Search for GeV and X-Ray Flares Associated with the IceCube Track-like Neutrinos

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Abstract

Dozens of high-energy neutrinos have been detected by the IceCube neutrino telescope, but no clear association with any classes of astrophysical sources has been identified so far. Recently, Kadler et al. reported that a PeV cascade-like neutrino event occurred in positional and temporal coincidence with a giant gamma-ray flare of the blazar PKS B1424-418. Since IceCube track-like events have much better angular resolution, we here search for possible short-term gamma-ray flares that are associated with the IceCube track-like events with Fermi Large Area Telescope (LAT) observations. Among them, three track-like neutrino events occur within the field of view of Fermi-LAT at the time of the detection, so searching for the prompt gamma-ray emission associated with neutrinos is possible. Assuming a point source origin and a single power-law spectrum for the possible gamma-ray sources associated with neutrinos, a likelihood analysis of 0.2–100 GeV photons observed by Fermi-LAT on the timescales of ∼12 hr and one year are performed, and for the three special neutrinos, the analyses are also performed on the timescales of thousands of seconds before and after the neutrino detection. No significant GeV excesses over the background are found and upper limit fluxes at the 95% confidence level are obtained for different timescales. We also search for possible the Swift hard X-ray transient sources associated with the IceCube track-like neutrino events, but the search also yields null results. We discuss the implication of the non-detection of gamma-ray flares for the constraints on the neutrino source density.

Key words: galaxies: active – gamma rays: galaxies – gamma rays: general – neutrinos

1. Introduction

The IceCube telescope has detected TeV–PeV neutrinos from extraterrestrial sources for the first time (IceCube Collaboration 2013; Aartsen et al. 2014; The IceCube Collaboration et al. 2015), which opens a new window to explore the high-energy universe. The explanation of a single atmospheric origin of these high-energy neutrino events collected over 4 years has been strongly unfavored at around a 6.5σ level of confidence (Aartsen et al. 2014; The IceCube Collaboration et al. 2015). The best fit result for the high-energy astrophysical neutrino flux reaches a level of \( E^{-2}_\nu \phi_\nu \sim 10^{-8} \text{ GeV cm}^{-2} \text{s}^{-1} \text{ sr}^{-1} \) per flavor between around 60 TeV and 2 PeV, and the spectral index of the power-law model is \( -2.5 \sim -2.0 \) (Aartsen et al. 2014, 2015a).

The astrophysical neutrinos have shown no significantly directional clustering (Aartsen et al. 2014). They also show no clear association with any known classes of astrophysical sources so far. High-energy neutrino emission results from the decays of charged pions produced in the interaction between relativistic protons and ambient gas (pp) or ambient radiation (pγ), and the same processes inevitably produce high-energy gamma-ray photons via the neutral pion decays. Although very high-energy photons above, e.g., 100 GeV, may be absorbed in the source or during the propagation in the intergalactic space, GeV photons could escape and arrive at the Earth accompanying neutrinos. The potential astrophysical sources that could produce high-energy neutrinos and photons include star-forming galaxies (Loeb & Waxman 2006; He et al. 2013; Murase et al. 2013; Anchordoqui et al. 2014; Liu et al. 2014; Tamborra et al. 2014; Wang et al. 2014; Chang et al. 2015), tidal disruption events (TDEs) (Wang & Liu 2016), gamma-ray bursts (GRBs) (Waxman & Bahcall 1997; Cholis & Hooper 2013; Liu & Wang 2013; Murase & Ioka 2013), active galactic nuclei (AGNs) (Anchordoqui et al. 2008; Kalashev et al. 2013; Stecker 2013; Dermer et al. 2014; Murase et al. 2014), double white dwarf mergers (Xiao et al. 2016), and even Galactic sources (Fox et al. 2013; Razzake 2013; Ahlers & Murase 2014; Lunardini et al. 2014; Neronov et al. 2014); see Ahlers & Halzen (2015) for a review. However, combined data analysis between IceCube neutrinos events and γ-ray source samples, such as GRBs, AGNs, soft γ-ray repeaters, supernova remnants, pulsars, microquasars, and X-ray binaries (Krauß et al. 2014; Padovani & Resconi 2014; Aartsen et al. 2015a, 2015b, 2016; Glüsenkamp 2016; Padovani et al. 2016; Wang & Li 2016), do not reveal any firm associations to date.

