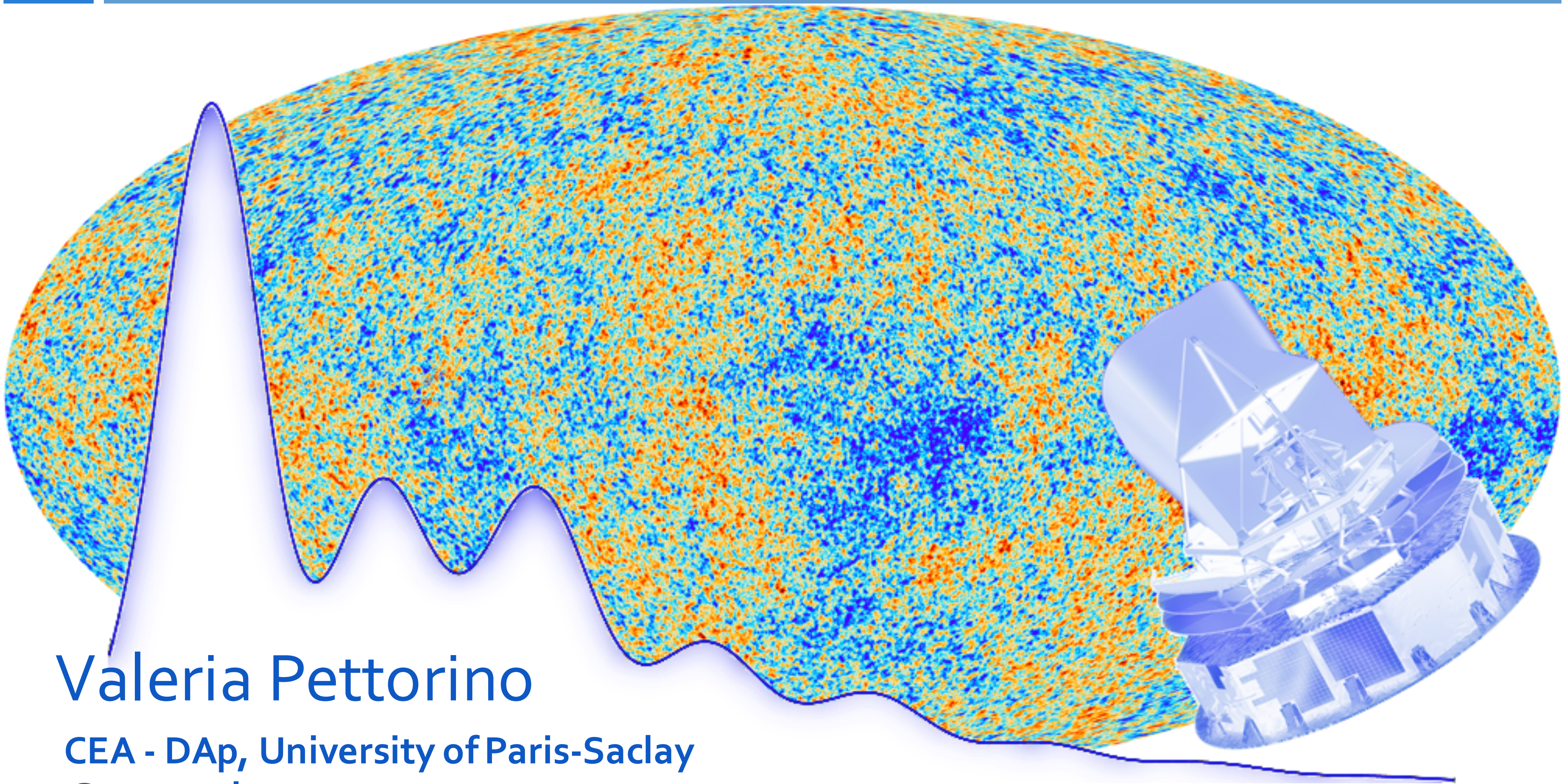
Dark energy and modified gravity: from Planck to future surveys



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LPNHE, Paris – 22nd May 2017

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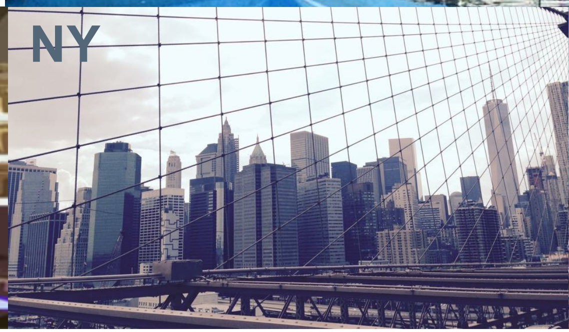
Research Interests:
Cosmology, Theory and phenomenology of Dark Energy and Modified Gravity, CMB, neutrinos, Supernovae

Experiments:
ICARUS: hep-ph/0408031
Planck: ArXiv 1502:10590
Euclid: ArXiv: 1606.00180



Results of this talk will mainly be based on:

Planck 2015 results. XIV. Dark energy and modified gravity

Planck collaboration: ArXiv 1502:10590

February 5, 2015

ABSTRACT

We study the implications of *Planck* data for models of dark energy (DE) and modified gravity (MG), beyond the standard cosmological constant scenario. We start with cases where the DE only directly affects the background evolution, considering Taylor expansions of the equation of state $w(a)$, as well as principal component analysis and parameterizations related to the potential of a minimally coupled DE scalar field. When estimating the density of DE at early times, we significantly improve present constraints and find that it has to be below $\approx 2\,\%$ (at 95% confidence) of the critical density even when forced to play a role for $z < 50$ only. We then move to general parameterizations of the DE or MG perturbations that encompass both effective field theories and the phenomenology of gravitational potentials in MG models. Lastly, we test a range of specific models, such as k-essence, $f(R)$ theories and coupled DE. In addition to the latest *Planck* data, for our main analyses we use background constraints from baryonic acoustic oscillations, type-Ia supernovae and local measurements of the Hubble constant. We further show the impact of measurements of the cosmological perturbations, such as redshift-space distortions and weak gravitational lensing. These additional probes are important tools for testing MG models and for breaking degeneracies that are still present in the combination of *Planck* and background data sets.
All results that include only background parameterizations (expansion of the equation of state, early DE, general potentials in minimally-coupled scalar fields or principal component analysis) are in agreement with ΛCDM. When testing models that also change perturbations (even when the background is fixed to ΛCDM), some tensions appear in a few scenarios: the maximum one found is $\sim 2\sigma$ for *Planck* TT+lowP when parameterizing observables related to the gravitational potentials with a chosen time dependence; the tension increases to at most 3σ when external data sets are included. It however disappears when including CMB lensing.

Key words. Cosmology: observations – Cosmology: theory – cosmic microwave background – dark energy – gravity

1. Introduction

The cosmic microwave background (CMB) is a key probe of our cosmological model (Planck Collaboration XIII 2015), providing information on the primordial Universe and its physics, including inflationary models (Planck Collaboration XX 2015) and constraints on primordial non-Gaussianities (Planck Collaboration XVII 2015). In this paper we use

⋆ Corresponding author: Valeria Pettorino, v.pettorino@thphys.

Results of this talk will mainly be based on:

arXiv:1703.01271v1

Linear and non-linear Modified Gravity forecasts with future surveys

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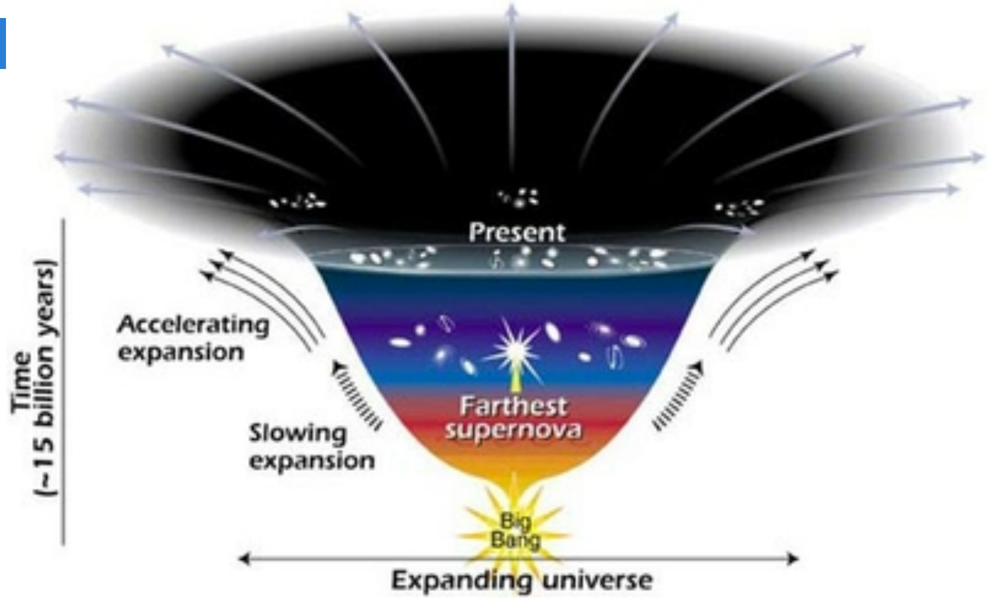
Modified Gravity theories generally affect the Poisson equation and the gravitational slip (effective anisotropic stress) in an observable way, that can be parameterized by two generic functions (η and μ) of time and space. We bin the time dependence of these functions in redshift and present forecasts on each bin for future surveys like Euclid. We consider both Galaxy Clustering and Weak Lensing surveys, showing the impact of the non-linear regime, treated with two different semi-analytical approximations. In addition to these future observables, we use a prior covariance matrix derived from the *Planck* observations of the Cosmic Microwave Background. Our results show that η and μ in different redshift bins are significantly correlated, but including non-linear scales reduces or even eliminates the correlation, breaking the degeneracy between Modified Gravity parameters and the overall amplitude of the matter power spectrum. We further decorrelate parameters with a Zero-phase Component Analysis and identify which combinations of the Modified Gravity parameter amplitudes, in different redshift bins, are best constrained by future surveys. We also extend the analysis to two particular parameterizations of the time evolution of μ and η and consider, in addition to Euclid, also SKA1, SKA2, DESI: we find in this case that future surveys will be able to constrain the current values of η and μ at the 2-5% level when using only linear scales (wavevector k $<$ 0.15 h/Mpc), depending on the specific time parameterization; sensitivity improves to about 1% when non-linearities are included.

Plan of the talk

- Introduction
- Dark Energy and Modified Gravity
- The Cosmic Microwave Background
- Results on Dark Energy and Modified Gravity after Planck
- Forecasts for future surveys (Euclid)

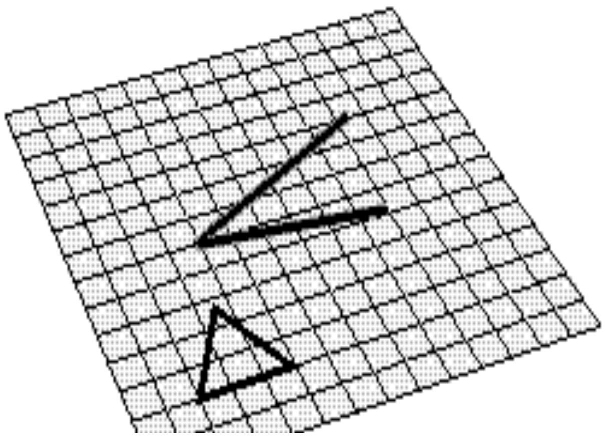

Bicep2 and SPT
Planck
Polarbear
ACTpol
DASI
Cosmic Background Imager
MAXIMA
BOOMerang
ACBAR
COBE
MSAM
WMAP
2dF Galaxy Redshift Survey
Sloan Digital Sky Survey
HST
ESO

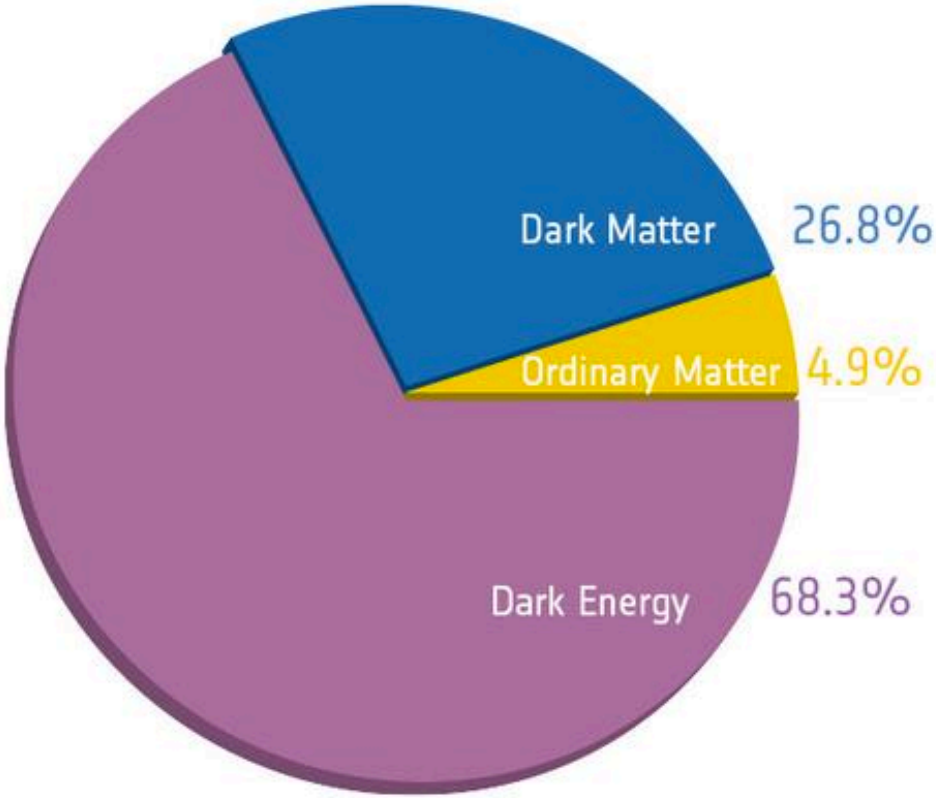
The *standard* cosmological picture



Accelerated expansion

Flatness





$$\Omega_i \equiv \frac{\rho_i}{\rho_{cr}}$$

What causes cosmic acceleration?

Cosmological constant?

agrees with experiments, but theoretically not understood.

Parameter.

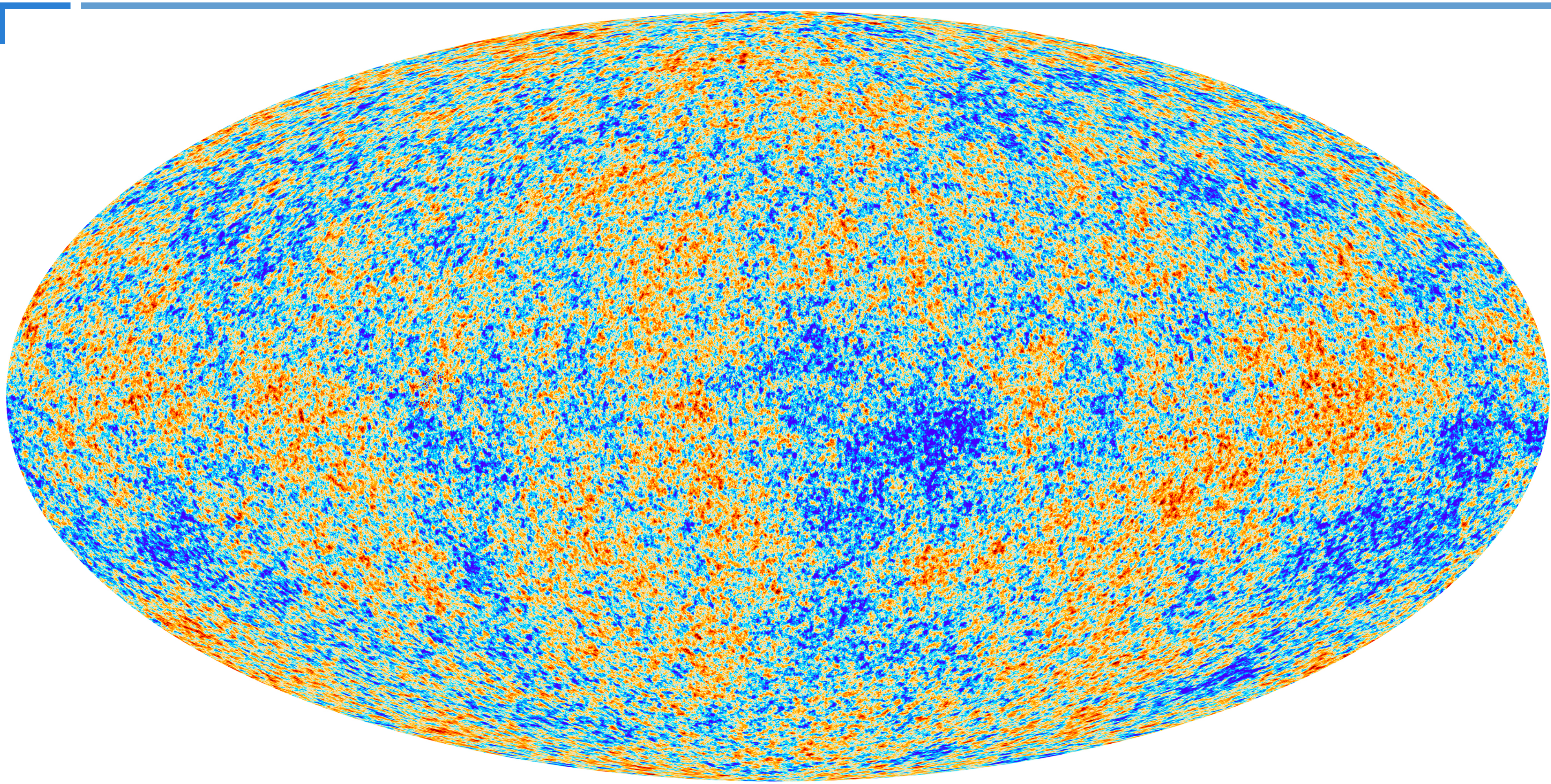
Dynamical Dark Energy?

