Updated constraints from the PLANCK experiment on modified gravity

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A modification of the action of the general relativity produces a different pattern for the growth of the cosmic structures below a certain length-scale leaving an imprint on the cosmic microwave background (CMB) anisotropies. We re-examine the upper limits on the length-scale parameter $B_0$ of $f(R)$ models using the recent data from the Planck satellite experiment. We also investigate the combined constraints obtained when including the Hubble Space Telescope $H_0$ measurement and the baryon acoustic oscillations measurements from the SDSS, WiggleZ and BOSS surveys.

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I. INTRODUCTION

One of the major challenges for modern cosmology is understanding the nature of the cosmic acceleration. Theories that modify general relativity in low-density and large-scale regimes are one possible appealing solution to the phenomenon, since they can reproduce the accelerated phase in only-matter universes.

The Cosmic Microwave Background measurements (CMB hereafter) recently provided from the satellite experiment PLANCK \cite{1,2} offer a new opportunity to investigate modified gravity scenarios.

It is already well-known that modified gravity (MG) theories deeply influence the features of the CMB temperature anisotropies power spectrum (see e.g. \cite{3,4}). As a matter of fact, MG generally introduces modifications at large scales, through the late integrated Sachs–Wolfe effect \cite{7}, and at small scales, through the weak lensing effect \cite{8}.

In this brief report we are interested in updating the constraints on MG we have found from the latest CMB measurements of the South Pole Telescope and the Atacama Cosmology Telescope in \cite{9}, in light of the new high resolution CMB data from PLANCK. For this reason, as in the previous work, we focus on a particular class of MG models, the $f(R)$ theories (see e.g. \cite{10}), exploiting the parametrization proposed in \cite{11}. This parametrization fixes the background expansion to the standard ΛCDM scenario and encodes the changes in the growth of perturbations in a single parameter $B_0$ that represents the length-scale of the theory \cite{12}.

Other authors have already probed $f(R)$ theories trough this kind of parametrization using combinations of previous CMB measurements, supernovae luminosity distances, galaxy cluster distribution and cluster abundance measurements \cite{2,11,13,14}. Adding the cluster abundance to other data sets actually provides a very tight limit on $B_0$ ($B_0 < 0.001$ 95\% c.l. \cite{14}). Our analysis demonstrates that the high resolution CMB measurements from PLANCK provide strong constraints on $f(R)$ even without combination with other experiments. Moreover we are interested in evaluating if MG alleviates some tensions between the parameter values measured by PLANCK and other experiments.

The report is organized as follows. In Section II we briefly resume the modified gravity model considered in the analysis, in Section III we describe the method of analysis and present the results, in Section IV we draw our conclusions.

II. PARAMETRIZED MODIFIED GRAVITY

In the following analysis we adopt the generic MG parametrization from \cite{11} where the deviations from the general relativity equations are introduced through two parametric functions $\mu(k,a)$ and $\gamma(k,a)$

$$k^2\Psi = -\mu(k,a)4\pi Ga^2\{\rho\Delta + 3(\rho + P)\sigma\} \quad (1)$$

$$k^2[\Phi - \gamma(k,a)\Psi] = \mu(k,a)12\pi Ga^2(\rho + P)\sigma \quad (2)$$

where $\Psi$ and $\Phi$ are the scalar metric potentials in the Newtonian gauge, $\sigma$ is the anisotropic stress, $\delta \equiv \delta\rho/\rho$ is the density contrast and $\rho\Delta$ is the comoving density perturbation.

In \cite{15} it has been proved that we can effectively reproduce the perturbations of $f(R)$ theories choosing the following parametric form for $\mu(k,a)$ and $\gamma(k,a)$

$$\mu(k,a) = \frac{1 + \frac{4}{3} \lambda_1^2 k^2 a^s}{1 + \lambda_1^2 k^2 a^s}, \gamma(k,a) = \frac{1 + \frac{2}{3} \lambda_1^2 k^2 a^s}{1 + \lambda_1^2 k^2 a^s} \quad (3)$$

where the parameter $s$ must be $\sim 4$ in order to closely mimic the ΛCDM expansion \cite{16}.

