Stacking Search for IceCube Neutrinos from Fermi-LAT Active Galactic Nuclei

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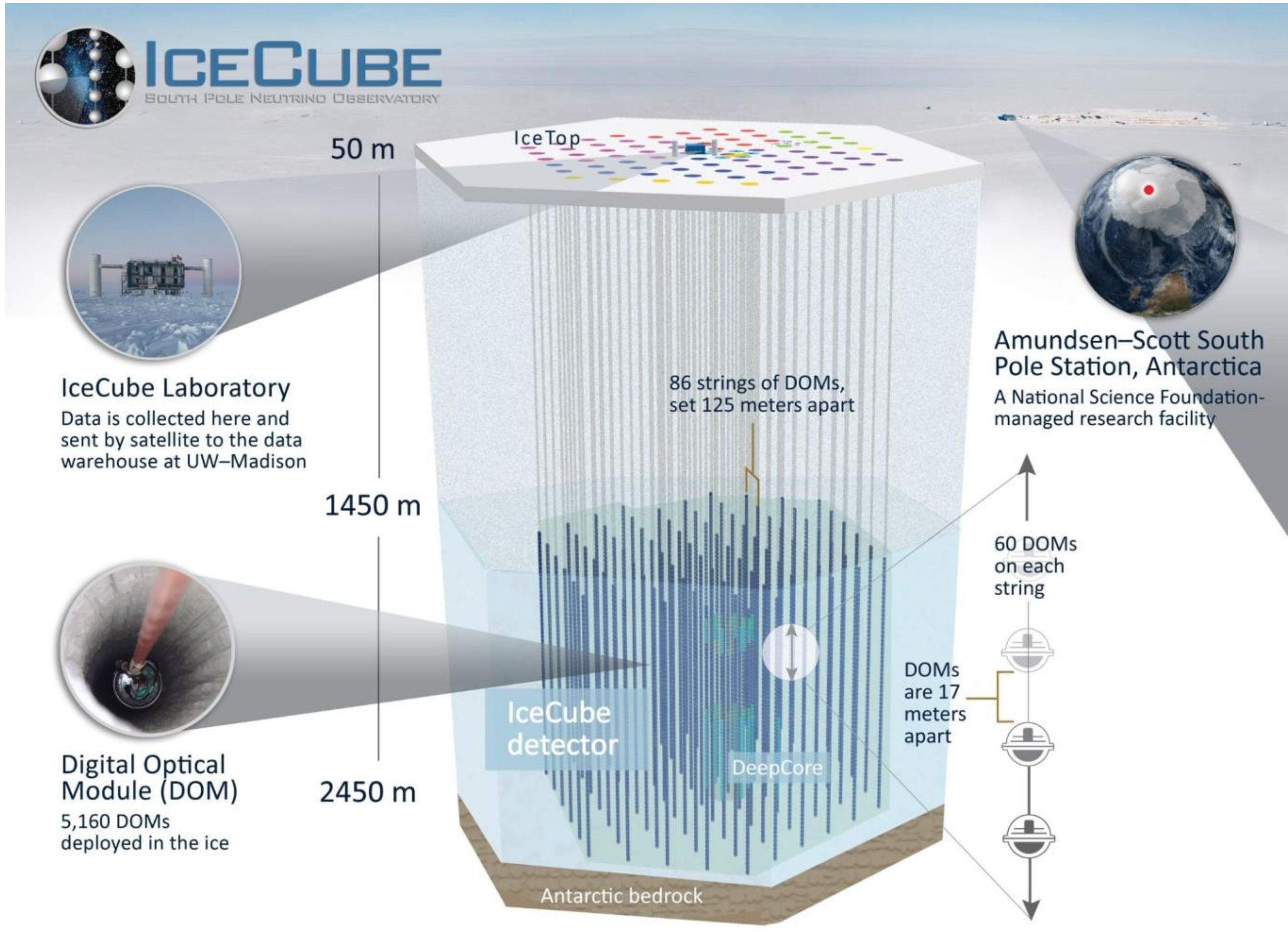
For the IceCube Collaboration

11th Fermi Symposium -- 9/11/2024

IceCube Neutrino Observatory

- Cubic kilometer of instrumented ice
- Spacing optimized for TeV-PeV neutrinos
- Sensitive to all flavors of neutrino
  - Muon neutrino charged current interactions (“tracks”) have best angular resolution but large cosmic ray background in southern sky



Active Galactic Nuclei

- Supermassive black hole accreting matter
- Blazars dominate sample in gamma rays
- Divide AGN into 3 classes for this analysis
  - BL Lacertae (BLL)
  - Flat Spectrum Radio Quasar (FSRQ)
  - Non-blazar AGN