Wetterich 1988, Ratra & Peebles 1988

Does it involve a modification of Gravity as described in General Relativity ?

CMB anisotropies

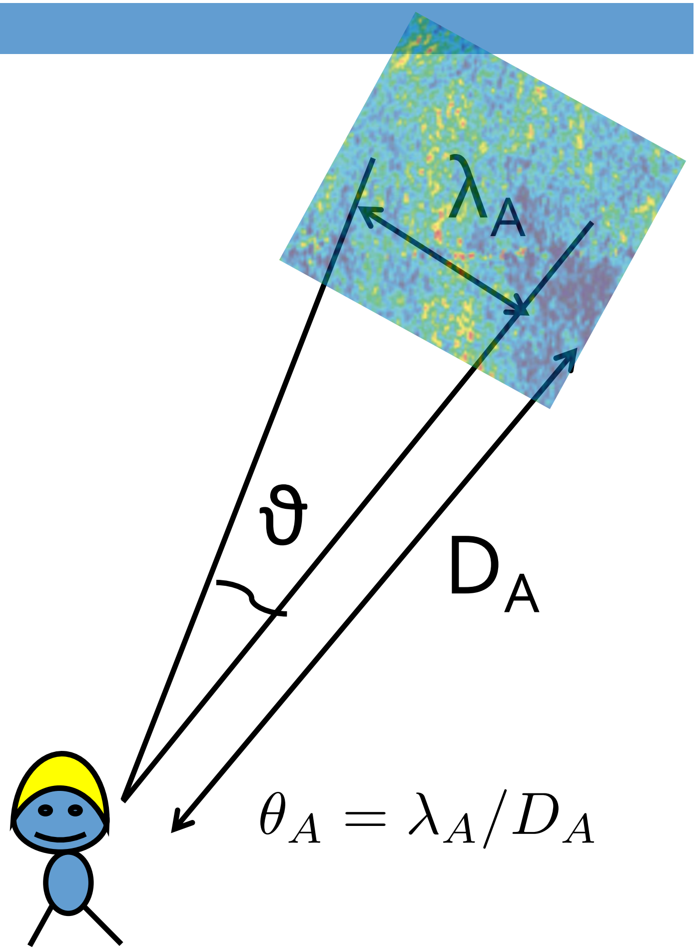
Light emitted 380.000 yrs after the Big Bang, relic of the early Universe



Temperature fluctuations are related to primordial density fluctuations.

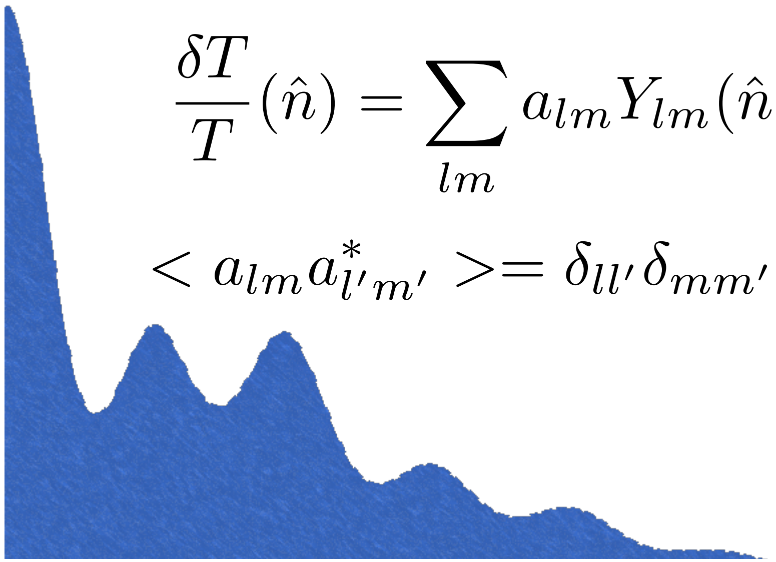
Evolution of perturbations

- Expand in Fourier space
- Project the fluctuations in the sky
- Spectra as 2 point correlation function of the coefficients of the expansion in spherical harmonics

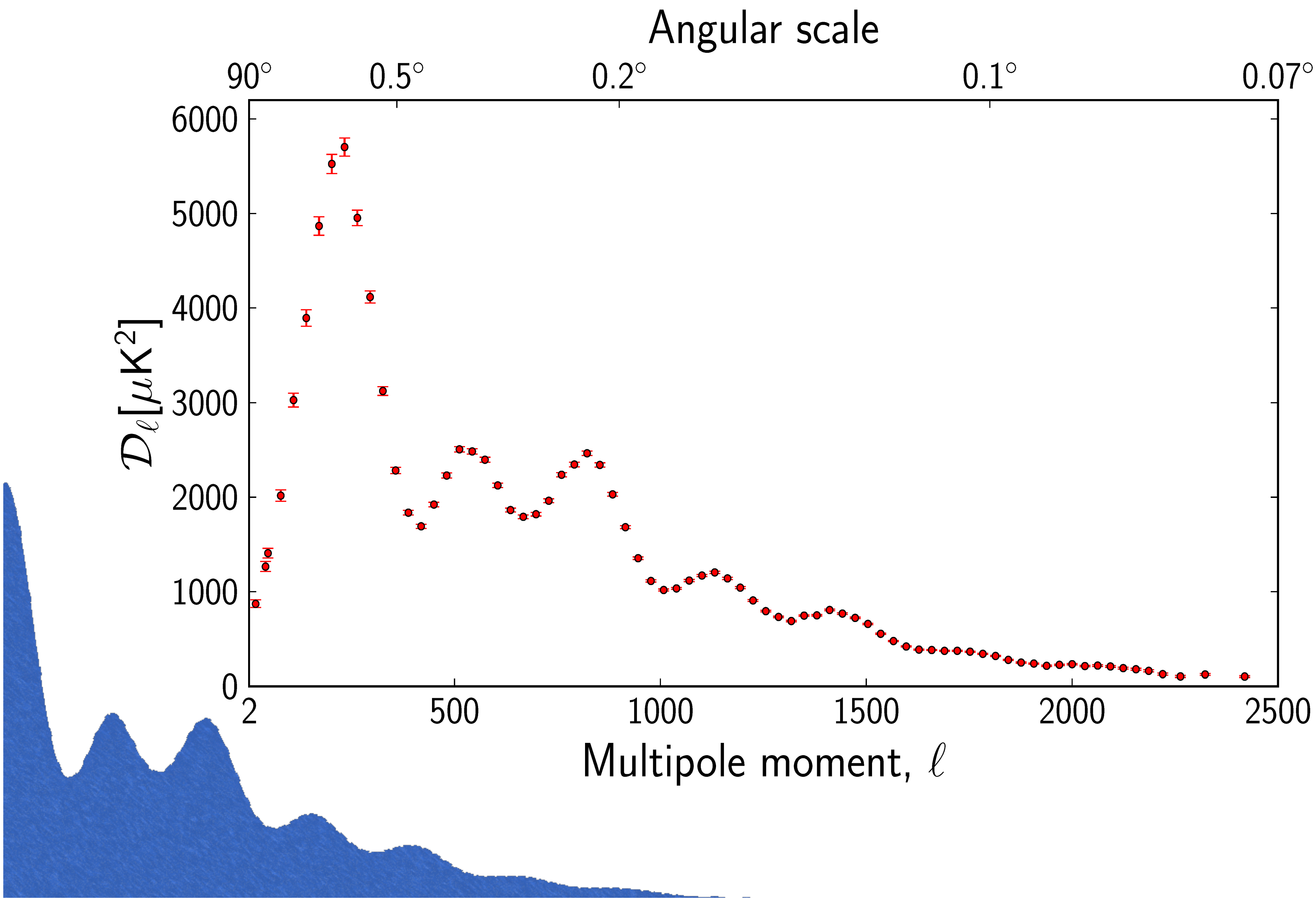


$$\frac{\delta T}{T}(\hat{n}) = \sum_{lm} a_{lm} Y_{lm}(\hat{n})$$

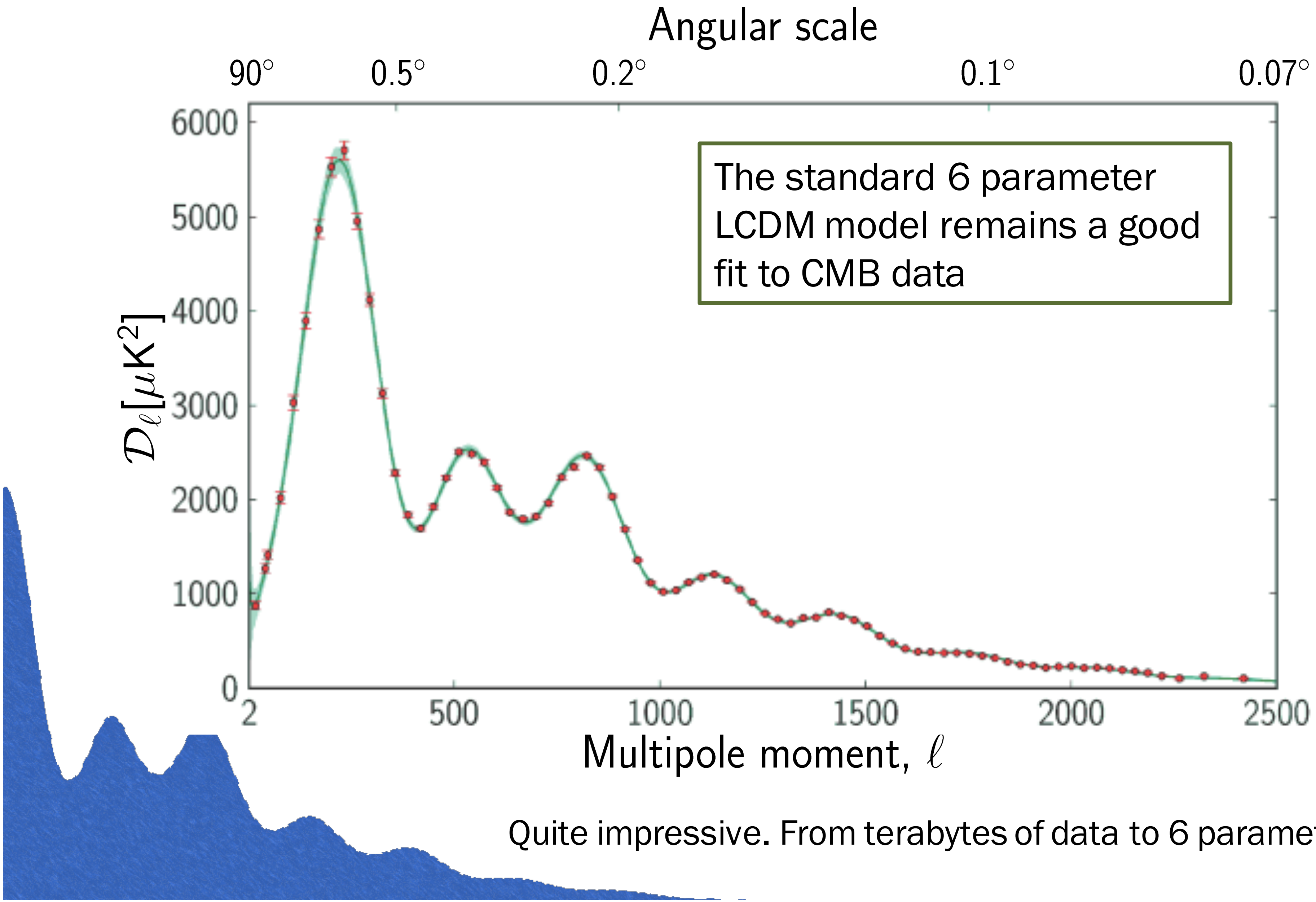
$$< a_{lm} a^*_{l'm'} > = \delta_{ll'} \delta_{mm'} C_l$$



Power spectrum

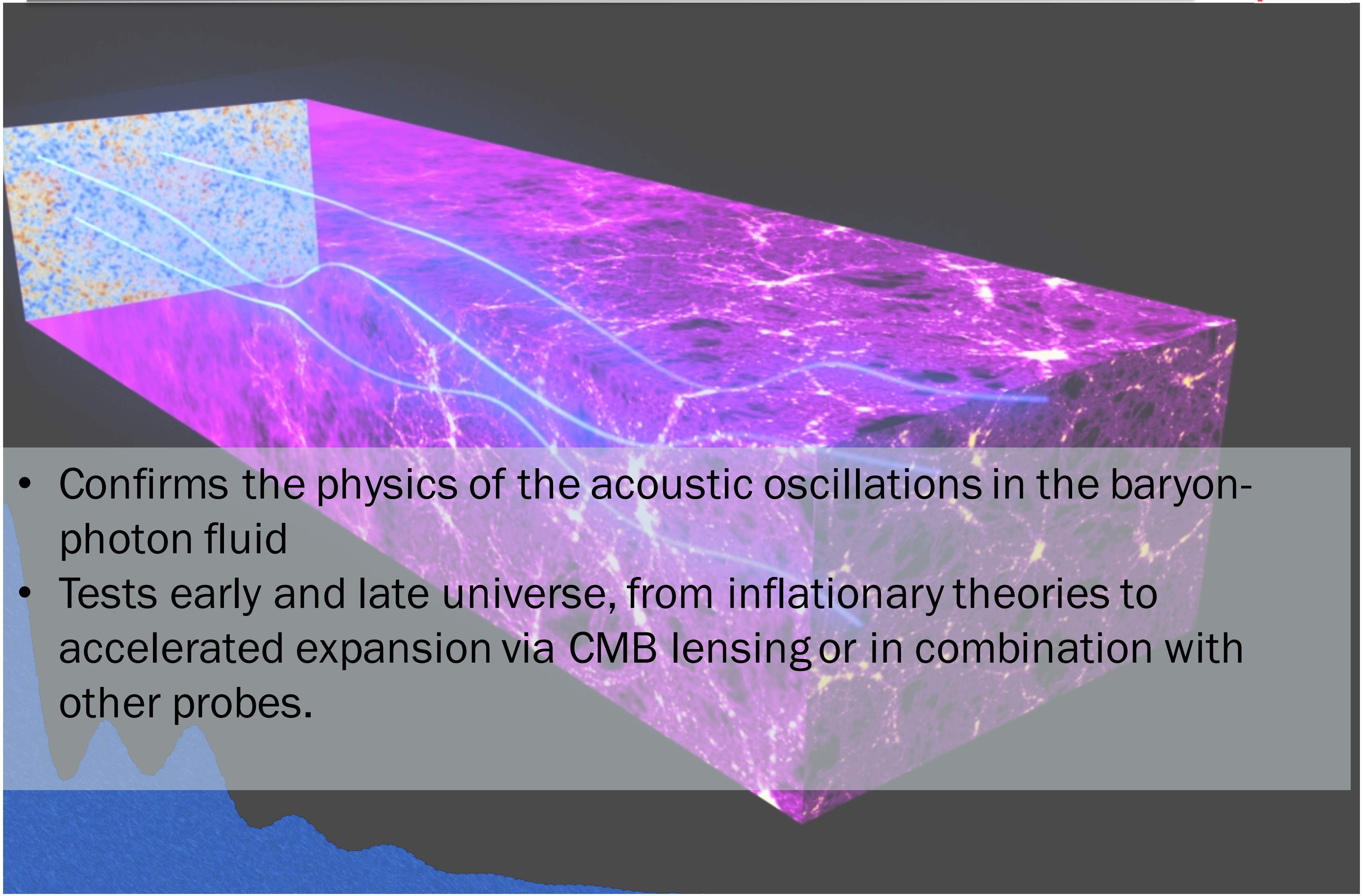


ΛCDM is a very good fit



Quite impressive. From terabytes of data to 6 parameters

Window to the early and late Universe



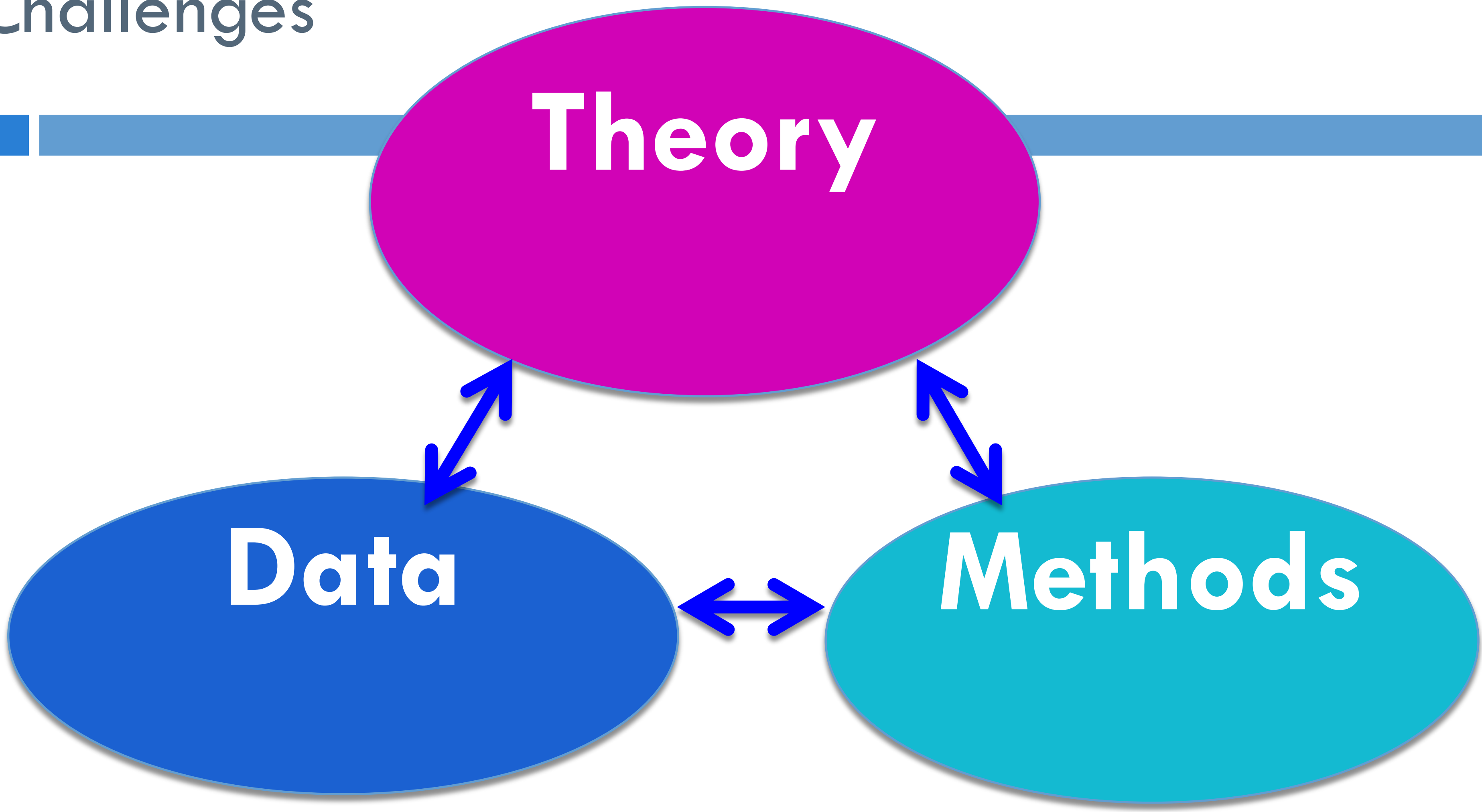
- Confirms the physics of the acoustic oscillations in the baryon-photon fluid
- Tests early and late universe, from inflationary theories to accelerated expansion via CMB lensing or in combination with other probes.

