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Astrophysical interpretation of small-scale neutrino angular correlation searches with IceCube

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ABSTRACT

The IceCube Neutrino Observatory has discovered a diffuse all-flavor flux of high-energy astrophysical neutrinos. However, the corresponding astrophysical sources have not yet been identified. Neither significant point sources nor significant angular correlations of event directions have been observed by IceCube or other instruments to date. We present a new method to interpret the non-observation of angular correlations in terms of exclusions on the strength and number of point-like neutrino sources in generic astrophysical scenarios. Additionally, we constrain the presence of these sources taking into account the measurement of the diffuse high-energy neutrino flux by IceCube. We apply the method to two types of astrophysically motivated source count distributions: The first type is obtained by considering the cosmological evolution of the co-moving density of active galaxies, while the second type is directly derived from the gamma ray source count distribution observed by Fermi-LAT. As a result, we constrain the possible parameter space for both types of source count distributions.

1. Introduction

1.1. Astrophysical neutrino observation by IceCube

The IceCube Neutrino Observatory [7] at the Geographic South Pole has discovered an all-sky diffuse flux of high-energy cosmic neutrinos [1,2] based on neutrinos of all flavors interacting within the detector. However, no astrophysical sources of this flux could be identified yet. Recently, this all-flavor flux has been confirmed by the measurement of an excess of uncontained up-going muons [4] at high energies above the background originating from interactions of atmospheric neutrinos. These muons are produced by charged current interactions of muon neutrinos in the ice, where the direction of the muon and the neutrino agree well within $\sim 1^\circ$ in the considered energy range. Muons propagate large distances through the ice, and can be measured with good angular resolution, i.e. $<1^\circ$. Though such events are ideally suited for the identification of the sources, neither searches for angular autocorrelations of neutrino arrival directions nor correlations of neutrino arrival directions with the positions of known astrophysical sources have resulted in a significant observation [3,5]. In conclusion, the total number of sources of the observed flux is presumably large as so far the individual sources have been too weak to be detectable with respect to the atmospheric neutrino background.

1.2. Angular correlations of neutrino arrival directions

This paper focuses on the non-observation of an angular correlation within 108 310 up-going muons in IceCube data measured from 2008 to 2011 with the detector configurations *IC40*, *IC59* and *IC79* [5]. That result was obtained based on two analyses. The first is a binned correlation analysis and the second uses the power coefficients of a multipole expansion of the sky map of detected neutrino arrival directions. In this work, we focus on the second result. Here, weak sources, constituting the signal, were assumed to be isotropically distributed over the sky. The signal was benchmarked according to different signal hypotheses, characterized by three quantities: the total *number of sources* in the full sky N_{Sou}, a universal *strength* of each source μ, and the *spectral index* γ of the energy spectrum. The parameter μ is the mean number of measured neutrinos per source at the horizon. While at the horizon the detection efficiency is largest, each source off the horizon is assigned a lower number of neutrinos according to the declination dependent detector acceptance.

The analysis from [5] uses a test statistics (TS) that denotes how significantly the angular correlations of muon directions in the specific skymap are distinguishable from the random atmospheric background. The expected TS shift for signal with respect

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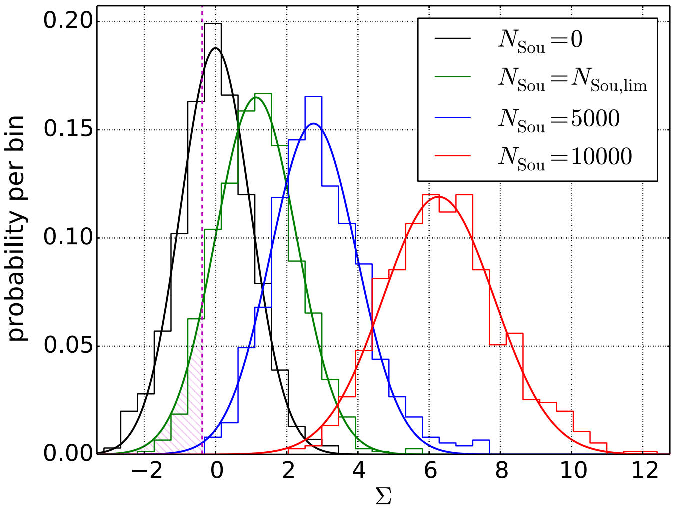

Fig. 1. Distributions of the test statistic (TS) for different numbers of sources in the full sky $N_{\rm Sou}$, fixed source strength $\mu = 3$ and energy spectrum $\gamma = 2.5$; dashed vertical line: result from the experimental skymap $\Sigma_{\rm exp} = -0.3$ [5]; hatched area: lower 10% quantile of the TS distribution for a signalness $\Sigma_{\rm lim} = 1.07$ corresponding to observed the upper limit.

