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The recent measurements of cosmic microwave background (CMB) temperature and polarization anisotropies made by the Planck satellite have provided impressive confirmation of the  $\Lambda$ CDM cosmological model. However interesting hints of slight deviations from  $\Lambda$ CDM have been found, including a 95% C.L. preference for a “modified gravity” (MG) structure formation scenario. In this paper we confirm the preference for a modified gravity scenario from Planck 2015 data, find that modified gravity solves the so-called  $A_{\text{lens}}$  anomaly in the CMB angular spectrum, and constrains the amplitude of matter density fluctuations to  $\sigma_8 = 0.815^{+0.032}_{-0.048}$ , in better agreement with weak lensing constraints. Moreover, we find a lower value for the reionization optical depth of  $\tau = 0.059 \pm 0.020$  (to be compared with the value of  $\tau = 0.079 \pm 0.017$  obtained in the standard scenario), more consistent with recent optical and UV data. We check the stability of this result by considering possible degeneracies with other parameters, including the neutrino effective number, the running of the spectral index and the amount of primordial helium. The indication for modified gravity is still present at about 95% C.L., and could become more significant if lower values of  $\tau$  were to be further confirmed by future cosmological and astrophysical data. When the CMB lensing likelihood is included in the analysis the statistical significance for MG simply vanishes, indicating also the possibility of a systematic effect for this MG signal.

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**I. INTRODUCTION**

The recent measurements of cosmic microwave background (CMB) anisotropies by the Planck satellite experiment [1,2] have fully confirmed, once again, the expectations of the standard cosmological model based on cold dark matter, inflation and a cosmological constant.

While the agreement is certainly impressive, some hints for deviations from the standard scenario have emerged that certainly deserve further investigation. In particular, an interesting hint for modified gravity (MG), i.e. a deviation of the growth of density perturbations from that expected under general relativity (GR), has been reported in [3] using a phenomenological parametrization to characterize non-standard metric perturbations.

In past years, several authors (see e.g. [3–18]) have constrained possible deviations of the evolution of perturbations with respect to the  $\Lambda$ CDM model, by parametrizing the gravitational potentials  $\Phi$  and  $\Psi$  and their linear combinations. Considering the parameter  $\Sigma$ , which modifies the lensing/Weyl potential given by the sum of the Newtonian and curvature potentials  $\Psi + \Phi$ , the analysis of [3] reported the current value of  $\Sigma_0 - 1 = 0.28 \pm 0.15$  at 68% from Planck CMB temperature data, i.e. a deviation from the expected GR null value at about two standard deviations. The discrepancy with GR increases when weak

lensing data are included, bringing the constrained value to  $\Sigma_0 - 1 = 0.34^{+0.17}_{-0.14}$  (again, see [3]).

This result is clearly interesting and should be further investigated. Small systematics may still certainly be present in the data and a further analysis, expected by 2016, from the Planck collaboration could solve the issue. In the meantime, it is certainly timely to independently reproduce the result presented in [3] and to investigate its robustness, especially in view of other anomalies and tensions currently present in cosmological data.

Indeed, another anomaly seems to be suggested by the Planck data, i.e. the amplitude of gravitational lensing in the angular spectra. This quantity, parametrized by the lensing amplitude  $A_{\text{lens}}$  as first introduced in [19], is also larger than expected at the level of two standard deviations. The Planck + LowP analysis of [2] reports the value of  $A_{\text{lens}} = 1.22 \pm 0.10$  at 68% C.L. This anomaly persists even when considering a significantly extended parameter space as shown in [20]. It is therefore mandatory to check if this deviation is in some way connected with the “ $\Sigma_0$ ” anomaly performing an analysis by varying both parameters at the same time. This has been suggested but not actually done in [3].

Moreover, some mild tension seems also to be present between the large angular scale Planck Low Frequency Instrument (LFI) polarization data (that, alone, provides a

constraint on the optical depth  $\tau = 0.067 \pm 0.023$  [2]) and the Planck High Frequency Instrument (HFI) small-scale temperature and polarization data that, when combined with large-scale LFI polarization, shifts the constraint to  $\tau = 0.079 \pm 0.017$  [2]. Since the Planck constraints on  $\tau$  are model dependent, it is meaningful to check if the assumption of MG could, at least partially, resolve the “ $\tau$ ” tension.

Another tension concerns the amplitude of the rms density fluctuations on scales of  $8 \text{ Mpc } h^{-1}$ , the so-called  $\sigma_8$  parameter. The constraints on  $\sigma_8$  derived by the Planck data under the assumption of GR and  $\Lambda$ CDM are in tension with the same quantity observed by low-redshift surveys based on cluster counts, lensing and redshift-space distortions (see e.g. [21] and [2]). This tension appears most dramatic when considering the weak lensing measurements provided by the CFHTLenS survey (see discussion in [3]), which prefer lower values of  $\sigma_8$  with respect to those obtained by Planck. Several solutions to this mild tension have been proposed, including dynamical dark energy [22], decaying dark matter [23,24], ultralight axions [25], and voids [26]. It is therefore timely to further check if the “ $\sigma_8$  tension” could be reconciled by assuming MG. This approach has already been suggested, for example, by [17].

Finally, there are also extra parameters such as the running of the spectral index  $dn_s/dlnk$ , the neutrino effective number  $N_{\text{eff}}$  (see e.g. [27]), and the helium abundance  $Y_p$  (see e.g. [28]) that could be varied and that could in principle be correlated with MG. Since the values of these parameters derived under  $\Lambda$ CDM (see [2]) are consistent with standard expectations, it is crucial to investigate whether the inclusion of MG could change these conclusions.

This paper is organized as follows: in the next section we describe the MG parametrization that we consider, while in Sec. III we describe the data analysis method adopted. In Sec. IV, we present our results and in Sec. V we derive our conclusions.

