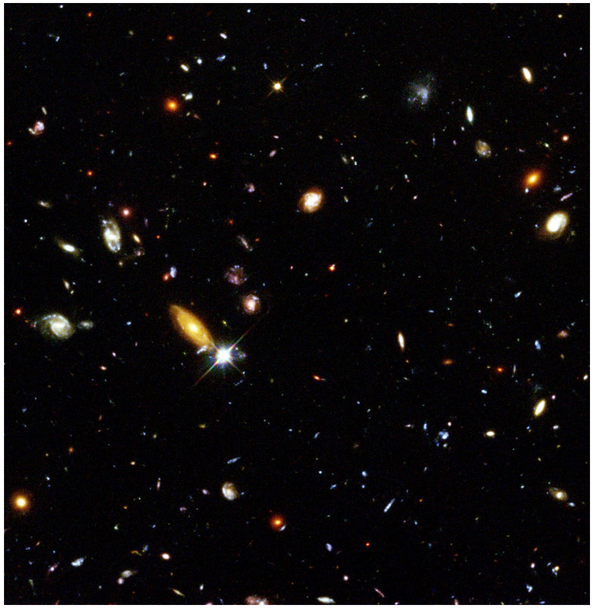
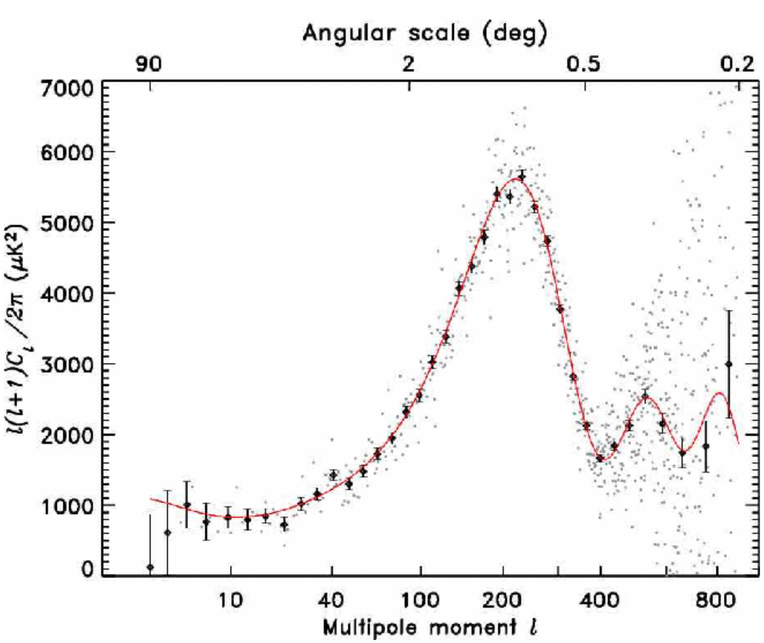
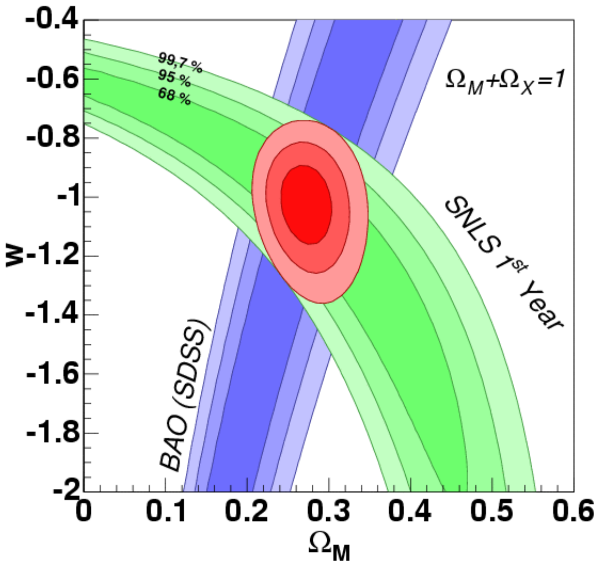
Cosmology and Dark Energy







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July 24th 2007

Dark Energy : (pre)history

Indirect evidences (that remain true today...)

- Age of oldest stars seemed larger than the age of the universe
  (~< 10 Gy for $\Omega_M = 1$, H_0=70)
- Indications in favor of a low $\Omega_M \sim 0.3$
  - Large scale (> 10 Mpc) galaxy correlations
  - Baryonic/total mass in galaxy clusters ~ 0.1
    + baryon density from nucleo-synthesis (He/H ratio) $\Omega_b \sim 0.03$
- Theoretical prejudice in favor of flatness ($\Omega_{tot} = 1$)

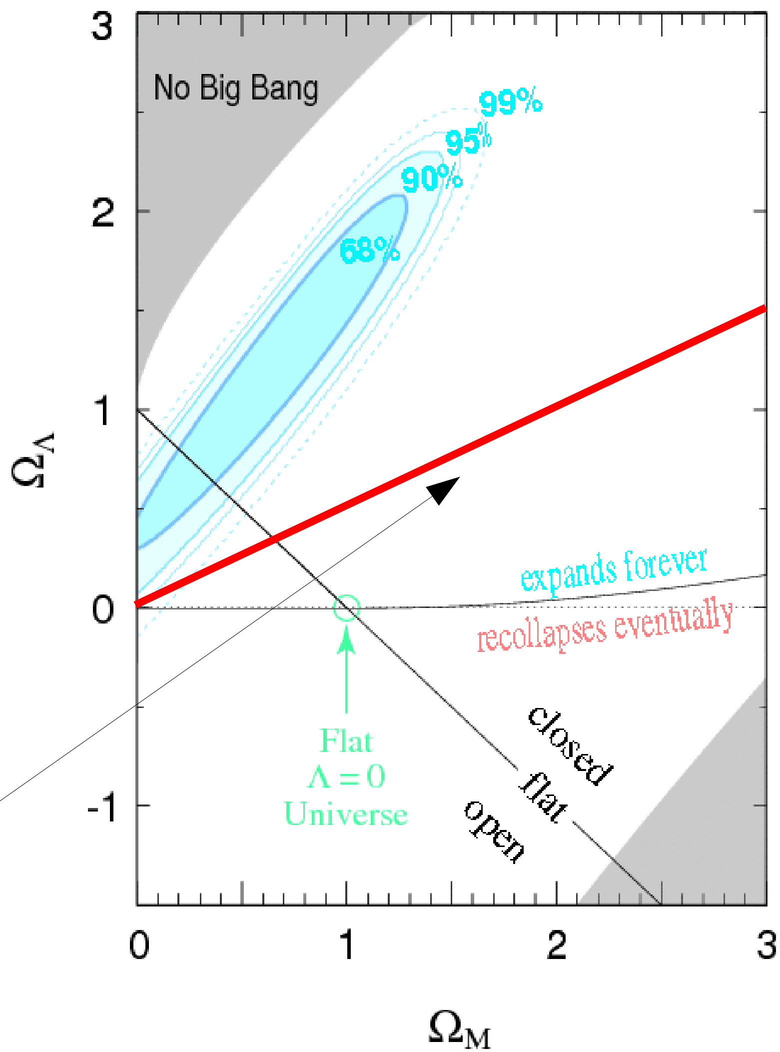
==> There is probably something else than matter.

Dark Energy : history

1998 : two groups find that distant (z~0.5) SNe Ia appear fainter than expected in a matter-dominated universe.

Confidence contours, assuming that this "something else" is a cosmological constant

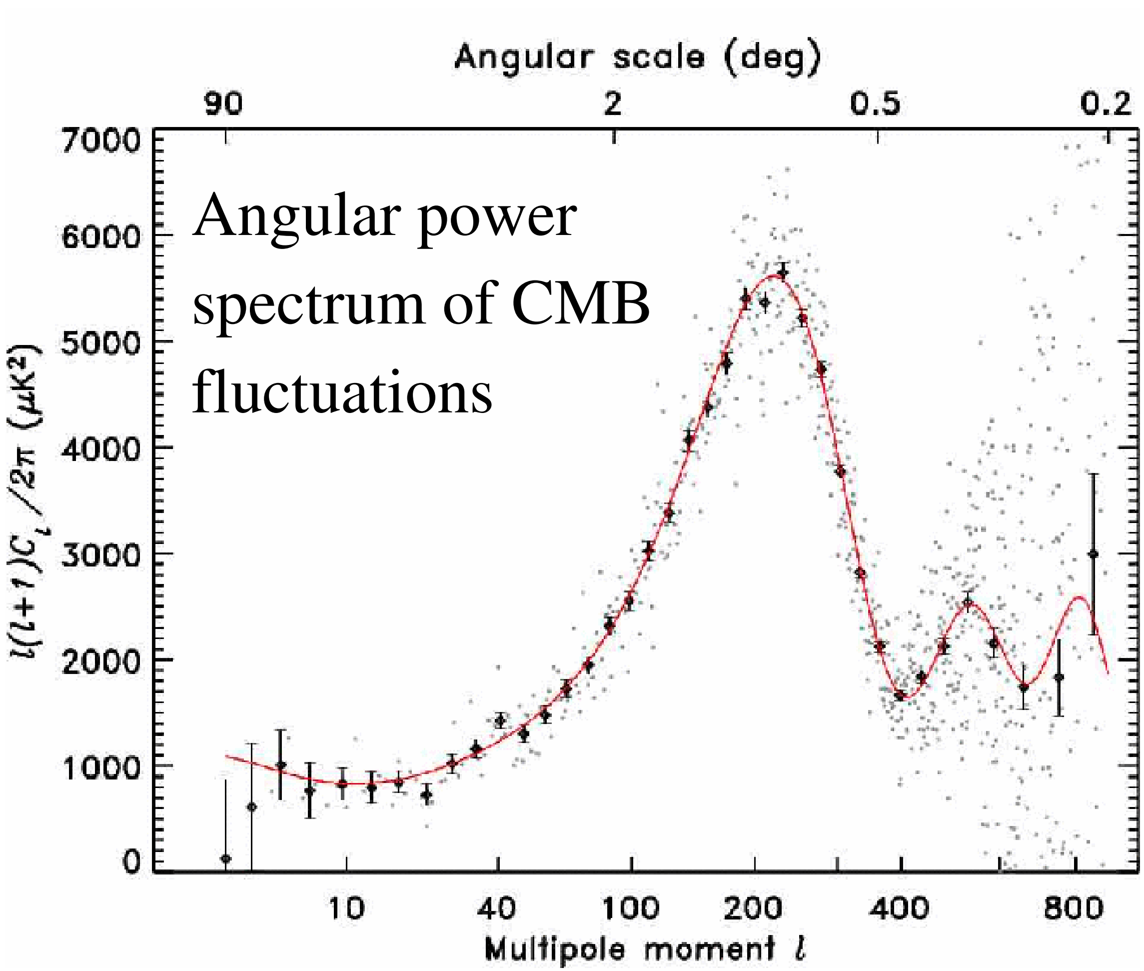
$d^2a/dt^2 = 0$ today



(Perlmutter et al 1999)

CMB : WMAP 3-year data-set

(astro-ph/0603449, Spergel et al, 2006)



Angular power spectrum of CMB fluctuations

Universe is ~ flat

Ω_{tot} = 1.01+/- 0.015

(wmap + others)

now set $\Omega_{tot} = 1$:

Ω_M = 0.234+/- 0.035

Ω_b = 0.042+/- 0.003

h=0.735 +/- 0.03

(h^2 = 0.54 +/0.04)

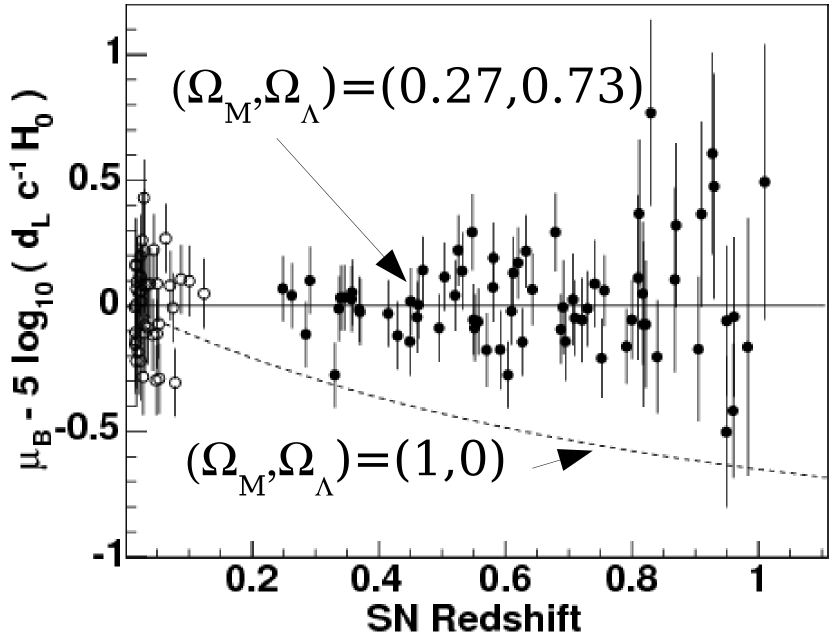
$\Omega_M h^2 = 0.126 \pm 0.01$

$\Omega_b h^2 = 0.022 \pm 0.001$

Dark Energy existence : 2 ways

"direct"

SNe Ia Hubble diagram :



(SNLS Collaboration, 2005)

" Subtraction":

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

$$-\ \Omega_M \sim= 0.25$$ (CMB. + flatness)

(or BAO or ...)

