Constraints on Dark Energy from the Supernova Legacy Survey three year data set

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Outline

Usage of standard candles for cosmology 1/2

The metric for a homogeneous and isotropic universe + general relativity → Friedman-Lemaitre-Robertson-Walker equations

$$H \equiv \left(\frac{dR/dt}{R}\right)^2 = \frac{8\pi G}{3}\rho_M + \Lambda/3 - \frac{k}{R^2}$$

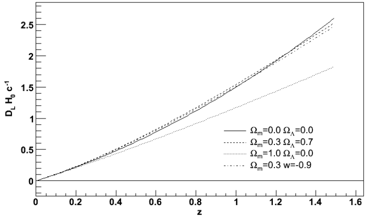
which links the expansion rate of the universe to its content and spatial curvature. With light as a messenger, we have four observables connected to the expansion history.

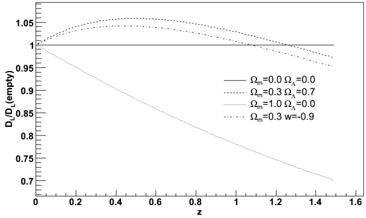
- the redshift $z = R_0/R_{emission} - 1$
- fluxes of objects of known luminosity → luminosity distance $d_L(z) = (1+z)r(z)$
- angular size of objects of known physical size → angular distance $d_a(z) = r(z)/(1+z)$
- counts of objects of known number density → volume element

where $r(z) = \frac{c}{\sqrt{\Omega_k}} S_k\left(\sqrt{\Omega_k}\int \frac{dz}{H}\right)$, $\Omega_k = -\frac{k}{(R_0 H_0)^2}$

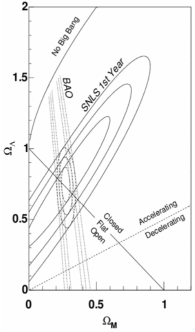
Usage of standard candles for cosmology 2/2

$$flux = L/4\pi d_L^2$$



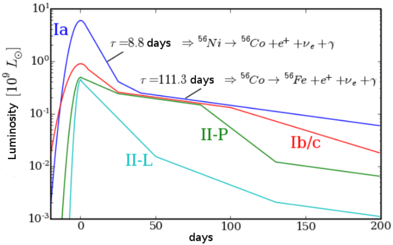


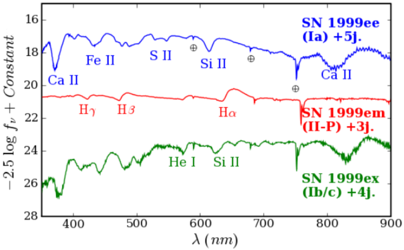
- Both low z and distant candles needed to distinguish models
- Parameters degeneracy: standard candles at $0 < z < 1$ measure with precision a singe parameter.



Type Ia Supernova (SN Ia)

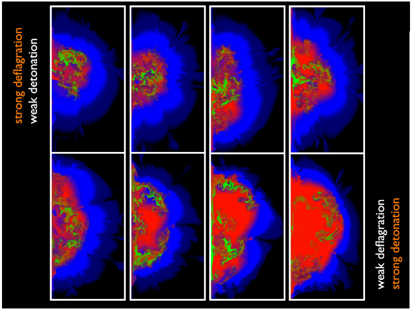
- very bright : 10^{10} sun luminosity
- rare : about one per galaxy per millennium
- light curve duration : $\simeq$ 1 month
- peak brightness dispersion $\simeq$ 40%
- precision on distance modulus $\simeq$ 0.15
- identified by spectroscopy (broad absorption features give ejecta velocity and chemical composition)

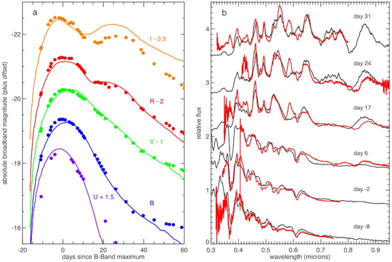




SN Ia simulations

Thermonuclear explosion of C+O white dwarf fed by companion star
State of the art: Kasen (2009)





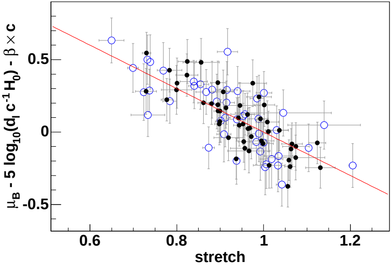
- reproduces brighter-slower and brighter-bluer relations
- good qualitative description of the observations
- but not precise enough for usage as fitter to estimate distances

