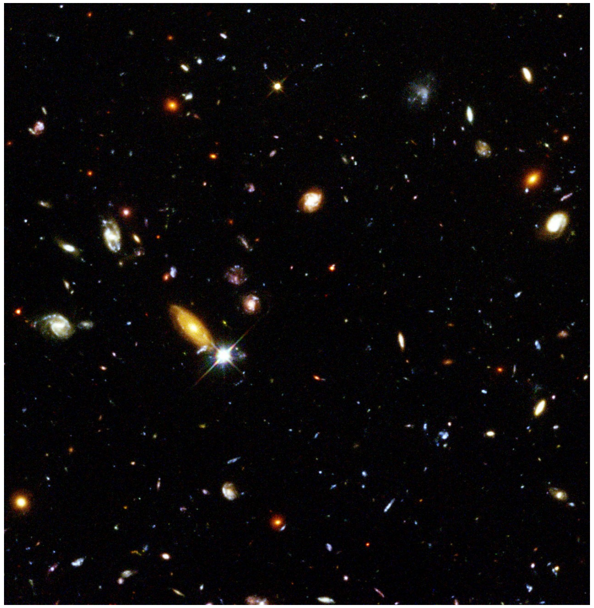
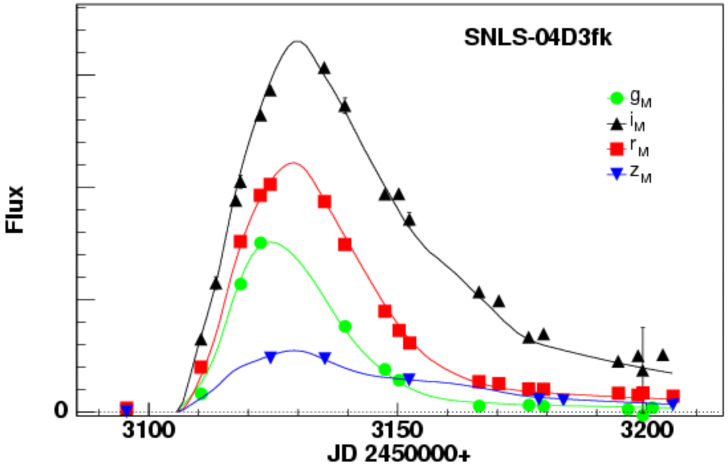
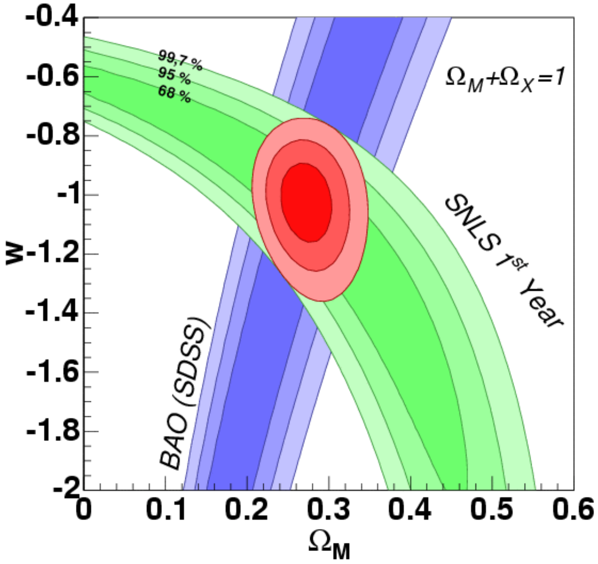
Dark Energy Observations







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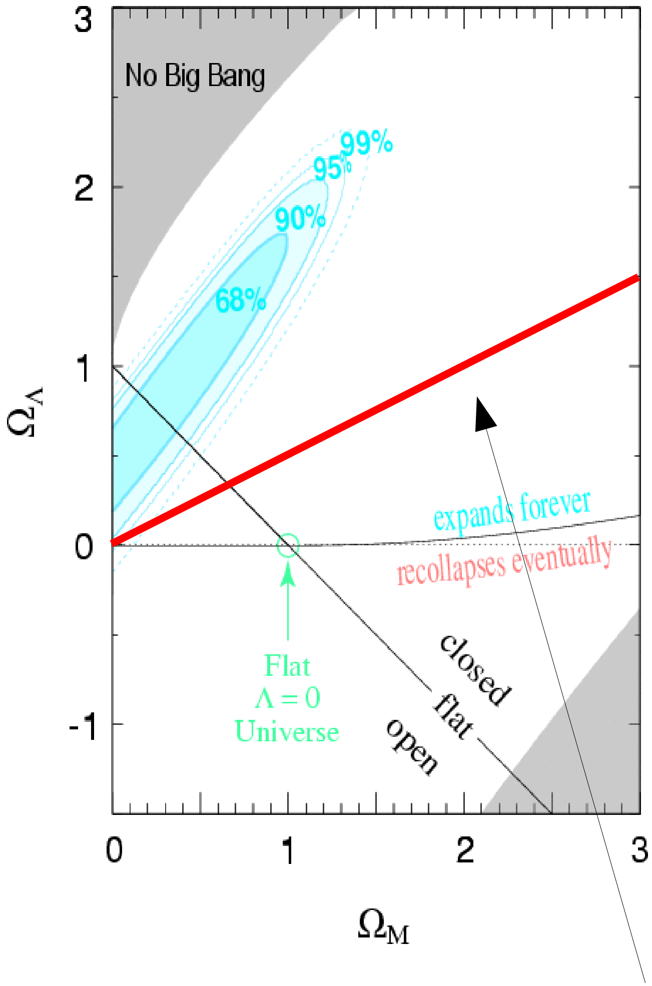
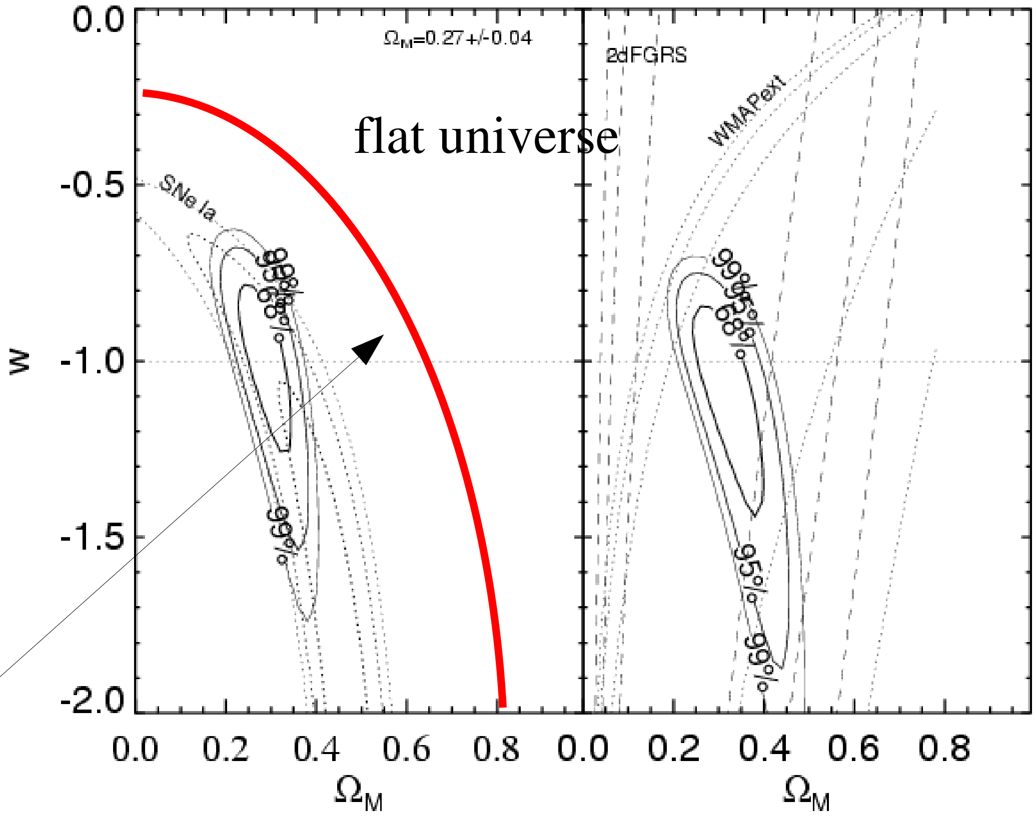
Ecole Chalonge
« Physics of the Universe
confronts observations »

Dark Energy : history

Distances to type Ia supernovae strongly favor a recent accelerated expansion of the Universe



Knop et al 2003



flat universe

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

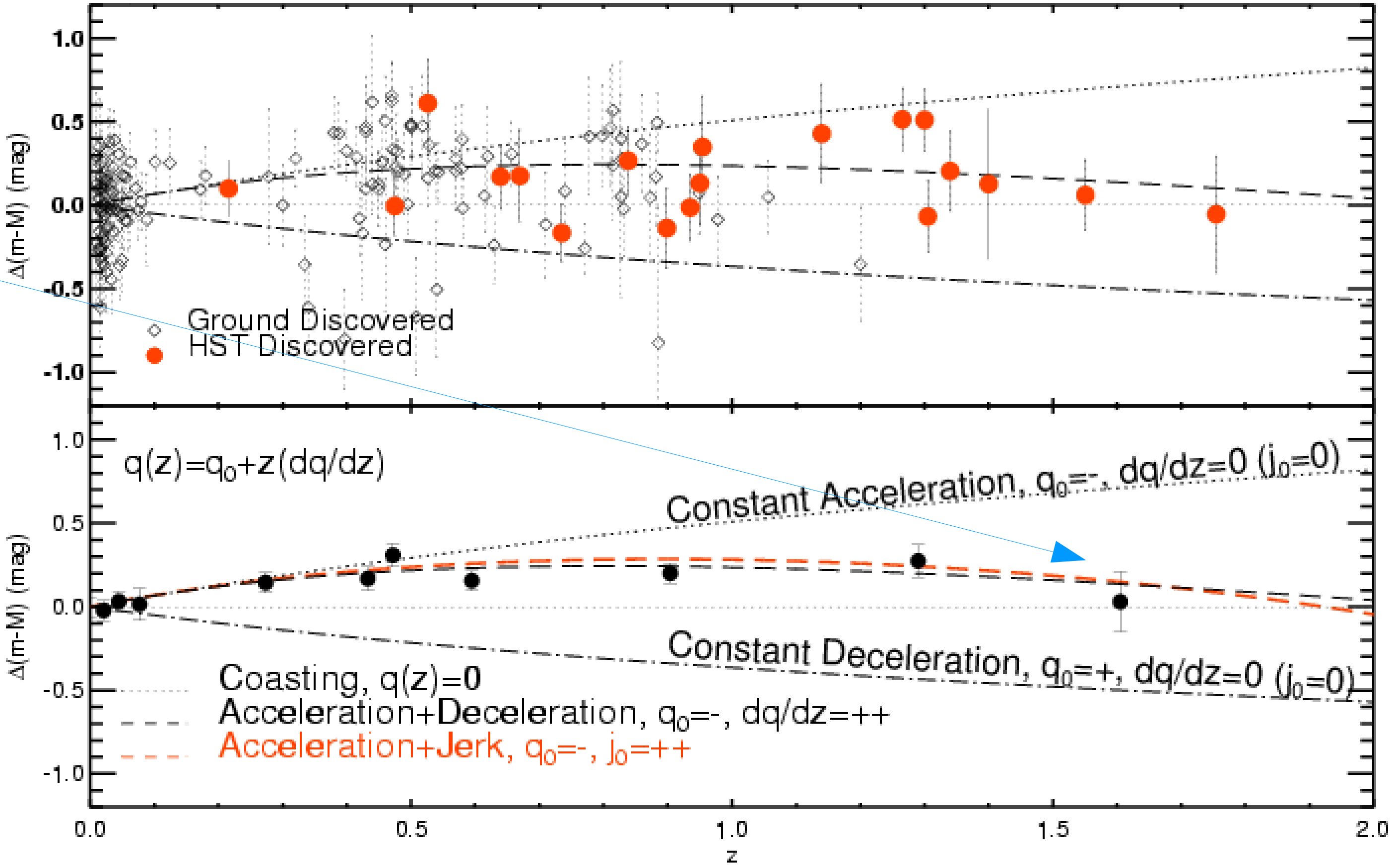
Riess et al 2004

Acceleration ?

We need a recent acceleration, but only recent.

The expansion was decelerating in the past:

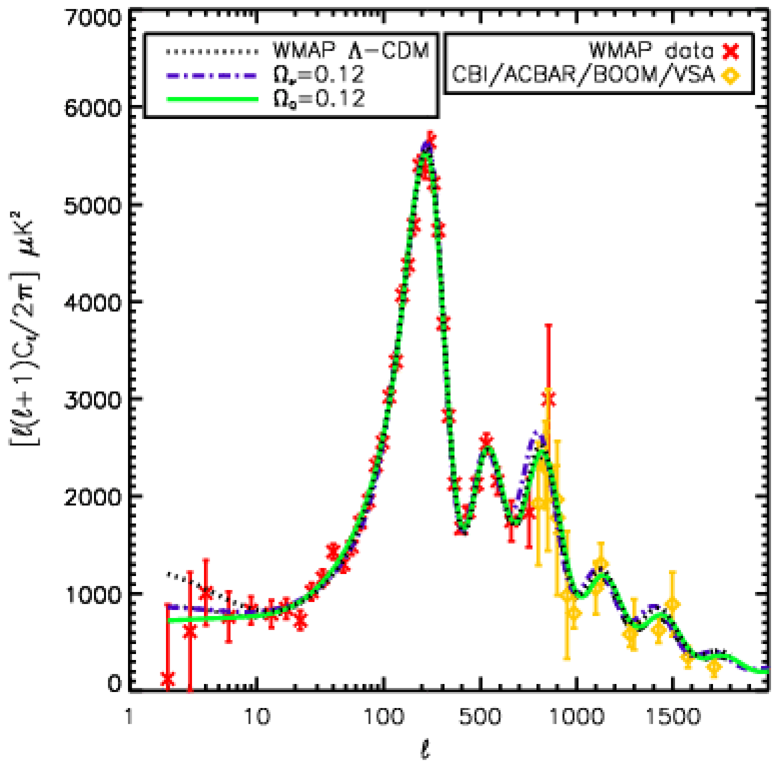
Λ does the job.



SNe Ia, Riess et al, 2004

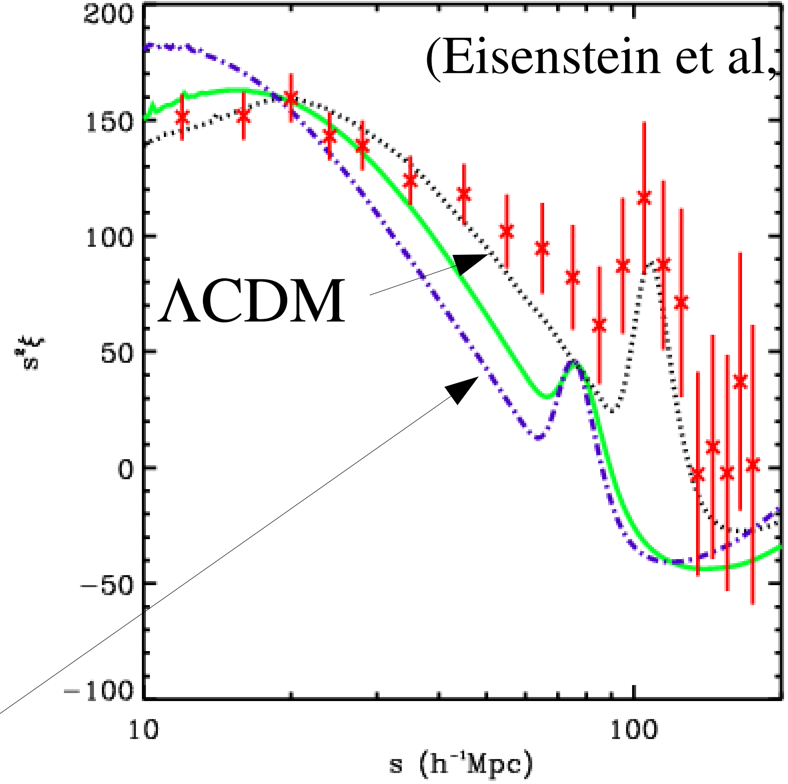
Do we really need Dark Energy ?

NO



YES

SDSS LRG
correlation function
(Eisenstein et al, 2005)



ΛCDM

Blanchard et al 2003,
$\Omega_M = 0.88$, Ω_v=0.12, $H_0 = 46$
SNe ignored.

Blanchard et al 2005,
cannot accommodate
Λ=0 with baryon acoustic peak.

$\Omega_{DE}(z)$

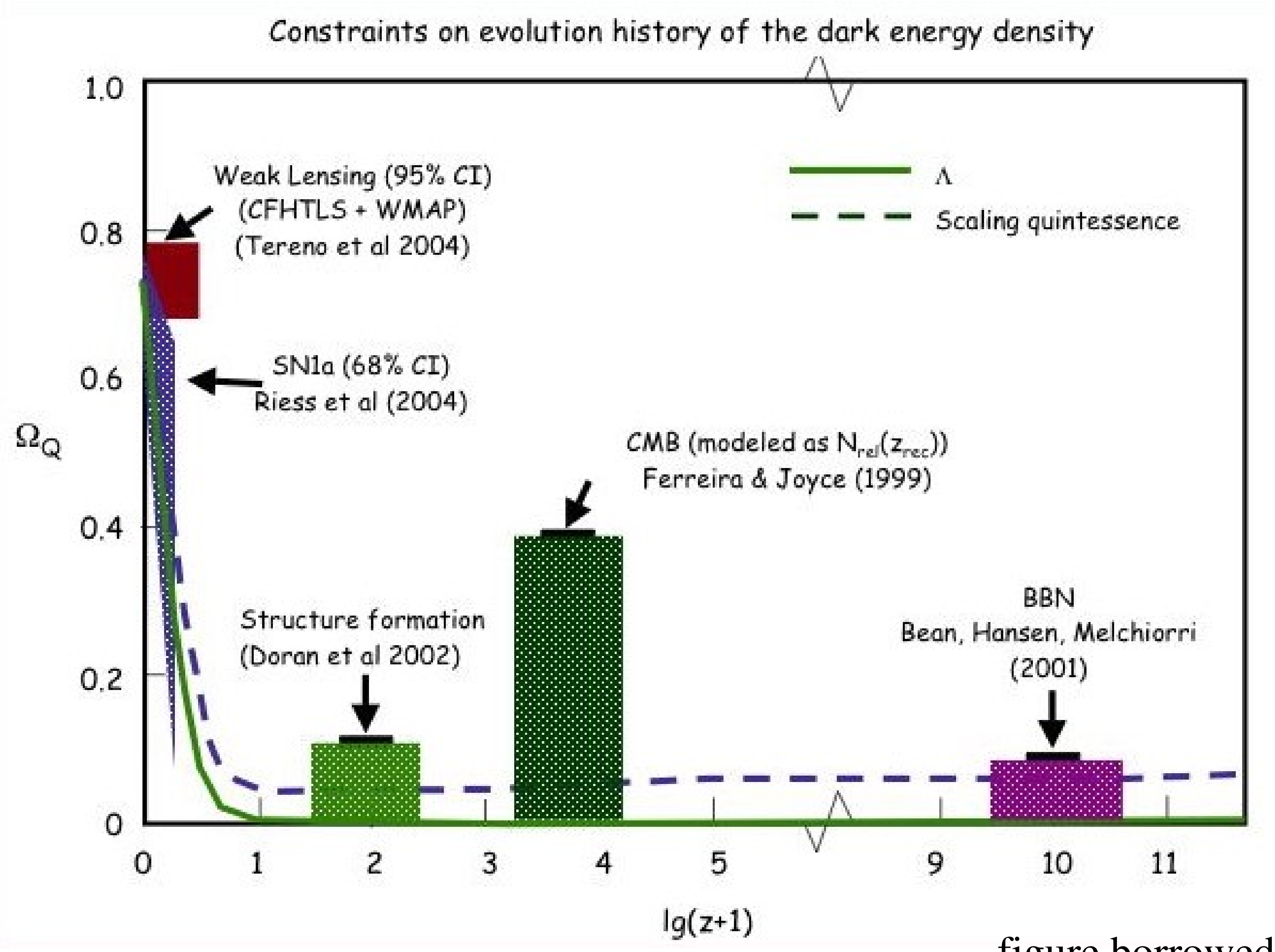
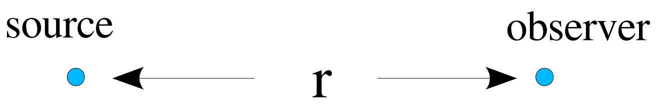


figure borrowed from R. Bean

Distances and cosmological parameters



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

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.,

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

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

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

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

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 from fits of r(z)

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

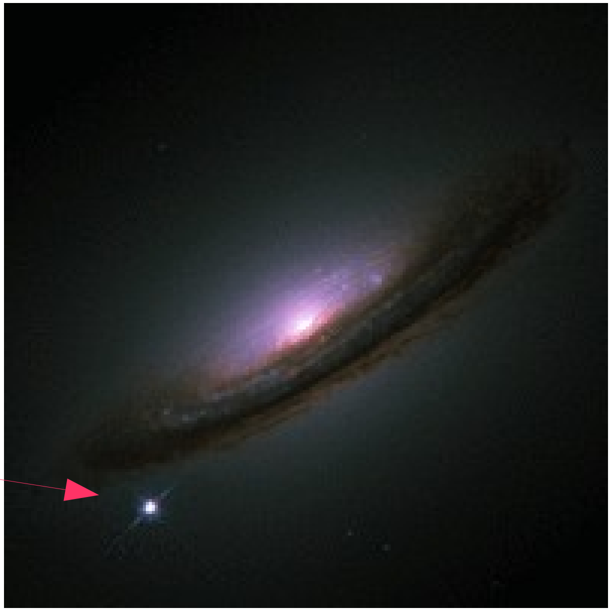
Observing Dark Energy(!)

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

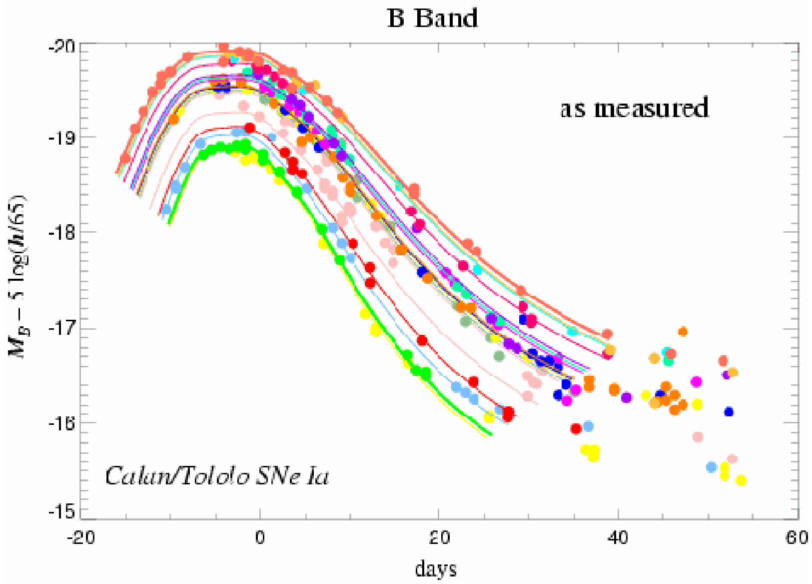
Particularly sensitive methods (for $z < \sim 1$):	measures combinations of
- **Supernovae Ia** Optical (and IR) telescopes, imaging and spectroscopy Figure of merit : number of SNe, z span	$r(z)$
- **Weak gravitational shear** Optical telescopes, imaging Figure of merit : surveyed area on the sky (up to $z\sim 1$)	$r(z)$ $r(z_{lens},z_{source})$ $P(k;z)$
- **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})

Supernovae Ia

Thermonuclear explosions of stars
which appear to be reproducible

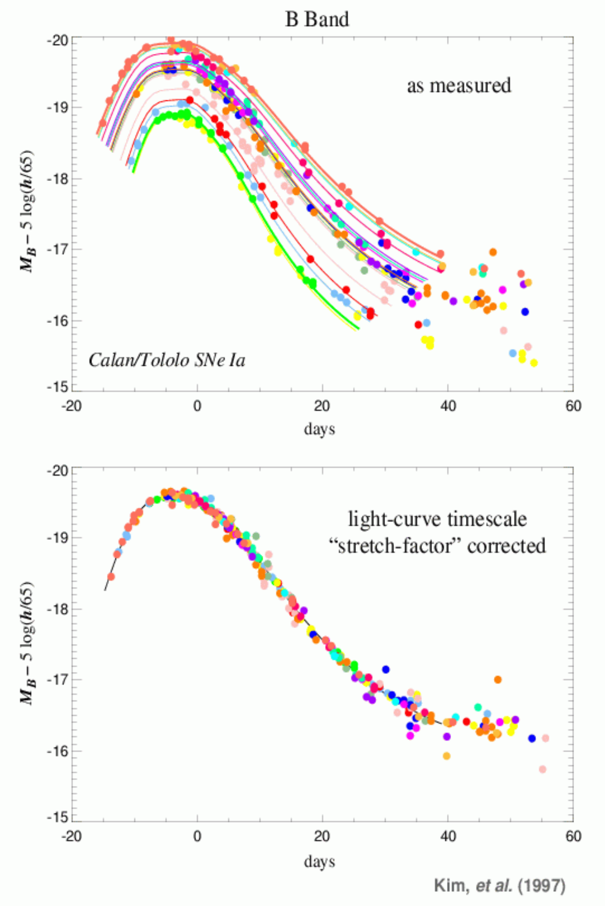


- Very luminous
- Can be identified (spectroscopy)
- Transient
  (rise ~ 20 days)
- Scarce (~1 /galaxy/millenium)
- Fluctuations of the peak
  luminosity : 40 %
- Can be improved to ~14 %

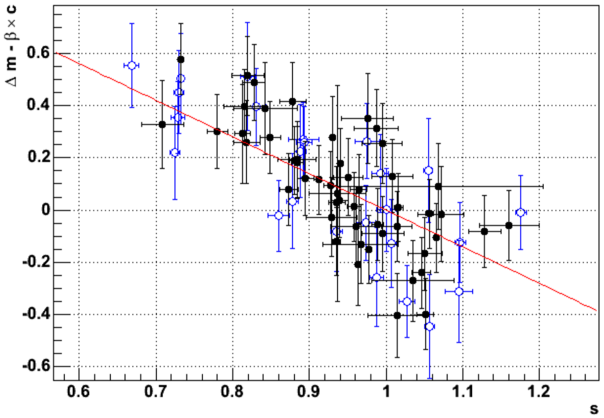


Intrinsic luminosity indicators (for Ia's)

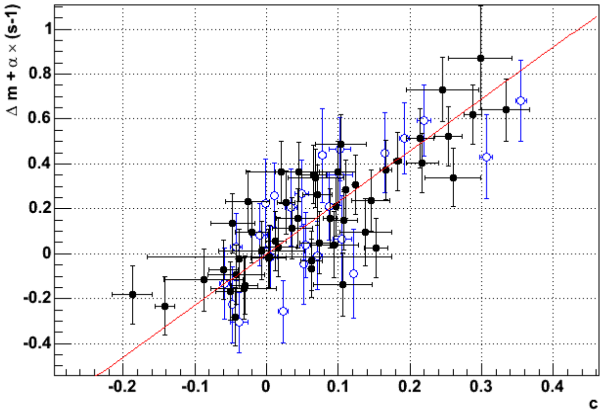
Brighter - slower



Kim, *et al.* (1997)



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 (e.g B-V)

(rest frame) at peak.

