

Viable secret neutrino interactions with ultralight dark matter

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ABSTRACT

Several anomalies in neutrino oscillation experiments point to the existence of a ~ 1 eV sterile neutrino ν_s mixing with ν_e at the level of $U_{e4} \cong 0.1$, but such a neutrino is strongly disfavored by constraints on additional light degrees of freedom (δN_{eff}) and total neutrino mass ($\sum_\nu m_\nu$) from cosmology. “Secret neutrino interactions” that have been invoked to suppress the cosmological production of ν_s typically falter, but recently it was pointed out that ν_s could get a large mass in the early universe by coupling to ultralight dark matter ϕ , which can robustly suppress its production. The model has essentially two free parameters: m_ϕ , and $m_{s,0}$, the mass of the sterile neutrino at early times, enhanced by its coupling to ϕ . I determine the parameter regions allowed by limits on δN_{eff} and $\sum_\nu m_\nu$ from the cosmic microwave background and big bang nucleosynthesis, using a simplified yet accurate treatment of neutrino oscillations in the early universe. This mechanism could have an important impact on laboratory experiments that suggest oscillations with sterile neutrinos.

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1. Introduction

Short baseline (SBL) neutrino oscillation experiments at nuclear reactors suggest at 3σ an eV-scale sterile neutrino ν_s that mixes with ν_e [1–5]. A persistent deficit of low-energy solar ν_e flux in gallium experiments lends support to this interpretation. The NEOS [6] and DANSS [7] experiments that also search for ν_e - ν_s oscillations observe features that could be consistent with the SBL anomalies, though are not yet conclusive. Recent fits to the data favor a mass $m_4 = 1.1$ eV and mixing matrix element $U_{e4} = 0.11$ [8]. Moreover there are hints from other experiments, LSND [9] and MiniBooNE [10], of $\nu_\mu \rightarrow \nu_e$ oscillations via a sterile neutrino with similar mass and mixing parameters. The sterile neutrino interpretation of $\nu_\mu \rightarrow \nu_e$ is clouded by constraints on ν_μ - ν_s oscillations from MINOS [11] and IceCube [12,13]. In this work I focus on the simpler ν_e - ν_s scenario that could explain the SBL deficits. The KATRIN experiment will provide an independent probe in the near future [14].

A generic challenge to the existence of sterile neutrinos in the indicated mass and mixing range are their oscillations in the early universe that would fully equilibrate the sterile species [15–17]. This is strongly excluded by big bang nucleosynthesis (BBN) and cosmic microwave background (CMB) constraints on additional effective neutrino species, δN_{eff} , as well as the sum of neutrino

masses $\sum m_\nu$. Some means of suppressing oscillations in the early universe while allowing them at the present time is needed.

The use of sterile neutrino interactions to inhibit oscillations has a long history [18–20]. With respect to the current anomalies, refs. [21,22] suggested that self-interactions of the sterile neutrino could impede the oscillations and thereby satisfy the cosmological constraints. This mechanism is referred to as “secret neutrino interactions,” despite the efforts of PRL to censor the name. Subsequent investigation showed that although the self-interactions in this context could prevent ν_4 production until freezeout of the active neutrinos, in accordance with bounds on N_{eff} , at lower temperatures their self-scattering combines with oscillations to convert active neutrinos to ν_4 and violate the CMB bound on $\sum m_\nu$. [23–27]. (An exception is found for self-interactions mediated by a light gauge boson of mass $\lesssim 10$ MeV [28].)

It was recently pointed out that an effective realization of secret interactions is to couple ν_s to ultralight bosonic dark matter ϕ [29]. In that case the scalar behaves as a coherent condensate, that has not yet started oscillating at early times. It can easily give a large mass to ν_s during this epoch, inhibiting the oscillations. Once the Hubble rate drops below m_ϕ , the field oscillates and redshifts with scale factor as $a^{-3/2}$ as the universe expands. Its contribution to m_s quickly disappears, leaving only the bare Lagrangian mass of ~ 1 eV. The “secret interaction” moniker is especially appropriate in this case, since the required coupling of ν_s to ϕ was shown to be exceedingly weak, $\lambda \sim 10^{-23}$. Similar interactions of light dark

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matter to standard model neutrinos were considered with respect to their effects on laboratory neutrino oscillations in refs. [30–33].