Measuring Luminosity Distances with SNe Ia

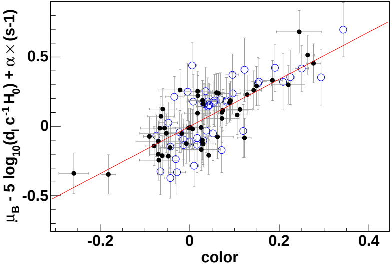
Distance modulus $\mu = 5 \log_{10} D_L$ estimated using apparent magnitude in a rest-frame (or redshifted) filter + correction factors based on the shape of the SN light curve and its color

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

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



brighter-slower relation

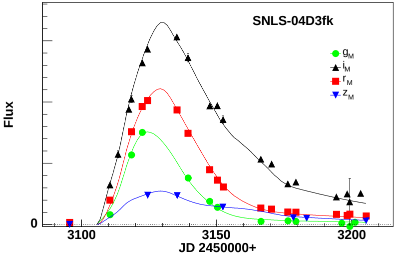


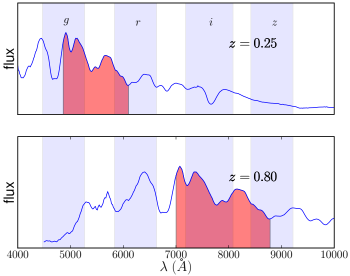
brighter-bluer relation

Measuring Luminosity Distances with SNe Ia

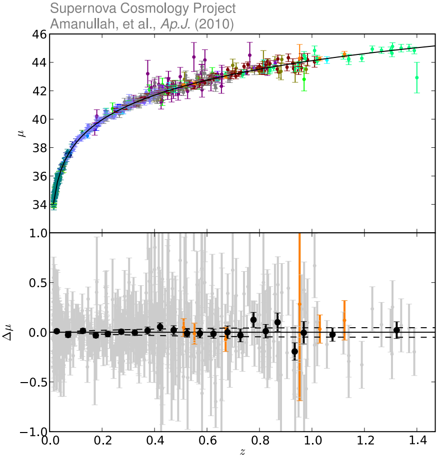
- $m_B^\star$, *shape* and *color* determined from observed SNe light curves in a limited set of filters
- Requires a model of the SN spectral evolution to correct for redshift effect (*k-corrections*)

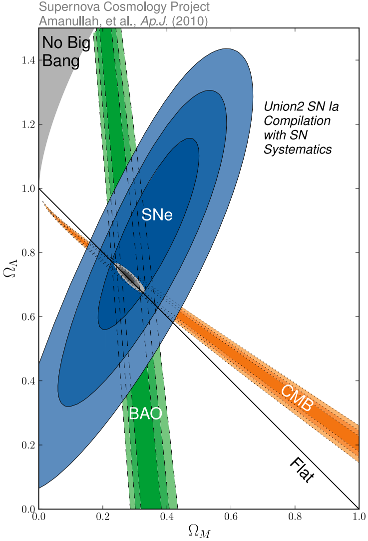
$$\frac{f(z_1, T_{rest})}{f(z_2, T_{rest})} = \left(\frac{d_L(z_2)}{d_L(z_1)}\right)^2$$



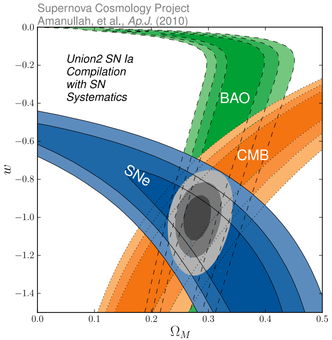


Hubble diagram and cosmological constraints





Dark Energy?



