



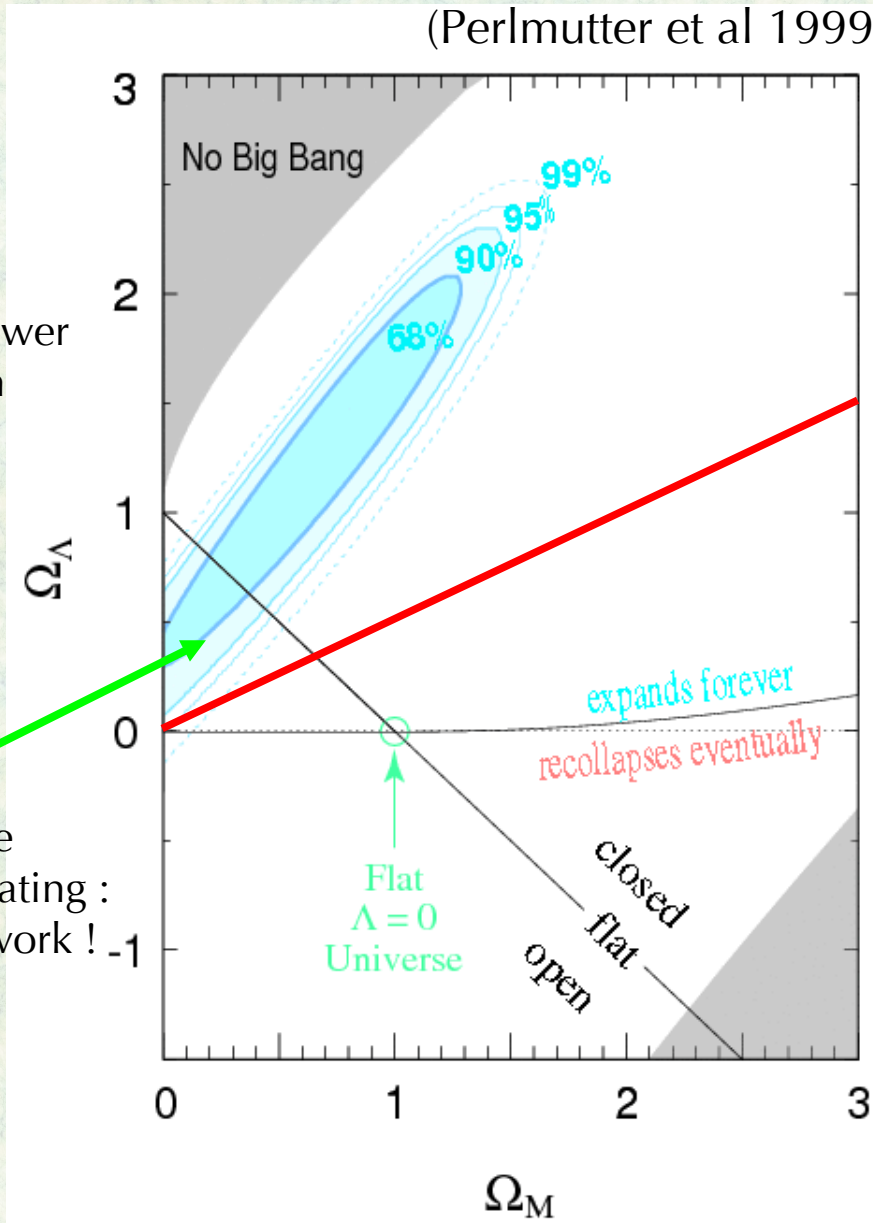
Cosmological Probes Experimental Review

Emmanuel Gangler – LPC – Clermont-Ferrand (France)

Dark Energy : 1998-2015 ... 17 years !



Evidence in 1998 that distant Type Ia have lower recession velocity than expected



Smoking gun that the expansion is accelerating : a Dark Energy is at work !



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".

Nobel 2011

Dark Energy : 1998-2015 ... 17 years and still there

Supernovae : sensitive to expansion rate evolution \square dark energy equation of state

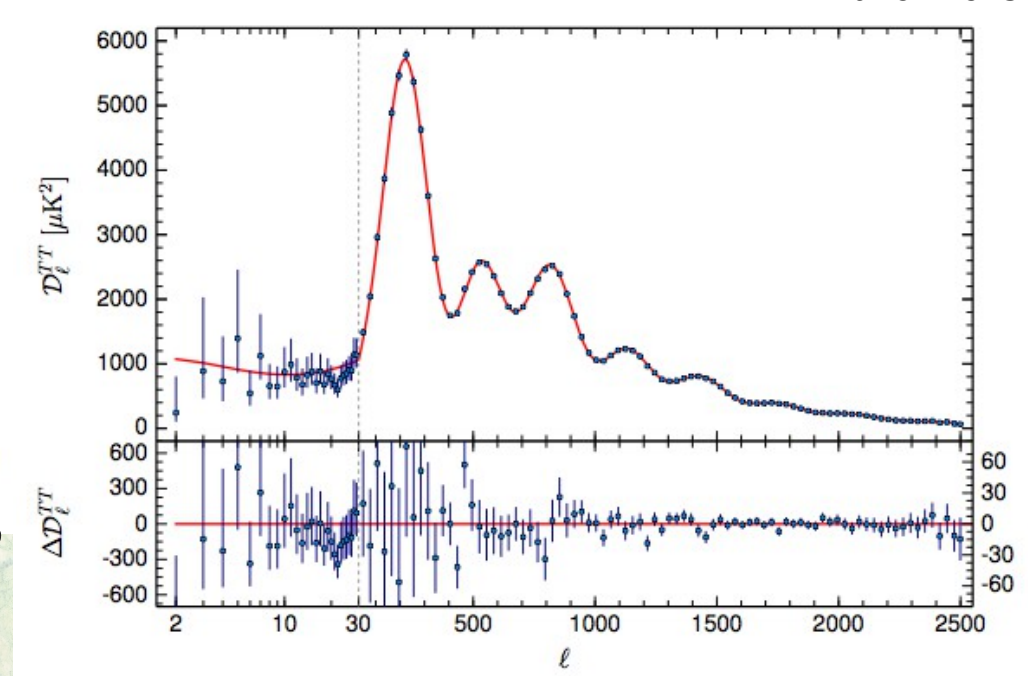
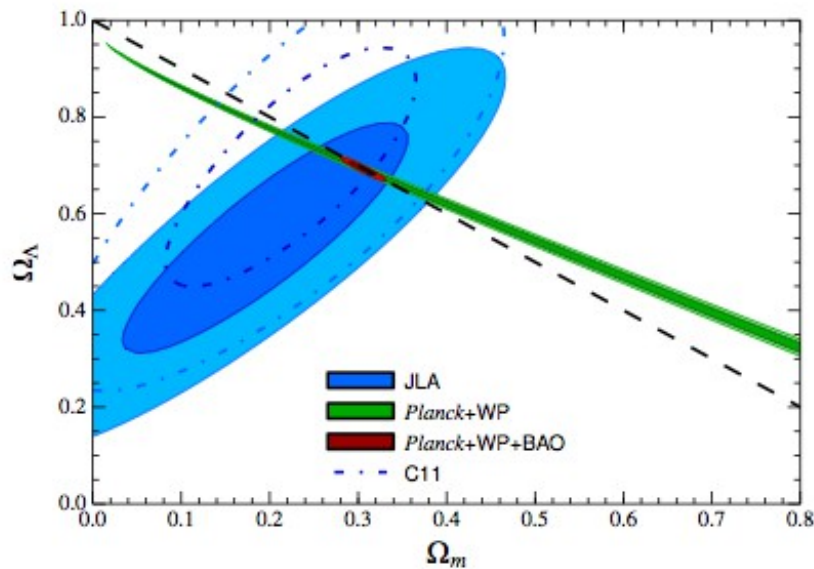
Betoule 2014

CMB, BAO : scale parameter evolution

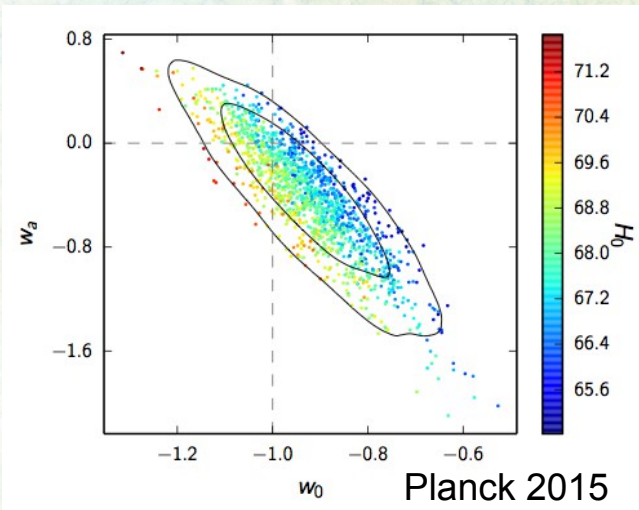
\square sensitive to Ω_{tot}

+ power spectrum, polarization ...

Planck 2015



Equation of state $P = w \rho = [w_0 + w_a(1 - a)] \rho$



Structure growth \rightarrow sensitive to Ω_M & GR

\rightarrow **Concordance model** flat- Λ CDM quite robust ... so far ?

... Energie Noire ???? Le point de vue des théoriciens

Une constante cosmologique (le terme « standard » de l'équation d'Einstein)

- Peut-on ignorer le reste du XX ième siècle ? : Energie du Vide ... Plus de 120 ordres de grandeur à pomper !

Le principe anthropique

- Le « dégrissant » de la physique théorique : quand la « science » un peu de principe anthropique et ça repart ...

Quintessence

- Un bon vieux champ scalaire « à la mode » de la physique théorique , ou comment « fixer » un problème Méthode des « preuves » ...

Relativité générale, extra dimension ...

- A chaque changement de Relativité Générale ... penser à vérifier les fusibles ...

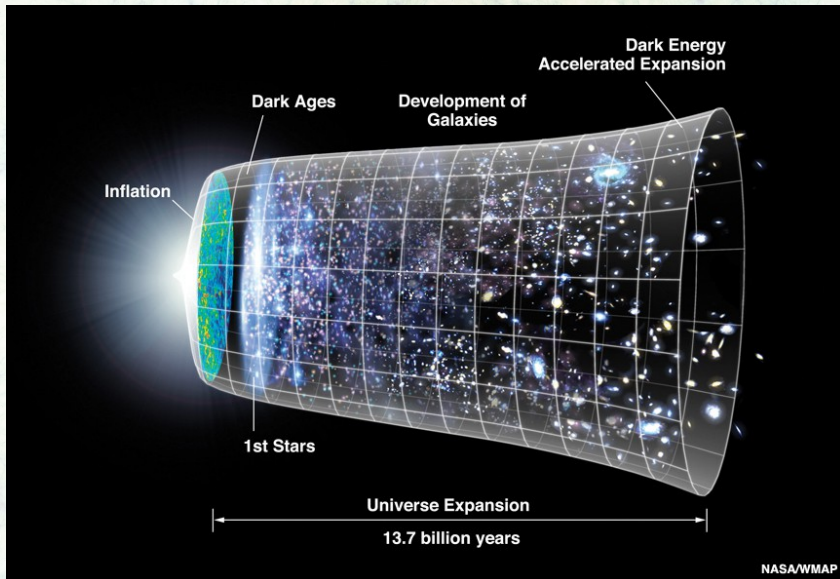
Back Reaction (pas de nouvelle physique) : La formation de structure induit une accélération moyenne apparente (densité non uniforme)

- C'est ce qu'il faut étudier aujourd'hui... si si ... hum ... non... Quelle amplitude au fait ?

Le couteau suisse de l'observateur : w_0 , w_a / FLRW

See talk by P. Binetruy

The cosmological probes



CMB :

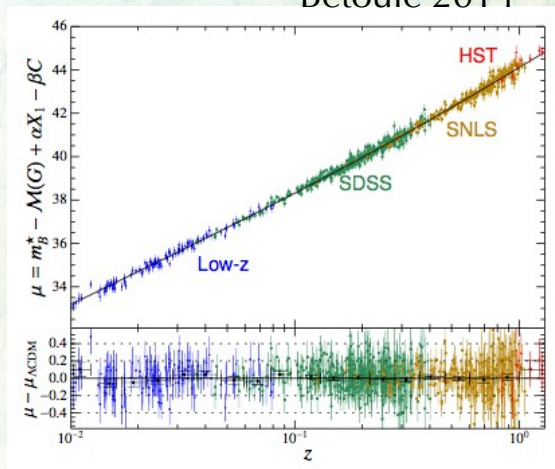
- Microwave range
- Sensitive to whole Universe history
 - Inflation
 - Recombination
 - Forgrounds
- Fixes nuisance parameters for Dark Energy

Recent univers probes :

- Visible and IR range
- Powerful with CMB (lever arm)
- Dark Energy parameters and GR tests

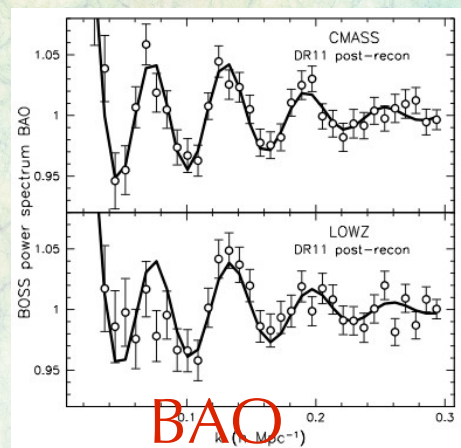
CMB

Bétoule 2014



Ia Supernovae

Anderson 2014



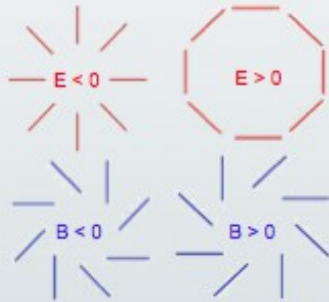
BAO



Weak Lensing

+ Clusters,
Redshift distortions,
AP effect,
H0,

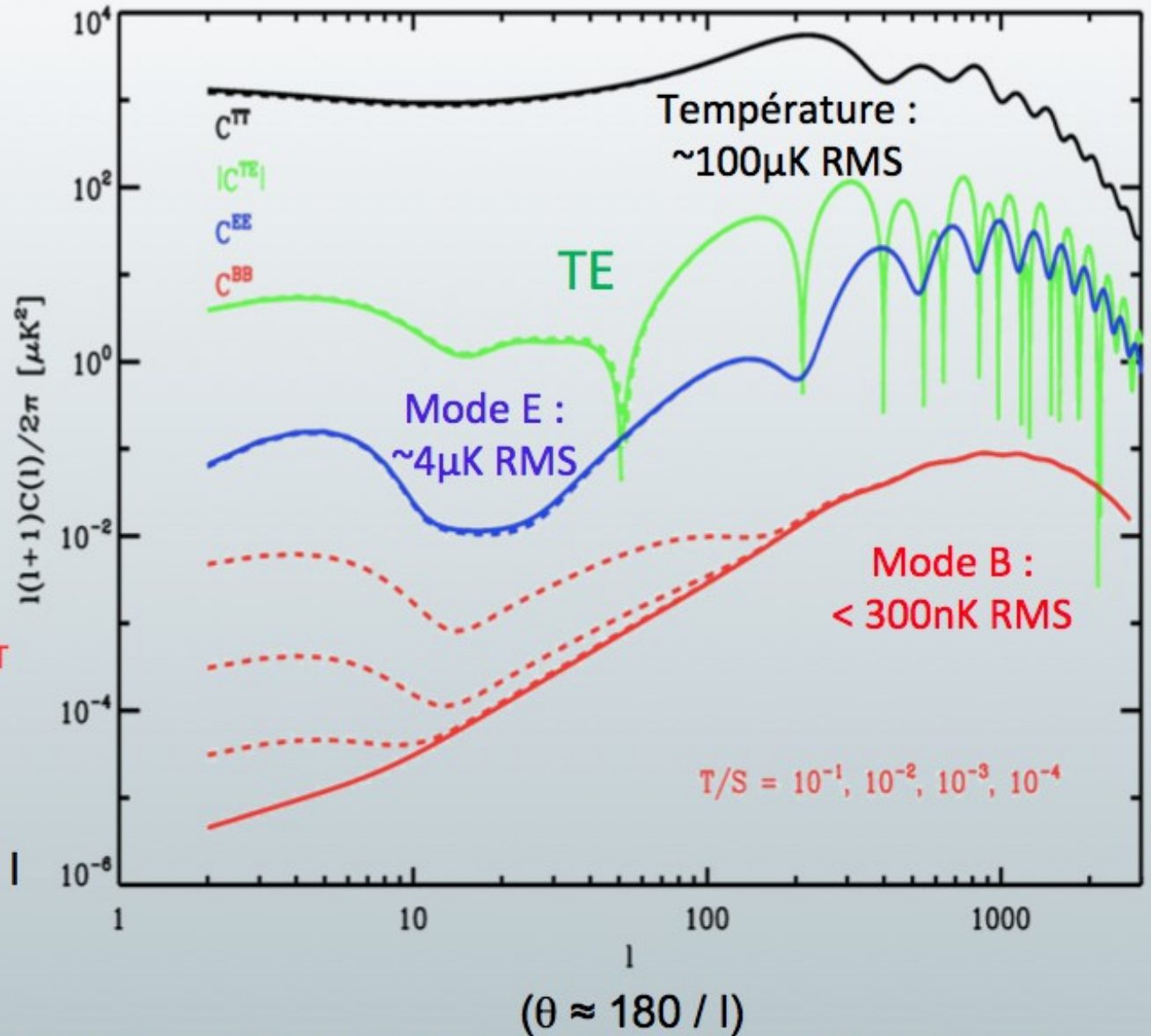
- 3 observables : T, E, B



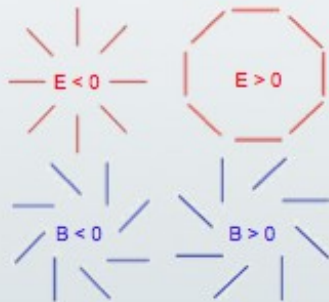
- B Modes:

- Not generated by scalar modes
- "Smoking gun" of tensorial perturbations
- At best 300 times weaker than T fluctuations
- case $T/S = r = 0.1$ (cf. fig),
- $E_{\text{inf}} = 2 \times 10^{16}$ GeV (GUT).

