

Multi-Domain Blazar Modelling with B13

An event is an event is an event.

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High Energy Astrophysics in Southern Africa
September/October 2026



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- 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.

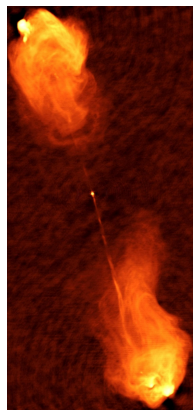


Figure: Radio image of the radio galaxy Cygnus A (NRAO)

Blazars - Spectral Features

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

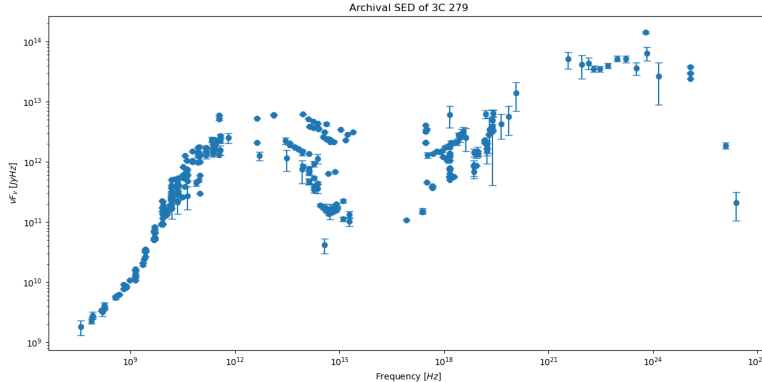


Figure: Archival SED of 3C 279 - Sourced from the NASA/IPAC Extragalactic Database

