Cosmology and Dark Energy

Pierre Astier

LPNHE / IN2P3 / CNRS , University of Paris

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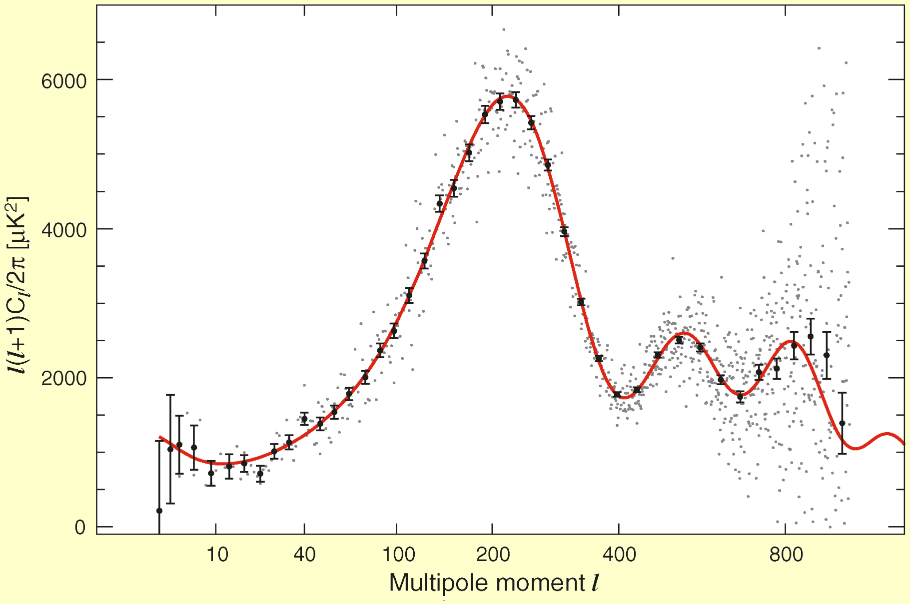
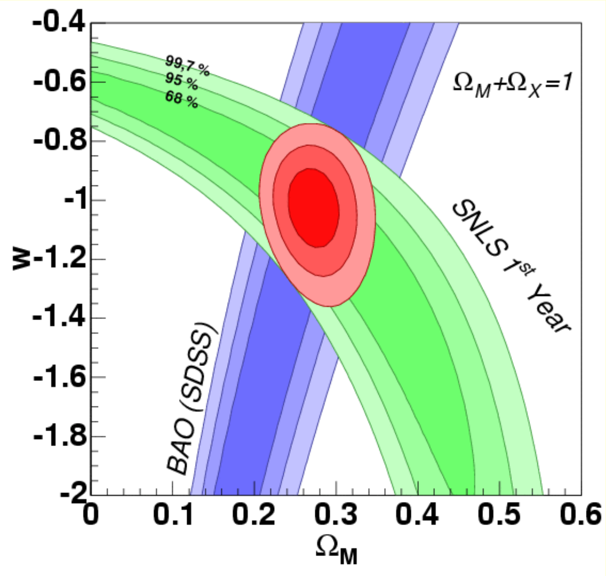
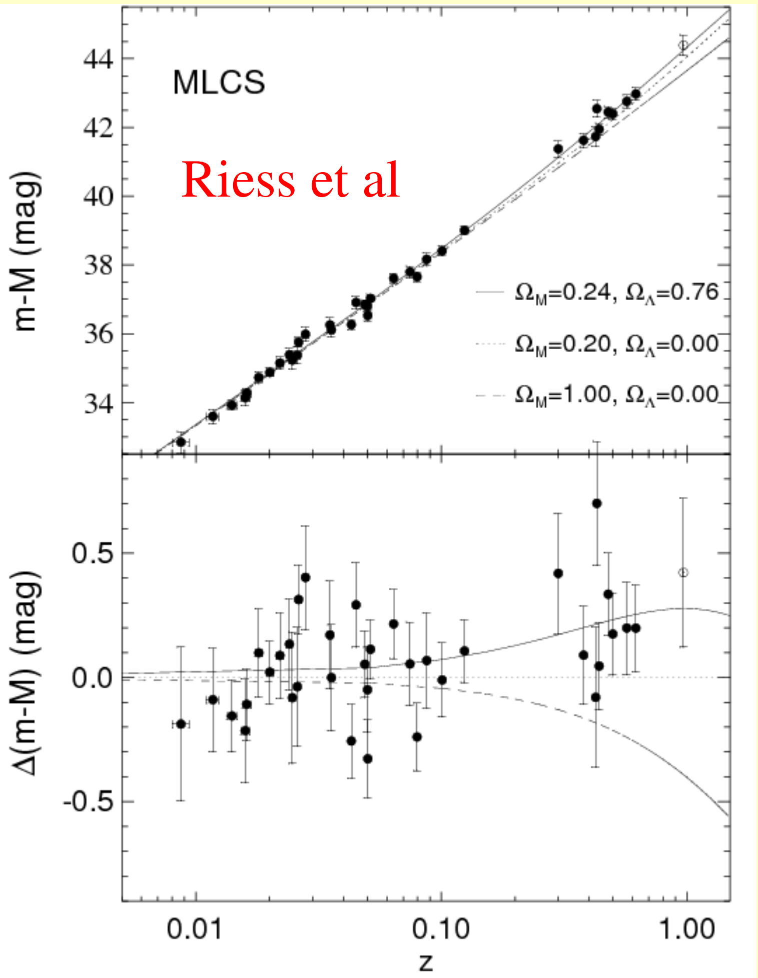
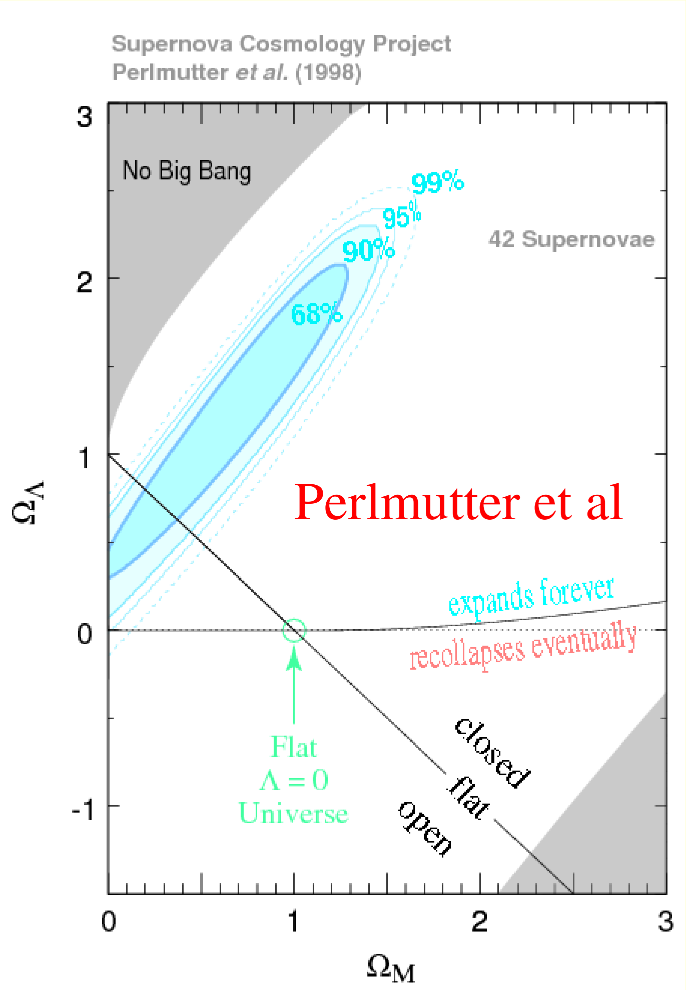




1998 : the twin papers

Two groups present measurement of distances to supernovae at z~ 0.5



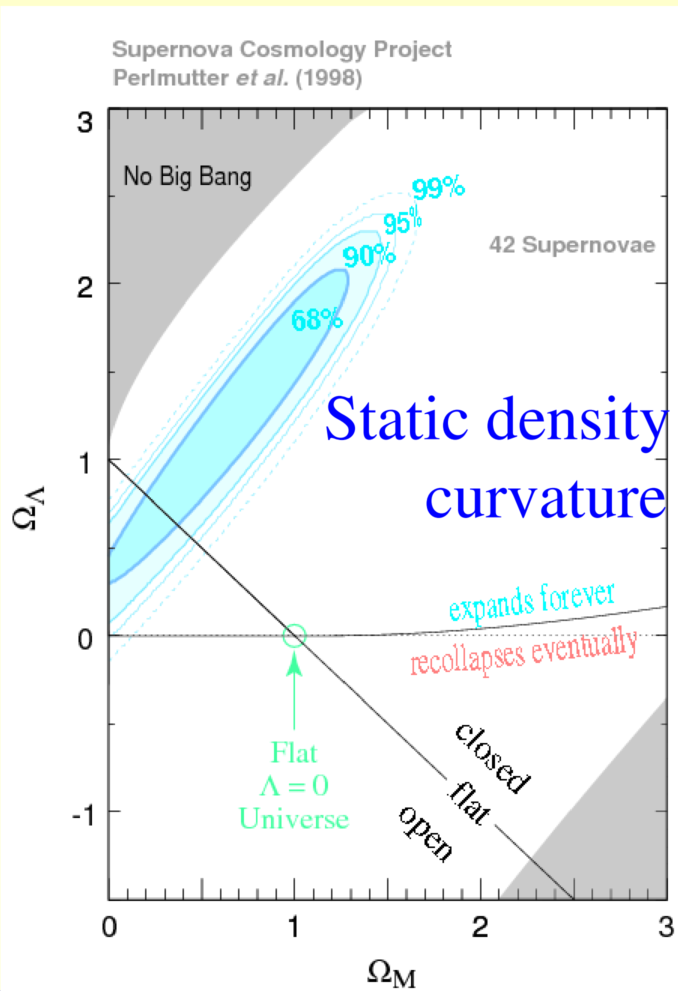


There is more than just matter

Supernovae appear fainter than expected in a matter-dominated universe:

== > Two-components universe : matter & dark energy

Dark energy density varies slowly (or not at all) with time.

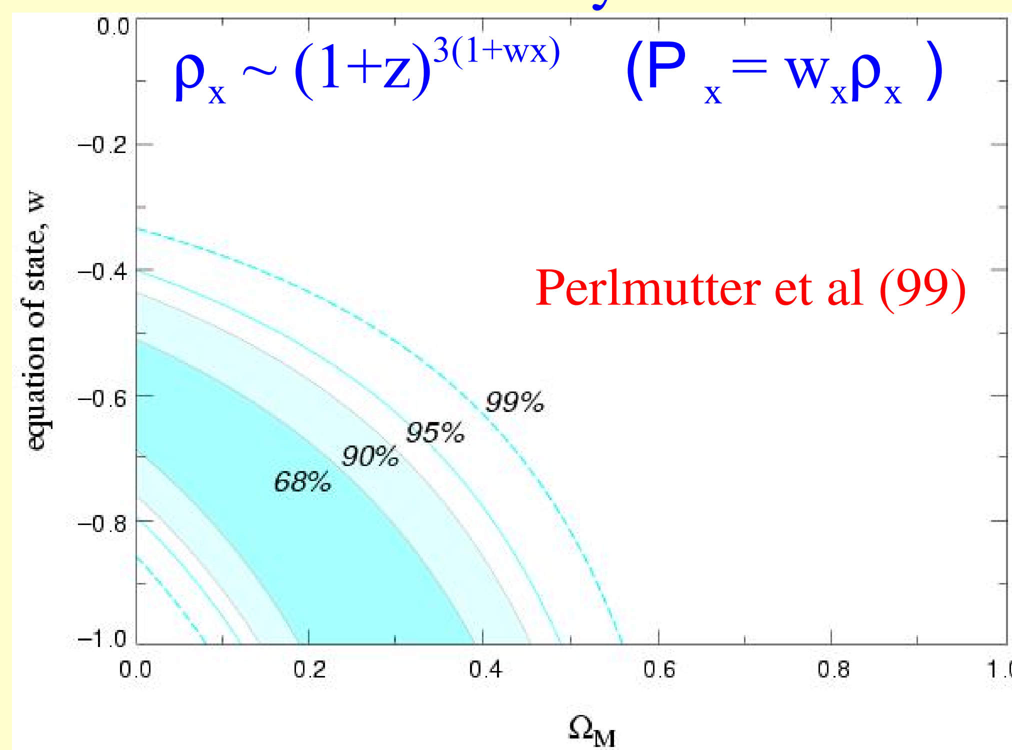


Static density (i..e Λ)
curvature free

Zero curvature
allowed density variation :

