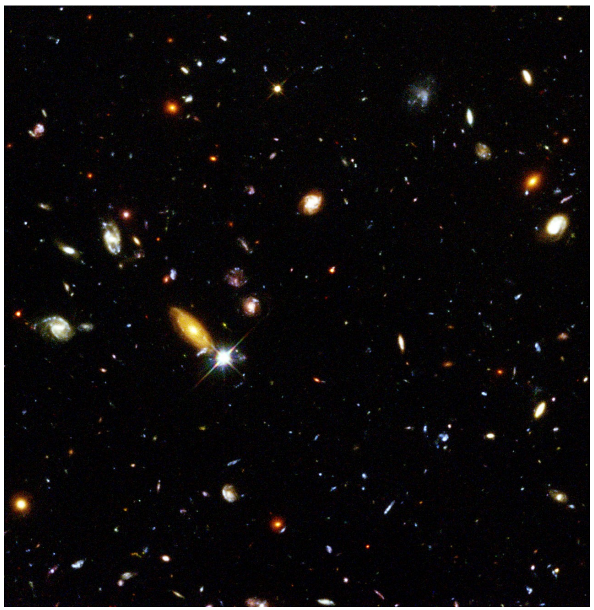
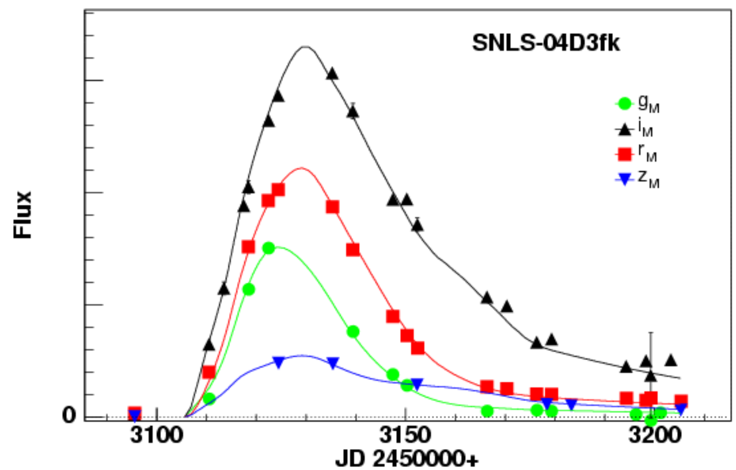
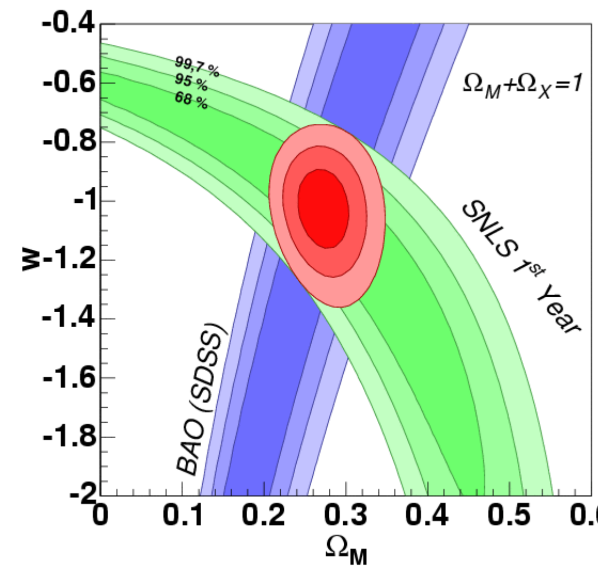
Cosmology with type Ia Supernovae







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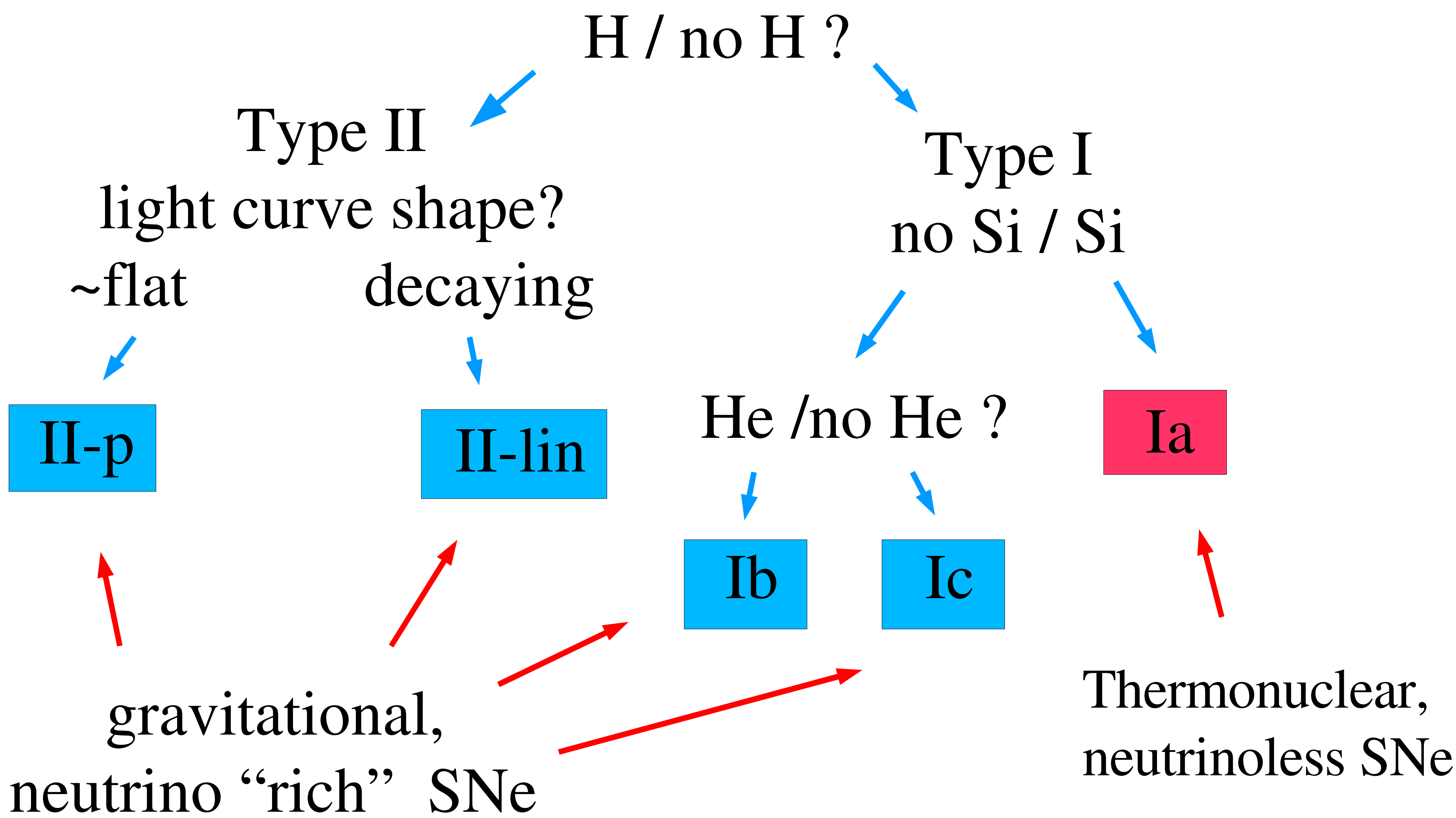
Universités Paris VI&VII

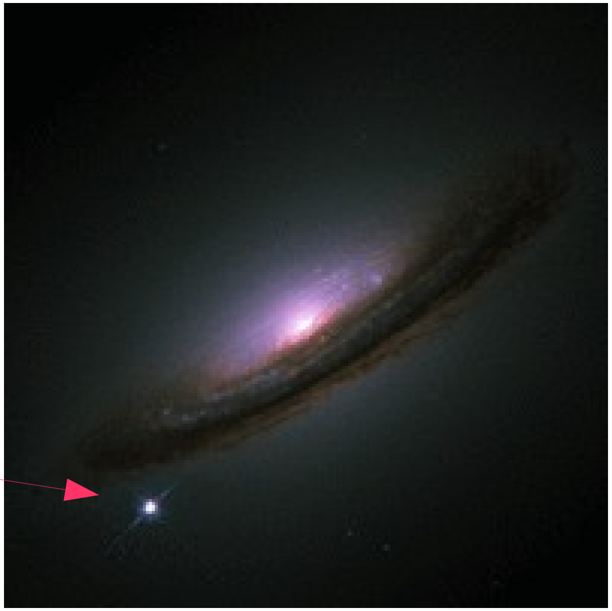
XII International Workshop on "Neutrino Telescopes"

