SNLS 3rd Year Cosmological Results

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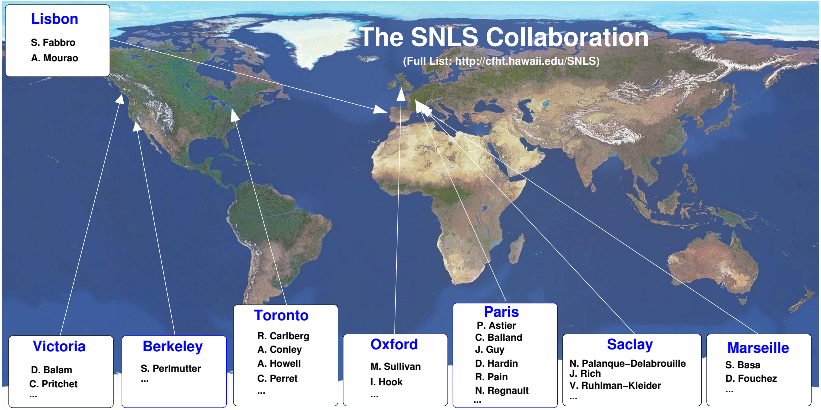
Invisible Universe, UNESCO, Paris, 2009

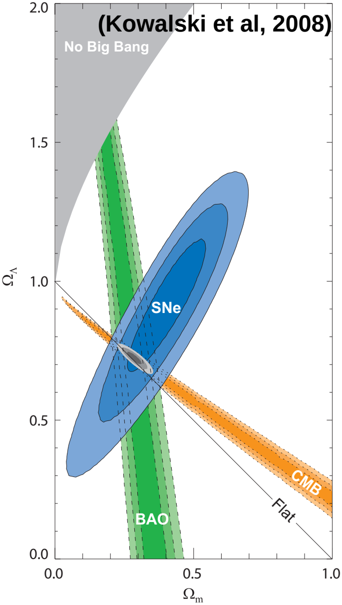
The SNLS Collaboration



Outline

Outline

Dark Energy



The Universe seems to be flat (CMB) with a low matter density (clusters) and its energy density seems to be dominated by some repulsive dark energy (supernovae).

Dark Energy Equation of State

- $p = w\rho \qquad w < -1/3$

$$\rho(z) \propto exp\left(\int 3\frac{w(z)+1}{1+z}dz\right)$$

- $w = -1 \rightarrow$ cosmological constant
- $w > -1 \rightarrow$ scalar fields
- $w < -1 \rightarrow$ exotic fields

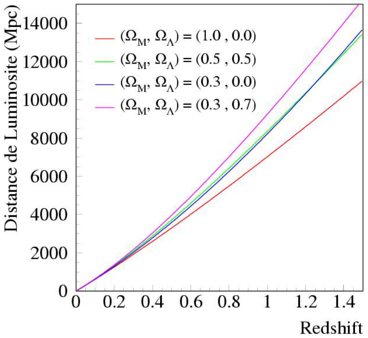
Hubble Diagram

Luminosity distance versus redshift: $d_L(z)$

- Observables
  - redshift, $z = \delta\lambda/\lambda$
  - apparent flux
- Standard Candles

$$\phi_(\lambda_{obs}) = \frac{L\left(\lambda_{obs}/(1+z)\right)}{4\pi(1+z)d_L^2}$$

- $d_L(z)$ $\rightarrow$ integrated history of the expansion



$$d_L(z) = (1+z)\frac{c}{H_0}\int dz' \left(\Omega_M(1+z')^3 + \Omega_k(1+z)^2 + \Omega_X \exp\left(\int_0^z 3\frac{1+w(z')}{1+z'}dz'\right)\right)^{-1/2}$$

Hubble Diagram

Luminosity distance versus redshift: $d_L(z)$

Exact or quasi-degeneracies

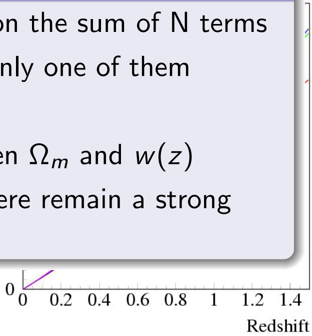
- The expansion history depends on the sum of N terms
- the equation of state enters in only one of them

$\Rightarrow$ need to know Ω_k (from CMB)

$\Rightarrow$ if $w(z)$ arbitrary, relation between Ω_m and $w(z)$

$\Rightarrow$ even assuming a constant w, there remain a strong degeneracy

- $d_L(z)$ $\longrightarrow$ integrated history of the expansion



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SNLS: A Large Photometric Survey . . .