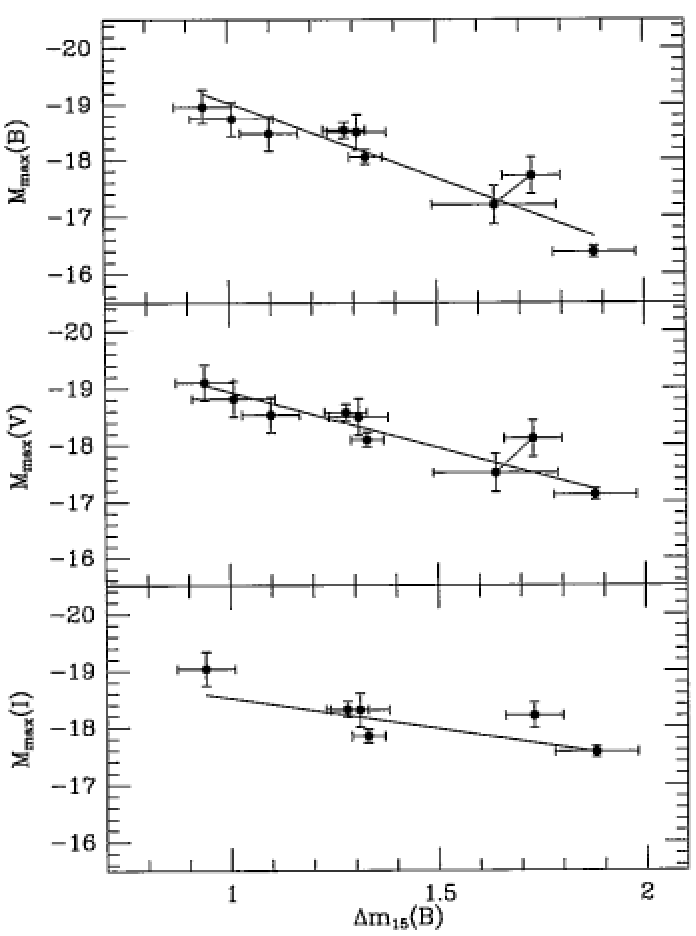
Color = Log(flux(V)/flux(B))

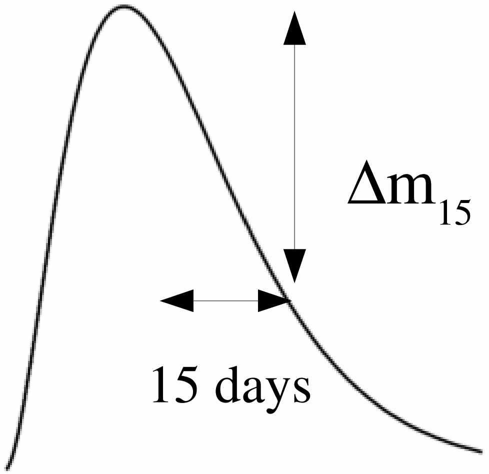
B ~ [400,500] nm

V ~ [500,650] nm

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

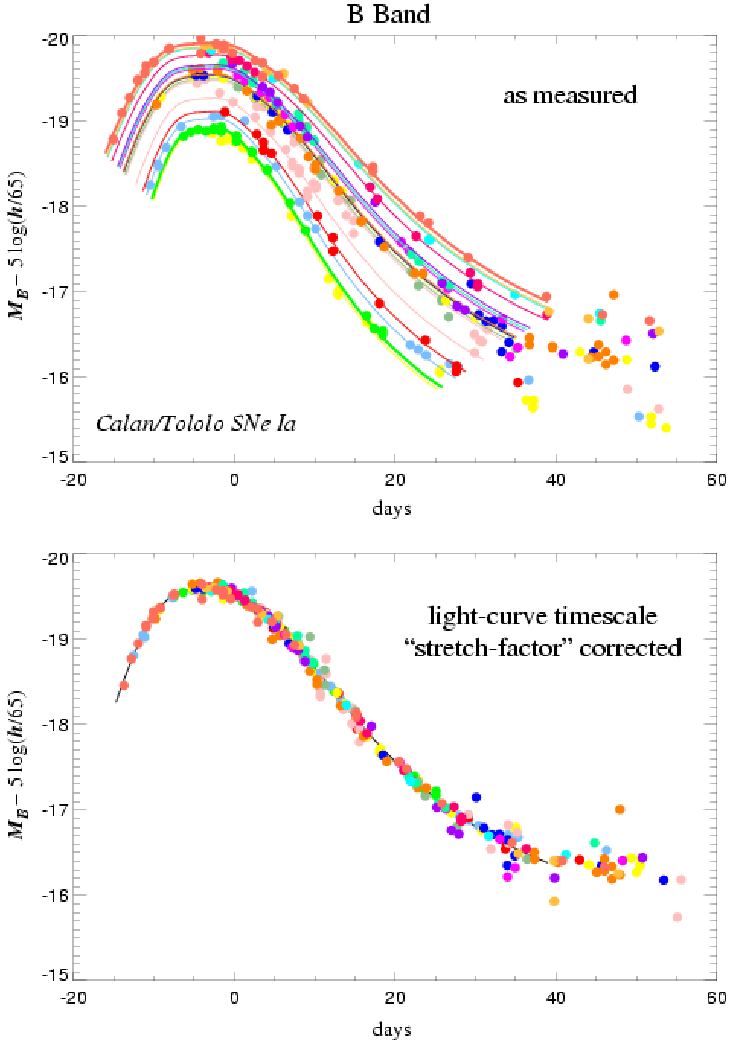
Brighter-Slower





Δm_{15}

15 days

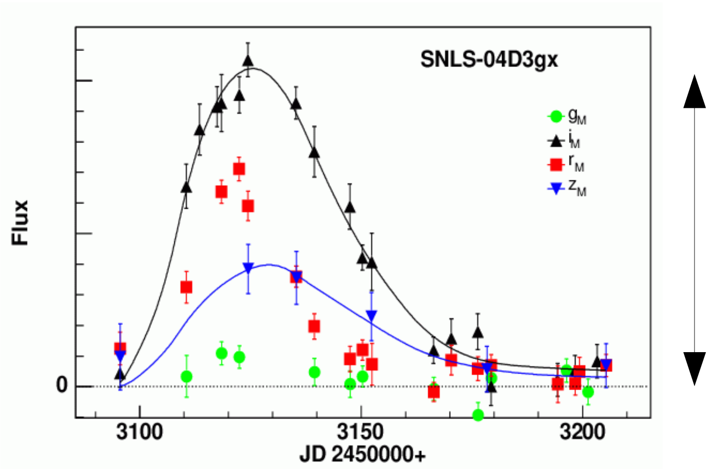


Kim, *et al.* (1997)

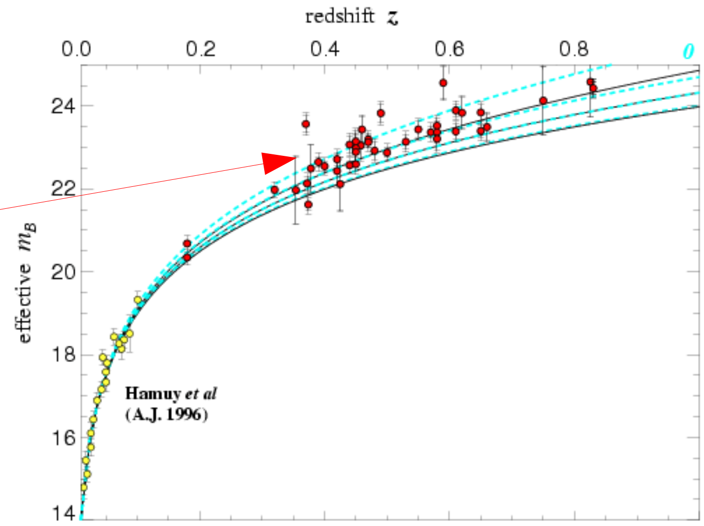
Δm_{15} : Phillips (1993)

Timescale stretch factor

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

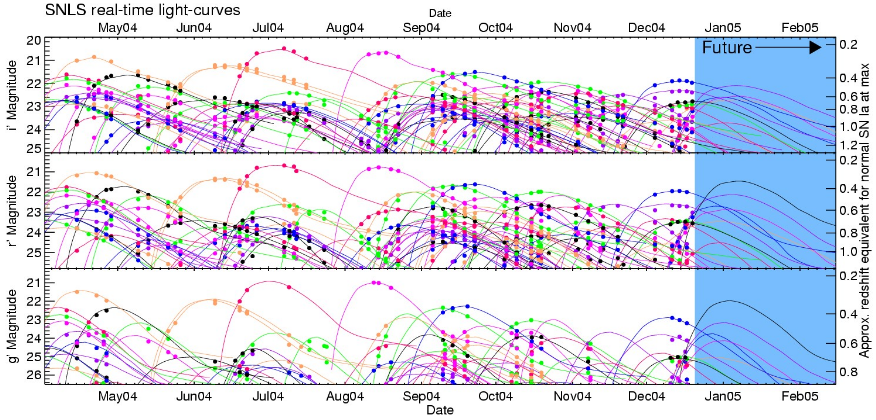
Old observing way is a many-step process:

- 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



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Rolling search mode:

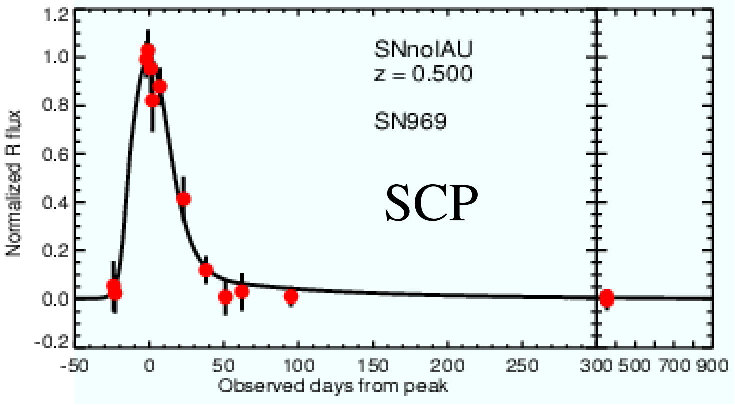
- Repeated imaging of the same fields
- Spectroscopy near peak
- Built-in photometric follow-up

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
- .....

SNe Ia surveys: from workshops to factories (2)

Rolling search is THE way to go for SNe surveys



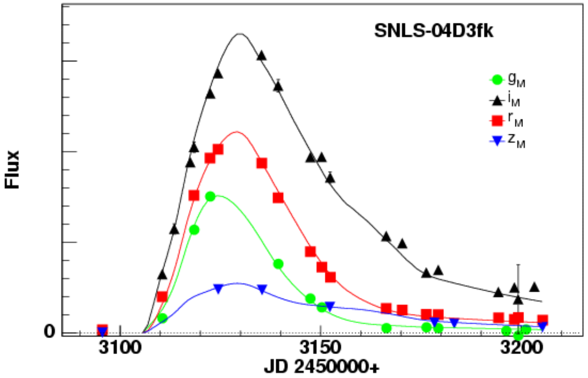
Three ongoing projects:

- 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 (!!)

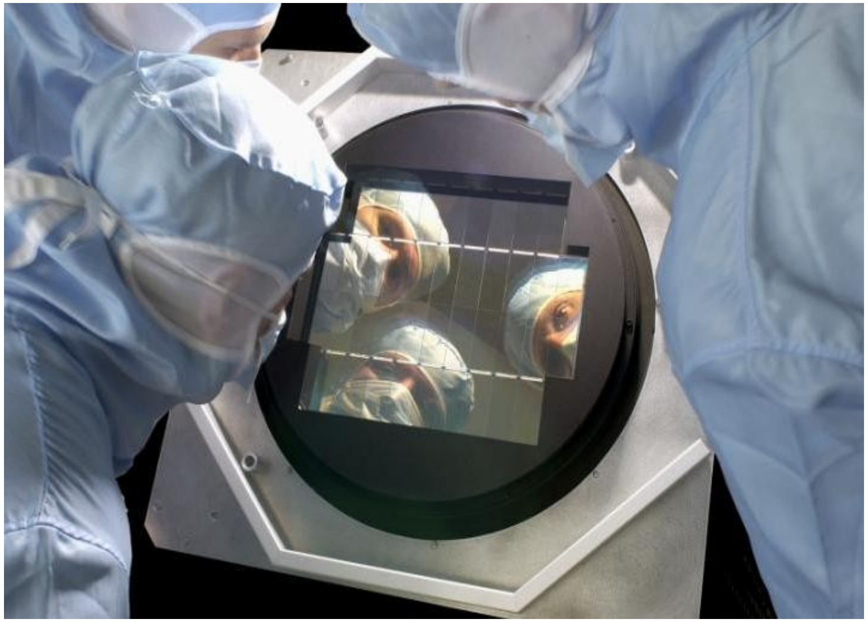
- VLT (Europe 120 h/y), Gemini (US/UK/Can 120 h/y), Keck (US 30 h/y).

http://snls.in2p3.fr

MegaCam at CFHT

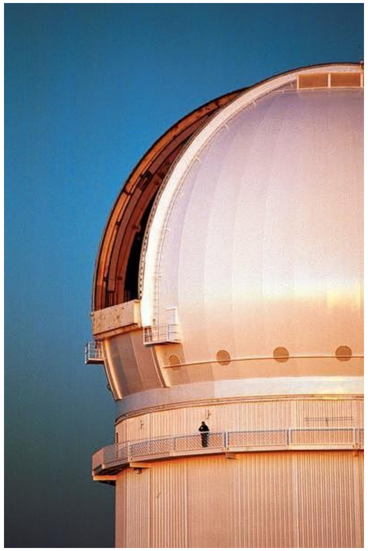
MegaCam:

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



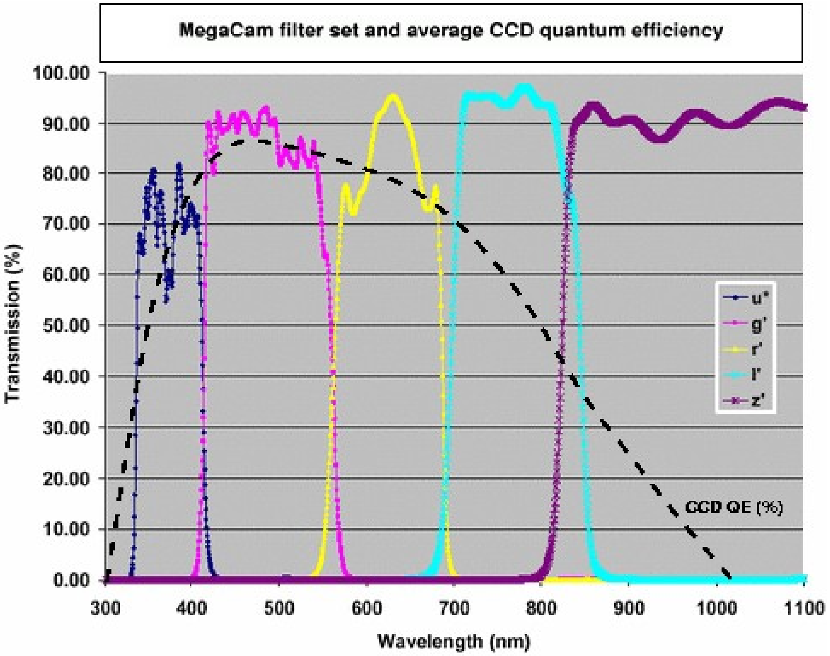
CFHT:

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



CFHTLS/Deep : Observing mode

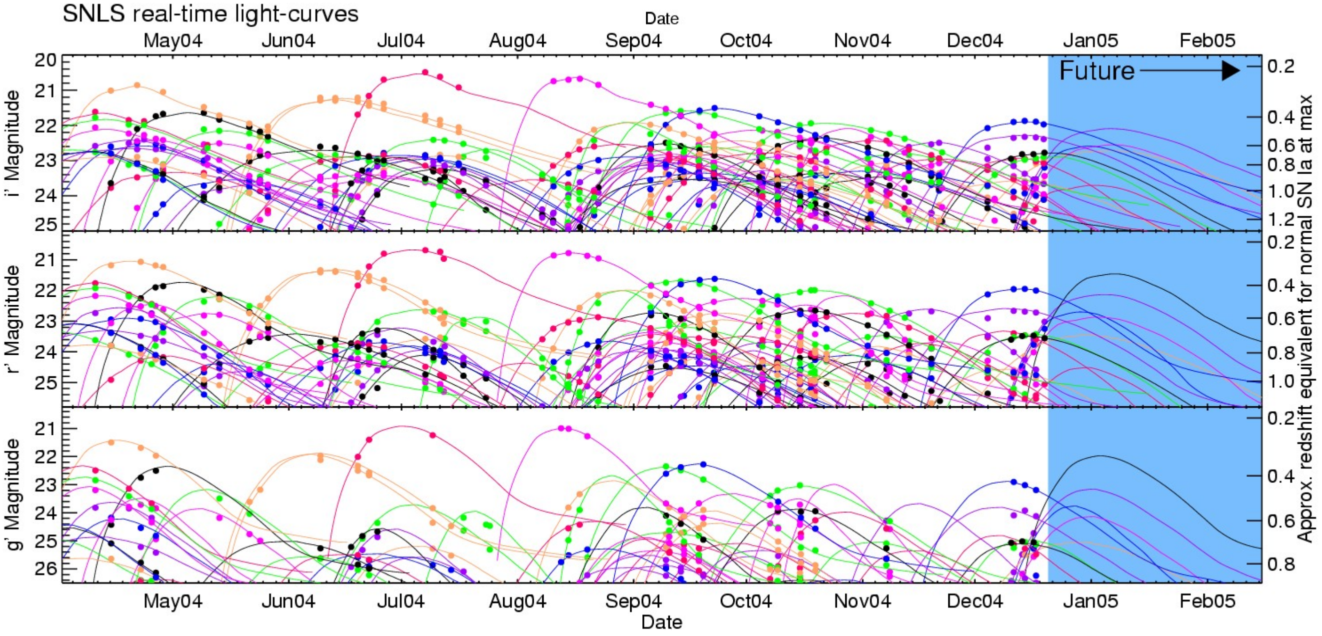
- 40 nights/year for 5 years.
- Repeated observations every ~4 night ("rolling search"), service mode
- 4 bands g,r,i,z
- 4 one deg^2 fields monitored ~ 6 month/year



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

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

-> Repeated calibration of field stars



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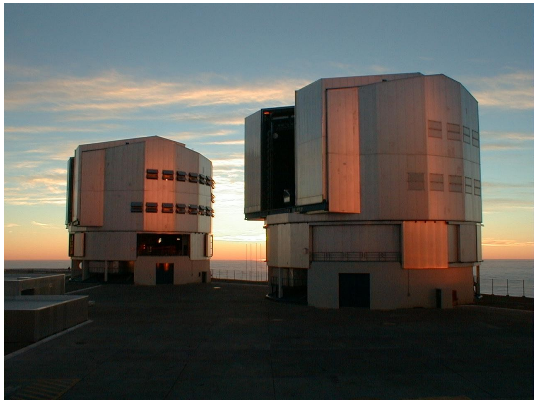
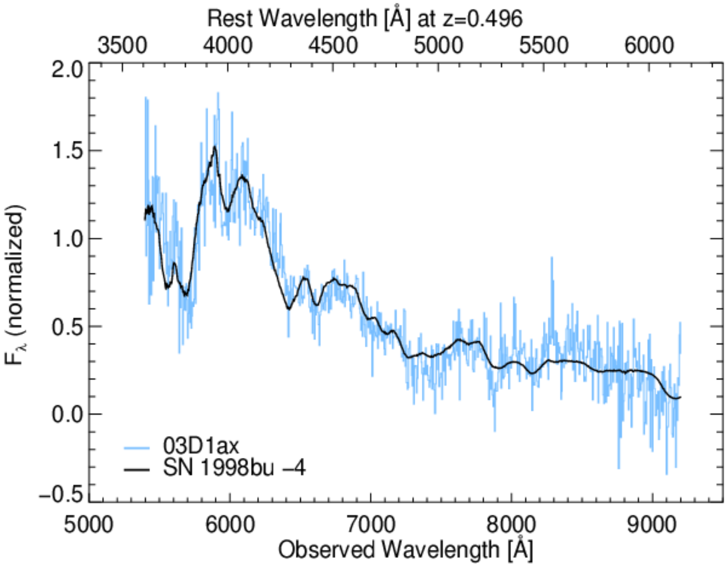
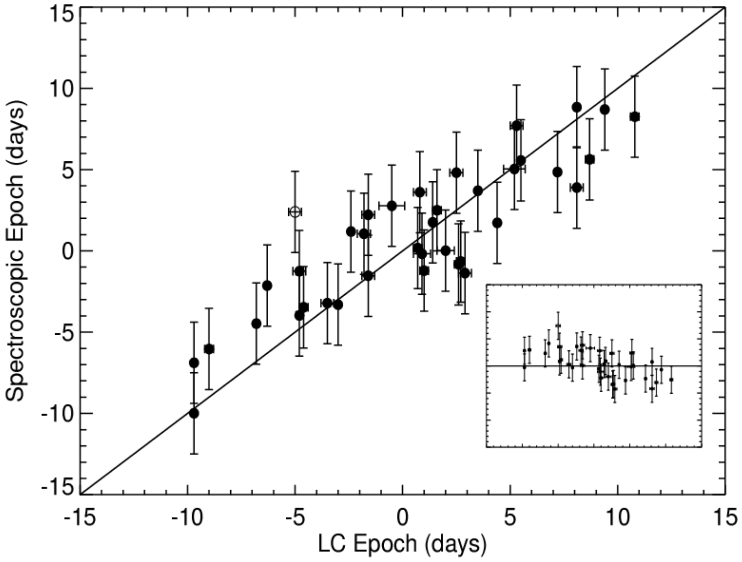
Spectroscopy



