Sterile neutrinos, dark matter, and resonant effects in ultra high energy regimes

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Abstract

The interest in light dark matter candidates has recently increased in literature; in many of these studies additional neutrinos, either active or sterile, appear. On the other hand, the study of sterile neutrinos has been growing due to different theoretical and phenomenological motivations. We study in this work the potential of these models to induce a resonant oscillation effect due to an interaction potential between active or sterile neutrinos and dark matter candidates. This picture has the attractive characteristic that connects two elusive sectors and might give a positive signal if future ultra high energy neutrino fluxes can be measured.
It is well known that neutrinos propagating through a material medium suffer an enhancement effect in the oscillation probability, the so called MSW effect [1]. The standard MSW effect takes into account the interaction of active neutrinos with electrons and quarks. Sterile neutrino oscillations have also been considered in literature: as an explanation for the reactor neutrino anomaly [2] and the LSND and Miniboone experiments [3], or in the context of big bang nucleosynthesis [4–9]. Sterile neutrinos also appear in models that try to explain the dark matter problem, either as the main responsible for the dark matter content or as an additional particle that forms part of a complete model. Couplings between such neutrino (either active or sterile) and other dark matter components have also been studied [10–18].

Here we propose that, if there is a mixing between active and sterile neutrinos, astrophysical neutrinos interacting with dark matter may suffer a similar MSW effect when they propagate in a dark matter medium. We consider that, if there is an interaction of sterile neutrinos with dark matter, there would be a potential that might induce a resonant effect, just in the same way as active neutrinos are affected by the interaction with electrons. We discuss how this effect could strongly modify the expected flux of high energy astrophysical neutrinos. In particular, for the pseudo-Dirac case, recently studied in the context of GRB neutrinos [31], such a resonant effect could appear for ultra high energy (UHE) neutrinos arriving from any neutrino source outside our galaxy.

We start our analysis by showing the neutrino evolution equation considering both ordinary and dark matter potentials. We study a simplified picture with one sterile neutrino, $\nu_s$, and an active neutrino, $\nu_{\alpha=e,\mu,\tau}$. For a neutrino energy, $E$, the evolution equation can be written as

$$i\frac{d}{dt}\begin{pmatrix} \nu_\alpha \\ \nu_s \end{pmatrix} = \frac{1}{4E} M_\alpha \begin{pmatrix} \nu_\alpha \\ \nu_s \end{pmatrix},$$  

where,

$$M_\alpha = \begin{pmatrix} -\Delta m_{i4}^2 \cos 2\theta + V_{\nu_\alpha f} + V_{\nu_\alpha \chi} & \Delta m_{i4}^2 \sin 2\theta \\ \Delta m_{i4}^2 \sin 2\theta & \Delta m_{i4}^2 \cos 2\theta + V_{\nu_\alpha \chi} \end{pmatrix},$$  

where $\Delta m_{i4}^2 = m_i^2 - m_4^2$, for $i = 1, 2, 3$, and the angle, $\theta$, is the vacuum mixing angle between
the sterile neutrino and an active neutrino; \( V_{\nu_{\alpha}f} = V_{\nu_{\alpha}f}^{CC} + V_{\nu_{\alpha}f}^{NC} \), accounts for the well known interaction potential of the active neutrino with ordinary fermions; \( V_{\nu_{\alpha}X} \) takes into account the potential due to a possible interaction between active neutrinos and dark matter. We also study in this work the effect of the potential \( V_{\nu_{\alpha}X} \), coming from the interaction of sterile neutrinos with dark matter. This interaction appears naturally in different extensions of the Standard Model, where many dark particles, including sterile neutrinos, could populate the dark sector and interact among themselves \([17–19]\).

