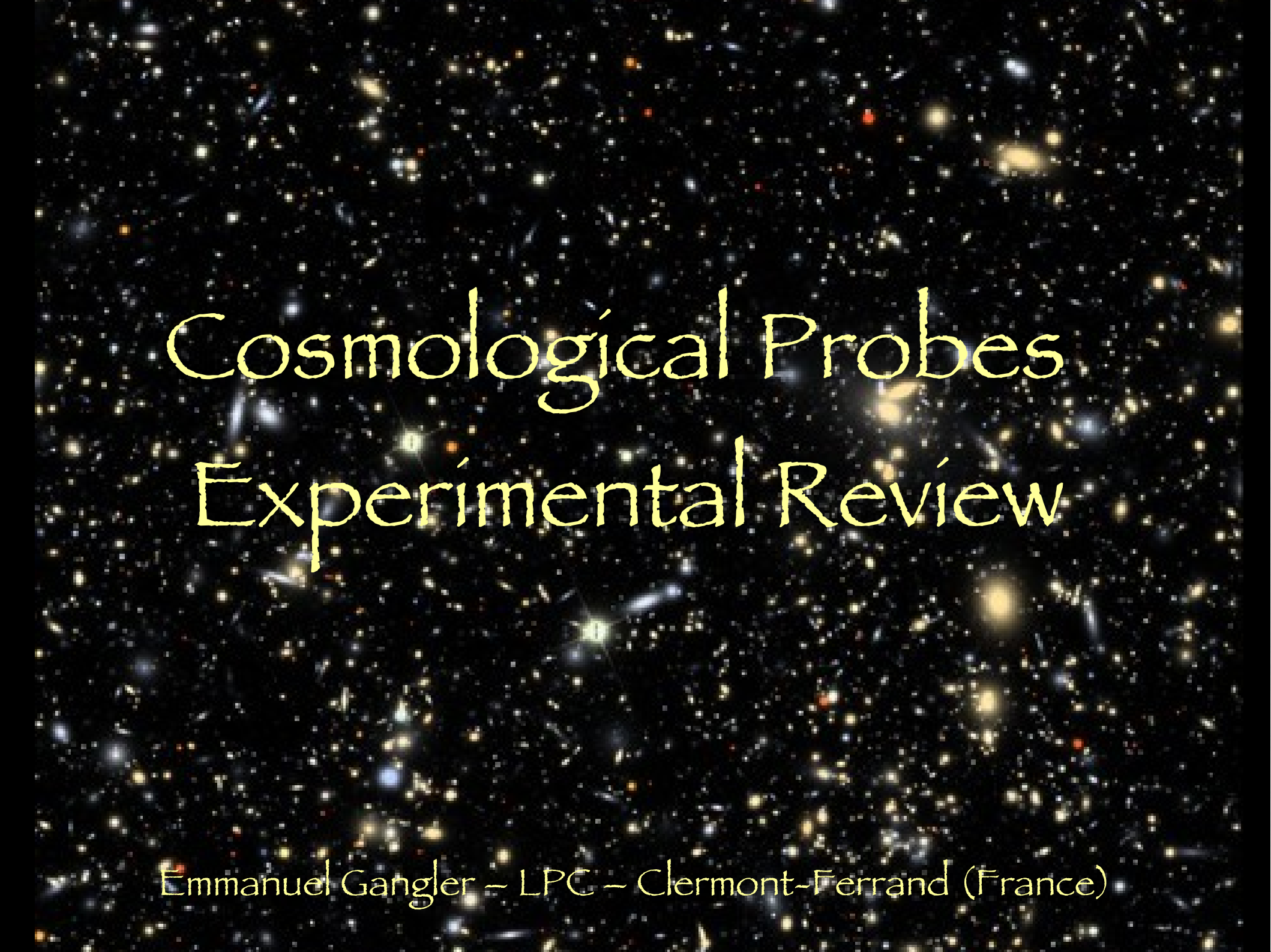
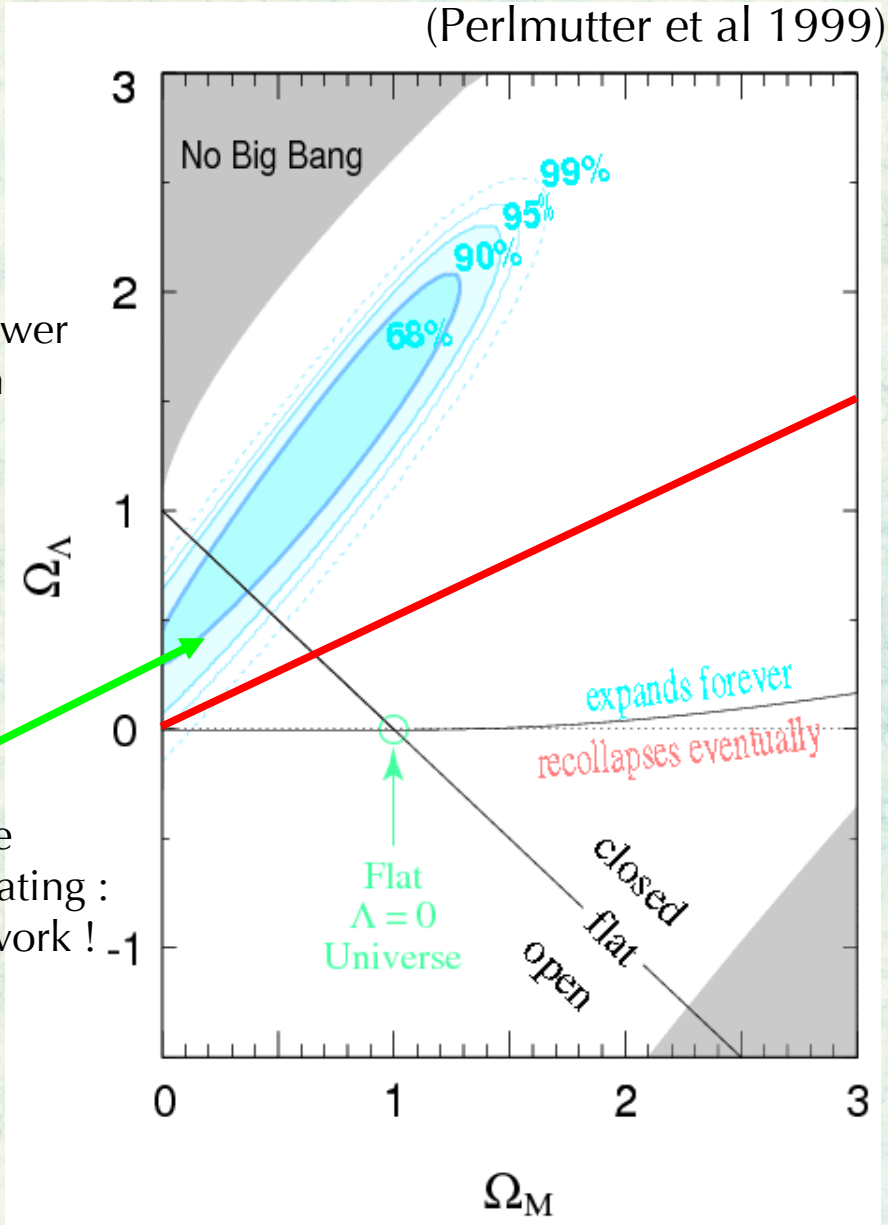

Cosmological Probes
Experimental Review
Emmanuel Gangler – LPC – Clermont-Ferrand (France)

Dark Energy : 1998-2015 … 17 years !

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

(Perlmutter et al 1999)



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

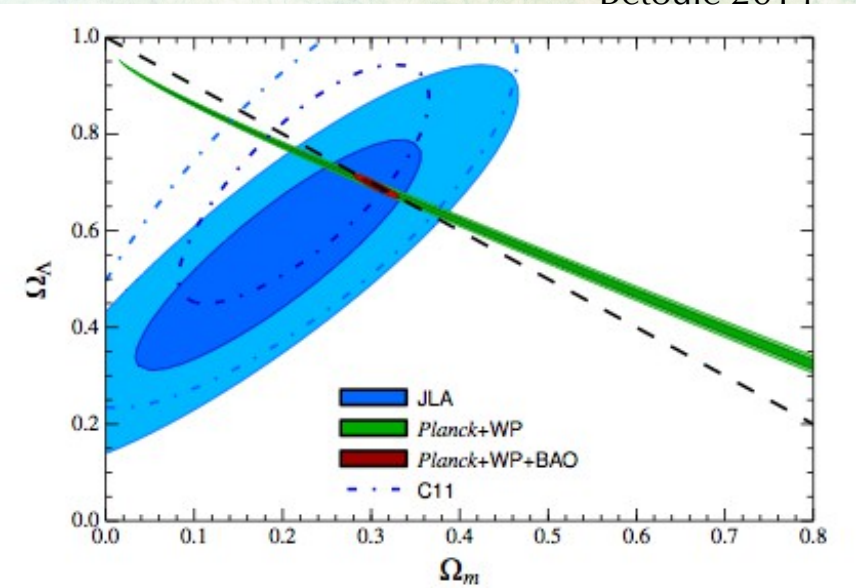
The Nobel Prize in Physics 2011 was divided, one half awarded to Saul Perlmutter, the other half jointly to Brian P. Schmidt and Adam G. Riess *"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"*.

Nobel 2011

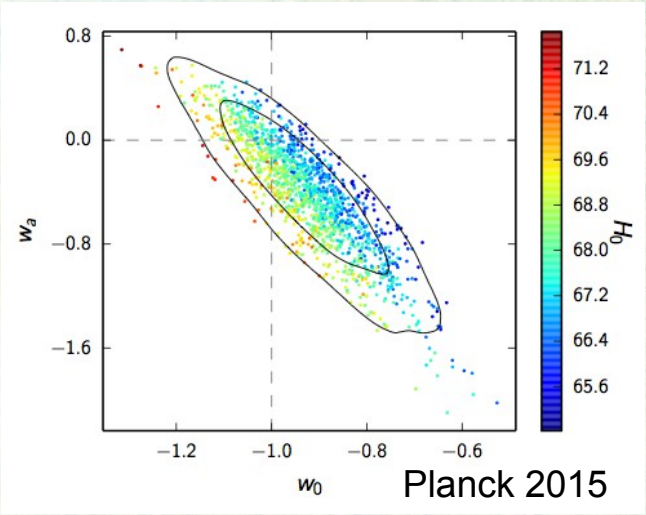
Dark Energy : 1998-2015 … 17 years and still there

Supernovae : senstive to expansion rate evolution dark energy equation of state

Betoule 2014



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



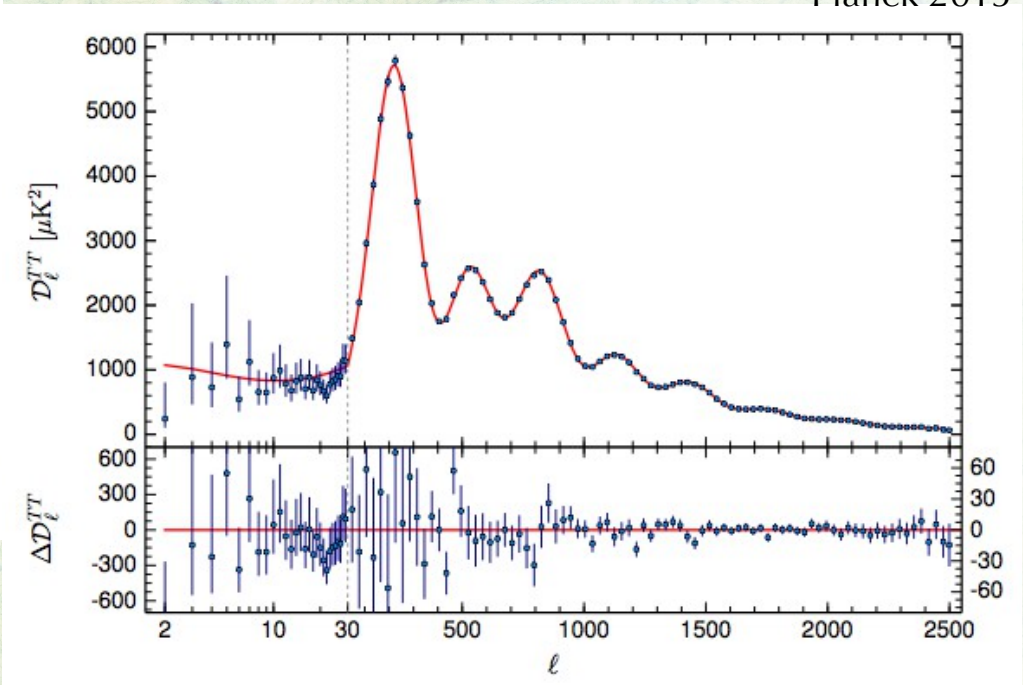
Planck 2015

CMB, BAO : scale parameter evolution

 sensitive to Ω_{tot}

+ power spectrum, polarization …

Planck 2015



Structure growth → sensitive to Ω_M & GR

→ **Concordance model** flat-ΛCDM quite robust … so far ?

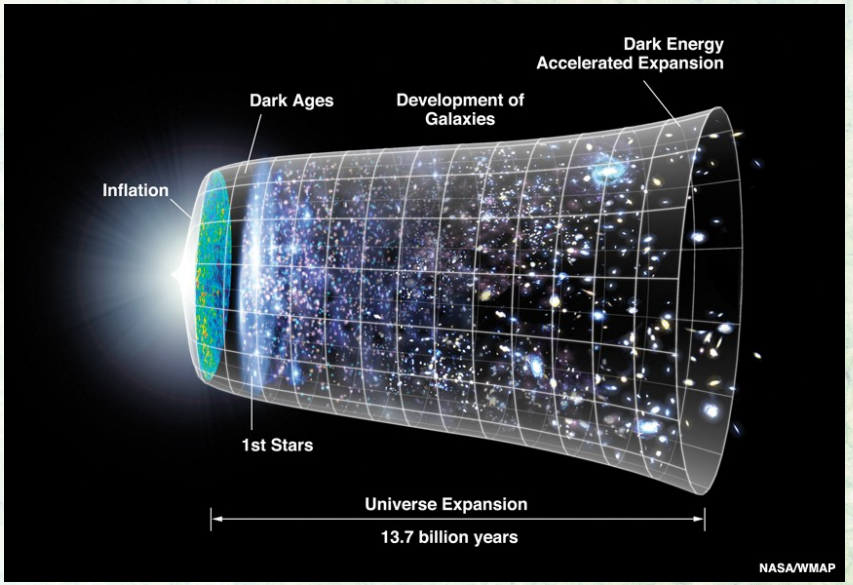
… Energie Noire ???? Le point de vue des théoriciens

- **Une constante cosmologique (le terme « standard » de l'équation d'Einstein)**
  - **Peut-on ignorer le reste du XX ième siècle ? : Energie du Vide … Plus … 120 ordres de grandeur à pomper !**
- **Le principe anthropique**
  - **Le « dégrippant » de la physique théorique : quan… nce » un peu de principe anthropique et ça repart …**
- **Quintessence**
  - **Un bon vieux champ scalaire… » de la physique théorique , ou comment « fixer » un problème …. Méthode… ses « preuves » …**
- **Relativité générale… extra dimension …**
  - **A chaque ch… ent 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 : w0, wa / FLRW

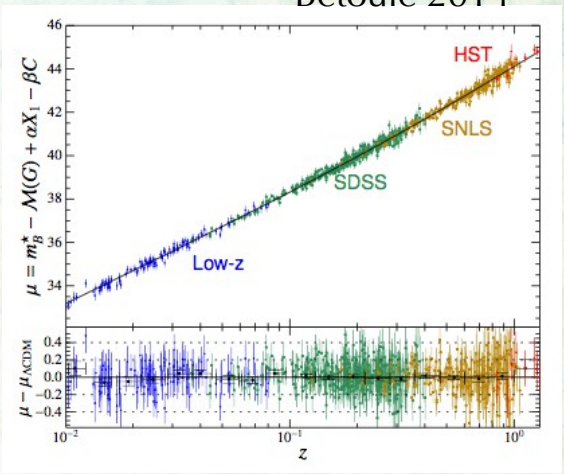
See talk by P. Binetruy

The cosmological probes



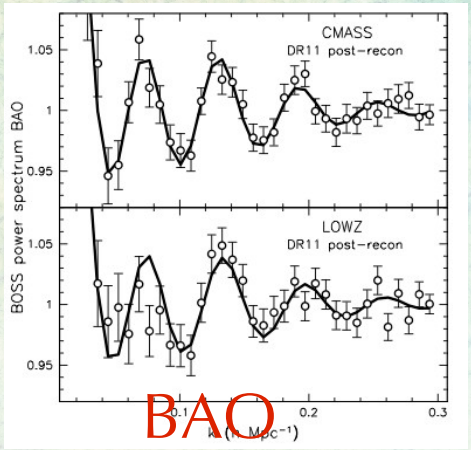
CMB

Bétoule 2014



Ia Supernovae

Anderson 2014



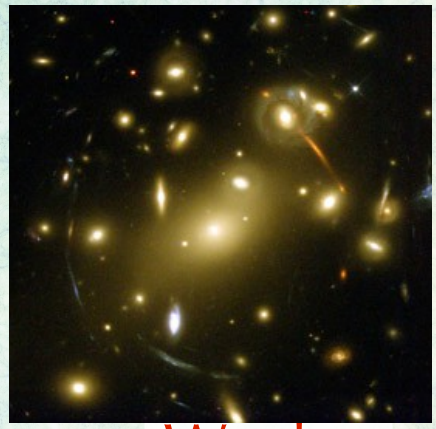
BAO

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

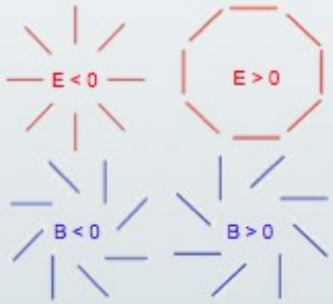


Weak Lensing

+ Clusters,
Redshift distorsions,
AP effect,
H0,

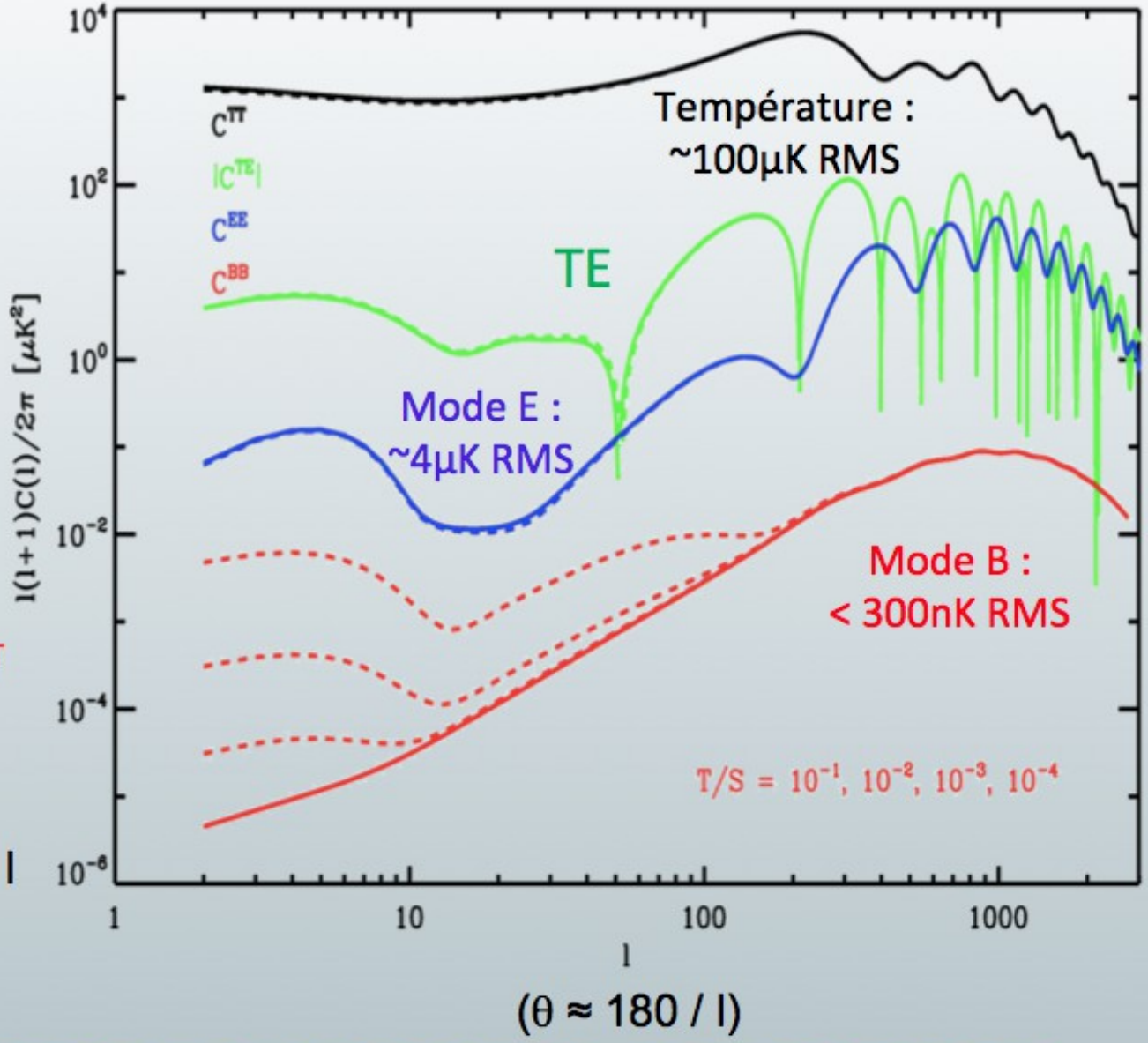
CMB angular power spectra

- 3 observables : T, E, B



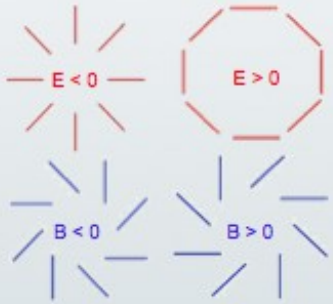
- B Modes:
  - **Not** generated by scalar modes
  - "Smoking gun" of tensorial perturbations
  - At best 300 times weaker than T fluctuations
  - case T/S = r = 0.1 (cf. fig),
  - E_{inf}=2 x 10^{16} GeV (GUT).

