Massive neutrino self-interactions with a light mediator in cosmology

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Nonstandard self-interactions can alter the evolution of cosmological neutrinos, mainly by damping free streaming, which should leave traces in cosmological observables. Although overall effects are opposite to those produced by neutrino mass and a larger $N_{\text{eff}}$, they cannot be totally canceled by these last. We harness cosmological data that includes Cosmic Microwave Background from Planck 2018, BAO measurements, local $H_0$, Ly-α and SNIa, to constrain massive neutrino self-interactions with a very light scalar mediator. We find that the effective coupling constant, at the 95% C.L., should be $g_{\text{eff}} < 1.94 \times 10^{-7}$ for only Planck 2018 data and $1.97 \times 10^{-7}$ when Planck + BAO are considered. This bound relaxes to $2.27 \times 10^{-7}$ ($2.3 \times 10^{-7}$) for $H_0$ (H0+SNe+Ly-α) data. Using the Planck + BAO dataset, the $H_0$ tension lowers from 4.3σ (for ΛCDM) to 3.2σ. The Akaike Information Criterion penalizes the self-interacting model due to its larger parameter range interactions via a NSI neutrino-scalar interactions in the presence of neutrino decays, annihilations or long-range interactions via a NSI neutrino-scalar interactions. Furthermore, non-desirable NSI effects change $N_{\text{eff}}$, by increasing [28], or reducing its value [50]. The neutrino self-interactions effects on linear perturbation cosmology have been studied in [51, 52], where the authors found a $2\sigma$ bound for the effective neutrino-scalar coupling $g_{\text{eff}} \lesssim 2 \times 10^{-7}$. So far, self-interactions with light mediators have not shown any preference for a larger $H_0$-value [52].

I. INTRODUCTION

Cosmology provides frontier conditions to uniquely study neutrinos. The cosmological constraints on the standard neutrinos are consistent with three active neutrinos [1,2,3], which is consistent with the theoretical prediction $N_{\text{eff}}^{\text{std}} = 3.045$ [4,8]. Furthermore, the cosmological bound on the sum of the neutrino masses is the more restrictive so far with a consensus value of $\sum m_{\nu} < 0.12$ eV [9,10]. Cosmology is also expected to robustly show a preference for the correct neutrino mass hierarchy, wherein the normal (inverted) hierarchy $m_3 > m_1$ ($m_3 < m_1$). Once the bound on the sum of the neutrino masses reaches a precision below the minimum bound in the IH, $\sum m_{\nu}^{\text{eff}} > 0.0986 \pm 0.00085$ eV [11], a preference for one the hierarchies would be plausible [12,14]. However, neutrino cosmological constraints may change significantly in the presence of neutrino nonstandard interactions (NSI). For instance, in such a scenario, an extra degeneracy arises with other cosmological parameters. Additionally, the impact on the cosmological observables does depend heavily on the nature of the NSI and on the mediator mass.

A neutrino self-interaction mediated by a heavy particle is an interesting model that could ease the $H_0$ tension [13,21]. Late and early observations of the Hubble parameter today are, on average, not consistent with each other [9,22,26]. This tension is now above $4\sigma$. If it were confirmed, new physics in the early Universe might be needed to explain the discrepancy. In this sense, among several ideas for physics beyond the Standard Model, neutrino NSIs are particularly appealing because their validity can soon be proved right or wrong by experiments and astrophysical observations [27,37].

On the other hand, a neutrino NSI mediated by a light scalar particle is one of the preferred proposals since it could be related to the solution to the anomaly observed by the MiniBooNE and LSND experiments [38,41]. Although the interpretation of the excess signal produced by single electron neutrinos was recently disfavored by the MicroBooNE collaboration [42]. The origin of the neutrino excess observed by MiniBooNE/LSND is still to be explained and a neutrino NSI mediated by a light particle is a possible explanation.

