Constraints On Gravity from CMB data: an Effective Field Theory approach

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We use the Effective Eield Theory of Dark Energy formalism to constrain dark energy models belonging to the *Horndeski* class with the recent Planck 2015 CMB data. We disentangle in our analysis the constraining power of data from that of the theory, by considering different set of viability conditions. We find that such criteria severely restrict the allowed parameter space. As a result we confirm that no theory performs better than ΛCDM when CMB data alone are analysed. Indeed any healthy dark energy model belonging to the large class here considered can reproduce the best-fitting phenomenological behaviours reported in previous studies [3].

1 Introduction

Understanding the origin of the present acceleration of the universe is one of the key challenge for cosmology. Recent progress in the analysis of the Cosmic Microwave Background [1] has significantly strengthen the case for the so called ΛCDM model. Although a pletora of different and more complex dark energy scenarios, where the acceleration is produced by time varying dark energy fluid or modifications in the action of the gravitational field, still survive the comparison with data. Particularly, the fact that the measurements of structure formation consistently seems to point towards a lower growth rate than expected in the ΛCDM model [2,3] leaves opened the tantalizing possibility that non-standard gravity emerges on cosmological scale. Furthermore, large-scale surveys as EUCLID and LSST, will soon provide an incredible large amount of data with enough sensitivity to discriminate modified gravity effects on cosmological scales, making the exploration of modified gravity even more crucial and timely.

In this context, it has became clear that individuating an efficient and widely-shared strategy for exploring the space of dark energy theories is essential to advance in the dark energy quest. Here we propose to describe deviations from the standard scenario in terms of "constitutive parameters" of alternative gravitational theories. This is made possible by the *effective field theory of dark energy* (EFT of DE) formalism, that allows to describe all dark energy and modified gravity models that contain one additional scalar degree of freedom in a unified language [4,5].

Particularly we use EFT of DE to explore which modified gravity models are compatible with current CMB data. Our goal is twofold. On the one hand, we want to single out specific MG models, in the Horndeski class, that are compatible with data and assess whether these models are more likely than the standard picture. On the other hand we want to disentangle in our analyses the constraining power of data from that of the theory, highlighting which portion of the parameter space is excluded not because of tension with observations, but because no healthy physical model is allowed there.

The paper is organised as follows. In Section 2 we recall the main elements of the EFT formalism and we describe the parametrization we adopt. In Section 3 we present the results in the space of parameters in the space of observables. In Section 5 we draw our conclusions.

2 Theory and Methodology

The EFT of dark energy allows to describe a vaste range of dark energy models by using a limited number of time dependent couplings [4,5]. Here we focus on the large class of Horndeski theories. Upon use of the Friedmann equations, the relevant couplings can be reduced to a minimal set of independent functions. While there is now a consensus on the power and the advantages of this formalism, there is no universal agreement on the conventions for the coupling functions yet. Here we use those of [6], that maintain a more direct link with the underlying theories. We parametrize the time behaviour of the coupling functions with the following expansion:

$$\mu(x) = (1-x)\left[p_1 + p_1^{(1)}\left(x - \Omega_m^0\right)\right] H(x)\,, \tag{1}$$

$$\mu_3(x) = (1-x)\left[p_3 + p_3^{(1)}\left(x - \Omega_m^0\right)\right] H(x)\,, \tag{2}$$

$$\epsilon_4(x) = (1-x)\left[p_4 + p_4^{(1)}\left(x - \Omega_m^0\right)\right]\,, \tag{3}$$

where the p_i are order-one coefficients that we want to constrain with our analysis and x is the fractional matter density of the background at each time. We set to zero the function $\mu_2(t)$, which only affects the sound speed of the scalar fluctuations. Requiring no early dark energy imposes an additional constraint between the p_i parameters, such that $p_1^{(1)}$ is not a free parameter [6]. One of the main advantages of the EFT formalism is the possibility of treating cosmological perturbations independently of the expansion history. We fix the background to that of a spatially flat ΛCDM model in this analysis.

2.1 Viability conditions

The theory that we are describing contains one scalar and two tensor degrees of freedom. In this work we consider three main viability conditions:

stable :	absence of ghosts and gradient instabilities,
stable & $c_s < 1$:	the above *and* scalar propagation speed not superluminal ,
stable & $c_s < 1$ & $c_T < 1$:	the above *and* tensor propagation speed not superluminal.

