HOW FAR AWAY ARE THE SOURCES OF ICECUBE NEUTRINOS? CONSTRAINTS FROM THE DIFFUSE TERA ELECTRONVOLT GAMMA-RAY BACKGROUND

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ABSTRACT

The nearly isotropic distribution of terraelectronvolt to petaelectronvolt neutrinos recently detected by the IceCube Collaboration suggests that they come from sources at a distance beyond our Galaxy, but how far away they are is largely unknown because of the lack of any associations with known sources. In this paper, we propose that the cumulative TeV gamma-ray emission accompanying the production of neutrinos can be used to constrain the distance of these neutrino sources, since the opacity of TeV gamma rays due to absorption by the extragalactic background light depends on the distance these TeV gamma rays have traveled. As the diffuse extragalactic TeV background measured by Fermi is much weaker than the expected cumulative flux associated with IceCube neutrinos, the majority of IceCube neutrinos, if their sources are transparent to TeV gamma rays, must come from distances larger than the horizon of TeV gamma rays. We find that above 80% of the IceCube neutrinos should come from sources at redshift $z > 0.5$. Thus, the chance of finding nearby sources correlated with IceCube neutrinos would be small. We also find that, to explain the flux of neutrinos under the TeV gamma-ray emission constraint, the redshift evolution of neutrino source density must be at least as fast as the cosmic star formation rate.

Key words: cosmic rays – neutrinos

1. INTRODUCTION

The IceCube Collaboration recently announced the discovery of extraterrestrial neutrinos (Aartsen et al. 2013, 2014a, 2015a). The sky distribution of these events is consistent with isotropy (Aartsen et al. 2014a). Such an isotropic distribution could be produced as long as the distance to the source is significantly larger than the size of the Galactic plane, so extragalactic astrophysical objects are usually proposed as their sources, but a Galactic halo origin is also possible (Taylor et al. 2014). The proposed extragalactic sources include galaxies with intense star formation (Loeb & Waxman 2006; He et al. 2013; Murase et al. 2013; Chang & Wang 2014; Liu et al. 2014; Tamborra et al. 2014; Bartos & Marka 2015; Chakraborty & Izaguirre 2015; Chang et al. 2015; Senno et al. 2015a), jets or cores of active galactic nuclei (AGNs) (Stecker et al. 1991; Kalashev et al. 2014; Padovani & Resconi 2014; Kimura et al. 2015), and gamma-ray bursts (Waxman & Bahcall 1997; He et al. 2012; Liu & Wang 2013; Murase & Ioka 2013; Bustamante et al. 2015; Fraija 2015). The large uncertainty in our current knowledge about the distance to the source of the neutrinos exists because so far no associated astrophysical sources have been identified.

A common way to produce high-energy neutrinos is the decay of charged pions created in inelastic hadronuclear (pp) or photodihadronic (pγ) processes of cosmic rays (CRs), in which high-energy gamma rays will also be generated from the decay of synchronously created neutral pions. The emissivities of gamma rays and neutrinos are related through $E_E(Q,Q) \approx (2/3) E_E(Q,E) \mid_{E=E/2}$ (for the pp process), where $Q$ represents the emission rate per source. Very high energy (VHE) gamma rays ($\gtrsim 100$ GeV), unlike neutrinos, which propagate through the universe almost freely, will be significantly absorbed by the extragalactic background light (EBL) and cosmic microwave background (CMB) during the propagation through intergalactic space if the source distance is larger than the mean free path of these gamma rays. For a terraelectronvolt (TeV) gamma-ray photon, the optical depth would be larger than unity when the source is located at $z \gtrsim 0.1$. Therefore, the cumulative flux of VHE gamma rays associated with neutrinos carries the information about the distance of the sources of these neutrinos.

Significant progress has been made in our understanding of the extragalactic gamma-ray background (EGB) in recent years. The spectrum of the EGB has now been measured with the Fermi-LAT in the energy range from 0.1 to 820 GeV (Ackermann et al. 2015a). New studies of the blazar source count distribution at gamma-ray energies above 50 GeV place an upper limit on the residual nonblazar component of the EGB (Ackermann et al. 2016). In this paper, we use this upper limit at TeV energy to constrain the distance and the evolution of the bulk population of neutrino sources. The distance information has important implications for the search for correlations between observed neutrino events and nearby gamma-ray sources. If the inferred distances of the majority of neutrino sources are large, the search for nearby correlated sources would be a challenge. It may also explain the negative result4 of searches for the correlation between neutrinos and ultrahigh-energy CRs obtained by Aartsen et al. (2016), which originate within $\lesssim 100$ Mpc.