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

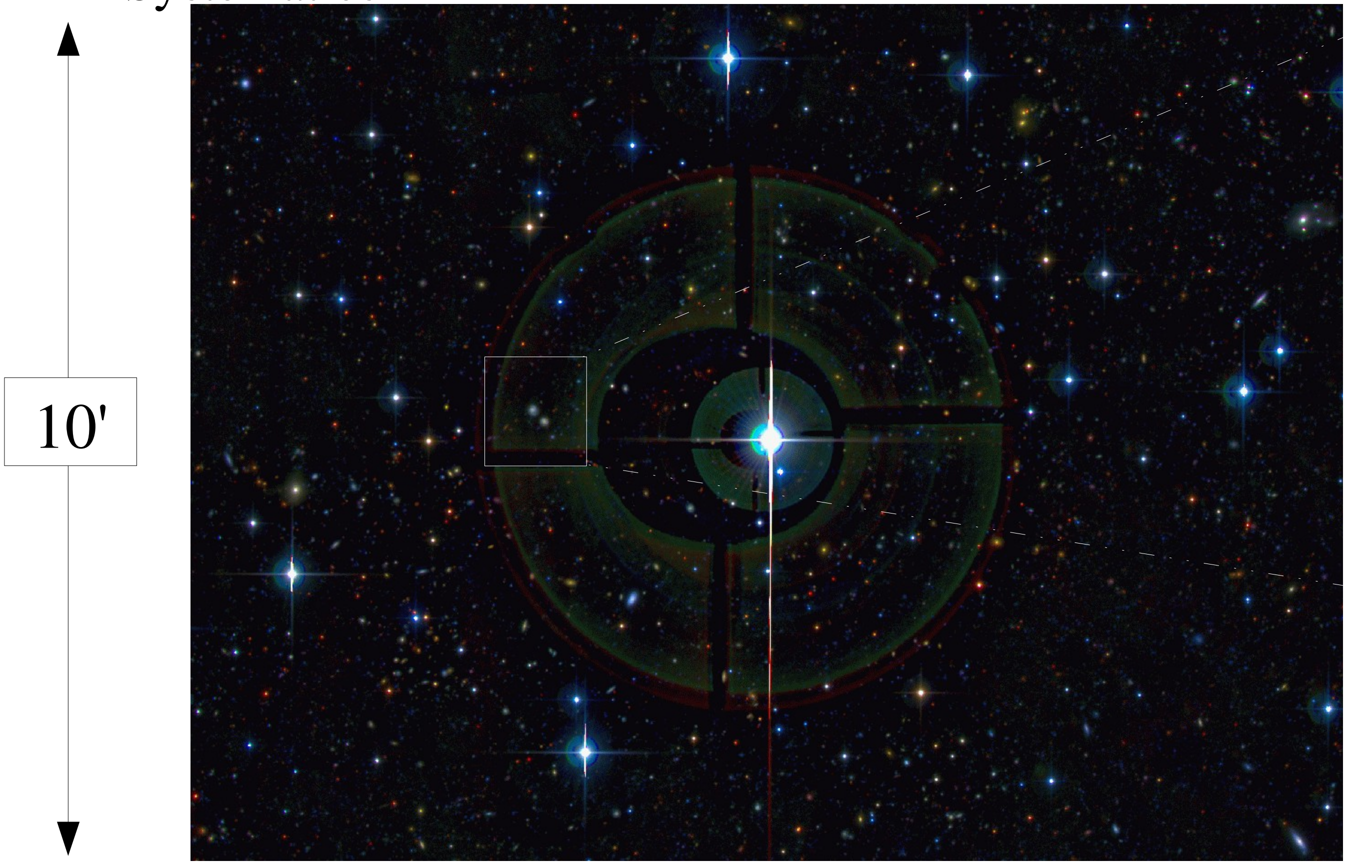
Telescopes
- VLT Large program (service)
  240h in 2003+2004, idem 2005+2006
- Gemini : 60h/semestre
  (Howell 2005, astro-ph/0509195)
- Keck :

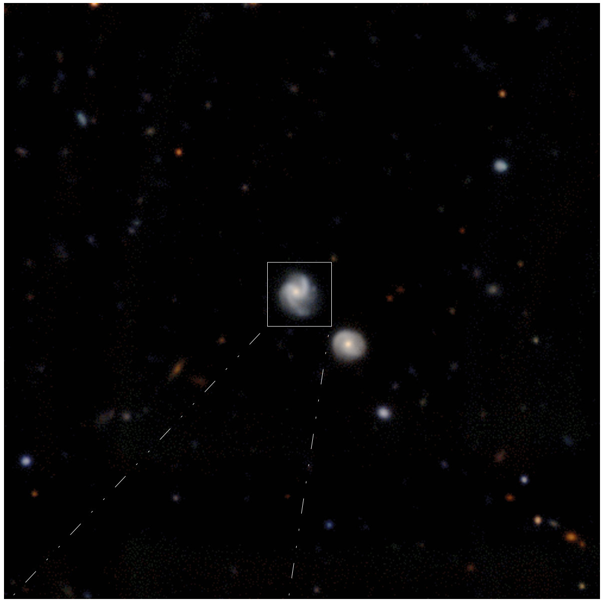


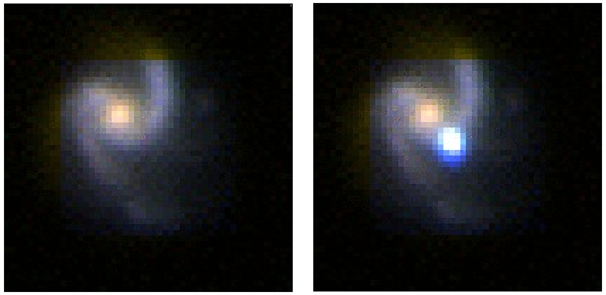


Analysis for cosmology of the SNLS first year data sample August 2003 – July 2004

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





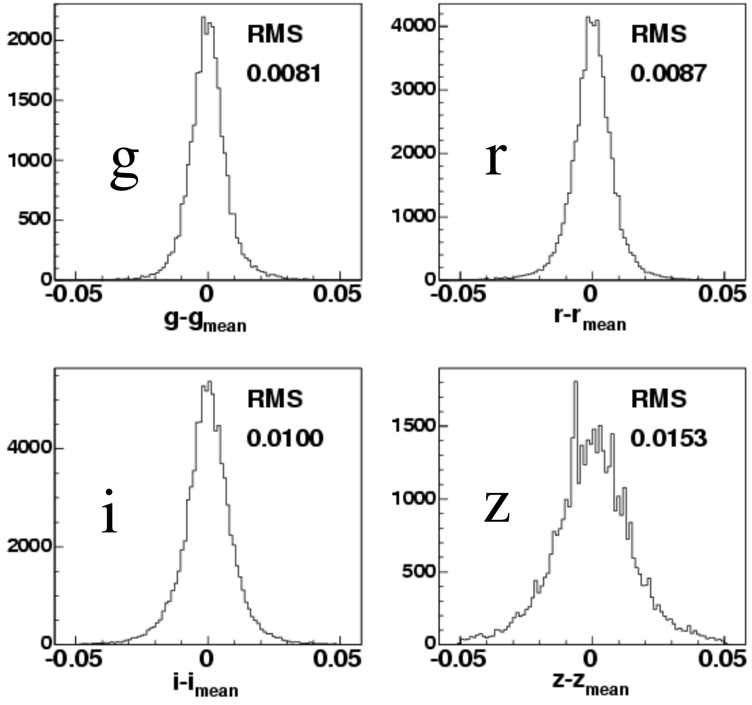


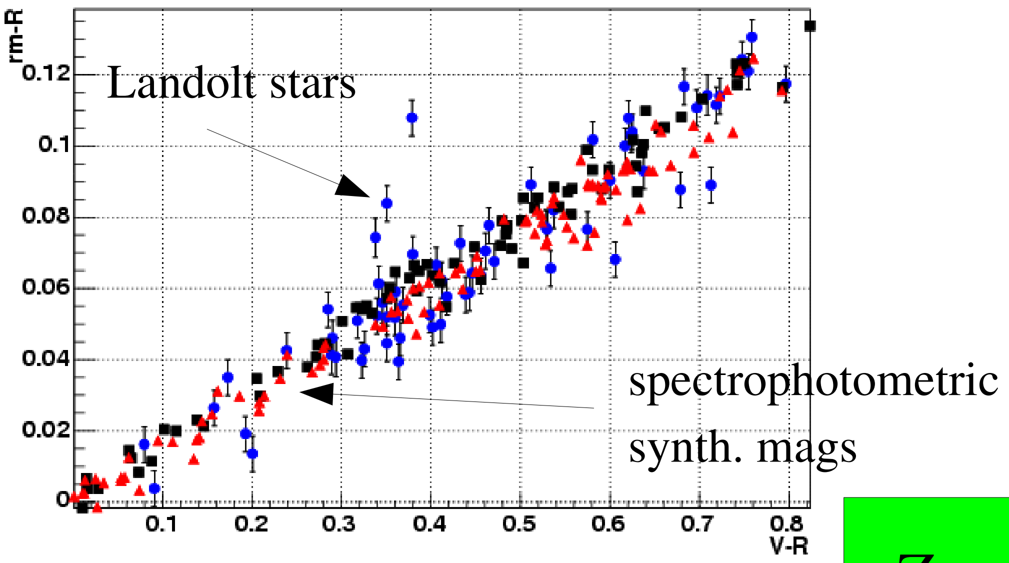
SNLS-03D4ag in the D4 Field

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)





Landolt stars

spectrophotometric synth. mags

-Zero points @ 0.01 (0.03 in z)

-Repeatability better than 0.01 (0.015 in z)

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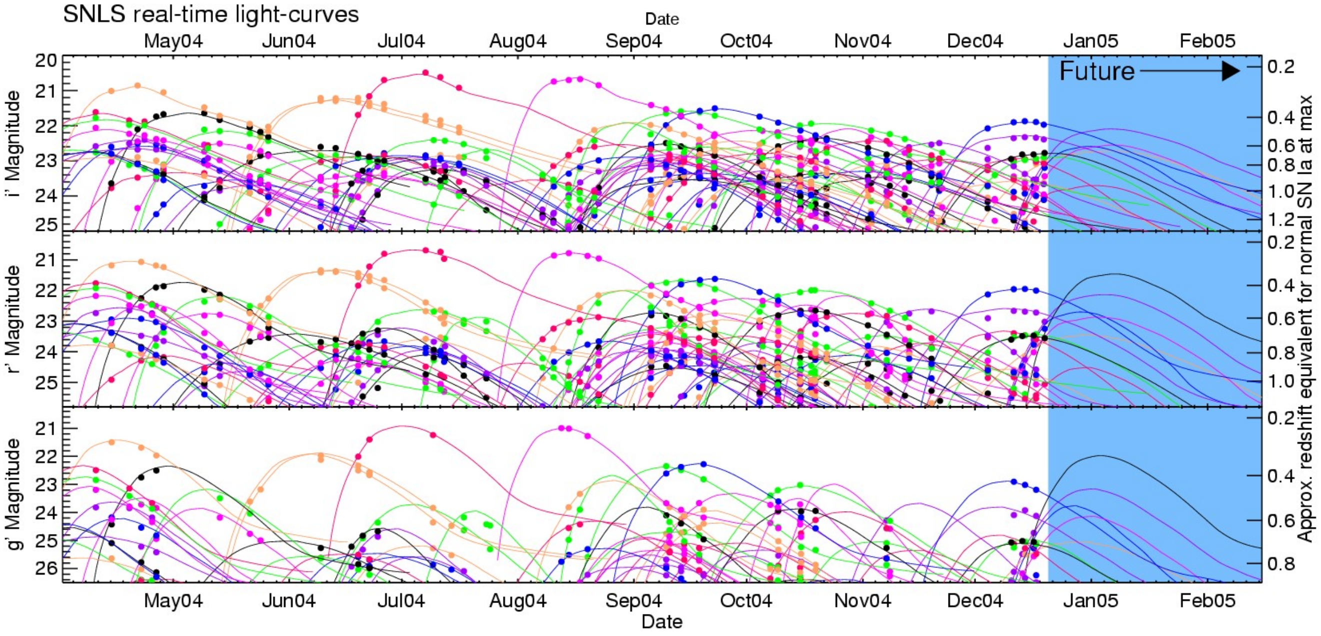
First year SNLS data set

(up to July 2004)



142 acquired spectra:

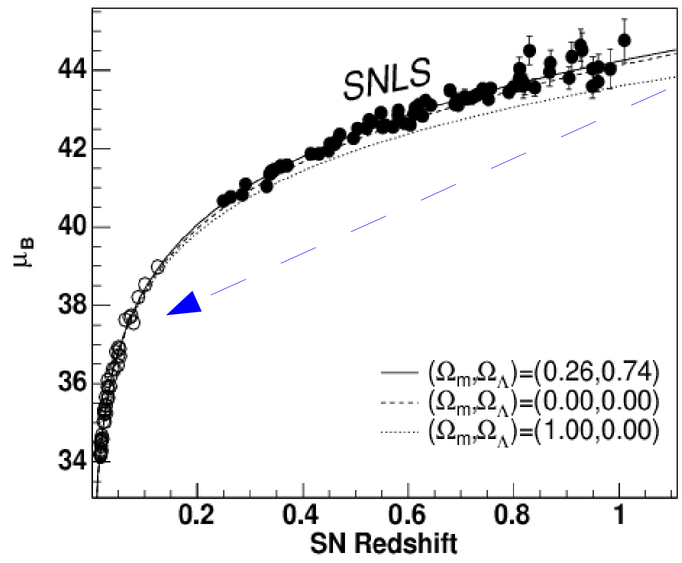
- 20 Type II SNe
- 9 AGN/QSO
- 4 SN Ib/c
- 91 SNe Ia

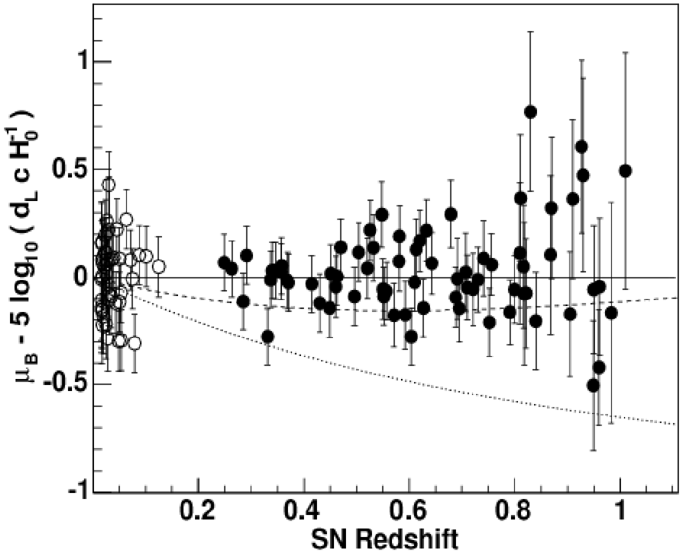
-10 miss references (are now usable)

- 6 only have 1 band (lost)

75 usable Ia events

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:

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

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

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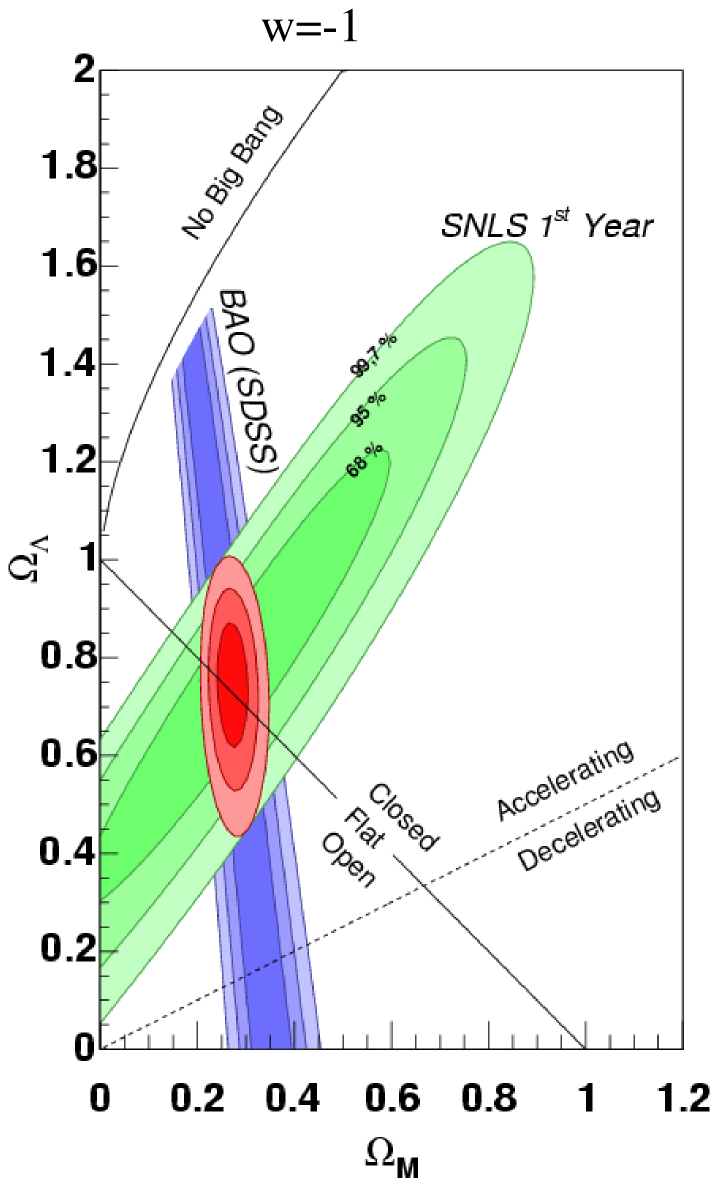
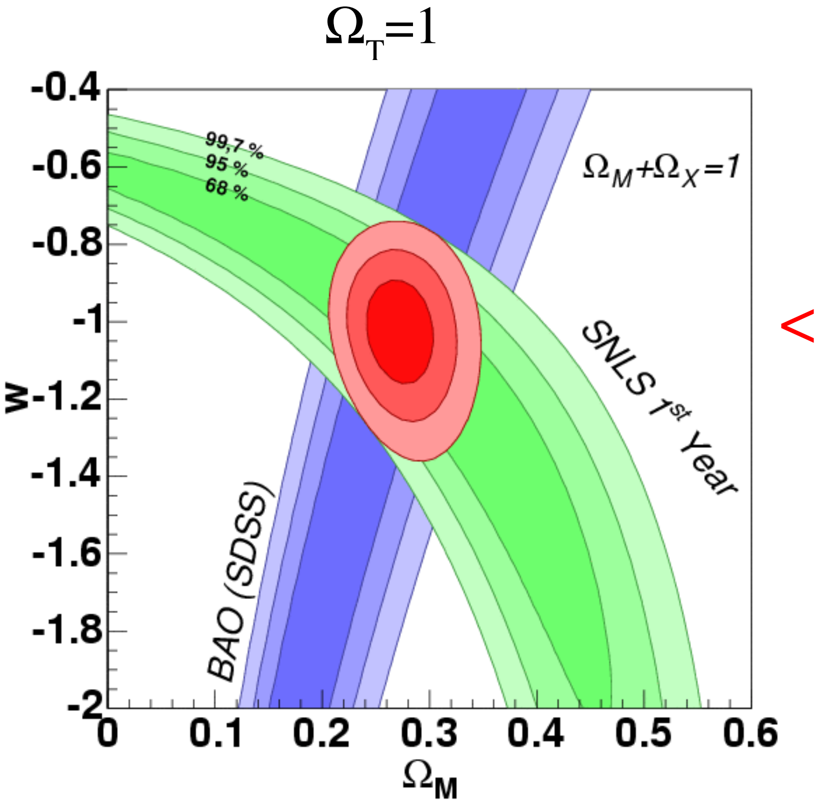
Confidence Contours



68.3, 95.5 et 99.7% CL



<-- Λ

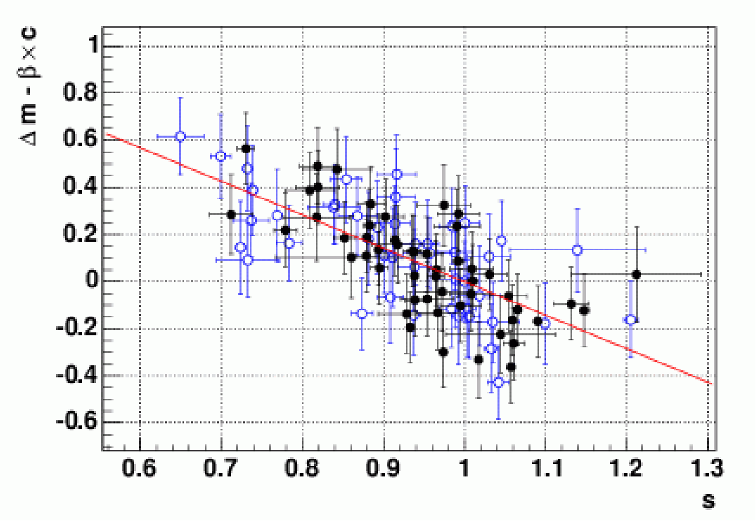
BAO: Baryon Acoustic Oscillations
(Eisenstein et al 2005, SDSS)

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

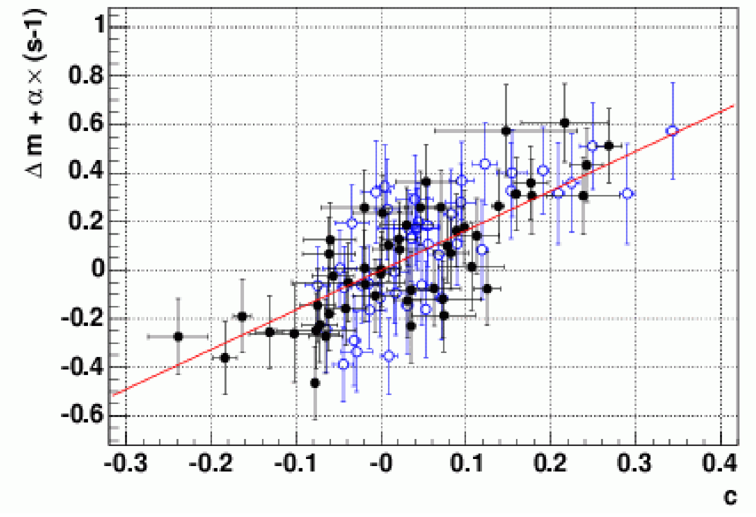
(astro-ph/0510447)

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

Brighter - slower

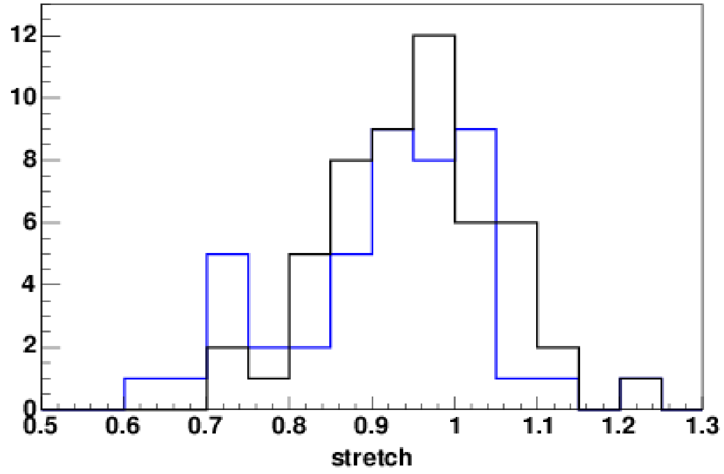


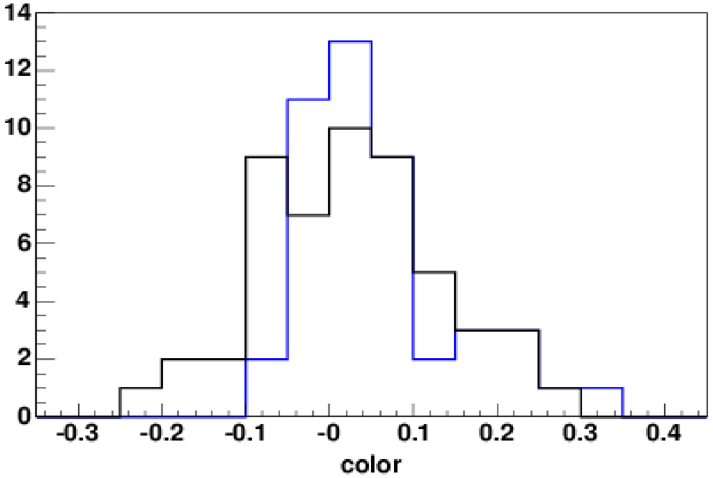
Brighter - bluer



Blue: nearby SNe

Black: SNLS SNe





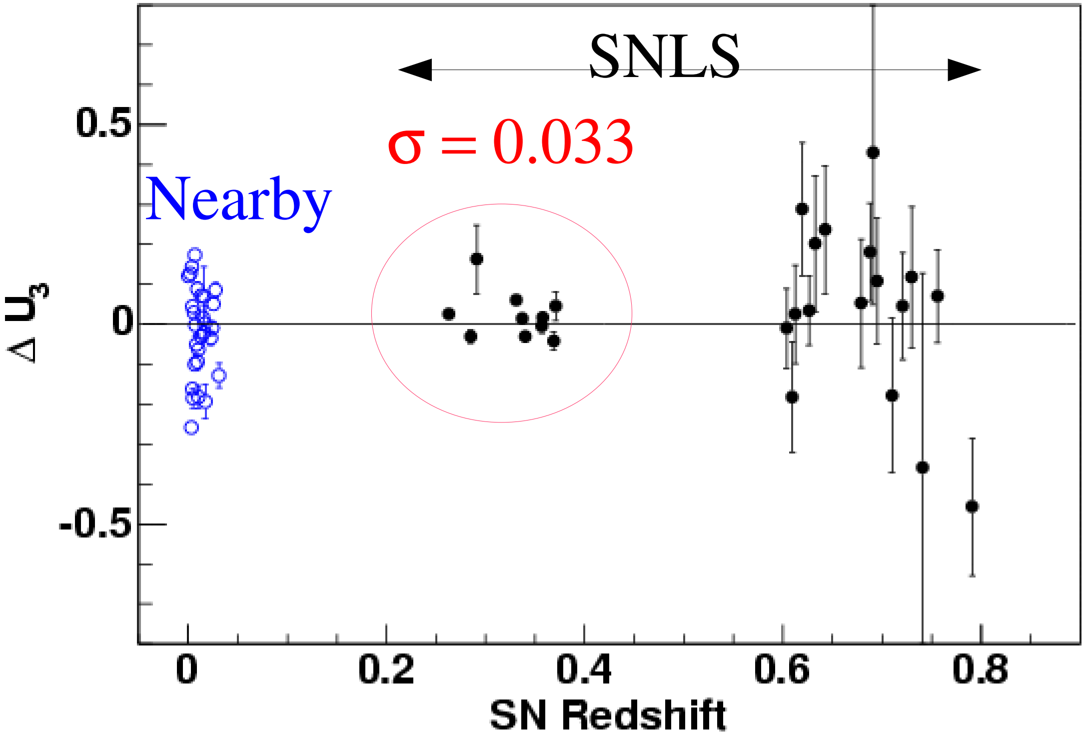
Stretch, color and relations with luminosity are essentially compatible between nearby and distant events.