This model is quite economical, depending only upon m_ϕ and the ν_s - ϕ coupling λ , assuming ϕ constitutes all of the dark matter (DM) so that its initial amplitude is determined by its relic density. Equivalently, one can trade λ for the new contribution $m_{s,0}$ to the ν_s mass at early times, before ϕ has started to oscillate. The purpose of this note is to determine the allowed parameter space, more quantitatively than was done in ref. [29].

2. Theoretical framework

Considering mixing between ν_s and ν_e only, the neutrino mass matrix is

$$\begin{pmatrix} m_{ee} & m_{es} \\ m_{es} & m_{ss} \end{pmatrix} \quad (1)$$

It is assumed that $m_{ss} \gg m_{ee}$. Then for small mixing one can show that m_{es} is related to the mass eigenvalue $m_4 \sim 1$ eV by

$$m_{es} \cong U_{e4} m_4 \quad (2)$$

Fits to the SBL data favor $m_4 = 1.13 \pm 0.04$, $U_{e4} \in [0.04, 0.13]$ [4]; for definiteness I adopt the central value $m_4 = 1.1$ eV and $U_{e4} = 0.11$ of ref. [8], giving $m_{es} = 0.12$ eV and $m_{ss} \cong m_4$.

The sterile neutrino, taken to be Majorana, couples to bosonic DM via

$$\frac{1}{2} \lambda \bar{\nu}_s \phi \nu_s \quad (3)$$

leading to the effective mass $m_{\text{eff}} = m_{ss} + \lambda \phi$ when DM has a VEV. For ultralight DM, such a VEV is presumed to exist [34,35], assuming some initial value in the early universe, that persists to account for the present relic density. If ϕ is sufficiently weakly coupled, it never thermalizes and remains coherent, behaving like a classical field. Its time dependence in the expanding cosmological background is¹

$$\phi(t) \cong 1.08 \phi_0 \frac{J_{1/4}(m_\phi t)}{(m_\phi t)^{1/4}} \equiv \phi_0 \hat{\phi}(t) \quad (4)$$

during radiation domination (when $a(t) \sim t^{1/2}$). The relevant combination of parameters affecting neutrino oscillations is

$$m_{s,0} = \lambda \phi_0 \quad (5)$$

so that $m_{\text{eff}} = m_{ss} + m_{s,0} \hat{\phi}(t)$.

For $t \gg m_\phi$ (but before matter-radiation equality) it can be shown that $\rho_\phi \cong 0.37 m_\phi^2 \phi_0^2 (m_\phi t)^{-3/2}$. Matching to the present DM density, one finds

$$\phi_0 = 1.0 \times 10^{15} \text{ GeV} \left(\frac{10^{-15} \text{ eV}}{m_\phi} \right)^{1/4} \quad (6)$$

Such a large VEV could arise if ϕ is an axion-like particle, the phase of a complex field $\Phi = |\Phi| e^{i\phi/f_\phi}$, with decay constant $f_\phi > \phi_0$. At early times $\rho_\phi \sim m_\phi^2 \phi_0^2$ would be negligible compared to the energy density of radiation, and ϕ_0 could take random values in the interval $[0, 2\pi f_\phi]$.

3. Production of ν_s

Although a rigorous study of ν_s - ν_e oscillations in the early universe requires solving the Boltzmann equation for the density matrix [36–38], a good approximation can be obtained in a simpler approach, described in refs. [20,39], which in some regimes leads to analytic results.² The method is based upon solving the Schrödinger equation for the two-state system, including an imaginary term $-i\Gamma/2$ in the Hamiltonian representing scattering of ν_e in the plasma, that causes decoherence.

The solution yields the probability for a ν_e to oscillate into ν_s between an arbitrary initial time and a later time t . From this, a rate of ν_s production is derived, and the associated Boltzmann equation can be solved for the ratio of ν_s occupation number relative to that of ν_e , as a function of temperature and neutrino momentum,³

$$R \equiv \frac{n_{\nu_s}}{n_{\nu_e}} = \frac{1}{2} \left(1 - \exp \left[-2 \int_T^{T_i} \left(\frac{\Gamma \sin^2 \theta_m}{HT'} \right) dT' \right] \right). \quad (7)$$

Here θ_m is the mixing angle including matter effects, and the initial temperature T_i can be taken to infinity. The total interaction rate, including elastic scattering, is

$$\Gamma \cong \left(8 + 5 e^{-m_e/T} \right) \frac{7\pi}{216} G_F^2 T^4 p \quad (8)$$

for a ν_e of momentum p [20,41]. The exponential factor approximates the change at low temperatures when electrons have decoupled from the plasma. For relativistic neutrinos,

$$\sin^2 2\theta_m \cong \frac{4m_{es}^2 m_{\text{eff}}^2}{4m_{es}^2 m_{\text{eff}}^2 + (m_{\text{eff}}^2 - m_{ee}^2 + 2V_e p)^2} \quad (9)$$

