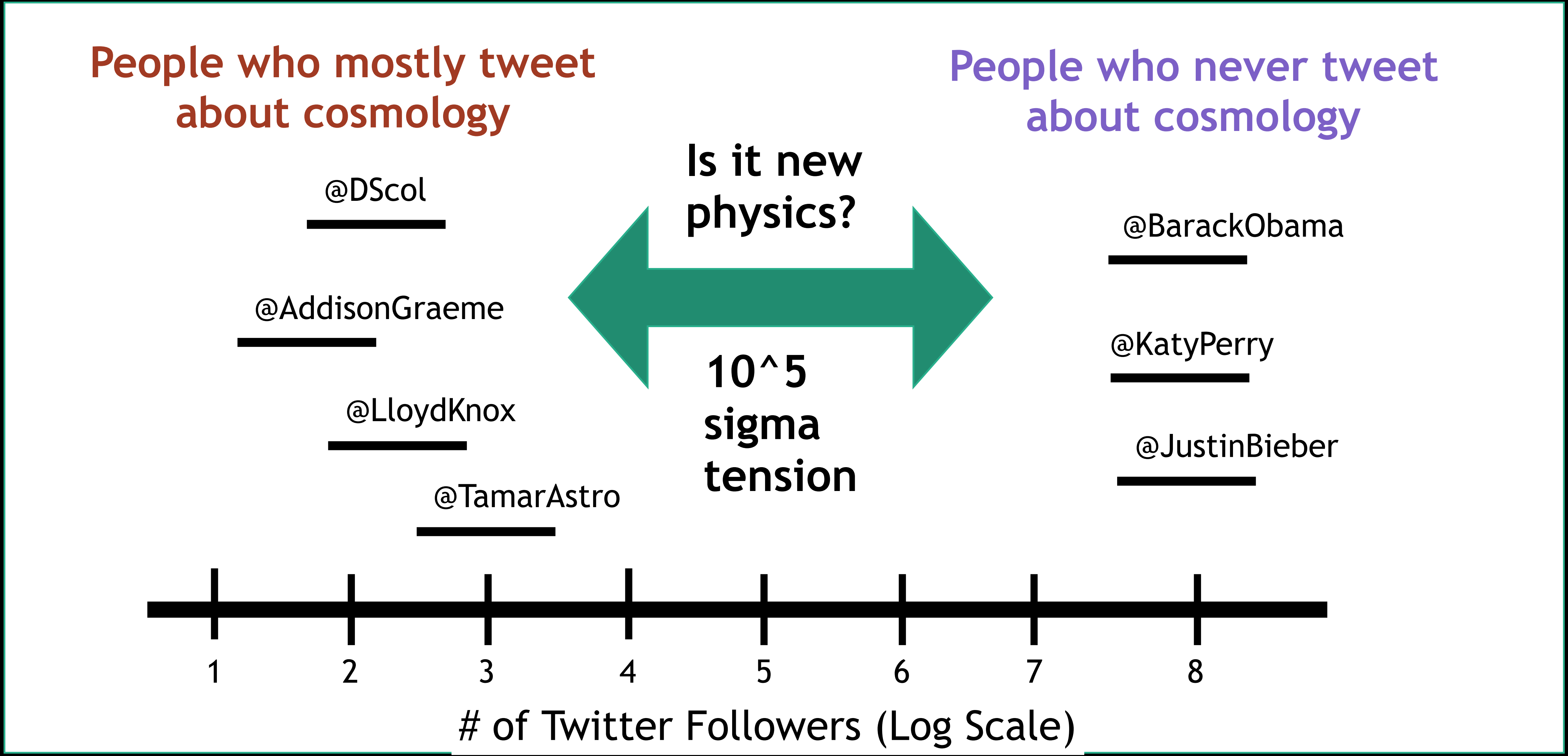
Type Ia Supernovae as the Middle-person

Dan Scolnic [will share results from SH0ES, PS1/Foundation and DES collaborations]
Asst. Professor at Duke University
KITP Early-Late Universe

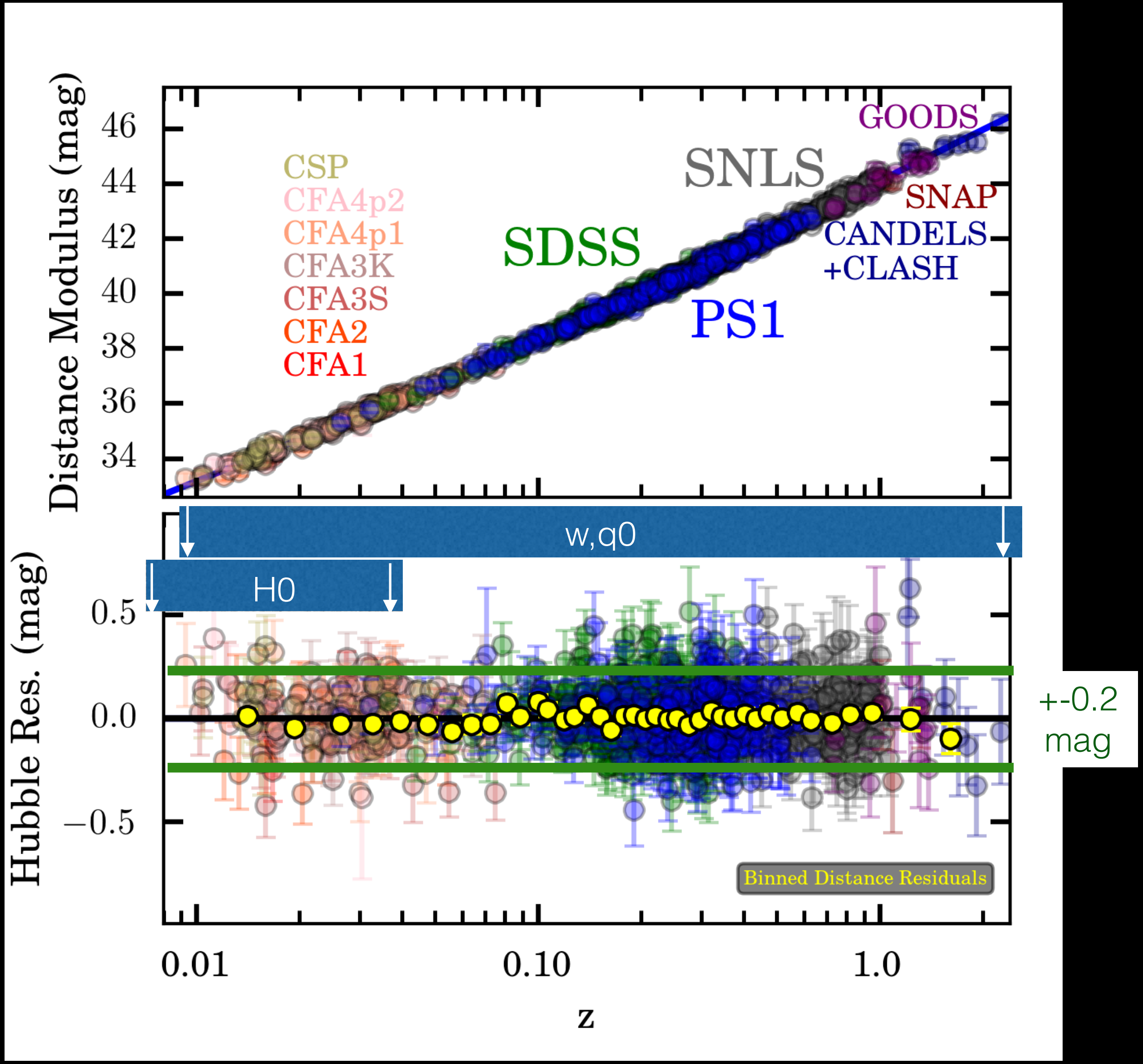
I have found an interesting trend with regards to Twitter Cosmology #KITP_H0tTakes



Measurement of H0 is significantly easier than measurement of w

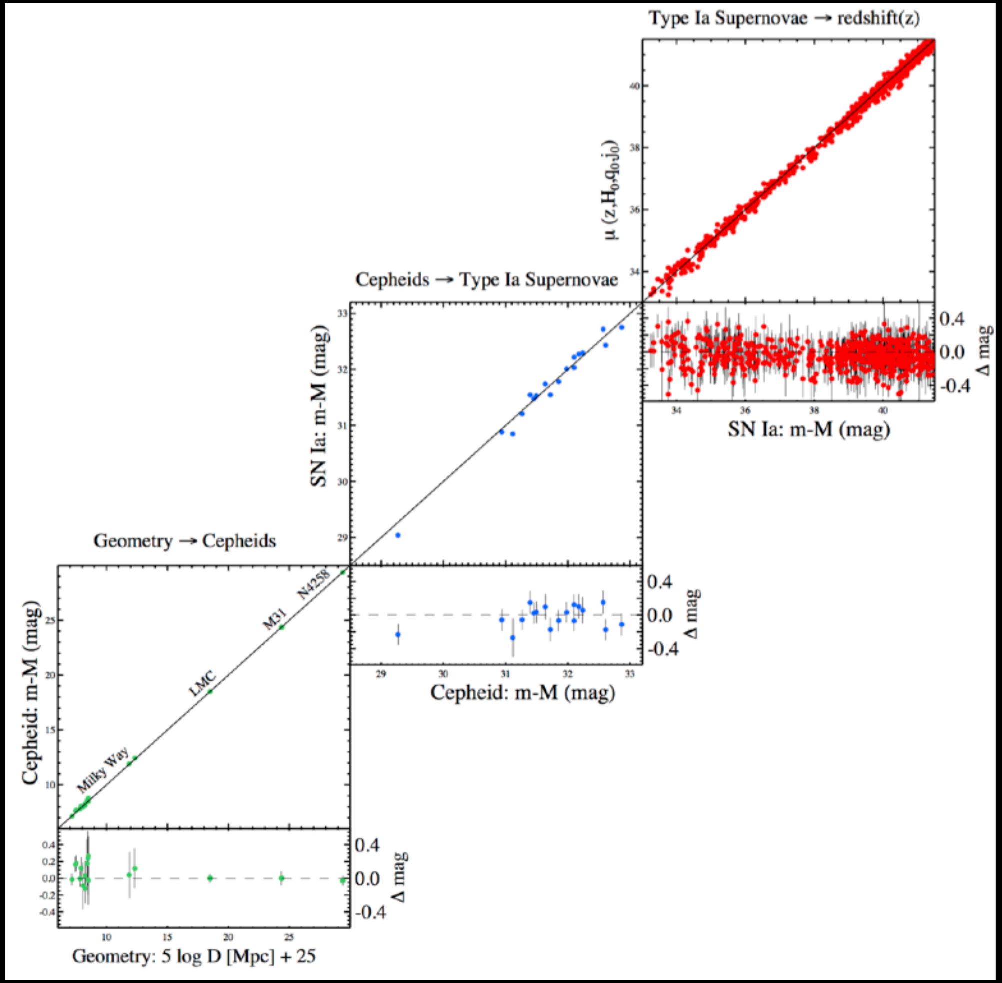
For w: Care about 1% difference between z=0.05 and z=0.5

For H0: Care about 4% difference between z=0.005 and z=0.05



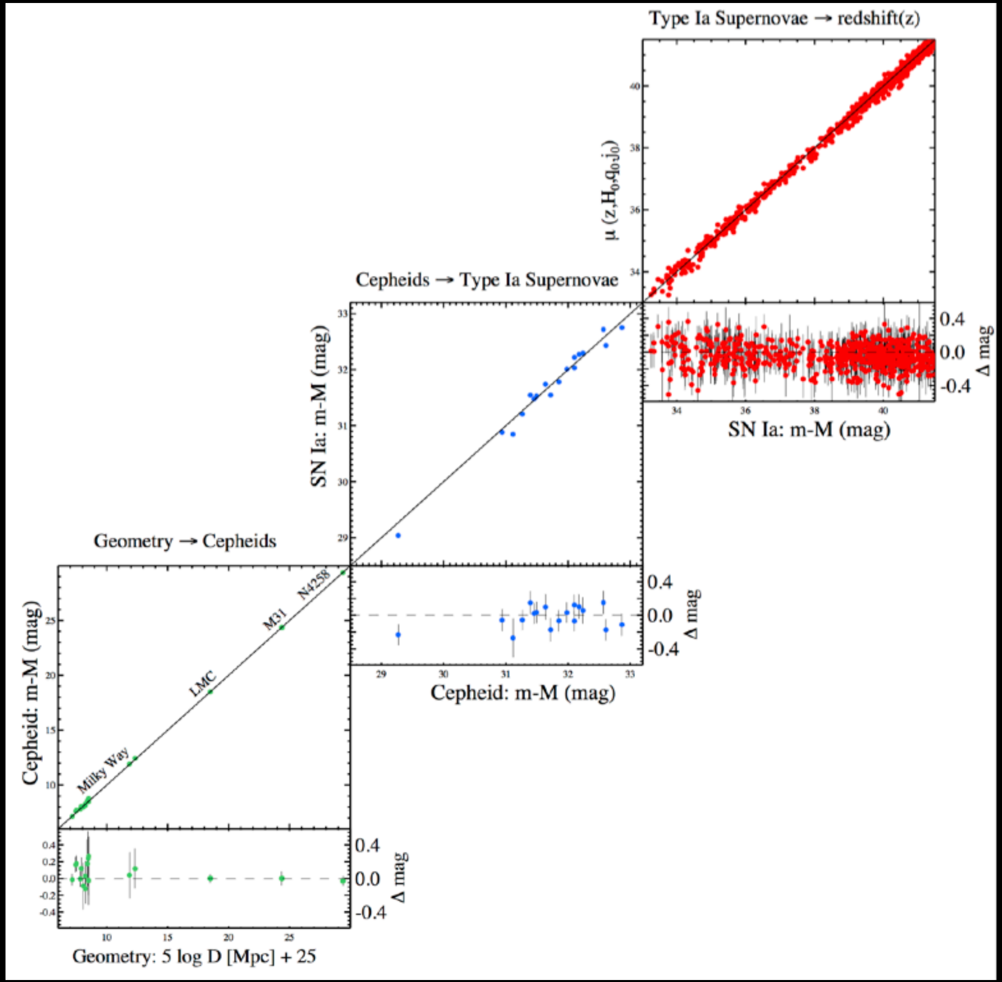
For H0:
Most important aspect of the distance ladder measurement is that analysis and samples between rungs are self-consistent. This means same telescopes, zero points, calibration, fitting methods, higher-order corrections…

For w: This is naturally harder. Have to deal with k-corrections, different surveys, different filters, evolution…



