Time-Integrated Sub-TeV Neutrino Astrophysics with IceCube-DeepCore

Andrew Wang for the IceCube Collaboration
TeVPA 2025 Neutrinos Parallel Talk for November 4th, 2025

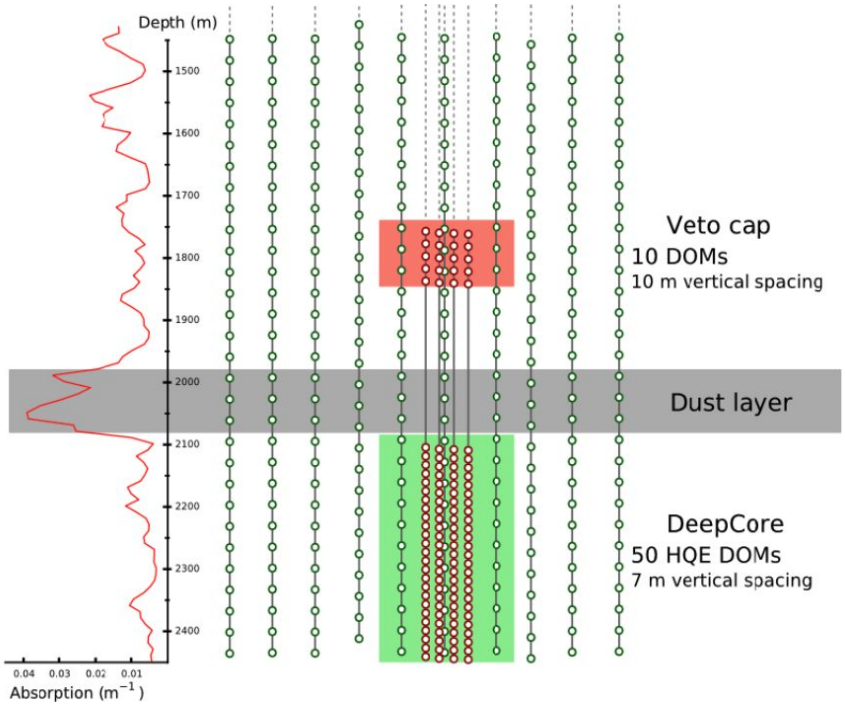
ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

Andrew Wang - a.w@gatech.edu

Georgia Institute of Technology

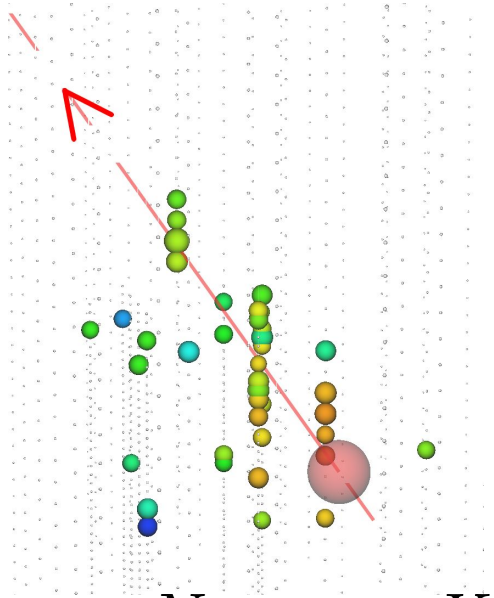
The DeepCore Subarray

- Located at the bottom center of IceCube.
- 350 m tall and 125 m in radius.
- Smaller DOM-to-DOM spacing lowers energy threshold to ~10 GeV.

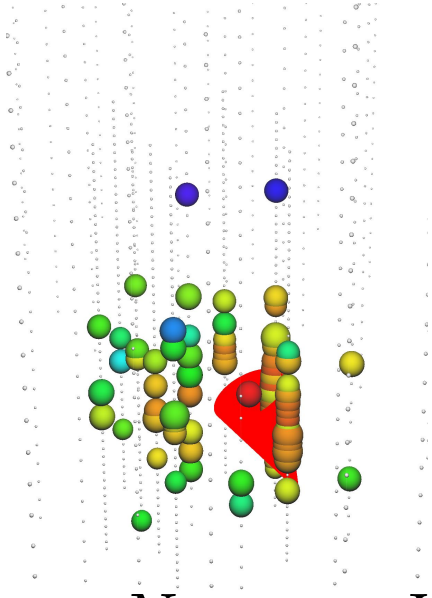


IceCube, Astro. Part. Phys. (2012)

