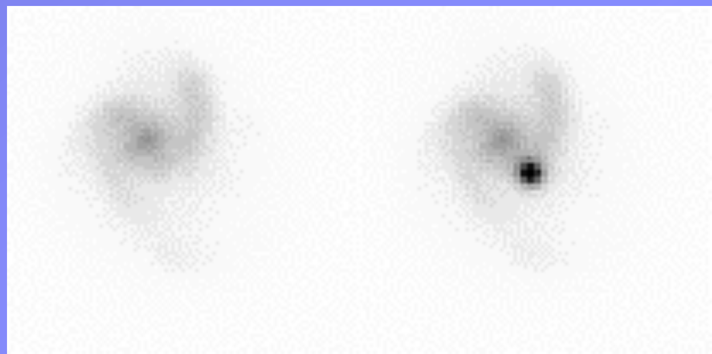
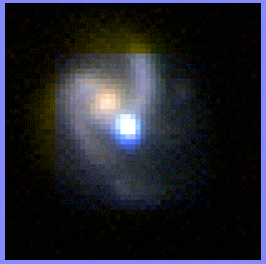
Precision cosmology with Type Ia Supernovae ?



Reynald Pain

LPNHE, CNRS/IN2P3 & Universités Paris 6 and Paris 7

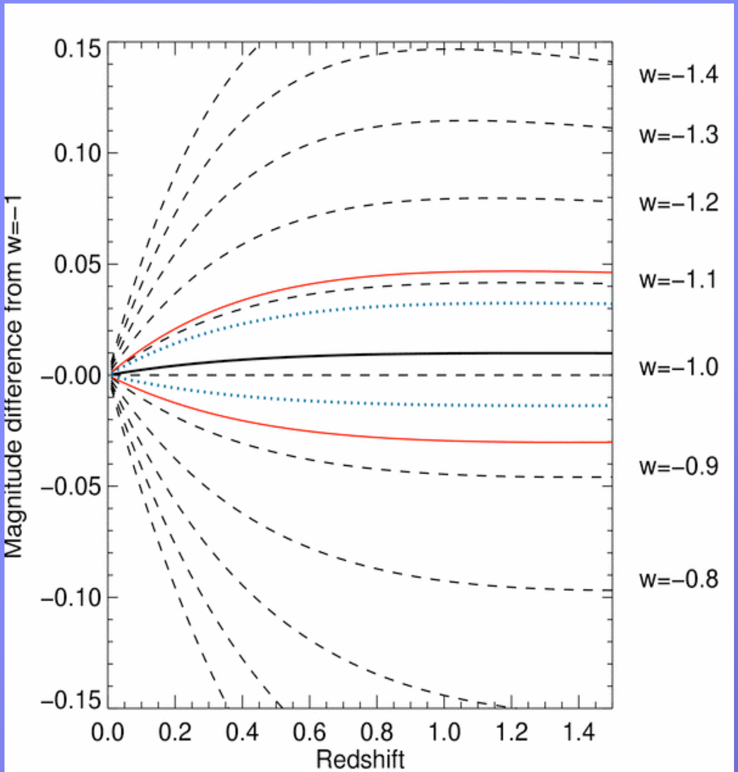
Outline



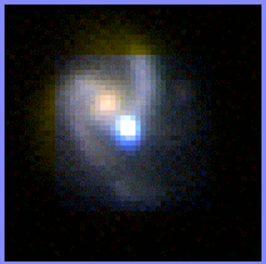
I will used the SNLS 1st year data and analysis to try answer the following questions :

1 - to what level can we trust the currrent precison on w ?

2 - can we hope to do better ?



The Paris SN cosmology group
(http://supernovae.in2p3.fr)



Group of 8 faculty/researchers + 3 PhD students at LPNHE, CNRS/IN2P3 University Paris VI & VII Part. phys. Lab (http://www-lpnhep.in2p3.fr/, Babar, D0, ATLAS, LHCB and SN, HESS, AUGER)

- involved in :
  - high-z SN : SCP, SNLS
  - low-z SN : SNF
  - preparation of future SN programs (SNAP, DUNE, LSST, S4)

What do we do ?

- Instrumentation

  - construction of the SNIFS for SNF

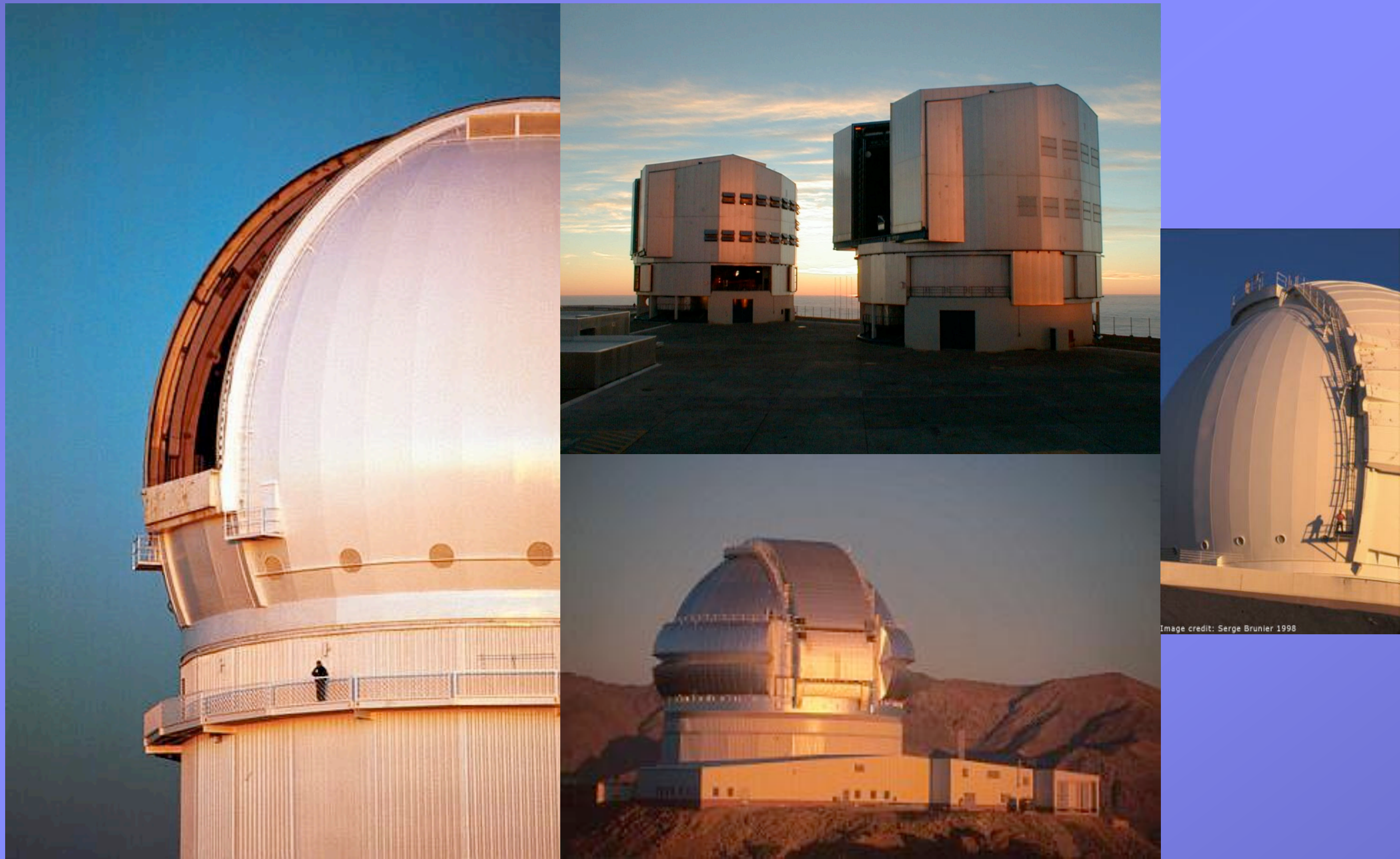
  (Collab. with LBNL + 3 French labs)

  - R&D « calibration » (future SN programs)

- Data analysis (+ obs) of SNe Ia for Cosmology

  ex : SNLS (P. Astier, J. Guy, N. Regnault et al.

SNLS – The SuperNova Legacy Survey



Observing strategy : “Rolling Search”

