Interacting dark energy after the latest Planck, DES, and $H_0$ measurements: an excellent solution to the $H_0$ and cosmic shear tensions

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(Dated: August 13, 2019)

We examine the most well-studied model featuring non-gravitational interactions between dark matter and dark energy in light of the latest cosmological observations. Our data includes Cosmic Microwave Background (CMB) measurements from the Planck 2018 legacy data release, galaxy clustering and cosmic shear measurements from the Dark Energy Survey Year 1 results, and the 2019 local distance ladder measurement of the Hubble constant $H_0$ from the Hubble Space Telescope. We find that the presence of interactions among the two dark sectors can bring the significance level of the long-standing $H_0$ tension below the 1σ level. The very same model also significantly reduces the $\Omega_m - \sigma_8$ tension between CMB and cosmic shear measurements. Interactions between the dark components of our Universe remain therefore as an extremely promising solution to these persisting cosmological tensions. The results presented in this paper are among the first constraints on exotic physics from the Planck 2018 legacy dataset. In a companion paper, we will further investigate these tensions when allowing for more freedom in the dark energy sector.

Introduction — The concordance ΛCDM cosmological model has been incredibly successful at describing cosmological observations at high and low redshift [1–5]. Yet, as uncertainties on cosmological parameters keep shrinking, a number of weaknesses have emerged: one of the most intriguing ones is the "$H_0$ tension", referring to the mismatch between the value of the Hubble constant $H_0$ inferred from Planck Cosmic Microwave Background (CMB) data and direct local distance ladder measurements [6,7]. In the past decade we have witnessed the tension between these two values grow in significance level from 2σ to 4.4σ: the latest determinations from the Planck 2018 results and from the observations of Large Magellanic Cloud Cepheids by the Hubble Space Telescope (HST; measurement denoted as R19 hereafter) give $h = (0.6737\pm0.0054)$ [8] and $h = (0.7403\pm0.0142)$ [9] respectively, with $h \equiv H_0/(100\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1})$ the reduced Hubble constant. A very appealing possibility is that the $H_0$ discrepancy might be a hint of physics beyond the canonical ΛCDM model. The most economic possibilities in this direction involve phantom dark energy or some form of dark radiation [10–12], but a number of more complex scenarios have been studied, e.g. [13–65].

On the other hand, tensions between cosmic shear surveys (such as [66–68]) and CMB measurements have also emerged [67,69,74]. For instance, the quantity $S_8 \equiv \sigma_8 (\Omega_m/0.3)^{0.5}$ as measured by the KiDS weak lensing survey was shown to be in 2.6σ tension with the same quantity as measured by Planck [71,72] (see also Refs. [71,72] for previous analyses of CFHTLenS data). Focusing on the joint galaxy clustering and lensing likelihoods from the Dark Energy Survey (DES) [5,73,74], the Planck collaboration found modest tension with the DES results when galaxy clustering measurements are included, as the latter prefer an $\approx 2.5\sigma$ lower value of $S_8$ [8]. A number of exotic scenarios have been advocated in the past to alleviate the $S_8$ tension, see for instance [14,16,24,29,32,33,39,40,50,68].

Within the ΛCDM model, dark matter (DM) and dark energy (DE) behave as separate fluids not sharing interactions beyond gravitational ones. However, from a microphysical perspective it is hard to imagine how non-gravitational DM-DE interactions can be avoided, unless forbidden by a fundamental symmetry. This has motivated a large number of studies based on models where DM and DE share interactions other than gravitational, usually referred to as interacting dark energy (IDE) models (see e.g. [75,117], for a recent comprehensive review see [118]). Several studies in the literature have been devoted to exploring whether DM-DE interactions may help resolve the enduring $H_0$ tension, see e.g. [119,130].

In this Letter we (re)assess whether IDE cosmologies
still provide a viable solution to the $H_0$ tension in light of the latest Planck and HST measurements. We find that IDE provides an extremely compelling solution to the $H_0$ tension, which is brought below the 1σ level. Intriguingly, when combining the latest Planck and HST measurements we find very strong indications for an interaction between the two dark components. We find that IDE also provides a compelling solution to the $S_8$ tension between Planck and DES.