Recently, Kadler et al. (2016) found that a cascade-like PeV neutrino event occurred in positional and temporal coincidence with a giant gamma-ray flare of the flat spectrum radio quasars (FSRQs) PKS B1424-418, with a chance probability of 5% for such a coincidence (i.e., a 2σ confidence level correlation). This cascade-like neutrino has an angular error of ∼15′. In contrast to cascade-like events, the median angular resolution of muon track neutrino events is much better (≤1′), and hence they are good candidates to search for electromagnetic counterparts. Brown et al. (2015) performed a search for gamma-ray counterparts of the first seven IceCube track-like neutrinos (\( E_\nu > 30 \text{ TeV} \)) using 70 month Fermi-Large Area Telescope (LAT) data, and no steady γ-ray counterparts were found. For the purpose of examining whether short-term transient sources like PKS B1424-418 are associated with neutrinos, we here search for possible transient gamma-ray counterparts (on a timescale as short as hours) of 12 track-like events3 observed by IceCube up to 2016 August 6 (Aartsen et al. 2014; Schoenen & Raedel 2015; The IceCube Collaboration...)

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3 http://gcn.gsfc.nasa.gov/amon_bese_events.html http://gcn.gsfc.nasa.gov/amon_ebe_events.html
et al. 2015; Blaufuss 2016). We select neutrino events with energies larger than 60 TeV to reduce contamination from the atmospheric background (Aartsen et al. 2014). This analytical method, rather than cross-correlating with known catalogs, uses Fermi-LAT survey data to search for new γ-ray transients related to the IceCube track-like events, or flux variability of known γ-ray sources. In contrast to Brown et al. (2015), our work aims to find possible short-term or prompt GeV emission associated with these neutrinos, such as X-ray transients or gamma-ray transients (e.g., AGN gamma-ray flares), which could be missed in a 70 month long timescale analysis similar to Brown et al. (2015). We note that the gamma-ray flare of PKS B1424-418 is extremely strong and lasts for more than one year. Sources with flares at such flux levels and durations from neutrino directions examined in Brown et al. (2015) would have been observed as significant excesses. However, for sources like short-term bright flares of AGNs or GRBs, the signal may be diluted and become undetectable at a longer time interval. Our analysis is most sensitive to gamma-ray sources that are transient only in a short time interval and are quiet over a long time interval. For example, a radio-intermediate quasar III Zw 2 exhibits distinct GeV flares in the short term, but no significant gamma-ray signal has been detected in the time-averaged 7 year Fermi-LAT data (Liao et al. 2016). Fermi All-sky Variability Analysis has found that, among 518 flaring gamma-ray sources, 77 sources lack gamma-ray counterparts in the 7.4 years of Fermi observations (Abdollahi et al. 2016). Some TDEs show short-duration luminous X-ray flares. Although high-energy emissions from TDEs have not been detected by Fermi-LAT so far (Peng et al. 2016), they are potential sources of giant gamma-ray flares (Farrar & Gruzinov 2009). GRBs also have bright GeV emission during the prompt and afterglow phase, although there is no evidence of association with IceCube high-energy neutrinos to date. Our analysis would be sensitive to such short-term gamma-ray transients.

The organization of this paper is as follows. In Section 2, we describe the search results with the Fermi-LAT observations, and the result for the search of the Swift hard X-ray transient sources is described in Section 3. In Section 4, we discuss the implication of the non-detection of gamma-ray transients for constraining the source number density. Finally we give conclusions and discussions in Section 5.

2. Fermi-LAT Data Analysis

2.1. Fermi-LAT Data Analysis

The newly released Fermi-LAT (Atwood et al. 2009) Pass 8 SOURCE data (P8R2 Version 6) and Fermi science tools version v10r0p5 are used in the present work. An unbinned maximum likelihood analysis is performed on a region of interest (ROI) with a radius 10° centered on the R.A. and decl. of the each IceCube track-like neutrino. All FRONT+BACK converting photons with energies between 0.2 and 100 GeV are taken into consideration. We apply the maximum zenith-angle cut $\gamma_{\text{max}} = 90^\circ$ to eliminate the Earth’s limb emission. The expression of $(\text{DATA\_QUAL} > 0)$ and $(\text{LAT\_CONFIG} == 1)$ is used to further filter the data. A source model is generated containing the position and spectral definition for all the point sources and diffuse emission from the 3FGL (Acero et al. 2015) within 15° of the ROI center. The Galactic and extragalactic diffuse models are gll_iem_v06.fits and iso_p8r2_source_v6_v06.txt, respectively. We add a point source with power-law spectrum $(d\nu/dE = A \times (E/E_0)^{-1})$ on each track-like neutrino position in the source model file. Since we pay attention to the short-term behavior of γ-ray emission on the timescales of hours or months, the spectral indices of all point sources in the source model file are fixed to their 3FGL catalog values to solve convergence problems. The normalization factors of point sources, the extragalactic diffuse emission, and the Galactic diffuse emission are left free to vary. After each successful fit, a test-statistic (TS) map centered on the neutrino position is created to check if there is any excess γ-ray emission above the background beyond the 3FGL catalog. All the upper limit fluxes are reported at the 95% confidence level with fixed spectral index $\Gamma = 2$. We have tested assuming different spectral indices would result in a slight but insignificant difference.

