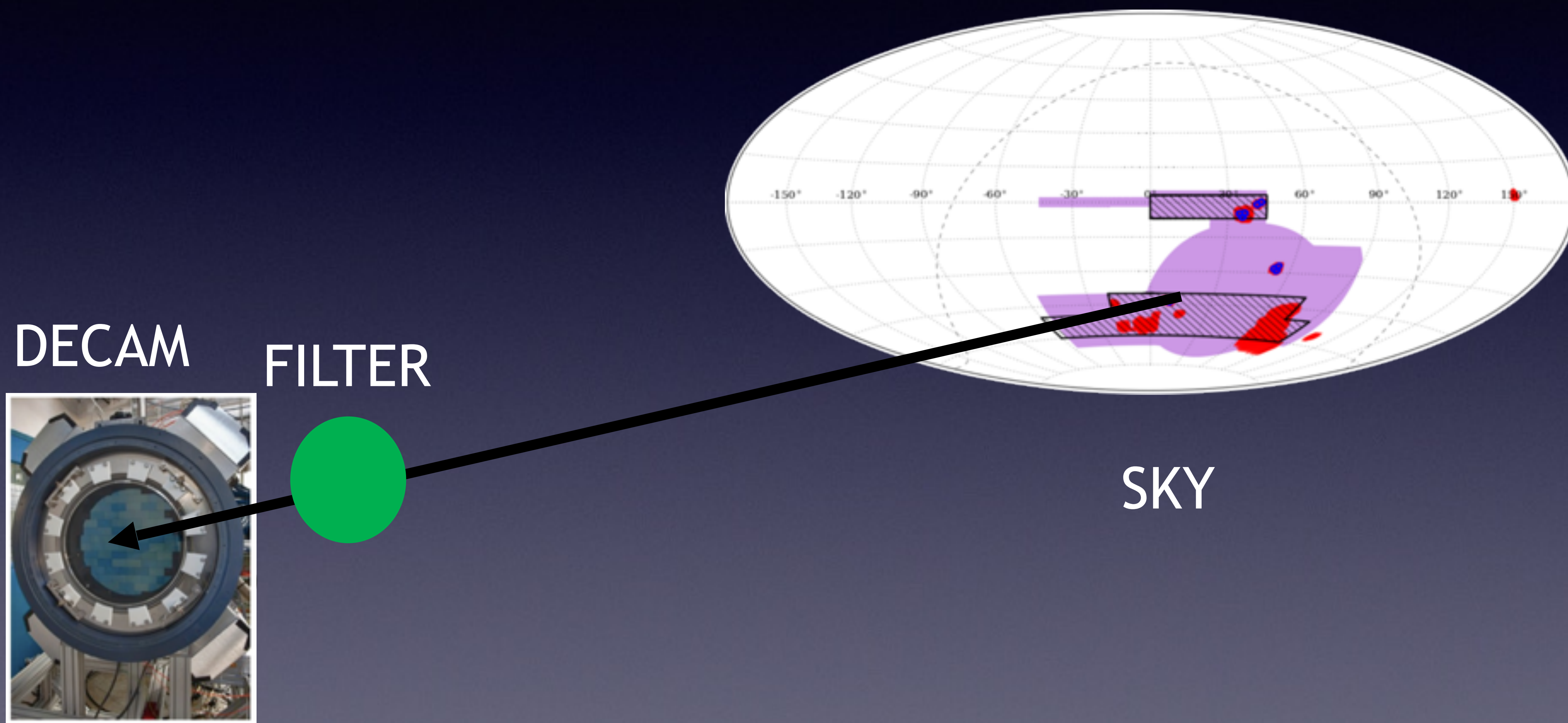
Calibration is critical because the light of the SN will peak in different filters depending on its redshift. If filters aren't calibrated against each other, can introduce a cosmological bias.

The Path to Calibration….

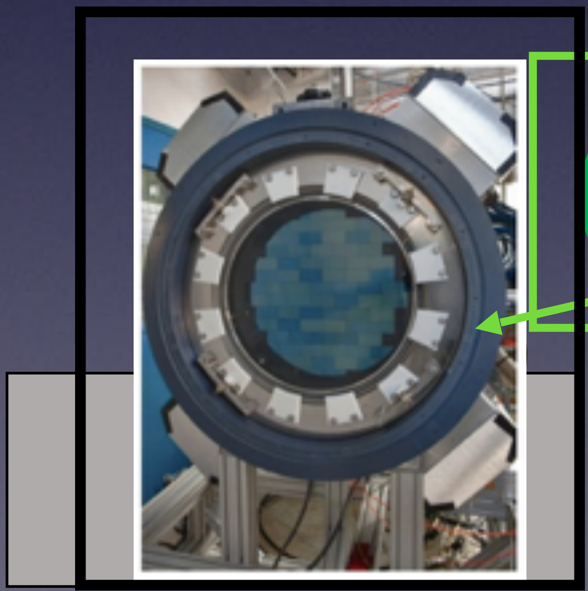


Courtesy of our own James Lasker

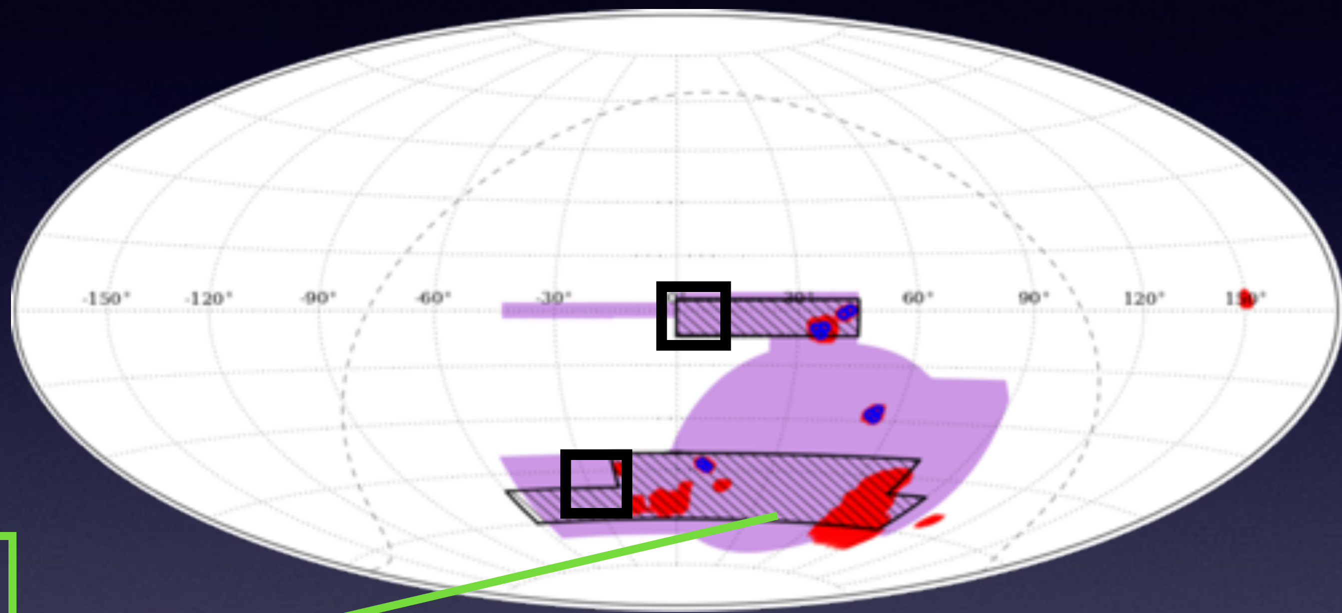
Possibilities for error abound!