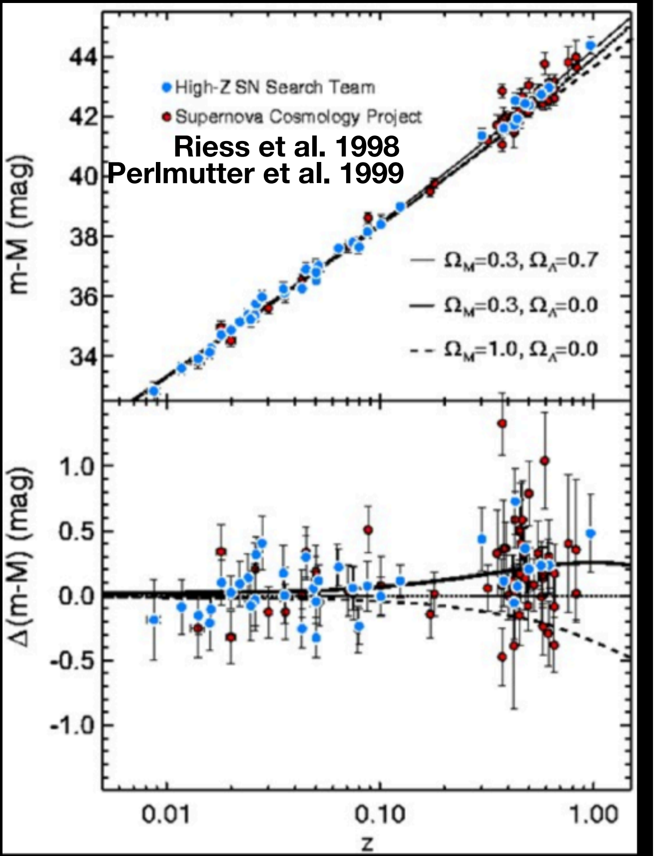
For H0:
Most important aspect of the distance ladder measurement is that analysis and samples between rungs are self-consistent. This means same telescopes, zero points, calibration, fitting methods, higher-order corrections…

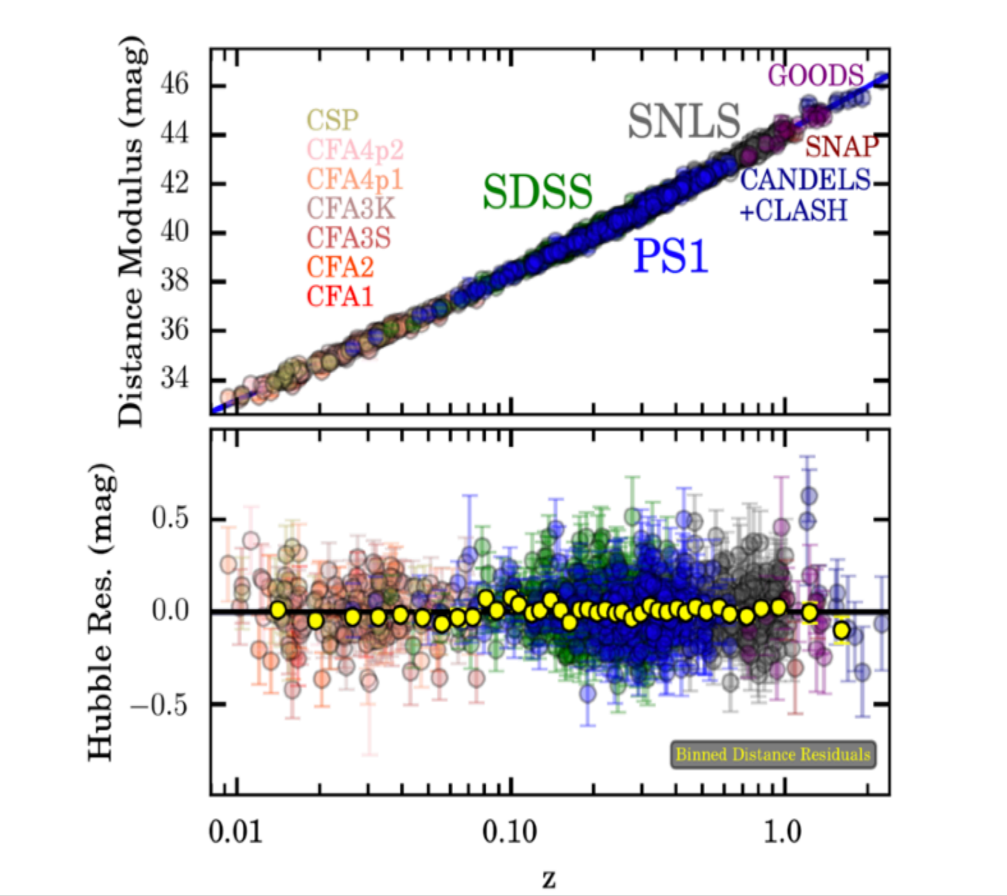
For w: This is naturally harder. Have to deal with k-corrections, different surveys, different filters, evolution…

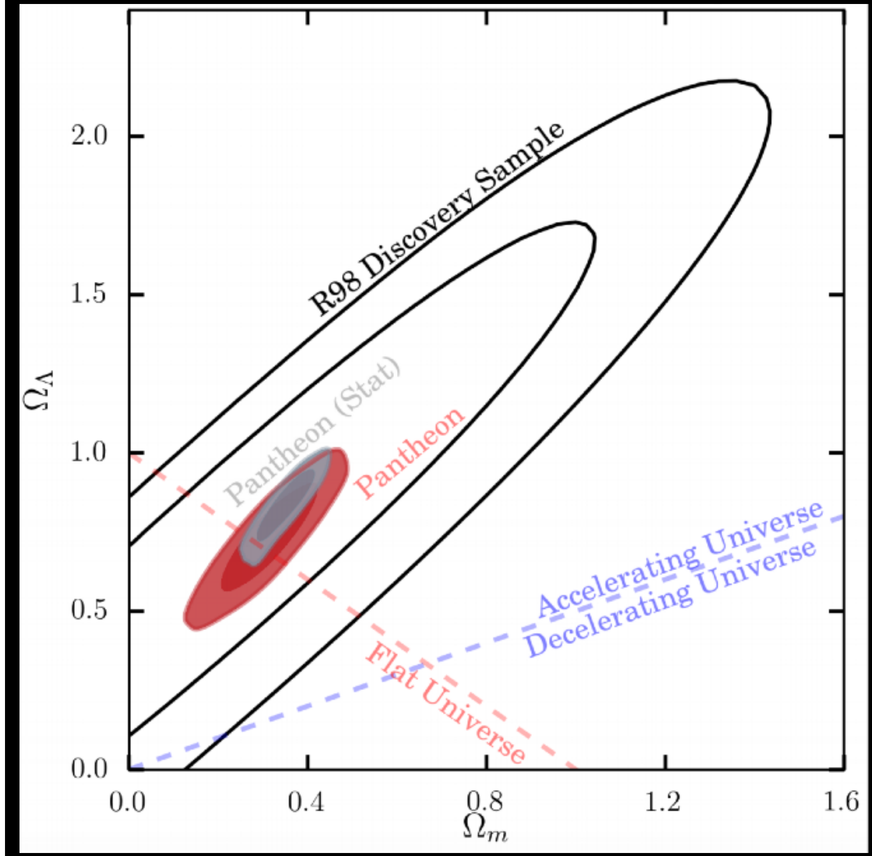


Riess+ (2016)

Supernova cosmology sample public, accessible, and shows while continual improvements, progress has been relatively straightforward

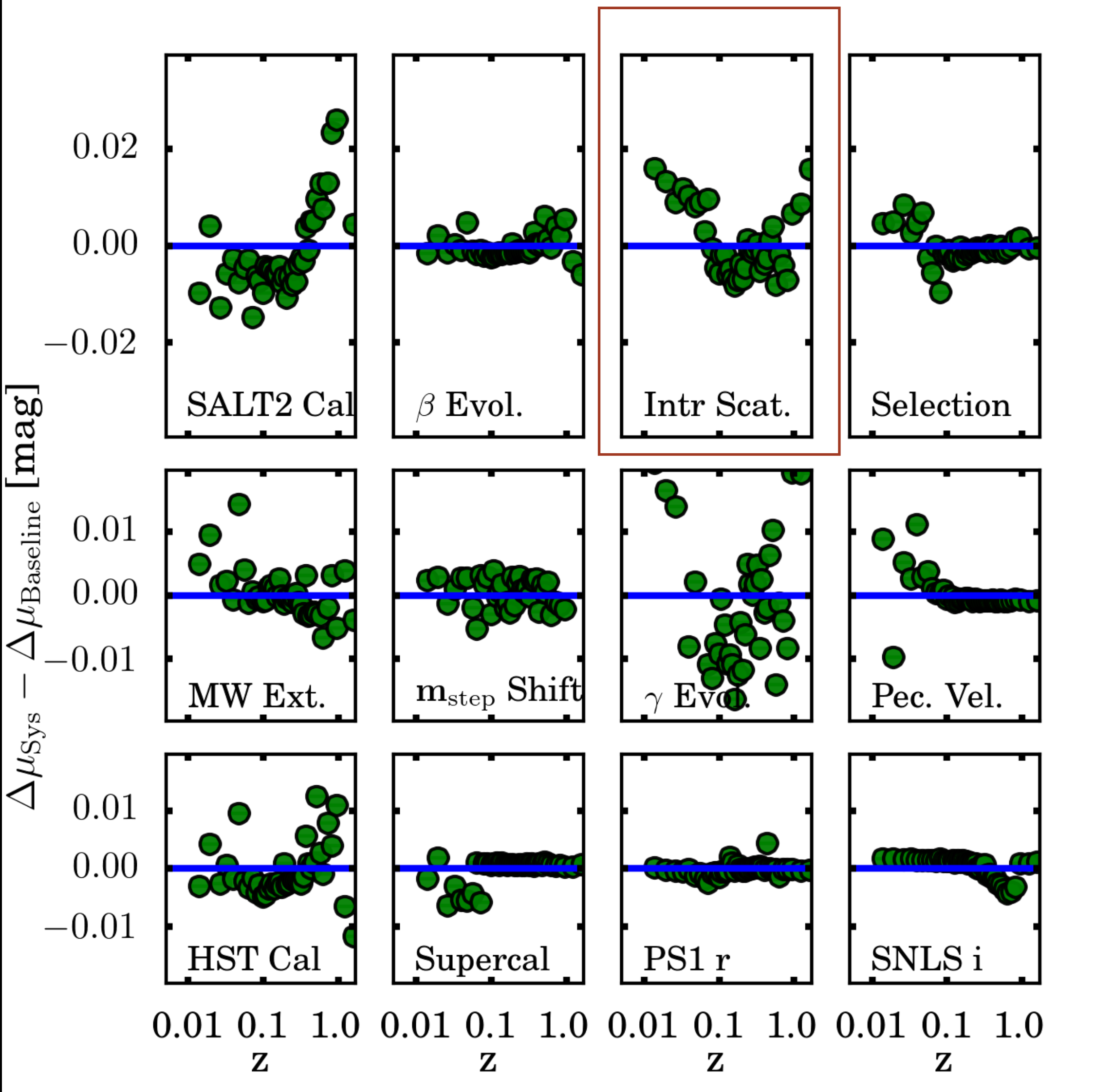




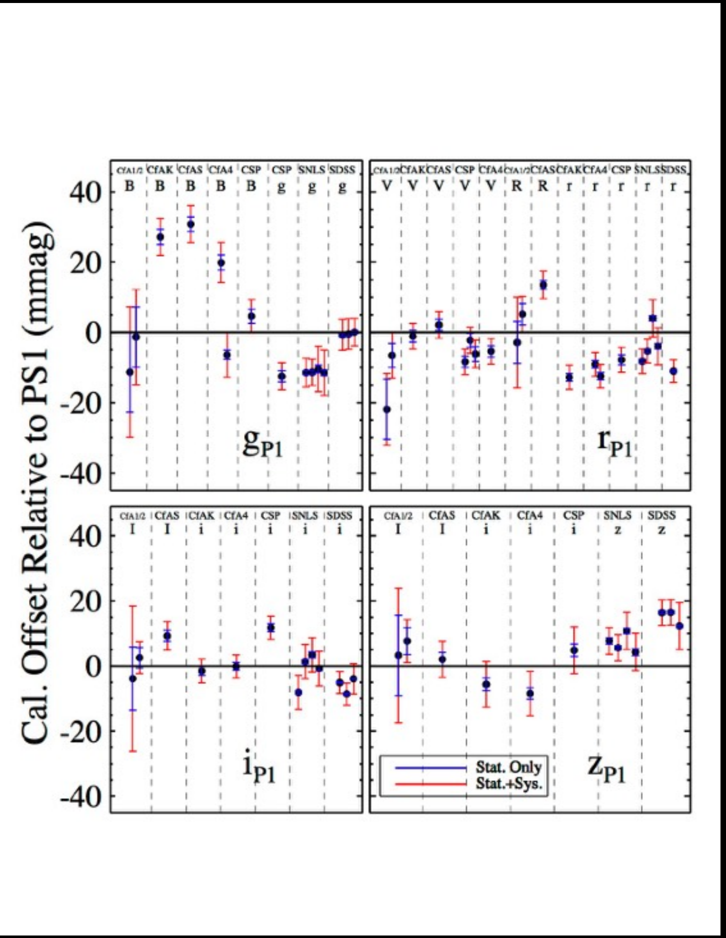


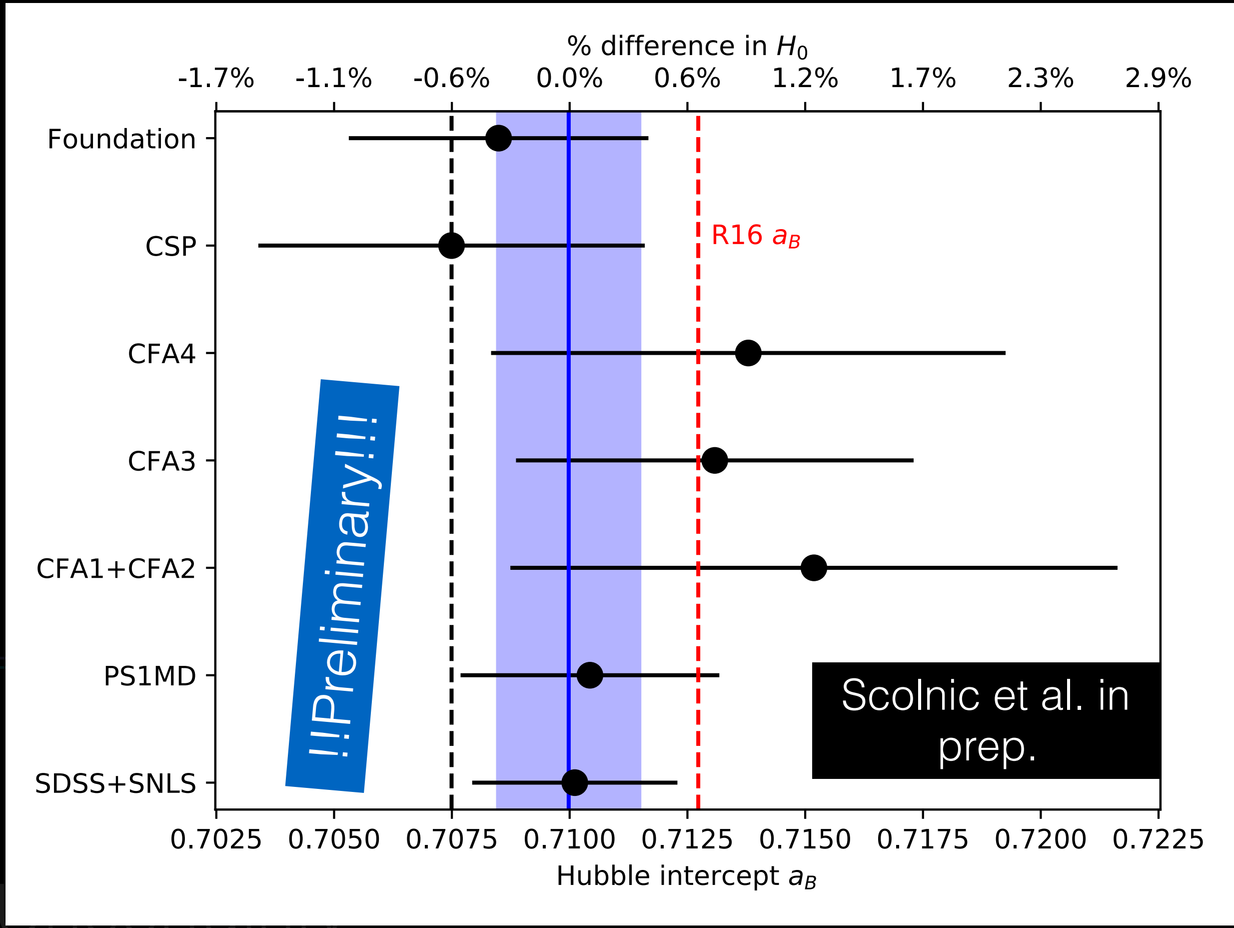
Analyzed 1,050 SNIa [PS1+Low-z+SNLS+SDSS+HST] from z=0.01 to z=2.3
Biggest SN sample to date and first homogeneously calibrated sample

When Pantheon is binned down, one is going to see ‘curiosities’, but a lot of these are systematics. Most of our time is trying to reduce these, but can’t eliminate (yet) on 1-2% level. Still this is 10x smaller than H0 tension.



