TXS 0506–056 as a neutrino source.
What can be derived from IceCube and Baikal-GVD observations?

Ivanova A., Sheshukov A., Sirenko A., Volchugov P., Yablokova Y.

April 2025

1 Introduction

The Baikal-GVD Collaboration reported [2] neutrino events near the position of the blazar TXS 0506–056, a location previously associated with a high-energy neutrino observed by IceCube [3]. This raises the question: is this spatial coincidence significant, and what does it reveal about the nature of the source?

Goal: Quantify the probability that both experiments would detect neutrino event near the same astrophysical source by chance, and explore what constraints such observations place on source models and detection systematics

1.1 Tasks

1. Build a Numerical Model
   - Simulate neutrino events from both astrophysical background and source-related flux
   - Include directional uncertainties and effective areas of IceCube and Baikal-GVD
   - Model the TXS 0506–056 neutrino flux under different scenarios (e.g. steady vs flaring activity, isotropic vs jet emission)
2. Probability Space and Coincidence Analysis
   - Define the probability space of "coincidences" in time and space between events in both detectors
   - Calculate the chance probability of detecting spatially close neutrinos by both observatories
   - Vary source model parameters to study how this affects the coincidence likelihood
3. Inference on Source Properties
   - Using the simulated distributions, assess which source models are compatible with the data
   - Consider both steady emission and flaring activity
4. Impact of Systematic Uncertainties
   - Analyze how angular resolution, energy reconstruction, and background estimation errors affect the significance of the observed coincidence
   - Quantify how much systematics weaken or strengthen conclusions about the source

1.2 Deliverables:

- Code and Plots: a working simulation with adjustable source parameters and outputs for event distributions, coincidence probabilities, and sensitivity studies
- Scientific Report: a concise LaTeX–written report presenting the model, results, interpretation, and impact of uncertainties
- Presentation: a 10–15-minute talk summarizing the approach, findings, and implications for interpreting TXS 0506–056 as a neutrino source

2 Signal model definition

In general the model defines the differential neutrino flux from a given direction $\vec{\Omega}$

$$\Psi(\vec{\Omega}, t, E) \equiv \frac{d^3 N_\nu}{dt\, d\vec{\Omega}\, dE}\ [s^{-1} srad^{-1} m^{-2} GeV^{-1}]$$

2.1 Factorization

In our study we assume the energy, time and angular dependencies to be independent and factorizable

$$\Psi(\vec{\Omega}, t, E) = \Phi(\vec{\Omega}, t) \cdot g(E) = C \cdot f(t) \cdot F(\vec{\Omega}) \cdot g(E)$$

where C is an average integral rate $[s^{-1}m^{-2}]$:

$$\int\limits_T dt \int d\vec{\Omega} \cdot \Phi(\vec{\Omega}, t) = CT$$

and other factors are normalized to one:

$$\int\limits_T dt f(t) = T; \quad \int d\vec{\Omega}\ F(\vec{\Omega}) = 1$$

In our study we consider the following source models:

1.1 Isotropic constant source $\bar{\Phi}$:

$\bar{F}(\vec{\Omega}) = \frac{1}{4\pi}; \quad \bar{f}(t) = 1$

$$\bar{\Phi}(\vec{\Omega}, t|C) = \frac{C}{4\pi}$$

1.2 Point-like constant source $\bar{\Phi}^*$

The angular dependency is singular:

$$F^*(\vec{\Omega}) = \delta^2(\vec{\Omega} - \vec{\Omega}^*)$$

$$\bar{\Phi}(\vec{\Omega}, t|C, \vec{\Omega}) = C\delta^2(\vec{\Omega} - \vec{\Omega}^*)$$

1.3 Point-like flaring source $\tilde{\Phi}^*$

Intensity is assumed to be a periodic function. We can approximate it with a set of square pulses with period T and width τ:

$$\tilde{f}(t) = \sum_{n=0}^{\infty} \Theta(t - Tn) \cdot \Theta(Tn + \tau - t)$$

$$\tilde{\Phi}(\vec{\Omega}, t | C, \vec{\Omega}, T, \tau) = C \cdot \delta^2(\vec{\Omega} - \vec{\Omega}^*) \sum_{n=0}^{\infty} \Theta(t - Tn)\, \Theta(Tn + \tau - t)$$

