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Hide-and-seek with cosmic tau neutrinos

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We first revisit the possibility of preserving the original flavor ratio of high energy cosmic neutrino flux by turning on a coupling between these neutrinos and ultra-light dark matter. We discuss the bound that can be set on such a coupling from the recent ν_τ observation by ICECUBE and outline the implications of the coupling for the EeV range cosmic neutrino flux to be observed by upcoming neutrino detectors. We then focus on the $3+1$ scheme when the active sterile oscillation length is of order of 1000 km for EeV range cosmic neutrinos. We show that within this scenario, the probability of survival of an active neutrino passing through the Earth can be sizable, despite the fact that the mean free path of the EeV neutrinos is much smaller than the Earth radius. This opens up the possibility to have neutrino events similar to the two anomalous events reported by ANITA.

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1. Introduction

Within the Standard Model (SM), there are three neutrinos, ν_e, ν_μ and ν_τ which have universal couplings to the SM gauge bosons. While in recent decades the interactions of ν_e, ν_μ and their antiparticles have been studied in great detail by various experiments, the available data on ν_τ and $\bar{\nu}_\tau$ interactions is only meager. This makes the third generation of leptons more enigmatic, raising the hope to discover new physics through more precise study of ν_τ and $\bar{\nu}_\tau$. In near future, the third generation neutrinos will be pushed towards spotlight by upcoming experiments. FASERν and SND@LHC will collect ~ 70 Charged Current (CC) events produced by the ν_τ and $\bar{\nu}_\tau$ fluxes emitted from the ATLAS Interaction Point (IP) during the run III of the LHC in 2022-2024 [1]. The detection of cosmic neutrinos with energies higher than ~PeV at neutrino telescopes opens new possibilities for studying ν_τ and $\bar{\nu}_\tau$. Going beyond EeV, ν_τ and $\bar{\nu}_\tau$ enjoy special privilege in detection because they can lead to Extensive Air Shower (EAS) signals to be detected by radio telescopes such as ANITA and by future observatories such as POEMMA [2], TRINITY [3] and GRAND [4].

What makes studying high energy ν_τ and $\bar{\nu}_\tau$ even more intriguing is the two anomalous events registered by ANITA in 2006 and 2014 [5]. The two events look like Extensive Air Shower from ν_τ and $\bar{\nu}_\tau$ events with energies of 0.6 ± 0.4 EeV and $0.56^{+0.4}_{-0.2}$ EeV emerging from $-27.4 \pm 0.3^\circ$ and $-35.0 \pm 0.3^\circ$ which correspond to chord sizes of 5800 km and 7300 km [5]. The reason why these events are anomalous is that at these energies, the Earth is opaque for neutrinos. Although some interpretation within SM, like reflection of the radio waves from layers inside the arctic ice, have been suggested [6, 7], the report has stirred activity among particle physicists to come up with beyond SM explanations for these two events [8, 9]. One of the first ideas that was put forward to explain the two anomalous events was fourth sterile neutrino mixed with ν_τ. Following [10], in this letter, we shall revisit this explanation.

2. Flavor composition of cosmic neutrinos with and without dark matter effects

Ultra high energy cosmic neutrinos can be produced by collision of very high energy protons accelerated at sources such as Active Galactic Nuclei (AGN) or gamma ray bursters on a background photon gas or on protons. For example, the scattering of cosmic ray protons off the Cosmic Microwave Background (CMB) can lead to the famous cosmogenic neutrinos with energies of EeV. Regardless of whether protons scatter off photons or protons, the flavor composition of neutrinos at the source will be $F_{\nu_e} : F_{\nu_\mu} : F_{\nu_\tau} = 1 : 2 : f$ with $f \ll 1$. In case of pp scatterings, there will be only a small ν_τ flux from the decay of D mesons that are produced via Charged Current (CC) interaction of the s partons. In case of $p\gamma$ scattering, the ν_τ component of the flux at the source will be even smaller and suppressed by intrinsic c parton density. Nevertheless, the neutrino propagation from the cosmic sources to the Earth will lead to neutrino oscillation and therefore a democratic flavor composition when they reach the Earth: $F^\oplus_{\nu_e} : F^\oplus_{\nu_\mu} : F^\oplus_{\nu_\tau} = 1 : 1 : 1$. This prediction turns out to be quite robust against varying the conditions at the source. Even by invoking new physics, it is not so trivial to obtain an arbitrary flavor composition at the Earth. It has been shown in [11] that as long as the flux arriving at the Earth is an arbitrary incoherent composition of the neutrino mass eigenstates, the deviation from the 1 : 1 : 1 prediction will be small. In particular, the ν_τ flux at the Earth will be nonzero.

