Dark Energy,
a panorama

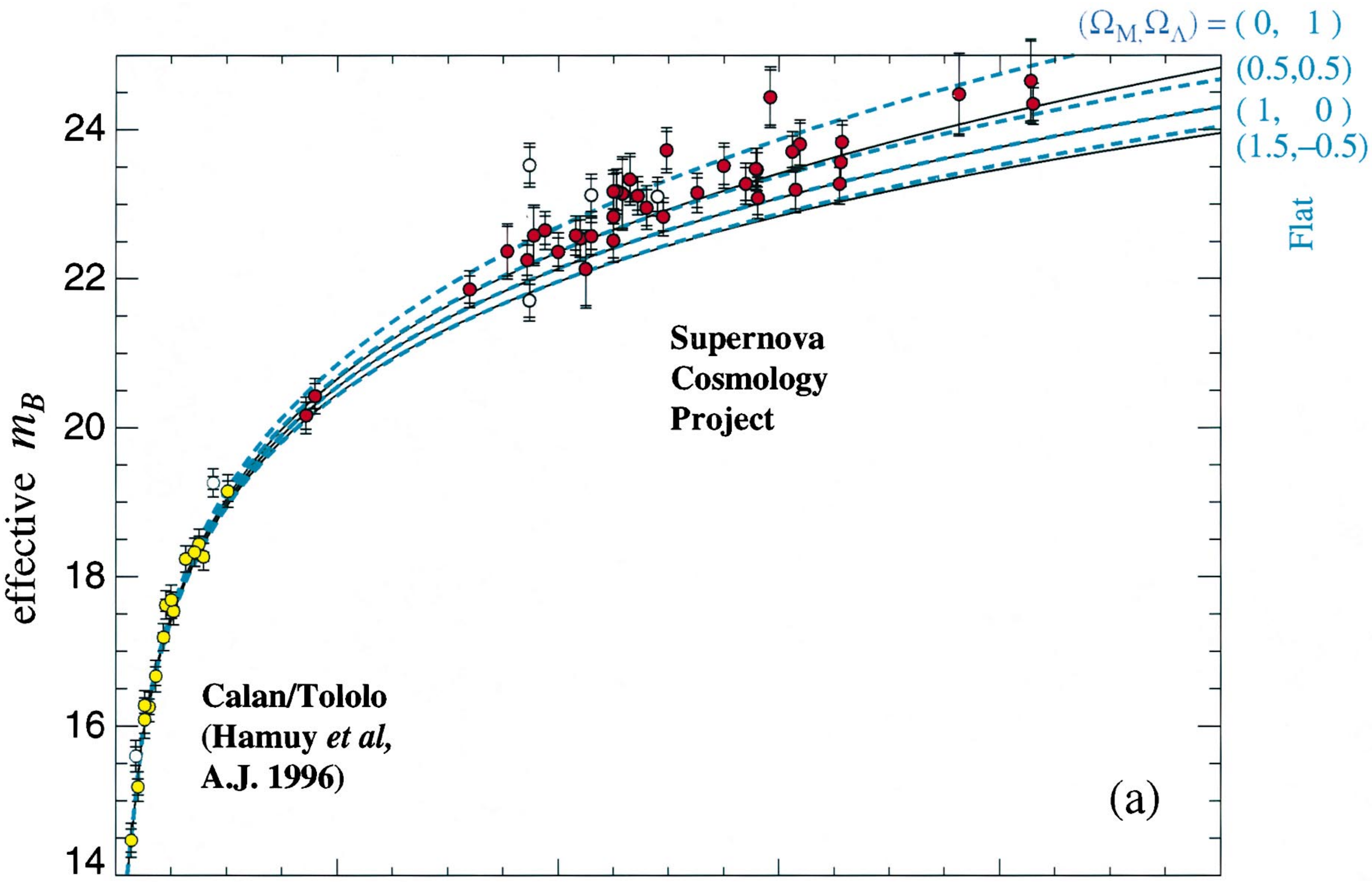
Éric Aubourg

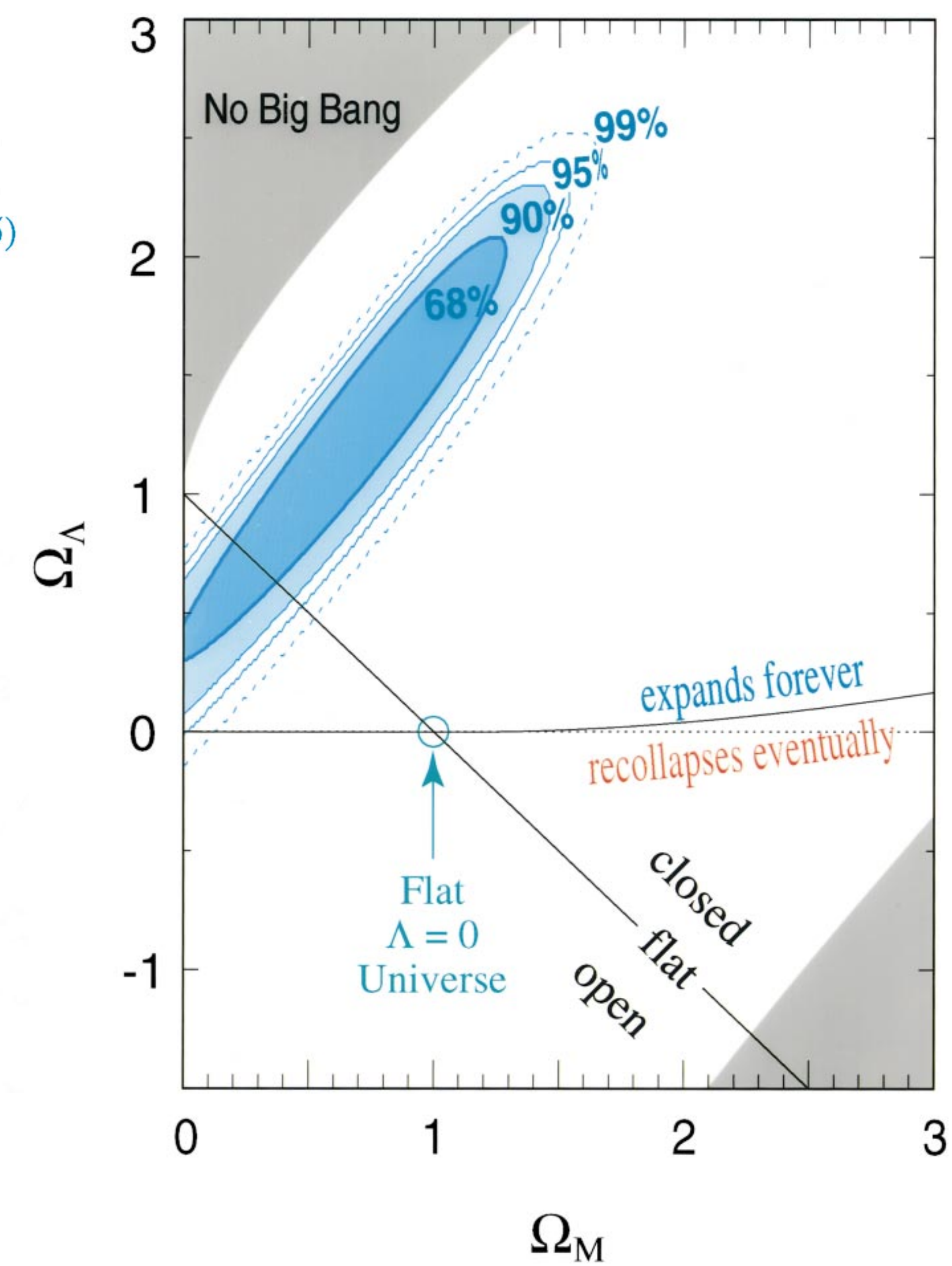
CS IN2P3 october 2012

Introducing dark energy and the theoretical framework

Dark energy probes

Current, mid-term and long term projects





Perlmutter et al., 1999

The need for dark energy

SNIa: the Universe is currently in an accelerated expansion phase.

Also:

- CMB indicates flat universe, and $\Omega_m < 1$ (lensing, BAO...)
- Age of the universe constraints combined with H_0 + flatness
- Observation of Integrated Sachs-Wolfe effect
- General consistency of the ΛCDM model with all observations

Why is the expansion accelerating?

Extra component?

Equation of state $p = w\rho$, with $w < -1/3$

Modified general relativity?

Those models have different impact on the Universe **expansion history** and on the **growth of structures**.

