SNLS 3rd Year Cosmological Results

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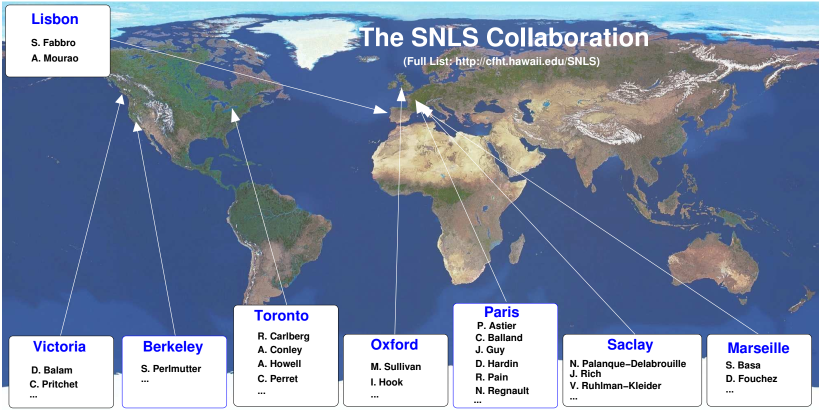
Paris-Berkeley workshop, Sept. 2009

Outline

1. SNLS
   - Survey description
   - SNLS 1st year results
2. SNLS 3rd year analysis
   - Photometric calibration
   - Light-curve fitters
   - Hubble diagram
   - Constraints on w

The SNLS Collaboration



SNLS: A Large Photometric Survey . . .

~ 300h / year on a 3.6-m

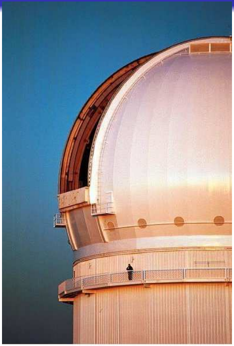
- CFHT @ Hawaii

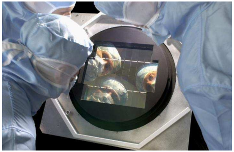
Wide Field Camera

- Megacam (CEA/DAPNIA)
- 1 deg^2, 36 2k×4k CCDs
- Good PSF sampling 1 pix = 0.2"
- Excellent image quality: 0.7" (FWHM)

Rolling search mode

- Component of the CFHTLS survey
- 40 nights / year during 5 years
- Four 1-deg^2 fields
- repeated observations (3-4 nights)
- in 4 bands (*griz*)
- queue observing (minimize impact of bad weather)





SNLS: A Large Photometric Survey . . .

∼ 300h / year (

- CFHT (

Wide Field Cam

- Megaca
- 1 deg^2,
- Good P
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Rolling search n

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- Four 1-
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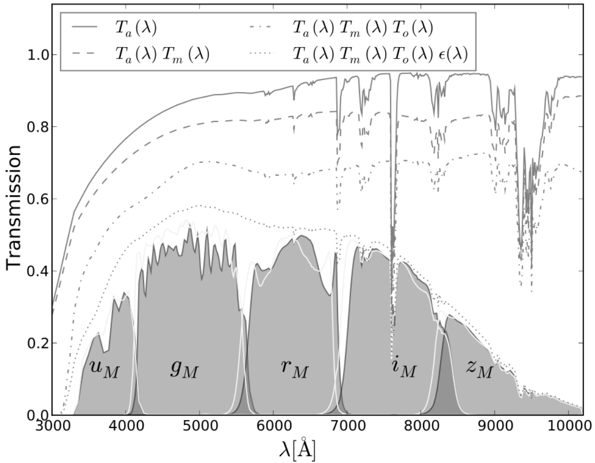
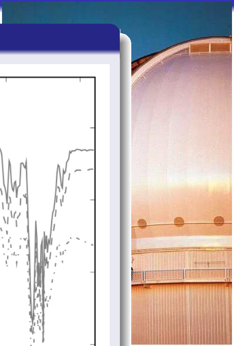
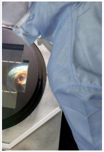
- queue c

