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Massive neutrino self-interactions and the Hubble tension

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Abstract.
We consider flavour independent neutrino self-interactions among massive neutrinos mediated by a heavy scalar against cosmological data. Such a model had previously shown to have potential in completely resolving the Hubble tension for the very strong interaction case with coupling strength $\sim 10^9$ times the Fermi constant, by delaying the onset of neutrino free-streaming until matter-radiation equality. Our cosmological model consists of a total nine parameters which includes the six ΛCDM parameters and three parameters related to neutrinos: sum of neutrino masses ($\sum m_\nu$), neutrino energy density ($N_{\rm eff}$), and the effective coupling strength, $\log_{10}\left[\mathrm{G_{eff}MeV^2}\right]$. With the latest CMB data from the Planck 2018 data release as well as auxiliary data, we find that the region in parameter space with such strong interactions is still present in the posterior distribution. However, high-l polarisation data from the Planck 2018 release disfavours this strongly interacting mode even though it cannot yet be excluded. Our resuts show that the neutrino mass bounds obtained from cosmological data remain robust against when considering neutrino self-interactions. We also find that the high-l polarisation data also does not allow for high values of H_0 that can solve the current Hubble discrepancy, i.e. this model is not a viable solution to the same.

1. Introduction

While neutrino oscillations experiments have provided a rare proof of a Beyond Standard Model physics by confirming that at least two neutrinos are massive, the tightest bounds on the sum of neutrino masses, $\sum m_\nu$ come from cosmology, which is currently around $\sum m_\nu < 0.09$ eV (95% C.L.) [1] in the $\Lambda\mathrm{CDM} + \sum m_\nu$ model with 3 degenerate neutrino masses. The bound can relax up to a factor of 3 in simple extensions to ΛCDM cosmology [2, 3]. We introduce self-interactions between neutrinos via a majoron-like model of neutrino mass generation where neutrinos are Majorana particles, and the $U(1)_{B-L}$ symmetry [4] is spontaneously broken giving rise to a new Goldstone boson, i.e. the majoron, denoted here by ϕ. This majoron couples to the neutrinos via the Yukawa interaction [5],

$$\mathcal{L}_{\rm int} = g_{ij}\bar{\nu}_i\nu_j\phi + h_{ij}\bar{\nu}_i\gamma_5\nu_j\phi. \quad (1)$$

Here g_{ij} and h_{ij} are the scalar and pseudo-scalar coupling matrices, respectively, and ν_i is a left-handed neutrino Majorana spinor. The indices i, j label the neutrino mass eigenstates. We

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emphasize here that this kind of interaction is not limited to the majoron-like model we have considered here. For instance, ϕ can be linked to the dark sector [6].

In [7], we consider a special case of equation (1) where $g_{ij} = g\delta_{ij}$ and $h_{ij} = 0$. Here δ_{ij} is the Kronecker delta. Such an approach might be unrealistic for real particle physics models but it provides a simple way to test the sensitivity of the cosmological data to a neutrino-majoron coupling. We also consider that the mass of the majoron, $m_\phi >> T_{\rm CMB}$, where $T_{CMB} \simeq 0.26$ eV is the photon decoupling temperature. Then we can treat it as an effective 4-fermion $\nu\nu \to \nu\nu$ self-interaction with a self-interaction rate per particle $\Gamma \sim g^4 T_\nu^5/m_\phi^4 = G_{\rm eff}^2 T_\nu^5$, where $G_{\rm eff} = g^2/m_\phi^2$ is the effective self-coupling [8]. Any initial population of ϕ in the early universe would completely decay by the time of the CMB formation epoch as long as we have a typical $m_\phi >$ keV. We note here that an interaction via a heavy vector boson will lead to a similar 4-fermion interaction [9] and would draw the same cosmological conclusions.

Currently, the Cepheid calibrated Type Ia Supernovae (SNe Ia) in the local universe provide a value of the Hubble constant, $H_0 = 74.03 \pm 1.42$ km/s/Mpc (68% C.L.) [10] (hereafter R19). This is in 4.4σ tension with the value of $H_0 = 67.27 \pm 0.60$ km/s/Mpc (68% C.L.) [11] obtained in the ΛCDM model with Planck 2018 CMB temperature and polarization power spectra. This is popularly known as the Hubble tension. Strong neutrino self-interactions via a heavy mediator have been proposed as a solution to the Hubble tension as the introduction of neutrino self-interactions in a cosmological model has very important cosmological consequences.

