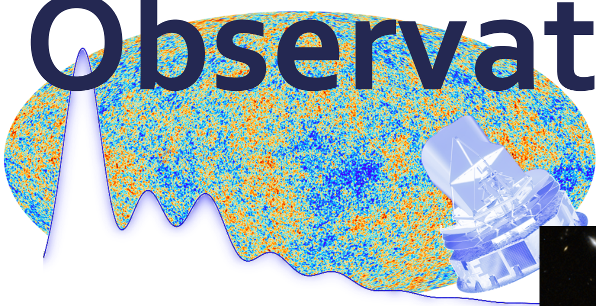
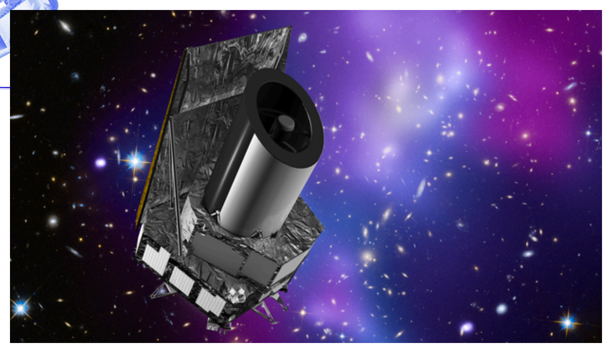
From Theories to Observations



$$v'_\phi = -\mathcal{H}(1-3w_\phi)v_\phi - \beta(\phi)\phi'(1-3w_\nu)\frac{\rho_\nu}{\rho_\phi}v_\phi - \frac{w'_\phi}{1+w_\phi}v_\phi + kc_\phi^2\frac{\delta_\phi}{1+w_\phi} + k\Psi - \frac{2}{3}\frac{\cdots}{1+w_\phi}k\pi_{T_\phi} + k\beta(\phi)\delta\phi\frac{\rho_\nu}{\rho_\phi}\frac{1-3w_\nu}{1+w_\phi}, \quad (10)$$

$$v'_\nu = (1-3w_\nu)(\beta(\phi)\phi' - \mathcal{H})v_\nu - \frac{w'_\nu}{1+w_\nu}v_\nu + kc_\nu^2\frac{\delta_\nu}{1+w_\nu} + k\Psi \cdots - k\beta(\phi)\delta\phi\frac{1-3w_\nu}{1+w_\nu}$$



$$\delta'_\phi = 3\mathcal{H}(w_\phi - c_\phi^2)\delta_\phi - \beta(\phi)\phi'\frac{\rho_\nu}{\rho_\phi}[(1-3w_\nu)\delta_\phi - (1-3c_\nu^2)\delta_\nu] - (1+w_\phi)(kv_\phi + 3\Phi') + \frac{\rho_\nu}{\rho_\phi}(1-3w_\nu)\left(\beta(\phi)\delta\phi' + \frac{d\beta(\phi)}{d\phi}\phi'\delta\phi\right), \quad (8)$$

$$\delta'_\nu = 3(\mathcal{H} - \beta(\phi)\phi')(w_\nu - c_\nu^2)\delta_\nu - (1+w_\nu)(kv_\nu + 3\Phi') - \beta(\phi)(1-3w_\nu)\delta\phi' - \frac{d\beta(\phi)}{d\phi}\phi'\delta\phi(1-3w_\nu) \quad (9)$$

Valeria Pettorino

CEA – Astrophysics Department, Paris-Saclay

@vpettorino

CosmoStat

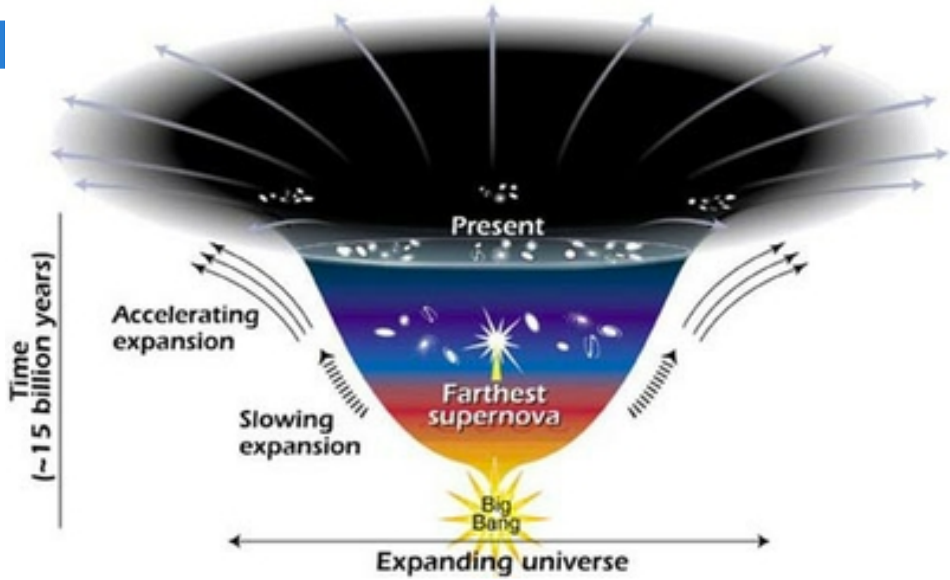
Colloque National *Dark Energy*, LAL (Orsay)

Plan of the talk

- Introduction
- Dark Energy and Modified Gravity
- Current observations and results
- Challenges
- Future prospects

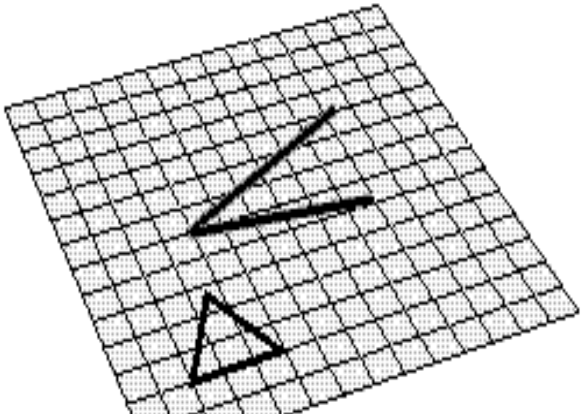

Bicep2 and SPT
Planck
Polarbear
ACTpol
DASI
Cosmic Background Imager
MAXIMA
BOOMerang
ACBAR
COBE
MSAM
WMAP
2dF Galaxy Redshift Survey
Sloan Digital Sky Survey
HST
ESO

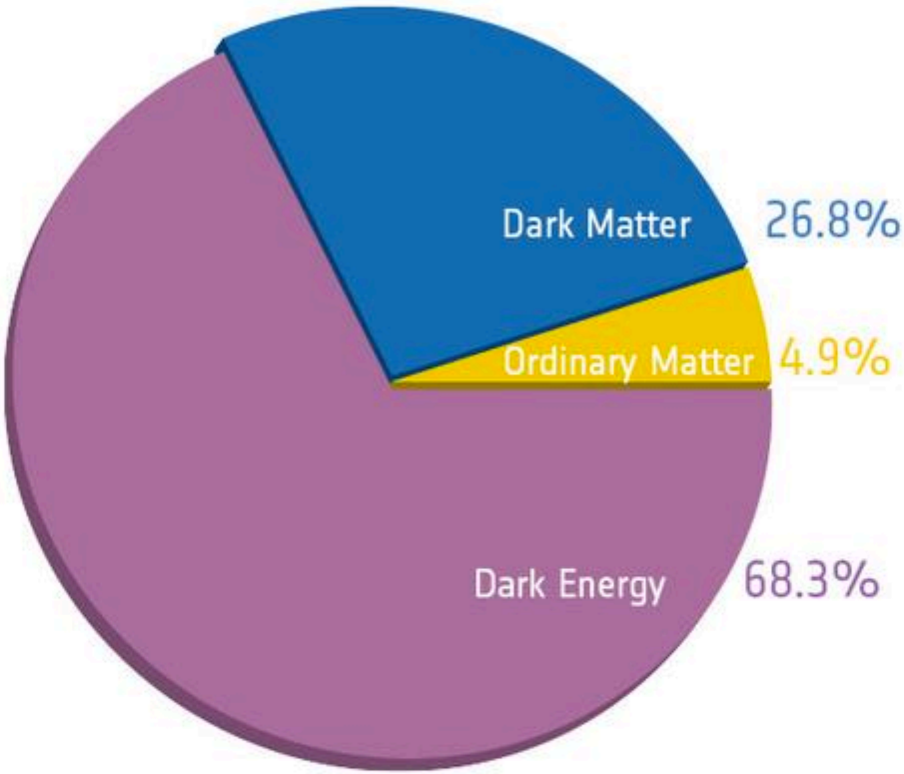
The *standard* cosmological picture



Accelerated expansion

Flatness





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

Two different problems?

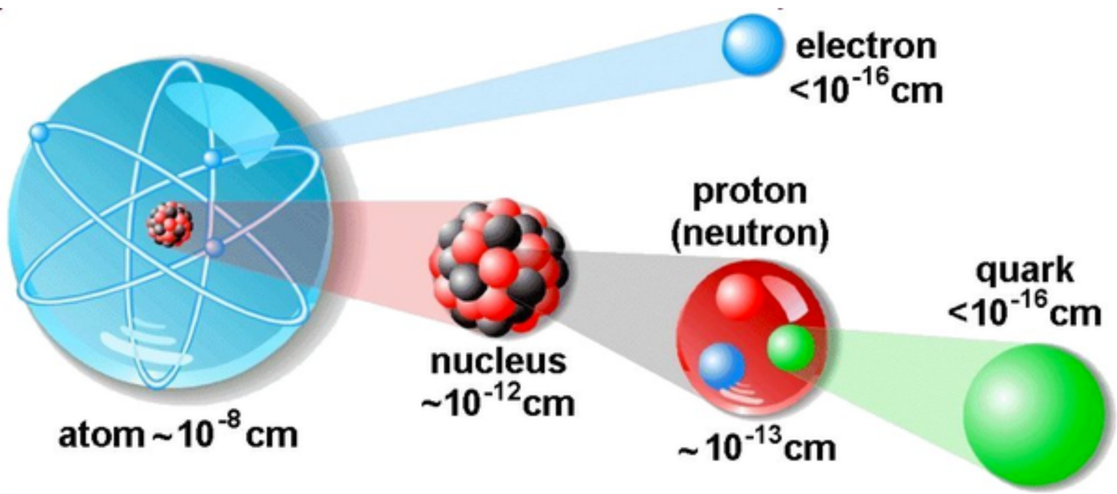
Modified Gravity

Dark Matter ↔ Dark Energy

A new particle or a new force at cosmological scales

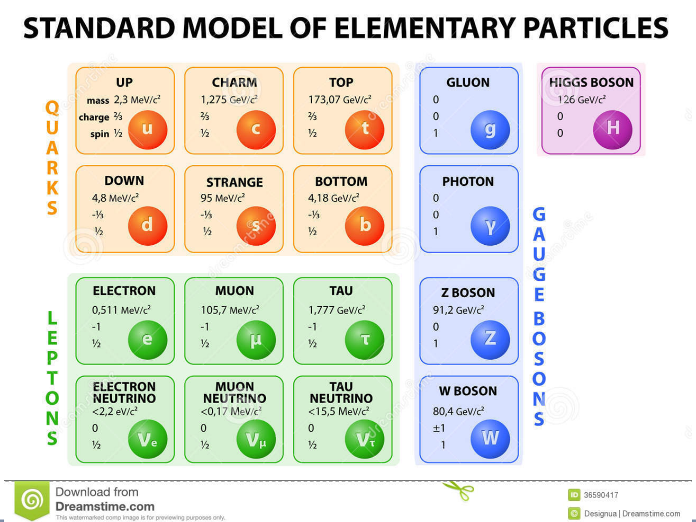
Is this ‘exotic’?

A Dark person looking at 4% of its Universe



Fundamental Force Particles

Force	Particles Experiencing	Force Carrier Particle	Range	Relative Strength*
Gravity acts between objects with mass	all particles with mass	graviton (not yet observed)	infinity	much weaker
Weak Force governs particle decay	quarks and leptons	W^+, W^-, Z^0 (W and Z)	short range	
Electromagnetism acts between electrically charged particles	electrically charged	γ (photon)	infinity	
Strong Force** binds quarks together	quarks and gluons	g (gluon)	short range	much stronger



We are much more exotic than any MG model.

Physics at solar system scales extrapolated to cosmology?

Cosmic acceleration

Einstein equations

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

Acceleration equation: $$\frac{1}{a}\frac{d^2a}{dt^2} = -\frac{4\pi G}{3}\sum_i(\rho_i + 3p_i)$$

Density and pressure $\boxed{p_i = w_i \rho_i}$

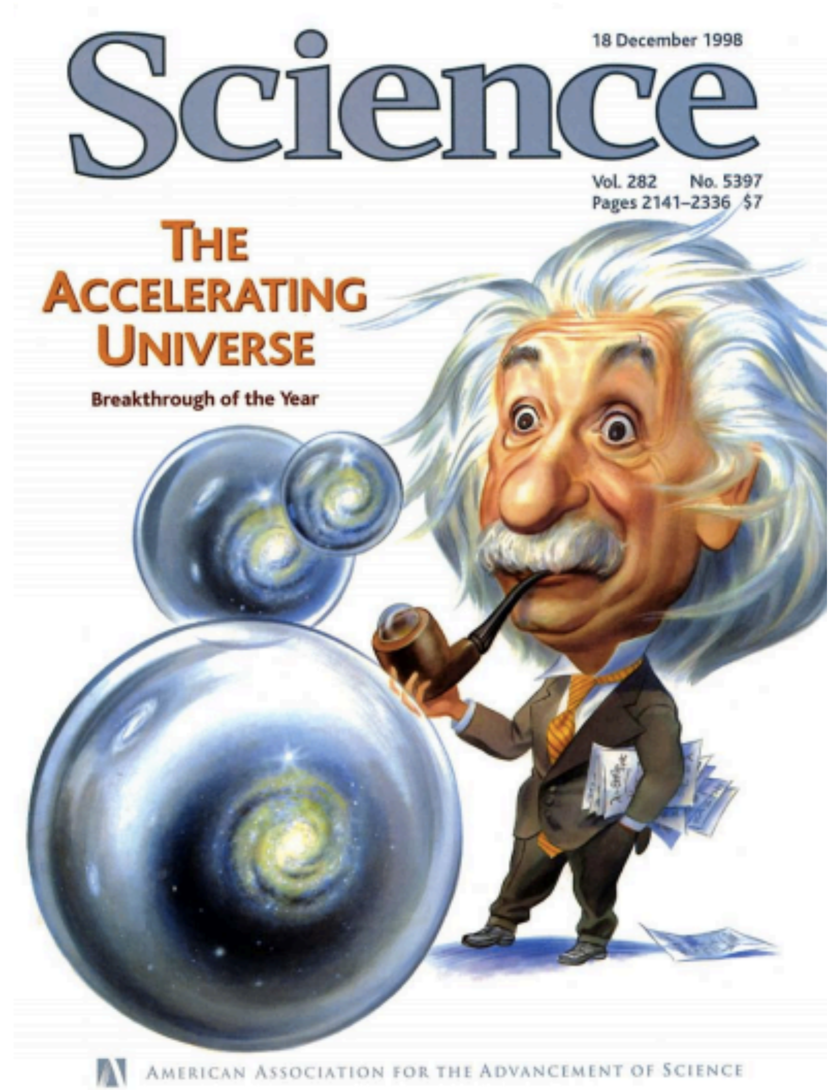
Matter	w = 0	$\rho_m \sim a^{-3}$	$\ddot{a} < 0$
Radiation	w = 1/3	$\rho_r \sim a^{-4}$	deceleration

Most of the universe is not made of ordinary matter!

Supernovae

Supernova Cosmology Project and the High-z Team

In 1994 the High-z Team was formed: “To Measure the Cosmic Deceleration
of the
Universe with Type Ia Supernovae”



What causes cosmic acceleration?

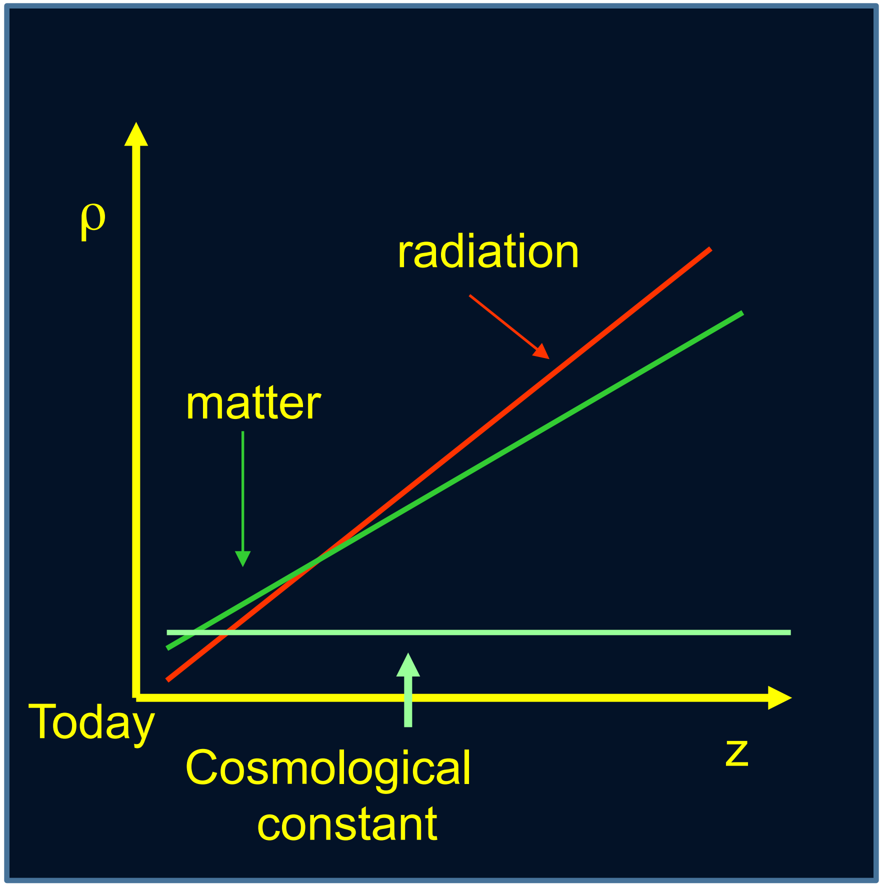
Cosmological constant?

