
Active Galactic Nuclei as sources of the diffuse astrophysical neutrino flux

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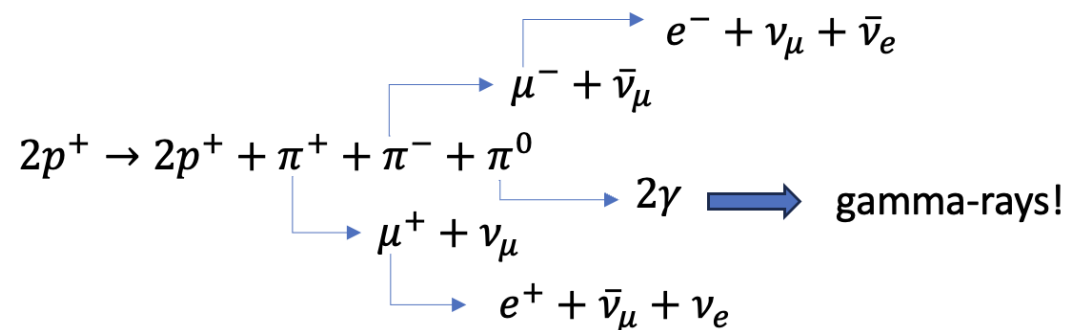
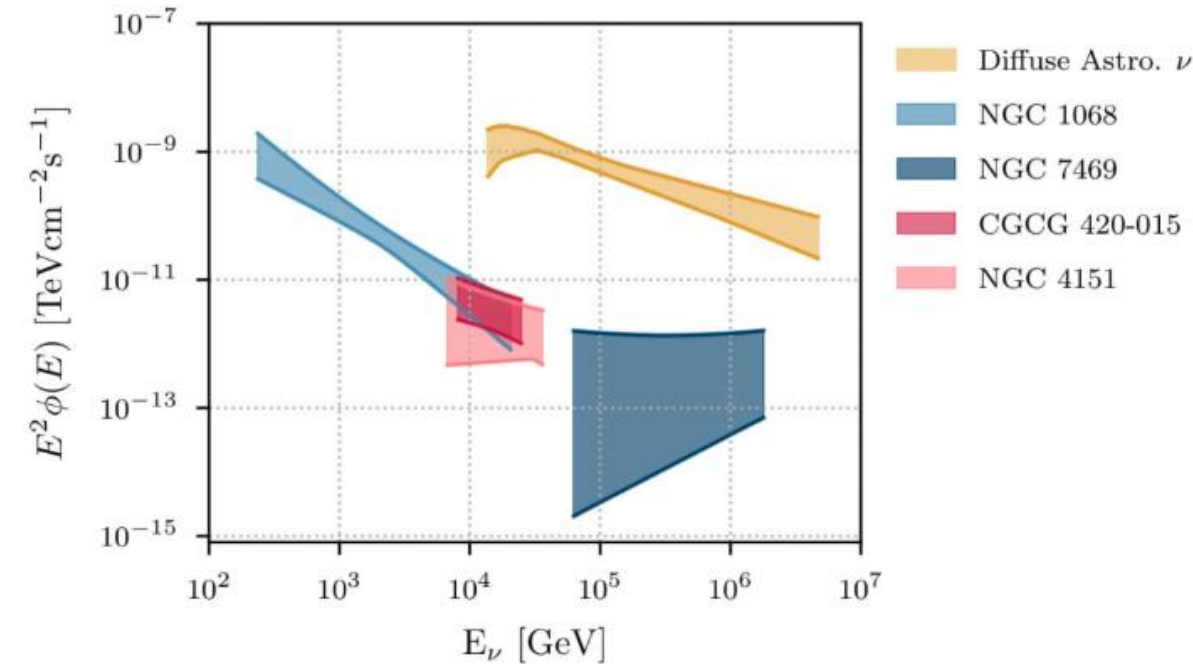
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Neutrinos astronomy – status and questions