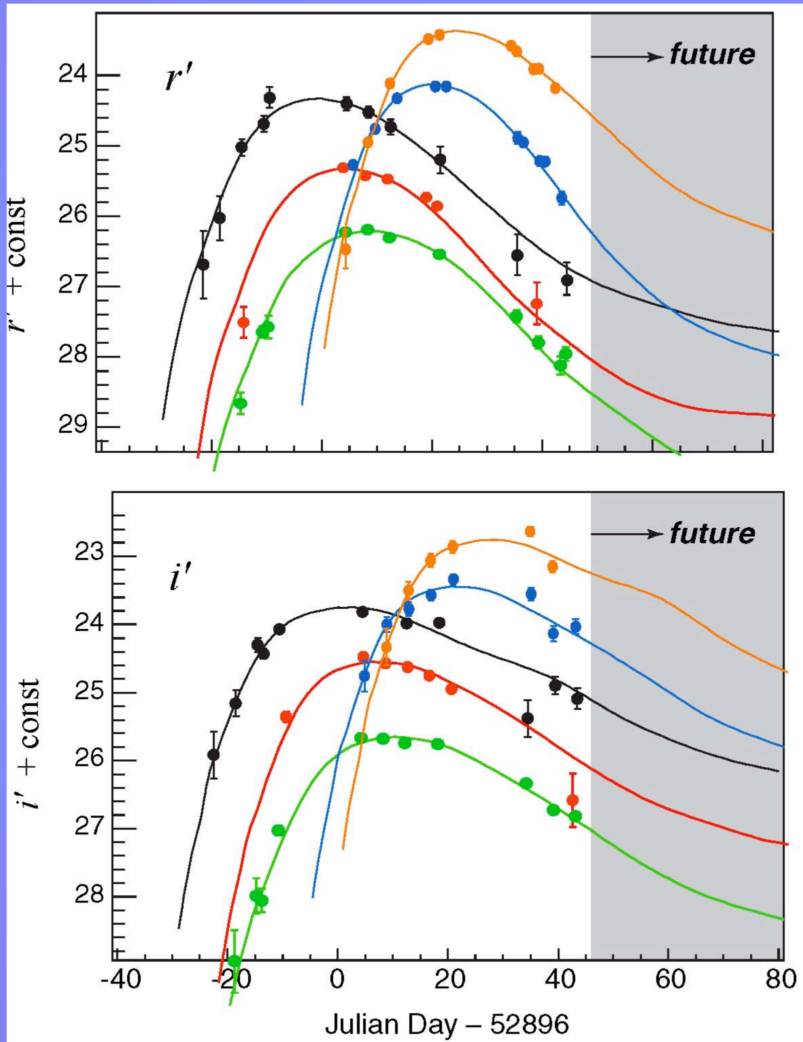
Each lunation (~18 nights) :
repeated observations
(every 3-4 night) of
2 fields in four bands (griz)+u

for as long as the fields stay
visible (~6 months)

for 5 years

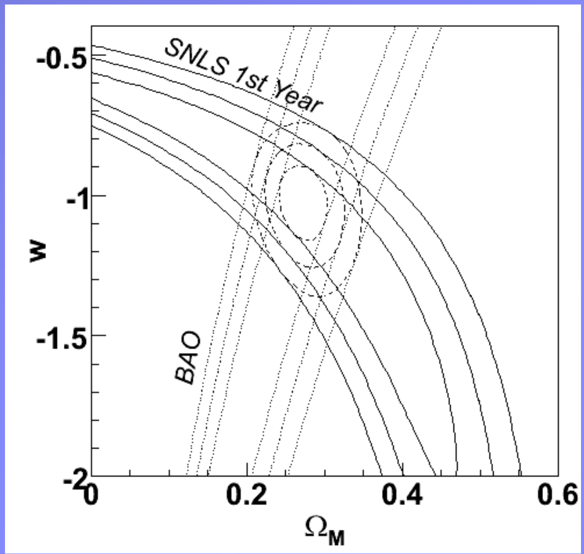
+

Queue scheduled spectroscopy
(weather)



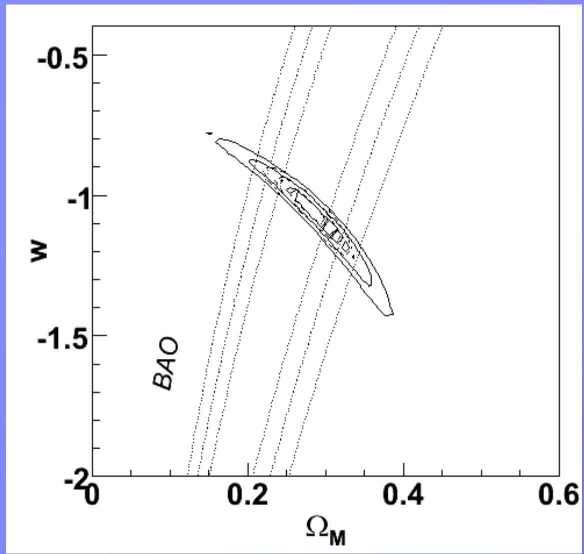
Precision Cosmology with SNe Ia ?

2006
44 nearby SNe
71 from SNLS



?

20..
1000 nearby SNe
2000 distant



(ex: LSST ~250000 SNe/yr !)

Enter Abstract Words/Keywords   Require text for selection
(Combine with: OR AND simple logic boolean logic)
supernovae systematic uncertainties cosmology

SNLS, Astier et al. 2006 (A06):

$$w = -1.023 \pm 0.090\ (stat) \pm 0.054\ (sys)$$

Query Results from the ADS Database

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#	Bibcode / Authors	Score	Date / Title	List of Links / Access Control Help
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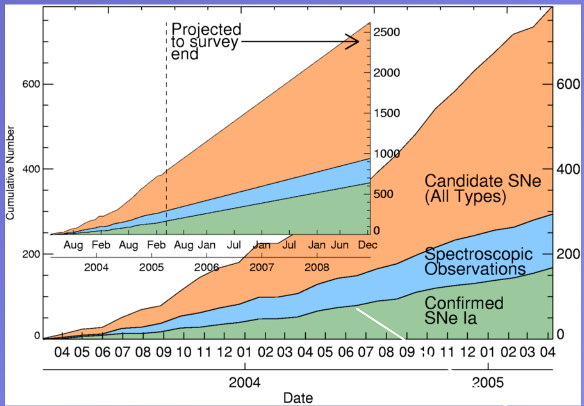
2	2007astro.ph..1904D Davis, T. M.; James, J. B.; Schmidt, B. P.; Kim, A. G.	1.000	01/2007 Type Ia supernova diversity: Standardizing the candles	A X R U H
3	2007astro.ph..1692K Krauss, Lawrence M.; Jones-Smith, Katherine; Huterer, Dragan	1.000	01/2007 Dark Energy, A Cosmological Constant, and Type Ia Supernovae	A X R U H
4	2006AAS...209.9818A Allyn Smith, J.; Bohlin, R. C.; Deustua, S. E.; Allam, S. S.; Kent, S. M.; Lampton, M. L.; Mostek, N.; Mufson, S. L.; Richmond, M. W.; Smadja, G.; and 3 coauthors	1.000	12/2006 Development of Spectrophotometric Standards to Support the SNAP	A U
5	2006AAS...209.9011M Miknaitis, Gajus A.; Wood-Vasey, W.; ESSENCE team	1.000	12/2006 Constraints on Dark Energy from the ESSENCE Supernova Survey	A U
6	2006A&A...460..793S Stritzinger, M.; Mazzali, P. A.; Sollerman, J.; Benetti, S.	1.000	12/2006 Consistent estimates of ^{56}Ni yields for type Ia supernovae	A E F X R C U
7	2006astro.ph.10397R Regnault, N.	1.000	10/2006 Photometric Calibration of the Supernova Legacy Survey Fields	A X R U H

Expected near term precision on w (~2008-9)



Expected « realistic » statistical uncertainty on Ω_M and w

(KAIT+CFA+SNF+CSP)

# nearby SNe	44	44	132
# distant SNe	71	213	500
$\sigma\Omega_M$ (current BAO)	0.023	0.019	0.018
σw (current BAO)	0.088	0.064	0.055
$\sigma\Omega_M$ (BAOx2)	0.016	0.014	0.013
σw (BAOx2)	0.081	0.054	0.044

+ systematics…

SNLS 1st yr 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
Meas. errors	0.037	0.52	0.09	0.020	0.087
U-B color(stat)	0.020	0.10	0.05	0.003	0.021
Sum (stat)	0.042	0.53	0.10	0.021	0.090

Calibration

Nearby sample !

SN modelling

What about by SNLS end and later ?

(known) sources of “systematic” uncertainties

Flux measurement
- Photometry (measurement bias, linearity)
- Calibration

Distance measurement
- SNe Ia identification
- « k-corrections» :
  spectral sequence, instrument model

Evolution
- Selection biases
- Contamination level
- progenitor properties
- SN Ia sub-types ?
- Line of sight properties :
  (grey) dust, host galaxy nature, gravitational lenses

SNe Ia (ratio of) distance measurement

We want :

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

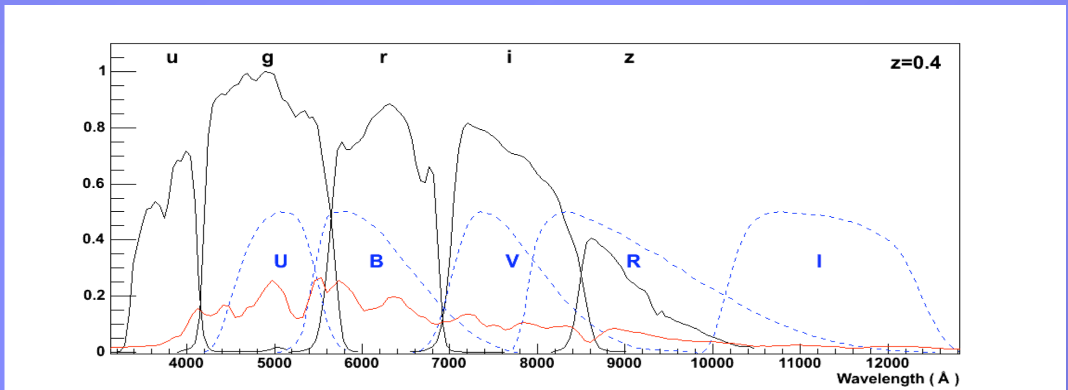
$$f(z, T_{rest}) = 10^{-0.4(m(T_{obs}) - m_{ref}(T_{obs}))} \times \frac{\int \phi_{SN}(\lambda) T_{rest}(\lambda) d\lambda}{\int \phi_{SN}(\lambda) T_{obs}(\lambda(1+z)) d\lambda} \int \phi_{ref}(\lambda) T_{obs}(\lambda) d\lambda$$

SN observed magnitude
(photometry+calibration)

reference spectrum + magnitude
system (AB / Vega)

k-correction
(modelisation of SN luminosity
as function of time and wavelength)

Instrument model
(response vs wavelength)



What is calibration ?