Supernovae: present classification scheme

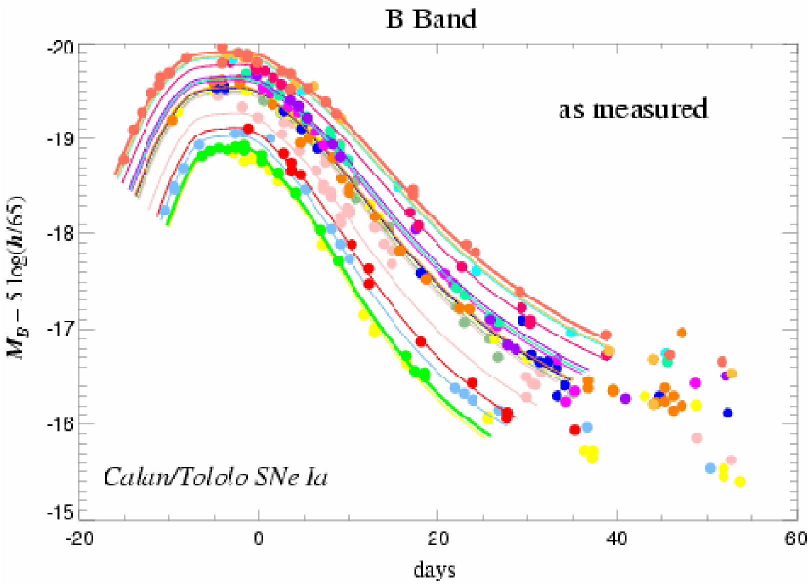


Supernovae Ia

Thermonuclear explosions of stars
which appear to be reproducible

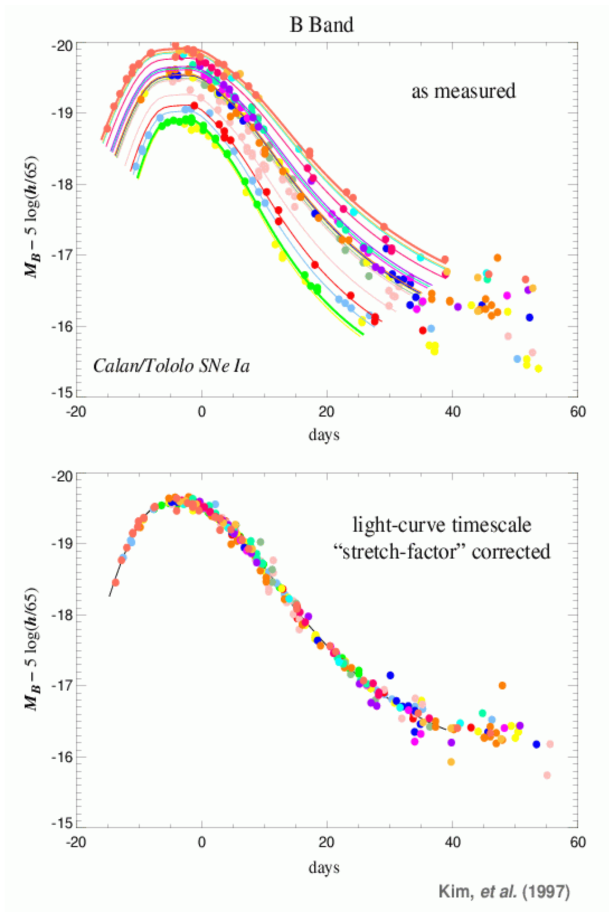


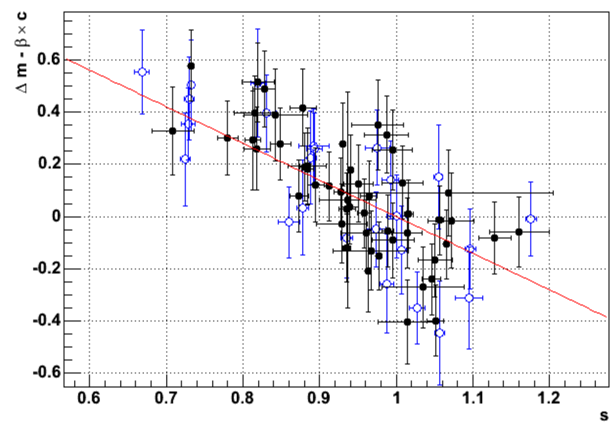
- Very luminous
- Can be identified
- Transient
  (rise ~ 20 days)
- Scarce (~1 /galaxy/millenium)
- Fluctuations of the peak
  luminosity : 40 %
- Can be improved to ~14 %



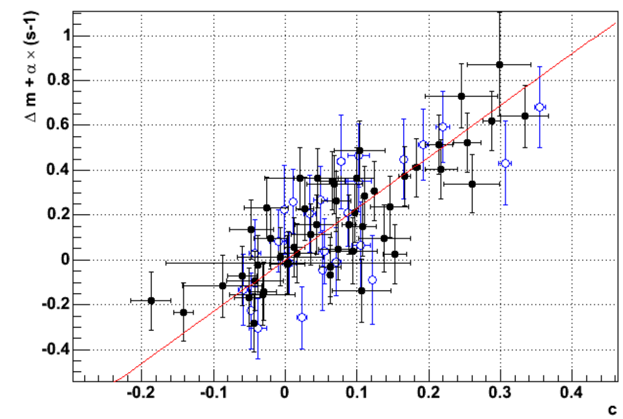
Intrinsic luminosity indicators (for Ia's)

Brighter - slower





Brighter - bluer



stretch: time-scale parameter of the (B) lightcurve, corrected for (1+z)

or

decline rate: decrease of flux at 15 (RF) days from max

color B-V (rest frame) at peak.

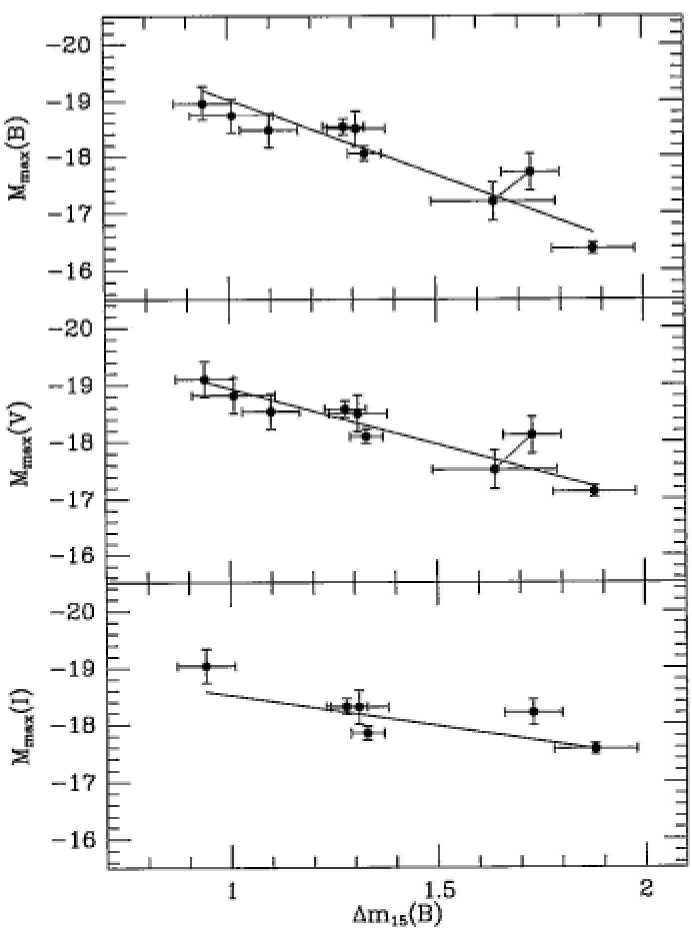
Color = Log(flux(V)/flux(B))

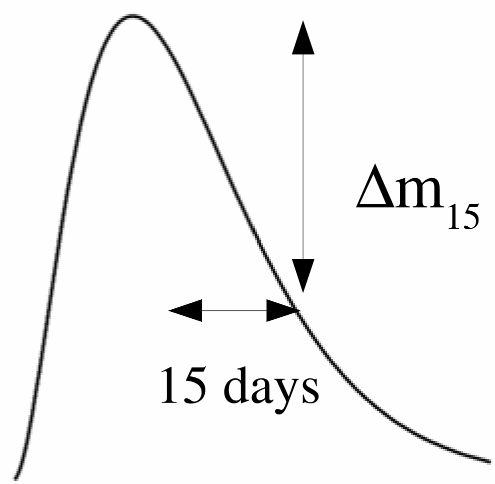
B ~ [400,500] nm

V ~ [500,650] nm

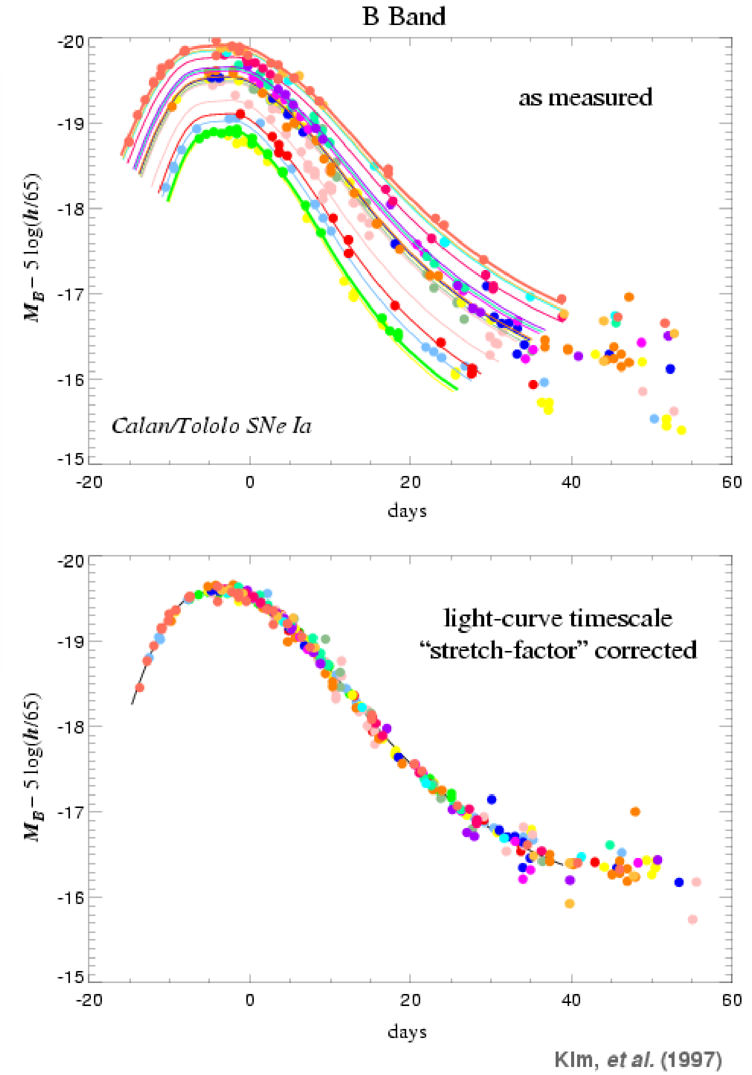
=> enable to reduce brightness scatter to ~13 % (0.13 mag)

Brighter-Slower



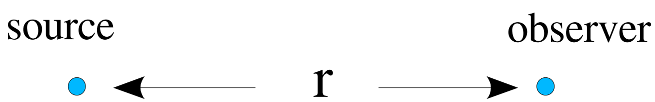


Δm_{15} : Phillips (1993)



Timescale stretch factor

Distances and cosmological parameters



$$ds^2 = dt^2 - R^2(t)\left(\frac{dr^2}{1-kr^2} + r^2(d\theta^2 + sin^2\theta d\phi^2)\right)$$

r(z) =(comobile) distance to a source at a redshift z.

Source and observer are themselves comobile

Messenger : light -> ds = 0. With the Friedmann eq.,

$$r(z) = \frac{c}{H_0\sqrt{|\Omega_k|}} \mathcal{S}\left(\sqrt{|\Omega_k|}\int_0^z \frac{dz'}{\sqrt{(1+z')^2(1+\Omega_M z') - z'(2+z')\Omega_\Lambda}}\right)$$

$$\mathcal{S}(x) = \begin{cases} sin(x) & \text{si} \quad k = 1 \\ x & \text{si} \quad k = 0 \\ sinh(x) & \text{si} \quad k = -1 \end{cases}$$

How to measure cosmological distances ?

