New constraints on Coupled Dark Energy from Planck

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We present new constraints on coupled dark energy from the recent measurements of the Cosmic Microwave Background Anisotropies from the Planck satellite mission. We found that a coupled dark energy model is fully compatible with the Planck measurements, deriving a weak bound on the dark matter-dark energy coupling parameter $\xi = -0.49^{+0.19}_{-0.31}$ at 68% c.l.. Moreover if Planck data are fitted to a coupled dark energy scenario, the constraint on the Hubble constant is relaxed to $H_0 = 72.1^{+3.2}_{-2.3}$ km/s/Mpc, solving the tension with the Hubble Space Telescope value. We show that a combined Planck+HST analysis provides significant evidence for coupled dark energy finding a non-zero value for the coupling parameter ξ, with $-0.90 < \xi < -0.22$ at 95% c.l.. We also consider the combined constraints from the Planck data plus the BAO measurements of the 6dF Galaxy Survey, the Sloan Digital Sky Survey and the Baron Oscillation Spectroscopic Survey.

I. INTRODUCTION

The Planck satellite experiment has recently provided new and precise measurements of the Cosmic Microwave Background (CMB) anisotropy, covering a wide range of angular scales up to multipole $\ell \sim 2500$ [1–3]. The new data are in full agreement with the expectations of the so-called standard ΛCDM scenario.

There exist however some tensions when the value of a number of cosmological parameters, as measured by Planck data, are compared with the values of the same parameters as measured by independent cosmological probes.

The most notable case concerns the constraint on the Hubble constant H_0. The value measured by the Planck team , $H_0 = 67.3 \pm 1.2$ km/s/Mpc (at 68% c.l.), is significantly lower than the previous measurement of $H_0 = 73.8 \pm 2.4$ km/s/Mpc (at 68% c.l.) from the Hubble Space Telescope (HST) arising from optical and infrared observations of ~ 600 Cepheid variables [4]. While systematics can certainly be present in both measurements, it is timely to investigate if this discrepancy can be explained by the inclusion of new physical phenomena.

Very recently, Marra et al. [5], have pointed out that the HST value could be affected by the cosmic variance of the local expansion rate and inhomogeneities. In this approach, the HST value is therefore biased and the correct value is given by Planck measurements.

On the other hand, one has to consider that the CMB determination of the Hubble parameter is not a direct measurement but it is based on the assumption of an underlying theoretical model.

For example, the inclusion in the Planck data analysis of an extra relativistic energy component, parameterized via the effective number of relativistic degrees of freedom N_{eff}, changes the constraint on the Hubble constant to $H_0 = 70.7 \pm 3.2$ km/s/Mpc at 68% c.l. [2], totally compatible with the HST determination. Several phys-

ical candidates have been recently examined to account for the extra dark radiation component (see e.g. [6] and references therein). A combined Planck and HST data analysis yields evidence for dark radiation at more than 95% c.l. ([2],[7]).

In this paper we investigate the possibility that the solution of the Planck-HST tension could arise from an interaction between dark energy and dark matter. The assumption of a coupled dark energy model can change significantly the CMB constraints on the Hubble parameter (see e.g. [8–11]). In particular, if coupled models are fitted to a (wrong) ΛCDM cosmology, the reconstructed H_0 from CMB will be shifted from its real value [12]. A mismatch between low and high redshift H_0 measurements could therefore be a smoking gun for an interaction in the dark sector.

Moreover, even if a cosmological constant Λ is a good fit to the current data, the dark matter-dark energy interaction alleviates the well-known coincidence problem that plagues the ΛCDM scenario (see e.g. [13]). Several candidates for coupled dark energy models have been proposed and investigated (see e.g. [14]). Since coupled quintessence models can resemble to scalar-tensor or brans dicke gravitational theories, it has been suggested that coupled dark energy can also hint to a modification of general relativity on cosmological scales (see e.g. [15–17]).

The paper is organized as follows. In Section II we briefly present the coupled dark energy model we consider for our analysis, in Sec. III we describe the analysis method, in Sec. IV we show our results and in SectionV we draw our conclusions.

II. DARK INTERACTION PARAMETRIZATION

We assume a flat universe described by the Friedmann-Robertson-Walker metric. We parametrize the interaction as follows:

$$\nabla_\mu T^\mu_{(dm)\nu} = Q\, u^{(dm)}_\nu /a \,, \tag{1}$$

$$\nabla_\mu T^\mu_{(de)\nu} = -Q\, u^{(dm)}_\nu /a \,, \tag{2}$$

where $T^\mu_{(dm)\nu}$ and $T^\mu_{(de)\nu}$ are the energy-momentum tensors for the dark matter and dark energy components respectively, $u^{(dm)}_\nu$ is the dark matter four-velocity and the coefficient Q encodes the interaction rate between the two dark components.

In particular we restrict the parametrization to the case where the interaction rate is proportional to the dark energy density ρ_{de}:

$$Q = \xi \mathcal{H} \rho_{de} \tag{3}$$

where ξ is a dimensionless parameter and $\mathcal{H} = \dot{a}/a$ (the dot indicates derivative respect to conformal time $d\tau = dt/a$). Such an interacting model is in agreement with cosmological constraints and it does not suffer from early time instabilities if the coupling ξ is negative and the dark energy equation of state w satisfies $w > -1$ [18, 19]. We shall follow here the former stability conditions.

