“Constraints on the Effective Field Theory from theory and observations”

Valentina Salvatelli

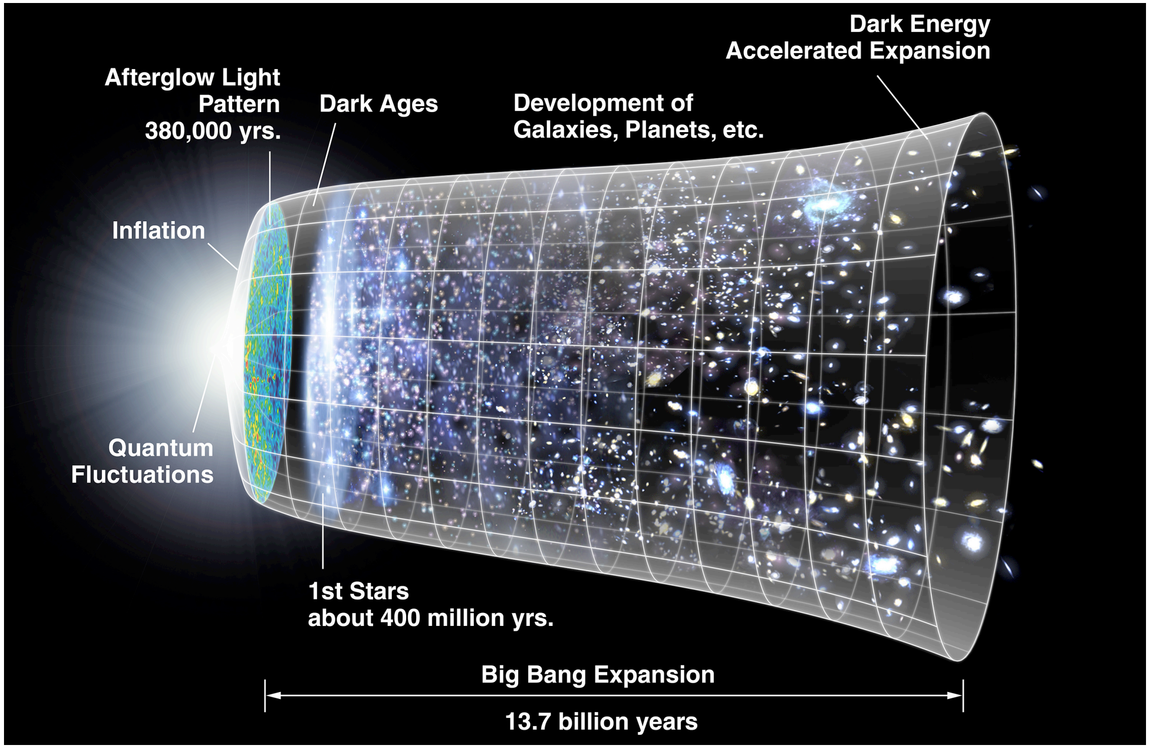
COBESIX meeting, February 9th 2016

Outline

- Introduction
- Short summary on the EFT of Dark Energy
- Current results from viability conditions and CMB measurements
- What's next?

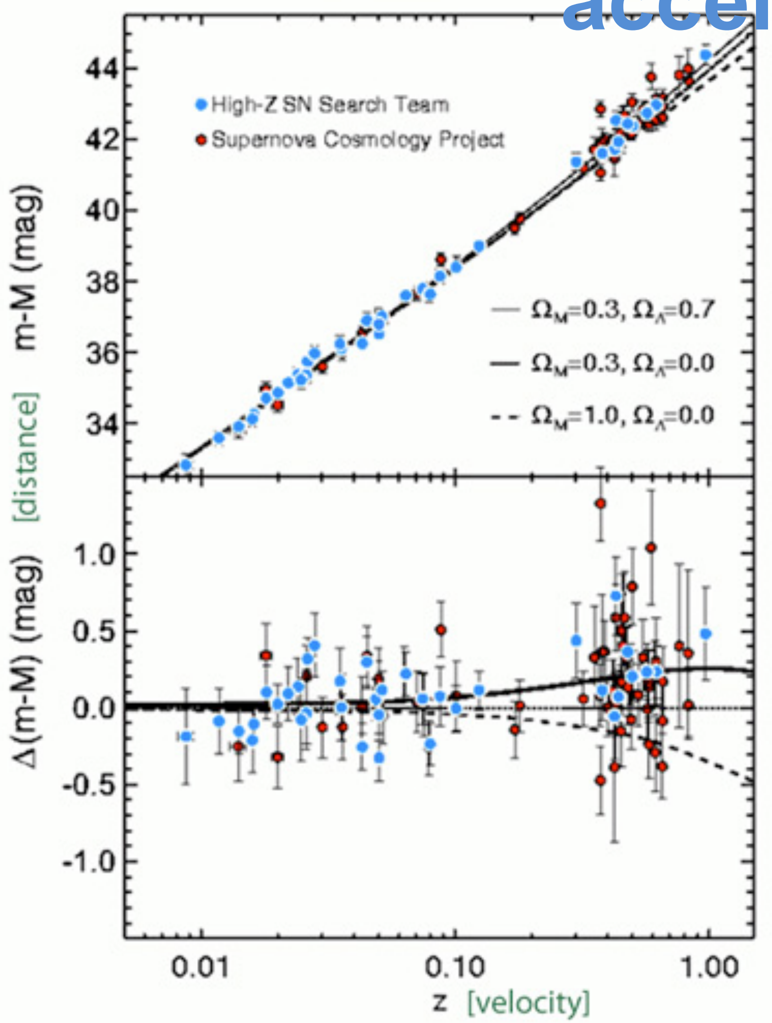
Introduction

The GR-based standard cosmological model, LCDM, is in good agreement with observations



yet it invokes an unknown dark matter component and a ‘not-very-well-understood’ cosmological constant

