

Testing modified gravity with Planck: The case of coupled dark energy

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The Planck collaboration has recently published maps of the cosmic microwave background (CMB) radiation, in good agreement with a Λ CDM model, a fit especially valid for multipoles $\ell > 40$. We explore here the possibility that dark energy is dynamical and gravitational attraction between dark matter particles is effectively different from the standard one in general relativity: this is the case of coupled dark energy models, where dark matter particles feel the presence of a fifth force, larger than gravity by a factor $2\beta^2$, defining an effective gravitational constant $G_{\text{eff}} = G(1 + 2\beta^2)$. We investigate constraints on the strength of the coupling β in view of Planck data. Interestingly, we show that a nonzero coupling is compatible with data and find a likelihood peak at $\beta = 0.036 \pm 0.016$ [Planck + WMAP polarization (WP) + baryonic acoustic oscillations (BAO)] (compatible with zero at 2.2σ). The significance of the peak increases to $\beta = 0.066 \pm 0.018$ [Planck + WP + Hubble Space Telescope (HST)] (around 3.6σ from zero coupling) when Planck is combined to HST data by [16]. This peak comes mostly from the small difference between the Hubble parameter determined with CMB measurements and the one coming from astrophysics measurements and is already present in the combination with BAO. Future observations and further tests of current observations are needed to determine whether the discrepancy is due to systematics in any of the data sets. Our aim here is not to claim new physics but rather to show that a clear understanding of such tension has a considerable impact on dark energy models: it can be used to provide information on dynamical dark energy and modified gravity, allowing us to test the strength of an effective fifth force.

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I. INTRODUCTION

Our knowledge of the cosmic microwave background (CMB) has impressively grown in the past few months. The South Pole Telescope (SPT, [1]) and Atacama Cosmology Telescope (ACT, [2]) allowed to detect the first compelling evidence of CMB lensing, pushing our knowledge of the temperature power spectrum of primordial acoustic oscillations up to multipoles $l \sim 3000$ and very small scales. More recently, the Planck collaboration has released the first cosmological papers providing the highest resolution, full sky, maps of the CMB temperature anisotropies, with an accuracy now set by fundamental astrophysical limits. The corresponding analysis of cosmological parameters has been illustrated in [3]. This extends and increases the resolution of previous measurements of temperature power spectrum (Wilkinson microwave anisotropy probe 9, [4]).

Planck data are in good agreement with a Λ CDM cosmology, especially for $\ell > 40$. They can provide interesting bounds on the early Universe, putting stringent limits to primordial non-Gaussianity [5] and testing inflationary models [6]. They can be used to test isotropy [7] and infer properties of large scale structures via the Sunyaev-Zel'dovich (SZ) effect [8]. In general, they can be used to estimate cosmological parameters [3] assuming a given model for the background and evolution of perturbations as well as for the foreground components. Such a detailed

picture of primordial fluctuations is also able to provide constraints on late time cosmology, for example via CMB lensing [9–11]. First tests of late time cosmology using Planck data have been presented in [3] on simple parametrizations of the equation of state and early dark energy. Here we want to show further how CMB probes such as Planck are powerful tests also for dynamical dark energy (DE) and extensions of general relativity that modify gravitational interactions, extending and updating the work done in [12].

The simplest framework for dark energy models considers dark energy as a cosmological constant Λ , contributing to about 68% of the total energy density in the Universe and providing late time cosmic acceleration, while cold dark matter (CDM) represents about 27% (Λ CDM model). Though theoretically in good agreement with present observations, a cosmological constant is somewhat unpleasantly affected by coincidence and fine-tuning problems which seem unavoidable in such a framework. In a Λ CDM cosmology, dark energy density ρ_Λ is constant; however we usually describe constituents of the Universe in terms of ratios of densities $\Omega_i = \rho_i/\rho_{\text{cr}}$, where the subscript indicates the (i) constituent of the Universe (DE, CDM, radiation) and ρ_{cr} is the energy density corresponding to a spatially flat geometry. In particular, in a Λ CDM, Ω_Λ is completely negligible in the past and changes rapidly just at recent times, increasing from nearly zero to about 68% of the total energy budget. In this

framework, for the whole evolution of the Universe, its equation of state is $w = -1$.