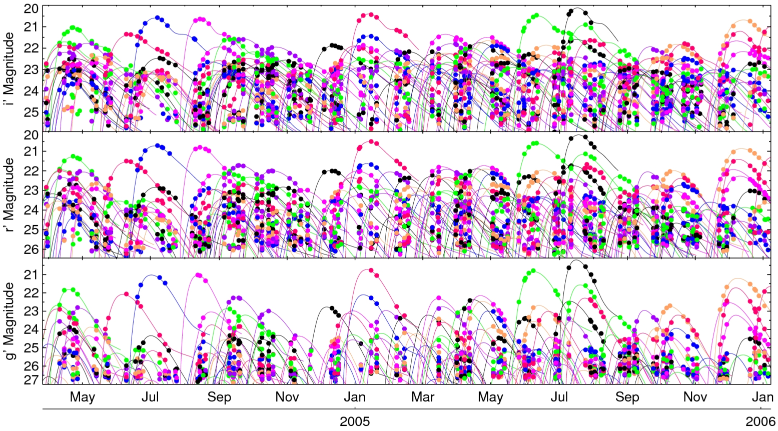
Megacam Passbands







. . . Operated in Rolling Search Mode



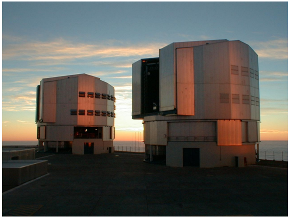
. . . and a Large Spectroscopic Survey

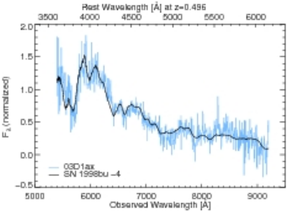
Goals

- spectral identification of SNe Ia ($z < 1$)
- redshift determination (host galaxy lines)
- complementary programs
  - detailed studies of SNe Ia

Telescopes

- VLT large program (120h / year)
- Gemini (120h / year)
- Keck (30h / year)





(Howell et al, 2005 – ApJ 634, 1190)

Statistics

Public list of candidates:
http://legacy.astro.utoronto.ca

May 2008

Telescope	SNIa (/?)	SNII (/?)	Total SN (/?)	Other	Total
Gemini	161	16	235	0	235
Keck	106	26	197	7	204
VLT	182	28	309	12	321
Total	449	70	741	19	760

$\sim$ 450 Identified Type Ia Supernovae now on disk
$\sim$ similar number with photometric identification

Survey ended in June 2008

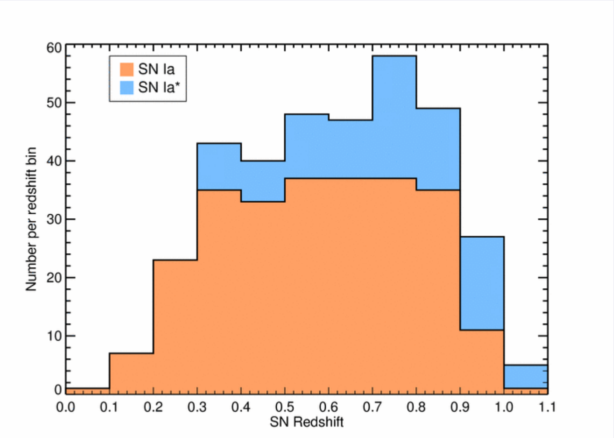
Statistics

Public list of candidates:

http://legacy.astro.utoronto.ca

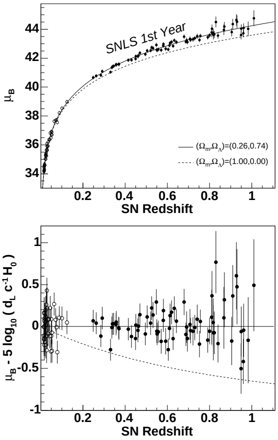
May 200

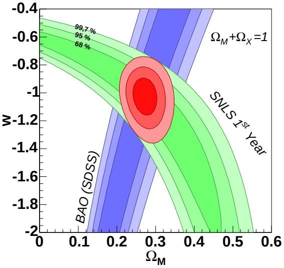
Telesco	otal
Gemi	35
Keck	04
VLT	21
Tota	60



Constraints on *w*

Astier et al, 2006





- 44 nearby SNe Ia from the literature, 71 distant SNe Ia.
- BAO = Baryon Accoustic Peak (Eisenstein, 2005)
- 68.3, 95.5 and 99.7 CL

fit	parameters (stat only)
$(\Omega_m, \Omega_\Lambda)$	$(0.31 \pm 0.21, 0.80 \pm 0.31)$
$(\Omega_m - \Omega_\Lambda, \Omega_m + \Omega_\Lambda)$	$(-0.49 \pm 0.12, 1.11 \pm 0.52)$
$(\Omega_m, \Omega_\Lambda)$ flat	$\Omega_m = 0.263 \pm 0.037$
$(\Omega_m, \Omega_\Lambda)$ + BAO	$(0.271 \pm 0.020, 0.751 \pm 0.082)$
(Ω_m, w)+BAO	$(0.271 \pm 0.021, -1.023 \pm 0.087)$

Systematic Uncertainties
(Astier et al, 2006)

Source	$\sigma(\Omega_m)$ (flat)	$\sigma(\Omega_{tot})$	$\sigma(w)$	$\sigma(\Omega_m)$ (with BAO)	$\sigma(w)$ (with BAO)
Zero-points	0.024	0.51	0.05	0.004	0.040
Vega spectrum	0.012	0.02	0.03	0.003	0.024
Filter bandpasses	0.007	0.01	0.02	0.002	0.013
Malmquist bias	0.016	0.22	0.03	0.004	0.025
Sum (sys)	0.032	0.55	0.07	0.007	0.054
Sum (stat)	0.042	0.53	0.10	0.021	0.090

