PROCEEDINGS OF SCIENCE

Blazars: from radio waves to high-energy neutrinos

Alexander Plavin,[a,*] **Yuri Y. Kovalev,**[c,a,b] **Yuri A. Kovalev**[a] **and Sergey Troitsky**[d]

[a] *Astro Space Center of Lebedev Physical Institute, Profsoyuznaya 84/32, 117997 Moscow, Russia*

[b] *Moscow Institute of Physics and Technology, Institutsky per. 9, Dolgoprudny 141700, Russia*

[c] *Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany*

[d] *Institute for Nuclear Research of the Russian Academy of Sciences, 60th October Anniversary Prospect 7a, Moscow 117312, Russia*

E-mail: alexander@plav.in

Blazars are studied through multimessenger eyes over a wide energy spectrum, from radio waves to TeV and PeV neutrinos. We present complete-sample statistical analyses, and demonstrate that very long baseline radio interferometry is uniquely positioned in the multimessenger space. Its high resolution selects beamed parsec-scale synchrotron emission, and neutrinos are likely to experience comparable beaming effects. Evidence for this connection is provided by directional and temporal correlations. We provide new insights on neutrino production in blazars motivated by our recent observational findings.

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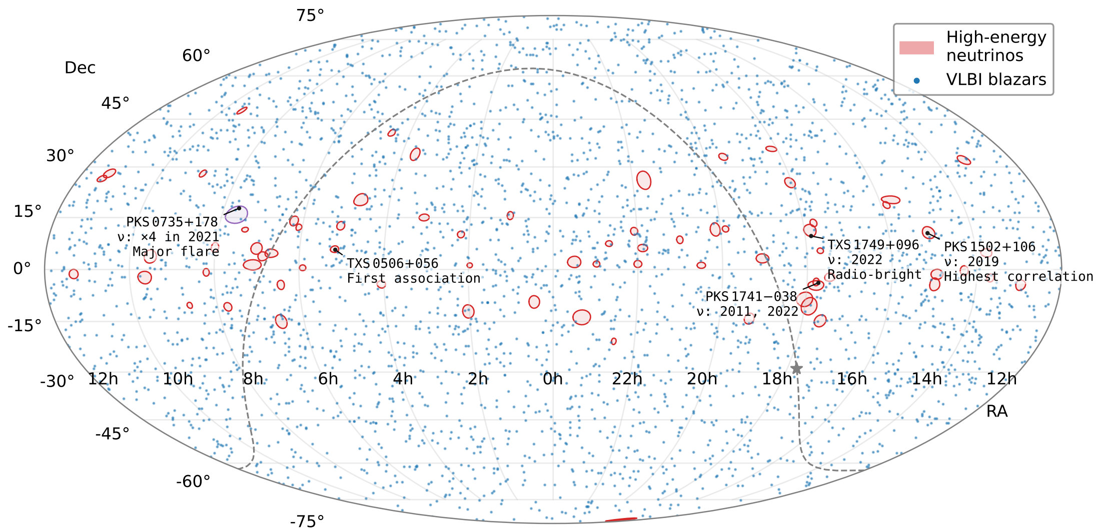

Figure 1: Directions of the IceCube high-energy events as red ellipses and radio bright blazars as blue points (section 2). The red ellipses represent the event error regions enlarged by $\Delta = 0.45°$ to account for systematic errors, as detailed in the text. The five blazars that we consider the most notable neutrino associations are labeled here.

1. Introduction

Blazars are among the most energetic astrophysical sources, they have been gaining more and more attention as potential sources of neutrinos. Mounting evidence indicates the presence of high-energy neutrinos arriving from blazars, as seen by all neutrino observatories [e.g. 1–4].

Despite these compelling indications, the underlying physical mechanisms involved in neutrino production in blazars remain uncertain. Moreover, the association between neutrinos and blazars has not been consistently detected across all search efforts [5, 6]. To shed light on these unresolved questions, we embark on a comprehensive examination by revisiting and augmenting our previous findings.

In the present study, we expand upon our earlier findings [2] by utilizing an updated dataset of IceCube events arrived since 2020. Our aim is twofold: to test the reproducibility of this result, and then to refine the understanding of the observational neutrino-blazar connection.

2. Neutrinos arrive from bright radio blazars

We utilize the largest sample of blazars observed with Very Long Baselimne Interferometry (VLBI) that is collected in the Radio Fundamental Catalog[1] (RFC). The catalog includes precise positions and historical average radio flux measurements, and the catalog is considered complete for the VLBI flux density $S_{8\mathrm{GHz}}^{\mathrm{VLBI}} > 150$ mJy at 8 GHz. This complete sample consists of 3412 objects shown as dots in Figure 1.