Given the degeneracy in the reionization epoch, WMAP polarization (WP) likelihood [4,13] can be used in addition to Planck likelihood [3]. The combination with astrophysical probes further tightens bounds on the equation of state w . Such external measurements include geometrical measurements like baryonic acoustic oscillations (BAO) [14,15], which are in nice agreement with Planck results for a Λ CDM model, as well as constraints on the Hubble parameter or Supernovae (see [3] for a detailed discussion on the different data sets). In particular, when a constant w is assumed for dark energy, this parameter is constrained to be $w = -1.13^{+0.24}_{-0.25}$ at 95% C.L. when using Planck + WP + BAO [3], in good agreement with $w = -1$; when measurements on H_0 from the Hubble Space Telescope (HST) [16] are combined with Planck + WP, [3] found $w = -1.24^{+0.18}_{-0.19}$ at 95% C.L. which is in tension with $w = -1$ at more than 2σ level. Such discrepancy, however, has to be treated with care as it may very well depend on systematics in the measurement of H_0 .

Many alternative models have been proposed, though it is fair to say that so far none of them completely avoids the fine-tuning and coincidence problems nor provides a better fit to data than Λ CDM. Some encouraging arguments have been put forward in the framework of dynamical dark energy models, where a scalar field (quintessence or cosmon) rolls down a suitable potential [17,18]. Small changes of the equation of state around its present value w_0 have also been tested, using the parametrization (w_0, w_a) in which a time dependent $w(a)$ is Taylor expanded as $w(a) \equiv p/\rho = w_0 + (1-a)w_a$: in this case, $w_0 = -1.04^{+0.72}_{-0.69}$ and $w_a < 1.32$ at 95% C.L. when using Planck + WP + BAO [3]. As expected, adding H_0 data moves these values slightly further away from $(-1, 0)$. Effectively, w_a tells us how rapidly Ω_{de} changes from zero to 68%.

Whether dark energy was effectively zero or not at early times can be tested, complementary, using early dark energy (EDE) [19]. Assuming a constant early dark energy Ω_e at all times from decoupling [20] down to when, at recent epochs, a Λ CDM is restored, provides tight bounds: $\Omega_e \lesssim 0.009$ at 95% C.L. for Planck + WP + HighL. Previous bounds, using different data sets, had been found in [21–23]. As shown in [23] such constraints on a constant Ω_e do not depend on how rapid the transition is from Ω_e to the present value: it is enough to have an EDE parametrization that depends on Ω_e only (and not on w_0). On the other hand, [23] also showed that such bounds strongly depend on the redshift z_e at which early dark energy becomes non-negligible: constraints are substantially weaker if dark energy becomes non-negligible only after decoupling.

In this paper we want to extend the investigation carried out in [3] to models of dynamical dark energy in which the gravitational interaction between dark matter particles is

modified with respect to standard general relativity. We can quite generally say that modified gravity theories deal with at least one extra degree of freedom that can be associated to a scalar field, that can be seen as the mediator of a fifth force in addition to standard interactions. This happens in scalar-tensor theories [including $F(R)$ cosmologies], massive gravity and all coupled dark energy models, both when matter is involved [24–26] or when neutrino evolution is affected [27–32]. Interactions and fifth forces are therefore a common characteristic of many models, the difference being whether the interaction is universal (i.e. it affects all species with the same coupling, as in scalar-tensor theories) or is different for each species (as in coupled dark energy or growing neutrino models). It is therefore interesting to understand the effect of such interactions on the CMB and how large they can be when compared to data.

In the following we consider the case of coupled dark energy [25], in which dark matter particles feel an interaction mediated by the dark energy scalar field. In this framework, baryons are not affected and still feel standard gravity, while dark matter typically feels a fifth force which is $2\beta^2$ times stronger than gravity. Such an interaction introduces effectively a coupling β between the evolution of the dark energy scalar field and dark matter particles. When seen in the Jordan frame, a coupling between matter and dark energy can be reformulated in terms of scalar-tensor theories [or $f(R)$ models] [24,26]. This is exactly true when the contribution of baryons is neglected. Alternatively, in the Jordan frame, scalar-tensor theories [$f(R)$ models] require some sort of screening mechanism (like chameleon [33–36] or symmetrons [37]) that protects the dark energy scalar field and its mass within high density regions, so that local solar system constraints are satisfied. To avoid this problem, in the Einstein frame it is instead common use to neglect a coupling to baryon and consider only dark energy—dark matter interactions.