$\sim$ 300h / year on a 3.6-m

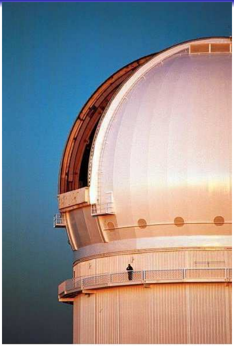
- CFHT @ Hawaii

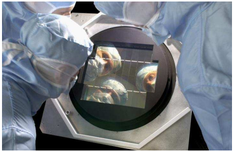
Wide Field Camera

- Megacam (CEA/DAPNIA)
- 1 deg^2, 36 2k$\times$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

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- 1 $\deg^2$,
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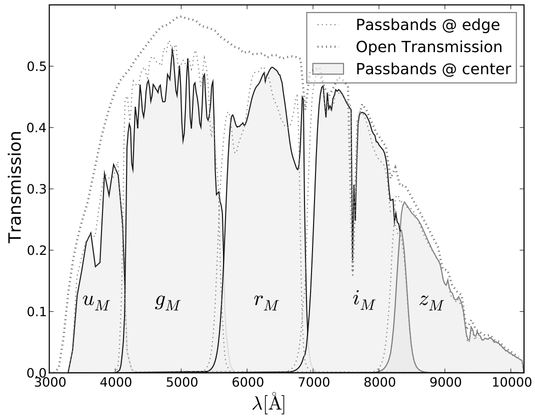
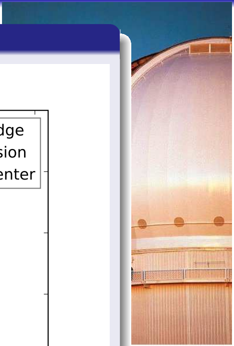
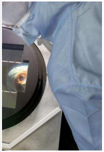
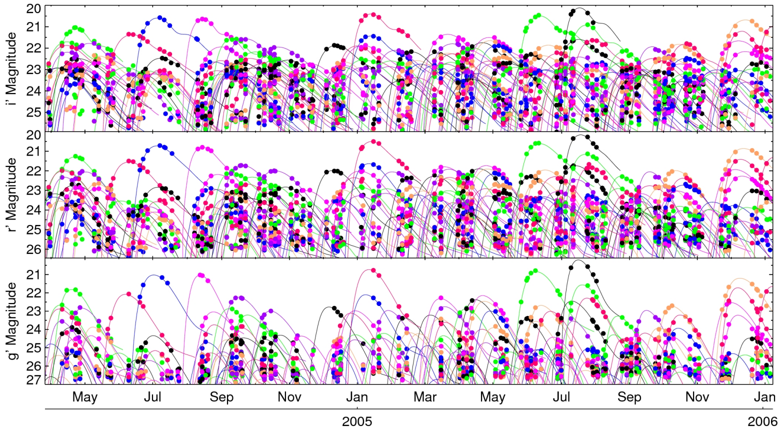
Megacam Passbands







. . . Operated in Rolling Search Mode



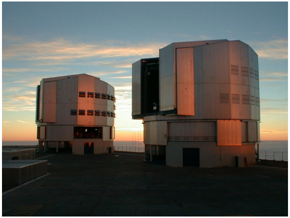
. . . and a Large Spectroscopic Survey

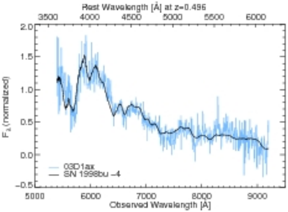
Goals

- 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

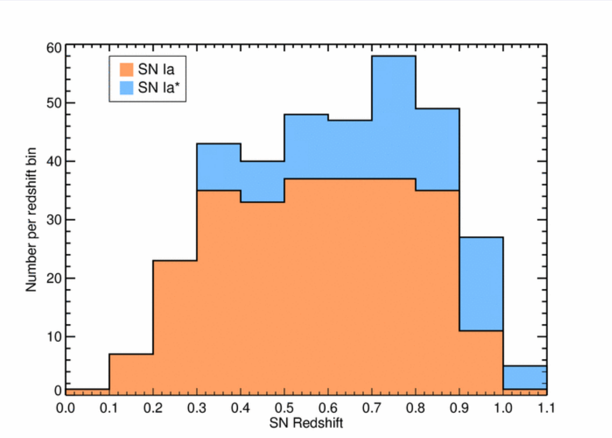
Survey ended in June 2008

Statistics

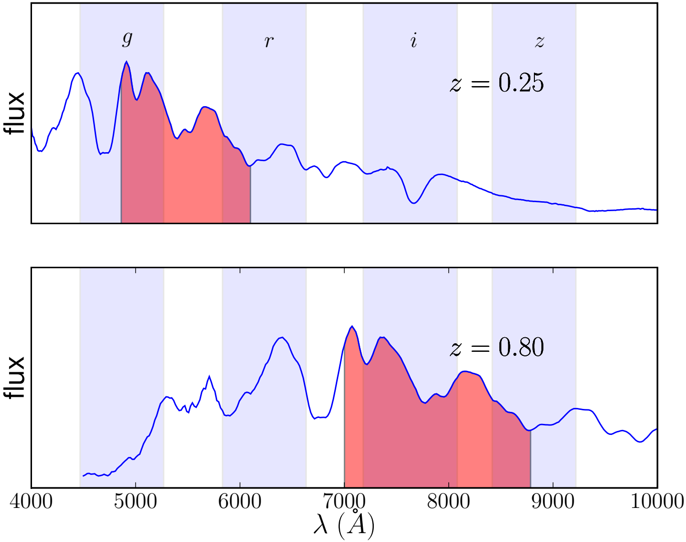
Public list of candidates:
http://legacy.astro.utoronto.ca