$$\Omega_X \sim= 0.75$$

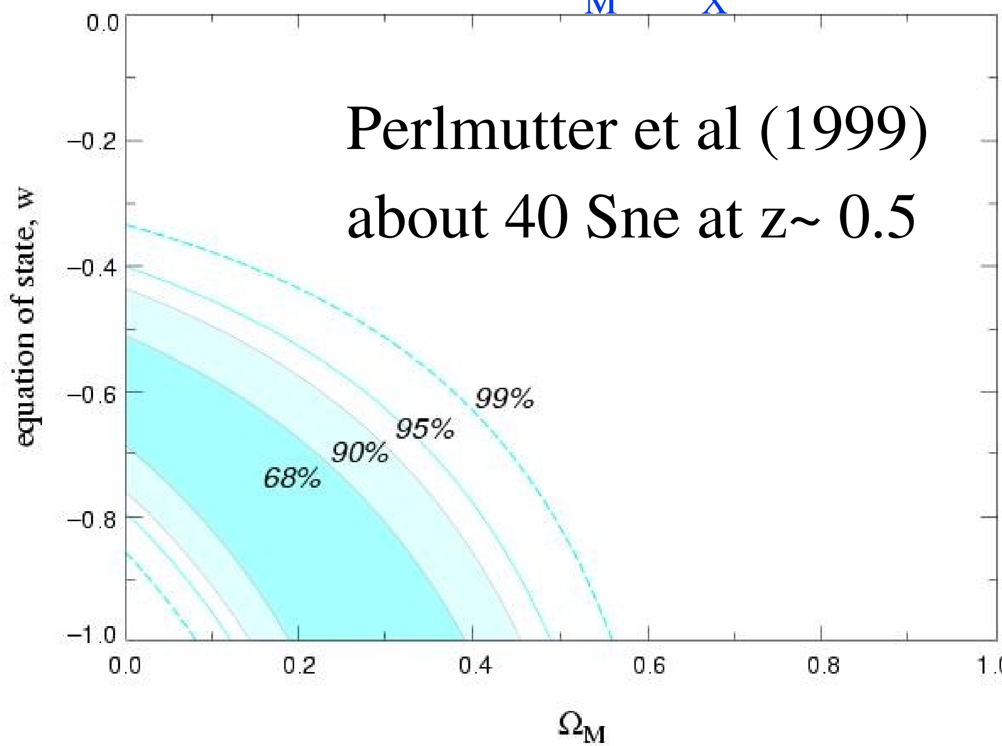
Dark Energy nature

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

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

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

$\Omega_M + \Omega_X = 1$



Concordance model : a strange brew

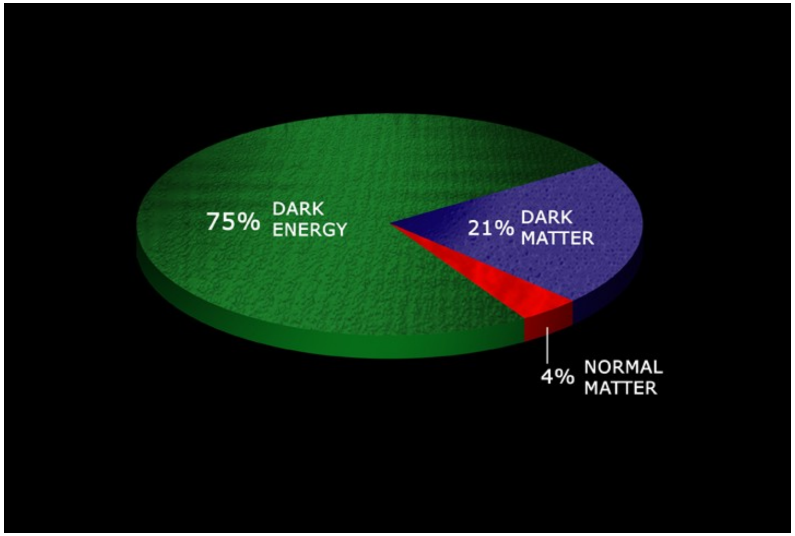
•Universe is flat (within uncertainties).

•Matter (density~ R^{-3}) represents about 25 % of the total energy.

• Baryonic matter only represents 4 % of the total

• There is ~20 % of so-called dark matter... about which we know almost nothing...

• And ~75 % of dark energy(density~ $R^{\sim 0}$)...
... about which we know less than nothing



Dark Energy : casting for theoreticians

- A bare cosmological constant

  (the standard term in Einstein's equations)

- Adjustment to gravity : Non-minimal couplings

  or extra dimensions

  (change General Relativity, but don't forget to check the fuses)

- Quintessence and variants

  (add a new scalar field, with little or no kinetic energy)

- Back Reaction (no new physics)

  (Formation of structures influences average apparent expansion)

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

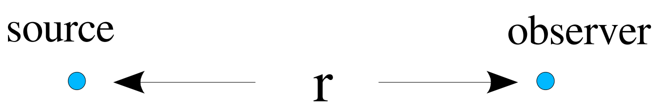
- Distances to standard candles as a function of z (SNe Ia)
- Angular size of a standard rod as a function of z
  (Baryon Acoustic Oscillation , BAO)

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

Growth of (matter) structures

- Large scale matter power spectrum
  evolution with z (weak shear)
- Galaxy cluster statistics

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 equation:

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

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

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

$$\left(\frac{H(z)}{H_0}\right)^2 = \Omega_M(1+z)^3 \; + \; \Omega_X \; \exp(3\int_0^z \frac{1+w(z')}{1+z'} dz') \; + \; \Omega_k(1+z)^2$$

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

The expansion history depends on the sum of 3 terms.

The equation of state only enters in one of them.

--> exact or quasi degeneracies from fits of r(z)

1) need to know Ω_k (from C.M.B + something)

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):

	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})

DE probes : current development

Type Ia supernovae (distances to standard candles):

Established acceleration/Dark Energy (1998)

Now in a second round of observing programs.

BAO (primordial peak in the galaxy correlation function):

Signal detected in the SDSS and 2dF (at a single redshift) (2005)

Second round programs planned or under way.

Weak Lensing (galaxy shear correlations due to DM):

Signal detected in 2000.

z dependence of the signal to be quantified soon.

Galaxy clusters (counting)

Feasibility unclear: efficiency & modeling issues

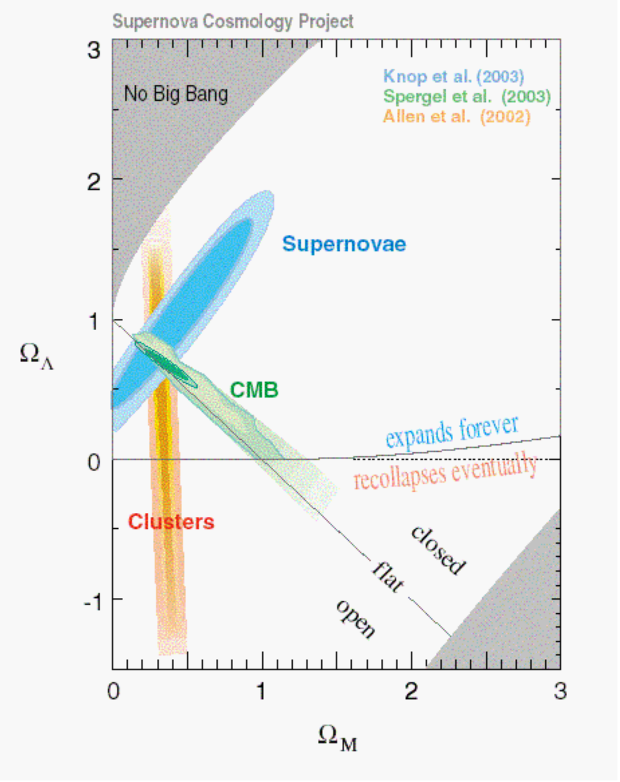
Distances to SNe Ia : some history

Early days:

- Riess et al 1998 (10(+6) SNe Ia)
- Perlmutter et al 1999 (42 SNe Ia)

=> Acceleration of expansion

=> Gruber prize to the ~50 authors of these 2 papers !

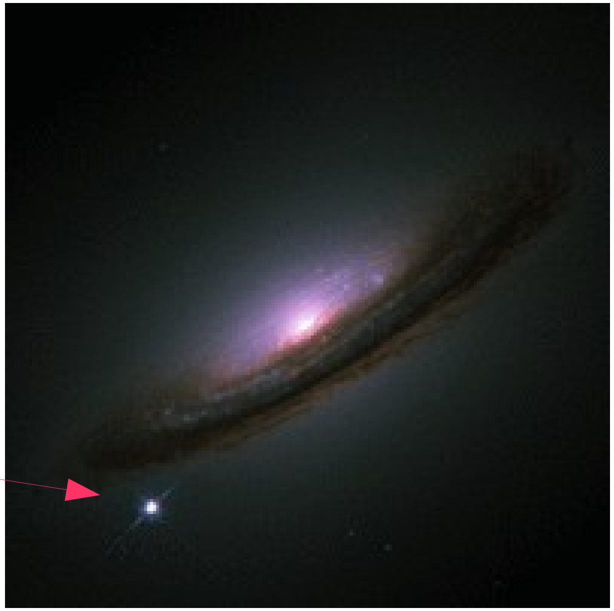


Later on:

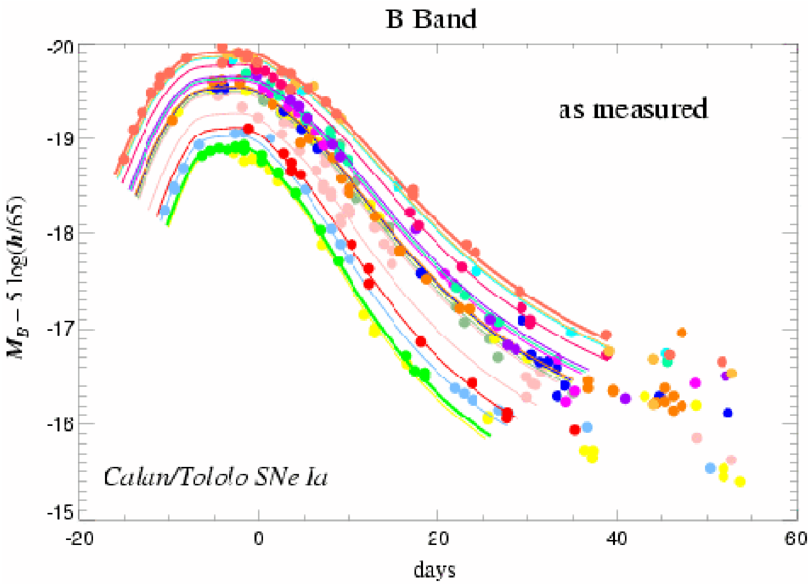
- Sullivan et al 2002 Hubble diagrams by galaxy types (non-evolution test)
- Tonry et al 2003 (+8)
- Barris et al 2003 (+23 SNe Ia, z<1)
- Knop et al 2003 (+11 SNe Ia measured with HST)
- Riess et al 2004: (+16 SNe Ia found and measured with HST) up to z~1.6
- Riess et al 2006: (+17 SNe Ia found and measured with HST) up to z~1.6

Supernovae Ia

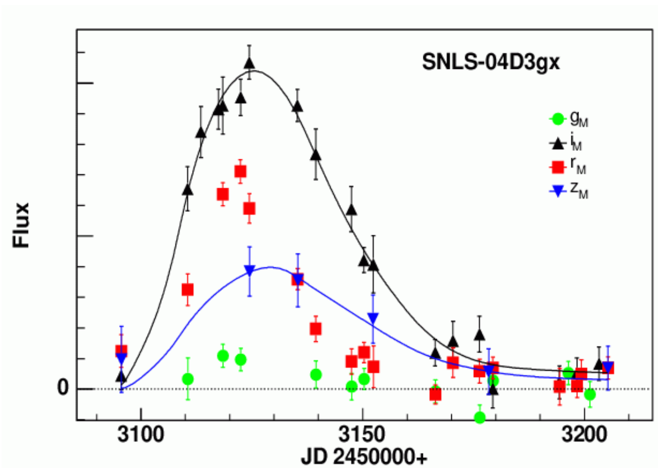
Thermonuclear explosions of stars
which appear to be reproducible



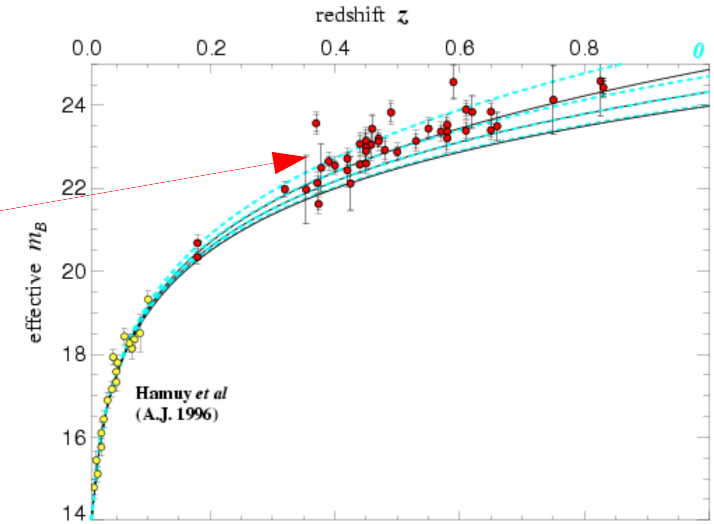
- Very luminous
- Can be identified (spectroscopy)
- Transient
  (rise ~ 20 days)
- Scarce (~1 /galaxy/millenium)
- Fluctuations of the peak
  luminosity : 40 %
- Can be improved to ~14 %



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)
  - -> measurements in several bands

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).