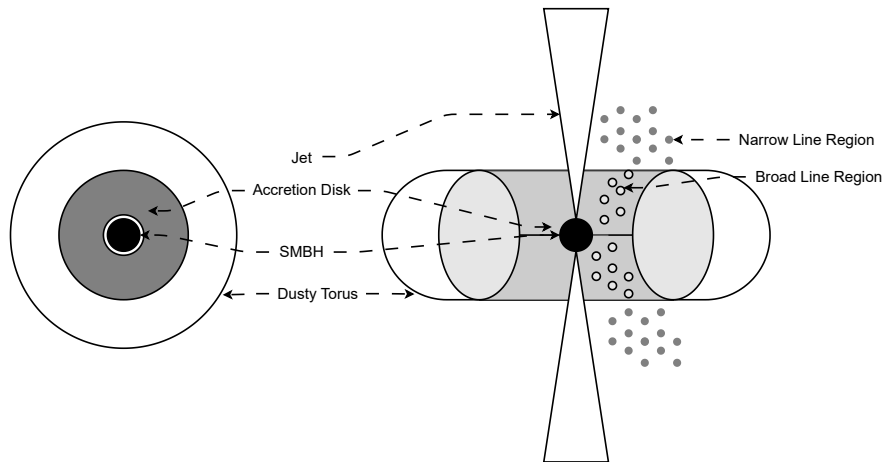


Figure: Simplified schematic of a blazar

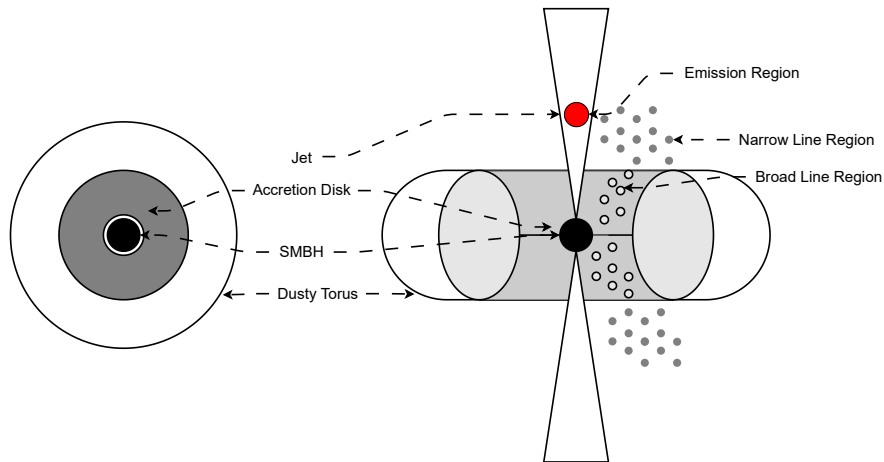


Figure: Simplified schematic of a blazar one-zone model

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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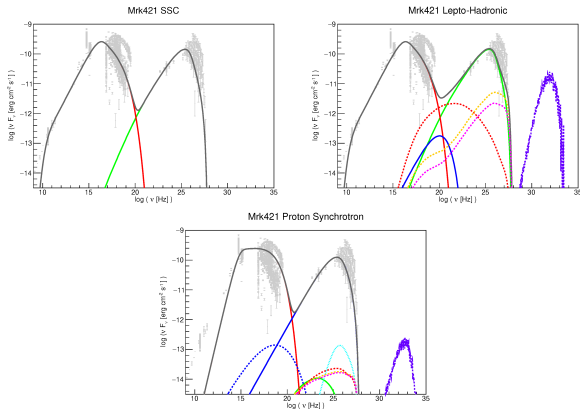


Figure: Blazar parameter space degeneracy (Figure from Cerruti (2020))

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.

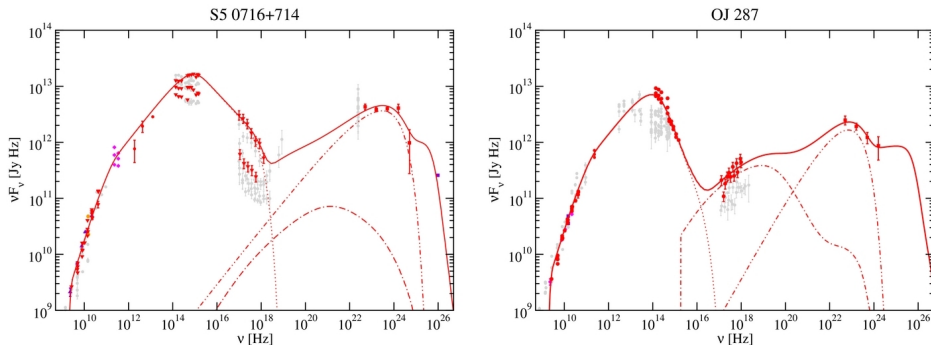


Figure: Example fits using the B13 code. Figure from Böttcher et al. (2013)

B13 has received a few upgrades in the recently:

- 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.

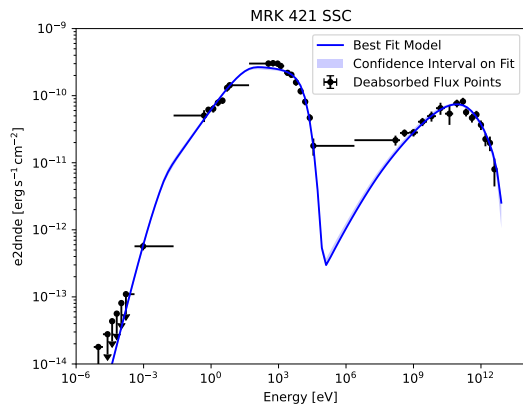


Figure: Spectral Fit of MRK421

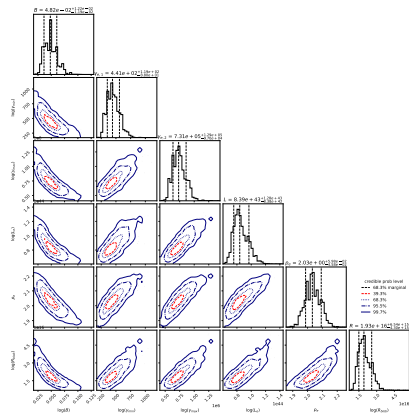


Figure: Corner Plot for De-absorbed MRK421 Data

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 used to fit the more expensive **physical** model.