(recall that $m_{\text{eff}}(t)$ is the total ν_s mass) and

$$V_e \cong \left(2e^{-m_e/T} + \cos^2 \theta_W \right) \frac{14\pi}{90\alpha} \sin^2 \theta_W G_F^2 T^4 p \mp c_1 \left(\frac{2 - y_n}{2 + y_n} \right) \eta_b G_F T^3 \begin{cases} 1, & T \gg m_e \\ 4/11, & T \ll m_e \end{cases} \quad (10)$$

is the thermal self-energy for ν_e or $\bar{\nu}_e$. The second line incorporates effects of the electron and baryon asymmetries, where $c_1 \cong 0.95$, η_b is the baryon-to-photon ratio, and y_n is the neutron to proton ratio as a function of temperature, which I take to be the standard result as shown in ref. [42]. Numerically it turns out to have a negligible effect ($< 0.1\%$) on the following results; hence we can treat ν_e and $\bar{\nu}_e$ on the same footing.

Eq. (9) shows that the mixing angle can become maximal, signaling resonant oscillations, whenever $m_{\text{eff}}^2 - m_{ee}^2 + 2pV_e$ vanishes. This occurs at low temperatures such that $2pV_e \sim G_F^2 T^2 \lesssim m_{ee}^2 \lesssim (0.05 \text{ eV})^2$, i.e., for $T \lesssim 10$ MeV. However because m_{ee} is so small compared to the amplitude of m_{eff} , these resonances are extremely narrow, and have no impact on the following results. We find that it is a good approximation (to 0.1%) to set $m_{ee} = 0$.

The effective number of extra neutrino species produced by the oscillations requires integrating over momentum, weighted by the massless Fermi-Dirac distribution function $f(p)$ for ν_e ,

² The quantitative agreement of the two formalisms was recently demonstrated in ref. [40].

³ The factors of 2, missing in [20], account for the back-reaction from $\nu_s \rightarrow \nu_e$ [40].

¹ The normalization is such that $\hat{\phi}(0) = 1$.

$$\delta N_{\text{eff}}(T) = \frac{\int d^3 p f(p) R(T, p)}{\int d^3 p f(p)} \quad (11)$$

Before numerically evaluating δN_{eff} , an analytic result can be found, in the regime where $m_\phi \lesssim 10^{-14}$ eV, sufficiently small that ϕ does not start oscillating until the integral in eq. (7) has converged. In that case $m_{\text{eff}} \cong m_{s,0}$ can be treated as constant, and m_{es}^2 can be ignored in the denominator. The integral can be evaluated analytically (ignoring the weak T -dependence of g_* in the Hubble rate $H = 1.66\sqrt{g_*} T^2/M_p$), to obtain

$$\delta N_{\text{eff}} \cong \frac{1}{2} \left[1 - \exp \left(- \frac{65\sqrt{7} \alpha^{1/2} G_F M_p m_{\text{es}}^2}{576 s_W (2 + c_W^2)^{1/2} g_*^{1/2} m_{s,0}} \right) \right] \quad (12)$$

where W denotes the Weinberg angle, M_p is the unreduced Planck mass, and $g_* \cong 10.75$ for the parameters of interest. The dependence on T and p is negligible for $T \lesssim 1$ MeV, making it unnecessary to integrate over momenta.

4. BBN constraints

For larger values of m_ϕ , the DM starts oscillating before nucleosynthesis, which tends to activate the neutrino oscillations. This can be compensated by also increasing $m_{s,0}$, but an analytic treatment is no longer possible. One should numerically integrate over T' and p in eqs. (7), (11).

Additionally for BBN, we should distinguish between oscillations that produced a real excess in N_{eff} , occurring before the freezeout temperature $T_f = 3.2$ MeV of ν_e , versus the subsequent oscillations that conserve total neutrino number but convert some ν_e into ν_s . The reduction in ν_e density impacts BBN by changing the $p \leftrightarrow n$ equilibrium. One can account for this by defining an effective $\delta N_{\text{eff}}^{\text{BBN}}$ [16],

$$\delta N_{\text{eff}}^{\text{BBN}} = \frac{4}{7} \left(\frac{4g_* + 7\delta N_{\text{eff}}}{(1 + Y_{\nu_e})^2} - g_* \right) \quad (13)$$

where $g_* = 10.75$ and $Y_{\nu_e} \lesssim 1$ is the relative abundance of ν_e , reduced by oscillations between T_f and nucleosynthesis, $T_n \cong 0.1$ MeV. We estimate Y_{ν_e} by computing the change in δN_{eff} from the temperature interval $[T_f, T_n]$, using eqs. (7), (11).