We compiled neutrino detections from a set of catalogs containing alerts and alert-like events from the IceCube observatory. The approach and criteria are exactly the same as we did before in

[1] http://astrogeo.org/sol/rfc/rfc_2022b/

[2, 7], and events from 2009 to November 2022 are included. Overall, we select 71 tracks with (i) energy $E \geq 200$ TeV, and (ii) angular resolution $\Omega < 10$ sq. deg. These events are also visualized in Figure 1.

The main goal of the statistical analysis in this work is to test and refine the results and predictions given in [2, 7] using a larger sample of neutrino detections. First, we evaluate the neutrino-blazar correlation using IceCube events detected since the publication of [2]. There are 14 new high-energy events from 2020 to November 2022, and we cannot expect to reach a high statistical significance focusing on them alone: for comparison, 56 events were included in the [2] analysis. The main goal of using these new events is to check earlier results for consistency and reproducibility. Then, we repeat the same statistical calculation using the whole sample of 71 events. This lets us obtain the most up-to-date significance estimates of the blazar — high energy neutrino correlation.

Here, we briefly motivate and describe the statistical procedure; for more details on the algorithm, see [2, 8]. Compact parsec-scale radio emission from blazars is an indicator of energetic relativistic processes happening in the jet and of the Doppler boosting effect [9]. This is exactly the emission measured by VLBI. We take the geometric average of $S^{\mathrm{VLBI}}_{8\,\mathrm{GHz}}$ of all blazars within the neutrino event error regions as the test statistic. The event error regions are taken as IceCube uncertainties enlarged by a certain value Δ, interpreted as a measure of the systematic error. Accounting for systematic errors in more direct ways using simulations remains hard or impossible for now [10]. Our analysis involves trying out Δ values from the $0°, 0.01°, \ldots, 1°$ range and determining the optimal value. Then, a Monte-Carlo method is employed to test if the average is significantly higher than could arise by chance: the p-value is the fraction of random realizations yielding more extreme test statistic values than the real data. When trying out multiple Δ values, we report the post-trial p-value that accounts for the multiple comparisons.

This statistical analyses resulted in the post-trial $p = 0.2\%$ using only events before 2020 in [2]; see Figure 2 for a visualization. Repeating it with the 14 new events since 2020, while keeping the same Δ yields a p-value of 6%. This is a completely independent check of our earlier predictions, that also hints towards a spatial correlation of high-energy neutrinos and radio-bright blazars. Taking into account that the new 2020 – 2022 sample of events is thrice smaller compared to [2], the p-value of 6% is in agreement with the findings reported in that paper. Furthermore, we repeat the statistical analysis in full on the entire sample of 71 high-energy neutrino events. The optimal Δ value remains the same, $\Delta = 0.4°$; the post-trial p-value for the correlation is $3 \cdot 10^{-4}$. See the 2009-2022 line in Figure 2.

The steady increase in neutrino-blazar correlation significance compared to our earlier analysis from 2020 demonstrates that the association is real and was not caused by a random fluctuation originally.

3. Discussion and prospects

In this work, we presented the updated observational results on the association of high-energy neutrinos with blazars that exhibit bright radio emission from parsec scales. The association can be explained by relativistic beaming: blazar jets point towards the observer, both photons and neutrinos are emitted predominantly in our direction, and their detection on Earth becomes more

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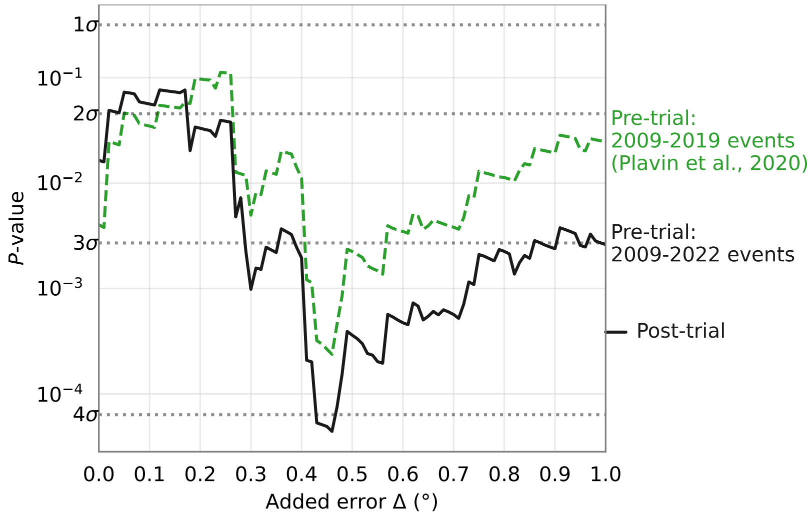

