Supernovae and Cosmology

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Gentner Colloquium, Heidelberg

Outline

Outline

Expansion History

On very large scales ($\sim 100\mathrm{Mpc}$), the Universe is
Isotropic and Homogeneous

- Friedmann - Lemaître - Robertson - Walker (FLRW) Metric

$$ds^2 = dt^2 - a^2(t) \times \left[\frac{dr}{1 - k\, r^2} + r^2 \left(d\theta^2 + \sin^2\theta \; d\phi^2 \right) \right]$$

- Scale factor $a(t)$
  - common to all distances.
  - describes the expansion of the Universe.

Geometry

- $k = \begin{cases} +1 & \text{closed} \\ 0 & \text{flat} \\ -1 & \text{open} \end{cases}$

Friedmann Equation(s)

- General Relativity connects the properties of space-time (the metric) with the energy content of the Universe.
- Einstein Equations + FLRW metric → Friedmann Equations

$$H(t) \equiv \left(\frac{\dot{a}}{a}\right) = \frac{8\pi G}{3}\sum_i \rho_i + \frac{\Lambda}{3} - \frac{k}{a^2}$$

- Energy density
- Cosmological Constant
- Curvature

⇒ Mapping the expansion history of the Universe, allows one to obtain information on its energy contents (non-relativistic matter, radiation, . . .)

Cosmological Parameters

- Critical Density $\rho = \rho_c(no\Lambda) \Leftrightarrow k = 0$

$$\rho_c = 3H_0^2/8\pi G \sim 5 \text{ protons}/m^3 \sim 1 \text{ Galaxy}/Mpc^3$$

- Densities & equations of state of all fluids populating the universe, in units of ρ_c

non relativistic matter	Ω_m	$w_m = 0$	$\rho_m \propto a^{-3}$
radiation	Ω_r	$w_r = +1/3$	$\rho_r \propto a^{-4}$
Cosmological Constant	Ω_Λ	$w_\Lambda = -1$	$\rho_\Lambda = \text{constant}$
Dark Energy	Ω_X	$w_X = ?? < -1/3$	$\rho_x \propto a^{-3(1+w_x)}$

...

Luminosity Distances

- Observables
  - redshift $z = \delta\lambda/\lambda$
  - apparent flux
- Luminosity distance $d_L(z)$

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

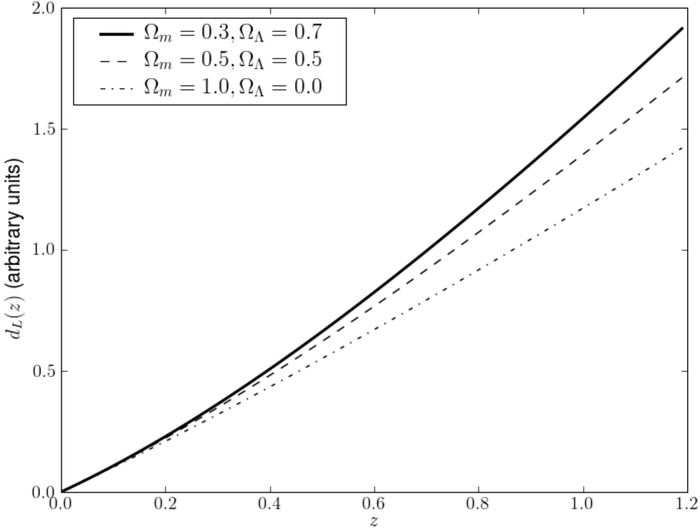
  - integrated history of the expansion

$$d_L(z) = (1+z)\ S_k\left(\frac{c}{H_0}\int_0^z \frac{dz'}{\dot{a}/a}\right)$$

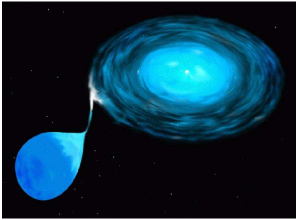
  - function of the cosmological parameters

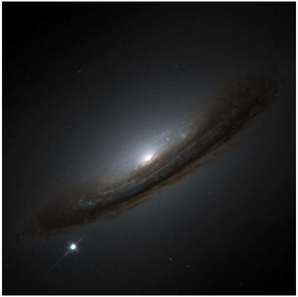
$$d_L(z) = (1+z) S_k\left(\frac{c}{H_0}\int dz'\left(\Omega_M(1+z')^3 + \Omega_k(1+z')^2 + \Omega_X \exp\left(\int_0^z 3\frac{1+w(z')}{1+z'}dz'\right)\right)^{-\frac{1}{2}}\right)$$