Three-band measurements: color compatibility of Sne Ia

Compare restframe peak U, guessed from B and V, and measured U

ΔU_3 = U(measured) – U(guessed from B and V)

SN Ia restframe UBV relations are very reproducible: U&B are sufficient to measure a distance



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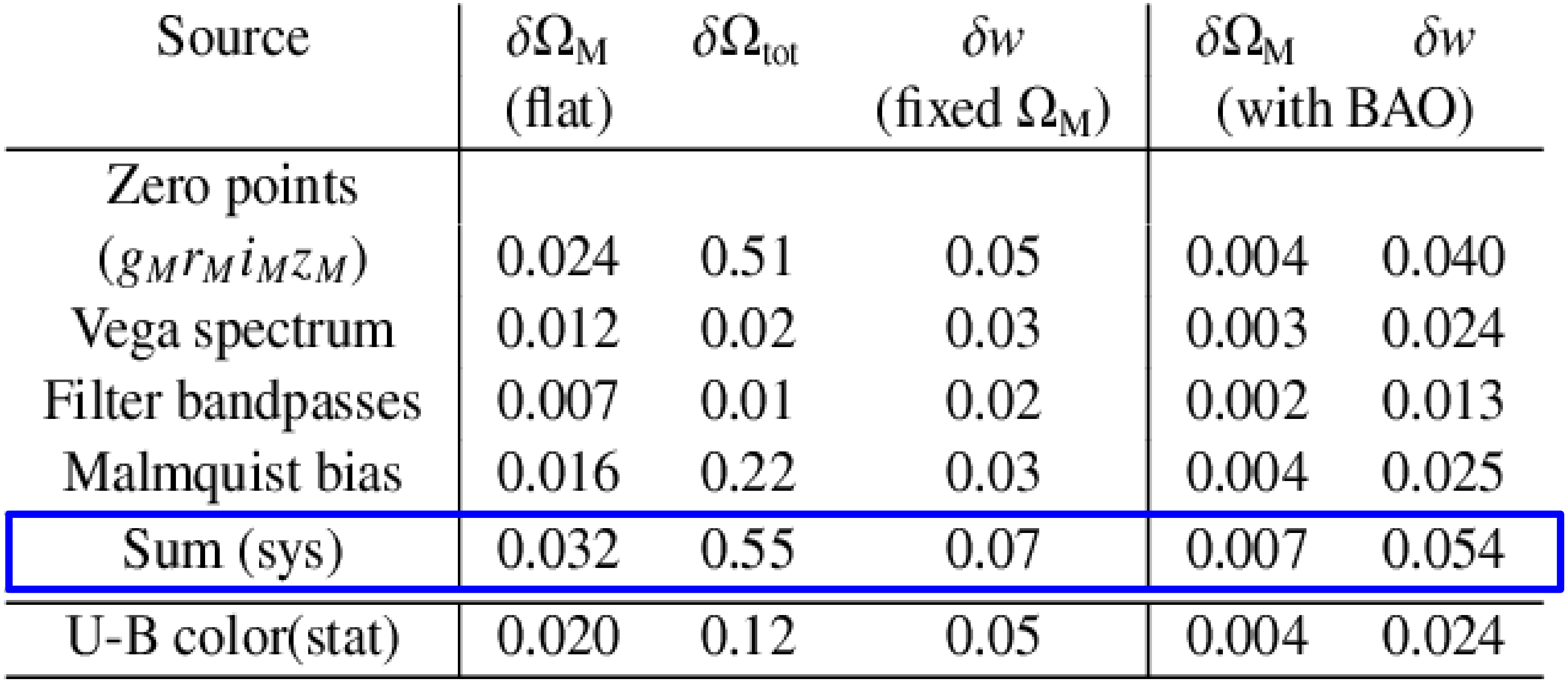
Systematic uncertainties

Summary:



Source	$\delta\Omega_M$ (flat)	$\delta\Omega_{tot}$	δw (fixed Ω_M)	$\delta\Omega_M$ (with BAO)	δw
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

For a flat ΛCDM cosmology:

(SNLS alone)

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

For a flat Ω_M,w cosmology :

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

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

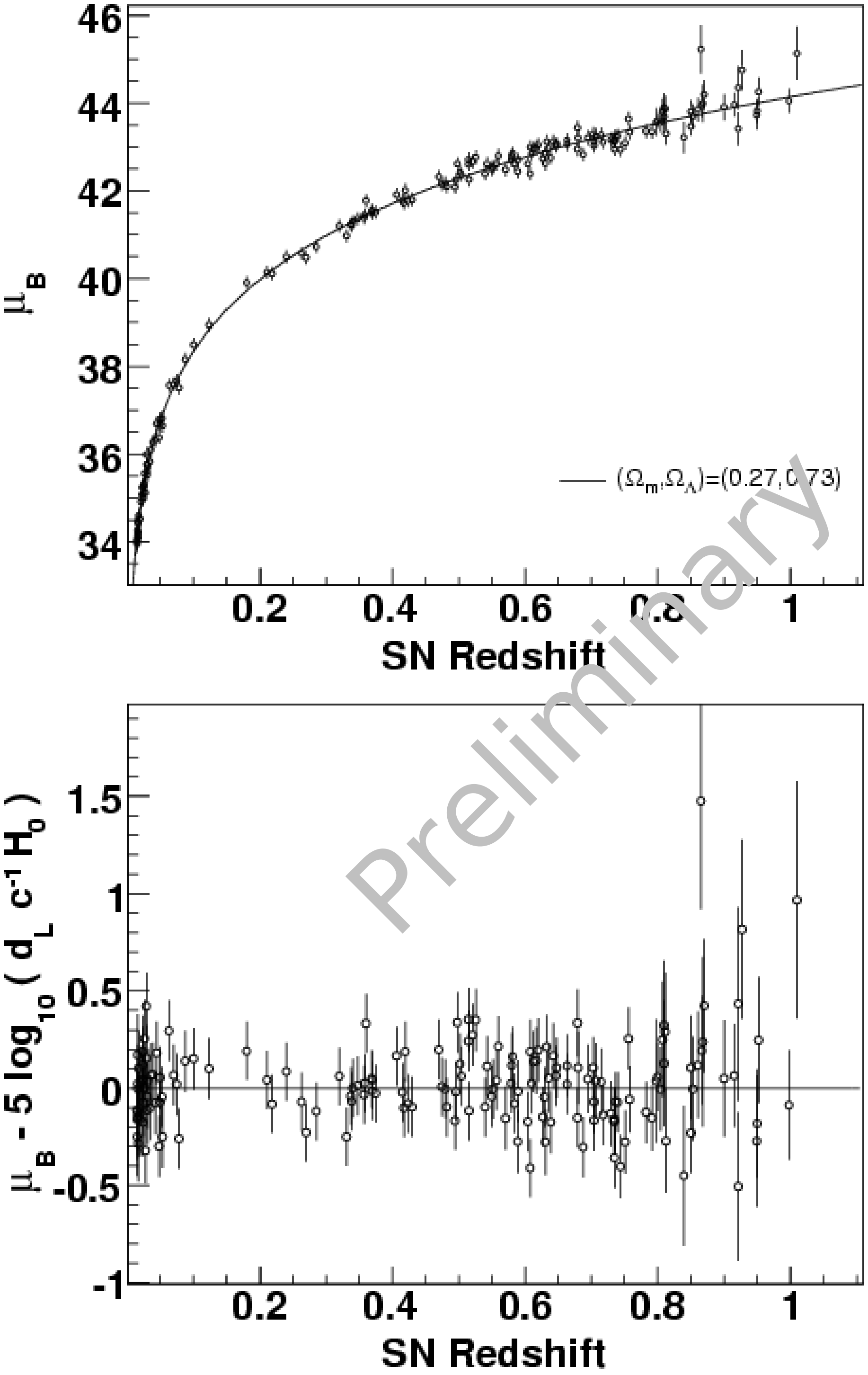
- **Confirmation of acceleration of expansion** with 71 (new!) distant SNe Ia.
- Use **color-corrected distance estimate without prior** on color.
- Careful study of systematics
- Photometric calibration will improve with specific measurements at CFHT

(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.



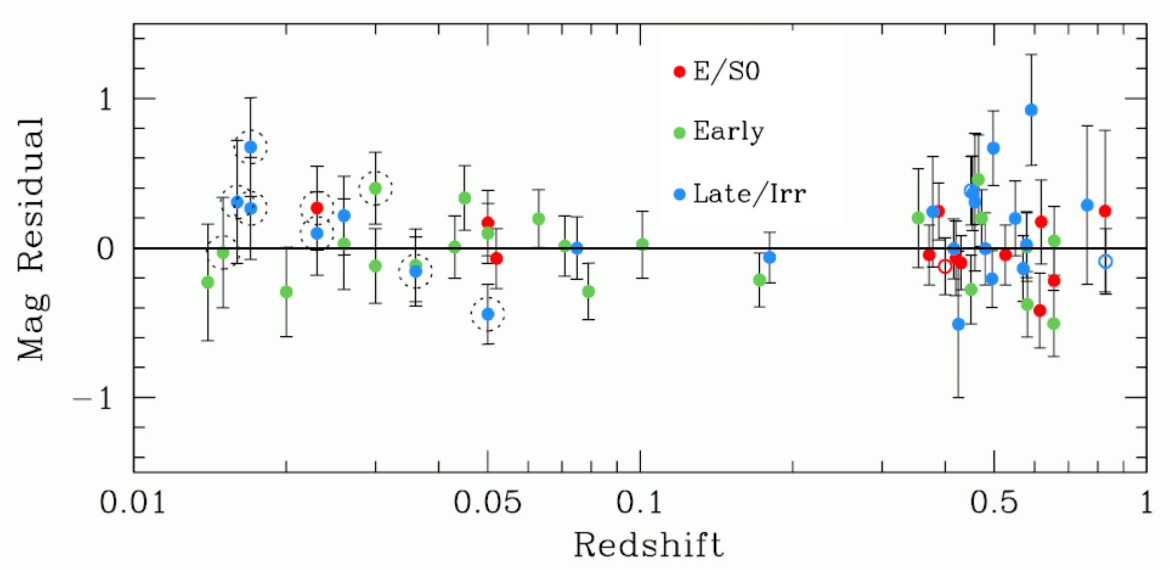
Current issues : SN properties vs galaxy types

Host galaxy types should evolve with redshift. However:

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

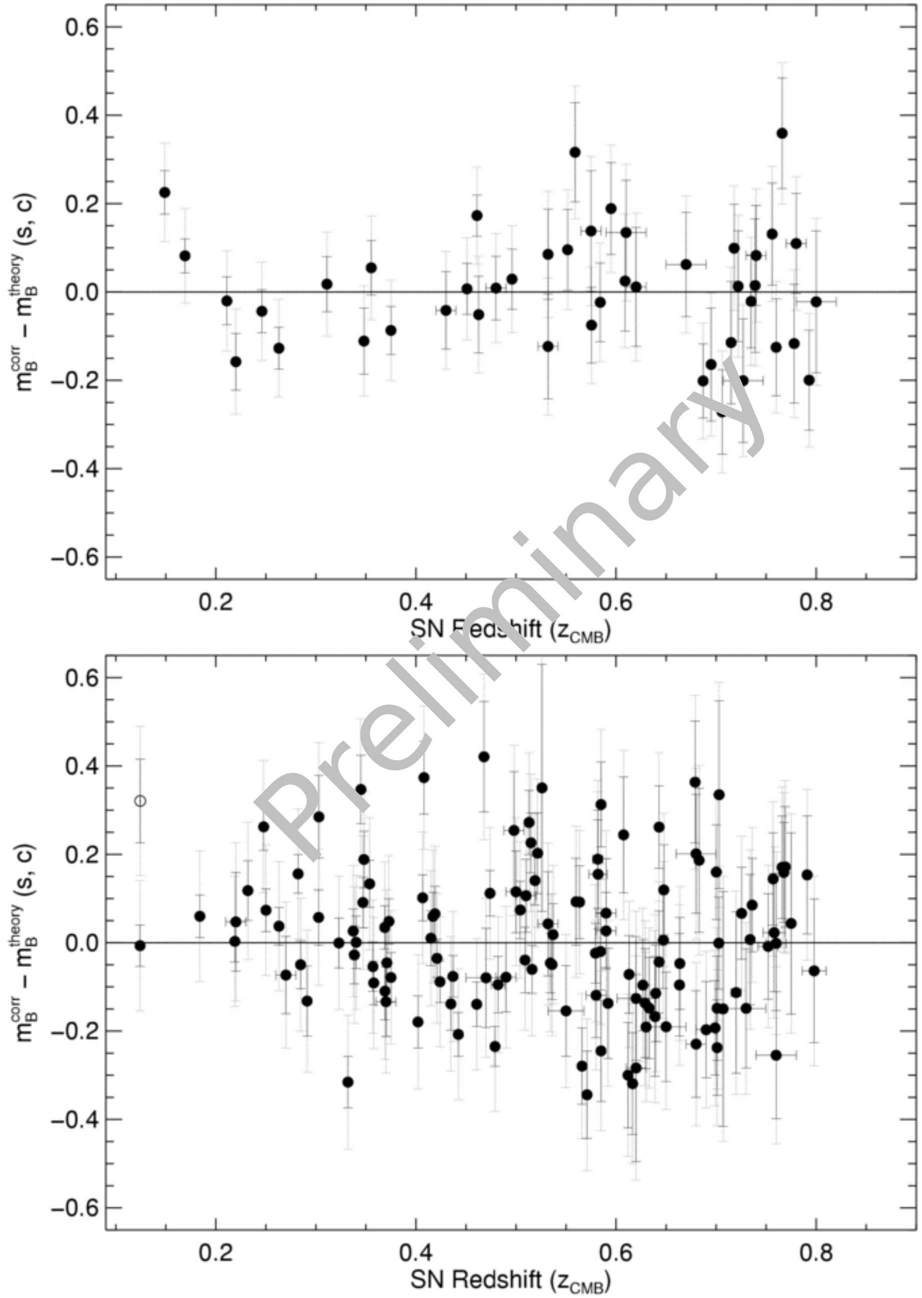
Strategy :

- 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
- Obvious



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

Split by host galaxy type



Passive

α=1.34 ± 0.24
β=2.52 ± 0.16
σ~0.10 mag

Star-forming

α=1.19 ± 0.15
β=2.71 ± 0.17
σ~0.14 mag

compatible
brighter-slower
and
brighter-bluer
relations

preliminary results by Sullivan et al, following Sullivan et al (2006)

Current issues : Photometric calibration

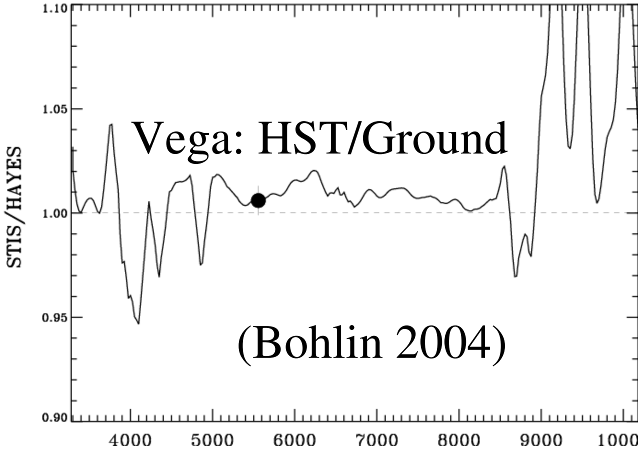
SNe cosmology requires ratio of fluxes measured in different spectral bands

Magnitudes provide ratio of fluxes measured in the same band.

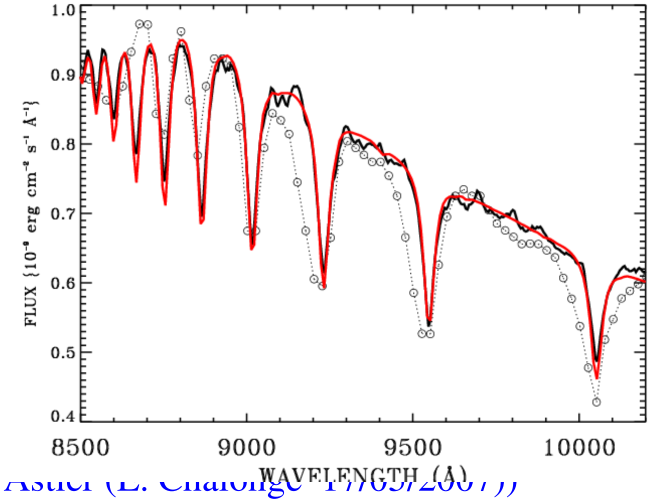
Hence magnitudes have to be converted into fluxes...

... which requires the spectrum of standard stars.

- Vega spectrum known to ~ 1% (Hayes 1985, Bohlin 2004)


Vega: HST/Ground

(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.

Photometric calibration and EOS accuracy

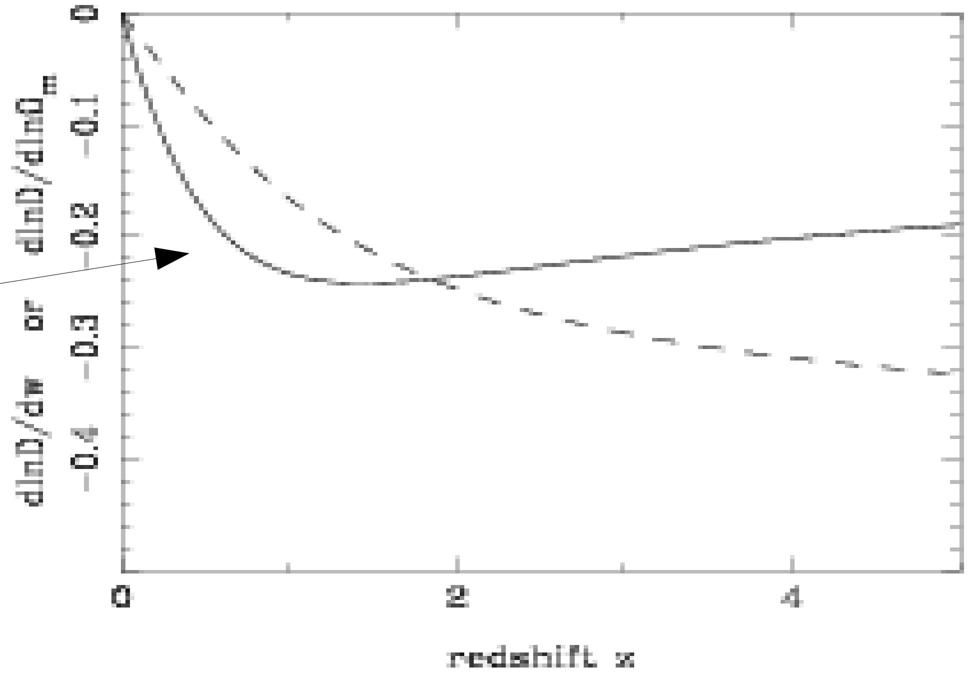
for a constant EOS:

d log(d)/ dw <~ 0.2

hence:

a 2% error in flux translates to

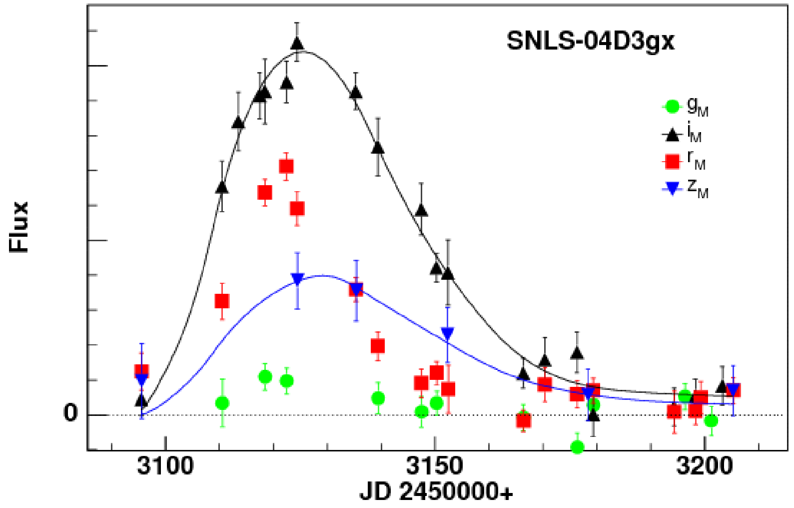
- a 1% error in distance
- a 0.05 error in w

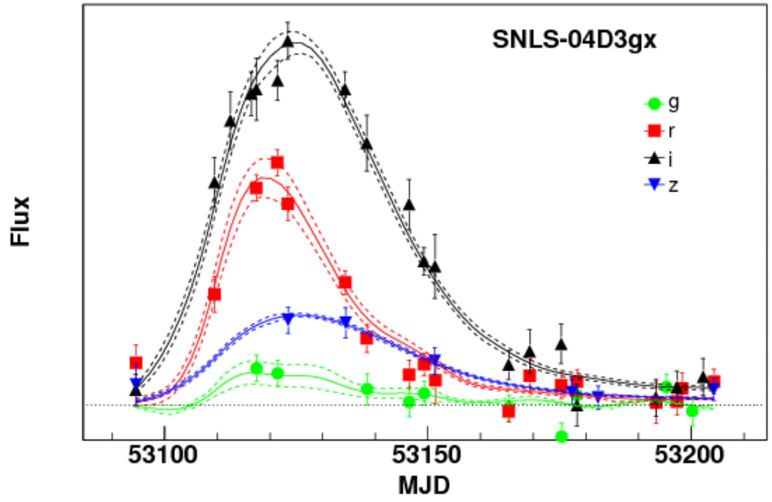


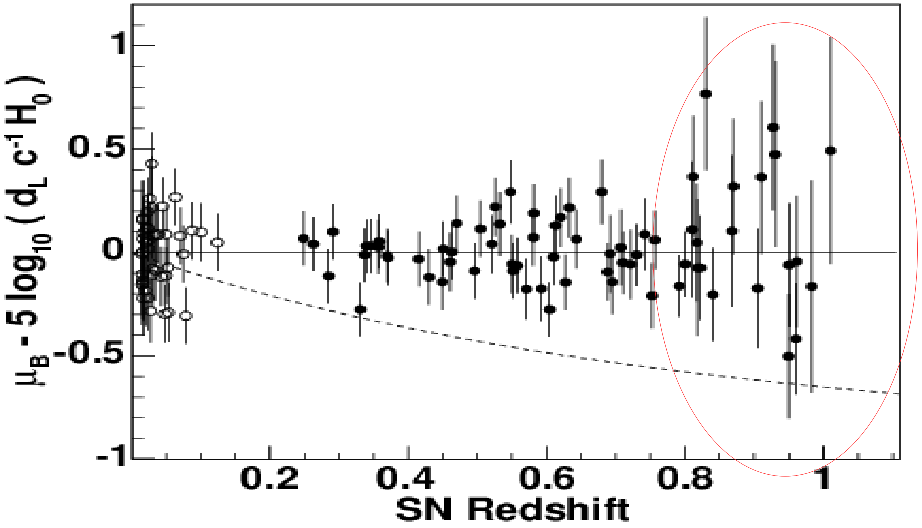
(from astro-ph/0610906)

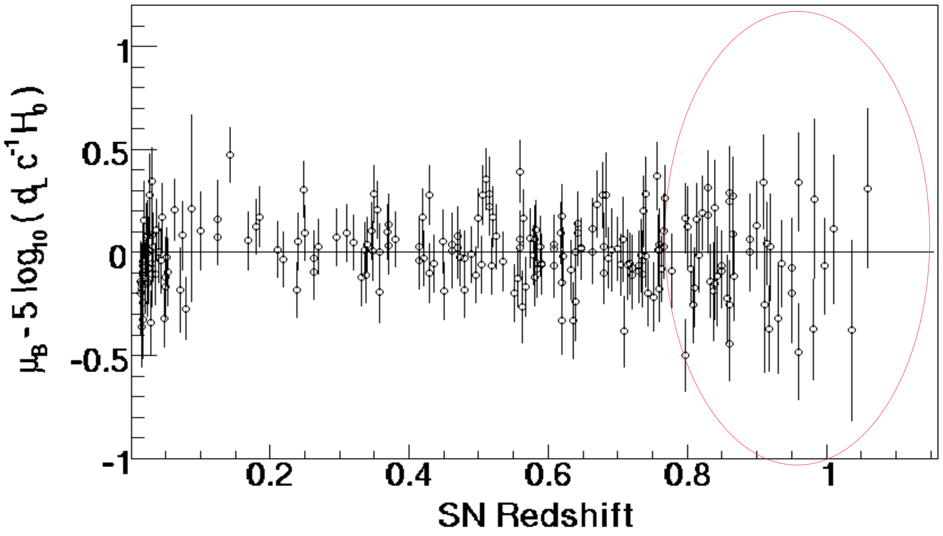
Improving distances at high redshift

By modelling the UV behavior of SNe, we improve high z distance estimates









(Guy et al, astro-ph/0701828)

SNe Ia cosmology : HST searches

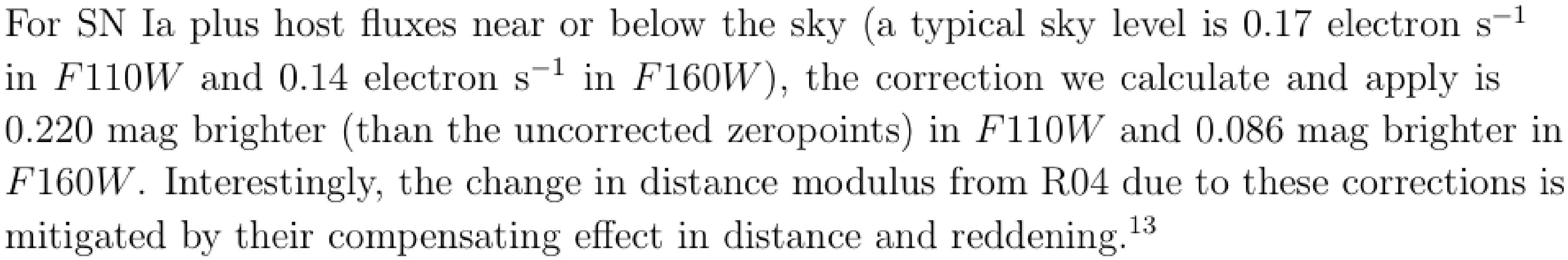
PANS survey : an HST based survey

- 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)

Recalibrated SN HST Magnitudes


For SN Ia plus host fluxes near or below the sky (a typical sky level is 0.17 electron s^{-1} in $F110W$ and 0.14 electron s^{-1} in $F160W$), the correction we calculate and apply is 0.220 mag brighter (than the uncorrected zeropoints) in $F110W$ and 0.086 mag brighter in $F160W$. Interestingly, the change in distance modulus from R04 due to these corrections is mitigated by their compensating effect in distance and reddening.[13]

Riess et al. (2006) astro-ph 0611572

Calibration uncertainty not included in any previous HST SN cosmology paper! (nor in Riess et al (2006) ...)