It has been shown in [12] that if neutrinos couple to the background of ultralight DM, the original flavor ratio of neutrinos from a source located in a DM halo can be maintained. That is even at the Earth, we expect vanishing ν_τ and $\bar{\nu}_\tau$ fluxes, $F_{\nu_e} : F_{\nu_\mu} : F_{\nu_\tau} = 1 : 2 : 0$. The reason is that the DM background induces an effective flavor diagonal mass for neutrinos which in regions where DM density is relatively high can dominate over the mass term (more precisely, DM induces effective mass$\gg \Delta m^2/E_\nu$). As a result, in the DM halo of the galaxies, the energy and flavor eigenstates coincide so there will be no oscillation. Since the variation of the DM density along the route of neutrinos from the source to the Earth is smooth, the flavor transition will be adiabatic. Thus, if both source and detector are inside some DM halos, the original flavor ratios will not change. As discussed in [10], the observation of the two ν_τ events by ICECUBE [13] with energies of O(PeV) constrains this scenario, putting an upper bound on the relevant coupling. Saturating this bound, it is still possible for EeV neutrinos to maintain their original flavor composition provided that they originate in a region with relatively high DM density. The preservation of the original flavor ratio does not apply for neutrinos coming from regions outside the galactic DM halos where the density of DM is at the level of the average DM density in the Universe [10]. As a result, even if DM induced effective mass in our halo is large, the flavor of cosmogenic neutrinos arriving at the Earth will still be the canonical prediction: $F^\oplus_{\nu_e} : F^\oplus_{\nu_\mu} : F^\oplus_{\nu_\tau} = 1 : 1 : 1$.

The ARA and ARIANNA detectors are sensitive to Askaryan emission from all three flavors. On the other hand, detectors such as GRAND can measure the flux of Earth skimming ν_τ. As discussed in [10], observation of ν flux through Askaryan effect along with null result on the ν_τ component will hint towards dark matter effect. Moreover, it will be an indication that the flux is not of cosmogenic origin but the source is located in a DM halo.

At energies of EeV, the Earth is opaque for neutrinos. The ν_e and ν_μ fluxes with such energies will be completely absorbed but the ν_τ flux can go through regeneration by producing τ via scattering on the nuclei and the subsequent τ decay into ν_τ with lower energy. An EeV ν_τ flux entering the Earth from one side will lead to a flux of PeV energy neutrino flux detectable by ICECUBE. From this consideration, a bound can be obtained on the flux of EeV ν_τ flux arriving at the Earth from the lack of detection of a lower energy counterpart by ICECUBE. Indeed, Ref. [14] shows that the ν_τ flux required to explain the two anomalous events reported by ANITA overshoots the bound by more than seven orders of magnitudes.

3. Ultra high energy neutrino flux within the 3+1 neutrino scheme

Let us now discuss the propagation of ultra high energy cosmic neutrinos within the 3+1 scheme. In general, the neutrino flavor states $(\nu_e, \nu_\mu, \nu_\tau, \nu_s)$ are related to neutrino mass eigenstates $(\nu_1, \nu_2, \nu_3, \nu_4)$ via a unitary 4×4 matrix that can be denoted by U. In the flavor basis, the evolution of neutrinos (in absence of dark matter effects) are governed by the following relation

