PROCEEDINGS OF SCIENCE

# Hadronic processes at work in 5BZB J0630−2406

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Recent observations are suggesting that active galactic nuclei (AGNs) play in the production of high-energy neutrinos. Even if blazars are good candidates to be neutrino emitters, our understanding of the physical processes and locations of production remains limited. In this study, we focus on one object, 5BZB J0630−2406, which is one of the blazars recently associated with neutrino emission [7]. Modelling the quasi-simultaneous, broad-band spectrum energy distribution (SED) of the selected blazar, we explore various scenarios from purely leptonic to lepto-hadronic models, testing the inclusion of external photon fields. This theoretical study provides a complementary testing ground for the proposed neutrino – blazar association. Despite being historically classified as a BL Lac, our results show that 5BZB J0630−2406 is a high power FSRQ, producing a neutrino flux within the reach of the IceCube detector.

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## 1. Introduction

The IceCube observatory, situated at the South Pole, is currently the most advanced detector for high-energy neutrinos (above TeV). While the majority of the high energy astrophysical neutrinos observed by IceCube remains unclear, various claims of associations with AGN, such as the blazar TXS 0506+56, have been made at different statistical levels [3]. Numerical studies of these objects have revealed the importance of external fields in neutrino production and the presence of markers indicating hadronic processes in the observed electromagnetic spectrum energy distribution (SED). Another approach to studying these correlations involves analyzing the time-integrated neutrino information over a specific period or conducting stacking analyses of populations. However, such analyses for different types of AGN have led to conflicting results. Recently, we reported statistically significant evidence for a correlation between blazars (objects listed in the 5BZCat catalog [19]) and IceCube hotspots [7–9] which are sky positions exhibiting anisotropies in the distribution of IceCube events. The observed chance probability of the correlation between blazars and high-energy (HE) neutrinos is $2.59 \times 10^{-7}$. The study finds a set of 52 objects, i.e. PeVatron blazars, as probable sources of HE neutrinos. The statistical analysis was based solely on the spatial sky positions of the objects, without any selection based on their classification or electromagnetic properties.

The objective of this study is to provide an initial understanding of the underlying physics of the associated objects from a theoretical perspective. This understanding is crucial for determining the common factors responsible for neutrino emission in blazars and advancing our knowledge of the emission processes involved. The focus of the investigation is on one particular, PeVatron blazar, 5BZB J0630−2406. Despite the lack of emission lines, a lower limit has been established at $z \geq 1.239$ [27], and presence of absorption lines indicate the presence of the host galaxy have been observed [25]. 5BZB J0630−2406 was pinpointed as an exemplary blazar, it displays properties typical of "blue flat spectrum radio quasar" [11, 12, 20, a.k.a. "high-power high-synchrotron-peak blazars"], i.e. high-emitting power sources that are intrinsically FSRQs where their broad emission lines are swamped by the jet synchrotron emission. For reference, this typology of blazars has also been recently called "masquerading BL Lacs" [21]. In contrast to "true" high-frequency-peaked BL Lacs which have intrinsically poor radiation fields, these objects host powerful jets and radiatively efficient accretion. This can foster the production of neutrinos, similarly to TXS 0506+056 and PKS 1424+240, suggested as promising candidate neutrino emitters [21–23].

This study focuses on modeling the SED of 5BZB J0630−2406, utilizing simultaneous and quasi-simultaneous multi-wavelength data and a one-zone model. Through parameter space exploration and analysis, we derive the properties of the source and its central engine, and we discuss the current paradigm of neutrino production in blazars.

## 2. Neutrino observations

In our recent study [7], we utilized a sky map covering the Southern Hemisphere ($\delta < -5$) based on IceCube observations from 2008 to June 2015 [2]. The map focuses on events with an energy-proxy greater than 100 TeV and provides integrated information over a period of 7 years, and is sensitive to potential long-term neutrino emitters.

