Implications of *Fermi*-LAT observations on the origin of IceCube neutrinos

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**Abstract.** The IceCube (IC) collaboration recently reported the detection of TeV-PeV extraterrestrial neutrinos whose origin is yet unknown. By the photon-neutrino connection in \(pp\) and \(p\gamma\) interactions, we use the *Fermi*-LAT observations to constrain the origin of the IC detected neutrinos. We find that Galactic origins, i.e., the diffuse Galactic neutrinos due to cosmic ray (CR) propagation in the Milky Way, and the neutrinos from the Galactic point sources, may not produce the IC neutrino flux, thus these neutrinos should be of extragalactic origin. Moreover, the extragalactic gamma-ray bursts (GRBs) may not account for the IC neutrino flux, the jets of active galactic nuclei may not produce the IC neutrino spectrum, but the starburst galaxies (SBGs) may be promising sources. As suggested by the consistency between the IC detected neutrino flux and the Waxman-Bahcall bound, GRBs in SBGs may be the sources of both the ultrahigh energy, \(\gtrsim 10^{19}\text{eV}\), CRs and the 1–100 PeV CRs that produce the IC detected TeV-PeV neutrinos.

**Keywords:** neutrino astronomy, cosmic ray theory, ultra high energy cosmic rays, gamma ray bursts theory

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1 Introduction

Recently, IceCube (IC) reports the detections of two PeV neutrinos [1] and 26 sub-PeV additional events [19] within two years operation of IC-79 and IC-86. In comparison with the expected number of 10.6 events from atmospheric muons and neutrinos, the observed flux corresponds to an excess with a significanation of $4.3\sigma$ [19]. This may mark the first detection of high energy ($\gtrsim$ TeV) extraterrestrial neutrinos. Later on the three years of IC data improve the significanation up to $5.7\sigma$ [2]. These neutrinos are consistent with a flat energy spectrum, equal flavor ratio of 1:1:1 and isotropic sky distribution. The single flavor intensity of these extraterrestrial neutrinos is

$$E^2_\nu \Phi_{\nu, \text{IC}} \approx 10^{-8}\text{GeVcm}^{-2}\text{s}^{-1}\text{sr}^{-1},$$

(1.1)

corresponding to a $4\pi$ all sky integrated flux of

$$E^2_\nu J_{\nu, \text{IC}} \approx 1.2 \times 10^{-7}\text{GeVcm}^{-2}\text{s}^{-1},$$

(1.2)

from 60 TeV to 3 PeV energy range, and there is a lack of detected $> 2$ PeV neutrinos.

There are many scenarios that have been discussed regarding the origin of these extraterrestrial neutrinos, both Galactic and extragalactic models. The Galactic origins include the point source contribution [13], and extended and diffuse sources due to Galactic cosmic ray (CR) interaction with the interstellar medium (ISM) during their propagation [7, 15, 16, 20, 30, 37, 40, 46] even propose the diffuse neutrinos from an extended Galactic halo. By assuming Galactic origin, the IC detected neutrinos have been used to constrain the Galactic CR sources [10]. On the other hand, extragalactic sources, e.g., gamma-ray bursts (GRBs) [27, 34], active galactic nuclei (AGNs) [35, 45], and star forming galaxies [17, 28, 47] have been discussed, as well as extragalactic diffuse neutrinos due to CR propagation in cosmic background photons [22, 24, 42]. The IC detection, assuming extragalactic origin, has been used to constrain the extragalactic CR source physics, e.g., the CR spectrum [33], the production rate density [23], and the physical condition of the CR accelerators [51].
The Fermi-Large Area Telescope (LAT) provides a survey of the \( \gamma \)-ray sky from 30 MeV to several hundred GeV with a sensitivity more than an order of magnitudes surpassing its predecessor EGRET. Many more point sources, as well as more precise diffuse \( \gamma \)-ray background, have been detected by LAT. The Fermi-Gamma-ray Burst Monitor (GBM) complements the LAT in its observations of transient sources, especially gamma-ray bursts (GRBs). In this paper we will use the \( \gamma \)-ray observations of Fermi-LAT and GBM to constrain the Galactic and extragalactic origins of the IC detected neutrinos, by assuming the \( \gamma \)-ray and neutrino connection and extrapolation of the \( \gamma \)-ray spectra.

The organization of the paper is as following. In section 2 we discuss the Galactic models, including the diffuse neutrino emission from CR interactions with ISM and extended halo matter (section 2.1) and the neutrinos from Galactic point sources (section 2.2). Our constraint does not favor these Galactic sources. In section 3, we discuss the extragalactic model, especially the GRB neutrino model. Combining with the LAT constraints of triggered GRBs, we do not favor GRB model either (section 3.1). We further propose that extragalactic neutrinos from AGN jets (section 3.2) and SFGs (section 3.3) may be the possible source of IC neutrinos. Finally section 4 is conclusion and discussion.

2 Galactic origin

The first question we need to ask about the IC detected neutrinos is whether they can be produced in the Milky Way (MW), including the contribution by point sources and the diffuse neutrinos from CR propagation. Here we will derive the neutrino flux by extrapolation of the \( \gamma \)-ray spectrum from Fermi-LAT observations, and then compare it with the IC detected flux.

Both \( \gamma \)-rays and neutrinos can be produced by the interactions between CR particles and medium matter (\( pp \)) or background photons (\( p\gamma \)). We can simply consider only \( pp \) interactions and neglect \( p\gamma \) because the background photons are relatively rare and \( p\gamma \) time scale is much longer than \( pp \) collisions.

In the case of \( pp \) collisions, the flux ratio of \( \pi^+\)'s, \( \pi^-\)'s and \( \pi^0\)'s is \( \sim 1 : 1 : 1 \) at high energies. Neutrinos are produced via charged pion’s decay: \( \pi^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu \), \( \pi^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu + \bar{\nu}_\mu \). Each neutrino carries one quarter of the pion’s energy. Photons are produced via neutral pion’s decay, \( \pi^0 \rightarrow \gamma + \gamma \), and each photon carries one half of pion’s energy. The flavor ratio of the produced neutrinos is \( (\nu_e + \bar{\nu}_e) : (\nu_\mu + \bar{\nu}_\mu) : (\nu_\tau + \bar{\nu}_\tau) = 1 : 2 : 0 \), and after oscillation the flavor ratio detected on earth becomes \( (\nu_e + \bar{\nu}_e) : (\nu_\mu + \bar{\nu}_\mu) : (\nu_\tau + \bar{\nu}_\tau) = 1 : 1 : 1 \) \([39]\). The number ratio of \( \gamma \)-rays and each flavor of neutrinos generated via the processes above is \( \sim 1 : 1 : 1 : 1 \), so the relation between the detected fluxes of diffuse \( \pi^0 \)-decay \( \gamma \) rays and single flavor neutrinos at energies \( E_\gamma \simeq 2E_{\nu_\alpha} \) (\( \alpha = e, \mu \) or \( \tau \)) is

\[
E_\gamma^2 \Phi_\gamma(E_\gamma) \simeq 2E_{\nu_\alpha}^2 \Phi_{\nu_\alpha}(E_{\nu_\alpha}).
\]  

Note that we neglect any attenuation of the \( \gamma \)-rays below 100 GeV, which we use, in the sources and during propagation.