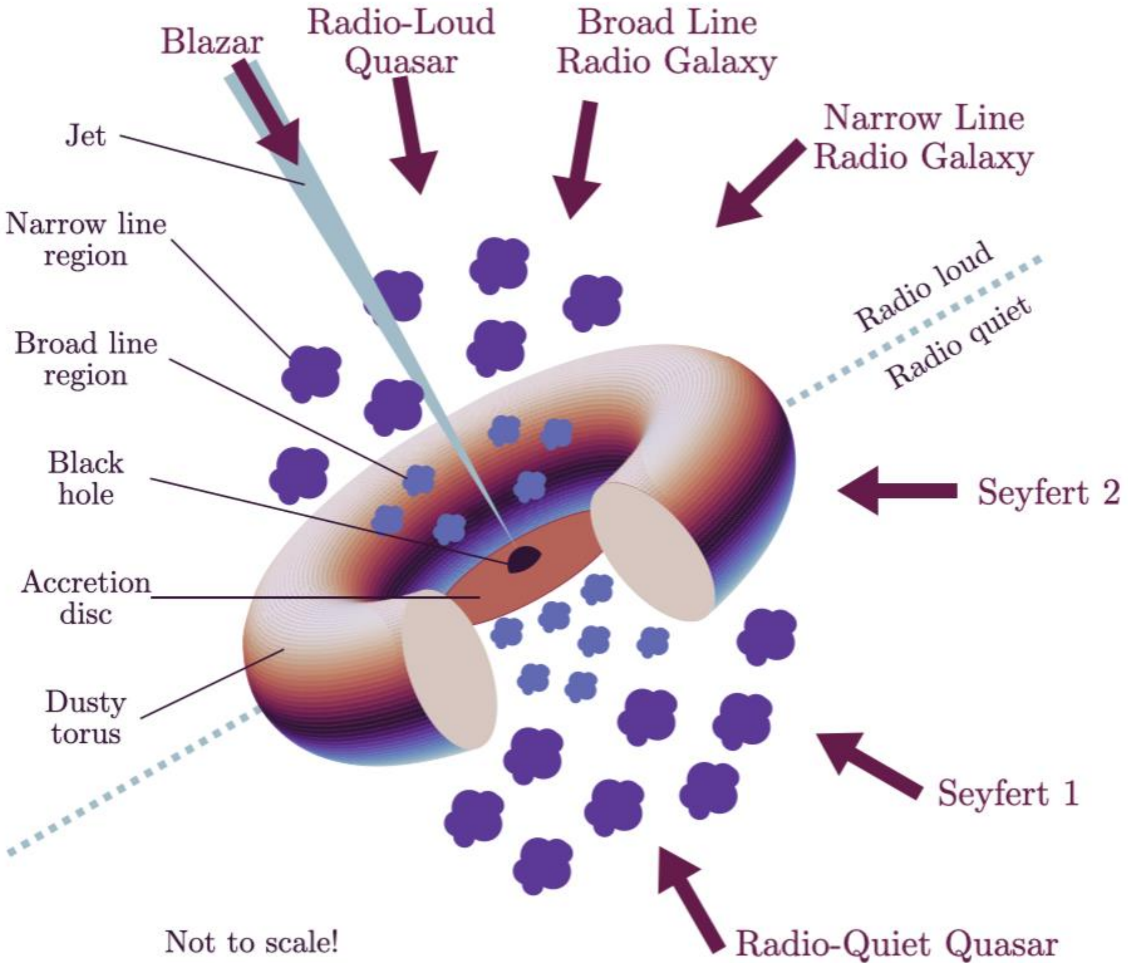
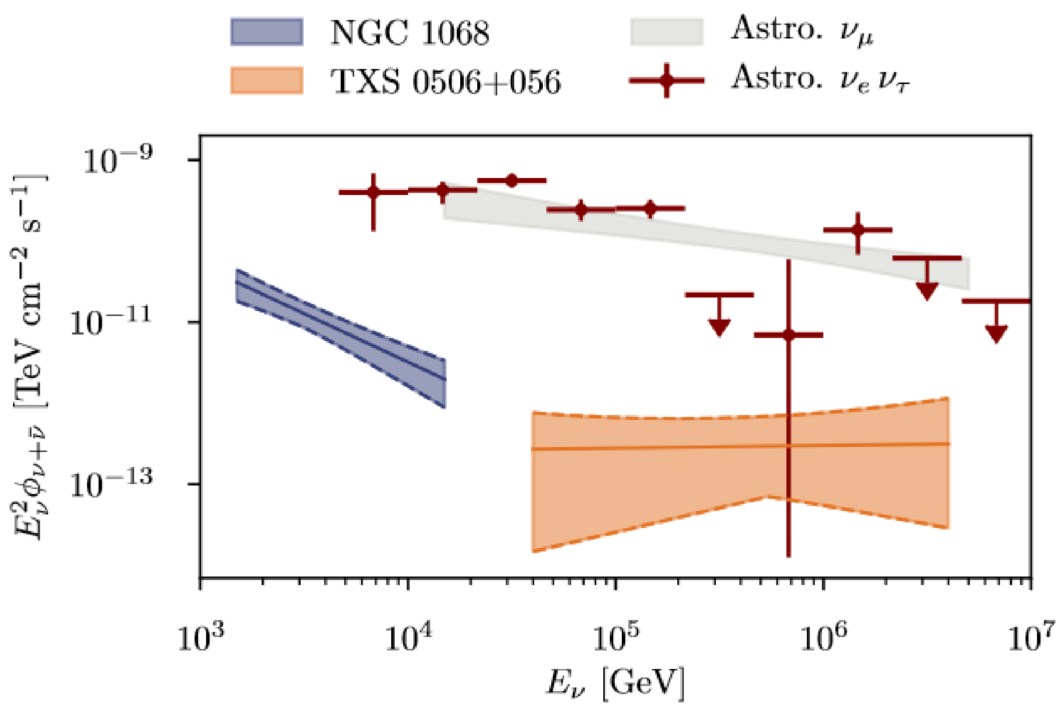


Image Citation: Emma Alexander

Neutrino Emission by AGN

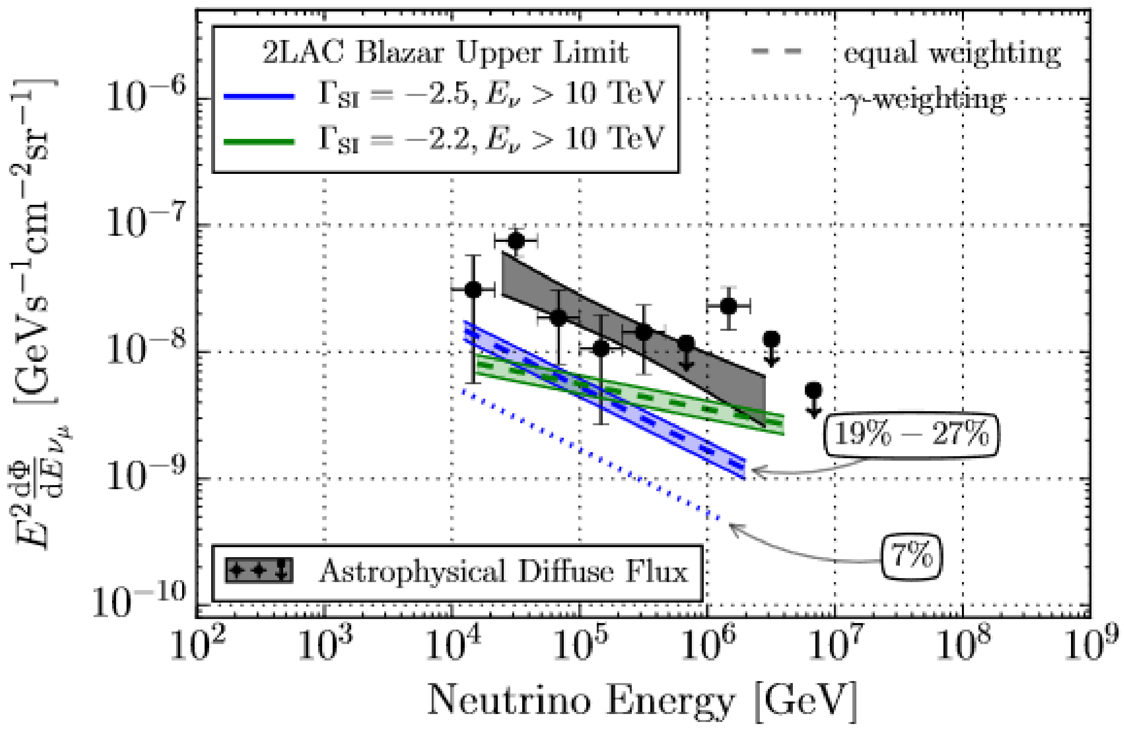
- TXS 0506+056
  - 2017 gamma-ray flare in coincidence with high energy neutrino.
  - Follow-up IceCube analysis found previous neutrino flaring period
  - One of the brightest gamma-ray blazars
- NGC 1068
  - Seyfert type II found as a time-integrated neutrino source
  - GeV gamma-rays believed to originate from starburst region



R. Abbasi et al. Science (2022)

Previous IceCube Limits on Fermi-LAT AGN

- Population studies are more sensitive to neutrino emission from a source class than individual source analyses
- Previous IceCube studies placed limits on neutrino emission from Fermi-LAT AGN (2LAC, 3FHL, 1FLE analyses)
  - 2LAC analysis used 3 years of IceCube data with 862 blazars
  - 3FHL analyzed 1301 hard blazars with 8 years of data
  - 1FLE analyzed 137 soft blazars with 10 years of data
  - Limits reject case where the gamma-ray blazars emit entire diffuse IceCube flux (under tested models)