Dynamical Dark Energy?

Wetterich 1988, Ratra & Peebles 1988

Does it involve a modification of Gravity?

Cosmological constant



$$G_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

$$T^{vac}_{\mu\nu} = (\Lambda/8\pi G) g_{\mu\nu}$$

$$p_{vac} = -\rho_{vac} = \Lambda/8\pi G$$

$$w \equiv p/\rho \quad =-1$$

agrees with experiments, but theoretically not understood.

Is it a theory?

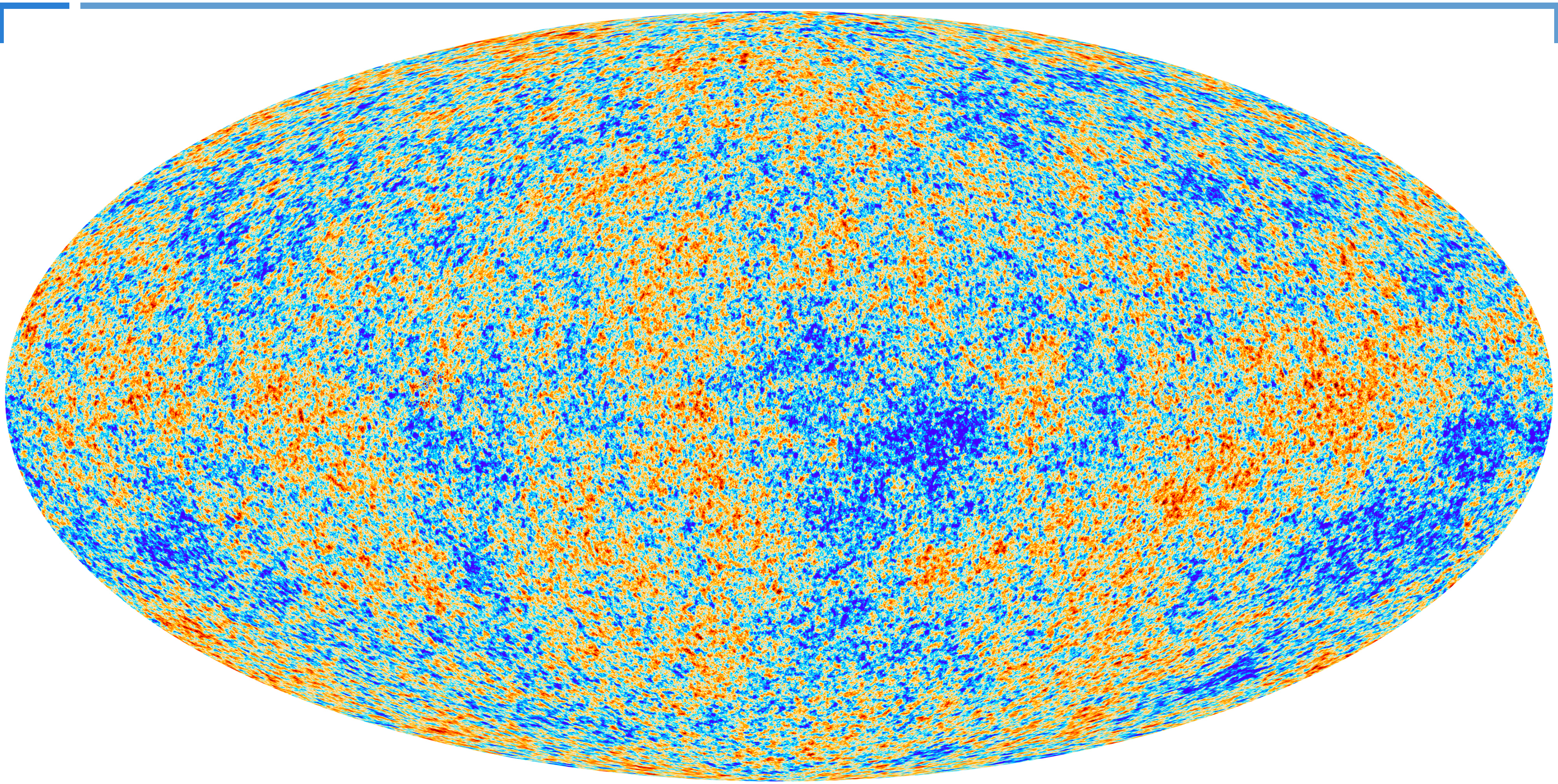
$$\rho_\Lambda = (10^{-3} eV)^4$$

Contribution from quantum zero-point vacuum fluctuations of each field of the standard model. It is necessary to introduce a cutoff and hope that a more complete theory will hold at higher energies. If the cutoff is at the Planck scale,

$$\rho_{vac} = (10^{18} GeV)^4$$

$$\rho_\Lambda^{(theory)} \sim 10^{120} \rho_\Lambda^{(obs)}$$

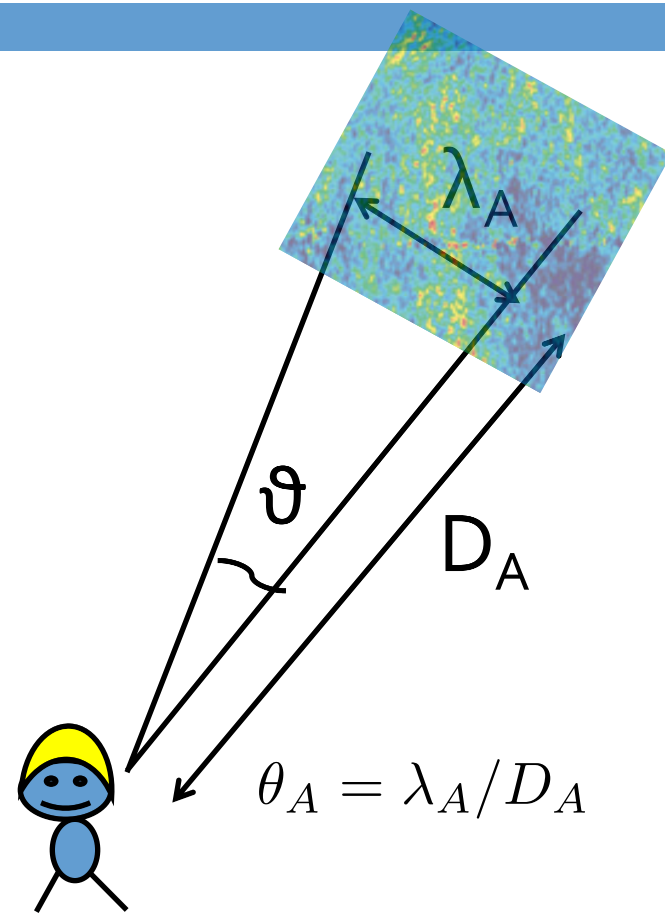
CMB anisotropies



Temperature fluctuations are related to primordial density fluctuations.
CMB + CMB lensing alone are enough to require cosmic acceleration (at 20+ sigma).

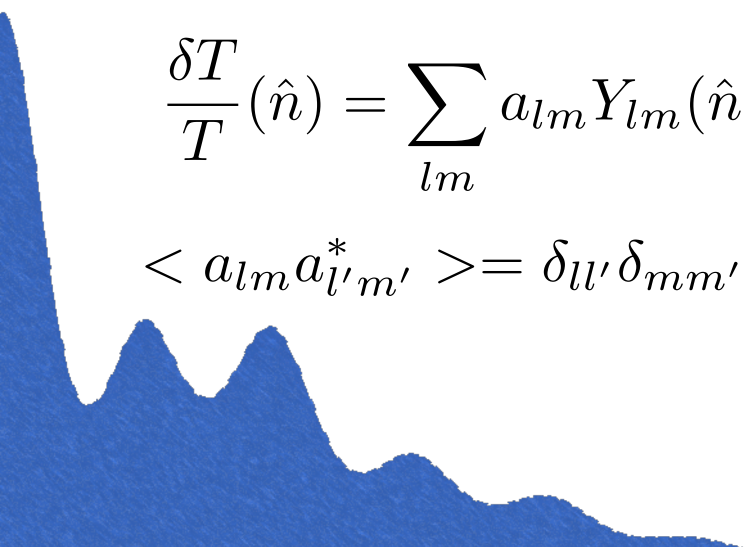
Evolution of perturbations

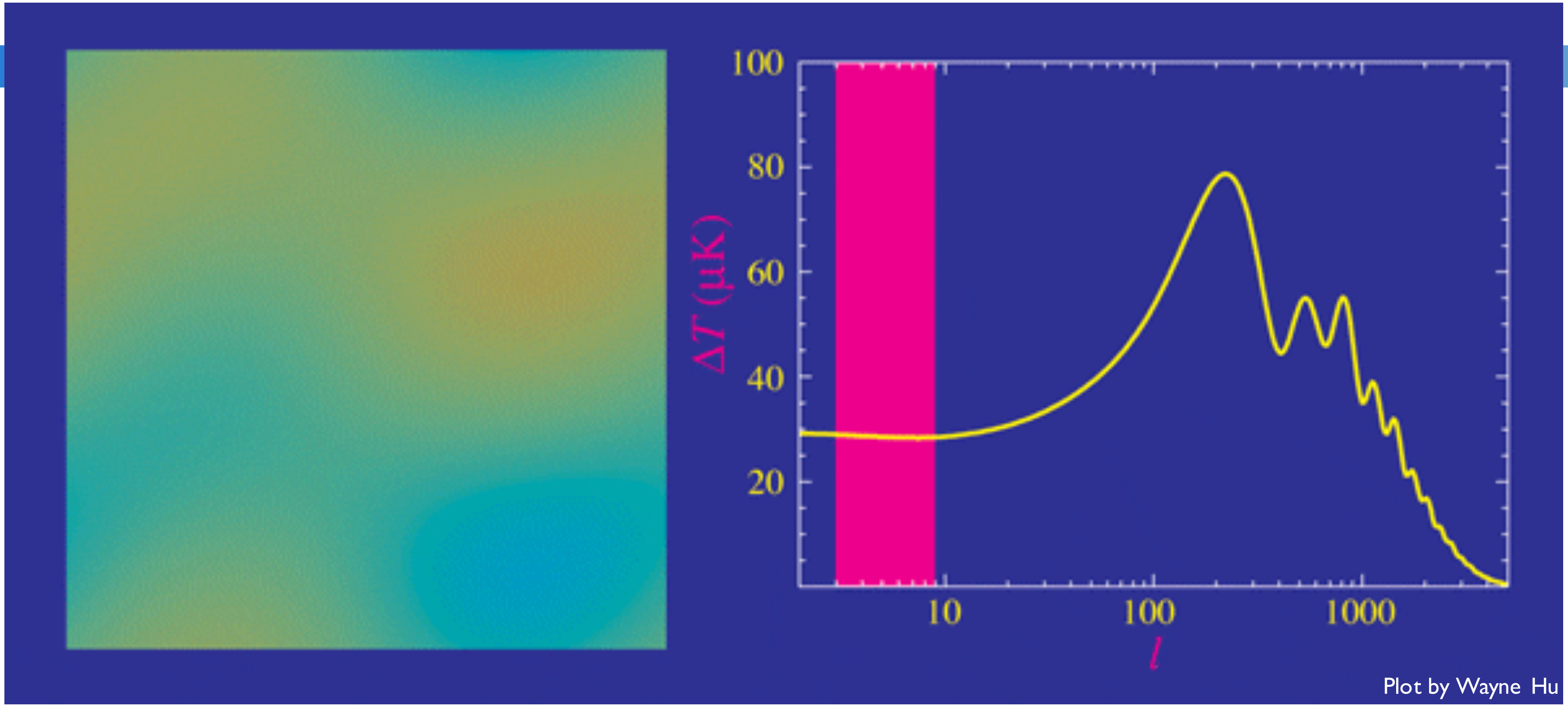
- Expand in Fourier space
- Project the fluctuations in the sky
- Spectra as 2 point correlation function of the coefficients of the expansion in spherical harmonics



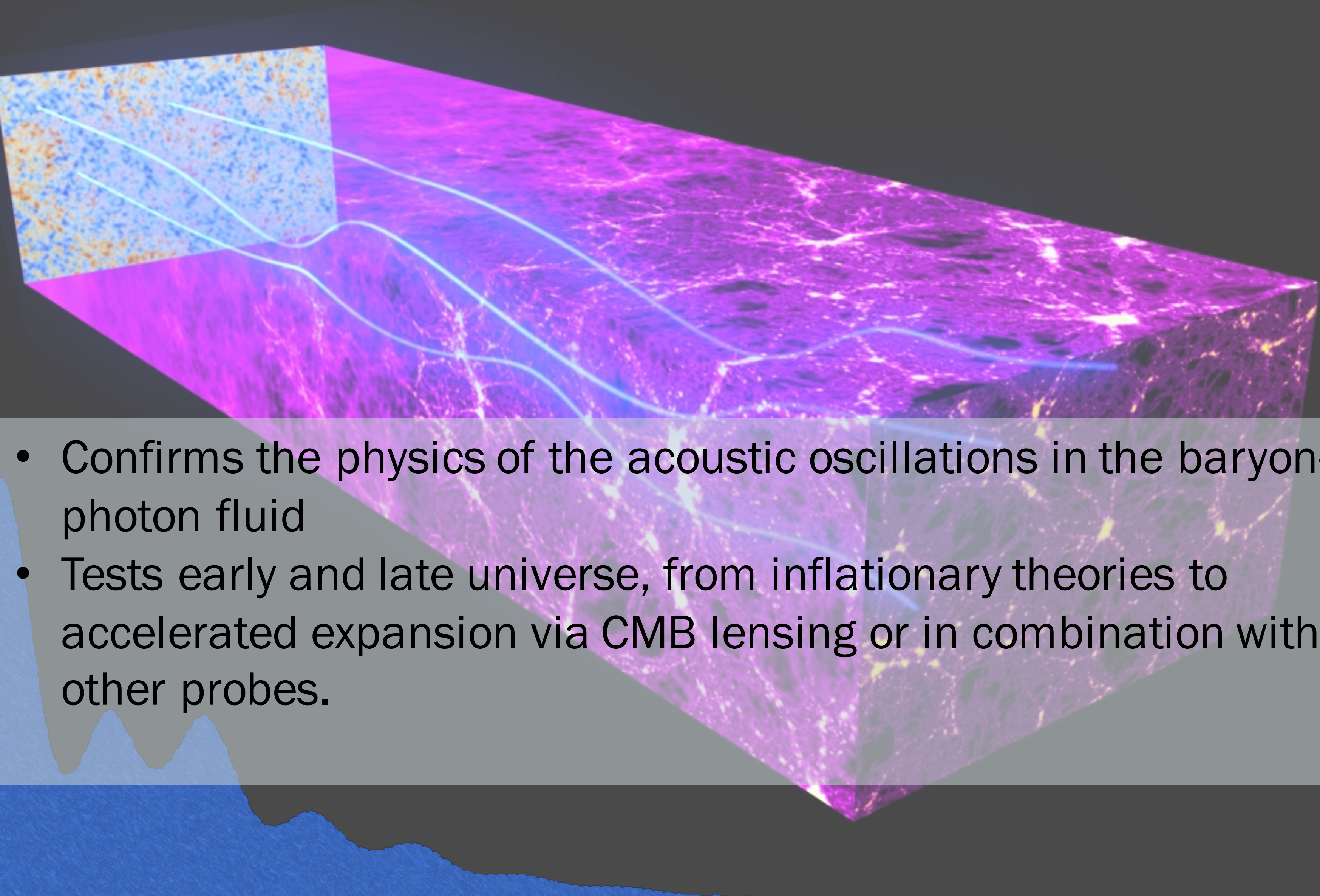
$$\frac{\delta T}{T}(\hat{n}) = \sum_{lm} a_{lm} Y_{lm}(\hat{n})$$