Goal of current projects: characterize as best as possible those effects, using clusters, baryon acoustic oscillations, supernovae, gravitational lensing, CMB…

Theoretical framework

Homogen and isotropic universe (> 100 Mpc)

General relativity

FLRW metric

➥ Friedmann equations for each component

Standard model ingredients

Baryons: Ω_b

Dark matter (cold): Ω_m

Neutrinos: Ω_ν ($< 10^{-2}$)

Photons: Ω_γ ($\sim 6.\ 10^{-5}$)

Dark energy: Ω_Λ

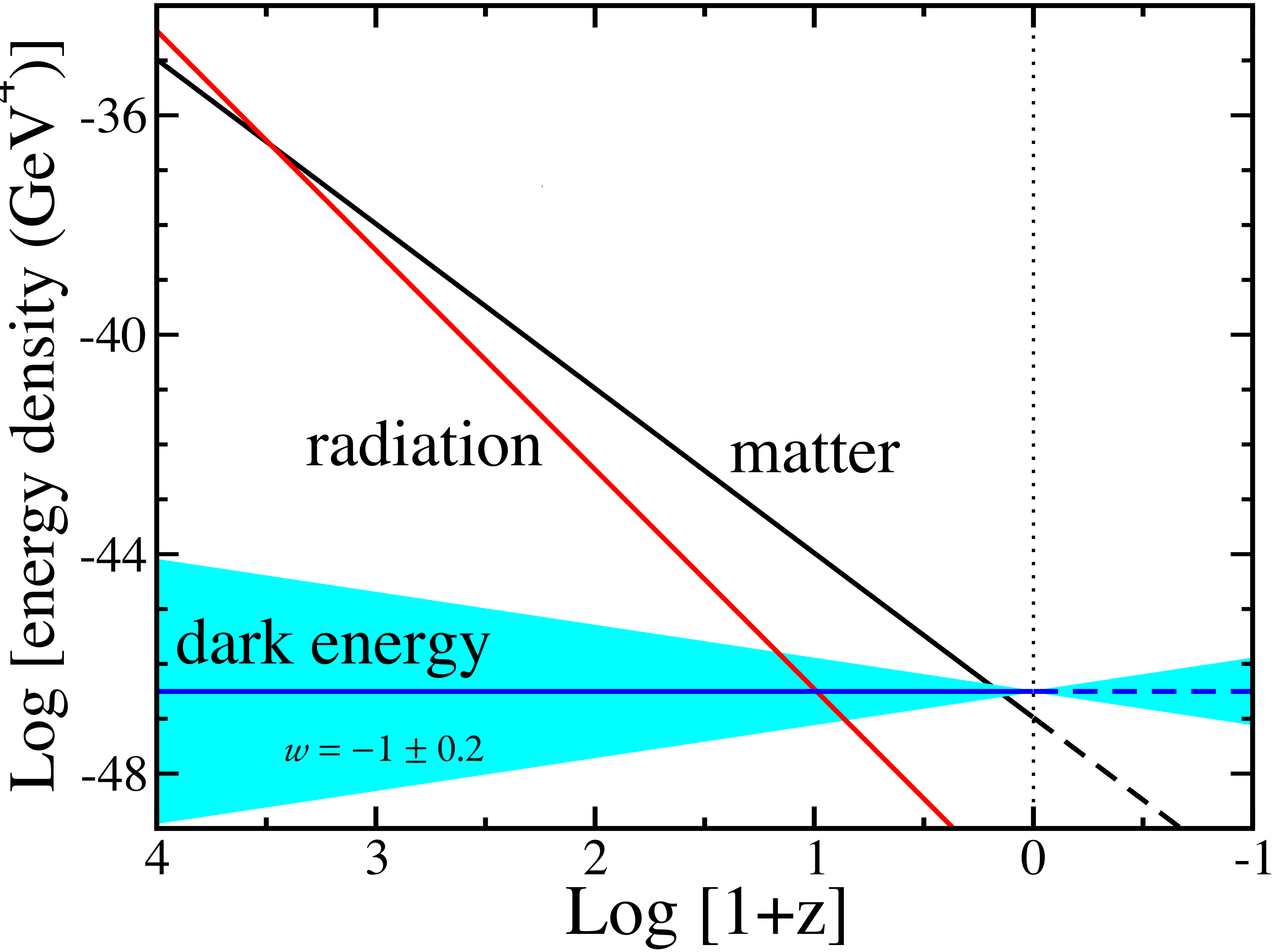
equation of state $p = w\rho$, $w < -1/3$

Curvature, or not: $\Omega_k = 1 - \Sigma\Omega_i$

ΛCDM: $w=-1$, $\Omega_k = 0$.

In units of the critical density

$\Omega_{tot} = 1 \Leftrightarrow$ flat



Log [energy density (GeV^4)]
-36
-40
-44
-48
radiation
matter
dark energy
$w = -1 \pm 0.2$
4
3
2
1
0
-1
Log [1+z]

Alternatives

Dark energy equation of state:

$w \neq -1$

non constant w

(expected in theories like quintessence)

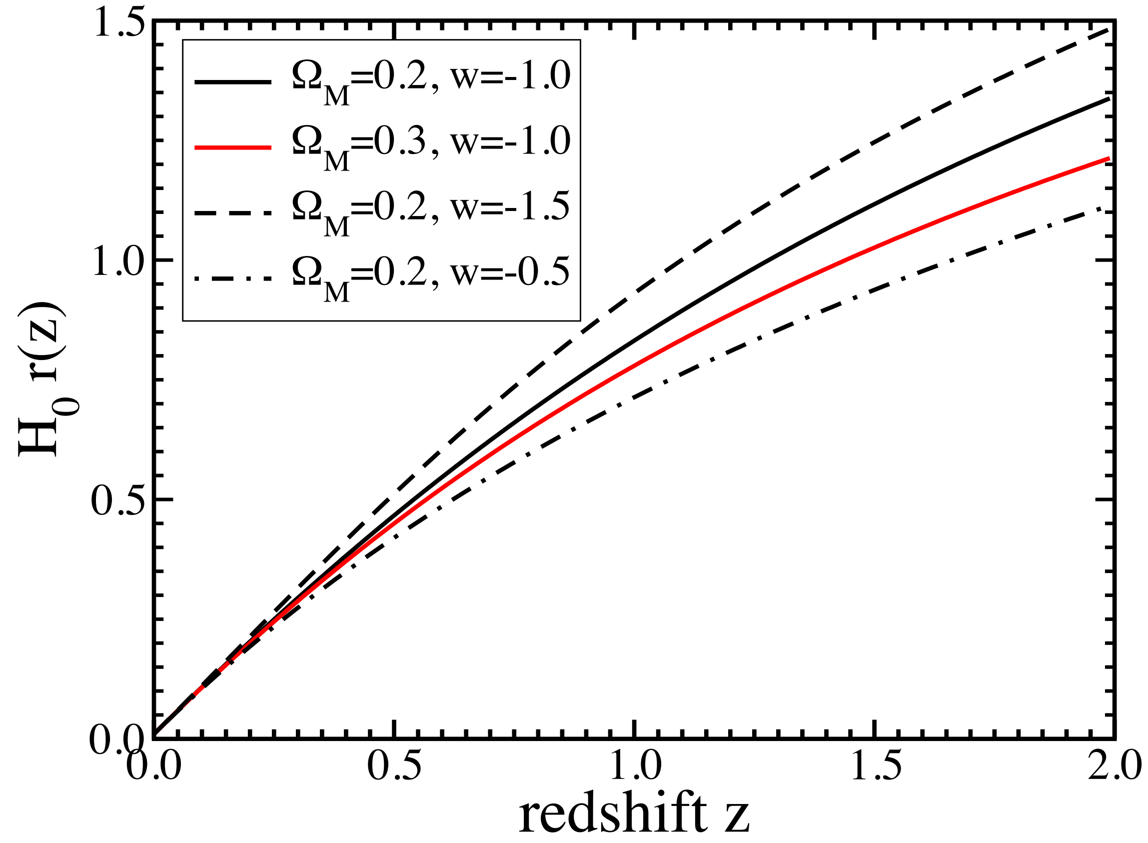
Modified general relativity

f(R) theories, extra dimensions...

Cosmological principle revision

Inhomogeneous universe...