2LAC analysis upper limits
(M. G. Aartsen *et al* 2017 *ApJ* 835 45)

Stacking Test

- Test the hypothesis that all objects in sample emit neutrinos with the same spectrum with relative fluxes given by a weighting scheme

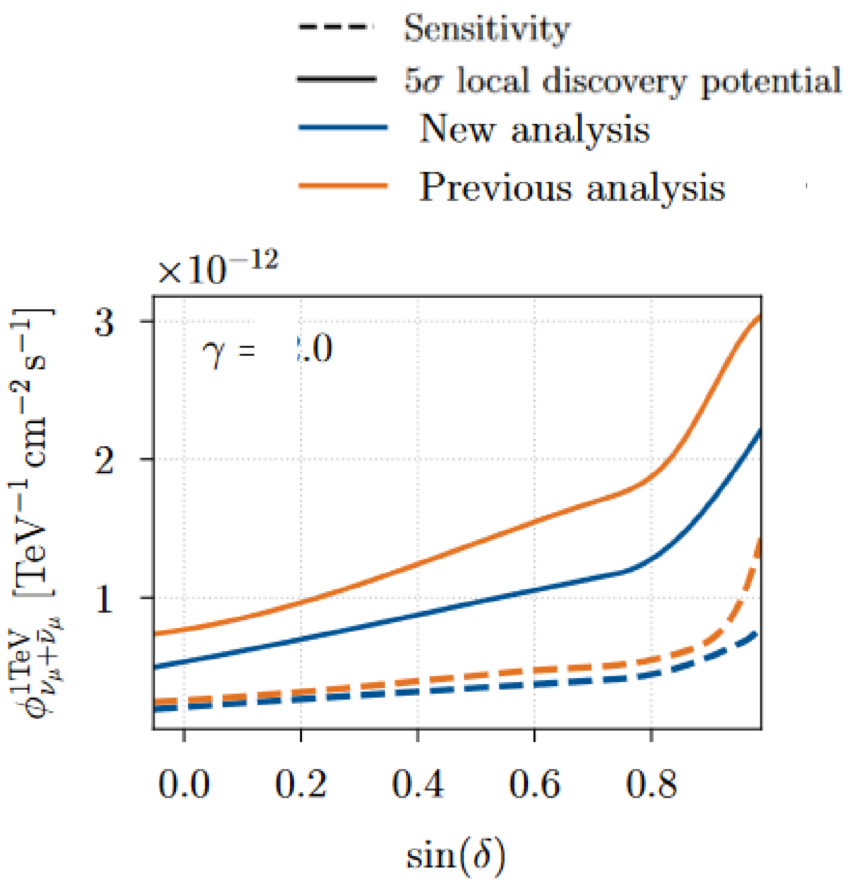
$$S_i^{stacked}(x_i, \sigma_i, E_i, \gamma) = \frac{\sum_{k=1}^{M} w_k R_k(\delta_k, \gamma) * S_i^k\left(x_i, x_{S_k}, \sigma_i, E_i, \gamma\right)}{\sum_{k=1}^{M} w_k R_k(\delta_k, \gamma)}$$

$$\mathcal{L}(n_s, \gamma) = \prod_i^N \left(\frac{n_s}{N} * S_i^{stacked}\ (x_i, \sigma_i, E_i, \gamma)\right) + \left(\left(1 - \frac{n_s}{N}\right) *\ B_i(x_i, \sigma_i, E_i)\right)$$

- N neutrinos (indexed with i), each with energy E_i, location $x_i = \ (\alpha_i, \delta_i)$, angular uncertainty σ_i
- M sources (indexed with k), each with weight w^k, location x_{S_k} and detector response R
- Overall normalization of n_s (number of detected neutrinos) with recovered power law spectrum of γ

IceCube Dataset

- IceCube dataset “Northern Tracks”
  - Only in declinations between -3-81 degrees
  - Improved PSF modeling(“KDEs”)
  - 10 year version used in the NGC 1068 result
  - Additional three years of data (13 years) used in this work



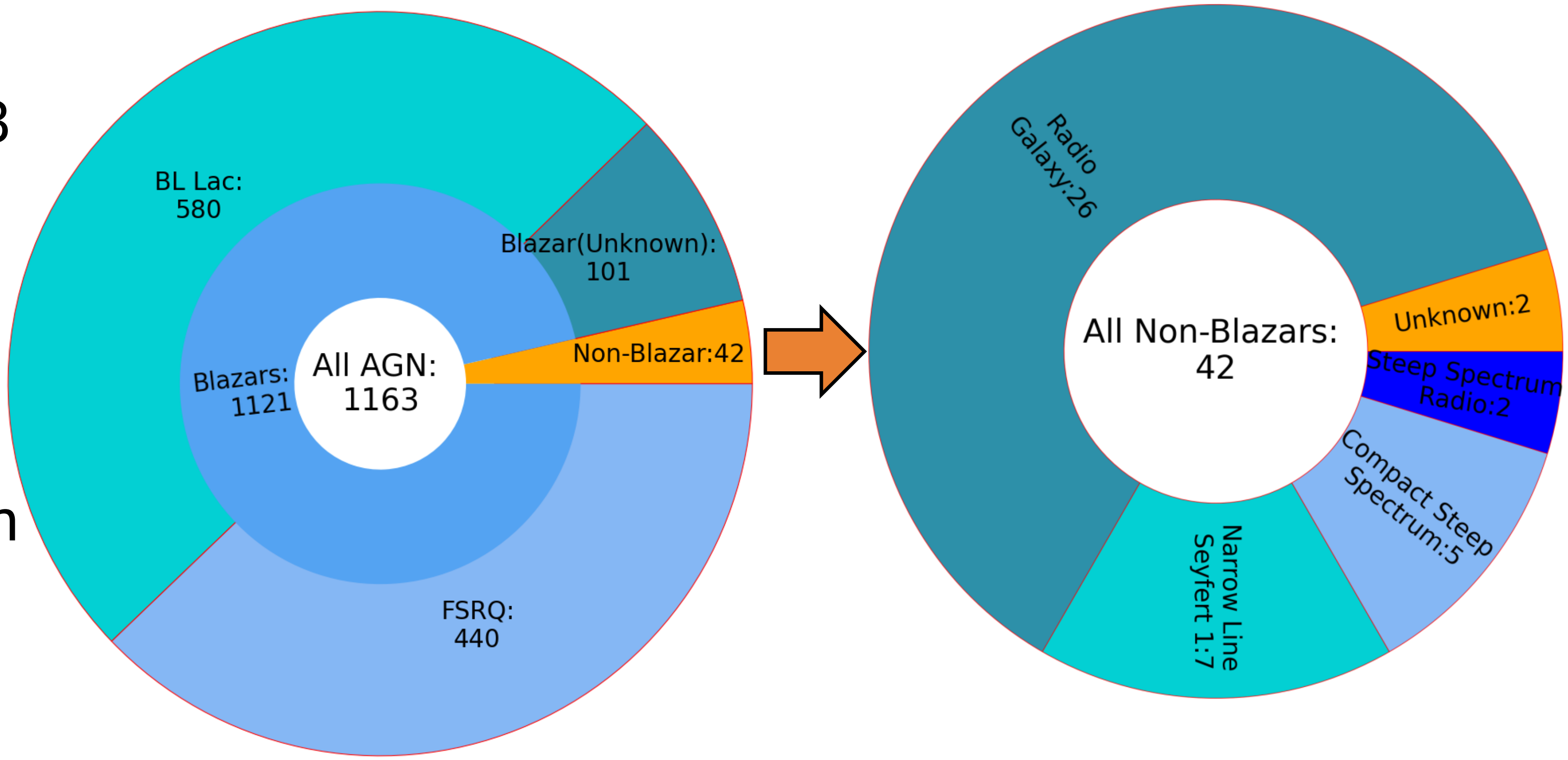
10 year Northern Tracks sensitivity compared to a previous 10 year point source analysis (results in about 20-30% improvement)
R. Abbasi et al. Science (2022)

