Measurement of the Dark Energy Equation of State with the Supernova Legacy Survey

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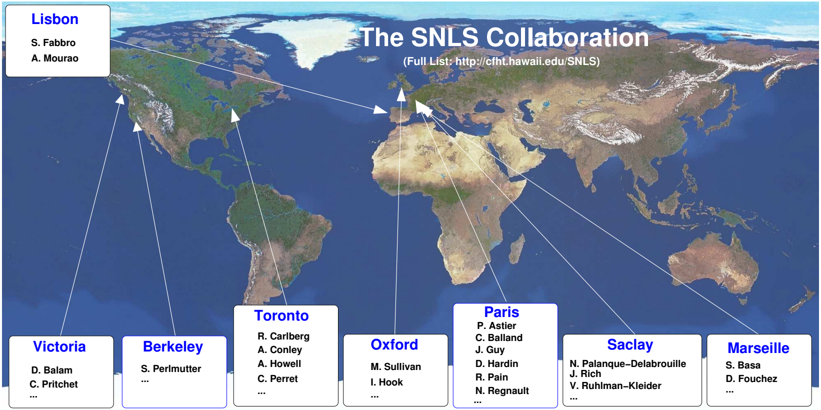
ICHEP 2008

The SNLS Collaboration



Outline

1. Measuring the Dark Energy Equation of State
2. The SNLS Survey
3. 3 Year Dataset

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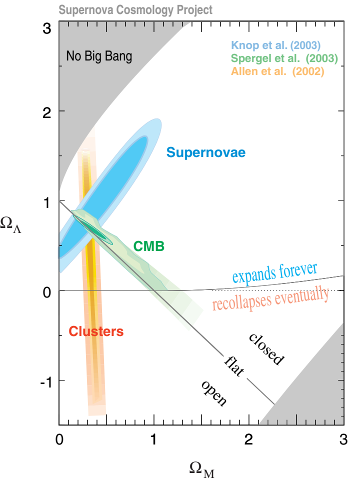
Dark Energy



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

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

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

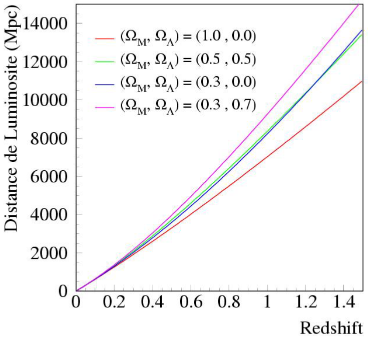
- $w = -1 \rightarrow$ cosmological constant
- $w > -1 \rightarrow$ scalar fields
- $w < -1 \rightarrow$ exotic fields

Standard Candles

- 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



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

Standard Candles

Exact or quasi-degeneracies

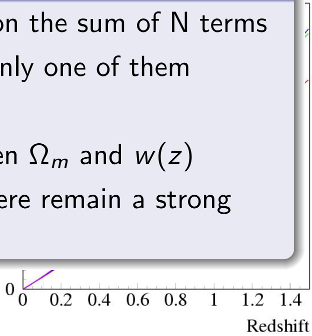
- The expansion history depends on the sum of N terms
- the equation of state enters in only one of them

⇒ need to know Ω_k (from CMB)

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

⇒ even assuming a constant w, there remain a strong degeneracy

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



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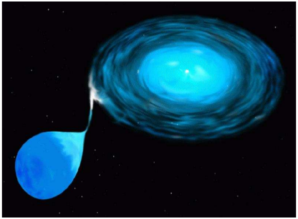
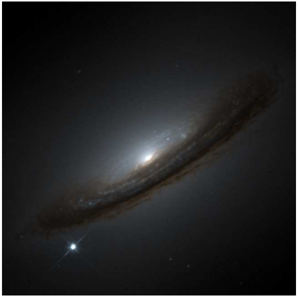
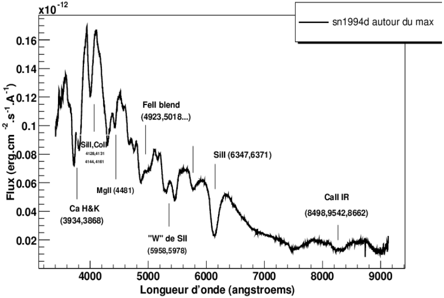
Type Ia Supernovae