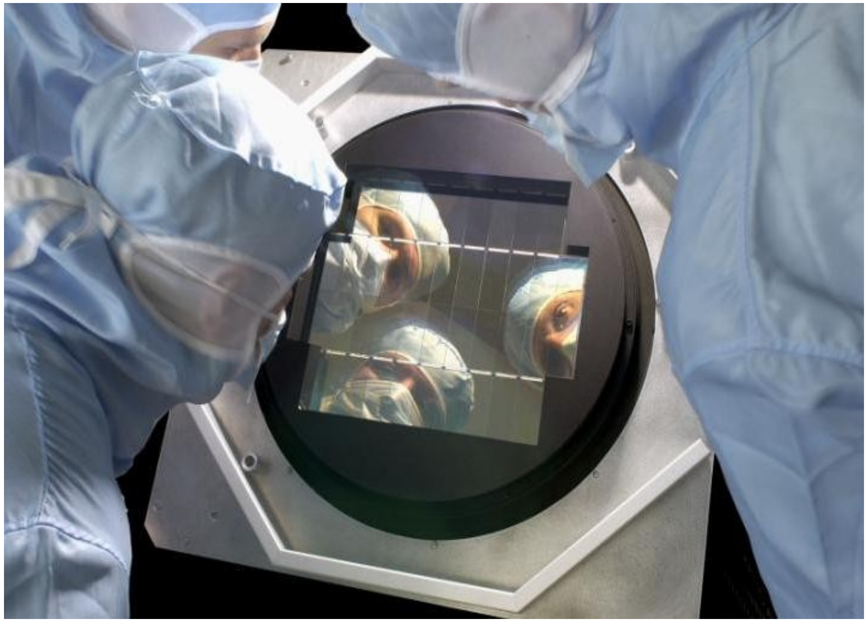
http://snls.in2p3.fr

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

MegaCam at CFHT

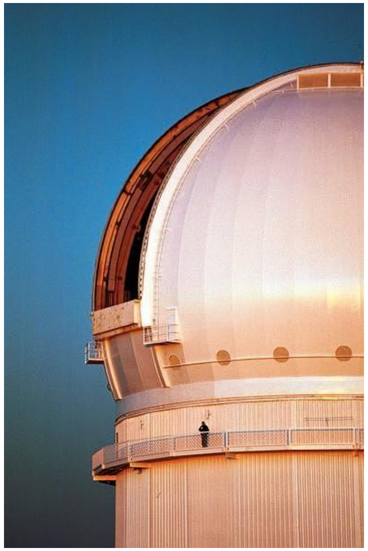
MegaCam:

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



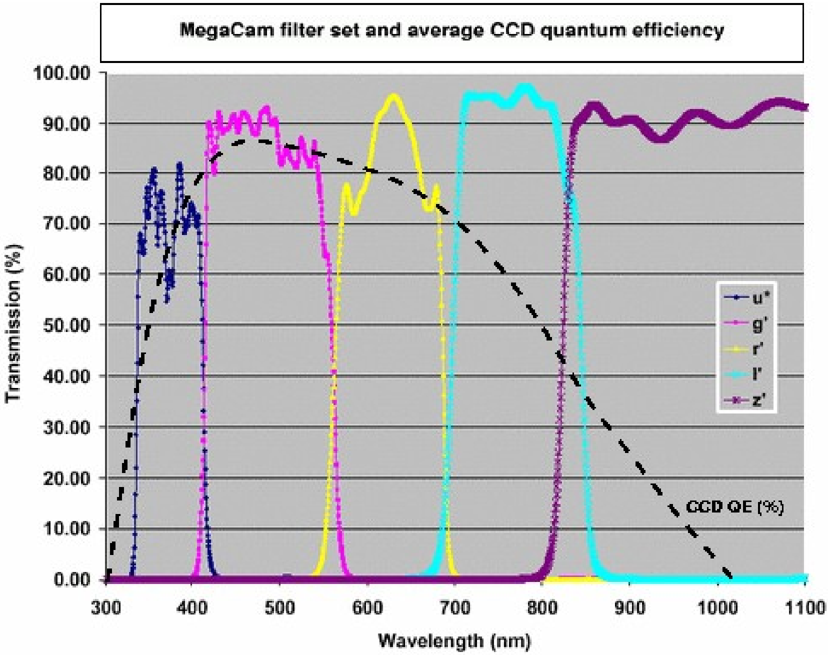
CFHT:

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



CFHTLS/Deep : Observing mode

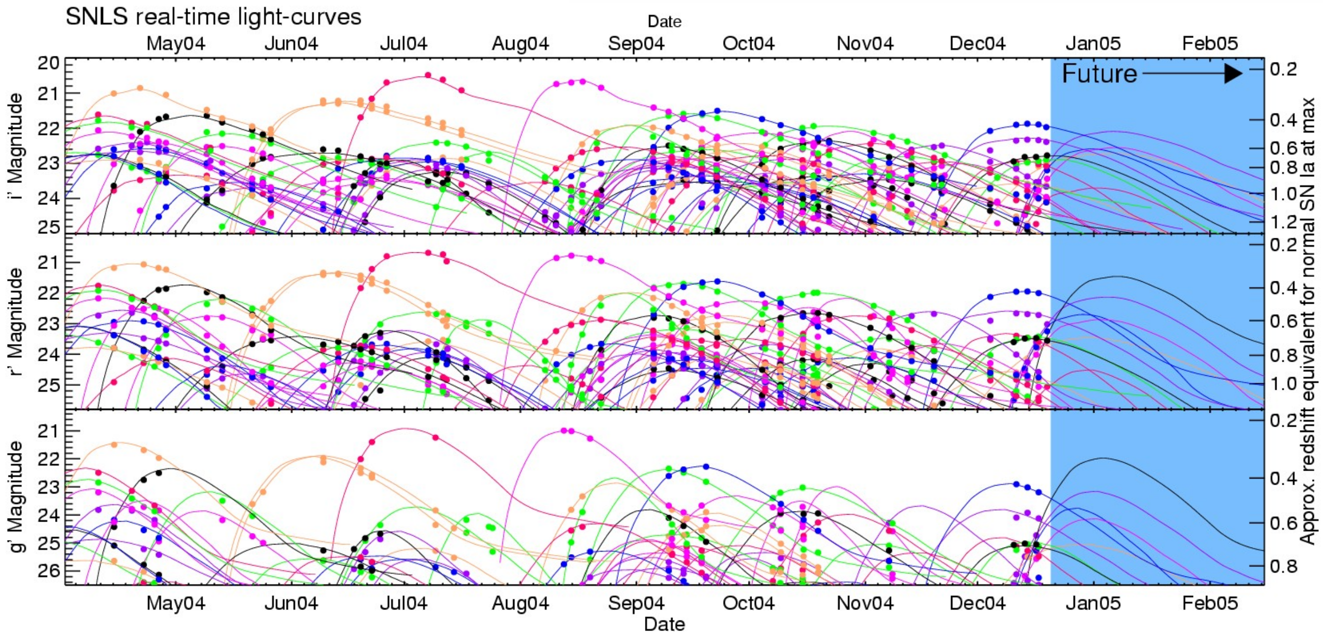
- 40 nights/year for 5 years.
- Repeated observations every ~4 night ("rolling search"), service mode
- 4 bands g,r,i,z
- 4 one deg^2 fields monitored ~ 6 month/year



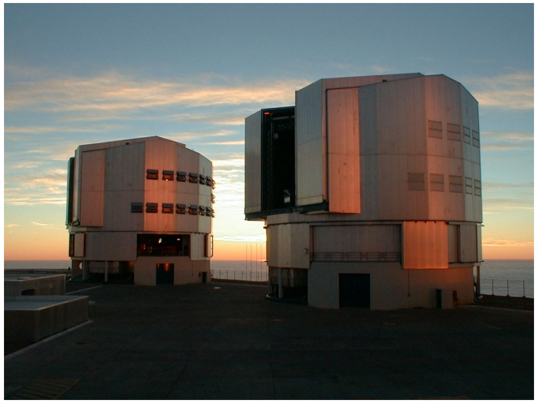
-> Photometric data **before** objects are detected

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

-> Repeated calibration of field stars



Spectroscopy



Identification of SNe Ia

Redshift (usually of the host galaxy)

Detailed studies of a (small) sample of SNe Ia/II

Telescopes

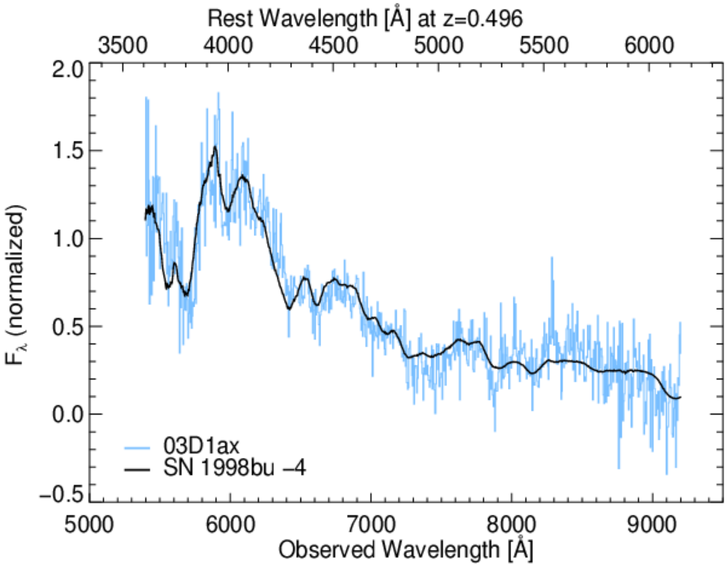
- VLT Large program (service)

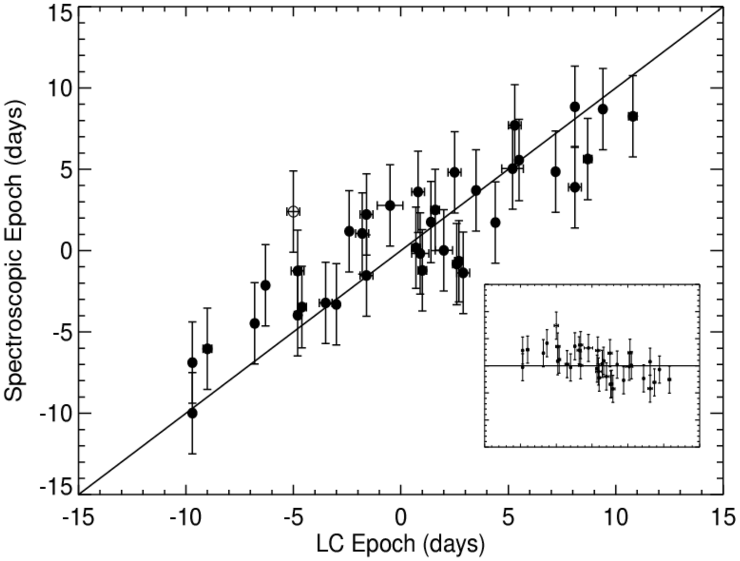
  240h in 2003+2004, idem 2005+2006

- Gemini : 60h/semestre

  (Howell 2005, astro-ph/0509195)

- Keck :

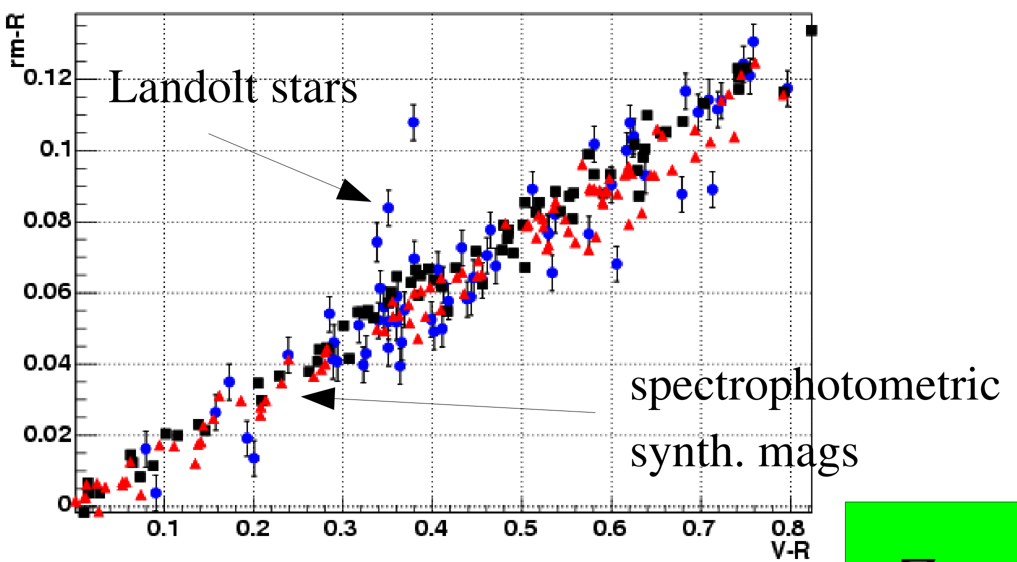


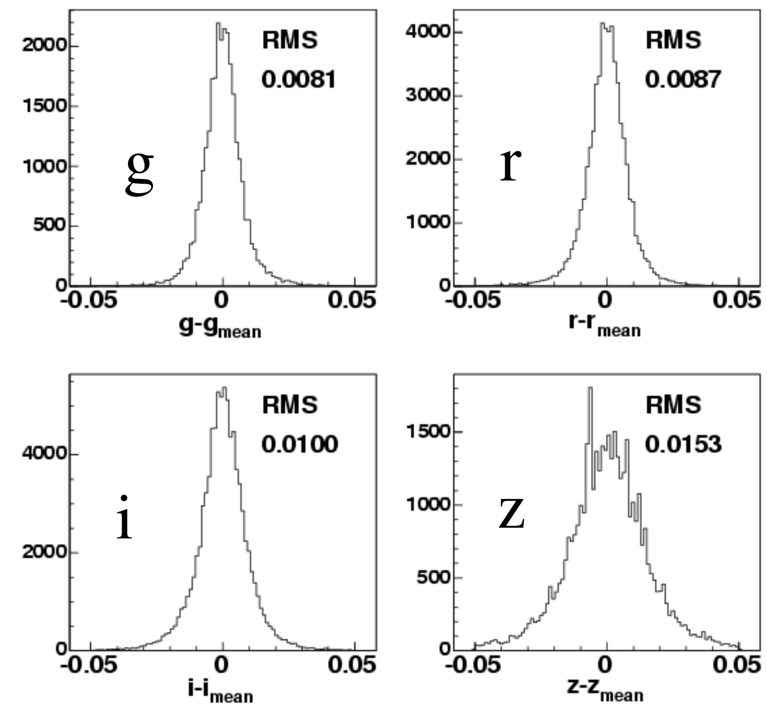


Photometric calibration

- 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)



