Mesure de l'équation d'Etat de l'Energie Noire avec le Supernova Legacy Survey

Vers une cosmologie de précision.

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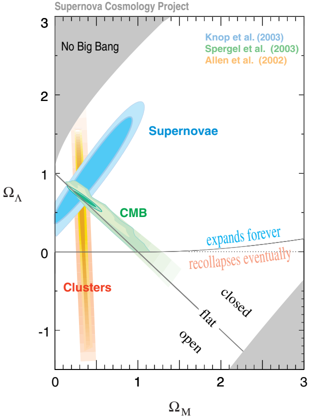
Séminaire IPHC

Outline

Outline

Dark Energy



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).

- Cosmological constant ?
- rolling scalar field ?
- modified gravity ?

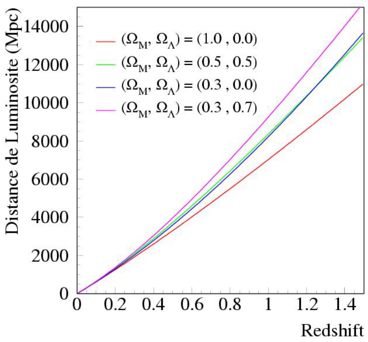
Dark Energy Equation of State

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

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

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

Luminosity Distance



Standard Candles

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

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

Luminosity Distance

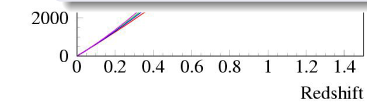
Exact or quasi-degeneracies

- 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)

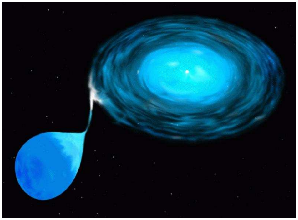
$\Rightarrow$ if $w(z)$ arbitrary, relation between Ω_m and $w(z)$

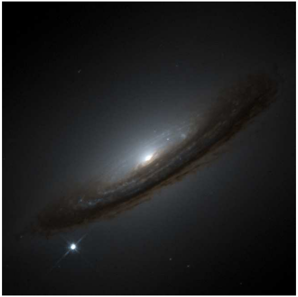
$\Rightarrow$ even assuming a constant w, there remain a strong degeneracy



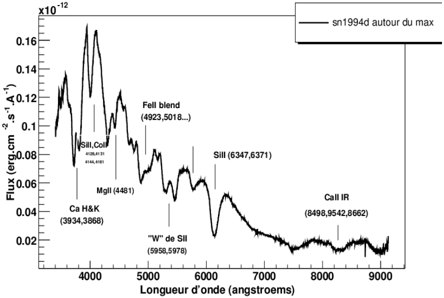
$$d_L(z) = (1+z)\frac{c}{H_0}\int dz'\left(\Omega_M(1+z')^3 + (1-\Omega_M)\exp\left(\int_0^z 3\frac{1+w(z')}{1+z'}dz'\right)\right)^{-1/2}$$

Type Ia Supernovae

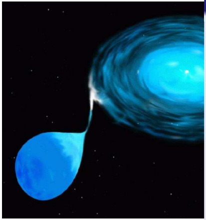




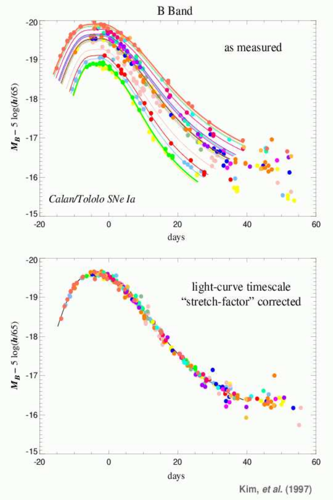
- very luminous ($10^{10} - 10^{11} L_\odot$)
- can be identified (spectra)
- fluctuations of $L_{max} \sim 40\%$
- can be reduced to $\sim 14\%$



Type Ia Supernovae



Standardizable Candles

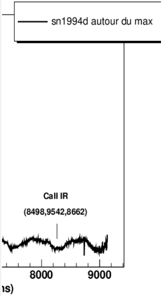


$.0 - 10^{11} L_{\odot})$

spectra)

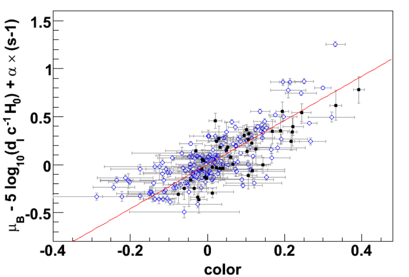
$ax \sim 40\%$

$\sim 14\%$



Standardization Relations

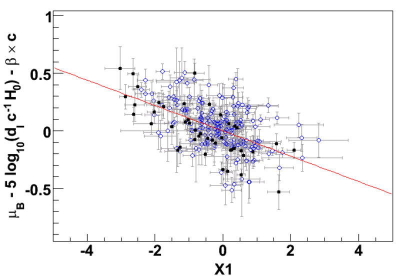
Brighter-Bluer



Hul

diagram residuals
(no color corrections applied)
as a function of color.

Brighter-slower

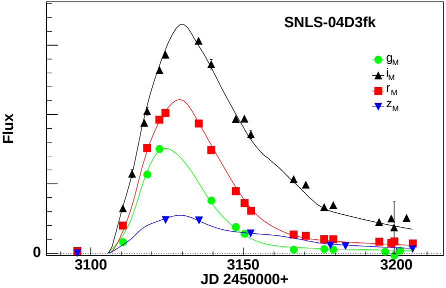


Hub

diagram residuals
(no stretch corrections applied)
as a function of stretch.

