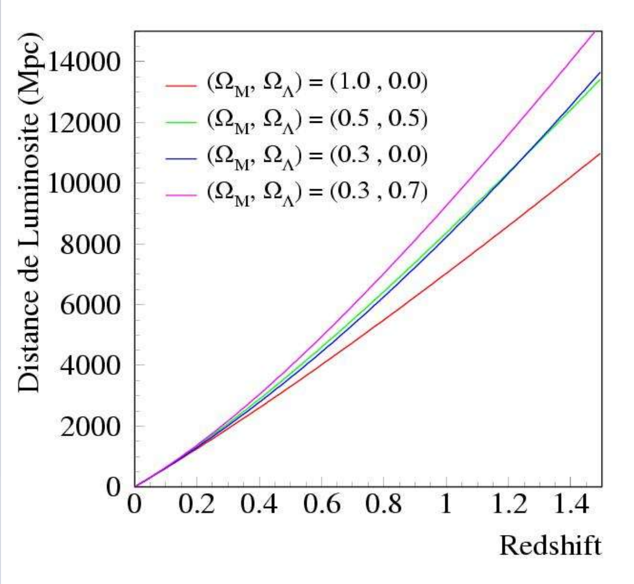
The Supernova Legacy Survey
Measurement of Ω_M, Ω_X and w from the First Year Data Set

Astier et al., astro-ph/0510447, A&A in press
http://www.cfht.hawaii.edu/SNLS

Julien Guy,
on behalf of the SNLS collaboration

Cosmology with Type Ia supernovae

Luminosity distance vs redshift $d_L(z)$



=> Direct measurement of expansion history

$$\text{For } \Omega_T = 1, \quad d_L(z) = c\,(1+z) \int_{(1+z)^{-1}}^{1} \frac{da}{\dot{a}\,a}$$

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

Type Ia supernovae (SNe Ia):

• Very bright => visible at cosmological distances M_B~-19.4 (10^{10} suns)
(can be brighter than host galaxy)

• Absolute peak magnitude with small dispersion (~0.35 mag, i.e. ~35 %)
(~ same initial conditions, white dwarf @ Chandrasekar mass)

• Correlations between light curve shapes, colors and peak brightness =>
decrease dispersion to 0.15 mag

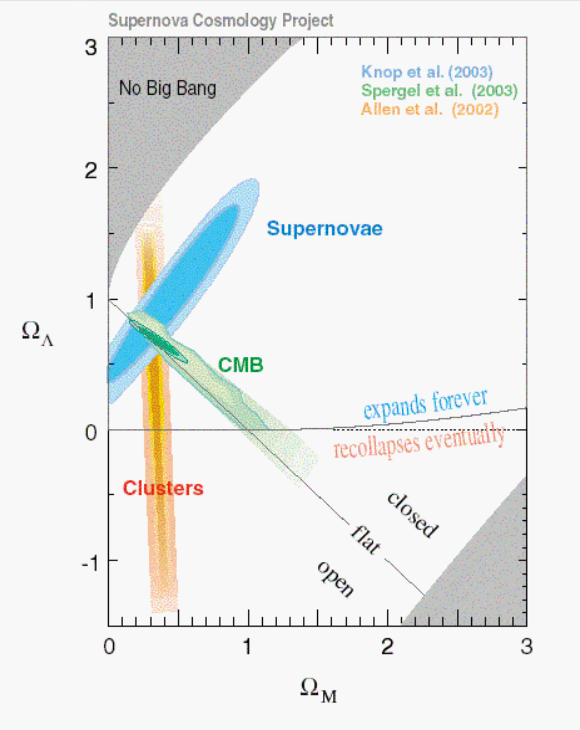
History

Type Ia Supernovae (SNe Ia):
- Riess 1998 (10(+6) SNe Ia)
- Perlmutter 1999 (42 SNe Ia)

=> Acceleration of expansion

- Allen 2002, X-ray clusters -> Ω_m
- Spergel 2003, CMB (WMAP) -> Ω_T

=> Concordance model:
Flat Universe with Dark Energy
compatible with a cosmological constant, $\Omega_\Lambda \sim 0.7$



SNe:
- Sullivan 2002 Hubble diagram vs Host galaxy type (test of evolution)
- Tonry 2003 (+8)
- Barris 2003 (+23 SNe Ia, z<1)
- Knop 2003 (+11 SNe Ia, follow-up at HST)
- Riess 2004: (+16 SNe Ia discovery at HST) up to z~1.6

- Astier 2005 (71 SNe), ~700 at the end of SNLS

SNLS

<u>Goals:</u>

- ~700 SNe Ia   z<1.1 (x10 previous statistics)
- observed in 4 bands (g,r,i,z) ~ SDSS
- good sampling of light curves
- spectroscopic identification (of all 700 SNe)

-> large statistics help controlling systematic uncertainties
-> photometry with a single telescope: better understanding of the detector

  - useful for calibration
  - better control of selection bias

-> multi-color observations :

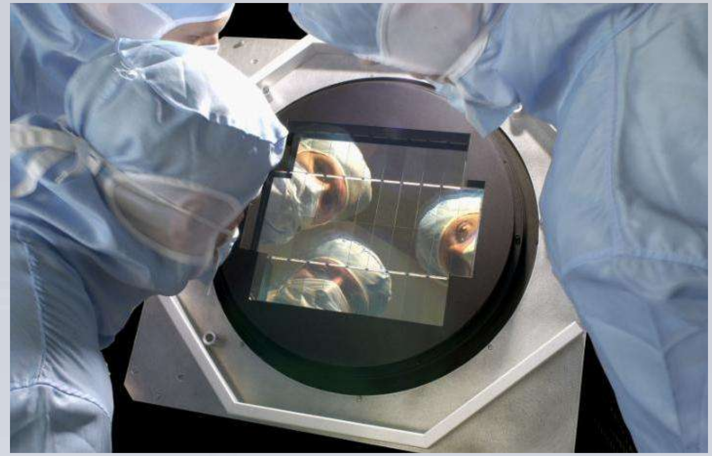
  - required to follow the same spectral region at different z:

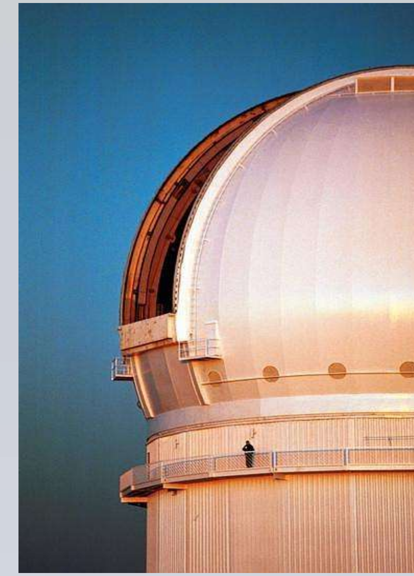
    (B,V) z=0 <=> (g,r) z=0.2
    <=> (r,i) z=0.4
    <=> (i,z) z=0.8

  - help for SNe modeling at z~0.4

Imaging survey with Megacam at CFHT (Hawaii)

CFHT : ∅ 3.6 m (1979)
Megacam (CEA/DAPNIA):
1 deg^2 , 36 CCD 2k*4K
First light, fall 2002