The background evolution equations in the coupled model considered here read [20]

$$\dot\rho_{dm} + 3\mathcal{H}\rho_{dm} = \xi \mathcal{H} \rho_{de} \,, \tag{4}$$

$$\dot\rho_{de} + 3\mathcal{H}(1+w)\rho_{de} = -\xi \mathcal{H} \rho_{de} \,. \tag{5}$$

In the synchronous gauge, the evolution of the dark matter and dark energy perturbations in the linear regime reads [20]

$$\dot\delta_{dm} = -(kv_{dm} + \frac{1}{2}\dot h) + \xi\mathcal{H}\frac{\rho_{de}}{\rho_{dm}}(\delta_{de} - \delta_{dm}) \tag{6}$$

$$+\xi\frac{\rho_{de}}{\rho_{dm}}\left(\frac{kv_T}{3} + \frac{\dot h}{6}\right) \,,$$

$$\dot\delta_{de} = -(1+w)(kv_{de} + \frac{1}{2}\dot h) - 3\mathcal{H}(1-w) \tag{7}$$

$$\left[\delta_{de} + \mathcal{H}\left(3(1+w) + \xi\right)\frac{v_{de}}{k}\right] - \xi\left(\frac{kv_T}{3} + \frac{\dot h}{6}\right) \,,$$

$$\dot v_{dm} = -\mathcal{H}v_{dm} \,, \tag{8}$$

$$\dot v_{de} = 2\mathcal{H}\left(1 + \frac{\xi}{1+w}\right)v_{de} + \frac{k}{1+w}\delta_{de} - \xi\mathcal{H}\frac{v_{dm}}{1+w} \tag{9}$$

where $\delta_{dm,de}$ and $v_{dm,de}$ are the density perturbations and velocities of the dark matter and dark energy fluids, respectively, v_T is the center of mass velocity for the total fluid and h is the usual synchronous gauge metric perturbation. Equations (6)-(9) include the contributions of the perturbation in the expansion rate $H = \mathcal{H}/a + \delta H$,

the dark energy speed of sound has been fixed to 1, i.e. $\hat{c}^2_{s\,de} = 1$, and the equation of state for dark energy w has been taken to be constant.

Also notice that in our numerical analysis, we have considered adiabatic initial conditions for all components, see appendix A.

The dark interaction we consider affects the CMB temperature spectrum in several ways. In Fig. 1, we illustrate the impact of ξ up to multipole $l = 2500$ for $\xi = -0.2, -0.5$ assuming a cold dark matter density $\Omega_c h^2 = 0.1186$ and $H_0 = 67.9$ km/s/Mpc. Notice that the presence of a coupling among the dark matter and the dark energy fluids shifts the position of the peaks to larger multipoles. At low multipoles, a value of ξ different from zero contributes to the late integrated Sachs-Wolfe (ISW) effect, while at high multipoles changes the amplitude of the gravitational lensing.
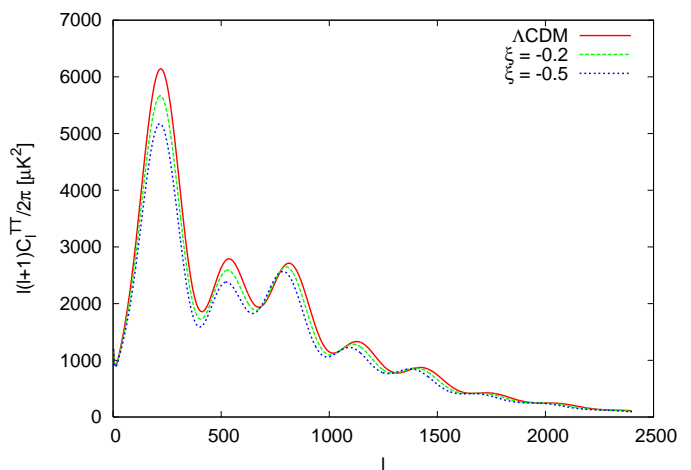

FIG. 1: CMB temperature power spectrum in the ΛCDM case and in the coupled cases for $\xi = -0.2, -0.5$, $\Omega_c h^2 = 0.1186$, $H_0 = 67.9$ km/s/Mpc. The main effects of the coupling are shifting the position of the acoustic peaks and varying their amplitude.

III. DATA ANALYSIS METHOD

The theoretical CMB angular spectra are computed with a modified version of the CAMB code [21], in which we have included the background and linear density perturbation equations in the presence of a coupling between the dark matter and the dark energy sectors. For the Planck data set[1], we consider the high-ℓ TT likelihood, including measurements up to a maximum multipole number of $\ell_{\max} = 2500$, combined with the low-ℓ TT likelihood which includes measurements up to

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[1] Planck data set is publicly available at *http://pla.esac.esa.int/pla/aio/planckProducts.html*

Parameters	Prior
$\Omega_b h^2$	[0.005, 0.100]
$\Omega_c h^2$	[0.005, 0.100]
100θ	[0.5, 10]
τ	[0.01, 0.80]
n_s	[0.9, 1.1]
$\log(10^{10} A_s)$	[2.7, 4.0]
ξ	[-1,0]

TABLE I: Ranges for the priors of different cosmological parameters considered in the analysis.