$$\begin{aligned} i\frac{d\psi}{dt} &= \Big[U \cdot \mathrm{diag}(0, \Delta m^2_{21}/(2E_\nu), \Delta m^2_{31}/(2E_\nu), \Delta M^2/(2E_\nu)) \cdot U^\dagger \\ &+ \mathrm{diag}(\sqrt{2}G_F(N_e - N_n/2), -\sqrt{2}G_F N_n/2, -\sqrt{2}G_F N_n/2, 0) \\ &- i\,\mathrm{diag}(\Gamma/2, \Gamma/2, \Gamma/2, 0)\Big]\,\psi \qquad (1) \end{aligned}$$

where ΔM^2 denotes the mass splitting of the fourth neutrino ($\Delta M^2 \equiv m_4^2 - m_1^2$) and Γ in the last line takes care of scattering of active neutrinos off the nuclei. The evolution of antineutrinos are given by similar equation replacing $U \to U^*$ and changing the sign of the matter effect in the second line. The evolution in presence of Γ is non-unitary simply because we have not included the charged particles produced by ν interaction in our analysis. That is the system under consideration is not closed. From this relation, it is obvious that in the limit $\Gamma L \gg 1$ and $\Delta M^2 L/2E_\nu \ll 1$, the propagation will remove the active components of a mass eigenstate. That is $|\nu_i\rangle \to U_{si}^*|\nu_s\rangle$. As a result, the notion that $|\nu_4\rangle$ propagating in the matter survives longer than active neutrinos is correct because the cross section is suppressed by $1 - |U_{s4}|^2$ but the active components of ν_4 becomes absorbed. Thus, the survived components, being sterile, cannot lead to charged current interactions. As a result, contrary to the claims in the literature, explaining the ANITA anomalous events by ν_4 with a mean free path of the size of the Earth radius $\Gamma R_\oplus \sim 1$ is not so trivial. In the following, we examine this solution for $\Delta M^2 R_\oplus/(2E_\nu) \sim 1$.

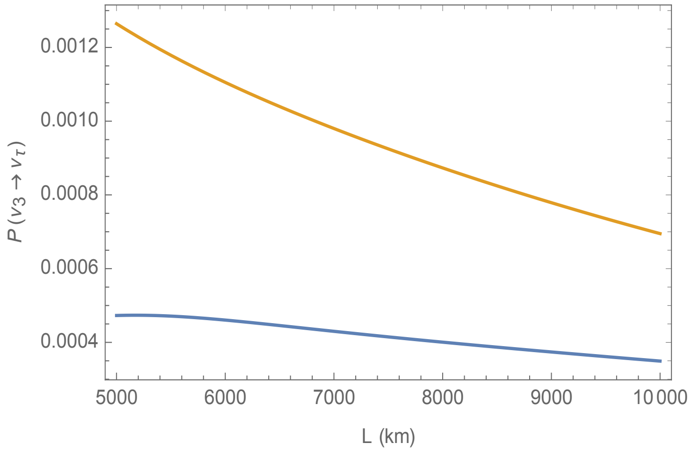

Figure 1: Probability $\nu_3 \to \nu_\tau$ and $\bar{\nu}_3 \to \bar{\nu}_\tau$ versus the size of the traversed chord. We have taken $|U_{\tau 4}|^2 = 0.1$, $|U_{e4}|^2 = |U_{\mu 4}|^2 = 0$, $\Gamma = 2.96 \times 10^{-3}$ km^{-1} and $\Delta M^2/E_\nu = 10^{-3}$ km^{-1}. The blue and orange lines respectively correspond to the neutrino and anti-neutrino modes.

