Constraining dark energy

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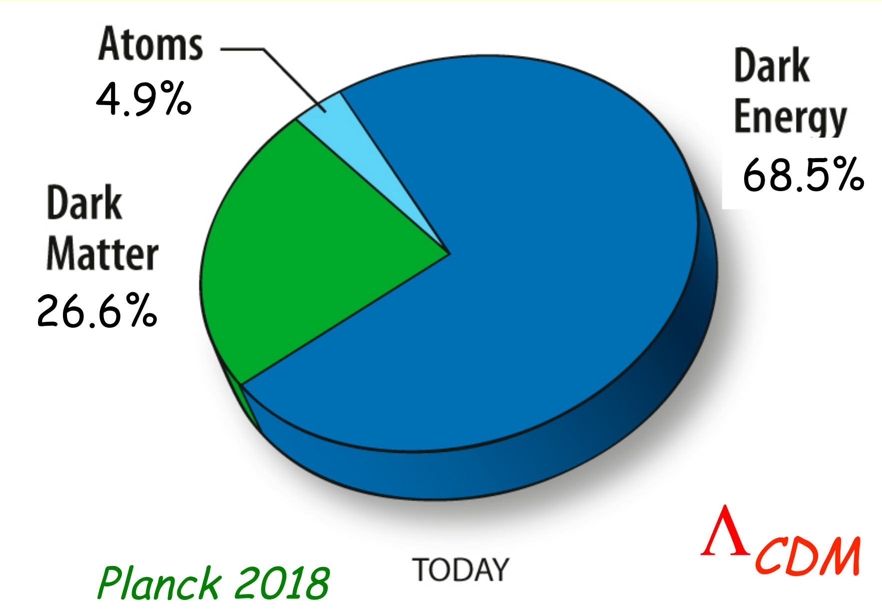
1) **State of the art, Type Ia supernovae (SNe Ia)**
2) Baryonic acoustic oscillations (BAO) and beyond (RSD)
3) Weak lensing (WL)
4) The H_0 tension

State of the art

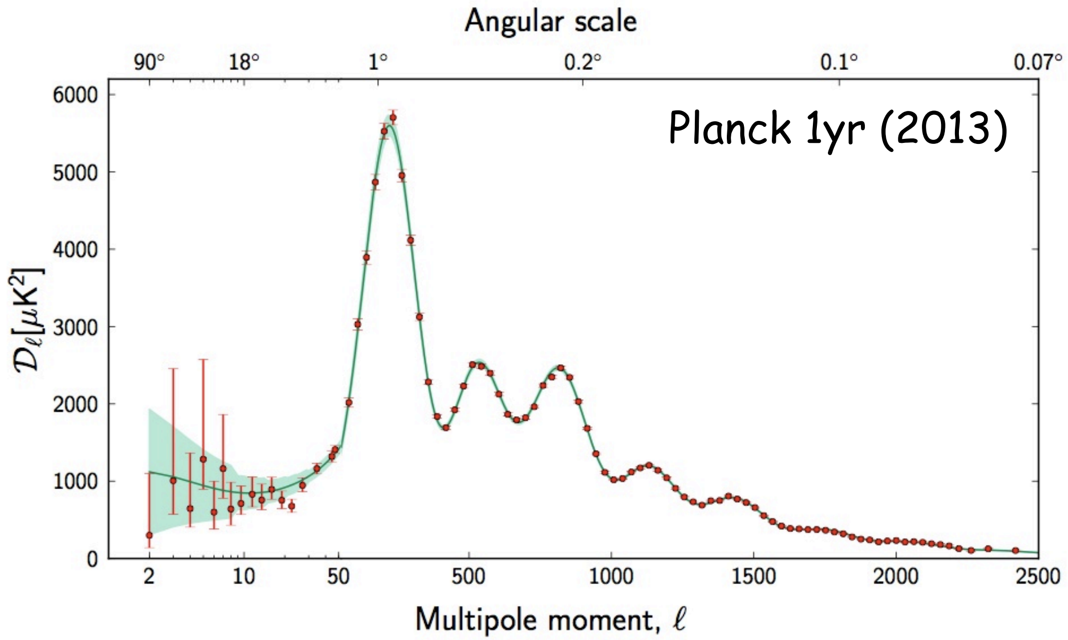


$$\Omega_m + \Omega_\Lambda + \Omega_k = 1$$

today

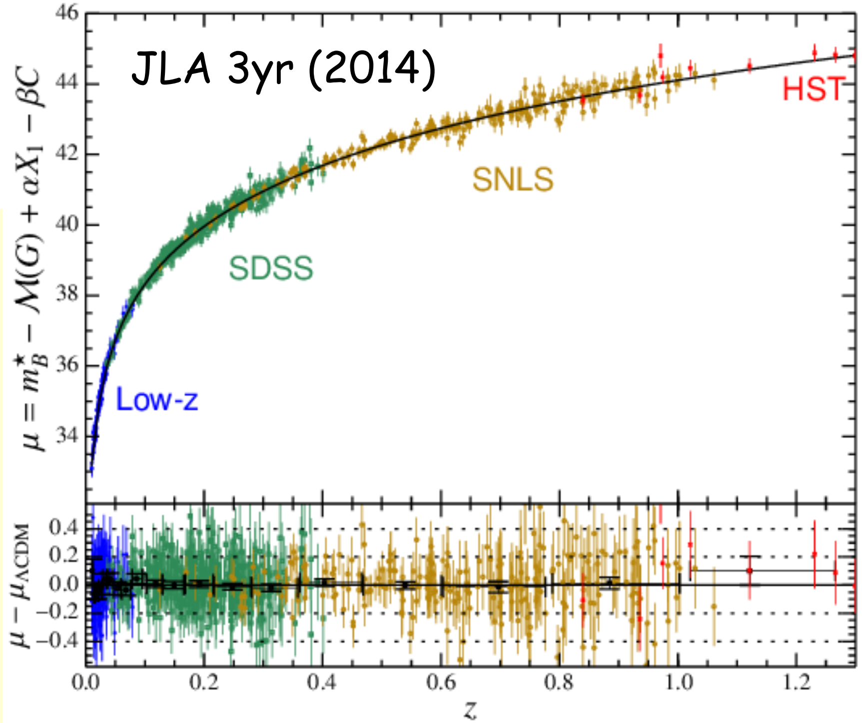
1. Precise cosmological probes (CMB, SNe Ia, BAO)
2. Present cosmological constraints on dark energy

dark energy = Λ, additional field (from modified GR or phenomenology) or modeling as an extra fluid with negative pressure

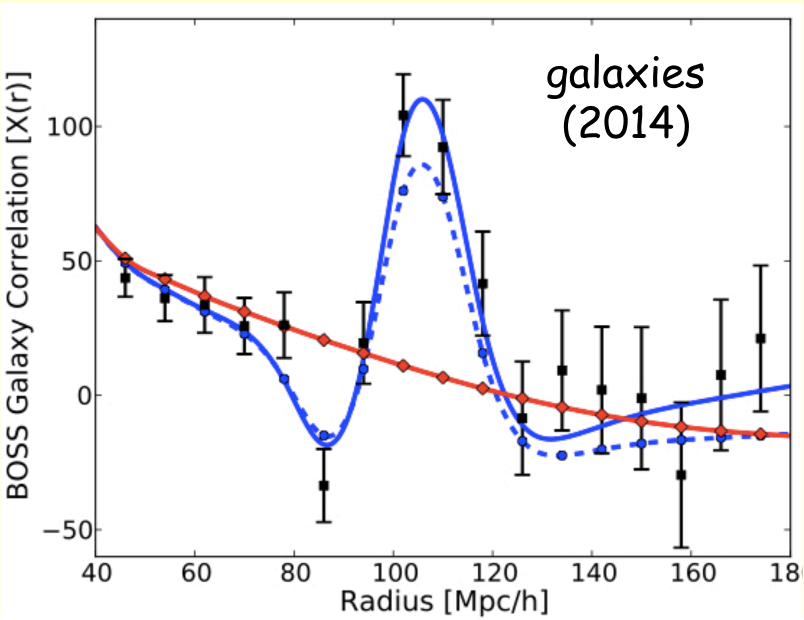


Cosmological probes

CMB spectra: imprint of acoustic oscillations at the last scattering surface (z=1089)



