Cosmological Constraints from the SNLS and SDSS datasets

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on behalf of the SNLS/SDSS JLA program

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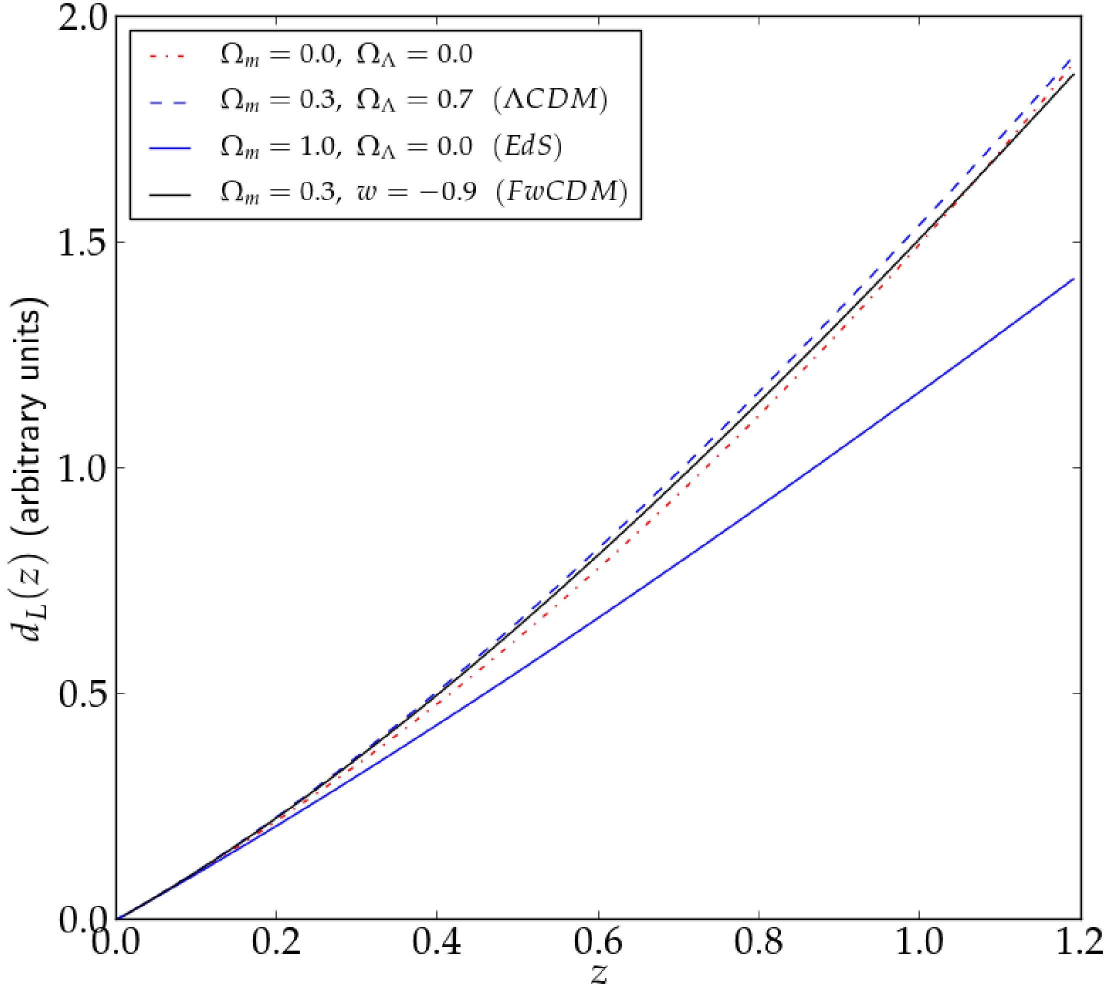
Outline

- Cosmology with Type Ia supernovae
- Constraints on w from the SNLS-3 dataset
- The SNLS/SDSS JLA effort
  - Photometric calibration
  - SN Ia studies
  - (Preliminary) cosmological constraints
- Conclusion

Cosmology with SNe Ia



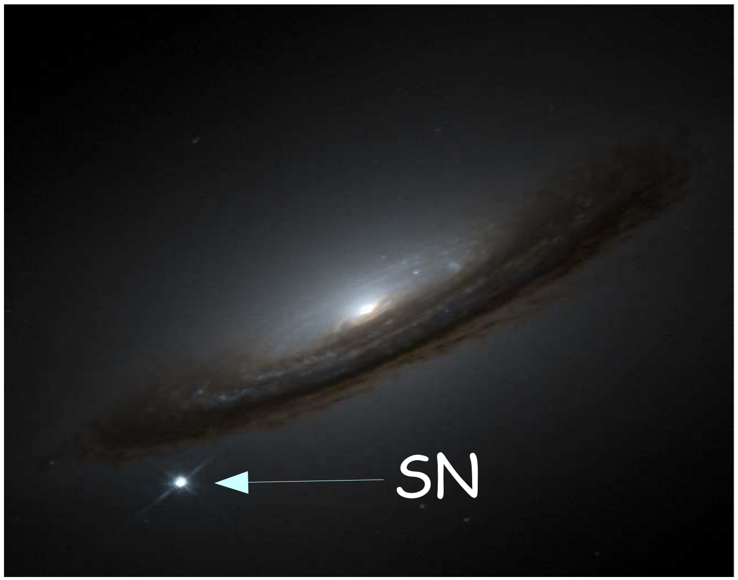
- Observables
  - Redshift
  - Apparent flux
- Luminosity distance

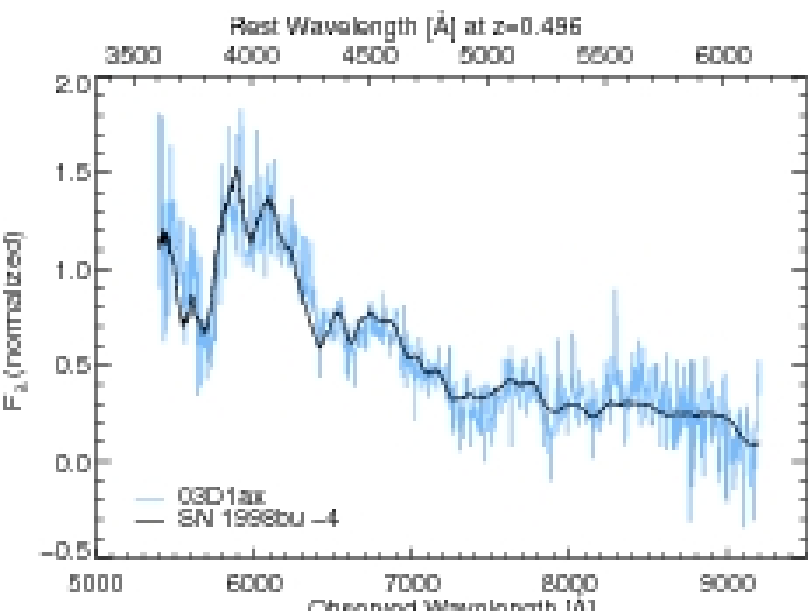
$$f = \frac{\mathcal{L}}{4\pi {d_L}^2(z)}$$