Measuring Luminosity Distances w/ SNe Ia

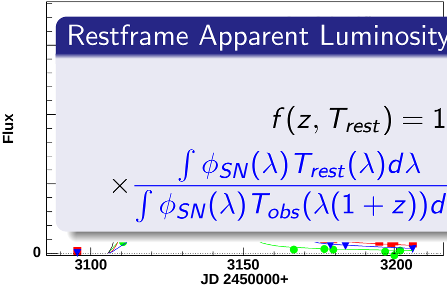
$$\frac{f(z_1, T_{rest})}{f(z_2, T_{rest})} = \left(\frac{d_L(z_2)}{d_L(z_1)}\right)^2$$



- 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

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



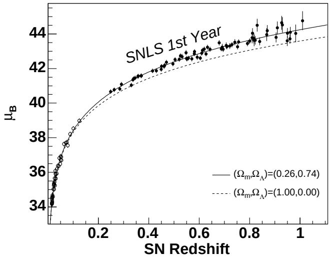
Restframe Apparent Luminosity

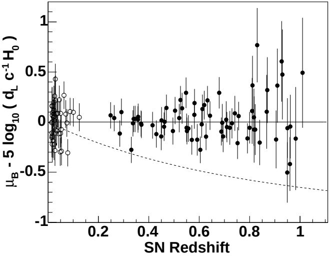
$$f(z, T_{rest}) = 10^{-0.4(m(T_{obs}) - m_{ref}(T_{obs}))} \times \frac{\int \phi_{SN}(\lambda) T_{rest}(\lambda) d\lambda}{\int \phi_{SN}(\lambda) T_{obs}(\lambda(1+z)) d\lambda} \int \phi_{ref}(\lambda) T_{obs}(\lambda) d\lambda \quad (1)$$

of

- color ⇒ 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

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

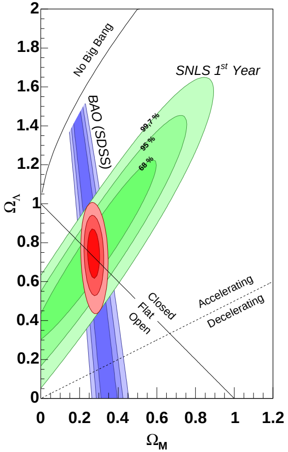
Cosmological Fit

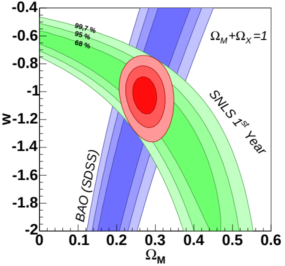
$$\chi^2 = \sum_i \frac{\mu_{B_i} - 5 \log_{10} d_L(\theta, z_i)^2}{\sigma^2(\mu_{B_i}) + \sigma^2_{int}}$$

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

Confidence Contours

Astier et al, 2006





- 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)

Outline

The Supernova Legacy Survey

$O(1000)$ SNe Ia – $10\times$ present statistics

- detected before maximum
- followed-up in 4 passbands (g_M, r_M, i_M, z_M) ($\sim$ SDSS bands)
- a good sampling of the lightcurves (1 point every 3 days)
- spectroscopic identification of all the SNe Ia

Justifications

- Large statistics $\longrightarrow$ better control of the systematics
- One detector $\longrightarrow$ control of calibration & selection bias
- Multiband obs. $\longrightarrow$ follow same spectral region @ different z

BV @ $z \sim 0$	$\longrightarrow$	gr @ $z \sim 0.2$
	$\longrightarrow$	ri @ $z \sim 0.4$
	$\longrightarrow$	iz @ $z \sim 0.8$

- Multiband obs. $\longrightarrow$ redundant measurements of distances

A Large Photometric Survey . . .

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

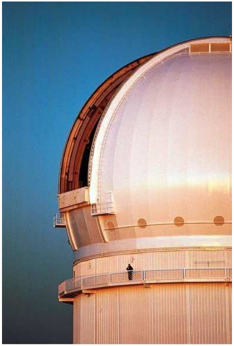
- CFHT @ Hawaii

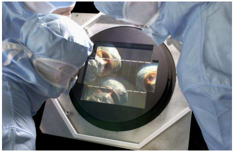
Wide Field Camera

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

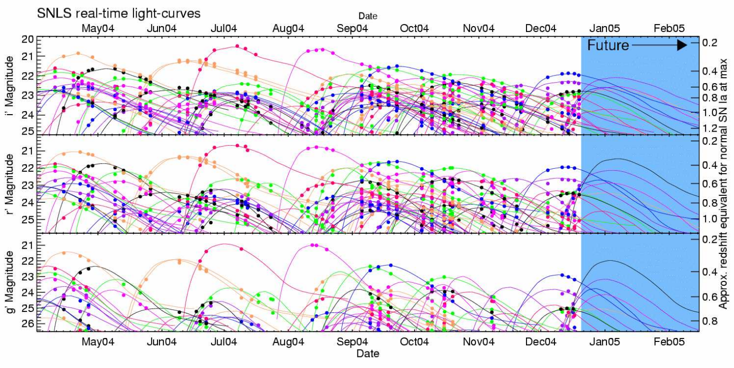
***Rolling search* mode**

- 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)





. . . Operated in Rolling Search Mode



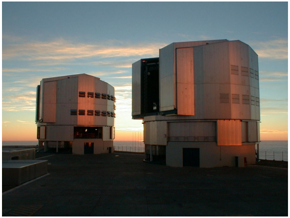
A Large Spectroscopic Survey

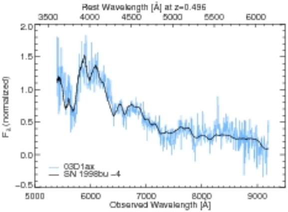
Goals

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

Telescopes

- VLT large program (80h / semester)
- Gemini (60h / semester)
- Keck (30h / semester, Spring Semester)





(Howell et al, 2005 – ApJ 634, 1190)