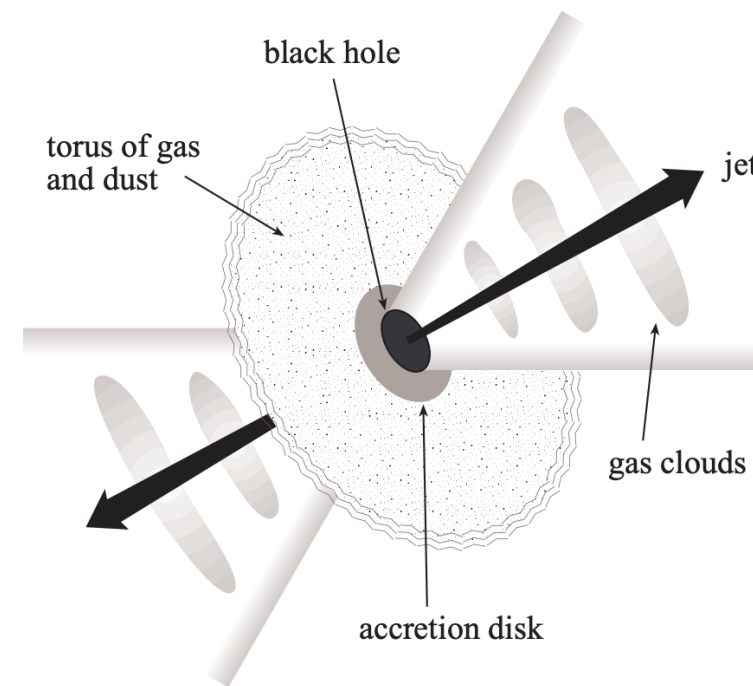
- High energy neutrinos are a smoking gun for cosmic ray acceleration
- IceCube has detected a few significant neutrino sources –
 - NGC 1068 – X-ray bright AGN (4.7σ)
 - TXS 0506+56 – flaring blazar (3.5σ)
- Also detected an extragalactic diffuse flux of astrophysical neutrinos – where does it come from?
- Expect correlated neutrino and gamma-ray fluxes, but gamma-ray bright sources have been largely excluded as neutrino sources. Why?



Active Galactic Nuclei (AGNs) as sources of the diffuse flux



- AGNs - galaxies with supermassive black-holes at the core actively accreting matter, among the most luminous objects in the universe
- Intense magnetic fields make them promising cosmic-ray accelerators
- NGC 1068, the brightest neutrino source identified so far, is an X-ray bright AGN, with
 - Strong neutrino emission between 1-10 TeV
 - Strongly constrained gamma-ray flux in the same energy regime
 - A dense, optically thick corona around the SMBH