The IceCube hotspot IC J0630−2353 indicates an anisotropic distribution of the observed IceCube events, indicating a discrepancy with background expectation. This hints for the possible presence of an astrophysical source. As a matter of fact, a spatial correlation between IC J0630−2353 and the blazar 5BZB J0630−2406 suggests that this blazar could be a source of neutrinos. If confirmed, this would imply that the blazar has the capability to accelerate cosmic rays to energies in the PeV range or even up to several EeV, assuming proton acceleration.

## 3. Multiwavelength observations and data analysis

In this study, we focused on modeling the multiwavelength SED of 5BZB J0630−2406 during the period of IceCube observations (2008-2015). We employed nearly simultaneous multiwavelength data from various instruments, including GROND, Swift, XMM-Newton, NuSTAR, and the Fermi-LAT satellite. These observations, taken around October 17, 2014, provided valuable data for constraining the higher-energy synchrotron component of the SED.

Near-infrared (NIR) aperture photometry observations in the JHK bands were obtained by GROND [14]. Optical observations were carried out by KAIT [17], ASAS-SN [16], ZTF [18], and SMARTS [6], and the collected magnitudes were corrected for reddening and converted to flux units. The X-ray data from quasi-simultaneous observations by XMM-Newton and NuSTAR [15] were analyzed using spectral fitting techniques with models such as simple power-law, log-parabola, and broken power-law. The log-parabola and broken power-law models provided the best fit to the X-ray data based on statistical considerations, underlying the presence of a broken spectral shape.

Concerning the $\gamma$-ray data, we utilize the LAT spectrum published in [4]. It was obtained from *Fermi* observations spanning the period between August 4, 2008, and January 31, 2015. To characterize statistically-significant variations in the $\gamma$-ray light curve, we adopt the Bayesian algorithm available in Astropy[1] [5]. Applying this approach to the yearly binned light curve, the first $\sim$ 7-yr of LAT observations, up to $\sim$ MJD 57250, are overall consistent with a steady state, indicating that if variability is present at these frequencies it may be below the sensitivity of the LAT data. During the more recent LAT observations, since $\sim$ MJD 57250, the source is undergoing a long-term enhanced state. This result is in agreement with [4].

Overall, the data analysis provided crucial insights into the multi-wavelength observations of 5BZB J0630−2406, and allow us to build the broadband SED for the period of interest. In Fig. 2, we display the quasi-simultaneous data in black and radio archival data in gray points. The latter are obtained from the ASI Science Data Center database (SSDC), and are displayed for reference.

## 4. Theoretical modeling description

In this work, we use a one-zone leptonic and lepto-hadronic model with the AM$^3$ code [10] to describe the multi-wavelength emission of 5BZB J0630−2406. The model describes the emission of a spherical region, or “blob”, moving at relativistic speed inside a jet. The jet is launched from a central engine composed of a supermassive black hole, an accretion disk and a dust torus. Relativistic electrons and protons are injected into the blob that interacts with external photon fields, included the reprocessed emission by a broad-line-region (BLR) from the accretion disk. In order

[1]More details at http://docs.astropy.org/en/stable/api/astropy.stats.bayesian_blocks.html

