Tensions in the dark: shedding light on Dark Matter-Dark Energy interactions

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Abstract. The emergence of an increasingly strong tension between the Hubble rate inferred from early and late time observations has reinvigorated interest in non-standard scenarios, with the aim of reconciling these measurements. One such model involves interactions between Dark Matter and Dark Energy. Here we consider a specific form of the coupling between these two fluids proportional to the Dark Energy energy density, which has been shown to mitigate the Hubble tension. We complement the work already discussed in several previous analysis and show that, once all relevant cosmological probes are included, the value of the Hubble parameter in this model is $H_0 = 69.82^{+0.63}_{-0.70}$ km/(s Mpc). Furthermore, we also perform a statistical model comparison, finding a $\Delta \chi^2$ of $-2.15$ with the inclusion of one additional free parameter. In order to fully test this model as a solution to the $H_0$ tension, future missions such as Euclid will prove vital. For this reason, we also forecast the sensitivity of upcoming planned missions to the main parameters affected by these dark sector interactions and show that within the next decade we will be able to conclusively confirm or disprove the validity of this model as a solution to the $H_0$ tension.
1 Introduction

Despite the remarkable success of the standard ΛCDM model across many different scales, recent advances in precision cosmology have yielded discrepancies in observations at different redshifts (see e.g., [1] for a nice historical overview), which have opened the door to several alternative models.

The most striking examples of so-called tensions between the ΛCDM predictions inferred from the latest analysis of the Planck collaboration [2] and independent observational sources involve the expansion rate of the universe, quantified with the Hubble parameter \( H_0 \), and the value of \( \sigma_8 \), a quantity reflecting the amount of late-time matter clustering. The former has been measured by the Hubble Space Telescope (HST) using local distance ladder measurements, with the SH0ES collaboration reporting \( H_0 = 74.03 \pm 1.42 \text{ km/(s Mpc)} \) [3], which is at a 4.4σ difference to the value measured by the Planck satellite, \( H_0 = 67.4 \pm 0.5 \text{ km/(s Mpc)} \) [2]. Furthermore, for the latter quantity cosmic shear surveys such as Kilo Degree Survey (KiDS) [4] or the Dark Energy Survey (DES) [5–7] have been employed, leading to tensions in the \( \sigma_8 \) measurements of the order of 2-3σ.

Many different models have been proposed to solve these tensions (for a non-exhaustive list see e.g., [8–28]), including models which question the nature of Dark Matter (DM) or Dark Energy (DE). For instance, one particularly promising and well-studied model consists in interacting DM and DE (henceforth iDMDE, see e.g., [29] for a recent review).

Although the first studies on iDMDE already appeared in the ’90s [30–35], this class of theories saw renewed interest roughly a decade ago, with the first computations of the cosmological perturbation equations [36–41]. Furthermore, in recent years additional effort has been dedicated to the evaluation of cosmological constraints on iDMDE [42–62]. Most recently, these models have also been tested using the gravitational wave observations from Ligo and Virgo [63–65].

However, as already argued in e.g., [29] (see in particular Sec. 2 therein), the choice made to describe the energy transfer term \( Q \) between DM and DE is – to a large extent – arbitrary. In fact, from a QFT perspective, the Lagrangian defining the interaction between
the fermionic DM field \( \psi \) and a quintessential field \( \varphi \) reads \( [29, 35] \)

\[
\mathcal{L} = \frac{1}{2} \partial^{\mu} \varphi \partial_{\mu} \varphi - V(\varphi) + i \bar{\psi} \gamma^\mu \partial_\mu \psi + M(\varphi) \bar{\psi} \psi,
\]  

where \( V(\varphi) \) is the scalar field potential and \( M(\varphi) \) is a time-varying mass term which describes the effective interaction between the two fields. However, although some attempts have been made to justify a particular form of the coupling term \([66–70]\), in most cases the definition of \( M(\varphi) \) has only been assumed to be linearly \([29, 32, 35, 71]\) or exponentially \([72]\) dependent on \( \varphi \). The same arbitrariness is also common in the choice of the potential \( V(\varphi) \), which can have either a power-law \([73–76]\) or an exponential \([72]\) behavior, or a combination of the two \([76, 77]\). One can then show that the value of \( Q \) in the cosmological conservation equations is a function of \( V(\varphi) \) and \( M(\varphi) \) \([29]\), and thus inherits the same justification problems.

