Ultra-high energy cosmic neutrinos from gamma-ray bursts

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ABSTRACT

Based on the recent association of IceCube TeV and PeV neutrino events with gamma-ray bursts (GRBs) by considering the Lorentz violation of neutrinos, we provide a new estimate on the GRB neutrino flux with a more significant result compared to the previous constraint by the IceCube Collaboration. Among these 24 neutrino “shower” events above 60 TeV, 12 events are associated with GRBs. Such a result is compatible with the prediction from GRB fireball models. Analysis of track events provides a consistent result with the shower events to associate high energy cosmic neutrinos with GRBs under the same Lorentz violation features of neutrinos. We also make a background estimation and reveal GRBs as a significant source for the ultra-high energy IceCube neutrino events. Our work supports the Lorentz violation and CPT-violation of neutrinos, indicating new physics beyond relativity.

1. Introduction

Cosmogenic ultra-high energy neutrinos are important to reveal new features of the Universe. After around ten years of measurements, the IceCube Collaboration has observed plenty of neutrino events with energies above 30 TeV including also several PeV-scale events [1–6]. However, the source of these ultra-high energy cosmic neutrinos still remains obscure. The neutrino emission associated with gamma-ray burst (GRB) was proposed from the fireball model of GRBs [7–10]. By associating GRBs and some lower-energy neutrinos within a time difference of several hundred seconds, the IceCube Collaboration [11–13] reported the constraint on GRB neutrinos with a small flux to exclude some fireball models [9,14].

However, because of the ultra-high energy of these detected neutrinos and the long propagating distance between the GRB source and the detector, a neutrino detected months around the GRB trigger time might be associated with the GRB by taking into account the Lorentz violation (LV) effect, since the small residual effects of LV can be accumulated into observable effects of several billion light-years [15]. Based on the IceCube data, Amelino-Camelia and collaborators associated TeV scale neutrino events with GRB candidates within a longer time range of three days [16–18]. It is also found in a recent study [19] that all of the four events of the PeV scale neutrinos observed by the IceCube observatory are associated with GRBs, by extending the temporal window with a longer time range of three months. The above associations of neutrino events with GRBs are obtained from the assumption of Lorentz violation of neutrinos and anti-neutrinos [18,19], together with also an asymmetry between neutrinos and anti-neutrinos to explain the existence of both time “delay” and “advance” events [19,20]. Therefore it is necessary to re-evaluate the GRB neutrino flux from the new association of IceCube TeV and PeV neutrino events with GRBs [18,19]. In this work, we provide a new constraint on the GRB neutrino flux based on the suggested association of GRBs with the IceCube TeV and PeV events [18,19] observed during 2010 to 2014 [21]. Among these 24 neutrino “shower” events above 60 TeV, 12 events are associated with GRBs [18,19]. We calculate the differential limit of GRB neutrino flux and find it compatible with the prediction from GRB fireball models. We also perform the analysis on the “track” events of IceCube neutrinos with energies higher than 30 TeV and find a consistent result with the “shower” events under the same Lorentz violation features of neutrinos. We therefore reveal GRBs as a significant source for ultra-high energy cosmic neutrinos provided that there are Lorentz violation of neutrinos and anti-neutrinos [18,19] with opposite signs to imply also an asymmetry between neutrinos and anti-neutrinos [19,20].

2. GRB neutrino flux

The phenomenological observations of GRBs can be well described by a relativistically expanding fireball of electrons, photons, and protons [22–24]. Ultra-high energy neutrinos can be emitted during the fireball expansion [7–10]. From the viewpoint of the fireball model, the
accelerated protons can scatter with the intense γ-ray background within the GRB fireball, and generate pions:

\[ p + γ \rightarrow Δ^+ \rightarrow n + π^+ \]  

(1)

The charged pions and their muon daughters generate ultra-high energy cosmic neutrinos by the decay chains:

\[ π^+ \rightarrow μ^+ + ν_μ - e^+ + ν_ν + ν_μ \]  

(2)