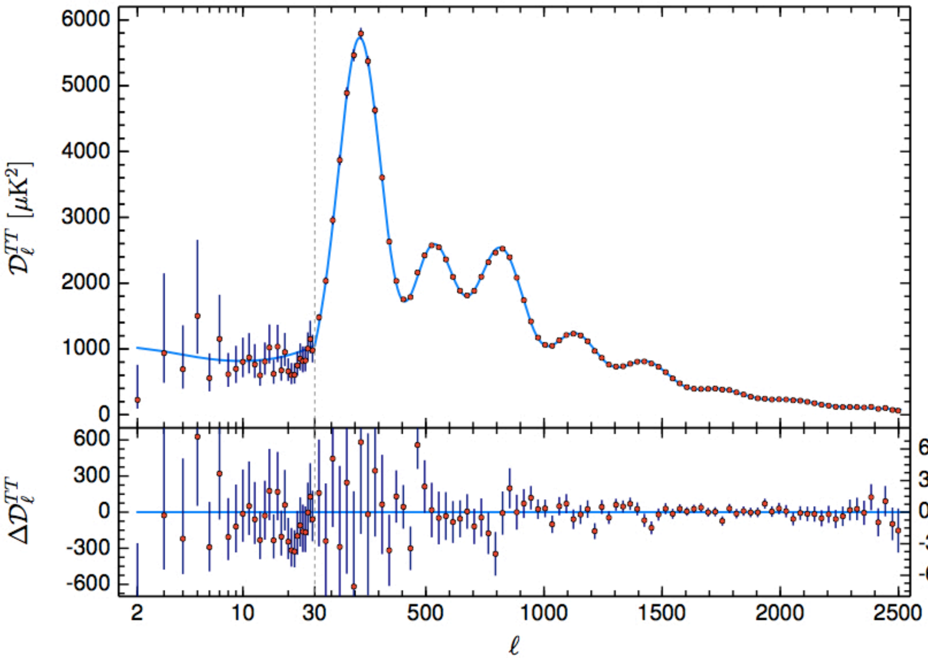
SN Ia luminosity distances (z≤1.5)

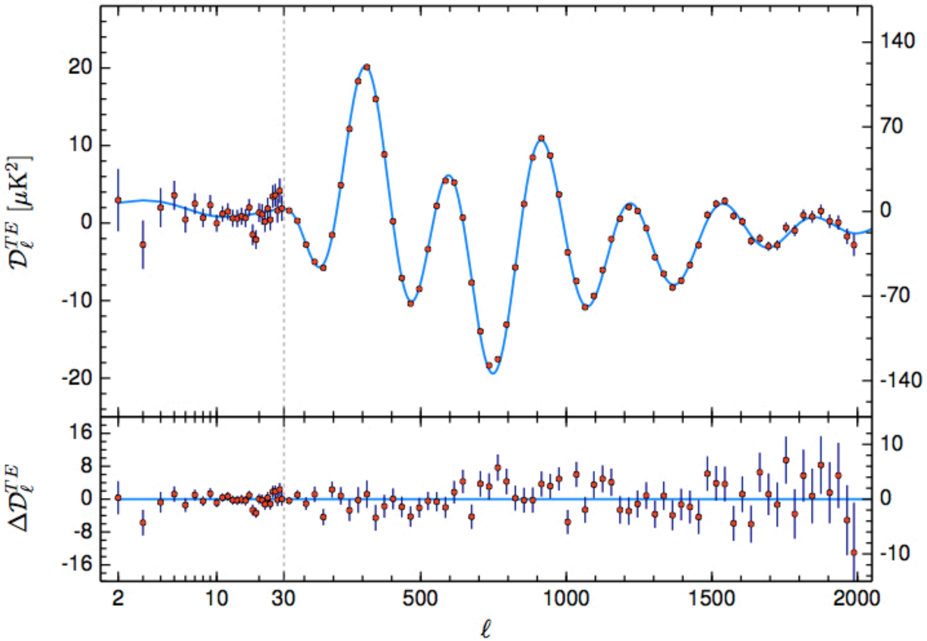


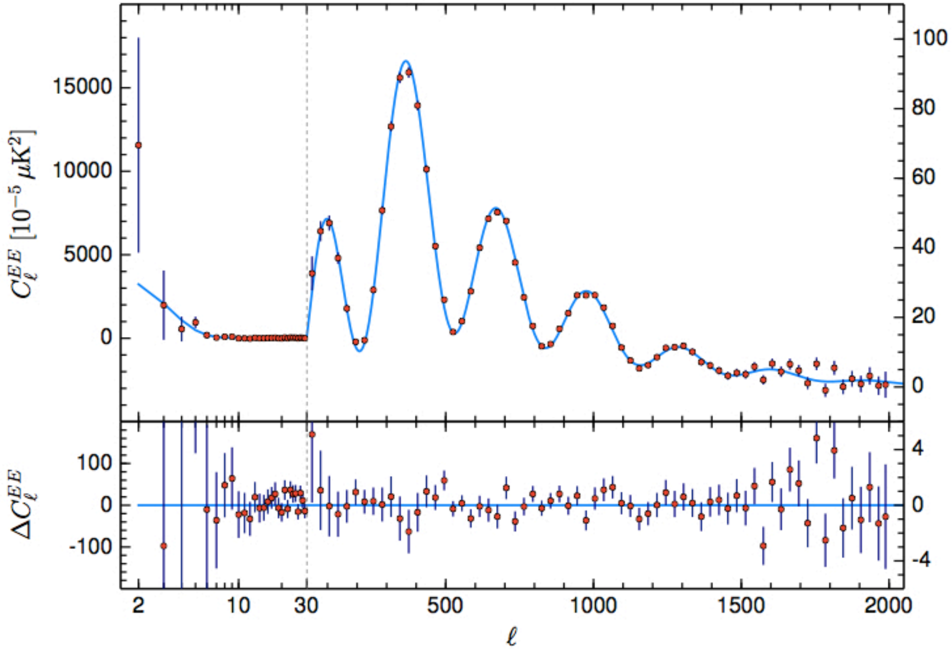
BAO: imprint of acoustic oscillations in the distribution of ordinary matter (galaxies, quasars, intergal. H clouds..z<2.3)

CMB: Planck 2018

- TT power spectrum: up to 7th peak, unprecedented accuracy
- Improved polarization data (low l)



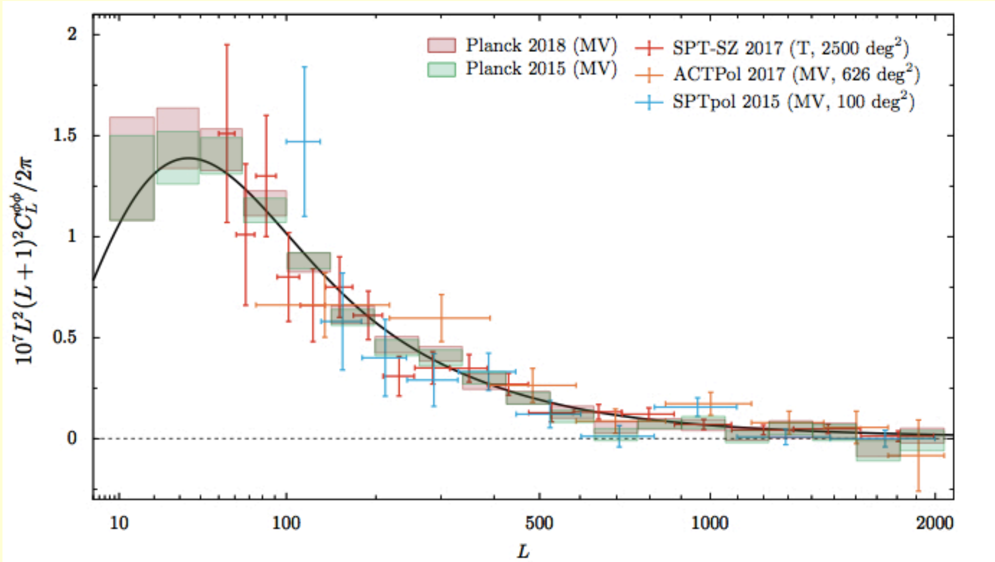




Planck Collaboration., arXiv:1807.06209

CMB: Planck 2018

- 40σ direct detection of CMB lensing signal (temperature + polarization data) *Planck Collaboration., arXiv:1807.06210*



=> CMB data alone constrain cosmology both at decoupling and later and so can probe dark energy

- Prospects: several projects (CMB-S4, LiteBIRD...), main aim is on polarization (inflation) but also on lensing (dark energy)

-> see lectures on CMB

Constraints

Models

- ΛCDM: dark matter, cosmological constant, flat or curved Universe $\rightarrow \Omega_m, \Omega_k$ (or Ω_Λ)
- wCDM: dark matter, dark energy with constant equation of state, flat or curved Universe $\rightarrow \Omega_m$, w, Ω_k (or Ω_{de})

