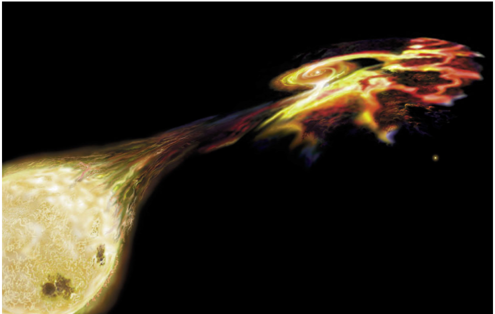
Improved cosmological constraints from a joint analysis of the SNLS and SDSS SN-Ia surveys

Marc Betoule
on behalf of the SNLS/SDSS JLA collaboration

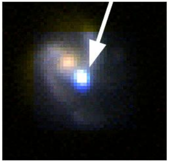
LPNHE

CPPM, Feb 10^{th} 2014



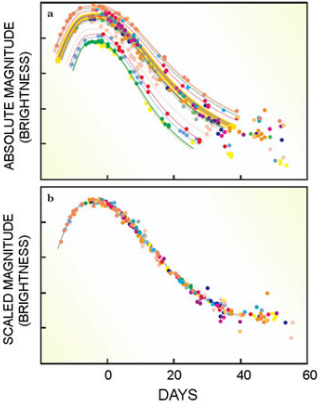
Type-Ia Supernovae as “standardizable” candles

An homogeneous class of transient



- Thermonuclear explosion
- High Luminosity: $M_B \sim -19$
- Similar shape
- $\sigma(M_B) \sim 0.40$

Light-curves from the Calan-Tololo SN survey



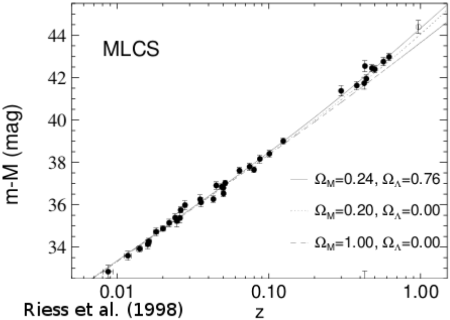
“Standardizable”

Empirical correlation of luminosity with other observables

- Strech (s): Brighter-slower
- Color (C): Brighter-bluer

More precise estimate:
$M_{cor} = M_0 - \alpha s + \beta C$ with $\sigma(M_{cor}) \sim 0.15$

Mapping the expansion history with standard candles



Riess et al. (1998)

1. Redshift measurement
2. Apparent flux measurement
3. Standardization

$\downarrow$

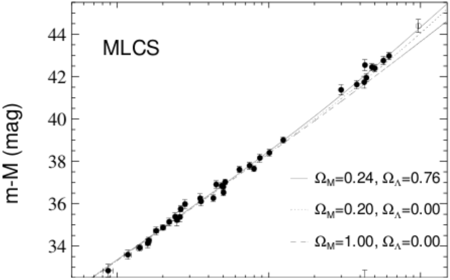
luminosity distance ratios

Probe of the expansion history at late time

- Independent of the CMB
- Very complementary for dark energy studies

$$d_L(z) = (1+z)\frac{c}{H_0}\int dz\left(\Omega_m(1+z)^3 + \Omega_x(1+z)^{3(1+w)}\right)^{-1/2} \quad \text{with: } w = \frac{p_x}{\rho_x}$$

Pioneering work



Riess et al. (1998)

- High-Z Team (Riess et al. 1998)
- Supernovae Cosmology Project (Perlmutter et al. 1999)

First convincing evidence for expansion acceleration

Awarded with the 2011 physic Nobel Prize

Photo: U. Montan

Saul Perlmutter

Photo: U. Montan

Brian P. Schmidt

Photo: U. Montan

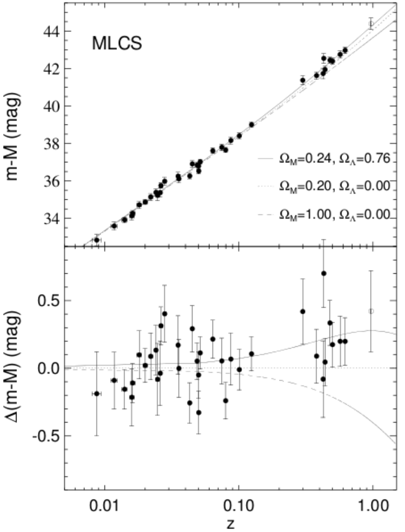
Adam G. Riess

LPNHE PARIS

Constraining dark energy with SN-Ia: OUTLINE

1. Increasing the statistics
2. Improving measurement accuracy
3. Cosmological results from the SNLS/SDSS Joint Light-Curve Analysis (JLA)
4. Perspectives

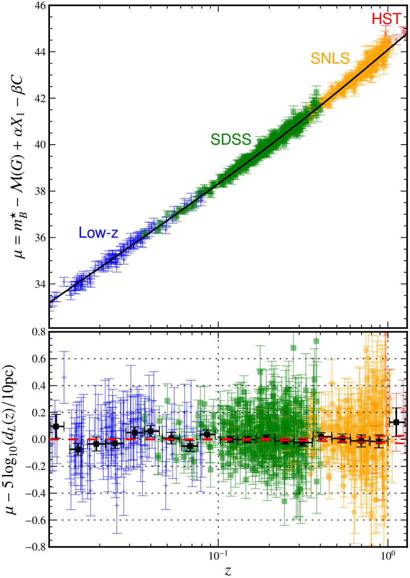
Results from a decade of industrial SN-Ia search



