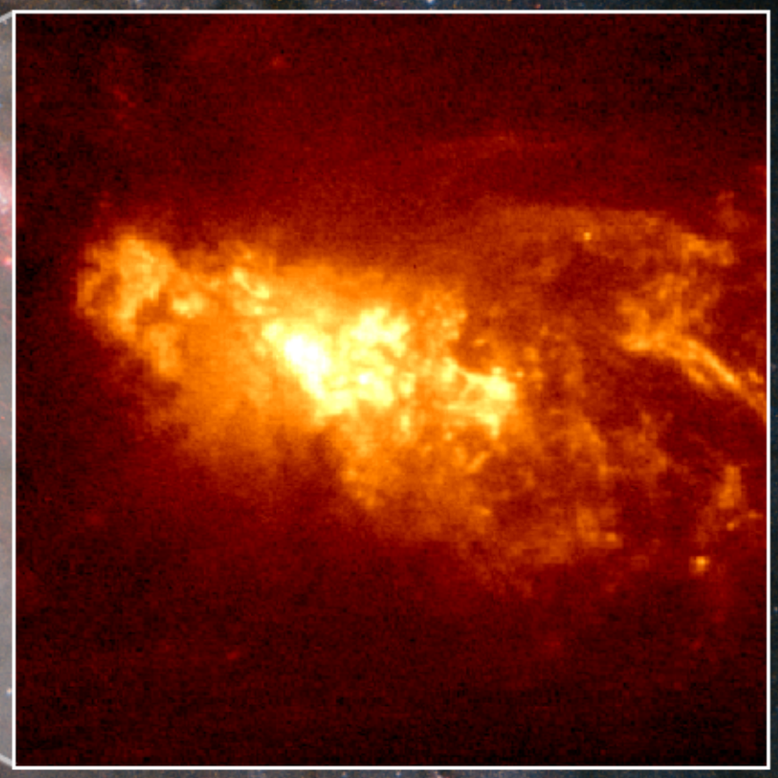
IceCube observations of northern Seyfert galaxies and implications for the extragalactic neutrino flux



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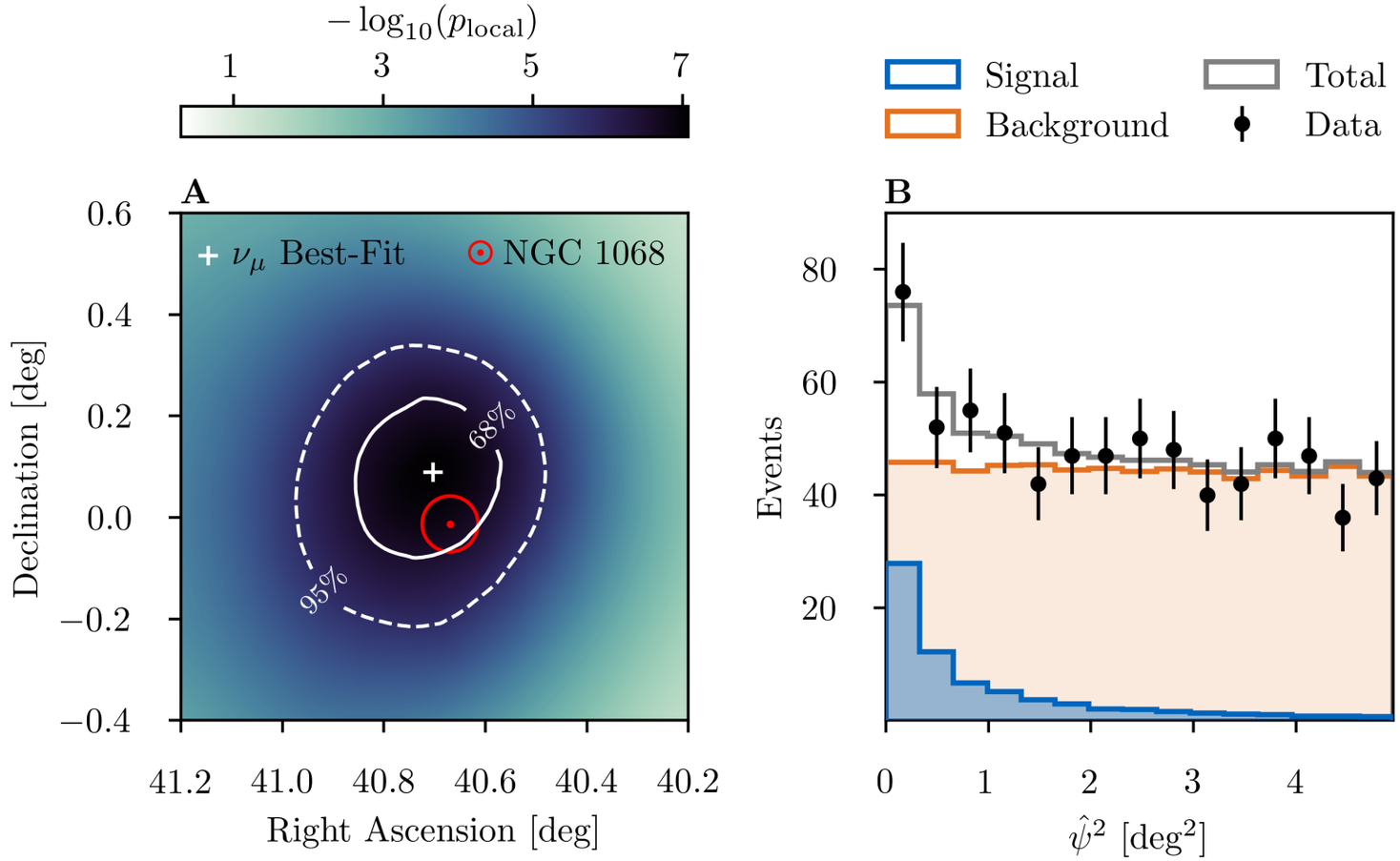
NGC 1068 image credit: NASA, ESA, A. Filippenko (UC Berkeley), W. Sparks (STScI), L. C. Ho (KIAA-PKU), M. A. Malkan (UCLA), A. Capetti (STScI); A. Pagan (STScI)

