# GRB 221009A Gamma Rays from the Radiative Decay of Heavy Neutrinos?

Alexei Y. Smirnov * and Andreas Trautner †
*Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany*

(Received 1 December 2022; revised 17 April 2023; accepted 13 June 2023; published 13 July 2023)

We consider a mechanism that causes a decrease in the attenuation of high energy gamma-ray flux from gamma ray burst GRB 221009A. The mechanism is based on the existence of a heavy $m_N \sim (0.1 - 1)$ MeV mostly sterile neutrino $N$ which mixes with active neutrinos. $N$'s are produced in the gamma-ray burst (GRB) in $\pi$ and $K$ decays via mixing with $\nu_\mu$. They undergo the radiative decay $N \to \nu\gamma$ on the way to Earth. The usual exponential attenuation of gamma rays is lifted to an attenuation inverse in the optical depth. Various restrictions on this scenario are discussed. We find that the high energy $\gamma$ events at 18 TeV can be explained if (i) the GRB active neutrino fluence is close to the observed limit, (ii) the branching ratio of $N \to \nu\gamma$ is at least of the order 10%.

DOI: 10.1103/PhysRevLett.131.021002

*Introduction.*—Recently GRB 221009A set a new record for the brightest gamma ray burst ever detected. The initial detection was by BAT, XRT, UVOT on Swift, as well as GBM and LAT on Fermi satellite, see [1]. The redshift was determined by X-shooter of VLT (GCN 32648) as well as GTC (GCN 32686) to be $z = 0.1505$ corresponding to a distance of $d \approx 645$ Mpc. Large high altitude air shower observatory (LHAASO) WCDA as well as KM2A instruments detected $\mathcal{O}(5000)$ photons with $E_\gamma \gtrsim 500$ GeV from GRB 221009A within 2000 s after the initial outburst (GCN 32677) (detection significance for WCDA and KM2A is above 100 and 10 standard deviations, respectively). The photon energies reconstructed by LHAASO extend up to 18 TeV (the relative error of energy determination at 18 TeV is roughly 40% [2]), and even a single candidate $\gamma$ ray with an energy of 251 TeV and arrival time 4536 s has been reported by Carpet-2 at Baksan Neutrino Observatory [3].

These observations are puzzling because the flux of such high energy $\gamma$ rays should be severely attenuated in the intergalactic medium by electron pair production on background photons [4–6]. Standard propagation models [7–13] typically give optical depths of $\tau \sim 5, 15, 6000$ for photons of $E_\gamma \sim 10, 18, 250$ TeV, respectively, see [14] and references therein. While the observation of a high energy $\gamma$ event at 18 TeV can be borderline consistent with standard model physics [15], observation of a 251 TeV $\gamma$ ray from GRB 221009A is robustly excluded for all standard model propagation scenarios. The exponential attenuation of high energy $\gamma$ rays could be overcome in beyond the standard model scenarios with axion and/or ALP-photon mixing [14,16–21] (see [22] for a review) or violation of Lorentz invariance [14,23,24] (see [25] for a review). GRB 221009A observations have also triggered further investigations of gamma-ray bursts (GRBs) as a source of ultrahigh energy cosmic rays (UHECRs) [26–28], Earth ionospheric distortions [29], and the intergalactic magnetic field [30].

Here, we will consider an entirely different explanation of the observed excess of high energy $\gamma$ rays based on the existence of a heavy, $\mathcal{O}(0.1 - 1)$ MeV mass scale, mostly sterile neutrino $N$ which mixes with active neutrinos. Heavy neutrinos are produced in GRBs via mixing and then undergo the radiative decay $N \to \nu\gamma$ on the way to Earth. This produces additional high energy flux of $\gamma$ rays that would experience less attenuation.

*Fluxes of $\nu$ and $N$.*—GRBs are powerful sources of high energy neutrinos [31]. However, the predicted neutrino fluxes $\Phi_\nu$ are highly uncertain, see, e.g., [32,33] and [34] for a review, with a conservative uncertainty estimate of larger than 2 orders of magnitude. The time integrated fluxes (fluences) could reach $E_\nu^2 \Phi_\nu^{\mathrm{int}} \simeq \mathcal{O}(10^{-5})$ TeV cm$^{-2}$ at energies of $\mathcal{O}(\mathrm{TeV})$ and the general expectation is that $E_\nu^2 \Phi_\nu^{\mathrm{int}}$ rises with energy for energies up to $\mathcal{O}(10^3)$ TeV.