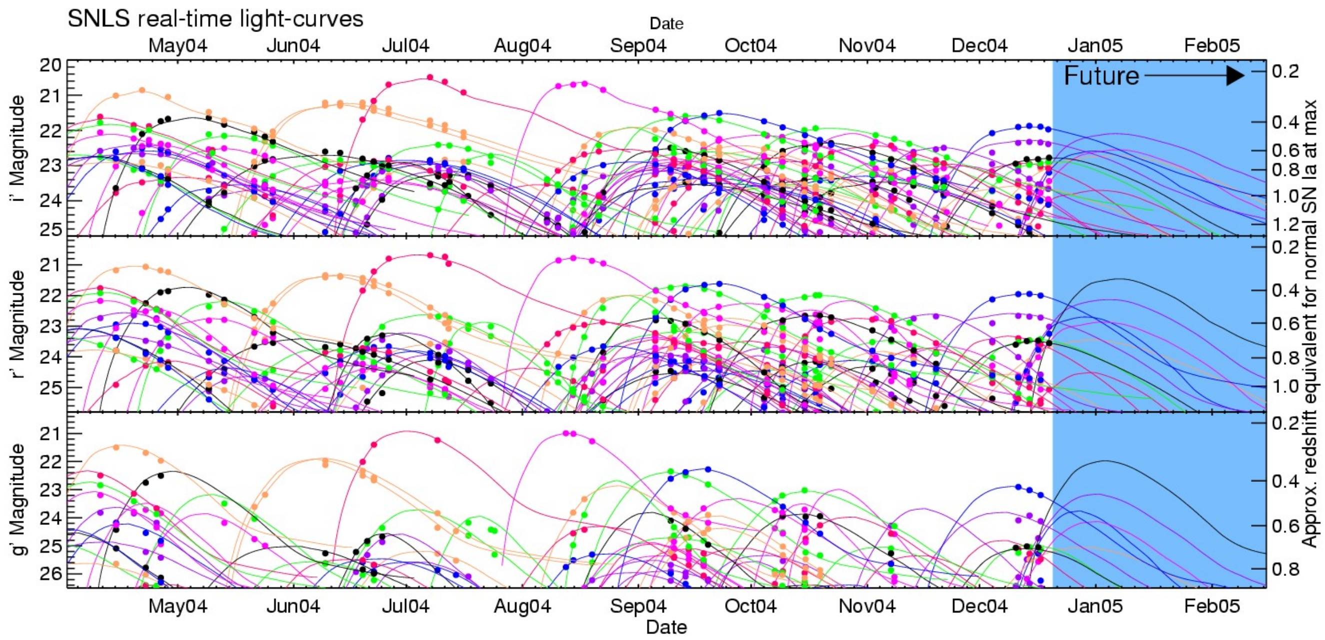


-Zero points @ 0.01 (0.03 in z)

-Repeatability better than 0.01 (0.015 in z)

First year SNLS data set

(up to July 2004)



142 acquired spectra:

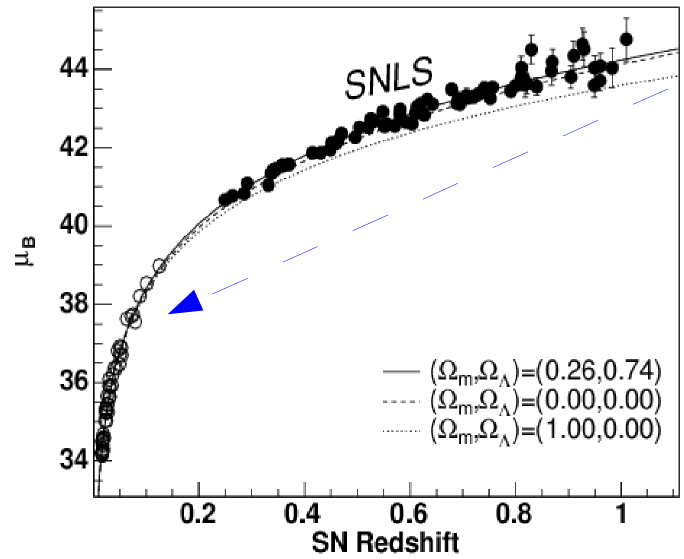
- 20 Type II SNe
- 9 AGN/QSO
- 4 SN Ib/c
- 91 SNe Ia

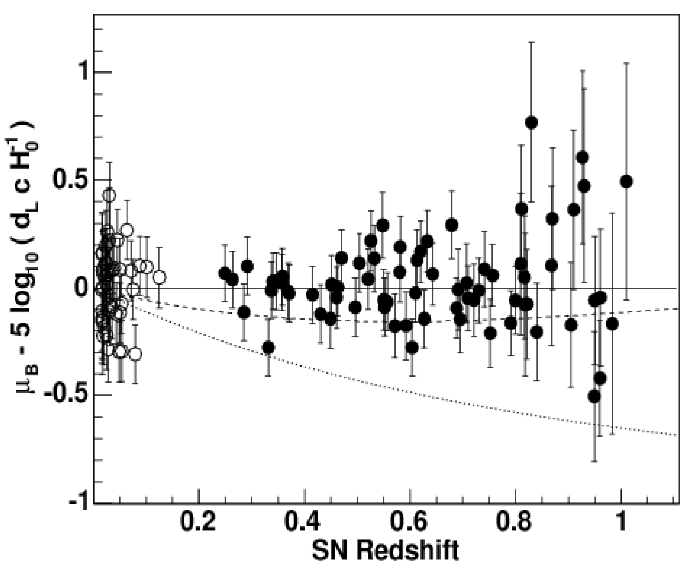
-10 missed references (are now usable)

- 6 only have 1 band (lost)

75 usable Ia events

Hubble Diagram of SNLS (first year)





Final sample :

45 nearby SNe from literature

+71 SNLS SNe

(2 events lightcurves are badly fitted,

2 are strong Hubble Diagram outliers)

Distance estimator:

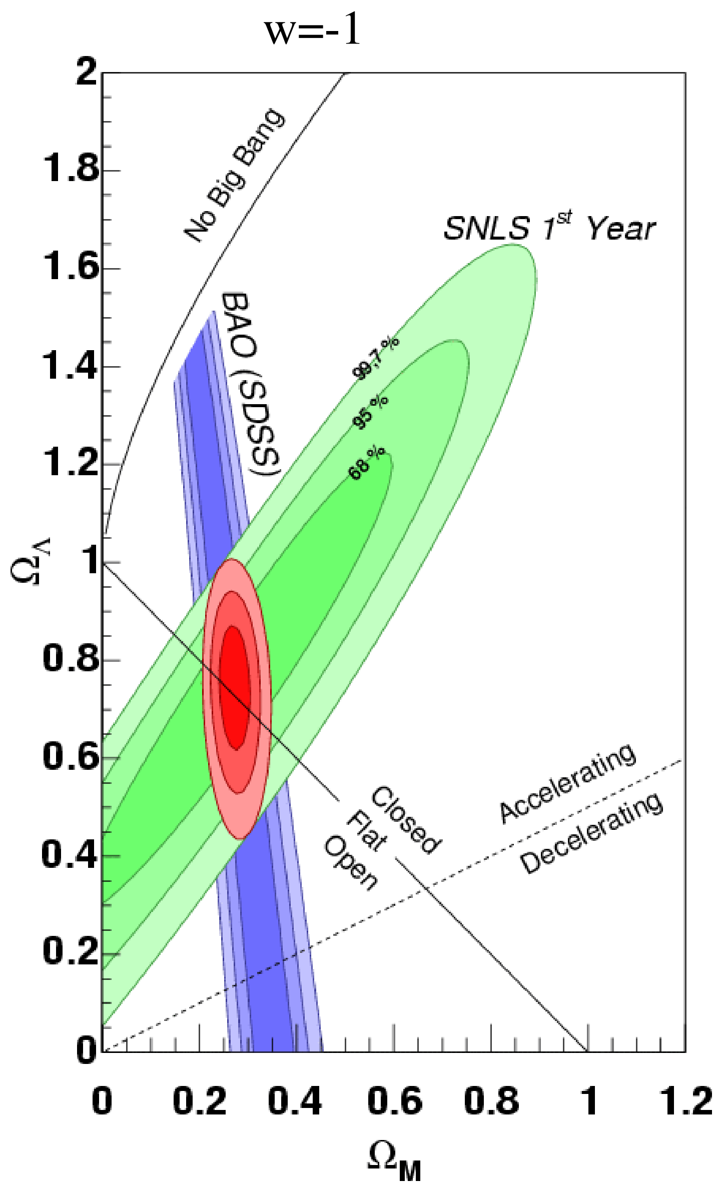
$$\mu_B = m_B^* - \mathcal{M} + \alpha(s-1) - \beta c$$

brighter-slower brighter-bluer

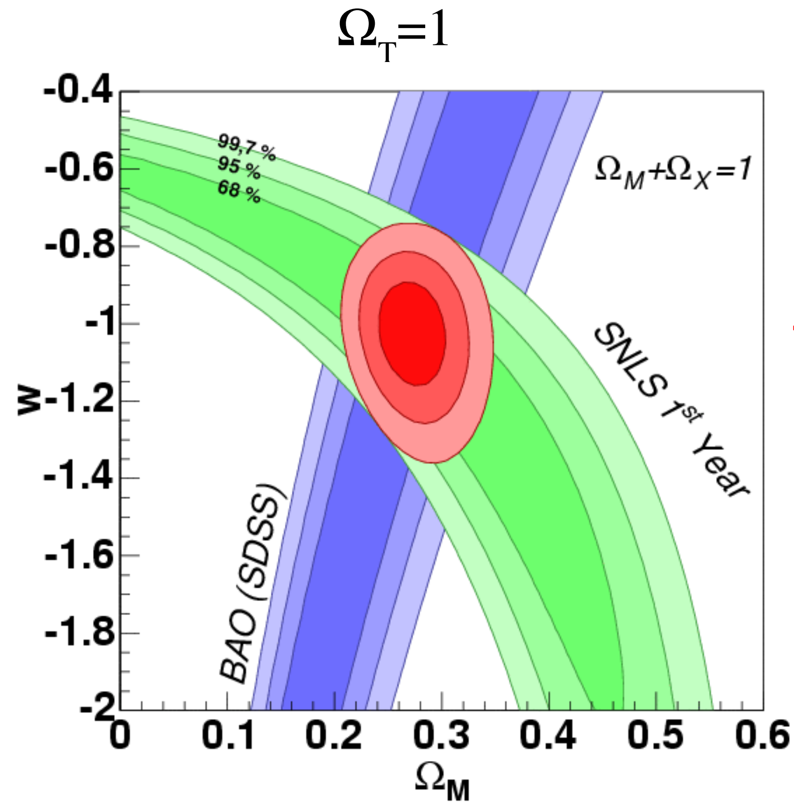
$$\chi^2 = \sum_{objects} \frac{(\mu_B - 5\log_{10}(d_L(\theta,z)/10pc))^2}{\sigma^2(\mu_B) + \sigma_{int}^2}$$

- 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



68.3, 95.5 et 99.7% CL



<-- Λ

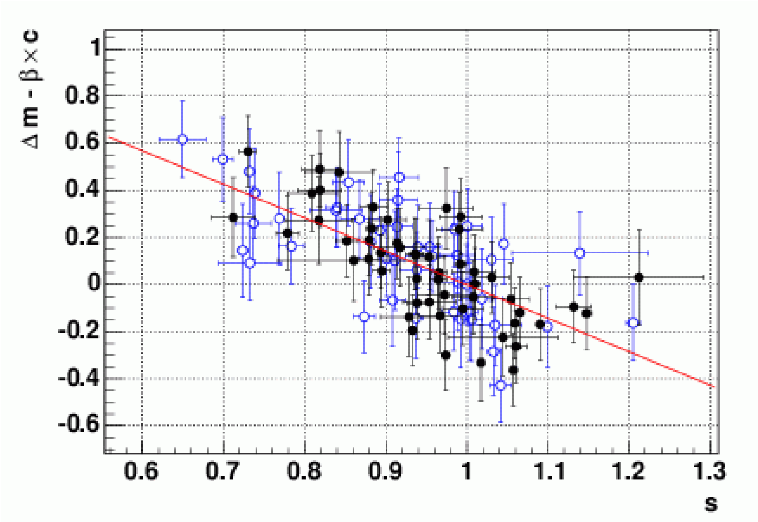
BAO: Baryon Acoustic Oscillations
(Eisenstein et al 2005, SDSS)

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

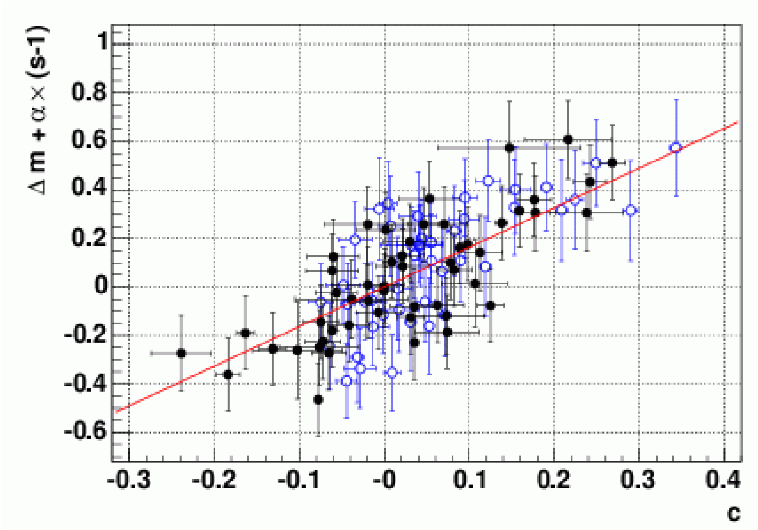
(astro-ph/0510447)

