Published for SISSA by Springer

Received: *June 17, 2021*
Revised: *November 6, 2021*
Accepted: *November 9, 2021*
Published: *November 29, 2021*

Erratum: Interactions of astrophysical neutrinos with dark matter: a model building perspective

Sujata Pandey, Siddhartha Karmakar[1] and Subhendu Rakshit

Discipline of Physics, Indian Institute of Technology Indore,
Khandwa Road, Simrol, Indore, 453 552, India
E-mail: phd1501151007@iiti.ac.in, phd1401251010@iiti.ac.in, rakshit@iiti.ac.in

Erratum to: JHEP01(2019)095

ArXiv ePrint: 1810.04203

1 Introduction

In ref. [1] we studied whether the neutrino-dark matter (DM) interactions can cause a suppression of astrophysical neutrino flux. We singled out the interactions which reduce the neutrino flux by $\gtrsim 1\%$, dubbed as 'significant flux suppression' throughout the paper. In light of the collider and electroweak precision constraints, we concluded that out of the eleven effective and three renormalisable neutrino-DM interactions studied in ref. [1], three could still lead to at least 1% suppression of astrophysical neutrino flux at IceCube. These three scenarios involve ultralight scalar DM interacting with neutrinos through (*i*) Topology I 3 from eq. (3.3), (*ii*) Topology III in section 3.3, and (*iii*) vector-mediated interaction in section 4.3.3 of ref. [1].

In this erratum we add that, as the Big Bang Nucleosynthesis (BBN) constraints forbid neutrinos to be in thermal equilibrium with light scalar DM after the neutrino decoupling epoch, two out of the aforementioned three scenarios fail to lead to any significant flux suppression. To be precise, Topology III in section 3.3 and vector-mediated interaction in section 4.3.3 cannot lead to significant neutrino flux suppression, while Topology I 3 still can. The BBN bounds on these three scenarios are discussed in a more detail in the next section.

[1] Now at: Department of Physics, Indian Institute of Technology Bombay, Powai, Mumbai, 400 076, India; karmakars@iitb.ac.in.

https://doi.org/10.1007/JHEP11(2021)215

2 Details of BBN bounds on neutrino-DM interactions

To satisfy the Big Bang Nucleosynthesis (BBN) constraints on neutrino interactions with ultralight scalar DM Φ, the rate of $\nu\nu \leftrightarrow \Phi\Phi$ at the neutrino decoupling temperature $T_\nu \sim 2\,\text{MeV}$ must be less than Hubble expansion rate H. Thus, at T_ν, the cross-section of $\nu\nu \leftrightarrow \Phi\Phi$ has to be $\lesssim H/n_\nu \sim 3.5 \times 10^{-34}\,\text{eV}^{-2}$. For the interaction given by Topology I 3,

$$\mathcal{L} \supset \frac{c_l^{(3)}}{\Lambda} \bar{\nu^c}\nu\ \Phi^\star\Phi\,, \tag{2.1}$$

the aforementioned bound translates to $c_l^{(3)}/\Lambda \lesssim 2.5 \times 10^{-5}\,\text{GeV}^{-1}$ in the limit $m_\Phi \ll T_\nu$. For the maximally allowed value of the coupling strength, $c_l^{(3)}/\Lambda = 2.5 \times 10^{-5}\,\text{GeV}^{-1}$, this interaction can lead to 1% flux suppression of neutrinos at IceCube, i.e., $\exp(-n_{\text{DM}}\sigma_{\nu\text{DM}}L) \sim 0.01$, if $m_{\text{DM}} \lesssim 4\times10^{-8}\,\text{eV}$. Here, we consider the length traversed by neutrinos $L = 200$ Mpc and isotropic DM density $\rho_{\text{DM}} = n_{\text{DM}}m_{\text{DM}} \sim 1.2 \times 10^{-6}\,\text{GeV cm}^{-3}$, as mentioned on pg. 4 of ref. [1]. For Topology I 3, the neutrino-DM scattering cross-section $\sigma_{\nu\text{DM}}$ is independent of DM mass, but neutrino flux suppression still depends on the value of m_{DM} as lighter DM would imply a larger value of DM number density.

Contrary to Topology I 3, there are models for which ν-DM scattering cross-section increases with m_{DM}, as shown in figures 3(b) and 8(b) of ref. [1]. BBN constraint on such models disfavours neutrino flux suppression for the entire range of ultralight scalar DM mass. For instance, in Topology III, i.e.,

$$\mathcal{L} \supset C_1(\Phi^*\partial_\mu\Phi - \Phi\partial_\mu\Phi^*)Z'^\mu + \frac{c_l^{(9)}}{\Lambda}(\bar{\nu^c}\sigma_{\mu\nu}P_L\nu)Z'^{\mu\nu}\,, \tag{2.2}$$

the BBN bound reads $C_1c_l^{(9)}/\Lambda \lesssim 2.5 \times 10^{-6}\,\text{GeV}^{-1}$, which disfavours any significant flux suppression.