2.2. Fermi-LAT Data Search Results

We first perform the data analysis over ~12 hr, i.e., 6 hr before and 6 hr after the neutrino detection time, to search for possibly prompt GeV emission accompanying these neutrino events. No significant gamma-ray emissions at the position of the track-like neutrino events are found, and thus their upper limit fluxes are obtained, see Table 1 and Figure 1. There is no new γ-ray source around the region of the neutrino position identified by checking the TS map. For comparison, the Fermi-LAT data analysis for the gamma-ray flaring blazar PKS B1424-418 in a similar time period (centering at the detection time of the neutrino event number 35 ) is also carried out and the result is presented in Table 1 and Figure 1. For the same period of time, PKS B1424-418 shows bright emission with a detection significance of $\text{TS} = 57$, and the photon flux is $3.54 \pm 0.99 \times 10^{-7} \text{ph cm}^{-2} \text{s}^{-1}$ (i.e., the corresponding energy flux is $4.05 \pm 1.14 \times 10^{-10} \text{erg cm}^{-2} \text{s}^{-1}$ in 0.2–100 GeV). As we can see in Figure 1, the upper limit fluxes of any possible point sources associated with the track-like neutrinos are below the flux of the PKS B1424-418. We also find that all the 3FGL sources within the $2 R_{50}$ angular error of track-like neutrinos are too weak to be detected by Fermi-LAT for 12 hr observations (here $R_{50}$ means angular error at the 50% confidence level).

As some blazar outbursts occur on the timescale of months, we further choose one year for the time window to search for gamma-ray flares. The likelihood analysis of Fermi-LAT data of each track-like neutrino event is conducted, which also yields a null result. The upper limit fluxes covering the period of half year before and half year after the neutrino detection time are given in Table 1 and also shown in Figure 2. Similarly, over one year Fermi-LAT observation centering at the detection time of the neutrino event number 35, PKS B1424-418 shows high photon flux $5.89 \pm 0.06 \times 10^{-7} \text{ph cm}^{-2} \text{s}^{-1}$ (TS = 50770), which corresponds to an energy flux of $8.17 \pm 0.14 \times 10^{-10} \text{erg cm}^{-2} \text{s}^{-1}$. The upper limit gamma-ray fluxes for the track-like neutrinos are far below the flux of PKS B1424-418. We note that neutrino event number 5 has a known 3FGL γ-ray source J0725.8-0054 (BL Lac object PKS 0723-008) located ~1° from the neutrino’s position. Another 3FGL γ-ray source J2227.8+0040 (BL Lac object PMN J2227
Table 1
Upper Limit Gamma-ray Fluxes of the Track-like Neutrino Events as Observed by Fermi-LAT on the Timescales of 12 hr and 1 Year

