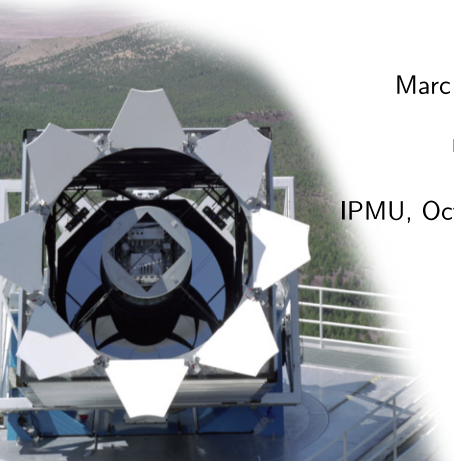
Cosmic distance measurements with SN-Ia
SNLS+SDSS JLA Hubble Diagram



Marc Betoule

LPNHE

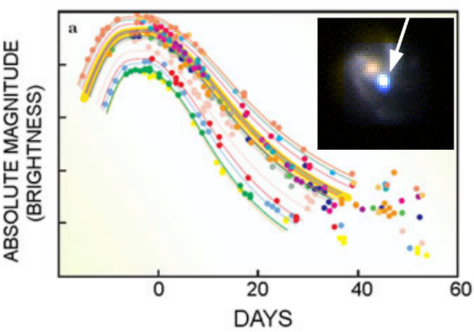
IPMU, October 22^{th} 2014

Mapping the distance-redshift relation with SNe-Ia

Probe of the expansion history at late time

$$d_L(z) = (1+z)c \int \frac{dz}{H(z)}$$

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



SNe Ia as standard candles

1. Standardization
   - Color + shape → L at 12%
2. Apparent flux measurement

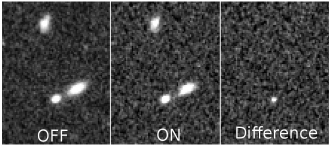
   ↓

   Luminosity distance
3. Redshift measurement

We need to be able to:

1. Find SNe Ia
2. Measure their redshift
3. Measure their apparent flux
4. Estimate their (relative) intrinsic flux

Detecting SNe

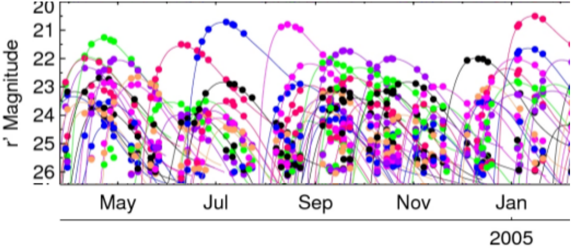


Take images of the same sky region at different epochs

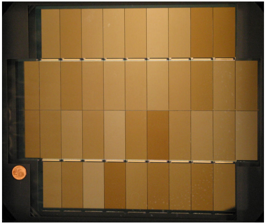
- Transient pops out in the difference

Finding SNe Ia efficiently: A key technology

The rise of the rolling-search approach...



with large CCD matrices



Requirements

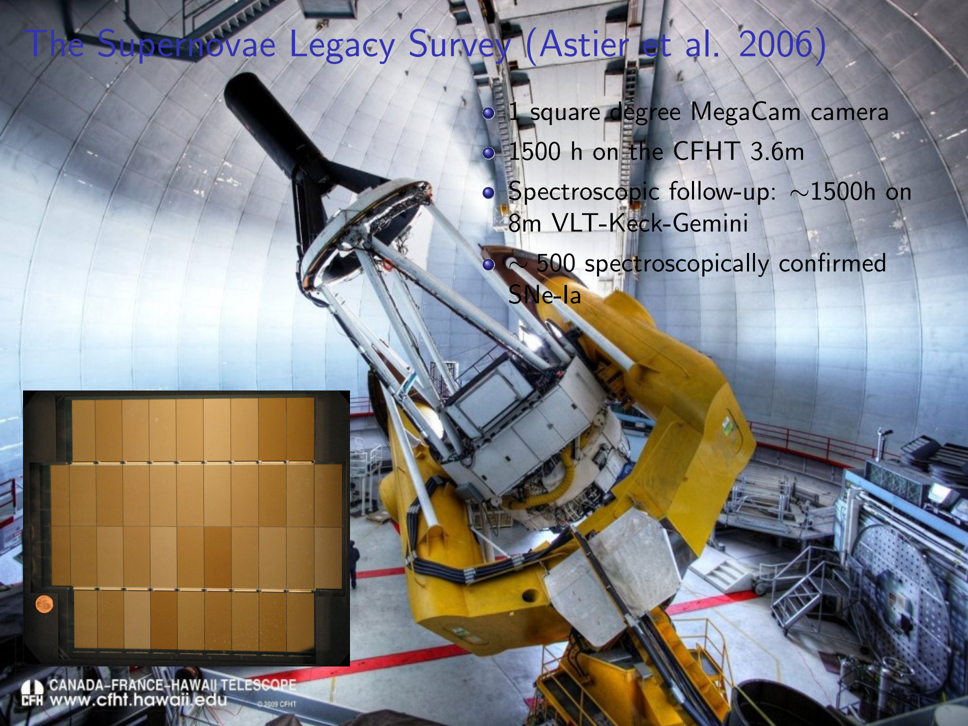
1. Discovery in images subtraction
2. Flux evolution measurement
3. Host galactic flux model
4. Spectroscopic follow-up: identification and redshift measurement

