EPJ Web of Conferences **319**, 06005 (2025) https://doi.org/10.1051/epjconf/202531906005
RICAP-24

The physical properties of candidate neutrino-emitter blazars

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Abstract. High-energy neutrinos detected by the IceCube Observatory provide a unique opportunity to study the origin of cosmic rays and the nature of the sources producing them. Among the putative birthplaces of astrophysical high-energy neutrinos, blazar jets stand out due to their capability of accelerating particles and providing intense external radiation fields. Blazars are active galactic nuclei (AGN), a class of luminous extragalactic objects powered by a central supermassive black hole, with the jets pointing in the observer's line of sight. In this contribution, we focus on a selected sample of 52 blazars that have been proposed as candidate IceCube neutrino counterparts (post-trial statistical significance 5σ). We use multiwavelength data, both archival and proprietary, in the radio, optical, and γ-ray bands and characterize the sources' nature and their central engine's peculiarities. Properties such as redshift, black hole mass, accretion regime, radiation field, and jet power are crucial to investigate the properties of these blazars and the potential link with the acceleration of cosmic rays. Our study shows that these 52 neutrino-emitter blazar candidates show a mild tendency toward radiatively efficient accretion and high jet power. However, statistical tests show they are compatible with the overall population of blazars.

1 Introduction

The origin of the astrophysical diffuse neutrino flux detected by the IceCube Neutrino Observatory in the energy range $\gtrsim$ 100 TeV to $\sim$ 10 PeV [1] is still a matter of debate. Among the most promising candidates, are blazars, a subclass of radio-loud active galactic nuclei (AGN) with the relativistic jet pointing toward the observer's line of sight. Several particle acceleration processes can take place in the blazars' jets [2–4]. Upon the first evidence of a correlation between the γ-ray blazar TXS 0506+056 with the high-energy IceCube event IC 170922A in 2017 [5], further studies led to increased evidence of a connection between blazars and neutrinos [6–9]. Within the lepto-hadronic/hadronic scenario, hadrons are accelerated alongside leptons in blazar jets. The efficient particle acceleration combined with external radiation fields, such as from the accretion disk and the re-processed disk emission by the broad and narrow line region, and the dusty torus, can foster neutrino production in blazars via p-γ interactions [4]. The photo-pion production efficiency, i.e. the physics governing the production of neutrinos, is tightly linked to the different modes of accretion [4]. These are primarily traced by emission in the optical/IR band.

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A positional cross-correlation analysis [10–12] between IceCube neutrino data and blazars of the 5th Edition of the Roma-BZCat catalog (5BZCat, [13]) pinpointed 52 blazars as promising neutrino-emitter candidates (see also [14]). The correlation between the blazar sample and neutrinos is found to be statistically significant and, hence unlikely to arise by chance. However, among the 52 individual candidate associations, one should expect a non-negligible number of spurious associations simply by Poisson probability. Bearing this in mind, in this contribution, we study the physical properties of the full sample of 52 candidate neutrino-emitter blazars exploiting optical spectroscopy, complemented by radio and γ-ray information from the literature. We provide a first characterization of the intrinsic nature of these sources [15].