- B mode Spectrum peaks at $l < 200$, i.e. $\theta > 1$ deg



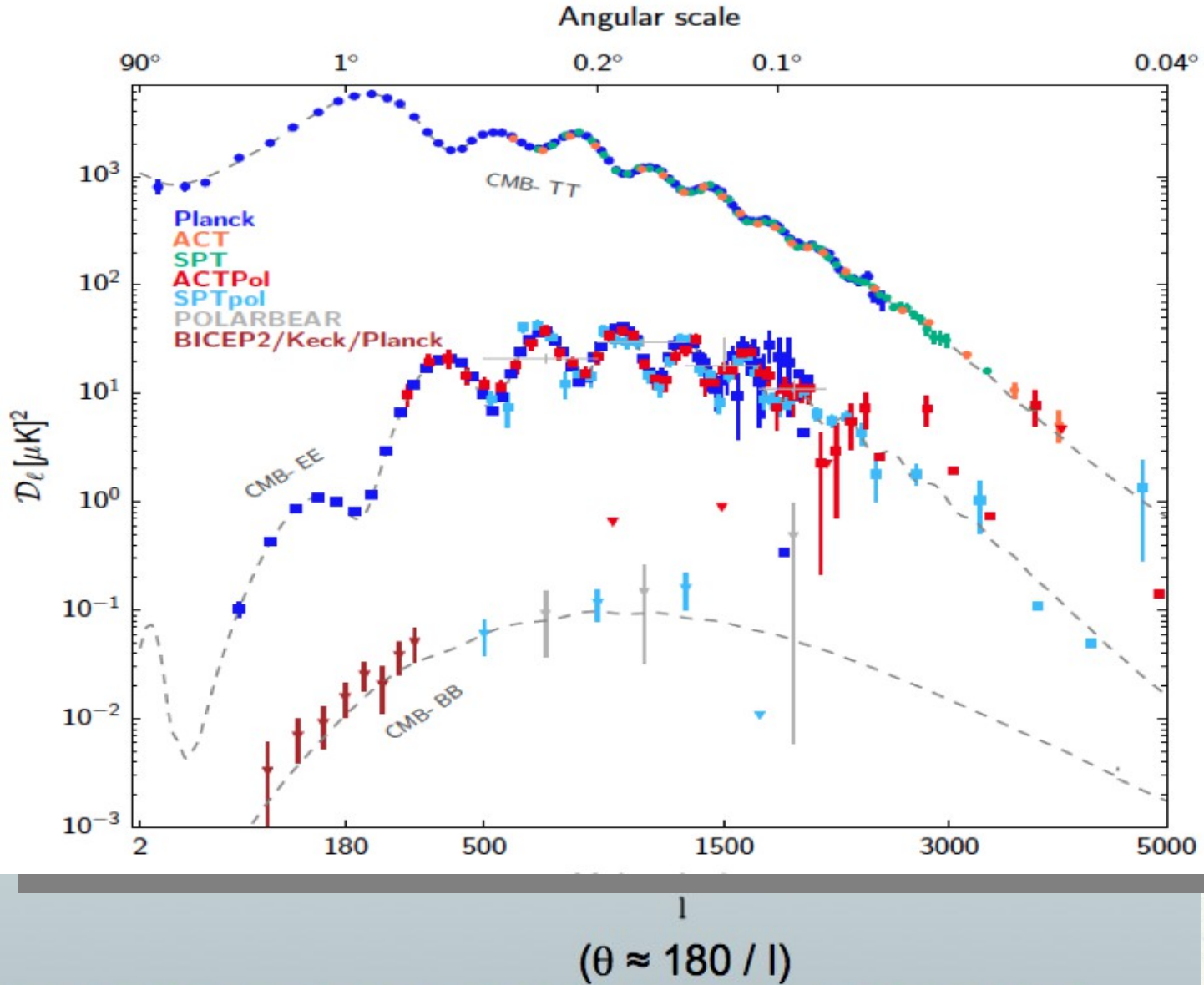
■ 3 observables : T, E, B



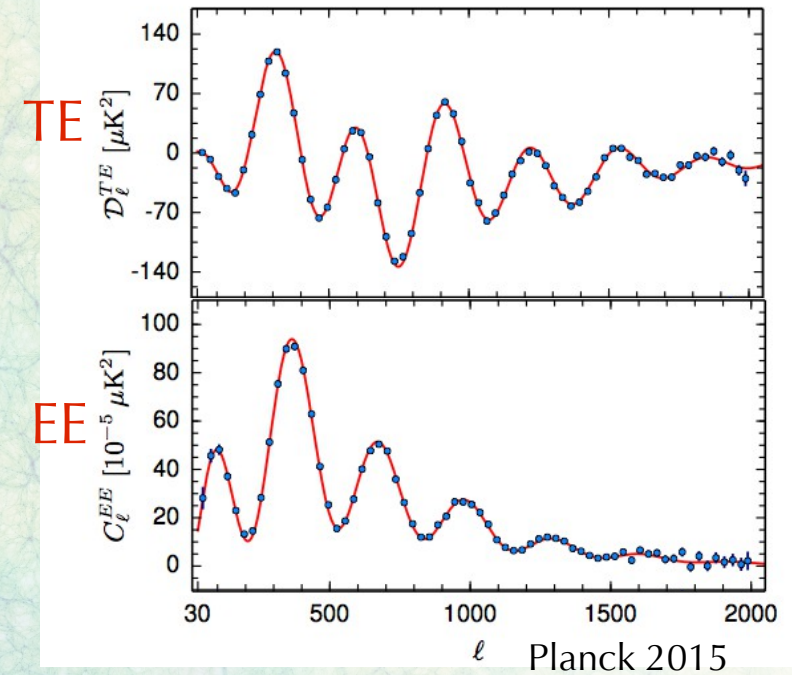
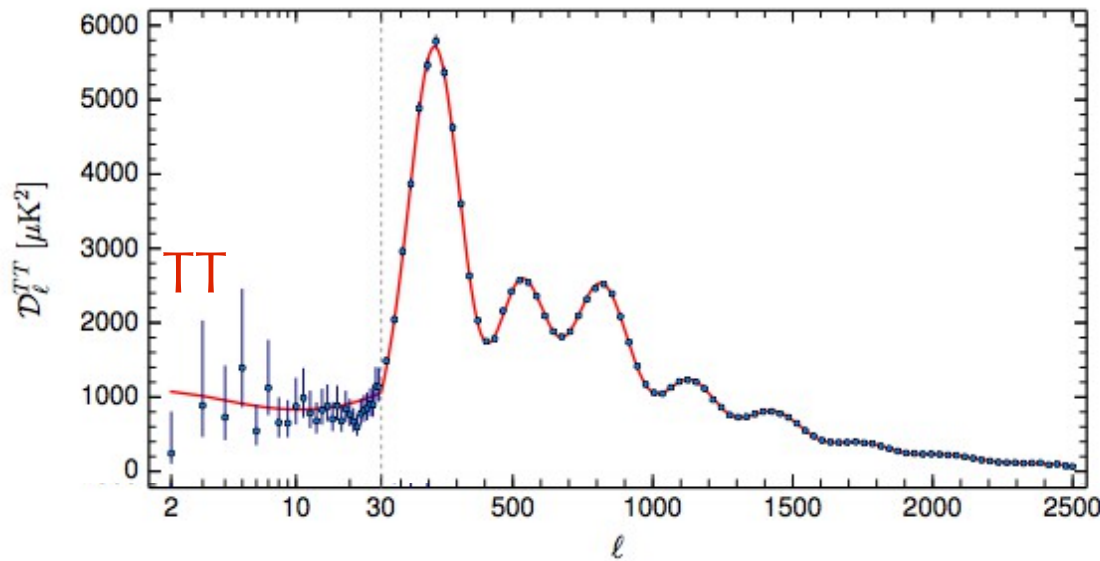
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CMB Cosmological fit : flat- Λ CDM



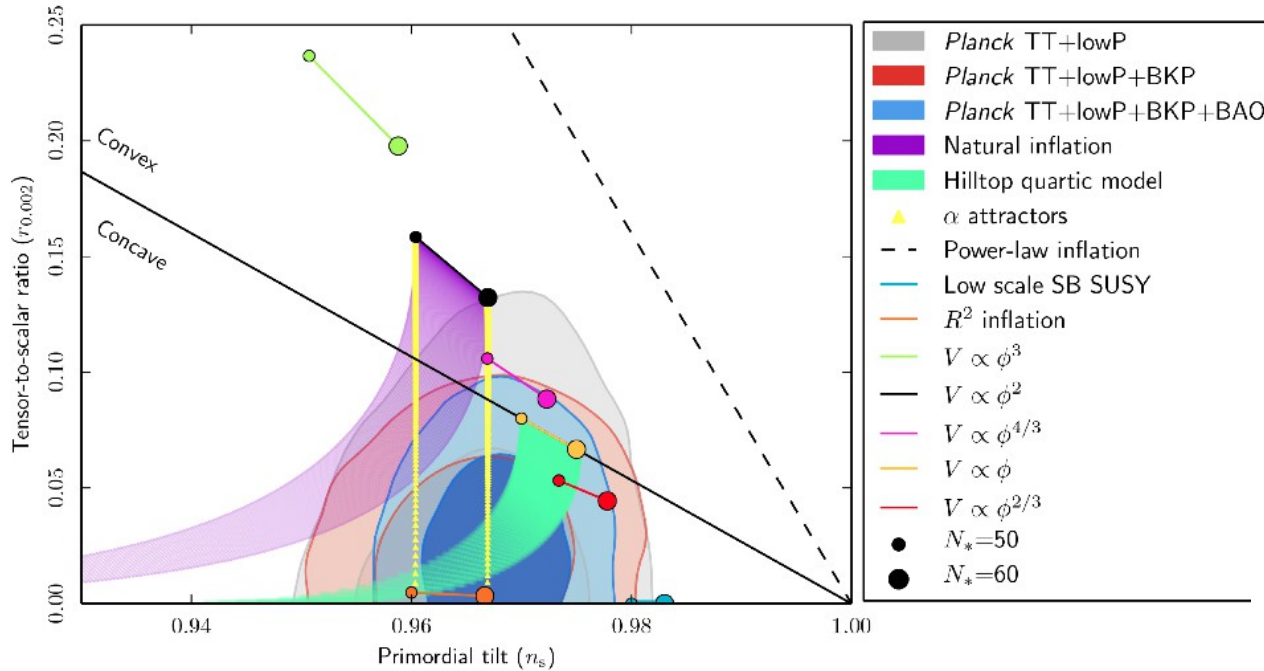
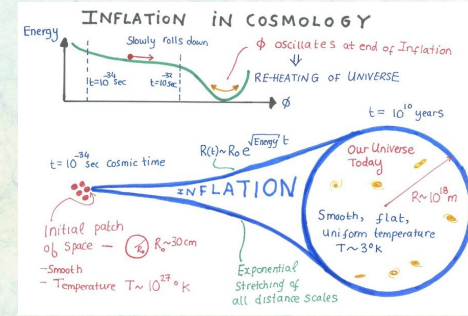
Parameter	[1] <i>Planck</i> TT+lowP
$\Omega_b h^2$	0.02222 ± 0.00023
$\Omega_c h^2$	0.1197 ± 0.0022
$100\theta_{MC}$	1.04085 ± 0.00047
τ	0.078 ± 0.019
$\ln(10^{10} A_s)$	3.089 ± 0.036
n_s	0.9655 ± 0.0062
H_0	67.31 ± 0.96
Ω_m	0.315 ± 0.013
σ_8	0.829 ± 0.014
$10^9 A_s e^{-2\tau}$	1.880 ± 0.014

6-parameter fit

- Baryon density
- Cold Dark Matter density
- Sound horizon
- Reionisation depth
- Amplitude of primordial fluctuation
- Spectral index of primordial fluctuations

Many degeneracies

CMB : inflation

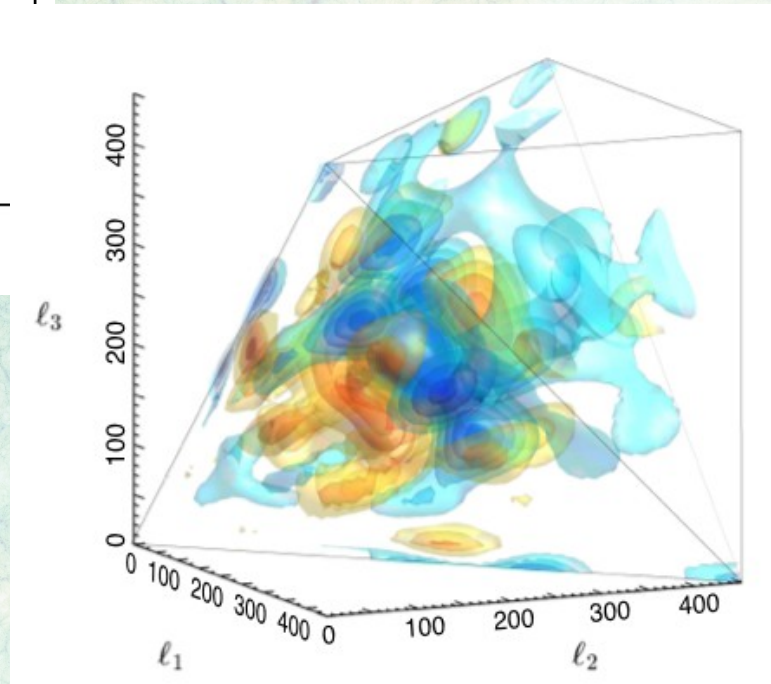


Non-gaussianities :

- Prediction from inflation
- Higher order statistics
- No detection

Primordial Gravitational Waves

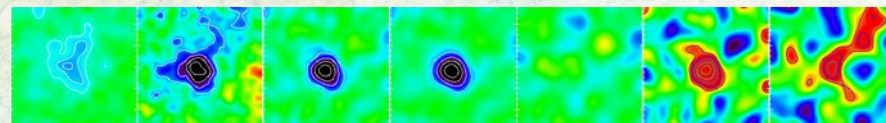
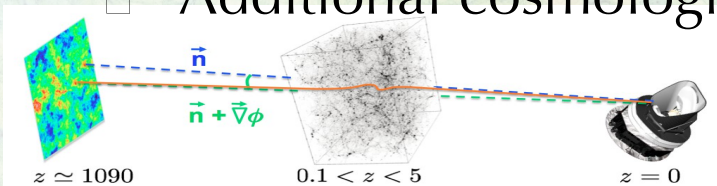
- Visible in B modes at large scale
- $n_s < 1$: prédiction générique
- Constraining models
- *No detection ... yet !*



$$f_{NL}^{local} = 0.8 \pm 5.0, f_{NL}^{equil} = -4 \pm 43 \text{ and } f_{NL}^{ortho} = -26 \pm 21 \text{ (68 \% CL statistical)}$$

CMB : Foregrounds

- Sensitive to **structure of matter**
- **Correlation with foregrounds** observations (clusters, galaxies...)
- Additional cosmological constraints