Statistics

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

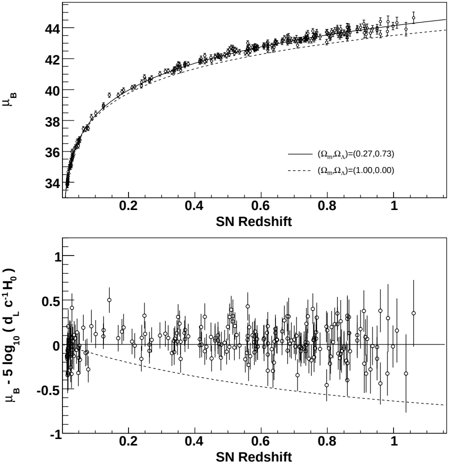
Sept. 2006

Telescope	SNIa (/?)	SNII (/?)	Total SN (/?)	Other	Total
Gemini	96	9	151	0	151
Keck	77	21	139	4	143
VLT	120	22	235	13	248
Total	293	52	525	17	542

$\sim$ 300 Identified Type Ia Supernovae on disk

$\sim$ 500 Identified Type Ia Supernovae at the end of the Survey

SNLS 3 Year Hubble Diagram – Preliminary



Distance Estimator

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

Objects

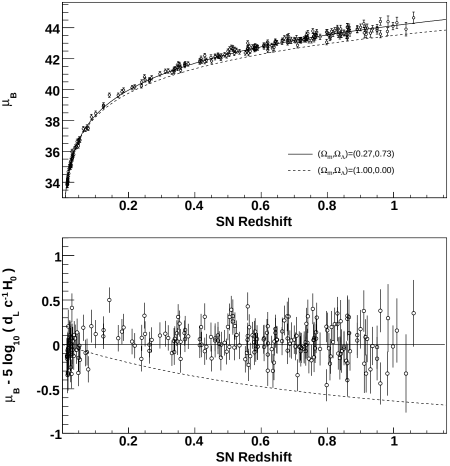
- 44 nearby SNe Ia
- $\sim$ 250 SNLS SNe Ia

Cosmology

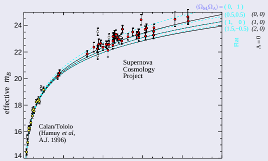
$$\chi^2 = \sum_i \frac{\left(\mu_{B_i} - 5 \log_{10} d_L(\theta, z_i)\right)^2}{\sigma^2(\mu_{B_i}) + \sigma_{int}^2}$$

- Minimize w.r.t. θ, α, β and $\mathcal{M}$.
- σ_{int} so that $\chi^2 = \mathrm{NDOF}$
- marginalize over α, β and $\mathcal{M}$.

SNLS 3 Year Hubble Diagram – Preliminary



1999 Hubble Diagram



- ∼ 250 SNLS SNe Ia

Cosmology

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

- Minimize w.r.t. θ, α, β and $\mathcal{M}$.
- σ_{int} so that $\chi^2 = \mathrm{NDOF}$
- marginalize over α, β and $\mathcal{M}$.

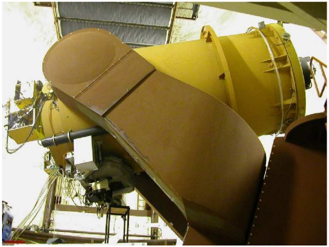
Current Surveys
Nearby Supernova Surveys

Nearby Factory: $z \sim 0.05$

- 500 deg^2 / day
- Integral Field Spectrometer
- 5 years, from 2003.

SDSS-II: $z \sim 0.35$

- 300 deg^2, *ugriz*-bands, 3 years from 2005.
- $\sim 300+$ SNe Ia.



Current Surveys

Intermediate and Distant Supernova Surveys

SNLS @ CFHT: $0.2 < z < 1$

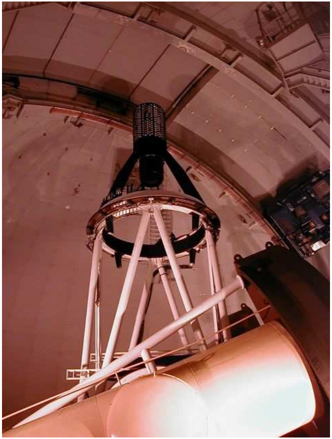
- 4 deg^2, *ugriz*-bands, 5 years, started in 2003.
- $\sim$ 500 SNe Ia.

ESSENCE @ CTIO: $0.2 < z < 0.8$

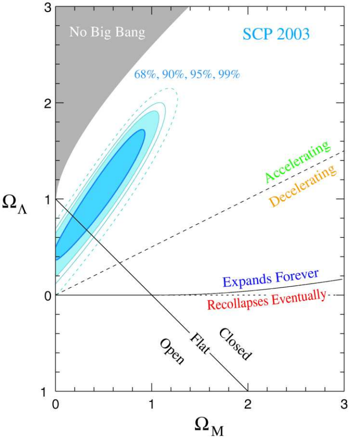
- 8 deg^2, *RI*-bands, 5 years, started in 2002.
- $\sim$ 200 SNe Ia.

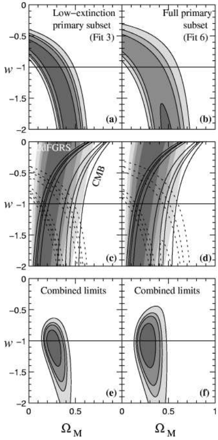
HST/ACS $z > 1$

- PANS (Riess et al), $\sim$ 50 SNe, $< z > \sim 0.8$



Recent Constraints on w
Knop et al, 2003

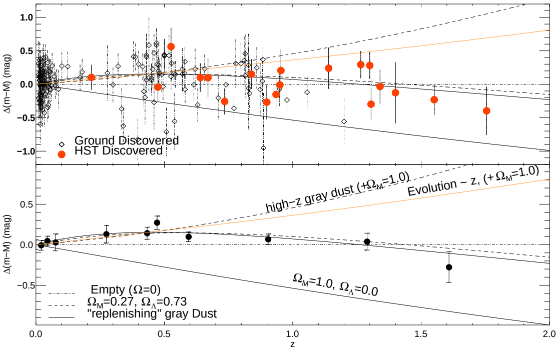




$$w = -1.05^{+0.15}_{-0.20}(stat) \pm 0.09(sys)$$

Recent Constraints on *w*

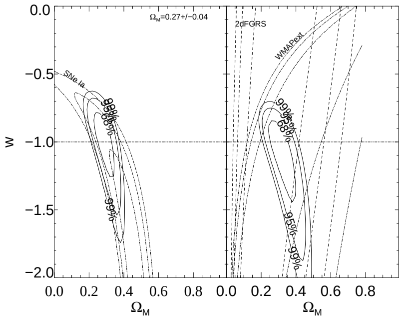
Riess et al, 2004 (GOOD/ACS Survey)

