

# How many of the observed neutrino events can be described by cosmic ray interactions in the Milky Way?

Jagdish C. Joshi,<sup>1★</sup> Walter Winter<sup>2★</sup> and Nayantara Gupta<sup>1★</sup>

<sup>1</sup>Raman Research Institute, Sadashivanagar, Bangalore 560080, India

<sup>2</sup>Institut für theoretische Physik and Astrophysik, Universität Würzburg, Am Hubland, D-97074 Würzburg, Germany

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## ABSTRACT

Cosmic rays diffuse through the interstellar medium and interact with matter and radiations as long as they are trapped in the Galactic magnetic field. The IceCube experiment has detected some TeV–PeV neutrino events whose origin is yet unknown. We study if all or a fraction of these events can be described by the interactions of cosmic rays with matter. We consider the average target density needed to explain them for different halo sizes and shapes, the effect of the chemical composition of the cosmic rays, the impact of the directional information of the neutrino events, and the constraints from gamma-ray bounds and their direction. We do not require knowledge of the cosmic ray escape time or injection for our approach. We find that, given all constraints, at most 0.1 of the observed neutrino events in IceCube can be described by cosmic ray interactions with matter. In addition, we demonstrate that the currently established chemical composition of the cosmic rays contradicts a peak of the neutrino spectrum at PeV energies.

**Key words:** neutrinos.

Cosmic ray propagation in our Galaxy has been studied in the past several decades using many models and with increasing complexities to explain the observational results successfully. The transport equation written by Ginzburg & Syrovatskii (1964) contains various terms to include the possible gains and losses in the flux of cosmic rays. The simple leaky box model and its variants were widely used to explain the observed secondary-to-primary GeV cosmic ray flux ratios (Shapiro & Silberberg 1970; Cowsik & Wilson 1973). Cosmic rays diffuse through the Galaxy, interact with matter and background radiations producing secondary particles of lower atomic numbers ( $Z$ ). More complex models of cosmic ray propagation including the effects of energy-dependent diffusion coefficient ( $D$ ) and re-acceleration were subsequently introduced by Gupta & Webber (1989), Gaisser (1991), Berezhinskii et al. (1990), and Letaw, Silberberg & Tsao (1993).

In this work, we consider the steady state flux of cosmic rays for the calculation of the diffuse neutrino flux produced in cosmic ray interactions, directly based on cosmic ray observations. Thus, our results neither depend on the unknown injection spectrum nor on the escape time of very high energy cosmic rays (VHECRs).

The detection of very high energy and ultrahigh energy cosmic rays by air shower experiments (Chou et al. 2005; Risse et al. 2005; Abbasi et al. 2010; Apel et al. 2013; Knurenko & Sabourov

2013; The Pierre Auger Collaboration 2013) have an enormous impact on our understanding of the high-energy phenomena in the Universe. The compilation of cosmic ray data from various air shower experiments show a knee region near 3 PeV and ankle region near  $10^4$  PeV in the all-particle cosmic ray spectrum (Gaisser, Stanev & Tilav 2013).

If we consider the propagation of these cosmic rays within the Galaxy, secondary gamma rays and neutrinos will be produced by their interactions with Galactic matter (Evoli, Grasso & Maccione 2007; Gupta 2012, 2013; Stecker 2013). The IceCube experiment has detected some neutrino events in TeV–PeV energies which are unlikely to be of atmospheric origin (Aartsen et al. 2013; IceCube Collaboration 2013). The implication of the IceCube neutrinos for cosmic ray transition models has been studied in Anchordoqui et al. (2013), assuming that these could be of Galactic origin. Cosmic ray interactions in the inner Galaxy have been considered as the possible origin of the some of the IceCube-detected events and *Fermi*/Large Area Telescope (LAT)-observed gamma rays in Neronov, Semikoz & Tchernin (2013). The five shower-like events correlated with the Galactic Centre region (Razzaque 2013) could have originated from cosmic ray accelerations in supernova remnants. The correlation of the gamma-ray and the neutrino fluxes and the Galactic origin of the IceCube events have been studied in Ahlers & Murase (2013). They point out that within wide angular uncertainties of the Galactic plane, it is plausible that about 10 events are of Galactic origin. Recently, the sub-PeV and PeV neutrinos have been correlated with the cosmic rays above the second knee in the VHECR spectrum,