NGC 1068

IceCube Coll., *Science* 278 (2022)

- Prototypical Seyfert II galaxy (Seyfert 1943): Compton-thick AGN with obscured core, but also hosting starburst activity and outflows
  - Discussed as a potential neutrino emitter as early as ICRC 1979 (Silberberg & Shapiro)
- 79 event excess (4.2σ) observed in IceCube 10-year catalog search
  - $\gamma = 3.2 \pm 0.2$, much softer than diffuse extragalactic flux
  - Neutrino luminosity much higher than VHE gamma rays



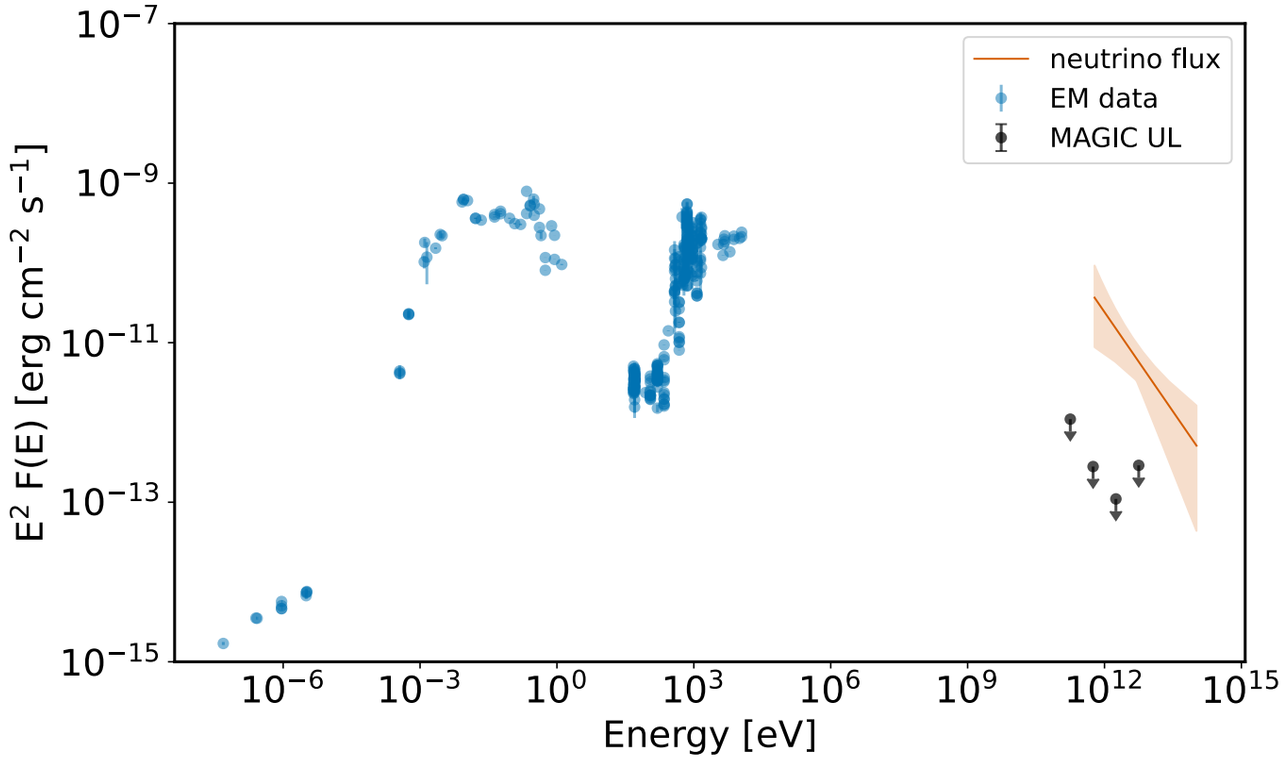
So, Are There More?

