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GRB221009A gamma-ray events from nonstandard neutrino self-interactions

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The flux of high-energy astrophysical neutrinos observed by the present generation of neutrino detectors has already indicated a few hints of new physics beyond the Standard Model. In this work, we show that high-energy gamma-ray observations can also be considered as a complementary probe for unveiling the source of high-energy astrophysical neutrino events and new physics. Recently, the LHAASO collaboration has reported $\mathcal{O}(5000)$ gamma-ray events in the energy range between 0.5–18 TeV from gamma-ray burst GRB 221009A within 2000 seconds after the initial outburst. We showed that some of the high-energy gamma rays can be produced from the interaction of astrophysical neutrinos with CMB neutrinos through nonstandard self-interaction of neutrinos mediated by light scalar bosons. The nonstandard interaction of neutrinos recently took a lot of attention in cosmology for its role in reducing Hubble tension. We have constrained the parameter space of nonstandard self-interacting neutrinos from the flux of photons observed by LHAASO and showed consistency of the same with the resulting parameter space from Hubble tension requirements and other recent constraints from laboratory/cosmology.

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I. INTRODUCTION

The results from various cosmological and astrophysical observations have convinced us that neutrinos play a significant role in multimessenger astronomy as one of the messengers used to study exotic astrophysical phenomena as well as in understanding the evolution of the universe. In the standard model (SM) of particle physics, neutrinos are considered to interact very weakly through the weak force, thus making them challenging to detect. However, recently, there has been a lot of debate about the possibility of moderately strong nonstandard interaction of neutrinos with each other through a new mediator, typically known as self-interaction of neutrinos (νSI) [1]. It plays an important role in reducing the Hubble tension [2–8], allowing KeV sterile neutrino as viable dark matter (DM) candidate [9–12] and supernova neutrino emission [13]. As the new mediator required to include self-interaction between neutrinos naturally invokes the existence of physics beyond the Standard Model (BSM), one can study its implications in explaining other issues in astrophysics and cosmology that might include BSM physics. In this work, we have considered the presence of self-interaction of neutrinos in explaining the flux of high-energy photons obtained from gamma-ray bursts.

Recently, on 09 October 2022, a prodigious bright gamma-ray burst (dubbed GRB221009A) was first recorded by the Burst Alert Telescope (BAT) on the Swift satellite [14] and later confirmed by Fermi Gamma-ray burst Monitor (GBM) [15,16] and Fermi-LAT [17,18] at red-shift $z_0 \sim 0.15$ [19,20]. The extremely energetic gamma rays emitted from the cosmic burst were detected by Large High Altitude Air Shower Observatory (LHAASO) [21] and Carpet-2 experiment [22]. More specifically, the Square kilometer array (KM2A) of LHAASO ([21]) reported the observation of around 5000 very-high-energy photons with energy up to 18 TeV in a 2000 sec time window while the carpet-2 experiment reported the claim for detection of 251 TeV photon-like shower events [22]. The reported red-shift corresponds to a co-moving distance d of around 643 Mpc from the Earth. The observation of these events is quite astonishing as the flux of such photons would be severely attenuated because of the pair production of electrons and positrons via interaction with extragalactic background light (EBL) ($\gamma + \gamma_{\mathrm{EBL}} \to e^- e^+$). Therefore, the photons would hardly arrive on the earth. This has speculated many proposals by invoking BSM Physics. The observation of such events has been explained from sterile neutrino decay [23–26], scalar decay [27], Lorentz invariance violation [28,29], axion-photon conversion [30–41] and inverse Compton mechanism [42–44] etc.

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In the case of models explaining the production of such events from the sterile neutrino decay [23–26], the sterile neutrinos are produced through oscillations of SM neutrinos emitted from the decay of kaons/muons during Gamma-ray bursts. The produced sterile neutrinos decay into photons through standard electroweak interactions at a one-loop level after propagating for a long distance so that EBL would not significantly attenuate this secondary photon flux. As the IceCube collaboration has also performed dedicated searches for co-relating some of the GRB events with diffuse extragalactic neutrino background of very high energy neutrinos [45,46], there already exists a bound on the time-integrated flux of neutrinos from GRB221009A at Earth [47,48]. This bound suppresses the overall magnitude of unattenuated secondary flux by a factor of around 0.01 in comparison to primary gamma-ray flux. Other than that, the flux gets an additional suppression due to two reasons in [24]: (i) suppression by a mixing angle between sterile neutrino and active neutrino, which is usually considered to be very small of the order 10^{-3}. (ii) As sterile neutrino decays dominantly into neutrinos and sub-dominantly (radiatively) into photons through standard electroweak interaction. For a fixed value of weak coupling, the decay length of photons turns out to be less than the observed distance ($\mathrm{d} = 643$ MPc) by branching ratio $B_\gamma \sim O(10^{-3})$ for MeV-scale sterile neutrino. As a result, the flux of photons produced from the sterile neutrinos also gets a suppression of around $O(10^{-3})$ and one obtains maximum $\mathcal{O}(0.001\text{–}1)$ events in such models [24]. The entire parameter space also gets ruled out by various cosmological and astrophysical constraints [26].

In this work, we consider the possibility of producing secondary photons by considering the self-interaction of high-energy neutrinos (and their leptonic partner) with each other through a new scalar mediator. In the presence of the same, the high energy neutrinos produced through kaon/muon decay during gamma-ray burst can strongly interact with background cosmic microwave background (CMB) neutrinos present in the universe while traveling to Earth. The interaction of high-energy neutrinos with CMB neutrinos can also produce high-energy photons and background CMB photons at a one-loop level. The mean free path for the photons can be calculated from the loop-suppressed scattering cross section. As the given cross section depends on the new couplings and the mediator mass in addition to standard electromagnetic couplings, we can tune these parameters such that the mean free path of photons generated through loop-suppressed scattering gives $\lambda_{\mathrm{MFP}} = d(643\ \mathrm{Mpc})$. By calculating this cross section, we have observed that the given condition requires quite a high value of self-interacting neutrino coupling in the given range of the mass of the mediator. However, we also notice that the cross section will exhibit a resonance at a certain energy for a specific mass of the mediator which can give the required value of mean free path even for relatively small values of couplings at energies close to the resonance. Overall, the condition $\lambda_{\mathrm{MFP}} = d$ can be satisfied for self-interacting neutrino coupling $g_{\nu_\mu} \sim \mathcal{O}(10^{-3} - 1)$ for the mass of scalar mediator between $m_\phi \sim \mathcal{O}(0.1\text{–}10)$ MeV.