Aside from possible solutions to the mentioned tensions and anomalies, the phenomenological consequences of neutrino NSI with a light mediator are vast. For instance, the neutrino mass bounds may relax or completely vanish in the presence of neutrino decays, annihilations or long-range interactions via a NSI neutrino-scalar interactions [43,49], or massless scalar particle on the evolution of cosmological density perturbations and temperature and matter power spectra. We extend the previous works in Refs. [51,52].
where they studied self-interactions without taking into account the neutrino mass. We compare our results to the latest cosmological observations in order to constrain the parameters of the model. Finally, we use model comparison criteria to test the self-interacting neutrinos versus the standard cosmological model.

The rest of the paper is organized as follows, in section II we introduce the computation of the neutrino self-interaction collision term, then we use the relaxation time approximation (RTA) to write down the Boltzmann hierarchy of neutrino perturbations. In section III we constrain the parameter space for neutrino self-interactions using different cosmological data sets. We conclude and highlight some future directions in section IV.

II. COSMOLOGICAL PERTURBATIONS IN THE PRESENCE OF NEUTRINO SELF-INTERACTIONS

Along with the present discussion, we shall focus on the thermal history of neutrinos, its impact on the evolution of the other species, and the imprints that this last should leave on current cosmological data, which can be appropriately described by the evolution of its full distribution function in phase space, through Boltzmann equation formalism. In the standard approach, neutrinos are only subject to electroweak interactions, which keep neutrinos in thermal equilibrium well down to about $1\sim\text{MeV}$, its decoupling temperature. Once decoupled, the ultrarelativistic neutrinos free-stream, damping neutrino density fluctuations at scales below the free-streaming length, feeding $\ell \gg 2$ moments in the neutrino Boltzmann hierarchy. As a consequence, metric perturbations also get reduced as a back reaction within those scales. As they travel through matter they gravitationally pull wavefronts, phase shifting CMB power spectra towards larger scales, also damping its amplitude. The signature of this effect appears as a photon sound dampening of CMB acoustic oscillations, on the affected scales. In addition to that, although neutrino tiny mass barely affects neutrino free streaming, neutrino abundance is proportional to it, and thus, increasing the neutrino mass amplifies mentioned free streaming effects. Famously, the neutrino mass suppresses the matter power spectrum for small scales. From this point of view, neutrino mass could compensate for a portion of the NSI effects. However, neutrino masses had not been so far considered as part of the variables involved in the outcomes of NSI effects. This is one of the issues we would like to address along with this paper.

In this work we assume that the geometry of the space–time is described by a perturbed FLRW metric, which in the notation by Ma and Bertschinger (MB) and in a synchronous gauge is written as

$$ds^2 = a^2(\tau) [-d\tau^2 + (\delta_{ij} + h_{ij})dx^idx^j], \quad (1)$$

where $a$ is the scale factor, $\tau$ the conformal time and the scalar part of the metric perturbation, $h_{ij}(x, \tau)$, is described in the Fourier space through two fields, $h = h(\vec{k}, \tau)$ and $\eta = \eta(\vec{k}, \tau)$,

$$h_{ij}(\vec{x}, \tau) = \int d^3k e^{i\vec{k} \cdot \vec{x}} \left\{ k_i k_j h + (k_i k_j - \frac{\delta_{ij}}{3})(6\eta) \right\}. \quad (2)$$

In such a Universe the metric potentials are coupled to the matter constituents through the Einstein equations, from which the conservation of the energy-momentum tensor is derived and, in turn, do so the continuity and Euler equations that dictate the evolution of matter.

To proceed with our analysis, we shall first elaborate on neutrino Boltzmann hierarchy equations. For this, we start by writing at linear order in perturbation theory the phase space distribution function, $f(x^i, q^j, \tau)$, as

$$f(x^i, q^j, \tau) = f_0(q) \left[ 1 + \Psi(x^i, q, \mathbf{\hat{n}_j}, \tau) \right], \quad (3)$$

where $x^i$ denotes the spatial coordinates, $q_j = q\hat{n}_j$ is the comoving tri–momentum oriented along the unitary vector $\hat{n}_j$, and with magnitude $q = |q|$. This last term is
related to the proper momentum $\vec{p}$, through the expansion parameter such that $\hat{q} = a\hat{p}$. On the above expression, $f_0(q)$ is the distribution function at the background (considered in thermal equilibrium) that in the case of neutrinos is the Fermi–Dirac distribution,

$$f_0(q, \tau) = \frac{1}{e^{\epsilon(q, \tau)/T} + 1}.$$  \hspace{1cm} (4)