The coupling affects the dynamics of the gravitational potential (and therefore the late integrated Sachs-Wolfe effect), the shape and amplitude of perturbation growth, as illustrated in detail in [38]. Moreover, the coupling is degenerate with the amount of cold dark matter Ω_c , the spectral index n , the Hubble parameter $H(z)$ (see [38] for a review) and can therefore depend very much on the estimates by Planck as well as from the combination of Planck data with other astrophysical data sets that can break these degeneracy. By means of numerical Monte Carlo simulations we show how, despite the agreement with Λ CDM scenarios, other dynamical dark energy models are well feasible. Since a fifth force modifies the expansion rate, the consistency (or not) between CMB and astrophysical measurements of the Hubble parameter is a crucial test for dark energy. Even a small difference in H_0 would allow a non-zero coupling to be compatible with data, alleviating the tension in the measurements of the Hubble parameter present when Λ CDM is assumed [12].

This paper is organized as follows. In Sec. II we recall the main features of coupled dark energy (CDE) cosmologies. In Sec. III we describe the methods used, both with regard to the implementation of the numerical code and the data used for this paper. In Sec. IV we illustrate our results and in Sec. V we derive our conclusions.

II. COUPLED DARK ENERGY

Cosmologies in which an interaction is present between dark energy and dark matter [25,26,39–42] have to be seen within the framework of modified gravity, since effectively the gravitational interaction acting among dark matter particles is modified with respect to standard general relativity. Many papers have investigated in details such cosmologies, including spherical collapse ([43,44] and references therein), higher-order expansions with the time renormalization group [45], N -body simulations [46–48], effects on supernovae, CMB and cross correlation of CMB and large-scale structure [41,42,49–56] together with Fisher matrix forecasts analysis combining power spectrum and baryonic acoustic oscillation measurements as expected by the Euclid satellite [57–59] and CMB as expected from Planck [38]. The most updated bounds so far were provided in [12] who found $\beta < 0.063$ at 68% confidence level when combining WMAP7 + SPT data [1,60] and first pointed out the impact the a difference in the measurement of H_0 between CMB and astrophysical data sets can give in the estimate of the coupling. When adding constraints on the Hubble constant from [16] a small likelihood peak around $\beta = 0.041$ was found, still compatible with zero at one σ . The robustness of these constraints has also been tested against a number of tests that investigate the degeneracy with other parameters such as curvature, the relativistic number of degrees of freedom N_{eff} , the amplitude rescaled factor of the lensing power spectrum A_L and, most of all, massive neutrinos [12,50,51].

We here recall the main equations for coupled dark energy, in order to define the parameters, and refer to [26,40] for a detailed description of all equations involved. Effects on the CMB have recently been reviewed in [12,38].

Coupled dark energy cosmologies considered here are described by the Lagrangian:

$$\mathcal{L} = -\frac{1}{2}\partial^\mu\phi\partial_\mu\phi - U(\phi) - m(\phi)\bar{\psi}\psi + \mathcal{L}_{\text{kin}}[\psi], \quad (1)$$

in which the mass of matter fields ψ is a function of the scalar field ϕ and can be related to the coupling β as illustrated below. Conservation equations for the energy densities of each species read in general as

$$\rho'_\phi = -3\mathcal{H}\rho_\phi(1 + w_\phi) - Q, \quad \rho'_c = -3\mathcal{H}\rho_c + Q, \quad (2)$$

where Q is a generic function and the subscript “c” indicates cold dark matter. Here we have treated each component as a fluid with $T^\nu_{(\alpha)\mu} = (\rho_\alpha + p_\alpha)u_\mu u^\nu + p_\alpha\delta^\nu_\mu$, where $u_\mu = (-a, 0, 0, 0)$ is the fluid 4-velocity and $w_\alpha \equiv p_\alpha/\rho_\alpha$ is the equation of state. Primes denote derivative with respect to conformal time τ . The class of models considered here corresponds to the choice:

$$Q = -\beta\rho_c\phi', \quad (3)$$

the simplest one that can be embedded in a Lagrangian, with an exponential dependence of the mass of dark matter particles on the dark energy scalar field and a constant coupling β [25,26]. We express the dark energy scalar field in units of the reduced Planck mass $M = (8\pi G_N)^{-1/2}$. The source Q that appears in the conservation equations (and in the Bianchi identities for these theories) is related to the mass dependence appearing in the Lagrangian:

$$Q_{(\phi)\mu} = \frac{\partial \ln m(\phi)}{\partial \phi} \rho_c \partial_\mu \phi. \quad (4)$$