In Section 2, we first present how we use the TeV emission to place constraints. Then, in Section 3, we give the input conditions and assumptions. We give our results in Section 4. Finally, we give the conclusions and discussions in Section 5.

Footnote:

4 See, however, the result obtained by Moharana & Razzaque (2015), who find that the arrival directions of the cosmic neutrinos are correlated with $\gtrsim 10$ TeV UHE CR arrival directions. This can be explained only if the sources are opaque to TeV gamma rays.
2. THE METHOD FOR CONSTRAINTS

In the astrophysical origin scenarios, neutrinos (and gamma rays) are produced in various discrete astrophysical objects, so the total observed neutrino flux is the sum of the contributions of each individual source, rather than from truly diffuse emissions. We assume that the neutrino sources are transparent to TeV gamma rays, and we only consider the attenuation in the intergalactic space due to EBL and CMB absorption. For simplicity, we assume here a Poisson distribution for the closest sources; then the probability density that the nth-closest source is located at a comoving distance r can be expressed as

\[ p(n, r) = \frac{4\pi N^{n-1}}{(n-1)!} e^{-N} r^2 \rho_0 \]

where \( N \) is the expectation number of the sources within a spherical comoving volume \( V \) with radius \( r \), i.e., \( N = \int_0^\infty \rho_0 4\pi r^2 dr \). So the expected comoving distance where the nth-closest source is located is \( r(n) = \int_0^\infty p(n, r) rdr \). For distant sources, the effect of fluctuation of distances is unimportant, and the distribution can be treated as a uniform distribution, so \( p = \rho(z) \).

The influence of source number density on the gamma-ray background is complicated. If the spatial number density of the sources is low, given a measured diffuse neutrino flux, the corresponding gamma-ray luminosity of each source should be relatively high, so these kinds of sources are easier to resolve by instruments. By contrast, if the spatial number density of the source is high, the luminosity of each source should be relatively small. As a result, these sources are more likely to be unresolved, and hence the emitted gamma rays contribute to the isotropic, diffuse gamma-ray background (IGRB). If more nearby sources are resolved from the background, the distant sources are allowed to be brighter without violating the IGRB data. Such a requirement can be expressed as

\[ \Phi_{\gamma,\text{un}}(E_\gamma) = \sum_{F_0 > F_{\text{sen}}} F_0(\Phi_{\gamma,\text{un}}(E_\gamma)) \leq \Phi_{\text{IGRB}}(E_\gamma), \]  

where \( \Phi_{\gamma,\text{un}}(E_\gamma) \) represents the cumulative flux of unresolved sources, \( F_0(\Phi_{\gamma,\text{un}}(E_\gamma)) \) represents the flux of the nth-closest source, and \( F_{\text{sen}} \) is the point-source sensitivity of Fermi-LAT.

At the same time, the resolved sources contribute to the EGB together with the unresolved ones, so they must satisfy

\[ \Phi_{\gamma,\text{tot}}(E_\gamma) = \sum_{n} F_n(\Phi_{\gamma,\text{tot}}(E_\gamma)) \leq \Phi_{\text{EGB}}(E_\gamma), \]

where \( \Phi_{\gamma,\text{tot}}(E_\gamma) \) represents the cumulative flux of all sources, including both resolved and unresolved ones. In our calculation, we use the broadband sensitivity provided by Fermi-LAT performance in Pass 8. Assuming the gamma-ray spectral index \( \gamma = 2 \), the sensitivity reaches a level of \( F_{\text{sen}} \sim 2 \times 10^{-10} \text{erg cm}^{-2} \text{s}^{-1} \). According to this, we can determine whether a point source is resolved or not. Based on the above two requirements (Equations (2) and (3)), we will study how the maximum neutrino contribution from a certain source is constrained by the Fermi data.

