Neutrino Emission from Bright Blazar Flares

Robinson and Böttcher (2024)

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Blazars - Background

- Sub class of Active Galactic Nuclei (AGNs) with jets oriented directly at the observer (us).
- Relativistic jets lead to relativistic beaming of emitted light, increasing the luminosity and frequency of spectra.
- Emission is variable, across multiple wavebands.

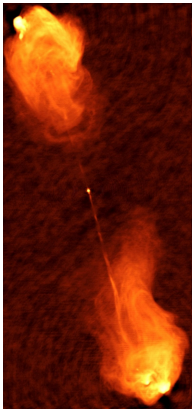

Figure: Radio image of a radio galaxy (NRAO)

Blazars - Background

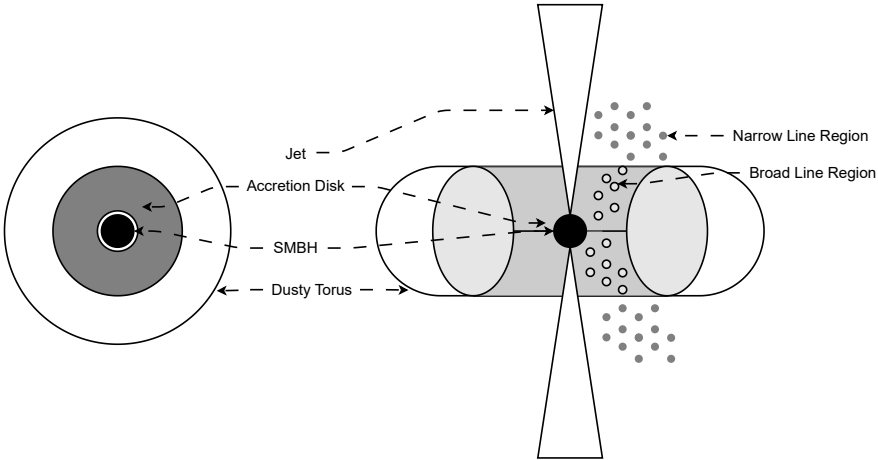

Figure: Simplified schematic of a blazar

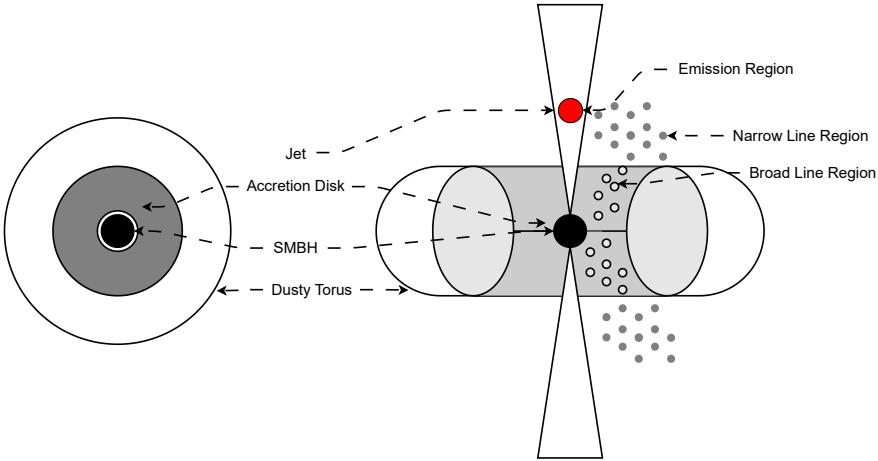

Figure: Simplified schematic of a blazar one-zone model

The multiwavelength spectral energy distributions of blazars exhibit two distinct broad, non-thermal peaks.

Figure: Archival SED of 3C 279 - Sourced from the NASA/IPAC Extragalactic Database

Blazars - Modeling

While the lower-energy peak is well described by the synchrotron emission from a population of relativistic electrons, the exact origin of the higher energy peak is still an open question. There are a few competing mechanisms:

- SSC - The synchrotron radiation from the electron population is Compton scattered by the electrons themselves
- EIC - The electron population Compton scatters some external radiation field
- Proton Synchrotron - Assumes a population of relativistic protons within the jet, which emit powerful enough synchrotron radiation to produce the higher energy peak.

The degeneracy between these models is very difficult to break from spectral features alone.

While the lower-energy peak is well described by the synchrotron emission from a population of relativistic electrons, the exact origin of the higher energy peak is still an open question.