The flux of ultra-high energy neutrinos coincides with γ-rays, and the energy of produced neutrinos can be up to a few PeVs. After long-distance propagation in cosmic space, these high energy ν_μ and ν_ν neutrinos can interact with water or ice through charged-current interactions to produce high energy muons that manifest as extended Cherenkov light patterns in ice and can be detected by the IceCube detector as “track” events. Since the cosmic-ray-induced muon background is hard to remove, the Southern Hemisphere bursts are often excluded. To improve the sensitivity, another low-background channel named “Shower” is introduced [25]. “Shower” events include cascades from ν_μ, ν_e, charged-current interactions and all-flavor neutral-current interactions. Charged-current cascades include contributions from the electron (or tau decay products), as well as the hadronic shower from the scattered parton.

The event rate detected on the Earth can be described by the integration [13]:

\[ N = \int \frac{dΔΩ}{Ω} dE \frac{\Delta ν_{\text{el}} \langle E, Ω \rangle}{E} \times Φ_{ν_n}(E, Ω) \]  

(3)

where \( N \) is the rate of neutrino events, \( Ω \) is the solid angle, \( E \) is the neutrino energy, \( A_{\text{el}}(E, Ω) \) is the effective area of the IceCube detector and \( Φ_{ν_n}(E, Ω) \) is the signal neutrino flux. The effective area \( A_{\text{el}}(E, Ω) \) for full-sky shower-like event searches with the 79-string IceCube detector is provided by the IceCube Collaboration [13]. In the case of null observation, the quasi-differential limit of the neutrino flux can be written as [6,26]:

\[ Φ_{ν_n}(E) = \frac{3}{4πE} \frac{N}{T \log \Omega} \sum A_{\text{el}}(E_i) \]  

(4)

where \( N \) is the event number, and \( T \) is the observation time. The summation includes effective areas of all three neutrino flavors. An “equal” flavor ratio of neutrino fluxes \( ν_μ : ν_e : ν_x = 1 : 1 : 1 \) at the Earth is assumed under the standard neutrino oscillation scheme, though both neutrino oscillations and neutrino decays may make the propagation pattern in the Universe more complicated [27]. In our discussion, we use the four years IceCube data with the observation time \( T = 1347 \) days [21].

3. IceCube shower events

From 2010 to 2014, the IceCube detector observed 32 neutrino events with energies above 60 TeV, and 24 of them are “shower” events. To select probable GRB neutrinos we use time and direction criteria to find the associated GRB for each neutrino event [17–19]. The time mismatch could be extended by the ultra-high energy and the long propagation distance of neutrinos. Thus, it is reasonable to extend the time range with the increase of energy. For the TeV neutrinos, a time window of three days is adopted [18]. For the two 1 PeV events, we include the GRBs detected within one month before or after the neutrinos. For the 2 PeV event, the time window is two months [19]. By adopting these time windows, we find that each IceCube neutrino event may have more than one GRB candidates. To choose the most likely associated GRBs, we use the maximum correlation criterion [17–19] and the strict time criterion that requires [19]:

\[ \frac{Δν_{\text{Sel}}}{1 + z} \cdot s < 30.0 \cdot \frac{K}{Δν_{\text{LV}}} \]  

(5)

where \( E_{\text{LV}} \) is the Lorentz violation scale, \( K \) is the LV factor and \( s = ±1 \) is the sign factor of the LV correction term. Since the linear LV correction implies the CPT-odd term in an effective field theory, neutrinos and anti-neutrinos have opposite sign factors, i.e., there is an asymmetry between neutrinos and anti-neutrinos [19,20]. This time criterion requires that the observed time difference between the IceCube event and its associated GRB satisfies the possible Lorentz violation regularity proposed from GRB photons [28–30], TeV and PeV neutrinos [18,19], with the consideration of errors. The maximum correlation criterion and the strict time criterion can effectively depress the effects of GRB backgrounds. While considering the backgrounds, one should focus on the refined strict time criterion, rather than a rough time window of months. For the directional criterion, a two-dimensional circular Gaussian [17]:

\[ P(ν, GRB) = \frac{1}{2πσ^2} \exp \left( -\frac{ΔΨ^2}{2σ^2} \right) \]  