CMB as a probe for DE and MG

Even if the background is very close to LCDM, perturbations can be different.
CMB is a clean probe, important to test DE and MG models.

- Expansion and distance to last scattering
- Gravitational potentials and decay (ISW)
- Lensing potential
- Growth, leading to a mismatch between primordial amplitude and late time measurements of σ_8
- Ratio between odd and even peaks
- Polarization and B modes

Challenges



Theory

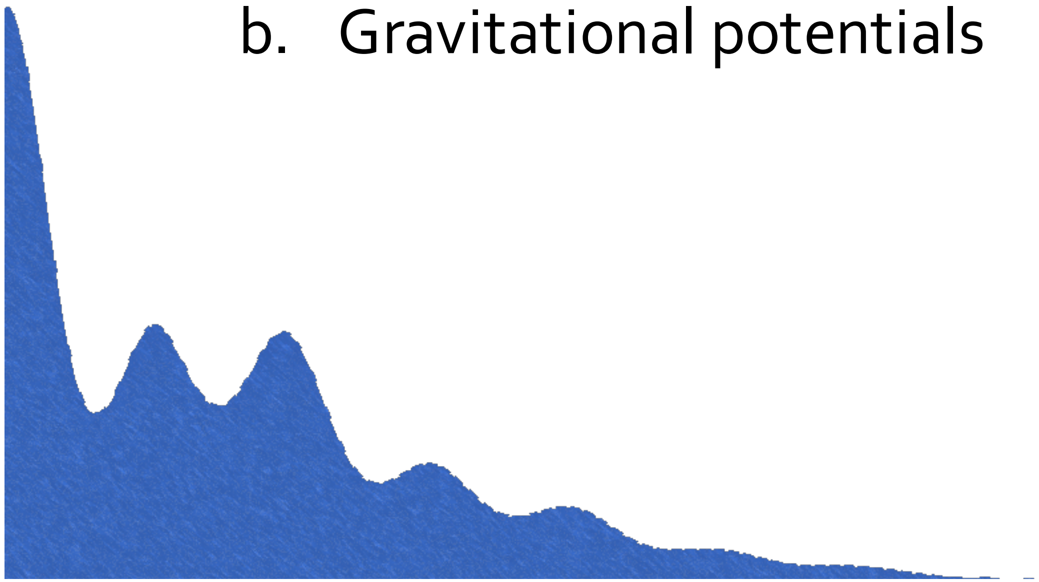
Models and parameterizations

Background parameterizations

a. w expansion and PCA
b. Early Dark Energy
c. Generic potentials

Perturbation parameterizations

a. Effective Field Theory (EFT)
b. Gravitational potentials



Data and probe combination

careful about possible systematics, impact of non-linear physics

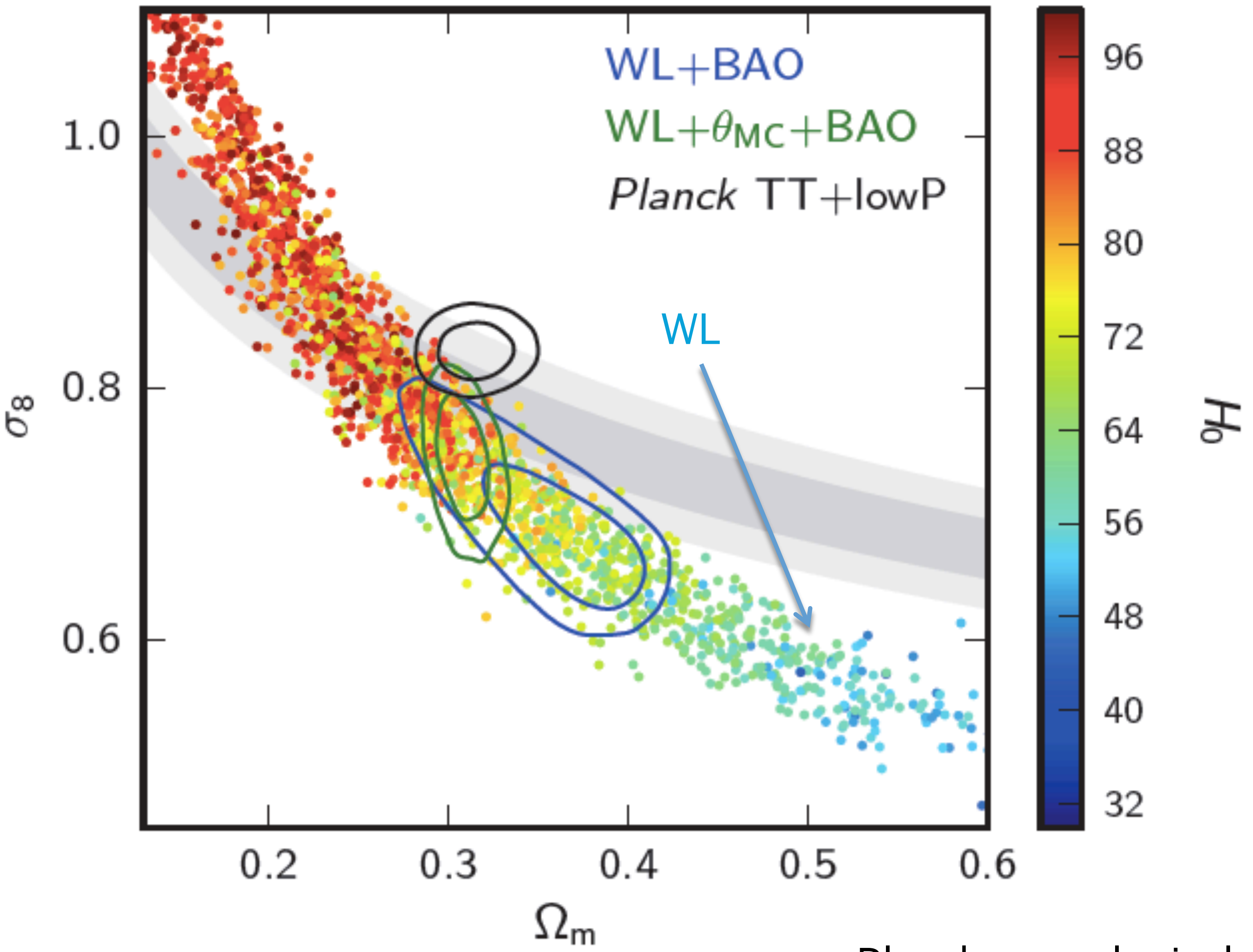
Planck baseline: Planck TT + low-ℓ Polarization

Useful to test the background:
BSH: BAO + SNe + H_0

Planck
Planck + BSH
Planck + WL
Planck + RSD
Planck + WL + RSD

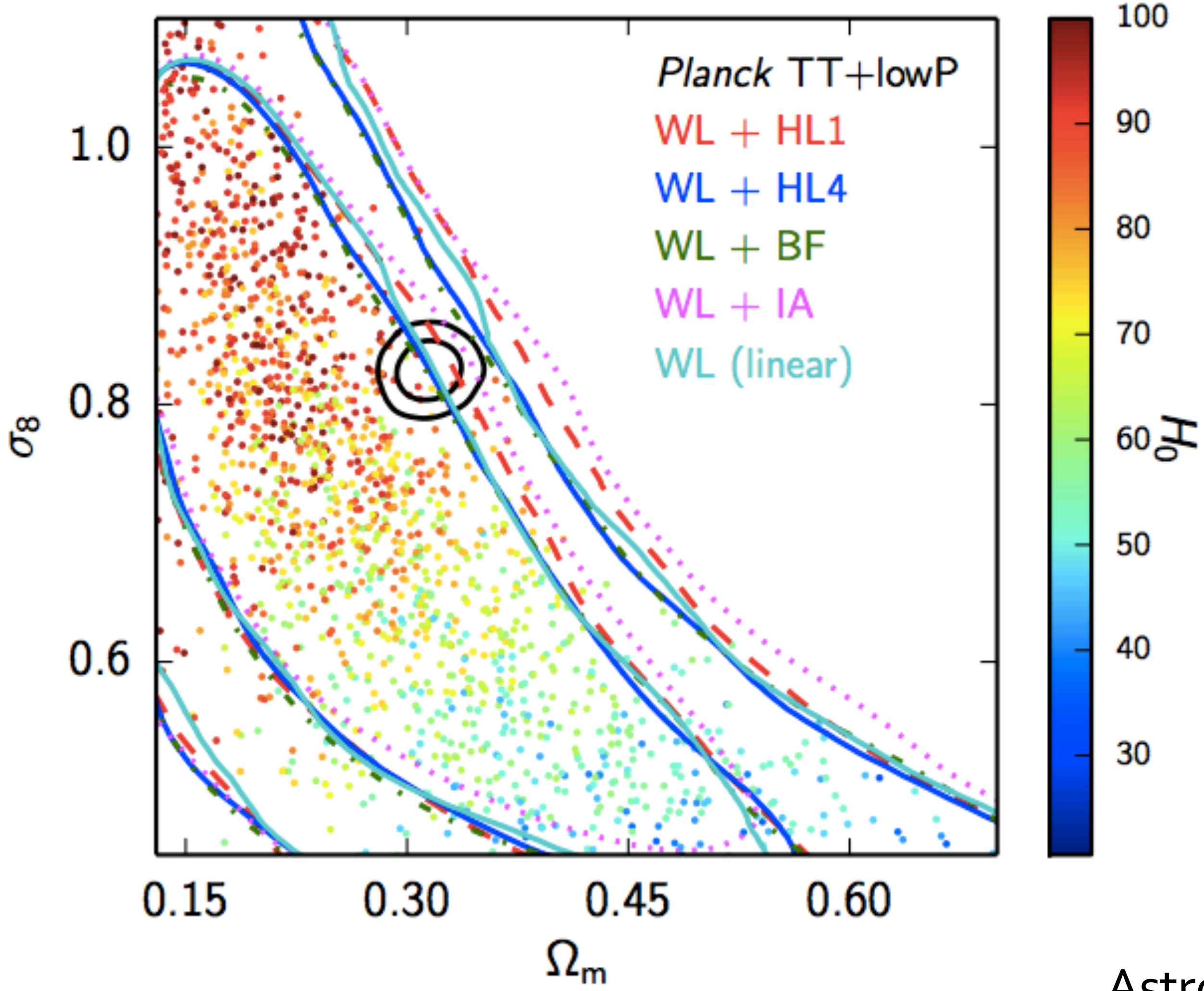
Useful to test perturbations:
RSD: Redshift Space Distortions (BOSS DR11, Samushia etal 2014)
WL: Weak Lensing (CFHTLens, Kilbinger etal 2013, Heymans etal 2013, Kitching etal 2014 + ultraconservative cut of non-linear scales)

Comparing Planck with WL



Planck cosmological parameter paper

Ultra conservative WL



Astro-ph: 1502.01590
DE and MG Planck paper

Methods

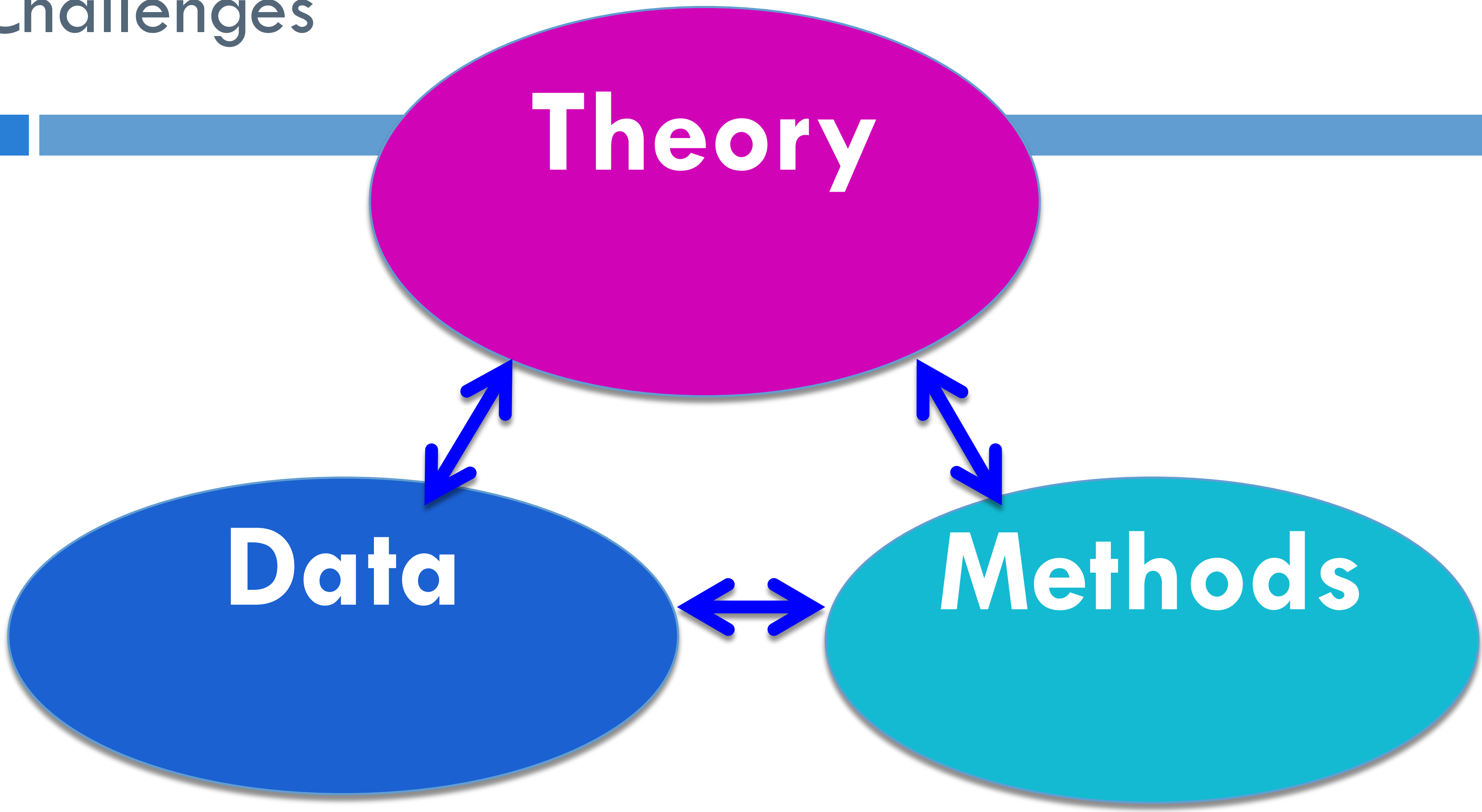
No agreement yet on well tested set of codes in the Dark Energy community

Ultra Conservative cuts (for WL)

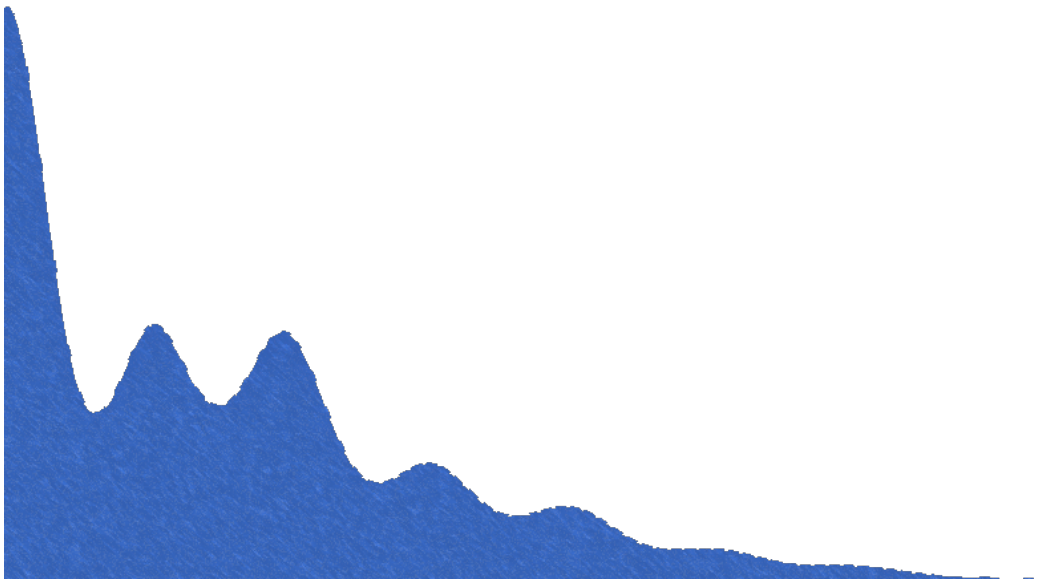
Tested data sets separately to see what drives results

Tested/debugged new MCMC codes for MG (EFTCAMB, MGCAMB and others): pointed out limits of available numerical codes and helped to implement them further; compared results among different codes; tested new codes in different limits (quasi-static and full relativistic approximations).