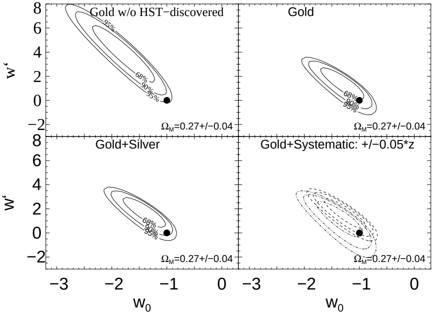


- in the past, dark matter was dominating, Universe was *decelerating*
- excludes the grey dust hypothesis

Recent Constraints on w

Riess et al, 2004





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

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

Future Programs

Ground Based Projects

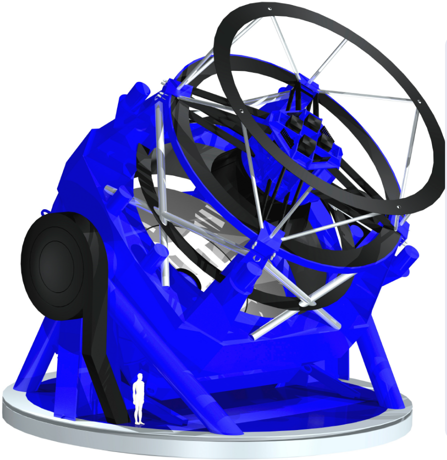
- Pan-Starrs (@HAWAII): 4 1.5-m telescopes, FOV=3 deg^2
- Dark Energy Camera (@CTIO) FOV=3 deg^2, *griz*
- Large Synoptic Survey Telescope: one 8-m telescope, FOV=9 deg^2 (250000 SNe/year)

SNe Ia from Space

- JDEM/SNAP: 2-m telescope, 1 deg^2 FOV, $0.35\mu m - 1.7\mu m$ spectrograph
- DUNE: 1.5-m telescope, 0.5 deg^2 FOV, 5 filters. No spectrograph

LSST

Design Telescope and Camera as a Single Instrument



- 8.4-m primary aperture
  - $\sim$ 6-m equivalent aperture
- 9 deg^2 FOV
- 3.2 GigaPixel Camera
  - $\sim$ 200 4k$\times$4k CCDs
  - 6 filters
  - 65 cm diameter
- 30 sec Cadence
- Acc Depth: 27 mag (10 yr)
- 18Tb / night

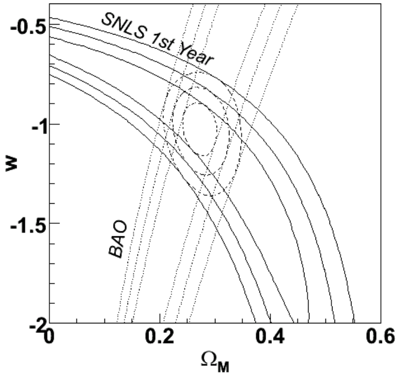
LSST

6-band Survey: *ugrizy* 320–1050 nm

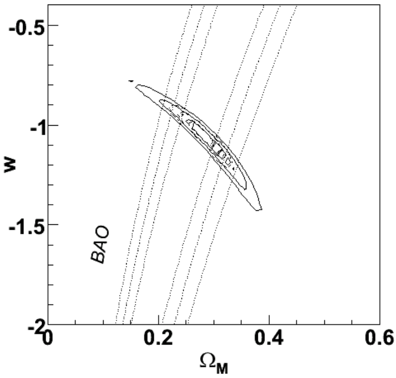
- Sky area covered: 20,000 deg^2 0.2 arcsec / pixel
- Each 9.6 sq.deg FOV revisited >300 times/band
- Time resolution: >20 sec
- Limiting magnitude: 26.5 AB magnitude @10σ (24.5 in u)
  24 AB mag in 15 seconds
- Photometry precision: 0.01 mag requirement, 0.005 mag goal
- Galaxy density: 50 galaxies/sq.arcmin
- 3 billion galaxies with color redshifts
- Time domain: Log sampling, seconds – years

Outline

Statistical Improvements



44 Nearby SNe
71 Distant SNe (SNLS)



1000 Nearby SNe
2000 Distant SNe

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

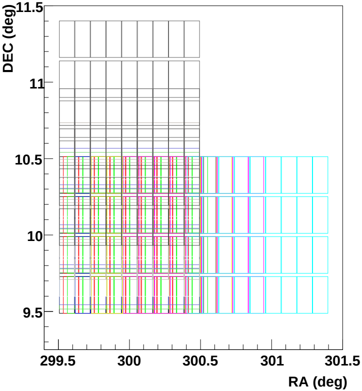
Identified Sources of Systematics

- Photometric calibration & modeling of the passbands
- Empirical modeling of lightcurves
  - restframe region used: $(B, V)) \rightarrow (U*, B)$ at large z
  - modeling of the SED in the far-UV 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

Photometric Calibration

- Internal calibration
  - linearity
  - uniformity
  - repeatability (stability of the calibration procedure)
- ADUs → magnitudes
  - calibration into a photometric system (which relies on one primary spectrophotometric standard)
- magnitudes → physical fluxes
  - integrate the (measured) primary standard spectrum into the instrument transmissions.