Then we calculate the flux of high-energy photons by using the procedure given in [24]. As we do not consider the production of photons due to sterile neutrino, we will not have suppression of the flux by a mixing parameter, suppressed branching ratio, etc. Therefore, the maximal flux in our work can be higher than the flux due to sterile neutrino by a factor of 10^6 and we can obtain $\mathcal{O}(1000)$ number of events for an appropriate choice of coupling parameters and the mass of the mediator. Though most of the parameter space related to large values of couplings gets ruled out by laboratory and cosmology constraints, a tiny parameter space (attributed to high flux close to resonance) remains compatible with the parameter space required to resolve/reduce Hubble tension, an allowed region of $(g-2)_\mu$ constraints and safe from other astrophysical and cosmological constraints. Thus, the astrophysical high-energy photons produced through the scattering of high-energy neutrinos with CMB neutrinos can turn out to be a potential source of some of the high-energy gamma rays observed on Earth.

The plan of the rest of the paper is as follows: In Sec. II, we motivate the role of self-interacting neutrinos in cosmology, specifically for alleviating Hubble tension. In Secs. II(a) and II(b), we discuss the toy model of particle physics by involving the interaction of the scalar mediator with neutrino and its leptonic partner. Then we explain the possibility of producing high-energy astrophysical photons from the scattering of high-energy astrophysical neutrinos with CMB neutrinos. In Sec. III, we estimate the effect of such interactions on the astrophysical flux of photons generated from loop-level scattering. We also discuss that a tiny part of the resulting parameter space can be compatible with constraints from Hubble tension requirement and $(g-2)_\mu$ discrepancy. Finally, in Sec. IV, we discuss our results with interesting conclusions and future directions.

II. SELF-INTERACTING NEUTRINOS

The self-interacting neutrinos refer to a scenario where neutrinos interact strongly with each other secretly through a new interaction mediated by either scalar or vector boson [1]. This will allow neutrinos to remain in thermal equilibrium with each other till later times. Thus, the epoch of neutrino decoupling gets delayed until even close to the onset of matter-radiation equality. The effect of the same on the CMB power spectrum has been analyzed in detail in literature [2–7] in the context of Hubble tension. Below, we have briefly discussed the impact of strong self-interactions in increasing the value of the Hubble constant measured by CMB in the context of the ΛCDM model.

The position of CMB multiple for a particular mode k can is given by [5]

$$l \approx \frac{(m\pi - \phi_\nu)}{\theta_*}, \quad \text{with} \quad \theta_* = \frac{r_s^*}{D_A^*}, \tag{1}$$

where $m\pi$ corresponds to the position of peaks, ϕ_ν corresponds to the phase shift, D_A^* is the distance between the surface of the last scattering and today, and r_s^* corresponds to the radius of the sound horizon at the epoch of recombination. The quantities D_A^* and r_s^* can be expressed as a function of the Hubble parameter $H(z)$ as [5]: $D_A^* = \int_0^{z^*} \frac{1}{H(z)} dz$ and $r_s^* = \int_{z^*}^{\infty} \frac{c_s(z)}{H(z)} dz$, where $c_s(z) \approx 1/\sqrt{3}$ is the speed of sound in the baryon-photon plasma. The phase shift (ϕ_ν) depends on the ratio of free-streaming neutrino energy density to the total radiation energy density [5]. The decrease in the number density of free-streaming neutrino will decrease the phase shift ϕ_ν, which further leads to a shift in the position of the CMB multiple toward a high l value. This change can be avoided by increasing the value of θ_*, which can be achieved either by decreasing the value of D_A^* while keeping r_s^* unchanged or increasing the value of r_s^* while keeping D_A^* unchanged. In the standard cosmological model, the evolution of Hubble constant evolves with red-shift z is given by $H(z) = H_0\sqrt{\Omega_r(1+z)^4 + \Omega_m(1+z)^3 + \Omega_\Lambda}$, with Ω_m, Ω_r, and Ω_Λ being the fraction of the energy density acquired by radiation, matter, and vacuum respectively. If we slightly increase the value of H_0 and Ω_Λ such that there is an increase in the value of $H(z)$ at low red-shift while there is negligible change for $H(z)$ at high red-shifts, one can decrease D_A^* in such a way that the position of observed CMB multipoles will not be changed. In this way, the presence of self-interacting neutrinos impels a higher value of H_0 and reduces the discrepancy between the value of H_0 measured by CMB and low red-shift observations.

A. The model

The minimal model of self-interaction typically involves neutrinophilic interaction given by $\mathcal{L} \supset g_\nu \nu_i \nu_i$, where $i = e, \mu, \tau$ corresponds to different flavors of active neutrinos. As IceCube has searched only for track-like events from GRB221009A, we consider self-interaction only between muon flavors of neutrinos. Interestingly, the interaction of scalar with muons is also considered in the literature for resolving the discrepancy between the theoretical and experimental values of $(g-2)_\mu$ [49]. Therefore, in this work, we consider a model in which the real singlet scalar at low energies couples both to muon neutrinos as well as muons. The interaction couplings are given as:

$$\mathcal{L} \supset g_\mu \phi \bar{\mu} \mu + g_{\nu_\mu} \phi \nu_\mu \nu_\mu. \tag{2}$$

Assuming the Majorana nature of neutrinos, we have used Weyl notation to represent neutrino coupling to the scalar. For muons, we are considering Dirac notation to represent its coupling with the scalar boson. The interaction coupling g_{ν_μ} can be generally estimated from the mechanism of neutrino mass generation, while g_μ can be obtained from the nonrenormalizable coupling involving Higgs field and a new scalar field. As we are not interested in the UV completion of the model, we just assume that both the couplings can be the same or different depending on the particular model used to generate such couplings.