## II. PERTURBATION EQUATIONS

Let us briefly explain here how MG is implemented in our analysis, discussing the relevant equations. Assuming a flat universe, we can write the line element of the Friedmann-Lemaître-Robertson-Walker metric in the conformal Newtonian gauge as

$$ds^2 = a(\tau)^2[-(1 + 2\Psi)d\tau^2 + (1 - 2\Phi)dx^i dx_i], \quad (1)$$

where  $a$  is the scale factor,  $\tau$  is the conformal time,  $\Psi$  is Newton’s gravitational potential, and  $\Phi$  is the space curvature.<sup>1</sup>

<sup>1</sup>In the synchronous gauge, that is the one adopted in Boltzmann codes as CAMB [29], we have

$$ds^2 = a(\tau)^2[-d\tau^2 + (\delta_{ij} + h_{ij})dx^i dx^j], \quad (2)$$

where  $h_{ij}$  are defined as in [30].

Given the line element of Eq. (1), we can use a phenomenological parametrization of the gravitational potentials  $\Psi$  and  $\Phi$  and their combinations. We consider the parametrization used in the publicly available code MGCAMB [31,32], introducing the scale-dependent function  $\mu(k, a)$  that modifies the Poisson equation for  $\Psi$ :

$$k^2\Psi = -4\pi G a^2 \mu(k, a) \rho \Delta, \quad (3)$$

where  $\rho$  is the dark matter energy density and  $\Delta$  is the comoving density perturbation. Furthermore one can consider the function  $\eta(k, a)$  that takes into account the presence of a nonzero anisotropic stress:

$$\eta(k, a) = \frac{\Phi}{\Psi}. \quad (4)$$

We can then easily introduce the function  $\Sigma(k, a)$ , which modifies the lensing/Weyl potential  $\Phi + \Psi$  in the following way,

$$-k^2(\Phi + \Psi) \equiv 8\pi G a^2 \Sigma(k, a) \rho \Delta, \quad (5)$$

and that can be obtained directly from  $\mu(k, a)$  and  $\eta(k, a)$  as

$$\Sigma = \frac{\mu}{2}(1 + \eta). \quad (6)$$

Of course, if we have GR then  $\mu = \eta = \Sigma = 1$ .

It is now useful to give an expression for  $\mu$  and  $\eta$ . Following Ref. [3], we parametrize  $\mu$  and  $\eta$  as

$$\mu(k, a) = 1 + f_1(a) \frac{1 + c_1(\lambda H/k)^2}{1 + (\lambda H/k)^2}; \quad (7)$$

$$\eta(k, a) = 1 + f_2(a) \frac{1 + c_2(\lambda H/k)^2}{1 + (\lambda H/k)^2}, \quad (8)$$

where  $H = \dot{a}/a$  is the Hubble parameter,  $c_1$  and  $c_2$  are constants and the  $f_i(a)$  are functions of time that characterize the amplitude of the deviation from GR.

Again, following [3] we choose a time dependence for these functions related to the dark energy density

$$f_i(a) = E_{ii} \Omega_{\text{DE}}(a), \quad (9)$$

where  $E_{ii}$  are, again, constants and  $\Omega_{\text{DE}}(a)$  is the dark energy density parameter. As discussed in Ref. [3], the inclusion of scale dependence does not change significantly the results; we can therefore consider the scale-independent parametrization, in which  $c_1 = c_2 = 1$ . In other words, we modify the publicly available code MGCAMB [31,32] by substituting to the original  $\mu$  and  $\eta$  the following parametrizations:

$$\mu(k, a) = 1 + E_{11} \Omega_{\text{DE}}(a); \quad (10)$$

$$\eta(k, a) = 1 + E_{22}\Omega_{\text{DE}}(a). \quad (11)$$

A detection of  $E_{\text{ii}} \neq 0$  could therefore indicate a departure of the evolution of density perturbations from GR. In order to further simplify the problem, we assume a cosmological constant for the background evolution.

### III. METHOD

We consider flat priors listed in Table I on all the parameters that we are constraining. They are the following: the six parameters of the  $\Lambda$ CDM model, i.e. the Hubble constant  $H_0$ , the baryon  $\Omega_b h^2$  and cold dark matter  $\Omega_c h^2$  energy densities, the primordial amplitude and spectral

TABLE I. External flat priors on the cosmological parameters assumed in this paper.

Parameter	Prior
$\Omega_b h^2$	[0.005, 0.1]
$\Omega_c h^2$	[0.001, 0.99]
$\Theta_s$	[0.5, 10]
$\tau$	[0.01, 0.8]
$n_s$	[0.8, 1.2]
$\log[10^{10}A_s]$	[2, 4]
$E_{11}$	[-1, 3]
$E_{22}$	[-1.4, 5]
$\frac{dn_s}{d\ln k}$	[-1, 1]
$N_{\text{eff}}$	[0.05, 10]
$A_{\text{lens}}$	[0, 10]
$Y_P$	[0.1, 0.5]

index of scalar perturbations,  $A_s$  and  $n_s$  respectively, (at pivot scale  $k_0 = 0.05 h \text{Mpc}^{-1}$ ), and the reionization optical depth  $\tau$ ; the constant parameters of MG,  $E_{11}$  and  $E_{22}$ ; and the several extensions to the  $\Lambda$ CDM model. In particular, we vary the neutrino effective number  $N_{\text{eff}}$  (see e.g. [27]), the running of the scalar spectral index  $dn_s/d\ln k$ , the primordial Helium abundance  $Y_P$  and the lensing amplitude in the angular power spectra  $A_{\text{lens}}$ . We also vary foreground parameters following the same method of [33] and [2].

We constrain these cosmological parameters by using recent cosmological data sets. First of all, we consider the full Planck 2015 release on temperature and polarization CMB angular power spectra, including the large angular scale temperature and polarization measurement by the Planck LFI experiment and the small-scale temperature and polarization spectra by Planck HFI. We refer to the Planck HFI small angular scale temperature data plus large angular scale Planck LFI temperature and polarization data as *Planck TT*, while when we include small angular scale polarization from Planck HFI we refer to this as *Planck pol* (see [33]). We also use information on CMB lensing from Planck trispectrum data (see [34]) and we refer to this data set as lensing. Finally, we consider the weak lensing galaxy data from the CFHTLenS [35] survey with the priors and conservative cuts to the data as described in [2] and we refer to this data set as WL.