Hypotheses Tested

- 3 source classes
  - FSRQ
  - BL Lacs
  - Non-blazar AGN
- 2 tested weighting hypotheses
  - $L_\nu \propto L_\gamma$
  - $L_\nu \propto L_\gamma^2$
    - Motivated by models where neutrino flux scales with jet power and target field density (and where both correlate with gamma-ray flux) (e.g. Tavecchio & Ghisellini 2015)
    - Requires redshift
  - Using number flux between 1 GeV-100 GeV in the source frame corrected for extragalactic background light absorption to compute L_γ

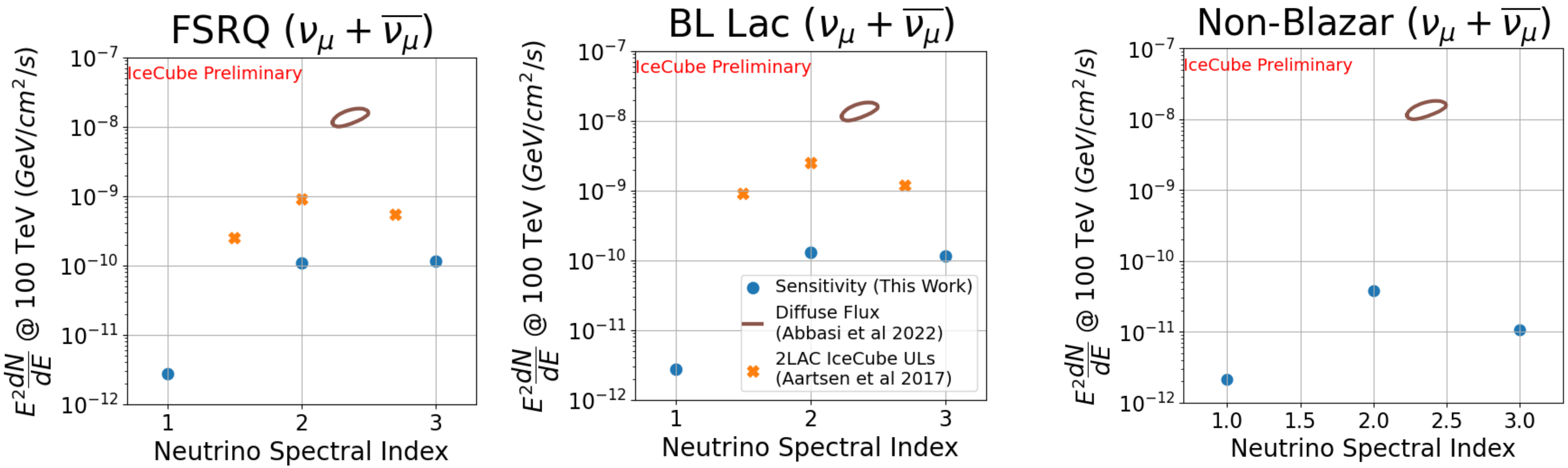
Fermi-LAT Catalog

- Using Fermi 4FGL-DR4 and 4LAC-DR3
- Require sources have redshift
- Require sources between -3 and 81 degrees declination (for IceCube dataset)



Stacking Sensitivities

- Under model $L_\nu \propto L_\gamma$, median upper limit under the null hypothesis
- Previous ULs not exactly comparable with this work (power law cutoff below 10 TeV and different catalog)
- No completeness corrections



Binomial Test

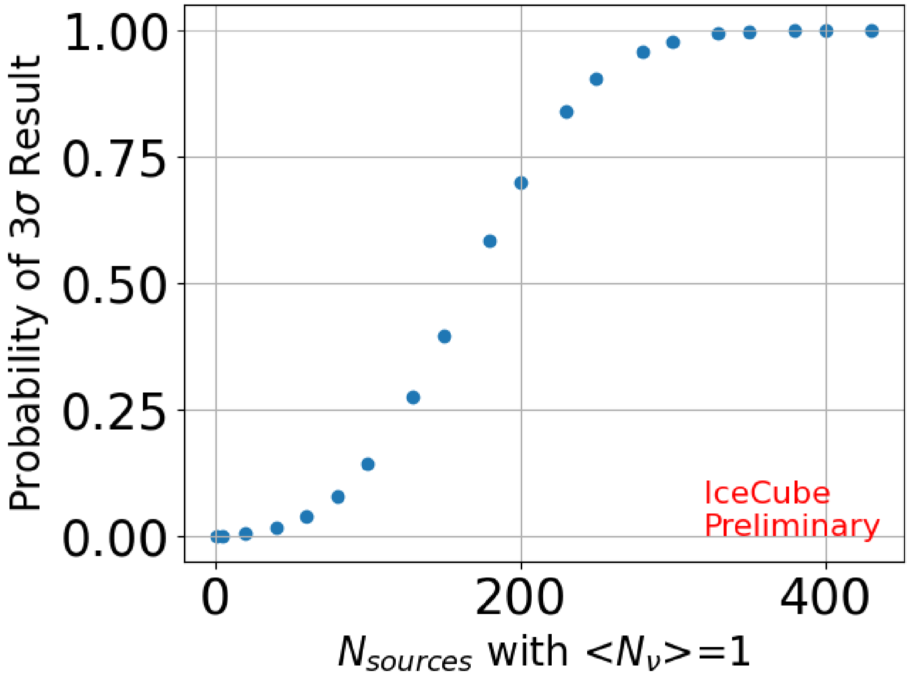
- Model-independent population test analyzing all sources passing redshift and declination cuts
- Calculate individual p-values and look for subthreshold population