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

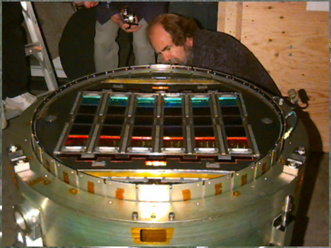
The Supernovae Legacy Survey (Astier et al. 2006)

- 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

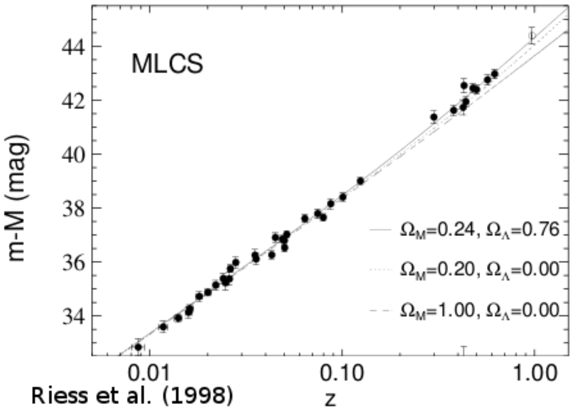


The SDSS-II Supernovae Survey (Kessler et al. 2009)

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



From acceleration discovery to Dark Energy characterization



Riess et al. (1998)

Discovery of accelerated expansion

- Riess et al. (1998), Perlmutter et al. (1999)

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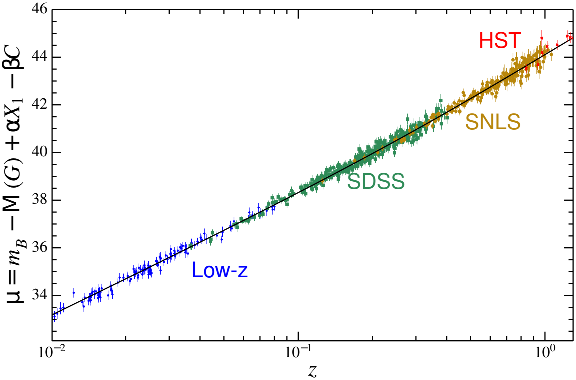
From acceleration discovery to Dark Energy characterization



Betoule et al. 2014

Discovery of accelerated expansion

- Riess et al. (1998), Perlmutter et al. (1999)

In the last decade

- $\times 20$ increase of the statistics

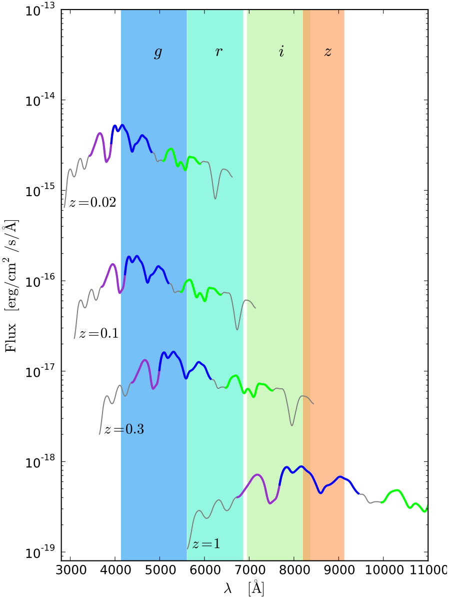
Redshift measurements

Spectroscopic measurements

- Host galaxy lines $\rightarrow \delta z \sim 0.001$
- Supernova spectrum $\rightarrow \delta z \sim 0.005$