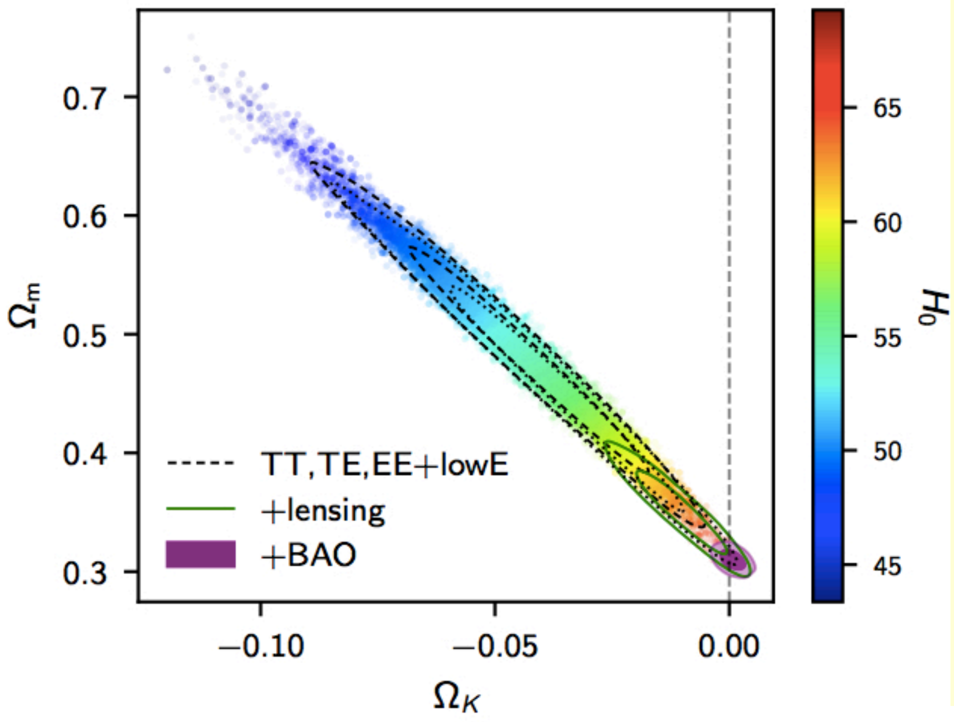
$$w = \frac{p_{de}}{\rho_{de}} \qquad \frac{1}{\rho_{de}} \frac{d\rho_{de}}{dt} = -3H(1+w)$$

- w(z)CDM or ow(z)CDM: same as wCDM with time-dependent dark energy e.o.s, e.g.

$$w(z) = w_0 + w_a \frac{z}{1+z} = w_0 + w_a(1\text{-}a)$$

excellent approximation to a wide variety of dark energy models (scalar fields…) $\rightarrow \Omega_m$, w_0, w_a, Ω_k (or Ω_{de})

- Others: specific modified GR models, model-independent way (tomography on w(z), deviations from GR)



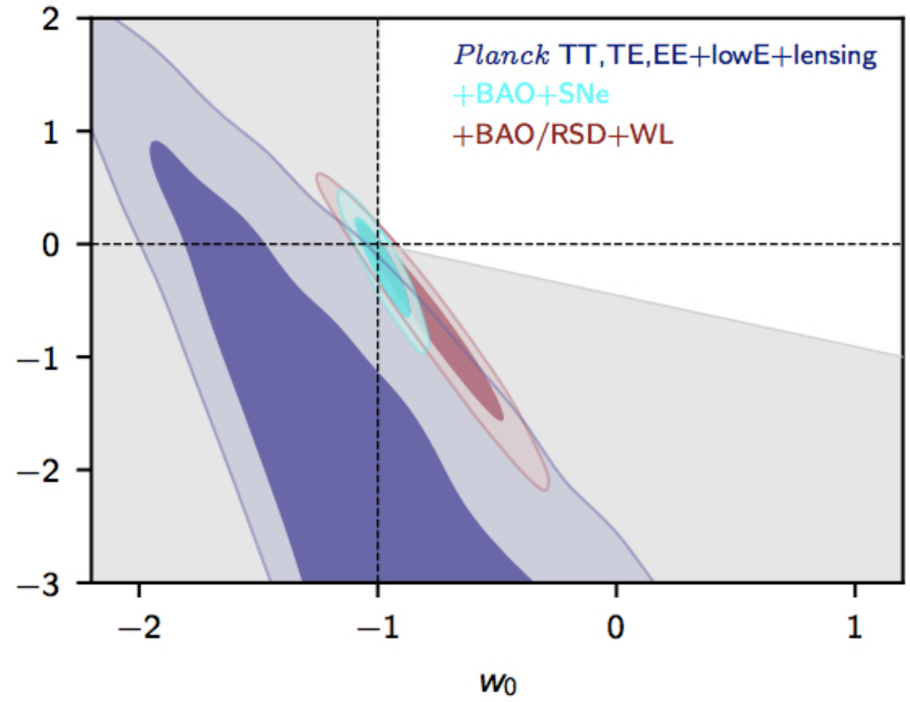
ΛCDM

- our Universe is spatially flat to a 1σ accuracy of 0.2%
- matter accounts for 30% of energy budget, dark energy required

w(z)CDM, flat

- w_a~0 & w_0~-1 (=ΛCDM) preferred by data
- cosmological constant OK to describe dark energy

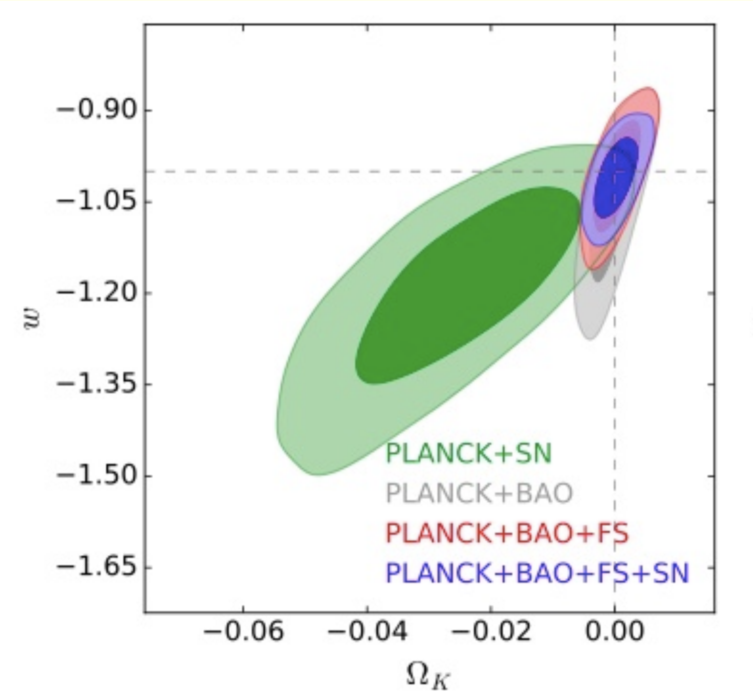
Planck Collab., arXiv:1807.06209



Intermediate Summary

- Dark energy constraints today from: CMB, SNeIa, BAO.
- Best explanation for dark energy : cosmological constant.

wCDM, open



S. Alam et al., 2017, MNRAS,470, 2617A

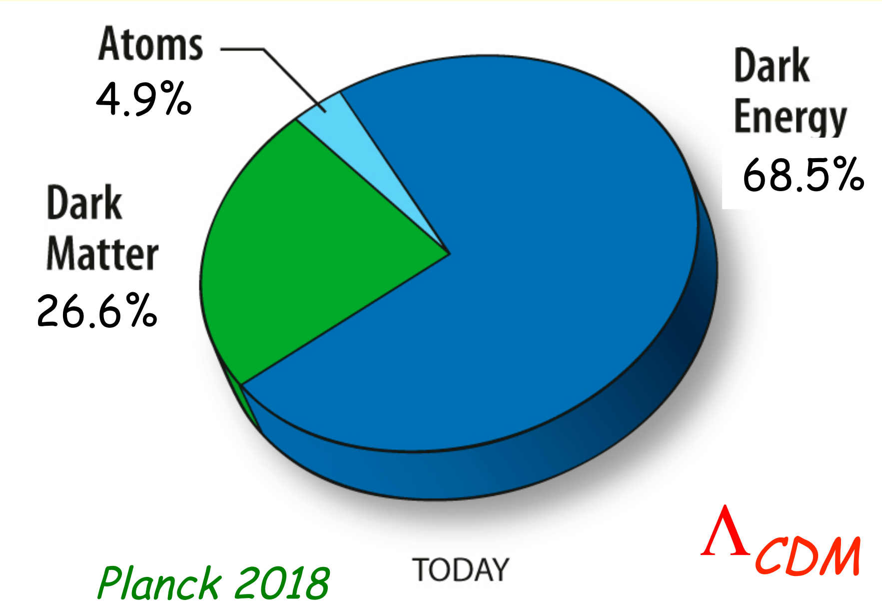
- CMB & BAO: probes of curvature and dark energy
- SNeIa: probe of dark energy, especially in case of time varying e.o.s

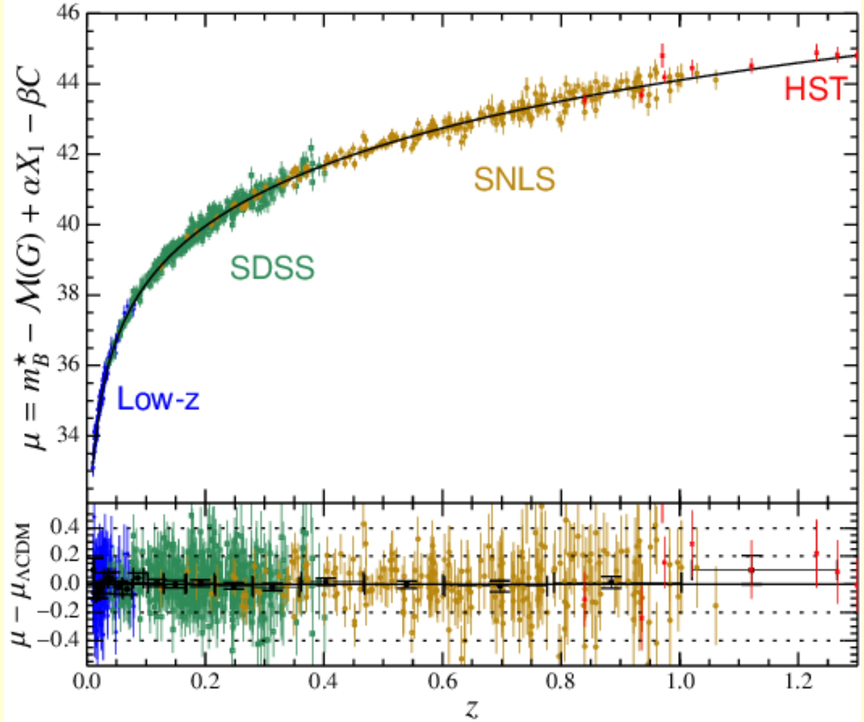
Current precisions, flat wCDM and w(z)CDM:

$\boldsymbol{\delta w}=0.032$ / $\boldsymbol{\delta w_0}=0.08$ $\boldsymbol{\delta w_a}\approx 0.3$

Planck Collab., arXiv:1807.06209

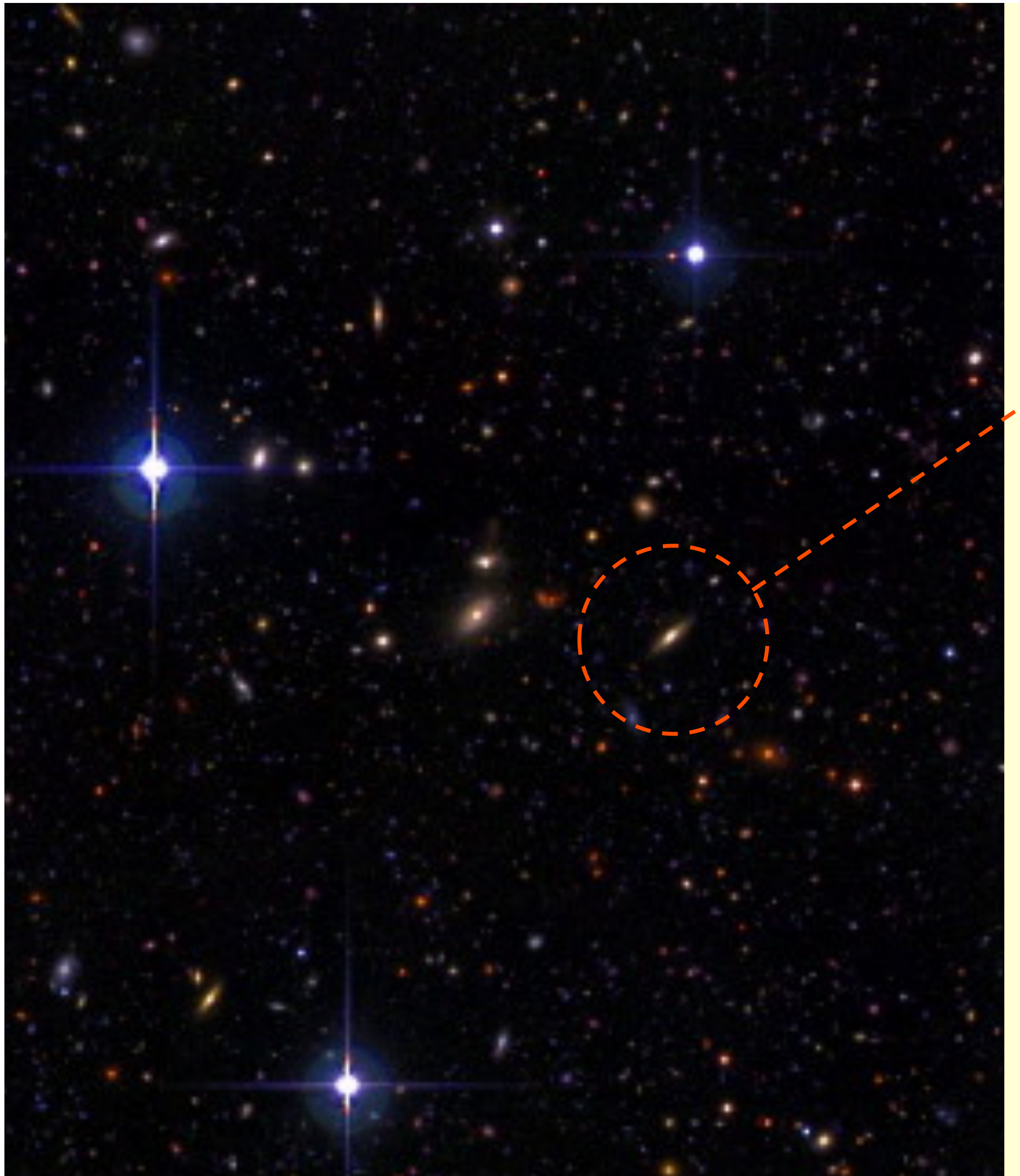
Type Ia supernovae



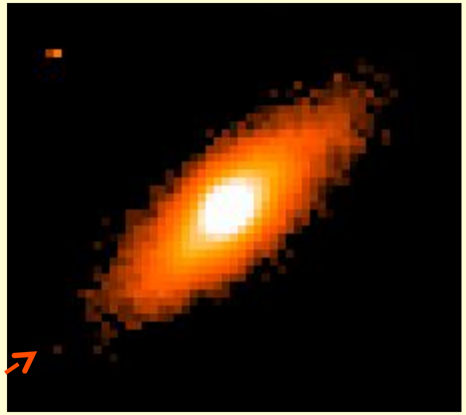


1. Cosmology analysis, principle of the method
2. Requirements for a precise cosmology analysis
3. Future prospects: LSST, WFIRST

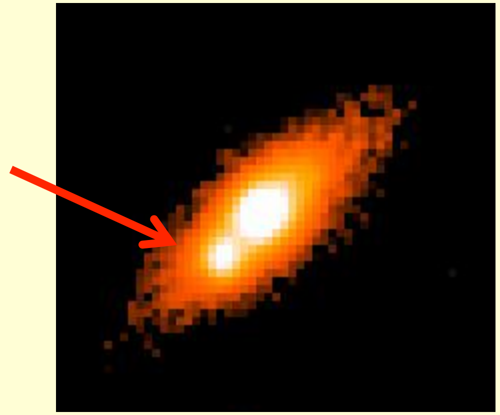
Method



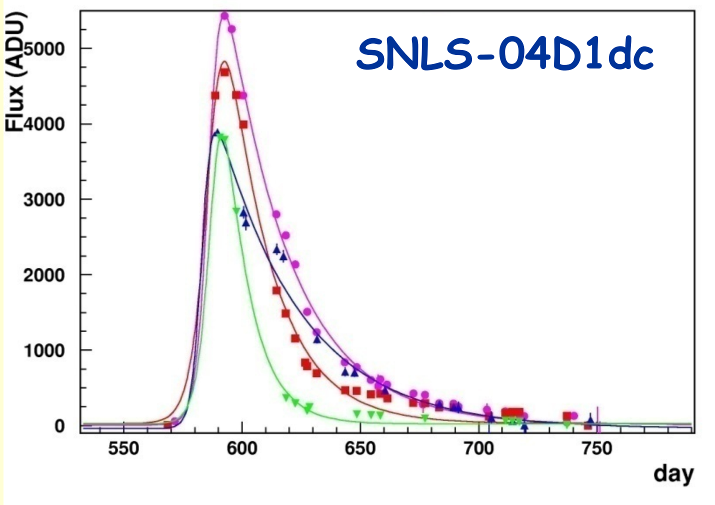
Photometry: detection and light curves
Spectroscopy: type and redshift