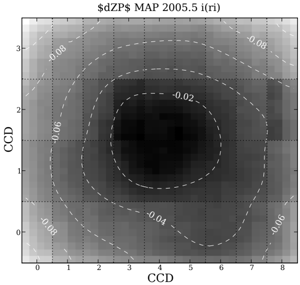
Photometric Calibration
Uniformity

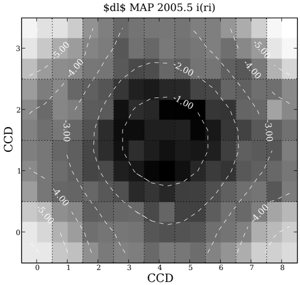


- Modeling the non-uniformities of the photometric response
  - Plate scale variations
  - scattered light
- Dense stellar fields (`RA=20:00:00`, `DEC=10:00:00`)
- 13 dithered exposures variable steps: $\sim$ 100 pixels $\longrightarrow$ half a camera
- Reobserved after each significant modification of the optics
- No control observations

- grid corrections applied to the pixels by the `Elixir` pipeline (*scatter flats* or *photometric flats*)

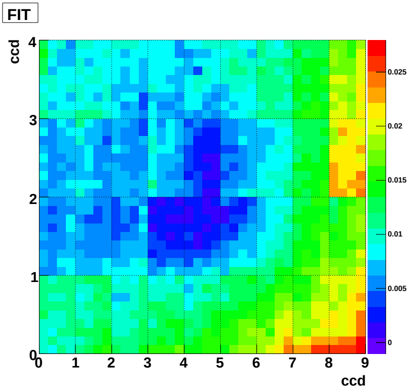
Photometric Calibration
Uniformity



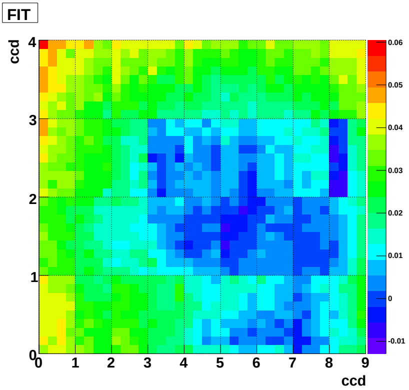


Photometric Calibration

Instrument uniformity

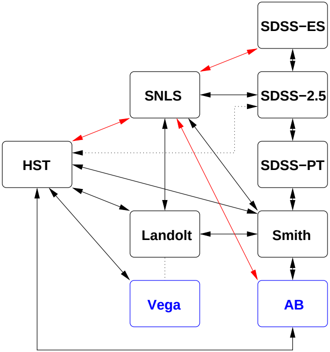


2003B (Elixir Corrected)

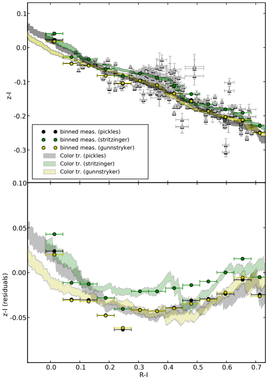


2005B (Elixir Corrected)

Photometric Calibration
Magnitude Systems



Calibration system determined by the Nearby SN sample



(g: 2%, ri: 1%, z: 3%)

Photometric Calibration
Physical Spectrum of the Reference Star

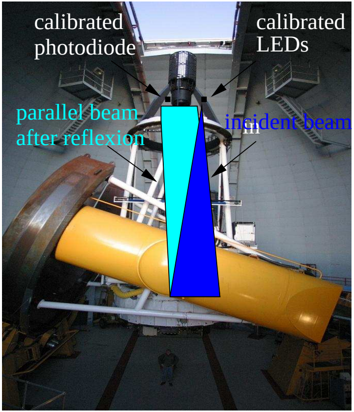
- Luminosity distance ratios are a function of the reference spectrum integrated flux ratios in distinct bands:

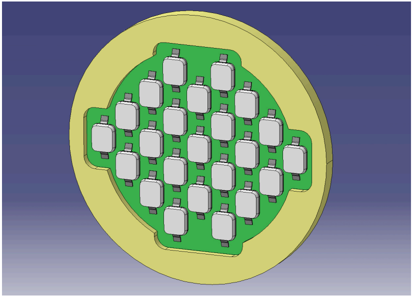
$$\left(\frac{d_L(z_2 = 0.5)}{d_L(z_1 = 0)}\right)^2 = \propto 10^{-0.4(m_{ref}(R)) - m_{ref}(B)} \frac{\int \phi_{ref}(\lambda) R(\lambda) d\lambda}{\int \phi_{ref}(\lambda) B(\lambda) d\lambda}$$

- New determinations of the Vega spectrum, based on WD stellar models, (Bohlin et al), compatible 0.01 with older calibrations (Hayes, 1985).

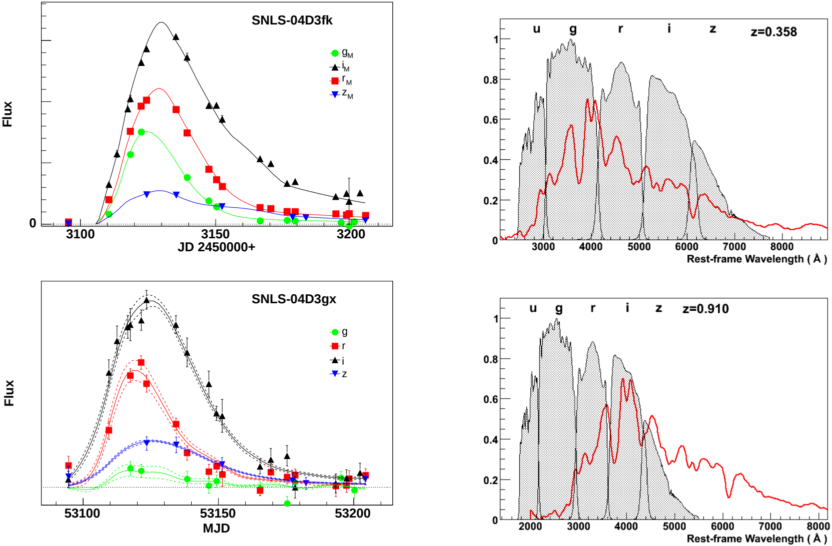
$$0.01 \text{ mag} \Leftrightarrow 250 \text{ SNe Ia at } z \sim 0.5$$

