Multi-Instrument, Multi-Messenger Blazar Modelling

An event is an event is an event.

Joshua Robinson, PhD candidate
28804716@mynwu.ac.za

Supervised by Prof. M. Böttcher

Centre for Space Research
North-West University, Potchefstroom, South Africa

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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.

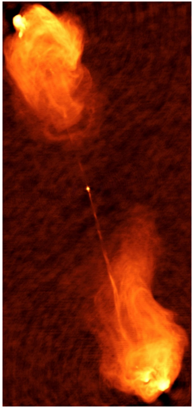

Figure: Radio image of the radio galaxy Cygnus A (NRAO)

Blazars - Spectral Features

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

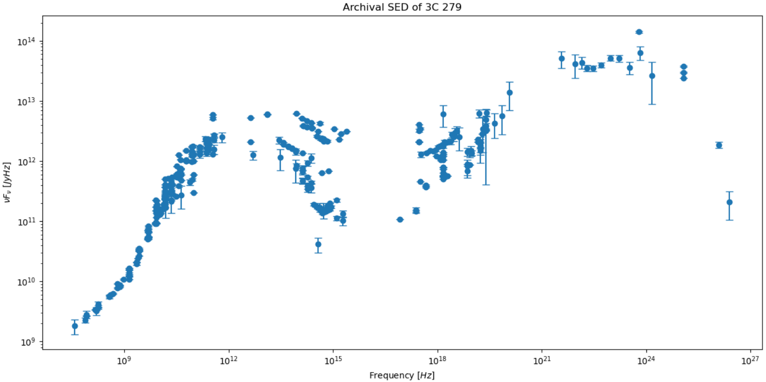

Figure: Archival SED of 3C 279 - Sourced from the NASA/IPAC Extragalactic Database

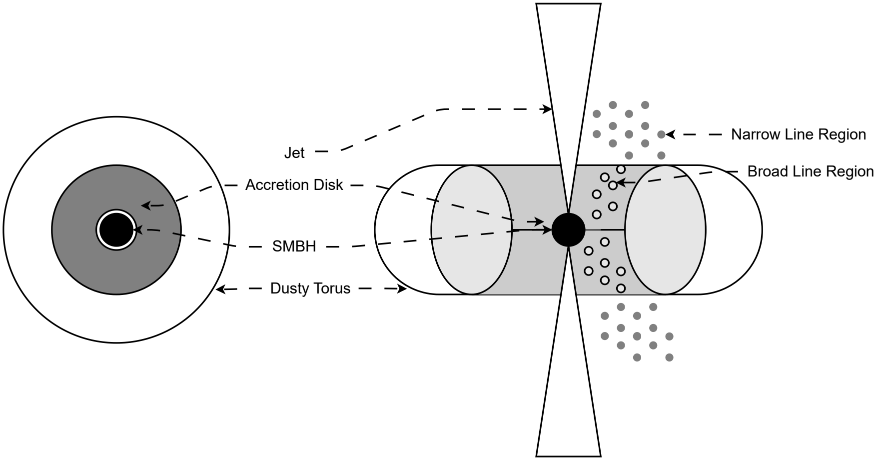

Figure: Simplified schematic of a blazar

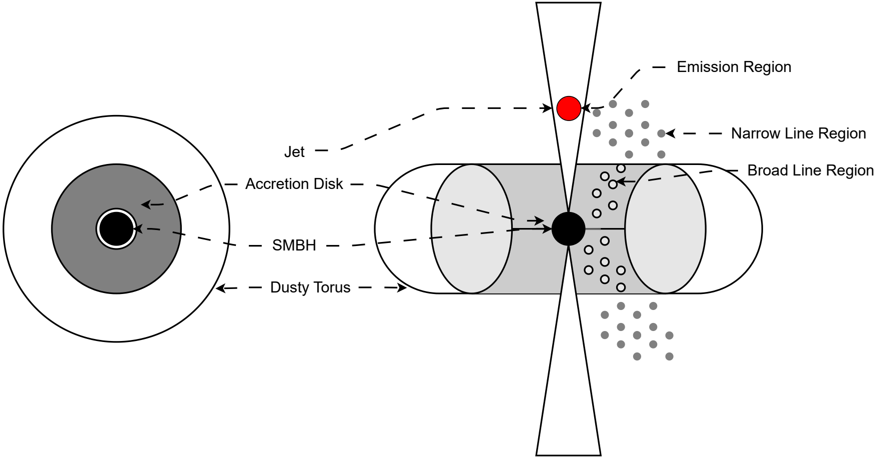

Figure: Simplified schematic of a blazar one-zone model

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.