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

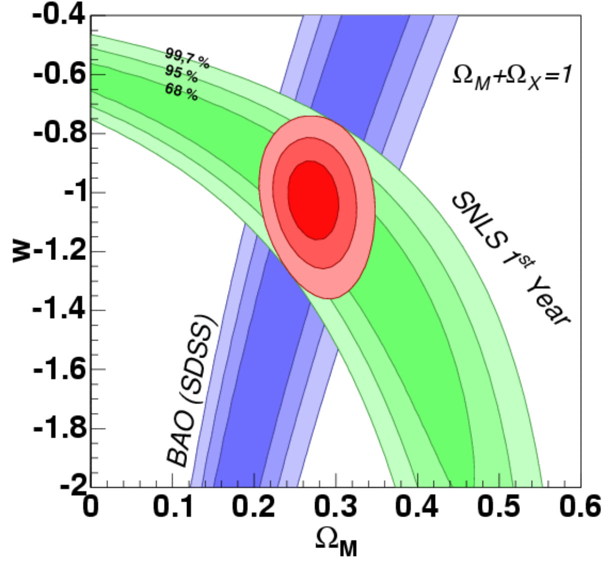
SNLS+Essence + nearby SNe + B.A.O w = -1.07 +/- 0.09 +/- 0.13

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	$\sigma(\Omega_M)$	0.023	0.019	0.019	0.019	0.018	0.018
BAO accuracy	$\sigma(w_0)$	0.088	0.073	0.076	0.064	0.060	0.055
BAO x 2	$\sigma(\Omega_M)$	0.016	0.014	0.014	0.013	0.013	0.013
(4000->8000 deg^2)	$\sigma(w_0)$	0.081	0.062	0.067	0.054	0.049	0.044

P. Astier (E. Chalonge 17/05/2007))

Dark Energy EOS : current status

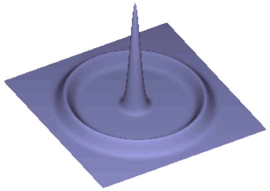
Dark Energy looks like Λ (SNe+BAO)

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

(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

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

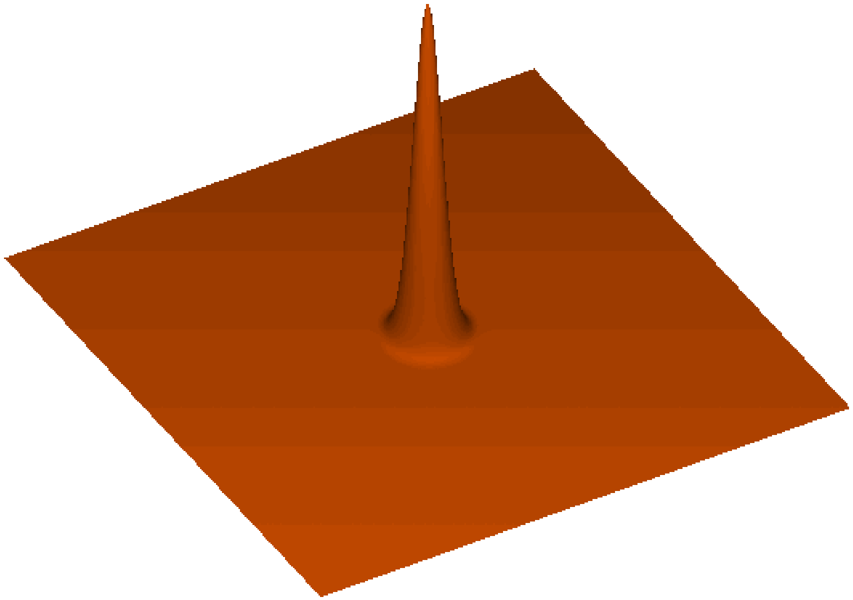


Baryon Acoustic Oscillations

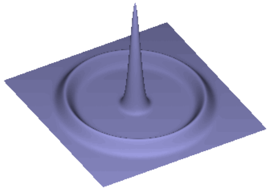
- Before recombination, sound waves propagate in the universe.

- 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

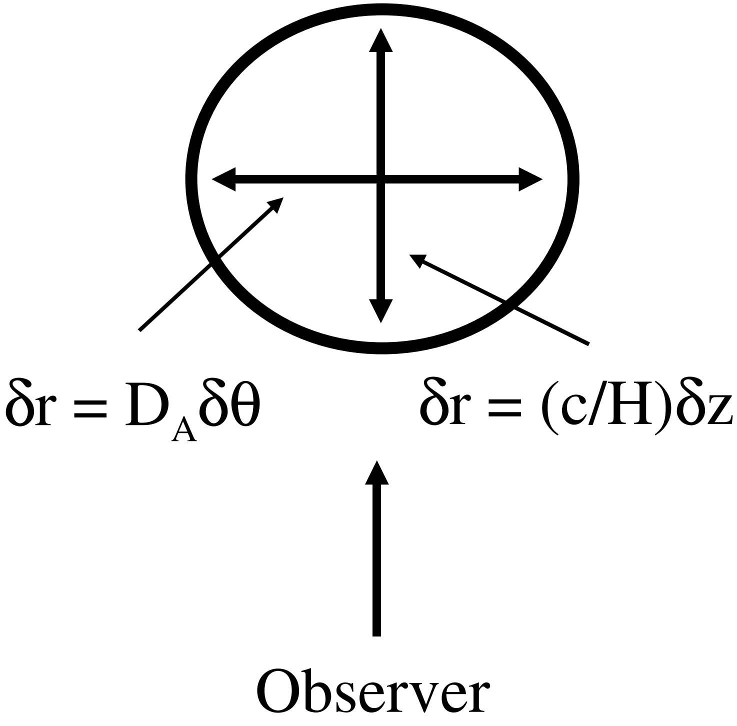


propagation of a fluctuation
from BB to recombination



A Standard Ruler

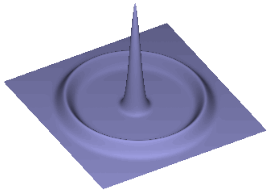
- The acoustic oscillation scale depends on the sound speed and the propagation time.
  - These depend on the matter-to-radiation ratio ($\Omega_m h^2$) and the baryon-to-photon ratio ($\Omega_b h^2$).
- The CMB anisotropies measure these and fix the oscillation scale.
- In a spectroscopic redshift survey,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



$\delta r = D_A \delta\theta$

$\delta r = (c/H)\delta z$

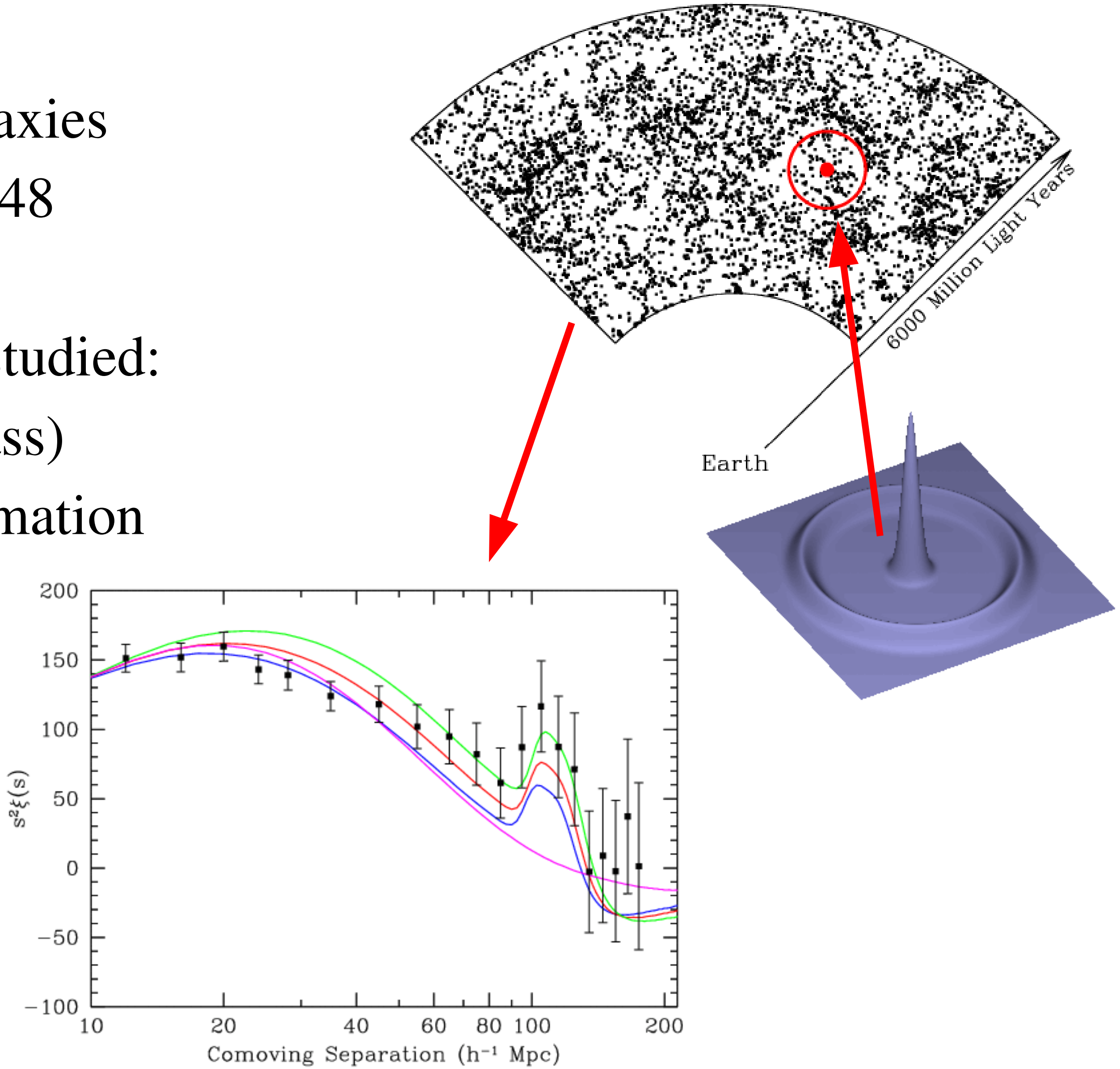
Observer

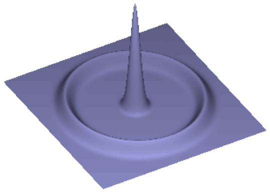


Detection in the SDSS

(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



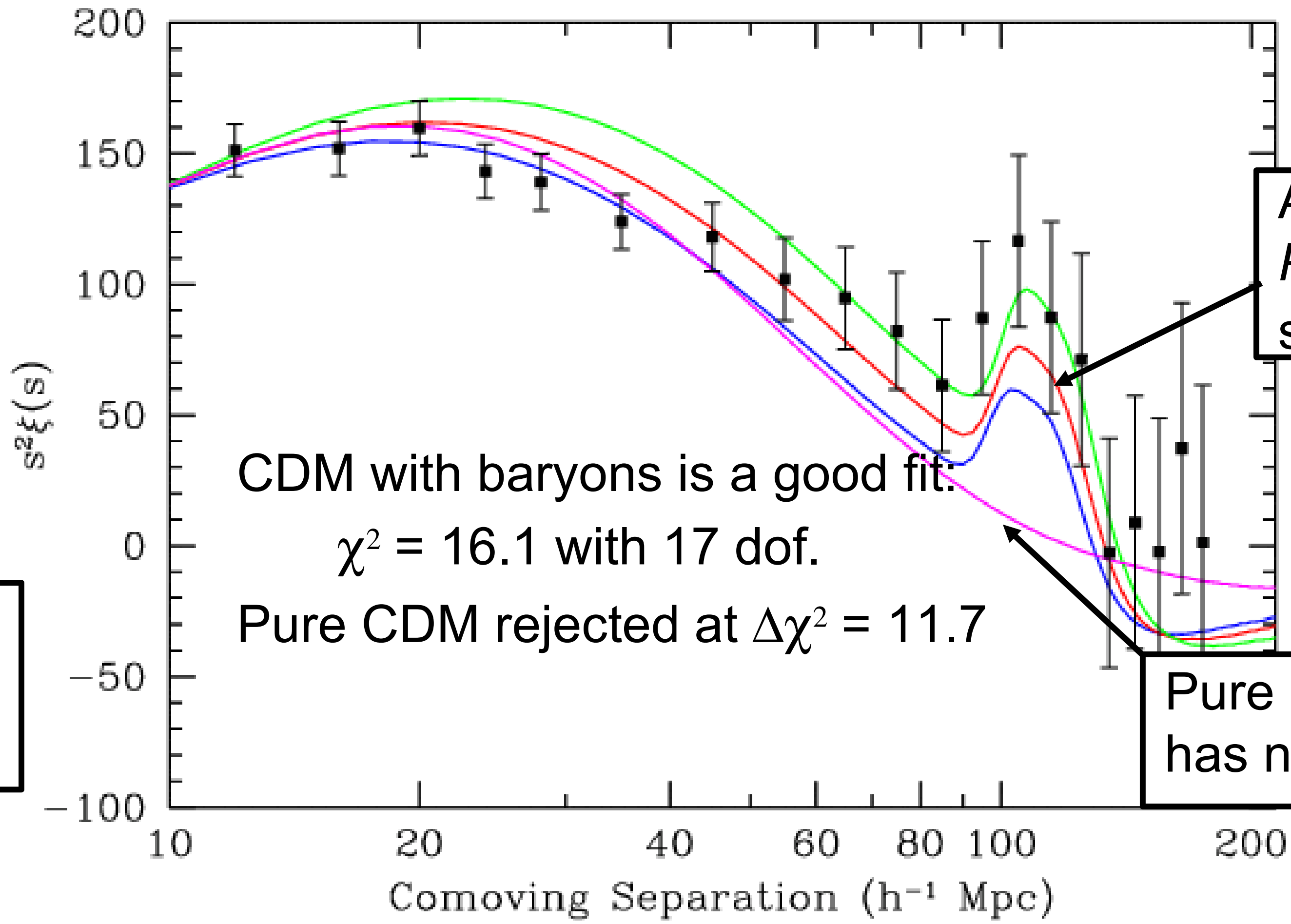


Large scale correlations

$\Omega_m h^2 = 0.12$

$\Omega_m h^2 = 0.13$

$\Omega_m h^2 = 0.14$



Acoustic series in $P(k)$ becomes a single peak in $\xi(r)$

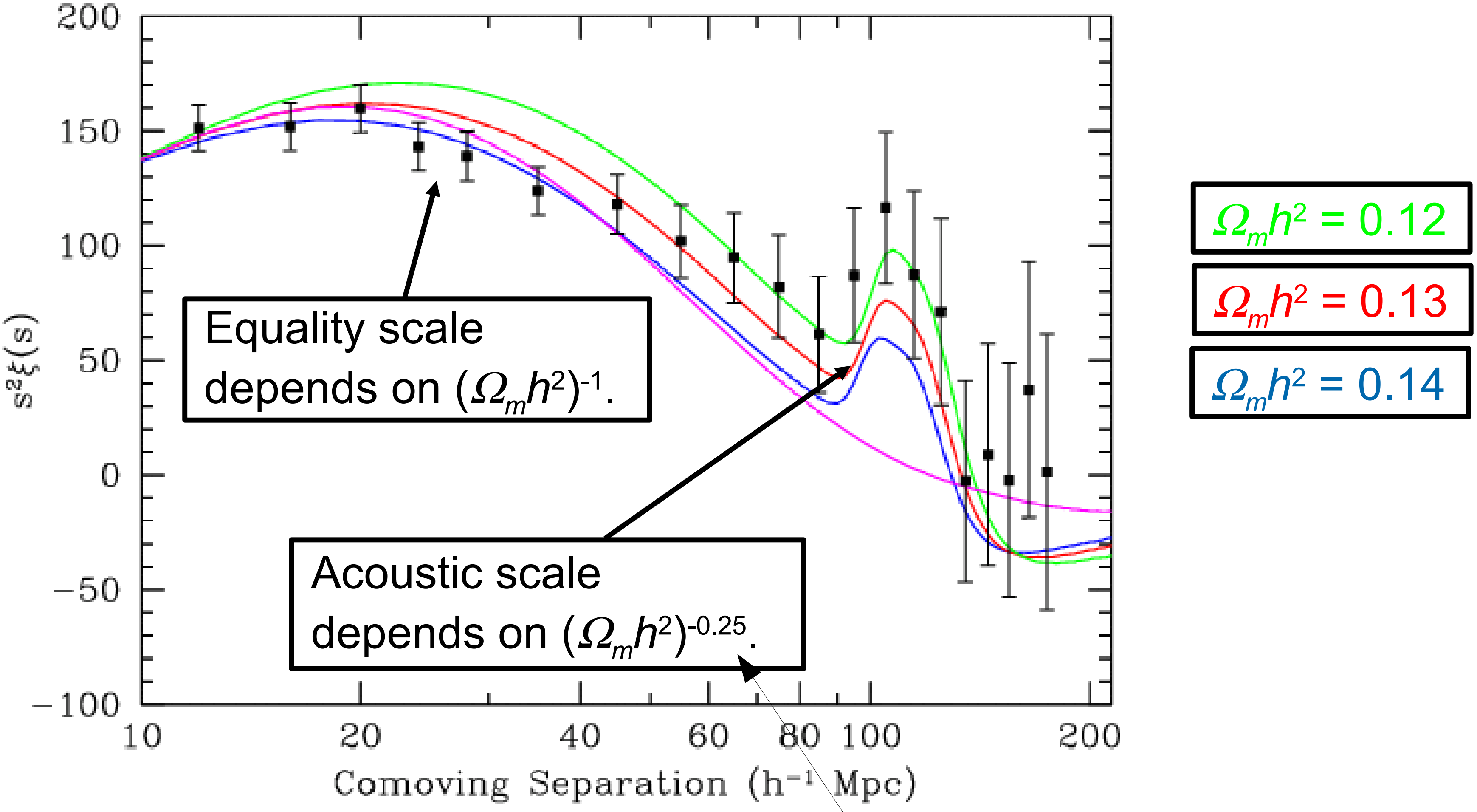
CDM with baryons is a good fit: $\chi^2 = 16.1$ with 17 dof.

Pure CDM rejected at $\Delta\chi^2 = 11.7$

Pure CDM model has no peak.

Warning: Correlated Error Bars

Two Scales in Action



$\Omega_m h^2 = 0.12$

$\Omega_m h^2 = 0.13$

$\Omega_m h^2 = 0.14$

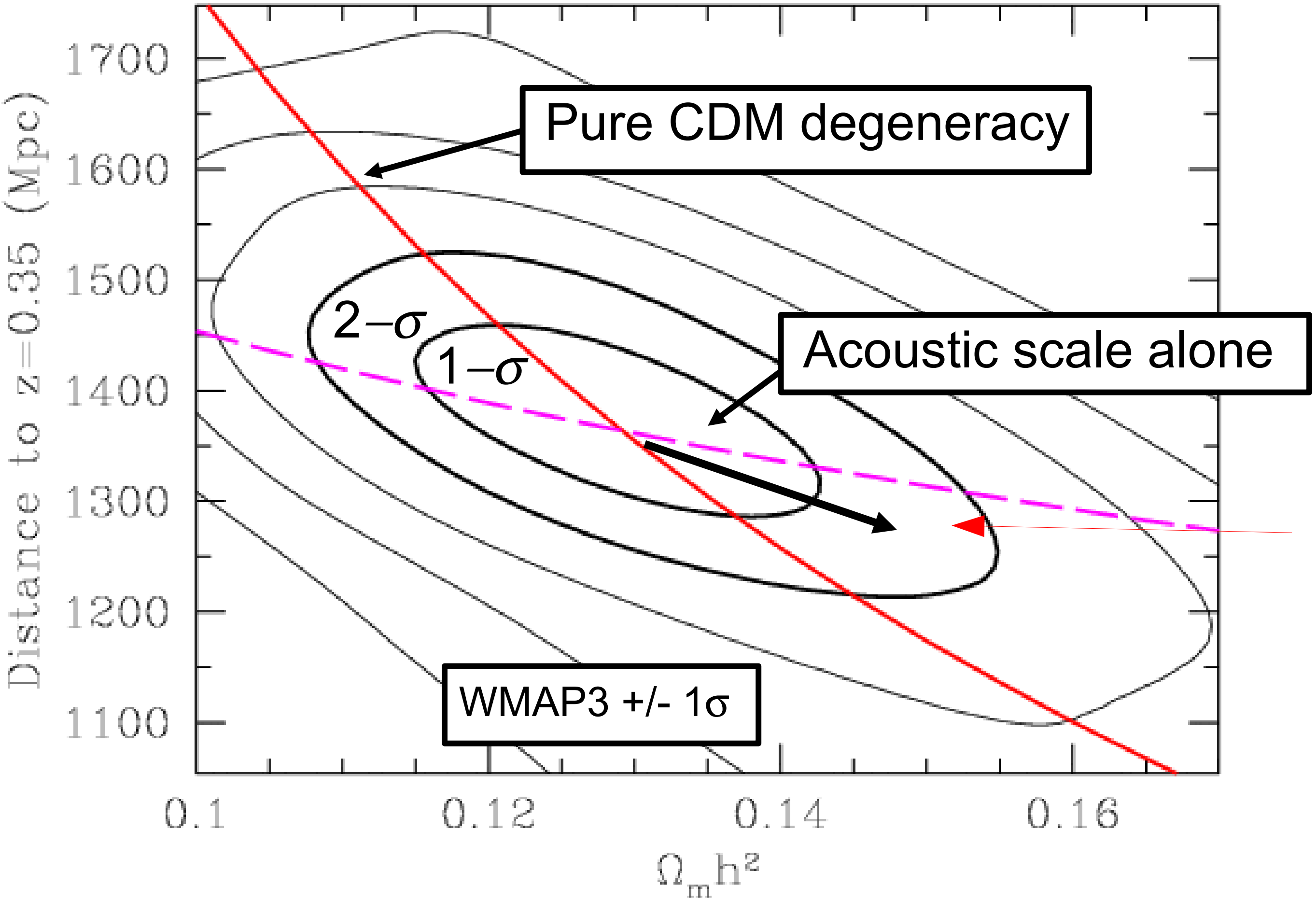
Equality scale depends on $(\Omega_m h^2)^{-1}$.

Acoustic scale depends on $(\Omega_m h^2)^{-0.25}$.

not a consequence of first principles

See Hu, 0407158

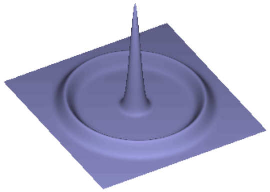
Cosmological Constraints



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.