May 200

Telesco	otal
Gemi	35
Keck	04
VLT	21
Tota	60



Measuring Luminosity Distances with SNe Ia



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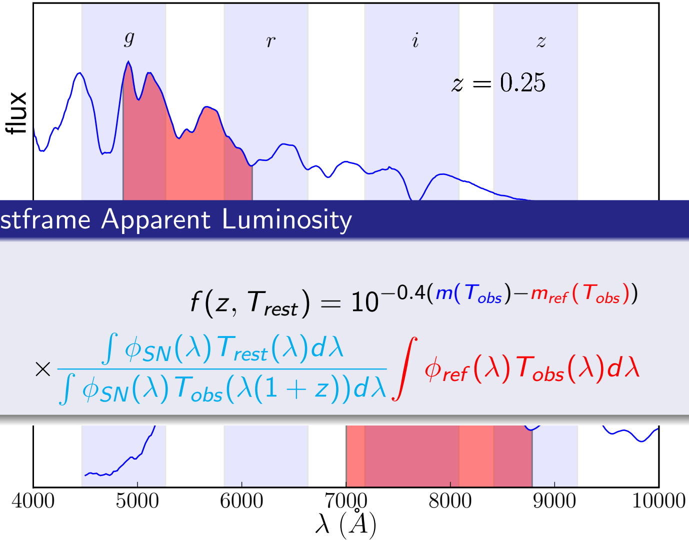


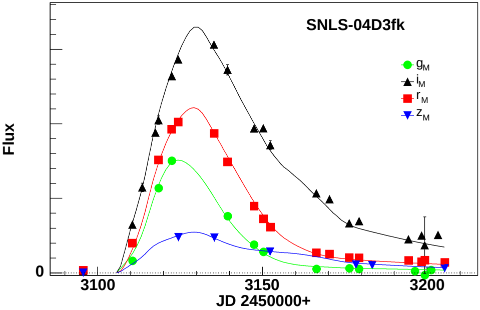
Restframe Apparent Luminosity

$$f(z, T_{rest}) = 10^{-0.4(m(T_{obs}) - m_{ref}(T_{obs}))}$$

$$\times \frac{\int \phi_{SN}(\lambda) T_{rest}(\lambda) d\lambda}{\int \phi_{SN}(\lambda) T_{obs}(\lambda(1+z)) d\lambda} \int \phi_{ref}(\lambda) T_{obs}(\lambda) d\lambda$$

Measuring Luminosity Distances with SNe Ia

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

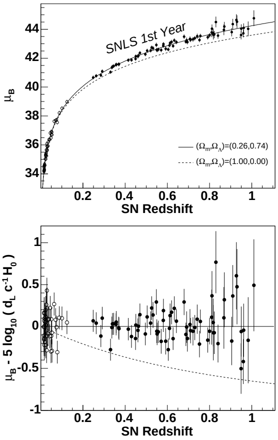


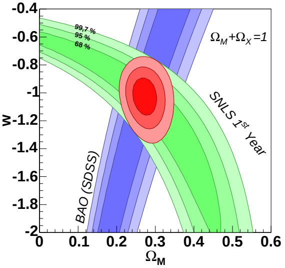
- Restframe apparent luminosity @ peak, in a given spectral region
- shape parameter $\Rightarrow$ good sampling of LC
- color $\Rightarrow$ observations in several passbands

$$\mu_B = m^\star_B - \mathcal{M}_B + \alpha \times (s-1) - \beta \times c$$

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

Identified Sources of Systematics

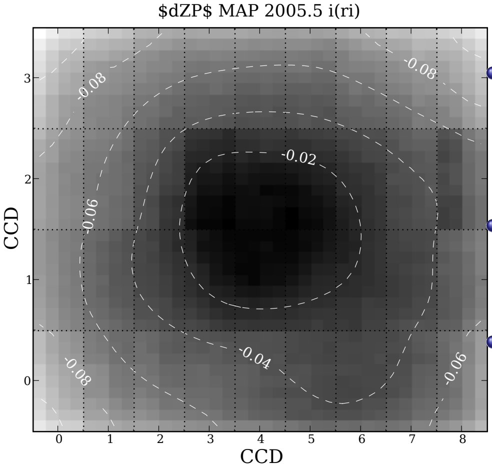
- Photometric calibration & modeling of the passbands
- Empirical modeling of lightcurves
  - restframe region used: $(B, V)) \rightarrow (U*, B)$ at large z
  - modeling of the SN Spectra around $\lambda \sim 300\mathrm{nm}$ is crucial for $z > 0.8$
- Detection biases
  - simulation of the detection pipeline
- Contamination
- Evolution effects
  - study of SN Ia properties as a function of Host Galaxy
  - comparison of nearby and distant SNe Ia
- Extinction by intergalactic dust
- Gravitational lensing