2.1 Cosmic ray propagation in the Milky Way

Consider the diffuse neutrino flux from the MW. After the Galactic CRs escape from their sources, they propagate through the ISM. CR particles are being scattered in the Galactic magnetic fields and diffuse away from their sources, interacting with ambient gas. The hadronic interactions produce not only neutrinos but also \( \gamma \)-rays. Given the connection of
Table 1. The γ-ray flux at 100GeV in different Galactic regions observed by Fermi-LAT.
below the knee, and $\sim -3$ between the knee and the ankle. Beyond the ankle the CR spectrum flattens with an index of $\sim -2.75$, and then a cutoff appears at $\sim 50\text{EeV}$. The ankle feature may suggest an extragalactic CR component starts to dominate. Although the exact CR energy where the transition from Galactic to extragalactic CRs happens is under debates, it is generally believed that the CRs below $\sim 1\text{EeV}$ are of Galactic origin.

Both the daughter $\gamma$-rays and neutrinos are roughly a constant fraction of the primary protons, $E_{\gamma} \approx 0.1E_p$ and $E_{\nu} \approx 0.05E_p$.\(^1\) Thus the $\gamma$-ray and neutrino spectra both follow that of the Galactic CRs. We further assume that the CR spectrum anywhere in the Milky Way is the same as the one observed on Earth. Therefore we set the diffuse Galactic neutrino spectral index $\alpha = -2.75$ for energies of $50\text{GeV}–150\text{TeV}$, and a fixed index $\beta = -3$ for energies of $150\text{TeV}–50\text{PeV}$ for simplification.

Assuming that the DGE all comes from $\pi^0$-decay photons, with Equation (2.1) and the all sky integrated $\gamma$-ray flux from table 1, we obtain an upper limit to the flux of the diffuse Galactic neutrinos, $E_{\nu}^2J_{\nu} = \sum E_{\nu}^2\Phi_{\nu}\Delta\Omega_i \approx 3.74 \times 10^{-6}\text{GeVcm}^{-2}\text{s}^{-1}$ ($i = $ Local, inner, outer) at $E_{\nu} = 50\text{GeV}$. The extrapolation of neutrino flux from $E_{\nu} = 50\text{GeV}$ to $50\text{PeV}$ with spectral profile assumed above is shown in figure 1, which is significantly below the IC detected neutrino flux, $E_{\nu}^2J_{\nu,\text{IC}}$.

We also assume another harder CR spectrum with index of $-2.6$, then the single-flavor diffuse neutrino flux at $E_{\nu} = 60\text{TeV}$ is $E_{\nu}^2J_{\nu} = 5.31 \times 10^{-8}\text{GeVcm}^{-2}\text{s}^{-1}$, which is still about 3 times lower than the IC detected flux. Therefore the IC detected neutrinos can not be produced by CR propagation in the MW, unless the CR spectrum observed on Earth is not universal in the MW, and can be much harder than $-2.7$, so that the DGE at $E_\gamma > 100\text{GeV}$ can be much harder as well. In order to account for the IC detected neutrino flux at $E_{\nu} = 1\text{PeV}$, the $\gamma$-ray spectrum should be extrapolated from $100\text{GeV}$ with a photon index of $\Gamma \sim -2.3$. Consider a spectral break, corresponding to the CR knee, and the index of $\beta = -3$ above the knee, even harder spectrum below the knee is required, $\Gamma \sim -2.2$.

### 2.1.1 Galactic halo

\cite{46} recently proposes that CRs produced by a Galactic-center outflow may propagate into an extended Galactic halo of a size $R_h \sim 100\text{kpc}$ and a mass $M_h \sim 10^{11}M_\odot$, and lose most of their energy by $pp$ interactions. Given the IC flux and the size, the total PeV-neutrino luminosity of the Galactic halo will be $L_\nu \approx 4\pi R_h^2 E_{\nu}^2\Phi_{\nu} \approx 10^{59}\text{erg s}^{-1}$. According to our constraint, this requires that the DGE at $\gtrsim \text{TeV}$ (without background radiation absorption) should be flatten to be an index of $-2$. This is not in confliction with current observations. However the following argument may not favor this proposal for IC neutrinos.

Let us estimate the total neutrino flux from all the galaxies in the universe since we expect the other galaxies, especially those similar to the MW, also produce neutrinos in their halos. The neutrino energy density in the universe can be estimated to be $u_{\nu} \approx \xi_zL_{\nu}\rho_GT_{\text{H}}$, where $L_{\nu}$ is the typical neutrino luminosity of each galaxy, $\rho_G$ is the galaxy number density, $t_{\text{H}}$ is the Hubble time scale, and $\xi_z$ accounts for the redshift evolution of the neutrino production rate density in the universe. Thus the neutrino intensity is $I_{\nu} = (c/4\pi)u_{\nu} = \xi_z(c/4\pi)L_{\nu}\rho_GT_{\text{H}}$. The star formation rate (SFR) density in the local universe is $\rho_{\text{SFR}} = 0.015M_\odot\text{yr}^{-1}\text{Mpc}^{-3}$ \cite{18}, while the SFR in the MW is $\text{SFR}_{\text{MW}} \approx 2M_\odot\text{yr}^{-1}$ \cite{11}, thus we can estimate $\rho_G \approx \rho_{\text{SFR}}/\text{SFR}_{\text{MW}} \approx 10^{-2}\text{Mpc}^{-3}$. If the neutrino production rate evolves following the SFR density or the AGN activity in the universe, then $\xi_z \sim 3$ \cite{50}.