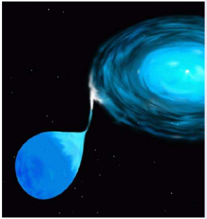




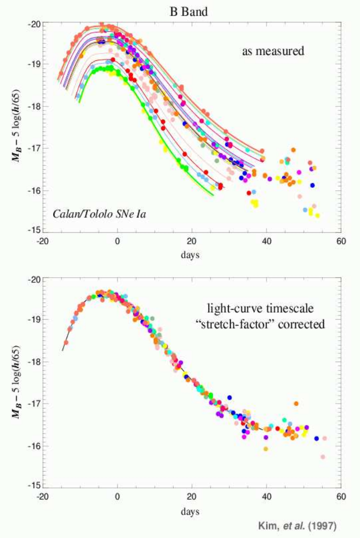
- very luminous ($10^{10} - 10^{11} L_\odot$)
- can be identified (spectra)
- fluctuations of $L_{max} \sim 40\%$
- can be reduced to $\sim 14\%$



Type Ia Supernovae



Standardizable Candles



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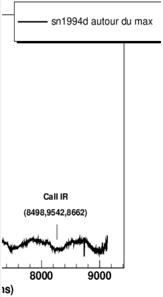
$\sim 14\%$



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SNLS: A Large Photometric Survey . . .

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

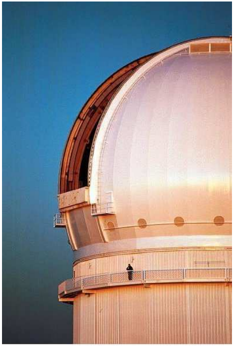
- CFHT @ Hawaii

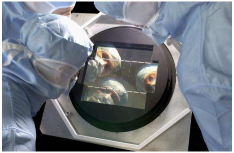
Wide Field Camera

- 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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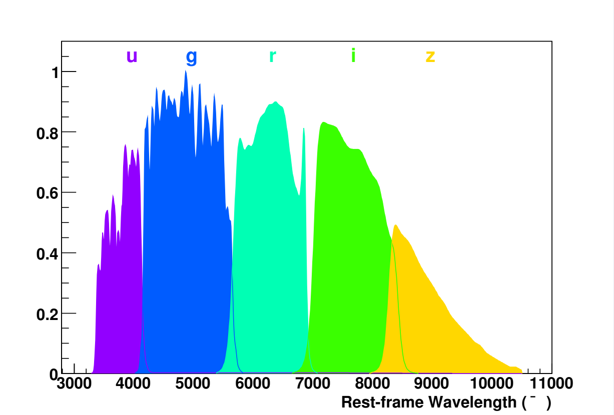
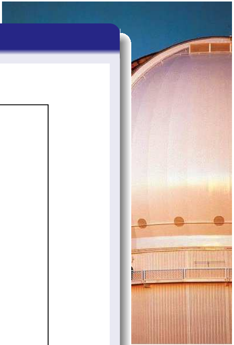
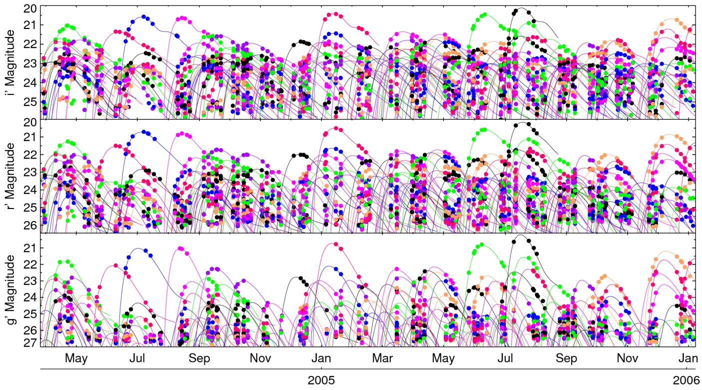
Megacam Passbands





