From JLA to Pantheon and Foundation

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Irfu/DPhP

- Reminder: the JLA sample

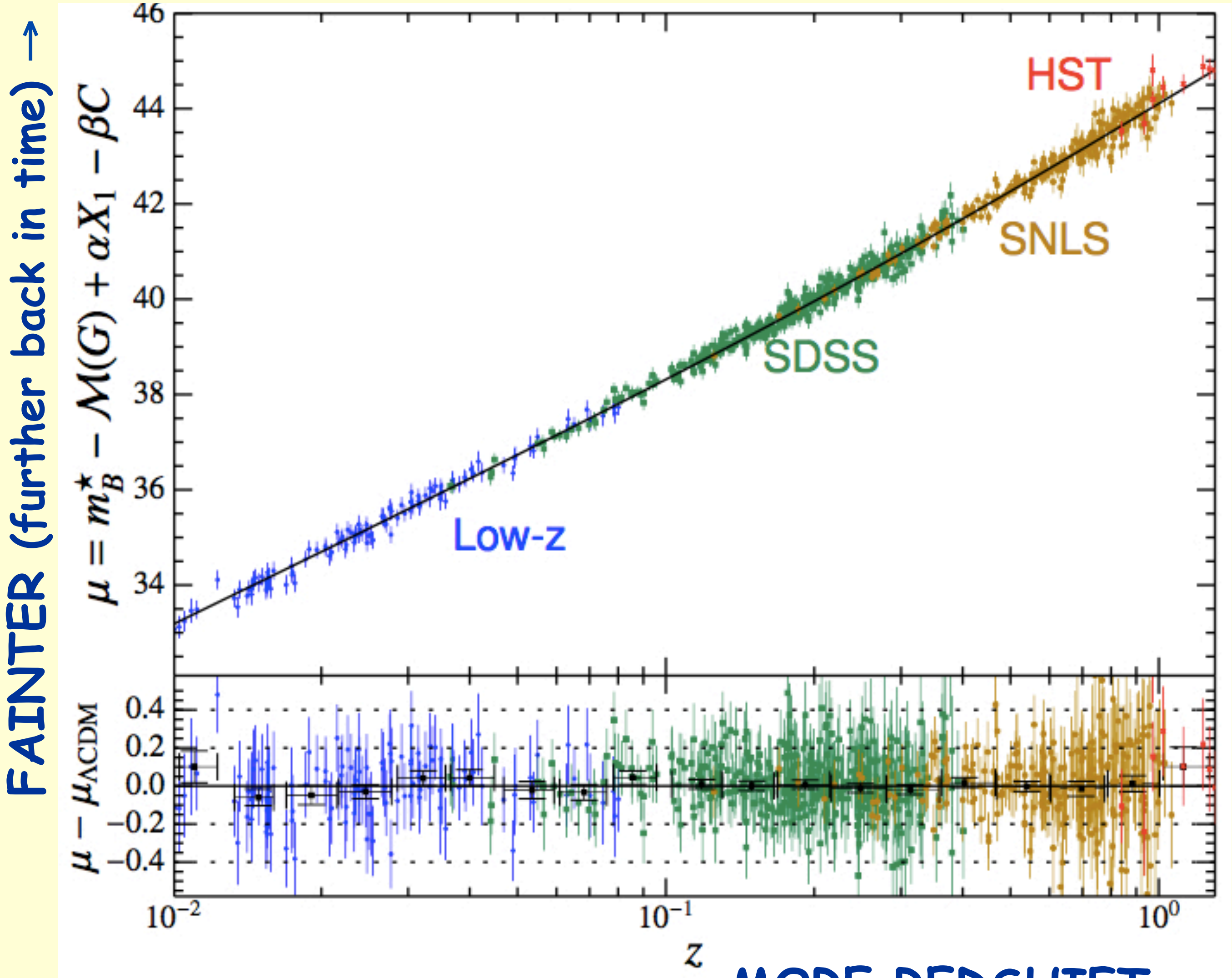
  M.Betoule et al., 2014, A&A, 568, A22c, arXiv:1401.4064
- The Pantheon sample

  D.M.Scolnic et al., 2018, ApJ, 859, 101S, arXiv:1710.00845
- The Foundation sample

  D.O.Jones et al., submitted to ApJ, arXiv:1811.09286

The JLA sample, 2014

High quality data for **740** SNeIa with spectroscopic redshifts



MORE REDSHIFT→
(more expansion since explosion)

- different surveys combined
  - high z: rolling-search mode (SDSS, SNLS)

  homogeneous and well controlled sample
  - low z: targeted mode, heterogeneous
- high quality light curves (multi-band, sampling…)
- direct cross-calibration of SNLS and SDSS (@a few mmag), calibration of all data wrt precise standards (among which BD +17 4708)

Source	Number
Cálan/Tololo	17
CfAI	7
CfAII	15
CfAIII[a]	55
CSP[a]	13
Other low-z	11
SDSS[a]	374
SNLS	239
HST	9
Total	740

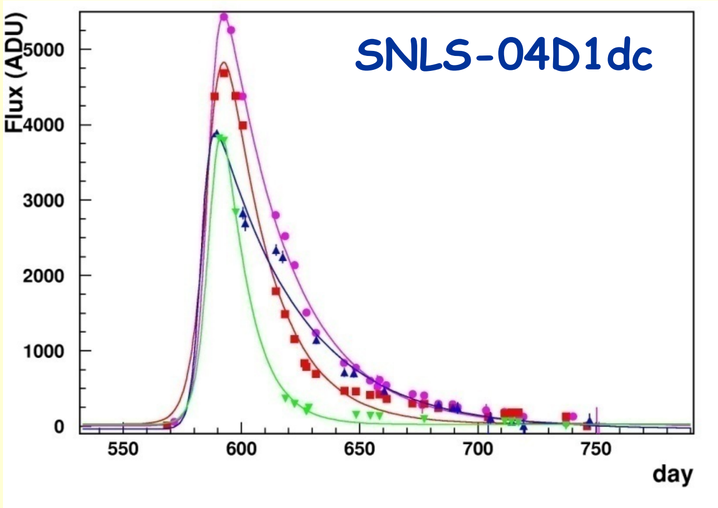
Table 11. Contribution of various source of measurement uncertainties to the uncertainty in Ω_m.

Uncertainty sources	$\sigma_x(\Omega_m)$	% of $\sigma^2(\Omega_m)$
Calibration	0.0203	36.7
Milky Way extinction	0.0072	4.6
Light-curve model	0.0069	4.3
Bias corrections	0.0040	1.4
Host relation[a]	0.0038	1.3
Contamination	0.0008	0.1
Peculiar velocity	0.0007	0.0
Stat	0.0241	51.6

→ stat ~ syst

main syst = calib

SN light curve



distance indicator

light curve fitter -> m_B, x_1, C

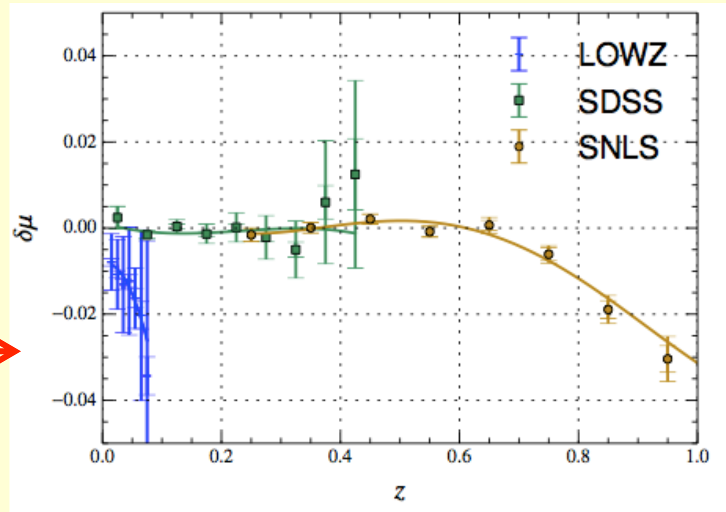
(SALT2 v2.4)

SNIa diversity

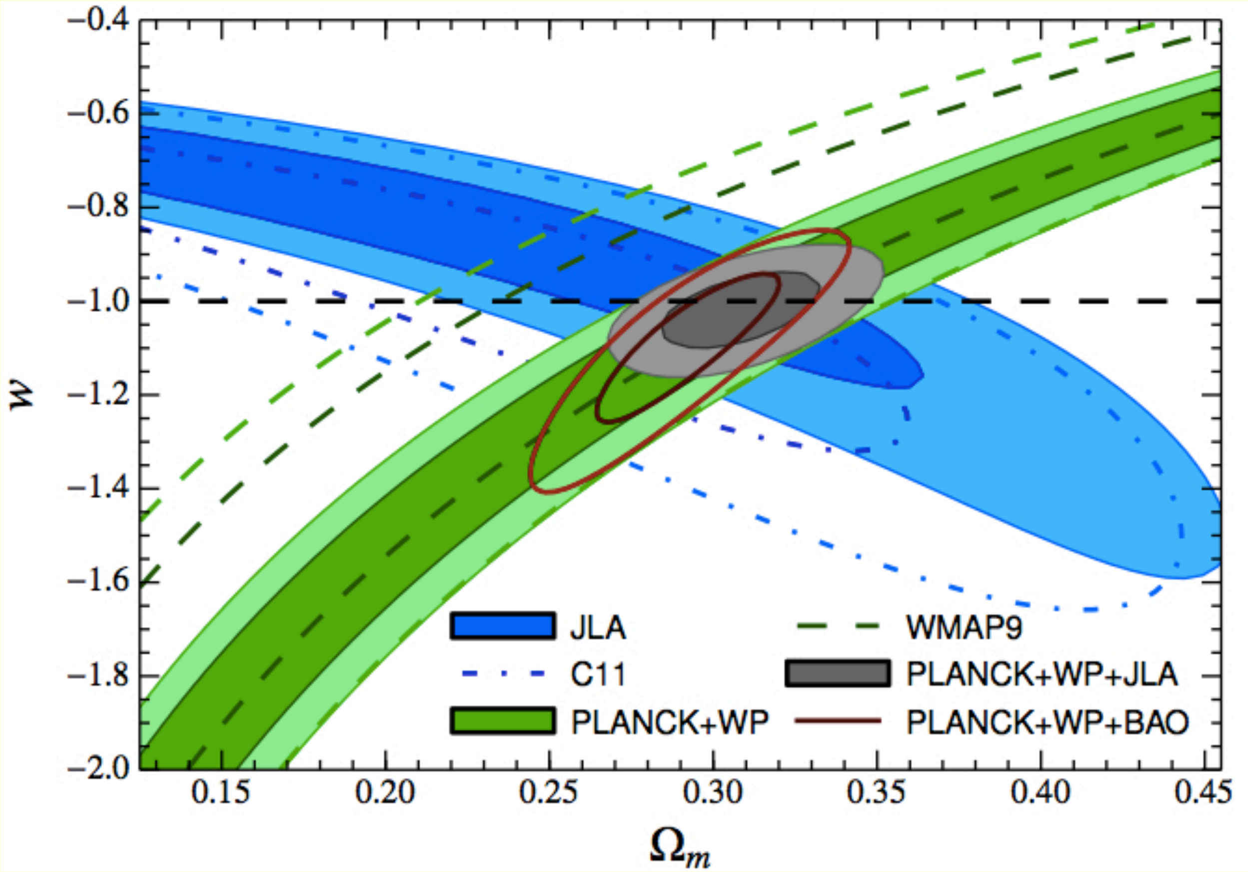
- SN distance modulus :

$$\mu = m_B - \mathcal{M} + \alpha \times x_1 - \beta \times c + \Delta_B(z) + \Delta_M$$