The BBN constraint on renormalisable vector mediated ν-DM interaction,

$$\mathcal{L} \supset f_l'\bar{l}\gamma^\mu P_L l Z'_\mu + ig'(\Phi^*\partial^\mu\Phi - \Phi\partial^\mu\Phi^*)Z'_\mu\,, \tag{2.3}$$

reads $f_l'g' \lesssim 6 \times 10^{-8}$ for $m_{Z'} \sim 10\,\text{MeV}$. This does not allow for any significant change in the astrophysical neutrino flux. Though this interaction can still lead to changes in the flavour of astrophysical neutrinos passing through solitonic core of ultralight DM [2].

The key constraints on the effective and renormalisable interactions for light DM are summarised in tables 1 and 2 below. For DM with higher masses, the cosmological constraints such as, relic density, collisional damping, and N_{eff} ensure that the mentioned interactions do not lead to any significant flux suppression, as shown in figure 5 of ref. [1].

3 Conclusion

In this erratum we point out, Topology III and the renormalisable vector-mediated model of neutrino-DM interactions are already too constrainted by BBN to show up at the IceCube neutrino observatory. Only Topology I 3 can lead to a suppression of astrophysical neutrino flux even after imposing the BBN bounds. Tables 1 and 2 are similar to tables 4 and 5 of ref. [1] respectively, but are improved with these BBN bounds.

JHEP11(2021)215

Topology	Interaction	Constraints	Remarks
I 1	$\frac{c_l^{(1)}}{\Lambda^2}\,(\bar{\nu}i\not{\partial}\nu)(\Phi^*\Phi)$	$c_l^{(1)}/\Lambda^2 \lesssim 8.8\times10^{-3}\,\text{GeV}^{-2}$, $c_e^{(1)}/\Lambda^2 \lesssim 1.0\times10^{-4}\,\text{GeV}^{-2}$, $c_\mu^{(1)}/\Lambda^2 \lesssim 6.0\times10^{-3}\,\text{GeV}^{-2}$, $c_\tau^{(1)}/\Lambda^2 \lesssim 6.2\times10^{-3}\,\text{GeV}^{-2}$	disfavoured
I 2	$\frac{c_l^{(2)}}{\Lambda^2}(\bar{\nu}\gamma^\mu\nu)(\Phi^*\partial_\mu\Phi$ $-\Phi\partial_\mu\Phi^*)$	$c_l^{(2)}/\Lambda^2 \lesssim 1.8\times10^{-2}\,\text{GeV}^{-2}$, $c_e^{(2)}/\Lambda^2 \lesssim 2.6\times10^{-5}\,\text{GeV}^{-2}$, $c_\mu^{(1)}/\Lambda^2 \lesssim 1.2\times10^{-2}\,\text{GeV}^{-2}$, $c_\tau^{(1)}/\Lambda^2 \lesssim 1.3\times10^{-3}\,\text{GeV}^{-2}$	disfavoured
I 3	$\frac{c_l^{(3)}}{\Lambda}\bar{\nu^c}\nu\,\Phi^*\Phi$	$c_l^{(3)}/\Lambda \leq 0.5\,\text{GeV}^{-1}$, $c_l^{(3)}/\Lambda \lesssim 2.5\times10^{-5}\,\text{GeV}^{-1}$	favoured[a]
I 4	$\frac{c_l^{(4)}}{\Lambda^3}(\bar{\nu^c}\sigma^{\mu\nu}\nu)(\partial_\mu\Phi^*\partial_\nu\Phi$ $-\partial_\nu\Phi^*\partial_\mu\Phi)$	$c_l^{(4)}/\Lambda^3 \lesssim 2.0\times10^{-3}\,\text{GeV}^{-3}$	disfavoured
I 5	$\frac{c_l^{(5)}}{\Lambda^3}\partial^\mu(\bar{\nu^c}\nu)\partial_\mu(\Phi^*\Phi)$	$c_l^{(5)}/\Lambda^3 \lesssim 7.5\times10^{-4}\,\text{GeV}^{-3}$	disfavoured
I 6	$\frac{c_l^{(6)}}{\Lambda^4}(\bar{\nu}\partial^\mu\gamma^\nu\nu)(\partial_\mu\Phi^*\partial_\nu\Phi$ $-\partial_\nu\Phi^*\partial_\mu\Phi)$	$c_l^{(6)}/\Lambda^4 \lesssim 2.5\times10^{-5}\,\text{GeV}^{-4}$, $c_e^{(6)}/\Lambda^4 \lesssim 1.2\times10^{-6}\,\text{GeV}^{-4}$, $c_\mu^{(6)}/\Lambda^4 \sim c_\tau^{(6)}/\Lambda^4 \lesssim 10^{-5}\,\text{GeV}^{-4}$	disfavoured
II 1	$\frac{c_l^{(7)}}{\Lambda^2}(\partial^\mu\Phi^*\partial^\nu\Phi$ $-\partial^\nu\Phi^*\partial^\mu\Phi)Z'_{\mu\nu}$ $+f_i\bar{\nu}_i\gamma^\mu P_L\nu_i Z'_\mu$	$f_l c_l^{(7)}/\Lambda^2 \lesssim 4.2\times10^{-2}\,\text{GeV}^{-2}$, $f_e c_e^{(7)}/\Lambda^2 \lesssim 1.9\times10^{-5}\,\text{GeV}^{-2}$, $f_\mu c_\mu^{(7)}/\Lambda^2 \sim f_\tau c_\tau^{(7)}/\Lambda^2 \lesssim 8.1\times10^{-3}\,\text{GeV}^{-2}$, $[f_e, f_\mu, f_\tau] \lesssim [10^{-5}, 10^{-6}, 0.02]$ for $m_{Z'} \sim 10\,\text{MeV}$	disfavoured
II 2	$\frac{c_l^{(8)}}{\Lambda}\partial^\mu\lvert\Phi\rvert^2\partial_\mu\Delta + f_l\bar{\nu^c}\nu\Delta$	$m_\nu \sim f_l v_\Delta \lesssim 0.1\,\text{eV}$, $m_\Delta \gtrsim 150\,\text{GeV}$	disfavoured
III	$C_1(\Phi^*\partial_\mu\Phi - \Phi\partial_\mu\Phi^*)Z'^\mu$ $+\frac{c_l^{(9)}}{\Lambda}(\bar{\nu^c}\sigma_{\mu\nu}P_L\nu)Z'^{\mu\nu}$	$C_1 c_l^{(9)}/\Lambda \lesssim 3.8\times10^{-3}\,\text{GeV}^{-1}$ and $C_1 c_l^{(9)}/\Lambda \lesssim 2.5\times10^{-6}\,\text{GeV}^{-1}$ for $m_{Z'} \sim 10\,\text{MeV}$	disfavoured
IV	$\frac{c_l^{(10)}}{\Lambda^2}\bar{L}F_R\Phi\lvert H\rvert^2 + C_L\bar{L}F_R\Phi$	Same as in fermion case in table 5	disfavoured