Some observables

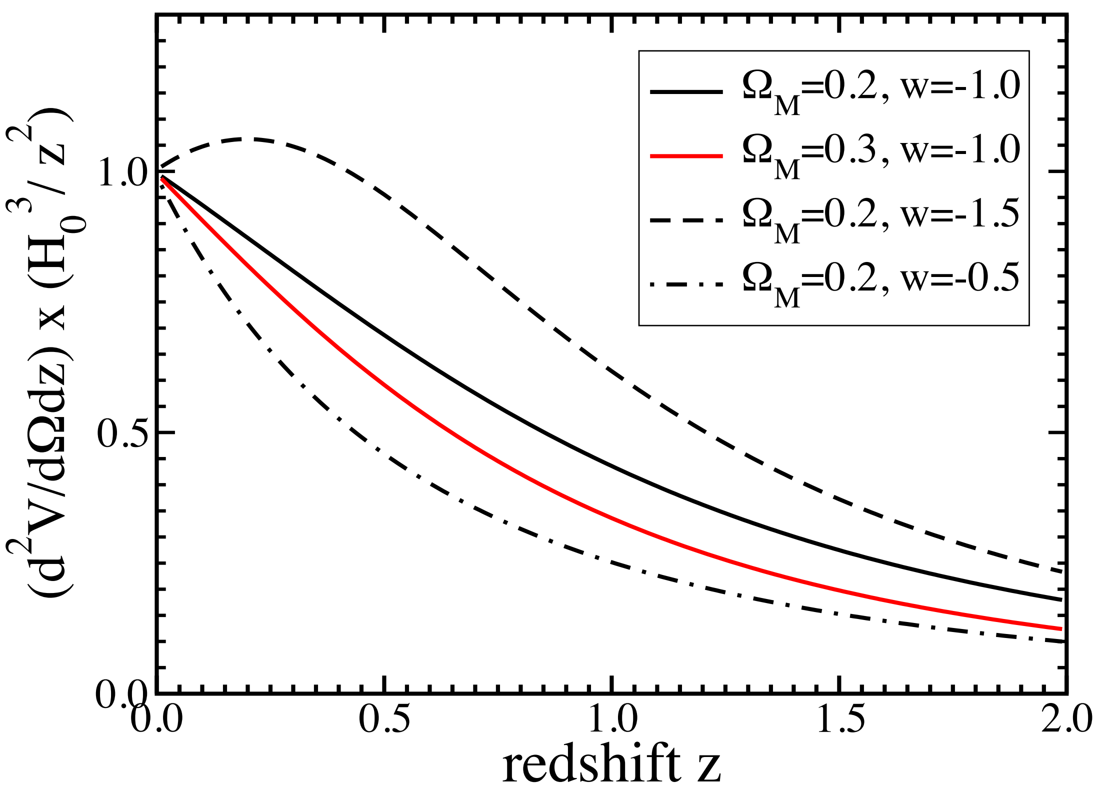


distances

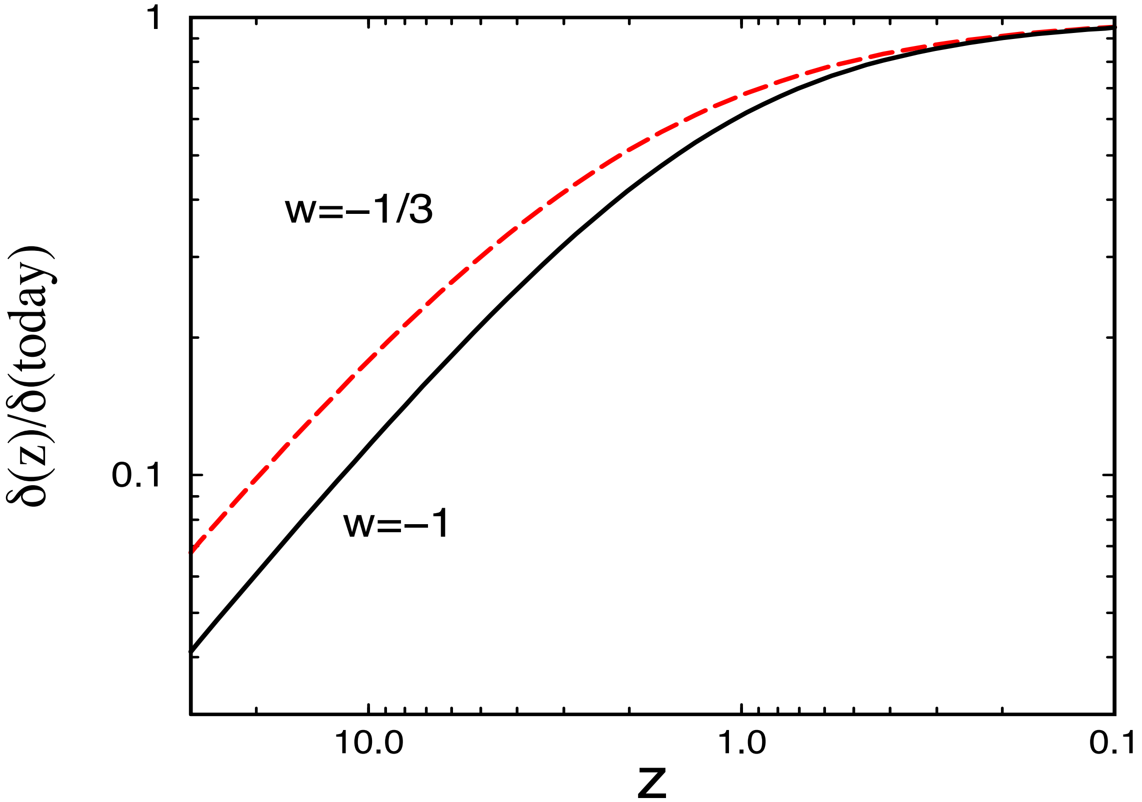
$d_A = r(z)/(1+z)$

$d_L = (1+z)\, r(z)$

volume element



Some observables



Structure growth

The main probes

Supernovae

Galaxy clusters

Baryon acoustic oscillations

Gravitational lenses

CMB

CMB probes the Universe at z=1000

- Not directly sensitive to dark energy, subdominant at that stage
- Very important to lift degeneracies between cosmological parameters
- Provides the amplitude of density fluctuations at z=1000
- For BAO, allows to measure the sound horizon at z=1000

CMB foregrounds can probe dark energy (more on this later)

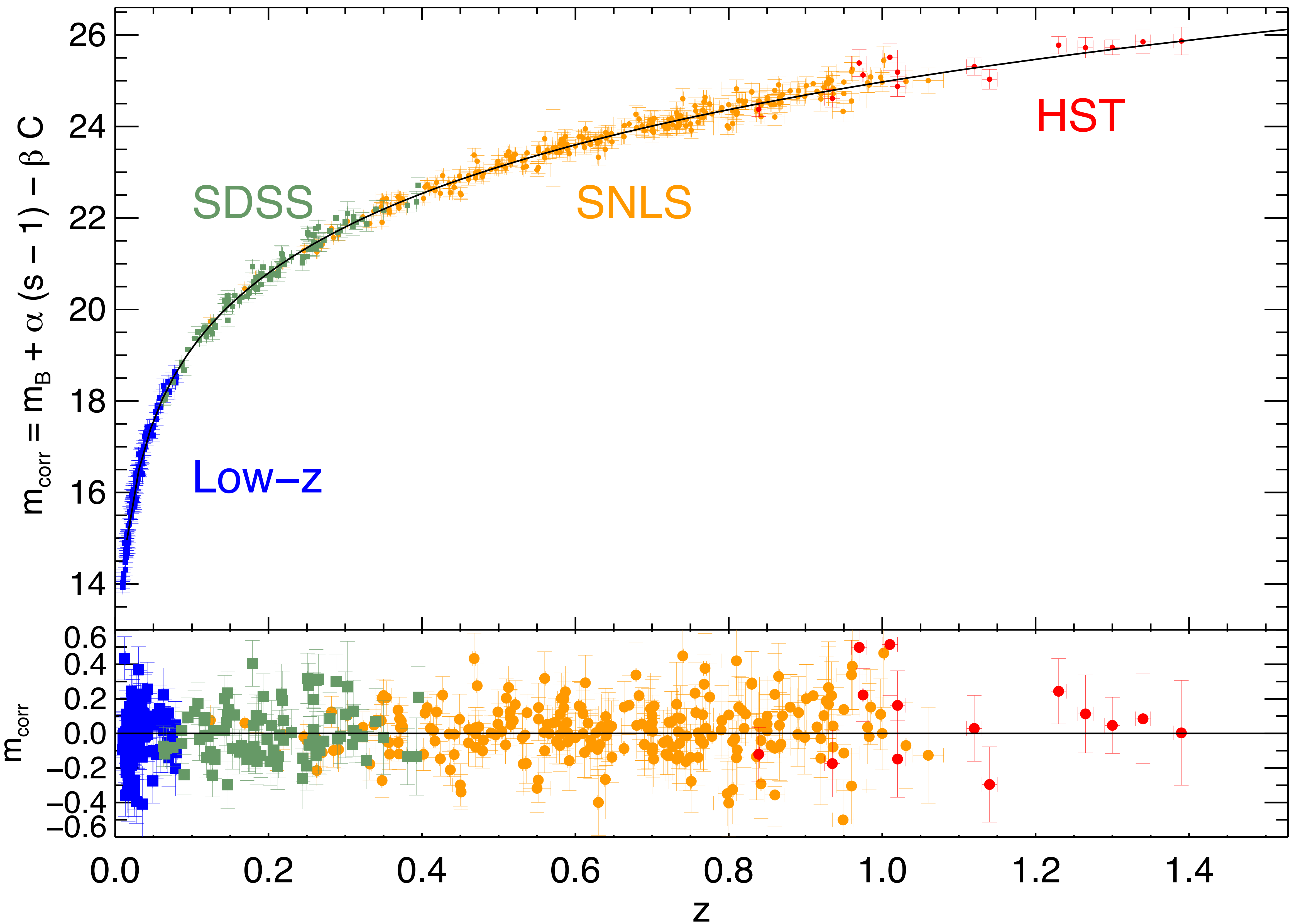
Supernovae

SN Ia = standardizable candles

➥Measure of $d_L(z)$

1998 : confirm previous hints towards ΛCDM

Current SNIa sample from local searches, SNLS, SDSS, HST...