B. Scattering of self-interacting neutrinos with CMB neutrinos

Neutrinos are often considered to be astounding "messengers" because of their capability to carry insight into various astrophysical processes and events happening in the universe. In SM, neutrinos can traverse large distances on their way to Earth because the probability of an interaction between neutrinos and matter is very small. In the presence of new nonstandard interaction of neutrinos, the high energy neutrinos emitted from various astrophysical objects such as gamma-ray bursts, galaxy sources, etc. might scatter with other new particles while traveling to Earth. Thus, there is a possibility that the mean free path of neutrino will become smaller. In the case of self-interacting neutrinos, the mean free path of neutrinos can be affected due to the secret self-interaction of astrophysical neutrinos with the cosmic neutrino background. The high-energy astrophysical neutrinos can scatter strongly with CMB neutrinos while traveling to Earth and impact the flux of astrophysical neutrinos observed from various sources. Thus, the flux of high-energy astrophysical neutrinos obtained from various sources can provide complementary probes to constrain the strength of the nonstandard interaction of neutrinos. The effect has been analyzed in [50–55] by analyzing constraints on the self-interacting neutrino coupling from the flux of astrophysical neutrino point sources obtained from NGC and IceCube results. In addition to this, the nonstandard neutrino interactions also affect GRB-like transients via delayed neutrino emission, as studied in [56]. The Feynman diagram representing the s-channel scattering of astrophysical neutrinos ($\nu_{\mu a}$) with CMB neutrinos ($\nu_{\mu b}$) has been shown in Fig. 1.

In this work, we have proposed that the s-channel scattering of astrophysical neutrinos can also produce high-energy gamma rays at the radiative level if the mediator interacts with both muon neutrinos and muons. Thus, the flux of high-energy gamma rays obtained from various sources can also be considered to constrain the strength of nonstandard interactions of neutrinos. The one-loop level Feynman diagram for producing photons from radiative s-channel scattering of astrophysical neutrinos ($\nu_{\mu a}$) with CMB neutrinos ($\nu_{\mu b}$) has been shown in Fig. 2.

In the forthcoming sections, we will analyze constraints on the strength of the nonstandard interaction of neutrinos from the flux of high-energy gamma-ray events observed

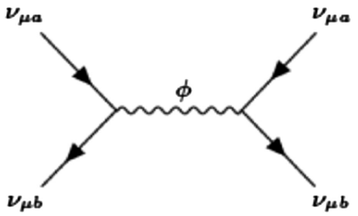


FIG. 1. Feynman diagram for scattering of high energy astrophysical neutrinos with CMB neutrinos. Here, $\nu_{\mu a}$ and $\nu_{\mu b}$ correspond to high-energy astrophysical neutrinos and background CMB neutrinos respectively.

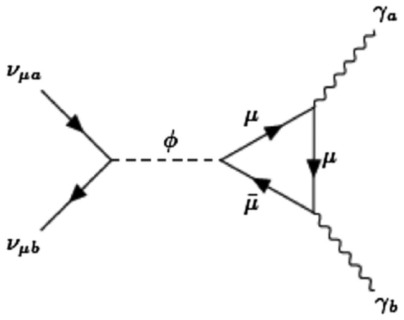


FIG. 2. Feynman diagram for scattering of high energy astrophysical neutrinos ($\nu_{\mu a}$) with CMB neutrinos ($\nu_{\mu b}$) into high energy astrophysical photons (γ_a) and CMB background photons (γ_b).

by GRB221009A. We will also analyze if the self-interaction coupling required to produce such high-energy photons is consistent with the values required to address the Hubble tension and other recent laboratory/cosmological constraints.

III. IMPACT ON ASTROPHYSICAL GAMMA-RAY FLUX FROM GRB221009A

As discussed earlier, the LHAASO collaboration has recently reported an extremely bright and long-duration Gamma Ray Burst, named GRB221009A [14]. They have detected $\mathcal{O}(5000)$ events of photons with energies ranging from 0.5 to 18 TeV within a time window of 2000 at red-shift $z = 0.15$. The violent reactions around GRB normally produce a large number of pions or kaons which can further decay into photons and neutrinos. As the photon will interact with background photons to annihilate into electron-positron pairs, the flux of astrophysical neutrinos will be significantly attenuated. Thus, the detection cannot be explained due to extragalactic background light coming from GRB events. Interestingly, the observed flux of high and very-high-energy photons can be obtained from neutrinos emitted during GRB events through the interaction of emitted high-energy astrophysical neutrinos with CMB neutrinos. Thus, GRB events would provide a unique opportunity to probe the nonstandard interaction of neutrinos.

In this section, we calculate the probability of producing high-energy gamma rays from the scattering of high-energy astrophysical neutrinos with CMB neutrinos. The unattenuated γ flux of GRB 221009A obtained by extrapolating the flux measured by FermiLAT in the energy range (0.1–1) GeV to higher energies (around TeV) is given by [24]

$$\phi^0_\gamma(E_\gamma) = \frac{2.1 \times 10^{-6}}{\mathrm{cm}^2\,\mathrm{s}^{-1}\,\mathrm{TeV}} \left(\frac{E_\gamma}{\mathrm{TeV}}\right)^{-1.87\pm 0.04}. \tag{3}$$

The emission of neutrinos from GRB221009A has been analyzed by complementary experiments such as IceCube. The nonobservation of track-like neutrino events in the energy range 0.8 TeV–1 PeV has set constraints on neutrino fluence $E^2_\nu \phi^{\mathrm{int}}_\nu \leq 3.9 \times 10^{-5}\ \mathrm{TeV\,cm^{-2}}$ [47,48]. As neutrinos would mainly be emitted from muon and kaon decay, they would mostly consist of astrophysical muon neutrinos ($\nu_{\mu a}$). Therefore, the ratio of the flux of neutrinos to the flux of unattenuated gamma rays will be given by

$$r_{\nu\gamma} = \frac{\phi_{\nu_{\mu a}}}{\phi^0_\gamma(E_\gamma)}. \tag{4}$$

By dividing the neutrino fluence with a long period ($\Delta\tau \sim 600$ sec) of intense gamma-ray emission, one gets the ratio of the fluxes $r_{\nu\gamma} \lesssim 3 \times 10^{-2}$ [24].