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\(^1\)Comes from the fact that each pion carries $\sim 1/5$ of the primary proton’s energy.
Following the 2FGL, the abbreviations used for the Galactic source types are: spp: special case (potential association with SNR or PWN); pwn: pulsar wind nebula; psr: pulsar (include both those identified by pulsations and those no pulsations seen in LAT yet); snr: supernova remnant; glc: globular cluster; hmb: high-mass binary; and nov: nova.

Table 2. γ-ray fluxes of 2FGL sources at 100GeV.

| Source type   | $E_\gamma^2 J_\gamma(100\text{GeV})/\text{GeVcm}^{-2}\text{s}^{-1}$ |
|---------------|---------------------------------------------------------------|
| Galactic      | 1.29 × 10$^{-7}$                                             |
| spp           | 5.77 × 10$^{-8}$                                             |
| pwn           | 4.04 × 10$^{-8}$                                             |
| psr           | 1.39 × 10$^{-8}$                                             |
| snr           | 1.21 × 10$^{-8}$                                             |
| glc           | 4.01 × 10$^{-9}$                                             |
| hmb           | 5.06 × 10$^{-10}$                                            |
| nov           | 1.60 × 10$^{-13}$                                            |
| US            | 2.58 × 10$^{-7}$                                             |
| extragalactic | 1.43 × 10$^{-6}$                                             |

$L_\nu \sim 10^{39}\text{erg s}^{-1}$ and $t_H \sim 10\text{Gyr}$, we have $I_\nu \sim 3 \times 10^{-7}\text{GeV cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$. This is more than an order of magnitude larger than the IC observed flux. Therefore in order for the IC excess being contributed by the Galactic halo emitted neutrinos, our MW is required to be either an unique galaxy or acting actively in a special phase.

2.2 Galactic point sources

Next consider the contribution of Galactic point sources by $pp$ interactions in the sources. Fermi-LAT has detected many new sources in sky survey. The LAT 2-year Point Source Catalog (2FGL) contains 1873 high energy γ-ray sources detected by LAT during the period of August 4, 2008 to July 31, 2010 [38]. Among these sources, there are 195 Galactic sources, 1102 extragalactic sources, and 576 unknown sources (US). The spectral shapes of these sources are divided into three types: power law, pow law with exponential cutoff, and log-parabola. We calculate photon fluxes from each source at 100GeV with the given spectral parameters in 2FGL. The total fluxes for different types of sources at 100GeV are shown in table 2. We obtain that the total fluxes of identified Galactic and US at $E_\gamma = 100\text{GeV}$ are $E_\gamma^2 J_\gamma,\text{MW} = 1.29 \times 10^{-7}\text{GeV cm}^{-2}\text{s}^{-1}$ and $E_\gamma^2 J_\gamma,\text{MW} = 2.58 \times 10^{-7}\text{GeV cm}^{-2}\text{s}^{-1}$, respectively.

A significant fraction of the USs may be Galactic other than extragalactic sources. We estimate the contribution of those USs that are of Galactic origin to the γ-ray flux on Earth. According to 2FGL, we show the Galactic latitude distribution of γ-ray flux of identified Galactic sources and USs at $E_\gamma = 100\text{GeV}$ in figure 2. The US distribution consists of Galactic and extragalactic components. We assume that the Galactic latitude distribution of the Galactic USs follows the same shape of the identified Galactic sources, and that the extragalactic one is isotropically distributed. We should subtract the isotropic extragalactic component from the total US flux to obtain the flux of Galactic USs. By comparing the latitude distributions of the identified Galactic sources and the USs, we can find that the emission at $|\sin b| > 0.1$ is dominated by extragalactic component. Subtracting an isotropic background flux to all the $\sin b$ bins, the expected contribution of USs to the Galactic point source flux
is \( E_\gamma^2 J_\gamma \sim 1 \times 10^{-7} \text{GeVcm}^{-2}\text{s}^{-1} \) at \( E_\gamma = 100 \text{ GeV} \). So the total \( \gamma \)-ray flux of all Galactic point sources (including identified sources and USs) is \( E_\gamma^2 J_\gamma \approx 2.3 \times 10^{-7} \text{GeVcm}^{-2}\text{s}^{-1} \). With eq. (2.1), the neutrino flux at \( E_\nu = 50 \text{ GeV} \) is \( E_\nu^2 J_\nu \sim 1 \times 10^{-7} \text{GeVcm}^{-2}\text{s}^{-1} \).

We assume that the neutrino spectrum is flat \( E_\nu^2 \Phi_\nu \propto E_\nu^0 \). This may be an optimistic estimate of the neutrino flux because CR spectrum is expected to be flat in a strong shock, and the secondary \( \gamma \)-ray and neutrino spectra follow the CR spectrum. So the expected PeV neutrino flux from Galactic point sources is

\[
E_\nu^2 J_{\nu, \text{point}} \approx 1 \times 10^{-7} \text{GeVcm}^{-2}\text{s}^{-1},
\]

(2.2)

not larger than the IC excess.

Following the discussion by [38] (their section 5.4), the contribution of USs to the Galactic source neutrino flux can be even lower, and the above conclusion may be more robust: (1) Despite the flux of USs increases sharply in Galactic plane, it is attributable to the relative lack of sources at \( |b| < 10^\circ \) in many of the extragalactic source catalogs used for source identification; (2) The USs in galactic plane with curved spectra tend to cluster in bright Galactic diffuse emission regions, suggesting that at least a fraction of them may be DGE maxima, that are not adequately modeled by DGE model; (3) Some USs may be unreal because there are much more fraction (51\%) of USs with doubt being a source in contrast to the fraction of identified sources (14\%). Moreover, the \( \gamma \)-ray flux may be dominated by electron emission, other than pp interactions. In conclusion, the flux of PeV neutrinos from Galactic point sources may be far below that in equation (2.2), and may not reach the IC excess flux.

3 Extragalactic origin

Since Galactic origins of IC neutrinos are not favored, we turn to discuss the extragalactic origin.

The scenario that the IC neutrinos are cosmogenic neutrinos produced via \( p\gamma \) interactions between CR particles and cosmic background photons is disfavored, because normalizing
the expected neutrino flux to that observed by IC at 1 PeV leads to an over predicted neutrino flux at EeV range \[24, 42\]. We discuss the other extragalactic neutrino sources below, i.e., GRBs, AGN jets, and starburst galaxies (SBGs).