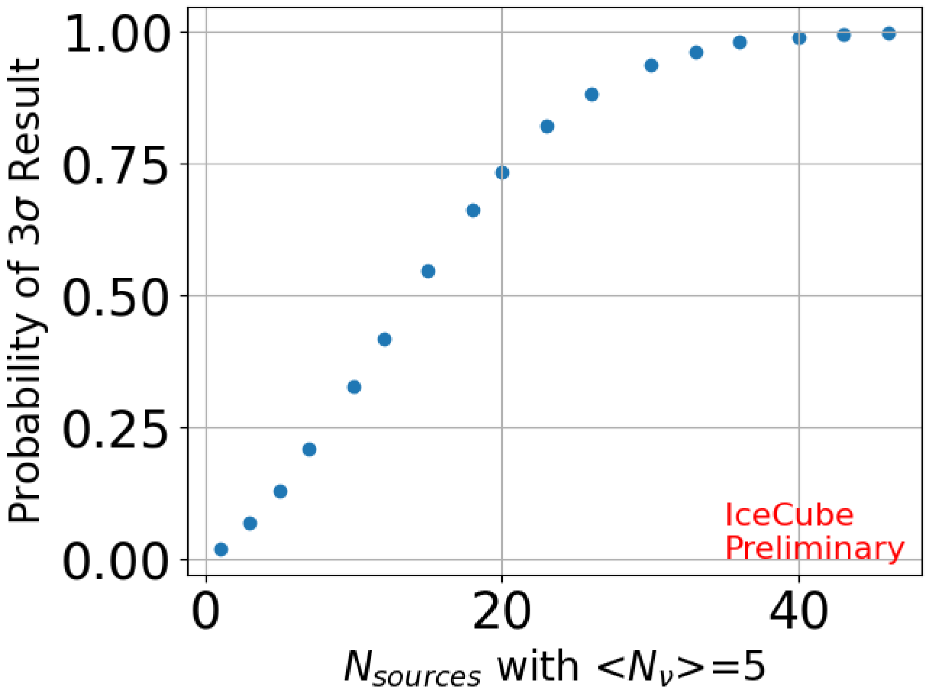
$$TS_{binomial} = min_k \sum_{m=k}^{N} \binom{N}{m} * p_k^m * (1 - p_k)^{N-m}$$

- Probability that more than *k* out of *N* binomial trials would pass if the binomial probability was the kth largest p-val p_k
- Sensitive to scenarios outside of tested models (unknown populations, unknown relationship between gamma rays and neutrinos)

Binomial Test Sensitivities

- N randomly selected neutrino sources in sample,
  - Each with a power law spectrum with $\gamma = 2.0$
  - Same expected value of the number of neutrinos for each source
- Sensitive to reasonably sized subset of subthreshold sources





Summary

- Some previous evidence that gamma-ray bright AGN are sources of IceCube neutrinos
- Significant improvement over previous IceCube gamma-ray AGN population searches
  - Improvements in the quantity of data and analysis methods
- A more model-independent test (binomial test) than previous IceCube analyses
  - Sensitive to any large subset of subthreshold neutrino sources
- Working toward unblinding soon!

Backup Slides

Stacking Test

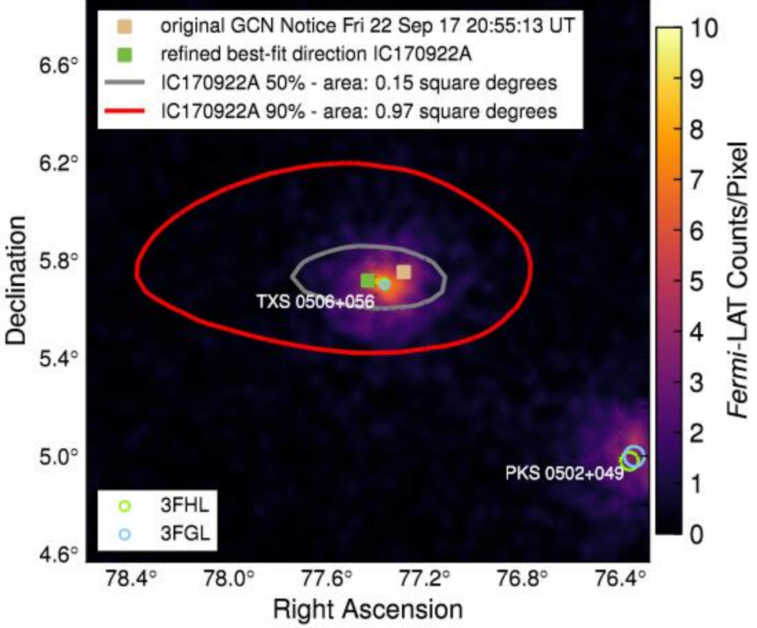
$$S_i^k\left(x_i, x_{S_k}, \sigma_i, E_i, \gamma\right) = S_{i,spatial}^k\,(x_i, x_{S_k}, \sigma_i)^{*} S_{i,energy}^k(E_i, \gamma)$$
$$B_i\,(x_i, \sigma_i, E_i) = B_{i,spatial}(x_i, \sigma_i)^{*}\, B_{i,energy}\,(E_i)$$

$$S_i^{stacked}(x_i, \sigma_i, E_i, \gamma) = \frac{\sum_{k=1}^{M} w^k R^k(\delta_k, \gamma) * S_i^k\left(x_i, x_{S_k}, \sigma_i, E_i, \gamma\right)}{\sum_{k=1}^{M} w^k R^k(\delta_k, \gamma)}$$
$$\mathcal{L}(n_s, \gamma) = \prod_i^N \left(\frac{n_s}{N} * S_{i,stacked}\,(x_i, \sigma_i, E_i, \gamma)\right) + \left(\left(1 - \frac{n_s}{N}\right) * \; B_i(x_i, \sigma_i, E_i)\right)$$
$$TS = 2 * \ln\left(\frac{min_{n_s,\gamma}\,\mathcal{L}(n_s, \gamma)}{\mathcal{L}(n_s = 0)}\right)$$

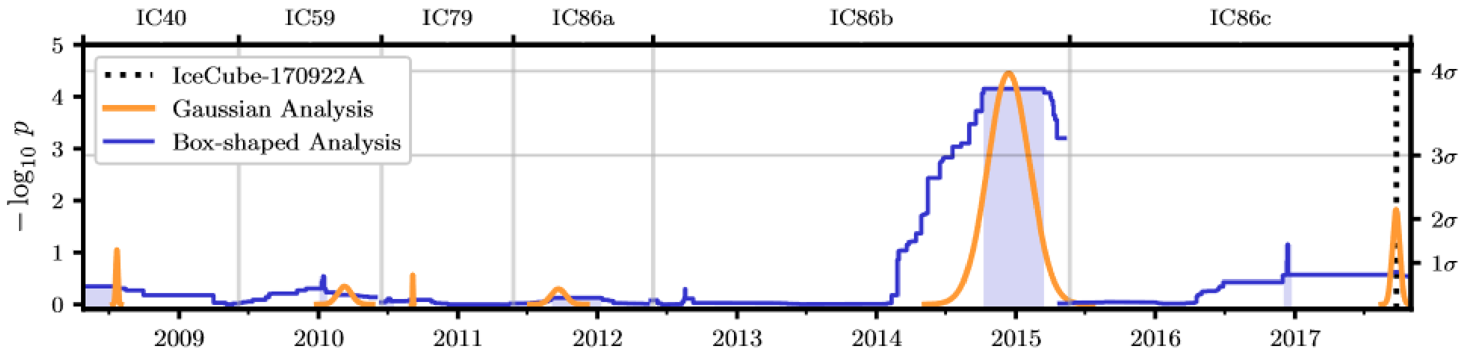
- N neutrinos (indexed with i), each with energy E_i, location $x_i = \;(\alpha_i, \delta_k)$,angular uncertainty σ_i
- M sources (indexed with k), each with weight w^k, location x_{S_k} and detector response R
- Overall normalization of n_s (number of detected neutrinos) with recovered power law spectrum of γ