### Interacting dark energy

We consider a non-gravitational DM-DE interaction with energy exchange proportional to the DM four-velocity, extensively studied in [79, 80, 84, 134]. We assume a pressureless cold DM component and a DE component with equation of state (EoS) $w$, and denote the DM and DE energy densities by $\rho_c$ and $\rho_x$ respectively. At the background level, the DM-DE coupling modifies the continuity equations for the two dark fluids as follows [80]:

$$\dot{\rho}_c + 3H\rho_c = Q, \quad (1)$$

$$\dot{\rho}_x + 3H(1+w)\rho_x = -Q, \quad (2)$$

where the dot denotes derivative with respect to conformal time $\tau$, and $H \equiv \dot{a}/a$ is the conformal Hubble rate. In the notation of Eqs. (1-2), $Q > 0$ and $Q < 0$ indicate energy transfer from DE to DM and vice versa. We choose to focus on one of the most well-studied IDE models, wherein the coupling $Q$ takes the following form [79, 80]:

$$Q = \xi\dot{H}\rho_x, \quad (3)$$

where $\xi$ is a dimensionless coupling governing the strength of the DM-DE interaction.

The presence of the DM-DE coupling also modifies the evolution of perturbations. In synchronous gauge, the linear perturbation equations for the evolution of the DM and DE density perturbations $\delta$ and velocity divergences $\theta$ are given by [79, 80, 135]:

$$\dot{\delta} = -\theta - \frac{1}{2} H + \xi H \frac{\rho_x}{\rho_c} (\delta - \delta_s) + \xi \frac{\rho_x}{\rho_c} \left( \frac{k v_T}{3} + \frac{\dot{h}}{6} \right), \quad (4)$$

$$\dot{\theta} = -H\theta, \quad (5)$$

$$\delta_s = -(1+w) \left( \delta_s + \frac{\theta}{2} - \xi \left( \frac{k v_T}{3} + \frac{\dot{h}}{6} \right) - 3H(1-w) \left[ \delta_s + \frac{H\theta}{k^2} (3(1+w) + \xi) \right] \right), \quad (6)$$

$$\dot{\delta}_s = 2H\delta_s + \frac{k^2}{1+w} \delta_s + 2H \frac{\xi}{1+w} \theta - \frac{\theta_c}{1+w}. \quad (7)$$

We appropriately modify the initial conditions for $\delta_s$ and $\theta_s$ following [87, 123, 135].

In the presence of DM-DE interactions, care must be given to the stability of the interacting system. For $w = 1$ (i.e. interacting vacuum), IDE models can suffer from gravitational instabilities [79, 136]. However, even when $w \neq 1$, one has to worry about early-time instabilities, leading to curvature perturbations blowing up on superhorizon scales. For IDE models in which $Q \propto \rho_x$, these instabilities are absent if the signs of $\xi$ and $(1+w)$ are opposite [79, 85, 133, 137] (see also [138, 144] for alternative approaches to avoiding these instabilities).

### Methodology and Cosmological Observations

We consider an IDE model characterized by the coupling given by Eq. (3). The model is described by the usual six cosmological parameters of $\Lambda$CDM ($\Omega_b h^2, \Omega_c h^2, \theta_s, A_s, n_s$, and $\tau$), in addition to the DM-DE coupling $\xi$. To circumvent the instability problem, we fix the DE EoS to $w = -0.999$. The rationale behind this approach (already followed in [87, 123]) is that for $w$ sufficiently close to $-1$ the effect of DE perturbations in Eqs. (5,7) is basically unnoticeable: consequently, these equations are essentially only capturing the effect of the DM-DE coupling $\xi$, while at the same time ensuring the absence of gravitational instabilities present when $w = -1$. Such a model provides therefore a rather accurate surrogate for a $\Lambda$CDM+$\xi$ cosmology, and we shall refer to this model as $\Lambda$CDM. In order to avoid early-time instabilities, we need to impose $\xi < 0$, implying that we are considering a model where energy flows from DM to DE.

Data-wise, we first consider measurements of CMB temperature and polarization anisotropies, as well as their cross-correlations, from the Planck 2018 legacy data release [8, 145]. This dataset is referred to as Planck TT,TE,EE+lowE in [8], whereas we refer to it simply as Planck. In addition to CMB data, we also consider a Gaussian prior on the Hubble constant $H_0 = 74.03 \pm 1.42$ km s$^{-1}$ Mpc$^{-1}$, consistent with the latest measurement by HST in [9]. We refer to this prior as $R19$. Finally, we include galaxy clustering and cosmic shear measurements from the Dark Energy Survey combined-probe Year 1 results [5, 73, 74], and refer to this dataset as DES.