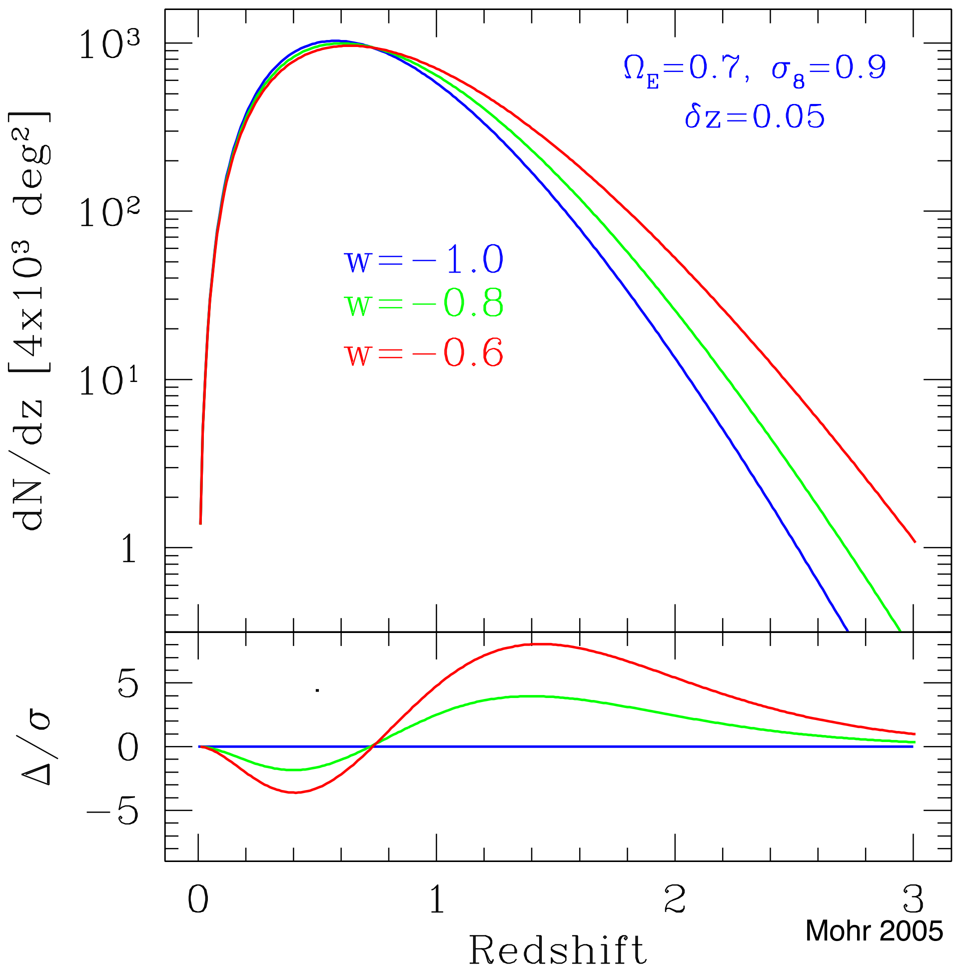
SDSS
SNLS
HST
Low−z
$m_{corr} = m_B + \alpha\,(s-1) - \beta\,C$
m_{corr}
z
Conley et al. 2011

Supernovae

- Latest surveys are limited by systematic errors
  - Calibration, K-correction…
  - Astrophysical uncertainties : environment (metallicity), age (stellar evolution paths)…
- Can very high statistics (LSST) allow testing for systematics?

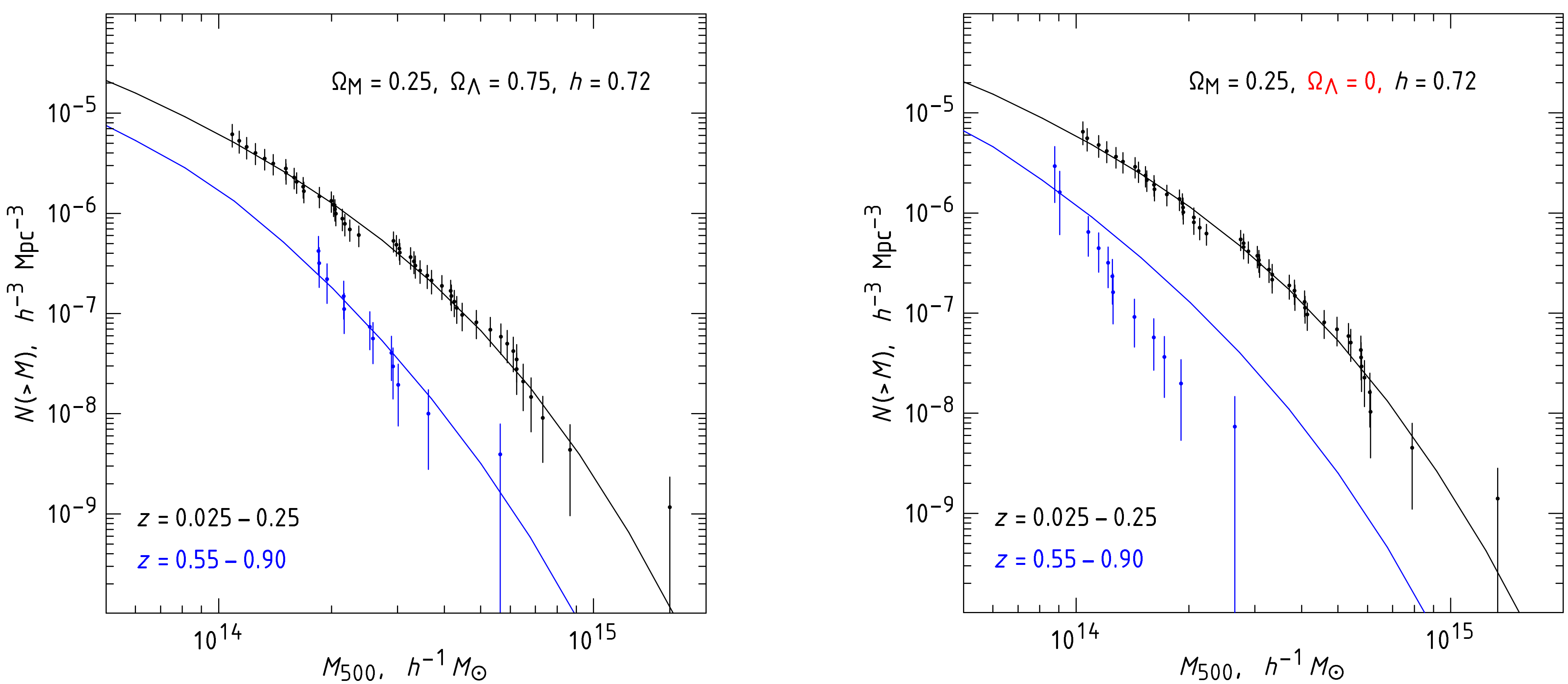
Galaxy clusters

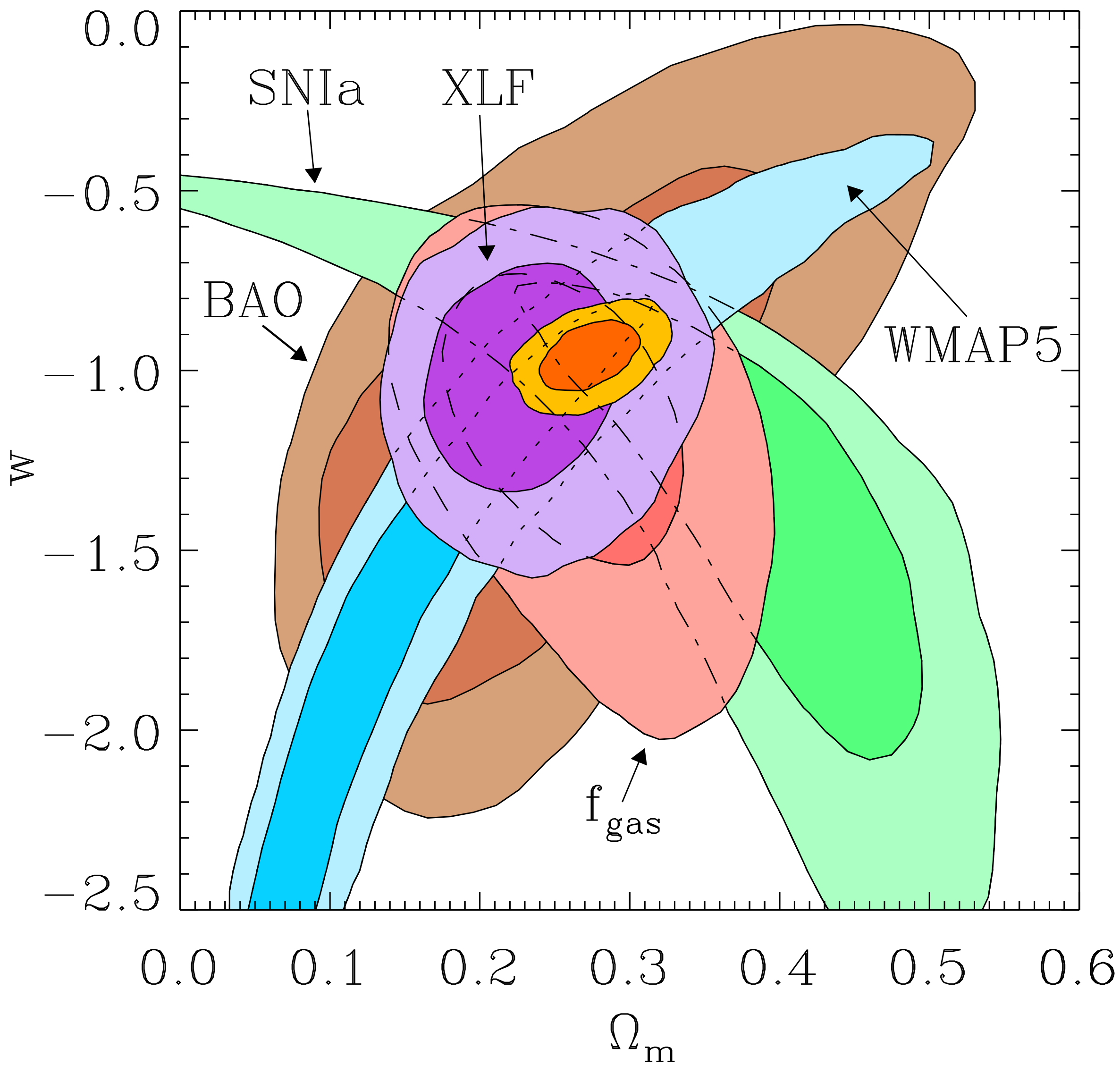
Cluster density (for a given mass limit) is very sensitive to both the expansion of the Universe and the growth of structures.



