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# Gamma-ray counterpart of the IceCube neutrinos

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**Abstract.** A  $\gamma$ -ray excess at high Galactic latitudes starting at energies 300 GeV was recently discovered in the data of the Fermi telescope. The multi-TeV  $\gamma$ -ray emission found has spectral characteristics at both low and high Galactic latitudes compatible with those of the IceCube neutrinos in the same sky regions. This suggests that these  $\gamma$ -rays are the counterpart of the IceCube neutrino signal, implying that a sizeable part of the IceCube neutrino flux originates from the Milky Way. The diffuse neutrino and  $\gamma$ -ray signal at high Galactic latitudes may originate either from a nearby cosmic ray "PeVatron" cosmic ray source, an extended Galactic cosmic ray halo or from decays of heavy dark matter particles.

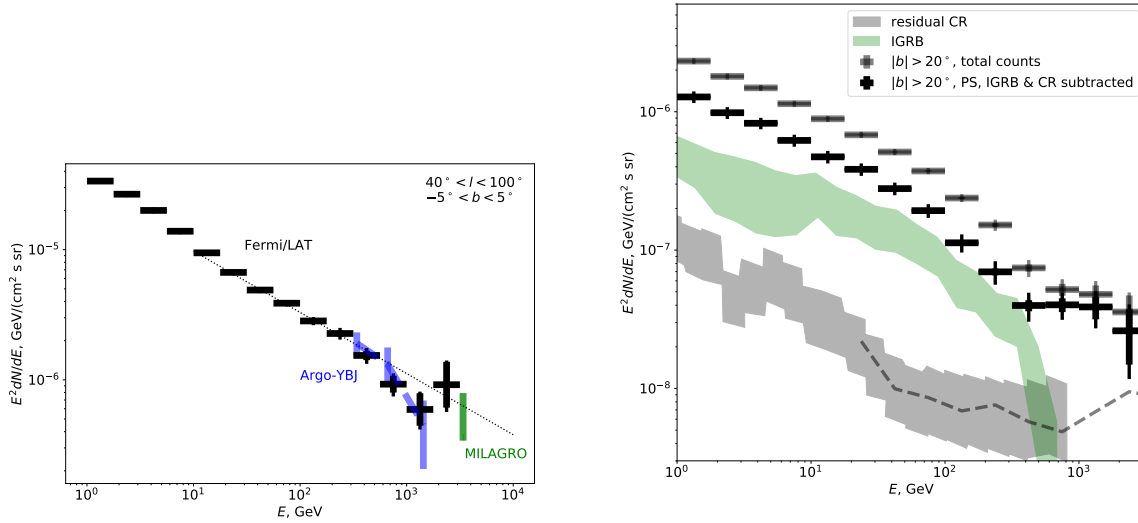
## 1. Introduction

The discovery of an extraterrestrial neutrino signal in the TeV–PeV energy range by the IceCube collaboration has opened the era of multi-messenger astronomy [1]. The source(s) of this neutrino signal have remained unidentified so far. Since the production of high-energy neutrinos is accompanied by  $\gamma$ -rays, these neutrino sources could be identified using a "multi-messenger" approach by combining neutrino and  $\gamma$ -ray data. The TeV–PeV  $\gamma$ -ray flux from distant sources is suppressed by electron-positron pair production in interactions with low-energy photons of the extragalactic background light and the cosmic microwave background. Therefore, the presence or absence of a  $\gamma$ -ray counterpart can be used to clarify the origin of the neutrino signal: If the signal originates from extragalactic sources at cosmological distances, no  $\gamma$ -ray counterpart is expected in the multi-TeV to PeV band. In contrast, a Galactic origin implies the presence of a comparable multi-TeV  $\gamma$ -ray flux.

The search for the  $\gamma$ -ray counterpart of the neutrino signal is challenging with both ground and space-based  $\gamma$ -ray telescopes. Ground-based telescopes or air shower arrays suffer from a high background of events produced by charged CRs. The arrival directions of the CR background events are distributed over large angular scales, similar to the expected  $\gamma$ -ray counterpart of the neutrino signal. Space-based telescopes like the Fermi Large Area Telescope (LAT) achieve a much better suppression of the charged CR background, but they have small collection areas which severely limit the signal statistics.

