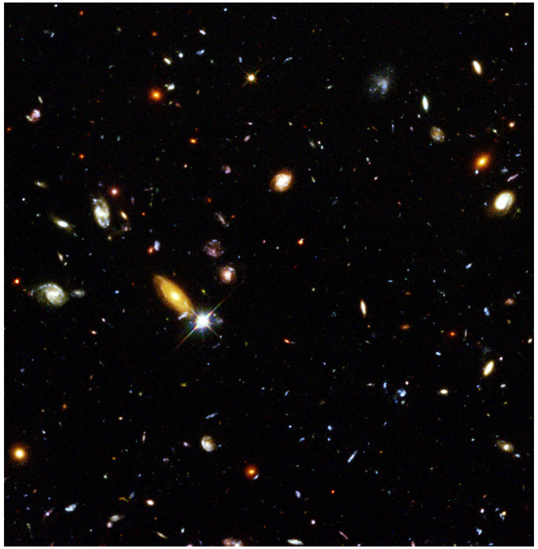
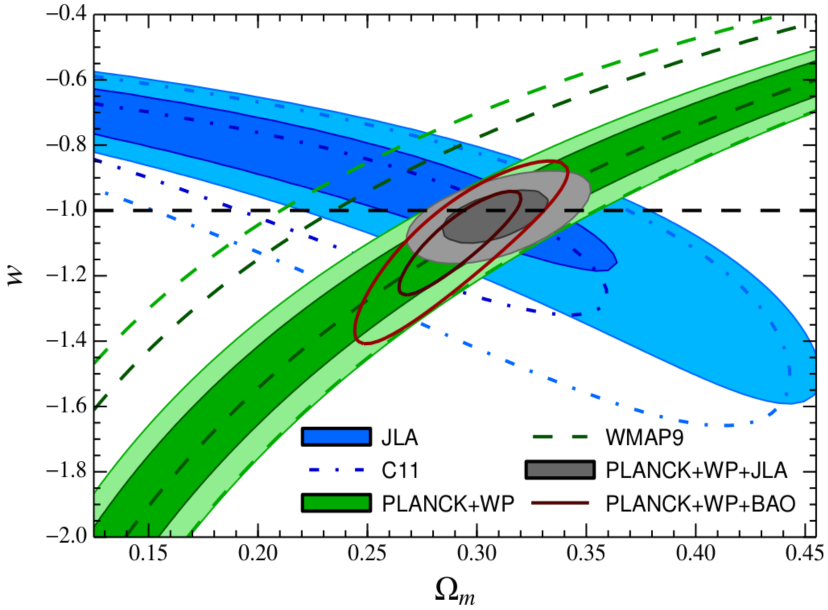
Supernovae for Dark Energy

Pierre Astier (LPNHE/IN2P3/CNRS, SU, Paris)



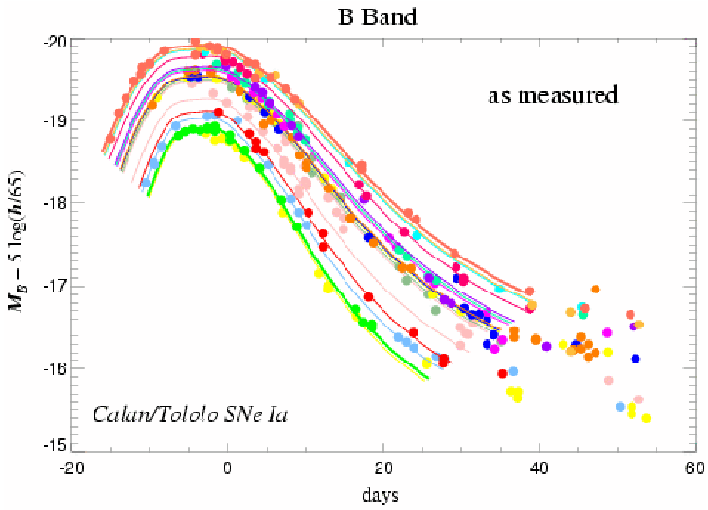
(Mar 13th 2023)



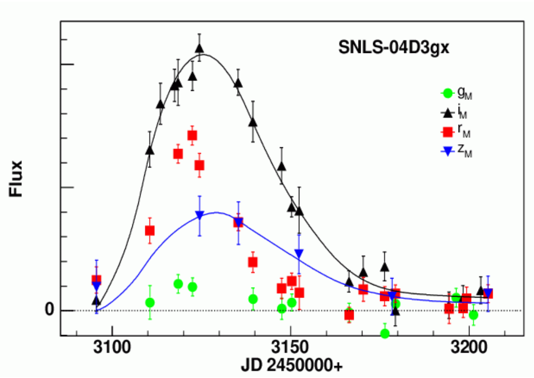
Type Ia supernovae

Thermonuclear explosions of stars
which appear to be reproducible

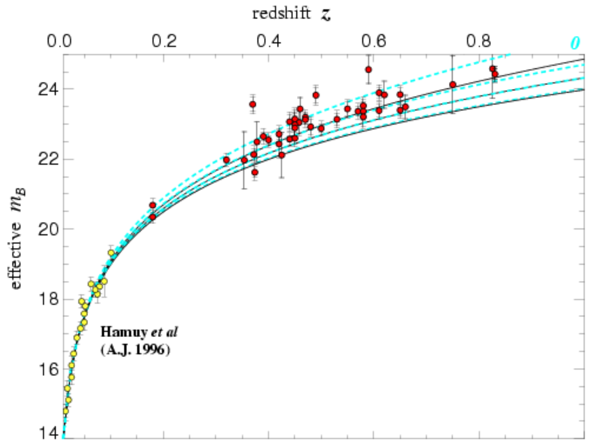
Very luminous
Can be identified (spectroscopy)
Transient (rise ~ 20 days)
Scarce (~1 /galaxy/millennium)
Fluctuations of the peak
luminosity : 40 %
With luminosity indicators :
~14 %



Hubble diagram : flux vs redshift



peak flux

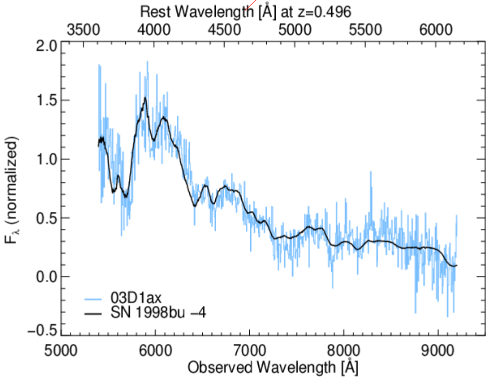


z

multi-band photometry
=> distance

The Hubble diagram probes the "kinematics of the universe"