For simplicity, we assume that all the sources have the same intrinsic gamma-ray luminosity \( L' \), which is related to the gamma-ray spectral emissivity \( Q'(E') \) by

\[ L' = \int_{E_{\text{min}}}^{E_{\text{max}}} Q'(E')dE', \]

where \( E_{\text{max}} \) and \( E_{\text{min}} \) are the maximum and minimum energy of the emitted photons, respectively. Here the prime denotes quantities measured in the rest frame of the source (i.e., \( E' = E_{\gamma}(1+z) \)). While low-energy gamma rays can freely propagate to us from the sources, high-energy gamma rays may be absorbed by the EBL and CMB photons in intergalactic space. The produced electron–positron pairs will also interact with EBL and CMB photons and generate secondary gamma rays by inverse-Compton scattering. Such a cycle is called a cascade, and it will continue until the newly generated photons are not energetic enough to produce electron–positron pairs by interacting with the background photons. As a result, the absorbed high-energy gamma rays are reprocessed to a bunch of lower-energy ones. So the total gamma-ray flux after propagation consists of a primary component, which is the unabsorbed gamma rays, and a cascade component:

\[ F(E_\gamma) = \left\{ Q'(1+z)E_\gamma \right\} e^{-\tau(E_\gamma)} + Q_{\gamma,\text{cas}}(E_\gamma) \right\} / 4\pi\rho^2, \]

where \( \tau(E_\gamma) \) is the optical depth for a photon of energy \( E_\gamma \). In this paper, we use the optical depth provided by Finke et al. (2010) and discuss the effect of other EBL models later.

Since the results depend on the density of the neutrino source, we will consider three different cases:

1. A high-density source case, such as star-forming or starburst galaxies. The density of starburst galaxies is about \( 4 \times 10^{-4} \text{Mpc}^{-3} \). Starburst galaxies, because of their high star-formation rates (SFRs), and hence large number of supernova or hypernova remnants therein, are huge reservoirs of CR protons with energies up to exaelectronvolt levels (Wang et al. 2007). These CRs produce high-energy neutrinos by colliding with gases in galaxies (Loeb & Waxman 2006; Liu et al. 2014).

2. A medium-density case, such as clusters of galaxies. The density of clusters of galaxies is about \( \sim 10^{-6} \text{Mpc}^{-3} \). Galaxy clusters have been argued to be able to accelerate CRs and are considered as possible sources for high-energy neutrinos (Murase et al. 2008).

3. A low-density case, such as blazars (e.g., BL Lacs and flat-spectrum radio quasars (FSRQs)). Their density ranges from \( 10^{-9} \text{Mpc}^{-3} \) to several \( 10^{-7} \text{Mpc}^{-3} \) (Ajello et al. 2012, 2014). We choose \( 4 \times 10^{-8} \text{Mpc}^{-3} \) as a reference value. As blazars are powerful gamma-ray sources, there have been extensive discussions about the possibility that they are high-energy neutrino sources (see Ahlers & Halzen (2015) for a review).

It should be noted that the three densities we chose are just reference values to study the effect of different source densities. Any specific sources should refer to the corresponding results based on their spatial densities.

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5 The distribution of the closest galaxies may be clumpy, which suggests an overdensity of the nearby sources. Since the total mass fraction in the nearby universe is small, we find that this overdensity hardly affects our results.

6 http://www.slac.stanford.edu/exp/glast/groups/canda/lat_performance.htm

7 http://www.physics.ohiou.edu/~finke/EBL/index.html
3. ASSUMPTIONS ABOUT THE EXTRAGALACTIC NEUTRINO FLUX AND INJECTION SPECTRA OF GAMMA RAYS

The latest combined maximum-likelihood analysis of IceCube neutrinos gives a best-fit power-law spectrum with a spectral index of $\gamma = 2.50 \pm 0.09$ in the energy range between 25 TeV and 2.8 PeV, and an all-flavor flux of $\phi = (6.7^{+1.3}_{-1.2}) \times 10^{-18}$ GeV$^{-1}$ s$^{-1}$ sr$^{-1}$ cm$^{-2}$ at 100 TeV (Aartsen et al. 2015a). Interestingly, the IceCube Collaboration has tested the hypothesis of isotropy by analyzing data in the northern and southern sky, respectively. Compared to the all-sky result, the spectrum of the events in the northern sky can be better fitted by a harder power law ($\gamma = 2.0^{+0.2}_{-0.3}$), while the southern one favors a slightly softer spectrum ($\gamma = 2.56 \pm 0.12$). However, the result is not conclusive, as the discrepancy could be simply caused by a statistical fluctuation. Alternatively, it could be due to an additional component that is present in only one of the hemispheres (either an unmodeled background component or, e.g., a component from the inner Galaxy).

