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Search for high-energy neutrino emission from hard X-ray AGN with IceCube

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ABSTRACT: The IceCube Neutrino Observatory has detected high-energy astrophysical neutrinos in the TeV-PeV range. These neutrinos have an isotropic distribution on the sky, and therefore, likely originate from extragalactic sources. Active Galactic Nuclei form a class of astronomical objects which are promising neutrino source candidates given their high electromagnetic luminosity and potential ability to accelerate cosmic rays up to energies greater than 10^{16} eV. Interactions of these cosmic rays within the AGN environment are expected to produce both neutrinos and pionic gamma rays. Some hadronic models of AGN emission suggest that such gamma rays can in turn interact with the dense photon fields of AGN and cascade down to hard X-rays and MeV gamma rays. We present an update on the IceCube stacking analysis searching for high-energy neutrinos from hard X-ray sources sampled from the *Swift*-BAT AGN Spectroscopic Survey.

KEYWORDS: Large detector systems for particle and astroparticle physics; Data analysis; X-ray detectors and telescopes

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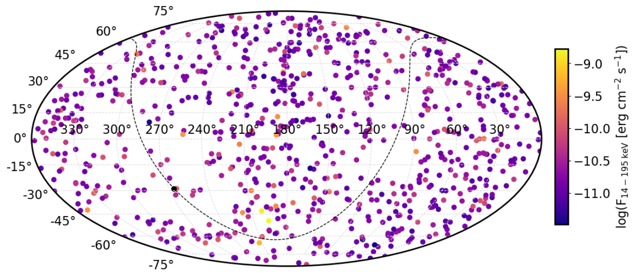
Contents

1 Introduction

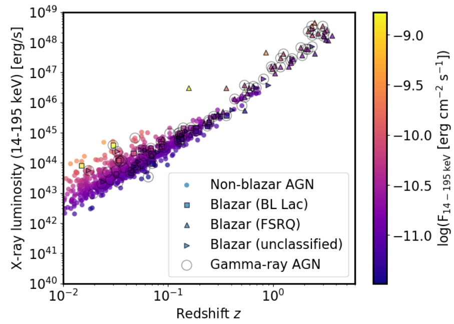
IceCube has detected astrophysical neutrinos in the TeV-PeV range that show an isotropic angular distribution, and their dominant origin remains unidentified [1]. Active Galactic Nuclei (AGN) is one such promising class of candidate sources of very-high-energy (VHE) neutrinos. According to the unified model of AGN [2], these sources have a central supermassive black hole surrounded by an accretion disk and are sometimes accompanied by relativistic jets. Blazars are the AGN with the orientation of the jet lying close to our line of sight.

An IceCube study from 2016 searched for neutrino point sources from the second *Fermi*-LAT AGN catalog (2LAC) [3, 4]. No significant excess of neutrinos was observed but upper limits were obtained for a contribution to the diffuse flux of cosmic neutrinos from blazars. However, a neutrino detected by IceCube on September 22, 2017, was found to be in temporal and spatial coincidence with a blazar, TXS 0506+056, that was in a flaring state [5]. This was the first evidence of a correlation between any astrophysical source and a high-energy neutrino. Another study conducted with 10 years of IceCube data, searched for point-like sources of neutrinos and found an excess of neutrinos from a Seyfert II galaxy, NGC 1068, at a significance level of 2.9σ [6]. These observations provide evidence in favor of AGN as possible neutrino sources.

There are various models that explain the production mechanisms of high-energy neutrinos from AGN. Purely leptonic models can reproduce the spectral energy distribution (SED) of blazars without neutrino production, while purely hadronic models may fail to reproduce the SED completely [7]. According to some hybrid (leptohadronic) models, the TeV-PeV gamma rays produced alongside neutrinos can interact with the ambient photons in AGN and cascade down to hard X-rays (high energy X-rays $\gtrsim 10\,\text{keV}$) or MeV gamma rays [8–10]. This creates a scenario where we can no longer observe the TeV-PeV gamma rays but possibly find signatures of hard X-rays and MeV gamma rays. Hard X-rays could therefore be an important probe into the emission of neutrinos through hadronic processes.



(a)



(b)

Figure 1. (a) Skymap in equatorial coordinates showing the BASS sources and their intrinsic flux in the hard X-ray band of energy 14–195 keV. The dashed black line shows the Galactic plane (figure from [15]). (b) The figure shows the hard X-ray luminosity of the different classes of AGN in the BASS catalog as a function of their redshift. The color represents the intrinsic flux of the sources in the energy range of 14–195 keV. AGN sources with likely counterparts in the *Fermi*-LAT 4FGL catalog are circled in gray (figure from [15]).

2 The catalog of hard X-ray sources

The sources in our analysis are selected from the *Swift*-BAT 70-Month hard X-ray Survey [11]. It is a collection of objects observed by the Burst Alert Telescope (BAT) hard X-ray detector onboard the Niel Gehrels *Swift* gamma-ray burst observatory for a period of 70 months [12]. There are 1171 sources detected in the >10 keV band which are associated with 1210 counterparts.

The BAT AGN Spectroscopic Survey,[1] or the BASS catalog Data Release-1, is a selection of AGN sources from the 70-month BAT catalog [13]. It has 838 AGN sources. The BASS catalog is the most complete all-sky catalog of hard X-ray sources observed in the range of 14–195 keV and includes soft X-ray spectra in the range of 0.3–10 keV. Spectral parameters such as the column density of the sources have been determined by the analysis of the X-ray data, both hard and soft, along with the available optical spectroscopic data [14].