(6)

is introduced, where \( ΔΨ \) is the angular separation between GRB and neutrino, and \( σ = \sqrt{σ_{\text{GRB}}^2 + σ_{\text{GRB}}^2} \) is the standard deviation based on the angular uncertainties of GRB and neutrino measurements. The detailed values of both \( ΔΨ \) and \( σ \) can be found in the previous studies [17–19]. In our analysis, we consider the GRB whose angular separation is smaller than 3°. Regarding the redshift, some of the GRB candidates do not have determined redshift yet. As discussed in previous studies [17–19], here we use a most likely estimated value obtained as the average value of all known redshifts that have been measured so far. What needs to be emphasized is that a relatively wide error range of 0.5z ± 2z is considered for the unknown redshifts in our analysis. Such a range covers most of the known redshifts of GRBs detected so far and can also separate the “long burst” and the “short burst”, since the two error ranges have no overlap. In our analysis, the error of redshift plays a role in the errors of fitting parameters. Among the 24 “shower” events above 60 TeV, 12 events can be associated with GRBs. The properties of probable GRB neutrinos that satisfy both time and direction criteria are listed in Table 1.

We estimate the statistical significance of these 12 associated GRBs by calculating the background GRB number \( N_b \), which is defined as:

\[ N_b = \frac{1}{4} N_s \times ΔΩ \]  

(7)

where \( ΔΩ \) is the space angle obtained from the angular separation \( ΔΨ \), and \( N_s \) is the total number of GRBs that satisfy the time criterion Eq.5 of neutrino events. Here we count all GRBs collected in the GRB catalog [31]. The localization information of the GRBs that associated with 9 shower events with the energy from 60 to 500 TeV can be found in

| event | GRB | z | Δν_{\text{Sel}} (10^7 s) | E (TeV) | \( N_s \) | \( N_b \) |
|-------|-----|---|---------------------|--------|------|------|
| #2    | 100605A | 1.497* | −113.051 | 117.0 | 0.024 | 0.019 |
| #9    | 110503A | 1.613 | 80.335 | 63.2 | 0.083 | 0.07 |
| #11   | 110531A | 1.497* | 185.146 | 88.4 | 0.36 | 0.47 |
| #12   | 110625B | 1.497* | 160.909 | 104.1 | 0.06 | 0.13 |
| #14   | 110725A | 2.15 | 1320.217 | 1040.7 | 0.02 | 0.05 |
| #19   | 111229A | 1.3805 | 73.960 | 71.5 | 0.008 | 0.004 |
| #20   | 120119C | 2.15 | −1940.176 | 1140.8 | 1.8 | 4.1 |
| #26   | 120219A | 1.497* | 229.039 | 210.0 | 0.22 | 0.22 |
| #33   | 121023A | 0.6 | −171.072 | 308.7 | 0.19 | 0.14 |
| #35   | 130121A | 2.15 | −2091.621 | 2003.7 | 0.05 | 0.14 |
| #40   | 130730A | 1.497* | −179.641 | 157.3 | 0.069 | 0.05 |
| #42   | 131118A | 1.497* | −146.960 | 76.3 | 0.88 | 0.91 |