Recorded in the detector: ADU

-> physical flux (photons s^{-1} cm^{-2})

2 steps :

1) ADUs -> magnitude :
   flux ratios to (secondary) stars calibrated on a primary star

2) magnitude -> flux :
   known primary spectrum integrated in the instrument response model

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

1 2

From ADUs -> magnitudes

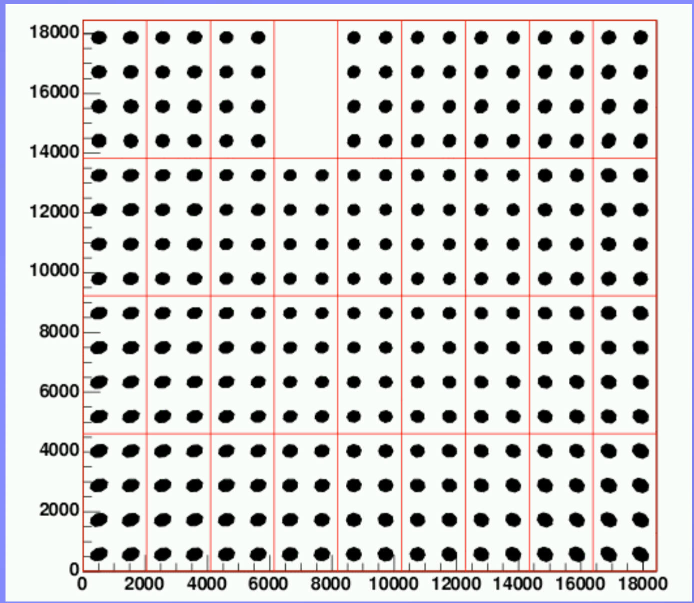
1) Calibration of field stars

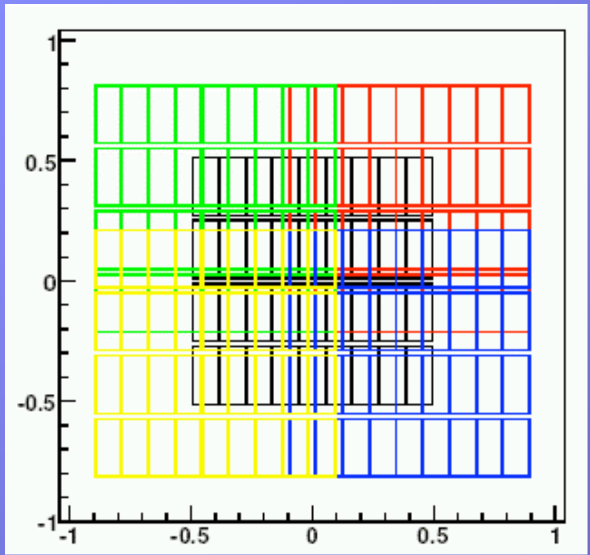
- "photometric nights".
aperture photometry of field and secondary stars

- require good uniformity over the entire field
=> Observation with large dithering to measure Camera uniformity

+ repeat many nights to average instrumental effect and atmosphere

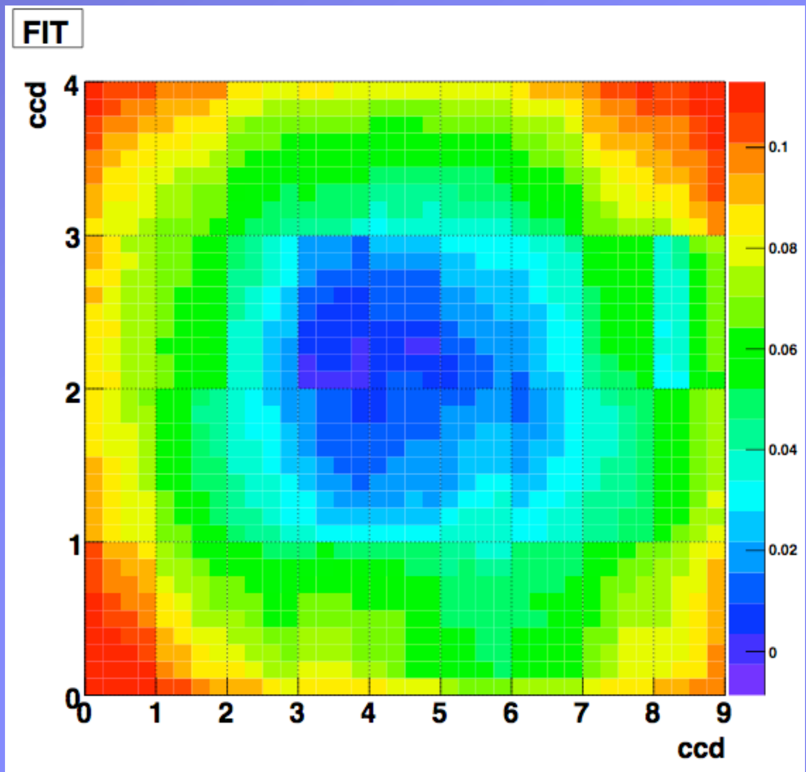
=> control of repeatability

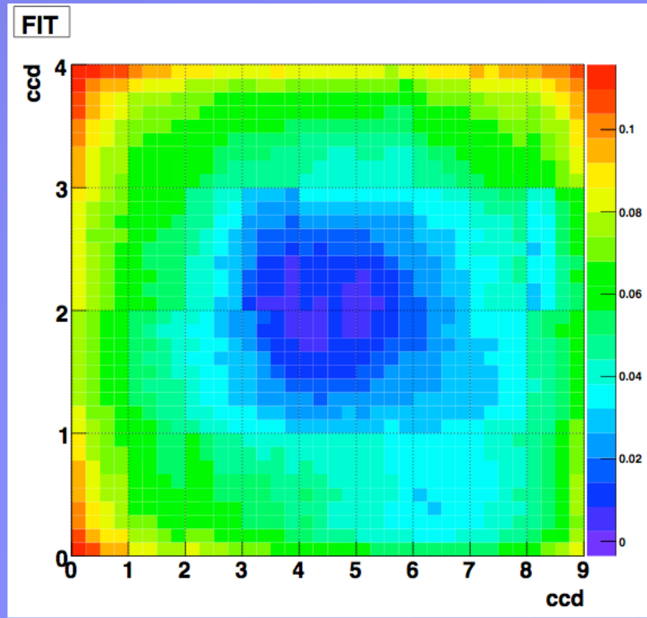


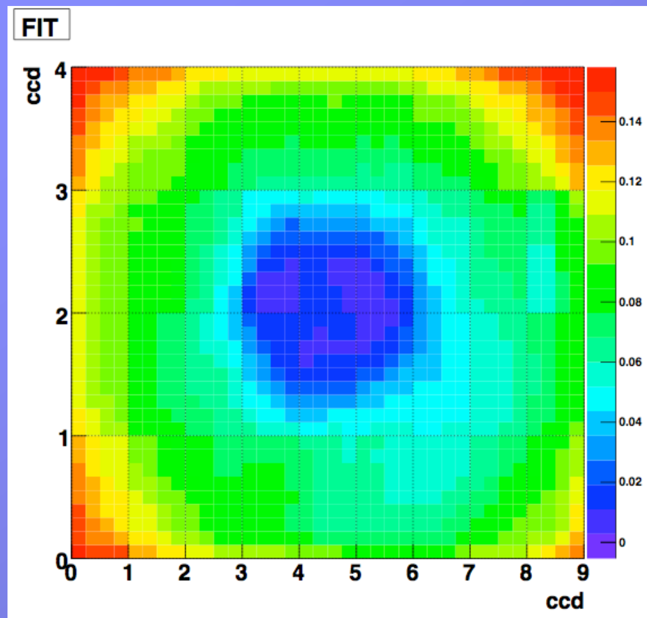


No irreducible uncertainties

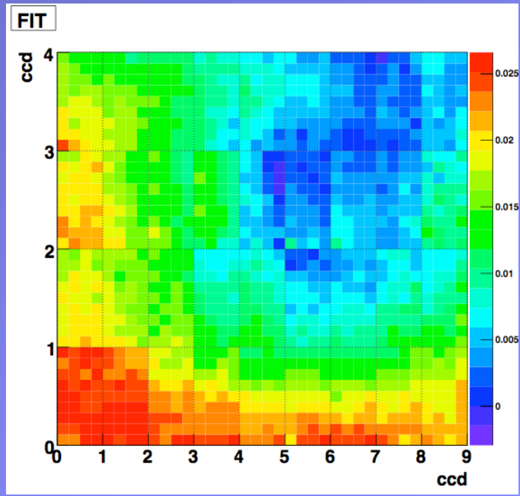
CFHT/Megacam « natural » mosaic non uniformity