Hubble Diagram

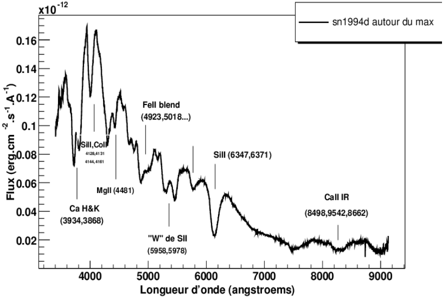


Type Ia Supernovae

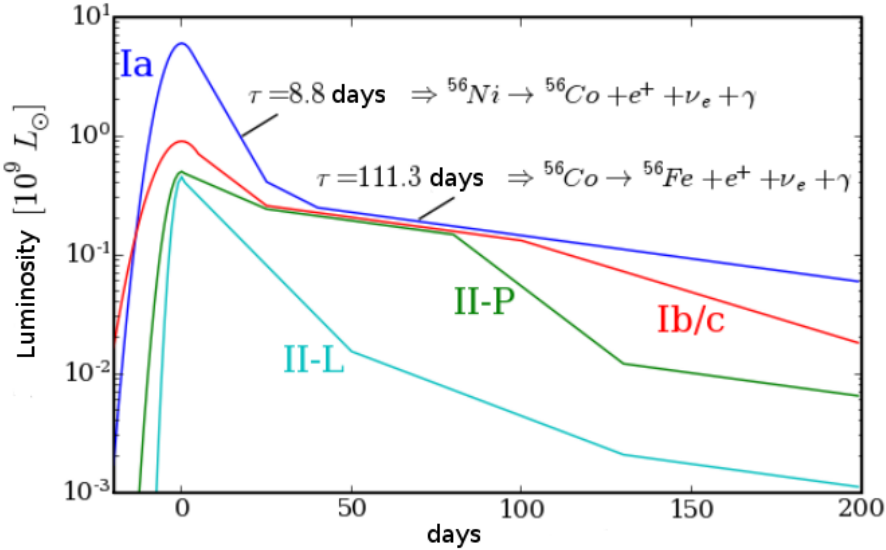




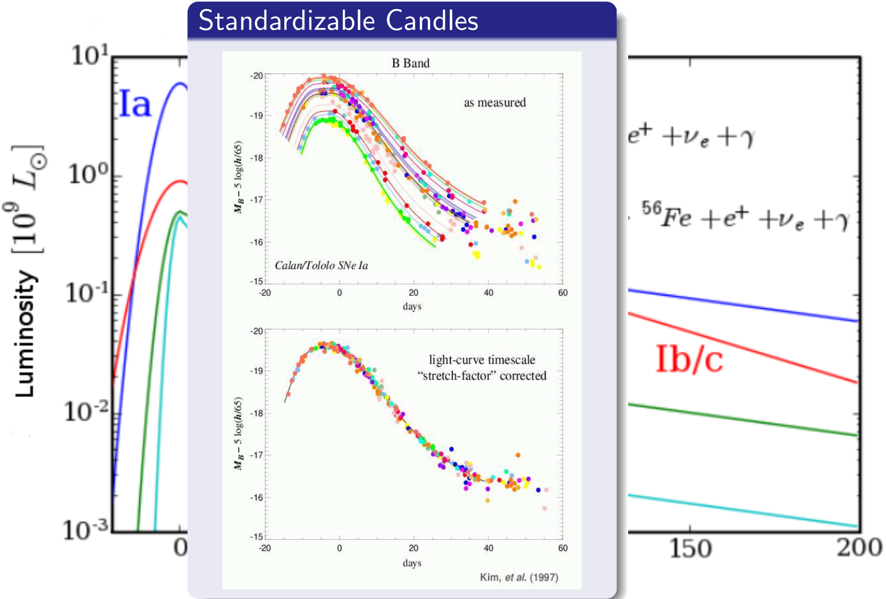
- very luminous ($10^{10} - 10^{11} L_{\odot}$)
- can be identified (spectra)
- fluctuations of $L_{max} \sim 40\%$
- can be reduced to $\sim 14\%$



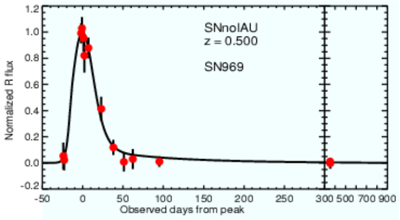
Supernova Lightcurves

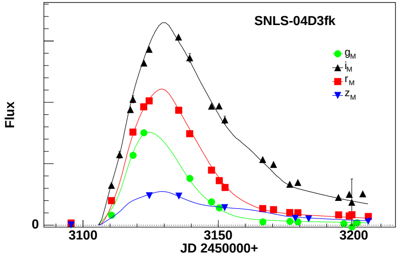


Supernova Lightcurves



Measuring Luminosity Distances

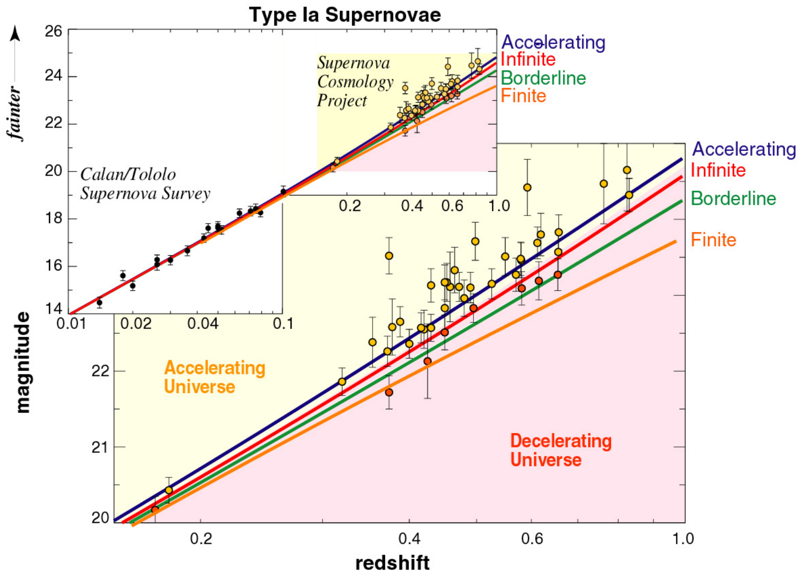




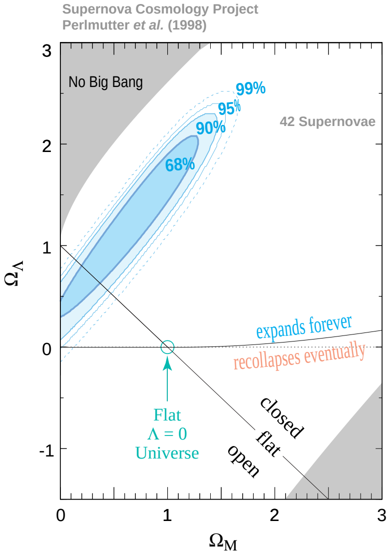
- Measure supernova apparent luminosity @ peak, *in a reference spectral region*
- Use additional observables to improve distance indicator
  - lightcurve width / *stretch* (⇒ good sampling of lightcurve)
  - color (⇒ observations in several passbands)

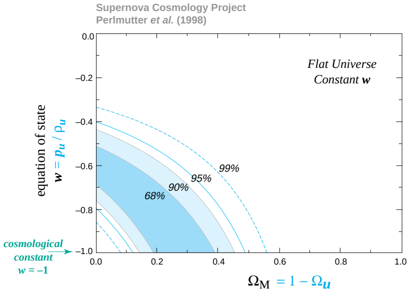
Accelerated Expansion

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



Accelerated Expansion
(Perlmutter et al. 1999)

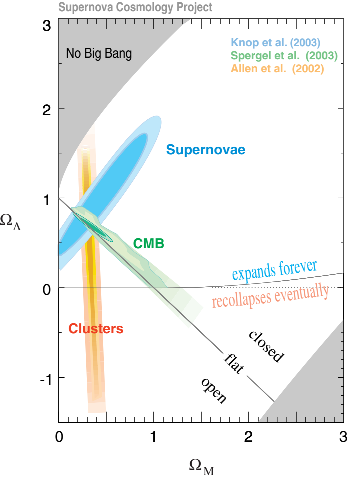




- Unknown Energy Density: Ω_X
- First weak constraints on w_X (assuming a flat Universe)

$$w_X < -1/3 \quad (90\%\ CL)$$

Concordance Model



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

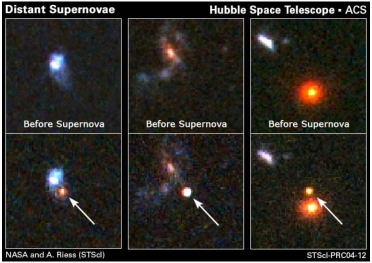
- $p = w\rho \qquad w < -1/3$

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

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

2004: SNe from Space (GOOD / ACS Survey)