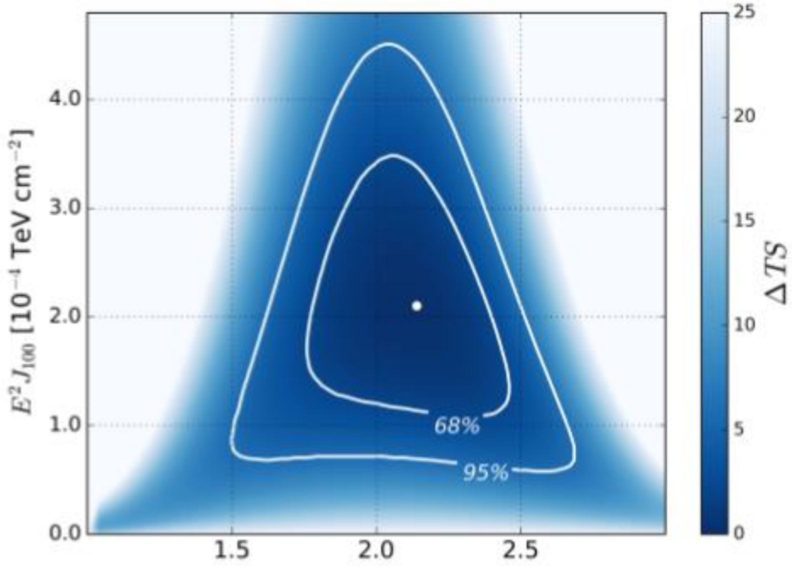
TXS 0506+056

- 2017 neutrino in coincidence with blazar flare
- IceCube follow-up found evidence of 2014 neutrino flare



The IceCube Collaboration *et al.*, Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A. *Science* **361**, eaat1378(2018). DOI: 10.1126/science.aat1378

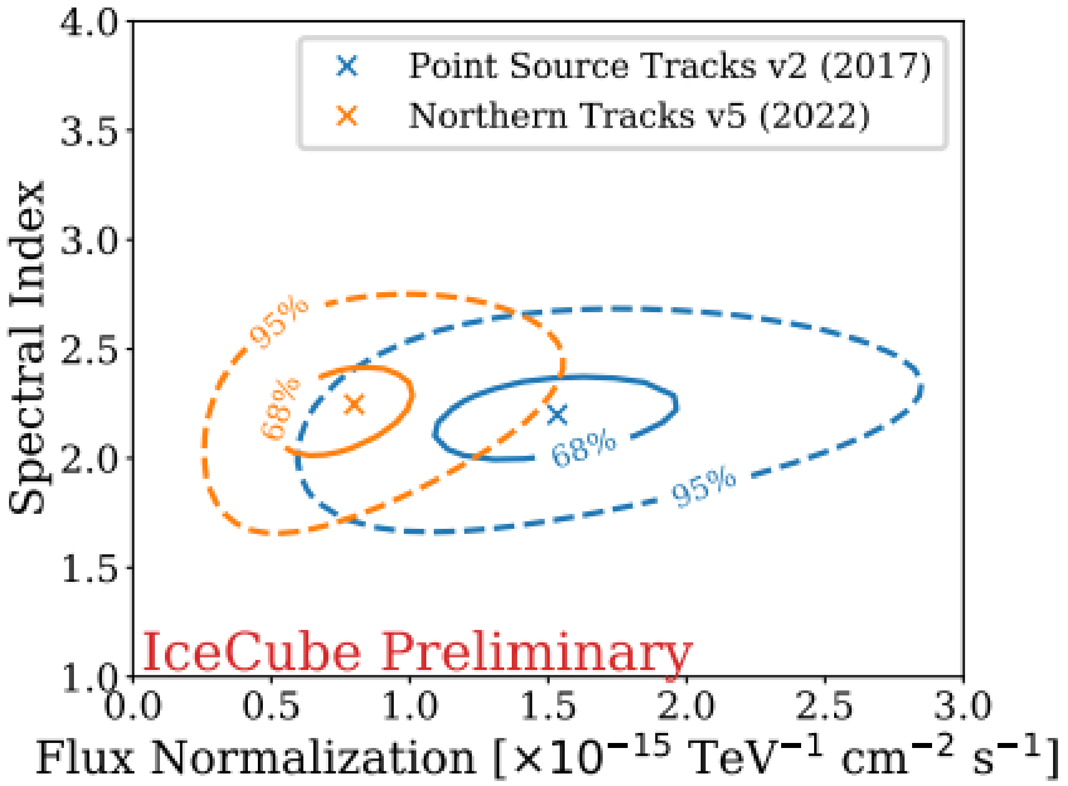




IceCube Collaboration *et al.*, Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert. *Science* **361**, 147-151(2018). DOI: 10.1126/science.aat2890

Updated TXS 0506+056 Analysis

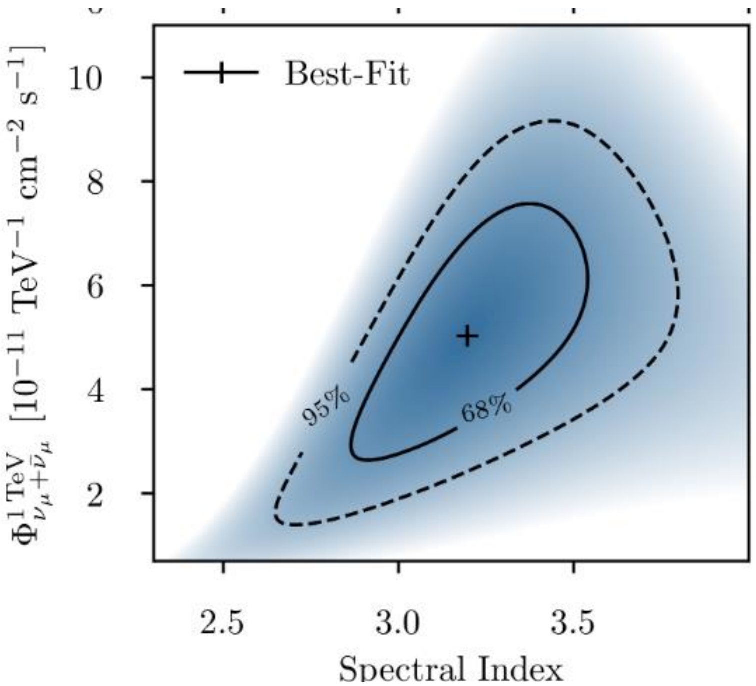
- Updated dataset ("Northern Tracks" with new PSF parametrization)
- Lowered best fit for 2014 flare neutrino flux