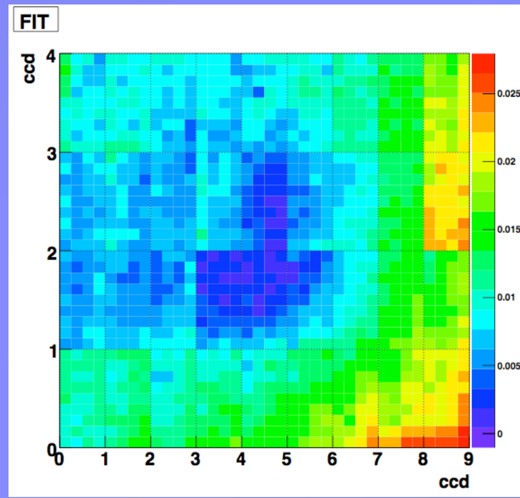


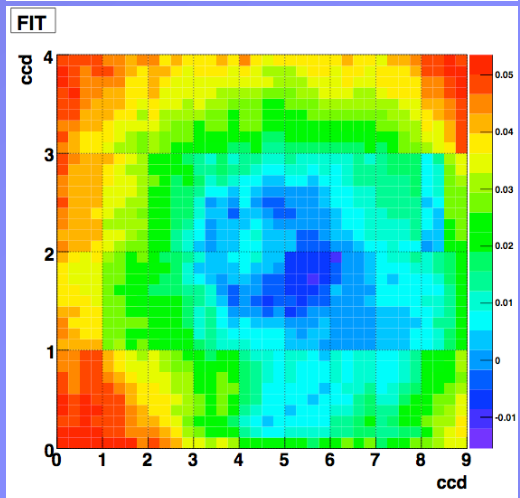
Megacam corrected Zero-point uniformity



g

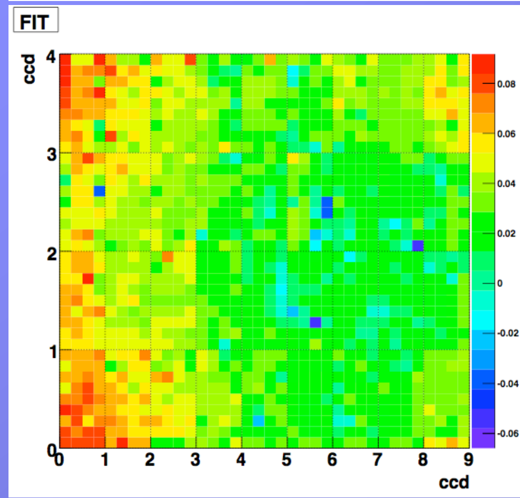
i



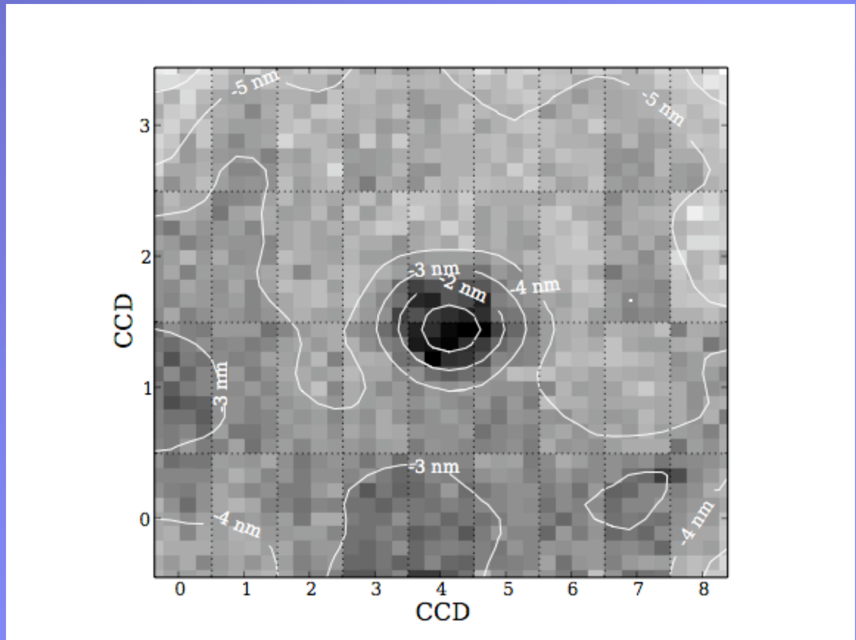


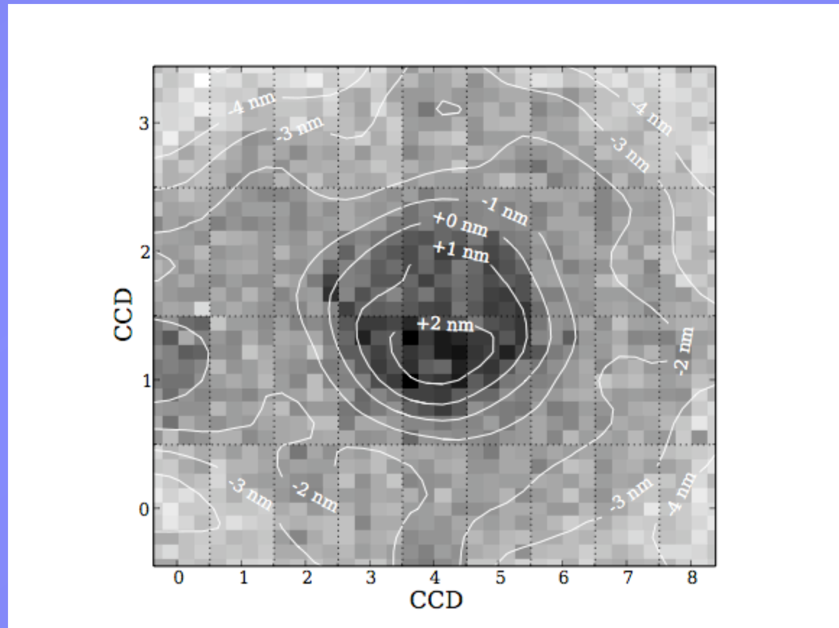
r

z



Color non uniformity



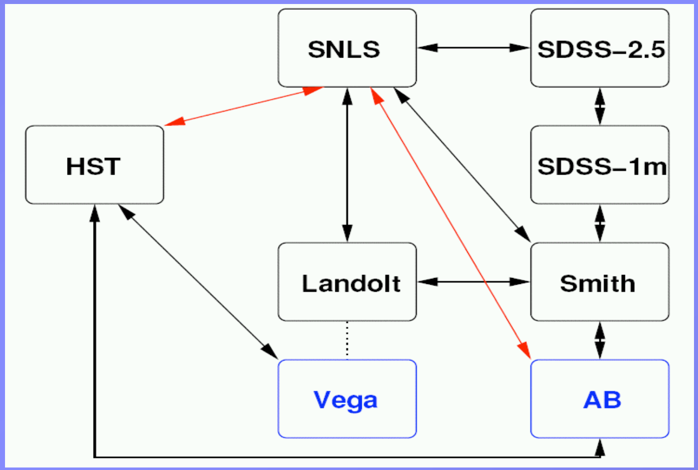


g-gr

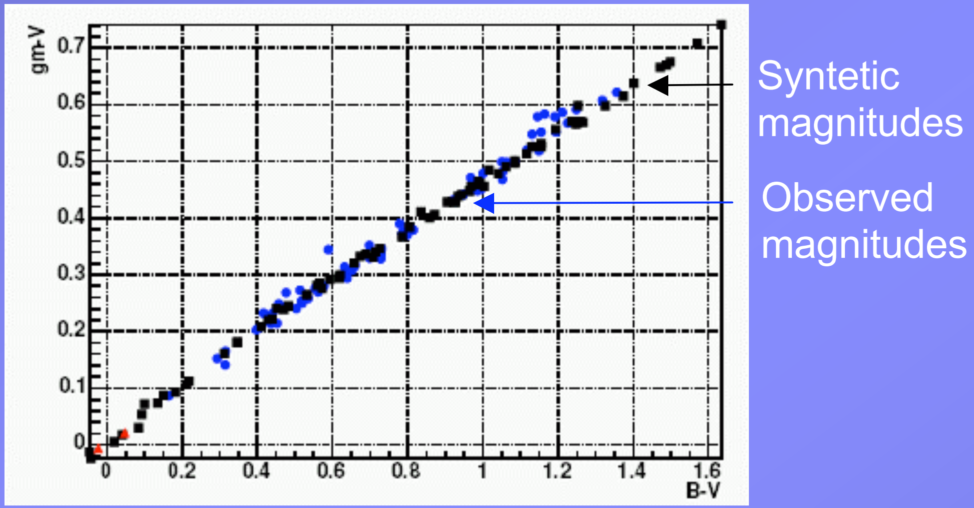
r-ri

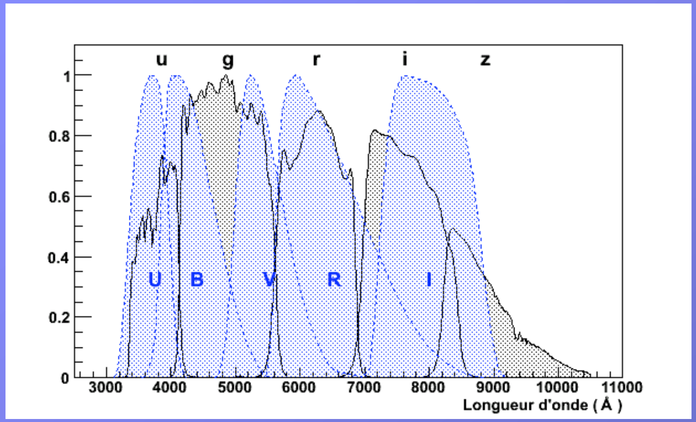
Mag system and Instrument modelisation

2) Magnitude system
- non unique
Distance ratios to nearby SNe
-> same calibration
-> Landolt system



3) Instrument modelisation





modelisation of the instr. Response

Both need to be done simultaneusly

No irreducible uncertainties (in principle)

Physical spectrum of the reference star

=>we need to know the flux ratio of the reference star in 2 distinct filters
ex :

$$\begin{aligned}\left(\frac{d_L(z_2=0.5)}{d_L(z_1=0)}\right)^2 &= \frac{f_2(z_2=0.5,\hat{B})}{f_1(z_1=0,\hat{B})} \\ &= 10^{-0.4\,[m_2(R)-m_1(B)]} \\ &\quad \times \frac{\int \phi_{SN}(\lambda)B(\lambda(1+z_1))d\lambda}{\int \phi_{SN}(\lambda)R(\lambda(1+z_2))d\lambda} \\ &\quad \boxed{\times 10^{0.4\,[m_{ref}(R)-m_{ref}(B)]} \times \frac{\int \phi_{ref}(\lambda)R(\lambda)d\lambda}{\int \phi_{ref}(\lambda)B(\lambda)d\lambda}}\end{aligned}$$