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



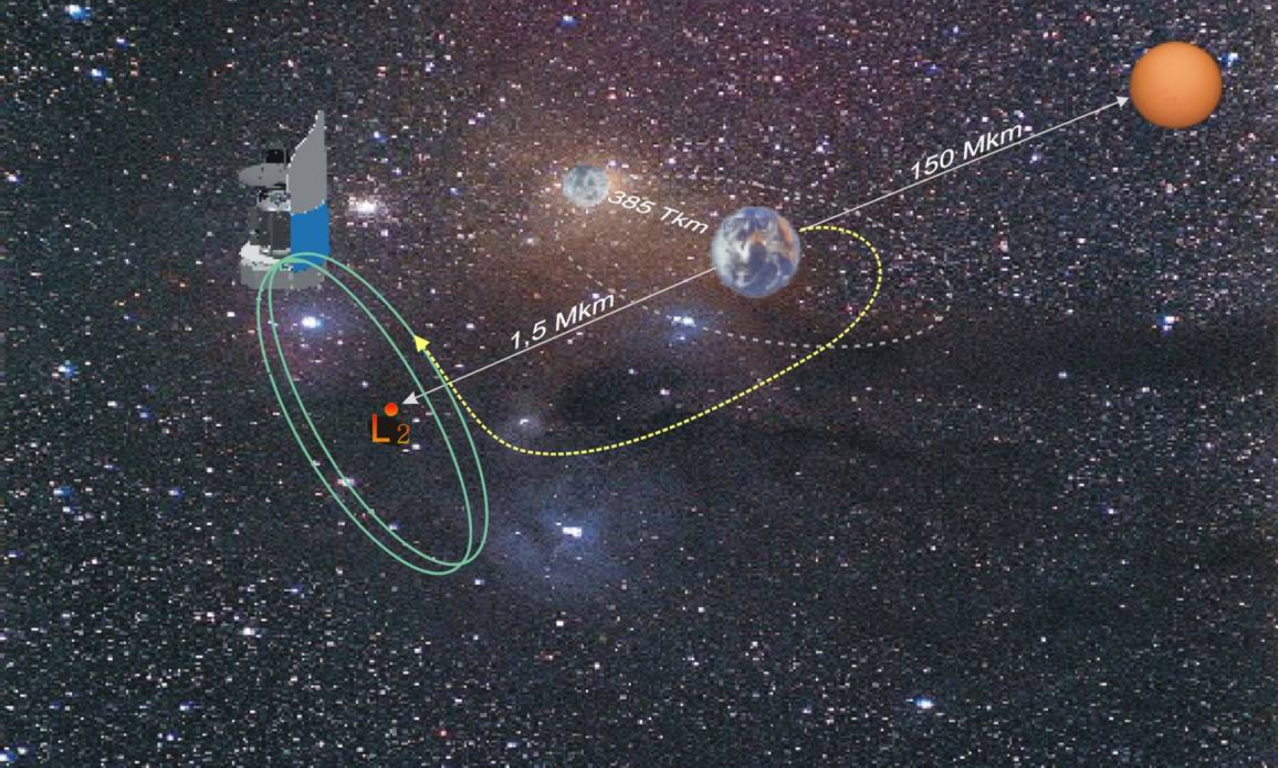

100
80
60
40
20
ΔT (μK)
10
100
1000
l
Plot by Wayne Hu

Window to the early and late Universe



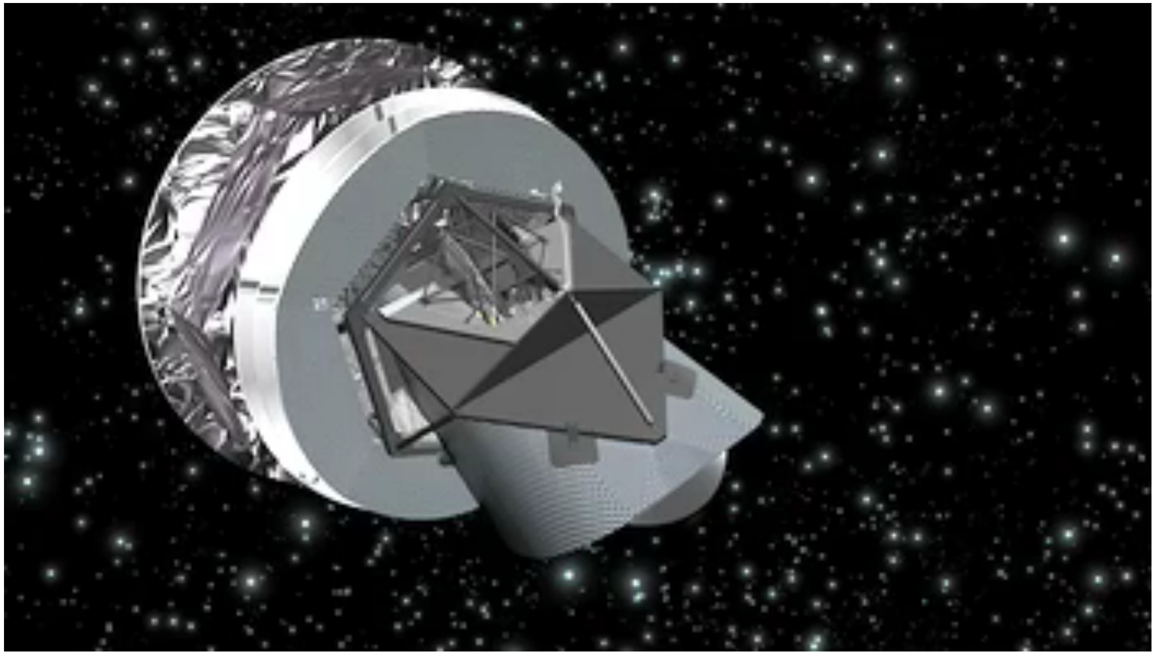
- Confirms the physics of the acoustic oscillations in the baryon-photon fluid
- Tests early and late universe, from inflationary theories to accelerated expansion via CMB lensing or in combination with other probes.

Planck

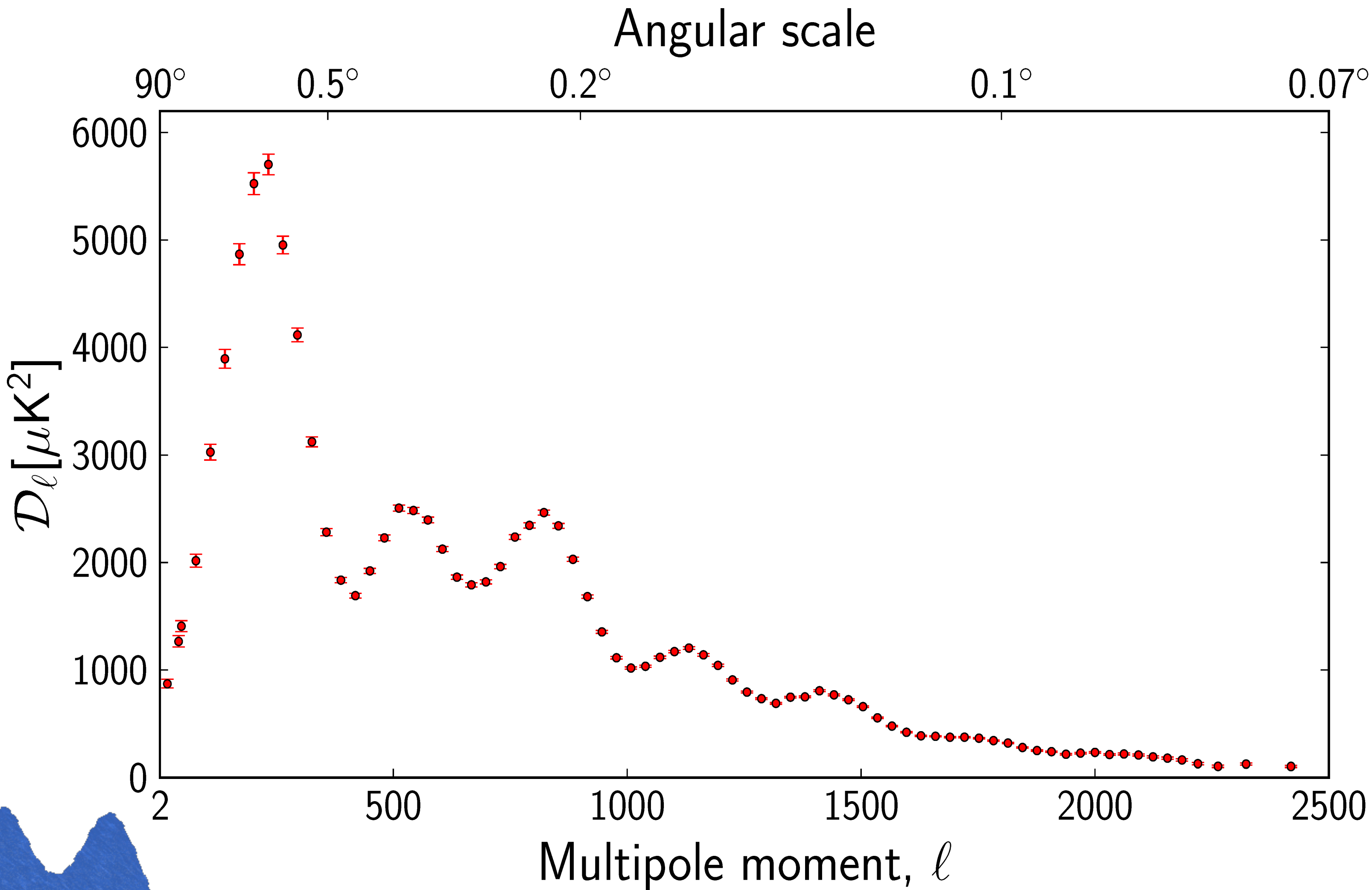


- Launch in 2009
- Nominal mission completed in November 2010 (15.5 months, full surveys: 5 HFI; 8 LFI)
- Releases in 2013, 2015, final one in 2017

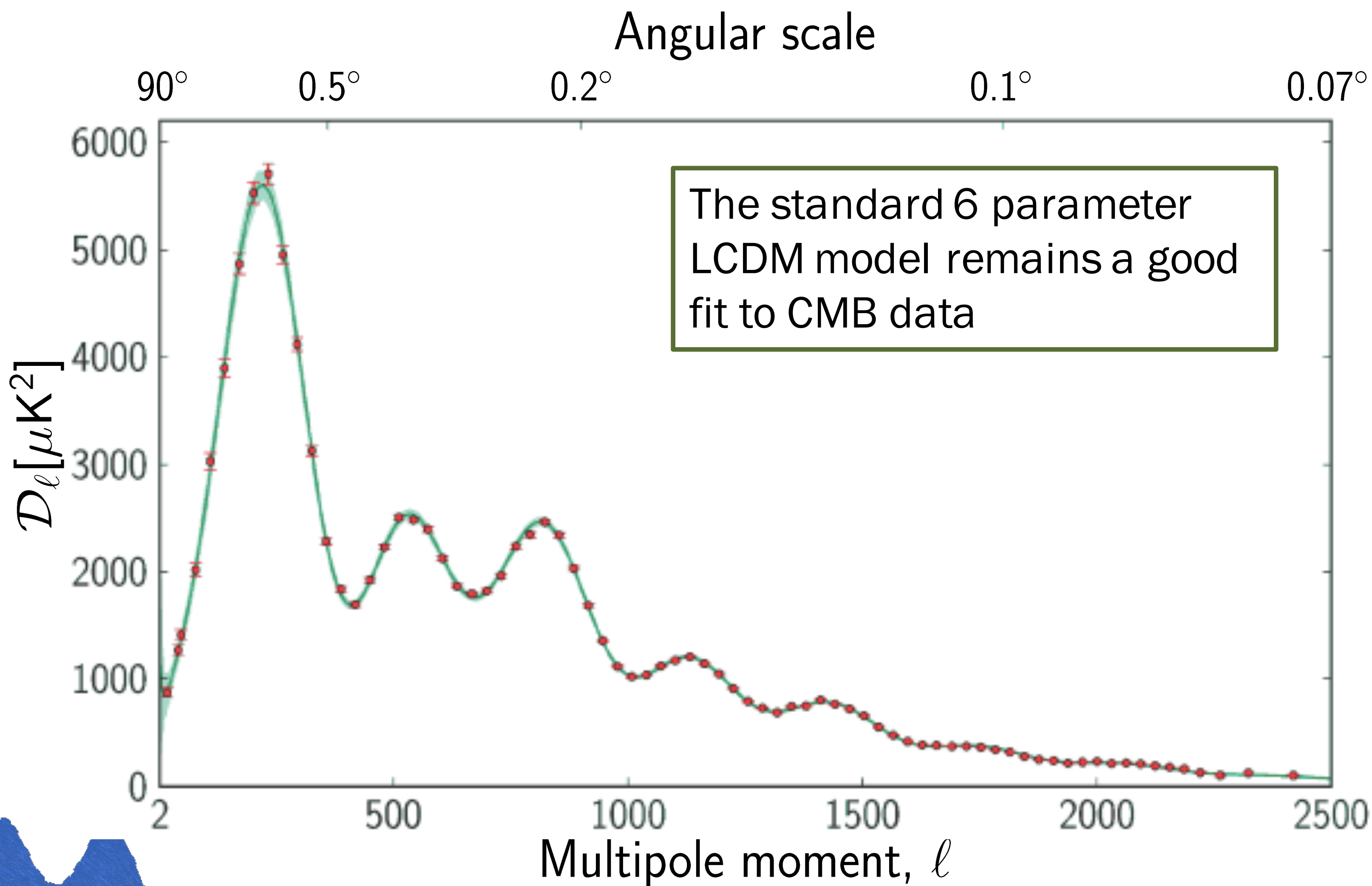
Placed in orbit around L2.
Scans the entire sky twice per year.
The spacecraft spins with 1 rotation per minute, tracing circles on the celestial sphere.



Power spectrum



ΛCDM is a very good fit



Quite impressive. From terabytes of data to 6 parameters

(1) Contents and expansion		***(1) Contents and expansion rate***	
Baryon density	$\Omega_b h^2$	Baryon fraction	Ω_b
CDM density	$\Omega_c h^2$	CDM fraction	Ω_c
Peak position	$\theta\ (\sim r_s/D_A)$	Cosmol constant fraction	$\Omega_\Lambda = 1 - \Omega_b - \Omega_c$
		Expansion rate	H_0
(2) Initial fluctuations		***(2) Late-time size of fluctuations***	
Amplitude at k=0.05/Mpc	A_s	Amplitude on 8 Mpc/h scales	σ_8
Spectral index	n_s		
(3) Impact of reionization		***(3) Reionization***	
Reionization optical depth	τ	Redshift of reonization	z_{re}

In addition, you can add the parameter w and test if it is different by -1
Result: it is very close to -1!

J. Dunkley

How much Dark Energy can you have in the past?

$$w(a) = w_0 + w_a(1-a)$$

$$\Omega_e \lesssim 0.007$$

Dark Energy models can be roughly divided in two categories: with and without Early Dark Energy

Planck Collaboration
A&A and ArXiv 1502:10590

[see Martin Kunz talk]

Dark Energy at late time:

w_{DE} is very close to -1, so it's ΛCDM

Even w0,wa is (-1,0)

Dark Energy at early times: strong constraints on how much DE you can have.

Solid confirmation of ΛCDM!

There is always choices you make when you tell a story.

In the characters you pick, in the challenges you highlight, and in the conflicts you encounter.

Let’s highlight also some of the challenges and conflicts, that are part of this story.