An upper bound on the neutrino fluence of GRB 221009A has been set from the nonobservation of tracklike neutrino events in the energy range 0.8 TeV − 1 PeV by IceCube and is given by (GCN 32665 and [35,36])

$$E_\nu^2 \Phi_\nu^{\mathrm{int}} < 3.9 \times 10^{-5}\ \mathrm{TeV\,cm^{-2}}. \tag{1}$$

Let us introduce the ratio of the neutrino flux $\Phi_\nu$ to the unattenuated $\gamma$ flux $\Phi_\gamma^0$,

$$r_{\nu\gamma} \equiv \frac{\Phi_\nu}{\Phi_\gamma^0}. \tag{2}$$

The unattenuated $\gamma$ flux of GRB 221009A can be obtained by extrapolating the flux measured by Fermi-LAT (GCN 32658) in the energy range $(0.1-1)$ GeV to higher (TeV scale) energies [14]:

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

This extrapolation is justified by earlier observations of TeV scale $\gamma$ ray emission of GRB 180720B [37], GRB 190114C [38] (MAGIC), and GRB 190829A [39] (HESS). There, the TeV scale spectrum decayed with a power law index closely following the x-ray light curve, and showed a luminosity of a few percent of the latter (see GCN 32802 and references therein). In consistency with that, a retrospective Monte Carlo determination of the unattenuated flux necessary to reproduce the $\mathcal{O}(5000)$ events seen by LHAASO [15] has found the most likely unattenuated flux to be roughly 2 orders of magnitude smaller than (3) (for spectral index $-2$, taking into account detector properties and uncertainty of the attenuation models). In the following we will use the flux in Eq. (3) and the $\mathcal{O}(100)$ smaller flux found by [15] as upper and lower limit benchmarks for the unattenuated $\gamma$ flux, see Fig. 1.

Dividing the IceCube bound on neutrino fluence (1) by the $\Delta t \simeq 600$ s long period of the most intense $\gamma$ emission we obtain an average neutrino flux $\Phi_\nu = \Phi_\nu^{\mathrm{int}}/\Delta t$ and, using (3) as unattenuated $\gamma$ flux, a flux ratio of $r_{\nu\gamma} \lesssim 3\times 10^{-2}$. For shorter periods of time, or smaller unattenuated $\gamma$ flux, much larger flux ratios are possible. Notice that the total number of events is given by the integral over time and, therefore, does not depend on the value of $\Delta t$.

Since GRB neutrinos are predominantly produced in pion and muon decays [34] the flux of heavy neutrinos for $m_N \lesssim 1$ MeV can be parameterized as

$$r_{N\nu} \equiv \frac{\Phi_N}{\Phi_\nu} = \frac{\sum_{\ell=e,\mu}|U_{N\ell}|^2\Phi_{\nu_\ell}}{\sum_{\ell=e,\mu}\Phi_{\nu_\ell}}. \tag{4}$$

If $N$ would exclusively mix with $\nu_\mu$ and the total highest energy neutrino flux is dominated by $\nu_\mu$, then $r_{N\nu} = |U_{N\mu}|^2$ is simply given by the corresponding mixing matrix element. We adopt this case as a benchmark.

The angular dispersion of $\gamma$'s produced in decays of $N$'s with energy $E_N$ is $\Theta \simeq m_N/E_N \sim 10^{-8}$. If the GRB jet opening angle is bigger than $\Theta$, then there is no additional suppression of the $\gamma$ flux from $N$ at the Earth.

*Propagation scenario.*—Let us compute the $\gamma$ flux at Earth originating from $N$ decays. In terms of the total decay rate $\Gamma_N$ the decay length is given by

$$\lambda_N = \frac{E_N}{\Gamma_N m_N}. \tag{5}$$

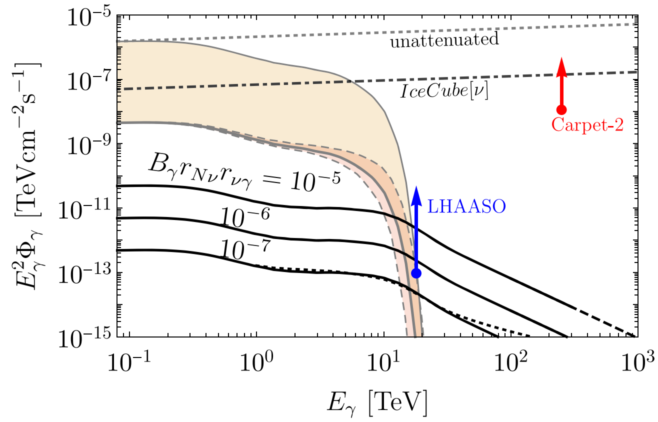


FIG. 1. The $\gamma$ fluxes from GRB 221009A at Earth as functions of $E_\gamma$. Dashed gray line: unattenuated $\gamma$ flux as in Eq. (3). Gray band upper end: direct $\gamma$ flux as obtained in [14] from the extrapolation of the Fermi-LAT flux and attenuation by $\tau(E_\gamma)$ from [10]. Gray band lower end: direct $\gamma$ flux and attenuation as obtained by [15] in order to reproduce $\mathcal{O}(5000)$ total events with $E_\gamma \gtrsim 500$ GeV at LHAASO; the dashed lines show the uncertainty of the optical depth [10]. Blue (red) arrows: lower limit on the flux set from LHAASO (Carpet-2) for one observed event at 18 TeV(251 TeV) (Poissonian 95% C.L., see [24]). Solid black line (this work): $\gamma$ flux induced by $N\to\nu\gamma$ decay for different values of prefactors in Eqs. (8) and (9) under the assumption that $\lambda_N = d$ at $E_N = 40$ TeV. Shown in a dash-dotted line is also the upper bound on the neutrino flux obtained from the IceCube bound on the neutrino fluence divided by $\Delta t = 600$ s. The dashed black line shows the approximation of Eq. (9) for the case $B_\gamma r_{N\nu} r_{\nu\gamma} = 10^{-7}$.