- luminosity distance $d_L = (1+z)\, r(z)$

  -> observed flux of an object of known (or reproducible) luminosity

- angular distance $d_A = r(z)/(1+z)$

  -> angle that sustains a known length

  - Correlations of CMB anisotropies.
  - Correlations of galaxies.

Degeneracies from distance data

$$\left(\frac{H(z)}{H_0}\right)^2 = \Omega_{\rm M}(1+z)^3 + \Omega_{\rm X}\,\exp\left(3\int_0^z \frac{1+w(z')}{1+z'}dz'\right) + \Omega_{\rm k}(1+z)^2$$

defines r(z) — Matter — Dark Energy — E.O.S — Curvature

The expansion history depends on the sum of 3 terms.
The equation of state enters in only one of them.
--> exact or quasi degeneracies

1) need to know Ω_k (from C.M.B)

2) if w(z) is arbitrary, the expansion history (via r(z)) constrains a relation between Ω_M and w(z), not both of them independently.

3) even assuming a constant w, there remain a strong (although not exact) degeneracy.

--> distance data alone does not fix unambiguously the E.O.S

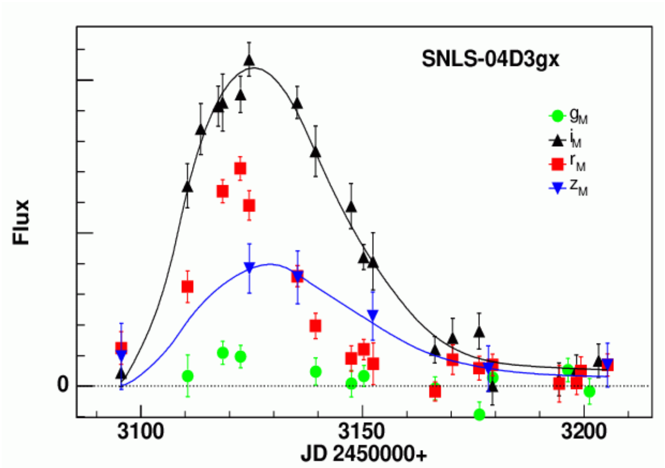
Observing Dark Energy(!)

Dark energy plays an important role in the recent universe (z <~1). Its effect decreases (vanishes?) with increasing z.

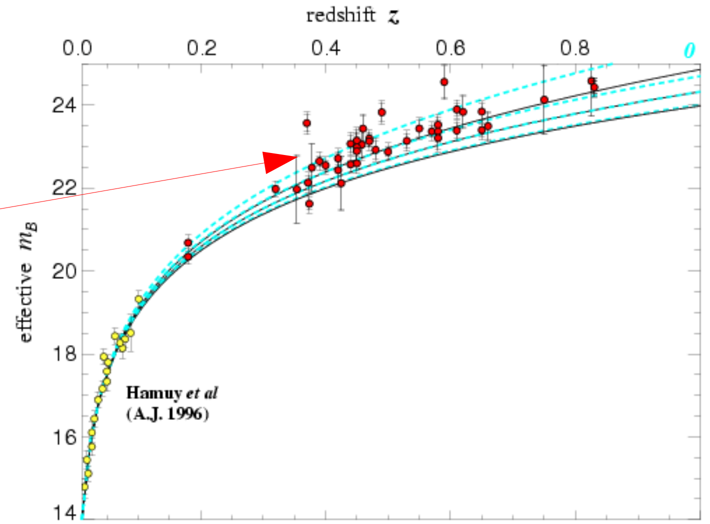
Particularly sensitive methods (for z < ~1):

Method	measures combinations of
- Supernovae Ia Optical (and IR) telescopes, imaging and spectroscopy Figure of merit : number of SNe, z span	$r(z)$
- Weak gravitational shear Optical telescopes, imaging Figure of merit : surveyed area on the sky (up to z~1)	$r(z)$ $r(z_{lens},z_{source})$ $P(k;z)$
- Baryon Acoustic Oscillations Optical telescopes, imaging and spectroscopy. Figure of merit : surveyed universe volume	$r(z)$, $H(z)$ $\Omega_m h^2$ (via z_{eq} and c_{sound})

Measuring distances to SNe Ia



peak flux

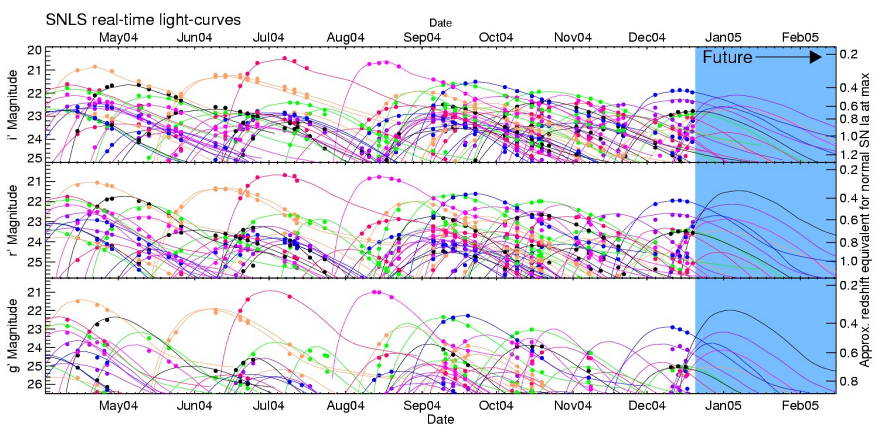


Sne Ia are observed to exhibit reproducible peak luminosities
- Dispersion ~ 40 % caused by luminosity variations.
--> Have to use intrinsic luminosity indicators:
  - decline rate (or light curve width)
    -> fair time sampling of light curves
  - color (i.e. ratio of fluxes in different bands)
    -> measurement in several bands

SNe Ia surveys: from workshops to factories

Old observing way is a many-step process:
- search: imaging at two epochs, ~3 weeks apart
- spectroscopy of candidates found
- Photometry of identified Ia's

Drawbacks:
- Extremely vulnerable to bad weather
  - poor yield of observations
- Many telescopes involved
  - proposals/scheduling issues
  - Photometric calibration issues



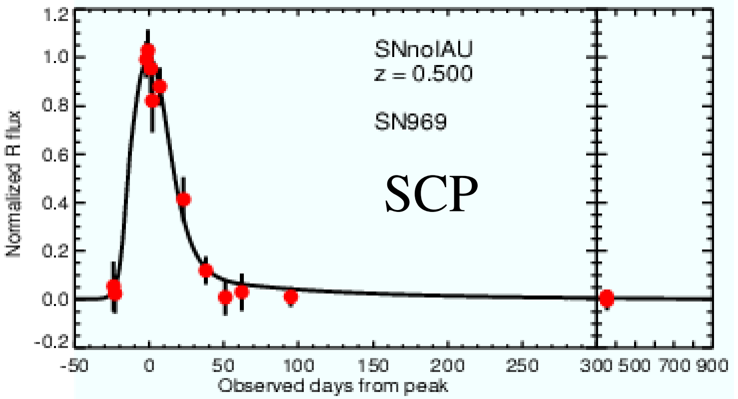
Rolling search mode:
- Repeated imaging of the same fields
- Spectroscopy near peak
- Built-in photometric follow-up

Bonuses:
- Mutiplex: many measurements/exposure
- Detection on a time sequence
- LC sampling independent of phase
- Imaging robust to bad weather
- Spectroscopy in service mode possible
- Only one imaging telescope to calibrate
- Deep stack at the end of the survey
- .....

Drawback:
- Imaging instrument failures...

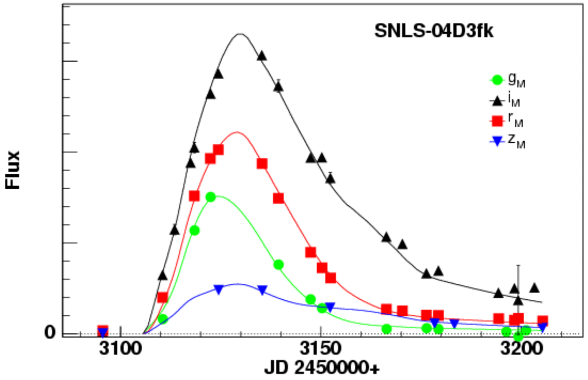
SNe Ia surveys: from workshops to factories (2)

Rolling search is THE way to go for SNe surveys



Three ongoing projects:

- Essence@CTIO
  ~8 deg^2, RI bands, 0.2<z<0.8, 5 years from 2002.
- SNLS@CFHT (within the CFHTLS)
  4 deg^2, griz bands, 0.2<z<1, 5 years from 2003.
- SNe in SDSS-II
  300 deg^2, ugriz bands, z<~0.35, 3 years from fall 2005.



Rolling searches become increasingly difficult as z decreases
- Requires very wide field imaging ~10 deg^2
- Large area -> Large data volume.

- Many ground-based wide-field imaging projects are in the landscape:
  Pan-Starss, DES (@CTIO), LSST, Hyper Suprime Cam, ...

SNLS SuperNova Legacy Survey

French-Canadian led Collaboration to discover, identify and measure SNe Ia in the CFHT Legacy Survey(DEEP). About 40 persons.

Targets 500 well measured SNe Ia at 0.2<z<1

Rolling search over four 1 deg^2 fields in 4 bands (griz):
~250 hours/year at CFHT.

Spectroscopy : ~ 250 h/year on 8m-class (!!)