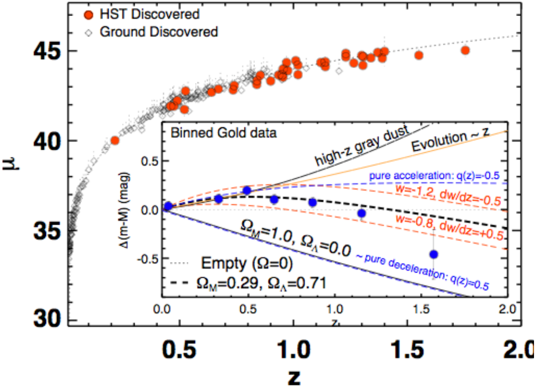
(Riess, 2004)



- Find $z > 1.2$ SNe Ia with HST
- 16 + 21 SNe Ia found w/ ACS. Among them, 23 SNe @ $z > 1$.
- Probe the deceleration era

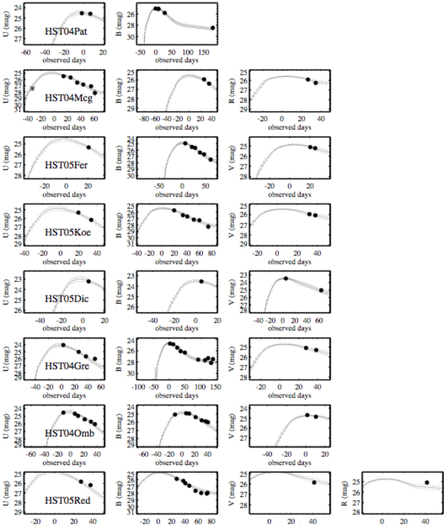
2004: SNe from Space (GOOD / ACS Survey)

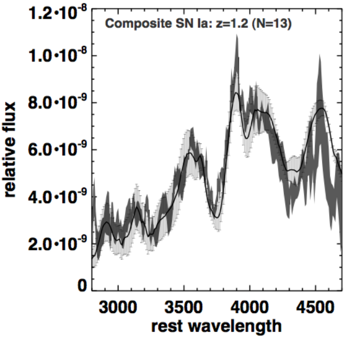
(Riess, 2004)



- Hubble diagram up to $z \sim 2$
- Expansion went from deceleration to acceleration
- Exclude grey dust hypothesis

ACS Lightcurves (restframe UV) & Spectra

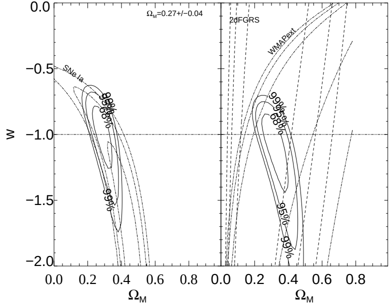


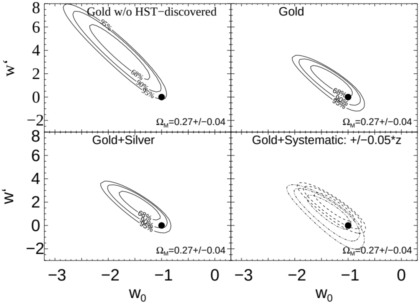


- Limited statistics
- Limited time coverage
- Large calibration uncertainties

Constraints on w and w'

Riess et al, 2004





$$w = -1.02^{+0.13}_{-0.19} \quad \text{and} \quad w < -0.76 (95\% CL)$$

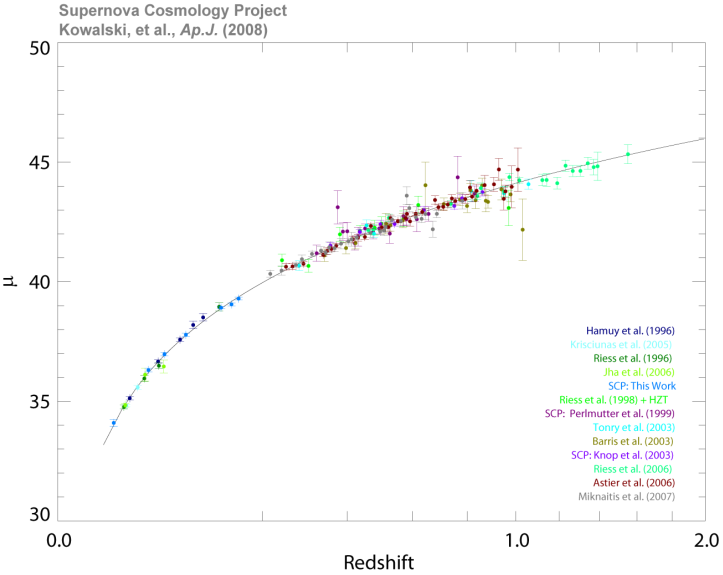
Consistent with $w_0 = -1$ and $dw/dz = 0$ (Λ)

Second Generation Supernova Programs

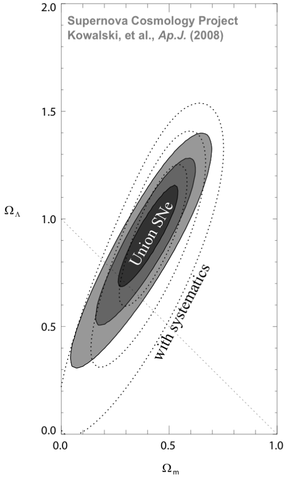
- Low redshift
  - CfA
  - Kait (UCB)
  - Carnegie
  - SN Factory / SNIFS
- Medium redshift ($0.1 < z < 0.3$)
  - SDSS-II (SN)
- High-z Programs
  - ESSENCE
  - SNLS
- Ongoing space programs with ACS/HST
  - PANS (Riess et al)
  - Clusters (Perlmutter et al)
  - now stopped due to ACS failure

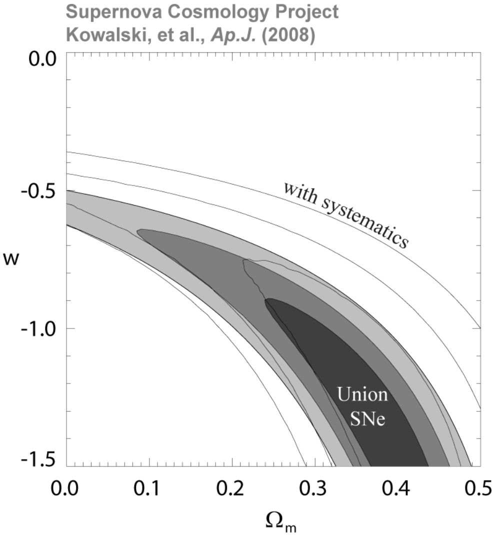
Today

"Union Sample" (Kowalski et al, 2008)