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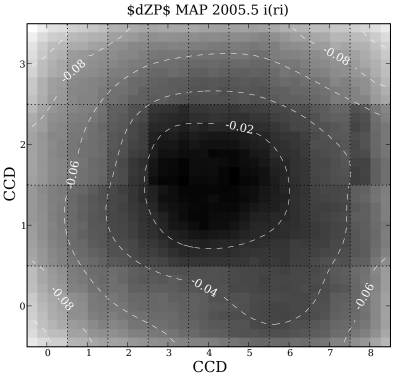
SNLS 3 Year Analysis

- statistics $\times 3.5$ 71 $\rightarrow \sim 250$
- Independant analyses (Fr, Ca), being carefully cross-checked
- Improved Photometric calibration
  - Better control of the Megacam array uniformity
  - 3-year monitoring of the same fields
- Improved Supernova modeling trained on the SNLS data
  - Two independant lightcurve fitters: SALT2 (Guy et al, 2007), SIFTO (Conley et al, 2008).
  - Allow to use the bluer part of the spectrum ($z > 0.8$)
- Detailed studies of the SN properties w.r.t. host galaxy type (elliptical $\sim$ old, vs spiral $\sim$ new)
  - tests for evolution of the SN properties with redshift
- Systematics included in the cosmological fits

Photometric Calibration

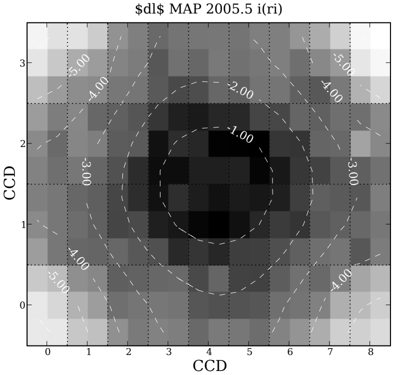
(Regnault et al, 2009) Uniformity of the Photometric Response



- Wide field cameras have an intrinsically non-flat photometric response $\sim$ 10% from center to edge.
- Careful mapping of it using dithered observations.
- Residual non-uniformities $\sim$ 1%.

Photometric Calibration

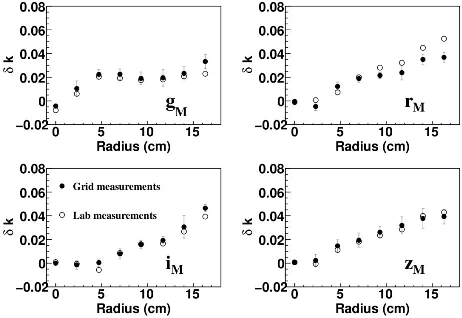
Filter non-uniformities



- Intrinsic filter non-uniformities (up to $\sim 5nm$).
- Mapped with dithered observations.
- Must be accounted for in the lightcurve fits.

Photometric Calibration

Filter non-uniformities: consistency with manufacturer measurements



- Filled circles : derived from dithered observations
- Open circles : synthetic, using stellar spectral library and manufacturer measurement of filter transmission

Photometric Calibration

Intercalibrating the low-z and high-z data

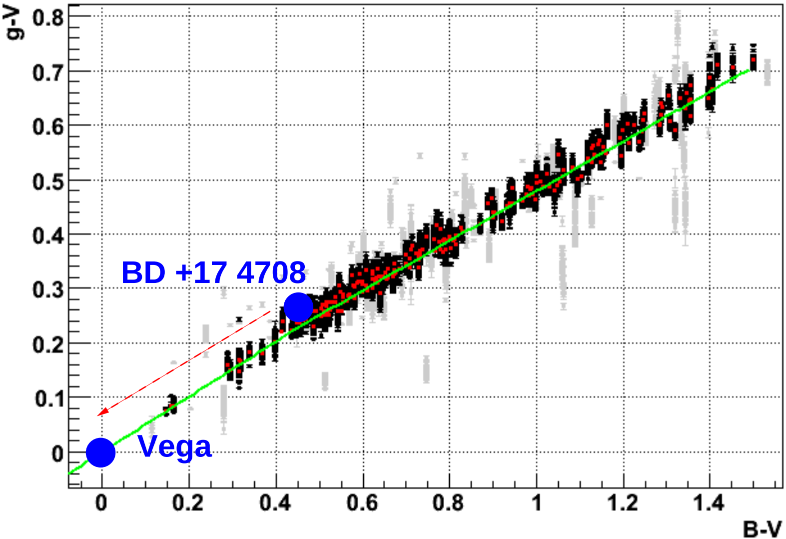
- Magnitude systems do not define their physical flux scale
- We rely on a fundamental flux standard, with (1) a known spectrum and (2) known magnitudes, in order to convert magnitudes into physical fluxes

$$\Phi = 10^{-0.4(m - m_{ref})} \times \int S_{ref}(\lambda) T(\lambda) d\lambda$$

- The HST has selected 3 pure hydrogen white dwarfs as primary standards. Models of these stars' spectra were used to calibrate the HST instruments.
- This calibration was then propagated to a larger network of secondary HST standards. We use one of them, BD +17 4708 as our fundamental flux standard.