| ID   | Energy (TeV) | R.A. (°) | Decl. (°) | Angular Error (°) | Flux($\times 10^{-8}$) ph cm$^{-2}$ s$^{-1}$ | Flux($\times 10^{-10}$) ph cm$^{-2}$ s$^{-1}$ |
|------|--------------|----------|-----------|-------------------|---------------------------------------------|---------------------------------------------|
| 3    | 78.7±10.8    | 127.9    | −31.2     | 1.4               | 8.05                                        | 3.75                                        |
| 5    | 71.4±9.0     | 110.6    | −0.4      | 1.2               | 5.94                                        | 17.4                                       |
| 13   | 253±22       | 67.9     | 40.3      | 1.2               | 9.25                                        | 8.17                                       |
| 23   | 82.2±8.8     | 208.7    | −13.2     | 1.9               | 9.80                                        | 19.9                                       |
| 38   | 200.5±16.4   | 93.34    | 13.98     | 1.2               | 18.1                                        | 35.0                                       |
| 44   | 84.6±7.9     | 336.71   | 0.04      | 1.2               | 32.4                                        | 4.19                                       |
| 45   | 429.9±49.1   | 218.96   | −86.25    | 1.2               | 5.71                                        | 14.5                                       |
| 47   | 74.3±7.9     | 209.36   | 67.38     | 1.2               | 3.81                                        | 7.40                                       |
| 55a  | 2600 ± 300   | 110.34   | 11.48     | 0.27              | 11.3                                        | 8.61                                       |
| 160427A  | ...       | 240.57   | 9.34      | 0.6               | 9.95                                        | 20.8                                       |
| 160731A  | ...       | 215.109  | −0.4581   | 0.35              | 12.5                                        | 24.7                                       |
| 160806A  | ...       | 122.81   | −0.8061   | 0.5               | 3.22                                        | 5.15                                       |

PKS B1424-418 35.4 ± 9.92 5889 ± 60

Notes. The first column is the neutrino ID. The second column represents the energy of each neutrino event. The third and forth columns describe the positions of the neutrinos. The fifth column represents the median angular error $\sigma_{\text{med}}$. The last two columns are the upper limit fluxes (0.2–100 GeV) over 12 hr and 1 year observations by Fermi-LAT around the neutrino detection time, respectively. The measured fluxes of the gamma-ray flare of PKS B1424-418 on the timescales of 12 hr and 1 year are also shown for comparison.

a Neutrino event number 55 is a PeV event with $R_{50} \approx 0^\circ 27$ (Schoenen & Raedel 2015).

b 160427A—Blaufuss (2016); 160731A—http://gcn.gsfc.nasa.gov/notices_amon/6888376_128290.amon; 160806A—Cowan (2016).

c For the neutrino events with number 160427A, 160731A, and 160806A, their deposited energy are not given in the literature or GCN Circulars.

Figure 1. Comparison of the upper limit gamma-ray fluxes on the timescales of 12 hr and $\sim 1000$ s, as reported in Table 1 (blue data) and Table 3 (green data) respectively, with the flux of the gamma-ray flare (red line) from PKS B1424-418. The dashed red lines indicate the 1σ flux range of the gamma-ray flare from PKS B1424-418.

Figure 2. Upper limit gamma-ray fluxes of the track-like neutrino events for one year Fermi-LAT observations, as reported in Table 1. The flux of the gamma-ray flare of PKS B1424-418 (red lines) is presented for comparison.

PKS B1424-418. No new $\gamma$-ray source around the region of the neutrino position is discovered.

We calculate the significance of the spatial coincidence of 3FGL sources with the IceCube track-like neutrinos, running 10,000 simulations in which the decl. and the R.A. of each 3FGL sample are randomized. For each simulation, we obtain a count number $n$ of 3FGL sources within $R_{50}$ of our track-like neutrino events sample. The chance probability is calculated as the ratio between the number of the simulations that have $n \geq 2$ and the total number of simulations. This approach results in a chance probability $\sim 98\%$, suggesting that the coincidence between two 3FGL sources, J0725.8-0040 (PKS 0725-008) and J2227.8+0040 (PMN J2227+0037), and the track-like neutrino events is merely by chance. If the decl. is fixed and the R.A. is randomized only, the chance probability

+0037) is located $\sim 0^\circ 7$ from the number 44 neutrino event. The two sources are detected at TS = 83 and TS = 35 in one year of observation respectively. The one year fluxes of the two sources are consistent with the values published in the 3FGL catalog, which are two orders of magnitude lower than those of PKS B1424-418. While these two 3FGL sources appear to have a hard spectral index, there is no evidence that they are TeV gamma-ray sources (http://tevcat.uchicago.edu/). Moreover, when a spatial error of $2R_{50}$ is considered, an additional nine 3FGL sources, most of which are blazars, are in positional agreement with the these track-like neutrino events (see Table 2 for more details). Their gamma-ray fluxes are, however, too low to account for the observed neutrino flux, in contrast to
Table 2

| ID | $R_{50}$ | $2R_{50}$ |
|----|---------|----------|
| 3  | J0825.8-3217 |
| 5  | J0725.8-0054 J0721.5-0221 1.09±0.19 |
| 13 | J0423.8 +4150 2.8±0.31 |
| 23 | J1349.6-1133 J1351.8-1524 J1355.0-1044 J1400.5-1437 4.61±0.23 0.77±0.17 |
| 44 | J2227.8 +0040 +0103 0.62±0.16 |
| 47 | J1404.8 +6554 0.32±0.09 |

