MULTIMESSENGER ASTRONOMY IN THE NEUTRINO ERA

First associations of high-energy neutrinos with cosmic sources

DISCLAIMER

All comments on future prospects are absolutely personal and up for discussion!

Chiara Bellenghi, PhD, chiara.bellenghi@tum.de

—

MACROS 2026 Workshop, Penn State

The plan for this talk

SFB 1258 Neutrinos Dark Matter Messengers

State of the art

Key results on astrophysical neutrinos detections and possible associations to sources

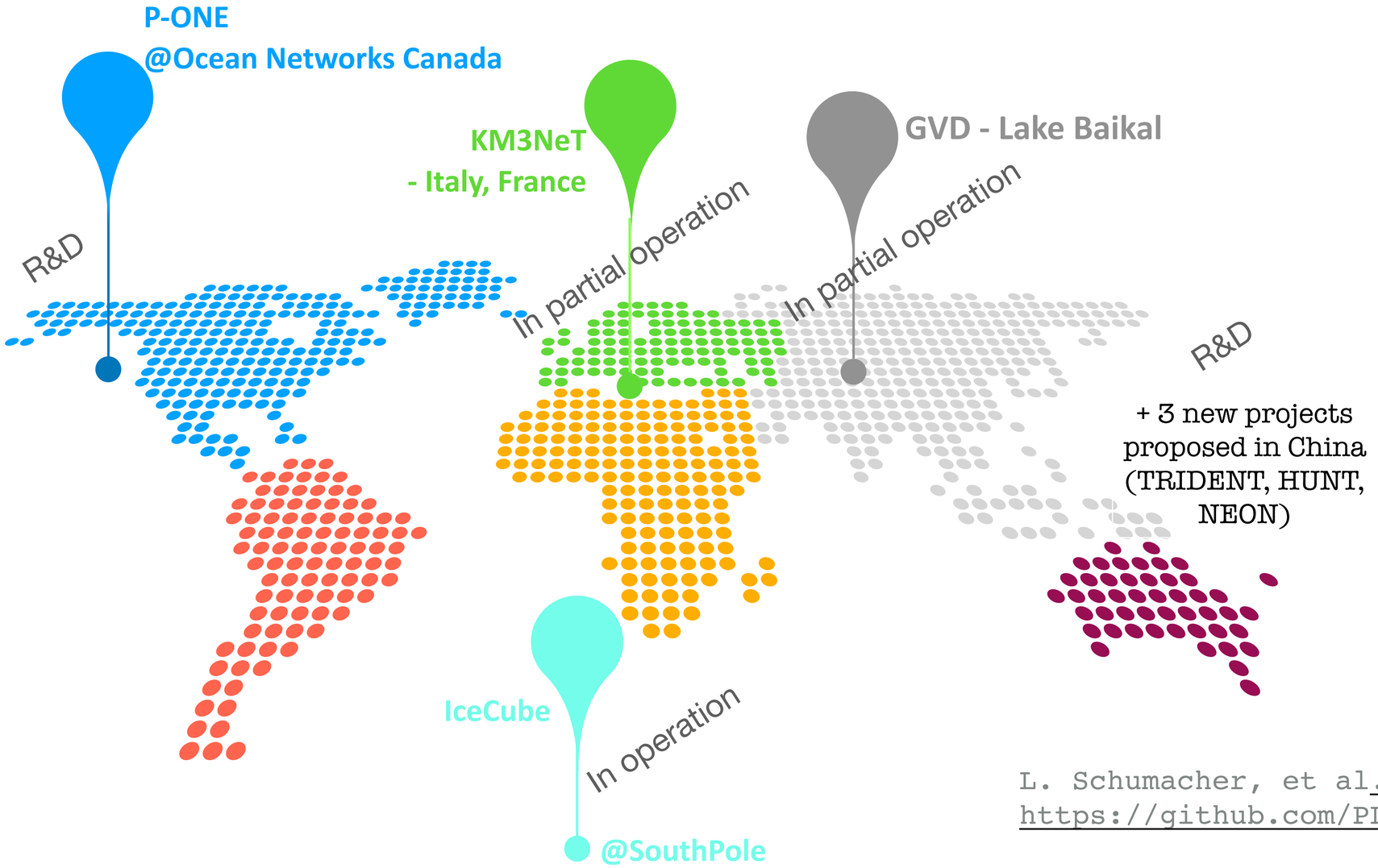
Limitations

In one sentence:
We don't have enough statistical power

Future prospects

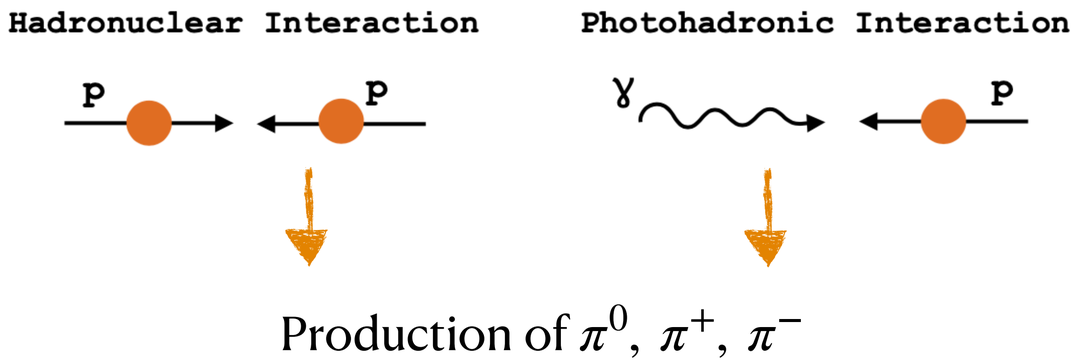
Several km^3-scale telescopes with complementary sensitivity to the sky

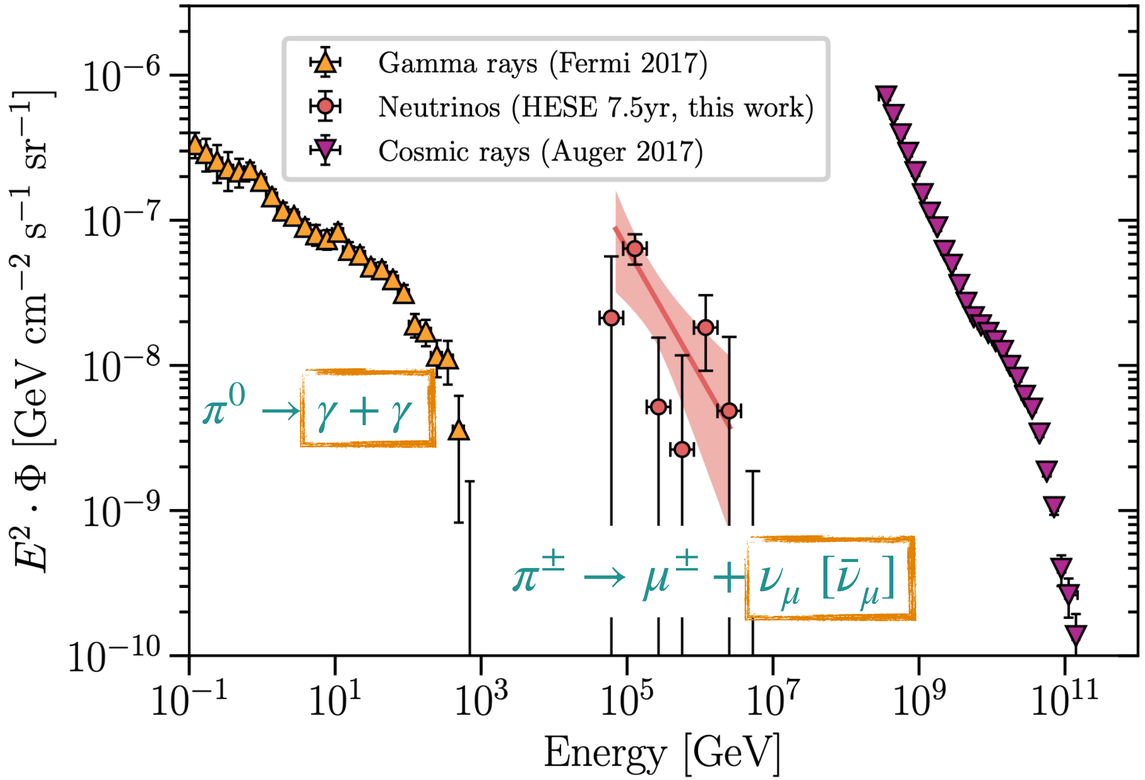
The observatories, today & tomorrow



L. Schumacher, et al., ***PRD '25***, PLEnuM https://github.com/PLEnuM-group/Plenum

Neutrinos trace cosmic hadronic acceleration and interactions

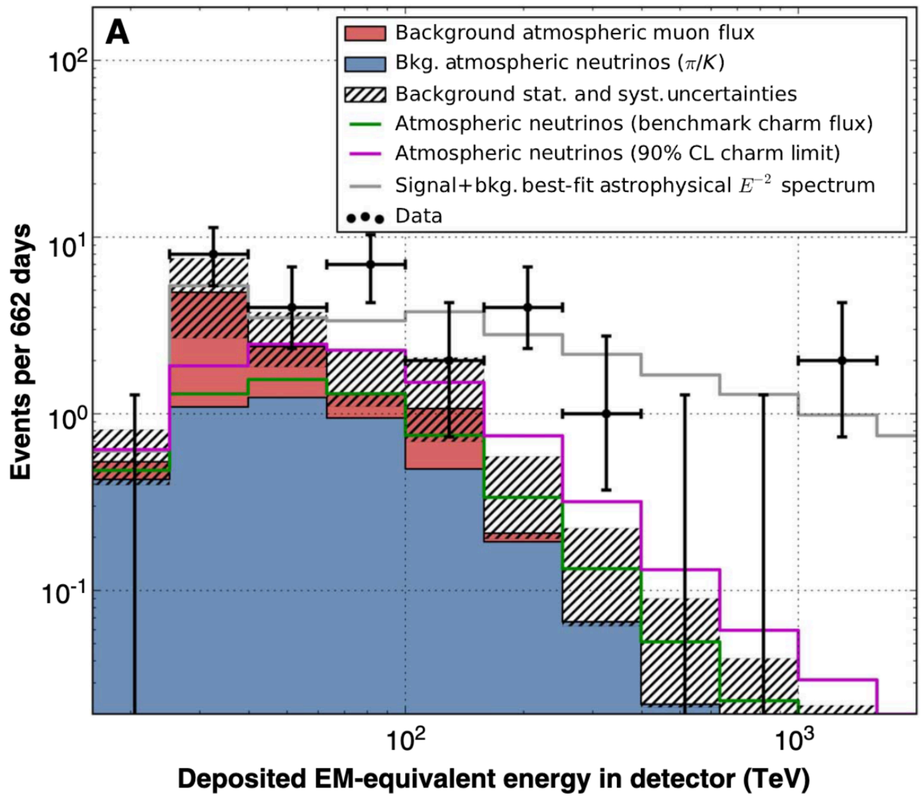




IceCube Coll. Phys. Rev. D 104, 022002

* γ rays are also produced in purely leptonic processes though

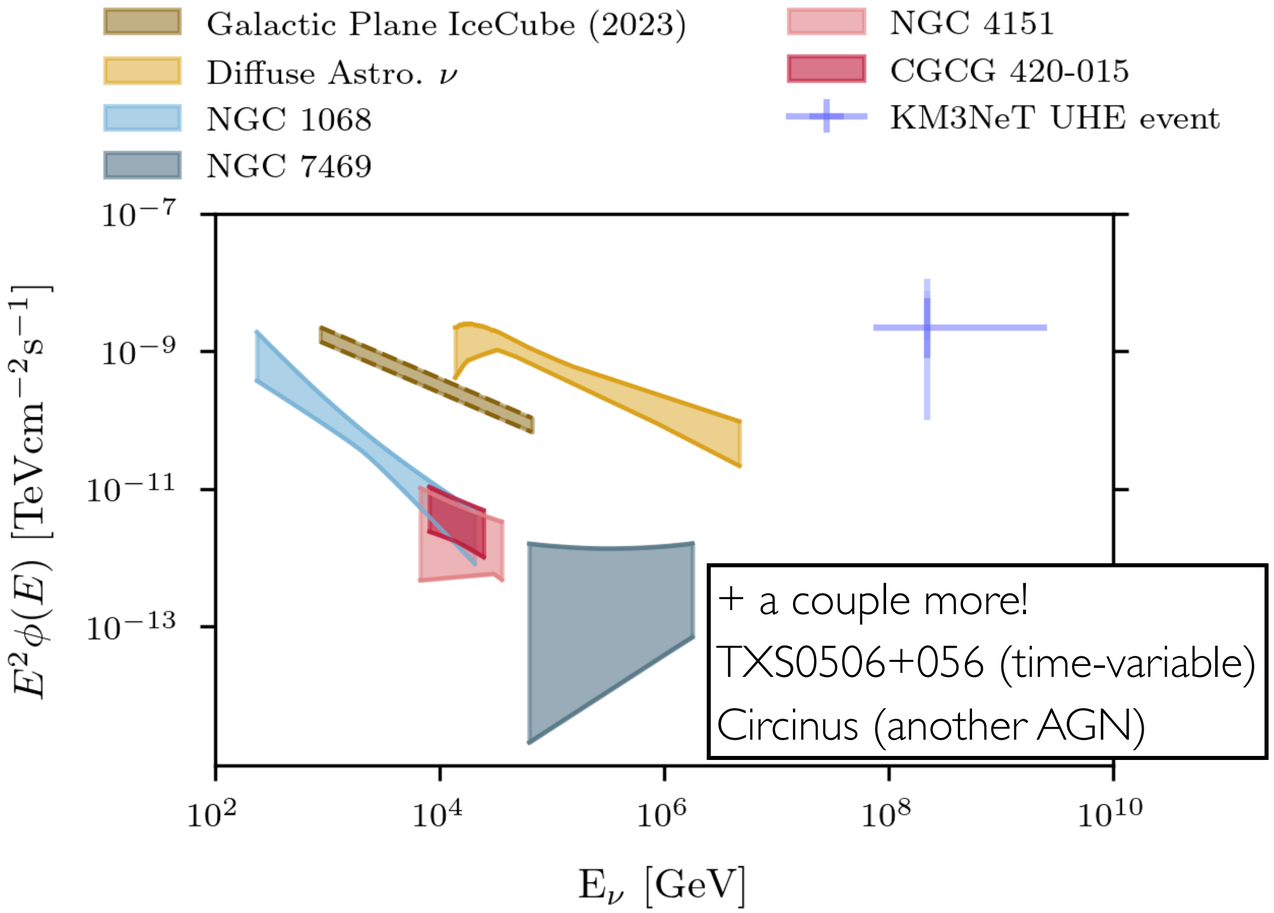
The field is moving rapidly



IceCube observation of extraterrestrial neutrinos
Science 342, 1242856 (2013)

Results: We observed 28 neutrino candidate events (two previously reported), substantially more than the $10.6^{+5.0}_{-3.6}$ expected from atmospheric backgrounds, and ranging in energy from 30 to 1200 TeV. With the current level of statistics, we did not observe significant clustering of these events in time or space, preventing the identification of their sources at this time.

The field is moving rapidly

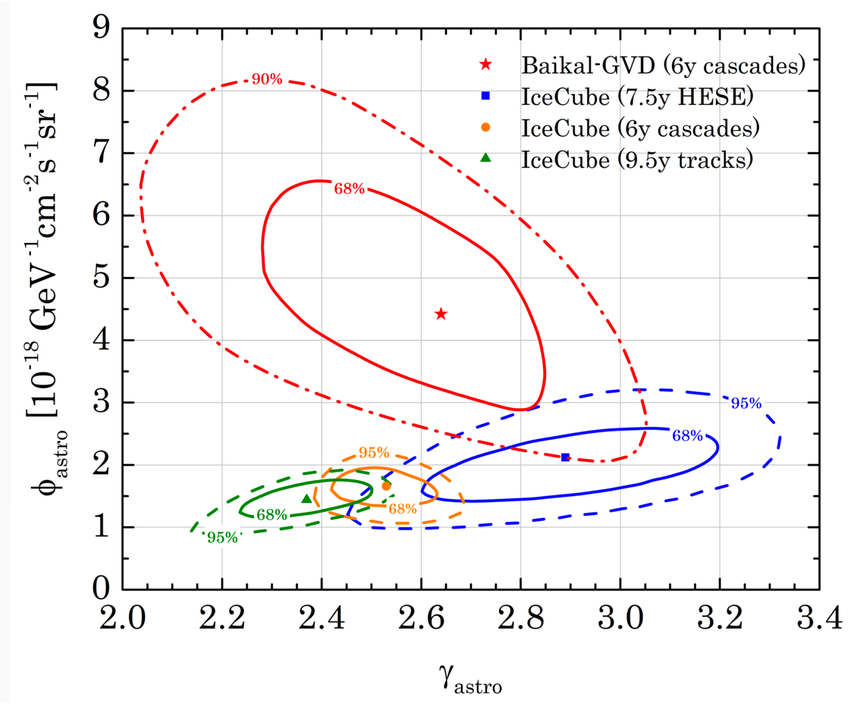


Today we have

- A new understanding of the diffuse neutrino emission
- We are seeing our own galaxy with neutrinos
- We are associating the first extragalactic sources
- More telescopes are coming online in the next decade!

Diffuse neutrinos — The extragalactic flux

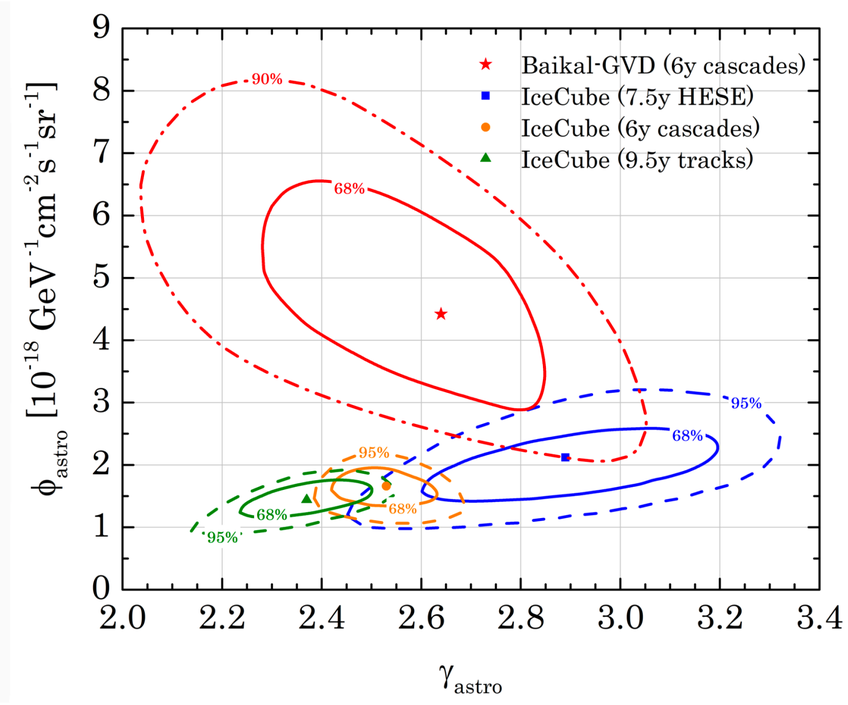
- Discovered by IceCube in 2013
- Recently independently re-discovered by GVD (**5.1σ**)



Baikal-GVD PoS(ICRC2025)

Diffuse neutrinos — The extragalactic flux

- Discovered by IceCube in 2013
- Recently independently re-discovered by GVD (**5.1σ**)
- NEW! For the first time, the LH fit prefers a broken PL!



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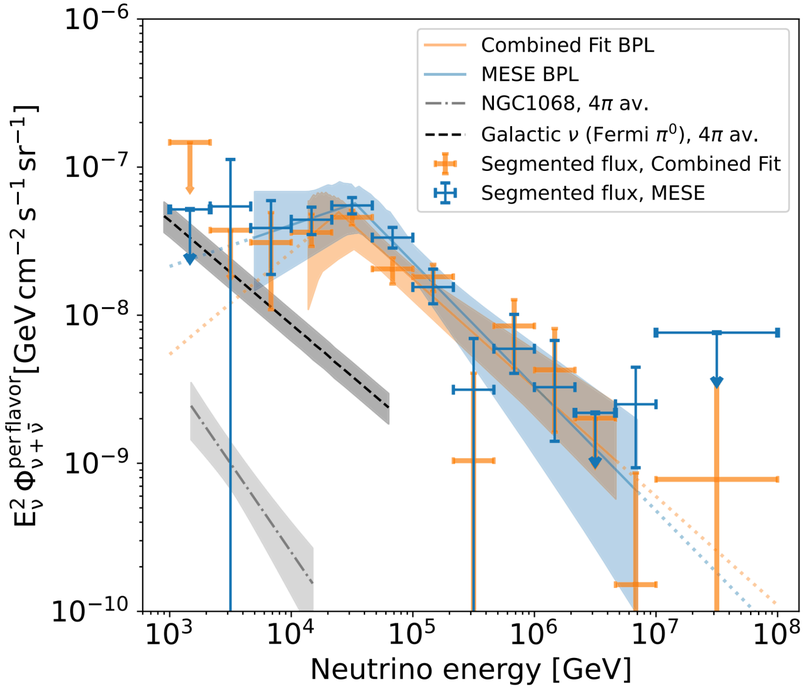

IceCube PRL 2026

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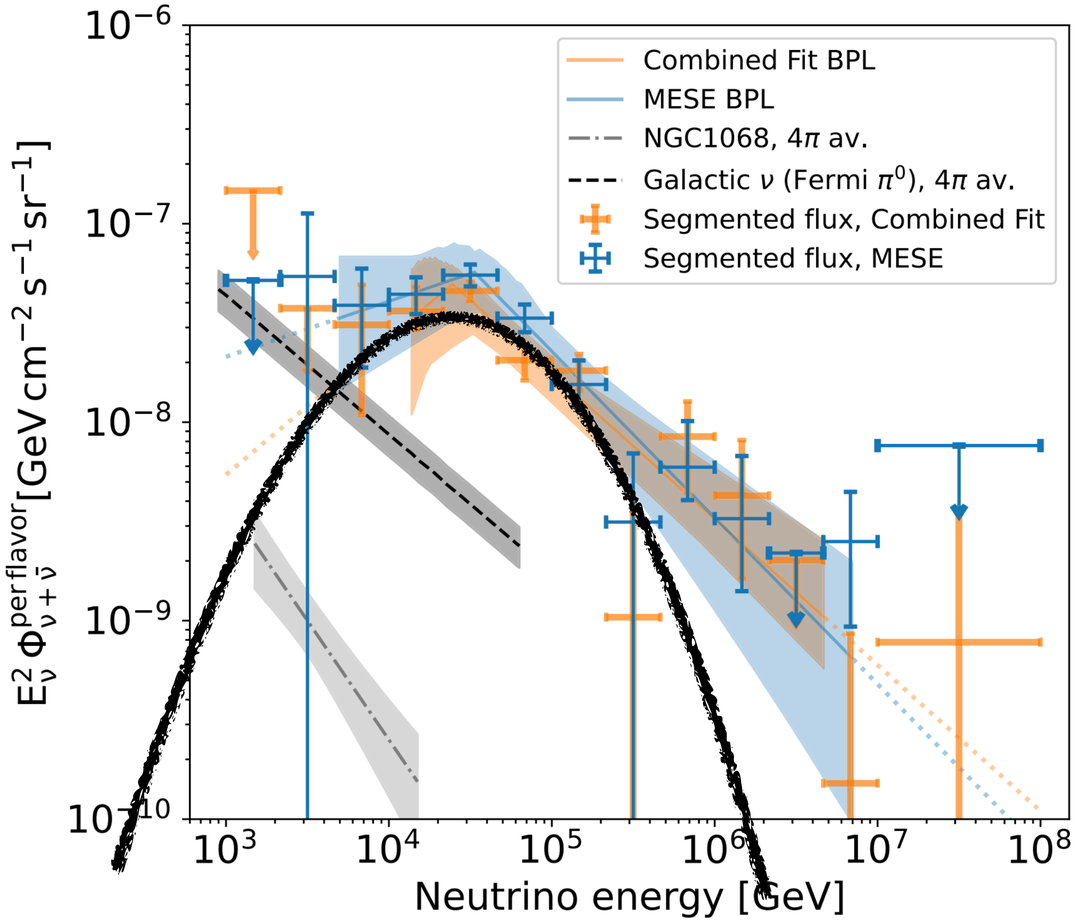
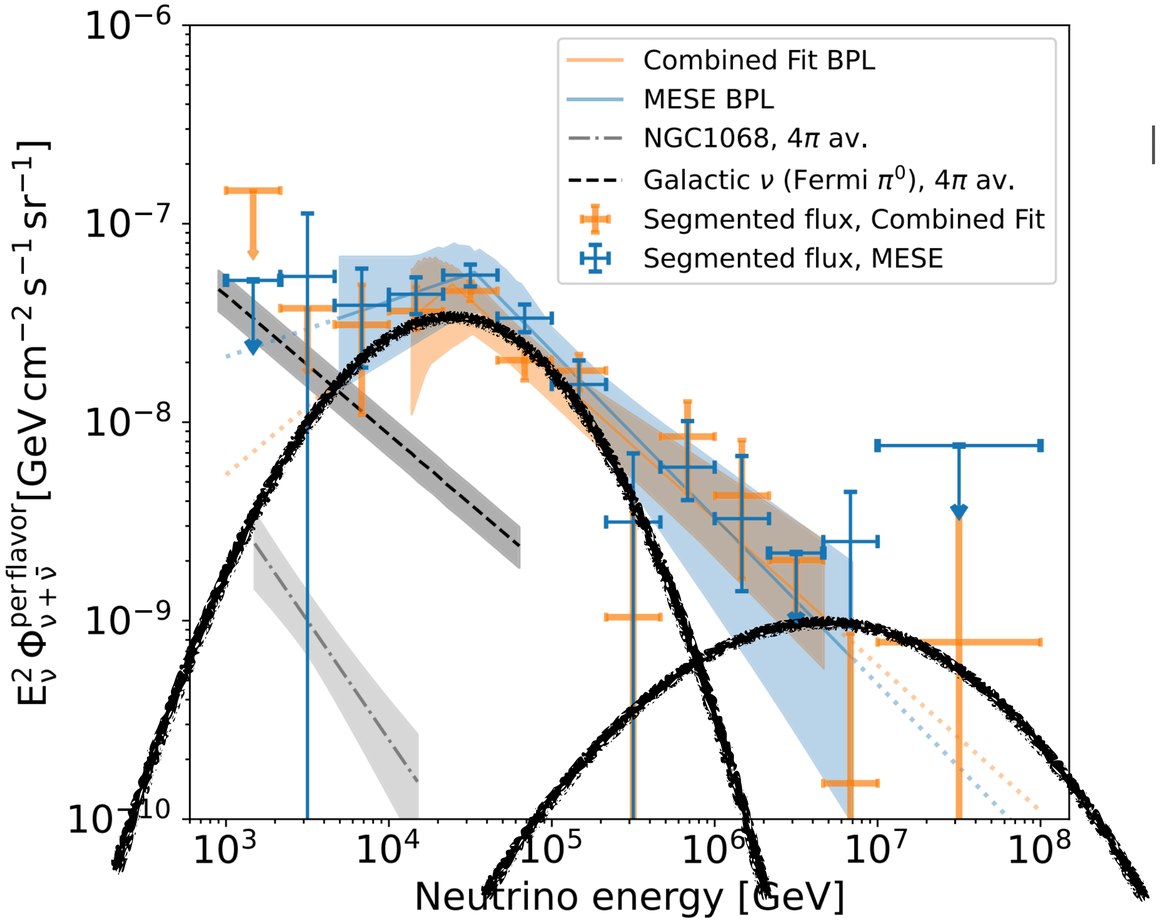


Is the spectral break a sign of a population feature?