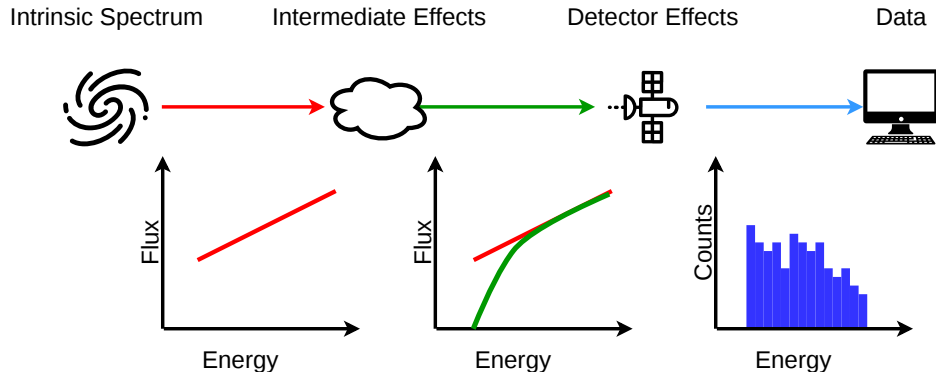


Figure: The production of data from astronomical measurements.

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

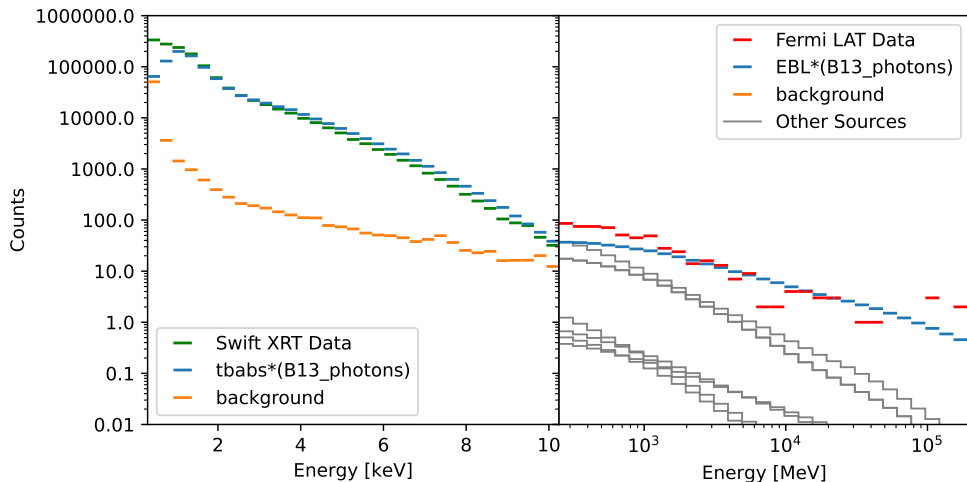


Figure: Forward folded B13 spectrum for Swift XRT and Fermi LAT

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).

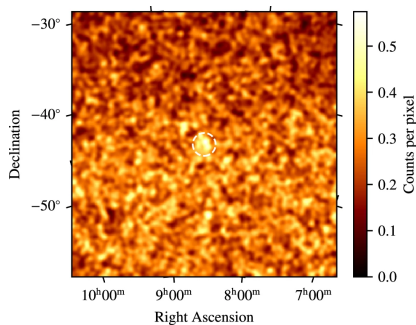


Figure: Simulated KM3NeT counts. Figure from Unbehaun (2020)

*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.