Simulated DeepCore Events



$$\nu_\mu + N \rightarrow \mu + X$$

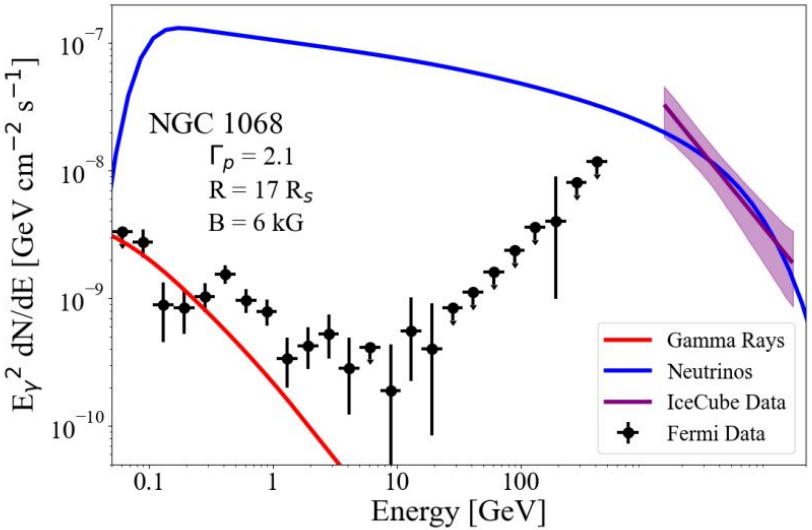


$$\nu_e + N \rightarrow e + X$$

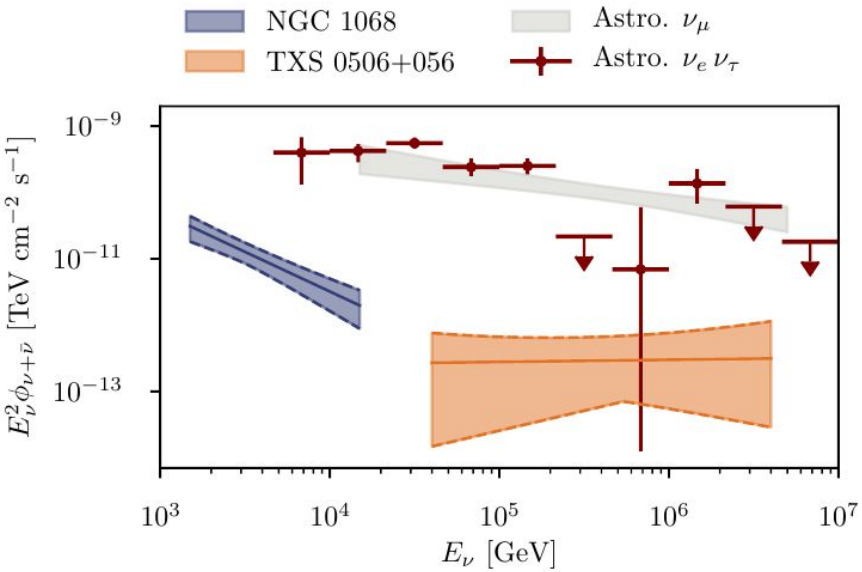
~100 GeV for both events.

Motivation

- Most IC analysis focus on >1 TeV, want to push down to ~10 GeV.



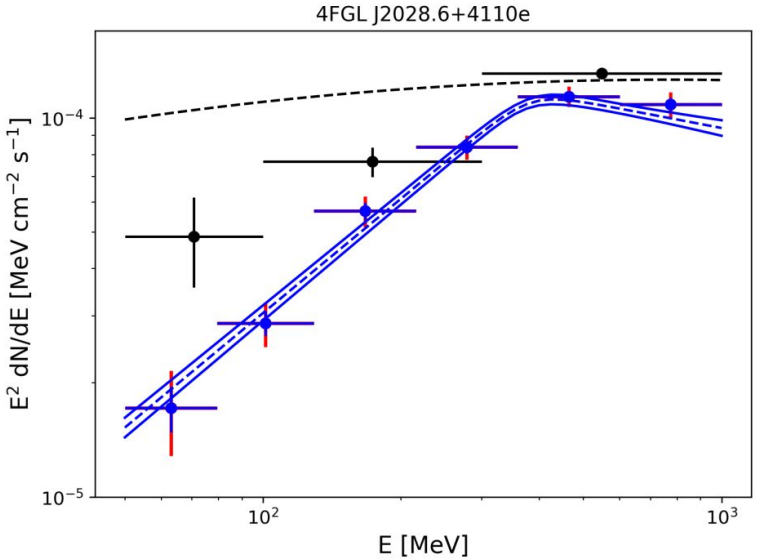
Blanco et al, arXiv:2307.03259 (2023)



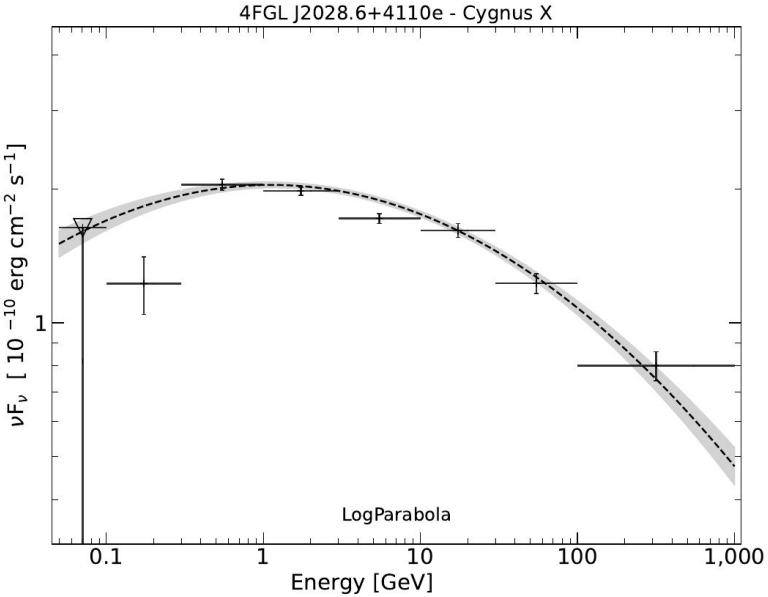
IceCube, Science (2022) 378 538

Motivation cont.

