

Multi-Messenger, Multi-Instrument Blazar Modelling

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Multi-Messenger and Numerical Techniques in Astrophysics
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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.

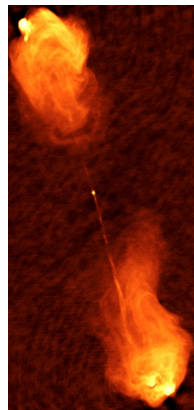


Figure: Radio image of a radio galaxy (NRAO)

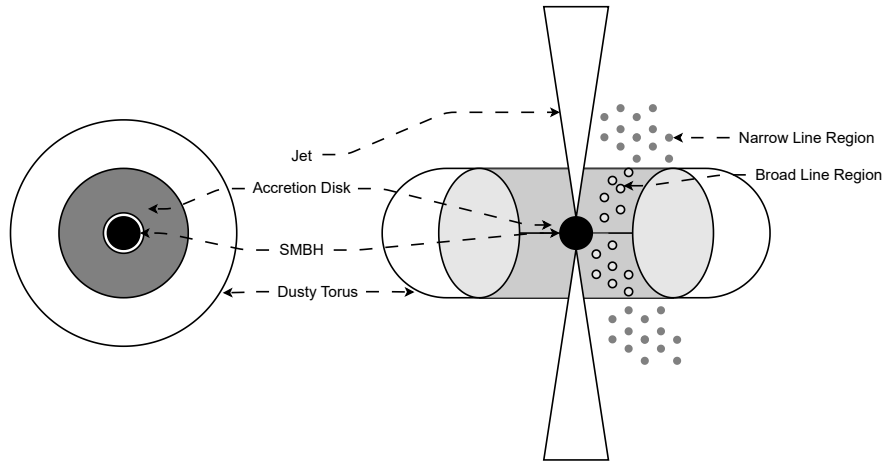


Figure: Simplified schematic of a blazar

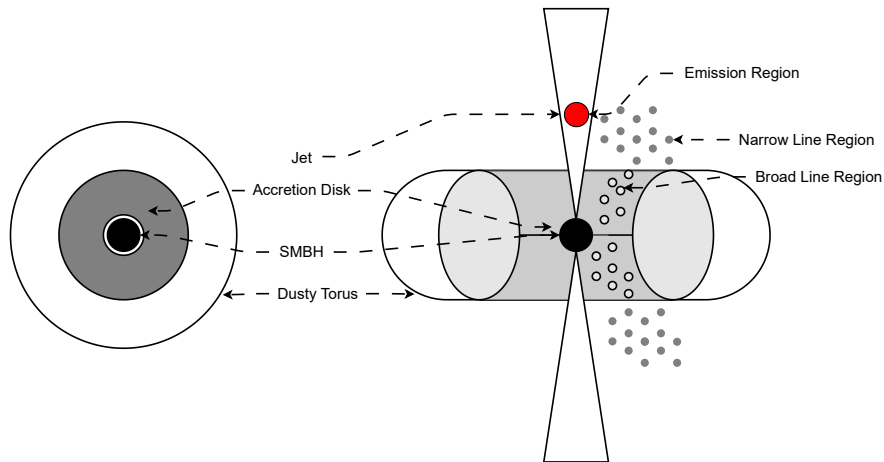


Figure: Simplified schematic of a blazar one-zone model

Blazars - Spectral Features

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

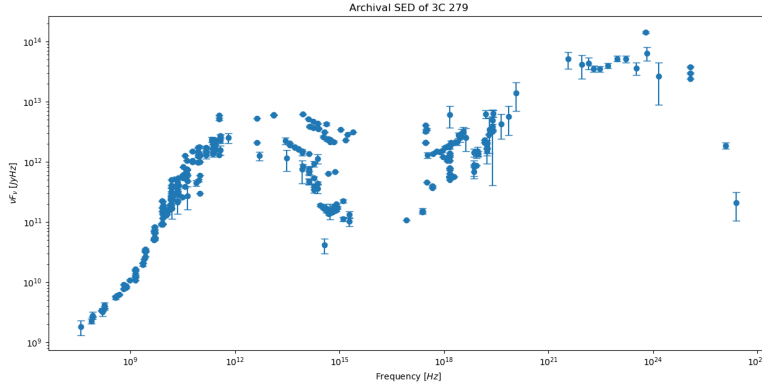


Figure: Archival SED of 3C 279 - Sourced from the NASA/IPAC Extragalactic Database