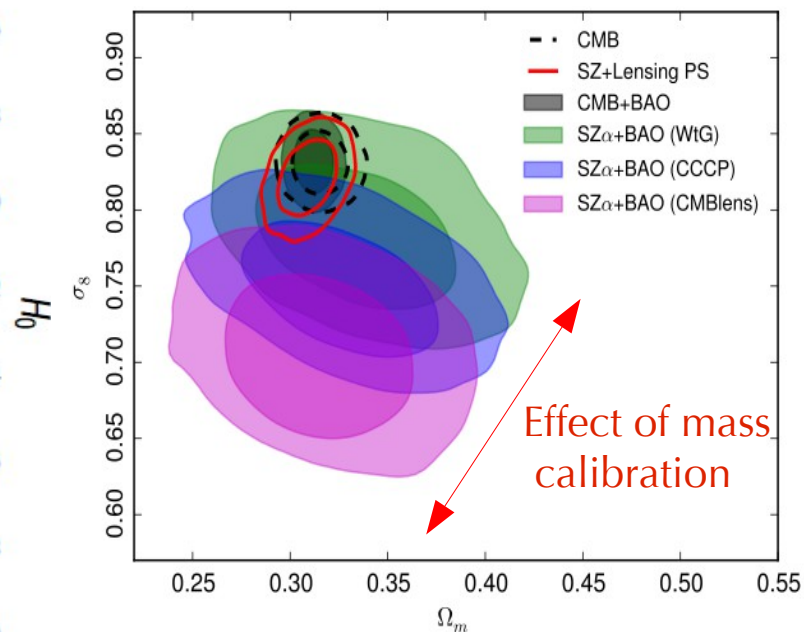
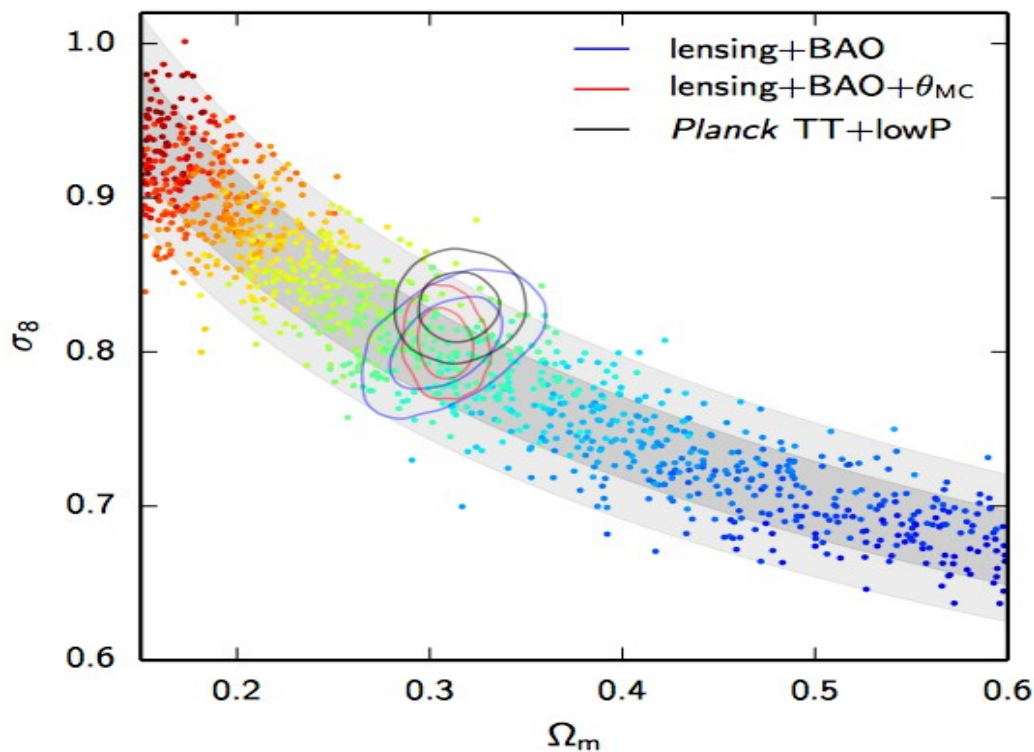


CMB Lensing : sensitive to total mass

- Temperature and polarisation signal
40 σ detection
- Background for inflation B modes

SZ effect : sensitive to clusters

- compton scattering by hot e^- gas
- 439 clusters detected
- Bottleneck is mass calibration



CMB : The future

B modes : Gravitational waves

SZ projects

Bicep3



SPT



ACT



+ polarization capabilities

Polarbear /
Simons Array



Qubic



NIKA



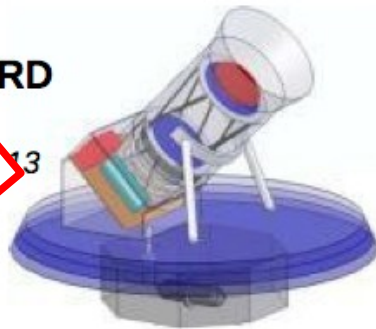
IN2P3 :
APC, LAL,
LPSC

Satellites ?

A next-generation CMB satellite mission ?

LiteBIRD

Matsumura et al., 2013



Discussed 2016



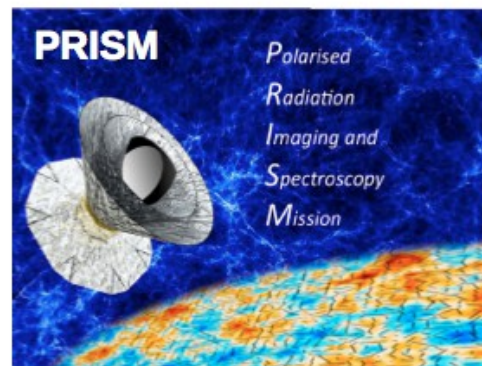
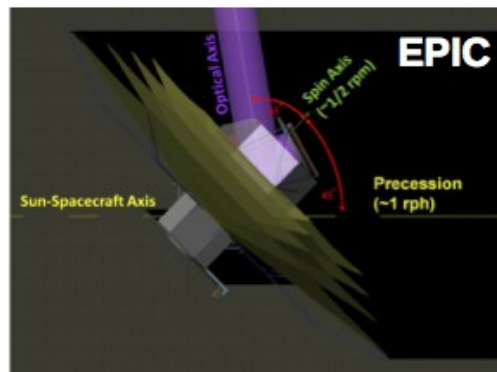
CORE

CORE Conceptual Design Study, 2011

No launch before 2029



Bock et al., 2008

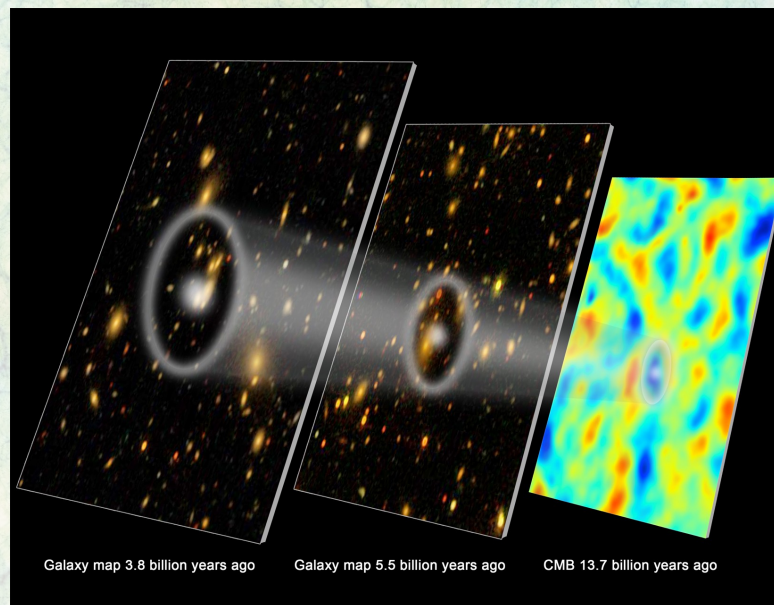


André et al., 2014

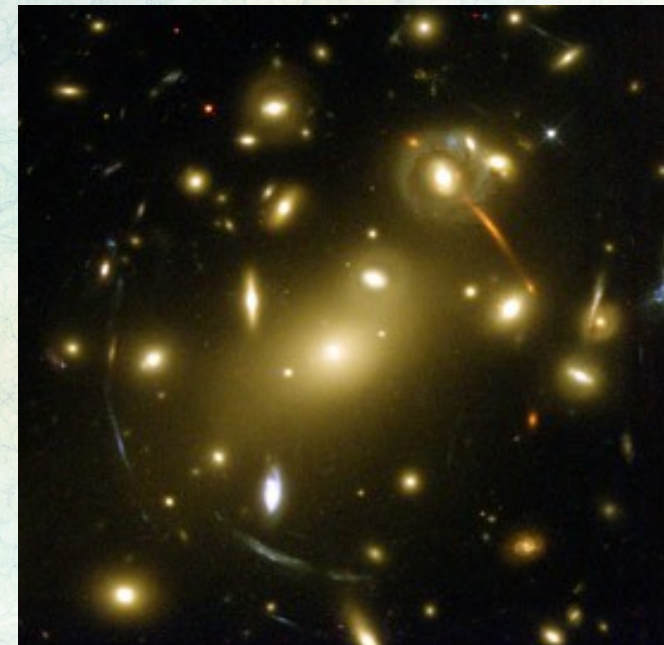
The Recent Universe Probes



22/10/15

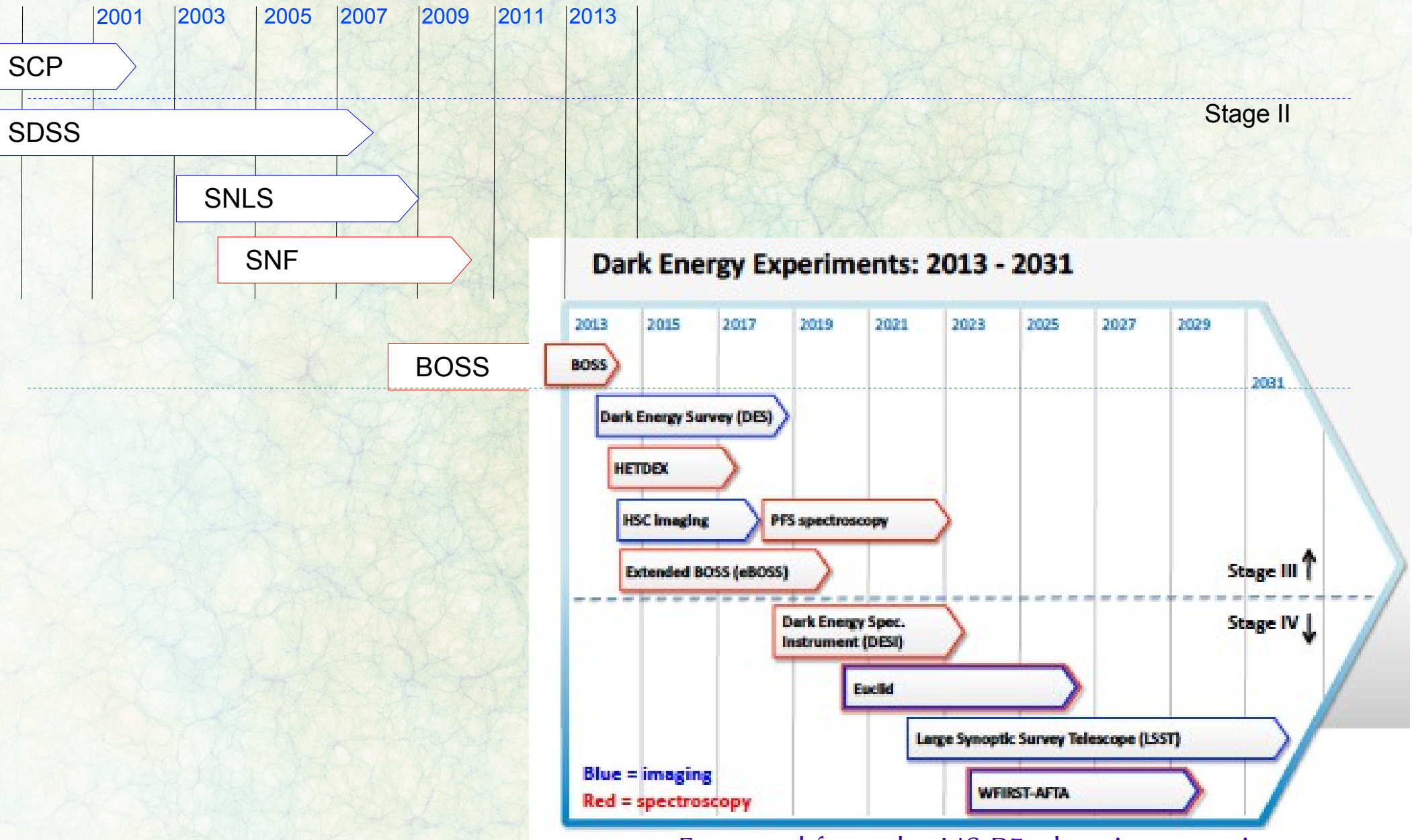


Emmanuel Gangler – CS IN2P3

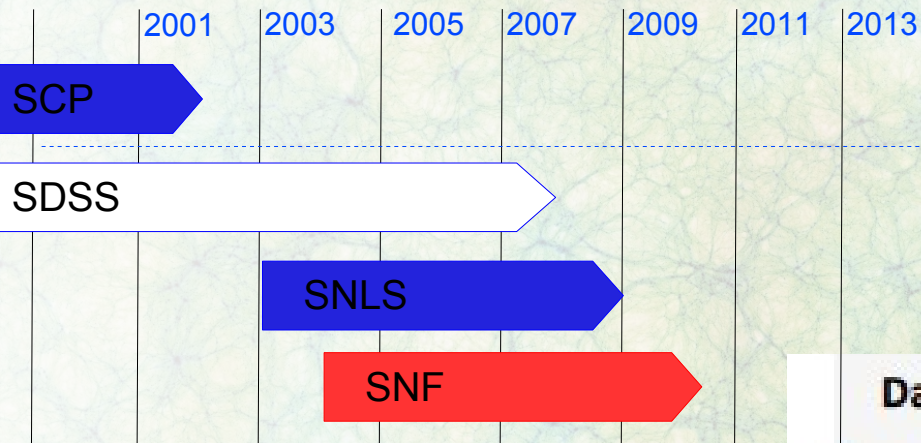


13/32

Projects Timeline



Projects @ IN2P3



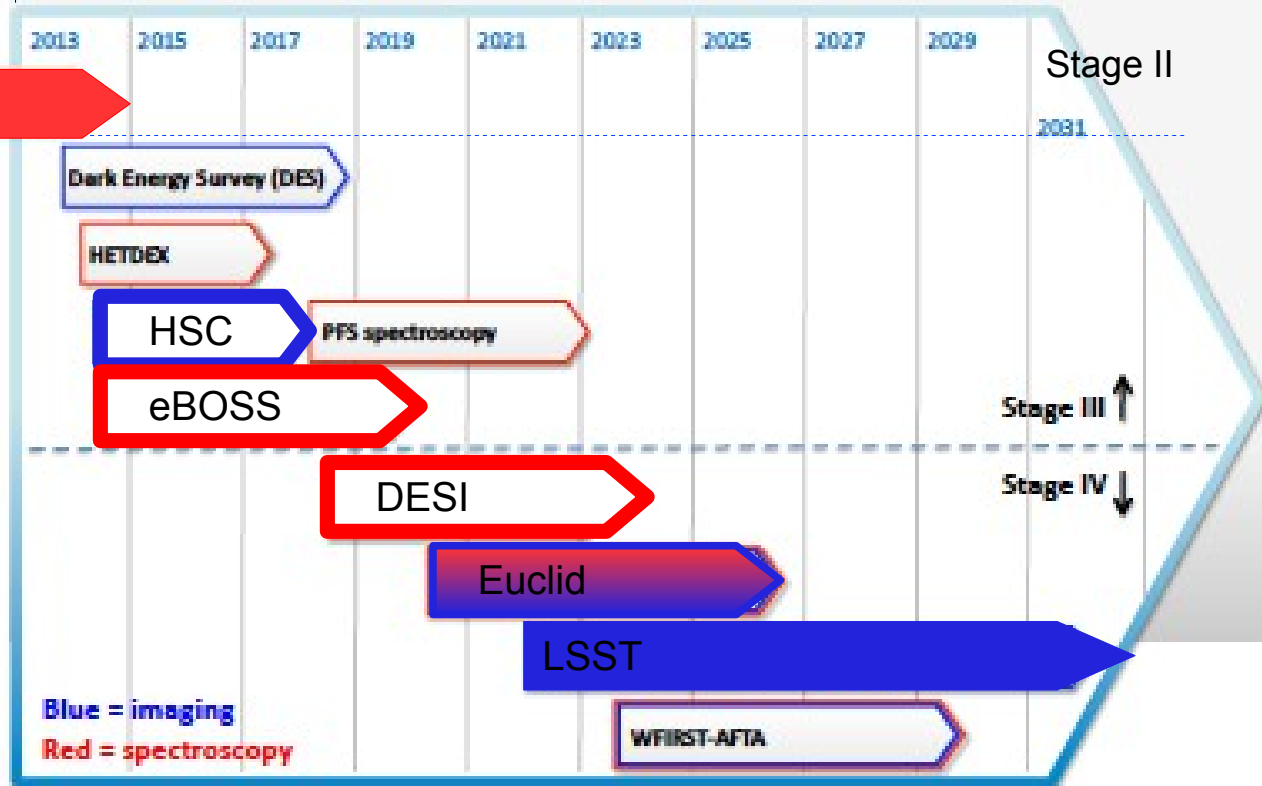
Clusters :