Diffuse neutrinos – The extragalactic flux



Is the spectral break a sign of a population feature?

SFB 1258 Neutrinos Dark Matter Messengers

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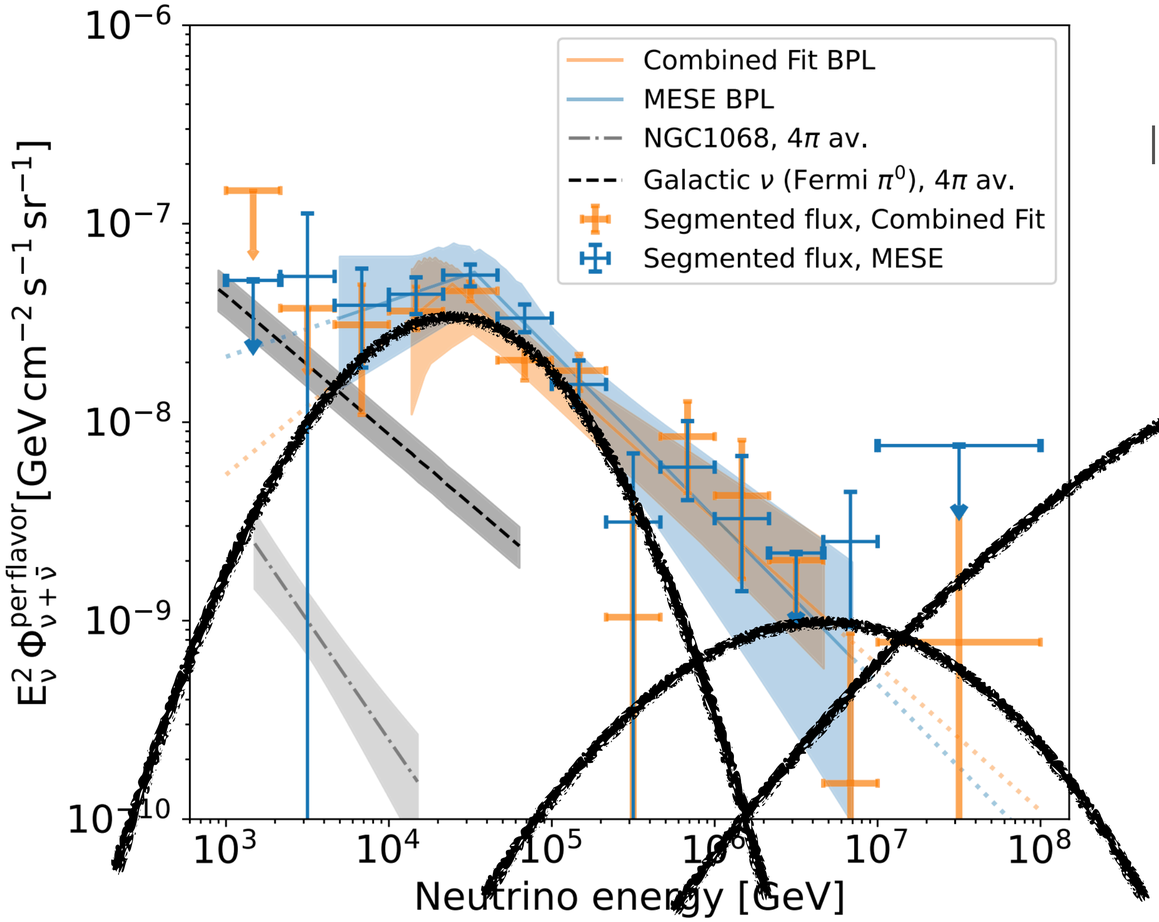

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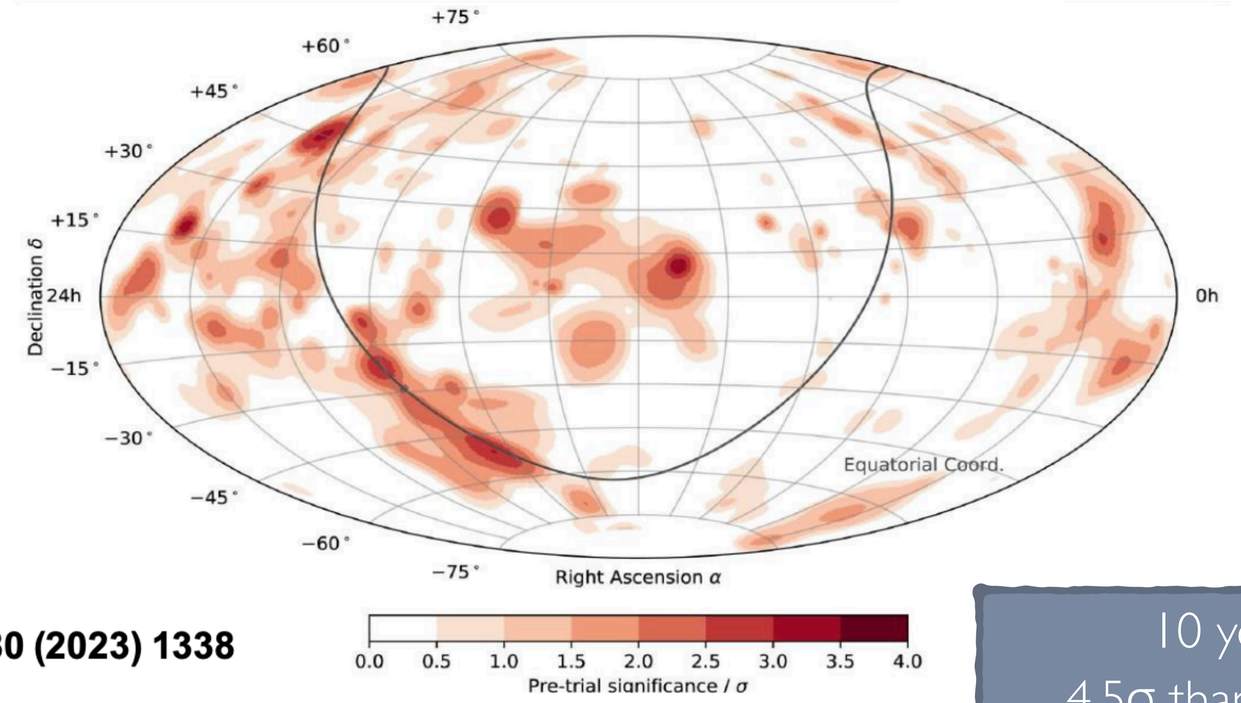
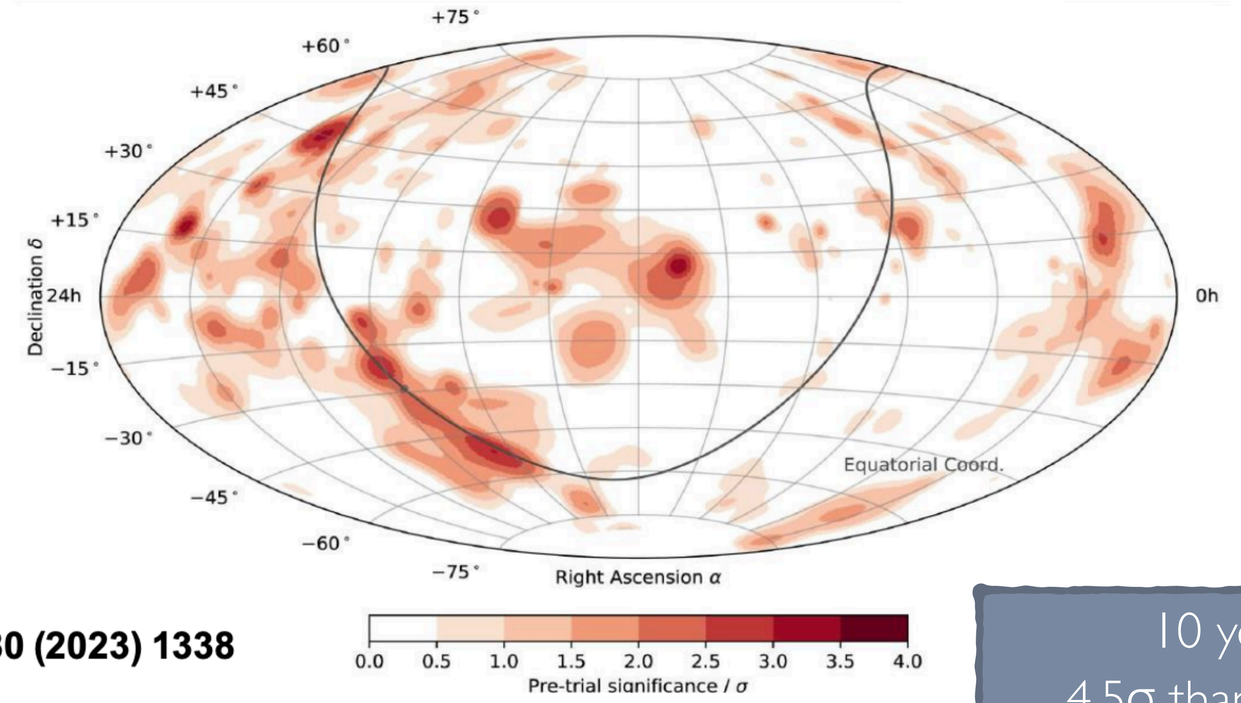
Diffuse neutrinos – The Milky Way



Science 380 (2023) 1338

10 years of data
4.5σ thanks to improved calibrations and reconstructions

Diffuse neutrinos – The Milky Way



Science 380 (2023) 1338

10 years of data
4.5σ thanks to improved calibrations and reconstructions

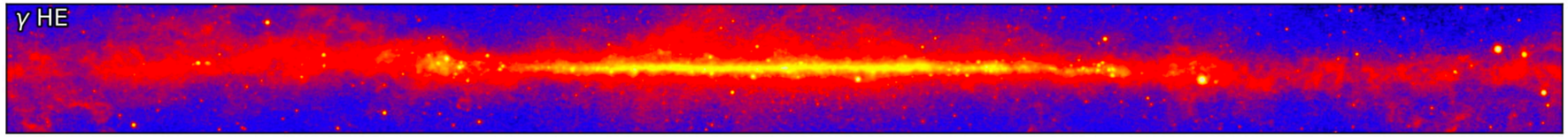
Now at 5.7σ with a combined sample!

Presented at ICRC 2025, to be published soon

State of the art

Diffuse neutrinos – The Milky Way

A template analysis



SFB 1258 Neutrinos Dark Matter Messengers

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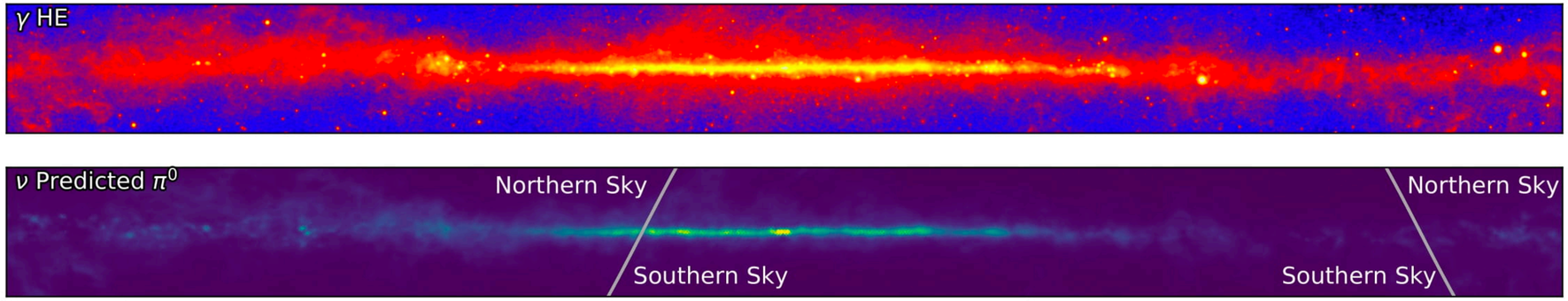

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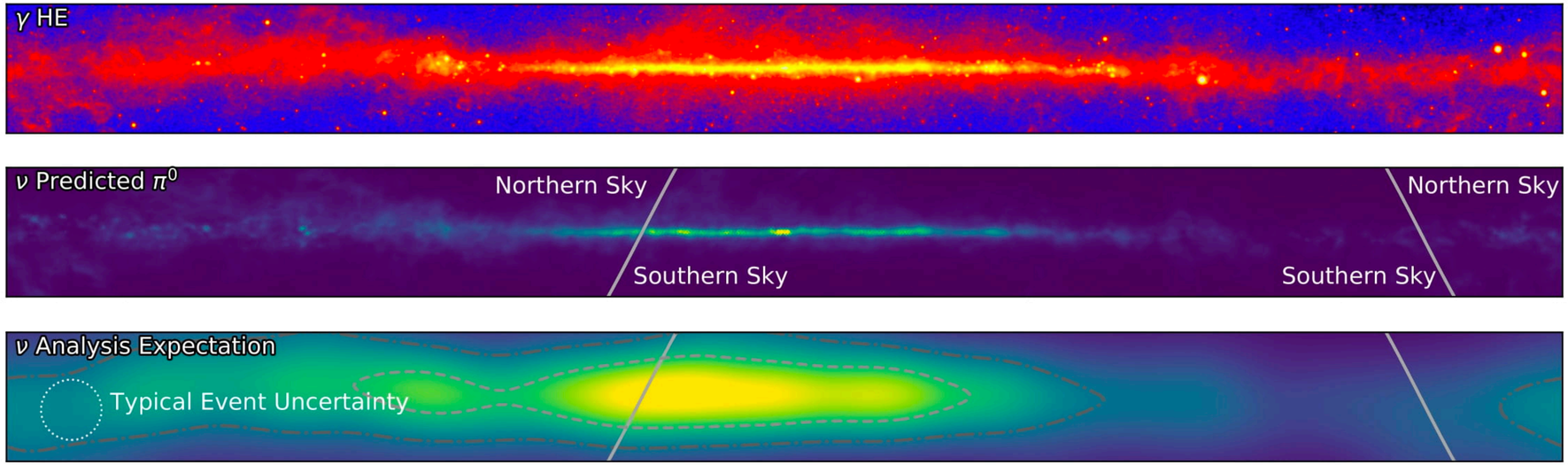

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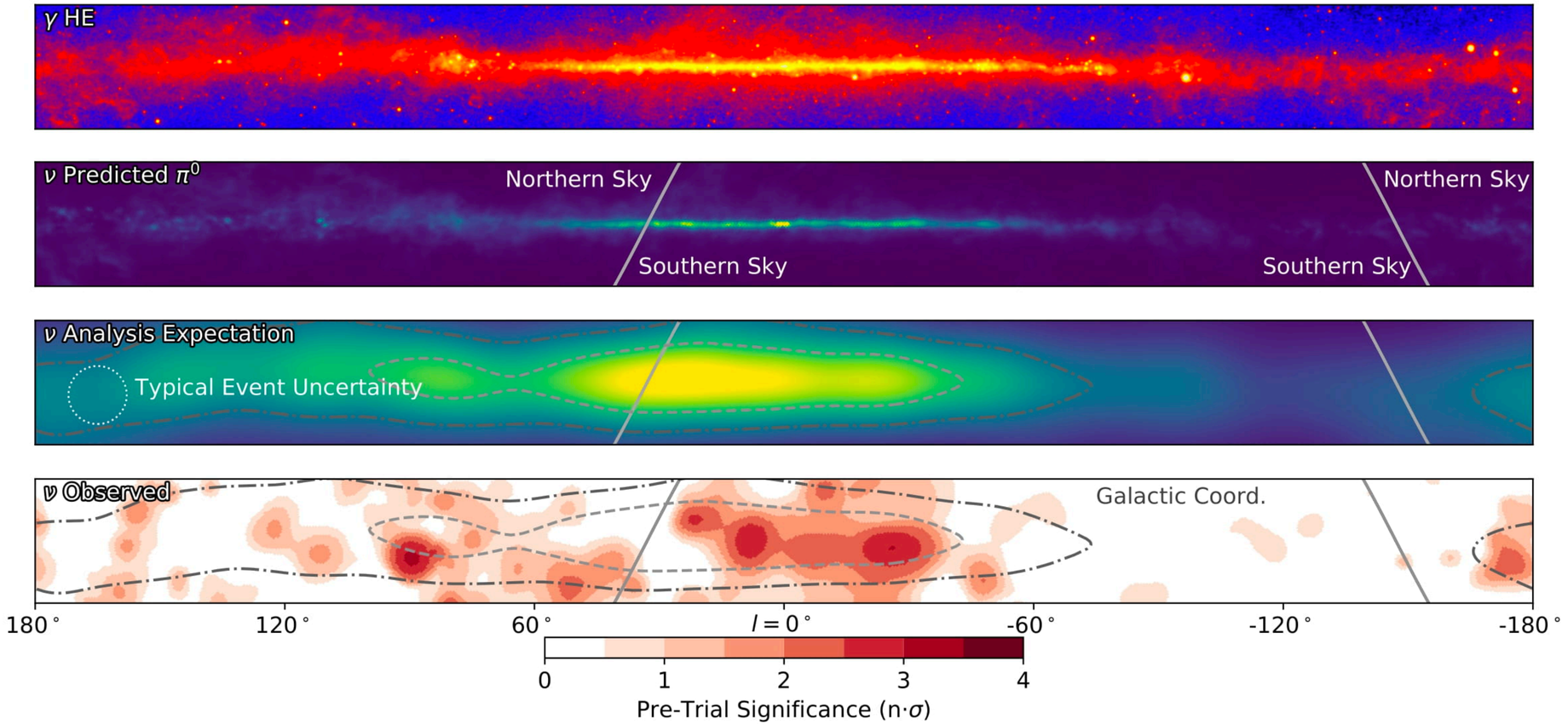
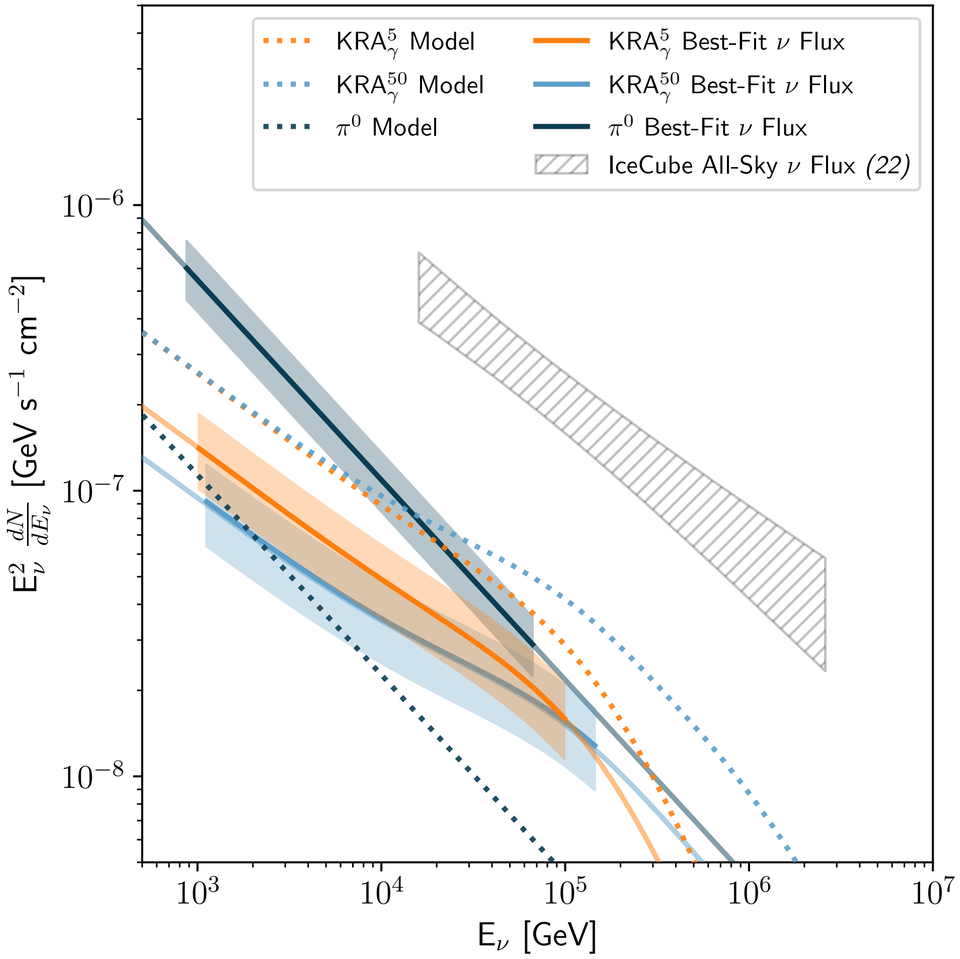


Limitations

SFB 1258 Neutrinos Dark Matter Messengers

Diffuse neutrinos – The Milky Way



	Flux sensitivity Φ	*P* value	Best-fitting flux Φ
	Diffuse Galactic plane analysis		
π^0	5.98	1.26×10^{-6} (4.71σ)	$21.8^{+5.3}_{-4.9}$
KRA$_\gamma^5$	0.16 × MF	6.13×10^{-6} (4.37σ)	$0.55^{+0.18}_{-0.15} \times$ MF
KRA$_\gamma^{50}$	0.11 × MF	3.72×10^{-5} (3.96σ)	$0.37^{+0.13}_{-0.11} \times$ MF