2.2 Method of analysis and data

The aim of the analysis is to simultaneously evaluate the constrains on the six standard cosmological parameters that define a flat universe with a ΛCDM background history plus the p_i coefficients that encode the modified gravity effects, as described in (1)-(3).

Instead of solving the full set of linear perturbation equations for the couplings, we encode the modifications of gravity in two functions of the time, $\mu_{\rm MG} = G_{\rm eff}/G_N$ and $\gamma_{\rm MG} = \Psi/\Phi$, following the approach implemented in the MGCAMB code [7] and feeding the code with the EFT expressions of $\mu_{\rm MG}$ and $\gamma_{\rm MG}$ that have been derived and discussed in [6]. This method has the remarkable advantage of allowing a simpler numerical implementation while keeping a clear mapping between the μ_{MG}-γ_{MG} functions and the underlying EFT theory.

We use in this analysis the most recent CMB data from the Planck experiment [8]. In particular we include in our dataset the temperature high-l power spectra (PlikTT likelihood), the temperature and polarization spectra at low-l and the lensing from the CMB trispectrum.

We consider two different extensions of the standard model. The *3D*-Model, that corresponds to a minimal extension with one free parameter for every non-minimal coupling. And the *5D*-Model that, by adding a term in the Taylor expansion (1)-(3) of the coupling functions, gives more freedom to the functional space.

3 Constraints on EFT operators

In Fig. 1 and 2 we present constraints on the minimal EFT extension of the standard model of cosmology (*3D model*). The most prominent feature visible in the one-dimensional posteriors of p_1, p_3 and p_4 in Fig 1 is that the theoretical requirement of subluminality (for both scalar and tensor modes) significantly narrows the posterior interval of the EFT parameters. The theoretical viability conditions are thus powerful instruments that complement and increase the discriminatory power of data. Specifically, the main effect of the subluminality prior on p_1 and p_4 parameters is a reduction of the distribution width around the null value, while the net effect on p_3 is instead to shift it towards lower values, corresponding to no modified gravity signals.

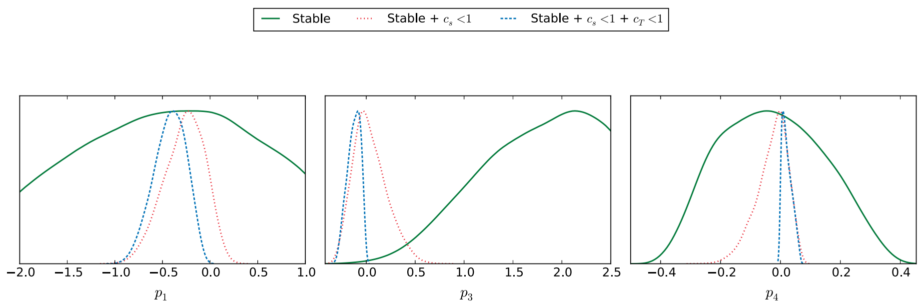

Figure 1 – Planck constraints on the *3D*-model: marginalised PDF for the EFT parameters p_1, p_3 and p_4.

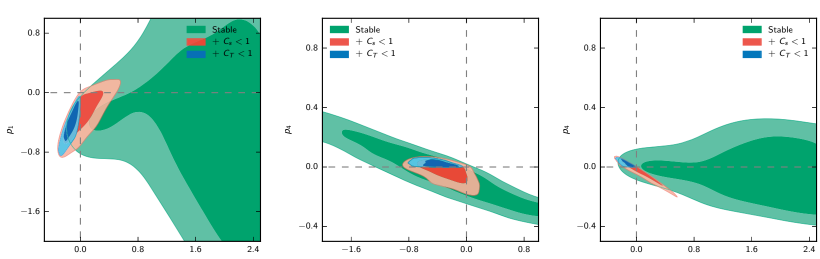

Figure 2 – Planck constraints on the *3D*-model: marginalised 2D PDF at 68% and 95% c.l. of EFT parameters.

While the one dimensional PDF peaks at around zero for both p_3 and p_4, a negative value of p_1 is preferred under any viability conditions. Although the χ^2 value associated to the best fitting EFT model is not lower enough, with respect to the ΛCDM model, to claim any evidence of modified gravity.

The bi-dimensional projected posterior PDF of the *model 3D* parameters is shown in Fig. 2 for the three combinations of parameters. This picture shows that asking for subluminal velocities considerably narrows the confidence regions. Interestingly, the viability priors not only impose tighter constraints as compared to those derived from cosmological measurements alone, but they also compensate both the statistical insensitivity and the parameter degeneracy.