3 Background

Astrophysical background: parameterisation from [4, eq. 4]

$$\Phi_A = \int\limits_{E_{min}}^{\infty} dE\ \Phi_0 \cdot \left(\frac{E}{E_0}\right)^{-\gamma} \times 10^{-18} GeV^{-1} cm^{-2} s^{-1} sr^{-1} =$$

$$= E_0 \Phi_0 \cdot \left.\frac{(E/E_0)^{1-\gamma}}{1-\gamma}\right|_{E_{min}}^{\infty} = \frac{E_0 \Phi_0}{(\gamma - 1)(E_{min}/E_0)^{\gamma-1}}$$

Energy scale $E_0 = 100\ TeV$ and in our case the minimal energy $E_{min} = 200\ TeV$.

Model parameters from [4] are shown on Tab.1

Table 1. IceCube and ANTARES Neutrino Analysis Results

Analysis	Energy Range	Φ_0	γ
HESE 2020	69.4 TeV–1.9 PeV	$2.12^{+0.49}_{-0.54}$	$2.87^{+0.20}_{-0.19}$
Cascades $\nu_e + \nu_\tau$ 2020	16 TeV–2.6 PeV	$1.66^{+0.25}_{-0.27}$	2.53 ± 0.07
MESE 2014	25 TeV–1.4 PeV	$2.06^{+0.4}_{-0.3}$	2.46 ± 0.12
Inelasticity 2018	3.5 TeV–2.6 PeV	$2.04^{+0.23}_{-0.21}$	2.62 ± 0.07
IceCube ν_μ 2016	194 TeV–7.8 PeV	$0.90^{+0.30}_{-0.27}$	2.13 ± 0.13
IceCube ν_μ 2019	40 TeV–3.5 PeV	$1.44^{+0.25}_{-0.24}$	$2.28^{+0.08}_{-0.09}$
ANTARES 2019	N/A	1.5 ± 1.0	2.3 ± 0.4

Baikal-GVD

Based on [1]

Astrophysical neutrino event selection efficiencies were tested assuming a flux with equal numbers of neutrinos and anti-neutrinos, and with an equal neutrino flavor mixture at Earth: $(\nu_e : \nu_\mu : \nu_\tau) = 1 : 1 : 1$. The one flavor (1f) flux presented by IceCube in was chosen as baseline: MESE 2014

Atmospheric neutrino

IceCube

1. Vivek Agrawal et al. "Atmospheric neutrino flux above 1 GeV". In: Phys. Rev. D 53 (3 Feb. 1996), pp. 1314–1323. DOI: 10.1103/PhysRevD.53.1314. 2. Carlo Mascaretti and Francesco Vissani. "On the relevance of prompt neutrinos for the interpretation of the IceCube signals". In: Journal of Cosmology and Astroparticle Physics 2019.08 (Aug. 2019), p. 004. DOI: 10.1088/1475-7516/2019/08/004.