Note. The energy fluxes (in units of $10^{-11} \text{ erg cm}^{-2} \text{s}^{-1}$) for one year Fermi-LAT observations are presented for sources only with TS > 25 (under each 3FGL source name respectively).

of such spatial coincidence reaches $\sim 83\%$. We therefore find no evidence of gamma-ray emission associated with the IceCube track-like neutrino events. Considering the $\gamma$-ray flux limits for one year Fermi-LAT observation, we suggest that any gamma-ray flares that are associated with the IceCube track-like neutrino events must be at least one order of magnitude dimmer than those of PKS B1424-418$^4$ (see Figure 2).

2.3. IceCube Neutrino Event Numbers 23, 45, and 160806A

We note that three IceCube track-like neutrino events, i.e., numbers 23, 45, and 160806A, are located at a small angle ($< 70^\circ$) from Fermi-LAT boresight at the neutrino detection time. In other words, the region around the track-like neutrino events is within the Fermi-LAT field of view during the $\sim 1000$ s before and after the neutrino detection. Therefore, the above three neutrinos are very suitable for searching for prompt GeV emission accompanying the neutrino emission. The angular distance between neutrino position and Fermi-LAT boresight (denoted as $\Theta$) versus time is shown in Figure 3. The time intervals for Fermi-LAT data analysis are selected with the criterion $\Theta < 70^\circ$, which are also presented in Table 3. The likelihood analysis centered on each neutrino position results in upper limit fluxes given in Table 3. No new $\gamma$-ray point sources are found within $2R_{50}$ of the neutrino’s position. For neutrino event number 23, there are four 3FGL sources within $2R_{50}$, while for the other two neutrino events, there are no sources within $2R_{50}$. The four 3FGL sources mentioned above are very weak, and none of them show any significant detection over $\sim 1000$ s of Fermi-LAT observations. In brief, we find no evidence of prompt GeV emissions following the IceCube track-like neutrino events.

3. Cross-correlation with Swift Hard X-Ray Transient Sources

The high-energy photons from pion decay could be accompanied by X-ray emissions that are produced by secondary electrons and positrons via, e.g., synchrotron radiation in the magnetic fields of the source (Kistler 2015; Murase et al. 2016). Swift Burst Alert Telescope (BAT) is very useful for discovering new X-ray transient sources or detecting the flux variability of known X-ray sources (Barthelmy et al. 2005; Krimm et al. 2013). We thus make a cross-correlation analysis between the Swift/BAT transient sources catalog and the IceCube track-like neutrino events. The catalog includes 1009 X-ray transient sources (see http://swift.gsfc.nasa.gov/results/transients/), including Galactic and extragalactic sources. No Swift/BAT transient source is found inside the error box $R_{50}$ of the IceCube track-like neutrino events. Within $2R_{50}$, four Swift/BAT transient sources are in positional agreement with the IceCube track-like neutrino event numbers 23, 44, and 47 (see Table 4). To investigate their temporal characteristics around the time that the corresponding neutrino events are detected, we extract the day-bin light curves for these X-ray sources. No significant flares are observed at the neutrino detection time for the four X-ray transient sources, as shown in Figure 4. Similarly, a chance probability of $\sim 60\%$ for the positional coincidence is estimated using Monte Carlo simulations with the sample data randomized in R.A. Therefore, considering the insignificant spatial coincidence and the observed temporal behavior of the X-ray transients, we suggest that these Swift/BAT transient sources are not in physical association with the IceCube track-like neutrino events.