Note: The 12 GRB candidates are suggested from the associated GRBs of IceCube neutrinos with energies above 60 TeV by the maximum correlation criterion [17–19]. The event serial numbers here are provided by the IceCube database. Only “shower” events from refs. [17–19] are listed, while a 2.6 PeV “track” event in ref. [19] is discussed in next section. The mark * represents the estimated value of the redshift of the corresponding GRB. \( N_s \) is the estimated background GRB number of each event, and \( N_b \) is another option of the estimated background GRB number with fixed GRB rate.
The directionality of gravitational waves can be associated with GRB candidates due to the regularity of energy dependent speed variation found in both TeV and PeV shower events [19]. This solid line represents the energy dependence of speed variation found in both TeV and PeV shower events. The error bars here are estimated according to the same method in the reference [19]. We can find that the two track events are in good accordance with the regularity. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
The 12 probable GRB neutrinos are based on track events of the 2010 to 2014 IceCube data [21]. $E$ is the deposited energy of the track event, and it can be taken as the lower bound of the neutrino energy. In the top part of the table, the events marked by $^*$ has a 50% upper error which is 3 times of the energy. In the bottom part of the table, the estimated total energy of neutrinos is up to 2 PeV [19]. The event serial numbers here are provided by the IceCube database, except the #7856 which is the ATel ID of the GRB 140427A. The mark $^*$ represents the estimated value of the redshift of the corresponding GRB. $N_y$ is the estimated background GRB number of each event, and $N_y'$ is another option of the estimated background GRB number with fixed GRB rate.

On the other hand, the “deposited energy” (the particle energy collected by the IceCube detector) of the track event may be only a part of the muon energy, since the produced vertex of muon tracks may be located outside the instrumental volume [11]. The muon energy is only a part of the total energy of the neutrino too. Therefore, the deposited energy of track events may be much lower than the true energy of neutrinos. So the neutrino energy can range from the track energy to a large value of a few PeV in principle. Such large energy uncertainties lead to up to months errors in time windows.

To estimate the energy uncertainties, we consider three different levels. The first method is the same as our previous estimation [19], assuming that the positive error of energy is 50% and the negative error is provided by IceCube measurements. In this method, we find that two TeV scale track events, i.e., event #23 and #44, and the 2.6 PeV event ATel #7856 can be associated with GRBs and satisfy the regularity of energy-dependent speed variation found in shower events [19]. The accuracy between these three track events and shower events in Table 1 are shown in Fig. 1 and 2. The properties of the three probable GRB neutrinos from track events are listed in Table 2 with the mark $^*$. The detailed values of both $\Delta E$ and $\sigma$ for the track events can be found in Table 2.

Since the energy of track events is just a part of the muon energy, and the muon energy is also just a part of the total energy of neutrinos, the real neutrino energy may be much higher than the energy of the track events. So as the second estimation method, we assume that the positive error is three times of the deposited energy, i.e., the energy detected in the instrumental volume is assumed to be only 25% of the total neutrino energy. According to this error estimation, we find another track event #13 can also be associated with GRB. The event #13 is also shown in Fig. 2 and in Table 2 with the mark $^*$. Furthermore, since the PeV scale neutrinos are observed in both shower-like and track-like signals, we may reasonably assume that the total neutrino energy of track events can be up to PeV, though most of the energy are not detected. Such large energies lead to long time windows. Here we adopt a two months time window as our third estimation method, which is the same as the 2 PeV shower event. We find that in this method, another eight events can be also associated with GRBs, whose properties are listed in the bottom part of Table 2. Now we can see that, most of the track events (12 of 15 events) can be associated with GRBs, if the large uncertainties of track events are completely considered.

To estimate the significance of the associated GRBs, we also calculate the background GRB number $N_y$ of track events in two options. The calculation methods are similar to that of shower events. The only difference is that the uncertainty of energies, as well as that of the LV factor $K$, is too large to restrict the time criterion. Therefore, the GRB total number $N_T$ here consists of GRBs whose observed time $T$ satisfy:

$$|T - \Delta t_{\text{obs}}| < 30\% \cdot \Delta t_{\text{obs}}$$

where $\Delta t_{\text{obs}}$ is the observed time of the associated GRB of a track event. $N_y$ of each event can be obtained immediately, as listed in Table 2. The sum of $N_y$ is 2.89. If regarding the large background event ATel #7856 as the statistical error and excluding it, we obtain $\Sigma N_y = 1.75$ for the 11 candidates of track events. Therefore, the associations between GRB candidates and the track events are also significant in comparison with the background.