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

Brighter - slower

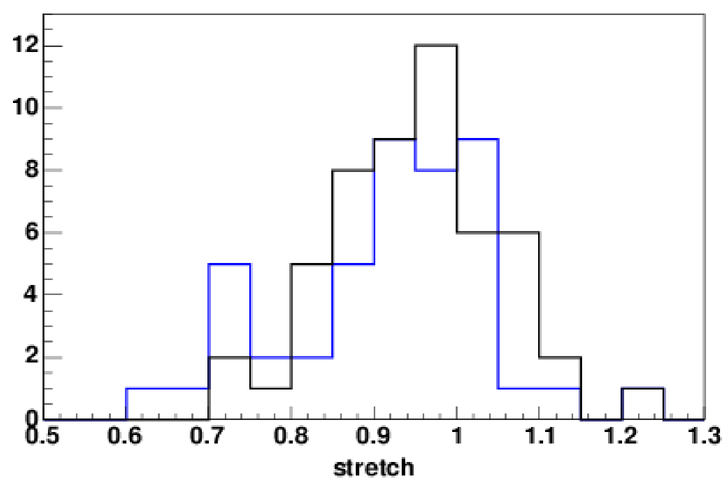


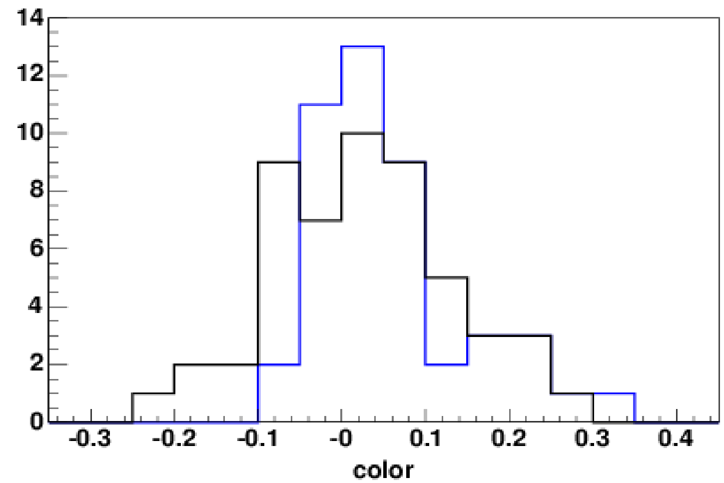
Brighter - bluer



Blue: nearby SNe

Black: SNLS SNe





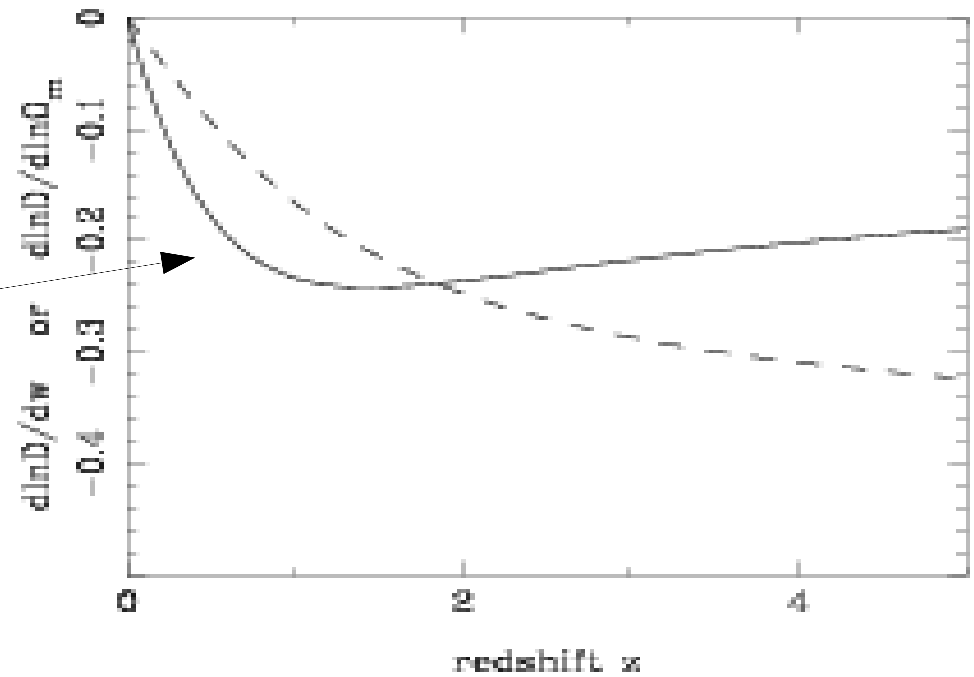
Stretch, color and relations with luminosity are essentially compatible between nearby and distant events.

P. Astier (Mancheste

Photometric calibration and EOS accuracy

For a constant EOS:

d log(d)/ dw <~ 0.2



(from astro-ph/0610906)

Hence:

a 2% uncertainty on flux translates to

- a 1% uncertainty on distance
- a 0.05 uncertainty on w

SNLS 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

SNLS Cosmological results

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

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):

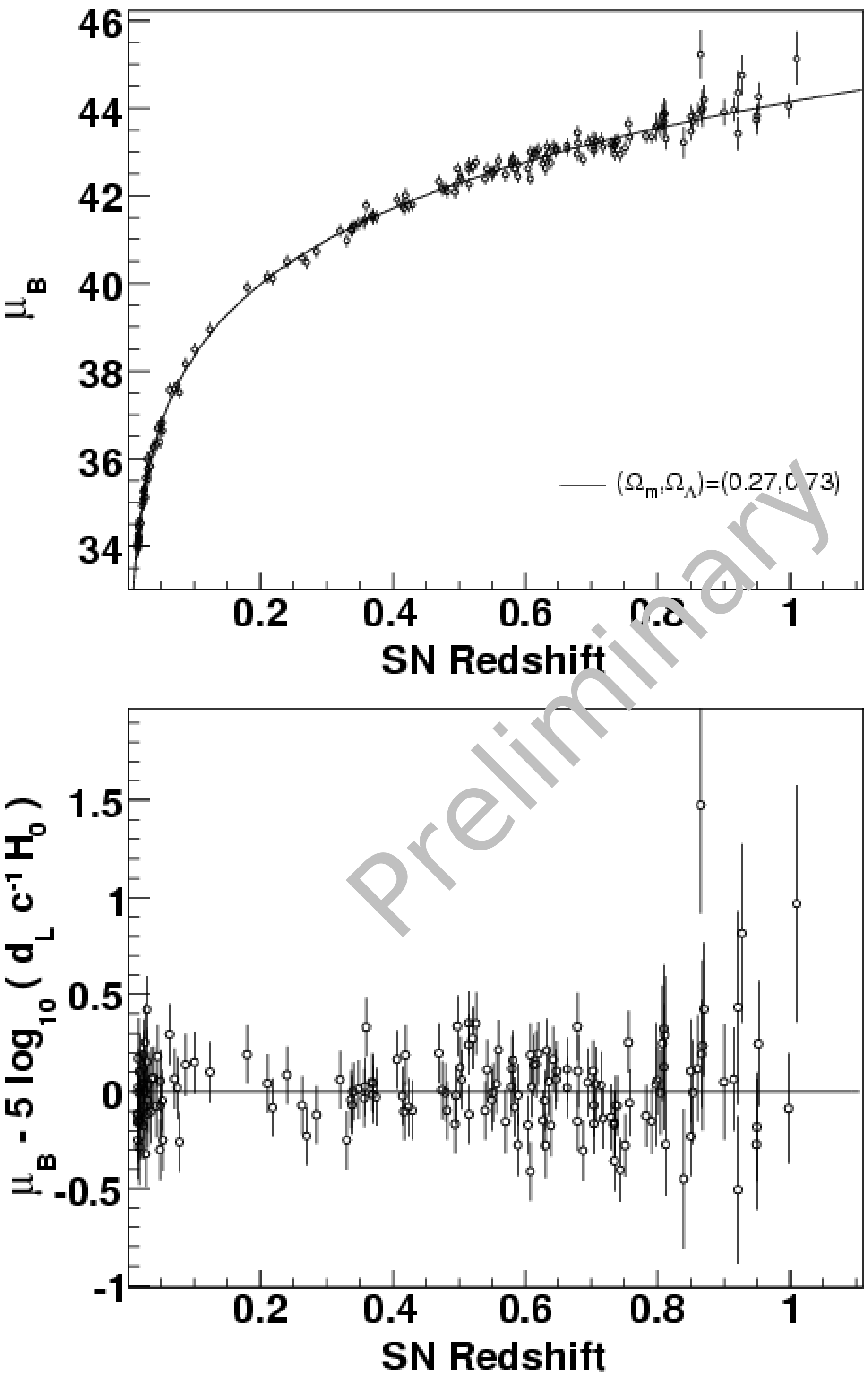
$$\Omega_M = 0.271 \pm 0.021\ (stat) \pm 0.007\ (sys)$$
$$w = -1.02 \pm 0.09\ (stat) \pm 0.054\ (sys)$$

- **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 2.5 years Hubble Diagram

Up to March 2006,

~230 distant SNe Ia

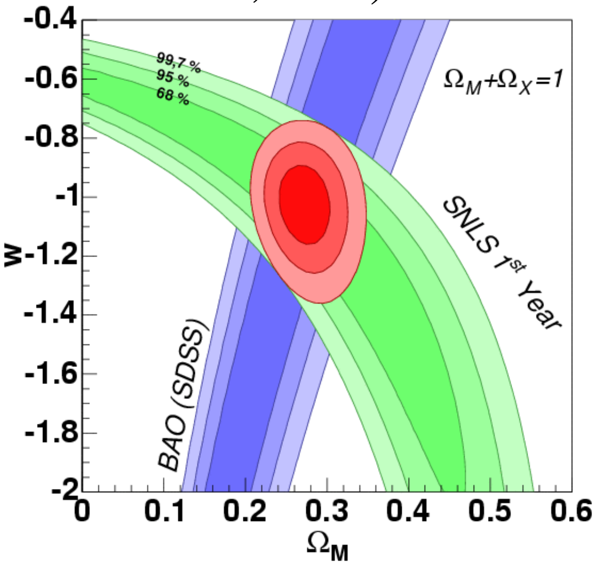


More Data Coming Soon

- High-z Supernovae (z>0.3)
  - SNLS, Essence, SCP, PANS(HST)
- Medium-z Supernovae (0.05<z<0.3)
  - SDSS
- Local Supernovae
  - CfA, KAIT, CSP, SNFactory,...

SNe+BAO:Short term forecasts for w

(SNLS Collab., 2005)

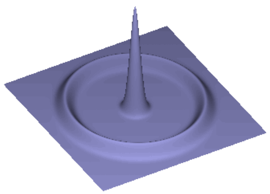


Expected "realistic" statistical improvements of the (Ω_M,w) constraints.

SNfactory
SDSS SNe
SNLS SNe

	Nearby SNe	44	inf.	44	132	132	250
	Distant SNe	71	71	213	213	500	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

Material from D. Eisenstein (et al).
I added mistakes on my own.

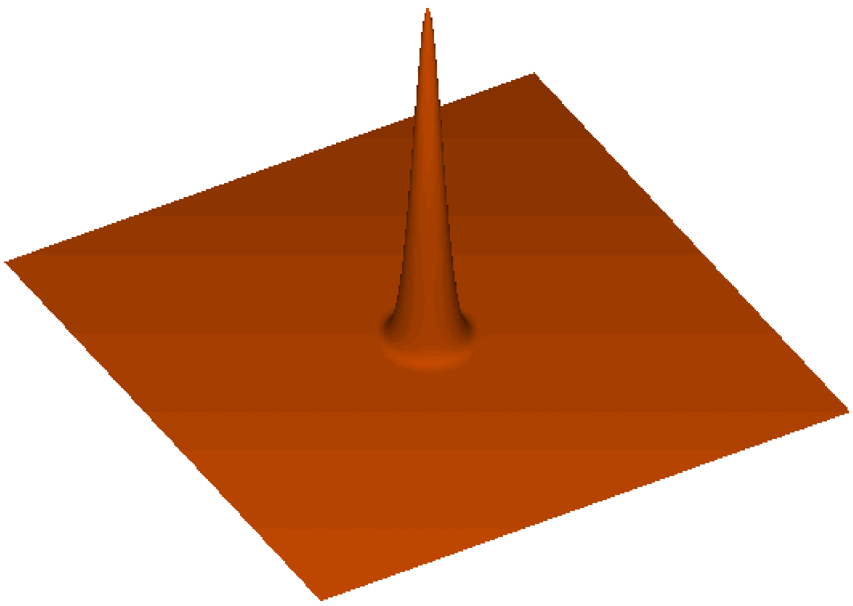


Baryon Acoustic Oscillations

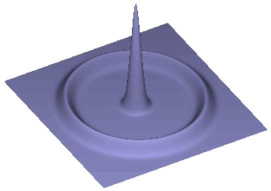
• Before recombination, sound waves propagate in the universe.

• Acoustic oscillations are seen in the CMB
Look for the the same waves in the galaxy correlations.