The probability that an individual $N$ decays in the distance interval $[x, x+dx]$ and the produced photon reaches Earth equals

$$B_\gamma e^{-x/\lambda_N}\frac{dx}{\lambda_N}e^{-(d-x)/\lambda_\gamma}. \tag{6}$$

Here, $B_\gamma$ is the branching ratio of the radiative decay, $d$ is the distance to the source, and the last factor describes the survival probability of $\gamma$ in terms of its absorption length $\lambda_\gamma$, which in turn corresponds to an optical depth $\tau \equiv d/\lambda_\gamma$. Multiplying the expression in Eq. (6) by the $N$ flux, $\Phi_N$, and integrating over $x$, we find the $N$-induced $\gamma$ flux

$$\Phi_\gamma^{(N)} = \Phi_N B_\gamma \frac{1}{\lambda_N/\lambda_\gamma - 1}[e^{-d/\lambda_N} - e^{-d/\lambda_\gamma}]. \tag{7}$$

Normalizing (7) to the direct unattenuated $\gamma$ flux, $\Phi_\gamma^0$, gives

$$\frac{\Phi_\gamma^{(N)}}{\Phi_\gamma^0} = B_\gamma\frac{\Phi_N}{\Phi_\gamma^0}\frac{1}{\tau\lambda_N/d - 1}[e^{-d/\lambda_N} - e^{-\tau}]. \tag{8}$$

Varying $d/\lambda_N$ for fixed $\tau$, we find that the maximal flux is obtained for $d/\lambda_N \approx 1$. Assuming $d/\lambda_N \approx 1$ and using the flux ratios $r_{N\nu}$ and $r_{\nu\gamma}$ with $\Phi_N/\Phi_\gamma^0 = r_{N\nu} r_{\nu\gamma}$, as defined earlier, as well as expanding in $\tau \gg 1$ as expected for high energy $\gamma$ rays, we obtain

$$\frac{\Phi_\gamma^{(N)}}{\Phi_\gamma^0} \approx B_\gamma \, r_{N\nu} \, r_{\nu\gamma} \, \frac{0.37}{\tau}. \tag{9}$$

Recall that the $\gamma$ flux produced directly in the GRB is attenuated as

$$\frac{\Phi_\gamma^d}{\Phi_\gamma^0} = e^{-d/\lambda_\gamma} = e^{-\tau}. \tag{10}$$

Equations (9) and (10) clearly show how the usual damping of the high energy $\gamma$ ray flux, exponential in $\tau$, can be overcome by the presence of decaying heavy neutrinos.

Let us underline that there is strong energy dependence in all of the above expressions. There, $\Phi_N$ and $\lambda_N$ depend on $E_N$, while $\lambda_\gamma$ (or equivalently $\tau$) strongly depends on $E_\gamma$. The explicit $E_N$ dependence of the attenuation factor can be displayed writing $\lambda_N/d = E_N/E_N^d$ with $E_N^d \equiv \Gamma_N m_N d$ being the energy at which $\lambda_N = d$. Then Eq. (8), neglecting the last term in brackets, reduces to

$$\frac{\Phi_\gamma^{(N)}}{\Phi_\gamma^0} \approx B_\gamma \frac{\Phi_N}{\Phi_\gamma^0} \frac{e^{-E_N^d/E_N}}{\tau(E_\gamma) E_N/E_N^d - 1}. \tag{11}$$

At the borders of the interval $\lambda_N/d = E_N/E_N^d = 0.5 - 2$ the attenuation increases by 20%.

In Fig. 1 we show the secondary $\gamma$ flux from $N$ decay for GRB 221009A. We use the approximation $E_\gamma \approx 0.5 E_N$, the maximal $\nu$ flux allowed by IceCube, and the full energy dependence of $\tau(E_\gamma)$ as extracted from [10], as well as the assumption that $\lambda_N = d$ at $E_N = 40$ TeV.

*Model independent constraints.*—The radiative decay of heavy neutrinos produces $\gamma$ rays with energy $E_\gamma \lesssim E_N$. The existence of nonzero mass of $N$ leads to dispersion of the $\gamma$ signal in time. Assuming that the direct $\gamma$'s and $N$'s are emitted during the same time interval and requiring that secondary $\gamma$'s of highest energies 18 TeV arrive at the detector within $\Delta t \leq 2000$ s, the heavy neutrino mass is bounded by

$$m_N \lesssim 4.5 \text{ MeV} \left(\frac{\Delta t}{2000 \text{ s}}\right)^{\frac{1}{2}} \left(\frac{E_N}{18 \text{ TeV}}\right). \tag{12}$$

Note that the detected $\gamma$ rays originating from the lowest energy heavy neutrinos set the most stringent bound here. For example, if $\gamma$'s with an energy as low as 0.5 TeV could be identified as originating from $N$ decay this would tighten the bound to $m_N \lesssim 0.25$ MeV but such an identification is unlikely given the large background from conventional $\gamma$'s in this region. On the other hand, if neutrinos and $N$ are emitted before the direct $\gamma$ emission then the bound can be substantially weakened. This is plausible, since $\gamma$'s and $N$'s can originate from different mechanisms and different spatial locations in the source. Furthermore, direct $\gamma$'s detected at Earth can only be emitted when the outer layers of the source become transparent enough. The bound can also be affected by the finite interval of pion production and time dependence of the energy of accelerated protons, and therefore pions. Detailed information on the arrival time of $\gamma$'s of different energies will allow the bound to be refined.