Temporal + spatial varying camera efficiency

Atmospheric Fluctuations



Imprecise Filter Measurements

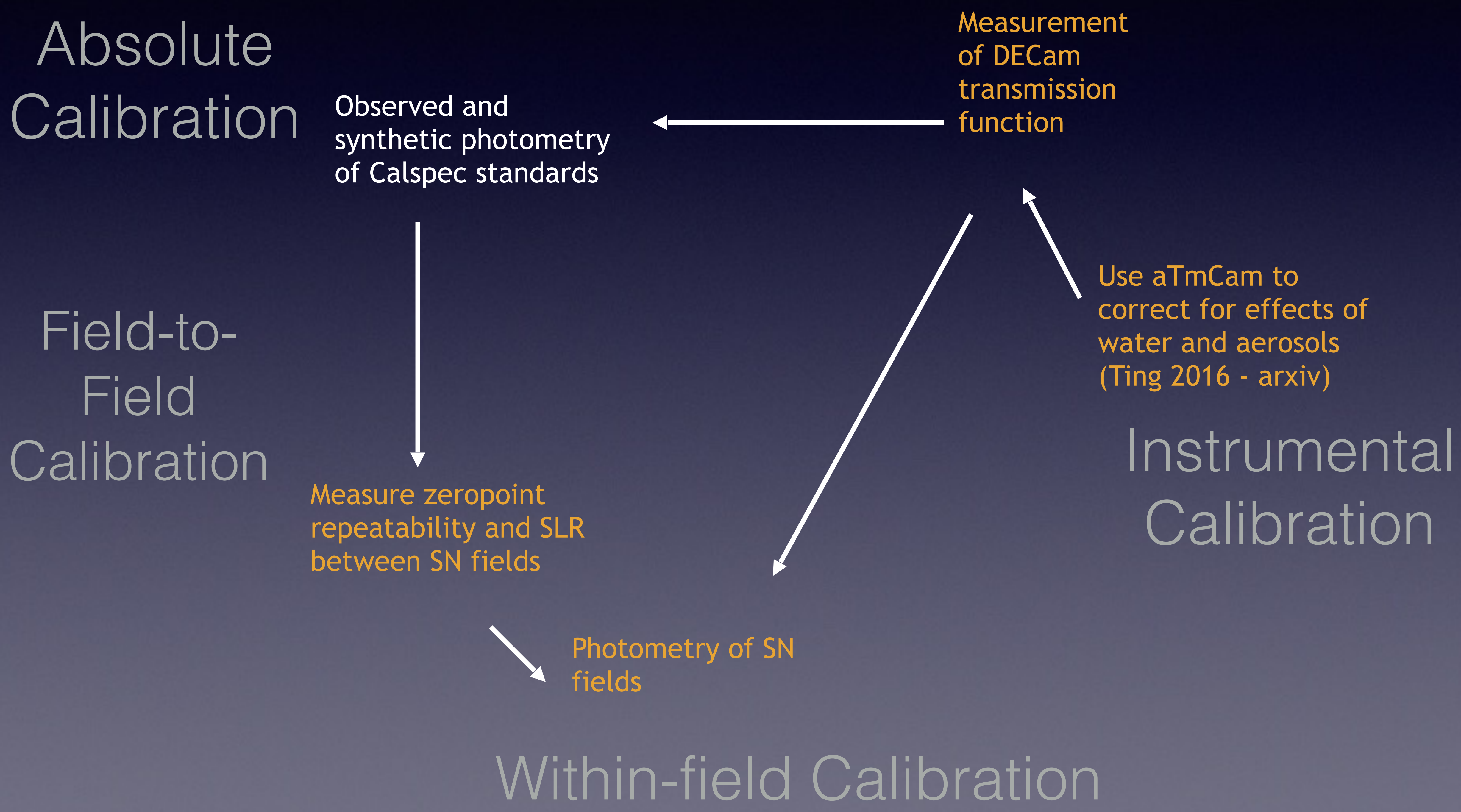


Difference across sky

Calibration:

-Dominant systematic in past analyses

-Joint effort with Wide Area Survey



To improve systematic uncertainty, the key is to improve calibration between surveys

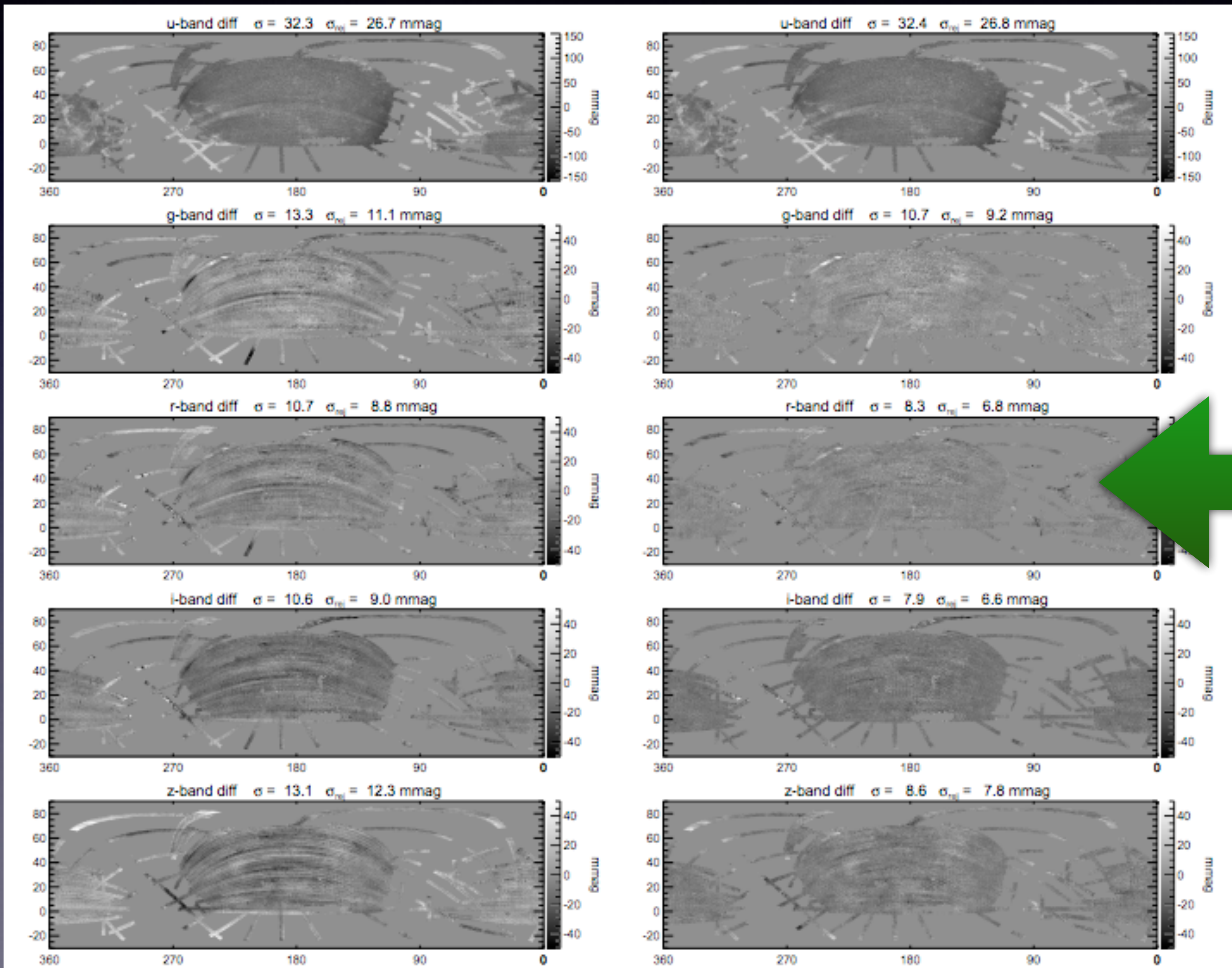


FIG. 1.— The mean difference (PS1 minus SDSS) in 15 arcminute

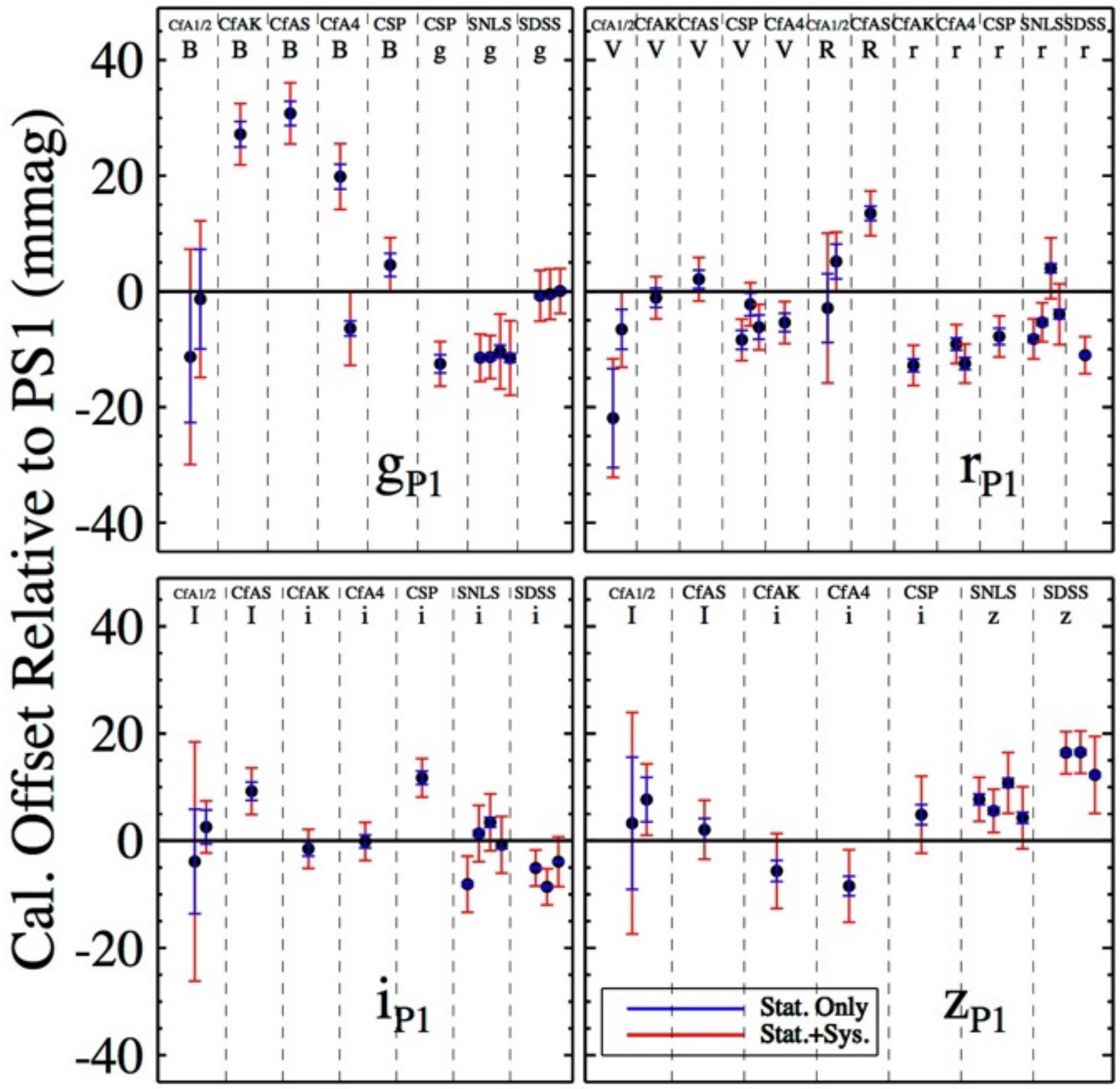
FIG. 2.— Same as Fig. 1, but after recalibration. The cali-

Schlafly, Finkbeiner et al. did PS1 Ubercal, relative calibration across sky <5mmag, <3 mmag for MD fields

Compared PS1 to SDSS, found SDSS issues

Scolnic et al. 2015 cross-calibrates all supernova samples!