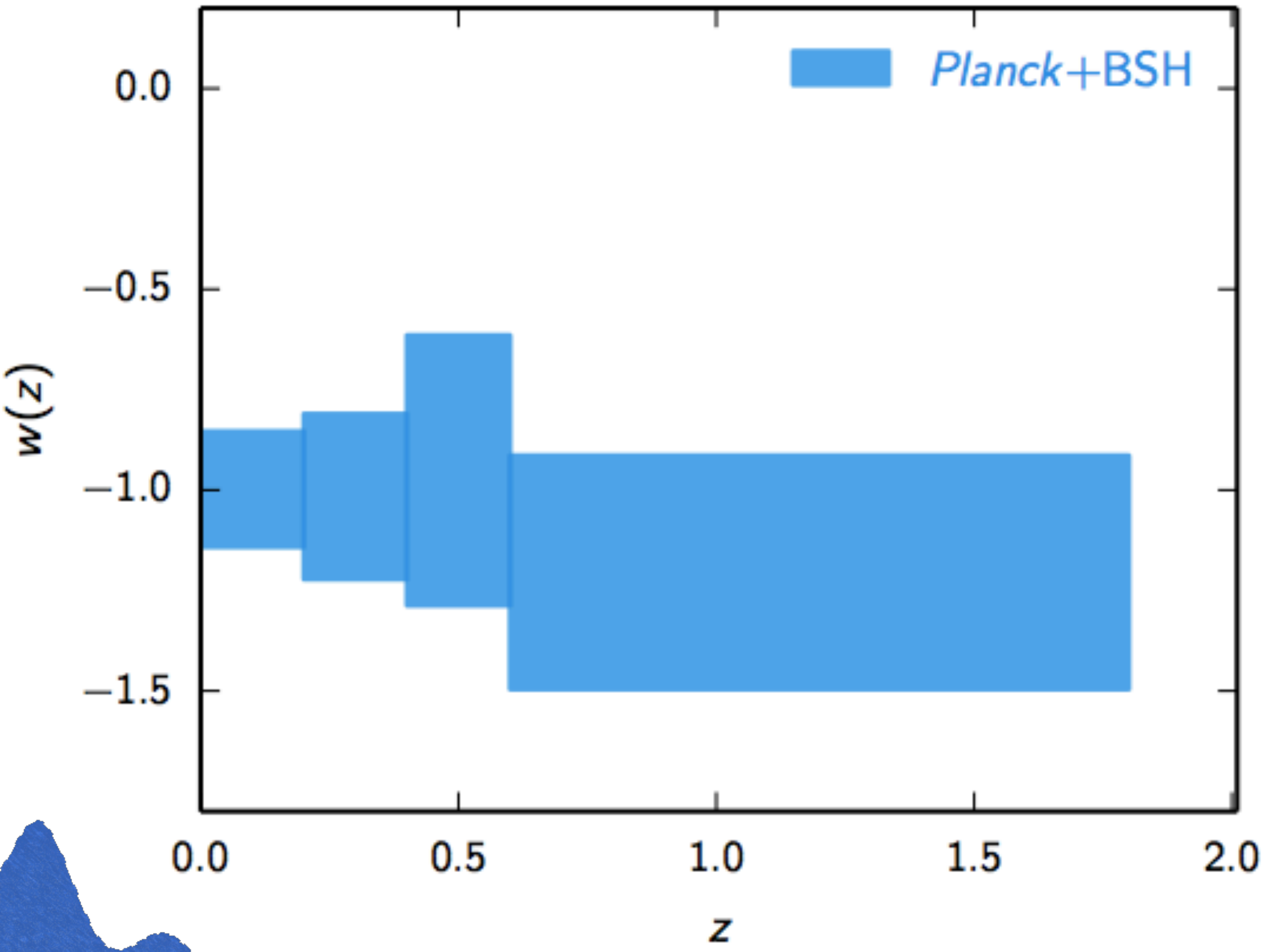
Challenges



Results from Planck

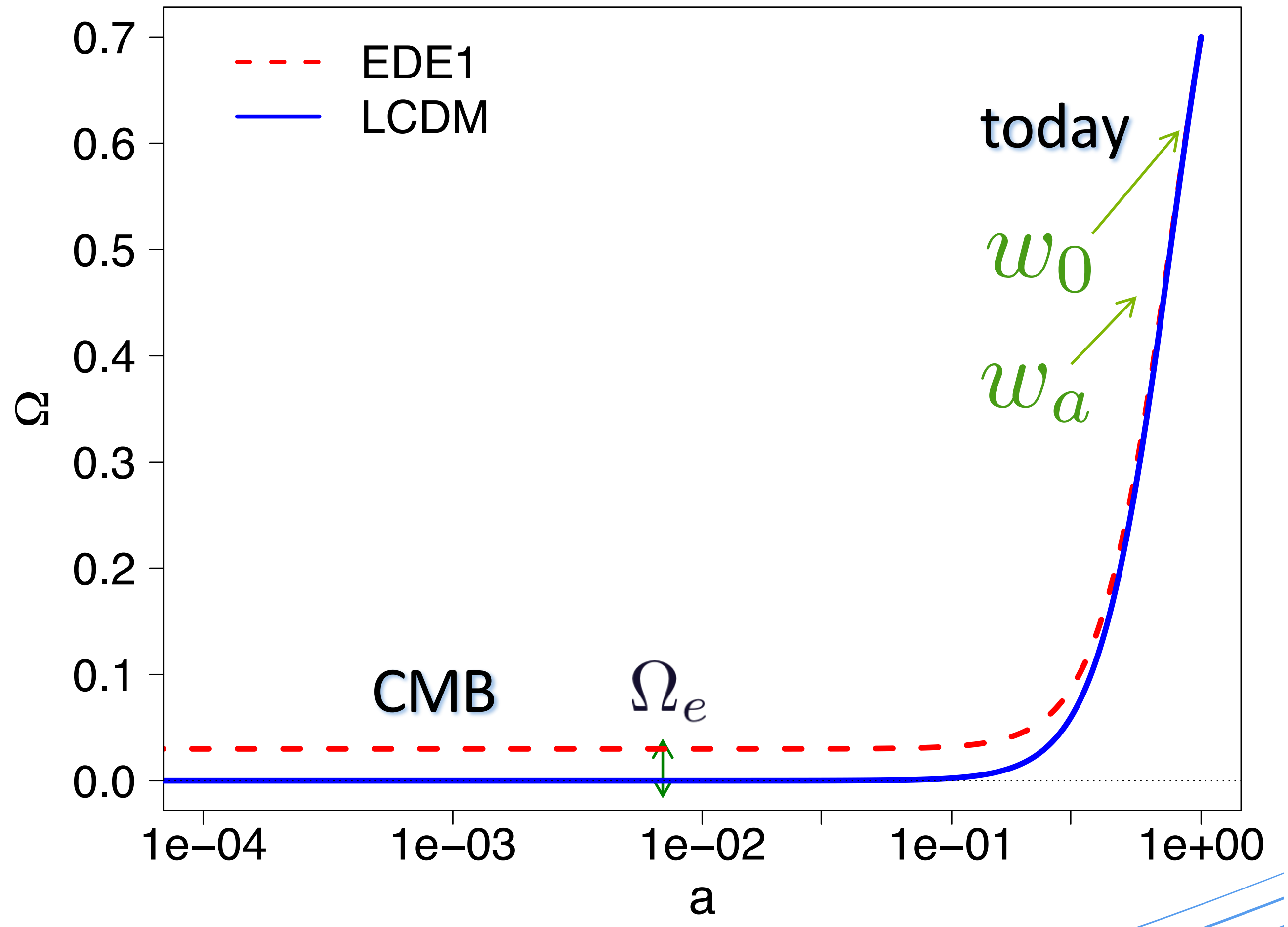


PCA



Early Dark Energy parameterization

Wetterich 2004
Doran & Robbers 2006
Pettorino et al 2013

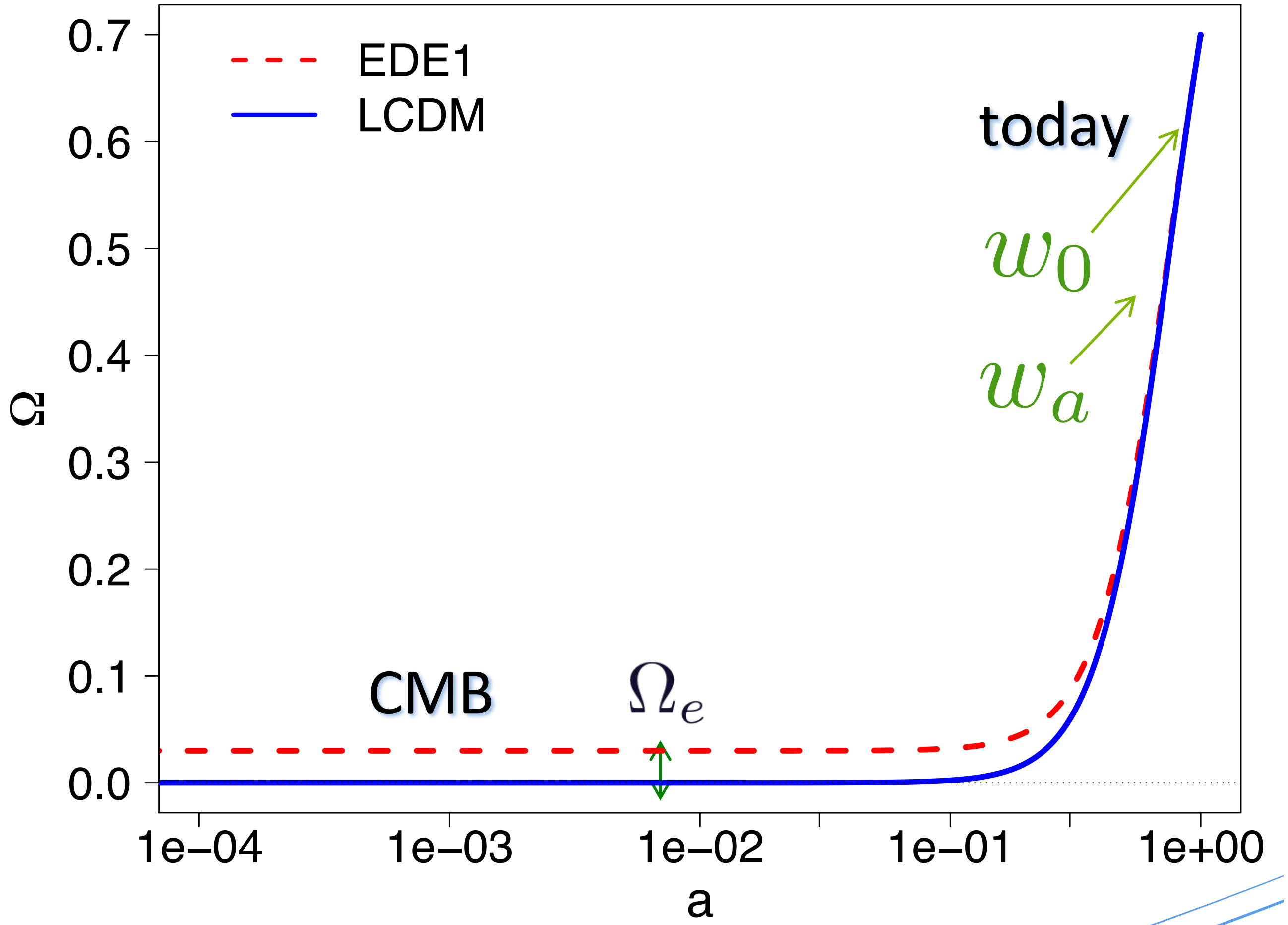


Early Dark Energy parameterization

Wetterich 2004
Doran & Robbers 2006
Pettorino et al 2013

$$\Omega_e \lesssim 0.007$$

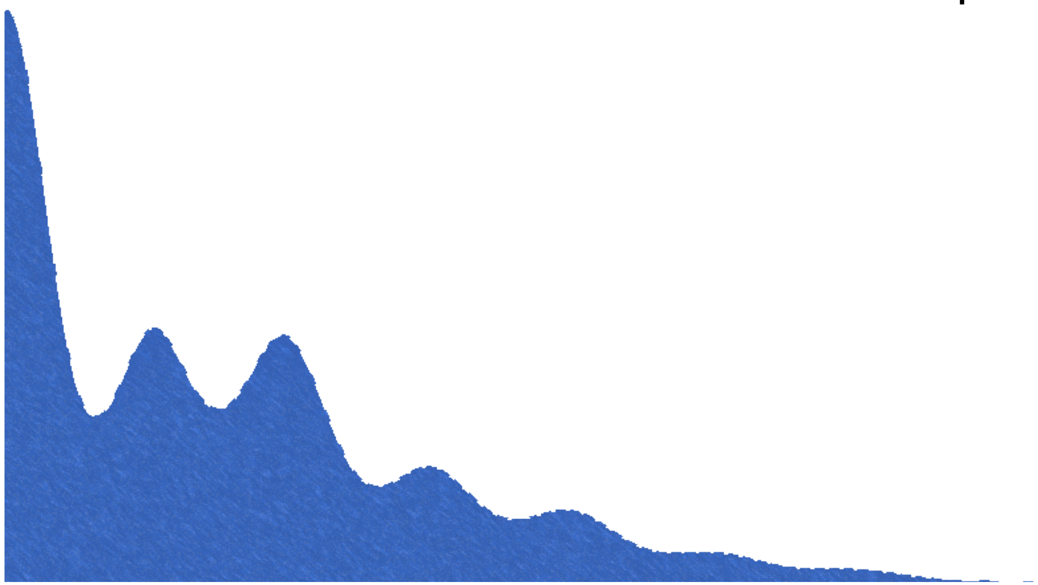
Planck + BSH, 95% C.L.



Modifying perturbations

1. Top down approach → Start from theory and a very generic action

2. Bottom up approach → Start from observations and parameterize two independent functions of the gravitational potentials

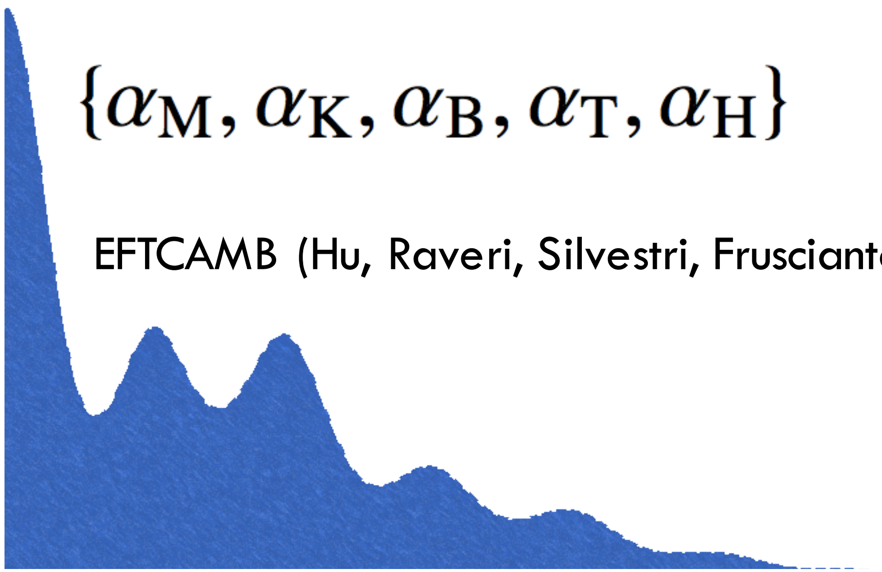


Effective Field Theory & Horndeski

$$
\begin{aligned}
S = \int d^4x\sqrt{-g}\Big\{ &\frac{m_0^2}{2}[1+\Omega(\tau)]R + \Lambda(\tau) - a^2 c(\tau)\delta g^{00} \\
&+ \frac{M_2^4(\tau)}{2}(a^2\delta g^{00})^2 - \bar{M}_1^3(\tau)2a^2\delta g^{00}\delta K^\mu_\mu \\
&- \frac{\bar{M}_2^2(\tau)}{2}(\delta K^\mu_\mu)^2 - \frac{\bar{M}_3^2(\tau)}{2}\delta K^\mu_\nu \delta K^\nu_\mu + \frac{a^2\hat{M}^2(\tau)}{2}\delta g^{00}\delta R^{(3)} \\
&+ m_2^2(\tau)(g^{\mu\nu}+n^\mu n^\nu)\partial_\mu(a^2 g^{00})\partial_\nu(a^2 g^{00})\Big\} + S_m[\chi_i, g_{\mu\nu}].
\end{aligned}
$$