$\times$20 increase of the statistics

- 37 events in 1998

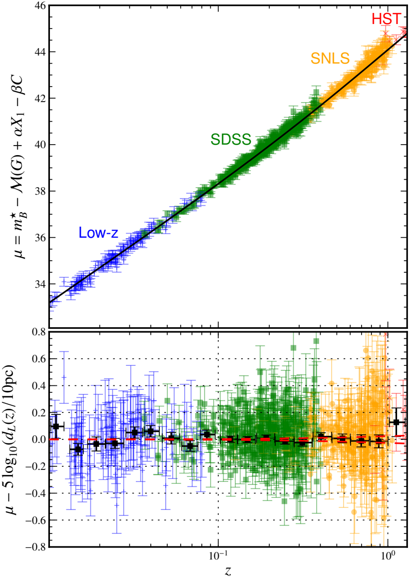
Results from a decade of industrial SN-Ia search



$\times$20 increase of the statistics

- 37 events in 1998
- $>$ 750 in 2013

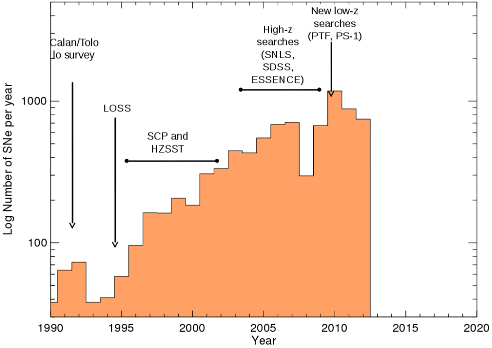
Results from a decade of industrial SN-Ia search



×20 increase of the statistics

- 37 events in 1998
- > 750 in 2013

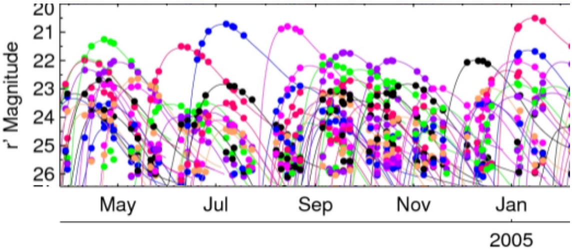
Increase in the discovery rate



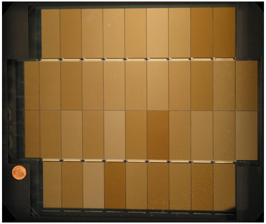
Central Bureau for Astronomical Telegrams

A key technology

The rise of the rolling-search approach...



with large CCD matrices



Requirements

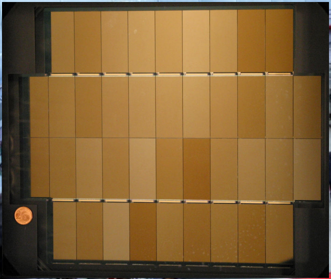
1. Discovery in images subtraction
2. Flux evolution measurement
3. Host galactic flux model
4. Spectroscopic follow-up: identification and redshift measurement

Multiplex step 1-3 for several SNe-Ia in the same image

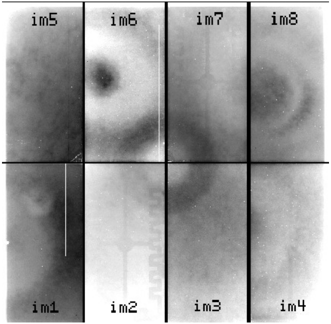
- Repeated imaging of the same sky portion
- Implemented in 3 major survey
- Classical spectroscopic follow-up

The Supernovae Legacy Survey (Astier et al. 2006)

- 1 square degree MegaCam camera
- 1500 h on the CFHT 3.6m
- Spectroscopic follow-up: ~1500h on 8m VLT-Keck-Gemini
- ~ 500 spectroscopically confirmed SNe-Ia



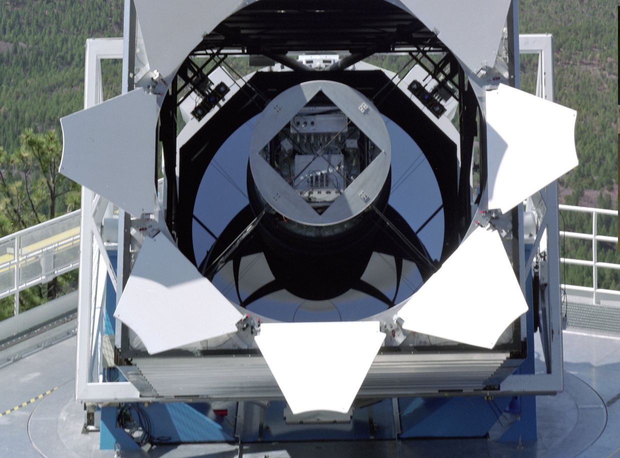
ESSENCE (Wood-Vasey et al. 2007)