Here $T$ is the neutrino temperature and $\epsilon = \epsilon(q, \tau) = \sqrt{q^2 + a^2m^2}$ the comoving energy, related to the proper energy by $\epsilon = aE$. Since the distribution function $f$ provides the number of particles in a differential volume in phase space, $dN = fdx^1dx^2dx^3dP^1dP^2dP^3$, with $P^i$ the canonical conjugate momentum which in the synchronous gauge is given as $P_i = (\delta ij + \frac{1}{2}\delta_{ij})q^j$, in the presence of local collisions, it evolves according to the Boltzmann equation

$$\frac{Df}{D\tau} = \frac{\partial f}{\partial \hat{q}} \cdot \frac{\partial \hat{q}}{\partial \tau} + \frac{\partial f}{\partial \hat{E}} \cdot \frac{\partial \hat{E}}{\partial \tau} + \frac{\partial f}{\partial \hat{P}} \cdot \frac{\partial \hat{P}}{\partial \tau} = C[f],$$  \hspace{1cm} (5)

where $C[f] = \left(\frac{\partial f}{\partial \tau}\right)_c$ is the collision term.

To first order, the Boltzmann equation for the distribution (3) in Fourier space, has the generic expression 69,

$$\frac{\partial \Psi}{\partial \tau} + \frac{q}{\epsilon} (\hat{k} \cdot \hat{n})\Psi + \frac{d\ln f_0}{d\ln q} \left[ \frac{\dot{\hat{h}} + 6\dot{h}\hat{n}}{2} (\hat{k} \cdot \hat{n}) \right] = \frac{1}{f_0} C[f].$$  \hspace{1cm} (6)

Of course, for a vanishing $C[f]$ we recover the collisionless Boltzmann equation or Vlasov equation that describes free streaming neutrinos. As it is usual, to partially reduce the dimensionality of the problem we should expand the perturbation $\Psi$ into a Legendre series

$$\Psi(\hat{k}, \hat{n}, q, \tau) = \sum_{\ell=0}^{\infty} (-i)^\ell (2\ell + 1)\Psi_\ell(\hat{k}, q, \tau)P_\ell(\hat{k} \cdot \hat{n}),$$  \hspace{1cm} (7)

which transforms the former equation (6) into an infinite moment hierarchy for the $\Psi_\ell(\hat{k}, q, \tau)$ weights.

In principle, one should solve the collisional Boltzmann equation by calculating the integrals of the collision terms for the specific interaction, however as a first approach we use the relaxation time approximation (RTA) 90 in which the collision term $C[f]/f_0$ is well approximated by $-\Psi/\tau_c$, where $\tau_c$ is the mean time between collisions, which can be written as $\tau_c^{-1} = \hat{a} T = a\Gamma/\sigma T$. Using this approach one obtains the following Boltzmann hierarchy,

$$\dot{\Psi}_0 = -\frac{qk}{\epsilon} \Psi_0 + \frac{\dot{h}}{6} \frac{d\ln f_0}{d\ln q},$$  \hspace{1cm} (8)

$$\dot{\Psi}_1 = \frac{qk}{3\epsilon} (\Psi_0 - 2\Psi_2),$$  \hspace{1cm} (9)

$$\dot{\Psi}_2 = \frac{qk}{5\epsilon} (2\Psi_1 - 3\Psi_3) - \frac{\dot{h}}{15} + \frac{2\dot{h}}{5} \frac{d\ln f_0}{d\ln q} - a\Gamma \Psi_2,$$  \hspace{1cm} (10)

$$\dot{\Psi}_{l\geq 3} = \frac{qk}{(2l + 1)\epsilon} (l\Psi_{l-1} - (l + 1)\Psi_{l+1}) - a\Gamma \Psi_l.$$  \hspace{1cm} (11)