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

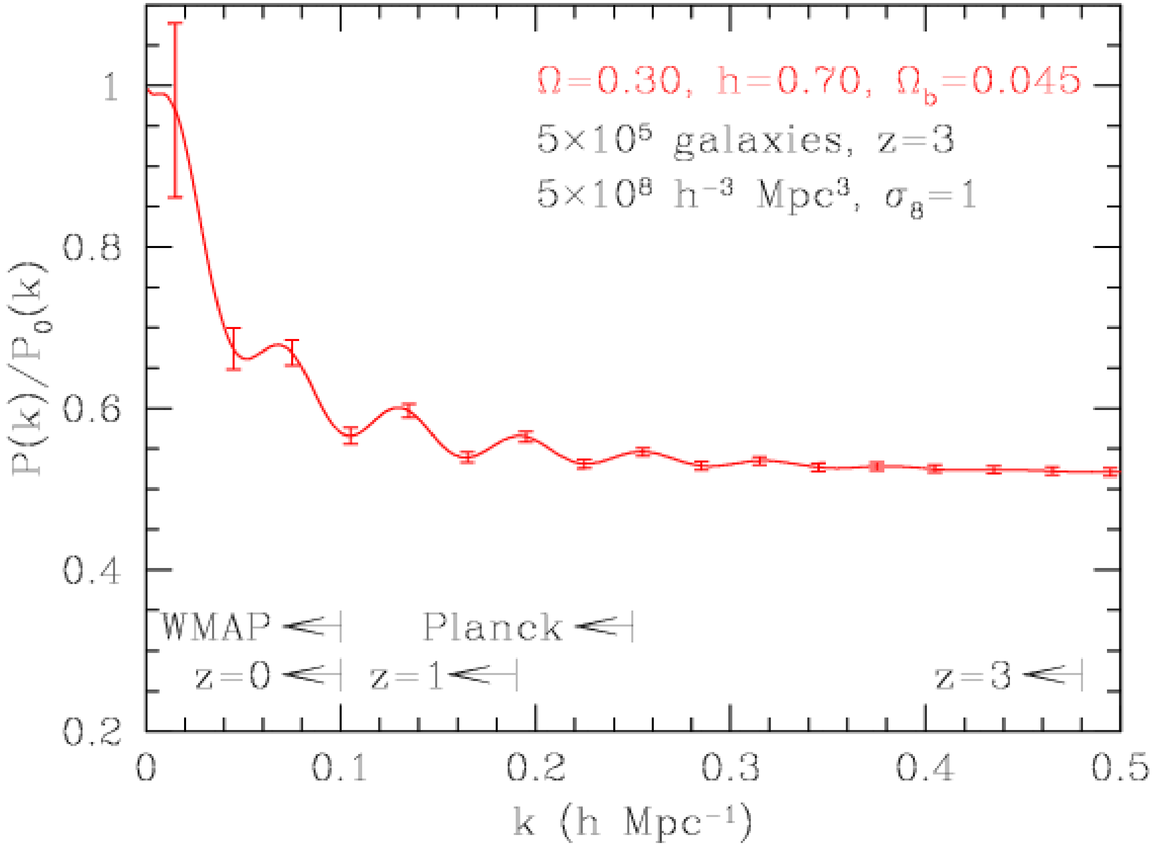
Eisenstein et al [SDSS], ApJ (2005)



BAO : Beyond SDSS

- By performing large spectroscopic surveys at higher redshifts, we can measure the acoustic oscillation standard ruler across cosmic time.
- Higher harmonics are at $k \sim 0.2h$ Mpc^{-1} (λ=30 Mpc)
- Measuring 1% bandpowers in the peaks and troughs requires about 1 Gpc^3 of survey volume with number density $\sim 10^{-3}$ comoving h^3 Mpc^{-3} =
  ~1 million galaxies!
- ~~We~~ They have considered surveys at z=1 and z=3.
  - Hee-Jong Seo & DJE (2003, ApJ, 598, 720)
  - Also: Blake & Glazebrook (2003), Linder (2003), Hu & Haiman (2003).

A Baseline Survey at $z = 3$

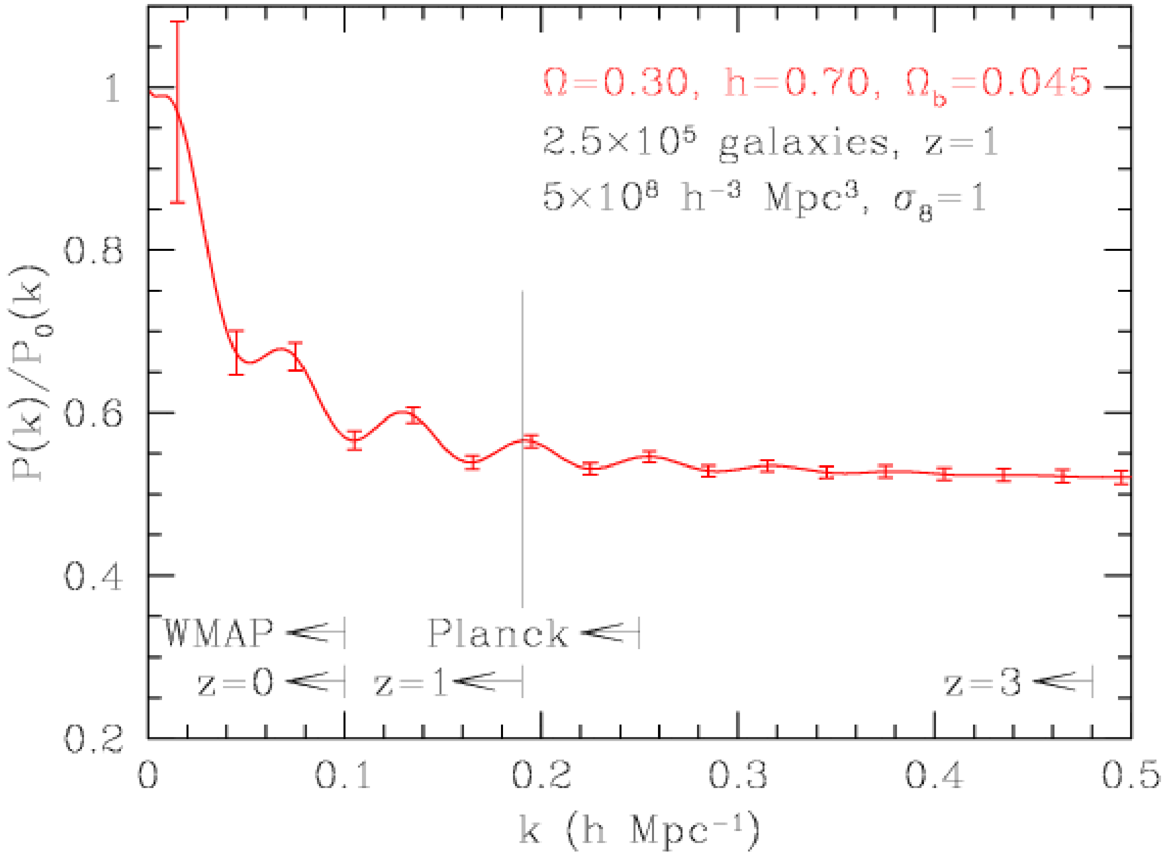


Statistical Errors from the z=3 Survey

- 600,000 gal.
- ~300 sq. deg.
- 10^9 Mpc^3
- 0.6/sq. arcmin

- Linear regime k<0.3h Mpc^{-1}
- 4 oscillations

A Baseline Survey at *z* = 1

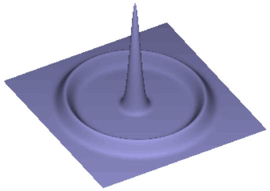


Statistical Errors from the *z*=1 Survey

- 2,000,000 gal., z = 0.5 to 1.3
- 2000 sq. deg.
- 4x10^9 Mpc^3
- 0.3/sq. arcmin

- Linear regime k<0.2h Mpc^{-1}
- 2-3 oscillations

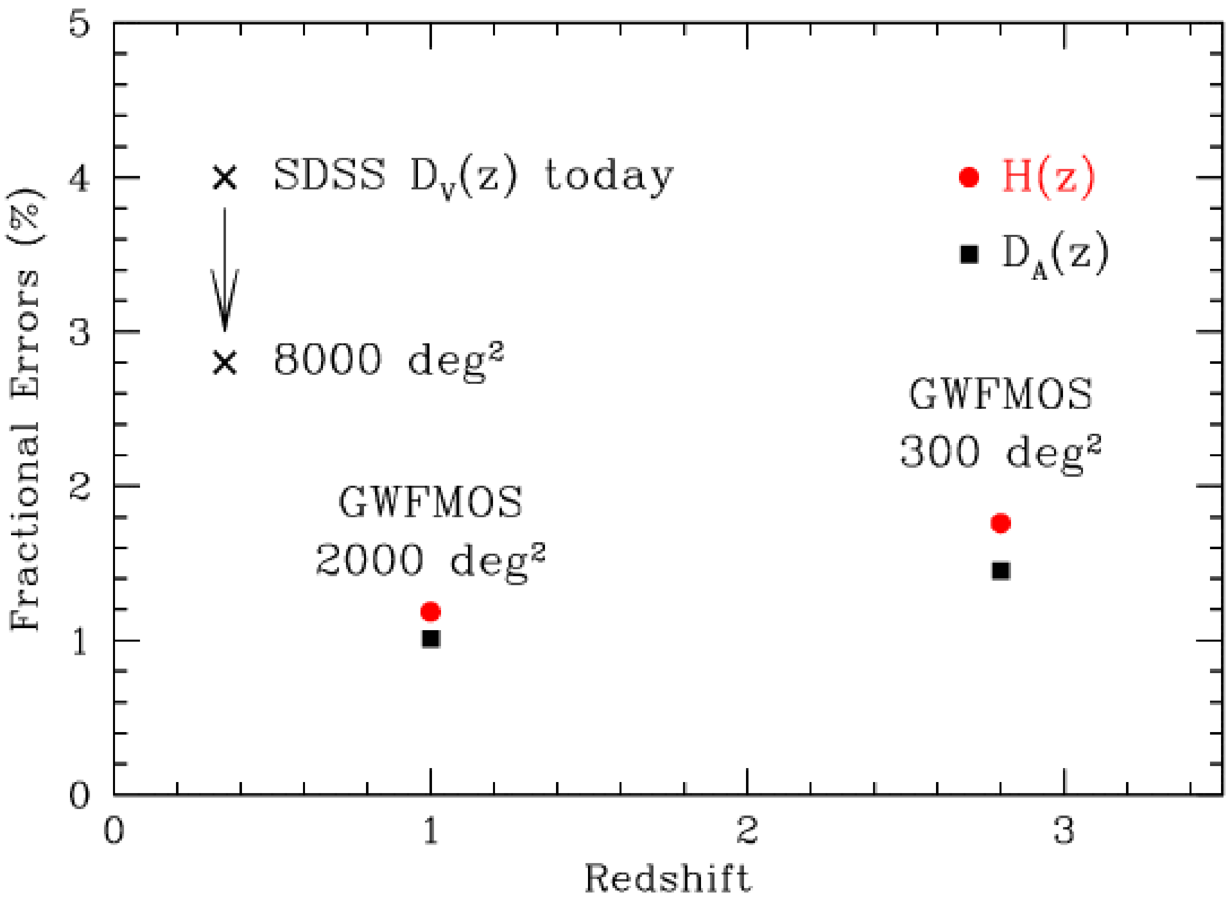
BAO forecast Methodology



Hee-Jong Seo & D. Eisenstein (2003)

- Fisher matrix treatment of statistical errors.
  - Full three-dimensional modes including redshift and cosmological distortions.
  - Flat-sky and Tegmark (1997) approximations.
  - Large CDM parameter space: $\Omega_m h^2$, $\Omega_b h^2$, n, T/S, Ω_m, plus separate distances, growth functions, β, and anomalous shot noises for all redshift slices.
- Planck-level CMB data
- Combine data to predict statistical errors on $w(z) = w_0 + w_1 z$.

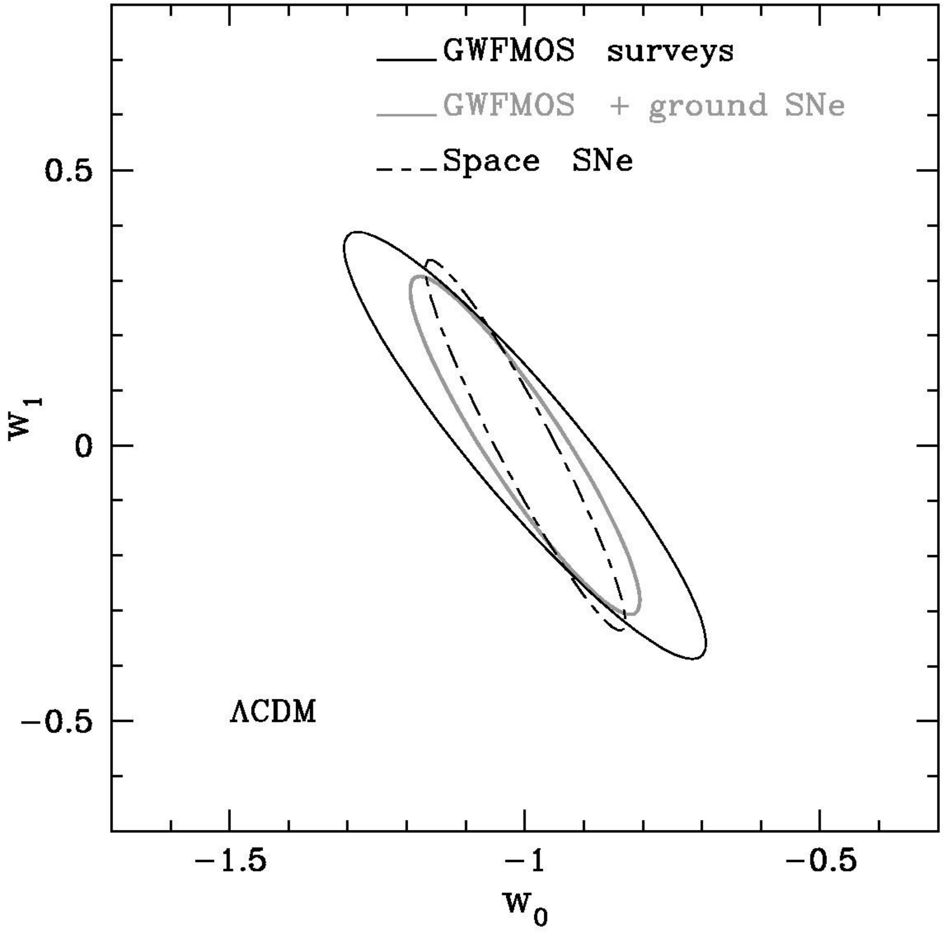
Baseline Performance



Distance Errors versus Redshift

Results for ΛCDM

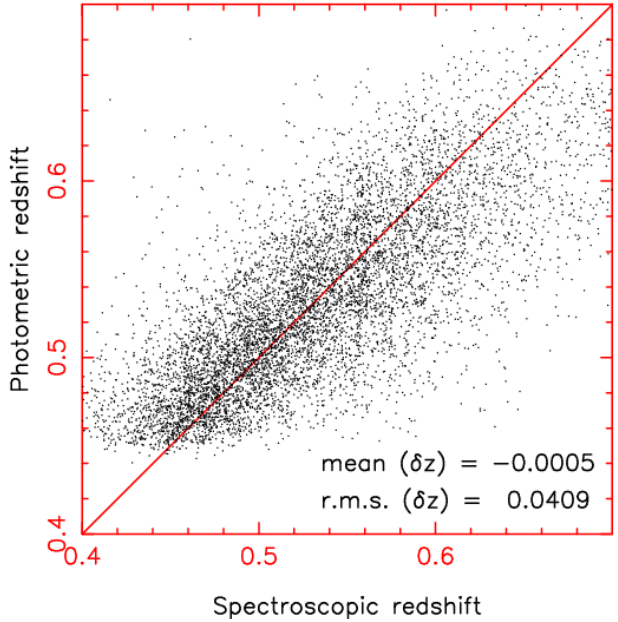
- Data sets:
  - CMB (*Planck*)
  - SDSS LRG (z=0.35)
  - Baseline *z*=1
  - Baseline *z*=3
  - SNe (1% in Δ*z*=0.1 bins to *z*=1 for ground, 1.7 for space)
- $\sigma(\Omega_m) = 0.027$
  $\sigma(w) = 0.08$ at $z=0.7$
  $\sigma(dw/dz) = 0.26$
- $\sigma(w) = 0.05$ with ground SNe

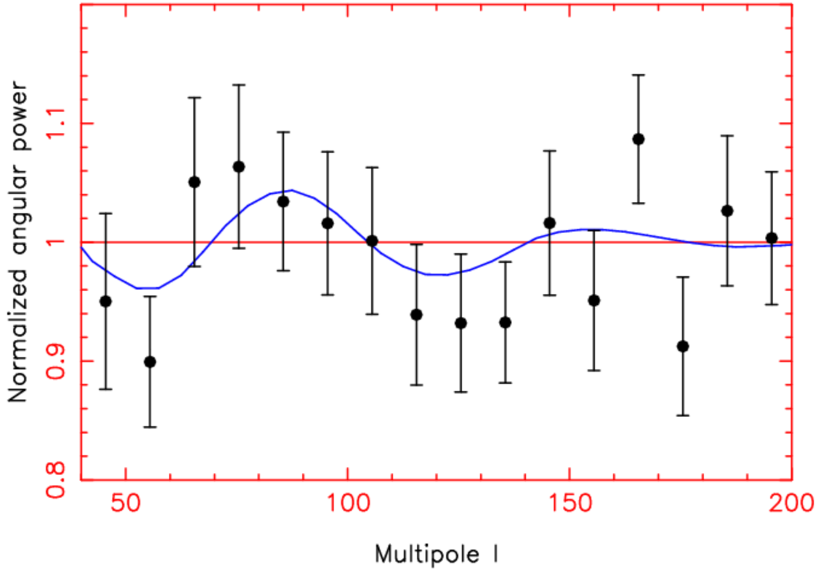


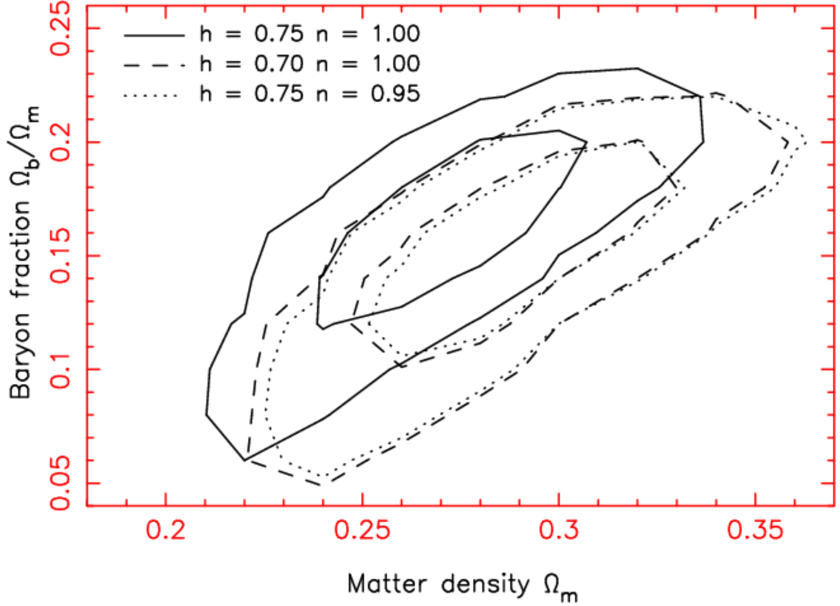
BAO with photometric redshifts

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

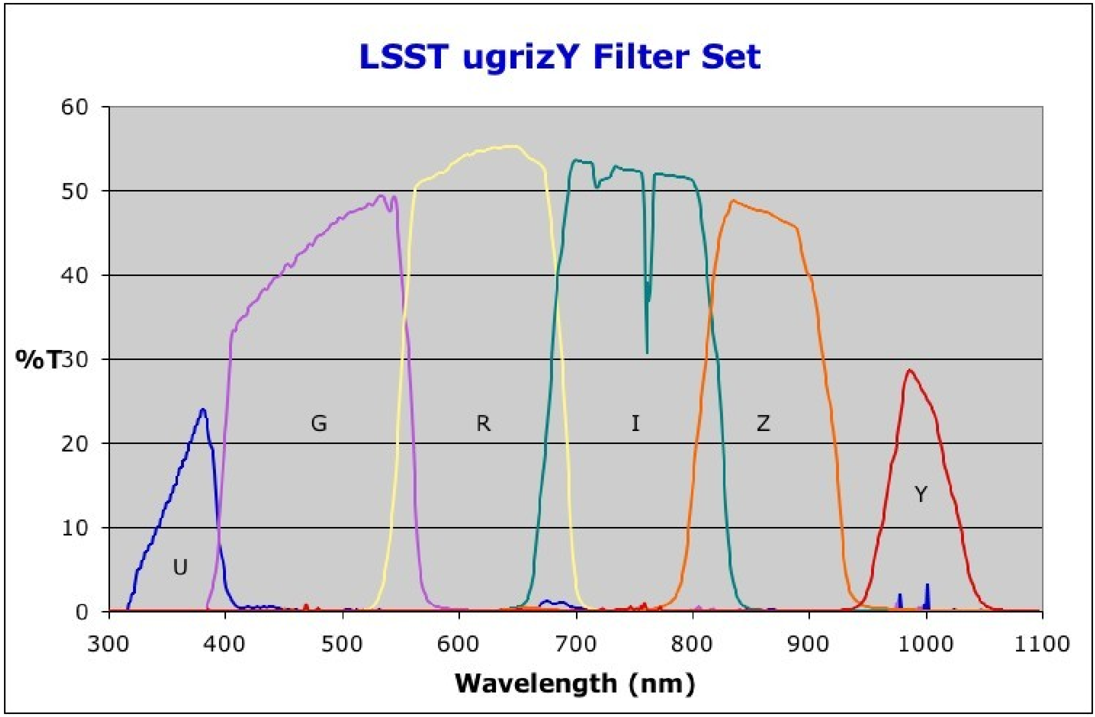
	FOV	diameter	first light	status	who/where
VST @ ESO	1 deg2	2.6 m	2008	funded	ESO
DARKCam	2 deg2	3.6 m	??	refused at ESO	Brits
HyperSuprimeCam	2-3 deg2	8 m	2012	~funded	Japan
Dark Energy Survey	2 deg2	CTIO-4m	2012	not funded	Fermilab
Pan StarsS	7 deg2	1.8 m	2007	funded	Univ. Hawaii
Pan StarsS 4	7 deg2	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, clusters
- Ground based : visible, from space : IR(+visible)

LSST : Concept

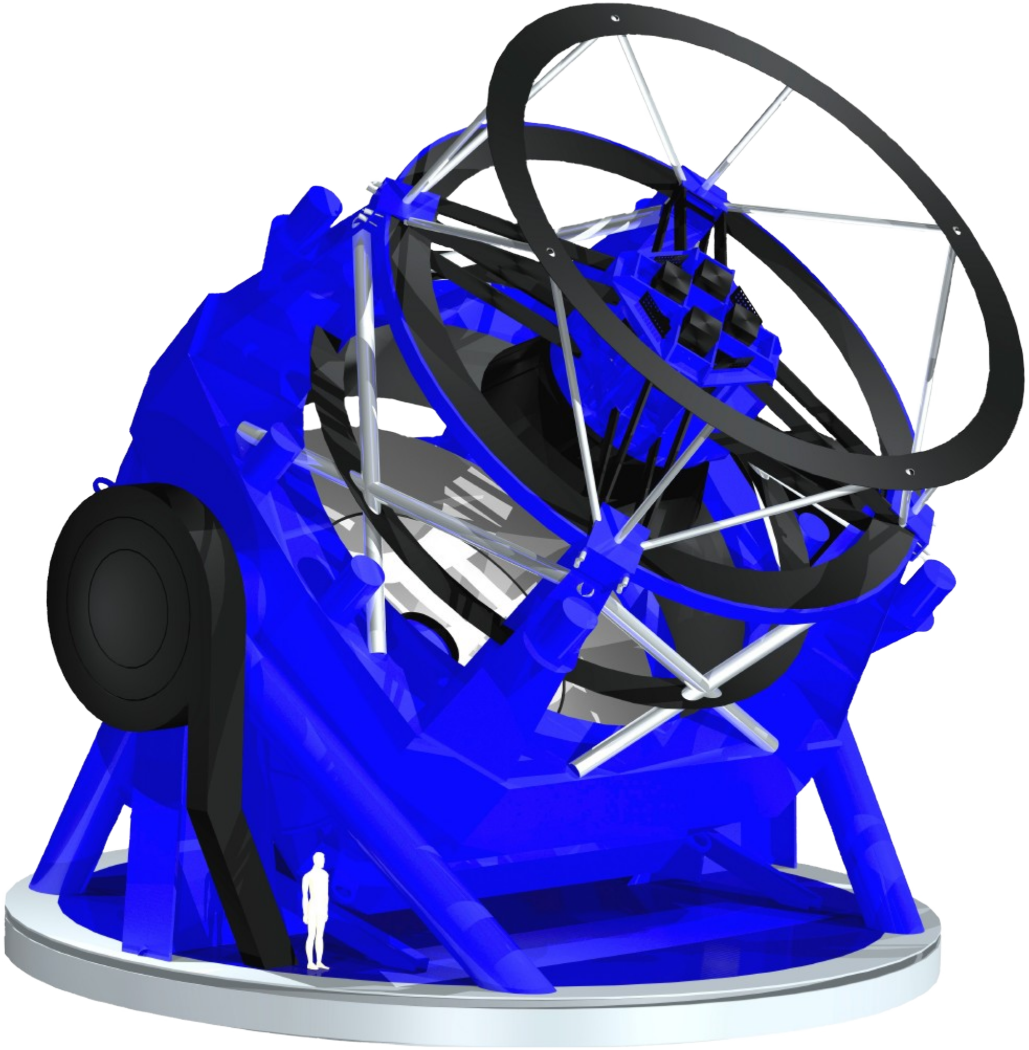
The ultimate machine for ground-based imaging in the visible

- 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
- Almost no open observing time.