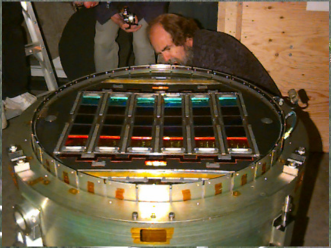


- CTIO Blanco 4m telescope
- $36' \times 36'$ Mosaic camera
- ~ 100 SNe-Ia

The SDSS-II Supernovae Survey (Kessler et al. 2009)

- 1.5 square-degree fast-scanning SDSS Camera
- $\sim$ 2000 hours on the 2.5m SDSS telescope
- $\sim$ 500 spectroscopically confirmed SNe-Ia





The gathered sample

Follow-up of low-z supernovae: $0.01 < z < 0.1$

- Discovery at $z < 0.1$ provided by LOSS and amateurs
- About ~ 500 followed, dominated by 2 samples:
  - Harvard Center for Astrophysic (Hicken et al. 2009, 2012)
  - Carnegie Supernovae Project (Contreras et al. 2010, Stritzinger et al. 2011)

Rolling search survey: $0.1 < z < 1$

- ~ 2000 SN-Ia
- Spectroscopic identification for about half of them.

High-z events with the HST: $0.9 < z < 1.5$

- Successful search with the ACS (continuing with WFC-3)
- About 40 events today (Riess et al. 2007, Dawnson et al. 2009)

A very successful quest

Statistical power of the gathered sample

Currently published data + SNLS:

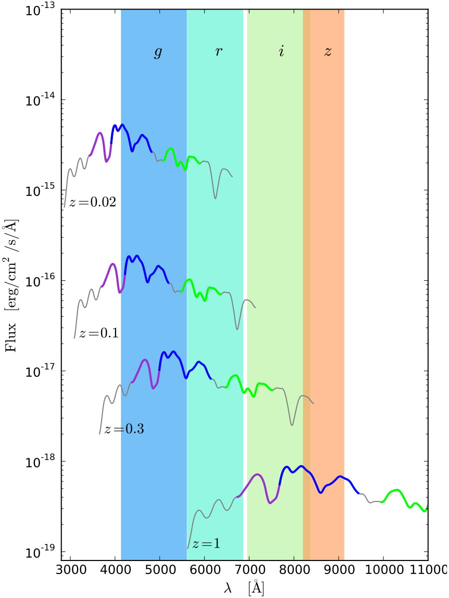
- Neglecting all systematics: measure w at $\sim 3\%$
- To be compared to the 10% target for 2^{nd} generation surveys

About 3/4 analyzed at this stage

The limiting factor is now measurement systematics

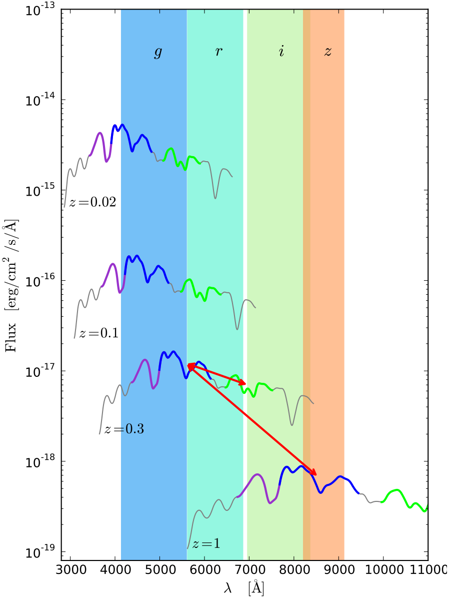
Outline

The problem of measurement systematics



Required ingredients

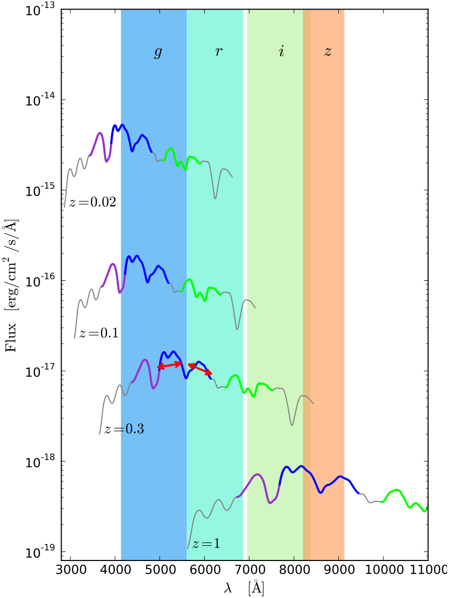
The problem of measurement systematics



Required ingredients

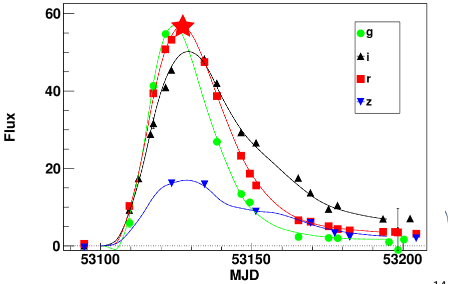
- Being able to measure flux ratios between different observer-frame band
  $\rightarrow$ inter-calibration

The problem of measurement systematics

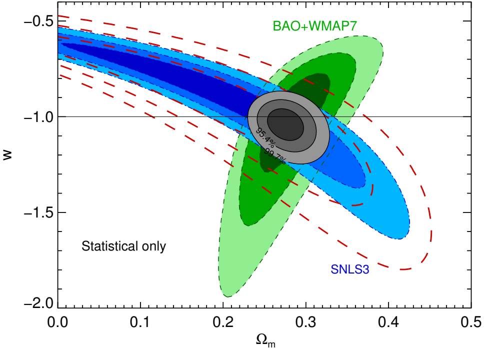


Required ingredients

- Being able to measure flux ratios between different observer-frame band
  → inter-calibration
- Being able to interpolate in time and wavelength
  → Light-curve model



A limiting factor !