The first two hierarchy equations, for the monopole and dipole modes, are related to density and energy momentum conservation, which require that

$$\int d^3q C[f] = 0 = \int d^3q \hat{k} \cdot \hat{n} C[f]$$

respectively, and therefore they should get no contribution from the interaction 51 55 whose impact becomes more relevant for the higher modes, since it enters as a damping term. We adopt a phenomenological recipe for the neutrino scattering rate for a light mediator 52 for which we take

$$\Gamma = 0.183 \delta_{\text{eff}}^3 T_\nu,$$  \hspace{1cm} (12)

with $\delta_{\text{eff}}$ an effective coupling constant that generically encodes the subtleties of the interaction.

Once this formalism has been introduced, it is possible to obtain the numerical solutions of the density contrasts and understand the physical effect of the interaction term. In order to explore the self-interacting neutrino effects, we first show the effect on the density contrasts of the standard cosmological species. In Fig. 1 we show cold dark matter, photon, baryonic and neutrino perturbations at different $k$ modes and for two $g_{\text{eff}}$ values, 0 and $5 \times 10^{-7}$. For $g_{\text{eff}} = 0$, there is no interaction and the contrast of massive neutrinos behaves as expected (left panels), however, when the interaction turns on (right panel) the neutrino fluid undergoes acoustic oscillations because free streaming is not efficient enough to damp the perturbations. This lack of free-streaming ultimately will translate into non-desired changes that could be partially compensated by changing other neutrino or cosmological parameters.
Changes in density perturbations are carried over the matter power spectrum, for example, in Fig. 2 we show that a larger sum of neutrino masses produce an attenuation at small scales (as expected). However, the value of the coupling constant plays an opposite role since larger values of $g_{\text{eff}}$ are associated with an increasing power spectrum, so that, bigger couplings could be observationally valid if neutrino masses are increased too. As a matter of fact, this non-trivial effect, regarding its $k$-dependence, was also observed in the heavy mediator scenario [19]. As we can see in the figure, the neutrino mass and the coupling cannot vanish each other effect, thus, we expect cosmology to prefer negligible values of these two parameters when employing data to constrain them.

Massive self-interacting neutrinos through eq. (12) also imprint an effect in the CMB spectra, as shown in Figs. 3 and 4. In Figs. 3 and 4 we show the TT spectrum for different $g_{\text{eff}}$-values, while also changing values of $\sum m_\nu$ and $N_{\text{eff}}$ respectively. We notice that $g_{\text{eff}}$ enhances the spectrum for high multipoles, while the neutrino mass damps and shifts the overall spectrum to the left. Furthermore, $N_{\text{eff}}$ causes a phase shift in the acoustic peaks. In Fig. 5 we also show that the neutrino self-interaction enhances the polarization spectra, however, notice that for the selected values it is harder to distinguish from $\Lambda$CDM. As in the MPS graph, we do not observe any non-null combination of parameters that could mimic $\Lambda$CDM in the CMB, this ultimately will reflect on different model-fit results that can be distinguished from the standard cosmological model.

In the next section, we are going to show the results on the global fits for the self-interacting neutrino model while allowing all three neutrino parameters ($g_{\text{eff}}$, $N_{\text{eff}}$, $\sum m_\nu$) to be free.

FIG. 2. Effects of $g_{\text{eff}}$ and $\sum m_\nu$ on the matter power spectrum. Solid lines correspond to $\sum m_\nu = 0.06$ eV, and dashed ones correspond to $\sum m_\nu = 0.23$ eV. Black indicates non-interacting neutrinos, while blue and purple lines are for self-interacting neutrinos.

FIG. 3. Temperature power spectrum of self-interacting massive neutrinos. Solid lines correspond to $\sum m_\nu = 0.06$ eV, while dashed lines indicate $\sum m_\nu = 0.23$ eV. Black indicates non-interacting neutrinos, while colored lines are for self-interacting neutrinos. In the middle and bottom panels $\Delta D_\ell$ means $D_\ell,\text{NSI} - D_\ell,\Lambda\text{CDM}$. 