. . . Operated in Rolling Search Mode



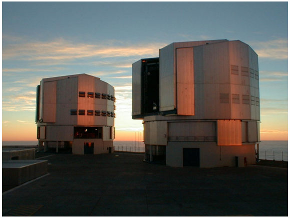
. . . and a Large Spectroscopic Survey

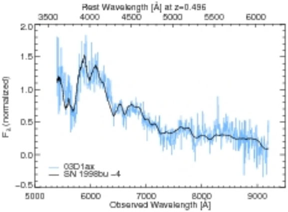
Goals

- 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	131	13	235	0	235
Keck	91	22	195	4	199
VLT	156	21	309	12	321
Total	378	56	739	16	755

$\sim$ 400 Identified Type Ia Supernovae now on disk
$\sim$ similar number with photometric identification

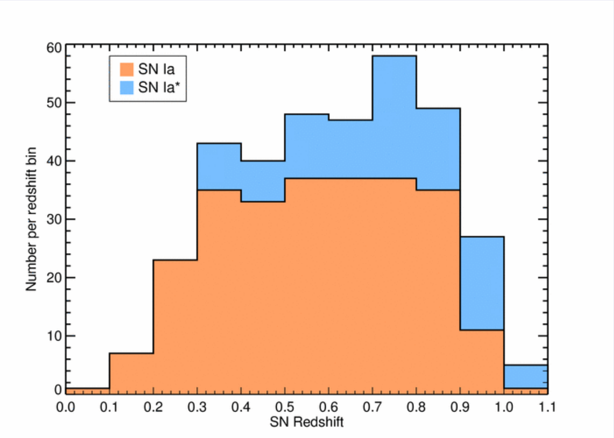
Survey ended in June 2008

Statistics

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

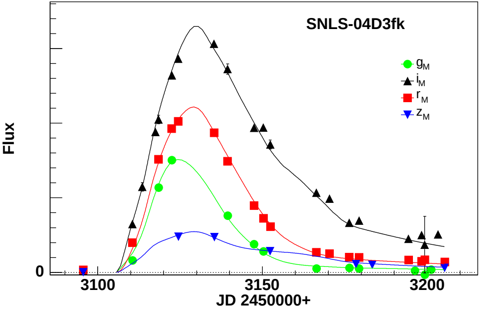
May 200

Telesco	otal
Gemi	35
Keck	99
VLT	21
Tota	55



Measuring Luminosity Distances w/ 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
- decline rate / lightcurve width ⇒ good sampling of LC
- color ⇒ observations in several passbands

Measuring Luminosity Distances w/ SNe Ia

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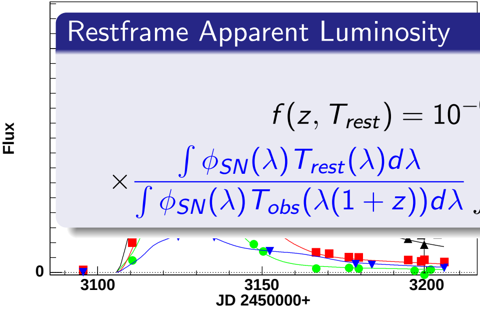


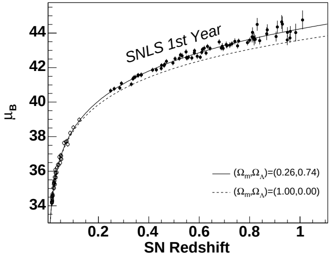
Restframe Apparent Luminosity

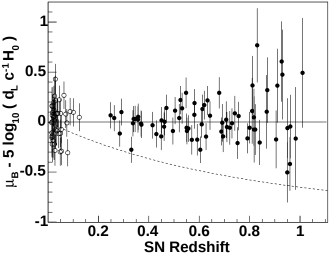
$$f(z, T_{rest}) = 10^{-0.4(m(T_{obs})-m_{ref}(T_{obs}))} \times \frac{\int \phi_{SN}(\lambda) T_{rest}(\lambda) d\lambda}{\int \phi_{SN}(\lambda) T_{obs}(\lambda(1+z)) d\lambda} \int \phi_{ref}(\lambda) T_{obs}(\lambda) d\lambda \quad (1)$$