$\ell = 49$. We also consider low-ℓ ($\ell < 23$) TE,EE,BB likelihood which includes polarization measurements from nine years of observation of the Wilkinson Microwave Anisotropy Probe (WMAP) [22]. We refer to this data combination as the PLANCK data set.

We also consider the effect of a gaussian prior on the Hubble constant $H_0 = 73.8 \pm 2.4 \, \text{km s}^{-1} \, \text{Mpc}^{-1}$ consistent with the measurements of the Hubble Space Telescope as in [4]. We refer to this prior as HST.

Finally we analyze the impact of baryon acoustic oscillations (BAO) measurements, using the data of three surveys at different redshifts: the 6dF Galaxy Survey measurement at $z = 0.1$ provided in [23], the SDSS DR7 measurement at $z = 0.35$ from [24] and the BOSS DR9 measurement at $z = 0.57$ discussed in [25]. We refer to this combination as the BAO data set.

We sample a seven-dimensional set of cosmological parameters, adopting flat priors on them (see Tab. I): the ξ coupling parameter, 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 θ, the optical depth to reionization τ, the scalar spectral index n_s and the amplitude of the primordial scalar perturbation spectrum, A_s at $k = 0.05 \, \text{Mpc}^{-1}$. We fix the relativistic number of degrees of freedom parameter to $N_{eff} = 3.046$, the helium abundance to $Y_p = 0.24$, the total neutrino mass to $\sum m_\nu = 0.06 eV$, the spectrum lensing normalization to $A_L = 1$ and the dark energy equation of state to $w = -0.999$. We marginalize over all foregrounds parameters as described in [2]. We also consider the effect of letting w free to vary under the condition $w > -1$.

Our analysis follows a Markov chains approach and is based on a modified version of the public available code CosmoMC [26, 27], setting the statistical convergence for Gelman and Rubin $R - 1$ values below 0.03.

IV. RESULTS

We have initially performed four runs, fixing the dark energy equation of state to $w = -0.999$: a first run with no coupling, $\xi = 0$, which corresponds to the ΛCDM case (as in [2]). We have then let the coupling parameter to vary freely, performing separately an analysis with Planck data alone, Planck data plus the HST prior on the Hubble constant and Planck data plus BAO data.

The constraints on the parameters and the best fit values are reported in Tab. II while we plot the 1-D posteriors for the parameters in Fig. 2 and the 2-D posterior for the main parameter degeneracies in Fig. 3, 4, 5. Note that the coupling is only between cold dark matter and dark energy, therefore the bounds on the baryon density remain unchanged when ξ is allowed to freely vary.

The presence of a dark coupling is perfectly compatible with the PLANCK data set. Coupled cosmologies provide even a slightly better best fit χ^2 than the ΛCDM model, see Tab. II. Looking at the marginalized value of ξ in Tab. II it seems to exist also a preference for $\xi < 0$ but this is mainly due to the large number of coupled dark models compatible with the data. The PLANCK data set alone does not exclude $\xi = 0$ 2.

As expected (see e.g [12]), there exists a strong degeneracy between ξ and the cold dark matter density $\Omega_c h^2$, see Fig. 3. Negative values of the coupling ξ implies a larger matter density in the past. Since the PLANCK data are sensitive to the amount of cold dark matter density at recombination, $\xi < 0$ leads to a lower value of the cold dark matter density today. The degeneracy is nearly perfect and for large negative values of ξ the PLANCK data set is compatible with even negligible values of $\Omega_c h^2$.

This degeneracy affects the geometrical parameters values and, in particular, the Hubble constant value, which in this case assume values significantly larger than in the standard ΛCDM case. The introduction of a coupling ξ changes the constraint of $H_0 = 67.3 \pm 1.2$ km/s/Mpc (at 68% c.l.), obtained in the ΛCDM case, to $H_0 = 72.1^{+3.2}_{-2.3}$ km/s/Mpc (at 68% c.l.).

It is therefore not surprising that, when the HST prior is included, the PLANCK+HST data combination suggests a value for the coupling different from zero. The best fit values and the 68% c.l. constraints we have obtained in this case are reported in the third column of table II while 2-D posteriors are shown in Fig. 4. The combined PLANCK+HST constraint excludes a zero value of the coupling parameter ξ at more than 2 sigma ($\xi < -0.22$ at 95% c.l.), while the value of the Hubble constant is $H_0 = 73.3^{+2.6}_{-1.6}$ km/s/Mpc at 68% c.l..

If we add instead the BAO low-redshift measurements to the Planck data, we can observe that a zero coupling it is admitted but not favoured and that the tension between the Hubble constant measurements is still alleviated, as in the Planck alone case. The results of this run

are shown in the fourth column of table II and in Fig. 5.

We have verified that none of the foreground parameters is sensitive to the coupling component, confirming that our analysis is not biased by the foreground marginalization.

We have also explored the effect of a freely varying dark energy equation of state w in our results. If w is added in the MonteCarlo analyses, the parameters constraints are comparable and the same degeneracies appear, even if in this case the constraint on H_0 is weaker when we consider PLANCK alone. This is due to the fact that CMB measurements alone can weakly constrain w in general, also in the ΛCDM case, and can not break the degeneracy between the coupling parameter ξ and w.