- Pion bump sources demonstrate hadronic processes.



Fermi Collab. ApJ (2022) 933 204



Fermi Collab. ApJS (2020) 247 33

Analysis Details

- Data sample: GeV Reconstructed Events with Containment for Oscillation (GRECO) Astronomy.
  - Spans from May 2012 - November 2023 (11.6 years).
  - Detailed description in IceCube, Phys. Rev. D 99, 032007 (2019).
- Low-energy events makes time-integrated analysis difficult.
- Angular uncertainty mismatch makes analysis impossible.
- Mediated with cuts.
- Cut in this analysis focuses on muon-induced track-like events.

Methods

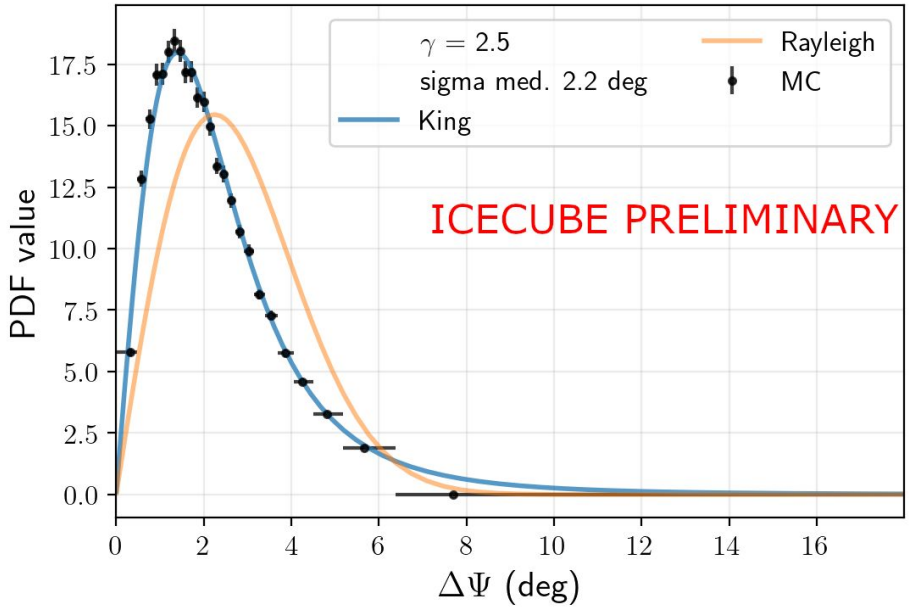
- Standard unbinned maximum likelihood search.

$$\mathcal{L}\left(\{\vec{x}_i\}, \mathbf{x}_\mathrm{S}; n_\mathrm{S}, \gamma\right) = \prod_i^N \left[\frac{n_\mathrm{S}}{N}\mathcal{S}_i\left(\vec{x}_i, \mathbf{x}_\mathrm{S}; \gamma\right) + \left(1 - \frac{n_\mathrm{S}}{N}\right)\mathcal{B}_i\left(\vec{x}_i\right)\right]$$

- Fit parameters:
  - Number of signal events, n_s.
  - Spectral index, gamma.
- Observables:
  - Energy, direction, and spatial uncertainty.
- Signal spatial PDF uses King's function, more details in next slide.