- In gamma-ray opaque environments, photons from π_0 decay may cascade down to keV energies (X-ray regime). Alternatively, X-ray radiation fields may act as targets for $p\gamma$ interactions



X-ray bright AGN may be promising neutrino sources!

Can we find correlations between X-ray/Gamma-ray and neutrino luminosities of AGNs?



Setting up the analysis

- Stacking – look for signal from an ensemble of sources under a common hypothesis for the neutrino luminosity for each source
- Let us consider a hypothesis $F_{\nu}^i = c F_X^i$ for a common spectral index α of the neutrino flux
- For a single source and energy bin, for n_s out of N events coming from the source, we construct the likelihood (probability of obtaining a given event distribution) as

$$\mathcal{L}(n_s) = \prod_i^N \left[\frac{n_s}{N} S_i(|\vec{x}_s - \vec{x}_i|) + \left(1 - \frac{n_s}{N}\right) B_i(\sin \delta_i) \right]$$

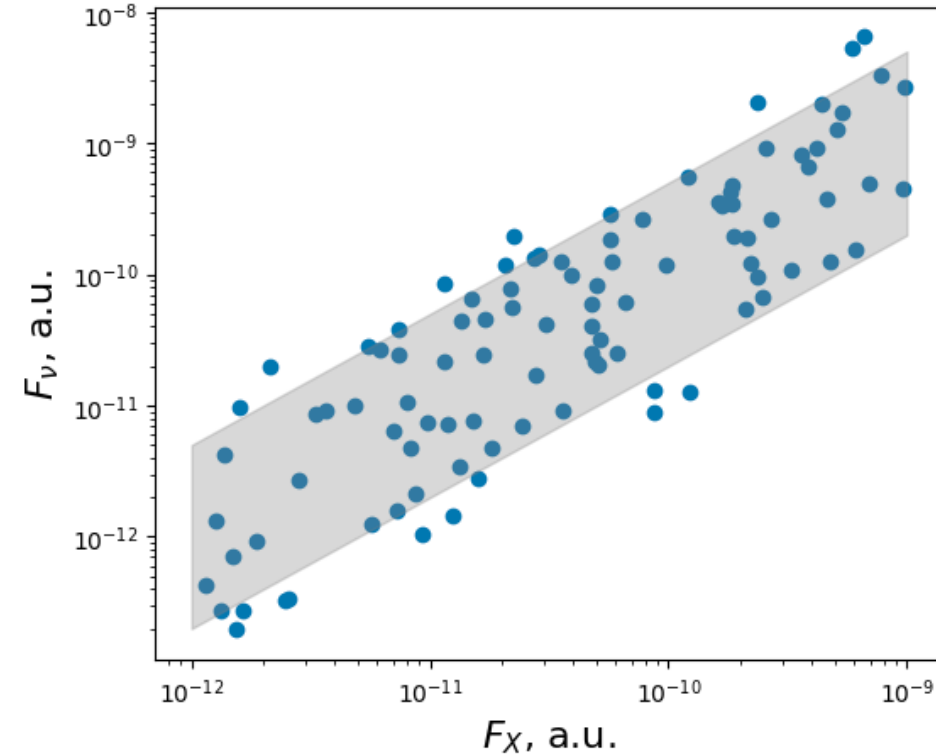
This likelihood is multiplied across all events, energy bins, and sources