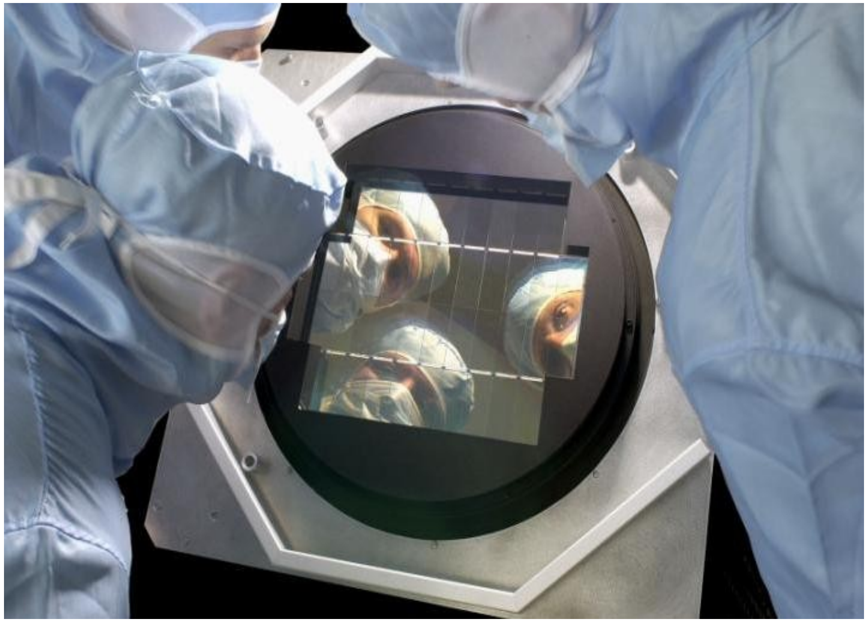
- VLT (Europe 120 h/y), Gemini (US/UK/Can 120 h/y), Keck (US 30 h/y).

http://snls.in2p3.fr

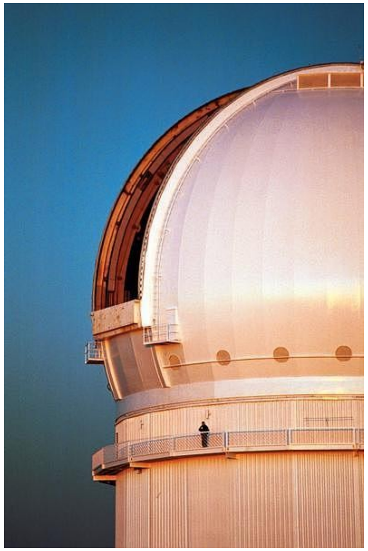
CFHTLS IN2P3 CNRS CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CFH cea INSTITUT NATIONAL DES SCIENCES DE L'UNIVERS INSU NSERC CRSNG

MegaCam at CFHT

MegaCam:
- 36 CCDs 2k x 4.5k pixels
- 1 pixel = 0.185"
- field of view : 1 deg^2
- 1rst light at end of 2002.

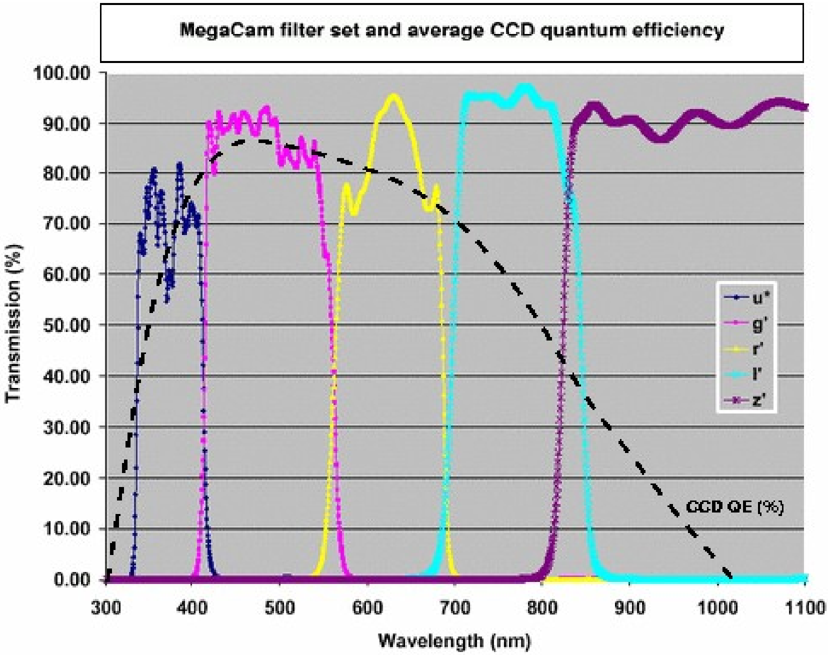


CFHT:
- diametre 3.6m
- Mauna Kea, Hawaii
- 4200 m
- <seeing> = 0.8"



CFHTLS/Deep : Observing mode

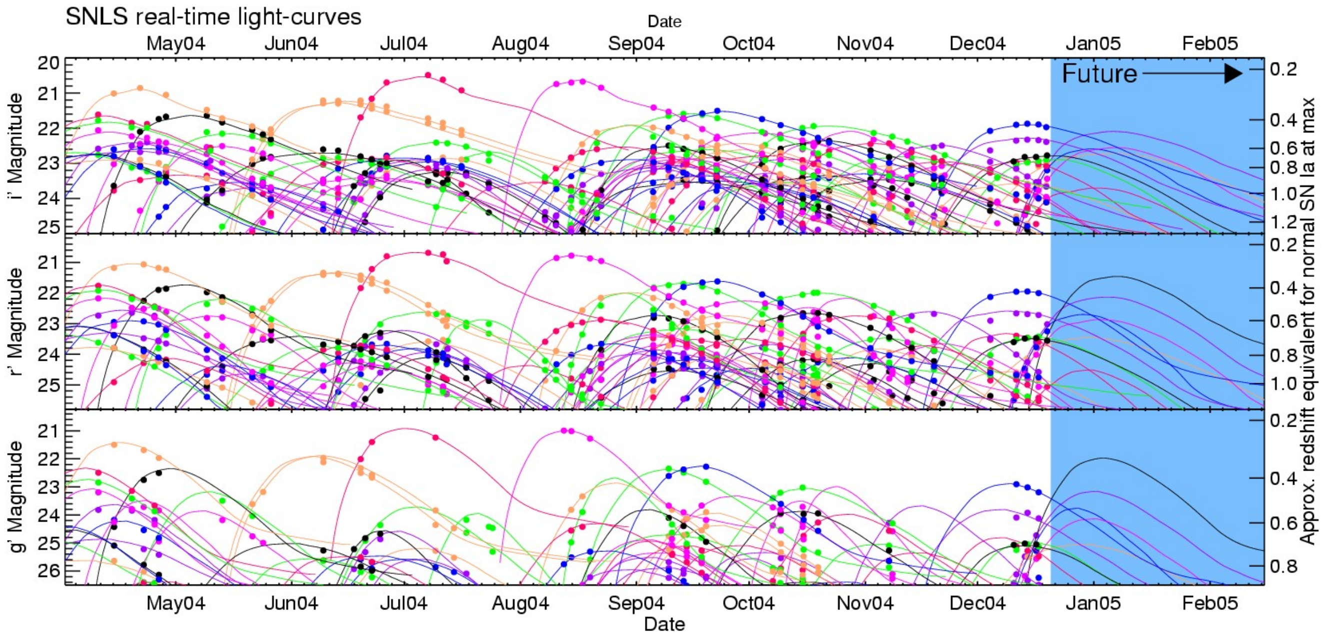
- 40 nights/year for 5 years.
- Repeated observations every ~4 night ("rolling search"), service mode
- 4 bands g,r,i,z
- 4 one deg^2 fields monitored ~ 6 month/year



-> Photometric data **before** objects are detected

-> **Multiplexing :** several SNe per field in a single exposure

-> Repeated calibration of field stars



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Detecting Supernovae

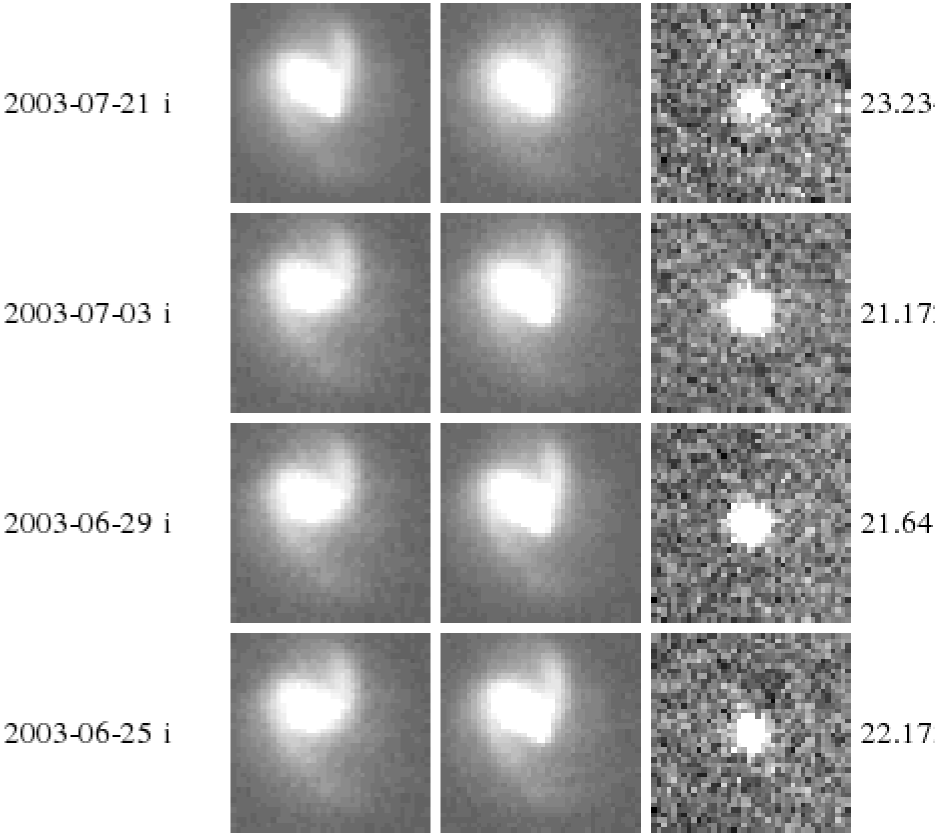
- New images (of the previous night) are subtracted off a reference image of the field (e.g. a stack of last year images)
  - before subtraction one has to "align" images:
    - geometrically
    - photometrically
    - PSF (bring to the same star shape).

- Detection of (positive) excesses (typically above 3σ)

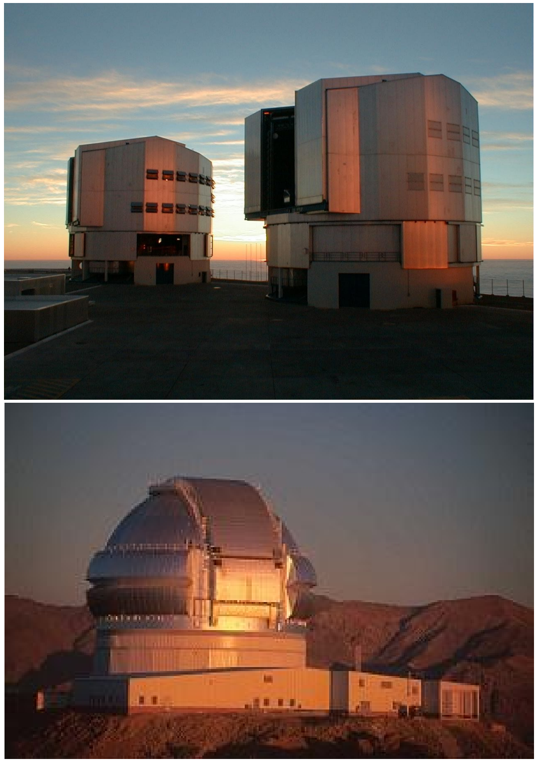
-> Association of detections over nights/bands to reach ~ 8σ

–> Lightcurves are fit to a SNe Ia template to evaluate a "Ia likelihood"

-> Spectroscopy.