Doing this for all available public data, measure an offset for each filter for each system.



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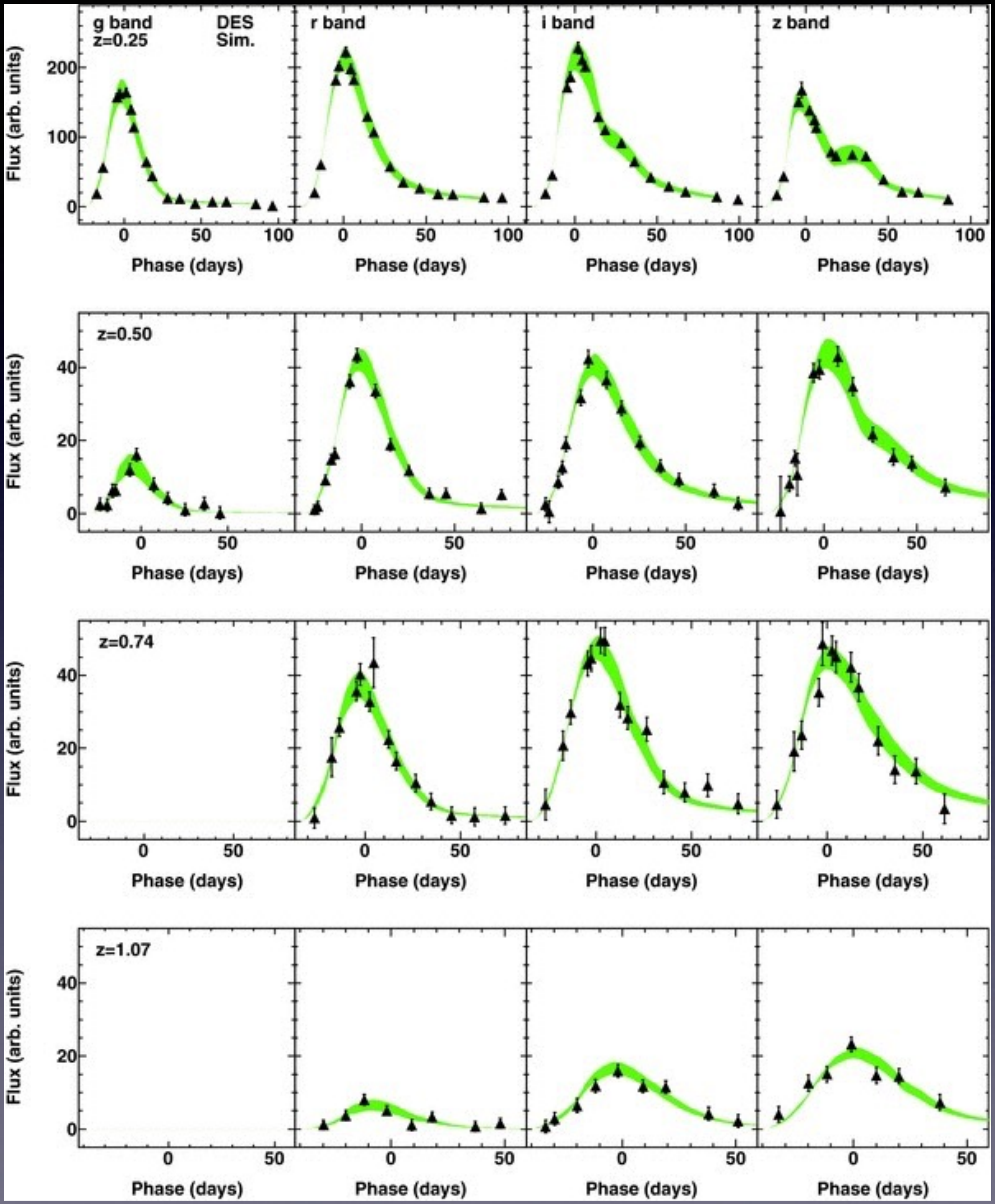
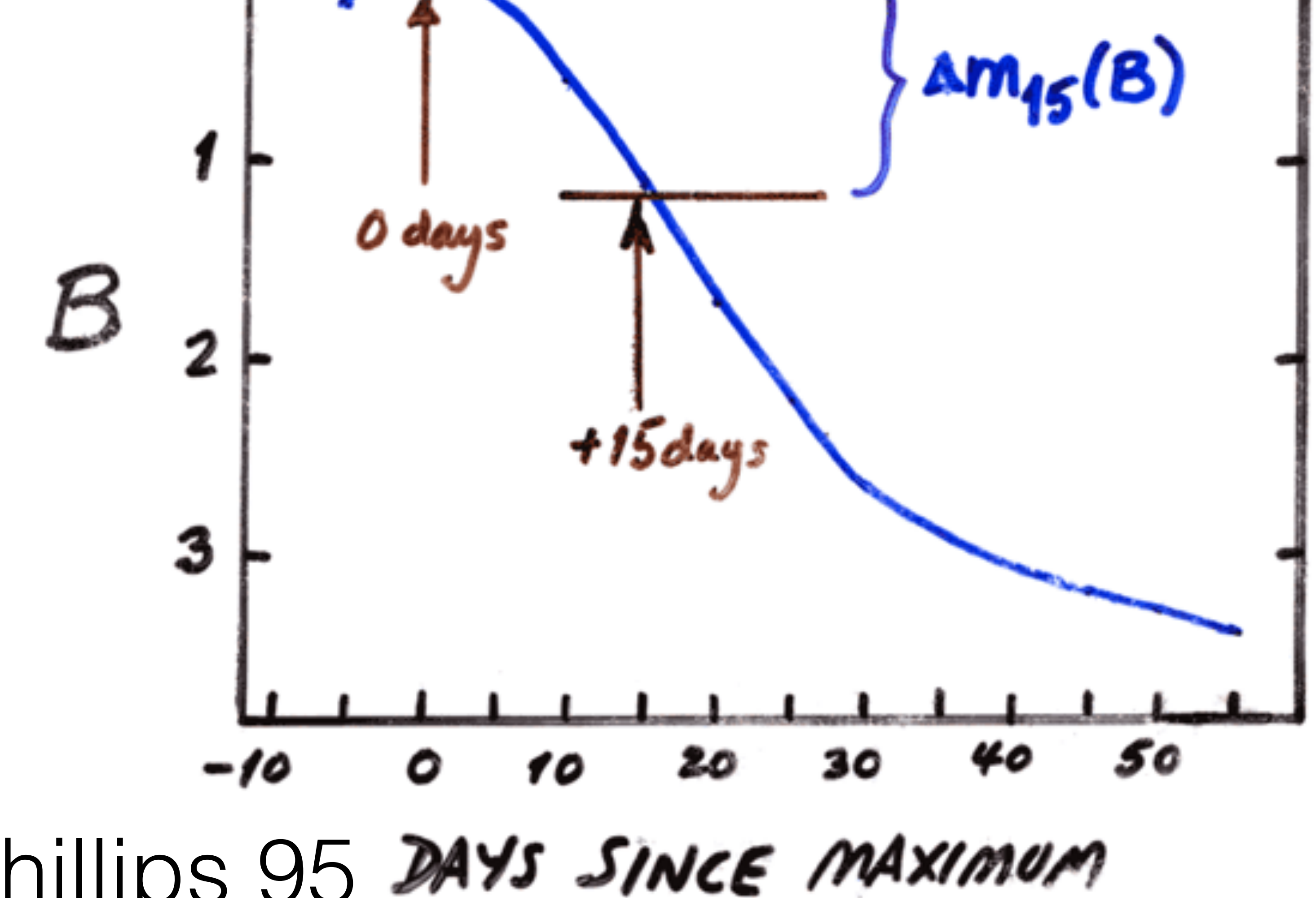
Light-curve fitting is what translates your light curve into fit parameters that can be converted into a distance.