$M > 2\ 10^{14}\ M_o$

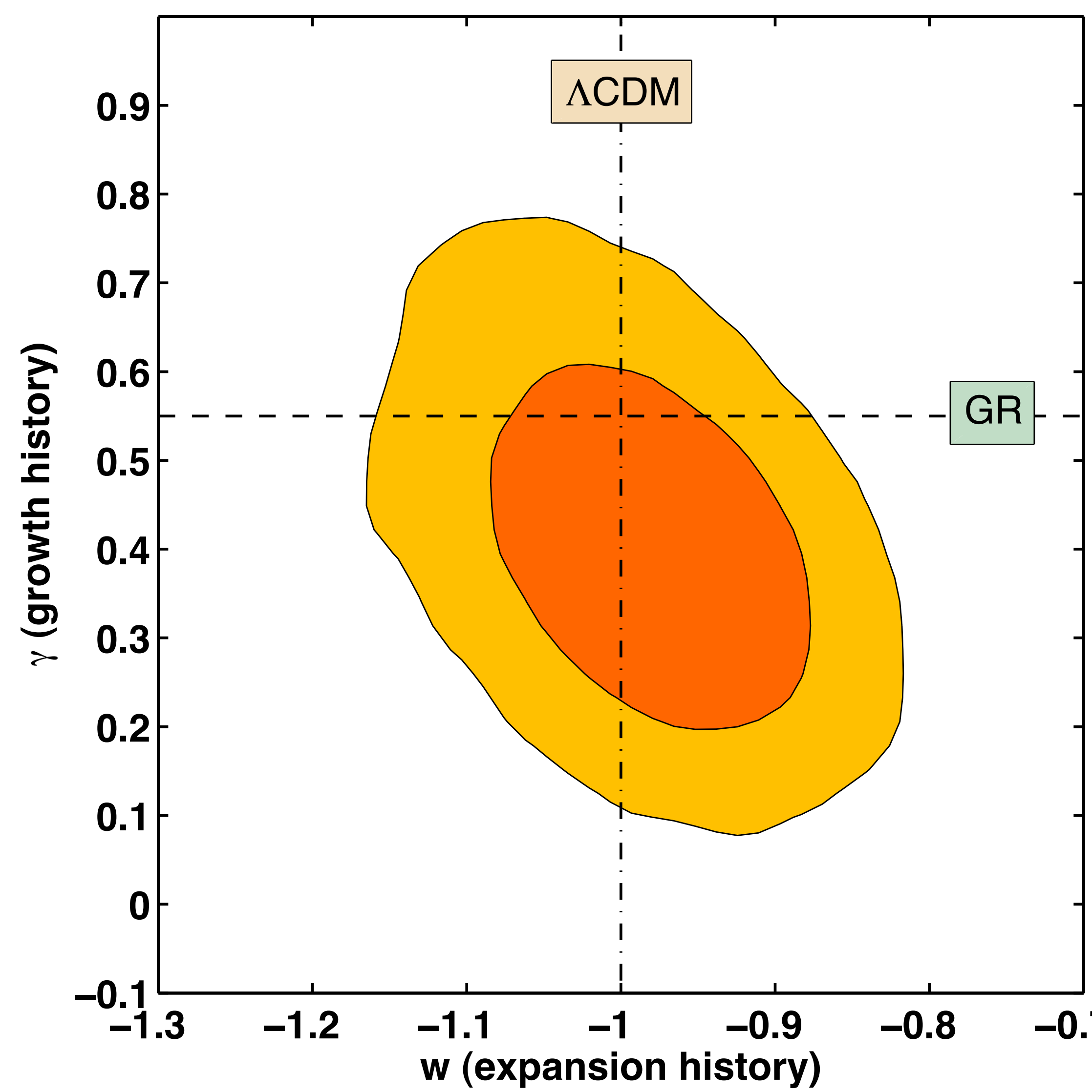
Vikhlinin et al. 2009





ΛCDM+w

Parameterized departure from GR / ΛCDM+w



Allen et al. 2011

Galaxy clusters

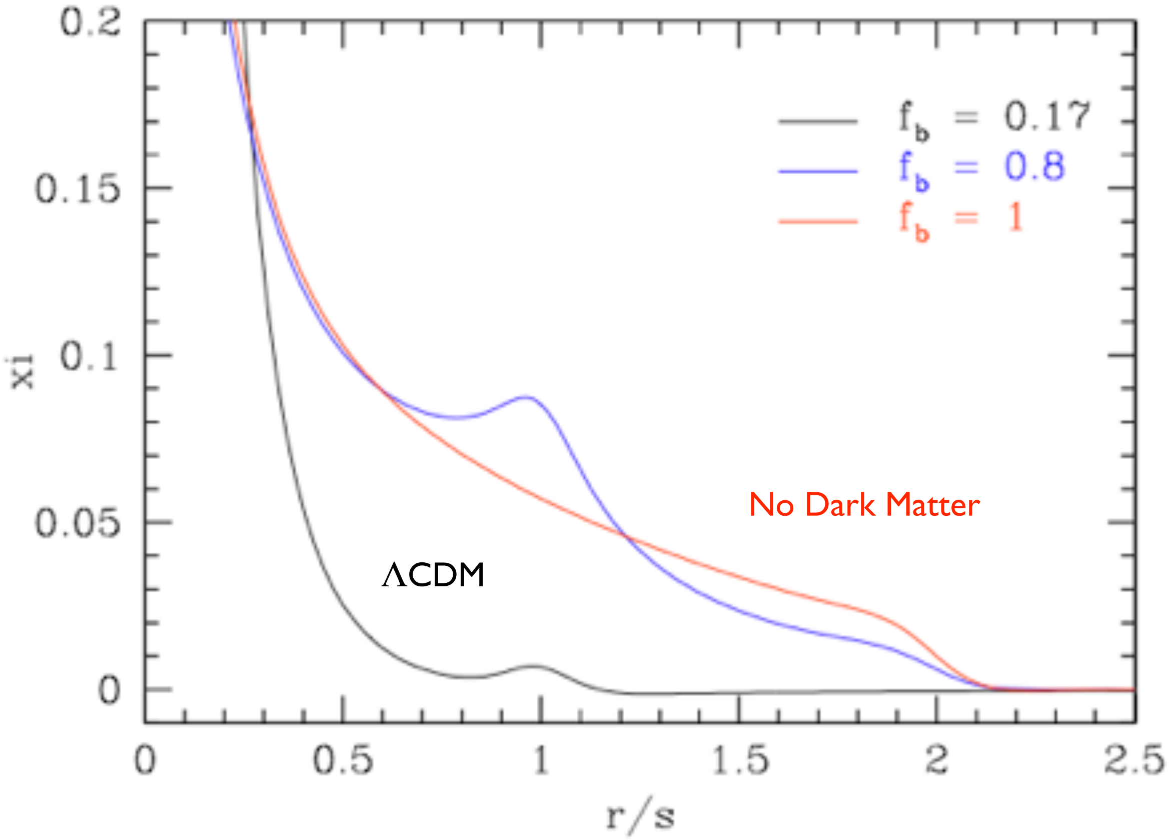
Mass are determined from scaling relations

