Investigating the blazar-neutrino connection with public IceCube data

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IceCube observatory

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Detection principle

- $\nu + N \rightarrow l_\nu + X$, lepton emits Cherenkov light
- detected in instrumented volume through photomultipliers

Data (Abbasi et al. 2021)

- 6 year muon tracks (IC86_II)
- instrument response function (IRF) provided
- reconstructed energies, directions and time stamps

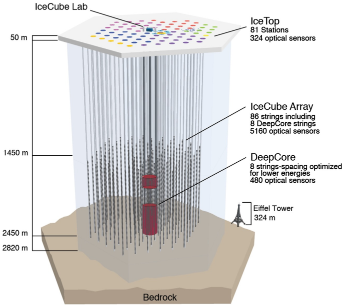

Figure 1: IceCube detector (Aartsen et al., 2018).

NGC 1068 and TXS0506+056 as neutrino sources

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NGC 1068

- 2.9σ (Aartsen et al. 2018), 4.2σ (Abbasi et al. 2022)
- likelihood analysis, catalog search $\rightarrow$ trial correction

TXS0506+056

- IceCube-170922A during 6 month flare
- 3σ significance (IceCube collaboration et al., 2018)

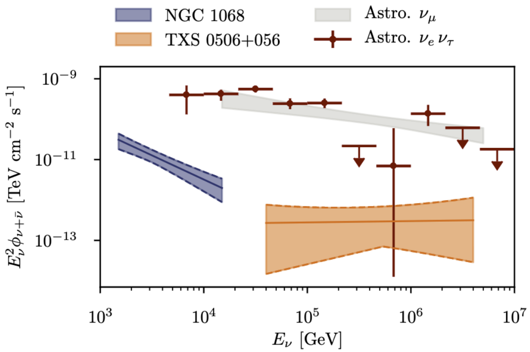

Figure 2: Reconstructed neutrino spectra (Abbasi et al. 2022)

icecube_tools

Point source search

- likelihood ratio test (Frequentist!)
- see Braun et al. (2008)
- github.com/icecube/skyllh
- github.com/cescalara/icecube_tools
- work in progress

NGC 1068

- $\gamma = 3.2^{+0.4}_{-0.3}$, $n_s = 62^{+18}_{-17}$
- $-\log_{10}(p) = 3.15$

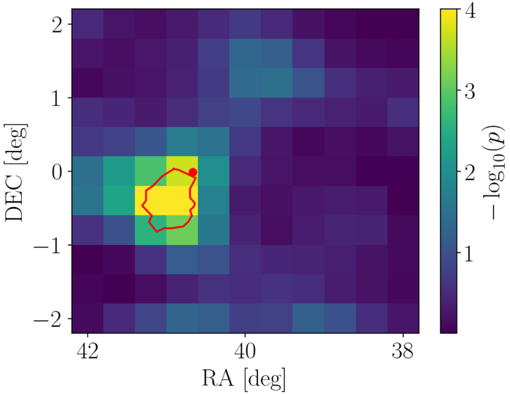

Figure 3: Local p-value around NGC 1068 (red dot), $p = 10^{-5}$ contour of Aartsen et al. (2019) in red.

Bayesian statistics

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Bayes' theorem

- $$\underbrace{P(\text{parameter}|\text{data})}_{\text{posterior}} \propto \underbrace{P(\text{data}|\text{parameter})}_{\text{likelihood}} \times \underbrace{P(\text{parameter})}_{\textit{prior}} \tag{1}$$

- `cmdstanpy` and `stan`, Hamiltonian Monte Carlo
- probability model from first principles

Benefits of Bayesian hierarchical modeling

- more parameters, increased complexity
- no trial correction

Model building

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Likelihood function

extended likelihood function (Cowan, 1998)

$$L = \frac{e^{-\bar{N}}}{N!} \prod_{i=1}^{N} \sum_{k=1}^{N_S} \bar{N}_k p(\hat{\omega}_i, \hat{E}_i | k) \qquad (2)$$

Definitions

- $i \in [1, \ldots, N]$: event label
- $k \in [1, \ldots, N_S]$: source component
- $\bar{N} = \sum_{k=1}^{N_S} \bar{N}_k$: # expected events
- $\hat{E}_i, \hat{\omega}_i$: detected energy/direction of muon event, E_i: true neutrino energy

Model likelihood

	point source	background
spatial	Gaussian or vMF	uniform
energy	$\mathrm{pdf}\left(\hat{E}_i \| E_i, \hat{\omega}_i\right), \propto E_i^{-\gamma}$	$\mathrm{pdf}\left(\hat{E}_i \| E_i, \hat{\omega}_i\right)$, MCEq (Fedynitch et al., 2015)
detection	effective area, $\hat{E}_i$ within some thresholds	