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



CMB angular power spectra

- 3 observables : T, E, B



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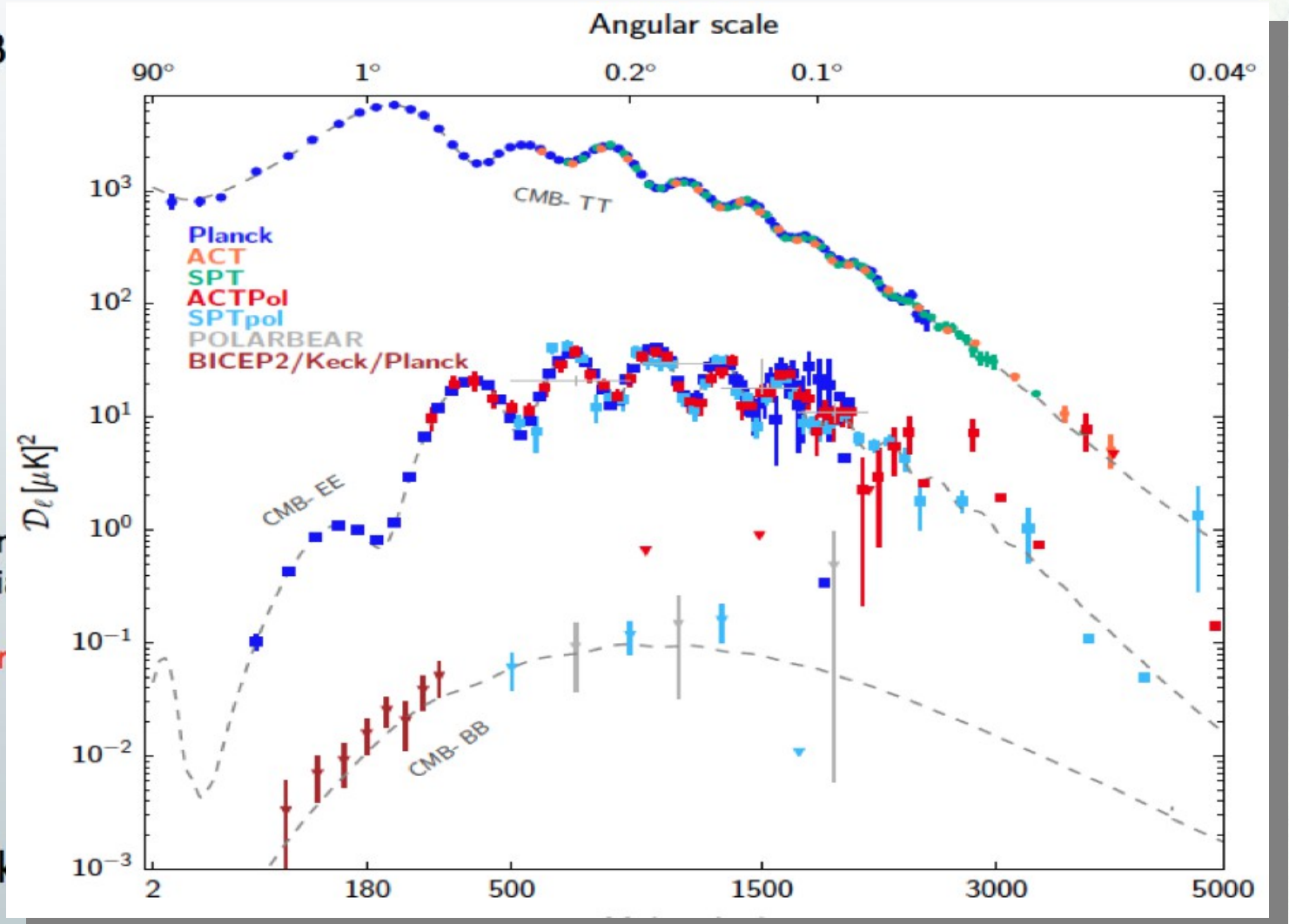
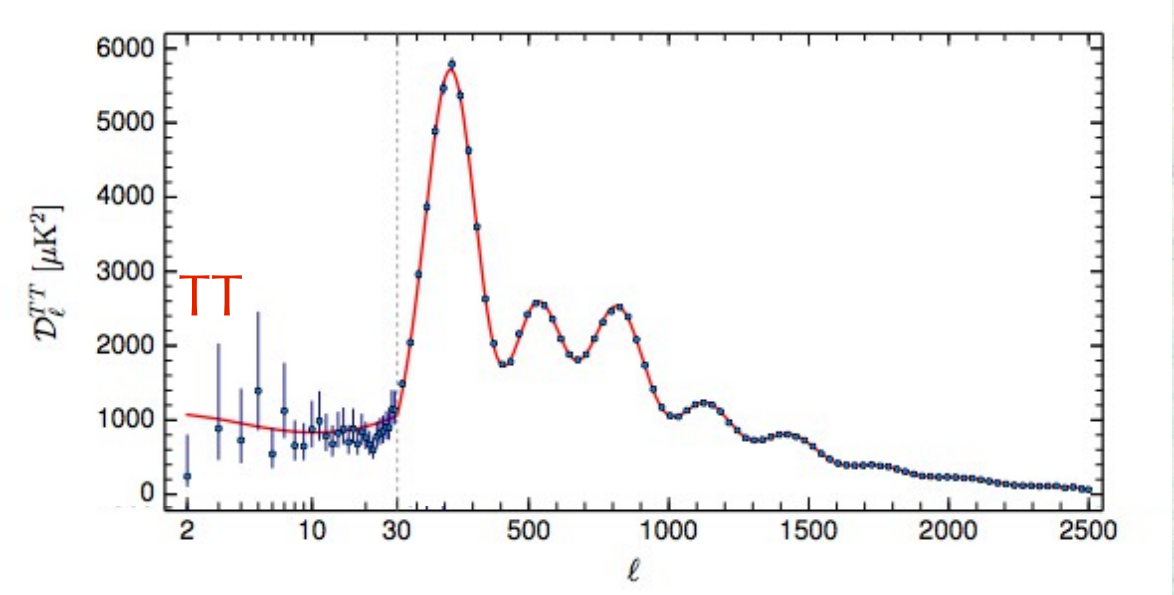
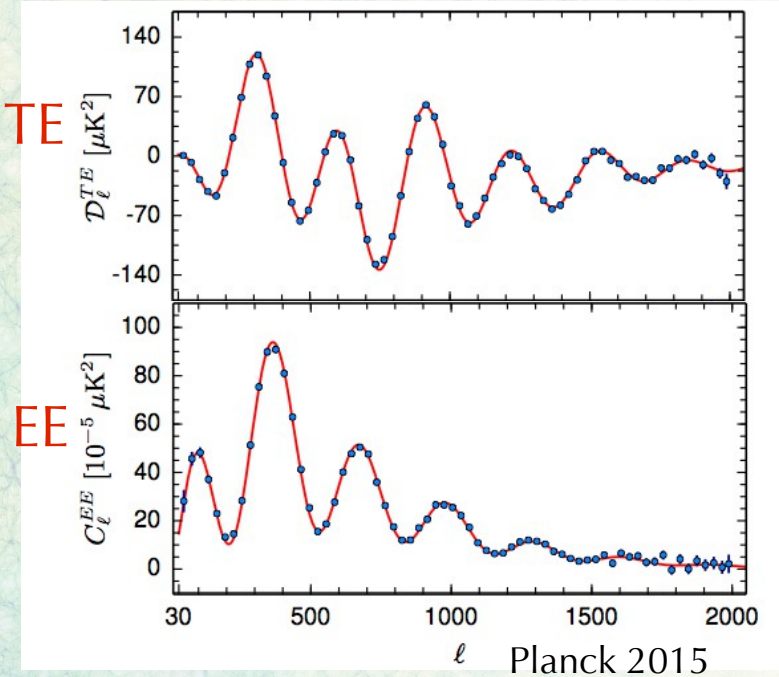


(θ ≈ 180 / l)

CMB Cosmological fit : flat-ΛCDM





Planck 2015

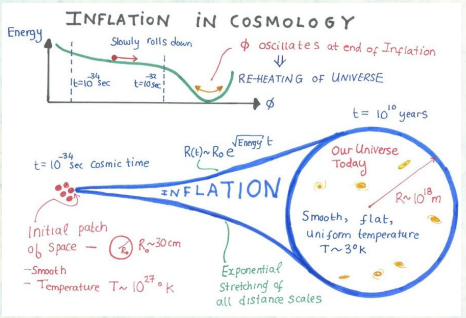
Parameter	[1] *Planck* TT+lowP
$\Omega_b h^2$	0.02222 ± 0.00023
$\Omega_c h^2$	0.1197 ± 0.0022
$100\theta_{MC}$	1.04085 ± 0.00047
τ	0.078 ± 0.019
$\ln(10^{10} A_s)$	3.089 ± 0.036
n_s	0.9655 ± 0.0062
H_0	67.31 ± 0.96
Ω_m	0.315 ± 0.013
σ_8	0.829 ± 0.014
$10^9 A_s e^{-2\tau}$	1.880 ± 0.014

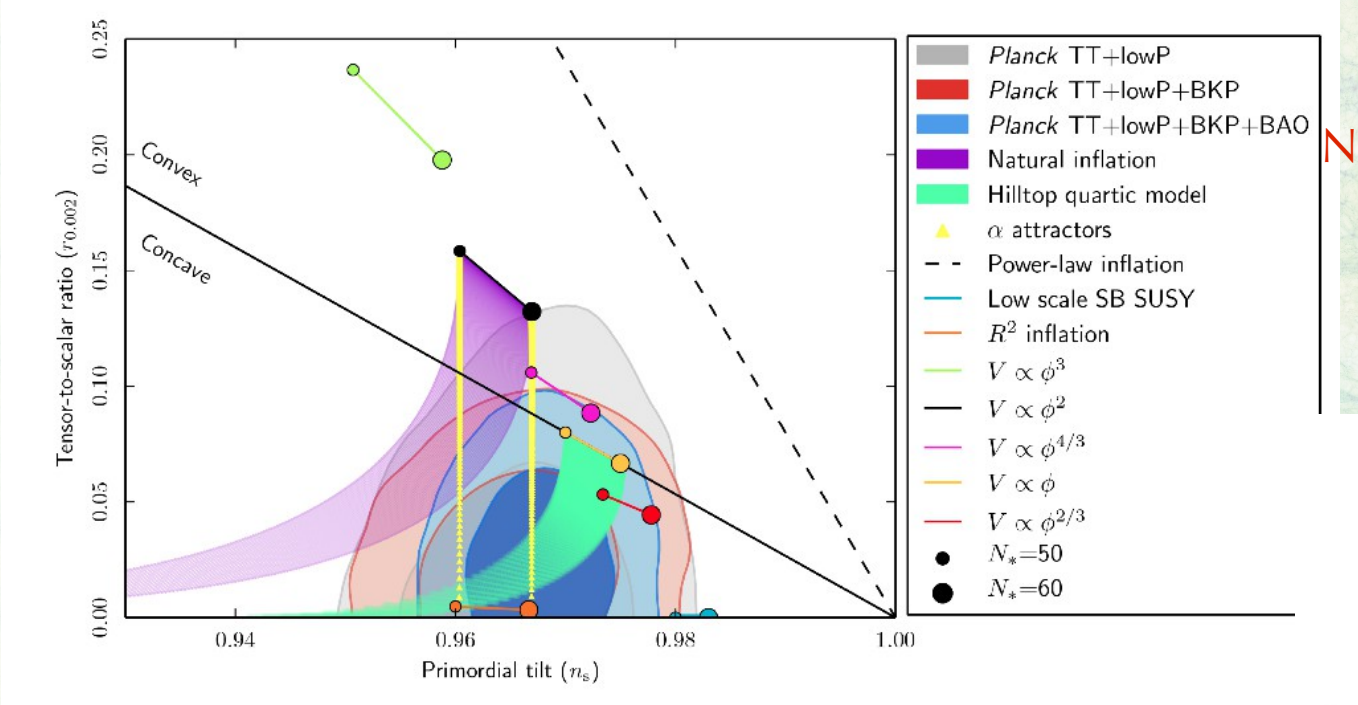
6-parameter fit

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

Many degeneracies

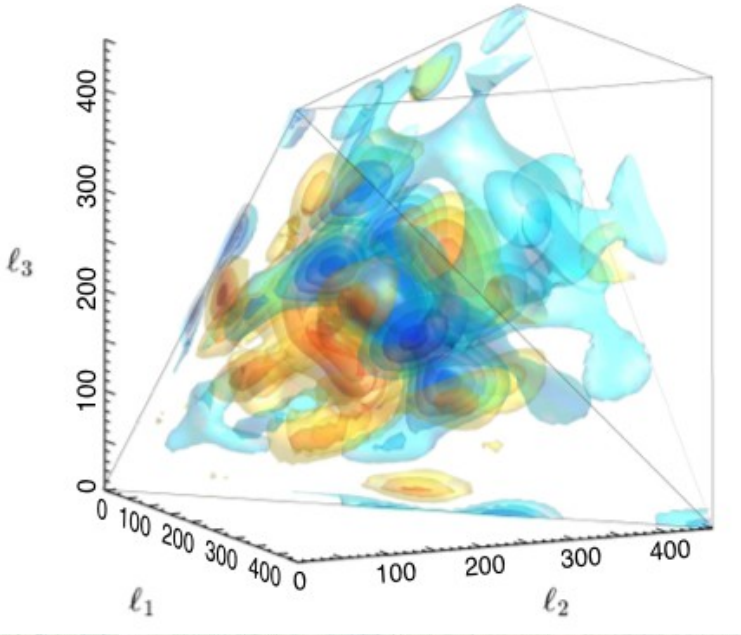
CMB : inflation





Non-gaussianities :

- Prediction from inflation
- Higher order statistics
- No detection



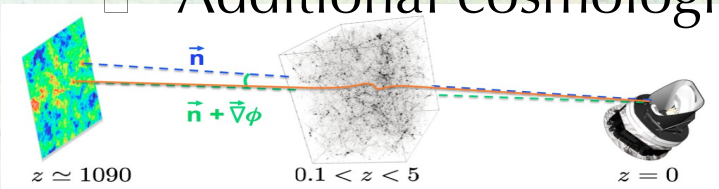
Primordial Gravitational Waves

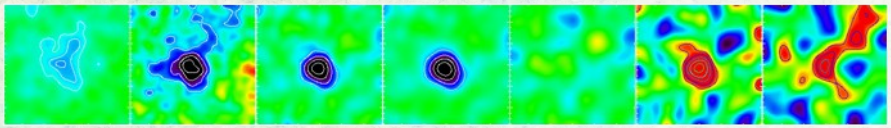
- Visible in B modes at large scale
- n_s<1 : prédiction générique
- Constraining models
- *No detection* … yet !

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

CMB : Foregrounds

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



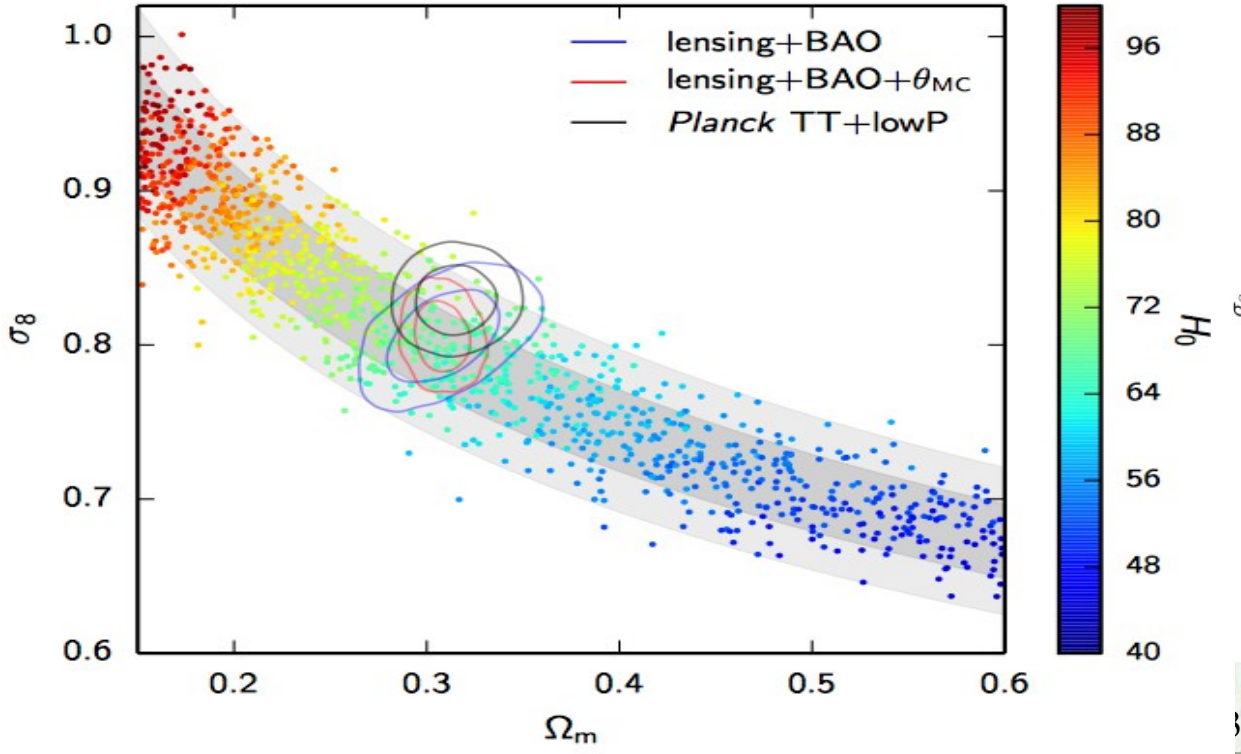


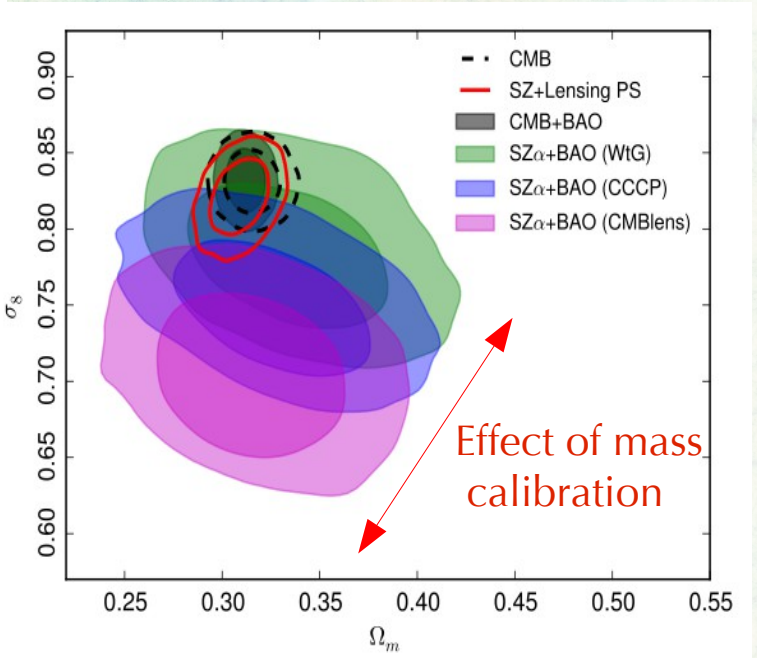
CMB Lensing : sensitive to total mass

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

SZ effect : sensitive to clusters

- compton scatering by hot e^- gaz
- 439 clusters detected
- Bottleneck is mass calibration





CMB : The future

B modes : Gravitational waves

Bicep3

Polarbear / Simons Array

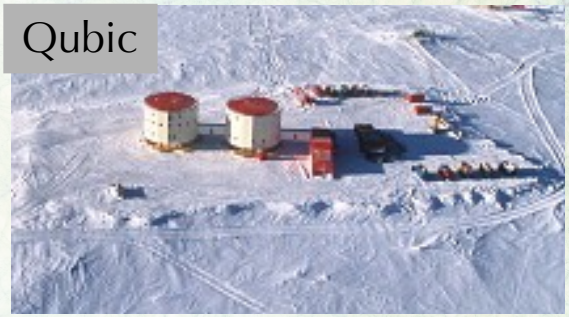
SZ projects

SPT

ACT

+ polarization capabilities

Qubic



NIKA

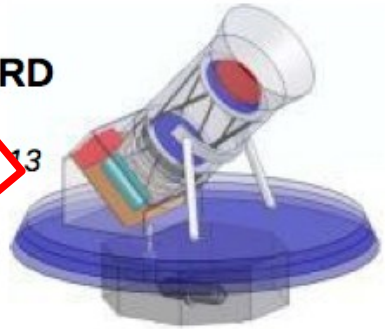
IN2P3 :
APC, LAL, LPSC

Satellites ?

A next-generation CMB satellite mission ?