\*E-mail: jagdish@rri.res.in (JCJ); winter@physik.uni-wuerzburg.de (WW); nayan@rri.res.in (NG)

for various sources within hadronic interaction (Murase, Ahlers & Lacki 2013) and hypernova remnants have been suggested as their sources (Liu et al. 2013). The neutrino events discovered by IceCube can also come from  $py$  interactions, as it is, for instance, discussed by Winter (2013), Murase & Ioka (2013), and Stecker (2013).

In this work, we study if the TeV–PeV neutrino events detected by IceCube above the atmospheric background have originated from interactions of VHECRs with Galactic matter or gas. The interactions of cosmic rays with Galactic matter also lead to the production of high-energy gamma-rays which contribute to the background measured by *Fermi*/LAT.

## 1 PROTON INTERACTIONS AND TARGET GEOMETRY

VHECRs interacting with Galactic matter give charged and neutral pions. The charged pions decay to muons and muon-type neutrinos ( $\pi^\pm \rightarrow \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$ ). The muons subsequently decay to electrons, electron-type neutrinos and muon-type neutrinos ( $\mu^\pm \rightarrow e^\pm + \nu_e(\bar{\nu}_e) + \bar{\nu}_\mu(\nu_\mu)$ ). The ratio of the neutrino fluxes of different flavours produced in this way is  $\nu_e + \bar{\nu}_e : \nu_\mu + \bar{\nu}_\mu : \nu_\tau + \bar{\nu}_\tau = 1:2:0$ .

The fluxes of neutrinos of each flavour are expected to be roughly equal on Earth after flavour mixing  $\nu_e + \bar{\nu}_e : \nu_\mu + \bar{\nu}_\mu : \nu_\tau + \bar{\nu}_\tau \simeq 1:1:1$  (Gaisser 1991). For the numerical calculations, however, we compute the flavour mixing precisely using the current best-fitting values from (Gonzalez-Garcia et al. 2012, first octant solution).

For the description of the  $pp$  interactions, we follow Kelner, Aharonian & Bugayov (2006). The  $pp$  interaction time is given by  $t_{pp}(E_p) = 1/(n_H \sigma_{pp}(E_p) c)$ , where  $n_H$  is the mean hydrogen number density of Galactic matter and the cross-section of the interaction is  $\sigma_{pp}(E_p) = 34.3 + 1.88 \ln(E_p/1 \text{ TeV}) + 0.25 (\ln(E_p/1 \text{ TeV}))^2$  mb. The average (over different experiments) cosmic ray spectrum above 100 TeV from Gaisser et al. (2013) has been approximated with power laws with several breaks for our calculation; the spectrum has been linearly interpolated among (5, 0), (6.5, 0), (8.5, -0.85), (9.7, -1.7), (10.5, -1.7), (11, -2.3) on a double log scale in ( $\log_{10} E [\text{GeV}]$ ,  $\log_{10} E^{2.6} J [\text{GeV}^{1.6} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}]$ ).

