Searching for high-energy neutrino emission from hard X-ray AGN with IceCube

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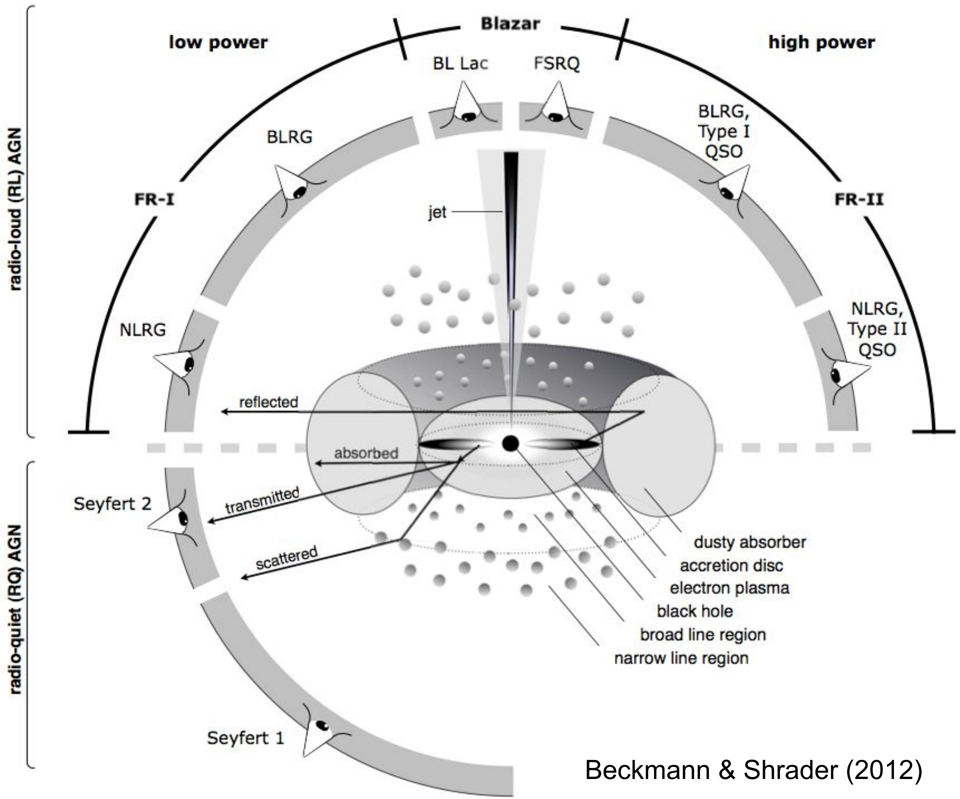
TeVPA 2023
Napoli, Italy
Sept 14th 2023