Photometric Calibration

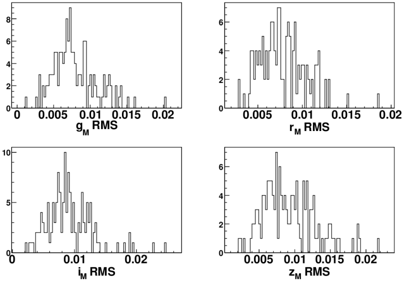
Landolt → SNLS



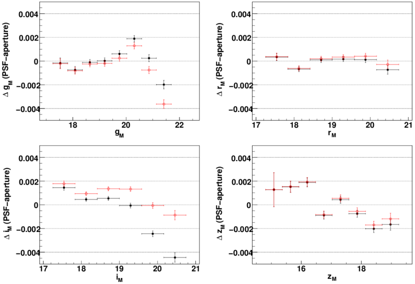
Photometric Calibration

Tertiary stars mags: aperture → PSF

Residuals PSF - aperture photometry



Effect of residual background in aperture photometry



Photometric Calibration

Uncertainty Budget

	g	r	i	z
Zero Points (stat)	± 0.002	± 0.002	± 0.002	± 0.005
Aperture corr.	< 0.001	< 0.001	< 0.001	< 0.001
Background sub	< 0.001	< 0.001	± 0.005	< 0.001
Shutter	± 0.002	± 0.002	± 0.002	± 0.002
Linearity	< 0.001	< 0.001	< 0.001	< 0.001
2nd order airmass corr.	< 0.001	< 0.001	< 0.001	< 0.001
Grid reference colors	< 0.001	< 0.001	< 0.001	< 0.001
Grid color corrs	< 0.001	< 0.001	± 0.002	< 0.001
Landolt catalogs	± 0.001	± 0.001	± 0.001	± 0.002
Magnitudes of BD $+17$	± 0.002	± 0.004	± 0.003	± 0.018
Transfer to SNe	± 0.002	± 0.002	± 0.002	± 0.002
Total	± 0.005	± 0.006	± 0.007	± 0.019

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Measuring Luminosity Distances with SNe Ia

Distance modulus $\mu = 5\log_{10} D_L$ estimated using apparent magnitude in a rest-frame (or redshifted) filter + correction factors based on the shape of the SN light curve and its color

$$\mu_B = m_B^\star - \mathcal{M}_B + \alpha \times shape - \beta \times color$$

$\mathcal{M}_B$, α and β fitted at the same time as cosmology.

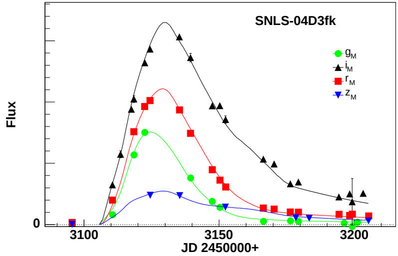
$\neq$ MCLS2k2

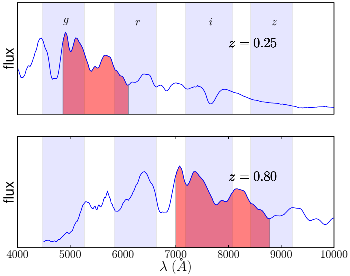
- $a\Delta + b\Delta^2$ ($\Delta \equiv shape$)
- $\beta \times color \rightarrow R_B \times E(B-V)$: color excess is dust reddening

Measuring Luminosity Distances with SNe Ia

- $m_B^\star$, *shape* and *color* determined from observed SNe light curves in a limited set of filters
- Requires a model of the SN spectral evolution to correct for redshift effect (*k-corrections*)

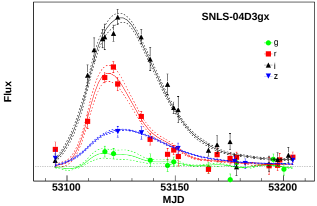
$$\frac{f(z_1, T_{rest})}{f(z_2, T_{rest})} = \left(\frac{d_L(z_2)}{d_L(z_1)}\right)^2$$





Light Curve Fitters

- Goal:
  - flux *ratio* of SNe at different z
  - lightcurve shape parameter
  - SN restframe color



- Tool: Empirical model of the SN Ia spectral sequence
  - physical simulations not precise enough
  - model trained on a large sample of lightcurves and spectra
  - accounts for the diversity of SNe Ia

SALT2 & SiFTO
(Guy et al, 2007), (Conley et al, 2008)

Two methods to derive $m_B^\star, color, shape$.
Differences $\longrightarrow$ systematics

SALT2

- Empirical model of the Spectral Sequence $\simeq$ PCA

$$\begin{aligned} F &= x_0 \\ &\times [M_0(p,\lambda) + x_1 M_1(p,\lambda)] \\ &\times \exp(c\ CL(\lambda)) \end{aligned}$$

SiFTO

- SN Ia spectral sequence from (Hsiao, 2007)
- Pure stretching with time : $M(p,\lambda,s) = M(p/(s-1),\lambda)$
- $s \longrightarrow s(\lambda)$
- Color relations