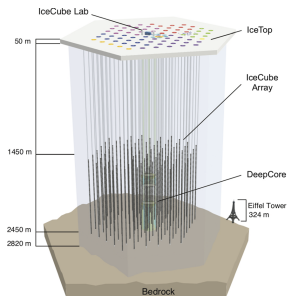


Figure: Diagram of the IceCube Detector. Adapted from Ahlers et al. (2018)

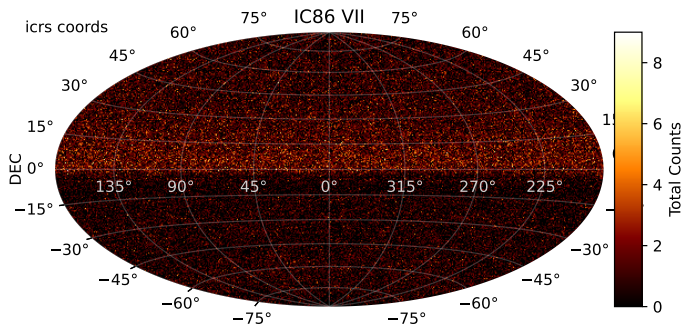


Figure: Total Counts for the IC86 IV (2017/2018) season. $1^\circ \times 1^\circ$ binning.

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 $\text{DEC}+90^\circ$

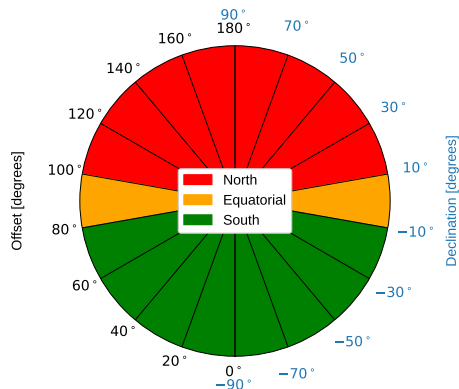


Figure: Current detector coordinate system.

The effective area of the detector is dependant on the incident angle of the neutrino as well as the effectiveness of detection at that energy.

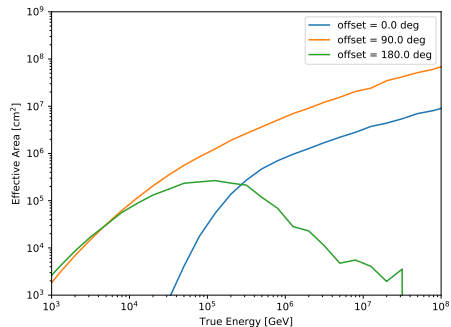


Figure: Energy dependent effective area of the IceCube 86 II configuration

The **reconstruction** of the energy of incoming neutrinos is not a perfect process, and involves a **statistical determination** of the most likely energy of an event.

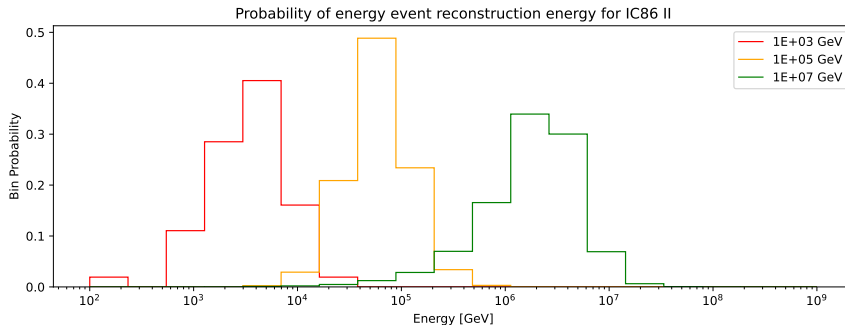
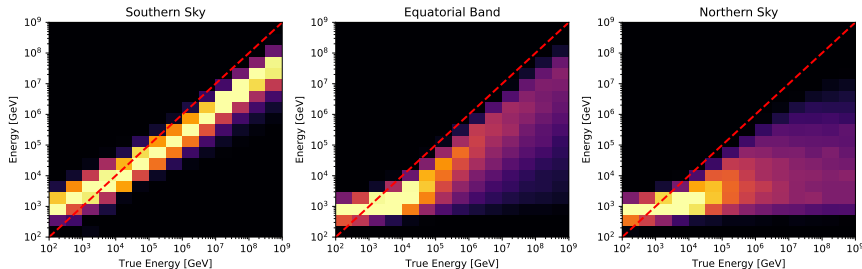