The absence of any $3D$-model EFT parameters performing better than ΛCDM, together with the above remarks on the statistical power of the viability constraints, suggest to extend our parameter space to the $5D$-model, by including one order more in the Taylor expansion in Eqs. (2) and (3). The main results of this analysis are displayed in Fig. 3.

As expected, EFT parameters are somewhat less constrained when the *5D* model is considered, since we are dealing with more degrees of freedom. Nevertheless, the contours in Fig. 3

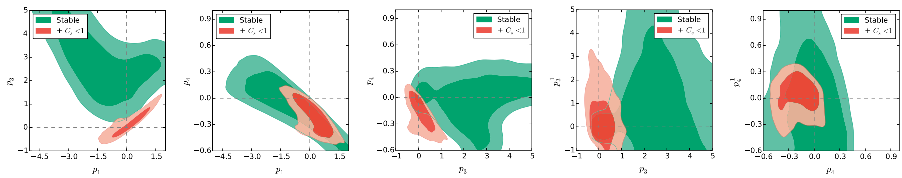

Figure 3 – Planck constraints on the *5D* model: 2D, marginalised, posterior PDF at 68% and 95% c.l. for the full set of EFT parameters contained in Eqs. (1) - (3).

show that the degeneracies between the 0^{th}-order parameters are unaffected by the additional parameters. Also, no remarkable degeneracies are evident between the 0^{th}-order parameters p_3, p_4 and the 1^{st}-order parameters $p_3^{(1)}$, $p_4^{(1)}$. This implies that the *3D* model already catches the main features of the modifications of gravity. Additionally, the enlargement of the constraints completely washes out the indication of a preferred negative p_1. As a consequence, no signals of new physics emerge, also within this enlarged parameter space.

4 Constraints on cosmological observables

Constraining phenomenological quantities that are close to modified gravity observables is a complementary approach to the exploration in the space of the theories. We consider here the pair of functions $\mu_{\rm MG}(t)$ (the effective Newton constant) and $\gamma_{\rm MG}(t)$ (the gravitational slip). Any deviations from the unity of these functions, at any redshift, is notably considered a smoking gun for modified gravity. Interestingly, the Planck Collaboration recently highlighted a deviation from the standard value, at about 3 sigma, of both these functions at redshift $z = 0$ (see Fig. 14 of Ref. [3]) when combining CMB with low-redshift probes. Namely, values of $\mu_{\rm MG}(0)$ lower than 1 and values of $\gamma_{\rm MG}(0)$ higher than 1 seem to be preferred by this combination of probes.

Differently to the approach followed in [3], here, the expressions of $\mu_{\rm MG}$ and $\gamma_{\rm MG}$ are theoretically determined within the context of the EFT theory and they can be tracked back to underlying physical healthy theories.

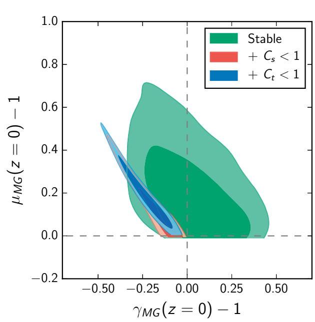

Figure 4 – 68 % and 95 % contour plots for the two parameters ($\mu_{\rm MG}$, $\gamma_{\rm MG}$) evaluated at the present time using the minimal parameterisation of the *3D* model.

The results of our analysis are presented in Fig. 4 and show the importance of not neglecting viability conditions in phenomenological constraints. First we note that there is no stable EFT model that lives in the portion of the space of observables characterised by a negative value of $\mu_{\rm MG} - 1$ today. More importantly, the best-fitting region arising by combining CMB and RSD and/or WL lays in the unstable region. That means that, even if confirmed by following experiments, that signal do not corresponds to the effects of any viable Horndeski theory. Even more stringent conclusions emerge if subluminal propagation speed of scalar and tensor perturbations is required. In this case we find an additional tight constrain on the present value of $\gamma_{\rm MG}$ that is strictly lower than 1 in viable theories.

5 Conclusions

In this paper we extend the constraints on the EFT of DE formalism from Planck 2015 data. Particularly we show that theoretical viability conditions substantially reduces the allowed parameter space, tightly constraining the PDFs of the EFT parameters. Additionally we demonstrate that no healthy Horndeski theories can explain phenomenological results reported in [3].

Acknowledgments

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