APC, CC, LPNHE, LPSC
(+INSU,CEA)

Supernova :
CPPM, IPNL,
LPC, LPNHE
(+CEA)

BAO :
APC, CPPM, LAL, LPNHE, LPSC
(+INSU,CEA)

Dark Energy Experiments: 2013 - 2031



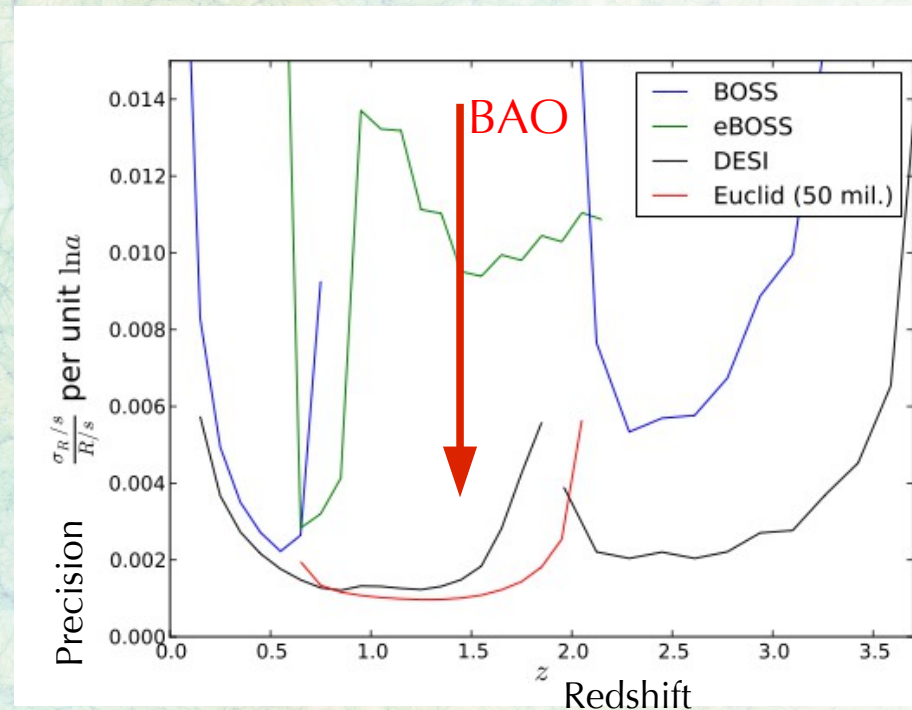
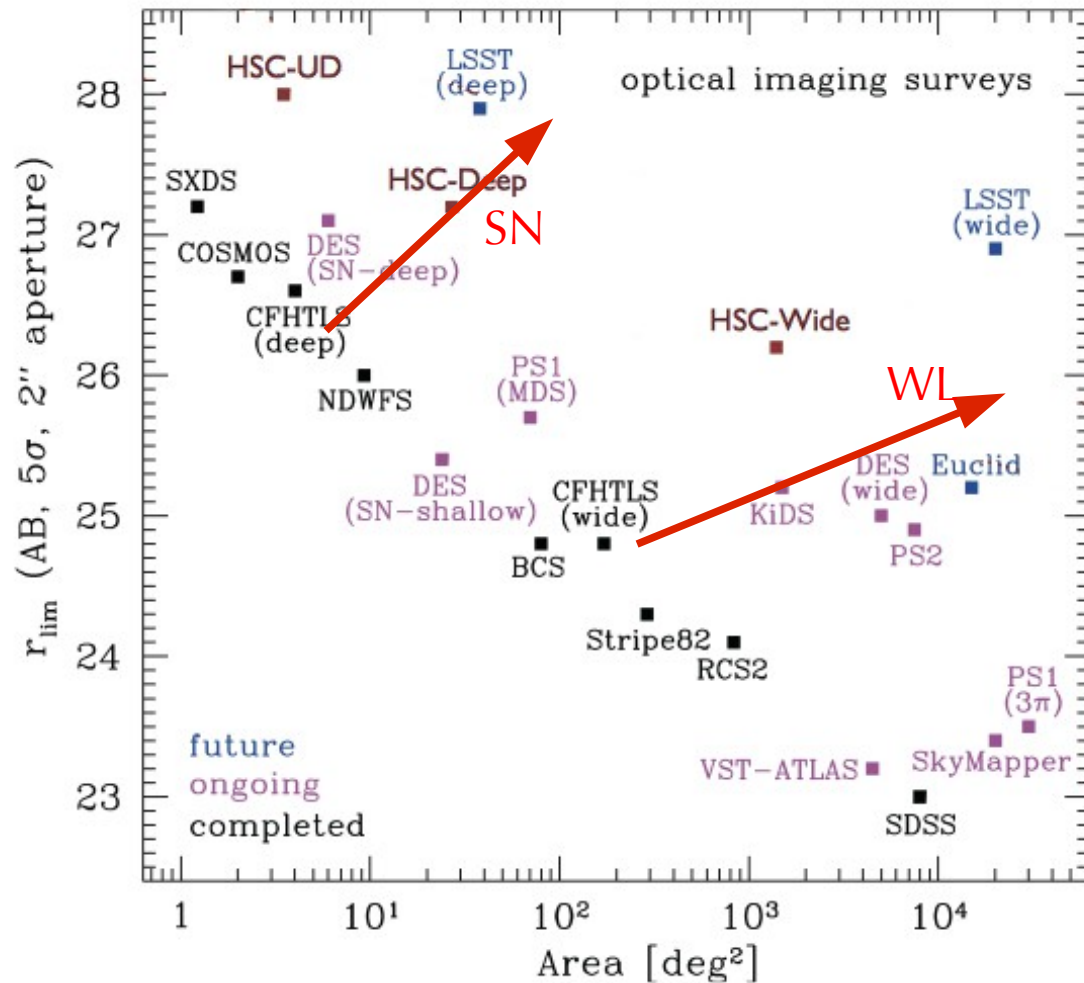
Blue = imaging
Red = spectroscopy

Extracted from the US P5 planning exercise

Projects evolution

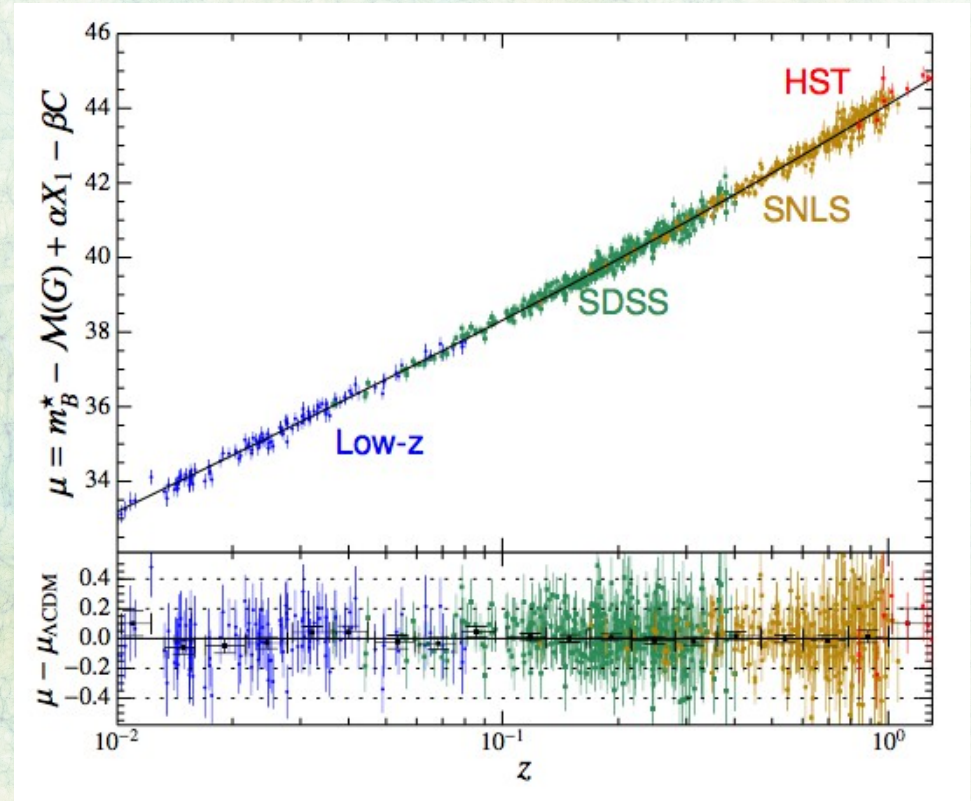
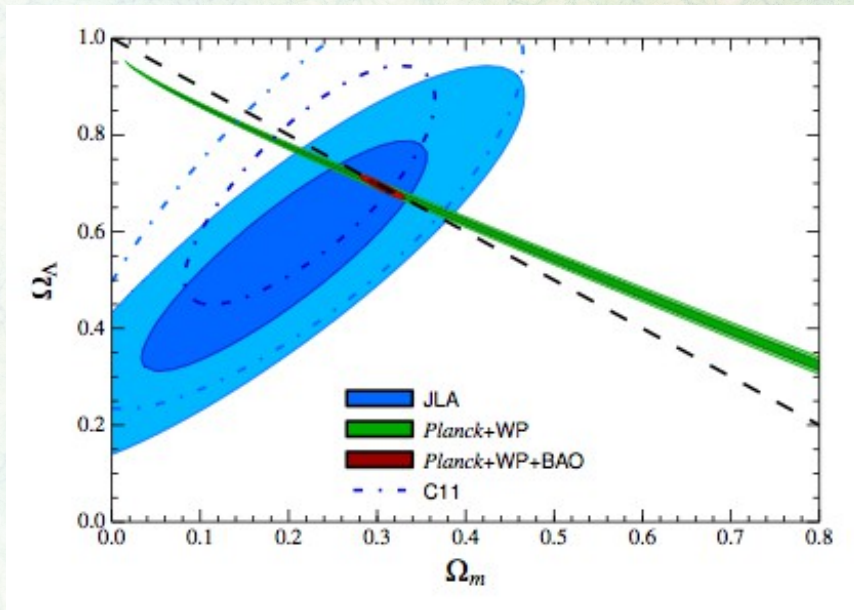
Photometry

Spectroscopy



Supernova state of the art :

Bétoile 2014 : 720 SNIa
Joint Light-Curve Analysis (SDSS+SNLS)



Flat- Λ CDM model with SN alone:
uncertainties on Ω_M : 0.034

Stat: 0.018

Calibration: 0.020


Other syst: 0.012

This is (already) precision cosmology !

Future improvements :

- Statistics (granted by new projects)
- Calibration (under scrutiny)
- Standardization (0.08 mag difficult to beat)
- Astrophysical biases
- Transient methodology

This is under scrutiny by ongoing projects !



automated transient
identification in the
dark energy survey
(1504.02936)

danny goldstein

for the DES supernova
working group

lsst desc sn telecon
june 3, 2015

DES survey :
1M transient/season

Goal : 3000 SN in 5 years

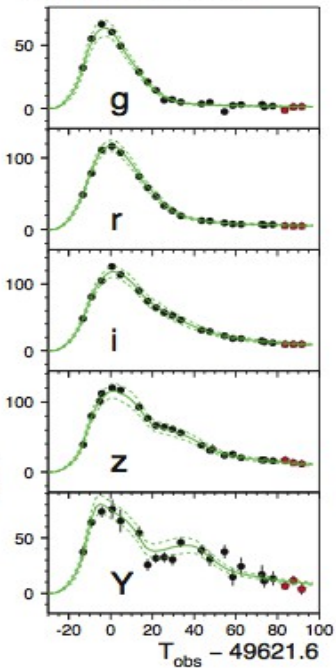
And an opportunity of interdisciplinary research with INS2I

SN in LSST

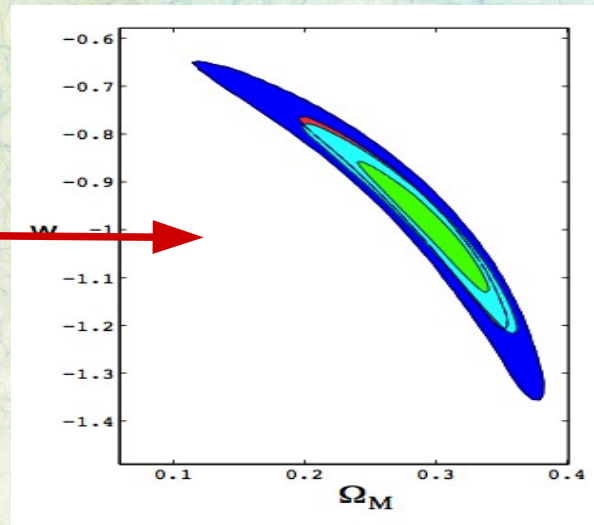
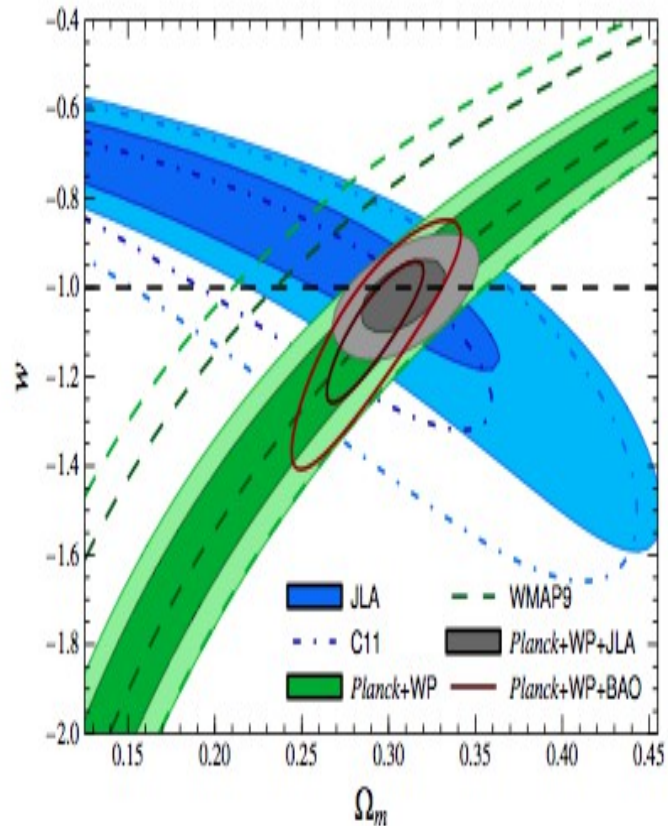
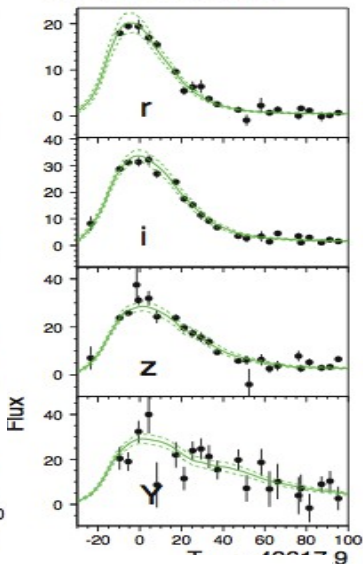
- *10 000 well sampled SN/season*
- Systematics dominated (short in IR)
- No **spectroscopy** (for now...)
- Redshift from external measurement

Huge improvement still !