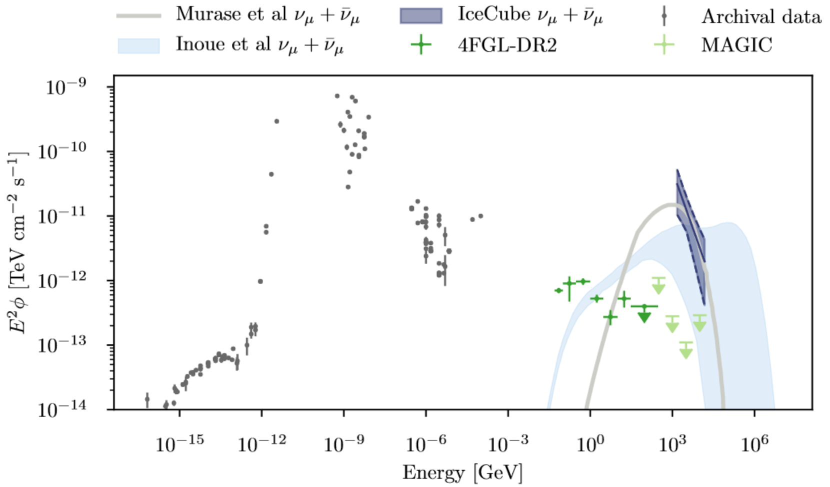


Luszczak, William. "TXS 0506+ 056 with Updated IceCube Data." *arXiv preprint arXiv:2307.14559* (2023).

NGC 1068

- Seyfert and starburst galaxy
- Gamma-ray emission likely associated with starburst
- First known non-transient source of neutrinos
- Neutrino flux exceeds prediction from gamma-ray flux

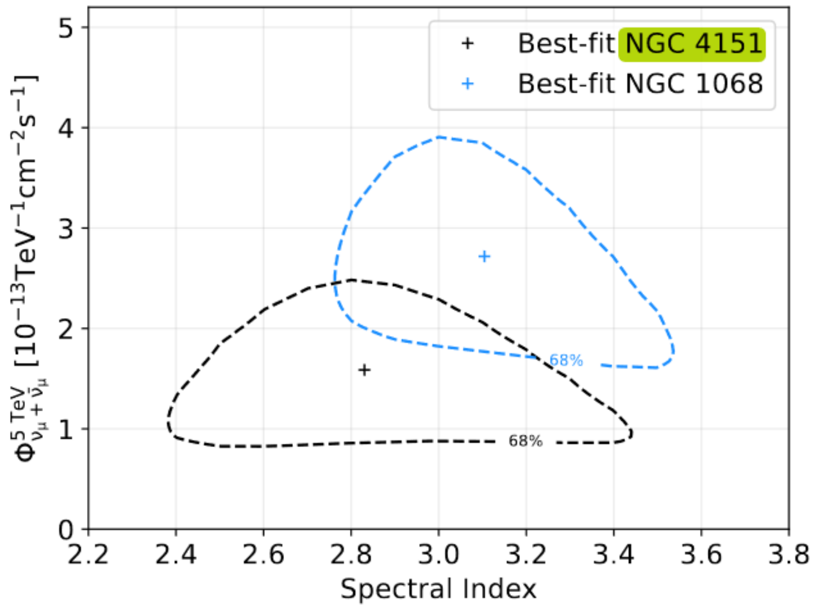


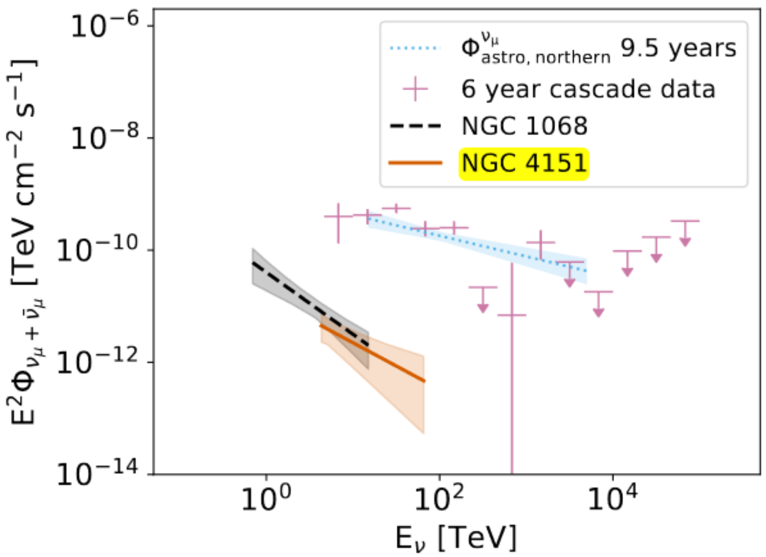


[IceCube Collaboration "Evidence for neutrino emission from the nearby active galaxy NGC 1068." *Science* 378.6619 (2022): 538-543.]

Seyfert

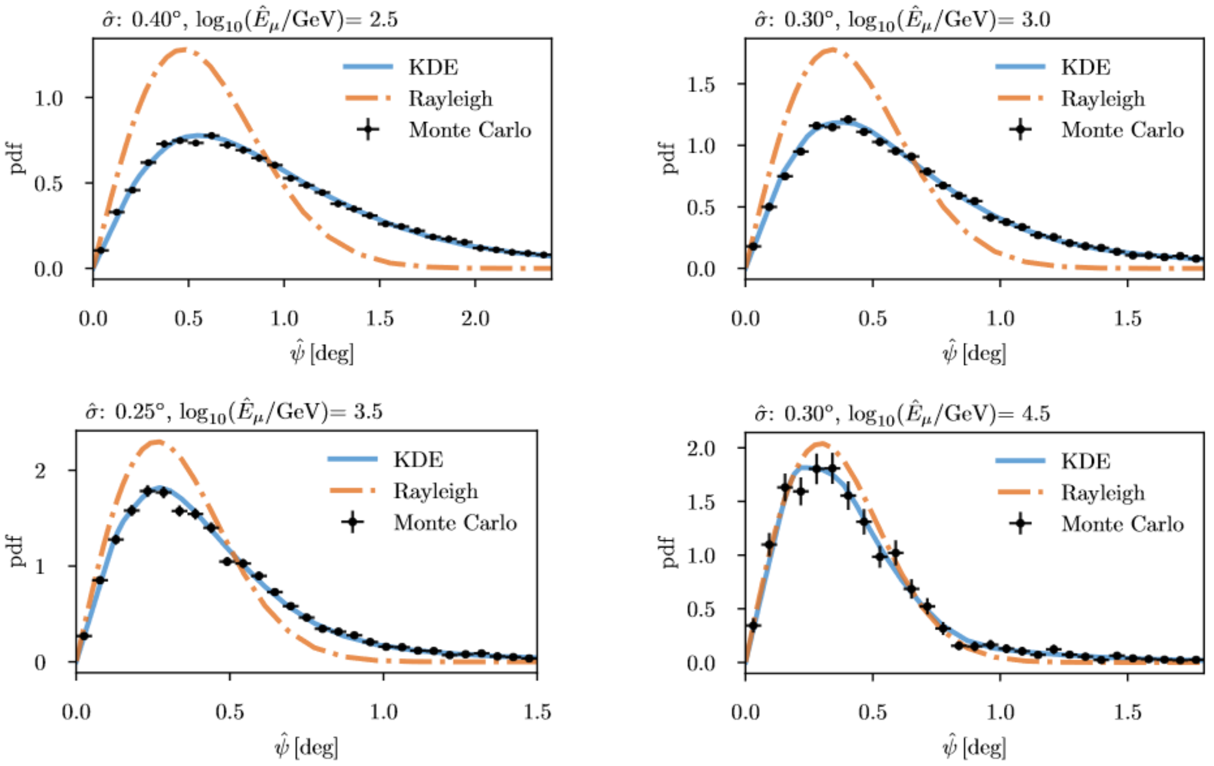
- NGC 1068 detected at over 4σ
- NGC 4151 at 2.9σ