- prediction: $5\log_{10}(d_L(\text{cosmo},z)/10\text{pc})$
- $\mathcal{M}, \alpha, \beta, \Delta_M$ nuisance parameters
- $\Delta_B(z)$ Malmquist bias correction (from simulation)



wCDM constraints from CMB+BAO+SNIa data



$\Omega_m^0 = 0.303 \pm 0.012$

$w = -1.027 \pm 0.055$

$(\delta_{stat} \oplus \delta_{syst})$

- Planck 2015 update using JLA sample : $w = -1.006 \pm 0.045$

Planck collaboration. 2015, arXiv:1502.01589

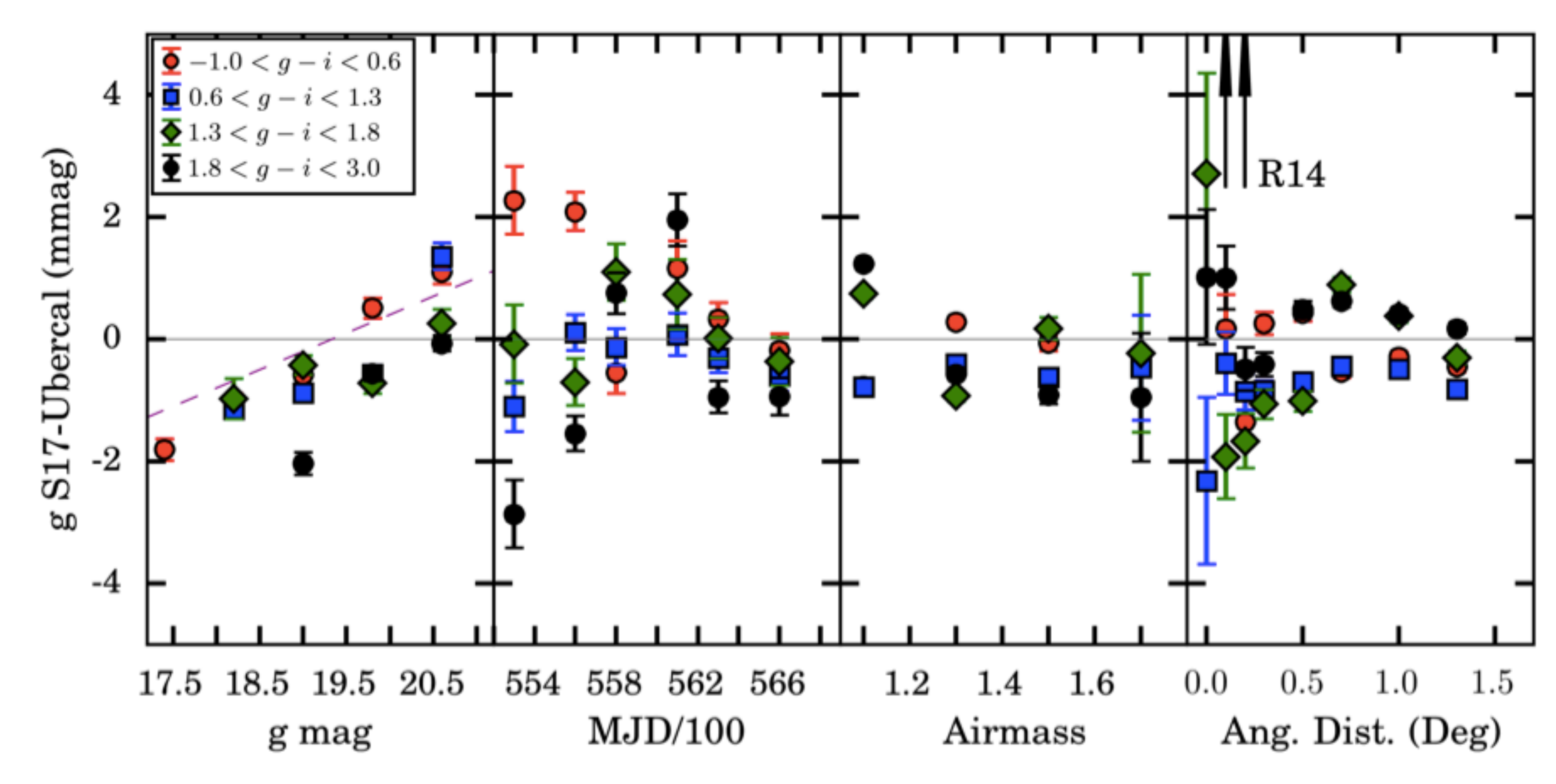
The PANTHEON sample, 2018

ABSTRACT

We present optical light curves, redshifts, and classifications for 365 spectroscopically confirmed Type Ia supernovae (SNe Ia) discovered by the Pan-STARRS1 (PS1) Medium Deep Survey. We detail improvements to the PS1 SN photometry, astrometry and calibration that reduce the systematic uncertainties in the PS1 SN Ia distances. We combine the subset of 279 PS1 SN Ia ($0.03 < z < 0.68$) with useful distance estimates of SN Ia from SDSS, SNLS, various low-z and HST samples to form the largest combined sample of SN Ia consisting of a total of 1048 SN Ia ranging from $0.01 < z < 2.3$, which we call the 'Pantheon Sample'. When combining *Planck 2015* CMB measurements with the Pantheon SN sample, we find $\Omega_m = 0.307 \pm 0.012$ and $w = -1.026 \pm 0.041$ for the wCDM model. When the SN and CMB constraints are combined with constraints from BAO and local H_0 measurements, the analysis yields the most precise measurement of dark energy to date: $w_0 = -1.007 \pm 0.089$ and $w_a = -0.222 \pm 0.407$ for the $w_0 w_a$CDM model. Tension with a cosmological constant previously seen in an analysis of PS1 and low-z SNe has diminished after an increase of $2\times$ in the statistics of the PS1 sample, improved calibration and photometry, and stricter light-curve quality cuts. We find the systematic uncertainties in our measurements of dark energy are almost as large as the statistical uncertainties, primarily due to limitations of modeling the low-redshift sample. This must be addressed for future progress in using SN Ia to measure dark energy.

see Foundation sample

- PS1 MDS survey (2009-2014): detection and *griz* follow-up of 0.03<z<0.65 SNe Ia, Pan-STARRS1 telescope
- Improved astrometry, photometry, internal calibration => PS1 photometric system controlled at the mmag level.



- Final : 279 SNe after cuts

- PS1 MDS combined with other SN samples:
  - CfA1-4, CSP, SDSS, SNLS, HST ~ JLA
    (more at low/high z)

  => Pantheon sample: 1048 SNe, 0.01 < z < 2.3

Table 4.

Sample	Number	Mean z
CSP	26	0.024
CFA3	78	0.031
CFA4	41	0.030
CFA1	9	0.024
CFA2	18	0.021
SDSS	335	0.202
PS1	279	0.292
SNLS	236	0.640
SCP	3	1.092
GOODS	15	1.120
CANDELS	6	1.732
CLASH	2	1.555
Tot	1048	

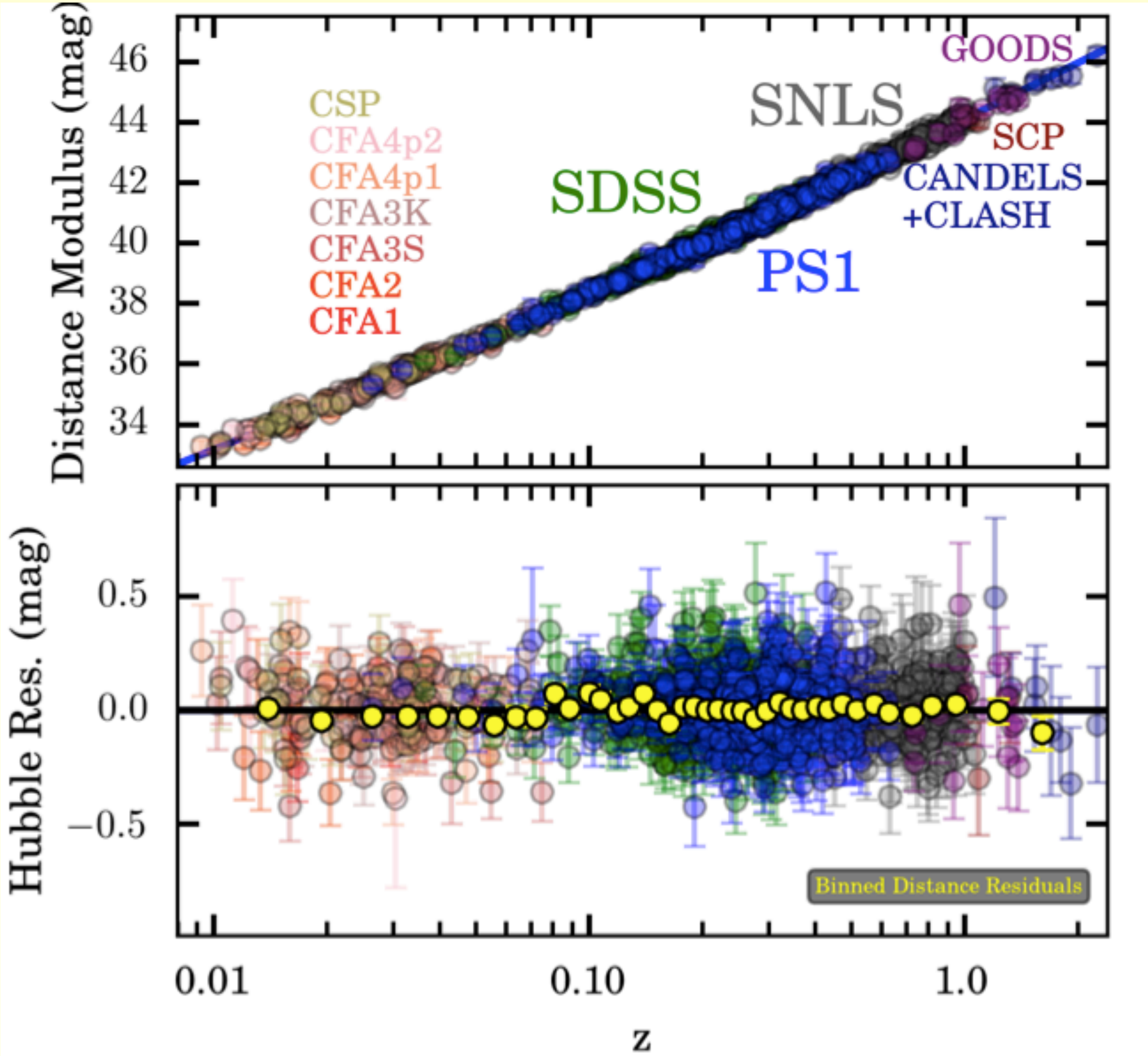
- Inter-calibration of all samples:
  - PS1 3π survey: <1% relative calibration over 3π sr of sky

  ⇒ photometry of tertiary stars from each survey compared: differences < 1% except for CfA (2 to 4%)

  ⇒ determine calibration offsets for each survey so as to reduce differences in the cross-calibration between PS1,SDSS,SNLS

  ⇒ All systems tied to HST standards, as for JLA

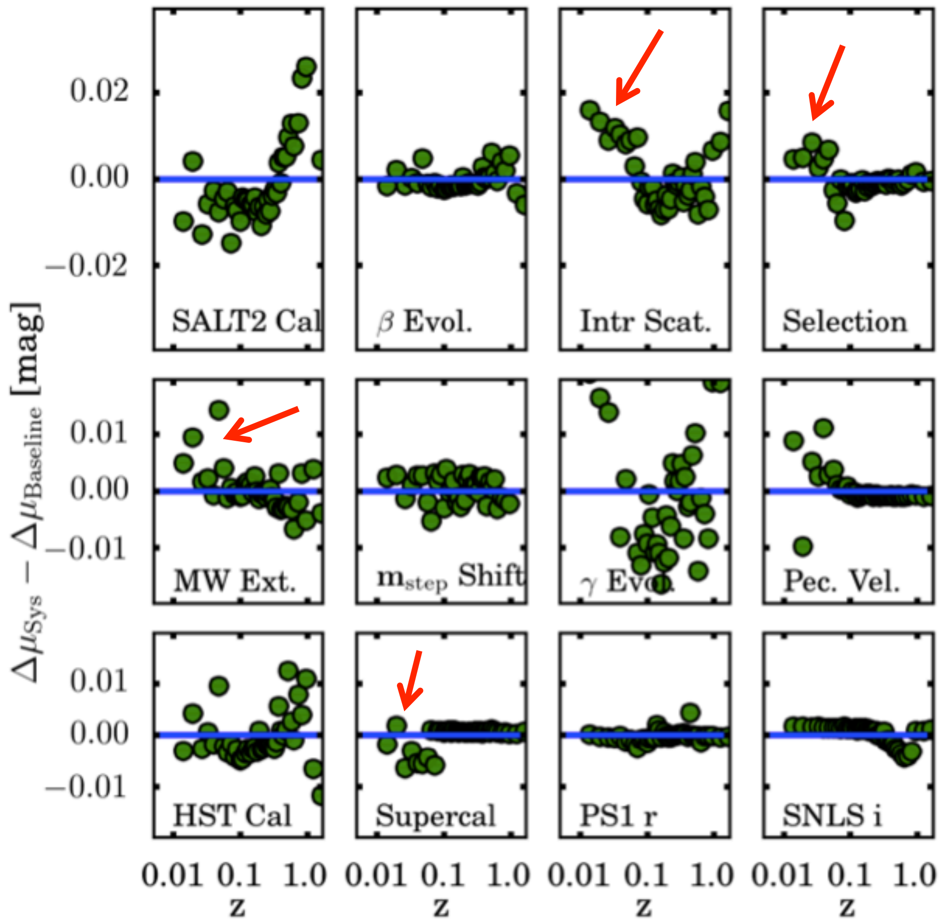
- Hubble diagram:



- Systematic uncertainties:

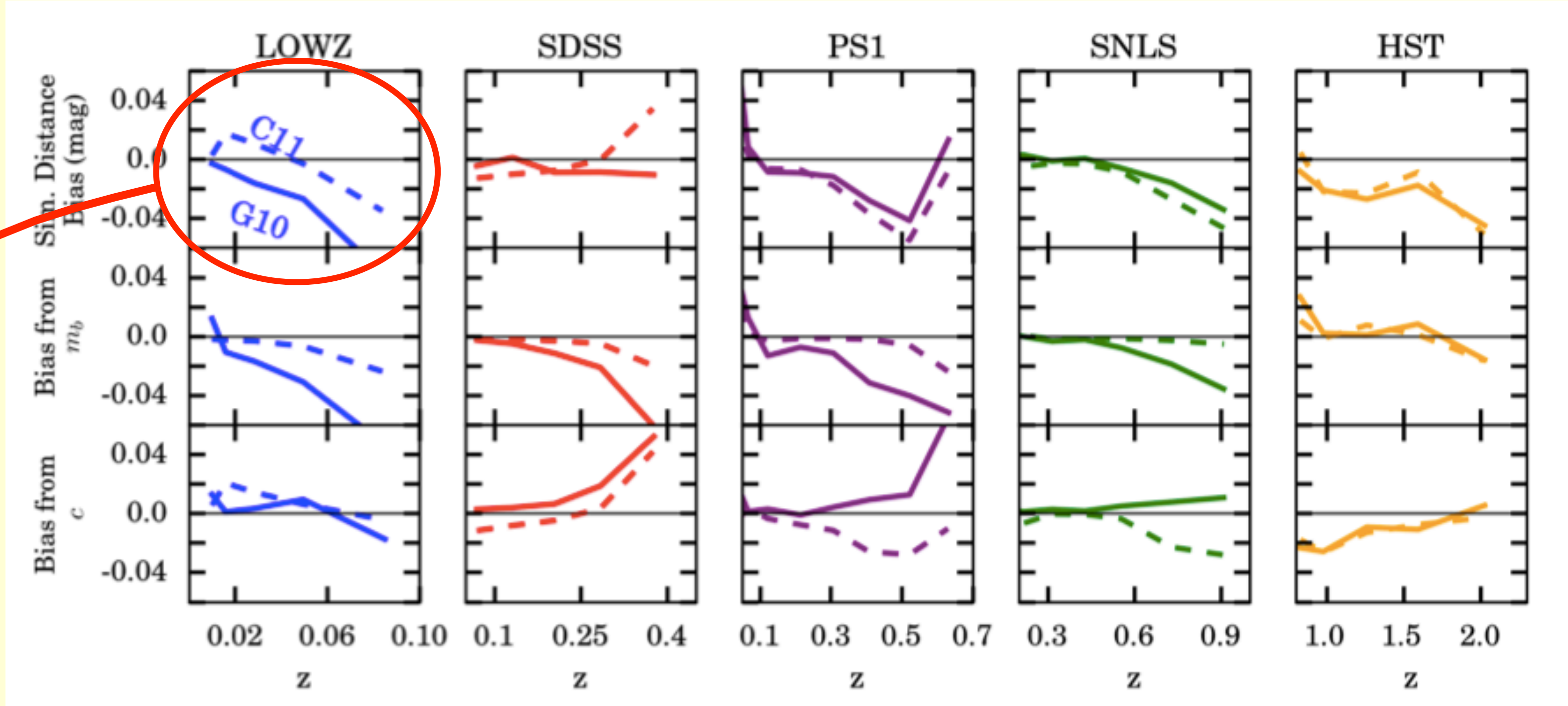
Table 9.

	w shift	$\sigma_w^{\rm syst}$	Fraction of $\sigma_w^{\rm (stat)}$
Stat. Uncertainty	+0.000	0.031	1.000
Total Sys Uncertainty	+0.031	0.025	0.814
Calibration			
SALT2 Cal	-0.002	0.014	0.457
Survey Cal	+0.006	0.009	0.285
HST Cal	-0.006	0.006	0.177
Supercal	+0.002	0.003	0.098
SN Modeling			
Selection	+0.010	0.007	0.233
Intrinsic Scatter	+0.019	0.005	0.170
β Evol.	-0.001	0.007	0.238
γ Evol.	-0.002	0.000	0.000
$m_{\rm step}$Shift	-0.002	0.002	0.064
External			
MW Extinction	+0.010	0.008	0.262
Pec. Vel.	+0.000	0.003	0.103



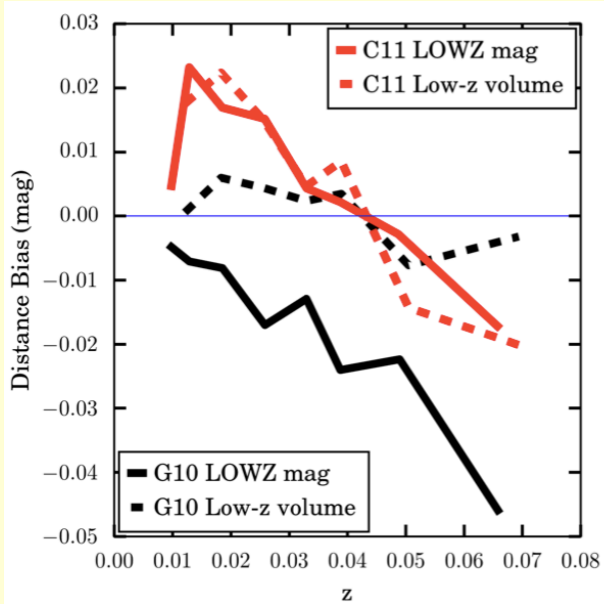
- syst ≤ stat
- main err: calibration (66%)
- low-z: large impact (selection, MW extinction, intrinsic scatter, calibration)

- Selection effect (data/simulation with no cut, 2 intrinsic scatter models):

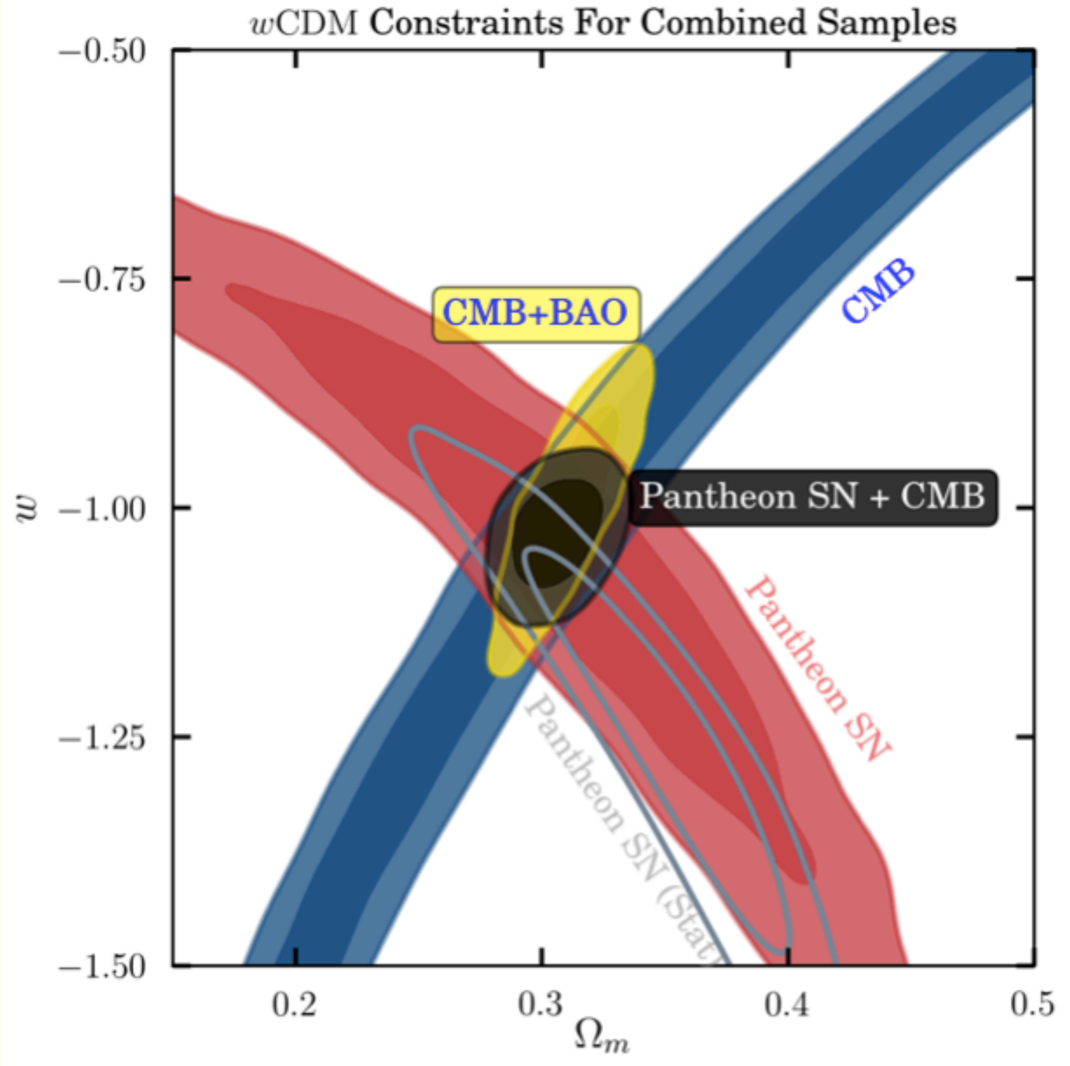


- main effect : low-z sample
  - sample biased in colour
  - uncertainty in selection function

  magnitude-limited or volume-limited ?
- baseline = C11+G10/2 (mag-lim@lowz)
- differences vs baseline = systematics



wCDM constraints from CMB+BAO+SNIa data



- CMB=Planck 2015

Ω_m^0=0.307±0.012

w=−1.026±0.041

($\delta_{stat} \oplus \delta_{syst}$)

- Planck 2018 update using Pantheon sample : w=−1.028±0.032

Planck collaboration. 2018, arXiv:1807.06209

The FOUNDATION sample, 2019

ABSTRACT

Measurements of the dark energy equation-of-state parameter, w, have been limited by uncertainty in the selection effects and photometric calibration of $z < 0.1$ Type Ia supernovae (SNe Ia). The Foundation Supernova Survey is designed to lower these uncertainties by creating a new sample of $z < 0.1$ SNe Ia observed on the Pan-STARRS system. Here, we combine the Foundation sample with SNe from the Pan-STARRS Medium Deep Survey and measure cosmological parameters with 1,338 SNe from a single telescope and a single, well-calibrated photometric system. For the first time, both the low-z and high-z data are predominantly discovered by surveys that do not target pre-selected galaxies, reducing selection bias uncertainties. The $z > 0.1$ data include 875 SNe without spectroscopic classifications and we show that we can robustly marginalize over CC SN contamination. We measure Foundation Hubble residuals to be fainter than the pre-existing low-z Hubble residuals by 0.046 ± 0.027 mag (stat+sys). By combining the SN Ia data with cosmic microwave background constraints, we find $w = -0.938 \pm 0.053$, consistent with ΛCDM. With 463 spectroscopically classified SNe Ia alone, we measure $w = -0.933 \pm 0.061$. Using the more homogeneous and better-characterized Foundation sample gives a 55% reduction in the systematic uncertainty attributed to SN Ia sample selection biases. Although use of just a single photometric system at low and high redshift increases the impact of photometric calibration uncertainties in this analysis, previous low-z samples may have correlated calibration uncertainties that were neglected in past studies. The full Foundation sample will observe up to 800 SNe to anchor the LSST and *WFIRST* Hubble diagrams.

