How large is the galactic contribution to IceCube neutrino events?

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Abstract. After 4 years of data taking there is a disagreement between the spectra that IceCube observes from the Southern sky and those from the Northern sky, obtained with passing muons: the significance is about 3 sigma. The inclusion of a galactic component, mainly seen by the southern sky and with a softer spectrum, solves this disagreement. The galactic component leads to about 20% of the total events, with large uncertainties. Plausibly, this component lies near the galactic plane ($b \sim 0$). The observed angular distribution of the events is not incompatible with an isotropic distribution but, when the galactic component is included, goodness of fit improves greatly.

1. Introduction
The discovery of high energy extraterrestrial neutrinos has opened a new era for neutrino astronomy. The observations of IceCube are compatible with cosmic neutrinos, that undergo three flavor oscillations. The topologies of the events were used to probe ordinary and exotic physics.

However many important questions, raised by these findings, are still unresolved: what is the source and the mechanism of production of the cosmic neutrinos seen by IceCube? Are they all extragalactic or there is also a galactic population?

The last question is noteworthy. There are hints that the spectra measured by IceCube from Northern sky and Southern sky are different; particularly, there is a tension of 3.6 sigma between passing muons and the dataset of high energy starting events. The angular distribution of these events has an excess near to the plane of the Galaxy, in an interval of galactic coordinates between $-10^\circ$ and $10^\circ$.

These observational features are compatible with the existence of a significant galactic component of the high energy neutrinos, and indeed the Galactic center and the surrounding regions of the disk fall in the Southern sky. This interpretation points to a Galactic population of neutrinos characterized by a soft spectrum that gives a contribution of 20-30% to the total number of events and that dominates below some 100 TeV. Above this energy, an isotropic population, most likely of extragalactic origin and with a much harder spectrum, close to $E^{-2}$, becomes dominant.

New experiments in the Northern hemisphere (Antares, KM3NeT, Baikal, GVD) will observe the Galaxy via through-going muons with a sub-degree angular resolution, and will be therefore crucial to confirm or refute this hypothesis.
2. The North-South asymmetry

The flux of IceCube neutrinos has been summarized by a single power law:

\[
\frac{d\phi}{dE_\nu} = \phi_0 \times 10^{-18} \frac{E_\nu}{100 \text{ TeV}}^{-\alpha}
\]

The flux measured with High Energy Starting Events (HESE) from Southern hemisphere seems to prefer a soft spectrum with \( \alpha = 2.56 \pm 0.12 \) [1], whereas the spectra measured from Northern hemisphere, i.e. HESE and passing muons, prefers an harder spectrum with respectively \( \alpha = 2.0^{+0.4}_{-0.3} \) [1] and \( \alpha = 1.91 \pm 0.20 \) [2]. Since the uncertainty on the passing muons slope is smaller we have chosen this dataset for our analysis. We can notice that HESE North and passing muons are compatible whereas there is a tension of about 3\( \sigma \) between HESE South and passing muons dataset. This was also remarked in [3], where a new dataset related to the passing muons is reported.

The asymmetry could be due to a Galactic component of high energy neutrinos mainly seen from the Southern hemisphere. The Galactic neutrinos could be produced by single point-sources or by a \( pp \) interaction between galactic cosmic rays and the gas contained in the Galaxy. Therefore we expect that such events are concentrated near to the galactic plane and within a galactic longitude \( |l| \leq 50^\circ \), as happens for \( \gamma \)-rays detected by Fermi experiment; anyway, due to the bad angular resolution of the showers (about 10-15 degrees), we have to take into account a larger region around the galactic plane. In the case of neutrinos and \( \gamma \)-rays of common hadronic origin it is plausible to expect that neutrinos come from the same region of \( \gamma \)-rays. This region can be seen largely from the Southern hemisphere, as can be noticed from the Fig.1. Therefore, it is obvious to expect a contamination of Galactic neutrinos from Southern hemisphere and an almost pure flux of extragalactic neutrinos from Northern hemisphere.

3. The galactic component

There are two ways to estimate the galactic component, the spectral analysis and the analysis of the angular distribution of events.

3.1. Spectral analysis

Assuming that the flux from Northern hemisphere is representative of the extragalactic neutrinos, we can use it to estimate the expected number of events from the Southern hemisphere above 60 TeV, using the effective areas [4]. In order to restore agreement with the observations another component is required; therefore we hypothesize that the flux from Southern hemisphere can be summarized by two power-laws and we assume \( E^{-2} \) for the extragalactic component (it
Figure 2. On the left panel: the double component spectrum in red (extragalactic plus galactic) compared with the spectra measured by IceCube from Northern (green, passing muons) and Southern hemisphere (blue, HESE). On the right panel: cumulative function of the angular distribution of events from Southern hemisphere with deposited energy above 60 TeV [5].

is in agreement with the observations) and $E^{-2.7}$ for the Galactic component [5], as suggested by the spectral index of Galactic cosmic rays. Indeed, in the $pp$ interactions the spectral index of neutrinos is the same of primary protons. We found that to reproduce the IceCube observations the normalizations at 100 TeV of the Galactic component must be $2.5^{+2.5}_{-1.3}$ in units of $\text{GeV}^{-1} \text{cm}^{-2} \text{sec}^{-1} \text{sr}^{-1}$; it means a contribution of $34\%^{+33\%}_{-17\%}$ to the expected number of events from Southern sky above 60 TeV. The subset of events, detected from South and with deposited energy above 60 TeV, represents about half of the total number of events. In Fig.2 the double component flux (red) is compared with the passing muons flux (green) and the HESE Southern sky flux (blue).

3.2. Angular analysis

Another independent possibility is to extract the contribution of Galactic neutrinos from the angular distribution of events. The hypothesis is that the total flux observed from South is given by an isotropic flux plus a Gaussian flux with a peak in $b = 0$ (galactic plane) and a standard deviation of $10^{\circ}$, to simulate the angular resolution of shower-like events. With this approach we find that the contribution of Galactic neutrinos, to the subset of data, is $0.26^{+0.15}_{-0.15}$. The result is compatible with what was found using spectra but the uncertainty is smaller in this case.

Performing hypothesis tests we found that the purely Galactic flux can be rejected (probability < 0.01). On the contrary both isotropic flux (probability ~ 0.5) and double component flux (probability > 0.9) are compatible with the data; anyway we can notice that the last one works much better.

4. Conclusion

Due to the position of the Earth in the Galaxy it is plausible that from Southern hemisphere a Galactic component of high energy neutrinos have been seen. This is supported by two independent analysis. Combining the results of the two analysis we found that about 15% of the total number of events could be given by a diffuse Galactic flux. Anyway IceCube is not in the ideal position to detect with precision the Galactic flux. The experiments placed in the Northern hemisphere can detect it much better using the passing muons.

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