For each light curve for all bands, measure a light curve amplitude, color (diff between bands) and width

Distance=mb+ax1-b*c
mb=amplitude
x1=width
c=color
a,b are coefficients



Standardization works because of Phillips relation

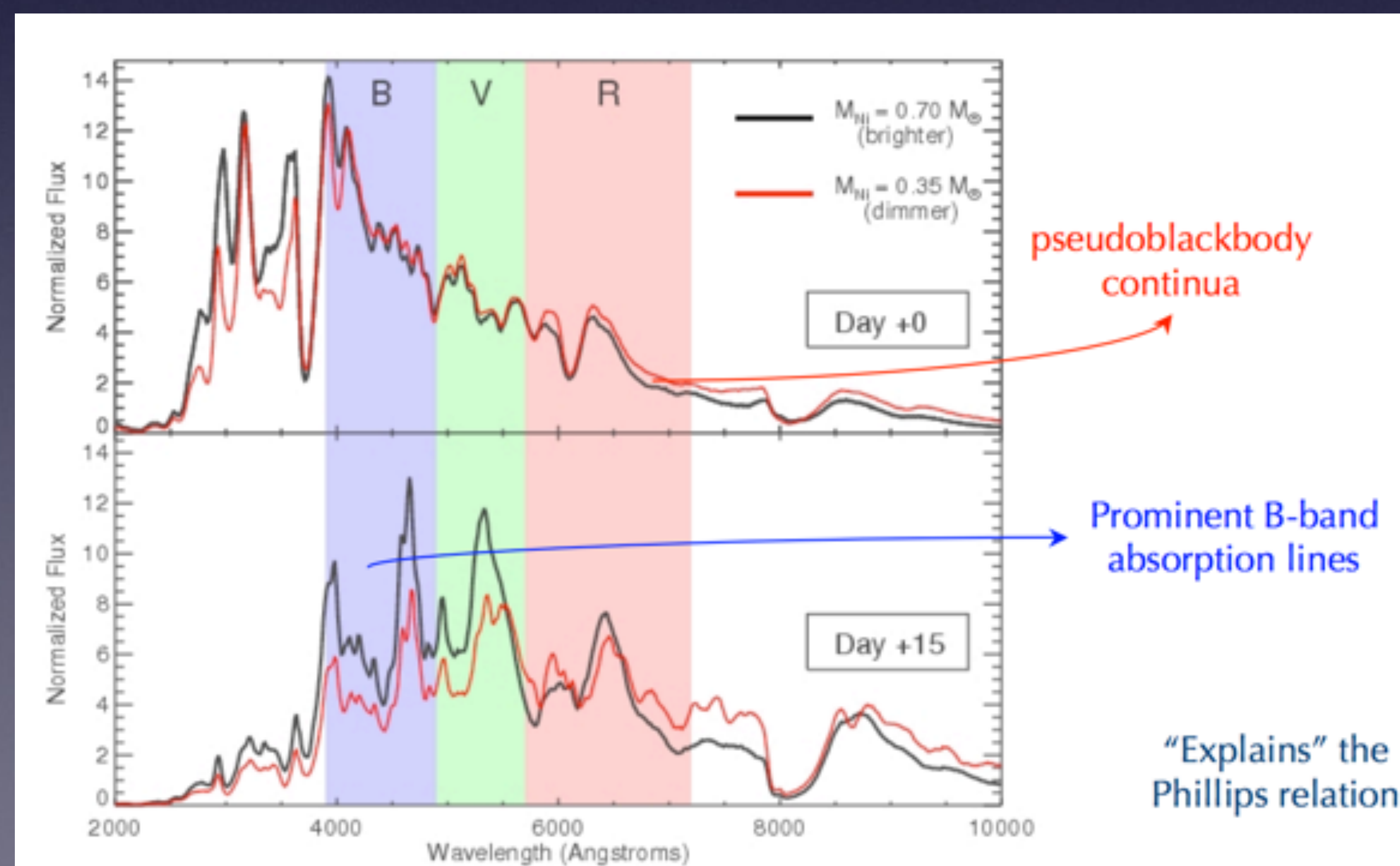


Phillips 95

Following maximum light, the SN colors are increasingly governed by the blanketing of numerous Fe II and Co II lines that particularly affect the B band

Because dimmer SNe Ia are cooler, they experience an earlier onset of Fe III to Fe II recombination, resulting in more rapid evolution of the SN colors to the red

The faster B-band decline rate of dimmer SNe Ia thus reflects their faster ionization evolution



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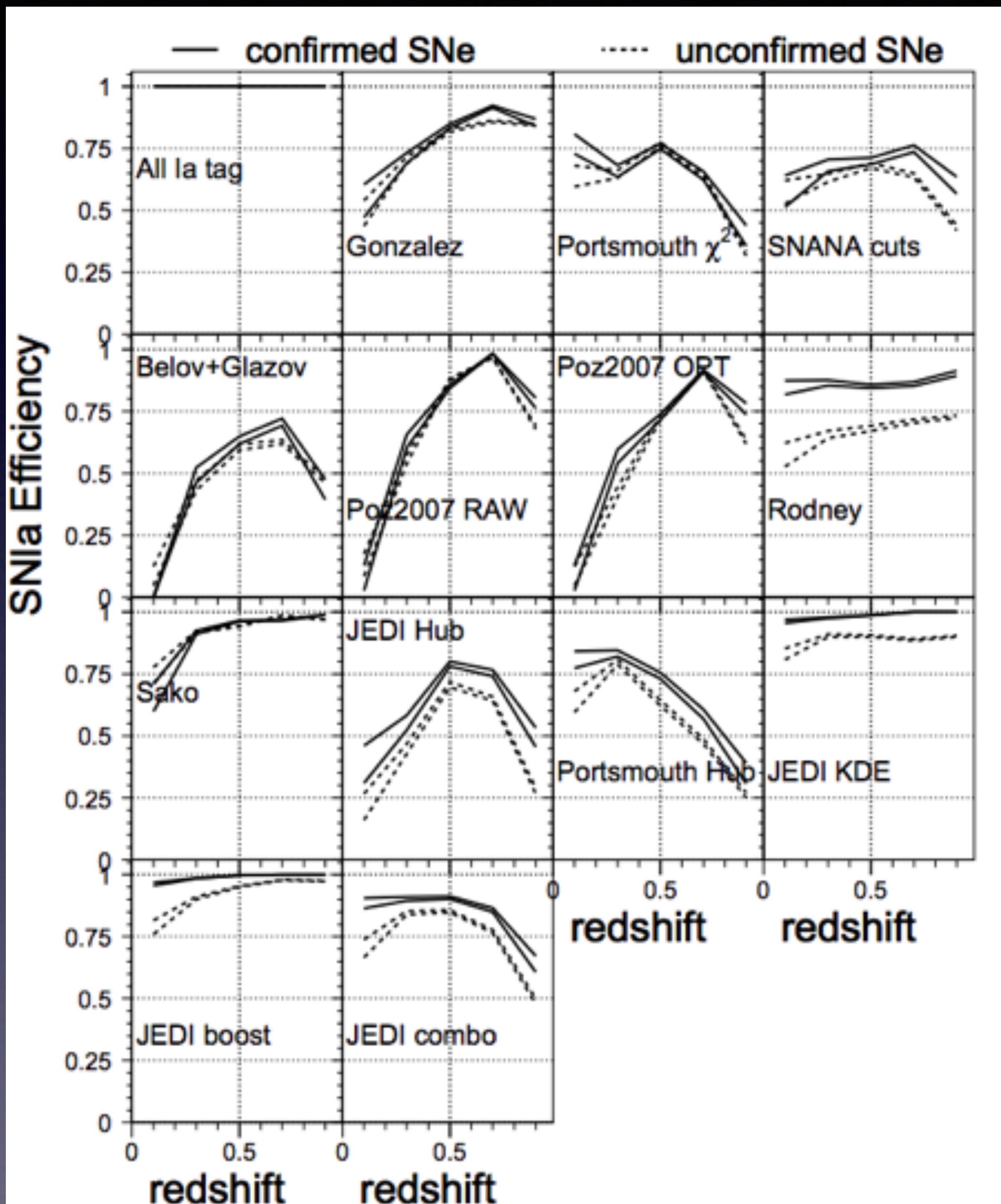
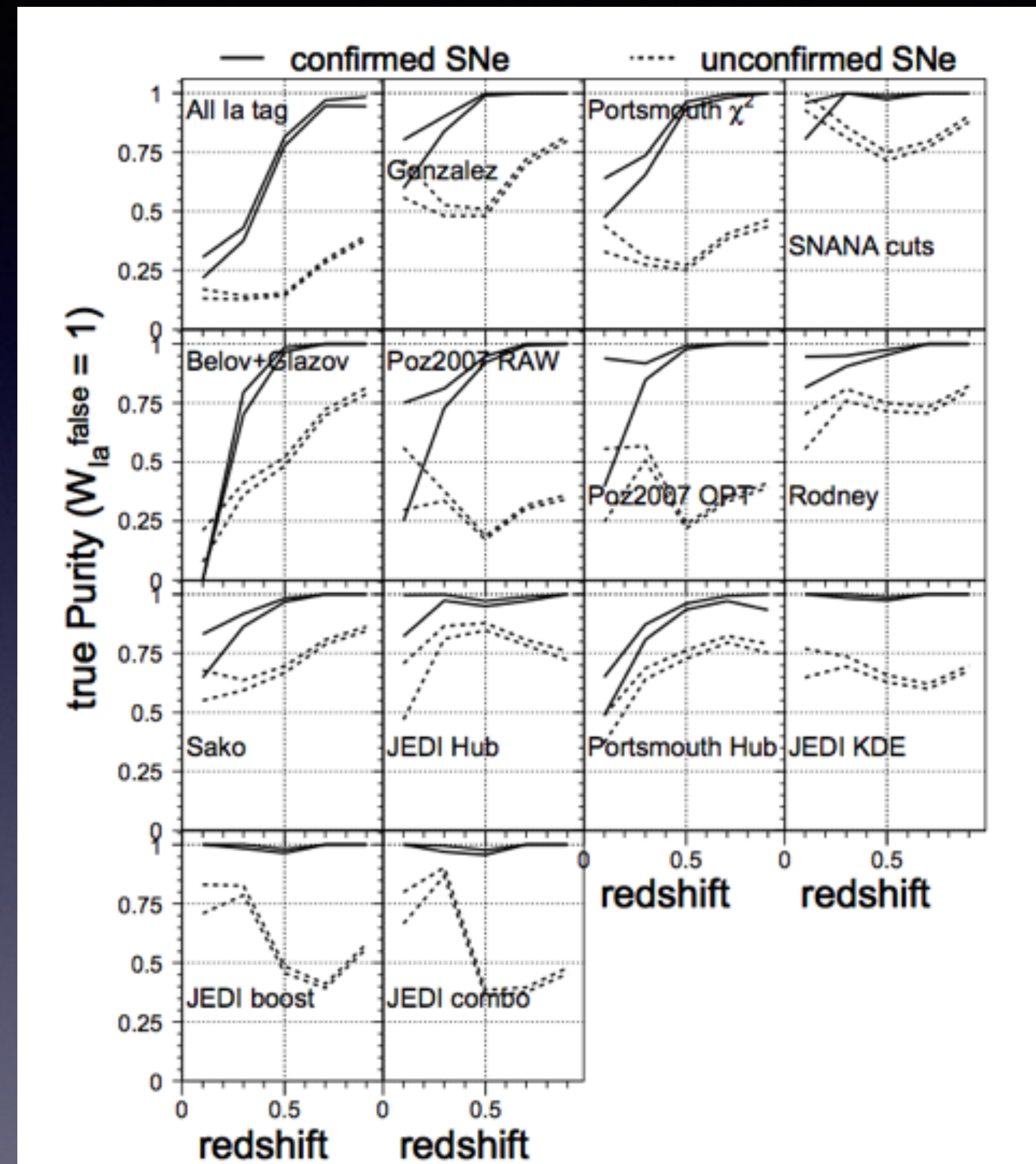
With DES, can’t spectroscopically confirm each SN like in past surveys. But only SNIa are useful for cosmology analysis. So we need to photometrically classify SN.