The neutrino injection spectra  $Q_\nu$  [ $\text{cm}^{-3} \text{s}^{-1} \text{GeV}^{-1}$ ] are given by

$$Q_\nu(E_\nu) = c n_H \int_0^1 \sigma_{pp} \left( \frac{E_\nu}{x} \right) N_p \left( \frac{E_\nu}{x} \right) f \left( x, \frac{E_\nu}{x} \right) \frac{dx}{x} \quad (1)$$

for the appropriate flavour-dependent parametrizations of the distribution functions given in equations 62 and 66 of Kelner et al. (2006), which include the proper pion multiplicities. The integration over  $x \equiv E_\nu/E_p$  is carried out to include the contributions from all protons having energy equal to or higher than  $E_\nu$ . However, on the average, 5 per cent of a proton’s energy goes to a secondary neutrino, which means that the maximum contribution to the neutrino flux at energy  $E_\nu$  comes from the protons of energy 20 times  $E_\nu$ . Note that the neutrino injection is computed from the proper density  $n_H$  [ $\text{cm}^{-3}$ ] and the steady state density  $N_p$  [ $\text{cm}^{-3} \text{GeV}^{-1}$ ] obtained from solving the cosmic ray transport equation. If we assume that the cosmic ray density is the same everywhere in the Galaxy (or hydrogen halo), we can directly use the observed cosmic ray flux to compute  $N_p = 4\pi/c J_p$ , where the fluxes are given in units [ $\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{GeV}^{-1}$ ]. That is, the neutrino production neither relies on the cosmic ray injection nor on the cosmic ray escape time. The observed neutrino flux can be computed by

$$J_\nu = \frac{1}{4\pi} \int dV \frac{Q_\nu}{4\pi r^2}, \quad (2)$$

where  $r$  is the distance between Earth and production region. For a (hypothetical) spherical hydrogen halo with radius  $R$  centred at Earth and a homogeneous target density, it is easy to show that  $J_\nu = Q_\nu R/(4\pi)$ . For an arbitrary halo shape, we can re-write equation (1) as

$$J_\nu(E_\nu) = R_{\text{eff}} n_H \int_0^1 \sigma_{pp} \left( \frac{E_\nu}{x} \right) J_p \left( \frac{E_\nu}{x} \right) f \left( x, \frac{E_\nu}{x} \right) \frac{dx}{x}. \quad (3)$$

Here, the effective radius  $R_{\text{eff}} \equiv \int dV/(4\pi r^2)$  for a homogeneous halo, integrated over the appropriate production region; for a halo centred at Earth, one recovers  $R = R_{\text{eff}}$ . If the hydrogen density or cosmic ray density depends on the location, this effect can be also expressed in terms of the effective radius  $R_{\text{eff}}$  in a more complicated scheme; for a detailed study of the spatial distribution of hydrogen and cosmic rays, see Evoli et al. (2007).

In some models (Evoli et al. 2007), the average atomic hydrogen density in the Galaxy modelled with radii of tens of kpc and height hundreds of pc is calculated to be  $\sim 0.5 \text{cm}^{-3}$ . The density of ionized, neutral, and molecular hydrogen as a function of the height from the Galactic plane relative to the Earth’s location and the radial distance from the Galactic Centre have been calculated in Feldmann, Hooper & Gnedin (2013) using the gamma-ray data observed by *Fermi* gamma-ray space telescope. Relative to the Earth’s location, the density of atomic and molecular hydrogen gas drops from 1 to  $0.1 \text{cm}^{-3}$  within a distance of 1–1.5 kpc above the Galactic plane. The density of ionized hydrogen gas steeply falls from 0.3 to  $0.001 \text{cm}^{-3}$  within the same distance. The hydrogen densities of  $1 \text{cm}^{-3}$  are unlikely for the tens of kpc of spherical halo as discussed in Dickey & Lockman (1990), Kalberla & Kerp (2009), and Blitz & Robishaw (2000).

It is expected to be much higher closer to the Galactic Centre. Please note that they have used a time-dependent injection spectrum proportional to  $E_p^{-2.4}$  and solved the diffusion equation to derive the steady state cosmic ray proton spectrum. We are using the observed cosmic ray spectrum in our calculations. We completely independently derive the average hydrogen density from the neutrino observations, assuming that the observed events come from interactions between cosmic rays and hydrogen within the halo. We consider different shapes of the hydrogen halo. The effective radii from equation (3) for the different geometries and the Earth 8.33 kpc off the Galactic Centre are listed in Table 1, where we denote the radius of the spherical region around the Galactic Centre by  $R_{\text{GC}}$ .

