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New insights on ν–DM interactions

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ABSTRACT

We revisit the possibility of using cosmological observations to constrain models that involve interactions between neutrinos and dark matter. We show that small-scale measurements of the cosmic microwave background (CMB) with a few per cent accuracy are critical to uncover unique signatures from models with tiny couplings that would require a much higher sensitivity at lower multipoles, such as those probed by the *Planck* satellite. We analyse the high-multipole data released by the Atacama Cosmology Telescope, both independently and in combination with *Planck* and baryon acoustic oscillation measurements, finding a compelling preference for a non-vanishing coupling, $\log_{10} u_{\nu\mathrm{DM}} = -5.20^{+1.2}_{-0.74}$ at 68 per cent confidence level. This aligns with other CMB-independent probes, such as Lyman-α. We illustrate how this coupling could be accounted for in the presence of dark matter interactions with a sterile neutrino.

Key words: neutrinos – cosmic background radiation – dark matter.

1 INTRODUCTION

Precision measurements of cosmic microwave background (CMB) radiation (Choi et al. 2020; Planck Collaboration VI 2020c; Balkenhol et al. 2022) have substantially furthered our understanding of dark matter (DM) by offering a convincing, albeit indirect, supporting evidence for its existence and precise constraints on its properties. Nevertheless, despite these advances, DM is still elusive, as confirmed by a variety of unsuccessful experiments, including direct searches and astrophysical observations.

The enigmatic nature of DM can be attributed to its poorly understood interactions with other particles: apart from gravitational interactions, its fundamental couplings to the Standard Model remain unknown and debated. Building on this unresolved uncertainty surrounding the interaction strengths of DM with other particles, a fascinating and persistent idea is the possibility of a coupling between DM and neutrinos through an as-yet-undiscovered interaction channel. The literature offers a wide range of possible forms of the cross-section governing such interactions, with significant implications for various observables spanning from cosmology to astrophysics and accelerator-based searches (Kolb & Turner 1987; Palomares-Ruiz & Pascoli 2008; Serra et al. 2010; Shoemaker 2013; Wilkinson, Lesgourgues & Boehm 2014a; Wilkinson, Boehm & Lesgourgues 2014b; Bertoni et al. 2015; de Salas, Lineros & Tórtola 2016; Shoemaker & Murase 2016; Di Valentino et al. 2018; Escudero et al. 2018; Olivares-Del Campo et al. 2018; Batell et al. 2018a; Batell, Han & Shams Es Haghi 2018b; Blennow et al. 2019; Choi, Kim & Rott 2019; Kelly & Zhang 2019; Pandey, Karmakar & Rakshit 2019; Kelly et al. 2022). In this work, we revisit the possibility of using CMB observations to constrain models that involve interactions between neutrinos and dark matter (νDM) described in terms of a single parameter

$$u_{\nu\mathrm{DM}} = \frac{\sigma_{\nu\mathrm{DM}}}{\sigma_\mathrm{T}} \left(\frac{m_\mathrm{DM}}{100\,\mathrm{GeV}}\right)^{-1}, \tag{1}$$

where $\sigma_{\nu\mathrm{DM}}$ and σ_T are the νDM and Thomson scattering cross-sections and m_DM is the mass of the DM particle, respectively. The impact of such an interaction on the CMB angular power spectra and the late-time matter power spectrum can be significant, depending on its strength. Therefore, extensive studies have been conducted to understand the cosmological implications of these effects and constraints from current CMB and large-scale structure observations, as well as forecasts for next-generation surveys (Escudero et al. 2015), are available in the literature.