LiteBIRD

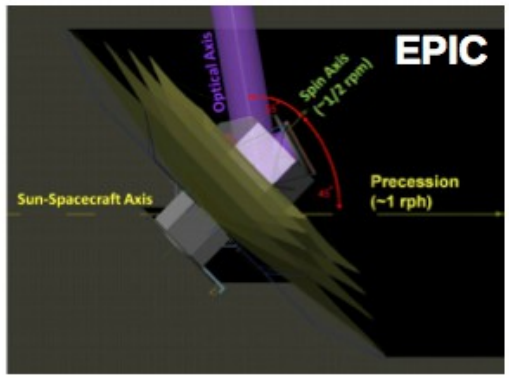
Matsumura e… 13



Discussed 2016

K… , 2011

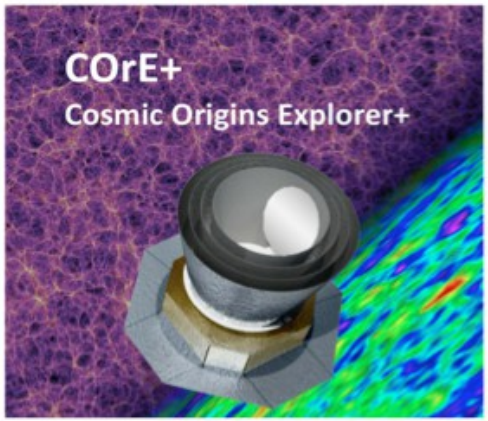
Bock et al., 2008

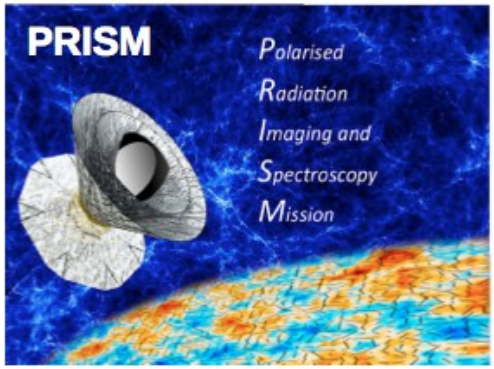


COrE

COrE C… on et al., 2011

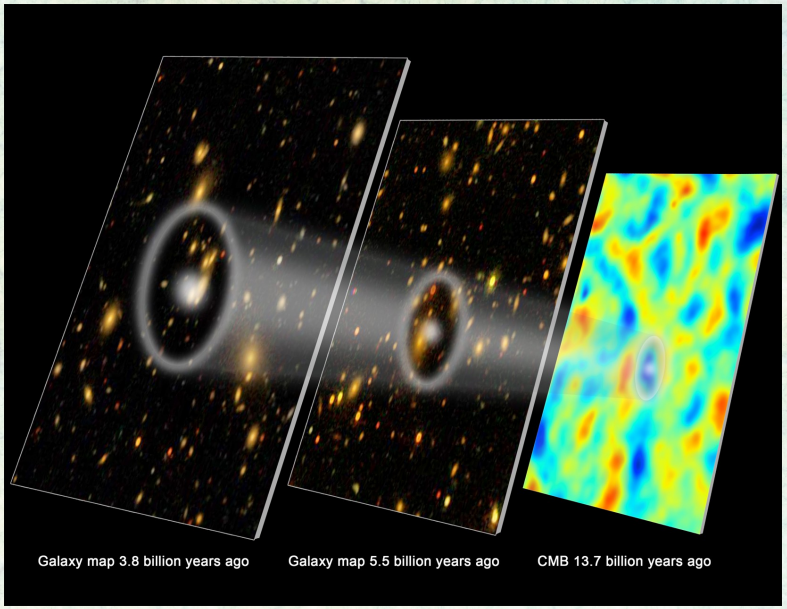
No launch before 2029



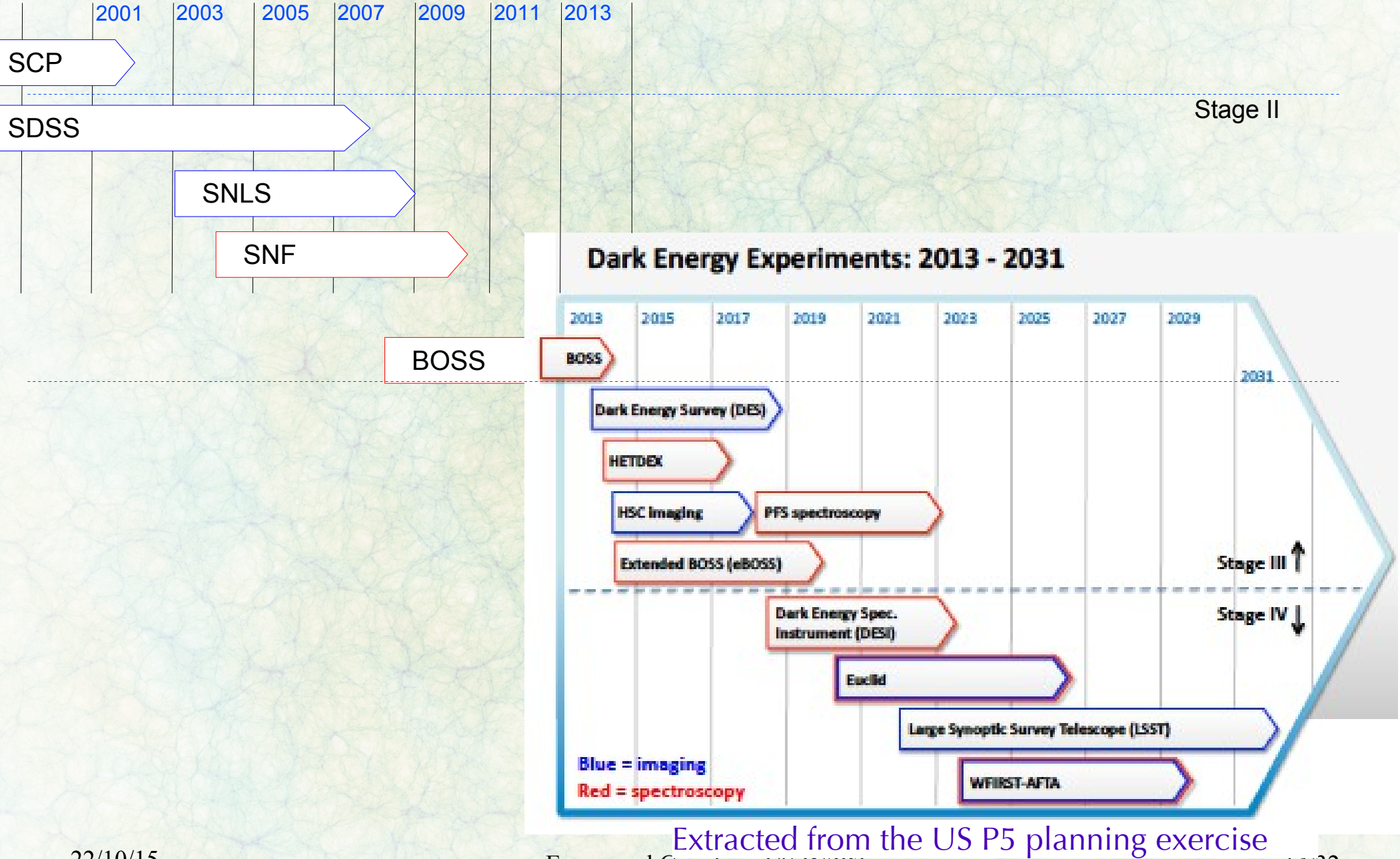


André et al., 2014

The Recent Universe Probes

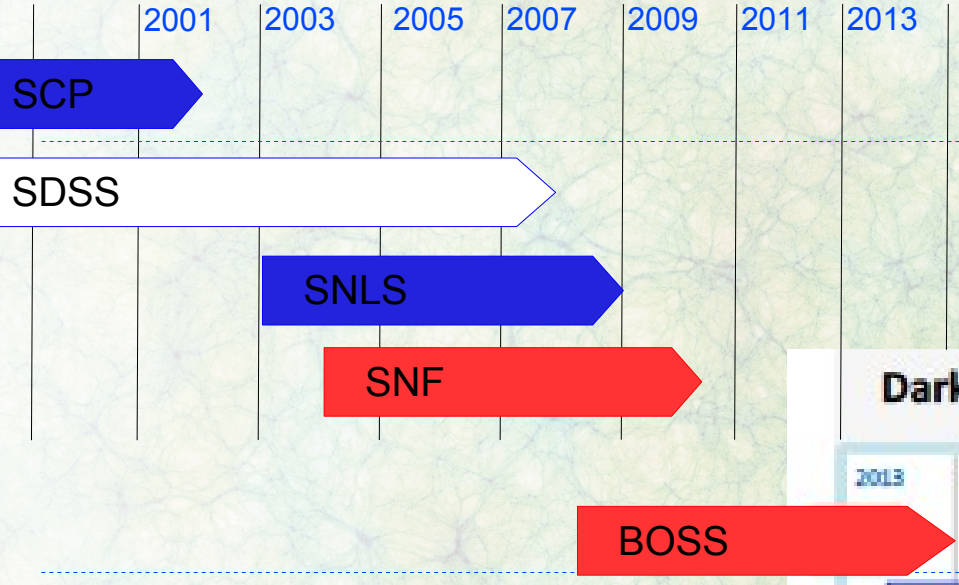


Projects Timeline



Extracted from the US P5 planning exercise

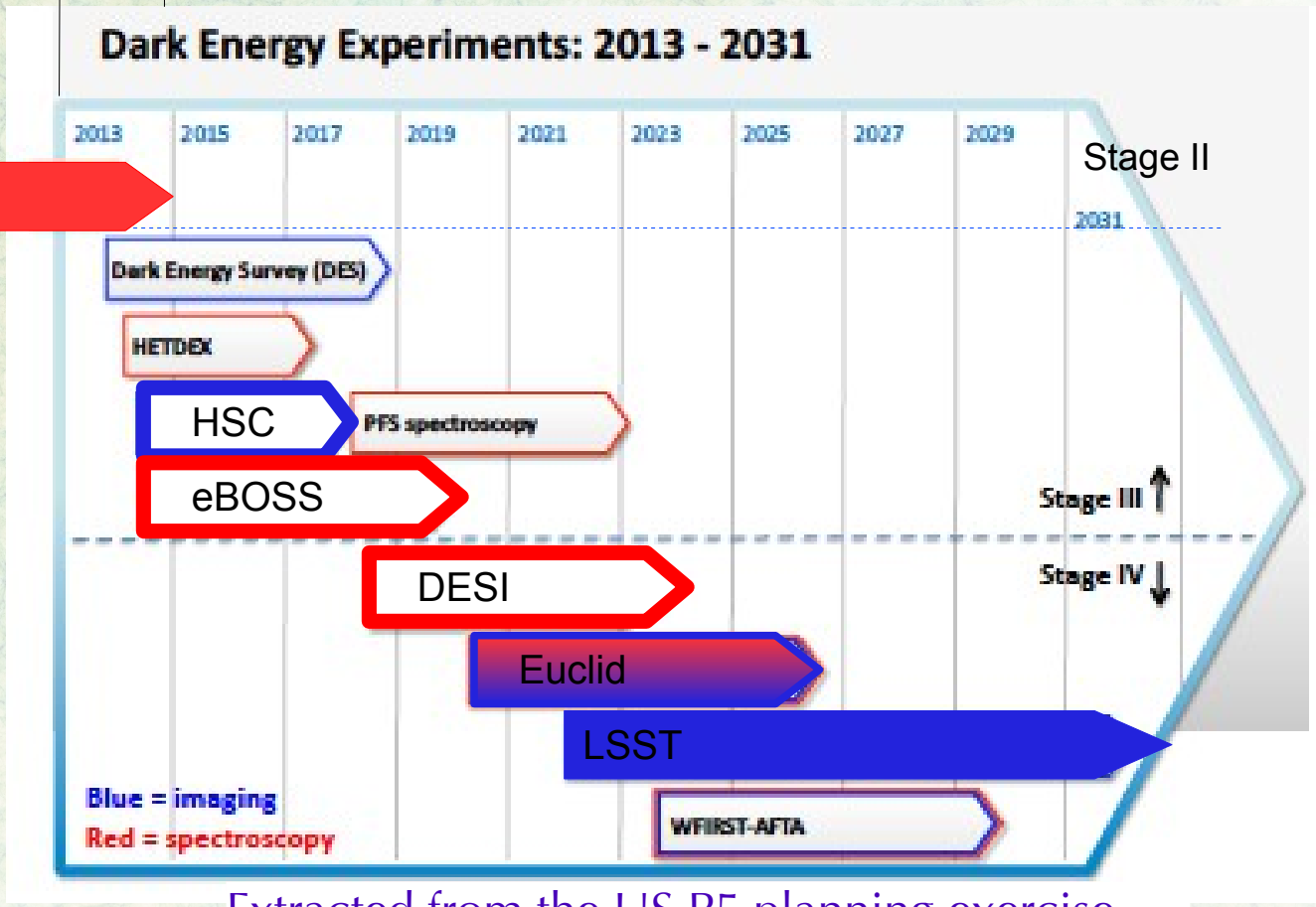
Projects @ IN2P3



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

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

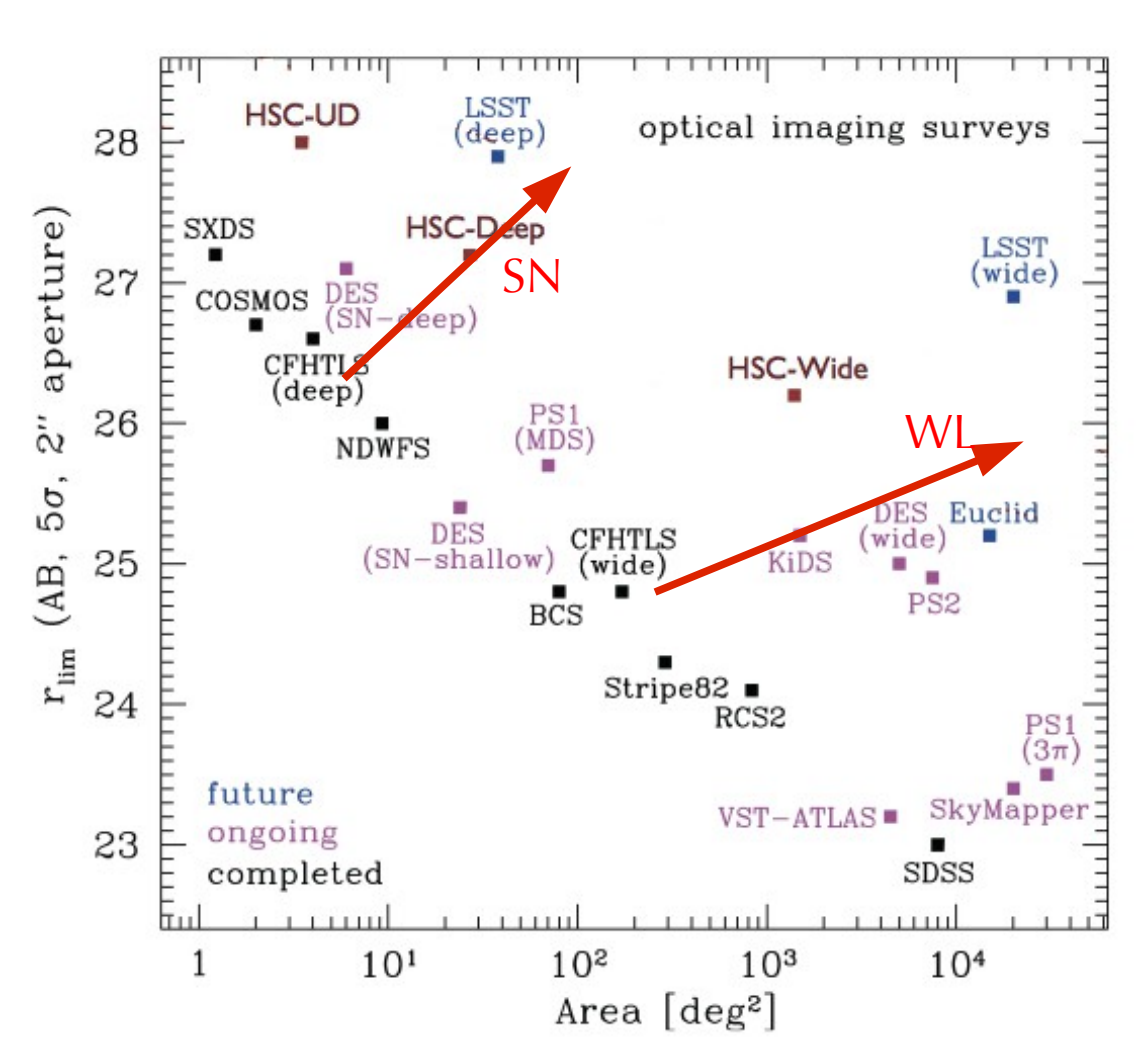
BAO :
APC, CPPM, LAL, LPNHE, LPSC
(+INSU,CEA)



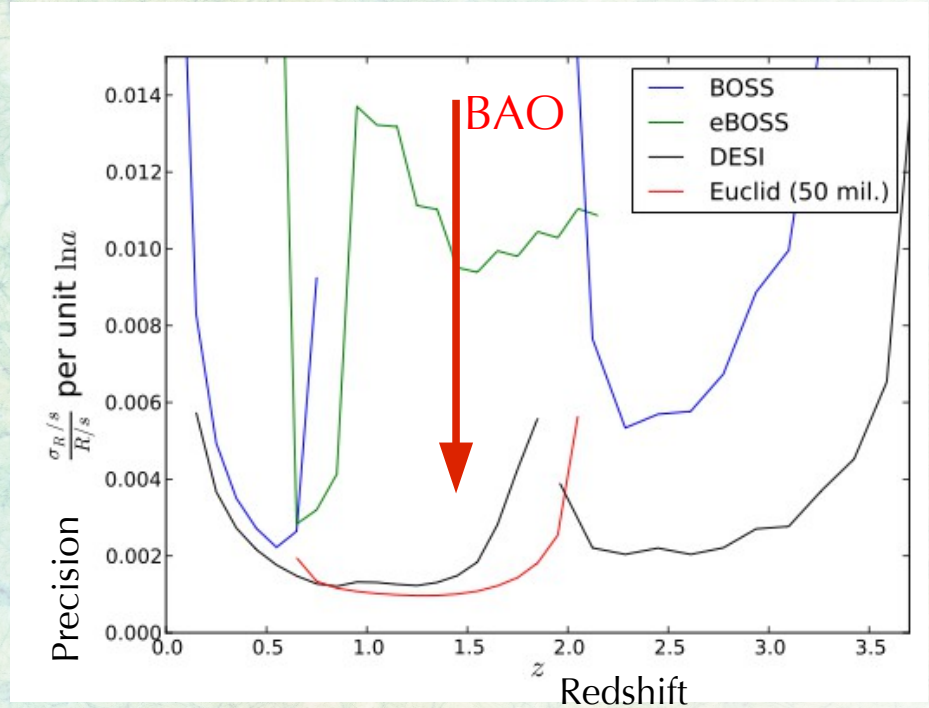
Extracted from the US P5 planning exercise

Projects evolution

Photometry

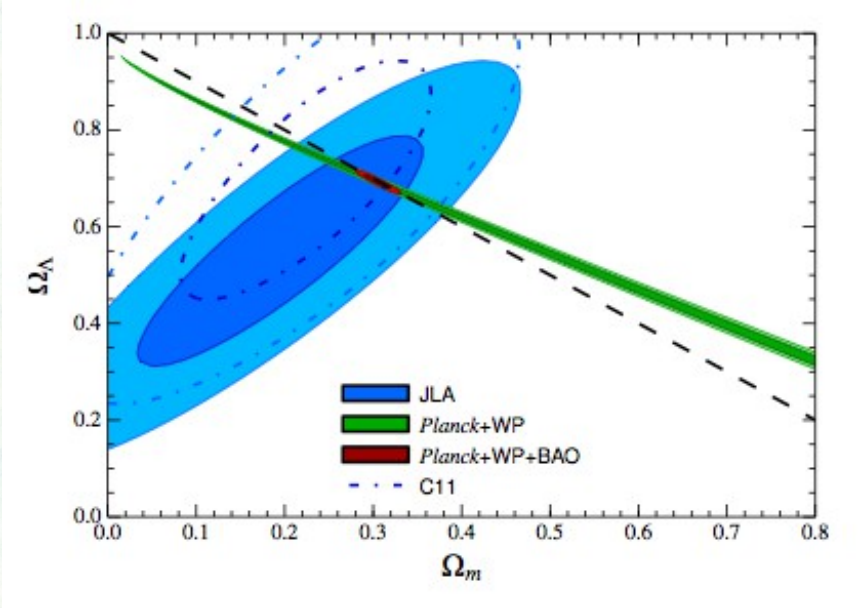


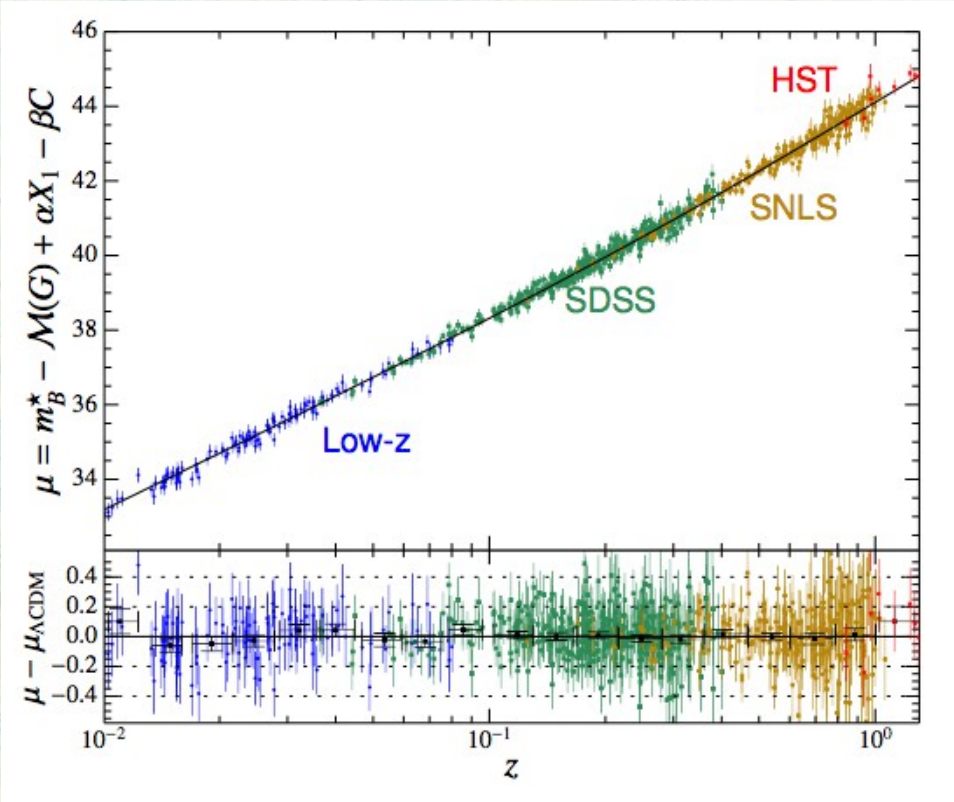
Spectroscopy



Supernova state of the art :

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





Flat-ΛCDM model with SN alone:

uncertainties on Ω_M : 0.034

Stat: 0.018

Calibration: 0.020

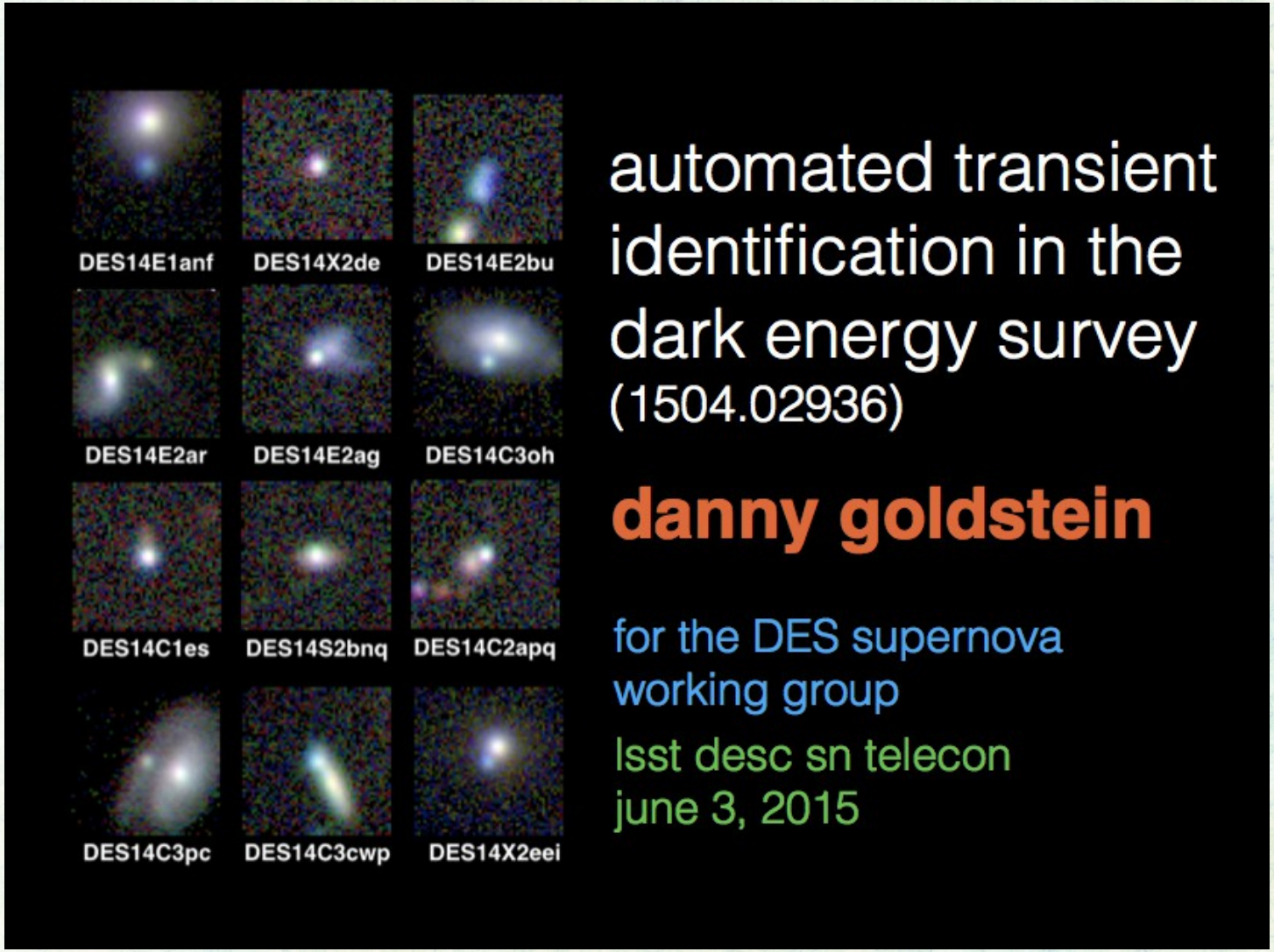
Other syst: 0.012

This is (already) precision cosmology !

Future improvements :

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

This is under scrutiny by ongoing projects !

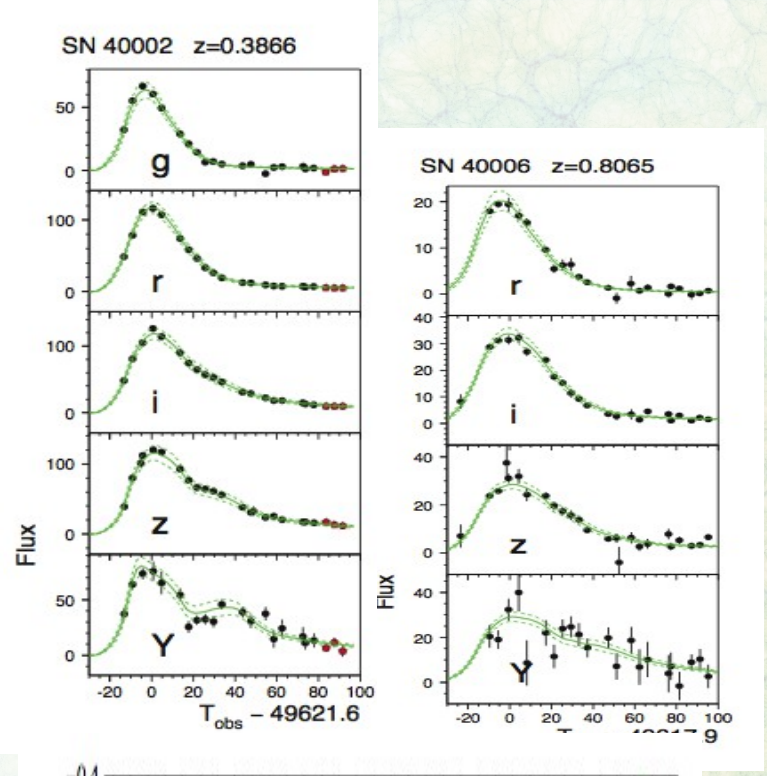


DES survey :
1M transient/season

Goal : 3000 SN in 5 years

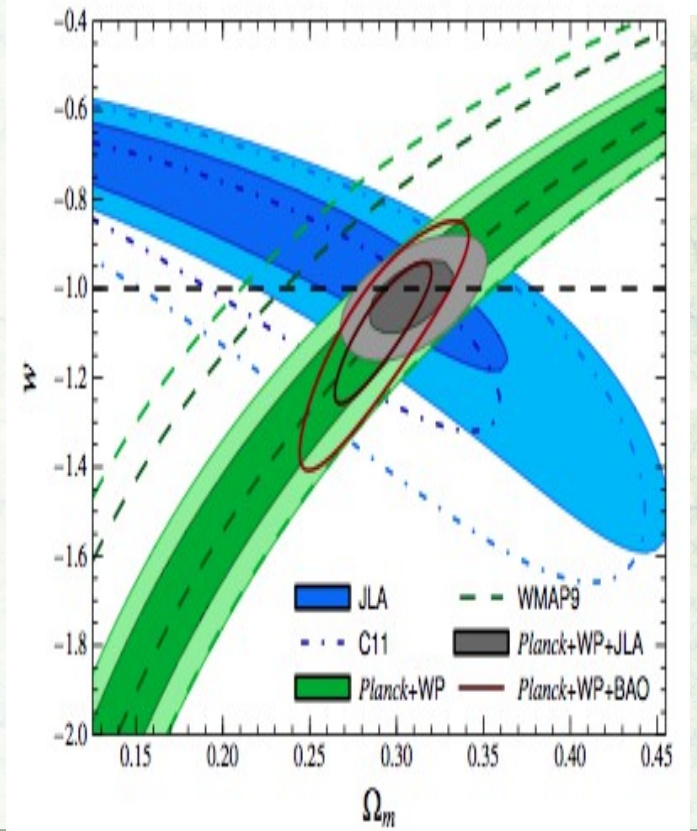
And an opportunity of interdisciplinary research with IN2P3

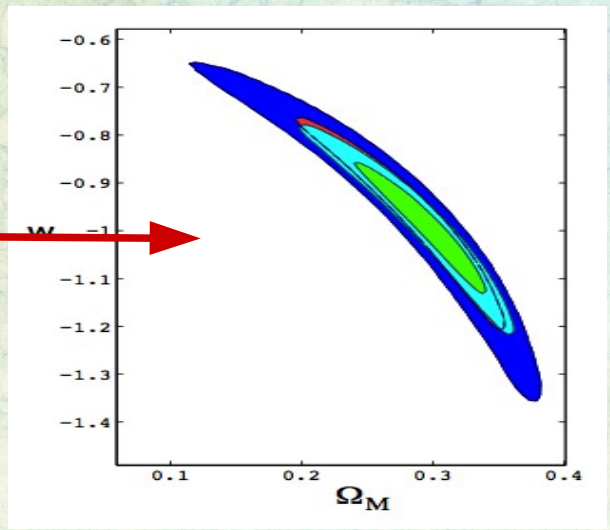
SN in LSST



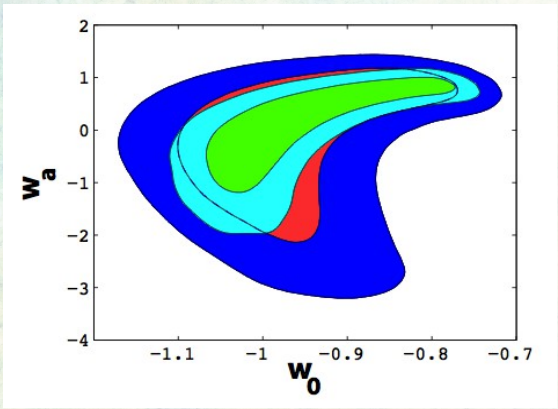
- *10 000 well sampled SN/season*
- Systematics dominated (short in IR)
- No spectroscopy (for now…)
- Redshift from external measurement

Huge improvement still !