[a]Disfavoured if realised with a $SU(2)_L$ triplet scalar. Also disfavoured for $m_{\text{DM}} \gtrsim 4\times10^{-8}\,\text{eV}$.

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+$\not{E}_T$, $Z\to\mu^+\mu^-$, $Z\to\tau^+\tau^-$, BBN and $(g-2)_{e,\mu}$. We also remark whether the interactions are favoured in context of the 1% flux suppression criteria.

Mediator	Interaction	Constraints	Remarks
Fermion	$(C_L\bar{L}F_R + C_R\bar{l}_R F_L)\Phi +$ $h.c.$	$m_F \gtrsim 100\,\text{GeV}$, $m_{\text{DM}} \gtrsim 10^{-21}\,\text{eV}$, $C_L C_R \lesssim \{2.5, 0.5\}\times10^{-5}$ for e and μ	disfavoured
Scalar	$f_l\bar{L}^c L\Delta + g_\Delta\Phi^*\Phi\lvert\Delta\rvert^2$	$m_\nu \sim f_l v_\Delta \lesssim 0.1\,\text{eV}$, $g_\Delta \sim v_\Delta^2/m_{\text{DM}}^2$	disfavoured
Vector	$f'_l\bar{L}\gamma^\mu P_L L Z'_\mu + ig'(\Phi^*\partial^\mu\Phi$ $-\Phi\partial^\mu\Phi^*)Z'_\mu$	$[f'_e, f'_\mu, f'_\tau] \lesssim [10^{-5}, 10^{-6}, 0.02]$ and $f'g' \lesssim 6\times10^{-8}$ for $m_{Z'} \sim 10\,\text{MeV}$	disfavoured

Table 2. Summary of renormalisable neutrino-DM interactions. Colour coding is the same as in table 1.

Overall, our key conclusion remains the same: building effective and renormalisable models of neutrino-DM interactions which can lead to significant neutrino flux suppression at IceCube is rather hard when confronted with the existing precision, collider, astrophysical, and cosmological constraints.

References

[1] S. Pandey, S. Karmakar and S. Rakshit, *Interactions of Astrophysical Neutrinos with Dark Matter: A model building perspective*, *JHEP* **01** (2019) 095 [arXiv:1810.04203] [INSPIRE].

[2] S. Karmakar, S. Pandey and S. Rakshit, *Astronomy with energy dependent flavour ratios of extragalactic neutrinos*, *JHEP* **10** (2021) 004 [arXiv:2010.07336] [INSPIRE].

JHEP11(2021)215