$$\text{TS} = 2[\ln \mathcal{L}(c) - \ln \mathcal{L}(0)]$$



Source to source variation

- Realistically, one would expect some random scatter around such a correlation



Mock
correlation
with scatter

- We thus introduce a parameter δ , such that each source's neutrino flux follows a log-normal PDF –

$$\frac{dP}{dF} = \frac{1}{\sqrt{2\pi}\delta F} \exp\left(-\frac{(\ln F/F_0)^2}{2\delta^2}\right)$$

where F_0 is the flux one would expect without any source-to-source variation

Not accounted for in
traditional stacking
analyses



Source to source variation

- Since the PDF is log-normal, the average flux expectation is given by

$$\langle F \rangle = \int_0^\infty F \frac{dP}{dF} dF = F_0 \exp\left(\frac{\delta^2}{2}\right)$$

- We thus define our final likelihood in terms of the total *average* flux from the source population and δ as

$$\mathcal{L}(\vec{F}, \delta) = \prod_k \int_0^\infty \mathcal{L}(F'_k) \frac{1}{\sqrt{2\pi} \delta F'_k} \exp\left(-\frac{(\ln F'_k / F_k^0)^2}{2\delta^2}\right) dF'_k$$



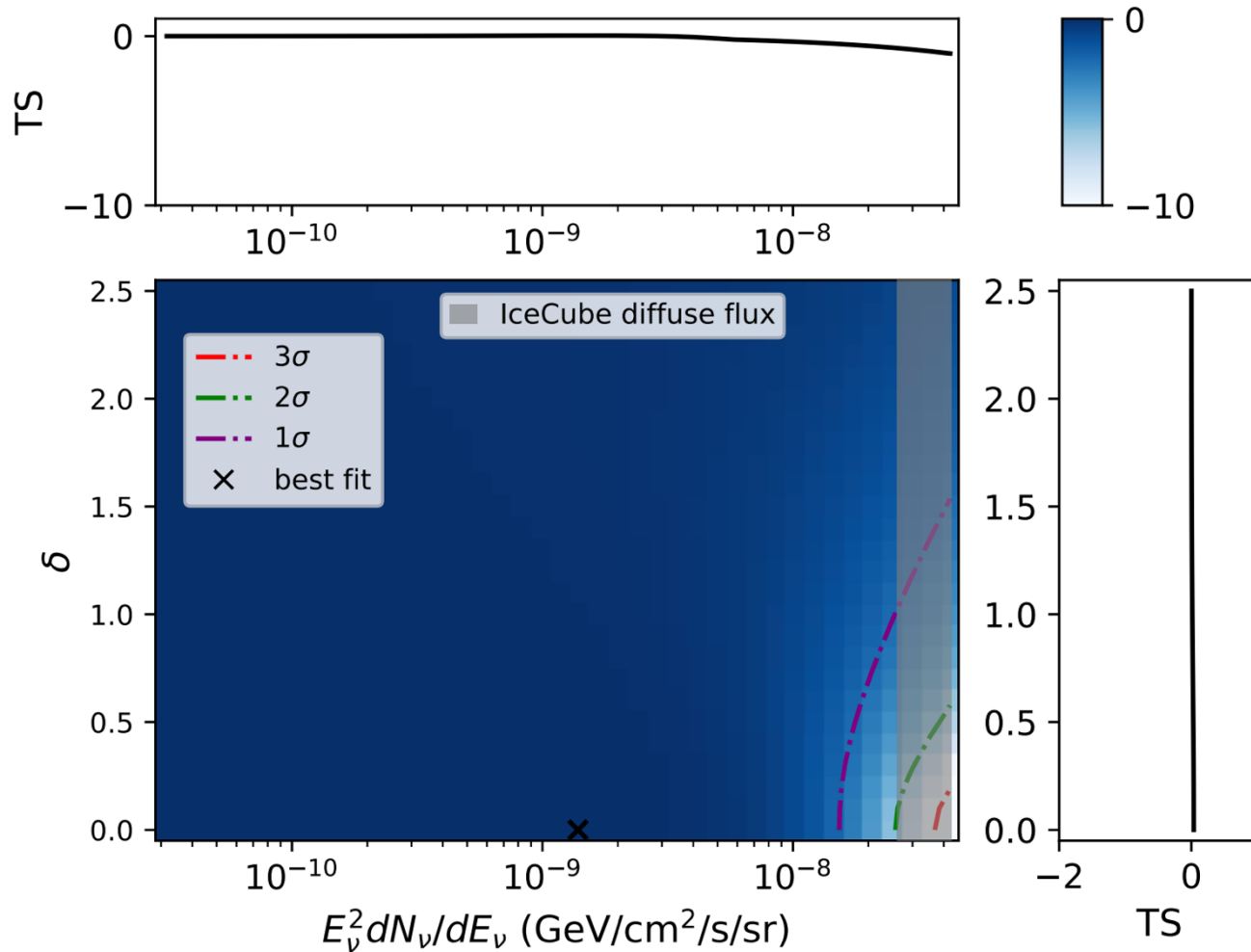
Methods

- Fermi 4LAC and Swift-BAT 70-month surveys provide the γ -ray and X-ray bright populations. IceCube's 10-year dataset of track events used.
- For each population, we test the
 - X-ray/Gamma-ray proportionality where applicable
 - geometrical scaling - $F \sim \frac{1}{D_L^2}$, where D_L is the luminosity distance
- Treat blazars and non-blazars separately, and test 2 spectral indices – 2.5 (diffuse flux) and 3 (NGC 1068)
- Obtain TS profiles in terms of total *average* flux at 30 TeV and δ
- Scale the total average flux via a completeness factor to obtain constraints on the flux from the entire source class
- How much can each source class contribute to the diffuse neutrino flux (at 30 TeV)?



