Investigating the blazar-neutrino connection with public IceCube data

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IceCube public data releases

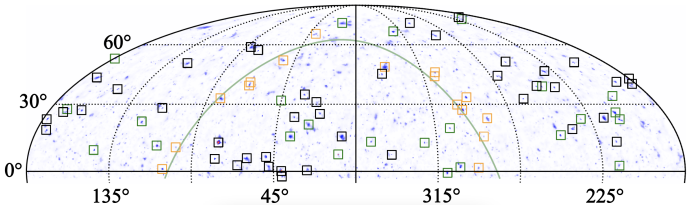

Figure 1: IceCube *p*-value map (R. Abbasi et al. 2022), adapted from Buson et al. (2023).

Data

- 6 year muon tracks (IC86_II)[a]
- instrument response function (IRF) provided
- reconstructed energies, directions, angular uncertainties and time stamps of muons

[a] IceCube Collaboration. 2021. eprint: 2101.09836.

Bayesian hierarchical modeling

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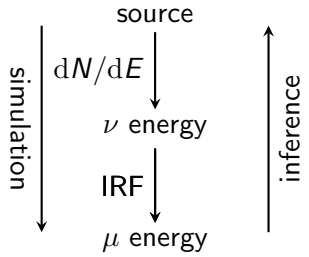
Differences to Frequentist

- parameters as random variables
- no explicit trial correction needed
- results not relative to null hypothesis

Hierarchical model[a]



[a] Francesca Capel et al. 2023. eprint: PoS(ICRC2023)1576.

Validation — Recover point source parameters

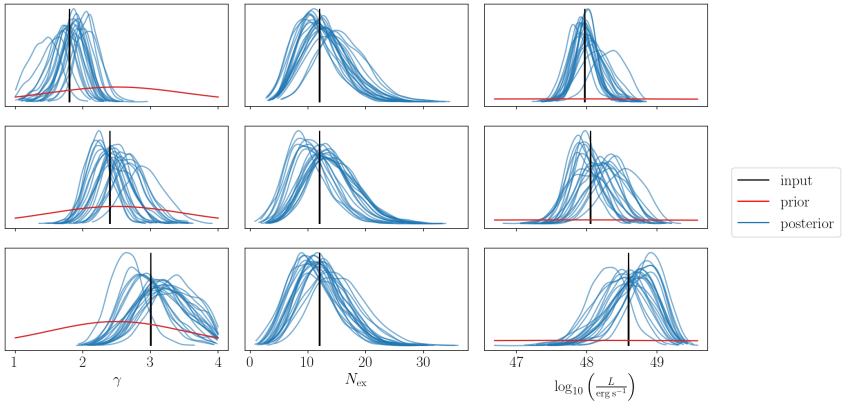


Figure 2: Fits to simulated data of background and point source at 5° declination.

Why blazars?

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- IC170922 associated with TXS0506+056[b]
- TXS "archival" flare[c]
- theoretical models[d]
- evidence for intermediate-high-energy-peaked blazars as ν emitters[e]
- source list[f] subset of Roma-BZCAT[g]

[b] Mark Aartsen et al. 2018. eprint: 1807.08816.
[c] Mark Aartsen et al. 2018. eprint: 1807.08794.
[d] eg Karl Mannheim. 1995. eprint: 10.1016/0927-6505(94)00044-4.
[e] Paolo Giommi and Paolo Padovani. 2021. eprint: 2112.06232.
[f] Sara Buson et al. 2023. eprint: 2305.11263.
[g] E. Massaro et al. 2015. eprint: 1502.07755.

