Bayesian ICECAT analysis

Thara Caba[1]

Supervisor: PhD Francesca Capel[2]

Work made as part of the Hanrieder Research Fellowship at the MPI for Physics.

September 20, 2024

[1] University of Rome "Tor Vergata", tharacaba@gmail.com
[2] Max Planck Institute for Physics, capel@mpp.mpg.de

Contents

Acknowledgements 4

Abstract 5

1 Introduction 6

2 Methods 6

3 Results and discussion 8

4 Conclusions and recommendations 9

References 10

List of Figures

List of Tables

1 Key parameters and assumptions used in the power-law analysis. 7
2 Key parameters and assumptions used in the $p\gamma$ analysis. 8

Acknowledgements

This internship was possible thanks to the Hanrieder Research Fellowship at the MPI for Physics, Erasmus Mundus Joint Master (EMJM) scholarships and the Autonomous University of Santo Domingo.

Abstract

Astrophysical neutrinos provide a unique probe into the most energetic and extreme phenomena in the universe, such as blazar jets and Active Galactic Nuclei (AGN). This study investigates the association between the high-energy neutrino event IC170922A and the blazar TXS 0506+056 using Bayesian statistical techniques. We apply two different spectral models—power-law and $p\gamma$—to analyze how varying assumptions about the source spectrum affect the probability of a connection between the neutrino event and the blazar. The power-law model yields a 0.54 probability of connection, while the $p\gamma$ model results in a slightly lower probability of 0.42. These findings highlight the sensitivity of neutrino source interpretation to spectral assumptions and emphasize the importance of testing multiple models to account for the physical processes driving high-energy neutrino production. The Bayesian approach used in this study allows for a more nuanced and robust analysis by incorporating prior knowledge and accounting for uncertainties in both source flux and detector response.

1 Introduction

Astrophysical neutrinos are a valuable window into the most energetic phenomena in the universe. Detected by the IceCube Neutrino Observatory, these high-energy particles allow us to probe environments like blazar jets and Active Galactic Nuclei (AGN) where conditions are extreme. However, determining the exact origin and properties of these neutrinos remains a challenge. While the detection of neutrino events provides an initial clue, extracting meaningful insights requires sophisticated statistical and physical modeling.

In this study, I use Bayesian statistical techniques to explore the connection between astrophysical neutrinos and their potential sources, particularly focusing on TXS 0506+056, a blazar associated with a high-energy neutrino event (IC170922A) THE ICECUBE COLLABORATION et al. (2018). This analysis leverages public IceCube data and aims to explore how different spectral assumptions affect the interpretation of neutrino events.

The Bayesian statistical framework offers several advantages over traditional frequentist methods. In frequentist statistics, hypothesis testing focuses on rejecting or failing to reject the null hypothesis. While useful for point-estimation, this method has limitations when it comes to making probabilistic inferences about model parameters, especially in complex systems like astrophysical neutrino sources. Frequentist methods treat parameters as fixed values and assess the likelihood of observing data under different models.

In contrast, the Bayesian approach explicitly incorporates prior knowledge or assumptions about the parameters, which are updated based on the data using Bayes' theorem. The result is a posterior distribution that gives a probabilistic assessment of the parameter values. This is particularly beneficial when dealing with sparse or uncertain data, such as in the case of astrophysical neutrinos, where events are rare and the sources are not fully understood. Moreover, Bayesian methods provide a natural way to quantify uncertainties, and the hierarchical models we employ can account for multiple layers of uncertainty—such as the uncertainty in the source flux and the detector response—simultaneously. This is in line with recent work in neutrino astronomy that emphasizes the importance of moving beyond simple hypothesis testing to more physics-driven searches for sources Capel et al. (2024).

Our goal in this study is to test how the choice of spectral model—power-law versus $p\gamma$ (as described in Rodrigues et al. (2024))—affects the interpretation of the neutrino event IC170922A.

2 Methods

For this study, I used the ICECAT-1 event catalog Abbasi et al. (2023), which is the first comprehensive compilation of alerts from the IceCube Neutrino Gold and Bronze Track Alert program.

Each entry in the catalog represents a high-energy neutrino event potentially originating from astrophysical sources. The catalog includes real-time alerts distributed via GCN notices and circulars, as well as historical events dating back to 2011, when the complete IceCube detector became operational. These earlier events would have triggered alerts had the program been active. For this analysis, I specifically selected Gold events due to their higher likelihood of being associated with identifiable astrophysical sources.

Since ICECAT-1 only provides the most probable neutrino energy associated with each event, and the software requires muon energy, I cross-referenced the ICECAT-1 data with the All-sky point-source IceCube data: years 2008-2018 Collaboration et al. (2021), which includes the necessary muon energy information. This cross-matching yielded 26 neutrino events suitable for further analysis.

To refine this event list, I filtered it based on sources listed in Rodrigues et al. (2024). After applying this filter, five source-event candidates were identified. Of these, I focused on the well-known source TXS 0506+056 and its corresponding neutrino event, IC170922A, for detailed analysis.

The first step was to replicate the analysis made with a power-law source presented in Capel et al. (2023). The key parameters and assumptions used for this analysis are summarized in Table 1.

Table 1: Key parameters and assumptions used in the power-law analysis.