We homogenize calibration systems as best as we can, but still left with ~1% systematics and small sample differences.



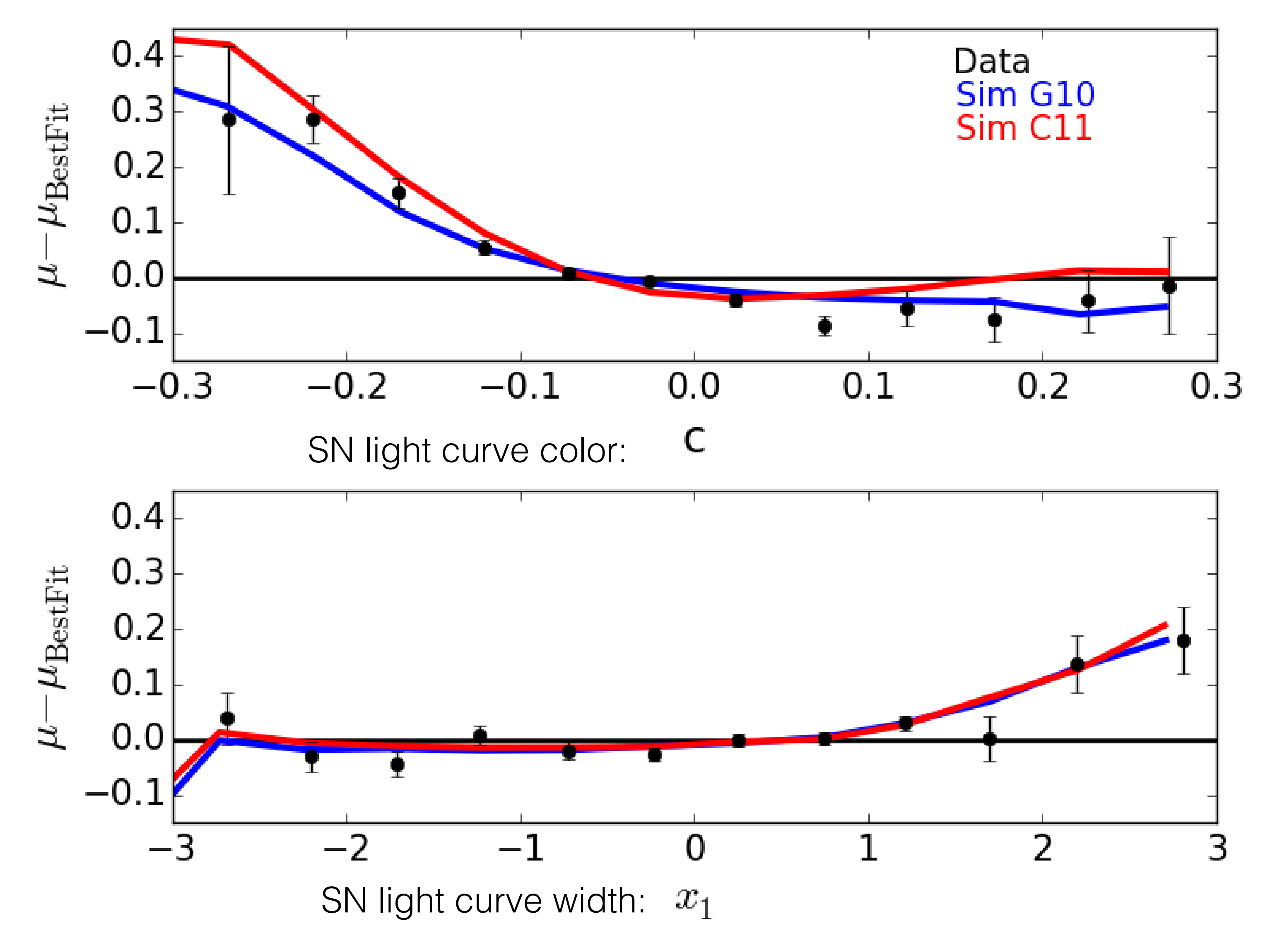


With new Foundation, would shift our H0 measurement by 0.5%. This is pulled by CSP (new release) and Foundation. Still CMB value is 9% away, here we show 0.4% error in mean.

One of key elements of Pantheon analysis is using the BBC methodology which accounts for [expected] distance biases. Scolnic & Kessler 2016 can use fully realized simulations to forward model distance biases, then correct for them with Kessler & Scolnic 2017.

This is like SN's version of BAO's "Distance Reconstruction"

The observed color and stretch distribution is: underlying distribution + physical scatter + measurement error



The signal of this bias, which is entirely predicted from simulations, is 15σ in the Pantheon sample! Way larger than any host effect! And reduces dispersion more than any host effect.

One rather technical word about ‘Model Dependance’ of Pantheon and JLA

- JLA gives light curve fit parameters, user can fit for nuisance parameters at same time as cosmology. However, they also give bias corrections which are set for a fixed nuisance parameters and cosmology

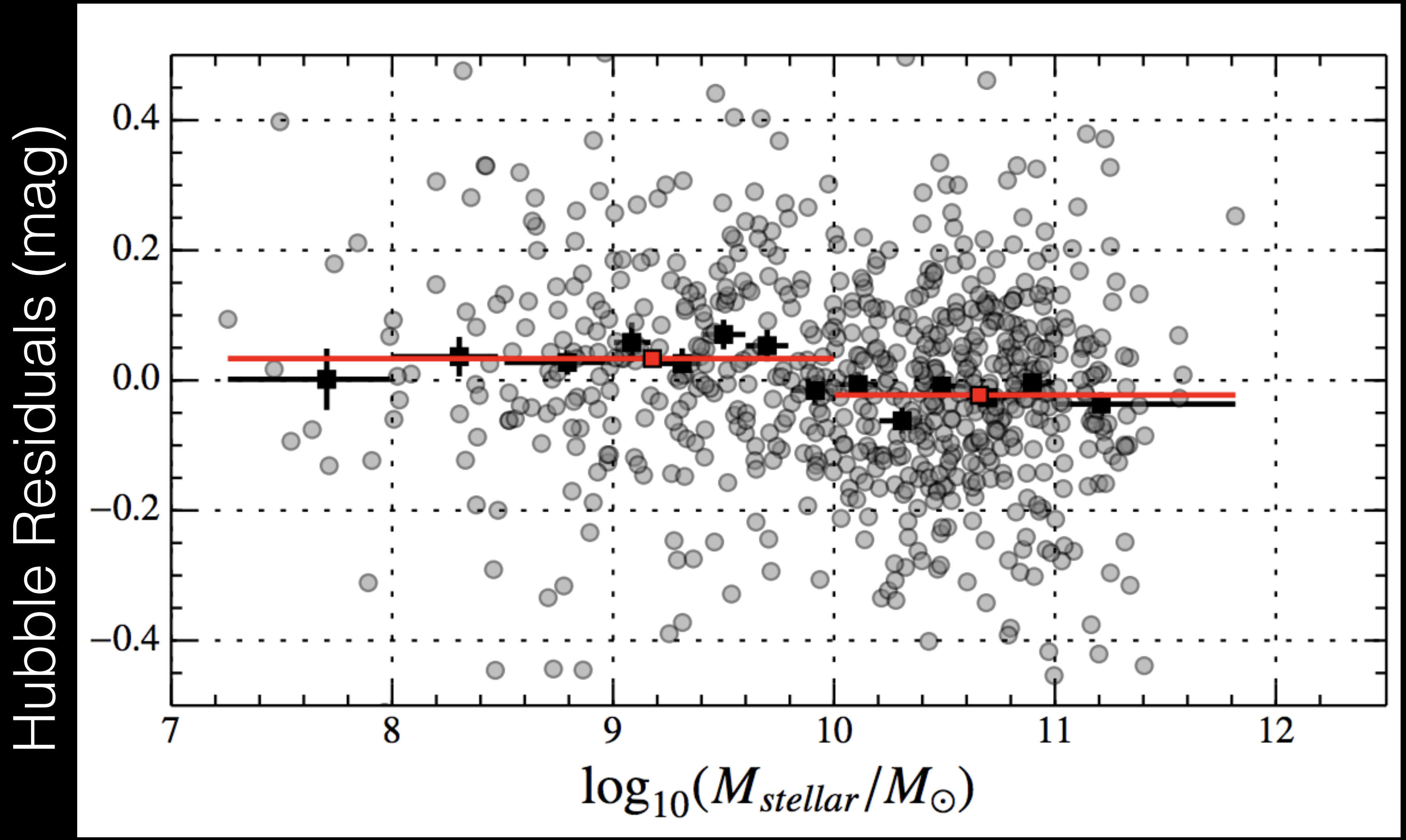
Same biascor applied independent of alpha, beta, cosmology

```
#name zcmb zhel dz mb dmb x1 dx1 color dcolor 3rdvar d3rdvar cov_m_s cov_m_c cov_s_c set ra dec biascor
03D1au 0.503084 0.504300 0.000000 23.001698 0.088031 1.273191 0.150058 -0.012353 0.030011 9.517000 0.110500 0.000790 0.000440 -0.000030 1 36.043210 -4.037469 0.001697
03D1aw 0.580724 0.582000 0.000000 23.573937 0.090132 0.974346 0.273823 -0.025076 0.036691 9.169000 0.088000 0.002823 0.000415 0.001574 1 36.061634 -4.517158 0.000843
03D1ax 0.494795 0.496000 0.000000 22.960139 0.088110 -0.728837 0.102069 -0.099683 0.030305 11.580000 0.112500 0.000542 0.000475 -0.000024 1 36.097287 -4.720774 0.00169
03D1bp 0.345928 0.347000 0.000000 22.398137 0.087263 -1.155110 0.112834 -0.040581 0.026679 10.821000 0.123500 0.001114 0.000616 0.000295 1 36.657235 -4.838779 -0.00027
```

- Pantheon solves for nuisance parameters and bias corrections simultaneously while attempting to minimize the model dependance of the simulations. Does this by introducing redshift binning, subtracting out cosmology, and also iterating over best fit cosmology. Then ultimately gives redshifts and distances for minimal cosmology dpeendance.

```
#name zcmb zhel dz mb dmb x1 dx1 color dcolor 3rdva
03D1au 0.50349 0.504299 0.0 22.93445 0.12605 0 0 0
03D1ax 0.4952 0.496005 0.0 22.8802 0.11765 0 0 0 0
03D1co 0.6782 0.678997 0.0 24.0377 0.2056 0 0 0 0
03D1ew 0.8672 0.868006 0.0 24.34685 0.17385 0 0 0
03D1fq 0.7992 0.799997 0.0 24.3605 0.17435 0 0 0 0
03D3ay 0.37129 0.370894 0.0 22.28785 0.1245 0 0 0
03D3bl 0.35568 0.355297 0.0 22.05915 0.12645 0 0 0
03D4ag 0.28391 0.284998 0.0 21.40915 0.1028 0 0 0
```

There is evidence for a fourth standardization parameter that is related to host galaxy properties



Host galaxy mass.

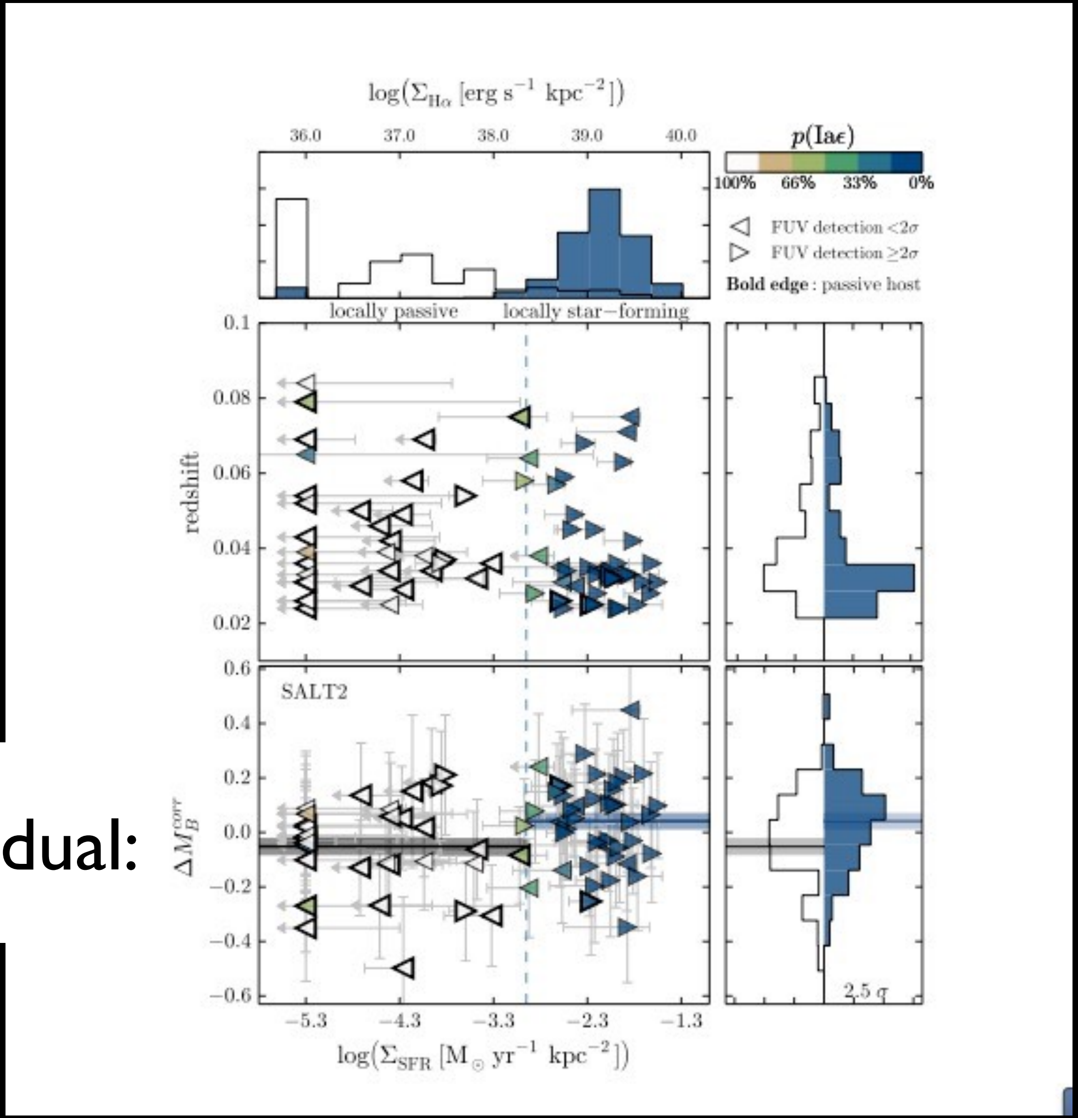
Betoule 14

We correct for this effect. But lots of discussion on other galaxy properties…

A changing Hubble step has been predicted by Rigault 2015 due to correlation of local star formation with Hubble residual. Fraction of galaxies with local sfr changes with redshift.