A matter-of-fact: **the universe is accelerating**



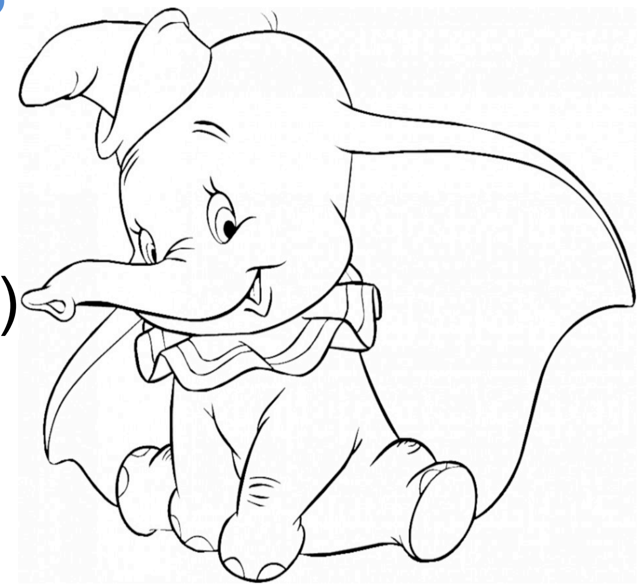
Nobel Prize

Physics 2011

What is sourcing the cosmic acceleration?

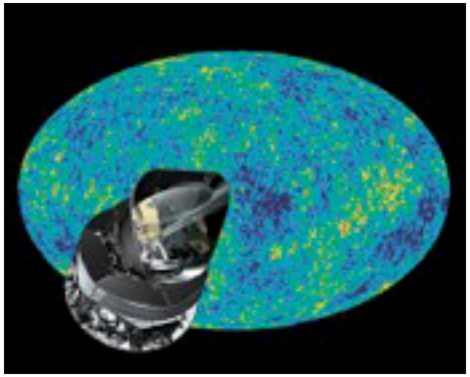
- Cosmological Constant

  (a good fitting solution so far)



- Dark Energy ?

- Modified gravity ?



Large Synoptic Survey Telescope

SDSS

DARK ENERGY SURVEY

On-going and short coming experiments have discriminating sensitivity to test gravity effects on cosmological scales

euclid consortium

EUCLID

Mapping the geometry of the dark Universe

PLANCK 2015: a big input to the field

- In February 2015 the Planck experiment released the first results from the full-mission measurements

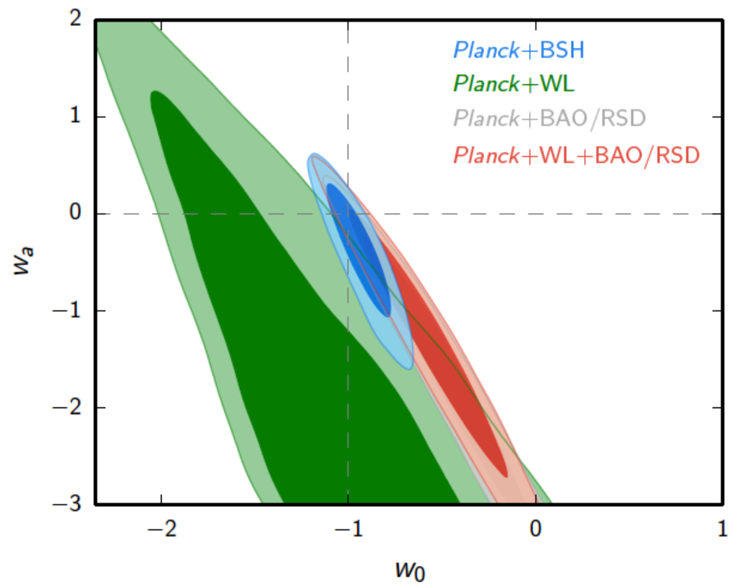
- In July 2015 all the likelihoods (temperature + polarization) became available

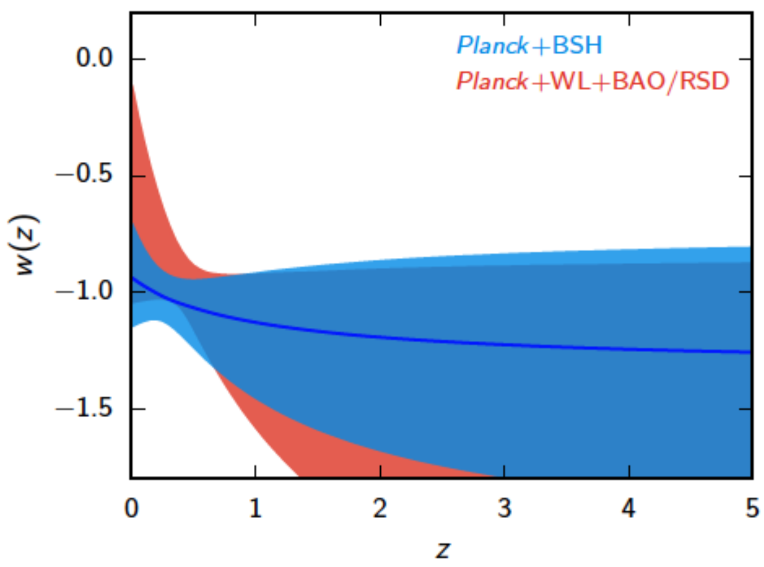
- One paper of the collaboration fully dedicated to the exploration of dark energy and modified gravity models (CMB and other probes)

Main outcomes of PLANCK

Scientific perspective:

➢ No evidence for significant deviation from LCDM at the background level.





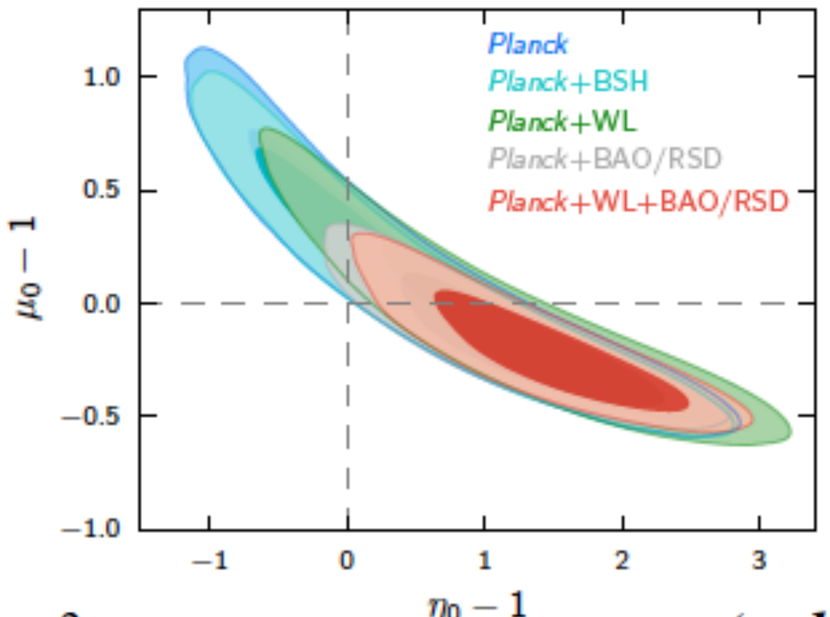
$$w(a) = w_0 + (1 - a)w_a$$

Planck 2015 results. XIV. Dark energy and modified gravity

Main outcomes of PLANCK

Scientific perspective:

