Technical University of Munich

IceCube Neutrino Observatory

SFB 1258 Neutrinos Dark Matter Messengers

High-energy neutrinos from NGC 1068

And the emerging class of Seyfert galaxies

Chiara Bellenghi on behalf of the IceCube collaboration

RENCONTRES DU VIETNAM

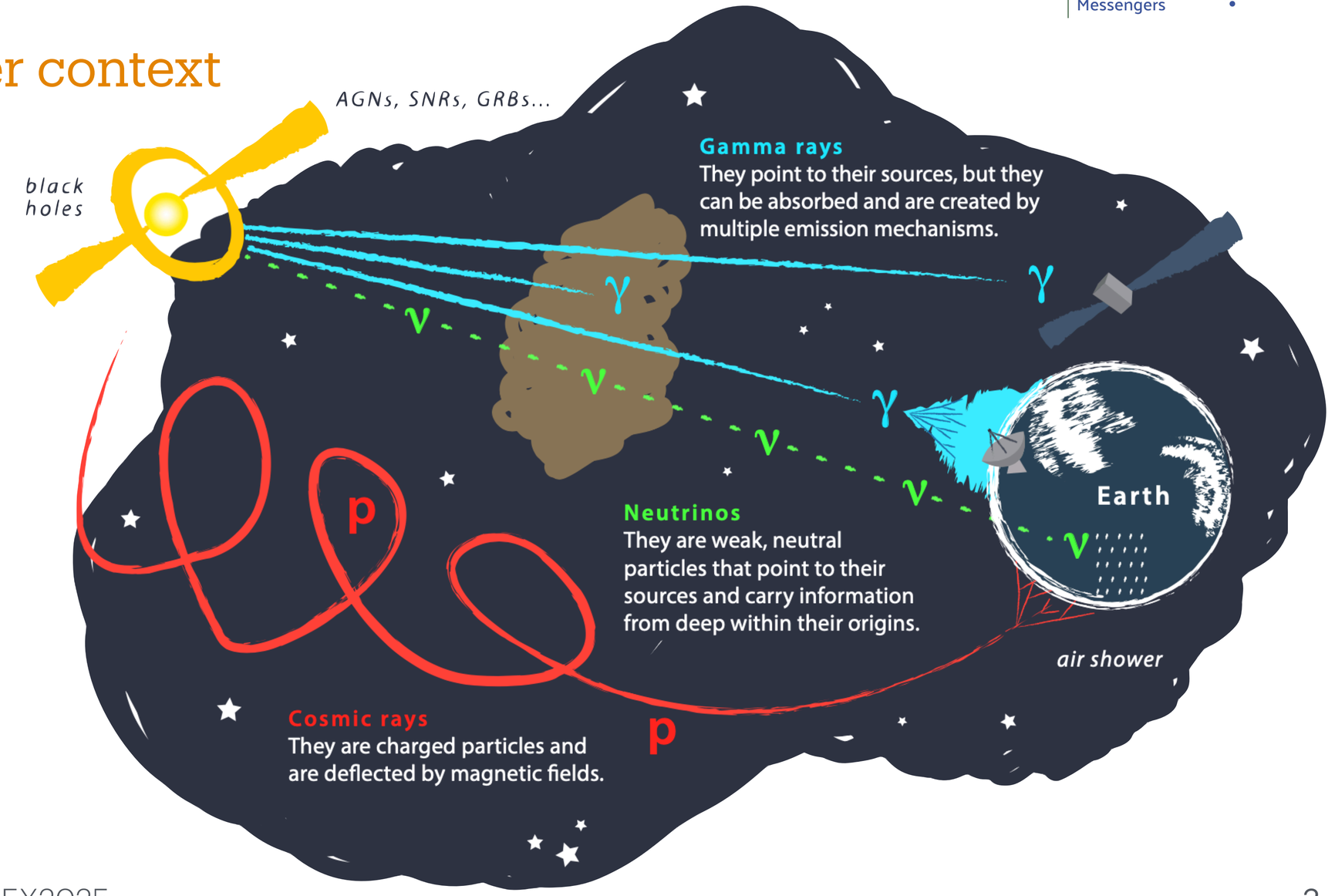
SFB 1258 Neutrinos Dark Matter Messengers

Multimessenger connections

Neutrinos

In the multimessenger context

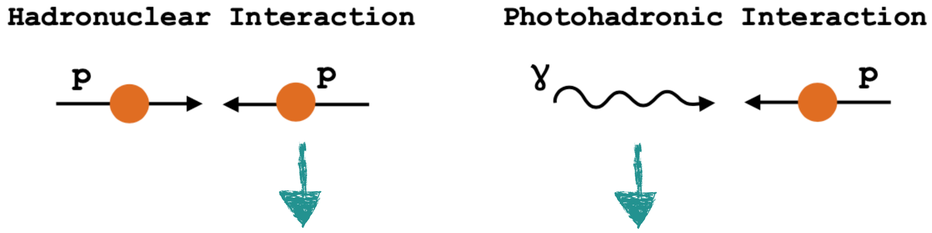
- A cosmic **proton** accelerator
  → **neutrinos & γ-rays**.



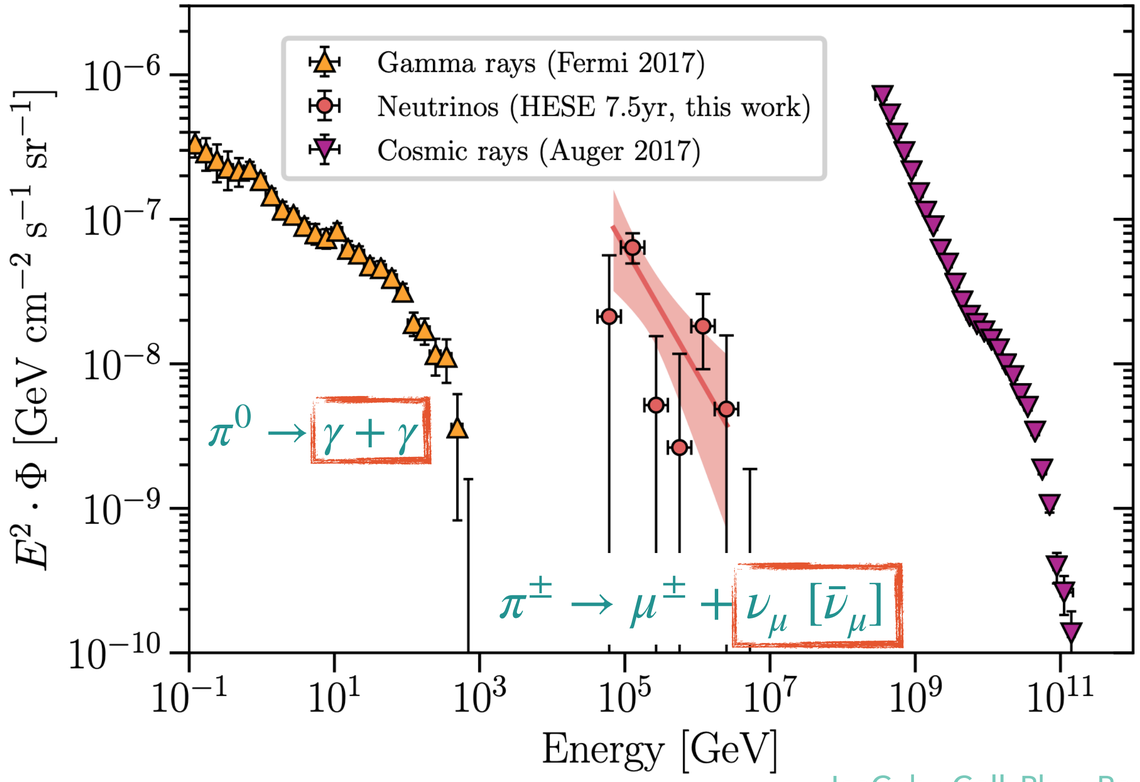
Neutrinos

In the multimessenger context

- A cosmic **proton** accelerator → **neutrinos & γ-rays**.
- Standard picture: **Expect similar fluxes of neutrinos and gamma-rays on Earth**.
- The cosmic-ray, neutrino, and gamma-ray backgrounds support this scenario.