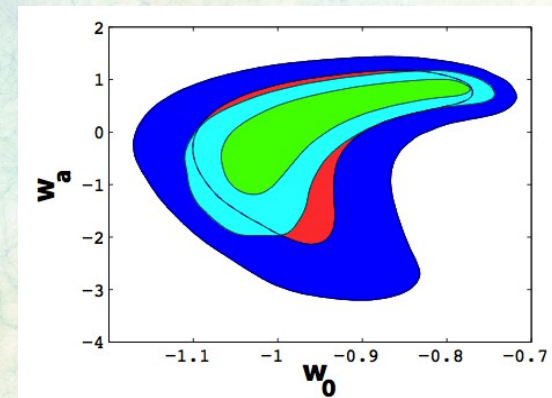
SN 40002 $z=0.3866$



SN 40006 $z=0.8065$



LSST 10 000 SN

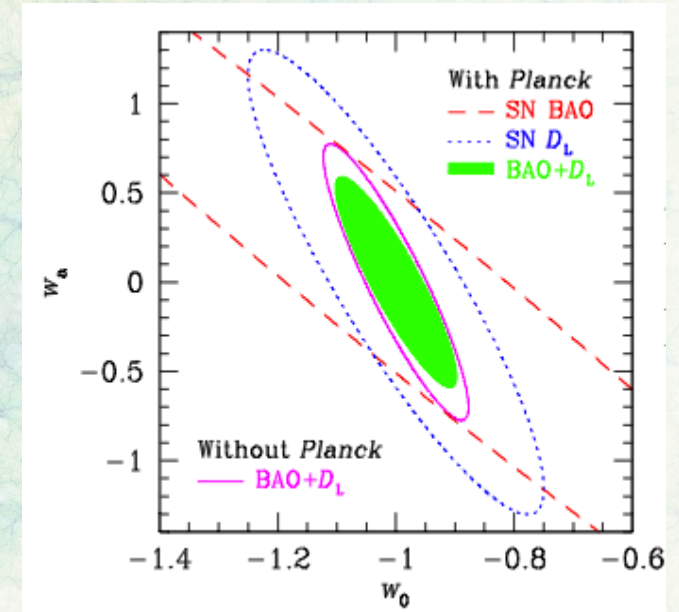
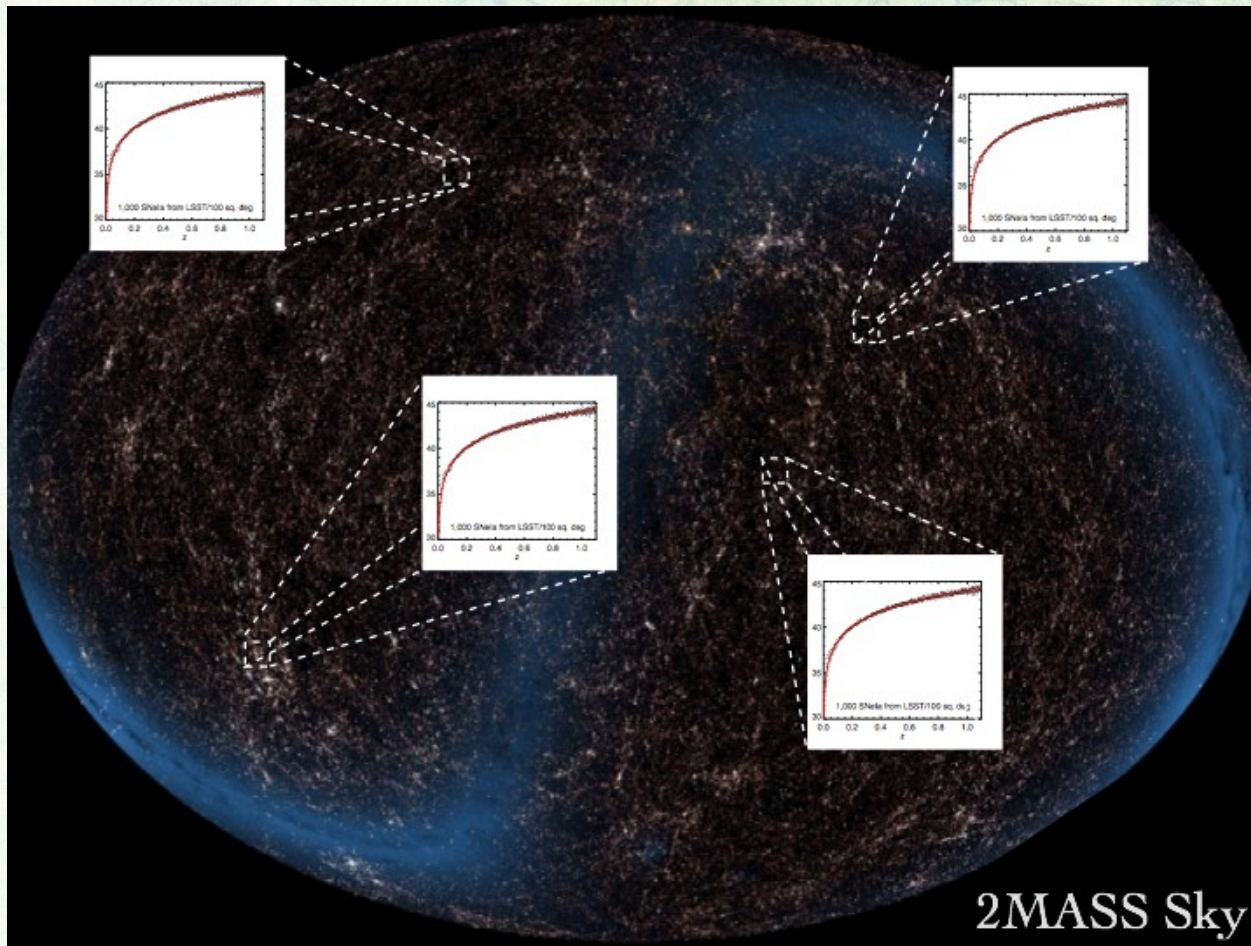


LSST 50 000 SN

Massive SN set :

- 10^{5-6} supernovae \square spatial repartition
- Homogeneity, isotropy

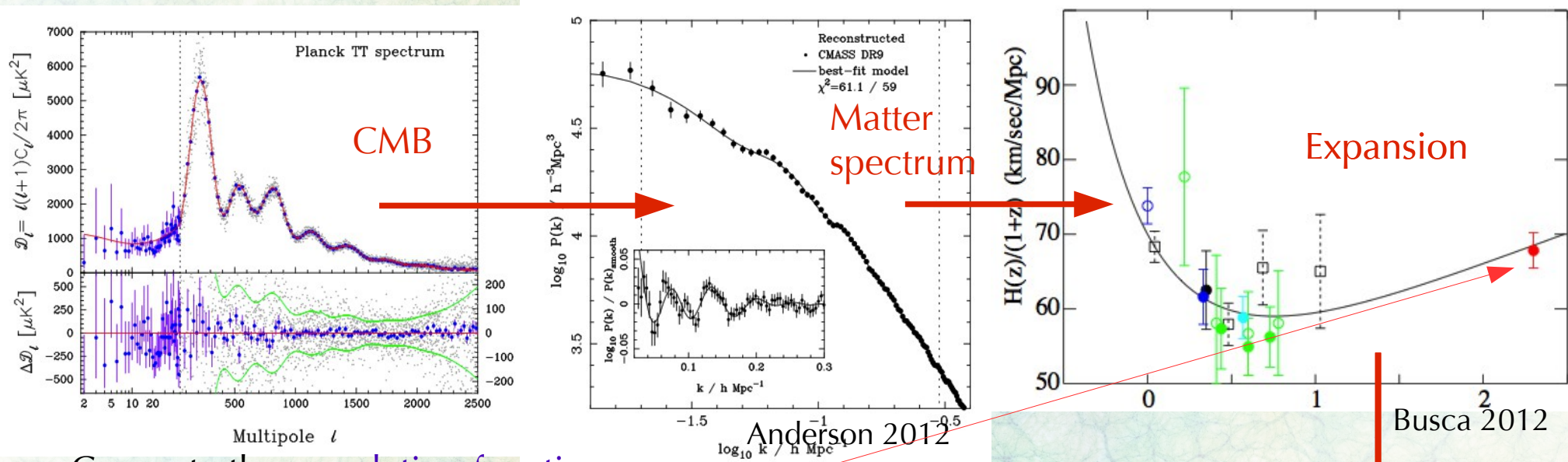
- BAO with SNIa



- + SN II, ...

Cosmology with BAO

Standard ruler approach



Compute the correlation function

- Of galaxies
- Quasar's Ly- α forest

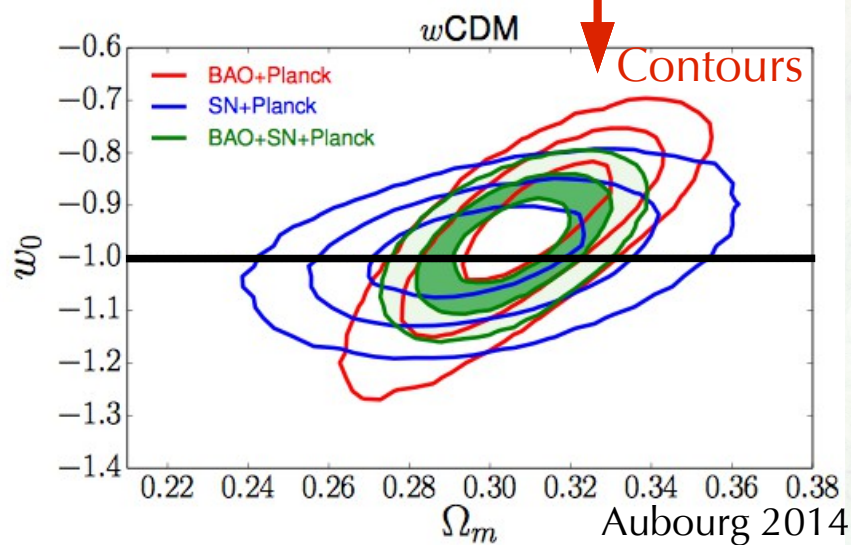
First détection 2005

Ongoing effort since !

Difficulties :

- Redshift determination (spectro/photo)
- Statistics \square not really an issue

Tacer of **matter density**



Spectroscopic BAO

BOSS : 1000 fibers (150/deg)

- 1.5 M Galaxies $z < 0.7$
- 160 k **Ly- α forest** $2.2 < z < 3$

eBOSS

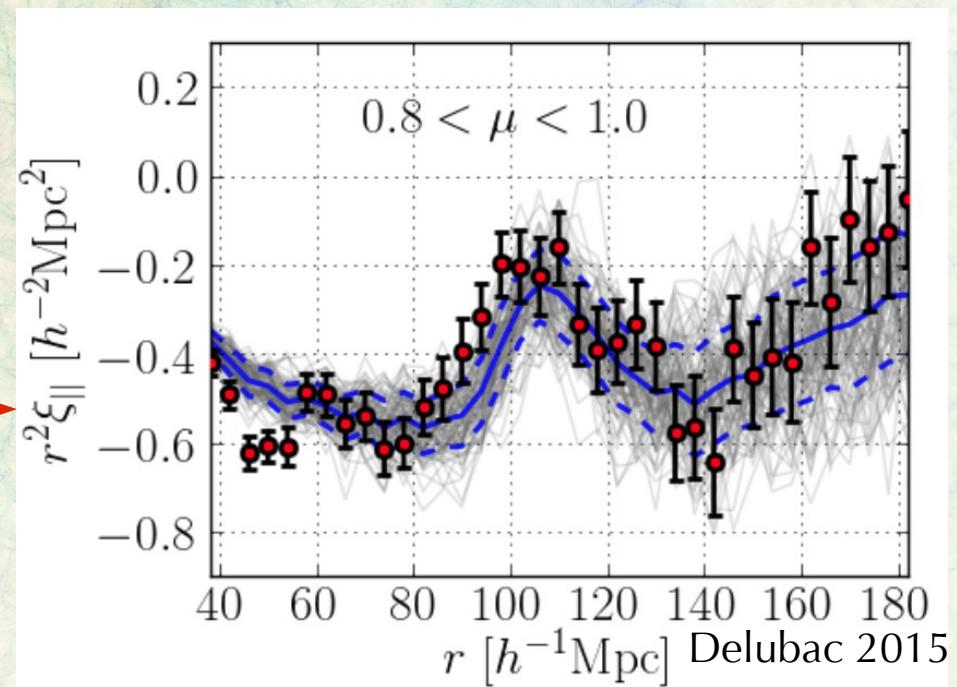
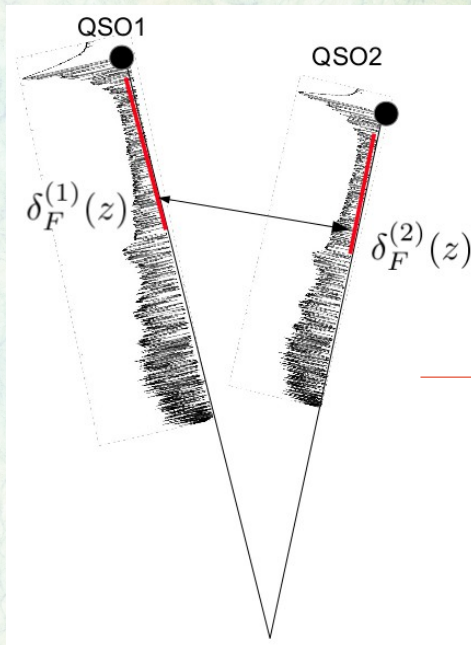
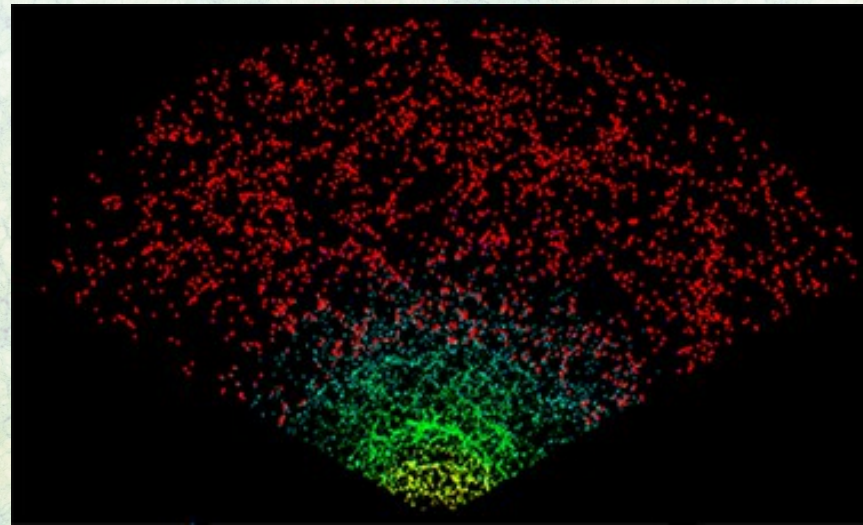
- 635 kGalaxies $0.6 < z < 1.0$
- 740 Quasars $0.9 < z < 3.5$

DESI : 5000 fibers (2800/deg)

- 32 M Galaxies
- 2.4 M Quasars
- (10 M Milky Way's stars)

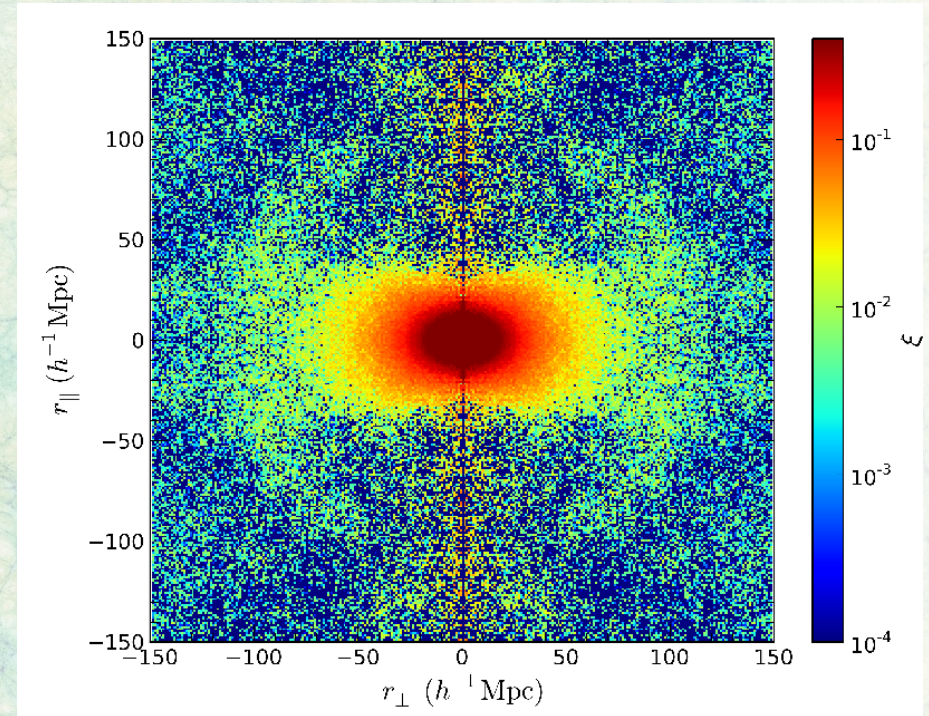
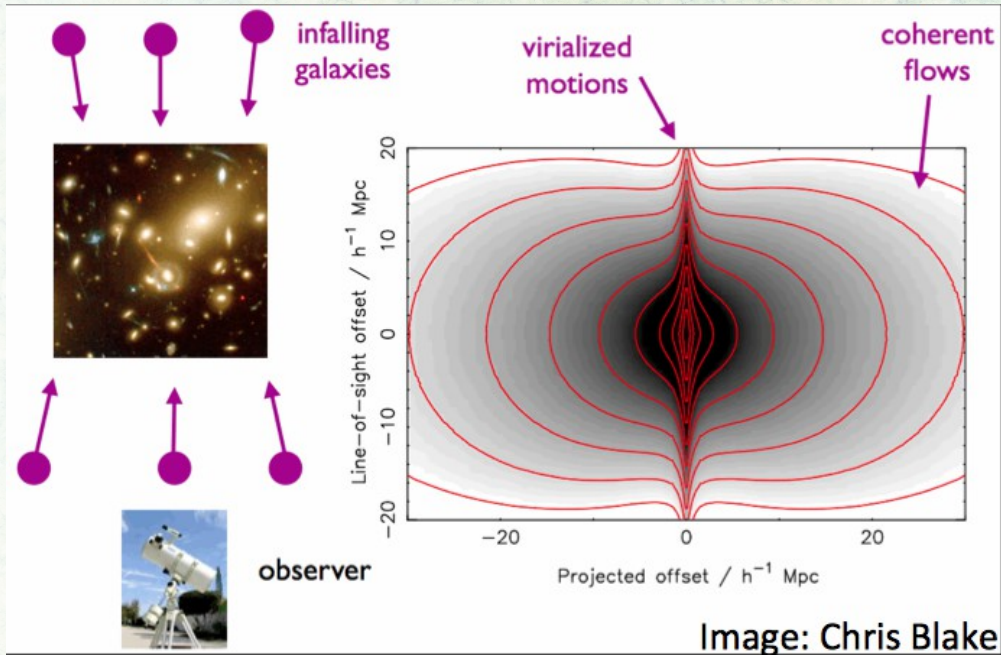
Euclid :