spectroscopy:
- identification
- redshift



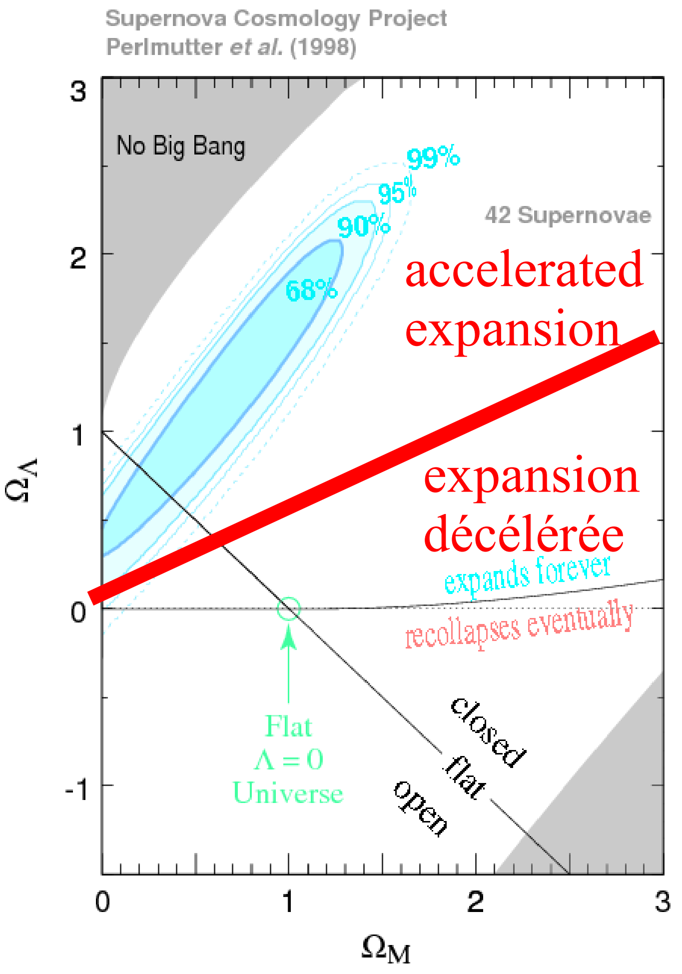


Photo: U. Montan

Saul Perlmutter

Photo: U. Montan

Brian P. Schmidt

Photo: U. Montan

Adam G. Riess

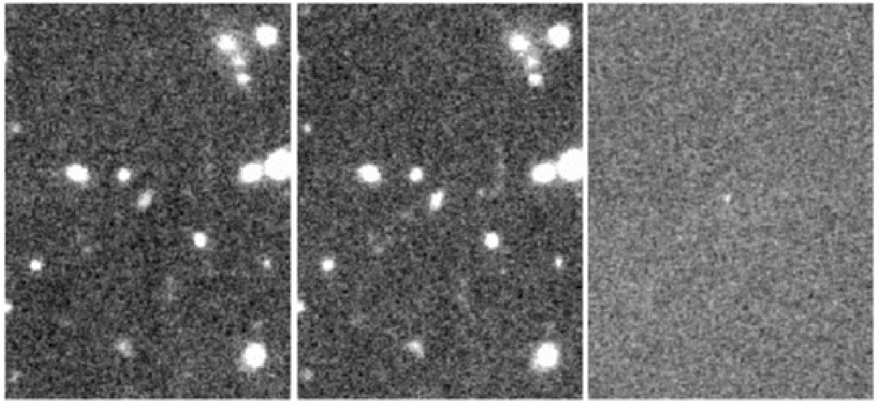
The Nobel Prize in Physics 2011
was divided, one half awarded to
Saul Perlmutter, the other half jointly to
Brian P. Schmidt and Adam G. Riess
"*for the discovery of the accelerating expansion of the Universe through observations of distant supernovae*".

Observing SNe Ia

3 steps :

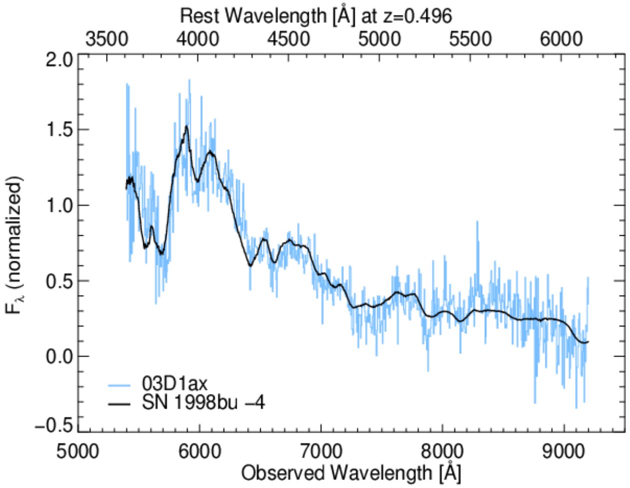
Detection

difference imaging



Identification & z

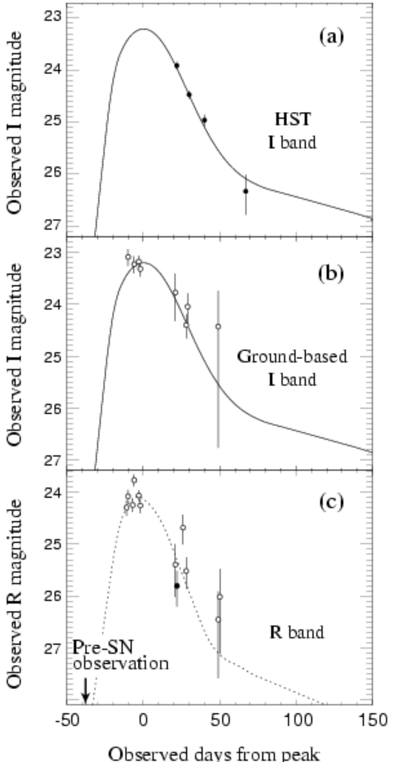
spectroscopy



Photometry

multi-band

mostly around rest-frame B band (400 nm)



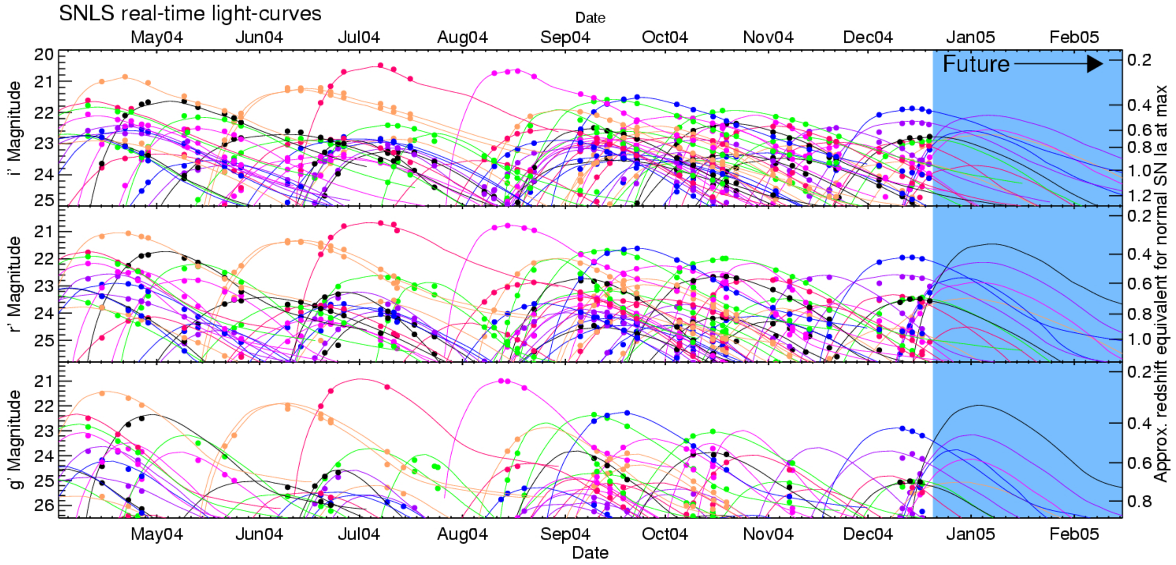
Rolling searches

Concept : repeatedly image the same field(s) to detect AND measure supernovae in the same images

Bonuses :

- Multiplexing : several supernovae in the **same** image
- Single instrument to calibrate
- Light curve sampling independent of SN phase