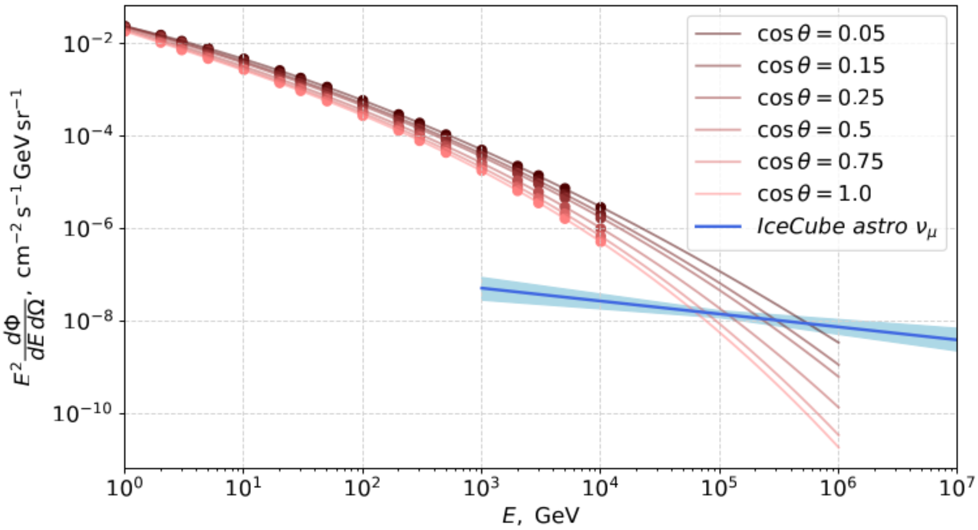

Fig 1. Parameterization of the spectrum of atmospheric neutrinos as a function of the zenith angle θ (shades of red) and astrophysical muon neutrinos (blue) [M. Kleimenov, 2024]

Baikal-GVD

1. Based on Allakhverdyan et al. https://arxiv.org/pdf/2211.09447

The conventional atmospheric neutrino flux from pion and kaon decays was modeled according to [L. V. Volkova, Sov. J. Nucl. Phys. 31, 784 (1980)]. Atmospheric prompt neutrinos were simulated according to the BERSS model [A. Bhattacharya et al., JHEP 06, 110 (2015)].

2. Based on M. Kleimenov Thesis: Parametrization of atmospheric neutrino flux based on Vivek Agrawal et al. "Atmospheric neutrino flux above 1 GeV". In: Phys. Rev. D 53 (3 Feb.1996), pp. 1314–1323. PhysRevDDOI: 10.1103/PhysRevD.53.1314. Table of bartol flux points in file atmospheric_nu_flux.txt

Obtained atmospheric neutrino spectrum at energies greater than 100 TeV is below astrophysical background. Therefore to simplify the background model we neglect it.

4 Detector model

The detector model for the neutrino detection includes many complex features: * interaction cross-section (E) * Detection & selection efficiency vs. the neutrino angle and energy $(\vec{\Omega}, t, E)$ * detector exposure fraction for the given part of the sky $(\vec{\Omega})$ * ...

This is estimated by the collaborations and as an *effective area* $A_eff(\vec{\Omega}, t, E)$.

Prediction of the observed event numbers

Observed event numbers are given by the integral

$$N = \int\limits_{\Delta T} dt \int\limits_{\Delta\Omega} d\vec{\Omega} \int\limits_{\Delta E} dE \;\; A_{eff}(\vec{\Omega}, t, E) \cdot \Psi(\vec{\Omega}, t, E)$$

where ΔT, $\Delta\Omega$ and ΔE are the regions considered in the analysis.

Source spectrum	$A_{eff}^{IceCube}$	A_{eff}^{BGVD}
$E^{-2.0}$	$55.46\ cm^2$	$3.23cm^2$
$E^{-2.5}$	$31.27\ cm^2$	$2.9cm^2$

Table 2. Detector parameters from [2, Table 3]

In this analysis we just consider counting events $E_\nu > 200$ TeV, energy resolution (within reasonable limits) does not affect the result.

Angular region $\Delta\Omega$ is defined by the angular resolution. Time region is the total detector exposure.

Using our factorization from signal models description:

$$N = C \int\limits_{\Delta T} dt f(t) \int\limits_{\Delta\Omega} d\vec{\Omega} F(\vec{\Omega}) \int\limits_{\Delta E} dE\ g(E)\ A_{eff}(\vec{\Omega}, t, E)$$

$$\bar{A}_{eff} = \int\limits_{\Delta T} dt f(t) \int\limits_{\Delta\Omega} d\vec{\Omega} \int\limits_{\Delta E} dE\ g(E)\ A_{eff}(\vec{\Omega}, t, E)$$

