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Evidence the Galactic contribution to the IceCube astrophysical neutrino flux

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ABSTRACT

We show that the Galactic latitude distribution of IceCube astrophysical neutrino events with energies above 100 TeV is inconsistent with the isotropic model of the astrophysical neutrino flux. Namely, the Galactic latitude distribution of the events shows an excess at low latitudes $|b| < 10°$ and a deficit at high Galactic latitude $|b| \gtrsim 50°$. We use Monte–Carlo simulations to show that the inconsistency of the isotropic signal model with the data is at $\gtrsim 3\sigma$ level, after the account of trial factors related to the choice of the low-energy threshold and Galactic latitude binning in our analysis.

1. Introduction

The discovery of astrophysical neutrino signal by IceCube experiment has started a new field of neutrino astronomy [1–6]. The signal is a relatively soft (i.e. softer than $dN_\nu/dE \propto E^{-2}$) powerlaw. Recent analysis of the data [5] excludes the $1/E^2$ type spectrum at more the 3.8 σ level. The signal is consistent with a powerlaw $dN_\nu/dE = A(E/100\ \text{TeV})^{-\Gamma_\nu}$ with normalisation $A = 6.7^{+1.1}_{-1.2} \times 10^{-18}$ $(\text{GeV cm}^2\ \text{s sr})^{-1}$ and slope $\Gamma_\nu = 2.50 \pm 0.09$ [5].

It is not clear yet what kind of astronomical source(s) are detected by IceCube. The overall distribution of the three-year event sample is consistent with an isotropic distribution [3], while a separate fit of the Northern and Southern hemisphere signals in the four-year signal shows a preference to a harder spectrum in the Northern hemisphere [5] which could potentially be due to the presence of a softer contribution of the flux from the inner Galaxy in the Southern hemisphere [7,8]. Otherwise, the overall approximate isotropy of the signal would point to its extragalactic origin.

The unexpected properties of the observed signal challenge pre-existing theoretical models. Softness of the spectrum disfavours a range of models of extragalactic sources in which the neutrino flux is generated via interactions of high-energy protons with soft photon backgrounds. In such models charged pion production and decay which results in neutrino emission is characterised by a relatively high energy threshold. Neutrino energies in the 10–100 TeV range are typically much below the threshold and the neutrino spectrum in this energy range is expected to be much harder than observed [9–13].

Models which are favoured by the data are those in which the neutrino flux is produced in proton-proton (or, more generally, nuclei-nuclei) interactions. In this case, the energy threhshold for the pion production is as low as $\sim$100 MeV. The neutrino spectrum above this threshold approximately repeats the parent proton/nuclei spectrum [14]. Measurement of $\Gamma_\nu \simeq 2.5$ just tells that the parent proton/nuclei spectrum is a powerlaw with the slope $\Gamma_p \simeq \Gamma_\nu \simeq 2.5$ [7]. The parent protons/nuclei with such spectrum could be cosmic rays residing in the Milky Way galaxy [7,15–19] (the Galactic component of neutrino flux). Otherwise, if the average spectrum of Galactic cosmic rays is much softer, the Galactic neutrino flux contribution to the IceCube signal is expected to be negligible [19,20] and neutrinos have to originate from extragalactic sources, like star forming galaxies [21,22] or radio galaxies/BL Lacs [12,23] (the extragalactic component of the flux).

The extragalactic component of the neutrino flux is rather strongly constrained by the measurements of the isotropic γ-ray background (IGRB) [7,21]. The IGRB spectrum is a powerlaw with the slope comparable to that of the neutrino spectrum, $\Gamma_\gamma \simeq 2.4$, but with normalisation which is approximately an order of magnitude lower than that of the neutrino spectrum [24,25]. At the same time, the fluxes of γ-rays and neutrino produced in pp interactions are expected to have approximately equal both normalisations and slopes of the spectra [14]. The IGRB constraint could be avoided if one assumes that the slope of the neutrino spectrum varies with energy, i.e. if the neutrino spectrum gets harder below $\simeq$ 1 TeV. The broken powerlaw spectrum hardening at low energies is naturally expected in a situation when

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the low energy protons are trapped in the source (or its host galaxy), while protons with energies higher than a certain threshold E_τ escape. This could be the case, e.g. for protons accelerated in the central engines and/or jets of radio loud active galactic nuclei [23]. The slope of the neutrino spectrum changes around $(0.01..0.1)E_\tau$ [14]. Below this energy it follows original proton spectrum, which has power law index 2.1–2.2 for usual Fermi acceleration models, while at higher energies diffusion of protons from the source through the turbulent magnetic field with Kolmogorov turbulence spectrum is expected to soften the spectrum to 2.5 [23].

The possibility of non-negligible Galactic contribution is indicated by the consistency of the all-sky γ-ray and neutrino spectra, which follow the same powerlaw over some five decades in energy (from 10 GeV up to PeV) [7]. The γ-ray all-sky spectrum is dominated by the Galactic contribution, so that it is natural to expect that the Galactic component is also present in the neutrino flux. The analysis of Ref. [3] has searched for the correlation of the arrival directions of neutrinos with energies above 30 TeV in the three-year data set of IceCube. This analysis has found that the best correlation is at the level of $\simeq 2.5\,\sigma$ pre-trial in the angle $\pm\,7.5°$ around the Galactic Plane and at the $\simeq 2.2\,\sigma$ level (2.8% chance coincidence probability) after the trial factor is taken into account.

Below we demonstrate that the neutrino four-years IceCube signal in the energy band above 100 TeV [3,26], which is free from the residual atmospheric neutrino and muon background [3], shows an evidence for the Galactic component.