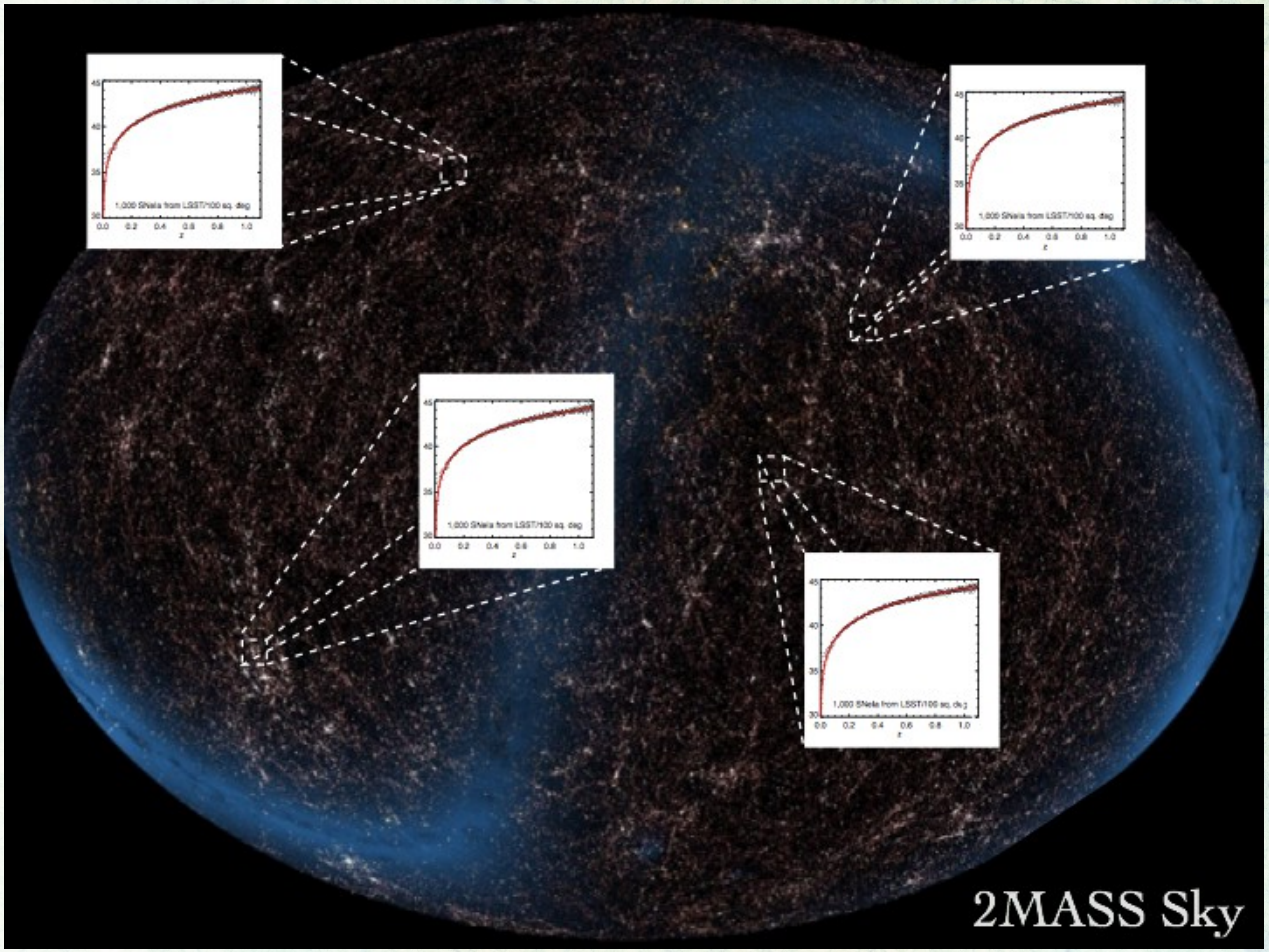
LSST 10 000 SN



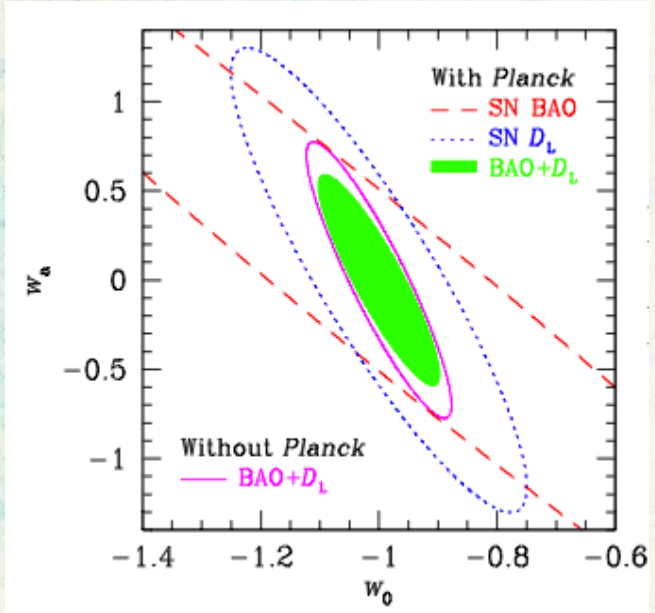
LSST 50 000 SN

Massive SN set :

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



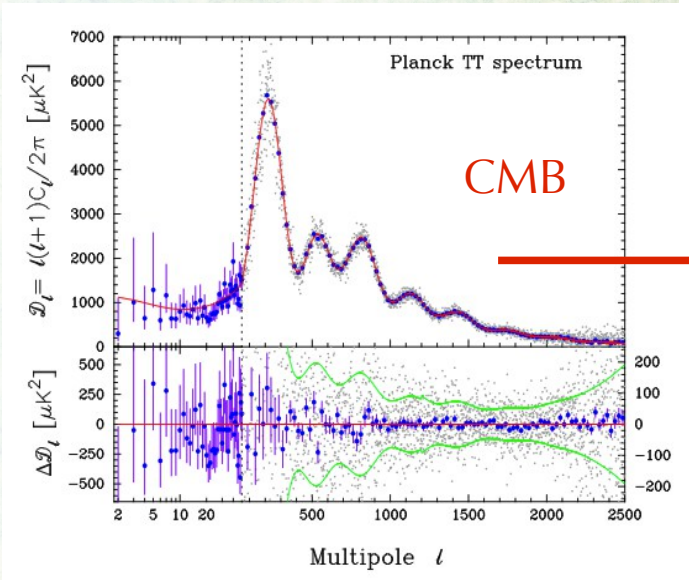
- BAO with SNIa



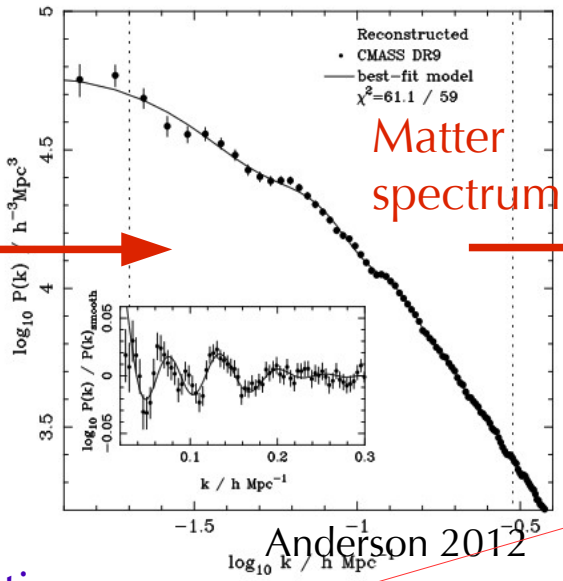
- + SN II, ...

Cosmology with BAO

Standard ruler approach

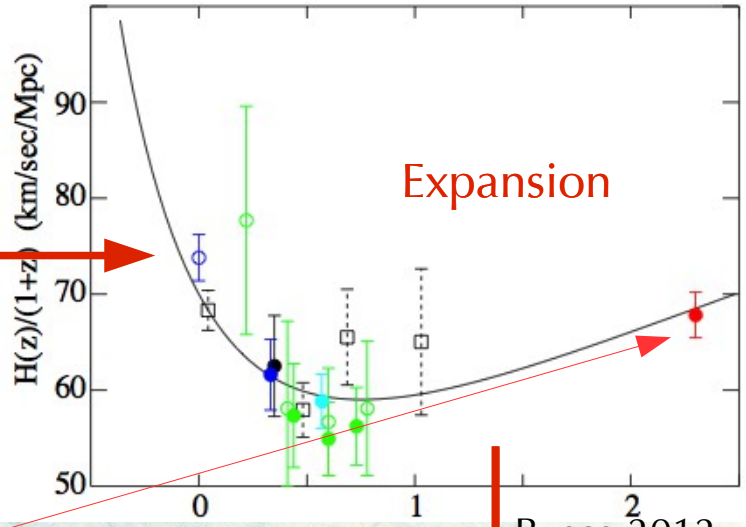


CMB



Matter spectrum

Anderson 2012



Expansion

Busca 2012

Compute the correlation function
- Of galaxies
- Quasar's Ly-α forest

First détection 2005

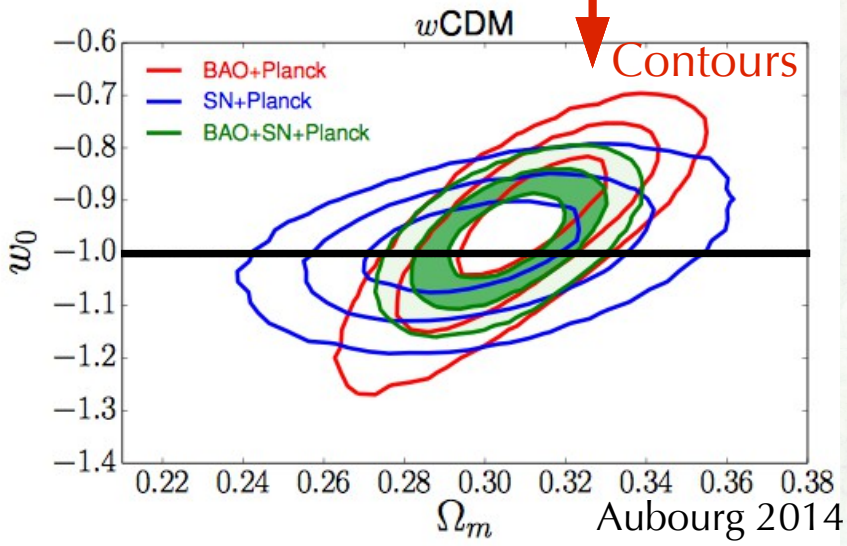
Ongoing effort since !

Difficulties :

Redshift determination (spectro/photo)

Statistics not really an issue

Tacer of **matter density**



Contours

Aubourg 2014

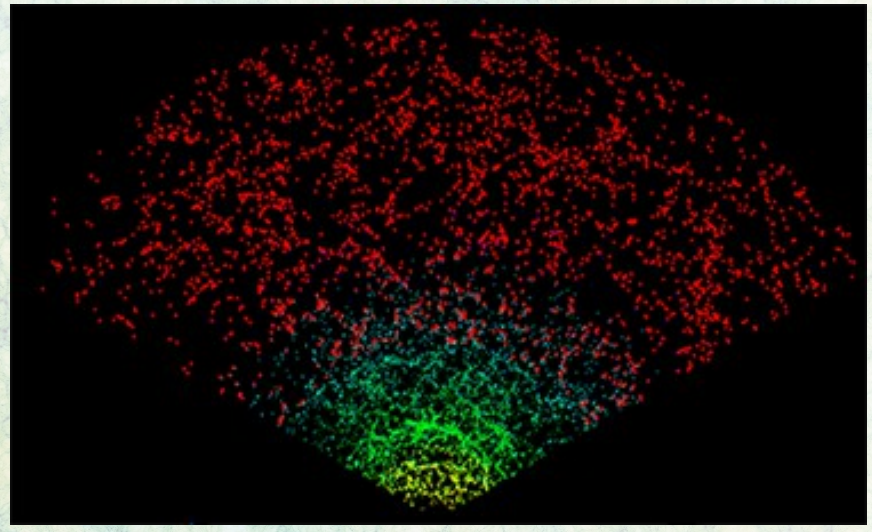
Spectroscopic BAO

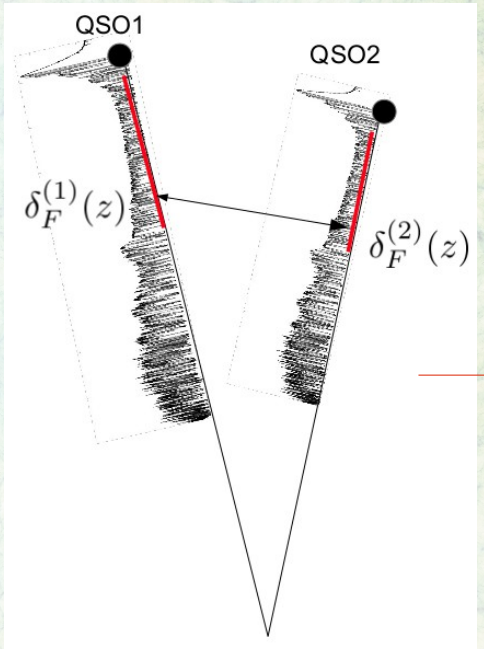
BOSS : 1000 fibers (150/deg)
- 1.5 M Galaxies z<0.7
- 160 k **Ly-α forest** 2.2 <z< 3

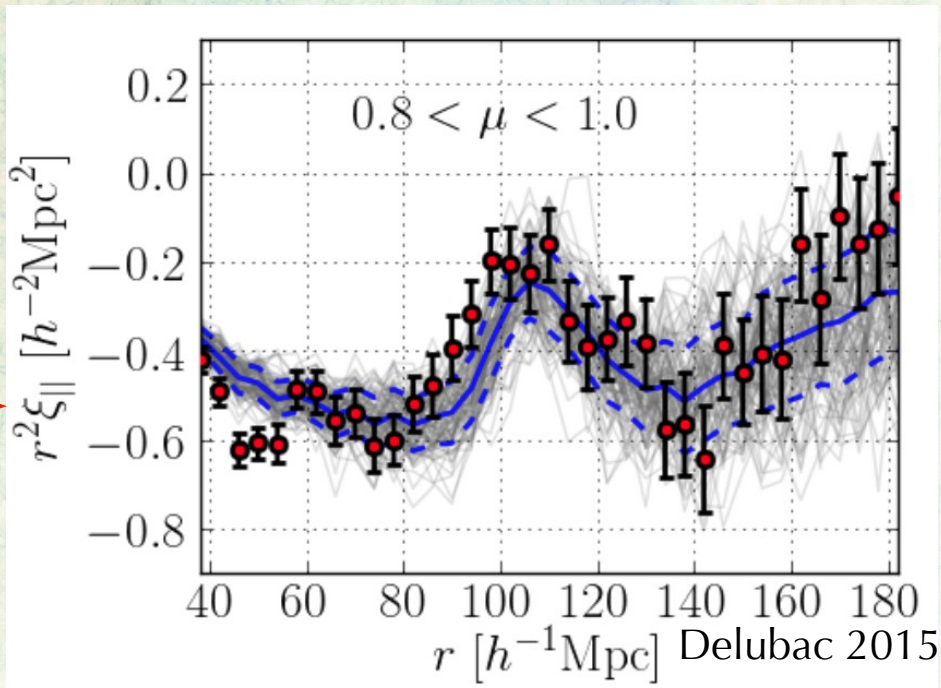
eBOSS
- 635 kGalaxies 0.6 <z< 1.0
- 740 Quasars 0.9 <z< 3.5

DESI : 5000 fibers (2800/deg)
- 32 M Galaxies
- 2.4 M Quasars
- (10 M Milky Way's stars)

Euclid :
- 50M Galaxies



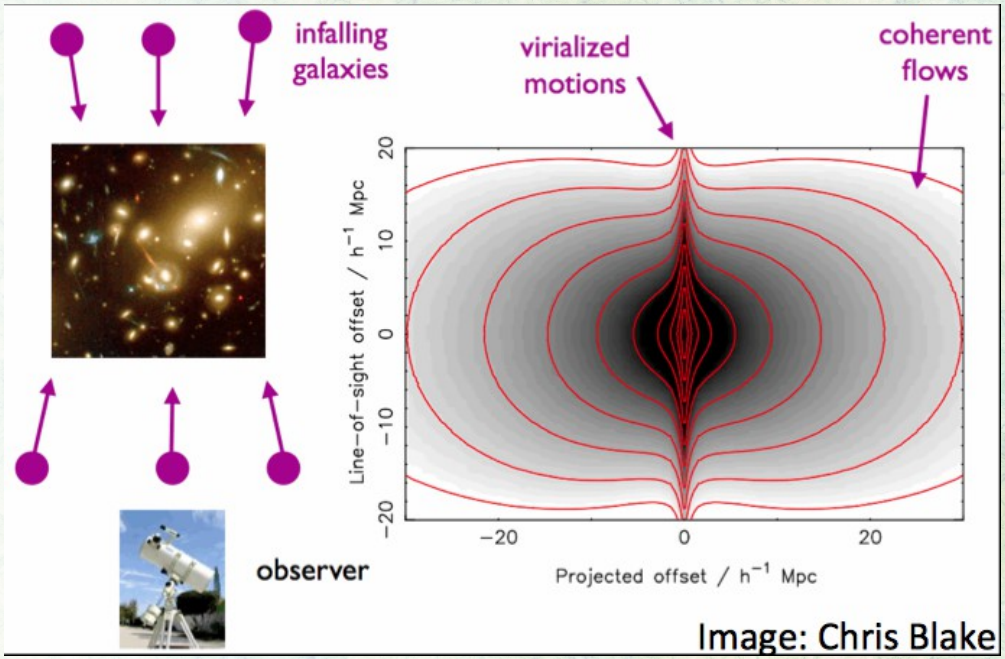


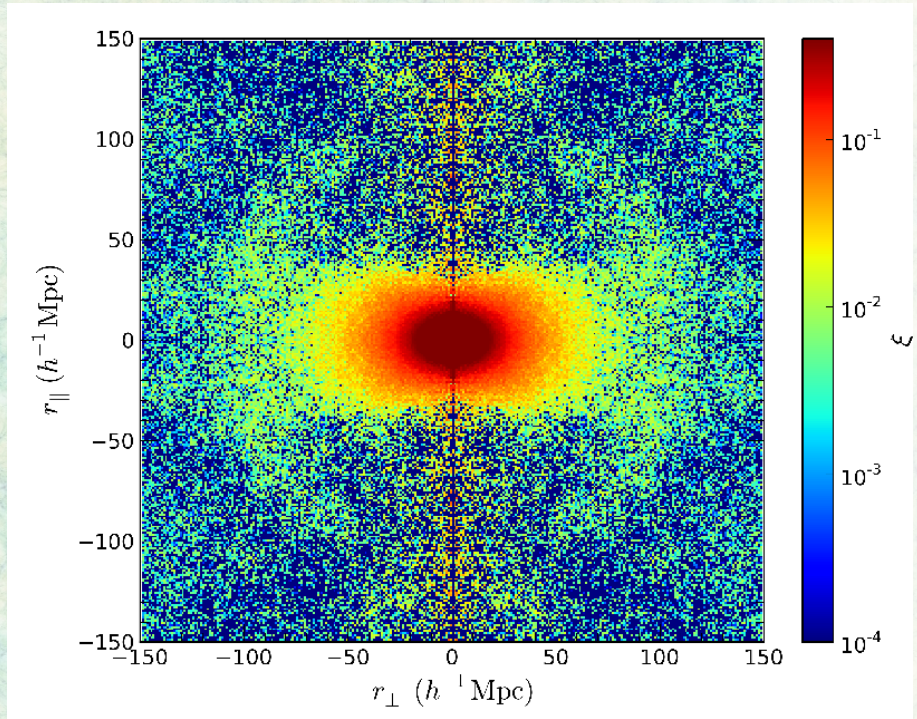


Delubac 2015

Redshift distortions:

Samushia 2014

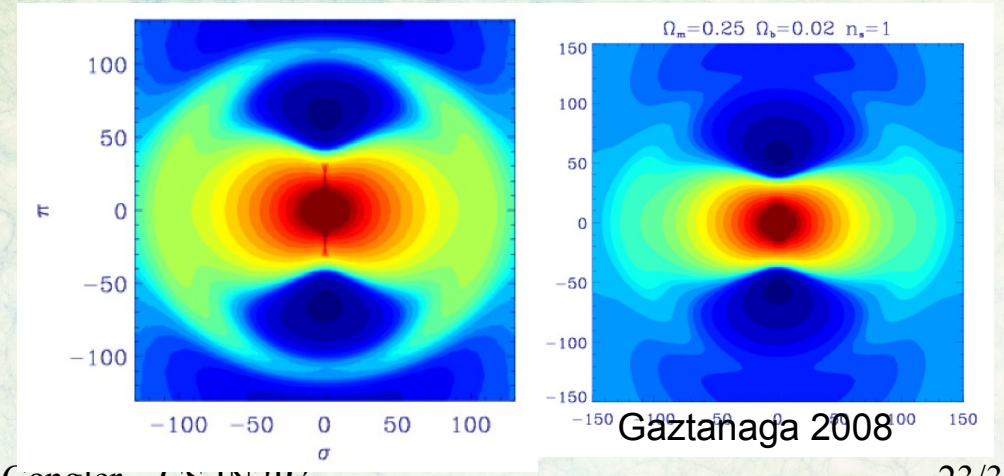




Fingers of god = central part of clusters

Coherent flow

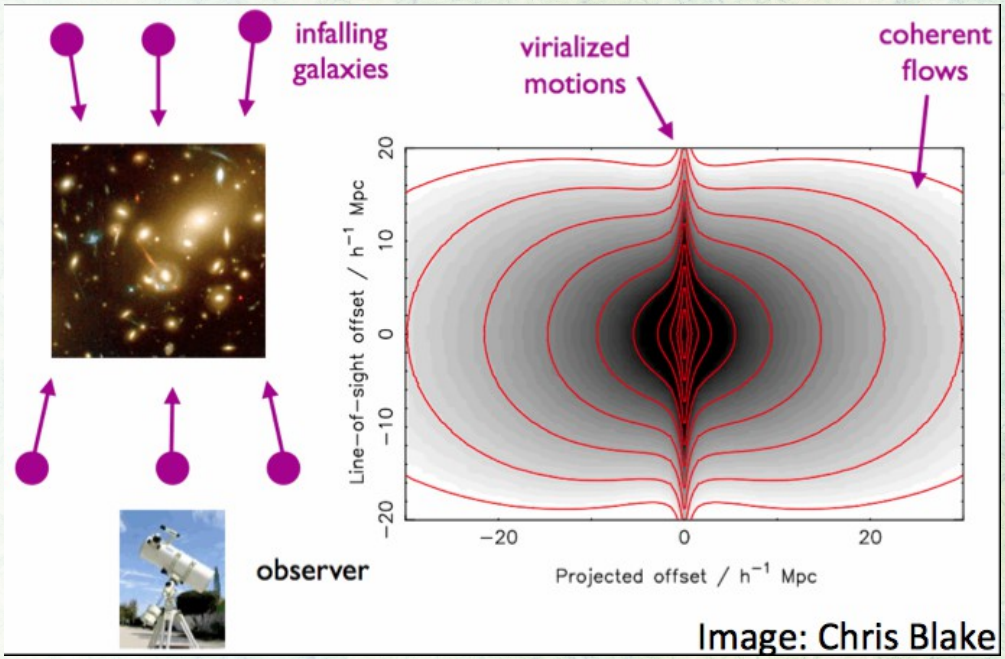
- Sensitive to cosmological parameters

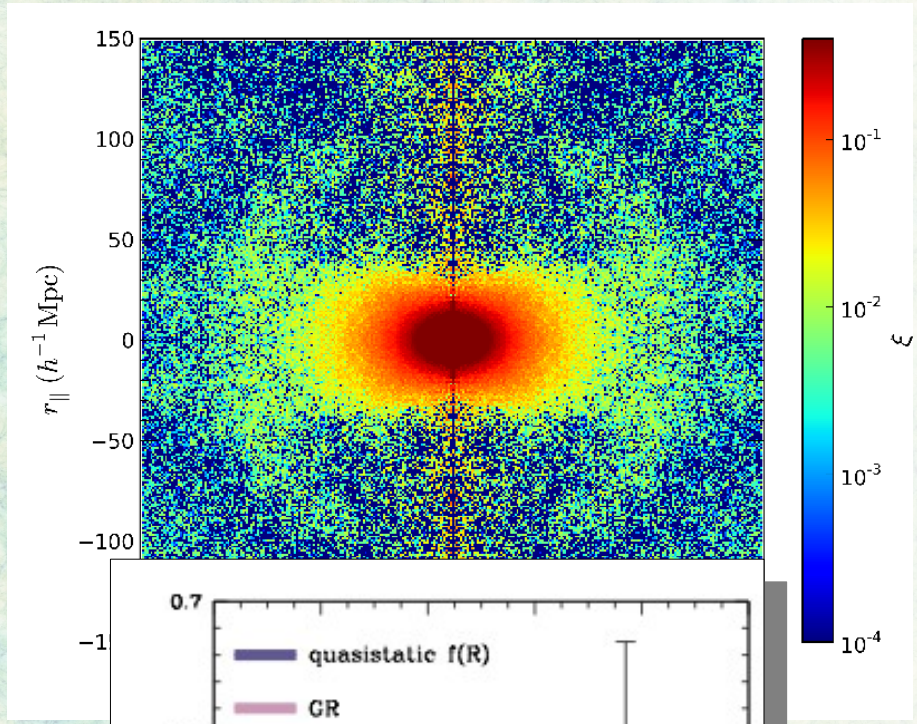


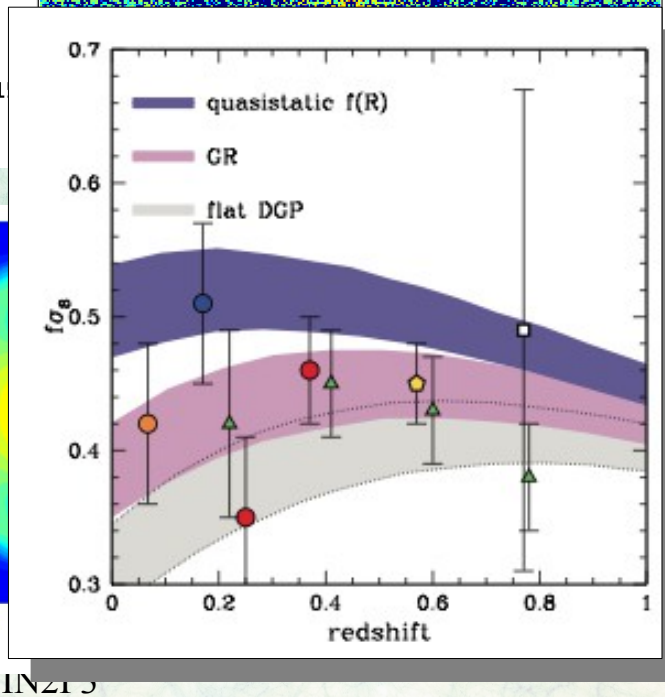
Gaztanaga 2008

Redshift distortions:

Samushia 2014





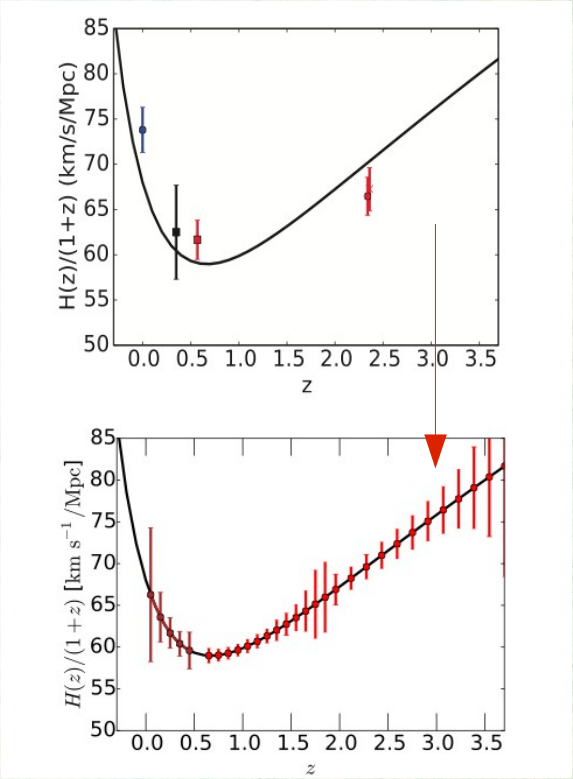


Fingers of god = central part of clusters

Coherent flow

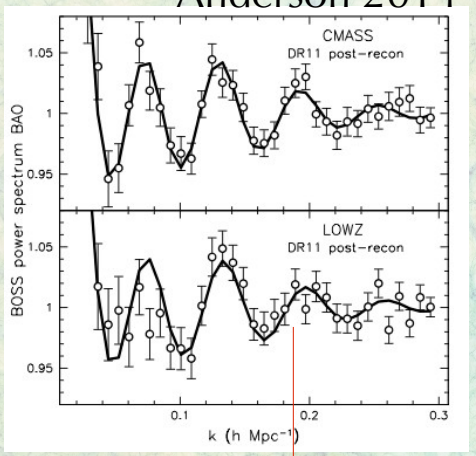
- Sensitive to cosmological parameters
- Test of General Relativity
- Tomography growth of structures

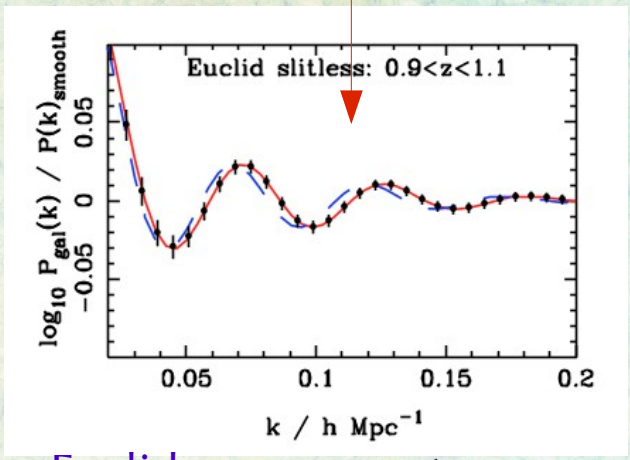
Galaxy clustering in DESI & Euclid



DESI Hubble diagram

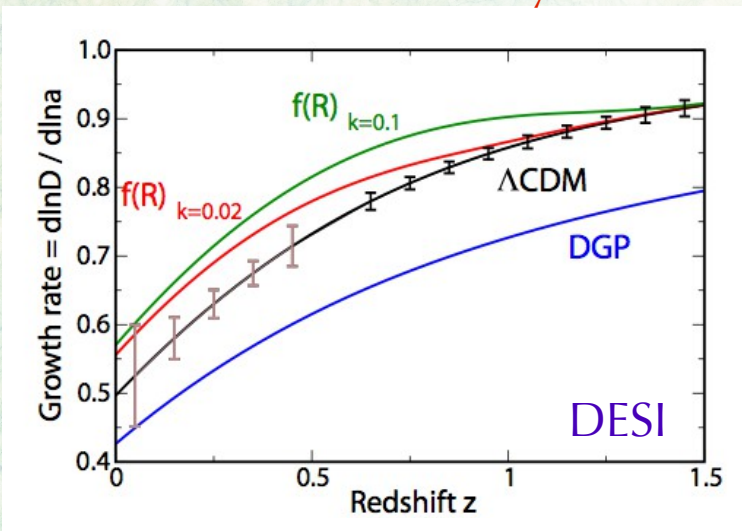
Anderson 2014

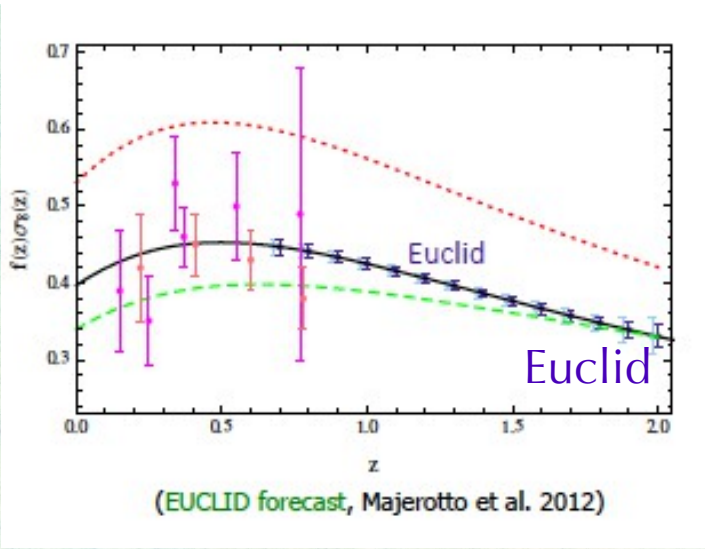




Euclid power spectrum
(1 bin)

General Relativity tests

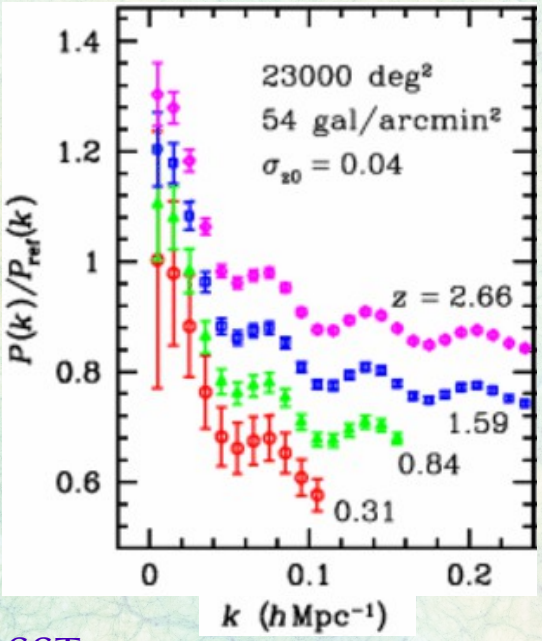




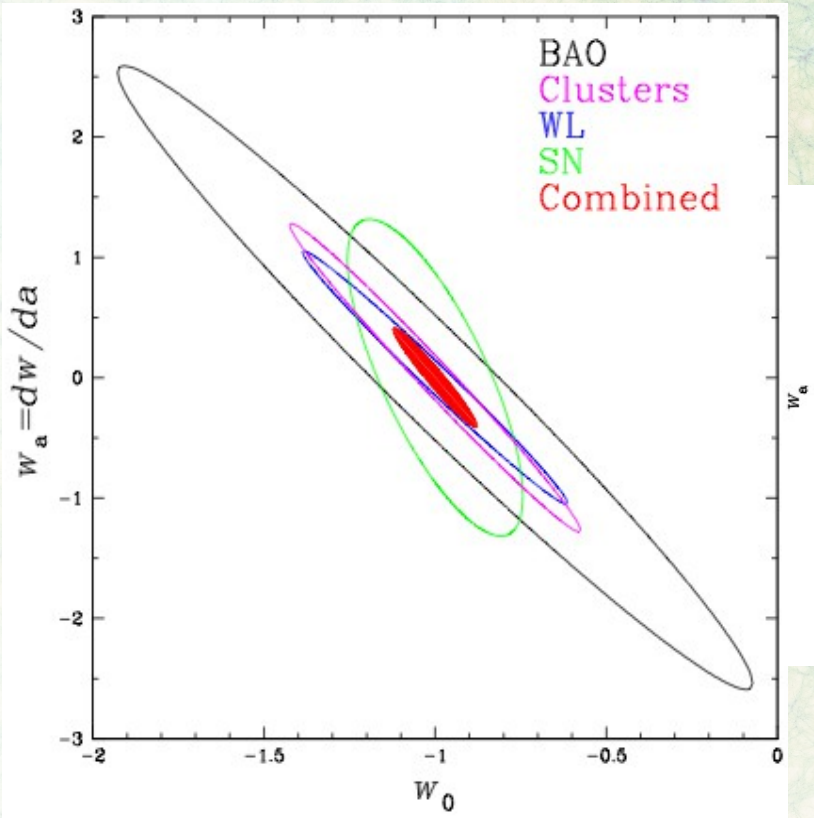
Photo/Spectro BAO sensitivity :

LSST :

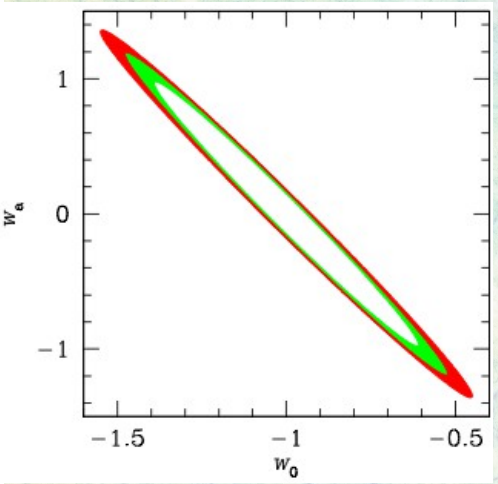
- 10 B galaxies in 20000□
- 4B in gold sample (i<25.3)
- Up to z < 2.5



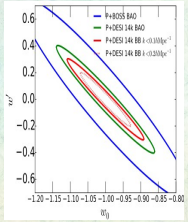
DES



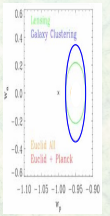
LSST



BOSS
DESI



Euclid



… BAO complementary to other probes !

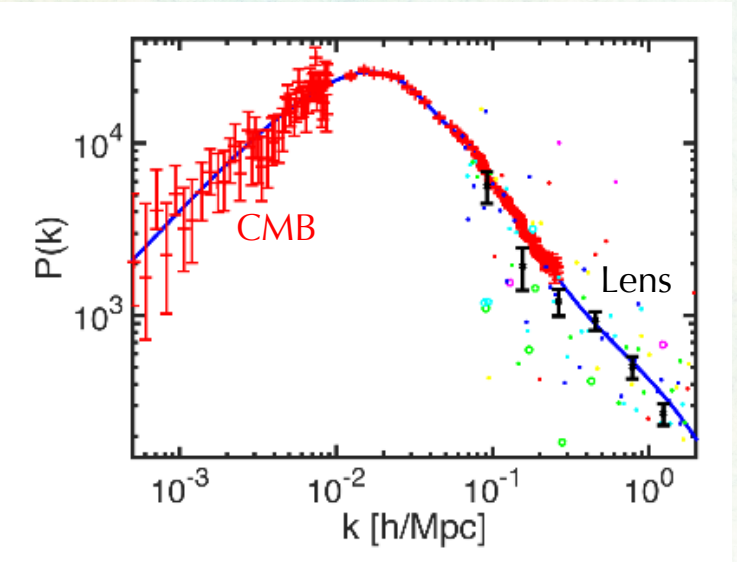
Cosmology with WL

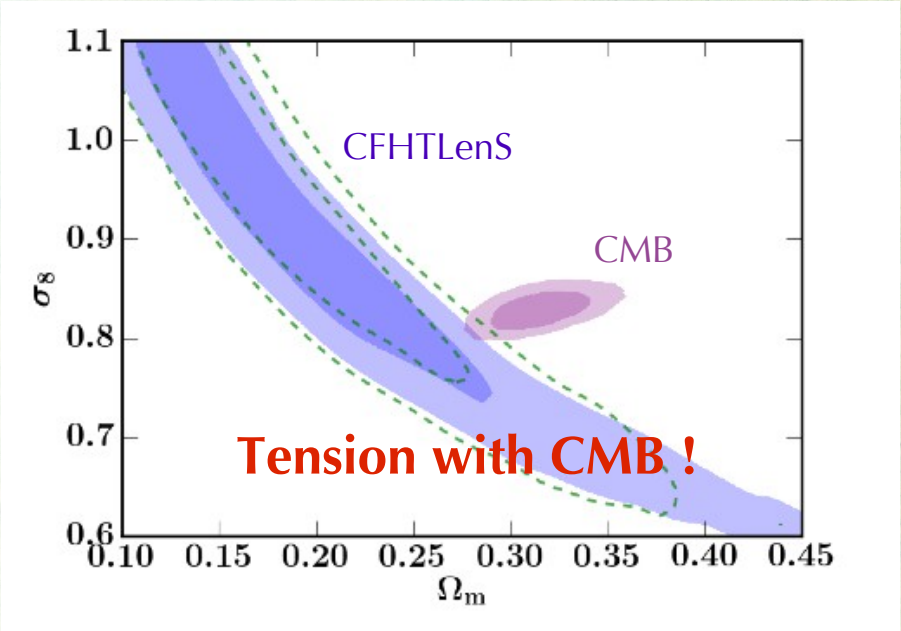
Shear correlation sensitive to $\sigma_8\Omega_m^{\alpha}$

And to distance/velocity relation

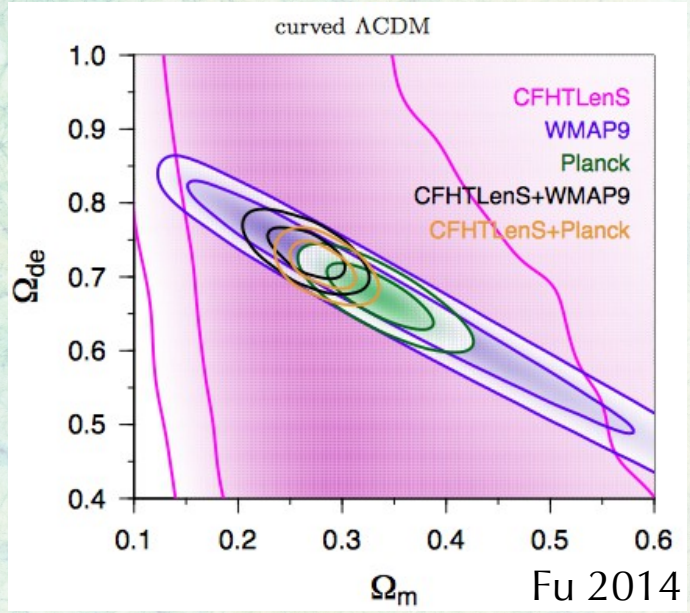
Galaxy-galaxy lensing calibrate bias

Galaxy Intrinsic alignements to be controlled





MacCrann 2014



Fu 2014

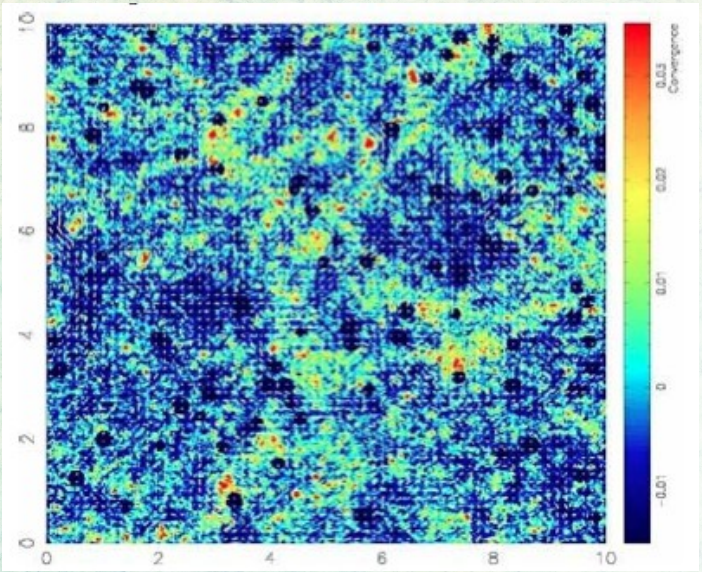
- Expected to be most precise probe in LSST/Euclid

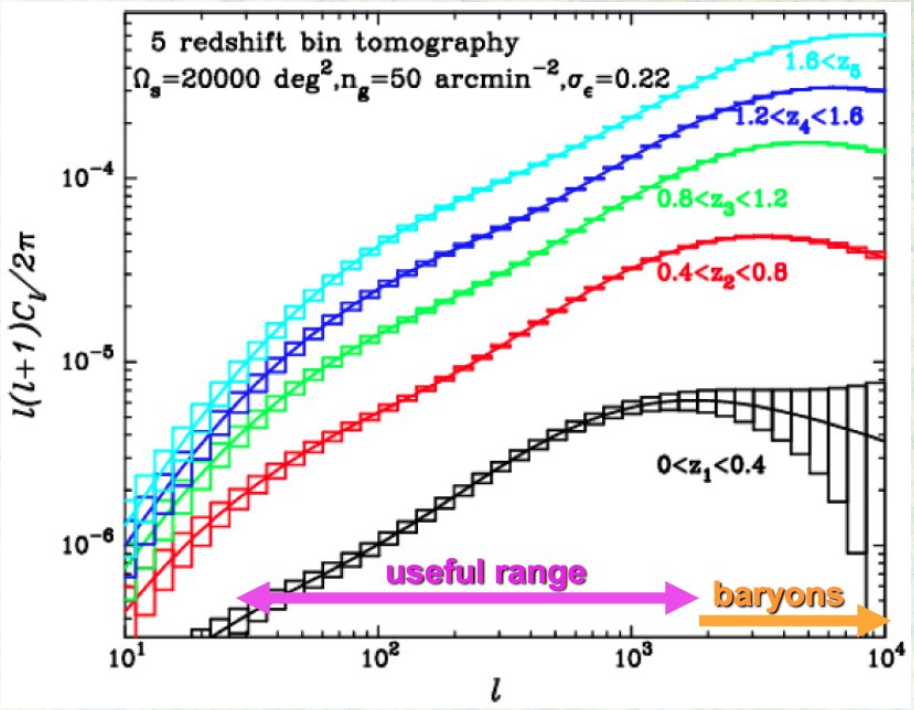
Lensing with LSST / Euclid

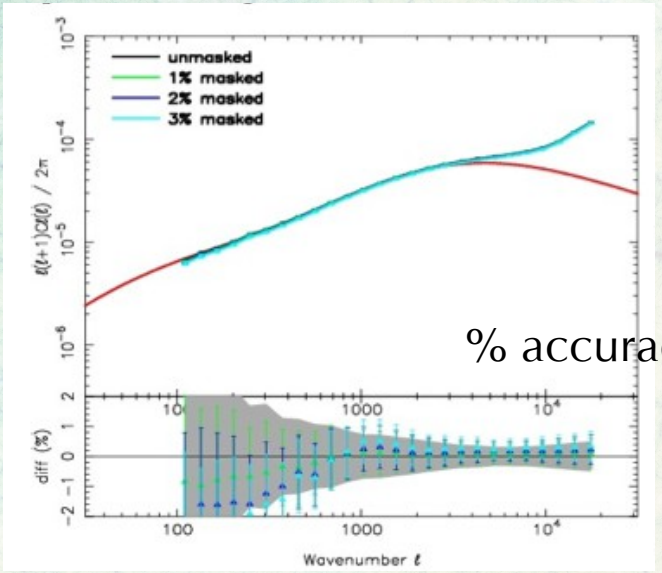
Lensing is sensitive to all dark matter components, including neutrinos