We modify the Boltzmann solver CAMB [146] to incorporate the effect of the DM-DE coupling as in Eqs. (4,7). We sample the posterior distribution of the cosmological parameters by making use of Markov Chain Monte Carlo (MCMC) methods, through a modified version of the publicly available MCMC sampler CosmoMC [147]. We monitor the convergence of the generated MCMC chains through the Gelman-Rubin parameter $R \rightarrow 1$ [148], requiring $R - 1 < 0.02$ for our MCMC chains to be considered as converged. We impose flat priors on all cosmological parameters unless otherwise stated. In particular, as required by stability considerations, we impose $\xi < 0$ at the prior level.

Finally, we use our MCMC chains to compute the Bayesian evidence for the IDE model (for different choices of datasets) using the MCEvidence code [149]. We then compute the (logarithm of the) Bayes factor with respect to $\Lambda$CDM. In $B$, with a value in $B > 0$ indicating that the IDE model is preferred. We qualify the strength of the obtained values of $\ln B$ using the modified version of the Jeffreys scale provided in [150].

### Results

Our main results are shown in Tab. I and Fig. I. As shown in Tab. I from the Planck dataset alone,
FIG. 1. Left panel: 68% and 95% C.L. contours in the $(\xi, H_0)$ plane for the Planck and Planck+R19 dataset combinations. Right panel: 68% and 95% C.L. contours in the $(\sigma_8, \Omega_m)$ plane for the DES, Planck and Planck+DES dataset combinations.

| Parameter             | Planck         | Planck+R19  |
|-----------------------|----------------|-------------|
| $\Omega_b h^2$        | $0.02239 \pm 0.00015$ | $0.02239 \pm 0.00015$ |
| $\Omega_c h^2$        | $< 0.105$      | $< 0.0615$  |
| $1000\theta_s$        | $1.0458^{+0.0033}_{-0.0021}$ | $1.0470 \pm 0.0015$ |
| $\tau$                | $0.0541 \pm 0.0076$ | $0.0534 \pm 0.0080$ |
| $\xi$                 | $-0.54^{+0.12}_{-0.28}$ | $-0.66^{+0.09}_{-0.13}$ |
| $H_0$ [km s$^{-1}$ Mpc$^{-1}$] | $72.8^{+1.0}_{-1.5}$ | $74.6^{+1.2}_{-1.0}$ |

TABLE I. Mean values with their 68% C.L. errors on selected cosmological parameters within the $\xi\Lambda$CDM model, considering either the Planck 2018 legacy dataset alone, or the same dataset in combination with the R19 Gaussian prior on $H_0$ based on the latest local distance measurement from HST. The quantity quoted in the case of $\Omega_c h^2$ is the 95% C.L. upper limit.

The value of the Hubble constant $H_0$ inferred within the $\xi\Lambda$CDM model is $H_0 = 72.8^{+3.0}_{-1.5}$ km s$^{-1}$ Mpc$^{-1}$. While the uncertainty is larger than that reported in Ref. [8] within the standard $\Lambda$CDM scenario, the central value has significantly shifted upwards. Indeed, this value is perfectly consistent with the HST measurement of $H_0$, showing an agreement well below the 1$\sigma$ level. Therefore, within this IDE model, the $H_0$ tension is compellingly solved.

The reason for such a high value of $H_0$ from CMB measurements alone can be found in the strong degeneracy between $H_0$ and $\xi$, as depicted in the left panel of Fig. 1. The origin of this degeneracy resides in the fact that for the IDE model considered here, the background evolution of the DM energy density has an extra contribution proportional to the absolute value of $\xi$ and growing with $(1+z)^3$. Due to the presence of this extra term, the amount of DM today, $\Omega_c$, must be smaller. However, the acoustic peak structure of the CMB (and in particular the relative height of odd and even peaks, as well as the overall height of all peaks) accurately fixes the value of $\Omega_c h^2$: in order to accommodate a lower value of $\Omega_c$, a
higher value of $H_0$ is required. An inverse correlation between $\xi$ and $H_0$ is therefore expected, which is perfectly reflected in the contours in the left panel of Fig. 1.