Frequentist

- maximum likelihood method[a]
- similar to SkyLLH[b]

Bayesian

- prior $\Longleftrightarrow$ question to the data
- model complexity

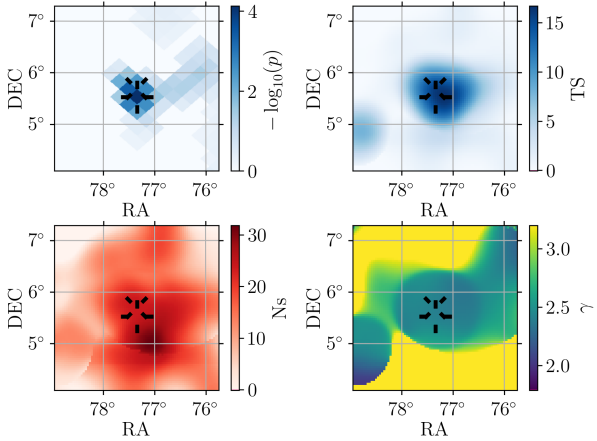


Figure 3: Frequentist analysis of TXS0506+056. x: hotspot position, +: source location.

[a] Jim Braun et al. 2008. eprint: 0801.1604.

[b] Chiara Bellenghi et al. 2023. eprint: 2308.12742.

TXS0506+056 - high level parameters

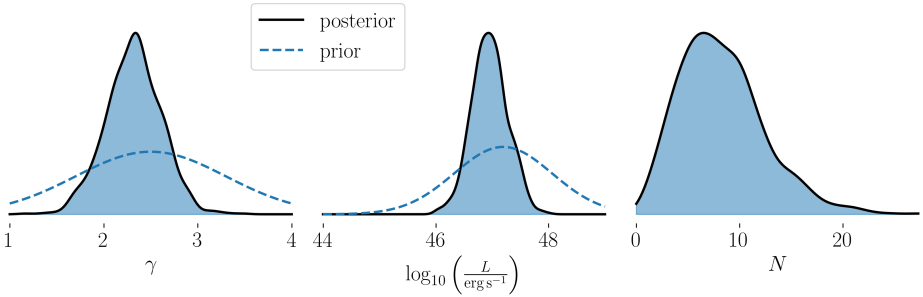


Figure 4: Bayesian analysis of 2014/2015 flare (MJD $\in [56917, 57113]$[h]).

[h] IceCube Collaboration. 2021. eprint: 2101.09836.

TXS0506+056 - event association

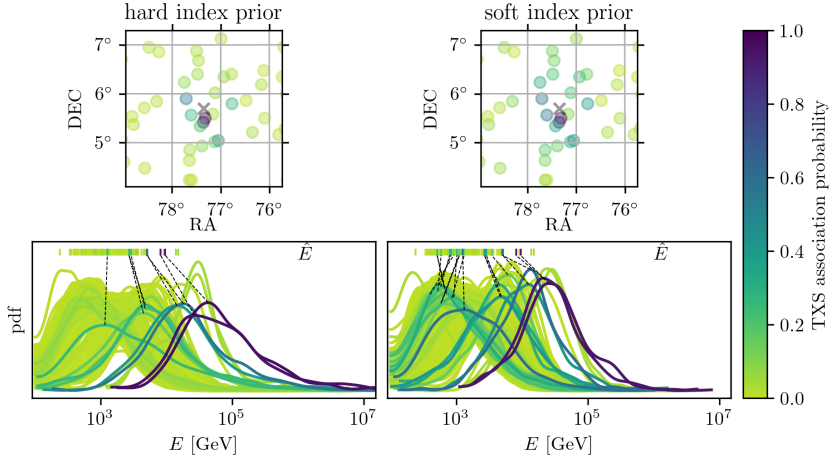
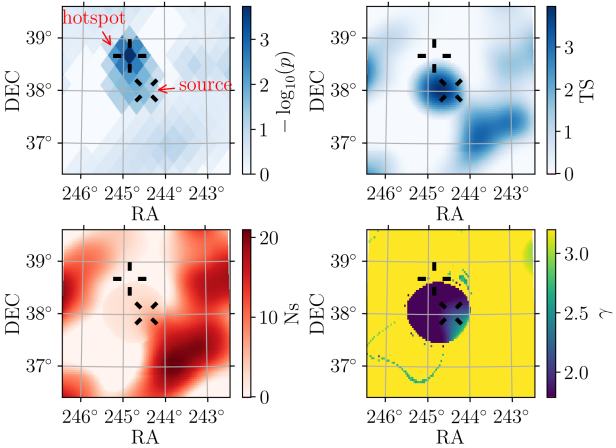


Figure 5: Event association and energy posteriors of flare.

