Published for SISSA by Springer

Received: *August 1, 2023*
Revised: *April 23, 2024*
Accepted: *May 14, 2024*
Published: *June 19, 2024*

Addendum: A seesaw model for large neutrino masses in concordance with cosmology

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Addendum to: JHEP02(2023)142

Abstract: Massless sterile neutrinos represent the core of the mechanism we studied in detail in [1] to relax stringent cosmological neturino mass bounds. Here we show that bounds on the mixing between these sterile states and active neutrinos are further relaxed due to a dark MSW effect. This turns out to be relevant only for the gauge scenario and implies that mixing angles as large as $\theta_{\nu\chi} \lesssim 0.1$ are allowed by $N_{\rm eff}$ bounds for relatively small values of the dark gauge coupling $g_X \gtrsim 10^{-6}$. This can open up parameter space for the gauge case at large mixing angles. We highlight the implications of the relaxation for the gauge case for the relevant regions of parameter space in the m_X-v_Φ plane. Finally, we also comment the corresponding phenomenology in the scalar case and on the potential exponential χ production pre-BBN.

ArXiv ePrint: 2211.01729

https://doi.org/10.1007/JHEP06(2024)119

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Contents

1 Impact of self-interactions on BBN and CMB constraints on the mixing between active and sterile neutrinos

As discussed in section 4 of [1], the mixing between χ and ν states is bounded by $N_{\rm eff}$ constraints resulting from the oscillations between them prior to neutrino decoupling in the early Universe at $T \sim$ MeV. In the published version of the manuscript we reported constraints on the mixing $\theta_{\nu\chi}$ assuming that χ particles were not interacting with the plasma in any appreciable way and did not feel any potential energy in the thermal bath at $T > 2\,$MeV. Despite the small couplings and number densities this is actually not strictly true and very tiny interactions can still modify and relax the constraints on $\theta_{\nu\chi}$ for the gauge case. The reason is that in the gauge version of the mechanism, the χ states feel a potential energy arising from the forward scattering between them in resemblance to the MSW effect in the sun. In particular, the potential for χ species can be written at the 1-loop level as [2–4]:[1]

$$V_{\chi\chi} = \frac{g_X^2 T_\nu^2}{8E}\left[\frac{2}{3}\frac{n_{Z'}}{n_{Z'}^{\rm eq}} + \frac{1}{3}\frac{n_\chi}{n_\chi^{\rm eq}}\right], \tag{1.1}$$

where E is the energy of a given χ state, T_ν is the neutrino temperature, g_X is the U$(1)_X$ gauge coupling, n are number densities, and $n^{\rm eq}$ refers to the equilibrium density of a given species. The factors of $1/3$ and $2/3$ arise from the contribution from fermions and bosons in the loop respectively, see [2]. Note that in addition, the oscillations between $\nu - \chi$ are also subject to effects coming from the active neutrino thermal potential in the Standard Model ($V_{\nu\nu}$) which is relevant in the early Universe [5].

There are two implications from these thermal potentials. Firstly, if $|V_{\nu\nu} - V_{\chi\chi}| \gg m_\nu^2/(2E_\nu)$ then the in-medium mixing angle will be strongly suppressed in the early Universe, which can happen already for rather small couplings, $g_X \gtrsim 10^{-7}$. Secondly, in our particular case of interest, the χ species is *lighter* than active neutrinos which means that it is resonantly produced in the early Universe. Since the thermal potentials are in turn dependent upon the χ number density this could potentially augment the resonant production.

[1] Note that compared to [3, 4], we choose to parametrize the dark sector distribution functions as $f_{\chi/Z'} = \xi_{\chi/Z'}[e^{p/T_\nu} \pm 1]^{-1}$, meaning the dark sector particles have $\langle E\rangle \simeq 3T_\nu$, but their number density is allowed to be smaller than the equilibrium value, with $\xi_{\chi/Z'} = n_{\chi/Z'}/n_{\chi/Z'}^{\rm eq}$. On the other hand, refs. [3, 4] parametrize the dark sector with just a dark sector temperature, T_s. Although the functional form of the potentials only match with $\xi_{\chi/Z'} = 1$ and $T_s = T_\nu$, in the relevant regions of parameter space the results for the energy density of χ states one finds at the end are very similar.