ICECUBE NEUTRINO OBSERVATORY
NSF
THE UNIVERSITY OF ALABAMA

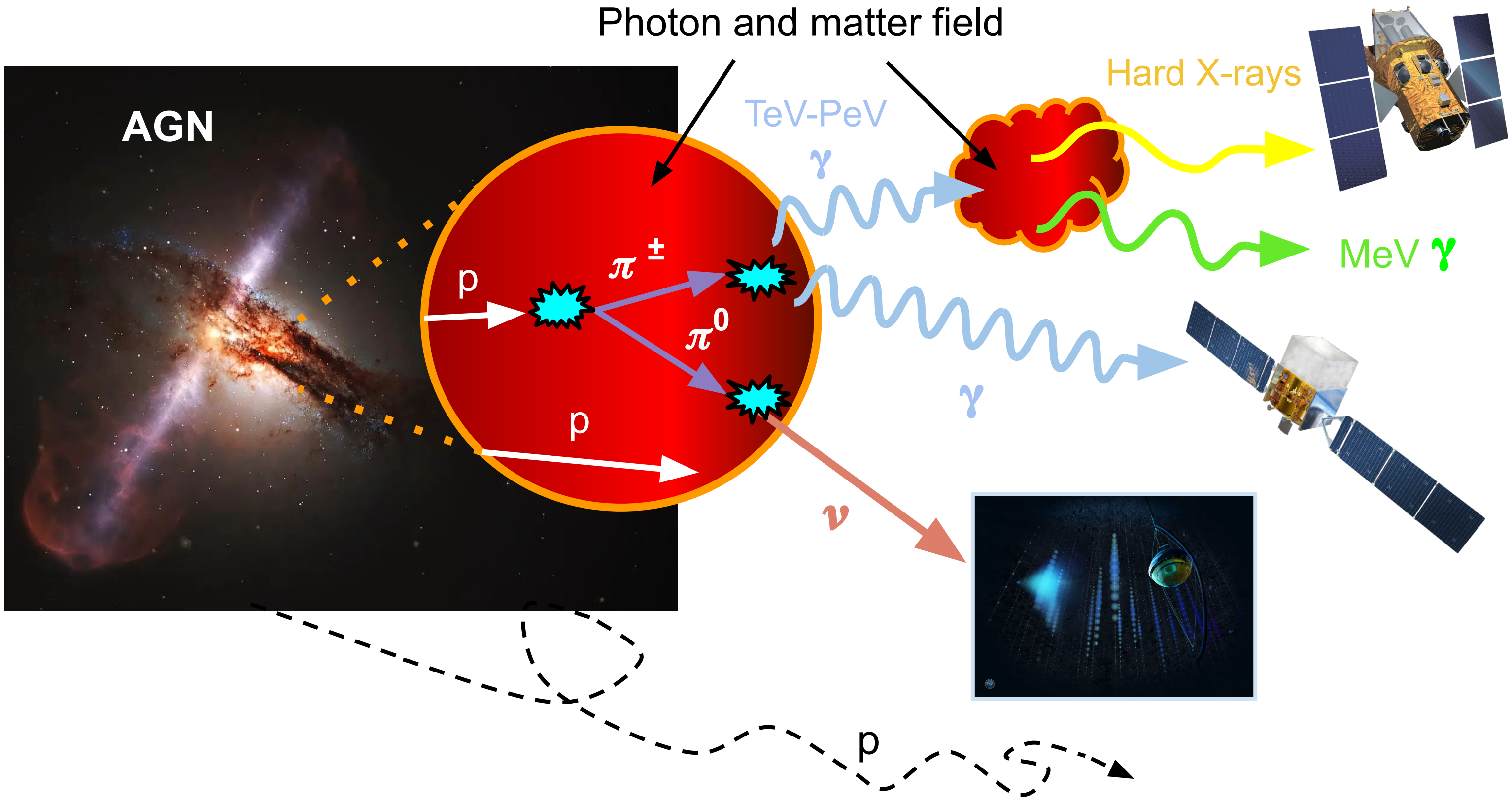
High-Energy Neutrinos from AGN

- Long-time candidate for hadronic acceleration and high-energy neutrinos
- Extremely luminous and large magnetic fields
- Evidence of neutrino emission from
  - Blazar TXS 0506 The IceCube Collaboration et al. Science (2018)
  - Seyfert NGC 1068 R. Abbasi et al. Science (2022)



Beckmann & Shrader (2012)

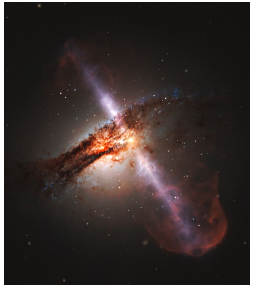
High-Energy Neutrino Production



Credit: ESA/Hubble, L. Calçada (ESO), Nicolle R. Fuller, IceCube/NSF, https://science.nasa.gov/get-involved/toolkits/spacecraft-icons Sreetama Goswami

Why Hard X-rays?