4. Implications for Constraining the Neutrino Source Density

The production of neutrinos is accompanied by high-energy gamma-rays, so the point source gamma-ray flux limits could, in principle, provide useful constraints on the neutrino sources. For the $pp$ collision mechanism of TeV–PeV neutrinos, one expects that GeV gamma-ray flux lies at the power-law extrapolation of TeV gamma-rays. The gamma-ray flux scales with the neutrino flux through the relation $F_\gamma \sim 2(E_\gamma/2E_\nu)^{-2}F_\nu$ (Murase et al. 2013), assuming that the parent cosmic rays are produced with a power-law spectrum, $dN_{\mathrm{CR}}/dE_{\mathrm{CR}} \propto E_{\mathrm{CR}}^{-p}$. For the $p\gamma$ mechanism, the flux of hadronic GeV gamma-rays depends on the properties of soft target photons in the source. For simplicity, below we assume that $F_\nu(60–2000 \text{ TeV}) = \eta F_\nu(0.2–100 \text{ GeV})$, with $\eta \approx 0.5$ for $p = 2$ in the $pp$ interaction model. We assume that the sources are transparent to gamma-rays, i.e., they are not the hidden sources in gamma-rays. Our study has found that the sources of the track-like neutrino events should be weak in $\gamma$-rays in $0.2–100$ GeV, even during the neutrino emitting period. Given a measured neutrino background flux by IceCube, one can obtain a lower limit on the source number density with the upper limit on the neutrino luminosity of individual sources under the above assumptions. The observed background

$^4$ Interestingly, Gao et al. (2016) find that a hybrid model with a sub-dominant hadronic component is needed to explain the multi-waveband observation of PKS B1424-418 flares.
neutrino detection time. The black horizontal dotted line represents $\Theta = 70^\circ$.

Figure 3. Angular distance ($\Theta$) between the neutrino position and Fermi-LAT boresight as a function of time for the three IceCube track-like neutrino events. $T_0$ is the neutrino detection time.

| ID     | Time+$T_0$(s) | Flux $10^{-7}$ ph cm$^{-2}$ s$^{-1}$ |
|--------|---------------|--------------------------------------|
| 23     | [−660, 950]   | 4.39                                 |
| 45     | [−1070, 1910] | 2.26                                 |
| 160806A| [−2080, 440]  | 5.56                                 |

Note. The first column is the neutrino ID, the second column is the time interval when the angular distance between the neutrino position and the Fermi-LAT Boresight is less than $70^\circ$, and the last column is the upper limit flux in 0.2–100 GeV.

**Table 3**
Upper Limit Gamma-ray Fluxes of the Three IceCube Track-like Neutrino Events that Are Located within the Fermi-LAT’s Field of View at the Neutrino Detection Time

The neutrino flux implies a local energy production rate of

$$n_0L_{\nu} \approx 3 \times 10^{44} \text{ erg Mpc}^{-3} \text{ yr}^{-1} \left( \frac{\xi}{3} \right)^{-1} \times \frac{\sum E^2 \Phi_{\nu,i}}{3 \times 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}}, \quad (1)$$

where $n_0$ is the local number density, $L_{\nu}$ is the averaged neutrino luminosity of each source throughout the universe, $\xi$ is a dimensionless parameter that accounts for the redshift evolution of the sources, and $\sum E^2 \Phi_{\nu,i}$ is the all-flavor neutrino flux. The upper limit gamma-ray flux for one year Fermi-LAT observations is on average $F_\gamma \approx 7 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$, so the limit on the neutrino flux of an individual source is also $F_\nu \approx \xi \times 7 \times 10^{-13} \eta$ erg cm$^{-2}$ s$^{-1}$. As the neutrino source density is expected to peak at $z \sim 1–2$ following the cosmic star formation rate, we take the luminosity distance of these neutrino sources as $d_L = 10^{28}$ cm (Chang et al. 2016). Then we obtain an upper limit of the neutrino luminosity of an individual source

$$L_{\nu} \lesssim 4\pi d_L^2 F_\gamma \approx 9 \times 10^{44} \eta \text{ erg s}^{-1}. \quad (2)$$

Thus, a lower limit on the continuous source density under the above assumptions may be written as

$$n_0 \gtrsim 10^{-8} \text{ Mpc}^{-3} \eta^{-1} \left( \frac{\xi}{3} \right)^{-1} \left( \frac{F_\gamma}{7 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}} \right)^{-1}. \quad (3)$$

For short-term transient neutrino sources, the upper limit gamma-ray flux for $\sim$1000 s observations is about $F_\gamma \approx 5 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$, so the energy released in neutrinos per event should be smaller than $7 \times 10^{50} \eta$ erg. Using a similar approach, we find a lower limit on the event rate of the transients, i.e.,

$$n_0 \gtrsim 4 \times 10^2 \text{ Gpc}^{-3} \eta^{-1} \left( \frac{\xi}{3} \right)^{-1} \times \left( \frac{F_\gamma}{5 \times 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1}} \right)^{-1}. \quad (4)$$