Results – Gamma-ray bright non-blazars

Fermi-4LAC Non-Blazar AGN
Gamma-Ray Scaling, $\alpha = 3$



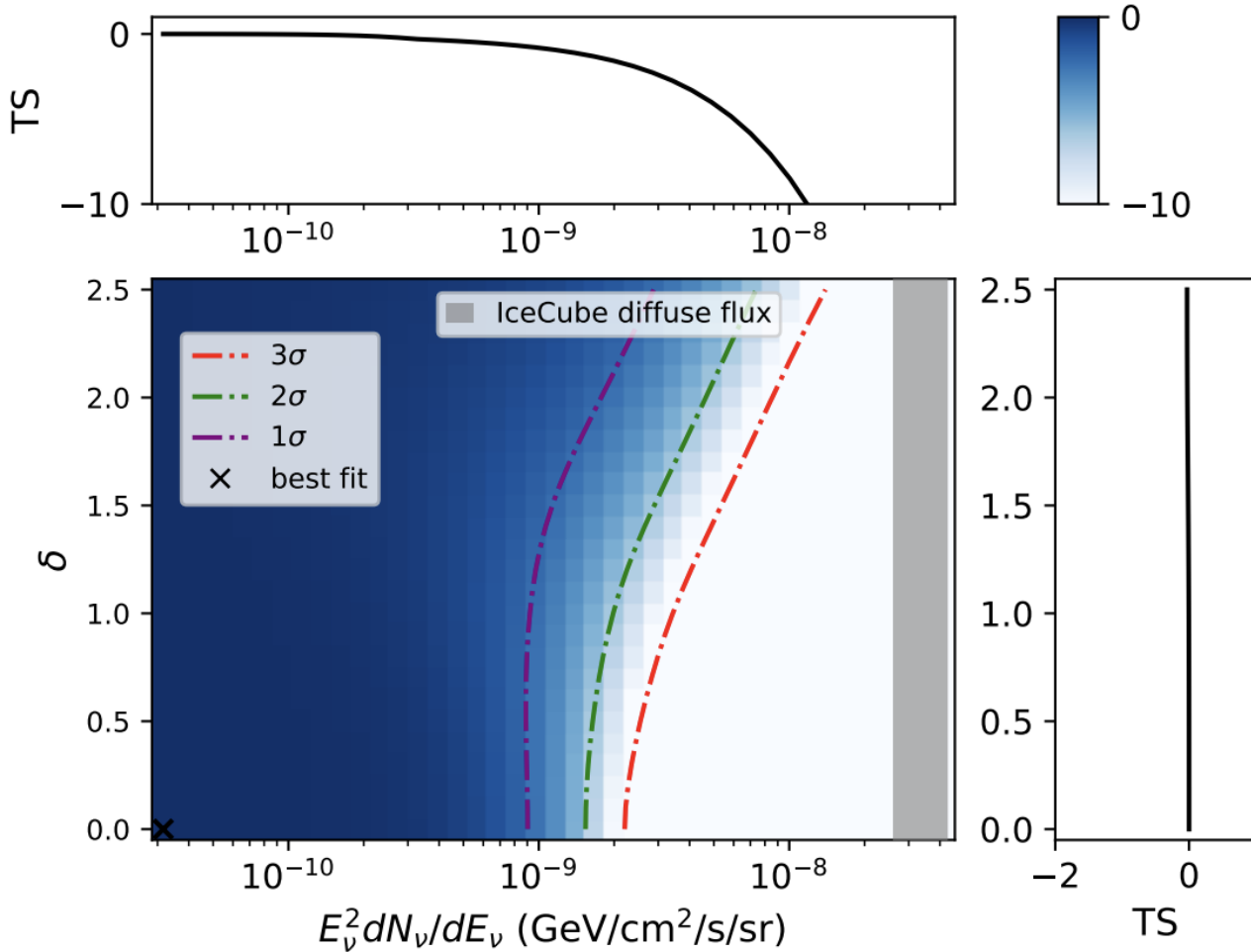
Gamma-Ray-Bright, Non-Blazar AGN (Fermi, 4LAC-DR3)

Hypothesis	Significance (σ)	Contribution to F_ν^{diffuse} (2σ)
Gamma-Ray Scaling, $\alpha = 2.5$	0.0	No Constraint
Geometric Scaling, $\alpha = 2.5$	0.0	No Constraint
Gamma-Ray Scaling, $\alpha = 3.0$	0.02	No Constraint
Geometric Scaling, $\alpha = 3.0$	0.0	No Constraint