Instrumental Calibration: SNDICE





SN Ia Modeling

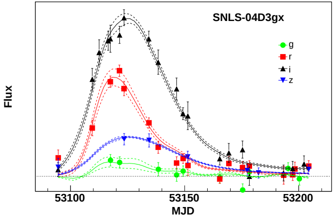


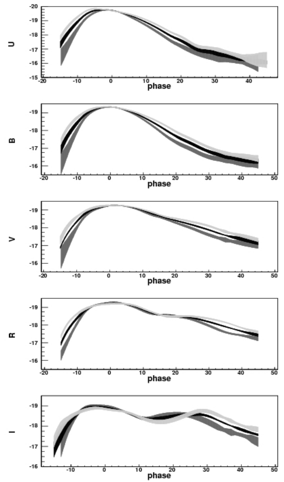
SALT2: modeling SN Ia SED in the far-UV

J. Guy et al, 2006

SALT2: J. Guy et al, 2006

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





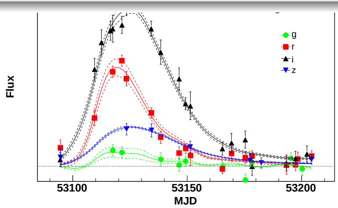
SALT2: modeling SN Ia SED in the far-UV

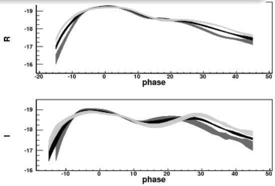
J. Guy et al, 2006

SALT2: J. Guy et al, 2006

- 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

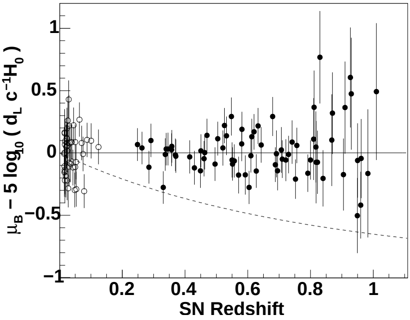
$\Rightarrow$ errors $\propto 1/\sqrt{N}$

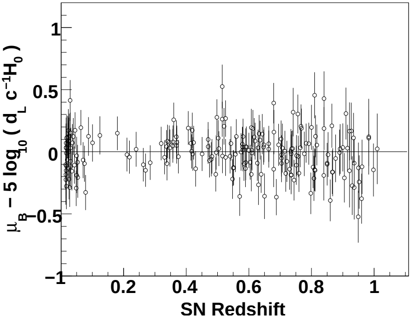




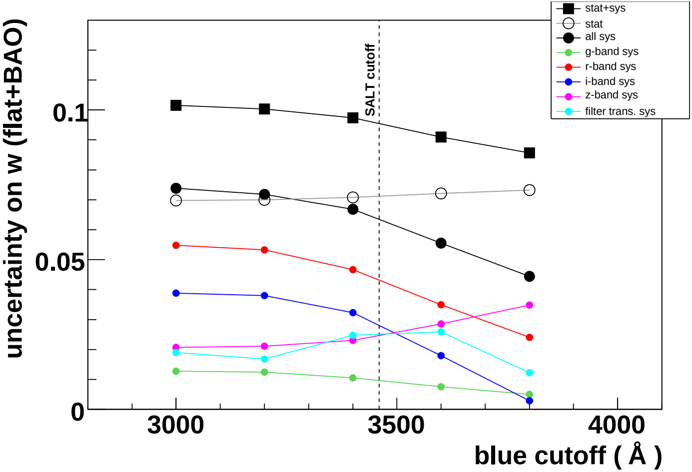
SALT2: modeling SN Ia SED in the far-UV

J. Guy et al, 2006

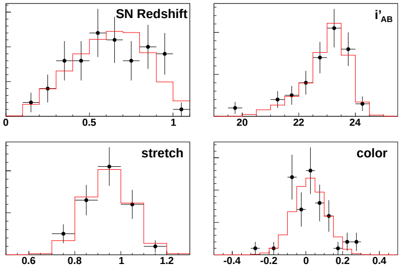


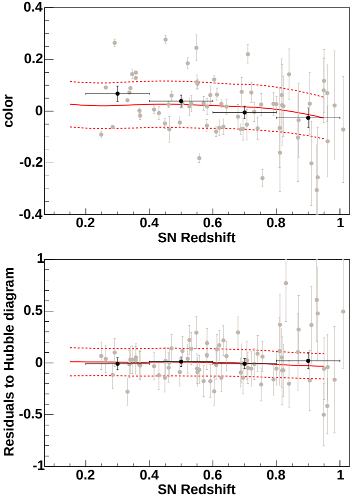


Calibration + Training



Selection Effects



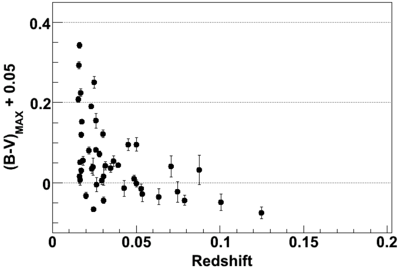


Impacts on Ω_m

- As we get closer to the detection limit, we are more likely to detect brigther (bluer, slower) supernovae
- affects nearby sample and SNLS sample
- $\delta\Omega_m$(Nearby SNe): $+0.019 \pm 0.012$
- $\delta\Omega_m$(SNLS SNe):-0.020 ± 0.010

Nearby Supernova Sample

- Only ~ 40 SNe with good lightcurve coverage at $z \sim 0,05$
- Evidences for systematic calibration errors in the U-band
- Selection bias of the nearby sample ?