This is instead of the mass correction, use local sfr

Hubble Residual:



Hardest part: SNFactory data (2005-2010) not public!

Is there something special about SH0ES SNe?
Set complete for z<0.01 for late type hosts.

With next data release -> doubling of the CC sample, and cutting to late-type hosts, we will reduce sensitivity HF-CC differences to 0.2 dex in H0

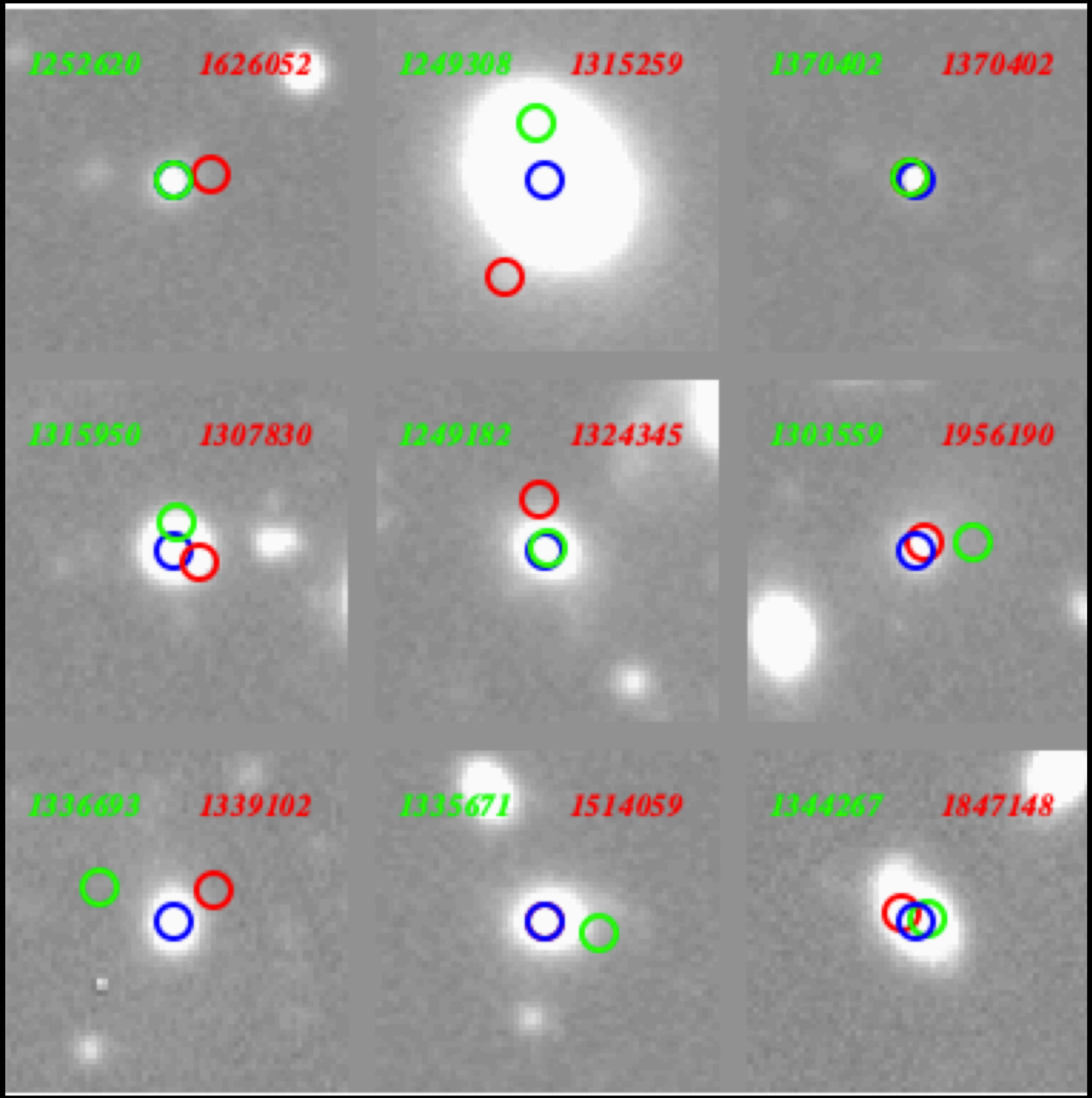
SN Host Property in R16 (Pantheon z<0.15) sample	Step Size	Step Significance	% HF-CC R16	Delta H_0 R16 (km/s/Mpc)	% HF-CC R20 in prep	Delta H_0 R20 in prep (km/s/Mpc)
Local mass > 8.3 dex	0.055 +/- 0.17	3.2	15.3%	-0.28	-15.2%	+0.28
Global mass > 10 dex	-0.002 +/- 0.018	0.1	22.6%	0.02	-8.7%	0.00
Local u-g > 1.3	0.033 +/- 0.020	1.7	39.5%	-0.44	18.7%	-0.21
Global u-g>1.3	0.035 +/- 0.020	1.8	20.2%	-0.24	17.3%	-0.21
Local sSFR < -10.6	0.035 +/- 0.021	1.7	30.9%	-0.37	15.1%	-0.18
Global sSFR < -10.6	0.029 +/- 0.020	1.4	21.1%	-0.21	19.3%	-0.19
			Mean=24.9% Max=39.5% Only Sig=15.3%	-0.31 -0.44 -0.28	Mean=11.0% Max=19.3% Only Sig=-15.2%	-0.10 -0.21 +0.28

There will continue to be ‘new’ host prioperties found that seem to correlate. How do we constrain this?

With DES sample, can do first systematic study of ‘Supernova Siblings’. Can use this to study host-SNIa correlations…

Have ~9 from DES alone.

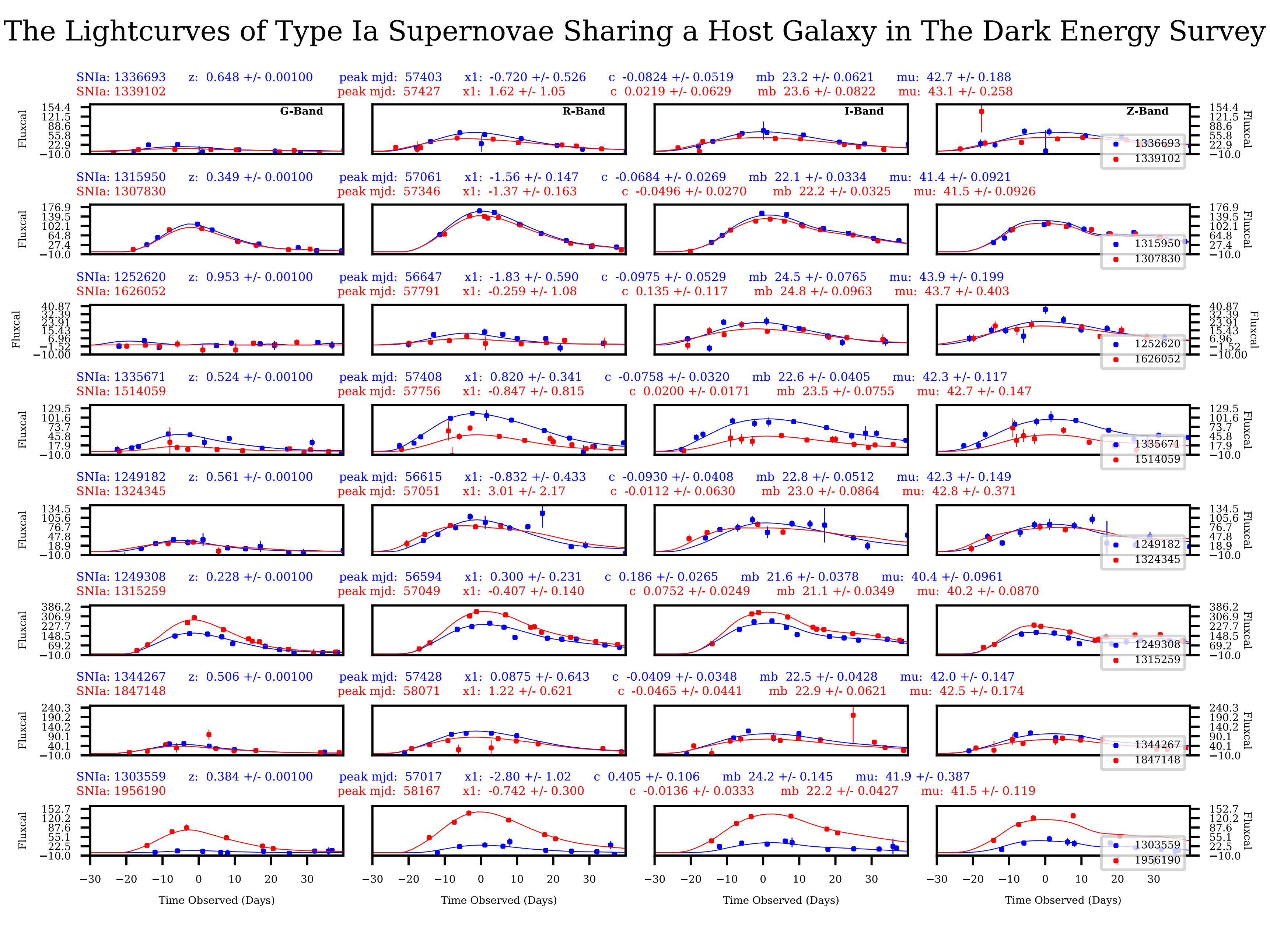
[Scolnic et al. 2019 in prep.]



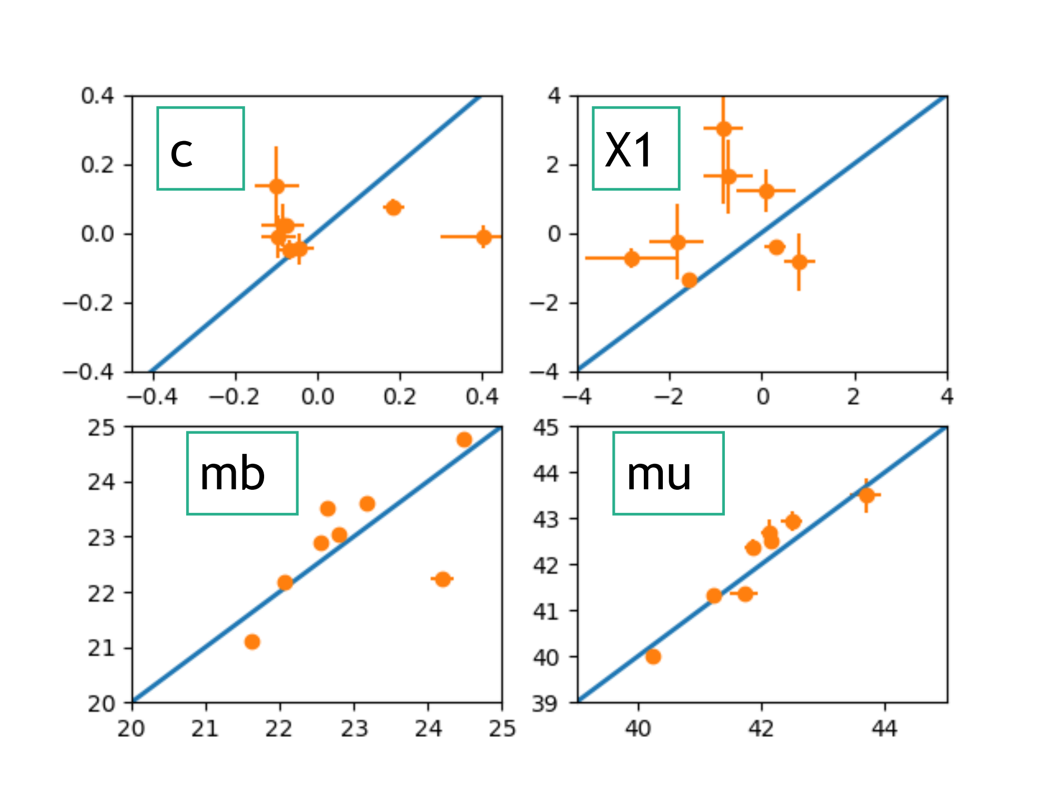
With DES sample, can do first systematic study of ‘Supernova Siblings’. Can use this to study host-SNIa correlations…

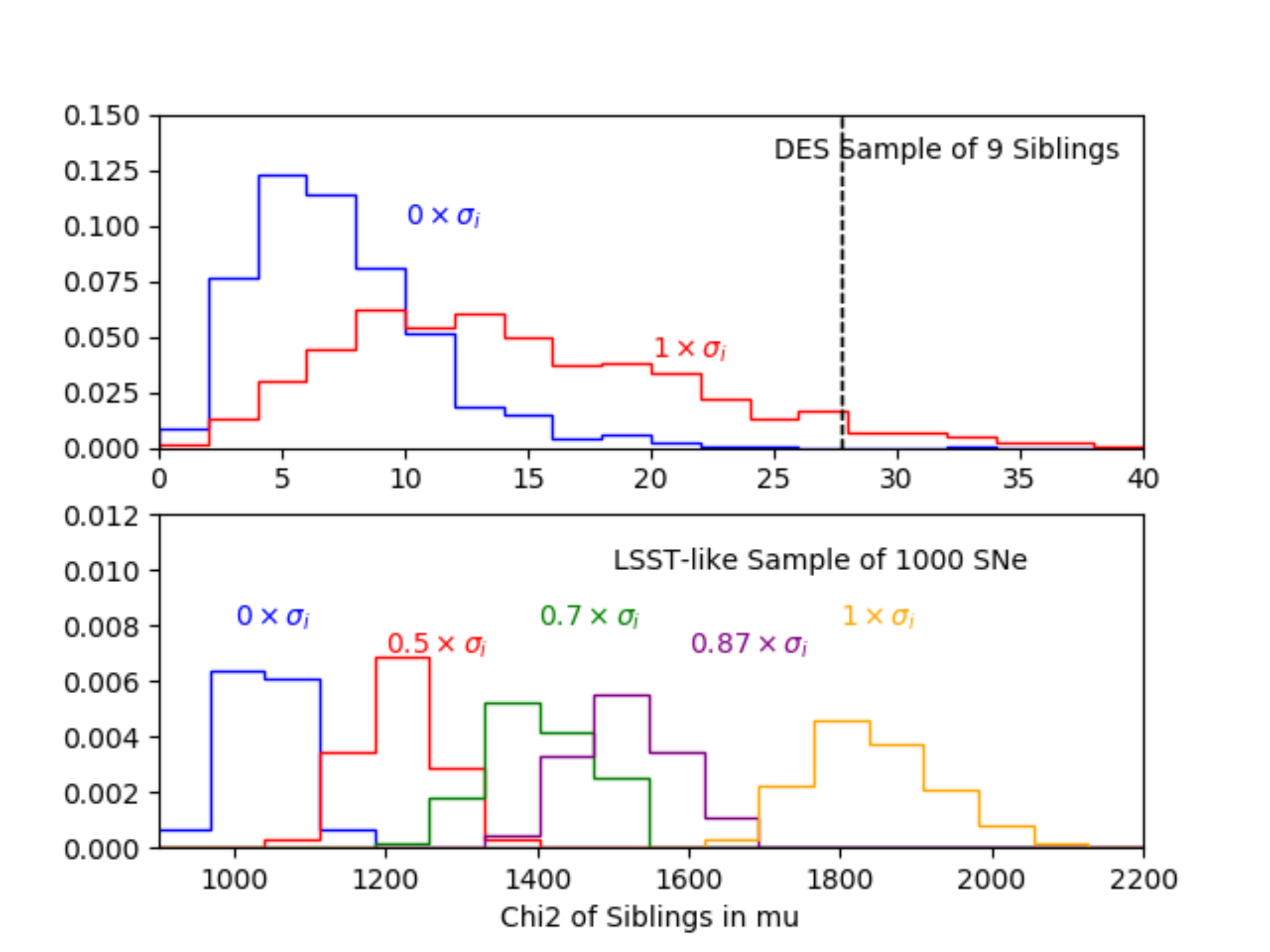
Have ~9 from DES alone.