As indicated in some recent studies (Ackermann et al. 2016), the EGB above 50 GeV is dominated by blazars at a level of 86$\pm$14%. These are mostly low-luminosity hard-spectrum BL Lacs. If this is correct, it implies a strong suppression of contributions from other sources, which can contribute at most a flux of $\lesssim 2-3 \times 10^{-8}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ at 50 GeV. If the neutrino sources are transparent to gamma rays, the neutrino flux per flavor is then constrained to be at most $\sim 10^{-8}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$, which can explain the measured neutrino flux at petaelectronvolt (PeV) energy but is insufficient to explain the flux at $\sim$25 TeV. To solve this tension, it has been proposed that TeV neutrinos may come from some hidden sources; that is, they are not transparent to gamma rays (Bechtol et al. 2015; Murase et al. 2016).

Considering the above uncertainties, we divide our discussions into two cases. In the first case, we adopt the nonblazar EGB obtained by Ackermann et al. (2016) to place constraints. We assume that the gamma-ray background is only relevant to $\gtrsim 100$ TeV neutrinos whose sources are transparent to gamma rays, and $\sim$25 TeV neutrinos may originate from some hidden sources or from a component of the inner Galaxy. Possible hidden sources were suggested (Stecker et al. 1991; Murase et al. 2016; Senno et al. 2016; Tamborra & Ando 2016; Wang & Liu 2016). The gamma-ray spectrum at the source should follow the spectrum of neutrinos, which is assumed to be a flat spectrum with index $\gamma = 2.0$ below 1 PeV, as predicted by the Fermi acceleration mechanism, and a steeper spectrum with $\gamma = 2.5$ above 1 PeV (Aartsen et al. 2014a). Then the injection spectrum of gamma rays can be expressed as

$$
Q_\gamma(E_\gamma) \propto E_\gamma^{-2}, \quad E_\gamma < (1+z)\text{PeV}
$$

$$
Q_\gamma(E_\gamma) \propto E_\gamma^{-2.5}, \quad E_\gamma \geq (1+z)\text{PeV}.
$$

In the second case, we relax this requirement by considering the full EGB given in Ackermann et al. (2015a), allowing blazars to contribute to IceCube neutrinos. The neutrino spectrum at the source is assumed to follow a broken power law with the spectral index $\gamma = 2.0$ at $E_\nu < 25$ TeV and $\gamma = 2.5$ at $E_\nu > 25$ TeV (Aartsen et al. 2015a). Then the injection spectrum of gamma rays can be expressed as

$$
\begin{align*}
Q_\gamma(E_\gamma) & \propto E_\gamma^{-2}, \quad E_\gamma < 50(1+z)\text{TeV} \\
Q_\gamma(E_\gamma) & \propto E_\gamma^{-2.5}, \quad E_\gamma \geq 50(1+z)\text{TeV}.
\end{align*}
$$

4. RESULTS

When the cumulative TeV flux is fixed, as constrained by the IGRB and EGB data, the total neutrino flux is affected by two factors. First, as mentioned above, the spatial density of the sources is an important factor. If the density is smaller, the luminosity of an individual source is larger, and hence more nearby sources will be resolved. Gamma rays from these resolved sources will not be counted into the IGRB while they still contribute to the diffuse neutrino flux. The second factor is the evolution of the source density with redshift. TeV photons from more distant sources will be more likely to be absorbed during propagation to the Earth, while neutrinos will not, so the neutrino flux will be higher if the fraction of distant sources is higher (or the density evolution with redshift is stronger). In our calculation, we adopt two forms of redshift evolution for the purpose of illustration: one is the constant-density evolution, which means that the comoving density of the sources does not change with redshift; the other is the SFR evolution, for which the source density evolves as $\propto (1+z)^{3.4}$ at $z < 1$, $\propto (1+z)^{-0.3}$ at $1 < z < 4$, and $\propto (1+z)^{-3.5}$ at $z > 4$ (Hopkins & Beacom 2006; Yiiksel et al. 2008).

4.1. Nonblazar EGB Case

In this case, we assume that EGB and IGRB are only relevant to $\gtrsim 100$ TeV neutrinos and adopt the nonblazar EGB obtained by Ackermann et al. (2016) as an upper limit of the cumulative gamma-ray flux from neutrino sources. First, we want to study what fraction of the observed neutrino flux is contributed by nearby sources. In Figure 1, we fix the limit of gamma-ray flux to be $2.5 \times 10^{-9}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ at 820 GeV, which corresponds to 14% of the total EGB (i.e., the nonblazar EGB$^8$), and calculate the maximally allowed neutrino flux at PeVs as a function of the boundary distance $z_{\text{max}}$. The boundary distance $z_{\text{max}}$ means that all the sources contributing to the IGRB or EGB are located within the redshift $z_{\text{max}}$. The spectra of gamma rays and neutrinos are assumed to follow Equation (5).