The degeneracy between the coupling parameter ξ, H_0 and w when we consider a varying w for PLANCK data set is shown in Figure 6. Note that the values of H_0 obtained for reasonable values of $w \sim -1$ are in a much better agreement with low redshift measurements of the Hubble constant, if compared to the values of H_0 obtained in the ΛCDM PLANCK case.

The best fit values and the 68% c.l. constraints from the three dataset combinations when w is marginalized over are shown in the table III. While the 1D and 2D posterior distributions are presented in Fig.7 and 8, 9, 10.

V. CONCLUSIONS

In this paper we have presented novel cosmological constraints on a dark matter-dark energy interaction from the new CMB measurements provided by the Planck experiment. We have found that a dark coupling interaction is compatible with Planck data and that the coupling parameter ξ is weakly constrained by Planck measurements $\xi = -0.49^{+0.19}_{-0.31}$. However, the inclusion of a dark coupling opens up new degeneracies and affects strongly the constraints on the remaining cosmological parameters. The model with the dark interaction gives a lower matter density $\Omega_{\rm m} = 0.155^{+0.050}_{-0.11}$ and a larger Hubble parameter $H_0 = 72.1^{+3.2}_{-2.3}$km/s/Mpc. Since the value of the Hubble constant is compatible with the HST value, we have combined the Planck and HST data sets, finding

that, in this case, a non-zero value of the dark coupling is suggested by the data, with $-0.90 < \xi < -0.22$ at 95% c.l.. The analysis presented here points out that an interaction in the dark sector is not only allowed by current CMB data but can even resolve the tension between the Planck and the HST measurements of the Hubble parameter. The results we have found are in agreement with the results obtained in former analyses for similar models using previous cosmological data [9, 12, 28, 29].

Acknowledgements

Appendix A: Adiabatic initial conditions

In ref. [20], the evolution equations for the coupled dark matter dark energy model considered here were studied in a gauge invariant way. It was demonstrated that, assuming adiabatic initial conditions for all the standard cosmological fluids (photon, baryons,...), the coupled dark energy fluid also obeys adiabatic initial conditions, see also Ref. [30] in the uncoupled case and Ref. [31] for another coupled example. At leading order in $x = k\tau$, in the synchronous gauge, the initial conditions read:

$$\delta_{de}^{in}(x) = (1 + w - 2\xi)\frac{(1 + w + \xi/3)}{12w^2 - 2w - 3w\xi + 7\xi - 14}\left(\frac{-2\delta_\gamma^{in}(x)}{1 + w_\gamma}\right),$$

$$v_{de}^{in} = \frac{x(1 + w + \xi/3)}{12w^2 - 2w - 3w\xi + 7\xi - 14}\left(\frac{-2\delta_\gamma^{in}(x)}{1 + w_\gamma}\right),$$

where $\delta_\gamma^{in}(x)$ are the initial conditions for the photon density perturbations and $w_\gamma = 1/3$ is the equation of state of the photon. The latter reduce to the adiabatic initial conditions for dark energy perturbations in the synchronous gauge obtained in Ref. [32] in the uncoupled case.

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Parameters	PLANCK + ΛCDM Best fit	68% limit	PLANCK+ ξ Best fit	68% limit	PLANCK+ HST+ ξ Best fit	68% limit	PLANCK+ BAO+ ξ Best fit	68% limit
$\Omega_b h^2$	0.02203	0.02205 ± 0.00028	0.02204	0.02200 ± 0.00027	0.02201	0.02203 ± 0.00027	0.02195	0.02192 ± 0.00025
$\Omega_c h^2$	0.1204	0.1199 ± 0.0027	0.0664	< 0.074	0.0450	< 0.056	0.096	$0.0069^{+0.040}_{-0.022}$
100θ	1.04119	1.04131 ± 0.00063	1.0445	1.0456 ± 0.0026	1.0461	1.0466 ± 0.0021	1.0427	1.0445 ± 0.0021
τ	0.093	$0.089^{+0.012}_{-0.014}$	0.0867	$0.087^{+0.012}_{-0.014}$	0.080	$0.088^{+0.017}_{-0.013}$	0.090	$0.085^{+0.012}_{-0.013}$
n_s	0.9619	0.9603 ± 0.0073	0.9543	0.9580 ± 0.0071	0.9586	0.9589 ± 0.0070	0.9596	0.9556 ± 0.0060
$\log(10^{10} A_s)$	3.098	$3.089^{+0.024}_{-0.027}$	3.090	$3.083^{+0.023}_{-0.025}$	3.070	$3.084^{+0.024}_{-0.027}$	3.090	$3.082^{+0.023}_{-0.026}$
ξ	———	———	-0.46	$-0.49^{+0.19}_{-0.31}$	-0.58	$-0.58^{+0.090}_{-0.22}$	-0.22	$-0.42^{+0.29}_{-0.21}$
Ω_m	0.318	$0.315^{+0.016}_{-0.018}$	0.177	$0.155^{+0.050}_{-0.11}$	0.127	$0.122^{+0.033}_{-0.070}$	0.246	$0.187^{+0.085}_{-0.063}$
Ω_Λ	0.682	$0.685^{+0.018}_{-0.016}$	0.823	$0.845^{+0.11}_{-0.050}$	0.873	$0.878^{+0.070}_{-0.033}$	0.754	$0.813^{+0.063}_{-0.085}$
z_{re}	11.4	11.1 ± 1.1	10.9	10.9 ± 1.1	10.2	10.9 ± 1.1	11.2	10.7 ± 1.1
H_0[km/s/Mpc]	67.0	67.3 ± 1.2	71.0	$72.1^{+3.2}_{-2.3}$	73.0	$73.3^{+2.0}_{-1.6}$	69.3	$70.8^{+1.9}_{-2.1}$
Age/Gyr	13.824	13.817 ± 0.048	13.747	$13.733^{+0.062}_{-0.065}$	13.720	$13.711^{+0.051}_{-0.046}$	13.785	13.765 ± 0.044
$\chi^2_{\min}/2$	4902.95		4902.45		4902.52		4902.71	