**Table 1.** The effective halo radius  $R_{\text{eff}}$ , calculated for different halo shapes and parameters. Here,  $R_{\text{GC}}$  refers to the radius around the Galactic Centre and  $\pm h_{\text{kpc}}$  to the extension of the cylinder beyond the Galactic plane for the cylindrical shape.

Shape	$R_{\text{GC,kpc}}$	$h_{\text{kpc}}$	$R_{\text{eff,kpc}}$
Spherical	10.0		7.2
Spherical	15.0		13.3
Cylindrical	10.0	2.5	4.7
Cylindrical	10.0	1.5	3.5
Cylindrical	10.0	0.5	1.7
Cylindrical	10.0	0.25	1.0
Cylindrical	15.0	2.5	6.5
Cylindrical	15.0	0.5	2.1
Cylindrical	15.0	0.1	0.58

In the following, we use  $R_{\text{eff}} = 10$  kpc or  $R_{\text{eff}} = 1$  kpc for different extreme models, but our results can be easily re-scaled with Table 1. While for the spherical halo around the Galactic Centre and extending beyond Earth  $R_{\text{eff}} \sim 7\text{--}13$  kpc seems plausible, smaller values are obtained for the cylindrical haloes. For realistic scale heights,  $h \lesssim 250$  pc,  $R_{\text{eff}} \simeq 1$  kpc.

## 2 EFFECT OF COSMIC RAY COMPOSITION

The observed cosmic ray flux contains protons, helium, carbon, oxygen, iron, and heavier nuclei. In Gaisser et al. (2013), the helium nuclei flux exceeds the proton flux above 10 TeV, and at 1 PeV, helium and iron nuclei fluxes are comparable (shown with curves of different colours in fig. 4 of Gaisser et al. 2013). At 100 PeV, the cosmic ray flux contains mostly iron nuclei, and at 1 EeV, protons dominate over iron nuclei. Each nucleon in the nucleus interacts with a Galactic hydrogen atom and pions are produced, which subsequently decay to neutrinos and gamma rays. In the case of composite nucleus, the (observed) cosmic ray flux of nuclei with mass number  $A$  is  $J_A(E_A) = dN_A(E_A)/dE_A$ .

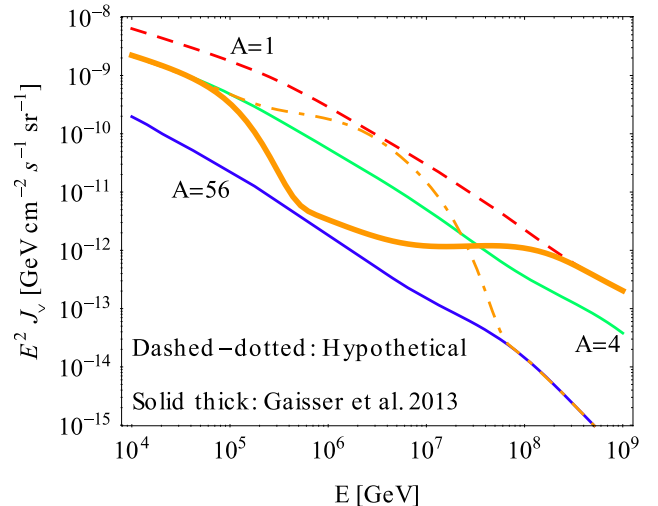
We tested two different approaches to compute the neutrino flux for heavier compositions. One is essentially the superposition model: we assume that the nucleus with mass number  $A$  and energy  $E_A$  behaves as  $A$  nucleons with energy  $E_A/A$ . As a consequence, we can use equation (3) to compute the neutrino flux by replacing  $J_p(E_p) = dN_p(E_p)/dE_p \rightarrow A^2 J_A(AE_p) = A^2 dN_A(AE_p)/dE_A$ . For a simple power law with spectral index  $\alpha$ , one has  $J_p(E_p) = A^{2-\alpha} E_p^{-\alpha}$ , and as a consequence, the result is identical to protons for  $\alpha = 2$ . As another approach, we rather follow Anchordoqui et al. (2007) and take into account that the cross-section  $\sigma_{Ap}$  is higher by a factor of  $A^{3/4}$  than  $\sigma_{pp}$ . In this case, we can re-write equation (3) as