As shown in Fig. 1, the high energy neutrinos emitted from muon/kaon decay produced during GRB at redshift $z = 0.15$ can scatter with CMB neutrinos. The optical depth of neutrino would be given by:

$$\tau_{\nu_\mu} = \frac{\lambda_{\nu_\mu}}{d}, \tag{5}$$

where λ_{ν_μ} corresponds to total mean free path of neutrinos. The mean free path of neutrinos annihilating into gamma rays will be given by $\lambda_{\nu_\mu \to \gamma} = \mathcal{BR}(\nu_{\mu a}\nu_{\mu b} \to \gamma_a \gamma_b)\lambda_{\nu_\mu}$.

Thus, the probability of receiving gamma rays on earth from the scattering of astrophysical neutrinos with CMB neutrinos in the distance interval [x, x + dx] will be given by:

$$e^{-x/\lambda_{\nu_\mu \to \gamma}} \frac{dx}{\lambda_{\nu_\mu \to \gamma}} e^{-(d-x)/\lambda_\gamma}, \tag{6}$$

where $\lambda_{\nu_\mu \to \gamma}$ is the mean free path for the scattering of neutrinos into gamma rays and λ_γ corresponds to the mean free path of gamma rays. Multiplying Eq. (6) by neutrino flux and integrating over x, the secondary gamma-ray flux from the neutrino scattering will be given by:

$$\phi^\gamma_{\nu_\mu} = \phi_{\nu_\mu} \frac{1}{(\lambda_{\mu \to \gamma}/\lambda_\gamma) - 1} [e^{-d/\lambda_\mu} - e^{-d/\lambda_\gamma}] \tag{7}$$

For $\phi_{\nu_{\mu a}} = r_{\nu\gamma} \times \phi_\gamma^0(E_\gamma) = 0.03\ \phi_\gamma^0(E_\gamma)$ using Eq. (4), the secondary gamma-ray flux will be

$$\phi_{\nu_\mu}^\gamma = 0.03 \frac{\phi_\gamma^0}{(\lambda_{\mu\to\gamma}/\lambda_\gamma) - 1} [e^{-d/\lambda_{\mu\to\gamma}} - e^{-d/\lambda_\gamma}] \tag{8}$$

In the above expression, the second exponential factor corresponds to the gamma-ray flux produced directly in GRB and can be ignored, when $\lambda_{\mu\to\gamma} \sim d \approx 10^{27}$ cm. Hence, there is a possibility that the gamma-ray flux produced from the scattering of neutrinos will not be exponentially attenuated as compared to the gamma-ray flux produced directly from GRB. In forthcoming subsections, we numerically estimate the mean free path for astrophysical neutrinos and present results related to the flux of astrophysical gamma rays produced from the scattering of high-energy muon neutrinos.

A. Mean free path of neutrinos

The mean free path of neutrinos emitted from astrophysical sources can be calculated from the interaction rate of incident neutrinos with the background CMB neutrinos. The value of $\lambda_{\nu_\mu\to\gamma}$ will be given by [55]

$$\lambda_{\nu_\mu\to\gamma} = \frac{1}{\Gamma(\nu_{\mu a}\nu_{\mu b} \to \gamma_a\gamma_b)}, \tag{9}$$

where $\Gamma(\nu_{\mu a}\nu_{\mu b} \to \gamma_a\gamma_b)$ is the interaction rate of the incident neutrino with CMB neutrinos. The cross section for the production of gamma rays from the scattering of astrophysical neutrinos with CMB neutrinos (shown in Feynman diagram given in Fig. 2) is given by [57,58]

$$\sigma(\nu_{\mu a}\nu_{\mu b} \to \gamma_a\gamma_b) = \frac{81\alpha^2 s}{4\pi^3} \frac{(g_\mu g_{\nu_\mu})^2}{(s - m_\phi^2)^2 + m_\phi^2\Gamma_\phi^2} \times \left|1 + \sum_f Q_\mu^2 m_\mu^2 C_0^\gamma\right|^2, \tag{10}$$

where scalar Passarino–Veltman function C_0^γ is given by,

$$C_0^\gamma(s, m_\mu) = \frac{1}{2s} \ln^2\left(\frac{\sqrt{1 - 4m_\mu^2/s} - 1}{\sqrt{1 - 4m_\mu^2/s} + 1}\right). \tag{11}$$

By using the expression of cross section given in Eq. (10), the thermal interaction rate is given by [55]

$$\Gamma(\nu_{\mu a}\nu_{\mu b} \to \gamma_a\gamma_b) = \int \frac{d^3p}{(2\pi)^3} f_i(\vec{p_i}) v_{\mathrm{Mol}} \sigma(s(E_\nu, \vec{p})). \tag{12}$$

Today, the CMB neutrino background has a thermal distribution with total number density $n_{\mathrm{tot}} \approx 340\ \mathrm{cm}^{-3}$ and temperature $T_\nu = 1.9$ K. Given this, the background CMB neutrino can be considered as nonrelativistic with $m_{\nu_\mu} > T_\nu$. In this case, the center-of-mass energy $\sqrt{s}$ becomes independent of the momentum and we can get $\sqrt{s} = \sqrt{2m_{\nu_\mu}E_{\nu_{\mu a}}}$ and $v_{\mathrm{Mol}} = 1$. Using this, the integral can be easily solved in a lab-frame and the interaction rate for scattering with nonrelativistic background neutrinos reduces to

$$\Gamma(\nu_{\mu a}\nu_{\mu b} \to \gamma_a\gamma_b) = \sigma(2E_{\nu_{\mu a}} m_{\nu_\mu}) n_{\nu_{\mu b}}, \tag{13}$$