Unless there is a new mechanism for sterile neutrino production, the flavor composition of neutrinos at the source from meson (pion and Kaon) decay will be $(F_{\nu_e} : F_{\nu_\mu} : F_{\nu_\tau} : F_{\nu_s}) \simeq (1 : 2 : 0 : 0)$ which in the mass basis can be written as

$$(F_{\nu_1} : F_{\nu_2} : F_{\nu_3} : F_{\nu_4}) \simeq (|U_{e1}|^2 + 2|U_{\mu 1}|^2 : |U_{e2}|^2 + 2|U_{\mu 2}|^2 : |U_{e3}|^2 + 2|U_{\mu 3}|^2 : |U_{e4}|^2 + 2|U_{\mu 4}|^2).$$

In particular, if ν_s only mixes with ν_τ (as the model in [9]), $U_{e4} = U_{\mu 4} = 0$ so the ν_4 component vanishes. In absence of the DM induced effective mass, the propagation of the long distance between the source and the detector will lead to decoherence of mass eigenstates. Once these mass eigenstates with energies of EeV enter the Earth, their active components become eventually absorbed. On the other hand, the remaining sterile component can oscillate back to the active ones, thanks to the ΔM^2 splitting. Fig. 1 shows $P(\nu_3 \to \nu_4)$ and $P(\bar{\nu}_3 \to \bar{\nu}_4)$ versus the traversed chord size L taking $|U_{e4}| = |U_{\mu 4}| = 0$ but $|U_{\tau 4}| = 0.1$. Such large value of $|U_{\tau 4}|$ is still allowed [15]. The value of $\Gamma = 0.00296$ km^{-1} corresponds to the rate of neutrino absorption in the mantle for neutrinos of EeV energy [10]. The oscillation length between ν_s and ν_τ is taken equal to 1000 km. As seen from the Fig. 1, the oscillation probability can be as large as 0.0012. This probability should be compared to the survival probability of ν in the absence of ν_4, $e^{-\Gamma L} = 10^{-7} - 10^{-12}$. Thus, the $3+1$ scheme enhances the probability of ν_τ emerging after traversing chords with sizes larger than 5000 km by a factor larger than $10^4 - 10^9$. Such an enhancement raises the hope to see ν_τ-like events by future radio detectors such as POEMMA or GRAND. As mentioned before, Ref. [14] sets an upper bound on the flux of EeV neutrinos entering the Earth. Saturating this bound, a radio detector with an acceptance of $\sim 10^{10}$ cm^2 (*i.e.,* one order of magnitude above that of ANITA) can see handful of ν_τ events from chords that completely absorb the neutrino flux within the 3ν scheme.

4. Summary and discussion

We have reviewed two scenarios that can affect the cosmic high energy ν_τ flux: (i) effective neutrino mass induced by background ultra-light dark matter; (ii) the $3+1$ scheme with ν_s mixed with ν_τ. We argued that if both the source and the detector of high energy cosmic neutrinos are located in the dark matter halos, the dark matter induced effective mass can dominate over the Hamiltonian in the vacuum and therefore the original flavor composition of neutrinos can be maintained. This means that if flavor ratio at the source is $(F_{\nu_e} : F_{\nu_\mu} : F_{\nu_\tau}) = (1 : 2 : 0)$ (as predicted in the canonic scenario), the flux at the detectors will not have the ν_τ component. Observation of the two ν_τ events at ICECUBE sets an upper bound on the effective coupling between neutrinos and dark matter. Even satisfying this bound, the dark matter effects can maintain the original flavor ratio of EeV neutrinos coming from a source located in a dark matter halo. In future, if detectors such as ARA or ARIANNA detect a flux of EeV neutrinos via their Askaryan emission but POEMMA [2], TRINITY [3] and GRAND [4] do not detect matching ν_τ component, it will be very challenging to find an explanation within the standard picture or even within the famous beyond SM scenarios such as neutrino decay or sterile neutrino. In our scenario, this observation can however easily be attributed to the production of the neutrino in a source immersed in a halo of ultra-light dark matter with flavor-conserving couplings to the neutrinos. It will also implicitly mean the observed EeV neutrino flux is not of cosmogenic origin.

We then discussed the propagation of EeV neutrinos inside the Earth within the $3+1$ scheme with an oscillation length of 1000 km. We showed that active sterile oscillation will enhance the probability of the survival of an active component crossing the Earth by a factor of $10^4 - 10^9$ relative to the standard picture where neutrinos of EeV energy become absorbed inside the Earth. This increases the hope to observe EeV neutrinos emerging from deep down the Earth.

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