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

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

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

SNe+BAO(+CMB) $\rightarrow w \simeq -1 \pm 0.1(sys.)$

Outline

Increasing SN samples

Recent SN photometric high-z samples:

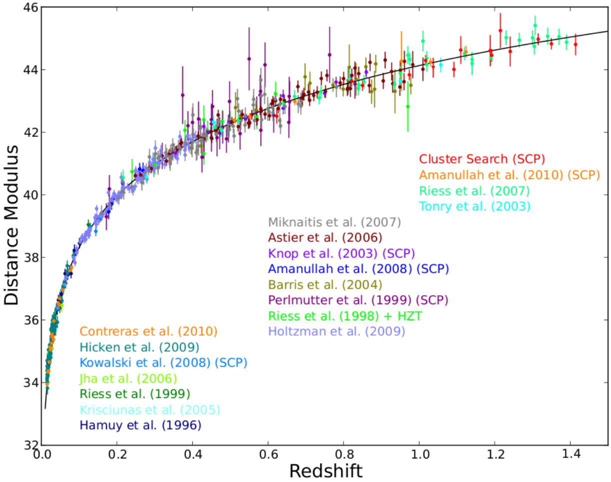
- Carnegie sample (I-band diagram) ($\simeq$**50**, Freedman 2009, Folatelli 2010)
- SDSS-II ($\simeq$**100**, Kessler 2009)
- ESSENCE ($\simeq$**60**,Wood-Vasey 2007)
- HST ($\simeq$**30**,Riess 2007, $\simeq$**20**, Suzuki 2011)
- SNLS, **SNLS-3** ($\simeq$**230**, G. 2010) SNLS-1: ($\simeq$**70**,Astier 2006),

Recent compilations:

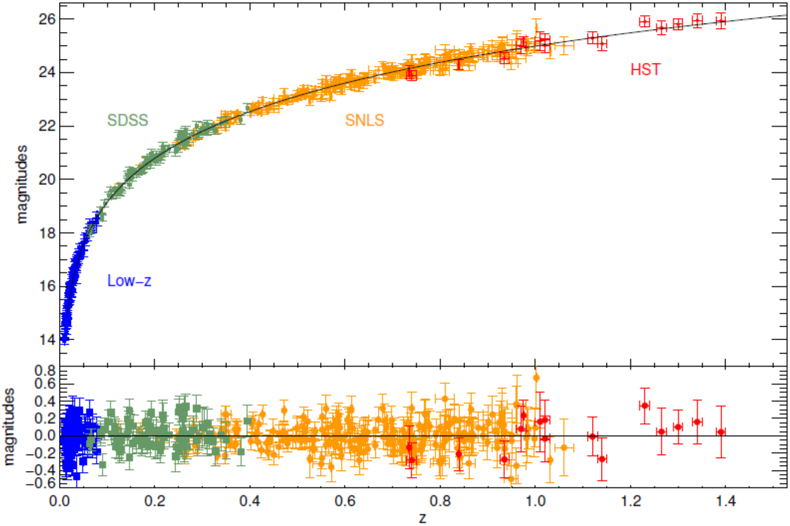
- Union2 sample (inc. 6 new SNe) (Amanullah 2010, updated in Suzuki 2011)
- Constitution sample (CfA3) (Hicken, 2009)
- Union sample (Kowalski, 2008)

Union 2.1 Hubble diagram

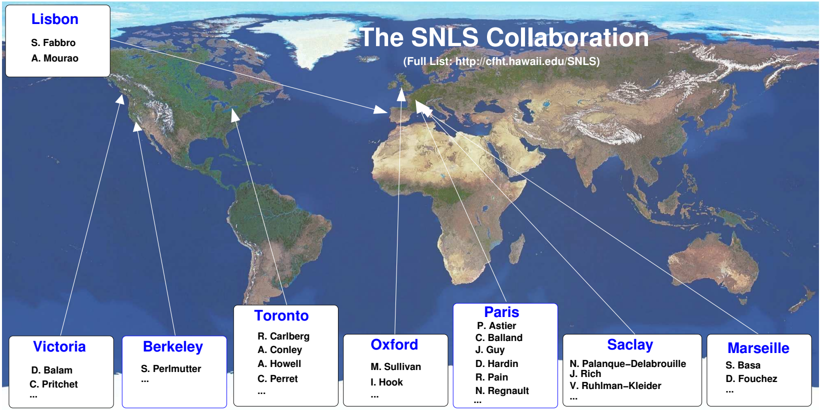
Suzuki 2011



SNLS-3 Hubble diagram
Conley 2011



The SNLS Collaboration



SNLS: A Large Photometric Survey . . .