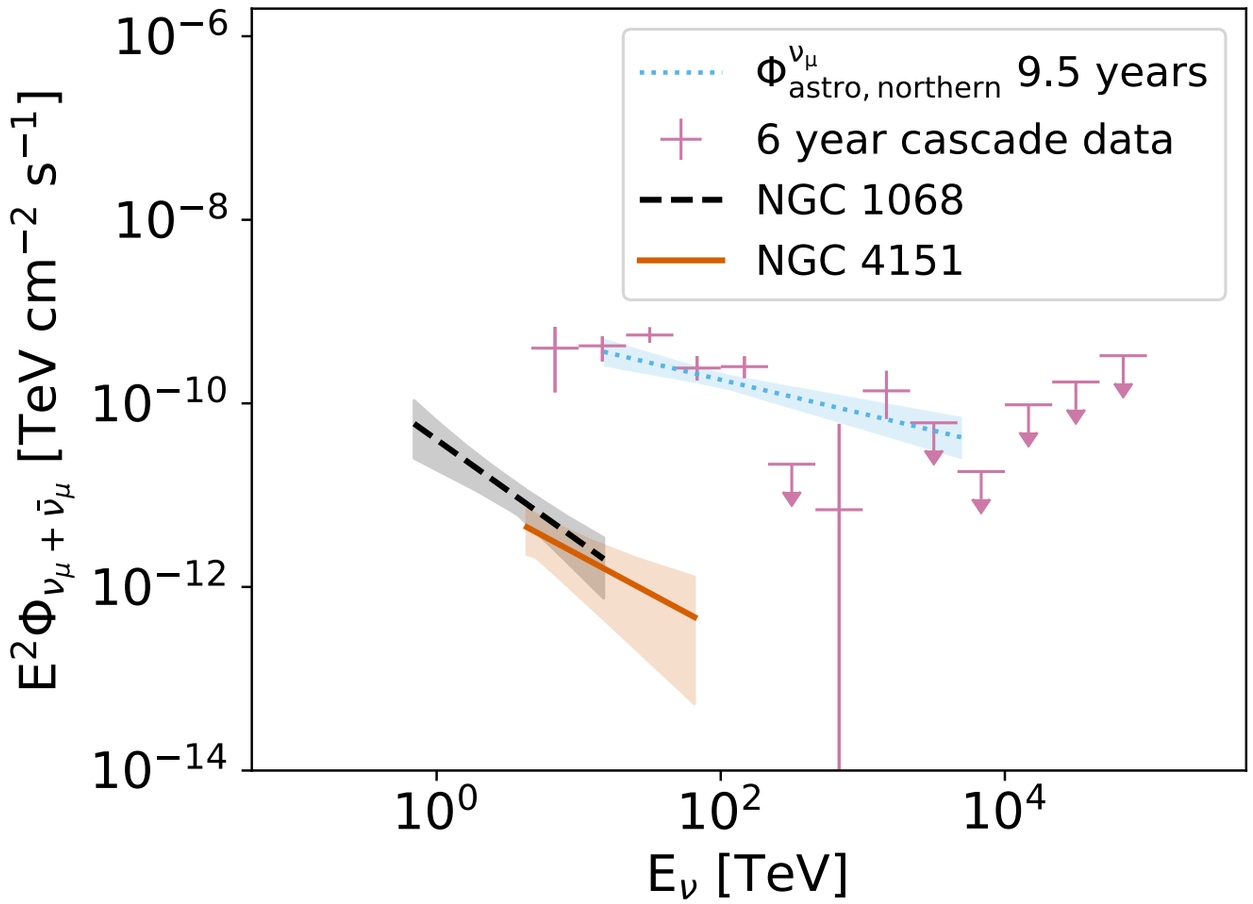
- Several follow-up searches with slightly different methods
  - Common theme: AGN with intense X-ray corona
- *Catalog searches*: check all the nearby ‘similar’ sources one by one
  - Trials corrections reduce sensitivity considerably
- *Stacking searches*: predict which other sources should be brightest (either with a detailed model, or just ranked by X-ray luminosity), and test whether there are excesses that scale according to the prediction
  - Improves sensitivity if model is correct, but less sensitive if it’s not
- *Binomial tests*: are there more excesses in the catalog than would be expected? (Model-independent except for selection of sources in the catalog to consider)