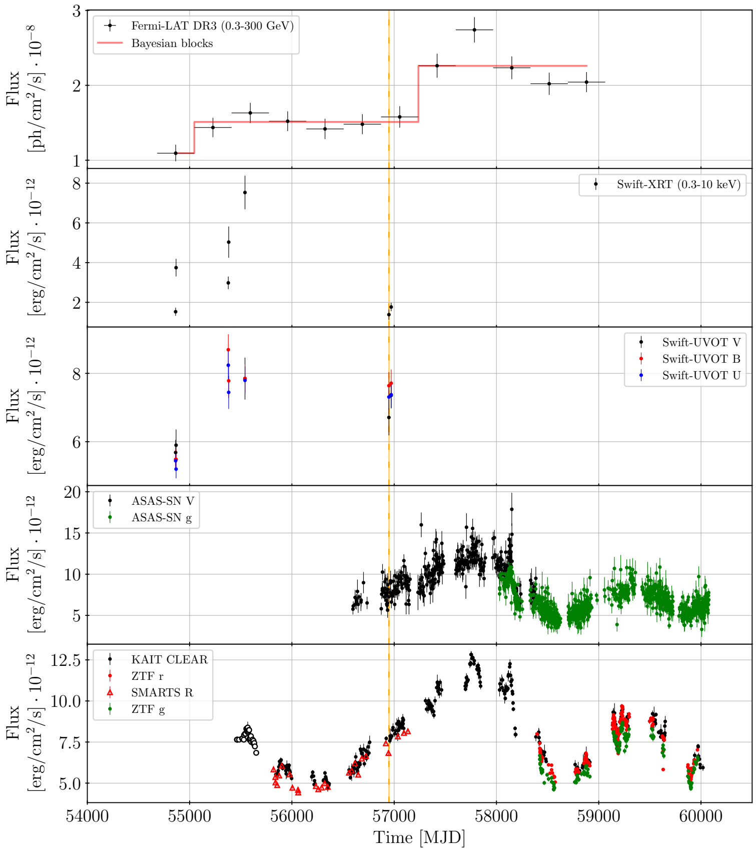



**Figure 1:** Multi-wavelength light curve of 5BZB J0630−2406 composed of $\gamma$-ray, X-ray and optical data. The top panel shows the $\gamma$-ray light curve (one year binning) taken from the 4FGL-DR3 catalog, the second panel X-ray measurements of Swift XRT. For the third panel, only the three optical filters of UVOT were analyzed due to strong L$\alpha$ contamination in the UV filters. The fourth panel shows the V-band and g-band monitored by ASAS-SN and the bottom panel shows a composition of the KAIT *Clear* band measurement, the SMARTS R-band and the ZTF r-band and g-band. The X-ray and optical light curves are corrected for galactic extinction. The orange line represents the time of quasi-simultaneous data used in the analysis.

to reproduce the SED, we employ a parameter search algorithm that optimizes multiple parameters by minimizing residuals between simulated and observed SEDs. The algorithm terminates when a low enough reduced $\chi^2$/d.o.f. value is achieved or when optimization stagnates. When hadrons are present, the model computes a muon neutrino flux. We can estimate the number of neutrino events with associated Poisson uncertainties at the 3$\sigma$ levels, using the IceCube instrument response functions. We also display on the SED the IceCube flux sensitivity assuming a neutrino power-law spectrum of $E^{-2}$ [2].

