Cosmology with type Ia Supernovae

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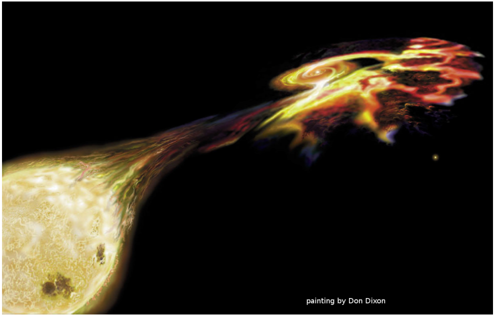
LPNHE

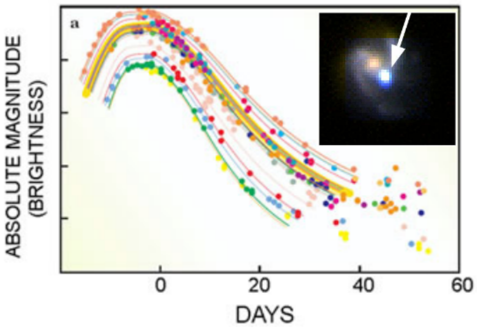
PONT d'Avignon, April 18^{th} 2014



Mapping the distance-redshift relation with SNe-Ia

Probe of the expansion history at late time

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



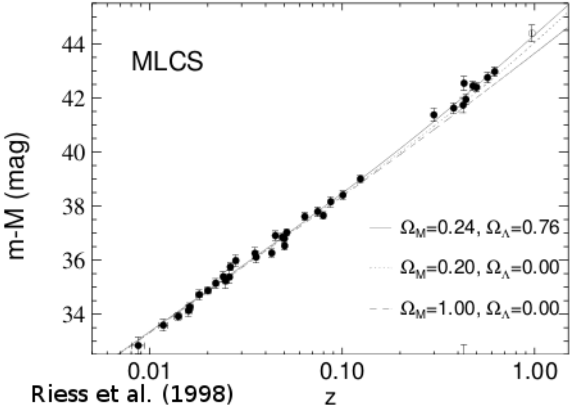
SNe Ia as standard candles

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

   ↓

   Luminosity distance
3. Redshift measurement

From acceleration discovery to Dark Energy characterization

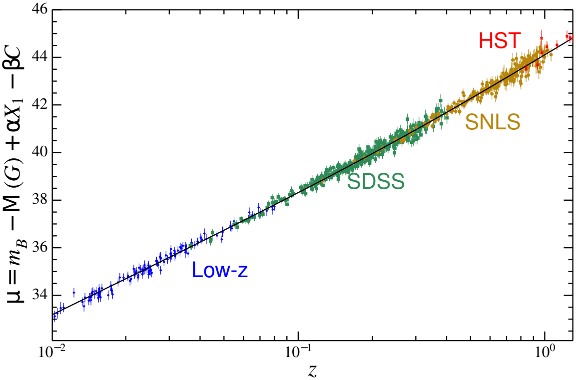


Riess et al. (1998)

Discovery of accelerated expansion

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

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

Constraining dark energy with SN-Ia: OUTLINE

1. Towards a 1000 SNe Ia sample
2. Improving measurement accuracy
3. Status of cosmological constraints from SNe Ia
4. Perspectives

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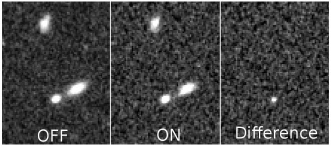
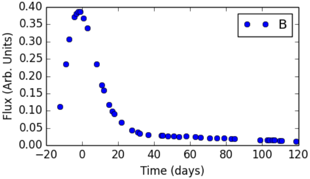
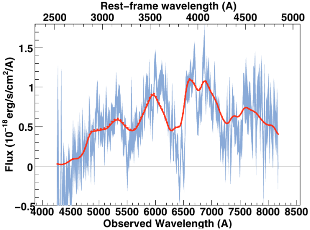
Where is the Supernovae ?

Detecting and measuring SNe







Take images of the same sky region at different epochs

- Transient pops out in the difference

Measure the apparent luminosity

- at several time → shape
- in several bands → color

Measure a spectrum

- Identification
- Redshift

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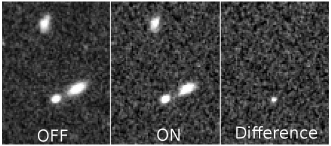
Detecting and measuring SNe



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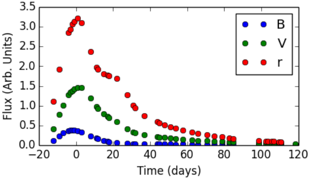

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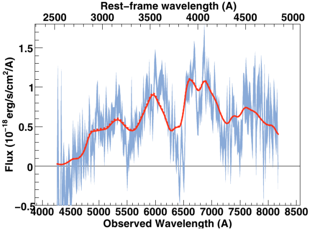

Measure a spectrum

- Identification
- Redshift

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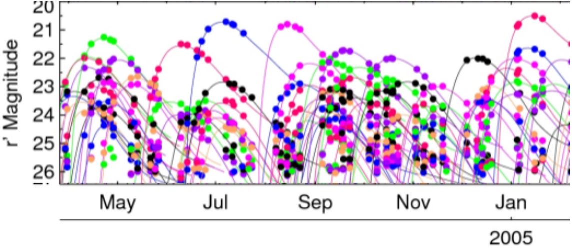
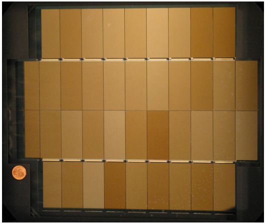
A key technology