Megacam@CFHT



The observing program

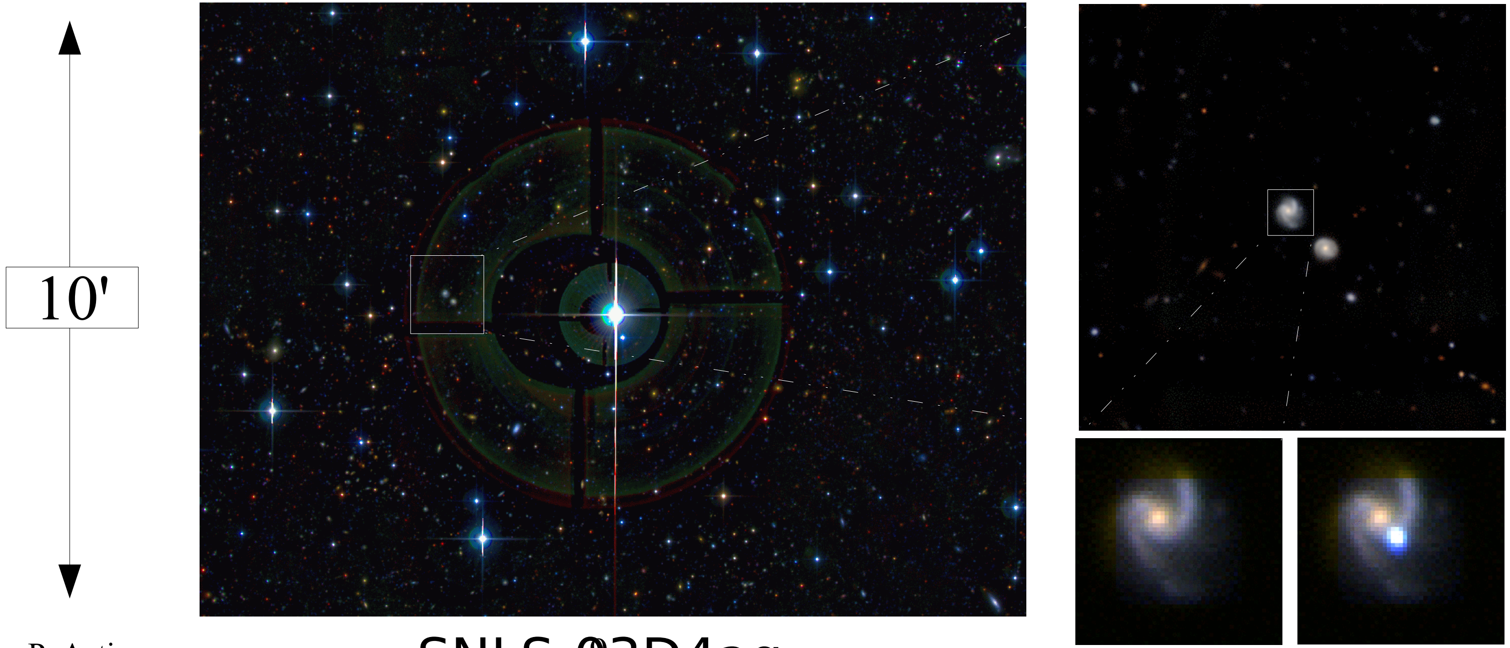
- CFHTLS (Legacy Survey) : ~ 500 nights over 5 years:
  - a wide component (~200 deg^2 in 5 bands)
  - a deep component (4 deg^2 in 4 bands), with ~ 4 visits per month
- This is a very large program aiming primarily at cosmic shear, supernovae, physics of galaxies.
- Images are delivered to the community (Canada and France)
- Observations are carried out by the observatory personnel
- Politics: survey steering group, Science Advisory Committee and mid-term review. No survey PI's.

The SNLS

- SuperNova Legacy Survey
- Collaboration involving mostly Canada, France, and some Europeans, and US members.
- All of them apply for spectroscopy time on >8-m telescopes:
  - VTL (about 50%, two large programs) , Gemini, Keck
- The primary goal is to optimize the use of this spectroscopy time
- Coordinate the real-time detection of supernovae
- ~500 events eventually identified
- No leverage on CFHT observations.

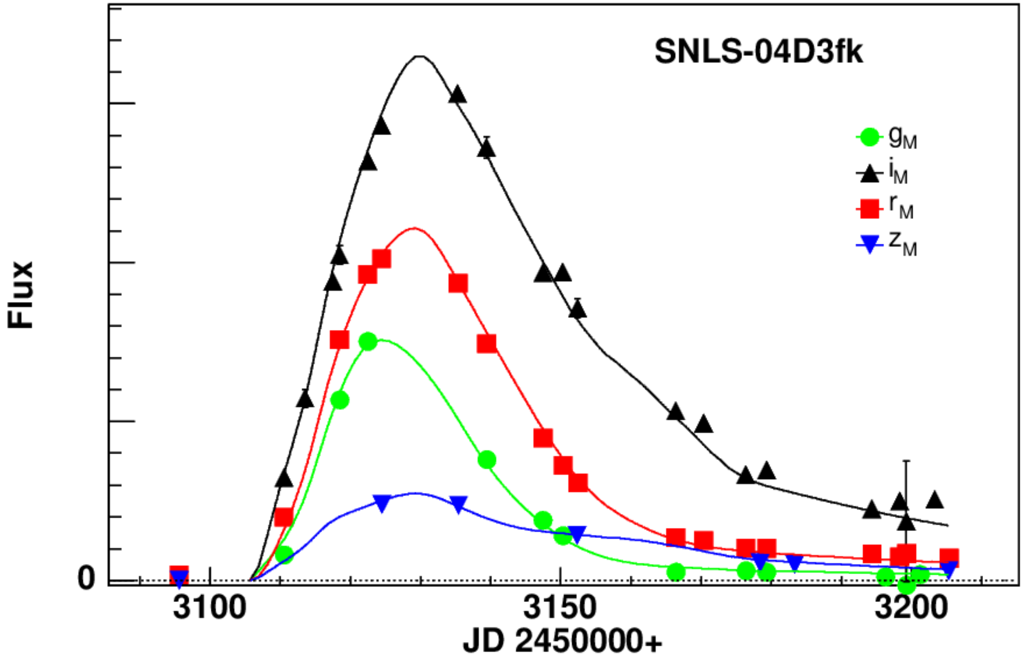
Analysis for cosmology of the SNLS first year data sample August 2003 – July 2004