The state-of-the-art cosmological analyses on νDM interactions arise primarily from the CMB data released by the Planck Collaboration, which provides precise measurements of the angular power spectra of temperature and polarization anisotropies in the multipole range $2 \lesssim \ell \lesssim 2500$. Assuming a temperature-independent νDM cross-section $\sigma_{\nu\mathrm{DM}} \sim T^0$, constraints on the interaction strength can be derived, typically resulting into upper limits $u_{\nu\mathrm{DM}} \leq (4.5\text{–}9.0) \times 10^{-5}$ at 95 per cent confidence level (CL; Di Valentino et al. 2018; Mosbech et al. 2021; Paul et al. 2021). As clearly shown in the bottom panel of Fig. 1, these bounds reflect the limited (albeit remarkable)

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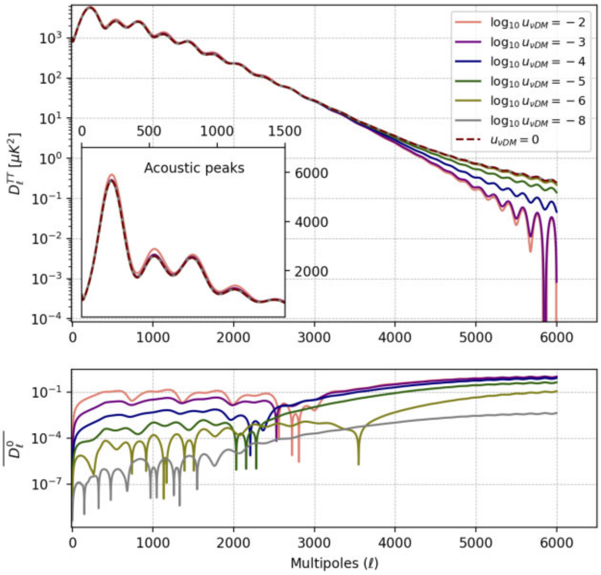

Figure 1. The top panel displays the theoretical D_ℓ^{TT}, while the percentage difference $|\Delta D_\ell|/D_\ell^0$ with respect to the non-interacting case (D_ℓ^0) for different coupling values is shown in the bottom panel. The figure highlights that feeble interactions can result in undetectable changes in the *Planck*'s probed multipole range, but can produce substantial differences on smaller scales (i.e. higher multipoles) like those measured by Atacama Cosmology Telescope (ACT).

sensitivity reachable by CMB observations. Indeed, on the scales probed by experiments similar to *Planck*, values $u_{\nu\rm DM} \lesssim 10^{-5}$ would produce corrections smaller than one part in 10^5 when compared to the non-interacting case. This implies that any differences between the two cases would essentially be undetectable as it would require a precision well beyond the current accuracy of data.

However, the key observation underlying our study is that small couplings have a more significant impact on smaller scales (higher multipoles), where differences can reach a few per cents when compared to the non-interacting case, as illustrated in Fig. 1. Therefore experiments with high precision in the damping tail at $\ell \gtrsim 3000$ provide a unique opportunity to gain novel insight into models that would otherwise be indistinguishable at lower multipoles. This holds true for both the next-generation of CMB experiments and recent measurements of the CMB angular power spectra released by ground-based telescopes. In fact, by probing higher multipoles than the *Planck* satellite, these measurements can provide valuable complementary information that can improve the sensitivity of current results and contribute to the study of νDM interactions.

2 ANALYSIS

Based on previous considerations, we extend the state-of-the-art analyses on neutrino DM interactions, investigating the impact of recent CMB measurements obtained from ground-based telescopes. Our analysis focuses specifically on the ACT temperature and polarization DR4 likelihood (Choi et al. 2020), which explores higher multipoles ($600 \lesssim \ell \lesssim 4500$) compared to the full Planck 2018 likelihood ($2 \lesssim \ell \lesssim 2500$) Planck Collaboration I, V, VI (2020a,b,c). This produces precise data on small scales where the effects of small couplings start to become comparable with the observational constraining power. Additionally, alongside CMB observations, we take into account measurements of baryon acoustic oscillations (BAO) and redshift space distortions (RSD) from the Baryon Oscillation Spectroscopic Survey (BOSS DR12) (Dawson et al. 2013).