In Ref. [2], we reported a study of the TeV diffuse gamma-ray sky based on the data of Fermi/LAT. We showed that the  $\gamma$ -ray flux and spectrum at low and high Galactic latitudes are compatible with the flux of the measured neutrino signal, in the energy range where the two signals overlap. This suggests that the  $\gamma$ -rays in the multi-TeV band are the counterpart of the soft part of the IceCube neutrinos, while the part with an  $1/E^{2.2}$  slope at the highest energies has an extragalactic origin.





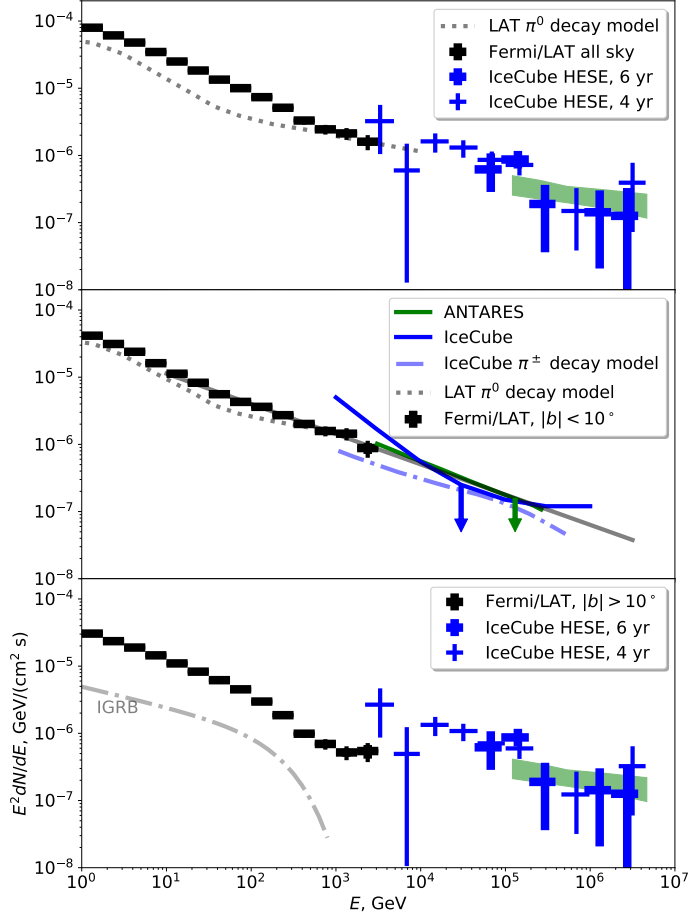
**Figure 1.** Left: Combined Fermi/LAT, ARGO-YBJ (blue) [5] and MILARGO (green) [6] spectrum of the  $40^\circ < l < 100^\circ$  stretch of the Galactic plane. Right: Fermi/LAT spectrum of diffuse  $\gamma$ -ray emission from high Galactic latitudes compared to the residual CR background (dotted thin line). The green shaded band shows the uncertainty of the IGRB derived in Ref. [7]. Grey data points below 3 TeV show total high Galactic latitude flux without subtraction of catalogue sources, IGRB and residual CR background contributions.

## 2. Cross-calibration of the LAT data in the multi-TeV band

The energy resolution and the calibration of the effective area of Fermi/LAT degrade in the TeV band [3, 4]. Therefore we performed an additional cross-calibration of the Fermi/LAT flux measurements with those of ground-based  $\gamma$ -ray telescopes via a comparison of stacked spectra of selected calibration sources, see Ref. [2] for details. We found that a cross-calibration factor  $\kappa = 1 - c \log(E/100 \text{ GeV})$  with  $c = 0.25 \pm 0.12$  applied to the LAT flux measurements above 300 GeV leads to a better consistency with the ground-based telescope measurements. The uncertainty of the parameter  $c$  is taken into account as an additional systematic error. We verified that the cross-calibration factor also assures the consistency of the Fermi/LAT measurements of diffuse TeV emission from large regions of the sky with the measurements by the ground-based air shower arrays ARGO-YBJ [5] and MILAGRO [6], as shown in the left panel of Fig. 1.