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In order to take into account the impact of these potentials on the production rate of χ states in the early Universe we proceed as in [6] and write down evolution equations for the neutrino temperature and the number density of χ states following [7, 8] and we solve for them using a modified version of the online NUDEC_BSM code. We take into account the $\nu - \chi$ oscillations and collisions by considering the collision term from [9] including the potential energy in eq. (1.1) in addition to the Standard Model one for neutrinos [5]. For simplicity, in eq. (1.1) we assume the same relative number density of Z' and χ states, i.e. $n_\chi/n_\chi^{\rm eq} = n_{Z'}/n_{Z'}^{\rm eq}$. This is motivated because of the strong self-interactions between these states.

In figure 1, we show isocontours of $N_{\rm eff}$ as relevant for BBN and CMB observations for two scenarios with $N_\chi = 1$ and $N_\chi = 10$. For the case with $N_\chi = 10$ we assume that all massless sterile neutrinos have the same mixing angle. For illustration we consider the case $m_\nu = 0.2\,{\rm eV}$ as the bounds do not change substantially for the parameter space of interest, $m_\nu < 0.8\,{\rm eV}$.

Current BBN and CMB constraints require $N_{\rm eff} \lesssim 3.3$ and we therefore notice that the cosmological bound on $\theta_{\nu\chi}$ can be evaded for rather small values of g_X. In particular, for the most relevant case of $N_\chi = 10$ we find that the cosmological bound on the mixing angle can be evaded provided that $g_X > 10^{-6}$. We do notice, however, an interesting region for $10^{-6} \gtrsim g_X \gtrsim 10^{-7}$ where actually the bound on $\theta_{\nu\chi}$ would be stronger than the one expected for a vanishing g_X. This can be explained as follows: the thermal potential depends on $n_\chi/n_\chi^{\rm eq}$ and there is resonant χ production when $\Delta m^2/(2E) \simeq V_{\chi\chi}(E)$. In the expanding Universe since E_ν decreases $\Delta m^2/(2E)$ increases, but $V_{\chi\chi}$ can also increase via the production of χ particles and therefore the $n_\chi/n_\chi^{\rm eq}$ ratio. That can allow χ particles to be in resonance for longer and in consequence it enhances the production. We have explicitly checked that indeed for this region of parameter space across a significant fraction of the thermal evolution $V_{\chi\chi} \simeq \Delta m^2/(2E_\nu)$ is fulfilled.

In figure 2, we highlight the parameter space in the m_X-v_Φ plane that opens up as a result of taking into account the χ self-interactions for the gauge case. In grey we highlight regions of parameter space where g_X is not large enough to evade the cosmological bound on $\theta_{\nu\chi}$. We clearly see that the parameter space for $\theta_{\nu\chi} = 0.1$ is very small while for $\theta_{\nu\chi} = 0.01$ substantial parameter space is allowed. We note that this could open up the possibility of detecting χ states in neutrino oscillation experiments as they can be sensitive to $\theta_{\nu\chi} \sim 0.1$, see e.g. [10] for a review. For $\theta_{\nu\chi} \lesssim 10^{-3}$ no new constraint appears and the allowed parameter space shown in figure 4 of [1] remains unchanged.

In the global U(1) version of the model, there is a potential mediated by a $N - \phi$ loop. We will consider $M_N \gg 100\,{\rm MeV}$ and in this regime of parameter space direct calculation shows that[2]

$$V_{\chi\chi} = Y_\Phi^2 \frac{2\pi}{45} \frac{T_\nu^4}{M_N^4} \frac{n_\phi}{n_\phi^{\rm eq}} E_\nu \,, \tag{1.2}$$

where here Y_Φ is the scalar coupling in eq. 3.1 of the main text and we work in the single flavor approximation. We clearly see that this potential is strongly suppressed by the sterile neutrino mass M_N, and that the phenomenology will be determined by Y_Φ and M_N which

[2]Technically speaking a potential mediated by the same interaction could contribute to the gauge version of the model too. However, it will be tiny because the masses of sterile neutrinos in that case are much larger and also it will become exponentially small for $T < m_\rho < M_N$ and therefore it is totally negligible.

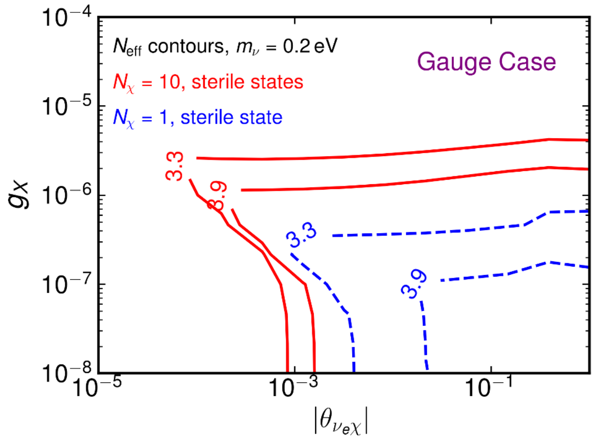

Figure 1. $N_{\rm eff}$ isocontours for $N_\chi = 1$ and $N_\chi = 10$ taking into account self-interactions between the χ states in the early Universe as a function of the $\nu - \chi$ mixing and the $\mathrm{U}(1)_X$ gauge coupling.