Therefore, our parametrization has only one degree of freedom that is encoded by the length-scale of the theory $\lambda_1$. For scales larger than $\lambda_1$ the dynamic recovers the standard general relativity, otherwise differences in the potentials $\Phi$ and $\Psi$ are allowed and a different growth pattern for the structures can arise.

In accordance to the previous literature, we present the constraints on the length-scale in units of the horizon scale, expressing them in terms of the dimensionless parameter $B_0$

$$B_0 = \frac{2H_0^2 \lambda_1^2}{c^2} \quad (4)$$
III. ANALYSIS AND RESULTS

We obtain the theoretical CMB power spectrum with the publicly available code MGCAMB [11] and perform a Markov Chain Monte Carlo analysis with a modified version of the COSMOMC package [17, 18].

Concerning the CMB data set, we consider the PLANCK measurements [29], that probes the CMB temperature angular power spectrum up to the multipole $\ell = 2500$, combined with the CMB polarization measurements performed by the WMAP experiment [19] up to the multipole $\ell = 23$. We refer to this combination as PLANCK data set.

We also consider the effect of imposing a gaussian prior on the Hubble parameter $H_0 = 73.8 \pm 2.4 \text{ km s}^{-1} \text{ Mpc}^{-1}$ based on the latest Hubble Space Telescope result [20]. We refer to this prior as HST.

Moreover we take in account a combination of baryon acoustic oscillations (BAO) measurements at different redshifts from four surveys: the 6dF Galaxy Survey measurement at $z = 0.1$ provided in [21], the first SDSS DR7 measurements at $z = 0.2$ and $z = 0.35$ from [22], the reanalyzed SDSS DR7 measurement at $z = 0.35$ from [23], the WiggleZ measurements at $z = 0.44, 0.60, 0.73$ extracted in [24], the BOSS DR9 measurement at $z = 0.57$ discussed in [25]. We refer to this combination as the BAO data set.

The cosmological parameters we sample in the Markov chains are: the MG parameter $B_0$, the baryon and cold dark matter densities $\Omega_B h^2$ and $\Omega_c h^2$, the ratio of the sound horizon to the angular diameter distance at decoupling $\theta$, the optical depth at the reionization $\tau$, the scalar spectral index $n_s$, the amplitude of the primordial scalar perturbation spectrum $A_s$ at $k = 0.05 \text{ Mpc}^{-1}$.

We also investigate the effect of adding to the former set of parameters the lensing amplitude parameter $A_L$ that simply rescales the lensing power spectrum $C_{\ell}^{\phi \phi} \to A_L C_{\ell}^{\phi \phi}$ as defined in [26].

We fix the helium abundance to $Y_p = 0.24$, the number of relativistic degrees of freedom to $N_{\text{eff}} = 3.046$, the total neutrino mass to $\sum m_\nu = 0.06 \text{ eV}$.

In the first part of the analysis we fix the lensing amplitude to $A_L = 1$ and we investigate the results from the PLANCK data set only, PLANCK plus HST prior, PLANCK plus BAO measurements. The results we obtain are shown in Tab. I.

With PLANCK alone we find a constraint on the MG parameter ($B_0 < 0.134$ at 95% c.l.) similar to the constraint obtained in [9] from the combination of WMAP 9 and South Pole Telescope measurements. As we expect, the combination PLANCK plus BAO data sets provides a tighter constraint ($B_0 < 0.085$ at 95% c.l.). As a matter of fact BAO measurements better constrain the growth of structures at low redshift. The latter combination also improves the tightest constraint found in [9] by a factor $\sim 1.6$. Instead, when we consider also the HST prior we get a weaker constraint ($B_0 < 0.195$ at 95% c.l.). This fact is due to the bimodal behavior of the posterior distribution of $B_0$ (see the left panel of Fig. 1).