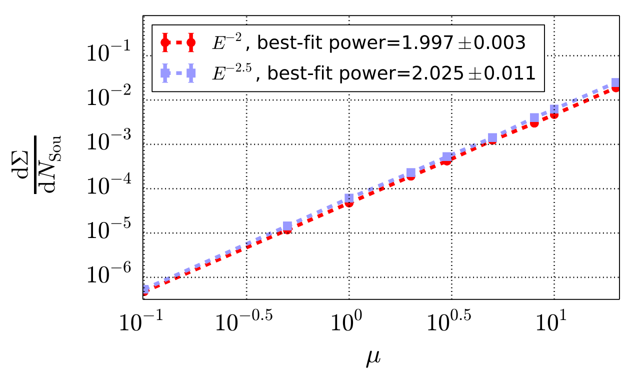

Fig. 2. Signalness per source $\frac{d\Sigma}{dN_{\rm Sou}}$ against source strength μ for astrophysical energy spectra E^{-2} and $E^{-2.5}$; legend: exponent of best-fit power law.

to the TS expectation for pure atmospheric background in units of the standard deviation of the background TS is called ***signalness*** Σ in the following. In Fig. 1, the TS distributions for signal hypotheses with different values for $N_{\rm Sou}$ are shown. The distributions are obtained by simulations of random skymaps using the information from [5] about the point spread function and zenith-dependent detector acceptance. We find that for a fixed source strength the signalness, i.e. the mean of the TS distribution, scales $\propto N_{\rm Sou}$. In Fig. 2, the signalness per source is shown as a function of the source strength μ. We find that the signalness per source increases with stronger sources consistently with $\frac{d\Sigma}{dN_{\rm Sou}} \propto \mu^2$, independent of the assumed energy spectrum.

The experimentally observed value is $\Sigma_{\rm exp} = -0.3$ [5]. The corresponding exclusion limits on the number of sources $N_{\rm Sou} = N_{\rm Sou,lim}$ for different values of μ are obtained from simulations as those values of $N_{\rm Sou}$ for which 90% of experiments would result in a larger signalness than the observed $\Sigma_{\rm exp}$. We find that for all different combinations of $N_{\rm Sou}$ and μ this results in the same signalness Σ, while the variance of the TS distribution is identical. Correspondingly, the median signalness corresponding to the observed upper limit is $\Sigma_{\rm lim} = 1.07$ and does not depend on the specific choice of signal parameters. Thus, $N_{\rm Sou,\,lim}$ is expressed as a simple function of the source strength μ.

1.3. Purpose of this work

Purpose of this work is to re-interpret the given exclusion limits for the number of sources of a fixed source strength in terms of astrophysically motivated distributions of source strengths $\frac{dN_{\rm Sou}}{d\mu}$. To do this, we calculate the expected signalness as a function of the respective astrophysical model parameters and compare this to the experimentally excluded signalness. For this, we make use of the dependencies of the signalness on the model parameters $N_{\rm Sou}$ and μ as introduced above. As benchmark scenarios, we use two astrophysical models. For the first model, we assume isotropically distributed sources with a number density following the red-shift dependent evolution of active galactic nuclei (AGNs). For the second model, we assume an isotropic distribution of sources with strengths analogous to the strengths of extragalactic sources of high-energy photons as observed by the Fermi-LAT satellite. Further details of the models that were taken into account in this work are given in Section 2.1.

Additionally, we take into account the measured diffuse astrophysical muon neutrino flux from the Northern hemisphere [4] in order to further constrain the scenarios. For both of the mentioned models, we test two astrophysical neutrino energy spectra $\propto E^{-\gamma}$ that are compatible with this measurement. That is a hard spectral index of $\gamma = 2.0$ and a soft spectral index of $\gamma = 2.5$.

It should be noted that other interpretations of a diffuse astrophysical neutrino flux—before and after the measurement by IceCube—have been published. These include different approaches as, for example, the interpretation of diffuse and/or stacking limits in terms of different production mechanisms [12] or the presence of point sources and their neutrino power density [25]. One recent approach is to constrain the presence of sources that are obscured in gamma rays but well visible in neutrinos such as choked GRBs [21]. Our approach differs from these in the manner that we additionally (and, in fact, primarily) interpret the absence of angular correlations in neutrino directions rather than the diffuse astrophysical flux. Taking this flux into account to further constrain our parameters of interest is technically just an optional addition but is still meaningful due to the relevance of this flux measurement. Also, while we apply our approach to specific source scenarios in this work, the method we present is generally applicable for other scenarios.

2. Method

2.1. Calculation of the source count distributions

2.1.1. Cosmologically distributed sources

For the application to sources motivated by the cosmological evolution of AGN, we assume standard sources that exhibit the same muon neutrino luminosity L in the energy range from 100 GeV to 100 TeV used in the IceCube angular correlation analysis. Due to red-shift of energy this leads to a red-shift dependency of the energy range that is used for the luminosity normalization. Using L, the source strength μ can be expressed in dependence on the cosmological redshift z:

$$\mu(z) = \frac{L}{4\pi\, d_L^2(z) \cdot (1+z)^{\gamma-2}} \cdot b(\gamma) \qquad (1)$$

where $d_{\rm L}(z)$ is the luminosity distance. The factor

$$b(\gamma) = \frac{\sum_{\rm IC} T^{\rm IC} \int_{100\ {\rm GeV}}^{100\ {\rm TeV}} dE\, A_{\rm eff}^{\rm IC}(E) E^{-\gamma}}{f(\gamma) \cdot \int_{100\ {\rm GeV}}^{100\ {\rm TeV}} dE\, E^{1-\gamma}} \qquad (2)$$

takes into account the observational parameters where $T^{\rm IC}$ denotes the livetime of IceCube for the operation of each detector configuration IC and $A_{\rm eff}^{\rm IC}(E)$ is the declination-averaged effective area of