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High-energy neutrinos from blazars

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Abstract. Identifying the origin of the majority of high-energy cosmic neutrinos observed by the IceCube Neutrino Observatory remains a significant challenge. Previous studies reported evidence of a spatial correlation between blazars listed in the 5th Roma-BZCat catalog and IceCube neutrino data in the southern celestial hemisphere. The statistical significance of this correlation was determined to be 2×10^{-6} after accounting for trials. In subsequent work, we investigated whether a similar correlation exists in the northern hemisphere, where IceCube predominantly detects neutrinos with energies $\lesssim 0.1$ PeV. Our analysis reveals a consistent correlation between blazars and neutrino data in the northern hemisphere, with a pre-trial p-value of 5.12×10^{-4} and a post-trial chance probability of 6.79×10^{-3}. By combining the post-trial probabilities from the southern and northern studies, we find a global post-trial probability of 2.59×10^{-7}, suggesting that the observed correlation is unlikely to occur by chance. Theoretical modeling of one of these proposed neutrino-associated objects suggests that proton interactions with external radiation fields can generate a neutrino flux detectable by IceCube. These results further support the hypothesis that blazars are promising candidates for high-energy cosmic neutrino sources.

1 Introduction

Despite the detection of a diffuse astrophysical neutrino flux in the $\gtrsim 100$ TeV to ~ 10 PeV range by the IceCube Observatory [1], the cosmic sources responsible remain largely unknown. Identifying their astrophysical origins is a key challenge in multi-messenger astrophysics. Recent studies suggest that a fraction of high-energy ($\gtrsim 0.1$ PeV) neutrinos may be linked to active galactic nuclei (AGN) − supermassive black holes at galaxy centers that emit non-thermal radiation, some of which produce relativistic jets aligned with Earth, classifying them as blazars. Most approaches used in the literature investigate potential connections between IceCube neutrinos and AGN selected with specific observational characteristics [e.g. 2]. However, AGN classification often relies on limited or single-waveband observations, which introduces biases in the selection, and may miss the depict in a comprehensive way the physical properties of the system due to variability or incomplete data. Moreover, while the currently proposed identification of neutrino point-sources are intriguing, conclusively demonstrating their genuineness remains challenging. Establishing a robust connection requires overcoming uncertainties in both the observational data and the theoretical models,

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highlighting the complexity of linking neutrinos to their astrophysical origins. Such challenge is exemplified by the two most promising neutrino point sources proposed to date: the non-jetted AGN NGC 1068 and the jetted AGN TXS 0506+056.

For the former source, the IceCube Observatory has reported an excess of high-energy neutrinos in its time-integrated 10-year skymap (see Fig. 1), originating from the direction of the Seyfert galaxy NGC 1068, with a post-trial statistical significance of 4.2σ. The result is based on the inclusion of NGC 1068 in a predefined list of 110 promising neutrino candidate sources, selected for their relatively bright MeV-GeV γ-ray emission. Initially considered a strong neutrino candidate due to its high-energy γ-ray properties, further studies revealed that the observed MeV/GeV γ-ray emission is primarily associated with star-forming activity within the galaxy rather than its AGN. Theoretical models suggest that if neutrinos are being produced in NGC 1068, the associated hadronic processes would generate γ-ray emission predominantly in the sub-MeV range [3], contradicting the MeV/GeV emission originally used to establish the connection.

The blazar TXS 0506+056 faces similar challenges. It was initially proposed as a neutrino emitter following the association of a high-energy neutrino event with a bright γ-ray flare observed in spatial and temporal coincidence with the blazar [3σ post-trial, 4]. However, lepto-hadronic modeling of the blazar's spectral energy distribution performed by several studies, consistently suggests that the bulk of the γ-ray emission is unlikely to originate from the same region where neutrinos are potentially produced. This may raise a controversy in associating the blazar with neutrino production, as the initial basis for the association relied on the concomitant detection of a γ-ray flare with transient neutrino emission. More recently, it has been pointed out that a time-integrated cluster of neutrinos is positionally consistent with TXS 0506+056, and, as reported by the IceCube collaboration, it appears in the 10-years skymap with a significance of 3.5σ (pre-trial, Fig. 1) [5].