The treatment (13) is valid when the effect of the oscillations is to deplete the density of ν_e without changing its energy spectrum too dramatically. Such spectral distortions can change the neutron-to-proton ratio and subsequent production of ${}^4\text{He}$ in a way that cannot be simply modeled by a reduction in ν_e density [43].

To check whether it is justified to neglect the spectral distortion effect, I computed the collision terms of the Boltzmann equations for n and p in the region of parameter space, relevant to the BBN constraint, where $R(T, p)$ has the strongest momentum dependence. This occurs along the BBN exclusion contour at its upper right-most extreme, at the lowest temperature ($T = 0.1$ MeV), where $R(T, p)|_{p=xT} \cong 0.1\sqrt{x}$. The thermally averaged value is $\bar{R} = 0.177$. The collision terms in the Boltzmann equation multiplying the neutron and proton densities are respectively

$$\begin{aligned} \frac{\Gamma_n}{c_2} &= \int_0^\infty dx \frac{\rho f(x, y)}{1 + e^{-x-y}} + \int_{(1+\zeta)y}^\infty dx \frac{(1-\rho)f(x, -y)e^{-x+y}}{1 + e^{-x+y}} \\ \frac{\Gamma_p}{c_2} &= \int_0^\infty dx \frac{(1-\rho)e^{-x-y} f(x, y)}{1 + e^{-x-y}} + \int_{(1+\zeta)y}^\infty dx \frac{\rho f(x, -y)}{1 + e^{-x+y}} \end{aligned} \quad (14)$$

where $c_2 = G_F^2(g_\nu^2 + 3g_A^2)T^5$, $\rho = Re^{-x}$, $f(x, y) = x^2(x+y) \times \sqrt{(x+y)^2 + \zeta^2 y^2}$, $y = (\Delta + m_e)/T$, $\Delta = m_n - m_p$ and $\zeta = m_e/\Delta$.

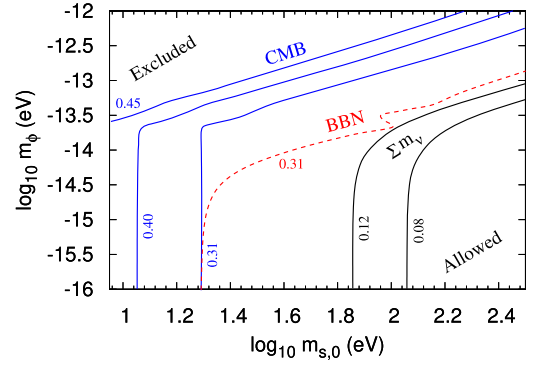


Fig. 1. Contours of δN_{eff} (solid blue for CMB and dashed red for BBN) and corresponding to $\sum m_\nu$ (solid black) in the $m_{s,0}$ - m_ϕ plane, illustrative of cosmological upper limits as described in the text.

In the absence of spectral distortions, the rates are given by $\bar{\Gamma}_{n,p}$ evaluated as in (14) but with $\bar{\rho} = \bar{R}e^{-x}$ in place of ρ . I find that the approximation $\Gamma_{n,p} = \bar{\Gamma}_{n,p}$ is good to (2–3)%, justifying the use of eq. (13) for determining the BBN constraint.

5. CMB constraints

For the CMB constraints, there is an analogous effect from late time $\nu_e \rightarrow \nu_s$ conversions. Even though oscillations occurring after freezeout of ν_e should not change δN_{eff} , they can increase the sum of neutrino masses by converting some ν_e to ν_s . Therefore the extra contribution to $\sum_\nu m_\nu$ can be estimated as m_{ss} times the asymptotic value of δN_{eff} that results at low $T \sim 1$ eV, neglecting the conservation of neutrino number below T_f .