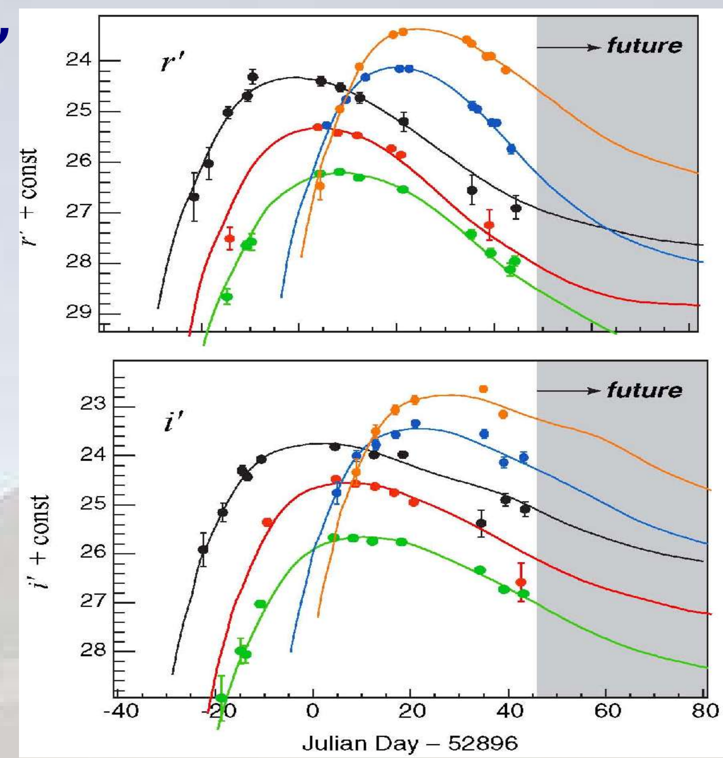




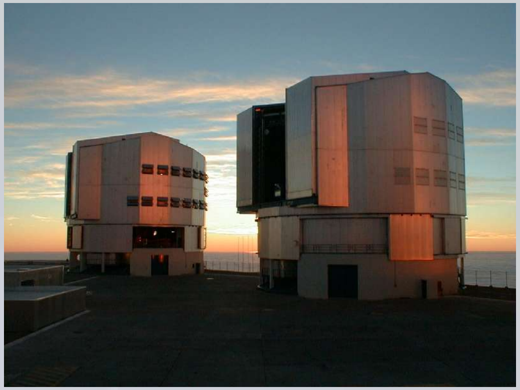
Observation strategy : "Rolling Search"

- Part of **CFHTLS/Deep survey**
- **40 nights/yr** during **5 years**
- **Repeated observations**
  (every 3-4 nights) of 4 fields
  of 1 sq. deg. each in ugriz

- Good PSF sampling, 1pix = 0.2''
- High Quality images: 0.7'' (FWHM)



The Spectroscopic survey



Goals :

- **spectral identification** of SNe up to z~1
- **redshift** (host galaxy)
- detailled study of a subsample of SNe, Type IIs (complementary programs, ...)

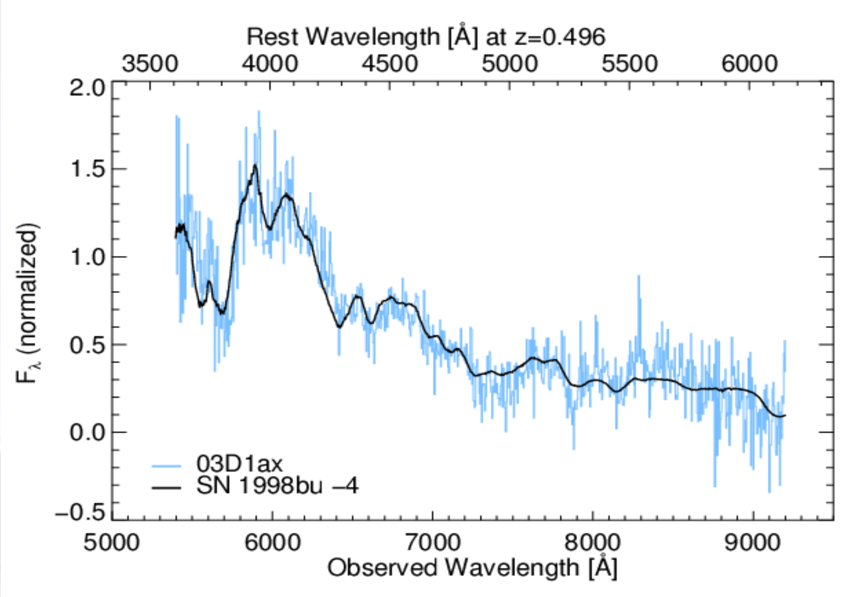
Where? :

- **VLT** Large program (service)
  240h in 2003+2004, idem 2005+2006

- **Gemini** : 60h/semester

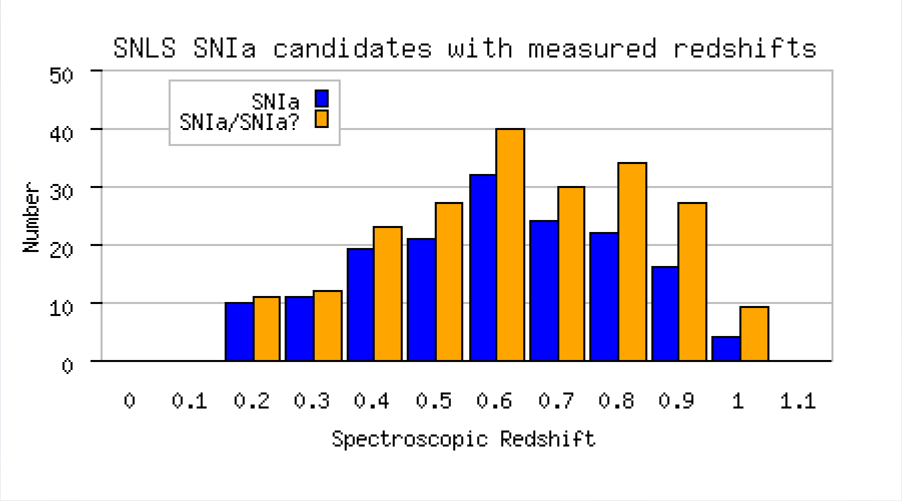
- **Keck** : 30h/an (in one semester)

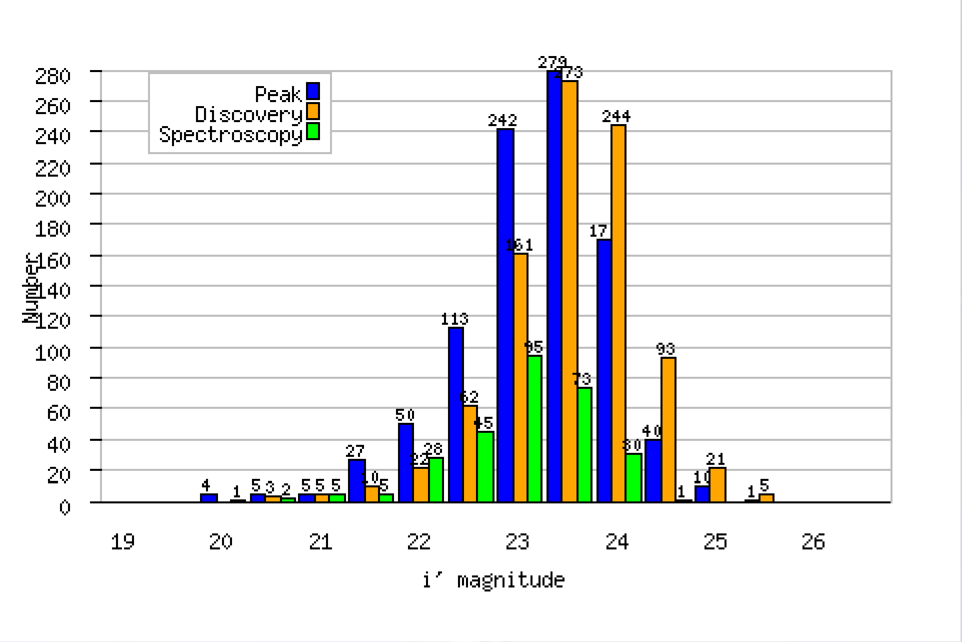
Example of an identified Type Ia SN at z=0.496
(Howell 2005, astro-ph/0509195)