B-R color of the ref star (Vega)

Today : depends on white dwarf stellar models
-> HST (Bohlin)
-> compatible ~0.01 with black body calibration (Hayes 1985)

Close to the systematic limit
(B-R) uncertainty of 0.01 <=> ~200 SN at <z>~0.5

Measurement of SN fluxes

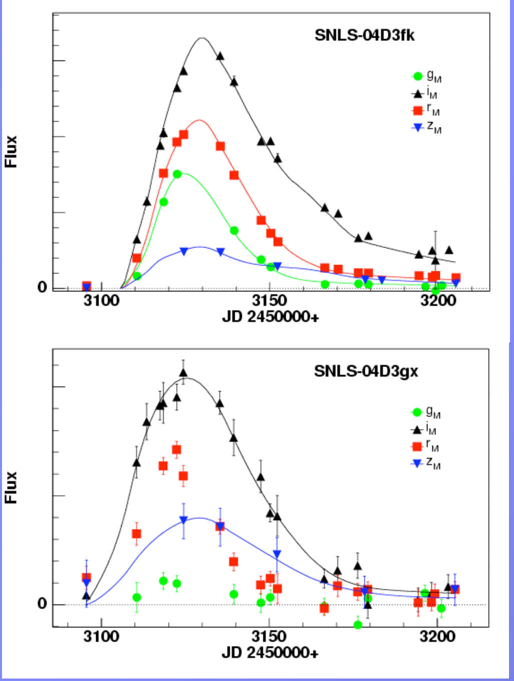
Need a SN spectral model
- as a function of time (time sampling) and wavelength (because of redshift)

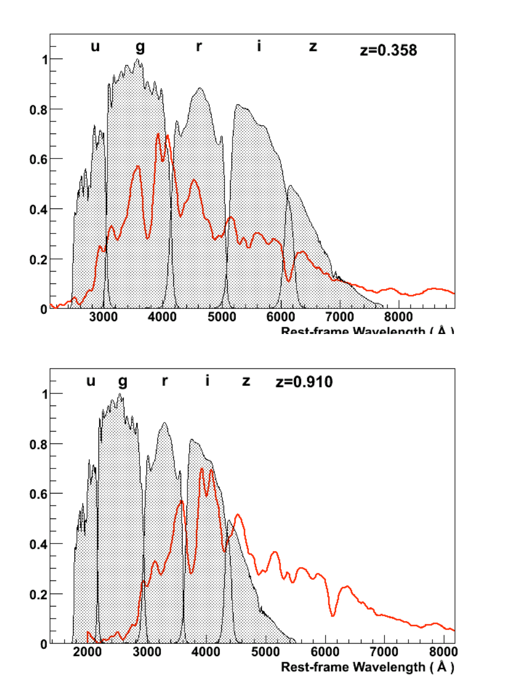
$$f(z, T_{rest}) = 10^{-0.4(m(T_{obs}) - m_{ref}(T_{obs}))} \times \frac{\int \phi_{SN}(\lambda) T_{rest}(\lambda) d\lambda}{\int \phi_{SN}(\lambda) T_{obs}(\lambda(1+z)) d\lambda} \int \phi_{ref}(\lambda) T_{obs}(\lambda) d\lambda$$

=> spectral sequence

z=0.358

z=0.91





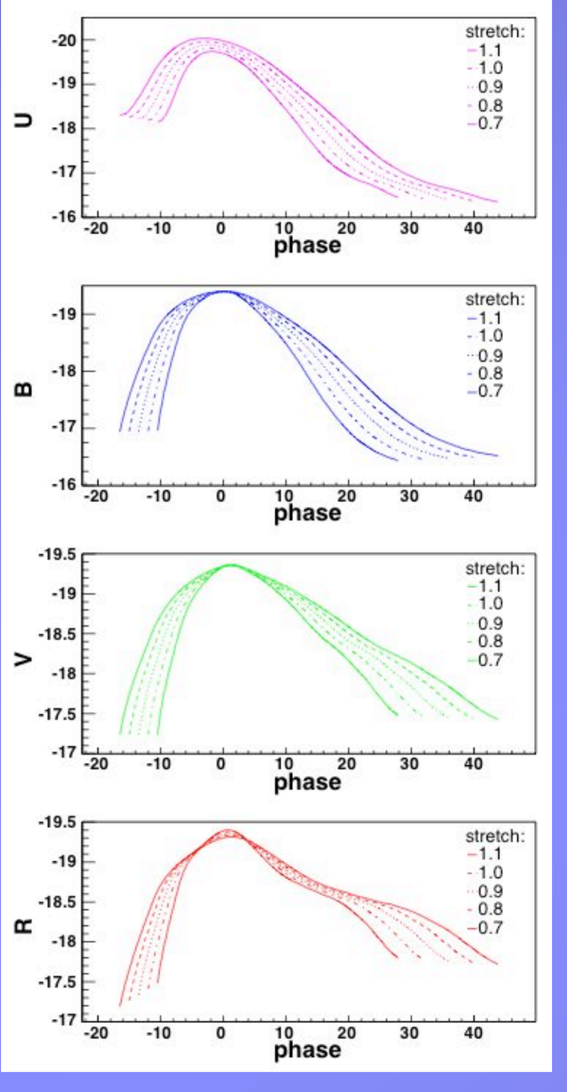
Light-curve modeling

Need to treat nearby and distant SNe the same way => no shape or color cuts should be allowed

available (2003) LC fitter:
- not tuned for (ground based) high-z SNe
- High-z SN poor late time photometry: cannot make use of Lira type relation to estimate extinction
- above z~0.8 need rest-frame U-band LC

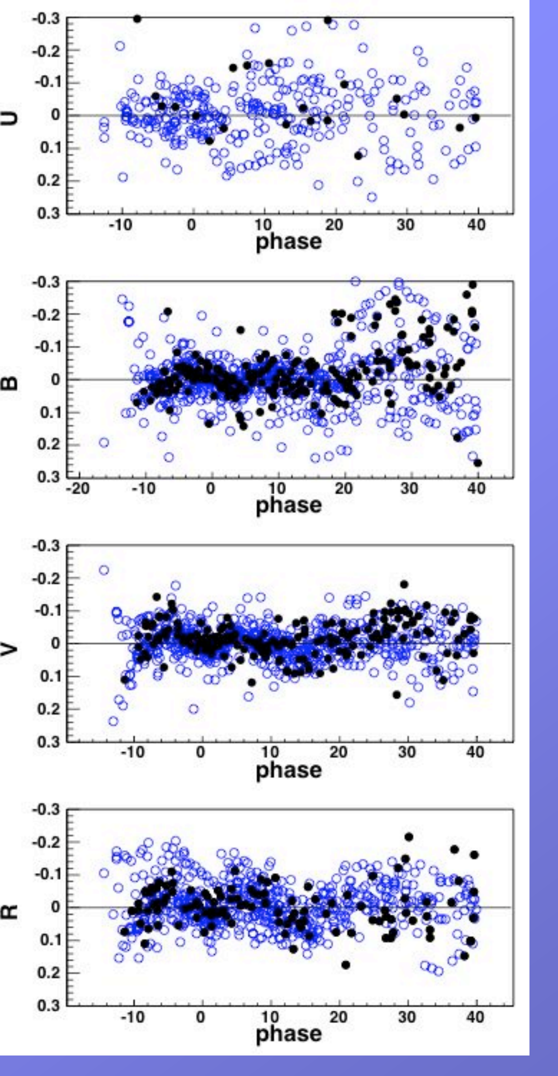
=> developed another model : “SALT” (2005) with the following requirements:
- describe rest-frame UBV LCs between -15d and + 35d
- Minimal set or parameters : Luminosity, Tmax, LC shape, single color
- Model SN flux continuously varying with phase, wavelength, LC shape and color

LC model/residuals



Training sample
(open symbols)
of 34 nearby SN Ia

Test sample
(filled symbols)
of nearby 26 SN Ia



SALT v2 (Guy et al. 2007)

Same basic philosophy as SALT v1

+ use *distant* SN LC to better describe UV part
+ be independent of a spectral time serie template
  by using nearby + SNLS *spectral* data

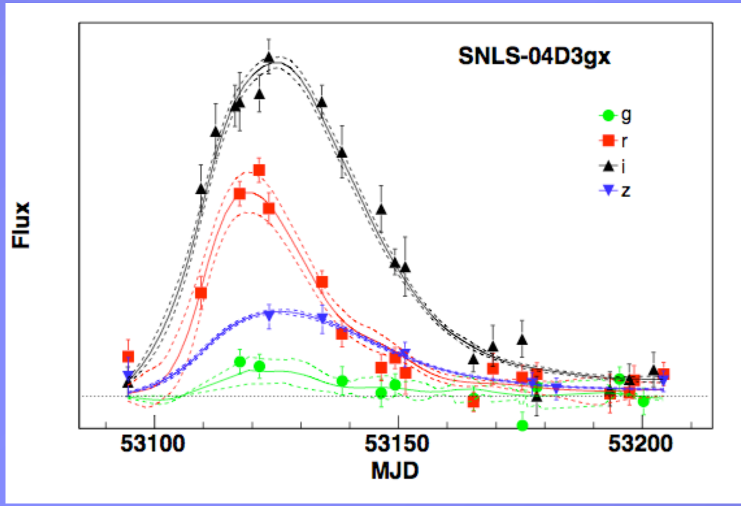
$$F(SN,p,\lambda) = x_0(SN)\left[M_0(p,\lambda) + x_1(SN)M_1(p,\lambda) + ...\right] \times \exp\left[c(SN)CL(\lambda)\right]$$