- 50M Galaxies



Redshift distortions:

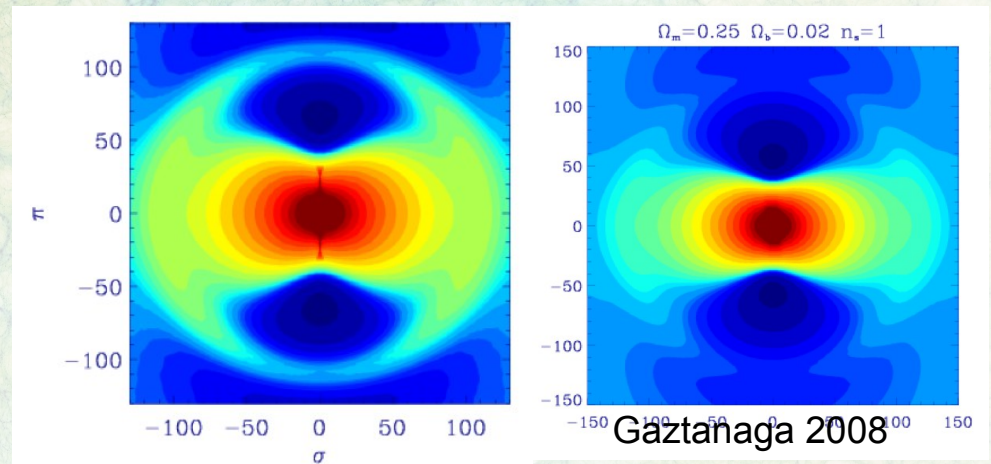
Samushia 2014



Fingers of god = central part of clusters

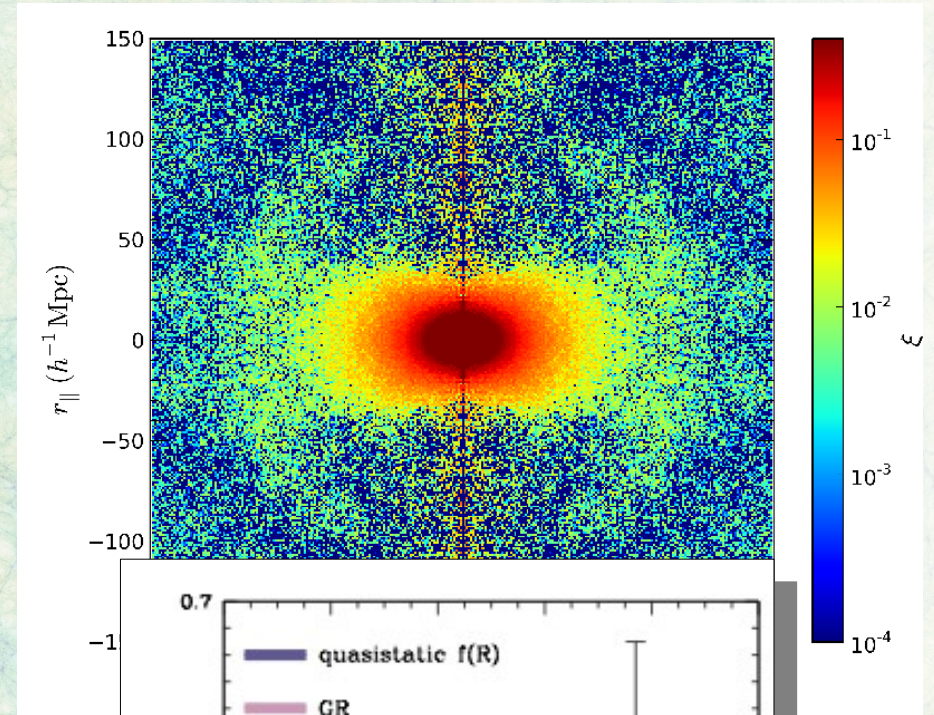
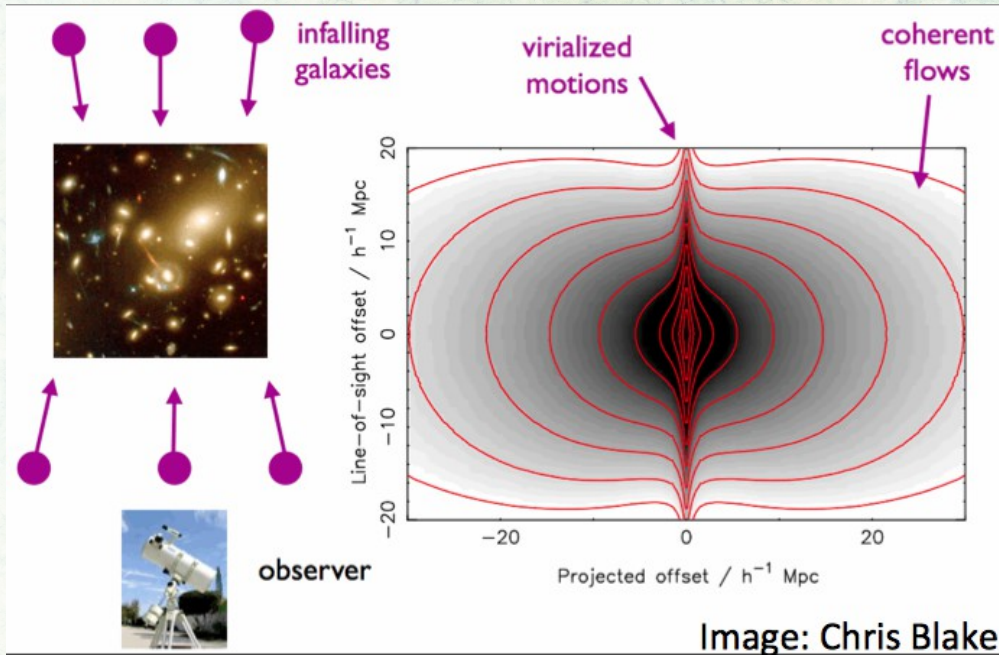
Coherent flow

- Sensitive to cosmological parameters



Redshift distortions:

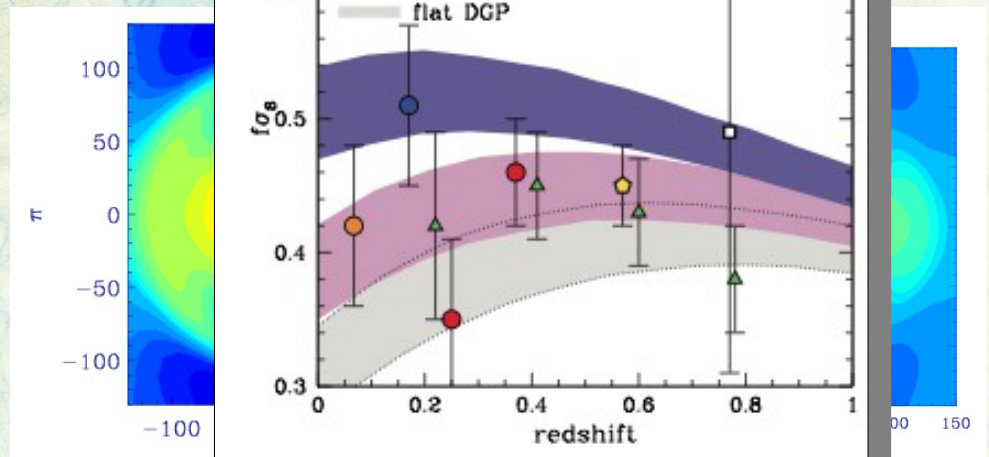
Samushia 2014



Fingers of god = central part of clusters

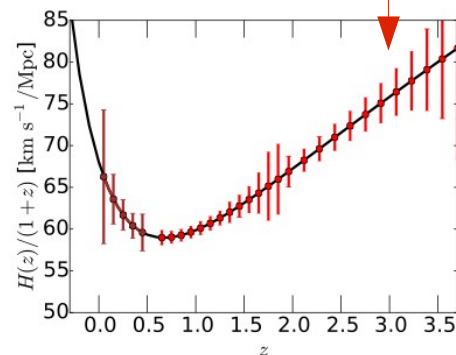
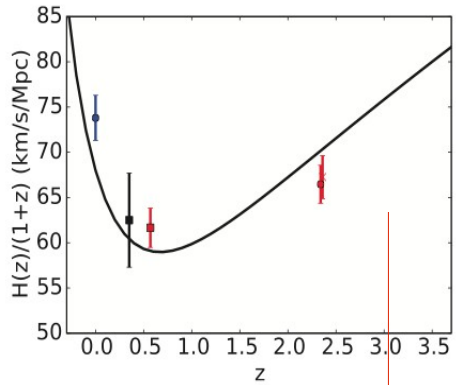
Coherent flow

- Sensitive to cosmological parameters
- Test of General Relativity
- Tomography \square growth of structures



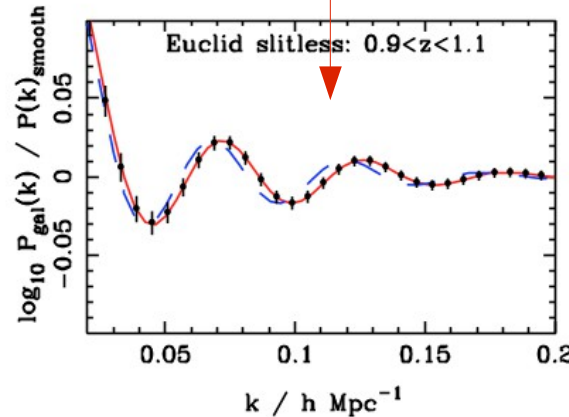
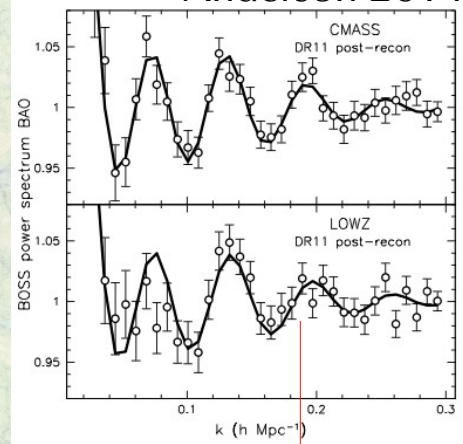
Galaxy clustering in DESI & Euclid

General Relativity tests

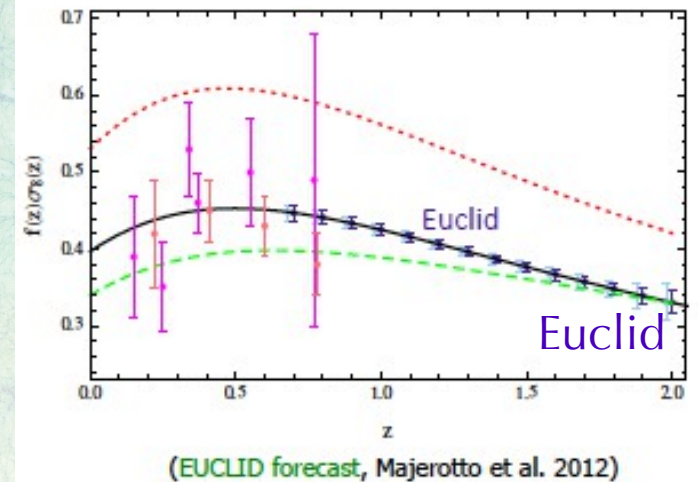
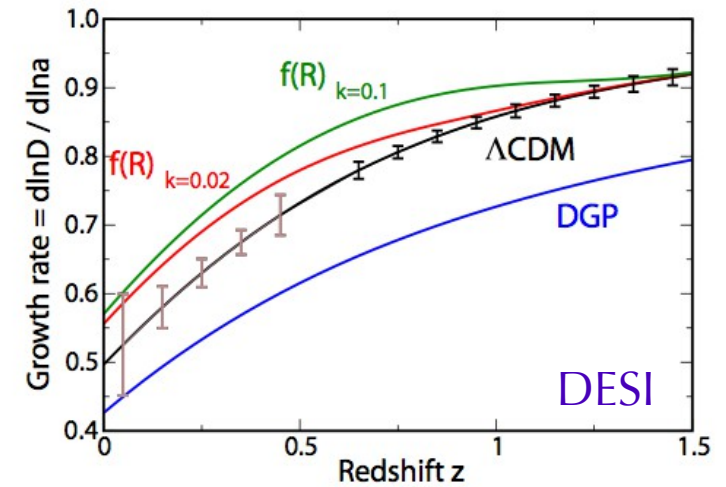


DESI Hubble diagram

Anderson 2014



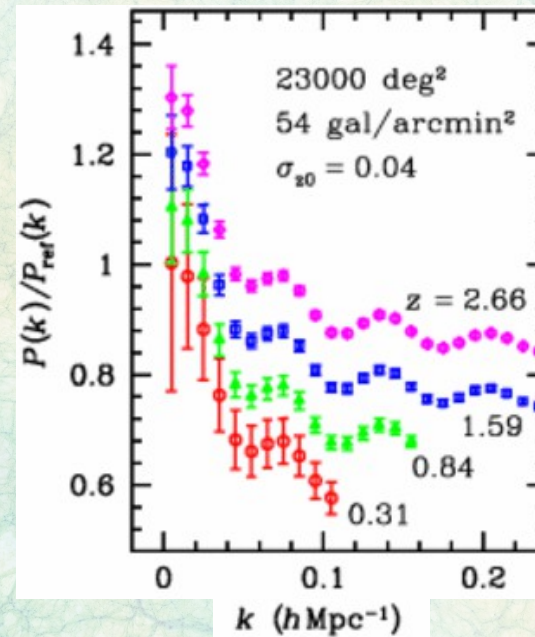
Euclid power spectrum (1 bin)



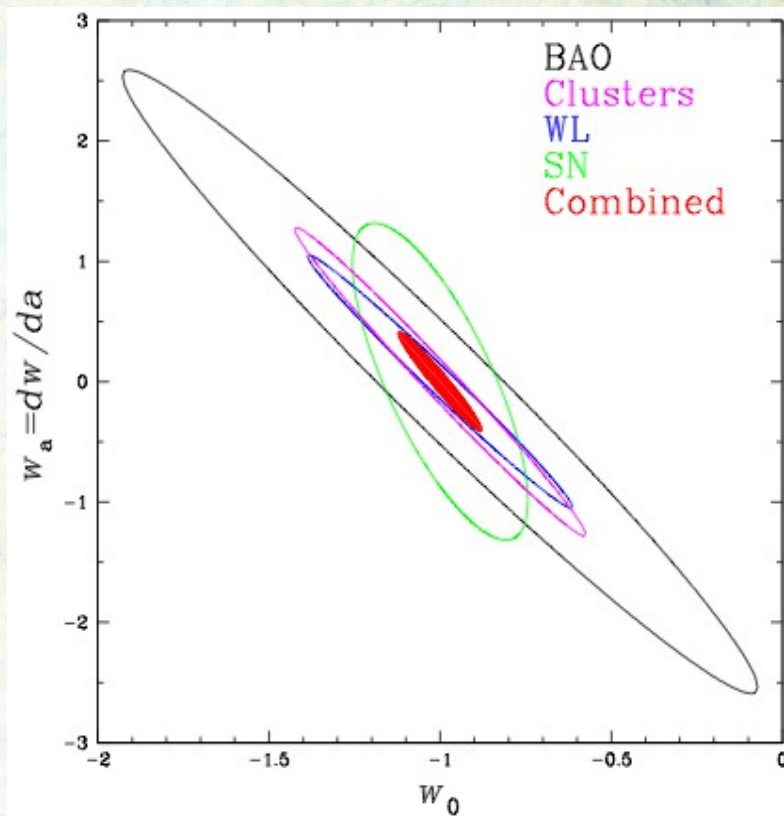
Photo/Spectro BAO sensitivity :

LSST :

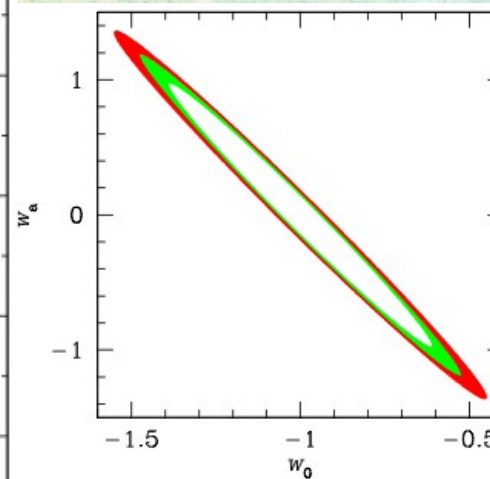
- 10 B galaxies in 20000[□]
- 4B in gold sample ($i < 25.3$)
- Up to $z < 2.5$



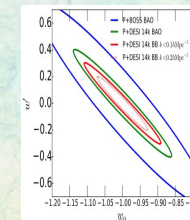
DES



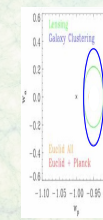
LSST



BOSS
DESI



Euclid



... BAO complementary to other probes !