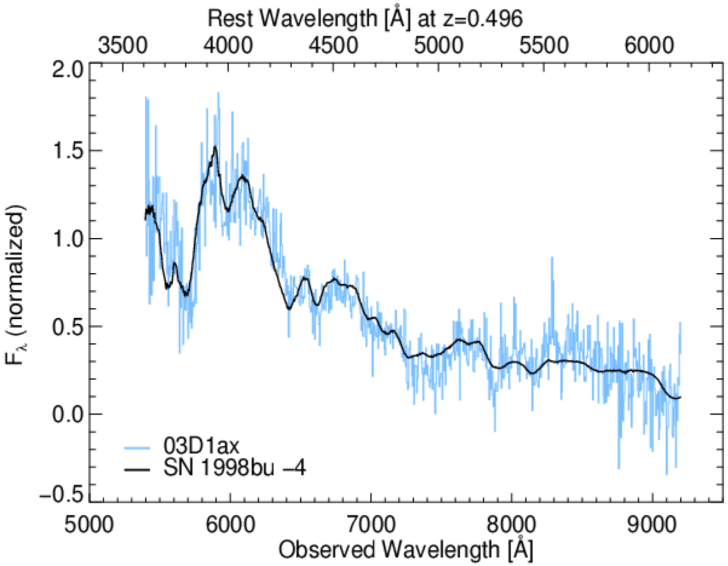


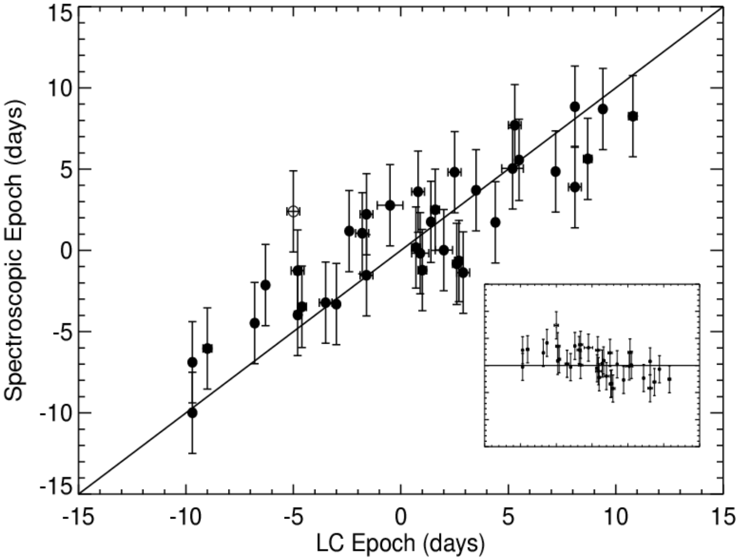
Spectroscopy



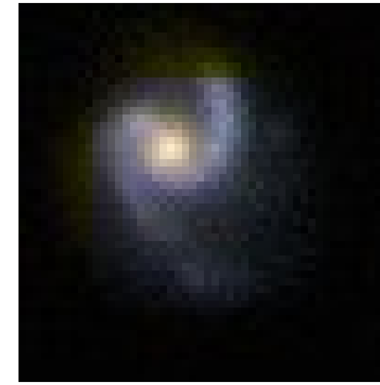
Identification of SNe Ia
Redshift (usually of the host galaxy)
Detailed studies of a (small) sample of SNe Ia/II

Telescopes
- VLT Large program (service)
  240h in 2003+2004, idem 2005+2006
- Gemini : 60h/semestre
  (Howell 2005, astro-ph/0509195)
- Keck : 30h/an (spring semester)

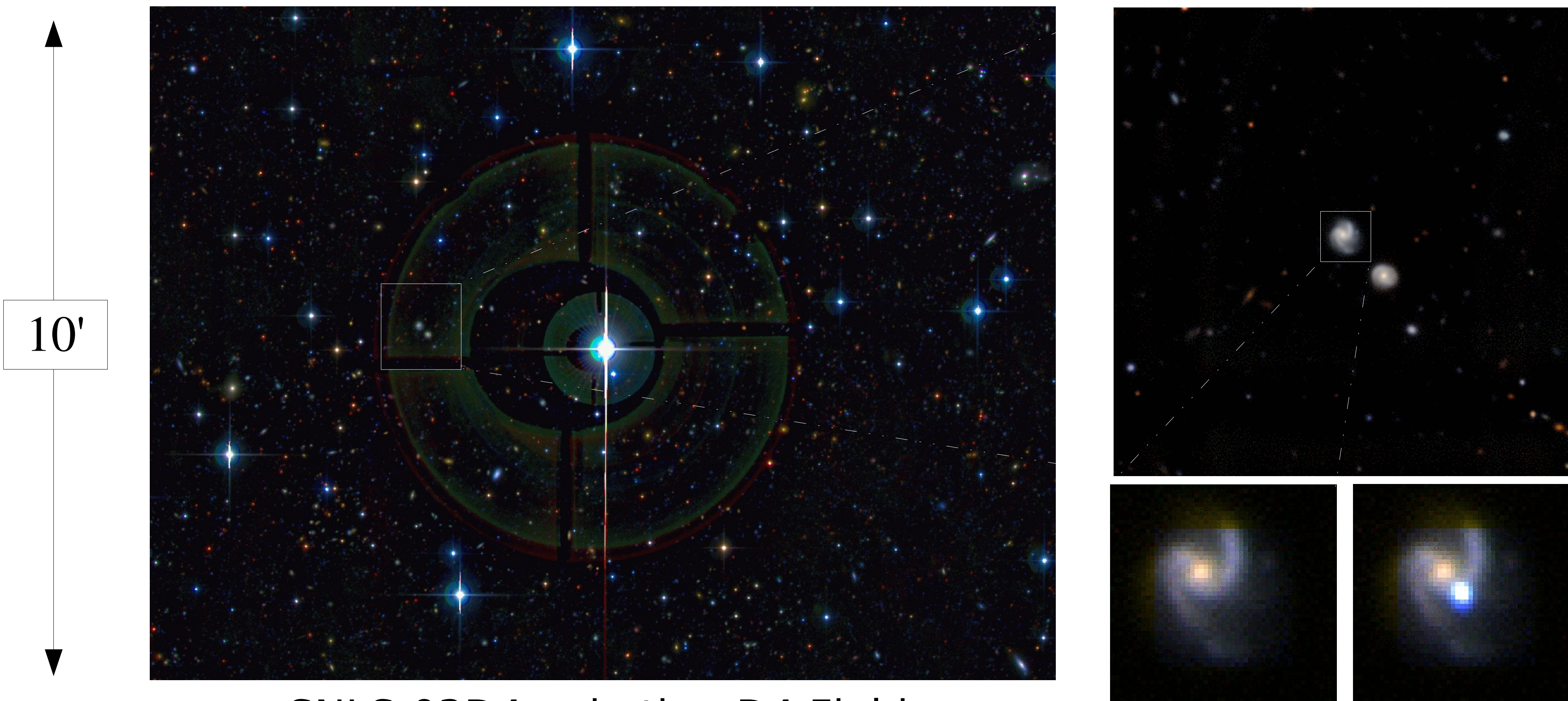




Analysis for cosmology of the SNLS first year data sample August 2003 – July 2004



- Differential photometry
- Photometric calibration
- Fitting lightcurves
- Fitting cosmology
- Systematics

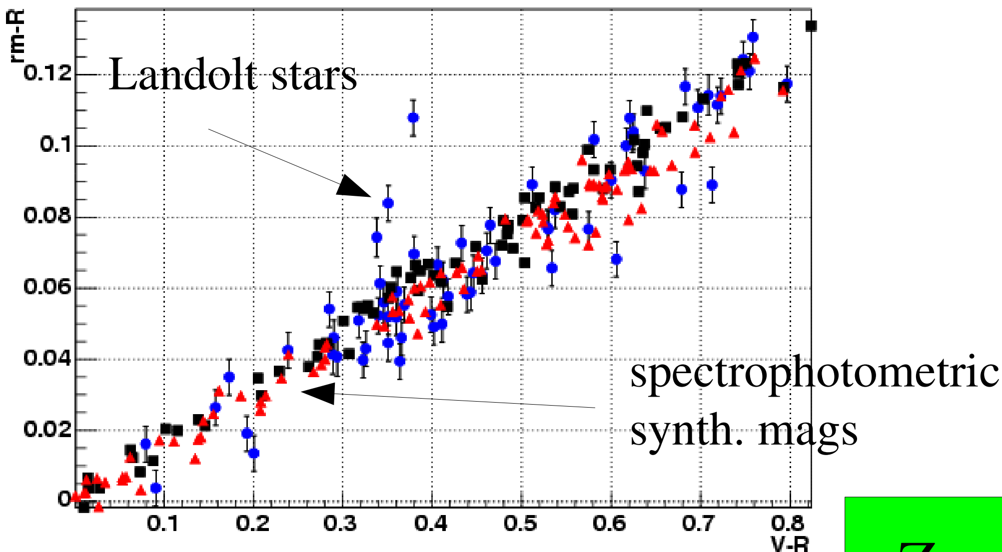


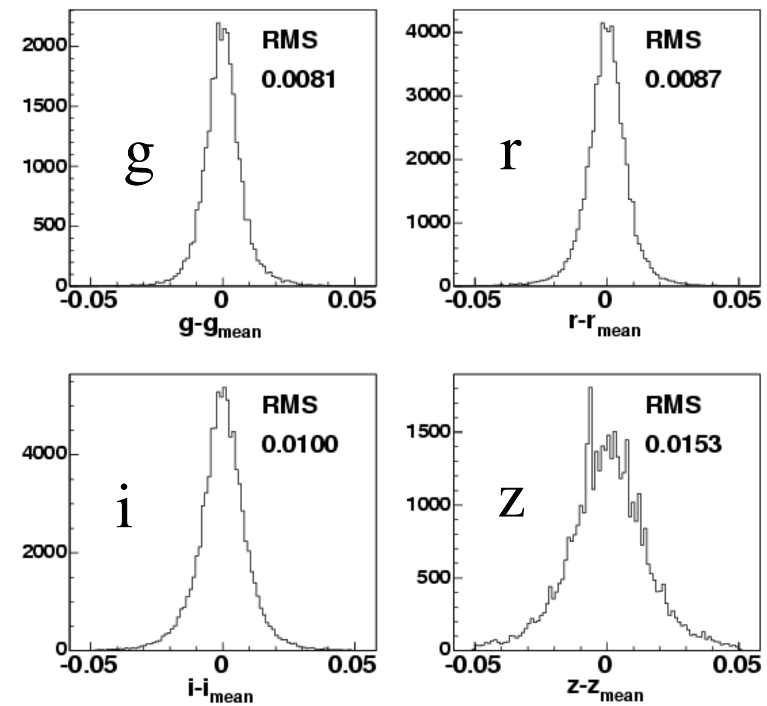
SNLS-03D4ag in the D4 Field

Photometric calibration

- Relies on repeated observations of Landolt standard stars.
- Calibration in “Landolt” (Vega) magnitudes because nearby SNe are calibrated this way
- Produces calibrated star catalogs in the CFHTLS Deep fields, in natural Megacam magnitudes.