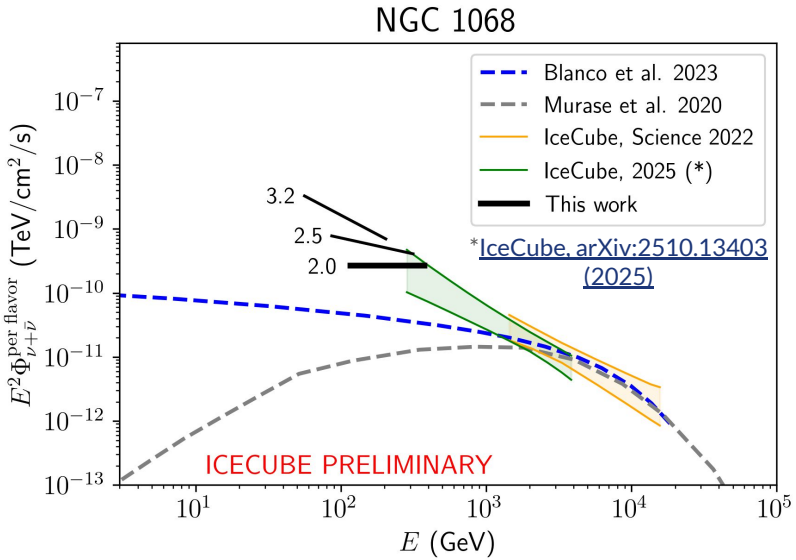
King's Point Spread Function

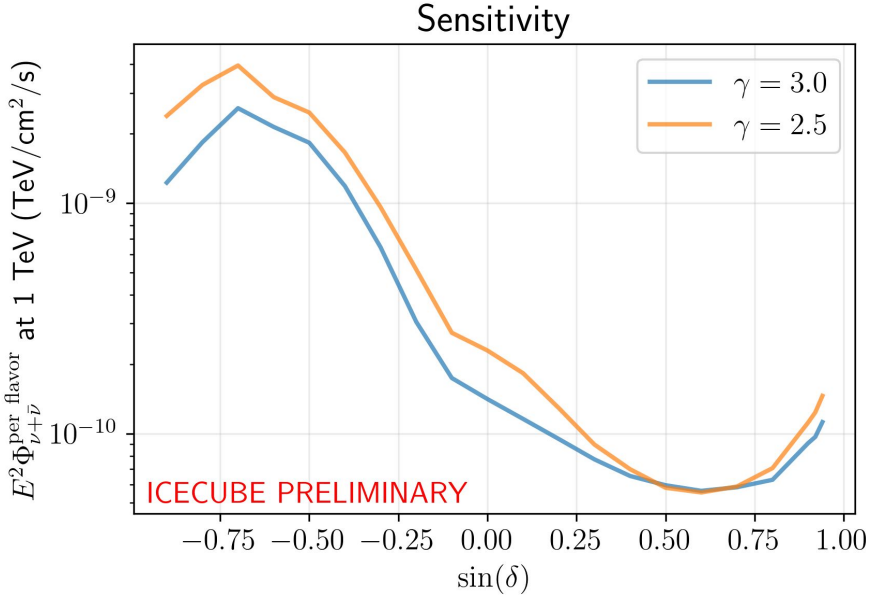
- Alternative description PSF used in other contexts. See: [Fermi-LAT, ApJ 765 54 (2013)].
- More accurate vs. traditional Rayleigh assumption.
- Parameters derived from fits to Monte Carlo.
- Reduce biases in analysis.



Analysis Performance: Sensitivity

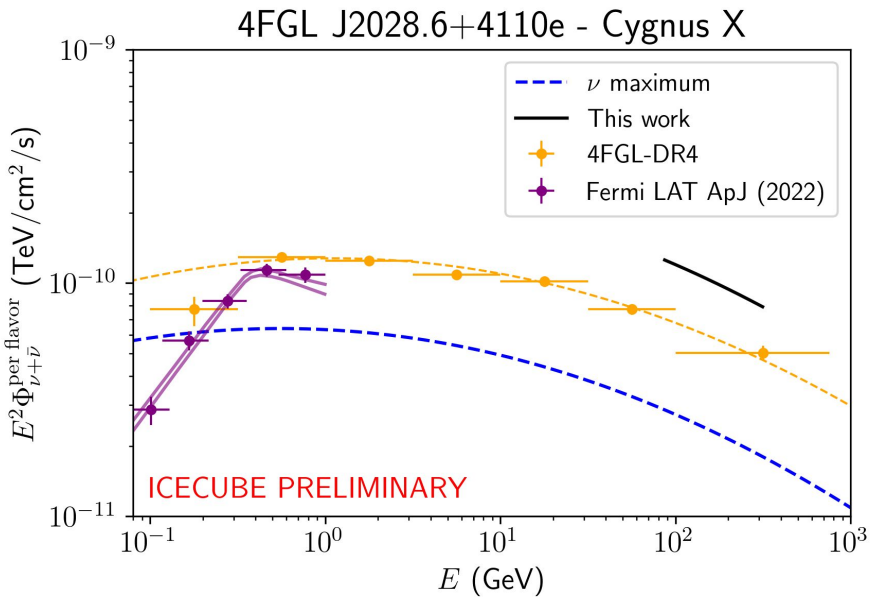
- Sensitivity about ~2x higher than the extrapolation of the best fit flux for NGC 1068.





Analysis Performance: Sensitivity

- Sensitivity about ~4x higher than extrapolation of brightest Galactic Plane source.