Equivalently, the scalar field evolves according to the Klein-Gordon equation, which now includes an extra term that depends on CDM energy density:

$$\phi'' + 2\mathcal{H}\phi' + a^2\frac{dV}{d\phi} = a^2\beta\rho_c. \quad (5)$$

Throughout this paper we choose an inverse power law potential defined as

$$V = V_0\phi^{-\sigma} \quad (6)$$

with σ and V_0 constants. The amplitude V_0 is fixed thanks to an iterative routine [38]. At the level of perturbations, as well as in N -body simulations, this corresponds to a fifth force that acts among dark matter particles with an effective gravitation constant G_{eff} related to the standard one G by

$$G_{\text{eff}} = G(1 + 2\beta^2), \quad (7)$$

stronger than standard gravity by a factor β^2 . As discussed in [38] the coupling shifts the position of the acoustic peaks to larger ℓ 's due to the increase in the distance to the last scattering surface (this is sometimes called projection effect, [61] and references therein); furthermore, it reduces the ratio of baryons to dark matter at decoupling with respect to its present value, since coupled dark matter dilutes faster than in an uncoupled model. Both effects are clearly visible in Fig. 1 for various values of β (see also [12]).

Theoretical CMB have been produced implementing the code IDEA (Interacting Dark Energy Anisotropies)

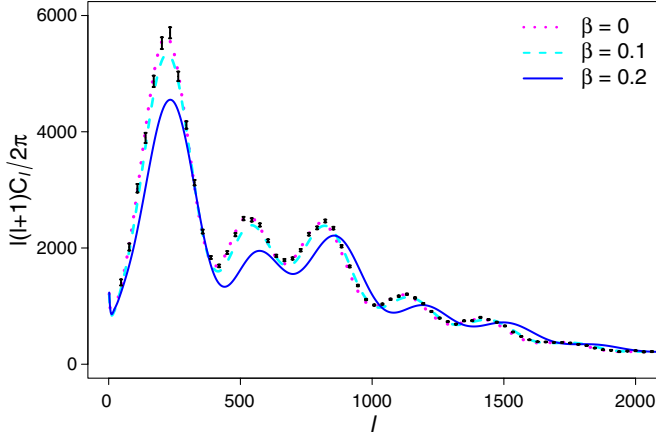


FIG. 1 (color online). CMB temperature spectra for three values of β . Black points are Planck data [72] (high frequency instrument only).

[12,23,38] in CAMB [62]: these modifications are able to include dynamical dark energy, early dark energy parametrizations (not included in this analysis) as well as interacting dark energy models. In order to include the coupling, both background and linear perturbations have been modified following Refs. [61,63]. The output has been compared to an independent code [42] that is built on CMBFAST and the agreement was better than 1%. The difficulty in the implementation relies on the fact that the initial conditions cannot be obtained analytically as in simple dark energy parametrizations [early dark energy or (w_0, w_a)): instead, they must be found by trial and error, through an iterative routine that finds the initial conditions required to get the desired present values of the cosmological parameters.

We have then performed a Monte Carlo analysis integrating IDEA within COSMOMC [64] comparing our theoretical predictions with the data presented in the next section.

III. COMPARISON WITH OBSERVED DATA

Constraints on β can be obtained if we combine Planck data with astrophysical measurements that break the degeneracy in the distance to last scattering. As described in [3] there is some tension in the estimate of the (derived) parameter H_0 (the value of the Hubble parameter at present) between CMB data and astrophysical data sets. For a detailed discussion on astrophysical data sets and possible sources of errors we refer to [3]. In particular, Planck data are more in agreement with BAO than with HST data, when a Λ CDM cosmology is assumed. In the absence of a known source of this slight discrepancy, we decide here to combine Planck separately either with BAO or with HST data. We do not combine all three data sets and we consider Planck + BAO [65] as the choice in which we can be more confident at present (a sort of

conservative choice); we still evaluate with Planck + HST the impact that HST results would have on our results and in doing so we use [16], based on HST observations of Cepheid variables in the host galaxies of eight SNaIa. This gives a best estimate of $H_0 = (73.8 \pm 2.4) \text{ km s}^{-1} \text{ Mpc}^{-1}$ at 1σ . Moreover, in including Planck data, we consider two possibilities:

- (1) Planck WP: Here we use TT data from Planck plus WMAP low- l polarization.
- (2) Planck WP + HighL: In this case we also add data from ACT [66] and SPT from [67], as done in [3].