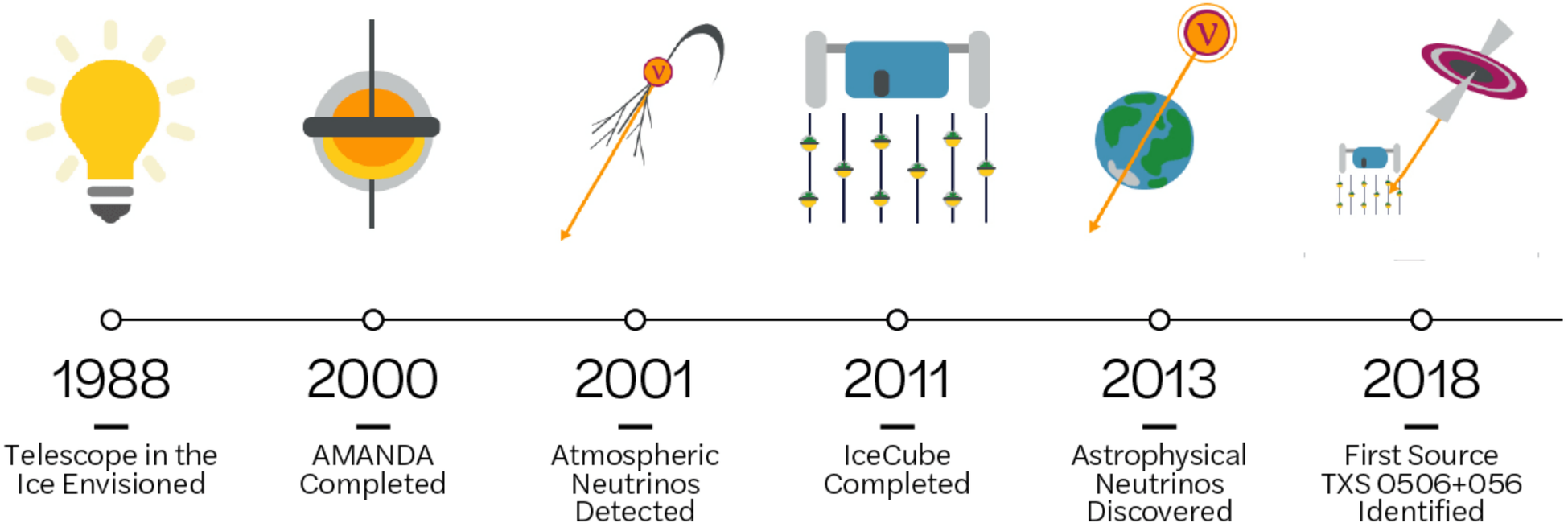


Production of π^0, π^+, π^-



IceCube Coll. Phys. Rev. D 104, 022002

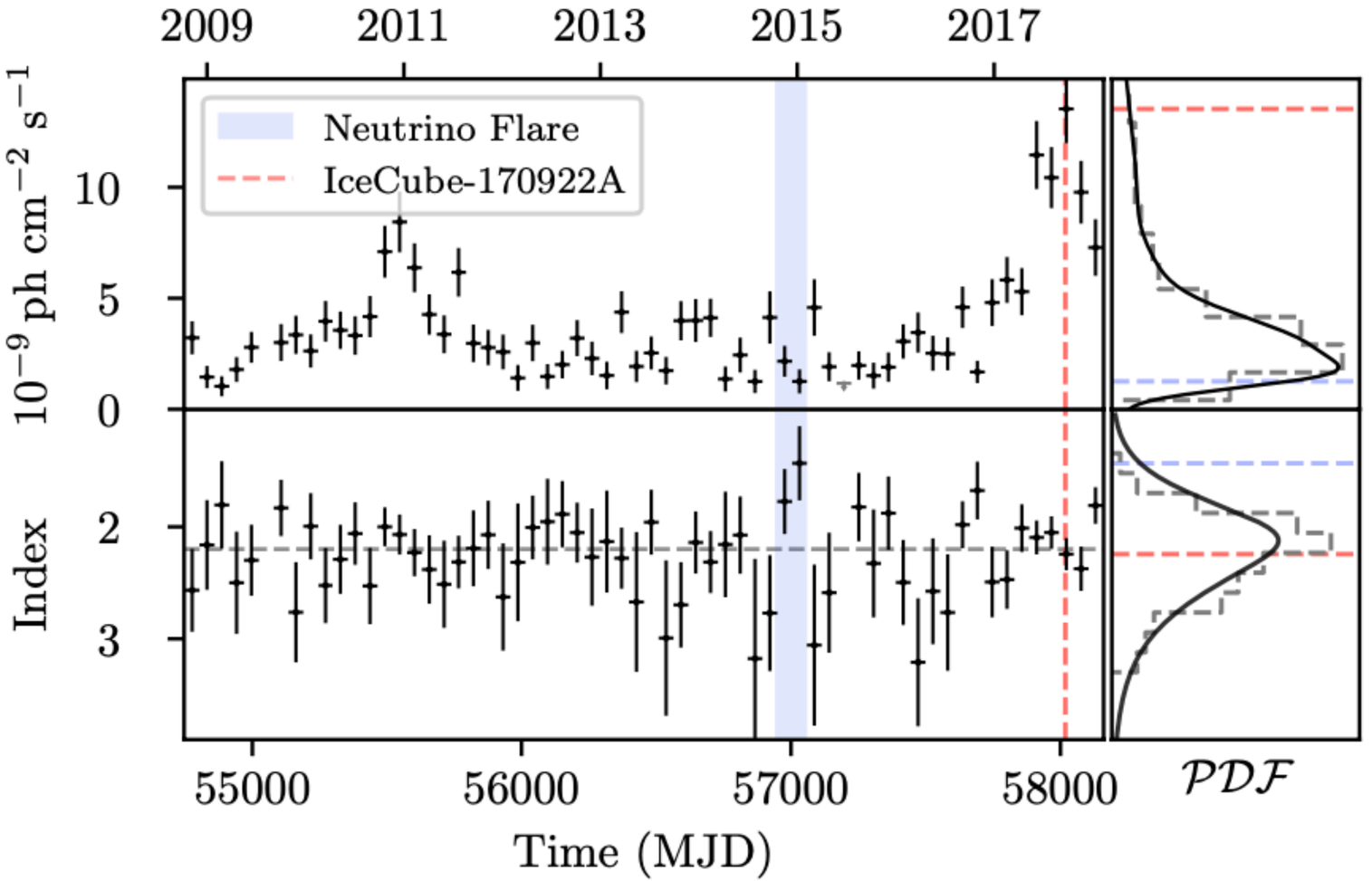
The first neutrino source

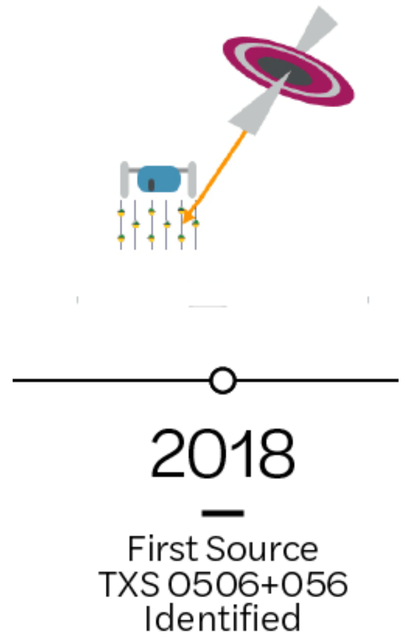


IceCube, Fermi-LAT, MAGIC, at al, Science (2018a)

IceCube, Science (2018b)

The first neutrino source





-LAT, MAGIC, at al, Science (2018a)

IceCube, Science (2018b)

Padovani, Giommi, Resconi, et al, MNRAS (2018)

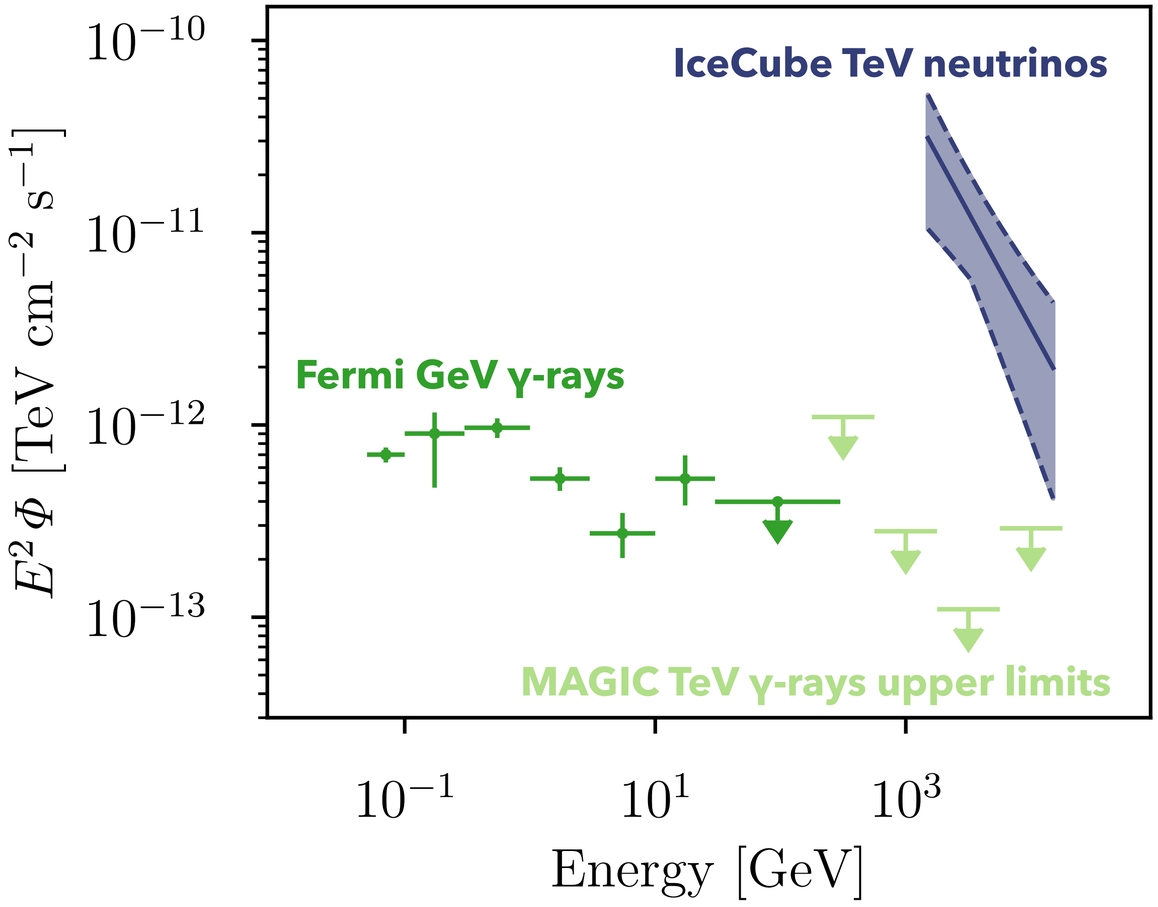
The second source and the puzzle of missing γ rays