Detection/observations through
visible imaging, lensing, X, SZ effect

Complex gastrophysics

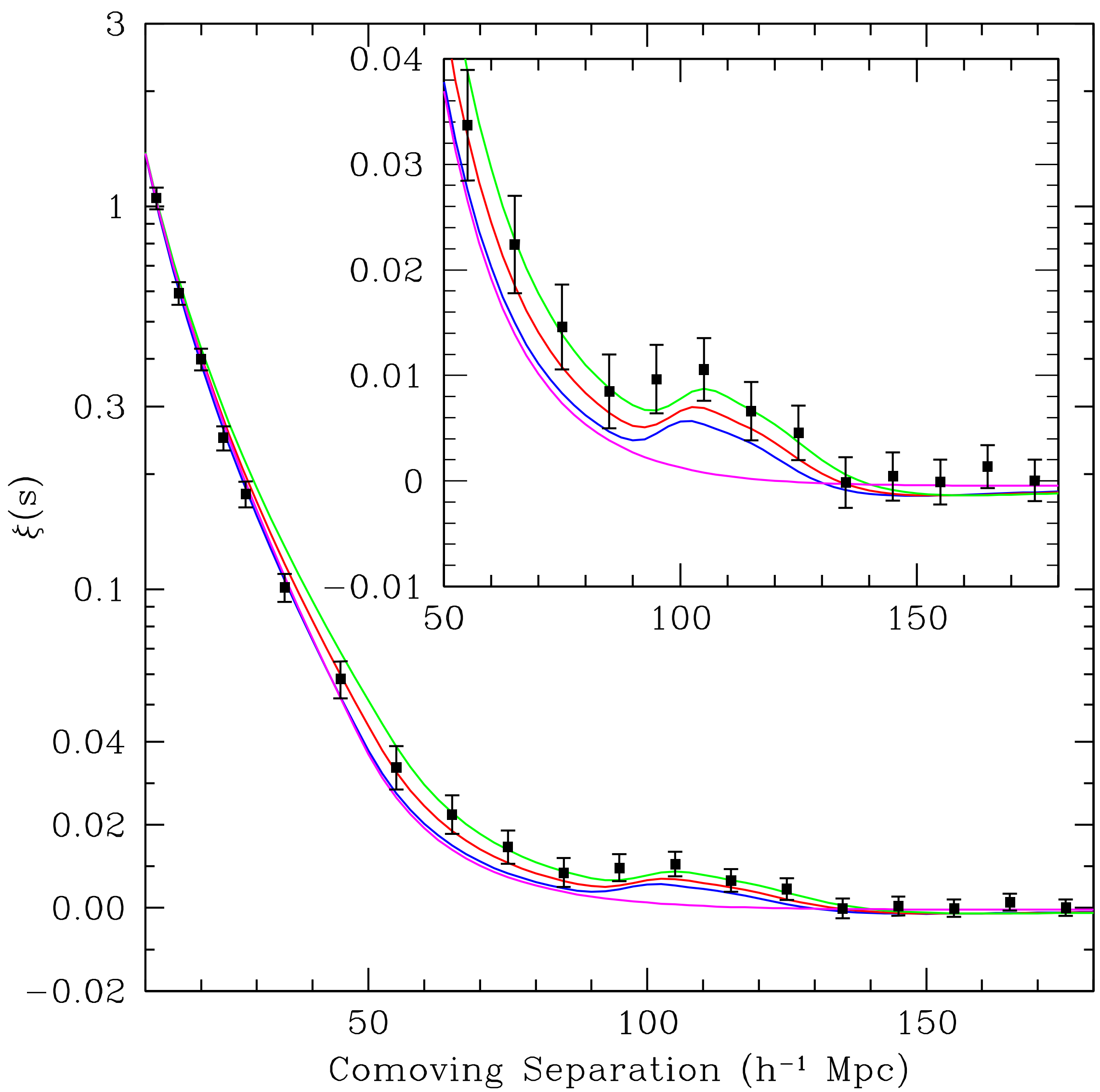
Baryon acoustic oscillations

A peak in the matter correlation function, relic of sound waves propagating in the primordial plasma, is used as a distance standard.



BAO with and without dark matter

Eisenstein et al., 2005



Baryon acoustic oscillations

Few systematic effects.

Can use a variety of probes depending on redshift (LRG, ELG, Lyman alpha forest, QSO) — each with a different bias.

Limited power — rapidly cosmic variance limited. 3D measurement requires spectroscopy.

Redshift space distorsions is a byproduct giving access to structure growth.

Lensing

IV. NEBULAE AS GRAVITATIONAL LENSES

As I have shown previously,[6] the probability of the overlapping of images of nebulae is considerable. The gravitational fields of a number of "foreground" nebulae may therefore be expected to deflect the light coming to us from certain background nebulae. The observation of such gravitational lens effects promises to furnish us with the simplest and most accurate determination of nebular masses. No

Zwicky, 1937

Lensing regimes and techniques

Strong lensing : multiple images and arcs.

Recovery of cluster total mass and mass profile

Weak shear : statistical measurement of galaxy shape distorsion.

Magnification bias (cosmic magnification) : change in the luminosity function of the background population, correlated with the foreground density.

Both are sensitive to the growth of structure, especially by comparing the effect at various redshifts (lensing tomography).

Lensing caveats

- On the long run, will be a very powerful technique
  - Tomography, combination with other probes, higher-order (3+) statistics, lensing peaks…
- Main sources of systematic effects:
  - PSF measurements (atmospheric/instrumental effects)
  - Photometric redshifts
  - Intrinsic galaxy alignments