The rise of the rolling-search approach...



with large CCD matrices



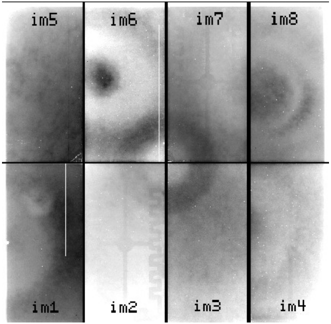
Requirements

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

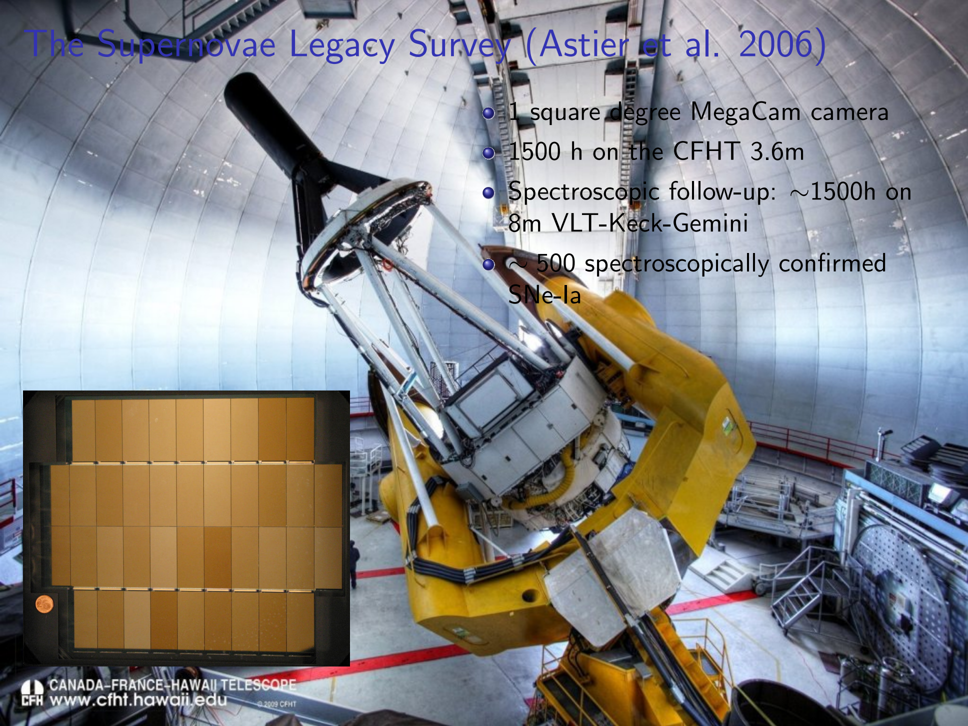
- Repeated imaging of the same sky portion
- Implemented in 3 major survey
- Classical spectroscopic follow-up

ESSENCE (Wood-Vasey et al. 2007)



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

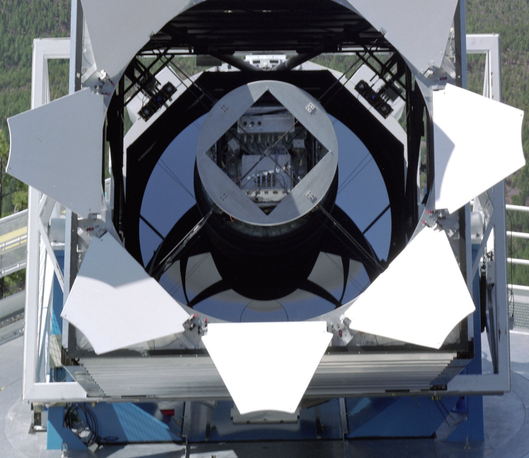
The Supernovae Legacy Survey (Astier et al. 2006)

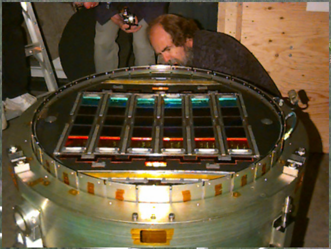


- 1 square degree MegaCam camera
- 1500 h on the CFHT 3.6m
- Spectroscopic follow-up: $\sim$1500h on 8m VLT-Keck-Gemini
- $\sim$ 500 spectroscopically confirmed SNe-Ia

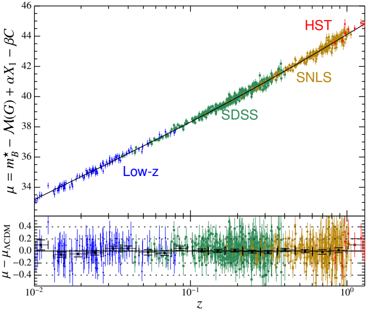
The SDSS-II Supernovae Survey (Kessler et al. 2009)

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





The available sample: > 1000 SNe with spectroscopic ID



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

- About ~ 500 followed, dominated by 2 samples:
  - Harvard Center for Astrophysic (Hicken et al. 2012)
  - Carnegie Supernovae Project (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)