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

Euclid : PSF diffraction limited







% accuracy

Cluster lensing

Cluster count is a powerful probe

Cluster mass relation is the bottleneck

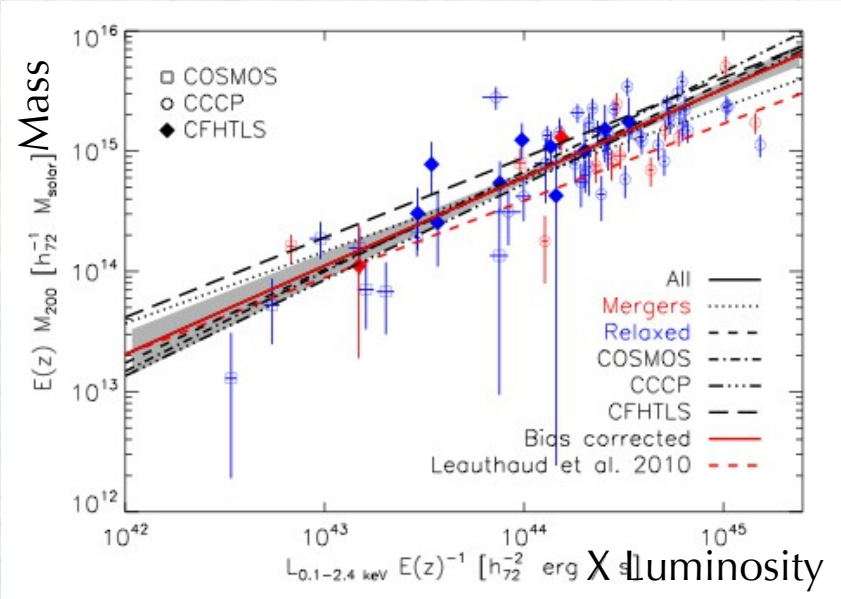
WL provides an estimate of the mass

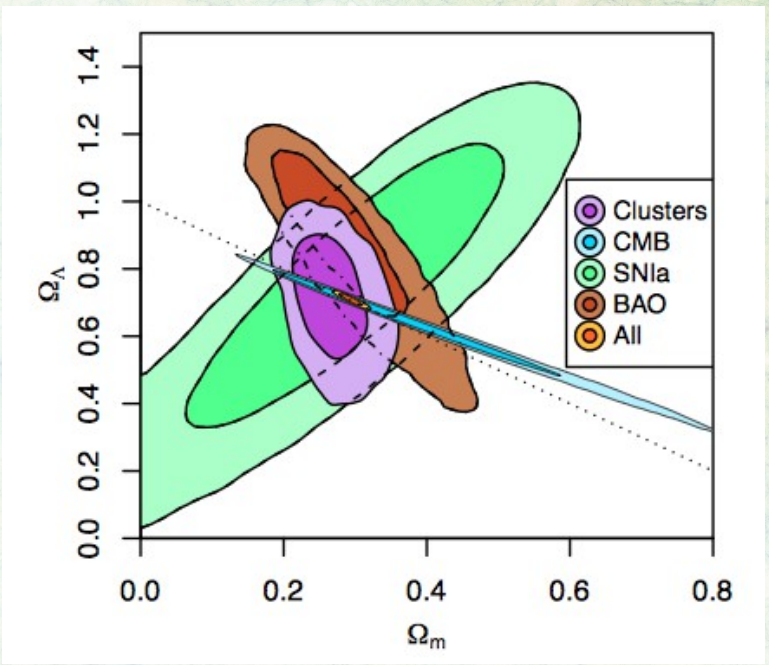
8% systematics now

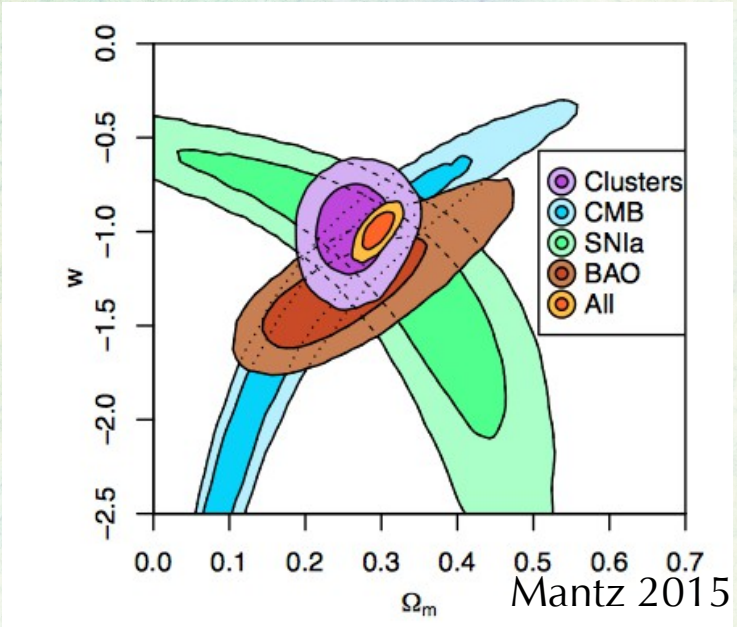
To calibrate SZ and/or X relation

- target a few % calibration

Kettula 2015







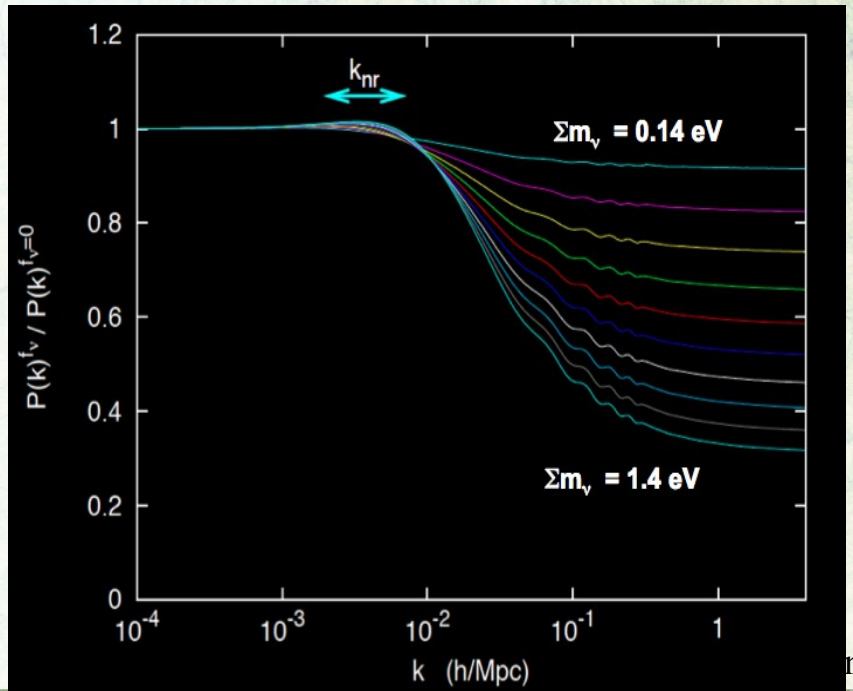
Mantz 2015

Neutrino mass

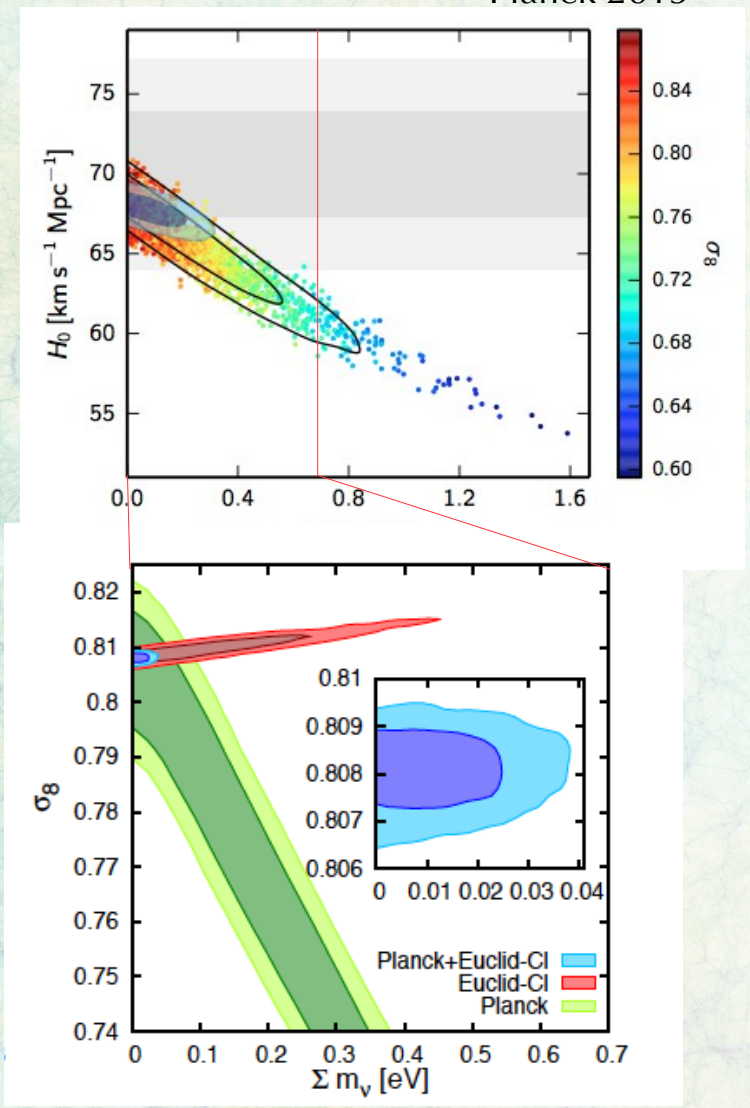
Neutrino suppress growth of structures

Smaller mass
- longer relativistic
- suppress growth on larger scales

Abazajian



Planck 2015



Expected 0.02 eV Sensitivity (all stage IV)

$\Sigma m_\nu > \sim 0.06$ eV

Long-term prospects on Dark Energy constraints

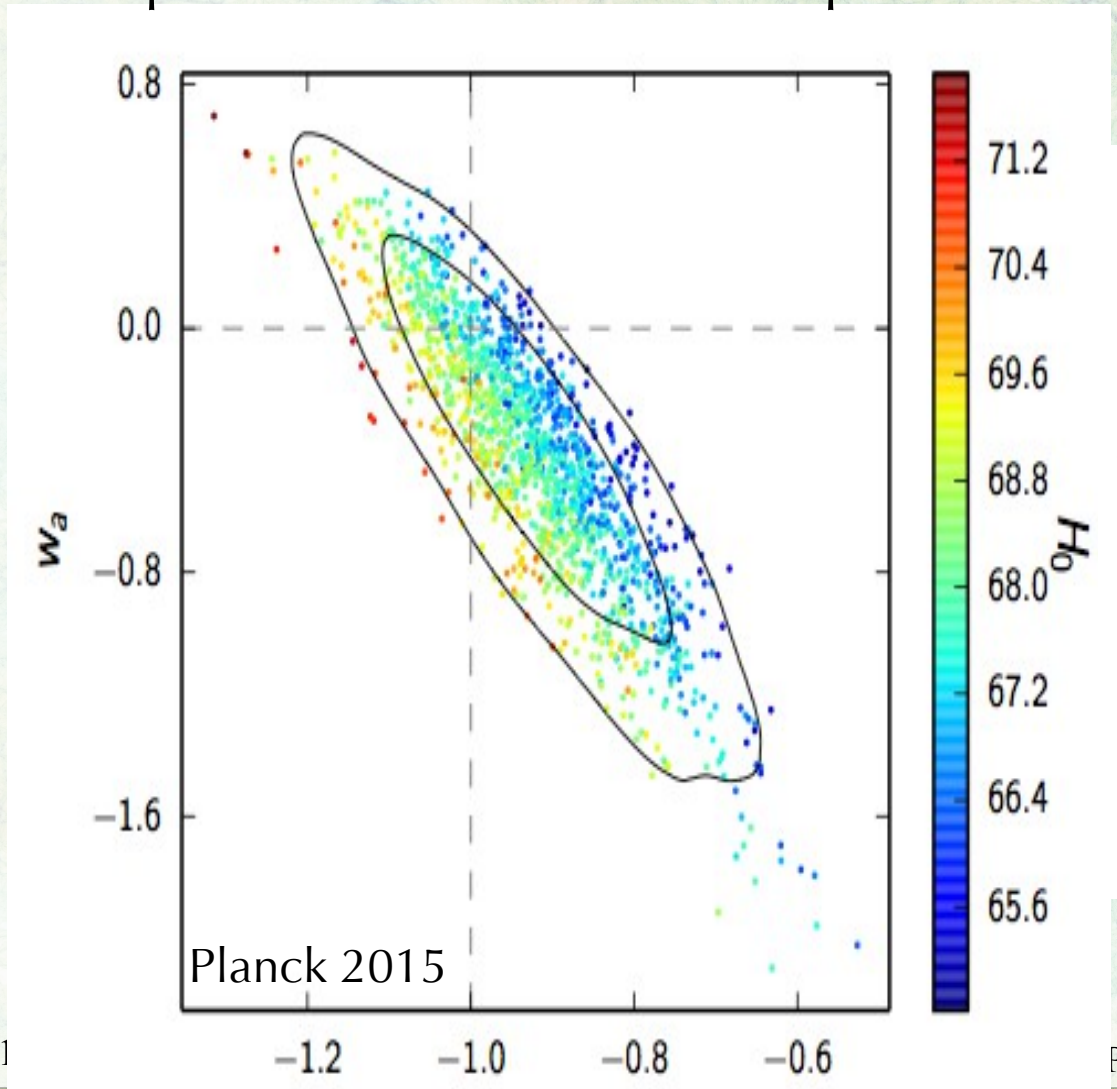
Sensitivity today : SN~BAO

Sensitivity >2020 : WL>BAO>SN

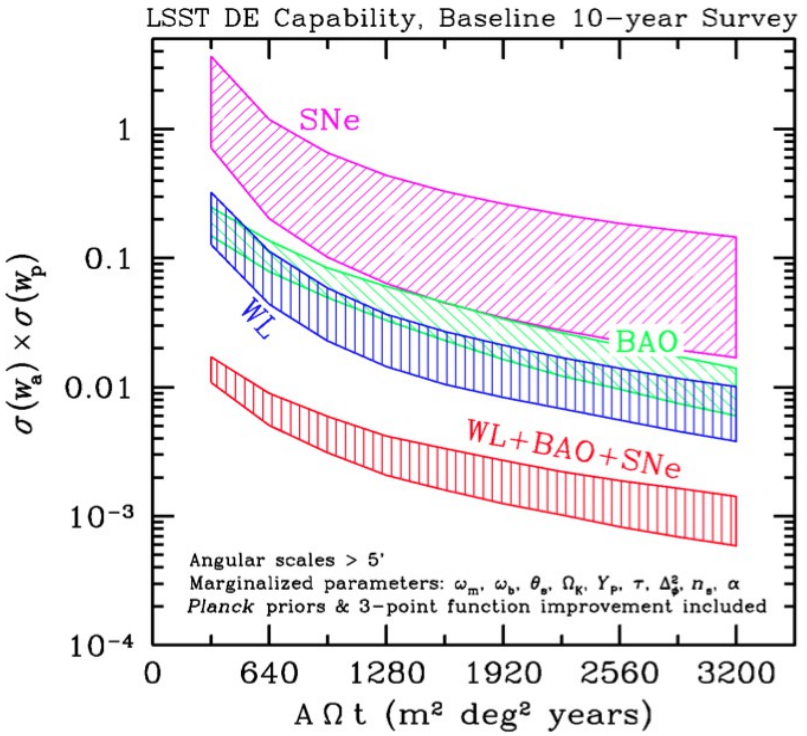
Probe combination fixes nuisance parameters

- precise determination of equation of state.

IN2P3 strategy ?

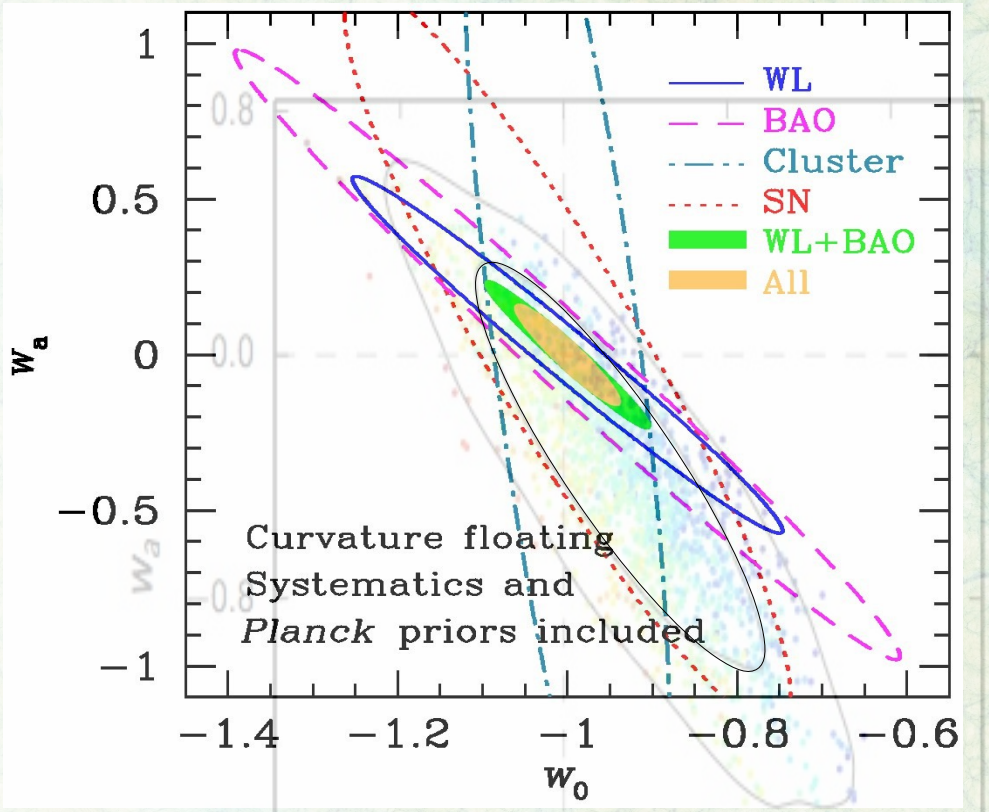


LSST projection

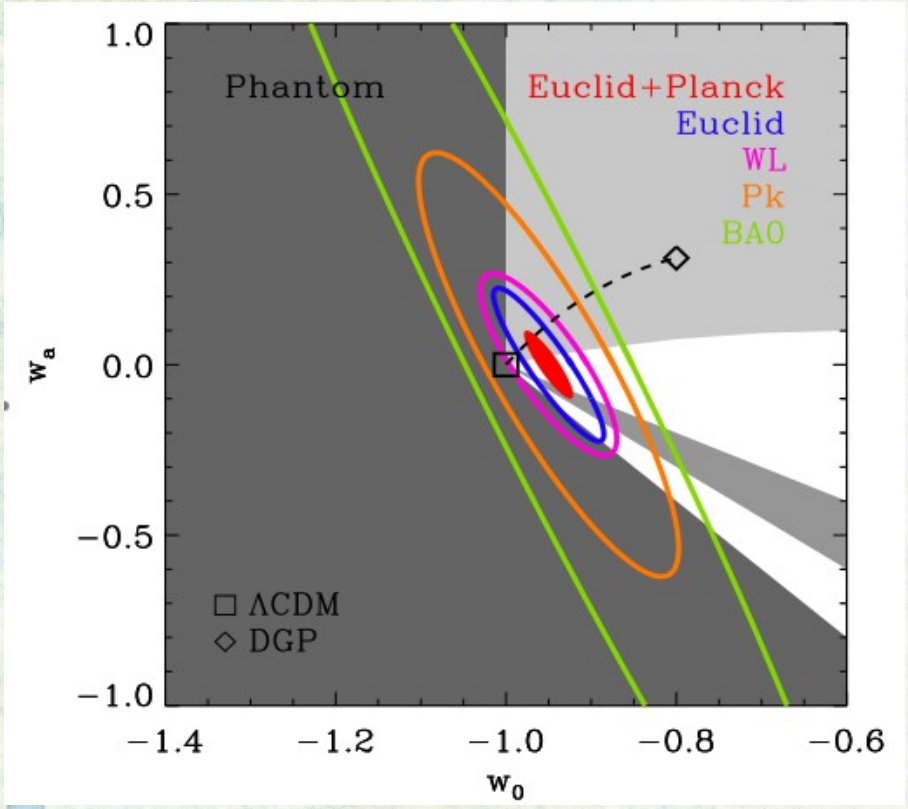


Long-term prospects on Dark Energy constraints

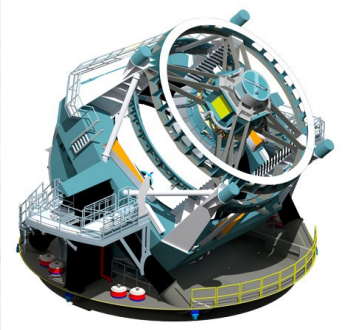
LSST projection



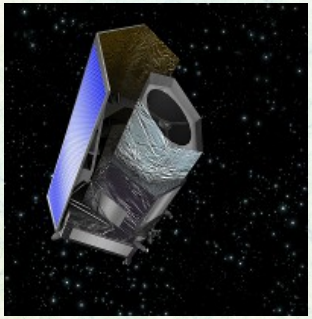
Euclid Projection



Errors will be systematics dominated !