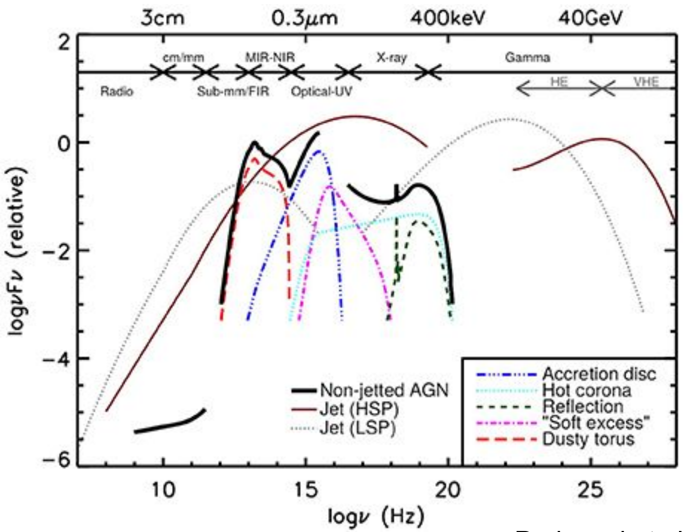
Hard X-rays let us peer into the core



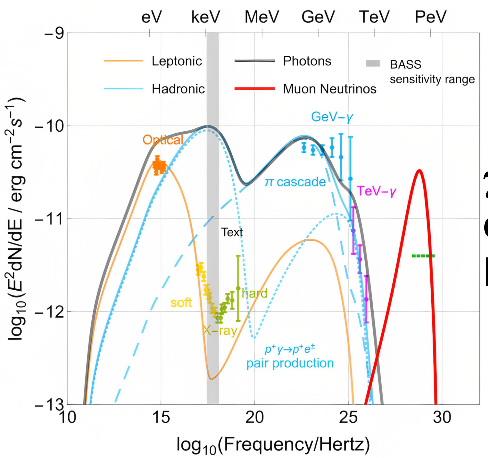
Credit: ESA/Hubble, L. Calçada (ESO)

Models of hadronic acceleration in corona
- Diffusive shock acceleration (Inoue et al. 2019)
- Stochastic acceleration (Murase et al. 2020, Kheirandish et al 2021)

Corona emission peaks in hard X-rays



Padovani et al. (2017)

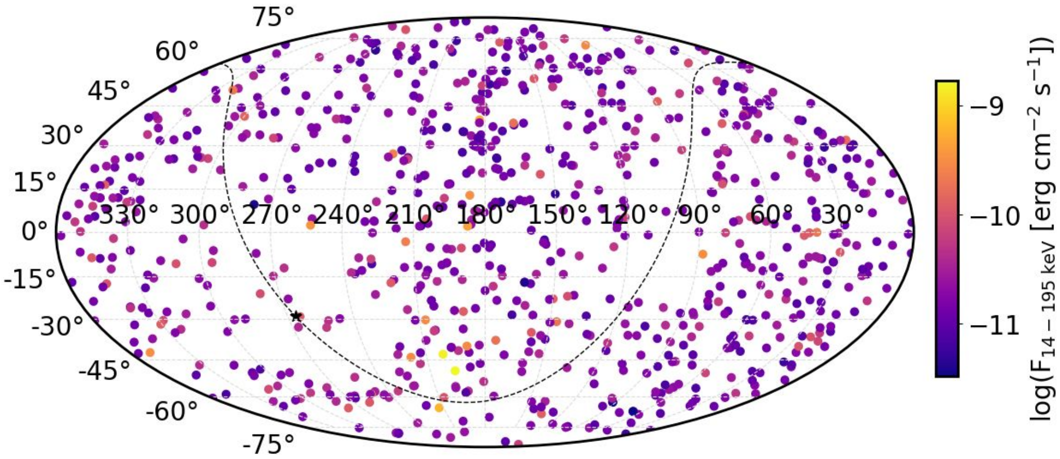


Credit: S. Gao et al. Nat. Astron. 3 (2019) 88–92.

$\gamma\gamma$ interactions cascade down to hard X-ray - MeV γ's

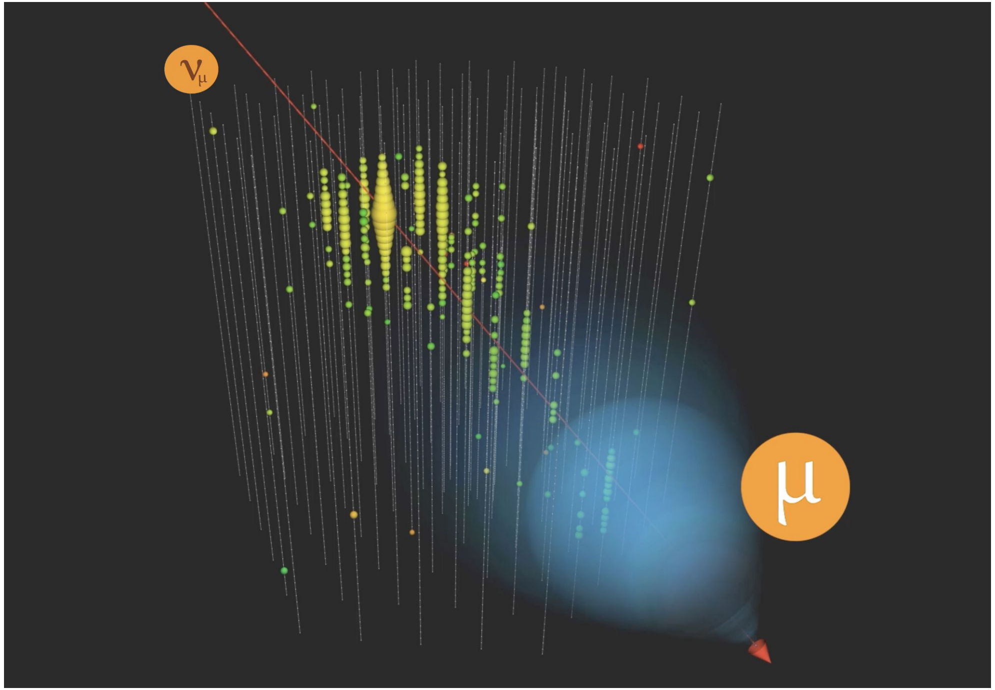
BAT AGN Spectroscopic Survey (BASS)