LSST Concept

Design Telescope and Camera as a Single Instrument



- 8.4 Meter Primary Aperture
  - 3.4 M Secondary
  - 5.0 M Tertiary
- 3.5 degree Field Of View
- 3.2 Gigapixel Camera
  - 4k x 4k CCD Baseline
  - ~200 detectors
  - 65 cm Diameter
  - Six Filters
- 30 Second Cadence
  - Highly Dynamic Structure
  - Highly Parallel Readout
- Accumulated depth ~27 mag. in each filter over 10y (20000 deg^2)
- Data Storage and Pipelines ~ 18Tb/night!

- Etendue = 270 m^2 deg^2

6-band Survey: *ugrizy* 320–1050 nm

- Sky area covered: 20,000 deg^2 0.2 arcsec / pixel
- Each 9.6 sq.deg FOV revisited >300 times/band
- Time resolution: >20 sec
- Limiting magnitude: 26.5 AB magnitude @10σ (24.5 in u)
  24 AB mag in 15 seconds
- Photometry precision: 0.01 mag requirement, 0.005 mag goal
- Galaxy density: 50 galaxies/sq.arcmin
- 3 billion galaxies with color redshifts
- Time domain: Log sampling, seconds – years

Massively Parallel Astrophysics

- Dark matter/dark energy via weak lensing
- Dark matter/dark energy via supernovae
- Dark Energy via Baryon Acoustic Oscillations
- Galactic Structure encompassing local group
- Dense astrometry over 20000 sq.deg: rare moving objects
- Gamma Ray Bursts and transients to high redshift
- Gravitational micro-lensing
- Strong galaxy & cluster lensing: physics of dark matter
- Multi-image lensed SN time delays: separate test of cosmology
- Variable stars/galaxies: black hole accretion
- QSO time delays vs z: independent test of dark energy
- Optical bursters to 25 mag: the unknown
- 6-band 27 mag photometric survey
- Solar System Probes: Earth-crossing asteroids, Comets
- Extragalactic stars

LSST Dark Energy Highlights

- Weak lensing of galaxies to z = 3.

  Two and three-point shear correlations in linear and non-linear gravitational regimes.

- Supernovae to z = 1.

  Discovery of lensed supernovae and measurement of time delays.

- Galaxies and cluster number densities as function of z.

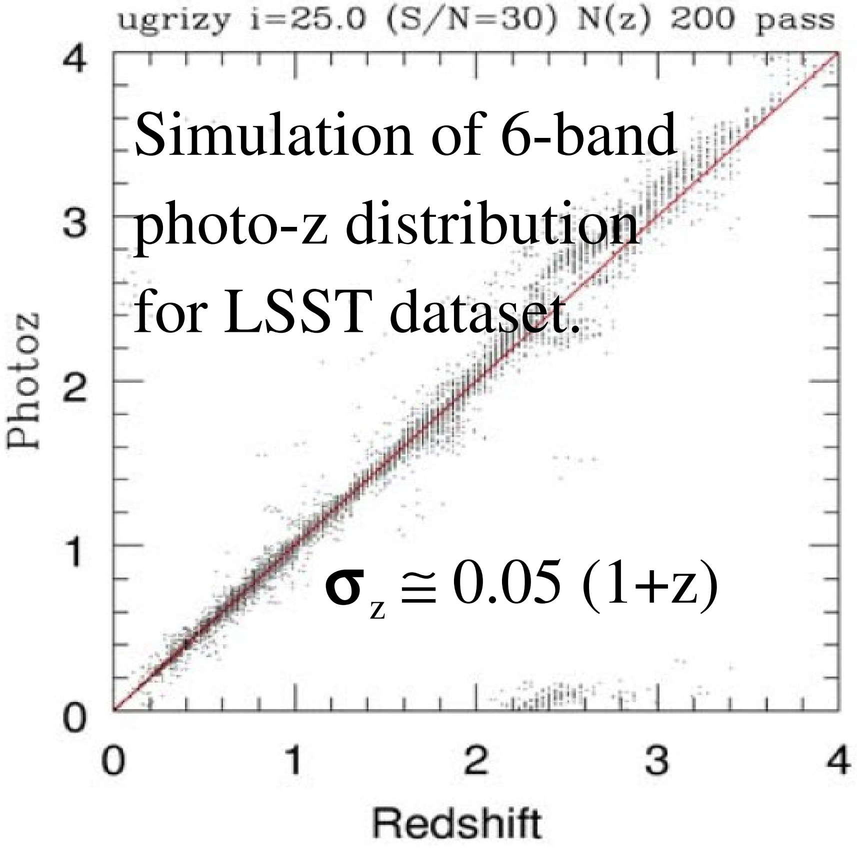
  Power spectra on very large scales $k \sim 10^{-3}\ h\ \mathrm{Mpc}^{-1}$.

- Baryon acoustic oscillations.

  Power spectra on scales $k \sim 10^{-1}\ h\ \mathrm{Mpc}^{-1}$.

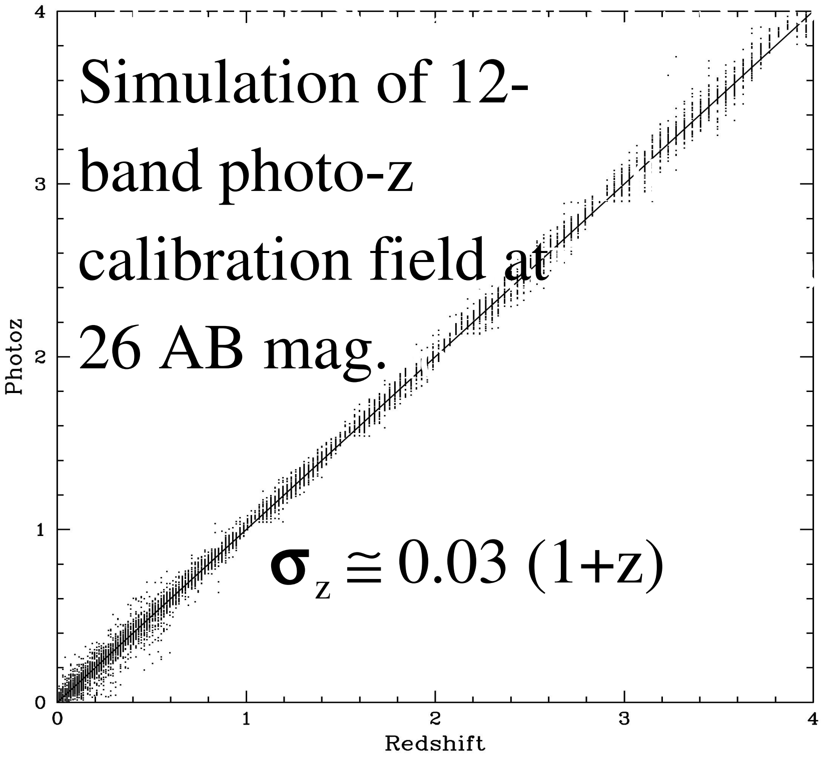
Photo-z Calibration Campaign

- Transfer fields - 200,000 galaxies with 12-band photo-z redshifts.
- Calibrate 12-band photo-z with subset of 20,000 spectroscopic redshifts.



Simulation of 6-band photo-z distribution for LSST dataset.

$\sigma_z \cong 0.05\ (1+z)$



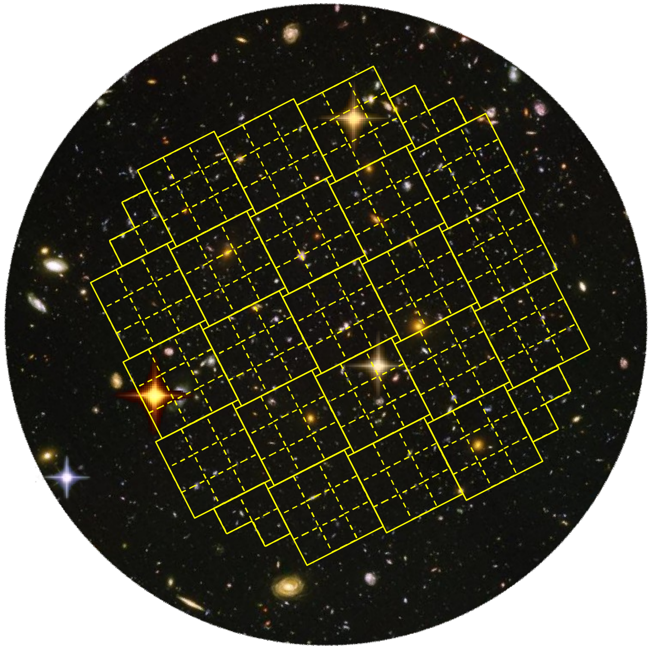
Simulation of 12-band photo-z calibration field at 26 AB mag.

$\sigma_z \cong 0.03\ (1+z)$

Need to calibrate transfer photo-z to 10% accuracy to reach desired precision

Multi-Epoch Data Archive

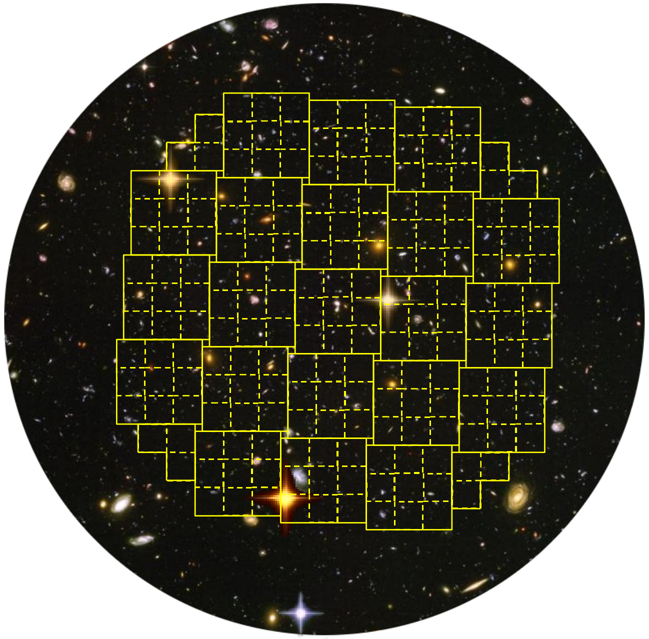
Average down instrumental and atmospheric statistical variations.



Large dataset allows systematic errors to be addressed by subdivision.

Multi-Epoch Data Archive

Average down instrumental and atmospheric statistical variations.



Large dataset allows systematic errors to be addressed by subdivision.

Repeating observation

LSST is designed to repeat short (~30 s) exposures

==> each object is measured several hundred times

This averages :

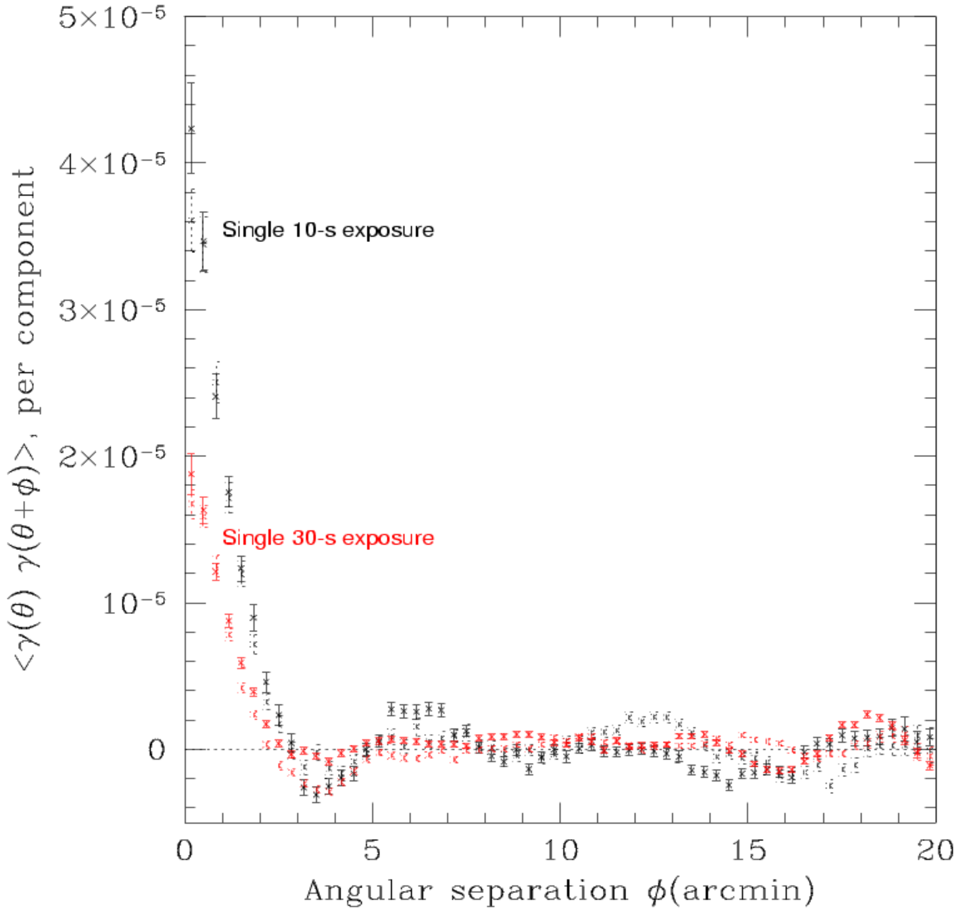
- systematics related to the position and orientation of focal plane.
- atmospheric conditions
- noise in the PSF modeling (lensing)

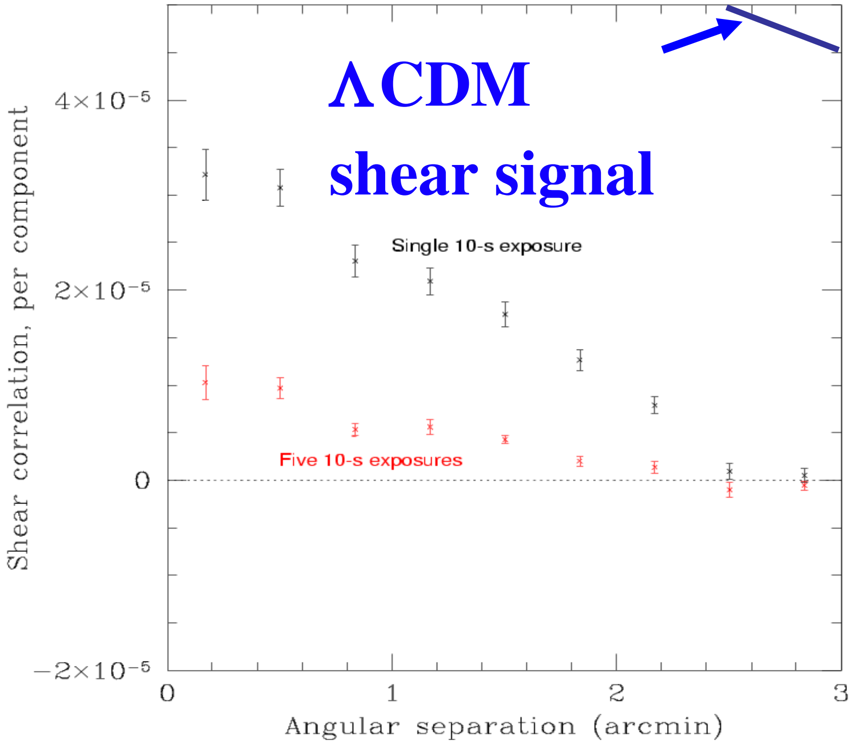
Important advantage for:

- ellipticity measurements.
- photometric calibration.

Residual 2-Point Shear Correlations

LSST multi-epoch survey provides sensitivity well below target signal.



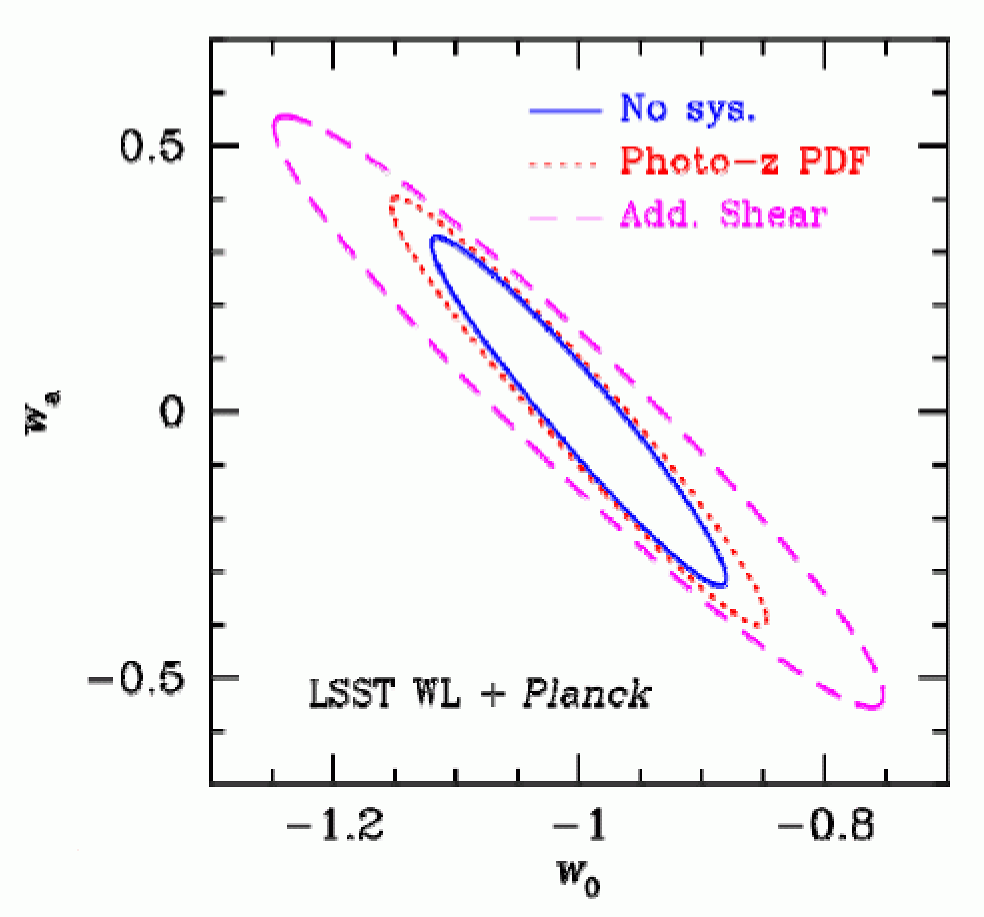


ΛCDM shear signal

Typical separation of reference stars in LSST exposures.

LSST-Lensing

2-point correlation tomography



10 z bins (0<z<3.5)

uncertainties on photo-z :

per galaxy: 0.05(1+z)

per redshift slice :

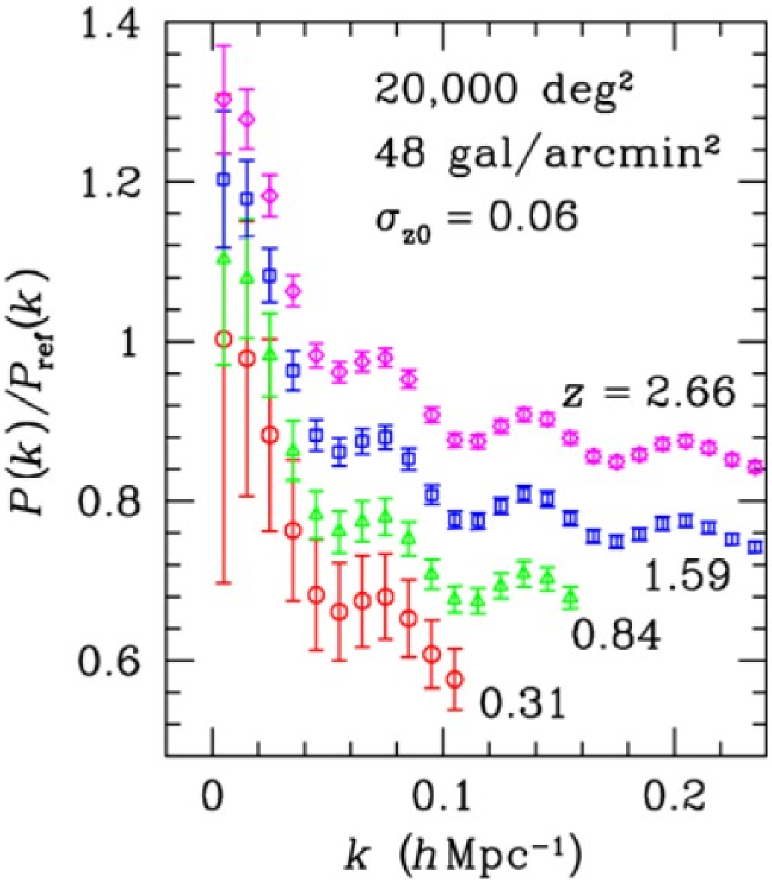
bias : 0.0025(1+z)

scatter : 0.0035(1+z)

Shear residuals:

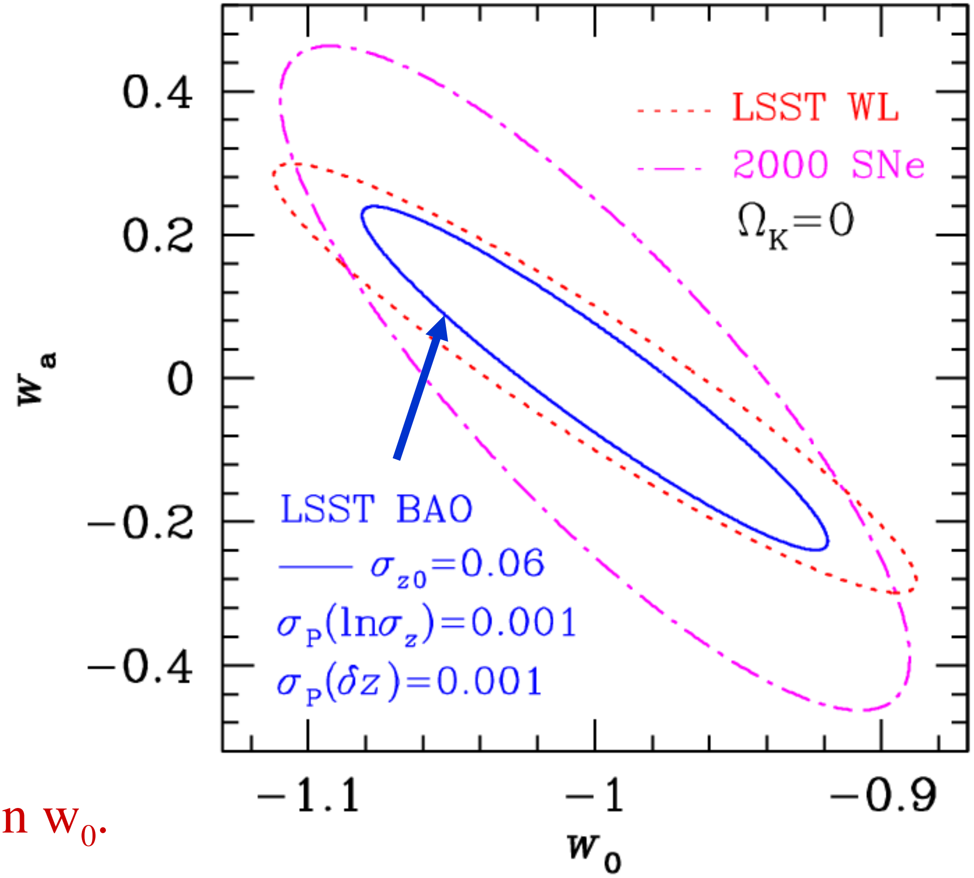
10^{-8} per C_l “bin”

BAO Power Spectra



Two-dimensions on the sky.

3 billion galaxies.