- Some tensions emerge when changes in perturbations are considered (if we combine PLANCK with weak lensing/redshift surveys and we consider phenomenological parametrizations).



$$-k^2\Psi \equiv 4\pi G a^2\mu(a,\mathbf{k})\rho\Delta$$

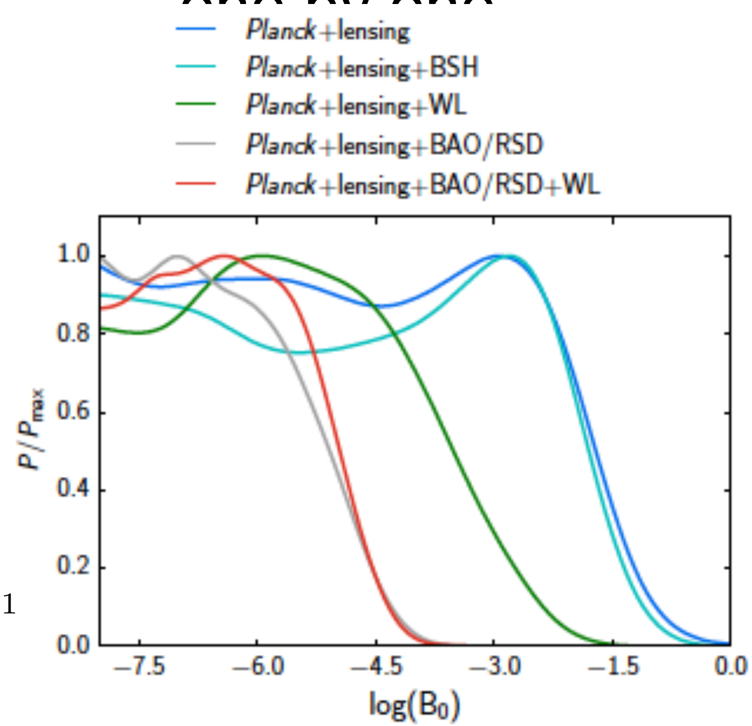
$$\eta(a,\mathbf{k}) \equiv \Phi/\Psi$$

Planck 2015 results. XIV. Dark energy and modified gravity

Main outcomes of PLANCK

Scientific perspective:

- No evidence for deviations when considering specific models, but very unpractical to test models one by one



i.e. f(R) case

$$B = \frac{f_{RR}}{1+f_R}\frac{dR}{d\ln a}\left(\frac{d\ln H}{d\ln a}\right)^{-1}$$

Planck 2015 results. XIV. Dark energy and modified gravity

The Effective Field Theory of Dark Energy

The origins

Effective Field Theory approach**:** *description of a system through the lowest dimensions operators compatible with the underlying symmetries*

Effective Field Theory of Inflation (Creminelli et al '06, Cheung et al. '07)

Main idea: the scalar field can be eaten by the metric (unitary gauge) $\phi(t,\vec{x}) \to \phi_0(t) \quad (\delta\phi = 0) \qquad -\frac{1}{2}\partial\phi^2 \to -\frac{1}{2}\dot{\phi}_0^2(t)\ g^{00}$

Effective Field Theory of Dark Energy (Gubitosi et al. 2012)

1 Assume WEP (universally coupled metric $S_m[g_{\mu\nu}, \Psi_i]$)

2 Write the most generic action compatible with residual unbroken simmetries (3-d spatial diff.)

The action

Dark energy effects encoded in 6 time functions

Gleyzes et al. 2013

Background (expansion history)

$$S = \int d^4x \sqrt{-g} \frac{M^2(t)}{2} \left[R - 2\lambda(t) - 2\mathcal{C}(t) g^{00} + \mu_2^2(t)(\delta g^{00})^2 - \mu_3(t)\delta K \delta g^{00} + \epsilon_4(t) \left(\delta K^\mu{}_\nu \delta K^\nu{}_\mu - \delta K^2 + \frac{R^{(3)}\delta g^{00}}{2} \right) + \dots \right]$$

only affect perturbations

Main advantages of the formalism:

1. Clear separation between background and perturbations quantities

Examples

$$S = \int d^4x \sqrt{-g} \frac{M^2(t)}{2} [R - 2\lambda(t) - 2\mathcal{C}(t) g^{00}$$
$$+ \mu_2^2(t)(\delta g^{00})^2 - \mu_3(t) \delta K \delta g^{00} + \epsilon_4(t) \left(\delta K^\mu{}_\nu \delta K^\nu{}_\mu - \delta K^2 + \frac{R^{(3)} \delta g^{00}}{2} \right) + \dots]$$

"Generalized Galileons" (≡ Horndeski) (Deffayet et al., 2011)

Main advantages of the formalism:

1. Clear separation between background and perturbations quantities
2. Unified language for several classes of dark energy/ modified gravity theories

Background redundancies/ separation

related by Friedmann eq.