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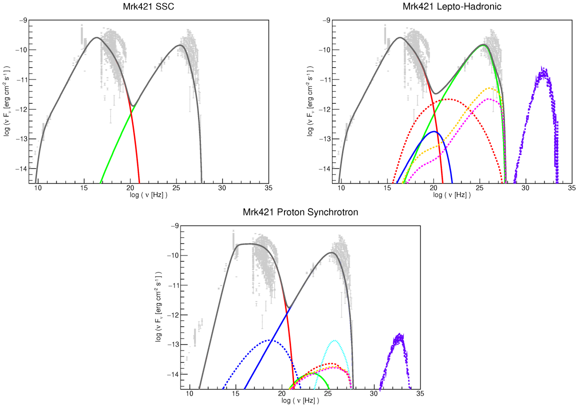


Figure: Blazar parameter space degeneracy (Figure from Cerruti (2020))

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.

B13 Description

The lepto-hadronic code from Böttcher et al. (2013) (B13) is a **one-zone**, stationary model which describes the blazar jet as an isotropic, homogeneous sphere in a **steady state**.

This assumption of **equilibrium** allows for **efficient computation** of blazar spectra.

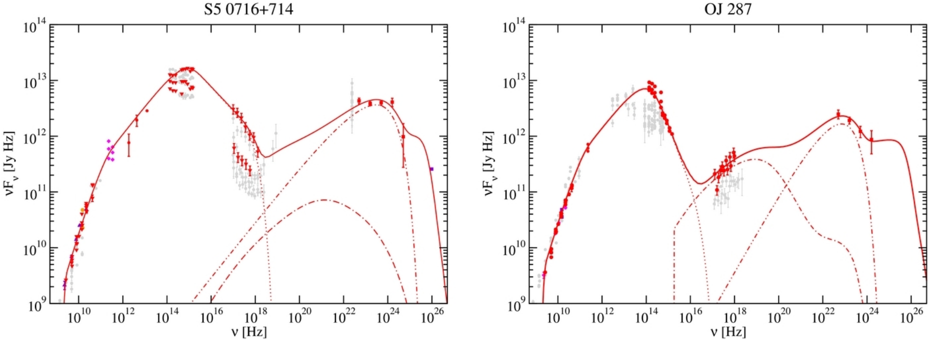


Figure: Example fits using the B13 code. Figure from Böttcher et al. (2013)

B13 Updates

`B13` has received a few upgrades in the past while:

- The implementation of the semi-analytical model of Karavola and Petropoulou (2024) for **Bethe-Heitler pair production**.
- The code has been unbound from file i/o, making **parallelisation** possible without needing multiple copies of the code.
- This allows it to be used as a callable `Gammapy` **spectral function** by using a `ctypes` binding.
- The `Gammapy` function uses a **cache** of the most recent function evaluations to avoid repeated computation in certain routines.

The use of `B13` as a spectral model in `Gammapy` allows for direct use of the **fitting** routines in the library. Shown here is a spectral fit using a **de-absorbed** set of **flux points** from MRK 421, along with the corner plot showing parameter **errors** and **correlations**.

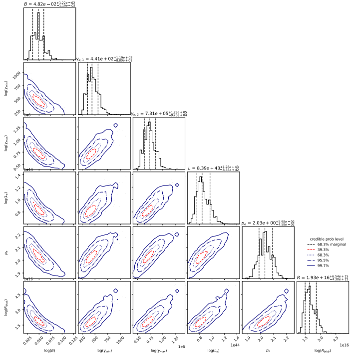


Figure: Corner Plot for De-absorbed MRK421 Data

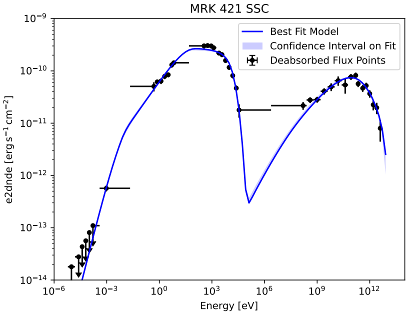


Figure: Spectral Fit of MRK421

Free Parameters	
Magnetic Field	(B)
Blob Radius	(R)
Electron injection	
Luminosity	(L_e)
Minimum γ_e	(γ_1)
Maximum γ_e	(γ_2)
Injection index	(p_e)