Using this, the mean free path (MFP) for secondary gamma rays can be calculated from

$$\lambda_{\nu_\mu\to\gamma} = \frac{1}{\sigma(2E_{\nu_{\mu a}} m_{\nu_\mu}) n_{\nu_{\mu b}}}, \tag{14}$$

For the scattering process involving $\nu_{\mu a}\nu_{\mu b} \to \gamma_a\gamma_b$, the energy of gamma rays can be approximately equal to the energy of emitted astrophysical neutrinos. Thus, we can keep $E_{\nu_{\mu a}} \approx E_{\gamma_a}$. Using this, we have calculated the mean free path of neutrino elastic scattering as well as neutrinos annihilating into gamma rays. The results are shown in Fig. 3. The red solid line gives mean free path for neutrino for elastic scattering of incident astrophysical neutrino with CMB neutrinos for $g_{\nu_\mu} = 0.01$ while the black dashed line gives mean free path of neutrino for $g_{\nu_\mu} = g_\mu = 0.01$ when the interaction of incident astrophysical neutrino with CMB neutrinos produces gamma rays. The dip in the curve shows the resonance enhancement of the cross section at $s \approx m_\phi^2$.

We can also see that the mean free path for inelastic scattering is less than the elastic scattering by a factor of

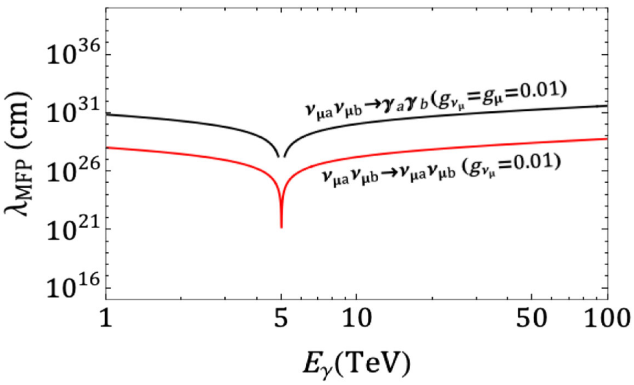


FIG. 3. The red solid line corresponds to the mean free path of neutrino for the elastic scattering of an incident astrophysical neutrino with CMB neutrinos for interaction coupling $g_{\nu_\mu} = 0.01$. The black dashed line shows the mean free path of neutrino for $g_{\nu_\mu} = g_\mu = 0.01$ when the interaction of an incident astrophysical neutrino with CMB neutrinos produces gamma rays. The dip in the curve shows the resonance enhancement of the cross section at $s \approx m_\phi^2$.

around 10^{-3}. However, as the cross section hits the resonance at specific energies, the mean free path for both processes can lie in the range $d \gtrsim 645\ \mathrm{Mpc} = 2 \times 10^{27}$ cm for appropriate choices of g_{ν_μ}, g_μ, and m_ϕ. Thus, the optical depth for neutrinos traveling to earth given by $\tau = e^{-d/\lambda_{\mu\to\gamma}}$ can be around $\mathcal{O}(1)$ for a narrow energy range above TeV. Therefore, it is possible that some of the high-energy gamma rays could have been originated from neutrino scattering.

B. Astrophysical gamma-ray flux

Now we calculate the secondary flux of astrophysical photons emitted from scattering of incident astrophysical neutrinos with CMB neutrinos by using Eqs. (8)–(14) for different values of couplings (g_{ν_μ}, g_μ) and fixing the mass of mediator around $m_\phi \sim$ MeV. We assume that the background CMB photons will not acquire much energy, therefore we can keep $E_{\gamma a} \approx E_{\nu a}$. Further, we have compared our results with the unattenuated and attenuated gamma-ray flux directly coming from GRB events. As discussed above, the final expression for calculating the secondary gamma-ray flux is given by:

$$\phi^{\gamma}_{\nu_\mu}(E_\gamma) = \frac{0.03\phi^0_\gamma(E_\gamma)}{(\lambda_{\mu\to\gamma}/\lambda_\gamma) - 1}\left[e^{-d/\lambda_{\mu\to\gamma}} - e^{-d/\lambda_\gamma}\right]. \qquad (15)$$

For calculating the flux, we need to determine both $\lambda_{\mu\to\gamma}$ and λ_γ. The value of $\lambda_{\mu\to\gamma}$ has been already calculated using Eq. (14). We have obtained the value of λ_γ at different energies by using publicly available data for the optical depth of photons (calculated at red-shift $z = 0.15$) given in [59] for energy up to 30 TeV. The behavior of secondary flux as a function of energy is shown in Fig. 4. We can see from the figure that the flux of astrophysical gamma rays produced from neutrino sources does not attenuate at high energies even though the magnitude of flux is lower than the direct gamma-ray flux at lower energies. Additionally, the flux gets much higher at a specific energy because the cross section around resonance turns out to be such that the mean free path becomes exactly equal to d.

The results are shown for three different benchmark values of the coupling of g_{ν_μ} and g_μ respectively. The choice of benchmark couplings has been motivated by Hubble tension requirement as well as the allowed region of g_μ from experimental results of $(g-2)_\mu$ etc. We will discuss the specific choice of coupling parameters in the next subsection.