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Limitations

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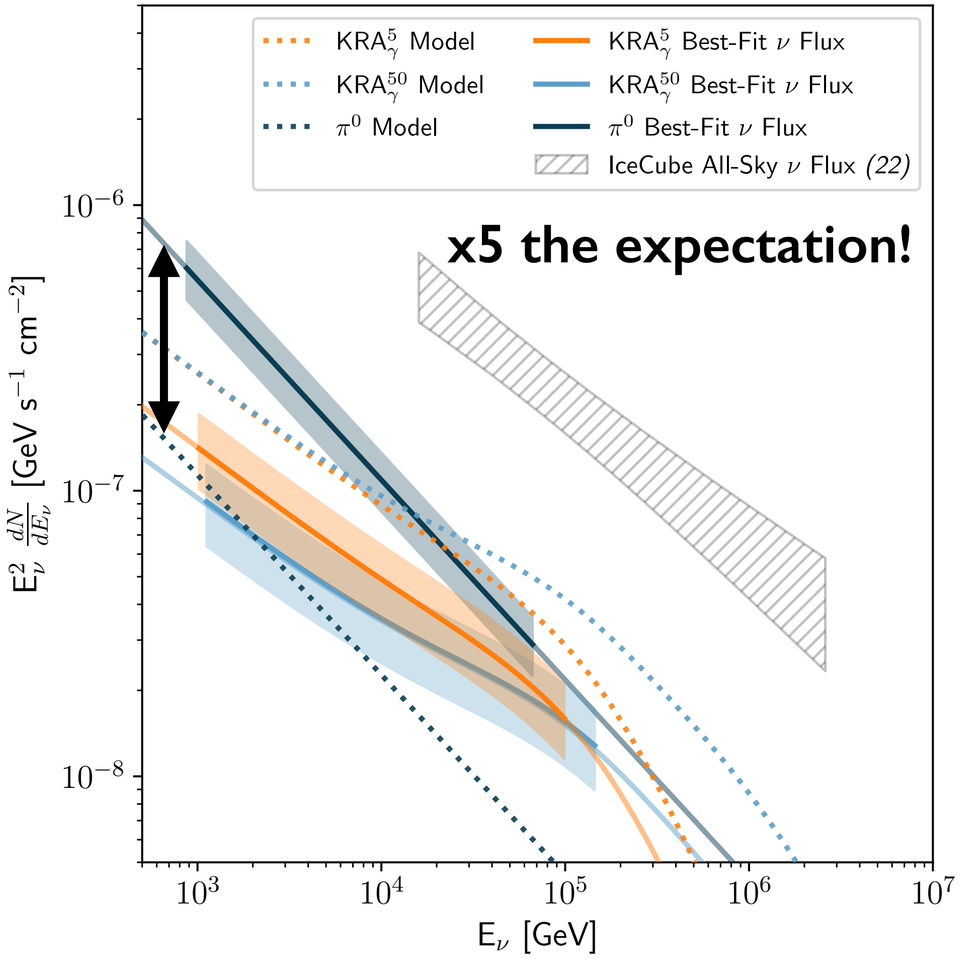

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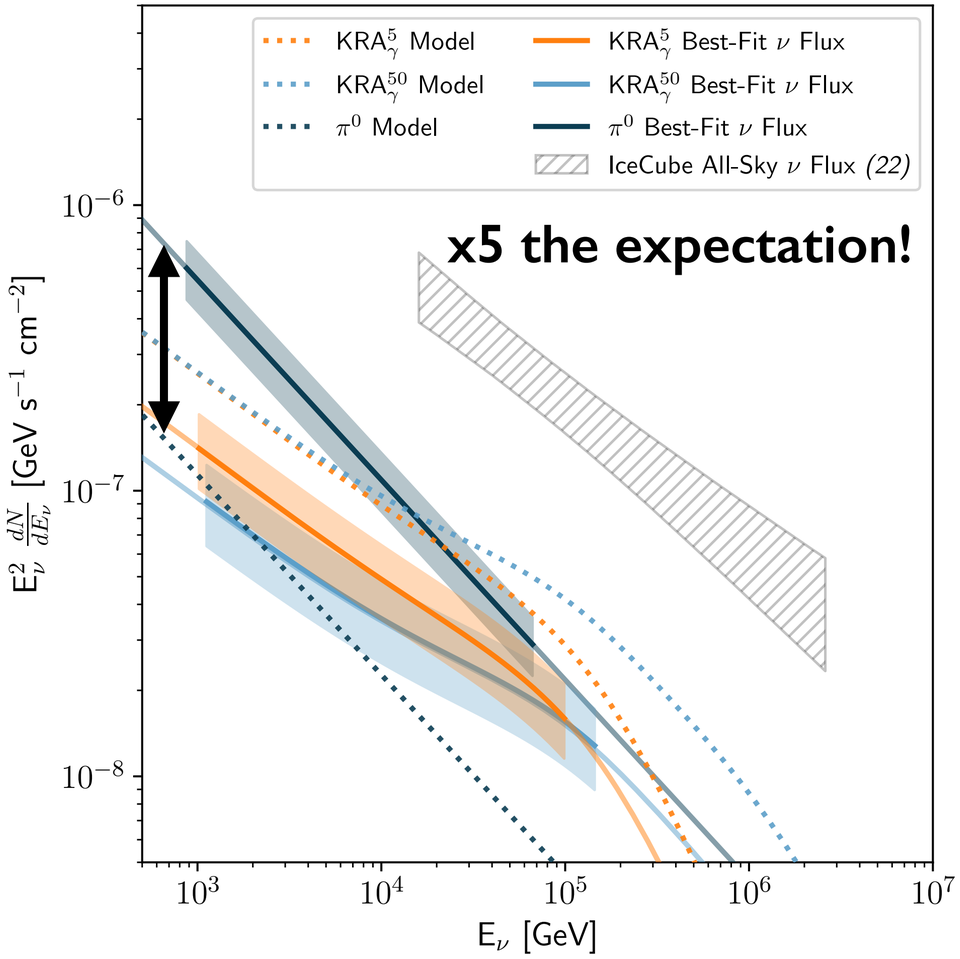

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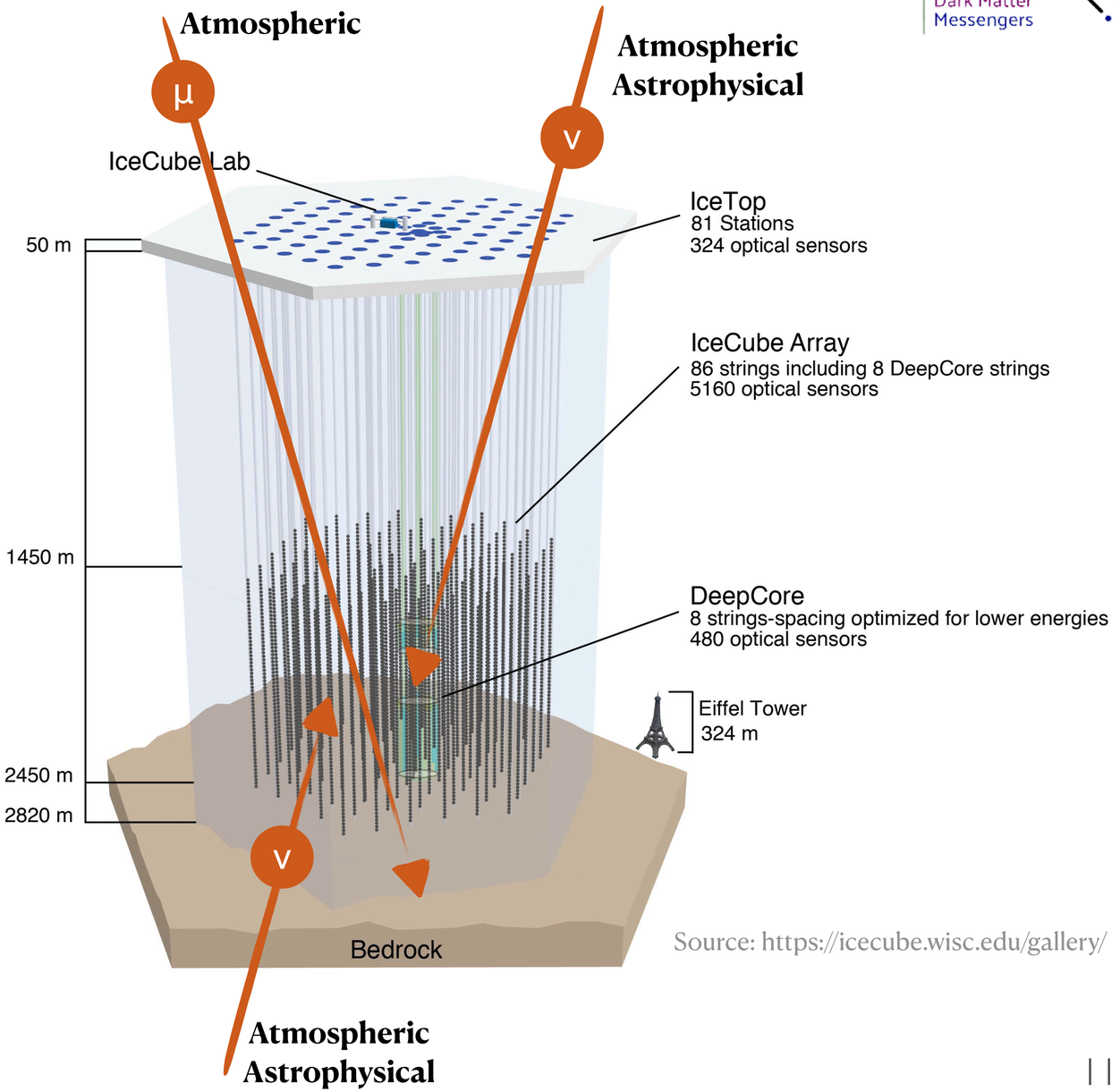
SFB 1258 Neutrinos Dark Matter Messengers

What do we need next?



Source: https://icecube.wisc.edu/gallery/

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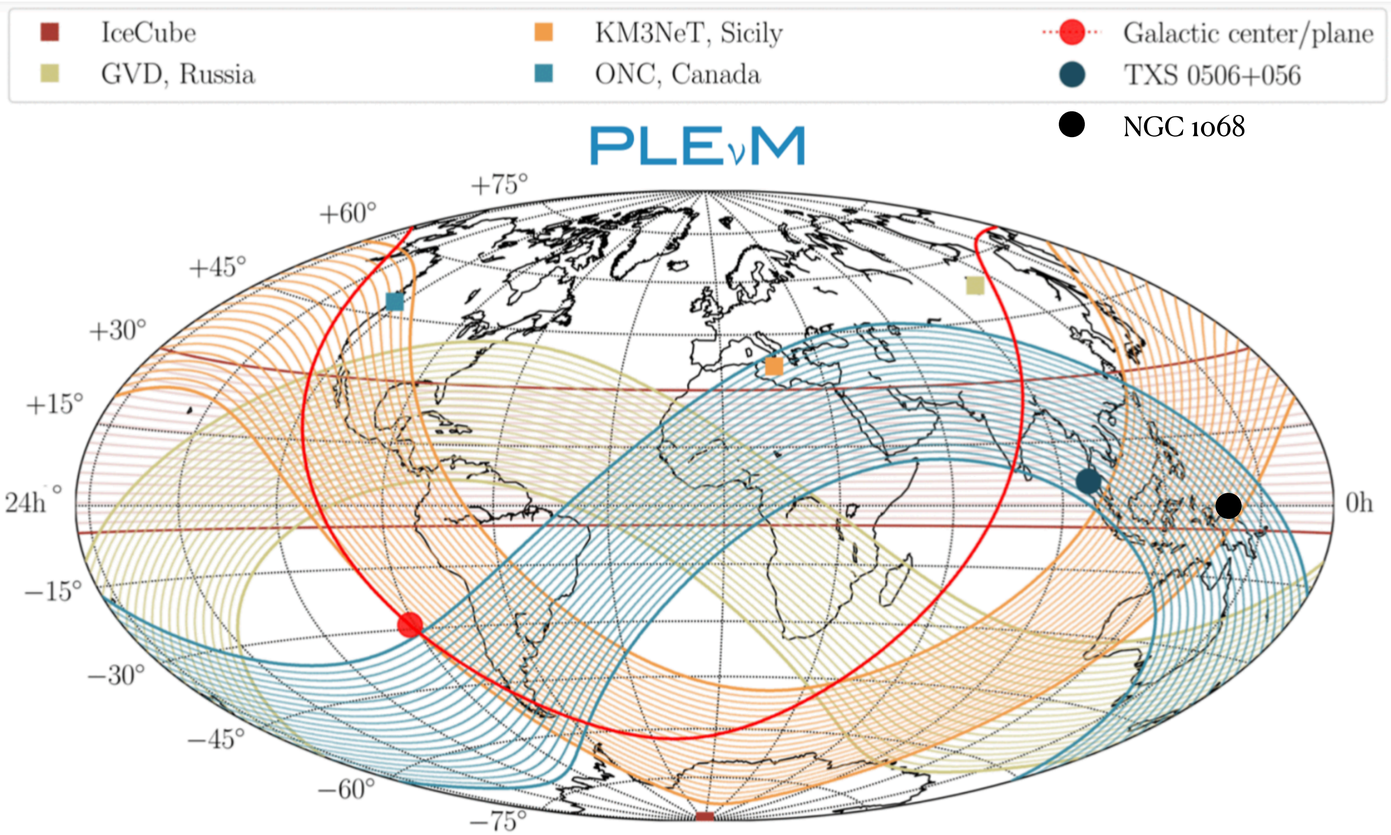

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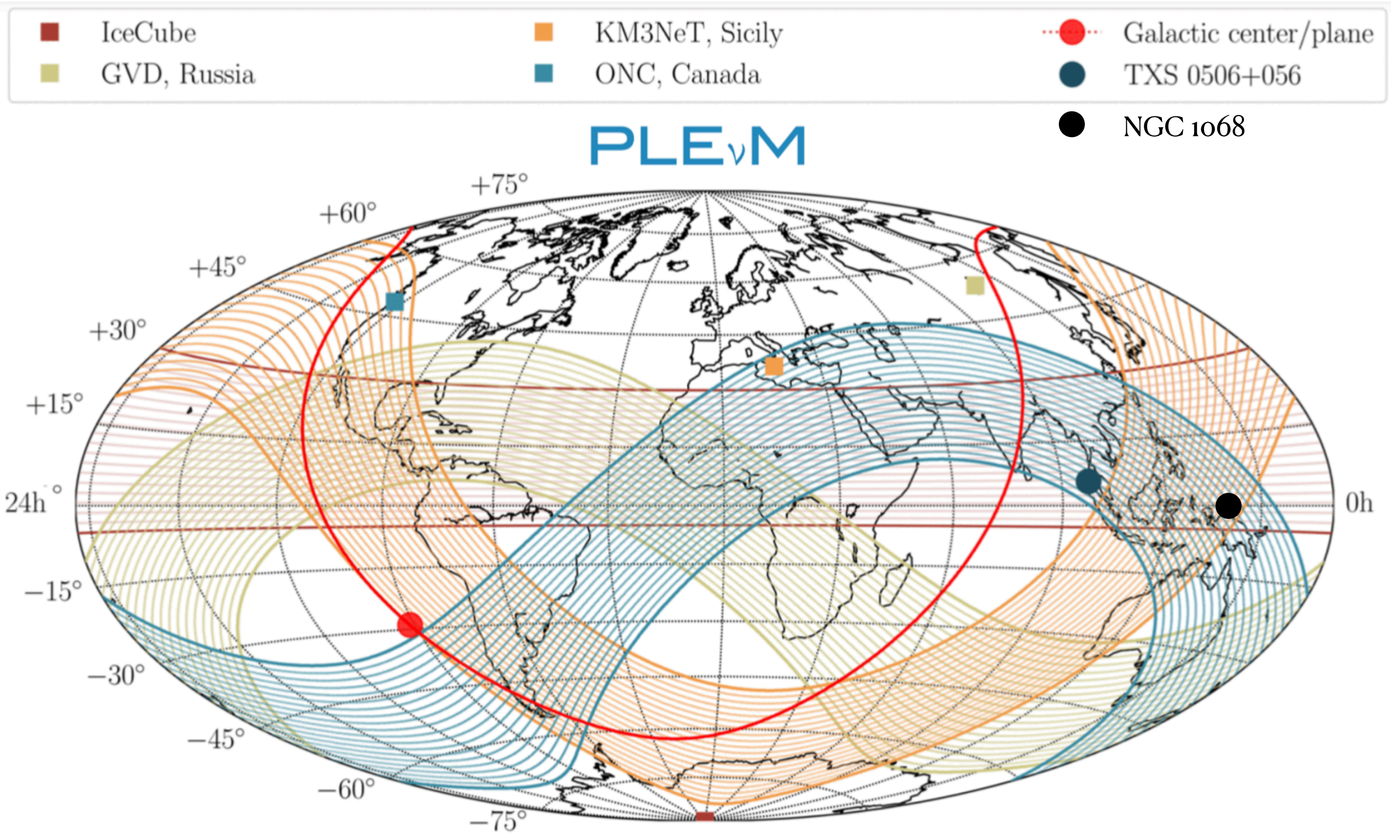
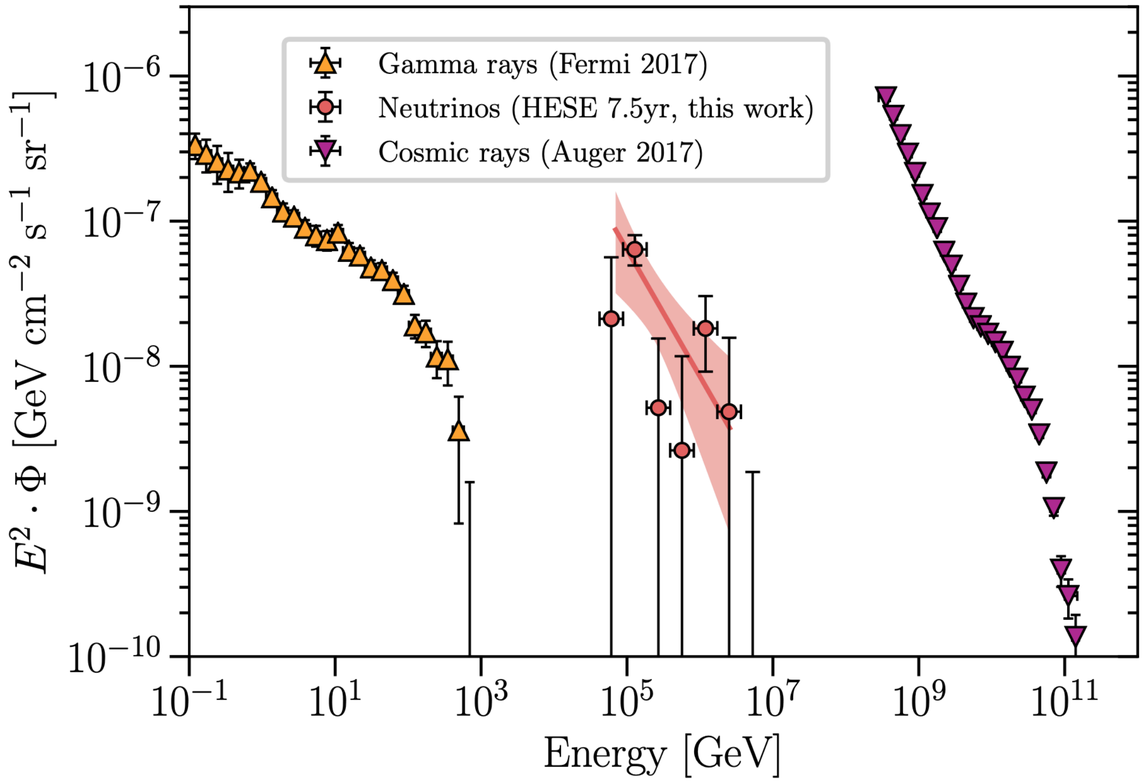


- Sensitive per-flavor measurement of the galactic neutrino emission
- Higher resolution to distinguish different hadronic models
- Resolve sources

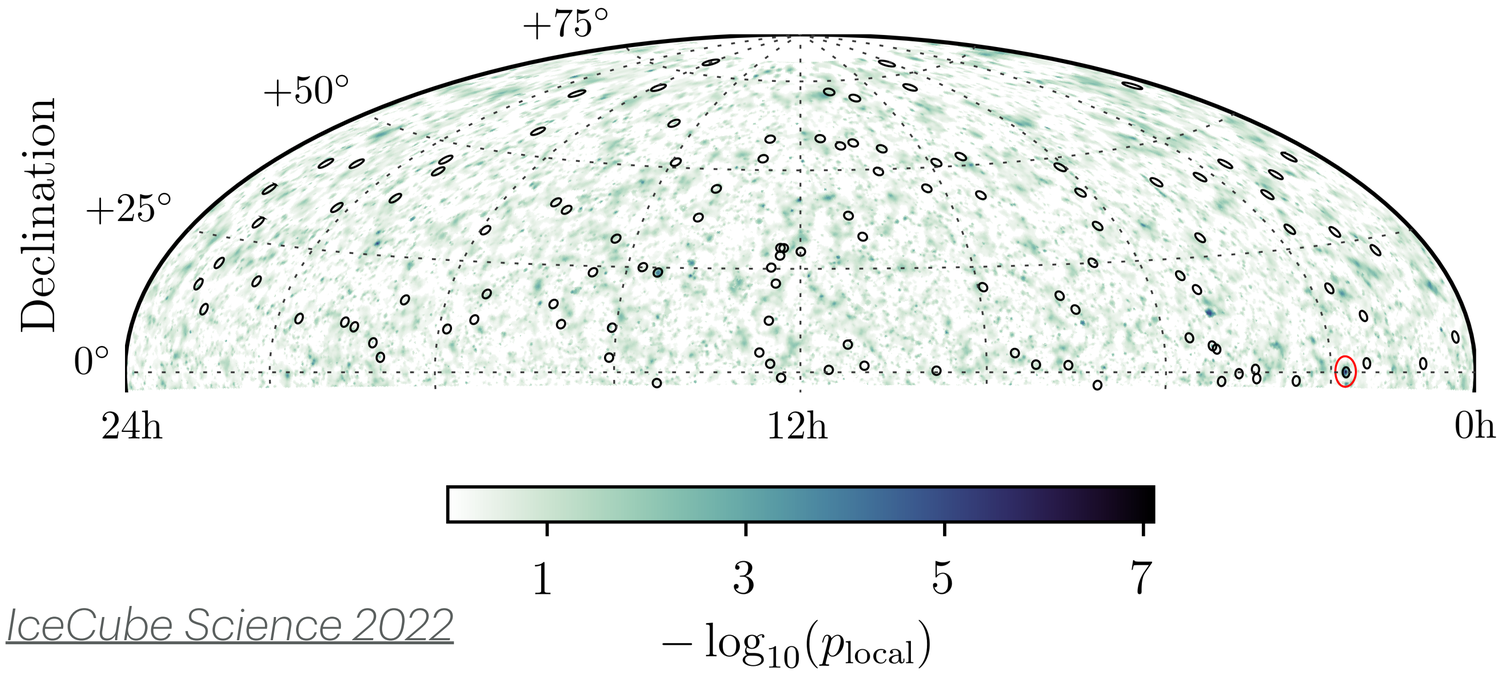
Extragalactic component – The sources

This connection has limited applications in reality



Extragalactic component – Sources

- Search from a preselected list of γ-ray emitters
- Use 9 years of neutrino-induced events from the Northern sky



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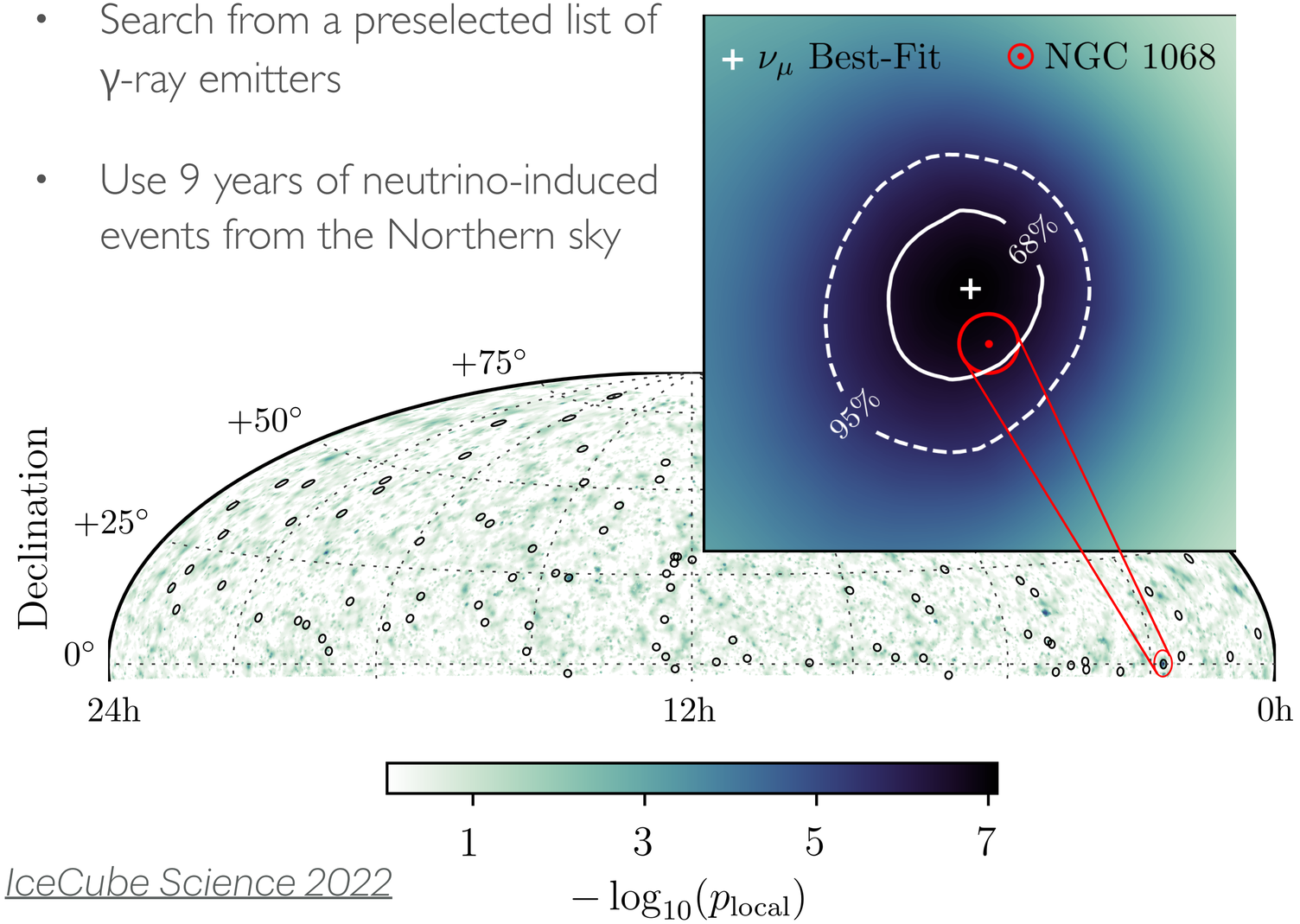