SNLS Progress
as of Nov. 2005

List of SNe candidates is public: http://legacy.astro.utoronto.ca/





Telescope	SNIa/SNIa?	SNII/SNII?	Total SN/SN?	Other	Total
Gem [list]	68	8	112	1	113
Keck [list]	57	17	104	4	108
VLT [list]	101	19	170	16	186

=> 226 SNe Ia/Ia?

Analysis of the 1st year data set
Aug. 2003 – Jul. 2004

Sketch :
- Calibration of Deep fields (**anchored to Landolt system**)
- Differential photometry of SNe (and PSF photom. of stars)
- Fit of multi-color light curves
- Final selection
- Fit of cosmology
- Study of systematics

91 spectroscopically identified Ia/Ia*
- 6 lost due to bad weather or instrument failure
- 10 missing data for reference (or software limitation)

=> 75 Ia/Ia* can be fitted

=> 71 in Hubble diagram

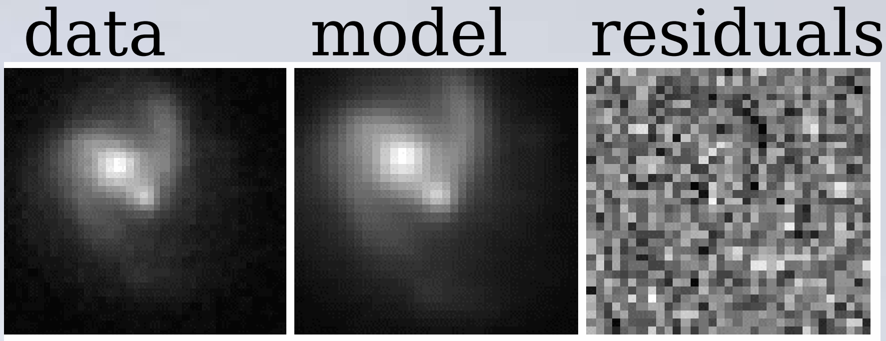
Differential Photometry of Sne light curves

- Several steps of image processing (flat-field, background subtraction, astrometric solution) + geometrical alignement + evaluation of covolution kernel from image of best quality

- Nearly optimal differential photometry:

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

- Fit galaxy(i,j) on a stamp
- Can fit constant background
- Sn flux using PSF model
- Fit accurate Sn position
(fit with about 3000 coefficients)



- Evaluate errors using dispersion of measurements per epoch.
  => errors are 12% larger than expected from pure photon statistics.
  i.e. little room for improvements

- Save full covariance matrix of fluxes for subsequent analysis

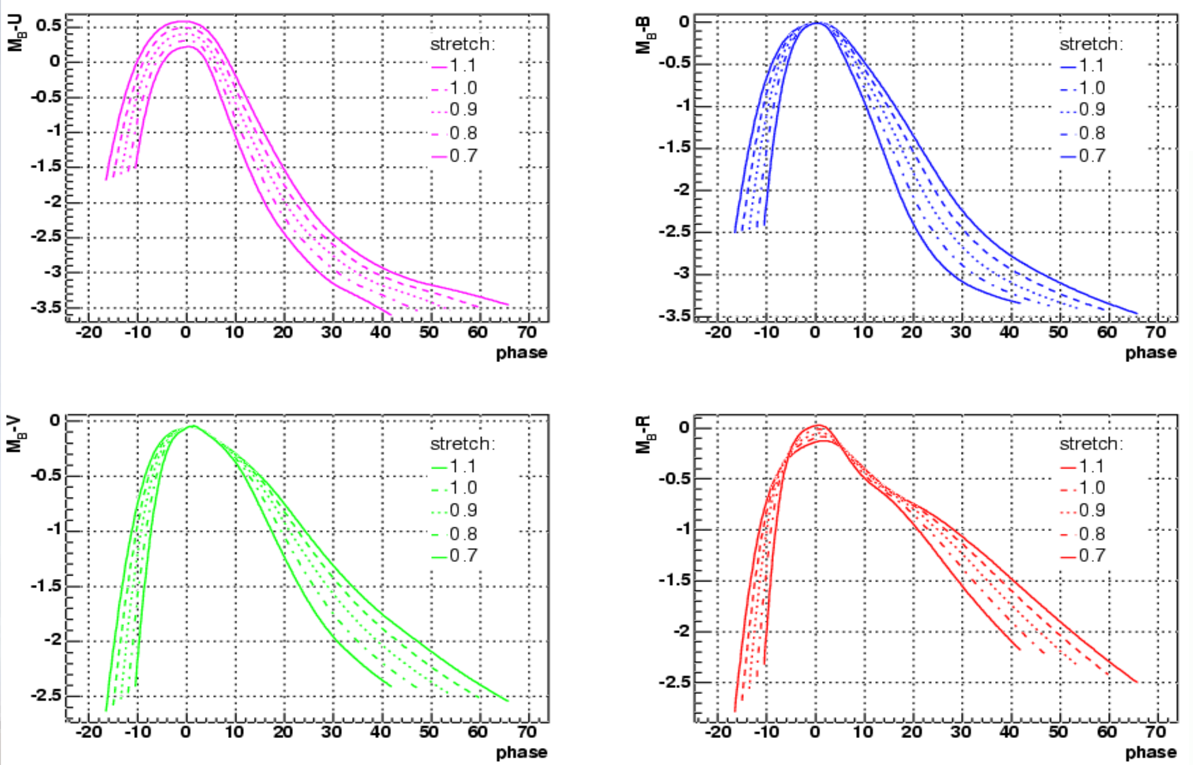
Multi-color light curve fit with a **Spectral Adaptive Light curve Template (SALT)**