Other probes

Lyman-α forest fluctuations

Alcock-Paczynski tests

Dark Energy anisotropies

Equivalence principle tests to check GR

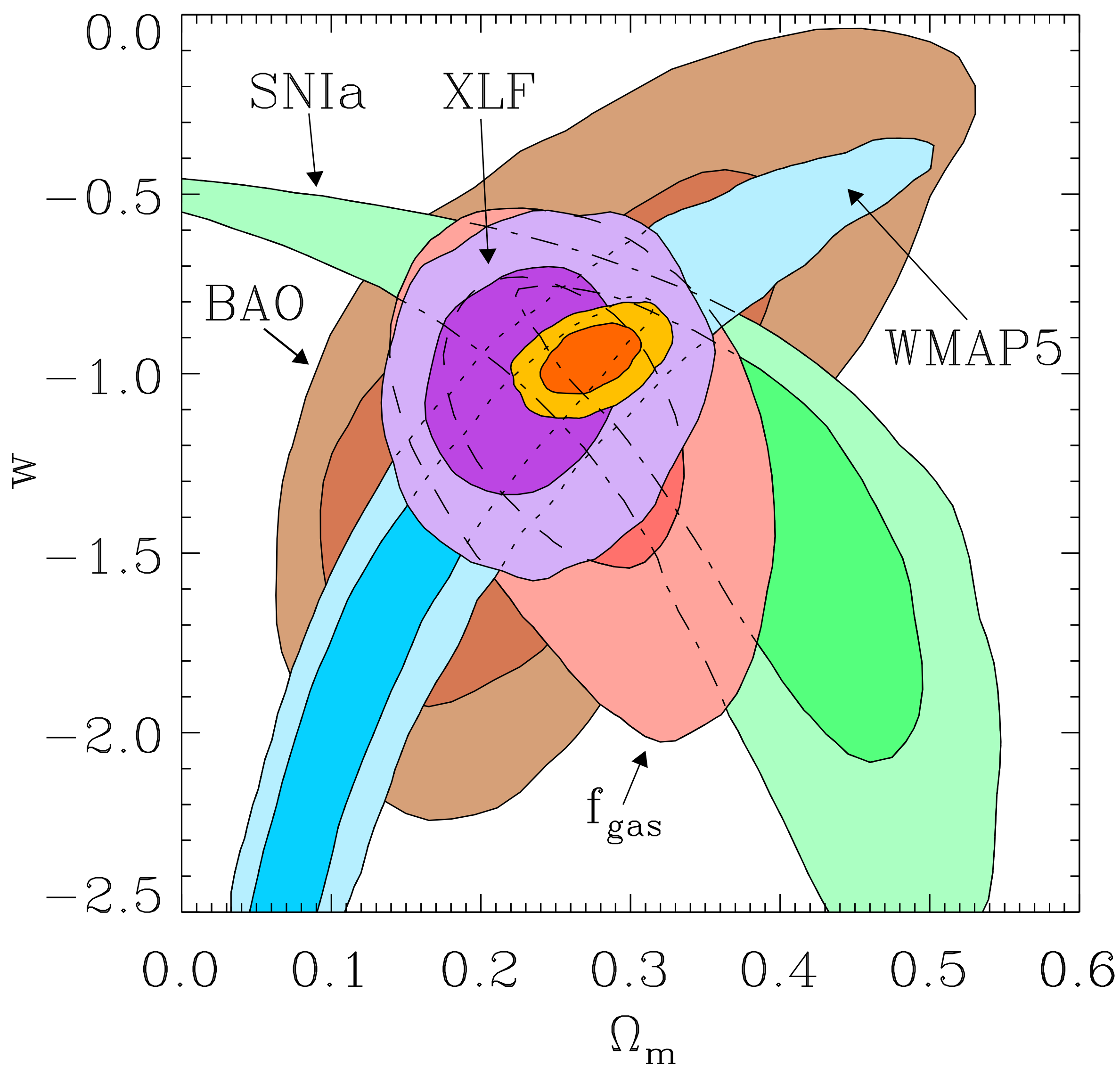
CMB foregrounds like ISW

measured by cross-correlation with large scale structure tracers

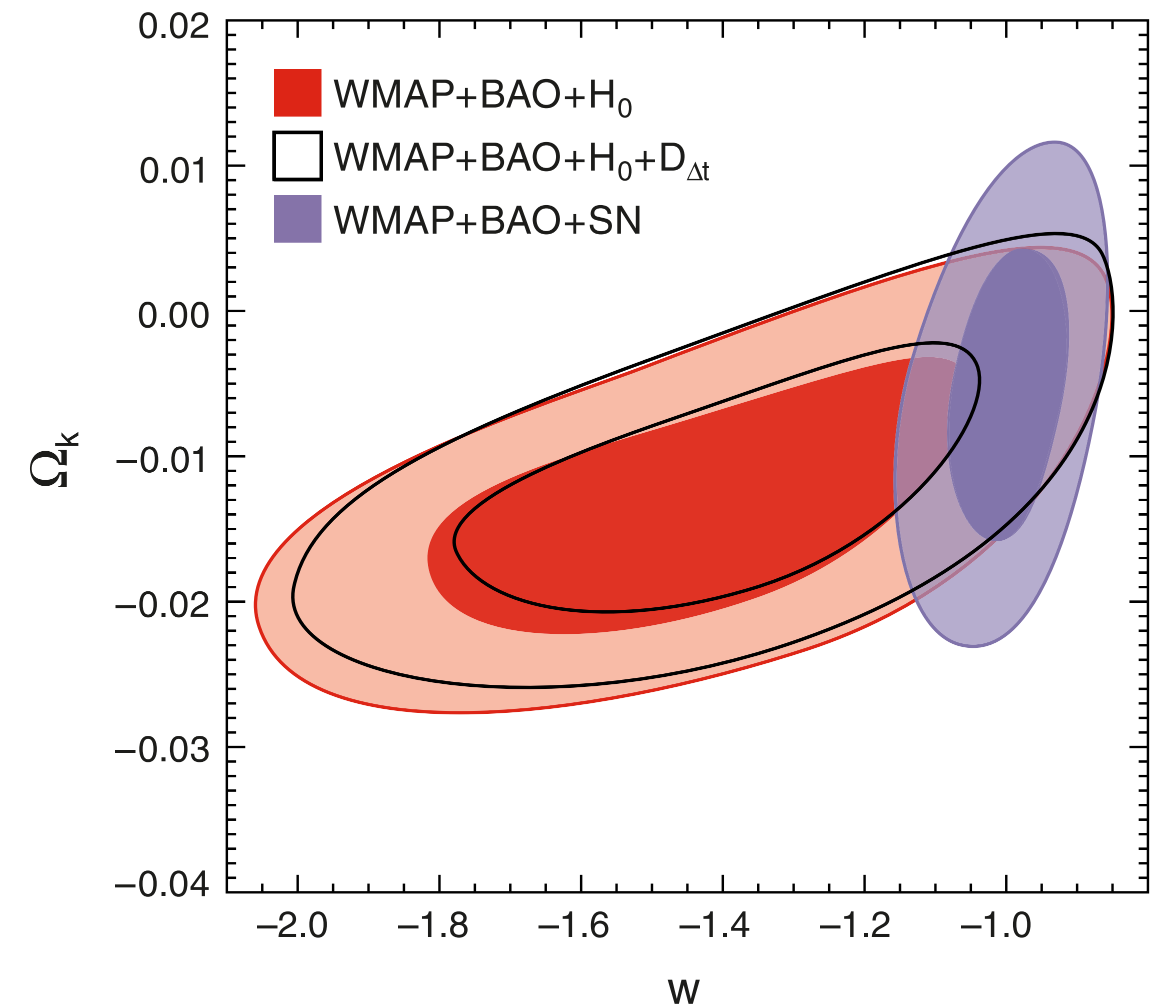
21-cm surveys (SKA and precursors) are massive and deep spectroscopic surveys

The future does not lie
in individual probes
but in data merging

Classical constraints combination



Allen et al. 2011



(w constant)

Komatsu et al., 2011

Some data-level combinations

Cross-correlation of weak-lensing and spectroscopic surveys is more powerful than a posteriori combination

Cai & Bernstein 2011

Degeneracies are broken, essentially through calibration of the bias of the spectroscopic galaxies via their lensing of photometric galaxies

Comparing growth measurements from lensing and redshift space distorsion tests modified gravity

Reyes et al. 2010

Some data-level combinations

If two surveys measure a shear field on the same sky patch, the shear cross-correlation will have less systematic effects that the auto-correlation

cf XSPECT techniques for CMB

If one of the surveys is from space, and the other one is from ground and deeper, they probe the same shear field using the core or the outskirts of the galaxies.

Some data-level combinations

Shear and cosmic magnification can also be combined on the same field

It helps reduce systematics linked to PSF correction, shear calibration and bias, and intrinsic alignment.

Van Waerbeke 2010

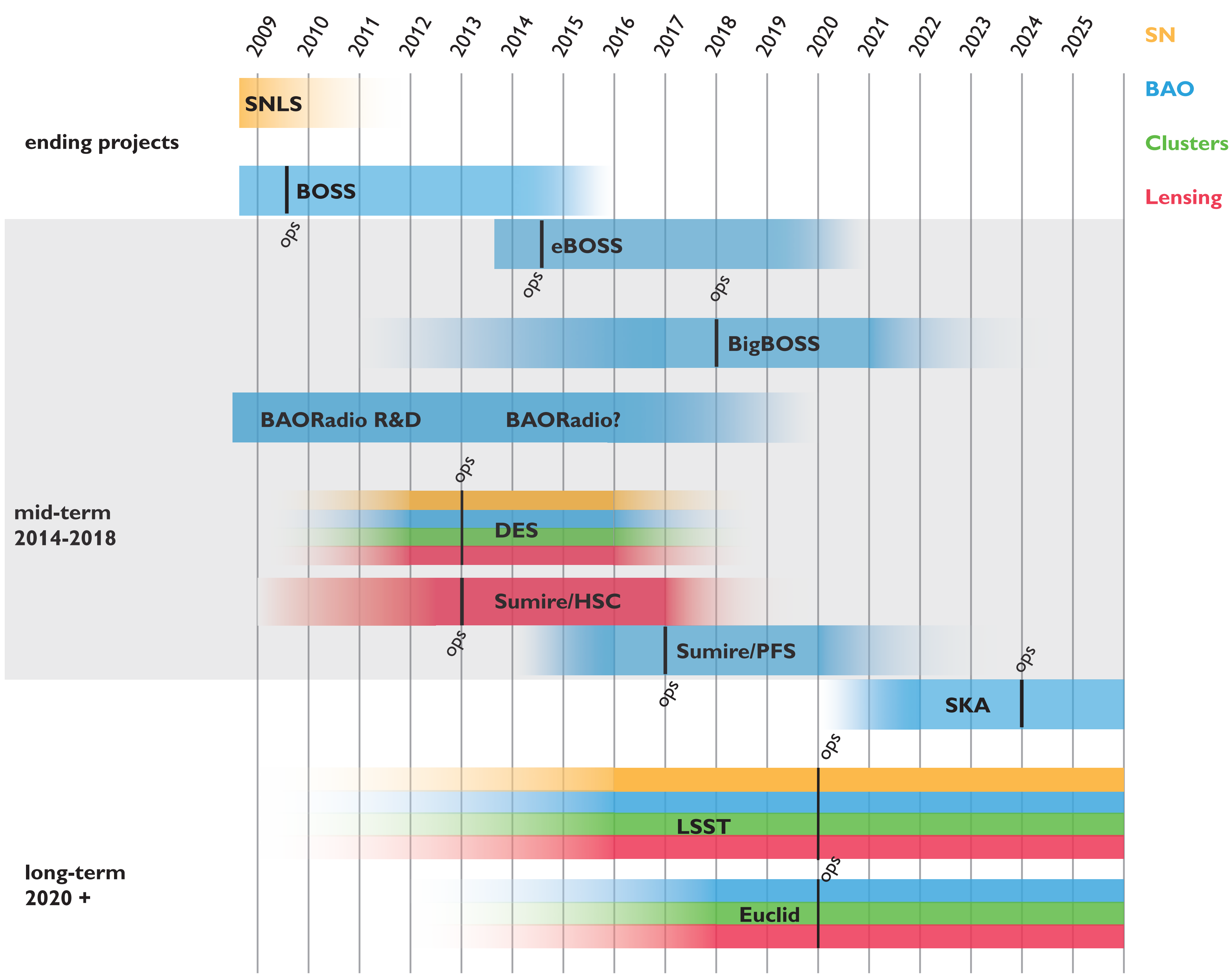
A necessary ingredient

For lensing, as well as photometric BAO, it is necessary to estimate the redshift of galaxies from multi-band imaging : *photometric redshifts*.

At high z (> 1.2), observations in the infrared significantly improve the accuracy of the photo-z

- Ground-space complementarity

The main projects (with French bias)



SDSS-III (BOSS)

Apache Point Observatory (NM) 2.5m telescope

Dual 1000-fiber spectrograph, 3 sq deg field

The Baryon Oscillations Spectroscopic Survey is the main survey of SDSS-III and targets BAO with

- 1.5 M luminous red galaxies
- 160k $z>2$ quasars (Lyman-α forest)