The resonance condition derived from Eq. (1) is then given by

\[
\Delta m^2_{i4} \cos 2\theta = 2E(V_{\nu_{\alpha}f} + V_{\nu_{\alpha}X} - V_{\nu_{s}X}).
\] (3)

We can write these potentials as follows:

\[
V_{\nu_{\alpha}f} = \frac{1}{4} \frac{g^2}{m_W^2} (N_{\alpha} - N_{n}/2) = \sqrt{2}G_F(N_{\alpha} - N_{n}/2);
\] (4)

\[
V_{\nu_{\alpha}X} \sim \frac{g_{\nu_{\alpha}G_F}N_{\chi}}{m_I^2} = G'_{\nu_{\alpha}}N_{\chi} = \varepsilon_{\nu_{\alpha}X}G_FN_{\chi};
\] (5)

\[
V_{\nu_{s}X} \sim \frac{g_{\nu_{s}G_F}N_{\chi}}{m_I^2} = G'_{\nu_{s}}N_{\chi} = \varepsilon_{\nu_{s}X}G_FN_{\chi}.
\] (6)

Here, \( N_{\alpha} \) is the number density of leptons, \( N_{n} \) the number density of neutrons, and \( N_{\chi} \) the number density of dark matter particles interacting with the neutrinos. \( g \) is the Standard Model coupling constant and \( m_W \) is the W boson mass; on the other hand \( g_{\nu_{\alpha}}, g_{\nu_{s}}, \) and \( g_{\chi} \) represent the coupling constant of the corresponding particle (active neutrino, sterile neutrino, and dark matter particles, respectively) with an intermediate gauge boson with mass \( m_I \). The parameters \( \varepsilon_{\nu_{\alpha,s\chi}} \) account for the coupling strength in terms of the Fermi constant \( G_F \).

Using the above expressions for the potentials the resonance condition can be written as

\[
\Delta m^2_{i4} \cos 2\theta = 2E_GF[\sqrt{2}(N_{\alpha} - N_{n}/2) + (\varepsilon_{\nu_{\alpha}X} - \varepsilon_{\nu_{s}X})N_{\chi}].
\] (7)

In order to estimate the dark matter density, \( N_{\chi} \), we consider that the main contribution comes from a single heavy dark matter particle with mass \( m_{\chi} \) and, therefore, the relevant density in our case will take the value \( N_{\chi} = \rho_{\chi}/m_{\chi} \) \([41]\). In order to have an estimate for \( \varepsilon_{\nu_{\alpha,s\chi}} \) it could be useful to study in more detail the coupling constants, \( g_{\nu_{\alpha}} \) and \( g_{\chi} \). Recently, the interest in models with an intermediary boson with a relatively light mass \( m_I \) has grown, specially in the context of the dark matter problem \([11–16]\). We show in Table II
We now turn our attention to the search for physical processes that could be sensitive to the effects of this neutrino potential, since it would give a signal of the interaction between two hidden sectors: the sterile neutrino sector and the dark matter one. Notice that the mixing parameters between sterile and active neutrinos have been constrained by studying primordial big bang nucleosynthesis \[4–9\], where the production rate of sterile neutrinos is given by the interaction rate of ordinary neutrinos multiplied by the oscillation probability to sterile neutrinos, \( \Gamma_{\nu_s} = (\langle P_{\nu_{\alpha} \rightarrow \nu_s} \rangle) \Gamma_{\nu_\alpha} \). Moreover, the conversion probability, \( \langle P_{\nu_{\alpha} \rightarrow \nu_s} \rangle \), depends on the interaction potential of neutrinos that has been calculated by considering the interaction of active and sterile neutrinos with the ordinary matter and is given by \( V = \sqrt{2} G_F N_\gamma \left( L - A \frac{T^2}{M_W} \right) \), where \( N_\gamma \) is the photon number density, \( L \) accounts for the fermion asymmetry and \( A \) is a numerical factor as can be found in \[3\]. In principle, the contribution of the interaction between sterile neutrinos and a dark matter component could be of interest in this context. A similar situation could happen for the supernova case \[20\].