- Expansion @ late time

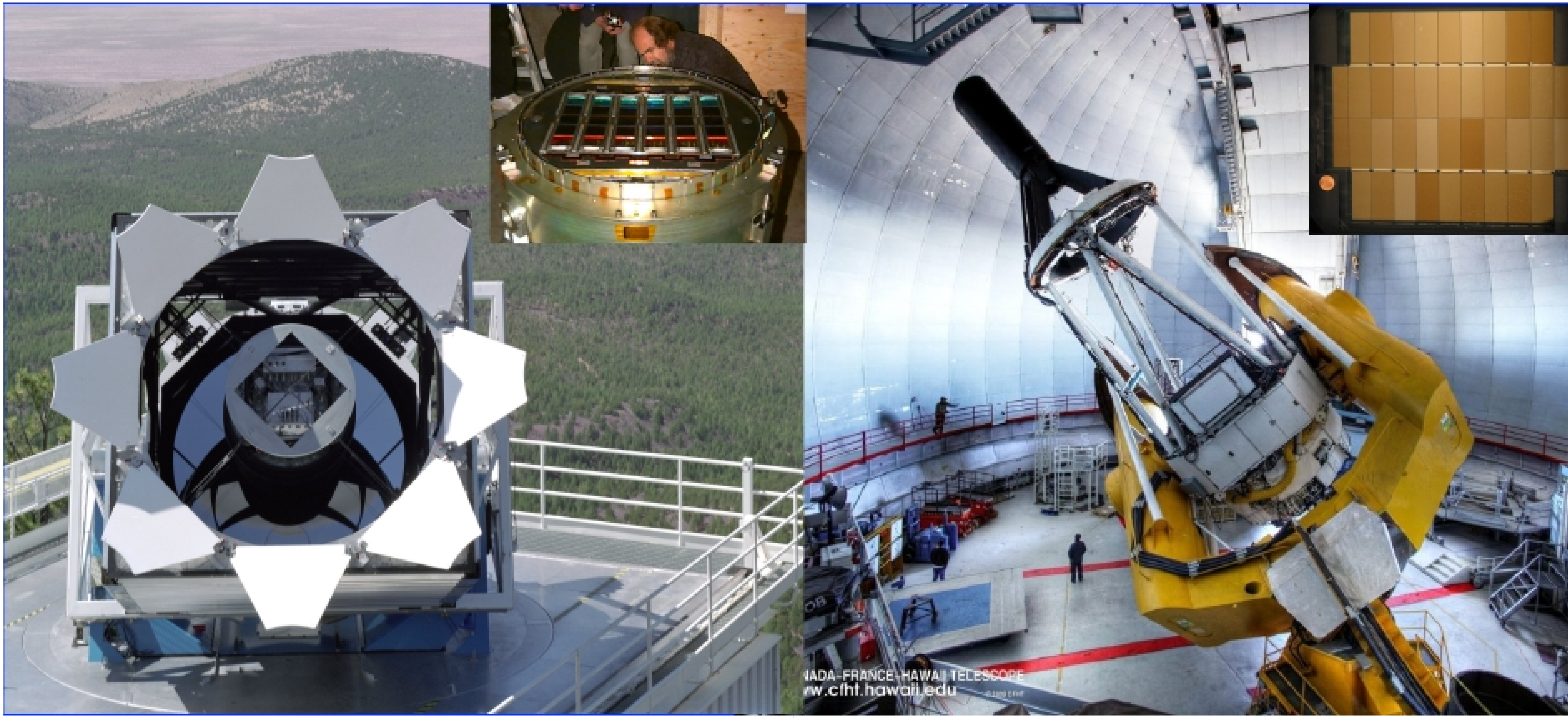
$$d_L(z) = (1+z)\frac{c}{H_0}\int dz \left(\Omega_m(1+z)^3 + \Omega_X(1+z)^{3(1+w)}\right)^{-1/2}$$

Type Ia Supernovae



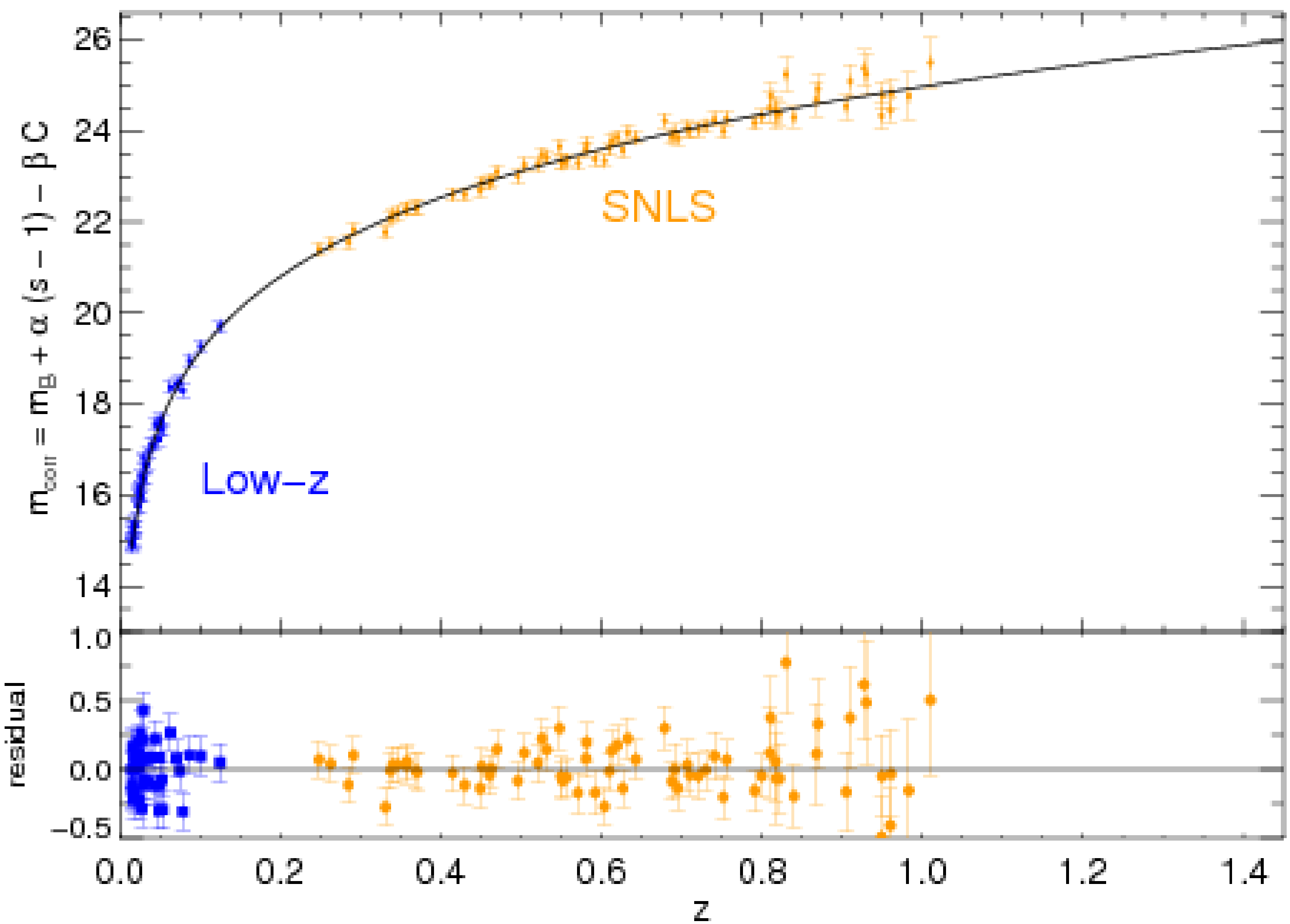


- Thermonuclear explosions
  - C/O White Dwarfs
  - Rare events (1 / Gal / 1000 yr)
  - Transients (1 month)
  - Very bright (10^{10} solar luminosities)
  - Standardizable → σ(Lmax) ~ 15%
- Spectroscopy
  - → Identification (broad features)
  - → Chemical composition & velocities