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



P. Astier

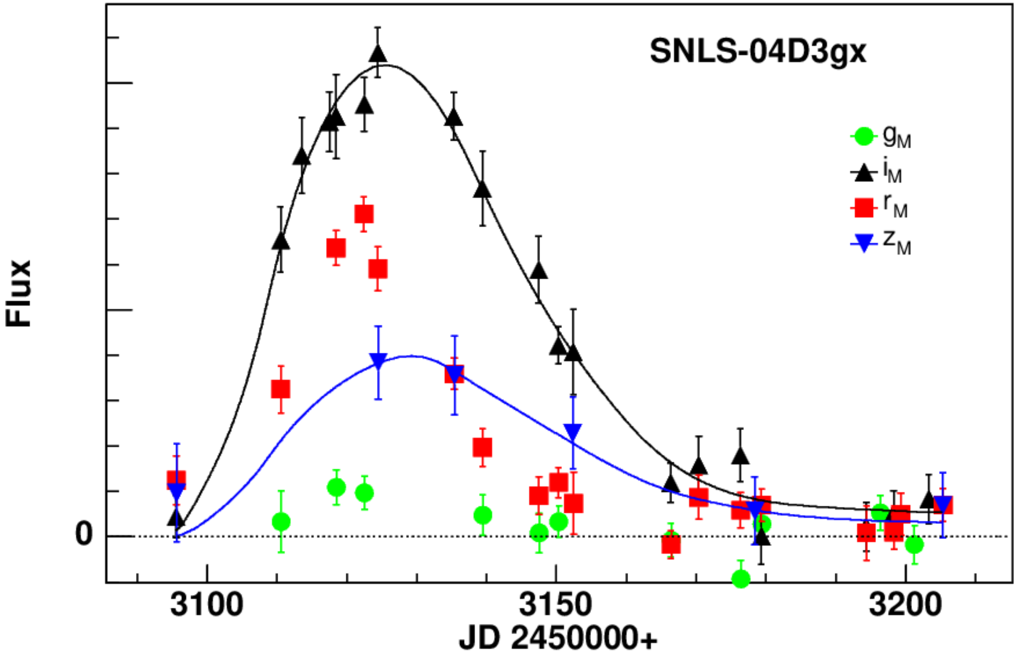
SNLS-03D4ag



z = 0.358

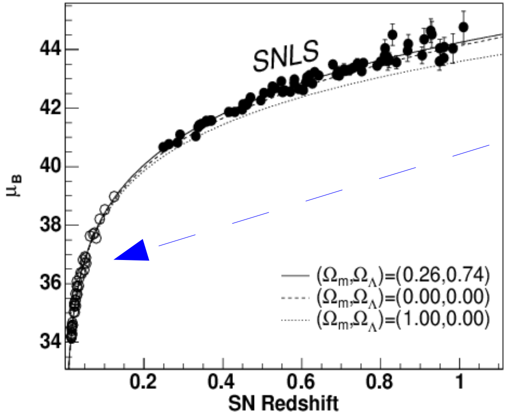
light curves

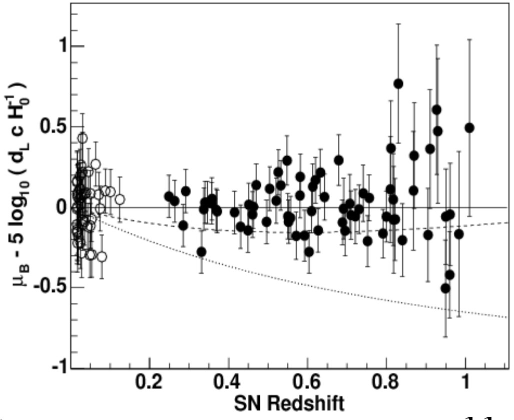
z = 0.910



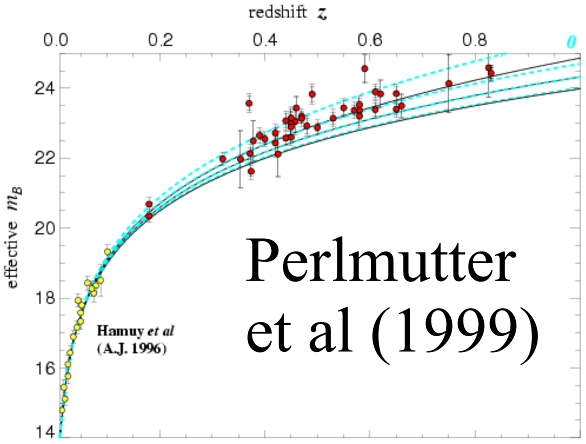
Hubble Diagram of SNLS (first year)

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





For comparison :

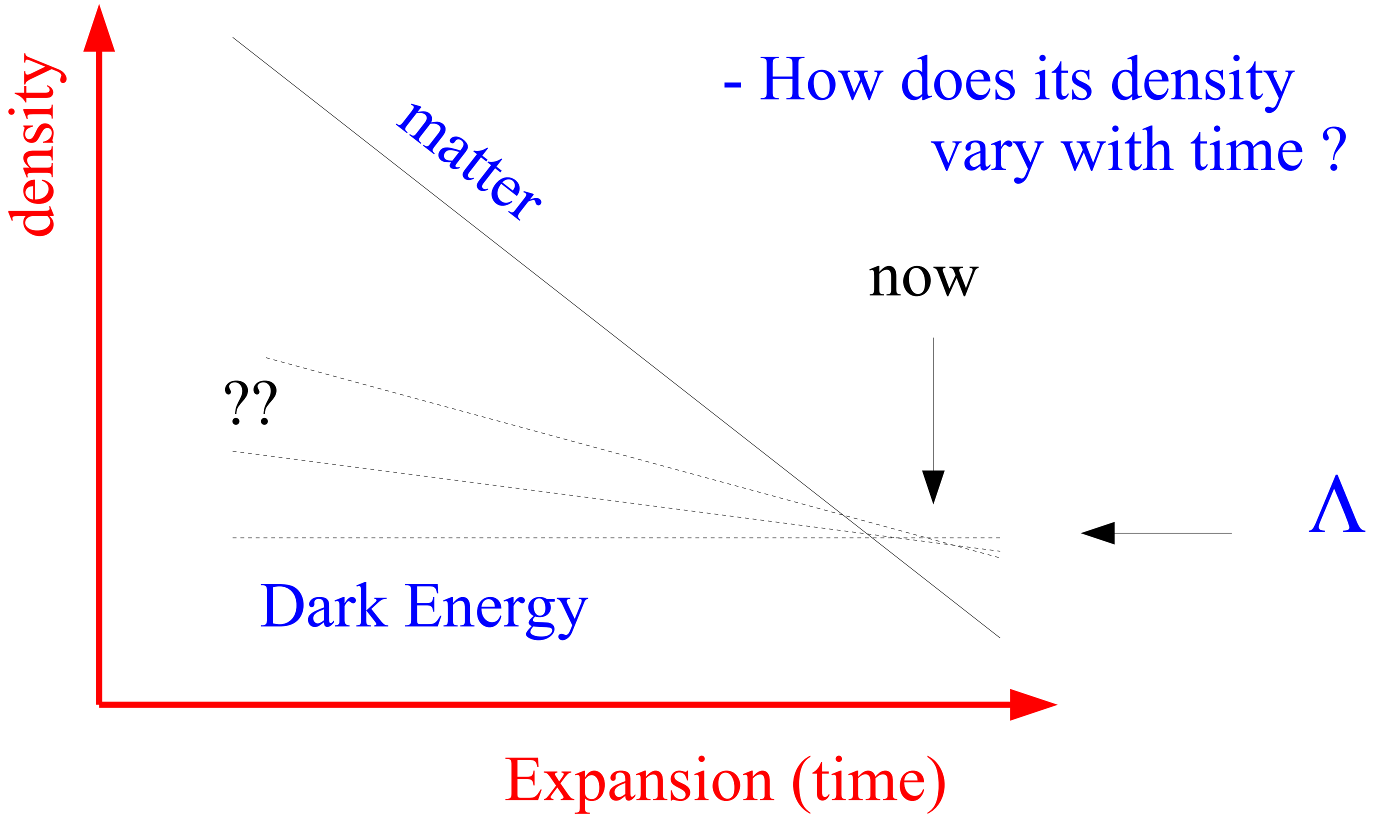


Perlmutter
et al (1999)

A two-component late universe

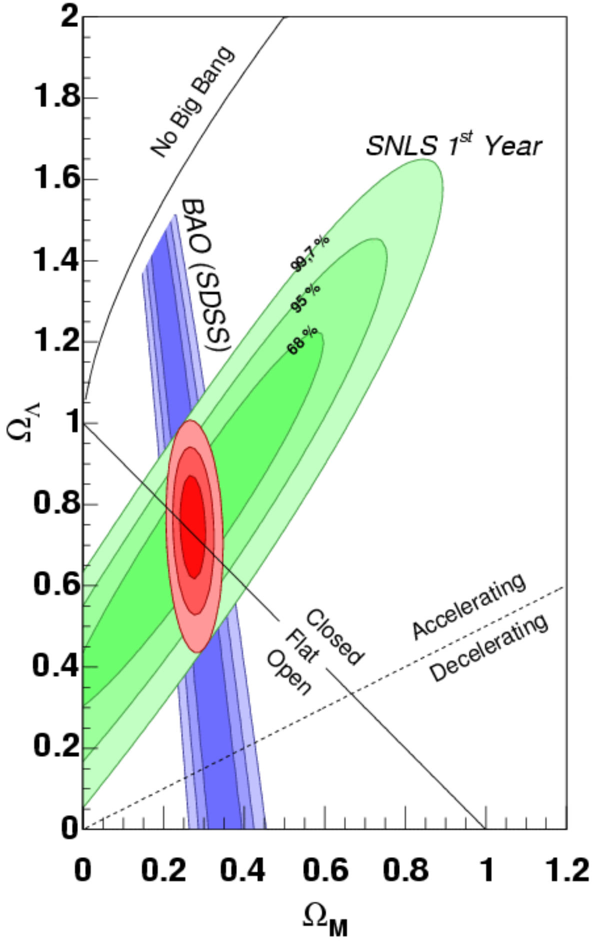
- What is the amount of dark energy today ?

- How does its density vary with time ?