As long as $G_{\rm eff} > G_{\rm F}$ (where $G_{\rm F} \simeq 1.166 \times 10^{-11}{\rm MeV}^{-2}$ is the standard Fermi constant), the neutrinos will continue to scatter among each other even after decoupling from the primordial plasma at around $T \sim 1$ MeV (determined via the weak interaction coupling strength). The self-scattering will die out when Γ falls below the Hubble rate, and thus larger the value of $G_{\rm eff}$, longer the delay in the neutrino free-streaming. Strong interactions due to large $G_{\rm eff}$ leads to a lack of anisotropic stress in the neutrino sector. This causes a phase shift in the peaks of the CMB anisotropy power spectra. This effect can be compensated partially by increasing θ_s (angular size of the sound horizon at recombination). Also, increasing $G_{\rm eff}$ causes a gradual increase in the power in small scales of the CMB which can be partially compensated by a smaller scalar spectral index, n_s [8]. These degeneracies allow the posterior of $\log_{10}\left[{\rm G_{eff}MeV^2}\right]$ to be bimodal, with the moderately interacting mode (MIν heareafter) being unbounded from below (i.e. the non-interacting limit), while the strongly interacting mode (SIν hereafter) corresponds to $G_{\rm eff} \sim 10^9 G_{\rm F}$ and is a distinct region in the posterior from MIν [8].

In [7], we consider a 9 parameter cosmological model: $\Lambda{\rm CDM} + \log_{10}\left[{\rm G_{eff}MeV^2}\right] + {\rm N_{eff}} + \sum m_\nu$, where, $N_{\rm eff}$ is the effective number of neutrino species. $G_{\rm eff}$ is also degenerate with $N_{\rm eff}$ and $\sum m_\nu$ in the CMB power spectra, and in principle, large values of $G_{\rm eff}$ for the SIν case can also lead to the large values of $N_{\rm eff} \sim 4$ being preferred, which can solve the H_0 tension since an increased $N_{\rm eff}$ increases the expansion rate in the early universe. Indeed, when we use only the Planck 2018 temperature data, we see such a scenario. However, when we include the Planck 2018 high-l polarization data, the model parameters are far more tightly constrained, including $N_{\rm eff}$, which does not allow for large values of $N_{\rm eff}$ that can solve the Hubble tension.

2. Methodology

Since we consider a heavy mediator, it can be safely assumed that it decays away far before the CMB epoch. Pair-annihilation/production can also be neglected because of the large rest mass of the mediator particle. Thus, this interaction does not affect the background evolution equations. However, the self-interaction does affect the neutrino perturbation equations, which we incorporate by modifying in the CAMB code [12]. We use the relaxation time approximation (RTA), which prescribes adding a damping term proportional to the neutrino self-interaction opacity $\dot{\tau}_\nu \equiv -aG_{\rm eff}^2 T_\nu^5$ to all terms in the neutrino Boltzmann hierarchy beyond $l = 1$. RTA was first introduced in this context in [13] and first used for a treatment of self-interactions in light