In cosmological contexts, in order to compensate the missing derivation of \( Q \) from first principles, one often intuitively assumes it to depend on the energy densities involved, i.e. \( \rho_c \) (for DM) and \( \rho_x \) (for DE), and on the expansion rate \( H \). Given this freedom, a variety of possible interactions have been considered in the literature (see e.g., Sec. 2 of \([29]\) and \([70]\) for more complete discussions). Following the steps of the recent analysis by \([60, 61]\), in this work we limit our selection to one single model that has gained great popularity due to its potential impact on the \( H_0 \) tension. In this model, the interactions between DM and DE over cosmological scales are ruled by a term linearly proportional to the DE energy density. Note that a similar dependence on, for instance, the DM energy density has been shown to be unstable for couplings larger than approximately \( 10^{-2} \), disfavoring this form of interactions \([36, 38, 70, 78]\).

In \([60, 61]\) it was shown that when using current data, such as temperature, polarisation, and lensing data from Planck, as well as the supernovae measurements from HST, this iDMDE model cannot fully solve the \( H_0 \) tension, but it can considerably alleviate it. Furthermore, the aforementioned papers found a preference for a non-zero value of the interactions when using the combination of Planck and the most recent SH0ES data. However, as suggested in \([61]\) and discussed further in this work, the additional inclusion Baryon Acoustic Oscillation (BAO) and Pantheon data leads to a lower value of the Hubble rate, partially restoring the original tension.

Given the presence of these discrepant results, future cosmological probes will be essential in order to discriminate the role of the single missions mentioned above, and thus the potential of the iDMDE model to alleviate the \( H_0 \) tension. With this in mind, it is fundamental to know which future cosmological experiments will yield the most information about these particular models. To that aim, an additional goal of this work is to investigate the sensitivity of upcoming probes – such as CMB-S4 \([79–81]\), LiteBIRD \([82, 83]\), and Euclid \([84, 85]\) – to the effects of iDMDE.

This paper is organised as follows. First in Sec. 2 we shortly review the theory describing the iDMDE model. In Sec. 3 we discuss the method we will use to first reproduce part of the results of \([60, 61]\), and then to extend these results with complementary combinations of current probes, as well as with the forecasts for upcoming missions. In Sec. 4 we present our results for current data, and compare these to the reach of future experiments. A final summary of this work and additional discussions are given in Sec. 5.
2 The mathematical setup

We have implemented the mathematical structure describing iDMDE in the Boltzmann code CLASS [86] (version 2.7.2).

In this work we investigate a very well-studied parametrization of the energy transfer function between the DM and DE fluids [39–41, 43, 47, 52, 59–61, 87, 88], which can be expressed in the 4-component notation as

\[ Q^\nu = \xi H \rho_c u^\nu_c, \]  

(2.1)

where \( \xi \) is the coupling constant and \( u^\nu_c \) is the DM 4-velocity. As in most of these references, we also choose \( Q^\nu \) to be parallel to \( u^\nu_c \), which avoids momentum transfer in the DM rest frame and circumvents fifth force constraints.

At the background level, the only modifications to the ΛCDM model are due to the fact that the DM and DE energy densities are not conserved singularly any more, but instead are coupled via the energy transfer \( Q \), leading to

\[ \dot{\rho}_c + 3H \rho_c = Q, \]  

(2.2)

\[ \dot{\rho}_x + 3H(1 + w) \rho_x = -Q, \]  

(2.3)

where the index \( c \) refers to cold DM, the index \( x \) to DE, and \( w \) is the DE equation of state (EOS) parameter. For our choice of \( Q \), Eqs. (2.2)-(2.3) can be analytically solved to find

\[ \rho_c = \rho_{c,0} a^{-3} + \frac{\xi \rho_{x,0} a^{-3}}{3w_{x,eff}} \left[ 1 - a^{-3w_{x,eff}} \right], \]  

(2.4)

\[ \rho_x = \rho_{x,0} a^{-3(1+w_{x,eff})}, \]  

(2.5)

where \( w_c = 0 \) is implicitly assumed for the DM EOS, and we have introduced

\[ w_{x,eff} = w + \frac{Q}{3H \rho_x} \]  

(2.6)

following [39, 41].