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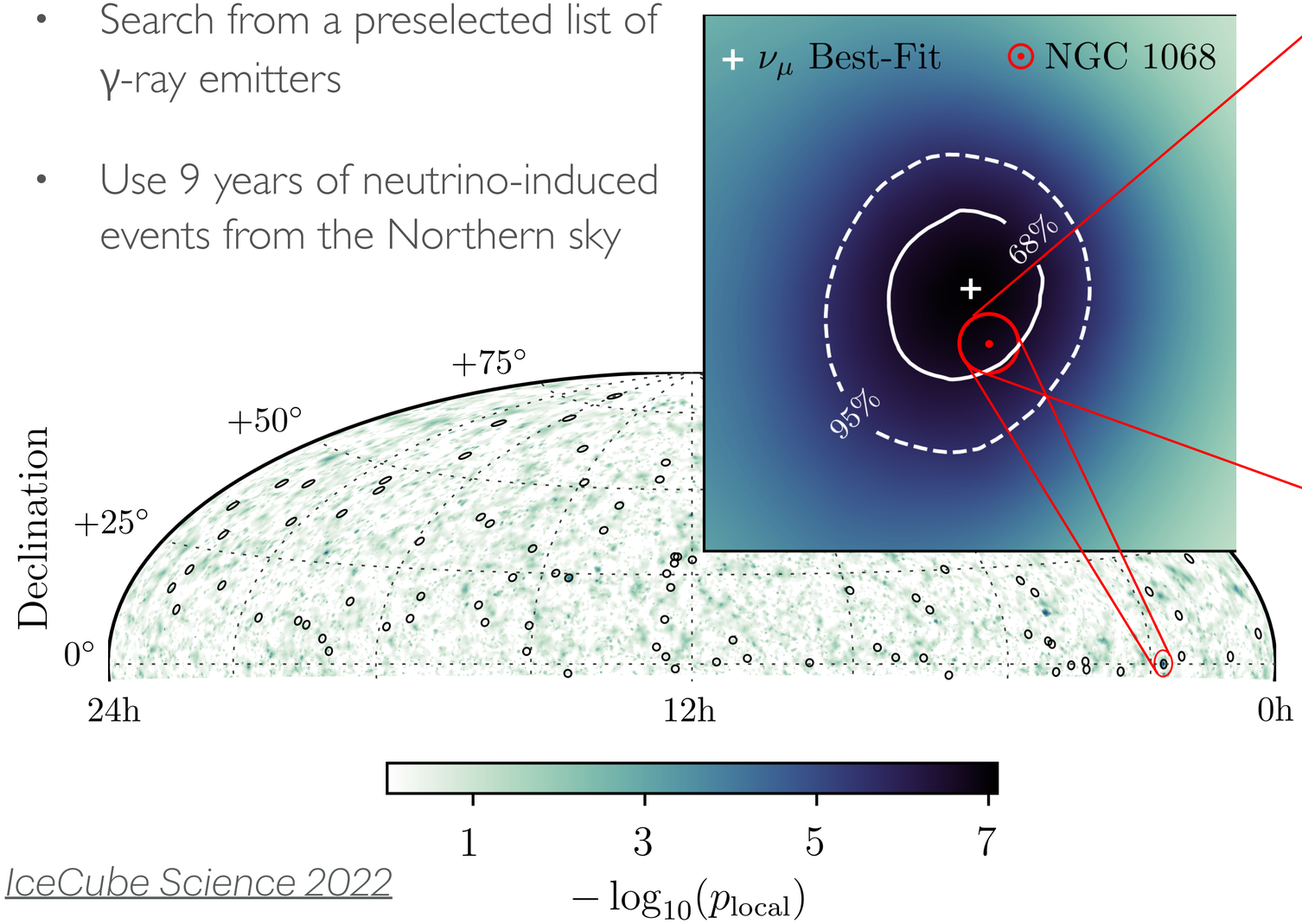

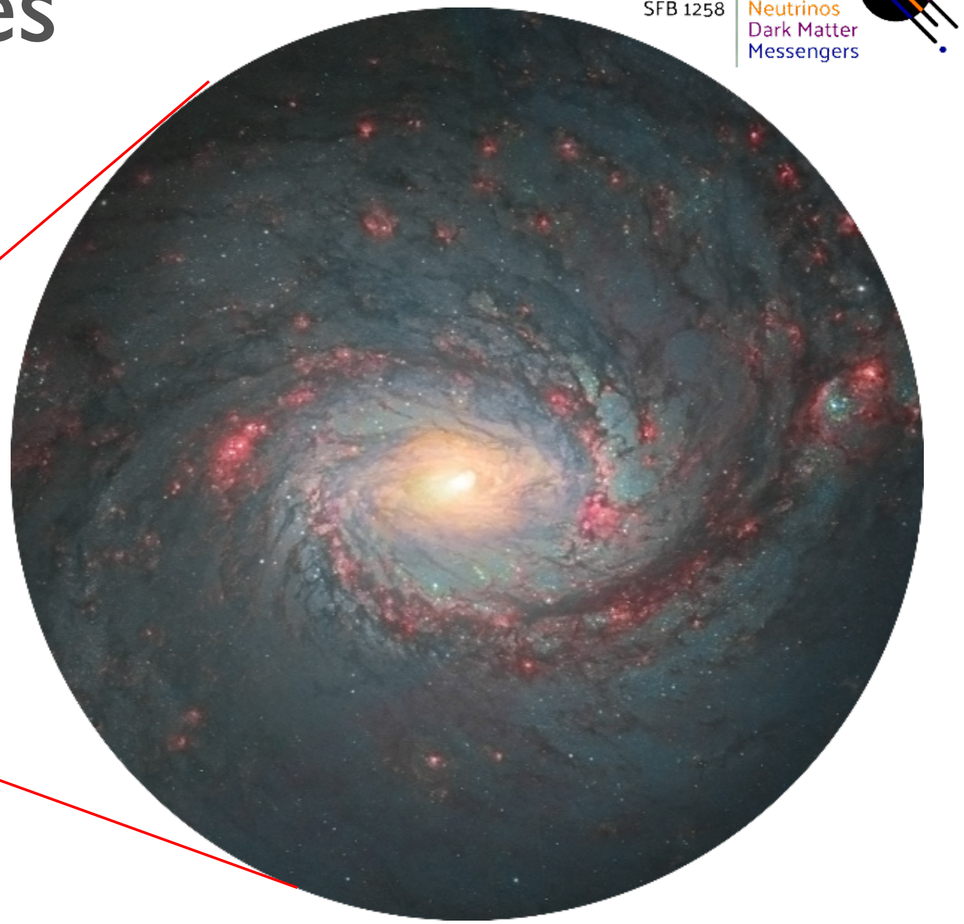

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State of the art

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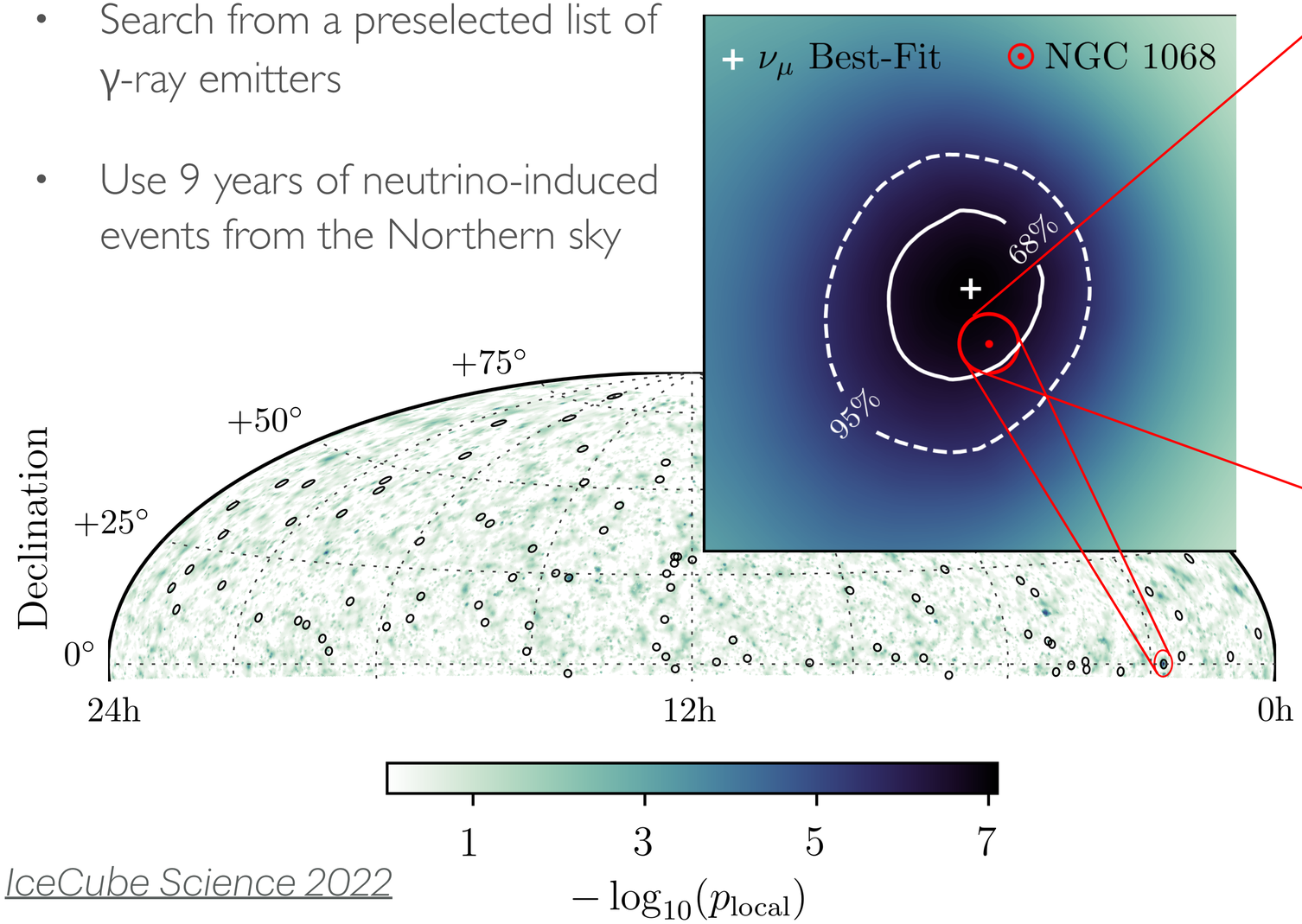

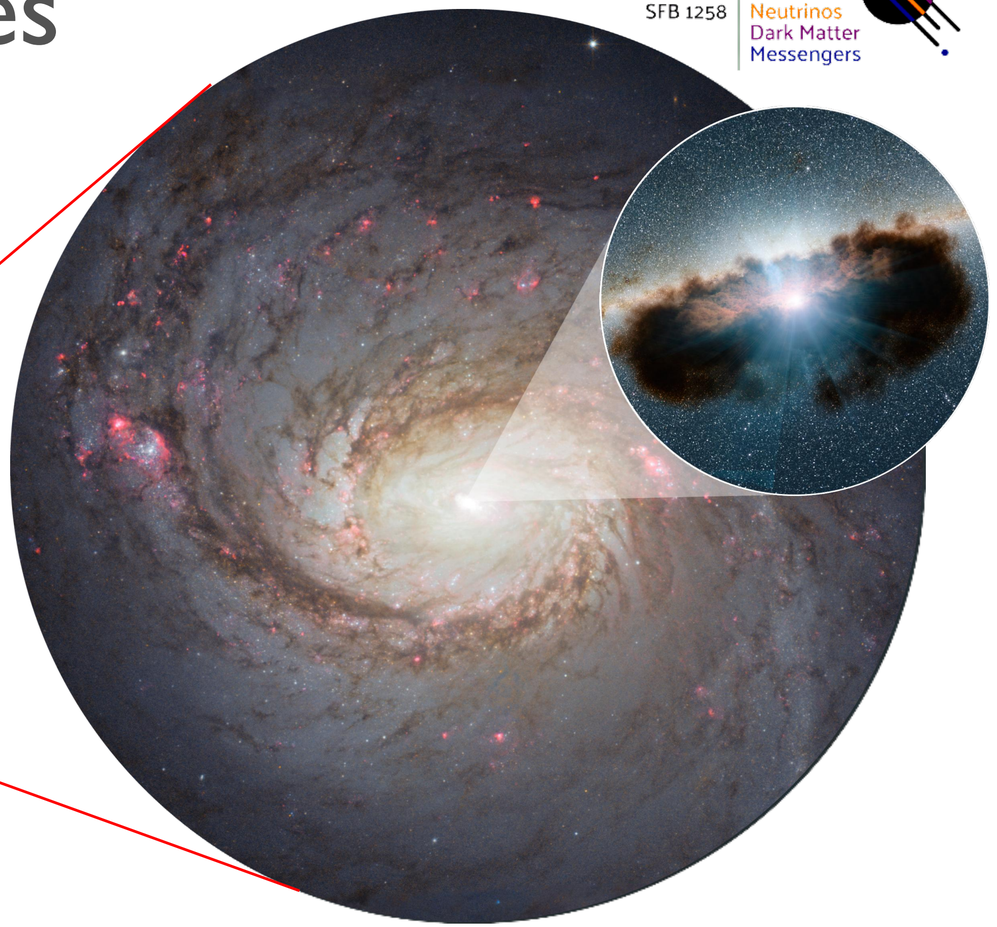

- The most significant emission is 0.1° away from the location of NGC1068 (**~4σ**)
- It's a heavily obscured AGN

IceCube Science 2022

CREDIT: NASA, ESA & A. van der Hoeven

NGC 1068, the prototype Seyfert 2

- We look at the nucleus edge-on, right through the torus.
- Very active **starburst** spiral galaxy.
- It is **close**! (~10 Mpc).
- It hosts a **Compton-thick AGN** showing no jet activity.
- AGN powered by a **SMBH** with mass ~10^6 - 107 M_{sol}.
- Intrinsically the brightest Seyfert in the X-ray band.

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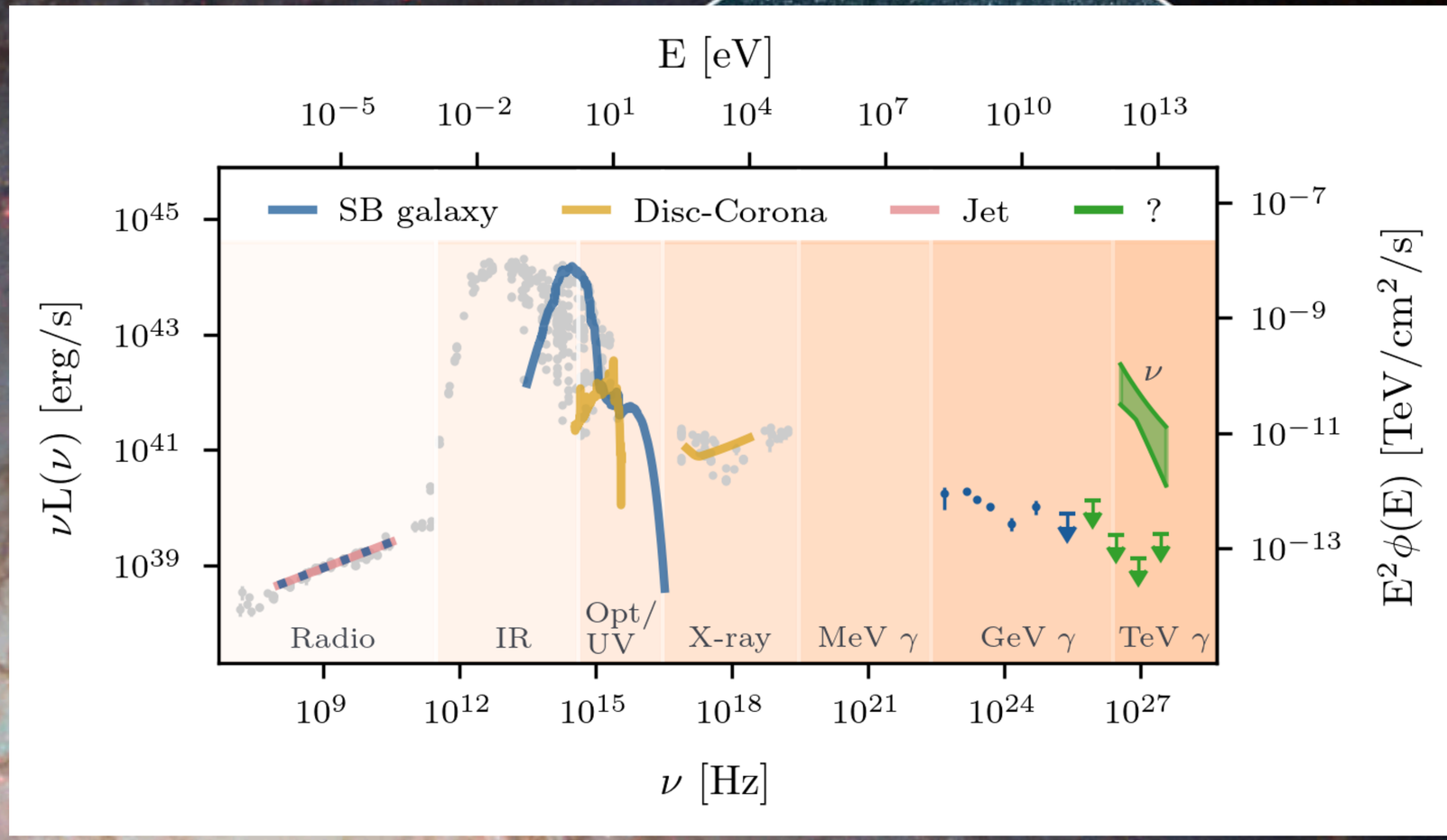

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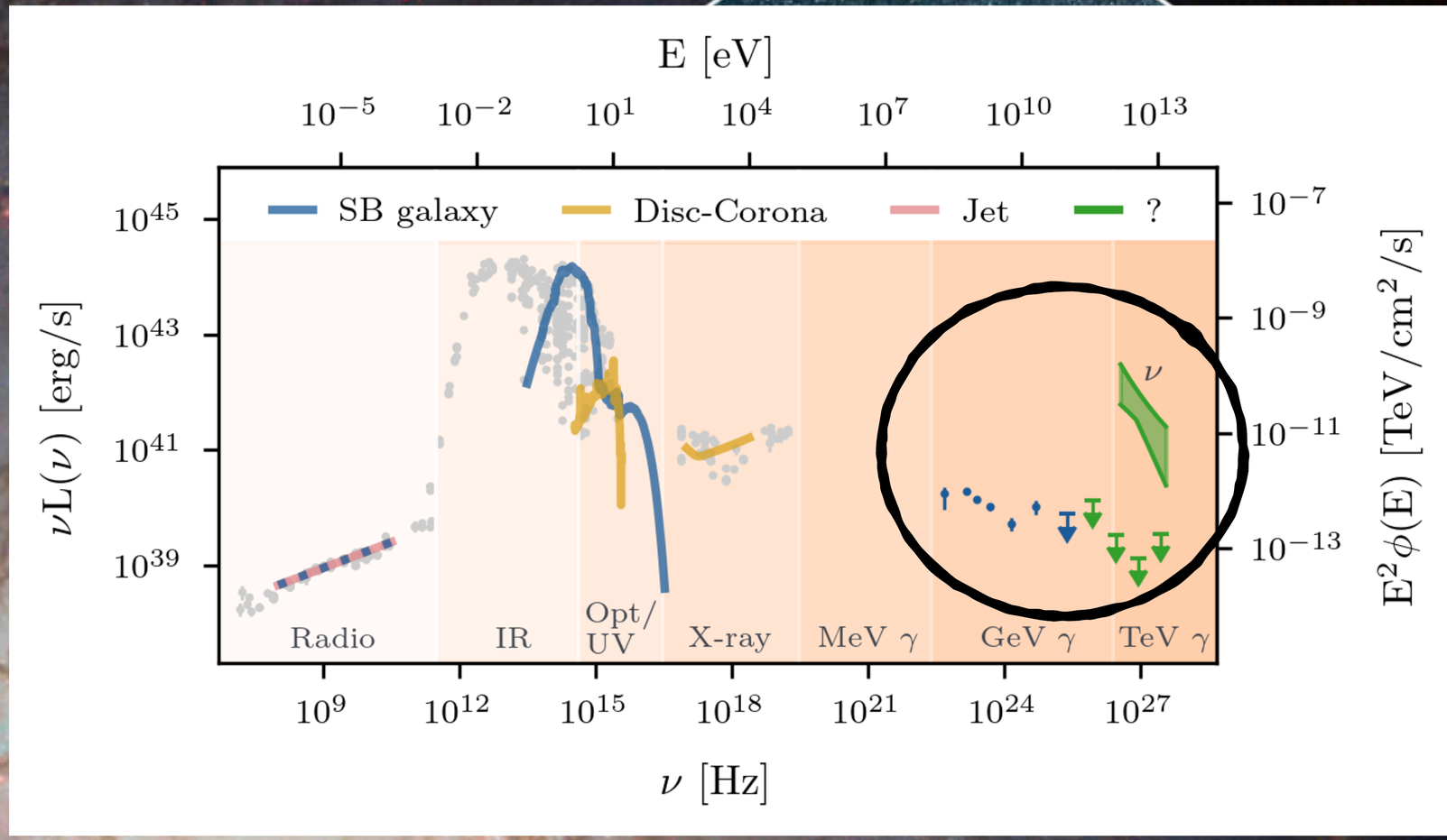

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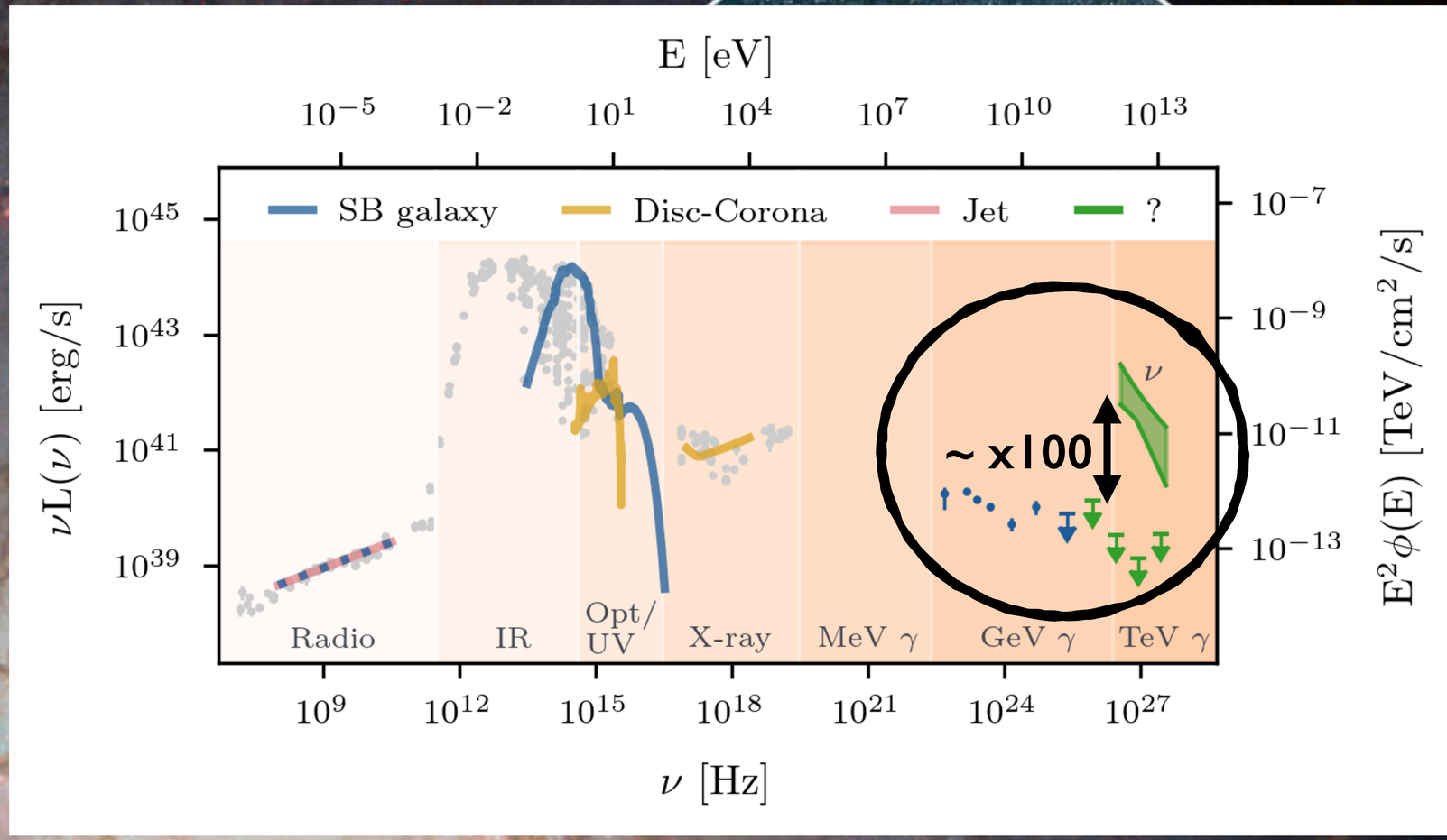
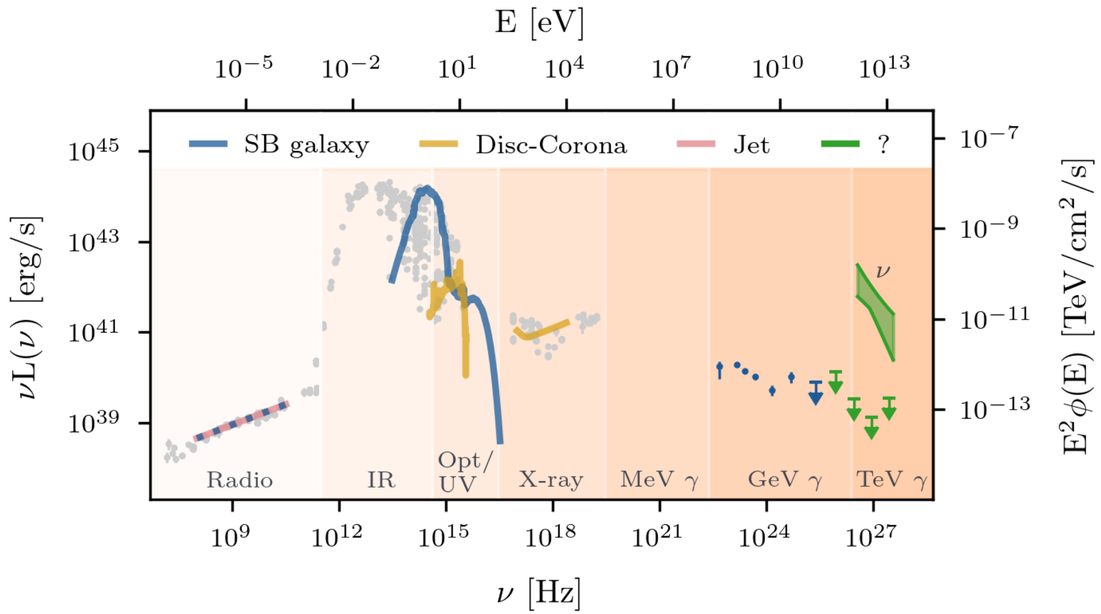


Extragalactic component – Hidden sources

Where are the neutrinos produced?