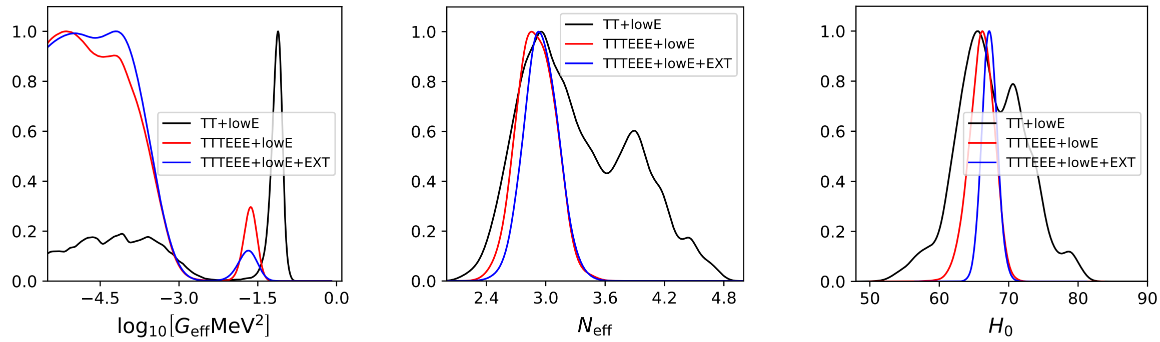

Figure 1: Posterior distributions for the analyses with full range of $\log_{10}\left[\mathrm{G_{eff}MeV^2}\right]$. H_0 is expressed in km/s/Mpc.

neutrinos in [14]. RTA was found to be very accurate when compared with the exact description of the collisional Boltzmann equations of neutrinos, in [8].

For the Bayesian analyses, we apply uniform priors on all the model parameters, the model being ΛCDM + $\log_{10}\left[\mathrm{G_{eff}MeV^2}\right]$ + $\mathrm{N_{eff}}$ + $\sum m_\nu$, as mentioned before. To compare with the non-interacting case, we also perform analysis in the ΛCDM + $\mathrm{N_{eff}}$ + $\sum \mathrm{m}_\nu$ model. We denote this case by NIν.

Our primary data is the CMB data from Planck 2018 data release [11]. Here, TT denotes the low-l and high-l temperature power spectra, whereas TTTEEE denotes the TT spectra combined with high-l TE and EE spectra. The low-ℓ E mode polarisation is denoted as lowE, and is included in all dataset combinations. On table 1 we also use the abbreviation "CMB" for TTTEEE+lowE. We use the full Plik likelihoods and not their "lite" versions. Additionally, we use an auxiliary dataset combination, which we denote by EXT. This consists of Planck 2018 CMB lensing [16], Baryon Acoustic Oscilation (BAO) and Redshift Space Distortion (RSD) measurements from SDSS-III BOSS DR12 [17], additional BAO measurements from MGS [18] and 6dFGS [19], and SNe Ia luminosity distance measurements from the Pantheon sample [20]. We sample the parameter space using the nested-sampler CosmoChord [21], which is the Polychord extension [22, 23] of CosmoMC [24, 25].

3. Results

We have provided some parameter constraints for the separate runs of NIν, MIν, and SIν for three different data combinations in table 1. The table also contains the difference in the best-fit log likelihoods, $[\log(\mathcal{L}/\mathcal{L}_{\mathrm{NI}\nu})]$ and the Bayesian evidence ratios $Z/Z_{\mathrm{NI}\nu}$ (w.r.t. the non-interacting case). The posterior distributions of the main parameters for the full range runs of $\log_{10}\left[\mathrm{G_{eff}MeV^2}\right] \in [-5.5, -0.1]$ can be found in figure 1.

From figure 1 it can be clearly seen that the posterior for $\log_{10}\left[G_{\mathrm{eff}}\mathrm{MeV}^2\right]$, which is consistent with earlier works. We see that the TT+lowE data allows for a large range of both N_{eff} and H_0, and allows for $N_{\mathrm{eff}} > 4$ and $H_0 > 74$ km/s/Mpc. However, runs which include the high-l polarization data (namely TTTEEE+lowE and TTTEEE+lowE+EXT), do not allow such high values of H_0 that can resolve the Hubble tension.

From table 1, we can see that except the case of SIν with TT+lowE data, there is no resolution to the Hubble tension. In fact, when the high-l polarization data is included, the H_0 values from MIν and SIν are quite close to the non-interacting case (NIν). There is currently no good reason to exclude the Planck high-l polarization data from the analyses, and thus the resolution of Hubble tension with the partial TT+lowE data is far less interesting.

Again, looking at table 1 we see that only one dataset combination (TT+lowE) leads to an

Table 1: Parameter constraints (95%), the difference in best-fit log-likelihoods, and the ratio of Bayesian evidences w.r.t. the non-interacting case NIν. CMB $\equiv$ TTTEEE+lowE.