We would like to stress that the above lower limits are obtained based on the assumptions mentioned at the beginning of this section. The validity of these assumptions depends heavily on the relation between photon and neutrino fluxes. The limits are useful for constraining the source models. FSRQs have a number density of $\sim 10^{-9}$ Mpc$^{-3}$ and a faster redshift evolution than the cosmic star formation rate (Ajello et al. 2012, 2014). Taking $\xi \approx 8.4$ for FSRQs, they are only marginally consistent with the above constraint. Starburst galaxies, one of the other hand, have a number density of $\sim 10^{-4}$ Mpc$^{-3}$ (Ackermann et al. 2012), so they fully satisfy the above constraints for a large parameter space of $\eta$. For short-term transient sources, since high-luminosity GRBs have a density of

| ID     | Angular Error (°) | X-ray Sources      | Type     | Separation (°) |
|--------|-------------------|--------------------|----------|----------------|
| 23     | 1.9               | PKS 1352–104       | Blazar   | 2.52           |
|        |                   | Swift J1117.1–0933 | LMXB     | 3.71           |
| 44     | 1.2               | 3C 445             | Seyfert Galaxy | 2.27 |
| 47     | 1.2               | Mrk 279            | Seyfert Galaxy | 1.98 |

Note. The last column is the angular separation between the positions of the neutrino and the X-ray sources. “LMXB” means low-mass X-ray binary.
~1 Gpc yr\(^{-1}\), one can rule out GRBs as the main contributing sources of these neutrinos if \(\eta < 100\) (i.e., the neutrino flux at TeV–PeV energies is a factor of <100 larger than that in GeV gamma-rays). Since low-luminosity GRBs have a density of 200–1000 Gpc yr\(^{-1}\), they cannot be ruled out by our Fermi-LAT data analysis. We note that the constraints on the source density are generally consistent with the results obtained by using the non-detection of high-energy neutrino multiplets in the IceCube data (Ahlers & Halzen 2014; Murase & Waxman 2016).

### 5. Conclusions and Discussions

By using Fermi-LAT observations, we searched for \(\gamma\)-ray transient emission on the timescales of hours to months coincident with the IceCube track-like neutrino events above 60 TeV. The null result suggests that any associated gamma-ray flares must be at least one order of magnitude dimmer than those of the blazar PKS B1424-418, to which PeV cascade-like neutrinos are claimed to be associated at the 95% confidence level. For three track-like neutrinos that occurred within the field of view of Fermi-LAT at the time of the neutrino detection, we also searched for prompt GeV emission coincident in time with these neutrinos. No significant GeV emissions associated with these neutrino events are found. A few 3FGL \(\gamma\)-ray objects are located within 2\(R_{50}\) of the neutrino position, but the probability for chance coincidence is large. They are also too weak in gamma-ray emission to be reconciled with the neutrino emission. Based on the non-detections of GeV emissions and some assumptions (see Section 4), the inferred local number density for continuous emitting sources to produce high-energy neutrinos should be \(n_0 \gtrsim 10^{-8}\) Mpc\(^{-3}\) by assuming a flat gamma-ray spectrum resulting from the \(pp\) mechanism for neutrinos. Similarly, for transient sources, we obtain an event rate of \(\dot{n}_0 \gtrsim 4 \times 10^2\) Gpc\(^{-3}\) yr\(^{-1}\). We also searched for possible hard X-ray transients observed by Swift/BAT that are coincident with the track-like neutrino events, but no X-ray flares are found to be spatially and temporally coincident with these neutrino events.

Some alternative explanations for non-detection of 0.2–100 GeV emission accompanying the IceCube track-like neutrino events are possible. For example, if the high-energy photons produced in the pion mesons process cannot escape freely from the source region (i.e., the hidden sources in gamma-rays), they would not suffer from the above constraints. Another possibility is that the gamma-ray luminosity at GeV

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Figure 4. Hard X-ray light curves of Swift/BAT transient sources within 2\(R_{50}\) of the neutrino positions. The neutrino detection time is denoted as \(T_0\).
energies is far below that of the TeV–PeV neutrinos in the $\rho\gamma$ scenario when the energy threshold of cosmic rays for pion production in interactions with radiation fields is too high. Future prompt follow-up observations in TeV energies by Imaging Cherenkov Telescopes, such as CTA, HAWC and LHAASO, would be useful to test the latter possibility.

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