Three tales

Expansion

w asymptotically close to -1 in nearly ***all models of DE and MG***

Linear perturbations and CMB

Even if the background expansion is very close to LCDM, perturbations can be different -> test with CMB

Non-Linear perturbations and structure formation

Even if linear perturbations are the same, structure formation can be different -> test with WL and GC

Planck collaboration: ArXiv 1502:10590

Tale of expansion + Tale of linear perturbations

arXiv:1502.01590v2

Planck 2015 results. XIV. Dark energy and modified gravity

February 5, 2015

ABSTRACT

We study the implications of *Planck* data for models of dark energy (DE [illegible] (MG), beyond the standard cosmological constant scenario. We start with cases where the DE only directly affect [illegible] ion, considering Taylor expansions of the equation of state $w(a)$, as well as principal component analysis and pa [illegible] o the potential of a minimally coupled DE scalar field. When estimating the density of DE at early times, we signi [illegible] constraints and find that it has to be below $\approx 2\,\%$ (at 95% confidence) of the critical density even when forced to pla [illegible] we then move to general parameterizations of the DE or MG perturbations that encompass both effective field theorie [illegible] of gravitational potentials in MG models. Lastly, we test a range of specific models, such as k-essence, $f(R)$ theori [illegible] dition to the latest *Planck* data, for our main analyses we use background constraints from baryonic acoustic oscill [illegible] e and local measurements of the Hubble constant. We further show the impact of measurements of the cosmologi [illegible] as redshift-space distortions and weak gravitational lensing. These additional probes are important tools for testing [illegible] aking degeneracies that are still present in the combination of *Planck* and background data sets.
All [illegible] background parameterizations (expansion of the equation of state, early DE, general potentials in minimally-coupled sca [illegible] cipal component analysis) are in agreement with ΛCDM. When testing models that also change perturbations (even when the [illegible] and 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

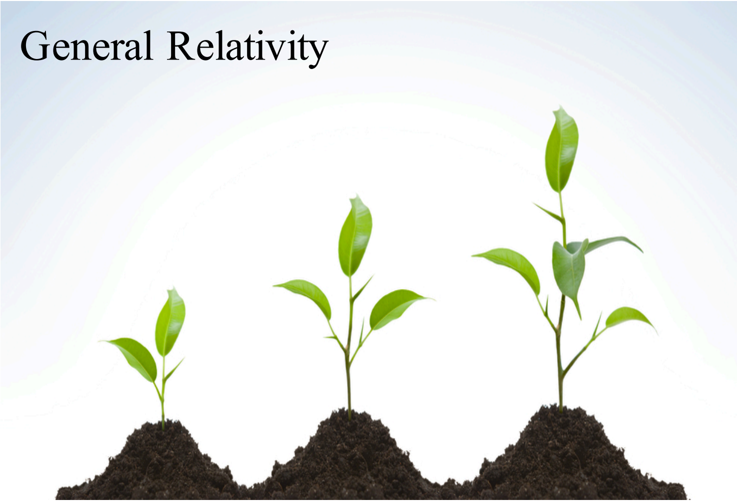
⋆ Corresponding author: Valeria Pettorino, v.pettorino@thphys.uni-heidelberg.de

CMB as a probe for DE and MG

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, can lead to a mismatch between primordial amplitude and late time measurements of σ_8
- Ratio between odd and even peaks
- Polarization and B modes

Modified Gravity changes the growth of structure



Modified Gravity

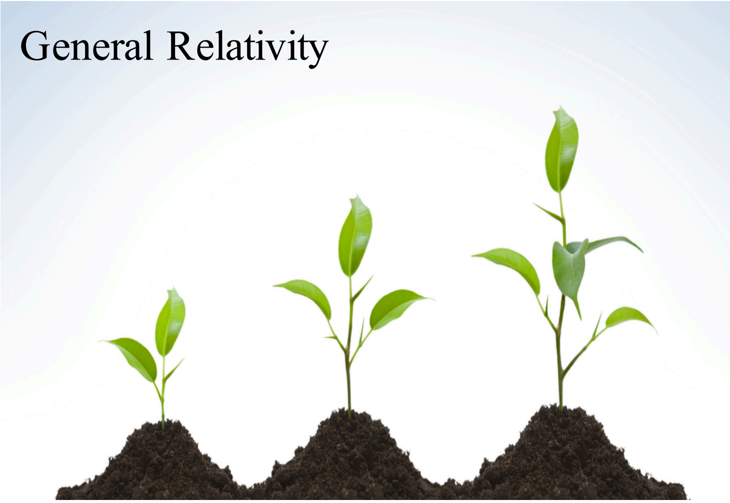
Growth ⟷ Density Velocities ⟷ Geometry (gravitational potentials)

$$f \equiv \frac{d\ln\delta}{d\ln a}$$

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

via modifications of the gravitational potentials

Dark Energy and Modified Gravity change the growth of structure



Modified Gravity

Growth ⟷ Density Velocities ⟷ Geometry (gravitational potentials)

(conservation/Euler equation)

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

(Poisson equation)

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

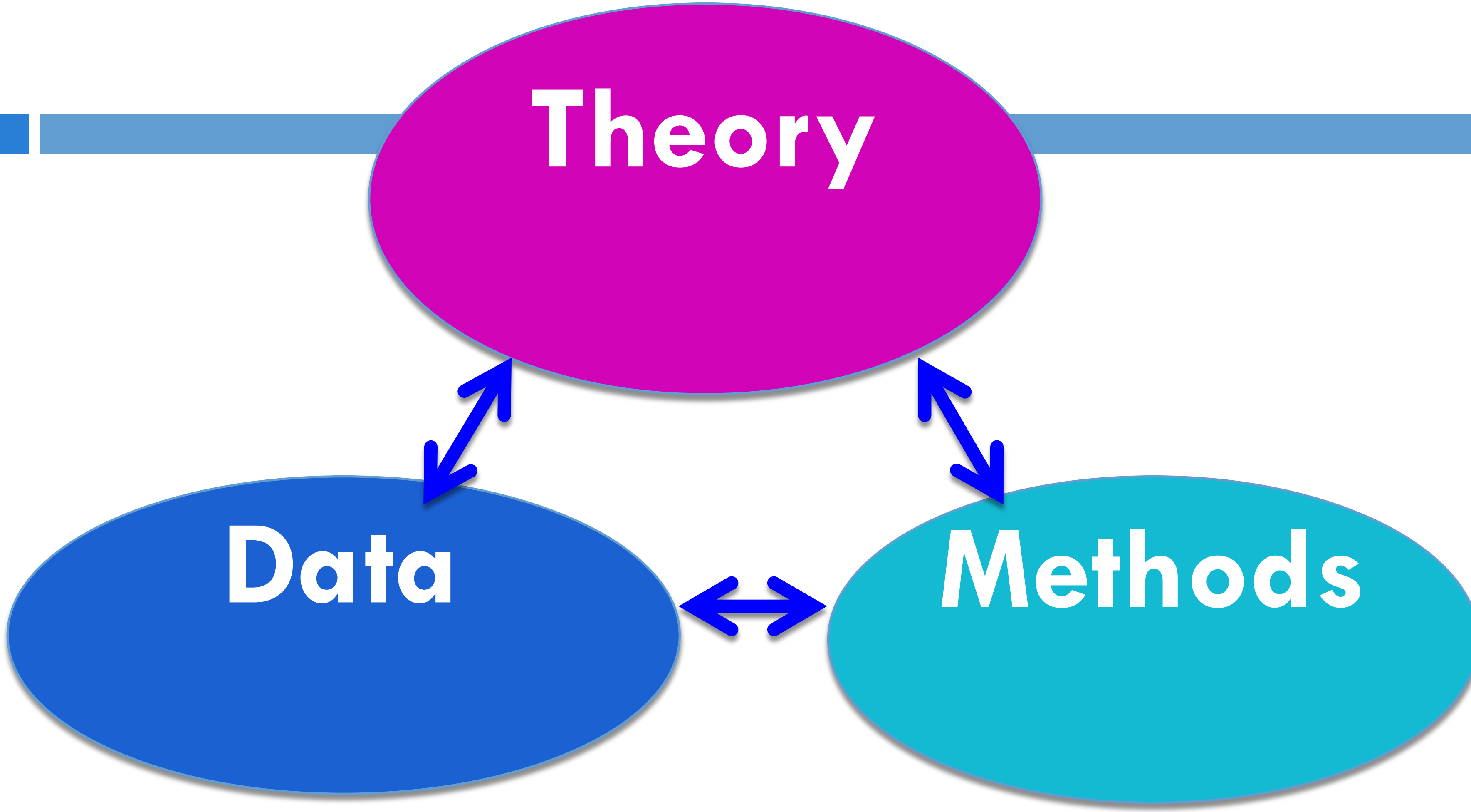
via modifications of the gravitational potentials

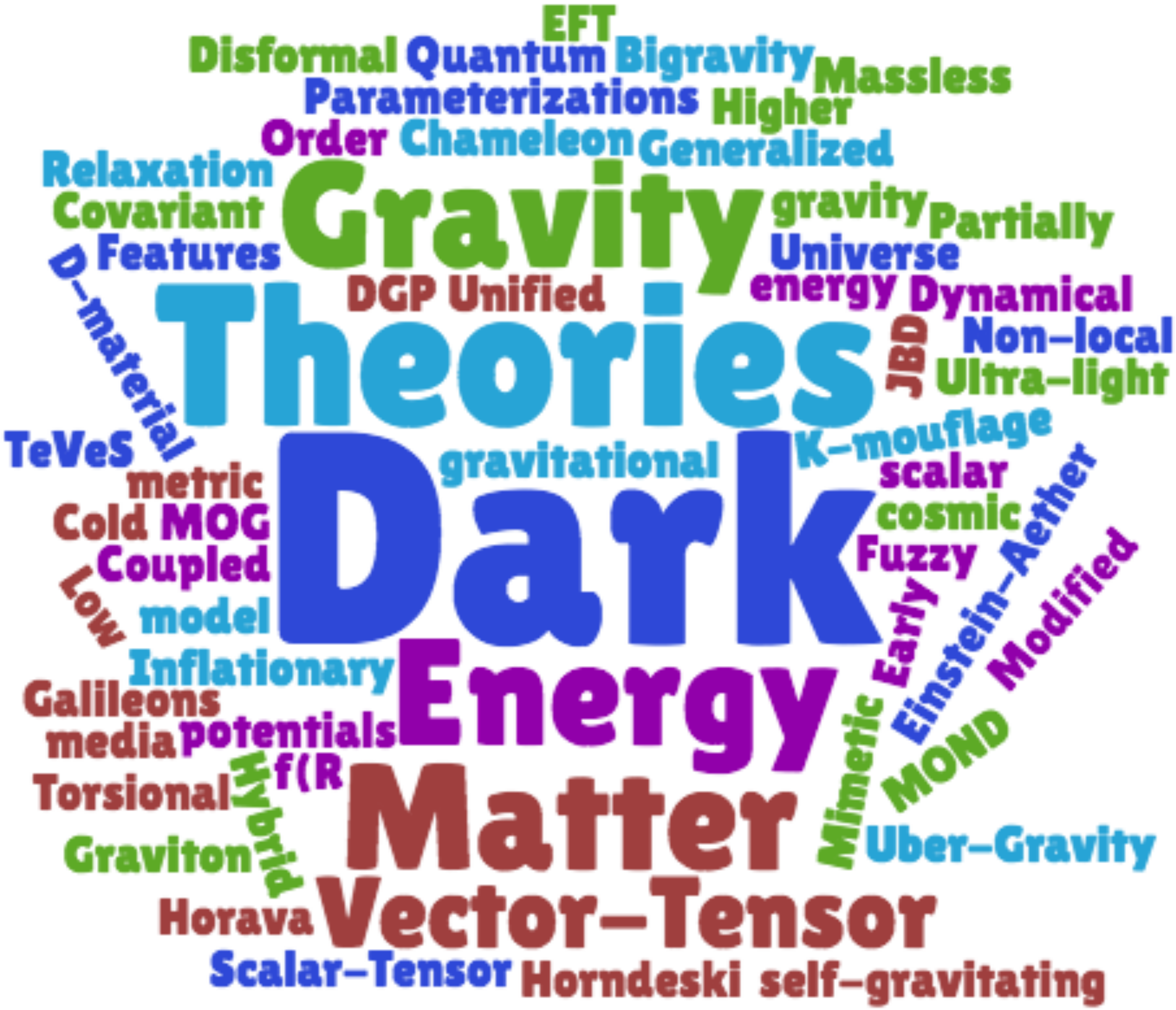
Then why don't we just test theories with different observations?

What has been tested so far?

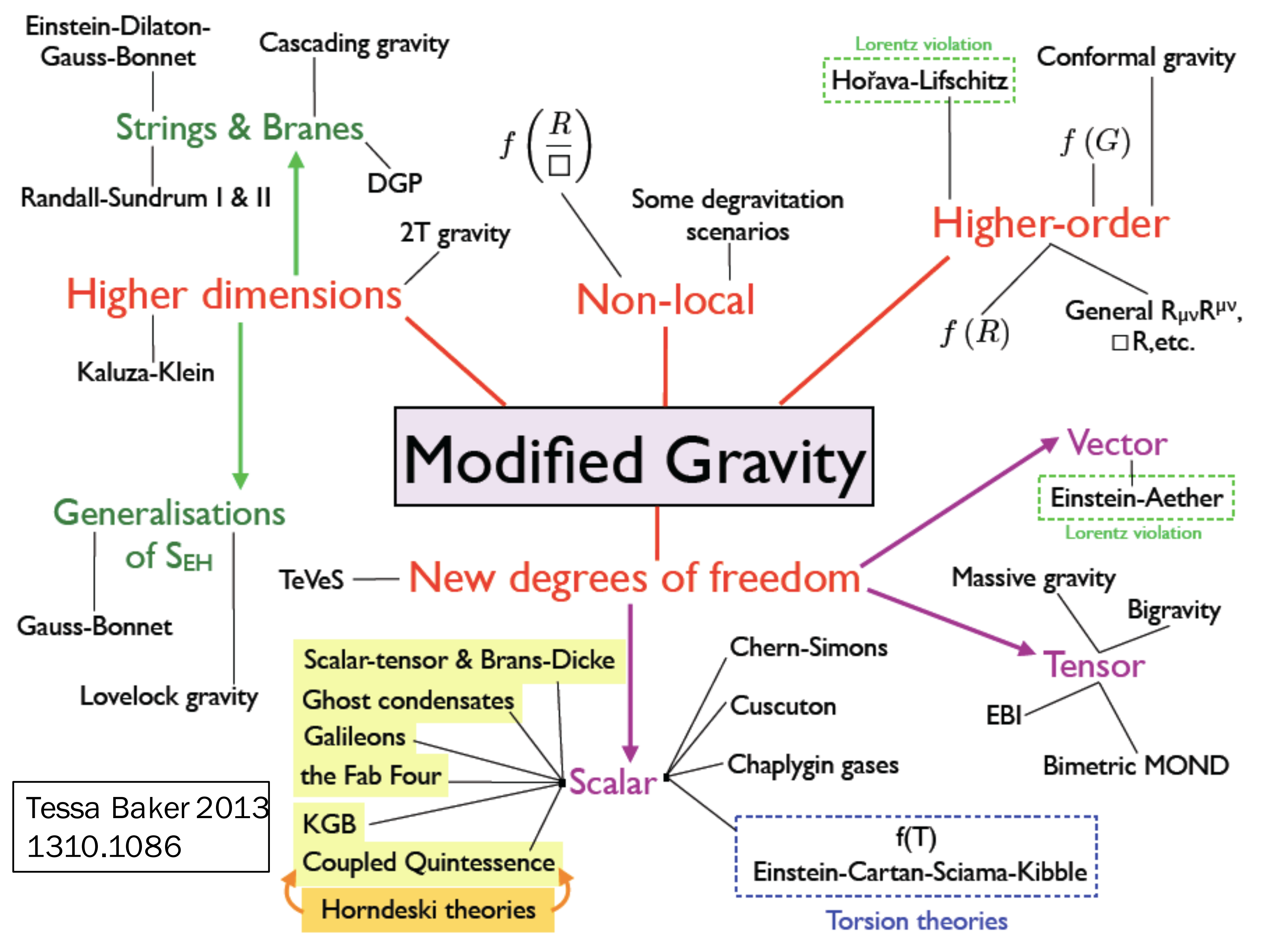
There is no significant tension anyway?

Our ability to test DE and MG is not in the 'precision' era yet


Theory
Data
Methods



Example of suggestions I got, to be tested with future experiments



Tessa Baker 2013
1310.1086

Testing theories

Challenges: step1

No agreement in the community on which models to test

Background formulations

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

Perturbation formulations

a. Effective Field Theory (EFT)
b. Horndeski
c. Beyond Horndeski
d. Gravitational potentials
e. Non-local theories
f. ...

Single models?

General Descriptions?

Interactions and forces beyond LCDM

Be aware of similarities, in order to identify differences

Get Cosmology to the precision level of particle physics.

For the first time general descriptions of stable theories.

	Dark Energy	Dark Matter	Gravity	Neutrinos	Baryons
Dark Energy	Early Dark Energy	Coupled Quintessence	ST, F(R), EQ	Growing neutrinos	
Dark Matter		Warm Dark Matter, Fuzzy,	Non minimal DM		
Gravity			Massive Gravity, Bigravity		Screenings F(R), K-moufflage, Horndeski and beyond, EFT
Neutrinos				Neutrino mass	
Baryons					Standard Model

Testing theories

Challenges: step1

In general descriptions like EFT or Horndeski or gravitational potentials, you need to parameterize several free functions (of time and/or scale, depending on the formalism)

Pros of general formalisms:

– Allow to include a large number of theories in Boltzmann codes (practical if you don't have a code)

Cons of general formalisms:

– if you pick one specific prediction, you end up using a very general formalism in a very specific model

Testing theories

Challenges: step1

Which models?
Which parameterizations?

Stability conditions?
Already excluded by theory (DGP)?
Already excluded by past data (MOND/TeVeS)?
Is there any range of parameters left which makes it any different from LCDM (massive gravity, bigravity)?