$$J_\nu(E_\nu) = R_{\text{eff}} n_{\text{H}} \int_0^1 \sigma_{Ap} \left( \frac{E_\nu}{x_A} \right) J_A \left( \frac{E_\nu}{x_A} \right) \times A f \left( Ax_A, \frac{E_\nu}{Ax_A} \right) \frac{dx_A}{x_A}, \quad (4)$$

where  $x_A = E_\nu/A$  is the fraction of the nucleus' energy going into the neutrino. For a simple power law, this yields a neutrino flux  $\propto A^{1.75-\alpha}$ , which is about a factor of  $A^{0.25}$  smaller than the one of the superposition models, with some compensation by the slightly higher cross-section. The reason is, roughly speaking, that the cross-section of the nucleus is somewhat smaller than that of  $A$  nucleons, because of the surface area/volume ratio  $\sim A^{2/3}$ . Note that these differences are very small (at the level of 20 per cent), and we use the (more realistic) model in equation (4) in the following, which allows us to implement variable compositions easily.

Our predicted neutrino fluxes after flavour mixing for different cosmic ray compositions,  $n_{\text{H}} = 1 \text{ cm}^{-3}$  and  $R_{\text{eff}} = 1$  kpc can be found in Fig. 1. The Gaisser et al. composition has been adopted from fig. 4 in Gaisser et al. (2013), where we interpret  $A(E_A)$  as a function of cosmic ray energy  $E_A$  in equation (4). In that case, we linearly interpolate  $A$  between  $A = 4$  at  $5 \times 10^4$  GeV,  $A = 4$  at  $4 \times 10^6$  GeV,  $A = 56$  at  $8 \times 10^7$  GeV, and  $A = 1$  at  $10^9$  GeV. For the 'hypothetical model', a helium composition between  $5 \times 10^4$  and  $4 \times 10^6$  GeV has been chosen, then proton between  $10^7$  and  $10^8$  GeV, and then iron at  $10^9$  GeV (and higher), linearly interpolated among these values.

First of all, since the flux roughly scales as  $A^{2-\alpha}$ , it is clear that the pure proton composition gives the highest flux and the pure



**Figure 1.** Predicted neutrino flux for different cosmic ray compositions,  $n_{\text{H}} = 1 \text{ cm}^{-3}$  and  $R_{\text{eff}} = 1$  kpc, corresponding to emission from a cylindrical halo with radius 10 kpc and half height 250 pc ( $\nu_\mu + \bar{\nu}_\mu$  flux including flavour mixing).

iron composition the lowest. The Gaisser et al. model shows an iron composition at about  $10^8$  GeV, which leads to a dip in the neutrino flux at PeV energies, exactly where the excess is observed. For comparison, we show a hypothetical model with a transition from heavier to lighter elements at these energies, with iron at the highest energies. This model produces a peak at exactly the right position, and therefore provides an especially good fit, but it contradicts the iron knee in the cosmic ray composition observed by the KASCADE experiment (Kampert et al. 2004). Note that all cases with a composition heavier than hydrogen at 100 TeV lead to a predicted neutrino flux about one order of magnitude below the flux required to describe the IceCube observation (IceCube Collaboration 2013).