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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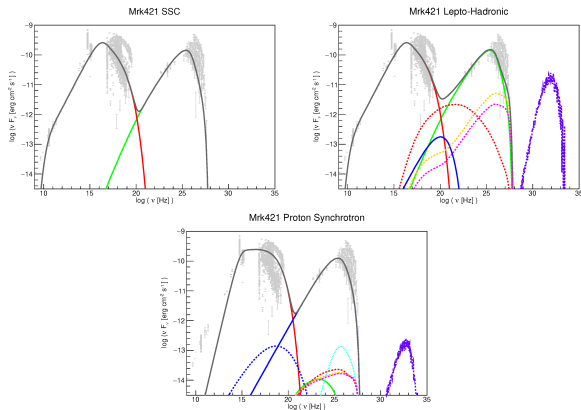


Figure: Blazar parameter space degeneracy (Figure from Cerruti (2020))

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.

Multi-Wavelength Fitting

The methodology in Rosillo et al. (2025) leverages `Gammapy` to perform multi-wavelength data analysis from the optical band all the way to γ -ray energies. This marks a significant step in reducing the biases inherent in other fitting methods, such as flux-point unfolding.

- 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.

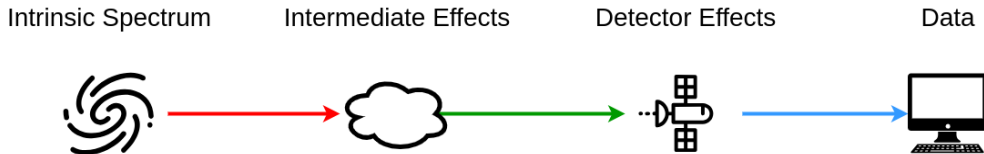
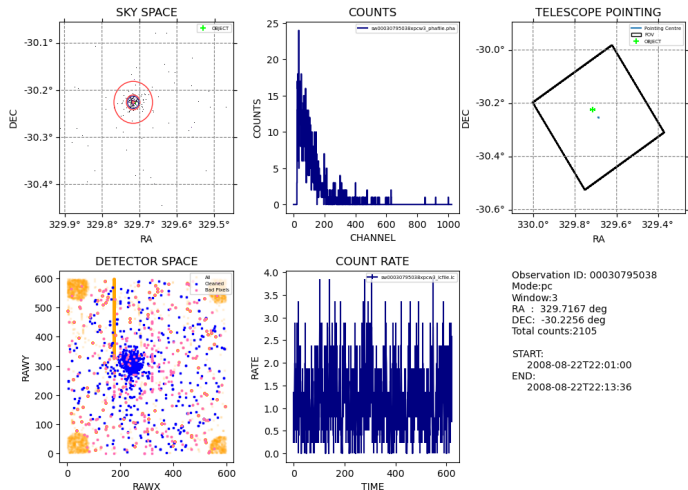


Figure: The production of data from astronomical measurements.

Swift XRT pipeline

To simplify the inclusion of Swift XRT data, a pipeline has been written to take the data products from server level, all the way to Gammapy compatible Datasets.



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.