1: X-Ray Bright AGN

- Stacked analysis of 836 AGN ranked by hard (14-195 keV) X-ray luminosity from BASS – null result

- Also a catalog search of 43 top sources (X-ray ranked)
  - Excess of 2.9σ from NGC 4151
  - Prototypical Seyfert I galaxy, also suggested as a neutrino emitter since Stecker 1991
  - Neutrino flux again much higher than gamma rays
  - Slightly harder spectrum than NGC 1068 at 2.83 — still softer than observed diffuse flux

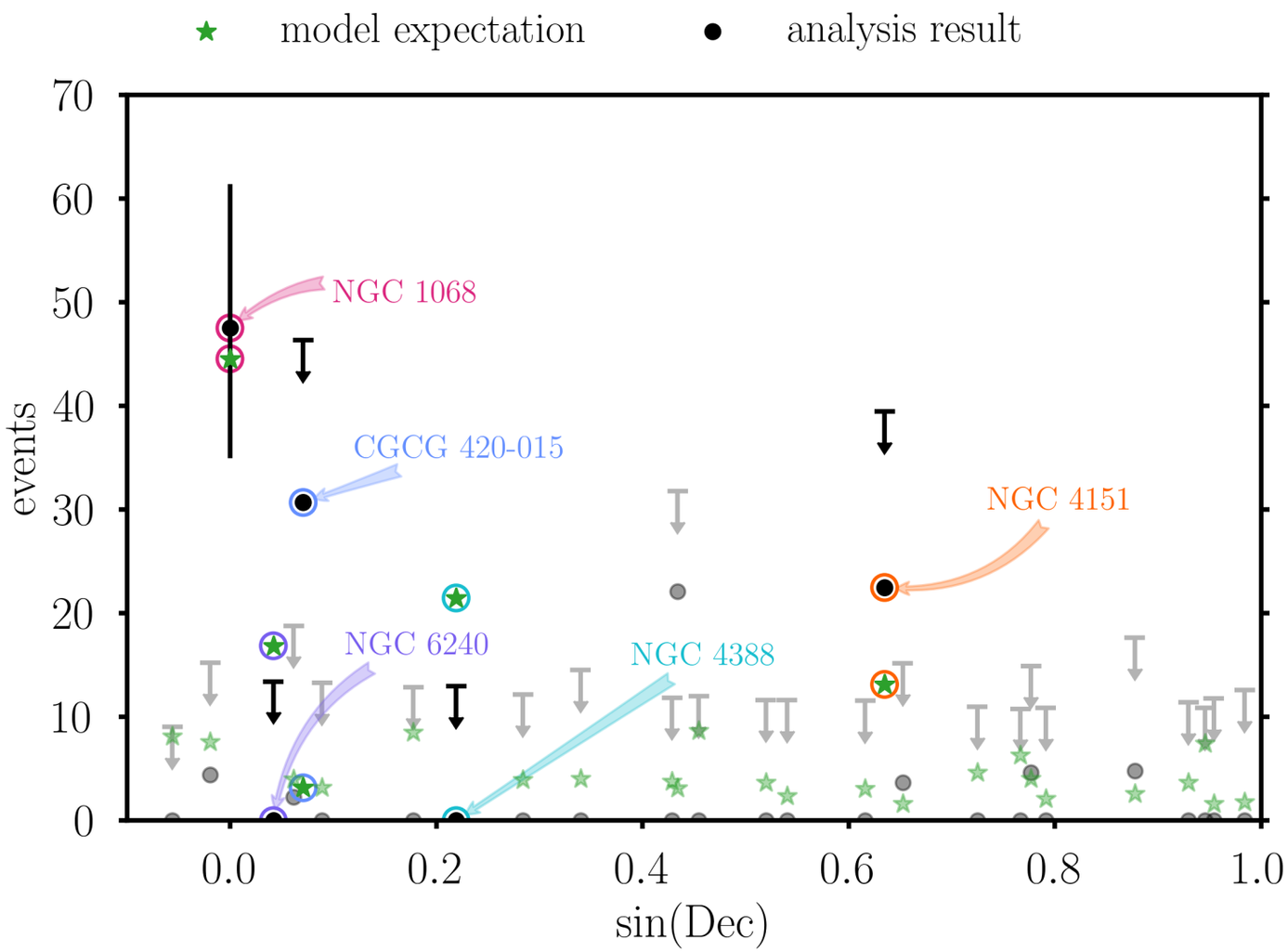




IceCube Coll., *Astrophys.J.* 981 (2025)