We note that analytical estimates are not very accurate because: (a) the usual energy conservation arguments do not hold for spectra much steeper than  $E^{-2}$ , (b) the cross-section increases with energy which induces a small spectral tilt, and (c) the distribution functions do have an impact.

## 3 RESULTS FOR THE TARGET DENSITY

The fluxes in Fig. 1 depend on the product  $R_{\text{eff}} \times n_{\text{H}}$ . Here, we fit the computed neutrino spectra to the data in order to see what values can reproduce that, and what can be said about the fraction of neutrinos from cosmic ray interactions. We follow the method described in Winter (2013) updated by IceCube Collaboration (2013). The neutrino events detected by the IceCube detector are binned in four energy intervals 30–200 TeV, 0.2–1, 1–2, and 2–100 PeV. We use two different approaches. (1) Ignoring direction, we assume that all non-atmospheric events needs to be described by the interactions with hydrogen, computing the atmospheric background with the method in Winter (2013); model 'All sky'. (2) We choose the events from the sky map (IceCube Collaboration 2013) which may potentially come from the cosmic ray interactions with the hydrogen halo within the directional uncertainties, and we correct for fraction of isotropically distributed events which may fall into the

**Table 2.** Best-fitting hydrogen density for different cosmic ray compositions (first column) and two different composition and halo models. Here also the  $1\sigma$  errors from the fit to neutrino data are given, as well as the  $\chi^2$  per degree of freedom for the fit. The errors are non-Gaussian because of Poissonian statistics.

Composition	All sky		Directional inf.	
	$R_{\text{eff}} = 10 \text{ kpc}$	$\chi^2$	$R_{\text{eff}} = 1 \text{ kpc}$	$\chi^2$
	$n_{\text{H}}$ [ $\text{cm}^{-3}$ ]	/d.o.f.	$n_{\text{H}}$ [ $\text{cm}^{-3}$ ]	/d.o.f.
Hydrogen ( $A = 1$ )	$1.6^{+0.3}_{-0.5}$	1.9	$72^{+48}_{-42}$	0.8
Helium ( $A = 4$ )	$5.9^{+1.7}_{-1.5}$	2.1	$280^{+190}_{-170}$	0.8
Iron ( $A = 56$ )	$130^{+38}_{-34}$	2.5	$6000^{+4300}_{-3800}$	0.9
Gaisser et al. (2013)	$9.3^{+3.2}_{-2.8}$	5.1	$370^{+350}_{-300}$	1.3
Hypothetical	$4.5^{+1.3}_{-1.2}$	1.4	$230^{+150}_{-130}$	0.7

Galactic plane; model ‘Directional inf.’<sup>1</sup> The rest of the events are treated as (extragalactic and atmospheric) isotropic background. In addition, we assume that the neutrino directions are correlated with the diffuse gamma-ray emission from the Galactic plane, which is limited to a Galactic latitude below  $5^\circ$ , see Ackermann et al. (2012). This reduces the IceCube exposure to that flux by about a factor of 10 because of the reduced solid angle.

We present our main results in Table 2, where the best-fitting target densities and the  $\chi^2/\text{d.o.f.}$  are shown for different composition models (rows) and two different extreme models for the directional information and halo sizes (columns). Note that  $R_{\text{eff}} = 10 \text{ kpc}$  has been chosen for the ‘All sky’ model and  $R_{\text{eff}} = 1 \text{ kpc}$  for the directional model; for different values, the results can be easily re-scaled using Table 1. From the All sky model, only the pure hydrogen composition produces realistic values for  $n_{\text{H}}$ , at the expense of a huge halo size.