The results are shown in Fig. 1, which displays three contours for δN_{eff} in a region constrained by CMB measurements [44]. The exact upper limit determined by the Planck Collaboration depends upon which data sets are combined. At 95% c.l. $\delta N_{\text{eff}} < 0.5$ is a typical value (using TT+lowE or TT,TE,EE+lowE+lensing+BAO+R18), although a more stringent bound $\delta N_{\text{eff}} < 0.23$ is derived from TT,TE,EE+lowE alone. To illustrate the BBN constraint I show the 2σ limit from ref. [45], which is somewhat weaker than that obtained in ref. [46]. The BBN contour at $\delta N_{\text{eff}} = 0.31$ illustrates the effect of conversions $\nu_e \rightarrow \nu_s$ after ν_e freezeout; for low m_ϕ it coincides with the corresponding CMB δN_{eff} (since no such conversions take place), but at higher m_ϕ , $\delta N_{\text{eff}}^{\text{BBN}}$ is seen to deviate from its CMB counterpart, as expected.

The strongest constraint is the CMB limit on neutrino masses. Their sum goes as

$$\sum m_\nu \cong [0.06 \text{ eV} + m_4 \delta N_{\text{eff}}] \quad (15)$$

taking account of the standard contribution, assuming normal mass hierarchy. Ref. [47] recently constrained $\sum m_\nu < 0.145$ eV for the normal hierarchy, implying $\delta N_{\text{eff}} < 0.08$. This implies a lower limit on $m_{s,0} > 160$ eV, hence $\lambda \gtrsim 10^{-22} \times (m_\phi/10^{-15} \text{ eV})^{1/4}$.

6. Discussion

For DM with $m_\phi \lesssim 10^{-14}$ eV, we have seen that the cosmological analysis is relatively simple, since ν_e has frozen out before ϕ starts to oscillate. A favored value for m_ϕ from considerations of cosmological structure formation is considerably lower, $m_\phi \sim 10^{-22}$ eV. In this regime, the de Broglie wavelength is so large that structure at galactic scales can be suppressed, providing a possible solution to the cusp/core problem of DM halos [34].

Such light DM has an oscillation frequency of order 1y, which could have interesting consequences for laboratory oscillation experiments, if λ is large enough to significantly impact the effective

mass m_{eff} of ν_s during the timescale of the experiment. For example, if the extra contribution to m_{eff} is as large as the bare mass m_4 , one would need $\lambda \sim 10^{-15}$, which is technically natural since there are no significant loop corrections. In this situation, the usual analysis of oscillation data could lead to ambiguous results, since the Δm^2 being fitted would be varying in time. This effect has already been considered with respect to active neutrinos coupling to ϕ in refs. [30–32]. It could be interesting to reconsider the experiments that suggest active-sterile neutrino oscillations in this light. A search for time dependence of the signal has been performed by the Daya Bay collaboration [48].

Note added

After completing this work, I became aware of ref. [49] where the mechanism discussed here was applied to suppressing oscillations of keV-scale sterile neutrinos in the early universe. See also the related references [50,51].