TABLE II: Best fit values and 68% c.l. constraints for the ΛCDM model (first column) and the dark coupled model described in the text from PLANCK data set (second column). We can see that the effect of the coupling, encoded by the parameter ξ, is to increase H_0 and to decrease $\Omega_c h^2$ respect to the standard model values. If we consider the combined constraint on the dark coupled model from PLANCK and HST (third column) we see similar bounds but now a negative coupling is significantly favoured. If we instead combine PLANCK and BAO measurements (fourth column) we observe that a lower value of $\Omega_c h^2$ is favoured, compared to coupled model in the PLANCK alone case, but the H_0 value is still in agreement with the Hubble Space Telescope measurement.

Parameters	PLANCK + wΛCDM Best fit	68% limit	PLANCK+ ξ Best fit	68% limit	PLANCK+ HST+ ξ Best fit	68% limit	PLANCK+ BAO+ ξ Best fit	68% limit
$\Omega_b h^2$	0.02220	0.02206 ± 0.00028	0.02207	0.02197 ± 0.00028	0.02207623	0.02205 ± 0.00027	0.02192	0.02197 ± 0.00025
$\Omega_c h^2$	0.1200	0.1199 ± 0.0026	0.0607	< 0.058	0.013	< 0.034	0.012	< 0.052
100θ	1.04125	1.04132 ± 0.00063	1.0445	1.0465 ± 0.0026	1.0492	1.0479 ± 0.0019	1.0487	1.0467 ± 0.0023
τ	0.090	$0.089^{+0.012}_{-0.014}$	0.093	$0.087^{+0.012}_{-0.014}$	0.094	$0.089^{+0.0087}_{-0.013}$	0.085	$0.088^{+0.012}_{-0.013}$
n_s	0.9598	0.9602 ± 0.0071	0.9614	0.9568 ± 0.0071	0.9582	0.9590 ± 0.0070	0.9563	0.9570 ± 0.0064
$\log(10^{10} A_s)$	3.093	$3.089^{+0.024}_{-0.027}$	3.095	$3.084^{+0.024}_{-0.025}$	3.098	3.086 ± 0.024	3.086	$3.085^{+0.023}_{-0.026}$
ξ	———	———	-0.48	$-0.58^{+0.13}_{-0.28}$	-0.76	$-0.67^{+0.086}_{-0.17}$	-0.82	$-0.61^{+0.12}_{-0.25}$
w	-1.92	$-1.49^{+0.25}_{-0.43}$	-0.870	$-0.855^{+0.041}_{-0.14}$	-0.952	$-0.932^{+0.35}_{-0.067}$	-0.887	$-0.883^{+0.033}_{-0.12}$
Ω_m	0.147	$0.218^{+0.023}_{-0.079}$	0.179	$0.148^{+0.034}_{-0.11}$	0.065	$0.098^{+0.017}_{-0.055}$	0.131	$0.187^{+0.032}_{-0.083}$
Ω_Λ	0.853	$0.682^{+0.079}_{-0.023}$	0.821	$0.852^{+0.11}_{-0.034}$	0.935	$0.902^{+0.055}_{-0.017}$	0.869	$0.813^{+0.083}_{-0.032}$
z_{re}	11.1	11.0 ± 1.1	11.4	10.9 ± 1.1	11.5	11.0 ± 1.1	10.8	10.9 ± 1.1
H_0[km/s/Mpc]	98.6	83^{+17}_{-5}	68.2	$68.5^{+4.4}_{-3.3}$	73.7	$72.2^{+2.1}_{-1.6}$	70.8	69.6 ± 2.0
Age/Gyr	13.449	13.817 ± 0.048	13.789	$13.609^{+0.080}_{-0.18}$	13.696	13.726 ± 0.048	13.770	13.783 ± 0.046
$\chi^2_{\min}/2$	4903.14		4902.02		4901.90		4902.59	

TABLE III: Best fit values and 68% c.l. constraints for the ΛCDM model (first column) and the dark coupled model described in the text from PLANCK data set alone (second column), PLANCK+HST (second column) and PLANCK+BAO (third column) when we marginalize over the dark energy equation of state parameter w. It is important to note that the prior on w in the coupled model ($w > -1$) is not the same of the ΛCDM case. As we can expect the constraints are weaker in this case compared to Tab. II, since both w and xi depends on ρ_{de}, but the same trends are evident. Also note that the constraints on the background evolution parameters, as H_0 or w, from CMB measurements alone are very large also in the ΛCDM model.