## 3. Diffuse TeV $\gamma$ -ray signal

Figure 2 compares Fermi/LAT  $\gamma$ -ray spectra of the full sky (upper panel), of the Galactic plane  $|b| < 10^\circ$  (middle panel) and at Galactic latitudes  $|b| > 10^\circ$  (lower panel) with the neutrino spectra of the same sky regions [8, 9, 10, 11]. In the spectra of the all-sky and the  $|b| > 10^\circ$  region we removed residual CR background, while the Galactic plane spectrum is calculated by subtracting high Galactic latitude background and residual cosmic ray contributions (see Ref. [2] for details). The  $\gamma$ -ray and neutrino all-sky flux and spectral slope measurements agree in the overlapping multi-TeV band. Figure 2 also shows the model of diffuse  $\gamma$ -ray emission from pion decays derived from an all-sky analysis of the LAT data [12]. It is this component which is expected to have the neutrino counterpart, since pion decays produce simultaneously  $\gamma$ -rays ( $\pi^0$  decays) and neutrinos ( $\pi^\pm$  decays).

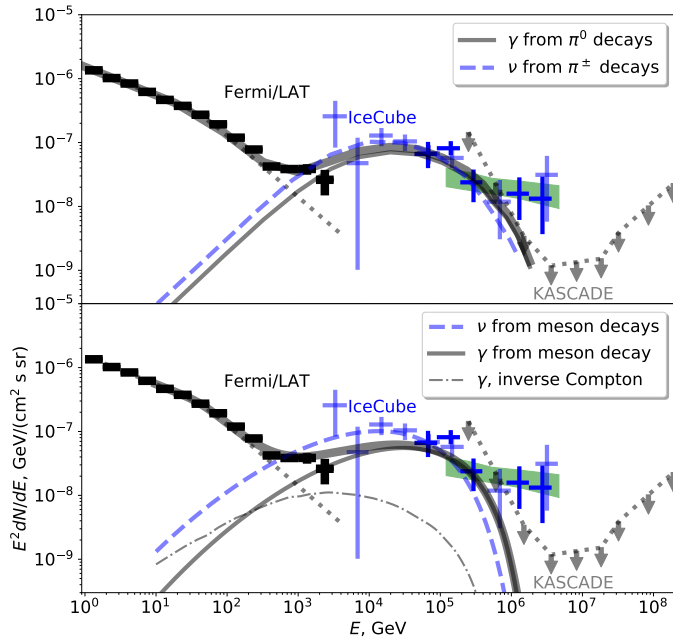


**Figure 2.** Top: the multi-messenger spectrum of the full sky: Fermi/LAT (black), IceCube (blue data and green bow-tie (from Ref. [8]) together with a model (dash-dotted) for the Galactic diffuse hadronic emission [12]. Middle: Fermi/LAT spectrum for  $|b| < 10^\circ$  with model-dependent upper limit on neutrino flux [10]. Bottom: Fermi/LAT spectrum of  $|b| > 10^\circ$  region, compared to the IceCube neutrino flux measurements. The dash-dotted curve shows the best-fit model of the IGRB [7].

The  $\gamma$ -ray flux below TeV is dominated by the emission from the Galactic plane, while only a moderate fraction of the neutrino flux in the 100 TeV range comes from the Galactic plane [9, 10, 8, 11]. Therefore, a multi-TeV  $\gamma$ -ray flux as counterpart of the neutrino signal should have a harder spectrum at high Galactic latitudes than at the Galactic plane so that its relative contribution to the all-sky flux can grow with increasing energy.

This hardening appears more pronounced in the analysis of the spectrum of the part of the sky at higher Galactic latitude,  $|b| > 20^\circ$ , shown in Fig. 3. In this figure we have removed contributions from resolved point sources, extragalactic isotropic diffuse  $\gamma$ -ray background (IGRB) and residual CR backgrounds thus leaving only the Galactic diffuse emission. The hardening of the spectrum of diffuse emission at high Galactic latitudes starts at 300 GeV and it can not be explained by instrumental effects (see the right panel of Fig. 1 and Ref. [2] for details). Below 300 GeV the spectrum is well fit by a smoothly broken power-law with the slope  $\Gamma = 2.906 \pm 0.015$  in the 30–300 GeV range. The spectrum in the 0.3–3 TeV range has the slope  $\Gamma = 2.09 \pm 0.09$ .