$$S = \int d^4x \sqrt{-g}\, \frac{M^2(t)}{2} \left[R - 2\lambda(t) - 2\mathcal{C}(t) g^{00} \right.$$
$$\left. + \mu_2^2(t)(\delta g^{00})^2 - \mu_3(t)\, \delta K\, \delta g^{00} + \epsilon_4(t) \left(\delta K^\mu{}_\nu\, \delta K^\nu{}_\mu - \delta K^2 + \frac{R^{(3)}\, \delta g^{00}}{2} \right) + \dots \right]$$

also participates in perturbations

$$\lambda(t),\ \mathcal{C}(t),\ \mu(t) \equiv \frac{d \ln M^2(t)}{dt}$$

$\bar{w}(t)$ Expansion History

$\mu(t)$

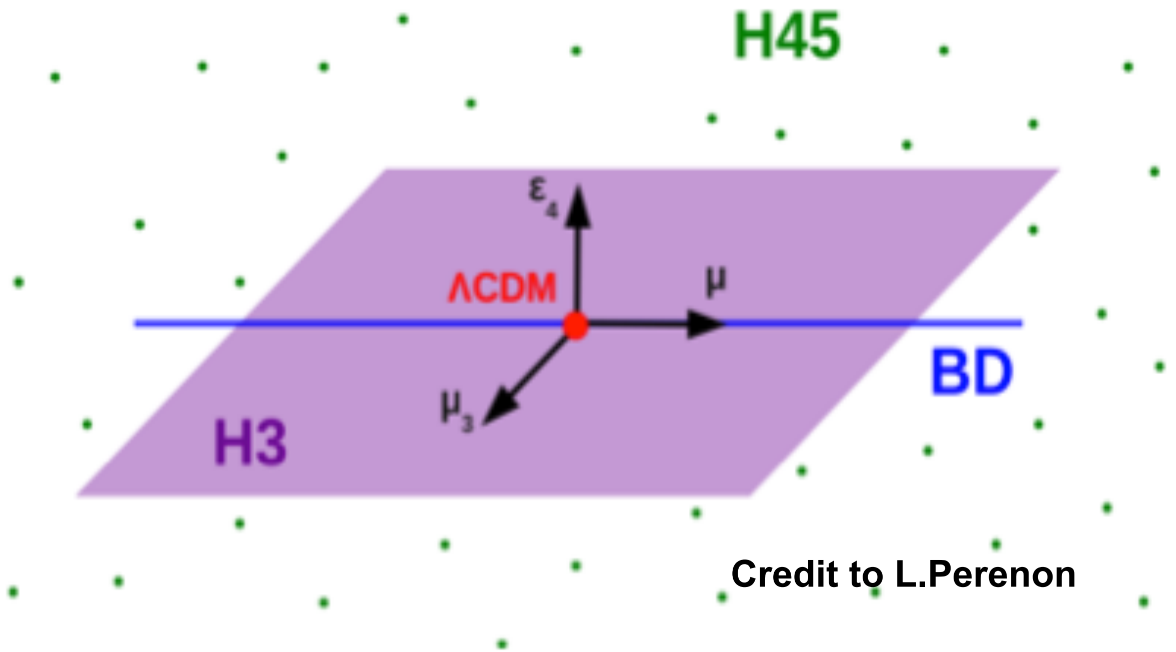
$\mu_3(t)$

$\epsilon_4(t)$ Perturbation sector

$\mu_2^2(t)$

Piazza et al. 2013

Why these functions?



- The advantage of choosing this set of functions is to work out constraints while maintaining a clear link with the theory space

Alternatives set of functions

Linked to physical effects

Bellini-Sawicki Parametrizatio n (HiCLASS)

$$M_* = M\sqrt{(1+\epsilon_4)}$$

$$\alpha_M = \frac{\dot{\epsilon}_4}{H(1+\epsilon_4)} + \frac{\mu}{H}$$

$$\alpha_K = \frac{2C + 4\mu_2^2}{H^2(1+\epsilon_4)}$$

$$\alpha_B = \frac{\mu_3 - \mu}{H(1+\epsilon_4)}$$

$$\alpha_T = -\frac{\epsilon_4}{1+\epsilon_4}$$

Linked to theory

$$\Omega = \frac{M^2}{m_0^2} - 1$$

$$\gamma_1 = \frac{(1+\Omega)\mu_2^2}{H_0^2}$$

$$\gamma_2 = \frac{1}{H_0}\left[(1+\Omega)(\mu - \mu_3) - \mathcal{H}\Omega'\right] = -\frac{(1+\Omega)\mu_3}{H_0}$$

$$\gamma_3 = (1+\Omega)\epsilon_4$$

$$\gamma_4 = -(1+\Omega)\epsilon_4$$

EFTCAMB parametrization

Constraints from theory and observations on the EFT of DE

Preliminary steps of the analysis:

- Which parametrization for the EFT functions?

- How to compute the observables in terms of the EFT parameters?

Which parametrization for the EFT functions?

No effects at early-time

$$\mu(x) = (1-x)\left[p_1 + p_1^{(1)}(x - x_0)\right] H(x)\,,$$

$$\mu_3(x) = (1-x)\left[p_3 + p_3^{(1)}(x - x_0)\right] H(x)\,,$$

$$\epsilon_4(x) = (1-x)\left[p_4 + p_4^{(1)}(x - x_0)\right]\,,$$

EFT free parameters

Fractional matter density

$$x = \frac{x_0}{x_0 + (1-x_0)(1+z)^{3w_{\rm eff}}}$$

$$x_0 \equiv \frac{\rho_m(t_0)}{3M_{\rm Pl}^2 H_0^2}$$

$$\boxed{p_1^{(1)} = \frac{p_1 \log(x_0) - 6\log\left(1 + (1-x_0)p_4\right)}{1 - x_0 + x_0\log(x_0)}}$$

Constrain due to No-early-DE condition

How to compute the observables in terms of the EFT parameters?