Results – Gamma-ray bright blazars

Fermi-4LAC Blazar AGN
Geometric Scaling, $\alpha = 2.5$



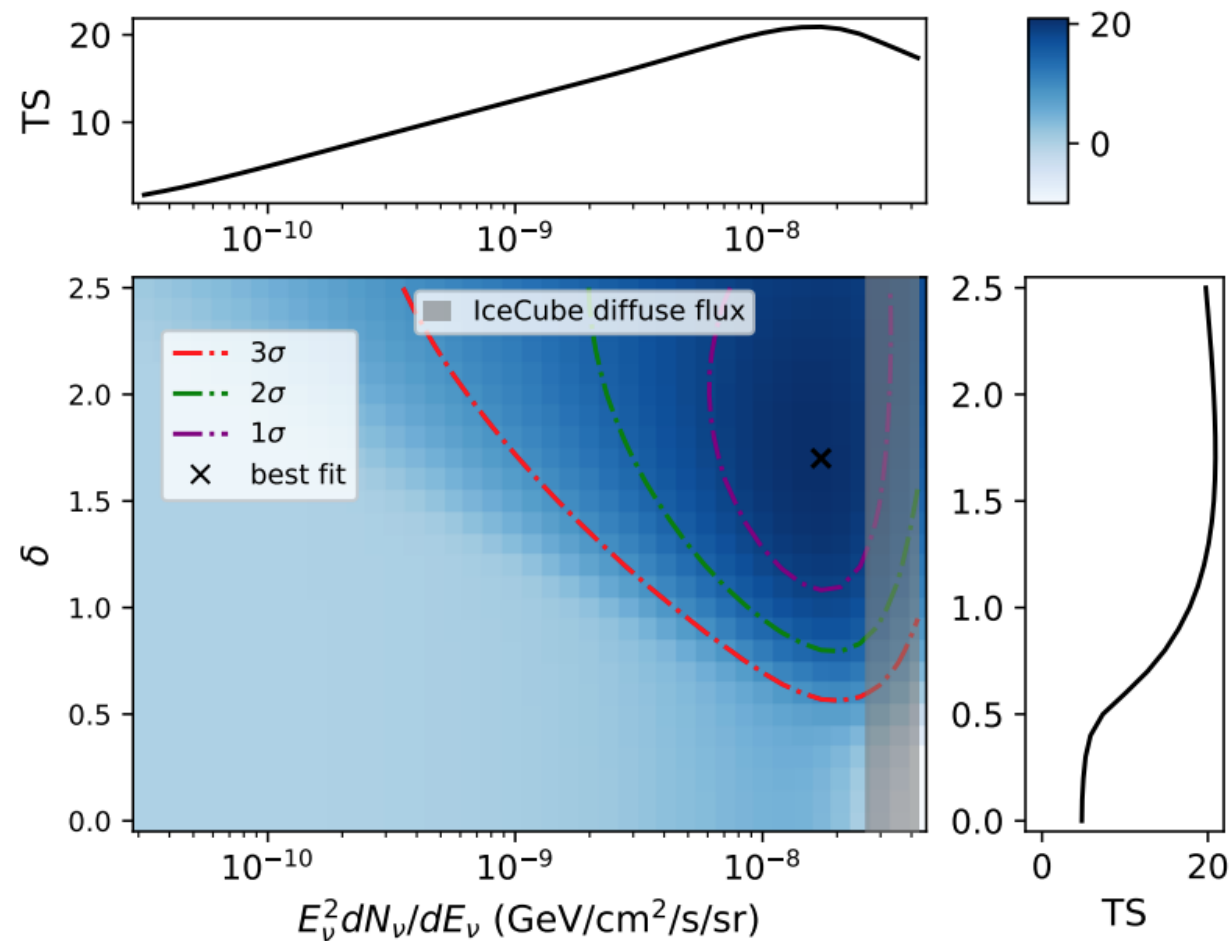
Gamma-Ray-Bright, Blazar AGN (Fermi, 4LAC-DR3)

Hypothesis	Significance (σ)	2σ Limits on Contribution to F_{ν}^{diffuse}
Gamma-Ray Scaling, $\alpha = 2.5$	0.0	$F_{\nu}^{\text{AGN}} < 7.0\%$
Geometric Scaling, $\alpha = 2.5$	0.0	$F_{\nu}^{\text{AGN}} < 14.5\%$
Gamma-Ray Scaling, $\alpha = 3.0$	0.0	$F_{\nu}^{\text{AGN}} < 3.2\%$
Geometric Scaling, $\alpha = 3.0$	0.0	$F_{\nu}^{\text{AGN}} < 4.7\%$