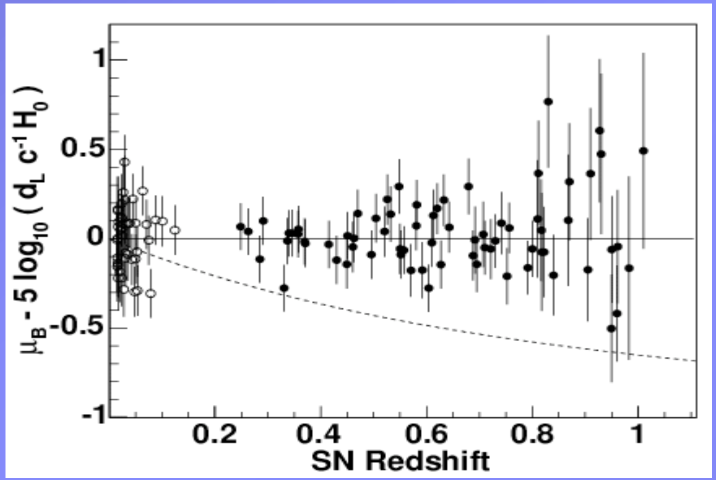
=> *output* a mean spectral time serie (M0) + a “stretch” (M1) component time series (pca like analysis)
and a color variation law

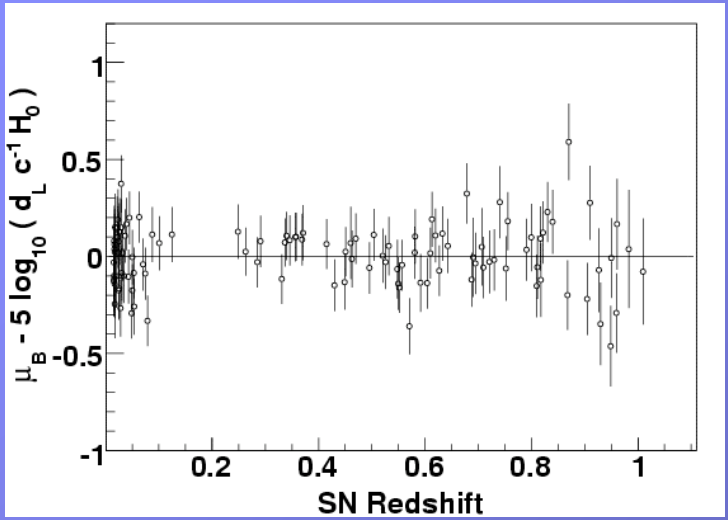
LC modeling does not (necessarily) generate systematic uncertainty:

The model can be adjusted on the survey data itself
-> errors ~ 1/sqrt(N)

Example with SNLS : (astro-ph/0701828, A&A)





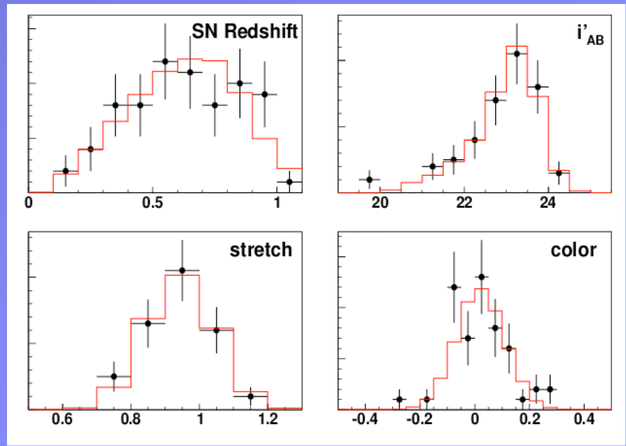


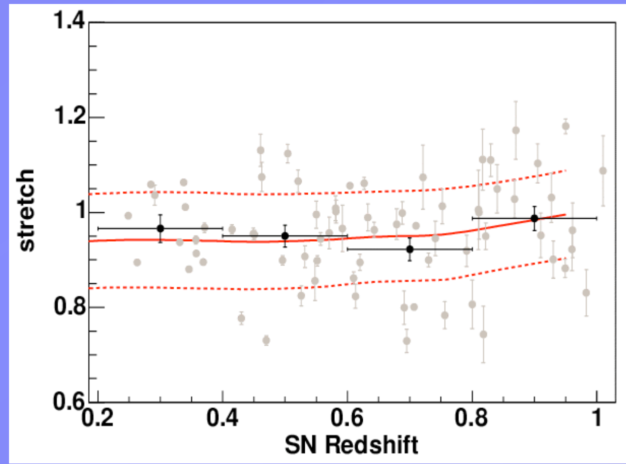
Selection Biases

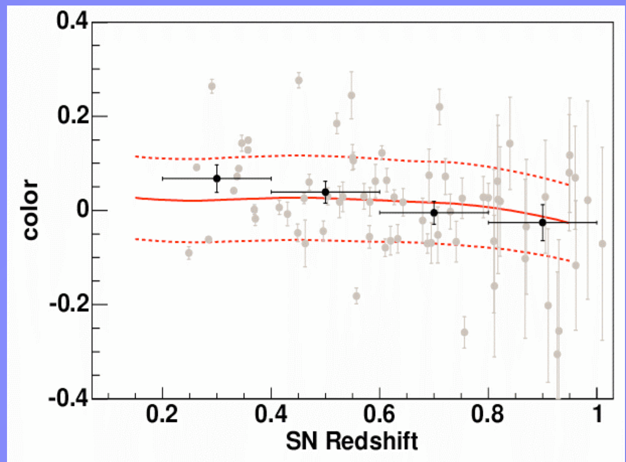
Model the SN LCs + instrument response

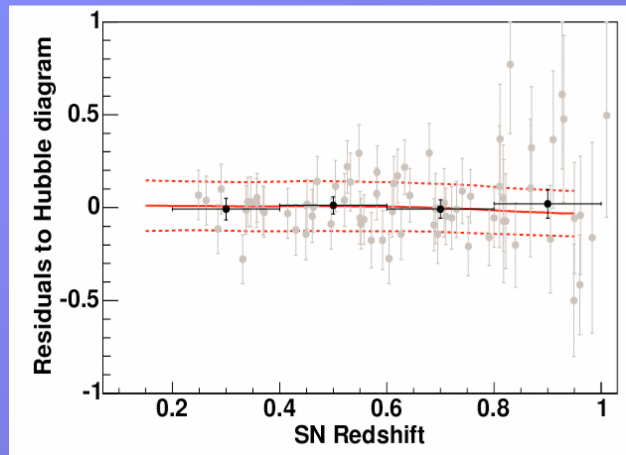
Black SNLS data
red: Simulations

Bias on distance modulus :
0.02 @ z=0.8
0.05 @ z=1.





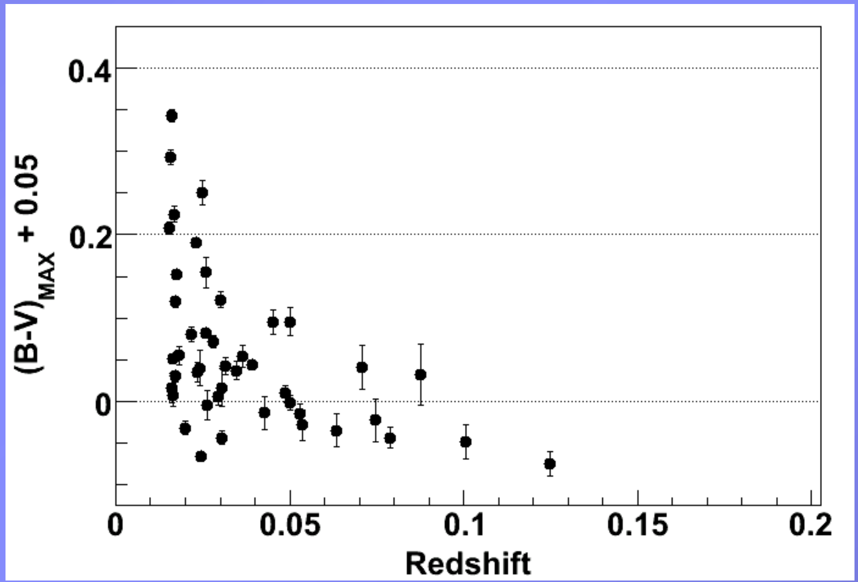




Selection bias in the nearby sample

“easy” to evaluate in SNLS (rolling search, one telescope).