While the proposed associations may still be genuine, this highlights our limited understanding in selecting the right criteria to efficiently identify promising counterparts to neutrino sources. Moreover, it calls into question the preference given to these two neutrino point-sources, especially when several similar neutrino candidates are present in the IceCube skymaps.

2 A correlation between IceCube skymaps and blazars

In our previous work, we propose to overcome the limitations of the previous searches employing the largest available neutrino dataset optimized for searches of point-like sources and an homogeneous clean sample of the blazar population. To search for counterparts to the neutrino data we use the fifth data release of the Roma-BZCat catalog [5BZCat, see 10]. The catalog is a compilation of 3561 objects where each one has been thoroughly inspected to fulfill the criteria defining a blazar-like nature in 5BZCat [6]. The catalog does not rely on any preferential observational energy band or blazar intrinsic physical properties. Then, we employed the IceCube 7-year skymap data [12, 13], as it was the only skymap released by the IceCube collaboration, publicly accessible, when performing the study. In our first investigation, we explored the southern hemisphere dataset, which is best suited to test the blazar hypothesis. As demonstrated by a sensitivity study carried out by the IceCube collaboration [14], the search for hard-spectrum neutrino sources – such as those predicted within the photo-hadronic framework for blazars – is more favorable in the IceCube southern hemisphere sky. The advantage arises from the instrument's enhanced sensitivity in this region for the relevant energy range ($\gtrsim$ 100 TeV).

Based on positional cross-correlation analysis, our study presents evidence of a statistically significant correlation between blazars listed in the 5BZCat catalog and a sample of

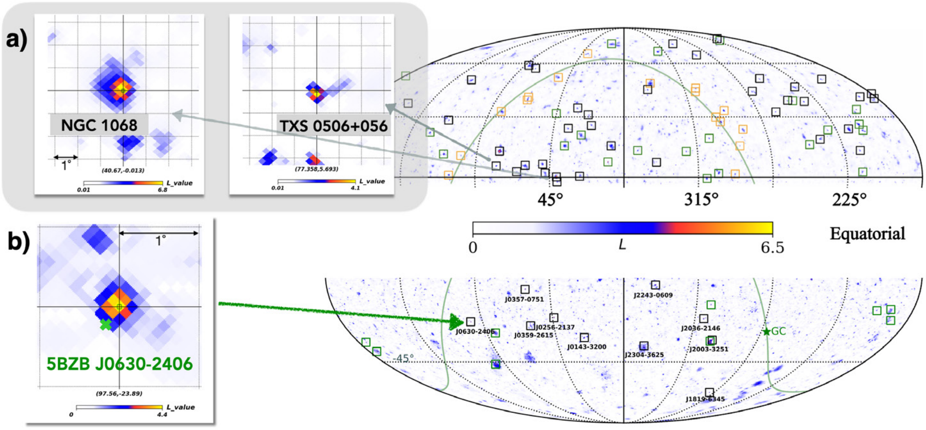

Figure 1: The IceCube collaboration has reported anisotropies in the events' arrival distribution, consistent with an astrophysical origin. These appear in the form of hotspots in the 10-yr skymaps, consistent with the AGN NGC 1068 and TXS 0506+056 (inset a). Other hotspots could be linked to an astrophysical origin. Our studies have unraveled a compelling evidence for a spatial correlation between other neutrino hotspots and a set of blazars [inset b), 6–8]. Preliminary work highlights the imprint of hadronic processes in one of the candidate associated blazars, 5BZB J0630-2406 [see Sect. 2.2, 9].

IceCube hotspots, which are anisotropies in the spatial distribution of IceCube events used in the skymap [6, 7]. IceCube skymaps are provided in the form of local probability maps defined by L values. The L values represent the inferred direction-dependent neutrino emission probability, with higher L values indicating a greater likelihood that a genuine astrophysical signal originates the spatial clustering of neutrino events in that particular region of the sky. Hotspots are identified as regions in the skymap where L values exceed those of the overall skymap distribution. The southern hemisphere analysis highlights 10 objects as associated with hotspots and, hence candidate HE neutrino emitters, i.e. candidate PeVatron blazars. Among them is the blazar 5BZB J0630-2406, shown in Fig. 1 (inset b).