Another place to search for an effect of this neutrino potential could be the UHE regime \[21–23\]. There are several constraints on the UHE neutrino flux from Icecube \[24\], Auger \[25\], and ANTARES \[26\]. Recently, Icecube has detected two neutrino events in the energy range of PeV \[27\]; in the near future, with the accumulation of data from IceCube (with energies around \( 10^{15} \text{eV} \)) and Auger (with a threshold just above \( 10^{17} \text{eV} \)) and KM3Net, we would have a better understanding of the galactic and extragalactic neutrino spectrum. The up to now negative results on UHE neutrino detection have stimulated the

| Ref | \( \frac{(g_{\chi})(g_{\nu})}{(m_f/\text{MeV})^2} \) | \( \varepsilon_{\nu_e \chi} \) | \( \varepsilon_{\nu_s \chi} \) | \( m_\chi \) (eV) |
|-----|------------------------------------|----------------|----------------|----------------|
| Aarssen et. al. \[11\] | \( \frac{(0.7)(10^{-0} - 10^{-1})}{10^{-2} - 10^0} \) | 0 | \( 10^5 \) – \( 10^{15} \) | \( 10^{12} \) |
| Mirror \[17, 18\] | \( \frac{(1)(1)}{(30 M_W)^2} \) | 0 | \( 10^{-3} \) | \( 10^9 \) |
| Fayet \[13, 14\] | \( < \frac{10^{-6}}{(10^3)^2} \) | \( < 10^5 \) | 0 | \( 10^7 \) |
| Mangano et. al. \[12\] | \( < \frac{10^{-3}}{10^7} \) | \( < 10^8 \) | 0 | \( 10^7 \) |

TABLE I: Coupling constants and mass estimates from different models.
FIG. 1: Resonance isocurves for the case of a pseudo-Dirac (anti)neutrino in the $\Delta m^2 = 10^{-12} - 10^{-18}$ eV$^2$ region for the case of a dark matter density value consisted with the estimates for our galaxy. We show in our plots two different models considered in the literature, those of Fayet [13, 14] (dark blue box) and Aarssen et al [11] (light blue box). The dark matter density value was considered as to coincide with the estimate for the halo region ($\rho_\chi = 0.3$ GeV cm$^{-3}$). We compute our results for two different neutrino energies, $E = 10^{18}$ eV (left panel), and $E = 10^{15}$ eV (right panel).

In this context, we would like to study whether our neutrino potential could have a resonance in the UHE region that could possibly be seen in the future. Notice that, if the future experiments collect enough neutrino data, it might be expected to observe a hint for a distortion in the UHE neutrino spectrum.

In order to show the regions where a resonance can take place, we compute the values of $\Delta m^2$, $\varepsilon_T = |(\varepsilon_{\nu_\alpha \chi} - \varepsilon_{\bar{\nu}_\alpha \chi})|$, and $m_\chi$ that, according to Eq. (7), induce such an effect. We present our results in the parameter space $\varepsilon_T$ vs $m_\chi$, for different values of $\Delta m^2$; as a first approximation we take $\theta \approx 0$. Notice that the difference $(\varepsilon_{\nu_\alpha \chi} - \varepsilon_{\bar{\nu}_\alpha \chi})$ change sign depending on wether we consider a coupling with sterile or with active neutrinos; therefore, depending on the type of coupling, the resonance condition is valid only for neutrinos (for $\varepsilon_{\nu_\alpha \chi} \neq 0$) or for antineutrinos (for $\varepsilon_{\bar{\nu}_\alpha \chi} \neq 0$).

We have done an analysis considering the dark matter around our galactic halo. In this case we have considered the electron potential $V_e = 5 \times 10^{-39}$ eV [38] and, consequently,
FIG. 2: Left panel: resonance isocurves of $\Delta m^2 = 10^6, 1, 10^{-6}$ eV$^2$ for the case of an electron (anti)neutrino with energy $E = 10^{18}$ eV. We also plot the pseudo-Dirac region $\Delta m^2 = 10^{-12} - 10^{-18}$ eV$^2$ (tilted magenta band). The dark matter density was considered as that expected for an AGN ($\rho_\chi = 7440$ GeV cm$^{-3}$). We also show regions of estimated coupling and dark matter mass for two different models considered in the literature, those of Fayet [13, 14] (dark blue box) and Aarssen et al [11] (light blue box). Finally, we show the region of the recent hints for a 10 GeV dark matter candidate. In the right panel we show the isocurves for the muon or tau antineutrino case, the values of dark matter density and neutrino energy are the same as for the left panel.