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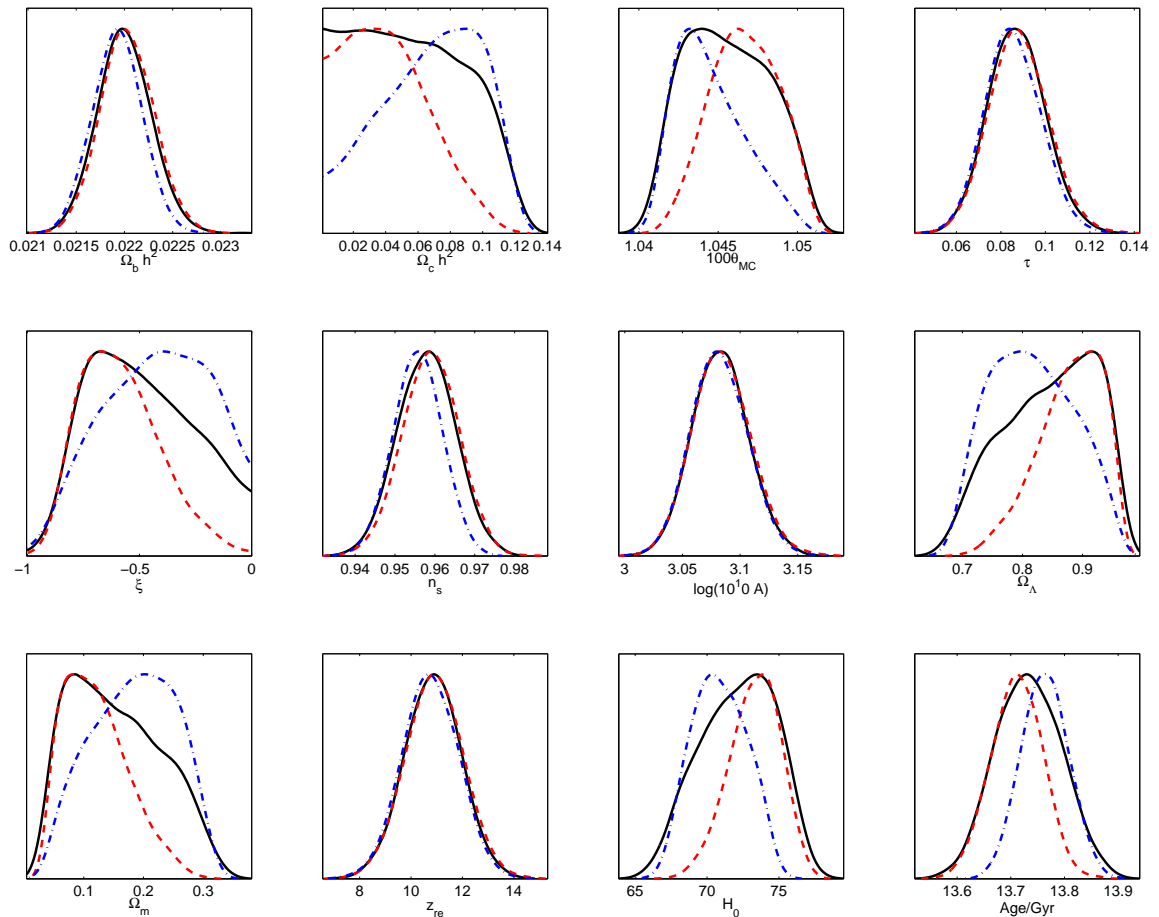[15] L. Amendola, Phys. Rev. D **62**, 043511 (2000) [astro-ph/9908023]

FIG. 2: Posterior distributions for the cosmological parameters presented in Tab.II from PLANCK data set alone (solid black line), PLANCK plus HST prior (red dashed line) and PLANCK plus BAO measurements (blue dot-dashed line). The effect of HST prior is to provide narrower distributions and stronger constraints, especially for the coupling parameter ξ.
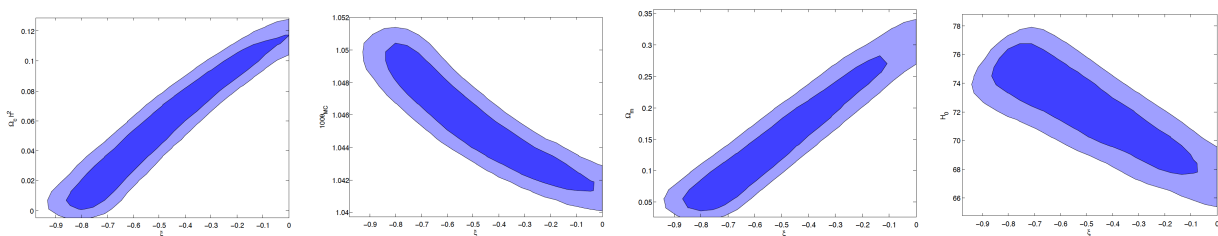

FIG. 3: 2-D posterior distributions of parameters most degenerate with the coupling ξ. A strong correlation is evident with the cold dark matter density parameter. A larger absolute value of the coupling ξ implies a decrement of the dark cold matter and a consequent decrease of the dark matter density. Since the assumption of a flat universe, it also implies a larger dark energy amount that brings to an increment of H_0 and consequently an increase of θ.