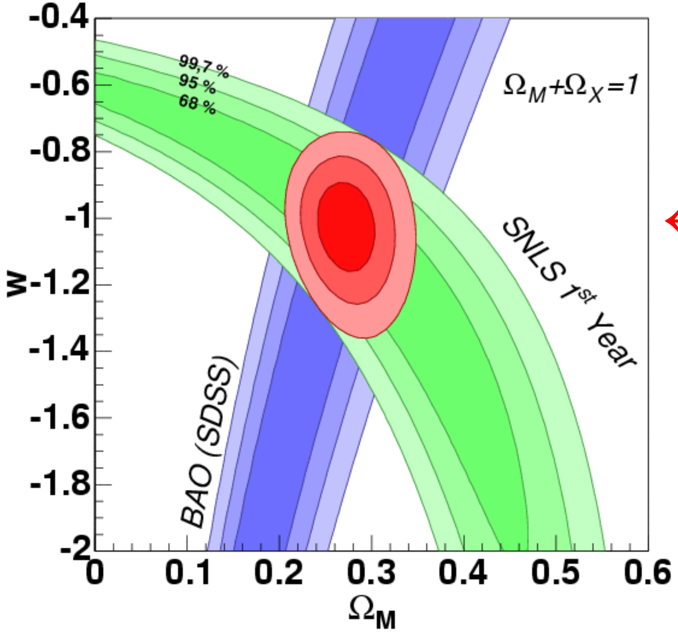


Confidence Contours

w=-1



Ω_T=1



$\leftarrow \Lambda$

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

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

P. Astier[1], J. Guy[1], N. Regnault[1], R. Pain[1], E. Aubourg[2,3], D. Balam[4], S. Basa[5], R.G. Carlberg[6], S. Fabbro[7], D. Fouchez[8], I.M. Hook[9], D.A. Howell[6], H. Lafoux[3], J.D. Neill[4], N. Palanque-Delabrouille[3], K. Perrett[6], C.J. Pritchet[4], J. Rich[3], M. Sullivan[6], R. Taillet[1,10], G. Aldering[11], P. Antilogus[1], V. Arsenijevic[7], C. Balland[1,2], S. Baumont[1,12], J. Bronder[9], H. Courtois[13], R.S. Ellis[14], M. Filiol[5], A.C. Gonçalves[15], A. Goobar[16], D. Guide[1], D. Hardin[1], V. Lusset[3], C. Lidman[12], R. McMahon[17], M. Mouchet[15,2], A. Mourao[7], S. Perlmutter[11,18], P. Ripoche[8], C. Tao[8], N. Walton[17]

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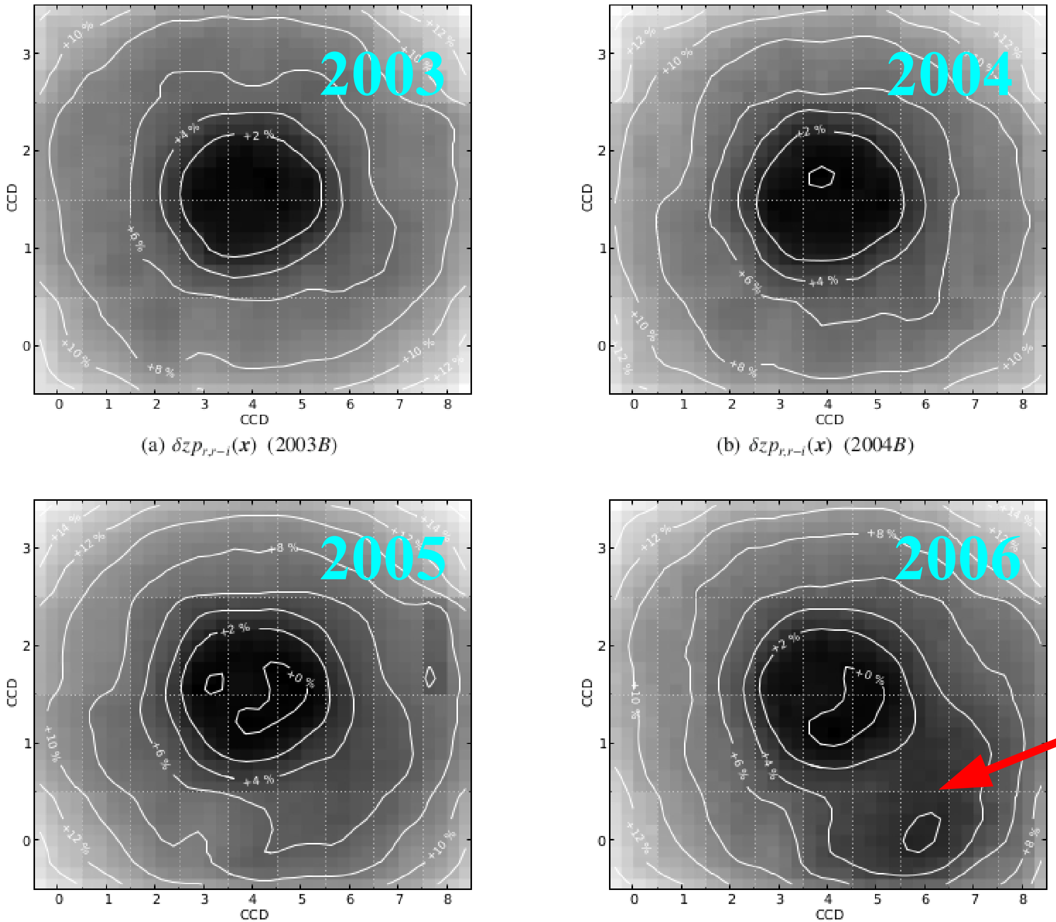
Fall 2005

This was the easy part….

- We had to re-design essentially all the important parts of the analysis:
  - Photometric calibration and instrument characterization (Regnault et al, 2009)
  - SN empirical model SALT2 (Guy et al, 2007, 2010)
  - SN photometry (Astier et al, 2013)
  - Calibration again (Betoule et al, 2013)

Regnault et al (2009)

N. Regnault et al.: Photometric calibration of the SNLS fields 1009



(a) $\delta zp_{r,r-1}(x)$ (2003B)

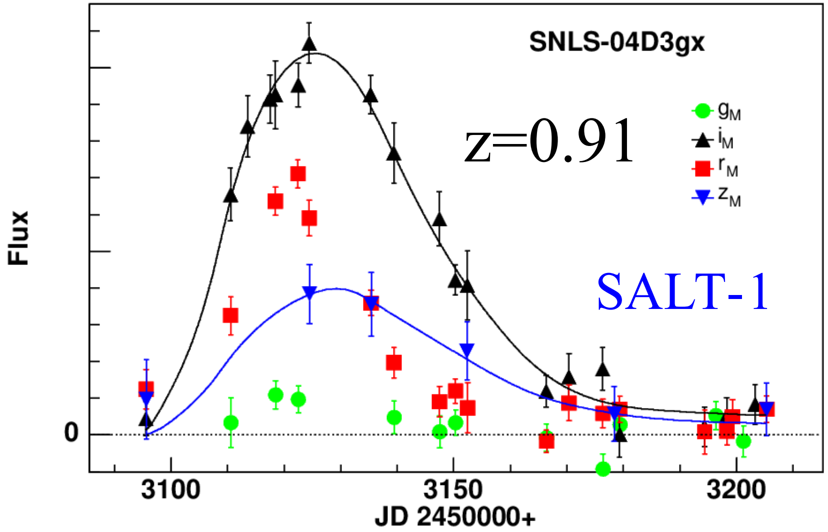
(b) $\delta zp_{r,r-1}(x)$ (2004B)

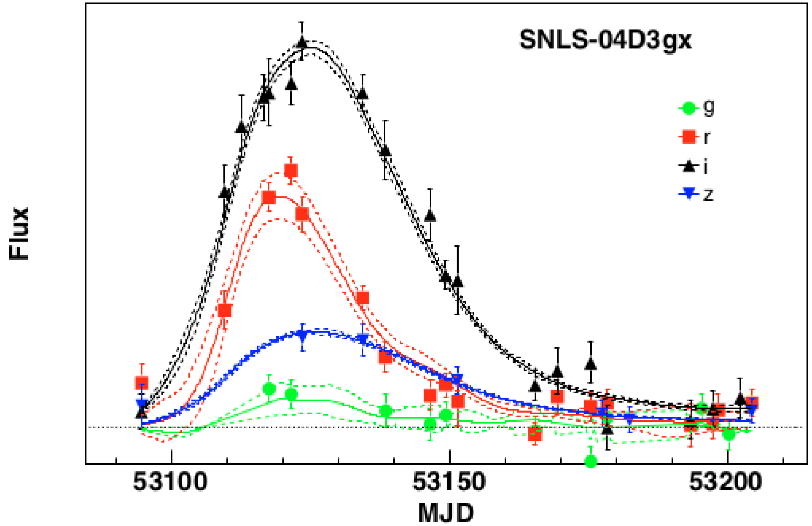
(c) $\delta zp_{r,r-1}(x)$ (2005B)

(d) $\delta zp_{r,r-1}(x)$ (2006B)

Photometric corrections in r band, as time goes.