• Typical CMB fluctuations are ~10^{-5}...
... expect 1% signal today in galaxy correlations

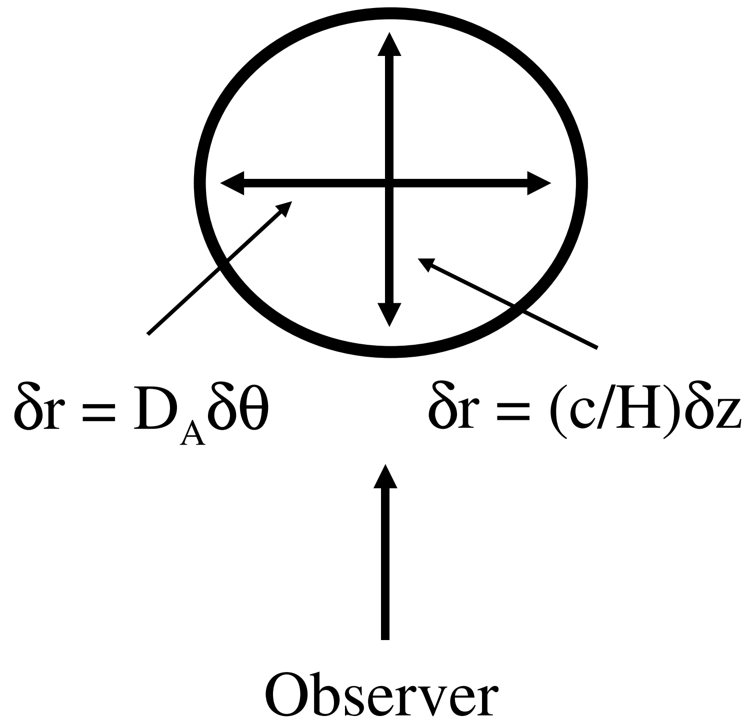


propagation of a fluctuation from BB to recombination



A Standard Ruler

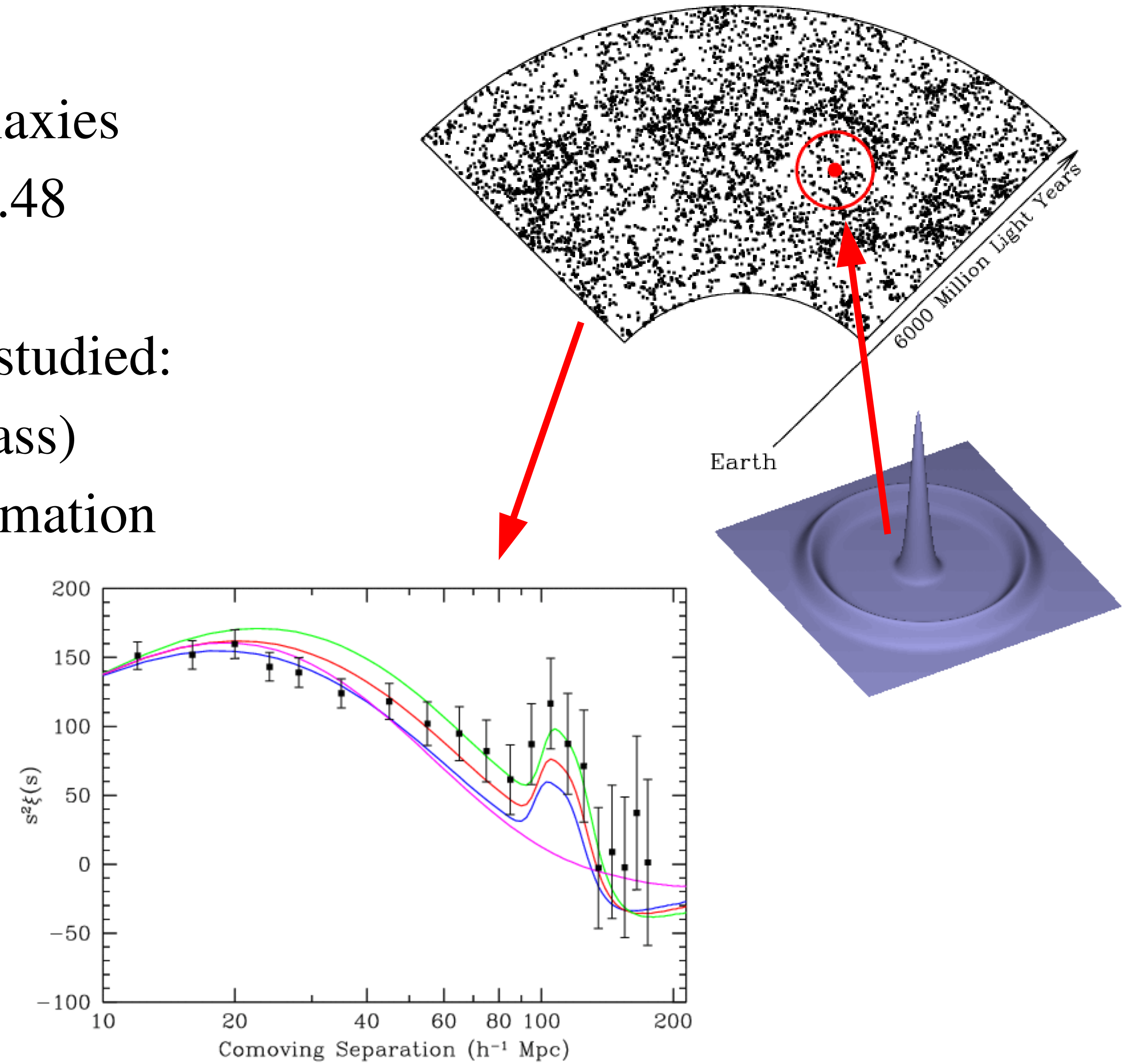
- The acoustic oscillation scale depends on the sound speed and the propagation time.
  - These depend on the matter-to-radiation ratio ($\Omega_m h^2$) and the baryon-to-photon ratio ($\Omega_b h^2$).
- The CMB anisotropies measure these and fix the oscillation scale.
- In a spectroscopic galaxy redshift survey, we can measure this along and across the line of sight.
- Yields $H(z)$ and $D_A(z)$!



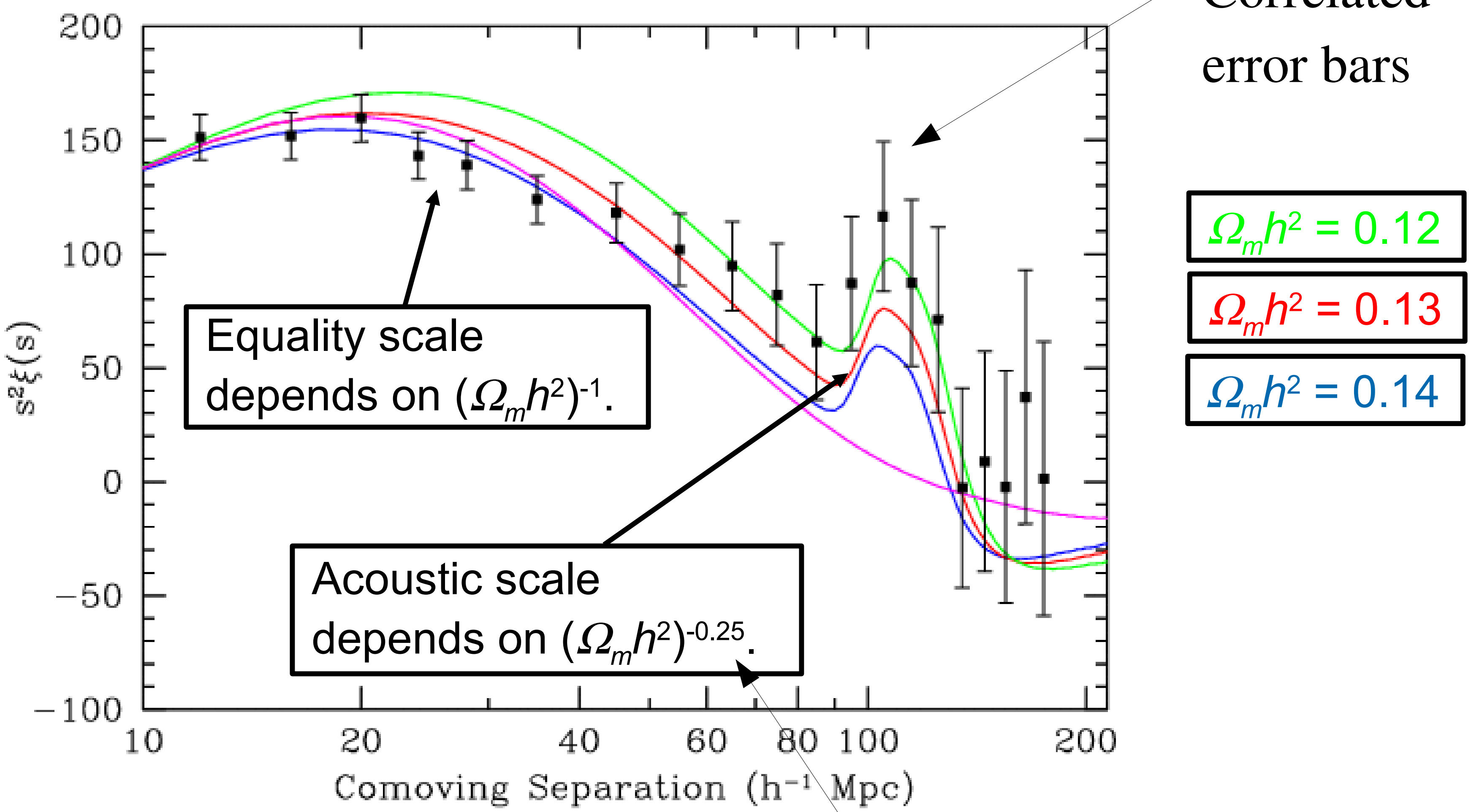
Detection in the SDSS

(D.Eisenstein et al [SDSS Collab.] 2005)

- 55000 Luminous Red Galaxies
- Over 4000 deg^2 up to z~0.48
- <z> = 0.35
- Sources of bias carefully studied:
  - galaxy bias (light vs mass)
  - non-linear structure formation
  - redshift distortions

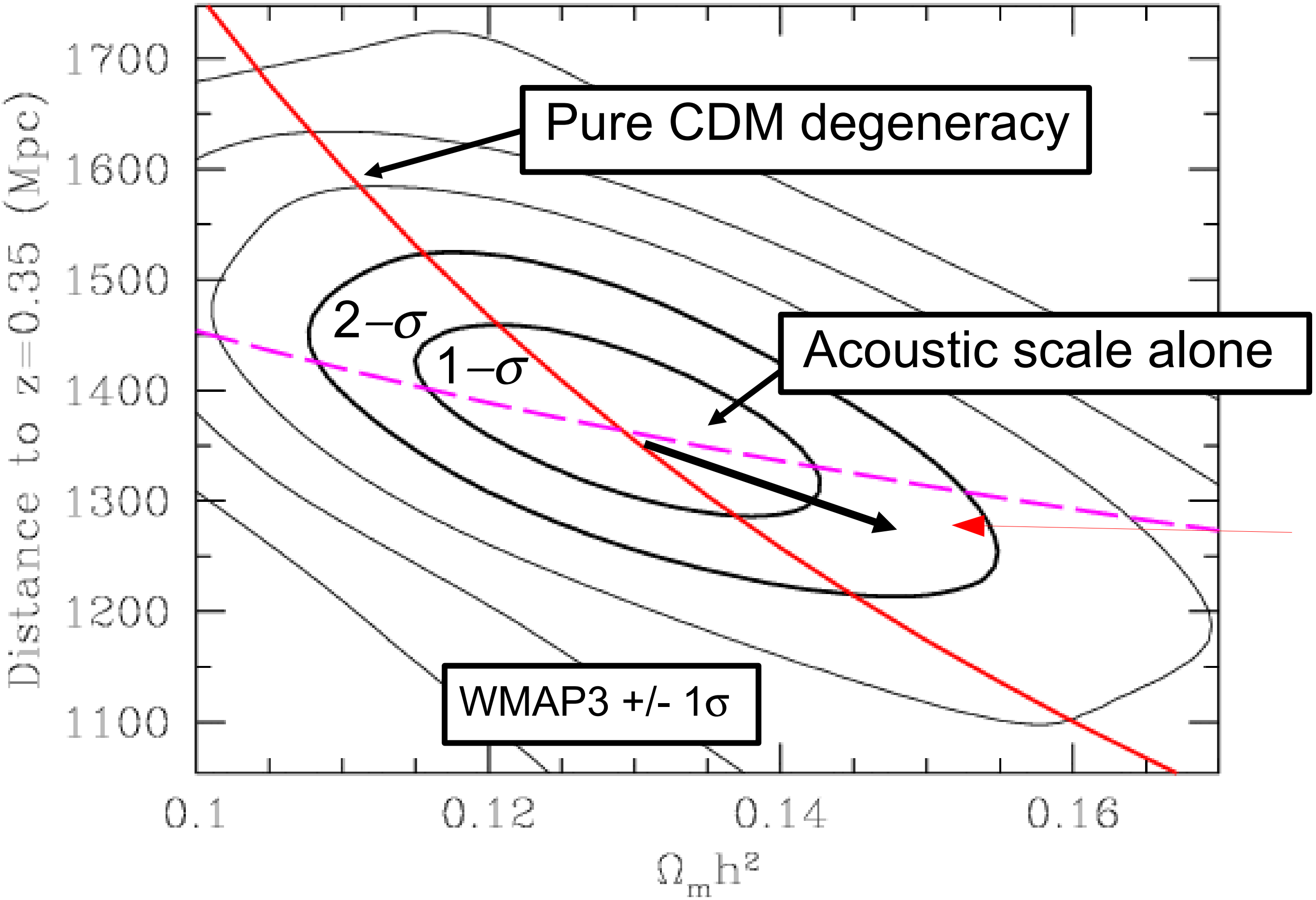


Two Scales in Action



not a consequence of first principles
See Hu, 0407158

Cosmological Constraints



The uncertainty in $\Omega_m h^2$ makes it better to measure $(\Omega_m h^2)^{1/2} D$. This is independent of H_0.