SALT2 & SiFTO

- Lightcurve fit separate from distance estimate (relative amplitude vs time and λ)
- Both trained using nearby and SNLS lightcurves :
  - More SNe with better calibration
  - Permits modeling of near UV $\lambda \in [300, 400]$ nm

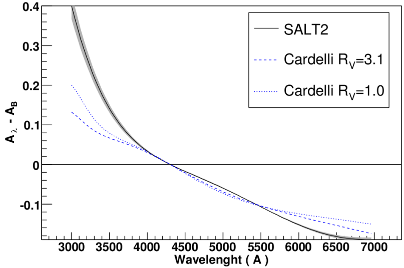
$\neq$ MCLS2k2

- Directly a distance estimator: need for the distances to SNe in training sample
- Trained on low-z SNe only: sensitive to U-band calibration (conv. to flux)

SALT2 & SiFTO

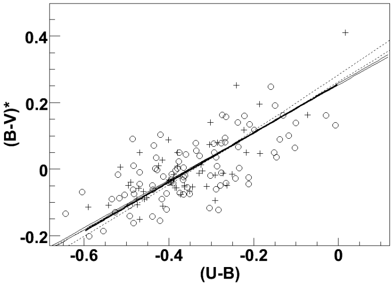
Color law(λ) vs color relations

Whatever R_V, CCM law inconsistent with SALT2 color law



SiFTO uses color relations

$(B-V) = a \times (U-B) + b \times (s-1) + c$

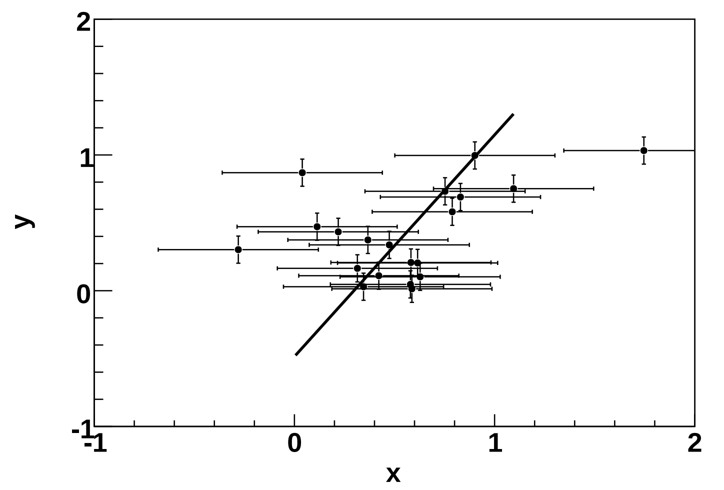


solid line: SiFTO, dashed line: SALT2

Agreement when using same assumption for residual scatter

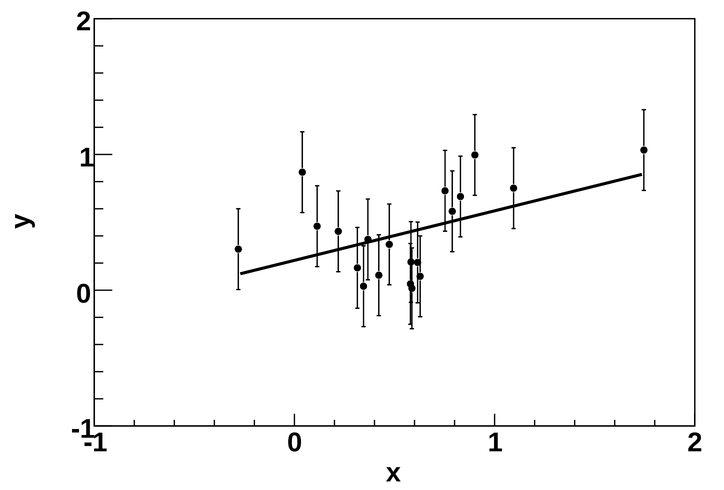
Uncertainties matter!

Linear fit assuming large uncertainties on x



Uncertainties matter!

Linear fit assuming large uncertainties on y

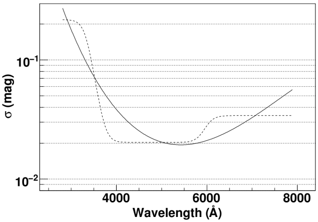


Estimating the residual scatter

Not all the SN variability accounted for by models.
Residual scatter $\longrightarrow$ parameter uncertainties
$\longrightarrow$ linear fits like color relations, α, β

- Covariance between lightcurves ignored
- Uncorrelated noise
- $+$ global lightcurve amplitude uncertainty (color dispersion)
    - estimated using SALT2 residuals
    - transfered to SiFTO for the fit of color relations

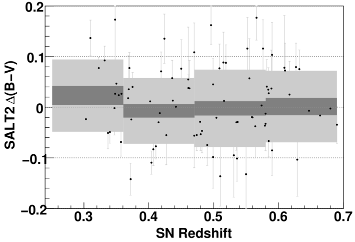
With two parametrization of scatter (λ)

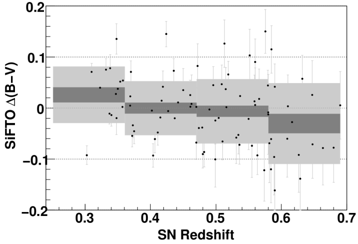


SALT2 / SiFTO

Consistency check

Difference of rest-frame $(B - V)$ color from independent fit of $r_m i_m$ and $g_m r_m$ lightcurves.