Accumulation of metal shavings in the optical path



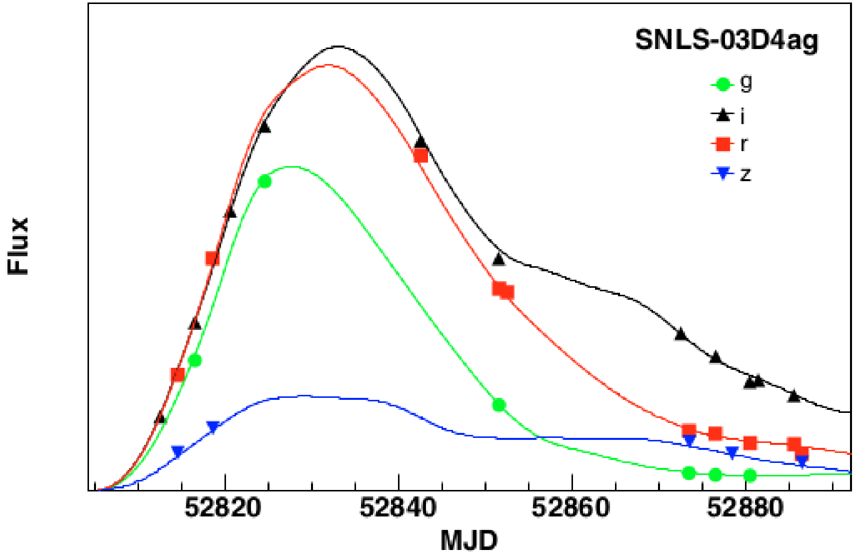


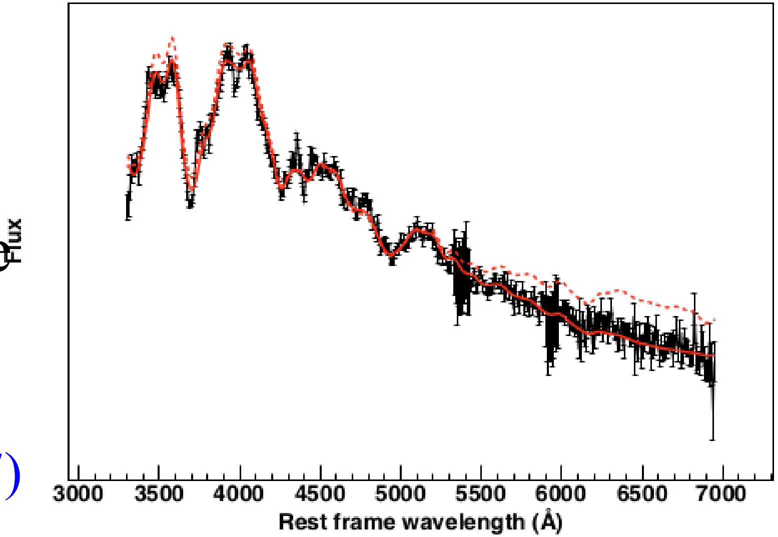
SALT-2

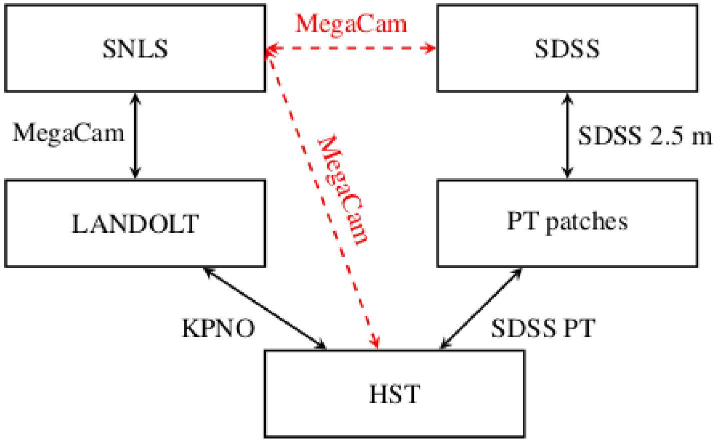
Empirical model
for SNe Ia

- Extends the spectral range
- Improves fidelity

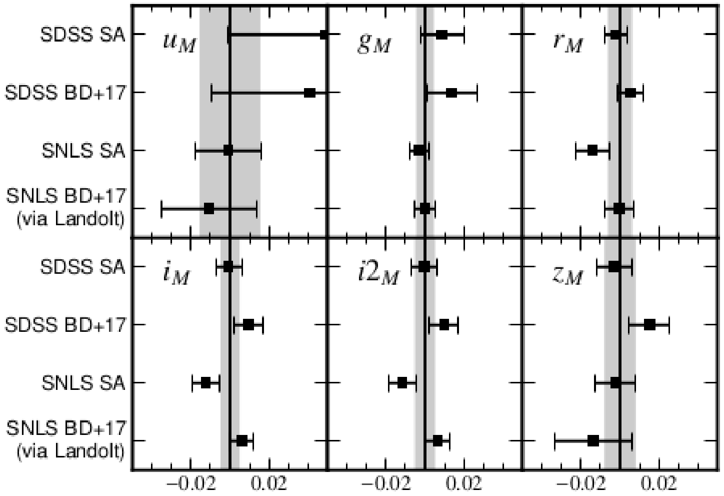
(Guy et al 2007)

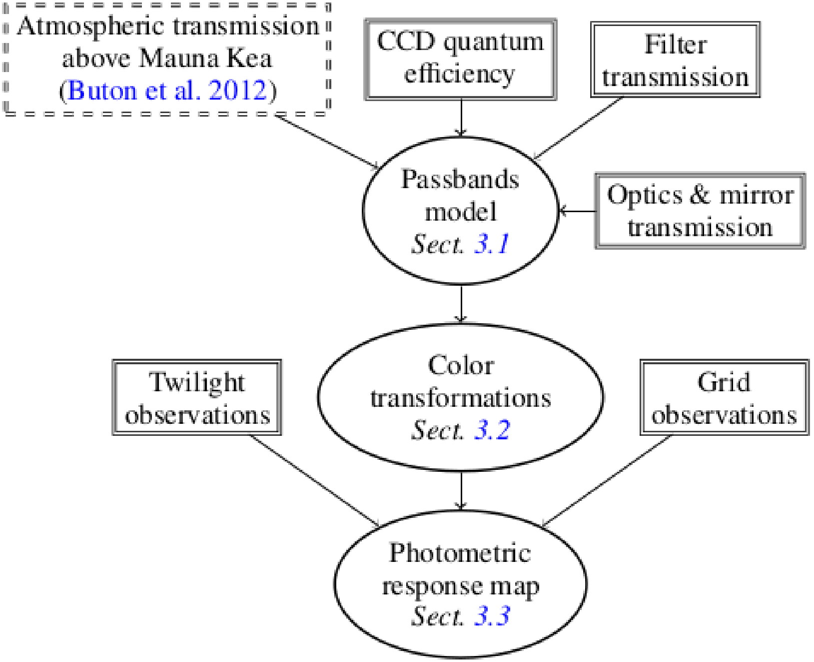






The photometric calibration scheme now provides redundancy:





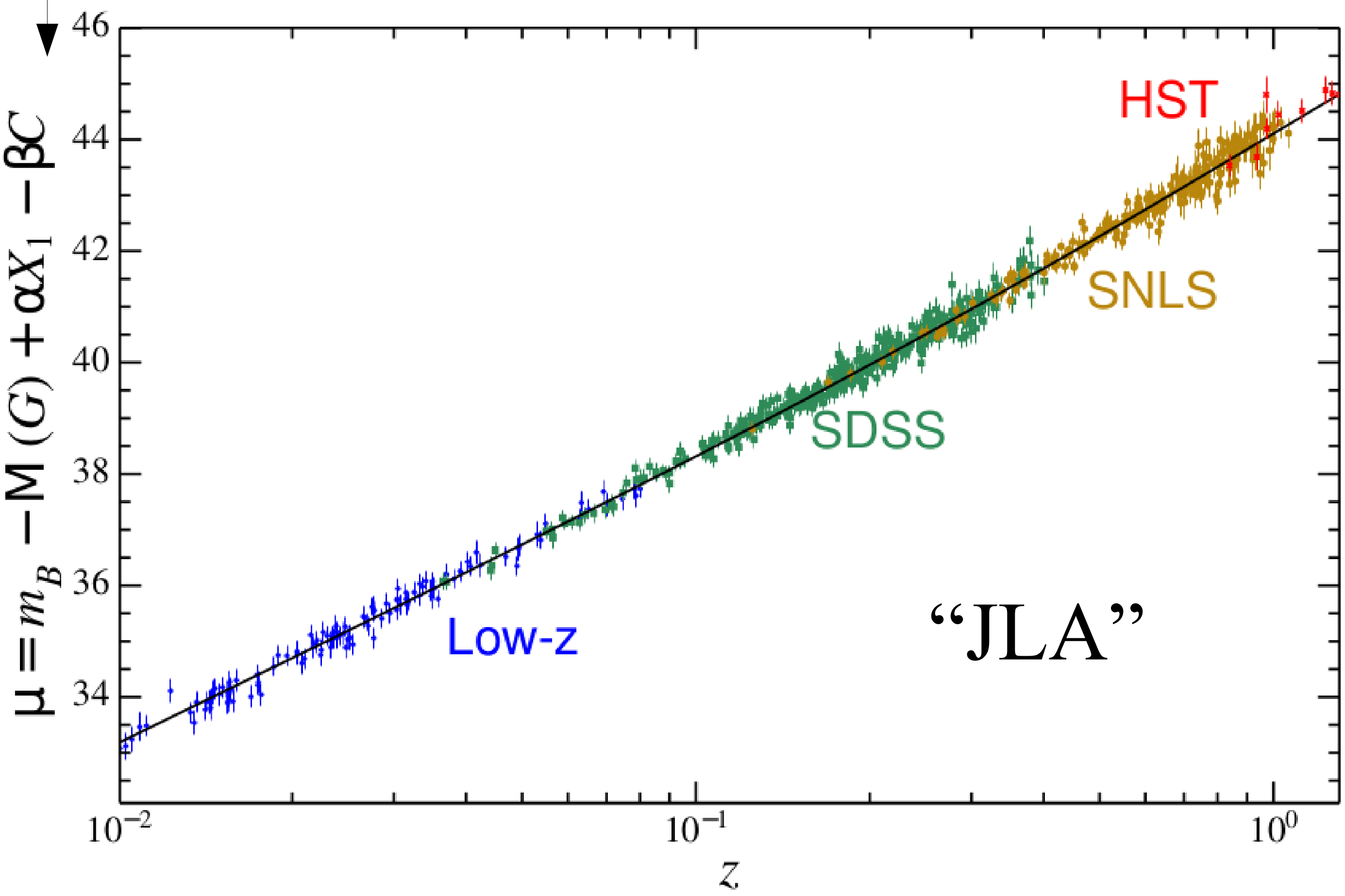
Instrument transmission model

Betoule et al (2013)

P. A

New results (2014)

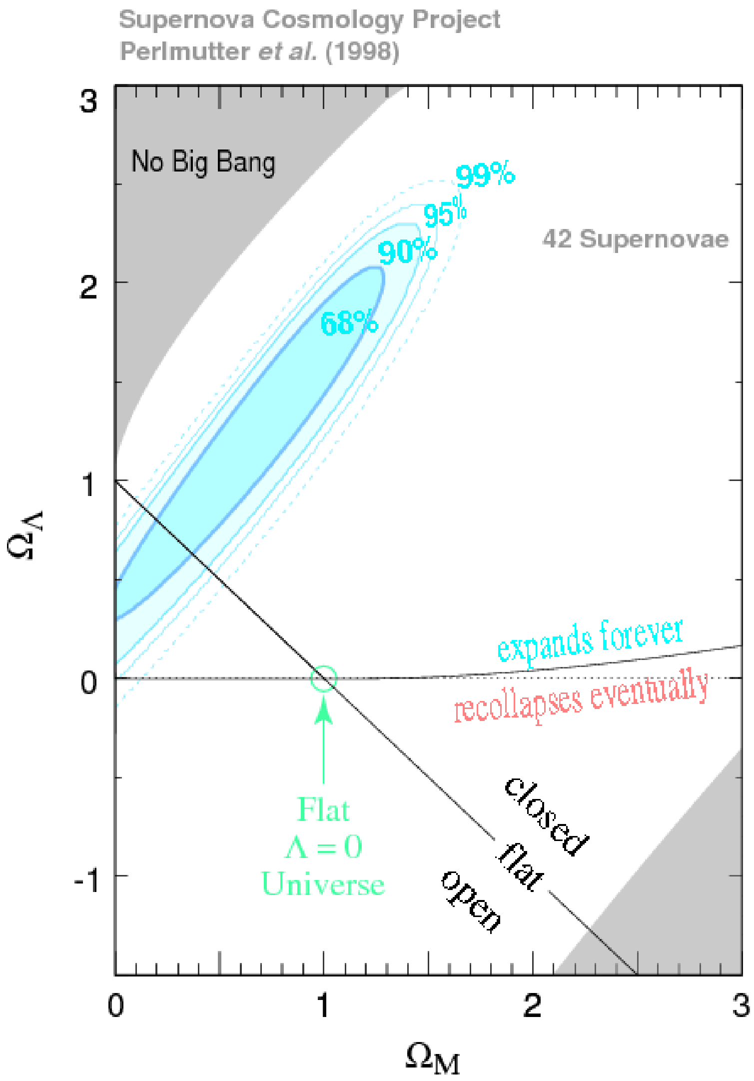
~Log(d_L(z))



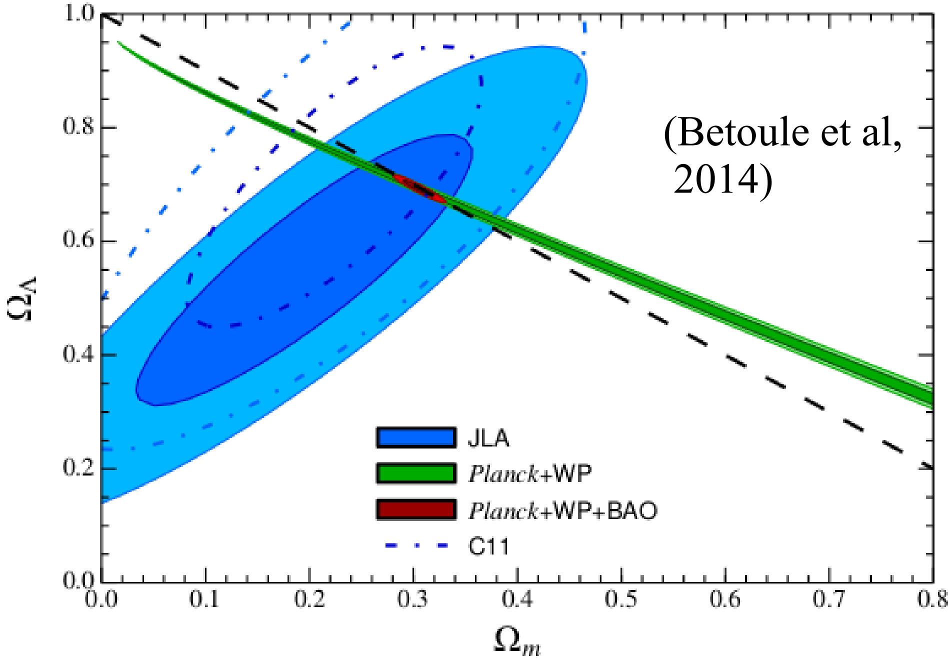
- 118 nearby SNe
- 366 SDSS
- 242 SNLS
- 14 HST