Combining Planck with high- l probes adds information from small scales; these scales are more affected by foregrounds and can be determined by high- l probes with higher precision. The analysis in Λ CDM provided in [3] seems to guarantee that foregrounds at small scales are properly accounted also in Planck data alone and therefore makes us more confident especially when analyzing extensions of the Λ CDM model.

The baseline set of parameters includes $\Theta = \Omega_b h^2, \Omega_c h^2, \theta_s, \log \mathcal{A}, n_s, \tau$. These parameters depend on the fractional abundances of the various species, as well as on the amplitude and shape of the primordial power spectrum, and the reionization optical depth; since we impose spatial flatness, the present dark energy density Ω_{de} becomes a derived parameter; in addition, coupled dark energy involves two more parameters: β and σ . Again, β represents the coupling between dark matter particles while σ is the parameter in the scalar field potential (6) that drives the long range interaction. As illustrated in [12] bounds on β do not depend on the value of σ , which can in turn be written in terms of w_0 via the expression $w = -2/(\sigma + 2)$; therefore, σ can be safely limited to a range in w_0 which is still reasonably within observations ($w < -0.8$). In this sense, we recall that this formulation of coupled dark energy models does not reduce exactly to a Λ CDM when $\beta = 0$, but rather to a quintessence scalar field in a very flat potential (but not exactly a Λ CDM). The helium abundance Y_{He} is derived following big bang nucleosynthesis consistency (see [1] for details). As done in [3], we assume a minimal-mass normal hierarchy for the neutrino masses, as a single massive eigenstate with $m_\nu = 0.06 \text{ eV}$. We note however that we expect dynamical dark energy (including the coupling) to be partially degenerate with massive neutrinos, as they both contribute to tilt the power spectrum, as it was pointed out in [38,50].

IV. RESULTS

Our results from different runs are illustrated in Table I. As we can see from the first two columns, the conservative case Planck WP + BAO data has a likelihood peak around a mean value of the coupling $\beta \sim 0.036$, different from zero at roughly 2.2σ . When adding HighL data, the bound on β is roughly the same. This goes along the line pointed

TABLE I. We report the mean (\pm standard deviation) for a selection of most interesting parameters. H_0 is in units of $\text{km s}^{-1} \text{Mpc}^{-1}$.

Parameter	PlanckWP + BAO	PlanckWP + HighL + BAO	PlanckWP + HST	PlanckWP + HighL + HST
$\Omega_b h^2$	0.02204 ± 0.00028	0.0221 ± 0.000269	0.0220 ± 0.00029	0.0221 ± 0.000281
$\Omega_c h^2$	0.1165 ± 0.0019	0.1169 ± 0.00197	0.1114 ± 0.00332	0.1121 ± 0.00338
β	0.0364 ± 0.01626	0.0346 ± 0.0155	0.0660 ± 0.0182	0.0611 ± 0.0188
σ	0.2895 ± 0.1052	0.2837 ± 0.105	0.2932 ± 0.1055	0.2681 ± 0.0996
Ω_{de}	0.6935 ± 0.0141	0.6910 ± 0.0144	0.7339 ± 0.0219	0.7295 ± 0.0223
H_0	67.437 ± 1.250	67.267 ± 1.247	71.123 ± 2.109	70.737 ± 2.093

out in [3] and can be seen as confirmation that Planck bounds are stable with respect to foregrounds parameters, whose knowledge (especially of the thermal SZ effect) is expected to be better determined in the HighL data than in Planck. With respect to a Λ CDM best fit model, the value of H_0 and $\Omega_c h^2$ are not much affected (note that for each parameter we write mean values and not best fits): $H_0 = 67.27 \pm 1.25 \text{ km s}^{-1} \text{Mpc}^{-1}$ instead of the

Λ CDM one [3] $H_0 = 67.80 \pm 0.77 \text{ km s}^{-1} \text{Mpc}^{-1}$ and $\Omega_c h^2 = 0.1169 \pm 0.0020$ instead of $\Omega_c h^2 = 0.1187 \pm 0.0017$. When we break the degeneracy with HST data the preference for a nonzero coupling increases as expected [12], with a value around $\beta \sim 0.066$ (different from zero at roughly 3.6σ). This peak comes mostly from a slight tension between the Hubble parameter HST result ($H_0 = 73.8 \pm 2.4 \text{ km s}^{-1} \text{Mpc}^{-1}$) and the best fit for