To perform the analysis, we use our modified version, according to Eqs. (10), of the publicly available code MGCAMB [31,32] that modifies the original publicly code CAMB [29] implementing the pair of functions  $\mu(a, k)$  and  $\eta(a, k)$ , as defined in [32]. This code has been developed and tested in a completely independent way to the one used in [3].

TABLE II. Constraints at 68% C.L. on the cosmological parameters assuming modified gravity (parametrized by  $E_{11}$  and  $E_{22}$ ) and varying the six parameters of the standard  $\Lambda$ CDM model.

	Planck TT	Planck TT + WL	Planck TT + lensing	Planck pol	Planck pol + WL	Planck pol + lensing
$E_{11}$	$0.08^{+0.33}_{-0.72}$	$-0.18^{+0.19}_{-0.49}$	$0.08^{+0.34}_{-0.59}$	$0.06^{+0.33}_{-0.66}$	$-0.21^{+0.19}_{-0.45}$	$0.08^{+0.35}_{-0.54}$
$E_{22}$	$1.0^{+1.3}_{-1.6}$	$1.9^{+1.4}_{-1.0}$	$0.4^{+0.9}_{-1.4}$	$0.9^{+1.2}_{-1.5}$	$1.7^{+1.3}_{-1.0}$	$0.4^{+0.8}_{-1.3}$
$\mu_0 - 1$	$0.05^{+0.23}_{-0.50}$	$-0.13^{+0.13}_{-0.35}$	$0.05^{+0.24}_{-0.41}$	$0.04^{+0.23}_{-0.45}$	$-0.15^{+0.13}_{-0.32}$	$0.05^{+0.24}_{-0.38}$
$\eta_0 - 1$	$0.7^{+0.9}_{-1.2}$	$1.3^{+1.0}_{-0.7}$	$0.31^{+0.61}_{-0.94}$	$0.6^{+0.8}_{-1.0}$	$1.20^{+0.91}_{-0.68}$	$0.26^{+0.56}_{-0.86}$
$\Sigma_0 - 1$	$0.28 \pm 0.15$	$0.34^{+0.16}_{-0.15}$	$0.11^{+0.09}_{-0.12}$	$0.23 \pm 0.13$	$0.27 \pm 0.13$	$0.10^{+0.09}_{-0.11}$
$\Omega_b h^2$	$0.02251 \pm 0.00027$	$0.02263 \pm 0.00026$	$0.02238 \pm 0.00024$	$0.02237 \pm 0.00017$	$0.02243 \pm 0.00017$	$0.02233 \pm 0.00016$
$\Omega_c h^2$	$0.1175 \pm 0.0024$	$0.1159 \pm 0.0022$	$0.1171 \pm 0.0021$	$0.1188 \pm 0.0016$	$0.1180 \pm 0.0015$	$0.1185 \pm 0.0014$
$H_0$	$68.5 \pm 1.1$	$69.2 \pm 1.1$	$68.47 \pm 0.99$	$67.78 \pm 0.71$	$68.15 \pm 0.69$	$67.83 \pm 0.66$
$\tau$	$0.065 \pm 0.021$	$0.061^{+0.020}_{-0.023}$	$0.050 \pm 0.019$	$0.059 \pm 0.020$	$0.054 \pm 0.019$	$0.045 \pm 0.017$
$n_s$	$0.9712 \pm 0.0071$	$0.9754 \pm 0.0067$	$0.9706 \pm 0.0062$	$0.9668 \pm 0.0051$	$0.9689 \pm 0.0050$	$0.9668 \pm 0.0047$
$\sigma_8$	$0.816^{+0.034}_{-0.052}$	$0.787^{+0.022}_{-0.039}$	$0.802^{+0.033}_{-0.039}$	$0.815^{+0.032}_{-0.048}$	$0.788^{+0.021}_{-0.035}$	$0.803 \pm 0.031$

We integrate MGCAMB in the latest July 2015 version of the publicly available Monte Carlo Markov chain package `cosmomc` [36] with a convergence diagnostic based on the Gelman and Rubin statistic. This version includes the support for the Planck data release 2015 Likelihood Code [33] and implements an efficient sampling using the fast/slow parameter decorrelations [37].

#### IV. RESULTS

We first report the results assuming a modified gravity scenario parametrized by  $\eta$  and  $\mu$  and varying only the six parameters of the standard  $\Lambda$ CDM model. The constraints on the several parameters are reported in Table II. When comparing the first and second column of our table, we see a complete agreement with the results presented in the first and third column of Table VI of [3]. Namely we find evidence at  $\sim 95\%$  C.L. for  $\Sigma_0 - 1$  different from zero for the Planck TT data set, and this indication is further confirmed when the WL data set is included.

As fully discussed in [33], the Planck polarization HFI data at small angular scales fail to satisfy some of the internal checks in the data analysis pipeline. The results obtained by the inclusion of this data set should therefore be considered as preliminary. We report the constraints from the Planck pol data set in columns 4–6 in Table II. As we can see, the small angular scale HFI polarization data improve the constraints on  $\Sigma_0$ , also slightly shifting its value towards a better compatibility with standard  $\Lambda$ CDM. We can see however that the inclusion of small angular scale polarization does not alter substantially the conclusions obtained when using just the Planck TT data set.

Considering just the Planck TT data set, it is interesting to note that in this modified gravity scenario, the Hubble constant is constrained to be  $H_0 = 68.5 \pm 1.1$  at 68% C.L., i.e. a value significantly larger than the  $H_0 = 67.3 \pm 0.96$  at 68% C.L. reported by the Planck collaboration assuming  $\Lambda$ CDM. Combining the Planck TT data set with the HST prior of  $H_0 = 73.0 \pm 2.4$  from the revised analysis of [38] as in [39] we found indeed an increased evidence for MG, with  $\Sigma_0 - 1 = 0.33^{+0.18}_{-0.15}$  at 68% C.L.

Moreover, the amplitude of the rms mass density fluctuations  $\sigma_8$  in our modified gravity scenario is constrained to be  $\sigma_8 = 0.816^{+0.034}_{-0.052}$  at 68% C.L., i.e. a value significantly weaker (and shifted towards smaller values) than the value of  $\sigma_8 = 0.829 \pm 0.014$  at 68% C.L. reported by the Planck collaboration again under  $\Lambda$ CDM assumption.