2.1 The northern hemisphere blazar and neutrino samples

In this contribution, we present the investigation of complementary samples. We expand the analysis to the northern celestial hemisphere, we select 5BZCat objects in the northern hemisphere and located at high latitudes, at $|b| > 10°$. The latter selection is motivated by the paucity of objects in the vicinity of the Galactic plane (due to observational biases). We employ an improved ~9-y northern-sky map which, recently, has been released publicly by the IceCube collaboration [5]. Similarly to [6], to limit trials, we focus on the skymap spots with strongest deviation from background expectations, and build three subsamples of putative-neutrino sources with decreasing minimum L-value (L_{min}). We consider the three spots subsamples defined by L_{min} in the range [3.0,3.5,4.0]. These contain 82, 34 and 17 spots, respectively. Consistently with the selection criteria applied to the blazar sample, we select only spots at $|b| > 10°$. Upon applying the Galactic plane cut, the final samples of neutrino spots $L3.0$, $L3.5$ and $L4.0$ comprise 66, 29 and 13 spots, respectively. To estimate the level of correlation between the blazar sample and these neutrino data we employ the positional cross-correlation technique presented in [6]. As association radius for the neutrino spots and

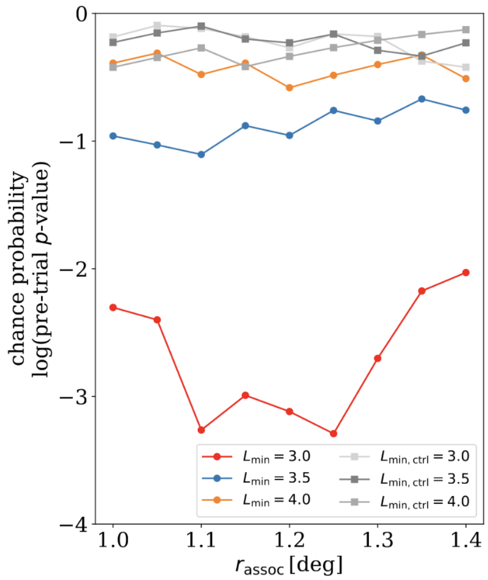

Figure 2: Pre-trial p-value for the 5BZCat blazar/neutrino correlation in the northern sky, as a function of the association radii r_{assoc}, for the neutrino data set with $L_{\text{min}} = [3.0, 3.5, 4.0]$ (red, blue, orange circles, respectively). The y-axis displays values in logarithm scale. See Section 2.1 for more details. As reference, the results for the northern hemisphere control sample are displayed as gray squares [8].

blazars we test separation values (r_{assoc}) close to the median angular resolution reported for this neutrino dataset, in the range from 1.0° to 1.4°, with a step of 0.05°. We perform a scan in the $\{L_{\text{min}}, r_{\text{assoc}}\}$ space where for each set of parameters we match the positions of the 5BZCat objects with the positions of the neutrino spots. The number of real matches constitutes our test statistics. The pre-trial p-value for the set of parameters is estimated by deriving the chance probability of obtaining a test statistic value equal or higher than the one observed for the real data [see 6, 8]. In order to estimate the chance correlation, we simulate 10^6 Monte Carlo catalogs by randomizing the blazar positions, record the number of hotspot/mock catalogs matches, and follow the procedure outlined in [6, 8] to correct for trials. The lowest pre-trial p-value indicates the highest level of correlation potentially present in the data. In the northern sky map analysis we observe to a pre-trial p-value of 5.12×10^{-4} which, corrected for trials, corresponds to a post-trial p-value of 6.79×10^{-3} (see Fig. 2; see also [11]).