C. Parameter space of neutrino self-interaction coupling vs mass of the mediator

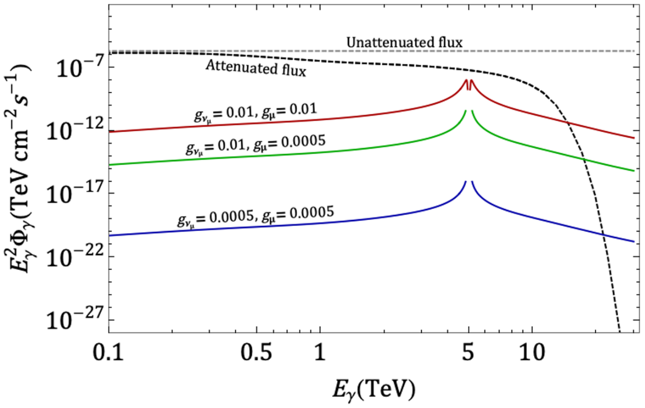


FIG. 4. The gray dashed line shows the unattenuated gamma-ray flux directly coming from GRB. The black dashed line shows the attenuated gamma-ray flux directly coming from GRB. The red, green, and blue solid lines show the secondary flux of astrophysical high energy gamma rays obtained from the scattering of astrophysical neutrinos with CMB neutrinos for different couplings of g_{ν_μ} and g_μ respectively. The mass of the mediator has been fixed to be $m_\phi \approx 1$ MeV. We can notice that at a specific energy, the flux gets much higher as the cross section turns out to be such that the mean free path becomes exactly equal to d.

In this subsection, we estimate the total number of secondary gamma-ray events observed from the scattering of astrophysical neutrinos with CMB neutrinos. The number of events can be computed by multiplying the flux with an effective cross section area and observation time. Using an effective area of 1 km^2 and observation time window of 2000 sec [24], the number of events in the energy range $E_\gamma \sim (1\text{–}30)$ TeV can be calculated from

$$N_\gamma = \int_{1\ \mathrm{TeV}}^{30\ \mathrm{TeV}} \phi^{\gamma}_{\nu_\mu}(E_\gamma)\, dE_\gamma\, dA\, dt, \qquad (16)$$

where $\phi^{\gamma}_{\nu_\mu}(E_\gamma)$ corresponds to flux given in Eq. (15). As N_γ depends on the self-interaction neutrino coupling (g_{ν_μ}) and mass of the mediator (m_ϕ), we can use Eq. (16) in order to constrain the parameter space of g_{ν_μ} as a function of m_ϕ. Thus, we have obtained $g_{\nu_\mu} - m_\phi$ parameter space by considering bounds on the number of observed events. In particular, we consider three cases for the observed number of events: (i) $N_\gamma = 100$, (ii) $N_\gamma = 1000$, and (iii) $N_\gamma = 5000$. The values of g_{ν_μ} and g_μ depend on the underlying model of BSM physics. As we do not consider any UV complete model of BSM physics, we are assuming that the values of both couplings can either be different or the same. Therefore, while obtaining the parameter space, we have considered two possibilities: (a) $g_{\nu_\mu} = g_\mu$, (b) $g_{\nu_\mu} \neq g_\mu$. For the second case, we have fixed the value of g_μ allowed by constraints from the recently measured value of $(g-2)_\mu$ [49]. The results are shown in Figs. 5 and 6 for both cases along with parameter space allowed by Hubble tension requirement and ruled out by other cosmological/laboratory constraints. The dashed, dotted, and solid black curves in both figures show the parameter space required to observe $N_\gamma = 100$, $N_\gamma = 1000$, $N_\gamma = 5000$ events respectively.

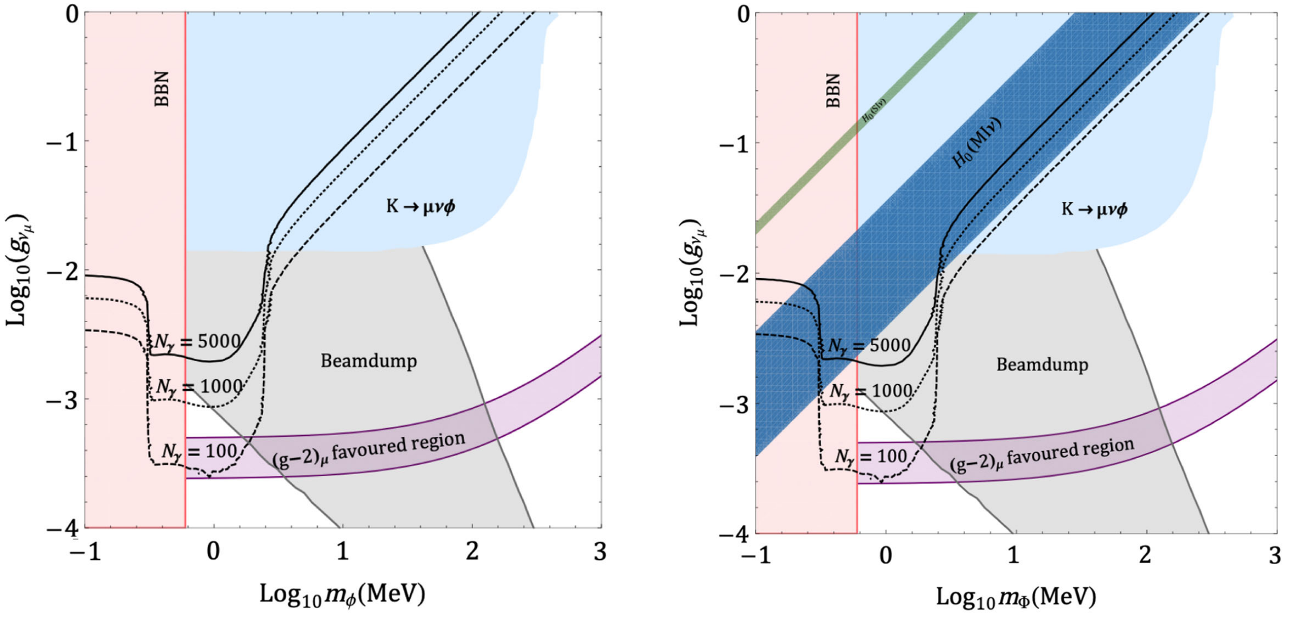
In both the figures, we can see that only for a small range of m_ϕ, the required number of events can be obtained for a relatively small value of g_{ν_μ}. This is due to the occurrence of high photon flux near the resonance in the cross section at $s \approx m_\phi^2$. Thus, the maximum number of events appears only at specific energies as the photon flux becomes much higher only at energies extremely close to the resonance. E.g. for $g_{\nu_\mu} = 0.01$ and $g_\mu = 0.0005$ in Figs. 5 and 6, most of the photons produced from the scattering of neutrinos will have an energy of around 5 TeV (depending on the mass of mediator). Now we discuss all other constraints shown in Figs. 5 and 6.