SNLS 3 Year Analysis

- statistics $\times 3.5$ 71 $\rightarrow$ ~ 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 (I)

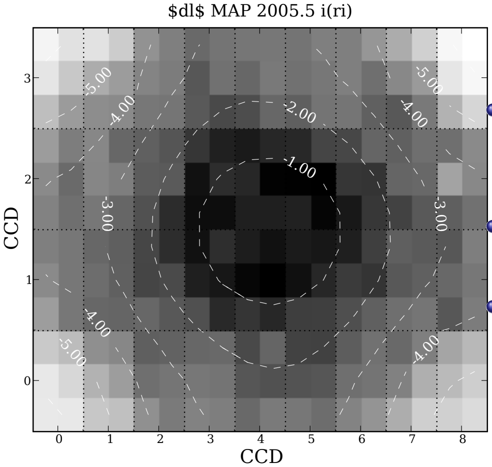
Uniformity of the Photometric Response



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

Photometric Calibration (II)

Uniformity of the Photometric Response



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

Photometric Calibration (III)

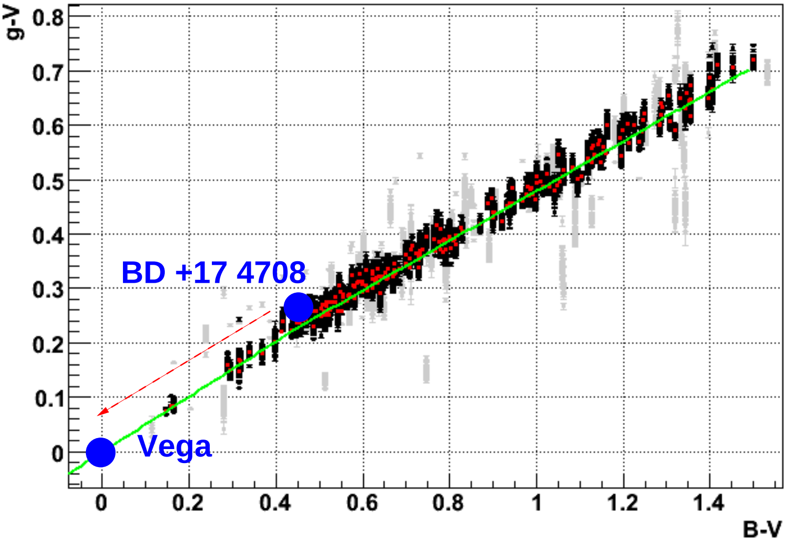
Intercalibrating the low-z and high-z data

- 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 (IV)



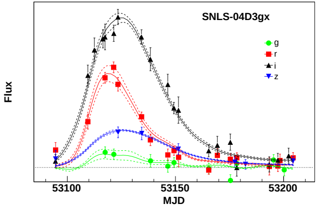
Photometric Calibration (V)

Uncertainty Budget

	g	r	i	z
Zero Points	± 0.002	± 0.002	± 0.002	± 0.005
Background sub	< 0.001	< 0.001	± 0.005	< 0.001
Shutter	± 0.002	± 0.002	± 0.002	± 0.002
scd order airmass corrs.	< 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
Total	± 0.004	± 0.005	± 0.007	± 0.0019

Light Curve Fitters

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



- Method: Interpolation of measurements
  - in different restframe bands
  - with different time sampling
- 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

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

SALT2

- Empirical model of the Spectral Sequence

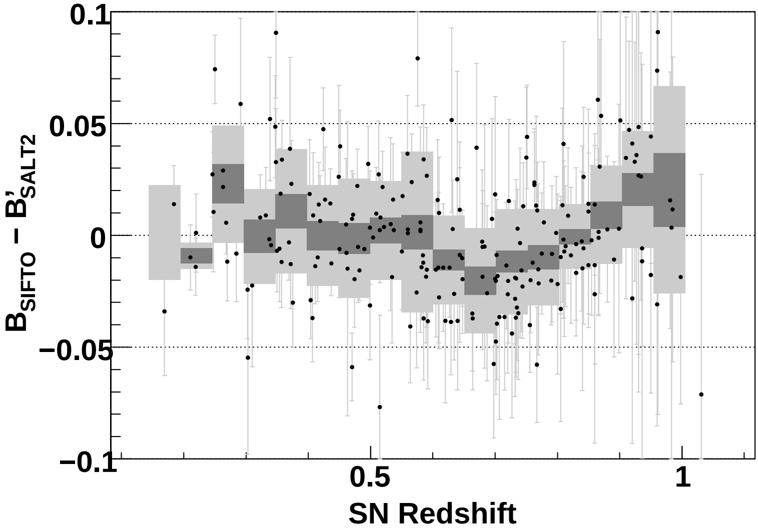
$$F = x_0 \times [M_0(p,\lambda) + x_1 M_1(p,\lambda)] \times \exp(c\ CL(\lambda))$$