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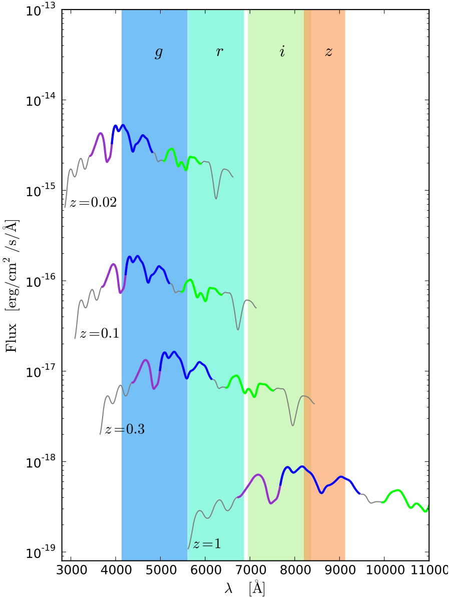
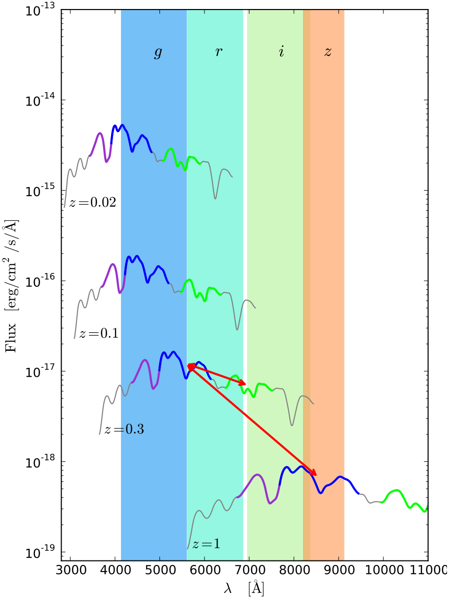
Measurement basics



Required ingredients

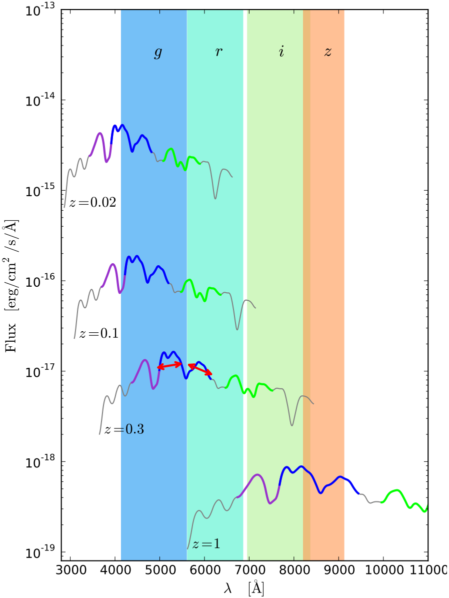
Measurement basics



Required ingredients

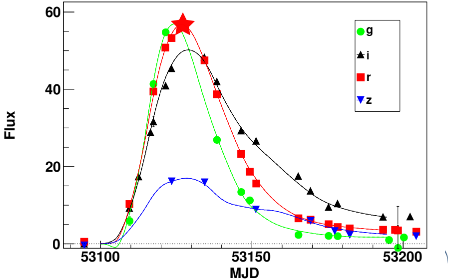
- Measure flux ratios in different observer-frame band
  $\rightarrow$ inter-calibration

Measurement basics



Required ingredients

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



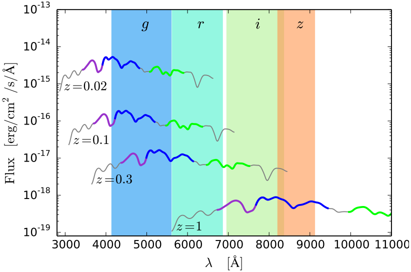
Short story of the model uncertainty

Controversy about light-curve models (e.g. Kessler et al 2009)

009 FIRST-YEAR SLOAN DIGITAL SKY SURVEY-II SUPERNOVA RESULTS

we find $w = -0.76 \pm 0.07\text{(stat)} \pm 0.11\text{(syst)}$, $\Omega_M = 0.307 \pm 0.019\text{(stat)} \pm 0.023\text{(syst)}$ using MLCS2K2 and $w = -0.96 \pm 0.06\text{(stat)} \pm 0.12\text{(syst)}$, $\Omega_M = 0.265 \pm 0.016\text{(stat)} \pm 0.025\text{(syst)}$ using the SALT-II fitter. We trace the discrepancy between these results to a difference in the rest-frame UV model combined with a different luminosity correction from color variations; these differences mostly affect the distance estimates for the SNLS and *HST* SNe. We present detailed discussions of systematic errors for both light-curve methods and find that

Essentially understood in the 2009 paper



1. MLCS2k2 trained only on low-z SNe → affected by Observer-frame U-band calibration problems
2. MLCS2k2 assumed that color variation was due to extinction by Dust (> 0) → Evidences for intrinsic color variation (e.g. Stritzinger et al. 2011)

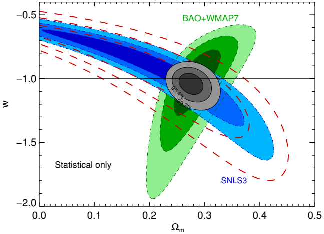
Brief history of the calibration uncertainty

Astier et al 2006

Table 6 Summary of uncertainties in the derived cosmological parameters. The dominant systematic uncertainty arises from the photometric calibration, itself dominated by the i_M and z_M band contributions.