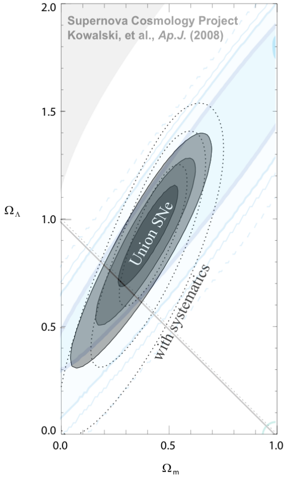
Today

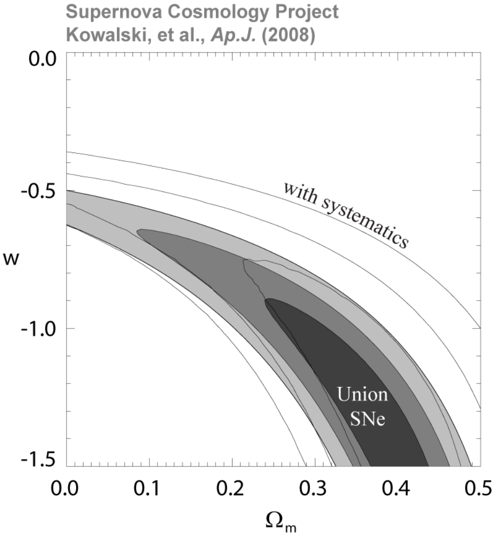




- >300 "good quality" SNe Ia

Today



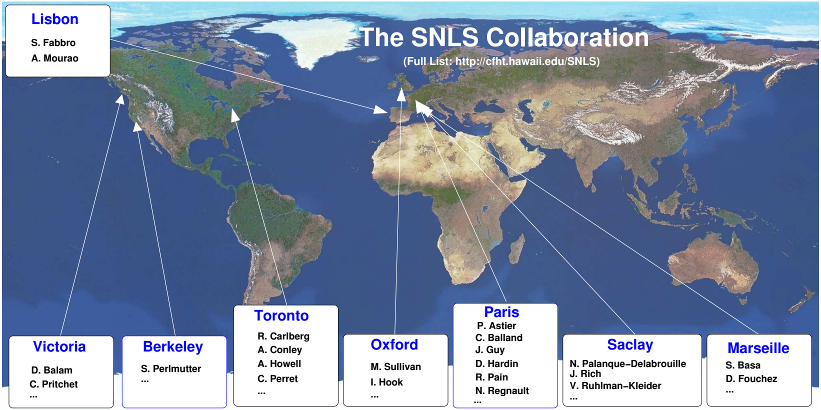


- $>$ 300 “good quality” SNe Ia
- Study of mean deviation and

Outline

1. Measuring the Dark Energy Equation of State
2. The SNLS Survey
3. From Luminosity Distances to the Cosmological Parameters
   - Photometric Calibration
   - Lightcurve Fitters
   - Systematics

The SNLS Collaboration



SNLS: A Large Photometric Survey . . .

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

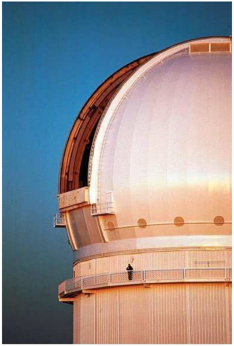
- CFHT @ Hawaii

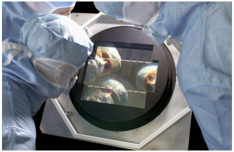
Wide Field Camera

- 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 . . .

$\sim$ 300h / year (

- CFHT (

Wide Field Cam

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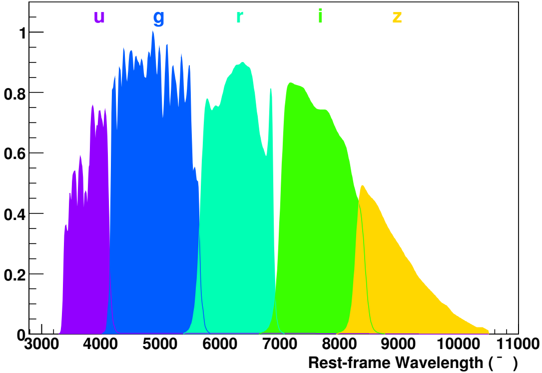
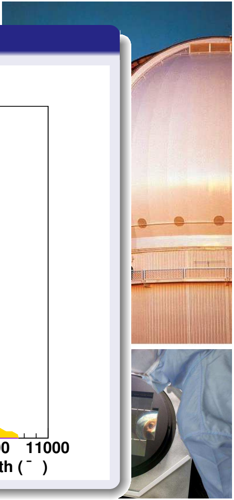
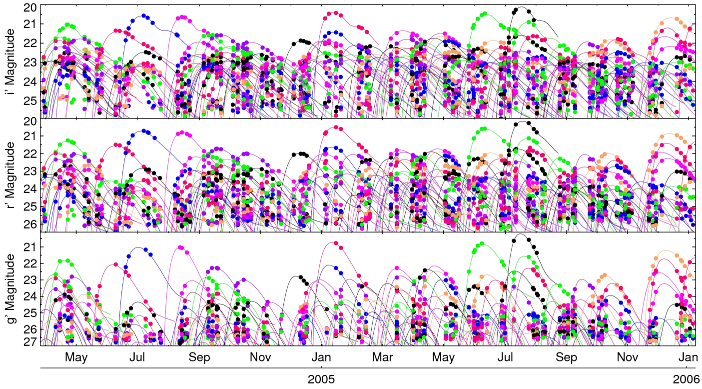
Megacam Passbands





. . . Operated in Rolling Search Mode



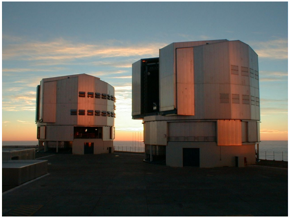
. . . and a Large Spectroscopic Survey

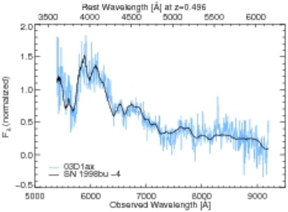
Goals

- 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

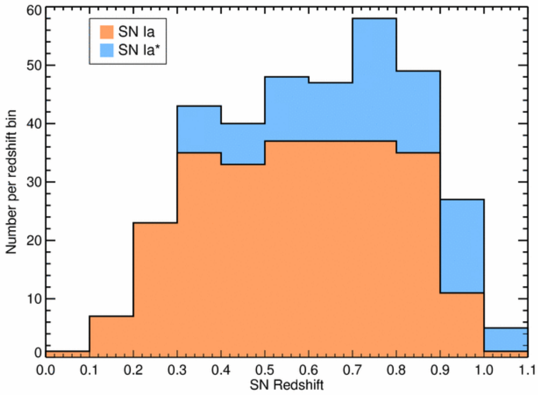
Survey ended in June 2008

Statistics

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

May 200

Telesco	otal
Gemi	35
Keck	99
VLT	21
Tota	55



Outline

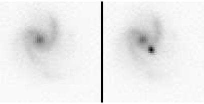
Analysis Steps

- Detection
  - two real time pipelines (Perret et al, Fouchez et al)
  - merging of candidates
  - ranking with photometric identification (Sullivan et al, 2005)
- Spectroscopic Identification
  - comparison with library of High-z SN spectra (Howell et al, 2005)
  - simultaneous fit of SN lightcurves and spectra (Baumont et al, 2008)
- Photometry
- Calibration
- Lightcurve fitting / distance estimates
- Cosmological constraints