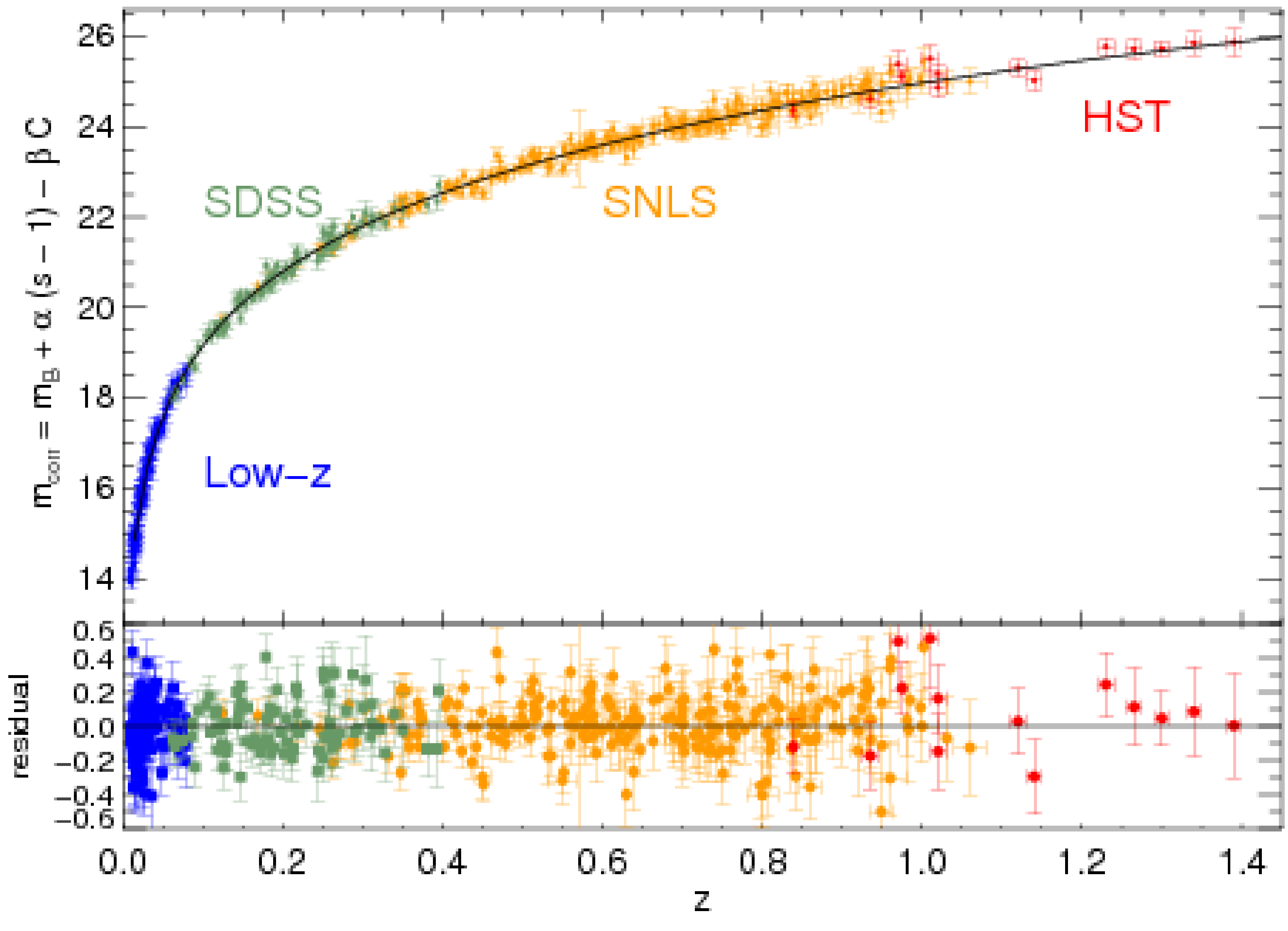
- SDSS
  - SDSS 2.5-m
  - 3 year rolling search
  - 500 SNe Ia
  - 300 “photometric” SNe Ia
- SNLS
  - CFHT 3.6-m + MegaCam
  - 5 year rolling search
  - 540 SNe Ia
  - 300 “photometric” SNe Ia (offline redshifts @AAT)

2006...



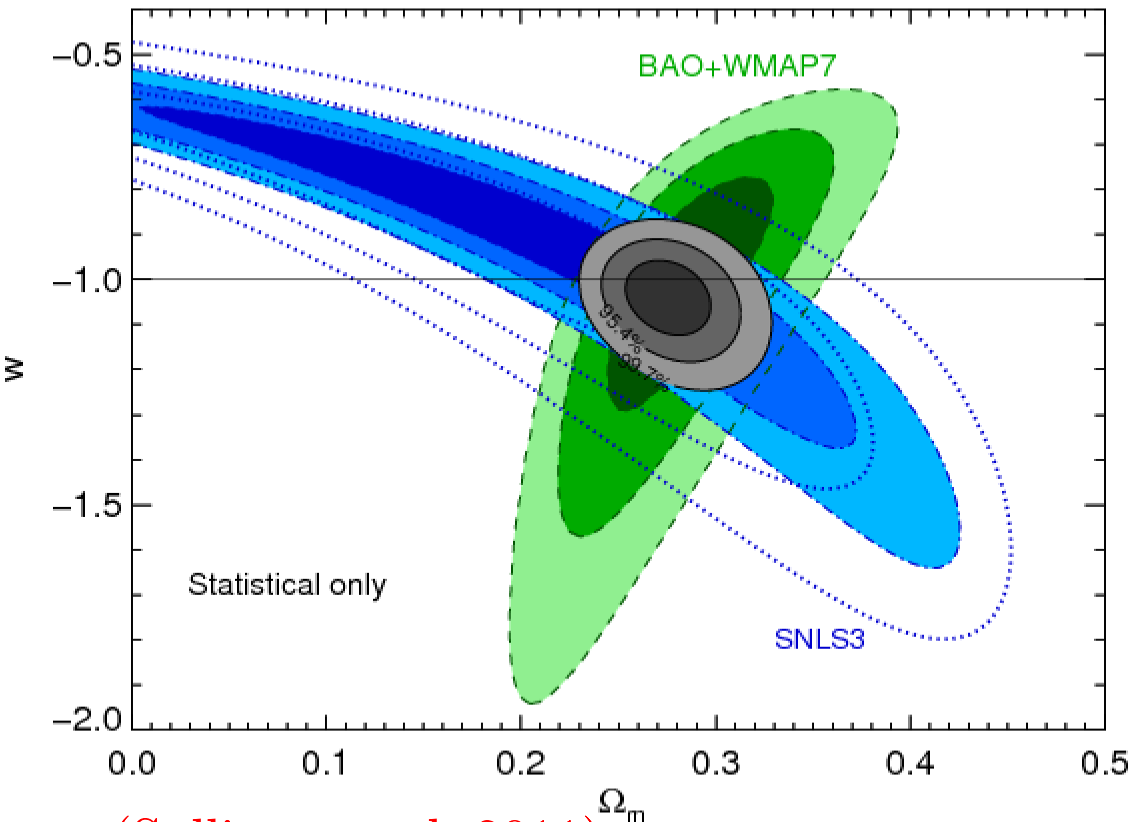
(Astier et al, 2006) w = -1.023 ± 0.090 (stat) ±0.054 (sys)

2011...