Position dependency



- association radius[a] 1.25° $\implies$ source $\neq$ hotspot
- different datasets $\implies$ hotspots move around
- separation injected source and hotspot $\mathcal{O}(0.2°)$[b]

[a] Sara Buson et al. 2023. eprint: 2305.11263.

[b] Chiara Bellenghi et al. 2023. eprint: 2309.03115.

Figure 6: Frequentist analysis of 5BZQ J1616+3801.

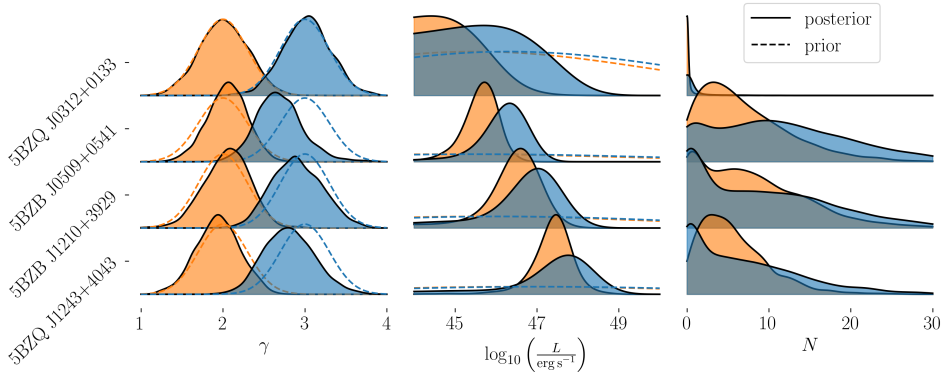


Figure 7: Prior dependency of results.

Conclusions

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Summary

- physics driven
  - position and prior dependency
  - enabled through Bayesian framework
  - allows for input from multi-messenger studies
- complementary to Frequentist

Outlook

- analyse more sources, stacking of sources $\Longrightarrow$ population studies
- add further 4 years of data

Likelihood

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$$\langle N_k \rangle = \int \Phi_k(E,\omega) A_{\text{eff}}(E,\omega) \text{pdf}\left(\hat{E},\hat{\omega};\Theta_k\right) \text{d}\mathcal{S} \tag{1}$$

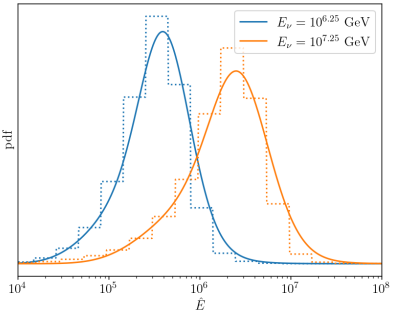
$$L = e^{-\langle N \rangle} \prod_{i=1}^{N} \sum_{k}^{K} \Phi_k(E_i,\hat{\omega}_i) A_{\text{eff}}(E_i,\hat{\omega}_i) \text{pdf}\left(\hat{E}_i,\hat{\omega}_i;\Theta_k\right) \tag{2}$$

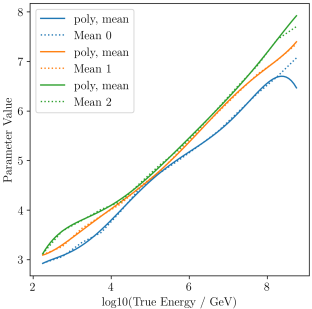
$$\mathcal{S} : \text{parameter space}, \langle N \rangle = \sum_k \langle N_k \rangle \tag{3}$$