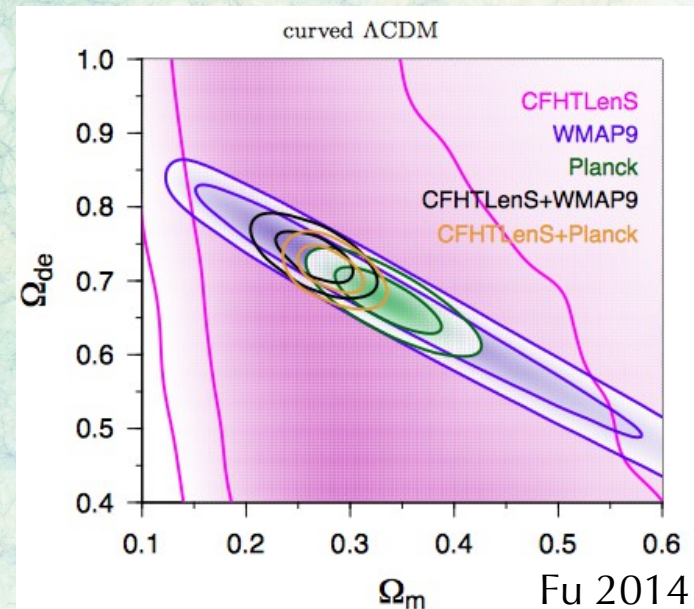
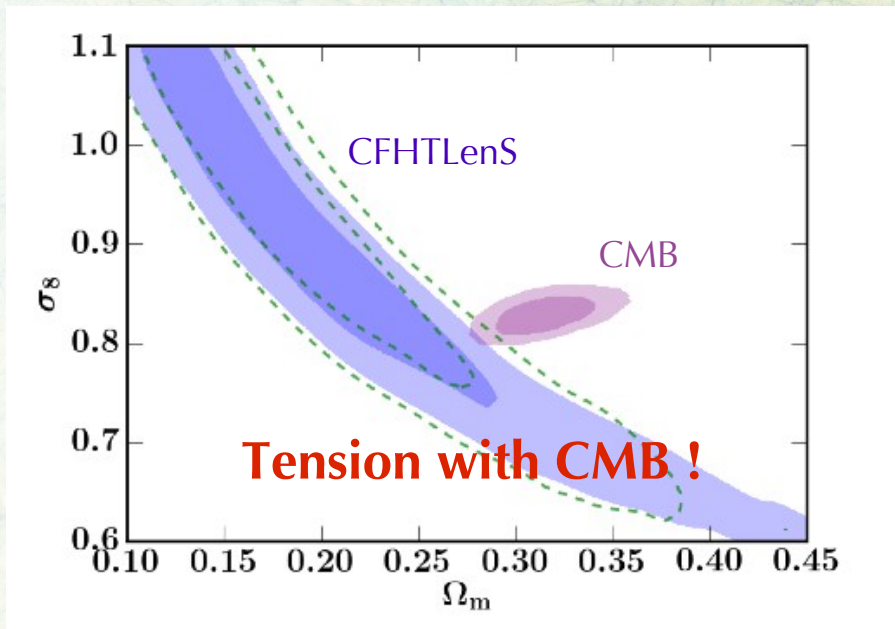
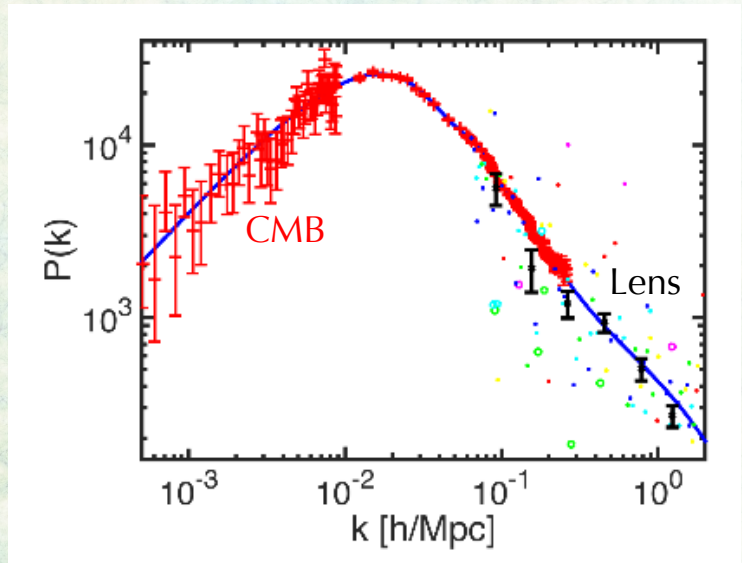
Cosmology with WL

Shear correlation sensitive to $\sigma_8 \Omega_m^\alpha$

And to distance/velocity relation

Galaxy-galaxy lensing calibrate bias

Galaxy Intrinsic alignments to be controlled



MacCrann 2014

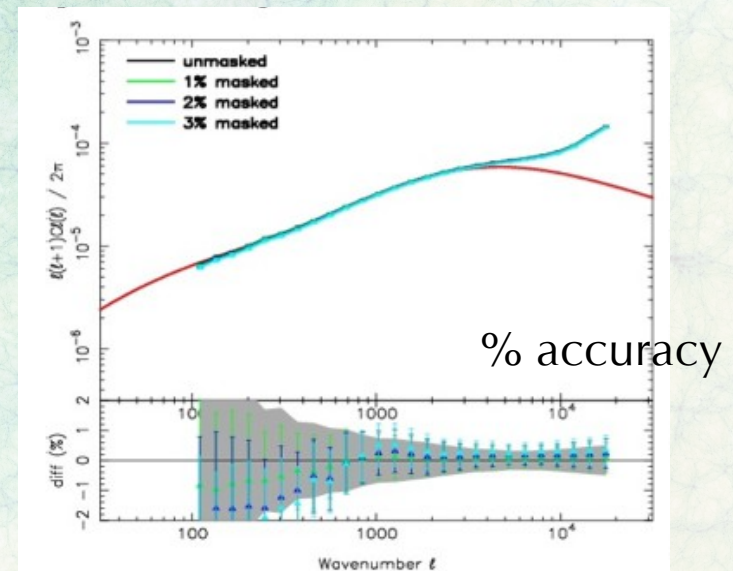
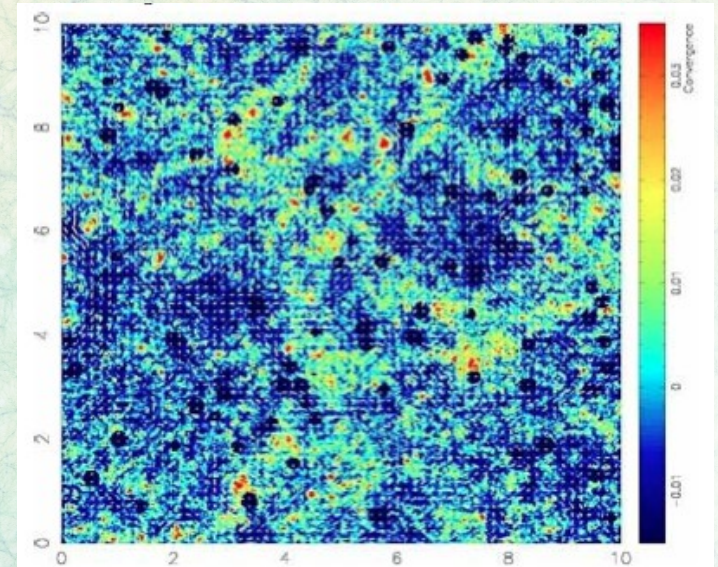
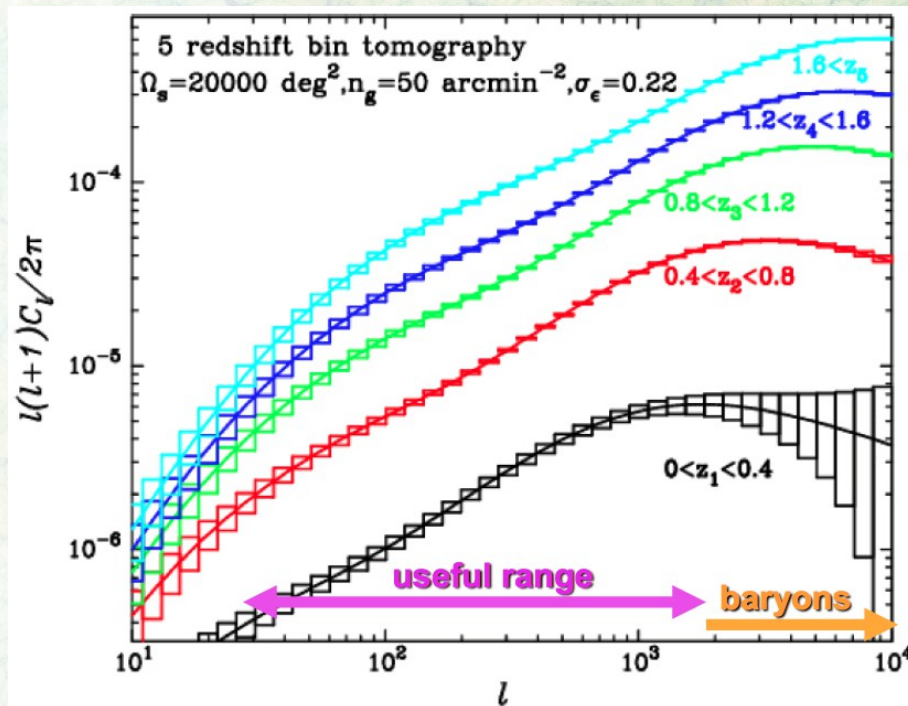
- Expected to be **most precise** probe in LSST/Euclid

Lensing with LSST / Euclid

Lensing is sensitive to **all dark matter components**, including neutrinos

LSST : ~ 100 visits will reduce the systematic shear correlations below the shot noise

Euclid : PSF diffraction limited



Cluster lensing

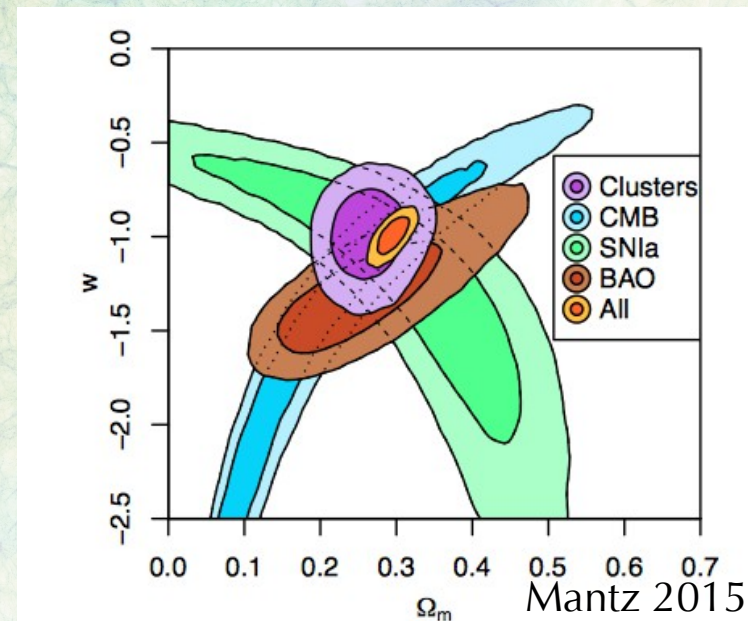
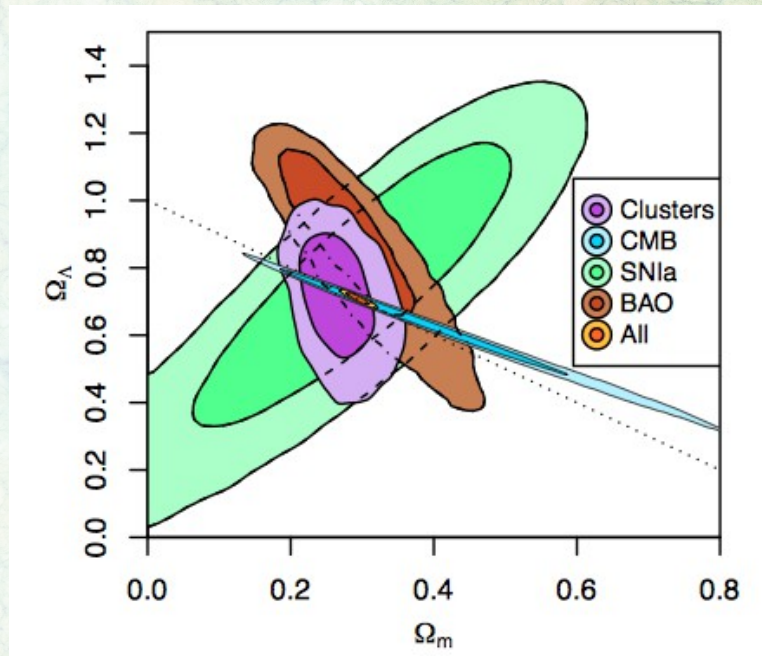
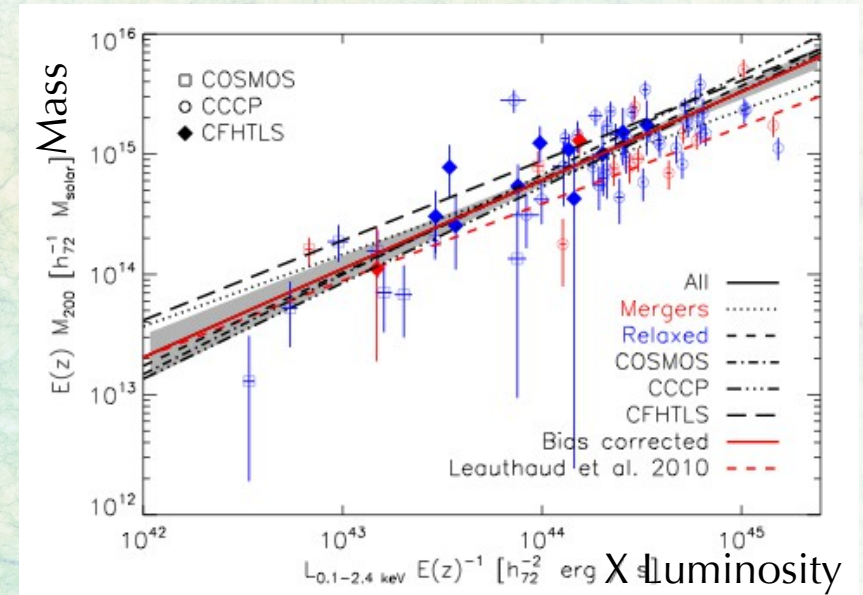
Kettula 2015