Make 3 extreme assumptions to maximize all ν powers:

1. All gamma-rays are hadronic $\rightarrow L_\nu \sim \frac{L_\gamma}{2}$
2. L_γ is as large as possible
3. Convert γ-ray to neutrino bands assuming $\Phi(E_\nu) \propto E_\nu^{-2}$



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Star formation	> kpc	$\sim 10^{40.9}$	$\lesssim 10^{40.1}$
Jet	~ kpc	$< 10^{41.7}$ (M87-like)	$< 10^{40.9}$
Outflow (UFO)	~ pc	$< 10^{41.2}$	$< 10^{40.4}$
BH vicinity	~ 0.02 mpc (~ 30 R_s)	?	?
	Total	$\lesssim 10^{41.9}$	$\ll 10^{41.1}$
	Observed	$10^{40.92\pm0.03}$	$10^{42.1\pm0.2}$

Padovani, Resconi, Ajello, C.B. et al, Nat. Astr. (2024)

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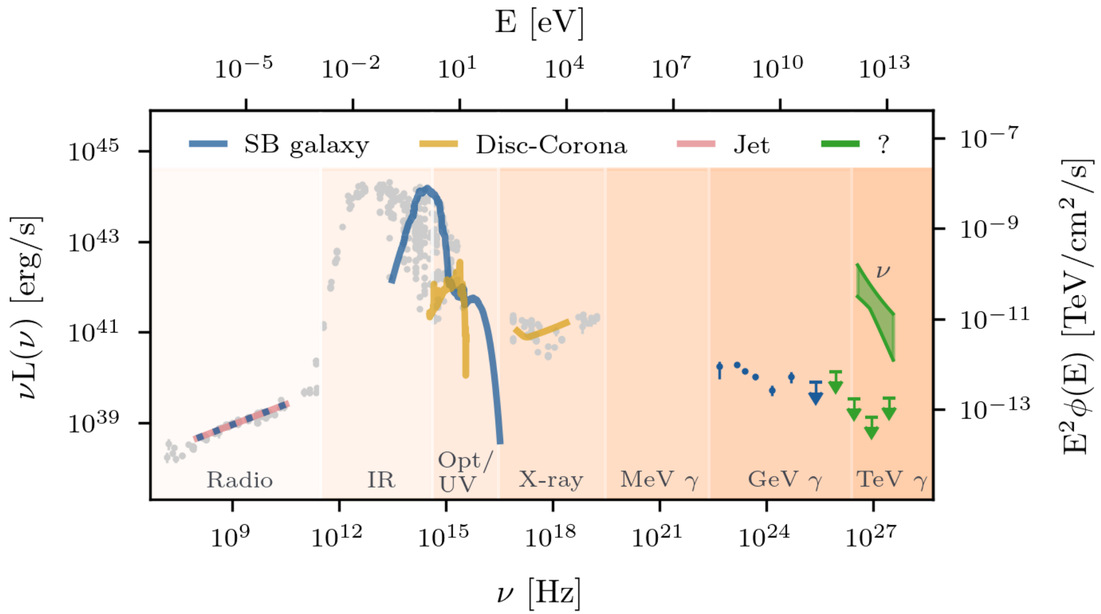

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Limitations

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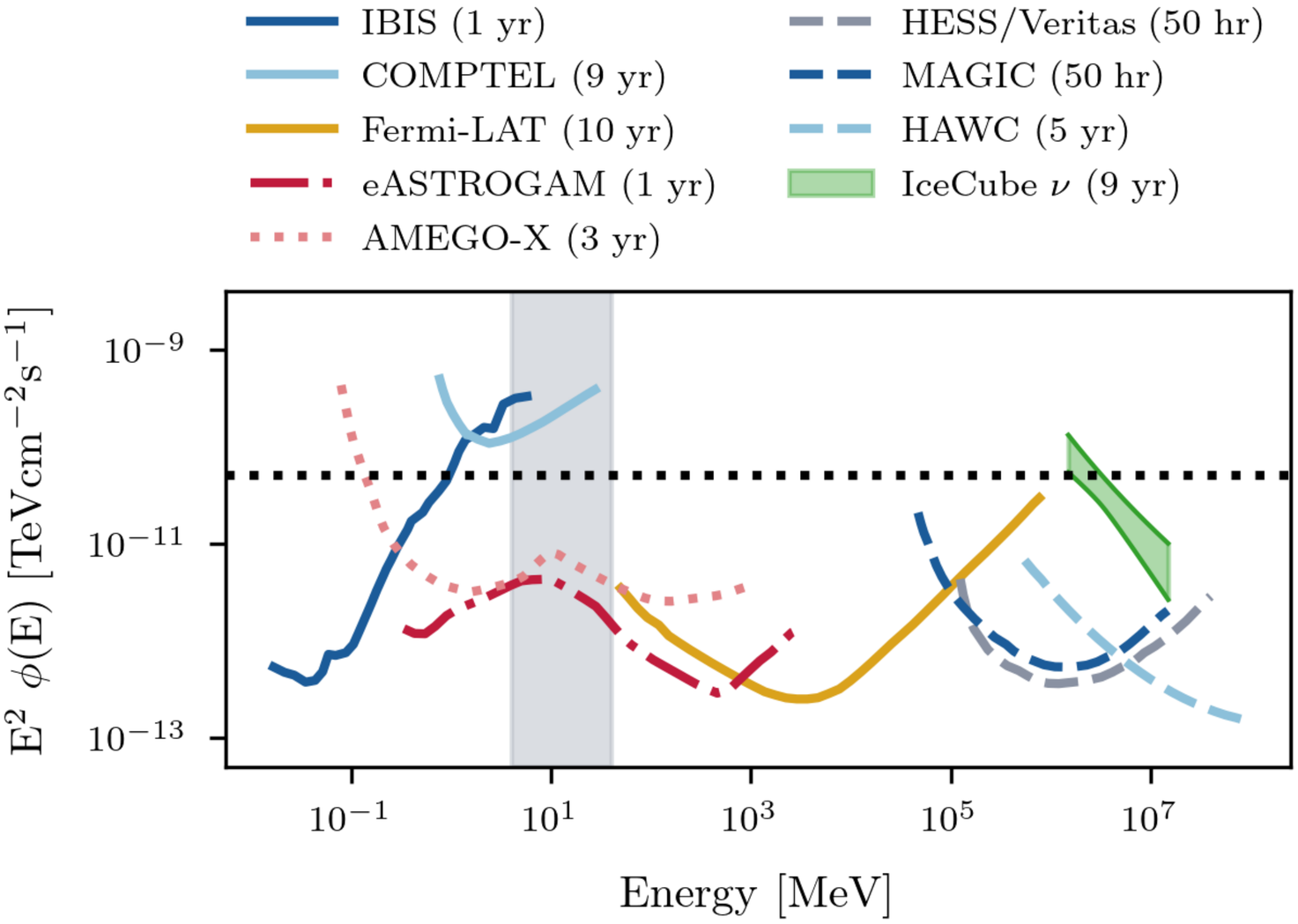
and COSI?

Limitations

Extragalactic component – Hidden sources



and COSI?

SFB 1258 Neutrinos Dark Matter Messengers

MORE ICECUBE SEARCHES TARGETING THE CORONAL X RAYS–NEUTRINO CONNECTION

(This is gonna be a lot… sorry)

SFB 1258 Neutrinos Dark Matter Messengers

Extragalactic component – More sources

Select candidate sources based on X-ray emission!

- X-rays are better neutrino tracers!
- Let's look at bright sources in the 14-195 keV band
- Search the Swift-BAT BASS catalog
  - Stacked search weighted by X-ray flux:
    background compatible result…
  - Individual source search: **NGC 4151 @ 2.9σ**

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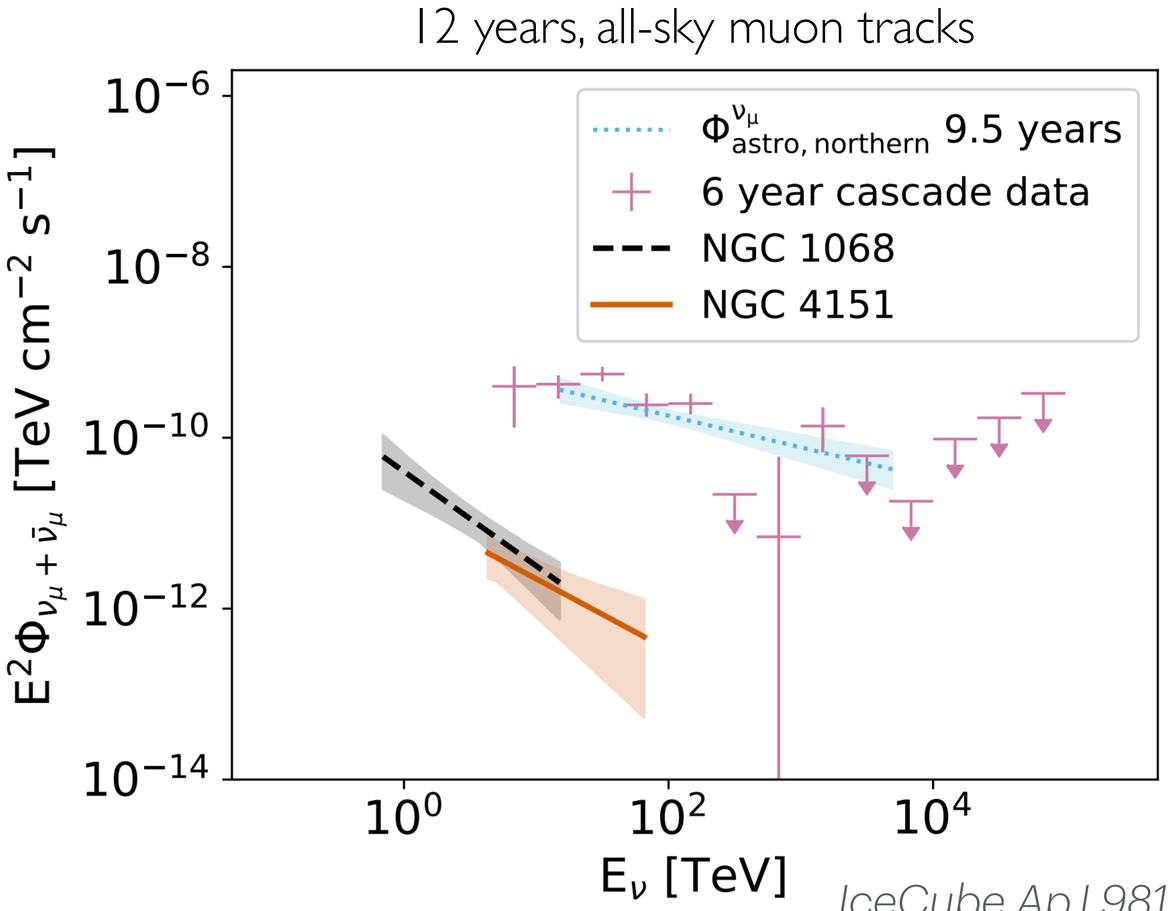
- **A Seyfert I galaxy!**

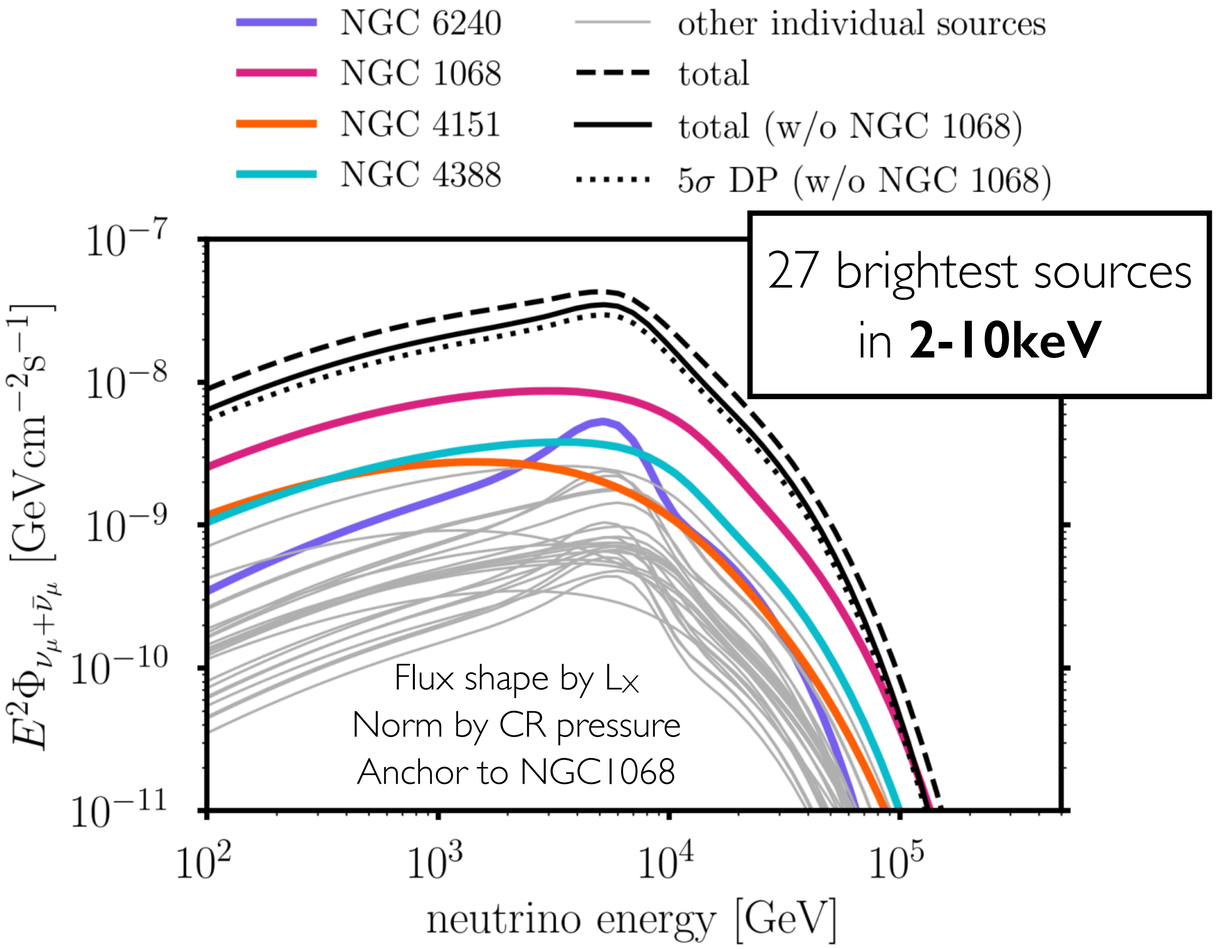


IceCube ApJ 981 131

Extragalactic component – More sources

Bring in the theoretical input and test spectral models

10 years, Northern-sky muon tracks



IceCube ApJ 981 131, *Kheirandish et al 2021*

SFB 1258 Neutrinos Dark Matter Messengers

Extragalactic component – More sources

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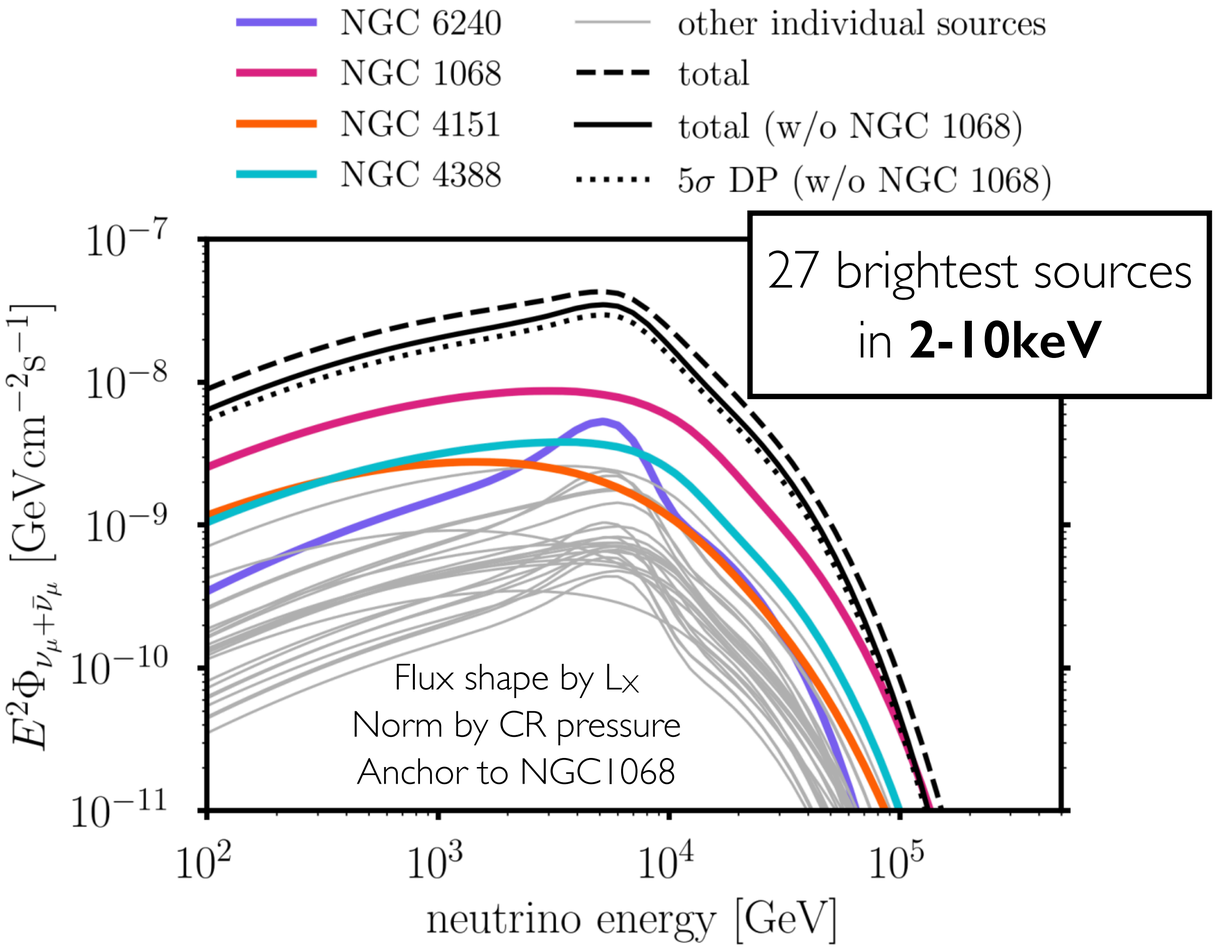

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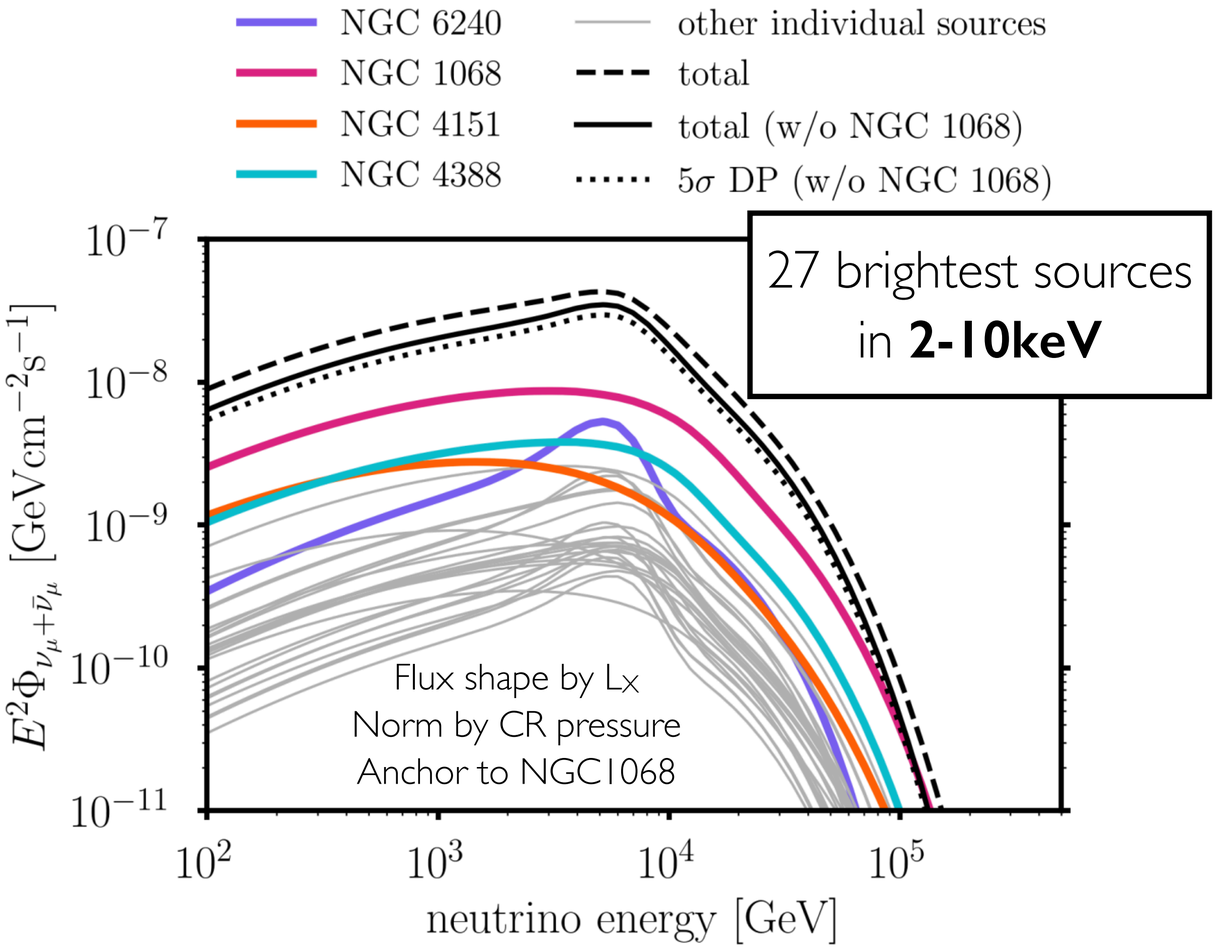