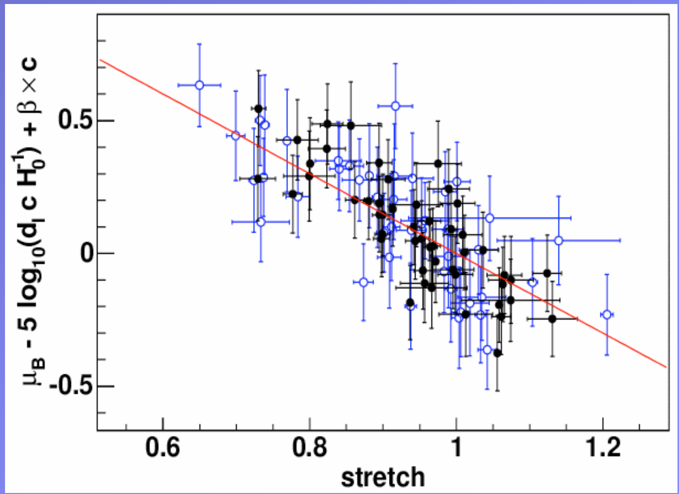
For nearby SNe : sample built from several “surveys”

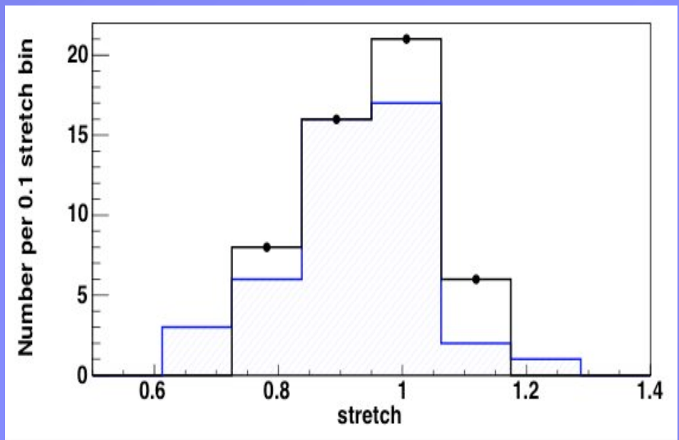


Today’s dominant systematic uncertainty
(everybody uses - approximately - the same nearby sample!)

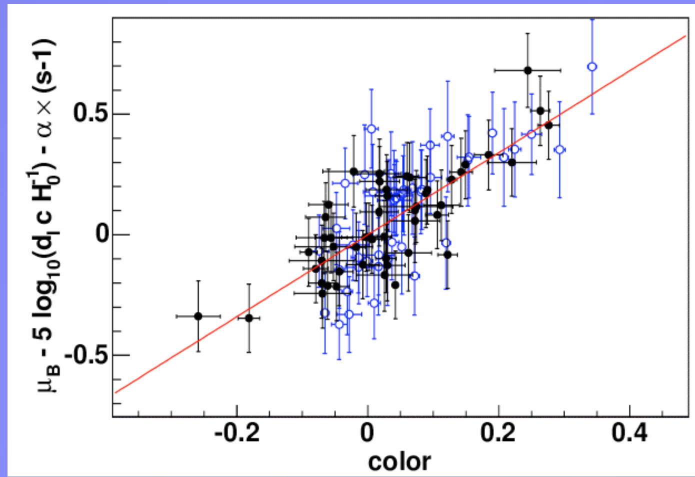
Evolution: are local and distant SN Ia alike ?

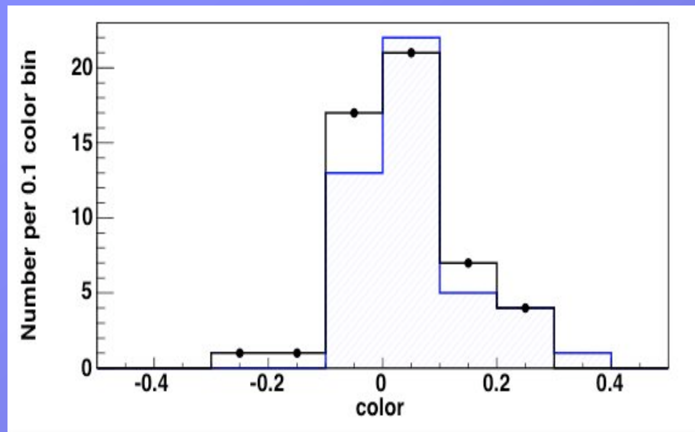
Brighter- Slower





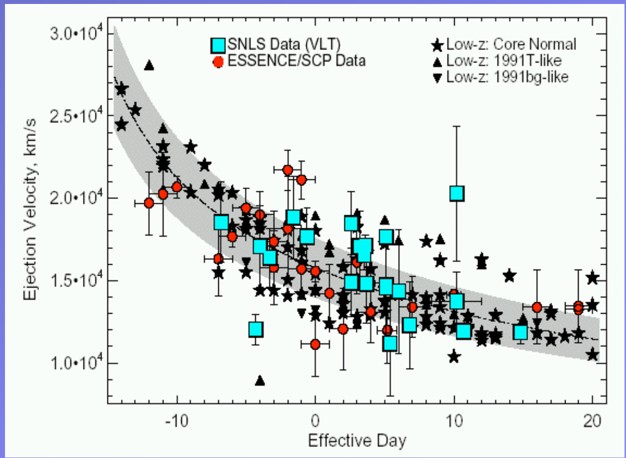
Brighter-Bluer



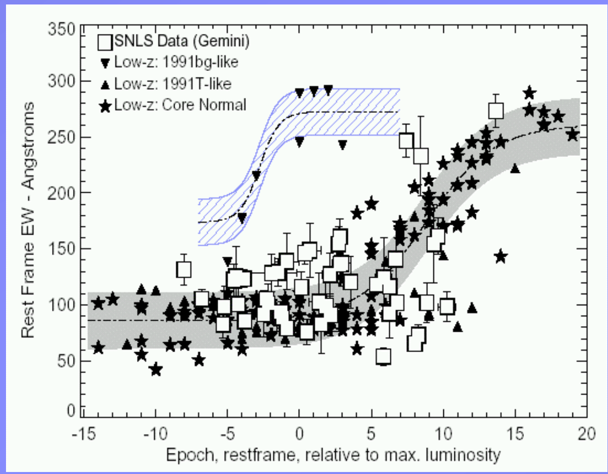


black: SNLS
blue: Nearby

Evolution: are local and distant SN Ia alike ?

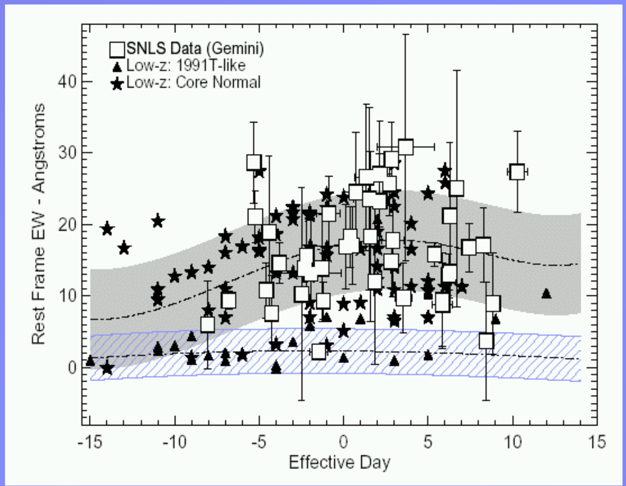


Ejection velocity CaII (H&K)



MgII (EW)

J. Bronder et al. submitted



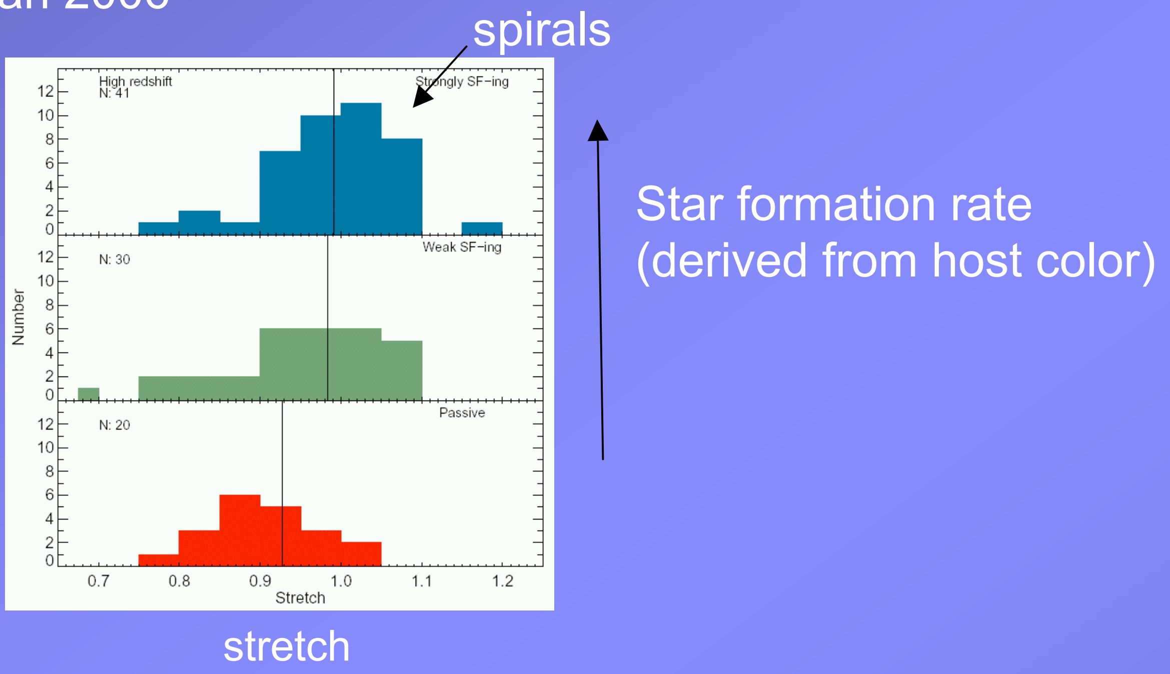
SiII (EW)

No systematic offset

Larger dispersion at higher z?

Evolution: SN properties vs host galaxy type

Sullivan 2006



SFR vary with z => what is the impact on cosmology?