The left-hand panel of Figure 1 shows the maximally allowed neutrino flux at 1 PeV without violating the nonblazar EGB. The figure indicates that, in all three source density cases, only a small fraction of neutrinos come from low-redshift sources. The sources below $z_{\text{max}} = 0.5$ can account for at most a fraction of 20% of the total neutrino flux. Thus, the majority of neutrinos observed by IceCube should come from distances farther than $z = 0.5$. We can also see that, to account for the observed neutrino flux, the redshift evolution of the sources should not be slower than that of the cosmic SFR. The constant evolution with respect to redshift can be ruled out. The above discussions only consider the constraints by the TeV gamma-ray background. However, in the low source density case, the nearest point sources could have been detected by IceCube, given a sensitivity of $E^2dE/dN \sim 10^{-12}$ TeV s$^{-1}$ cm$^{-2}$ for

$^8$ Ackermann et al. (2016) find that blazars constitute about 86% of the integrated photon flux above 50 GeV. We here assume that the spectrum of the summed emission of all blazars is identical to that of the observed EGB.
IceCube (Aartsen et al. 2014b), so we should also consider the constraints of the IceCube observation. This extra constraint suggests that the source density should not be too low, unless part of the gamma-ray emission of the sources does not come from the same hadronic process that produces neutrinos. Considering the latter possibility for the low-density source case and the constraint of IceCube nondetection of nearby sources, we recalculate the maximum neutrino flux which is shown in the right-hand panel of Figure 1. We find that the extra constraint affects the low-density case, and the requirement of a fast evolution is strengthened.

The requirement of a fast evolution of the source density with redshift can also be seen by comparing the expected cumulative TeV gamma-ray emission accompanying the production of neutrinos with the observed gamma-ray background data. Figure 2 shows the cumulative gamma-ray emission for different redshift-evolution scenarios. Here we adopt the high source density case for illustration, while the result holds for other source density cases. We can see that a faster redshift evolution will lead to a steeper gamma-ray spectrum. Since Ackermann et al. (2016) provide only the fraction of the integral contribution to the total EGB above 50 GeV by blazars, the exact fraction of nonblazar EGB flux at 820 GeV is unclear. Thus, we draw a series of horizontal lines in Figure 2 to show the different levels of the nonblazar EGB fraction at 820 GeV. If the nonblazar EGB flux is lower than $\lesssim14\%$ of the total EGB flux at 820 GeV, the source evolution is required to be faster than that of SFR. In all three density evolution scenarios, however, the flux at 10–100 GeV is quite similar, which is naturally expected since 10–100 GeV gamma rays are almost as transparent as neutrinos. This demonstrates the unique role of TeV gamma-ray flux in constraining the evolution of neutrino source density.

4.2. Blazar EGB Case

In this case, we allow blazars to contribute to IceCube neutrinos and use the full EGB as the upper limit (Ackermann et al. 2015a). The IGRB constraint becomes important for this case, and we need to consider this constraint as well. Thus, we fix the upper limits of the cumulative gamma-ray flux at 820 GeV to be $6 \times 10^{-9}\text{GeV cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$ for unresolved sources (IGRB) and $3 \times 10^{-8}\text{GeV cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$ for all the sources (EGB).

First, we assume that 10–100 TeV neutrinos originate from extragalactic sources that are transparent to TeV gamma rays. Figure 3 shows the maximally allowed neutrino flux at $\sim25$ TeV as a function of the boundary redshift $z_{\text{max}}$ by assuming a gamma-ray spectrum of Equation (6). The result suggests a similar preference for high-redshift sources. In the
high- and middle-density cases, the source density evolution should not be slower than the cosmic SFR evolution. Since the luminosities of these sources are relatively low, we find that the IceCube nondetection constraint hardly affects the result. On the other hand, for the low-density case, the observed neutrino flux can be achieved even for a constant source density evolution. However, when considering the neutrino nondetection constraint of nearby point sources, only \( \lesssim 15\% \) of the EGB flux at 820 GeV can be associated with neutrinos from the same hadronic process. Including this extra constraint of IceCube nondetection, we find that the source evolution should be faster than the SFR evolution for the low-density case, as shown in the right-hand panel of Figure 3. Like in the nonblazar case, we compare the cumulative gamma-ray emission of unresolved sources with the IGRB data in Figure 4 for the high source density case. We find that, in order not to exceed the IGRB at 820 GeV, the source density must evolve faster than the SFR evolution.