So if we assume that $A_{eff}(\vec{\Omega}, t, E) \approx \bar{A}_{eff}$ in the regions of interest, we can use formula

$$N = \bar{A}_{eff} \cdot C \int\limits_{\Delta T} dt f(t) \int\limits_{\Delta\Omega} d\vec{\Omega} F(\vec{\Omega}) \int\limits_{\Delta E} dE\ g(E)$$

Isotropic constant source (diffuse background):

$$\bar{N} = \bar{A}_{eff} \cdot C \cdot \Delta T \cdot \frac{\Delta\Omega}{4\pi}$$

Point source with constant rate:

$$\bar{N}^* = \bar{A}_{eff} \cdot C \cdot \Delta T$$

For this analysis we use the integrated $\bar{A}_{eff}$ for given point source, assuming the energy spectra and a flaring activity, as listed in Tab. 2.

For the angular uncertainty we used 6.2° for cascades in BGVD, and 0.25° for track in IceCube, which leads to $\Delta\Omega_C = 1.49\ srad$ and $\Delta\Omega_T = 9.2 \cdot 10{-}3\ srad$ respectively.

5 Observation significance

5.1 Hypotheses test

In order to test the significance of observation we need to consider the probability of our observation (1 track event in IceCube, and 1 cascade event in Baikal-GVD) to be a random coincidence from background neutrino source.

We consider an isotropic background source with integral Φ_0.

For the significance we need to define the probability of:

- having at least 1 track in considered sky fraction S_{sky}
- which has at least 1 cascade within the cascade angular resolution Ω_C

5.2 Coincidence probability

Coincidence probability is composed of:

- Probability $P(n_t|N_T)$ to observe n_t tracks in the considered fraction of the sky S_{sky}: Poisson distribution with mean $N_T = A^T_{eff} \times \Phi_0 \times S_{sky}$
- Probability that at least one cascade is within an angular area of given n_t tracks: Poisson with mean $N_C = A^C_{eff} \times \Phi_0 \times n_t \times \Omega_C/4\pi$

Which leads to a final expression:

$$P_{coinc}(\Phi_0, S_{sky}) = \sum_{n_t=1}^{\infty} P(n_t|N_T) \cdot P(n_c > 0|N_C(n_t)) =$$
$$= \sum_{n_t=1}^{\infty} P(n_t|\Phi_0 \times A^T_{eff} \times S_{sky}) \cdot \left(1 - \exp(\Phi_0 \times A^C_{eff} \times n_t \times \Omega_C/4\pi)\right) \quad (1)$$

5.3 Sky regions of interest

We perform the study for several regions of interest:

- Full sky $S_{sky} = 1$, assuming a sensitivity to tracks and cascades in all 4π region. While technically incorrect, this gives us the most pessimistic estimation of the random coincidence probability.
- Half sky $S_{sky} = 1/2$, taking into account that IceCube considers only upward-going track events i.e. neutrinos from Northern hemisphere.
- Tracks pointing to one of the $N_{sources}$ within the Ω_T angular uncertainty: $S_{sky} = N_{sources} \times \Omega_T/4\pi$. We used $N_{sources} = 1694$ - a half of 3388 blazars used in [Plavin et al, S. 2020, ApJ, 894, 101](https://ui.adsabs.harvard.edu/abs/2
- Finally we consider a probability to see the coincidence from a signle source (TXS 0506+056) direction $S_{sky} = \Omega_T/4\pi$.

5.4 Result

The resulting significance in σ vs. the integral background flux Φ_0 is show on Fig.2

We compare this integral flux with the flux estimations, considered in [4], integrated for $E_\nu > 200\ TeV$, as described in sec. 3

The probability of having a track and cascade coincidence, associated with one of 1694 sources, generated by diffuse astrophysical neutrino background is rejected at $3.8 - 4.2\sigma$ level.

6 Source parameters esitmation

We used Markov Chain Monte-Carlo approach to calculate the posterior distribution for the flux normalization parameter C.