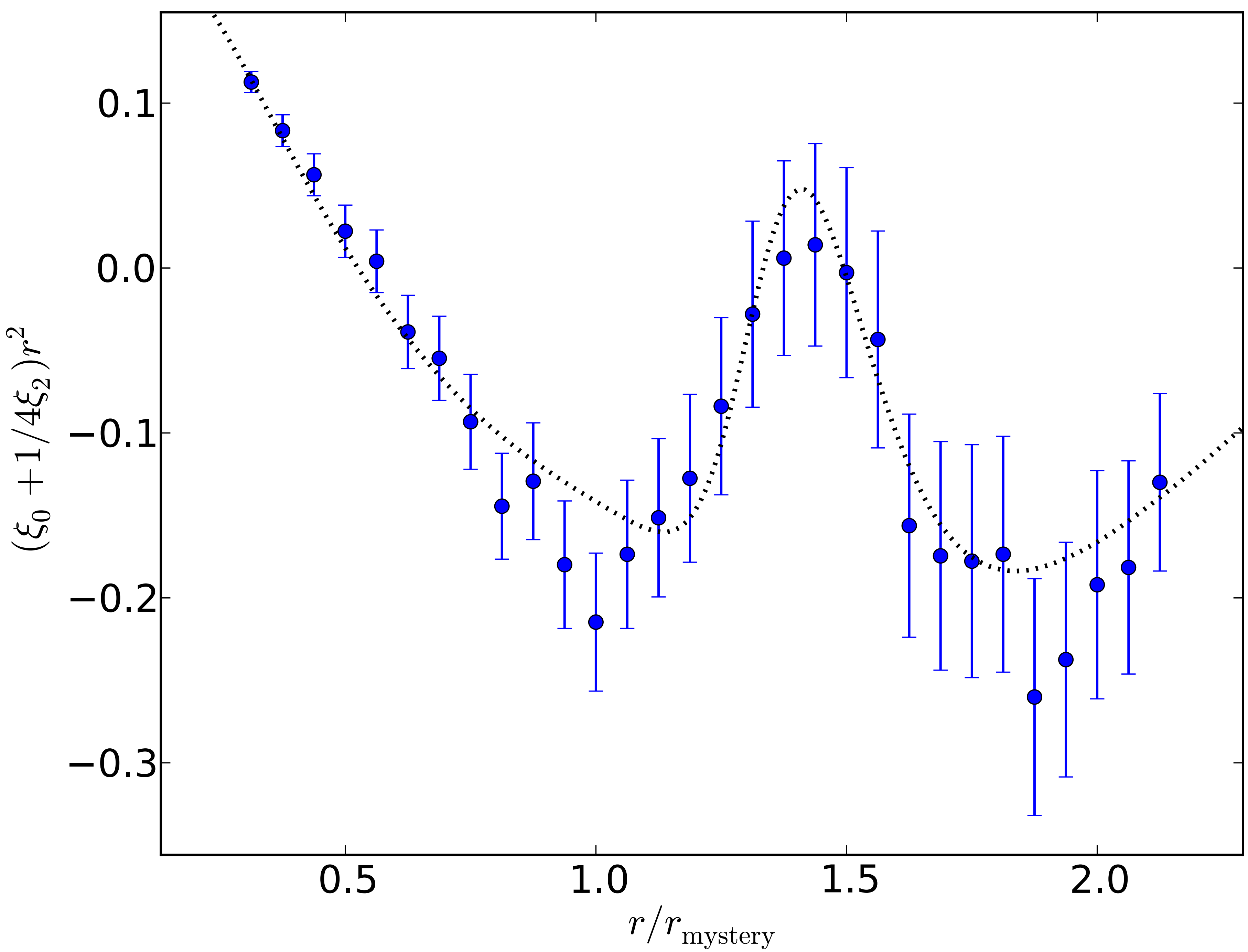
SDSS-III (BOSS)

French participation group (15 researchers in 6 labs + postdocs + students) funded by P2I, ANR (2009-2012 and 2013-2015), CEA, INSU/CSA and PNCG.

Mostly involved in BOSS but also SEGUE and APOGEE.

FPG took the lead on Lyman-a analysis.

SDSS-III (BOSS)

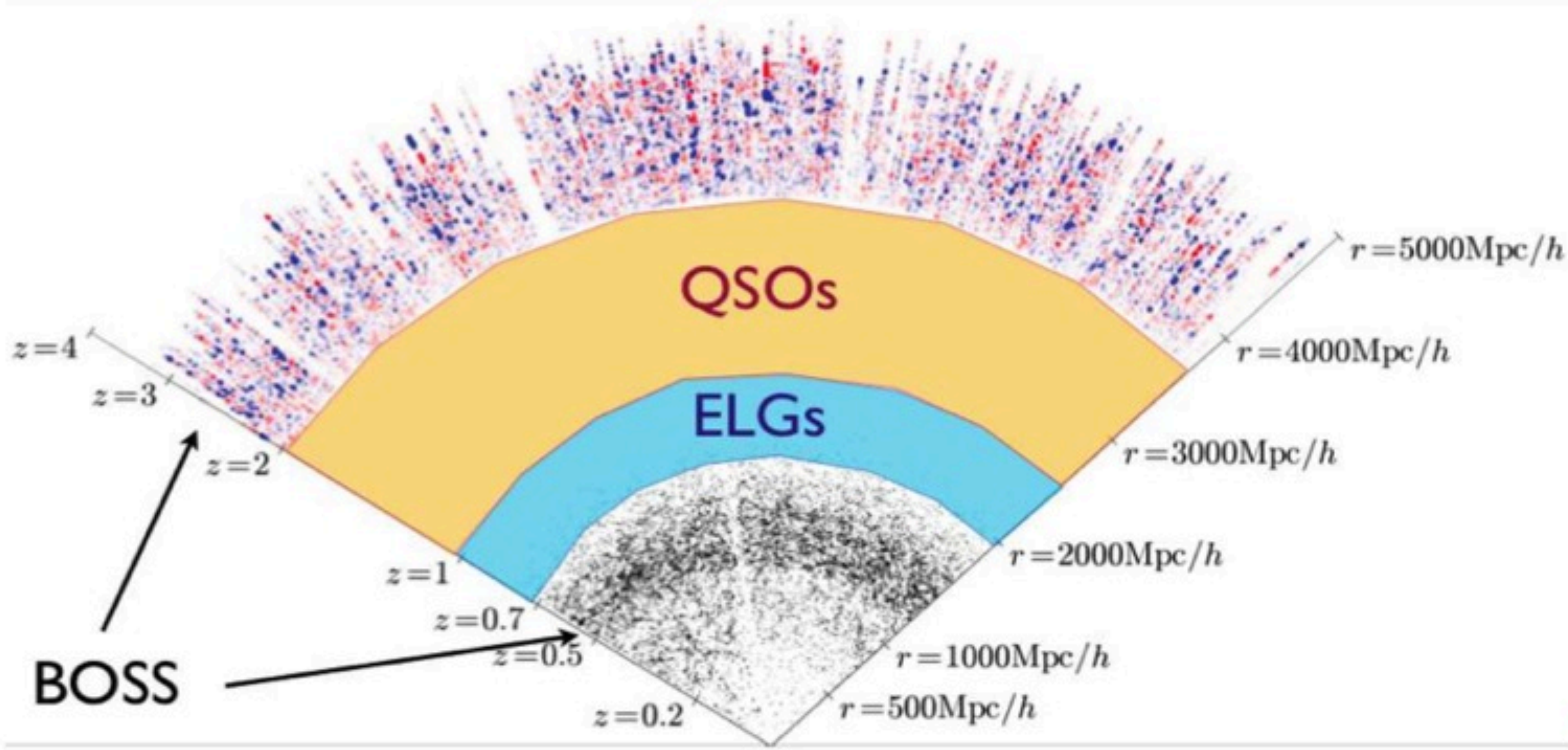


SDSS-IV (eBOSS)

SDSS-IV : 2014+ sequel

BAO survey will fill the BOSS redshift gap

Sloan committed $10M



BigBOSS

Same goals: BAO with LRG, ELG, QSO...

4-m telescope (Mayall, Kitt Peak), 7 sqdeg FOV, 5000-fiber spectrograph (3 arms 360–980nm) : Stage-IV spectroscopic survey, BOSS x10.

Last BigBOSS consortium meeting in Paris on october 8-10. Construction 2014, data 2017?

R&D in progress in France —consortium members: APC, IAP, CPPM, CPT, LAM, CEA/Irfu.

Southern sequel on twin telescope (Blanco) envisioned.

Dark Energy Survey (DES)

570 Mpix, 2.2 ° FOV imaging camera on 4-m Blanco telescope in Chile, grizY.

525 nights, 5000 sq deg survey 2012-2017.

SNIa (3k), clusters, lensing, BAO (photometric)

US/UK/Brazil/Spain/Germany

First light in September 2012.

DESpec

A spectroscopic sequel to DES : 4000 fibers on the Blanco 4-m.

Comparable to BigBOSS, in the South.

Interchangeable with DECam, 2017+

HyperSuPrime Camera (Sumire/HSC)

870 MPix imaging camera, 1.5 ° diameter FOV, on the 8.2m Subaru telescope (Hawai).

Lensing is the main focus.

Japan (NAOJ/IPMU...)/Princeton.

First light Aug 2012.

Prime Focus Spectrograph (Sumire/PFS)

2400 fibers, 3 arms (300–1300 nm), 1.3° FOV on 8.2 m Subaru

Japan (NAOJ/IPMU…)/US (Princeton/Caltech/JHU)/France(LAM)/Brazil.

Dark Energy (BAO) is an important goal. Also galaxy formation, and Galaxy studies (Gaia).

Square Kilometer Array (SKA)

A giant radiotelescope, covering 70 MHz to 30 GHz, 1 square kilometer collecting area spread over 3000 km, in South Africa and Australia.

Many science goals. Cosmology through the mapping of 1 billion galaxies in HI–21cm.

The South African phase two array (most relevant for cosmology) will be built between 2020 and 2024.

BAO/Radio

21-cm radio detection targeting BAO for $0.5<z<3$.

Low S/N, modest resolution (10 arcmin) : intensity mapping, not individual galaxies

R&D phase 2007-2011 IN2P3/INSU/CEA with CMU, CITA… Collaboration with Nançay.

2012- : Ongoing observations at Nançay. Construction could start: funding, partners, technology choice…

LSST/Euclid

See following presentations...

The main projects (with French bias)