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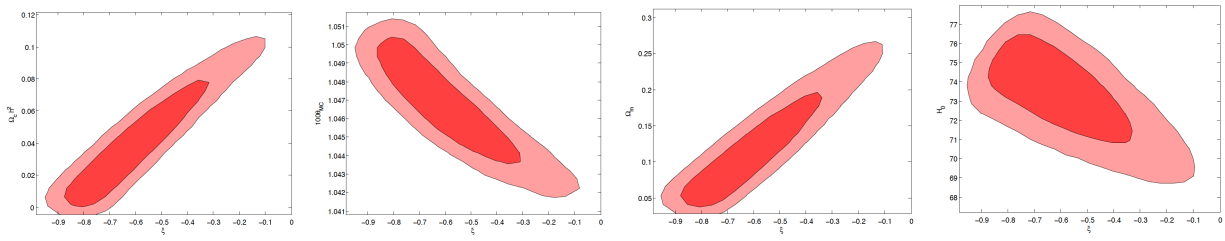
FIG. 4: 2-D posterior distributions in presence of the HST prior for the same parameters shown in Fig.3.
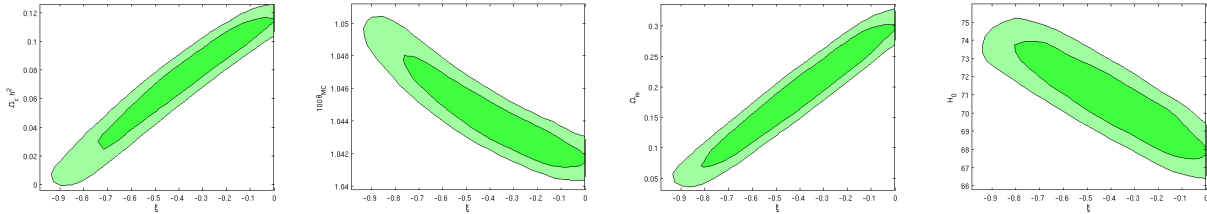

FIG. 5: 2-D posterior distributions in presence of the HST prior for the same parameters shown in Fig.3.
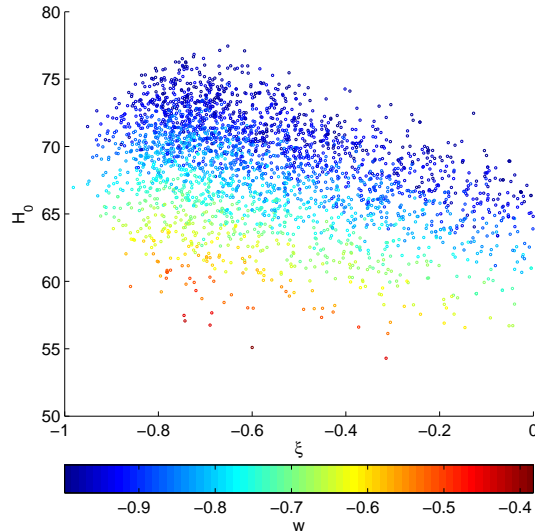

FIG. 6: 3D degeneracy between the coupling parameter ξ, H_0 and w from a run for the PLANCK data set with varying w. Note that the values of H_0 obtained for reasonable values of $w \sim -1$ are in a much better agreement with low redshift measurements of the Hubble constant, if compared to the values of H_0 obtained in the pure ΛCDM PLANCK case.

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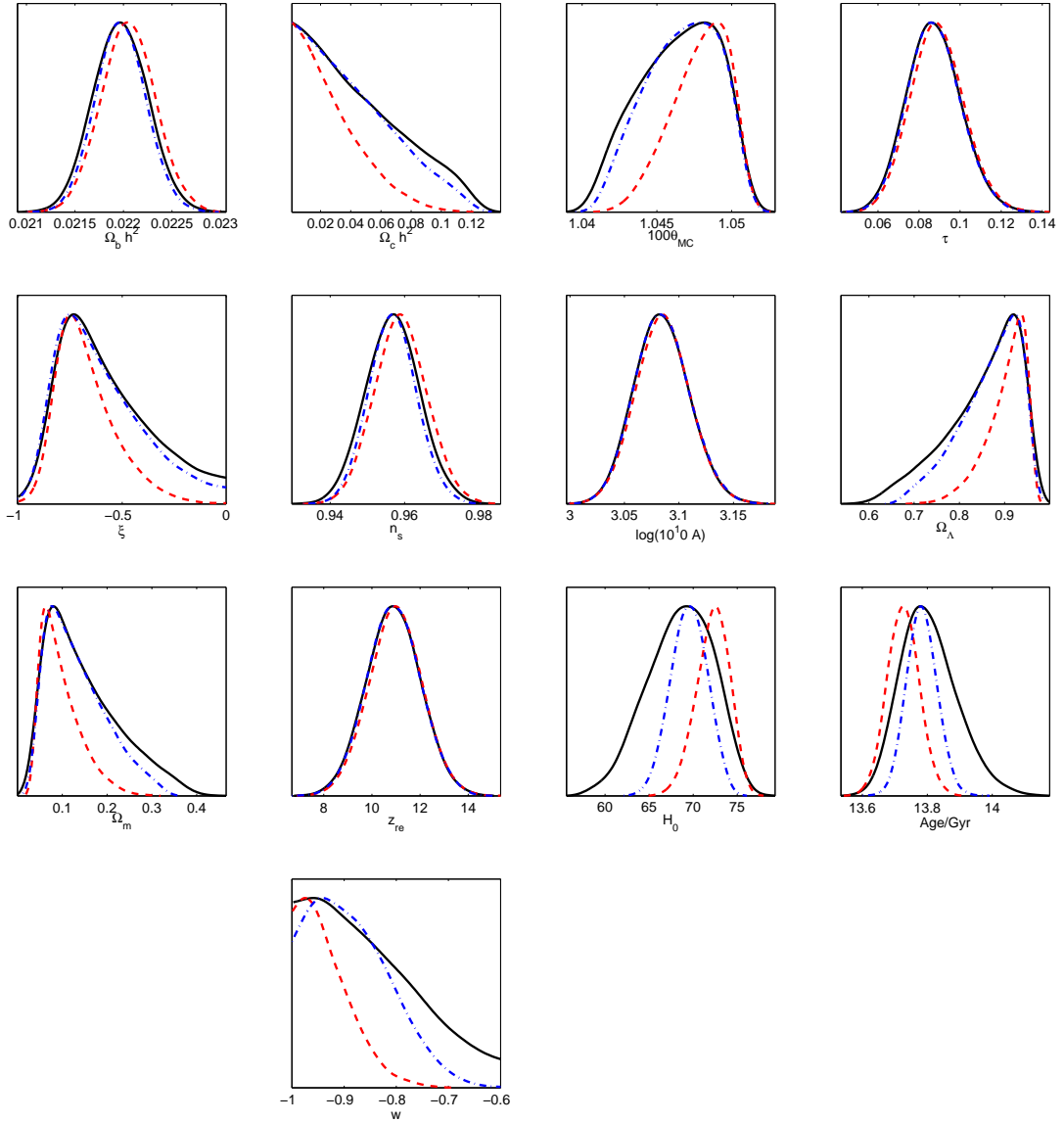
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FIG. 7: Posterior distributions for the cosmological parameters presented in Tab.I from PLANCK data set alone (solid black line), PLANCK plus HST prior (red dashed line) and PLANCK plus BAO measurements (blue dot-dashed line).