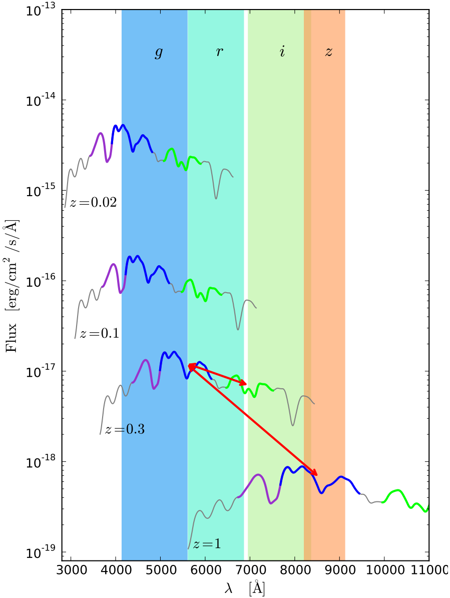
Large observation time investment

Flux measurements



Required ingredients

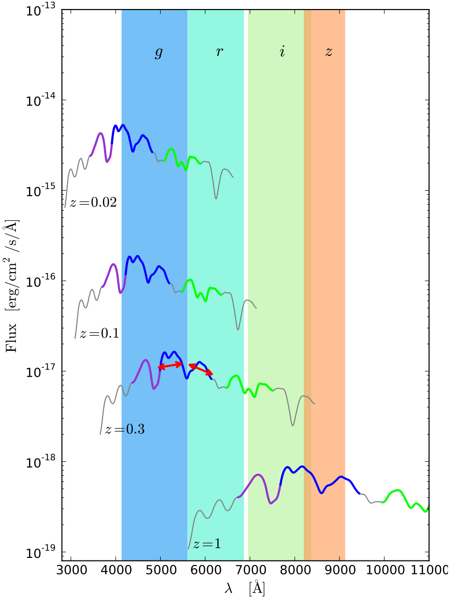
Flux measurements



Required ingredients

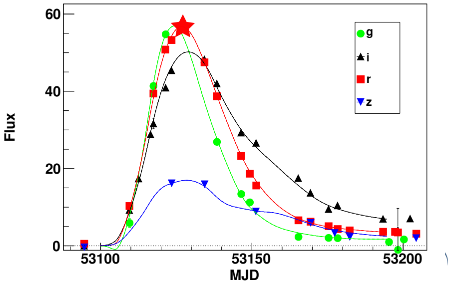
- Measure flux ratios in different observer-frame band
  → inter-calibration

Flux measurements

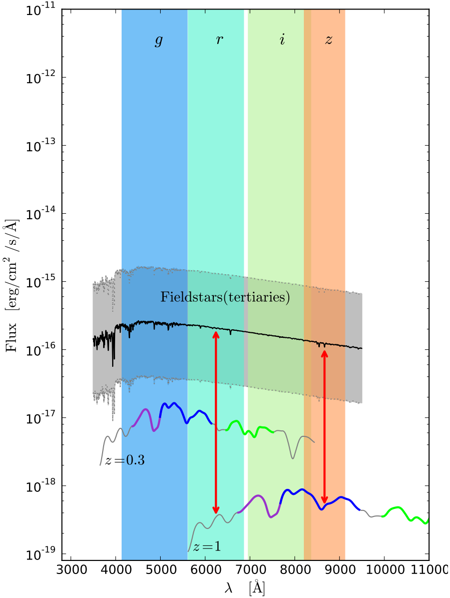


Required ingredients

- Measure flux ratios in different observer-frame band
  → inter-calibration
- Interpolate in time and wavelength
  → Light-curve model