Considering the Planck pol data set, the value of the optical depth is also significantly smaller in the MG scenario ( $\tau = 0.059 \pm 0.020$  at 68% C.L.) with respect to the value obtained under the standard  $\Lambda$ CDM model of  $\tau = 0.078 \pm 0.019$  at 68% C.L., i.e. reducing the tension with the Planck LFI large angular scale polarization constraint. Interestingly, a smaller value for the optical depth of  $\tau \sim 0.05$  is in better agreement with recent optical

and UV astrophysical data (see e.g. [40–42]) and the reionization scenarios presented in [43]. A value of  $\tau > 0.07$  could imply unexpected properties for high-redshift galaxies. Assuming an external Gaussian prior of  $\tau = 0.05 \pm 0.01$  (at 68% C.L.) as in [43] that would consider in a conservative way reionization scenarios where the star formation rate density rapidly declines after redshift  $z \sim 8$  as suggested by [44], we find that the Planck TT data set provides the constraint  $\Sigma_0 - 1 = 0.30 \pm 0.14$  at 68% C.L., i.e. further improving current hints of MG. In this respect, future, improved, constraints on the value of  $\tau$  from large-scale polarization measurements as expected from the Planck HFI experiment will obviously provide valuable information.

The degeneracies between  $\Sigma_0$ ,  $H_0$  and  $\tau$  can be clearly seen in Fig. 1 where we show the constraints at 68% and 95% confidence levels on the  $\Sigma_0 - 1$  vs  $\tau$  plane (top panel) and on the  $\Sigma_0 - 1$  vs  $H_0$  plane (bottom panel) from the Planck TT and Planck pol data sets. As we can see, a

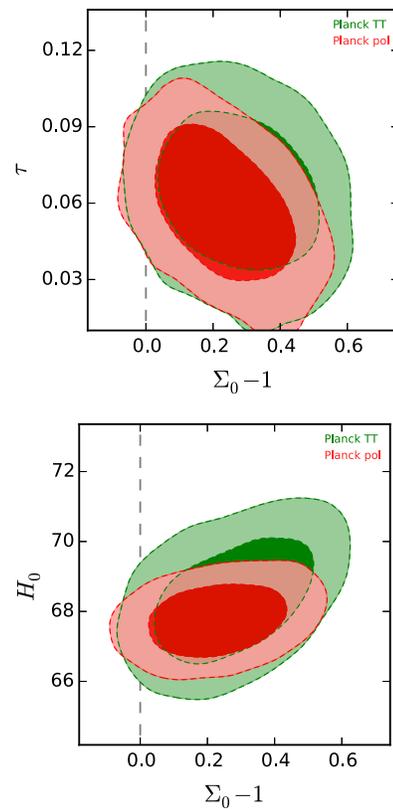


FIG. 1. Constraints at 68% and 95% confidence levels on the  $\Sigma_0 - 1$  vs  $\tau$  plane (top panel) and on the  $\Sigma_0 - 1$  vs  $H_0$  plane (bottom panel) from the Planck TT and Planck pol data sets. The six parameters of the  $\Lambda$ CDM model are varied. Notice that  $\Sigma_0$  is different from one (dashed vertical line) at about 95% confidence level. A small degeneracy is present between  $\Sigma_0$  and  $\tau$ : smaller optical depths are more compatible with the data if  $\Sigma_0$  is larger than one (see the top panel). Another degeneracy is present with the Hubble constant: larger values of the Hubble constant are more compatible with the considered data in the case of  $\Sigma_0$  different from one (bottom panel).

TABLE III. Constraints at 68% C.L. on the cosmological parameters assuming modified gravity (parametrized by  $E_{11}$  and  $E_{22}$ ) and varying the six parameters of the standard  $\Lambda$ CDM model plus  $A_{\text{lens}}$ .

	Planck TT	Planck TT + WL	Planck TT + lensing	Planck pol	Planck pol + WL	Planck pol + lensing
$E_{11}$	$0.06^{+0.33}_{-0.65}$	$-0.15^{+0.22}_{-0.51}$	$0.08^{+0.33}_{-0.63}$	$0.07^{+0.33}_{-0.62}$	$-0.18^{+0.21}_{-0.47}$	$0.06^{+0.33}_{-0.63}$
$E_{22}$	$0.8^{+1.1}_{-1.7}$	$1.4^{+1.4}_{-1.3}$	$0.8^{+1.0}_{-1.5}$	$0.7^{+1.0}_{-1.6}$	$1.4 \pm 1.2$	$0.8^{+1.1}_{-1.6}$
$\mu_0 - 1$	$0.04^{+0.23}_{-0.46}$	$-0.10^{+0.15}_{-0.36}$	$0.06^{+0.23}_{-0.44}$	$0.05^{+0.23}_{-0.43}$	$-0.12^{+0.15}_{-0.33}$	$0.04^{+0.22}_{-0.44}$
$\eta_0 - 1$	$0.6^{+0.7}_{-1.2}$	$1.0^{+1.0}_{-0.9}$	$0.5^{+0.7}_{-1.1}$	$0.5^{+0.7}_{-1.1}$	$0.95 \pm 0.81$	$0.6^{+0.7}_{-1.1}$
$\Sigma_0 - 1$	$0.21^{+0.16}_{-0.21}$	$0.22^{+0.17}_{-0.22}$	$0.21^{+0.15}_{-0.17}$	$0.19^{+0.14}_{-0.18}$	$0.20^{+0.14}_{-0.18}$	$0.22^{+0.14}_{-0.16}$
$\Omega_b h^2$	$0.02259 \pm 0.00029$	$0.02273 \pm 0.00028$	$0.02231 \pm 0.00026$	$0.02239 \pm 0.00017$	$0.02246 \pm 0.00017$	$0.02229 \pm 0.00016$
$\Omega_c h^2$	$0.1169 \pm 0.0025$	$0.1152 \pm 0.0023$	$0.1180 \pm 0.0025$	$0.1187 \pm 0.0016$	$0.1177 \pm 0.0015$	$0.1191 \pm 0.0015$
$H_0$	$68.8 \pm 1.2$	$69.6 \pm 1.1$	$68.1 \pm 1.2$	$67.82 \pm 0.73$	$68.26 \pm 0.69$	$67.59 \pm 0.70$
$\tau$	$0.059^{+0.021}_{-0.023}$	$0.054 \pm 0.021$	$0.059 \pm 0.021$	$0.056 \pm 0.020$	$0.049^{+0.019}_{-0.022}$	$0.057 \pm 0.021$
$n_s$	$0.9730 \pm 0.0073$	$0.9772 \pm 0.0068$	$0.9687 \pm 0.0070$	$0.9671 \pm 0.0050$	$0.9694 \pm 0.0049$	$0.9656 \pm 0.0049$
$\sigma_8$	$0.807^{+0.033}_{-0.049}$	$0.782^{+0.025}_{-0.038}$	$0.813^{+0.033}_{-0.046}$	$0.813^{+0.032}_{-0.044}$	$0.786^{+0.023}_{-0.035}$	$0.814^{+0.031}_{-0.046}$
$A_{\text{lens}}$	$1.09^{+0.10}_{-0.13}$	$1.13^{+0.10}_{-0.14}$	$0.924^{+0.065}_{-0.089}$	$1.04^{+0.08}_{-0.10}$	$1.07^{+0.09}_{-0.11}$	$0.914^{+0.062}_{-0.078}$