Note that even if the Planck dataset alone shows a preference for a non-zero negative $\xi$ at $>95\%$ C.L., this is likely due to a volume effect, i.e., more models with $\xi < 0$ are compatible with Planck than models with $\xi = 0$. This explanation is supported by the fact that the best-fit $\chi^2$ for $\xi \neq 0$ is almost the same as the best-fit $\chi^2$ for $\Lambda$CDM. Computing the Bayes factor for the IDE model with respect to $\Lambda$CDM for the Planck dataset we find $\ln B = 1.2$. According to the modified Jeffrey scale of $[150]$, this indicates a positive preference for the IDE model.

As the Planck and R19 datasets are now consistent, it is possible to combine them. When considering the Planck+R19 combination, we find an even stronger indication for non-zero $\xi$, inferring $\xi = -0.06^{+0.13}_{-0.09}$. Computing the Bayes factor, we find the extremely high value $\ln B = 10.0$, indicating a very strong preference for the IDE model.

The solution to the $H_0$ tension due to a lower intrinsic value for $\Omega_\Lambda$ at present within the $\xi\Lambda$CDM model implies a much larger degeneracy in the $\Omega_m - \sigma_8$ plane, reflected in the right panel of Fig. 1: the allowed contours from the Planck dataset follow a band, rather than reproducing the small region usually singled out. The reason is that once a coupling $\xi$ is switched on, the required DM energy density $\Omega_m$ must be smaller as we have seen, implying that the clustering parameter $\sigma_8$ must be larger to have a proper normalization of the (lensing and clustering) power spectra. This effect can be perfectly understood from the scatter plot in the $\Omega_m - \sigma_8$ plane depicted in Fig. 2, as the absolute value of $\xi$ is increased, the allowed region bends towards larger (smaller) values of $\sigma_8$ ($\Omega_m$).

The $\text{DES}$ contours follow the expected $S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5} = 0.79$ behavior. Notice that the DES and Planck contours overlap for a very large fraction of the parameter space in the $\Omega_m - \sigma_8$ plane, implying that the tension between Planck and DES is alleviated. Notice that this is not merely an effect due to the larger uncertainties in the Planck contours, but rather is due to the strong overlap between the two contours.

**Conclusions** — In this Letter, we have examined the persisting $H_0$ tension in light of the Planck 2018 legacy data release and the latest 1% determination of $H_0$ from HST. We find that within a well-studied interacting dark energy model, the value of $H_0$ inferred by Planck is consistent with the latest local distance measurement well within 1σ, representing an extremely compelling solution to the $H_0$ tension. Bayesian evidence considerations show that combining the Planck and HST measurements leads to a very strong preference for the interacting dark sector scenario explored here with respect to the baseline $\Lambda$CDM model. This finding reinforces the idea that the $H_0$ tension might be truly pointing towards new physics in the dark sector. The model at hand also appears extremely promising in terms of alleviating the tensions between CMB and cosmic shear measurements. In particular, we observe a considerable improved overlap between the Planck and DES contours in the $\Omega_m - \sigma_8$ plane.

To conclude, it is extremely intriguing that the interacting dark sector model we have considered provides not only one of the most compelling solutions to the $H_0$ tension to date, but at the same time can alleviate the tension between CMB and cosmic shear measurements. We shall further investigate several related issues, for instance the inclusion of low-redshift Baryon Acoustic Oscillation and Supernovae distance measurements. It is also worth exploring interacting scenarios with more freedom in the dark energy sector, for instance treating the dark energy equation of state as a free parameter (possibly time-dependent). We shall report on these and other issues in a companion paper to appear shortly.

**ACKNOWLEDGMENTS**

E.D.V. acknowledges support from the European Research Council in the form of a Consolidator Grant with number 681431. A.M. is supported by TASP, iniziativa specifica INFN. O.M. is supported by PROMETEO II/2014/050, by the Spanish Grant FPA2017-85985-P of the MINECO, by the MINECO Grant SEV-2014-0398 of the MINECO, by the MINECO Grant SEV-2014-0398, and by the European Union’s Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreements 690575 and 674896. S.V. acknowledges support by the Vetenskapsrådet (Swedish Research Council) through contract No. 638-2013-8993 and the Oskar Klein Centre for Cosmoparticle Physics, and from the Isaac Newton Trust and the Kavli Foundation through a Newton-Kavli fellowship. O.M. would like to thank the hospitality of the Fermilab Theory Department. This work is based on observations obtained with Planck (www.esa.int/Planck), an ESA science mission with instruments and contributions directly funded by ESA Member States, NASA, and Canada. We acknowledge the use of the Planck Legacy Archive.

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