- Foundation SN survey : *griz* follow-up of low z SNe Ia from untargeted surveys (ASAS-SN, ATLAS, PSST), using the same telescope (PS1) and same precise (mmag) photometric system => homogeneous, less biased, well controlled sample

- DR1: 180 SNe after cuts (ultimately: 800)
  $0.015<z<0.08$

- Better control of selection effects: →

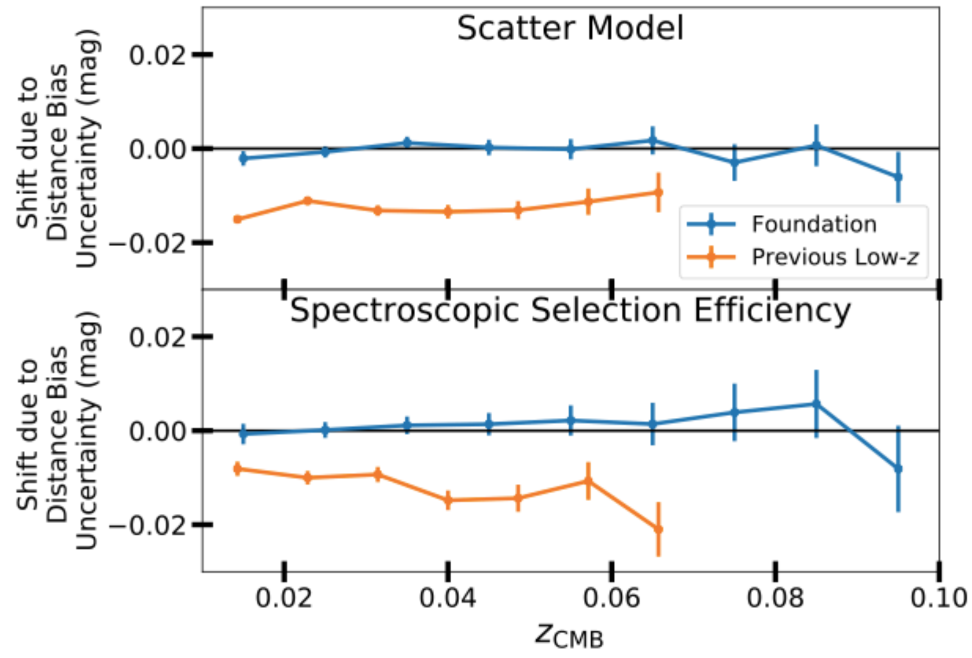
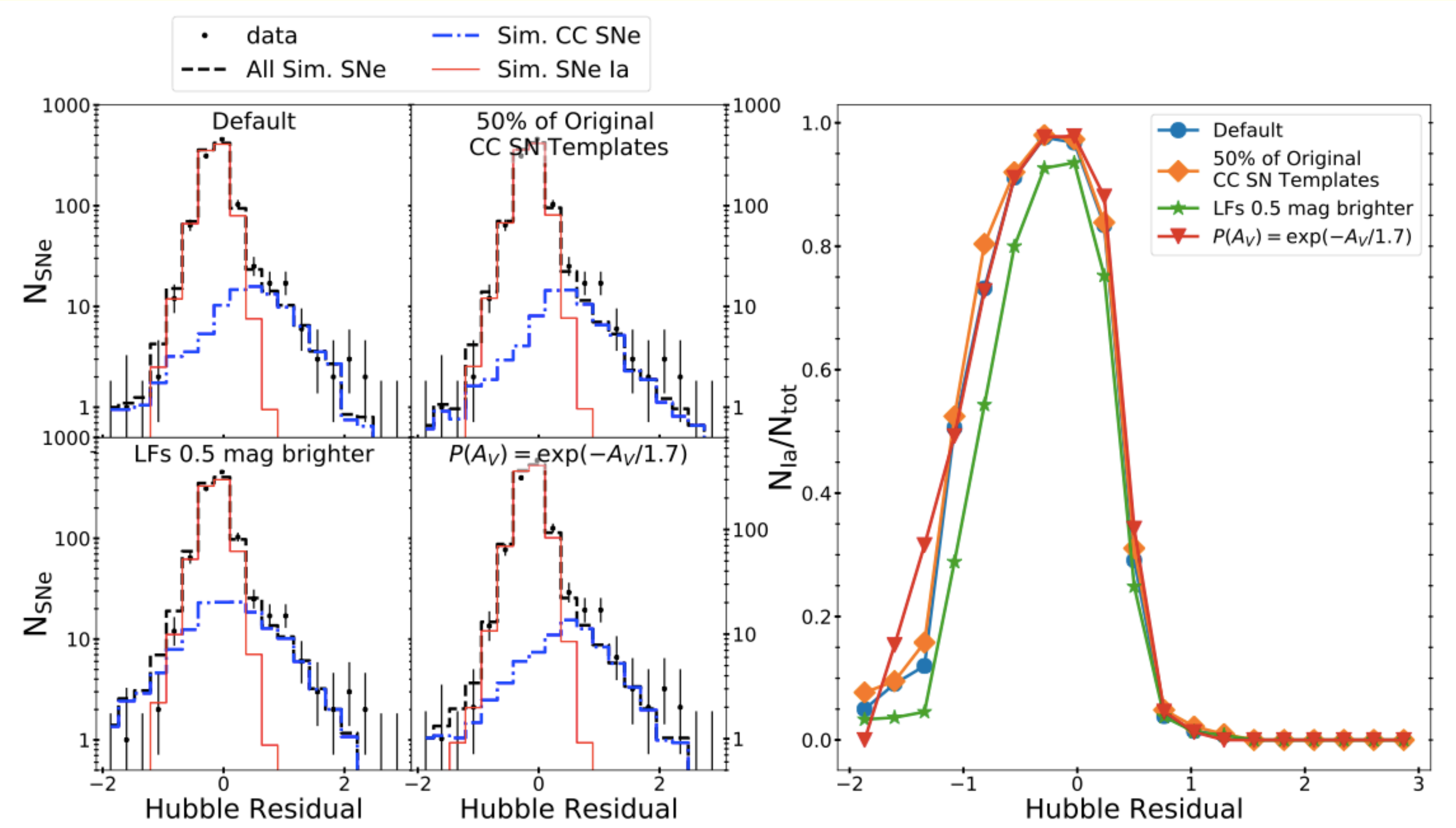
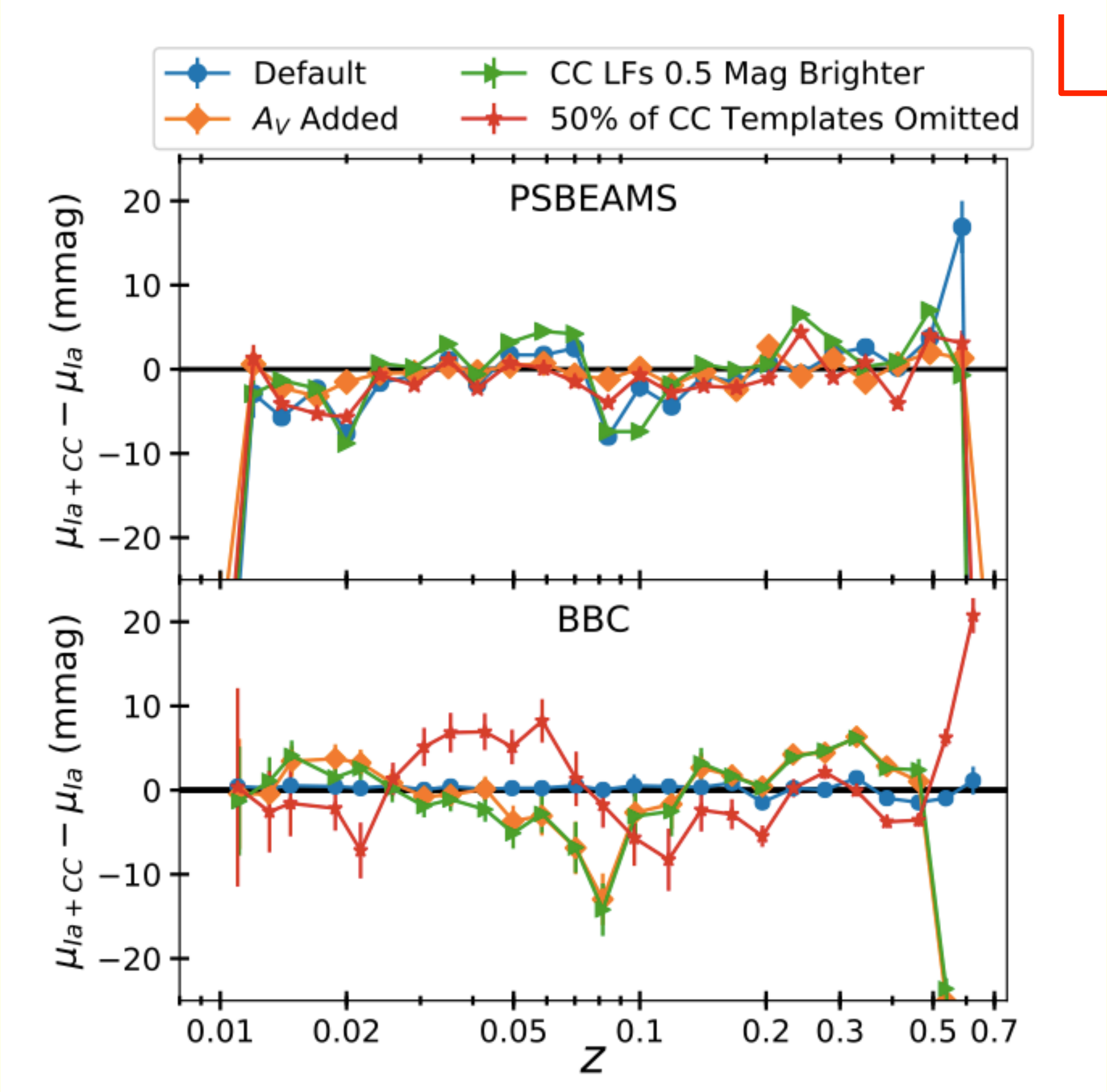


Figure 6. Comparison of systematic uncertainties due to bias correction as a function of redshift between the Foundation sample (blue) and the previous low-z SN sample (orange). We show the shift in distance due to the difference between the distance bias predictions of the G10 and C11 models (top) and due to adjusting the uncertain spectroscopic selection efficiency (bottom).