2 The classification of blazar

Blazars are traditionally classified in BL Lacertae (BL Lacs) and flat spectrum radio quasars (FSRQs) based on the observed strength of emission lines in the optical spectrum [16]. Within this purely empirical classification, coining a new nomenclature was necessary to explain blazars showing ambiguous properties of the two classes. For example, the “blue flat spectrum radio quasars” [17], a.k.a. “masquerading BL Lacs” [18] would be classified as BL Lacs based on the featureless optical spectrum and high synchrotron peak. However, they are proposed to be intrinsically FSRQs with their broad emission lines swamped by the jet’s powerful synchrotron emission. Literature studies [19–21] already put into question the traditional observational classification, in favor of a more physically driven scheme based on the different accretion modes onto the central SMBH. Within such new schemes, high-excitation radio galaxies (HERGs) are efficient accretors with cold gas accumulating in the nucleus. They show the traditional internal structure of an SMBH surrounded by a geometrically thin accretion disk (AD), surrounded by a hot corona and obscured by a dusty torus of molecular gas on larger scales. The radiation from the AD illuminates the clouds of gas of the broad line region (BLR), located close to it, and the narrow line region (NLR) further out. Low-excitation radio galaxies (LERGs), instead, are dominated by the kinetic energy of the jets and show radiatively inefficient accretion disks, with hot gas from the interstellar medium falling into the central core [22]. The BLR luminosity in Eddington units traces the accretion efficiency of blazars, and the dividing line lies at $L_{\rm BLR}/L_{\rm Edd} \sim 5 \times 10^{-4}$ [19, 21]. In terms of radio jet power (at 1.4 GHz), HERGs dominate at high radio power, while LERGs at lower values, with the dividing threshold falling at $\sim 10^{26}\,{\rm W \cdot Hz^{-1}}$ [22]. The γ-ray luminosity is also tracing the power of the jet, and the dividing line between HERG/LERG sources is suggested to lay at $L_\gamma/L_{\rm Edd} \sim 0.1$ [21]. Compared to the traditional BL Lac/FSRQ classification, the LERG/HERG discrimination brings less ambiguity in transitional objects. Blue FSRQs (masquerading BL Lacs) are naturally described as HERGs based on their physical properties [23]. In this work, we adopted the physically driven view of blazars as HERG and LERG sources, based on the radiative efficiency of accretion, the intensity of radiation fields, and jet power (in radio and γ-rays).

3 The blazar sample

To explore the potential link between blazars and neutrinos, in previous works [10–12] we performed a positional cross-correlation analysis between IceCube neutrino maps and the 5BZCat catalog. The latter is a compilation of 3561 sources of confirmed blazar nature, that does not suffer from selection biases in specific wavelength or survey strategies. In this contribution, we study the physical properties of the 52 5BZCat blazars that, as a result of the statistical analysis, were put forward as promising candidates for the emission of high-energy IceCube neutrinos [15]. Ten are located in the southern, and 42 in the northern celestial hemisphere. Based on the energy of the neutrino data, these candidates may accelerate hadrons to energies up to the petaelectronvolt (PeV) range. We refer to them as candidate "PeVatron blazars". Among the PeVatron blazar candidates, three objects had been proposed as blue FSRQs (masquerading BL Lacs) in the literature: TXS 0506+056 and PKS 1424+240 , which were also previously proposed as promising neutrino candidates, and 5BZB J0630-2406 . They are formally of the BL Lac type (LERG), but intrinsically HERGs, in which external radiation fields are likely present, but overcome by the jet's synchrotron emission [17, 23–25].

3.1 The comparison samples

We aim to characterize the properties of the 52 candidate PeVatron blazars in the radio, optical, and γ-ray ranges, and compare them with those of the overall population of blazars. To do so, we refer to previous literature studies that tackled the physical properties of sets of blazars using a methodology similar to ours. The samples in [21] (S12), [26] (P17), and [27] (P21) provide both measurements and upper limits on the optical spectral lines with a procedure comparable to ours, and allow us to explore the different regimes in optical and γ-rays.

4 The multi-wavelength properties

Optical spectroscopy is the main focus of our analysis. At these energies, we can delve into the mass accretion process onto the central SMBH. We collected data from public archives and the literature when available. We observed 12 objects for which neither a public spectrum was available in the archives, nor information in the literature. We visually inspected the optical spectra to identify possible emission lines. We are particularly interested in the lines emitted in the BLR. For the spectra lacking emission features, we placed upper limits on the not-detected lines [15, 21]. These lines (measurements or limits) allow us to derive the physical properties, among which the distance of the observed blazar (through the redshift), the luminosity of the broad line region, of the accretion disk, the mass of the central black hole, the mass accretion rate in Eddington units and the size of the BLR and dusty torus, of the central engines of the PeVatron blazar candidates [23, 26–28].

The $\gamma-$ray luminosity of blazars may be used as a proxy for the power of the relativistic jet [21]. Half of the 52 blazars of our interest have a detection in γ-rays. We collected the information for these sources from the Third Data Release of the Fourth *Fermi* Large Area Telescope (LAT) AGN Catalog (4LAC-DR3, [29]). We used the γ-ray energy flux and photon index of the power-law spectrum provided by the catalog to estimate the γ-ray luminosity L_γ of the detected sources. For the remaining 26 blazars with no LAT detection, we placed an upper limit on the γ-ray luminosity considering the sensitivity of the instrument for a power-law-spectrum point-source and 10-yr exposure.