SiFTO

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

- Both fitters trained using nearby and SNLS lightcuves (lightcurve fit separate from distance estimate).

SALT2 vs. SiFTO
(Guy et al, in prep.)



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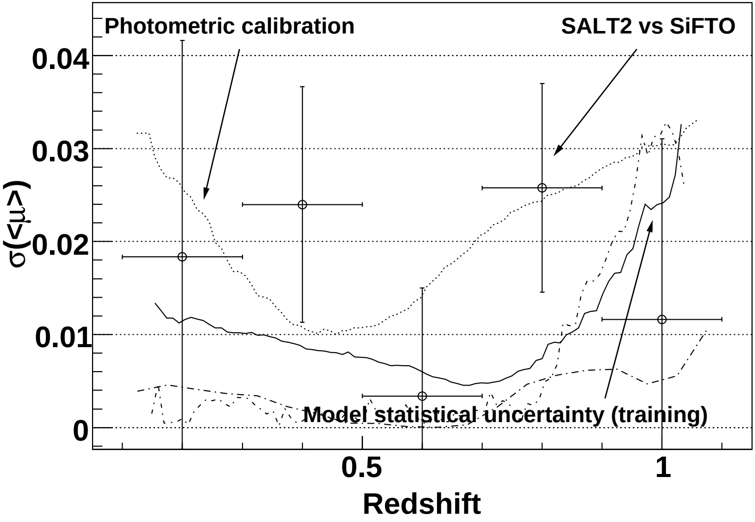
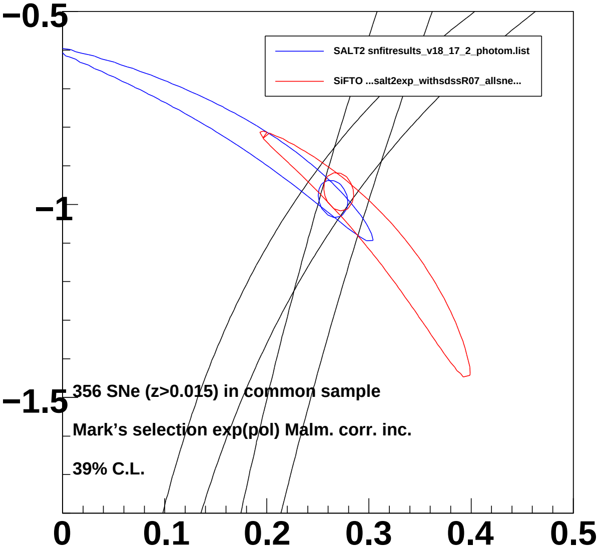
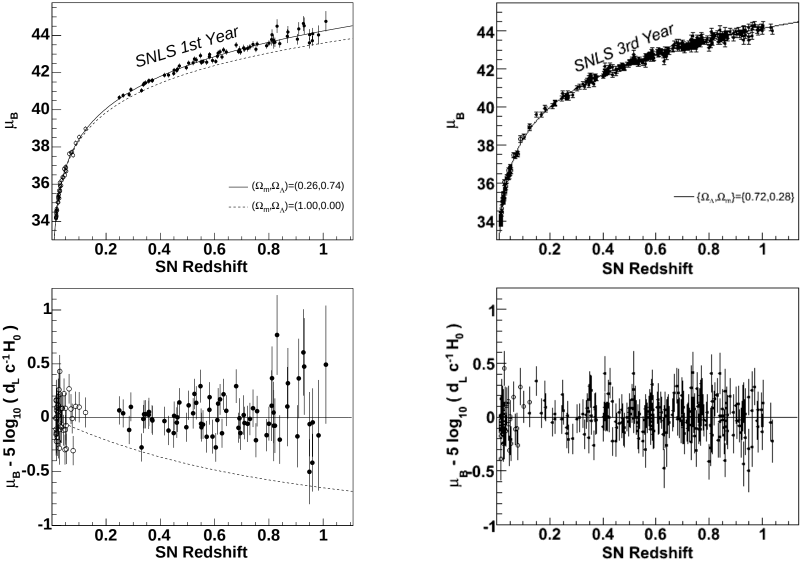