### 3.1 Gamma-ray bursts

GRBs have long been proposed to be a strong candidate of the source of ultrahigh energy (UHE) CRs \[48\], and the $\gamma\gamma$ collisions are expected to produce intense neutrino emission around PeV range \[49\], consistent with the current IC constraint on the neutrino spectrum. It is interesting to check whether GRB neutrinos can account for the IC diffuse neutrinos. In the following, assuming first that GRBs are the IC neutrino sources, we estimate the average neutrino flux of a triggered GRB, which should be compared to the upper limit IC puts on the triggered GRBs. By doing this, we should assume that the neutrino flux from a GRB is proportional to the MeV-range photon flux.

For a $\gamma$-ray detector monitoring the whole sky with a sensitivity of $p_{th}$, the GRB trigger rate is

$$\dot{N}_{\text{trig}} = \int_0^{z_{\text{max}}} \frac{R(z)}{1+z} \frac{dV}{dz} dz \int_{p_{\text{th}}4\pi D_L^2 k(z)}^\infty \phi(L) dL,$$

(3.1)

where $R(z)$ is the redshift dependence of GRB rate density, $\phi(L)$ is the GRB luminosity function, $D_L$ is the GRB luminosity distance, $dV/dz$ is the volume-redshift relation of the universe, and $k(z)$ corresponds to $k$-correction, depending on GRB spectrum and detector energy range (see below). The (time averaged) $\gamma$-ray flux from triggered GRBs is

$$\Phi_{\text{trig}} = \int_0^{z_{\text{max}}} \frac{R(z)}{4\pi D_L^2 (1+z)} \frac{dV}{dz} dz \int_{p_{\text{th}}4\pi D_L^2 k(z)}^\infty E(L) \phi(L) dL,$$

(3.2)

whereas the total one, including the contribution from untriggered GRBs is

$$\Phi_{\text{tot}} = \int_0^{z_{\text{max}}} \frac{R(z)}{4\pi D_L^2 (1+z)} \frac{dV}{dz} dz \int_0^\infty E(L) \phi(L) dL.$$

(3.3)

Here $E$ is the GRB energy, for which we simply assume $E \propto L$.

Recently the GRB rate density and luminosity function have been well constrained by using the large sample of Swift GRBs with redshift measurement \[26\]:

$$R(z) = R(0) \begin{cases} (1+z)^{n_1} & z < z_1 \\ (1+z_1)^{n_1-n_2}(1+z)^{n_2} & z \geq z_1 \end{cases}$$

(3.4)

$$\phi(L) = \phi_0 \begin{cases} (L/L_*)^x & L < L_* \\ (L/L_*)^y & L \geq L_* \end{cases}$$

(3.5)

where $R(0) = 0.84$Gpc$^{-3}$yr$^{-1}$, $z_1 = 3.6$, $n_1 = 2.07$, $n_2 = -0.7$, $L_* = 10^{52.05}\text{erg s}^{-1}$, $x = -0.65$, $y = -3$, and $\phi_0$ is defined such that $\int_0^\infty \phi(L) dL = 1$.

For Fermi-GBM the threshold is $p_{th} = 0.71$ photons cm$^{-2}$s$^{-1}$ in the energy range of 50-300 keV \[31\]. In this case we write

$$k(z) = \frac{\int_{1\text{MeV}}^{10\text{MeV}} E n(\epsilon) d\epsilon}{\int_{50\text{keV}}^{100\text{keV}} (1+z) n(\epsilon) d\epsilon},$$

(3.6)

\[\text{CR propagation in CMB may still produce IC neutrinos in some specific cases [22].}\]
where $n(\epsilon)$ is the GRB spectrum in the rest frame, for which we assume a broken power law with photon indices of $\alpha = -1$ and $\beta = -2.2$ and a sharp break at $\epsilon_{\text{break}} = 511$ keV. We will take $z_{\max} = 8$ and assume a flat $\Lambda$CDM universe with $\Omega_m = 0.27$, $\Omega_\Lambda = 0.73$, and $H_0 = 71\text{km s}^{-1}\text{Mpc}^{-1}$.

The GBM trigger threshold is $p_{th} = 0.71$ photons $\text{cm}^{-2}\text{s}^{-1}$ [31]. There were 183 GRBs triggered between 2008 July 11 and 2009 March 31, corresponding to a GRB trigger rate of $\sim 260$ burst $\text{yr}^{-1}$ [31]. Taking into account the Earth occultation and the South Atlantic Anomaly passage, only 65% of GRBs above the GBM threshold can be detected [27]. So for a detector monitoring all sky with the GBM threshold, the trigger rate should be $\dot{N}_{\text{trig}} \approx 400\text{yr}^{-1}$. On the other hand, if $p_{th} = 0.7, 0.5,$ and 0.3 photons $\text{cm}^{-2}\text{s}^{-1}$, we can calculate with the above formula that $\dot{N}_{\text{trig}} = 220, 306,$ and $480 \text{ yr}^{-1}$, and $\Phi_{\text{trig}} / \Phi_{\text{tot}} = 0.71, 0.75,$ and 0.8, respectively. To obtain the GBM trigger rate $\dot{N}_{\text{trig}} = 400\text{yr}^{-1}$ one needs $p_{th} = 0.37$ photons $\text{cm}^{-2}\text{s}^{-1}$.

Taking $\dot{N}_{\text{trig}} = 400 \text{ yr}^{-1}$ and $\Phi_{\text{trig}} / \Phi_{\text{tot}} = 0.7$, if GRBs can account for the IC neutrino flux $f_{\nu} = E^2 \Phi_{\nu,\text{IC}} \ln(2\text{PeV}/60\text{PeV}) = 4.2 \times 10^{-7} \text{GeV cm}^{-2}\text{s}^{-1}$ (4$\pi$ integrated and single flavor), the average neutrino fluence of a GBM-triggered GRB is required to be

$$F_{\text{trig}} = \frac{f_{\nu}}{N_{\text{trig}}} \frac{\Phi_{\text{trig}}}{\Phi_{\text{tot}}} \frac{2.3 \times 10^{-2}}{0.7 \Phi_{\text{tot}}} \frac{400\text{yr}^{-1}}{N_{\text{trig}}} \text{GeV cm}^{-2}. \quad (3.7)$$

The $p\gamma$ interactions produce not only neutrinos but also $\gamma$-rays, which generate electromagnetic cascade emission in GeV energy range, which can be observed by Fermi-LAT. Using the neutrino and $\gamma$-ray connection, the Fermi-LAT observations of GRBs help to constrain that the average neutrino fluence from a GBM triggered GRB is [25]

$$F_{\text{LAT-bound}} \sim 2 \times 10^{-3} \text{GeV cm}^{-2}, \quad (3.8)$$

smaller than the required neutrino flux (equation (3.7)). The IC has also given an upper limit to the neutrino fluence from a triggered GRB (averaged over 215 GRBs), $F_{\nu,\text{IC-bound}} \approx E^2 F_{\nu} \times \ln(10)/215 = 1.6 \times 10^{-4} \text{GeV cm}^{-2}$ (using $E^2 F_{\nu} \approx 0.15 \text{GeV cm}^{-2}$; see figure 1 in [4]). This is also smaller than required, although the comparison is not straightforward because these 215 GRBs include not only those detected by GBM but also the other detectors.