Large efforts on wide-field camera photometric accuracy

- e.g. Ivezic et al. (2007), Regnault et al. (2009)
- Reach percent level accuracy



Conley et al., Sullivan et al. (2011)

- Statistics ×3.5
- Statistical and calibration uncertainties at the same level

Recent dev: The SNLS/SDSS JLA working group

Formed to address the issue of measurement systematics

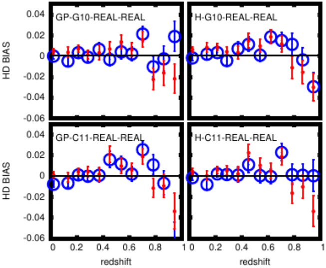
- Transverse WG joining the two main SNe-Ia surveys
- Started in June 2010
- Share data, code and expertise

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

JLA work to quantify systematics associated to SALT2

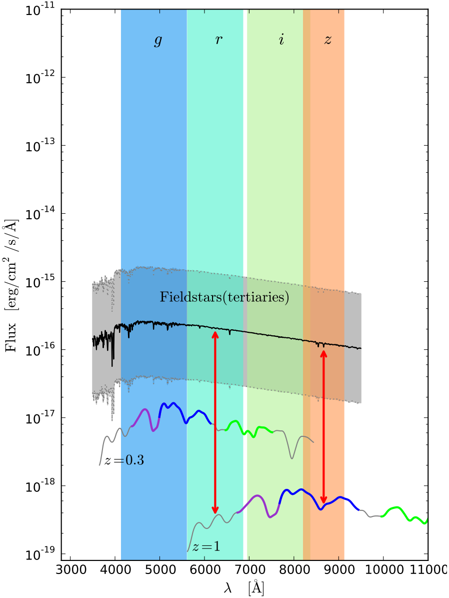
End-to-end test of the SALT2 method (Mosher et al. 2014.)



- 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: $\Delta\mu < 0.03$

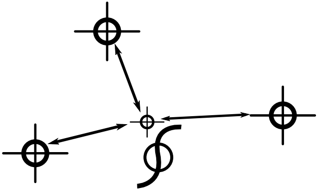
Well below the level of calibration uncertainties

What is photometric calibration ?



I) Characterization of the instrument response

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



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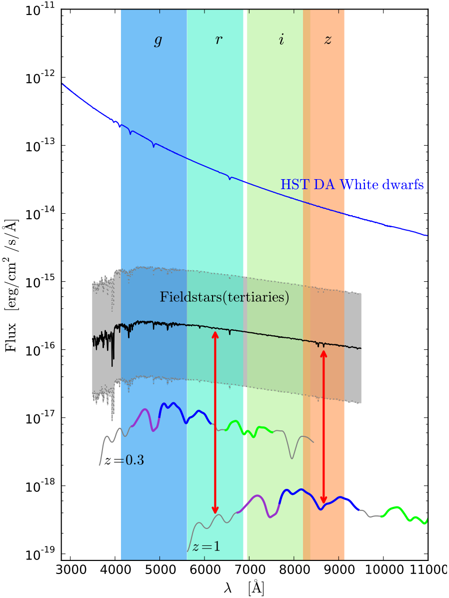

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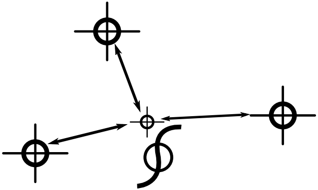
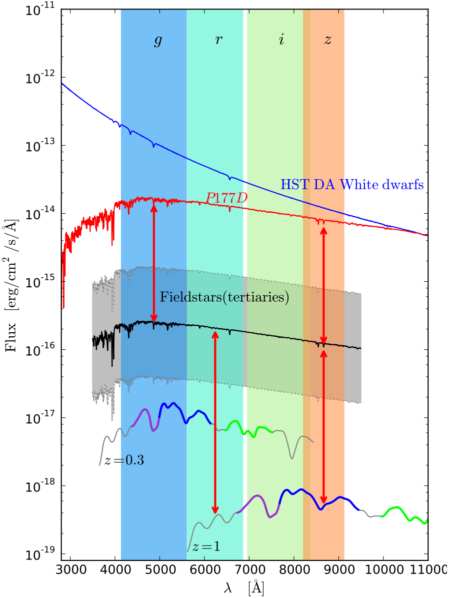


II) Calibration transfer

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

What is photometric calibration ?



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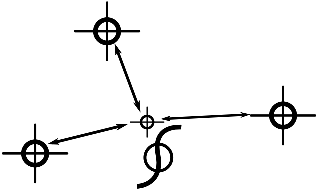

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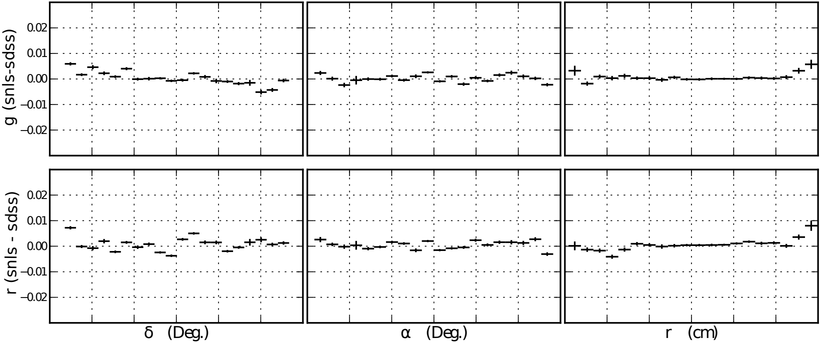
Result I: "Flat-fielding" 2 wide-field camera at 0.3%