Comparison of synthetic and observed color terms (Megacam/Landolt & Megacam SDSS 2.5m)



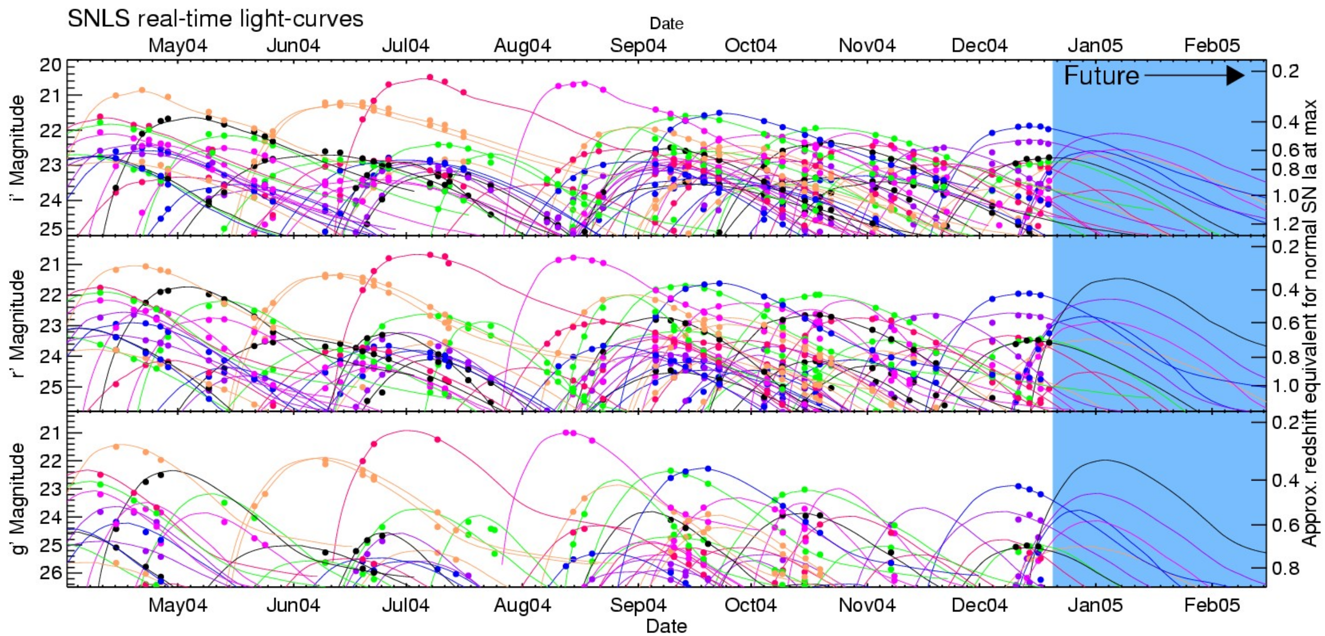


-Zero points @ 0.01 (0.03 in z)
-Repeatability better than 0.01 (0.015 in z)

First year SNLS data set
(up to July 2004)

142 acquired spectra:

- 20 Type II SNe
- 9 AGN/QSO
- 4 SN Ib/c
- 91 SNe Ia



-10 miss references (are now usable)

- 6 only have 1 band (lost)

75 usable Ia events

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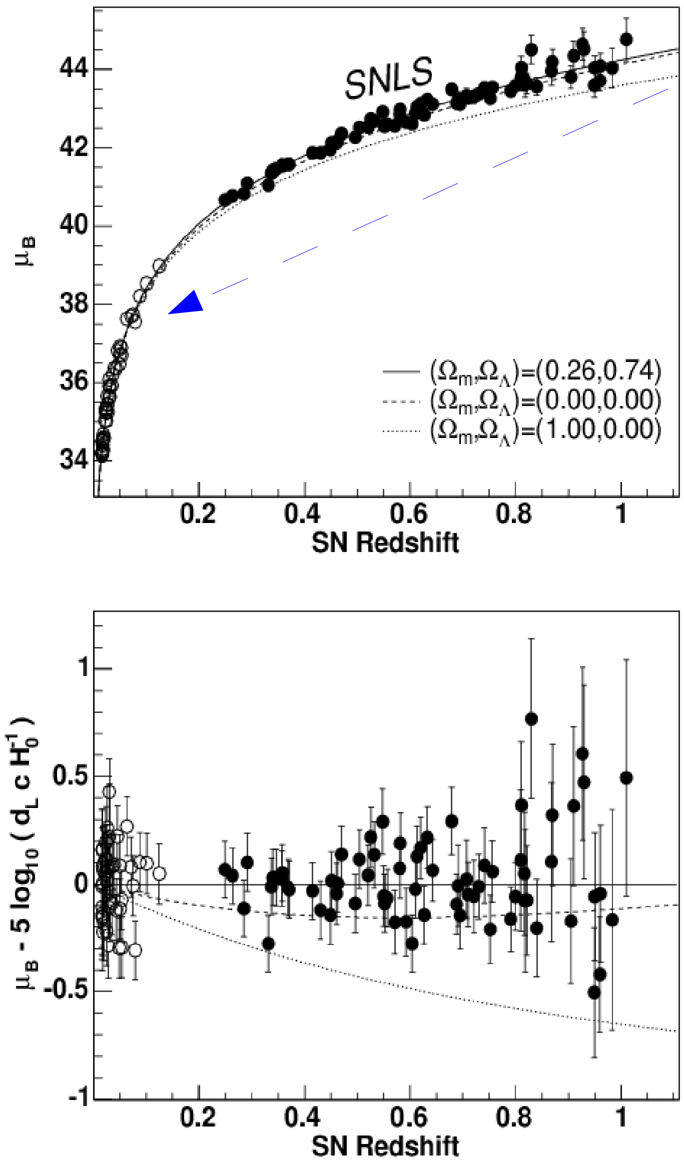
Hubble Diagram of SNLS (first year)



Final sample :
45 nearby SNe from literature
+71 SNLS SNe
(Drop 4 from SNLS sample because strong Hubble Diagram outliers)

Distance estimator:

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

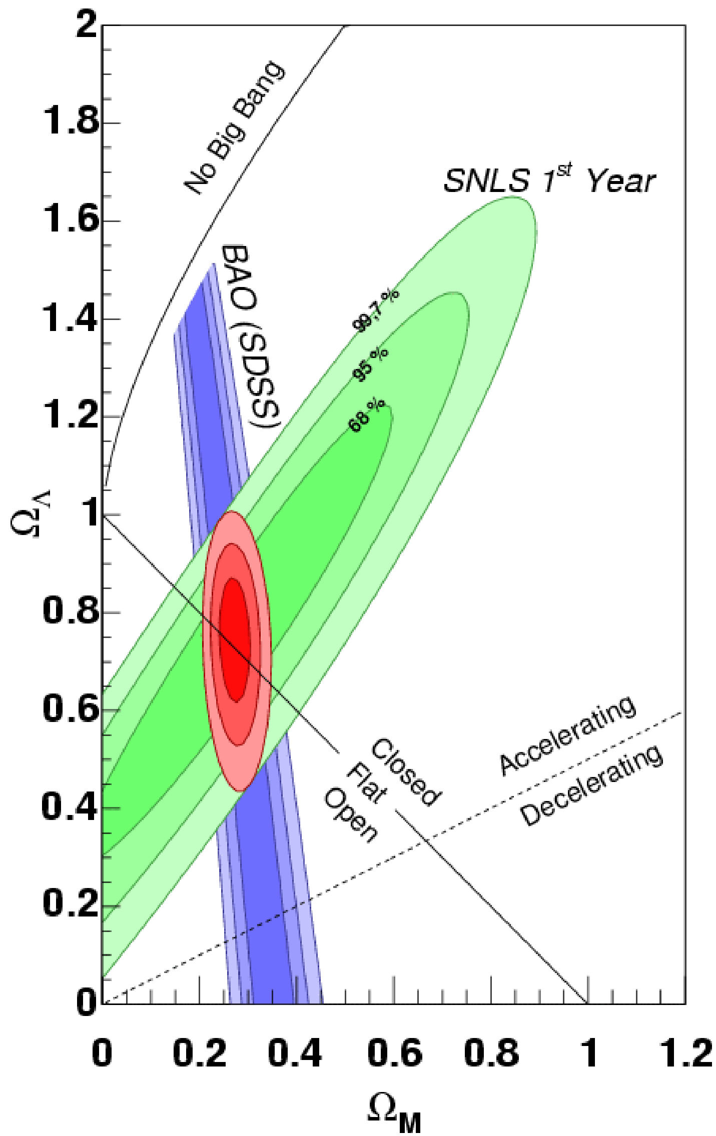
brighter-slower brighter-bluer

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

- minimize w.r.t θ, ***M***, α ,β
- compute σ_{int} so that $\chi^2 = N_{dof}$ ($\sigma_{int} = 0.13$)
- marginalize over ***M***, α ,β to draw contours