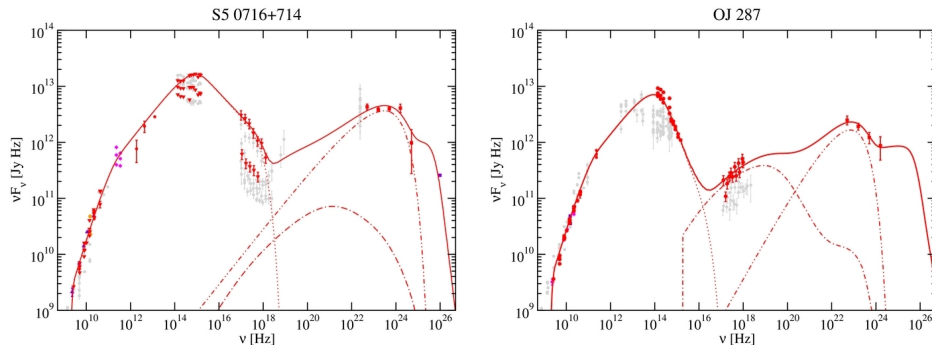


Figure: Example fits using the B13 code. Figure from Böttcher et al. (2013)

B13 has received a few upgrades in the 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 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).

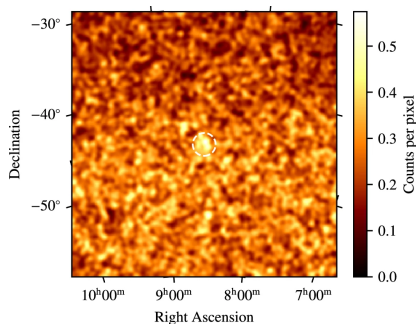


Figure: Simulated counts in the KM3NeT detector. Figure from Unbehaun et al. (2024)

*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.

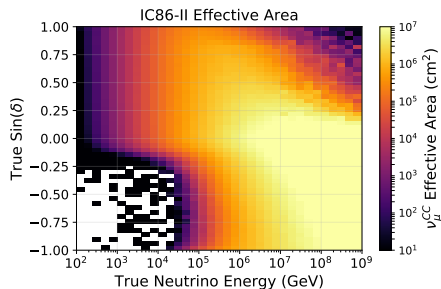


Figure: Effective area for IC86-II configuration

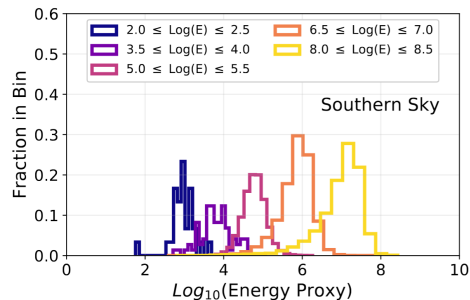


Figure: Energy Smearing of the IceCube detector. Figure from IceCube Collaboration et al. (2021).

Transforming these responses to a format useable by `Gammapy` may provide a **rudimentary** way to constrain parameter spaces, when combined with the count data from the same time period and detector configuration.

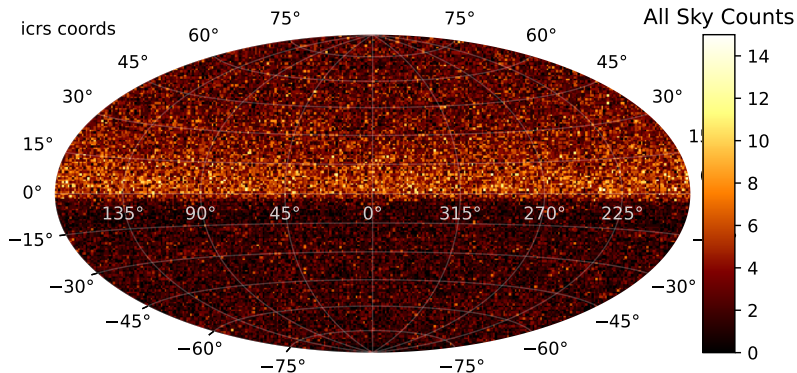


Figure: Counts from the 2012-2013 configuration (IC86-II)