$\rho_x \sim (1+z)^{3(1+wx)}$ $(P_x = w_x \rho_x)$

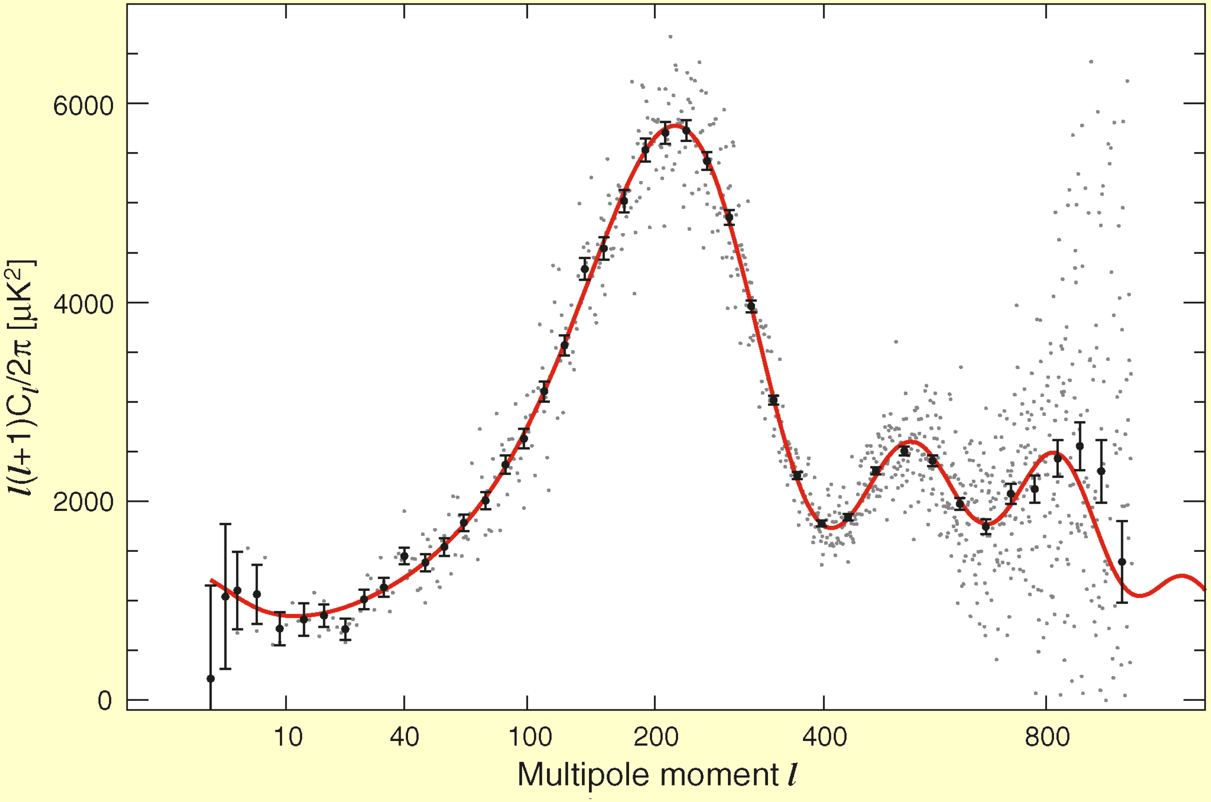
Perlmutter et al (99)



CMB : WMAP 5-year data set

(astro-ph/0803.0547, Komatsu et al, 2008)

Angular power spectrum
of CMB fluctuations



Universe is ~ flat

Ω_{tot} = 1.01+/- 0.015
(wmap + others)

now set Ω_{tot} = 1:

Ω_M = 0.258+/- 0.027

Ω_b = 0.044+/- 0.003

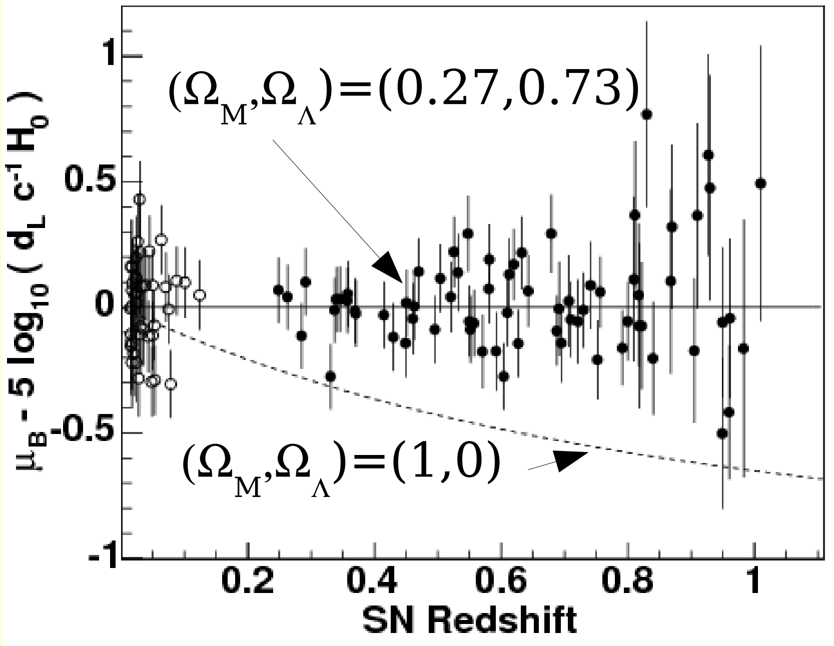
(h=0.719 +/- 0.027

$\Omega_M h^2$ = 0.133 +/– 0.006)

Dark Energy evidence : 2 ways

"Direct" :

SNe Ia Hubble diagram :



(SNLS Collaboration, 2005)

" Subtraction":

$$\Omega_{tot} \sim= 1 \quad \text{(CMB. + e.g. } H_0\text{)}$$

$$- \Omega_M \sim= 0.25 \quad \text{(CMB. + flatness)}$$

(or BAO or ...)

$$\Omega_X \sim= 0.75$$

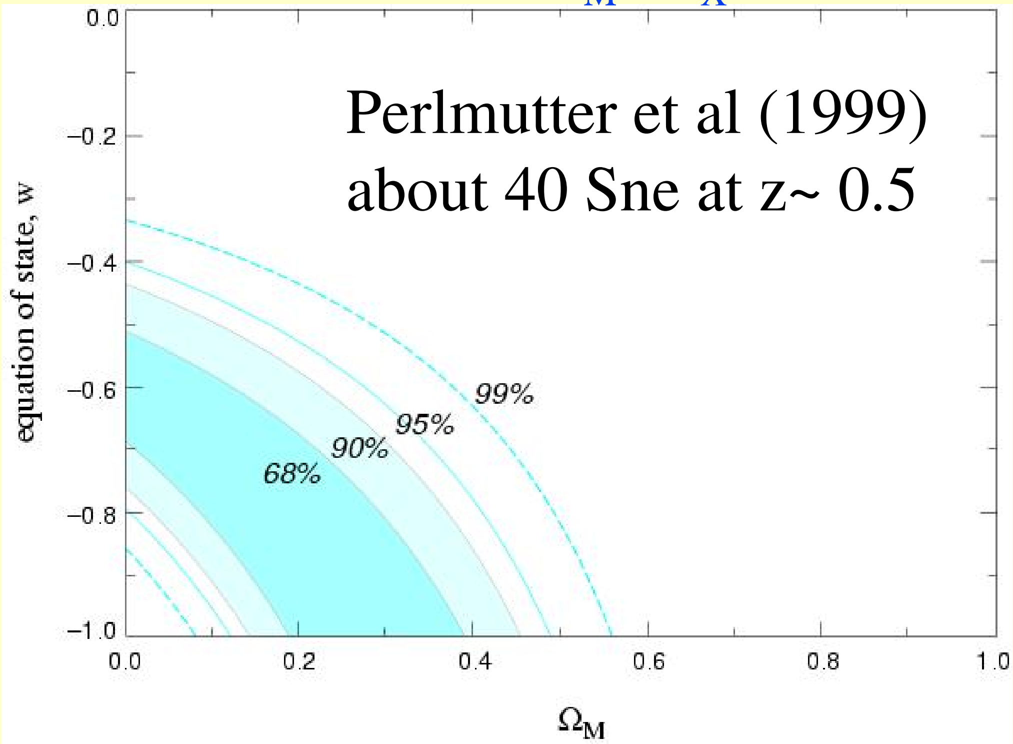
Dark Energy nature

"Nature" here means "Equation of state" w or how DE reacts to expansion

$P_x = w\rho_x$ or equivalently. $\rho_x \sim R^{-3(1+w)} \sim (1+z)^{3(1+w)}$

Type	w
Matter	0
Radiation	1/3
Cosmological cst	-1
Static scalar field	-1
Cosmic strings	-1/3
Domain walls	-2/3
"Quintessence"	<~-0.8
"Phantom energy"	<-1

$\Omega_M + \Omega_X = 1$



Dark Energy : observational handles

$$\left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G}{3}\rho_M + \frac{\Lambda}{3} - \frac{k}{R^2}$$

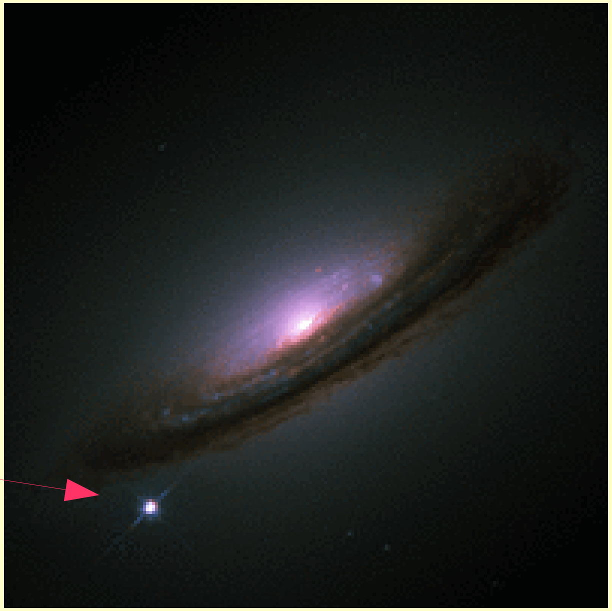
Expansion history H(z) constrains
the RHS of Friedmann's equation
- Distances to standard candles as a function of z (SNe Ia)
- Angular size of a standard rod as a function of z
(Baryonic Acoustic Oscillations , BAO)

Growth of (matter) structures
- Large scale matter power spectrum
evolution with z
via cosmic shear through lensing
- Redshift distortions
- Galaxy cluster counts

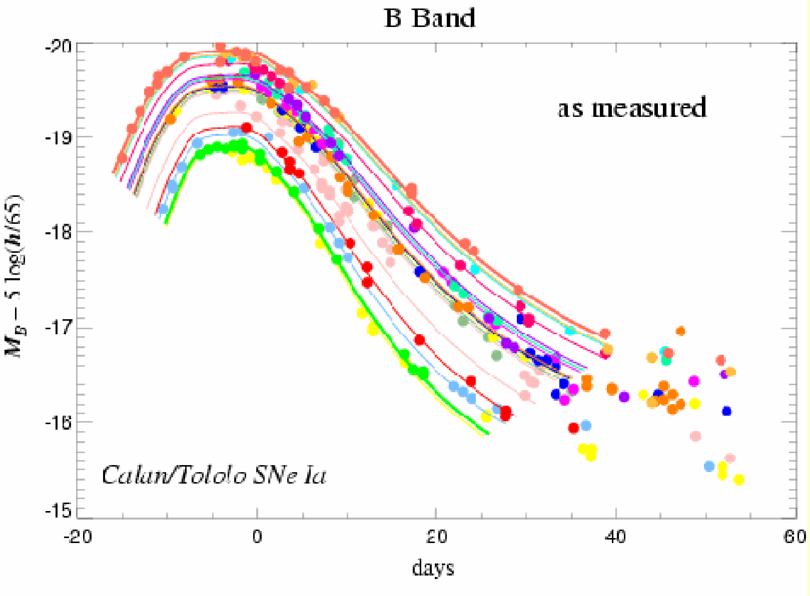
$$\ddot{\delta} + 2\left(\frac{\dot{R}}{R}\right)\dot{\delta} = 4\pi G\rho_{\mathrm{M}}\delta$$