(Guy et al, 2010, Conley et al, 2011)

SNLS-3 Cosmological Constraints



(Sullivan et al, 2011)

SN + WMAP7 + BAO + H0

→ Consistent with a cosmological constant

- Flat Universe

$w = -1.061 \pm 0.069$

$\Omega_m = 0.269 \pm 0.015$

- Relaxing flatness

$w = -1.069 \pm 0.091$

$\Omega_m = 0.271 \pm 0.015$

$\Omega_k = -0.002 \pm 0.006$

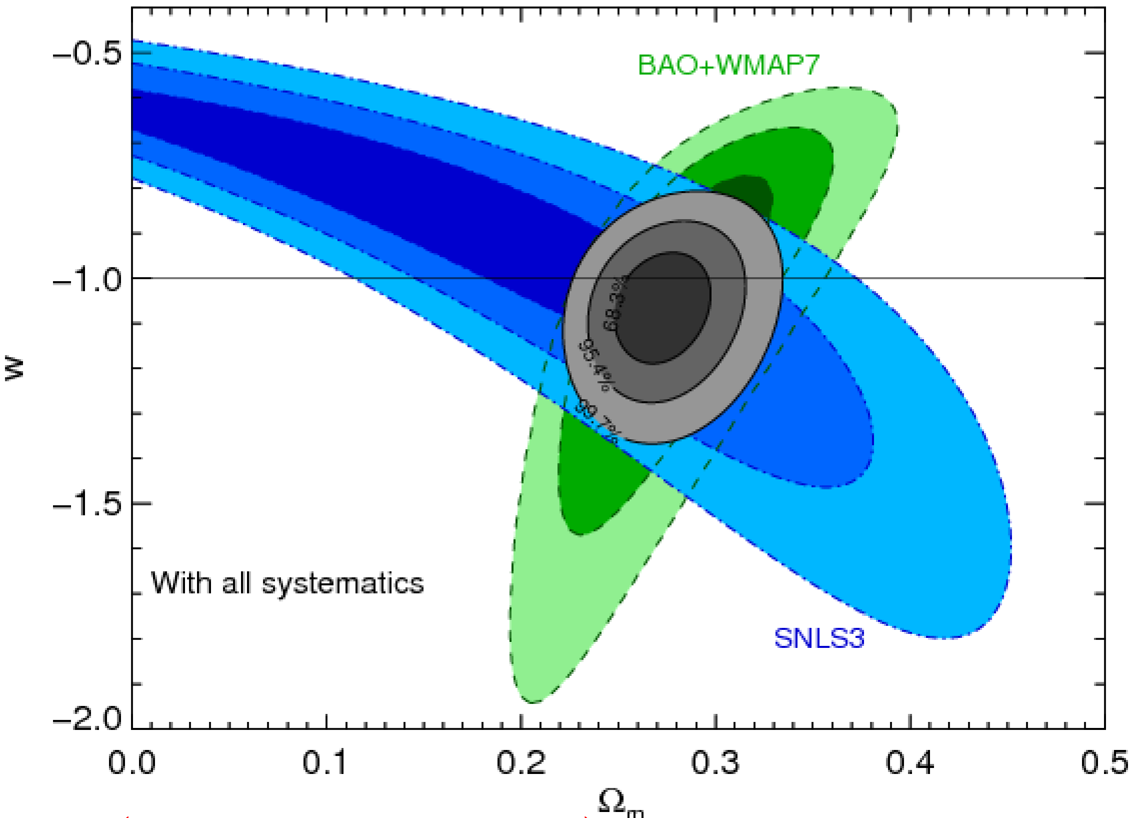
- WMAP7 + BAO + H0

$w = -1.412 \pm 0.333$

$\Omega_m = 0.259 \pm 0.030$

$\Omega_k = -0.009 \pm 0.008$

SNLS-3 Cosmological Constraints



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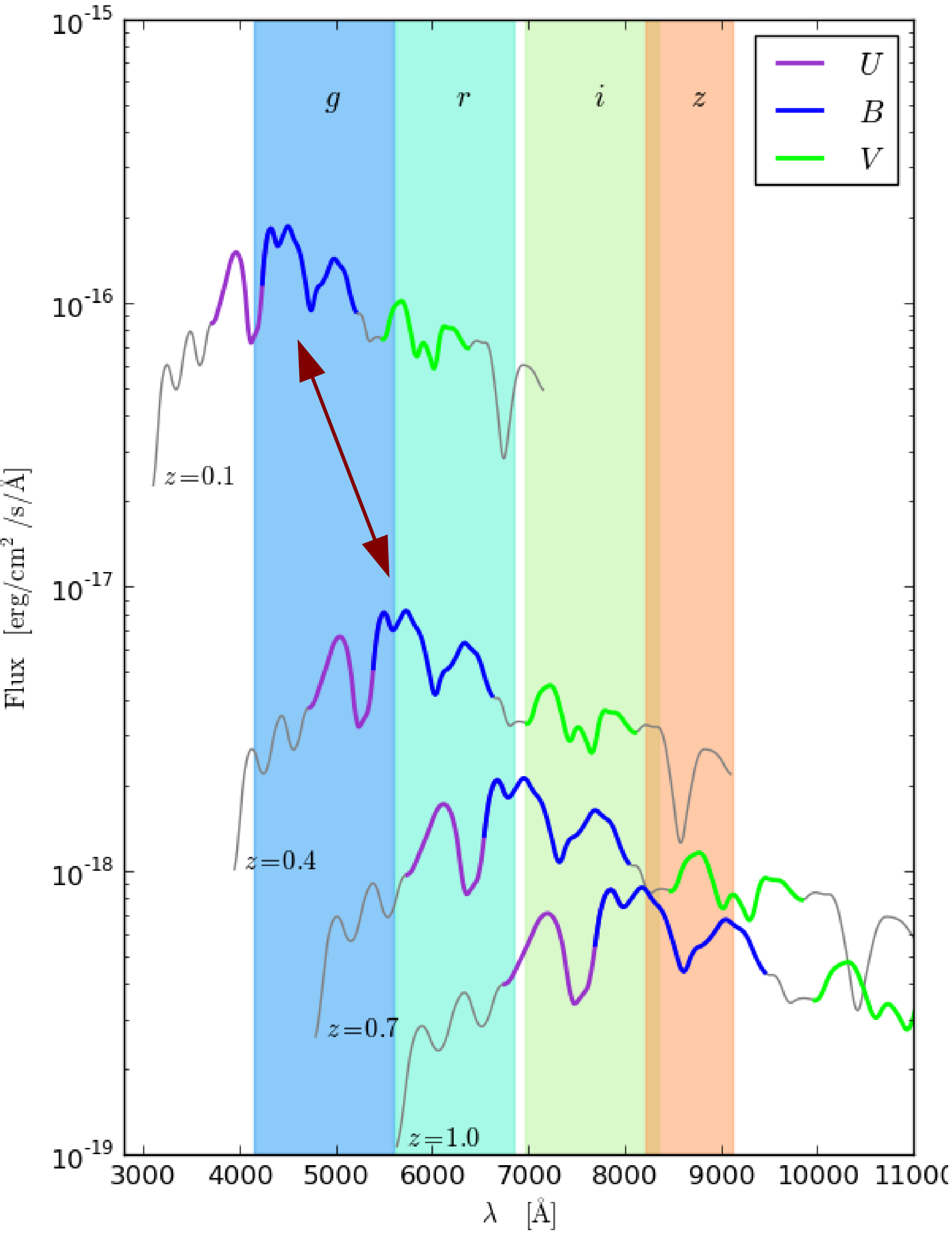
Systematics