- High z: PS1 MDS SNe Ia (spectroscopic and photometric classifications) => same telescope and photometric system for all data. Host spectroscopic redshifts for photo SNe Ia.
- correction for selection bias and CC contamination: from simulation + 2 different algorithms (Bayesian Estimation Applied to Multiple Species) and different internal options



- Check of CC contamination marginalization: real photometric SNe in full sample replaced by simulated photometric CCs



For all simulations

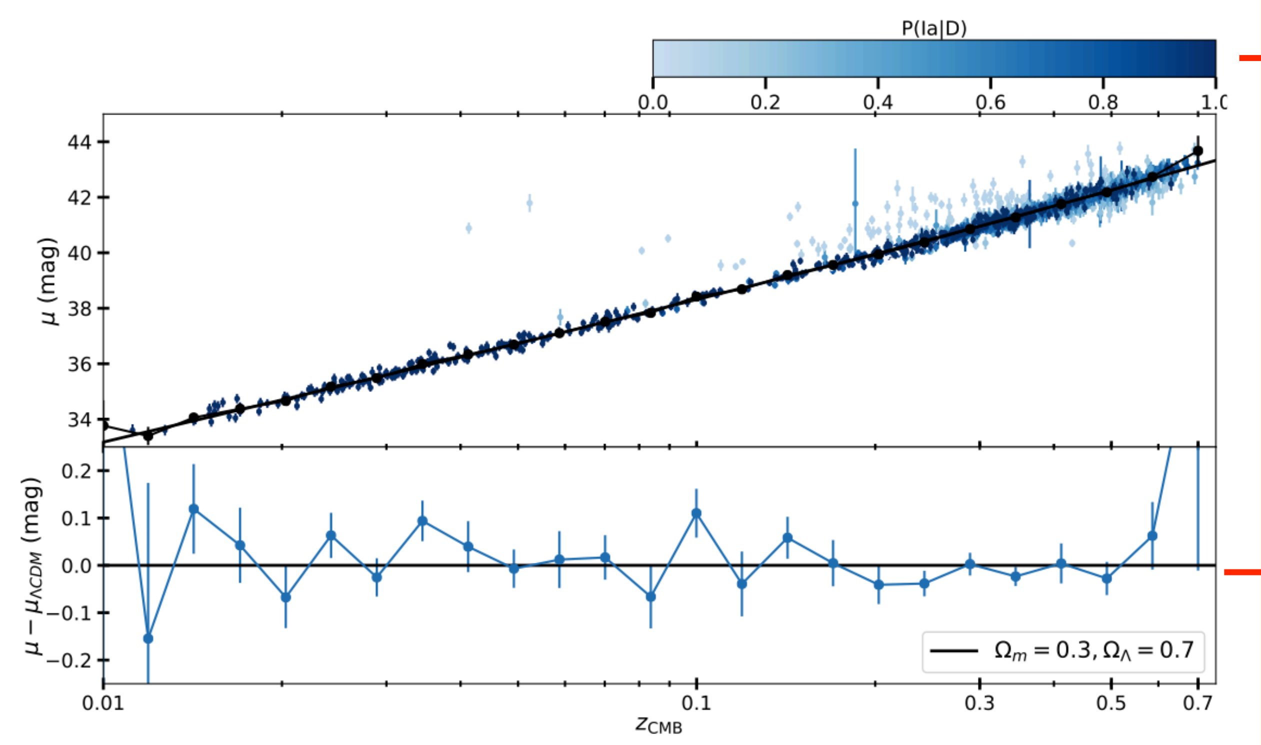
bias ≲ 5 mmag

Correct for bias in baseline simulation

Take biases in other simulations as systematic uncertainties

systematics due to changes in internal CC sim parameters treated in a similar way

- Hubble diagram Foundation+MDS: 1338 SNe (175 low z)

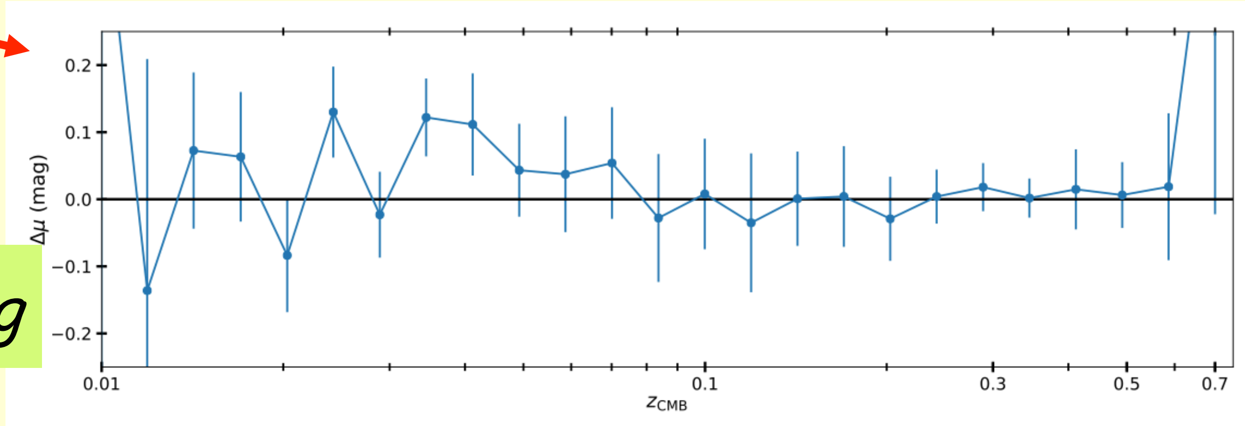


posterior Ia probability

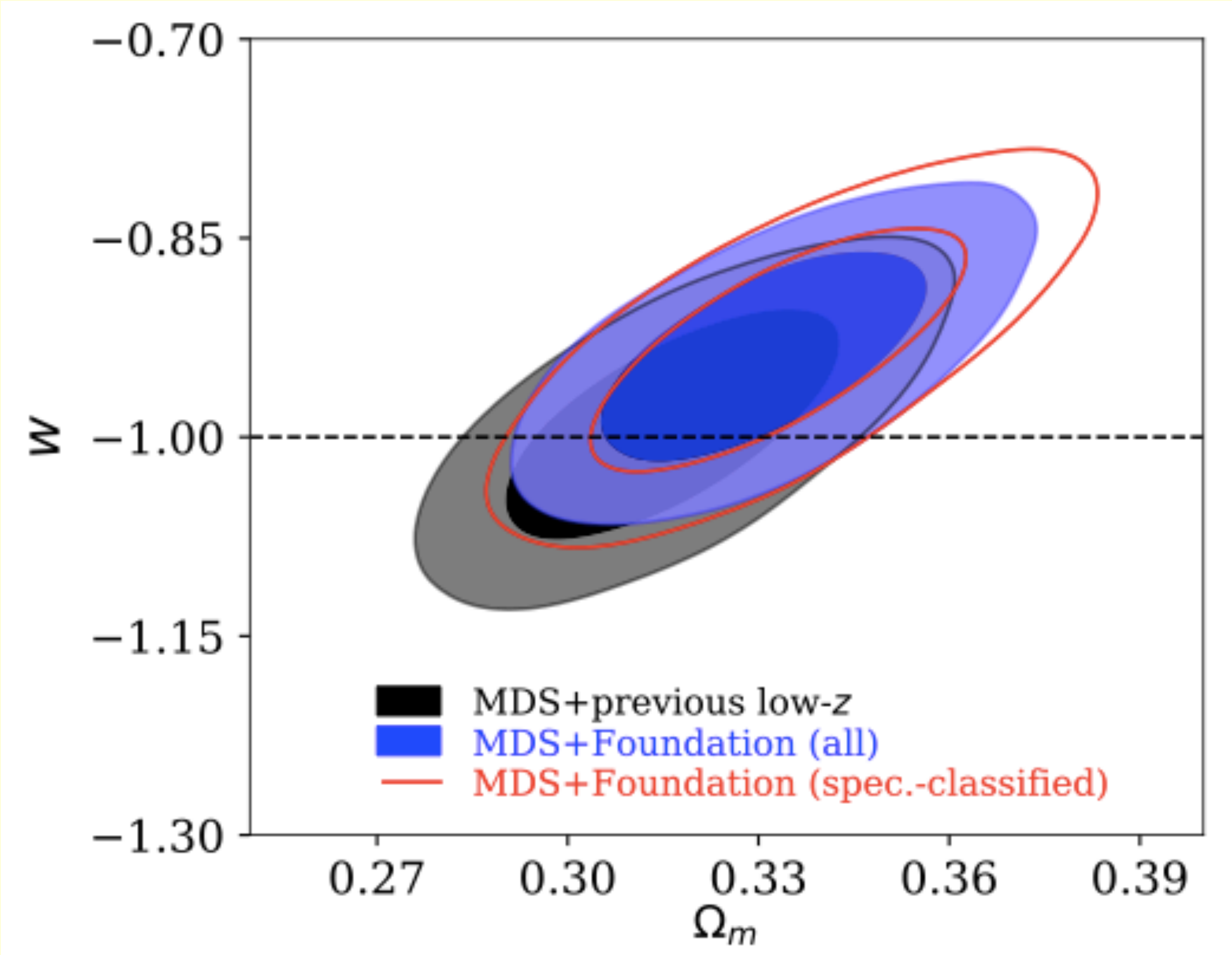
residuals to a nominal flat ΛCDM model with Ω_m=0.3

Foundation - old low z residual difference

$\Delta_{\mu}^{z\leq0.1}$=0.046±0.027*mag*

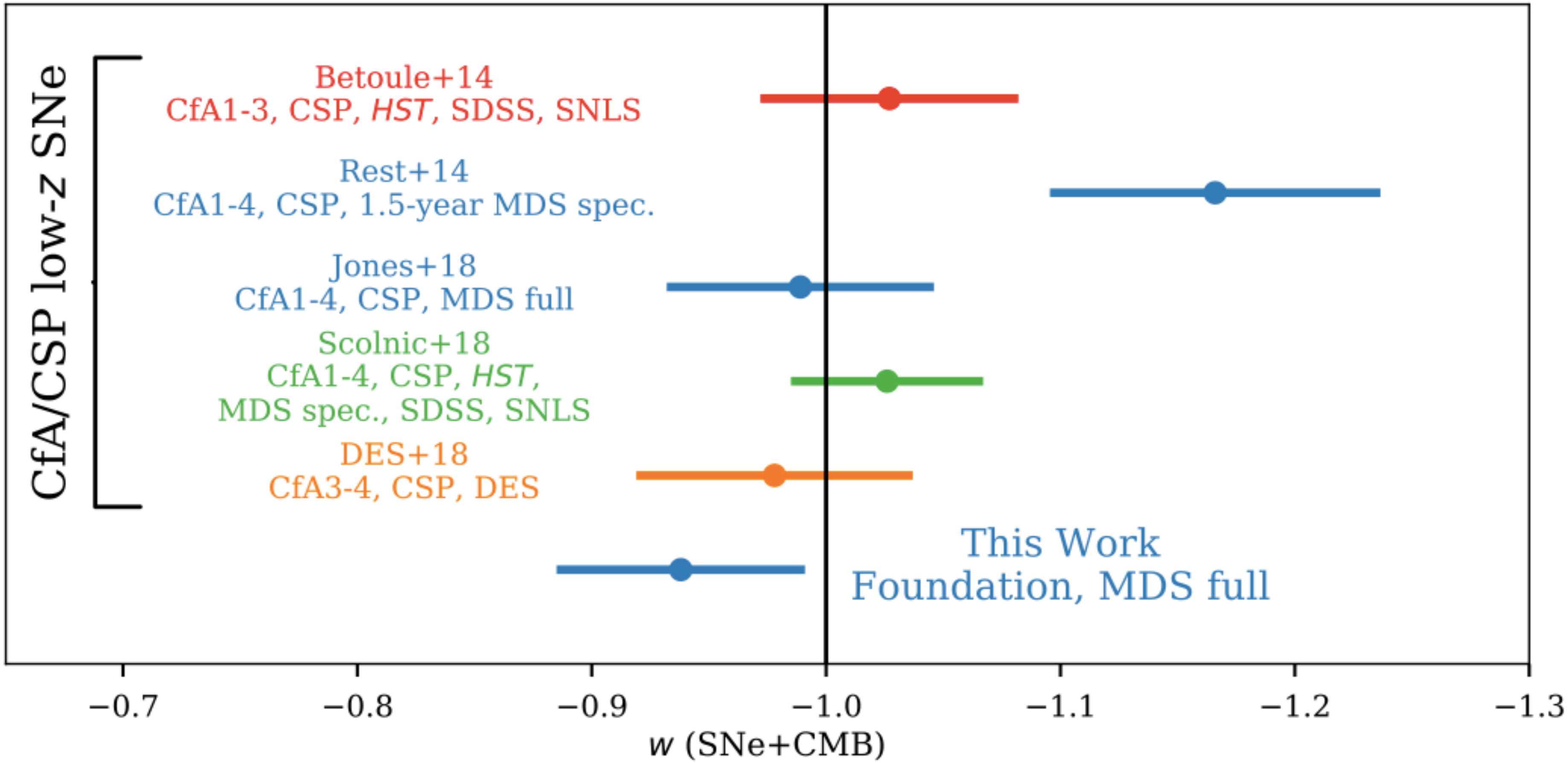


- wCDM constraints from SNIa data alone:



- difference wrt previous result stems from the low-z sample alone and not from any bias related to CC marginalization

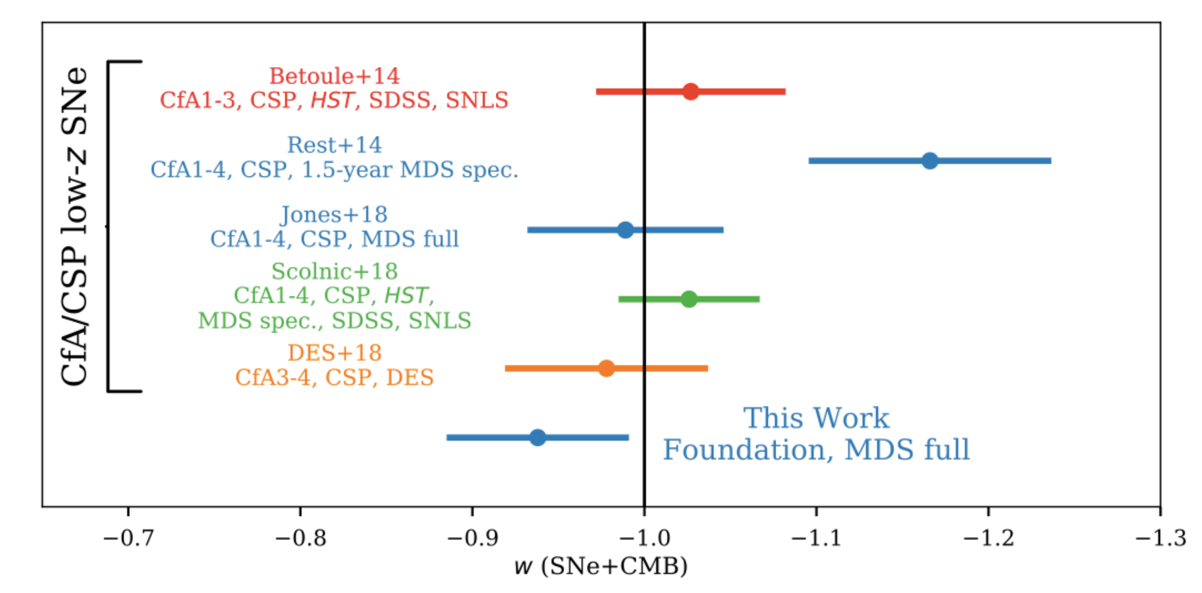
- wCDM constraints from SNIa data alone:



$w = -0.938 \pm 0.053$ wrt Jones+18: w shift +5%

$\sigma_w^{sys} = 0.043 \rightarrow 0.039$

- wCDM constraints from SNIa data alone:



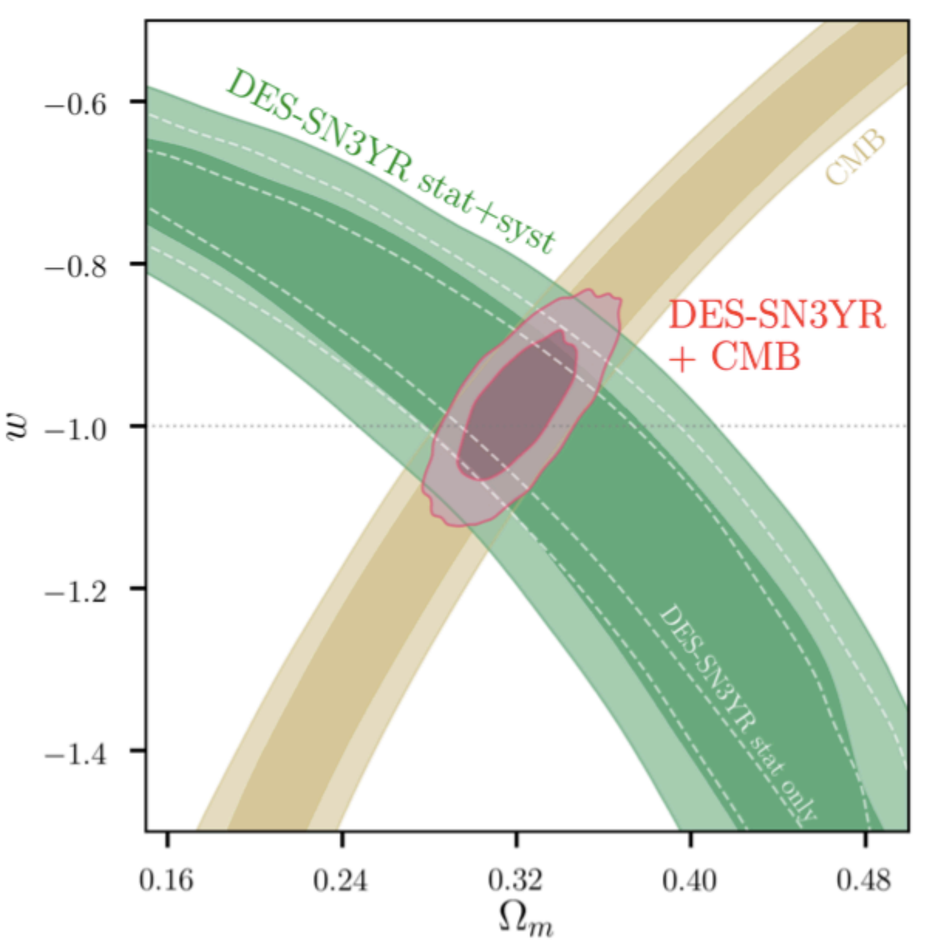
- SNe+CMB (Planck 2015)+BAO:

$$w = -0.949 \pm 0.043$$

=> similar precision as with JLA (0.045) or Pantheon (0.041) or DES 1YR (0.047)

Back-up slides

DES paper: wCDM constraints and systematics



SNe+CMB (Planck 2015)+BAO

$w = -0.977 \pm 0.047$

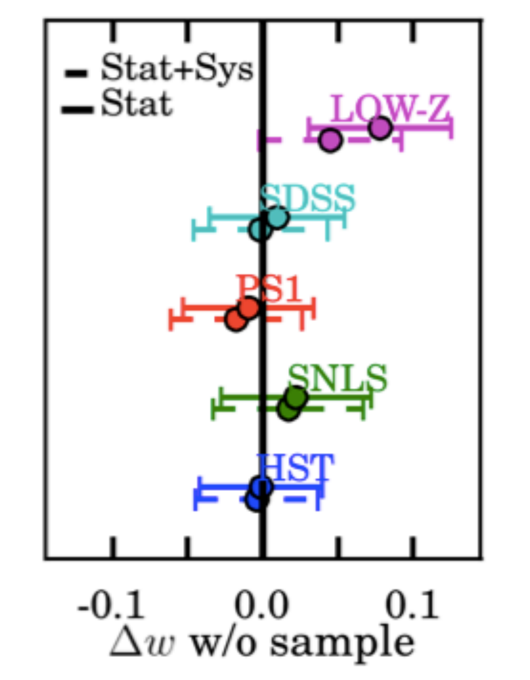
T.M.C Abbott et al., arXiv:1811.02374

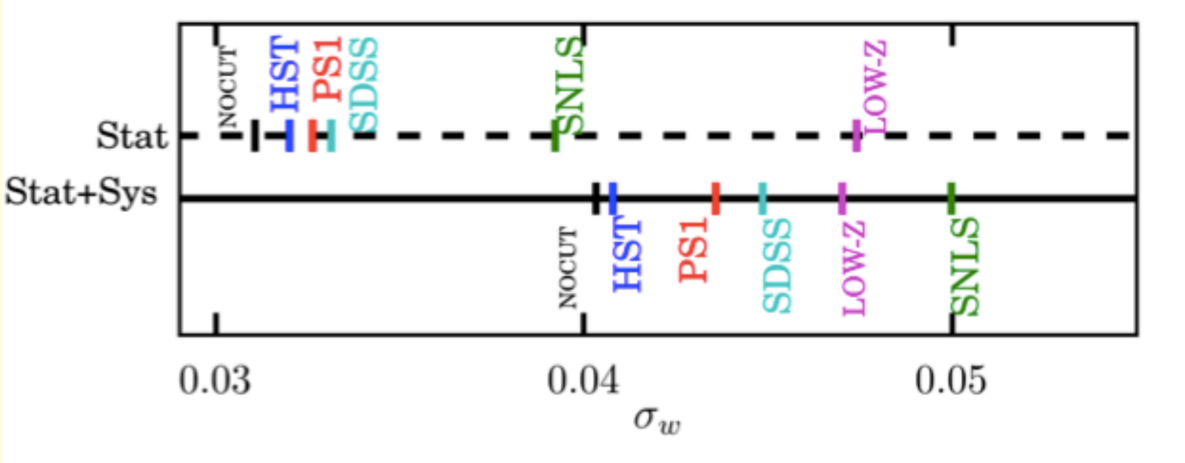
SNe alone

w UNCERTAINTY CONTRIBUTIONS FOR wCDM MODEL[a]

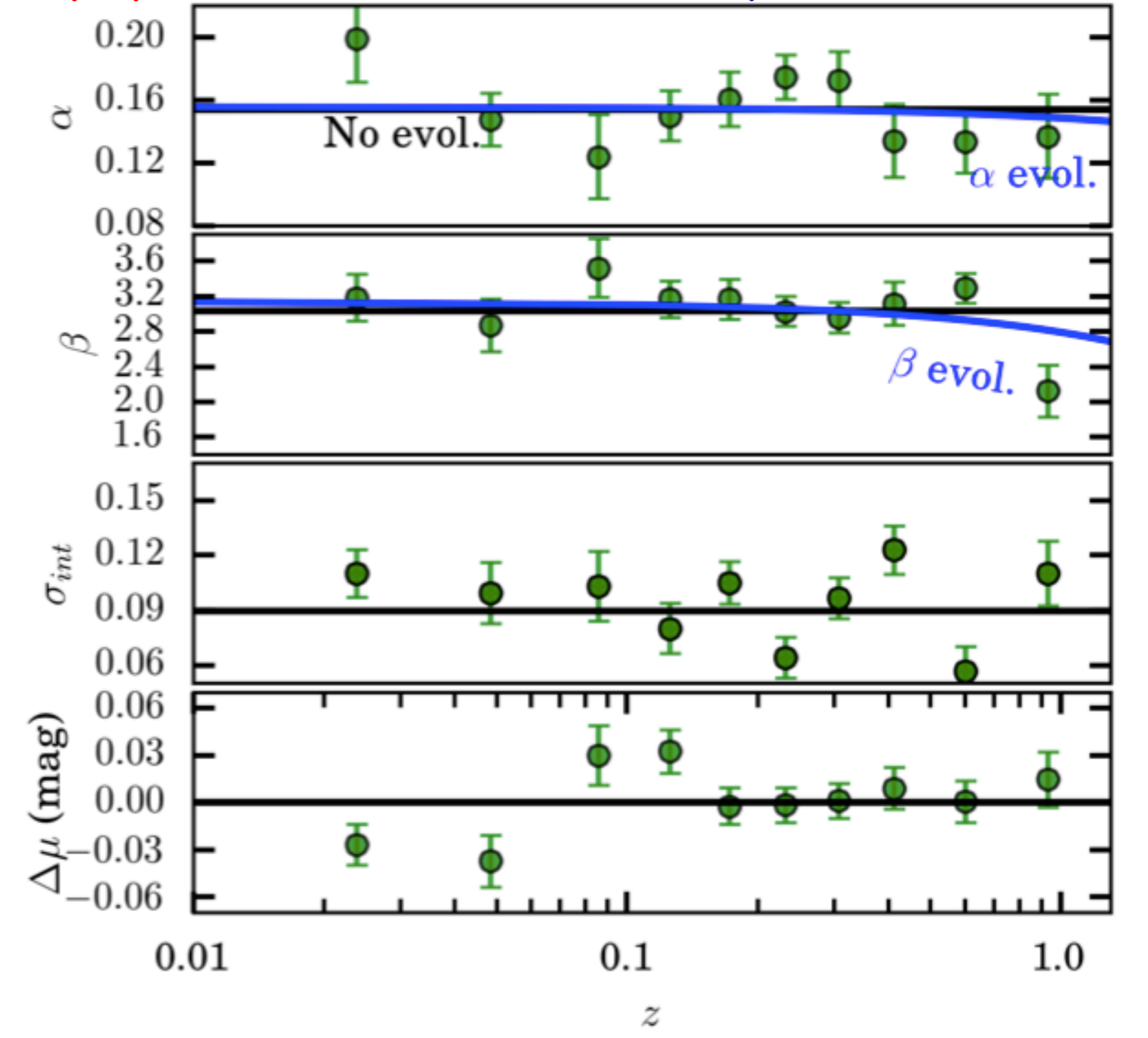
Description[b]	σ_w	$\sigma_w/\sigma_{w,\mathrm{stat}}$
Total Stat ($\sigma_{w,\mathrm{stat}}$)	0.042	1.00
Total Syst[c]	0.042	1.00
Total Stat+Syst	0.059	1.40
[Photometry & Calibration]	**[0.021]**	**[0.50]**
Low-z	0.014	0.33
DES	0.010	0.24
SALT2 model	0.009	0.21
HST Calspec	0.007	0.17
[μ-Bias Correction: survey]	**[0.023]**	**[0.55]**
†Low-z 3σ Cut	0.016	0.38
Low-z Volume Limited	0.010	0.24
Spectroscopic Efficiency	0.007	0.17
†Flux Err Modeling	0.001	0.02
[μ-Bias Correction: astrophysical]	**[0.026]**	**[0.62]**
Intrinsic Scatter Model (G10 vs. C11)	0.014	0.33
†Two σ_{int}	0.014	0.33
$\mathcal{C}$, x_1 Parent Population	0.014	0.33
†w, Ω_{m} in sim.	0.006	0.14
MW Extinction	0.005	0.12
[Redshift]	**[0.012]**	**[0.29]**
Peculiar Velocity	0.007	0.17
†$z + 0.00004$	0.006	0.14