a. Constraints from Hubble tension: As discussed in [2], the strength of self-interacting neutrino required to get the right value of Hubble constant can be categorized in two regimes, dubbed as strong-interacting neutrino (SIν) and moderately interacting neutrino (MIν). The values of G_{eff} in both regimes are given as:

$$G_{\text{eff}} = \begin{cases} (4.7^{+0.4}_{-0.6}\ \text{MeV})^{-2}, & \text{SI}\nu \\ (89^{+171}_{-61}\ \text{MeV})^{-2}, & \text{MI}\nu. \end{cases} \tag{17}$$

The resulting parameter space along with Hubble tension constraints is shown separately in Figs. 5(b) and 6(b) for both cases by superimposing allowed range of G_{eff} as blue-shaded and green-shaded band respectively.

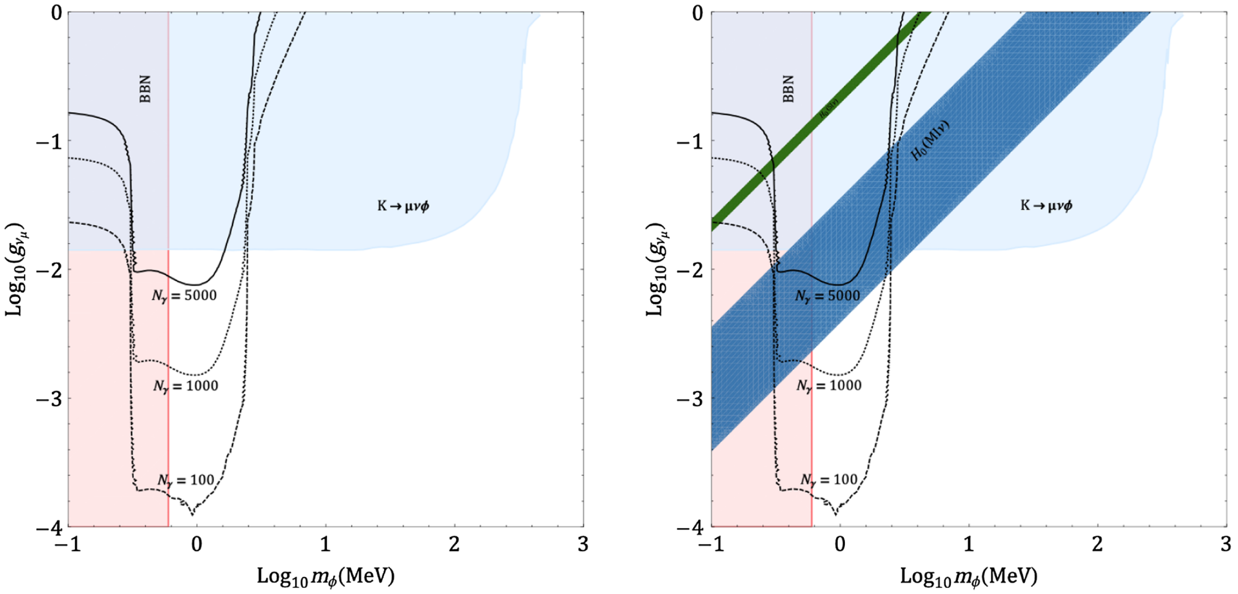
b. Various other cosmological and laboratory constraints: The new interaction between neutrinos and scalar mediator allows the light scalar mediator to be in thermal equilibrium before the onset of neutrino decoupling and affect the total number of relativistic degree of freedom (ΔN_{eff}) present in the universe. Therefore, the requirement $\Delta N_{\text{eff}} \lesssim 0.5$ puts a bound on the mass of real scalar mediator to be $m_\phi \gtrsim 0.16$ MeV [60]. The ruled-out region is shown as a light-red shaded band in both Figs. 5 and 6. The constraints from the laboratory originate from the possible decay channel of kaon to the light scalar given by $K \to \mu\nu_\mu\phi$. The experimental bounds on the kaon decay rate put a bound on the coupling g_{ν_μ} for $m_\phi \leq m_\mu$ [61], as shown in Figs. 5 and 6. The ruled-out parameter space from this bound is shown as a light-blue shaded region in both figures. In the presence of a new scalar mediator coupled to the muon, the experimentally allowed value of $\Delta a_\mu = (g-2)_\mu/2$ puts a bound on the coupling parameter g_μ. Therefore, for the case of $g_{\nu_\mu} = g_\mu$ as shown in Figs. 5(a) and 5(b), we have considered constraints from the updated value of $(g-2)_\mu$ [49]. The allowed region is shown as purple-shaded band in Figs. 5(a) and 5(b). Similarly, the interaction coupling g_μ also gets constrained from beam dump experiments [62]. The gray shaded region in



(a) $g_{\nu_\mu} = g_\mu$

(b) $g_{\nu_\nu} = g_\mu$ (including Hubble tension constraints)

FIG. 5. The dashed, dotted, and solid black curves correspond to parameter space required to observe $N_\gamma = 100$, $N_\gamma = 1000$, and $N_\gamma = 5000$ events respectively. The light-red shaded region represents the parameter space ruled out by constraints from BBN [60]. The light-blue shaded region shows the excluded parameter space from the constraint on the branching ratio of kaon decay: $K \to \mu\nu_\mu\phi$ [61]. The gray shaded region excludes the parameter space from beam-dump experiments [62]. In (b), the blue and green shaded bands correspond to MIν and SIν region allowed by Hubble tension constraints [2]. In (a), we can see that the small amount of parameter space available for $N_\gamma = 100$ events is also consistent with the allowed region from $(g-2)_\mu$ [49].