There are multiple techniques that use light curves to photometrically classify (Kessler Classification Challenge)

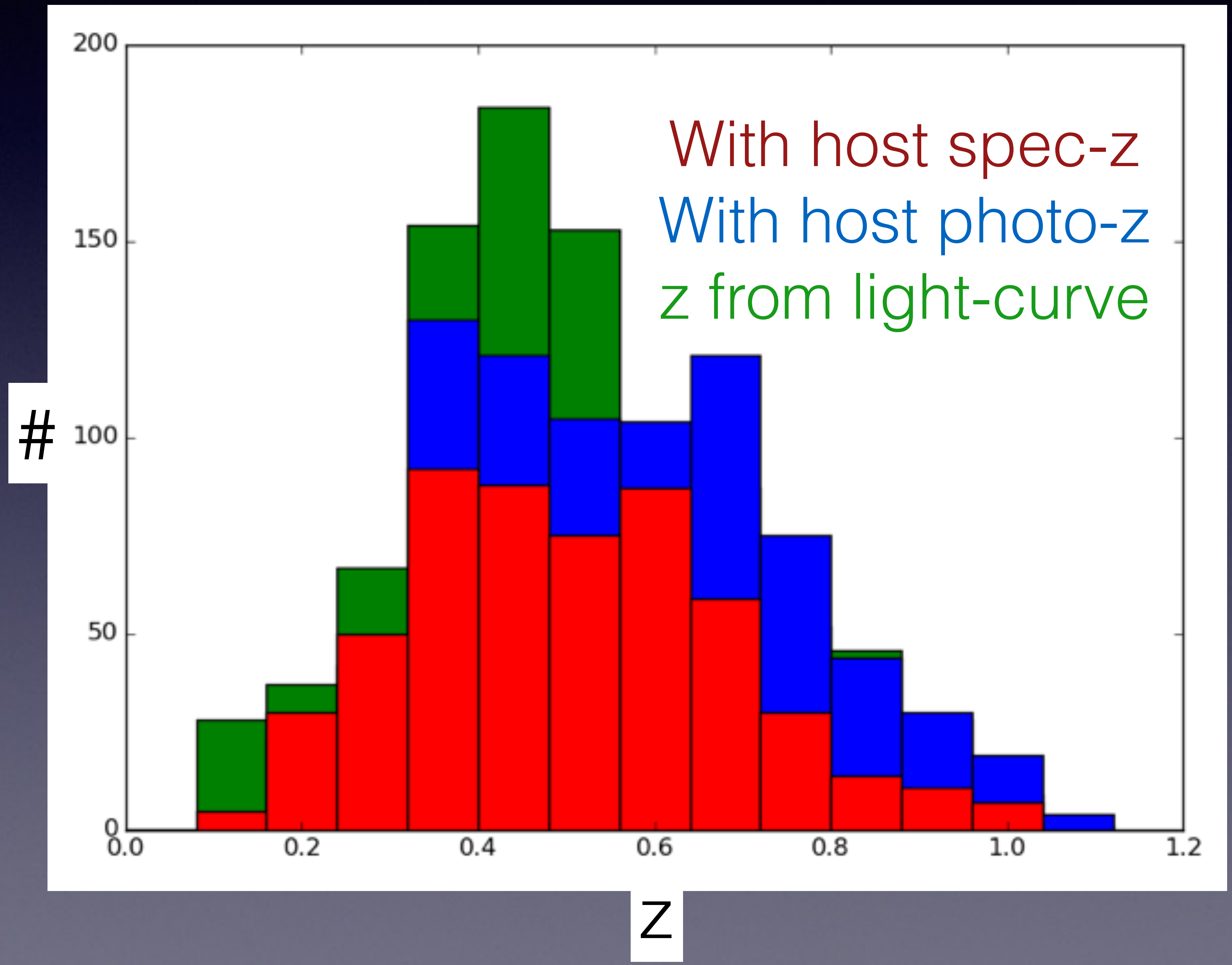




and some that use host galaxy properties (Jones 16)

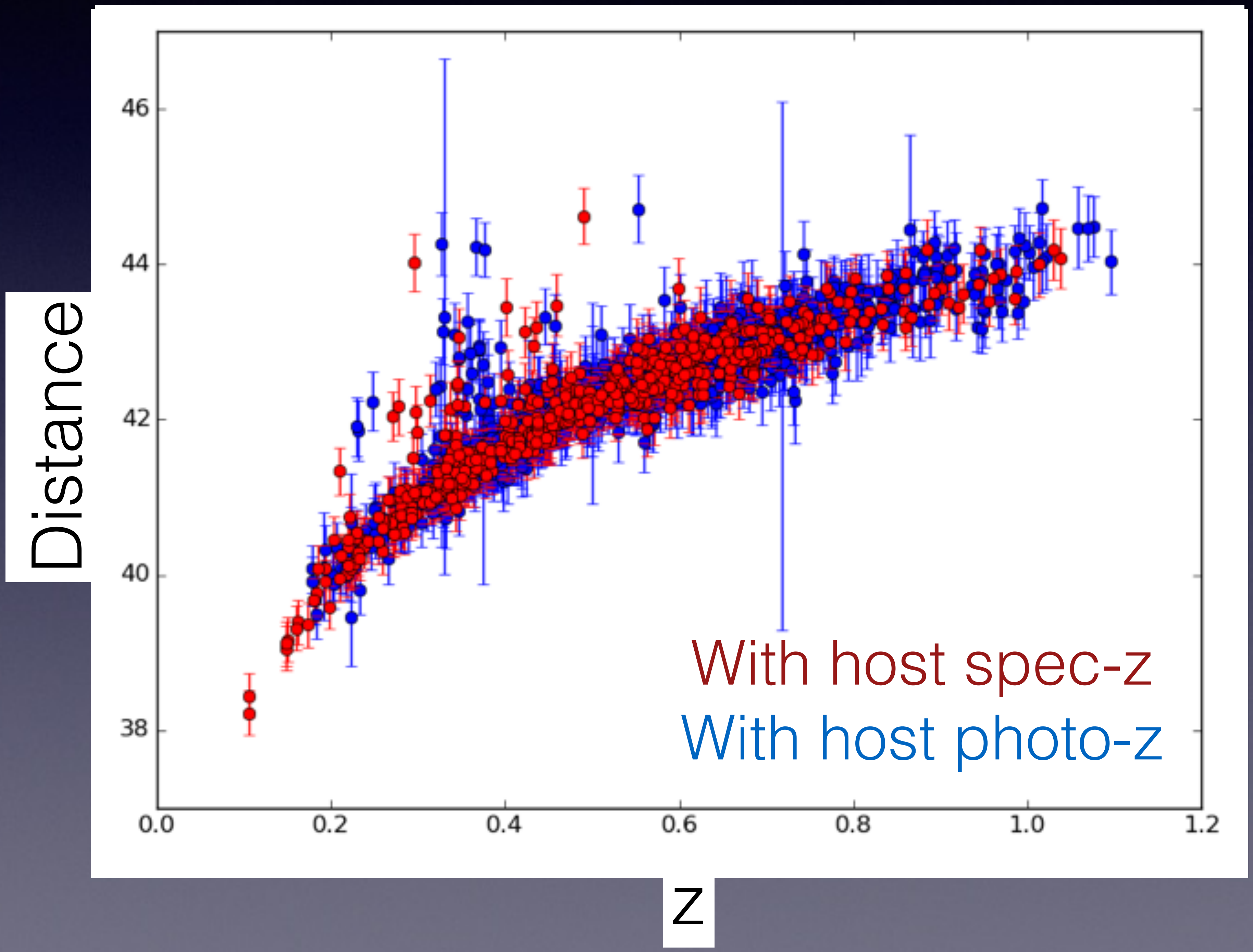
Photometric Classification

-900 (Y1+Y2) likely SNeIa for cosmology, pass rigorous cuts
-> 800 have good host photo-z
-> 530 have host spec-z