Requiring $\lambda_N \simeq d$ such that a substantial number of decays happen before the heavy neutrinos reach the Earth implies

$$\Gamma_N m_N \simeq 2 \times 10^{-31} \text{ MeV}^2 \left(\frac{E_N}{18 \text{ TeV}}\right) \left(\frac{d}{\lambda_N}\right). \tag{13}$$

For masses between 10 keV and a few MeV there are strong bounds on heavy *active* neutrino radiative decays from SN1987A [40–42]

$$\Gamma_\nu B_\gamma \lesssim 5 \times 10^{-14} \left(\frac{m_\nu}{\text{MeV}}\right) \text{s}^{-1}. \tag{14}$$

The flux of heavy neutrinos produced by SN1987A can be parametrized by the ratio

$$r_{N\nu}^{(SN)} \equiv \frac{\Phi_N^{(SN)}}{\Phi_\nu}. \tag{15}$$

Naively scaling the limit (14) by this ratio we obtain the constraint

$$\frac{\Gamma_N}{m_N} \lesssim \frac{3 \times 10^{-35}}{B_\gamma r_{N\nu}^{(SN)}}. \tag{16}$$

Combining this with condition (13) requires

$$B_\gamma r_{N\nu}^{(SN)} \lesssim 1.7 \times 10^{-4} \left(\frac{m_N}{\text{MeV}}\right)^2. \tag{17}$$

This shows that a saturation of the inequality $B_\gamma \leq 1$ is not excluded by the model independent constraints if $r_{N\nu}^{(SN)} \ll r_{N\nu} \approx |U_{N\mu}|^2$, which can be the case due to different production mechanisms and flavor composition. A persisting hint for an anomalously large, high energy $\gamma$ ray flux from GRB 221009A would motivate supernova simulations including the new heavy neutrinos, in order to scrutinize their production ratio and escape probabilities.

*Model dependent considerations.*—Because of mixing with active neutrinos, in the most minimal scenarios $N$

decays via three-body or two-body radiative channels with rates, see, e.g., [43]

$$\Gamma_N^{(3)} \approx \frac{G_F^2 m_N^5}{64\pi^3} |U_{N\mu}|^2, \tag{18}$$

$$\Gamma_N^{(2)} \approx \frac{9\alpha G_F^2 m_N^5}{512\pi^4} |U_{N\mu}|^2. \tag{19}$$

At face value this gives rise to a branching fraction

$$B_\gamma \approx \frac{9}{8}\frac{\alpha}{\pi} \approx 2.6 \times 10^{-3}. \tag{20}$$

Furthermore, one can use the explicit decay rates together with (13) in order to obtain

$$m_N \simeq \frac{0.125 \text{ MeV}}{|U_{N\mu}|^{\frac{1}{3}}} \left(\frac{E_N}{18 \text{ TeV}}\right)^{\frac{1}{6}} \left(\frac{d}{\lambda_N}\right)^{\frac{1}{6}}. \tag{21}$$

The bounds in Eqs. (12) and (21) leave a rather narrow range $0.2 \lesssim m_N \lesssim 4$ MeV.

There are strong constraints on the $|U_{N\ell}|^2 - m_N$ parameter space derived from energy loss of SN1987A [44,45]. These constraints are subject to theoretical, supernova modeling, and observational uncertainties and have recently been subject to further scrutiny [46–48] with the conclusion that they are generally not robust [[49], Sec. 7.1.3]. For large mixing parameter $|U_{N\mu}|^2 \sim 10^{-3}$ a protoneutron star is not transparent to $N$ and so the cooling arguments may not apply.

On the other hand, with such a large mixing, $N$'s thermalize in the early Universe, potentially distorting big bang nucleosynthesis (BBN), see, e.g., [50,51]. If the mass of $N$ is above MeV it is unconstrained by BBN, see, e.g., [52,53]. The BBN bounds can also be avoided in specific models with late phase transitions [54–57] or by invoking neutral lepton asymmetries [58].

Using (13), the lifetime of $N$ at rest is estimated to be $\tau_N \sim 10^2 (m_N/1 \text{ MeV})$ years, which is much shorter than the time of recombination epoch in the Universe $t_{\text{rec}} = 3 \times 10^5$ years. Therefore no substantial distortion of the cosmic microwave background is expected [59].

For this analysis, if we put aside the model dependent cosmological bounds, the strongest constraints on $|U_{N\mu}|^2$ arise from Pontecorvo–Maki–Nakagawa–Sakata (PMNS) matrix unitarity unitarity. We adopt as a benchmark $|U_{N\mu}|^2 \approx 10^{-3}$, see, e.g., [60].