SNLS3 Analysis (Guy et al. 2010, Conley et al. 2011, Sullivan et al. 2011)

- Systematic uncertainties: half of the error budget
- Mostly photometric calibration

Highest priority: tackling measurement systematics

Addressing systematics

A long story

e.g. Kessler et al. (2009), Regnault et al. (2009), Conley et al. (2011)

The SNLS/SDSS JLA working group

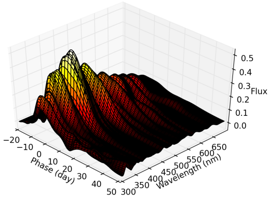
- Transverse WG joining the two main SNe-Ia surveys
- Started in June 2010
- Share data, code and expertise

3 papers on systematics:

- Calibration: Betoule et al. 2012
- Model systematic: Kessler et al. 2013, Mosher et al. 2014.

SN model systematics ?

Empirical description of the time sequence of SN spectra (e.g. the SALT2 model)



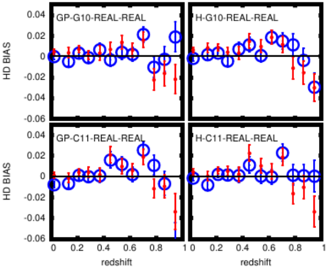
- Fitted on spectroscopic and photometric data: "training sample"
- The surface shape is parameterized by m_b, C and X_1
- m_b, C, X_1 fitted for each SN

Several points to check

- Missing spectra to constrain the model at early and late phase $\rightarrow$ regularization
- SALT2: first order description of the light-curve shape $\rightarrow$ holds ?
- Interplay between intrinsic dispersion and selection bias.

JLA work to quantify systematics associated to SALT2

End-to-end test of the SALT2 method (Mosher et al. 2014.)

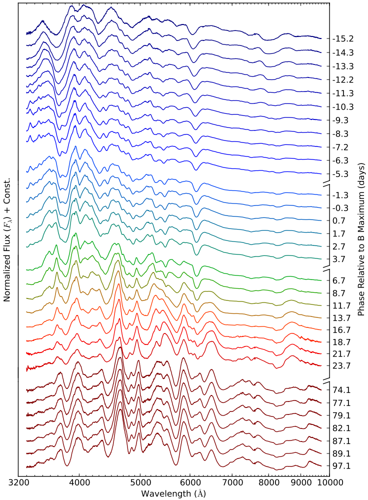


- Various SN models in input
- Extensive MC simulations
- Propagation through the whole chain
- Test the bias on reconstructed distances
- With the currently available "training" sample: $\Delta\mu < 0.03$

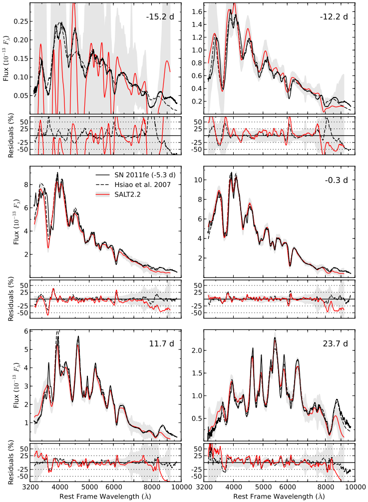
Well below the level of calibration uncertainties

Likely to improve with the new data samples

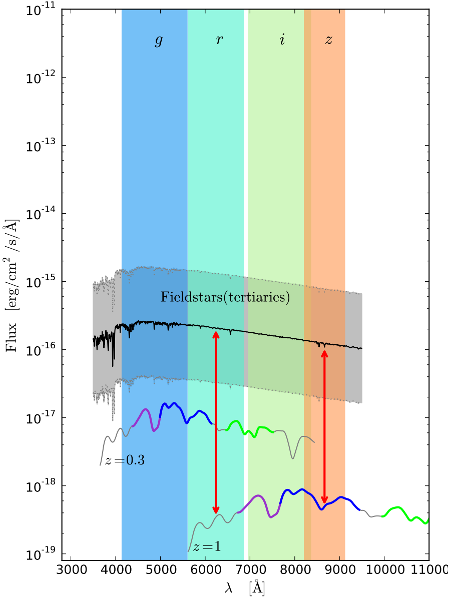
Time evolution of sn2011fe spectrum (Pereira et al. 2013)



Comparison with the SALT2 model

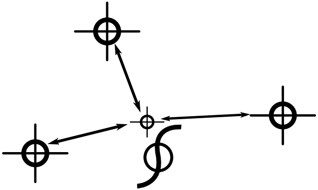


What is photometric calibration ?