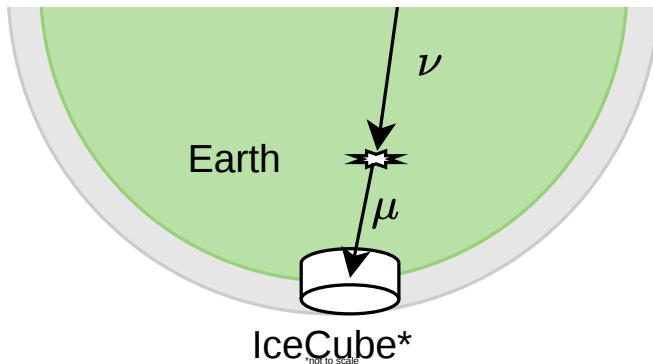
Figure: Energy reconstruction probabilities of various neutrino energies IceCube 86 II configuration.

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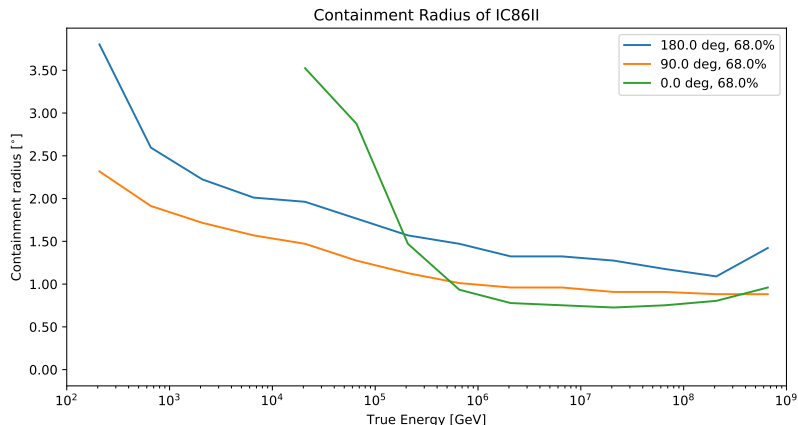


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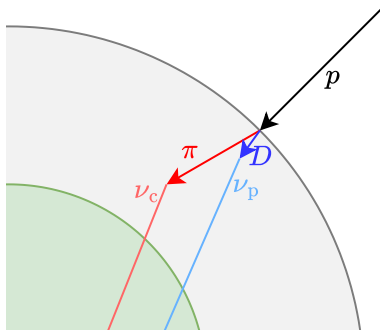
- Energy reconstruction in the Northern hemisphere suffers from possible interactions outside the detector volume.



The **reconstruction** of the **direction** of the muons is **imperfect** and needs to be taken into account. The point spread function characterises the detectors response to a hypothetical point-source by parameterizing the spatial spread of the resulting events.



- Atmospheric neutrino are also present in detector volumes!
- **Conventional**: Long-lived particles $\rightarrow$ time for interactions $\rightarrow$ **sharp** cutoff
- **Prompt**: Short-lived particles $\rightarrow$ no time for interactions $\rightarrow$ **gradual** cutoff



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.

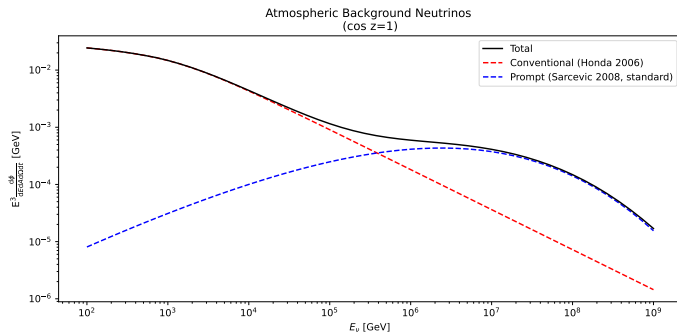


Figure: Atmospheric neutrino fluxes from `nuflux`.