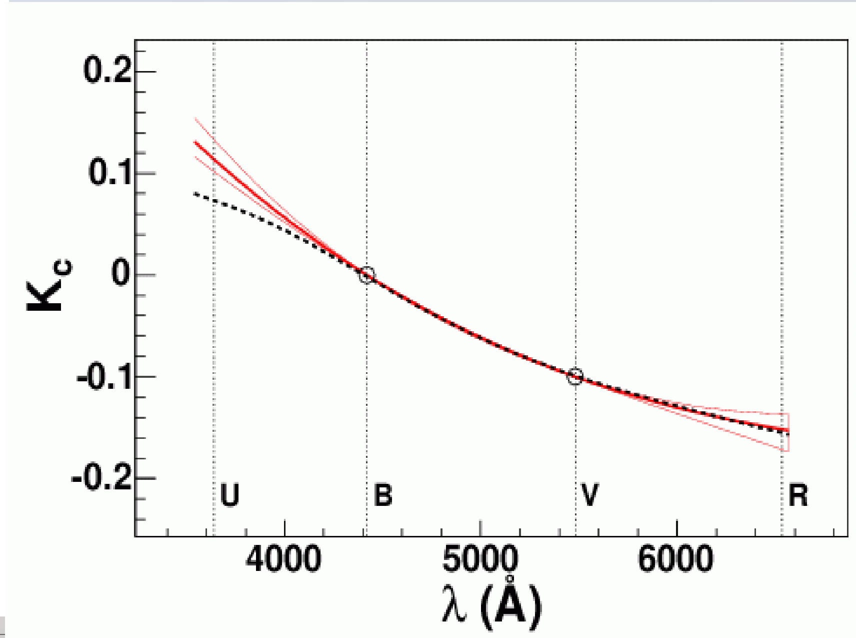
astro-ph/0506583 A&A, in press

Model SNe Ia SED as a function of

- phase (date with respect to B-band maximum)
- lambda (rest-frame wavelength)
- stretch s (dilatation of phase axis in B-band)
- color c=B-V+cst at B-band maximum

Trained with a sample of nearby SNe Ia in UBVR





Distance Estimate with SALT

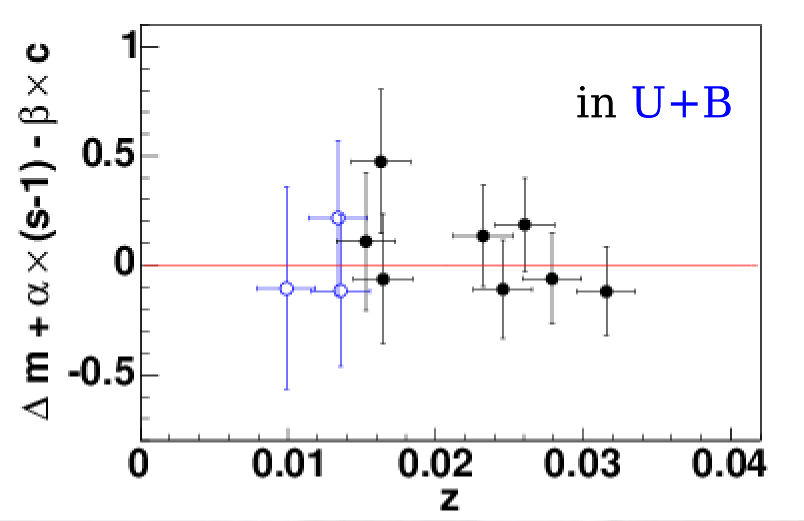
For each SN, the fit leads to 3 parameters:
global intensity (m_B), stretch (s), color (c)

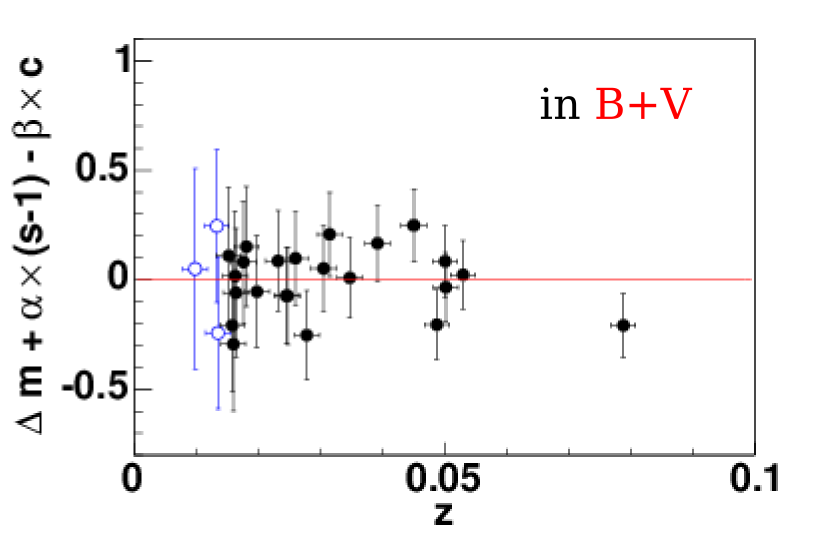
Distance estimate:

$$m_B(z) - M'_B - \alpha\,(s-1) + \beta\,c = 5\;\log_{10}\left(\frac{d_L\,H_0}{c}\right)$$

On a test sample of nearby Sne,
using either U+B or B+V bands

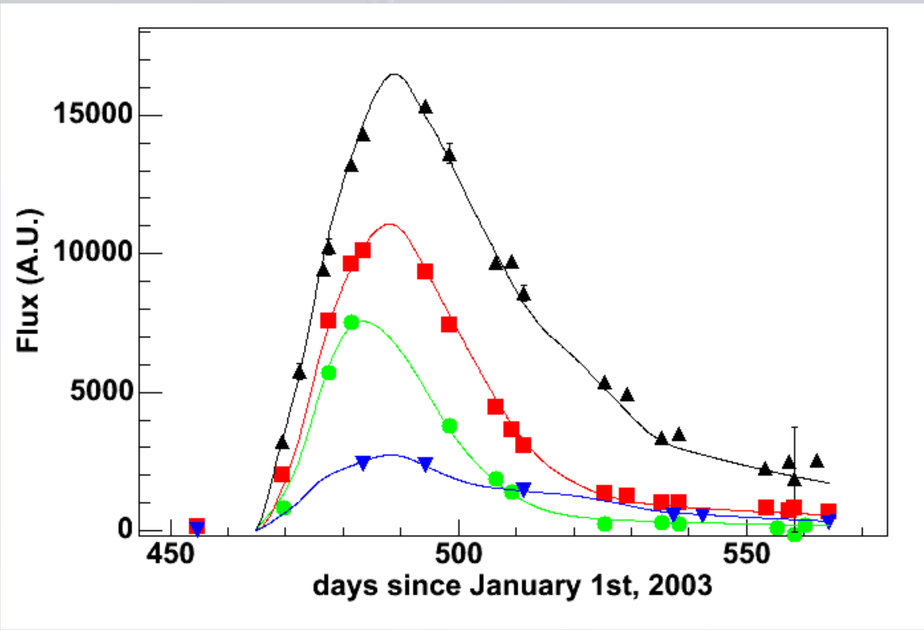
Residuals to Hubble Diagram, dispersion of ~0.16 mag :