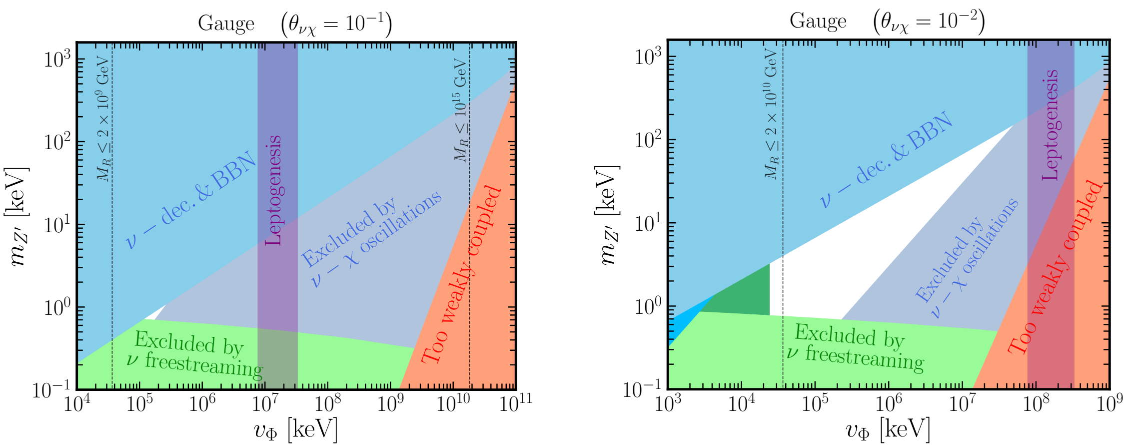

Figure 2. As figure 4 of [1] but for larger $\nu - \chi$ mixing angles, $\theta_{\nu\chi} = 10^{-1}$ and $\theta_{\nu\chi} = 10^{-2}$. The grey region is excluded by the BBN & CMB constraint $N_{\rm eff} < 3.3$ according to figure 1 for the case of $N_\chi = 10$.

are related to v_Φ and $\theta_{\nu\chi}$. It is easy to understand in which regime would this potential suppress the oscillations between ν_L and χ_L in the early Universe and this corresponds to $V_{\chi\chi} > \Gamma_{\rm osc}$ at $T \sim$ MeV. The reason is that since neutrinos decouple at $2-3\,$MeV even if the oscillation rate between them and χ states is large, no χ species will be generated as there are no more collisions in the plasma. By using the relations between M_N, m_ν, and v_Φ of section 3 of [1], we can turn this into a condition for v_ϕ which reads:

$$v_\phi < \mathrm{keV} \left[\frac{\theta_{\nu\chi}}{0.1}\right] \left[\frac{2}{Y_\Phi}\right]^{3/4} \qquad [\text{no}\, N_{\rm eff}\, \text{bound}]\,. \tag{1.3}$$

That is, for v_ϕ smaller than this number, the χ production in the early Universe will be significantly damped and the $N_{\rm eff}$ bound will not apply. By directly solving the appropriate Boltzmann equations we have explicitly checked that this condition depends only very mildly

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on m_ν or N_χ. The question to be addressed is whether this can open up relevant parameter space in the mechanism for mixings $\theta_{\nu\chi} > 10^{-3}$. The answer depends upon the value one chooses for Y_Φ, but this is in turn related to the sterile neutrino mass, $Y_\Phi = \theta_{\nu\chi}\sqrt{m_\nu M_N}/v_\Phi$. In this version of the model, the sterile neutrinos decay efficiently in the early Universe into the dark sector, and therefore in order to comply with $N_{\rm eff}$ bounds $T_{\rm RH} > M_N$. Taking the most plausible scenario with $T_{\rm RH} > 200\,\text{GeV}$ leads to the following constraint

$$v_\phi > \text{keV}\left[\frac{\theta_{\nu\chi}}{0.1}\right]\left[\frac{2}{Y_\Phi}\right] \qquad [M_N > 200\,\text{GeV}]\,. \tag{1.4}$$

We therefore see that these two bounds are conflicting, or in other words, that in the regime of parameter space where the potential in eq. (1.2) could be phenomenologically relevant, the plasma would be actually filled with a thermal bath of ϕ and χ states already and this is excluded by both BBN and the CMB.