[†]<https://github.com/icecube/nuflux>

On/Off Analysis

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**.

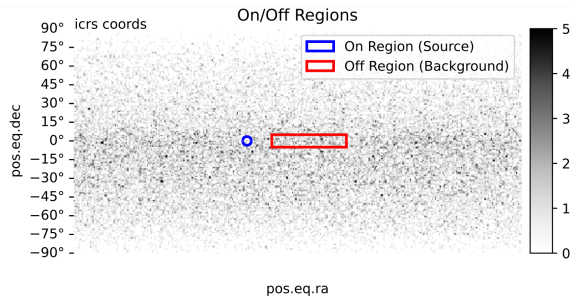


Figure: Total counts, with ON and OFF regions outlined.

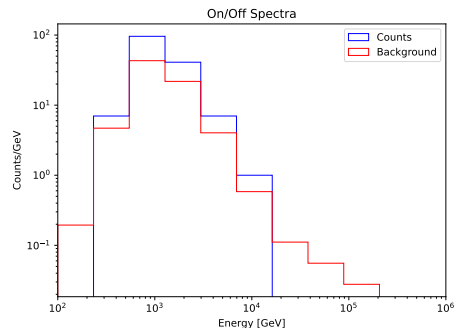


Figure: Respective spectra of the On and OFF region.

- Data Release: **Declination**-dependant bins
- Reality : **Zenith**-dependant bins
- Geographic location makes this difference negligible

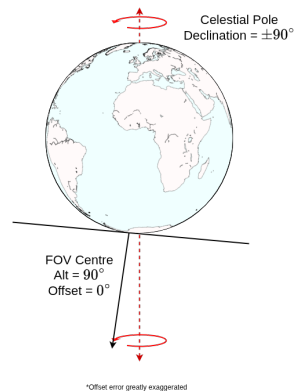


Figure: Geometry of the offset between $\text{Alt}=90^\circ$ at IceCube and the celestial South-Pole.

- Data Release: **Declination**-dependant bins
- Reality : **Zenith**-dependant bins
- Geographic location makes this difference negligible
- Atmospheric background is also zenith dependant.
- Relatively weak zenith dependence makes this error acceptable

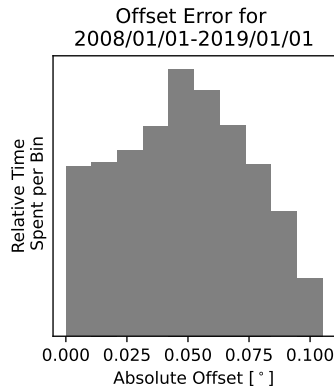


Figure: Alt=90° at IceCube
compared to the celestial South Pole

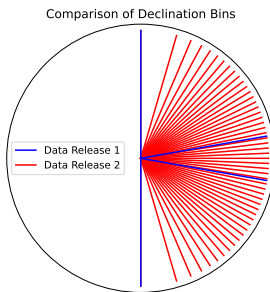
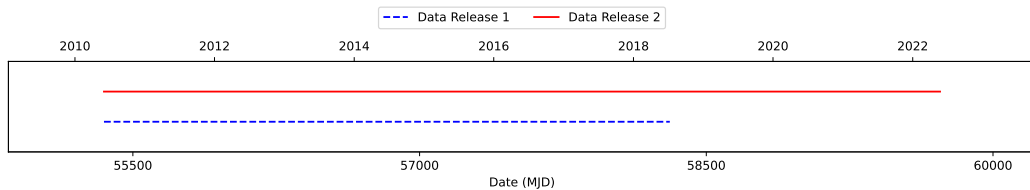
Summary of work done:

- 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.
- Publicly available IceCube data can be used within `Gammapy` to perform consistent fits within a multi-messenger framework.

In progress:

- Using and benchmarking fitting: competing datasets appear to have overpowering statistics.
- A new dataset has been released by IceCube containing:
 - More seasons
 - Much finer spatial binning.