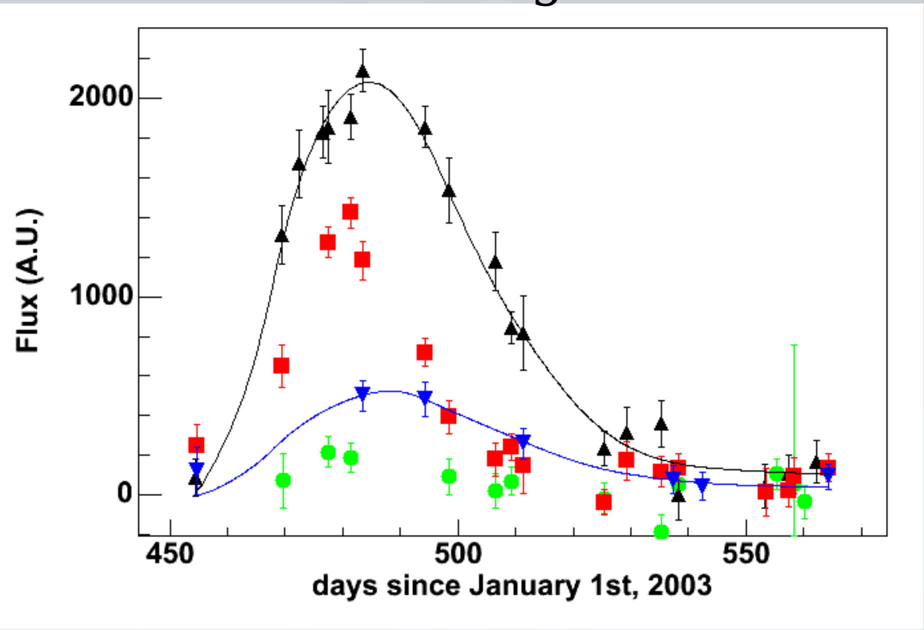


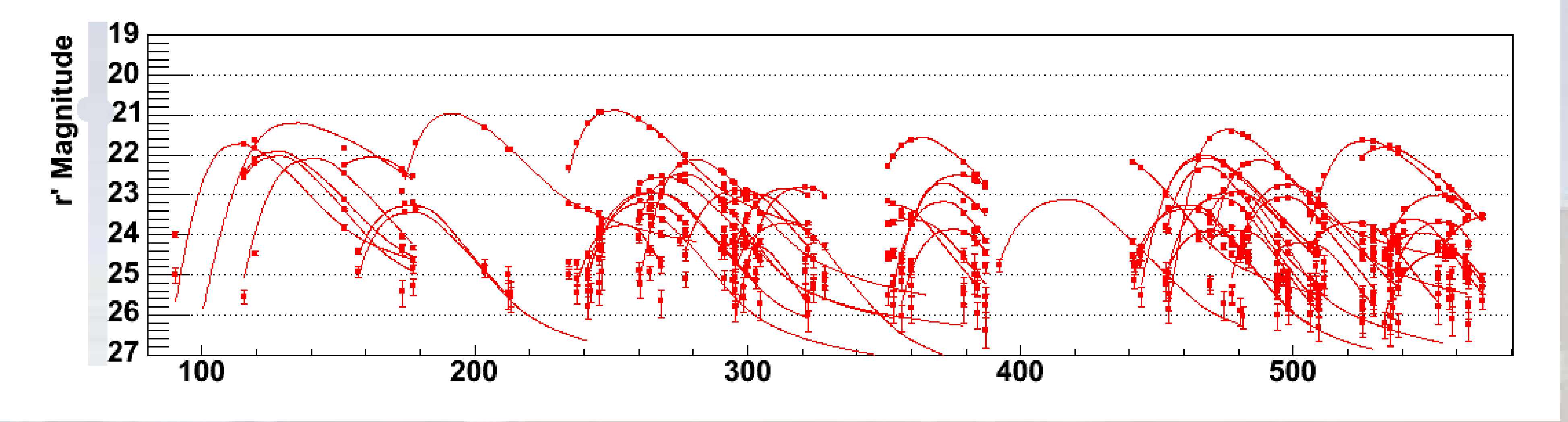
Multi-color light curves

SNLS-04D3fk z=0.3578

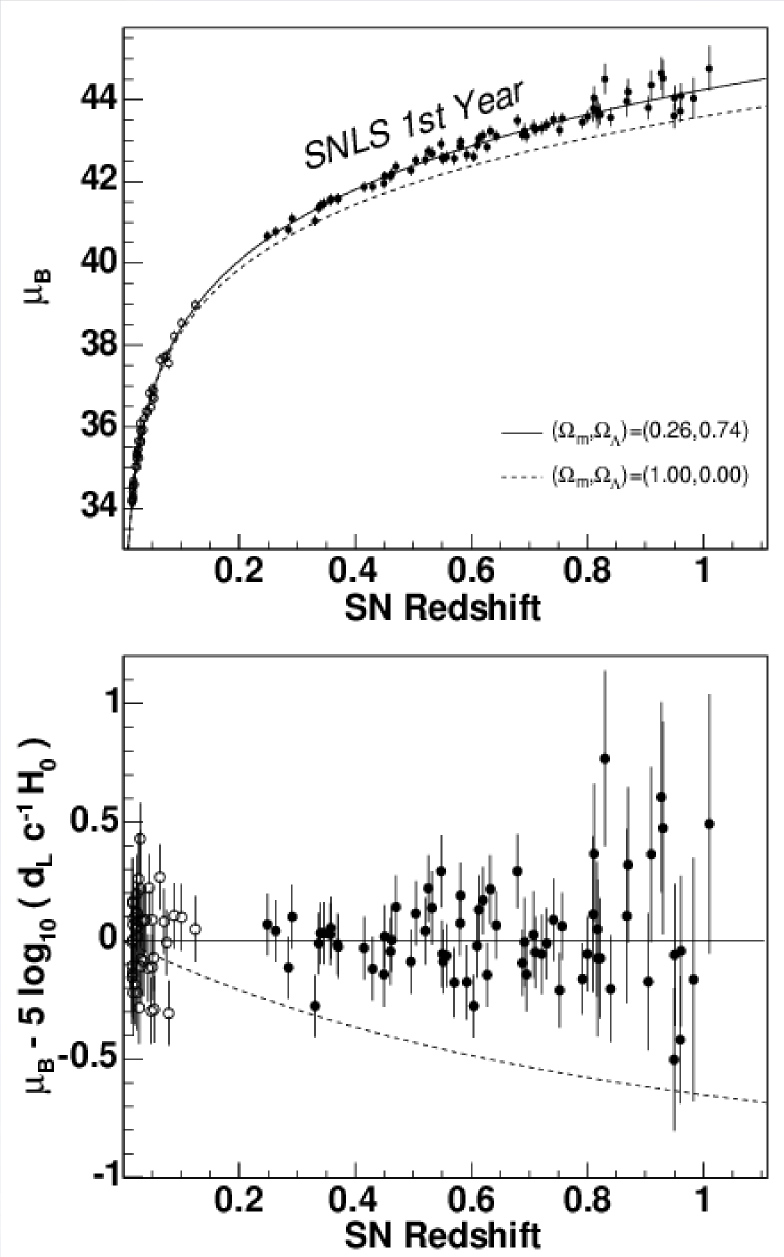


SNLS-04D3gx z=0.91





Hubble diagram of SNLS 1st Year



Final sample :
44 nearby SNe from literature
+71 SNLS SNe

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

$$\chi^2 = \sum_{objects} \frac{(\mu_B - 5\log_{10}(d_L(\theta,z)/10pc))^2}{\sigma^2(\mu_B) + \sigma_{int}^2}$$