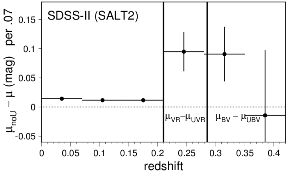




Same spirit as Kessler (2009), Fig. 40 :

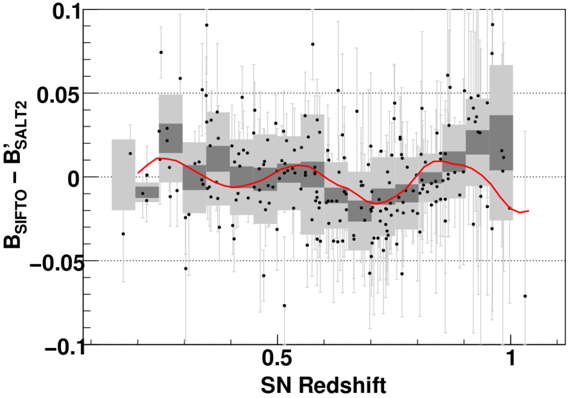
Marginally consistent with SNLS-1 and SDSS calibration systematics of $\simeq 0.01$ in each band.

$\sigma(\mu) \lesssim \sqrt{2 \times (0.01^2 + \beta^2 \times 2 \times 0.01^2)} \simeq 0.06.$



SALT2/SiFTO

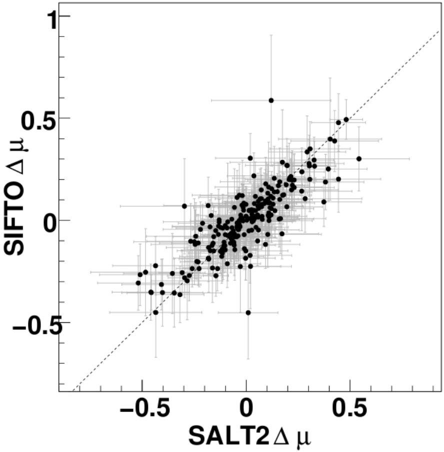
Comparison of rest-frame magnitudes



Systematics on rest-frame magnitudes $\simeq 0.02$. Explained by differences of spectral sequences Hsiao (2007) vs SALT2 despite "mangling". (red line)

SALT2/SiFTO

Residuals to Hubble diagram

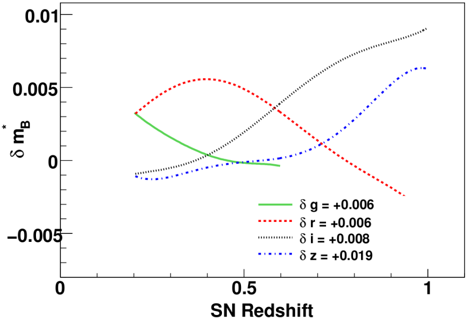


Equivalent precision

Light Curve Fitters

Propagation of uncertainties

- Statistical uncertainties of the models after training.
  - SALT2: model covariance matrix (4000x4000) $\rightarrow$ covariance matrix of distances (C_μ)
  - SiFTO: stat. uncertainties on color relations $\rightarrow$ C_μ
- Calibration uncertainties

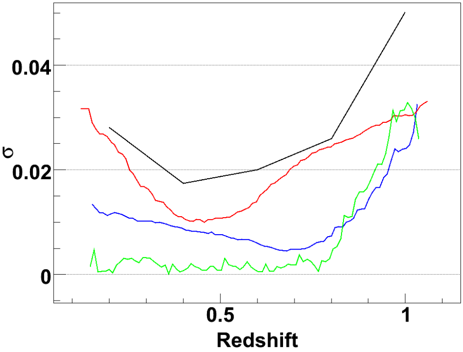


Light Curve Fitters

Photometry + calibration + fitter uncertainties

Uncertainties on $\langle \mu \rangle_{\Delta z=0.2}$

- statistical uncertainty
- calibration
- finite training sample
- residual scatter model
- Light curve fitter $\simeq 0.02$



External data sample
(Conley et al, in prep)

low redshift

- Hamuy et al. (1996)
- Riess et al. (1999)
- Jha et al. (2006)
- Hicken et al. (2009)
- +few others