2 Impact of exponential χ production on BBN constraints on $N_{\rm eff}$

In section 5 of [1] we discussed the constraint on neutrino interactions with the dark mediator as its decay would produce an initial abundance of χ before BBN. However in the published version it was not mentioned that, in the gauge case, the χ states can also be produced and reach equilibrium with neutrinos before BBN via the process $\nu\chi \to \chi\chi$, provided an initial primordial population of χ is present.[3] Though the initial abundance of χ is very very small, it experiences an exponential growth [11, 12]. For this not to happen before BBN, we require

$$\langle\Gamma(\nu\chi \to \chi\chi)\rangle \lesssim H(T = 0.7\,\text{MeV})\,, \tag{2.1}$$

setting an upper bound on the gauge coupling,

$$g_X \lesssim 1.1 \times 10^{-3}\left(\frac{10^{-3}}{\theta_{\nu\chi}}\right)^{\frac{1}{2}}. \tag{2.2}$$

This bound does not significantly affect the allowed parameter space for $\theta_{\nu\chi} \gtrsim 10^{-3}$, but removes part of the (already small) allowed region for $\theta_{\nu\chi} = 10^{-4}$.

Acknowledgments

We are very grateful to Toshi Ota, Enrique Fernandez Martinez and Pilar Coloma for pointing out the relevance of χ self-interactions in the gauge U(1) case. We are also very grateful to Xiaoyong Chu for pointing out the potential relevance of exponential production of χ particles prior to BBN. This project has received support from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 860881-HIDDeN. The work of JTC is supported by the Ministerio de Ciencia e Innovación under FPI contract PRE2019-089992 of the SEV-2015-0548 grant.

[3] This effect is absent in the global case, as there is no direct coupling of the scalars to two χ particles, see eq. (3.15c) of [1].

References

[1] M. Escudero, T. Schwetz and J. Terol-Calvo, *A seesaw model for large neutrino masses in concordance with cosmology*, JHEP **02** (2023) 142 [arXiv:2211.01729] [INSPIRE].

[2] H.A. Weldon, *Effective Fermion Masses of Order gT in High Temperature Gauge Theories with Exact Chiral Invariance*, Phys. Rev. D **26** (1982) 2789 [INSPIRE].

[3] B. Dasgupta and J. Kopp, *Cosmologically Safe eV-Scale Sterile Neutrinos and Improved Dark Matter Structure*, Phys. Rev. Lett. **112** (2014) 031803 [arXiv:1310.6337] [INSPIRE].

[4] X. Chu, B. Dasgupta and J. Kopp, *Sterile neutrinos with secret interactions—lasting friendship with cosmology*, JCAP **10** (2015) 011 [arXiv:1505.02795] [INSPIRE].

[5] D. Notzold and G. Raffelt, *Neutrino dispersion at finite temperature and density*, Nucl. Phys. B **307** (1988) 924 [INSPIRE].

[6] M. Escudero, J. Lopez-Pavon, N. Rius and S. Sandner, *Relaxing Cosmological Neutrino Mass Bounds with Unstable Neutrinos*, JHEP **12** (2020) 119 [arXiv:2007.04994] [INSPIRE].

[7] M. Escudero, *Neutrino decoupling beyond the Standard Model: CMB constraints on the Dark Matter mass with a fast and precise $N_{\rm eff}$ evaluation*, JCAP **02** (2019) 007 [arXiv:1812.05605] [INSPIRE].

[8] M. Escudero Abenza, *Precision early universe thermodynamics made simple: $N_{\rm eff}$ and neutrino decoupling in the Standard Model and beyond*, JCAP **05** (2020) 048 [arXiv:2001.04466] [INSPIRE].

[9] K. Abazajian, *Production and evolution of perturbations of sterile neutrino dark matter*, Phys. Rev. D **73** (2006) 063506 [astro-ph/0511630] [INSPIRE].

[10] S. Böser et al., *Status of Light Sterile Neutrino Searches*, Prog. Part. Nucl. Phys. **111** (2020) 103736 [arXiv:1906.01739] [INSPIRE].

[11] T. Bringmann et al., *Dark Matter from Exponential Growth*, Phys. Rev. Lett. **127** (2021) 191802 [arXiv:2103.16572] [INSPIRE].

[12] T. Bringmann et al., *Minimal sterile neutrino dark matter*, Phys. Rev. D **107** (2023) L071702 [arXiv:2206.10630] [INSPIRE].

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