2: Core-Corona Model-Driven Follow-Up

- Same model as southern search, tuned on NGC 1068 observation
- Stacking analysis of 27 Seyfert galaxies selected by 2-10 keV luminosity
  - Do not find excesses that scale according to model
  - Upper limits on several sources below predictions
- But 2.7σ support for emission from the group as a whole in binomial test
  - Binomial *p*-value driven by NGC 4151 and CGCG 420-015



IceCube Coll., *Astrophys.J.* 988 (2025)
Murase, Kimura & Meszaros, Phys. Rev. Lett. 125 (2020);
Kheirandish, Murase & Kimura, Astrophys.J. 922 (2021)

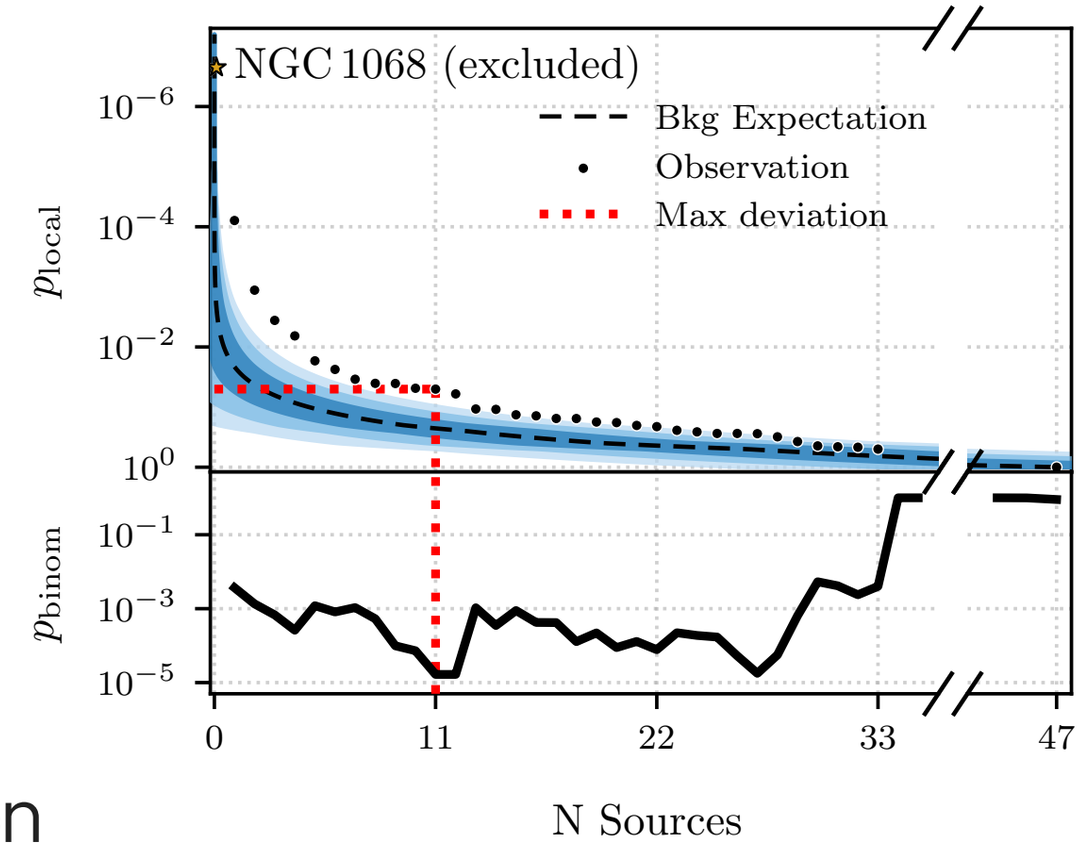
power-law fit ($\hat{\gamma} = 3.3$)
model expectation
($\log_{10} L_X$=42.9, d=12.7 Mpc)
model fit
NGC 1068
$E^2\Phi_{\nu_\mu+\bar{\nu}_\mu}$ [TeVcm^{-2}s^{-1}]
10^{-7}
10^{-9}
10^{-11}
10^{-13}
10^3
10^4
10^5

power-law fit ($\hat{\gamma} = 2.7$)
model expectation
($\log_{10} L_X$=42.3, d=12.7 Mpc)
model fit
NGC 4151
$E^2\Phi_{\nu_\mu+\bar{\nu}_\mu}$ [TeVcm^{-2}s^{-1}]
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^3
10^4
10^5

power-law fit ($\hat{\gamma} = 2.8$)
model expectation
($\log_{10} L_X$=44.0, d=128.8 Mpc)
model fit
CGCG 420-015
$E^2\Phi_{\nu_\mu+\bar{\nu}_\mu}$ [TeVcm^{-2}s^{-1}]
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^3
10^4
10^5
neutrino energy [GeV]