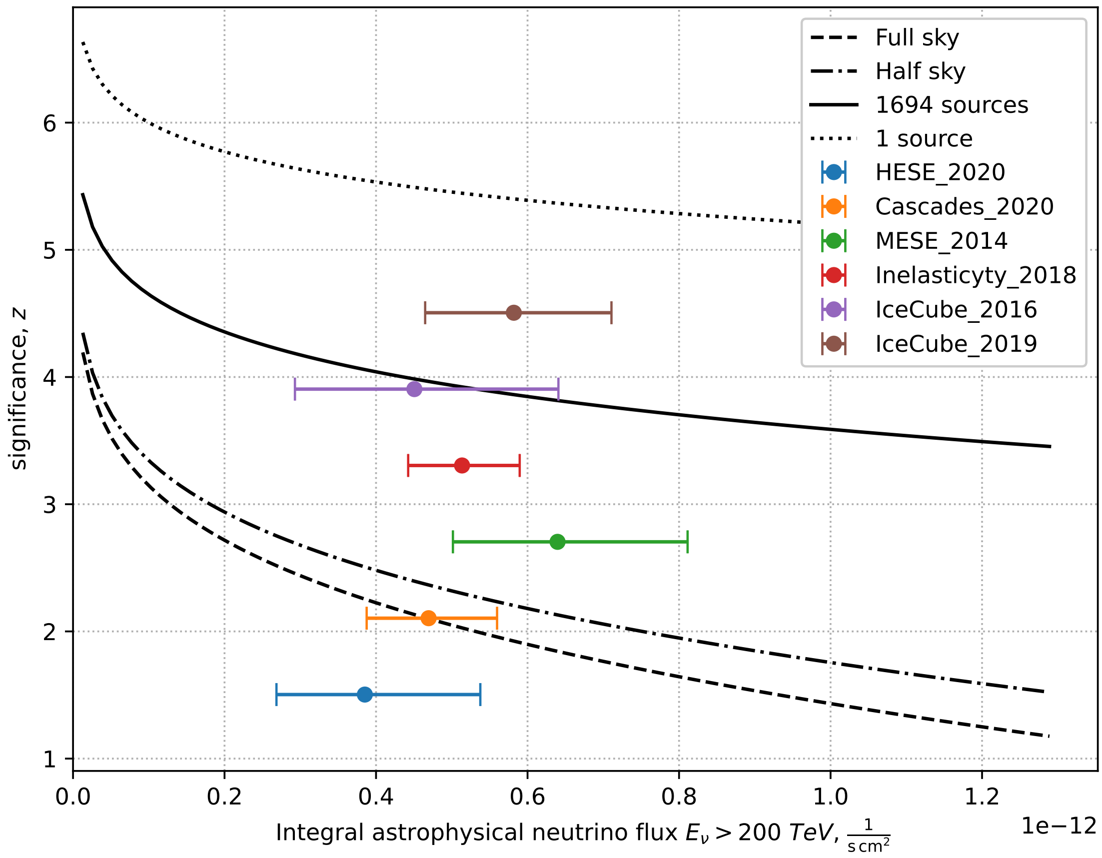

Fig 2. significances for different models

In a simple approach without the account for systematics we used the values

$$
\begin{aligned}
C &\sim \mathrm{Uniform}(1e-17,\ 1e-11) \\
\text{expected events IceCube} &\sim \mathrm{Poisson}(f(\mathrm{C})) \\
\text{expected events Baikal} &\sim \mathrm{Poisson}(f(\mathrm{C}))
\end{aligned}
$$