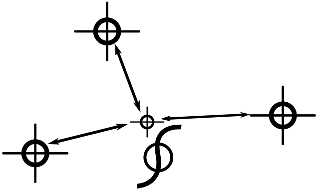


Flux measurements

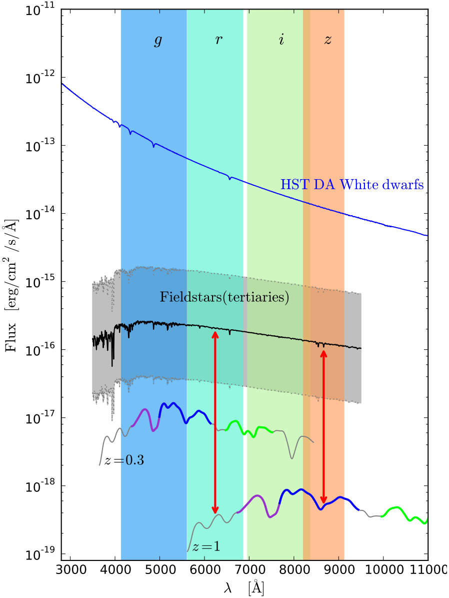


I) Characterization of the instrument response

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



Flux measurements



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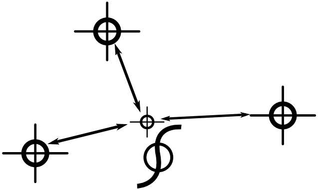
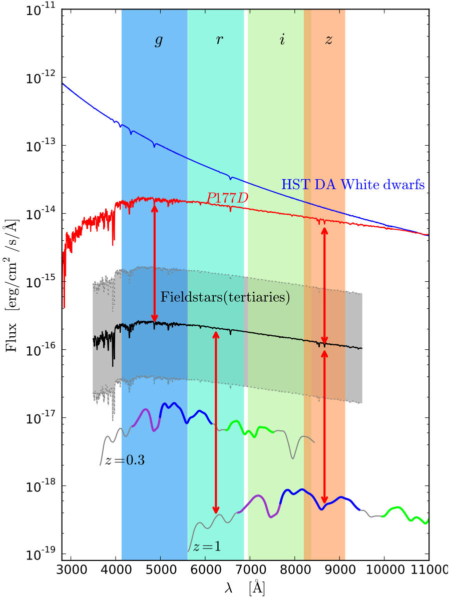


II) Calibration transfer

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

Flux measurements



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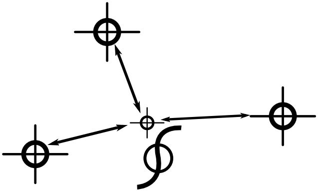
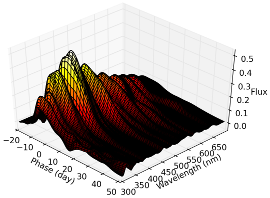


II) Calibration transfer

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

Example SN model: SALT2

Description of the evolution of SN spectrum with time



- 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

Purely empirical description (basically a PCA)

basically a PCA of the available spectro and photometric data

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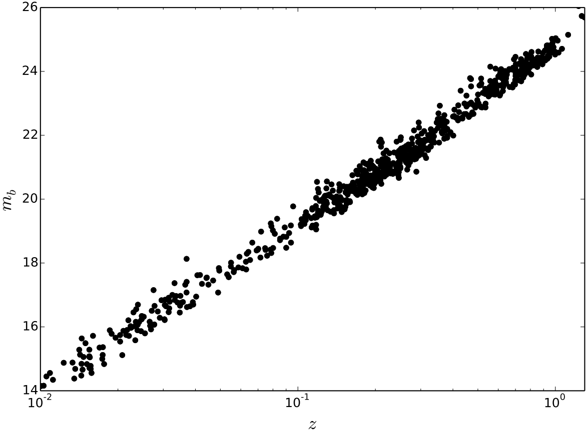
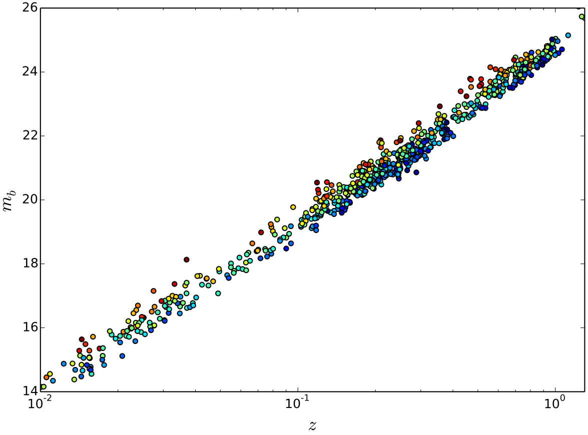
The distance estimates



$$\mu(z) = 5\log_{10}(d_l) \approx m(z) - M$$

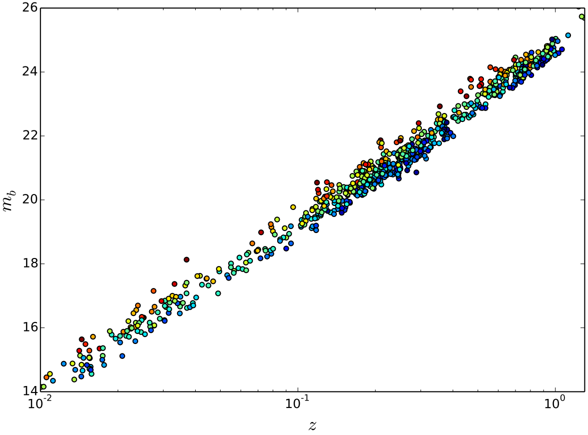
LPNHE PARIS

The distance estimates



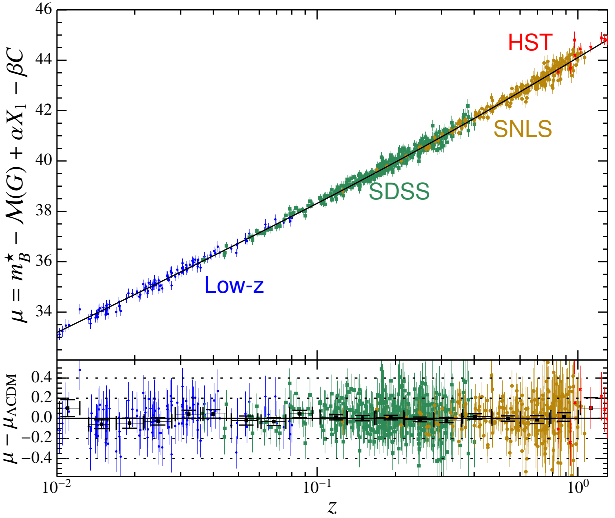
$$\mu(z) = 5\log_{10}(d_l) \approx m(z) - M$$