of

- color $\Rightarrow$ observations in several passbands

Hubble Diagram





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

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

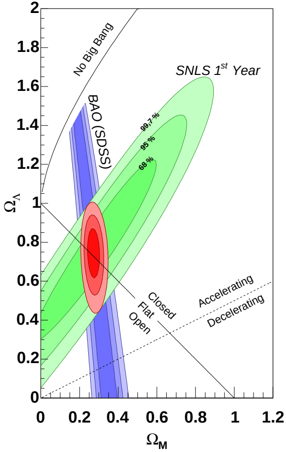
Cosmological Fit

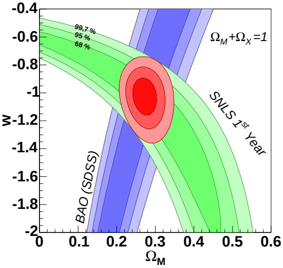
$$\chi^2 = \sum_i \frac{\mu_{B_i} - 5\log_{10} d_L(\theta, z_i)^2}{\sigma^2(\mu_{B_i}) + \sigma_{int}{}^2}$$

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

Confidence Contours

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

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

(From Astier et al, 2006)

Identified Sources of Systematics

- Photometric calibration & modeling of the passbands
- Empirical modeling of lightcurves
  - restframe region used: $(B, V)) \to (U*, B)$ 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

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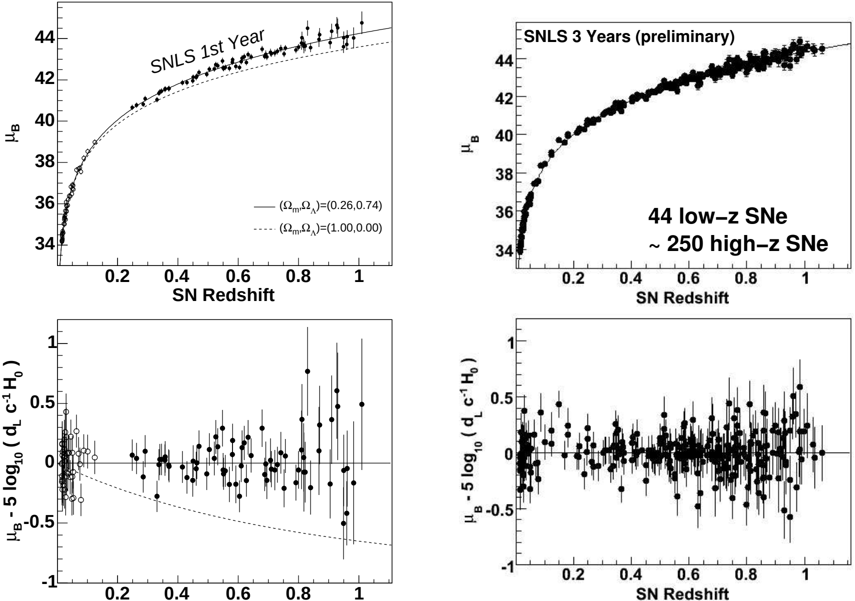
SNLS 3 Year Analysis

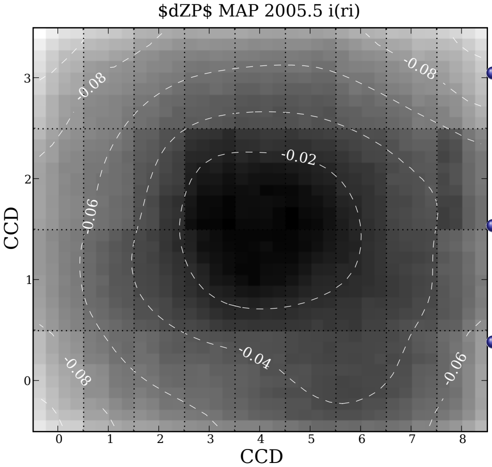
- statistics $\times 3.5$ 71 $\rightarrow \sim 250$
- Independant analyses (Fr, Ca), being carefully cross-checked
- Improved Photometric calibration
  - Better control of the Megacam array uniformity
  - 3-year monitoring of the same fields
- Improved Supernova modeling trained on the SNLS data
  - 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