Second IceCube Data Release



Thank you for your time!

This work was supported by the Department of Science and Innovation (DSI) and the National Research Foundation (NRF) of South Africa through the South African Gamma-Ray Astronomy Programme (SA-GAMMA). Opinions expressed and conclusions arrived at, are those of the author and are not necessarily to be attributed to the DSI, NRF or SA-GAMMA.

- Aartsen, M. G., Ackermann, M., Adams, J., Aguilar, J. A., Ahlers, M., Ahrens, M., and et al. (2020). Time-integrated neutrino source searches with 10 years of icecube data. *Phys. Rev. Lett.*, 124:051103.
- Ahlers, M., Helbing, K., and Pérez de los Heros, C. (2018). Probing particle physics with icecube. *The European Physical Journal C*, 78(11):924.
- 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.
- IceCube Collaboration, Abbasi, R., Ackermann, M., Adams, J., Aguilar, J. A., Ahlers, M., , and et al. (2021). IceCube Data for Neutrino Point-Source Searches Years 2008-2018. *arXiv e-prints*, page arXiv:2101.09836.
- Karavola, D. and Petropoulou, M. (2024). A closer look at the electromagnetic signatures of Bethe-Heitler pair production process in blazars. , 2024(7):006.
- Nigro, C., Hassan, T., and Olivera-Nieto, L. (2021). Evolution of Data Formats in Very-High-Energy Gamma-Ray Astronomy. *Universe*, 7(10):374.

- Rosillo, M. N., Acero, F., Otero-Santos, J., Acosta, M. V., Terrier, R., Morcuende, D., and Arbet-Engels, A. (2025). Unified multiwavelength data analysis workflow with gammapy - Constraining the broadband emission of the flat-spectrum radio quasar OP 313. *Astronomy & Astrophysics*, 693:A287.
- Unbehaun, T. (2020). *Joint-instrument analyses with Gammapy*. Master's Thesis in Physics, ECAP, Friedrich-Alexander-Universität Erlangen-Nürnberg.
- Unbehaun, T., Mohrmann, L., Funk, S., Aiello, S., Albert, A., , and et al. (2024). Prospects for combined analyses of hadronic emission from γ -ray sources in the Milky Way with CTA and KM3NeT. *The European Physical Journal C*, 84(2):112.

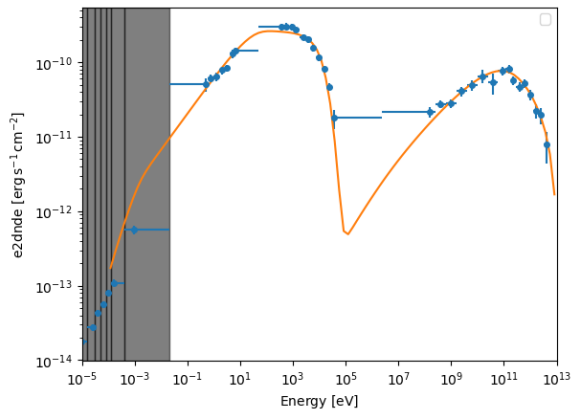


Figure: Flux points fit **without** radio take

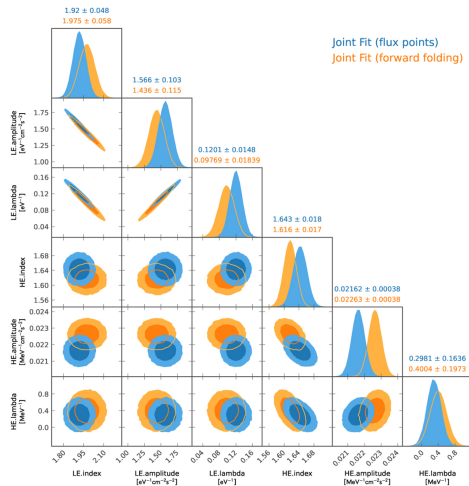


Figure: Biases introduced by flux point fitting. Figure from Rosillo et al. (2025).