A multimessenger puzzle

γ-ray-obscured AGN

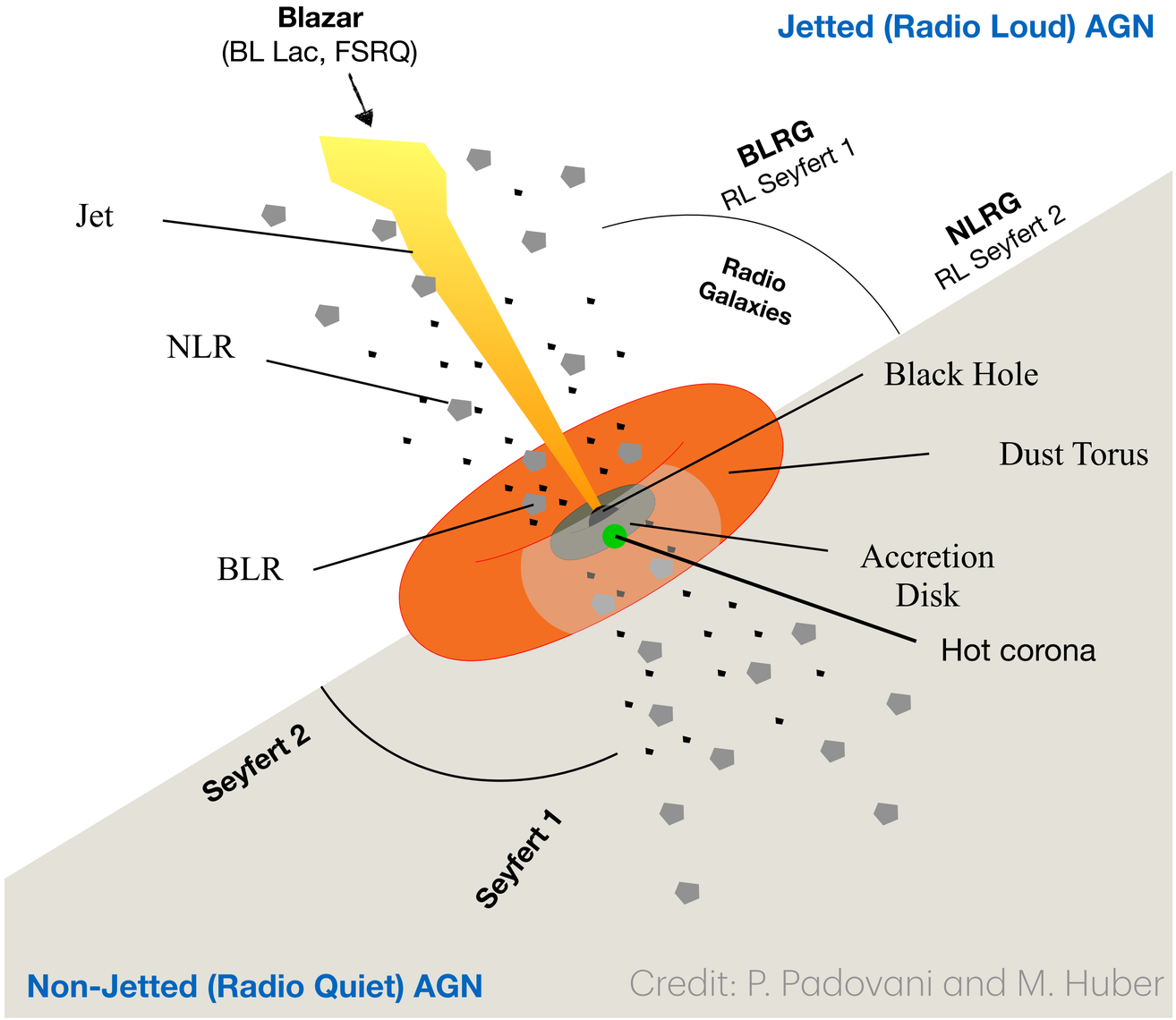
- November 2022: IceCube publishes **evidence for TeV neutrino emission from the nearby active galaxy NGC 1068**.
- GeV γ-ray flux measured by Fermi ~100x smaller than the neutrino flux.
- Upper limits from MAGIC constrain the TeV γ-ray flux ~100x below the neutrino flux.
- **No correlation between neutrino and high-energy γ-ray emissions in NGC 1068?**

High-energy emission from NGC 1068



IceCube, Science 2022

AGN — Main components



Credit: P. Padovani and M. Huber

[Padovani et al. Astron.Astrophys.Rev. (2017)]

The X-ray-bright Seyfert NGC 1068

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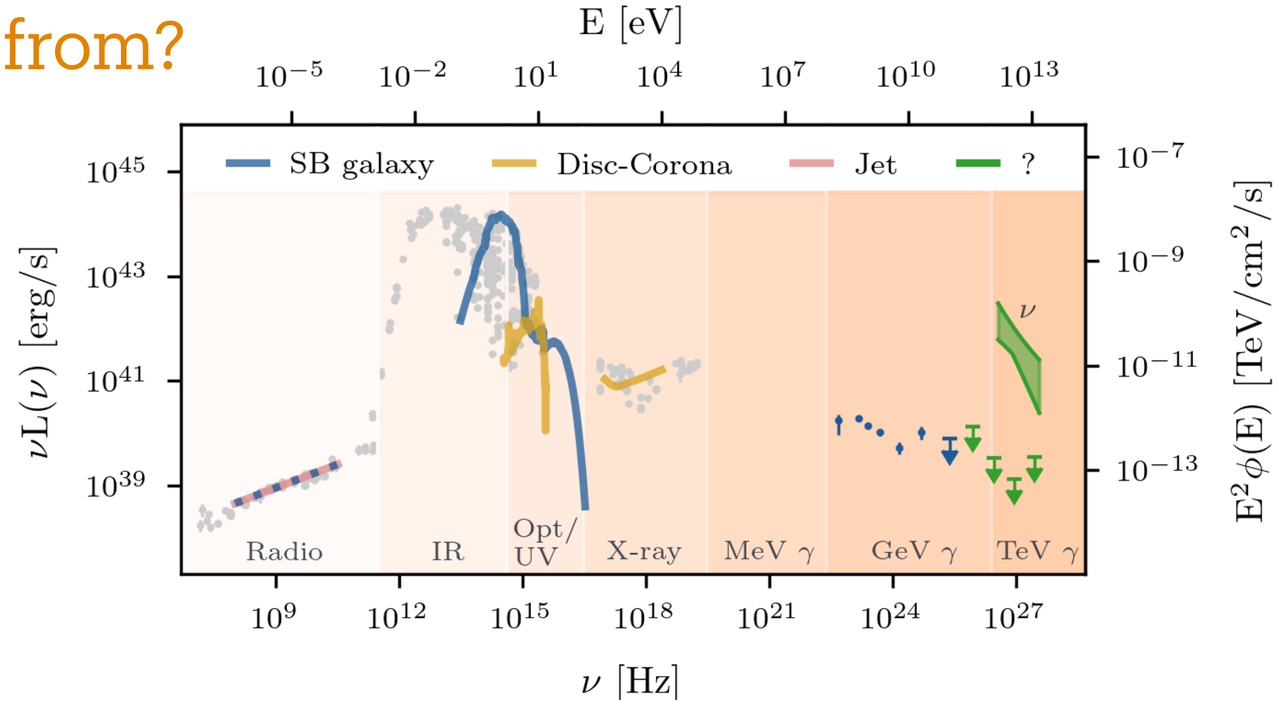
Where do IceCube neutrinos come from?

- The only region not proved to be too weak to provide the measured neutrino power is the region in the vicinity of the BH

The X-ray corona?

- NGC 1068 among the brightest X-ray AGN in the universe.
- The SB galaxy likely source of the observed γ rays.



Component	Scale	L_γ (0.1 – 10 GeV)	L_ν (1.5 – 15 TeV)
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)