Type Ia supernovae

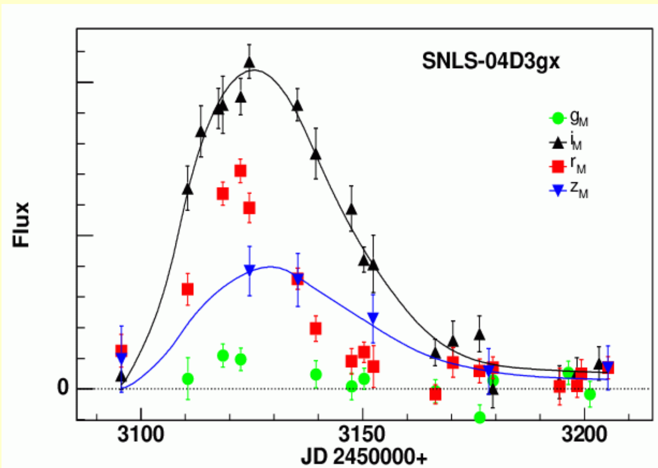
Thermonuclear explosions of stars
which appear to be reproducible



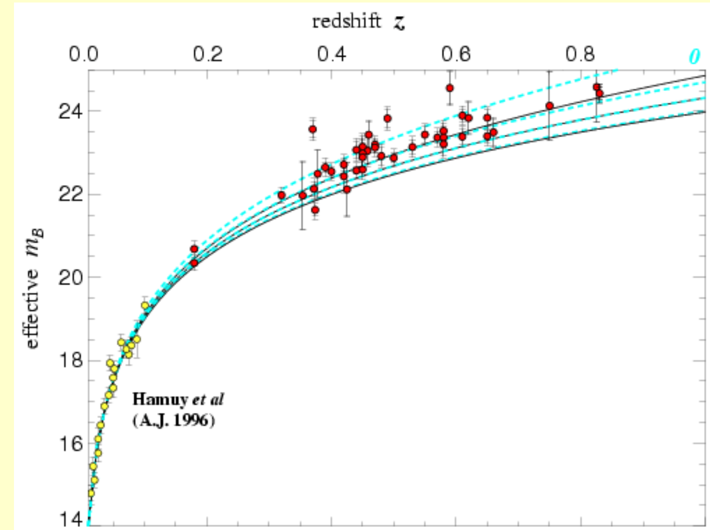
- Very luminous
- Can be identified (spectroscopy)
- Transient (rise ~ 20 days)
- Scarce (~1 /galaxy/millennium)
- Fluctuations of the peak luminosity : 40 %
- With luminosity indicators : ~14 %



Hubble diagram : flux vs redshift



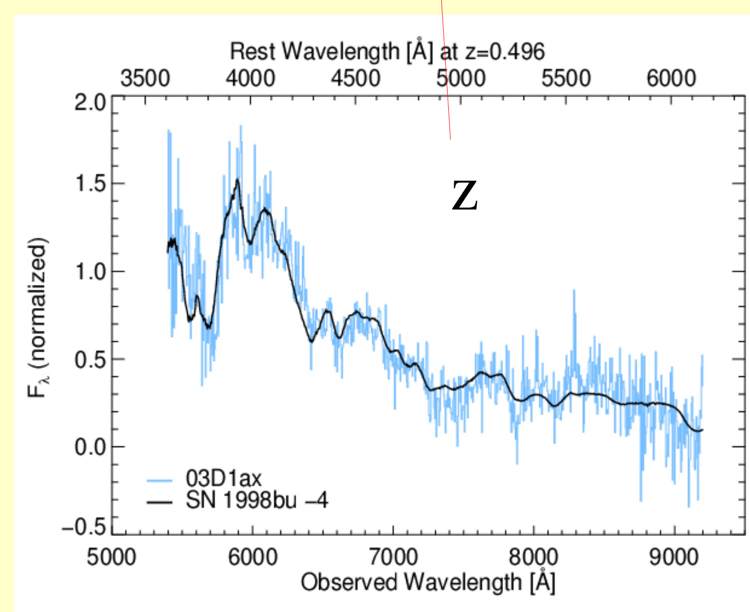
peak flux



multi-band photometry

=> distance

z



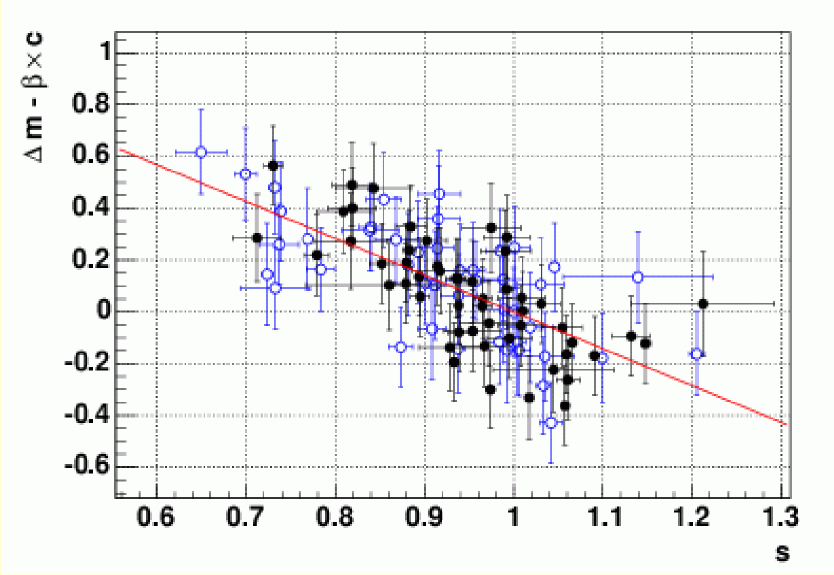
spectroscopy:

- identification
- redshift

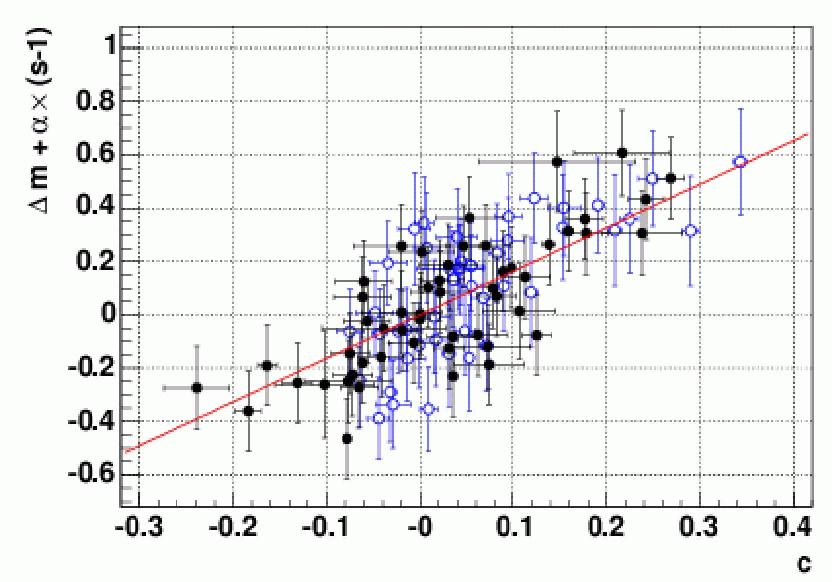
Empirical intrinsic luminosity indicators

Brighter – slower
(Phillips 1993)

Brighter - bluer



brighter



slower (lightcurve width)

bluer (B-V color at peak)

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

=> distances to ~ 7%

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Supernova surveys

Nearby:

Supernova factory (SNF) 0.03<z<0.08

2003-2009, analysis underway.

CFA, Carnegie, ...

PTF : starting now. SkyMapper :starting soon

.....

Intermediate:

SDSS : z<~0.4, 500 typed SNe Ia. Photometry in 5 bands

High z:

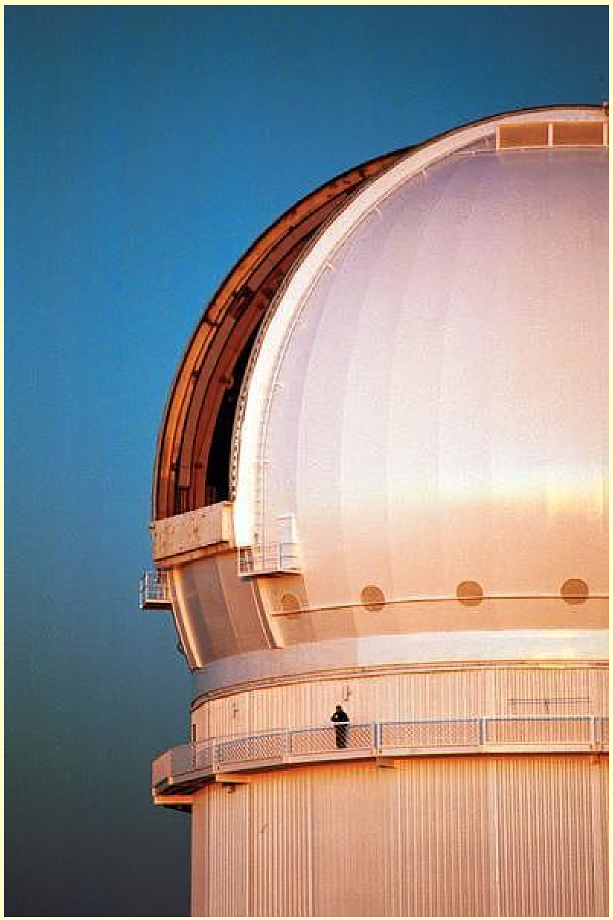
Essence : ~200 SNe Ia at z<~0.7, 2 bands. 2002-2007

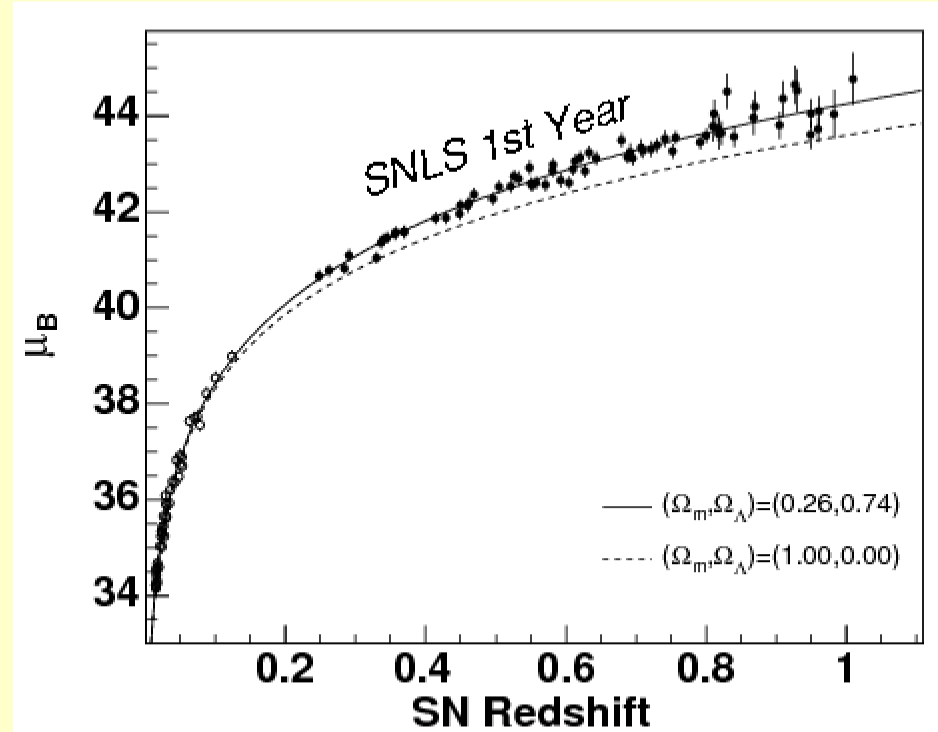
SNLS : ~450 SNe Ia at z<~1, 4 bands. 2003-2008.