- Straight way : solving the full set of EFT equations

  PRO: exact solution

  CON: hard numerical issues

the EFT formalism

PRO: easier computation

CON: relying on some approximations (QSA)

In this analysis we go for the 2nd way

Effective Newton constant & gravitational slip parameter

Effective Newton constant (satysfying the standard Poisson equation)

$$G_{\rm eff} = \frac{1}{8\pi M^2(1+\epsilon_4)^2}\,\frac{2\mathcal{C}+\mathring{\mu}_3-2\dot{H}\epsilon_4+2H\mathring{\epsilon}_4+2(\mu+\mathring{\epsilon}_4)^2}{2\mathcal{C}+\mathring{\mu}_3-2\dot{H}\epsilon_4+2H\mathring{\epsilon}_4+2\dfrac{(\mu+\mathring{\epsilon}_4)(\mu-\mu_3)}{1+\epsilon_4}-\dfrac{(\mu-\mu_3)^2}{2(1+\epsilon_4)^2}}\,.$$

- Scale-dependent terms negligible if the scalar degree of freedom is responsible for cosmic acceleration

Gravitational slip paramet $\eta \equiv \frac{\Psi}{\Phi}$ **)**

$$\eta = 1-\frac{(\mu+\mathring{\epsilon}_4)(\mu+\mu_3+2\mathring{\epsilon}_4)-\epsilon_4(2\mathcal{C}+\mathring{\mu}_3-2\dot{H}\epsilon_4+2H\mathring{\epsilon}_4)}{2\mathcal{C}+\mathring{\mu}_3-2\dot{H}\epsilon_4+2H\mathring{\epsilon}_4+2(\mu+\mathring{\epsilon}_4)^2}$$

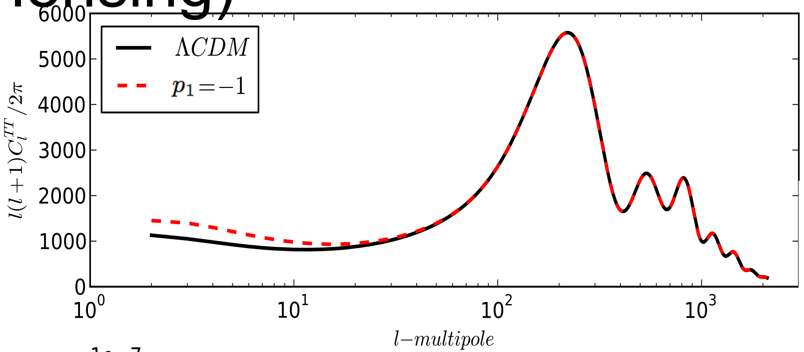
$$\mathring{\mu}_3 \equiv \dot{\mu}_3+\mu\mu_3+H\mu_3,$$
$$\mathring{\epsilon}_4 \equiv \dot{\epsilon}_4+\mu\epsilon_4+H\epsilon_4\,.$$

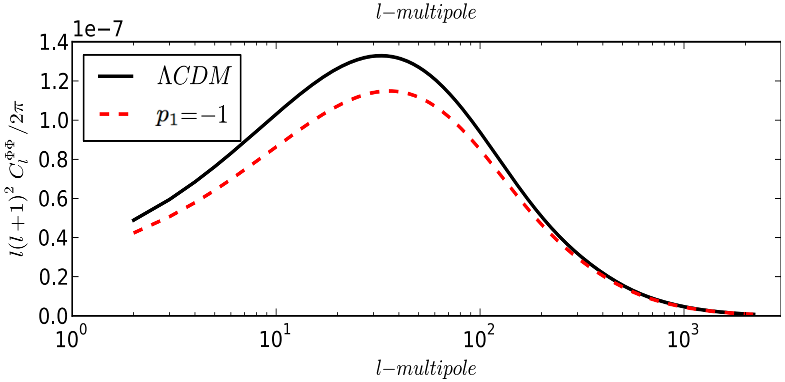
Piazza et al. 2013

Perenon et al. 2015

Data sets

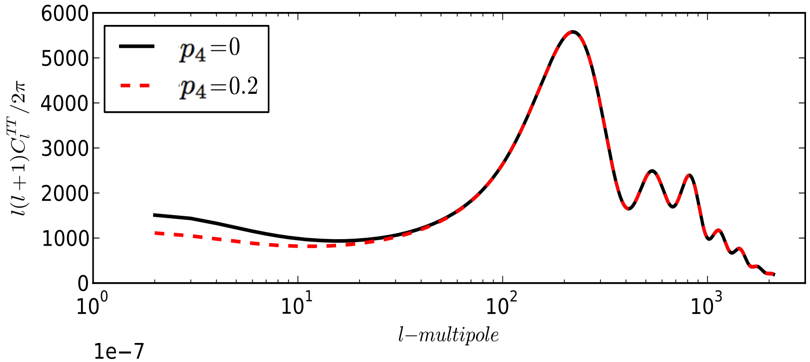
Planck 2015 (temperature + lowl polarization+ CMB lensing)

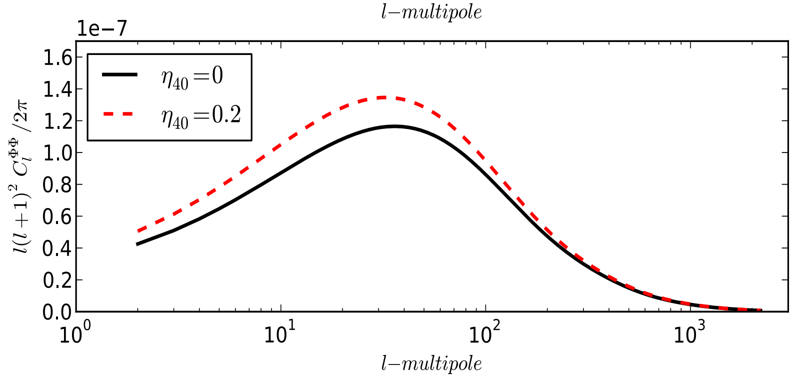




Main effects:

- ISW effect at TT low-l
- CMB lensing amplitude





Different parameters have similar effects

Theoretical viability conditions

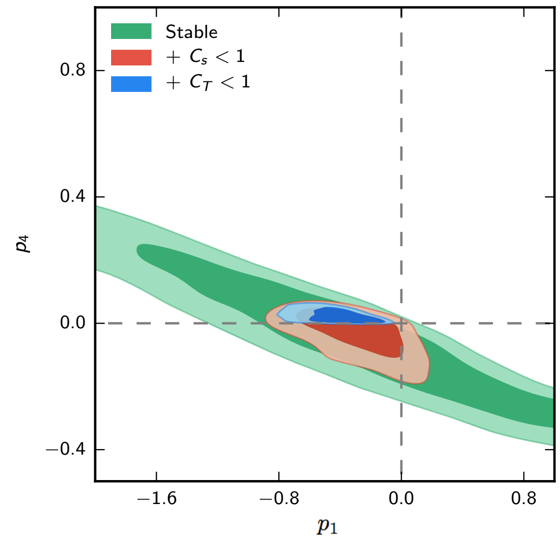
3 scenarios **Always enforced**

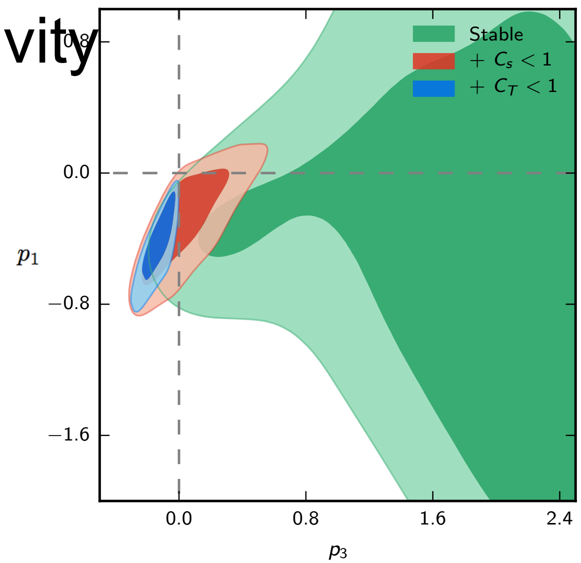
Results (Taylor expansion at 0th order):

