Exploring Neutrino-Dark Matter Interaction via Astrophysical Neutrinos at IceCube

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Abstract

Neutrinos can scatter off dark matter as they travel through the cosmos to reach the Earth. These interactions can alter neutrino spectrum at IceCube. We explore the possibility of changes in the neutrino spectrum as neutrino interact with the dark matter by considering various neutrino-dark matter interactions. In this context, interaction *via* light vector mediators are particularly interesting as they can lead to dip and cut-off like features in the neutrino spectrum at IceCube. We illustrate that various models of AGN, which predict more flux than the observed at IceCube, can be resolved through this mechanism. We have the scope to test such interactions in the upcoming detectors, e.g., IceCube- Gen2, GRAND, KM3NeT, *etc*.

Keywords: Astrophysical neutrino, Dark Matter, IceCube
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1. INTRODUCTION

IceCube has detected around 60 extragalactic neutrino events with the energy higher than 60 TeV [1]. Recently, the collaboration succeeded in pointing back to a specific blazar TXS 0506+056 [2] as the source of one high energy astrophysical neutrino event which begins a new chapter of multi-messenger astronomy. The astrophysical neutrino spectra observed hints towards many features. Scarcity of events between 400 TeV to 1 PeV, the paucity of Glashow events, and no events after a few PeV may be pointing at a dip around 500 TeV and a sharp cut-off after $\sim$ PeV. Further, cosmogenic neutrinos, which are guaranteed due to CMB interaction with UHECR, are yet to be observed. As a result, many models of astrophysical sources that predict large neutrino flux after a PeV [**?**] are disfavoured. In this context, it is interesting to explore neutrino-DM interactions as an explanation. Ultra-light Bose-Einstein Condensed (BEC) dark matter (DM) [4], due to small masses, provide large number density and may lead to flux suppression [5]. We show that all the features of the spectrum can be explained within a single framework of ν-DM interaction.

2. NEUTRINO-DARK MATTER INTERACTION

The neutrino-DM interaction can produce significant flux suppression only if the optical depth $n\sigma L \gtrsim 1$, where $n,\ \sigma,\ L$ are DM number density, cross-section of the interaction and distance traversed by the neutrinos in the DM background respectively. To explore large categories of models with neutrino-DM interactions, we take into account the renormalizable as well as the non-renormalizable models (up to dimension-eight). Thermal DM is strongly constrained by the cosmological bounds of relic density, effective degree of freedom ($N_{\rm eff}$), and collisional damping. $N_{\rm eff}$ dictates that the mass of the DM has to be greater than 10 MeV for non-negligible coupling to Z', leading to low DM number density. Also, constraints from relic density do not allow thermal DM to have enough cross-section, leading to no flux suppression on interaction with ν. However, ultralight scalar DM (Φ) interaction, both effective or *via* mediators (Z') are explored and may lead to flux suppression [6]. The key constraints on the effective and renormalizable interactions for light DM are summarised in tables 1 and 2. The interactions which do not lead to even 1% flux depletion for $L = 200$ Mpc and density 1.26×10^{-6} GeV/cc are declared disfavoured.

As can be seen from the table 2, the renormalisable interaction which leads to significant optical depth is given by the Lagrangian,

$$\mathcal{L} \supset f\bar{\nu}_\tau \gamma^\mu P_L \nu_\tau Z'_\mu + ig(\Phi^* \partial^\mu \Phi - \Phi \partial^\mu \Phi^*) Z'_\mu.$$

Here, f and g are the coupling strengths of ν_τ and Φ with a new vector boson Z'. Couplings for $\nu_e,\ \nu_\mu$ are constrained severely from the $g-2$ measurements whereas τ-flavoured neutrinos are constrained from the decay width of Z, W bosons and τ.

3. TRANSPORT OF NEUTRINOS

We calculate the change in the neutrino spectrum if the astrophysical neutrino interacts with 200 Mpc of uniform background of ultralight scalar DM. The final neutrino flux can be obtained by solving the integro-differential equation given as:

$$\frac{\partial F(E,x)}{\partial x} = -n\sigma(E)F(E,x) + n\int_E^\infty dE' \frac{d\sigma(E,E')}{dE} F(E',x), \tag{1}$$