Multi-Wavelength Fitting

A common workflow would be to first fit a simple **phenomenological** model to the data (for example an absorbed power law for x-ray data and a log-parabola for γ-ray data). This simple model would be used to calculate **flux points** based on the data set and these flux points would be be used to fit the more expensive **physical** model.

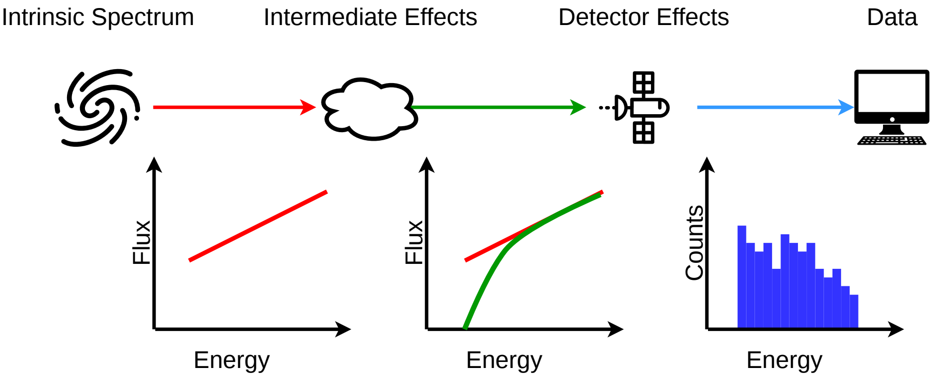


Figure: The production of data from astronomical measurements.

Multi-Wavelength Fitting

The methodology in **Rosillo et al. (2025)** uses the `Gammapy` package to perform **multi-wavelength** data analysis from the optical band all the way to γ-ray energies.

- **X-ray observations**, with a source and a background region, are treated as **On-Off** observation.
- **Optical/UV** observations are treated as being **single-channel** observations, with the response determined by the specific filter used.

This allows for the seamless and modular inclusion of effects such as dust, ISM, and EBL absorption, and **fits** data in **detector space**, rather than unfolded spectrum space.

Multi-Wavelength Fitting

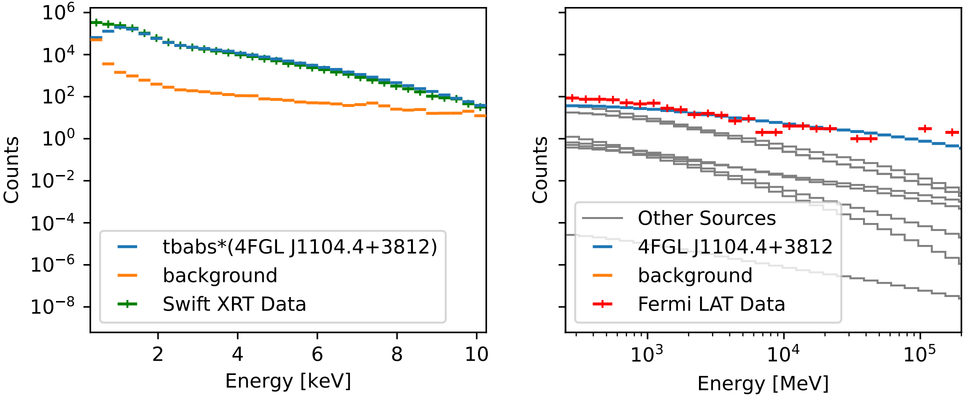


Figure: Forward folded B13 spectrum for Swift XRT and Fermi LAT

Joint KM3NeT-CTAO work

The works Unbehaun (2020) and Unbehaun et al. (2024) showed **multi-messenger** modelling within `Gammapy` to be possible, by establishing the KM3NeT neutrino observatory's various instrument response functions* in a format compatible with the specifications of the *Data formats for gamma-ray astronomy* (GADF)(Nigro et al., 2021).