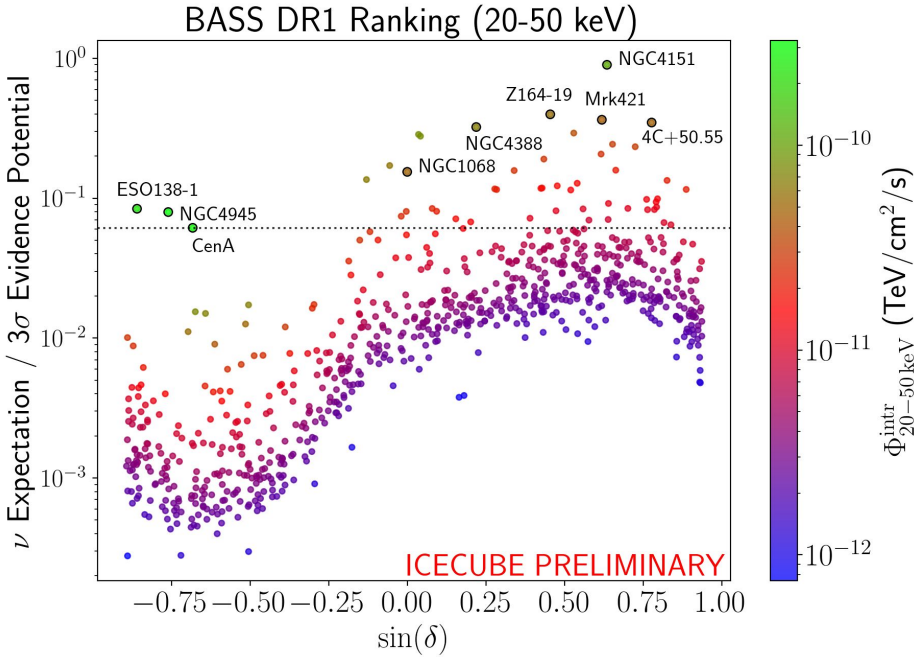


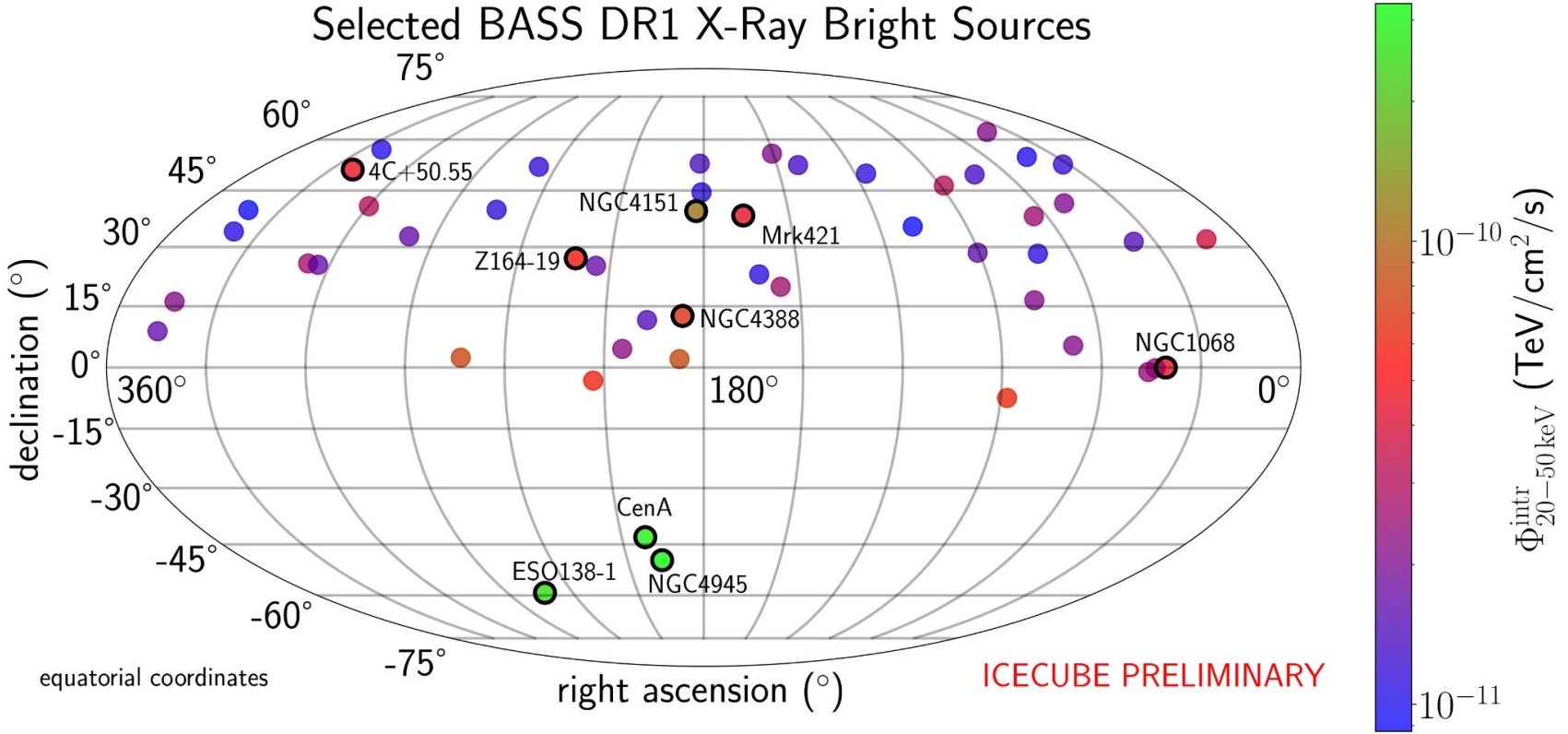
Searches

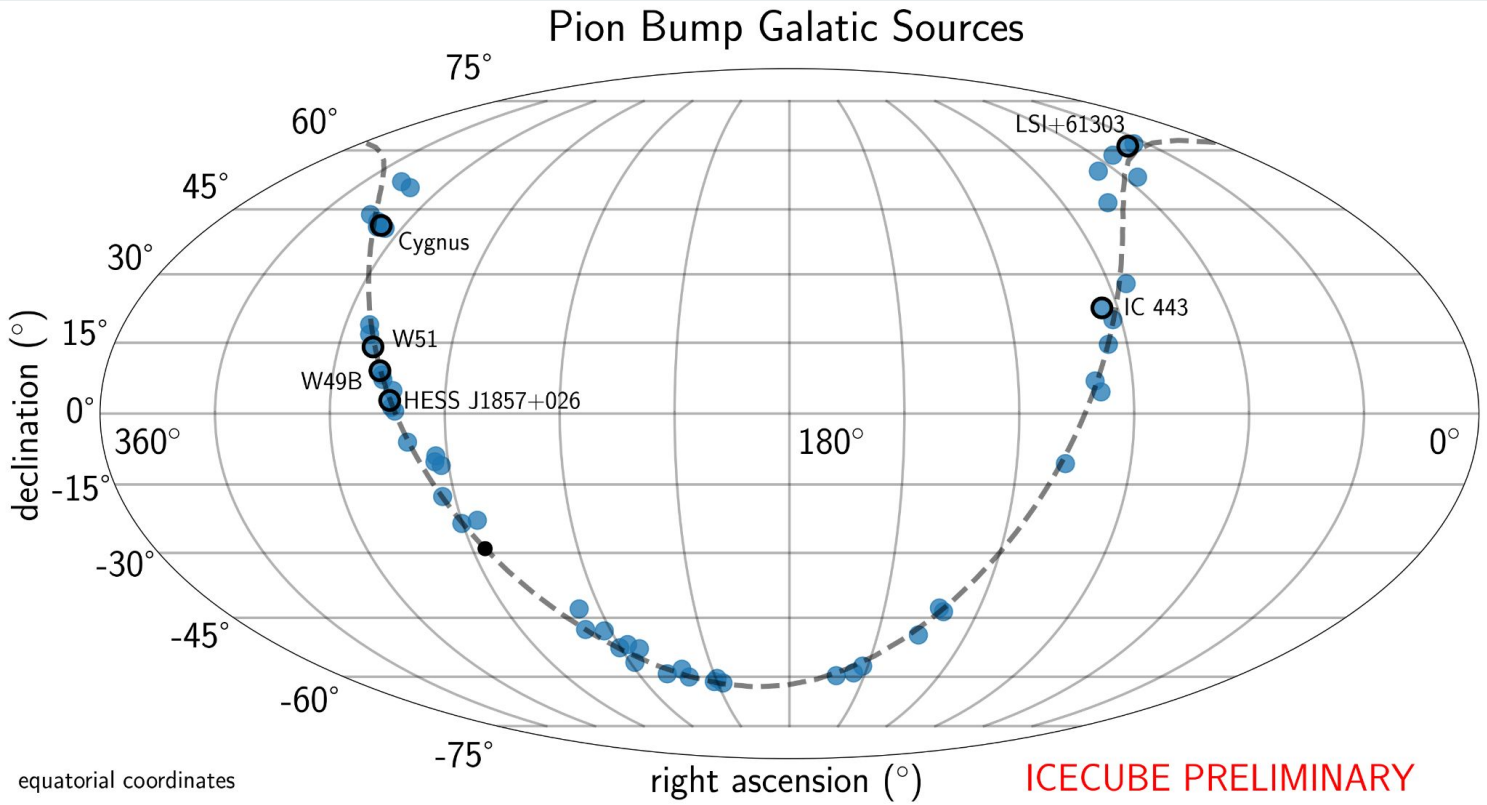
- Two catalog searches:
  - C. Ricci et al, ApJS 233 17 (2017): BASS DR1, Swift/BAT 70-month catalog of x-ray bright AGN - 50 sources.
  - S. Abdollahi et al, ApJ 933 204 (2022): Fermi-LAT detected pion bump sources - 56 sources.
- Sky scan:
  - Spans Northern and Southern sky.
  - ~0.82 deg^2 per pixel.

BASS Catalog Ranking

- Uses intrinsic x-ray flux in 20-50 keV band.
- Scaling factor based on NGC 1068's neutrino flux; applied to all sources.
- E^-3 spectrum assumed.
- Metric = Nu expectation / 3-sigma EP.
- Top 50 sources selected (above dotted line).




Selected BASS DR1 X-Ray Bright Sources
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
declination (°)
360°
180°
0°
right ascension (°)
equatorial coordinates
4C+50.55
NGC4151
Mrk421
Z164-19
NGC4388
NGC1068
CenA
ESO138-1
NGC4945
ICECUBE PRELIMINARY
10^{-10}
10^{-11}
$\Phi^{\mathrm{intr}}_{20-50\,\mathrm{keV}}$ (TeV/cm^2/s)


Pion Bump Galatic Sources
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
declination (°)
360°
180°
0°
right ascension (°)
LSI+61303
Cygnus
IC 443
W51
W49B
HESS J1857+026
equatorial coordinates
ICECUBE PRELIMINARY

Summary

- Time-integrated search using GRECO 11.6 years.
- Additional event selection performed to isolate well-reconstructed events.
- King's function PSF; used to improve analysis bias.
- Conducting two catalog searches and a skyscan.
- Foundational analysis for future analyses:
  - Time-integrated analysis using improved reconstruction.
  - Combined high and lower energy events analysis.
  - Analysis using IceCube Upgrade data.
- Results very soon!