The transition magnetic moment can be estimated as

$$\mu_N \simeq \sqrt{8\pi B_\gamma \Gamma_N / m_N^3}. \tag{22}$$

The decay rate of $N$ used here for $m_N = 0.2$ MeV and $|U_{N\mu}|^2 = 10^{-3}$ corresponds to the transition magnetic moment $\mu_N \simeq 10^{-15}\mu_B$, where $\mu_B$ is the Bohr magneton. Therefore the strongest bounds on neutrino magnetic moments are satisfied [61,62].

*Estimation of number of events.*—In the following we formulate the requirements on the heavy neutrino scenario in order to explain the observed GRB 221009A high energy events. The number of events corresponding to the unattenuated $\gamma$ flux $\Phi_\gamma^0$ is directly computed from (3). For an effective area of 1 km$^2$ [2,63] and observation time 2000 s there are approximately $5 \times 10^6$ events in the energy range $(10 - 40)$ TeV.

The corresponding flux of $N$-induced $\gamma$ events can be estimated via (9). Using $r_{N\nu} \approx |U_{N\mu}|^2 \approx 10^{-3}$, $r_{\nu\gamma} \approx 10^{-2}$, $\tau \approx 10$, and $B_\gamma \approx 10^{-3}$ we obtain an expected number of events of $10^{-3}$ in the energy range $(10 - 40)$ TeV. This agrees with the result of an exact integration using (8) and taking into account the energy dependence of $\lambda_N$ and $\tau$. While a detection would still be unlikely, secondary $\gamma$'s from heavy neutrino decays can increase the expected number of events by a few orders of magnitude as compared to most standard propagation models, cf. [14]. Note that $\Phi_\gamma^{(N)}$ is only linearly suppressed in $\tau$. Hence, the expected number of events at higher energies is tremendously increased over standard propagation models. For example, for parameters $B_\gamma r_{N\nu} r_{\nu\gamma} \approx 10^{-7}$ we find that the expected number of events in the energy range $(40 - 500)$ TeV is $\sim 10^{-4}$ while in standard propagation models it is suppressed by a factor smaller than $e^{-80}$.

We conclude that in order for the heavy neutrino scenario to explain the observed GRB 221009A highest energy $\gamma$ rays with high confidence, it is necessary to enhance the factor $B_\gamma r_{N\nu} r_{\nu\gamma}$ to $\sim 10^{-5}$. In turn, absence of a significant excess at $\gamma$ ray energies above 18 TeV would allow us to set tight constraints on this scenario in the future.

*Large $B_\gamma$.*—The expected number of events in the region $(10 - 40)$ TeV can be pushed to $0.1 - 1$ in agreement with the LHAASO observation, if $B_\gamma \approx 0.1 - 1$. This would also increase the number of expected events in the higher energy interval. However, taking into account the effective area of 50 m$^2$ the expected number of events at Carpet-2 in an energy interval $(40 - 500)$ TeV and in 4500 s is only of the order $\mathcal{O}(10^{-6})$, see Fig. 1, such that misidentification of a galactic foreground is still the most likely explanation for the 251 TeV event [64].

Large branching ratios for the radiative decay of $N$ can be obtained in more elaborate extensions of the standard model beyond just $\nu$-$N$ mixing. In the left-right symmetric models with right-handed current interactions of $N$, the radiative decay rate can be much bigger than that in Eq. (19). In this case the enhancement factor $32\sin^2 2\xi (m_\mu/m_N)^2$ appears, where $\xi$ is the mixing angle of $W_L$ and $W_R$. Taking $\sin^2 2\xi = 2 \times 10^{-6}$ we obtain the factor 16. Bigger enhancement ($\sim$100) can be obtained for tau-lepton mass (which implies $N$ mixing with $\nu_\tau$), thus leading to $B_\gamma \simeq 0.2$. Even bigger enhancement can be obtained in the models with charged scalars (the Zee-type models [65], see [66] and references therein for a recent discussion), so that $B_\gamma \simeq 1$ can be achieved. Larger branching ratios of $N \to \nu\gamma$ in these models correspond to larger transition magnetic moments and the corresponding decay widths can be computed with (22). Using (13) and the strongest laboratory constraints $\mu_N \lesssim 3 \times 10^{-11} \mu_B$ [62] the condition on the mass (21) can be relaxed to $m_N \simeq 10^{-2}$ MeV. If the strongest astrophysical constraints $\mu_N \leq 4.5 \times 10^{-12} \mu_B$ [61] are used (applicable only for $m_N \lesssim 20$ keV) the constraint on $m_N$ quantitatively agrees with Eq. (21). In the case of large transition magnetic moment for these lighter masses, the lifetime of $N$ can be as short as a few years.

For large $B_\gamma$ to be in agreement with the SN1987A constraints, Eq. (17) requires $r_{N\nu}^{(SN)}$ to be at least an order of magnitude smaller than $r_{N\nu}$, necessitating suppressed heavy neutrino production in supernovae as compared to GRBs.

*Conclusion.*—We have considered the production of heavy neutrinos in GRB and their sequential radiative decay on the way to Earth. We showed that in this way one can avoid the exponential suppression of the $\gamma$ flux with optical depth $e^{-\tau}$ and obtain $1/\tau$ suppression instead. This gives rise to an observable number of highest energy events at LHAASO if the mixing angle is large $|U_{N\mu}|^2 \sim 10^{-3}$ and the branching ratio is $B_\gamma \sim (0.1 - 1)$. We find that the preferred mass of $N$ is in a narrow range $(0.1 - 1)$ MeV.