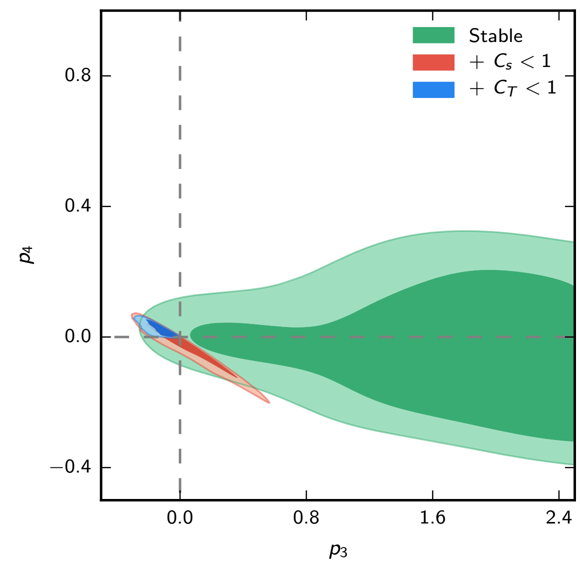
- p1, p4 are highly correlated

selective

compensate for the observational unsensitivity

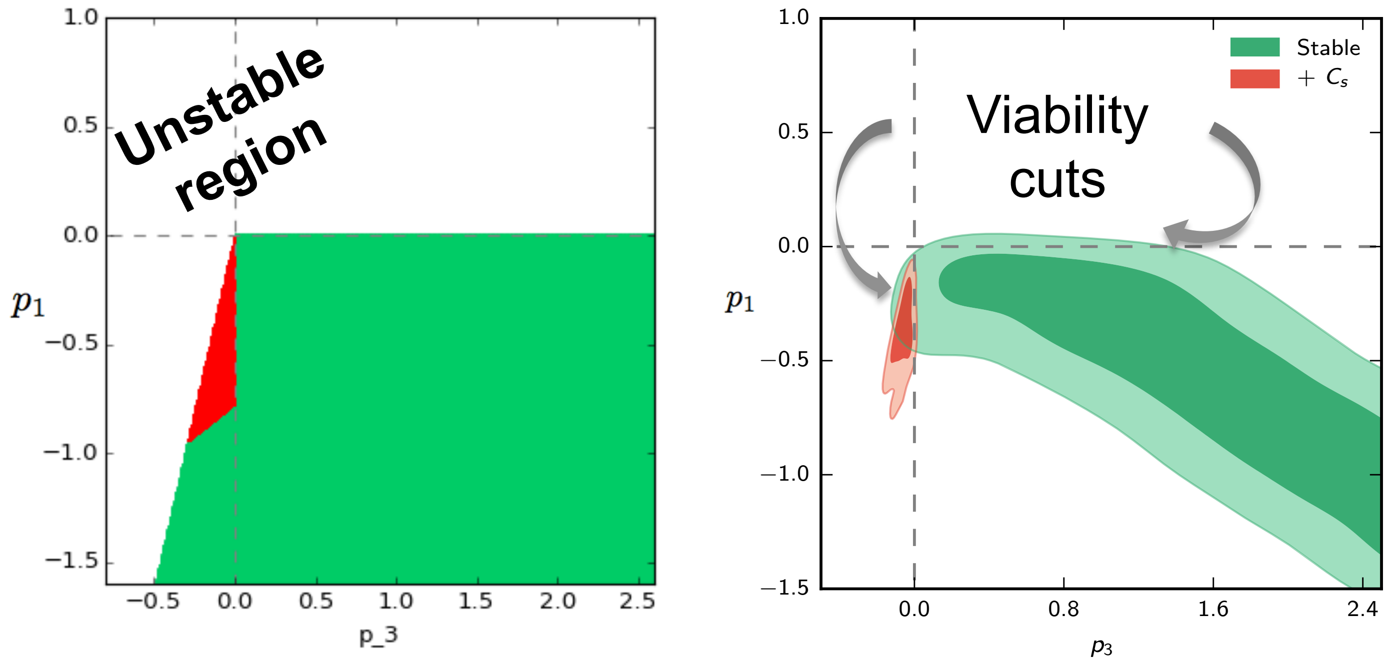






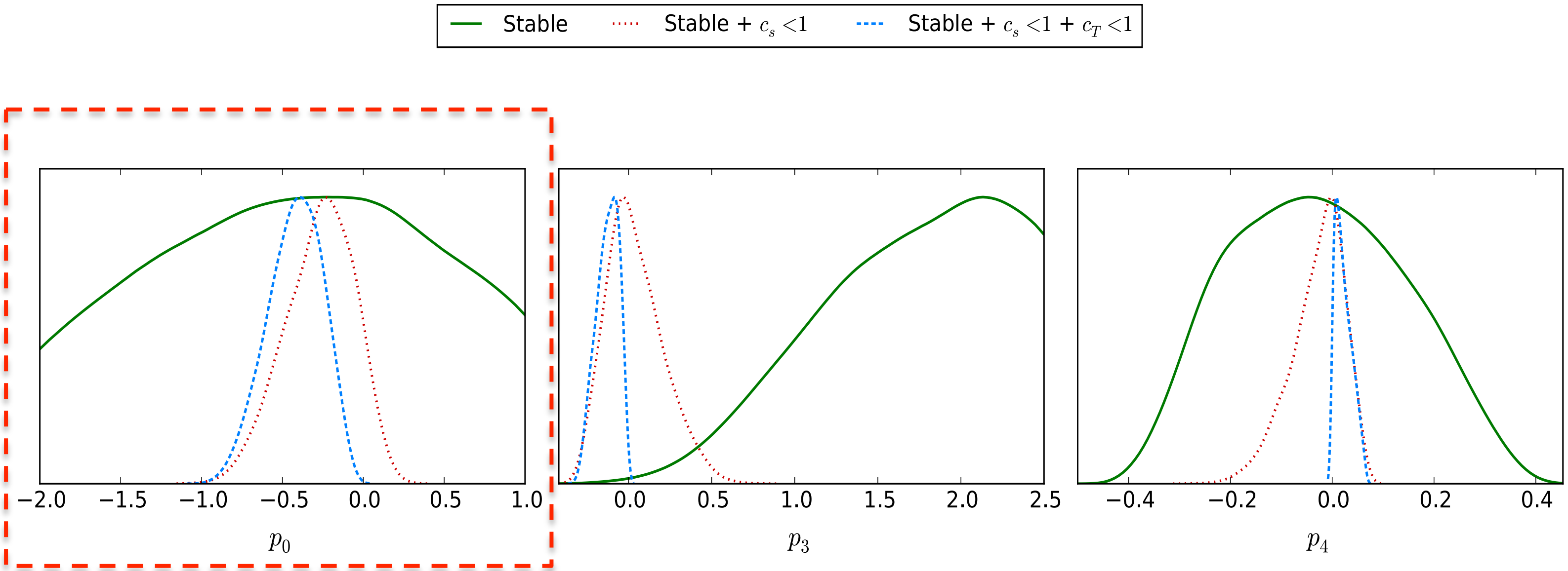
How the viability affects the constraints ?

An example easy to see : let's fix p4=0



Note: LCDM is always at the border of the stable region

Results (Taylor expansion at 0th order):



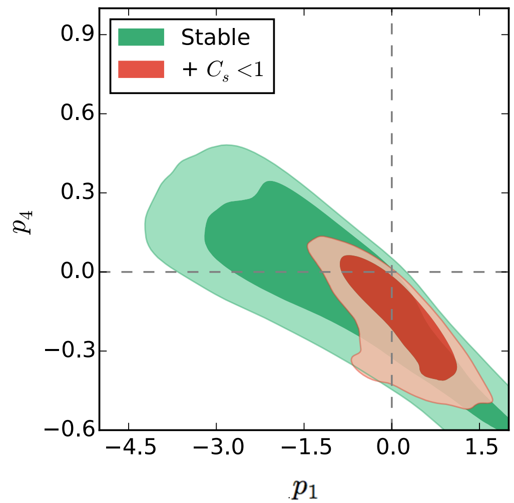
- No deviations from GR in p3 and p4
- A negative p1 is favoured by current measurements ?

… Not really. The chi-square do not improve!

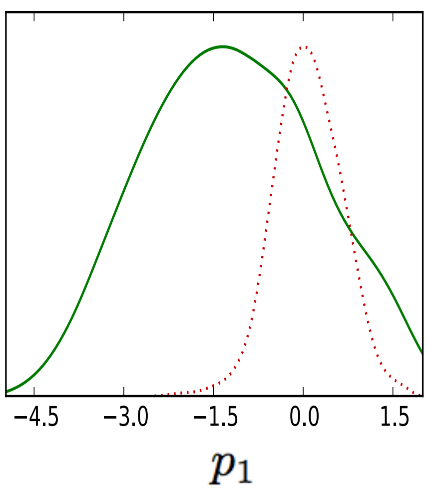
Maybe is an artefact of the chosen EFT parametrization. Let’s try with more freedom in the Taylor expansion

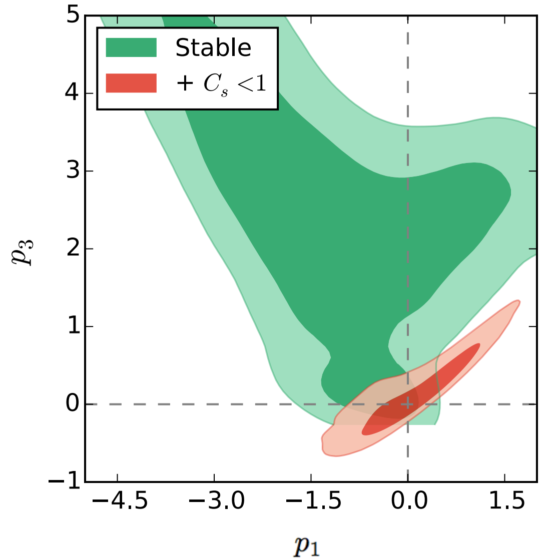
Results (Taylor expansion at 1th order):