The distance estimates



$$\mu(z) = 5\log_{10}(d_l) \approx m(z) - M = m(z) - (\mathcal{M}(G) - \alpha x_1 + \beta C)$$

The distance estimates



$$\mu(z) = 5\log_{10}(d_l) \approx m(z) - M = m(z) - (\mathcal{M}(G) - \alpha x_1 + \beta C)$$

Outline

1. Measurement principle
2. The joint light-curve analysis
3. SNLS5 and beyond

Recent dev: The SNLS/SDSS JLA working group

Formed to address the issue of measurement systematics

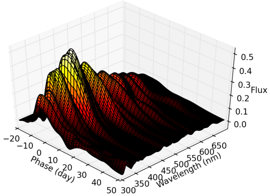
- Transverse WG joining the two main SNe-Ia surveys
- Started in June 2010
- Share data, code and expertise

2 main outcomes:

- SNe light curve model: Kessler et al. (2013), Mosher et al. (2014)
  → Validation of the SALT2 model
- Joint photometric calibration analysis: Betoule et al. (2013)
  → Recalibration of the SNLS and SDSS

Quantify systematics associated with the SALT2 SN model

Description of the evolution of SN spectrum with time



- 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

Purely empirical description (basically a PCA) but:

Incomplete: dispersion remains around the model. What if:

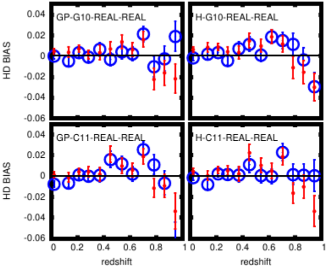
- part of the remaining dispersion correlates with intrinsic luminosity ?
- or color ?

→ Quantify the effect on simulations.

Several other points to check

- Do we propagate noise correctly
- interplay with selection bias, etc...

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

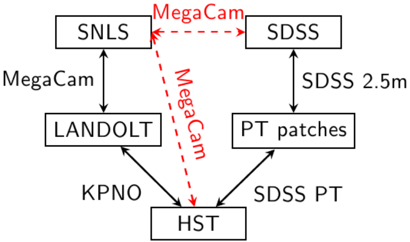


- Various SN models in input
- Extensive MC simulations
- Propagation through the whole chain
- Test the bias on reconstructed distances
- With the currently available "training" sample: $\Delta\mu < 0.03$

Well below the level of calibration uncertainties

New calibration data

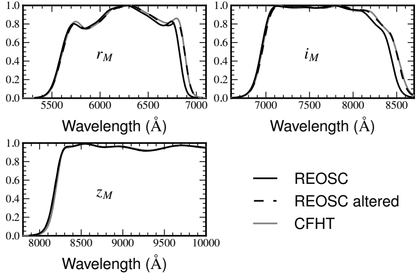
Short and redundant paths for calibration transfer



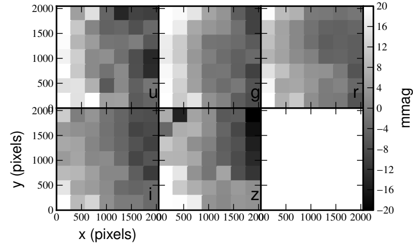
- Direct observation of HST stars
- Direct SNLS/SDSS cross-calibration