3: Revised X-Ray Selection Criteria

- Selected X-ray bright AGN based on 20-50 keV band rather than 14-195 keV or 2-10 keV
  - Balance between energies high enough to minimize absorption systematics, but low enough to be relevant for neutrino production



- 3.3σ (post-trials) evidence for emission from binomial test assuming power-law spectra
  - Core-corona spectral model yields lower significance

- Top contributors are NGC 7469 (very hard spectrum), then same objects identified previously (NGC 4151, CGCG 420)

IceCube Coll., arXiv:2510.13403, submitted to *Astrophys. J. Lett.*

There's Something Happening Here…

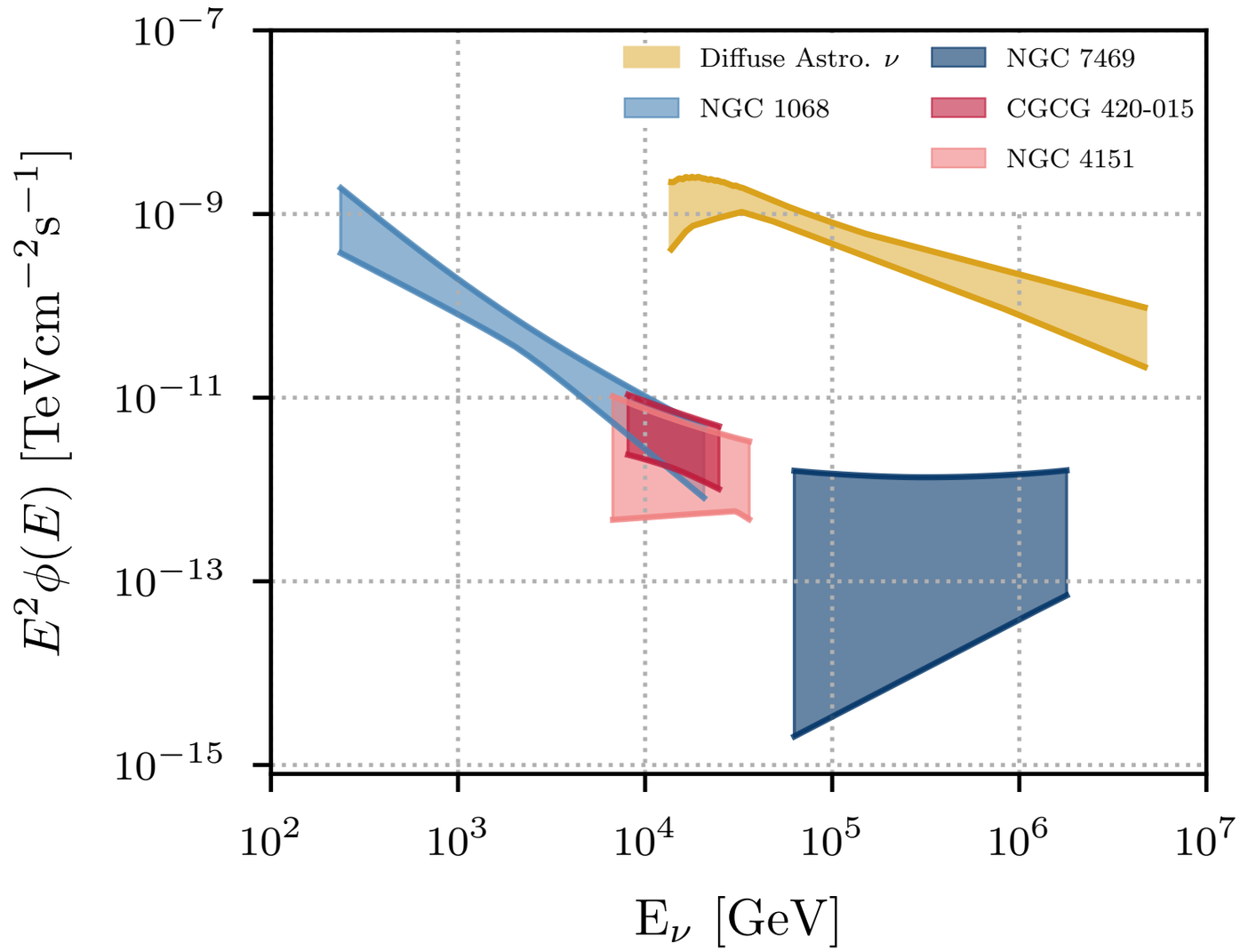
- Multiple follow-up analyses targeting X-ray bright AGN in the northern sky, all of which find excesses between 2.7σ – 3.3σ
  - The similar (and completely independent!) results from southern Seyferts suggest we really should pay attention to AGN with bright X-ray coronae
- Caveat: these (northern) analyses all use the same IceCube data
  - The conclusion that we see ~3σ evidence for emission from Seyfert galaxies, in both the northern and southern sky independently, seems robust
  - But individual sources appearing in multiple analyses is *not* independent confirmation: may be a statistical fluctuation picked up by each analysis
- More data from other neutrino telescopes will be critical!
  - And different regions of peak sensitivity may lead to more discoveries — soft sources in the southern sky are hard for IceCube to observe