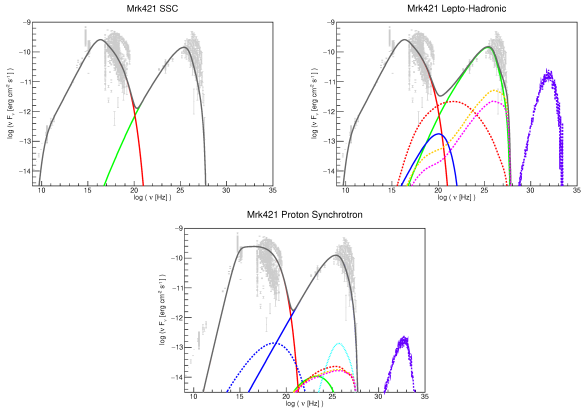

Figure: Blazar parameter space degeneracy (Figure from Cerruti (2020))

If relativistic protons are present in the jet, neutrinos may provide a helpful way to detect their presence. Photo-hadronic interactions provide a channel for neutrino production:

$$p + \gamma \rightarrow \begin{cases} p' + \pi^0 \\ n + \pi^0 \\ p' + \pi^+ + \pi^- \end{cases}$$

The decay of neutral pions into γ-rays can leave a distinct spectral feature in the blazar spectrum. The decay of charged pions would, in contrast, lead to neutrinos being emitted from the jet.

Blazars - Flares

Blazars undergo periods of increased activity, known as flares:

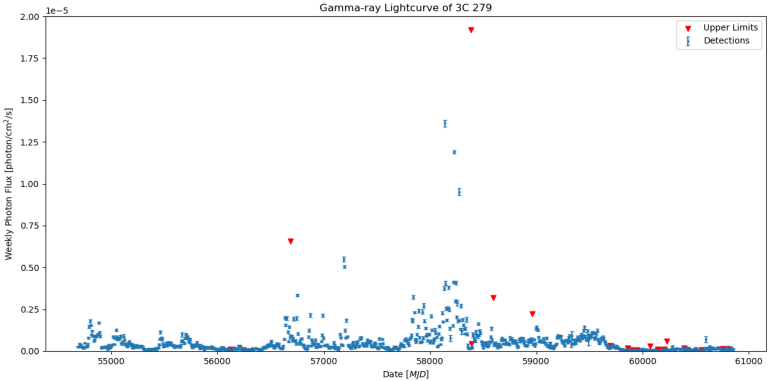

Figure: Photon flux from *3C 279* - Sourced from the Fermi LAT Light Curve Repository

Kreter et al. 2020

In Kreter et al. (2020), a calorimetric approach was used to estimate the expected number of neutrino events from a blazar flare:

$$N_\nu^{\text{predicted}} = 0.025 \cdot A_{\text{Eff}} \cdot \frac{\Phi_\gamma}{E_\nu} \cdot \Delta t$$

$N_\nu^{\text{predicted}}$	- Predicted number of neutrinos
Φ_γ	- Integrated gamma-ray flux (10 keV to 20 GeV)
A_{Eff}	- Effective area of IceCube
E_ν	- Neutrino energy (Mono-energetic, 2 PeV)
Δt	- Duration of flare

This was applied to the 50 brightest (at the time) blazar flares, and showed that short term blazar flares would not produce any substantial detectable neutrino flux.

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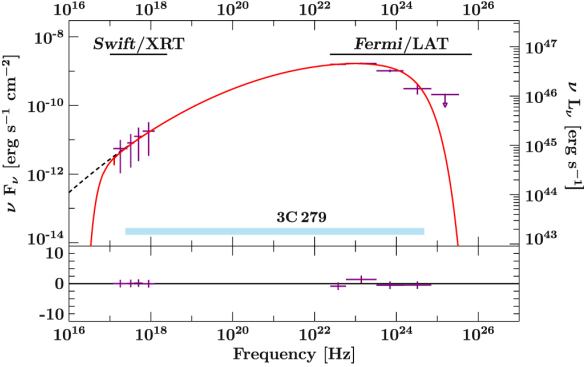


Figure: from Kreter et al. (2020)

This Work

The aim of this work was to check the accuracy of the calorimetric model against a full simulation of a blazar flare.
This was performed using `OneHaLe`, a time-dependent **one**-zone **ha**dro-**le**ptonic blazar code (Diltz and Böttcher, 2016; Zacharias, 2021; Zacharias et al., 2022).
First all sources in their quiescent state were fit. The proton injection parameters were then perturbed to reproduce the observed flare.