Stan Applied To Astrophysical Neutrinos

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- grey: data
- green: parameters
- gold: latent parameters

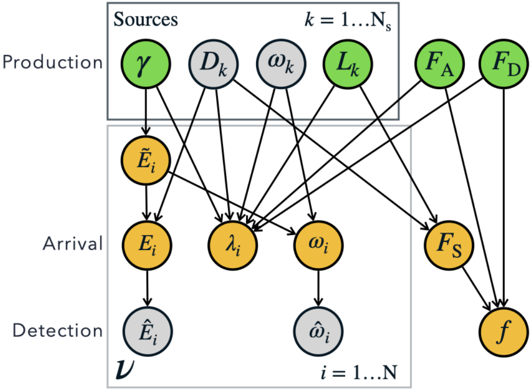

Figure 4: Hierarchical model.

Validation - point source

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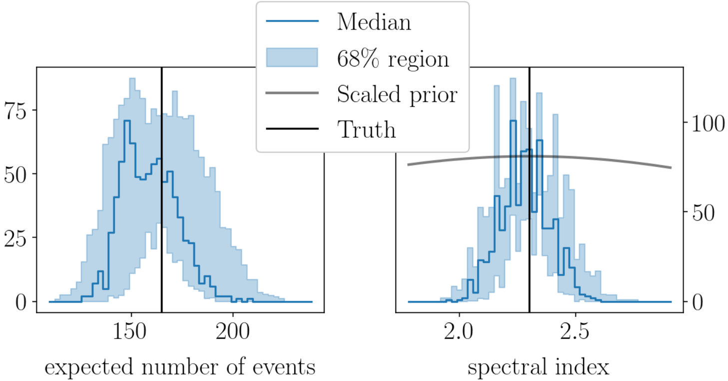

Figure 5: Point source at $\delta = -40^\circ$, $\hat{E}_{\text{min}} = 5 \times 10^5$ GeV.

Validation - isotropic diffuse source

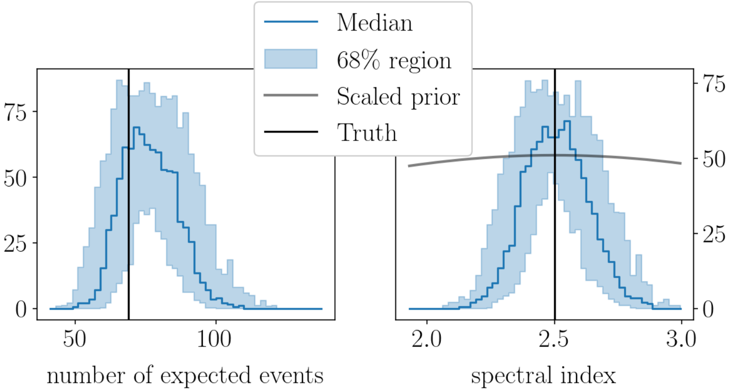

Figure 6: Isotropic diffuse source, $\hat{E}_{\mathrm{min}} = 1 \times 10^5$ GeV.

Single TXS0506+056 event

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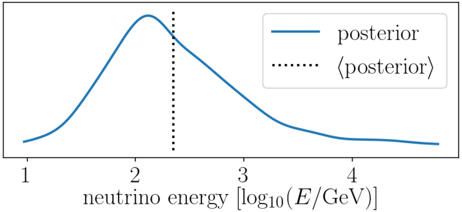

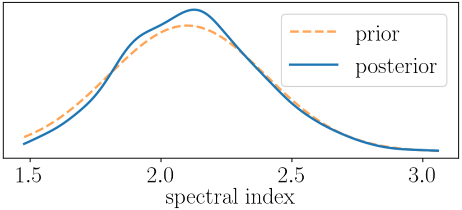

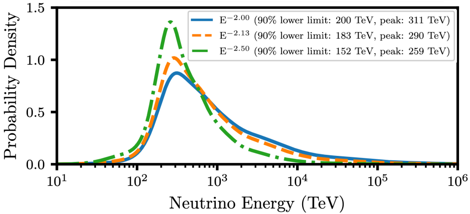

Figure 7: IceCube results, adapted from IceCube collaboration et al. (2018)

Results

- mode of distribution: 269 TeV
- cf. Aartsen et al. (2018): 290 TeV
- $10^{\langle \mathrm{pdf}[\log_{10}(E)] \rangle}$ TeV $= 223$ TeV

Conclusion

- similar results in likelihood analysis
- fit of spectral indices
- reconstruction of TXS event

Outlook

- fix bugs
- extend to 10 year detector live time
- apply to blazar catalog 5BZCAT (Massaro et al., 2015), subset of Buson et al. (2022)