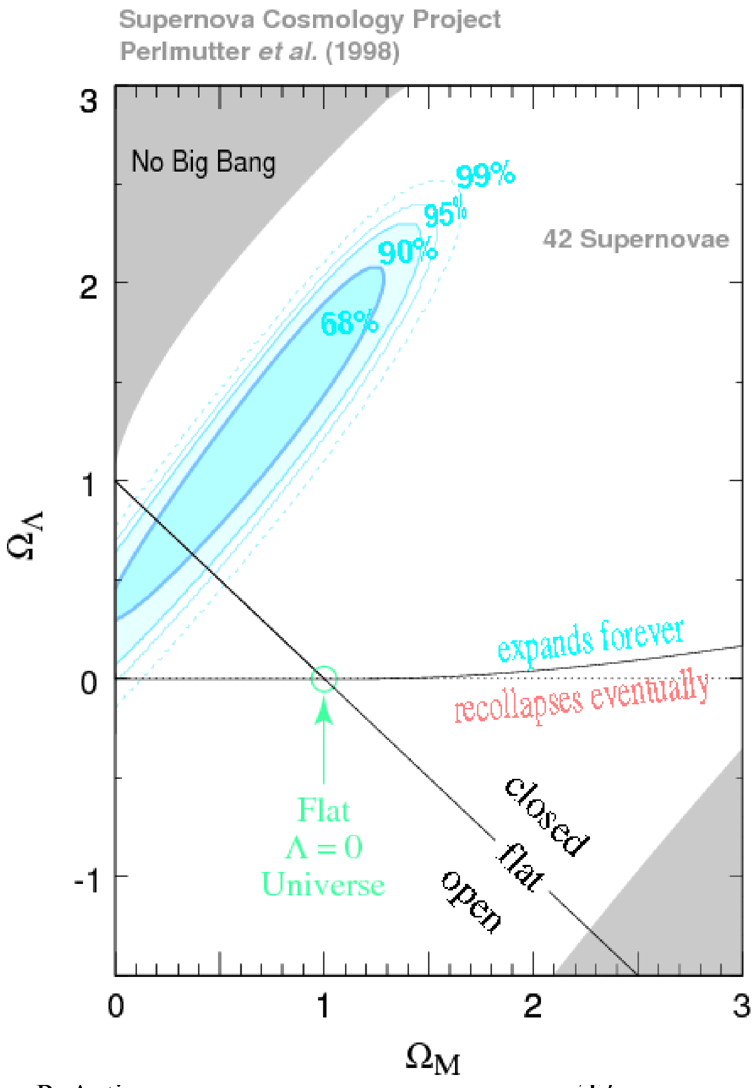
740 events

(Betoule et al, 2014)



From the discovery of acceleration to 2014





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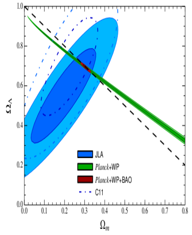
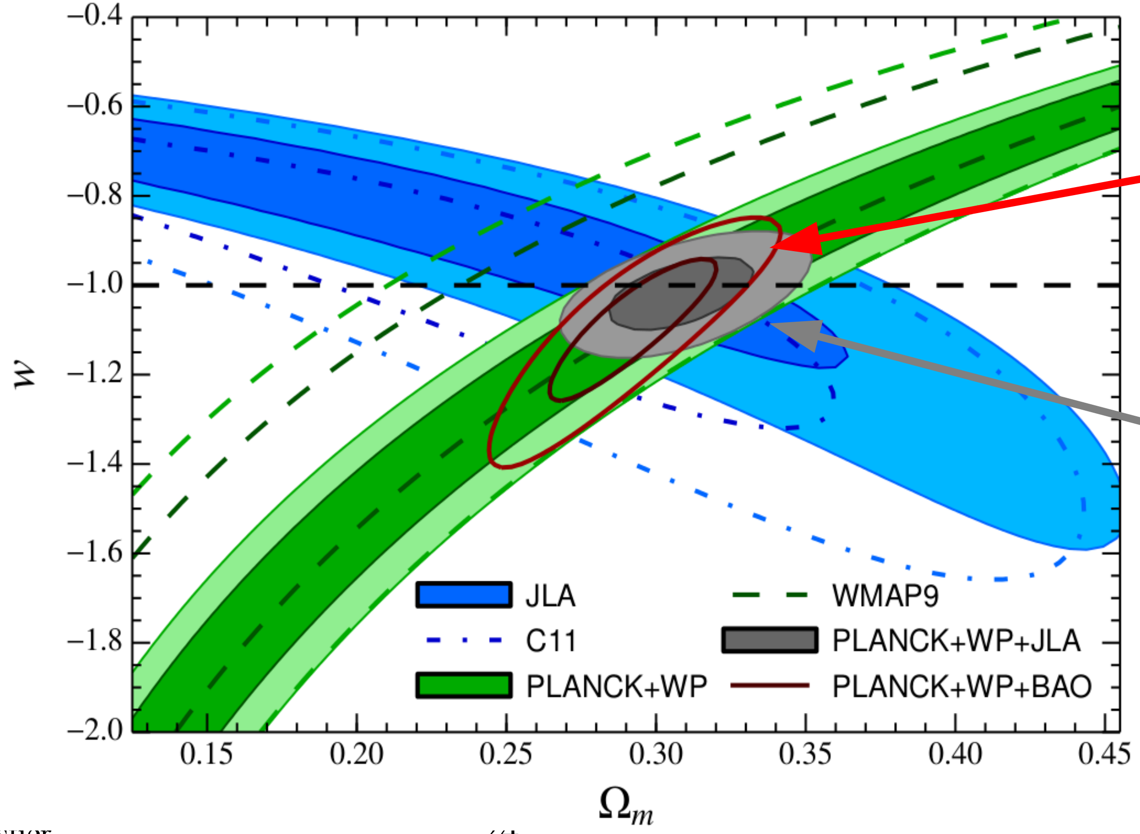


(Betoule et al, 2014)

Equation of state of dark energy



Planck + BAO:
$w = -1.01 \pm 0.08$

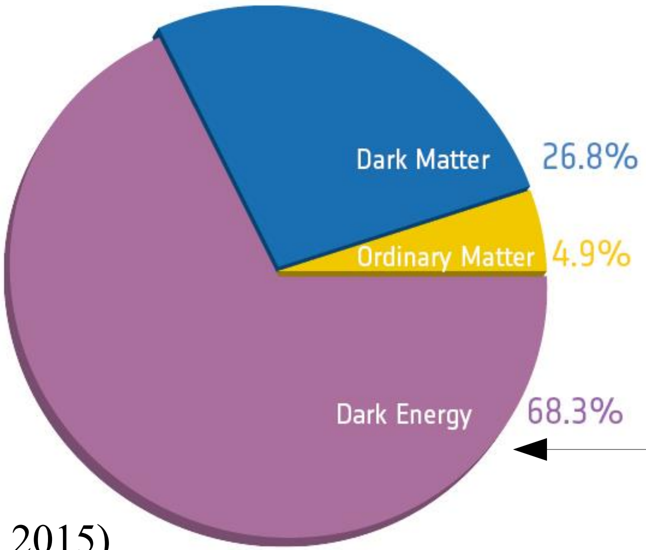
$\leftarrow \Lambda$

Planck + SN:
$w = -1.018 \pm 0.057$

Scientific summary

Expansion is accelerating : there is a component with a static or almost static density

Composition today :



(Planck 2015)

If we broaden the parameter space, we find :
$w = -1.02 \pm 0.05$
i.e. $\rho_{DE} \sim= \mathrm{Cst}$

Dark energy,
assuming w=-1
i.e. static density
(cosmological constant)

My comments

- Megacam@CFHT delivered the key data to measure the equation of state of dark energy with supernovae. The results turned out to be more precise than the simulations run before the survey.
- At this time, Megacam was the best wide-field imager in the world, and the observatory was dedicated to getting the most of it.
- The Legacy Survey paradigm turned out to be efficient: the promise of settling the scientific case (through a very large time allocation) is a very strong incentive to develop advanced reduction methods and to characterize the instrument.

Thanks to all the people who designed, built, and operate(d) the instrument