degeneracy is present between  $\Sigma_0 - 1$  and  $\tau$ : smaller optical depths are more compatible with the data if  $\Sigma_0$  is larger than one (see the top panel). As discussed, a second degeneracy is present with the Hubble constant: larger values of the Hubble constant are more compatible with the considered data in the case of  $\Sigma_0$  different from one (bottom panel).

As already noticed in [3] and as we discuss in the next paragraph, the indication for MG from the Planck data is strictly connected with the  $A_{\text{lens}}$  anomaly, i.e. with the fact that Planck angular spectra show “more lensing” than

expected in the standard scenario. It is therefore not a surprise that when the Planck lensing data (obtained from a trispectrum analysis) that are on the contrary fully compatible with the standard expectations are included in the analysis the indication for modified gravity is significantly reduced to less than one standard deviation, as we can see from the third column of Table II. On the other hand, when weak lensing data from the WL data set are included, the indication for MG increases, with  $\Sigma_0 - 1$  larger than zero at more than 95% C.L.

TABLE IV. Constraints at 68% C.L. on the cosmological parameters assuming modified gravity (parametrized by  $E_{11}$  and  $E_{22}$ ) and varying the six parameters of the standard  $\Lambda$ CDM model plus  $N_{\text{eff}}$ .

	Planck TT	Planck TT + WL	Planck TT + lensing	Planck pol	Planck pol + WL	Planck pol + lensing
$E_{11}$	$0.07^{+0.31}_{-0.73}$	$-0.13^{+0.20}_{-0.58}$	$0.09^{+0.35}_{-0.64}$	$0.07^{+0.34}_{-0.66}$	$-0.21^{+0.19}_{-0.48}$	$0.08^{+0.34}_{-0.53}$
$E_{22}$	$1.3 \pm 1.4$	$2.1^{+1.8}_{-1.0}$	$0.5^{+0.9}_{-1.5}$	$0.9^{+1.2}_{-1.5}$	$1.75^{+1.4}_{-1.0}$	$0.4^{+0.8}_{-1.2}$
$\mu_0 - 1$	$0.05^{+0.22}_{-0.53}$	$-0.09^{+0.15}_{-0.43}$	$0.06^{+0.25}_{-0.45}$	$0.05^{+0.23}_{-0.45}$	$-0.15^{+0.13}_{-0.33}$	$0.06^{+0.24}_{-0.37}$
$\eta_0 - 1$	$0.96 \pm 1.1$	$1.5^{+1.3}_{-0.8}$	$0.3^{+0.6}_{-1.1}$	$0.59^{+0.8}_{-1.0}$	$1.22^{+0.96}_{-0.69}$	$0.24^{+0.56}_{-0.83}$
$\Sigma_0 - 1$	$0.36 \pm 0.18$	$0.45^{+0.21}_{-0.17}$	$0.12^{+0.09}_{-0.14}$	$0.23^{+0.13}_{-0.15}$	$0.28^{+0.13}_{-0.15}$	$0.10^{+0.09}_{-0.10}$
$\Omega_b h^2$	$0.02294^{+0.00049}_{-0.00063}$	$0.02328^{+0.00048}_{-0.00063}$	$0.02252^{+0.00036}_{-0.00043}$	$0.02234 \pm 0.00025$	$0.02244 \pm 0.00026$	$0.02224 \pm 0.00024$
$\Omega_c h^2$	$0.1202 \pm 0.0041$	$0.1210^{+0.0041}_{-0.0046}$	$0.1185 \pm 0.0039$	$0.1184 \pm 0.0030$	$0.1181 \pm 0.0030$	$0.1173 \pm 0.0030$
$H_0$	$72.0^{+3.5}_{-4.8}$	$74.7^{+3.5}_{-4.9}$	$69.7^{+2.6}_{-3.2}$	$67.6 \pm 1.6$	$68.2^{+1.6}_{-1.8}$	$67.1 \pm 1.5$
$\tau$	$0.072^{+0.023}_{-0.026}$	$0.073 \pm 0.024$	$0.052^{+0.020}_{-0.025}$	$0.059^{+0.018}_{-0.021}$	$0.053^{+0.019}_{-0.021}$	$0.044^{+0.016}_{-0.019}$
$n_s$	$0.990^{+0.020}_{-0.025}$	$1.004^{+0.019}_{-0.025}$	$0.977^{+0.015}_{-0.017}$	$0.9655 \pm 0.0097$	$0.969 \pm 0.010$	$0.9625 \pm 0.0092$
$\sigma_8$	$0.827^{+0.033}_{-0.062}$	$0.812^{+0.028}_{-0.054}$	$0.808^{+0.035}_{-0.048}$	$0.814^{+0.032}_{-0.049}$	$0.788^{+0.022}_{-0.038}$	$0.799^{+0.031}_{-0.037}$
$N_{\text{eff}}$	$3.41^{+0.36}_{-0.46}$	$3.63^{+0.35}_{-0.48}$	$3.19^{+0.30}_{-0.34}$	$3.02 \pm 0.20$	$3.06 \pm 0.21$	$2.95 \pm 0.19$

TABLE V. Constraints at 68% C.L. on the cosmological parameters assuming modified gravity (parametrized by  $E_{11}$  and  $E_{22}$ ) and varying the six parameters of the standard  $\Lambda$ CDM model plus  $dn_s/dlnk$ .