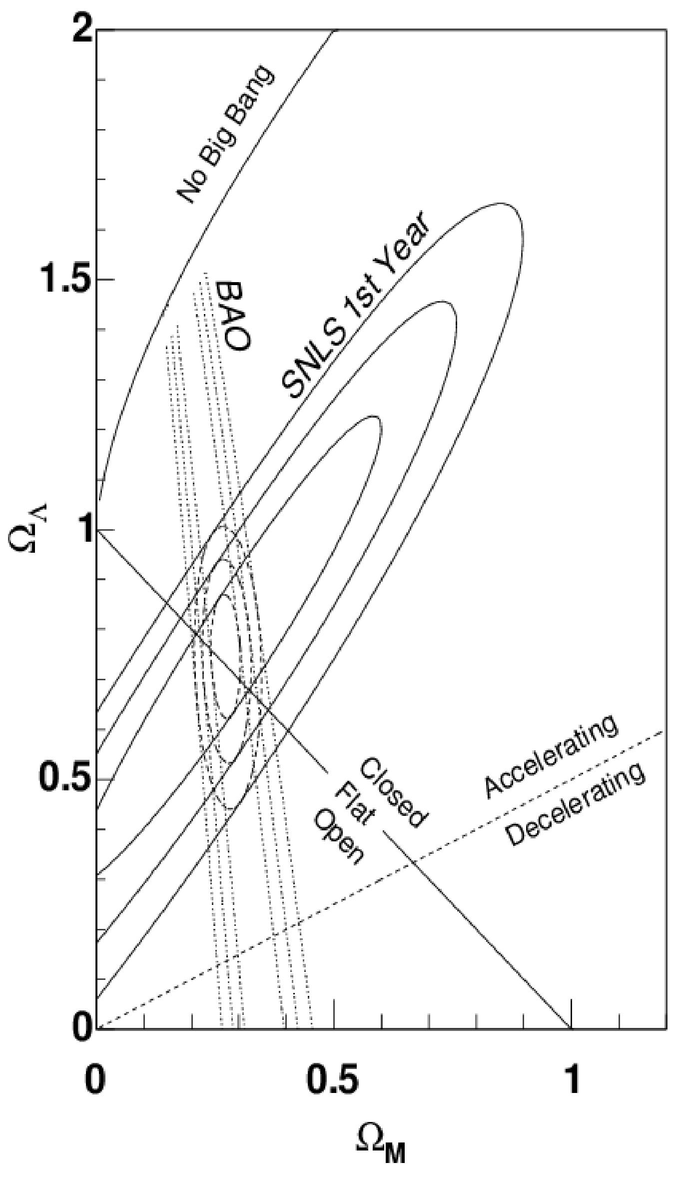
χ^2/d.o.f=1 with an additionnal intrinsic dispersion σ_{int}=0.13 mag

(errors take into account covariance matrix of fitted parameters m_B,s,c)

Next, cosmological fit -->

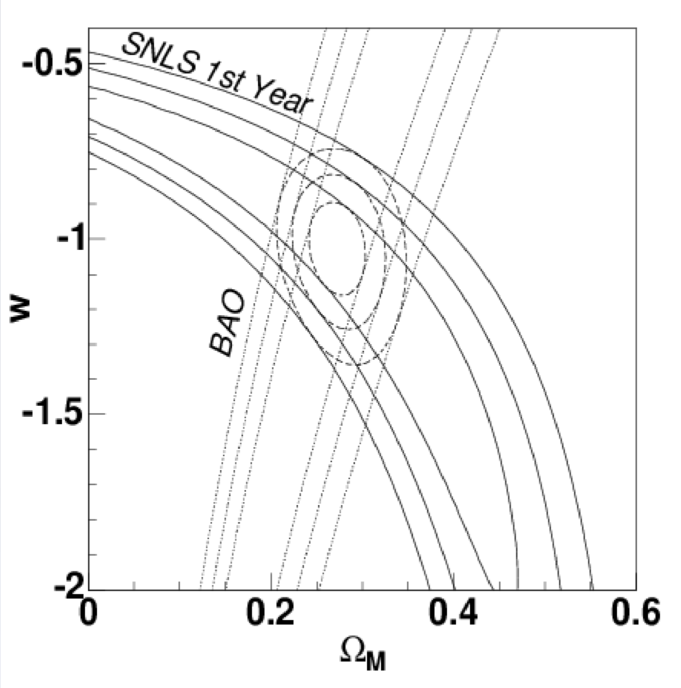
Cosmological parameters

w=-1



68.3, 95.5 and 99.7% CL

Ω_T=1



BAO: Baryon Acoustic Oscillations
Eisenstein 2005

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	$(0.271 \pm 0.021, -1.023 \pm 0.087)$

Identified systematic uncertainties

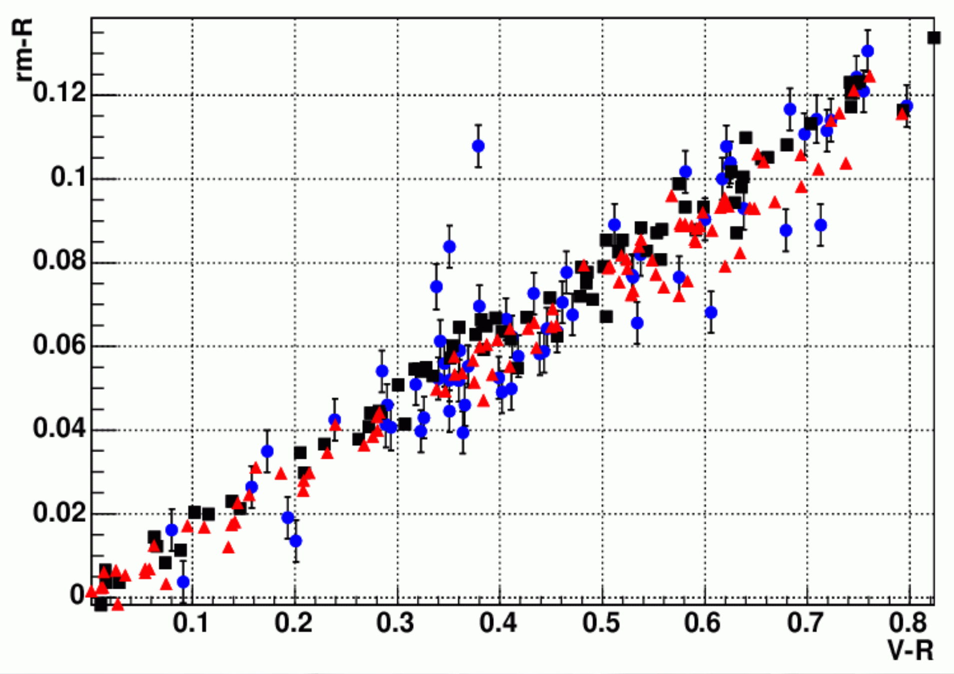
- (photometry, calibration, modeling of the detector response)
- Evolution:
  Need for predictive SNe Ia theory
  -> SNe observables vs host galaxy type
  -> Nearby and distant SNe comparisons

- Empirical modeling (k-corrections):
  Observations vary in phase and wavelength sampling
  fit (B,V) -> (U,B) at high z
  -> tests based on SNe at z~0.4
- Selection bias:
  Only the brightest SNe are detected at high z
  (=> Blue color, large stretching of light curves)

  -> Controled with simulations of the detection pipeline
- Contamination (interpolers):
  SN II, SN Ib/c spectroscopic id. is not always conclusive
- Grey Dust:
  Intergalactic absorption mimic acceleration of expansion
- Gravitational lensing at high z:
  Asymetric distribution of observed luminosities