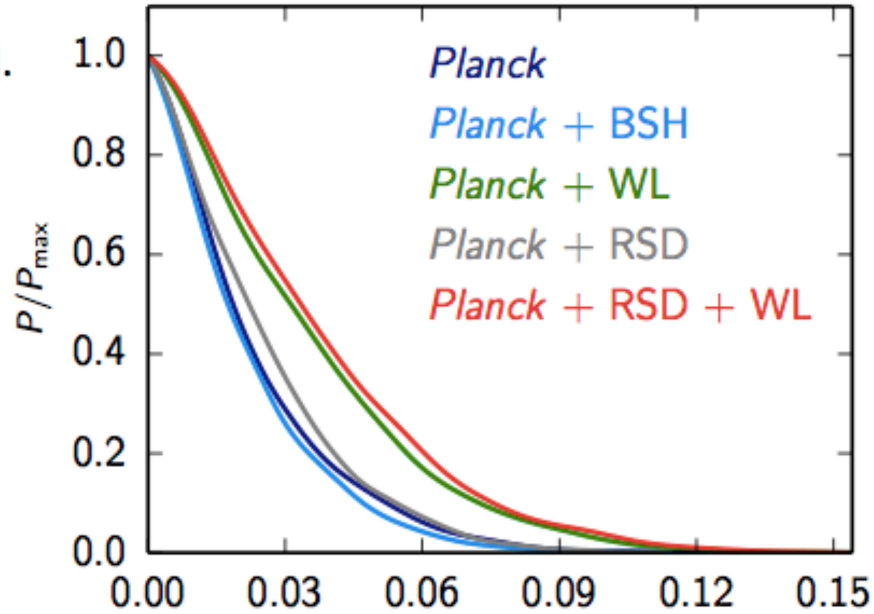
Gubitosi etal 2012

In general there are 9 functions of time that include majority of Modified Gravity models (with both anisotropic stress and generic sound speed)



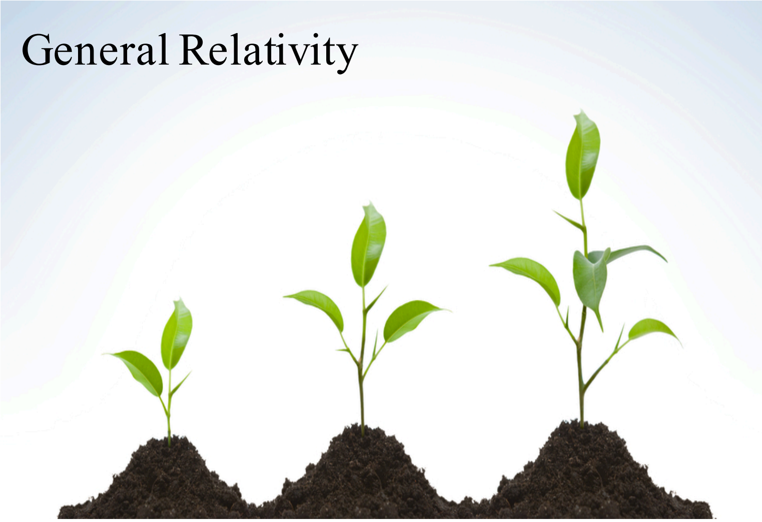
$$\{\alpha_{\mathrm{M}}, \alpha_{\mathrm{K}}, \alpha_{\mathrm{B}}, \alpha_{\mathrm{T}}, \alpha_{\mathrm{H}}\}$$

EFTCAMB (Hu, Raveri, Silvestri, Frusciante 2014)



$$\alpha_{M_0} = \Omega_0$$

Modified Gravity changes the growth of structure



Modified Gravity

Growth ⟷ Density Velocities ⟷ Geometry (gravitational potentials)

$$f \equiv \frac{dln\delta}{dlna}$$

$$\mathrm{d}s^2 = -(1+2\Psi)\mathrm{d}t^2 + a^2(1+2\Phi)\mathrm{d}x^i\mathrm{d}x^i$$

via modifications of the gravitational potentials

Modified Gravity changes the growth of structure

General Relativity

Modified Gravity

Growth ⟷ Density Velocities ⟷ Geometry (gravitational potentials)

(conservation/Euler equation)

$$f\delta = -\frac{\nabla\cdot v}{aH}$$

(Poisson equation)

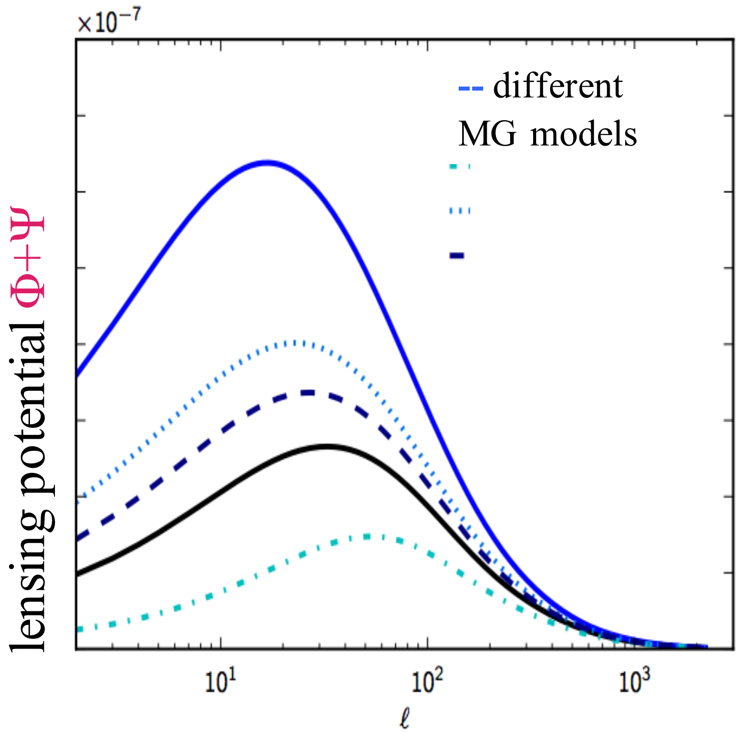
$$-k^2\Psi = 4\pi G a^2 \rho\Delta$$

via modifications of the gravitational potentials

Weak Lensing

The image of the galaxy is related to its true shape via convergence (modifies the size) and shear (distorts the shape)

Weak Lensing is sensitive to changes in the lensing potential $\Phi+\Psi$



Galaxy Clustering and Redshift Space Distortions

$$z_{obs} = Hr + v_{pec}$$

RSD sensitive to changes in Ψ

Parameterizing Modified Gravity

(problem to be set in both approaches)

Parameterizing Modified Gravity

2 functions of the gravitational potentials:

μ modifies the Poisson equation: directly observable

η is the ratio of the gravitational potentials

$$-k^2\Psi(a,k) \equiv 4\pi G a^2 \mu(a,k)\rho(a)\delta(a,k)$$
$$\eta(a,k) \equiv \Phi(a,k)/\Psi(a,k) \ .$$

In alternative:

$$-k^2(\Phi(a,k)+\Psi(a,k)) \equiv 8\pi G a^2 \Sigma(a,k)\rho(a)\delta(a,k)$$

Three different parameterizations

- **Bin the functions in z** and treat their amplitudes as independent parameters

- *Late-time* parameterization

$$\mu(a,k) \equiv 1 + E_{11}\Omega_{\rm DE}(a)$$
$$\eta(a,k) \equiv 1 + E_{22}\Omega_{\rm DE}(a)$$

[Planck DE&MG 2015, Alonso et al 2016, Hojjati et al 2004, Asaba et al 2013]

- *Early-time* parameterization

$$\mu(a,k) \equiv 1 + E_{11} + E_{12}(1-a)$$
$$\eta(a,k) \equiv 1 + E_{21} + E_{22}(1-a)$$

[Planck DE&MG 2015]

Results from Planck

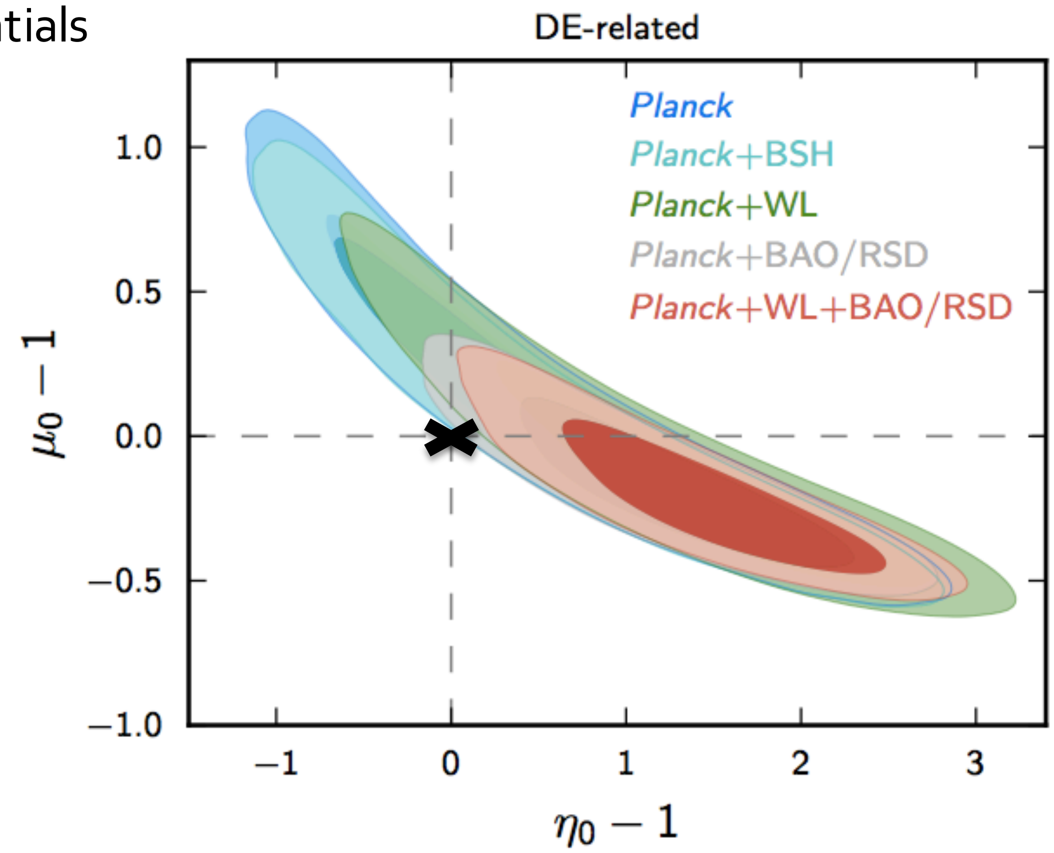
Planck Dark Energy & Modified Gravity paper
Astro-ph 1502.01590 & A&A

μ modifies the Poisson equation

η is the ratio of the gravitational potentials

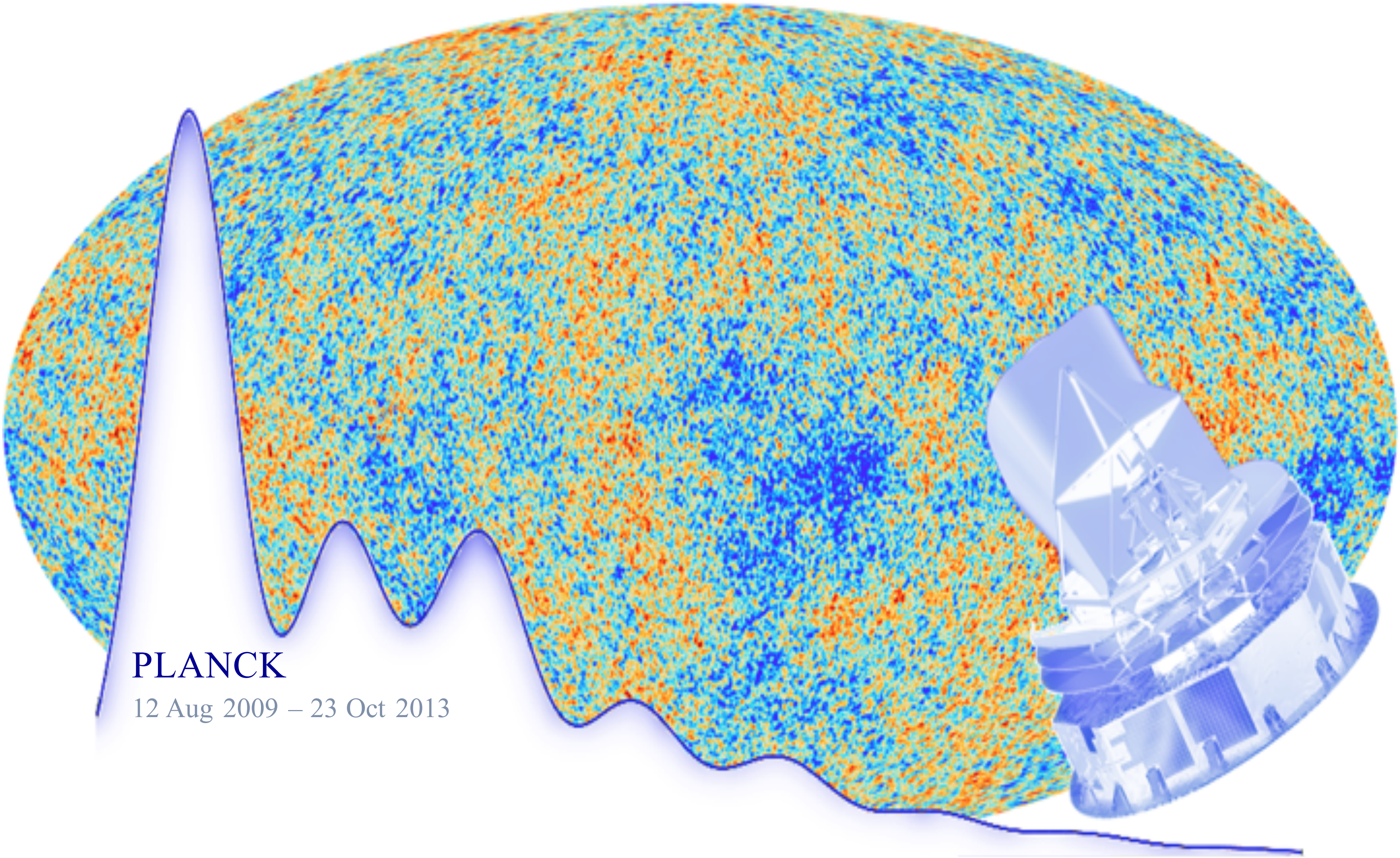
Planck alone lies at the 2 σ limit
Tension with ΛCDM at 3σ when combining RSD+WL

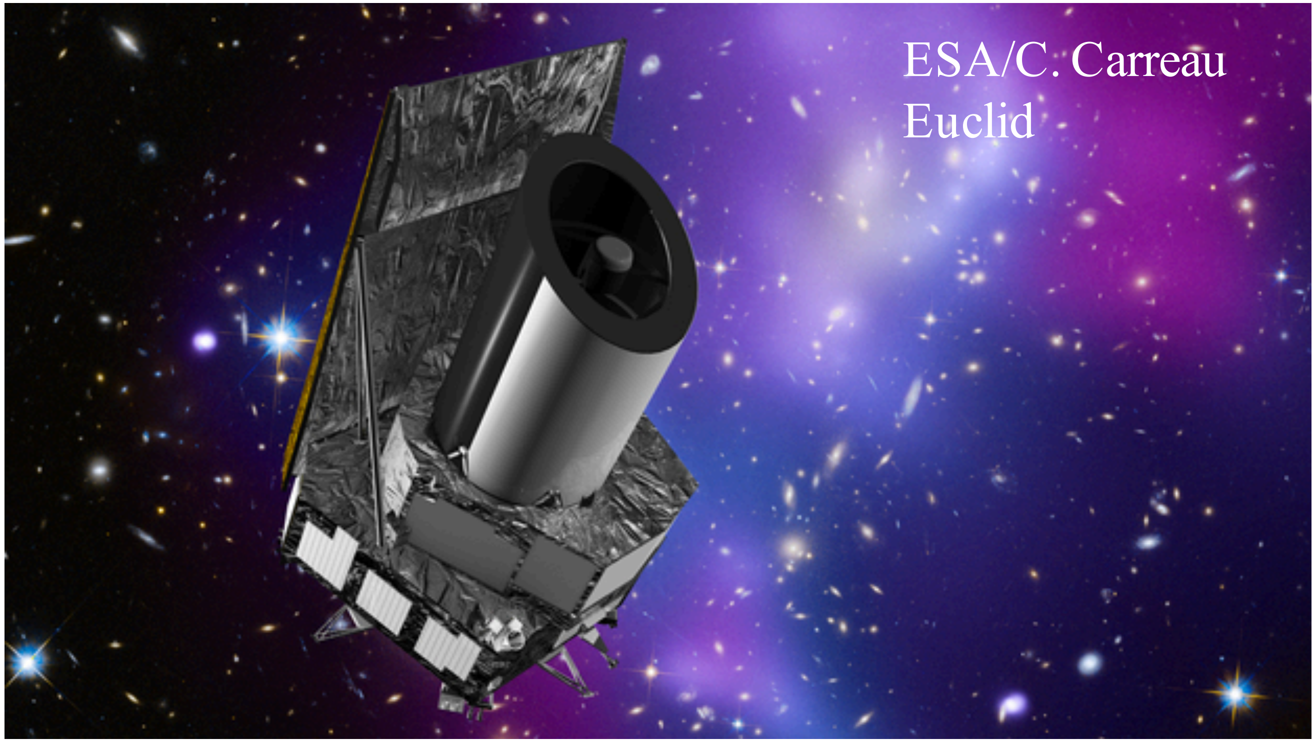
	Planck+WL+RSD (present)
μ	~ 17%
η	~ 25%



Future surveys

The Planck satellite agrees with this picture, but also reveals tensions with respect to late time probes