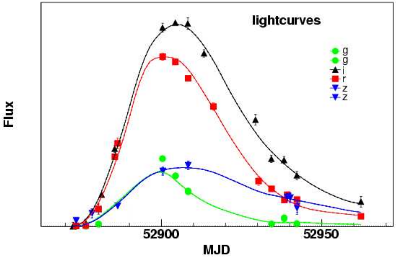
Is there a Hubble Bubble ?

- (Jha et al, 2007) says $H_0(cz < 7400 \text{ km/s}) < H_0(\text{homogeneous universe})$
- Local void in the mass density distribution
- (Conley et al, 2007), (Wang et al, 2007) show it is an artifact of the extinction corrections

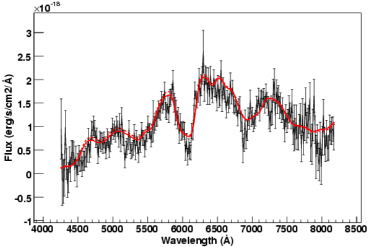
Contamination / SN Ia Identification

Combined fit of Lightcurves and Spectra

03D4dy at $z = 0.604$



Lightcurve fit (SALT2)



Spectrum fit (same model)

(Balland, Baumont, in prep).

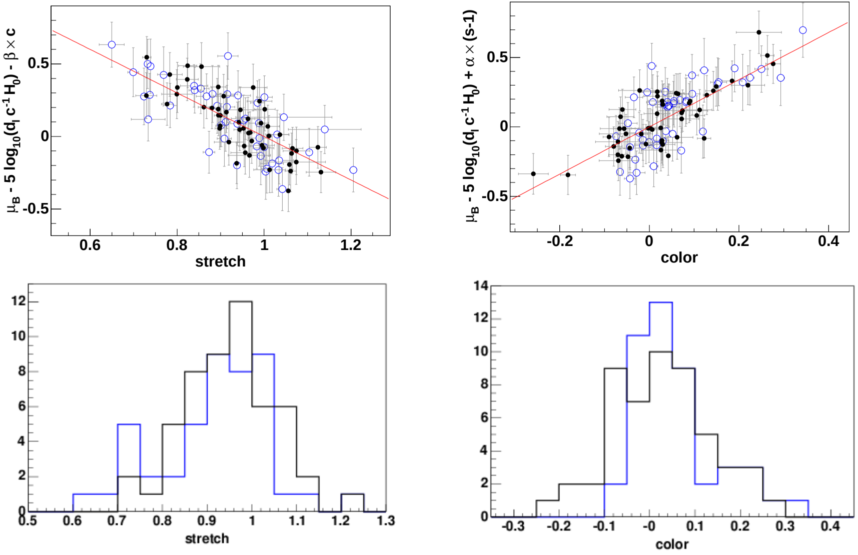
Evolution

- Different progenitors types with different lifetimes
- One single progenitor type w/ correlation between lifetime and luminosity
- Metallicity
- ...

⇒ Comparisons between high- / low-z SN observables

⇒ Comparisons SNe as a function of their host galaxy properties

Evolution

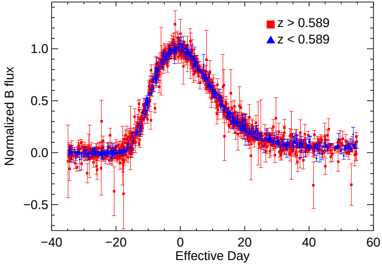

μ_B - 5 $\log_{10}(d_l\, c^{-1} H_0)$ - $\beta \times c$
stretch
μ_B - 5 $\log_{10}(d_l\, c^{-1} H_0)$ + $\alpha \times (s-1)$
color
stretch
color

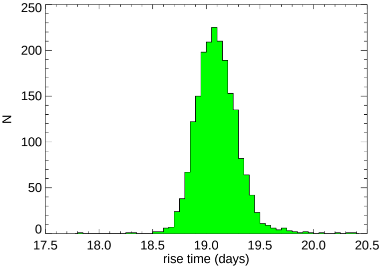
SN Ia Lightcurve Rise Time

Conley et al, 2006

SN Ia evolution check

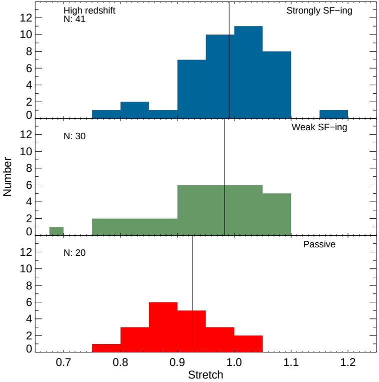
- Compare nearby and distant SN early lightcurve shape (*B*-band)
  - nearby: 19.58 ± 0.2
  - distant: $19.10 \pm 0.2(stat) \pm 0.2(sys)$





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 ?

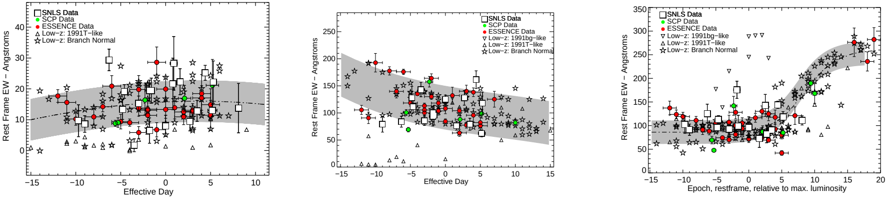
no impact on the distance measurement for the 1 year sample

Spectroscopic Measurements

Bronder et al, ApJ accepted

SN Ia evolution check (relying on spectroscopic measurements)

- No systematic offset
- Dispersion increases with z: likely to be S/N



Systematics

Many of the current "systematic uncertainties" are not systematics:

- Selection bias
- Evolution (SN Host galaxy classification)
- SN SED modeling
- gravitational lensing

Evolution

- We should see its effects when looking at the properties of SNe as a function of their host type (Sullivan et al.)
- Fit as many Hubble diagrams as there are types of galaxies
- Simple statistical test