2. Anisotropy properties of neutrino signal

The Galactic and extragalactic contributions to the neutrino flux could be distinguished based on the difference in the expected distribution of the signal over the sky. The extragalactic flux should be isotropic, while the Galactic flux should show anisotropy towards the Galactic Plane, where most of the target material for the cosmic ray interactions is found. Low statistics of the neutrino signal and uncertainties in the modelling of the Galactic neutrino flux prevented a sensible analysis which would give definitive conclusions on the presence of the Galactic and extragalactic contributions in the first three years of IceCube data [7,18]. The overall distribution of neutrino signal on the sky in the energy band above 30 TeV is consistent with an isotropic distribution [3,5], i.e. with the extragalactic signal. However, at 30 TeV the IceCube signal still has a significant contribution from the atmospheric neutrino and muon background which could dilute the weak anisotropy signal.

A more clean anisotropy analysis could be performed in the energy band above 100 TeV, where the signal is almost backgorund-free. The updated results of 4-years IceCube exposure show 19 events in this energy band with only one background [5,26]. Fig. 1 shows the distribution of the detected $E > 100$ TeV neutrino events in Galactic latitude. One could notice two features in this distribution. First, the low Galactic latitude bin $|b| < b_{low} = 10°$ contains a large number of events (9 out of 19). Next, the bins at high Galactic latitude (above $b_{high} = 50°$) contain no events at all.

To some extent, the lower number of counts in the bins at high Galactic latitude could be attributed to the smaller solid angle spanned by these bins. To verify if this would provide a satisfactory explanation of the deficit of neutrino counts at high Galactic latitudes, we have performed Monte–Carlo (MC) simulations of the expected sky distribution of the neutrino signal. The MC simulation takes into account of the declination dependence of the IceCube effective area, derived from the information reported in the Ref. [3]. This declination dependence leads to a difference in the effective exposure in different Galactic latitude bins. The MC simulation generates the number of events proportional to the exposure in each declination bin. The events are randomly distributed in the Right Accention. The MC events are then re-mapped in the Galactic coordinates.

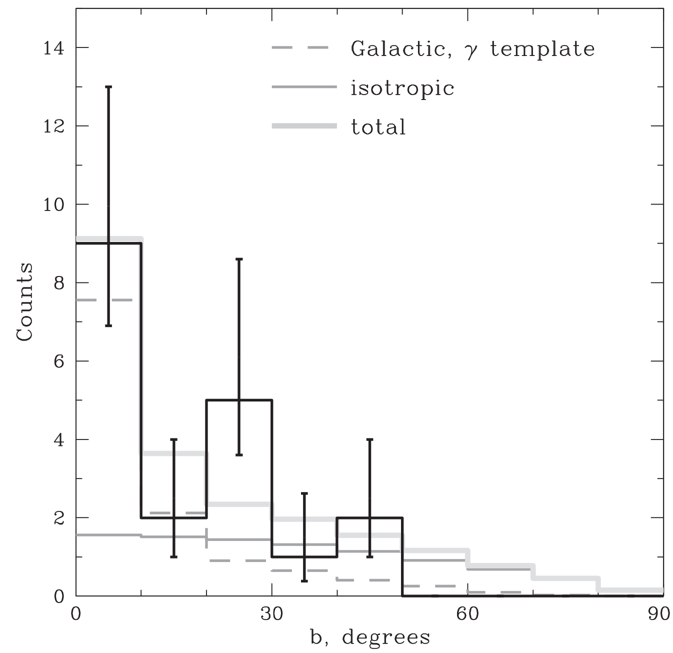

Fig. 1. Galactic latitude profile of the $E > 100$ TeV IceCube neutrino signal. Dark grey solid histogram shows the expected profile of the isotropic neutrino signal. Dashed dark grey histogram shows the Galactic component profile. Thick light grey solid histogram shows the sum of the Galactic and extragalactic components.

The Galactic latitude distribution of events expected in the isotropic flux model found from MC simulations is shown with the dark grey solid line histogram in Fig. 1. If the isotropic flux is normalised on the total number of events, the isotropic model predicts 4.6 events at $|b| > 50°$. The probability to find no events in this latitude range is $p_{|b|>50°} = 5 \times 10^{-3}$.

The isotropic model is also inconsistent with the low Galactic latitude data, which shows an excess over the data. The tension between the model and the high Galactic latitude/low Galactic latitude data could be characterised in a quantitative way using the MC simulations, which show that the probability to find simultaneously the 0 counts at $|b| > 50°$ and ≥ 9 counts in the $|b| < 10°$ bin is 10^{-5}. This corresponds to a $4.4\,\sigma$ level inconsistency between the model and the data in terms of equivalent Gaussian statistics signal.

The tension with the data could be readily removed via addition of the Galactic component of the flux. Following Ref. [7], we model this Galactic contribution based on the $E > 300$ GeV γ-ray data of Fermi/LAT. The Galactic component, convolved with the IceCube point spread function derived from the distributions of angular uncertainties of detected IceCube events, is shown by the dashed histogram in Fig. 1. One could see that the Galactic component explains the excess in the first bin and it gives a negligible contribution at high Galactic latitude. The neutrino flux model which contains only Galactic component is also inconsistent with the data, but at a lower significance level ($\simeq 2\,\sigma$). A model which contains 50% contributions from the Galactic and extragalactic components provides a satisfactory fit to the data (Fig. 1).

3. Account of the energy and angular binning trail factors

The above conclusion on the $4.4\,\sigma$ level inconsistency of the isotropic model with the data adopts certain choice of the energy range and angular binning for the calculation of probabilities. To have a fair judgement of significance of this inconsistency, one needs to take into account the trial factor related to the choice of the Galactic latitude bins where the inconsistency of the model with the data