SNLS 3 Year Analysis



Photometric Calibration (I)

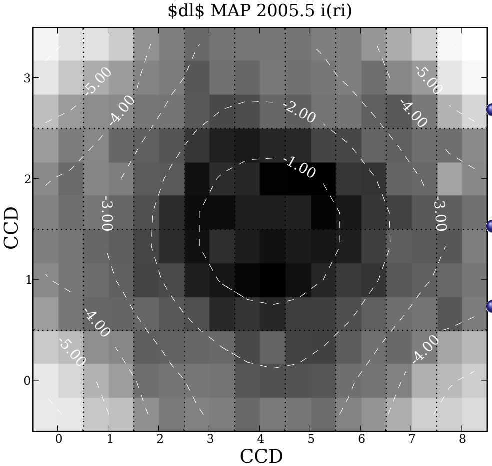
Uniformity of the Photometric Response



- 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)

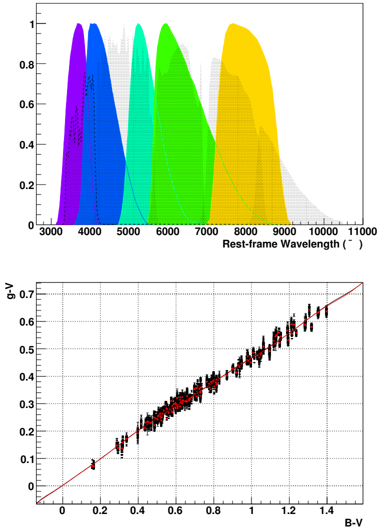
Uniformity of the Photometric Response



- 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



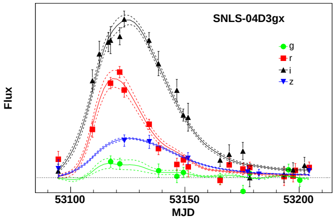
- Low-z and High-z photometric systems differ
- Large photometric corrections
- Two approaches: (1) physical model of both photometric systems (2) classical linear corrections.
- Main source of systematics today (won't be the case with newer low-z samples)

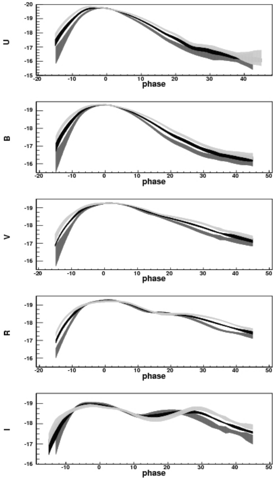
SALT2: modeling SN Ia Spectra and Lightcurves

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





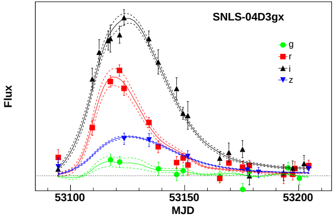
SALT2: modeling SN Ia Spectra and Lightcurves

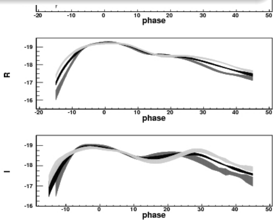
J. Guy et al, 2007

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 $\propto 1/\sqrt{N}$





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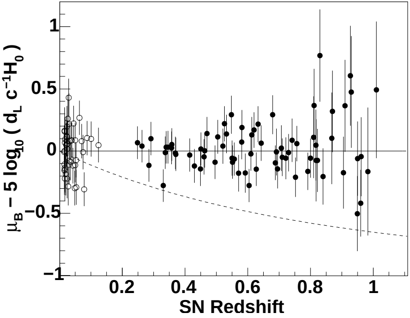
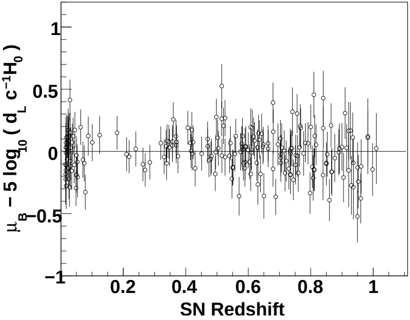