	Planck TT	Planck TT + WL	Planck TT + lensing	Planck pol	Planck pol + WL	Planck pol + lensing
$E_{11}$	$0.08^{+0.36}_{-0.79}$	$-0.21^{+0.20}_{-0.52}$	$0.05^{+0.34}_{-0.57}$	$0.06^{+0.34}_{-0.67}$	$-0.25^{+0.20}_{-0.43}$	$0.06^{+0.35}_{-0.53}$
$E_{22}$	$1.2^{+1.4}_{-1.9}$	$2.2^{+1.7}_{-1.1}$	$0.5^{+0.9}_{-1.3}$	$0.9^{+1.2}_{-1.6}$	$1.8^{+1.3}_{-1.0}$	$0.4^{+0.8}_{-1.2}$
$\mu_0 - 1$	$0.06^{+0.25}_{-0.55}$	$-0.15^{+0.14}_{-0.37}$	$0.03^{+0.24}_{-0.40}$	$0.04^{+0.24}_{-0.46}$	$-0.17^{+0.14}_{-0.30}$	$0.04^{+0.24}_{-0.36}$
$\eta_0 - 1$	$0.9^{+1.0}_{-1.3}$	$1.6^{+1.2}_{-0.8}$	$0.35^{+0.62}_{-0.94}$	$0.6^{+0.8}_{-1.1}$	$1.28^{+0.90}_{-0.69}$	$0.28^{+0.58}_{-0.85}$
$\Sigma_0 - 1$	$0.31 \pm 0.18$	$0.38^{+0.20}_{-0.18}$	$0.11^{+0.10}_{-0.13}$	$0.22^{+0.13}_{-0.15}$	$0.27 \pm 0.13$	$0.10^{+0.09}_{-0.11}$
$\Omega_b h^2$	$0.02267^{+0.00032}_{-0.00038}$	$0.02281^{+0.00033}_{-0.00039}$	$0.02238 \pm 0.00026$	$0.02238 \pm 0.00018$	$0.02243 \pm 0.00017$	$0.02232 \pm 0.00017$
$\Omega_c h^2$	$0.1170 \pm 0.0027$	$0.1154 \pm 0.0024$	$0.1171 \pm 0.0021$	$0.1188 \pm 0.0016$	$0.1180 \pm 0.0015$	$0.1186 \pm 0.0015$
$H_0$	$68.8^{+1.3}_{-1.4}$	$69.6^{+1.2}_{-1.3}$	$68.5 \pm 1.0$	$67.76 \pm 0.72$	$68.12 \pm 0.70$	$67.80 \pm 0.66$
$\tau$	$0.068^{+0.022}_{-0.025}$	$0.064^{+0.021}_{-0.025}$	$0.051^{+0.019}_{-0.022}$	$0.060^{+0.019}_{-0.022}$	$0.054^{+0.020}_{-0.043}$	$0.045 \pm 0.017$
$n_s$	$0.9721 \pm 0.0076$	$0.9765 \pm 0.0073$	$0.9708 \pm 0.0064$	$0.9665 \pm 0.0051$	$0.9686 \pm 0.0051$	$0.9669 \pm 0.0050$
$\sigma_8$	$0.816^{+0.036}_{-0.059}$	$0.784^{+0.022}_{-0.042}$	$0.800^{+0.033}_{-0.038}$	$0.815^{+0.033}_{-0.048}$	$0.785^{+0.021}_{-0.034}$	$0.803^{+0.030}_{-0.036}$
$\frac{dn_s}{dlnk}$	$-0.0073^{+0.0097}_{-0.0086}$	$-0.008^{+0.011}_{-0.009}$	$0.0002 \pm 0.0079$	$-0.0014 \pm 0.0072$	$-0.0005 \pm 0.0070$	$0.0016 \pm 0.0070$

In Tables III–VI we report constraints assuming one single parameter extension to  $\Lambda$ CDM. In particular, we report constraints when adding as an extra parameter the lensing amplitude  $A_{\text{lens}}$  (Table III), the neutrino effective number  $N_{\text{eff}}$  (Table IV), the running of the scalar spectral index  $dn_s/dlnk$  (Table V) and, finally, the Helium abundance  $Y_p$  (Table VI).

As expected, there is a main degeneracy between the  $A_{\text{lens}}$  parameter and  $\Sigma_0$ , as we can clearly see in Fig. 2 where we report the 2D posteriors at 68% and 95% C.L. in

the  $\Sigma_0 - 1$  vs  $A_{\text{lens}}$  plane from the Planck TT and Planck pol data sets. In practice, the main effect of a modified gravity model is to enhance the lensing signal in the angular power spectrum. The same effect can be obtained by increasing  $A_{\text{lens}}$  and some form of degeneracy is clearly expected between the two parameters. As we see from the results in Table III, the value of the  $A_{\text{lens}}$  parameter, when MG is considered, is  $A_{\text{lens}} = 1.09^{+0.10}_{-0.13}$ , fully consistent with 1, while for the standard  $\Lambda$ CDM the constraint is  $A_{\text{lens}} = 1.224^{+0.11}_{-0.096}$  at 68% C.L. When also varying  $A_{\text{lens}}$  we found

TABLE VI. Constraints at 68% C.L. on the cosmological parameters assuming modified gravity (parametrized by  $E_{11}$  and  $E_{22}$ ) and varying the six parameters of the standard  $\Lambda$ CDM model plus  $Y_p$ .