$N_\epsilon = 3 \times 10^{-6}$ eV$^3$. In the galactic halo is expected that $\rho_\chi = 0.3$ GeV · cm$^{-3}$. We compute our result for different values of $\Delta m^2$; in particular, we show a tilted band that corresponds to the region $\Delta m^2 = 10^{-12} - 10^{-18}$ eV$^2$, that is, to the pseudo-Dirac case, studied in a similar context before, although for just-so oscillations [31]. The left panel is computed for a neutrino energy of $10^{18}$ eV, while the right one is for an energy of $10^{15}$ eV. In the same plot we show the region of parameters $\varepsilon_T - m_\chi$ that is obtained from the work of Aarssen et al [11] (light box). These authors have discussed the possibility of an interaction between dark matter and neutrinos in order to address ΛCDM small-scale problems; the sterile neutrino case was also discussed in that work. We consider the couplings discussed there as a guidance for a sterile neutrino coupling with dark matter. On the other hand, for the interaction between active neutrinos and dark matter, there are constraints on the strength of such interaction; we show in the plot the constraint given in Ref. [13, 14]. As it should be expected, the higher the mass of the dark matter candidate, the higher the coupling needed to have a resonant effect. We can notice from Fig. 11 that there is an overlap between the pseudo-Dirac mass difference region and the region of parameters...
obtained from the couplings discussed by Aarssen et. al. while for the case of the constraints for a light dark matter candidate, there are values of $\varepsilon_T$ that are allowed. It is interesting to note that the pseudo-Dirac mass difference could have a resonance for certain values of its coupling to a dark matter candidate, specially because it has already been noticed that a just-so oscillation could lead an UHE neutrino deficit. Although the original proposal may suffer the need of a fine tuning, if the resonance discussed here happen in nature, the suppression mechanism could be considered as a more natural effect. It is also interesting to note that, if the dark matter surrounding our galaxy induces such a resonance effect there could be an energy region where neutrino conversion to sterile would make the local neutrino flux to vanish, independently of the nature of the neutrino source (as long as the source is extragalactic).

We have also computed the resonance condition in the neighborhood of an AGN, although this case is less likely for a pseudo-Dirac neutrino picture, since in this case the oscillation length is much larger than the AGN radius. Still, this oscillation length will be reduced for higher neutrino mass differences. We consider that, in an astrophysical environment, $N_n = 2N_e$ and $N_\mu = N_\tau = 0$; in particular, for an AGN, we will use $V_e = 1 \times 10^{-27}$ eV, $N_e = V_e/\sqrt{2}G_F = 6 \times 10^{-5}$ eV $^3$; and $\rho_\chi \approx 200 M_\odot pc^{-3} = 7.44 \times 10^3$ GeV $\cdot$ cm$^{-3}$. We show our results in Fig. 2. We compute our result for different values of $\Delta m^2$, namely, $10^6$, $10^0$, and $10^{-6}$ eV $^2$. We plot, in the left panel of Fig. 2 a tilted magenta band that shows the region $\Delta m^2 = 10^{-12} - 10^{-18}$ eV $^2$ that corresponds to the pseudo-Dirac case. Besides showing the same light and dark boxes as in the previous case, we also show, with a vertical region, the value corresponding to the recent reported hint on evidence of a dark matter candidate around 10 GeV. Notice that the left plot is computed for the case of an electron neutrino (or an electron antineutrino if $\varepsilon_{\nu_\chi} \neq 0$) while the right one is for the muon and tau neutrino case (or a muon and tau anti neutrino for $\varepsilon_{\nu_\chi} \neq 0$).

In summary, in this work we have studied the possibility that UHE neutrinos might have a resonant effect in the presence of additional sterile neutrino states and dark matter. We have made a qualitative analysis of the necessary couplings of dark matter with either active or sterile neutrinos in order to have such an effect. Our results show that, if the phenomenological models discussed here happen to be realized in nature, they may induce a resonant oscillation to sterile neutrinos with a mass difference lying in the pseudo-Dirac region. This pseudo-Dirac scenario had already been discussed in the absence of such a
We have also shown other values of $\Delta m^2$ where there could also be a resonant effect for an adequate value of neutrino couplings and dark matter mass. Although we have also speculated on the possibility of having this effect in the neighborhood of an AGN, the more appealing case seems to be that of our galaxy, where the effect might lead to a suppression of the neutrino flux irrespectively of the neutrino source.

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