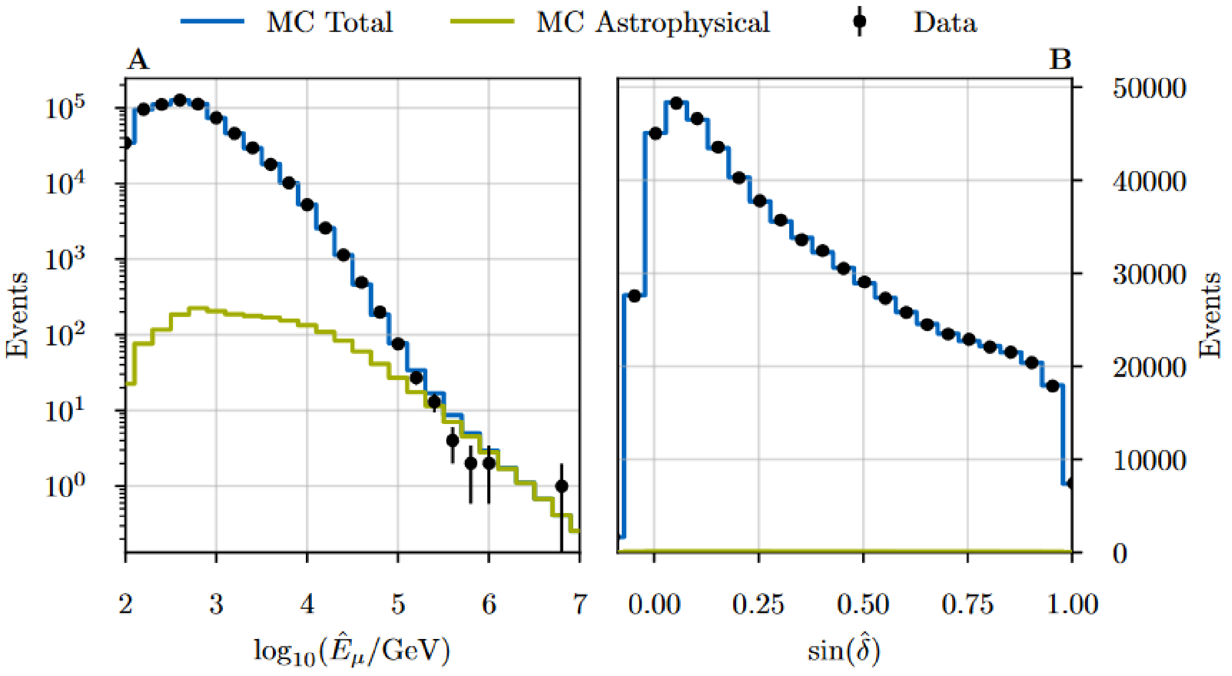


IceCube Search for Neutrino Emission from X-ray Bright Seyfert Galaxies
https://arxiv.org/abs/2406.07601

Northern Track Properties



Angular Reconstruction with KDE



Observed distribution of Northern Tracks events compared to MC expectation

IceCube Collaboration "Evidence for neutrino emission from the nearby active galaxy NGC 1068." *Science* 378.6619 (2022): 538-543.

LAT Population Analyses

Analysis	Source Catalog	Total Number of Blazars	Flux Weight Energy Range (GeV)
Aartsen et al. (2017b)	2LAC	862	0.1 - 100
Huber (2019)	3FHL	745	—
Abbasi (2022)	1FLE	137	0.03 - 0.1

- Tested Weights
  - 2LAC and 1FLE: gamma-ray proportion and equal
  - 3FHL: equal weights, but with decile subgroups constructed based on gamma-ray flux
- Tested subclasses:
  - 2LAC: All blazars, FSRQ, LSP-BLL, ISP/HSP
  - 1FLE: All blazars
  - 3FHL: All Blazar, FSRQ , HSP BLL, LSP/IBP BLL,

Brightest Objects

FSRQs		BL Lacs		Non-Blazar AGNs		
Fermi Name	Associated Source	Fermi Name	Associated Source	Fermi Name	Associated Source	Class
4FGL J2253.9+1609	3C 454.3	4FGL J2202.7+4216	BL Lac	4FGL J0319.8+4130	NGC 1275	rdg
4FGL J2232.6+1143	CTA 102	4FGL J1104.4+3812	Mkn 421	4FGL J0948.9+0022	PMN J0948+0022	nlsy1
4FGL J1504.4+1029	PKS 1502+106	4FGL J0721.9+7120	S5 0716+71	4FGL J1230.8+1223	M 87	rdg
4FGL J1159.5+2914	Ton 599	4FGL J1555.7+1111	PG 1553+113	4FGL J0850.0+5108	SBS 0846+513	nlsy1
4FGL J0108.6+0134	4C +01.02	4FGL J0222.6+4302	3C 66A	4FGL J1829.5+4845	3C 380	css
4FGL J1224.9+2122	4C +21.35	4FGL J0521.7+2112	TXS 0518+211	4FGL J1505.0+0326	PKS 1502+036	nlsy1
4FGL J0237.8+2848	4C +28.07	4FGL J1427.0+2348	PKS 1424+240	4FGL J0308.4+0407	NGC 1218	rdg
4FGL J1635.2+3808	4C +38.41	4FGL J1653.8+3945	Mkn 501	4FGL J0433.0+0522	3C 120	rdg
4FGL J0957.6+5523	4C +55.17	4FGL J0238.6+1637	PKS 0235+164	4FGL J0324.8+3412	1H 0323+342	nlsy1
4FGL J1048.4+7143	S5 1044+71	4FGL J1217.9+3007	B2 1215+30	4FGL J0418.2+3807	3C 111	rdg

4LAC-DR3

- Derived from 12 years of Fermi-LAT gamma-rays above 50 MeV
- Fermi-LAT 2LAC catalog constructed with 2 years with 1017 total gamma rat sources (360 FSRQ/423 BLL)