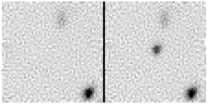
Differential Photometry

The Model: Simultaneous fit on $\sim$ 300 images

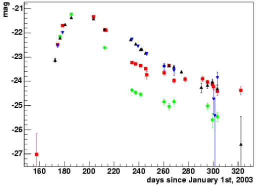
$$I(x,y) = \mathrm{Flux} \times [\mathrm{Kernel} \otimes \mathrm{PSF}_{\mathrm{best}}](x - x_{sn}, y - y_{sn}) + [\mathrm{Kernel} \otimes \mathrm{Galaxy}_{\mathrm{best}}](x,y) + \mathrm{Sky}$$

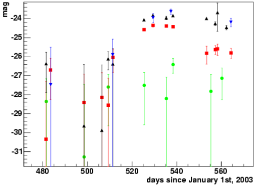


$(z = 0.28)$



$(z = 0.95)$

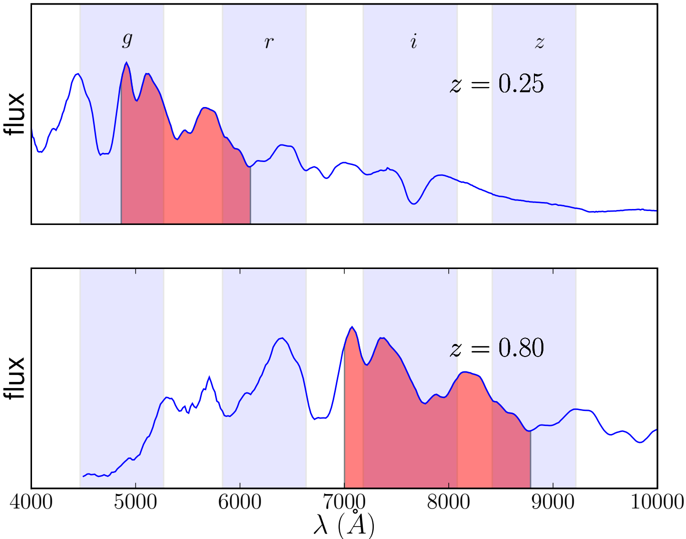




Differential Photometry (cont'd)

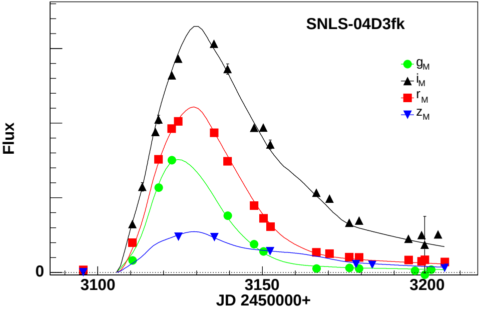
- Alternate technique
  - PSF photometry on subtractions
    - convolution and alignment of best quality reference image to each science field independantely
    - subtraction
    - PSF photometry on subtraction
- First method chosen after comparison

Measuring Luminosity Distances with SNe Ia



Measuring Luminosity Distances with SNe Ia

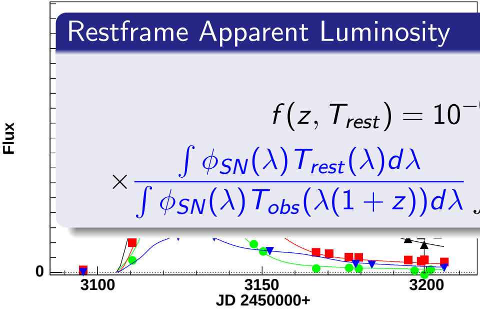
$$\frac{f(z_1, T_{rest})}{f(z_2, T_{rest})} = \left(\frac{d_L(z_2)}{d_L(z_1)}\right)^2$$



- Restframe apparent luminosity @ peak, in a given spectral region
- decline rate / lightcurve width ⇒ good sampling of LC
- color ⇒ observations in several passbands

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

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

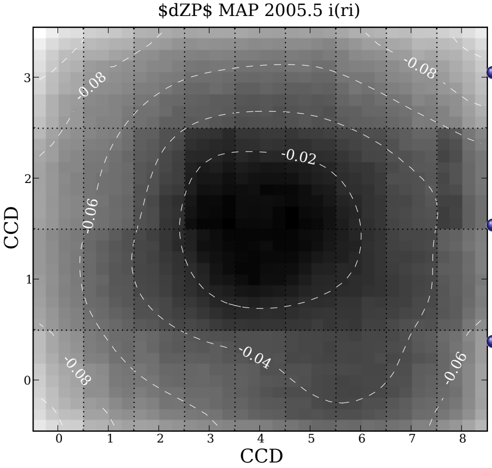
of

- color $\Rightarrow$ observations in several passbands

Outline

Photometric Calibration (I)

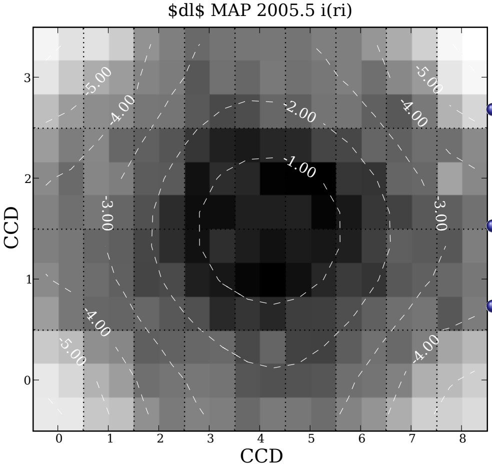
Uniformity of the Photometric Response



- 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)

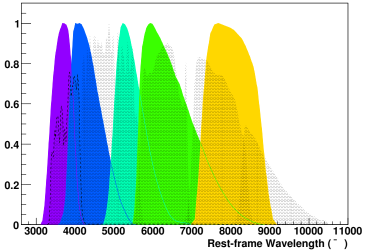
Uniformity of the Photometric Response

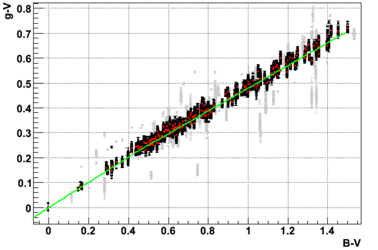


- Intrinsic filter non-uniformities (up to $\sim 5nm$).
- Mapped with dithered observations.
- Must be accounted for in the lightcurve fits.