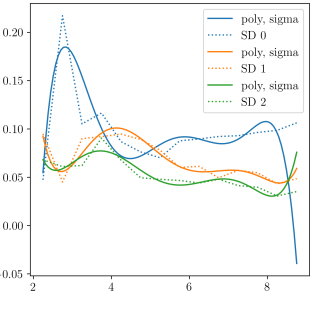
Under the hood

- `stan`, `cmdstanpy`
- Hamiltonian Monte Carlo

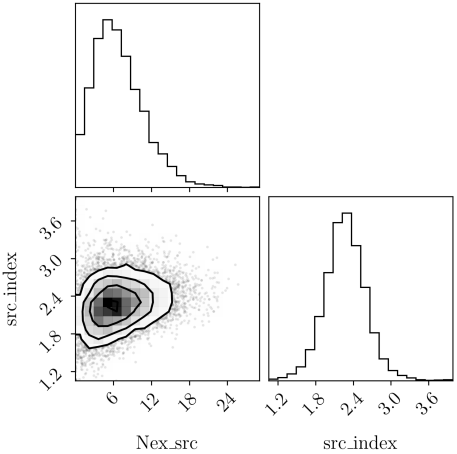
Energy resolution

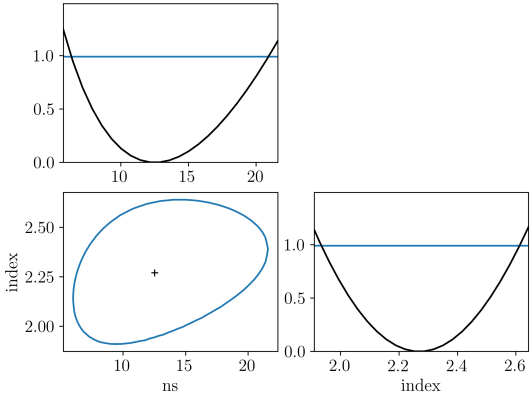




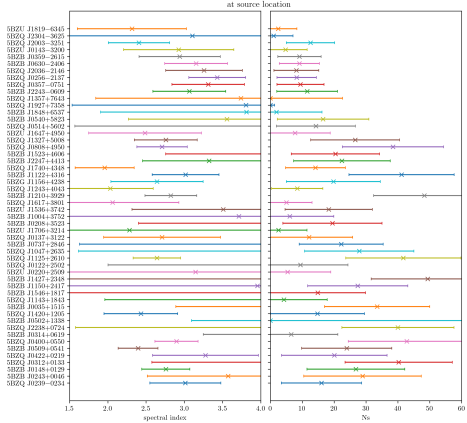


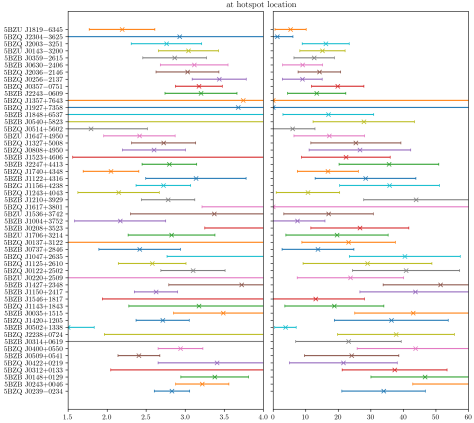
Bayes vs. Frequentist

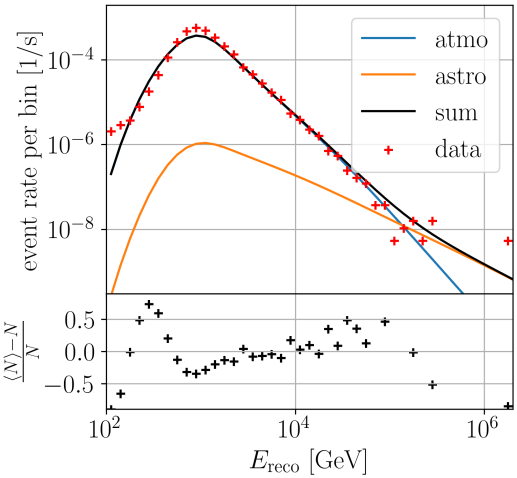




Source selection






atmo
astro
sum
data
event rate per bin [1/s]
10^{-4}
10^{-6}
10^{-8}
$\frac{\langle N\rangle - N}{N}$
0.5
0.0
−0.5
10^2
10^4
10^6
E_{reco} [GeV]