Dealing with Data

Challenges: step2

- Which data have publicly available likelihoods?
- Are data for the same probe compatible with that model? Problematic even for the same probe (ex. Kids vs DES) and sometimes from same collaboration, releasing different likelihoods/results!
- Are different probes compatible with that model?
- If yes, how do we combine them?
- How large/small is the effect of cross-correlation terms?
- Are there model dependent assumptions within the likelihood released? Which assumptions do they contain?
- Careful about possible systematics
- Impact of non-linear physics

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

CMB: Planck and polarization experiments

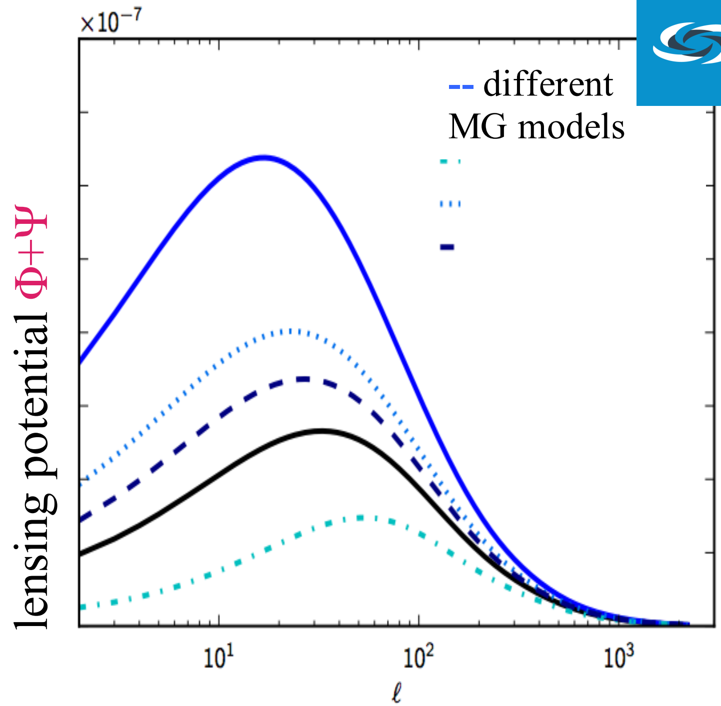
Useful to test the background story: BAO + SNe + H_0

Useful to test perturbations story: RSD and WL

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

Improving methods

Challenges: step3

No agreement yet on well tested set of codes in the Dark Energy community, including non-linear regime

After Planck analysis, where we debugged codes and pointed out several issues in MG codes, and after a similar initiative within Euclid, the need of 'validating codes' is getting more and more seen as a necessity (normal thing in other communities!)

EFTCAMB/HighClass now compared and validated (linear regime) (https://arxiv.org/abs/1709.09135)

In practice, LCDM is also the one model for which we have a reliable well tested code

Improving methods

Challenges: step3

- Open source and modular codes to facilitate implementation and validation
- Understand the non-linear regime (from theory and observer point of view)
- Profit of expertise in statistics (advanced and applied not only to astrophysics) to decorrelate ‘observable parameters’ and reconstruct the ‘theory parameters’: what is better constrained by data is not necessarily what we would like to observe; is there a smart basis or way to reconstruct theory?

Improving methods

Challenges: step3

- Need to break degeneracies

(DE, neutrinos, Ω_M, σ_8, scale dependence…)

- Remove correlations among different redshift bins: we mainly deal with new free functions of time, not sufficient to test their value today. PCA? Other statistical methods? New ideas?

Joining theory with observations: examples of results so far

Effective Field Theory & Horndeski

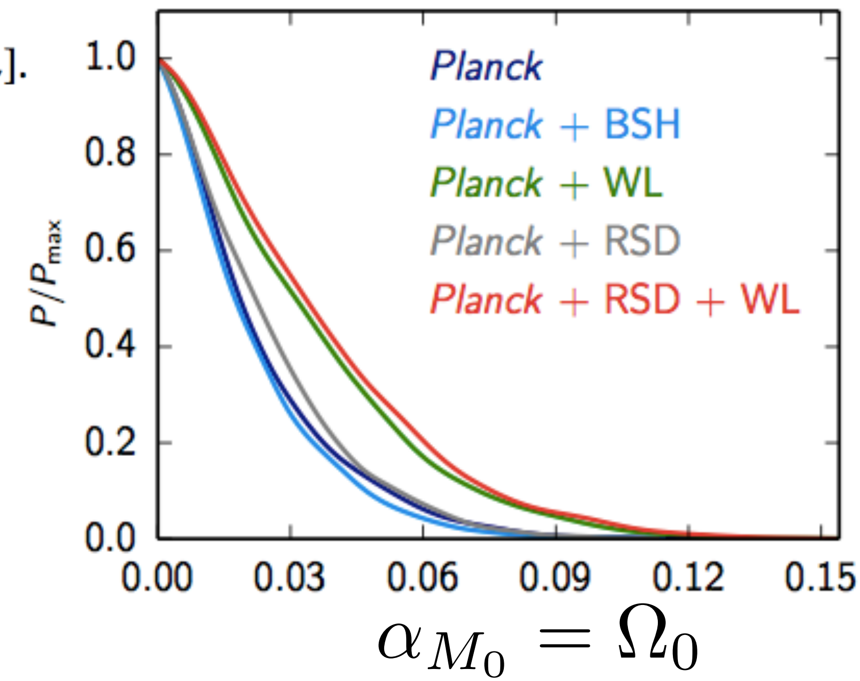
$$
\begin{aligned}
S = \int d^4x \sqrt{-g}\Big\{ & \frac{m_0^2}{2}[1+\Omega(\tau)]R + \Lambda(\tau) - a^2 c(\tau)\delta g^{00} \\
& + \frac{M_2^4(\tau)}{2}(a^2\delta g^{00})^2 - \bar{M}_1^3(\tau)2a^2\delta g^{00}\delta K_\mu^\mu \\
& - \frac{\bar{M}_2^2(\tau)}{2}(\delta K_\mu^\mu)^2 - \frac{\bar{M}_3^2(\tau)}{2}\delta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

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

EFTCAMB (Hu, Raveri, Silvestri, Frusciante 2014)

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)



Parameterizing Modified Gravity

2 functions of the gravitational potentials:

μ modifies the Poisson equation: directly observable

η is the ratio of the gravitational potentials

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

In alternative:

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

Results from Planck

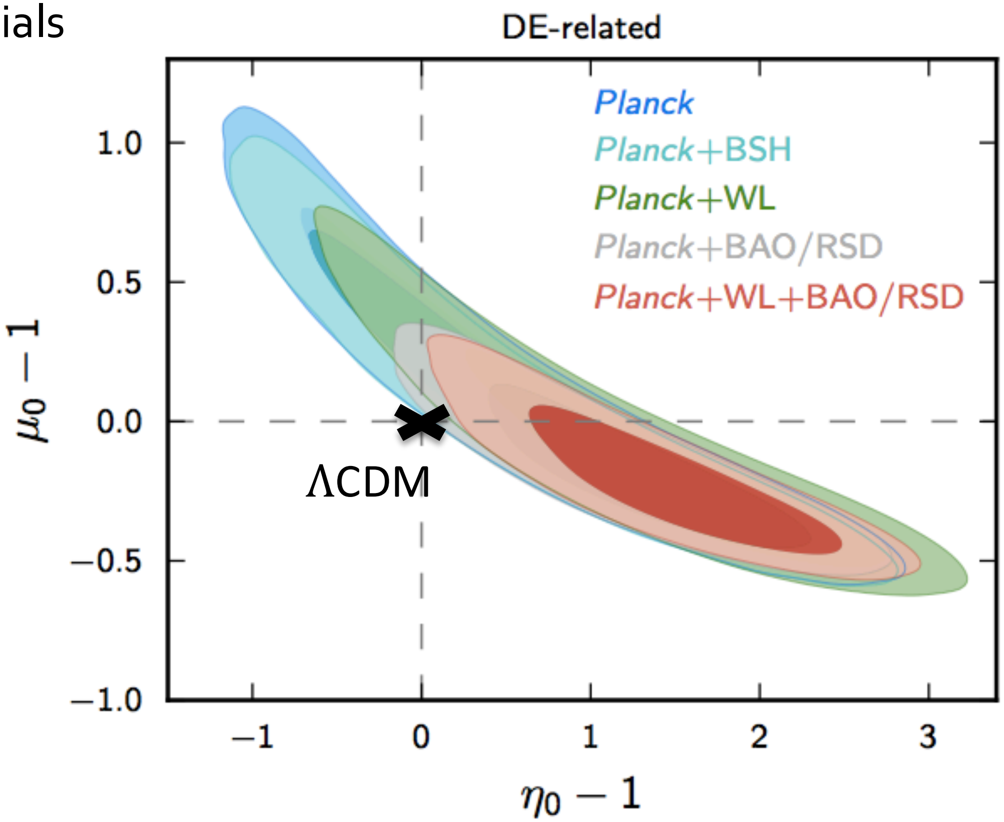
Planck Dark Energy & Modified Gravity paper
Astro-ph 1502.01590 & A&A

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%



Extra challenge: these are functions of z; amplitude in different bins is highly correlated

Tensions

Is there tension in H0?

Wilmar Cardona, Martin Kunz, Valeria Pettorino 2016

Riess etal 2016 (more than twice R11, weak metallicity prior, no period cut): 3.3 sigma tension with Planck value

We reanalyzed the data using Bayesian Hyperparameters, avoids subjective rejection criteria for outliers

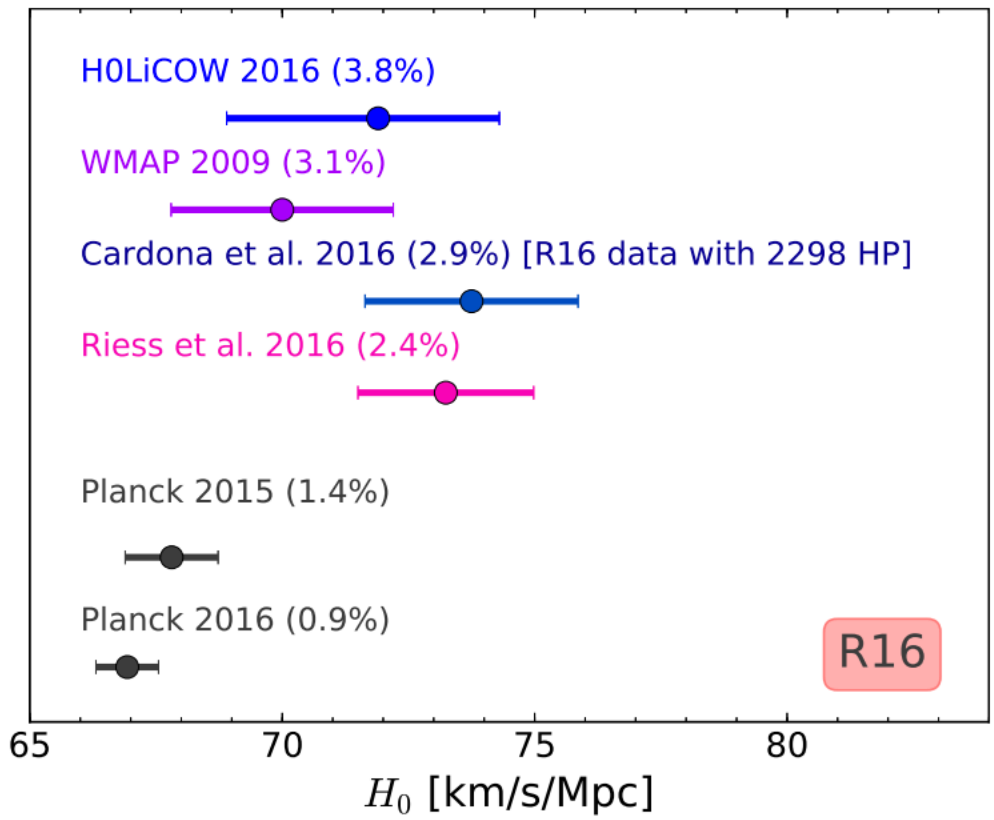
Agreement with Riess but with larger error bars (i.e. less tension):

H0 (Cardona) = 73.75 ± 2.11 km s−1 Mpc−1

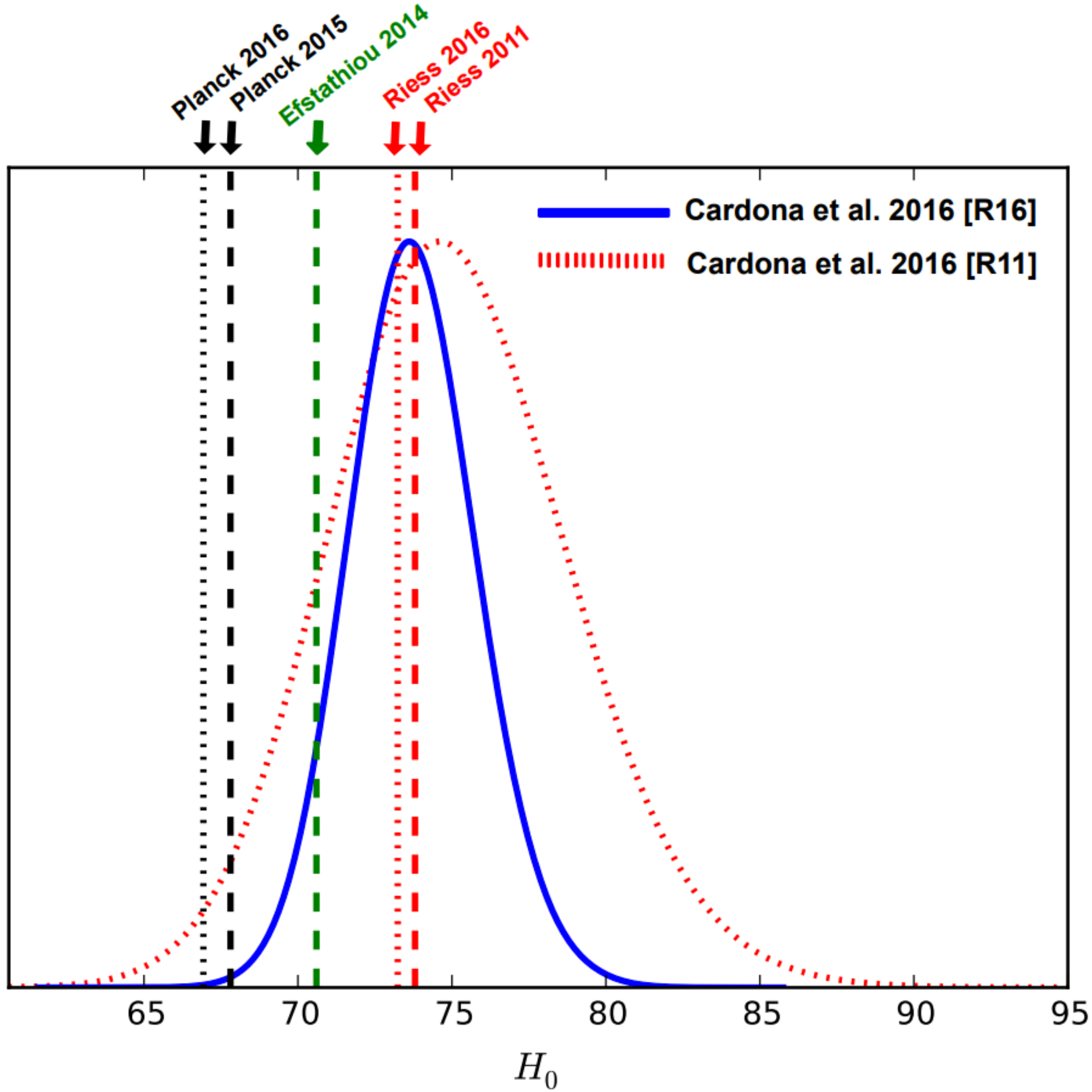
H0 (Planck) = 66.93±0.62 km s−1 Mpc−1

The choice of anchor distances affects the final value significantly: if we exclude the Milky Way from the anchors, then the value of H0 decreases.