Photometric Calibration (III)

Intercalibrating the low-z and high-z data





- Low-z and High-z supernovae observed with different filter systems.
- We anchor the photometric calibration on the same standard star network.
- Large photometric corrections.
- Modeled with piecewise-linear transformations.
- Main source of systematics today (won't be the case with future low-z samples).

Photometric Calibration (IV)

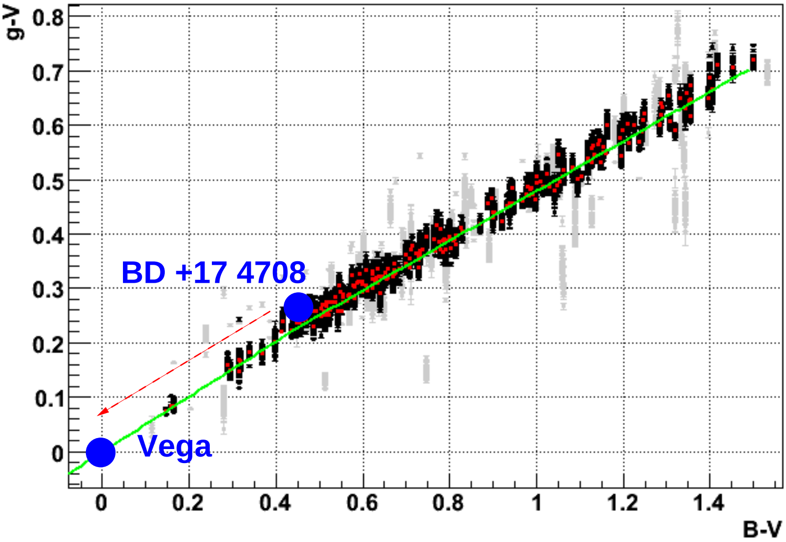
Intercalibrating the low-z and high-z data

- Traditional magnitude systems do not define their physical flux scale

$$\Phi = \Phi_0 \times 10^{-0.4m}$$

- We rely on a fundamental flux standard, with (1) a known spectrum and (2) known magnitudes, in order to convert magnitudes into fluxes
- 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 (V)



Photometric Calibration (VI)

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

Outline

1. Measuring the Dark Energy Equation of State
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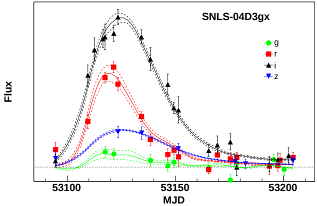
   - Lightcurve Fitters
   - Systematics

Light Curve Fitters

- Goal: Measure flux ratio of SNe at different z
  - same (restframe) wavelength
  - same phase
  - different redshifts



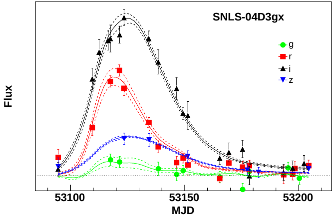
- Method: Interpolation of measurements
  - in different restframe bands
  - with different time sampling
- Tool: Empirical model of the SN Ia spectral sequence
  - physical simulations not precise enough
  - model trained on a large sample of lightcurves and spectra
  - accounts for the diversity of SNe Ia

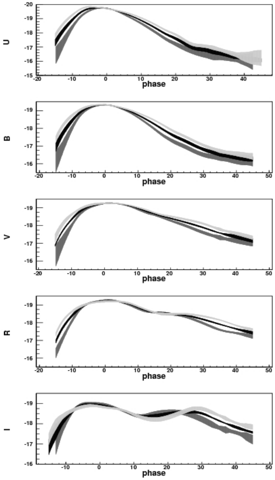
SALT2: modeling SN Ia Spectra and Lightcurves

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





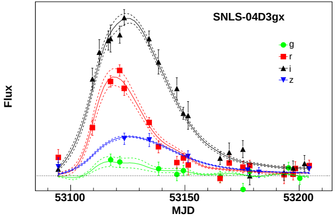
SALT2: modeling SN Ia Spectra and Lightcurves

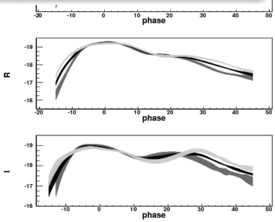
J. Guy et al, 2007

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

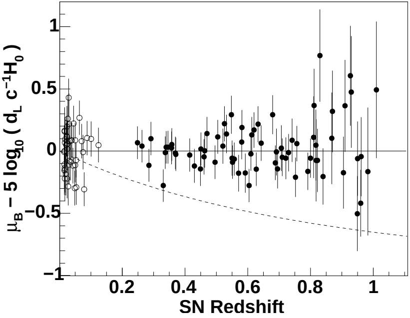
$\Rightarrow$ errors $\propto 1/\sqrt{N}$





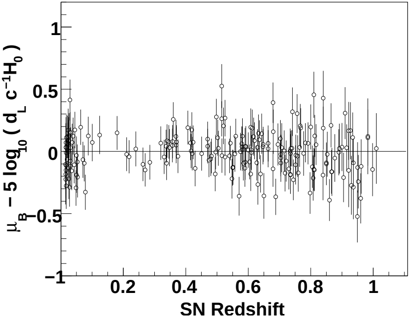
SALT2: modeling SN Ia Spectra and Lightcurves

J. Guy et al, 2007



SALT1

$\sigma \sim 0.20$



SALT2

$\sigma \sim 0.16$

Distance Estimator

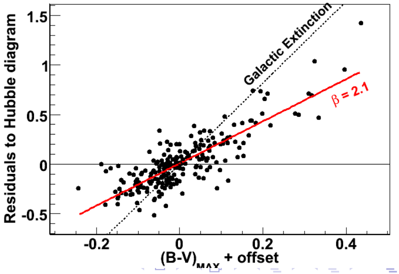
- Distance modulus estimator

$$\mu_B = m_B^\star - M + \alpha \times (s-1) - \beta \times c$$

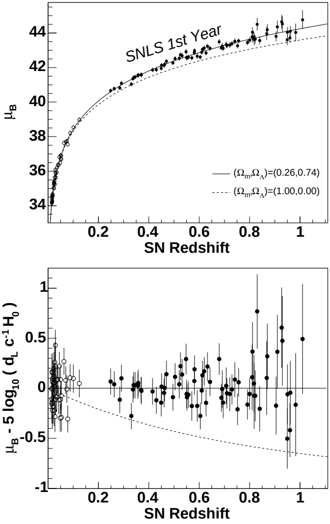
  - brighter slower correlation
  - brighter bluer correlation