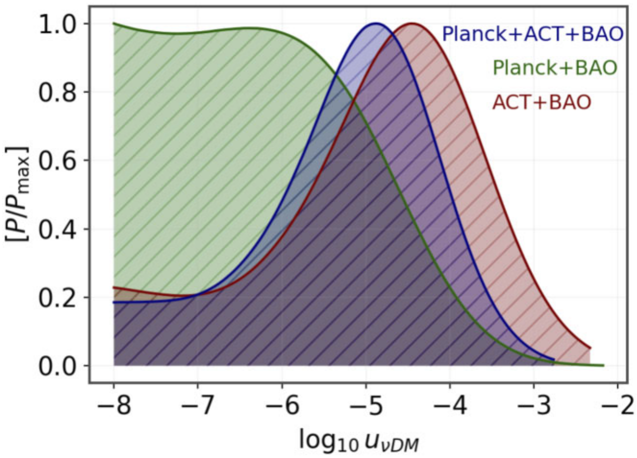

Figure 2. Posterior probability distribution functions for the coupling $\log_{10}u_{\nu\rm DM}$ resulting from different combinations of CMB and BAO + RSD measurements.

To parametrize our cosmological model, we employ a common approximation in the literature, i.e. treating neutrinos as massless and ultra-relativistic in the early universe. This simplifies calculations for scenarios involving interactions with DM. In addition, we examine the interplay between neutrinos and the entire fraction of energy-density associated with DM, with a specific focus on a temperature-independent cross-section. By doing so, we only need one extra parameter in addition to the usual six Lambda cold dark matter (ΛCDM) parameters, which is the logarithm of the coupling parameter $\log_{10} u_{\nu\rm DM}$, as defined in equation (1). To compute the cosmological model and study the effects of νDM interactions, we make use of a modified version of the Cosmic Linear Anisotropy Solving System code CLASS[1] (Blas, Lesgourgues & Tram 2011). We explore the posterior distributions of our parameter space by exploiting the publicly available code COBAYA (Torrado & Lewis 2020) and the Monte Carlo Markov Chain sampler developed for COSMOMC (Lewis & Bridle 2002).

Firstly, by considering the full temperature and polarization *Planck* likelihood in the multipole range of $2 \lesssim \ell \lesssim 2500$, in combination with BAO and RSD measurements, we are able to replicate the results previously discussed in the literature yielding an upper bound of $\log_{10}u_{\nu\rm DM} < -4.39$ at a 95 per cent CL. Fig. 2 displays (in green) the posterior distribution function of $\log_{10}u_{\nu\rm DM}$ for this combination of data. As illustrated in the figure, below a certain threshold of $u_{\nu\rm DM} \lesssim 10^{-5}$, all the models become indistinguishable, leading to a flat posterior distribution for smaller values.

In order to investigate the impact of small-scale CMB observations, we first consider the ACT data in combination with BAO and RSD measurements. In Fig. 2, we display (in red) the posterior distribution function for this case. It is interesting to note that, as evident from the figure, the posterior distribution function for this combination of data shows a clear preference for a non-zero coupling. This preference is translated into a 68 per cent CL result $\log_{10} u_{\nu\rm DM} = -4.86^{+1.5}_{-0.83}$. Although this indication is not supported by the *Planck* data, it is crucial to observe that the two data sets are

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[1] A publicly available version can be found at https://github.com/MarkMos/CLASS_nu-DM [see also Stadler, Bœhm & Mena (2019) and Mosbech et al. (2021)].