	Planck TT	Planck TT + WL	Planck TT + lensing	Planck pol	Planck pol + WL	Planck pol + lensing
$E_{11}$	$0.05^{+0.33}_{-0.71}$	$-0.18^{+0.20}_{-0.52}$	$0.05^{+0.35}_{-0.58}$	$0.08^{+0.34}_{-0.68}$	$-0.24^{+0.20}_{-0.44}$	$0.05^{+0.34}_{-0.52}$
$E_{22}$	$1.2 \pm 1.4$	$2.1^{+1.6}_{-1.0}$	$0.5^{+0.9}_{-1.4}$	$0.6^{+0.8}_{-1.1}$	$1.9^{+1.3}_{-1.0}$	$0.4^{+0.8}_{-1.2}$
$\mu_0 - 1$	$0.04^{+0.24}_{-0.51}$	$-0.13^{+0.14}_{-0.37}$	$0.04^{+0.25}_{-0.41}$	$0.06^{+0.24}_{-0.47}$	$-0.17^{+0.14}_{-0.31}$	$0.04^{+0.23}_{-0.36}$
$\eta_0 - 1$	$0.9^{+1.0}_{-1.2}$	$1.5^{+1.2}_{-0.8}$	$0.36^{+0.62}_{-0.99}$	$0.6^{+0.8}_{-1.1}$	$1.30^{+0.91}_{-0.72}$	$0.29^{+0.57}_{-0.83}$
$\Sigma_0 - 1$	$0.31 \pm 0.16$	$0.39^{+0.19}_{-0.15}$	$0.11^{+0.09}_{-0.12}$	$0.23^{+0.13}_{-0.16}$	$0.29 \pm 0.13$	$0.10^{+0.09}_{-0.11}$
$\Omega_b h^2$	$0.02269^{+0.00041}_{-0.00046}$	$0.02293 \pm 0.00042$	$0.02248 \pm 0.00034$	$0.02245^{+0.00024}_{-0.00026}$	$0.02254 \pm 0.00023$	$0.02236 \pm 0.00023$
$\Omega_c h^2$	$0.1167 \pm 0.0028$	$0.1147 \pm 0.0026$	$0.1169 \pm 0.0023$	$0.1187 \pm 0.0016$	$0.1178 \pm 0.0015$	$0.1185 \pm 0.0015$
$H_0$	$69.1^{+1.5}_{-1.7}$	$70.2^{+1.5}_{-1.7}$	$68.8^{+1.2}_{-1.4}$	$67.98^{+0.84}_{-0.94}$	$68.43 \pm 0.81$	$67.92 \pm 0.77$
$\tau$	$0.068^{+0.022}_{-0.024}$	$0.066^{+0.021}_{-0.025}$	$0.052^{+0.020}_{-0.023}$	$0.061^{+0.020}_{-0.022}$	$0.055^{+0.018}_{-0.022}$	$0.046 \pm 0.018$
$n_s$	$0.979^{+0.014}_{-0.016}$	$0.988 \pm 0.015$	$0.975 \pm 0.012$	$0.9700 \pm 0.0086$	$0.9732 \pm 0.0082$	$0.9681 \pm 0.0080$
$\sigma_8$	$0.816^{+0.033}_{-0.055}$	$0.791^{+0.022}_{-0.043}$	$0.803^{+0.035}_{-0.040}$	$0.819^{+0.032}_{-0.050}$	$0.788^{+0.021}_{-0.035}$	$0.803 \pm 0.031$
$Y_p$	$0.258 \pm 0.023$	$0.268 \pm 0.023$	$0.253 \pm 0.021$	$0.252 \pm 0.014$	$0.254 \pm 0.013$	$0.248 \pm 0.013$

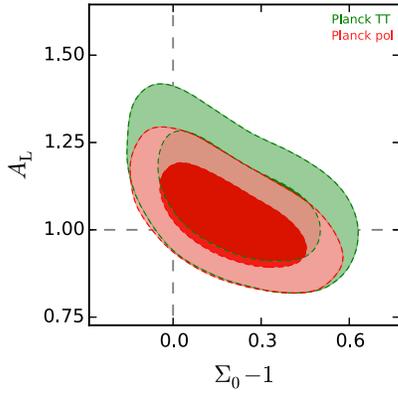


FIG. 2. Constraints at 68% and 95% confidence levels on the  $\Sigma_0 - 1$  vs  $A_{\text{lens}}$  plane from the Planck TT and Planck pol data sets. A strong degeneracy is present between  $\Sigma_0$  and  $A_{\text{lens}}$ : larger values of  $A_{\text{lens}}$  are more compatible with the data if  $\Sigma_0$  is smaller than one.

that the Planck pol data sets constrain the optical depth to  $\tau = 0.056 \pm 0.020$  at 68% C.L.

On the other hand, by looking at the results in Tables IV–VI we do not see a significant degeneracy between the MG parameters and the new extra parameters. A small degeneracy is however present between  $\Sigma_0$  and the effective neutrino number  $N_{\text{eff}}$ . We see from Table IV that Planck TT data provide the constraint  $N_{\text{eff}} = 3.41^{+0.36}_{-0.46}$  at 68% C.L. that should be compared with  $N_{\text{eff}} = 3.13^{+0.30}_{-0.34}$  at 68% C.L. from the same data set but assuming the standard  $\Lambda$ CDM model. While the possibility of an unknown “dark radiation” component (i.e.  $N_{\text{eff}} > 3.046$ ; see e.g. [45–47]) is therefore more viable in a MG scenario, it is important to note that when adding polarization data the constraint on the neutrino number is perfectly compatible with the expectations of the standard three neutrino framework.

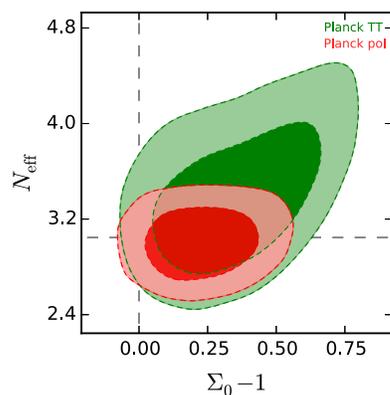


FIG. 3. Constraints at 68% and 95% confidence levels on the  $\Sigma_0 - 1$  vs  $N_{\text{eff}}$  plane from the Planck TT and Planck polarization data sets. Notice that  $\Sigma_0$  is different from unity (dashed vertical line) at about the 95% confidence level. A small direction of degeneracy is present between  $\Sigma_0$  and  $N_{\text{eff}}$ : larger  $N_{\text{eff}}$  are more compatible with the data if  $\Sigma_0$  is larger than one in the case of the Planck TT data set.