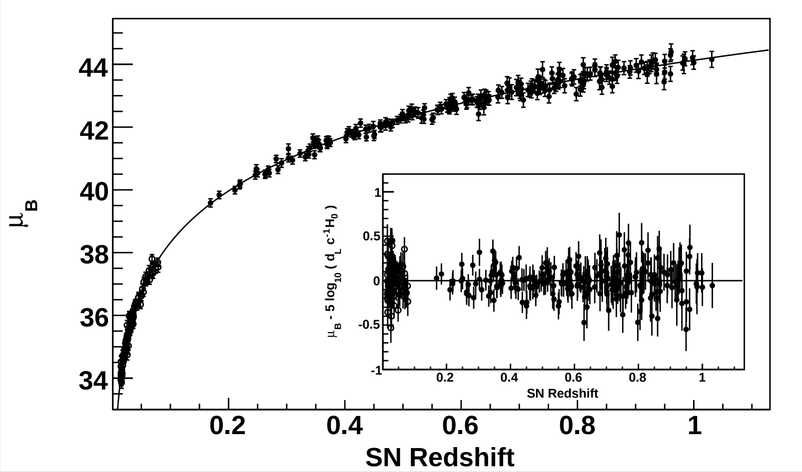
Not included here

- SDSS
- high redshift SNe from Riess et al. (2007)

Systematic uncertainties

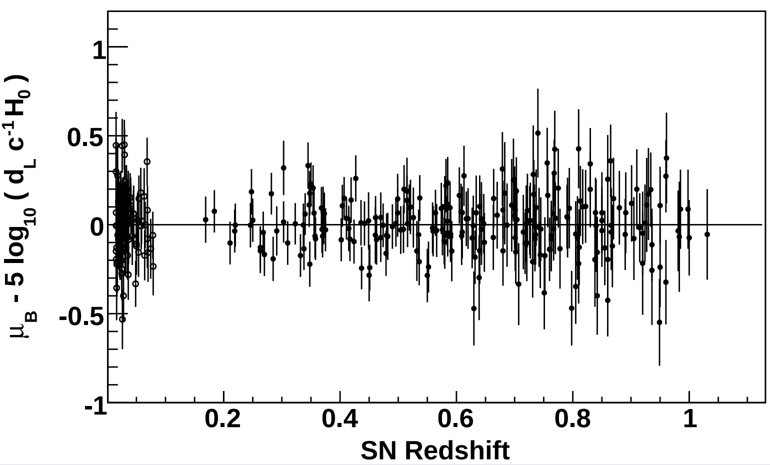
- Low redshift SNe Malmquist bias $\simeq 0.01$
- Calibration 0.05(U) 0.015(B,V,R)
- Filter transmission 20Å (U) 7Å (BV) 25Å (R)

Hubble diagram



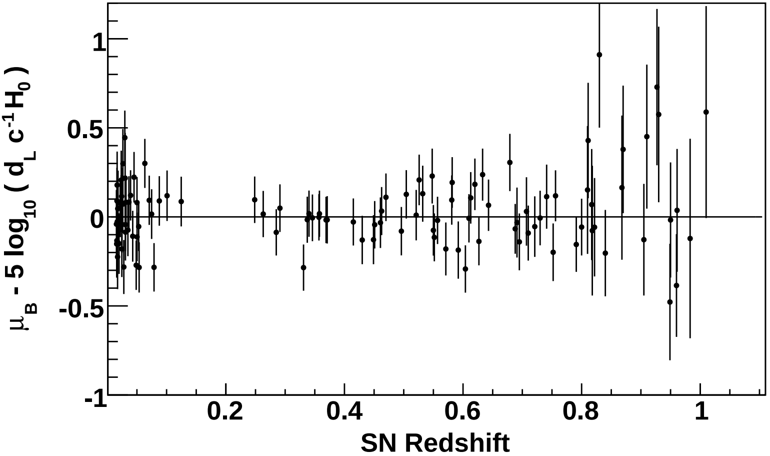
Hubble diagram

Residuals SNLS-3,preliminary



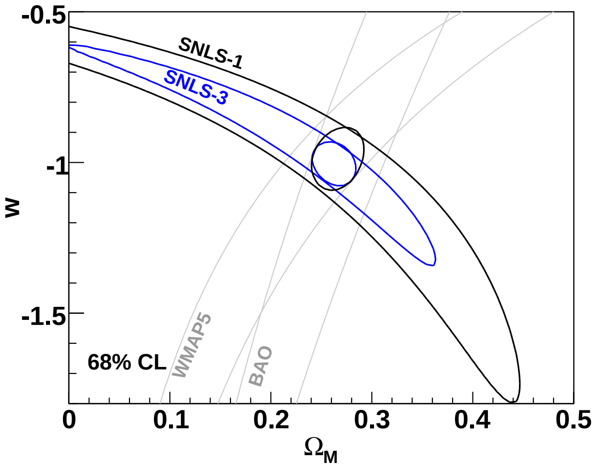
Hubble diagram

Residuals SNLS-1, Astier et al. (2006)