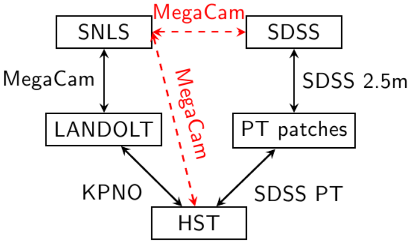
Comparison of SDSS/SNLS photometry

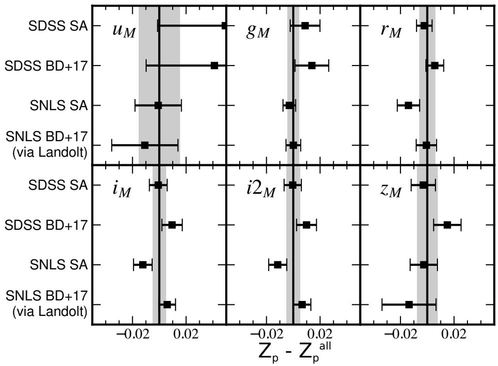


- SNLS and SDSS flat-fields obtained independently
- Achievement of wider interest (e.g. Photo-z)

Result II: ∼ 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

1 Towards a 1000 SNe Ia sample

2 Improving measurement accuracy

3 Status of cosmological constraints from SNe Ia

4 Perspectives

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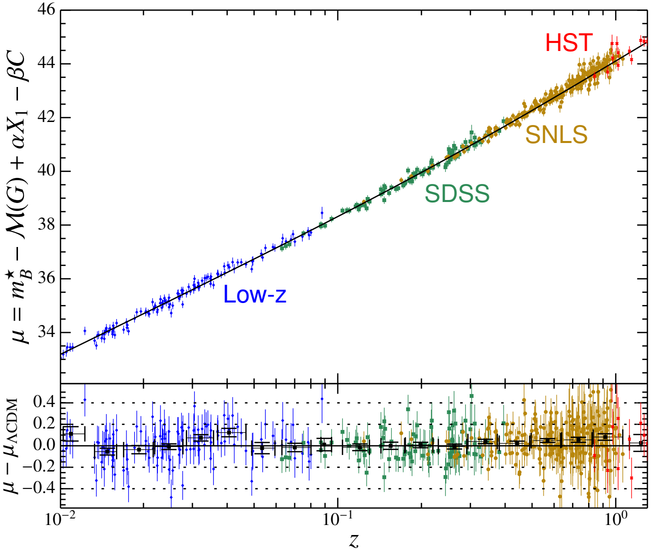
Start from the Conley et al. (2011) Salt2 Hubble diagram



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

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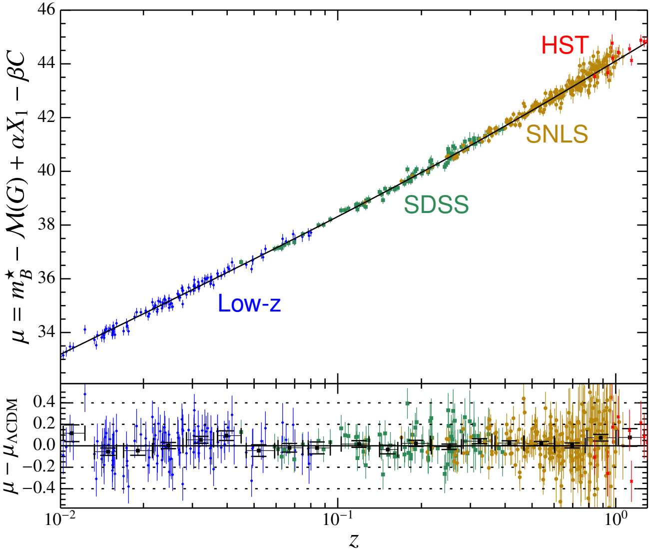

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Minimal update

1. Recalibrate SNLS and SDSS

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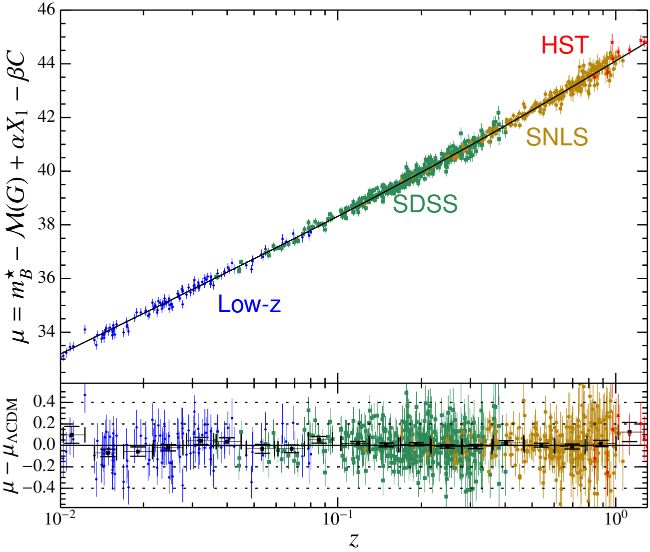