In the fixed GRB rate case, the time window is also adjusted according to Eq. 8, and the estimated GRB rate is 667 GRBs per year. The results of $N_y'$ are listed in Table 2. The sum of $N_y'$ is 8.272, and the $\Sigma N_y'$ of the 11 candidates except ATel #7856 is 4.242. So the number of GRB candidates that can be associated with track events is still larger than the GRB backgrounds. Considering the uncertain uncertainties in direction and the large uncertainties in energy, it is understandable that backgrounds of track events are larger than that of shower events.

From the above analysis of the track events, we find that 12 of 15 track events can be associated with GRBs if taking the large errors in both time and direction into consideration. What is more, even if we do not take these errors into consideration but use the same error estimation with shower events, we can still find 3 track events that can be associated with GRB candidates and satisfy the same regularity found in TeV and PeV shower events [18,19]. Therefore our results of track events are consistent with the shower events to associate high energy cosmic neutrinos with GRBs with a same Lorentz violation scale $E_{\gamma,Y}$, which is the only free parameter that can be determined by a single event in principle. One can easily figure out that the significance of our result is very high considering that 12 shower events and also 12 track events fall on the same line with a fixed $E_{\gamma,Y}$. It is interesting to notice that there are both “time” “delay” and “advance” events, as can be seen from Table 2, thus the track events also support the proposal [19] of Lorentz violation with different propagation properties between neutrinos and anti-neutrinos.

### 5. Results

Here we calculate the theoretical GRB neutrino flux according to two models, the proton escape model [9] and the neutron escape model [14]. We assume that there are 667 GRBs all over the full sky per year. The baryonic loading, which means the ratio of fireball energy in protons to electrons, is set as $f_p = 10$. The bulk Lorentz factor $\Gamma$ of the fireball is set as a benchmark value $\Gamma = 300$, which leads to a double broken power law of neutrino spectra peaking around 100 TeV [9]. To compare the theoretical results with the measurements of the ultra-high energy neutrino flux, we introduce a generic double broken power-law neutrino flux [11]:

$$\Phi_\nu(E_\nu) = \Phi_0 \times \begin{cases} \frac{E_\nu^{-1}}{E_0^{-1}}, & E_\nu \leq E_0, \\ \frac{E_\nu^{-2}}{E_0^{-2}}, & E_0 < E_\nu \leq 10E_0, \\ \frac{E_\nu^{-3}}{(10E_0)^2}, & 10E_0 < E_\nu, \end{cases}$$

where $\Phi_0$ is the first break energy and $\Phi_0$ is the quasi-diffuse spectral normalization flux. Considering Eq. 4, we get the generic double broken power-law neutrino spectrum as shown in Fig. 3. As a most conservative estimation on the order of magnitude, we only consider shower events in our analysis. Hence, it is acceptable that the GRB neutrino flux is two or three times larger than our estimation. For comparison, the IceCube
excluded regions for 68%, 90% and 99% confidence level (CL) [13] are also shown in the plot. We can find from Fig. 3 that our new limit of GRB neutrino flux is compatible with the proton escape model, whereas two fireball models were claimed to have been excluded by the IceCube limit at 90% CL [13].

In our discussion, IceCube “shower” events with energies above 60 TeV and “track” events with energies above 30 TeV are analyzed. 12 of 24 shower events and 12 of 15 track events can be associated with GRB candidates. This indicates that a part of these IceCube ultra-high energy neutrinos are emitted from the GRB source. The sources of ultra-high energy neutrinos might have more possibilities. As an example, some researches indicate that two ultra-high energy neutrinos might be emitted by blazars [24–36]. Such a small number of neutrino events associated with blazars does not conflict with the results to attribute GRBs as a significant source for IceCube TeV and PeV events [18,19].