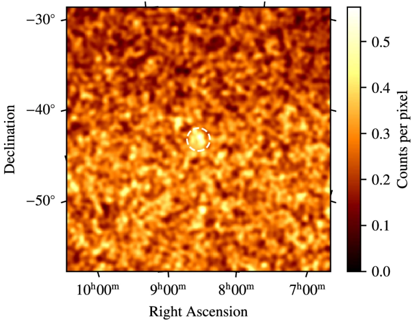


Figure: Simulated KM3NeT counts. Figure from Unbehaun (2020)

*The `km3irf` repository (https://github.com/KM3NeT/km3irf) also contains `Gammapy` compatible IRFs

Included in the IceCube **public data** release in 2021, associated with IceCube Collaboration et al. (2021) and Aartsen et al. (2020), are files containing neutrino event information, characterisations of the **effective area** of IceCube, as well as the **energy** and **spatial** resolutions of the detector.

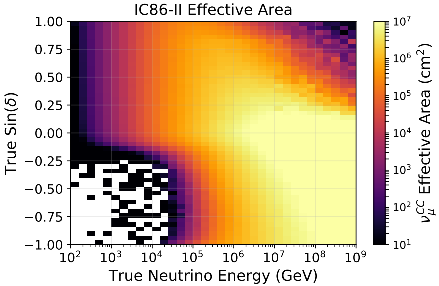


Figure: Effective area for IC86-II configuration. Figure from IceCube Collaboration et al. (2021).

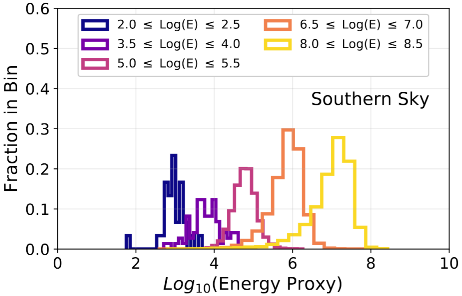


Figure: Energy Smearing of the IceCube detector. Figure from IceCube Collaboration et al. (2021).

Transforming the coordinates of the data release (RA,DEC) to pointing coordinates involves setting the **pointing** direction to the celestial **south pole**, with the FOV offset then equal the DEC$+90^\circ$

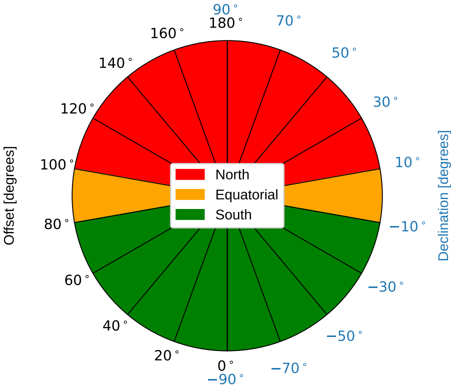
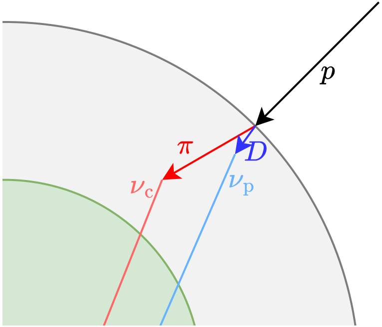


Figure: Current detector coordinate system.

Astrophysical sources are not the only origin of neutrinos present in the detector volumes, and these other neutrinos provide a **background signal** that cannot be suppressed. The main sources are **cosmic ray** interactions with the **atmosphere** with these interactions coming in two categories, conventional and prompt neutrinos. **Conventional** neutrinos are from **long-lived** particles which can interact with the atmosphere, leading to a sharp cutoff at higher energies.**Prompt** neutrinos originate from particles with a much **shorter lifetime** and, while the spectrum is not well measured, they do not drop off as sharply.



Detector Characterisation - Background Models (work-in-progress)

The current implementation relies on fluxes from the `nuflux`[†] library. Because of a Python version mismatch, the function call is not direct, but rather an **interpolation** from **pre-computed** tables.