…But What It Is Ain't Exactly Clear

- Evidence for neutrinos from Seyferts in the north comes from binomial searches, not stacking analyses
  - We are identifying the class of objects that are emitting neutrinos, but not predicting which ones will be brightest
- Some expected sources, like NGC 1068 & NGC 4151, contribute to the statistical excess, but others are much further down the list (who ordered CGCG 420-015?)
- Are uncertainties in X-ray survey data (e.g. obscuration) throwing off the model predictions?
- Do we have more complicated, source-dependent dynamics?
- Or is this just the statistics of small numbers?

Seyferts and the Extragalactic Flux

- The neutrino flux from the coronae of Seyfert galaxies is* much softer than the overall extra-galactic neutrino flux
  - *Except that for a handful of objects (NGC 7469, Cyg A, Circinus), the fits prefer hard power laws(...?)
- More modeling and multi-wavelength observations, and data from more neutrino telescopes, are needed!



(Fits to power-law spectra shown, the detailed models have even softer spectra)

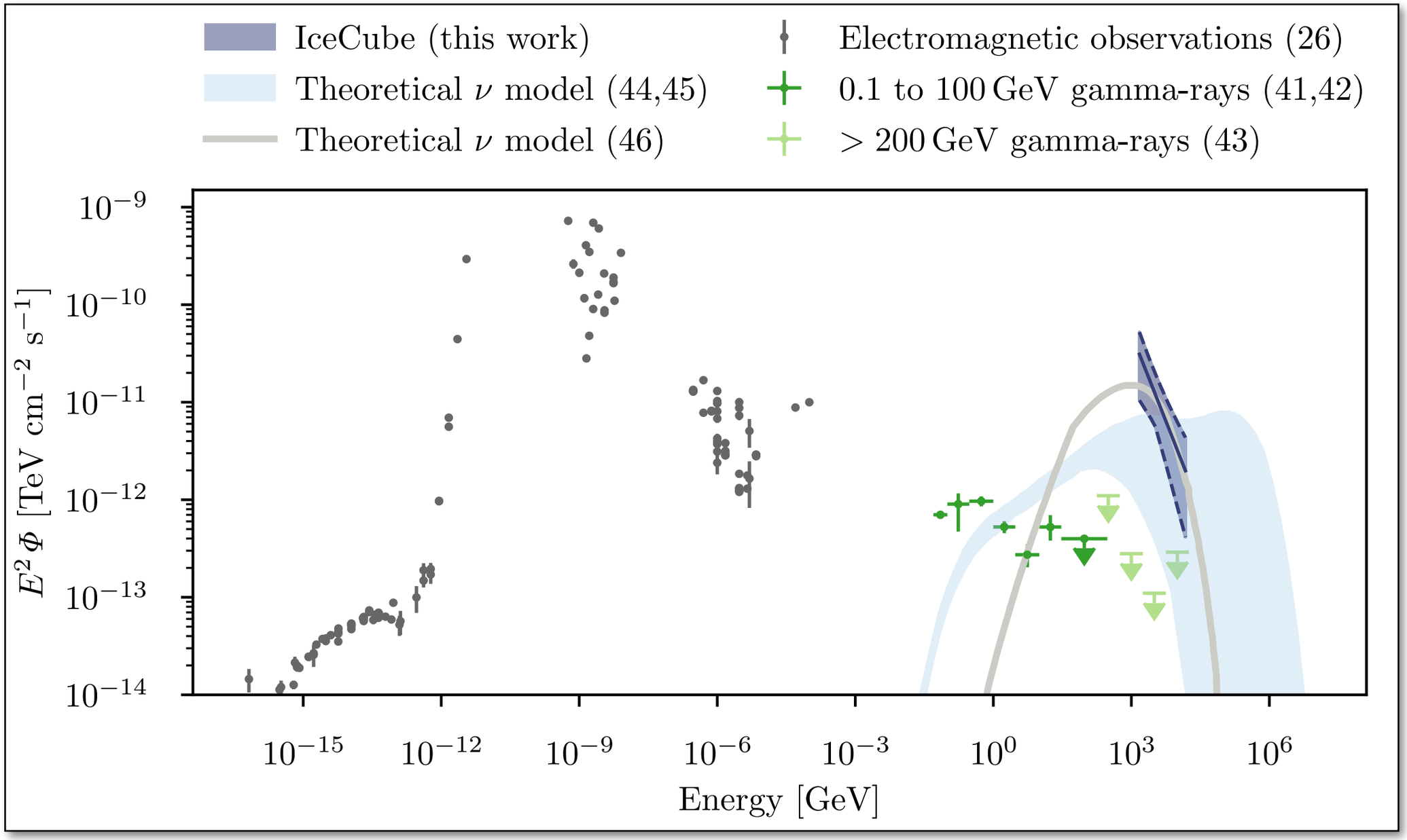
Thanks for your attention!