The other modification to the ΛCDM model is at the perturbation level. In the synchronous gauge, one obtains [40, 41, 52, 60, 61, 88]

\[ \dot{\delta}_c = -\theta_c - \frac{\dot{h}}{2} \left( 1 - \frac{\xi \rho_x}{3 \rho_c} \right) + \xi H \frac{\partial_x}{\rho_c} (\delta_x - \delta_c), \]  

(2.7)

\[ \dot{\theta}_c = -H \theta_c, \]  

(2.8)

\[ \dot{\delta}_x = -(1 + w) \left[ \theta_x + \frac{\dot{h}}{2} \left( 1 + \frac{\xi}{3(1+w)} \right) \right] - 3H(1 - w) \left[ \delta_x + \frac{H \theta_x}{k^2} (3(1 + w) + \xi) \right], \]  

(2.9)

\[ \dot{\theta}_x = 2H \theta_x \left[ 1 + \frac{\xi}{1 + w} \left( 1 - \frac{\theta_c}{2 \theta_x} \right) \right] + k^2 \frac{1}{1 + w} \delta_x, \]  

(2.10)

with initial conditions for the DE perturbations given by [52, 88]

\[ \delta_x^{in}(x) = (1 + w - 2\xi)C \quad \text{and} \quad \theta_x^{in} = k^2 \tau C, \]  

(2.11)
\[ C = - \frac{1 + w + \xi/3}{12w^2 - 2w - 3w\xi + 7\xi - 14 \Gamma + w} \cdot 2\delta^{in}_{\gamma}. \]  

(2.12)

In the above expression \( \delta^{in}_{\gamma} = \delta^{in}(k, \tau) \) are the initial conditions for the photon density perturbations, and \( w_\gamma = 1/3 \) is the photon EOS parameter. Here we have neglected the center of mass velocity for the total fluid, \( v_T \) in [40, 52, 60, 61]. Additionally, the DE sound speed has been set to unity, i.e., \( c^2_{s,x} = 1 \), while for the DE adiabatic sound speed we have \( c^2_{a,x} = w \) (see e.g. Sec. 2.3 of [36] for more details).

Moreover, it is interesting to notice that for the same model, [37, 43, 87, 89] employ a different set of equations compared to Eqs. (2.7)-(2.10). Although the analytical derivation of both sets of equations is beyond the scope of this work, we have cross-checked that the two formulations lead to the same results (a quantitative comparison will not be discussed further within this work but can be found in e.g., [67]). For sake of transparency and completeness, a version of CLASS including both versions of the perturbation equations will be included in a forthcoming release.

3 Method and cosmological probes

We have performed MCMC scans on the iDMDE model presented in Sec. 2 using the parameter inference code MontePython [90, 91] (version 3.2.0). We have judged the MCMCs to be converged using the Gelman-Rubin convergence criterion, requiring \( |R - 1| < 0.01 \) for all parameters [92].

In the choice of priors for the the initial parameters, particular care has been devoted to the DE EOS parameter \( w \) and the coupling constant \( \xi \). In fact, it is clear from Eqs. (2.7)-(2.10) that \( w = -1 \) would create divergences. Furthermore, [39] pointed out that the value of the coupling has to have opposite sign with respect to \( w + 1 \), i.e. for \( w + 1 > 0 \) one has \( \xi < 0 \) (and vice versa), in order to avoid early-time instabilities. For these reasons, we set \( w = -0.999 \), consistent with the literature [52, 60, 88], since this value is close enough to \(-1\) to recover \( \Lambda \)CDM if \( \xi = 0 \) and avoids the gravitational instabilities occurring at \( w = -1 \) at the same time. Note that, although the same result could have been achieved with \( w = -1.001 \), previous studies including \( w \) as free parameter suggest a solution of the type \( w > -1 \) [52] (see in particular the case including also BAO and JLA of the reference). As a consequence of this choice, we impose a negative value for \( \xi \) as a prior. While extensive analysis allowing \( w \) to vary as an additional free parameter can be found in e.g., [43, 61], we will not explore this avenue further in this work.