The 7-yr and 9-yr skymaps may be regarded as distinct neutrino datasets due to the non-overlapping, complementary sky coverage, differences in the energy range, event-data calibration and reconstruction, background characteristics and analysis techniques applied to the individual events [5, 6, 13]. Since the two cross-correlation tests carried out for these skymaps are independent, the p-values can be combined with the Fisher's method [15]. Combining the post-trial p-values estimated for the northern hemisphere, i.e. 6.79×10^{-3}, and the one for the southern hemisphere analysis, i.e. 2×10^{-6}, yields a global post-trial p-value of $= 2.59 \times 10^{-7}$. The global post-trial p-value on the experiment suggest that the observed blazar and neutrino correlation is unlikely to arise by chance.

2.2 Multi-messenger properties of a candidate PeVatron blazar

Located at an angular separation of 0.28° from the IceCube hotspot IC J0630−2353, the blazar 5BZB J0630-2406 has been proposed as candidate counterpart to the hotspot [6]. Prior to being included in the sample of PeVatron blazars and proposed as a high-energy neutrino emitter, 5BZB J0630-2406 stood out in the literature due to its peculiarities. Historically, it has been classified as a BL Lac object due to the featureless optical spectrum and its high synchrotron peak, with $\nu_{\rm pk}^{\rm sy} \sim 10^{15}$ Hz. 5BZB J0630-2406 was pinpointed as an exemplary blazar, it displays properties typical of "blue flat spectrum radio quasar" [16, 17, a.k.a. "masquerading BL Lacs"], i.e. high-emitting power sources that are intrinsically FSRQs where their broad emission lines are swamped by the jet synchrotron emission. In contrast to "true" high-frequency-peaked BL Lacs which have intrinsically poor radiation fields, these objects host powerful jets and radiatively efficient accretion.

The study presented in this contribution [see 9] allows us to provide conclusive evidence to the earlier speculations regarding the peculiar nature of 5BZB J0630-2406. The SED modeling reveals a bright accretion disk with $L_{\rm disk} \sim 4 \times 10^{45}$ erg · s^{-1} and re-processed emission by the broad line region. A relatively high accretion regime of 5BZB J0630-2406 is supported also by the ratio of the γ-ray luminosity L_γ (0.1 – 100 GeV) and the Eddington luminosity, $L_\gamma/L_{\rm Edd} \simeq 0.15$, highlighting that this source shares properties common to the FSRQ class [18].

The analysis of the simultaneous soft and hard X-ray spectra during a comparatively low state, provides evidence ($\gtrsim 3\sigma$) of a break in the X-ray band. If the break was to be intrinsic to the object, a pure leptonic model faces challenges in reproducing it. On the other hand, the proposed lepto-hadronic model shows a turnover of the spectrum in the X-ray band, that marks the kick-in of the hadronic component contribution. Based on our theoretical modeling, the SED is overall leptonic-dominated. We find that in 5BZB J0630-2406 the combination of an efficient particle acceleration and efficient external radiation fields fosters the production of neutrinos, with a predicted neutrino flux at reach of the IceCube detector sensitivity [9].

3 Conclusions

A positional cross-correlation analysis [6–8] between IceCube neutrino data and objects of the 5BZCat catalog, pinpointed 52 blazars as promising neutrino-emitter candidates. While the observed statistical significance indicates that the correlation between the two samples is unlikely to arise by chance, it should not be mistaken for the probability of individual neutrino/blazar associations. Among them, a non-negligible number of spurious associations exist, occurring simply by Poisson chance probability. Assessing the genuineness of these individual associations is challenging, and will be addressed in a forthcoming study.

Bearing this in mind, in this contribution, we provide a first characterization of the intrinsic nature of one of the objects proposed as associated with neutrino emission. The evidence for a spatial correlation between IC J0630−2353 and the blazar 5BZB J0630-2406 suggests that this blazar may contribute to the observed anisotropy in the neutrino hotspot. Supporting evidence is provided by theoretical modeling of its spectral energy distribution, which can be adequately modeled via lepto-hadronic scenarios, suggesting that the hadronic component is sub-dominant except in the X-ray and in the MeV bands. Our results predict that future missions in the MeV band, such as AMEGO-x and ASTROGAM [19, 20], have the potential to discriminate between pure leptonic and lepto-hadronic models in similar candidate neutrino-emitter blazars.

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