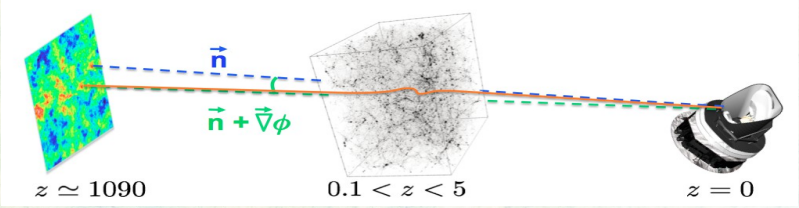
Conclusions

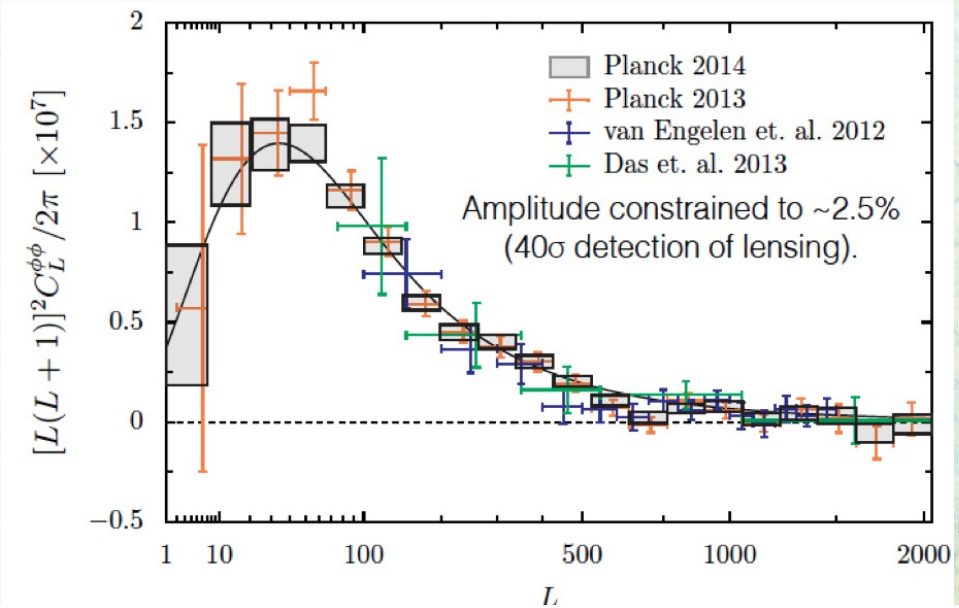


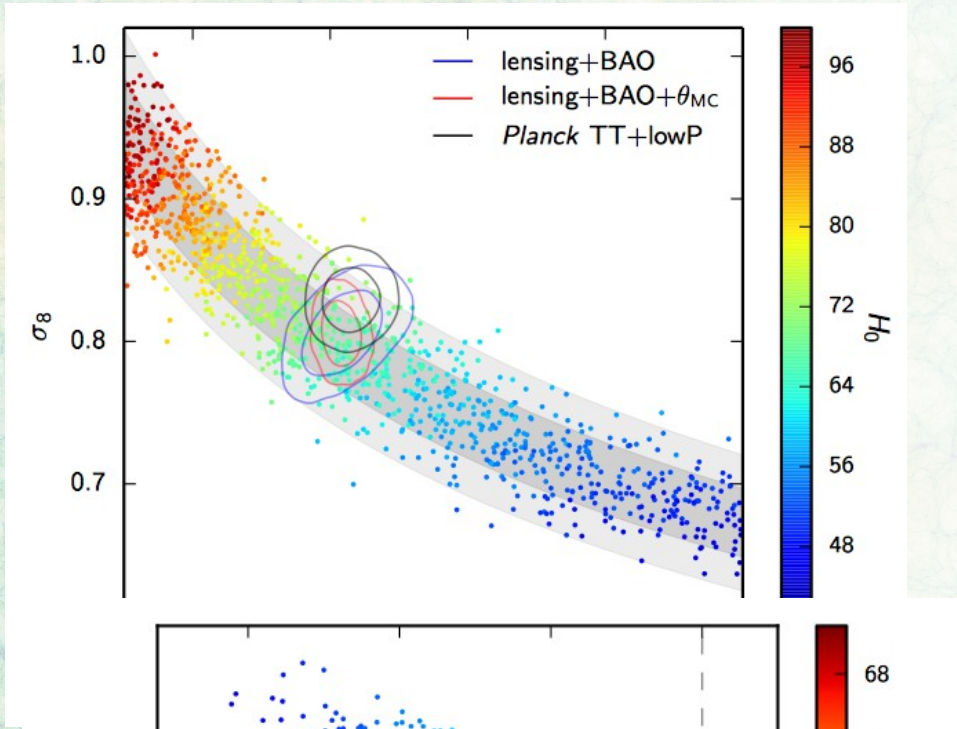
- **Key scientific questions to be answered by future projects**
  - Inflation and Primordial Gravitational Waves
  - Nature of Dark Energy
- **Probes are complementary**
  - CMB, SN, BAO, WL, Clusters combined for concordance model
  - Not only results, but also data can be complementary
    - Visible/IR ; 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

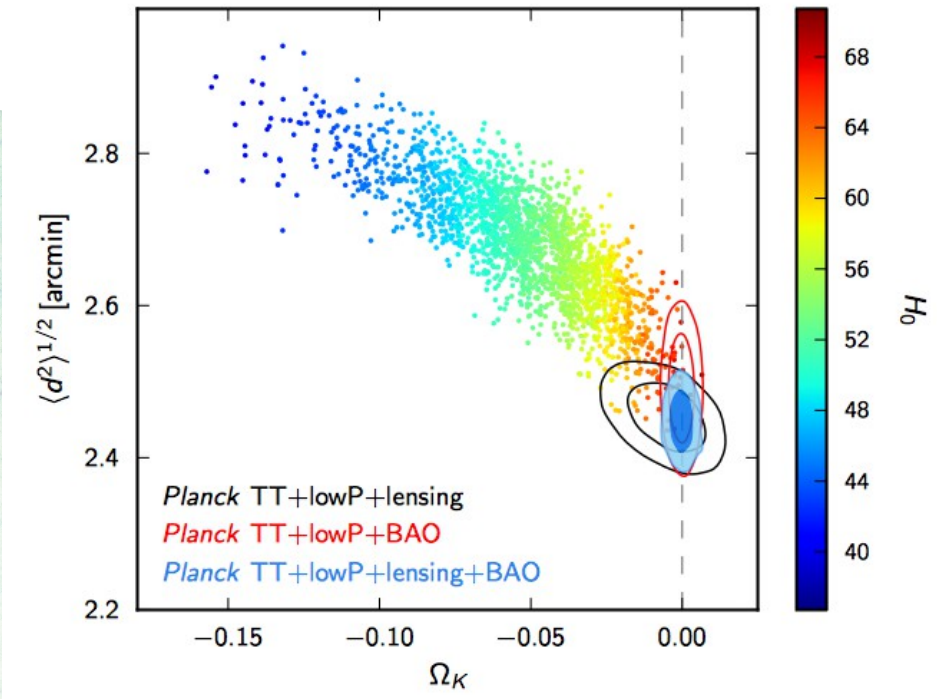
  … and to train next generation of cosmologists

CMB : lensing









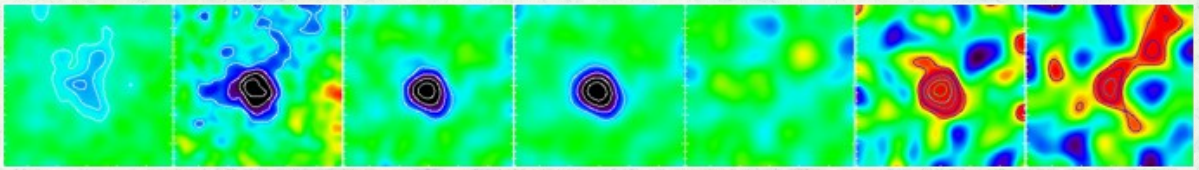
Planck 2014 XVII (Lensing)

- 20 sigma correlation with NVSS radio galaxies and quasars (z_{mean} = 1.1)
- 10 sigma with SDSS Luminous Red Galaxies (z_{mean} = 0.55)
- 7 sigma with the WISE satellite IR galaxies catalog (z_{mean} = 0.1)

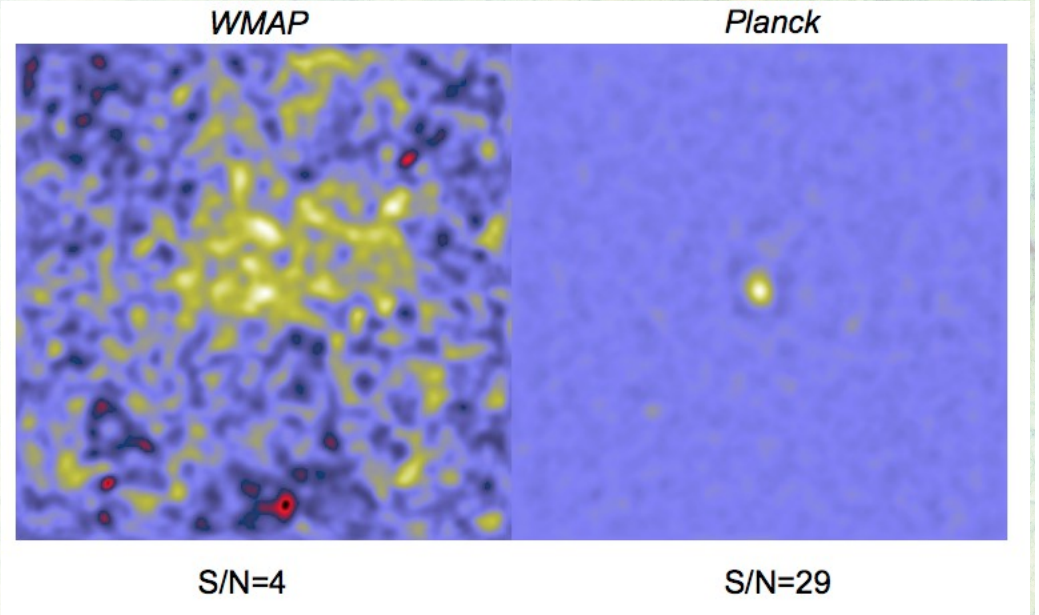
CMB Lensing :

- Temperature and polarisation signal
- Polarization-only detection (5σ)
- Correlation with foregrounds
- Additional constraints to cosmology

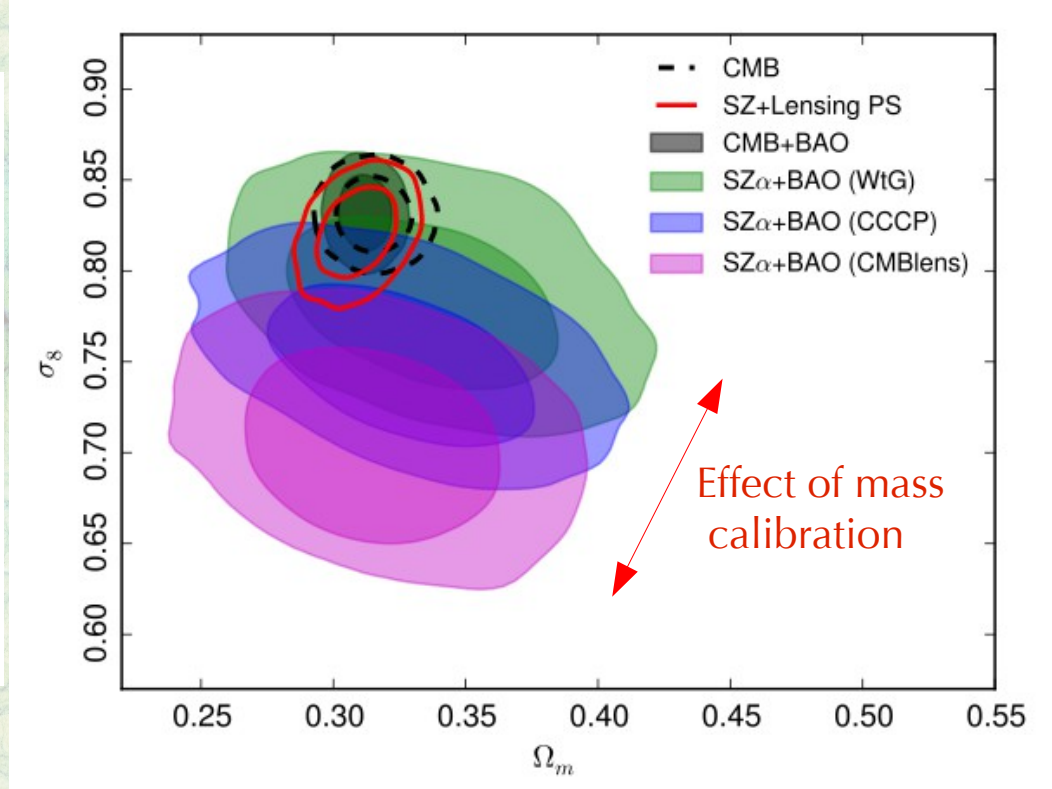
CMB : SZ Effect



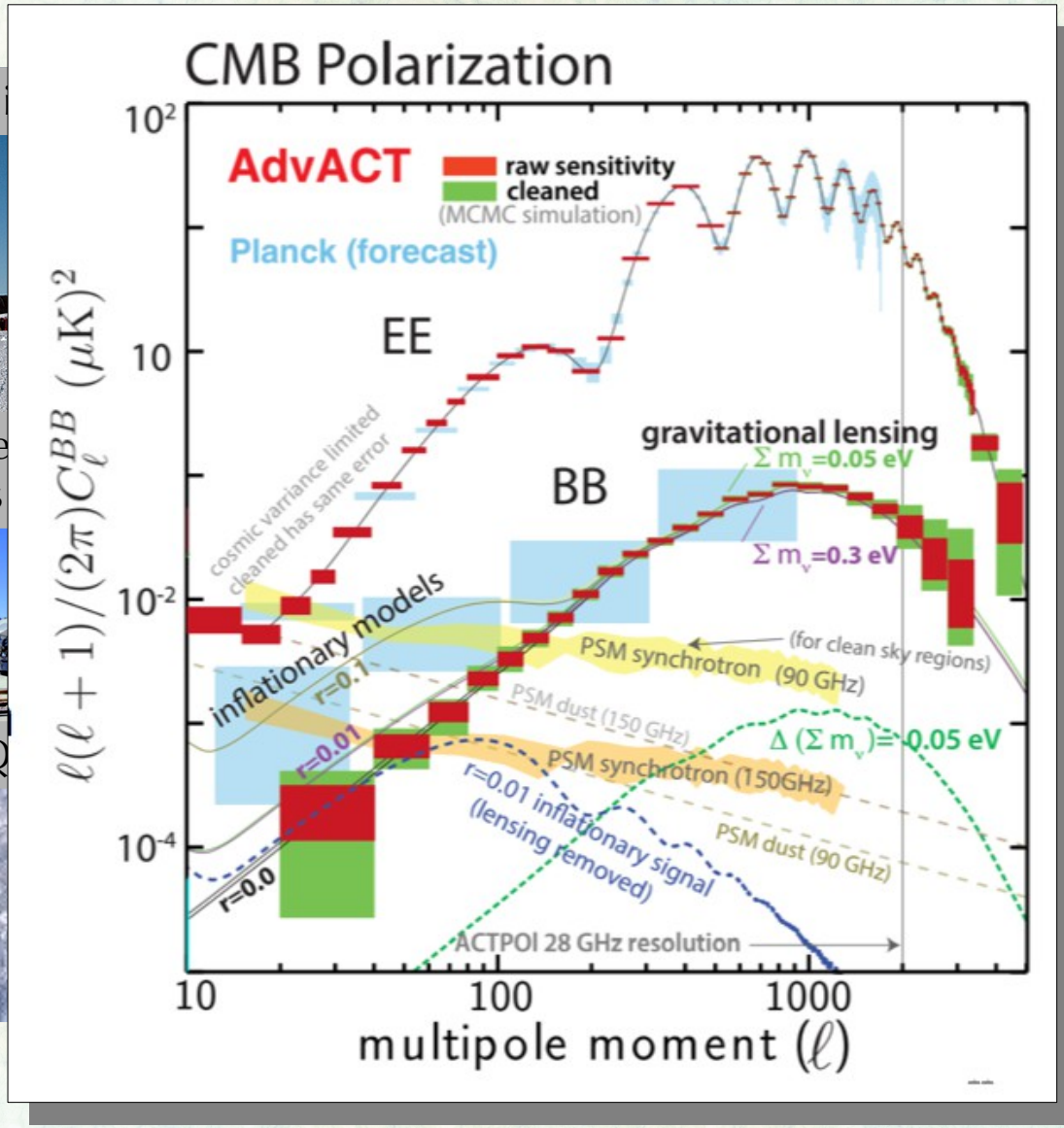
Compton effect on hot electron gas



Planck discovered 439 clusters



CMB : The future



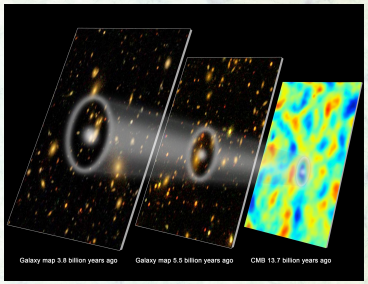
+ polarization capabilities

Projects Timeline

Sloan Digital Sky Survey (SDSS), including the Baryon Oscillation Spectroscopic Survey (BOSS) and e-BOSS, – Canada France Legacy Survey (CFHTLS), including the SNLS – DEEP II Redshift Survey - Virmos VLT Deep Survey (VVDS) - Panoramic Survey Telescope and Rapid Response System (Pann Starrs), 2 degrees Field (2DF) – 6 degree field (6DF) - Palomar Transient Factory (PTF, then ZTF) – Dark Energy Survey (DES) – VLT survey telescope (VST) – WiggleZ Dark Energy Survey (WIGGLEZ) – Stromlo Southern Sky Survey (SkyMapper), Large Synoptic Survey Telescope (LSST) – 2 MASS near IR survey – UKIRT, UKIDS Survey - Visible and Infrared Survey Telescope for Astronomy (VISTA) – Vista Hemisphere Survey (VHS) – Subaru HSC and PFS surveys – Dark Energy Spectroscopic Instrument (DESI) – Euclid – Wide Field Infrared Survey Telescpe (WFIRST), …

+ Radio (21 cm) surveys such as the planned Square Km Array (SKA)

Probe comparison

	Main requirements	Also provides	French Teams
Supernovae (SN) 	**Photometry :** Calibration Cadence Spectroscopy : Confirmation Hosts	**H0** (with anchor) Cepheids Maser Parallax Lens Time Delay	**CPPM, IPNL, LPC, LPNHE** (+CEA)
BAO 	**Photometry :** Target selection Photo-z Spectroscopy : Redshift + *Radio*	**Redshift Distorsions**	**APC, CPPM, LAL, LPNHE, LPSC** (+INSU,CEA)
Weak Lensing (WL) 	**Photometry :** PSF Dense galaxy field Photo-z Spectroscopy : Training photo-z	**Cluster mass** Relation with SZ or X Cluster counts **Galaxy alignements**	**APC, LPSC** (+ INSU, CEA)

Type Ia Supernovae

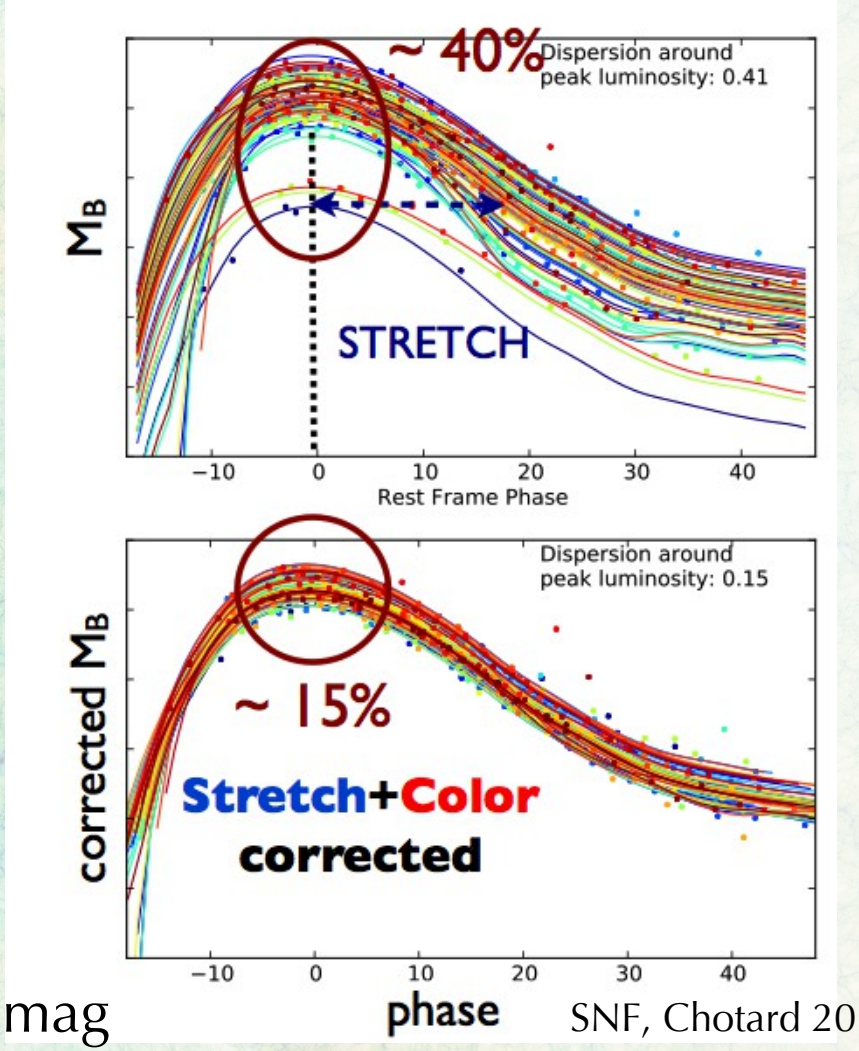
Luminosity distance (**Standard candle**):

SNIa are

- Luminous M_B=-19.3
  - good detection up to z~1.4
- **Transient** object
  - Find and follow
- *Spectroscopic* confirmation
- *Photometry* measurements

- **Empirical** correction :
  - Stretch (intrinsic)
  - Color (dust + intrinsic)
  - Host Mass (astrophysics)
- Accuracy after standardization ~0.12 mag

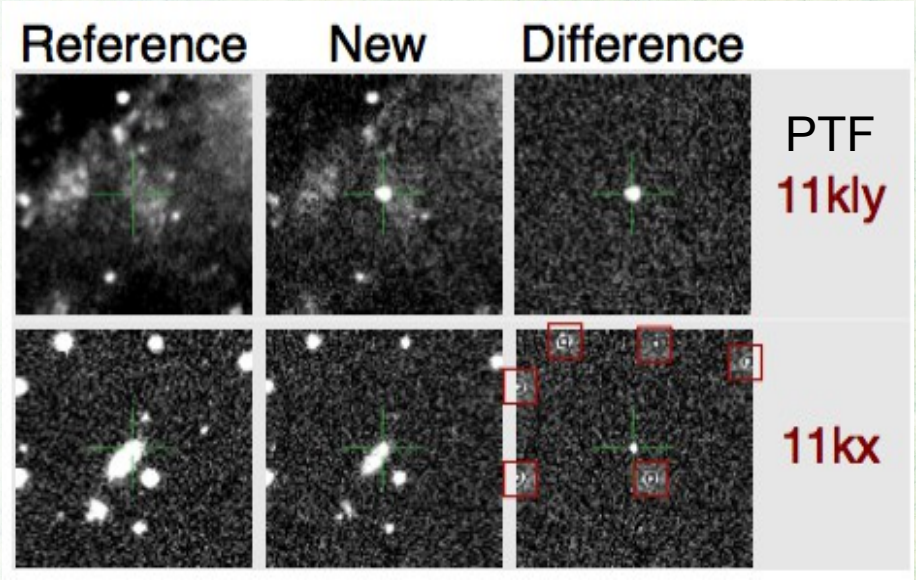
- Fit distance/velocity relation



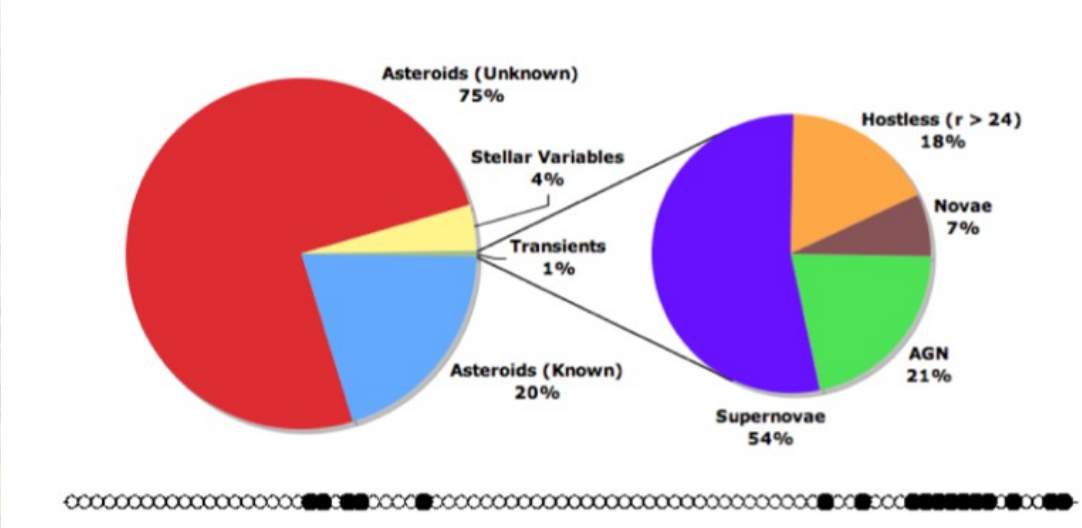
SNF, Chotard 2011

Hunting transients

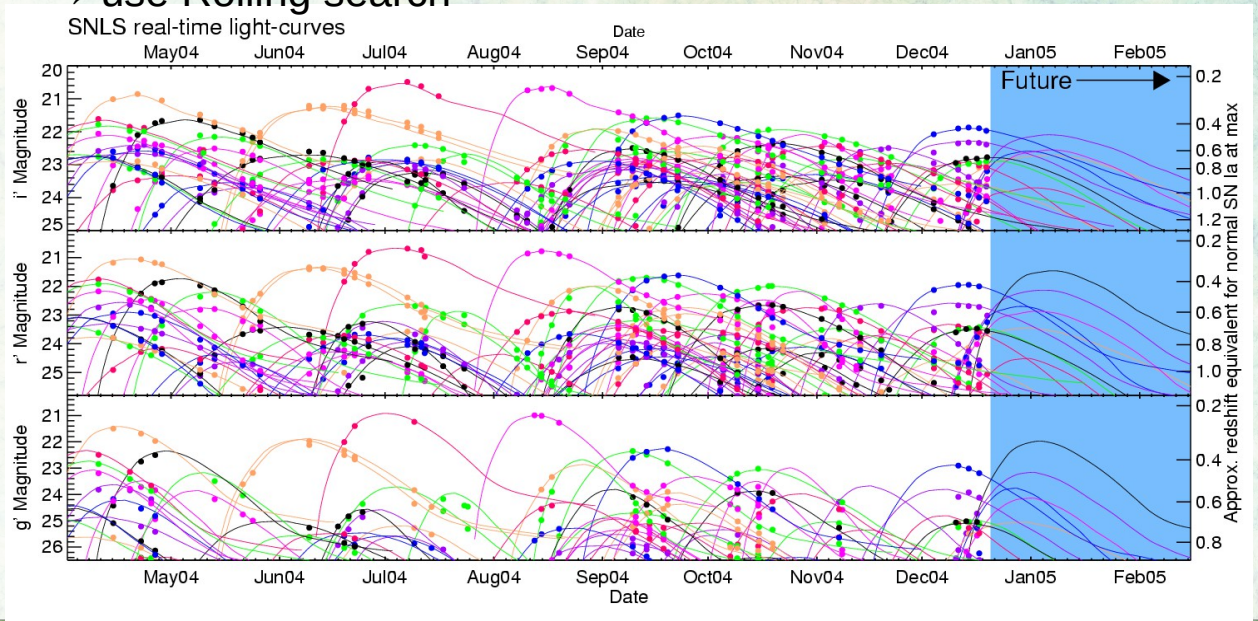
From a reference map, search detections by differential photometry.