- AGN detected by Swift-BAT in 70 month survey
  - Most complete hard X-ray (15-195 keV) survey of the sky
  - 838 AGN
- Additional optical and X-ray observations
- X-ray spectral modelling and classification
- See more about BASS here



IceCube Data

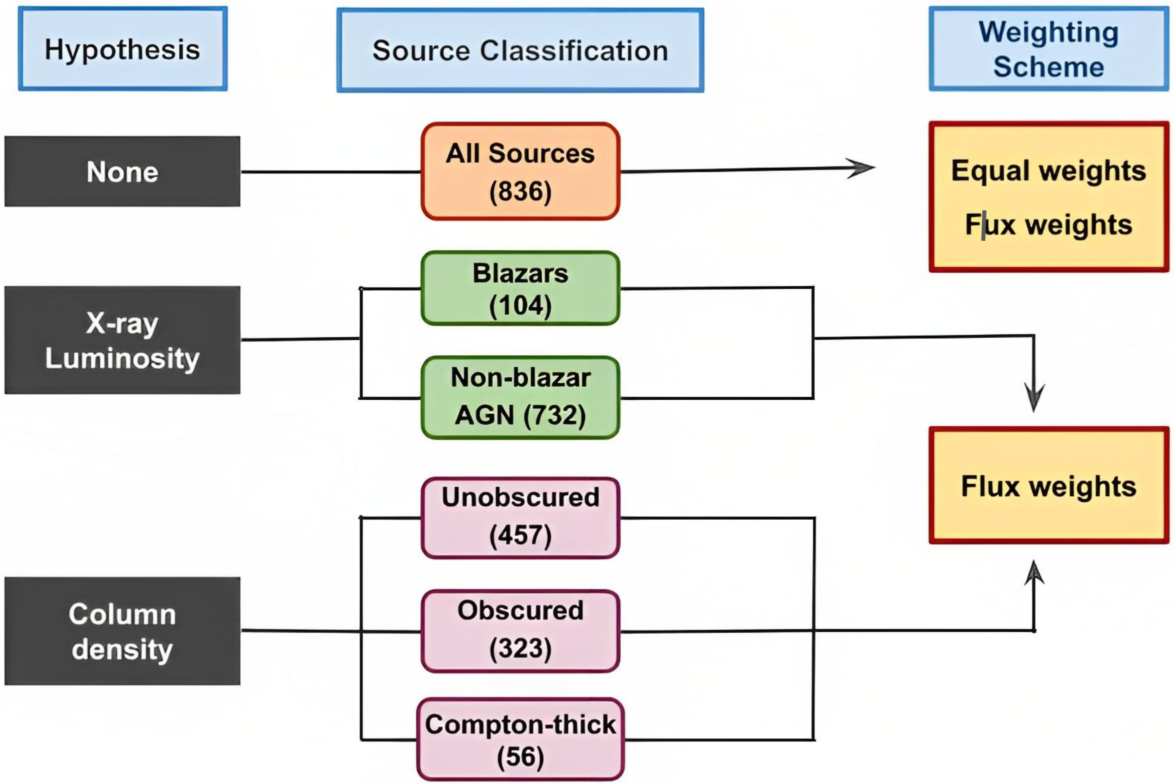
- Through-going tracks
- Full sky
- 12 years of data
- Background dominated
- Same selection criteria used in 10 year analysis that observed NGC 1068 at 2.9σ
  - +2 years of data
  - updated calibration