`OneHaLe` solves the Fokker-Planck equation in terms of the normalised particle momentum for electrons, protons, charged pions and muons:

$$\frac{\partial n_i(\chi,t)}{\partial t} = \frac{\partial}{\partial \chi}\left(\frac{\chi^2}{(a+2)t_{\rm acc}}\frac{\partial n_i(\chi,t)}{\partial \chi}\right) - \frac{\partial}{\partial \chi}\left(\dot{\chi}\cdot n_i(\chi,t)\right) + Q_i(\chi,t) - \frac{n_i(\chi,t)}{t_{\rm esc}} - \frac{n_i(\chi,t)}{\chi t_{\rm decay}}$$

where $\chi = \frac{p_i}{m_i\, c} = \gamma\beta$.

The injection term includes:

- Primary electrons & protons
- Secondary electrons (Bethe-Heitler pair production, $\gamma - \gamma$ interactions, muon decay)
- Charged pions (following (Hümmer et al., 2010))
- Muons resulting from pion production

`OneHaLe` solves the Fokker-Planck equation in terms of the normalised particle momentum for electrons, protons, charged pions and muons:

$$\frac{\partial n_i(\chi,t)}{\partial t} = \frac{\partial}{\partial \chi}\left(\frac{\chi^2}{(a+2)t_{\rm acc}}\frac{\partial n_i(\chi,t)}{\partial \chi}\right) - \frac{\partial}{\partial \chi}\left(\dot{\chi}\cdot n_i(\chi,t)\right) + Q_i(\chi,t) - \frac{n_i(\chi,t)}{t_{\rm esc}} - \frac{n_i(\chi,t)}{\chi t_{\rm decay}}$$

where $\chi = \frac{p_i}{m_i\, c} = \gamma\beta$.

The following emission is accounted for:

- Synchrotron emission from all charged particles
- Inverse Compton for electrons (on all radiation fields present)
- $\pi^0 \rightarrow \gamma + \gamma$

Absorption:

- BLR and DT photon fields
- Bethe-Heitler and $\gamma - \gamma$ interactions
- Synchrotron self-absorption

`OneHaLe` solves the Fokker-Planck equation in terms of the normalised particle momentum for electrons, protons, charged pions and muons:

$$\frac{\partial n_i(\chi,t)}{\partial t} = \frac{\partial}{\partial \chi}\left(\frac{\chi^2}{(a+2)t_{\text{acc}}}\frac{\partial n_i(\chi,t)}{\partial \chi}\right) - \frac{\partial}{\partial \chi}\left(\dot{\chi}\cdot n_i(\chi,t)\right) + Q_i(\chi,t) - \frac{n_i(\chi,t)}{t_{\text{esc}}} - \frac{n_i(\chi,t)}{\chi t_{\text{decay}}}$$

where $\chi = \frac{p_i}{m_i\, c} = \gamma\beta$.

Also present:

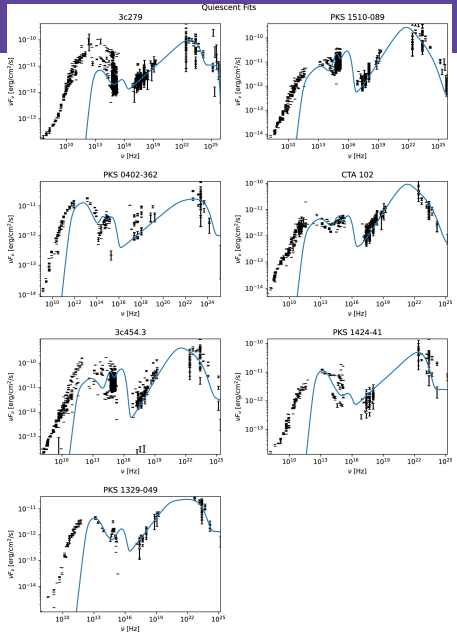
- Adiabatic cooling
- Particle and photon escape
- Particle re-acceleration ('Primary' particle power-laws are treated in the injection term)

Quiescent States

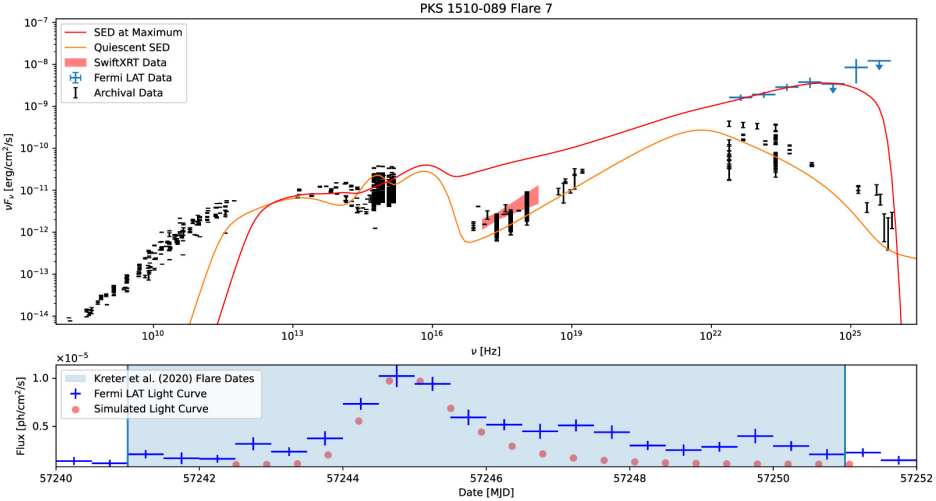
For each blazar a parameter set was found to fit their quiescent state, using archival data from the `SSDC SED builder`[a].
To minimise the amount of free parameters, wherever possible values available in literature were used.
Additionally some other free variables were eliminated:

- The temperatures of the broad-line region (BLR) and dusty torus (DT) were kept constant at 10^5 K and 2000 K, respectively
- $L_{BLR} = L_{DT} = \frac{1}{10} L_{AD}$
- $R_{DT} = 10^{17} \sqrt{L_{AD,45}}^{a}$ cm
- $R_{BLR} = 2.5 \times 10^{18} \sqrt{L_{AD,45}}$ cm

[a] https://tools.ssdc.asi.it/SED/
[a] $L_{AD,45} = \frac{1}{10^{45}} L_{AD}$



The Quiescent state for each blazar was then perturbed in order to reproduce the *Fermi*-LAT light curve, as well as the *Fermi*-LAT and *Swift*-XRT SED where available.



Expected Neutrino Counts

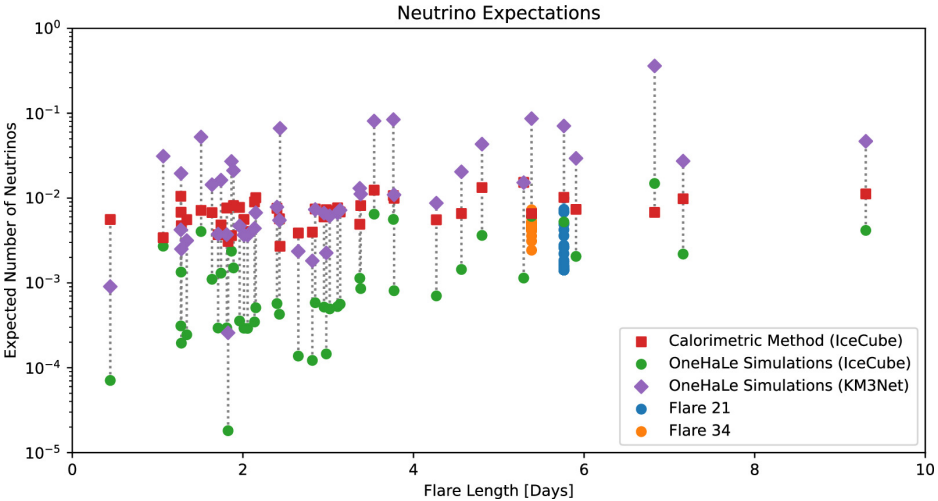


Figure: All flares that were fit

Conclusions

This work has shown that:

- Calorimetric methods of calculating neutrino counts can indeed provide a robust estimation for neutrino excesses during blazar flares.
- The general non-detection of neutrinos from short, bright blazar flares with current neutrino observatories does not necessarily exclude them from being neutrino production sites.
- Next generation neutrino observatories may either lead to much more common blazar neutrino detections or exclude larger parts of the parameter space through non-detection.

Future Work

Using a separate code (Böttcher et al., 2013) and a new semi-analytical method (Karavola and Petropoulou, 2024) we aim to analyse the possible presence of Bethe-Heitler electrons in the jet.
These electrons are produced through proton-photon interactions, not accelerated and are therefore not subject to the same energetic limitations of the "primary" electrons.

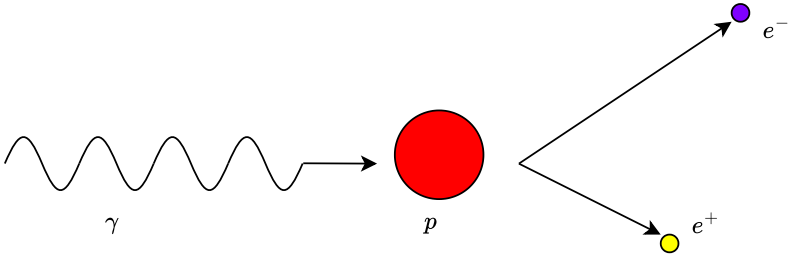


Figure: Bethe-Heitler Pair Production

Future Work

As this is expected to produce a rather subtle effect on the spectrum, a much more in-depth fitting procedure is being implemented using the `Gammapy` (Donath et al., 2023) python library to directly model photon counts for multiple detectors.