$$\Omega_m = 0.273 \pm 0.025 + 0.123(1+w_0) + 0.137\Omega_K.$$

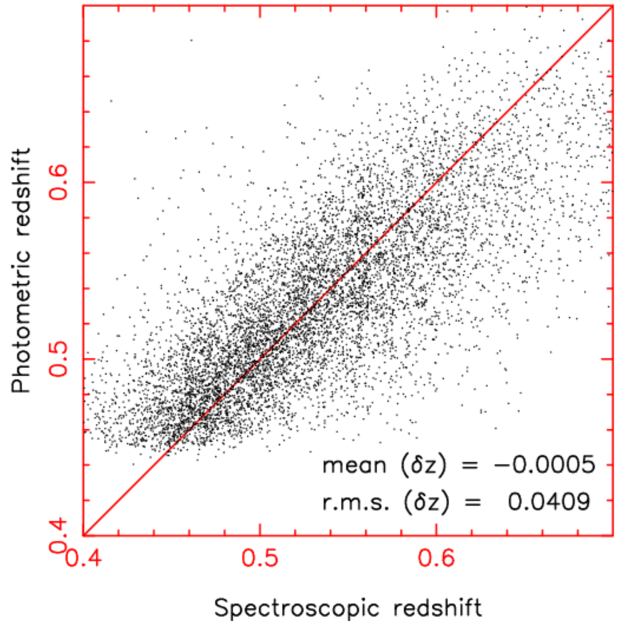
Eisenstein et al [SDSS], ApJ (2005) (astro-ph/0501171)

BAO : future

- SDSS is currently doubling its surveyed area (4000->8000 deg^2)
- The BOSS project : reach z ~ =0.8 over 10 000 deg^2 (2011?)
- The AAOmega project: reach z=0.7 over 3000 deg^2 (running)
- Next generation typically requires :
  - 8m-class telescope
  - wide-field spectrograph (~2 deg FOV)
  - Get ~5000 spectra in a single shoot
  - No project approved yet....
- What about BAO using photometric redshifts?

BAO with photometric redshifts

astro-ph/0605303 : 600 000 Luminous Red Galaxies from SDSS at 0.4<z<0.7, using photo-z (see also 0605302: same data, different analysis)

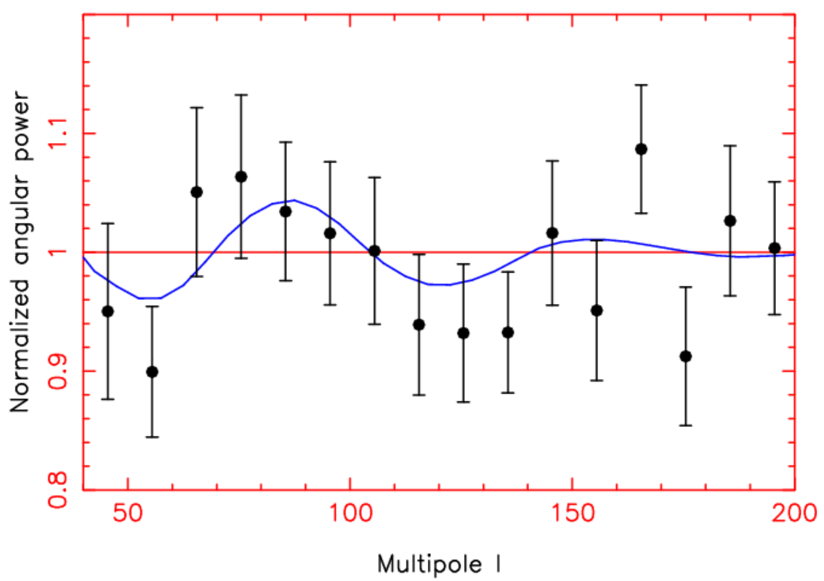


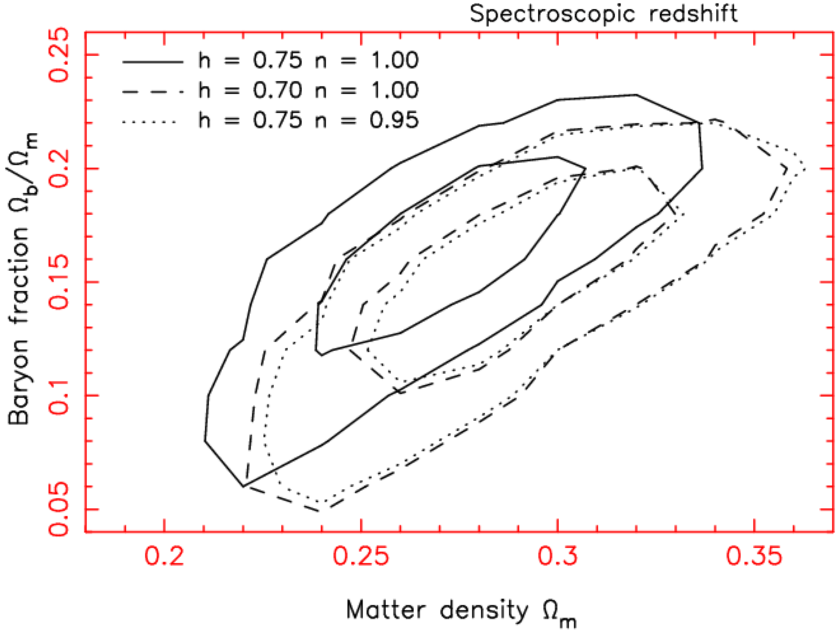
-> ~ < 3 sigma detection of BAOs

-> comparable to Eisenstein et al (2005)

-> 10 photo-z ~ 1 spectroscopic z

-> ..... and we just loose H(z)



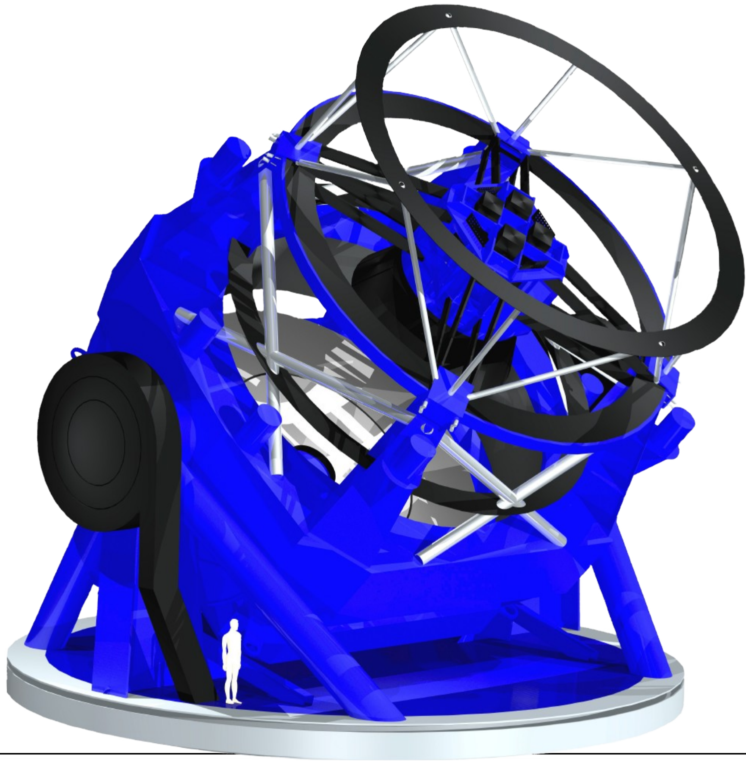


Wide field imaging projects

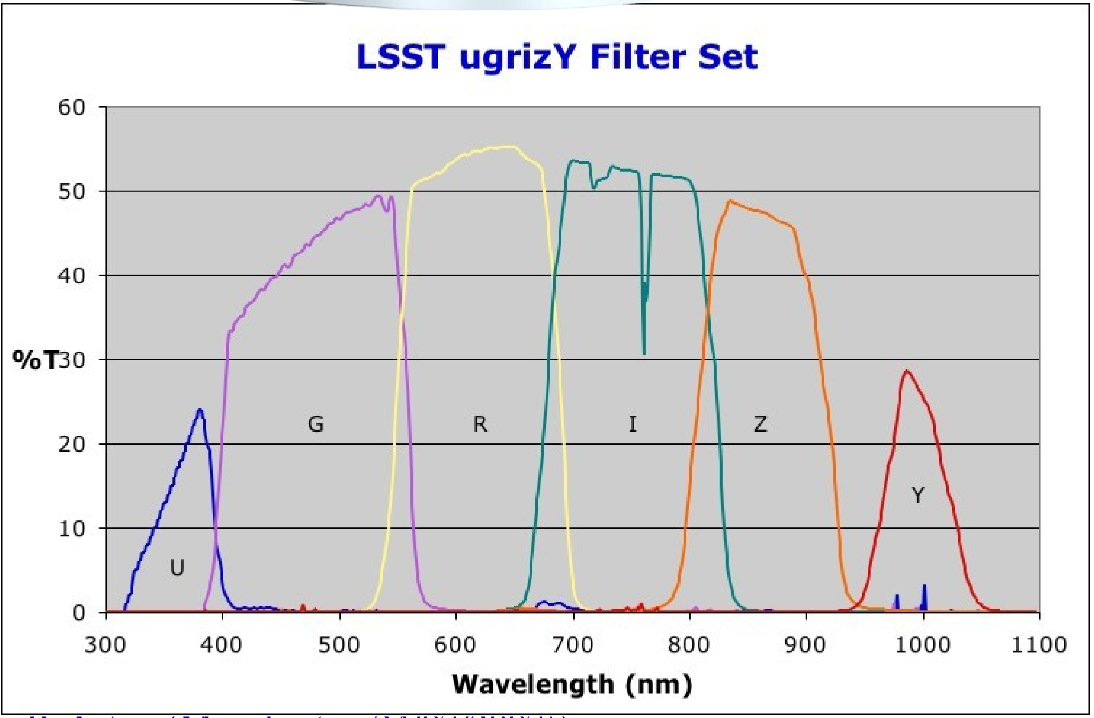
	FOV	diameter	first light	status	who/where
VST @ ESO	1 deg2	2.6 m	2008	funded	ESO/Paranal
DARKCam	2 deg2	3.6 m	??	refused at ESO	UK+...
HyperSuprimeCam	2-3 deg2	8 m	2012	~funded	Japan/Subaru
Dark Energy Survey	2 deg2	CTIO-4m	2012	~funded	Fermilab/CTIO
Pan StarsS	7 deg2	1.8 m	2007	funded	Univ. Hawaii
Pan StarsS 4	7 deg2	1.8 m x 4	2009 (+)	not funded	Univ. Hawaii
LSST	10 deg2	8 m	2014	not funded	DOE/NSF
SNAP	0.7 deg2	2 m	2017(+)	competing	DOE/NASA
DUNE	~1 deg2	1.2 m	2017(+)	competing	ESA

- Can target all DE probes : WL, SNe, BAOs, galaxy clusters
- Ground based : visible From space : near IR (+visible)