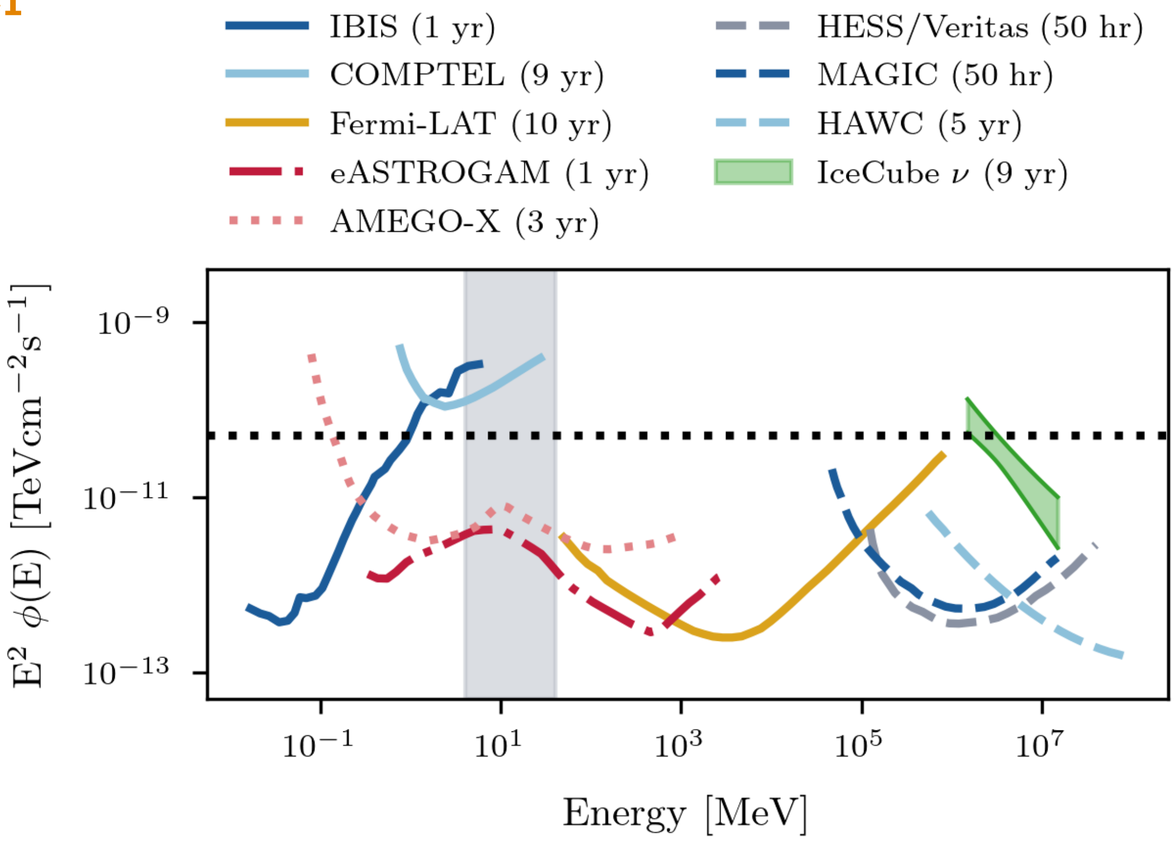
The X-ray corona

As neutrino source and γ-ray absorber

- Assume a p-γ standard scenario.
- X-ray photons are target for neutrino production:

$$E_{p,\mathrm{thr}} \propto \frac{m_p m_\pi}{E_\gamma} \rightarrow E_\nu \sim 40 - 400\ \mathrm{TeV}$$

- **Maybe the X-ray flux is directly related to the neutrino flux observed on Earth.**
- TeV γ rays need UV/optical photons to start cascading until they reach **MeV energies**.



An <u>incomplete</u> list of theoretical studies:

Inoue et al, ApJ (2019)
Murase et al, PRL (2020)
Murase et al, ApJ (2022)
Mbarek et al, PRD (2024)
Fiorillo et al, ApJL (2024)

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Population studies and hints of neutrino emission from similar sources

Non-jetted AGN and the diffuse flux

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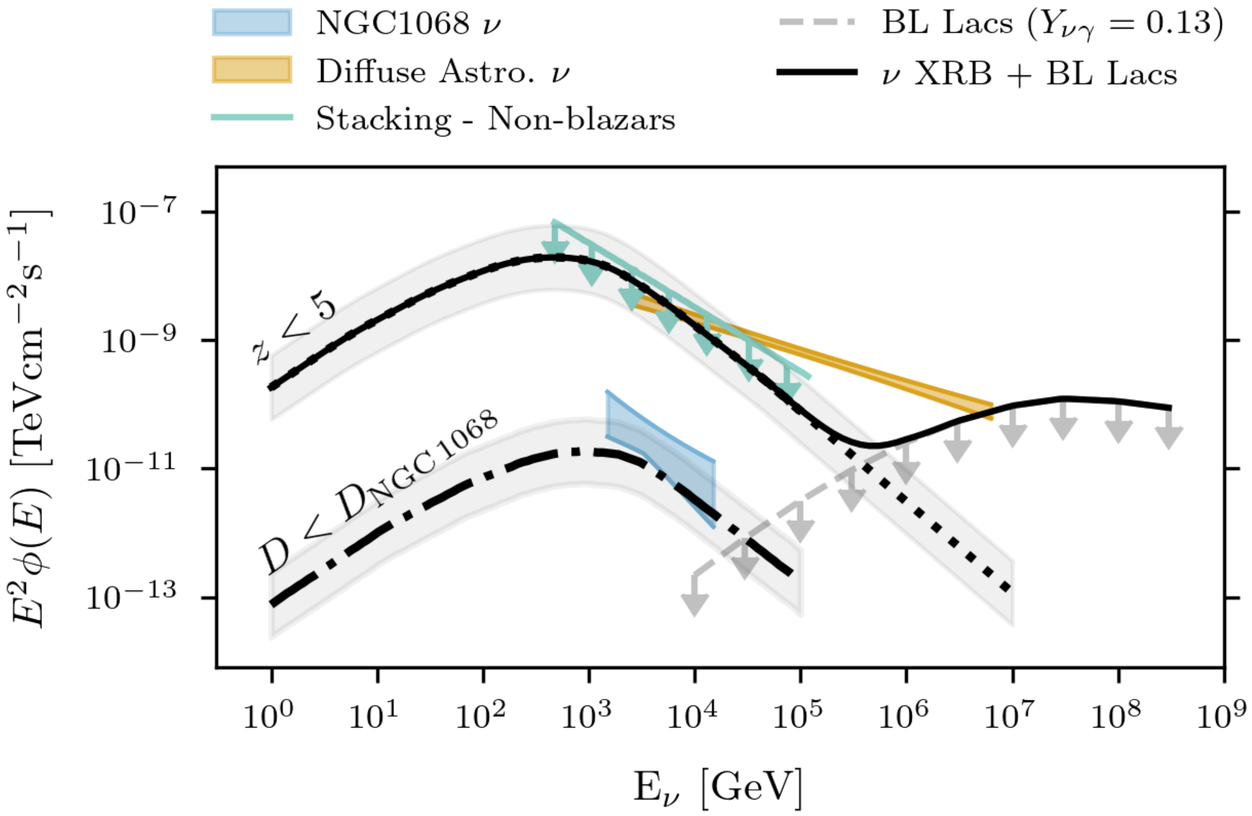
Potential contribution from the entire population

- Population synthesis from the CXB, dominated by non-jetted AGN.
- Assume NGC1068 X/ν ratio as constant.

Assumptions to extract population behaviors from one source...