Constraints in Ω_M w plane, for $\Omega_k = 0$

stat. only; comparison SNLS-1 SNLS-3

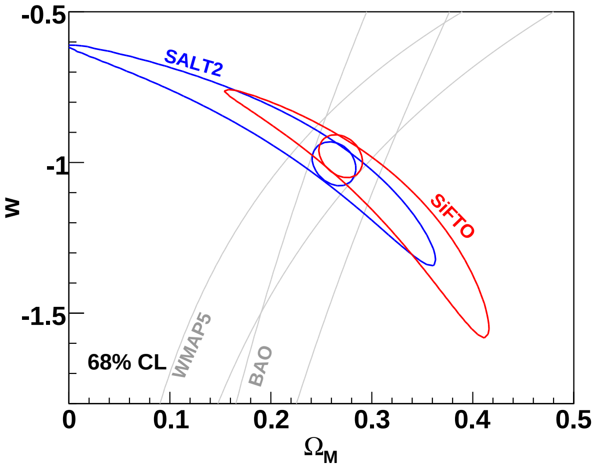


SNLS-1: 1st year results, Astier et al. (2006), WMAP5: Komatsu et al. (2009),

BAO (Baryon Acoustic Oscillations): Eisenstein et al. (2005)

Constraints in Ω_M w plane, for $\Omega_k = 0$

stat. only; comparison SALT2 SiFTO

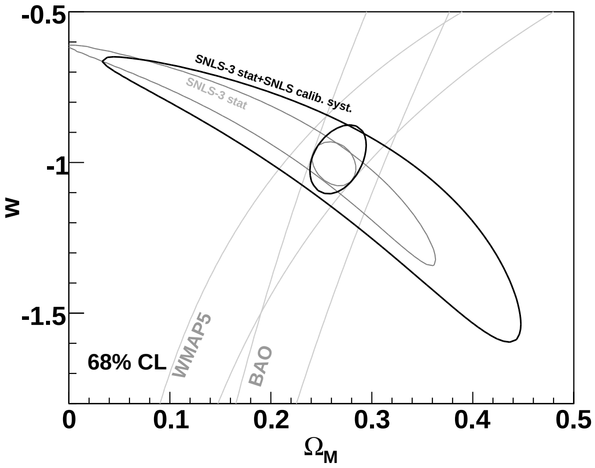


WMAP5: Komatsu et al. (2009),

BAO (Baryon Acoustic Oscillations): Eisenstein et al. (2005)

Constraints in Ω_M w plane, for $\Omega_k = 0$

stat.+ SNLS calibration systematics

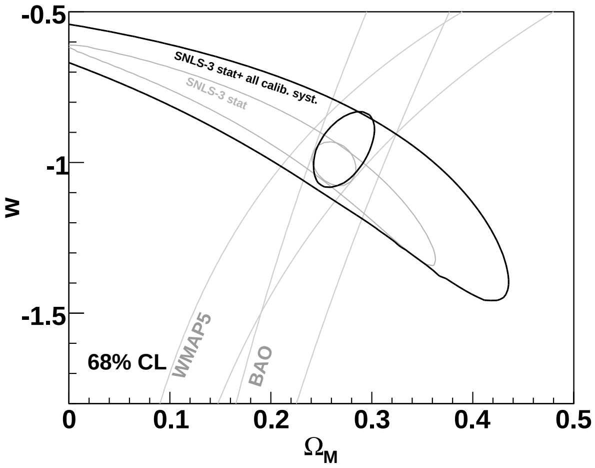


WMAP5: Komatsu et al. (2009),

BAO (Baryon Acoustic Oscillations): Eisenstein et al. (2005)

Constraints in Ω_M w plane, for $\Omega_k = 0$

stat.+ all calibration systematics



$\sigma(U) = 0.05$

$\sigma(B, V, R) = 0.015$

Constraints on (constant) w

low z + SNLS-3 SNe Ia + BAO + WMAP5

PRELIMINARY UNCERTAINTIES (some cross-check needed)

Statistical	0.047
SNLS calibration	0.057
Low-z calibration	0.035
Low-z selection bias	0.020
Lightcurve fitters	0.025
Total sys	0.069
Stat + sys	0.084

Missing : lightcurve fitter stat. uncertainties, contamination bias, lensing, inter-galactic dust, dust extinction evolution, progenitor age ...
Some more numbers :

- low z SNe $\delta m = 0.01 \rightarrow \delta w = 0.018$
- β evolution $\sigma(\beta(z = 1) - \beta(z = 0)) = 0.5 \rightarrow \sigma w = 0.035$

Conclusions

- Largest homogeneous high-z sample ~ 240 SNe Ia

$$w = -XX \pm 0.047(stat) \pm 0.069(sys)$$

- SNLS 3-year papers
  - calibration (Regnault et al, 2009)
  - photometric properties (Guy et al, 2009, in prep)
  - hubble diagram with SNe Ia (Conley et al, 2009, in prep)
  - cosmological constraints (Sullivan et al, 2009, in prep)
  - VLT spectroscopy (Balland et al, 2009, submitted)
  - ...
- Future: combined SNLS + SDSS analysis
  (same statistical uncertainty, lower systematics, implies a thorough cross calibration of both surveys)