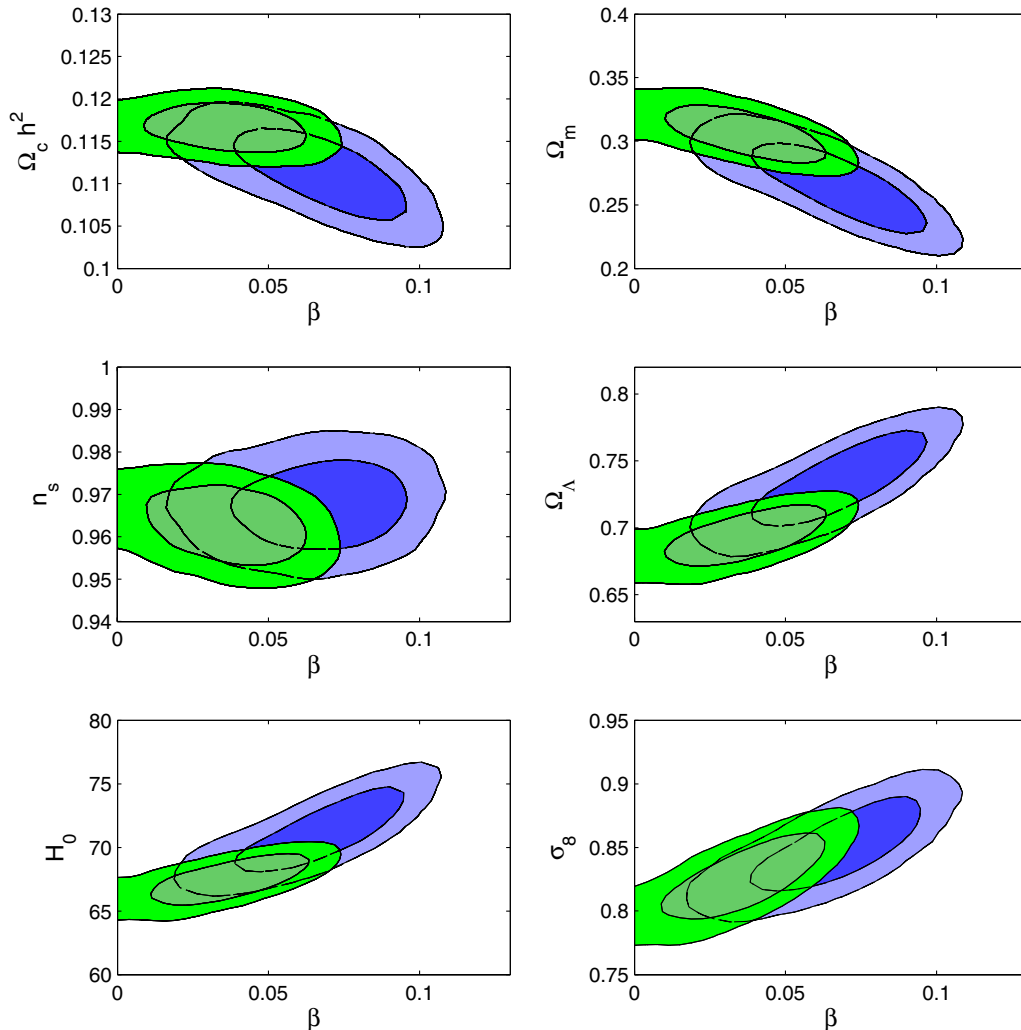


FIG. 2 (color online). Confidence contours for the cosmological parameters for coupled quintessence models. We compare runs PlanckWP + BAO (green, light left contours) and PlanckWP + HST (blue, dark right contours). 1σ and 2σ contours are shown.