With these considerations we end up with a 6+1 extension of the standard \( \Lambda \)CDM model including

\[ \{h, \omega_h, \omega_{cdm}, n_s, \ln(10^{10} A_s), \tau_{reio}\} + \xi. \]  

(3.1)

In order to constrain this set of parameters, we base our analyses on the combination of several cosmological probes.

First of all, we consider CMB temperature, polarisation, and lensing constraints from Planck 2018 [2], making use of the Planck baseline (high-\( \ell \) TT,TE,EE + low-\( \ell \) EE + low-\( \ell \)
Table 1. We show the mean and the 68% C.L. of the parameters most significantly affected by the presence of iDMDE (the lower bound is given at the 95% C.L. instead), for different dataset combinations. Additionally, we display the different $\Delta \chi^2$, compared to the $\Lambda$CDM scenario with the same datasets.

| Parameter       | Planck       | Planck + R19 | Planck + BAO + Pantheon | Planck + R19 + BAO + Pantheon |
|-----------------|--------------|--------------|-------------------------|-------------------------------|
| $\omega_{cdm}$  | 0.059$^{+0.017}_{-0.018}$ | 0.043$^{+0.021}_{-0.020}$ | 0.1099$^{+0.0093}_{-0.0037}$ | 0.0990$^{+0.011}_{-0.0081}$ |
| $H_0$ [km/(s Mpc)] | 72.7$^{+2.4}_{-3.2}$ | 74.0$^{+1.4}_{-1.3}$ | 68.78$^{+0.54}_{-0.74}$ | 69.82$^{+0.62}_{-0.76}$ |
| $\xi$           | $-0.45^{+0.16}_{-0.33}$ | $-0.56^{+0.13}_{-0.14}$ | $>-0.22$               | $-0.179^{+0.090}_{-0.074}$ |
| $\Delta \chi^2$ | $-3.60$      | $-17.58$     | $-0.14$                | $-2.15$                      |

TT + Planck lensing\(^1\), referred to henceforth as Planck). In order to test the ability of this model to solve the $H_0$ tension, we will additionally include a Gaussian prior of the form $H_0 = 74.03 \pm 1.42$ km/(s Mpc), as reported by the SH0ES collaboration [3] (referred to henceforth as R19), and also done in [60]. Additionally, we will include the Pantheon data [93], which contains distance moduli information of 1048 Supernovae Type Ia. Moreover, in this work we also investigate the constraining power of BAO data, using measurements of $D_V/r_{\text{drag}}$ by 6dFGS at $z = 0.106$ [94], by SDSS from the MGS galaxy sample at $z = 0.15$ [95], and additionally by BOSS from the CMASS and LOWZ galaxy samples of SDSS-III DR12 at $z = 0.2 - 0.75$ [96] (referred to henceforth as BAO). A similar set of probes has already been considered in [61].

These existing datasets will then be compared to planned future experiments with improved sensitivity and resolution, such as LiteBIRD [82, 83], CMB-S4 [79–81], and Euclid [84, 85]. All these missions are expected to be deployed within the next decade (see e.g., [97] for a comprehensive overview and more details on these upcoming missions). Furthermore, the combination of these probes offers an optimal complementarity: while the combination CMB-S4 + LiteBIRD will very accurately map the CMB anisotropies, offering a complete coverage of the multipoles up to $\ell = 3000$, the data gathered with the Large Scale Structure (LSS) survey Euclid will provide late-time information with unprecedented precision. The latter will be especially significant, as iDMDE mainly impacts the late-time evolution of cosmological quantities.