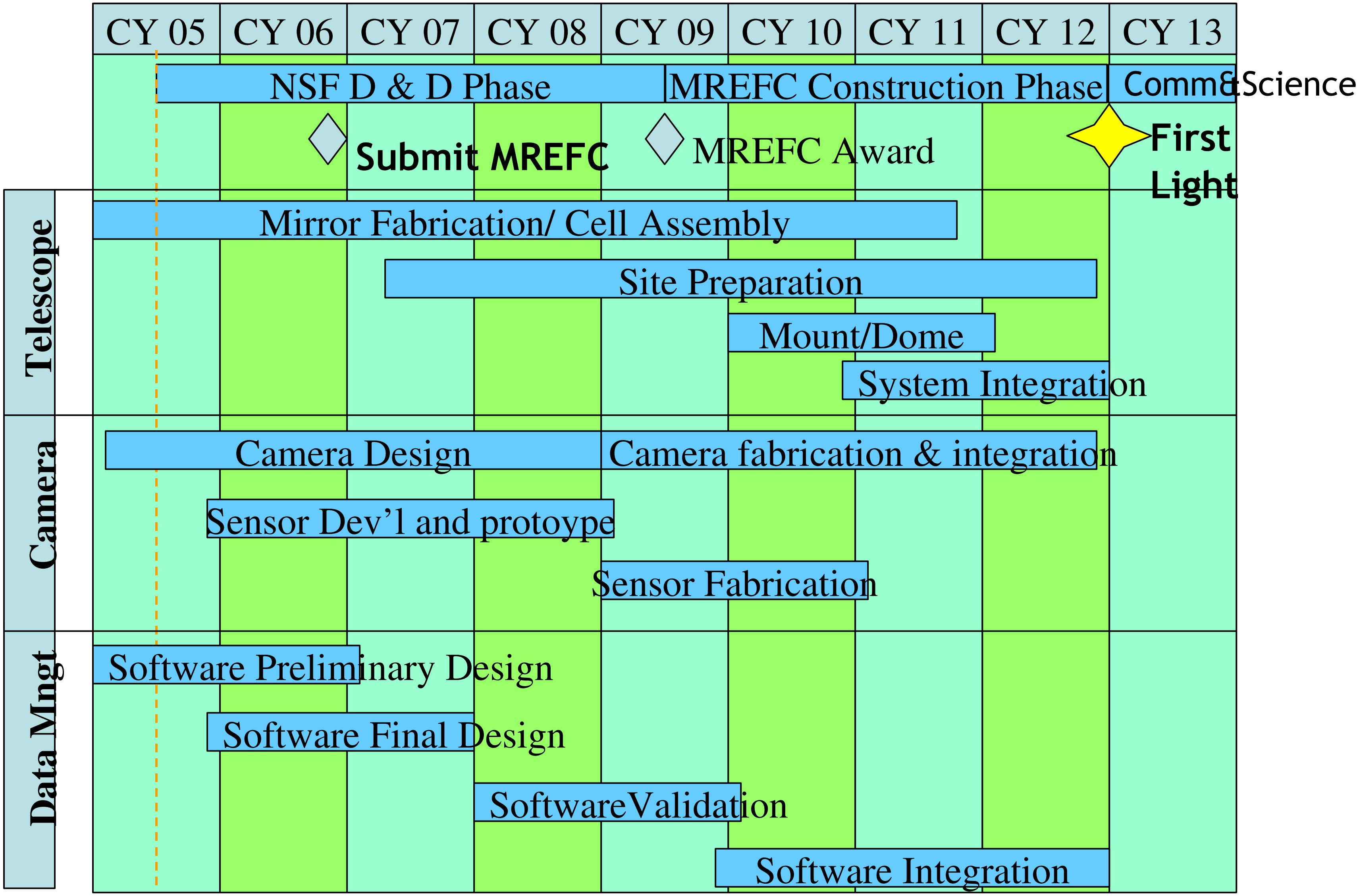
Combination yields accuracy ~ 2 % on w_0.

The LSST Collaboration

- *Brookhaven National Laboratory*
- *Harvard-Smithsonian Center for Astrophysics*
- *Johns Hopkins University*
- *Las Cumbres Observatory*
- *Lawrence Livermore National Laboratory*
- *National Optical Astronomy Observatory*
- *Ohio State University*
- *Pennsylvania State University*
- *Research Corporation*
- *Stanford Linear Accelerator Center*
- *Stanford University*
- *University of Arizona*
- *University of California, Davis*
- *University of Illinois*
- *University of Pennsylvania*
- *University of Washington*

Astronomes (NSF) & Physiciens (DOE)

Project Baseline Schedule Plans



CY 05 | CY 06 | CY 07 | CY 08 | CY 09 | CY 10 | CY 11 | CY 12 | CY 13

NSF D & D Phase

MREFC Construction Phase

Comm&Science

Submit MREFC

MREFC Award

First Light

Telescope

Mirror Fabrication/ Cell Assembly

Site Preparation

Mount/Dome

System Integration

Camera

Camera Design

Camera fabrication & integration

Sensor Dev'l and protoype

Sensor Fabrication

Data Mngt

Software Preliminary Design

Software Final Design

SoftwareValidation

Software Integration

more realistic : first light expected by 2014, if funded

Space based DE projects

The JDEM (Joint Dark Energy Mission) framework :

3 mission concepts

- ADEPT (BAO and Sne, all spectroscopic)
- Destiny (SNe and BAO, all spectroscopic)
- SNAP (SNe and WL) Imaging and spectroscopy

In Europe:

- DUNE (mainly WL) -> see Y. Mellier's talk

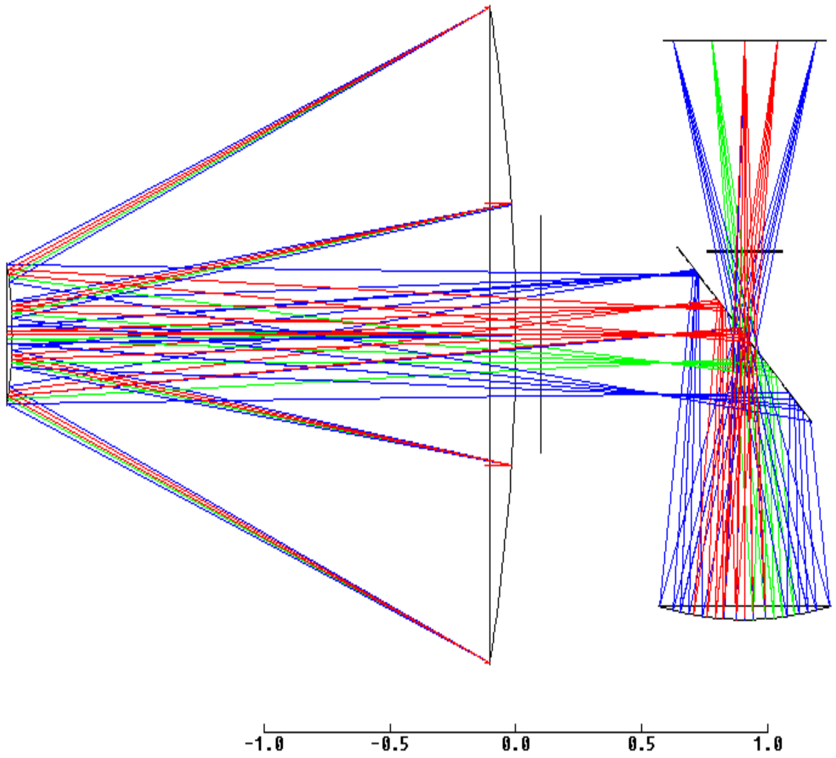
SNAP Concept

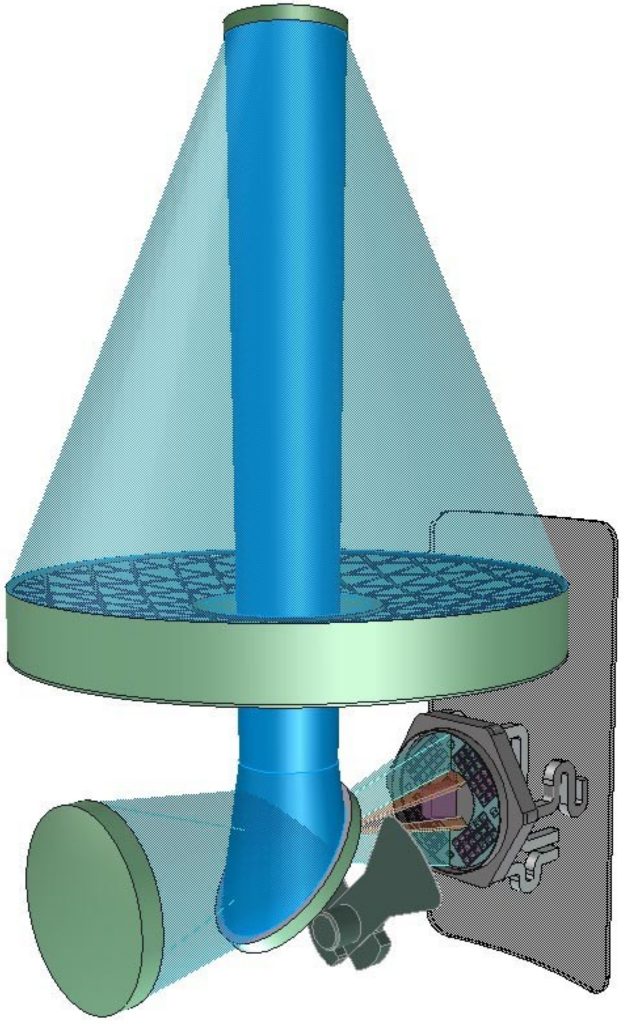
- Build a SNe Ia Hubble diagram up to z=1.7
  High S/N multiband photometry
  Identify all SNe spectroscopically
  -> onboard spectrograph

- moderate size very accurate WL survey,
  with excellent photo-z's

SNAP Telescope

- 2-m primary aperture, 3-mirror anastigmatic
- Provides a wide-field flat focal plane.





SNAP Imager : visible + NIR

- *A large solid-angle camera (0.7 square degrees) provides multiplexed supernova discovery and followup.*
- *Covers wavelength region of interest, 0.35-1.7 microns.*
- *Fixed filter mosaic on top of the imager sensors.*

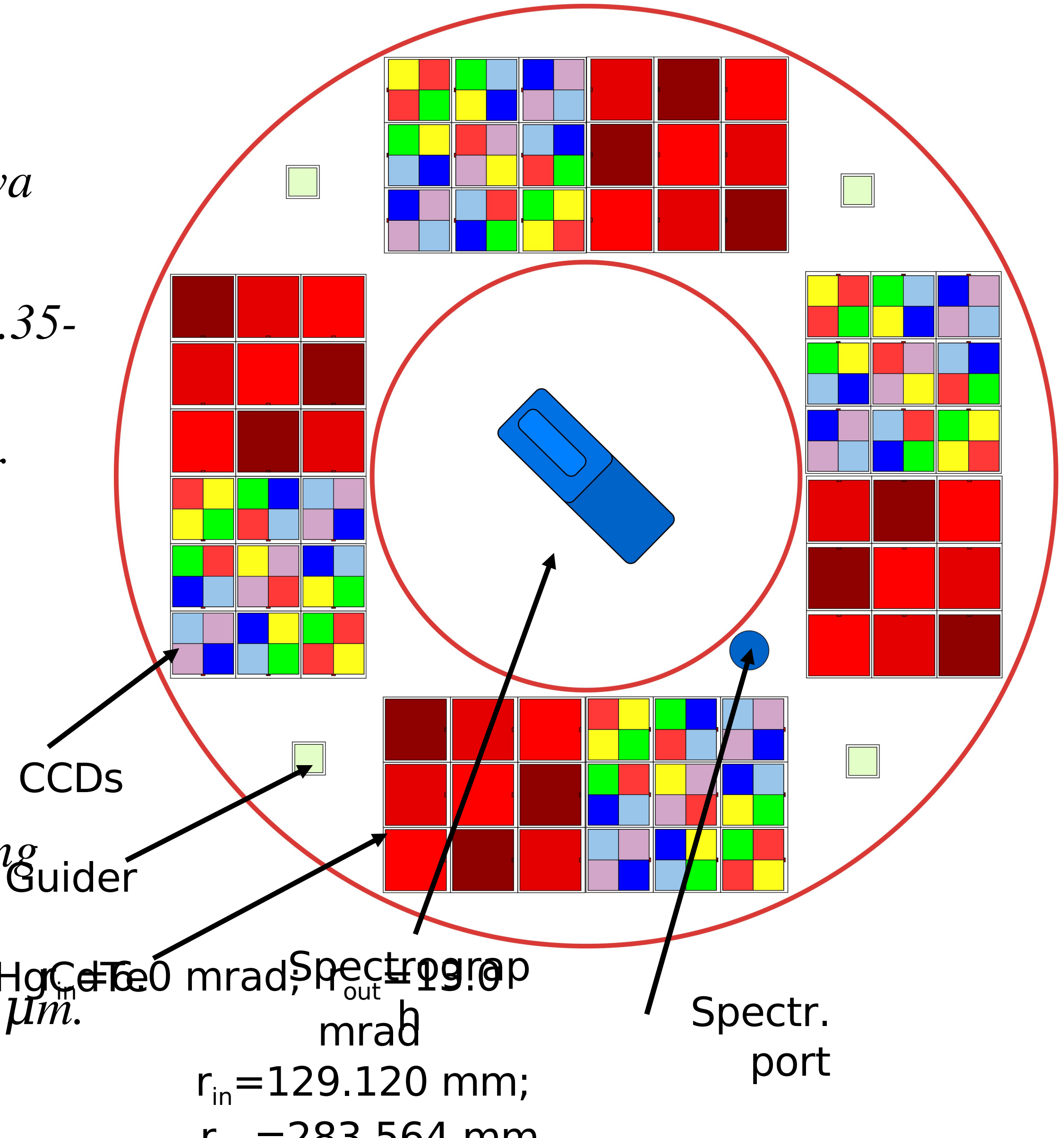
— 3 NIR bandpasses.

— 6 visible bandpasses.

- *Coalesce all sensors at one focal plane.*

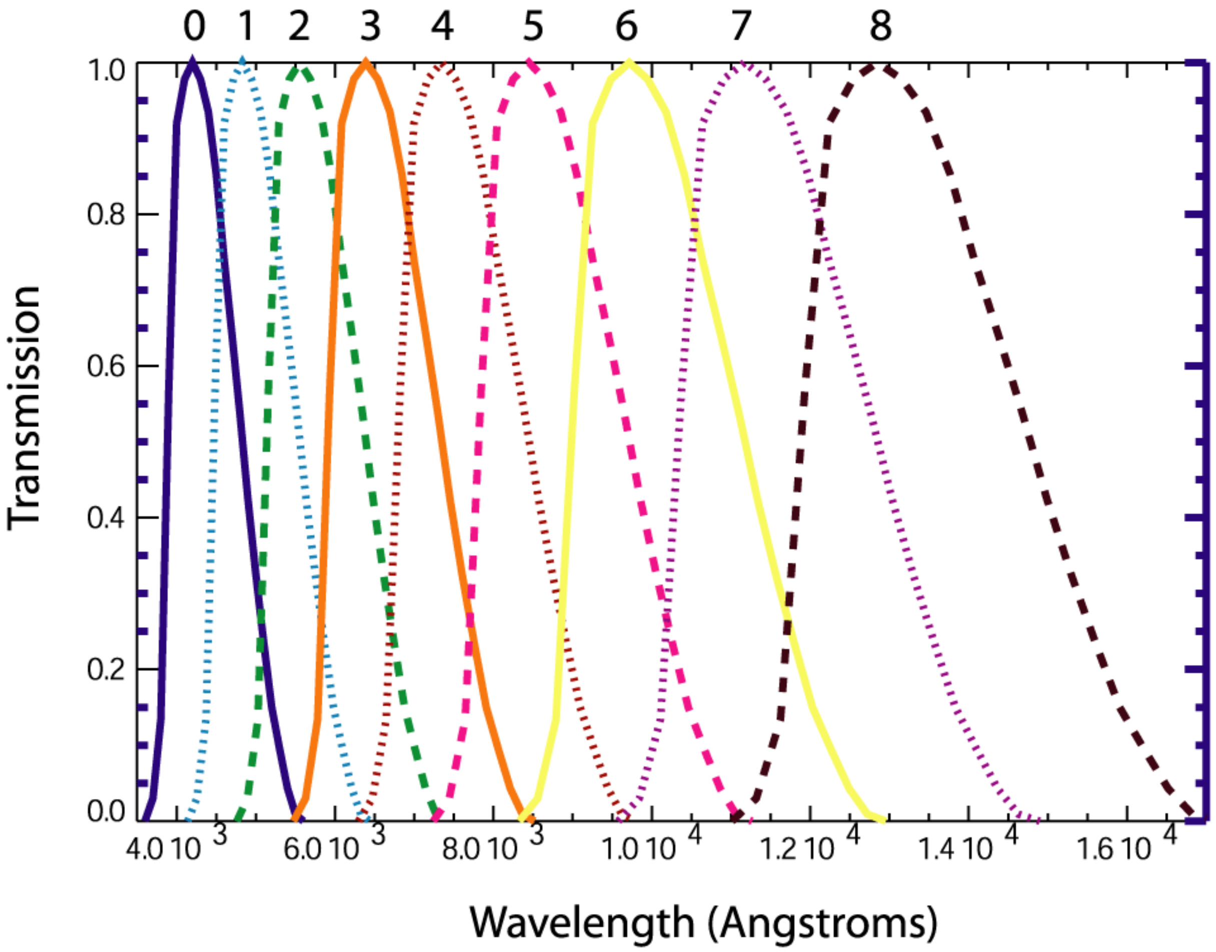
— 36 2k x 2k HgCdTe NIR sensors covering 0.9-1.7 µm.

— 36 3.5k x 3.5k CCDs covering 0.35-1.0 µm.

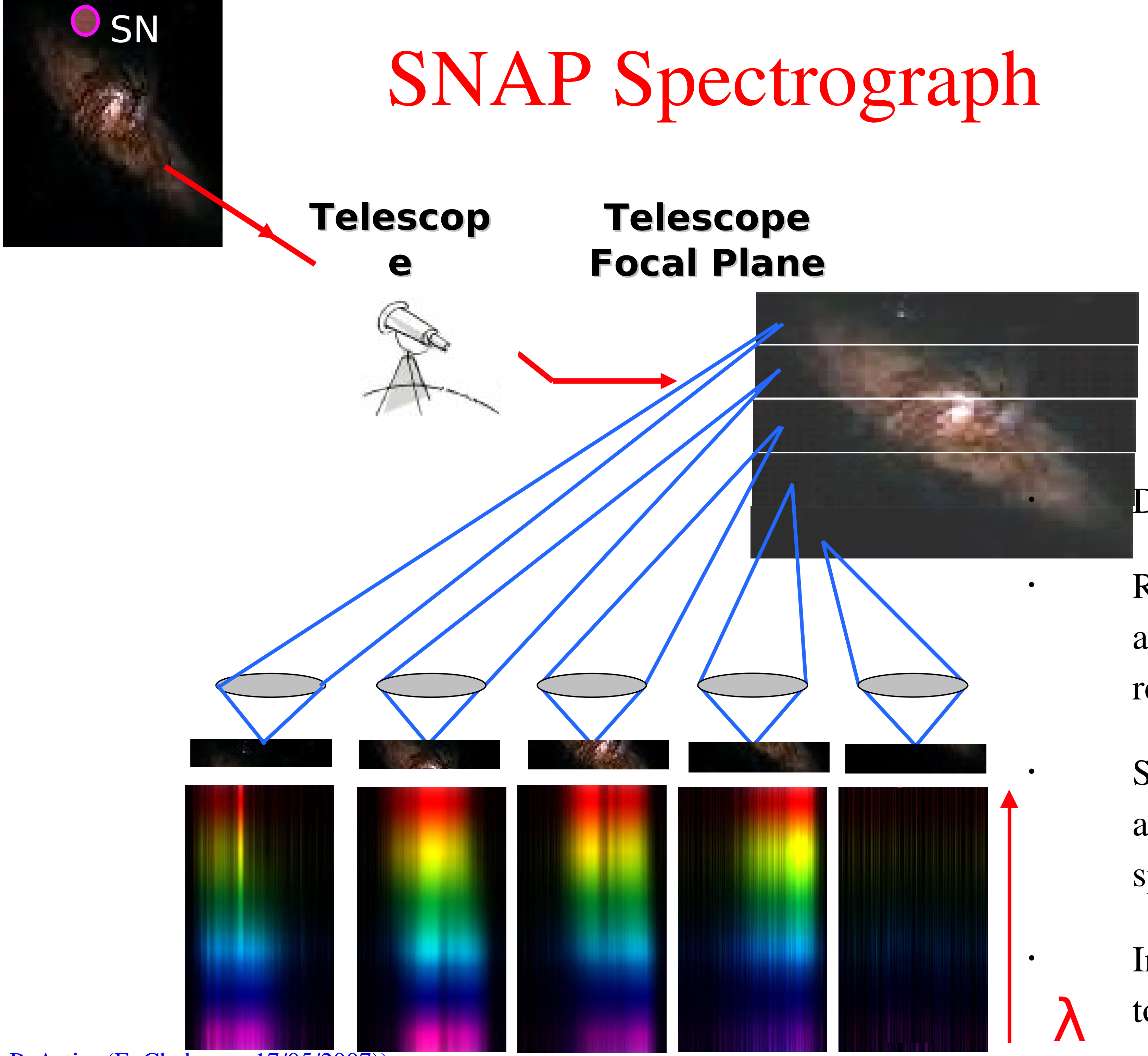


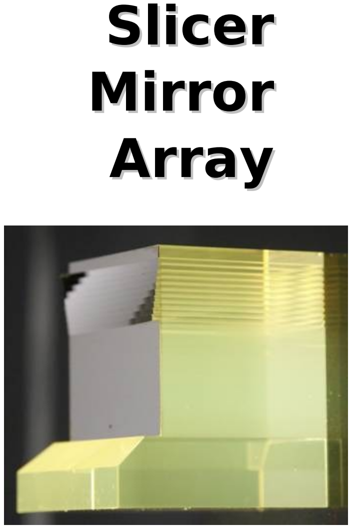
SNAP filters

9 redshifted B-band filters distributed logarithmically.



SNAP Spectrograph

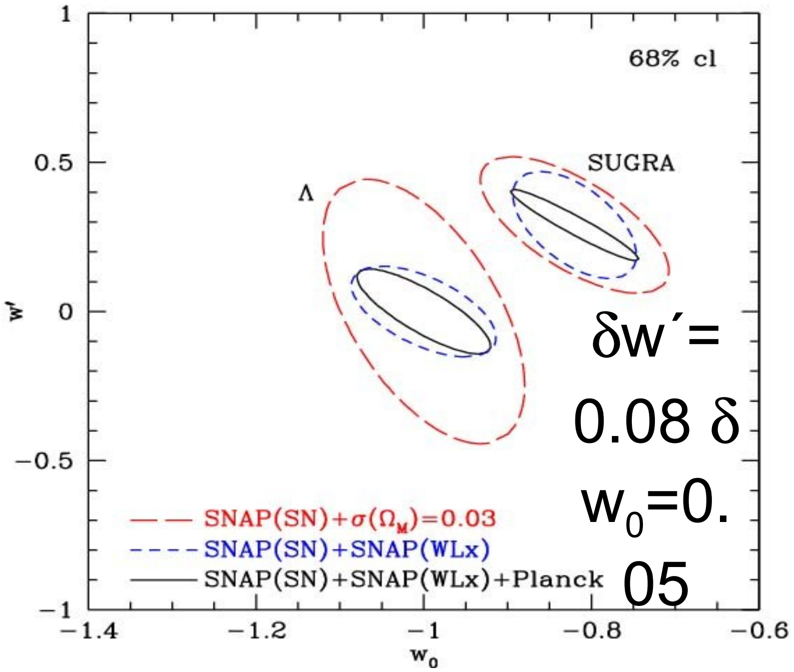




- Data cube
- Reduces pointing accuracy requirement
- Simultaneous SNe and host galaxy spectra
- Internal beam split to visible and NIR.

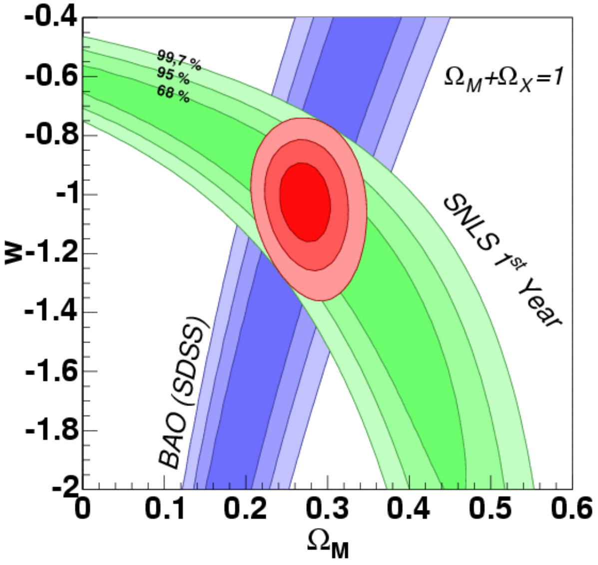
SNAP Data Products

- Supernovae
  - ~2000 SNe Ia @ 0.1<z<1.7
  - 9-band light curves with 4-day cadence
  - Spectrum near maximum (triggered)
- Weak Lensing
  - 1000 (+?) square degrees
  - 100 resolved galaxies per square arcmin
  - 9-band photo-z determination



$\delta w' = 0.08$ $\delta w_0 = 0.05$

Conclusions



- Dark Energy looks like a cosmological constant.
- Current ground-based efforts could reach <w> to 0.05
- Many expensive space projects in the landscape :
    - Agencies recognize the importance of DE science
    - Competitions are finally beginning, but it is not clear that a DE mission will come out.
    - Results (if any) by 2020+

- DE science will be ground-based during the next decade.