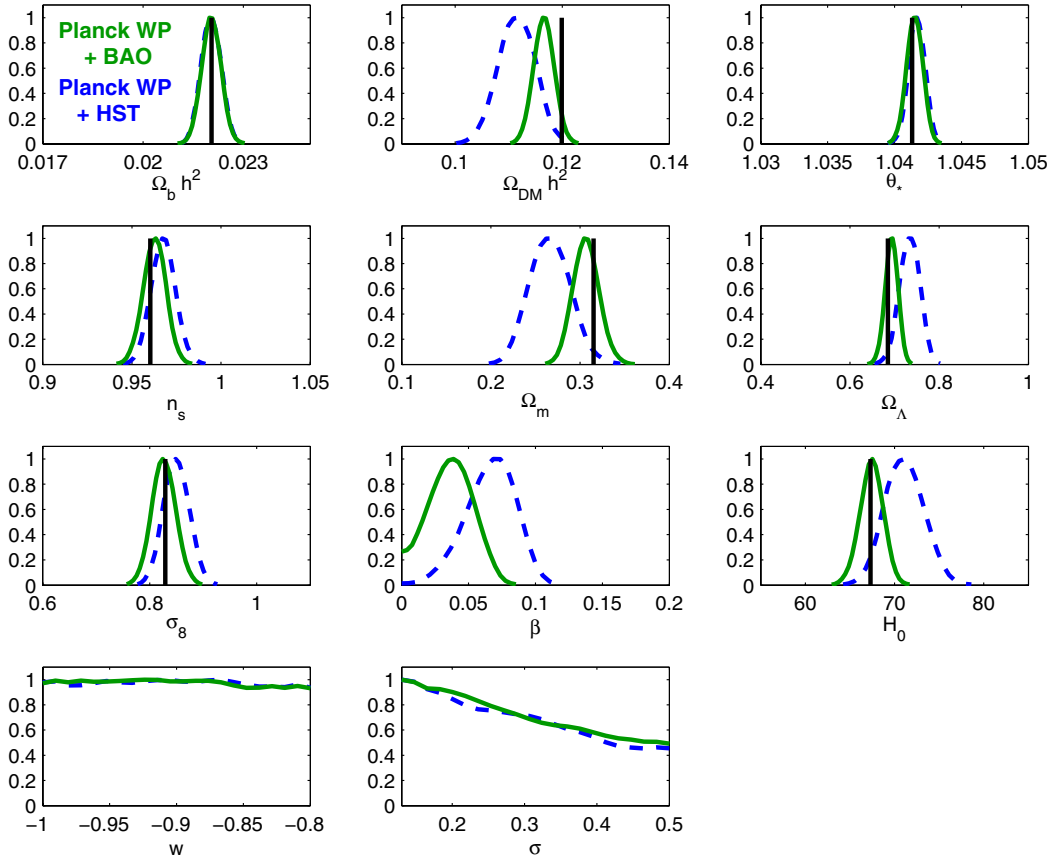


FIG. 3 (color online). 1D likelihoods for the cosmological parameters for coupled quintessence models. We compare runs from Planck WP + BAO (green, lighter) and Planck WP + HST (blue, darker). The black vertical line indicates the mean value for the corresponding parameter (when applicable) in a Λ CDM as found in Planck + WP only [3]. As expected, in coupled quintessence models, no dependence is seen on the value of σ and w , which are arbitrary and related to each other, as illustrated in the text.

$\beta = 0$; it is interesting to note that it is already marginally present in combination with BAO (at about 2.2σ). We recall, however, that even for $\beta = 0$ we are not in an exact Λ CDM since in our model w is close, but not exactly equal, to -1 . The 2D confidence contours for Planck WP + BAO and Planck WP + HST are plotted in Fig. 2, where we show a selection of the most interesting likelihood contours vs the coupling β . The tension with astrophysical experiments is compensated by an increase in the value of $H_0 \sim 71$ with a corresponding mild decrease of $\Omega_c h^2$ and Ω_M , the latter being still compatible with the values estimated in a Λ CDM scenario.

In Fig. 3 we also show the corresponding 1D likelihood contours. As expected, there is no determination of σ , since σ only affects late time cosmology. The value of w is arbitrary and approximately related to σ via the expression $w = -2/(\sigma + 2)$; the interval chosen for σ (small enough to get reasonable speed for the runs) is such that w still assumes reasonable values, at least smaller than -0.8 .

Finally, in Fig. 4 we plot the analogous of Fig. 3 in [68] for coupled dark energy models. The figure shows the parameter space H_0 vs $r_s/D_V(z_{\text{drag}} = 0.57)$. The latter is

the characteristic BAO parameter at the redshift reported by BOSS, where r_s is the comoving sound horizon at the baryon dragging epoch (when baryons became dynamically decoupled from the photons) and $D_V(z)$ is a combination of the angular-diameter distance $D_A(z)$ and the Hubble parameter $H(z)$:

$$D_V(z) = \left[(1+z)^2 D_A^2 \frac{cz}{H(z)} \right]^{1/3}. \quad (8)$$

While the green and blue contours refer to CMB likelihoods from Planck WP + BAO and Planck WP + HST data respectively, the grey ellipses show the ellipses from BOSS + H_0 (using [16] for the latter), as reported in [68]. The ellipses partly overlap and are compatible at about 2σ . We prefer however not to combine all three probes (CMB, BAO, H_0) and wait for further clarifications on these data sets, as discussed in [3]. We just note that a larger coupling corresponds to larger values of H_0 , as seen by the clear degeneracy plotted in Fig. 2.