NGC 4151 image credit, X-ray: NASA/CXC/CfA/J.Wang, et al.; Optical: Isaac Newton Group of Telescopes, La Palma/Jacobus Kapteyn Telescope; Radio: NSF/NRAO/VLA

NSF

IceCube

Measured VHE neutrino flux is an order of magnitude higher than upper limits on TeV gamma ray emission

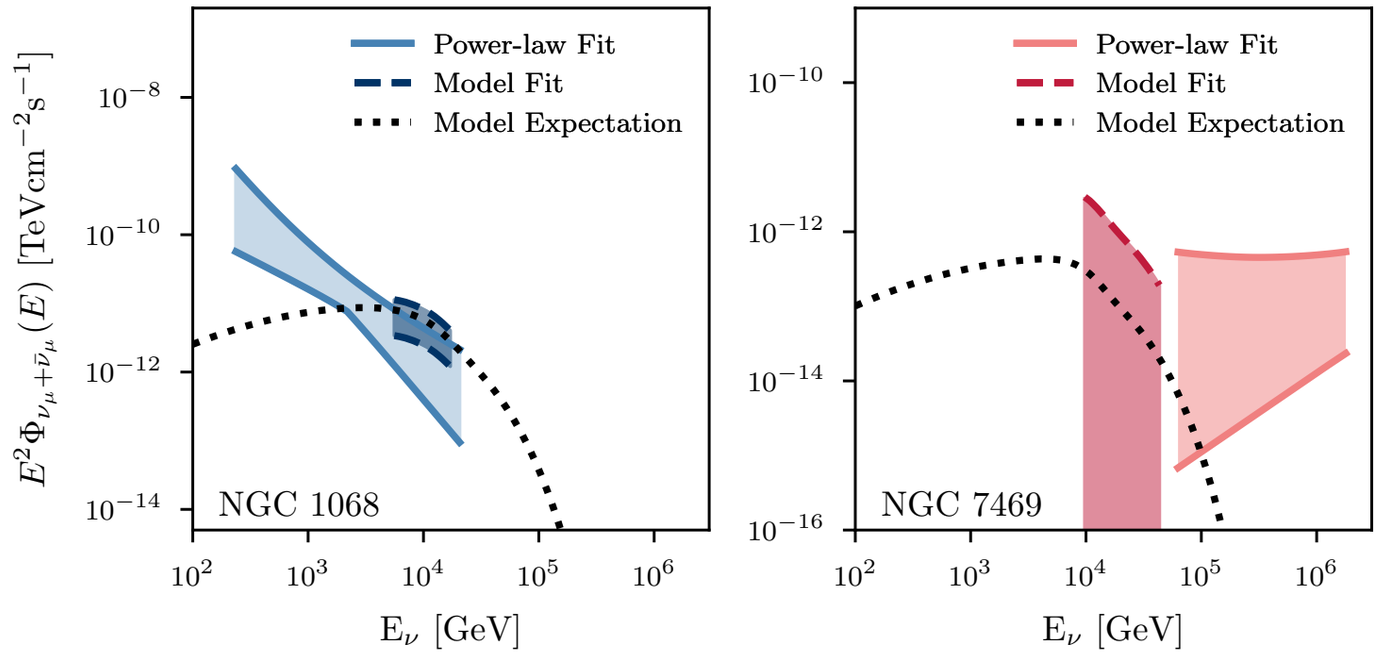


Implies environment is optically thick to gamma rays, since meson decay should produce them alongside VHE neutrinos

The Strange Case of NGC 7469

IceCube Coll., arXiv:2510.13403, *Astrophys.J. Lett.* in press

- When fit to a power law, the measured index is radically harder than NGC 1068 or the other Seyferts contributing to the binomial excess



- NGC 7469 excess dominated by two 100 TeV-scale (alert) events
  - If these are removed, the test statistic goes to zero
  - X-ray corona model does not predict neutrinos at those energies; when fit to this model, consistent with zero emission