[Scolnic et al. 2019 in prep.]



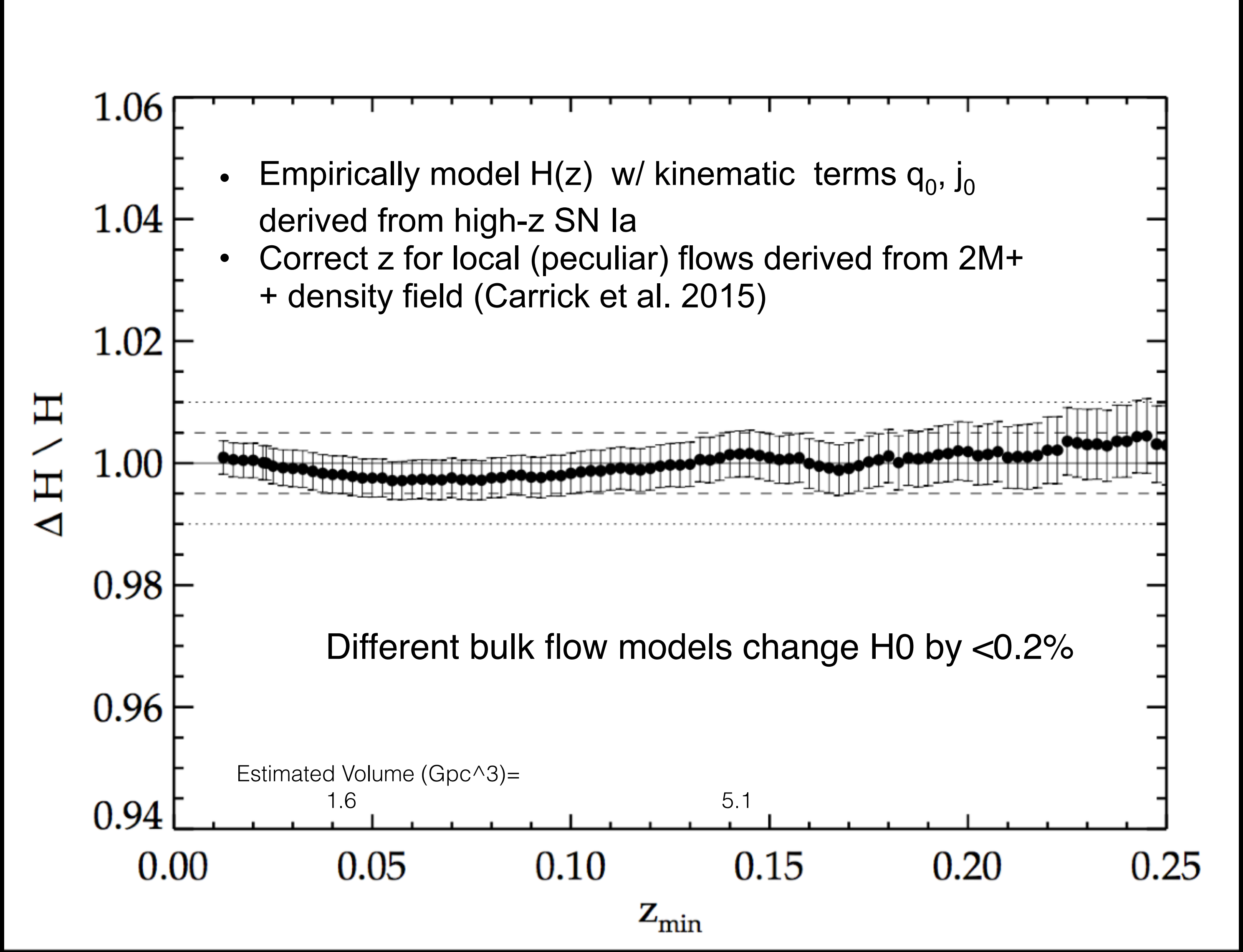
So far, do not see great evidence for agreement in parameters compared to two random SNIa





In R16, we claimed cosmic variance issues <0.5% (after correcting for peculiar flows)

Scolnic et al. 2018 compares z~0.01 SNe to z~0.05 SNe, computes much larger peculiar velocity scatter.

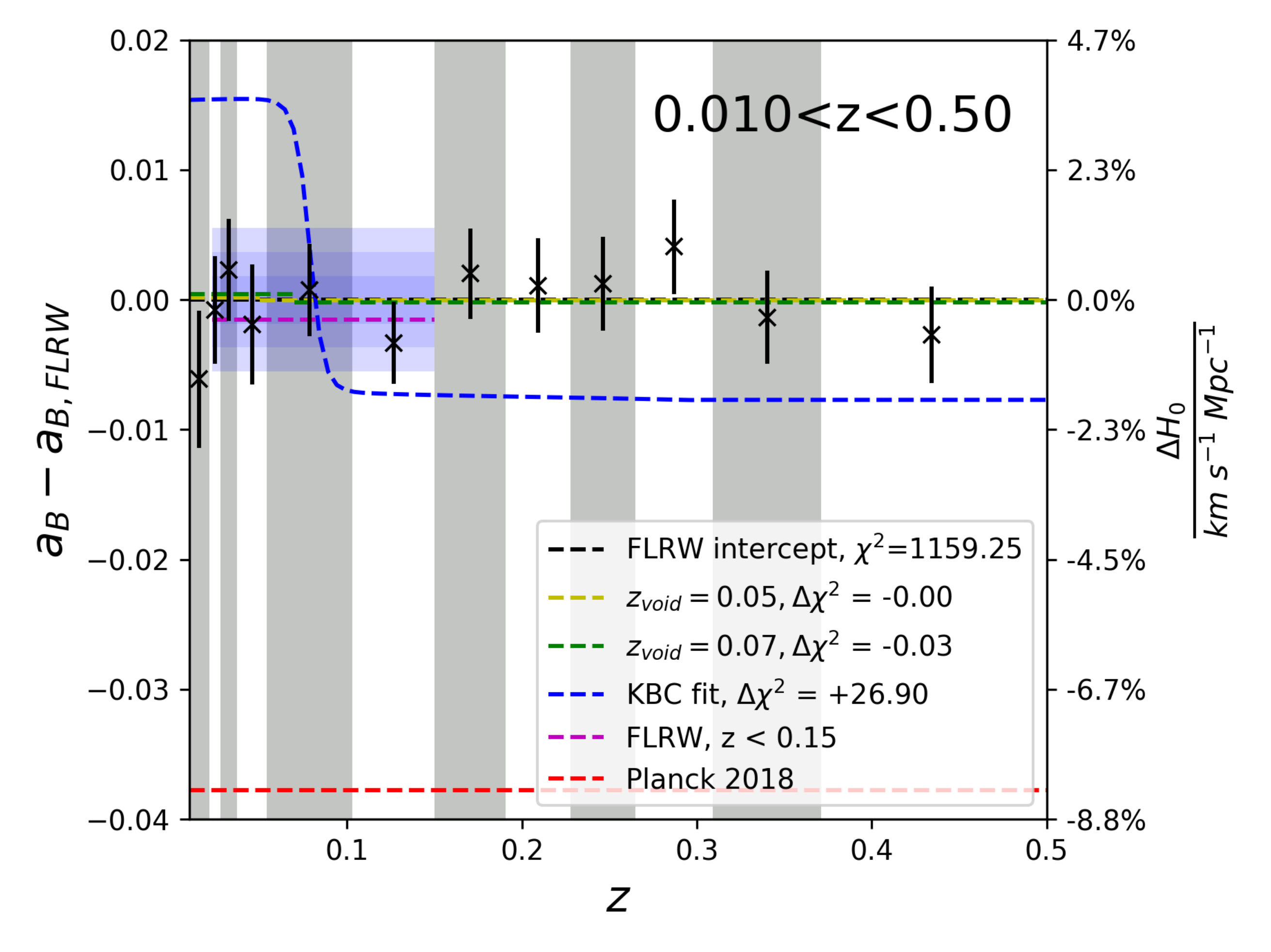


Test: explore larger volume, $z_{min}<z<z_{min}+0.15$, $\Delta H_0 < 0.4\%$

- N-body sims in 700 Mpc box → 0.3% (Odderskov et al. (2016)

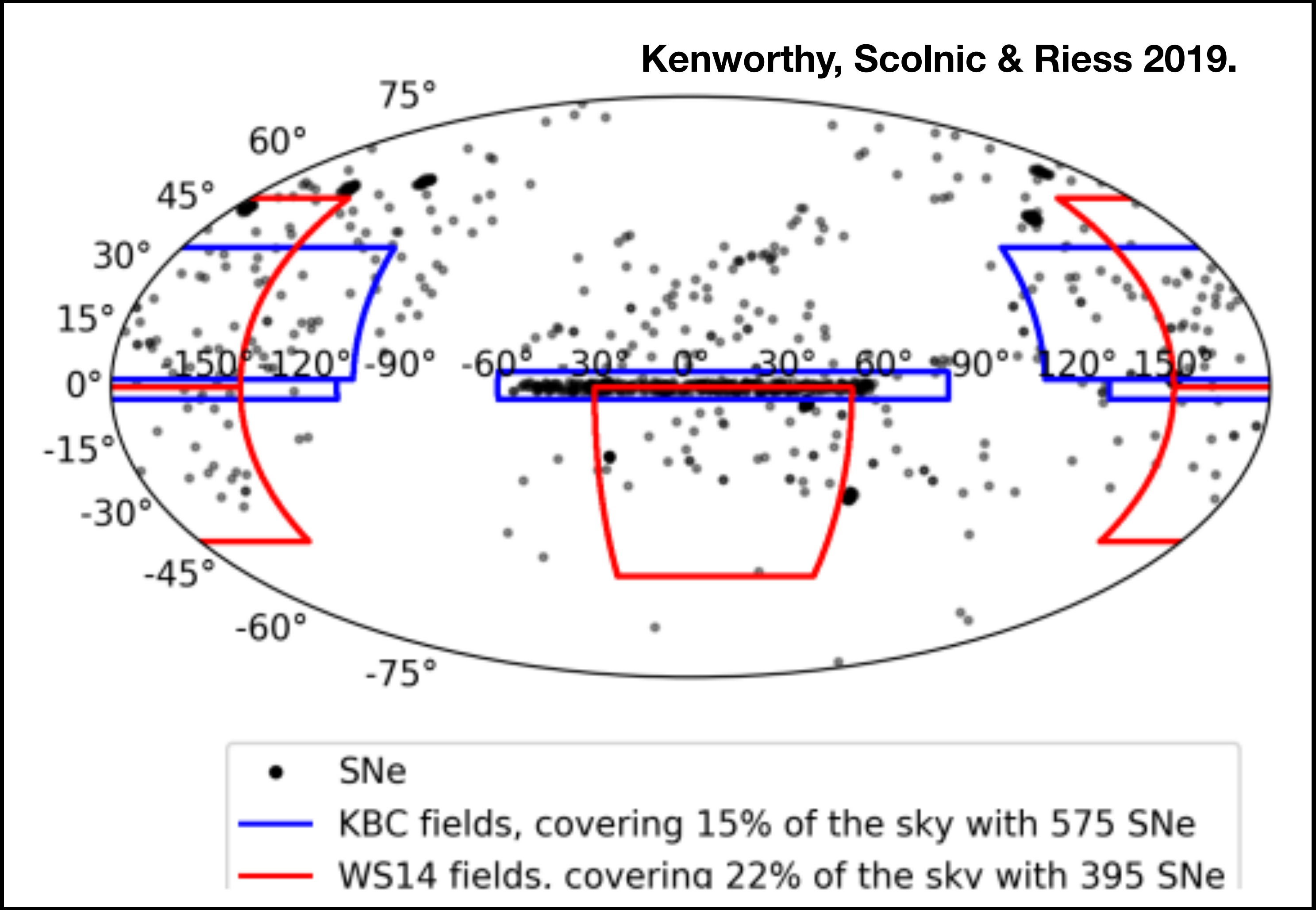
Better constraint from looking at intercept in individual bins.

Kenworthy, Scolnic & Riess 2019.



But with SN data we see no evidence for kink in Hubble Diagram.

Part of issue is that SNe unevenly distributed across the sky.
Data for void models are too..



Variance in H0 consistent with N-body simulations - <0.5% of H0

Can H0 tension be recast as Omegam tension? Hard to see how this works.