Table 7: Identified systematic uncertainties

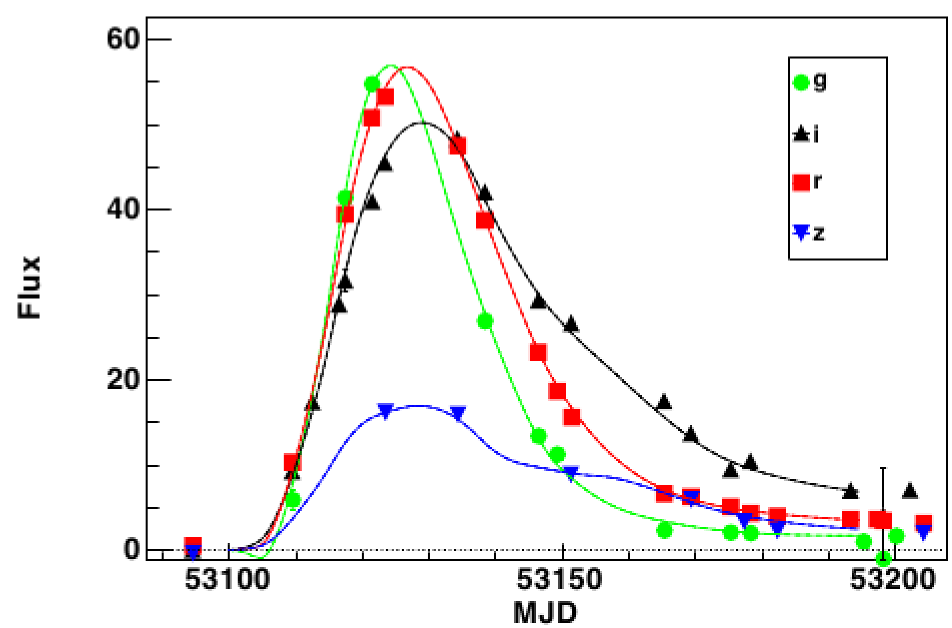
Description	Ω_m	w	Rel. Area [a]	w for Ω_m=0.27
Stat only	$0.19^{+0.08}_{-0.10}$	$-0.90^{+0.16}_{-0.20}$	1	-1.031 ± 0.058
All systematics	0.18 ± 0.10	$-0.91^{+0.17}_{-0.24}$	1.85	$-1.08^{+0.10}_{-0.11}$
Calibration	$0.191^{+0.095}_{-0.104}$	$-0.92^{+0.17}_{-0.23}$	1.79	-1.06 ± 0.10
SN model	$0.195^{+0.086}_{-0.101}$	$-0.90^{+0.16}_{-0.20}$	1.02	-1.027 ± 0.059
Peculiar velocities	$0.197^{+0.084}_{-0.100}$	$-0.91^{+0.16}_{-0.20}$	1.03	-1.034 ± 0.059
Malmquist bias	$0.198^{+0.084}_{-0.100}$	$-0.91^{+0.16}_{-0.20}$	1.07	-1.037 ± 0.060
non-Ia contamination	$0.19^{+0.08}_{-0.10}$	$-0.90^{+0.16}_{-0.20}$	1	-1.031 ± 0.058
MW extinction correction	$0.196^{+0.084}_{-0.100}$	$-0.90^{+0.16}_{-0.20}$	1.05	-1.032 ± 0.060
SN evolution	$0.185^{+0.088}_{-0.099}$	$-0.88^{+0.15}_{-0.20}$	1.02	-1.028 ± 0.059
Host relation	$0.198^{+0.085}_{-0.102}$	$-0.91^{+0.16}_{-0.21}$	1.08	-1.034 ± 0.061

(Conley et al, 2011)

Measurement Principle



- Relative flux ratios
  → Intercalibrate blue and red bands
- Interpolate in time and λ
  → light curve model

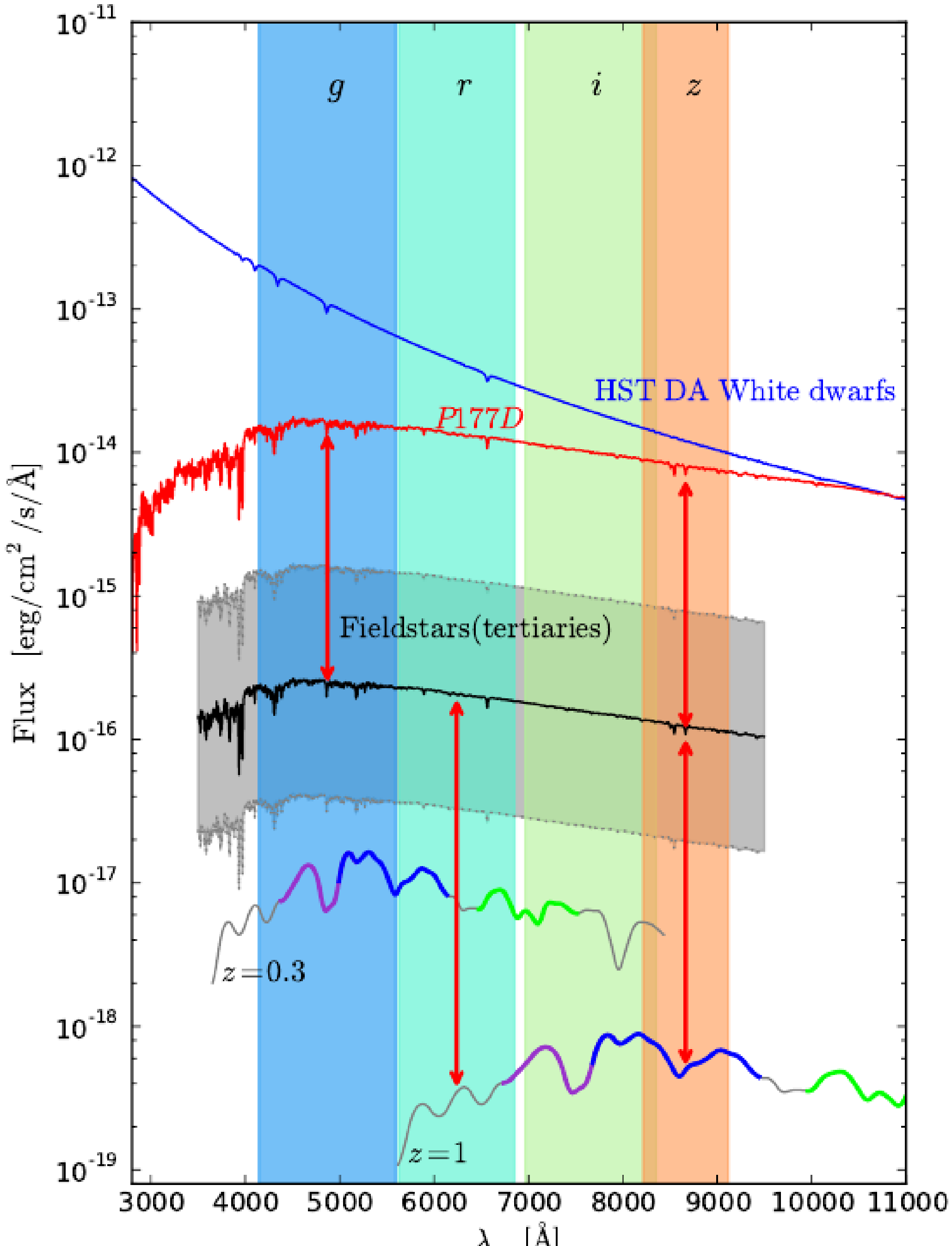


SALT2 (Guy et al, 2007), SifTO (Conley et al, 2008), MLCS2k2 (Jha et al, 2007), CMAGIC (Wang et al, 2003) ...