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

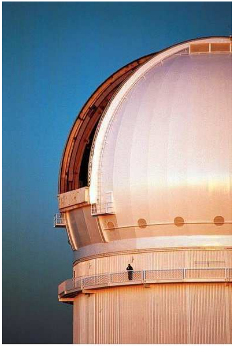
- CFHT @ Hawaii

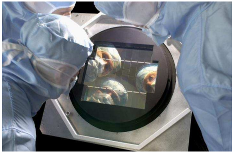
MegaCam: Wide Field Camera

- 1 deg^2, 36 2k$\times$4k CCDs
- Good PSF sampling 1 pix = 0.2”
- Excellent image quality: 0.7” (FWHM)

Rolling search mode

- Part of CFHTLS, 40 nights/year for 5 years
- Four 1-deg^2 fields
- repeated obs. (3-4 nights) in *griz* bands





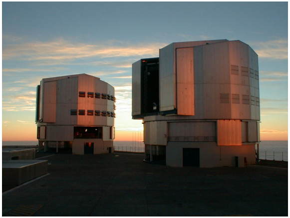
SNLS: . . . and a Large Spectroscopic Survey

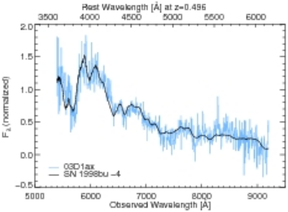
Goals

- 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)

SNLS: 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

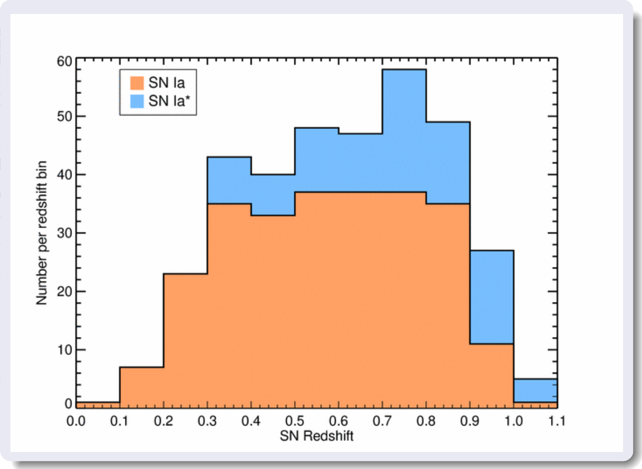
Survey ended in June 2008

SNLS: Statistics

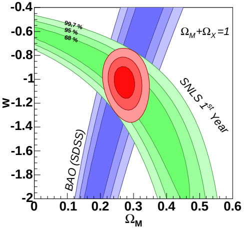
Public list of candidates:
http://legacy.astro.utoronto.ca

May 200

Telesco	otal
Gemi	35
Keck	04
VLT	21
Tota	60



SNLS 1st $\rightarrow$ 3 Year Analysis



1st Year analysis (Astier 2006):
$w = -1.023 \pm 0.090$ $(stat) \pm 0.054$ (sys) for a flat cosmology.
Syst. uncertainty on w dominated by calibration.

3 Year analysis :

- Statistics: 71 $\rightarrow$ ~ 250
- Independant analyses (Fr, Ca), being carefully cross-checked
- Improved photometric calibration
- Improved SN fitters trained on the SNLS data (two fitters SALT2 & SiFTO)
- Detailed studies of the SN properties w.r.t. host galaxy type
- Systematics included in the cosmological fits

SNLS3: Photometric Calibration

Uncertainty Budget, Regnault et al. (2009)

	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

SNLS3: SALT2 & SiFTO
(Guy et al, 2007), (Conley et al, 2008)

Two methods are used.
Differences provide an estimate of systematics.

SALT2

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

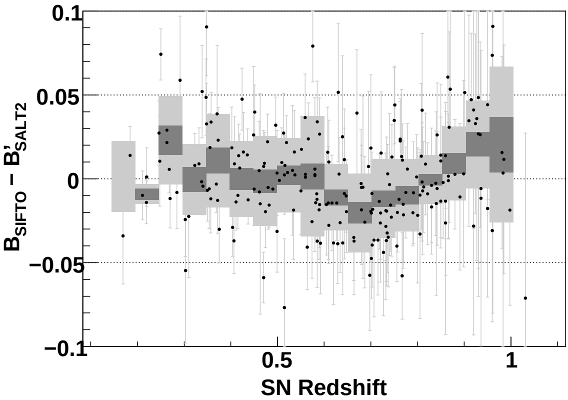
$$\begin{aligned} F &= x_0 \\ &\times [M_0(p,\lambda) + x_1 M_1(p,\lambda)] \\ &\times \exp(c\ CL(\lambda)) \end{aligned}$$