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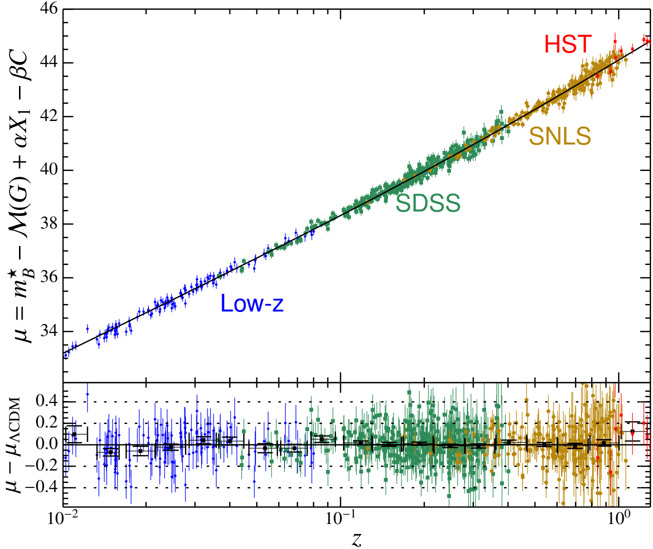

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JLA sample: 740 SNe (Betoule et al. 2014)

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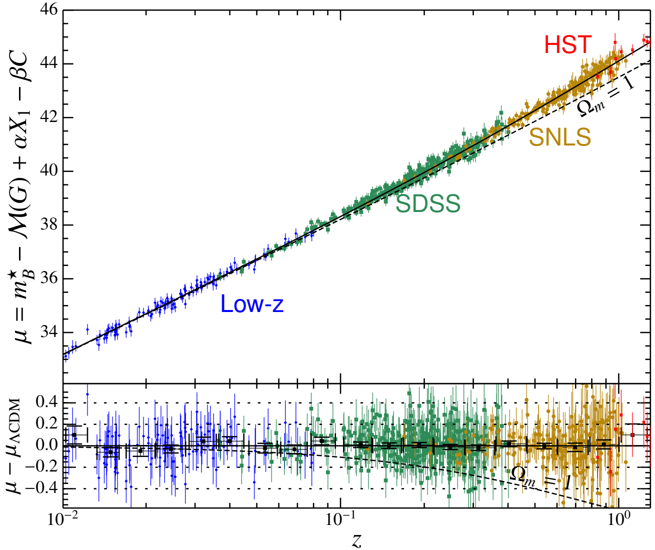

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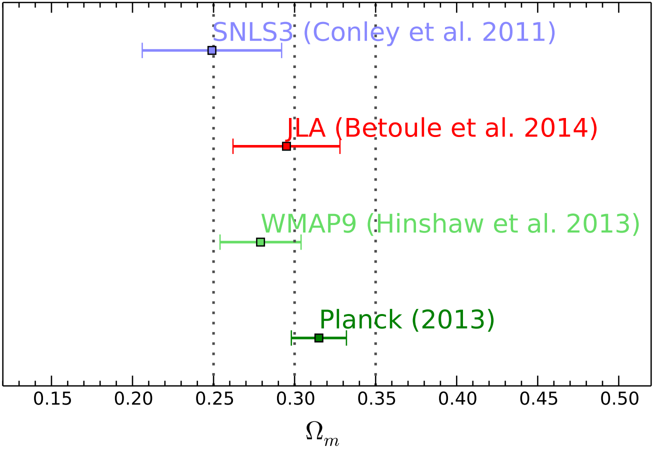
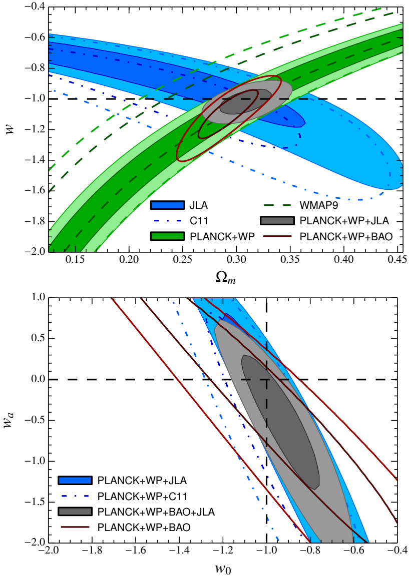
JLA compatible with CMB ΛCDM parameters



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)

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

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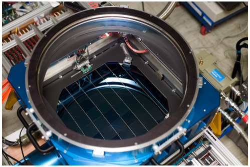
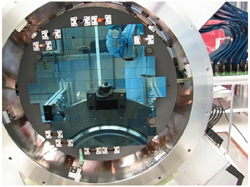
The discovery rate will continue to increase

Because we continue to build larger and larger CCD camera on powerful instruments

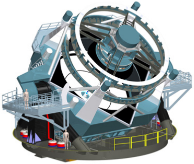
PAN-STARRS I



DES



LSST



But without significant live-spectroscopy

- SNLS: spectroscopic time on 8m ≈ photometric time at CFHT 3.5m
- Following every single SNe of DES would be prohibitively expensive
- Acquire the redshift of the host galaxies

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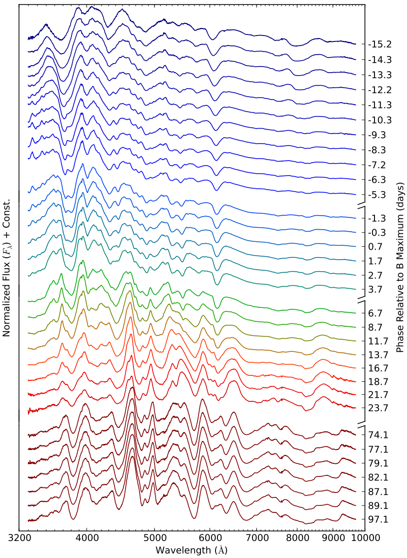
Completion of the 2nd generation surveys