Interesting also for theory: a tension can be explained adding early dark energy or modifying gravity



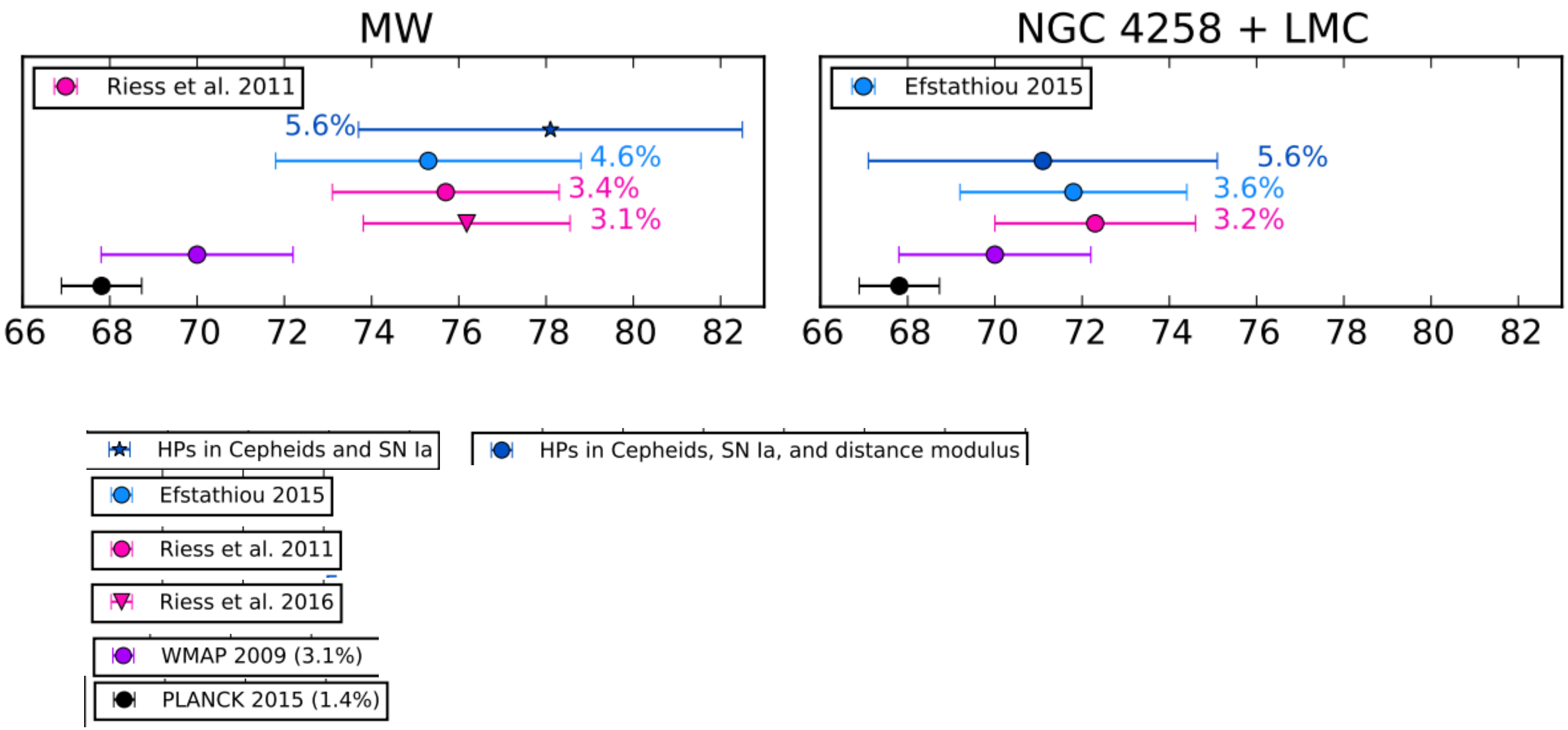
Low values of HPs might be due to unrecognised (or underestimated) systematics in the data sets



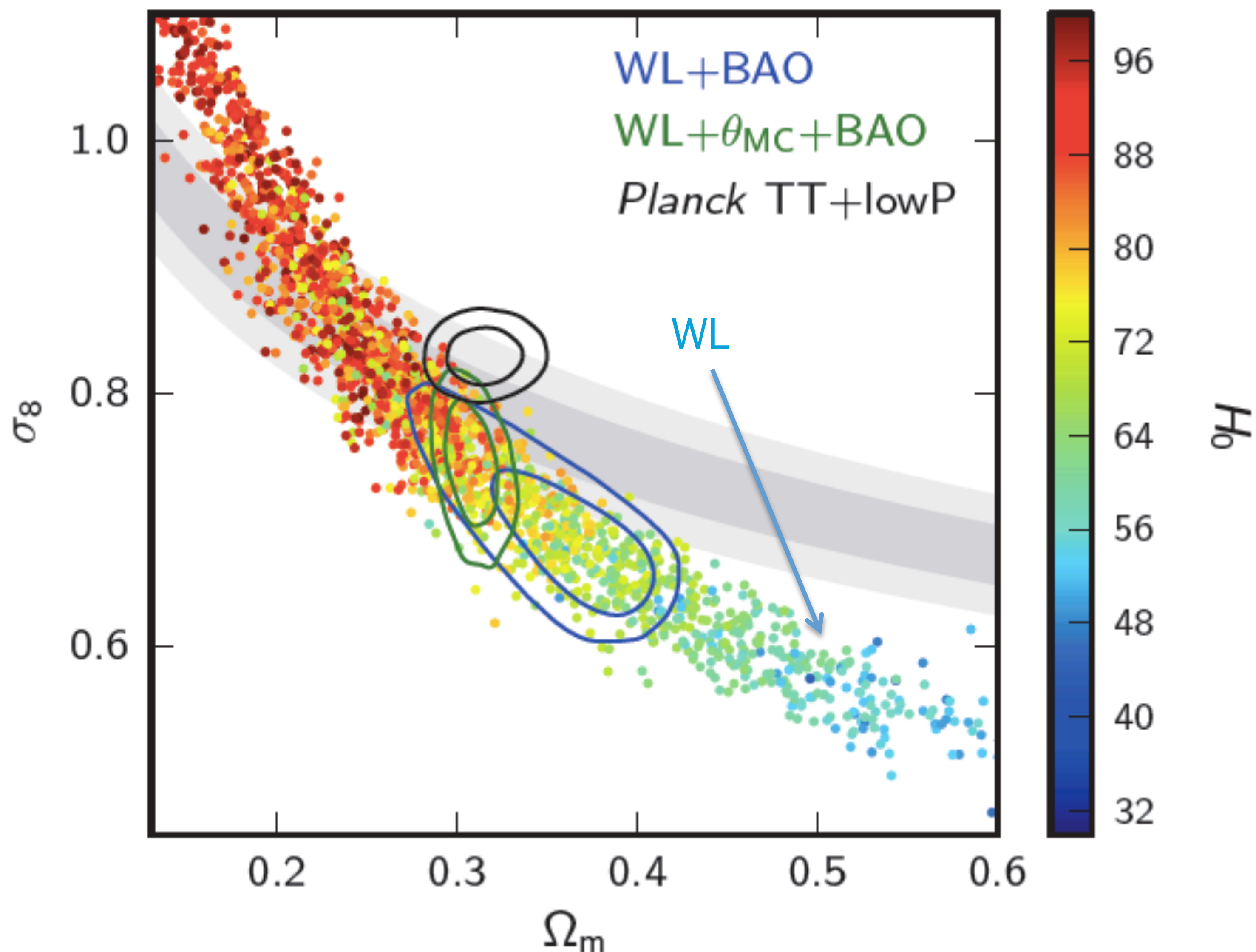
Planck 2016
Planck 2015
Efstathiou 2014
Riess 2016
Riess 2011
Cardona et al. 2016 [R16]
Cardona et al. 2016 [R11]
65
70
75
80
85
90
95
H_0

Robust against different assumptions in the analysis (e.g., period cut in the Cepheid variables data, prior on the metallicity parameter ZW of the period-luminosity relation, reddening law

the three sets of Cepheid variables in the galaxies LMC, MW, and NGC 4258 are consistent with each other: no argument to exclude any of them!

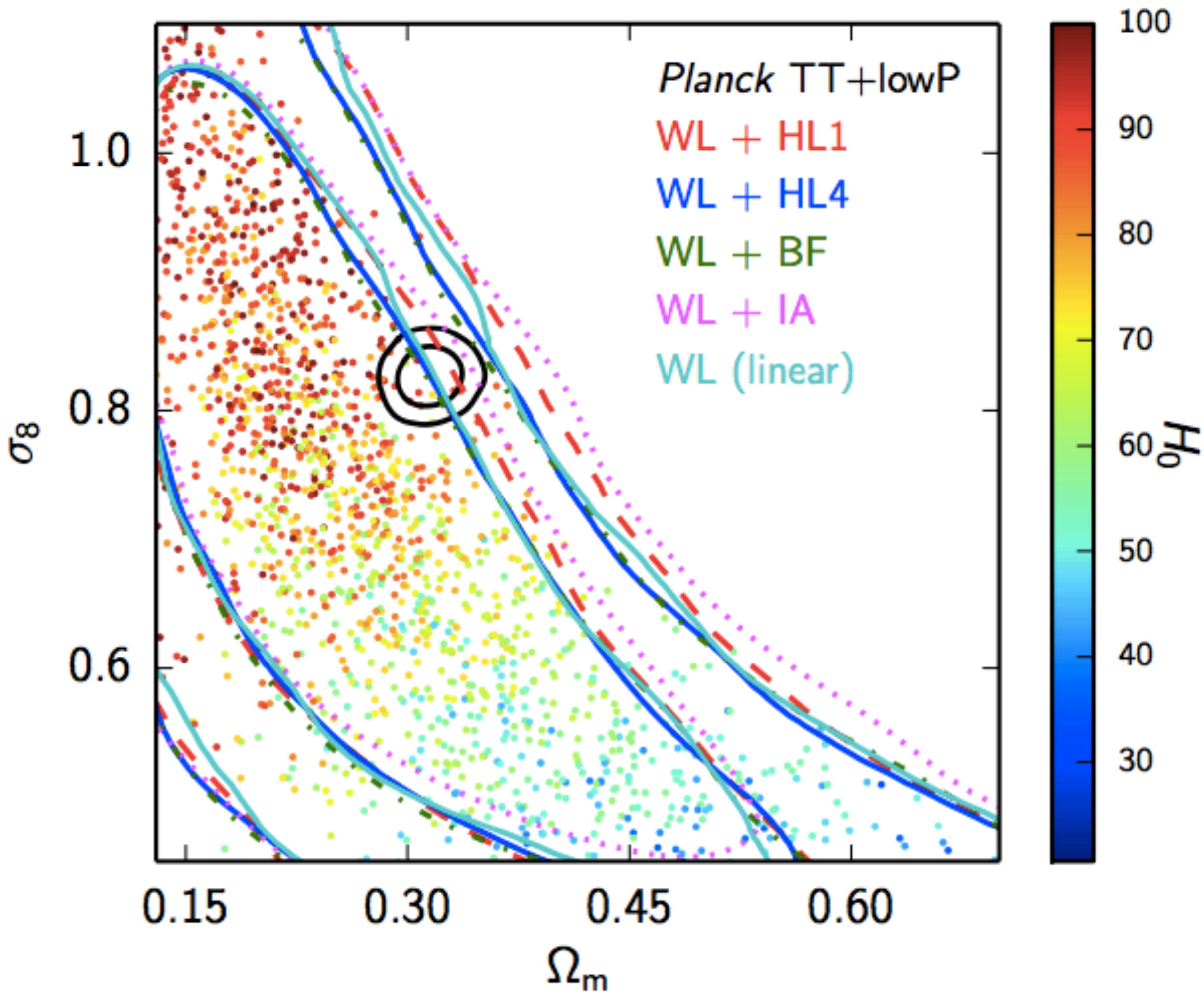


Comparing Planck with Weak Lensing



Planck cosmological parameter paper

Ultra conservative Weak Lensing



Astro-ph: 1502.01590
DE and MG Planck paper

Discarded almost all information at non-linear scales.

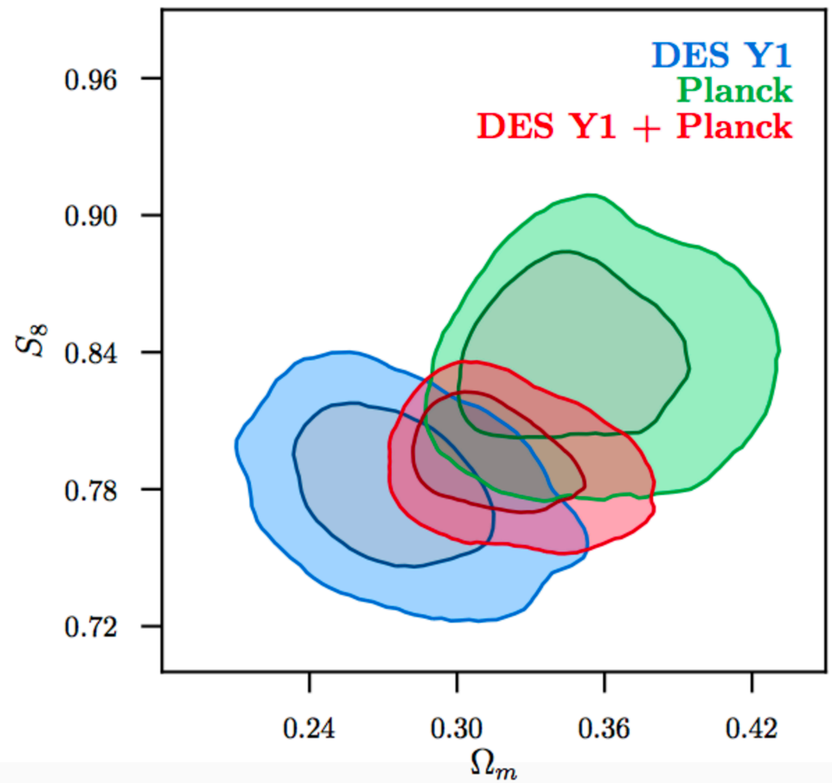
How do we model DE and MG at non-linear scales? Challenging and very much approximated even for LCDM

THE DARK ENERGY SURVEY

DES: arXiv:1708.01530v1

ΛCDM constraints from the three DES combined probes:

1) the cosmic shear correlation function of 26 million source galaxies in four redshift bins,
2) galaxy angular autocorrelation function of 650,000 luminous red galaxies (LRG) in five redshift bins
3) the galaxy-shear cross-correlation of LRG positions and source galaxy shears
4) Planck without CMB lensing



$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$

DES, comparing with Planck: https://arxiv.org/pdf/1708.01530.pdf

- DES Y1 constraints on Ω_m and S_8 in ΛCDM are competitive (in terms of their uncertainties) and compatible (according to tests of the Bayesian evidence) with constraints derived from Planck observations of the CMB. This is true even though the visual comparison (Figure 10) of DES Y1 and Planck shows differences at the 1 to 2-σ level, in the direction of offsets that other recent lensing studies have reported.

DES, comparing with KiDS

$$\begin{aligned} S_8 &= 0.797 \pm 0.022 \qquad \text{DES Y1} \\ &= 0.801 \pm 0.032 \qquad \text{KiDS+GAMA [62]} \\ &= 0.742 \pm 0.035 \qquad \text{KiDS+2dFLenS+BOSS [63]}, \end{aligned} \tag{VII.7}$$

<- [63] was claiming 2.6 sigma discordance with Planck

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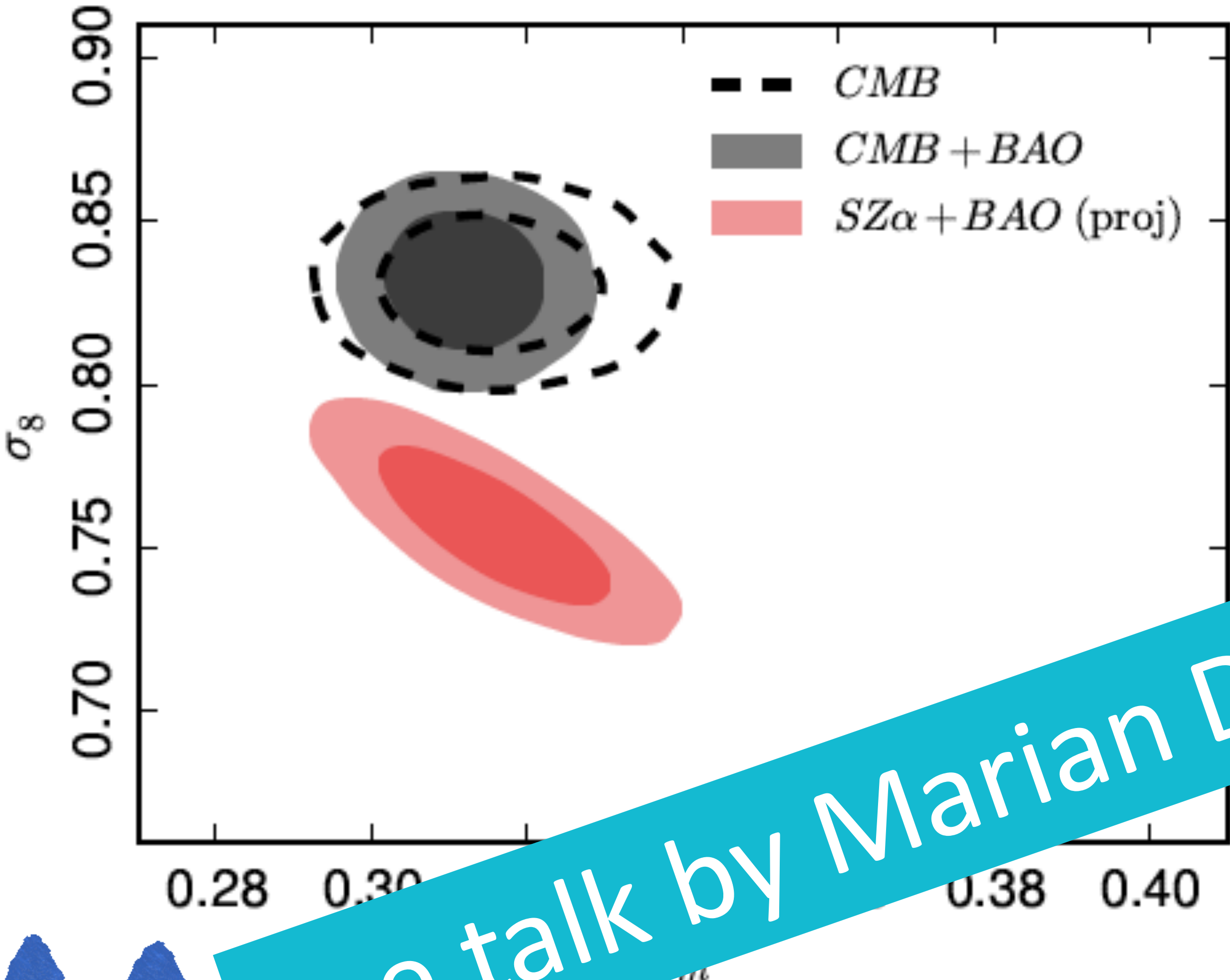
so we agree with KiDS+GAMA, but disagree with [63] at greater than 1-σ.