The JLA effort

- SNLS/SDSS Joint Lightcurve Analysis
  - Transverse working group
  - Goal : share data, code & expertise
- Photometric calibration
  - *Blind* recalibration of SNLS & SDSS (Betoule et al, (2013) A&A 552)
- Model systematics
  - Intrinsic dispersion of SNe Ia (Kessler et al (2013) ApJ 764)
  - Systematics of SALT2 LC fitter (Mosher et al, in prep)
- Combined Cosmological constraints (Betoule et al, in prep)

Photometric calibration

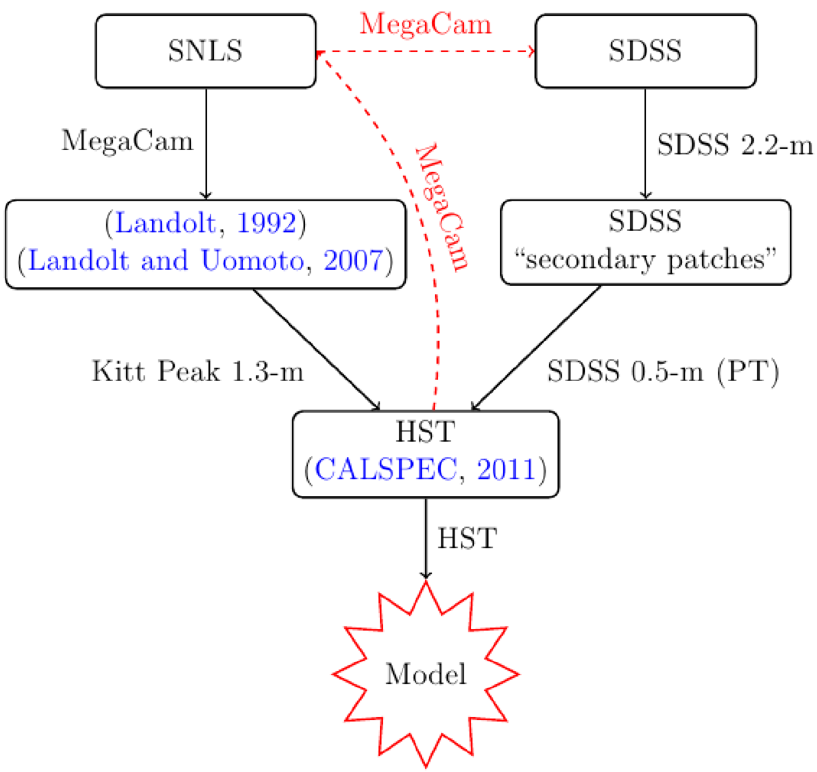


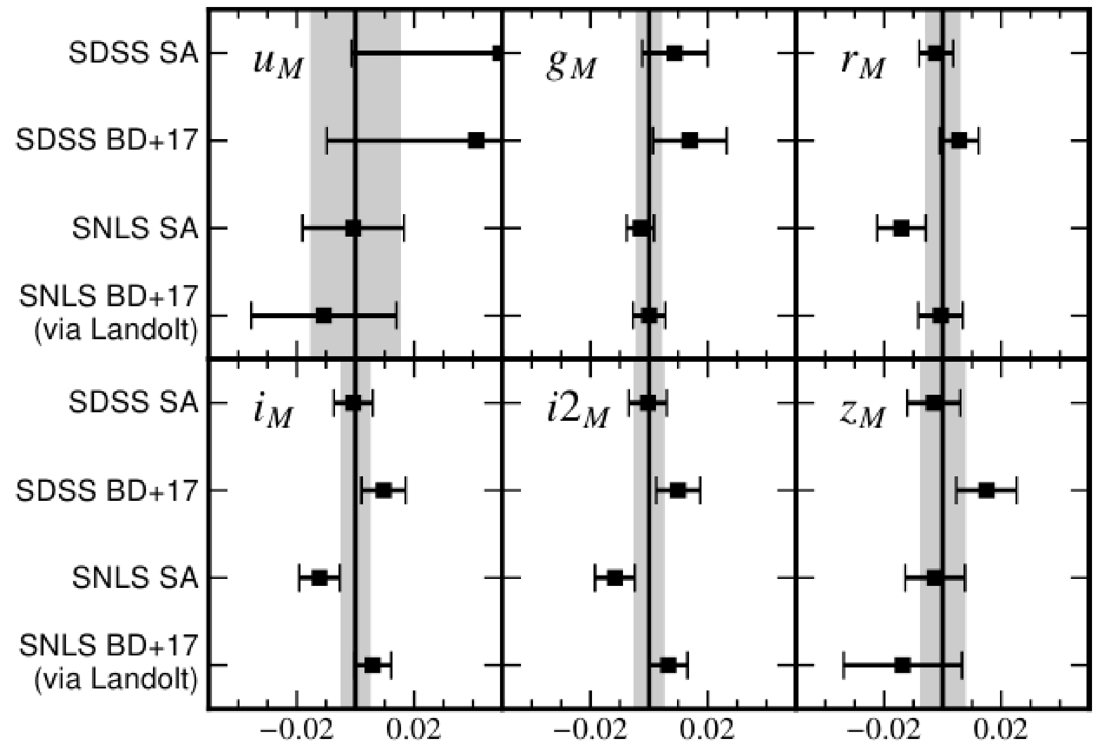
- Compare
  - SN fluxes vs field star fluxes.
  - Field star fluxes vs flux of HST calibration stars
  - HST calibration star spectra vs *physical models* of selected hot DA white dwarf spectra

(CALSPEC program)

- Also: monitor and measure imager passbands + imager uniformity.