In LSST : **~1 000 000 alerts / night !**
< 1/100 of them will be Ia
Most of Ia will be useless (cadence)



→ use Rolling search



In CHFTLS : spectroscopic identification
No spectroscopy in DES or LSST

LSST expects/year

- 150 000 SNIa in wide
- 10 000 SNIa in deep field

Statistics are not the limit.

A combined Euclid/LSST SN program :

A&A 572 80 (2014)

Extending the supernova Hubble diagram to $z \sim 1.5$ with the Euclid space mission

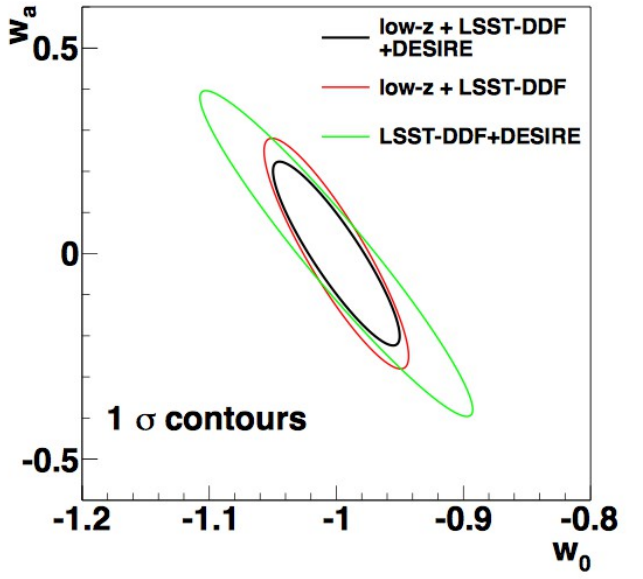
P. Astier[1], C. Balland[1], M. Brescia[2], E. Cappellaro[3], R. G. Carlberg[4], S. Cavuoti[5], M. Della Valle[2,6], E. Gangler[7], A. Goobar[8], J. Guy[1], D. Hardin[1], I. M. Hook[9,10], R. Kessler[11,12], A. Kim[13], E. Linder[14], G. Longo[5], K. Maguire[9,15], F. Mannucci[16], S. Mattila[17], R. Nichol[18], R. Pain[1], N. Regnault[1], S. Spiro[9], M. Sullivan[19], C. Tao[20,21], M. Turatto[3], X. F. Wang[21], and W. M. Wood-Vasey[22]

DESIRE survey :

2x 6-month seasons

45 visits / season

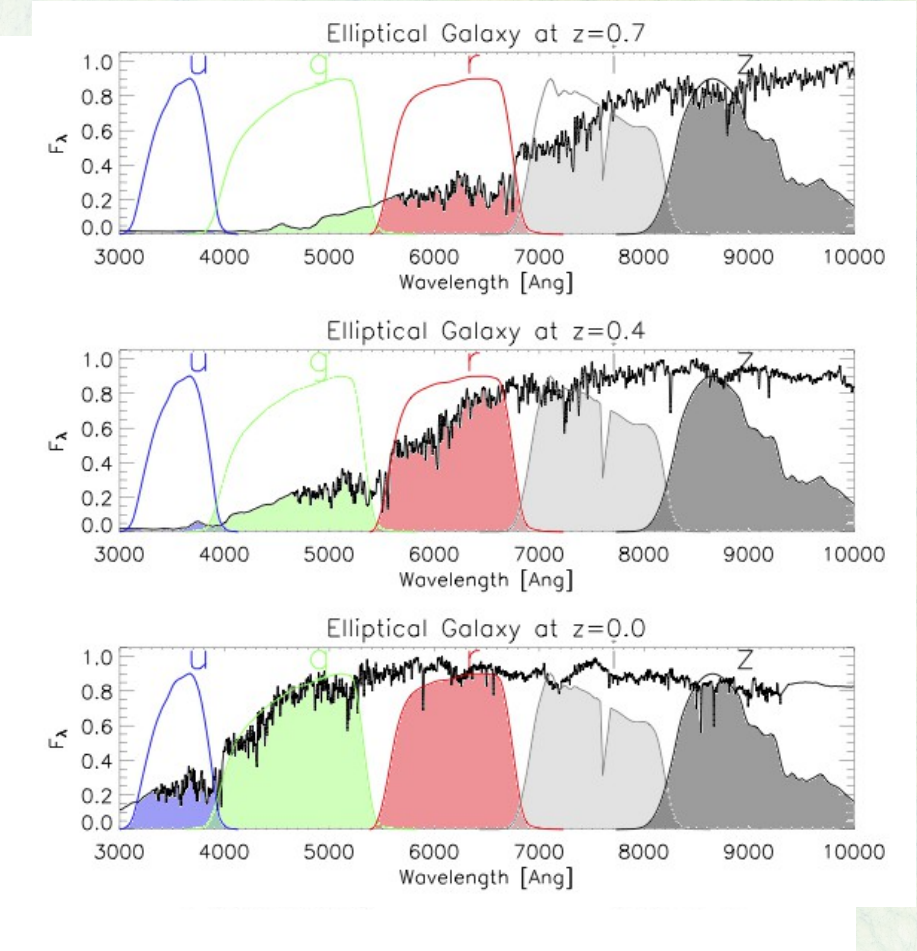
	z_{min}	z_{max}	area (deg^2)	duration (months)	events
DESIRE	0.75	1.55	10	2x6	1740
LSST-DDF	0.15	0.95	50	4x6	8800
Low z	0.05	0.35	3000	6	8000

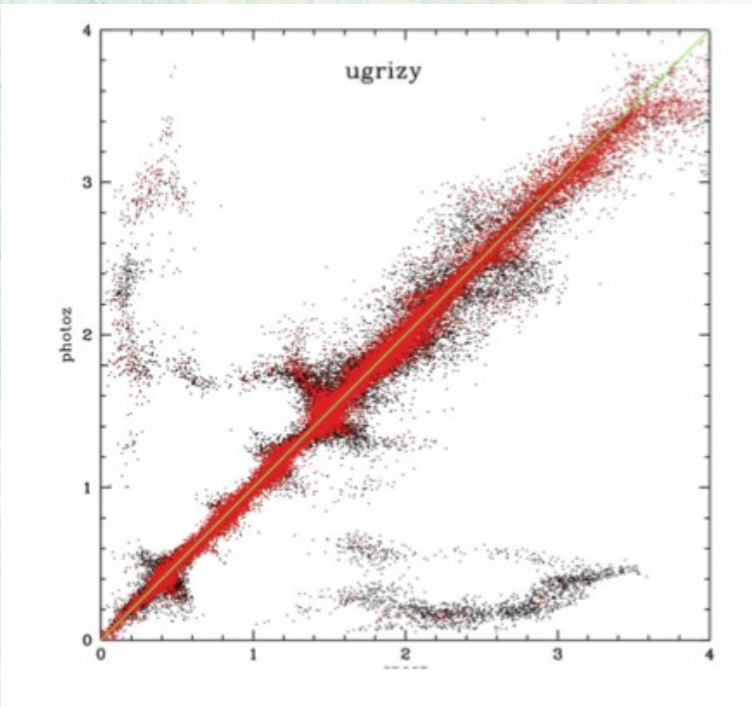


Photometric BAO ?

LSST requirements on 1+z
- 0.02 random error
- <0.003 bias
- <10% 3-σ outliers

Euclid
- Requires optical ground data !



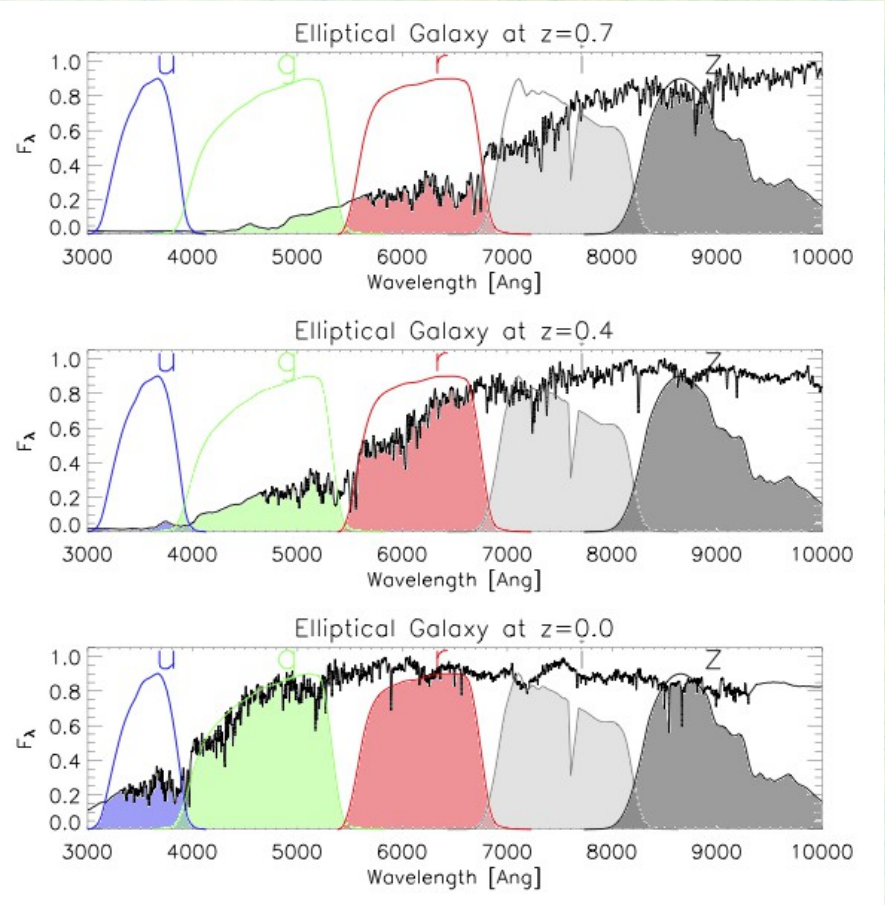


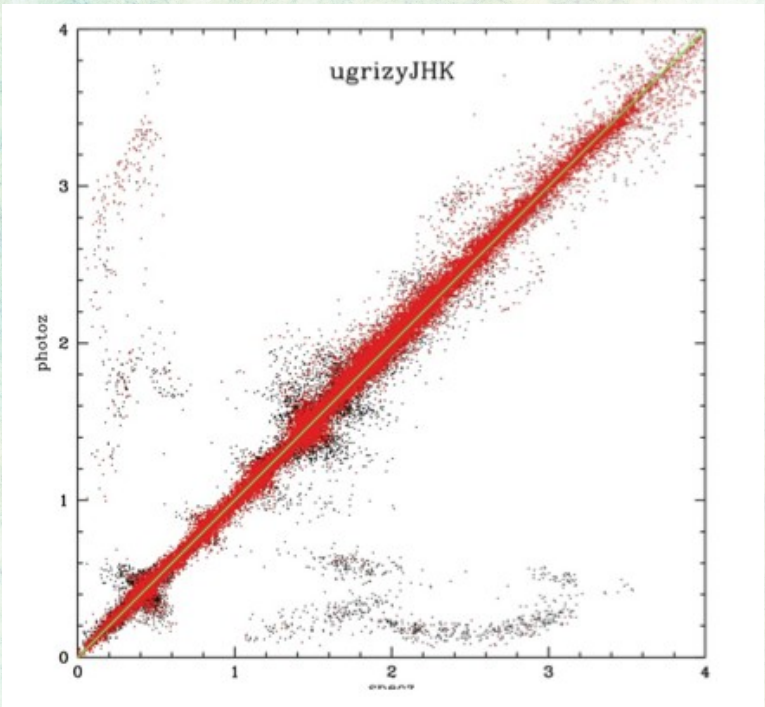
Photometric BAO ?

LSST requirements on 1+z
- 0.02 random error
- <0.003 bias
- <10% 3-σ outliers

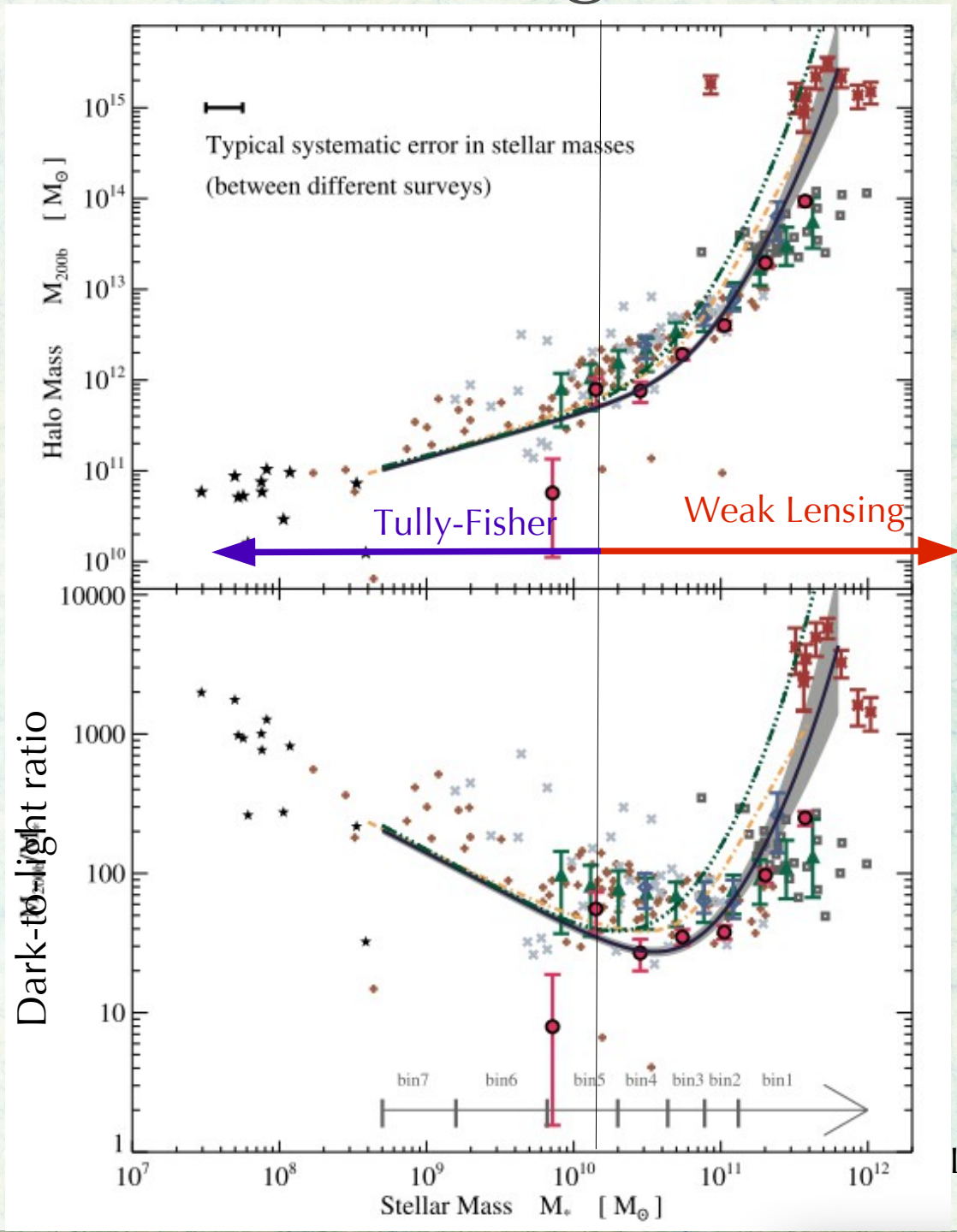
Euclid
- Requires optical ground data !

A few IR bands would clearly be of some help for LSST !





Probing dark matter



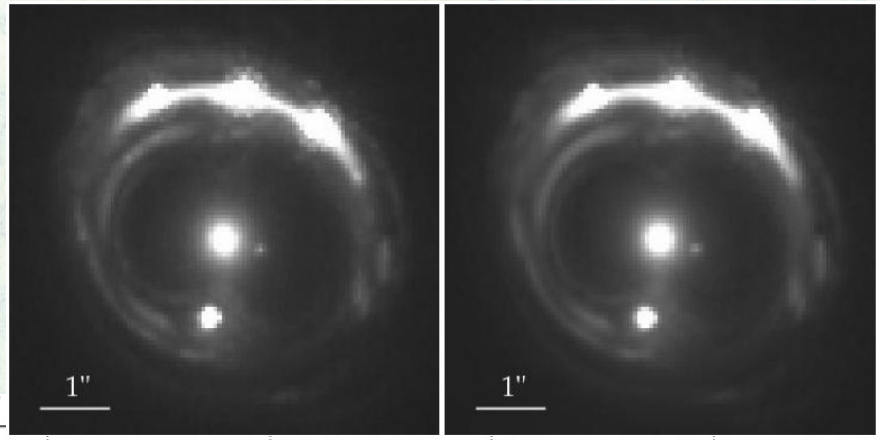
LSST/WL provides halo masses

… and evolution with z

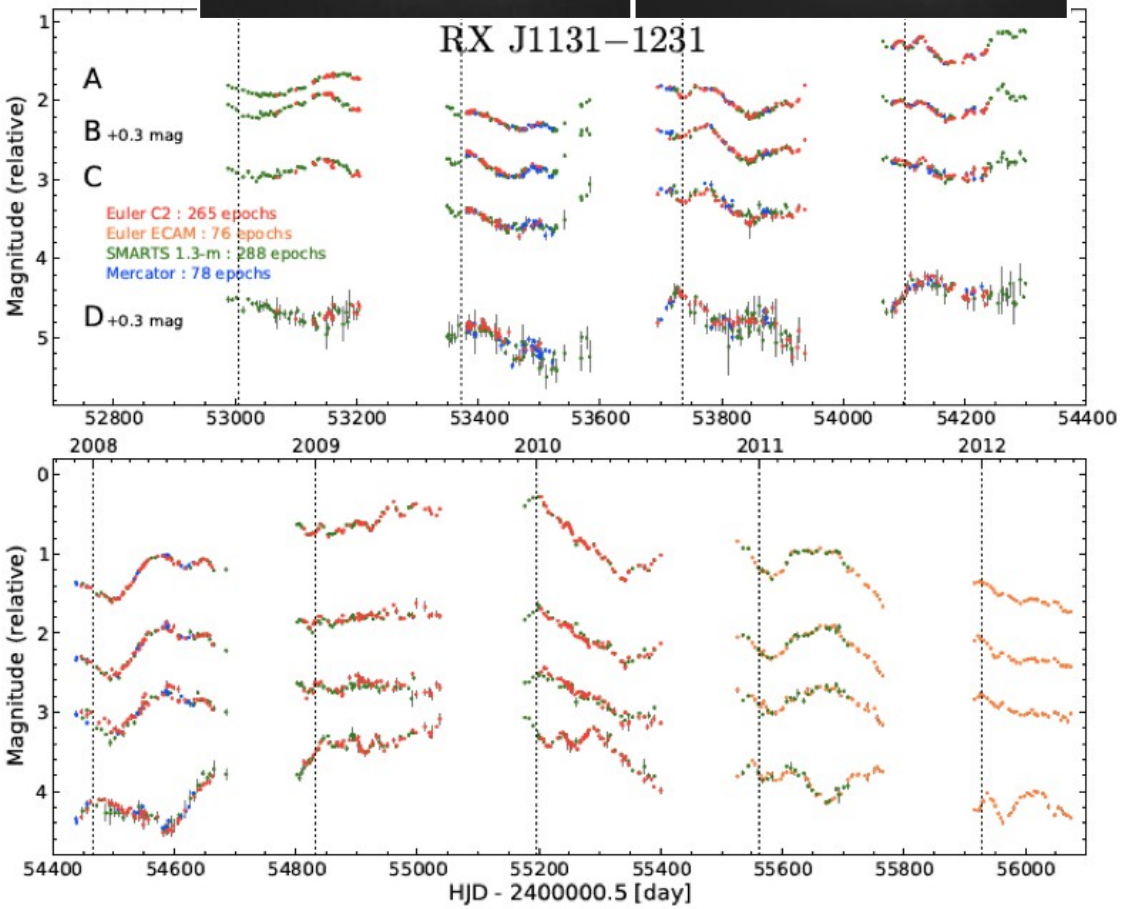
Similar prospects with Euclid

Leauthaud 2012

Strong lensing time delays



Treu 2013



LSST expects strong lensend variable sources

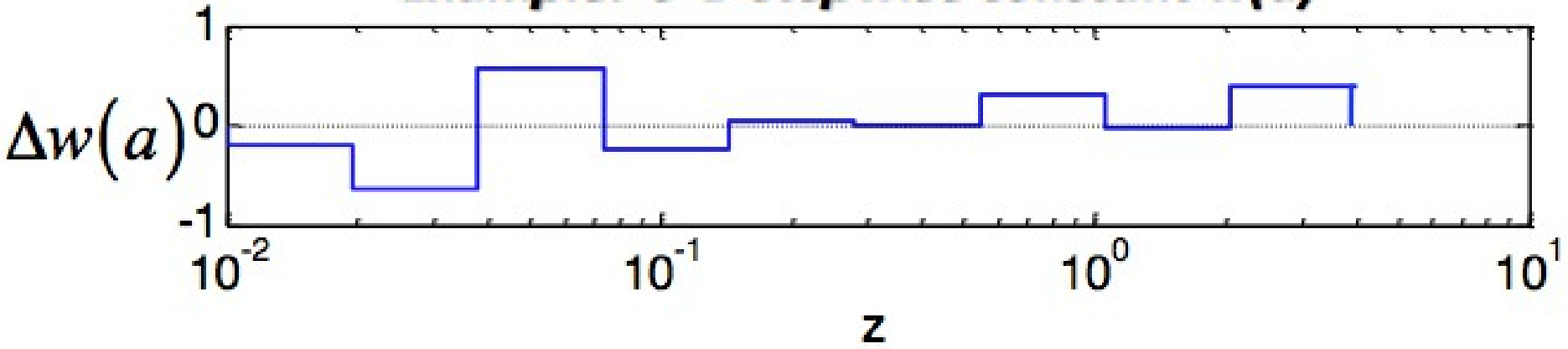
- ~2500 quasars
- ~300 SN (100 Ia)

Time delay gives access to

- measure of H0
- DE EoS
- GR consistency

Beyond w_o w_a

Example: 9-D stepwise constant w(a)



$$w(a) = -1 + \Delta w(a) = -1 + \sum_{i=1}^{9} \Delta w_i T(a_i, a_{i+1})$$

9 parameters are coefficients of the "top hat functions" $T(a_i, a_{i+1})$

Albrecht & Bernstein 2006

+ General models of Dark Energy