<- [63] was claiming 2.6 sigma discordance with Planck

Comparing Planck TT with clusters



Major uncertainty: mass calibration

Clusters prefer a lower value of σ_8

See talk by Marian Douspis)

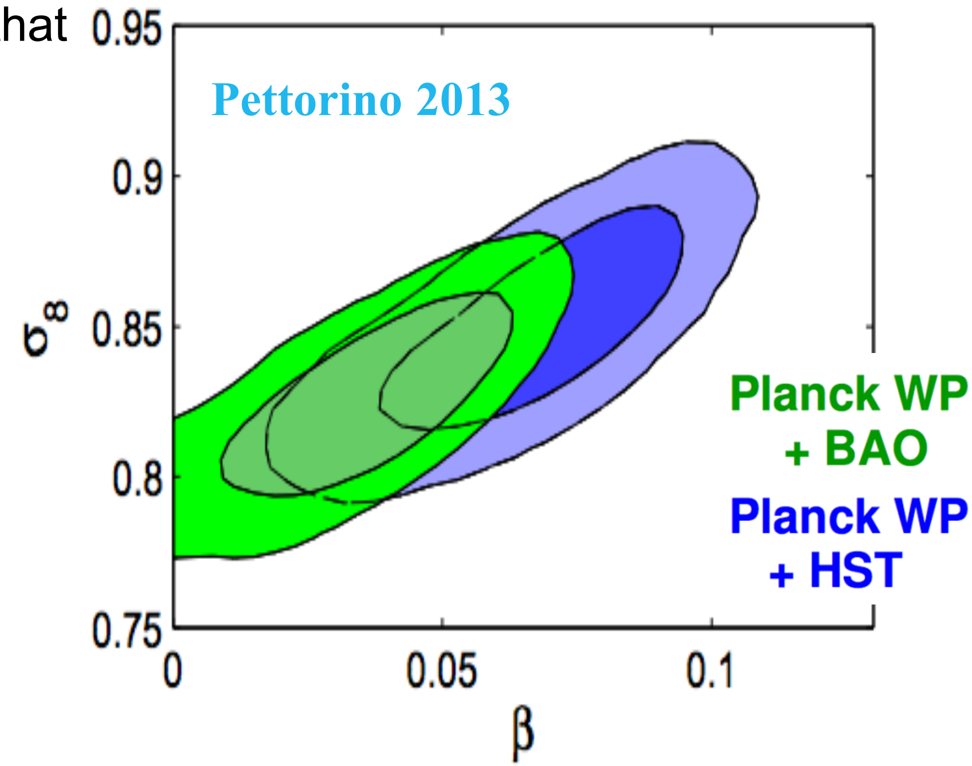
Astro-ph: 1502.01590

Can Modified Gravity release the tension?

Yes sure. A Coupling (i.e. fifth force), non-locality, a change in mu/eta, anything that effectively favors w < -1,
probably plenty of other ways..
can solve the tension

Planck WP + HST $\beta = 0.066 \pm 0.018$

A non zero coupling is favoured at 3.6 σ when using HST



Euclid can constrain
β at 2% (or $\omega_{JBD0} > 10^3$)

Comparable to interactions among atoms!

Amendola, Pettorino, Quercellini, Vollmer 2011

Prospects

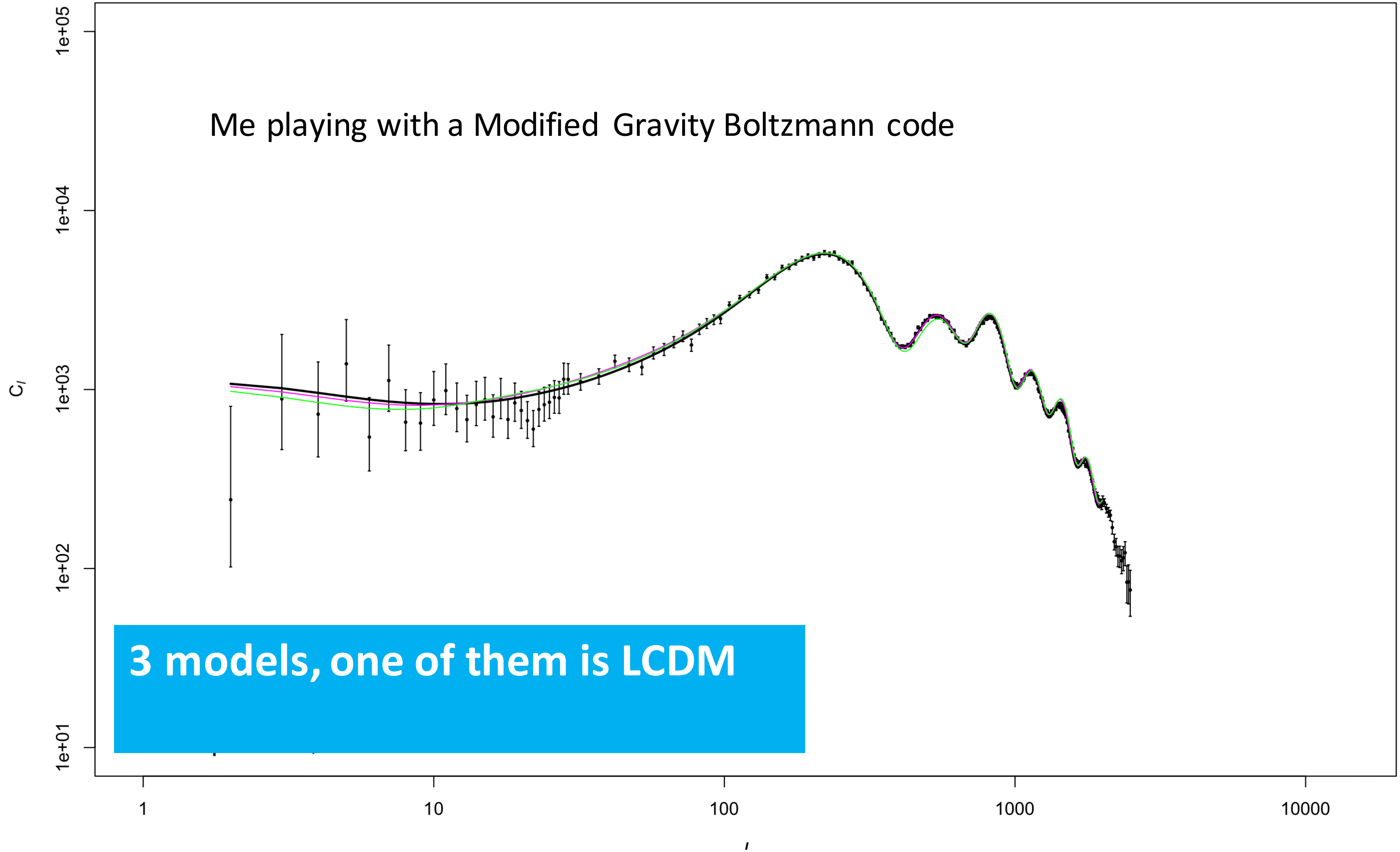
Challenge

$$\Lambda$$

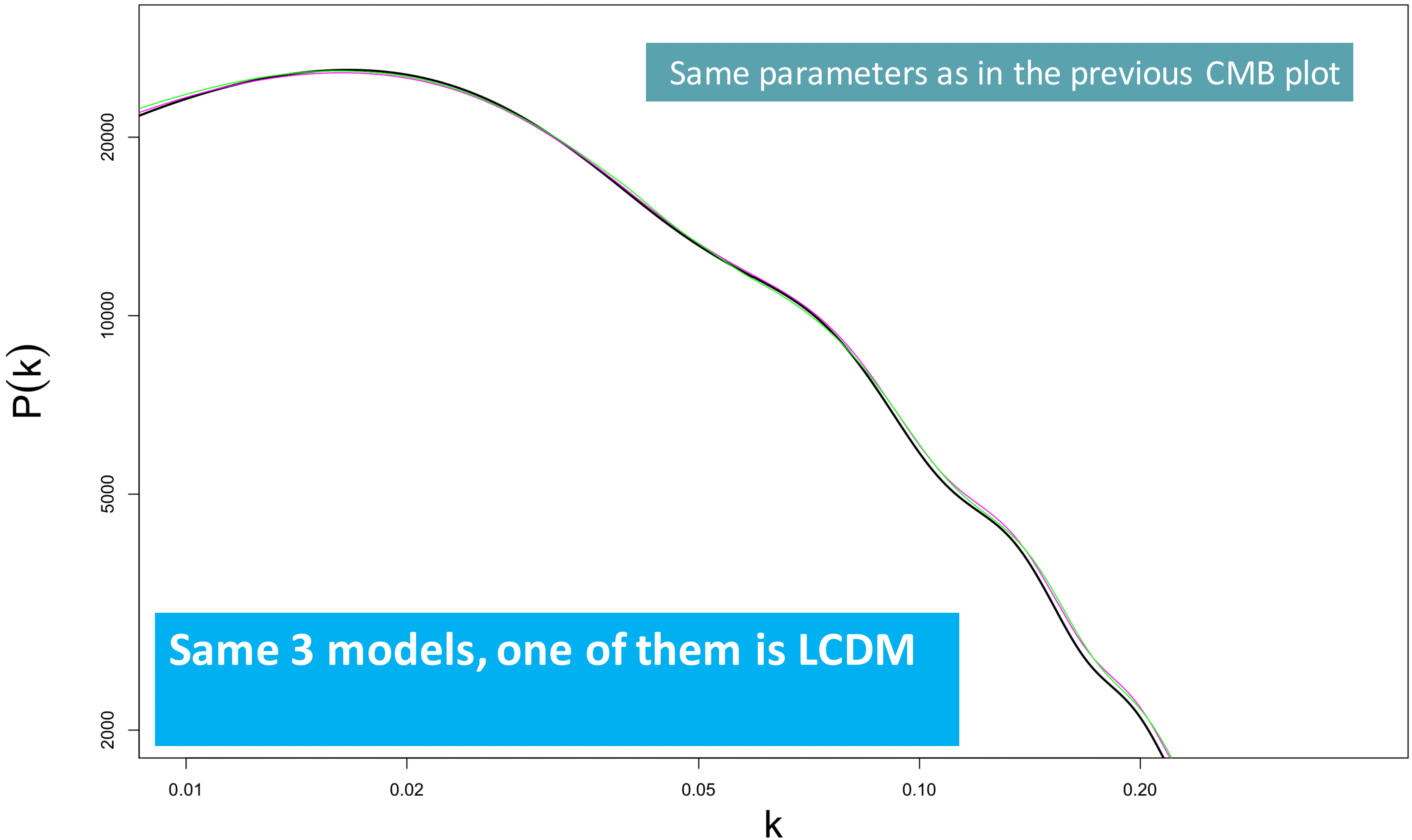
Can we falsify a cosmological constant?

Can we distinguish among the models present in literature?

Structure formation is the next challenge

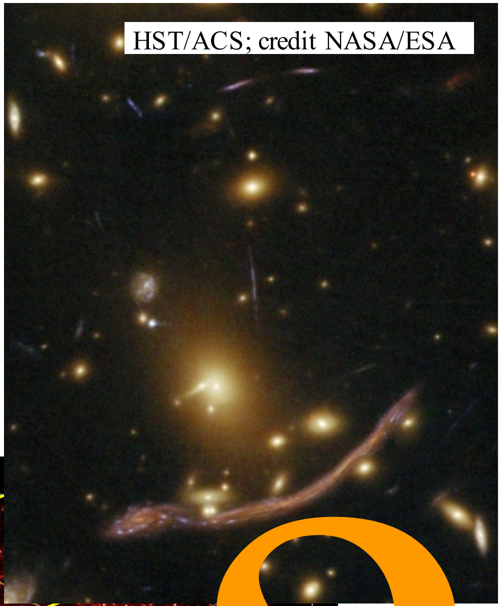


Me playing with a Modified Gravity Boltzmann code
3 models, one of them is LCDM
1e+05
1e+04
1e+03
1e+02
1e+01
C_l
1
10
100
1000
10000
l

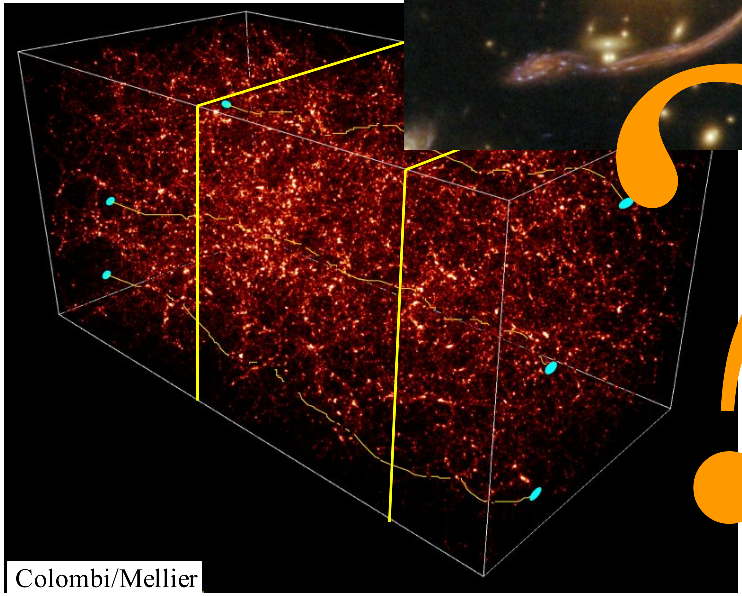


Same parameters as in the previous CMB plot
Same 3 models, one of them is LCDM
P(k)
20000
10000
5000
2000
0.01
0.02
0.05
0.10
0.20
k

New generation of experiments



using different probes scanning the sky in slices to test the growth of structure

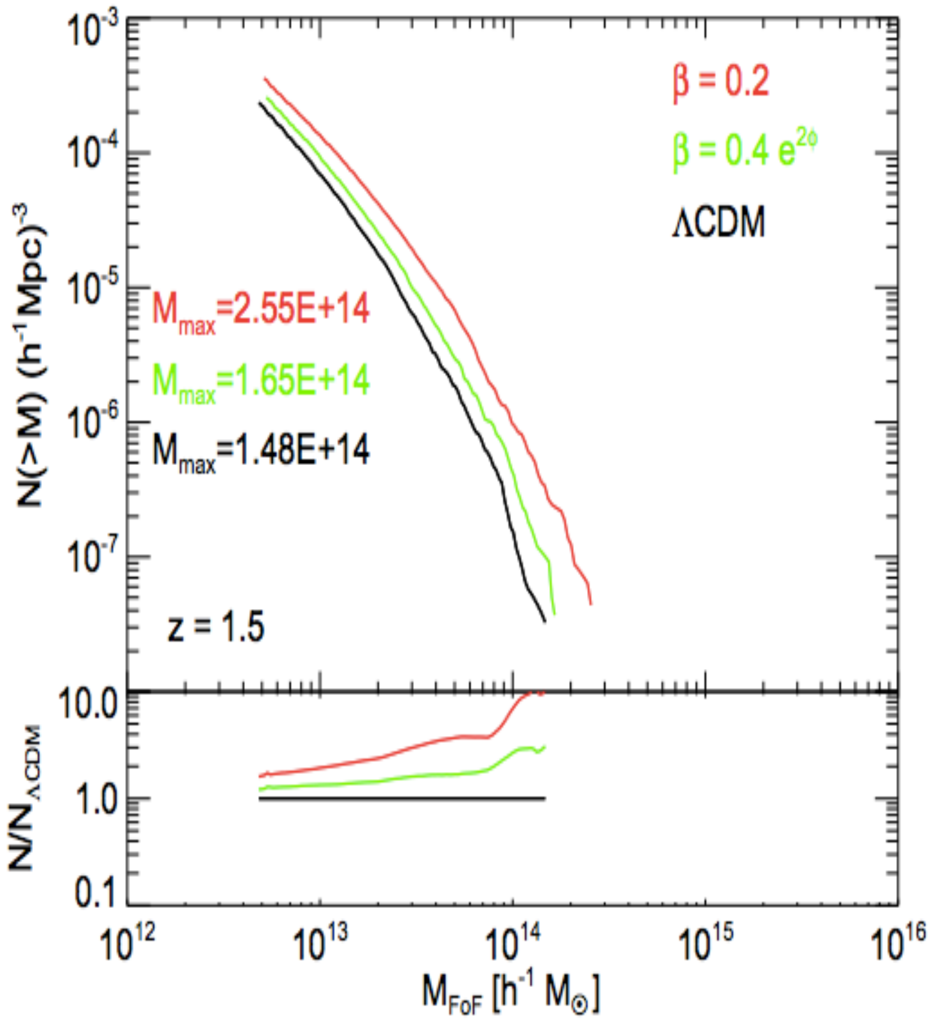


?