Remaining spectro identified SN

- $\sim$ 200 SNLS
- $\sim$ 150 Low-z from CSP and CfA (Stritzinger et al. 2011, Hicken et al. 2012)

Plenty of new spectroscopic data already available

- Blondin et al. 2012; Silverman et al. 2012; Maguire et al. 2012; Pereira et al. 2013
- SNFactory (Pereira et al. 2013)

Play the photometric ID game

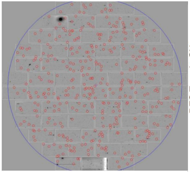
Increase the statistics for SDSS and SNLS by $\times 1.5$ (e.g. Campbell et al. 2013)

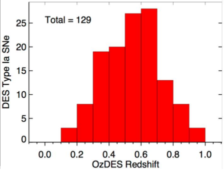
The start of the 3rd generation surveys

Pan-Starrs First results

- 112 *Spectroscopically confirmed* SNe Ia
- PSI+Planck+BAO+H_0: -1.186 ± 0.076
- PSI+Planck+BAO: -1.149 ± 0.078

DES Started last year (Bernstein et al. 2012)





Peter Melchior (Moriond 2014)

- 3500 SNe in 5 years
- Host-galaxy redshifts from OzDes

On the low-z side

- SkyMapper (delayed)
- Possibility to follow Gaia candidate (~ 400)

4th generation

Around 2020: LSST

- Able to rolling-search in the full redshift range
- > 10000 SNe

Synergy with EUCLID

- Possibility to follow a substantial number (~ 2000)
- high-z ($0.75 < z < 1.5$) LSST SNe
- from space with the infrared Euclid instrument

Numbers: Planck$+$ LSST and EUCLID SNe

- conservative estimate (no improvement on any topics but the statistics)
- $\sigma(w_p) = 0.02$ (FoM ~ 200)

Measurement systematics should continue to improve

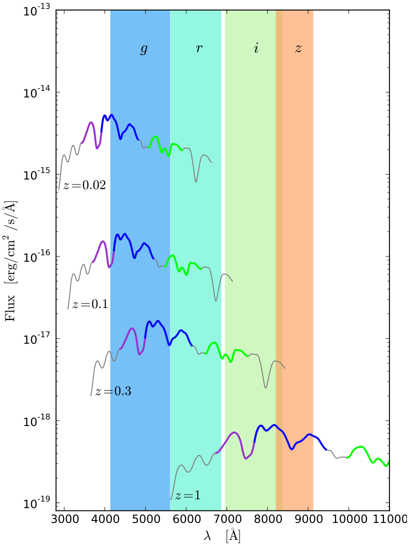
Calibration is still the dominant source of systematic uncertainty

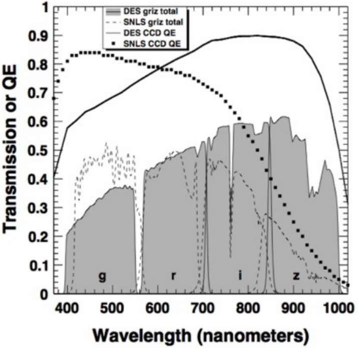
Improvements are possible

3 reasons from which improvements are expected

1. Sensitivity in the infrared
2. Fewer instruments
3. Instrumental effort

Sensitivity in the infrared





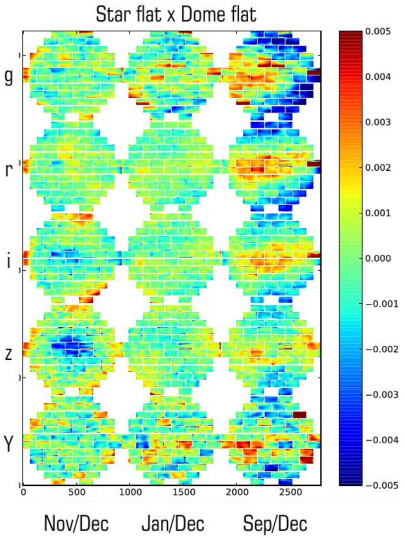
- Degeneracy between model, calibration and cosmology parameters
- New gen has increased infrared sensitivity from thick CCD
- Alleviate the degeneracy and sensitivity to calibration uncertainty

Larger surveys, larger collaborations, fewer instruments

For the same effort you get better characterized instruments

Replace the historical low-z sample (no-longer existing instruments)

Better instrumental control in the new generation



Gary Bernstein

Better stability

- SNLS experimented instrumental variation: (up to 6% in uniformity, 3nm filter changes)
- New gen is apparently 1 order of magnitude better
- And the problem was anticipated → better monitoring

Instrumental calibration projects

- All ongoing surveys have some kind of calibration device
- Instrument monitoring
- Atmosphere monitoring
- Replace stellar-based calibration with lab-made calibration sources

Improving the standardization process

Dispersion of the "standardized" luminosity estimate: 12%

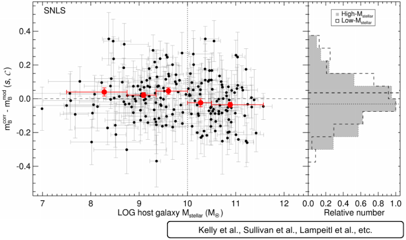
- There are parameters influencing the luminosity that are not catched by the standardization process
- Those are likely related:
  - to the initial explosion condition
  - to the environment of the SN
- And thus likely to evolve with redshift