SiFTO

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

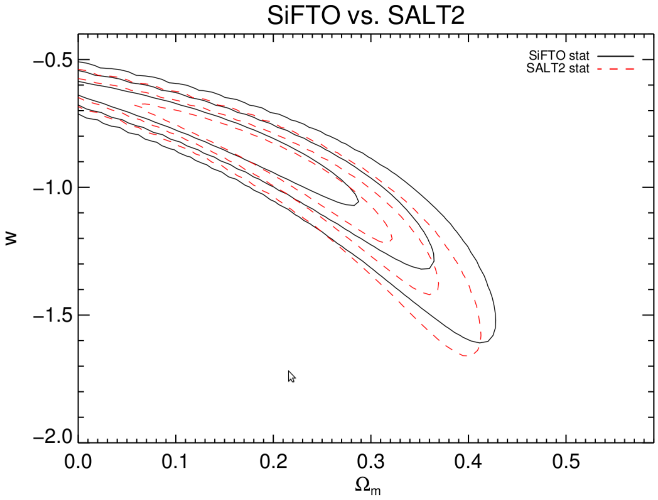
- Both fitters trained using nearby and SNLS lightcurves (lightcurve fit separate from distance estimate).

SNLS3: SALT2 vs. SiFTO
(G. 2010)



Systematics on rest-frame magnitudes $\simeq 0.02$

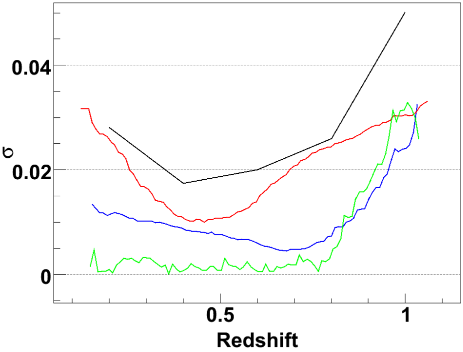
SNLS3: SALT2 vs. SiFTO
(Conley 2011)



SNLS3: Uncertainties on SNe distances

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

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



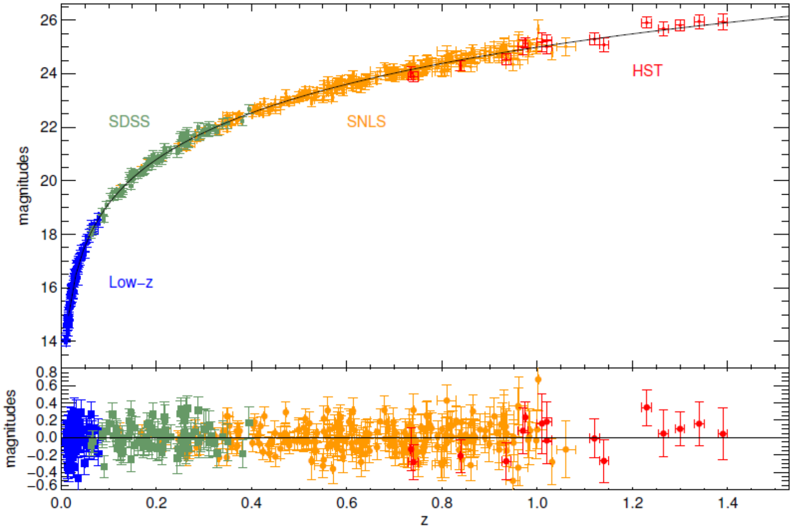
SNLS3: External data sample
(Conley 2011)

Sample	Redshift range	N_{SNe}	Ref.
Low-z	0.01 - 0.10	123	Hamuy (1996), Riess (1999), Jha (2006), Hicken (2009) ...
SDSS	0.06 – 0.4	93	Holzman (2009)
SNLS3	0.08 – 1.05	242	...
HST	0.7 – 1.4	14	Riess 2007

More systematic uncertainties for each survey:

- calibration
- survey incompleteness (Malmquist bias)

SNLS3: Hubble diagram

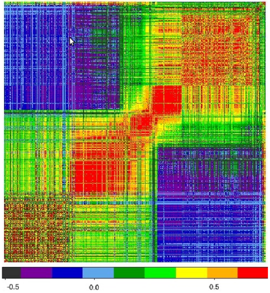


SNLS3: Other systematics

(other than light curve fitter, calibration, selection)