Two major sources of systematic uncertainties today

- Flux calibration: how to convert mags into fluxes ?
- The nearby SN sample

Conclusion (I)

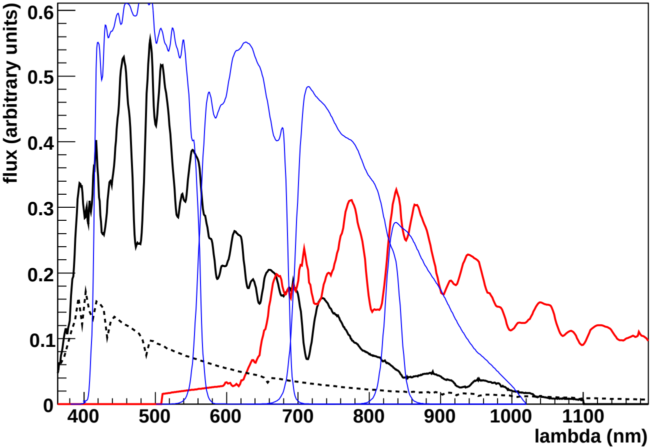
- Expected precision on w after the 2d generation surveys:

$$\pm 0.05(sys) \qquad \pm 0.05(stat)$$

- Lessons for the future
  - More and better quality Nearby SNe badly needed:
  - SDSS, Nearby Factory, SkyMapper
- Most of the known systematic uncertainties are not systematics: they can be reduced with high- statistics (nearby and distant surveys).
- Need to reduce the photometric calibration uncertainty, down to 0.1% (1-3% today).
  - internal (uniformity, stability, linearity)
  - external (standard catalogs, primary standard)

Photometric Calibration (2/5)

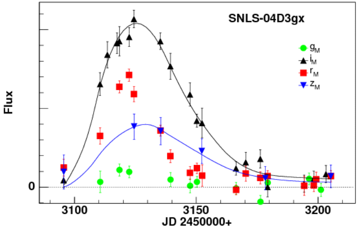
Passband Intercalibration

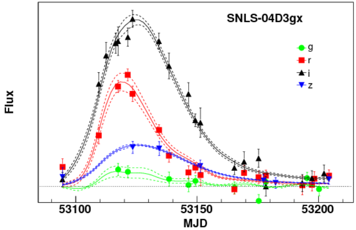


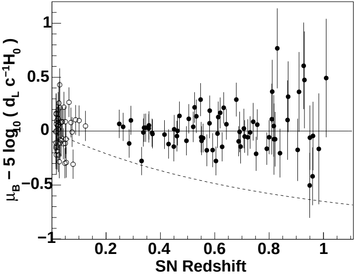
Offline Photometric Pipeline

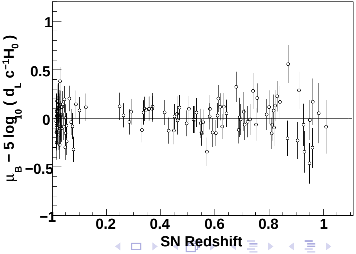
- Differential photometry
- PSF photometry of the field stars
- Calibration of the DEEP fields
- Fit of multicolor lightcurves
- Luminosity Distance Estimation
- Cosmological Results
- Systematics

SALT2

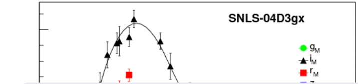

SNLS-04D3gx
g_M
i_M
r_M
z_M
Flux
0
3100
3150
3200
JD 2450000+

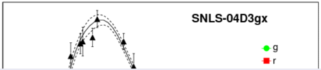

SNLS-04D3gx
g
r
i
z
Flux
53100
53150
53200
MJD


$\mu_B - 5\log_{10}(d_L\, c^{-1} H_0)$
1
0.5
0
−0.5
−1
0.2
0.4
0.6
0.8
1
SN Redshift

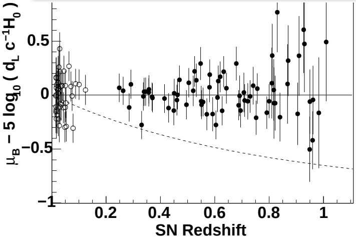

$\mu_B - 5\log_{10}(d_L\, c^{-1} H_0)$
1
0.5
0
−0.5
−1
0.2
0.4
0.6
0.8
1
SN Redshift

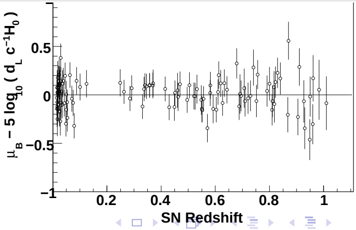
SALT2





- Same cosmology
- rms of Hubble diagram residuals 0.16 (0.20 in 1st year analysis)
- $\sigma(w)$ reduced by $\sim$ 20%
- figure of merit of DETF improved by 35%

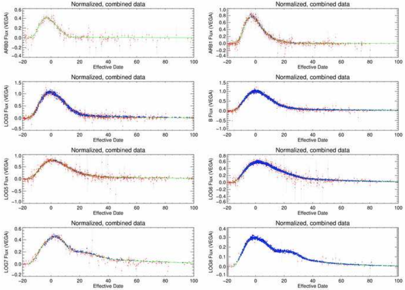




SIFTO
Canadian SALT

Objects

- Spectral sequence of (Hsiao et al, 2007)
- Lightcurve templates with dense filter set
- Trained w/ SNLS and Nearby SN photometry



Conclusion

SNLS is doing well

- $\sim$ 300 identified SNe Ia on disk
- $\sim$ 500 identified SNe Ia at the end of the survey (mid-2008)
  - impact of wheather on data taking (!)

Close to a 3-year Cosmology Analysis

- We have learned a lot during the last 3 years
  - SN modeling (UV), SN properties versus host
  - Large effort on calibration
- Statistical uncertainties improved by a factor ~ 2
- Close to the systematics limit
- Data quality allow us to improve on systematics