Description	**Variables**	**Implementation**
TXS 0506+056	(RA, Dec), z	(77.36°, +5.69°), 0.3365
IC-170922A	$\hat{E}$, (RA, Dec), σ_ω	23.7 TeV, (77.43°, +5.79°), 0.7°
Energy range	E_{min}, E_{max}	10 TeV, 100 PeV
Atmospheric flux prior	Φ_a, σ_{Φ_a}	9.54×10^{-10} cm^{-2}s^{-1}, 0.1
Diffuse flux prior	Φ_d, σ_{Φ_d}	6.25×10^{-11} cm^{-2}s^{-1}, 0.1
Diffuse spectrum prior	γ_d, σ_γ	2.6, 0.2

For this analysis, background events were simulated over a period of $T_{obs} = 0.5$ years with an energy threshold of $\hat{E}_{th} = 20$ TeV applied to the reconstructed events. I then incorporated a single alert event, IC-170922A, for further investigation. A narrow prior was placed on the spectral index $\gamma \sim$ Normal$(2.0, 0.1)$, while a wider prior was maintained for the luminosity $L \sim$ LogNormal$(10^{46}$ GeV/s, 8).

Next, I explored how the analysis would change when the source spectrum was modified to a $p\gamma$ model, as described in Rodrigues et al. (2024). The key parameters used for this analysis are listed in Table 2. For this analysis, I used a narrow prior for the source break energy $E0_{source} \sim$ LogNormal$(3.1 \times 10^7$ GeV, $0.1)$ and continued to use the wide prior on the luminosity $L \sim$

LogNormal(10^{49} GeV/s, 3).

Table 2: Key parameters and assumptions used in the $p\gamma$ analysis.

Description	Variables	Implementation
TXS 0506+056	(RA, Dec), z	(77.36°, +5.69°), 0.3365
IC-170922A	$\hat{E}$, (RA, Dec), σ_ω	23.7 TeV, (77.43°, +5.79°), 0.7°
Energy range	E_{min}, E_{max}	10 TeV, 1000 PeV
Atmospheric flux prior	Φ_a, σ_{Φ_a}	9.54×10^{-10} cm^{-2}s^{-1}, 0.1
Diffuse flux prior	Φ_d, σ_{Φ_d}	2.26×10^{-13} cm^{-2}s^{-1}, 0.19×10^{-13}
Diffuse spectrum prior	γ_d, σ_γ	2.6, 0.2

The source code used for this analysis can be found in the following repository.

3 Results and discussion

Using the power-law model I found that the probability of the single neutrino event being connected to the blazar TXS 0506+056 is $p_{assoc} = 0.54$. This suggests that, under the power-law assumption, there is a moderate likelihood that the neutrino originated from the blazar.

In contrast, when we applied the $p\gamma$ model the probability of a connection between the neutrino event and the blazar dropped to $p_{assoc} = 0.42$. While this probability is lower than that of the power-law model, it still indicates a non-negligible chance that the neutrino is related to the source.

The difference in probabilities between the power-law model and the $p\gamma$ model highlights the sensitivity of the analysis to the chosen spectral assumption. The power-law model has been widely used in astrophysical studies due to its simplicity and its ability to describe a variety of phenomena. However, the $p\gamma$ model offers a more physically motivated scenario for high-energy neutrino production in blazars.

The lower probability in the $p\gamma$ model suggests that this scenario might impose stricter conditions on the relationship between neutrino energy and the blazar's emission. However, it is important to note that while the probability is lower, the $p\gamma$ model still provides a reasonable likelihood of association. This indicates that both models should be considered when interpreting neutrino data from blazars, and further observational data could help clarify which model better describes the emission mechanisms at play.

4 Conclusions and recommendations

This study explored the association between the high-energy neutrino event IC170922A and the blazar TXS 0506+056 using Bayesian statistical techniques. By comparing two different spectral models—the widely used power-law model and the more physically motivated $p\gamma$ model—we sought to evaluate how different assumptions about the source's spectrum influence the interpretation of neutrino data.

Our results show that while the power-law model provides a slightly higher probability $p_{assoc} = 0.54$ of the neutrino being connected to the blazar, the $p\gamma$ model still offers a reasonable likelihood $p_{assoc} = 0.42$ and reflects more complex, hadronic interactions that are expected in environments like blazar jets. These findings underscore the importance of testing multiple spectral models, as each provides a complementary perspective on the physical processes at play in high-energy neutrino emission.

This analysis also highlights the power of the Bayesian approach, which allows for the incorporation of prior knowledge and the quantification of uncertainties at multiple levels. The hierarchical Bayesian model used in this study enabled us to account for the uncertainties in the source flux and detector response, making our conclusions more robust and comprehensive.

Ultimately, this study contributes to the growing body of work in multi-messenger astronomy, emphasizing the need for refined models and statistical methods to accurately characterize astrophysical neutrino sources. Future studies that combine Bayesian techniques with more detailed spectral modeling will be key to advancing our understanding of high-energy neutrino production and the environments that drive these emissions.

References

Abbasi, R. et al. 2023, The Astrophysical Journal Supplement Series, 269, 25, arXiv:2304.01174 [astro-ph]

Capel, F. et al. 2023, in Proceedings of 38th International Cosmic Ray Conference — PoS(ICRC2023) (Nagoya, Japan: Sissa Medialab), 1576

Capel, F. et al. 2024, A hierarchical Bayesian approach to point source analysis in high-energy neutrino telescopes, arXiv:2406.14268 [astro-ph]

Collaboration, I. et al. 2021, IceCube Data for Neutrino Point-Source Searches Years 2008-2018, arXiv:2101.09836 [astro-ph]

Rodrigues, X. et al. 2024, The Spectra of IceCube Neutrino (SIN) candidate sources – V. Modeling and interpretation of multiwavelength and neutrino data, arXiv:2406.06667 [astro-ph]

THE ICECUBE COLLABORATION et al. 2018, Science, 361, eaat1378, publisher: American Association for the Advancement of Science