SALT2 vs. SiFTO

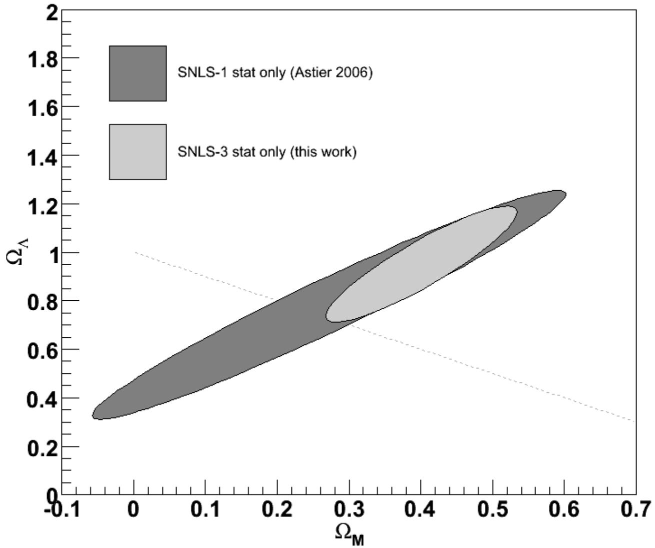
Preliminary



SNLS 3 Year Analysis
(Conley et al, in prep)

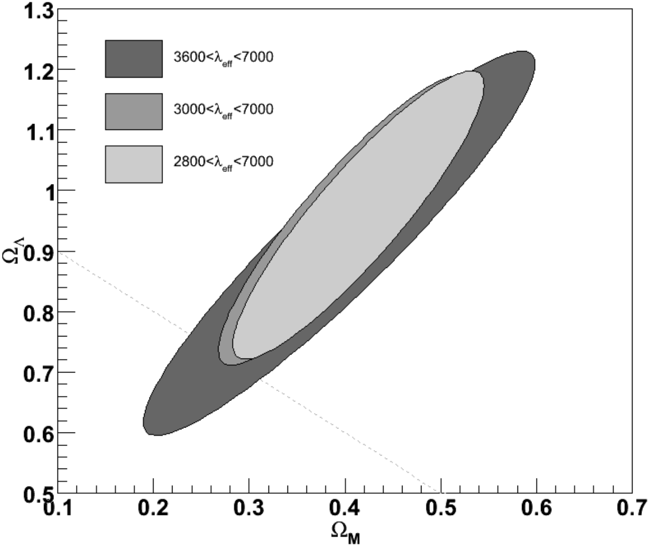


Statistical Uncertainties

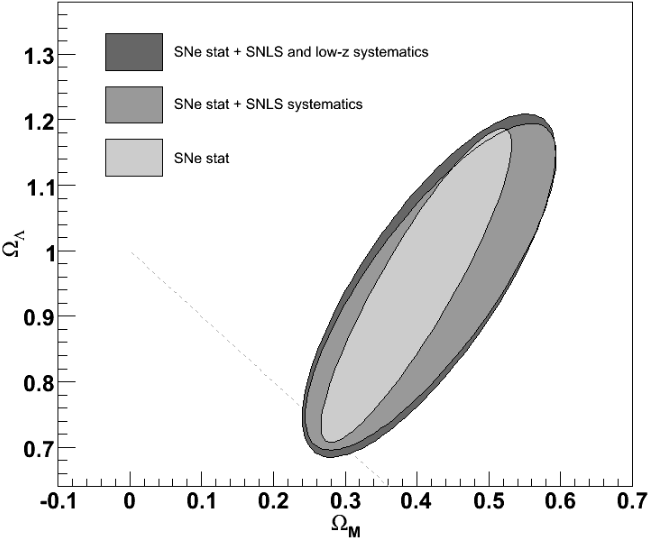


Statistical Uncertainties

Adding the UV helps a lot . . .



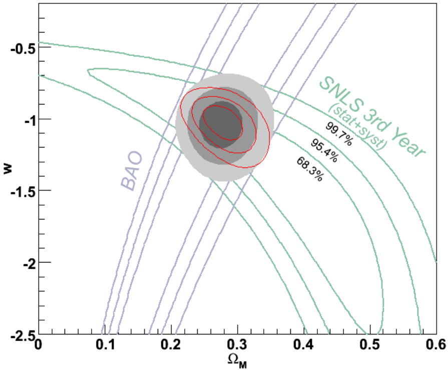
Systematics



Constraints on *w*
(Sullivan et al, in prep.)