Note that the statistics are good enough to derive lower bounds for the hydrogen density in the All sky case. In the directional model, the statistics are much poorer and the error bars therefore much larger. Because of the small solid angle coverage of the signal, the required target densities are extremely large, which is unlikely. However, the event rates in IceCube from the direction of the Galactic plane can be well reproduced, see Fig. 2. For the Gaisser et al. (2013) cosmic ray composition (left-hand panel), we obtain a relatively poor fit because of the dip at PeV (middle bins), exactly where the neutrino data require a peak (compare to Fig. 1). A better fit of the shape is, as expected, obtained for our hypothetical cosmic ray composition model, see right-hand panel. Although this model is incompatible with cosmic ray composition data, it may serve as a proof of principle that one can produce a peak at PeV with composition changes only. Note again that there is no direct dependence on the cosmic ray injection and escape time in our calculation.

We have calculated the secondary very high energy gamma-ray flux expected from  $\pi^0$  decays produced in pp interactions directly with Kelner et al. (2006). We show two different cases in Fig. 3:  $A = 1$  All sky model versus Gaisser et al. composition model with directional information. Note that this result is shown for the best fit of the models to neutrino data, i.e. the normalization is determined by the neutrino observation and does not depend on  $n_{\text{H}}$  or  $R_{\text{eff}}$  indi-

vidually. For illustration, we also show the curves for the gamma-ray fluxes corrected for absorption due to the background radiation with the mean free paths calculated in Protheroe & Biermann (1996) for  $d = 10 \text{ kpc}$ . The upper limits on the diffuse gamma-ray flux from various experiments are compared with our results. One strong constraint comes from the KASCADE and CASA-MIA limits at a few hundred TeV. On the other hand, the *Fermi*-LAT observation at 100 GeV (Ackermann et al. 2012) does not impose a problem for the  $A = 1$  ‘All sky’ model, whereas the directional model clearly exceeds the bound. The data above a few hundred TeV can be circumvented away by the attenuation of the gamma rays over long distances. The information given in Fig. 3 can be used to infer the fraction of neutrino events which can come from the interactions in our Galaxy by re-scaling the event rates to satisfy the bounds.

## 4 CONCLUSIONS

Taking into account the spectral shape of the observed neutrino spectrum, we have tested if it is plausible to describe the observed neutrino flux in the TeV–PeV range by interactions between cosmic rays and matter in the interstellar medium. We have discussed several composition models for the cosmic rays and several geometries for the target matter halo. For the directional information on the neutrino events, we have chosen two possibilities: either all events above the atmospheric backgrounds are to be described by the matter interactions or only the events compatible with the directions from the Galactic plane – whereas the rest forms an isotropic (atmospheric and extragalactic) background. In the latter case, we have also taken into account a probable correlation with the diffuse gamma-ray emission from the Galactic plane.

We have demonstrated that strong constraints arise from: (a) the expected target densities obtained from cosmic ray propagation models, (b) bounds on the diffuse gamma-ray emission from the Galactic plane, (c) the measured cosmic ray composition contradicting the flux shape observed in IceCube, and (d) the directional correlation with the diffuse gamma-ray emission from the Galactic plane, limiting the expected solid angle of the signal flux. In the most plausible scenario (directional information used, cosmic ray composition model by Gaisser et al. 2013), the required target density is about a factor of 100 above current expectations to describe the neutrino events from the direction of the Galactic plane. This means that only  $\mathcal{O}(0.1)$  event from the current IceCube observation would come from cosmic ray interactions for realistic target densities. Ignoring the directional information, a larger contribution  $\mathcal{O}(1)$  event is possible, taking into account the cosmic ray composition data, plausible halo sizes, and the gamma-ray constraints – which may serve as an upper limit for the estimate. However, this scenario requires unrealistically large target densities.