III. PARAMETER CONSTRAINTS AND DEGENERACIES

In this section, we use different sets of cosmological observations to constrain the parameters of the NSI scenario. The observations include CMB power spectra from Planck 2018, which include the combined TT, TE, EE, low E, and lensing likelihoods [61]. Baryonic acoustic oscillations (BAO) measurements from BOSS DR12 — both from galaxy [62] and Lyman-α forest correlations [63, 64], 6DF [65] and MGS [66]. In the following we refer to the galaxy measurements simply as BAO and to the BAO Lyman-α measurements simply as Ly-α. Local $H_0$ measurements from SH0ES [25] are also included as well as SNIa data from Pantheon [67].

In order to compare our model with the observations we run MCMC chains using the code MontePython [68, 69] with a modified version of CLASS [70, 71]. The model varies the usual $\Lambda$CDM parameters $\Omega_m$, $\Omega_{\text{cdm}}$, $\theta_s$, $A_s$, $m_\nu$ and $\tau_{\text{reio}}$ plus three extra parameters related with the neutrino dynamics which include the sum of
the neutrino masses, $\sum m_\nu$, and the interaction strength $g_{\text{eff}}$, as well as $N_{\text{ur}}$ corresponding to a possible extra ultra relativistic component in the early Universe, with $N_{\text{eff}} = 3.046 + N_{\text{ur}}$. The constraints obtained in the parameters are summarized in table I and in figures 6-7. These figures were created with the GetDist package [72].

In Fig. 6 we can see that the combination of Planck data only, the correlation between $\sum m_\nu$ and $H_0$ also with $g_{\text{eff}}$ is negative. However, this negative correlation disappears when including BAO (and $H_0$) data. Thus, having a larger neutrino mass does not prevent $H_0$ from taking larger values when the whole data pool is considered. Notice that this effect is not unique to this model, and it mainly depends on the dataset selection [73].

Among the possible solutions, self-interacting neutrinos do not free-stream, and thus, their phase shift effect on the acoustic peaks can be suppressed, this can be partially compensated with a larger $N_{\text{eff}}$-value and ultimately, due to their strong correlation, a larger value of
TABLE I. Constraints on the cosmological parameters in the self-interacting neutrino scenario for different data combinations.

We quote 68% credible intervals, except for upper bounds, which are 95%. For comparison purposes, the $\Delta$AIC values between the $\Lambda$CDM and the NSI models are included. The criterion favors the interacting model when $H_0$ data is included.

| Parameter       | Planck       | Planck+BAO   | Planck+BAO+$H_0$ | Planck+BAO+$H_0$+SNNe+Ly$\alpha$ |
|-----------------|--------------|--------------|------------------|----------------------------------|
| $\Omega_b h^2 \times 10^2$ | 2.229 ± 0.024 | 2.238 ± 0.019 | 2.271 ± 0.017 | 2.272 ± 0.016 |
| $\Omega_cdm h^2$   | 0.119 ± 0.037 | 0.119 ± 0.037 | 0.126 ± 0.031 | 0.126 ± 0.029 |
| $100\theta_s$   | 1.0422 ± 0.0007 | 1.0422 ± 0.0006 | 1.0413 ± 0.0005 | 1.0413 ± 0.0005 |
| $\ln 10^{10} A_s$ | 3.042 ± 0.019 | 3.044 ± 0.017 | 3.061 ± 0.016 | 3.061 ± 0.016 |
| $n_s$           | 0.964 ± 0.009 | 0.967 ± 0.009 | 0.983 ± 0.007 | 0.983 ± 0.007 |
| $\tau_{reio} \times 10^2$ | 5.54 ± 0.83 | 5.72 ± 0.78 | 5.97 ± 0.77 | 6.01 ± 0.80 |
| $\sum m_\nu$ [eV] | < 0.23 | < 0.12 | < 0.12 | < 0.10 |
| $g_{eff} \times 10^7$ | < 1.94 | < 1.97 | < 2.27 | < 2.30 |
| $H_0$           | 66.9 ± 1.9 | 67.7 ± 1.4 | 70.8 ± 1.1 | 70.9 ± 1.0 |
| $N_{eff}$       | 3.00 ± 0.24 | 3.03 ± 0.22 | 3.49 ± 0.19 | 3.50 ± 0.17 |
| $\sigma_8$      | 0.807 ± 0.018 | 0.814 ± 0.012 | 0.832 ± 0.011 | 0.833 ± 0.010 |
| $\Delta$AIC     | 4.49 | 5.76 | −3.88 | −5.20 |