Enabled the correction of several instrumental effects

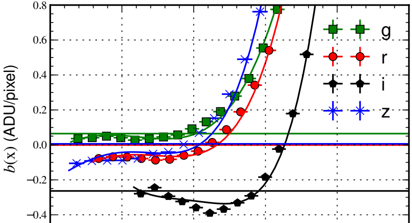
- Filter aging



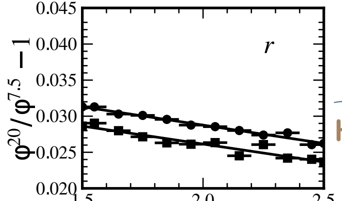
- SDSS PT flat-fielding error



- Background subtraction

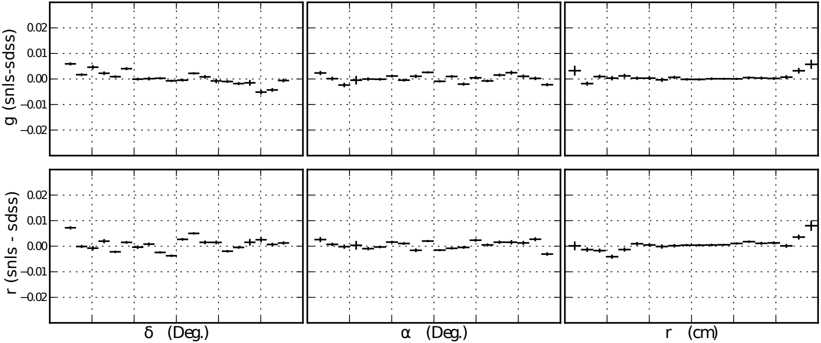


- 2nd order effects in photometry



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

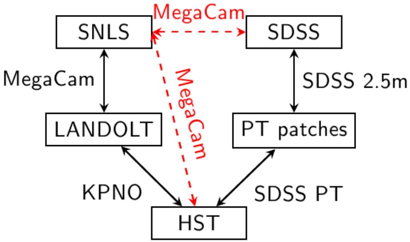
Comparison of SDSS/SNLS photometry



- 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

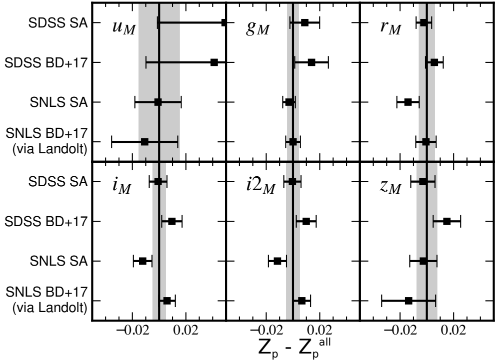


New data

- 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

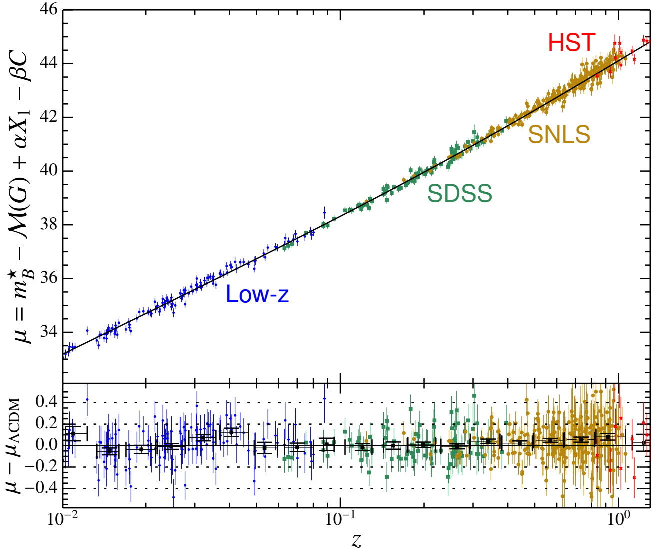
Changes at the percent level wrt SNLS3 calibration

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 ?)

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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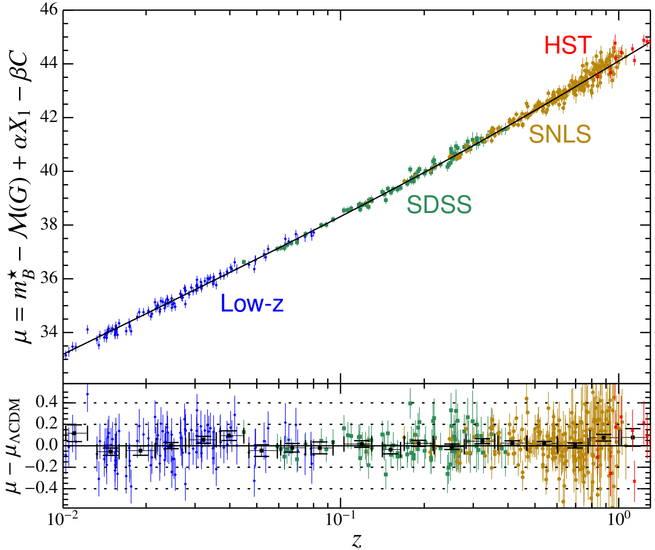