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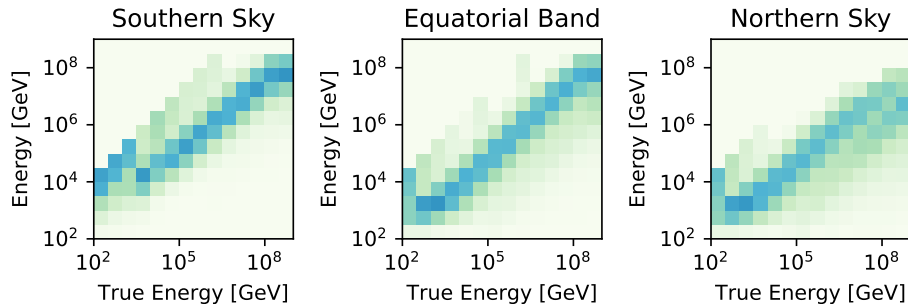


Figure: Energy dispersion matrices of the 2012-2013 configuration (IC86-II)

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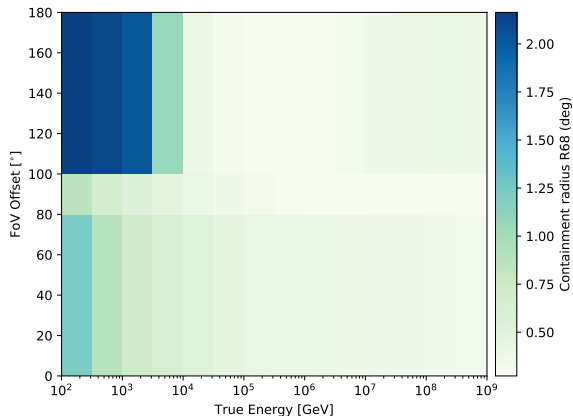


Figure: Point-spread function of the 2012-2013 configuration (IC86-II)

The data release include declination-dependant bins, but constant ICRS coordinates are needed in `Gammapy`. This introduces an error as the “upwards” direction from IceCube’s location precesses throughout the year.

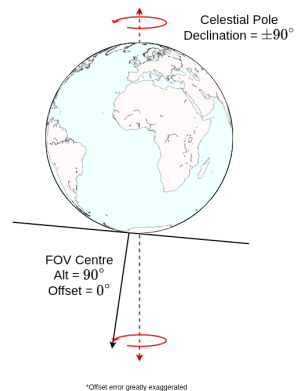


Figure: Geometry of the offset between Alt= 90° at IceCube and the celestial South-Pole.

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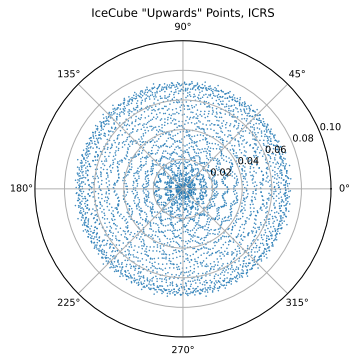


Figure: Alt=90° at IceCube compared to the celestial South Pole, for every hour within one year.

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This error is very small, but one possible way to avoid it, if the region is small enough, is to follow the treatment from Unbehaun (2020) and Unbehaun et al. (2024) and separate each observation into multiple ones which all share common bins, and analyse those time intervals separately.

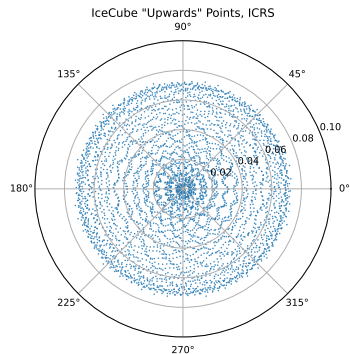


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The Ugly:

- Unfortunately, there are no physical results at this stage.
- The code to produce the Datasets is not (yet!) in a public repository, along with the Datasets themselves.

Thank you for your time!

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