Analysis I - Stacking

- Unbinned likelihood analysis
- Stacked and weighted by intrinsic flux 14-195 keV
- Testing 7 different subsets

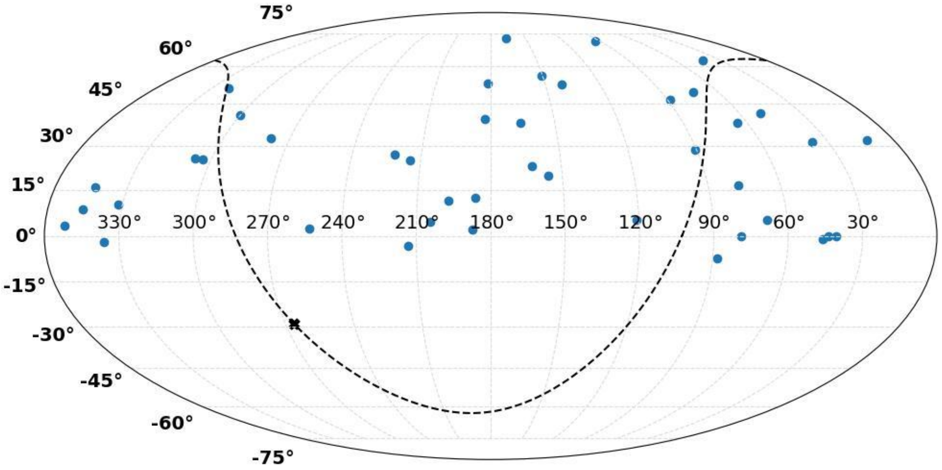
Column density class	log N_H in cm^{-2}
Unobscured	< 22
Obscured	22 - 24
Compton thick	> 24



Analysis II - Single Sources

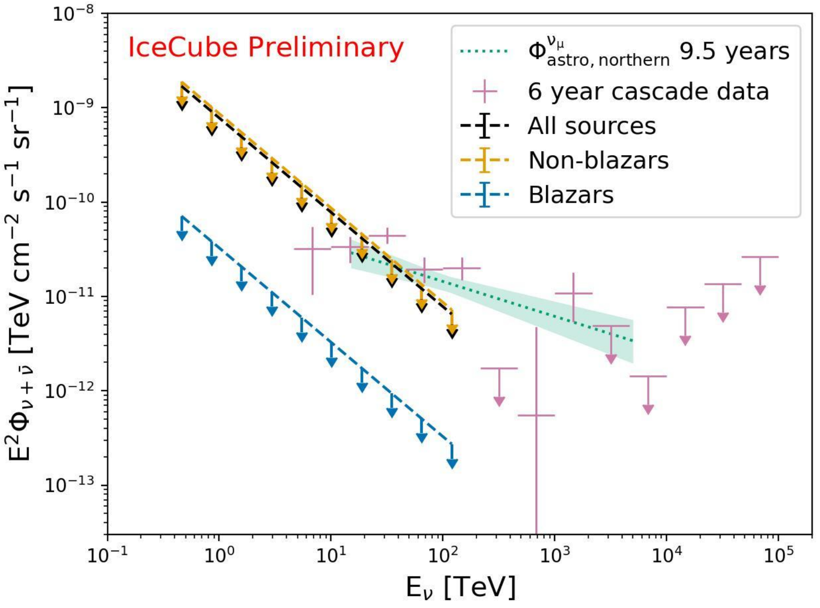
- Perform single source analyses on most optimistic sources, search for hottest source
- Select sources within factor of 10 of max "effective weight"