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Minimal update

1. Recalibrate SNLS and SDSS

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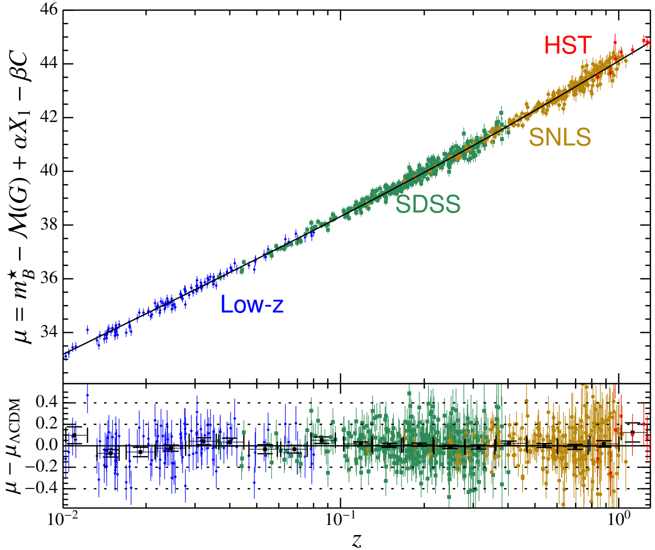

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Minimal update

1. Recalibrate SNLS and SDSS
2. Add $\sim$ 270 SNe-Ia

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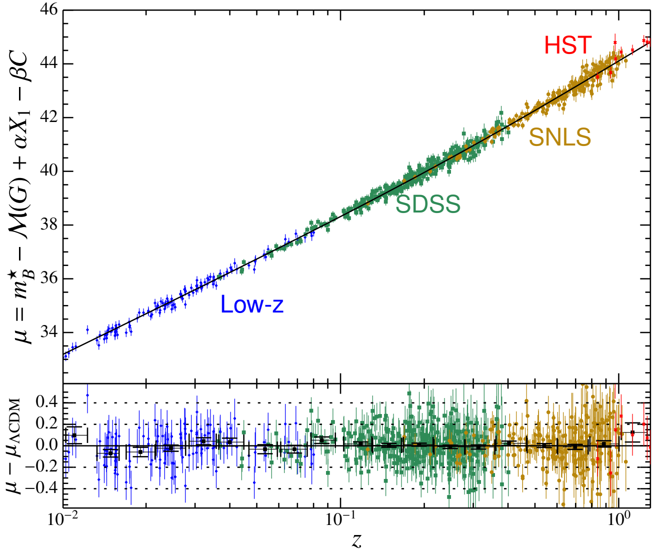

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JLA sample: 740 SNe (Betoule et al. 2014)

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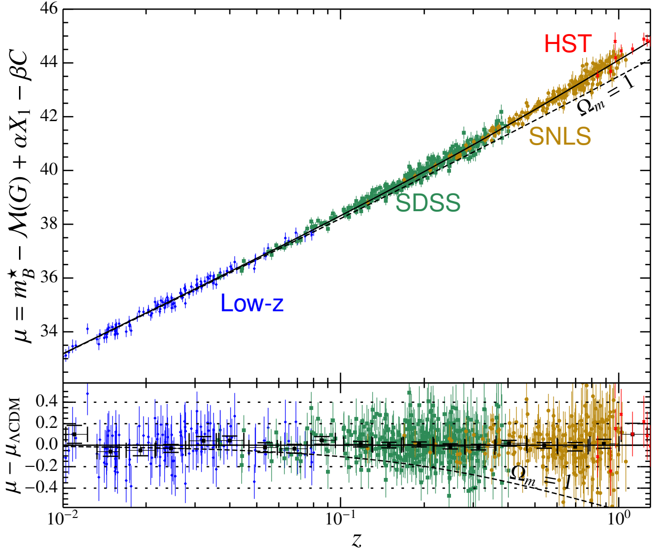

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JLA sample: 740 SNe (Betoule et al. 2014)

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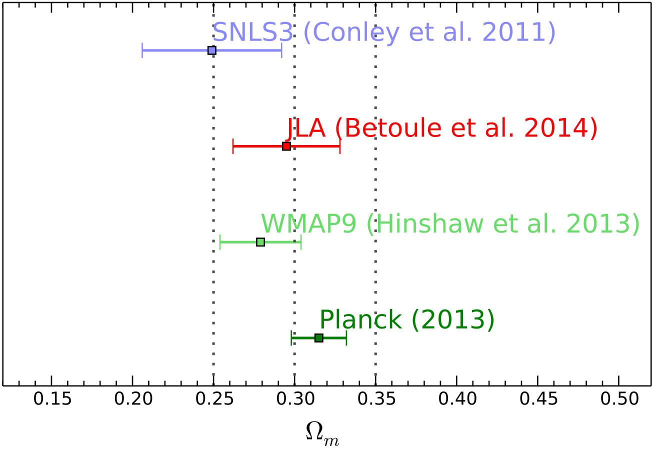
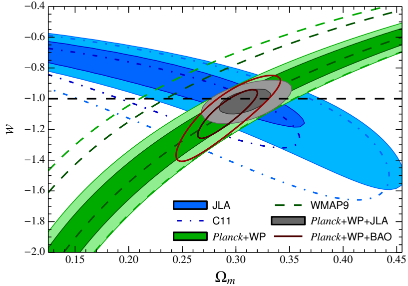
JLA compatible with CMB ΛCDM parameters