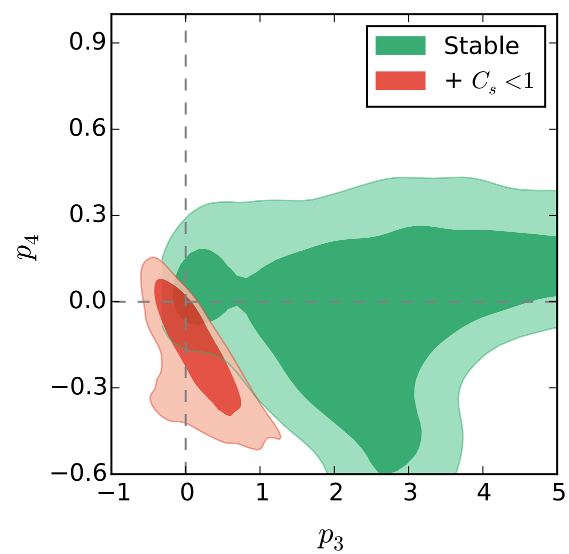
- More freedom → larger contours



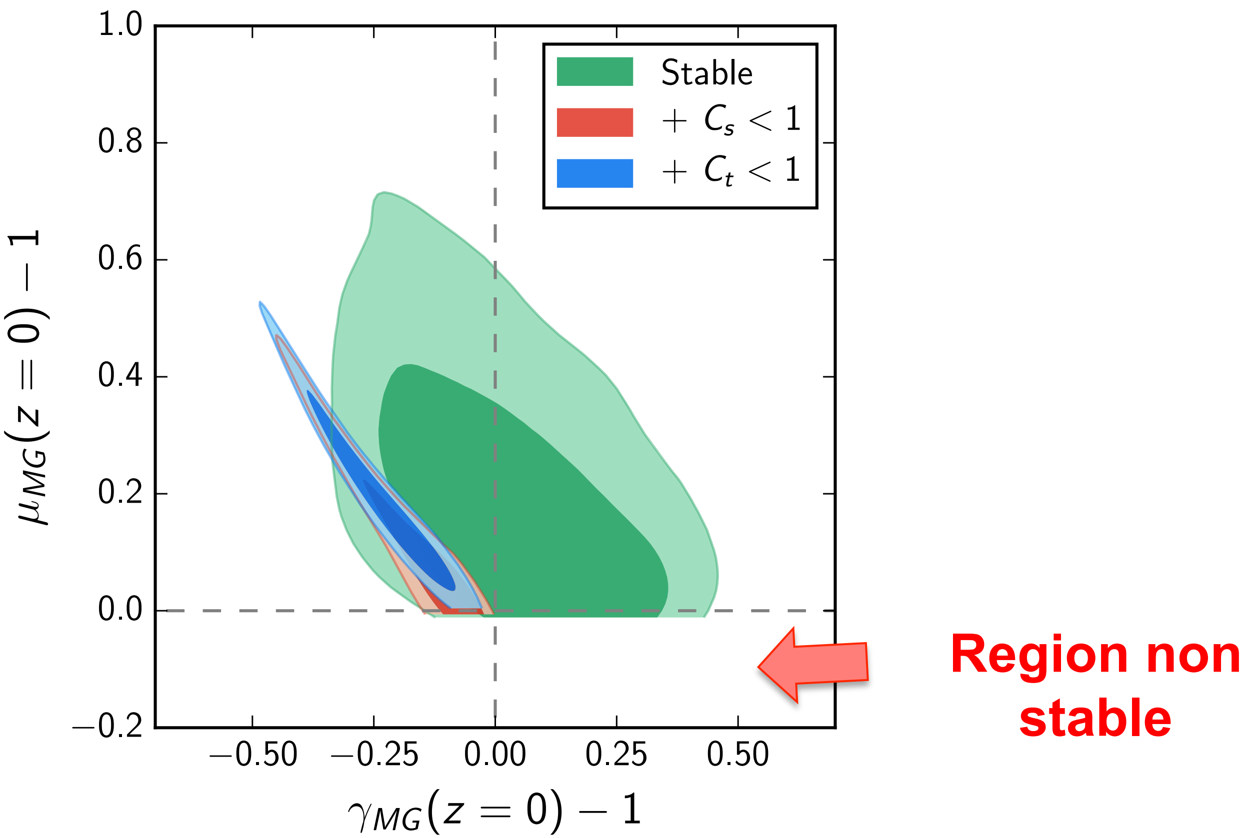
- p1 compatible with zero





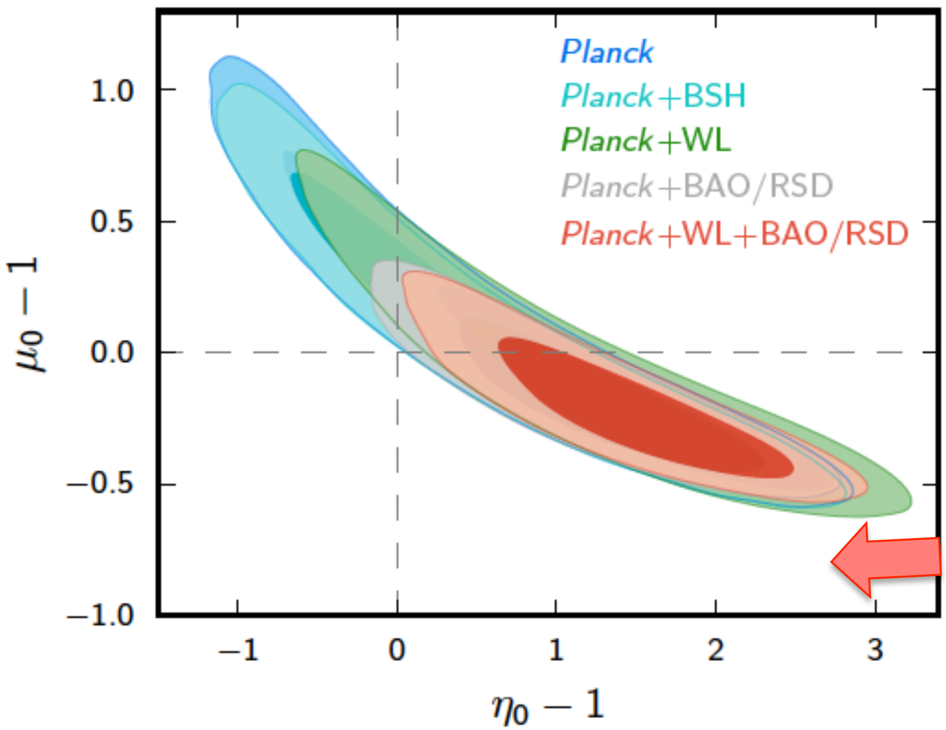


What about the Newton constant?



- Only the models with an effective Newton constant greater than in general relativity are stable!
- If also subluminarity is imposed, the slip parameter must be <1.

Do you remember the results with the phenomenological parametrization?



Region non stable

- Indications of deviation from GR lie in the unstable region.
- No control over the underlying theory in phenomenological (common-used) parametrizations.

What's next?

Future developments:

- Combination with low-redshift probes (for example cluster counts)
- Comparison with alternative parametrizations
- Early dark energy case
- COBESIX project ?

Merci!