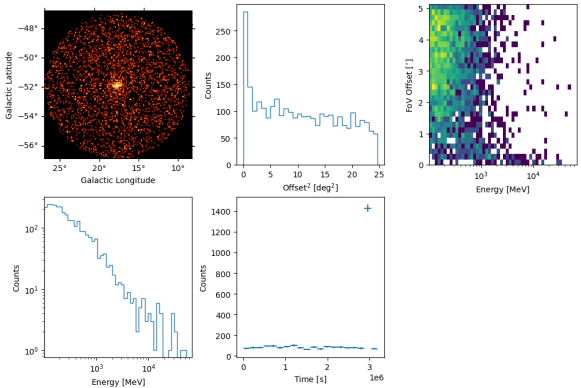


Figure: FermiLAT data within Gammapy

Acknowledgements

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Bibliography I

Böttcher, M., Reimer, A., Sweeney, K., and Prakash, A. (2013). Leptonic and Hadronic Modeling of Fermi-detected Blazars. , 768(1):54.

Cerruti, M. (2020). Leptonic and hadronic radiative processes in supermassive-black-hole jets. *Galaxies 2020, Vol. 8, Page 72*, 8:72.

Diltz, C. and Böttcher, M. (2016). Leptonic and lepto-hadronic modeling of the 2010 november flare from 3c 454.3. *The Astrophysical Journal*, 826:54.

Donath, A., Terrier, R., Remy, Q., Sinha, A., Nigro, C., Pintore, F., Khélifi, B., Olivera-Nieto, L., Ruiz, J. E., Brügge, K., Linhoff, M., Contreras, J. L., Acero, F., Aguasca-Cabot, A., Berge, D., Bhattacharjee, P., Buchner, J., Boisson, C., Carreto Fidalgo, D., Chen, A., de Bony de Lavergne, M., de Miranda Cardoso, J. V., Deil, C., Füßling, M., Funk, S., Giunti, L., Hinton, J., Jouvin, L., King, J., Lefaucheur, J., Lemoine-Goumard, M., Lenain, J.-P., López-Coto, R., Mohrmann, L., Morcuende, D., Panny, S., Regeard, M., Saha, L., Siejkowski, H., Siemiginowska, A., Sip"ocz, B. M., Unbehaun, T., van Eldik, C., Vuillaume, T., and Zanin, R. (2023). Gammapy: A python package for gamma-ray astronomy. *AA*, 678:A157.

Hümmer, S., Rüger, M., Spanier, F., and Winter, W. (2010). Simplified Models for Photohadronic Interactions in Cosmic Accelerators. , 721(1):630–652.

Bibliography II

Karavola, D. and Petropoulou, M. (2024). A closer look at the electromagnetic signatures of Bethe-Heitler pair production process in blazars. , 2024(7):006.

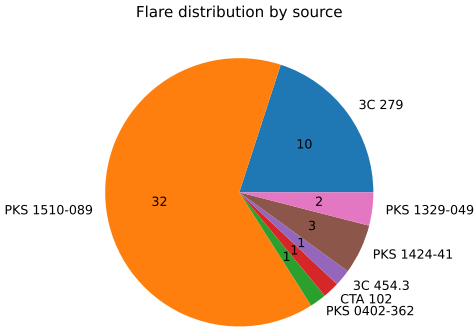
Kreter, M., Kadler, M., Krauß, F., Mannheim, K., Buson, S., Ojha, R., Wilms, J., and Böttcher, M. (2020). On the detection potential of blazar flares for current neutrino telescopes. *The Astrophysical Journal*, 902:133.

Robinson, J. and Böttcher, M. (2024). Neutrino Detection Rates from Lepto-hadronic Model Simulations of Bright Blazar Flares. , 977(1):42.

Zacharias, M. (2021). Studying the influence of external photon fields on blazar spectra using a one-zone hadro-leptonic time-dependent model. *Physics 2021, Vol. 3, Pages 1098-1111*, 3:1098–1111.

Zacharias, M., Reimer, A., Boisson, C., and Zech, A. (2022). Exhale-jet: an extended hadro-leptonic jet model for blazars – i. code description and initial results. *Monthly Notices of the Royal Astronomical Society*, 512:3948–3971.

Flare Distribution



The ROMABZCAT catalogue contains over 3500 blazars. Publishing statistics on 7 sources is questionable, to say the least.