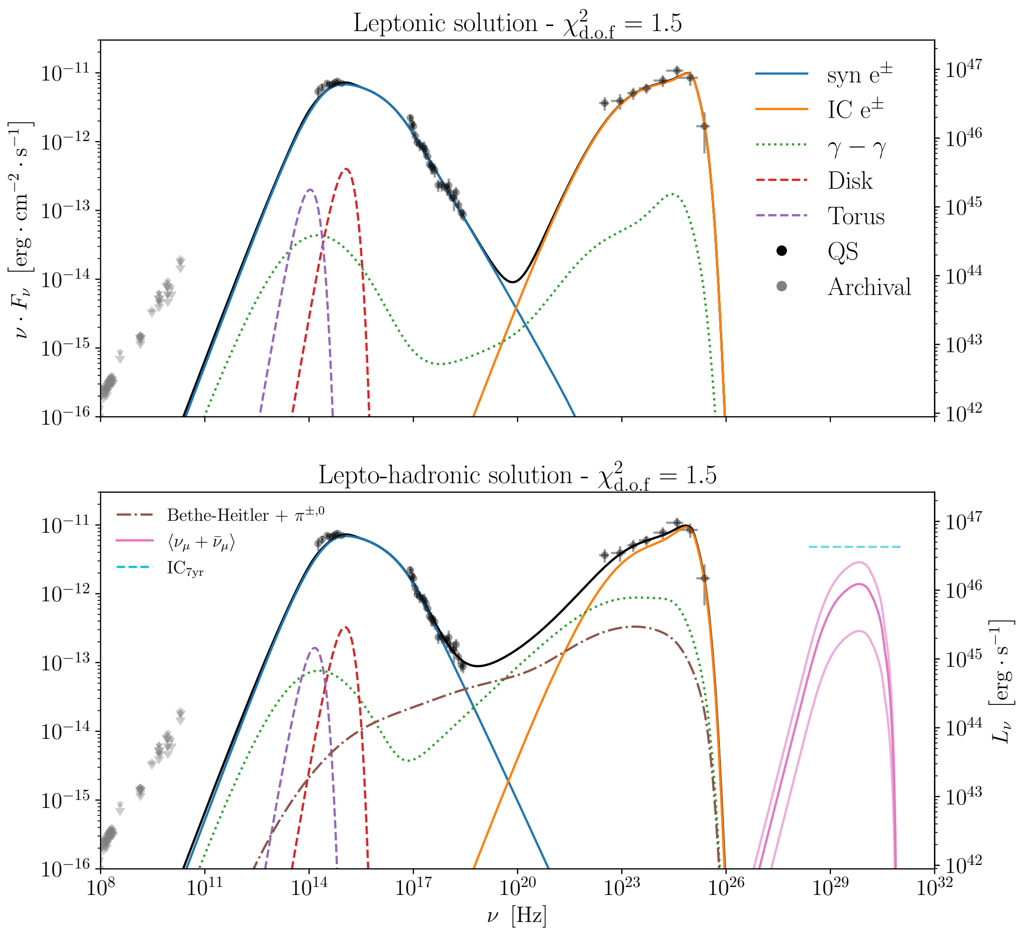
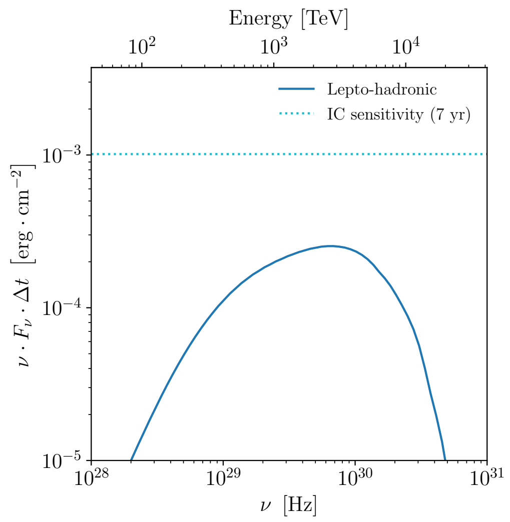



**Figure 2:** SEDs from (top) leptonic solution and (bottom) lepto-hadronic models of 5BZB J0630−2406 in the observer frame. Various components are displayed from the leptonic and hadronic processes to the external radiation fields (see legend). The muon neutrino flux is showed with Poisson uncertainties at the $3\sigma$ levels.

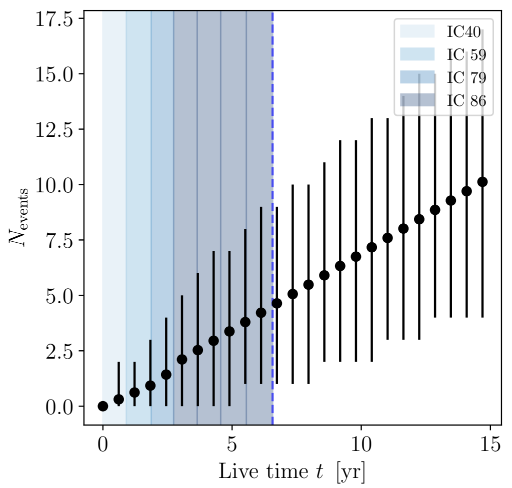
## 5. Results

In the purely leptonic model, we focused on reproducing the SED by considering a population of relativistic electrons visible on Fig 2 (top). The model parameters, visible in Tab. **??**, indicated a near equipartition state with a ratio of electron to magnetic field energy densities of $u_{\rm e}/u_{\rm b} \sim 3.9$. The shape of the GeV peak can only be explained by synchrotron-self Compton (SSC) and an external Compton (EC) contribution. Indeed, we model a bright accretion disk hiding in the synchrotron peak with $L_{\rm disk} \simeq 5 \times 10^{48}$ erg · s$^{-1}$. In fact, the location of the emission region is located at a dissipation radius of $R_{\rm diss}/R_{\rm BLR} = 1.7$, indicates that the blob and the BLR radiation field interaction is not negligible. This purely leptonic model failed to explain the broken spectral shape observed in the X-ray band, suggesting the presence of additional sub-dominant processes.