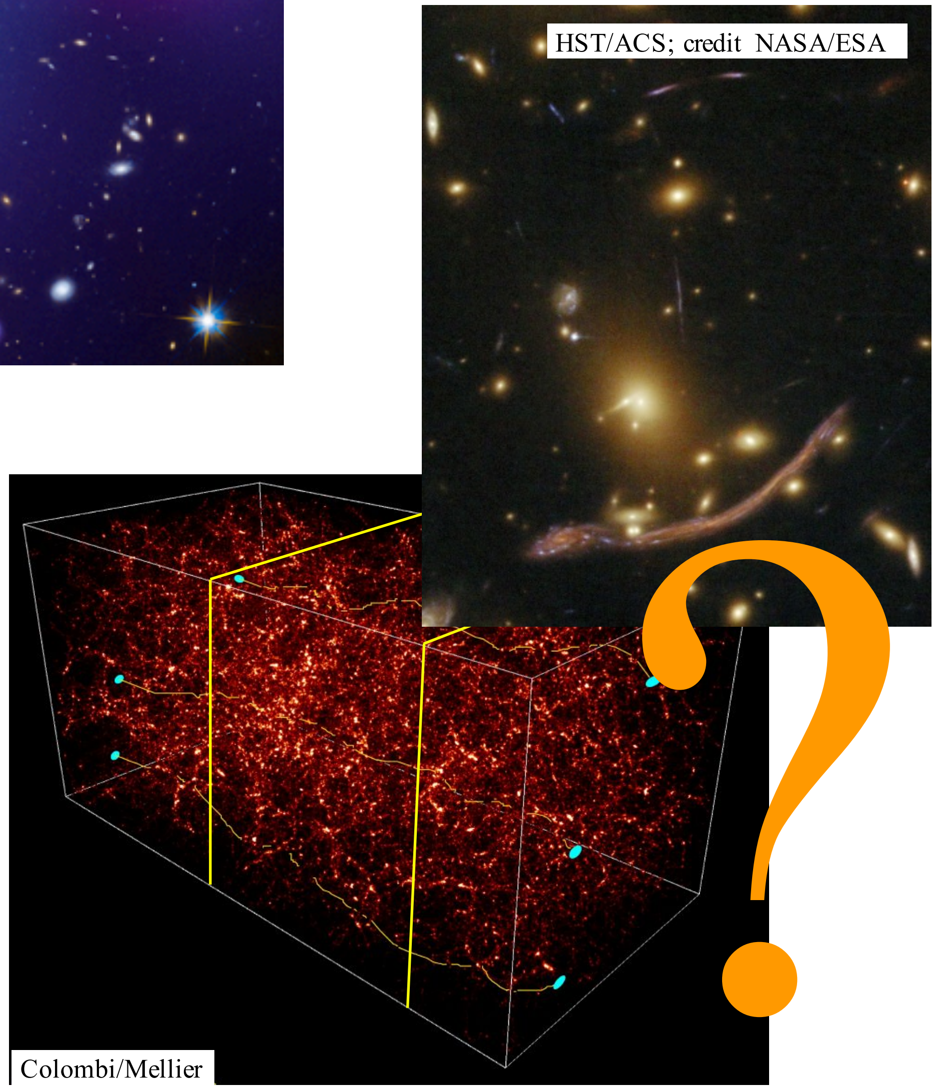




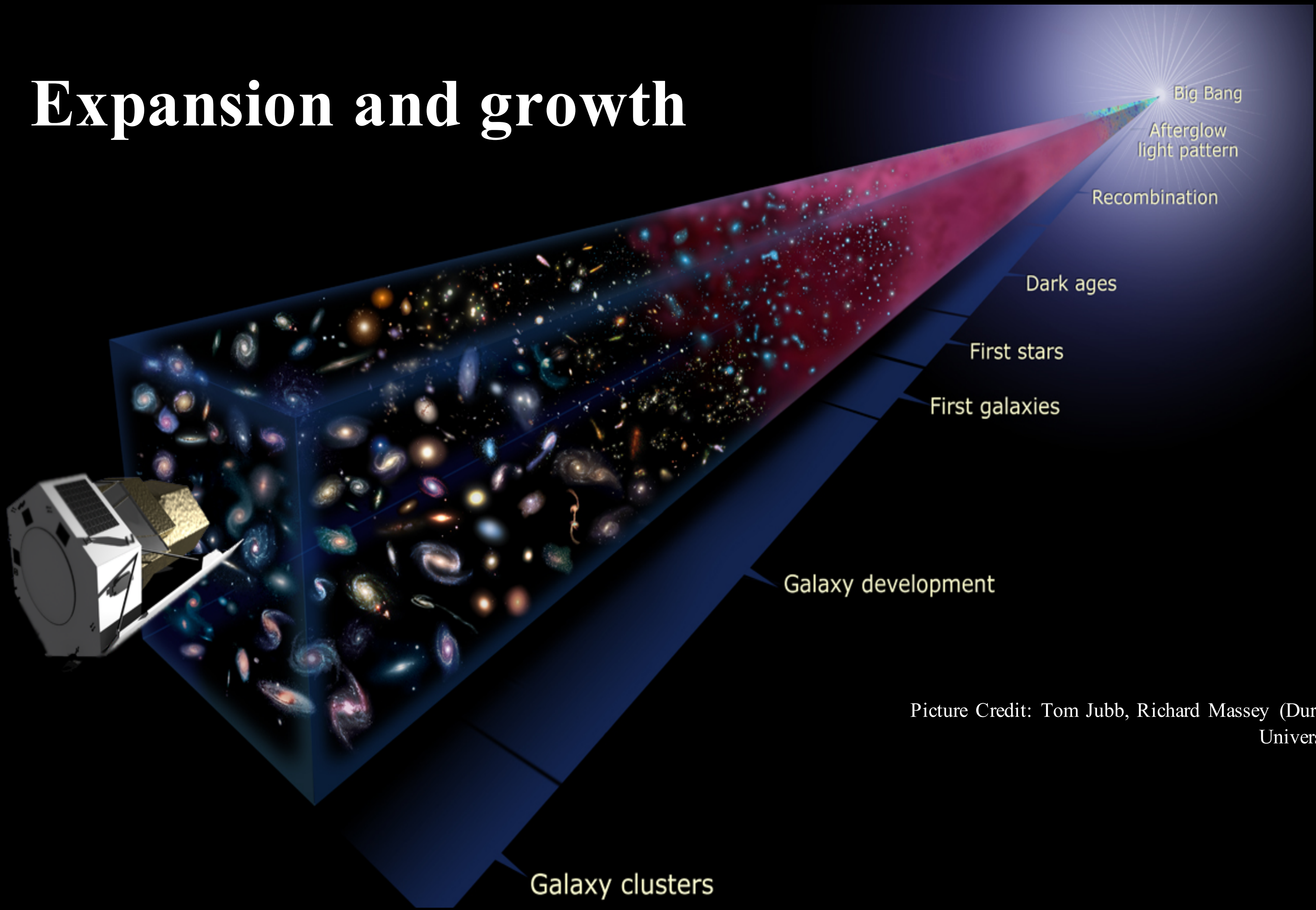
New generation of experiments

using different probes scanning the sky in slices

to disprove the standard picture

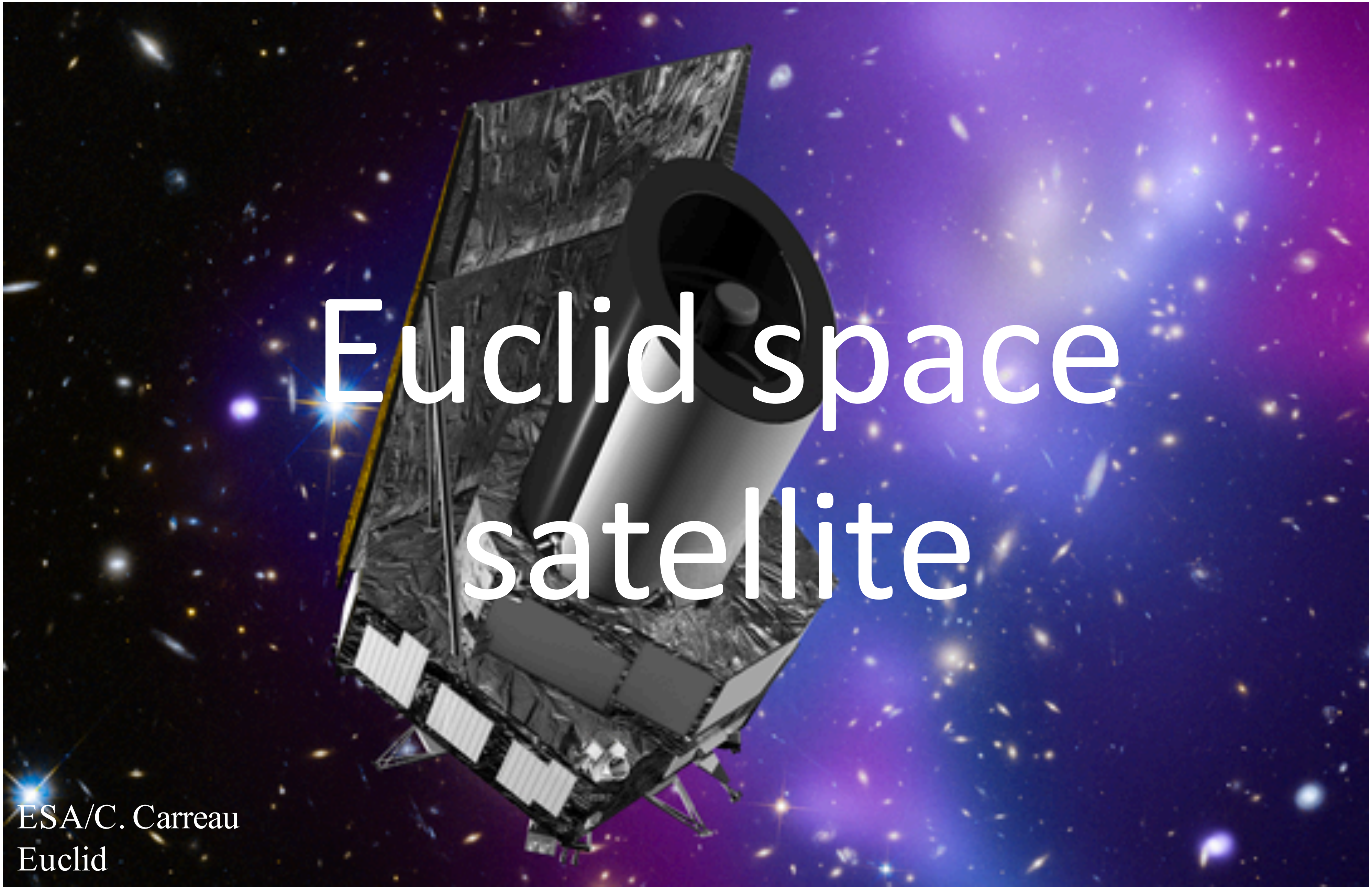


Expansion and growth



Picture Credit: Tom Jubb, Richard Massey (Durham University)

Observations of both expansion H(z) and the growth function f(z) can constrain the gravitational theory


Euclid space
satellite
ESA/C. Carreau
Euclid

Surveys

1.2 m telescope

WIDE SURVEY

will cover about 1/3 of the entire sky outside the Galactic plane (15000 deg^2); it will achieve galaxy shear measurements for 30-40 galaxies/arcmin^2 and spectroscopic measurements for 3500-5000 galaxies/deg^2 with redshift accuracy of $z < 0.001(1+z)$

DEEP SURVEY

will be 2 magnitudes deeper than the Wide Survey, cover nearly 40 deg^2 in patches greater than 10 deg^2

IMAGING

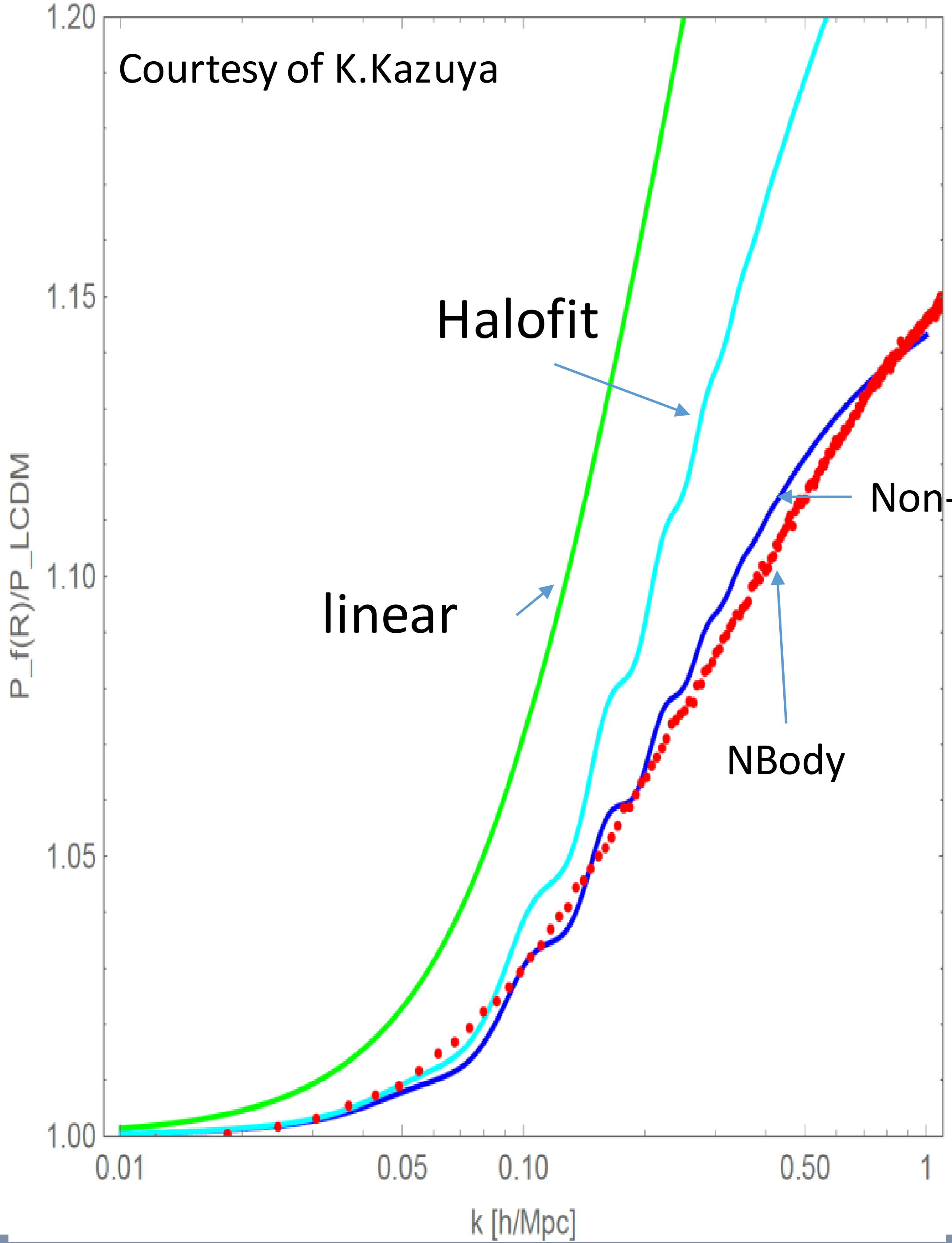
Measure shapes and distances (photometric redshift) of 2 billions galaxies to see the distribution of dark matter through weak lensing tomography

SPECTROSCOPY

Slitless spectrometer measures the tridimentional distribution of galaxies as a function of time, measuring 50 millions of redshifts.

Picture Credit: Tom Jubb, Richard Massey (Durham University)

Non-linear scales



$$P(k,z) = \frac{P_{\mathrm{non-GR}}(k,z) + c_{\mathrm{nl}}\Sigma^2(k,z)P_{\mathrm{GR}}(k,z)}{1 + c_{\mathrm{nl}}\Sigma^2(k,z)}$$

$$\Sigma^2(k,z) = \left(\frac{k^3}{2\pi^2}P_{\mathrm{lin}}(k,z)\right)^{1/3}$$

Casas et al, arXiv:1703.01271v1

Kazuya Koyama et al 2009
Phys.Rev. D79 (2009) 123512
arXiv:0902.0618

For a specific f(R) model

Forecasts

Methodology

Fisher Matrix analysis to derive predictions on cosmological parameters.