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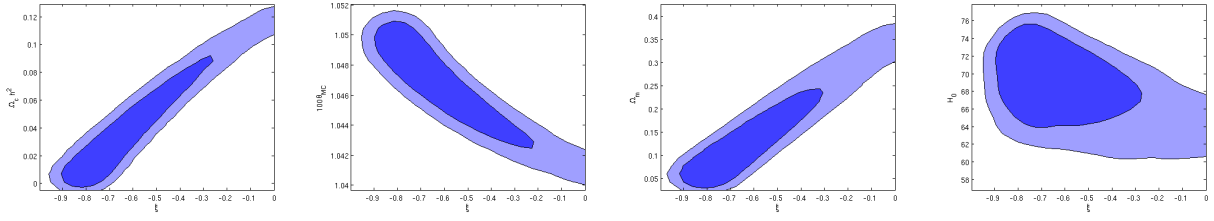[32] G. Ballesteros and J. Lesgourgues, JCAP **1010**, 014 (2010) [arXiv:1004.5509 [astro-ph.CO]].

FIG. 8: 2-D posterior distributions of parameters most degenerate with the coupling ξ. A strong correlation is evident with the cold dark matter density parameter. A larger absolute value of the coupling ξ implies a decrement of the dark cold matter and a consequent decrease of the dark matter density. Since the assumption of a flat universe, it also implies a larger dark energy amount that brings to an increment of H_0 and consequently an increase of θ.
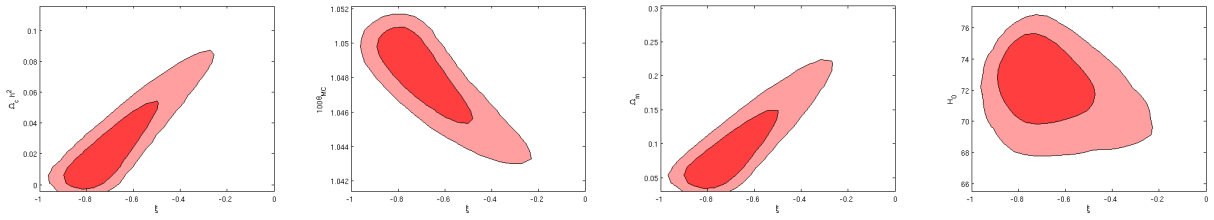

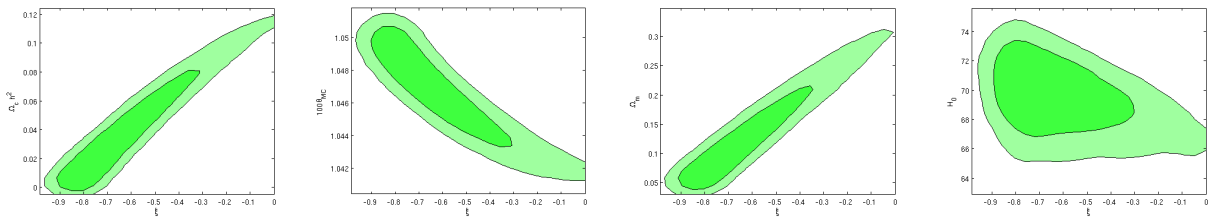FIG. 9: 2-D posterior distributions in presence of the HST prior for the same parameters shown in Fig.3.

FIG. 10: 2-D posterior distributions in presence of the HST prior for the same parameters shown in Fig.3.