HST : up to z~1.6, but poor lightcurve sampling and calibration issues

SNLS: SNe Ia at 0.2<z<1

Photometry
(CFHT, 3.6m)





Spectroscopy (VLT, Gemini, Keck)

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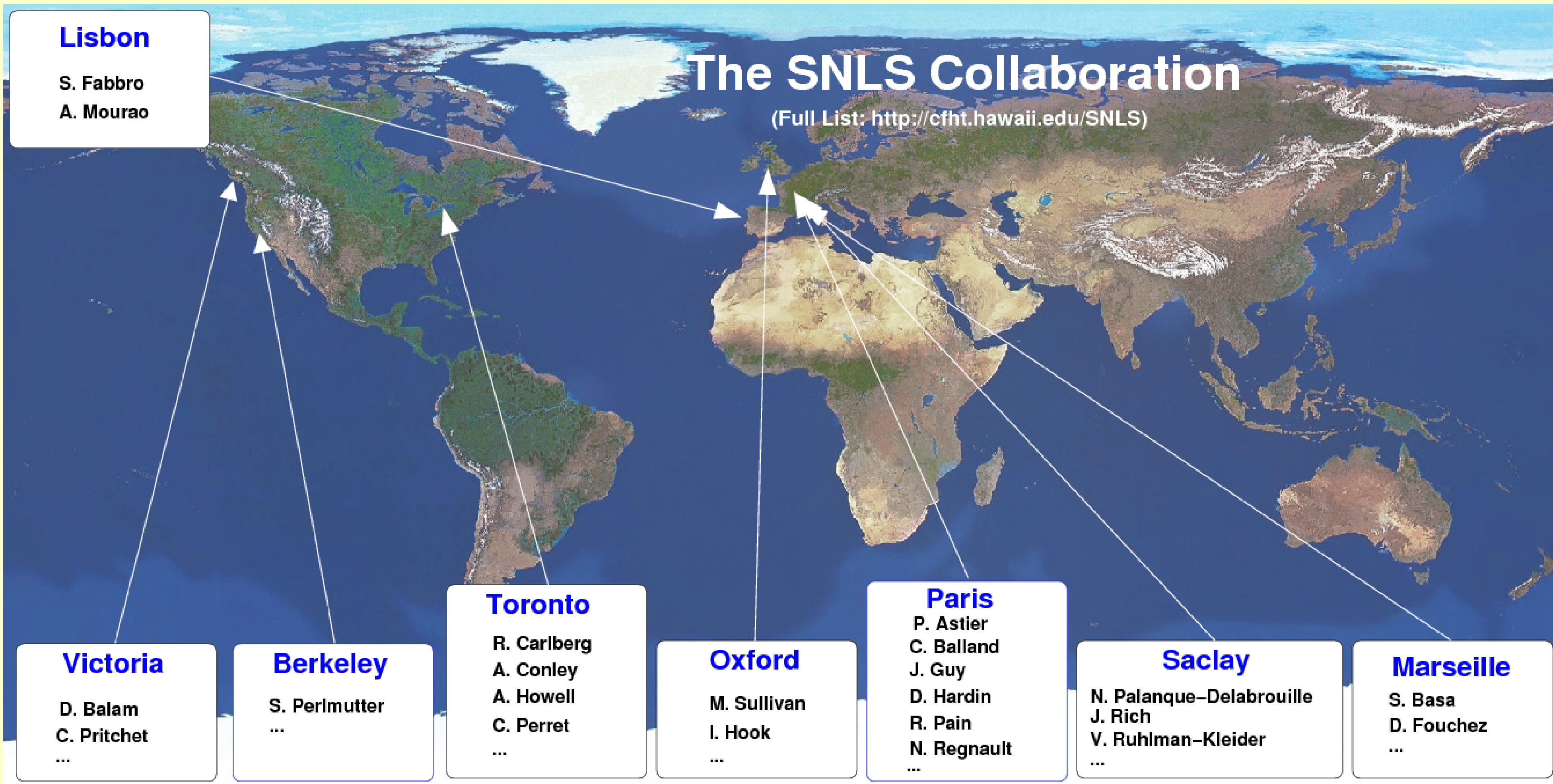
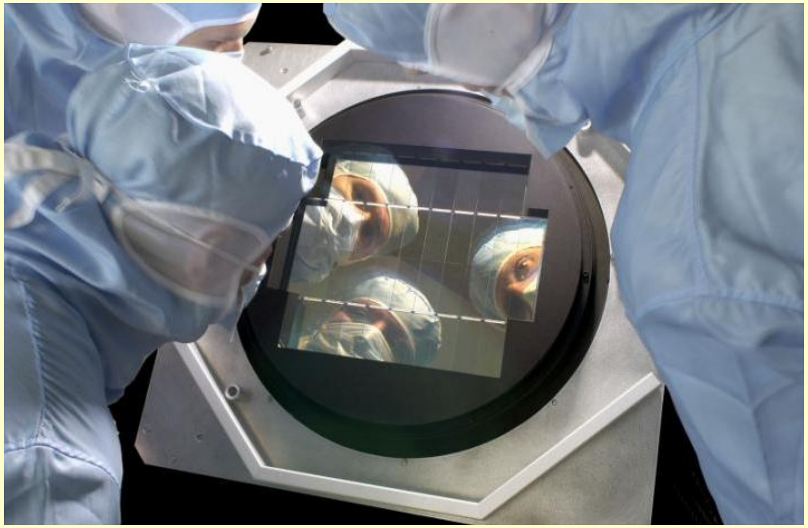
The SNLS Collaboration



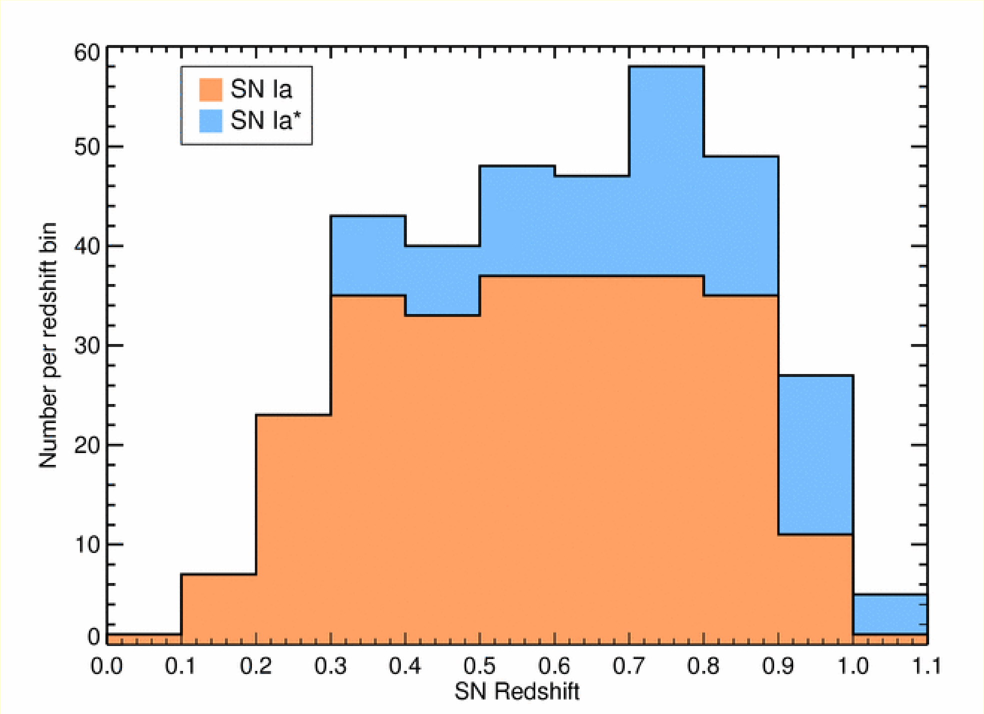
SNLS: vital statistics

- 5 year "rolling" SN survey (within CFHTLS)
- Goal: ~500 high-z SNe to measure "w"
- Uses 1 deg ^{2} "Megacam" imager on CFHT. griz bands every ~4 nights
- Spectroscopy on VLT,Gemini & Keck.



- SN Survey ended (June 2008)
- ~ 450 confirmed z>0.1 SNe Ia
- ~1000 SN detections in total
- Used ~1200 h for imaging

  and ~1200 h for spectroscopy



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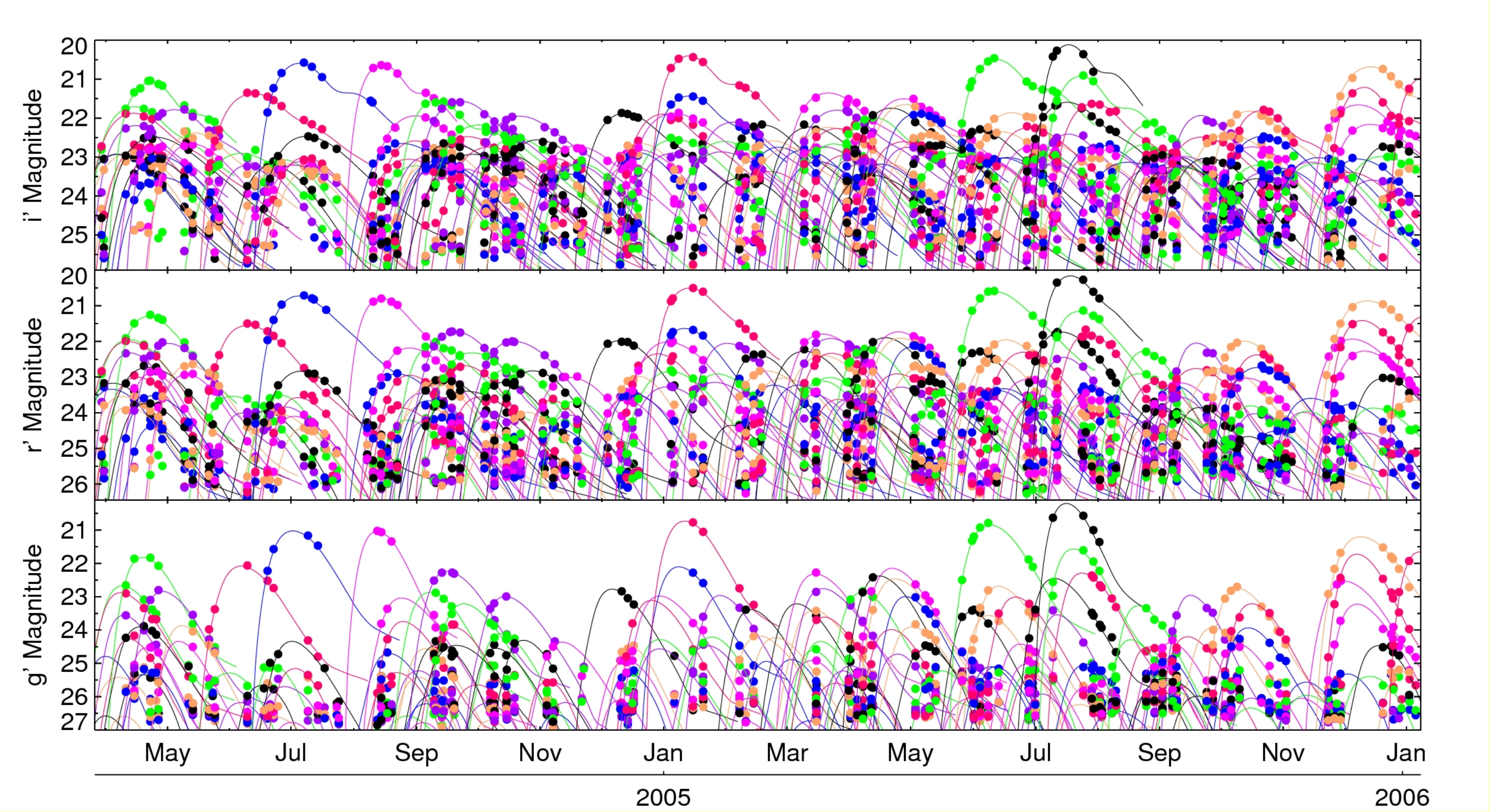
Rolling Search