Likelihood assumed to be a Gaussian function of parameters (and data)

$$\mathcal{L}(\boldsymbol{\theta}) \propto \exp -\frac{1}{2}\sum_{ij}\theta_i F_{ij}\theta_j$$

$$F_{ij} = \left\langle -\frac{\partial^2 \log \mathcal{L}(\mathbf{X}_\mu/\boldsymbol{\theta})}{\partial\theta_i\partial\theta_j} \right\rangle$$

θ_i cosmological parameters

X_μ observables

$$\boxed{F_{ij} = -\sum_k \frac{1}{\sigma_k^2}\frac{\partial^2 \hat{x}_k(\boldsymbol{\theta})}{\partial\theta_i\partial\theta_j}\bigg|_{\boldsymbol{\theta}=\hat{\boldsymbol{\theta}}}}$$

Errors on observables (in future experiments) -> estimate errors on parameters

Figure of Merit and Figure of Correlation

FoM: figure of merit

C covariance matrix = 1/F

- Stronger constraints -> higher FoM

$$\mathrm{FoM} = -\frac{1}{2}\ln(\det(\mathbf{C}))$$

FoC: figure of correlation

P correlation matrix

The larger -> the more correlated

- If the parameters are independent, fully decorrelated P=1 -> FoC = 0

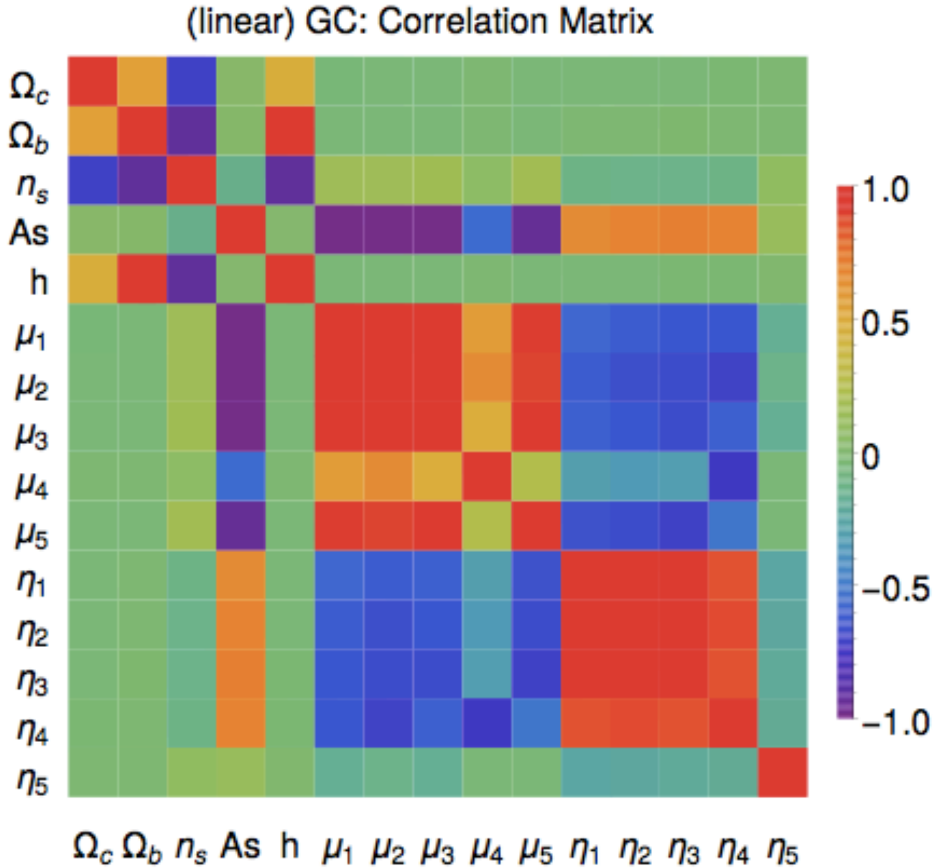
$$\mathrm{FoC} = -\frac{1}{2}\ln(\det(\mathbf{P}))$$

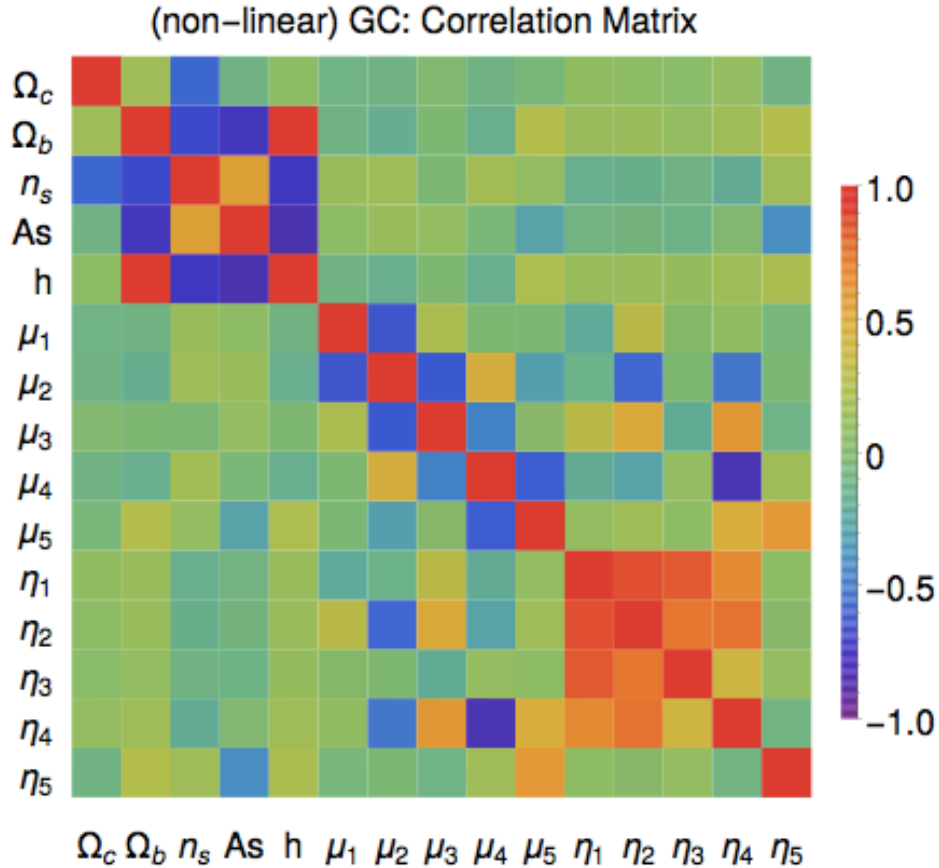
$$P_{ij} = \frac{C_{ij}}{\sqrt{C_{ii}C_{jj}}}$$

Surveys

- **Euclid** (2020, space satellite): WL & GC, 15000 deg2, z < 2
- **SKA**: radiotelescope, WL & GC,
- 1st phase: SKA1-SUR Australia; SKA1-MID South Africa (ending in 2023, 5000 deg2, z < 0.8)
- 2nd phase: SKA2
- (x10 sensitive, 2030, 30000 deg2, z < 2.5)
- **DESI** (stage IV): 2018, 14000 deg2, z < 1 (LRG), only GC

Non-linearities reduce correlation





FoC = 65

FoC = 32

As correlated to MG parameters only in the linear case

Results

Euclid (Redbook)	$\ell\mathcal{A}_s$	μ_1	μ_2	μ_3	μ_4	μ_5	η_1	η_2	η_3	η_4	η_5	MG FoM
Fiducial	3.057	1.108	1.027	0.973	0.952	0.962	1.135	1.160	1.219	1.226	1.164	relative
GC (lin)	160%	119%	159%	183%	450%	1470%	509%	570%	586%	728%	3390%	0
GC (nl-HS)	0.8%	7.0%	6.7%	10.9%	27.4%	41.1%	20%	24.3%	19.9%	38.2%	930%	19
WL (lin)	640%	165%	2210%	4150%	13100%	22500%	2840%	3140%	8020%	29300%	39000%	-27
WL (nl-HS)	7.3%	188%	255%	419%	222%	206%	330%	488%	775%	8300%	9380%	-10
GC+WL (lin)	11.3%	5.8%	10%	19.2%	282%	469%	7.9%	9.6%	16.1%	276%	2520%	12
GC+WL+*Planck* (lin)	1.1%	3.4%	4.8%	7.8%	9.3%	13.1%	6.2%	7.7%	9.1%	12.7%	23.6%	27
GC+WL (nl-HS)	0.8%	2.2%	3.3%	8.2%	24.8%	34.1%	3.6%	5.1%	8.1%	25.4%	812%	24
GC+WL+*Planck* (nl-HS)	0.3%	1.8%	2.5%	5.8%	7.8%	10.3%	3.2%	4.1%	5.9%	9.6%	19.5%	33
GC+WL+*Planck* (nl-Halofit)	0.4%	2.0%	2.4%	5.1%	7.4%	10.2%	3.5%	4.1%	5.8%	9.2%	18.9%	33

Considerable improvement, in both GC and WL, when Planck or non-linearities are included

Constraints on Sigma are better for WL

Zero-Phase Component Analysis (ZCA)

- Decorrelate parameters: apply a transformation matrix W to original vector of parameters p:
  q = Wp such that correlation matrix of q is diagonal.

- ZCA minimizes the squared norm of the difference between the qi and the pi vector: q will be as close as possible to the original variables p

Zero-Phase Component Analysis (ZCA)

Identify those combinations of parameters which are best constrained by data

Linear case (GC)

$$q_1 = +0.9\ell\mathcal{A}_s + 0.32\mu_4$$
$$q_3 = +0.75\mu_2 - 0.29\eta_1 + 0.50\eta_2$$
$$q_4 = -0.25\mu_2 + 0.74\mu_3 - 0.32\eta_2 + 0.49\eta_3$$
$$q_2 = +0.70\mu_1 - 0.30\mu_2 + 0.52\eta_1 - 0.36\eta_2$$

Non-linear case (GC)

$$q_1 = +0.99\ell\mathcal{A}_s$$
$$q_4 = -0.28\mu_2 + 0.76\mu_3 - 0.33\eta_2 + 0.47\eta_3$$
$$q_3 = +0.73\mu_2 - 0.32\eta_1 + 0.49\eta_2$$
$$q_2 = +0.68\mu_1 - 0.35\mu_2 + 0.52\eta_1 - 0.37\eta_2$$

a survey like Euclid, using GC only, will be sensitive to Modified Gravity parameters μ and η mainly in the first three redshift bins,

corresponding to a range $0. < z < 1.5$

Zero-Phase Component Analysis (ZCA)

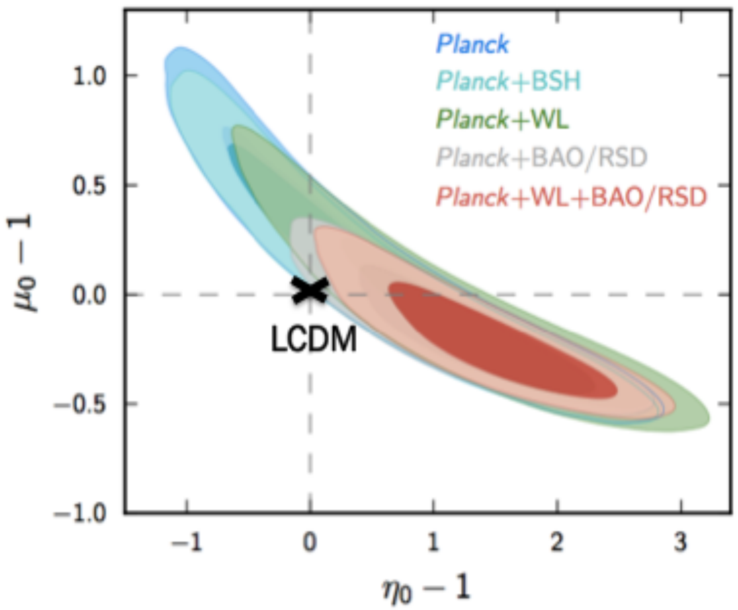
Identify those combinations of parameters which are best constrained by data

GC+WL+Planck

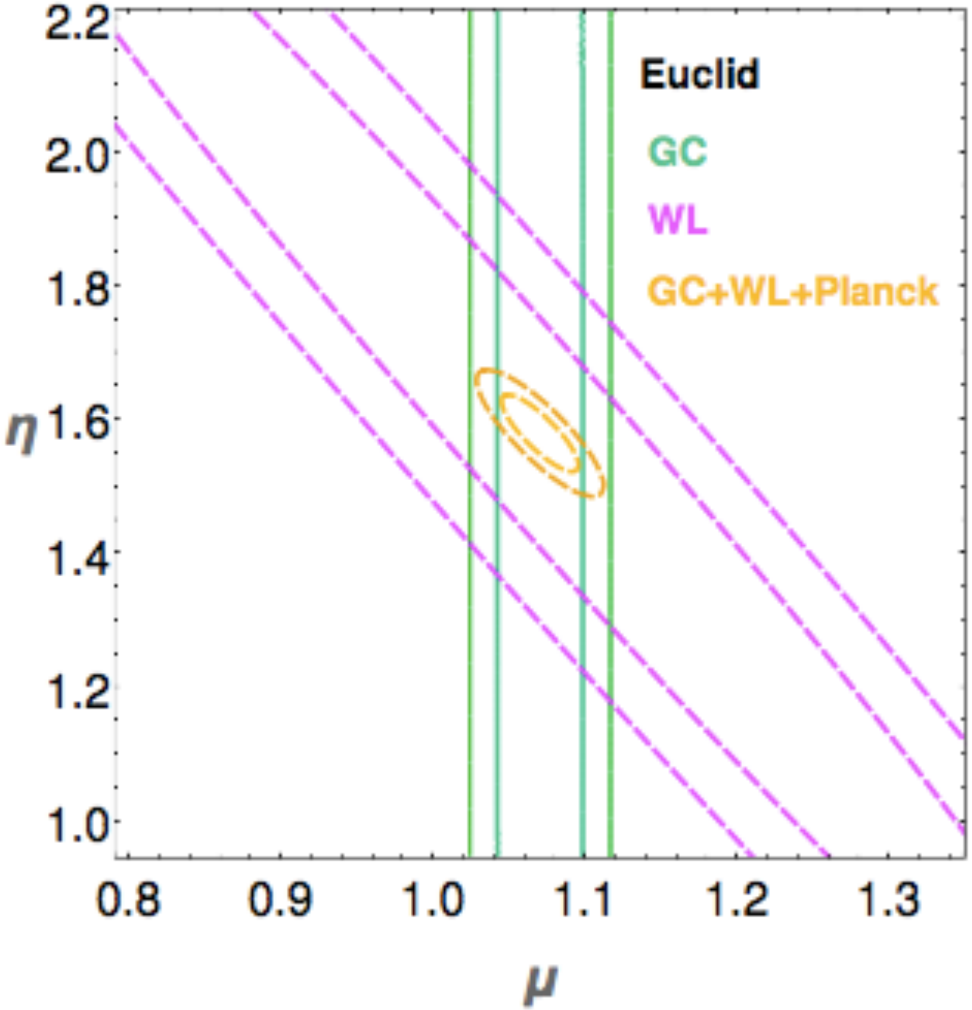
$$q_1 = +0.93\ell\mathcal{A}_s$$
$$q_2 = +0.84\mu_1 + 0.48\eta_1$$
$$q_3 = +0.80\mu_2 - 0.26\eta_1 + 0.45\eta_2$$
$$q_4 = +0.28\ell\mathcal{A}_s + 0.79\mu_3 - 0.29\eta_2 + 0.39\eta_3$$

Effectively the degeneracy line explored in DE&MG paper

Planck paper

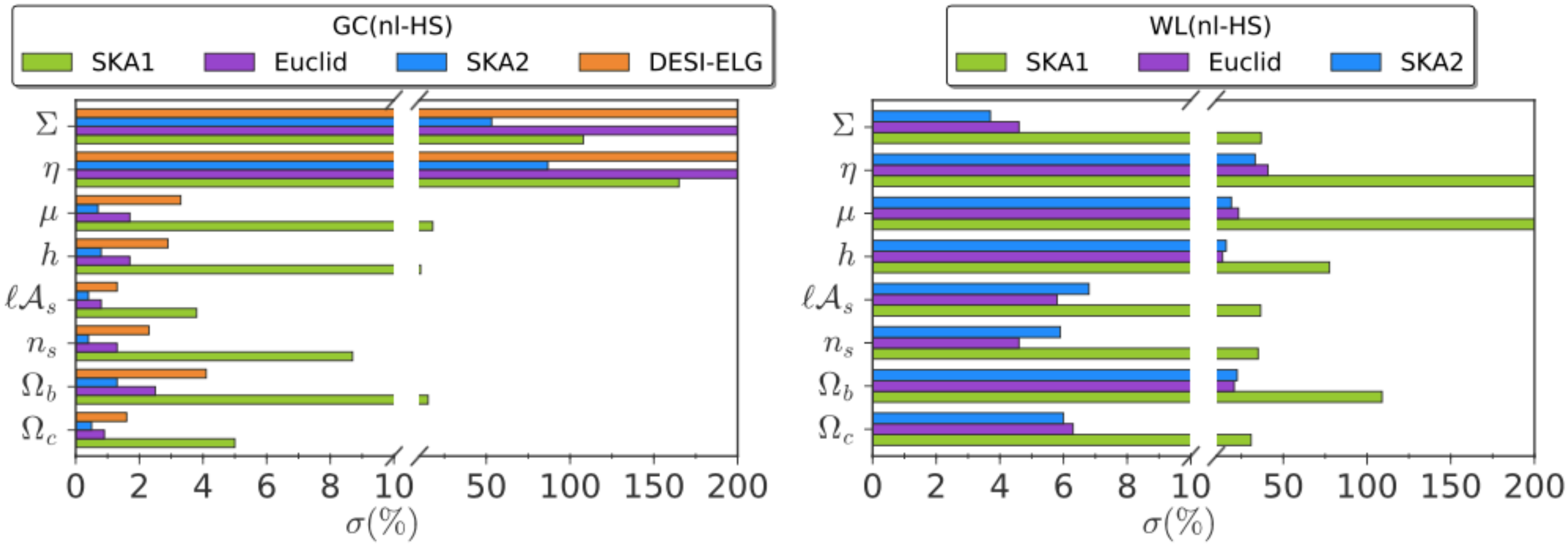


Combining GC and WL breaks degeneracies



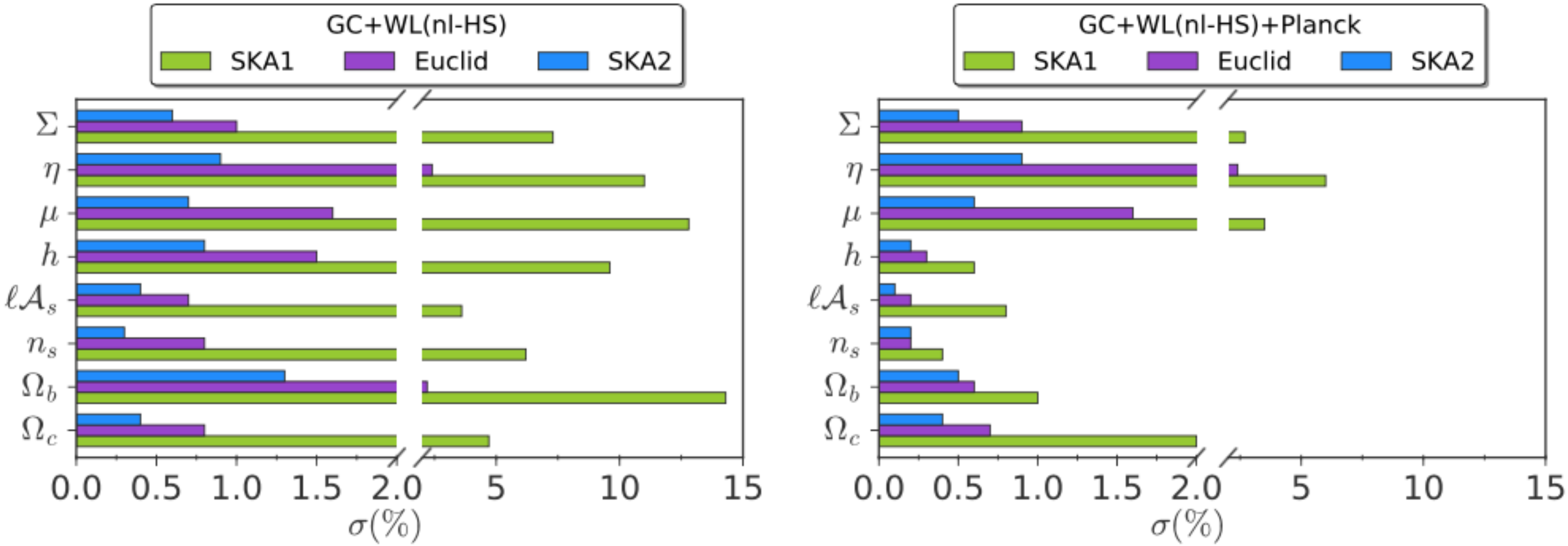
Smaller if you combine GC+WL+Planck

Different surveys



- On the standard parameters GC performs better than WL
- However, WL surveys perform better on MG parameters
- Euclid and SKA2 perform similarly well for the WL observable alone, if non-linearities are included