- Empirical coefficients, fitted along with the cosmology: M, α, β

- β accounts for (1) host galaxy extinction (dust) and (2) intrinsic SN properties.
- Control evolution of β with z



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

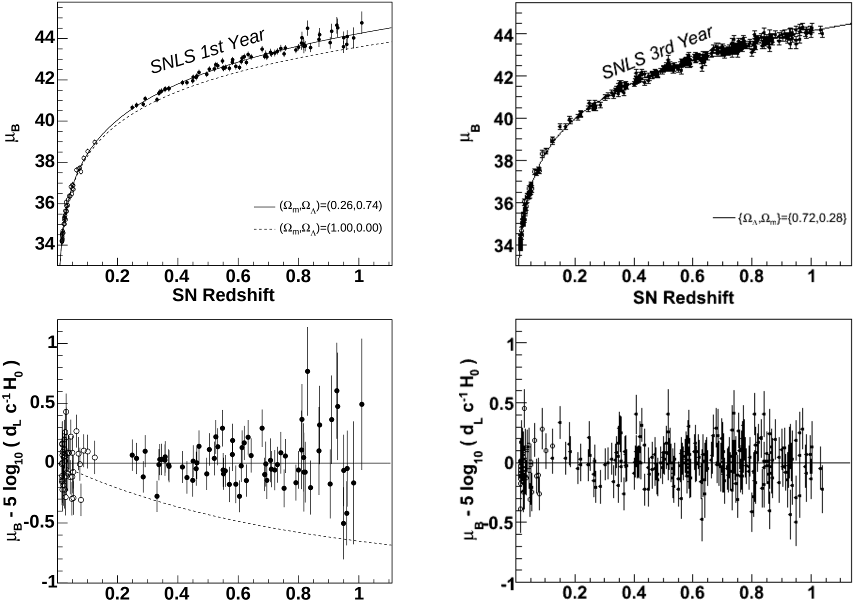
$$\chi^2 = \sum_i \frac{\mu_{B_i} - 5\log_{10} d_L(\theta, z_i)^2}{\sigma^2(\mu_{B_i}) + \sigma_{int}{}^2}$$

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

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

SNLS 3 Year Analysis



Cosmological Constraints
Uncertainty Budget

- Uncertainties on w_X

statistical	0.077
SNLS calib	0.053
Low-z calib	0.032
Low-z filters	0.016
Low-z select. bias	0.022
Lightcurve fitters	0.020
Total sys	0.071
Total stat + sys	0.104

plots/snls_3yr_w_contours.png

- (SNe + BAO (Eisenstein et al, 2005), assuming $\Omega_k = 0$)

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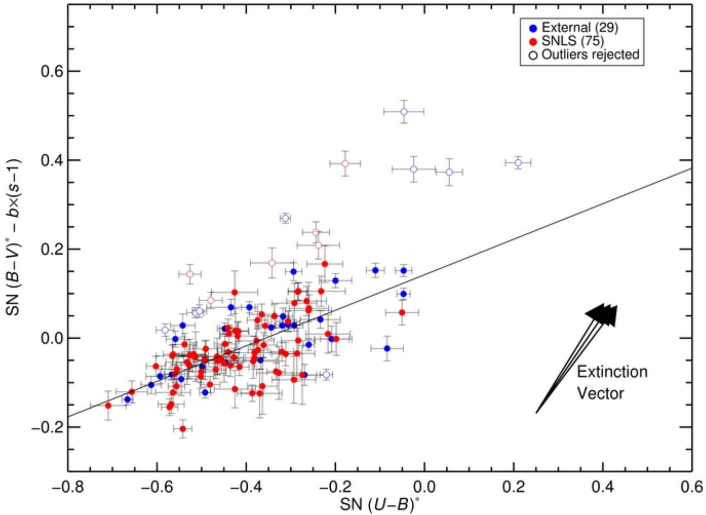
Identified Sources of Systematics

- 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

Systematics: low-z vs. high-z

- SNLS
  - dominated by calibration uncertainties
    - 0.005 in gri , 0.025 in zband
  - much smaller uncertainties from :
    - filters: well measured, in agreement with observed color terms
    - selection bias: controlled with image simulations
- low z sample
  - calibration uncertainties (linear color corrections or 'S'corrections)
    - 0.02 in Uband, 0.007 in BVR
  - filters (Landolt system is not a natural system)
    - 0.005 relative uncertainty on flux interpretation
  - selection bias (heterogeneous sample)
    - 0.01 uncertainty on average distance modulus

Understanding Color and Dust Extinction

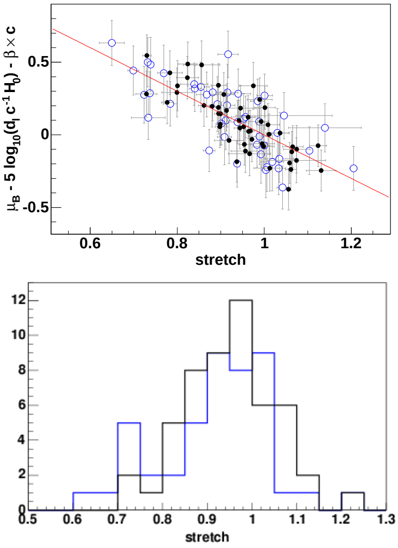


(Sullivan et al, 2008)

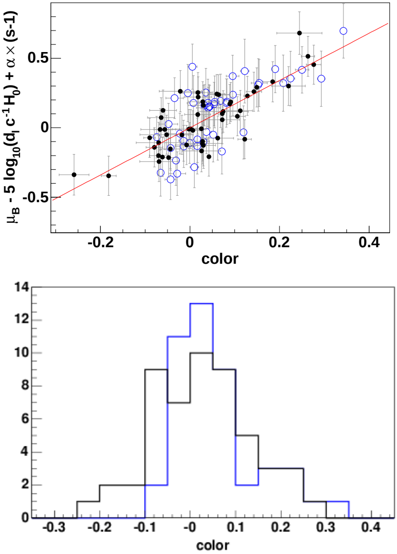
Evolution Tests

- 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



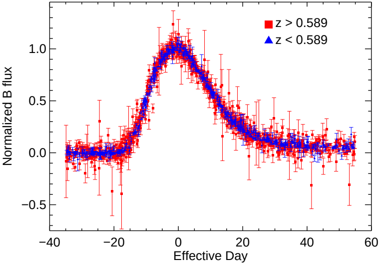
brighter-bluer relation

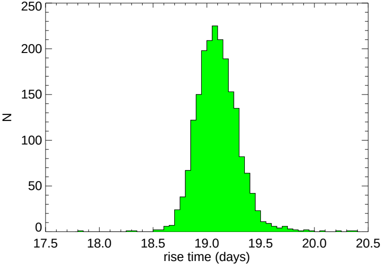
SN Ia Lightcurve Rise Time

Conley et al, 2006

SN Ia evolution check

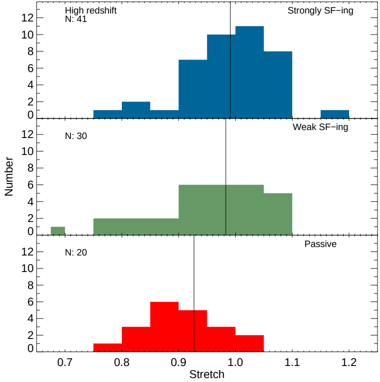
- Compare nearby and distant SN early lightcurve shape (B-band)
  - nearby: 19.58 ± 0.2
  - distant: $19.10 \pm 0.2(stat) \pm 0.2(sys)$