Not completely degenerated with cosmology

- Several stage of galaxy evolution coexists at a given redshift

Where are we at this stage

Detected correlations of Hubble residuals with global environment



- Estimate host-galaxy properties
- Best correlation: galaxy-mass 5σ
- Enable average correction of the Hubble diagram

Start scrutinizing the local environment (for a subset of nearby SNe Ia

(e.g. Childress 2013, Rigault et al. 2013)

Start placing direct constraints on progenitor scenario

(e.g. Li et al. 2011)

A very active research subject

Pinpoint the exact physical explanation

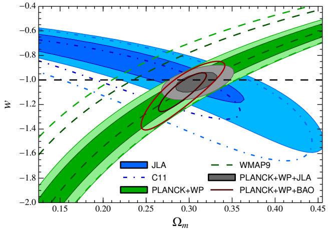
From the nearby detailed search

Look for a direct handle on the remaining variability

- In the spectra ?
- In the early part of the light-curve ?
- More and better unexploited data are now available
- And even more is coming

Conclusion

Highly successful quest for an Hubble diagram with ~ 1000 SNe-Ia



- Tightest constraints on dark energy to date (w at 6%)
- In agreement with ΛCDM
- Limited by measurement systematics
- Systematics continue to improve
- Open question on the probe

JLA data available (arXiv:1401.4064)

- Last cosmomc release
- `http://supernovae.in2p3.fr/sdss_snls_jla/`
- If you are interested only in homogenous universe: simpler product to come (direct distance estimates)

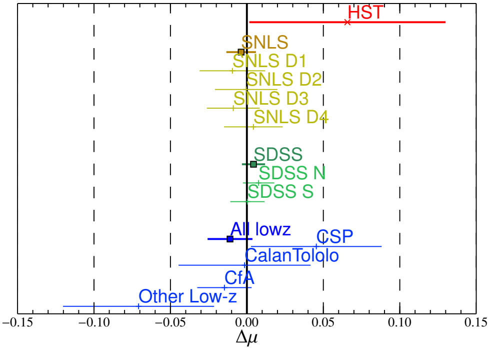
Ω_m constraints

Main paper result:

- JLA sample very compatible with ΛCDM

More compatible than SNLS3

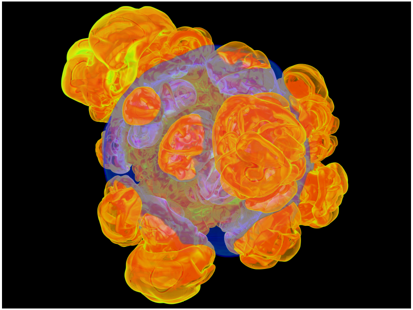
- Small tension between the ΛCDM model and the SNLS3 sample
- Fitted value depended on the weighting
- 20 χ^2 points gained in the recalibration



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

On the model side

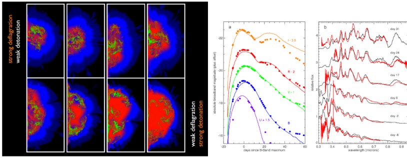
Lots of highly non-linear physics going on ...



(Jordan et al. 2008)

Sizeable progress

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

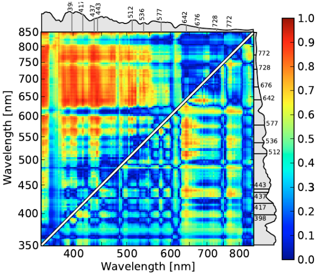


- Good qualitative agreement
- Reproduce brighter-slower relation

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.)

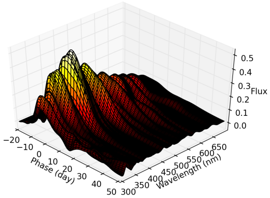
Non competitive with the usual distance estimate in cosmological analysis

- 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...

SN model systematics ?

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



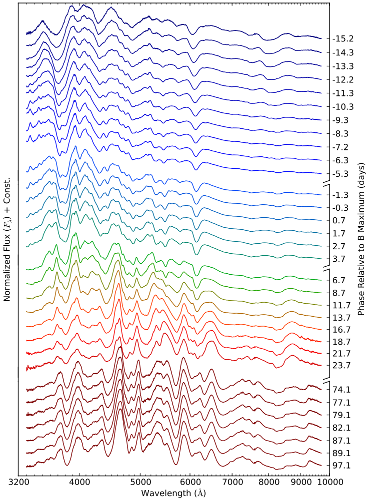
- Fitted on spectroscopic and photometric data: “training sample”
- The surface shape is parameterized by m_b, C and X_1
- m_b, C, X_1 fitted for each SN

Several points to check

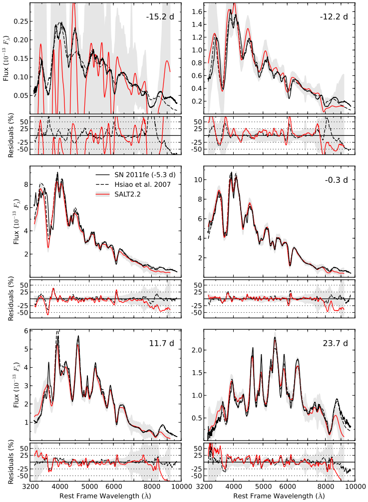
- Missing spectra to constrain the model at early and late phase $\rightarrow$ regularization
- SALT2: first order description of the light-curve shape $\rightarrow$ holds ?
- Interplay between intrinsic dispersion and selection bias.

Likely to improve with the new data samples

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



Comparison with the SALT2 model



Questionning the model of DA white dwarfs SED