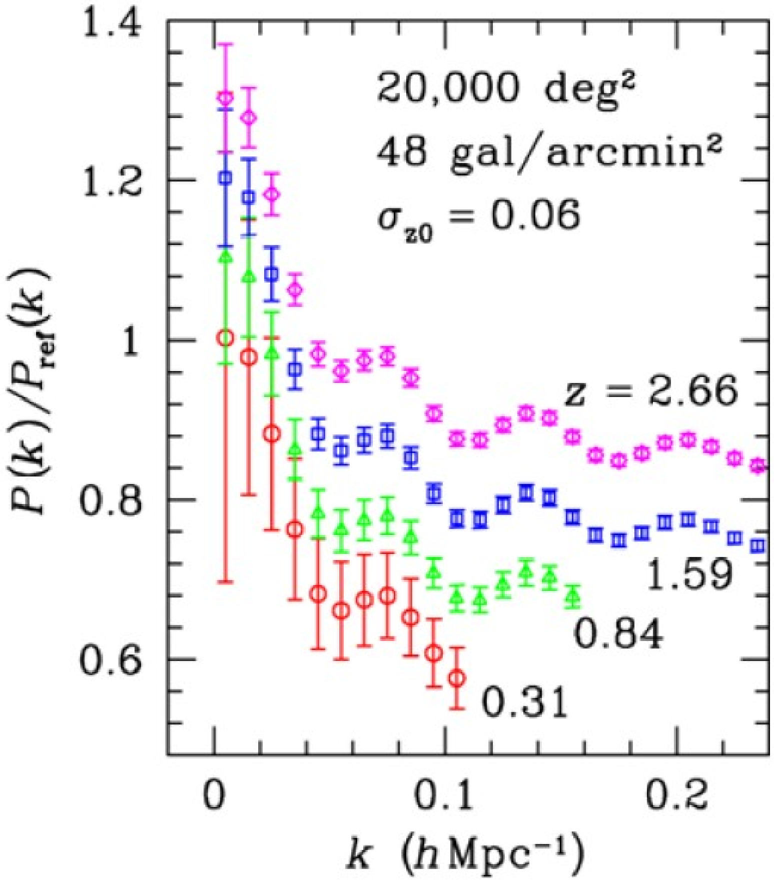
LSST concept



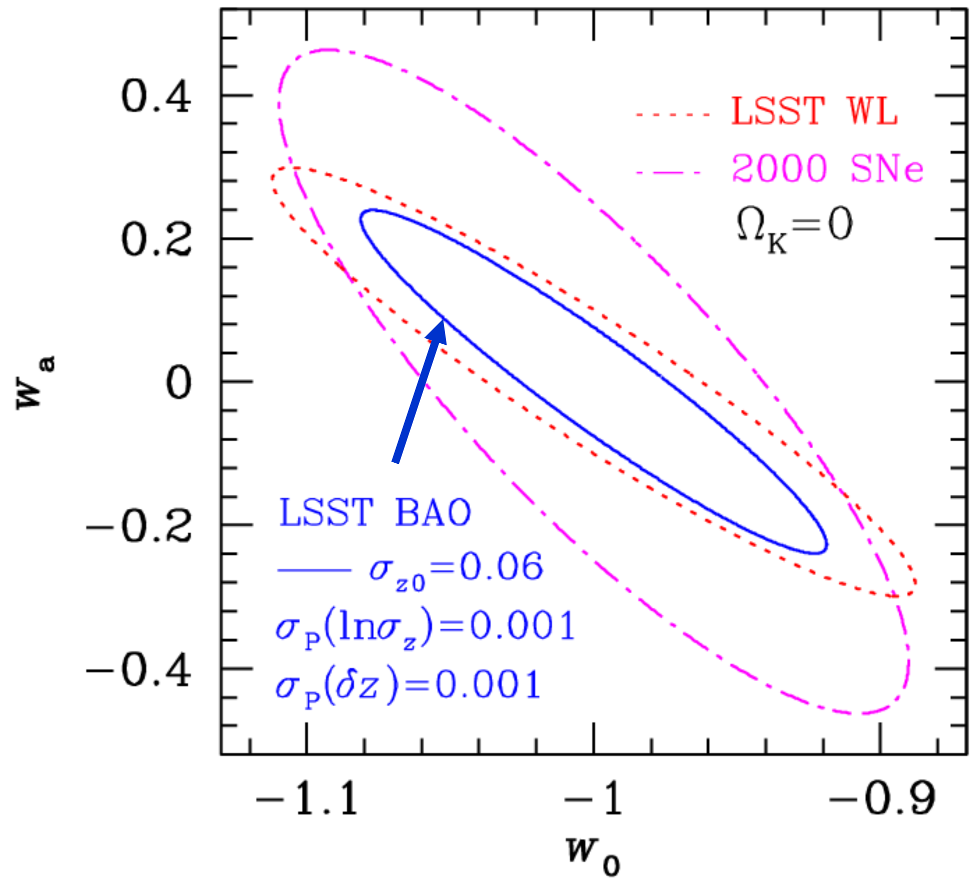
- Primary mirror :~ 8m
- Single instrument : imager
- with Field Of View~ 10 deg^2
- 6 bands from 330 to 1050 nm.
- Visits the whole dark sky
  in 2 bands within less than a week
- 20 Tb/night
- Science:
  - DM & DE through lensing
  - SNe, BAO
  - .....
- First light anticipated in 2014



LSST forecast : BAO Power Spectra



Two-dimensions on the sky.
3 billion galaxies.

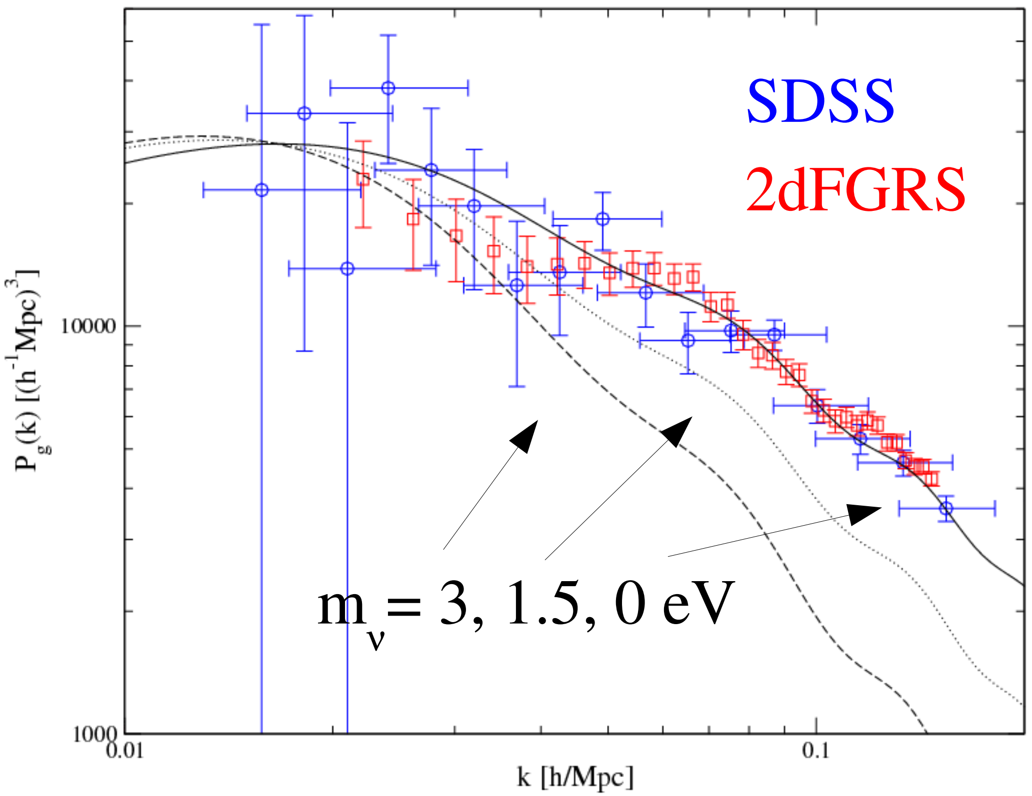


Combination yields accuracy ~ 2 % on constant w

Neutrino mass(es) from telescopes

Neutrino number density is known precisely from CMB temperature
-> m_ν translates to a physical density.

- Since neutrinos are light, they slow down the growth of structures on small scales (large k).
-> Impact correlations of galaxies



Neutrino mass(es) : limits

No positive detection yet, only upper limits.

Strongly dependent on the allowed parameter space and data samples

astro-ph/0602155 :

CMB, LSS, BAO and SNIa , reasonably open parameter space

---> $m_\nu < 0.62$ eV (95 % CL)

astro-ph /0604335:

CMB, LSS,BAO, SNIa and Ly alpha , narrower parameter space:

---> $m_\nu < 0.17$ eV (95 % CL)

Neutrino mass(es) : outlook

Weaknesses of this approach to neutrino mass detection:

(1) There are interesting degeneracies :
e.g: dark energy equation of state ~~is~~ was degenenerate with m_ν

(2) We now have to use a lot of probes to lift degeneracies
systematic uncertainties of probes are mainly ignored

(3) We measure galaxy correlations, we compute matter correlations
(general problem referred to as the bias)

==> Expecting simpler and safer analyses using matter power spectrum
measured via lensing (weak shear or CMB lensing)

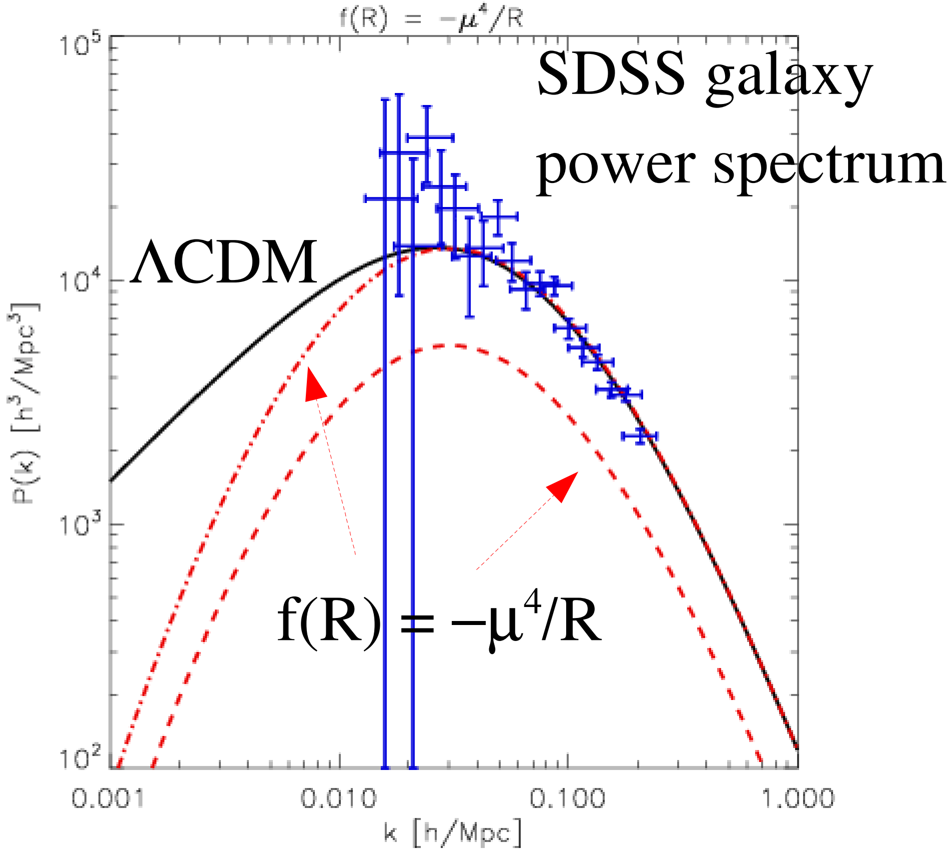
Modified gravity : non-minimal couplings

(R. Bean & al astro-ph/0611321)

$$S = \frac{1}{2\kappa^2}\int d^4x\sqrt{-g}\,[R + f(R)] + \int d^4x\sqrt{-g}\,\mathcal{L}_{\rm m}[\chi_i, g_{\mu\nu}]$$

Choose f so that it only impacts on large scales and preserves small scales

-> Cannot get CMB and galaxies power spectra with the observed ratio (as in ΛCDM)

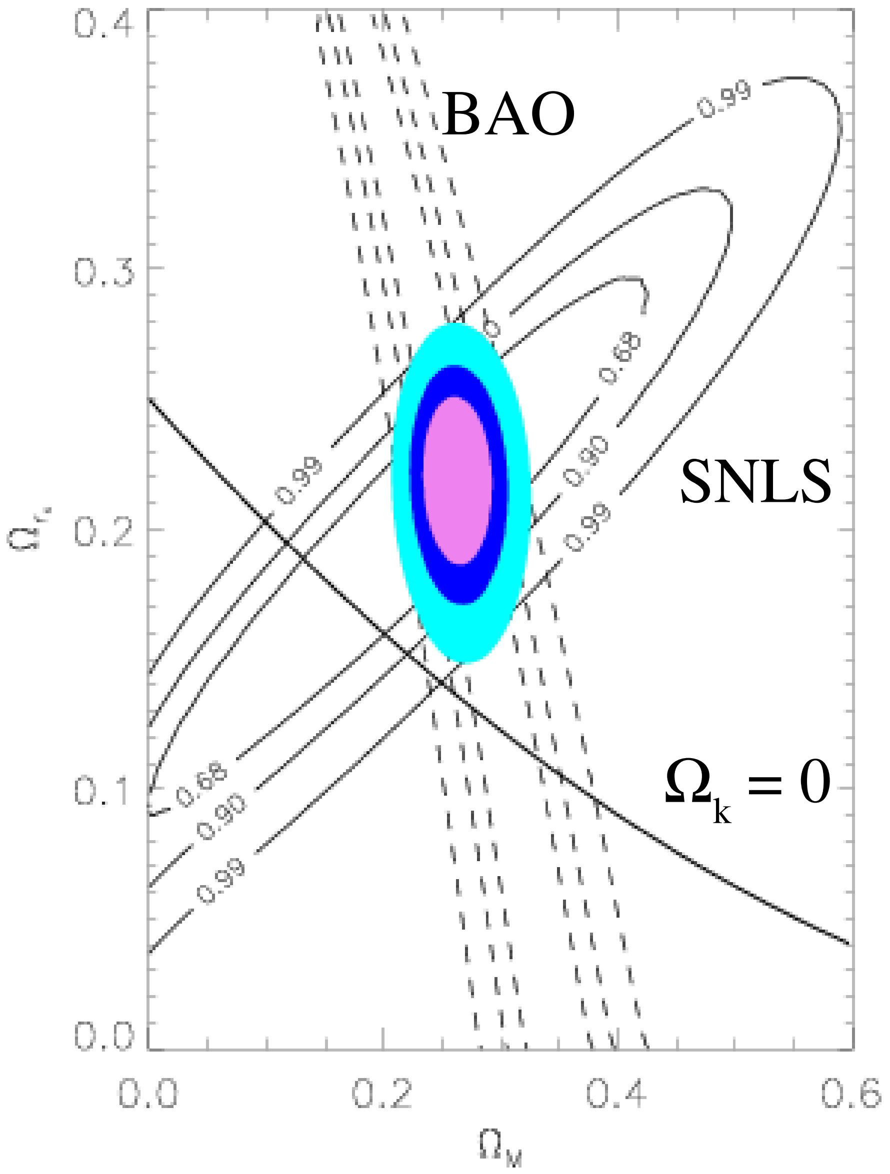


Extra dimension(s)

DGP model of 5D gravity :
(3+1)D brane in a (4+1)D bulk.

At odds with recent constraints assuming a flat universe.

Fairnbairn & Goobar (astro-ph/0511029)



Conclusions/summary

- Dark Energy looks like a cosmological constant:
  - w = ~ -1 +/- 0.09 (down to 0.07 using SNe, BAO, CMB)
  - improvements down to 0.05 are expected within ~ 2 years
  - drastic improvements will come from wide field imaging facilities ground- or space- based.

- Expected data for the coming years:
  - First results from second round spectroscopic BAO (AAOmega)
  - Final results from the CFHTLS weak shear analysis
  - Final results from the SNLS
  - Planck maps and power spectra
  - ....