before explosion

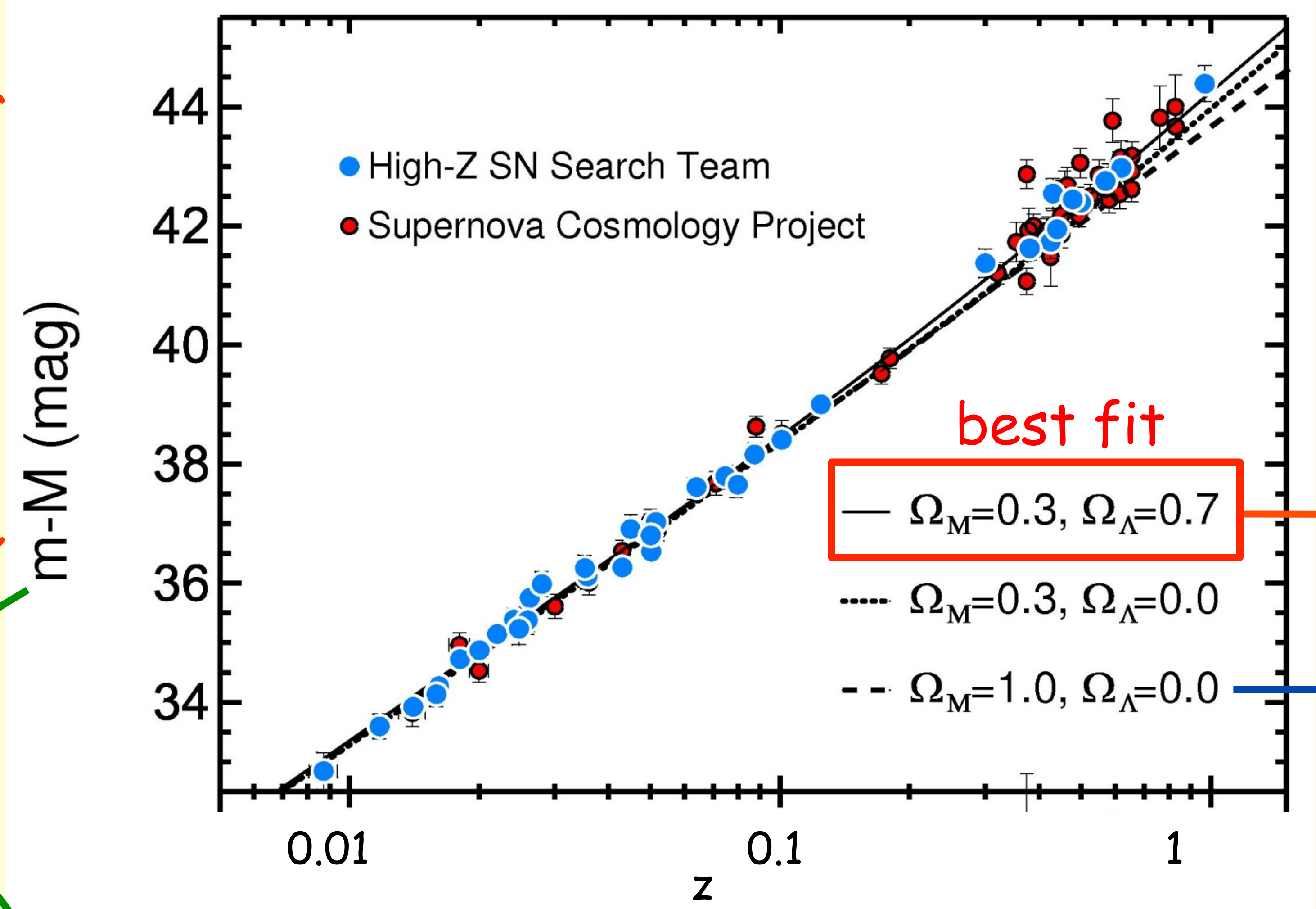


SN light curve



Accelerated expansion : SNIa, 1998

FAINTER →
(further back in time)



dark energy

matter only

MORE REDSHIFT→
(more expansion since explosion)

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

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

SNe Ia as distance indicators, 1/3

- Light curves (for a SN at redshift z) $\Rightarrow$ apparent peak magnitude :

$$m_B^*(z) = -2.5\log_{10}\frac{L}{4\pi D_L^2(z)} = 5\log_{10}\frac{D_L(z)}{10pc} + M_B$$

in the case of perfect standard candles

- Luminosity distance : $D_L(z) = \frac{c}{H_0} d_L(z)$

d_L dimensionless, $d_L(z,\Omega_i)$

e.g. in a flat ΛCDM Universe

$$d_L(z) = (1+z)\int_0^z \frac{d\tilde{z}}{H(\tilde{z})/H_0}$$

$$H(z)/H_0 = \sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}$$

- Distance modulus : $\boxed{\mu_B(z) \equiv m_B^*(z) - \hat{M}_B = 5\log_{10} d_L(z)}$

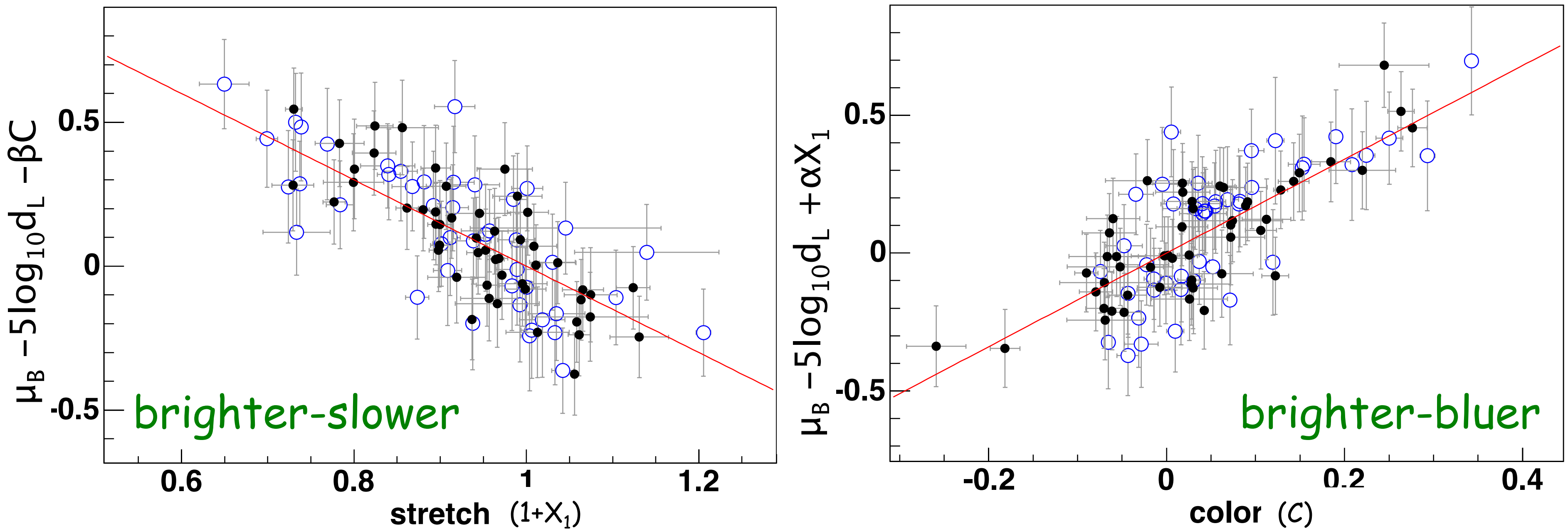
with :

$$\hat{M}_B = M_B - 5\log_{10}\frac{c}{H_0 x 1Mpc} - 25$$

Hubble diagram offset, degeneracy between M_B and H_0

- SNe Ia are not perfect candles but their diversity can be corrected for empirically :

P.Astier et al., 2006, A&A, 447, 31



light curves $\Rightarrow$ m_B^*, stretch and colour

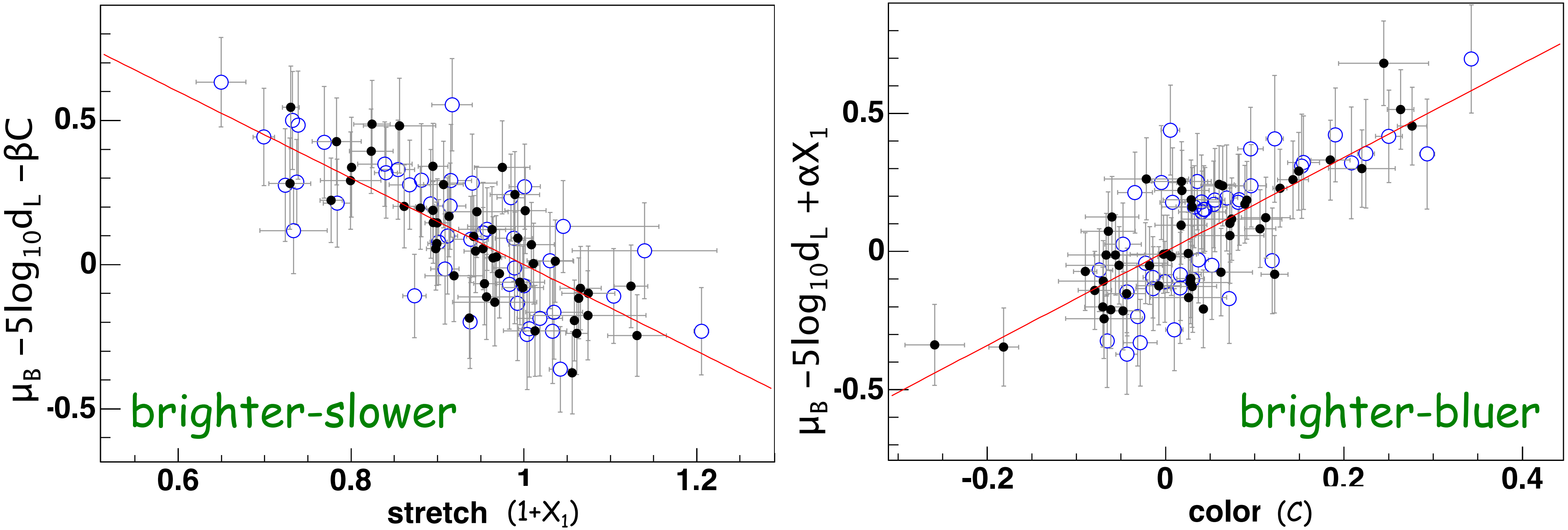
$$\mu_B = 5\log_{10} d_L = m_B^* - \alpha X_1 + \beta C - \hat{M}_B$$

lightcurve shape diversity

(B-V) colour diversity (intrinsic variation and extinction)