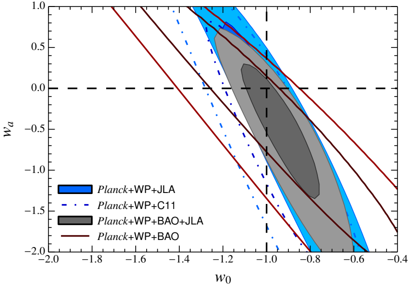


Ω_m measurement independent of CMB

- Recalibration shift SN measurement by 1σ
- Improve the uncertainty by 30%

Impact on Dark Energy constraints





Large improvement of SN constraints

- Stat: additionnal SDSS data
- Sys: joint calibration analysis

Best measurement of w

- Planck + SN: $w = -1.018 \pm 0.057$
- Planck + BAO: $w = -1.01 \pm 0.08$

Half of the improvement in the "figure of merite"

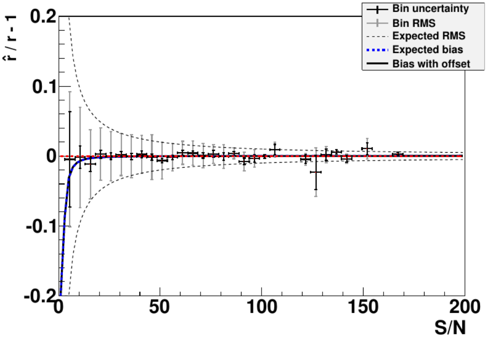
- 2012: FoM= 15 (WMAP+SDSS+SNLS)
- 2014: FoM= 30 (Planck+BOSS+JLA)

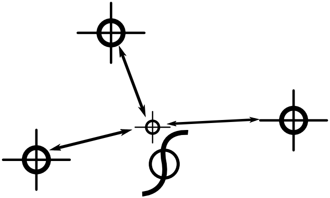
Outline

1. Measurement principle
2. The joint light-curve analysis
3. SNLS5 and beyond

Work on methods continue

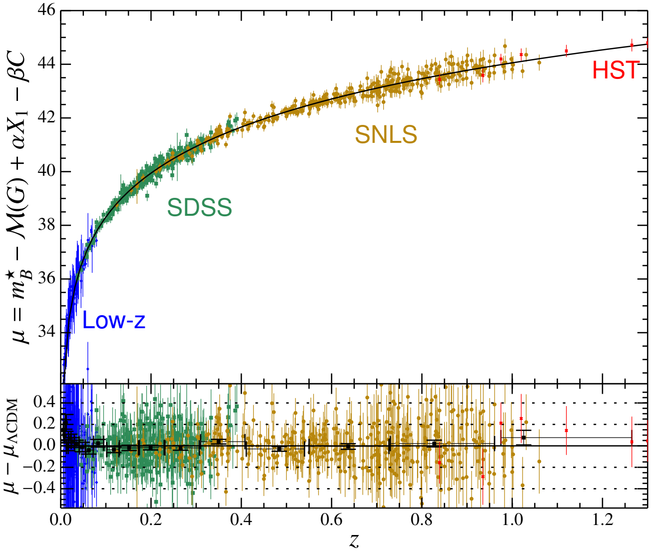
Differential photometry method (Astier et al. 2013)





- Method proven to be accurate down to the mmag level.

200 more SNe Ia in the last 2 years of SNe Ia data (Elhage et al. in prep.)



Going further

1. More and better low redshift SNe
2. Higher z SNe
3. Calibration
4. Evolution

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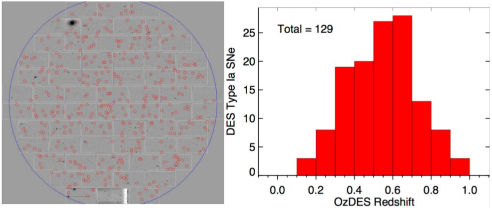
Higher and lower redshift SNe before LSST (2020)

The ongoing big SNe experiment is DES

- Cover about the same redshift range as SDSS+SNLS



Peter Melchior (Moriond 2014)

At low redshift: Pan-Starrs/SkyMapper

Only one instrument able to measure a significant number of higher redshift SNe: Subaru/HSC

Work on calibration continue

Replace stellar references with laboratory references

→

Thanks to SNDICE

(Nicolas Regnault seminar)

Conclusion

- SNe Ia are still the most sensitive probe for dark energy
- No hard limit identified yet
- Provided that measurement are carefully conducted
- One pending issue: Evolution