I) Characterization of the instrument response

- Enable measurement of **flux ratios** in a single image



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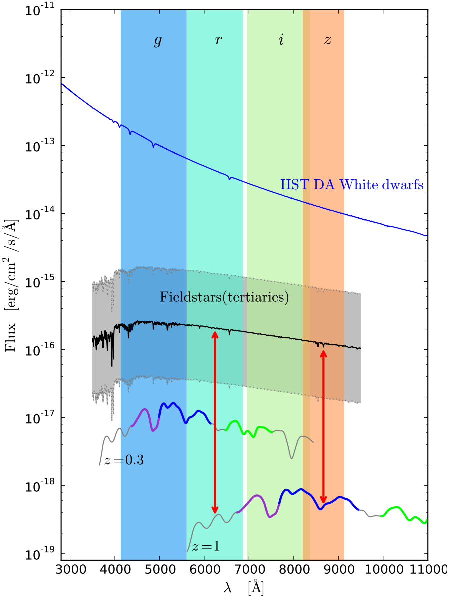

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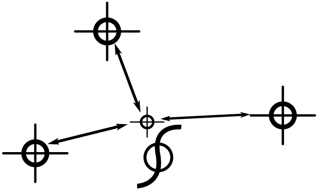

II) Calibration transfer

- HST standard stars as primary calibration source
- Enable comparison of flux in different bands/instruments

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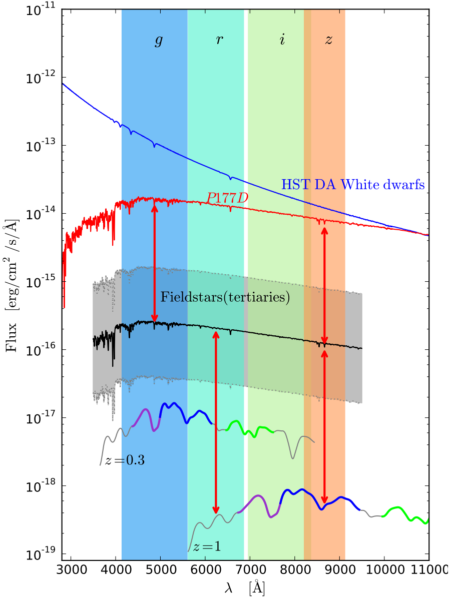

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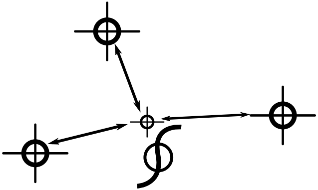

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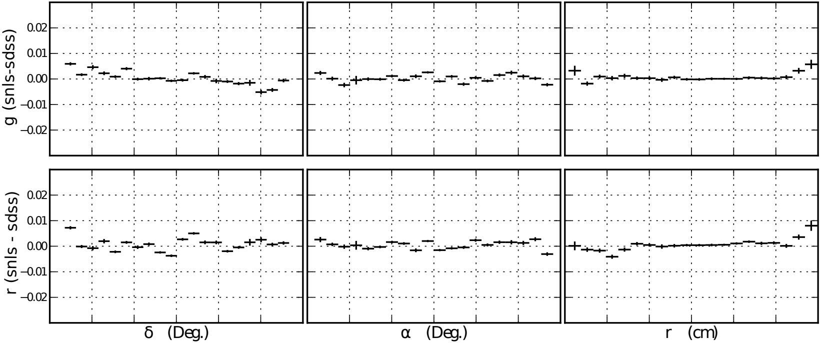
Result I: “Flat-fielding” 2 wide-field camera at 0.3%

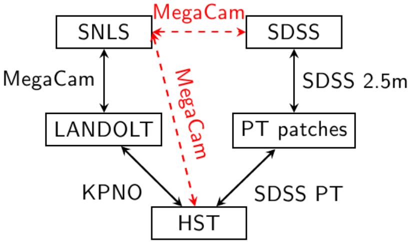
Comparison of SDSS/SNLS photometry

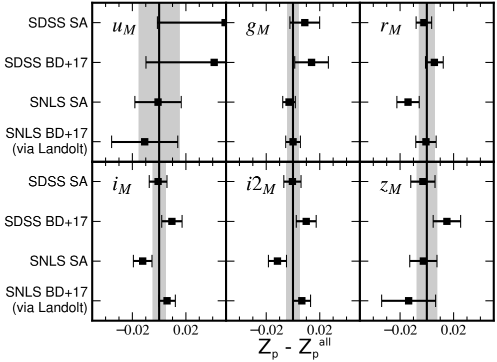


- SNLS and SDSS flat-fields obtained independently
- Achievement of wider interest (e.g. Photo-z)

Result II: $\sim$ 0.5% accuracy in absolute calibration

Short and redundant paths for calibration transfer





New data

- Direct observation of HST stars
- Direct SNLS/SDSS cross-calibration

Enable:

- Comparison of several paths
- 0.3% accuracy in *gri*

Final uncertainty dominated by HST calibration

In Summary

New SNLS and SDSS calibration (Blind wrt cosmology)

- More robust
- More accurate

Changes at the percent level wrt SNLS3 calibration

band	g	r	i	z
ΔZ_{SNLS} (mmag)	-12.9	-0.9	1.3	-17.9
ΔZ_{SDSS} (mmag)	-4.0	0.0	0.0	-6.0

Sets a milestone for next generation surveys

- Lessons to be learn
- Likely to improve in future survey
  - Better sensitivity in the infrared
  - Better characterization of the instruments
  - Better photometric standards (Lab-made calibration sources ?)