not in tension regarding the predicted value for this parameter. The ACT's indication for a non-zero coupling can be explained by the larger effects of couplings of the order of $u_{\nu\mathrm{DM}} \sim 10^{-6}$–$10^{-4}$ in the multipole range probed by this experiment, see Fig. 1. Therefore, while the effects of such a tiny coupling may not be detectable at the scales probed by *Planck*, they may be easier to unveil at the scales measured by ACT. It is also important to note that for smaller values ($u_{\nu\mathrm{DM}} \lesssim 10^{-6}$), the effects of a possible interaction between neutrinos and DM, although remaining some orders of magnitude larger than the scales probed by *Planck*, become too small to be distinguishable from the non-interacting case, even on multipoles probed by ACT (see Fig. 1). Consequently, the posterior distribution function also becomes flat (see Fig. 2). As a result of this effect, we lose the indication for a non-zero coupling at a 95 per cent CL, obtaining only an upper limit of $\log_{10}u_{\nu\mathrm{DM}} < -3.70$. However, this loss of evidence is related to the currently limited precision of data rather than a real preference for zero coupling values.

To validate further our argument that the preference for a non-vanishing νDM interaction comes from the high-ell ACT multipoles, we combine *Planck* data between $2 \lesssim \ell \lesssim 650$ with the small-scale DR4 ACT likelihood, along with BAO and RSD measurements.[2] We show the posterior distribution function of this case in Fig. 2 (blue line). As evident, the preference for a non-zero interaction rate is maintained by combining the two most precise CMB experiments, so that we obtain a robust indication $\log_{10} u_{\nu\mathrm{DM}} = -5.20^{+1.2}_{-0.74}$ at the 68 per cent CL. It is also important to note that including low-ℓ *Planck* data narrows the peak amplitude of the posterior distribution around its central value, leading to a stronger indication for an interaction between the two species. This improvement is due to the fact that *Planck* data provide information around the first acoustic peaks, which are not probed by ACT. Since values of $u_{\nu\mathrm{DM}} \gtrsim 10^{-4}$ substantially increase the amplitude of the first acoustic peaks (see Fig. 1), including precise measurements at lower multipoles improves the constraints in this region, leading to the observed shift in $\log_{10}u_{\nu\mathrm{DM}}$. This improvement also helps to isolate the impact of νDM on the ACT data by breaking the degeneracy with other cosmological parameters and shifting their values back close to ΛCDM preferred values obtained with the full *Planck* data set. None the less, it is important to emphasize that for interaction strengths below a certain threshold ($u_{\nu\mathrm{DM}} \lesssim 10^{-6}$), the same considerations as mentioned in the ACT-only case apply to this scenario where both ACT and *Planck* data are combined. In other words, the impact of such weak couplings on the CMB angular spectra becomes too small compared to the data accuracy in both the *Planck* and ACT multipole ranges. As a consequence, all models become indistinguishable, and the posterior distribution function becomes flat, as shown in Fig. 2. This behaviour of the posterior distribution function prevents us from obtaining a two-sigma constraint. Thus, at the 95 per cent CL, we can only derive an upper limit of $\log_{10}u_{\nu\mathrm{DM}} < -4.17$.

3 EXAMPLE

Given the preference in the cosmological data that we find towards non-diminishing DM–neutrino interactions, it is useful to consider briefly the implications of our findings for a sample specific scenario of beyond the Standard Model (BSM) neutrino interactions. We note that for $m_{\mathrm{DM}} \sim 1\,\mathrm{GeV}$ the 1σ ranges of the $\sigma_{\mathrm{DM}-\nu}$ cross section obtained in our analysis correspond to values of the order of at least one nano-barn, while being even larger for heavier DM species. As a result, it is challenging to couple directly DM to the $SU(2)_{\mathrm{L}}$ lepton doublet in the SM with such a large cross-section without violating stringent DM direct detection bounds from electron scatterings, cf. Ref. Akerib et al. (2022) for recent review. Large couplings between DM and charged leptons are further constrained by missing energy searches at Large Electron–Positron Collider (LEP) and indirect detection searches for DM annihilations into charged leptons (Shoemaker 2013; Blennow et al. 2019).