FIG. 6. Observational constraints for the NSI model, there are included the main parameters at 68% and 95% confidence limits; using Planck, Planck+BAO and, Planck+BAO+$H_0$ data combinations. We see that the inclusion of local $H_0$ data favors a non-zero interaction at least at 1-$\sigma$ level. Note that the combined posterior distribution Planck+BAO+$H_0$+SNNe+Ly$\alpha$ is not included here because it overlaps with the Planck+BAO+$H_0$ combination.
In this work, we studied the cosmological effects of a nonstandard interaction between massive neutrinos mediated by a light particle. Our work generalizes similar studies like those in Refs. 62 and 19, the former employing earlier Planck data and assuming a massless neutrino, and the latter using a heavy mediator. For our purpose, we used a modified version of the Boltzmann solver CLASS 70, 71 to include the neutrino self-interactions and the Markov chain Monte Carlo code MontePython 68, 69 to obtain the parameter constraints. Furthermore, we used several data sets including cosmic microwave background (CMB), baryonic acoustic oscillations (BAO), Ly-α forest, and local measurements of $H_0$.

The constrictions on the base-$\Lambda$CDM parameters reported in Table I are in good agreement with the known Planck 2018 results 01. The different data combinations are consistent with a null interaction at a 95% confidence level, but with a peak at positive $g_\text{eff}$ which is more prominent when data from Planck + BAO combine with local data from $H_0$. In all these cases the magnitude of this interaction is about $g_\text{eff} \lesssim 2 \times 10^{-7}$ (see Table I).

We should stress that although our bound from only Planck data is slightly tighter than the one reported in Ref. 62 for interaction between massless neutrinos, it softens once additional cosmological data is included. Bounds on neutrino masses are consistent with previously known results, tightening a bit when additional data to Planck and BAO is considered. A larger $N_{\text{eff}}$ is preferred by our analysis with all data sets which accompanies a larger $H_0$. The latter, however, does not suffice to resolve the $H_0$ tension.

During this analysis, we have deliberately ignored the neutrino decay/annihilation into a lighter neutrino state and/or the very light scalar particle. These processes may relax the neutrino mass bound 43, 49, while is not clear if this will have an important role in the determination of the $g_\text{eff}$-constraint or on the $H_0$ tension, we plan to pursue this in a future project.

The Akaike Information Criterion favors slightly the model with interactions, which contains a nonstandard interaction between massive neutrinos mediated by a light particle. This result is encouraging as it justifies the inclusion of the interaction. For the larger set of data corresponding to Planck, BAO, $H_0$, Supernovae, and Ly-α, the information criterion prefers the interaction model with an even larger margin.

IV. SUMMARY AND CONCLUSIONS

In this work, we studied the cosmological effects of a nonstandard interaction between massive neutrinos mediated by a light particle. Our work generalizes similar studies like those in Refs. 62 and 19, the former employing earlier Planck data and assuming a massless neutrino, and the latter using a heavy mediator. For our purpose, we used a modified version of the Boltzmann solver CLASS 70, 71 to include the neutrino self-interactions and the Markov chain Monte Carlo code MontePython 68, 69 to obtain the parameter constraints. Furthermore, we used several data sets including cosmic microwave background (CMB), baryonic acoustic oscillations (BAO), Ly-α forest, and local measurements of $H_0$.

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interactive model when data from Planck and $H_0$ combine. This results from the reduction in the tension between the local measurement of $H_0$ and its derivation from Planck + BAO data, from 4.3$\sigma$ for the $\Lambda$CDM model to 3.2$\sigma$ for the interactive neutrino model.

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