We have discussed constraints on the mixing and branching fractions and find that they are possible to meet in specific models. The required value of $B_\gamma$ can be obtained in further extensions of the standard model beyond just the mixing of $N$ with $\nu_\mu$.

More refined estimates of the event rate, $\gamma$ spectrum, and the available parameter space are possible by assuming specific forms for the spectral and time dependences of the $\gamma$ fluxes. The publication of a detailed spectrum of the high energy events by LHAASO and additional observations of future GRBs could clarify the situation. If the hint for unexplained high energy gamma rays from GRB 221009A persists, the heavy neutrino with the characteristics described here could become a worthwhile target for searches in terrestrial laboratories, for example in pion decay-at-rest or neutrino accelerator experiments. An improvement of cosmological constraints from BBN and a refined understanding of supernova bounds would provide further checks of our proposal.

We thank Evgeny Akhmedov and Sudip Jana for useful conversations as well as Jeffrey Kuntz for carefully reading the manuscript.

*Note added.*—Recently, Ref. [67] appeared, which also considers radiative decay of a heavy neutrino as a way to explain GRB 221009A observations. In [67], $N$ is produced via the transition magnetic moment (and not mixing). This leads to a suppression of the $N$ flux by factor $\mu_N^2 m_\pi^2 \sim 10^{-14}$ for the magnetic moment $\mu_N = 3 \times 10^{-9} \mu_B$. Such a suppression is too strong to yield an observable number of high energy events at LHAASO. Furthermore, this large value of $\mu_N$ is excluded by laboratory and especially astrophysical observations.

*smirnov@mpi-hd.mpg.de
†trautner@mpi-hd.mpg.de

[1] See NASA, Gamma-ray Coordinates Network (GCN) circulars GCN 32632, GCN 32636, GCN 32637, GCN 32658, GCN 32642. https://gcn.gsfc.nasa.gov.

[2] X.-H. Ma *et al.*, Chapter 1 LHAASO instruments and detector technology *, Chin. Phys. C **46**, 030001 (2022).

[3] D. D. Dzhappuev *et al.*, Swift J1913.1 + 1946/GRB 221009A: Detection of a 250-TeV photon-like air shower by Carpet-2, Astron. Telegram **15669**, 1 (2022).

[4] A. I. Nikishov, Absorption of high-energy photons in the universe, Zh. Eksp. Teor. Fiz. **41**, 549 (1962) [J. Exp. Theor. Phys. **14**, 393 (1962)].

[5] R. Gould and G. Schréder, Opacity of the Universe to High-Energy Photons, Phys. Rev. Lett. **16**, 252 (1966).

[6] G. G. Fazio and F. W. Stecker, Predicted high energy break in the isotropic gamma-ray spectrum: A test of cosmological origin, Nature (London) **226**, 135 (1970).

[7] A. Franceschini, G. Rodighiero, and M. Vaccari, The extragalactic optical-infrared background radiations, their time evolution and the cosmic photon-photon opacity, Astron. Astrophys. **487**, 837 (2008).

[8] J. D. Finke, S. Razzaque, and C. D. Dermer, Modeling the extragalactic background light from stars and dust, Astrophys. J. **712**, 238 (2010).

[9] T. M. Kneiske and H. Dole, A lower-limit flux for the extragalactic background light, Astron. Astrophys. **515**, A19 (2010).

[10] A. Domínguez, J. R. Primack, D. J. Rosario, F. Prada, R. C. Gilmore, S. M. Faber, D. C. Koo, R. S. Somerville, M. A. Pérez-Torres, P. Pérez-González, J. S. Huang, M. Davis, P. Guhathakurta, P. Barmby, C. J. Conselice, M. Lozano, J. A. Newman, and M. C. Cooper, Extragalactic background light inferred from AEGIS galaxy-SED-type fractions, Mon. Not. R. Astron. Soc. **410**, 2556 (2011).

[11] R. C. Gilmore, R. S. Somerville, J. R. Primack, and A. Domínguez, Semi-analytic modelling of the extragalactic background light and consequences for extragalactic gamma-ray spectra, Mon. Not. R. Astron. Soc. **422**, 3189 (2012).

[12] F. W. Stecker, S. T. Scully, and M. A. Malkan, An empirical determination of the intergalactic background light from UV to FIR wavelengths using FIR deep galaxy surveys and the gamma-ray opacity of the universe, Astrophys. J. **827**, 6 (2016); **863**, 112(E) (2018).

[13] A. Saldana-Lopez, A. Domínguez, P. G. Pérez-González, J. Finke, M. Ajello, J. R. Primack, V. S. Paliya, and A. Desai, An observational determination of the evolving extragalactic background light from the multiwavelength

HST/CANDELS survey in the Fermi and CTA era, Mon. Not. R. Astron. Soc. **507**, 5144 (2021).

[14] A. Baktash, D. Horns, and M. Meyer, Interpretation of multi-TeV photons from GRB221009A, arXiv:2210.07172.