Outline

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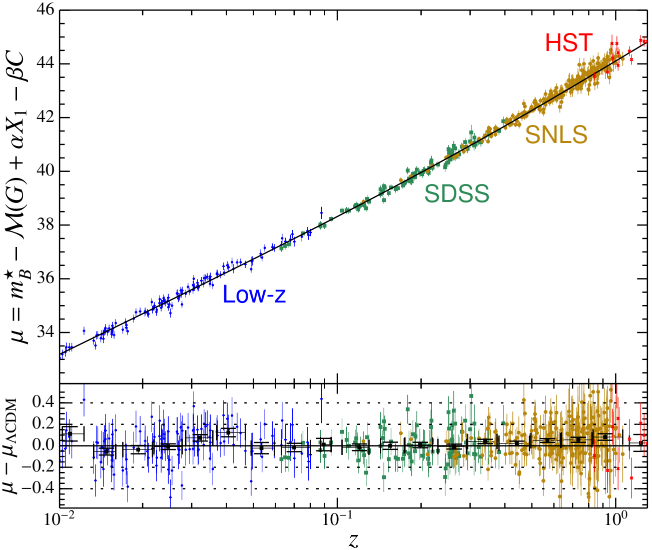
PARIS

Start from the Conley et al. (2011) Salt2 Hubble diagram



- 118 nearby SNe
- 93 SDSS SNe
- 242 SNLS SNe
- 14 HST SNe

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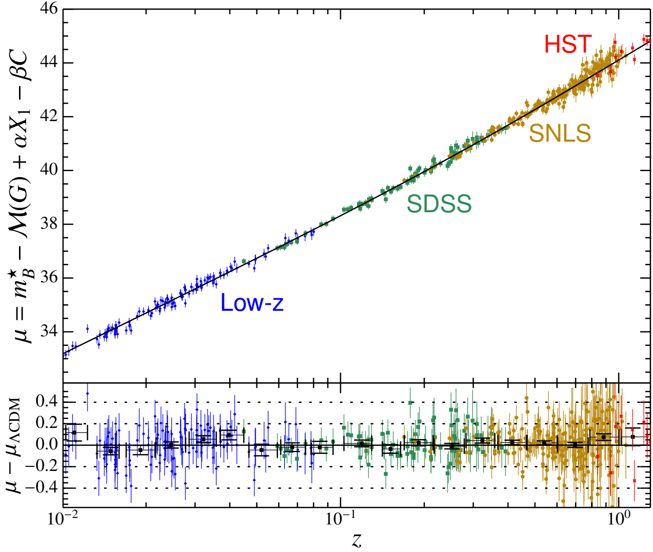

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Minimal update

1. Recalibrate SNLS and SDSS

LPNHE PARIS

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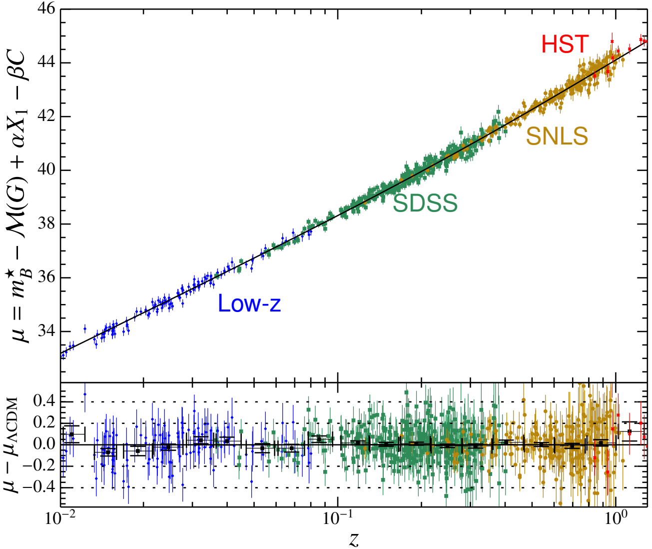

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2. Add $\sim$ 270 SNe-Ia

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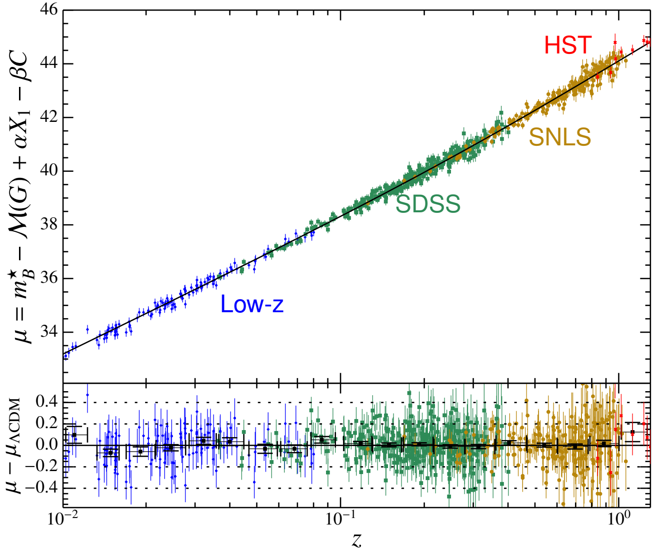

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JLA sample: 740 SNe (Betoule et al. 2014)