Cluster abundance in modified gravity

Pettorino Baccigalupi 2008
Baldi & Pettorino 2011
Baldi, Pettorino, Robbers, Springel 2008

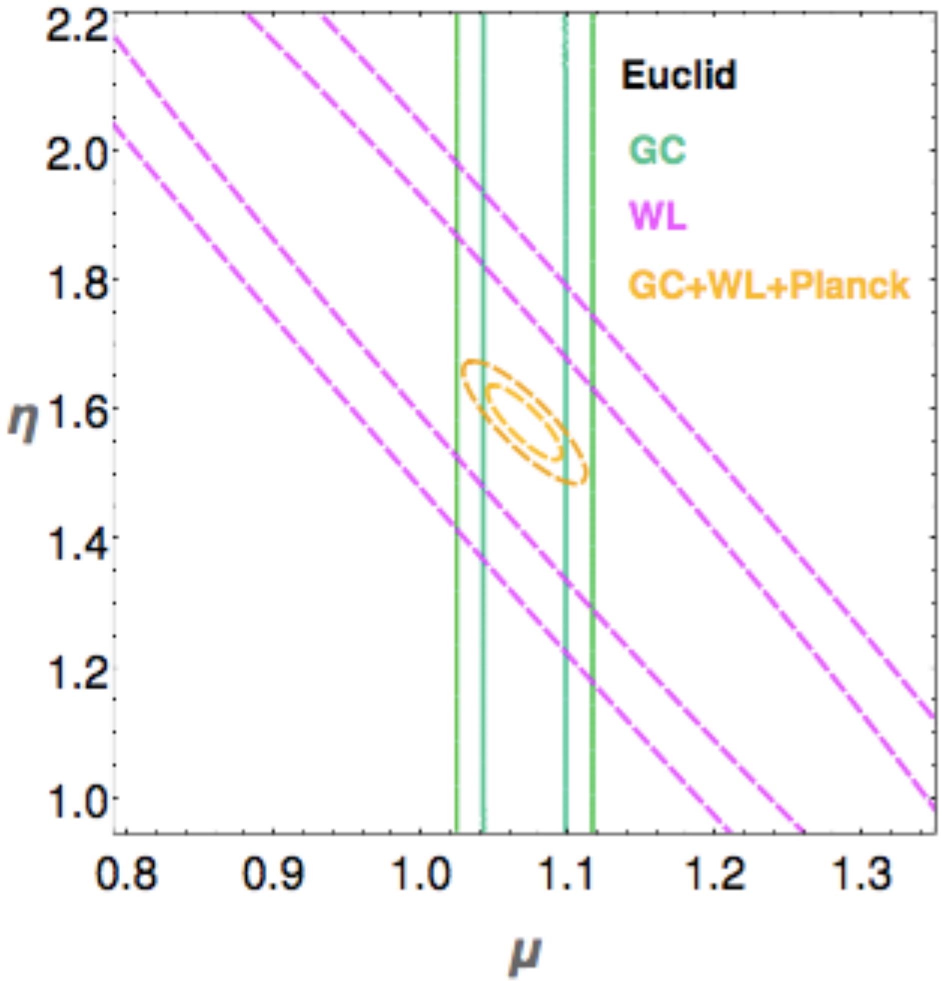
A fifth force can change the cluster abundance



Using the non-linear regime to decorrelate parameters

Casas et al 2017
arXiv:1703.01271

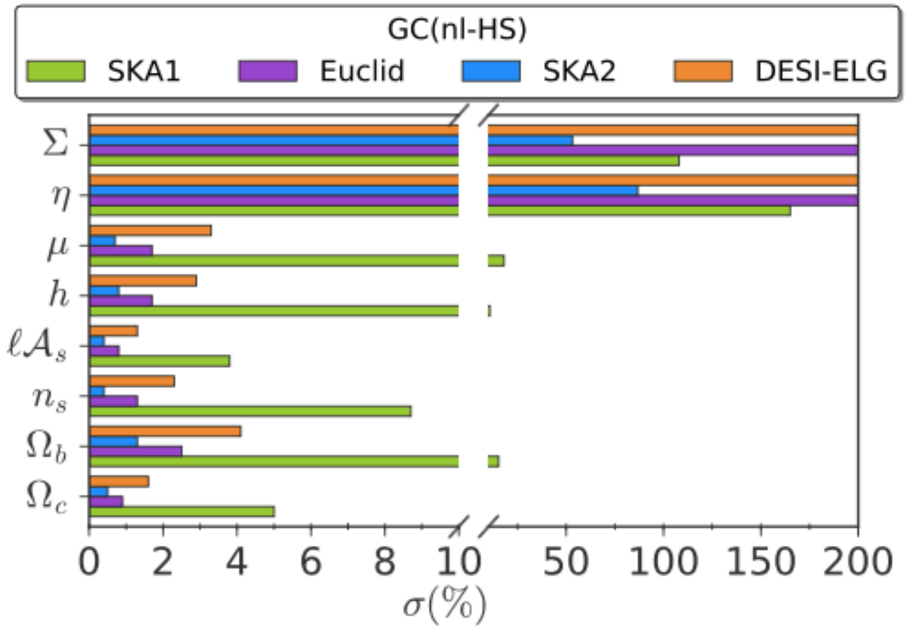
Combining GC and WL breaks degeneracies

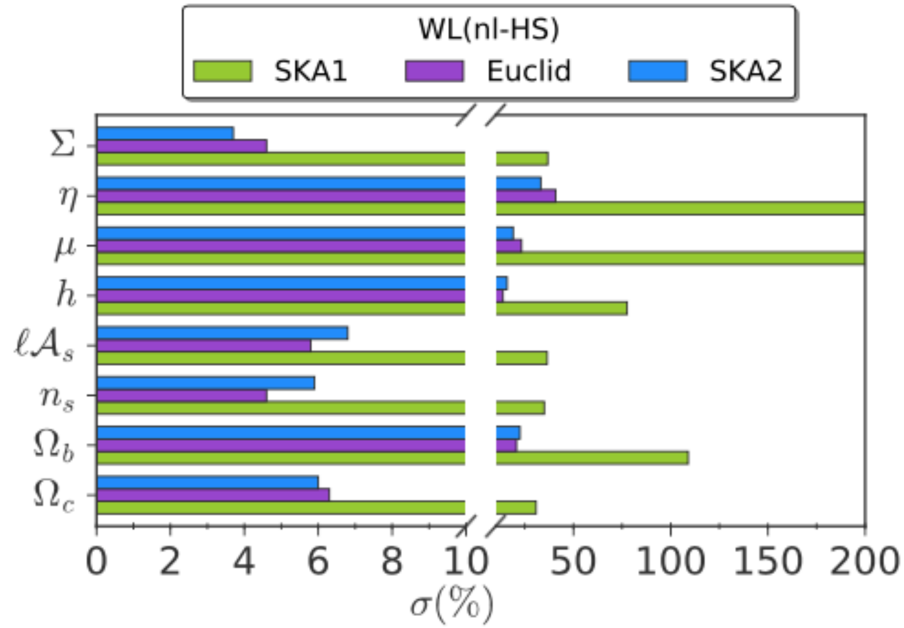


Casas et al 2017
arXiv:1703.01271

Different surveys

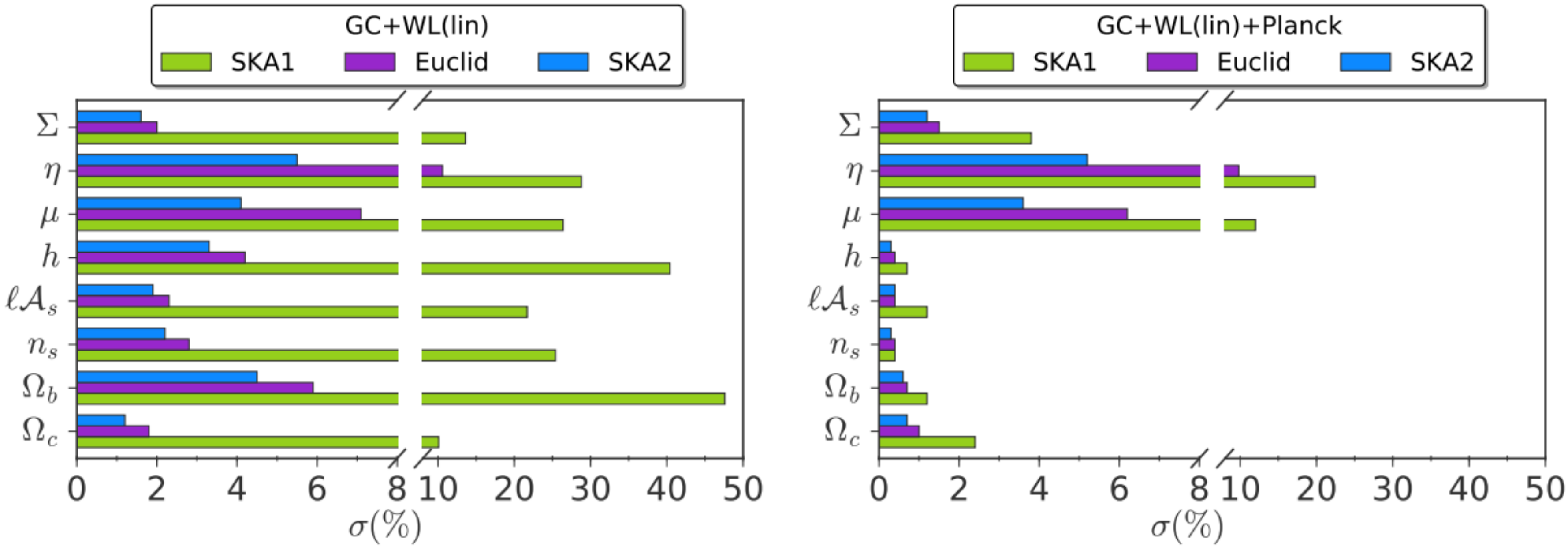
Casas et al 2017
arXiv:1703.01271



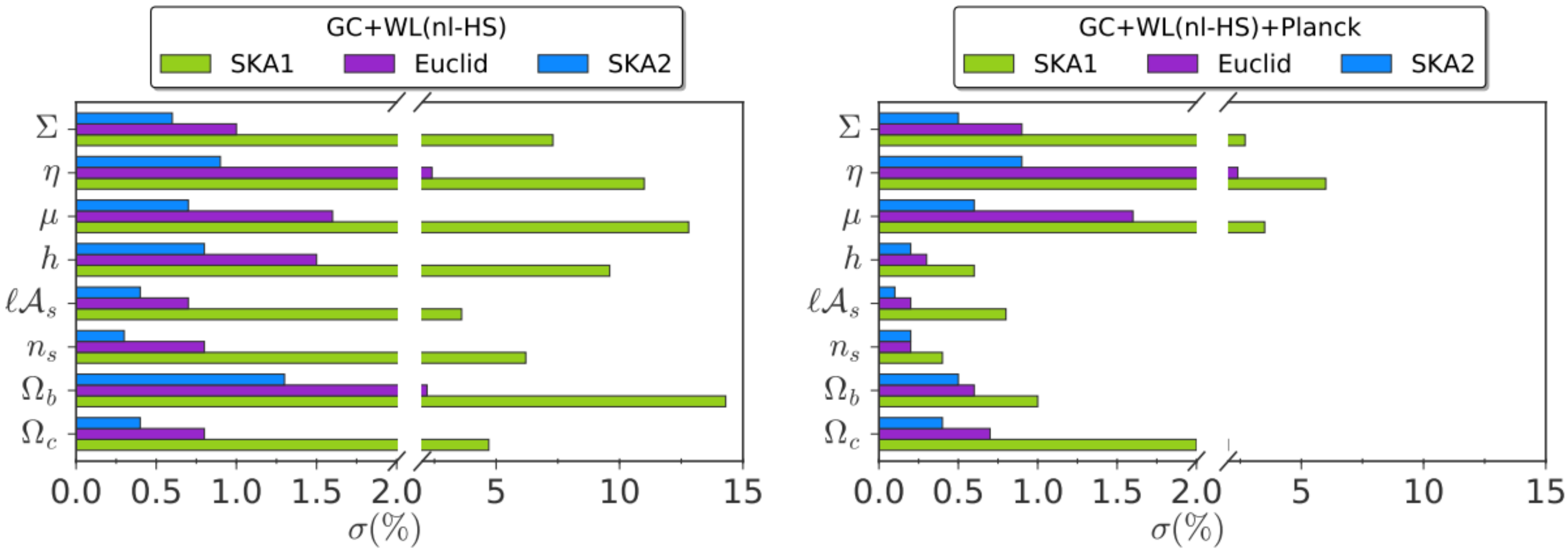


- On the standard parameters GC performs better than WL
- However, WL surveys perform better on MG parameters
- Euclid and SKA2 perform similarly well for the WL observable alone, if non-linearities are included

Casas et al 2017
arXiv:1703.01271

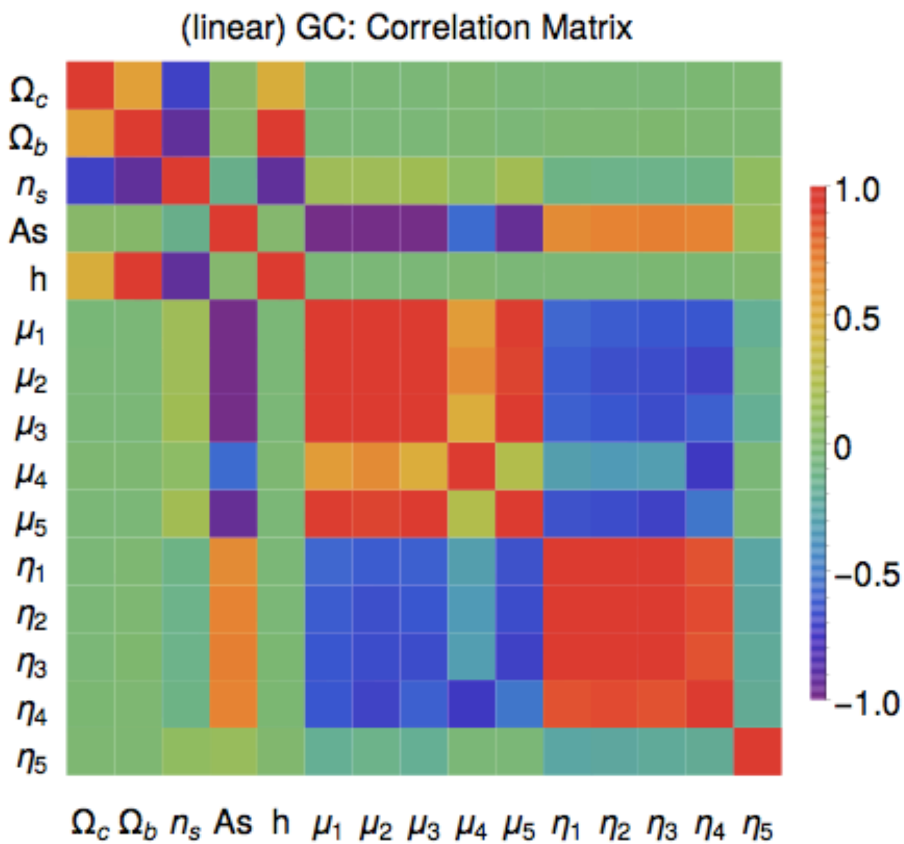


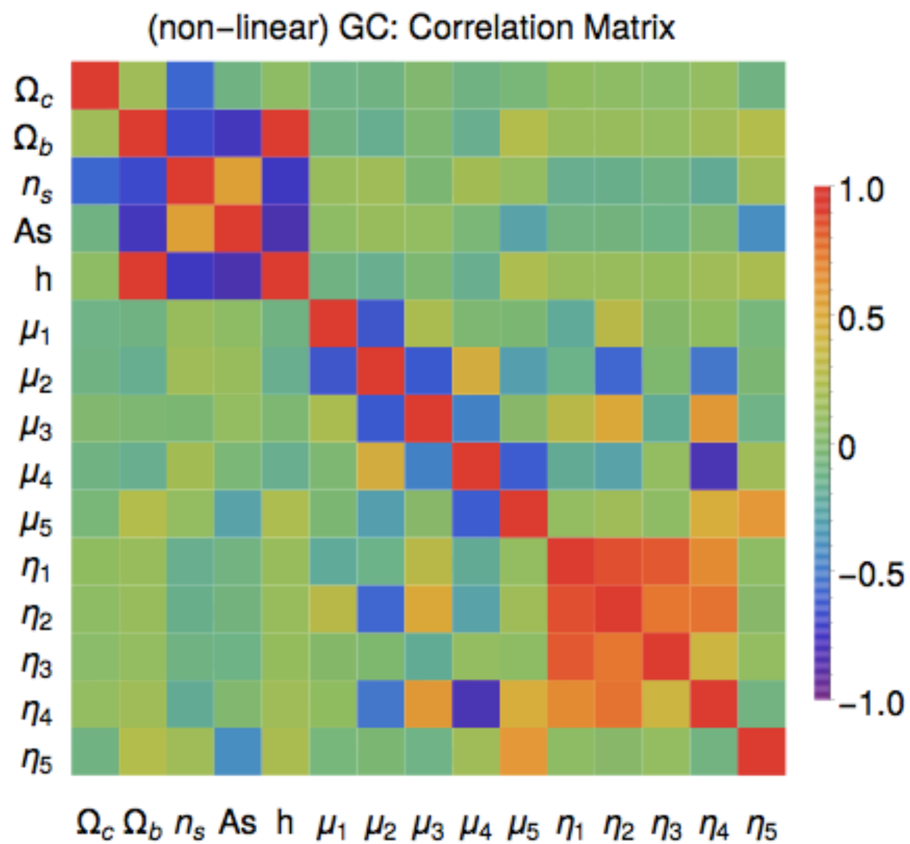
Casas et al 2017
arXiv:1703.01271



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**.

Non-linearities reduce correlation





Conclusions

Planck release is in very good agreement with a ΛCDM model

Tensions appear when combining Planck with external late time probes.

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

Challenges to be able to test DE and MG:
Predict the non-linear regime
Get reliable and fast codes
Identify the best observables to break degeneracies
…

Bright future for the Dark Universe! Join efforts in theory, data and statistical methods. This is only the start!