Thus we reach the conclusion that GRB neutrinos may not account for the IC detected neutrinos (though the other GRB neutrino models that cannot be constrained by the neutrino-$\gamma$-ray connection may still work [34]).

It may be noted that the reported GBM threshold and GRB detection rate seem not completely consistent with the GRB redshift and luminosity distributions derived by [26]. However our result of using $\dot{N}_{\text{trig}} = 400 \text{ yr}^{-1}$ and $\Phi_{\text{trig}} / \Phi_{\text{tot}} = 0.7$ is robust since $\Phi_{\text{trig}} / \Phi_{\text{tot}} \sim 0.7$ is not sensitive to $p_{th}$ and taking $\dot{N}_{\text{trig}} \sim 200 \text{ yr}^{-1}$ (for GBM threshold value) even enhances the neutrino emission (eq (3.7)).

Our conclusion is similar to [27], but the main difference in between is the following. [27] use several assumptions of the GRB model, e.g., the jet Lorentz factor, the variability timescale, the fraction of energy in accelerated protons, etc., in order to calculate the neutrino production. Here we only need to assume that the neutrino flux is proportional to the $\gamma$-ray one (eq (3.7)). This may be reasonable given that the MeV $\gamma$-rays essentially carry away all the energy of electrons which probably carry some constant fraction of the total jet energy, and that the neutrinos carry away some constant fraction of the energy of protons which also may carry some constant fraction of the total jet energy. These may be true in a statistical point of view, although it may not hold for individual GRBs.
3.2 Jets of active galactic nuclei

AGN jets have long been predicted to be high energy CR and neutrino sources, and the dominant contribution of neutrino emission may be quasar hosted blazars, in particular, the flat spectrum radio quasars [FSRQ; e.g., 35], where the high energy neutrino production is due to photopion interactions between jet produced CRs and the external broadline and dust radiation.

FSRQs are also bright in $\gamma$-ray emission, which is possible to be produced by the primary electrons accelerated in the jets accompanying the production of high energy CRs. We may use the Fermi-LAT observations of FSRQs to make constraint on neutrino production. [8] has reported the luminosity function and redshift evolution of the Fermi detected FSRQs, which imply that the diffuse $\gamma$-ray flux from FSRQs is $4.1 \times 10^{-6}$ MeV cm$^{-2}$s$^{-1}$sr$^{-1}$ from $\sim 0.1$ MeV to 10 GeV range (figure 11 therein), i.e., the whole sky integrated flux is

$$f_{\gamma} = 5.1 \times 10^{-5} \text{GeV cm}^{-2}\text{s}^{-1}. \quad (3.9)$$

Compared with the IC flux we have the ratio of neutrino to $\gamma$-ray flux, $\tau_{\nu/\gamma} = 3 f_{\text{IC}}/f_{\gamma} \simeq 1.4 \times 10^{-2}$, where the factor 3 comes from the equal flux in the three neutrino flavors. This ratio is consistent with the estimated photomeson production efficiency for CR protons above the threshold for interacting with the broadline emission, $f_{p\gamma} \sim 5 \times 10^{-2} f_{\text{cov}} L_{\text{AD}}^{1/2}$, where $f_{\text{cov}}$ is the cover factor of the broadline emission region and $L_{\text{AD}}$ is the accretion disk luminosity [35], if jet-produced high energy electrons and CRs have comparable energies and a significant fraction of CRs lie above the threshold of photopion production. Therefore, FSRQs may produce diffuse neutrinos with a flux comparable to the IC detection.

However, AGN jets may have difficulty in producing the detected, flat neutrino spectrum from tens TeV to few PeV [35, 51]. Because the low energy radiation peaks at infrared to UV range, the photopion interactions tend to produce high neutrino flux at >PeV, in contrast to the IC observation which appears as lack of neutrinos above few PeV. Because of the decreasing radiation above UV frequency, the predicted neutrino flux decreases fast below PeV range, also in contrast to the IC observation. Thus the $\lesssim$100 TeV neutrinos may need the other origins instead of AGNs, and future observations at EeV range are needed to test the high neutrino flux from AGN jets.

3.3 Starburst galaxies

Starburst galaxies (SBGs) have been expected to be promising neutrino sources [29], given that they are strong CR sources and that the high density ISM and high magnetic field lead to high efficiency of CR energy loss by $pp$ collisions. CRs at $\lesssim$100 PeV may significantly lose their energy [29]. It is noticed that the IC neutrino flux is well consistent with the Waxman-Bahcall bound [50], which may suggest that all the CR energy is lost in pion production.

Fermi-LAT has detected several SBGs in 0.1 - 100 GeV range [6]. By comparing with their SFRs estimated by radio and far infrared detections, we have the $\gamma$ ray luminosity and SFR relation in SBGs [6, 23]

$$\nu L_{\nu}(\text{GeV})/\text{SFR} \approx 10^{46} \text{erg}/M_\odot \quad (3.10)$$

(where $L_{0.1-100 \text{GeV}} \sim 7\nu L_{\nu}(\text{GeV})$ is used). Assuming this relation to be universal, the GeV $\gamma$-ray production rate density in the local universe is $E_{\gamma}^2 Q_{\gamma}(\text{GeV}) = \rho_{\text{SFR}}(\nu L_{\nu}(\text{GeV})/\text{SFR}) \approx 1.5 \times 10^{14} \text{erg yr}^{-1}\text{Mpc}^{-3}$. The GeV $\gamma$-ray intensity (without attenuation) is $E_{\gamma}^2 \Phi_{\gamma}(\text{GeV}) =$
\[\xi_{tH}(c/4\pi)E^2_\gamma Q_{\gamma}(\text{GeV}) \approx 3.4 \times 10^{-7}(\xi_z/3)\text{GeV cm}^{-2}\text{s}^{-1}\text{sr}^{-1}.\]