The most significant excess above the extrapolation of the power-law valid below 300 GeV is in the energy bin 1–1.7 TeV. The model prediction of the number of photon counts in this bin is 16.4. The observed number of counts is 39. The chance probability of such an excess is  $1.5 \times 10^{-6}$ . In the energy bin 1.7–3.16 TeV the expected number of counts is 3.8, while the



**Figure 3.** High Galactic latitude emission for the local PeVatron (top) and DM (bottom) models. Thick and thin error bars of Fermi/LAT data points (black) show statistical and systematic uncertainties, including the uncertainties of subtraction of IGRB and residual CR backgrounds. Vertical arrows show KASCADE upper limits on the  $\gamma$ -ray flux from Northern sky [13]. Solid thin lines show the gamma-ray emission from the additional hard component. Dotted line shows a broken power-law fit to the sub-TeV  $\gamma$ -ray spectrum.

observed one is 10. The chance probability of such an excess is  $5.8 \times 10^{-3}$ . In the energy bin 0.3-1 TeV, the model predicts less than 66.5 counts while the observed signal is 100 counts. The chance probability of the excess in this bin is  $8 \times 10^{-5}$ . The energy-binning independent combined chance probability of the excess above 300 GeV is less than  $8 \times 10^{-10}$ .

#### 4. Interpretation

The conventional high Galactic latitude diffuse emission components have soft spectra in the TeV range [7] and can not explain the observed spectral hardening above 300 GeV. The same is true for the IGRB, which is dominated by the cumulative flux of blazars [14], a special class of active galactic nuclei which do not provide the dominant contribution to the neutrino signal [15, 16]. Thus, the observed hardening of the  $\gamma$ -ray spectrum has to be interpreted as due to the presence of a new Galactic  $\gamma$ -ray flux component above 300 GeV. It is this component which is the counterpart of the neutrino signal with comparable flux in the multi-TeV range.

Only few source types could produce multi-TeV multi-messenger emission on large angular scales at high Galactic latitude with a hard spectrum. One possibility is interactions of CRs forming a previously unknown component of the Galactic CR population. If this new component would reside everywhere in the Galactic disk, an equivalent spectral hardening would be observed in the spectrum of the Galactic plane—which is not the case. Instead, the hard spectrum CRs could either reside in our local Galactic environment, or be a part of a very large halo.

The local source of CRs with a hard spectrum reaching PeV energies (a "PeVatron") should be a recent and nearby source, like e.g. the Vela supernova [17]. It should have injected CRs less than  $10^5$  year ago at a distance  $d$  not larger than several hundred parsecs. These two conditions are required for the presence of PeV CRs which produce 10–100 TeV neutrinos and the large angular extent  $\Omega$  of the multi-messenger emission [18]. Cosmic rays with total energy  $U_{CR} \sim 10^{50}$  erg injected by the PeVatron and losing their energy on the time scale  $t_{pp} \simeq 1.5 \times 10^8 (n_{ISM}/0.5 \text{ cm}^{-3}) \text{ yr}$  in interactions with the interstellar medium of the density

$n_{\text{ISM}} \sim 0.5 \text{ cm}^{-3}$  produce the  $\gamma$ -ray and neutrino flux  $F = U_{\text{CR}}/(4\pi d^2 \Omega t_{pp})$  with magnitude

$$F \sim 2 \times 10^{-7} \left( \frac{\Omega}{2\pi \text{sr}} \right)^{-1} \frac{n_{\text{ISM}}}{0.5/\text{cm}^3} \left( \frac{d}{0.3 \text{kpc}} \right)^{-2} \frac{\text{GeV}}{\text{cm}^2 \text{s sr}}.$$

This flux estimate matches the observed level, cf. with Fig. 3. Otherwise, the high Galactic latitude emission could be from a very large (hundred kiloparsec) CR "storage" around the Milky Way disk [19].

The local PeVatron model predicts strong variability of the multi-messenger signal across the sky. This variability is determined by the peculiarities of the energy-dependent spread of the CRs and of the matter distribution in the local Galaxy. Low energy CRs which had no time to escape from the source region would not contribute to the large angular scale emission. This leads to a low-energy hardening of the spectrum, as shown in the top panel of Fig. 3 [18]. In contrast, the signal is not expected to experience neither strong fluctuations nor a low-energy hardening in the large scale halo model [19].