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References

- [1] C. Giunti, M. Laveder, Y.F. Li, Q.Y. Liu, H.W. Long, Update of short-baseline electron neutrino and antineutrino disappearance, *Phys. Rev. D* 86 (2012) 113014, <https://doi.org/10.1103/PhysRevD.86.113014>, arXiv:1210.5715 [hep-ph].
- [2] C. Giunti, M. Laveder, Y.F. Li, H.W. Long, Short-baseline electron neutrino oscillation length after troitsk, *Phys. Rev. D* 87 (1) (2013) 013004, <https://doi.org/10.1103/PhysRevD.87.013004>, arXiv:1212.3805 [hep-ph].
- [3] J. Kopp, P.A.N. Machado, M. Maltoni, T. Schwetz, Sterile neutrino oscillations: the global picture, *J. High Energy Phys.* 1305 (2013) 050, [https://doi.org/10.1007/JHEP05\(2013\)050](https://doi.org/10.1007/JHEP05(2013)050), arXiv:1303.3011 [hep-ph].
- [4] M. Dentler, Á. Hernández-Cabezudo, J. Kopp, P.A.N. Machado, M. Maltoni, I. Martínez-Soler, T. Schwetz, Updated global analysis of neutrino oscillations in the presence of eV-scale sterile neutrinos, *J. High Energy Phys.* 1808 (2018) 010, [https://doi.org/10.1007/JHEP08\(2018\)010](https://doi.org/10.1007/JHEP08(2018)010), arXiv:1803.10661 [hep-ph].
- [5] A. Diaz, C.A. Argüelles, G.H. Collin, J.M. Conrad, M.H. Shaevitz, Where are we with light sterile neutrinos?, arXiv:1906.00045 [hep-ex].
- [6] Y.J. Ko, et al., NEOS Collaboration, Sterile neutrino search at the NEOS experiment, *Phys. Rev. Lett.* 118 (12) (2017) 121802, <https://doi.org/10.1103/PhysRevLett.118.121802>, arXiv:1610.05134 [hep-ex].
- [7] I. Alekseev, et al., DANSS Collaboration, Search for sterile neutrinos at the DANSS experiment, *Phys. Lett. B* 787 (2018) 56, <https://doi.org/10.1016/j.physletb.2018.10.038>, arXiv:1804.04046 [hep-ex].
- [8] J. Kostensalo, J. Suhonen, C. Giunti, P.C. Srivastava, The gallium anomaly revisited, *Phys. Lett. B* 795 (2019) 542, <https://doi.org/10.1016/j.physletb.2019.06.057>, arXiv:1906.10980 [nucl-th].
- [9] A. Aguilar-Arevalo, et al., LSND Collaboration, Evidence for neutrino oscillations from the observation of anti-neutrino(electron) appearance in a anti-neutrino(muon) beam, *Phys. Rev. D* 64 (2001) 112007, <https://doi.org/10.1103/PhysRevD.64.112007>, arXiv:hep-ex/0104049.
- [10] A.A. Aguilar-Arevalo, et al., MiniBooNE Collaboration, Significant excess of ElectronLike events in the MiniBooNE short-baseline neutrino experiment, *Phys. Rev. Lett.* 121 (22) (2018) 221801, <https://doi.org/10.1103/PhysRevLett.121.221801>, arXiv:1805.12028 [hep-ex].
- [11] P. Adamson, et al., MINOS + Collaboration, *Phys. Rev. Lett.* 122 (9) (2019) 091803, <https://doi.org/10.1103/PhysRevLett.122.091803>, arXiv:1710.06488 [hep-ex].
- [12] M.G. Aartsen, et al., IceCube Collaboration, Search for sterile neutrino mixing using three years of IceCube DeepCore data, *Phys. Rev. D* 95 (11) (2017) 112002, <https://doi.org/10.1103/PhysRevD.95.112002>, arXiv:1702.05160 [hep-ex].
- [13] B.J.P. Jones, IceCube Collaboration, IceCube sterile neutrino searches, EPJ Web Conf. 207 (2019) 04005, <https://doi.org/10.1051/epjconf/201920704005>, arXiv:1902.06185 [hep-ex].
- [14] A. Esmaili, O.L.G. Peres, KATRIN sensitivity to sterile neutrino mass in the shadow of lightest neutrino mass, *Phys. Rev. D* 85 (2012) 117301, <https://doi.org/10.1103/PhysRevD.85.117301>, arXiv:1203.2632 [hep-ph].
- [15] K. Enqvist, K. Kainulainen, M.J. Thomson, *Nucl. Phys. B* 373 (1992) 498, [https://doi.org/10.1016/0550-3213\(92\)90442-E](https://doi.org/10.1016/0550-3213(92)90442-E).
- [16] A.D. Dolgov, F.L. Villante, BBN bounds on active sterile neutrino mixing, *Nucl. Phys. B* 679 (2004) 261, <https://doi.org/10.1016/j.nuclphysb.2003.11.031>, arXiv:hep-ph/0308083.
- [17] S. Gariazzo, P.F. de Salas, S. Pastor, Thermalisation of sterile neutrinos in the early Universe in the 3+1 scheme with full mixing matrix, *J. Cosmol. Astropart. Phys.* 1907 (07) (2019) 014, <https://doi.org/10.1088/1475-7516/2019/07/014>, arXiv:1905.11290 [astro-ph.CO].
- [18] K.S. Babu, I.Z. Rothstein, Relaxing nucleosynthesis bounds on sterile-neutrinos, *Phys. Lett. B* 275 (1992) 112, [https://doi.org/10.1016/0370-2693\(92\)90860-7](https://doi.org/10.1016/0370-2693(92)90860-7).
- [19] K. Enqvist, K. Kainulainen, M.J. Thomson, Cosmological bounds on Dirac-Majorana neutrinos, *Phys. Lett. B* 280 (1992) 245, [https://doi.org/10.1016/0370-2693\(92\)90062-9](https://doi.org/10.1016/0370-2693(92)90062-9).
- [20] J.M. Cline, Constraints on almost Dirac neutrinos from neutrino - anti-neutrino oscillations, *Phys. Rev. Lett.* 68 (1992) 3137, <https://doi.org/10.1103/PhysRevLett.68.3137>.