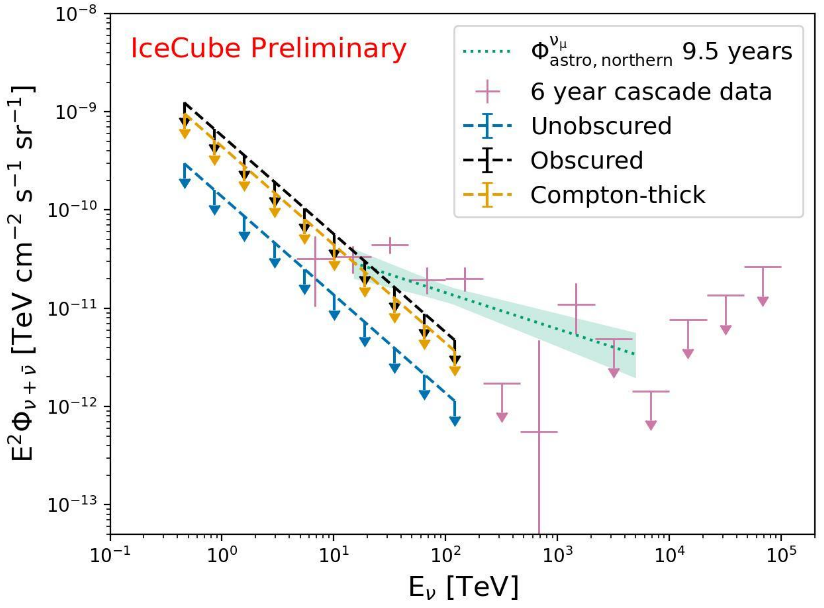
$$\text{Effective weight} = \frac{\text{Intrinsic hard X-ray flux in the 14-195 keV range}}{\text{Sensitivity flux at the source declination}}$$



- 43 sources
- Includes NGC 1068 (ignore in test)
- NGC 4151 highest weight

Results I - Stacking



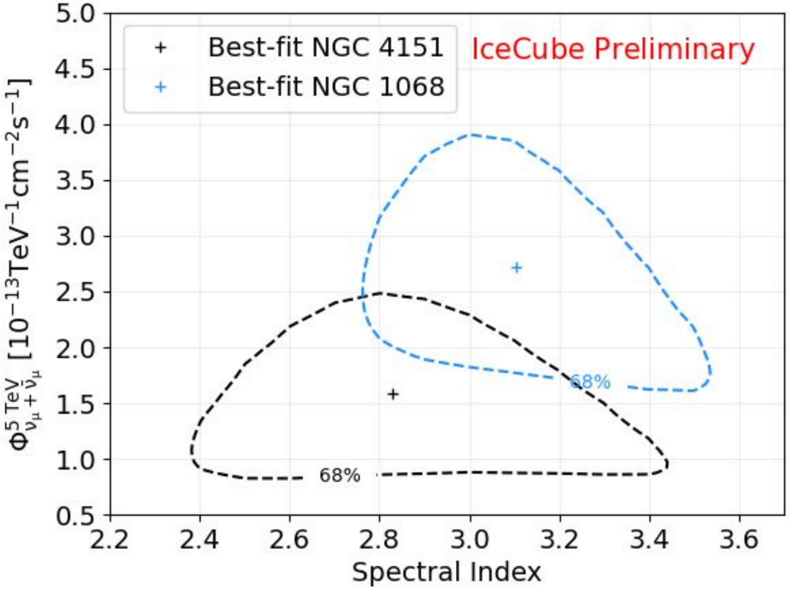


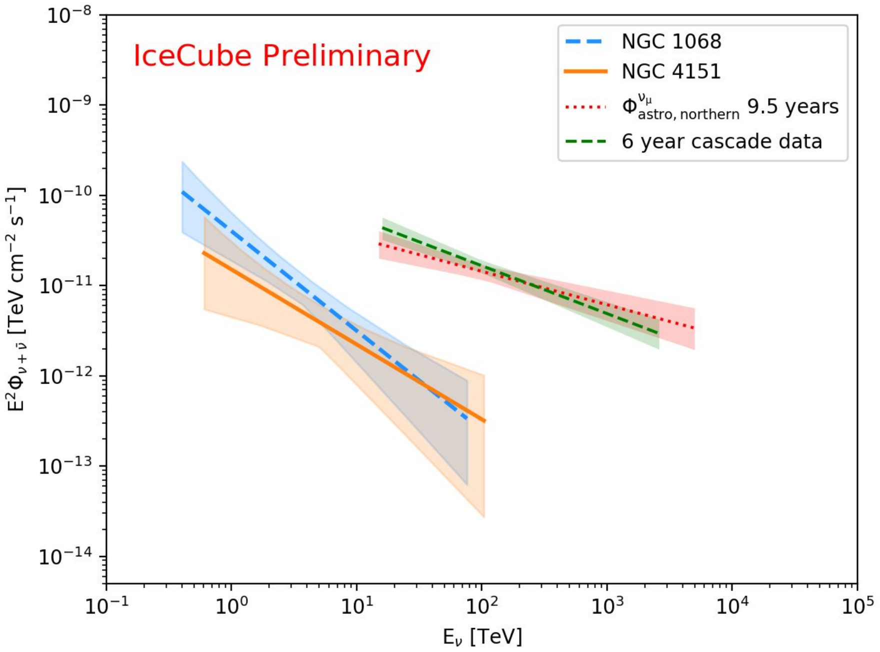
- Nothing significant found in all 7 tests.
- Upper limits corrected for completeness
- Can not rule out diffuse flux from all AGN / non-blazars