- **Two populations of sources:**
  - **X-ray bright non-blazar AGN at ~1–10 TeV.**
  - **Blazars @ PeV and beyond.**

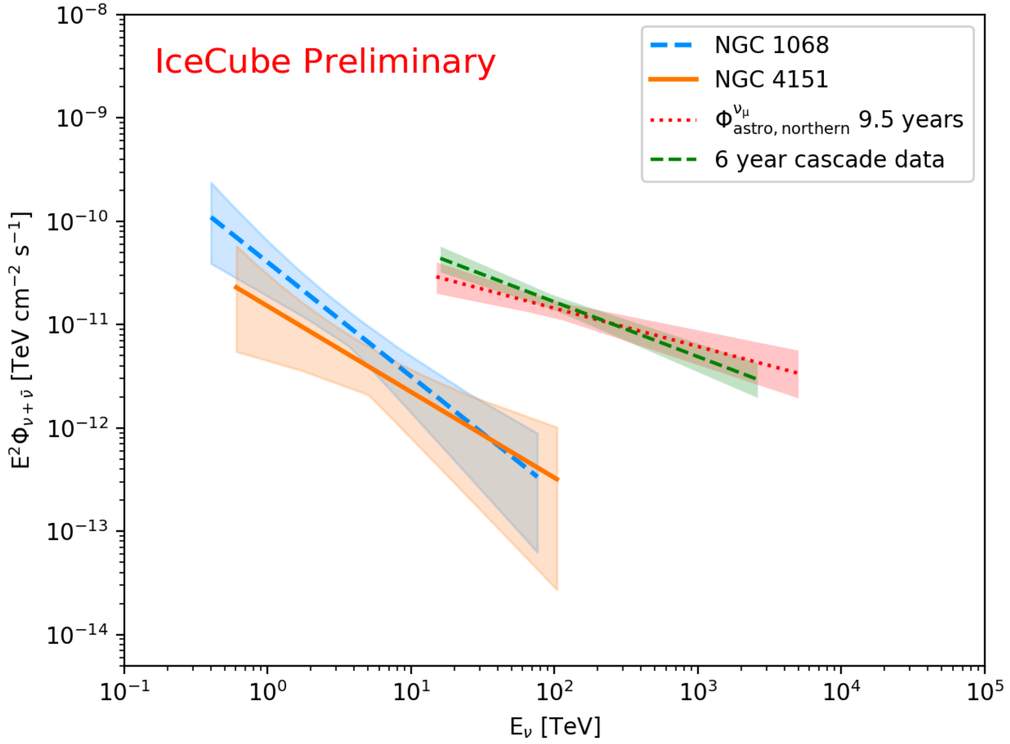


Padovani, Gilli, Resconi, CB, et al., A&A (2024)

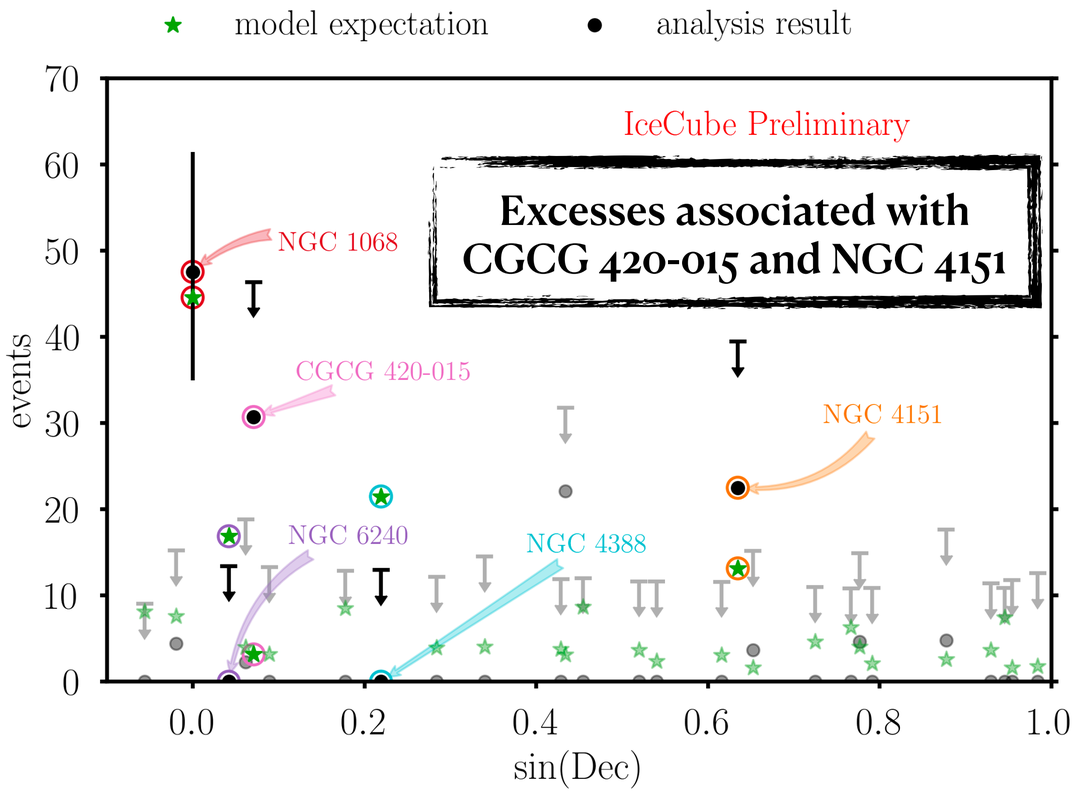
Other IceCube results

Hints to a population of non-jetted AGN

2.9σ excess from NGC 4151, X-ray-bright Seyfert
on *arXiv*, submitted to ApJ



2.7σ excess from a list of soft X-ray AGN
on *arXiv*, submitted to ApJ



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Searching for neutrino sources with IceCube