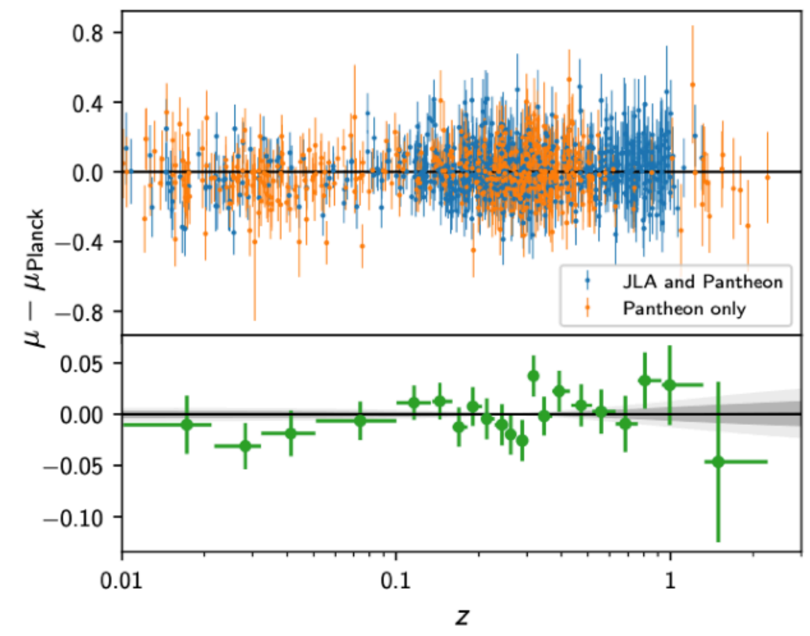
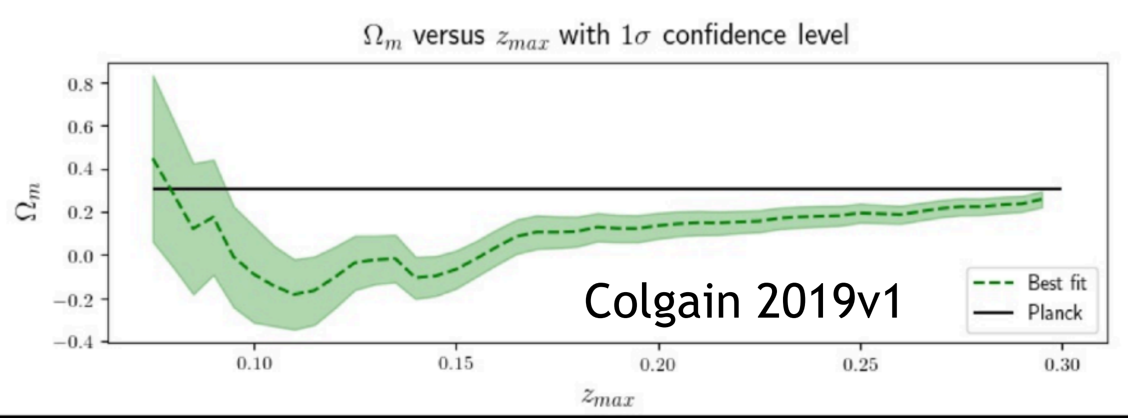
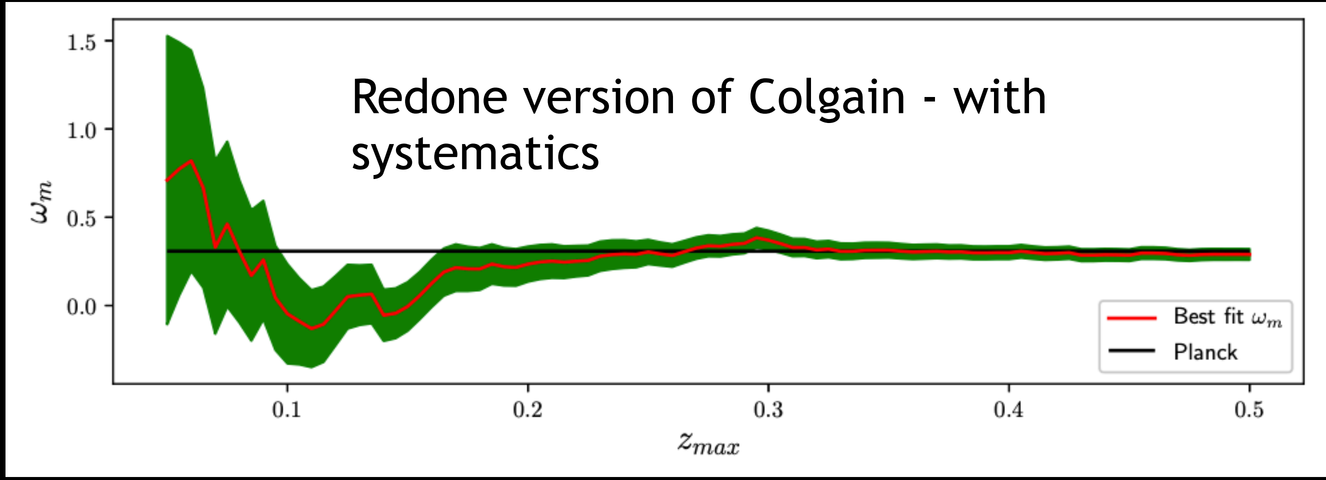


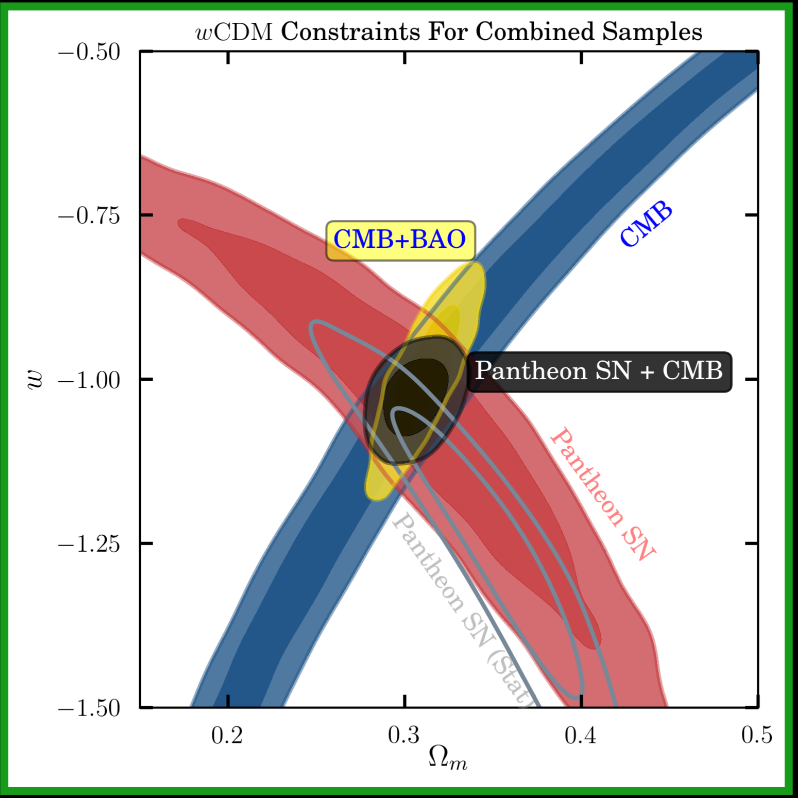
Fig. 13. Distance modulus $\mu = 5\log_{10}(D_{\rm L}) + \text{constant}$ (where $D_{\rm L}$ is the luminosity distance) for supernovae in the Pantheon sample (Scolnic et al. 2018) with 1σ errors, compared to the *Planck* TT,TE,EE+lowE+lensing ΛCDM best fit. Supernovae that were also in the older Joint Lightcurve Analysis (Betoule et al. 2014, JLA) sample are shown in blue. The peak absolute magnitudes of the SNe, corrected for light curve shape, colour and host-galaxy mass correlations (see Eq. 3 of Scolnic et al. 2018), are fixed to an absolute distance scale using the H_0 value from the *Planck* best fit. The lower panel shows the binned errors, with equal numbers of supernovae per redshift bin (except for the two highest redshift bins). The grey bands show the ±1 and 2σ bounds from the *Planck* TT,TE,EE+lowE+lensing chains, where each model is calibrated to the best fit as for the data.



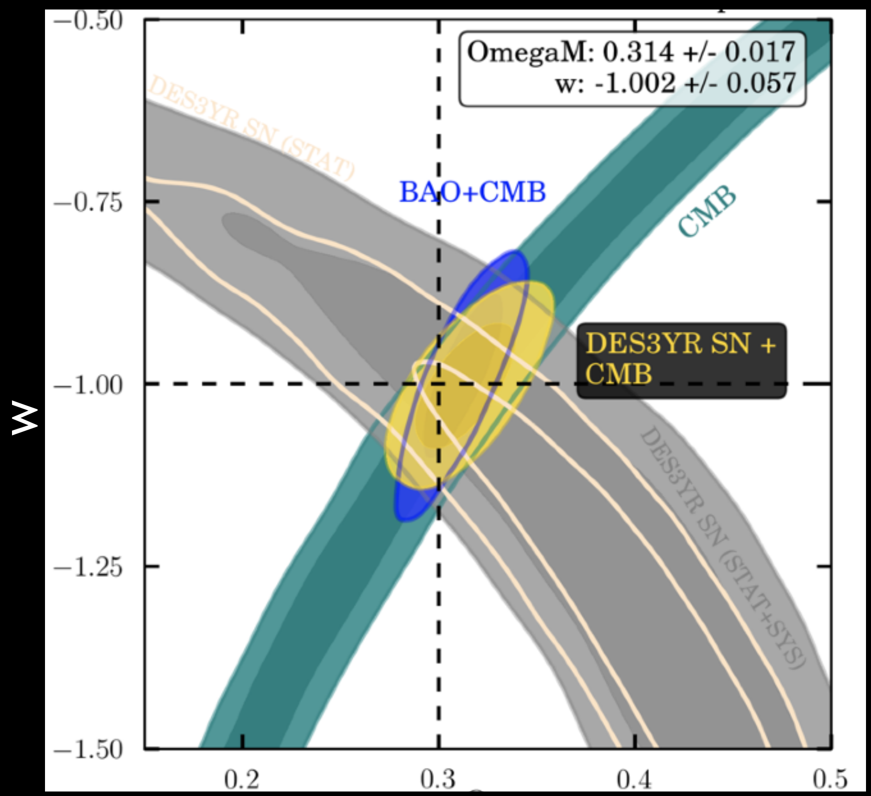


Pantheon in very good agreement with PS1-Photometric Sample, DES Photometric Sample.

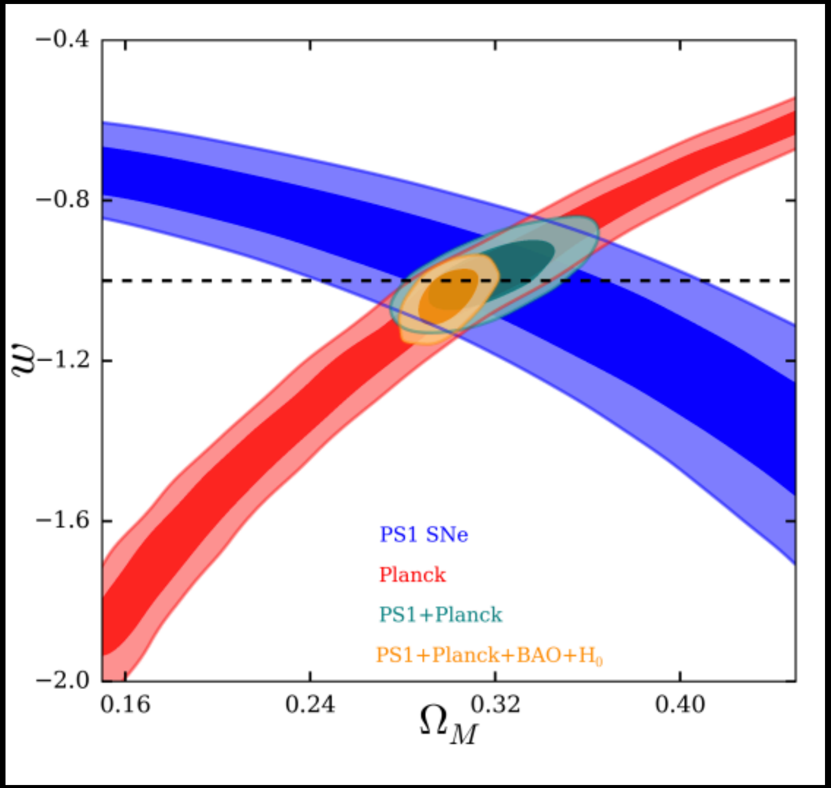
All analyses hare within 1sigma of w=-1



Scolnic et al. 2018



Brout et al. 2019



Jones et al. 2018

All samples share ~common low-z SNe, will be added to with new Foundation, in future ZTF…

#KITP_H0tTakes:

SNIa are just middleman in difference between SH0ES and CCHP.

Evidence: Calibrating same 10 overlapping SNIa with TRGB versus Cepheids, Fig. 9 shows 0.093 mag difference (0.06 unweighted)

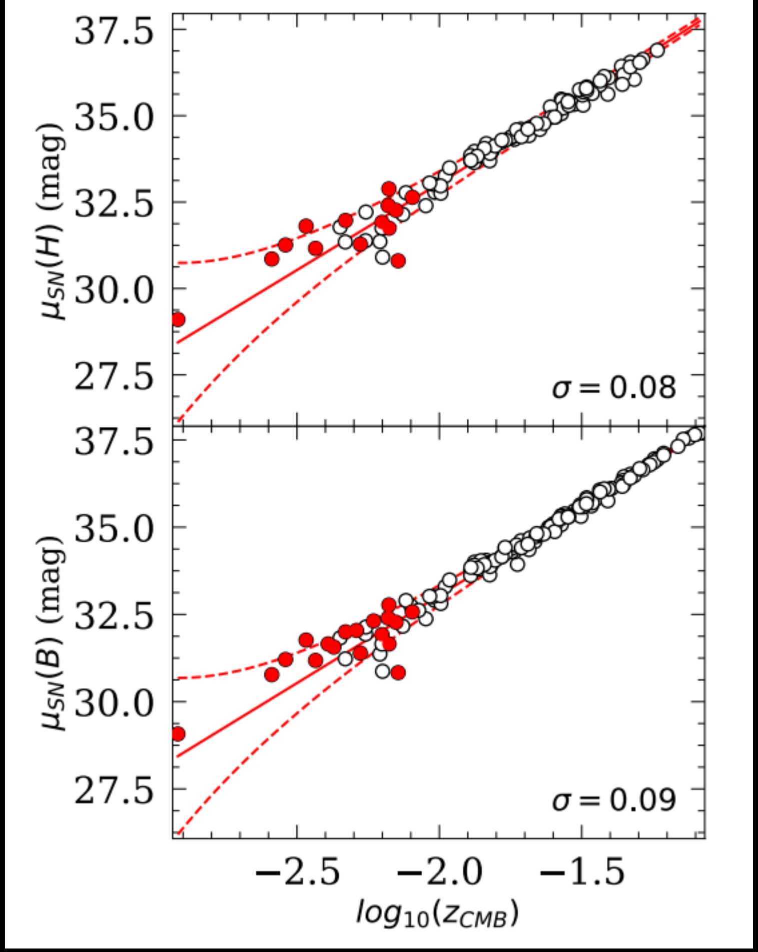
Zeropoint TRGB calibration before was -3.97 mag (Jang +Lee 17), now -4.05 mag. Difference of 0.08 mag.

—> This is a TRGB zero point discussion, not a SN discussion.