This can be circumvented in models employing a mixing between active and sterile neutrinos together with a coupling of the sterile neutrinos to the the DM species (Bertoni et al. 2015; Batell et al. 2018a; Batell, Han & Shams Es Haghi 2018b).[3] For instance, a new Dirac fermion N could interact with the SM via Yukawa-like couplings $\mathcal{L} \supset -\lambda\,(\bar{L}\,\hat{H})\,N_{\mathrm{R}}$, where L is the SM lepton doublet and H is the Higgs field. This gives rise to a mixing between the active and sterile neutrinos after electroweak symmetry breaking. The coupling of DM to N is given by $\mathcal{L} \supset -\phi\,\bar{\chi}\,(y_{\mathrm{L}}\,N_{\mathrm{L}} + y_{\mathrm{R}}\,N_{\mathrm{R}}) + \mathrm{h.c.}$, where additional fermionic χ and scalar ϕ SM-singlet fields have been introduced. Both of them can play the role of DM after imposing additional $U(1)_{\mathrm{d}}$ symmetry, depending on which one is the lightest of the BSM species. The heavier sterile neutrino dominantly decays into the dark states, $N \to \chi\phi$, therefore alleviating constraints from visibly decaying heavy neutral leptons (Batell et al. 2022; Abdullahi et al. 2023).

In the mass-degenerate regime in the dark sector, $m_{\mathrm{DM}} \equiv m_\chi \simeq m_\phi$, the χ DM elastic scatterings off neutrinos mediated by ϕ are characterized by an effectively temperature-independent cross-section,

$$\sigma_{\mathrm{DM}-\nu} \simeq 10^{-34}\left(\frac{g}{0.01}\right)^4\left(\frac{20\,\mathrm{MeV}}{m_{\mathrm{DM}}}\right)^2\,\mathrm{cm}^2, \qquad (2)$$

where $g = y_{\mathrm{L}}\,(|U_{e4}|^2 + |U_{\mu4}|^2 + |U_{\tau4}|^2)^{1/2}$ and $U_{\ell4}$ is the mixing angle between the sterile and active neutrino of a given flavor ℓ. In the following, we will assume that the dominant mixing is with the tau neutrino, while we set other mixing angles to zero. We also take $m_{\mathrm{N}} = 10\,m_{\mathrm{DM}}$. In Fig. 3, we illustrate a region in the parameter space of this BSM model in the $(m_{\mathrm{DM}},\,g)$ plane, in which one can simultaneously fit the cosmological bounds and avoid other constraints. At the top of Fig. 3, we show the grey-shaded region corresponding to an upper bound on the coupling constant g above which one predicts too large active-neutrino mixing angles for $y_{\mathrm{L}} = 1$. The leading constraints on $U_{\tau4}$, in this case, arise from atmospheric neutrino oscillation analyses, leptonic and semileptonic tau decays, and measurements of the lepton flavour universality in B meson decays, see (Cvetič et al. 2017; Batell et al. 2018a; BABAR Collaboration 2022). Light DM species that thermalize in the early Universe due to their interactions with neutrinos are subject to additional bounds from their possible contribution to the number of relativistic degrees of freedom, N_{eff}, which excludes DM mass below $\mathcal{O}(10\,\mathrm{MeV})$ (Boehm, Dolan & McCabe 2013). We note that bounds from heavy neutral lepton decays during the Big Bang

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[2] Note that the cut made to the *Planck* data is necessary to avoid including the region where the two experiments overlap, which would result in double counting of the same sky in the absence of a covariance matrix Aiola et al. (2020).

[3] While the strongest experimental bounds are associated with DM couplings to electrons and quarks, they could also be avoided in models employing light DM particles with flavour non-universal couplings to muons or tau leptons and to respective neutrinos, e.g. the $U(1)_{L_\mu - L_\tau}$ gauge boson portal to DM. We leave a detailed investigation of such scenarios for future studies.