For all these future experiments, we employ mock likelihoods: this means that we do not consider real data, but rather employ a likelihood with the same expected sensitivity, resulting in the same error bars, although centered around an arbitrary set of initial parameters. In our case, the choice of the fiducial values is based on the best-fitting parameters resulting from the combination of all current datasets considered within this work (the last column in Tab. 1). The interested reader can find more in-depth details on the use of mock likelihoods in general, and particularly on the ones employed within this work, in e.g., [97–99].

\(^1\)Note that our choice of including the lensing likelihood as part of the Planck baseline is justified by the compatibility of these likelihoods, as shown in Tab. 2 of [61]. We have confirmed that the inclusion of the lensing likelihood does not significantly modify the bounds on the resulting cosmological parameters presented in Tab. 1.
Figure 1. Two-dimensional contours (68% and 95% C.L.) of the $(\xi - H_0)$ plane. The different colors denote different combinations of probes considered within this work: Planck (red), Planck + R19 (blue), and Planck + BAO + Pantheon (green). The yellow band corresponds to the R19 measurement.

As a final remark, note that among these upcoming missions, the case of Euclid requires particular attention. In fact, its sensitivity to the late time non-linear dynamics of the universe is predicted to reach the percent level precision [84, 85], so it is fundamental to model these effects very accurately in the context of iDMDE. The most precise way of determining how DM-DE interactions affect the matter power spectrum $P(k)$ at non-linear scales would be by performing computationally demanding hydrodynamical N-body simulations, which are currently not available for the iDMDE model studied here, and are beyond the scope of this paper. Therefore, we will consider only wave-numbers below $k \approx 0.15 \, h/\text{Mpc}$, above which non-linear effects typically become relevant. This means that our results are only based on a subset of the full scales probed by Euclid, and can thus be considered as conservative. We leave a more extended analysis for future work, possibly involving dedicated N-body simulations.

4 Results

4.1 Current constraints

Here we present an overview of the current cosmological constraints on iDMDE. A summary of the parameters most significantly affected by iDMDE is presented in Tab. 1, where each column refers to a given combination of datasets. A similar set of detectors can be found in Tab. 1 of [61], with different combinations. Here we emphasize the important role of combining these different datasets, especially BAO and Pantheon. Furthermore, we also show our most relevant results in Fig. 1.
Table 2. Comparison of ΛCDM and iDMDE, showing the χ² contribution from each individual dataset, for three different runs. A negative ∆χ² indicates a preference for iDMDE, while a positive ∆χ² indicates a preference for ΛCDM.

|                  | Planck + R19 | Planck + BAO + Pantheon | Planck + R19 + BAO + Pantheon |
|------------------|--------------|-------------------------|-------------------------------|
|                  | ΛCDM iDMDE Δχ² | ΛCDM iDMDE Δχ² | ΛCDM iDMDE Δχ² |
| Planck high-ℓ TT | 2350.39 2346.24 −4.15 | 2346.57 2347.11 0.54 | 2348.39 2349.59 1.20 |
| Planck low-ℓ TT  | 22.84 23.85 1.01 | 23.57 23.75 0.18 | 23.31 22.98 −0.33 |
| Planck lensing   | 397.86 395.83 −2.03 | 396.77 395.69 −1.08 | 395.74 396.17 0.43 |
| R19              | 9.17 8.79 −0.38 | 8.81 8.87 0.06 | 9.27 8.84 −0.43 |
| Pantheon         | 12.06 0.04 −12.02 | − − − | 15.24 10.43 −4.81 |
| BAO              | − − − | − − − | − − − |
| Total            | 2792.33 2774.75 −17.58 | 3807.97 3807.83 −0.14 | 3824.45 3822.30 −2.15 |

The first two cases, Planck and Planck + R19, can be compared to the work already presented in [60]. As already suggested there, this combination allows iDMDE to reconcile the Planck predictions with the late-time R19 measurements, yielding a value of $H_0 = 74.0^{+1.4}_{−1.3}$ km/(s Mpc). However, when extending the analysis to the combination of Planck + BAO + Pantheon, the preference for a higher $H_0$ value is substantially mitigated.