Figure 2: *P*-values for bright VLBI blazars being spatially correlated with IceCube high-energy neutrinos section 2. The horizontal axis marks the added error Δ defined in the text. The two curves correspond to the sample of 56 neutrino detections until 2019 [2] and to the most up-to-date sample of 71 events used in this work. Minima of both curves are attained at $\Delta = 0.45°$. The final post-trial p-value for all 2009–2022 events is $p = 3 \cdot 10^{-4}$, marked in this plot; analogously, for 2009–2019 events, the post-trial $p = 2 \cdot 10^{-3}$.

likely. Together with a lack of strong associations between neutrinos and other classes of active galaxies, this localizes neutrino production to central parsecs of blazars. To produce neutrinos, highly relativistic protons accelerated along the jet direction need to be present in these regions.

However, beaming alone cannot explain the whole neutrino-blazar connection. Recent works [e.g. 2, 11, 12] also demonstrate a temporal correlation: neutrinos predominantly arrive during major flares in blazar jets, as evidenced by their enhanced radio emission. This correlation should be a manifestation of a closer physical relation between emission of electromagnetic waves and neutrinos; both are likely driven by particles injected into the jet by the central engine. Still, they could be produced by different mechanisms in different regions close to the jet origin or around it.

To obtain further insights on the neutrino production and proton content of inner blazar regions, it is important to look for and to study the potential connection between neutrinos and high-energy electromagnetic emission. Early hints of strong hard X-rays being a feature of neutrino-emitting blazars have started to appear recently [13]. Photons of these energies can be directly related to neutrino production through proton-photon interactions. If that is the case, further extending these high-energy studies is crucial to probe and quantify properties of neutrino production regions.

References

[1] IceCube Collaboration, *Science* **361** (July, 2018) eaat1378.

[2] A. Plavin, Y. Y. Kovalev, Y. A. Kovalev, and S. Troitsky, *ApJ* **894** (May, 2020) 101.

[3] J. Aublin, A. Plavin, and ANTARES Collaboration, PoS(395 - 37th International Cosmic Ray Conference (ICRC2021))1164 (Mar., 2022).

[4] Baikal-GVD Collaboration, A. K. Erkenov, N. A. Kosogorov, Y. A. Kovalev, Y. Y. Kovalev, A. V. Plavin, A. V. Popkov, A. B. Pushkarev, D. V. Semikoz, Y. V. Sotnikova, and S. V. Troitsky, *arXiv e-prints* (Oct., 2022) arXiv:2210.01650.

[5] B. Zhou et al., *Phys. Rev. D* **103** (June, 2021) 123018.

[6] IceCube Collaboration, *ApJ* **951** (July, 2023) 45.

[7] A. Plavin, Y. Y. Kovalev, Y. A. Kovalev, and S. Troitsky in *37th International Cosmic Ray Conference*, p. 967, Mar., 2022.

[8] A. V. Plavin, Y. Y. Kovalev, Y. A. Kovalev, and S. V. Troitsky, *MNRAS* **523** (Aug., 2023) 1799–1808.

[9] R. Blandford, D. Meier, and A. Readhead, *Ann. Rev. Astron. Astrophys.* **57** (Aug., 2019) 467–509.

[10] C. Lagunas, Y. Ashida, A. Sharma, and H. Thomas, *arXiv e-prints* (July, 2021) arXiv:2107.08670.

[11] T. Hovatta, E. Lindfors, S. Kiehlmann, W. Max-Moerbeck, M. Hodges, I. Liodakis, A. Lähteemäki, T. J. Pearson, A. C. S. Readhead, R. A. Reeves, S. Suutarinen, J. Tammi, and M. Tornikoski, *A&A* **650** (June, 2021) A83.

[12] G. Illuminati, A. Plavin, and ANTARES Collaboration, PoS(395 - 37th International Cosmic Ray Conference (ICRC2021))972 (Mar., 2022).

[13] A. V. Plavin, R. A. Burenin, Y. Y. Kovalev, A. A. Lutovinov, A. A. Starobinsky, S. V. Troitsky, and E. I. Zakharov, *arXiv e-prints* (June, 2023) arXiv:2306.00960.