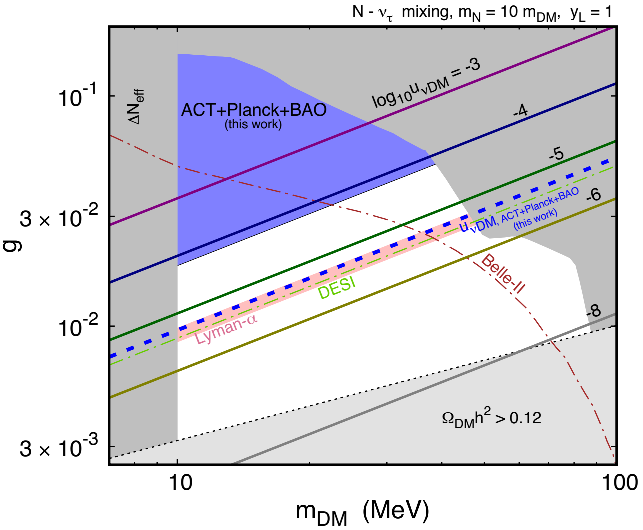

Figure 3. The parameter space of the neutrino portal DM model shown in the $(m_{\rm DM}, g)$ plane, where $m_{\rm DM} \equiv m_\chi \simeq m_\phi$ and one assumes $m_{\rm N} = 10\, m_{\rm DM}$, $y_{\rm L} = 1$. ACT + *Planck* + BAO exclusion bounds obtained in this study are shown as a blue-shaded region, while the mean value of $\sigma_{{\rm DM}-\nu}$ in our fit is obtained along the blue dashed line.

Nucleosynthesis (BBN) epoch can be avoided as N decays preferably in the dark sector in this scenario.

We indicate, in Fig. 3, the relic target line below which one predicts too large a thermal DM abundance, while a correct value of $\Omega_\chi h^2$ can be obtained, e.g. in the asymmetric DM scenario (Petraki & Volkas 2013; Zurek 2014). In this case, the symmetric DM component can be efficiently annihilated away in the early Universe due to the $\chi\bar{\chi} \to \nu\bar{\nu}$ process. The remaining DM abundance driven by the initial asymmetry between χ and $\bar{\chi}$ can be higher than in the standard freeze-out. In this way one also avoids DM indirect detection bounds (Argüelles et al. 2021) as the number of DM antiparticles is depleted. In Fig. 3, we show with a blue-shaded region cosmological constraints on DM–neutrino interaction cross-section that we obtain based on ACT + Planck + BAO data. We also present coloured lines with fixed values of the $u_{\rm urDM}$ parameter between -3 and -8, as well as with a blue dashed line the mean value of this parameter from our fit. For comparison, a light red-shaded region is shown, inside which Lyman-α observations can be better explained assuming non-negligible DM–neutrino interactions (1σ; Hooper & Lucca 2022). The DM–neutrino interaction strength obtained this way lies remarkably close to the mean value of $\sigma_{{\rm DM}-\nu}$ obtained in this work. Future cosmological data and Lyman-α observations will constrain further the allowed region in the parameter space of this model. In Fig. 3, we also illustrate expected sensitivity of the Dark Energy Spectroscopic Instrument (DESI) to probe νDM interaction strength following Escudero et al. (2015) and a (optimistic) future bound on the $U_{\tau 4}$ mixing angle from the Belle-II experiment where larger couplings would be excluded (Kobach & Dobbs 2015).

4 CONCLUSIONS

In this work, we have analysed the effects of the interaction between DM and neutrinos, assuming a temperature-independent interaction cross-section. Considering small-scale CMB data from the ACT, we find a preference for a non-zero interaction strength. This result remains consistent when combining observations from the two most accurate CMB experiments to date (*Planck* and ACT) and including astrophysical measurements of BAO and RSD. We have also indicated how scenarios involving a sterile neutrino portal between DM and the SM could accommodate such a coupling.

In order to validate the robustness of our findings, we have conducted a significant number of additional tests, all of which have confirmed this preference for a non-zero interaction. Specifically, we have observed the same preference when including or excluding BAO, and when varying or fixing the effective number of relativistic particles ($N_{\rm eff}$) in the cosmological model. Moreover, we have found that a similar preference emerges even when considering a temperature-dependent cross-section $\sigma_{\nu{\rm DM}} \propto T^2$, indicating that this is not an artifact of assumptions made in the parametrization of the interaction (Brax et al. 2023).