The neutrino and \(\gamma\)-ray connection in \(pp\) collisions leads to the neutrino intensity in GeV range of \(E^2_\nu \Phi_\nu(0.5 \text{GeV}) = (1/2)E^2_\gamma \Phi_\gamma(\text{GeV}) = 1.7 \times 10^{-7}(\xi_z/3)\text{GeV cm}^{-2}\text{s}^{-1}\text{sr}^{-1}\), which is one order of magnitude higher than the IC detected flux at PeV scale. However, as suggested by CR confinement time \((\propto E_p^{-0.5})\) and CR spectral slope \((\propto E_p^{-2.7})\) measurement of CRs in MW, the spectrum of injected CRs may be \(dn_p/dE_p \propto E_p^{-2.2}\). If the CRs lost most of their energy in \(pp\) interactions then the neutrino spectral slope follows that of the CRs, and the neutrino flux at PeV scale extrapolated from GeV range is

\[E^2_\nu \Phi_\nu \approx 3 \times 10^{-8}(\xi_z/3)\text{GeV cm}^{-2}\text{s}^{-1}\text{sr}^{-1}; \quad (3.11)\]

consistent with IC detection. Moreover, two SBGs, NGC253 and M82, have been detected in TeV range, which show TeV flux lower than GeV one by about one order of magnitude [6]. Thus Fermi-LAT observations suggest that neutrinos from \(pp\) interaction in SBGs may account for the IC detection.

The calculation above does not consider that the local SFR density is dominated by normal star forming galaxies other than SBGs. However it is suggested in observations that most of the stars in the universe formed in SBGs at high redshift \(z \sim 2 - 4\) [21, 41], thus the neutrino production is dominated by SBGs at \(z \gtrsim 2\). The above calculation is available since the local neutrino production does not contribute significantly to the total neutrino flux.

### 4 Conclusion and discussion

Using Fermi-LAT observations and with the neutrino and \(\gamma\)-ray connection, we have constrained the origin of IC neutrinos. The main conclusions are below.

First, the diffuse Galactic neutrino emission from CR propagation in MW cannot account for the IC detected neutrino flux if the CR spectral slope \(\propto E_p^{-2.75}\) is universal in MW. In order to account for the IC neutrinos at PeV scale, the DGE spectral slope at \(> 100 \text{GeV}\) should be harder than \(\Gamma \sim -2.3\).

We obtain that the upper limit to the diffuse Galactic neutrino flux at 60 TeV is \(\sim 3\) times lower than the IC excess by considering that the total Fermi-LAT detected emission is from \(pp\) interactions. However, \(pp\) interactions only contribute to a fraction of the DGE. By the modeling of [5], the \(\pi^0\)-decay photons contribute to \(\sim 1/3\) of the total LAT flux in the “local” and “outer Galaxy”, and \(\sim 1/2\) of the total LAT flux in the “inner Galaxy”. The expected diffuse Galactic neutrino flux should be at least a factor of \(\sim 2\) lower than the upper limit we obtain, so the diffuse Galactic neutrino flux may contribute to \(\sim 10\%\) of the IC detected neutrino flux.

A study of the Galactic latitude distribution of the detected neutrinos would be more powerful test than only considering the total neutrino flux, but needs much more statistics of neutrino events. Future IC detection of the latitude distribution should be compared with the prediction of [44]. On the other hand, the detection of diffuse PeV photons would be more direct test [7], other than extrapolation of \(\gamma\)-ray spectrum from GeV to PeV scale. However, the current TeV-PeV photon detections only cover limited parts of the sky, e.g., biased in the Northern Hemisphere, in contrast to Fermi-LAT’s deep survey of the whole sky.

Second, the high energy \(\gamma\)-ray point sources in MW cannot account for the IC excess, unless the \(\gamma\)-ray spectra of these sources at \(> 100 \text{GeV}\) is unexpectedly harder than a flat spectrum with photon index \(\Gamma = -2\).
The point source spectral indices beyond 100 GeV are the main uncertainty. However, photons from some types of sources, such as pulsars, are not hadronic dominant at 100 GeV, which further reduces the expected flux from point sources. Moreover, the Galactic point sources concentrate on the Galactic disk, very different from the sky location of IC neutrinos, which is consistent with isotropic distribution. It should also be mentioned that although the neutrino flux from Galactic sources can hardly reach IC excess, both are in the same order of magnitude, suggesting that the Galactic sources may contribute to a fraction of IC neutrinos.

Again, the Galactic latitude distribution of detected neutrinos is more powerful and straightforward test to the Galactic point source origin. The IC-detected neutrinos arriving from high Galactic latitudes seem to disfavor the Galactic point source origin, but more detections of neutrinos in the future are required to study the latitude distribution with high confidence level.

Third, neutrino productions in GRB jets may not account for the IC neutrino flux. This is based on the assumption that in GRBs the neutrino flux is proportional to the \( \gamma \)-ray flux. We have used the LAT observations of GRB GeV emission to constrain neutrino flux. As time goes by, IC collects more observational results on GRBs, the constraint on GRB neutrino will be more and more stringent.

Our method applies to the classic GRBs with the common picture that the neutrino production occurs in the region where the main burst of MeV \( \gamma \)-rays are produced, e.g., the internal shock region \[49\]. Thus we do not constrain the neutrino production when the jet is still deep inside the GRB progenitor \[32, 34\]. \[34\] find that low-power jets inside progenitors of GRBs may produce higher flux of TeV-PeV neutrinos. It would be important to measure the emissivity in the universe by more observations of these “low power GRBs”.

Forth, \textit{Fermi}-LAT observation suggests that AGN jets may produce neutrino flux as high as the IC flux. However, AGN jets may have difficulty in explaining the flat spectrum from tens of TeV to few PeV detected by IC. AGN jets may not account for the tens-TeV neutrinos detected by IC, and the future EeV neutrino experiments would be important to test the predicted AGN neutrino flux.

For the AGN jets to produce neutrinos reaching the IC detected flux, their local universe CR generation rate should be \( 10 - 100 \) times larger than the local UHE CR emissivity, because of the low photopion production efficiency \[12, 35\]. This is in contradiction with the consistency between IC detected neutrino flux and Waxman-Bahcall bound, unless that CR energy production rate decreases sharply by \( 10 - 100 \) times from \( \sim 100 \) PeV to \( \sim 10^{19} \) eV.