In order to have a feeling on how the coupling β is related to other common measurements of gravitational interactions, constraints on β can be converted into a

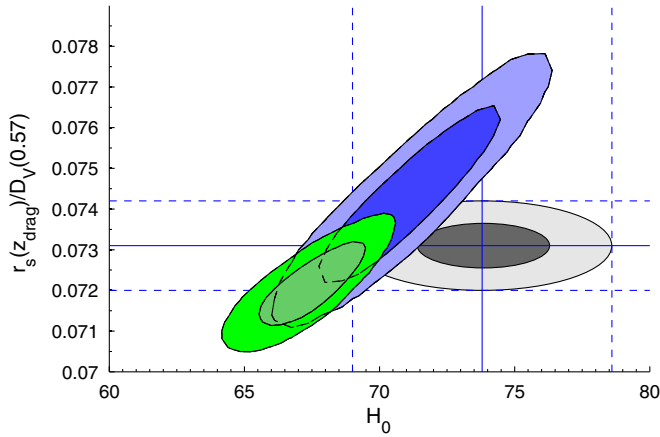


FIG. 4 (color online). This figure (based on Fig. 3 of [68]) investigates the consistency between CMB and BAO_{BOSS} and H_0 data sets for a coupled dark energy model. We compare runs Planck WP + BAO (green, lower left contours) and Planck WP + HST (blue, darker contours). 1σ and 2σ contours are shown. The grey ellipses correspond to the 1σ and 2σ region ellipses drawn in Fig. 3 of [68], which refer to the combination BAO_{BOSS} + H_0 (with H_0 from [16]). The horizontal (vertical) solid and dashed lines mark the central value and 1σ region.

constraint on the Brans-Dicke coupling parameter ω_{BD} as shown in [38] using

$$3 + 2\omega_{\text{BD}} = \frac{1}{2\beta^2}. \quad (9)$$

Therefore a value of $\beta \sim 0.036(0.066)$ would correspond to $\omega_{\text{BD}} \sim 191(56)$ and to a post-Newtonian parameter $\gamma_{\text{PPN}} = 1 - 2/(2\omega_{\text{BD}} + 3) \sim 0.99(0.98)$. These values have to be seen as complementary to the small-scale limits set by local gravity tests on Yukawa corrections [69,70] and refer to a dark matter–dark matter interaction on cosmological scales (baryons are assumed to follow general relativity, as explained above).

V. CONCLUSIONS

We have considered the possibility that the evolution of dark matter and dark energy might be connected by a

constant coupling, of the type illustrated in [25,26]. This effectively introduces a fifth force that modifies the gravitational attraction between dark matter particles. We have used current CMB data from Planck to constrain the coupling parameter β . This parameter measures the amount by which gravitational interaction between dark matter particles is modified. Constraints on β are complementary to the small-scale limits set by local gravity tests on Yukawa corrections [69,70]. Due to the degeneracy with the distance to last scattering, we combine CMB data with different astrophysical data sets (BAO or HST). We find that a small preference for nonzero coupling β , less or more significant depending on the astrophysical data set used. In particular we find $\beta = 0.036 \pm 0.016$ at 68% C.L. for Planck WP + BAO and $\beta = 0.066 \pm 0.018$ for Planck WP + HST data. These values are in less or more tension with zero at roughly 2.2σ or 3.6σ , respectively. It is interesting to notice that a small preference for a nonzero coupling is present also when combining Planck with BAO, whose astrophysical geometrical measurements seem to be more reliable [3]. Given the number of possible systematics which may affect data sets our attitude is to be conservative: we do not find this preference strong enough to claim a deviation from a Λ CDM. Our aim here is mainly to show that CMB data, though compatible with a Λ CDM, still contain significant information that does not exclude the presence of dynamical dark energy models and fifth forces. After completion of this paper, the article [71] was published on the ArXiv, finding similar results for a different set of coupled dark energy models, based on a coupling inserted through conservation equations rather than at the level of the Lagrangian (1).

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