The radio power at 1.4 GHz is a complementary marker for the intrinsic jet power, particularly for those blazars that are not detected in γ-rays [21, 30]. For the 52 candidate neutrino-emitter blazars, we used the value of $P_{1.4\,\mathrm{GHz}}$ provided by 5BZCat.

5 Results and conclusions

In the context of the physically driven HERG/LERG classification that we adopted in our work, $\sim$ 60% of the candidate PeVatron blazars fall in the HERG-like regime of radiatively efficient mass accretion and high radio jet power. This is displayed in Fig. 1, in which we show the accretion regime as a function of the jet power (see the caption for more details). We test the distribution of the candidate PeVatron blazars performing the Anderson-Darling statistical test on the derived physical properties. As a result, the 52 blazars of our interest are compatible with the overall population.

In summary, in this work, we studied the physical properties of a selected sample of 52 candidate neutrino-emitter blazars. We performed a multi-wavelength analysis in radio,

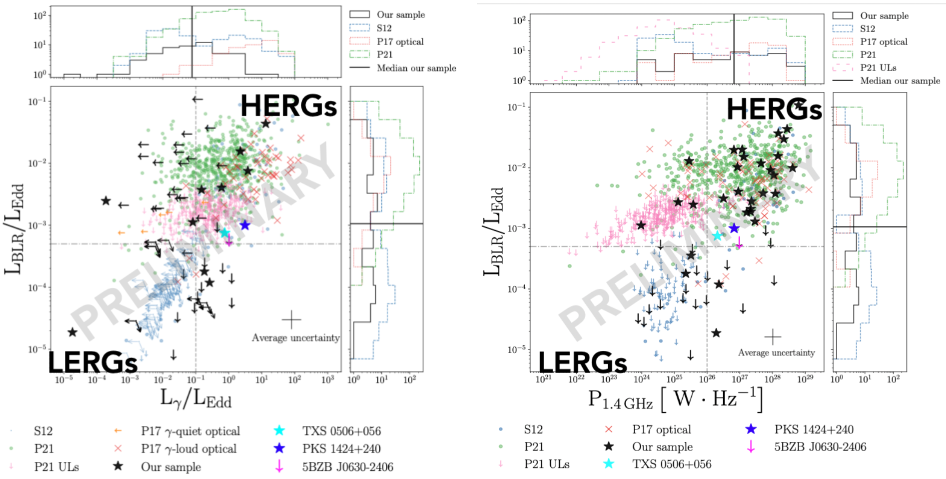

Figure 1: L_{BLR}/L_{Edd} (accretion regime proxy) vs. L_γ/L_{Edd} (power of the jet proxy, left panel) the radio power at 1.4 GHz (power of the jet proxy, right panel) of the candidate PeVatron blazars (black). The three highlighted sources are TXS 0506+056 , PKS 1424+240 , and 5BZB J0630-2406 (see Section 4). As a comparison, the plots also show the samples of S12, P17, and P21. The arrows represent upper limits on either one or both of the shown quantities. The dotted grey lines represent the boundaries HERG/LERG-like regimes, respectively $L_{BLR}/L_{Edd} \sim 5 \times 10^{-4}$, $L_\gamma/L_{Edd} \sim 0.1$ and $P_{1.4\,GHz} \sim 10^{26}\,W \cdot Hz^{-1}$ [19, 21, 22]. On the sides, are the histograms of the corresponding quantities for all the samples, excluding all the upper limits. Here, the black solid lines represent the median values for the candidate PeVatron blazars.

optical, and γ-rays to inspect the accretion regime of the central engine and the energy content of the jet. In the physically driven HERG/LERG classification that we adopted, the candidates of our interest show a mild tendency towards intense radiation fields, radiatively efficient accretion, and powerful jets (~ 60% are HERG-like). However, when considering the whole sample, they are compatible with the overall population based on statistical tests. Addressing the individual neutrino/blazar associations is challenging, and this prevents conclusive results. Further upcoming studies will tackle the genuineness of the associations, and shed more light on the link between blazars and neutrinos.

6 Acknowledgments

This work was supported by the European Research Council, ERC Starting grant *MessMapp*, S.B. Principal Investigator, under contract no. 949555.

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