Backup Slides

Likelihood Breakdown

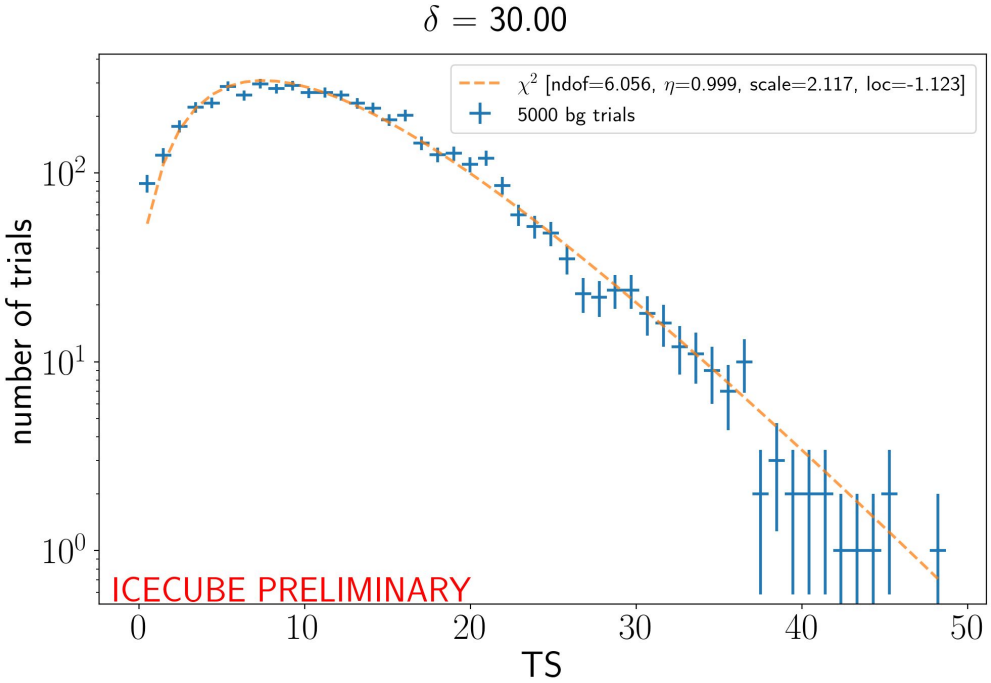
$$\mathcal{L}\left(\{\vec{x}_i\}, \mathbf{x}_\mathrm{s}; n_\mathrm{s}, \gamma\right) = \prod_i^N \left[\frac{n_\mathrm{s}}{N}\mathcal{S}_i\left(\vec{x}_i, \mathbf{x}_\mathrm{s}; \gamma\right) + \left(1 - \frac{n_\mathrm{s}}{N}\right)\mathcal{B}_i\left(\vec{x}_i\right)\right]$$

$$\mathcal{S}_i(\mathbf{x}_i, \sigma_i, E_i, \mathbf{x}_\mathrm{s}; \gamma) = \mathcal{S}_\mathrm{space}(\mathbf{x}_i, \sigma_i, \mathbf{x}_\mathrm{s}) \cdot \mathcal{S}_\mathrm{energy}(\mathbf{x}_i, E_i; \gamma)$$

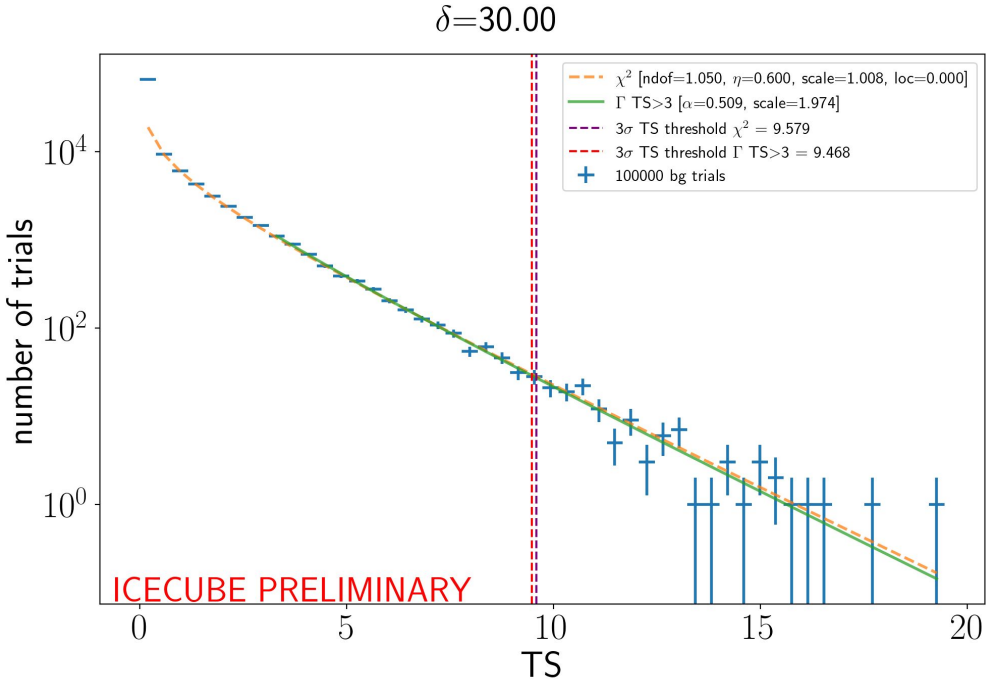
$$\mathcal{B}_i(\mathbf{x}_i, E_i) = \mathcal{B}_\mathrm{space}(\delta_i) \cdot \mathcal{B}_\mathrm{energy}(\delta_i, E_i)$$

$$\lambda = -2 \cdot \mathrm{sign}\left(\hat{n}_\mathrm{s}\right) \cdot \log\left[\frac{\mathcal{L}(\{\vec{x}_i\}, \mathbf{x}_\mathrm{s}; n_\mathrm{s}=0, \gamma)}{\mathcal{L}(\{\vec{x}_i\}, \mathbf{x}_\mathrm{s}; n_\mathrm{s}=\hat{n}_\mathrm{s}, \gamma=\hat{\gamma})}\right]$$