- Pantheon paper: effect of each sub-sample on w constraint
  - change in w and σ_w when each subsample is removed



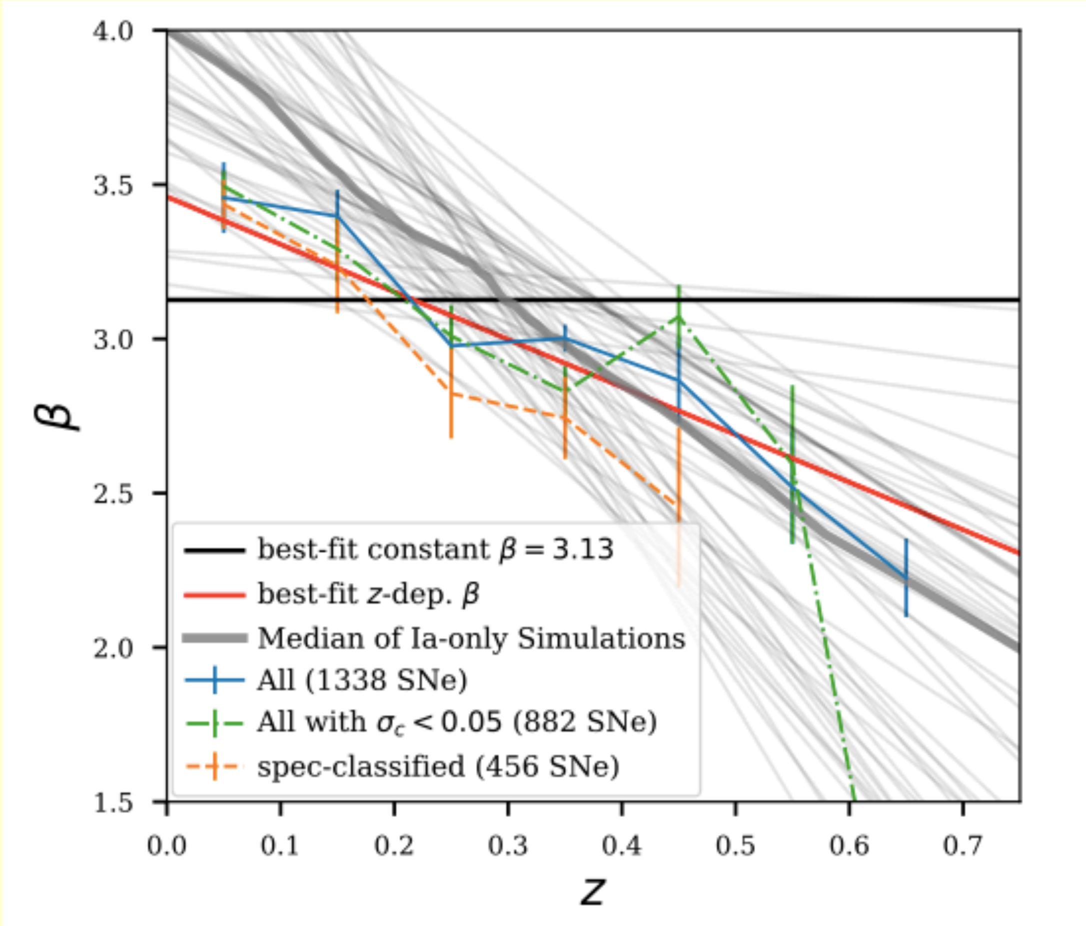


- PANTHEON paper: test for nuisance parameter evolution



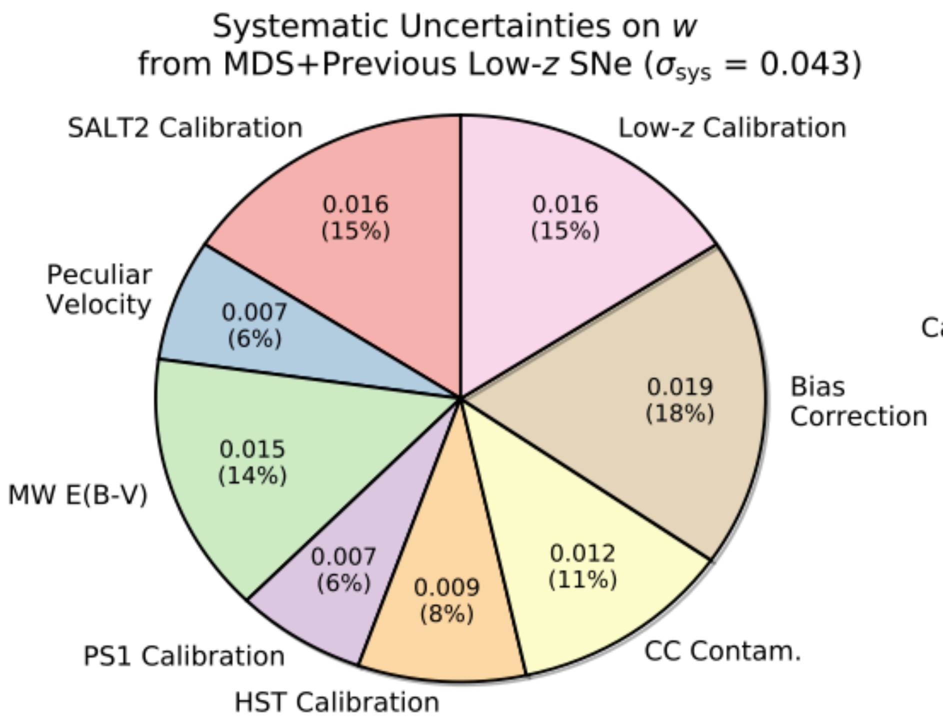
- No convincing evidence for α or β evolution
- No need for survey-specificf values of and σ_{int}

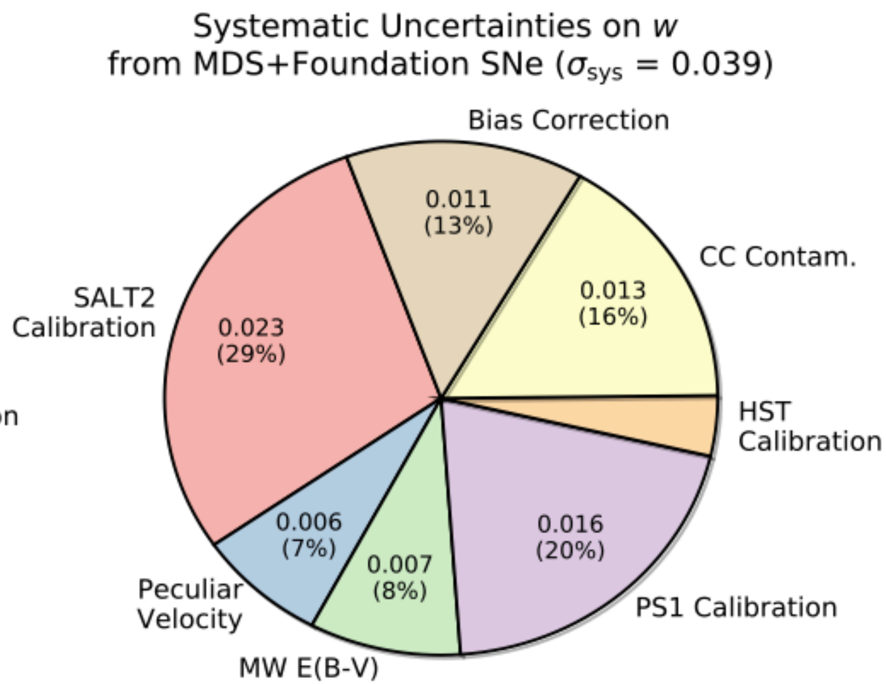
- Foundation paper : test for nuisance parameter evolution:
  - PS BEAMS: 3σ detection of β evolution
  - BBC: no detection



- Simulation : the observed evolution is not a physical effect

- Evolution of systematic error bugdet:



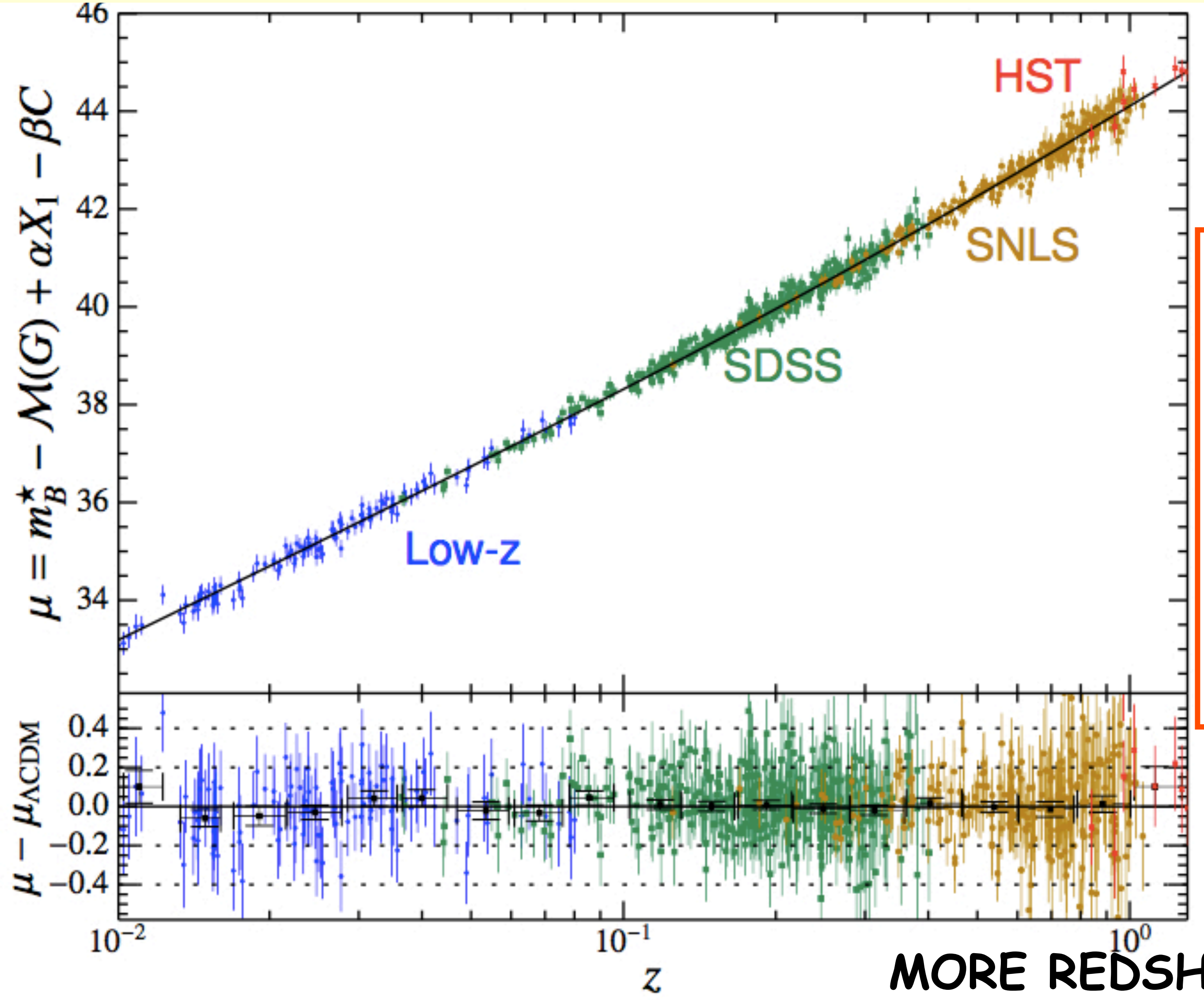


- Remaining calibration uncertainty:
  - PS1 ZPs for both high-z and low-z samples
  - consistent inter-calibration requires SALT2 re-training
- SALT2 re-training on redder rest frame λ required to use *iz* Foundation observations

The JLA sample, 2014

High quality data for **740** SNeIa

FAINTER (further back in time) →

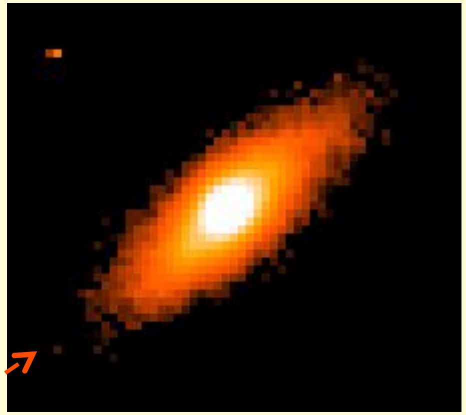


MORE REDSHIFT→

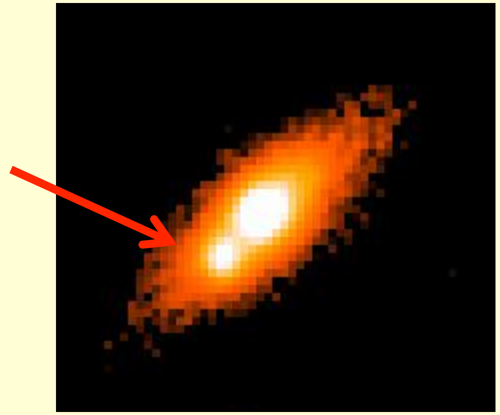
(more expansion since explosion)

flat Universe
Λ_{CDM} best-fit:
Ω_m=0.30±0.03:
accelerated
expansion
confirmed from
SNe Ia alone
(>99.9%CL)

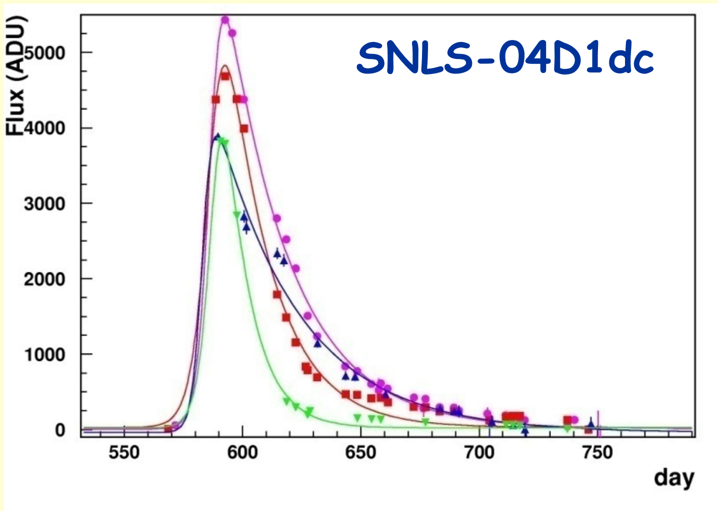
1. SNe Ia



before explosion



SN light curve



Cosmology with type Ia SNe

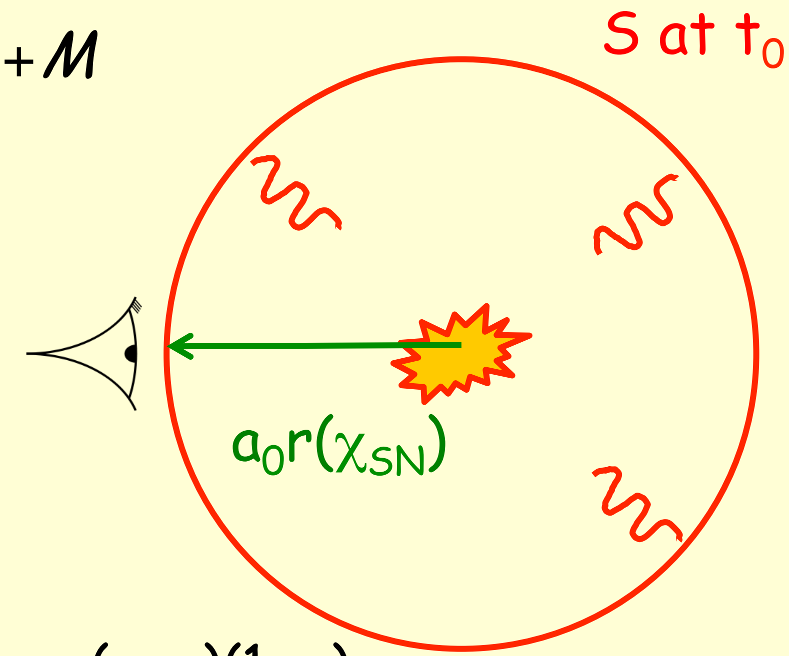
- Light curves ⇒ apparent peak magnitude:

$$m_B^* = -2.5\log\frac{\Phi}{\Phi_{cal}} = -2.5\log\frac{L}{4\pi d_L^2} + M$$

- Luminosity distance:

emission: $L = \frac{N_\gamma E_E}{\Delta t_E}$

observation: $\Phi = \frac{N_\gamma E_0}{\Delta t_0 S}$



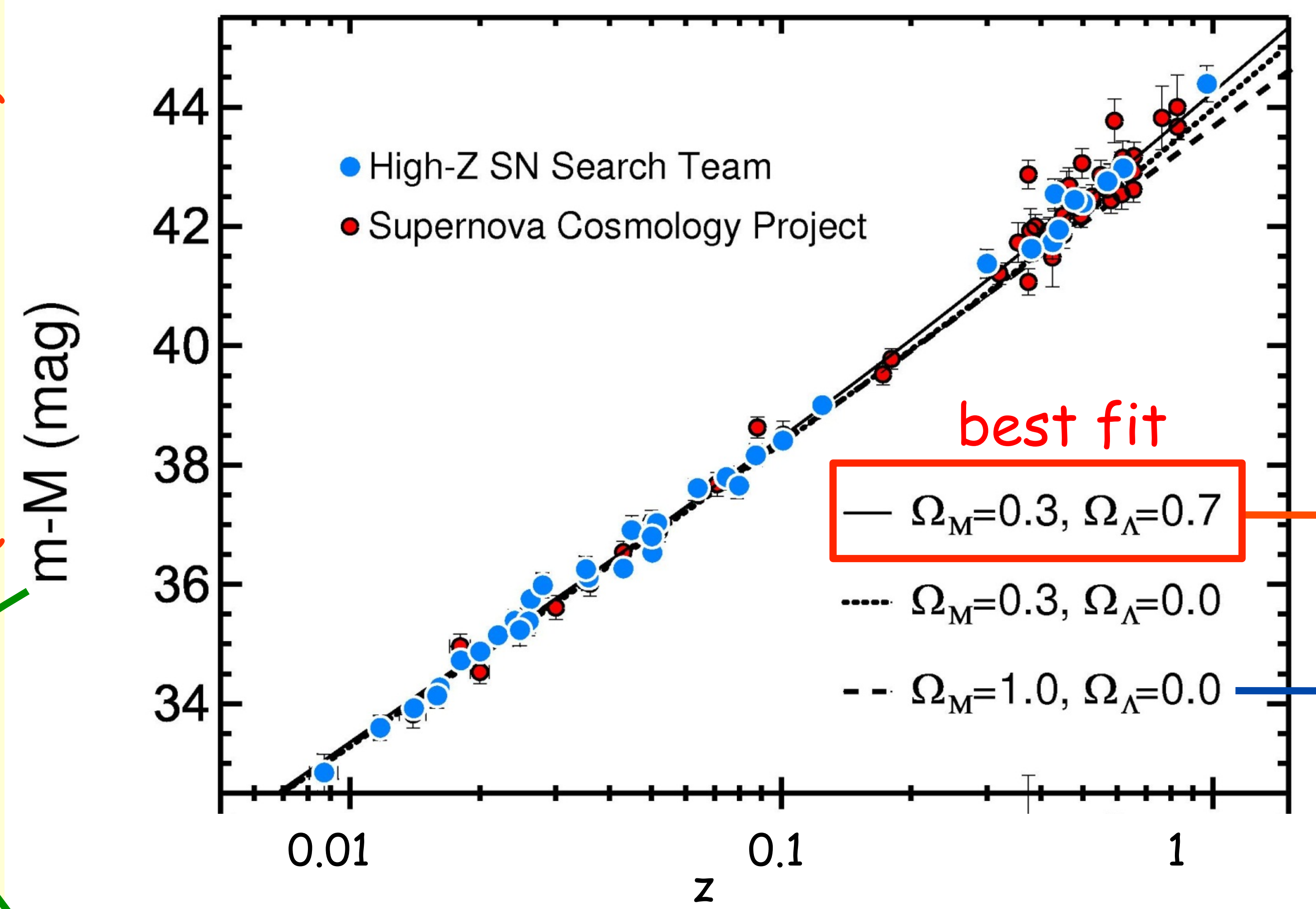
$$\Rightarrow \Phi = \frac{N_\gamma E_E}{\Delta t_E (1+z)^2 4\pi (a_0 r(\chi_{SN}))^2} \equiv \frac{L}{4\pi d_L^2} \Rightarrow d_L = a_0 r(\chi_{SN})(1+z)$$

$$\Rightarrow d_L = (1+z)\frac{c}{H_0 A}\begin{Bmatrix}\sin\\ 1\\ \sinh\end{Bmatrix}\left(A\int_0^z \frac{dz'}{\sqrt{\Omega_m^0(1+z')^3 + \Omega_r^0(1+z')^4 + \Omega_k^0(1+z')^2 + \Omega_\Lambda^0}}\right)$$

with $A = \sqrt{|\Omega_k^0|}$ *for* $k = -1, 1$ *and* $A = 1$ *for* $k = 0$ here, dark energy = Λ

Accelerated expansion : Type Ia SNe, 1998

FAINTER →
(further back in time)



dark energy

matter only

~ apparent magnitude
$= -2.5\log_{10}(\mathcal{L}/4\pi d_L^2)$

MORE REDSHIFT→
(more expansion since explosion)

S.Perlmutter et al., 1999, ApJ, 517, 565 & A.Riess et al., 1998, AJ, 116, 1009