To explore the potential production of neutrinos, we considered a lepto-hadronic solution that incorporated both leptonic and hadronic processes, the obtained SED is visible in Fig. 2 (bottom).




**(a)** Neutrino flux scaled according to the live time showed in [2] derived for both mixed lepto-hadronic modeling of 5BZB J0630−2406. The uncertainties are computed assuming Poisson statistics and $3\sigma$ levels. The dashed gray line represents the 7-years IceCube sensitivity, assuming $E^{-2}$ and $\delta = -24°.06$.




**(b)** Evolution of the number of observed events by the IceCube detector in time according to various string configurations. The uncertainties are evaluated assuming Poisson statistics ($3\sigma$ levels). The blue dashed line represents the integrated live time as in [2].

Due to the relatively low magnetic field, the hadronic processes are only sub-dominant, resulting in the SED as cascade components. In such case, those sub-dominant processes can explain the broken spectral shape observed in the X-ray, thanks to the Bethe-Heitler component. The second peak in the SED is, as the previous solution, well explained with SSC and EC due to the BLR. The dissipation radius in this model is 1.6 $R_{\rm BLR}$. The ratio of proton to magnetic field energy densities $u_{\rm p}/u_{\rm b} \sim 10^3$, indicates a deviation from equipartition. Nevertheless, the total luminosity injected in the protons stays below the Eddington luminosity of $L_{\rm Edd} \sim 3 \times 10^{48}$ erg · s$^{-1}$. In fact, despite the addition of protons, the characteristics of the accreting engine, such as the disk luminosity or the accretion rate remained consistent with those found in the leptonic model. In both models, the fraction of $\gamma$-ray luminosity is $L_\gamma/L_{\rm Edd} \sim 0.15$. The lepto-hadronic model predicts a muon neutrino flux, visible in Fig. 3a, close to the 7-yr flux sensitivity. We can also derive the expected number of neutrino events, as shown in Fig. 3b. The lepto-hadronic model provided predictions of $N_{\rm events} = 0.68^{+2.32}_{-0.68}$ over one year and $N_{\rm events} = 4.82^{+5.18}_{-3.82}$ over a 7-year period. For the 7-year period, we can estimate the $p$-value probability testing the null hypothesis of non detection. We obtained, 3% indicating a small tension.

## 6. Discussion and conclusion

The study presented here 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 $L_{\rm disk} \sim 5 \times 10^{45}$ erg · s$^{-1}$. The presence of external fields that are partly re-processed by the BLR naturally explains the peaky feature in the $\gamma$-ray band. Its accretion rate, i.e. the energy injected into these external fields, is of the order of $L_{\rm BLR}/L_{\rm Edd} \sim 2 \times 10^{-4}$, close to the values physically suggested for FSRQs [12]. The relatively high accretion regime of 5BZB J0630−2406 is supported also by the ratio of the $\gamma$-ray luminosity and the Eddington luminosity, $L_\gamma/L_{\rm Edd} \simeq 0.15$, highlighting that this source shares again properties common to the FSRQ class [26]. The location of the emitting region, outside but close to the BLR radius, makes the BLR radiation influence still important while at the same time it limits the absorption of $\gamma$ rays, leading to a bright $\gamma$-ray luminosity. We find that in 5BZB J0630−2406 the combination of enhanced particle acceleration efficiency and efficient external radiation fields fosters the production of neutrinos, similarly to TXS 0506+056 and PKS 1424+240, suggested as promising candidate neutrino emitters [21, 22].

We propose a scenario of a mixed lepto-hadronic model, conservatively injecting protons with $L_{\rm p} < L_{\rm Edd}$. The sub-dominant hadronic components in this model account for the observed hard X-ray data. In fact, the leptonic model failed to explain the broken spectral shape observed in the X-ray band. Consequently, we obtained a muon neutrino flux close to the IceCube 7-yr sensibility, with similar properties than for a source like TXS 0506+056. Our model predicts a number of neutrino events, with $N_{\rm events} = 4.82^{+5.18}_{-3.82}$ over a 7-year period, assuming a constant neutrino flux. The Poisson's $p$-value of 3% indicates a small tension with the null hypothesis of zero detection, going in the same direction as the findings visible in [7, 8].