A skymap of the BASS sources used in the study is shown in figure 1a. Several hard X-ray sources in the BASS catalog also exhibit gamma-ray emission (see figure 1b). For two sources in the BASS catalog, there are no column density values since they do not have a soft X-ray observation in the 0.3–10 keV range. They have not been included in our sample. Hence, we have 836 sources in our sample. 105 of the sources in the catalog are classified as blazars and 731 as non-blazars.

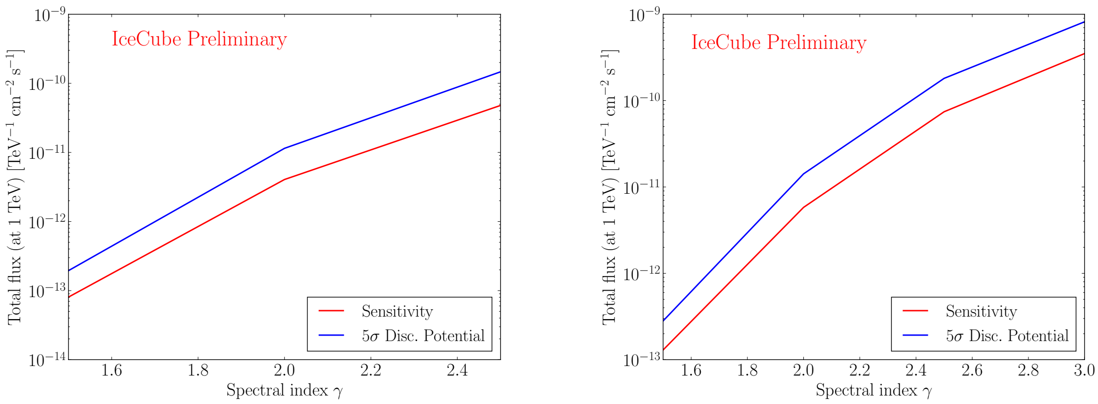
3 Analysis details

The analysis involves a stacked search for point sources using a time-integrated unbinned maximum-likelihood method [16, 17].

3.1 IceCube dataset

For this analysis, the IceCube dataset used is the gamma-ray follow-up (GFU) sample [18]. It solely contains muon neutrino tracks (the tracks are ascribed to ν_μ and $\bar{\nu}_\mu$ interactions and have

[1] https://www.bass-survey.com/.



(a) **(b)**

Figure 2. Plots showing the stacked flux at the normalization energy 1 TeV as a function of the spectral index under Hypothesis I with (a) flux weights and (b) equal weights.

typical angular resolutions of $<1°$) with an all-sky coverage that have been reprocessed offline for better sensitivity. 7.5 years of the GFU sample from the complete 86-string IceCube configuration between 2011-2018 have been used.

3.2 Current status

We plan to test different hypotheses with our analysis. Currently, we have only considered the hypothesis outlined below.

Hypothesis I. In this part, we use all 836 AGN to perform the analysis by stacking the sources according to two different *Weighting Schemes:*

1. *Flux weights*: it is proportional to the intrinsic flux of the sources in the range, 14–195 keV.
2. *Equal weights*: this is an unbiased weight that treats all sources in the catalog equally.

The sensitivity and the 5σ discovery potential are computed to give a sense of the power of the analysis performed. The sensitivity is defined as the flux required so that 90% of injected signal trials have a value of Test Statistic (TS) higher than in 50% of the background-only trials. The 5σ discovery potential is the flux required so that 50% of the time this flux will produce a result inconsistent with the background-only hypothesis at a significance of 5σ. Figure 2 shows that the analysis is more sensitive for harder spectra and, for flux weights as compared to equal weights, for e.g., the sensitivity (and discovery potential) flux at $\gamma = 2.0$ for flux weights is 4.06×10^{-12} (1.15×10^{-11}) TeV^{-1} cm^{-2} s^{-1} and for equal weights is 5.81×10^{-12} (1.42×10^{-11}) TeV^{-1} cm^{-2} s^{-1}.

4 Outlook

In future work, we will perform parts II and III of the analysis as described below.

Hypothesis II. We will search for a correlation between the luminosity of the sources and their neutrino emission by performing analyses separately on Blazars and non-blazars using *Flux weights*. The categorization follows the classification presented in the *Swift*-BAT catalog.

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Hypothesis III. X-rays are an important tracer of AGN properties such as the neutral hydrogen column density (N_H) which is a measure of the obscuring material along the line of sight. We will search for a correlation between the obscuring matter and the neutrino emission by dividing the sources in the catalog into three categories following the classification given in [14].

Unobscured sources are the sources with a column density, $N_H < 10^{22}\,\mathrm{cm}^{-2}$; obscured sources are the sources with a column density, $10^{22}\,\mathrm{cm}^{-2} \le N_H < 10^{24}\,\mathrm{cm}^{-2}$; and Compton-thick sources are the sources with a column density, $N_H \ge 10^{24}\,\mathrm{cm}^{-2}$. Results from the analysis of each of these categories will be compared. In this approach, only *Flux weights* will be applied.

We conclude from the preliminary results of our analysis that the total neutrino flux at energy 1 TeV for spectral indices between 2.0 and 3.0 with normalization coefficient for a 5σ discovery potential would be in the range of 10^{-11}–$10^{-9}\,\mathrm{TeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. From our analysis, we will either report the detection of a source and the associated neutrino flux or attain upper limits that constrain the contribution of AGN as a source class towards the diffuse flux of neutrinos observed by IceCube.

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