To gain a better understanding of our results, we have thoroughly examined the data provided by both experiments and verified that the peak in the distribution of the interaction strength is associated with a genuine reduction of the χ^2 of the fit. We have conducted a Bayesian model comparison to assess the plausibility of both interacting and non-interacting models in explaining the current observations. We found that while both models are plausible, the interacting case is often favoured over the non-interacting one with moderate preference. We will present the results of all the additional tests in a separate work (Brax et al. 2023).

Finally, it is important to note that the interaction strength value obtained from our analysis ($\log_{10} u_{\nu{\rm DM}} = -5.20^{+1.2}_{-0.74}$) is consistent with the result obtained in Hooper & Lucca (2022) from Lyman-α probes. The latter found a significant preference for an interaction strength ($\log_{10} u_{\nu{\rm DM}} = -5.42^{+0.17}_{-0.08}$) approximately 3σ away from zero when considering Lyman-α data. This effect is attributed to the additional tilt in the Lyman-α flux power spectrum which affects small scales and leads to an improved fit compared to the ΛCDM model. The remarkable correspondence between these two cosmological probes provides further hints of possible departures from the standard cosmological scenario. Interactions between DM and neutrinos can also affect the small-scale structure of the Universe and have been proposed to address some of the persisting problems of ΛCDM, e.g. the missing satellite issue (see Boehm et al. 2014; Bertoni et al. 2015; Schewtschenko et al. 2016). We leave detailed analyses of the interplay between these effects for future studies.

Our result will be testable and better bounds will be obtained with the next generation of CMB experiments, such as Abazajian et al. (2019), Ade et al. (2019), Hanany et al. (2019), and CMB-HD Collaboration (2022). Also see Escudero et al. (2015) for expected sensitivity of DESI reaching up to $\log_{10} u_{\nu{\rm DM}} \simeq -5.43$. Future surveys sensitive to high CMB multipoles will open a new window for probing DM couplings to neutrinos.

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DATA AVAILABILITY

All the data used are explained in the text and are publicly available.