[15] Z.-C. Zhao, Y. Zhou, and S. Wang, Standard physics is capable to interpret ∼18 TeV photons from GRB 221009A, Eur. Phys. J. C **83**, 92 (2023).

[16] G. Galanti, M. Roncadelli, and F. Tavecchio, Explanation of the very-high-energy emission from GRB221009A, arXiv: 2210.05659.

[17] W. Lin and T. T. Yanagida, Electroweak axion in light of GRB221009A, Chin. Phys. Lett. **40**, 069801 (2023).

[18] S. V. Troitsky, Parameters of axion-like particles required to explain high-energy photons from GRB 221009A, Pis'ma Zh. Eksp. Teor. Fiz. **116**, 745 (2022) [JETP Lett. **116**, 745 (2022)].

[19] S. Nakagawa, F. Takahashi, M. Yamada, and W. Yin, Axion dark matter from first-order phase transition, and very high energy photons from GRB 221009A, Phys. Lett. B **839**, 137824 (2023).

[20] G. Zhang and B.-Q. Ma, Axion-photon conversion of LHAASO multi-TeV and PeV photons, Chin. Phys. Lett. **40**, 011401 (2023).

[21] M. M. González, D. A. Rojas, A. Pratts, S. Hernández, N. Fraija, R. Alfaro, Y. P. Araujo, and J. A. Montes, GRB 221009A: A light dark matter burst or an extremely bright Inverse Compton component?, Astrophys. J. **944**, 178 (2023).

[22] S. V. Troitsky, Axion-like particles and the propagation of gamma rays over astronomical distances, JETP Lett. **105**, 55 (2017).

[23] H. Li and B.-Q. Ma, Lorentz invariance violation induced threshold anomaly versus very-high energy cosmic photon emission from GRB 221009A, Astropart. Phys. **148**, 102831 (2023).

[24] J. D. Finke and S. Razzaque, Possible evidence for Lorentz invariance violation in gamma-ray burst 221009A, Astrophys. J. Lett. **942**, L21 (2023).

[25] H. Martínez-Huerta, R. G. Lang, and V. de Souza, Lorentz invariance violation tests in astroparticle physics, Symmetry **12**, 1232 (2020).

[26] S. Das and S. Razzaque, Ultrahigh-energy cosmic-ray signature in GRB 221009A, Astron. Astrophys. **670**, L12 (2023).

[27] R. Alves Batista, GRB 221009A: A potential source of ultra-high-energy cosmic rays, arXiv:2210.12855.

[28] N. Mirabal, Secondary GeV-TeV emission from ultra-high-energy cosmic rays accelerated by GRB 221009A, Mon. Not. R. Astron. Soc. **519**, L85 (2022).

[29] L. A. Hayes and P. T. Gallagher, A significant sudden ionospheric disturbance associated with gamma-ray burst GRB 221009A, Res. Notes AAS **6**, 222 (2022).

[30] Z.-Q. Xia, Y. Wang, Q. Yuan, and Y.-Z. Fan, Measurement of the $\sim 10^{-16}\sim$ Gauss inter-galactic magnetic field with high energy emission of GRB 221009A, arXiv:2210 .13052.

[31] E. Waxman and J. N. Bahcall, High-Energy Neutrinos from Cosmological Gamma-Ray Burst Fireballs, Phys. Rev. Lett. **78**, 2292 (1997).

[32] H.-N. He, R.-Y. Liu, X.-Y. Wang, S. Nagataki, K. Murase, and Z.-G. Dai, Icecube non-detection of GRBs: Constraints on the fireball properties, Astrophys. J. **752**, 29 (2012).

[33] P. B. Denton and I. Tamborra, Exploring the properties of choked gamma-ray bursts with IceCube's high-energy neutrinos, Astrophys. J. **855**, 37 (2018).

[34] S. S. Kimura, Neutrinos from gamma-ray bursts, arXiv: 2202.06480.

[35] S. Ai and H. Gao, Model constraints based on the IceCube neutrino non-detection of GRB 201009A, Astrophys. J. **944**, 115 (2023).

[36] K. Murase, M. Mukhopadhyay, A. Kheirandish, S. S. Kimura, and K. Fang, Neutrinos from the brightest gamma-ray burst?, Astrophys. J. Lett. **941**, L10 (2022).

[37] H. Abdalla *et al.*, A very-high-energy component deep in the $\gamma$-ray burst afterglow, Nature (London) **575**, 464 (2019).

[38] V. A. Acciari *et al.* (MAGIC Collaboration), Teraelectronvolt emission from the $\gamma$-ray burst GRB 190114C, Nature (London) **575**, 455 (2019).

[39] H. Abdalla *et al.* (H.E.S.S. Collaboration), Revealing x-ray and gamma ray temporal and spectral similarities in the GRB 190829A afterglow, Science **372**, 1081 (2021).

[40] A. Dar and S. Dado, Constraints on the Lifetime of Massive Neutrinos from Sn1987a, Phys. Rev. Lett. **59**, 2368 (1987).

[41] E. W. Kolb and M. S. Turner, Limits to the Radiative Decays of Neutrinos and Axions from Gamma-Ray Observations of SN 1987a, Phys. Rev. Lett. **62**, 509 (1989).