An interesting feature of $f(R)$ models is that they seem to alleviate the tension between the value of the Hubble constant as inferred by PLANCK ($H_0 = 67.3 \pm 1.2 \text{ km s}^{-1} \text{ Mpc}^{-1}$) and as measured by HST. As a matter of fact in this scenario the value of $H_0$ increases compared to the $\Lambda$CDM case (see Fig. 2). The same feature has been already pointed out in quintessence models with an interaction in the dark sector (see [28] and references therein) that can effectively recover scalar-tensor gravitational theories when embedded in the Jordan frame.

In the second part of the analysis we consider the effects of varying the lensing amplitude $A_L$. The results are presented in Tab. I.

When the parameter $A_L$ is left free to vary the bimodal behavior of the $B_0$ posterior distribution appears also for the PLANCK only and the PLANCK+BAO data set combinations. Moreover in the HST case the effect is even increased (Right panel of Fig. 1). For this reason the constraints on $B_0$ are weaker respect to the case where $A_L$ is fixed (see Tab. I).

The bimodal behavior is due to the fact that the $f(R)$ model we consider acts on the CMB power spectrum in two ways. At high multipoles it imitates the effect of $A_L$ greater than one, favouring lower $A_L$ values compared to...
the $\Lambda$CDM case. At low multipoles instead it lowers the integrated Sachs-Wolfe effect plateau, contrary to the effect of an increased $H_0$ value, favoring the match between theory and data even in presence of large $H_0$ values. The tension between these effects creates the local maximum in the posterior distribution.

Remarkably in MG models the lensing amplitude return to be compatible with $A_L = 1$ at 68\% c.l. if we consider PLANCK or PLANCK combined with HST and even at 95\% c.l. if we consider PLANCK combined with BAO. While in the $\Lambda$CDM scenario the standard value $A_L = 1$ is compatible with PLANCK and PLANCK combined with BAO only at 95\% c.l. and is excluded at 95\% c.l. when in the combination PLANCK plus HST prior.

IV. CONCLUSIONS

In this brief report we provide updated constraints on the length-scale parameter $B_0$ of $f(R)$ theories, using the data recently released by the PLANCK experiment together with the $H_0$ measurement from HST and BAO data sets from four different surveys. We also investigate the effects of varying the lensing amplitude $A_L$ from its standard value.

Our analysis provides the tightest constraint on $B_0$ from CMB measurements only and from one single experiment in general ($B_0 < 0.134$ 95\% c.l.). It also improves by a factor $\sim 1.6$ the previous tighter constraint from the CMB measurements plus BAO data sets we reported in [9]. When we consider $A_L = 1$, the constraint we obtain from PLANCK plus BAO is $B_0 < 0.085$ at 95\% c.l. Moreover we found a bimodal behavior for the $B_0$ posterior distribution when the HST prior is present or when $A_L$ is free to vary, making the constraints weaker in these cases.

Furthermore we found that in the framework of the considered MG models the standard value of the lensing amplitude $A_L = 1$ returns to be in agreement with the PLANCK measurements, oppositely to what happens in the $\Lambda$CDM scenario.

Another tantalizing feature we infer is the fact that MG scenario mitigates the PLANCK-HST tension on the Hubble constant $H_0$ value.

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TABLE I: Best fit values and 68% c.l. constraints for the $f(R)$ models described in Sec. II in the case we fix $A_L = 1$ (upper table) or we let $A_L$ free to vary (bottom table) from PLANCK data set (first column), from PLANCK+BAO data set (second column) and from PLANCK+HST (third column). Only for the $B_0$ parameter we report an upper limit at 95% c.l.. The best fit values correspond to the $f(R)$ parameters we report an upper limit at 95% c.l.. The best fit values correspond to the $f(R)$ model that produces the minimum chi square value, they generally differ from the mean values of parameters at 68% c.l. unless all the posterior distributions are perfectly gaussian. The constraints on $B_0$ are weaker in the bottom case because a bimodal behavior appears in the likelihood distributions (see Fig. 3).
FIG. 4: Posterior distribution functions for the parameters described in the text when $A$ is free to vary. We report PLANCK (solid line), PLANCK+BAO (dashed line) and PLANCK+HST (dashed-dotted line).