REFERENCES

Abazajian K. et al., 2019, preprint (arXiv:1907.04473)
Abdullahi A. M. et al., 2023, J. Phys. G: Nucl. Part. Phys., 50, 020501
Ade P. et al., 2019, J. Cosmol. Astropart. Phys., 2019, 056
Aiola S. et al., 2020, J. Cosmol. Astropart. Phys., 2020, 047
Akerib D. S. et al., 2022, preprint (arXiv:2203.08084)
Argüelles C. A., Diaz A., Kheirandish A., Olivares-Del-Campo A., Safa I., Vincent A. C., 2021, Rev. Mod. Phys., 93, 035007
BABAR Collaboration, 2022, Phys. Rev. D, 107, 052009
Balkenhol L. et al., 2022, Phys. Rev. D, 108, 023510
Batell B., Han T., McKeen D., Shams Es Haghi B., 2018a, Phys. Rev. D, 97, 075016
Batell B., Han T., Shams Es Haghi B., 2018b, Phys. Rev. D, 97, 095020
Batell B. et al., 2022, preprint (arXiv:2207.06898)
Bertoni B., Ipek S., McKeen D., Nelson A. E., 2015, J. High Energy Phys., 2015, 170
Blas D., Lesgourgues J., Tram T., 2011, J. Cosmol. Astropart. Phys. , 2011, 034
Blennow M., Fernandez-Martinez E., Olivares-Del Campo A., Pascoli S., Rosauro-Alcaraz S., Titov A. V., 2019, Eur. Phys. J. C, 79, 555
Boehm C., Dolan M. J., McCabe C., 2013, J. Cosmol. Astropart. Phys., 2013, 041
Boehm C., Schewtschenko J. A., Wilkinson R. J., Baugh C. M., Pascoli S., 2014, MNRAS, 445, L31
Brax P., van de Bruck C., Di Valentino E., Giarè W., Trojanowski S., 2023, Phys. Dark Univ., 42, 101321
Choi K.-Y., Kim J., Rott C., 2019, Phys. Rev. D, 99, 083018
Choi S. K. et al., 2020, J. Cosmol. Astropart. Phys., 2020, 045
CMB-HD Collaboration, 2022, preprint (arXiv:2203.05728)
Cvetič G., Halzen F., Kim C. S., Oh S., 2017, Chin. Phys. C, 41, 113102
Dawson K. S. et al., 2013, AJ, 145, 10
de Salas P. F., Lineros R. A., Tórtola M., 2016, Phys. Rev. D, 94, 123001
Di Valentino E., Bøehm C., Hivon E., Bouchet F. R., 2018, Phys. Rev. D, 97, 043513
Escudero M., Mena O., Vincent A. C., Wilkinson R. J., Bœhm C., 2015, J. Cosmol. Astropart. Phys., 2015, 034
Escudero M., Lopez-Honorez L., Mena O., Palomares-Ruiz S., Villanueva-Domingo P., 2018, J. Cosmol. Astropart. Phys., 2018, 007
Hanany S. et al., 2019, preprint (arXiv:1902.10541)
Hooper D. C., Lucca M., 2022, Phys. Rev. D, 105, 103504
Kelly K. J., Zhang Y., 2019, Phys. Rev. D, 99, 055034
Kelly K. J., Kling F., Tuckler D., Zhang Y., 2022, Phys. Rev. D, 105, 075026
Kobach A., Dobbs S., 2015, Phys. Rev. D, 91, 053006
Kolb E. W., Turner M. S., 1987, Phys. Rev. D, 36, 2895
Lewis A., Bridle S., 2002, Phys. Rev. D, 66, 103511
Mosbech M. R., Boehm C., Hannestad S., Mena O., Stadler J., Wong Y. Y. Y., 2021, J. Cosmol. Astropart. Phys., 2021, 066
Olivares-Del Campo A., Bœhm C., Palomares-Ruiz S., Pascoli S., 2018, Phys. Rev. D, 97, 075039
Palomares-Ruiz S., Pascoli S., 2008, Phys. Rev. D, 77, 025025
Pandey S., Karmakar S., Rakshit S., 2019, J. High. Energy Phys., 2019, 095
Paul A., Chatterjee A., Ghoshal A., Pal S., 2021, J. Cosmol. Astropart. Phys., 2021, 017
Petraki K., Volkas R. R., 2013, Int. J. Mod. Phys. A, 28, 1330028
Planck Collaboration I, 2020a, A&A, 641, A1
Planck Collaboration V, 2020b, A&A, 641, A5
Planck Collaboration VI, 2020c, A&A, 641, A5
Schewtschenko J. A., Baugh C. M., Wilkinson R. J., Bœhm C., Pascoli S., Sawala T., 2016, MNRAS, 461, 2282
Serra P., Zalamea F., Cooray A., Mangano G., Melchiorri A., 2010, Phys. Rev. D, 81, 043507
Shoemaker I. M., 2013, Phys. Dark Univ., 2, 157
Shoemaker I. M., Murase K., 2016, Phys. Rev. D, 93, 085004
Stadler J., Bœhm C., Mena O., 2019, JCAP, 2019, 014
Torrado J., Lewis A., 2020, J. Cosmol. Astropart. Phys., 2021, 057
Wilkinson R. J., Lesgourgues J., Boehm C., 2014a, J. Cosmol. Astropart. Phys., 2014, 026
Wilkinson R. J., Boehm C., Lesgourgues J., 2014b, J. Cosmol. Astropart. Phys., 2014, 011
Zurek K. M., 2014, Phys. Rep., 537, 91

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