Calibration

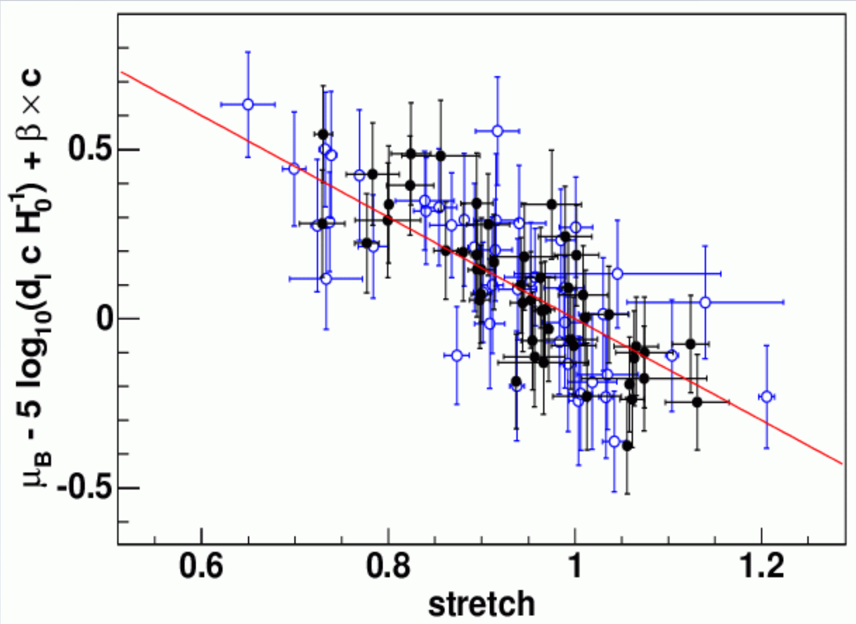
Band	zero-point shift	$\delta\Omega_M$ (flat)	$\delta\Omega_{tot}$	δw (fixedΩ_M)
g_M	0.01	0.000	-0.02	0.00
r_M	0.01	0.009	0.03	0.02
i_M	0.01	-0.014	0.17	-0.04
z_M	0.03	0.018	-0.48	-0.03
sum	-	0.024	0.51	0.05

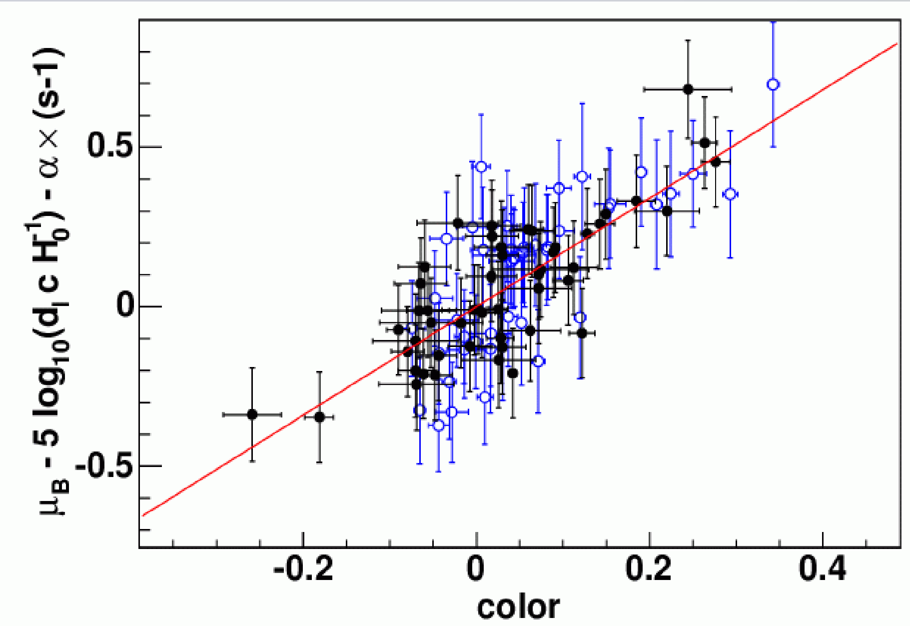


Blue : Megacam observations of Landolt stars
Red/Back : synthetic magnitudes from spectrophotometric standards + models

Evolution

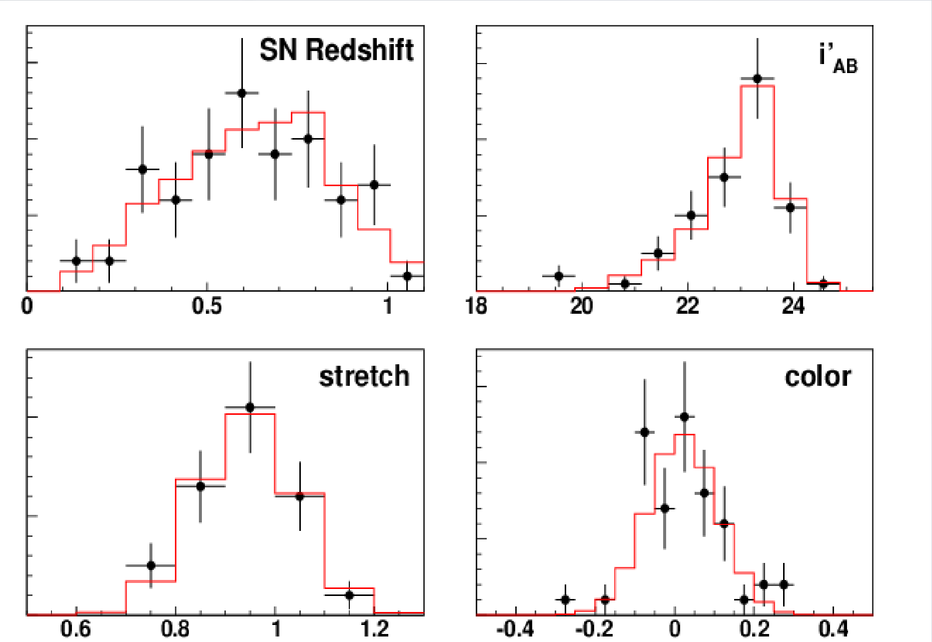
Same brighter-slower and brighter-bluer relations at z~0 and <z>~0.6