The IceCube Neutrino Observatory

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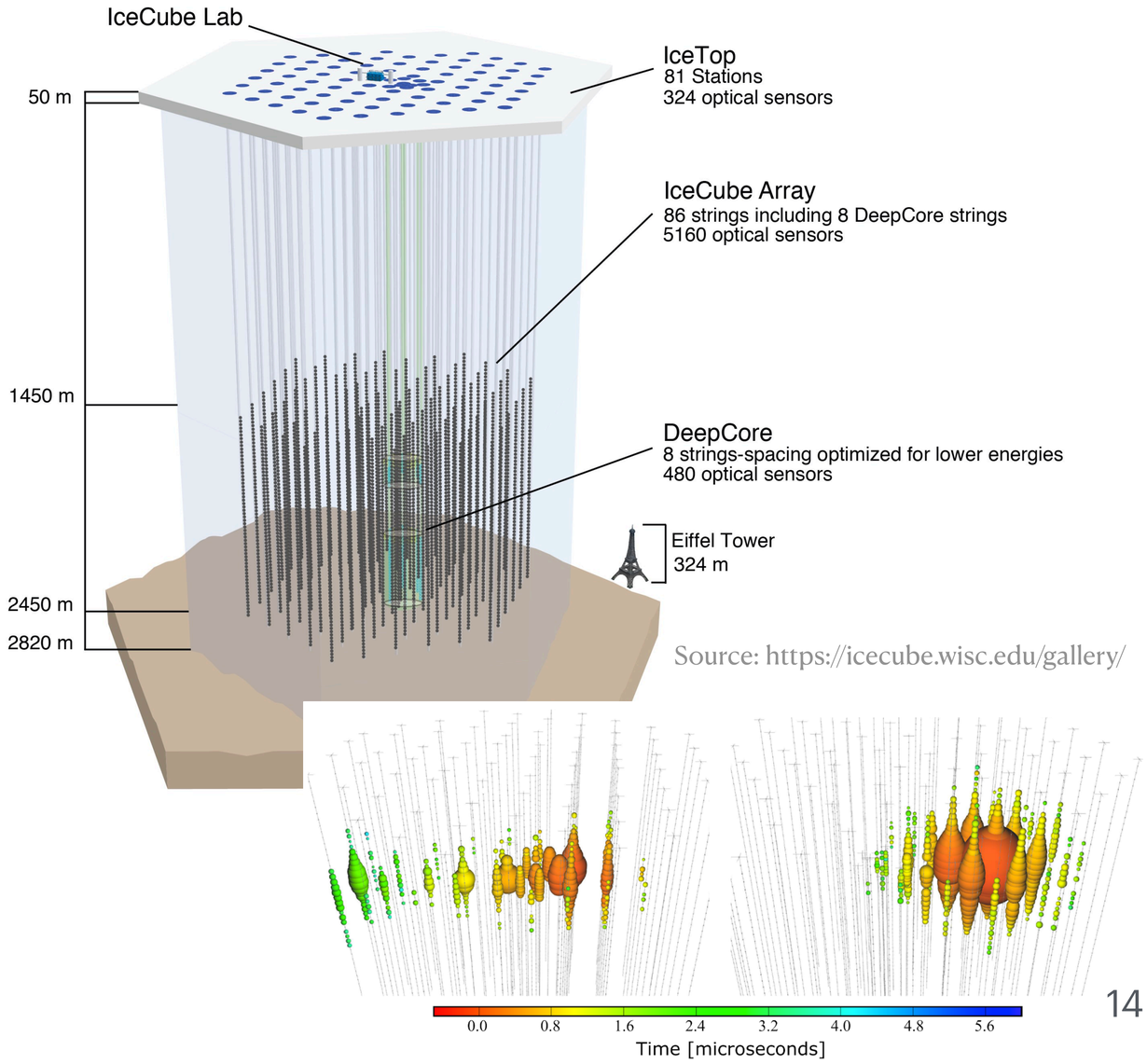
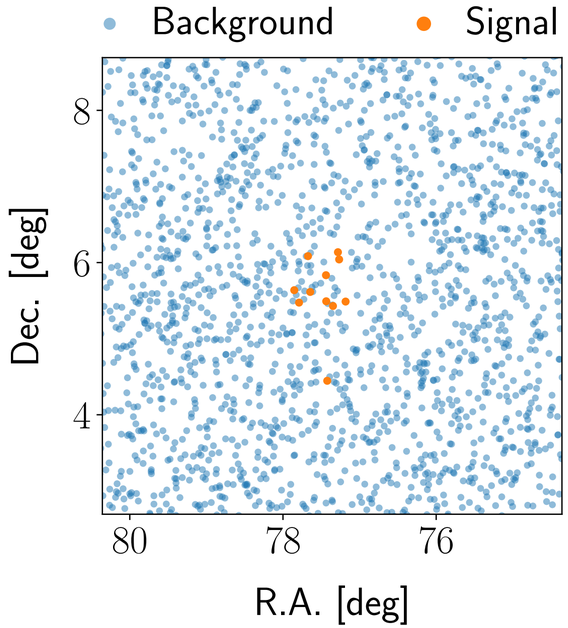
- A **km³ of antarctic ice** at a depth of ~1.5 km.
- 86 strings instrumented with 5160 optical modules.
- **Detects the Cherenkov light emitted by secondary charged particles** produced in neutrino interactions with the ice nuclei.
- **Reconstruct the parent neutrino properties** from the deposited light pattern: direction and energy.
- **Energies from ~100 GeV to several PeV**.