Topology	Interaction	Constraints	Remarks
I 1	$\frac{c_l^{(1)}}{\Lambda^2}\,(\bar{\nu} i \partial\!\!\!/ \nu)(\Phi^* \Phi)$	$c_l^{(1)}/\Lambda^2 \lesssim 8.8 \times 10^{-3}$ GeV^{-2}, $c_e^{(1)}/\Lambda^2 \lesssim 1.0 \times 10^{-4}$ GeV^{-2}, $c_\mu^{(1)}/\Lambda^2 \lesssim 6.0 \times 10^{-3}$ GeV^{-2}, $c_\tau^{(1)}/\Lambda^2 \lesssim 6.2 \times 10^{-3}$ GeV^{-2}	disfavoured
I 2	$\frac{c_l^{(2)}}{\Lambda^2}(\bar{\nu}\gamma^\mu \nu)(\Phi^* \partial_\mu \Phi - \Phi \partial_\mu \Phi^*)$	$c_l^{(2)}/\Lambda^2 \lesssim 1.8 \times 10^{-2}$ GeV^{-2}, $c_e^{(2)}/\Lambda^2 \lesssim 2.6 \times 10^{-5}$ GeV^{-2}, $c_\mu^{(1)}/\Lambda^2 \lesssim 1.2 \times 10^{-2}$ GeV^{-2}, $c_\tau^{(1)}/\Lambda^2 \lesssim 1.3 \times 10^{-3}$ GeV^{-2}	disfavoured
I 3	$\frac{c_l^{(3)}}{\Lambda}\bar{\nu^c}\nu\ \Phi^\star\Phi$	$c_l^{(3)}/\Lambda \leq 0.5$ GeV^{-1}	favoured[a]
I 4	$\frac{c_l^{(4)}}{\Lambda^3}(\bar{\nu^c}\sigma^{\mu\nu}\nu)(\partial_\mu \Phi^* \partial_\nu \Phi - \partial_\nu \Phi^* \partial_\mu \Phi)$	$c_l^{(4)}/\Lambda^3 \lesssim 2.0 \times 10^{-3}$ GeV^{-3}	disfavoured
I 5	$\frac{c_l^{(5)}}{\Lambda^3}\partial^\mu(\bar{\nu^c}\nu)\partial_\mu(\Phi^*\Phi)$	$c_l^{(5)}/\Lambda^3 \lesssim 7.5 \times 10^{-4}$ GeV^{-3}	disfavoured
I 6	$\frac{c_l^{(6)}}{\Lambda^4}(\bar{\nu}\partial^\mu\gamma^\nu\nu)(\partial_\mu \Phi^* \partial_\nu \Phi - \partial_\nu \Phi^* \partial_\mu \Phi)$	$c_l^{(6)}/\Lambda^4 \lesssim 2.5 \times 10^{-5}$ GeV^{-4}, $c_e^{(6)}/\Lambda^4 \lesssim 1.2 \times 10^{-6}$ GeV^{-4}, $c_\mu^{(6)}/\Lambda^4 \sim c_\tau^{(6)}/\Lambda^4 \lesssim 10^{-5}$ GeV^{-4}	disfavoured
II 1	$\frac{c_l^{(7)}}{\Lambda^2}(\partial^\mu \Phi^* \partial^\nu \Phi - \partial^\nu \Phi^* \partial^\mu \Phi) Z'_{\mu\nu} + f_i \bar{\nu}_i \gamma^\mu P_L \nu_i Z'_\mu$	$f_l c_l^{(7)}/\Lambda^2 \lesssim 4.2 \times 10^{-2}$ GeV^{-2}, $f_e c_e^{(7)}/\Lambda^2 \lesssim 1.9 \times 10^{-5}$ GeV^{-2}, $f_\mu c_\mu^{(7)}/\Lambda^2 \sim f_\tau c_\tau^{(7)}/\Lambda^2 \lesssim 8.1 \times 10^{-3}$ GeV^{-2}, $[f_e, f_\mu, f_\tau] \lesssim [10^{-5}, 10^{-6}, 0.02]$ for $m_{Z'} \sim 10$ MeV	disfavoured
II 2	$\frac{c_l^{(8)}}{\Lambda}\partial^\mu|\Phi|^2\partial_\mu\Delta + f_l \bar{\nu^c}\nu\Delta$	$m_\nu \sim f_l v_\Delta \lesssim 0.1$ eV, $m_\Delta \gtrsim 150$ GeV	disfavoured
III	$C_1(\Phi^*\partial_\mu\Phi - \Phi\partial_\mu\Phi^*)Z'^\mu + \frac{c_l^{(9)}}{\Lambda}(\bar{\nu^c}\sigma_{\mu\nu}P_L\nu)Z'^{\mu\nu}$	$C_1 c_l^{(9)}/\Lambda \lesssim 3.8 \times 10^{-3}$ GeV^{-1} for $m_{Z'} \sim 10$ MeV	favoured[b]
IV	$\frac{c_l^{(10)}}{\Lambda^2}\bar{L}F_R\Phi|H|^2 + C_L\bar{L}F_R\Phi$	Same as in fermion case in table V	disfavoured