Different surveys (non-linear)



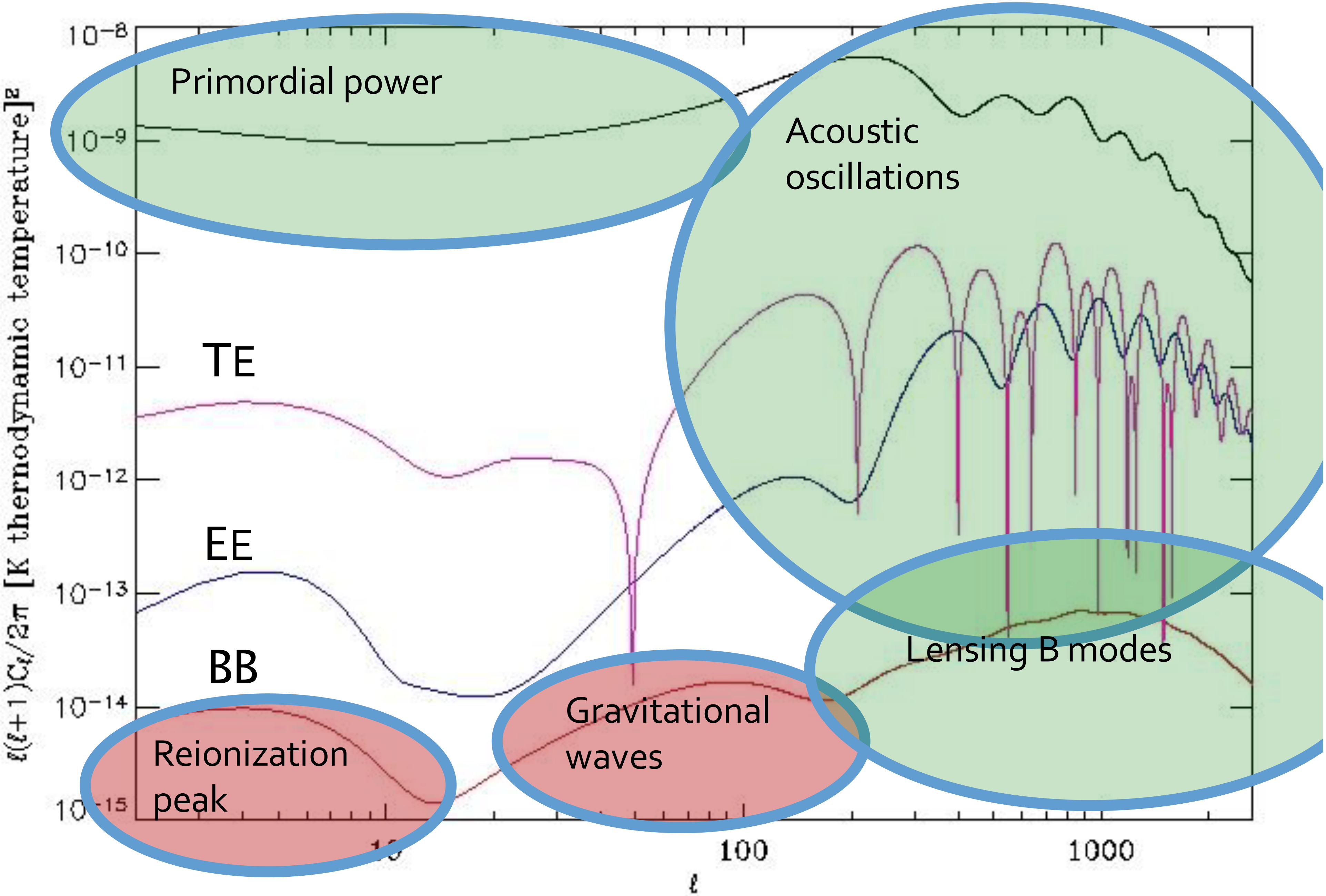
Uncertainties in the non-linear prescription

Remarkably, **the combination of GC and WL is still able to constrain all Modified Gravity parameters at the level of 1-2 % after marginalizing over the non-linear parameters**.

Euclid (Redbook)	Ω_c	Ω_b	n_s	$\ell\mathcal{A}_s$	h	μ	η	Σ	$c_{\rm nl}$	s	MG FoM
Fiducial	0.254	0.048	0.969	3.060	0.682	1.042	1.719	1.416	1	1	relative
GC(nl-HS)	1.0%	2.8%	1.3%	1.1%	2.0%	1.7%	784%	480%	372%	236%	2.4
WL(nl-HS)	6.5%	25%	8.3%	9.1%	19%	25%	46%	6.0%	1680%	899%	4.2
GC+WL(nl-HS)	1%	2.8%	1.2%	1%	1.9%	1.6%	2.6%	1.2%	333%	166%	8.5

Polarization and B-modes as a new test for Modified Gravity

Observed and not observed.



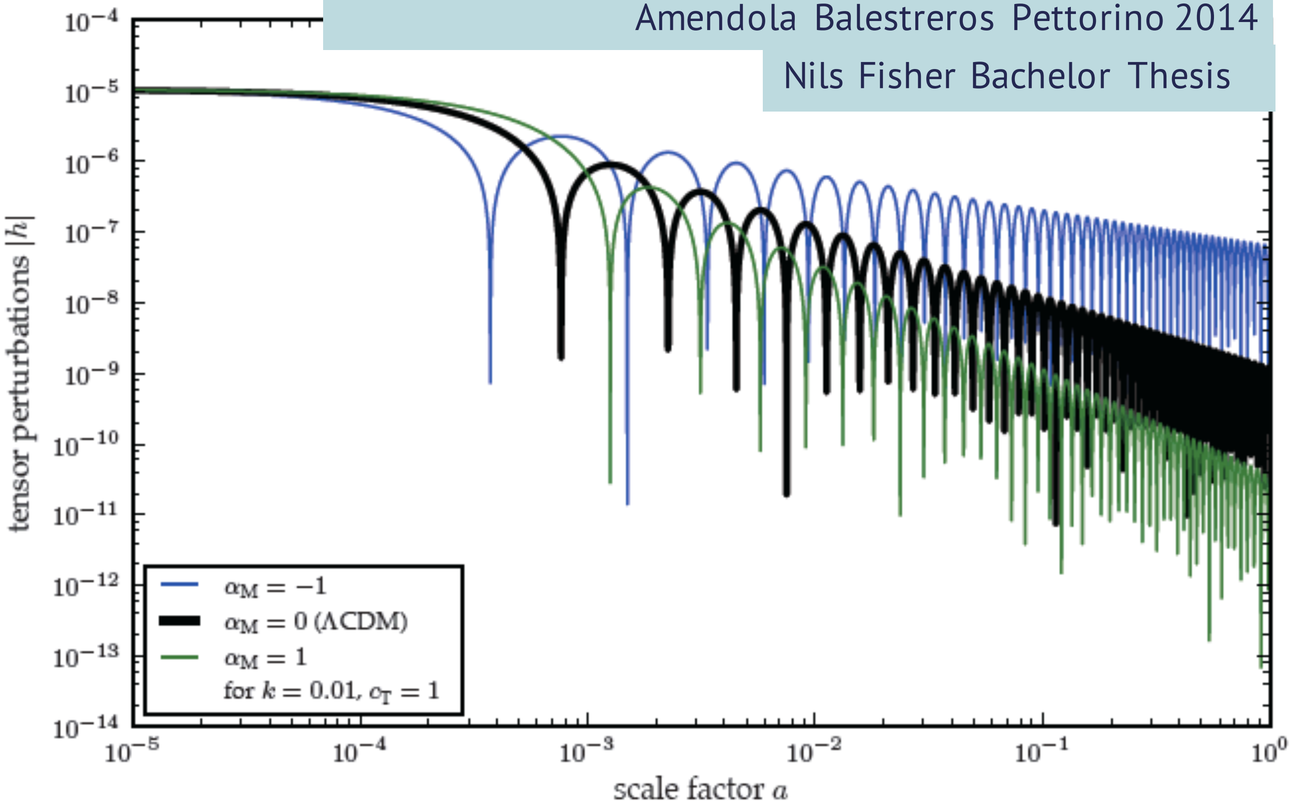
Tensor modes as a future probe for MG

Modified Gravity generically affects the anisotropic stress.
The tensor equation is modified in two ways:

- friction term
- speed of gravitational waves

$$\ddot{h} + (3 + \alpha_M) H \dot{h} + c_T^2 \frac{k^2}{a^2} h = 0$$

Pettorino & Amendola 2014,
Amendola Balestreros Pettorino 2014
Nils Fisher Bachelor Thesis



Amplitude changes (test of MG at late times)

Primordial peak is shifted (change in horizon crossing – test of MG at early times)

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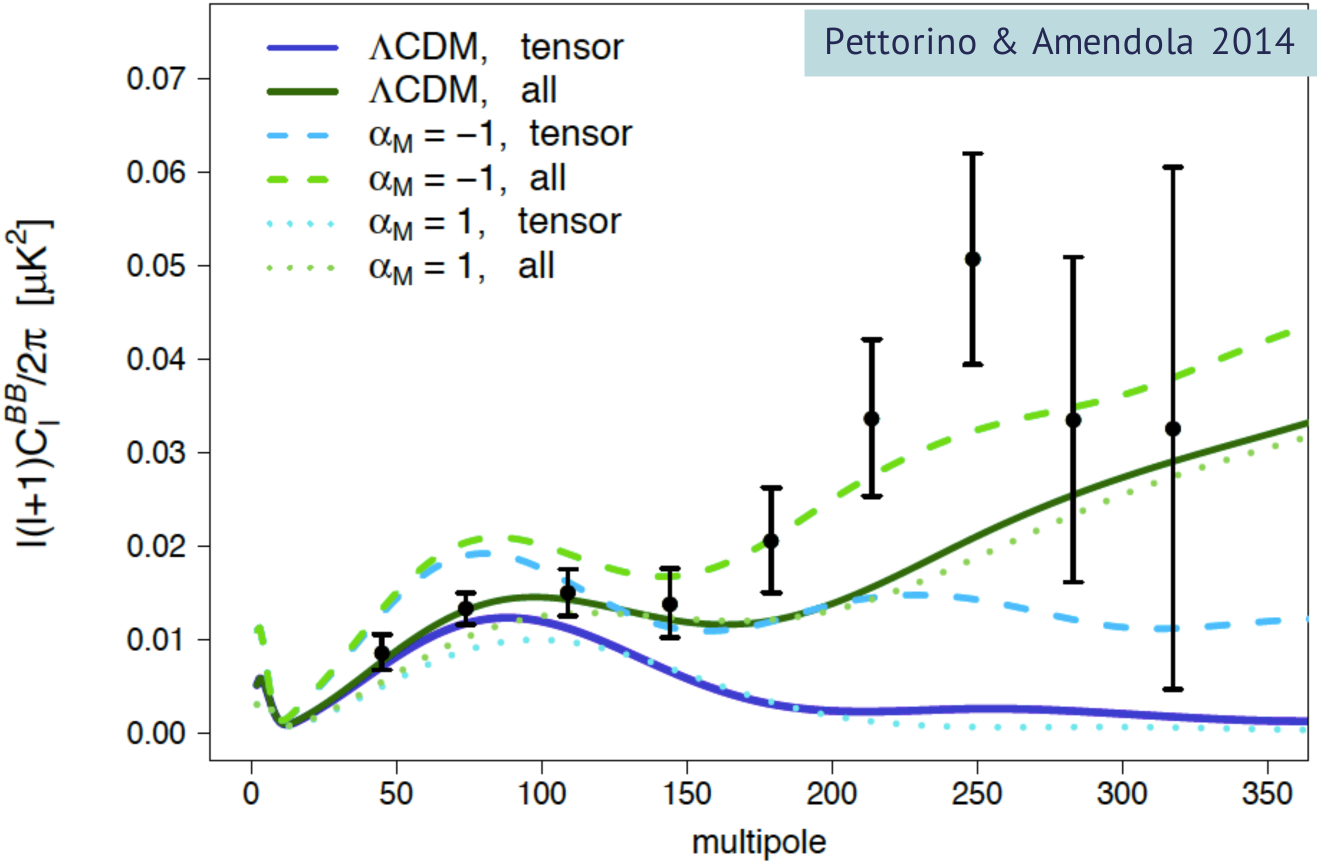


Amplitude changes (test of MG at late times)

Primordial peak is shifted (change in horizon crossing – test of MG at early times)

Conclusions

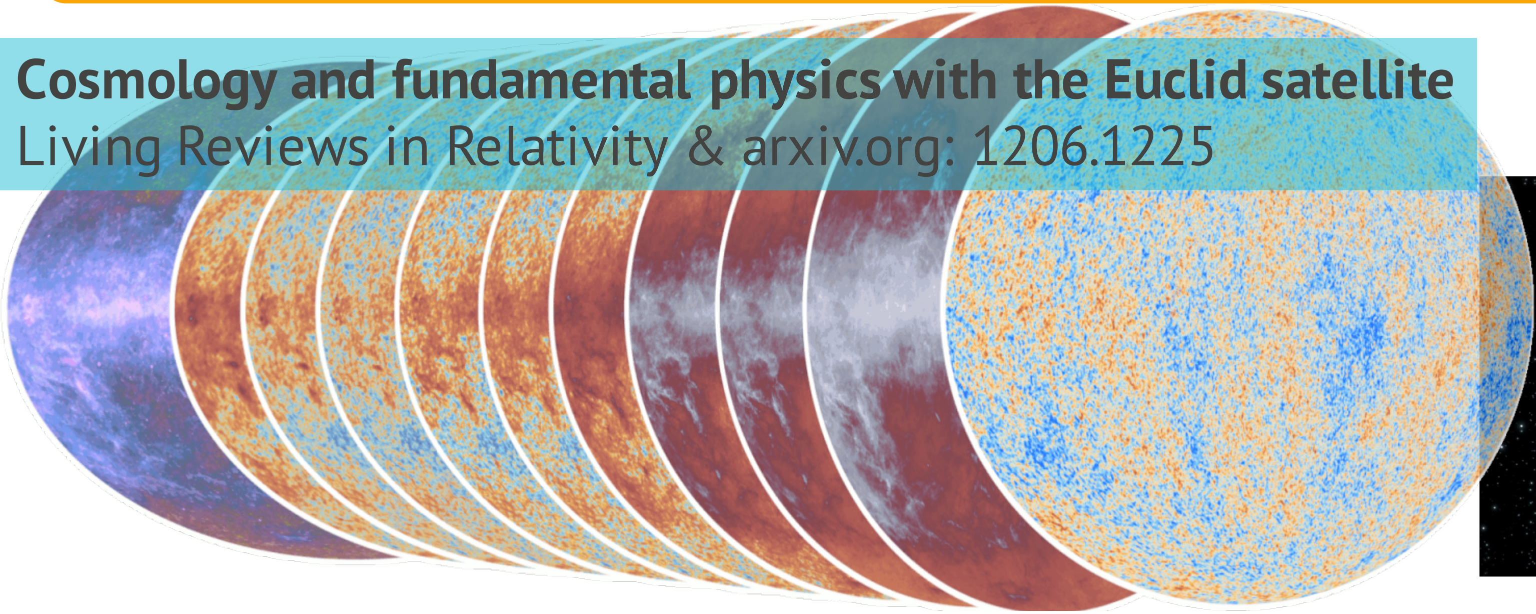
Planck release is in very good agreement with a LCDM model

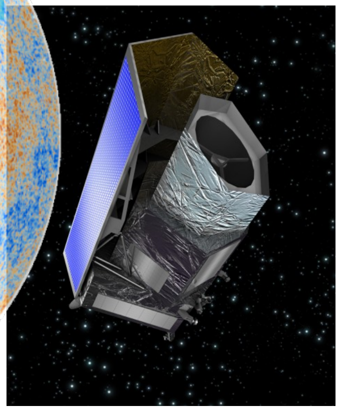
Some tension may appear when combining Planck with external late time probes: need of probe combination.

WL+RSD and CMB polarization will be in the future a promising tool to test the Dark Universe.

Bright future for the Dark Universe! Generic theory, lots of data and better numerical codes.

Cosmology and fundamental physics with the Euclid satellite
Living Reviews in Relativity & arxiv.org: 1206.1225





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