About 20 months – 1/3 – of all data

SNLS images the same fields 5 times per month in 4 filters

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SNLS empirical distance estimator

supernova measurements

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

Distance modulus

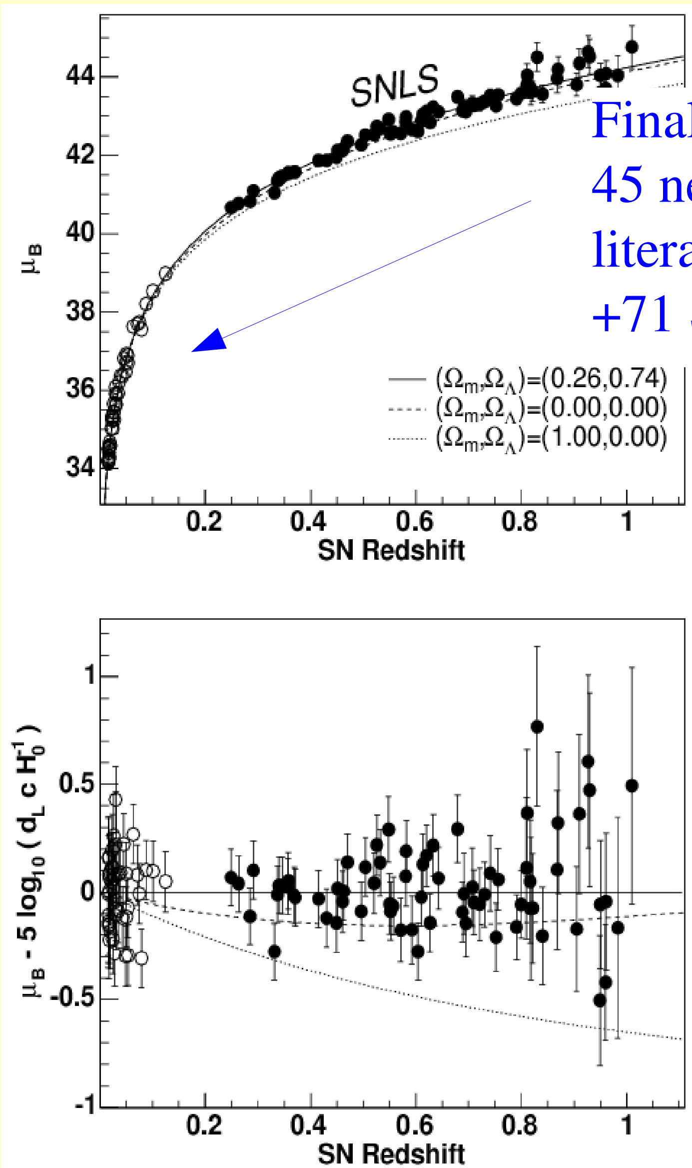
Global parameters

fitted together with cosmological parameters

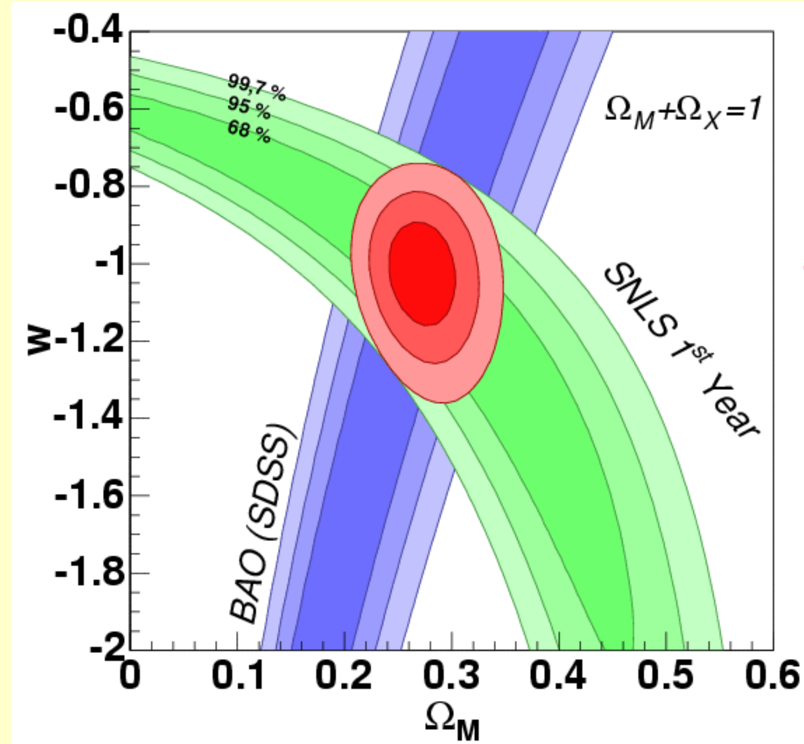
Tripp (1998)

(astro-ph/0510447)

Hubble diagram of SNLS (first year)



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



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

<-- Λ

$\Omega_T=1$

SNLS SNe + nearby SNe + BAOs :

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

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Systematic uncertainties (1)

SNLS (2005) figures:

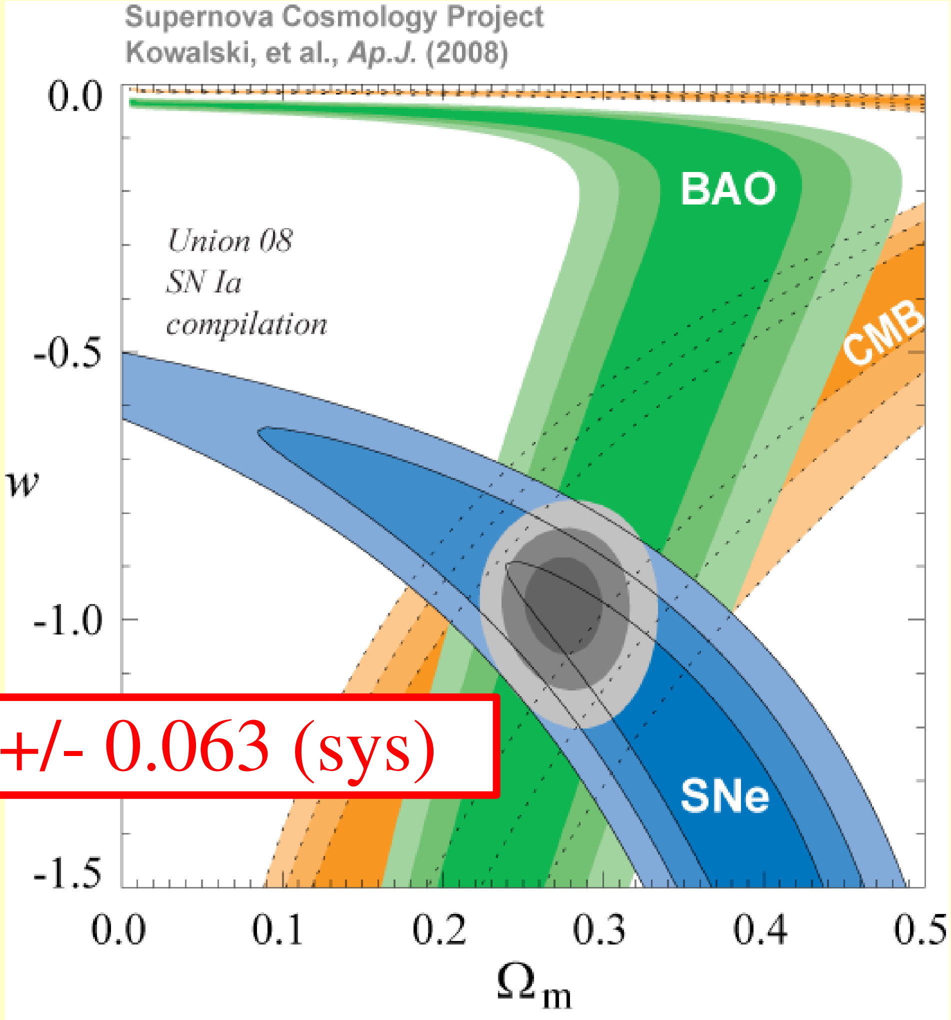
	$\sigma(w)$
Cross calibration with nearby SNe	0.04
Primary flux standard	0.024
Filter bandpasses	0.013
Malmquist bias	0.025

Photometric calibration is becoming
the bottleneck of SN cosmology

The "Union" compilation

(Kowalski et al [SCP] (2008))

- Gathers 414 SNe from many surveys
- Applies quality cuts
- Uses 307 SNe consistently fitted
- Systematic uncertainties included in the fit

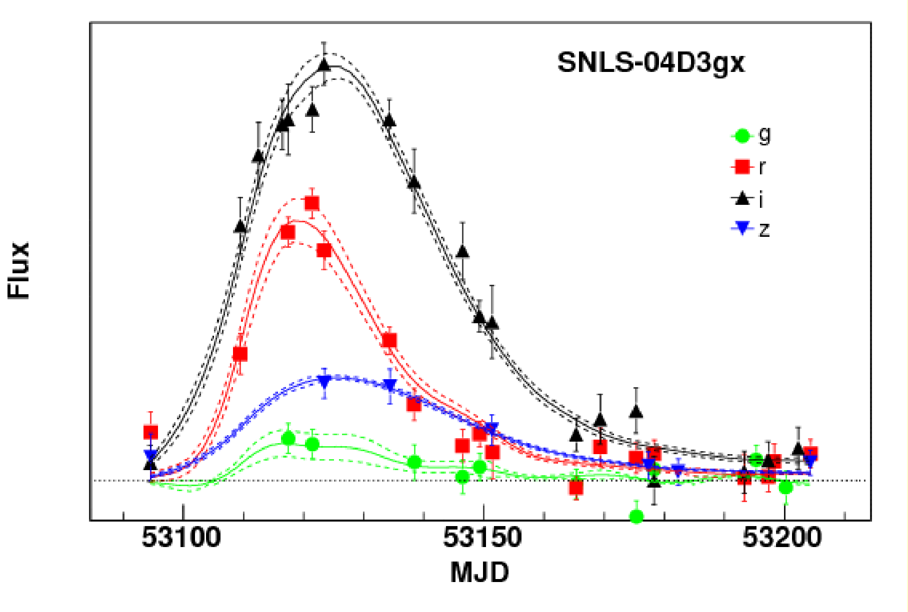


w=-0.97 +/- 0.061(stat) +/- 0.063 (sys)

SNLS: from first year to 3rd year analysis

- More distant supernovae : stat x 3.5 -> ~ 250 events
- Improved modeling of SN Ia
  - Two independent lightcurve fitters SIFTO and SALT2
  - New techniques exploit SN data at λ<4000A (restframe)
- Optimized survey calibration
  - Better characterisation of Megacam array
  - 3-year monitoring of fields
  - Better flux calibration.
- Independent analyses (“French” and “Canadian”)
  - All aspects of analysis cross-checked independently
- Systematics included directly in cosmological fits
  - Covariance matrix will be provided
- WMAP5 now available

Lightcurve fitters



Goals:

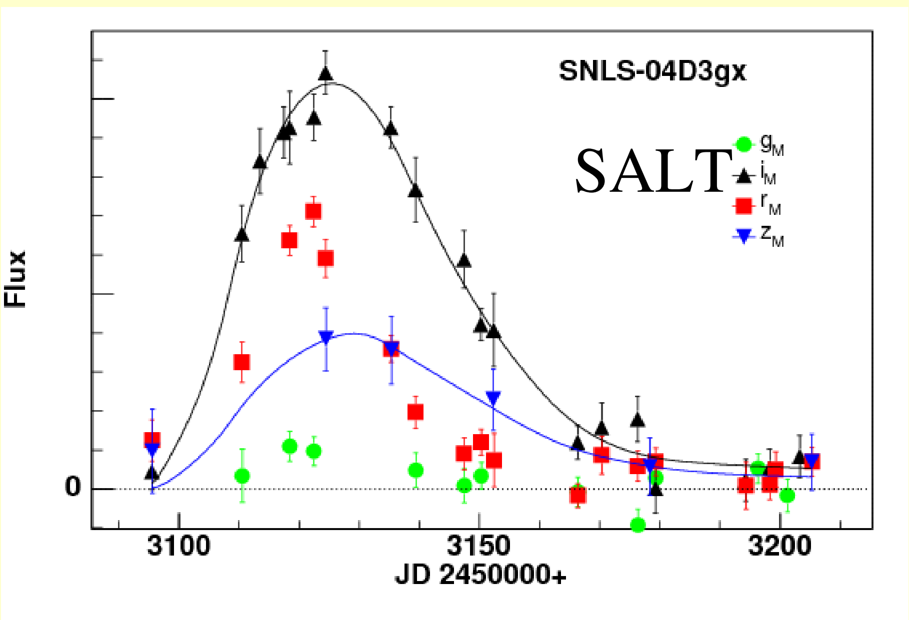
- Flux ratios at different z
- Measure light curve shape
- Measure rest-frame colors

Means: empirical modeling of lightcurves and spectra

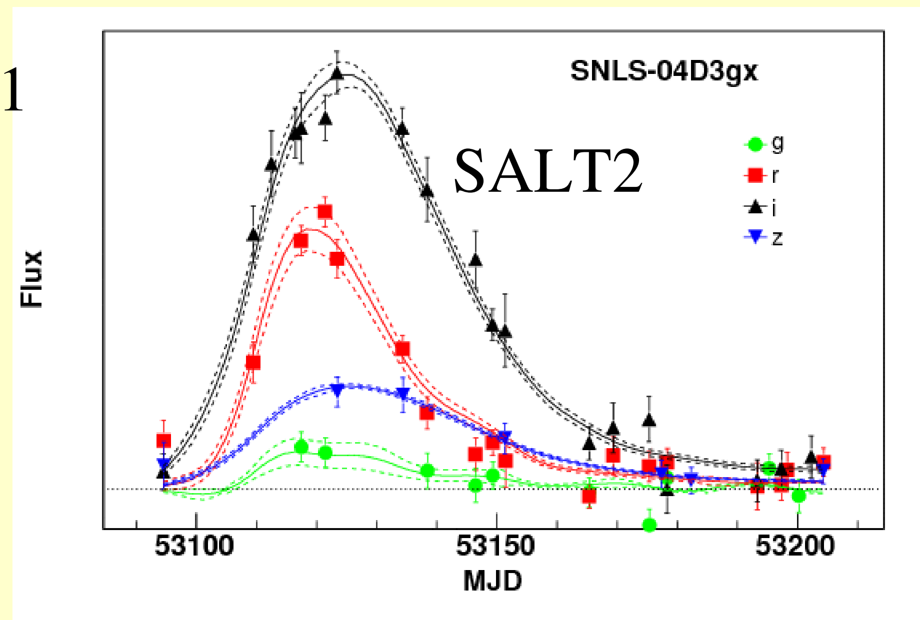
- Explosion simulations not precise enough (yet?)
- Model trained on a sample of good quality LC and spectra
- Modeling should account for diversity of events

Extend SN modeling towards blue

SALT2 (Guy et al, 2007) & SIFTO (Conley et al, 2008)
- No assumed relation between redshift and flux
--> can train with (very) nearby SNe and SNLS data.
- Spectrophotometric models



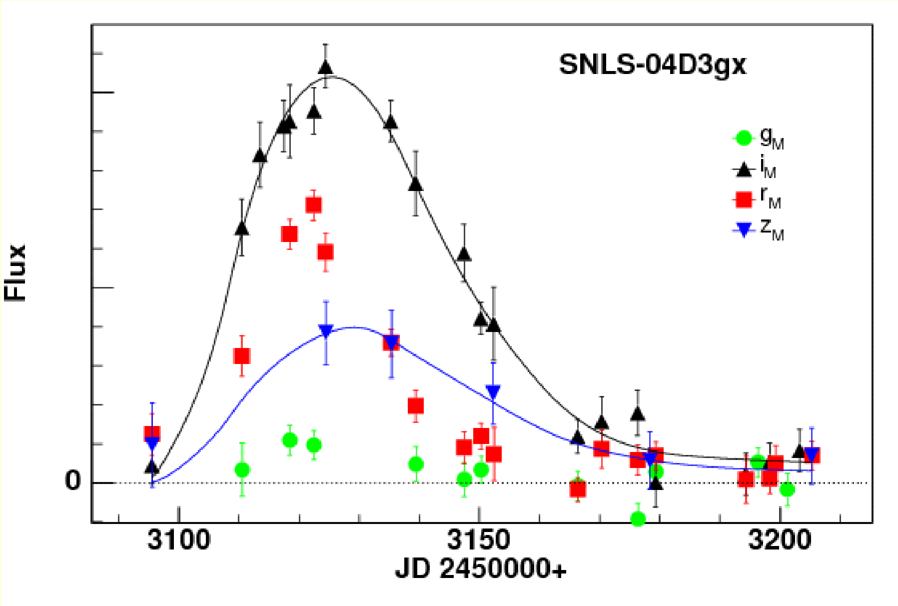
z=0.91

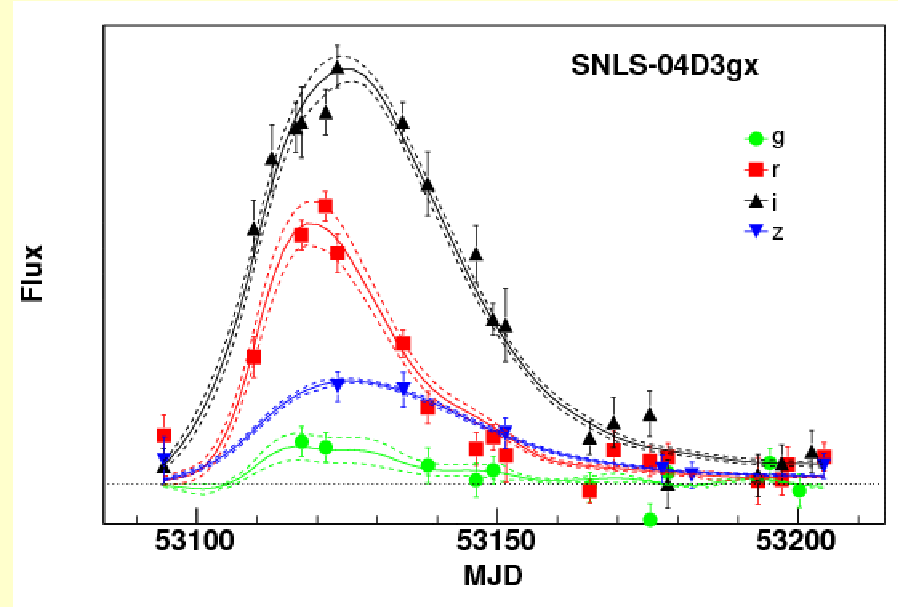


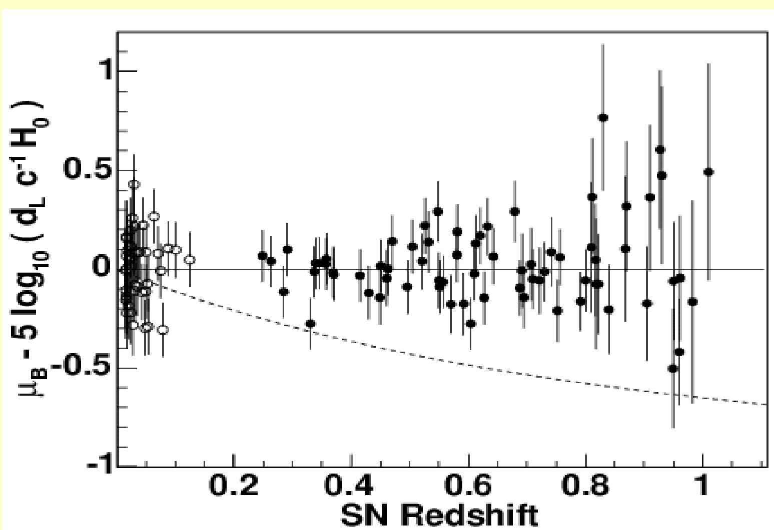
SALT 1 : No UV

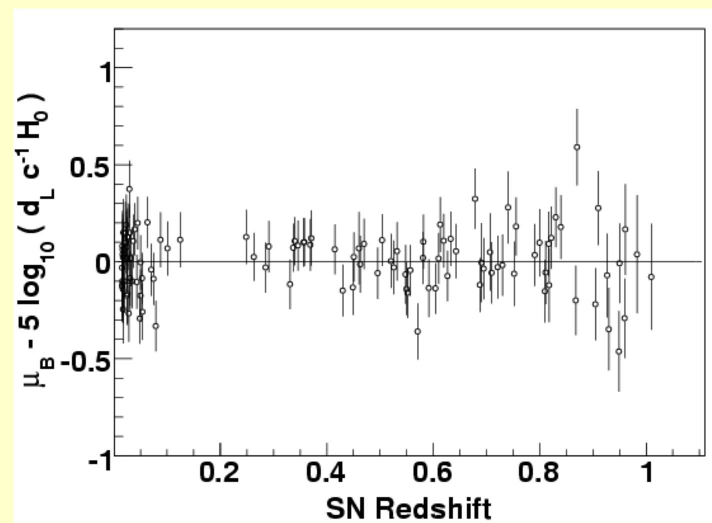
SALT2 : with UV

SNLS 3rd year









σ=0.20

σ=0.16

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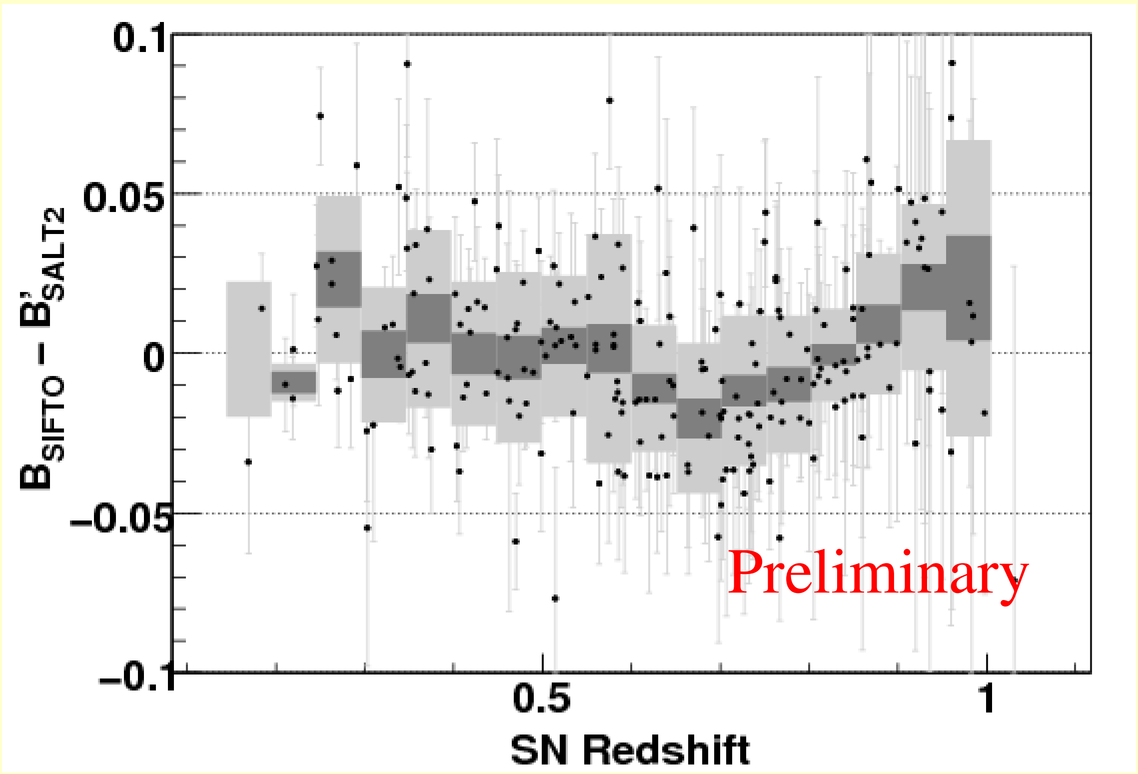
Light curve fitters : SALT2 vs SIFTO