SN Ia Properties and Host Galaxies

Sullivan, LeBorgne et al, 2006



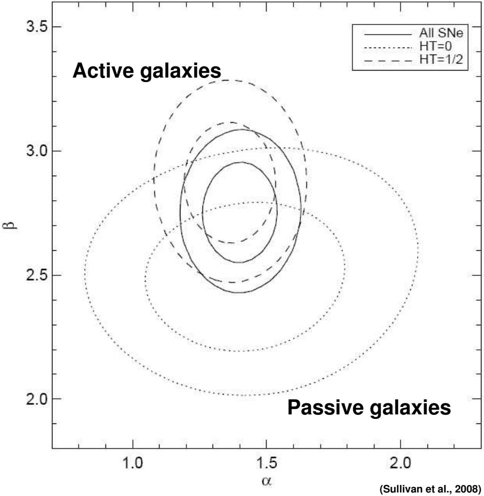
SNe exploding in a high SFR environment

- display a larger stretch (and are brighter)

⇒ younger progenitors produce brighter SNe Ia ?

no impact on the distance measurement for the 1 year sample

Evolution test: Standardization Parameters vs. Host Galaxy Type



(Sullivan, 2008)

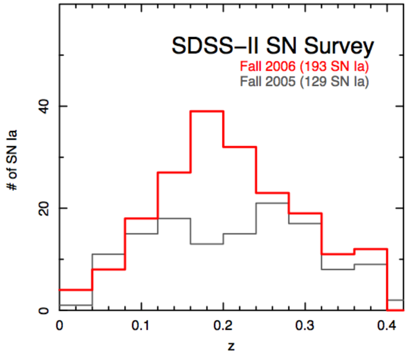
Summary

- SNLS3 : largest homogeneous highz SNe sample
  - 234 SNLS SNe Ia $0.1 < z < 1.05$
  - current world sample: 180(*) Kowalski et al. (2008)
- Uncertainties on w (lowz +SNLS3 SNe + BAO Eisenstein, 2005)

$$w = 1.xx + 0.077(stat) + 0.071(syst)$$

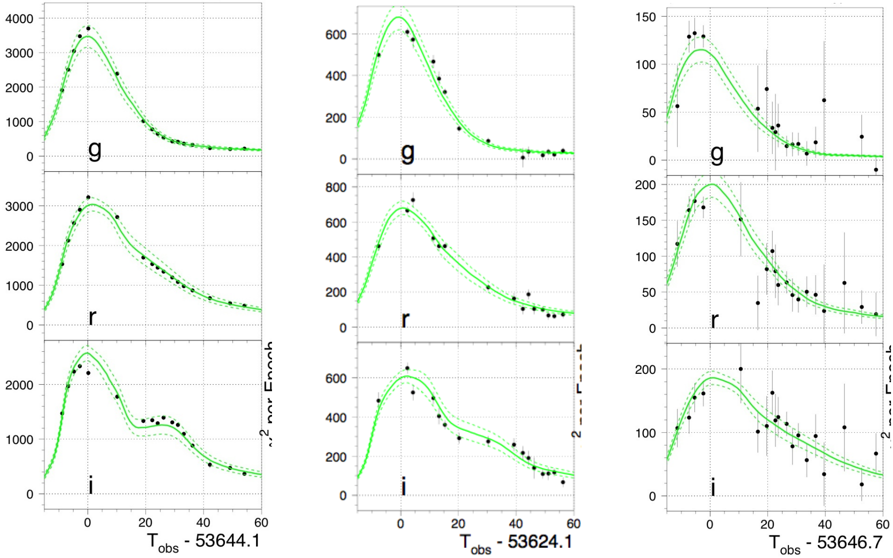
- Statistical uncertainty limited by lowz sample
- Systematic uncertainty dominated by
  - difficult calibration against UBVRI lowz photometry
  - lowz Malmquist bias
- Near future: combined SDSS/SNLS analysis (same statistics, lower systematics)

SDSS



- 2005 & 2006 Campaigns
  - 327 spectroscopically confirmed Ia's
  - 31 probable Ia
  - 44 confirmed other SN types
  - Galaxy redshifts for 60 additional candidates
  - 1st year analysis nearly complete
- $\sim$ 40% of all discovered SNe in 2005 & 2006

SDSS SN Ia Lightcurves



Forecasts for constant w (with BAO)

Expected realistic statistical improvements of the (Ω_m, w) constraints

	Nearby	44	∞	44	132	132	250
	Distant	71	71	213	213	500	500
current	$\sigma(\Omega_m)$	0.023	0.019	0.019	0.019	0.018	0.018
BAO	$\sigma(w_0)$	0.088	0.073	0.076	0.064	0.060	0.055
BAO $\times 2$	$\sigma(\Omega_m)$	0.016	0.014	0.014	0.013	0.013	0.013
(8000 deg^2)	$\sigma(w_0)$	0.081	0.062	0.067	0.054	0.049	0.044

- $+$ systematics . . .

Summary

- SNe Ia are excellent distance indicators. Significant constraints on w require combining with constraints from other experiments (M)
- 2nd generation projects (ESSENCE, SNLS, SLOAN/SN) are getting more and higher quality data toward building a systematic limited Hubble diagram with $\sim$ 1000 SN Ia
- Expected precision on (flat Univ., constant) w by 2009-2010 :

$$\pm 0.05(stat) \quad \pm 0.05(syst)$$

- Percent precision on w and significant precision on w' (w_a) with SN will require exquisite control of systematics

Summary

- Lessons for future high-z SN projects:
- More and better quality nearby SNe (badly) needed
- Statistics matters: most of the (known) systematic uncertainties are not systematics since they can (in principle) be reduced with high statistics of both low- and high-redshift (well measured) SNe
- Need to reduce the photometric calibration uncertainty:
  - "internal" (uniformity & stability)
  - "external" (primary standard or physical $(B - R)$) which both will need to be controlled/understood at $\sim 0.1\%$ ($\sim 1\%$ today)

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

Instrumental Calibration: SNDICE