Statistical method

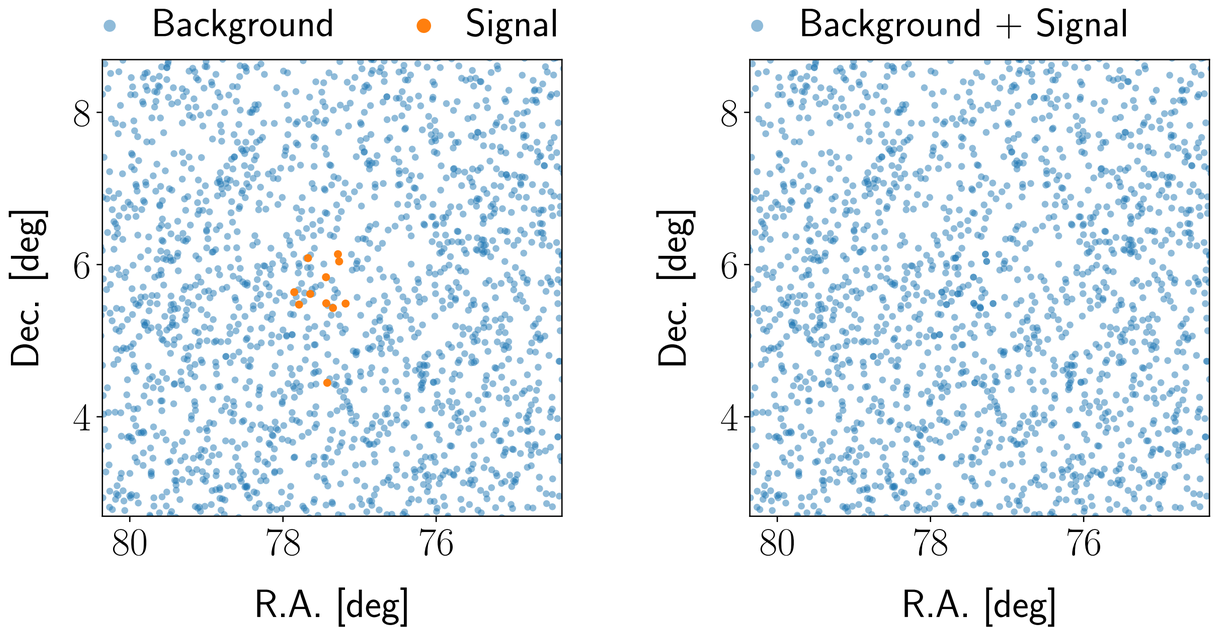
Maximum likelihood ratios



Spatial clustering of events above the background

Statistical method

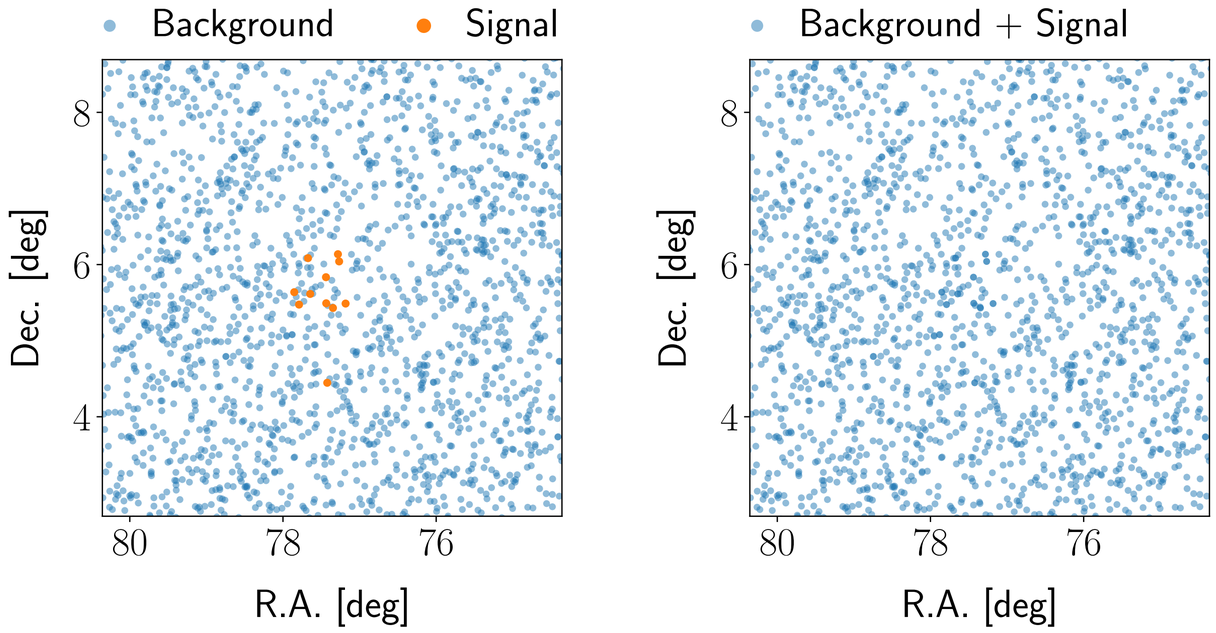
Maximum likelihood ratios



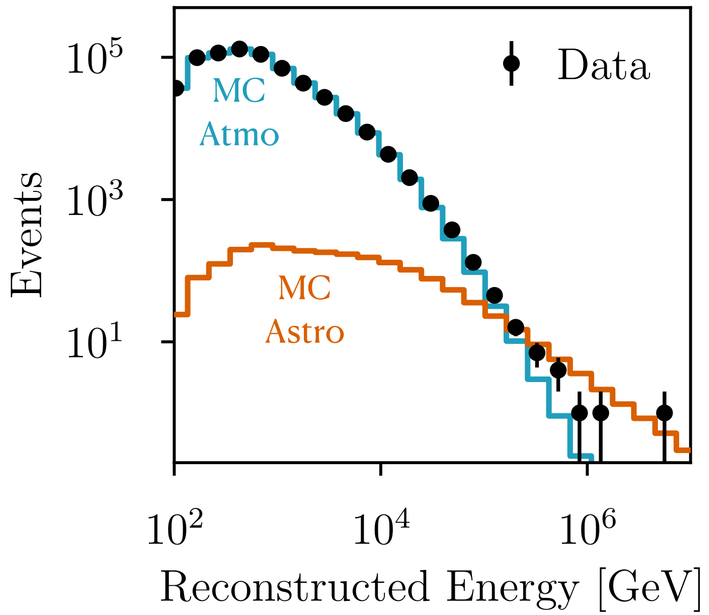
Spatial clustering of events above the background

Statistical method

Maximum likelihood ratios



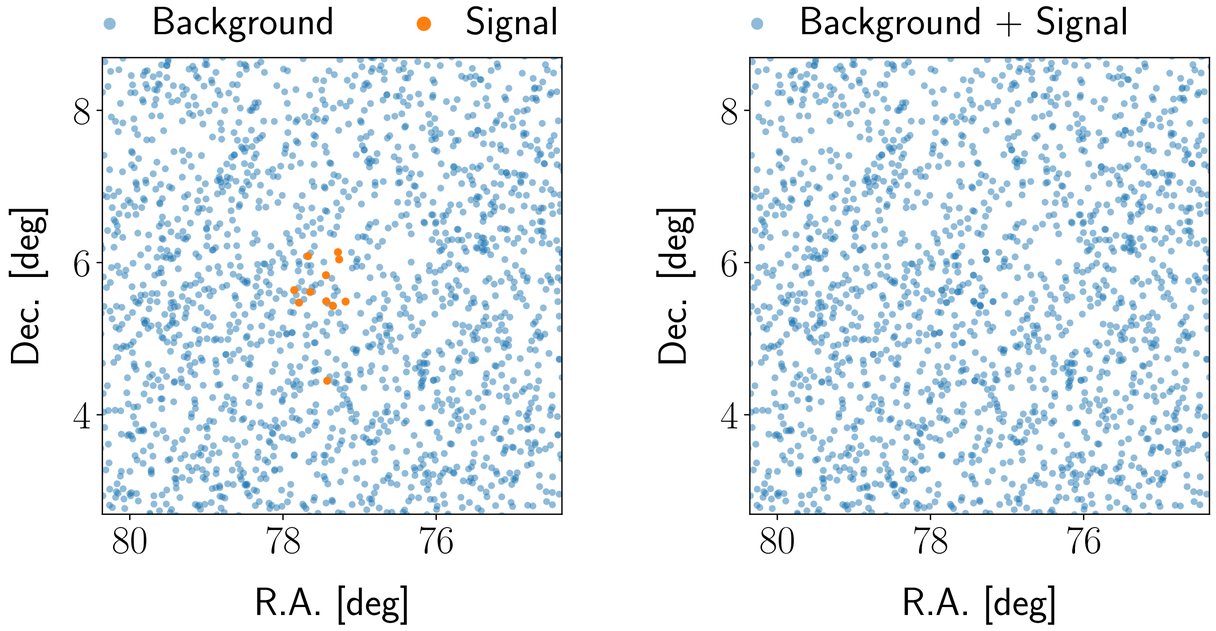
Spatial clustering of events above the background



Energy weight to help

Statistical method

Maximum likelihood ratios