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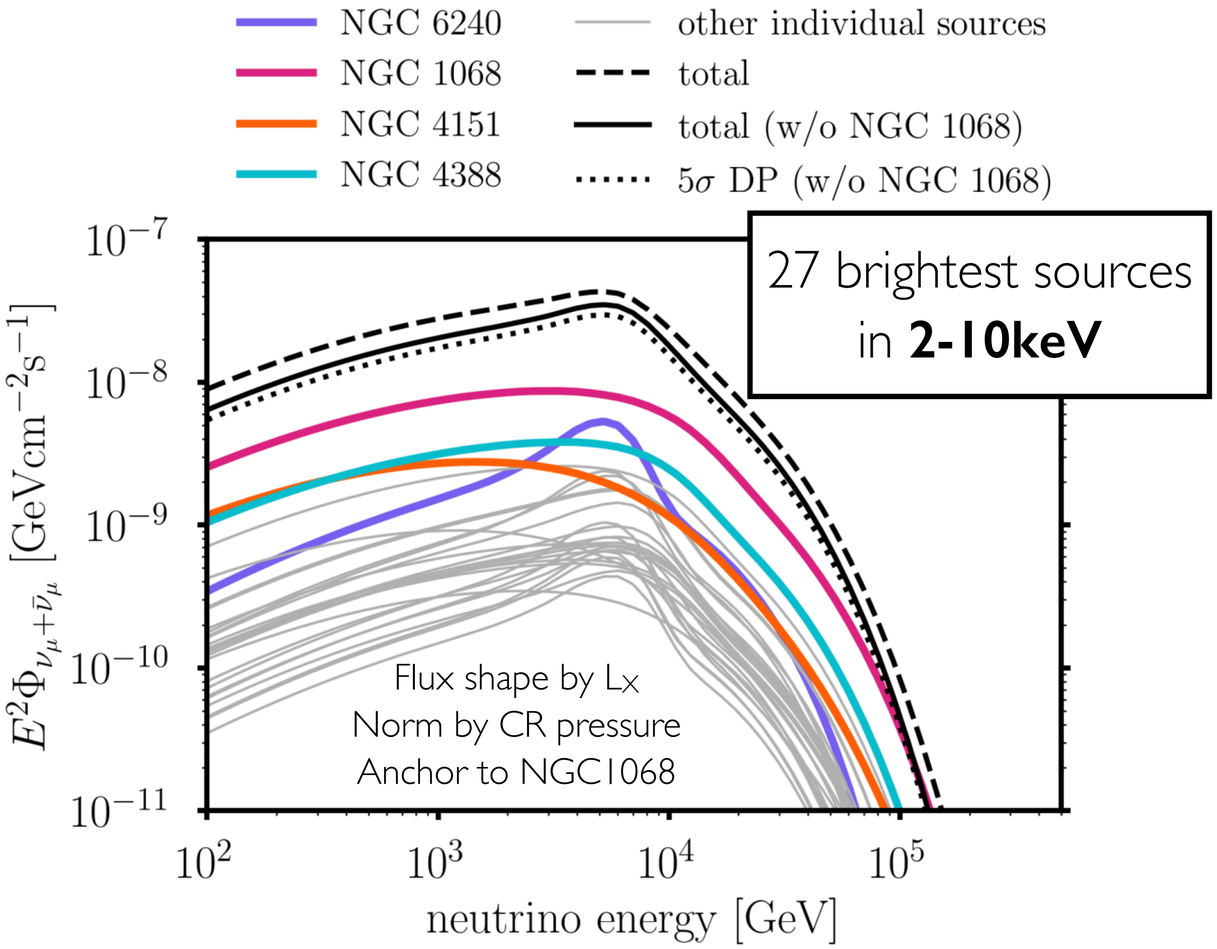

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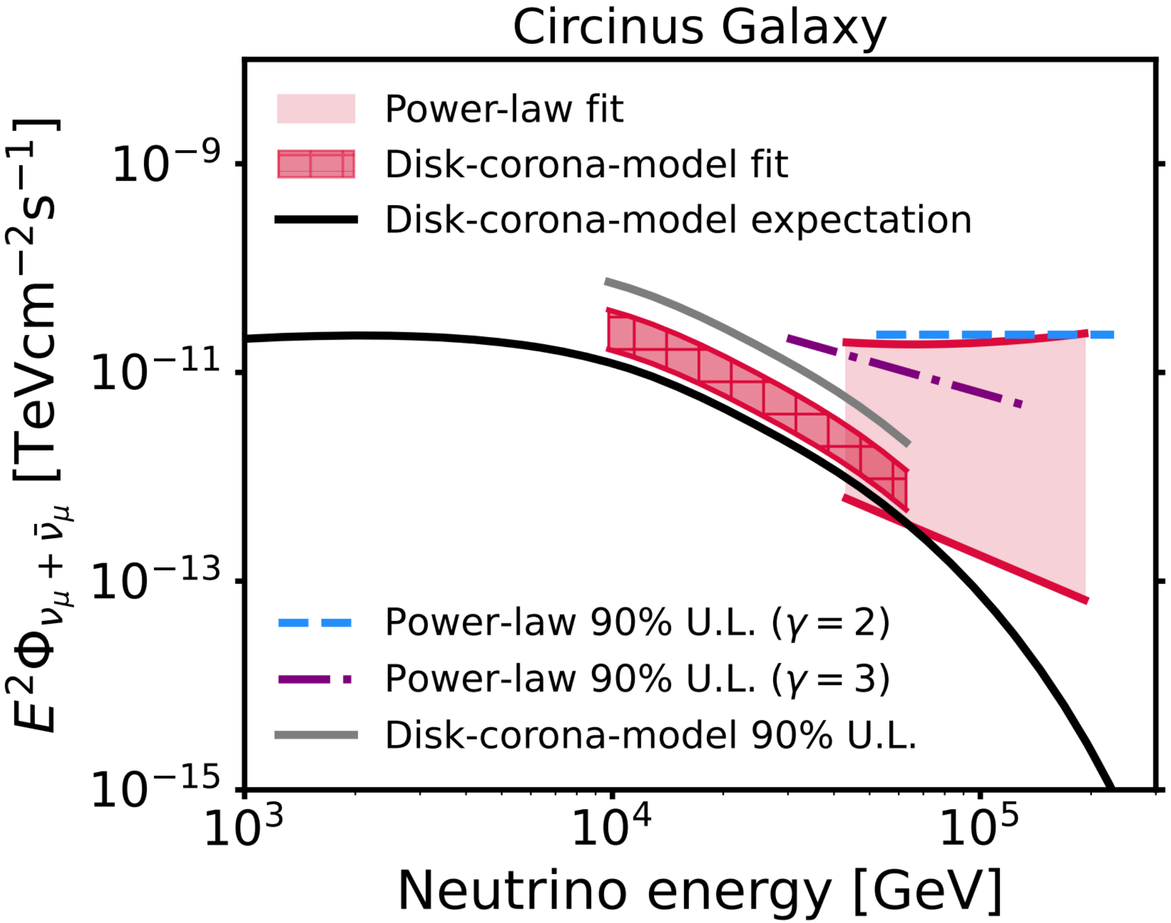
Binomial test: what's the background probability of observing k sources out of N with a local significance above a certain threshold?

IceCube ApJ 981 131, *Kheirandish et al 2021*

Extragalactic component – More sources

Independent mdoel test in the southern hemisphere

- 10 years, Southern sky muon (starting) tracks
- 13 brightest sources in the **2-10keV** band
- **Stacking of sources according to the disk-corona model ~3σ excess**
- The brightest source is the Seyfert 2 Circinus Galaxy (1.8σ)
  - Slightly more significant with a power-law fit



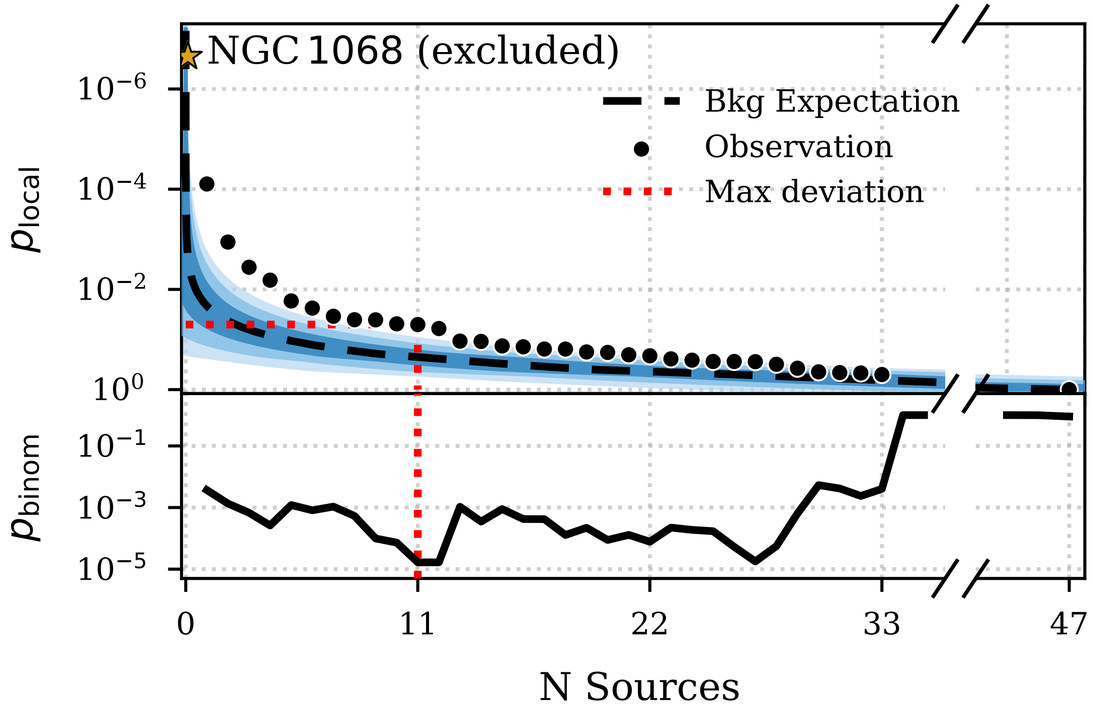
IceCube ApJL 1000, L37, (2026)

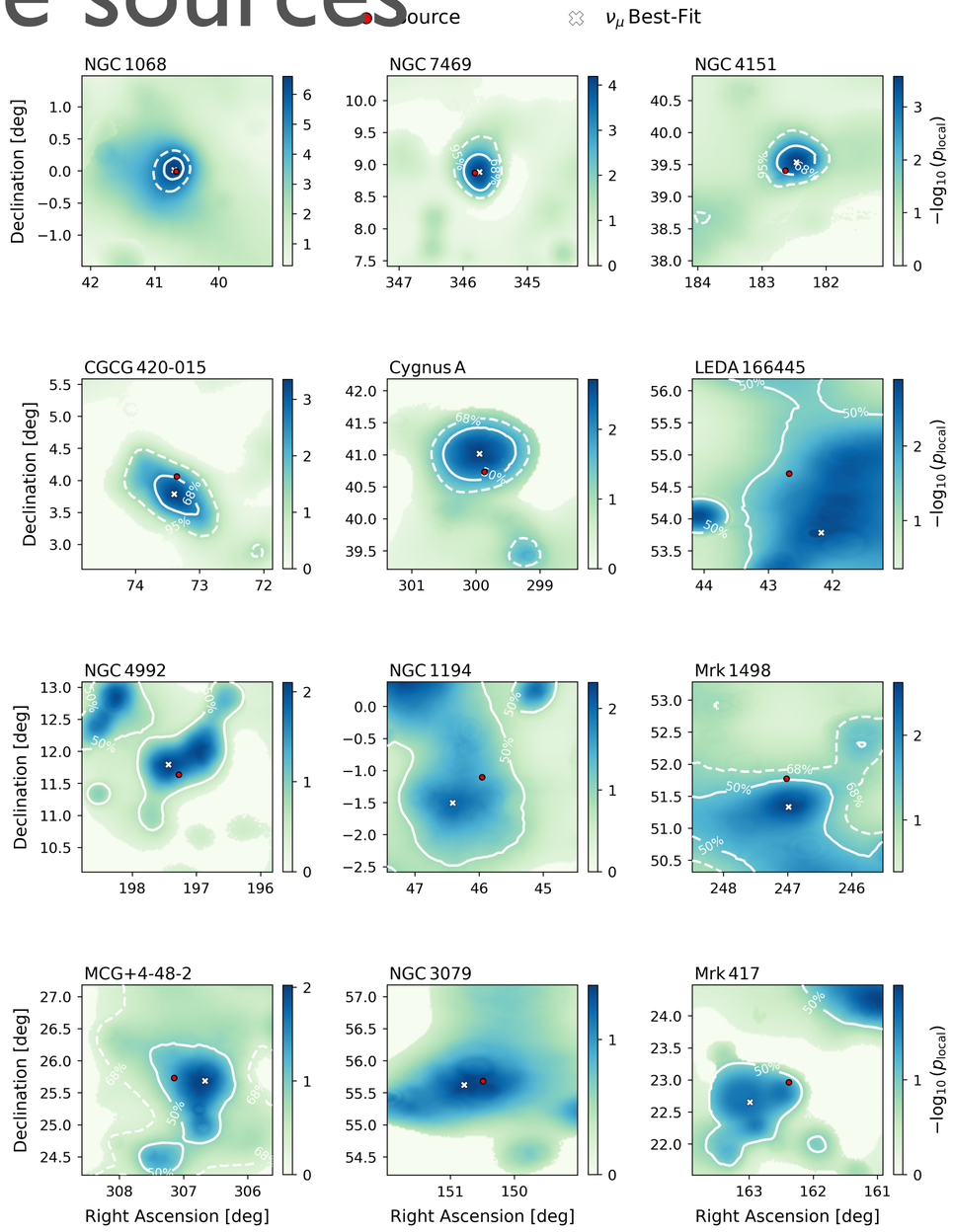
Extragalactic component – More sources

13 years Northern-sky tracks (~50% more statistics!)

47 candidates selected in the observed **20-50keV** band from the BASS catalog to suffer less absorption along the line-of-sight

Overlap with previous search: 24/47 (~50%)





IceCube ApJL 1000, L26, (2026)

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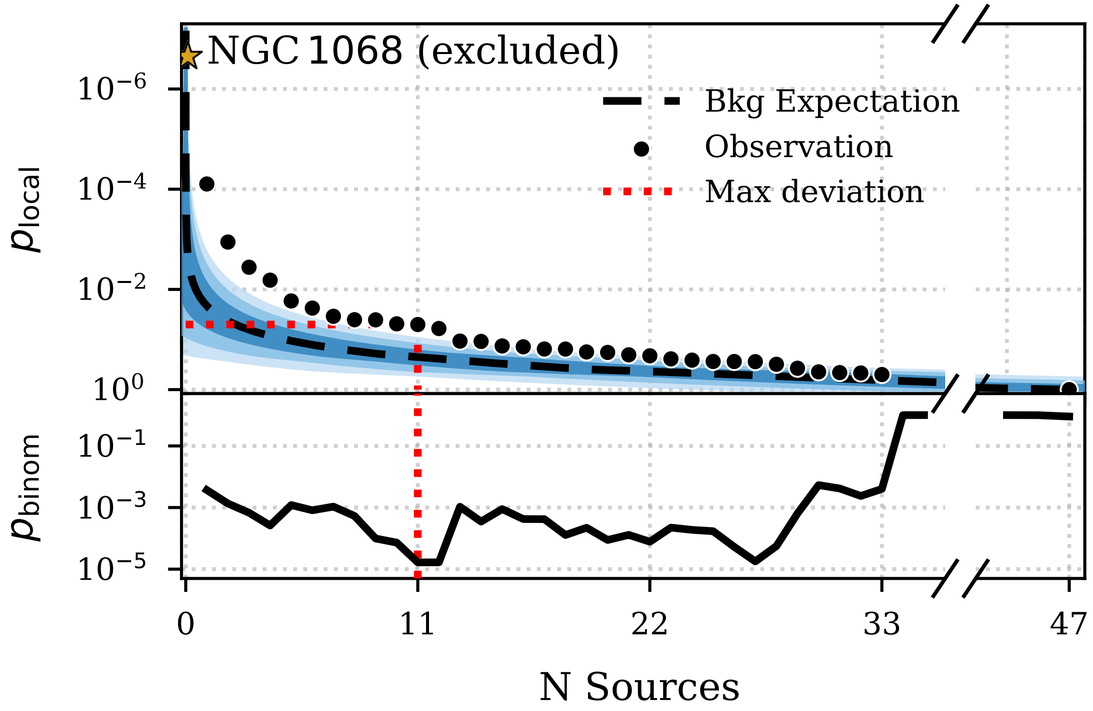
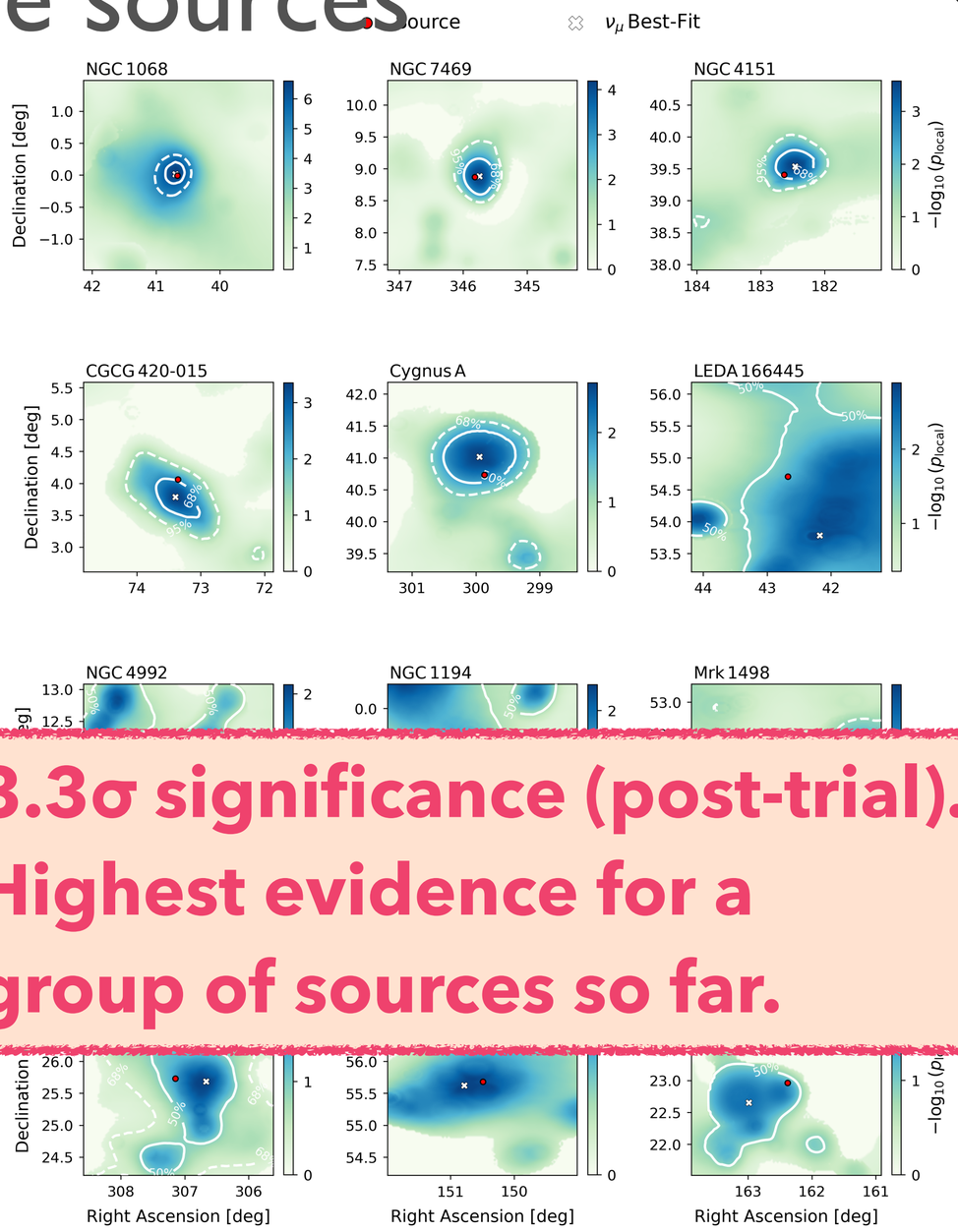




3.3σ significance (post-trial). Highest evidence for a group of sources so far.

IceCube ApJL 1000, L26, (2026)

Extragalactic component – More sources

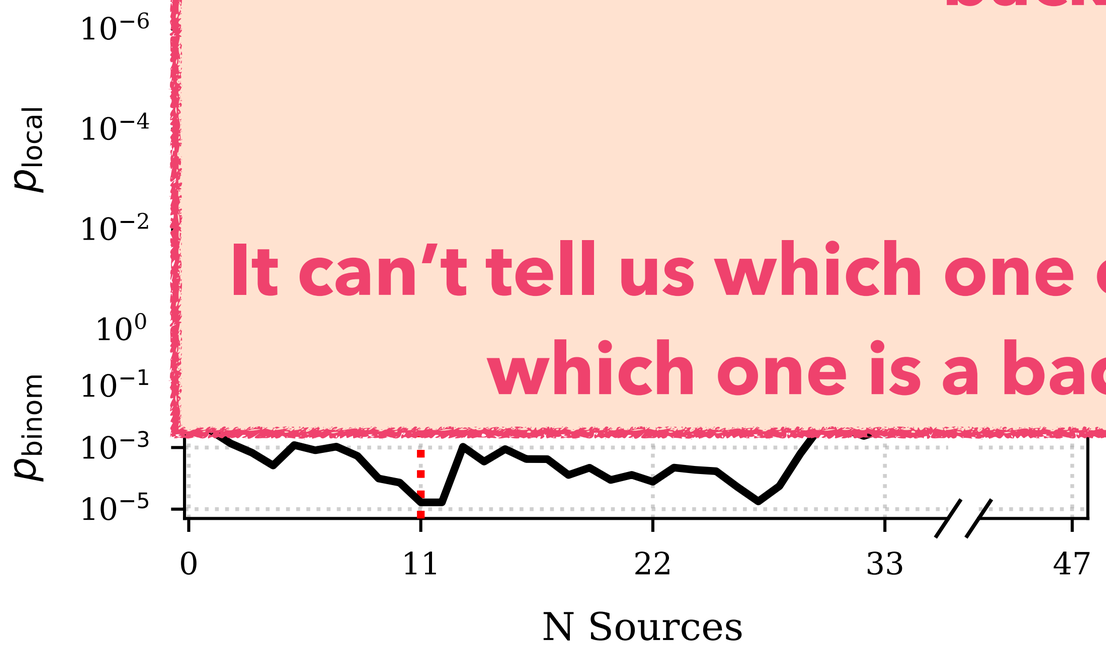
Select candidate sources based on X-ray emission!

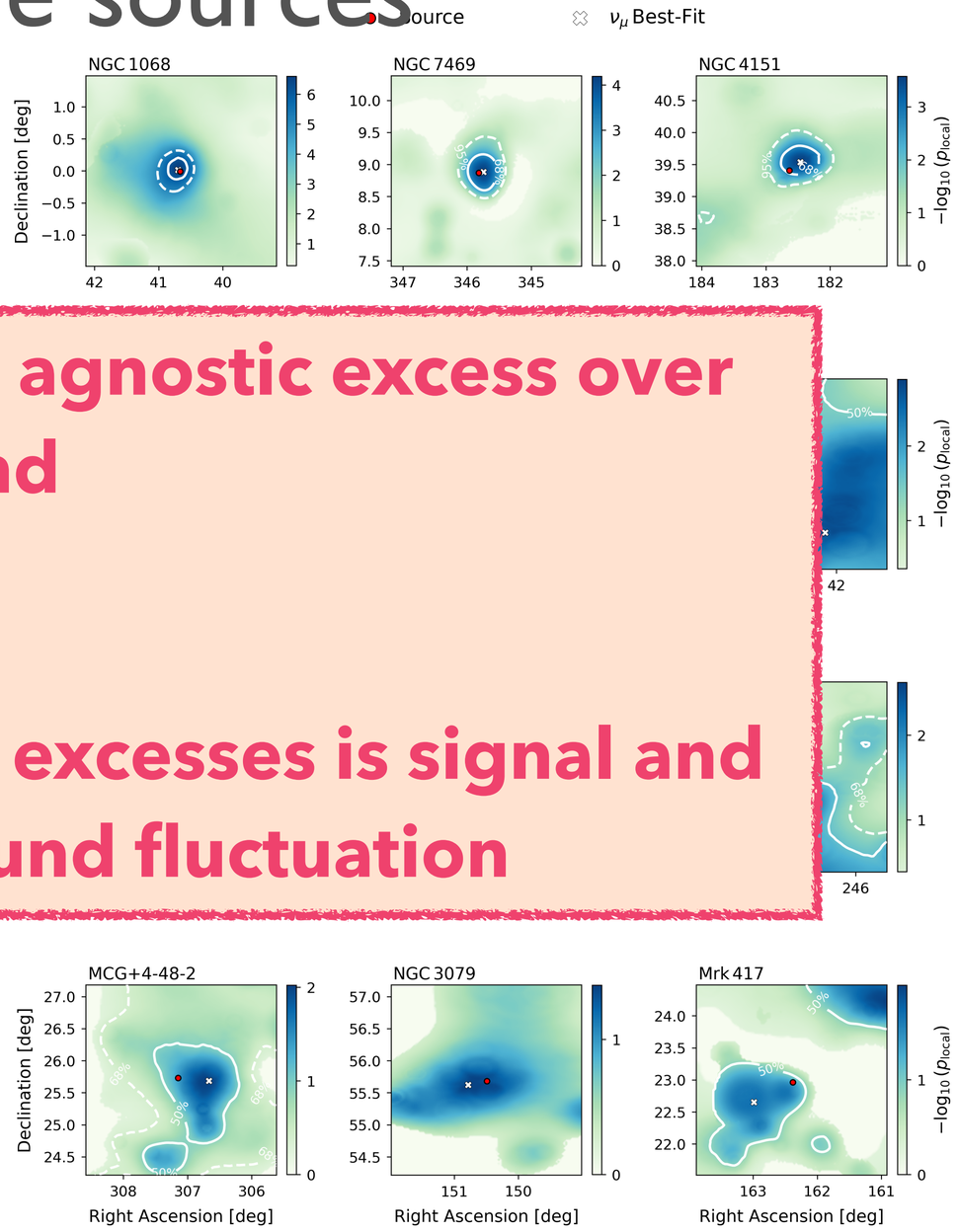
47 candidates selected in the 20-50keV band from the BASS catalog

Overlap wit

This type of test probes for an agnostic excess over background

It can't tell us which one of the excesses is signal and which one is a background fluctuation





IceCube ApJL 1000, L26, (2026)

NGC 7469… the prototype Seyfert I!