- SNe Ia are not perfect candles but their diversity can be corrected for empirically :

P.Astier et al., 2006, A&A, 447, 31



light curves ⇒ m_B^*, stretch and colour

$$\mu_B = 5\log_{10} d_L = m_B^* - \alpha X_1 + \beta C - \hat{M}_B(G)$$

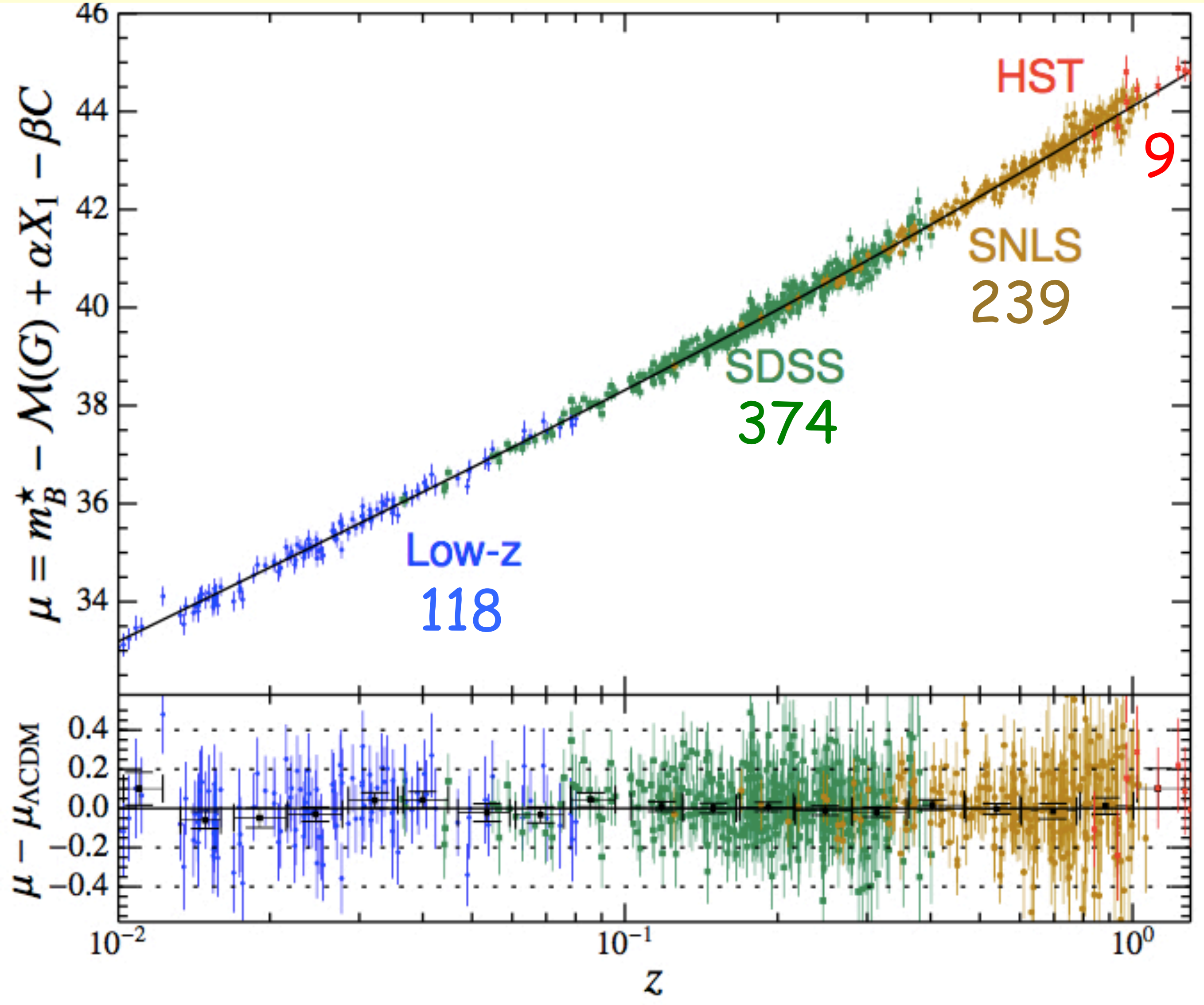
diversity related to host galaxy (brighter SN-higher galaxy mass)

⇒ $\alpha, \beta, \hat{M}_B(G)$: nuisance parameters in cosmological fits

(no z dependence)

SNIa HD, JLA sample, 2014

High quality data for **740** SNeIa, with **inter-survey calibrations**



Flat ΛCDM fit:

$\Omega_m^0 = 0.295 \pm 0.034$

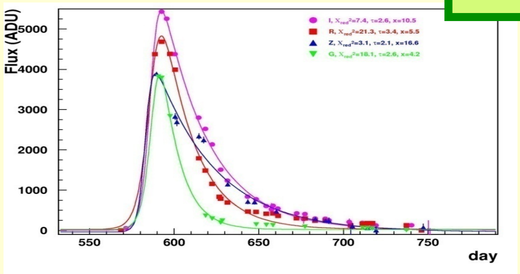
stat ≈ syst

accelerated expansion confirmed by 2nd generation SNIa surveys alone

M.Betoule et al., 2014, A&A, 568, A22c

Requirements

For a precise cosmology analysis



➔ light curve fitter (PCA model) ➔ m_{B^*}, X_1, C
(to be applied at the SN redshift)

SNLS (CFHTLS-DEEP survey)

- large, well controlled samples
- low z and high z
- multiple band photometry
- precise calibration
- good temporal sampling
- SNIa light curve model
- spectro. follow-up (type, z)

- rolling search strategy
- multi-survey approach
- 4 bands (griz)
- ~ 5 mmag
- 3 to 5 day cadences
- large training sample (LCs, spectra)
- spectroscopic time allocation

- main systematics: calibration, LC model
- JLA+Planck15+BAO, flat wCDM fit: $w=-1.006\pm0.045$

Recent progress (2018)

The Pantheon sample

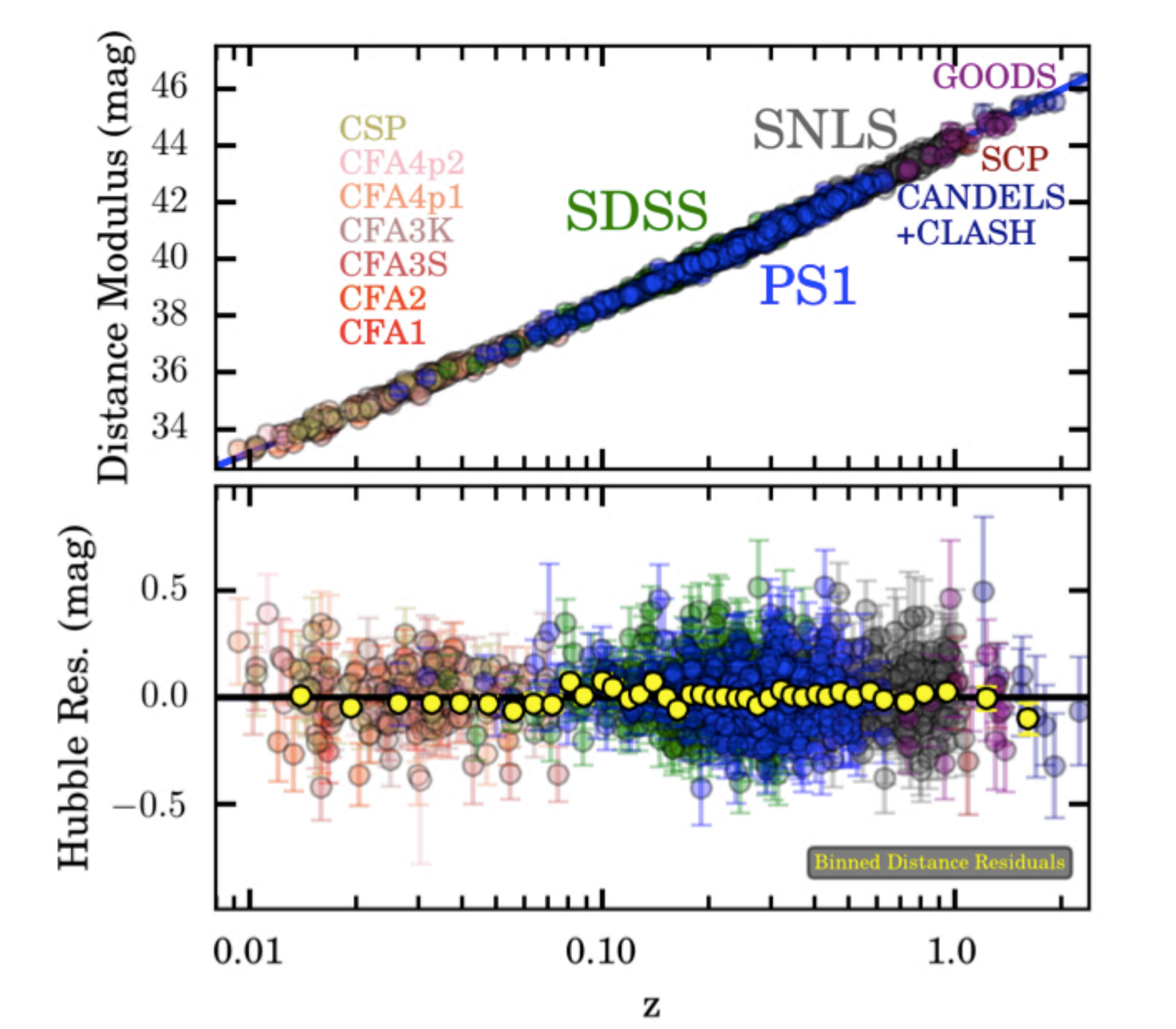
large, well controlled samples	high z PS1/MDS data (untargeted)
low z and high z	more low z data (targeted)
multiple band photometry	PS1/MDS: 4 bands (griz)
precise calibration	~5 mmag thanks to PS1 3π survey
good temporal sampling	PS1/MDS: 7 day cadence
SNIa light curve model	
spectro. follow-up (type, z)	spectroscopic time allocation