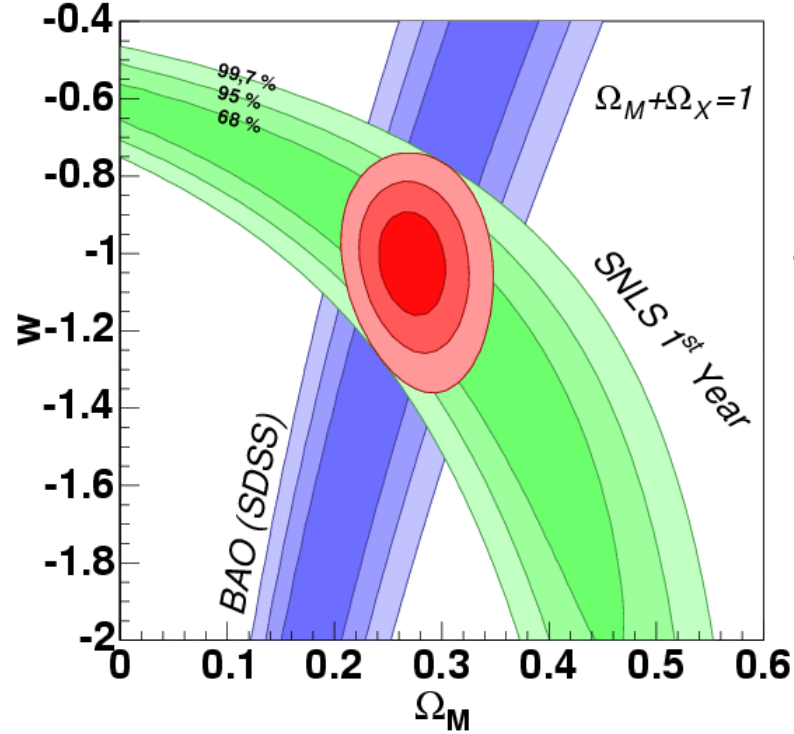
Confidence Contours

w=-1



68.3, 95.5 et 99.7% CL

Ω_T=1



<-- Λ

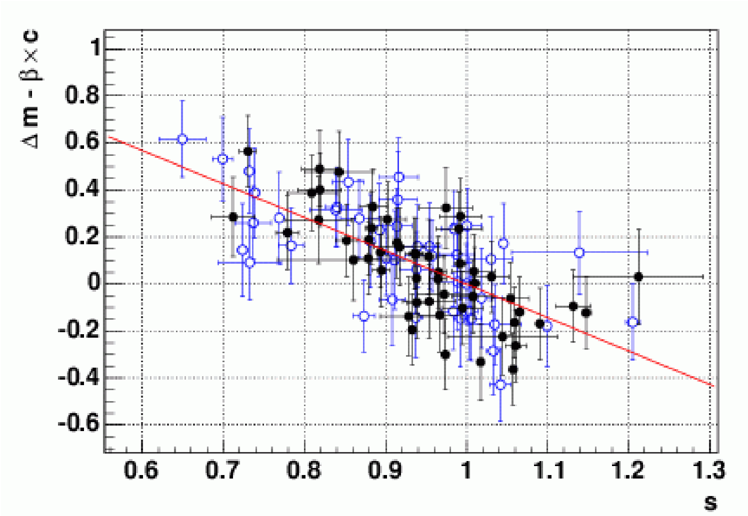
BAO: Baryon Acoustic Oscillations
(Eisenstein et al 2005, SDSS)

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

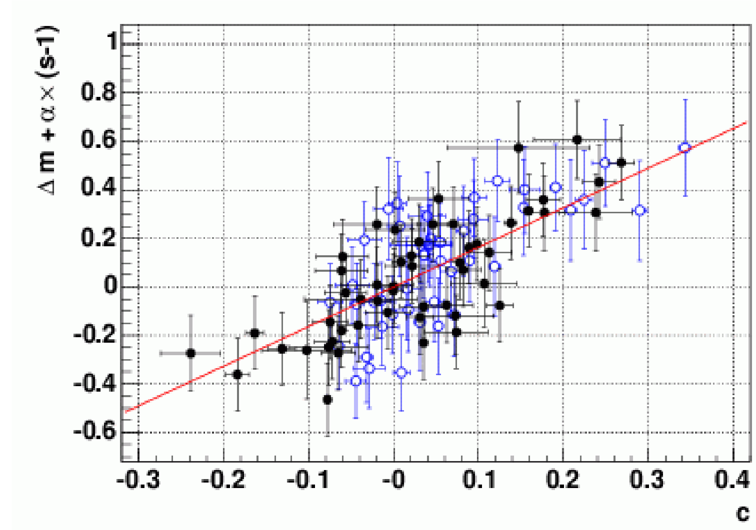
(astro-ph/0510447)

Evolution test: comparing distant (z<0.8) and nearby SNe

Brighter - slower

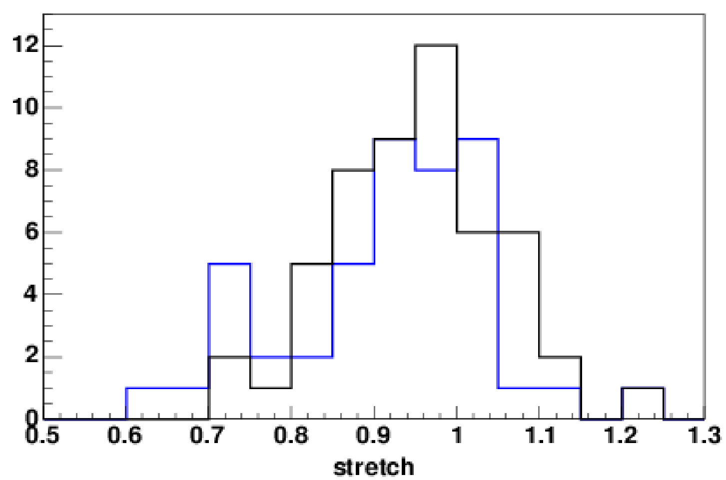


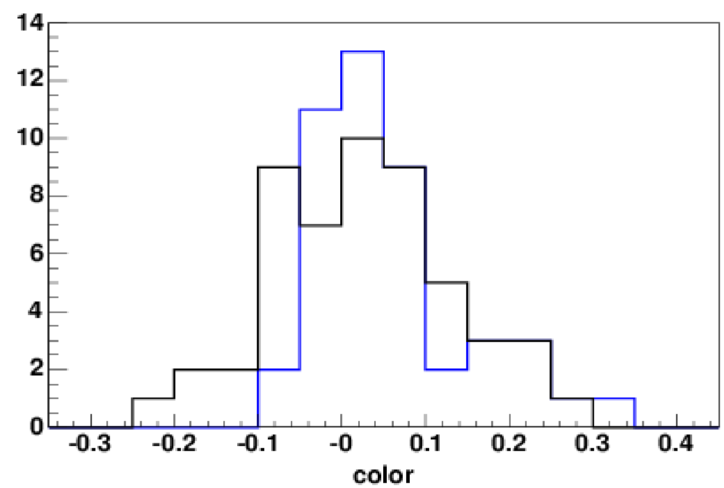
Brighter - bluer



Blue: nearby SNe

Black: SNLS SNe





Stretch, color and relations with luminosity are essentially compatible between nearby and distant events.

Systematic uncertainties

Summary:

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

Improvements foreseen on z calibration and Malmquist bias

Cosmological results

For a flat ΛCDM cosmology:

(SNLS alone)

$$\Omega_M = 0.264 \pm 0.042\ (stat) \pm 0.032\ (sys)$$

For a flat Ω_M,w cosmology :

SNLS + Baryon Acoustic Oscillations (Eisenstein et al, 2005):

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

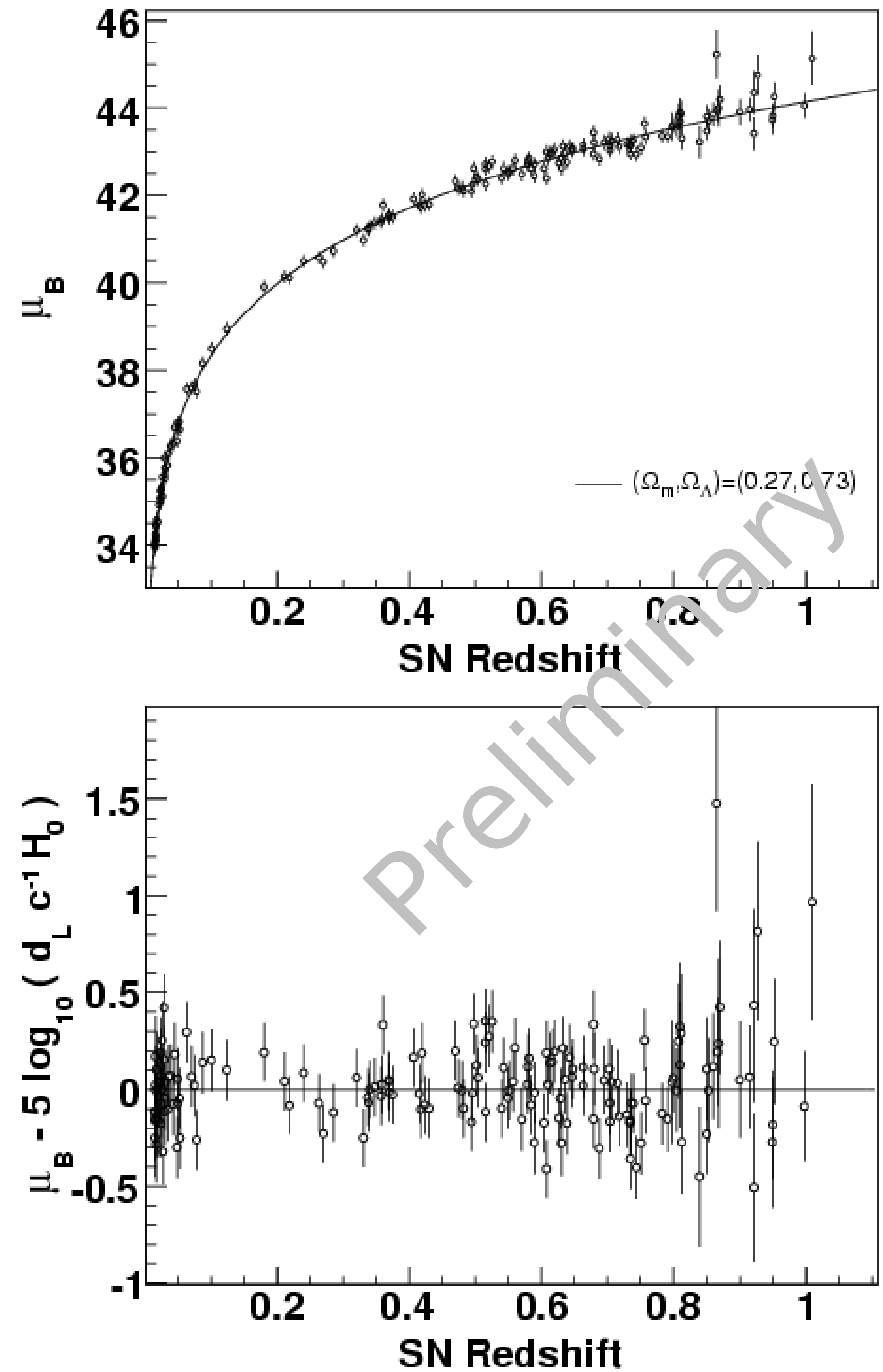
- **Confirmation of acceleration of expansion** with 71 (new!) distant SNe Ia.
- Use **color-corrected distance estimate without prior** on color.
- Careful study of systematics
- Photometric calibration will improve with specific measurements at CFHT

(SNLS collaboration, A&A 2006, astro-ph/0510447)

SNLS 2.5 years Hubble Diagram

Up to March 2006,
we have ~250 distant SNe Ia

Extremely bad weather
during winter 05/06.