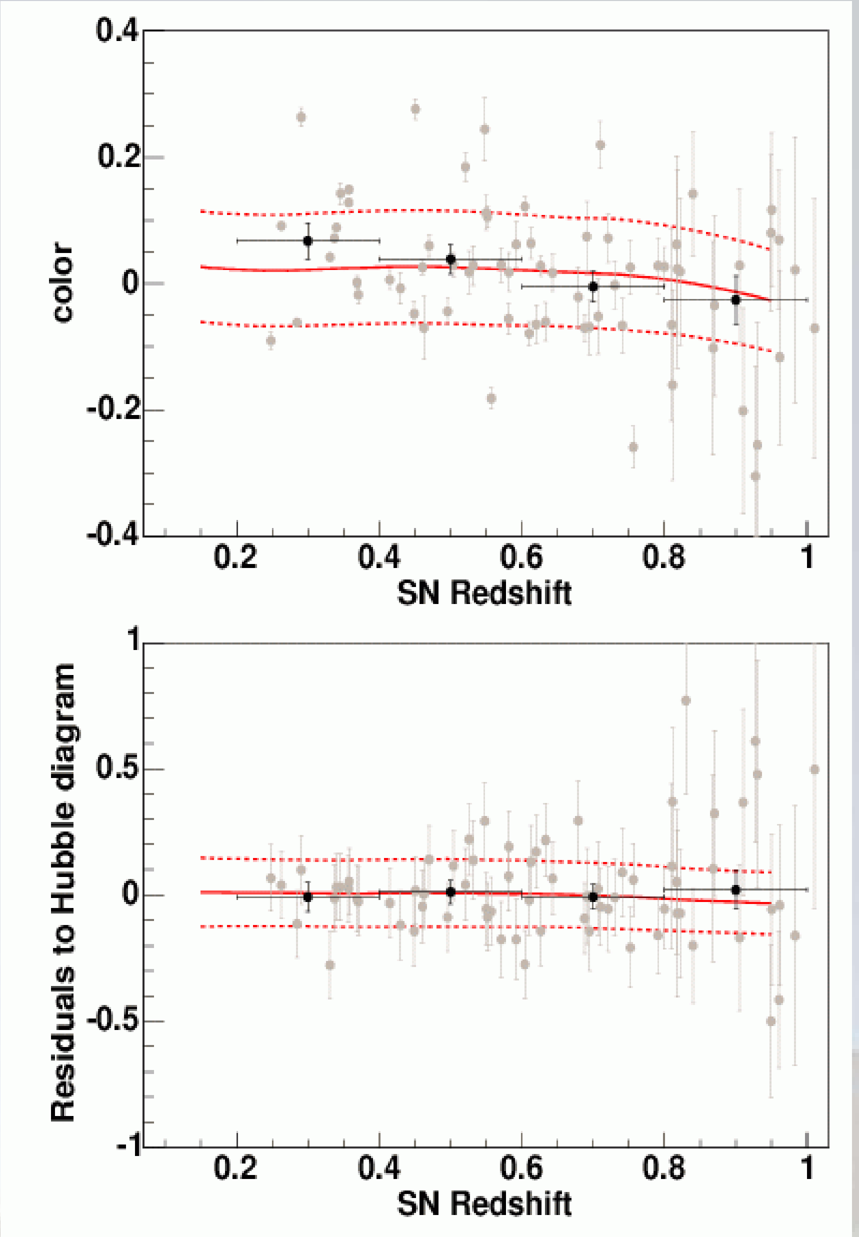


(black: SNLS   blue: Nearby SNe)

Malmquist Bias



Impact on Ω_m (flat LCDM):
Nearby SNe +0.019 +- 0.012
SNLS SNe - 0.02 +- 0.01



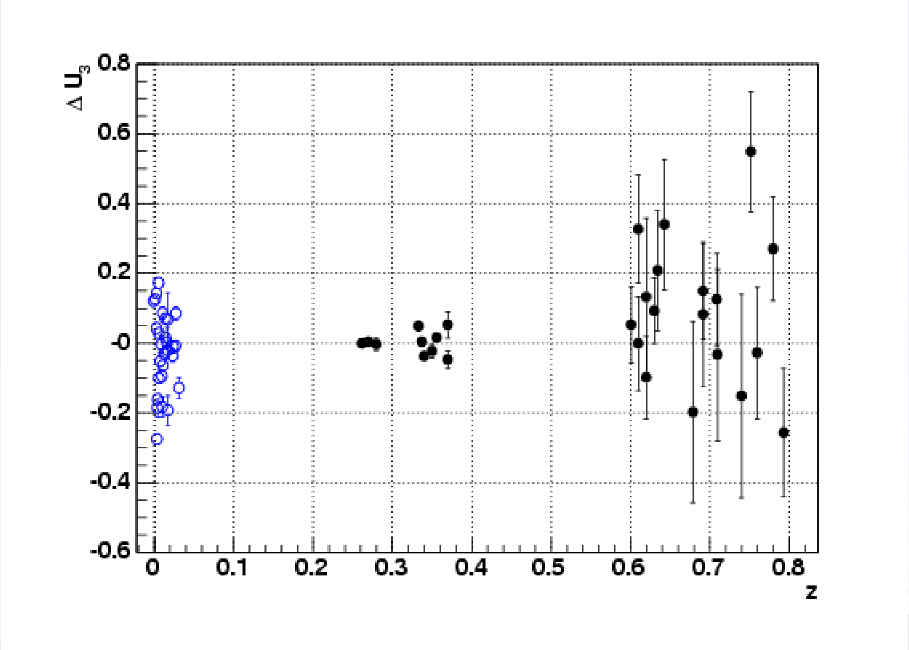
Black: SNLS SNe
Red: Simulations with SALT

Checks of SNe modeling with SALT

-> Measurement of m*B,s,c
 using rest-frame (U and B) or (B and V) light curves
 (référentiel de la SN)

-> SNLS LCs:

z	0	0.3	0.7
	U	g'	r'
	B	r'	i'
	V	i'	z'



ΔU_3 = U(B,V)-U(meas)

	Mean	RMS
UBV	0+-0.02	**0.12**
g'r'i'	0+-0.008	**0.03**
i'r'z'	0.09+-0.04	

-> good agrement UBV g'r'i'
-> 2 sigma i'r'z'

-> **small dispersion en g'r'i'**

Summary of systematics :

Source	$\delta\Omega_M$ (flat)	$\delta\Omega_{tot}$	δw (fixed Ω_M)	$\delta\Omega_M$ (with BAO)	δw (with BAO)
Zero points ($g_M r_M i_M z_M$)	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
U-B color(stat)	0.020	0.12	0.05	0.004	0.024

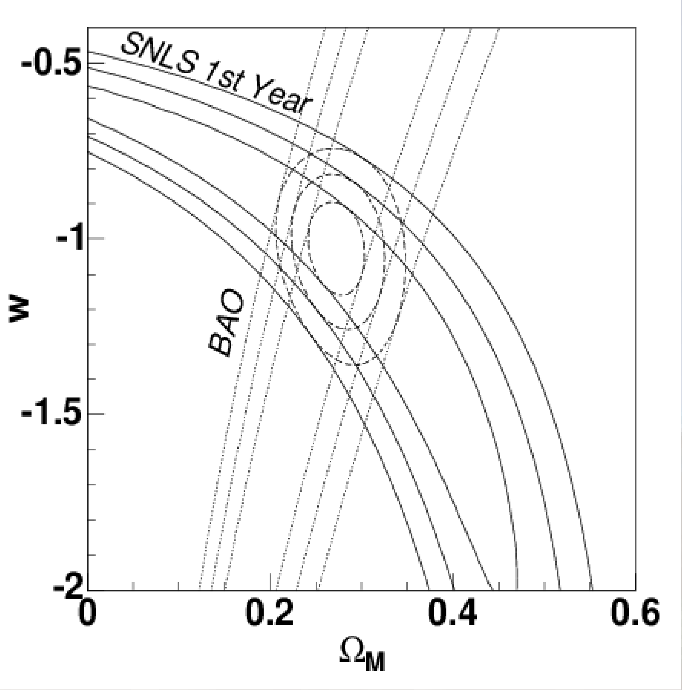
SNLS 1st year results on Cosmology

SNLS only, flat Universe with w=-1

$$\Omega_M = 0.263 \pm 0.042\ (stat) \pm 0.032\ (sys)$$

SNLS+BAO (Eisenstein 2005),
flat Universe

$$\Omega_M = 0.271 \pm 0.021\ (stat) \pm 0.007\ (sys)$$
$$w = -1.02 \pm 0.09\ (stat) \pm 0.054\ (sys)$$



Prospects

- Already ~ 200 new SNe Ia on disk
- Deeper reference images will improve photometry
- Statistical Errors x 1/2 at the end of the survey
- Survey is more efficient today :
    - Better image quality (wide field corrector fixed)
    - auto-focus : More science observations per night.

- Calibration is being improved
- Work on modeling to use rest-frame far UV observations
- Possibility to improve distance estimate
  => improvement of statistical errors
- Study of SNe properties vs Host Galxy type
  => Strong test of evolution
- Measurement of the SNe Ia explosion rate :
  requires a good understanding of the detection efficiency
  => benefits to the selection bias control
- Photometric Identification (=> +30% de SNe at high z)