- Peculiar velocities for low-z SNe
- Contamination by Core collapse SNe for high-z SNe
- Evolution of color-luminosity relation with redshift
- Evolution of SNe with z : age of stellar population or metallicity
- Gravitational magnification

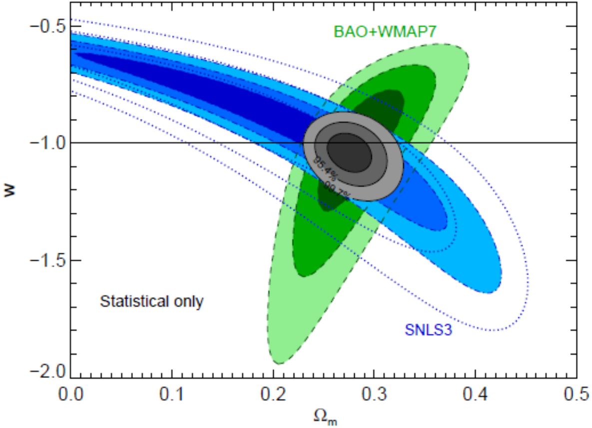
- about 200 different systematics (S_k) identified.
- Conversion of those systematics into a covariance matrix of SNe distance moduli (μ_i) $C_{sys,ij} = \sum_k \frac{\partial \mu_i}{\partial S_k} \frac{\partial \mu_j}{\partial S_k} (\Delta S_k)^2$



Cosmological constraints

SNLS-3 + SDSS-DR7 BAO + WMAP-7, Sullivan 2011

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

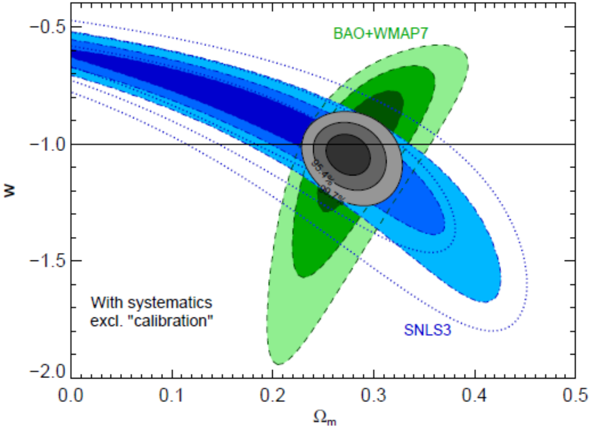


$$w = -1.043^{+0.054}_{-0.055} \text{ (stat)}$$

Cosmological constraints

SNLS-3 + SDSS-DR7 BAO + WMAP-7

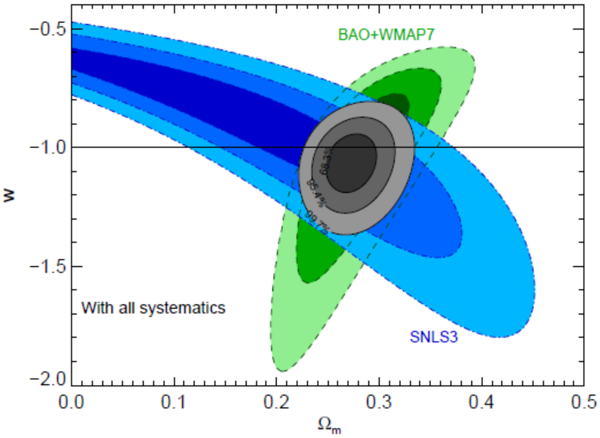
Constraints in Ω_M w plane, for $\Omega_k = 0$