Burns et al. 2018 does own SN - H0 analysis (keeps cepheid analysis from R16) and gets very good agreement to within ~0.5 km/s/Mpc

Main differences are:

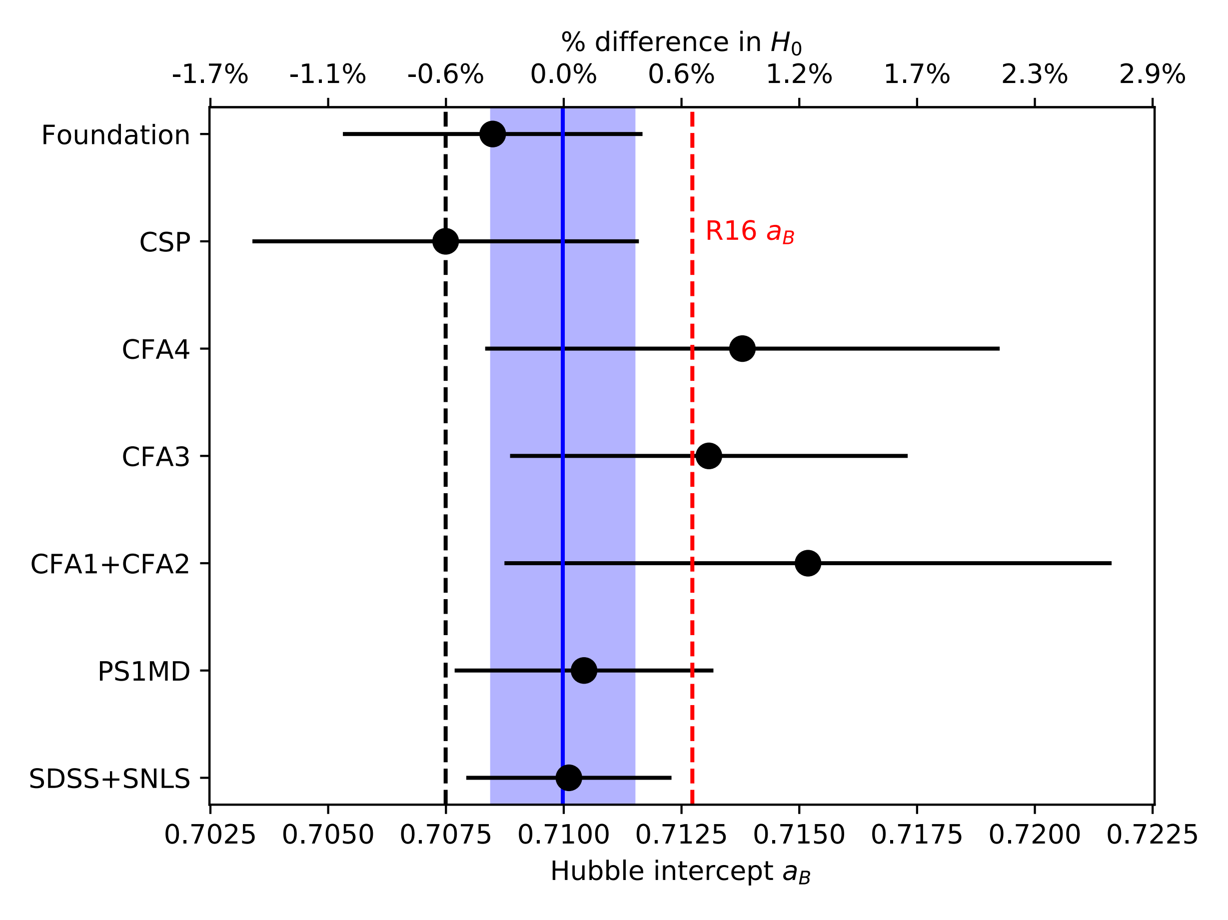
1. Use CSP SN for Hubble Flow sample, mix for CC set
2. Do linear correction for mass, can be very large for CC since limited sample
3. Don't do peculiar velocity corrections
4. Very sensitive to cosmic variance as z<0.06



Burns et al. 2018 does own SN - H0 analysis (keeps cepheid analysis from R16) and gets very good agreement to within ~0.5 km/s/Mpc

Main differences are:

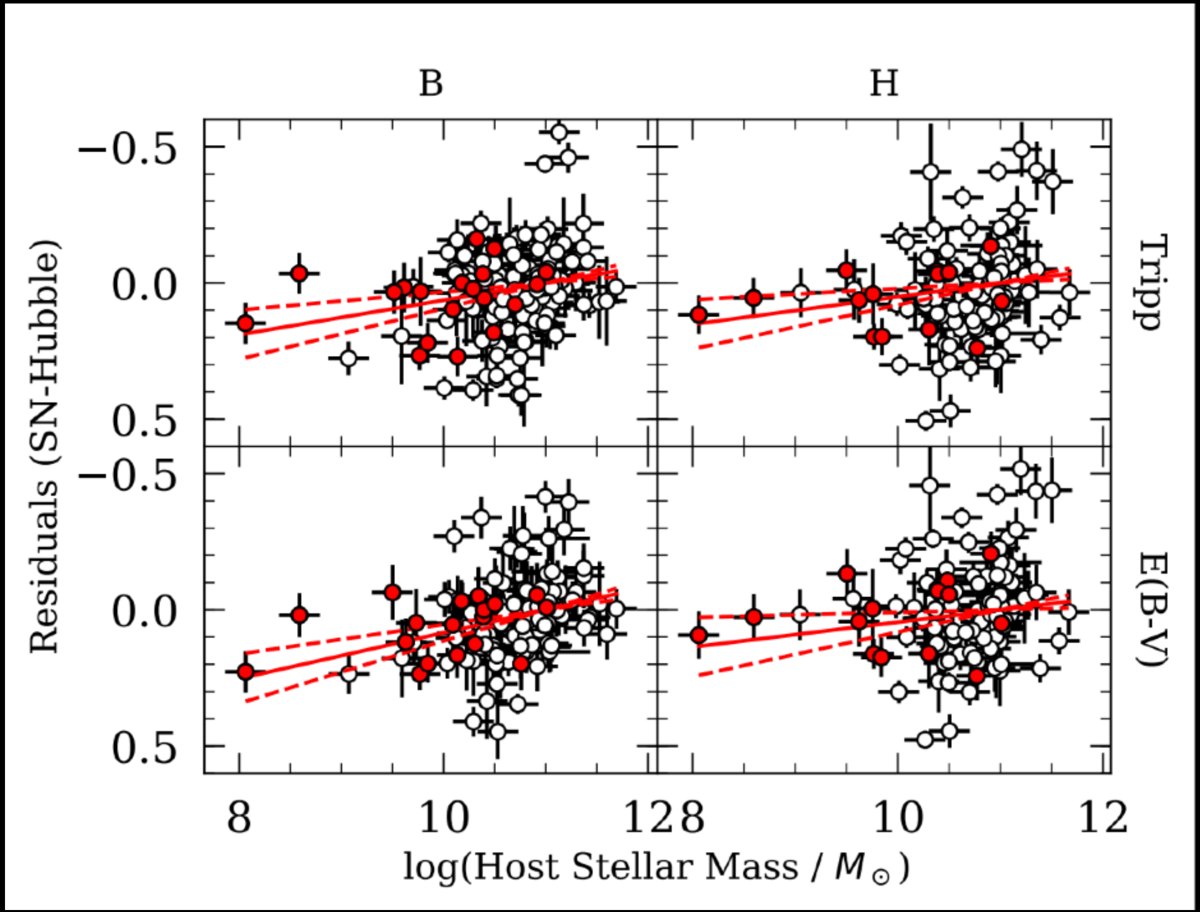
1. Use CSP SN for Hubble Flow sample, mix for CC set
2. Do linear correction for mass, can be very large for CC since limited sample
3. Don't do peculiar velocity corrections
4. Very sensitive to cosmic variance as z<0.06



Burns et al. 2018 does own SN - H0 analysis (keeps cepheid analysis from R16) and gets very good agreement to within ~0.5 km/s/Mpc

Main differences are:

1. Use CSP SN for Hubble Flow sample, mix for CC set
2. Do linear correction for mass, can be very large for CC since limited sample
3. Don't do peculiar velocity corrections
4. Very sensitive to cosmic variance as z<0.06

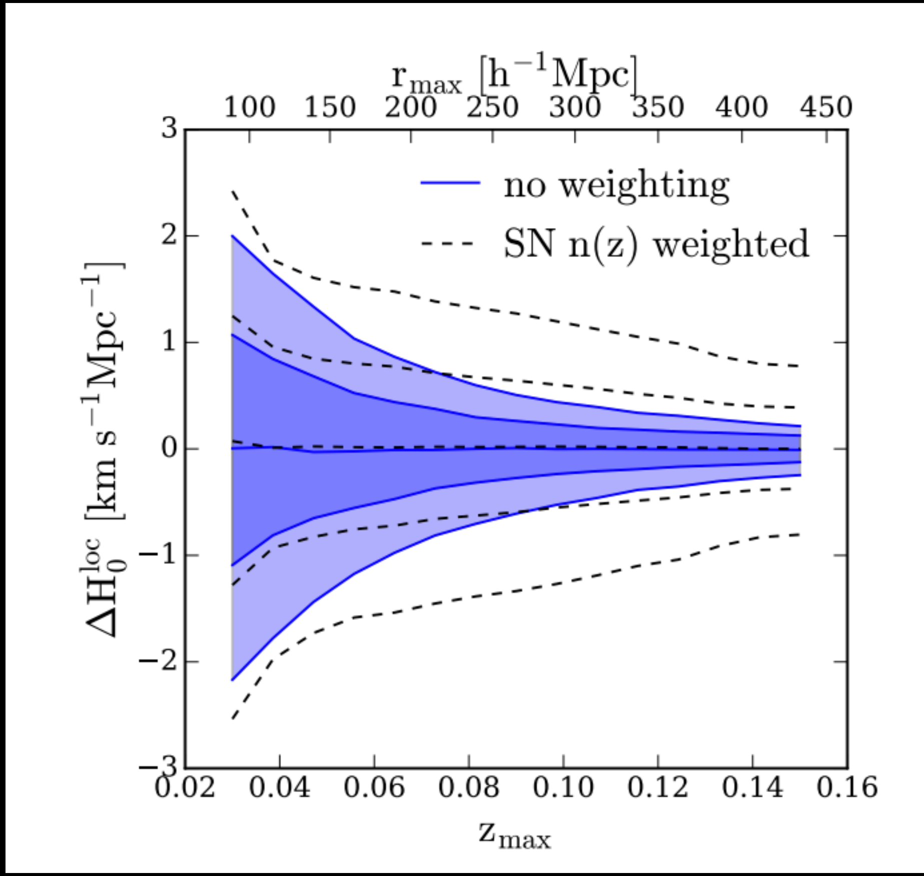


Less sensitivity to host properties in NIR, higher H0

Burns et al. 2018 does own SN - H0 analysis (keeps cepheid analysis from R16) and gets good agreement to within ~0.5 km/s/Mpc

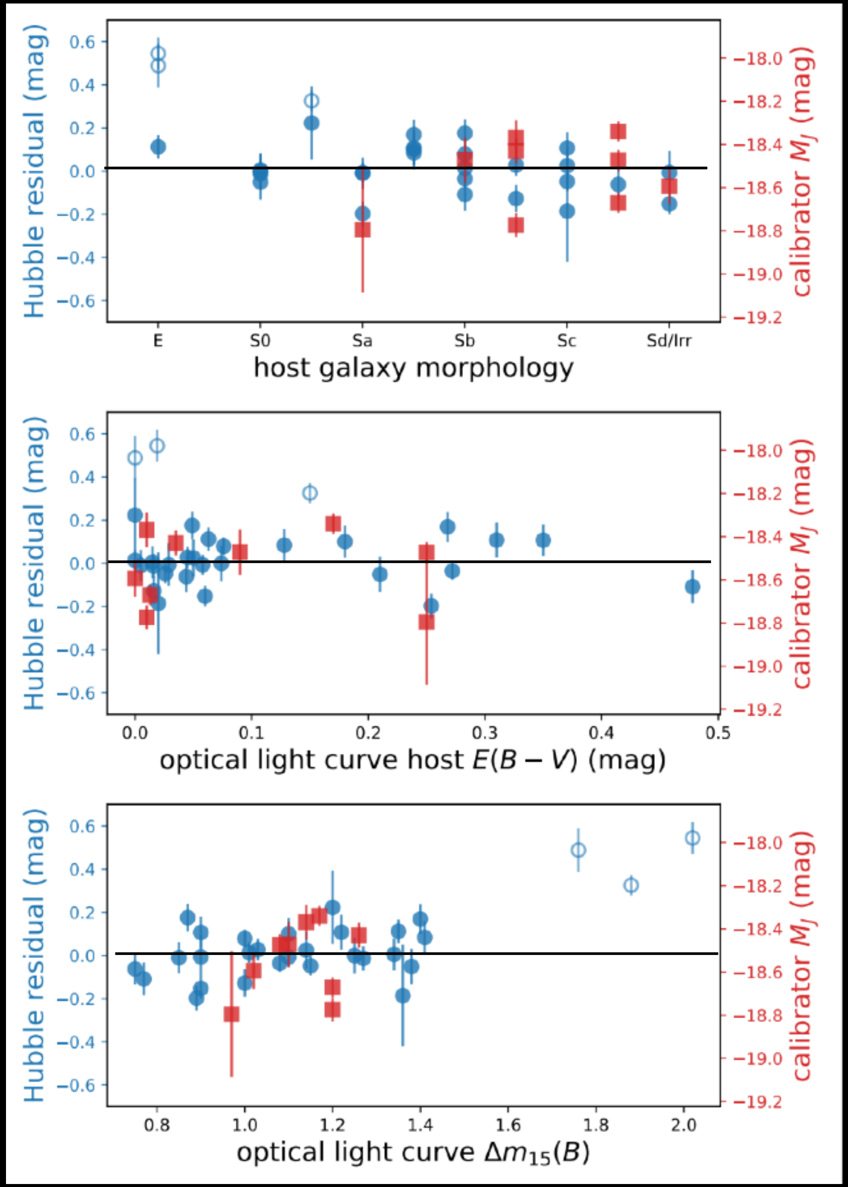
Main differences are:

1. Use CSP SN for Hubble Flow sample, mix for CC set
2. Do linear correction for mass, can be very large for CC since limited sample
3. Don't do peculiar velocity corrections
4. Very sensitive to cosmic variance as z<0.06



Wu+Huterer 2018

Dhawan et al. 2017 use NIR data of SN ‘standard candles’ and find very good agreement to within 0.2 km/s/Mpc.