SFB 1258 Neutrinos Dark Matter Messengers

Carl K. Seyfert (VANDERBILT SPECIAL COLLECTIONS AND UNIVERSITY ARCHIVES)

NGC 7469… the prototype Seyfert I!

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NUCLEAR EMISSION IN SPIRAL NEBULAE*

1943

CARL K. SEYFERT†

ABSTRACT

Spectrograms of dispersion 37–200 A/mm have been obtained of six extragalactic nebulae with high-excitation nuclear emission lines superposed on a normal G-type spectrum. All the stronger emission lines from λ 3727 to λ 6731 found in planetaries like NGC 7027 appear in the spectra of the two brightest spirals observed, NGC 1068 and NGC 4151.

Apparent relative intensities of the emission lines in the six spirals were reduced to true relative intensities. Color temperatures of the continua of each spiral were determined for this purpose.

The observed relative intensities of the emission lines exhibit large variations from nebula to nebula. Profiles of the emission lines show that all the lines are broadened, presumably by Doppler motion, by amounts varying up to 8500 km/sec for the total width of the hydrogen lines in NGC 3516 and NGC 7469. The hydrogen lines in NGC 4151 have relatively narrow cores with wide wings, 7500 km/sec in total breadth. Similar wings are found for the Balmer lines in NGC 7469. The lines of the other ions show no evidence of wide wings. Some of the lines exhibit strong asymmetries, usually in the sense that the violet side of the line is stronger than the red.

In NGC 7469 the absorption K line of *Ca* II is shallow and 50 A wide, at least twice as wide as in normal spirals.

Absorption minima are found in six of the stronger emission lines in NGC 1068, in one line in NGC 4151, and one in NGC 7469. Evidence from measures of wave length and equivalent widths suggests that these absorption minima arise from the G-type spectra on which the emissions are superposed.

The maximum width of the Balmer emission lines seems to increase with the absolute magnitude of the nucleus and with the ratio of the light in the nucleus to the total light of the nebula. The emission lines in the brightest diffuse nebulae in other extragalactic objects do not appear to have wide emission lines similar to those found in the nuclei of emission spirals.

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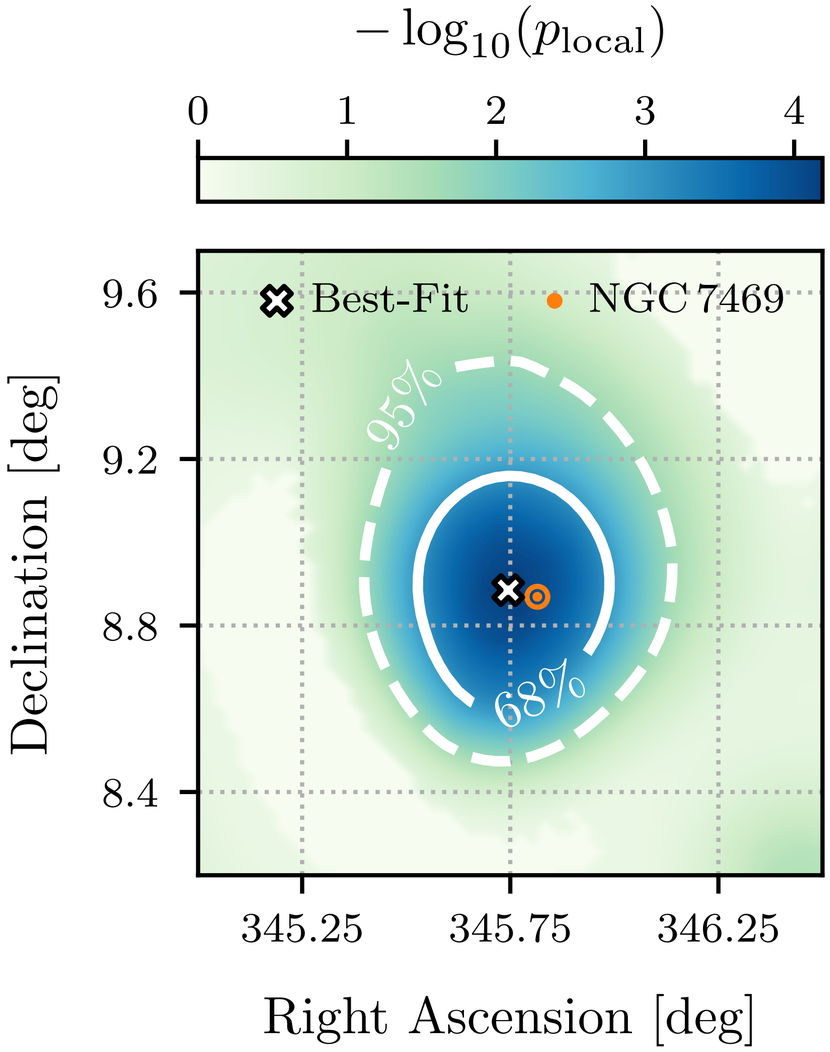

IceCube ApJL 1000, L26, (2026)

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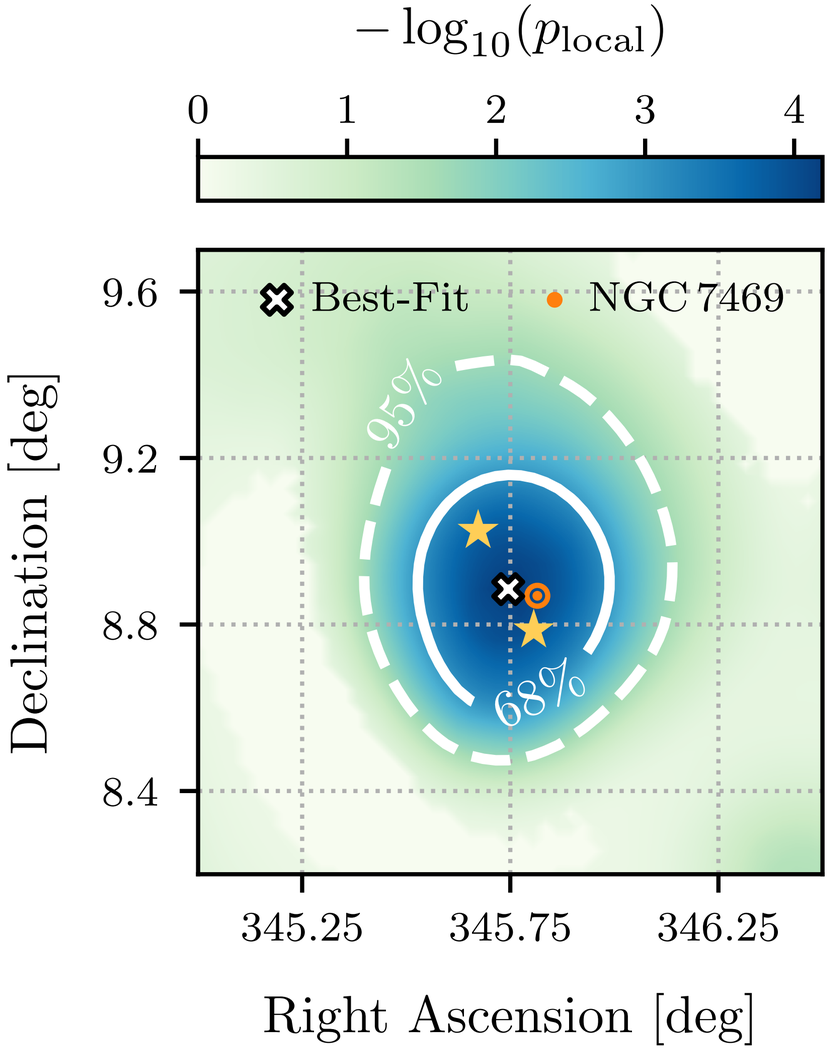

Two >100 TeV alert events very close to the source!
(see also *Sommani et al, 2025*)

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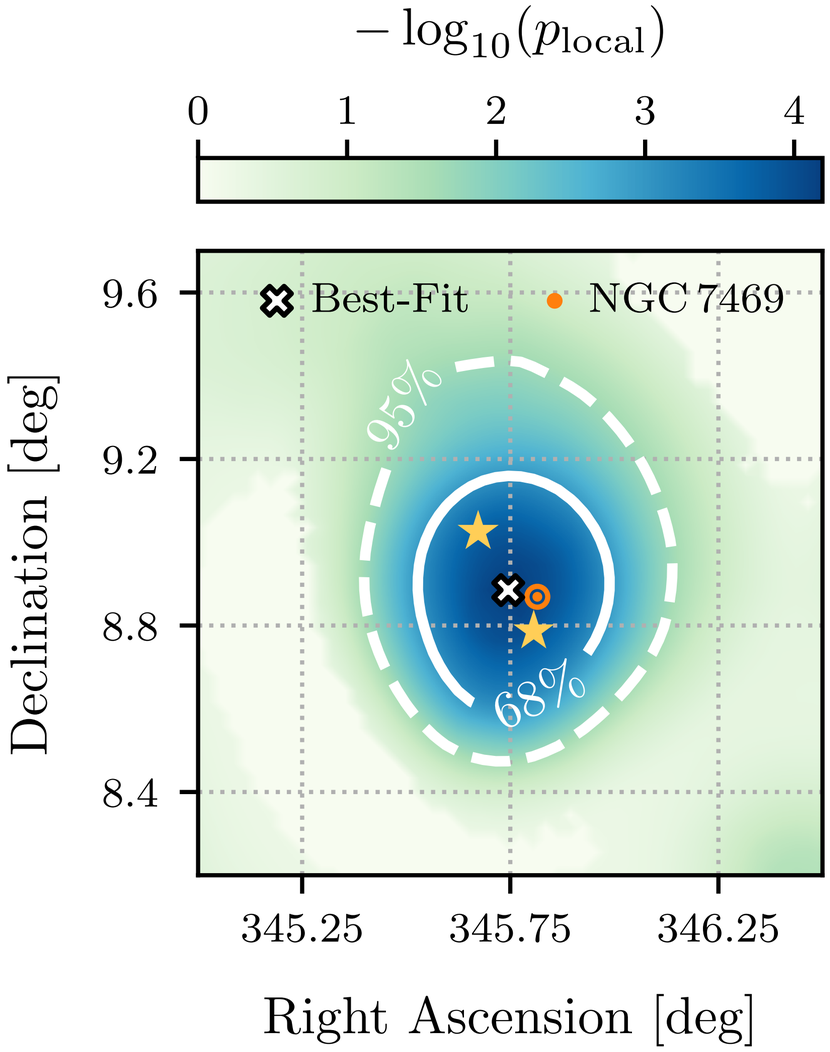

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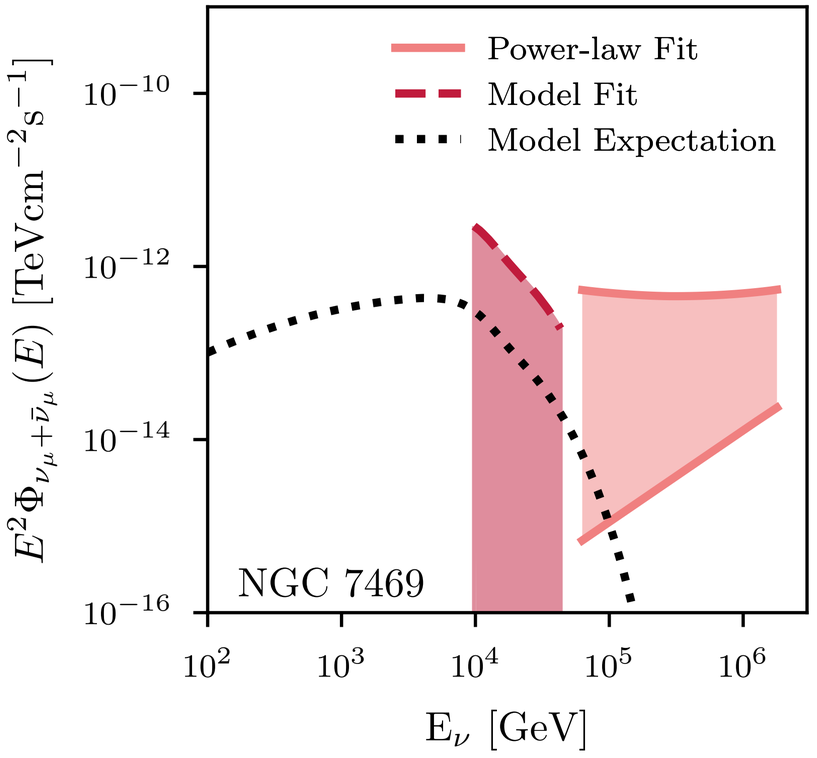

IceCube ApJL 1000, L26, (2026)

State of the art

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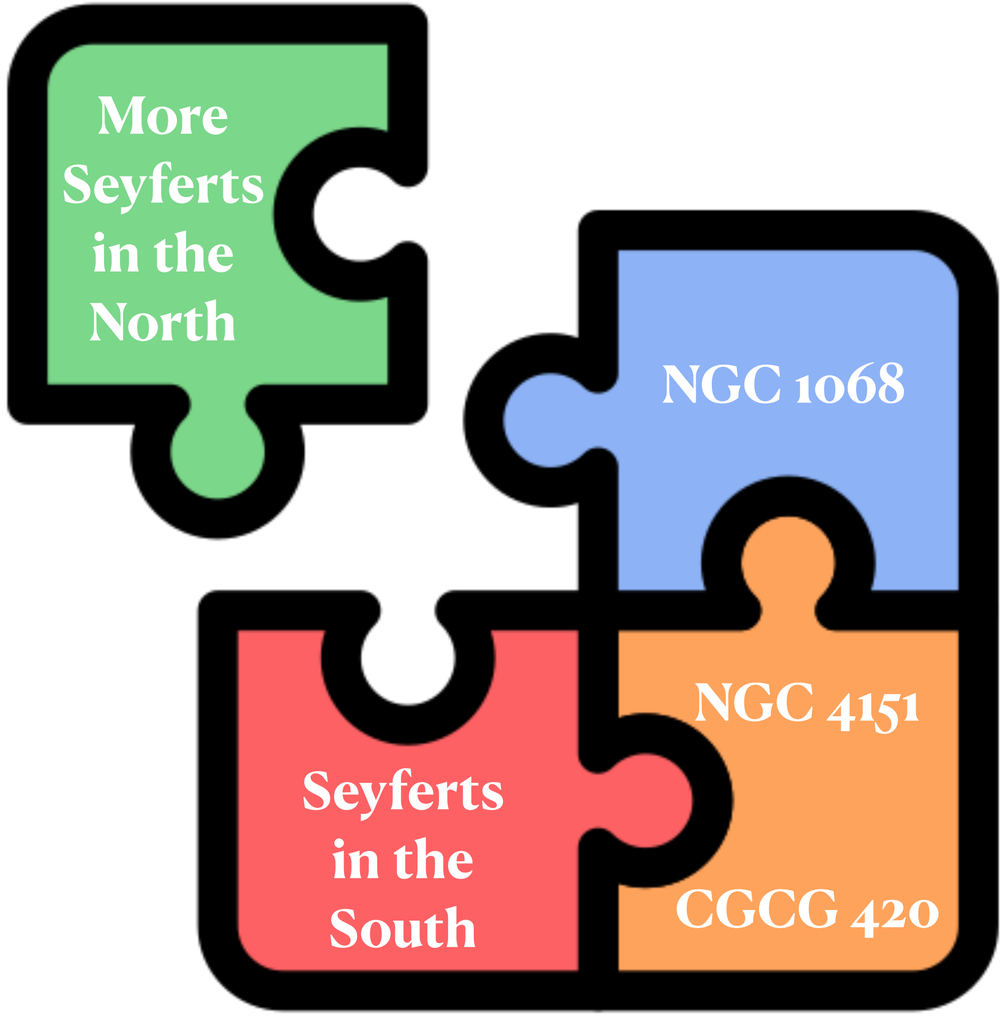
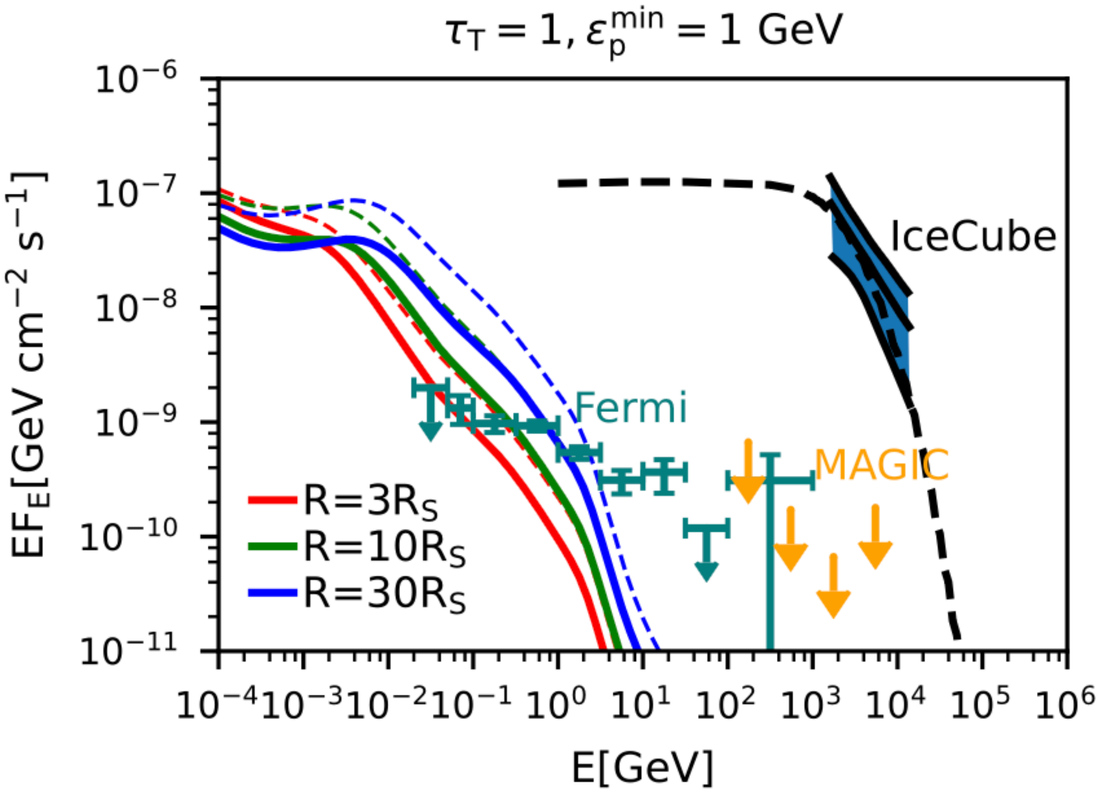
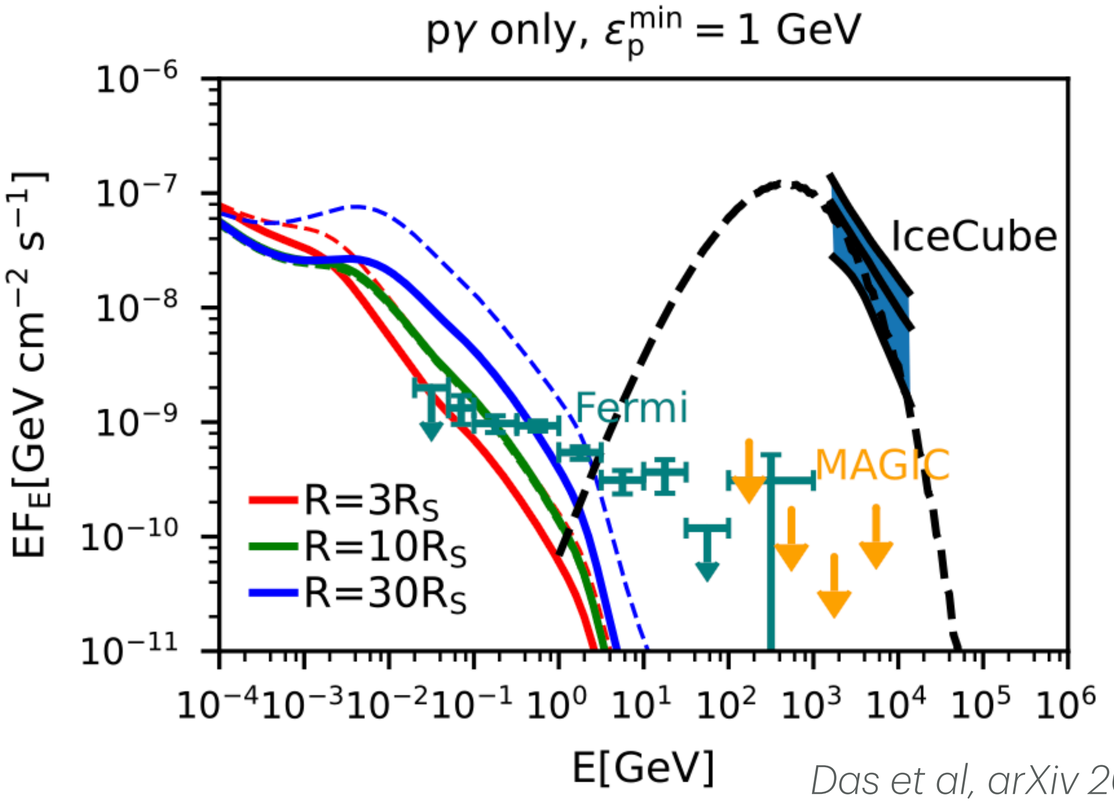