(a) $g_{\nu_\nu} \neq g_\mu, g_\mu = 5 \times 10^{-4}$ (b) $g_{\nu_\nu} \neq g_\mu, g_\mu = 5 \times 10^{-4}$(including Hubble tension constraints)

FIG. 6. The dashed, dotted, and solid black curves correspond to parameter space required to observe $N_\gamma = 100$, $N_\gamma = 1000$, and $N_\gamma = 5000$ events respectively. The light-red shaded region represents the parameter space ruled out by constraints from BBN [60]. The light-blue shaded region shows the excluded parameter space from the constraint on the branching ratio of kaon decay: $K \to \mu\nu_\mu\phi$ [61]. In (b), the blue and green shaded bands correspond to MIν and SIν region allowed by Hubble tension constraints [2].

Figs. 5(a) and 5(b) excludes the parameter space from beam-dump experiments [62]. For $g_{\nu_\mu} \neq g_\mu$, we have already fixed the value of $g_\mu = 5 \times 10^{-4}$ which is consistent with the allowed experimental value of Δa_μ. Thus, the bound from $(g-2)_\mu$ does not exist on g_{ν_μ} in Figs. 6(a) and 6(b). The bound from beam dump experiment will also not apply in the second case shown in Figs. 6(a) and 6(b).

Finally, we realize that a tiny amount of parameter space remains available for $N_\gamma = 100$ events for the case of $g_{\nu_\mu} = g_\mu$, which is also consistent with the allowed region of $(g-2)_\mu$. In this case, the region favored by Hubble tension constraints is ruled out by all other constraints. For $g_{\nu_\mu} \neq g_\mu$, the parameter space remains available for $N_\gamma \sim (100\text{–}5000)$ events. Interestingly, some of the parameter space for $N_\gamma = 5000$ events is also consistent with the MIν range allowed by Hubble tension constraints and free from other laboratory and cosmology constraints.

Thus, we conclude that the scattering of an astrophysical neutrino with CMB neutrinos can be one of the origins of high-energy astrophysical events observed from GRB, and some of the allowed region of g_{ν_μ} is also consistent with allowed values from Hubble tension constraints and $(g-2)_\mu$ discrepancy.

IV. CONCLUDING REMARKS

In the last few years, neutrino astronomy has turned out to be extremely useful in providing a more comprehensive understanding of the universe. In this work, we have emphasized the role of neutrinos in explaining high-energy gamma-ray events observed in GRB221009A through nonstandard self-interaction of neutrinos. The model of self-interacting neutrinos is primarily motivated in cosmology for resolving the discrepancy between the value of the Hubble constant measured by CMB observations and low red-shift experiments. The inclusion of the same can delay the epoch of neutrino decoupling and also modify the CMB power spectrum obtained in the ΛCDM model. As a result of this, the comparison of the modified CMB power spectrum with the measured CMB power spectrum allows a high value of Hubble constant in the ΛCDM model, thus reducing the Hubble tension. The detailed CMB analysis of the same allows a very specific range of self-interaction coupling vs. mass of the mediator. In this work, we assume that the same interaction of the scalar boson with neutrinos can also produce secondary gamma rays from the scattering of astrophysical neutrinos with CMB neutrinos if the new scalar mediator interacts both with muon neutrinos and its leptonic partner. The interaction of scalar with muons is already motivated by the discrepancy between the theoretical and experimental values of $(g-2)_\mu$. Basically, the interaction of an astrophysical neutrino with CMB produces a scalar boson, which can further decay into a high-energy astrophysical photon and a CMB photon at a one-loop level through the interaction of scalar mediator with muons.

By considering a toy model of a light scalar interacting with muon neutrinos and muons, we have calculated the mean free path of high-energy astrophysical gamma rays produced through such a process. As the scattering process involves new interactions governed by a new scalar mediator, we have shown that it is possible to obtain the mean free path $\lambda_{\nu_a\nu_b\to\gamma_a\gamma_b} = d(645\ \mathrm{MPc})$ for an appropriate choice of couplings (g_{ν_μ}, g_μ) and the mass of mediator m_ϕ. Thus, some of the high-energy gamma rays can be produced near the surface of the earth without getting attenuated. In most of the parameter space, the coupling required to obtain the relevant parameter space is quite large and ruled out by various astrophysical and laboratory constraints. However, given that the scattering cross section has a center-of-mass energy $\sqrt{s} = \sqrt{2m_\nu E_a}$, the scattering cross section exhibits resonance at $s = m_\phi^2$ for $m_\phi \sim$ 1–10 MeV and $E_a = 1$–30 TeV. As a result, the scattering cross section gets enhanced in an extremely narrow energy region around the resonance. In this given energy range, the mean free path is equal to d even for a relatively small value of neutrino self-interaction coupling. Thus, one can also find the maximal flux of photons for a relatively small value of neutrino self-interaction coupling in a narrow energy range. Interestingly, we have found that some of the resulting parameter space is also in agreement with the parameter space obtained from Hubble tension requirements, allowing $(g-2)_\mu$ region and free from other laboratory and cosmology constraints as well. We should also mention that the BBN and collider constraints shown in Figs. 6(a) and 6(b) have been obtained in a toy model of BSM physics. These constraints can be changed in a UV-complete model of particle physics (e.g. the BBN constraints are subjected to change if the UV completion takes into account the nonstandard cosmology). Thus, there is a possibility that the allowed parameter space might increase/decrease by taking into account the proper UV completion of a model.

To conclude, the self-interaction between neutrinos in the astrophysical environment can explain the origin of some of the high-energy gamma-ray events observed in GRB221009A. In the future, as CMB observations become more precise, the constraints on the allowed region of self-interaction between neutrinos will become even more stringent. Therefore, it would be interesting to study the consequences of the same in astrophysical processes. In other words, the exotic high-energy astrophysical gamma rays emitted from the scattering of neutrinos can act as a complementary probe to unveil the source of high-energy astrophysical neutrino events.

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