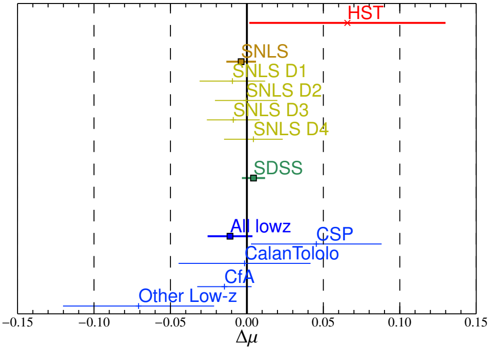
Ω_m constraints

Main paper result:

- JLA sample very compatible with ΛCDM

More compatible than SNLS3

- Small tension between the ΛCDM model and the SNLS3 sample
- Fitted value depended on the weighting
- 15 χ^2 points gained in the recalibration



SNLS3 SALT2/SiFTO differences explained by the tension and different weights

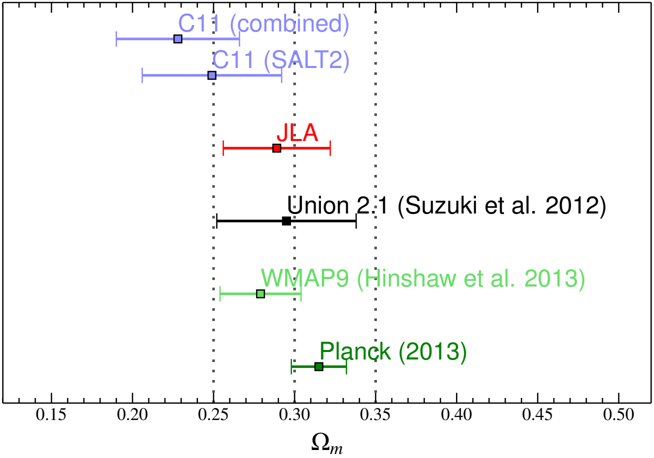
Is the JLA sample compatible with Λ-CDM ?

… And with Planck and Λ-CDM ?

Planck 2013 results. XVI. Cosmological parameters

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 precision 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 $N_{\mathrm{eff}} = 3.30 \pm 0.27$ 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 $N_{\mathrm{eff}} = 3.046$. 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.

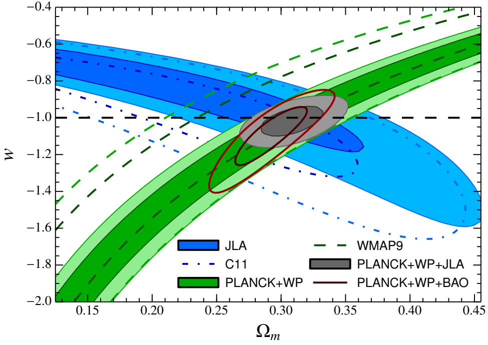
JLA compatible with Planck ΛCDM parameters



Change driven by the recalibration

30% improvement in the error

Cosmological constraints from the CMB+BAO+SN combination



Main paper result

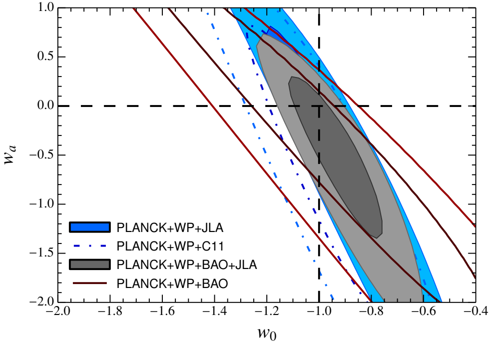
- In every tested case: compatible with the cosmological constant hypothesis

Notable point

- Best constraints to date w at $< 6\%$
- SNLS+SDSS alone (no low-z) beats SNLS3
- Calibration still dominant syst

Cosmological constraints from the CMB+BAO+SN combination: w_0, w_a

Reach a DOTF FoM of ~ 30



Thanks to

- The large SDSS stat
- The calibration improvement
- Better CMB and BAO constraints

About H_0

We measure relative distances

$$\frac{\ell(z)}{\mathcal{L}_0} \approx \frac{1}{d_L(z)}$$

with:

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

- $\mathcal{L}_0 H_0^2$ is a nuisance parameter for SN cosmology

None of the SDSS/SNLS work is going to affect the cepheid + SNe-Ia H_0 measurement

- Absolute measurement of distances
- Involves several astrophysical probes to build a distance ladder
- See e.g. Riess et al. (2011) for details

Outline

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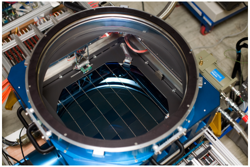
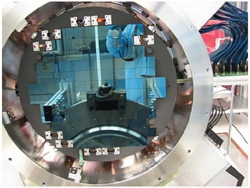
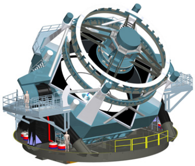
The discovery rate continue to increase







Ongoing surveys

- CfA and CSP continuing $z < 0.1$
- PTF (Law et al. 2009) $z < 0.1$
- SN factory (Aldering 2002) $z < 0.1$
- Pan-STARRS (Kaiser 2004) $z < 0.7$

Starting now

- DES (Bernstein 2011) $z < 1.2$.