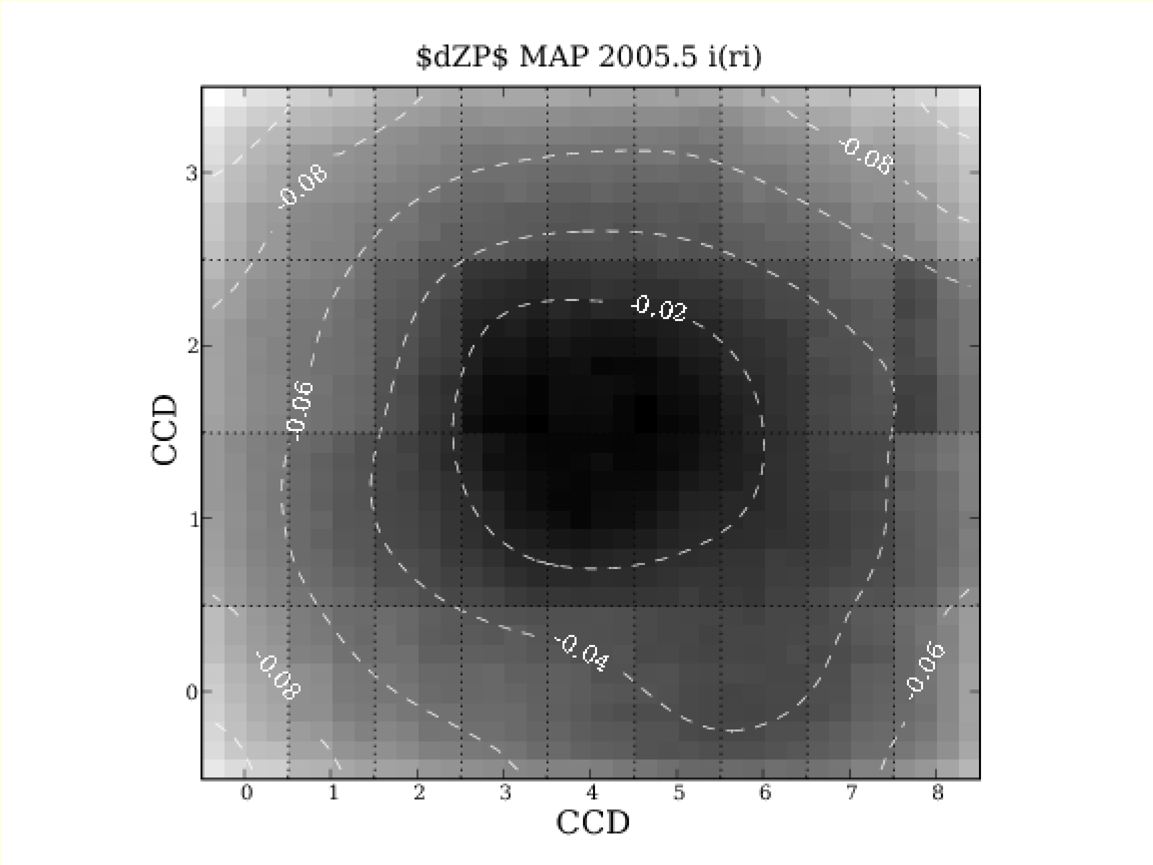
Differences in distance moduli on SNLS events:
r.m.s ~ 0.02 mag
1% in distance

(Guy et al, in prep)

Photometric calibration (1)

Non-uniformity of photometric response across the field of view

Intensity



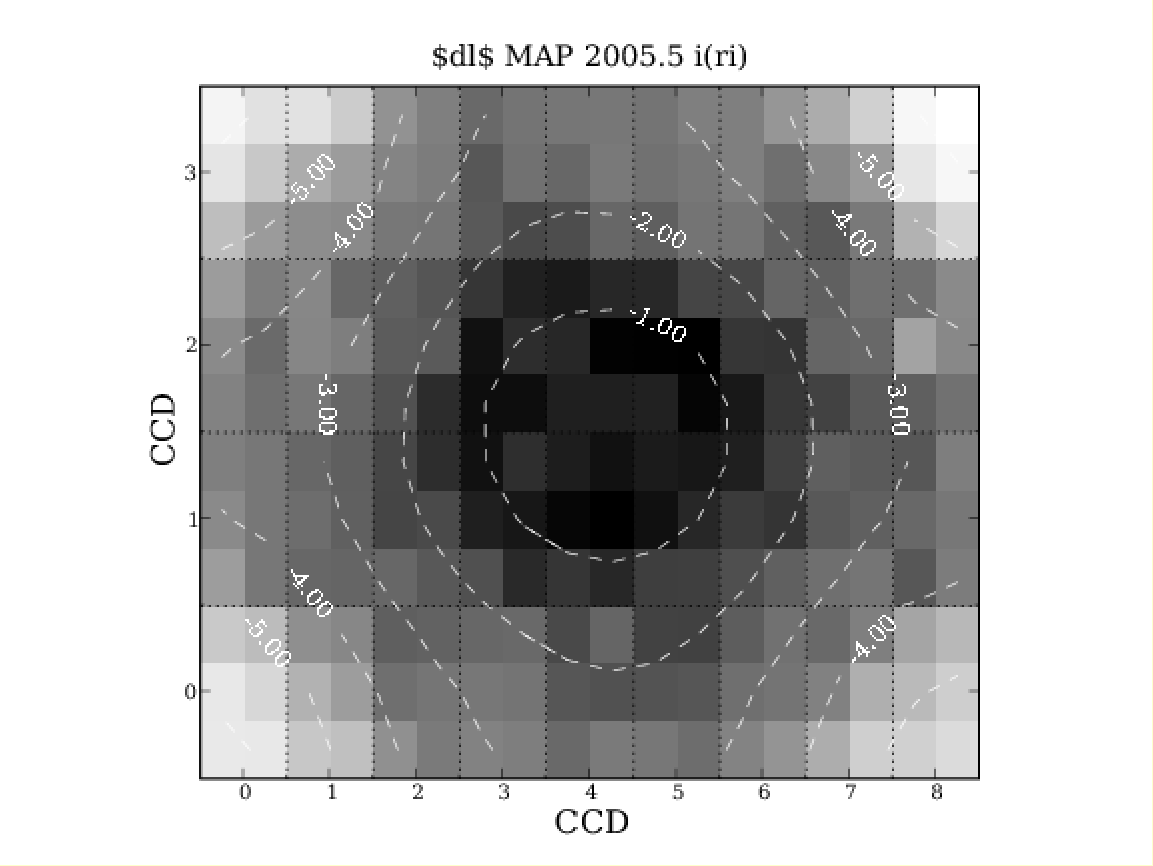
- Wide field imagers suffer from a non uniform photometric response.
- ~10 % center to edge on Megacam
- Mapped using dithered observations
- Residual noise ~ 1%

(Regnault et al, submitted)

Photometric calibration (2)

Non-uniformity of photometric response across the field of view

Central wavelength



- Megacam filters are not uniform
- Up to 5 nm center to edge
- Mapped using dithered observations
- Confirmed from manufacturer's measurements

(Regnault et al, submitted)

Photometric calibration (3)

(Regnault et al, submitted)

- Standard stars : Landolt catalog (same as nearby samples)
- Flux calibrator : BD+17 4708
  - Has an HST spectrum (typical uncertainty < 0.5 %)
  - Also has Landolt magnitudes
  - Similar colors as other Landolt stars and supernovae
- Overall systematic (from measurement to flux) :

  g : 0.005

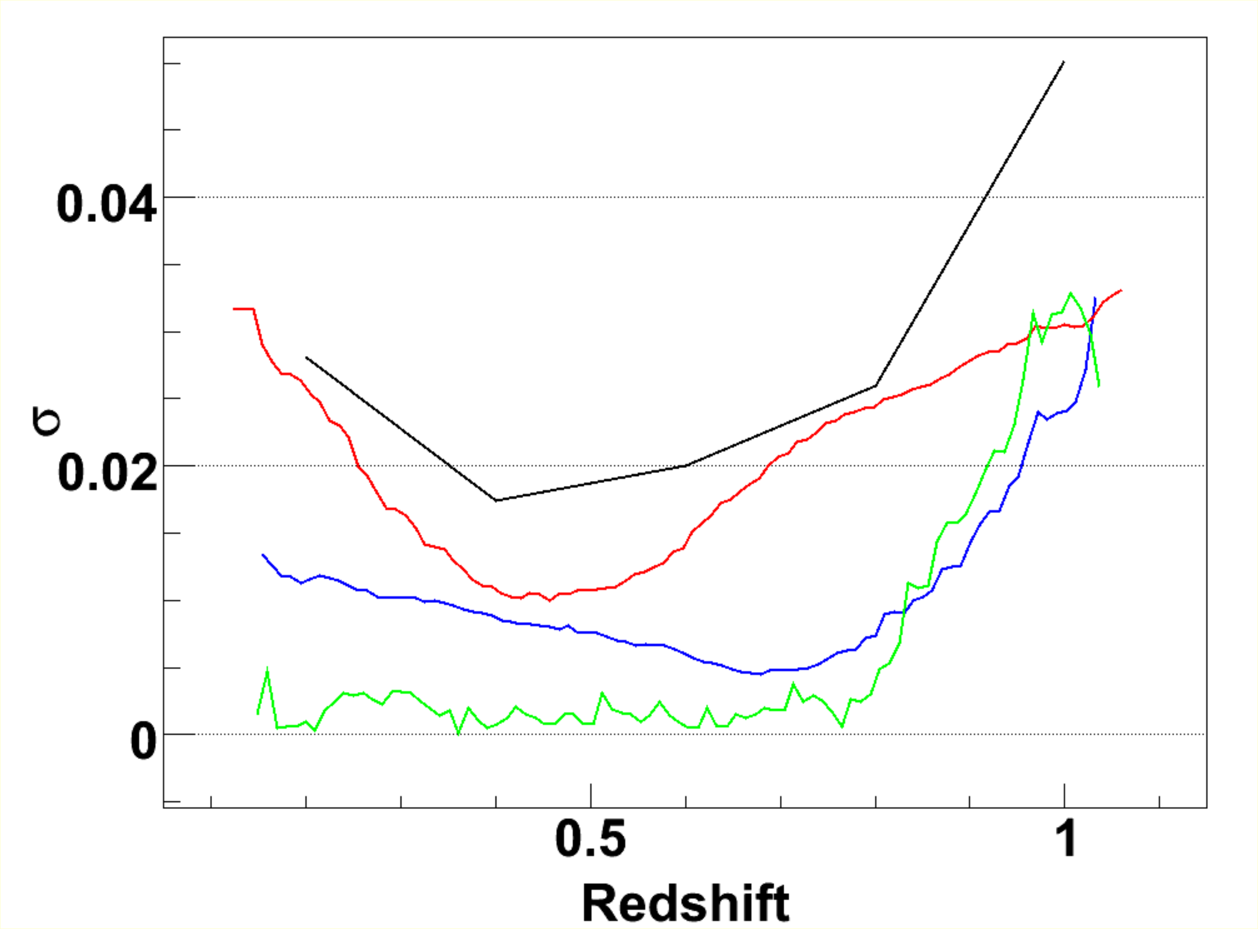
  r : 0.006

  i : 0.007

  z : 0.019 (z is extrapolated from Landolt R and I)

Uncertainties on distance modulus

Uncertainties averaged over $\Delta z = 0.2$



SNLS statistics

Calibration

SALT2 vs SIFTO

Finite LC training sample

LC scatter model

(Guy et al, in prep)

Other supernovae samples

Nearby SNe:

- Hamuy et al (1996)
- Riess et al (1999)
- Jha et al (2006)
- Hicken et al (2007)
- ... and a few others

-> ~ 130 nearby SNe (after cuts)

To be added :

- Riess et al (2007) ($0.9<z<1.3$)
- SDSS supernovae ($z<0.3$)

Systematic uncertainties (nearby):

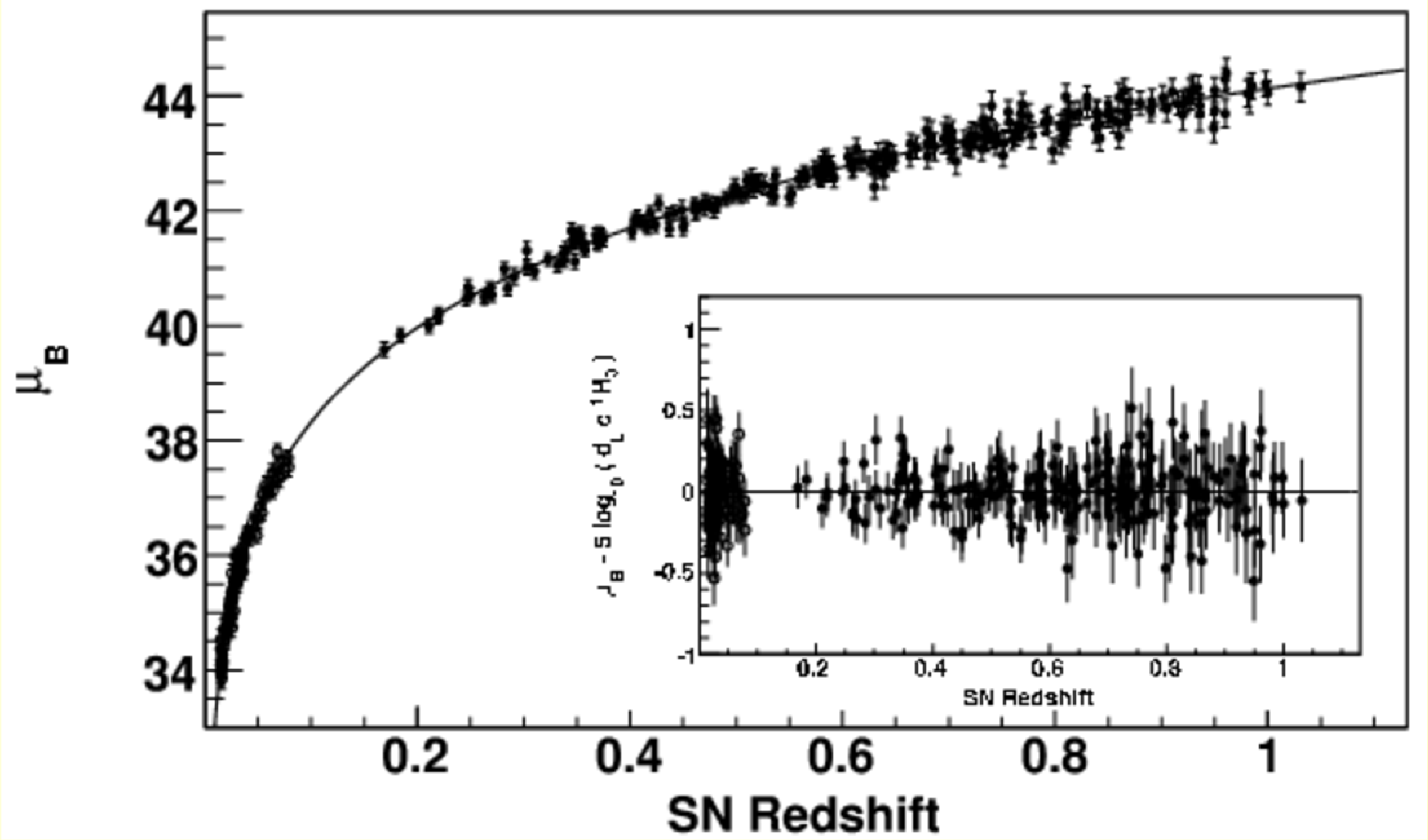
Low redshift Malmquist bias (prefer brighter supernovae) : 0.01

Photometric calibration : U : 0.05, B,V, R : 0.015

Filter bandpasses : U : 2 nm, B,V : 0.7 nm R : 2.5 nm

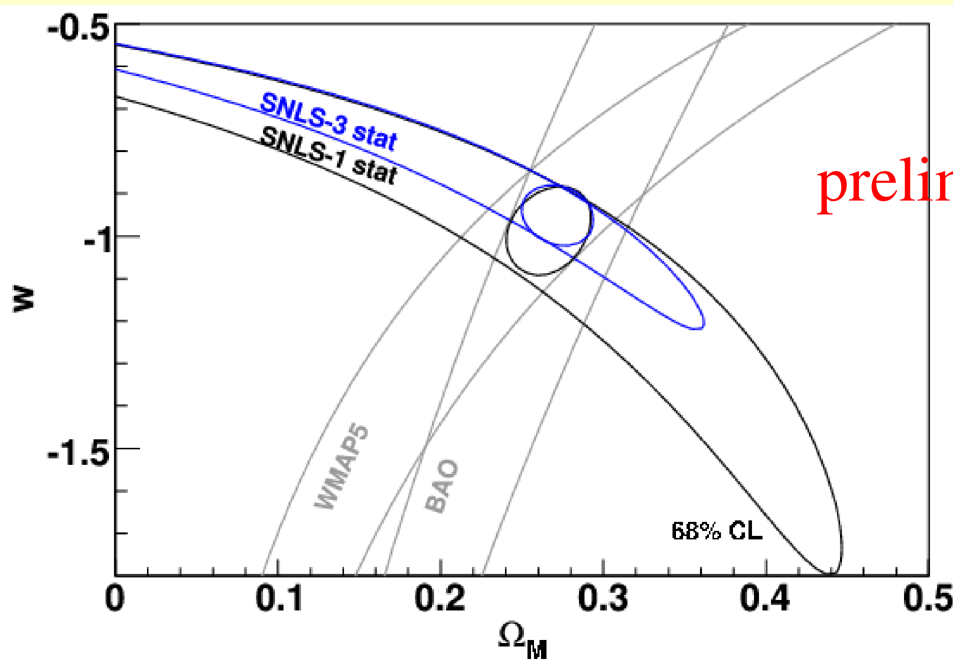
Nearby+SNLS 3rd year Hubble diagram

130 nearby + 240 SNLS



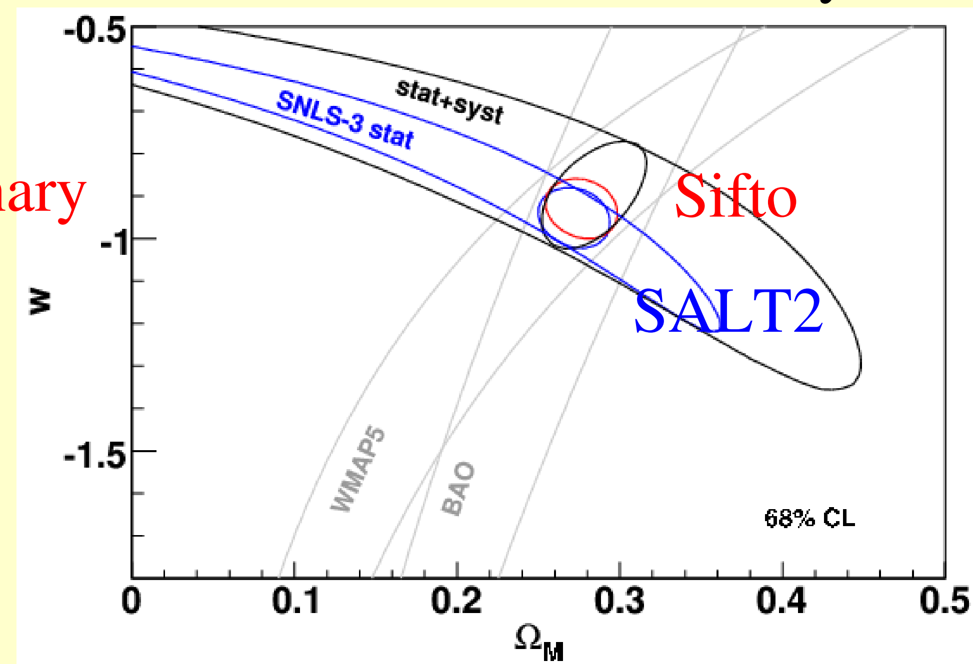
Comparisons

SNLS1 vs SNLS3 (stat only)



preliminary

SNLS3 : stat vs stat+sys



BAO : Eisenstein et al [SDSS] (2005)
WMAP5 : Komatsu et al (2008)

Systematics

r.m.s uncertainties on constant w (SN+BAO+CMB)

SNLS calibration	0.059
Low-z calibration	0.035
Low-z selection bias	0.020
Lightcurve fitter	0.025
Total	**0.069**

When the low-z sample is replaced by an SNLS-like sample (SDSS?, skymapper/PTF), the budget drops to ~0.04-0.05, using current calibration techniques.

- Indicative numbers, they might go down
- Dominated by Landolt system uncertainties. Driven by the low-z samples
- Most figures go down when we calibrate on a SDSS-like system.
- SNLS/SDSS cross-calibration possible (data on disk)

SNLS 3rd year analysis summary

- 240 SNLS + 130 Nearby (+17 HST + 80 SDSS)
- SNE + BAO + WMAP5 (constant w, flat universe) :

  w = xx +/- 0.047 (stat) +/- 0.069 (sys)

  (both uncertainties might go down)

- Publications underway:
  - Photometric calibration (Regnault et al, submitted)
  - Photometric properties of SNe (Guy et al, in prep).
  - Hubble diagram with SNe Ia (Conley et al, in prep)
  - Cosmological constraints (Sulllivan et al, in prep)
  - VTL spectroscopy (Balland et al, submitted)

Next round : SDSS+SNLS (full samples)

-> direct cross-calibration with the SDSS

-> similar statistical accuracy and reduced systematics

What else for dark energy?

Weak lensing (cosmic shear correlations as a function of z)

- The most promising technique
- Difficult and demanding (requires well controlled photo-z's)
- Should cover several thousands deg^2

BAO's

- Assumed to be simple and robust
- Golden way : galaxy redshift survey (i.e. spectroscopy)
- Provides distances, H(z), and growth rate (via redshift distortions)

Cluster counts:

- Capabilities still unclear.

Large survey projects : instruments

		FOV	diameter	first light	status	who/where
ground	SDSS-III	7 deg2	2.5m	2008	funded	Apache Point
	VST @ ESO	1 deg2	2.6 m	2009	funded	ESO/Paranal
	HyperSuprimeCam	2-3 deg2	8 m	2012	funded	Japan/Subaru
	Dark Energy Survey	2 deg2	CTIO-4m	2012	funded	Fermilab/CTIO
	Pan StarsS	7 deg2	1.8 m	2007	funded	Univ. Hawaii
	Pan StarsS 4	7 deg2	1.8 m x 4	2009 (+)	not funded	Univ. Hawaii
	BigBoss	7 deg2	4m	2015	not funded	DOE/NOAO
	LSST	10 deg2	8 m	2015	not funded	DOE/NSF
space	JDEM	0.7 deg2	1.5 m	2016(+)	competing	DOE/NASA
	Euclid	~1 deg2	1.2 m	2017(+)	competing	ESA

Large or very large projects which can address more than just dark energy !

Summary/conclusions

- On track for constant w at 0.05 (stat) +/- 0.05 (sys)
  with SNe (SNLS SDSS, ...) , BAO, CMB
  from data on disk.
- If dark energy is not Λ, the difference is subtle...
- BOSS BAO survey starting now.
- Several wide field imaging surveys starting shortly (DES, HSC, VST)
- Ground-based spectroscopic BAO projects (~2015) : BigBoss, ...
- Two space-based projects JDEM (NASA/DOE) & Euclid (ESA)
  - May tackle weak lensing, BAOs, Sne.
  - They may merge
  - 2017 (+)
- Planck will start observing shortly !