- [21] S. Hannestad, R.S. Hansen, T. Tram, How self-interactions can reconcile sterile neutrinos with cosmology, *Phys. Rev. Lett.* 112 (3) (2014) 031802, <https://doi.org/10.1103/PhysRevLett.112.031802>, arXiv:1310.5926 [astro-ph.CO].
- [22] B. Dasgupta, J. Kopp, Cosmologically safe eV-scale sterile neutrinos and improved dark matter structure, *Phys. Rev. Lett.* 112 (3) (2014) 031803, <https://doi.org/10.1103/PhysRevLett.112.031803>, arXiv:1310.6337 [hep-ph].
- [23] N. Saviano, O. Pisanti, G. Mangano, A. Mirizzi, Unveiling secret interactions among sterile neutrinos with big-bang nucleosynthesis, *Phys. Rev. D* 90 (11) (2014) 113009, <https://doi.org/10.1103/PhysRevD.90.113009>, arXiv:1409.1680 [astro-ph.CO].
- [24] J.F. Cherry, A. Friedland, I.M. Shoemaker, Short-baseline neutrino oscillations, Planck, and IceCube, arXiv:1605.06506 [hep-ph].
- [25] F. Forastieri, M. Lattanzi, G. Mangano, A. Mirizzi, P. Natoli, N. Saviano, Cosmic microwave background constraints on secret interactions among sterile neutrinos, *J. Cosmol. Astropart. Phys.* 1707 (07) (2017) 038, <https://doi.org/10.1088/1475-7516/2017/07/038>, arXiv:1704.00626 [astro-ph.CO].
- [26] X. Chu, B. Dasgupta, M. Dentler, J. Kopp, N. Saviano, Sterile neutrinos with secret interactions—cosmological discord?, *J. Cosmol. Astropart. Phys.* 1811 (11) (2018) 049, <https://doi.org/10.1088/1475-7516/2018/11/049>, arXiv:1806.10629 [hep-ph].
- [27] N. Song, M.C. Gonzalez-Garcia, J. Salvado, Cosmological constraints with self-interacting sterile neutrinos, *J. Cosmol. Astropart. Phys.* 1810 (10) (2018) 055, <https://doi.org/10.1088/1475-7516/2018/10/055>, arXiv:1805.08218 [astro-ph.CO].
- [28] A. Mirizzi, G. Mangano, O. Pisanti, N. Saviano, Collisional production of sterile neutrinos via secret interactions and cosmological implications, *Phys. Rev. D* 91 (2) (2015) 025019, <https://doi.org/10.1103/PhysRevD.91.025019>, arXiv:1410.1385 [hep-ph].
- [29] Y. Farzan, Ultra-light scalar saving the 3+1 neutrino scheme from the cosmological bounds, arXiv:1907.04271 [hep-ph].
- [30] A. Berlin, *Phys. Rev. Lett.* 117 (23) (2016) 231801, <https://doi.org/10.1103/PhysRevLett.117.231801>, arXiv:1608.01307 [hep-ph].
- [31] G. Krnjaic, P.A.N. Machado, L. Necib, Distorted neutrino oscillations from time varying cosmic fields, *Phys. Rev. D* 97 (7) (2018) 075017, <https://doi.org/10.1103/PhysRevD.97.075017>, arXiv:1705.06740 [hep-ph].
- [32] V. Brdar, J. Kopp, J. Liu, P. Prass, X.P. Wang, Fuzzy dark matter and non-standard neutrino interactions, *Phys. Rev. D* 97 (4) (2018) 043001, <https://doi.org/10.1103/PhysRevD.97.043001>, arXiv:1705.09455 [hep-ph].
- [33] J. Liao, D. Marfatia, K. Whisnant, Light scalar dark matter at neutrino oscillation experiments, *J. High Energy Phys.* 1804 (2018) 136, [https://doi.org/10.1007/JHEP04\(2018\)136](https://doi.org/10.1007/JHEP04(2018)136), arXiv:1803.01773 [hep-ph].
- [34] W. Hu, R. Barkana, A. Gruzinov, Cold and fuzzy dark matter, *Phys. Rev. Lett.* 85 (2000) 1158, <https://doi.org/10.1103/PhysRevLett.85.1158>, arXiv:astro-ph/0003365.
- [35] L. Hui, J.P. Ostriker, S. Tremaine, E. Witten, Ultralight scalars as cosmological dark matter, *Phys. Rev. D* 95 (4) (2017) 043541, <https://doi.org/10.1103/PhysRevD.95.043541>, arXiv:1610.08297 [astro-ph.CO].
- [36] L. Stodolsky, On the treatment of neutrino oscillations in a thermal environment, *Phys. Rev. D* 36 (1987) 2273, <https://doi.org/10.1103/PhysRevD.36.2273>.
- [37] K. Enqvist, K. Kainulainen, J. Maalampi, Refraction and oscillations of neutrinos in the early universe, *Nucl. Phys. B* 349 (1991) 754, [https://doi.org/10.1016/0550-3213\(91\)90397-G](https://doi.org/10.1016/0550-3213(91)90397-G).
- [38] G. Sigl, G. Raffelt, General kinetic description of relativistic mixed neutrinos, *Nucl. Phys. B* 406 (1993) 423, [https://doi.org/10.1016/0550-3213\(93\)90175-O](https://doi.org/10.1016/0550-3213(93)90175-O).
- [39] K. Kainulainen, Light singlet neutrinos and the primordial nucleosynthesis, *Phys. Lett. B* 244 (1990) 191, [https://doi.org/10.1016/0370-2693\(90\)90054-A](https://doi.org/10.1016/0370-2693(90)90054-A).
- [40] T. Bringmann, J.M. Cline, J.M. Cornell, Baryogenesis from neutron-dark matter oscillations, *Phys. Rev. D* 99 (3) (2019) 035024, <https://doi.org/10.1103/PhysRevD.99.035024>, arXiv:1810.08215 [hep-ph].
- [41] D. Notzold, G. Raffelt, Neutrino dispersion at finite temperature and density, *Nucl. Phys. B* 307 (1988) 924, [https://doi.org/10.1016/0550-3213\(88\)90113-7](https://doi.org/10.1016/0550-3213(88)90113-7).
- [42] E.W. Kolb, M.S. Turner, *The early universe*, *Front. Phys.* 69 (1990) 1.