Indeed, in Fig. 1 we can see that the Planck + R19 and the Planck + BAO + Pantheon contours do not overlap at the 2σ level. This indicates that the preference for a higher $H_0$ value is driven entirely by the inclusion of the R19 data, while Pantheon and BAO data favor a lower value of $H_0 = 68.78^{+0.54}_{−0.74}$ km/(s Mpc), which is 1.5σ different to the standard ΛCDM value from [2], and 3.3σ different to the R19 value. If we consider all datasets together, the BAO data lends more weight, leading to a final value of $H_0 = 69.82^{+0.62}_{−0.58}$ km/(s Mpc), which is 2.5σ from the standard ΛCDM value, and 2.6σ from the R19 value. As such, it seems that iDMDE does not allow to reconcile the different datasets considered here.

Moreover, in addition to the implications for the Hubble tension discussed above, several interesting conclusions on the ability of the iDMDE model to reconcile the different probes can be drawn by performing a χ² comparison with respect to ΛCDM. First, we can see that the Δχ² given in Tab. 1 are negative for all dataset combinations, indicating a preference for iDMDE over ΛCDM. For the cases of Planck alone and Planck + BAO + Pantheon, the improvement is not significant when taking into consideration the addition of the free parameter ξ, increasing the degrees of freedom by one. However, the inclusion of R19 data substantially increases the preference for iDMDE, with Δχ² = −17.58 (indicating a ∼ 4.2σ preference for iDMDE). The impact of each additional likelihood on the total χ² is explored in detail in Tab. 2, where we can see the biggest contribution to the negative Δχ² is from R19. Finally, as show in the last column of Tab. 2, when considering all datasets together, we find a Δχ² of −2.15 with the inclusion of one additional free parameter, thus finding no clear preference for this model.

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2Given that the datasets do not overlap at the 2σ level, any interpretation of their combination should be taken with great care.
Figure 2. Evolution of $H(z)$ for iDMDE, using the best-fit cosmological parameters from Tab. 1 for Planck + R19 (blue), Planck + BAO + Pantheon (green), and Planck + R19 + BAO + Pantheon (red). For comparison, the standard ΛCDM prediction is also shown in black. The shaded areas correspond to the 1σ bounds. Additionally, the R19 data point is shown, as well as several low-redshift BAO measurements.

This is further illustrated in Fig. 2, where we show the late-time evolution of $H(z)$ for iDMDE, using the best-fits obtained for the different data combinations from Tab. 1. For comparison, the evolution of $H(z)$ within ΛCDM is also shown, using the best-fits from the last column of Tab. 2 of [2]. When using Planck + R19, we are able to account for both the early-time $H(z_{CMB})$ and the late-time $H(z_{R19})$, thus bringing these datasets into closer agreement than in ΛCDM. However, when using BAO and Pantheon data, the former drive $H(z)$ to lower values today, no longer fully solving the $H_0$ tension.

Finally, note that, although not quantitatively shown in this work, the behavior we described in this section can also be observed in models where the DE EOS parameter $w$ is left as a free parameter (see e.g., Fig. 2 of [61]). Furthermore, the results obtained for extensions of the energy transfer function expressed in Eq. (2.1), such as those considered in [100], hint to the same conclusion found in this work, with similar tensions among the different datasets, although less pronounced (see e.g., Fig. 8 of the reference).

4.2 Forecasts for future missions

We have seen in the previous section that while iDMDE can mitigate the tension between Planck and R19, it is not able to reconcile all current datasets. Nonetheless, we are currently only considering late-time data from BAO and Supernovae and early-time data from the CMB: any intermediate information on $H(z)$, such as that expected from Euclid, will allow us to further constrain this model and its ability to alleviate the Hubble tension. In order to see the impact of future planned missions on iDMDE constraints, we performed different sensitivity forecasts following the procedure already discussed in Sec. 3. An overview of the resulting 1σ sensitivities can be found in Tab. 3.
Table 3. Expected 1σ sensitivity of future missions to the parameters most significantly affected by iDMDE.