- main systematics: calibration, LC model

- Pantheon+Planck18+BAO, flat wCDM fit: $w=-1.028\pm0.032$

SNIa HD, Pantheon sample, 2018

High quality data for **1048** SNeIa, with **inter-survey calibrations**



Flat ΛCDM fit:

$\Omega_m^0 = 0.298 \pm 0.022$

stat ≥ syst

D.M.Scolnic et al., 2018, ApJ, 859, 101S

Recent progress (2019)

The Foundation sample

- large, well controlled samples
- low z and high z
- multiple band photometry
- precise calibration
- good temporal sampling
- SNIa light curve model
- spectro. follow-up (type, z)

- z < 0.08: large, untargeted sample, photometric follow-up on PS1
- PS1: 4 bands (griz)
- ~5 mmag thanks to PS1 3π survey
- PS1: 8 day cadence
- spectroscopic time allocation

=> better controlled low z sample: homogeneous, less biased, well controlled selection effects (1st release: 225 SNe)

=> low z sample selection systematics reduced

=> ultimate goal: 800 SNe z < 0.1

Recent progress

Photometric MDS sample

- large, well controlled samples
- low z and high z
- multiple band photometry
- precise calibration
- good temporal sampling
- SNIa light curve model
- ~~spectro. follow-up (type, z)~~

- high z PS1/MDS data (untargeted)
- Low z : Foundation sample
- PS1: 4 bands (griz)
- ~5 mmag thanks to PS1 3π survey
- PS1: 8 day cadence
- MDS: spectroscopic host redshift
- MDS: photometric classification

+ a sample from a single telescope with a precise calibration

- CC contamination : to be marginalized over, adds a new systematics

- MDS+Foundation+Planck18+BAO, flat wCDM fit: $w = -0.949 \pm 0.043$

D.O.Jones et al., 2019, ApJ, 881, 19J

LSST

- 8.4 m (6.5 m eff) mirror
- 9.6 deg^2 FoV
- 3.2 Gigapixel camera
- 0.32-1.05 μm, u,g,r,i,z,y imaging only
- Cerro Pachòn, Chile
- 10 yrs from 2023 on
- 18,000 deg^2, 37 billion stars & galaxies

Science:

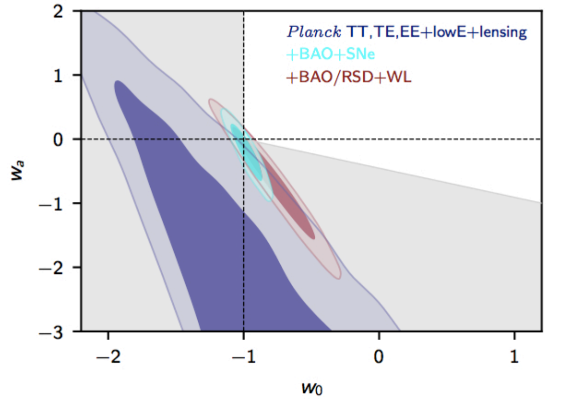
- Dark matter and Dark energy ➔ WL, LSS, clusters, SNe
- Cataloging the solar system
- Exploring the changing sky
- Milky Way structure & formation

LSST: a multi-purpose survey based on a single dataset

SNIa cosmology with LSST

- LSST main survey : Wide-Fast-Deep survey (90%)
  - rolling search, 3-4 day cadence, 6 bands, O(mmag) calibration on griz, photometry only
  - 400,000 photometrically-classified SNe Ia, griz band LCs, SN photometric redshifts : $\langle z \rangle = 0.45$, $z < 0.7$, $\sigma_z/(1+z) \sim 1\text{-}3\%$
    - ➔compare SN sub-samples split by redshift, host activity, sky region…
  - 100,000 with host spectroscopic follow-up (ie z) on multi-object spectrographs (e.g. 4MOST, PSF…)
    - ➔Hubble diagram with an independent low-z sample (e.g. Foundation)
  - Other topics: $f\sigma_8$ from SN peculiar velocities, H_0 from strongly lensed SNe

LSST forecast

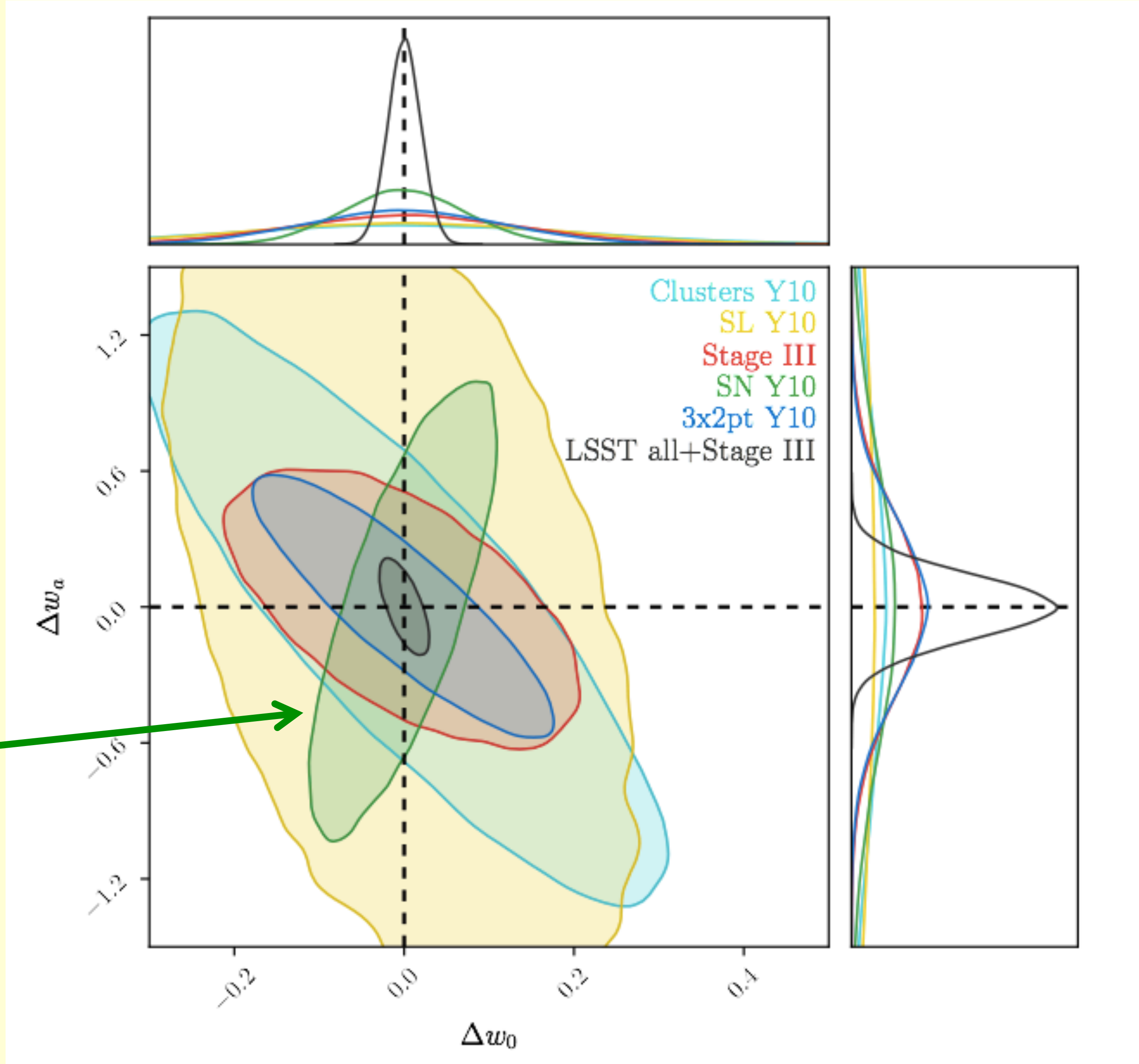


$\delta w = 0.032 = \delta w_p$

$\delta w_0 = 0.08 \quad \delta w_a \approx 0.3$

SNe Ia, 2nd most constraining probe

Note: multi-probe approach from a single survey, see L2 for combined forecast



LSST Dark Energy Science Collaboration, arXiv:1809.01669

WFIRST

- 2.4 m mirror
- 0.28 deg^2 FoV
- WFI: 300 Megapixels
- WFI imaging
  - 0.48-2.0μm, R,Z,Y,J,H,F,W
- WFI spectroscopy
  - 1.0-1.93μm (450-850) Gal
  - 0.8-1.8μm (70-140) SN
- satellite, L2
- launch mid 2020s, 5->10yrs
- 2,000 deg^2, a billion galaxies