SALT1

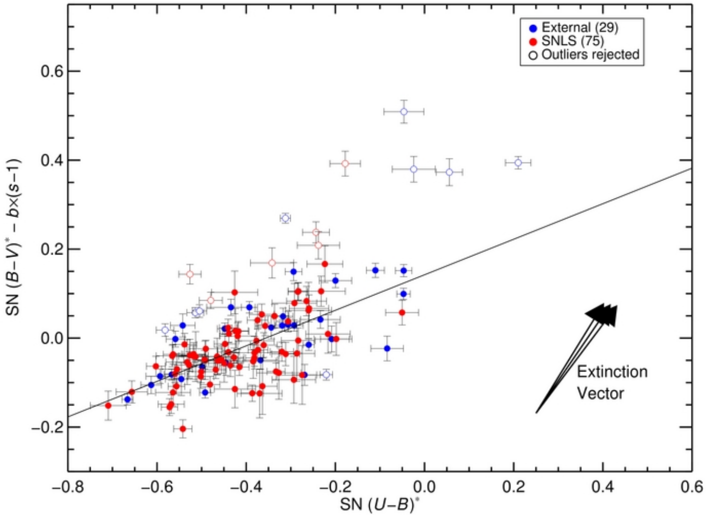
$\sigma \sim 0.20$



SALT2

$\sigma \sim 0.16$

Understanding Color and Dust Extinction

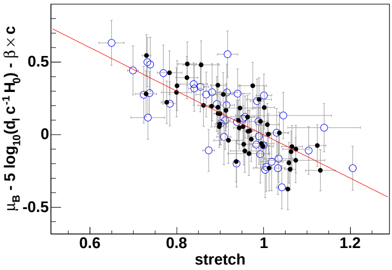


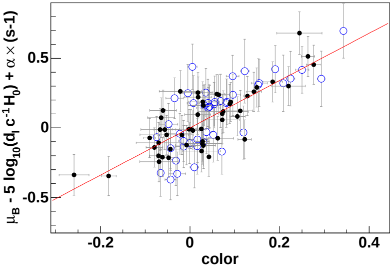
(Sullivan et al, 2008)

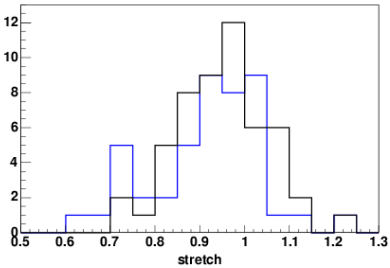
Evolution Tests

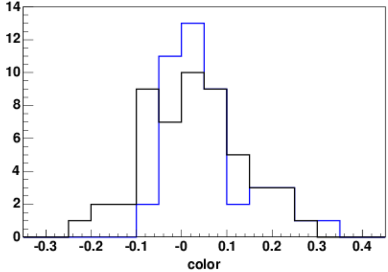
- Different progenitors types with different lifetimes
- One single progenitor type w/ correlation between lifetime and luminosity
- Metallicity
- ...
- Two kinds of evolution tests
  - ⇒ Compare low- and high-redshift events (Bronder et al. 2007)
  - ⇒ More sensitive: compare events at similar redshifts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

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





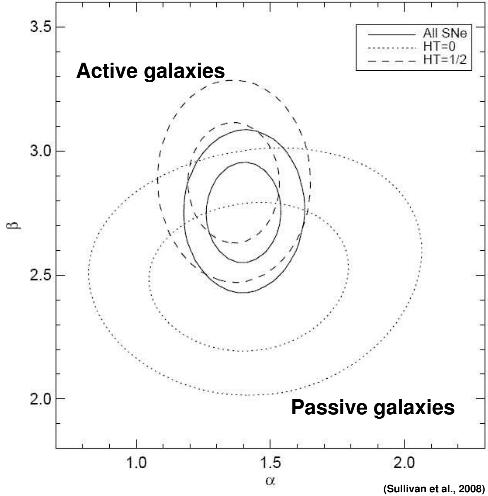




brighter-slower relation

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