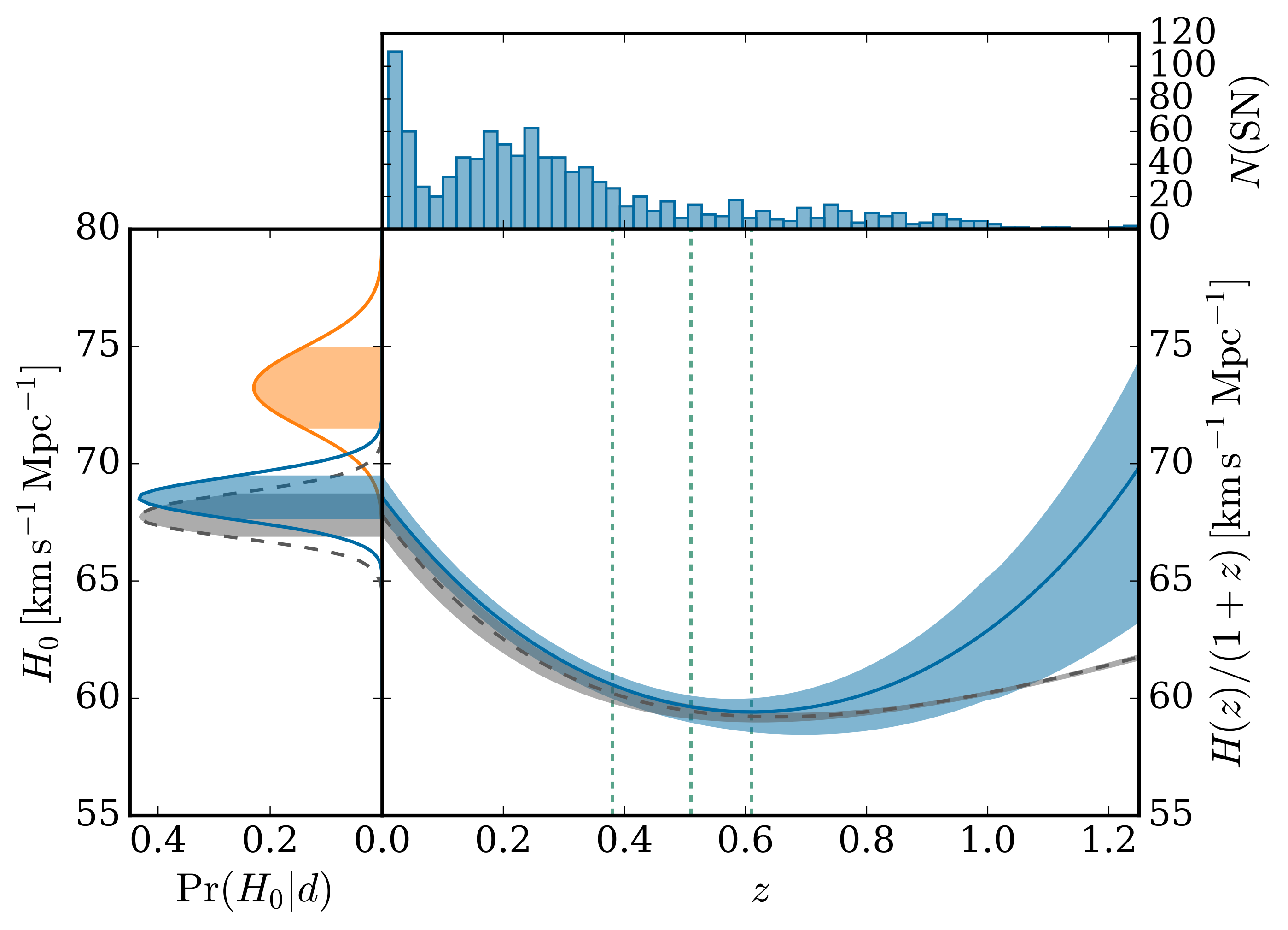


H0 = 72.8 ± 1.6 (statistical) ± 2.7 (systematic) km s−1 Mpc−1

One note:

1. Intrinsic scatter not understood - bigger for calibrator sample than Hubble Flow sample

New analyses are combining Pantheon with BAO and other combinations, find low H0.



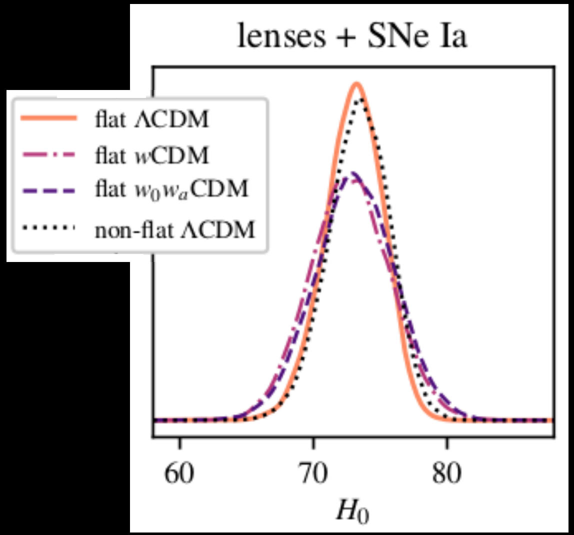
These SNe ~same as SNe used in R16 measurement!

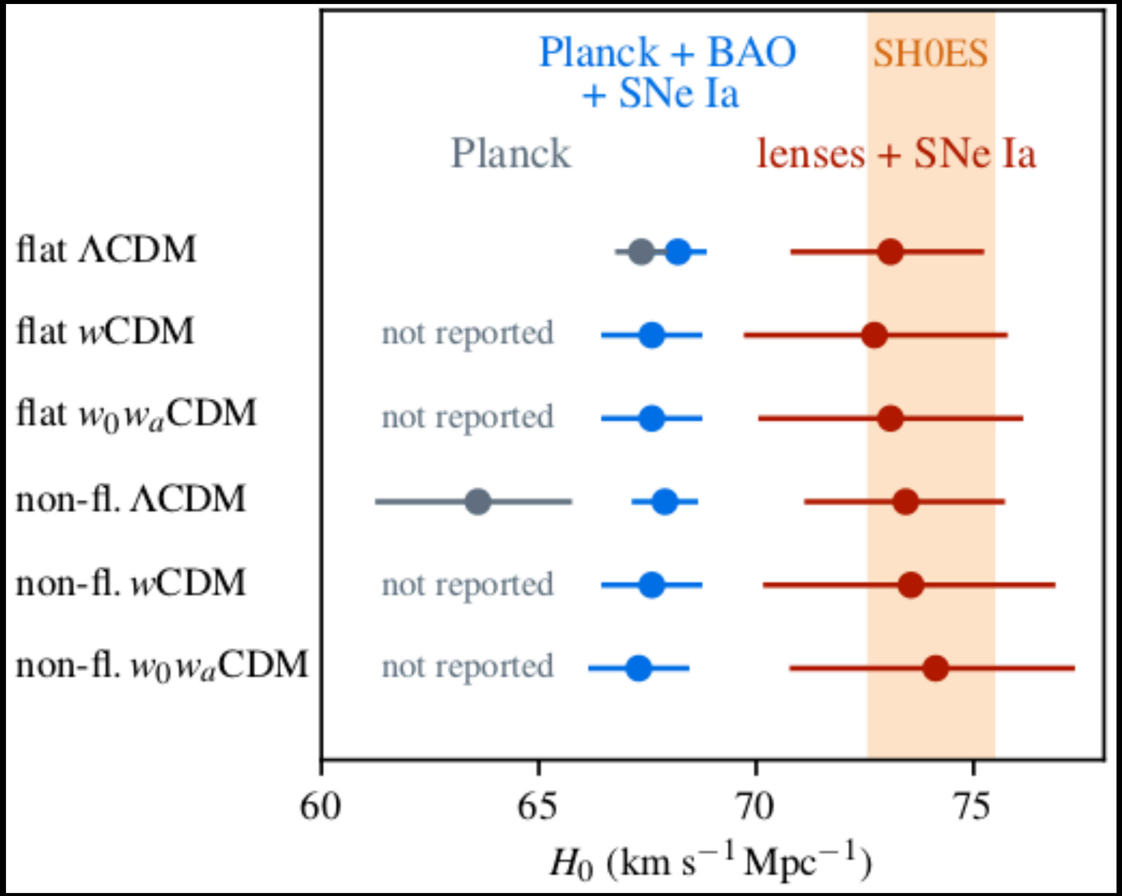
Feeney et al. 2018

Using Lens time delays+SNe Ia shows good agreement with SH0ES value and replaces cepheids.

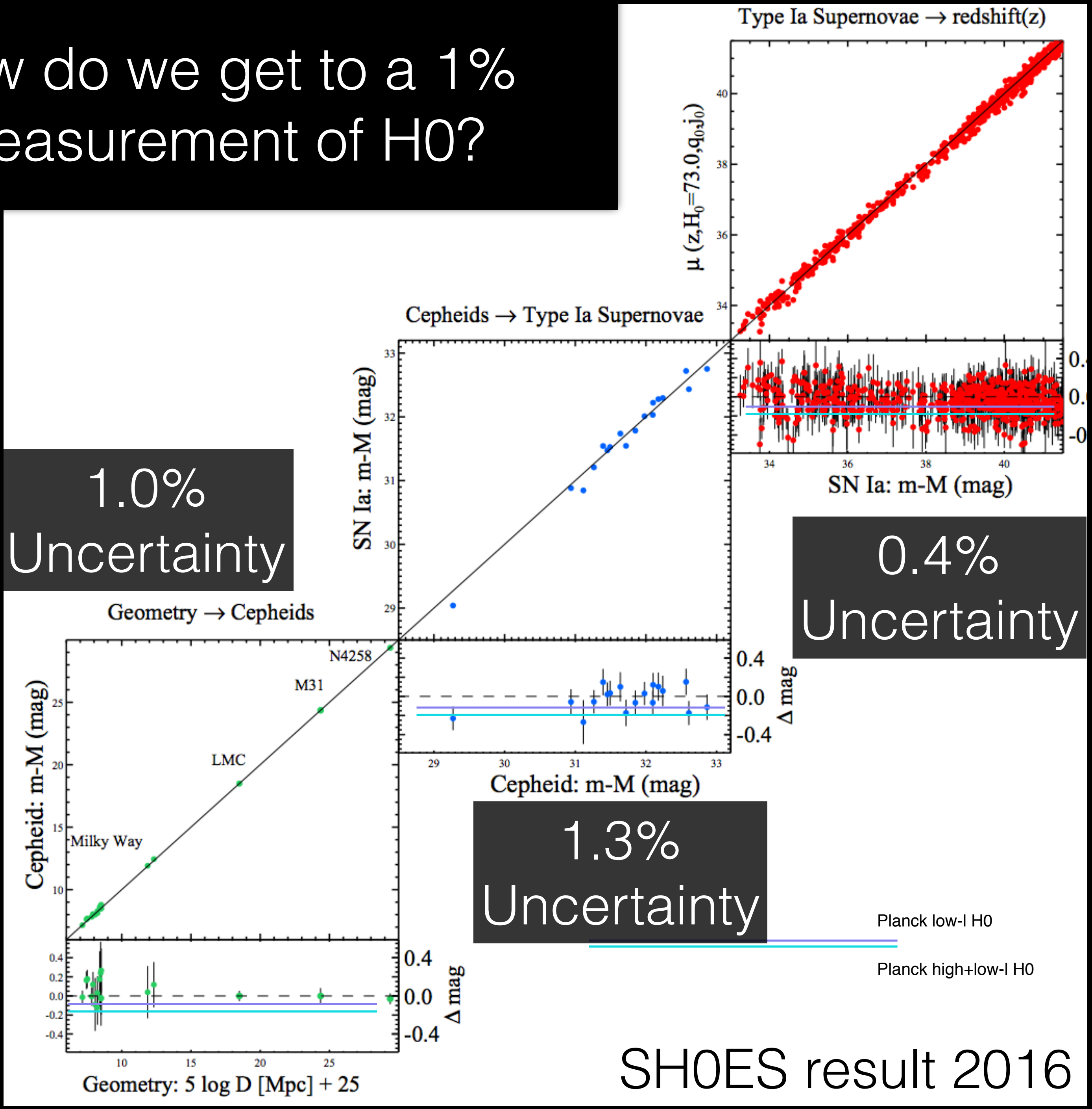
Independent cross-check of first two "rungs":
6 strong lensing time delays + 740 SNe Ia (Taubenberger+ 2019; arXiv: 1905.12496)

H_0=73.1±2.2 km s^{-1} Mpc^{-1} for ΛCDM
(73-74 for other cosmologies)





How do we get to a 1% measurement of H0?



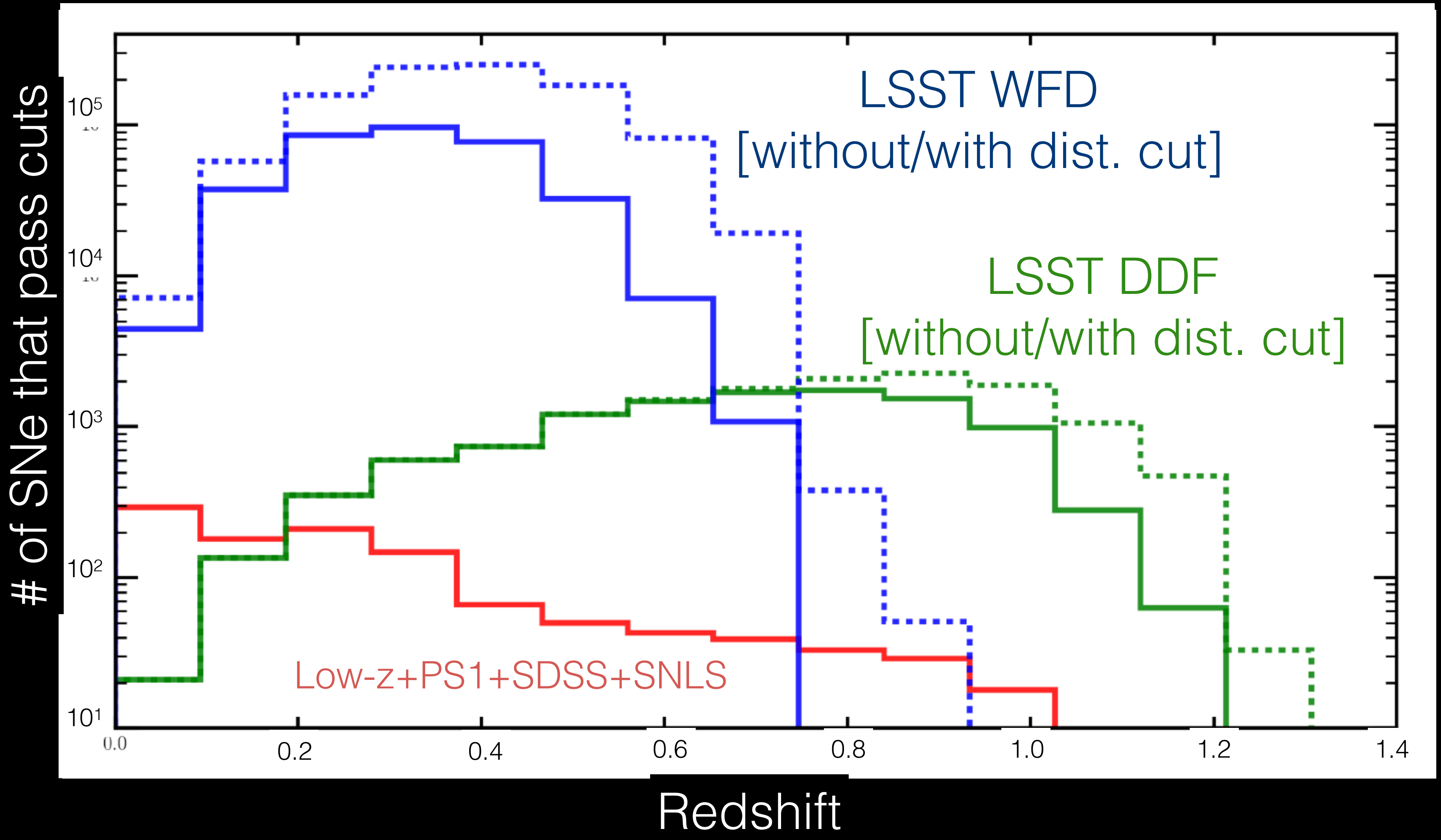
SH0ES result 2016

Doubling SNIa - calibrator set will get us part of the way.

Need to keep pushing similarity of SNIa in rung 2+3 to reduce systematics

Showing 10-year total for LSST, with typical quality cuts on peak constraints, shape constraints

WFD will have observed 380k[998k] good SNIa light curves
DDF will have observed 11k[14k] good SNIa light curves



LSST will answer ~every systematic question!

Conclusions

1. Cepheids + Supernova = High-H0
   Strong Lens + Supernova = High-H0
   BAO + Supernova = Low-H0
   TRGB + Supernova = Mid-H0

---

2. Working our way to next big SH0ES analysis, doubling of CC sample. We are open to all systematic checks.

3. There may not be perfect theory that explains this either, but we don't understand dark energy or dark matter, so need to pursue all avenues