Results II - Single Sources

Source	ns	Neutrino flux @ 1 TeV (GeV^{-1} cm^{-2} s^{-1})	γ
NGC 1068	81.7	4.02×10^{-14}	3.10
NGC 4151	49.8	1.51×10^{-14}	2.83

- NGC 1068 most significant source (but ignored for test)
  - Results consistent with other analyses
- Excess at NGC 4151 observed at **2.9σ** post-trials





Similar sources

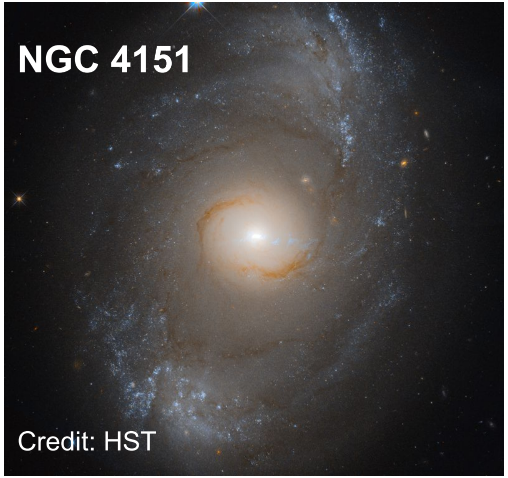
- Both Seyferts
- BH mass both ~10^7 $M_\odot$ (Caroline A. Roberts et al 2021, C. M. Violette Impellizzeri et al 2019)
- Distances: NGC 1068 ~ 11 Mpc, NGC 4151 ~ 14 Mpc (Tikhonov, N. A et al. 2021)

Similar soft flux

- Both well above gamma-ray flux (extrapolated from GeV energies)

Conclusions / Summary

- Nothing significant observed in stacking analysis
  - Not able to rule out AGN as major source of diffuse flux
  - Assuming power-law index = 2.5, Blazars contribute at most 7% of diffuse flux
- If excess is actually from NGC 4151
  - Second excess from Seyfert
  - Similar soft flux as seen from NGC 1068
    - Two of the brightest and closest Seyferts
  - May be an emerging population
    - Difficult to reproduce the harder diffuse flux with these soft sources
- Two excesses observed but nothing significant in stacking, hints that correlation between neutrino and hard X-ray flux may not be so simple



Backups

Analysis I - Stacking

$$\log \mathcal{L} = \sum_i^N \log \left(\frac{n_s}{N} \cdot S(\delta_i, \alpha_i, \sigma_i, E_i; \gamma) + (1 - \frac{n_s}{N}) B(\delta_i, E_i) \right)$$

$$\mathrm{S}(\delta_i, \alpha_i, \sigma_i, E_i; \gamma) \longrightarrow S(\delta_i, \alpha_i, \sigma_i, E_i; \gamma) = \frac{\sum_k^M w_k S_k(\delta_i, \alpha_i, \sigma_i, E_i; \gamma)}{\sum_k^M w_k}$$

Signal PDF

$$w_k = w_k^{\mathrm{model}} A(\delta_k)$$

Weight for the *k*th source

Detector Acceptance at the declination of source k

Full Stacking Results

Source Type	Weights used	ns	Neutrino flux @ 1 TeV (GeV^{-1} cm^{-2} s^{-1})	γ	Pre-trial p-value
All sources	Equal weights	0	0	0	1.0 (0.0σ)
All sources	Hard X-ray flux	161	1.16×10^{-13}	2.89	0.01 **(2.2σ)**
Blazars	Hard X-ray flux	10	8.80×10^{-16}	2.04	0.14 **(1.1σ)**
Non-blazars	Hard X-ray flux	180	1.47×10^{-13}	3.02	0.01 **(2.4σ)**
Compton-thick	Hard X-ray flux	45	5.90×10^{-14}	3.14	0.12 **(1.2σ)**
Obscured	Hard X-ray flux	148	1.06×10^{-13}	2.91	0.003 **(2.7σ)**
Unobscured	Hard X-ray flux	0	0	0	1.0 (0.0σ)