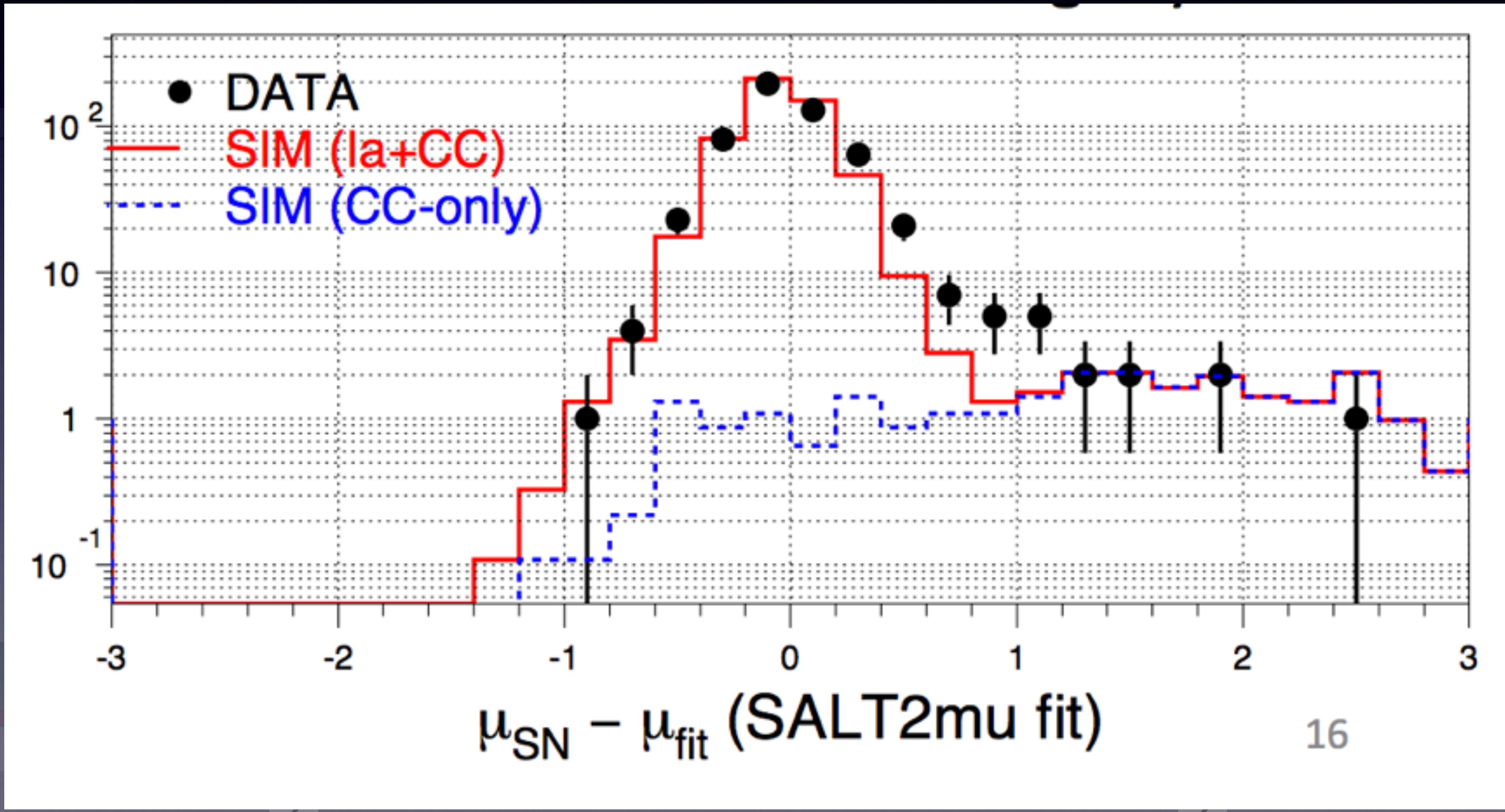


Hard part is that the redshift distributions are different cause only spectroscopically classify lower-z

This is what a Hubble diagram with photometrically classified SNe looks like. Those outliers are likely not SNIa. But what to do about this?



One idea is that we need to understand the shape of the outlier distribution by simulating samples with SNIa and CC SNe



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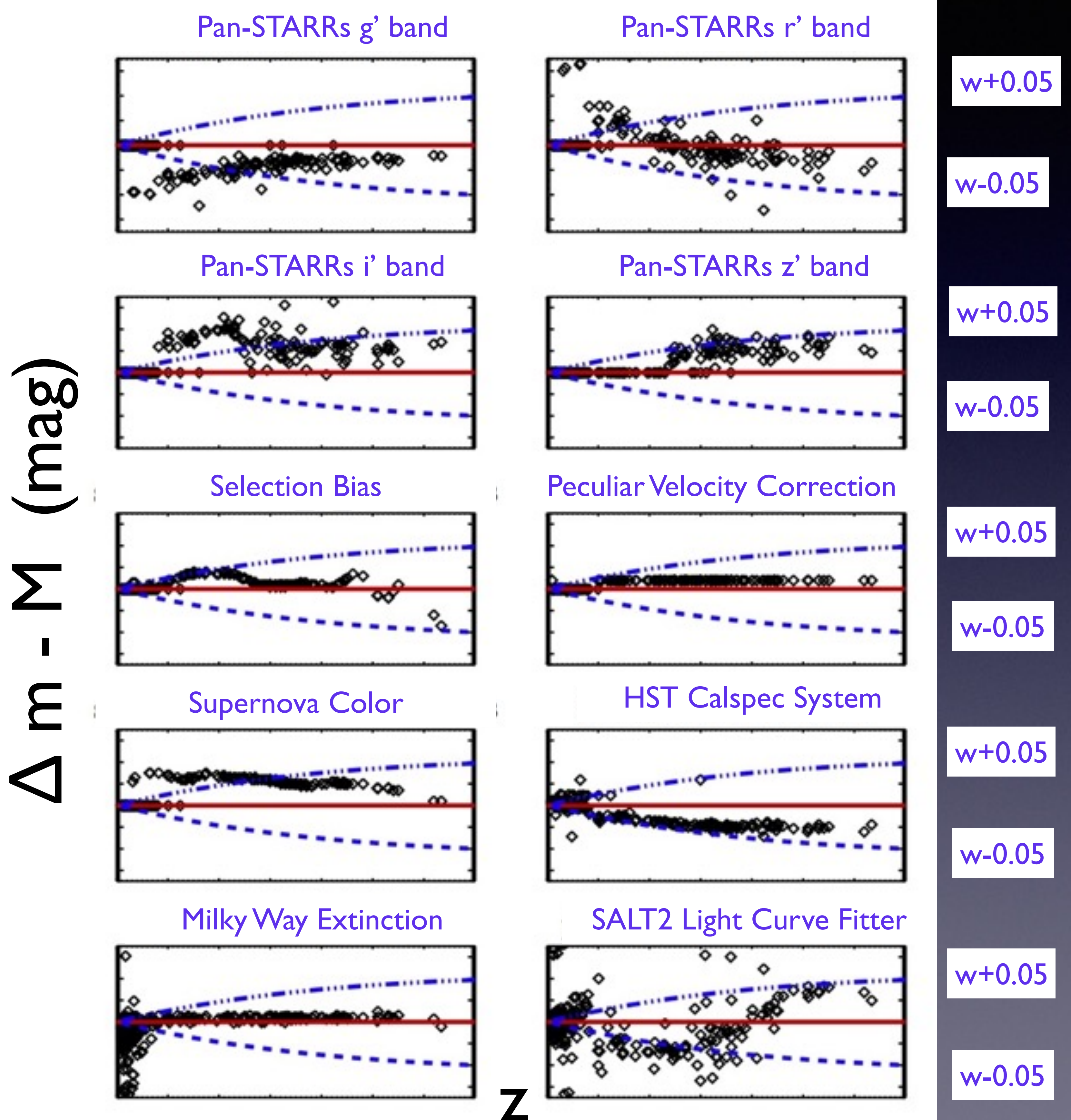
The error on cosmology measurements due to systematics are of equal size to statistical uncertainty.