Science:

- Dark energy ➔ WL, LSS, clusters, SNe
- Exoplanet microlensing
- Infrared astrophysics and planetary science topics

WFIRST: a multi-purpose project based on 3 specific surveys

SNIa cosmology with WFIRST

- WFIRST SNIa survey (0.5 yr in 2 yrs): definition still under debate
  - rolling search, 5 day cadence, 4 filters among RZYJHF, O(mmag) calib, with/without spectroscopic follow-up from WFI
  - with spectro: ~3,400 SNe, $0.1<z<1.8$, spectro z, sub-typing for 1,200-1,600 up to $z<1.2$

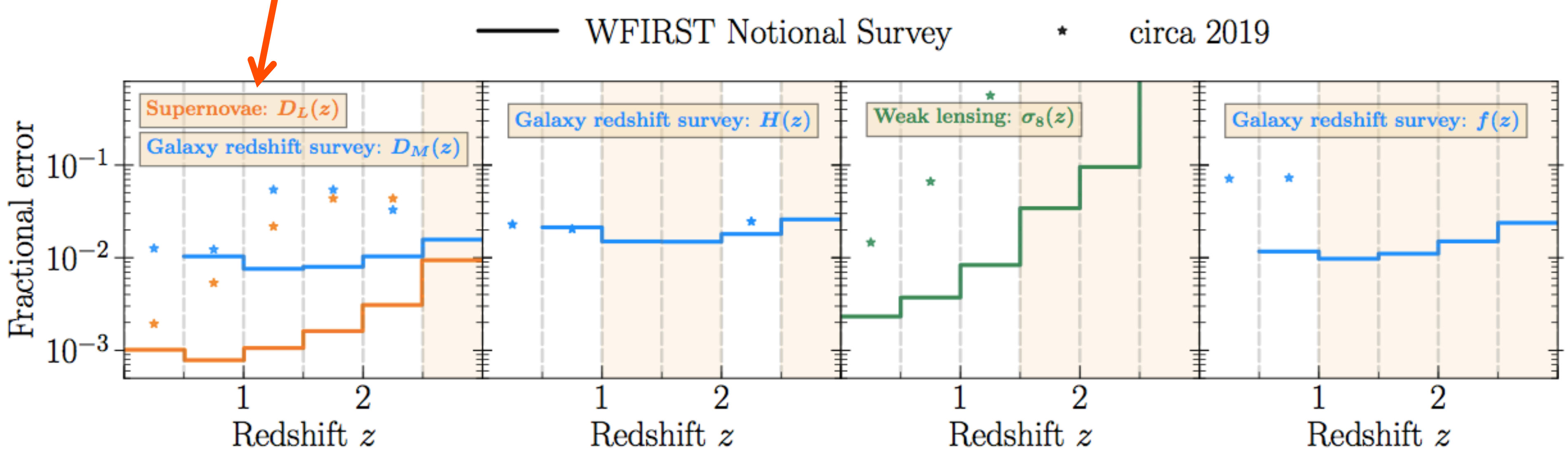
    ➔Hubble diagram with an independent low-z sample (e.g. Foundation)
  - all-imaging: 20,000 SNe Ia, $0.01<z<3$, light curves only

    ➔possible ugrizy LSST follow-up to improve distance precision, valuable training sample for SNIa modelling & photometric redshift calibration

    ➔HD if spectroscopic host redshifts from external sources
  - Others: SN magnification by WL, H_0 from strongly lensed SNe

WFIRST forecast

SNe Ia



O. Doré et al, Astro2020 science white paper, arXiv:1904.011174

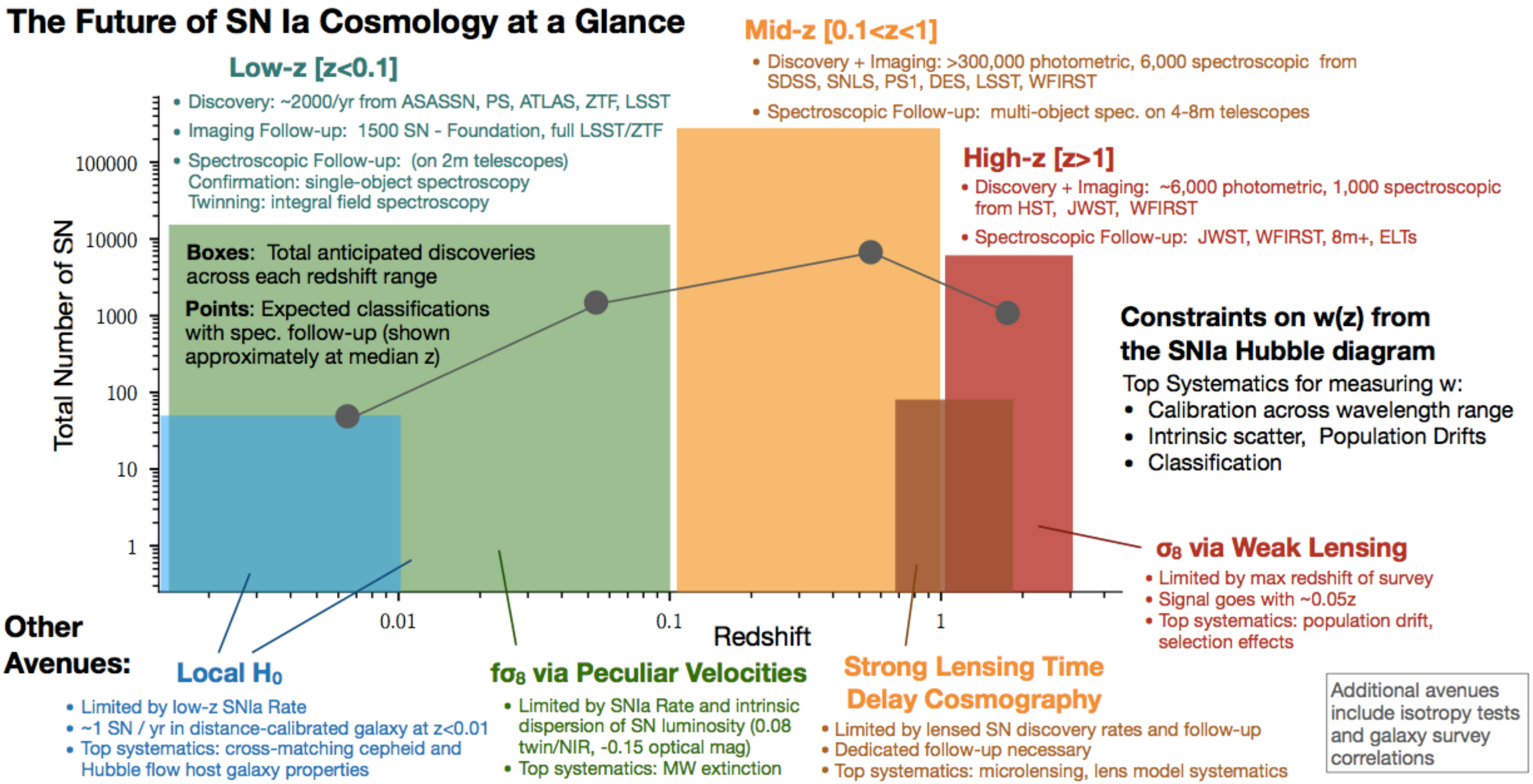
Note: multi-probe approach from a single survey, see L2 for global cosmological forecast

CONCLUSIONS

- SNe Ia: probe distance–redshift relation; high z vs low z, so H_0 independent test; current uncertainties syst ~stat

- dominant systematics:
  1. photometric calibration (accurate standards, in situ modelling of transmission filters, single survey to cover all z's)
  2. SNIa LC model (larger traning sample, with extension to IR/UV)
  3. SNIa standardization (environmental dependence of SN luminosity)

- Prospects:
  - Gaia spectroscopic standards, laboratory calibration sources -> 1
  - large samples from LSST, WFIRST (and possible synergies) -> 2 and 3
  - a major difficulty: systematic uncertainty from (SN/host) photo. z's for HD cosmology. A way out : host spectroscopic follow-up (OzDES)
  - new cosmology tests accessible with large samples of SNe Ia



D.M. Scolnic et al, Astro2020 science white paper, arXiv:1903.05128