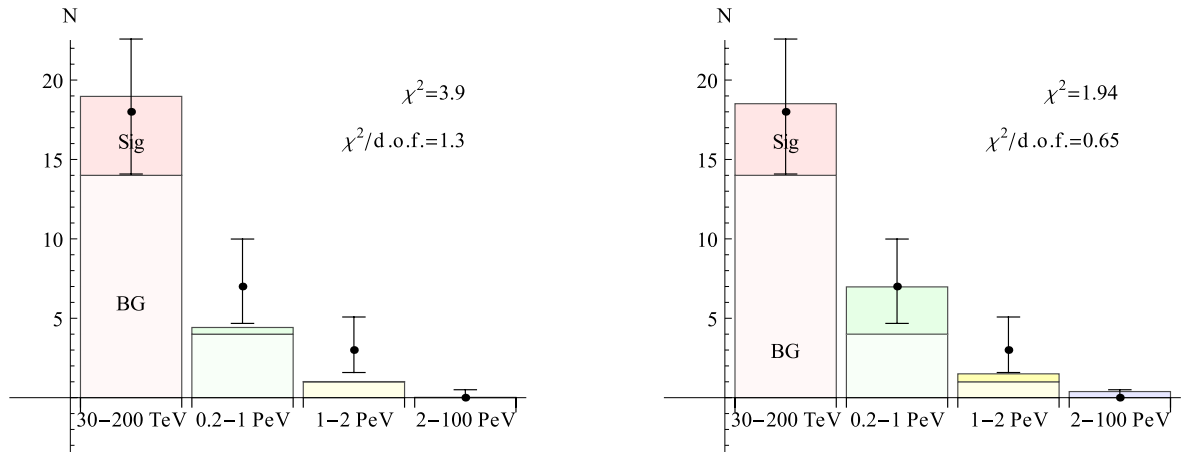
In conclusion, we have demonstrated that taking into account the known constraints, only a small fraction of the observed neutrino events may originate from the Galactic plane.

## ACKNOWLEDGEMENTS

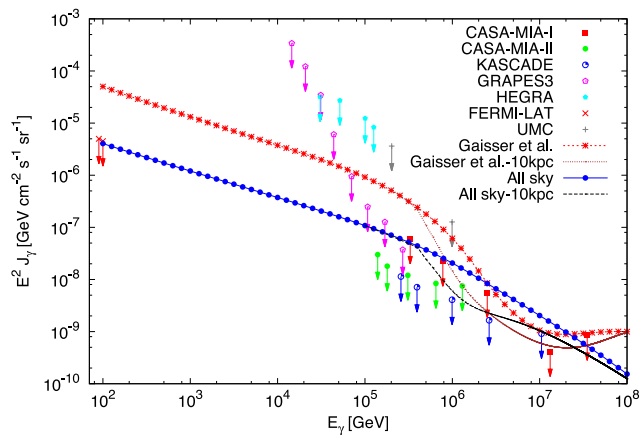
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<sup>1</sup> We remove the events at the lowest energies for that, as expected for the atmospheric background, in the ratio 2:1 showers to tracks. That is, the remaining signal events are 2, 3, 4, 13, 14, 15, 22, 25, 27 following the numbering in table 1 of IceCube Collaboration (2013).





**Figure 2.** Observed (dots) and fitted (bars) event rates in the different energy bins for the Gaisser et al. (2013) and hypothetical models in the left- and right-hand panels, respectively. Here, the model with directional information has been used. The required hydrogen densities are tabulated in Table 2.



**Figure 3.** Unattenuated gamma-ray flux for two different models ( $A = 1$ , All sky versus Gaisser et al. composition, directional information) compared with the limits from CASA-MIA-I (Chantell et al. 1997), KASCADE (Schatz et al. 2003), HEGRA (Karle et al. 1995), GRAPES-3 (GRAPES-3 Collaboration 2009), and UMC (Matthews et al. 1991). In addition, bounds from the *Fermi*-LAT Galactic plane diffuse emission (Ackermann et al. 2012, fig. 17) and CASA-MIA (Borione et al. 1998) are shown (CASA-MIA-II). The ‘10 kpc’ curves show the effect of absorption due to the background radiation for a distance of 10 kpc (Protheroe & Biermann 1996). The required hydrogen densities are tabulated in Table 2.

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