Independent calibration paths



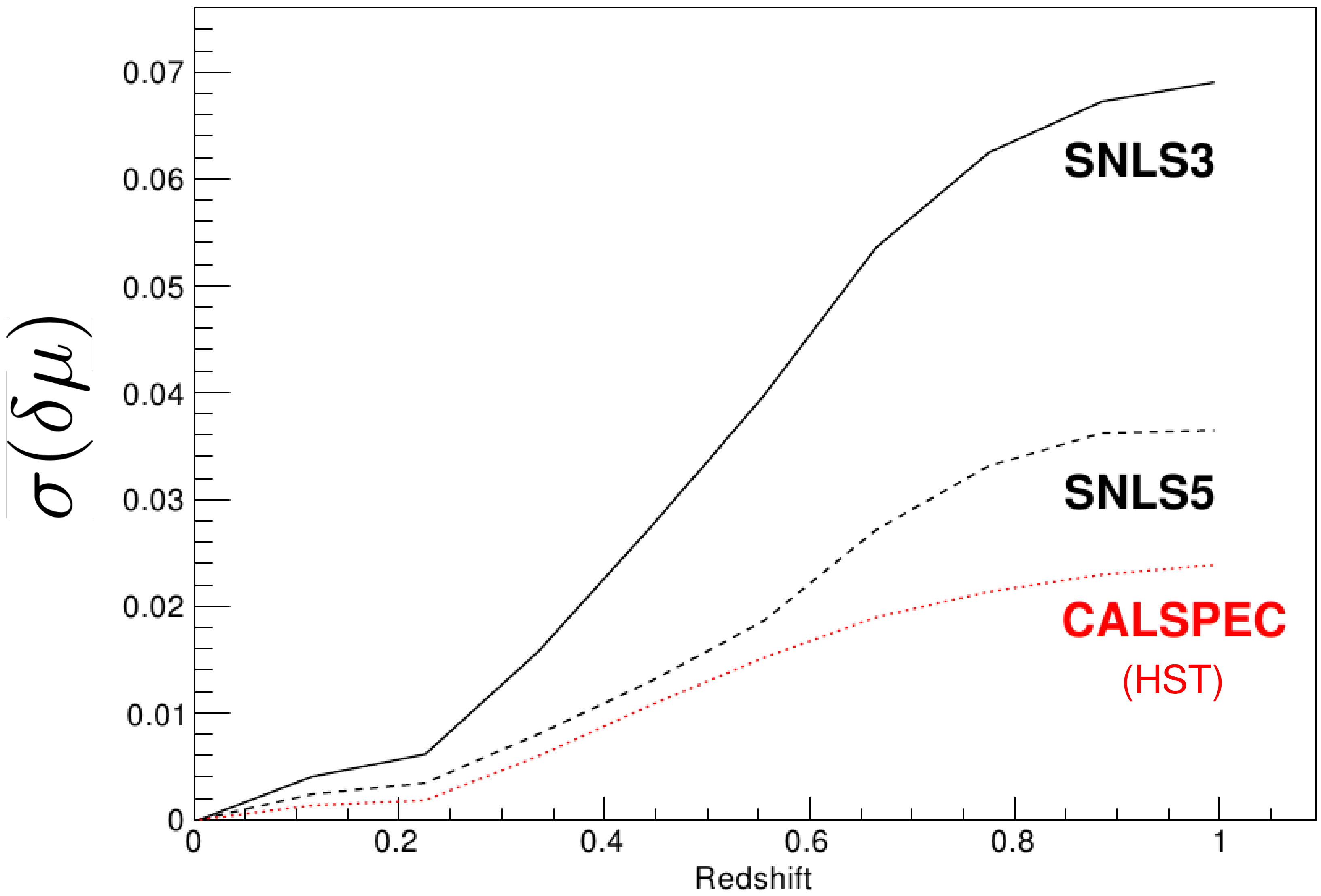


- Agree within the error bars

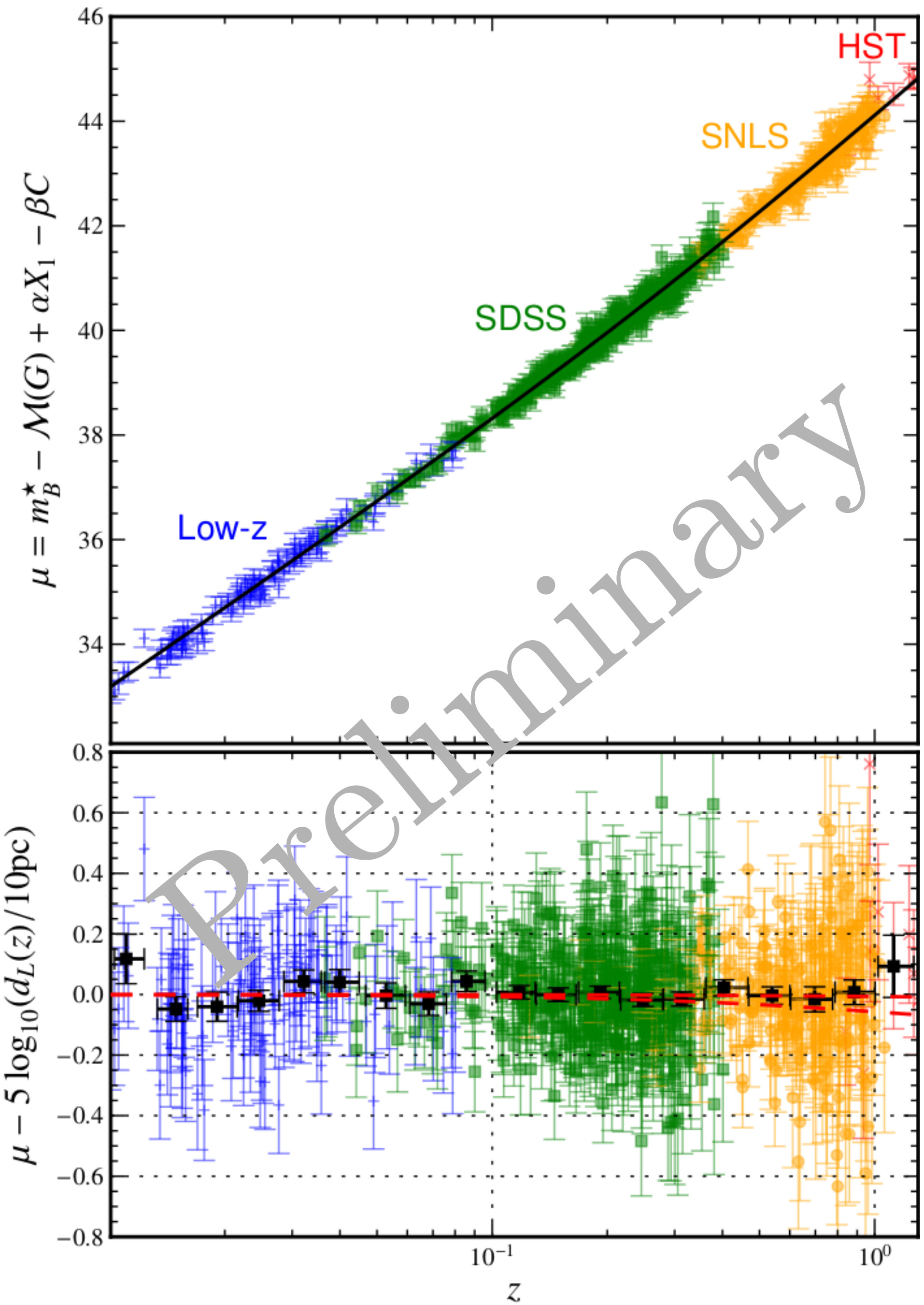
u	g	r	i	i2	z
0.0145	0.0035	0.0051	0.0042	0.0043	0.0069

(Betoule et al, 2012)

Impact on SNIa luminosity distances



The recalibrated Hubble Diagram



- SNLS3 combination
- + full SDSS sample
- Recalibration SNLS+SDSS
- Retraining of SALT2
- Reanalysis of the Malmquist bias

Constraints on *w*

$$\sigma_w \sim 0.055$$

(Betoule et al, 2013, in prep)

Summary

- Calibration has changed between SNLS3 and JLA
  - Shorter and more redundant metrology chain
  - Instrumental effects better taken into account
    - Filter aging
    - Improved flat fielding
    - PSF size variations (with color, flux, ...)
- Variations (in mmags)