TABLE 1: Summary of neutrino-DM effective interactions. c_l and $c_{e,\mu,\tau}$ represent the coefficients of interactions for the gauge non-invariant and gauge-invariant forms respectively. The colour coding for the constraints is: $Z \to inv$, LEP monophoton+$\not{E}_T$, $Z \to \mu^+\mu^-$, $Z \to \tau^+\tau^-$ and $(g-2)_{e,\mu}$. We also remark whether the interactions are favoured in context of the 1% flux suppression criteria as mentioned earlier.

[a] disfavoured if realised with a $SU(2)_L$ triplet scalar. [b] favoured if 0.08 eV $\lesssim m_{\rm DM} \lesssim$ 0.5 eV for $m_{Z'} \sim 10$ MeV and $E_\nu \sim 1$ PeV.

Mediator	Interaction	Constraints	Remarks
Fermion	$(C_L\bar{L}F_R + C_R\bar{l}_R F_L)\Phi + h.c.$	$m_F \gtrsim 100$ GeV, $m_{\rm DM} \gtrsim 10^{-21}$ eV, $C_L C_R \lesssim \{2.5, 0.5\} \times 10^{-5}$ for e and μ	disfavoured
Scalar	$f_l\bar{L}^c L\Delta + g_\Delta\Phi^*\Phi|\Delta|^2$	$m_\nu \sim f_l v_\Delta \lesssim 0.1$ eV, $g_\Delta \sim v_\Delta^2/m_{\rm DM}^2$	disfavoured
Vector	$f'_l\bar{L}\gamma^\mu P_L L Z'_\mu + ig'(\Phi^*\partial^\mu\Phi - \Phi\partial^\mu\Phi^*)Z'_\mu$	$[f_e, f_\mu, f_\tau] \lesssim [10^{-5}, 10^{-6}, 0.02]$ for $m_{Z'} \sim 10$ MeV	favoured only for ν_τ

TABLE 2: Summary of renormalisable neutrino-DM interactions. Here F, Δ, Z' are new fermion, scalar and vector mediators respectively. Colour coding is the same as in table 1.

where $F(E, x)$ represents the flux of neutrinos of energy E after traversing a distance x from the source. The first term in the RHS of eq. (1) represents the attenuation of the neutrinos, whereas the second term denotes the flux regenerated from the degradation of neutrinos of higher energies.

The final flux obtained for various initial flux and DM mass are shown in fig. 1. From fig. 1 (a), it can be seen that at lower energies, when σ is not appreciable, both attenuation and regeneration are negligible. At very high energies, when σ flattens, the neutrinos lost due to attenuation get regenerated from the higher energy bins leading to hardly any change. In between these two extremes, attenuation occurs. This kind of feature can explain the dip ~ 500 TeV at IceCube, *e.g.*, fig. 1 (c). This can also lead to a cut-off kind of feature at IceCube given the dip is broader for a low mass of DM with similar coupling, as in fig. 1 (b), where the cut-off shifts to lower energy by two orders of magnitude. Many models of non-blazar AGNs predict a much higher flux than what is seen at IceCube. The net flux suppression due to neutrino DM interaction can reconcile such AGN and cosmogenic neutrino models [7]. We illustrate this in fig. 1 (d), where we have used AGN core model S05, which is used as an archetype of such AGN models. Thus all the features of the IceCube neutrino spectrum can find explanation *via* this single framework.

In passing, it can be noted that in addition to flux changes ν-DM interaction can also lead to changes in flavour ratio. High energy neutrinos produced at the sources surrounded by ultra-light DM feel the DM potential, which changes their probability of flavour conversion and hence the flavour ratio at IceCube from the standard scenario (1:1:1).