Around 2020

- LSST able to rolling-search in the full redshift range
- EUCLID would allow infrared follow-up of high-z SNe-Ia

Going further on systematics

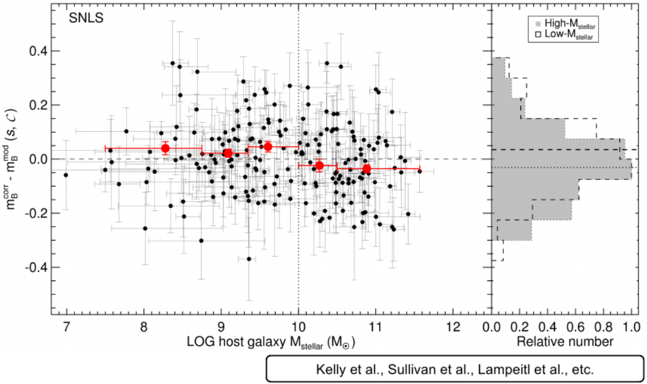
Calibration is still the dominant source of systematic uncertainty

- And still roughly at parity with the statistical uncertainty

Progress on instrumental calibration

A good reason to question the standardization process

Hubble Residuals correlates to host galaxy stellar mass

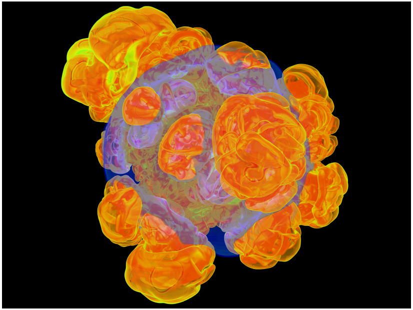


A patch on the Hubble diagram

Distance estimates now explicitly include dependence in galactic parameters

On the model side

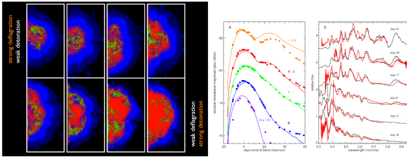
Lots of highly non-linear physics going on ...



(Jordan et al. 2008)

Sizeable progress

- Thermo-nuclear explosion of a C-O white-dwarf.
- e.g. Kasen (2009)

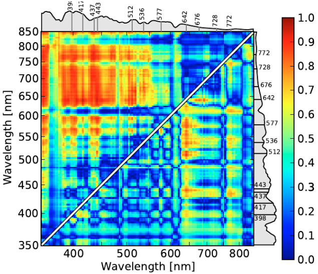


- Good qualitative agreement
- Reproduce brighter-slower relation

Not accurate enough to measure distances

Empirical search for better SN standardization

Spectroscopic standardization



- Systematic search in the SN Factory
- So far 1 alternative: the Bailey Ratio
- $\sigma(M_B) \sim 0.12$
- Other systematic investigations (Chotard et al. in prep.)

Non competitive with the usual distance estimate in cosmological analysis

- Statistical gain too small
- Does not pay back the cost of acquiring high quality spectra at high-z

So far the distance estimator remains essentially unchanged...

Finding the origin of the mass step: A very active research subject

Looking for a better (physical) explanation

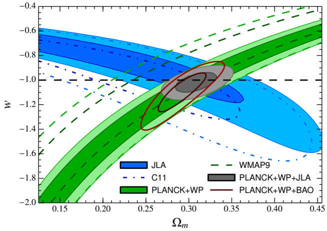
- Different progenitors ?
  Starting to place direct constraints on progenitors scenario (e.g. Li et al. 2011)
- Progenitor metallicity ?
- Local interstellar medium ?
  Scrutinizing the local environment of nearby SNe-Ia (e.g. Childress 2013, Rigault et al. 2013)

Looking for echos in the supernovae

- In the spectra ?
- In the early part of the light-curve ?
- More and better data are becoming available

Conlusion

Highly successful quest for an Hubble diagram with $\sim$ 1000 SNe-Ia



- Tightest constraints on dark energy to date (w at 6%)
- No tension with Planck and ΛCDM
- Limited by measurement systematics
- Systematics continue to improve

Open questions on the probe itself

- Active research field
- Might become a limitation for next generation surveys

Biases and fitter systematic

Full bias correction

$$\delta\mu_{all}(z) = <\mu>_{\text{fit}} - <\mu>_{\text{sim}}$$

- Based on SNANA simulations from Rick and Jen
- Representative of the full analysis (datasets, cuts ...)
- For the "nominal" assumptions about smearing (G10)

Associated method systematic:

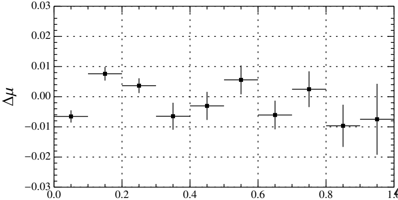
Stat uncertainties in the correction

- MC statistical noise
- uncertainty in survey selection functions (dominant)

And the method systematic from Mosher:

- Fitter bias
- Uncertainty on smearing

Encompasses e.g. Scolnic et al. (2013)



JLA result 2σ away from the SNLS3 result

Decomposing the changes

- New regularization in SALT / bias corrections ... $\rightarrow$ reanalyzed
- Recalibration $\rightarrow$ recalibrated
- Addition of SDSS SNe $\rightarrow$ JLA

Change in Ω_m driven by the recalibration

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