band	g	r	i	z
ΔZ (SNLS)	-12.9	-0.9	1.3	-17.9
ΔZ (SDSS)	-4.0	0.0	0.0	-6.0

Planck 2013 results. XVI. Cosmological parameters

Planck Collaboration: P. A. R. Ade[90], N. Aghanim[63], C. Armitage-Caplan[96], M. Arnaud[77], M. Ashdown[74,6], F. Atrio-Barandela[19], J. Aumont[63], C. Baccigalupi[89], A. J. Banday[99,10], R. B. Barreiro[70], J. G. Bartlett[1,72], E. Battaner[102], K. Benabed[64,98], A. Benoît[61], A. Benoit-Lévy[26,64,98], J.-P. Bernard[10], M. Bersanelli[37,53], P. Bielewicz[99,10,89], J. Bobin[77], J. J. Bock[72,11], A. Bonaldi[73], J. R. Bond[9], J. Borrill[14,93], F. R. Bouchet[64,98], M. Bridges[74,6,67], M. Bucher[1], C. Burigana[52,35], R. C. Butler[52], E. Calabrese[96], B. Cappellini[53], J.-F. Cardoso[78,1,64], A. Catalano[79,76], A. Challinor[67,74,12], A. Chamballu[77,16,63], R.-R. Chary[60], X. Chen[60], L.-Y Chiang[66], H. C. Chiang[29,7], P. R. Christensen[85,40], S. Church[95], D. L. Clements[59], S. Colombi[64,98], L. P. L. Colombo[25,72], F. Couchot[75], A. Coulais[76], B. P. Crill[72,86], A. Curto[6,70], F. Cuttaia[52], L. Danese[89], R. D. Davies[73], R. J. Davis[73], P. de Bernardis[36], A. de Rosa[52], G. de Zotti[49,89], J. Delabrouille[1], J.-M. Delouis[64,98], F.-X. Désert[56], C. Dickinson[73], J. M. Diego[70], K. Dolag[101,82], H. Dole[63,62], S. Donzelli[53], O. Doré[72,11], M. Douspis[63], J. Dunkley[96], X. Dupac[43], G. Efstathiou[67,*], F. Elsner[64,98], T. A. Enßlin[82], H. K. Eriksen[68], F. Finelli[52,54], O. Forni[99,10], M. Frailis[51], A. A. Fraisse[29], E. Franceschi[52], T. C. Gaier[72], S. Galeotta[51], S. Galli[64], K. Ganga[1], M. Giard[99,10], G. Giardino[44], Y. Giraud-Héraud[1], E. Gjerløw[68], J. González-Nuevo[70,89], K. M. Górski[72,104], S. Gratton[74,67], A. Gregorio[38,51], A. Gruppuso[52], J. E. Gudmundsson[29], J. Haissinski[75], J. Hamann[97], F. K. Hansen[68], D. Hanson[83,72,9], D. Harrison[67,74], S. Henrot-Versillé[75], C. Hernández-Monteagudo[13,82], D. Herranz[70], S. R. Hildebrandt[11], E. Hivon[64,98], M. Hobson[6], W. A. Holmes[72], A. Hornstrup[17], Z. Hou[31], W. Hovest[82], K. M. Huffenberger[103], T. R. Jaffe[99,10], A. H. Jaffe[59], J. Jewell[72], W. C. Jones[29], M. Juvela[28], E. Keihänen[28], R. Keskitalo[23,14], T. S. Kisner[81], R. Kneissl[42,8], J. Knoche[82], L. Knox[31], M. Kunz[18,63,3], H. Kurki-Suonio[28,47], G. Lagache[63], A. Lähteenmäki[2,47], J.-M. Lamarre[76], A. Lasenby[6,74], M. Lattanzi[35], R. J. Laureijs[44], C. R. Lawrence[72], S. Leach[89], J. P. Leahy[73], R. Leonardi[43], J. León-Tavares[45,2], J. Lesgourgues[87,88], A. Lewis[27], M. Liguori[34], P. B. Lilje[68], M. Linden-Vørnle[17], M. López-Caniego[70], P. M. Lubin[32], J. F. Macías-Pérez[79], B. Maffei[73], D. Maino[37,53], N. Mandolesi[52,5,35], M. Maris[51], D. J. Marshall[77], P. G. Martin[9], E. Martínez-González[70], S. Masi[36], S. Matarrese[34], F. Matthai[82], P. Mazzotta[39], P. R. Meinhold[32], A. Melchiorri[36,55], J.-B. Melin[16], L. Mendes[43], E. Menegoni[36], A. Mennella[37,53], M. Migliaccio[67,74], M. Millea[31], S. Mitra[58,72], M.-A. Miville-Deschênes[63,9], A. Moneti[64], L. Montier[99,10], G. Morgante[52], D. Mortlock[59], A. Moss[91], D. Munshi[90], P. Naselsky[85,40], F. Nati[36], P. Natoli[35,4,52], C. B. Netterfield[21], H. U. Nørgaard-Nielsen[17], F. Noviello[73], D. Novikov[59], I. Novikov[85], I. J. O'Dwyer[72], S. Osborne[95], C. A. Oxborrow[17], F. Paci[89], L. Pagano[36,55], F. Pajot[63], D. Paoletti[52,54], B. Partridge[46], F. Pasian[51], G. Patanchon[1], D. Pearson[72], T. J. Pearson[11,60], H. V. Peiris[26], O. Perdereau[75], L. Perotto[79], F. Perrotta[89], V. Pettorino[18],

Abstract: This paper presents the first cosmological results based on *Planck* measurements of the cosmic microwave background (CMB) temperature and lensing-potential power spectra. We find that the *Planck* spectra at high multipoles ($\ell \gtrsim 40$) are extremely well described by the standard spatially-flat six-parameter ΛCDM cosmology with a power-law spectrum of adiabatic scalar perturbations. Within the context of this cosmology, the *Planck* data determine the cosmological parameters to high precision: the angular size of the sound horizon at recombination, the physical densities of baryons and cold dark matter, and the scalar spectral index are estimated to be $\theta_* = (1.04147 \pm 0.00062) \times 10^{-2}$, $\Omega_b h^2 = 0.02205 \pm 0.00028$, $\Omega_c h^2 = 0.1199 \pm 0.0027$, and $n_s = 0.9603 \pm 0.0073$, respectively (68% errors). For this cosmology, we find a low value of the Hubble constant, $H_0 = 67.3 \pm 1.2\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$, and a high value of the matter density parameter, $\Omega_m = 0.315 \pm 0.017$. These values are in tension with recent direct measurements of H_0 and the magnitude-redshift relation for Type Ia supernovae, but are in excellent agreement with geometrical constraints from baryon acoustic oscillation (BAO) surveys. Including curvature, we find that the Universe is consistent with spatial flatness to percent level preci-

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sion using *Planck* CMB data alone. We use high-resolution CMB data together with *Planck* to provide greater control on extragalactic foreground components in an investigation of extensions to the six-parameter ΛCDM model. We present selected results from a large grid of cosmological models, using a range of additional astrophysical data sets in addition to *Planck* and high-resolution CMB data. None of these models are favoured over the standard six-parameter ΛCDM cosmology. The deviation of the scalar spectral index from unity is insensitive to the addition of tensor modes and to changes in the matter content of the Universe. We find a 95% upper limit of $r_{0.002} < 0.11$ on the tensor-to-scalar ratio. There is no evidence for additional neutrino-like relativistic particles beyond the three families of neutrinos in the standard model. Using BAO and CMB data, we find $N_{\rm eff} = 3.30 \pm 0.27$ for the effective number of relativistic degrees of freedom, and an upper limit of 0.23 eV for the sum of neutrino masses. Our results are in excellent agreement with big bang nucleosynthesis and the standard value of $N_{\rm eff} = 3.046$. We find no evidence for dynamical dark energy; using BAO and CMB data, the dark energy equation of state parameter is constrained to be $w = -1.13^{+0.13}_{-0.10}$. We also use the *Planck* data to set limits on a possible variation of the fine-structure constant, dark matter annihilation and primordial magnetic fields. Despite the success of the six-parameter ΛCDM model in describing the *Planck* data at high multipoles, we note that this cosmology does not provide a good fit to the temperature power spectrum at low multipoles. The unusual shape of the spectrum in the multipole range $20 \lesssim \ell \lesssim 40$ was seen previously in the *WMAP* data and is a real feature of the primordial CMB anisotropies. The poor fit to the spectrum at low multipoles is not of decisive significance, but is an "anomaly" in an otherwise self-consistent analysis of the *Planck* temperature data.

Key words. Cosmology: observations – Cosmology: theory – cosmic microwave background – cosmological parameters

ΛCDM constraints

A word on H_0

Marginalized over

$$f_{SN} = \frac{\mathcal{L}H_0^2}{4\pi c^2(1+z)^2}\int dz\left(\Omega_m(1+z)^3 + \Omega_X(1+z)^{3(1+w)}\right)^{1/2}$$

H0 degenerate with SN absolute luminosity !

- Measurement of H_0 : (Riess et al, 2011, ApJ 730)

→ Cepheids in NGC 4258

→ Galactic cepheids

→ Cepheids in LMC

$$H_0 = 73.8 \pm 2.4 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

Conclusion

- SNe Ia distances combined with BAO and CMB give the best constraints on w :
  - CMB + BAO + JLA → $\sigma_w \lesssim 6\%$ Betoule et al, 2013 (in prep)
- We are now sensitive to astrophysical uncertainties
  - SN evolution ?
  - Luminosity vs. host properties ?
- Future improvements
  - New data (SNLS5 spectroscopic sample, new low-z data)
  - Upcoming DETF Stage III experiments : DES, ...
  - Longer term stage IV, combining visible + IR observations (e.g. a combined LSST + Euclid SN survey)