However, it has been suggested that the EGB above 50 GeV is dominated by low-luminosity hard-spectrum BL Lacs (Ackermann et al. 2016), which have a negative evolution with redshift in source density (Ajello et al. 2014). If it is correct, we can exclude the possibility that these BL Lacs are the main sources of the 10–100 TeV neutrinos observed by IceCube. This is consistent with the conclusion in a previous study by summing up the neutrino flux from the individual BL Lacs (Padovani et al. 2015). Thus, the tension between the fact that the dominant sources producing the gamma-ray background have a negative evolution with redshift and our conclusion that the sources of the high-energy neutrinos must have a fast, positive evolution with redshift argues for hidden sources for 10–100 TeV neutrinos. Meanwhile, we should also note that some types of blazars such as FSRQs have a fast, positive evolution with redshift, and they only contribute a small part of the EGB/IGRB flux. These sources are still possible sources for \( \gtrsim 100 \) TeV IceCube neutrinos. This is consistent with the recent discovery of a (PeV) neutrino that is in temporal and positional coincidence with a high-fluence outburst from the FSRQ PKS B1424-418 at redshift \( z = 1.522 \) (Kadler et al. 2016). For these FSRQs, the situation is actually quite similar to the low-density sources in the nonblazar case.

5. DISCUSSIONS AND CONCLUSIONS

In the above calculation, we used the EBL model given by Finke et al. (2010). Different EBL models might affect the opacity of TeV gamma rays, and we thus study this effect. We use the upper and lower bounds on the opacity given by Stecker (2013) as the boundary for EBL uncertainties. Figure 5 shows the influence on cumulative gamma-ray emission when varying the EBL intensity model. In the calculation, we use the case of a source density of \( 4 \times 10^{-4} \) Mpc\(^{-3} \). The neutrino flux data are denoted by black and gray dots.
ray/neutrino luminosity of the source also varies with redshift, it is then the gamma-ray/neutrino emission rate density, rather than source number density, that is constrained. The emission rate density can be expressed as \( g(z)\rho(z)\), where \( \rho(z) \) represents the source number density and \( g(z) \) is the factor accounting for the luminosity evolution of the source. As long as their product \( g(z)\rho(z) \) has a fast evolution with redshift, the requirement is fulfilled. So the source number density may not need to evolve that fast if the factor \( g(z) \) evolves fast enough. The factor \( g(z) \) could originate from various physical causes. For example, in the starburst galaxy scenario for IceCube neutrinos, cosmic rays may have a higher pion production efficiency in higher-redshift galaxies due to higher gas densities therein, which leads to a larger \( g(z) \) at higher redshifts (Chang et al. 2015). Besides, we note that, although high-luminosity hard-spectrum BL Lacs show only a mild evolution in the redshift range of \( 1 < z < 2 \), they are severely deficient in the low-redshift \( (z < 0.5) \) universe (Ajello et al. 2014). These sources can be essentially regarded as a fast evolution case, so they may avoid the excess in the diffuse TeV gamma-ray background when accounting for IceCube neutrinos.

To summarize, we find that the extragalactic TeV gamma-ray background is a useful tool for studying the distance and density evolution of neutrino sources. We have considered blazar and nonblazar source models and used different injection spectra correspondingly. In both cases, we find that only a small fraction of neutrinos are allowed to come from low-redshift sources in order not to exceed the diffuse TeV gamma-ray background limit. To account for the IceCube neutrino flux, the density of neutrino sources must have a fast evolution with redshift. Interestingly, this is consistent with the independent result obtained by the tomographic constraints (Ando et al. 2015). In addition, even for a fast source density evolution, only the \( \gtrsim 100 \) TeV neutrino flux could be explained. As our result shows that the IceCube neutrinos mainly come from distant sources at high redshifts, any models arguing for nearby sources may be ruled out as long as these sources are transparent to TeV gamma rays. Also, any search for nearby sources correlated with IceCube neutrinos would face a challenge. Instead, we suggest a search for correlations with potential CR accelerators at high redshifts.

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