4. CONCLUSION

Astrophysical observations suggest that DM is abundantly distributed around the cosmos, and astrophysical objects produce neutrino flux detectable at IceCube. Therefore neutrino-DM interactions can lead to a significant change of neutrino spectrum as ν

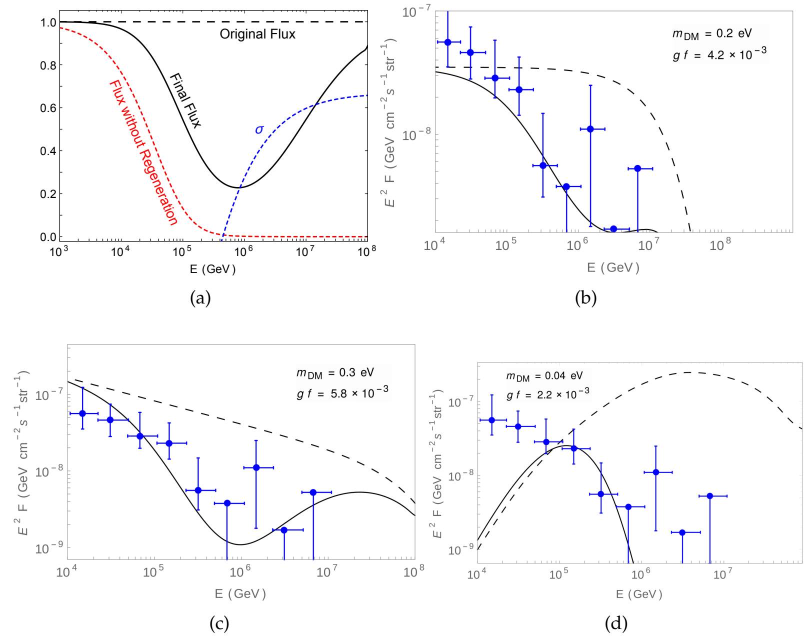

FIGURE 1: (a) The solid and dashed black, red lines represent the final and the original flux, multiplied by E^2, in units of GeV cm^{-2} s^{-1} str^{-1} and are scaled by a factor 3×10^9. The blue-dashed line refers to the neutrino-DM scattering cross-section in units of eV^{-2} and is scaled by 3×10^{21}. Here $m_{\rm DM} = 0.3$ eV and $gf = 7 \times 10^{-3}$. For all plots $m_{Z'} = 10$ MeV and $m_\nu = 0.1$ eV. (b) An early cut-off in a diffuse neutrino flux due to ν-DM interactions. The dashed line represents an E^{-2} original flux with a cut-off at 12 PeV. (c) Absorption dip due to ν–DM interaction for a diffuse neutrino flux which follows the $E^{-2.3}$ power law. (d) Attenuation of the diffuse neutrino flux for the AGN core model S05 [8]. The dashed and solid black lines represent the original flux and the flux degraded by ν–DM interactions. The blue bars denote the flux from 7.5 years of neutrino flux at IceCube [1].

travel through the cosmos and reach the Earth. In our work, we have found that such effects can be probed at IceCube if ν_τ interacts with DM *via* light vector boson. The attenuation and regeneration of neutrinos due to ν-DM interaction can lead to paucity of events around $\sim$ 600 TeV as well as a cut-off like feature after a few PeVs of neutrino energy. We show that by our mechanism, the flux of AGN gets attenuated, hence reconciling such sources. Many such astrophysical sources which are dominant at different neutrino energies, can together explain the entire neutrino spectrum observed. Along with DM, various non-standard interactions (NSI) with quarks can be constrained by IceCube, with bounds competing with that of LHC [9].

Such interactions can be useful to explore the interiors of astrophysical objects. Our new findings [10] suggest that the DM density profile might get imprinted in the energy dependence of neutrino flavour ratios. This will mark the beginning of another new era of neutrino astronomy. Though the present IceCube detector has started to observe various features of neutrino spectra, these effects can be better probed with IceCube Gen-2, which is proposed to be ten times bigger than the present detector. With more statistics from upcoming experiments, *e.g.*, IceCube-Gen2, KM3NeT, GRAND, *etc.*, ν-DM interactions will be well constrained.

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References

[1] A. Karle, Talk presented at La Palma 2018 on behalf of IceCube Collaboration.
[2] M. G. Aartsen *et al.*, Science **361**, no. 6398, eaat1378 (2018).
[3] K. Murase, arXiv:1511.01590.
[4] W. Hu, R. Barkana, and A. Gruzinov, Phys. Rev. Lett. **85**, 1158 (2000).
[5] For the literature on ν-DM interactions and the resulting neutrino absorption, please see the references [17-34] of Ref. [6].
[6] S. Pandey, S. Karmakar and S. Rakshit, JHEP **1901** (2019) 095.
[7] S. Karmakar, S. Pandey and S. Rakshit, arXiv:1810.04192 [hep-ph].
[8] F. W. Stecker, Phys. Rev. D **88**, no. 4, 047301 (2013).
[9] S. Pandey, S. Karmakar and S. Rakshit, JHEP **11** (2019), 046.
[10] S. Pandey, S. Rakshit, work in progress.