[42] L. Oberauer, C. Hagner, G. Raffelt, and E. Rieger, Supernova bounds on neutrino radiative decays, Astropart. Phys. **1**, 377 (1993).

[43] G. T. Zatsepin and A. Y. Smirnov, Neutrino decay in gauge theories, Yad. Fiz. **28**, 1569 (1978) [Sov. J. Nucl. Phys. **28**, 807 (1978)].

[44] S. Zhou, Supernova bounds on keV-mass sterile neutrinos, Int. J. Mod. Phys. A **30**, 1530033 (2015).

[45] M. Drewes *et al.*, A white paper on keV sterile neutrino dark matter, J. Cosmol. Astropart. Phys. 01 (2017) 025.

[46] V. Syvolap, O. Ruchayskiy, and A. Boyarsky, Resonance production of keV sterile neutrinos in core-collapse supernovae and lepton number diffusion, Phys. Rev. D **106**, 015017 (2022).

[47] A. M. Suliga, I. Tamborra, and M.-R. Wu, Lifting the core-collapse supernova bounds on keV-mass sterile neutrinos, J. Cosmol. Astropart. Phys. 08 (2020) 018.

[48] A. M. Suliga, J. F. Beacom, and I. Tamborra, Towards probing the diffuse supernova neutrino background in all flavors, Phys. Rev. D **105**, 043008 (2022).

[49] A. M. Abdullahi *et al.*, The present and future status of heavy neutral leptons, J. Phys. G **50**, 020501 (2023).

[50] A. Boyarsky, O. Ruchayskiy, and M. Shaposhnikov, The role of sterile neutrinos in cosmology and astrophysics, Annu. Rev. Nucl. Part. Sci. **59**, 191 (2009).

[51] B. D. Fields, K. A. Olive, T.-H. Yeh, and C. Young, Big-bang nucleosynthesis after Planck, J. Cosmol. Astropart. Phys. 03 (2020) 010; 11 (2020) E02.

[52] N. Sabti, J. Alvey, M. Escudero, M. Fairbairn, and D. Blas, Refined bounds on MeV-scale thermal dark sectors from BBN and the CMB, J. Cosmol. Astropart. Phys. 01 (2020) 004.

[53] N. Sabti, J. Alvey, M. Escudero, M. Fairbairn, and D. Blas, Addendum: Refined bounds on MeV-scale thermal dark sectors from BBN and the CMB, J. Cosmol. Astropart. Phys. 08 (2021) A01.
[54] G. M. Fuller and D. N. Schramm, Neutrino flypaper and the formation of structure in the universe, Phys. Rev. D **45**, 2595 (1992).
[55] Z. Chacko, L. J. Hall, S. J. Oliver, and M. Perelstein, Late Time Neutrino Masses, the LSND Experiment and the Cosmic Microwave Background, Phys. Rev. Lett. **94**, 111801 (2005).
[56] R. N. Mohapatra and S. Nasri, Avoiding BBN constraints on mirror models for sterile neutrinos, Phys. Rev. D **71**, 053001 (2005).
[57] L. Vecchi, Light sterile neutrinos from a late phase transition, Phys. Rev. D **94**, 113015 (2016).
[58] R. Foot and R. R. Volkas, Reconciling Sterile Neutrinos with Big Bang Nucleosynthesis, Phys. Rev. Lett. **75**, 4350 (1995).
[59] M. T. Ressell and M. S. Turner, The grand unified photon spectrum: A coherent view of the diffuse extragalactic background radiation, Comments Astrophys. **14**, 323 (1990).
[60] S. Parke and M. Ross-Lonergan, Unitarity and the three flavor neutrino mixing matrix, Phys. Rev. D **93**, 113009 (2016).
[61] N. Viaux, M. Catelan, P. B. Stetson, G. G. Raffelt, J. Redondo, A. A. R. Valcarce, and A. Weiss, Neutrino and Axion Bounds from the Globular Cluster M5 (NGC 5904), Phys. Rev. Lett. **111**, 231301 (2013).
[62] M. Agostini *et al.* (Borexino Collaboration), Limiting neutrino magnetic moments with Borexino Phase-II solar neutrino data, Phys. Rev. D **96**, 091103 (2017).
[63] S. Cui, Y. Liu, Y. Liu, and X. Ma (LHAASO Collaboration), Simulation on gamma ray astronomy research with LHAASO-KM2A, Astropart. Phys. **54**, 86 (2014).
[64] N. Fraija and M. Gonzalez (HAWC Collaboration), Swift J1913.1 + 1946/GRB 221009A: Galactic sources of > 100 TeV-photon in spatial coincidence with the 250-TeV photon-like air shower reported by Carpet-2, Astron. Telegram **15675**, 1 (2022).
[65] A. Zee, A theory of lepton number violation, neutrino Majorana mass, and oscillation, Phys. Lett. **93B**, 389 (1980); **95B**, 461(E) (1980).
[66] K. S. Babu, S. Jana, and M. Lindner, Large neutrino magnetic moments in the light of recent experiments, J. High Energy Phys. 10 (2020) 040.
[67] K. Cheung, The role of a heavy neutrino in the gamma-ray burst GRB-221009A, arXiv:2210.14178.