		TT+lowE	CMB	CMB+EXT
$\log_{10}\left[G_{\rm eff}{\rm MeV}^2\right]$	NIν	-	-	-
	MIν	< -3.04	< -3.47	< -3.37
	SIν	$-1.13^{+0.20}_{-0.21}$	$-1.69^{+0.27}_{-0.31}$	$-1.71^{+0.27}_{-0.31}$
$N_{\rm eff}$	NIν	$2.95^{+0.59}_{-0.59}$	$2.91^{+0.39}_{-0.37}$	$2.96^{+0.33}_{-0.35}$
	MIν	$2.96^{+0.61}_{-0.59}$	$2.91^{+0.38}_{-0.38}$	$2.97^{+0.34}_{-0.33}$
	SIν	$4.00^{+0.80}_{-0.82}$	$2.74^{+0.38}_{-0.35}$	$2.73^{+0.34}_{-0.31}$
$\sum m_\nu$ [eV]	NIν	< 0.705	< 0.297	< 0.122
	MIν	< 0.771	< 0.290	< 0.117
	SIν	< 0.848	< 0.325	< 0.152
H_0	NIν	$64.6^{+6.3}_{-8.2}$	$65.9^{+3.3}_{-3.8}$	$67.3^{+2.2}_{-2.2}$
	MIν	$64.6^{+7.0}_{-8.1}$	$66.0^{+3.5}_{-3.6}$	$67.4^{+2.2}_{-2.1}$
	SIν	73^{+9}_{-10}	$66.4^{+3.7}_{-3.7}$	$66.7^{+2.2}_{-2.1}$
$-2\left[\log\left(\mathcal{L}/\mathcal{L}_{{\rm NI}\nu}\right)\right]$	NIν	0	0	0
	MIν	-1.0	-1.2	0.2
	SIν	-2.9	3.0	3.4
$Z/Z_{{\rm NI}\nu}$	NIν	1	1	1
	MIν	0.67	0.47	0.45
	SIν	1.30	0.03	0.06

evidence ratio larger than unity for the SIν-mode. Again with the addition of high-l polarization data, SIν becomes strongly disfavoured compared to NIν. MIν is, in all cases, mildly disfavoured compared to NIν. The differences in best-fit log likelihoods provide similar conclusions.

Finally, we find that while, due to the degeneracy between $G_{\rm eff}$ and $\sum m_\nu$, the SIν mode prefers slightly larger values of $\sum m_\nu$ than MIν or SIν, the upper bound on $\sum m_\nu$ does not change significantly. This implies that the cosmological mass bounds quoted in literature are robust against the kind of new physics we have introduced here.

4. Conclusions

We have considered the non-standard massive neutrino self-interactions mediated by a heavy scalar in the 4-fermion interaction limit in the context of Hubble tension in cosmology. Among cosmological datasets, we have used the latest CMB temperature, polarisation, and lensing data from the Planck 2018 data release, BAO and RSD measurements from SDSS-III BOSS DR-12, additional BAO measurements from MGS and 6dFGS, and uncalibrated SNe Ia luminosity distance data from the Pantheon sample.

In our extended cosmological model: ΛCDM + $\log_{10}\left[{\rm G_{eff}MeV^2}\right]$ + ${\rm N_{eff}}$ + $\sum m_\nu$, we find a bimodal posterior distribution for the $\log_{10}\left[{\rm G_{eff}MeV^2}\right]$ parameter, which is consistent with earlier studies with older data. Among the two modes, the strongly interacting mode (with

$G_{\rm eff} \sim 10^9 G_{\rm F}$, where $G_{\rm F}$ is the Fermi constant) was shown, in earlier studies with older data, to resolve the Hubble tension by preferring high $N_{\rm eff}$ values. However, we find that as long as the Planck 2018 high-l polarization data is included, the strongly interacting mode no longer provides a viable solution to the H_0-tension. Also, both in terms of Bayesian evidence and from the raw likelihood, we find that the strongly interacting mode is disfavoured compared to a non-interacting scenario. We also find that the neutrino self-interactions studied here leave the neutrino mass bounds from cosmology almost unchanged so that the mass bounds found in the literature are robust against this new physics.

Finally, we note that while, in this work, the results were obtained with a heavy scalar mediator, they also apply to the case of a vector mediator, the expected changes in the values of $G_{\rm eff}$ being small.

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