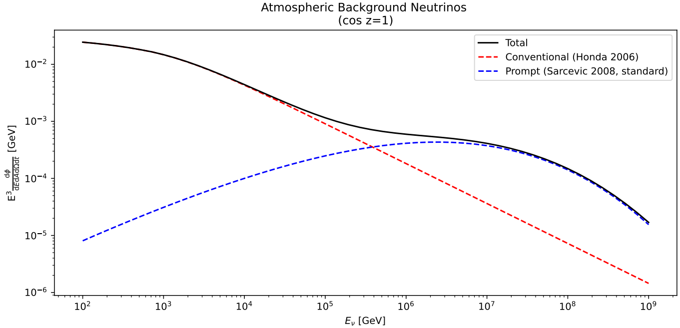


Figure: Atmospheric neutrino fluxes from `nuflux`.

[†] https://github.com/icecube/nuflux

One method used when background models are not available (or not yet implemented) is on-off analysis. The basic idea is that you have a region containing both the **source and background** signal, and a separate region that **only** contains **background** flux. In theory, the **difference** between these two can be attributed to the **source**.

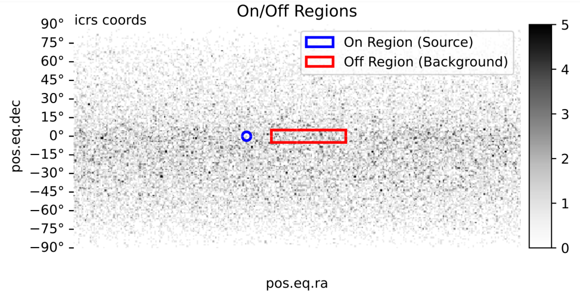


Figure: Total counts, with ON and OFF regions outlined.

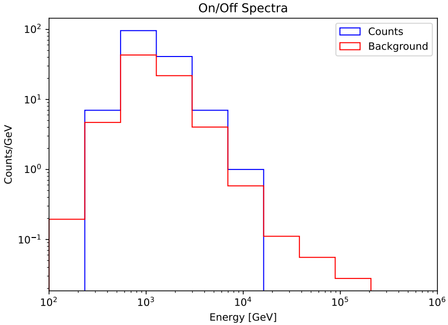


Figure: Respective spectra of the On and OFF region.

The data release include **declination**-dependant bins, but the reality is that the detector response is dependent on **zenith**. This introduces a **minor error** as the “upwards“ direction from IceCube’s location precesses on the sky throughout the year. This is simply a limitation of the publicly available response files, but is expected to average out over long-term analyses (per the data release).

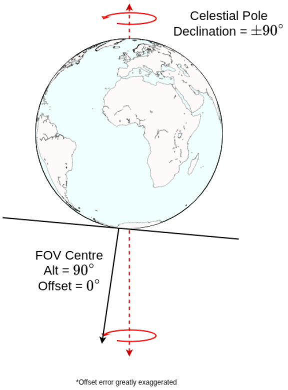


Figure: Geometry of the offset between Alt$=90^\circ$ at IceCube and the celestial South-Pole.

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The **atmospheric background** models also suffer from this **inaccuracy**. Due to the relatively **weak zenith dependence** of the atmospheric neutrino models and the very **small angular change**, it is assumed to be accurate enough for this work

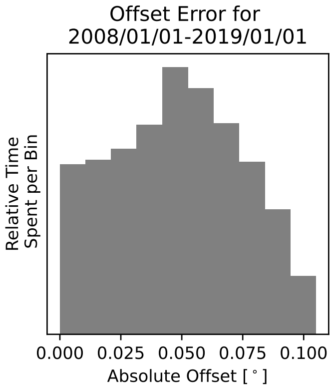

Figure: Alt=90° at IceCube compared to the celestial South Pole

IceCube Public Data - Summary

The Good:

- The `B13` code is now parallelised and optimised to allow for parameter estimation through minimisation algorithms.
- The use of the multi-wavelength workflow from Rosillo et al. (2025) allows for unprecedented fidelity for fits using the code.
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The Ugly:

- Coarse binning limits the usefulness of the IceCube parameterization.

Acknowledgements

Thank you for your time!

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