To summarize, 5BZB J0630−2406 is a high-power, radiatively efficient blazar. This is suggested by our modeling, and we show that the neutrino flux produced is within the reach of the IceCube experiment. Moreover, other objects in the PeVatron blazar sample display similar characteristics, i.e. TXS 0506+056, PKS 1424+240 and 5BZB J0035+1515. At the current status it remains unclear whether this peculiar, relatively rare characteristic describes the persistent behavior of their engine and/or linked to different environment properties, or may be tracing temporary physical changes, such as changes in the state of the accretion mode, as suggested for "changing-look blazars" [24], or changes in the location of the dissipation region [13]. Future investigation of the PeVatron blazar sample will enable us with a broader understanding of the neutrino/blazar physical relation.

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## References

[1] Astropy Collaboration et al. 2013, A&A, 558, A3

[2] Aartsen, M. G., Abraham, K., Ackermann, M., et al. 2017, ApJ, 835, 45

[3] Aartsen, M., Ackermann, M., et al. 2018, Science, 361, 147

[4] Ackermann, M., Ajello, M., An, H., et al. 2016, ApJ, 820, 72

[5] Robitaille, T. P., Tollerud, E. J., et al. 2013, A&A, 558, A33

[6] Bonning, E., Urry, C. M., Bailyn, C., et al. 2012, ApJ, 756, 1

[7] Buson, S., Tramacere, A., Pfeiffer, L., et al. 2022, ApJL, 933, L43

[8] Buson, S., Tramacere, A., Pfeiffer, L., et al. 2022, ApJL, 934, L38

[9] Buson, S., Tramacere, A., Oswald, L., et al. 2023, arXiv preprint

[10] Gao, S., Pohl, M., & Winter, W. 2017, ApJ, 843, 109

[11] Ghisellini, G., Tavecchio, F., Foschini, L., & Ghirlanda, G. 2011, MNRAS, 414, 2674

[12] Ghisellini, G., Tavecchio, F., Foschini, L., et al. 2012, MNRAS, 425, 1371

[13] Ghisellini, G., Tavecchio, F., et al. 2013, MNRAS, 432, L66

[14] Greiner, J., et al. 2008, Publ. Astron. Soc. Pac., 120, 405

[15] Harrison, F. A., Craig, W. W., Christensen, F. E., et al. 2013, ApJ, 770, 103

[16] Kochanek, C. S., Shappee, B. J., Stanek, K. Z., et al. 2017, PASP, 129, 104502

[17] Li, W., Filippenko, A. V., Chornock, R., & Jha, S. 2003, Publ. Astron. Soc. Pac., 115, 844.

[18] Masci, F. J., Laher, R. R., Rusholme, B., et al. 2018, Publ. Astron. Soc. Pac., 131, 018003

[19] Massaro, E., Maselli, A., Leto, C., et al. 2015, Ap&SS, 357, 75

[20] Padovani, P., Giommi, P., & Rau, A. 2012, Monthly MNRAS, 422, L48.

[21] Padovani, P., Oikonomou, F., Petropoulou, M., et al. 2019, MNRAS, 484, L104

[22] Padovani, P., Giommi, P., Falomo, R., et al. 2022, MNRAS, 510, 2671

[23] Padovani, P., Boccardi, B., Falomo, R., & Giommi, P. 2022, MNRAS, 511, 4697

[24] Peña-Herazo, H. A., Massaro, F., Gu, M., et al. 2021, AJ, 161, 196

[25] Rau, A., Schady, P., Greiner, J., et al. 2012, A&A, 538, A26

[26] Sbarrato, T., Ghisellini, G., Maraschi, L., & Colpi, M. 2012, MNRAS, 421, 1764

[27] Shaw, M. S., Romani, R. W., Cotter, G., et al. 2013, ApJ, 764, 135