$w = -1.048^{+0.057}_{-0.058}$ excluding calibration systematics

Cosmological constraints
SNLS-3 + SDSS-DR7 BAO + WMAP-7

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



$$w = -1.068^{+0.080}_{-0.082} \text{ (stat+sys)}$$

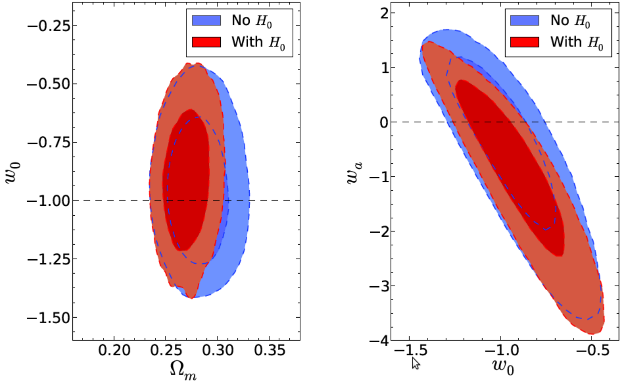
Cosmological constraints

SNLS-3 + SDSS-DR7 BAO + WMAP-7 + H_0 prior

Not much constraints on a varying w : $w(a) = w_0 + w_a(1-a)$

(with $a = 1/(1+z)$ the scale factor).

SNLS3+WMAP7+SDSS DR7 LRGs



$w_a = -0.535^{+1.109}_{-1.111}$ (stat+sys) (without H_0 constraints)

Conclusions 1/3

SNLS 3 year analysis

- 242 high-z SNe Ia in the Hubble diagram
- Dark Energy equation of state $w = -1.068^{+0.080}_{-0.082}$ (stat+sys) when combined with most recent BAO and CMB results
- SNe Ia are still the most precise probe for Dark Energy
- Uncertainty on w dominated by calibration uncertainties (± 0.058 without calib. sys.)
- Evidence for some evolution of SNe with redshift : observed correlation of SNe brightness with host galaxy properties (corrected for in cosmology fit)

Conclusions 2/3

On-going work on SNLS full (5 year) data set

- Reduction of SNLS final data set (about 450 SNe Ia) with improved techniques (for instance accounting for proper motion of stars in calibration)
- New observations for calibration
  - Intercalibration of SNLS and SDSS
  - Direct observation with CFHT of HST standard stars
  - R&D of instrumental calibration (SNDICE project)
- Improved light curve fitting with joined SNLS+SDSS effort
- Environmental studies, spectroscopic studies for SNe physics, photometric identification, SNe rates ...

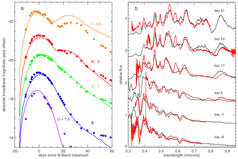
Conclusions 3/3

What is the future of SNe cosmology ?

- Short/mid-term: Pan-Starrs and DES are similar to SNLS, so the same difficulties (systematics) are expected.
- Long-term: LSST will find and monitor several 10000 SNe Ia. New methods are needed for identification and systematics.
- A bright possible future : a space-based SNe survey with IR observations (Astier 2011).
  - EUCLID + a filter wheel (in the visible channel) for 18 month
  - 13000 SNe Ia upto $z = 1.5$ (without selection bias)
  - much lower impact of systematics lead to a precision of 0.03 on w.

Backup slides : Tests of SNe evolution

Evolution Tests



We know what SNe Ia are: we are able to simulate explosions in qualitative agreement with observations. However, we don't know exactly what are the companions that feed the white dwarf.

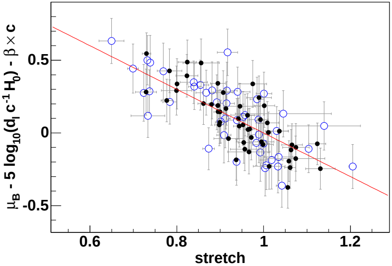
Potential sources of evolution:

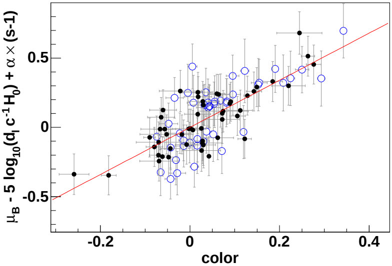
- Different progenitors types with different lifetimes
- One single progenitor type with correlation between lifetime and luminosity
- Luminosity vs Metallicity
- Change of dust amount and properties

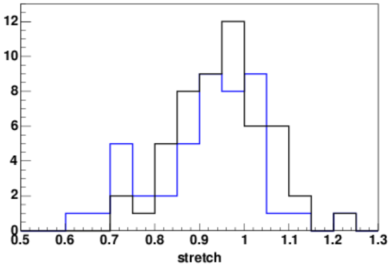
Two kinds of evolution tests:

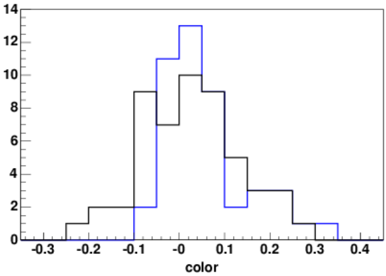
- Compare low- and high-redshift events (Bronder et al. 2007)
- More sensitive: compare events at similar redshifts as a function of their **host galaxy properties** (star formation rate, metallicity).