- SNe Ia + BAO
- constant *w*

Statistical	0.077
SNLS calibration	0.053
Low-z calibration	0.032
Low-z filters	0.016
Low-z selection bias	0.022
Lightcurve fitters	0.020
Total sys	0.071
Stat + sys	0.104



- (Hicken et al, 2009) low-z data + WMAP-5 constraints (preliminary):
  - $\sigma_{stat}(w) \rightarrow 0.042$
  - $\sigma_{sys}(w) \rightarrow 0.048$

Conclusions

- Largest homogeneous high-z sample $\sim$ 240 SNe Ia

$$w = -1.XX \pm 0.077(stat) \pm 0.071(sys)$$

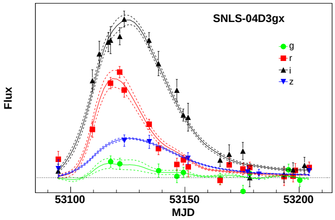
- SNLS 3-year papers
  - calibration (Regnault et al, 2009, submitted)
  - photometric properties (Guy et al, 2009, in prep)
  - hubble diagram with SNe Ia (Conley et al, 2009, in prep)
  - cosmological constraints (Sullivan et al, 2009, in prep)
  - VLT spectroscopy (Balland et al, 2009, submitted)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

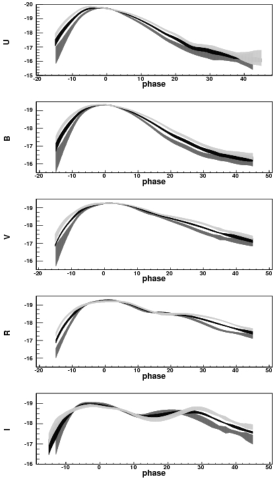
SALT2: modeling SN Ia Spectra and Lightcurves

J. Guy et al, 2007

SALT2: J. Guy et al, 2007

- Use photometric and spectroscopic data
- PCA to describe SN variability
- Derive model uncertainties
- Modeling of SN Ia Spectra in the far UV





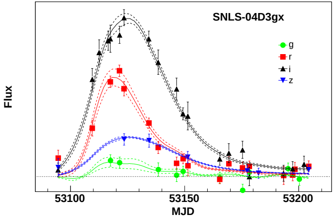
SALT2: modeling SN Ia Spectra and Lightcurves

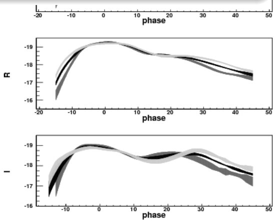
J. Guy et al, 2007

SALT2: J. Guy et al, 2007

- trained on Nearby Data + SNLS data
- Far UV coverage comes from the intermediate-z SNLS objects
- Uncertainties can be reduced w/ more data (LC & spectra) @ intermediate redshift

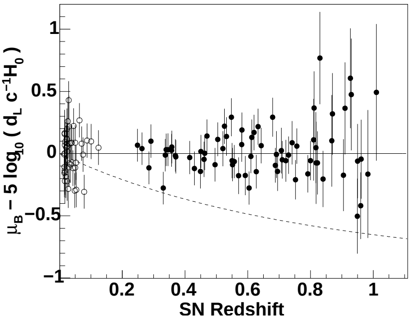
$\Rightarrow$ errors $\propto 1/\sqrt{N}$





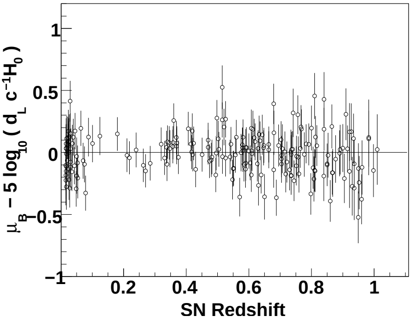
SALT2: modeling SN Ia Spectra and Lightcurves