To measure w to 10%, we need careful accounting of systematics

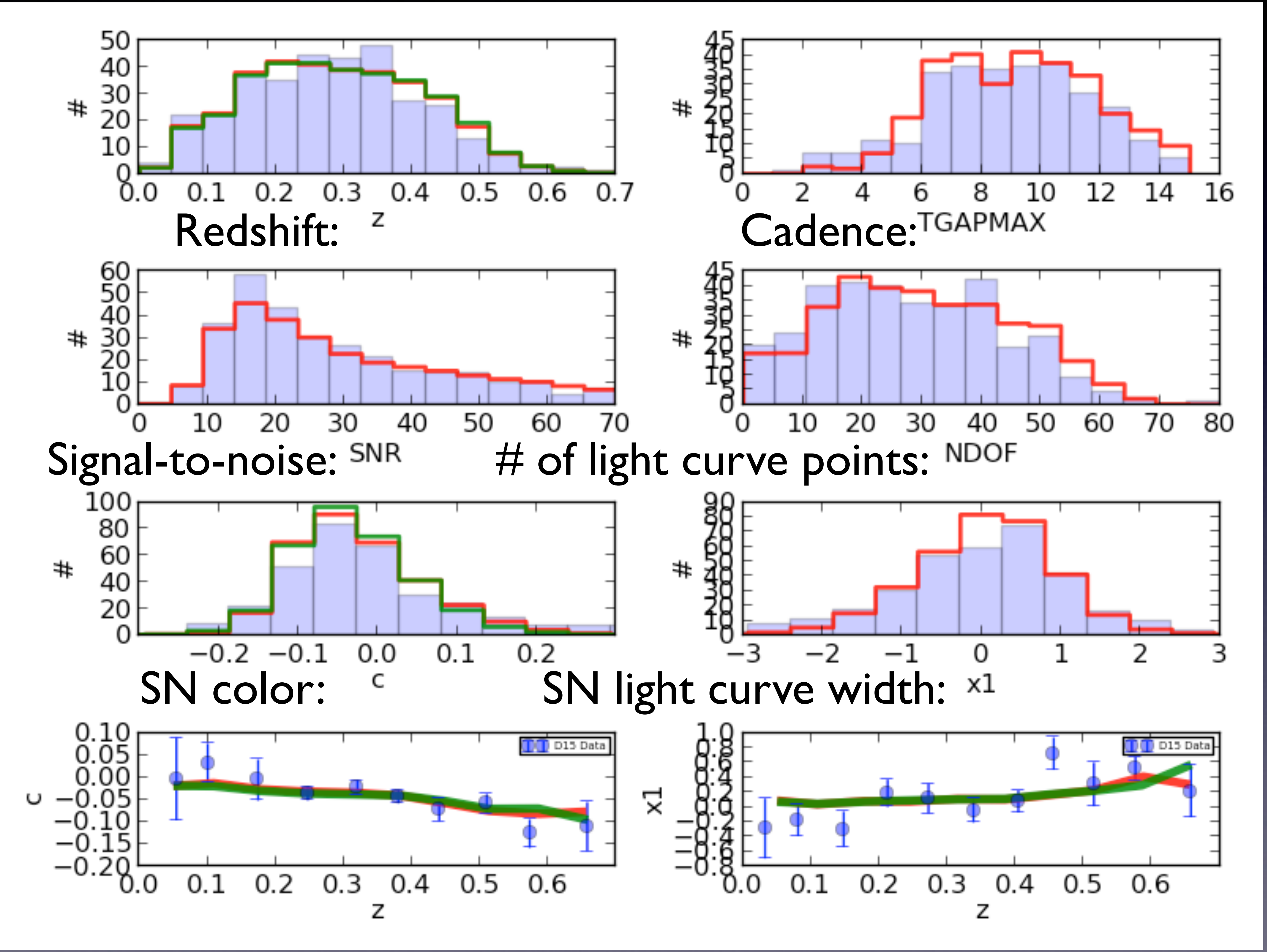
Here we show Hubble diagram differences when we change our biggest systematics by 1σ



Systematic uncertainties are of similar size to statistical uncertainties. Propagate systematic uncertainties to covariance matrix.

Based on Scolnic et al 14b

To properly analyze survey, critical to simulate survey very accurately.



Using SNANA (Kessler 09)

SN Analysis Basics

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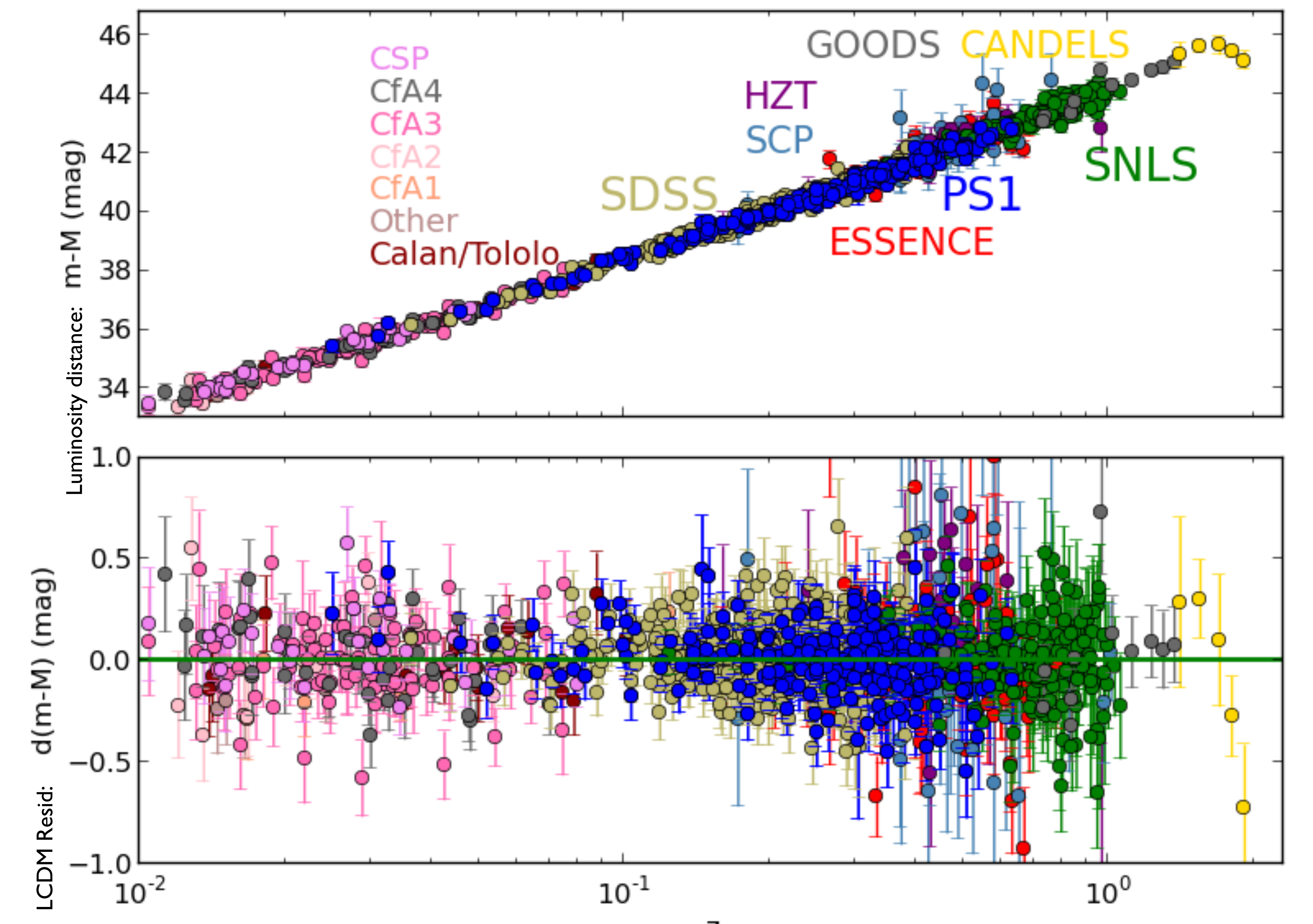
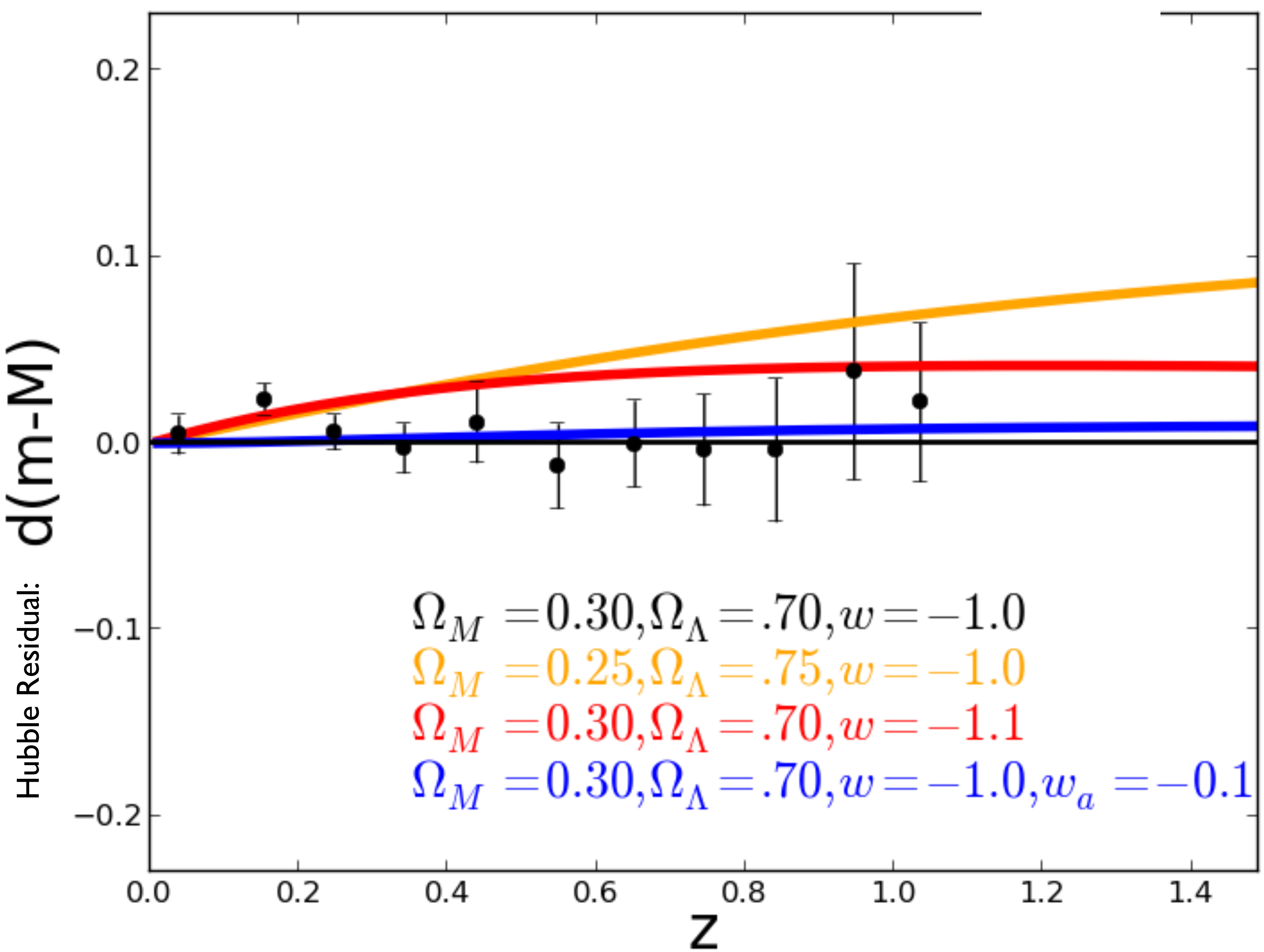
- Systematics
- **<u>Cosmology</u>**