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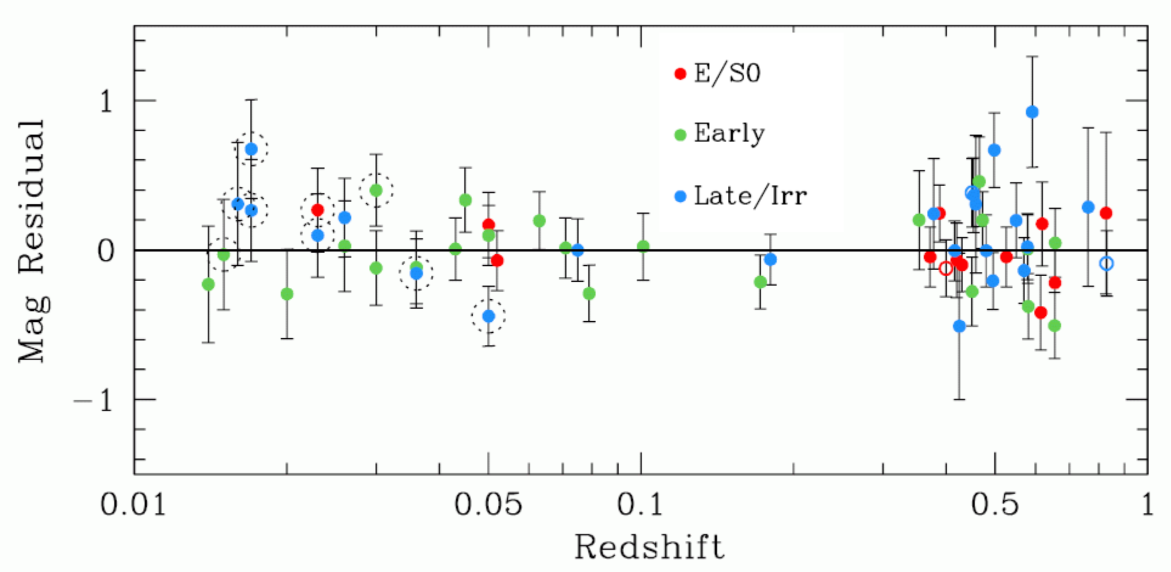
Current issues : SN properties vs galaxy types

Host galaxy types should evolve with redshift. However:

- No evolution of SNe Ia observables yet
  (marginal demographic evolutions compatible with selection biases)

Strategy :

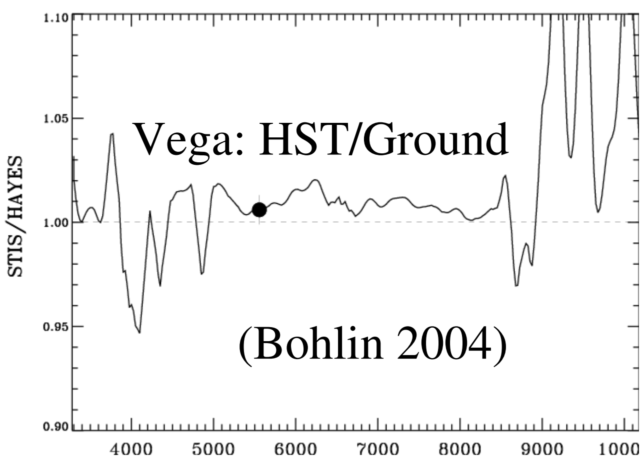
- Identify host galaxy type from colors (at known redshift) or spectrum.
- Compare SNe properties and brighter-bluer and brighter-redder correlations separately.
- Build separate Hubble diagrams if incompatible.
- Obviously, high statistics are necessary for these studies.

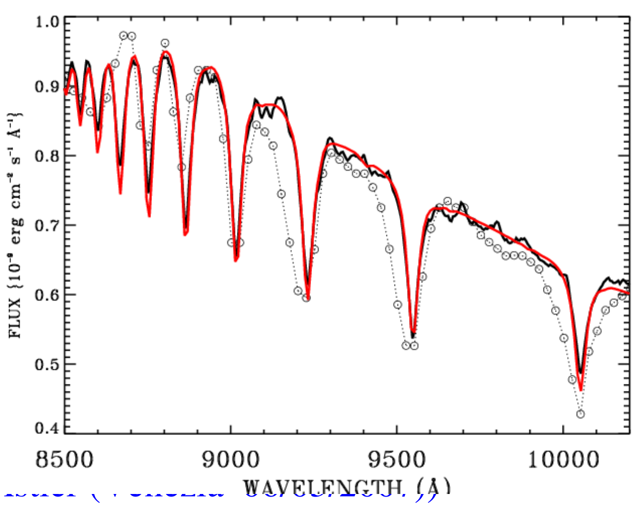


Residuals to Hubble diagram of Perlmutter et all 99 with host galaxy types
Sullivan et al (2003)
astro-ph/0211444

Current issues : Photometric calibration

SNe cosmology requires ratio of fluxes measured in different spectral bands
Magnitudes provide ratio of fluxes measured in the same band.
Hence magnitudes have to be converted into fluxes...
... which requires the spectrum of standard stars.
- Vega spectrum known to ~ 1% (Hayes 1985, Bohlin 2004)





- SNe cosmology forecasts usually assume ~1 % systematic uncertainty of relative (distant/nearby = red/blue) flux scales. This is realistic but may become pessimistic.

- Could we calibrate instruments against lab standards rather than sky standards ?
  - Essence has such a project underway (@CTIO)
  - SNLS is in the implemetation phase.

SNe Ia cosmology : HST searches

PANS survey : an HST based survey

- HST/ACS search (imaging in the visible)
- HST/ACS grism spectroscopy (resolution $\delta\lambda/\lambda$ ~ 1/100)
- HST follow-up with ACS (visible) and/or NICMOS (near IR) according to z.

Two published papers : Riess et al (2004, 2006):

- Statistical accuracy comparable to SNLS first year, despite larger statistics and a larger z span : due to a less accurate distance estimator (known as MLCS).
- The analysis applies a prior on measured color (!).
- HST/NICMOS photometric calibration uncertain : z>1 SNe distances are uncertain by at best 4% (δw ~ 0.1)

SNe Ia cosmology : ESSENCE result

ESSENCE is a ground-based rolling search running at CTIO-4m.
First cosmology paper :astro-ph 0701041

Data set :

60 supernovae (over 3 years) measured in only 2 observer bands (R & I)
--> measured restframe bands change a lot across the sample

Analysis :

- prior on measured colors
  (depends on z to compensate for selection biases ?!)
- noisy distance estimator

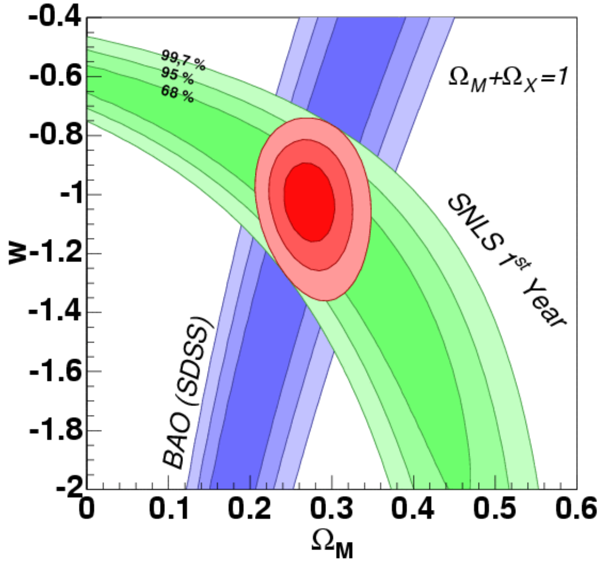
causes large "systematic" errors

Results :

Essence + nearby SNe + B.A.O   w = -1.05 +/- 0.12 +/- 0.13
SNLS+Essence + nearby SNe + B.A.O   w = -1.07 +/- 0.09 +/- 0.13

SNe+BAO:Short term forecasts for w

(SNLS Collab., 2005)



Expected "realistic" statistical improvements of the (Ω_M,w) constraints.

SNfactory
SDSS SNe
SNLS SNe

	Nearby SNe Distant SNe	44 71	inf. 71	44 213	132 213	132 500	250 500
with current BAO accuracy	$\sigma(\Omega_M)$	0.023	0.019	0.019	0.019	0.018	0.018
	$\sigma(w_0)$	0.088	0.073	0.076	0.064	0.060	0.055
BAO x 2 (4000->8000 deg^2)	$\sigma(\Omega_M)$	0.016	0.014	0.014	0.013	0.013	0.013
	$\sigma(w_0)$	0.081	0.062	0.067	0.054	0.049	0.044

SNe Ia surveys: from workshops to factories (3)

Discovery and photometry of SNe will become easier and easier...

Even for nearby SNe :

typically requires 2000 deg^2 in 3-4 bands twice a week to m_{AB}= 21.5

Within reach of Pan StarSS, LSST goes deeper, smaller telescopes would suffice.

What about spectroscopy?

- SNLS uses ~250 h/year on 8m-class telescopes :VLT, Gemini and Keck for ~140 SNe Ia/year.

- Multiply that by 10 ?
  - more than one dedicated 8m telescope
  -> (extremely) unlikely to happen shortly

Mandatory improvements for O(10000) cosmology/SNe surveys:

- Photometric identification of Ia's, from lightcurve shapes and colors
- Efficient wide-field (~1 deg^2) MOS spectroscopy to measure redshifts of host galaxies

Conclusions/summary

Dark Energy looks like Λ (SNe+BAO)

$$\begin{aligned} \Omega_M &= 0.271 \pm 0.021\,(stat) \pm 0.007\,(sys) \\ w &= -1.02 \pm 0.09\,(stat) \pm 0.054\,(sys) \end{aligned}$$

(astro-ph/ 0510447)

- w @ 0.05 within reach of current efforts
- Only next generation surveys will tackle dw/dz
  - SNe
  - BAO
  - Weak lensing
  - more probably a mixture of these