Results – X-ray bright non-blazars

Swift-BAT Non-Blazar AGN
Hard X-Ray Scaling, $\alpha = 3$



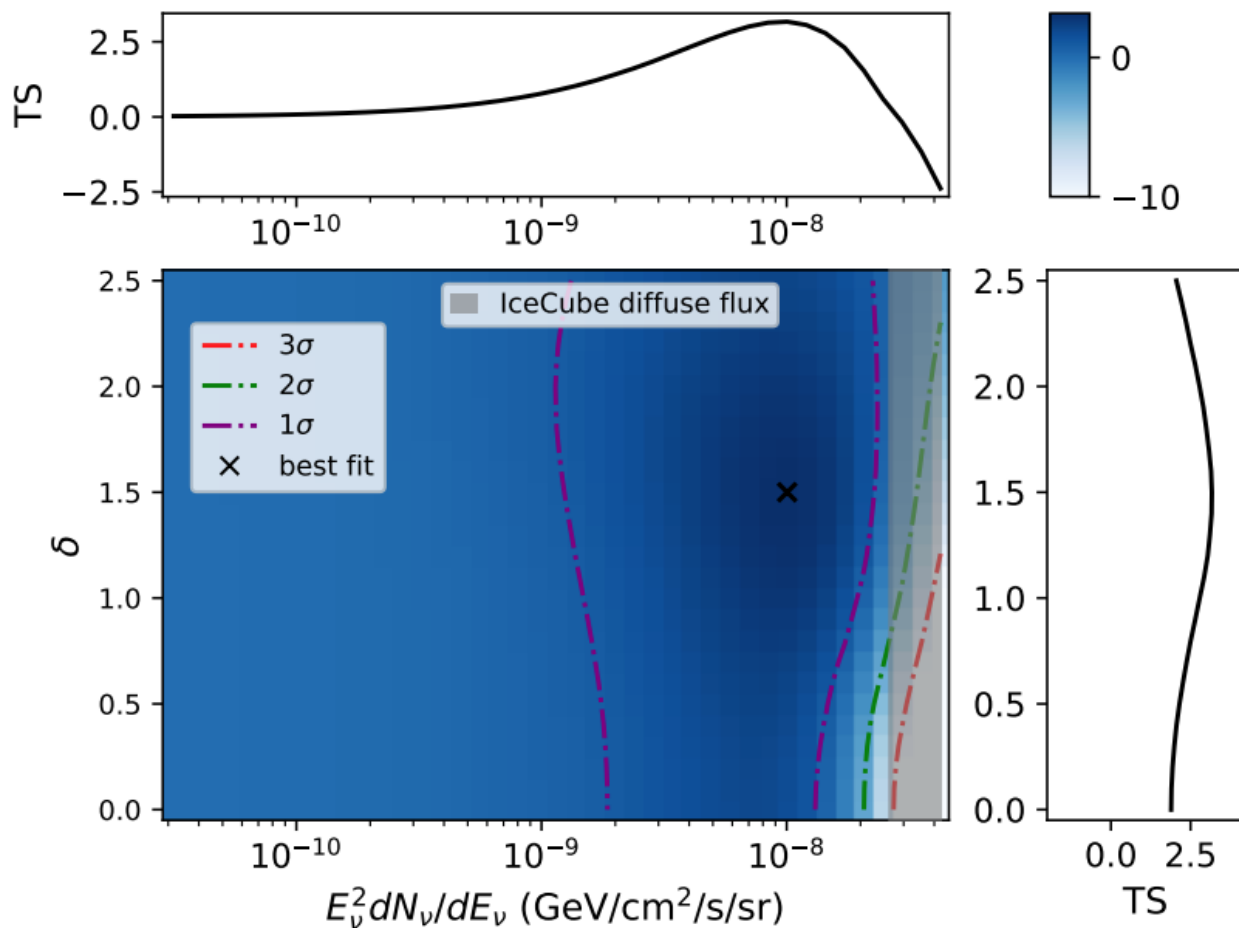
X-Ray-Bright, Non-Blazar AGN (Swift-BAT)

Hypothesis	Significance (σ)	Contribution to $F_\nu^{\text{diffuse}} (2\sigma)$
Hard X-Ray Scaling, $\alpha = 2.5$	3.41	$F_\nu^{\text{AGN}} > 28.9\%$
Soft X-Ray Scaling, $\alpha = 2.5$	3.21	$F_\nu^{\text{AGN}} > 15.7\%$
Geometric Scaling, $\alpha = 2.5$	1.71	$F_\nu^{\text{AGN}} > 11.8\%$
Hard X-Ray Scaling, $\alpha = 3.0$	4.18	$F_\nu^{\text{AGN}} > 11.2\%$
Soft X-Ray Scaling, $\alpha = 3.0$	3.98	$F_\nu^{\text{AGN}} > 5.0\%$
Geometric Scaling, $\alpha = 3.0$	3.15	$F_\nu^{\text{AGN}} > 13.1\%$