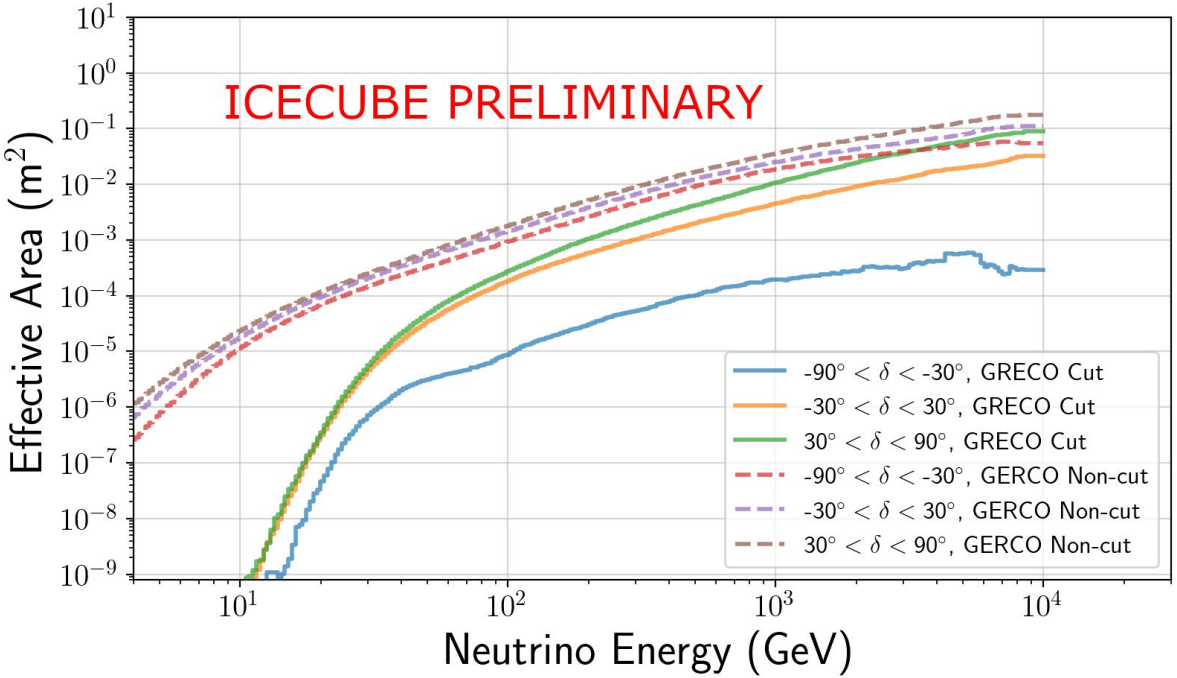
Background TS Distribution w/o Cuts



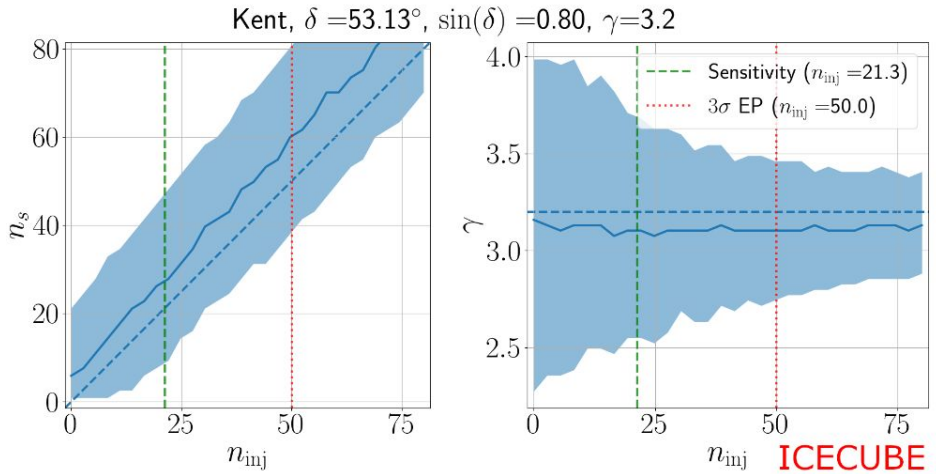
Background TS Distribution w/ Cuts

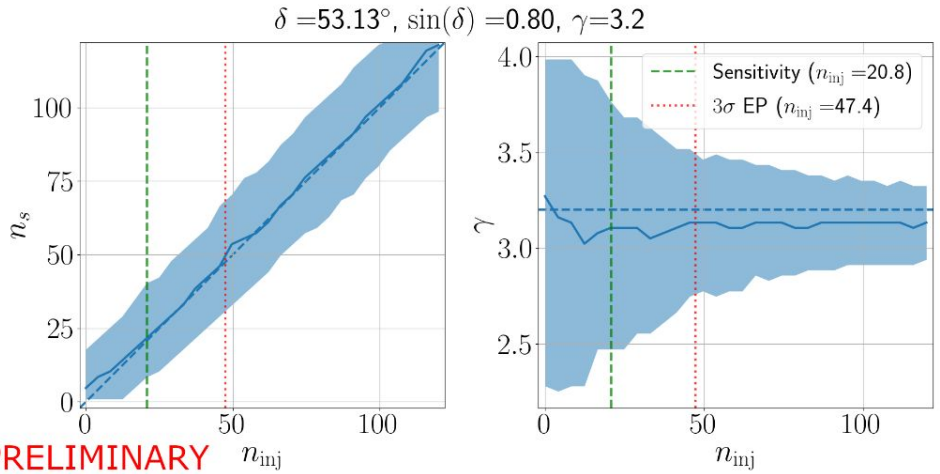


DeepCore Effective Areas



Injection/Recovery Biases





ICECUBE PRELIMINARY

2D Gaussian/Kent

King's Function

Angular Resolution Before and After Cuts