The constraints at 68% and 95% C.L. in the  $\Sigma_0 - 1$  vs  $N_{\text{eff}}$  planes are reported in Fig. 3.

We also consider the possibility of a running of the scalar spectral index  $dn_s/d\ln k$ . Results are reported in Table V and we find no degeneracy with MG parameters. The Planck TT constraint of  $dn_s/d\ln k = -0.0073^{+0.0097}_{-0.0086}$  at 68% C.L. is almost identical to the value  $dn_s/d\ln k = -0.0084 \pm 0.0082$  at 68% C.L. obtained using the same data set but assuming standard  $\Lambda$ CDM.

We also considered variations in the primordial helium abundance  $Y_p$  since it affects small angular scale anisotropies. Our results are in Table VI. The Planck TT constraint is found to be  $Y_p = 0.258 \pm 0.023$  at 68% C.L., slightly larger than the standard  $\Lambda$ CDM value of  $Y_p = 0.252 \pm 0.021$  at 68% C.L. obtained using the same data set. While a larger helium abundance is in better agreement with recent primordial helium measurements of [48], it is important to stress that the inclusion of polarization yields a constraint that is almost identical to the one obtained under  $\Lambda$ CDM. The constraints at 68% and 95% C.L. in the  $\Sigma_0 - 1$  vs  $dn_s/d\ln k$  and  $\Sigma_0 - 1$  vs  $Y_p$  planes are reported in Fig. 4.

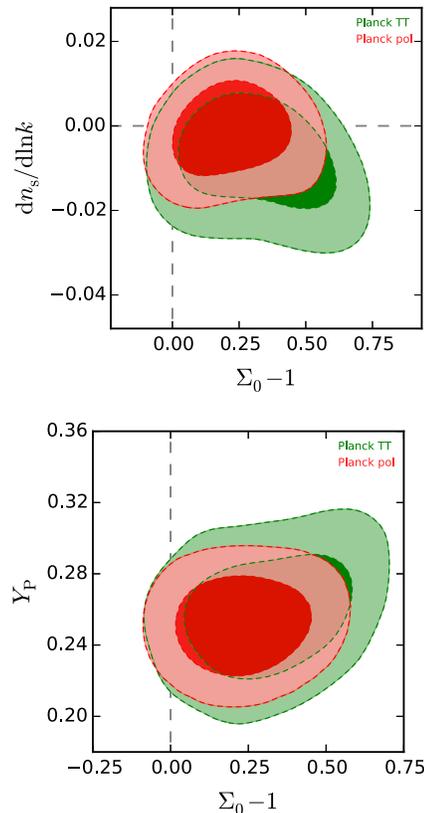


FIG. 4. Constraints at 68% and 95% confidence levels on the  $\Sigma_0 - 1$  vs  $dn_s/d\ln k$  plane (top panel) and on the  $\Sigma_0 - 1$  vs  $Y_p$  plane (bottom panel) from the Planck TT and Planck pol data sets. Notice that  $\Sigma_0$  is different from unity (dashed vertical line) at about 95% confidence level. There is virtually no degeneracy between  $\Sigma_0$ , the running of the scalar spectral index  $dn_s/d\ln k$  and the primordial helium abundance.

## V. CONCLUSIONS

In this paper, we have further investigated the current hints for a modified gravity scenario from the recent Planck 2015 data release. We have confirmed that the statistical evidence for these hints, assuming the conservative data set of Planck TT, is, at most, at  $\sim 95\%$  C.L., i.e. not extremely significant. The statistical significance increases when combining the Planck data sets with the WL cosmic shear data set. Indeed, the Planck data set seems to provide lower values for the  $\sigma_8$  parameter with respect to those derived under the assumption of GR and  $\Lambda$ CDM.

If future astrophysical or cosmological measurements point towards a lower value of the optical depth of  $\tau \sim 0.05$  or of the rms amplitude of mass fluctuations of  $\sigma_8 \sim 0.78$  then the current hints for modified gravity could be further strengthened.

However it is also important to stress that when the CMB lensing likelihood is included in the analysis the statistical significance for MG simply vanishes.

We also investigated possible degeneracies with extra, nonstandard parameters as the neutrino effective number, the running of the scalar spectral index and the primordial helium abundance showing that the results on these parameters assuming  $\Lambda$ CDM are slightly changed when considering the Planck TT data set. Namely, under modified gravity we have larger values for the neutrino effective number,  $N_{\text{eff}} = 3.41^{+0.36}_{-0.46}$  at 68% C.L., and for the helium abundance,  $Y_p = 0.258 \pm 0.023$  at 68% C.L. However, the constraints on these parameters are practically identical to those obtained under GR when including the Planck HFI polarization data.

We have clearly shown that the slight Planck hints of MG are strongly degenerate with the anomalous lensing amplitude in the Planck CMB angular spectra parametrized by the  $A_{\text{lens}}$  parameter. Indeed, the  $A_{\text{lens}}$  anomaly disappears when MG is considered. Clearly, undetected small experimental systematics could be the origin of this anomaly. However our conclusions are that modified gravity could

provide a physical explanation, albeit exotic, for this anomaly that has been pointed out already in pre-Planck CMB data sets [49], was present in the Planck 2013 data release [50] and seems still to be alive in the recent Planck 2015 release [2].<sup>2</sup>

An extra parameter we have not investigated here is the neutrino absolute mass scale  $\Sigma m_\nu$ . Since MG is degenerate with the  $A_{\text{lens}}$  we expect that in a MG scenario current constraints on the neutrino mass from CMB angular power spectra will be weaker. However a more detailed computation is needed and we plan to investigate it in a future paper [52].

During the submission process of our paper, another paper appeared [53], claiming an indication for MG from cosmological data. The data set used in that paper is completely independent from the one used here and the MG parametrization is also different. Clearly a possible connection between the two results deserves future investigation.

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<sup>2</sup>Another possible physical explanation for the  $A_{\text{lens}}$  anomaly has also been very recently proposed by [51] by considering the inclusion of compensated isocurvature perturbations.

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