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









brighter-slower relation

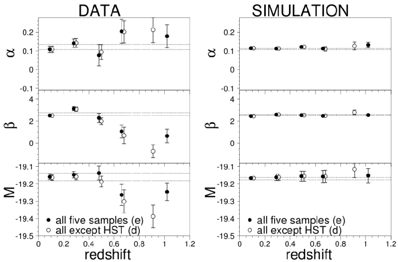
brighter-bluer relation

Evolution of the color-luminosity relation

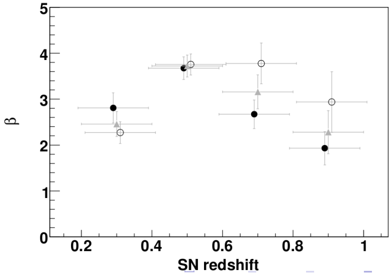
$$\mu_B = m_B^\star - \mathcal{M}_B + \alpha \times shape - \beta \times color$$

Kessler (2009) finds an evolution of β with redshift.
With an improved modeling and a better treatment of uncertainties: no clear evidence.

SDSS (Kessler 2009)



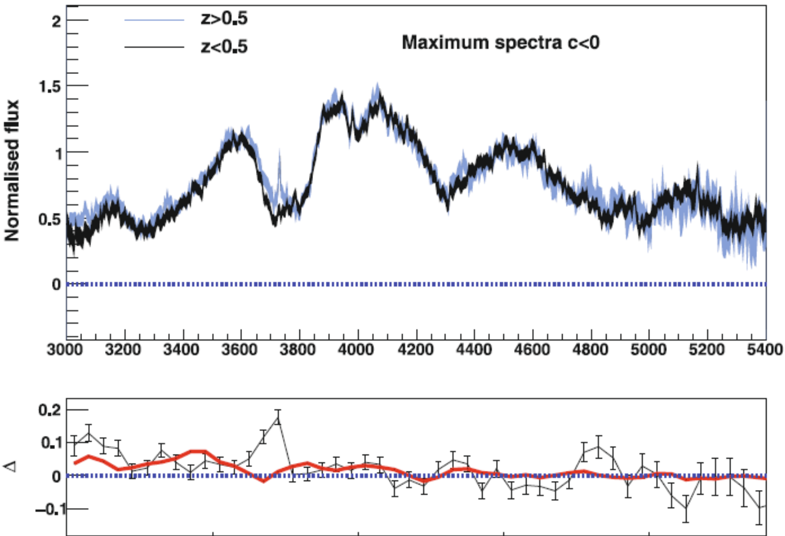
SNLS3



Evolution test: Spectra vs z

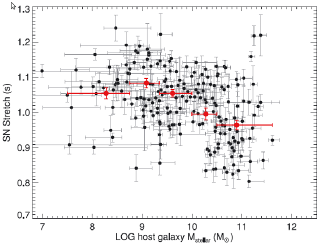
Balland (2009)

SNLS VLT spectra compared in two redshift bins.



Evolution test: Standardization Parameters vs. Host Galaxy Type

Sullivan (2010)



SNe in massive hosts (mostly passive ellipticals) have smaller stretch factors. They appear brighter (after correction for stretch and color relations) at $\simeq 4\ \sigma$.

$\rightarrow$ similar result found on low-z sample (Kelly 2010)

$\rightarrow$ and by SDSS (Lampeitl 2010)

$\rightarrow$ we account for this in SNLS3 cosmology fits

$\rightarrow$ future surveys will need to do the same (if signal is confirmed)

Evolution test: Standardization Parameters vs. Host Galaxy Type

Comparison with models

Galaxy mass $\simeq$ correlates with metallicity (bigger=older).

- observations: brighter SNe Ia in metal-rich galaxies after lightcurve shape correction
- theory: brigher SNe Ia in metal-poor galaxies
- Kasen 2009: both brightness and lightcurve width decrease with metallicity

Effect modifies zeropoint of width luminosity relation.