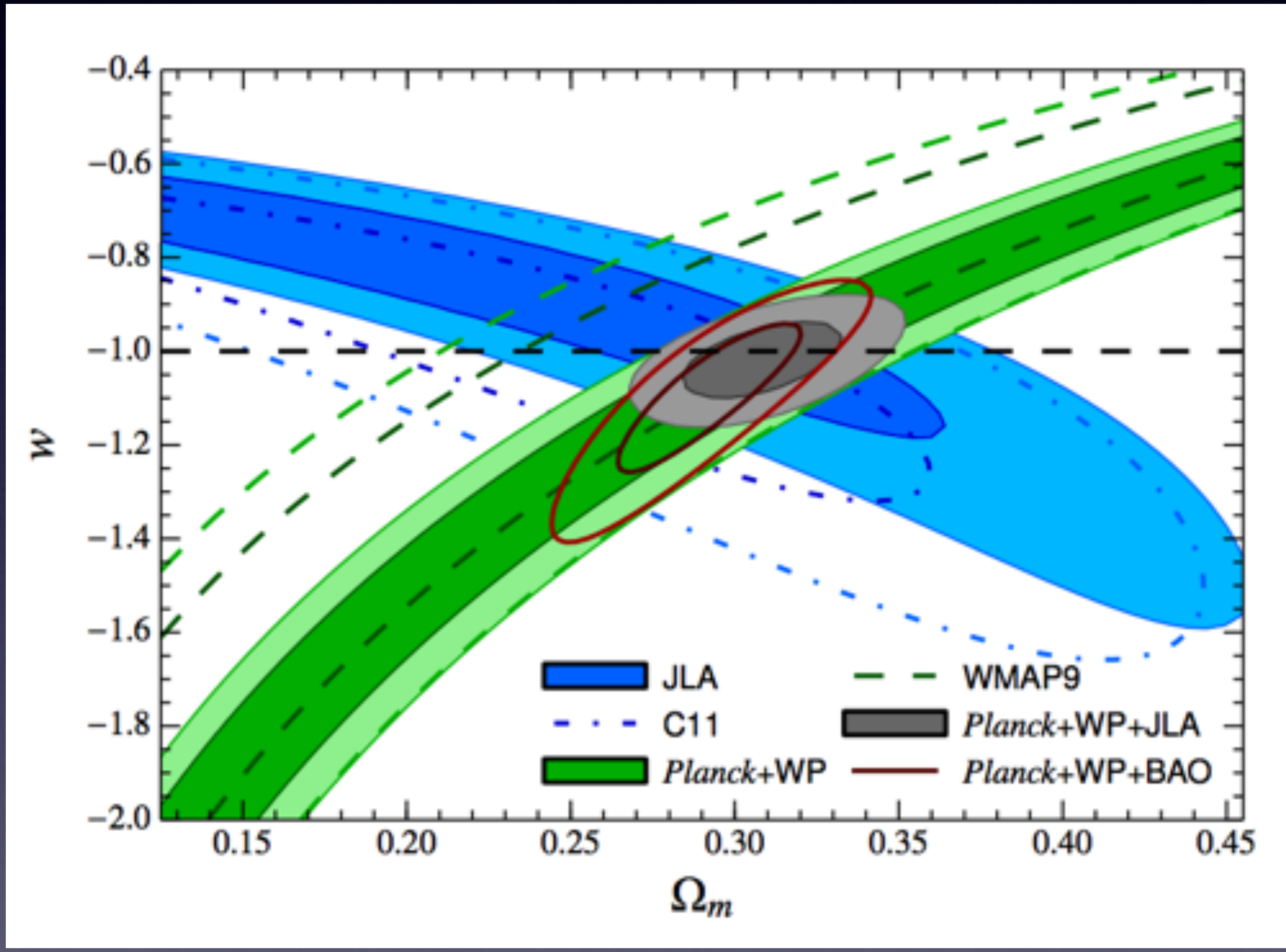
Measuring cosmology is why we are doing this survey in the first place.

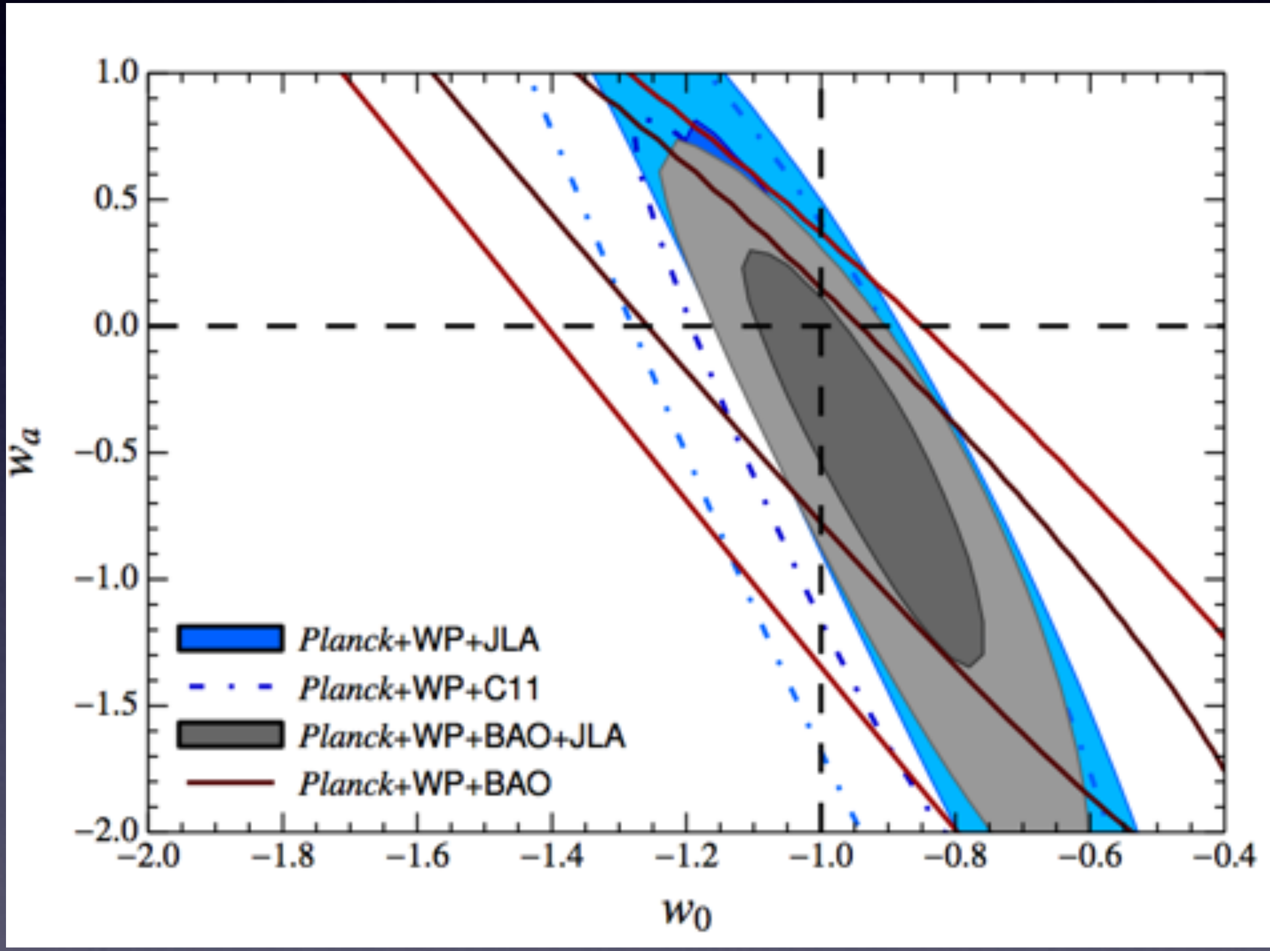

CSP
CfA4
CfA3
CfA2
CfA1
Other
Calan/Tololo
SDSS
HZT
SCP
GOODS
CANDELS
PS1
ESSENCE
SNLS
Luminosity distance: m-M (mag)
LCDM Resid: d(m-M) (mag)
z
46
44
42
40
38
36
34
1.0
0.5
0.0
−0.5
−1.0
10^{-2}
10^{-1}
10^{0}

Ultimately, you want to measure cosmology.



The parameters we typically measure are Om, w, wa





The constraints on wa are still really large, and that's where DES can make its biggest mark.

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