Finally, we use the \textit{Fermi}-LAT detections of individual SBGs to constrain the PeV neutrino flux from SBGs, and find that they can account for the IC excess. \[28\] have considered the neutrino emission from star forming galaxies, including SBGs, to explain the IC neutrinos. They use a more specific model, instead of the \( \gamma \)-ray and neutrino connection as we emphasize here.

It should be noted that \[50\] have derived an maximum diffuse neutrino flux by assuming all CRs lose energy in pion productions and normalizing the neutrino flux to the UHE CR production rate density. The 60TeV-2PeV neutrino flux detected by IC turns out to match the predicted Waxman-Bahcall bound, which implies that the CRs in \( 1 - 100 \) PeV is the same component as the UHE CRs \[23\] and all the CR energy is lost in pion production.\(^3\)

\(^3\)[28] do not need CRs losing all their energy inside the galaxies, because they do not normalize the CR flux in \( 1 - 100 \) PeV range to the observed UHE CR one, i.e., they are different CR components of different origins in the universe. The consistency of the IC neutrino flux with the Waxman-Bahcall bound happens to be so.
As there is no bright AGNs in the local universe within the UHE CR energy loss length (∼ 100 Mpc; due to interaction with cosmic microwave background photons), GRBs are the more promising sources for UHE CRs. Thus, a likely explanation to the IC neutrinos is that the CRs corresponding to the IC neutrinos are also produced by GRBs. These CRs do not lose significant fraction of their energy in GRB jets, as constrained by Fermi-LAT and IC observations of GRBs, but they lose most energy after escaping from GRB jets and propagate in GRB host galaxies, which are mostly SBGs. Future deeper observations of high energy γ-rays and neutrinos from individual GRBs and SBGs by, e.g., CTA and IC, etc, can test this interpretation [e.g., 3].

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References

[1] IceCube collaboration, M.G. Aartsen et al., First observation of PeV-energy neutrinos with IceCube, Phys. Rev. Lett. 111 (2013) 021103 [arXiv:1304.5356] [nsPIRE].
[2] IceCube collaboration, M.G. Aartsen et al., Observation of high-energy astrophysical neutrinos in three years of IceCube data, Phys. Rev. Lett. 113 (2014) 101101 [arXiv:1405.5303] [nsPIRE].
[3] IceCube collaboration, M.G. Aartsen et al., Searches for extended and point-like neutrino sources with four years of IceCube data, arXiv:1406.6757 [nsPIRE].
[4] IceCube collaboration, R. Abbasi et al., An absence of neutrinos associated with cosmic-ray acceleration in γ-ray bursts, Nature 484 (2012) 351 [arXiv:1204.4219] [nsPIRE].
[5] Fermi-LAT collaboration, Fermi-LAT observations of the diffuse gamma-ray emission: implications for cosmic rays and the interstellar medium, Astrophys. J. 750 (2012) 3 [arXiv:1202.4039] [nsPIRE].
[6] Fermi-LAT collaboration, M. Ackermann et al., GeV observations of star-forming galaxies with Fermi LAT, Astrophys. J. 755 (2012) 164 [arXiv:1206.1346] [nsPIRE].
[7] M. Ahlers and K. Murase, Probing the galactic origin of the IceCube excess with gamma-rays, Phys. Rev. D 90 (2014) 023010 [arXiv:1309.4077] [nsPIRE].
[8] M. Ajello et al., The luminosity function of Fermi-detected flat-spectrum radio quasars, Astrophys. J. 751 (2012) 108 [arXiv:1110.3787] [nsPIRE].
[9] L.A. Anchordoqui et al., Cosmic neutrino pevatrons: a brand new pathway to astronomy, astrophysics and particle physics, JHEAp 1-2 (2014) 1 [arXiv:1312.6587] [nsPIRE].
[10] L.A. Anchordoqui et al., Pinning down the cosmic ray source mechanism with new IceCube data, Phys. Rev. D 89 (2014) 083003 [arXiv:1306.5021] [nsPIRE].
[11] L. Chomiuk and M.S. Povich, Toward a unification of star formation rate determinations in the Milky Way and other galaxies, Astron. J. 142 (2011) 197 [arXiv:1110.4105] [nsPIRE].
[12] C.D. Dermer, K. Murase and Y. Inoue, Photopion production in black-hole jets and flat-spectrum radio quasars as PeV neutrino sources, JHEAp 3-4 (2014) 29 [arXiv:1406.2633] [nsPIRE].
[13] D.B. Fox, K. Kashiyama and P. Mészáros, Sub-PeV neutrinos from TeV unidentified sources in the galaxy, *Astrophys. J.* **774** (2013) 74 [arXiv:1305.6606] [SPIRE].

[14] C. Gruppioni et al., The Herschel PEP/HerMES luminosity function. I: probing the evolution of PACS selected galaxies to z ~ 4, *arXiv:1302.5209* [SPIRE].

[15] Y.Q. Guo, H.B. Hu, Q. Yuan, Z. Tian and X.J. Gao, Pinpointing the knee of cosmic rays with diffuse PeV γ-rays and neutrinos, *Astrophys. J.* **795** (2014) 100 [arXiv:1312.7616] [SPIRE].

[16] N. Gupta, Galactic PeV neutrinos, *Astropart. Phys.* **48** (2013) 75 [arXiv:1305.4123] [SPIRE].

[17] H.-N. He, T. Wang, Y.-Z. Fan, S.-M. Liu and D.-M. Wei, Diffuse PeV neutrino emission from ultraluminous infrared galaxies, *Phys. Rev. D* **87** (2013) 063011 [arXiv:1303.1253] [SPIRE].

[18] A.M. Hopkins and J.F. Beacom, On the normalisation of the cosmic star formation history, *Astrophys. J.* **651** (2006) 142 [astro-ph/0601463] [SPIRE].

[19] The IceCube collaboration, Evidence for high-energy extraterrestrial neutrinos at the IceCube detector, *Science* **342** (2013) 1.

[20] J.C. Joshi, W. Winter and N. Gupta, How many of the observed neutrino events can be described by cosmic ray interactions in the Milky Way?, *Mon. Not. Roy. Astron. Soc.* **439** (2014) 3414.

[21] S. Juneau et al., Cosmic star formation history and its dependence on galaxy stellar mass, *Astrophys. J.* **619** (2005) L135 [astro-ph/0411775] [SPIRE].

[22] O.E. Kalashev, A. Kusenko and W. Essey, PeV neutrinos from intergalactic interactions of cosmic rays emitted by active galactic nuclei, *Phys. Rev. Lett.* **111** (2013) 041103 [arXiv:1303.0300] [SPIRE].