Cluster count is a powerful probe

Cluster mass relation is the bottleneck
WL provides an estimate of the mass
8% systematics now

To calibrate SZ and/or X relation

- target a few % calibration



Mantz 2015

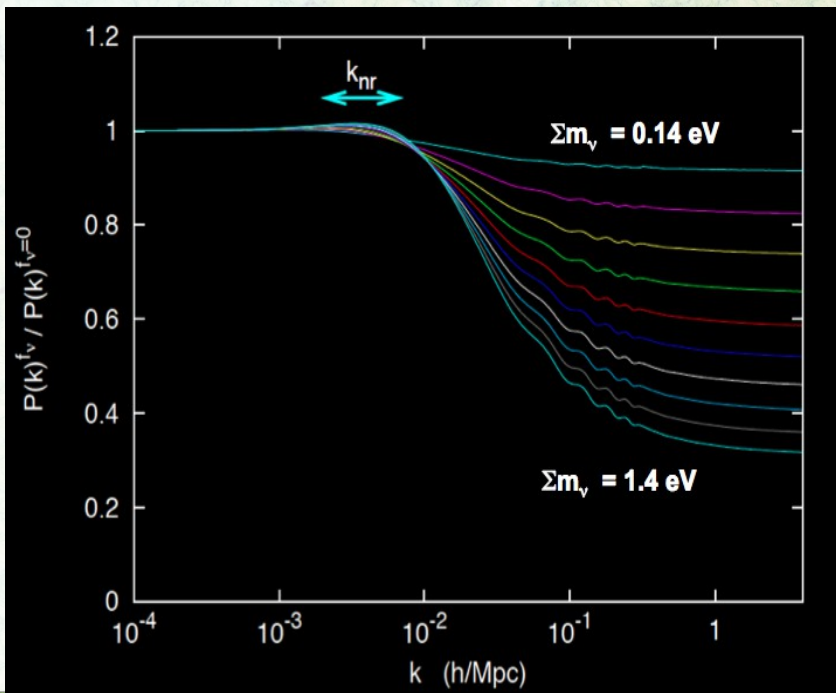
Neutrino mass

Neutrino suppress growth of structures

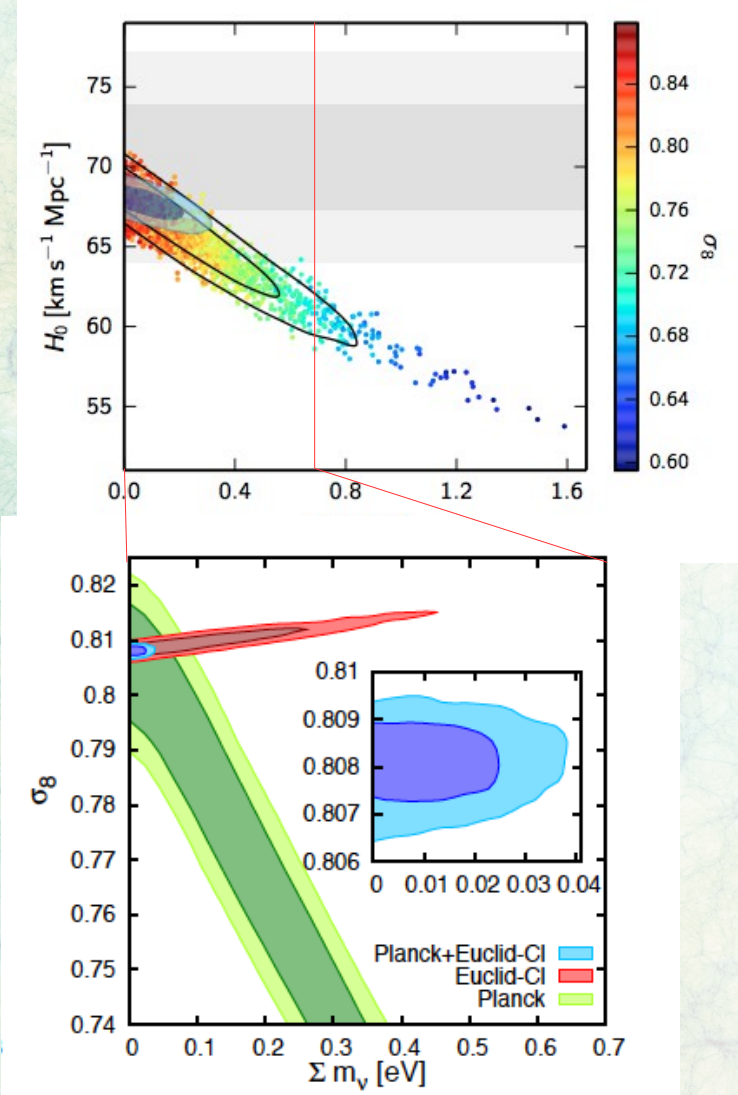
Smaller mass

- longer relativistic
- suppress growth on larger scales

Abazajian



Planck 2015



Expected 0.02 eV Sensitivity (all stage IV)

$\Sigma m_{\nu} > \sim 0.06 \text{ eV}$

Long-term prospects on Dark Energy constraints

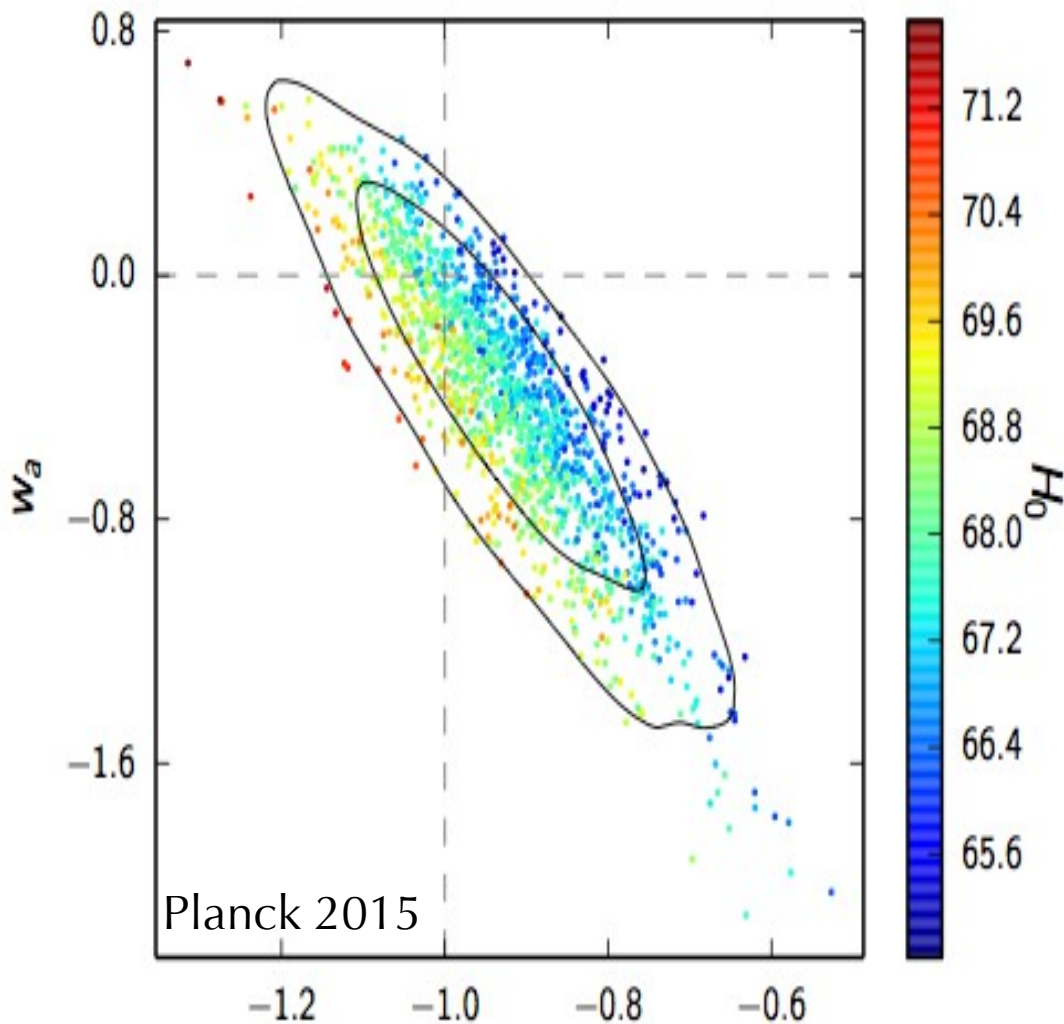
Sensitivity today : **SN~BAO**

Sensitivity >2020 : **WL>BAO>SN**

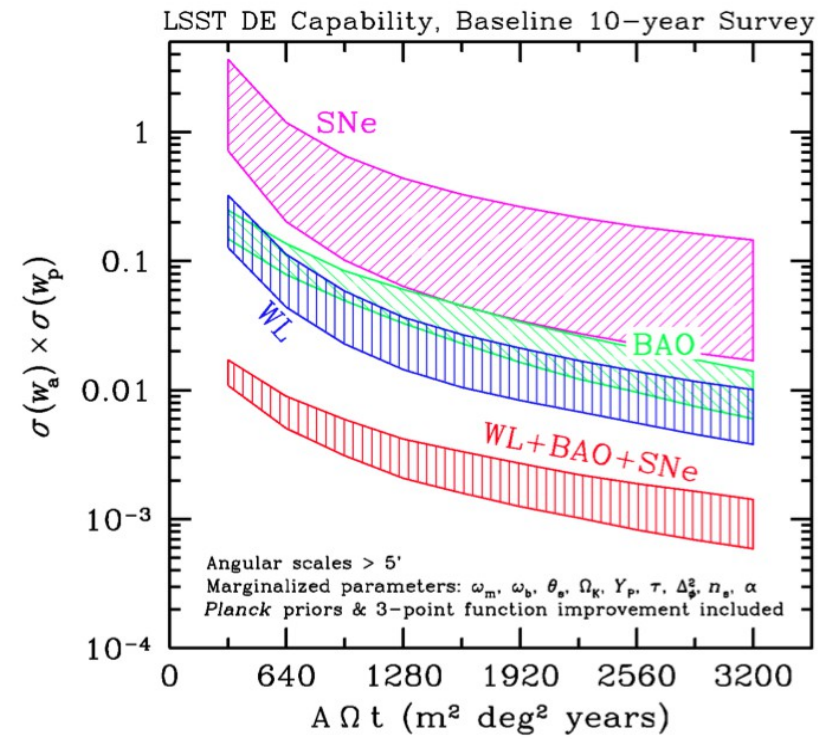
Probe combination fixes nuisance parameters

IN2P3 strategy ?

- precise determination of equation of state.

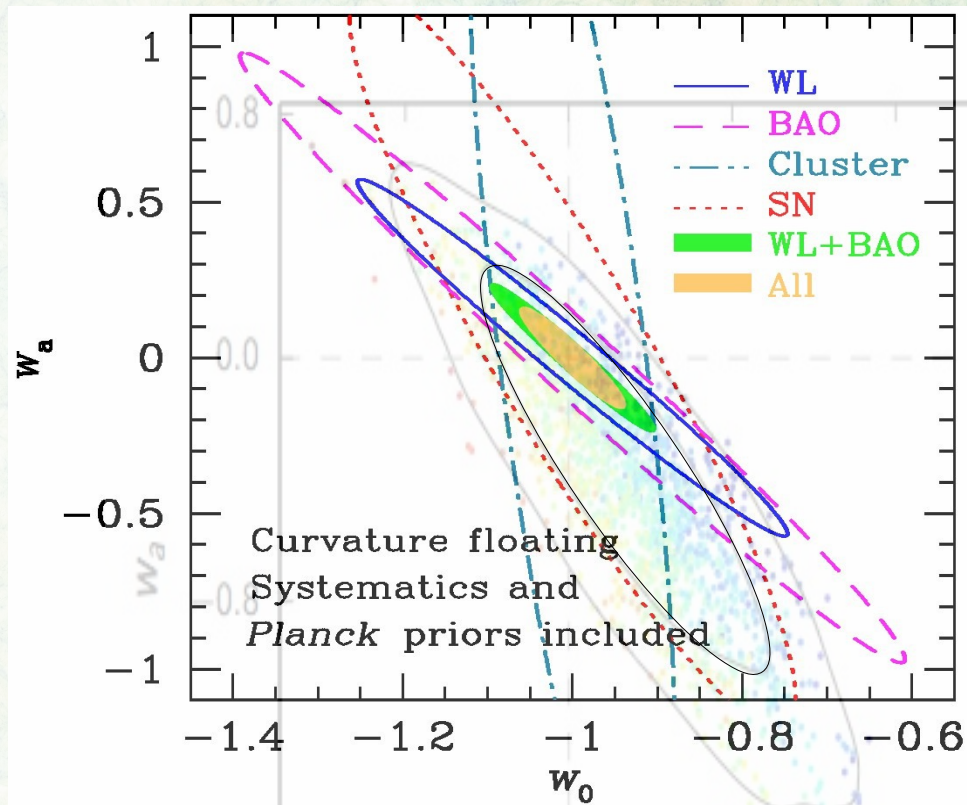


LSST projection

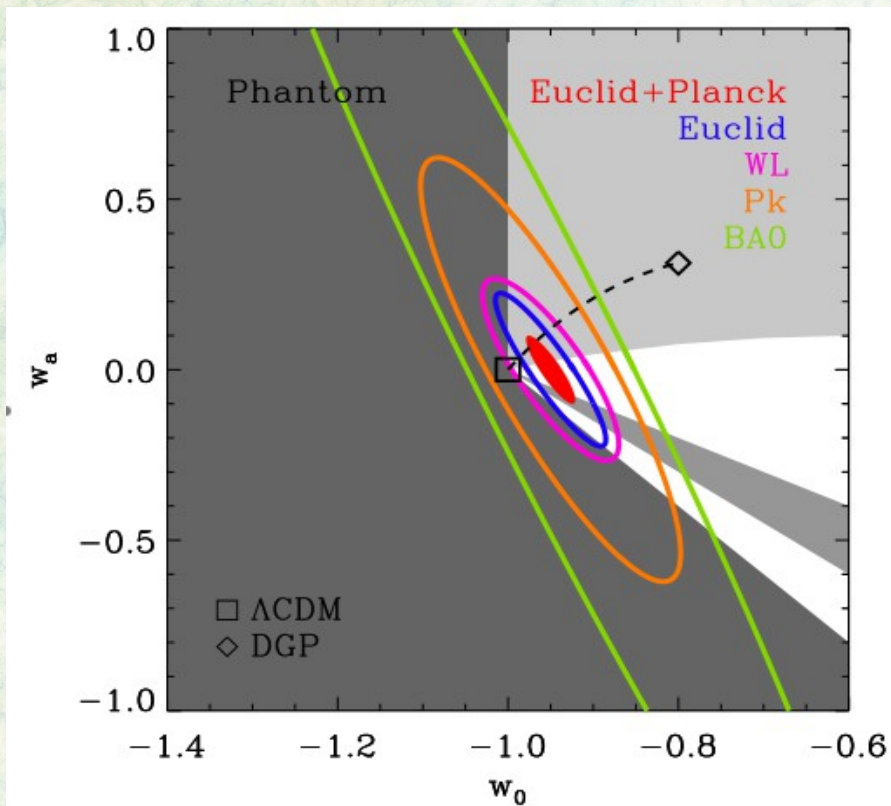


Long-term prospects on Dark Energy constraints

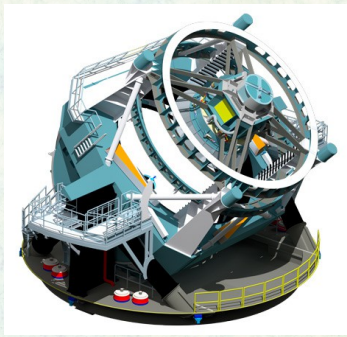
LSST projection



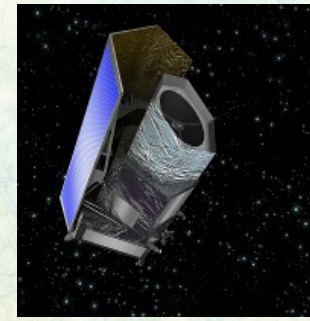
Euclid Projection



Errors will be systematics dominated !



Conclusions



- **Key scientific questions to be answered by future projects**
 - Inflation and **Primordial Gravitational Waves**
 - Nature of **Dark Energy**
 - **Probes are complementary**
 - CMB, SN, BAO, WL, Clusters combined for **concordance model**
 - Not only results, but also **data** can be complementary
 - Visible/IR ; Photometry/Spectroscopy ; CMB Forgrounds
 - **Intermediate projects to target top-level results**
 - **DES/HSC** to investigate variable w in **SN**
 - **DESI** is a competitive **BAO** project
 - Growing interest for **Cluster WL**
- ... and to train next generation of cosmologists