6. Discussion

We see that our result on the GRB neutrino flux differs significantly from that of the IceCube Collaboration [12,13]. This difference is due to the different time windows between the neutrino events and the associated GRBs. In our analysis, we adopt a larger time range from a few days for TeV events [18] to a few months for PeV events [19] by taking into account a sizable Lorentz violation effect of neutrinos and anti-neutrinos, whereas the constraints on the GRB neutrino flux proposed by the IceCube Collaboration are based on an assumption that GRB neutrinos should be detected in very close temporal coincidence with the associated GRBs within a few hundred seconds [12,13]. In the combined linear fitting of TeV and PeV neutrinos [19], we also obtained an intrinsic time difference between neutrino and photon emissions as $\Delta t_N = (1.7 \pm 3.6) \times 10^7$ s. The intrinsic time difference $\Delta t_N$ of the order of 1–2 h can be safely neglected in the fittings of TeV and PeV neutrinos, since it is much more shorter than the observed time differences of the order of days or even up to months.

In fact, the GRB neutrinos are emitted from long distant sources, and speed variation may be caused by different reasons [15]. The in vacuo dispersion due to Lorentz invariance violation is one of the probable options, as well as the cosmic matter effect. Therefore, the time difference between neutrino observed time and the GRB trigger time may be days or even months, depending on the neutrino energy with the assumption of a sizable Lorentz violation of neutrinos. On the other hand, ultra-high energy neutrinos can be distinguished from neutrinos produced in the atmosphere and other backgrounds. No matter from the theoretical analyses [15–18] or the IceCube measurements [2–6], ultra-high energy neutrinos above 60 TeV can stand out from backgrounds, thus rendering our analysis on the limit of GRB neutrino flux more convincing.

The idea of using neutrinos from GRBs to explore quantum-gravity-induced Lorentz violation was first proposed by Jacob and Piran in 2007 [15]. Amelino-Camelia and collaborators found the associations between GRBs and nine IceCube shower neutrino events with the energies between 60 to 500 TeV [17,18], and found roughly compatible energy-dependent speed variation features between GRB neutrinos and GRB photons [28–30]. In our former work, we found that all of the four IceCube events of PeV scale neutrinos can be associated with GRBs [19]. Furthermore, we also suggested different propagation properties between neutrinos and anti-neutrinos due to the existence of both time “delay” and “advance” events. Such different neutrino/anti-neutrino propagation properties can be described in an effective field theory framework with CPT-odd terms of Lorentz invariance violation [20]. Therefore both PeV and TeV neutrino events satisfy a same speed variation regularity based on the assumption of an observable Lorentz violation effect of neutrinos and anti-neutrinos. Recently, from the associations between GRBs and near-TeV events reported by IceCube Collaboration, it is found that 12 near-TeV northern hemisphere track events can fall on the same line [37]. In this current paper, we show that another 3 or more track events above 30 TeV can be associated with GRBs and satisfy the same regularity. Based on these results, the energy-dependent speed variation feature of ultrahigh-energy neutrinos with the LV scale $E_{LV} = (6.4 \pm 1.5) \times 10^{-17}$ GeV emerges as a more convincing regularity.

7. Summary

In summary, we analyze the IceCube data in four years from 2010 to 2014 and get a new constraint on the GRB neutrino flux. Among all 24 “shower” neutrino events above 60 TeV, 12 events are associated with GRBs by considering the Lorentz violation of neutrinos [18,19]. In this paper we make an estimate of the background of our previously analyzed events and show that they stand out well beyond the background. Furthermore, we find that “track” events can also be associated with GRBs under the same Lorentz violation features of neutrinos. Our results of track events are consistent with the shower events with a same Lorentz violation scale $E_{LV}$. These results can be considered as new supports to the obtained LV scale $E_{LV}$ from previous works [17–19]. It is also indicated that the neutrino flux from GRBs associated by us is compatible with the prediction from GRB fireball models. We therefore conclude that gamma ray bursts can serve as a significant source for the ultra-high energy IceCube neutrino events provided that there are Lorentz violation of neutrinos and anti-neutrinos. Our work supports the Lorentz violation and CPT-violation of neutrinos as proposed in ref. [19], indicating new physics beyond relativity.

Declaration of competing interest

The authors declare that they have no conflicts of interest in this work.

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