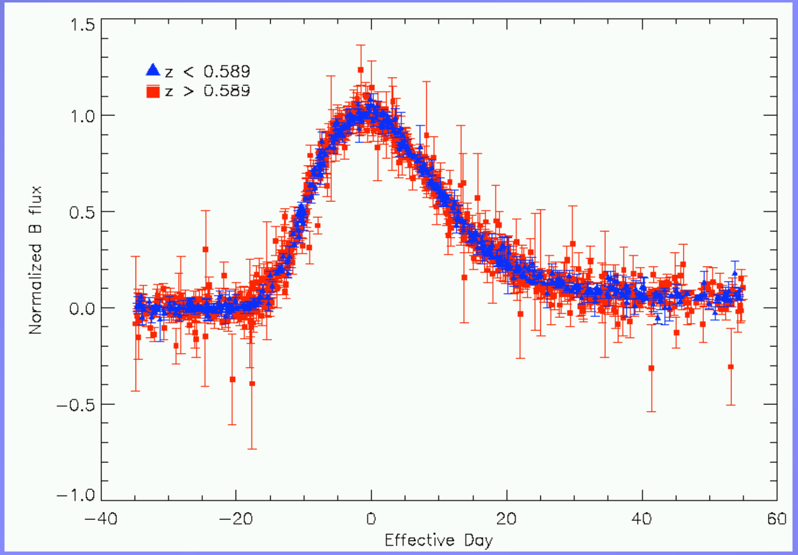
No sizeable effect on cosmology with SNLS 1st year data (when corrected for stretch) but …

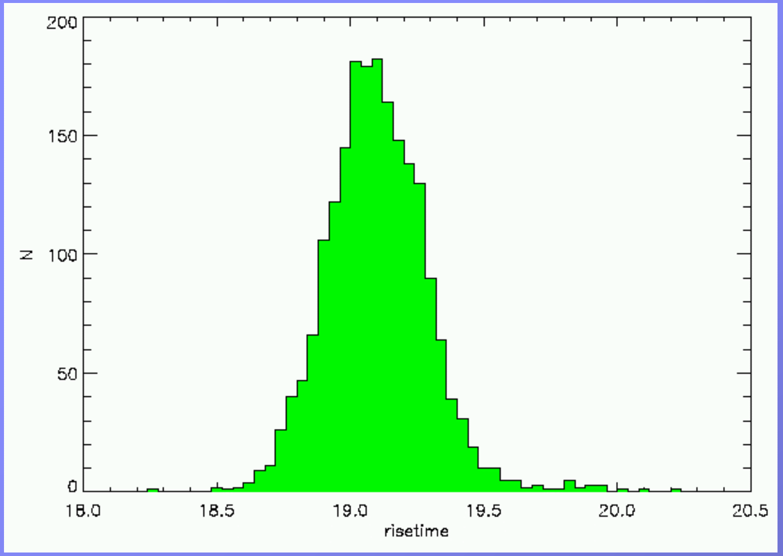
Evolution in rise time ?

Riess 1999 δt(Nearby-Distant SN) = 2.5 +- 0.4 days

Conley et al. 2006
Nearby : 19.58 +/- 0.2
Distant (SNLS) : 19.10 +/- 0.2 (stat) +/- 0.2 (syst)

=> Identical (so far)





But watch for if several progenitors

Distance measurement

Magnitude in redshifted blue filter

$$m_B^* = -2.5\ \log_{10}\left(\frac{f(z, T_B^*, t = t_{max,B})}{(1+z)\int \phi_{ref}(\lambda) T_B(\lambda) d\lambda}\right)$$

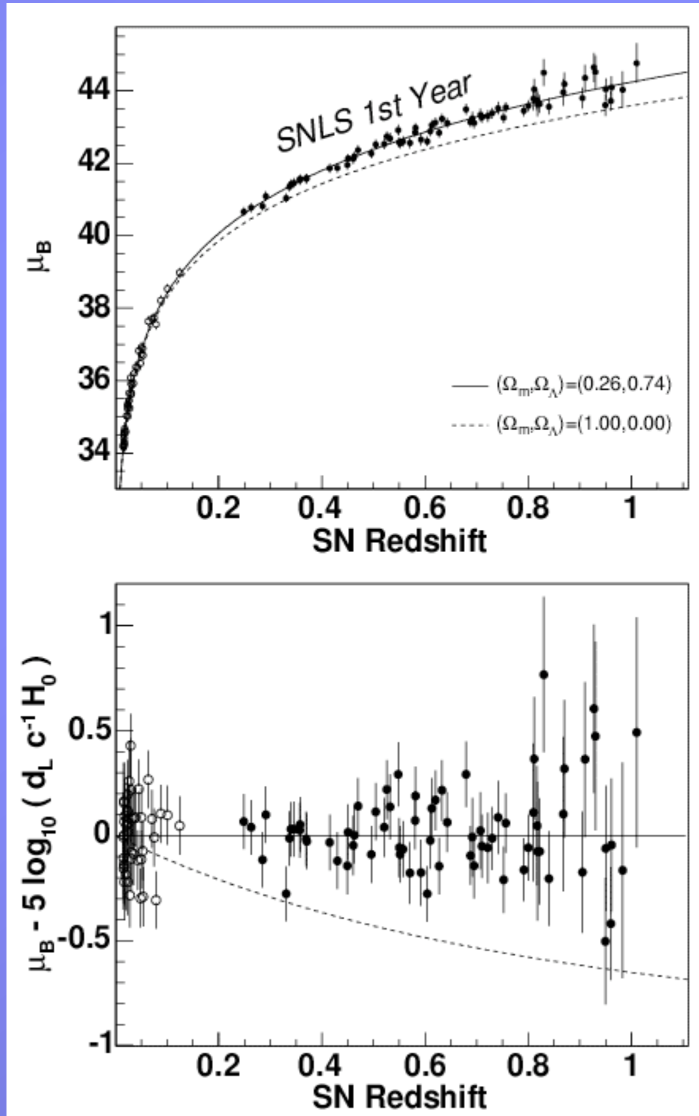
where $T_B^*(\lambda) \equiv T_B(\lambda/(1+z))$

Cosmological fit :

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

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

M, α et β simultaneously fit with the cosmology



Color correction

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

s = stretch
c = $(B\text{-}V)_{max}$ + cst

Simple linear dependency assumed (higher order currently not needed)

<u>fit of β : what is it ?</u>

Extinction correction? then $\beta=R_B$.
Often assumed R_B=4.1 (Milky way) + Cardelli law (1989)
But:
- who says that color variation = extinction ?
- Is Milky way RB the mean value of R ?
- the fit leads to a value ~2 (Tripp 1998, …)

Could it be mostly intrinsic (I.e. related to the SN explosion) ?
- (~temperature correlated to luminosity (CMAGIC).

"Extinction/color" evolution can be tested by fitting a different β for different host types (for the moment limited by statistics)

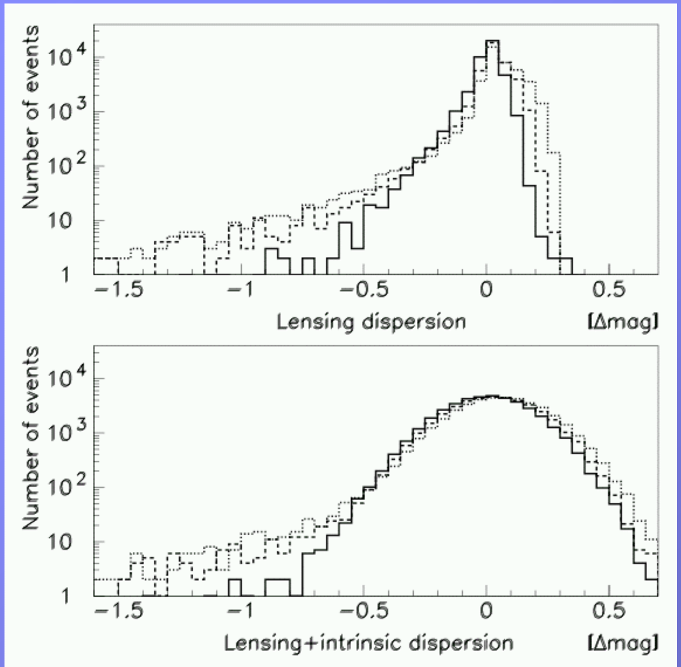
Line of sight "systematic" uncertainties :

Grey dust:
SDSS quasar color
=> limit on column density of dust

For a certain value of R_v

$\sigma(\Omega_m)<0.025$, $\sigma(w)<0.048$
(pour $R_v<12$, Ostman 2005)

Gravitationnal lenses:
flux conservation but:
- asymetric residuals
+ light lost when multiple images
Evaluated using SNOC (Bergstrom 2000)



$\sigma(\Omega_m)<0.005$, $\sigma(w)<0.01$

Conclusions

1 - Several “systematic” uncertainties » are not “systematic”
they can be reduced with more statistics :
- selection biases
- evolution (progenitor+dust)
via host type classification
- k-corrections (empirical modelisation of SN Ia spectra)
multi-filter observations (>=3) :
=> auto-calibration of the distance estimate
- gravitational lenses

2 - Today’s dominant systematic uncertainties come from:
- Nearby SN sample bias
=> need an unbiased nearby survey, stat >~1000
(SNF, SDSS, SkyMapper ...)
- Calibration :
primary standard (B-R) uncertainty of 0.01 <=> 225 SNe à <z>~0.5
instrumental (+ atmospheric) “calibration” needed

Conclusions

3 - to significantly go beyond SNLS/ESSENCE precision,
(δw (stat.) ~0.05 & δw (syst.)~0.05)

one will need:

- obtain large statistics (>10000) of well measured (both nearby and distant) SN to further reduce the “systematics” that scale with statistics (LC model, evolution, selection biases, k-corrections,..

- and work on calibration:
  - get primary reference (star of physical) color to well below %
  - monitor instrumental calibration to well below %
  - observe nearby and distant SN with the same telescope/instrument
  - (on the ground) monitor/measure atmosphere in real-time?