An alternative possibility shown in the bottom panel of Fig. 3 is that decays of metastable DM particles  $X$  with mass  $m_X \simeq 5 \text{ PeV}$  generate photons and neutrinos [20, 21, 22]. The spectral shape of the decay mode  $X \rightarrow \bar{q}q \rightarrow \text{hadrons}$  is determined by Quantum Chromodynamics (QCD). Since at the end of the QCD cascade quarks combine more easily to mesons than to baryons, mainly neutrinos and photons from pion decays are produced. The  $\gamma$ -ray and neutrino flux measurements constrain the  $X$  particle lifetime to be  $\tau_X \sim 2 \times 10^{27} (\Omega_X/\Omega_{\text{DM}})^{-1} \text{ s}$ , where  $\Omega_X/\Omega_{\text{DM}}$  is the fraction of the DM in the form of  $X$  particles [22, 21]. Since the mass  $m_X$  is above the unitarity limit, the  $X$  particles were never in thermal equilibrium. They should have been produced by gravitational interactions or other non-thermal processes and may serve as a tool to study the earliest phases of the Universe.

The DM decay neutrino signal has a sizeable extragalactic contribution, while its  $\gamma$ -ray component in the TeV-PeV range has only the Galactic part. This leads to a systematically lower normalisation of the multi-TeV  $\gamma$ -ray component. The same is true for the large scale CR halo, which should be present around all galaxies, so that the neutrino flux is expected to have a significant extragalactic contribution. To the contrary, the neutrino and  $\gamma$ -ray components in the local PeVatron model both originate from the Milky Way. The absence of the extragalactic component leads to similar  $\gamma$ -ray and neutrino fluxes (see top panel of Fig. 2).

The DM halo of the Galaxy is denser in the direction of the inner Galaxy. This means that in the DM model, the flux from the inner Galaxy should be stronger than that from the outer Galaxy. However, the signal from the Galactic plane shown in Fig. 3 contains both the direction toward the Galactic center and the anticenter, from which the strongest and the weakest DM decay signal should be observed. We have verified that the expected excess of the DM decay signal from the Galactic Plane is consistent with the IceCube upper bounds on the Galactic plane flux. The fraction of the DM decay signal from the region  $|b| < 10^\circ$  is 0.22. Combining the information from Fig. 2 and Fig. 3, one can see that the neutrino flux from the high Galactic latitude region which is supposed to account for the full neutrino signal at high Galactic latitude at 100 TeV is at the level  $6 \times 10^{-7} \text{ GeV/cm}^2\text{s}$  at this energy (cf. with the bottom panel of Fig. 3). Re-scaling it by a factor  $0.22/0.78 \simeq 0.3$ , one could check that the expected DM decay flux from the direction of the Galactic plane is at the level of  $2 \times 10^{-7} \text{ GeV/cm}^2\text{s}$ , i.e. marginally consistent with the IceCube upper limit on the neutrino flux from the Galactic plane (the IceCube upper limit is exactly at the level of the flux estimate, which means that the signal of DM origin should soon reveal an excess toward the inner Galaxy). There is, however, one important reservation which should be added. The IceCube upper limit on the Galactic emission is derived assuming certain spatial template for the signal distribution. This template does not correspond to the spatial template of the DM signal. Thus, the IceCube limit on the Galactic emission is not directly comparable to the DM model prediction.

For the local PeVatron model, there is no fixed spatial template because the source morphology is not known. No excess toward the Galactic Plane is generically expected. In this respect, the IceCube limit on the Galactic emission component does not provide constraints on the local PeVatron model.

The distinction between possible models of the multi-messenger signal based on spectral or spatial characteristics will be possible with next generation instruments neutrino telescopes and the space-based  $\gamma$ -ray telescope HERD which will accumulate higher signal statistics. The detection of the  $\gamma$ -ray part of the signal by ground-based telescopes requires a sufficiently high ( $\sim 10^5$ ) rejection level of the CR background.

## 5. Conclusions

We have demonstrated that the properties of the large scale diffuse Galactic  $\gamma$ -ray flux in multi-TeV band are compatible with the flux and spectrum of the neutrino signal in 1-100 TeV range, so that the two signals may be considered as different components of one and the same "multi-messenger" signal in the multi-TeV sky. The  $\gamma$ -ray flux at high Galactic latitude exhibits a pronounced hardening above 300 GeV, while no hardening is observed in the low Galactic latitude flux. This effect explains the lower contribution from the Galactic plane to the neutrino signal at higher energies, as observed by IceCube. We have suggested three possible models which could explain the observed hard spectrum high Galactic latitude multi-messenger emission above 300 GeV: (i) interactions of CRs injected by a recent nearby cosmic PeVatron, (ii) CR interactions in a large halo around the Milky Way, or (iii) decays of DM particles.

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