[23] B. Katz, E. Waxman, T. Thompson and A. Loeb, The energy production rate density of cosmic rays in the local universe is ~ 10^{44} – 45 erg Mpc^{-3} yr^{-1} at all particle energies, *arXiv:1311.0287* [SPIRE].

[24] R. Laha, J.F. Beacom, B. Dasgupta, S. Horiuchi and K. Murase, Demystifying the PeV cascades in IceCube: less (energy) is more (events), *Phys. Rev. D* **88** (2013) 043009 [arXiv:1306.2309] [SPIRE].

[25] Z. Li, Fermi limit on the neutrino flux from gamma-ray bursts, *Astrophys. J.* **770** (2013) L40 [arXiv:1210.6594] [SPIRE].

[26] A. Lien et al., Probing the cosmic gamma-ray burst rate with trigger simulations of the swift burst alert telescope, *Astrophys. J.* **783** (2014) 24 [arXiv:1311.4567] [SPIRE].

[27] R.-Y. Liu and X.-Y. Wang, Diffuse PeV neutrinos from gamma-ray bursts, *Astrophys. J.* **766** (2013) 73 [arXiv:1212.1260] [SPIRE].

[28] R.-Y. Liu, X.-Y. Wang, S. Inoue, R. Crocker and F. Aharonian, Diffuse PeV neutrinos from EeV cosmic ray sources: semi-relativistic hypernova remnants in star-forming galaxies, *Phys. Rev. D* **89** (2014) 083004 [arXiv:1310.1283] [SPIRE].

[29] A. Loeb and E. Waxman, The cumulative background of high energy neutrinos from starburst galaxies , *JCAP* **05** (2006) 003.

[30] C. Lunardini, S. Razzaque, K.T. Theodoseau and L. Yang, Neutrino events at IceCube and the Fermi bubbles, *Phys. Rev. D* **90** (2014) 023016 [arXiv:1311.7188] [SPIRE].

[31] C. Meegan et al., The Fermi gamma-ray burst monitor, *Astrophys. J.* **702** (2009) 791 [arXiv:0908.0450] [SPIRE].

[32] P. Meszaros and E. Waxman, TeV neutrinos from successful and choked gamma-ray bursts, *Phys. Rev. Lett.* **87** (2001) 171102 [astro-ph/0103275] [SPIRE].
[33] K. Murase, M. Ahlers and B.C. Lacki, Testing the hadronuclear origin of PeV neutrinos observed with IceCube, *Phys. Rev. D* **88** (2013) 121301 [arXiv:1306.3417] [inSPIRE].

[34] K. Murase and K. Ioka, TeV-PeV neutrinos from low-power gamma-ray burst jets inside stars, *Phys. Rev. Lett.* **111** (2013) 121102 [arXiv:1306.2274] [inSPIRE].

[35] K. Murase, Y. Inoue and C.D. Dermer, Diffuse neutrino intensity from the inner jets of active galactic nuclei: impacts of external photon fields and the blazar sequence, *Phys. Rev. D* **90** (2014) 023007 [arXiv:1403.4089] [inSPIRE].

[36] M. Nagano and A.A. Watson, Observations and implications of the ultrahigh-energy cosmic rays, *Rev. Mod. Phys.* **72** (2000) 689 [inSPIRE].

[37] A. Neronov, D.V. Semikoz and C. Tchernin, PeV neutrinos from interactions of cosmic rays with the interstellar medium in the Galaxy, *Phys. Rev. D* **89** (2014) 103002 [arXiv:1307.2158] [inSPIRE].

[38] P.L. Nolan et al., *FERMI* Large Area Telescope second source catalog, *Astropart. J. Suppl.* **199** (2012) 31.

[39] Particle Data Group collaboration, J. Beringer et al., Review of particle physics, *Phys. Rev. D* **86** (2012) 010001 [inSPIRE].

[40] J.C. Joshi, W. Winter and N. Gupta, How many of the observed neutrino events can be described by cosmic ray interactions in the Milky Way?, [arXiv:1310.5123] [inSPIRE].

[41] N.A. Reddy et al., A census of optical and near-infrared selected star-forming and passively evolving galaxies at redshift $z \sim 2$, *Astrophys. J.* **633** (2005) 748 [astro-ph/0507264] [inSPIRE].

[42] E. Roulet, G. Sigl, A. van Vliet and S. Mollerach, PeV neutrinos from the propagation of ultra-high energy cosmic rays, *JCAP* **01** (2013) 028 [arXiv:1209.4033] [inSPIRE].

[43] M.T. Sargent, M. Bethermin, E. Daddi and D. Elbaz, The contribution of starbursts and normal galaxies to infrared luminosity functions at $z < 2$, *Astrophys. J.* **747** (2012) L31 [arXiv:1202.0290] [inSPIRE].

[44] F.W. Stecker, Diffuse fluxes of cosmic high-energy neutrinos, *Astrophys. J.* **228** (1979) 919 [inSPIRE].

[45] F.W. Stecker, PeV neutrinos observed by IceCube from cores of active galactic nuclei, *Phys. Rev. D* **88** (2013) 047301 [arXiv:1305.7404] [inSPIRE].

[46] A.M. Taylor, S. Gabici and F. Aharonian, A galactic halo origin of the neutrinos detected by IceCube, *Phys. Rev. D* **89** (2014) 103003 [arXiv:1403.3206] [inSPIRE].

[47] I. Tamborra, S. Ando and K. Murase, Star-forming galaxies as the origin of diffuse high-energy backgrounds: gamma-ray and neutrino connections, and implications for starburst history, *JCAP* **09** (2014) 043.

[48] E. Waxman, Cosmological gamma-ray bursts and the highest energy cosmic rays, *Phys. Rev. Lett.* **75** (1995) 386 [astro-ph/9505082] [inSPIRE].

[49] E. Waxman and J.N. Bahcall, High-energy neutrinos from cosmological gamma-ray burst fireballs, *Phys. Rev. Lett.* **76** (1996) 2292 [astro-ph/9701231] [inSPIRE].

[50] E. Waxman and J.N. Bahcall, High-energy neutrinos from astrophysical sources: an upper bound, *Phys. Rev. D* **59** (1999) 023002 [hep-ph/9807282] [inSPIRE].

[51] W. Winter, Photohadronic origin of the TeV-PeV neutrinos observed in IceCube, *Phys. Rev. D* **88** (2013) 083007 [arXiv:1307.2793] [inSPIRE].