Limitations

SFB 1258 Neutrinos Dark Matter Messengers

Understanding the CR source





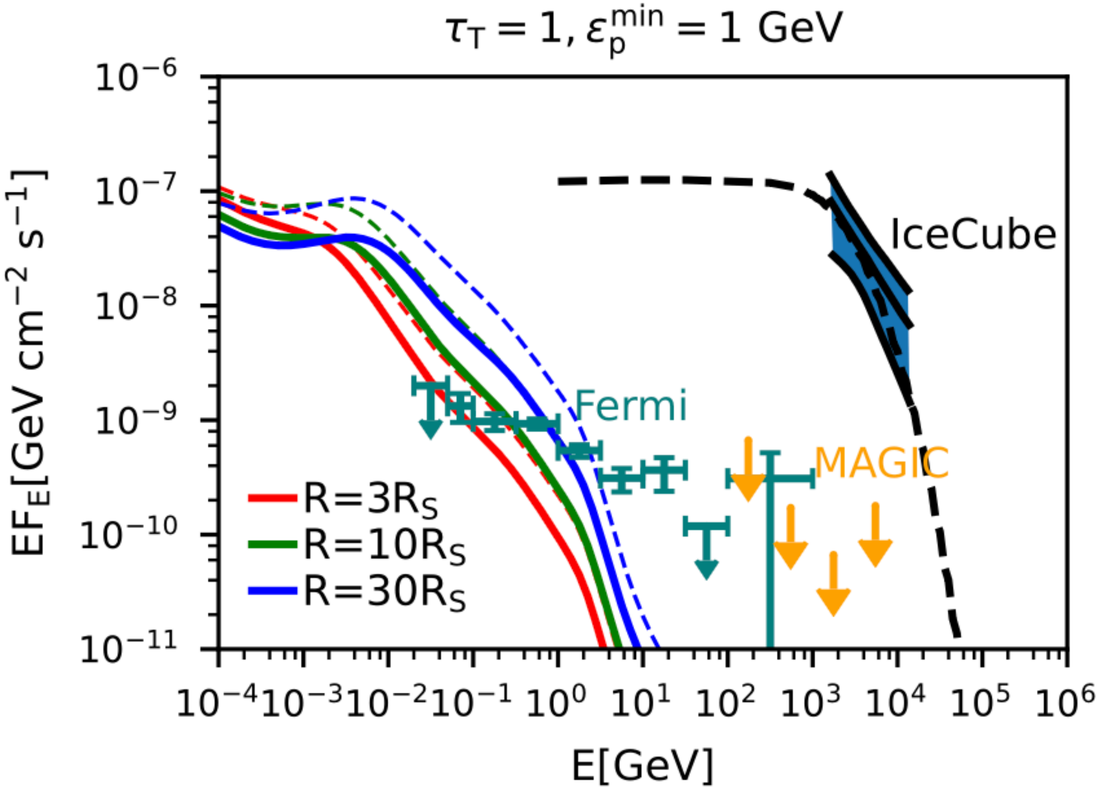
Das et al, arXiv 2026

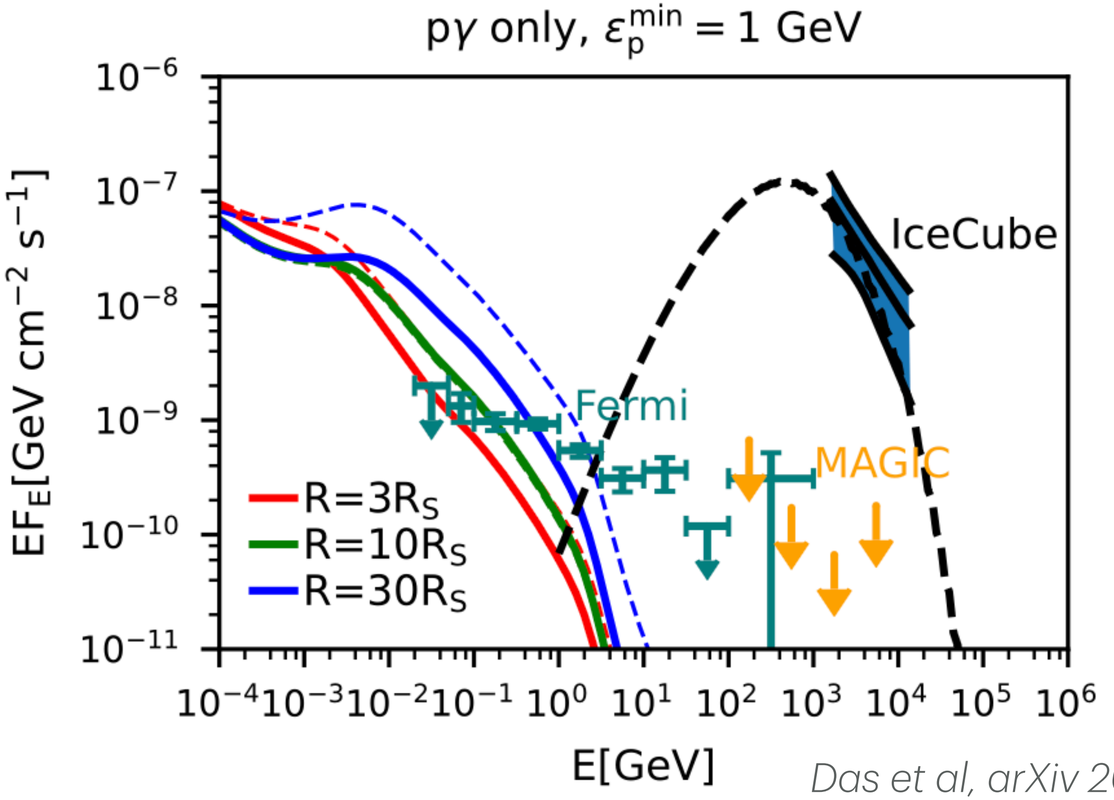
Today, we lack the sensitivity to tell whether the spectrum of NGC 1068 turns over at low energy or whether it flattens

Future prospects

Limitations

Understanding the CR source





Das et al, arXiv 2026

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Future prospects

We need more, better data

Things I'd like to talk about

SFB 1258 Neutrinos Dark Matter Messengers

With IceCube, in the discovery era:

- Do we have a chance of measuring the MeV emission from NGC1068 and friends?
- Can we be smarter in selecting our target candidate sources?

With more telescopes, in the astrophysics era:

- We are gonna have (maybe we already have it) a complex sky with multiple components
  - Joint fit of data, while also keeping systematics from different detectors under control
  - Plan for the release of data: common formats, comparable information, and release of simulations?

SFB 1258 Neutrinos Dark Matter Messengers

BACKUP

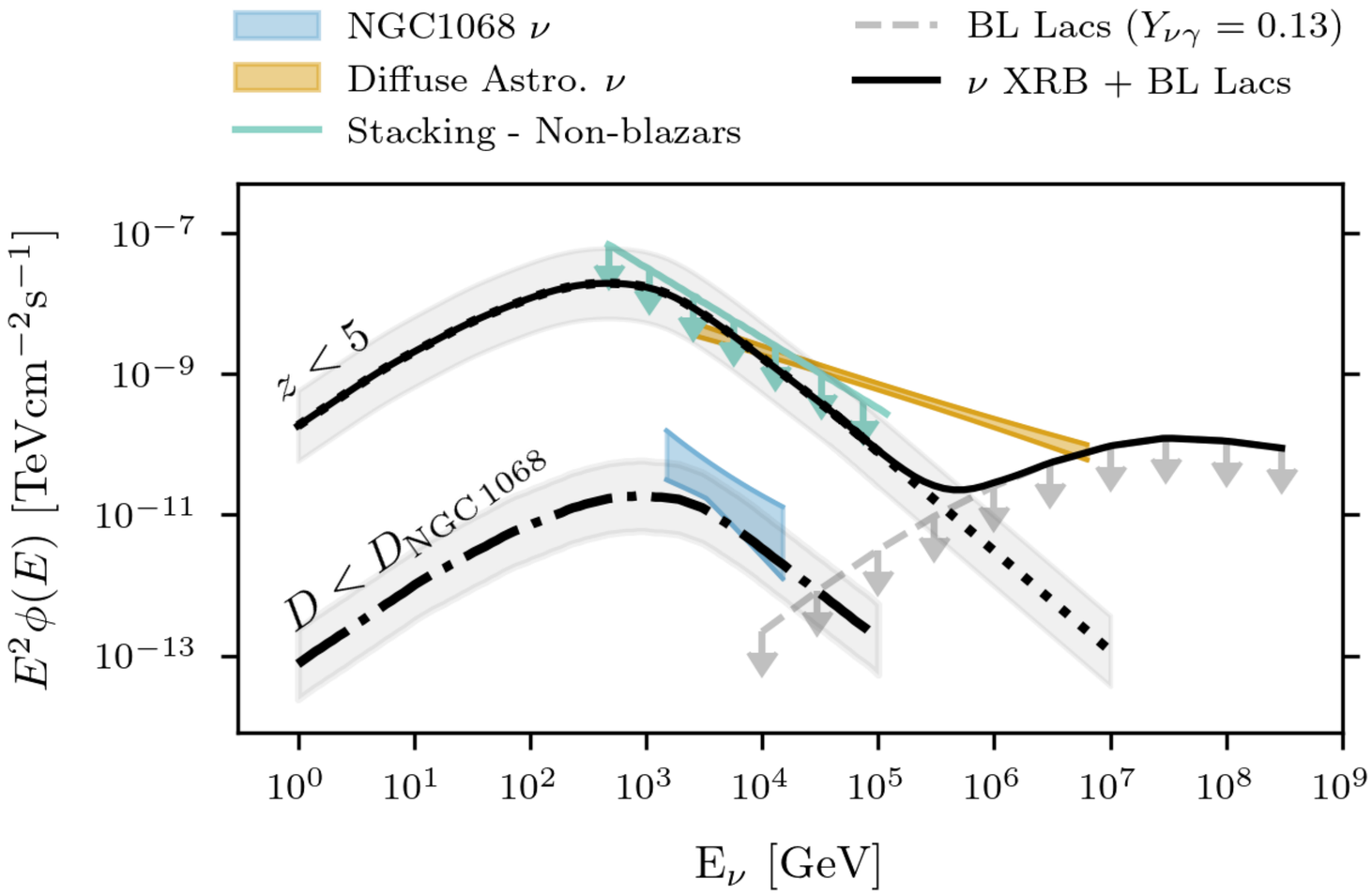
SFB 1258 Neutrinos Dark Matter Messengers

Extrapolating from one source to all

Generally not the best idea…

- Here an extremely simple approach:
  - Population synthesis model for the CXB (Gilli et al. 2007)
  - A spectral shape that does not violate the energetics of the source (Murase et al 2022)
  - Anchor the L_ν/L_X ratio to NGC 1068 (L_X from Marinucci et al 2016)

$$\nu f_X^{1\mathrm{keV}} / \nu f_\nu^{4\mathrm{TeV}} \simeq 32,$$

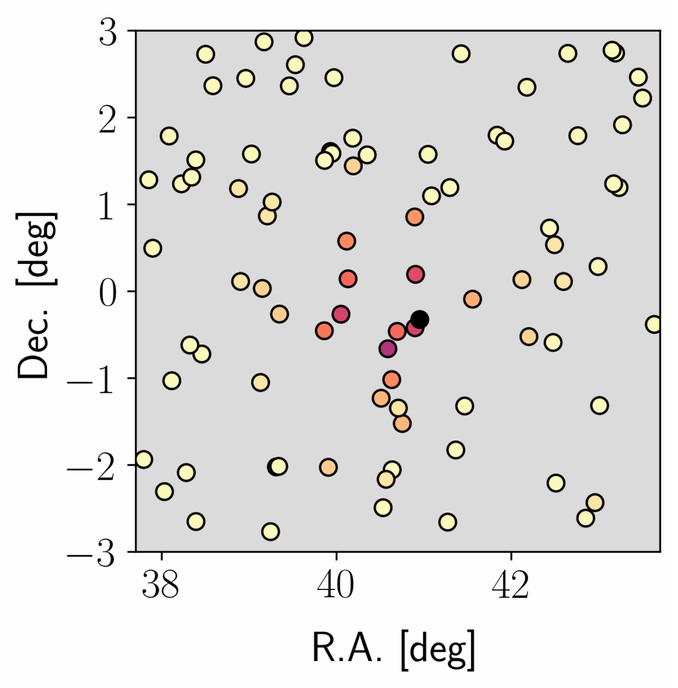


Gilli, [..], C.B. et al, A&A (2024)

Searching for neutrino sources

aka, looking for a needle in a haystack

Accumulation of events around NGC 1068 over 9 years.



Color scale = S/B

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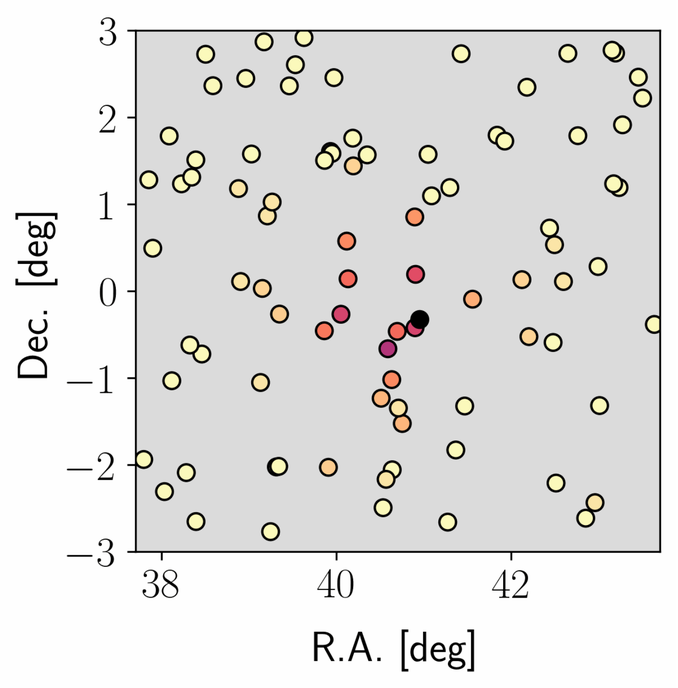

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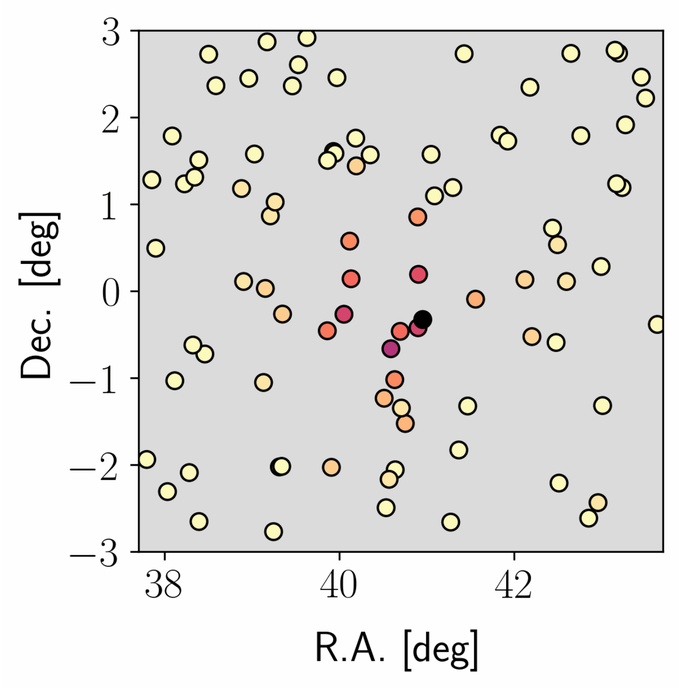
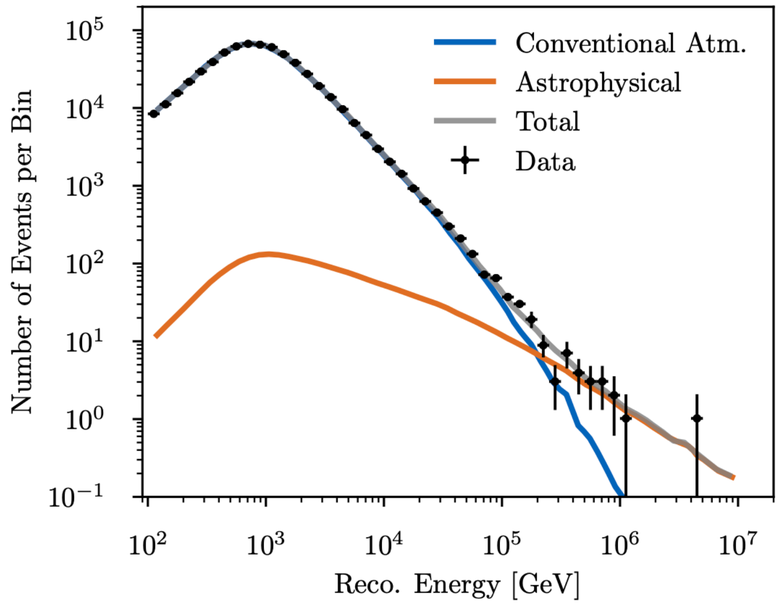


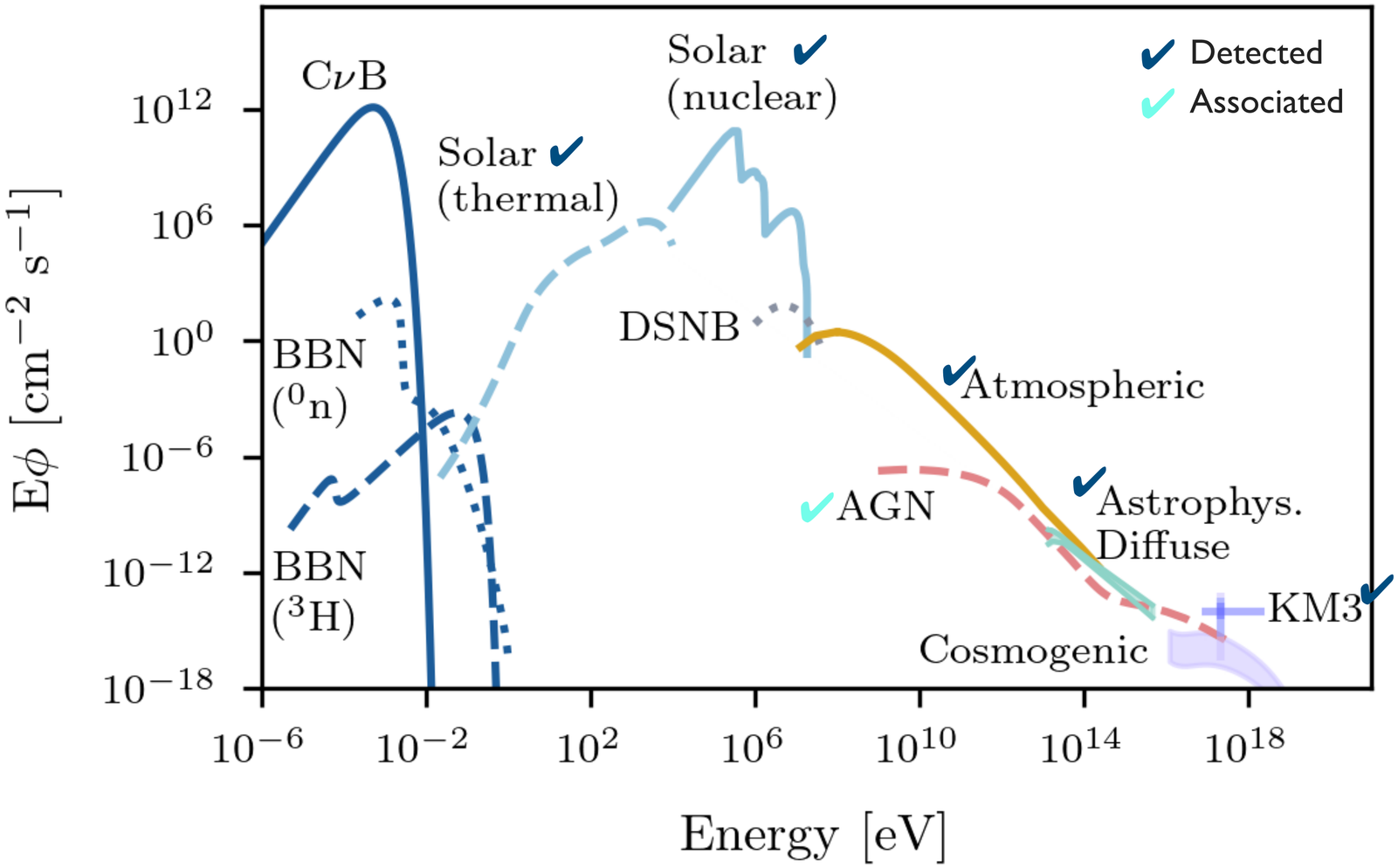
Color scale = S/B

- Use the maximum likelihood ratio method to search for clustering of events around the source.
- Include the energy information to increase the sensitivity to a potential signal.

Energy distribution in the Northern sky

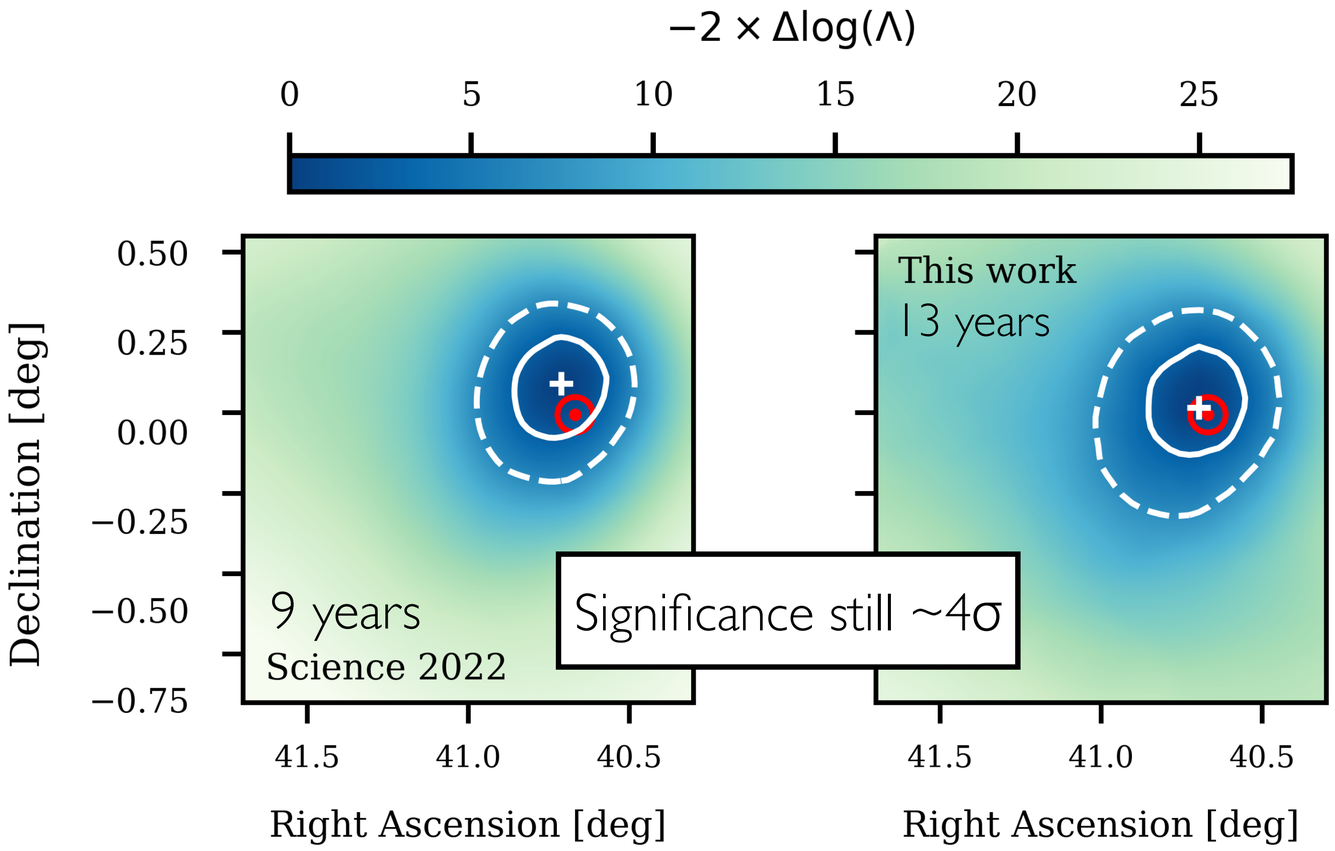


The neutrino spectrum

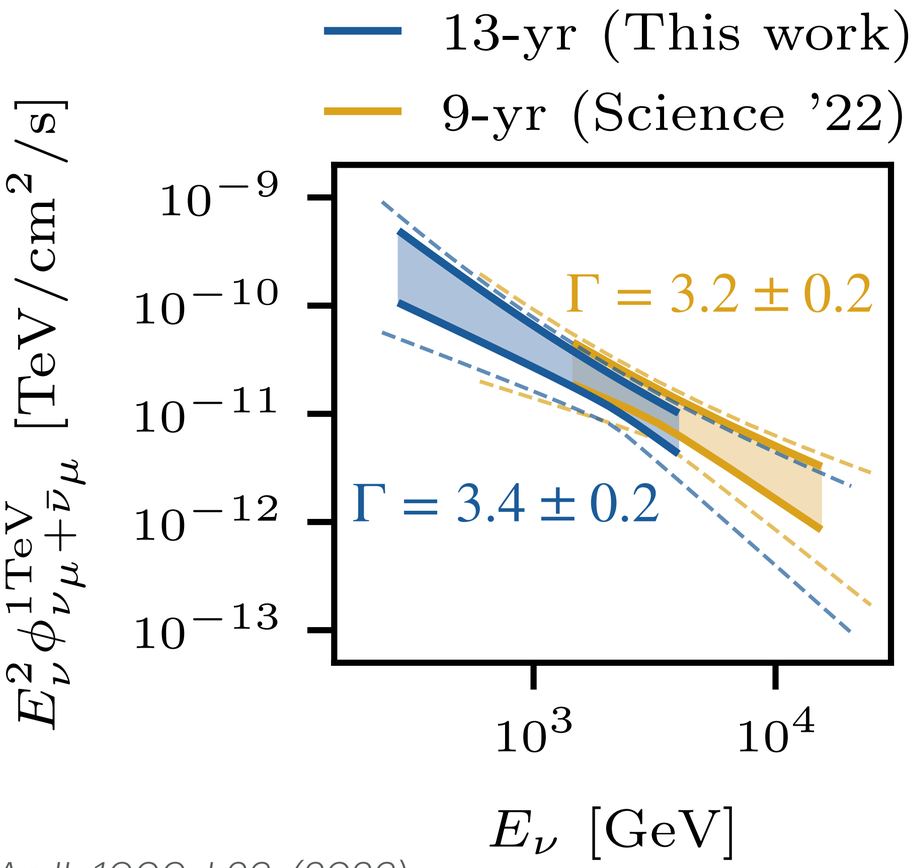


Updated measurement

13 years Northern-sky muon tracks (~50% more statistics!)



Spectrum shifted to lower energies, but fully compatible within 90% errors



IceCube ApJL 1000, L26, (2026)