J. Guy et al, 2007



SALT1

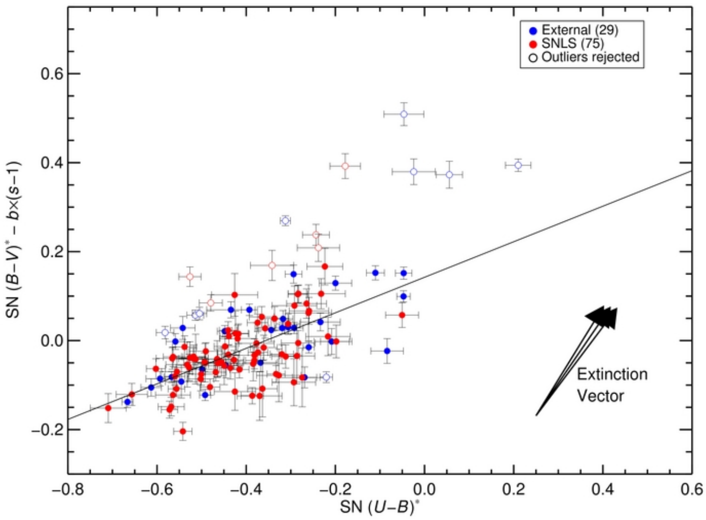
$\sigma \sim 0.20$



SALT2

$\sigma \sim 0.16$

Understanding Color and Dust Extinction

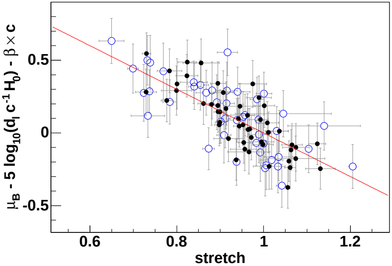


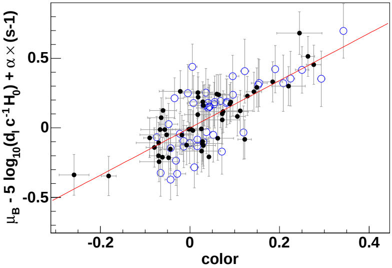
(Sullivan et al, 2008)

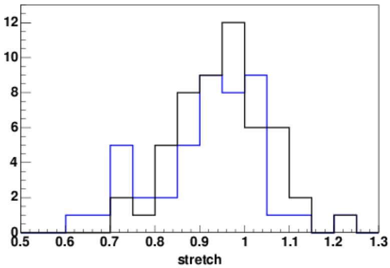
Evolution Tests

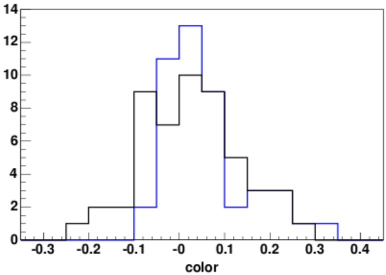
- Different progenitors types with different lifetimes
- One single progenitor type w/ correlation between lifetime and luminosity
- Metallicity
- ...
- Two kinds of evolution tests
  - ⇒ Compare low- and high-redshift events (Bronder et al. 2007)
  - ⇒ More sensitive: compare events at similar redshifts as a function of their host galaxy type.

Evolution test: Comparison of low- and high-redshift events





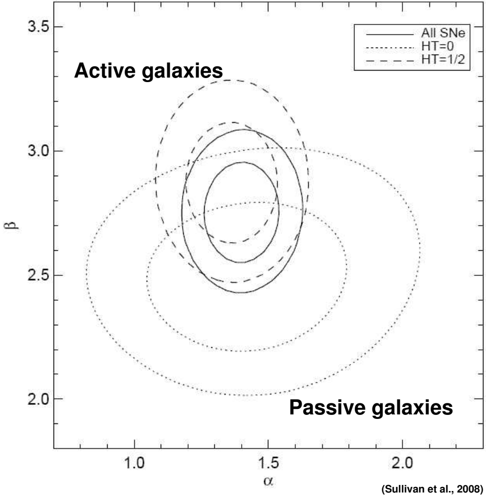




brighter-slower relation

brighter-bluer relation

Evolution test: Standardization Parameters vs. Host Galaxy Type



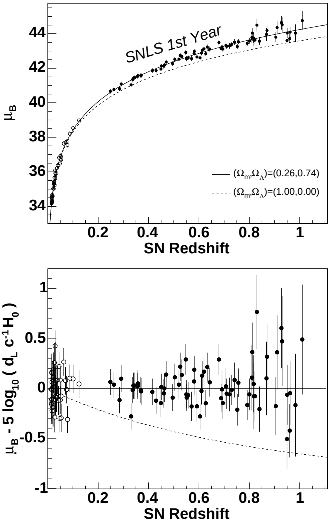
(Sullivan, 2008)

Summary

- SNLS Survey ended in June 2008
- 3-year analysis close to publication
- $\sigma_w \sim 6\%(\mathrm{stat})$ 8% (sys, dominated by low-z sample)
- Main challenges
  - Photometric calibration (will be a limiting factor is the future surveys)
  - Understanding the color corrections (dust ? intrinsic corrections ?)
  - SN properties w.r.t. their environment (evolution)
- Priorities
  - new low-z ($z < 0.1$) samples
    - in the same photometric system
    - with well controlled detection efficiency
    - with a wide spectral coverage

Hubble Diagram (SNLS 1 year)

(Astier et al, 2006)



Restframe Magnitude

$$m_B^\star = -2.5 \ \log_{10}\left(\frac{f(z,T_B,t=t_{max,B})}{(1+z)\int\phi_{ref}(\lambda)T_B(\lambda)d\lambda}\right)$$

Distance Estimator

$$\mu_B = m_B{}^\star - \mathcal{M}_\mathcal{B} - \alpha\ (s-1) + \beta\ c$$

Cosmological Fit

$$\chi^2 = \sum_i \frac{\mu_{B_i} - 5\log_{10} d_L(\theta, z_i)^2}{\sigma^2(\mu_{B_i}) + \sigma_{int}{}^2}$$

$$\sigma_{int} = 0.13 \text{ mag } (\chi^2/\text{dof} = 1)$$