| Parameter          | CMB-S4 + LiteBIRD | CMB-S4 + LiteBIRD + Euclid |
|--------------------|-------------------|---------------------------|
| $\sigma(\omega_{\text{cdm}})$ | 0.035             | 0.00040                   |
| $\sigma(H_0 \,[\text{km/(s Mpc)}])$ | 2.58             | 0.065                     |
| $\sigma(\xi)$ | 0.24              | 0.0041                    |

We first consider the future combination of the CMB missions CMB-S4 + LiteBIRD, where the latter is optimised for B-mode polarisation data. Comparing the error bars obtained for Planck given in the first column of Tab. 1, to the forecasted 1σ sensitivities for CMB-S4 + LiteBIRD given in Tab. 3, it is possible to notice that this particular combination of future missions would not significantly improve on the current bounds set by Planck. However, as DM-DE interactions would mostly affect the late-time evolution of the universe, the inclusion of the Euclid satellite, which is set to map the DM distribution up to $z \sim 2$, leads to a remarkable improvement, as clearly shown in the last column of Tab. 3. Indeed, the combination of CMB-S4 + LiteBIRD + Euclid, which will become a reality within the next decade, will reach a sensitivity to $H_0$ and $\xi$ more than 20 times better than the ones offered by current missions. This level of precision, in particular in the case of $H_0$, will be enough to clearly show if iDMDE can actually reconcile the $H_0$ tension, or if the model cannot address the existing tension, as hinted at by current constraints.

5 Conclusions

With the increasing level of precision obtained by CMB and local distance ladder measurements missions, such as Planck and HST, as well as by cosmic shear surveys, such as KiDS and DES, we have seen the rise of significant tensions in the cosmological landscape. One such tension that has gained a lot of attention is the 4.4σ discrepancy between the values of the expansion rate of the universe, $H_0$, as reported by the Planck and SH0ES collaborations.

In order to address this tension, a variety of different models have been proposed. Within this work, we focus on a class of models which allows for interactions between DM and DE. Specifically, we consider the possibility that a coupling term linking the energy density conservation equations for these two fluids is present, and is linear in the DE energy density.

This scenario has already been very well studied in the literature due to its potential to alleviate the $H_0$ tension. In fact, as shown in the literature as well as in this work, when considering the combination of Planck + R19 data, the model allows for significantly higher $H_0$ values than those predicted by $\Lambda$CDM. However, we have shown here that when considering Planck + BAO + Pantheon, this preference for a higher $H_0$ value is mitigated, leading to $H_0 = 68.78^{+0.54}_{-0.74}$ km/(s Mpc), which is within 1.5σ of the standard $\Lambda$CDM value from [2], and 3.3σ away from the R19 value. As such, we find that while the model can alleviate the $H_0$ tension, it does not seem to be able to completely solve it.

Furthermore, when all aforementioned cosmological probes are considered together, we find the preferred value of the Hubble parameter to be $H_0 = 69.82^{+0.63}_{-0.76}$ km/(s Mpc), which is
2.5$\sigma$ form the standard ΛCDM value and 2.6$\sigma$ from the latest local measurements. Moreover, for this combination of datasets, the detailed $\chi^2$ analysis performed in this work yields only a $\Delta\chi^2$ of $-2.15$ when compared to the base ΛCDM, with the inclusion of one additional free parameter.

The full analysis of current constraints on the dark sector interactions conducted in this work still shows the presence of a tension between the predictions of the many cosmological probes involved. For this reason, an unquestionable proof of the validity of this model to solve the $H_0$ tension will only be achieved with the help of future missions, which will reach an unprecedented level of precision. In order quantify these improvements, we have forecast the sensitivity of the CMB missions CMB-S4 and LiteBIRD, as well as the LSS mission Euclid (using only linear scales) in the iDMDE scenario. We have shown that, although the CMB probes will not yield a remarkable improvement on the current bounds set by Planck, the inclusion of data from the Euclid satellite will improve on existing constraints by a factor of approximately 20.

Therefore, with the improvement expected in CMB and LSS measurements within the next decade, we will soon be able to ultimately test the viability of iDMDE as a solution to the $H_0$ tension.

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