- [43] D.P. Kirilova, M.V. Chizhov, Cosmological nucleosynthesis and active sterile neutrino oscillations with small mass differences: the nonresonant case, *Phys. Rev. D* 58 (1998) 073004, <https://doi.org/10.1103/PhysRevD.58.073004>, arXiv: hep-ph/9707282.
- [44] N. Aghanim, et al., Planck Collaboration, Planck 2018 results. VI. Cosmological parameters, arXiv:1807.06209 [astro-ph.CO].
- [45] M. Hufnagel, K. Schmidt-Hoberg, S. Wild, BBN constraints on MeV-scale dark sectors. Part I. Sterile decays, *J. Cosmol. Astropart. Phys.* 1802 (2018) 044, <https://doi.org/10.1088/1475-7516/2018/02/044>, arXiv:1712.03972 [hep-ph].
- [46] R.H. Cyburt, B.D. Fields, K.A. Olive, T.H. Yeh, Big bang nucleosynthesis: 2015, *Rev. Mod. Phys.* 88 (2016) 015004, <https://doi.org/10.1103/RevModPhys.88.015004>, arXiv:1505.01076 [astro-ph.CO].
- [47] S. Roy Choudhury, S. Hannestad, Updated results on neutrino mass and mass hierarchy from cosmology, arXiv:1907.12598 [astro-ph.CO].
- [48] D. Adey, et al., Daya Bay Collaboration, Search for a time-varying electron antineutrino signal at Daya Bay, *Phys. Rev. D* 98 (9) (2018) 092013, <https://doi.org/10.1103/PhysRevD.98.092013>, arXiv:1809.04660 [hep-ex].
- [49] F. Bezrukov, A. Chudaykin, D. Gorbunov, Hiding an elephant: heavy sterile neutrino with large mixing angle does not contradict cosmology, *J. Cosmol. Astropart. Phys.* 1706 (2017) 051, <https://doi.org/10.1088/1475-7516/2017/06/051>, arXiv:1705.02184 [hep-ph].
- [50] F. Bezrukov, A. Chudaykin, D. Gorbunov, Induced resonance makes light sterile neutrino dark matter cool, *Phys. Rev. D* 99 (8) (2019) 083507, <https://doi.org/10.1103/PhysRevD.99.083507>, arXiv:1809.09123 [hep-ph].
- [51] F. Bezrukov, A. Chudaykin, D. Gorbunov, Scalar induced resonant sterile neutrino production in the early Universe, arXiv:1911.08502 [hep-ph].