Results – X-ray bright non-blazars without NGC 1068

Swift-BAT Non-Blazar AGN without NGC 1068
Hard X-Ray Scaling, $\alpha = 3$



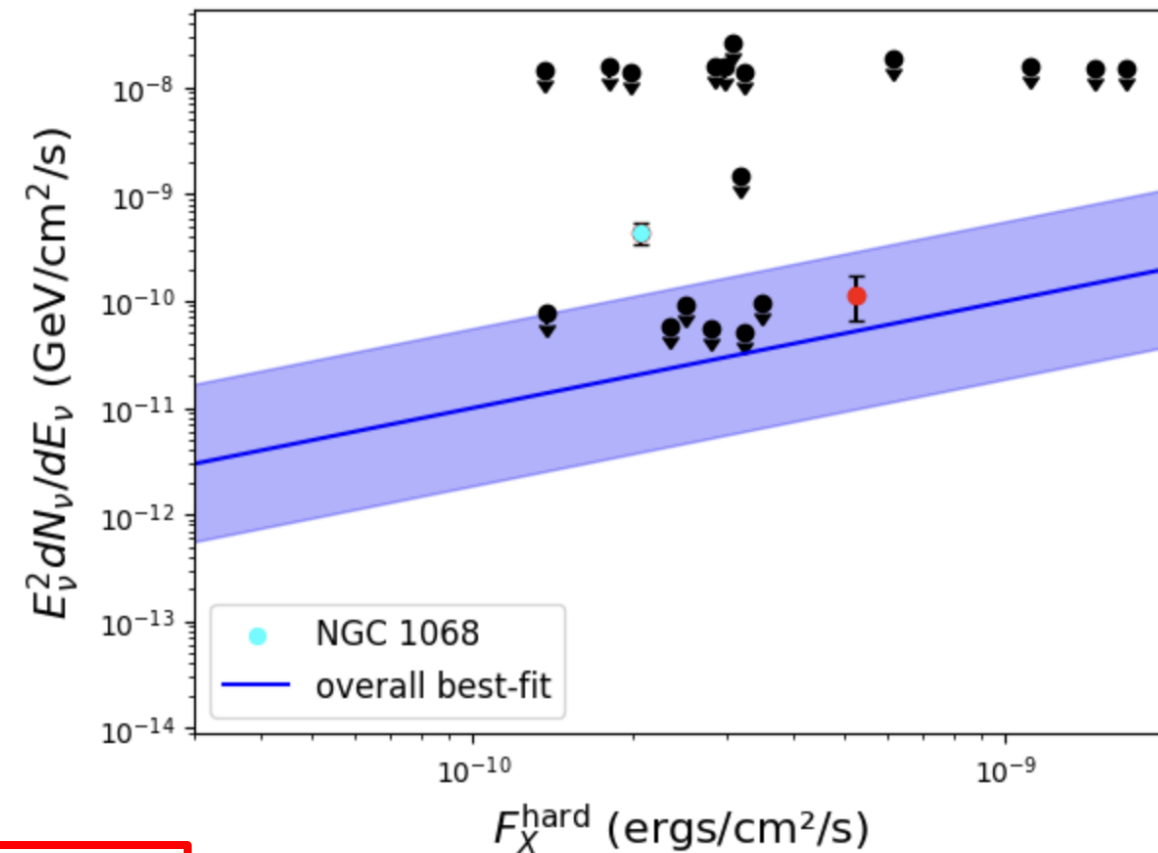
X-Ray-Bright, Non-Blazar AGN (Swift-BAT), Excluding NGC 1068

Hypothesis	Significance (σ)	Contribution to F_ν^{diffuse} (2σ)
Hard X-Ray Scaling, $\alpha = 2.5$	1.35	No Constraint
Soft X-Ray Scaling, $\alpha = 2.5$	0.25	No Constraint
Geometric Scaling, $\alpha = 2.5$	0.0	No Constraint
Hard X-Ray Scaling, $\alpha = 3.0$	1.27	$F_\nu^{\text{AGN}} < 99.1\%$
Soft X-Ray Scaling, $\alpha = 3.0$	0.10	No Constraint
Geometric Scaling, $\alpha = 3.0$	0.0	No Constraint



Conclusions

- We do not find significant neutrino emission from gamma-ray bright AGN
- We find gamma-ray bright blazars can produce <15% of the diffuse flux at 30 TeV, while non-blazars may produce the entirety of it
- We find significant neutrino emission from X-ray bright non-blazars, though it is dominated by NGC 1068. They produce between 11.2% and 100% of the diffuse flux at 30 TeV
- Our best-fit ($\delta \approx 1.7$) predicts a scenario where NGC 1068 is a major outlier (30x brighter than expected) from a much dimmer population of neutrino-bright AGN



**Gamma-ray obscured, X-ray bright AGNs
may be promising neutrino sources!**

BACKUP





Setting up the stacked likelihood

- Background PDF – for a given declination, average event rate over the azimuth (atmospheric muons + atmospheric neutrinos, dominate at lower energies)
- Signal PDF – a gaussian around the source with angular width given by the uncertainty of the event direction
- This likelihood is calculated individually for each energy bin and each source. The final likelihood is obtained by multiplying together the likelihoods across all energy bins and sources
- Our final Test-Statistic is given by

$$TS = 2[\ln \mathcal{L}(c) - \ln \mathcal{L}(0)]$$