$$
\begin{aligned}
\mathrm{C} &\sim \mathrm{Uniform}(1e-17,\ 1e-11) \\
\text{bg\_flux\_IC} &\sim \mathrm{TruncatedNormal}(4.64e-19,\ 3.21e-19,\ 0,\ inf) \\
\text{bg\_flux\_BGVD} &\sim \mathrm{TruncatedNormal}(2.85e-16,\ 1.98e-16,\ 0,\ inf) \\
\text{eff\_area\_IceCube} &\sim \mathrm{Normal}(3.13e+05,\ 3.13e+03) \\
\text{eff\_area\_Baikal} &\sim \mathrm{Normal}(2.9e+04,\ 290) \\
\text{sum\_flux\_IC} &\sim \mathrm{Deterministic}(f(\text{bg\_flux\_IC},\ \mathrm{C})) \\
\text{sum\_flux\_BGVD} &\sim \mathrm{Deterministic}(f(\text{bg\_flux\_BGVD},\ \mathrm{C})) \\
\text{expected\_events\_IceCube} &\sim \mathrm{Poisson}(f(\text{eff\_area\_IceCube},\ \text{bg\_flux\_IC},\ \mathrm{C})) \\
\text{expected\_events\_Baikal} &\sim \mathrm{Poisson}(f(\text{eff\_area\_Baikal},\ \text{bg\_flux\_BGVD},\ \mathrm{C}))
\end{aligned}
$$

Table 3. Constraints on the signal flux normalization

	16% percentile	50% percentile	84% percentile
without systematics, constant flux 5 year	2.5572×10^{-14}	4.8793×10^{-14}	8.4167×10^{-14}
with systematics, constant flux 5 year	2.5688×10^{-14}	4.9328×10^{-14}	8.6061×10^{-14}
without systematics, flare flux 2 year	6.3652×10^{-14}	1.2349×10^{-13}	2.1283×10^{-13}
with systematics, constant flux 2 year	6.3863×10^{-14}	1.2406×10^{-13}	2.1391×10^{-13}

7 Summary

7.1 Analysis and results

Coincidence probability

Calculated the likelihood of spatially coincident events arising from background:

- Poisson statistics for track (IceCube) and cascade (Baikal-GVD) events.
- Tested sky regions: full sky, northern hemisphere, regions around 1,694 blazars, and TXS 0506–056 specifically.
- The chance probability of a coincidence from background was rejected at 3.8–4.2σ when considering 1694 blazars, strengthening the case for TXS 0506–056 as a neutrino source.

Constraints on the neutrino source parameters

Key Implications

- The findings suggest that the observed neutrino events are unlikely to result from random background fluctuations.
- Systematic uncertainties (angular resolution, energy reconstruction) were shown to moderately affect significance but do not invalidate the conclusion.
- Both steady and flaring emission models are compatible with observations, though flaring scenarios require further temporal analysis.

References

[1] Baikal Collaboration et al. "Diffuse neutrino flux measurements with the Baikal-GVD neutrino telescope". In: *Physical Review D* 107.4 (Feb. 21, 2023), p. 042005. ISSN: 2470-0010, 2470-0029. DOI: 10.1103/PhysRevD.107.042005. arXiv: 2211.09447[astro-ph]. URL: http://arxiv.org/abs/2211.09447 (visited on 04/10/2025).

[2] Baikal-GVD Collaboration et al. "High-energy neutrino-induced cascade from the direction of the flaring radio blazar TXS 0506+056 observed by Baikal-GVD in 2021". In: *Monthly Notices of the Royal Astronomical Society* 527.3 (Nov. 27, 2023), pp. 8784–8792. ISSN: 0035-8711, 1365-2966. DOI: 10.1093/mnras/stad3653. arXiv: 2210.01650[astro-ph]. URL: http://arxiv.org/abs/2210.01650 (visited on 04/05/2025).

[3] The IceCube et al. “Multi-messenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A”. In: *Science* 361.6398 (July 13, 2018), eaat1378. ISSN: 0036-8075, 1095-9203. DOI: 10.1126/science.aat1378. arXiv: 1807.08816[astro-ph]. URL: http://arxiv.org/abs/1807.08816 (visited on 04/05/2025).

[4] Sergey Troitsky. “Constraints on the models of the origin of high-energy astrophysical neutrinos”. In: *Physics-Uspekhi* 64.12 (Dec. 1, 2021), pp. 1261–1285. ISSN: 1063-7869, 1468-4780. DOI: 10.3367/UFNe.2021.09.03906210.3367/UFNr.2021.09.039062. arXiv: 2112.09611[astro-ph]. URL: http://arxiv.org/abs/2112.09611 (visited on 04/10/2025).