Catalog Completeness

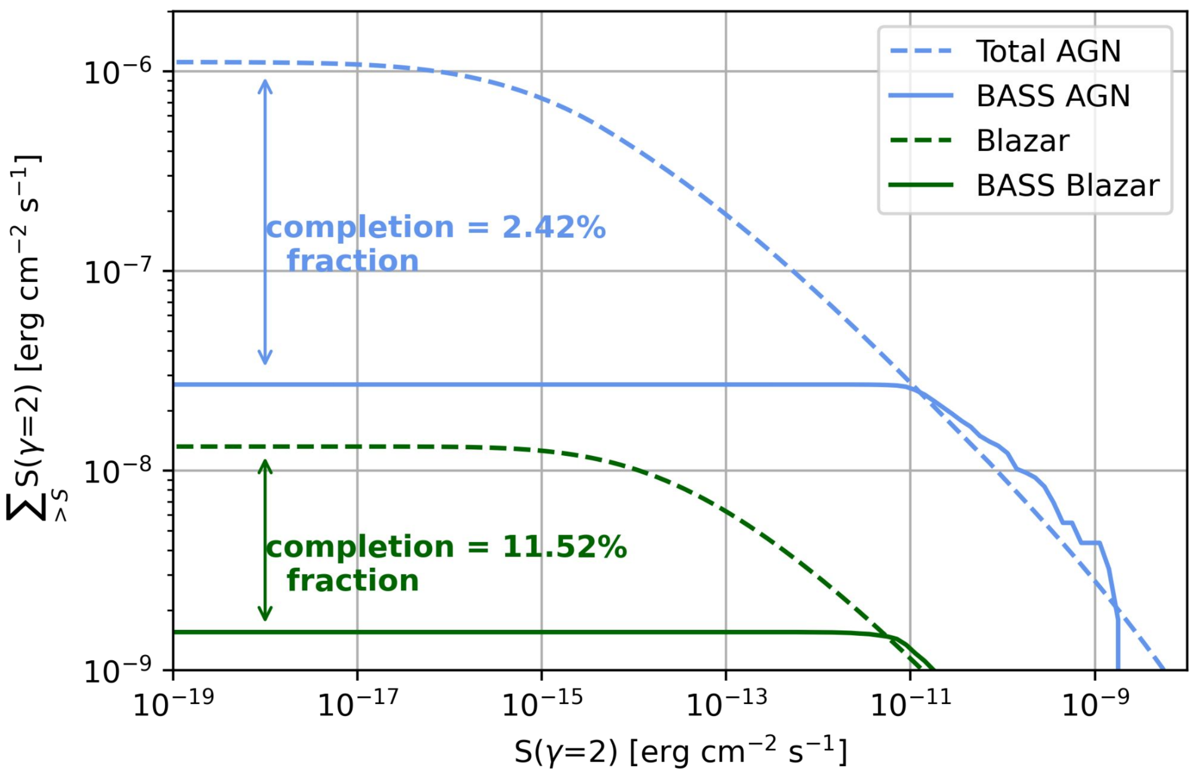
- Selected AGN form a subset of all AGN in observable universe ➞ Need to account for undetected AGN.
- Scale the resultant flux to evaluate contribution from entire source population.
- Hypothesis: neutrino flux ∝ intrinsic X-ray flux ➞ Adjusted for redshifted energy.
- Find total flux from whole source population by integrating luminosity function.

$$\text{Effective Completeness} = \frac{\text{Expected } \nu \text{ flux from catalog sources}}{\text{Expected } \nu \text{ flux from whole source population}}$$

Population	Effective Completeness (E^{-2})	Effective Completeness (E^{-3})
All AGN (flux weights)	2.42%	4.01%
Non-blazar AGN (flux weights)	2.3%	3.86%
Blazars (flux weights)	11.52%	17.97%
Unobscured (flux weights)	5.05%	8.06%
Obscured (flux weights)	2.26%	3.78%
Compton Thick (flux weights)	1.52%	2.59%

Luminosity function :

- Non-blazar AGN from Yoshihiro Ueda et al 2014
- Blazars from L. Marcotulli et al 2022



$S(\gamma) = F_{Int} * (1+z)^{-\gamma}$