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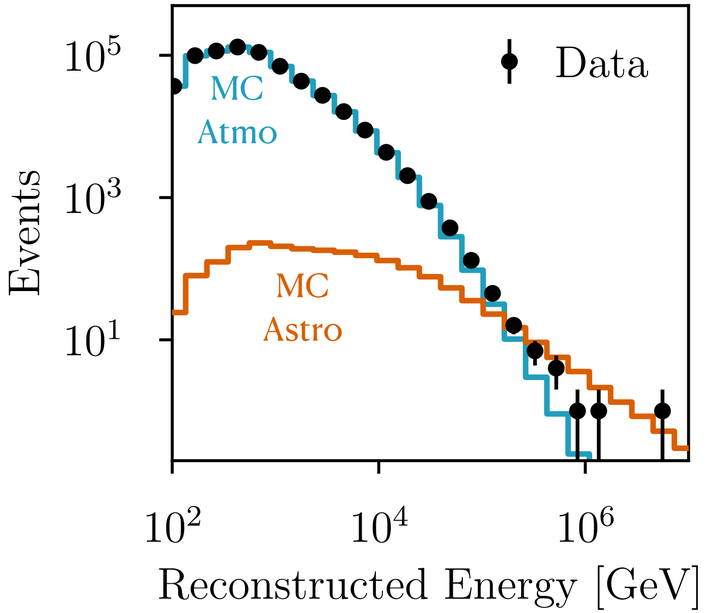

Energy weight to help

Signal PDF Background PDF

$$\mathscr{L}(\theta\,|\,\{x\},N) = \prod_{i=1}^{N}\left[\frac{n_s}{N}\cdot f_s(x_i\,|\,\theta_s) + \left(1-\frac{n_s}{N}\right)\cdot f_b(x_i\,|\,\theta_b)\right]$$

$$TS = -2\,\log\left[\frac{\mathscr{L}(n_s=0\,|\,\text{Data})}{\mathscr{L}(\hat{n}_s,\hat{\gamma}\,|\,\text{Data})}\right]$$

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Latest results

More sources like NGC 1068?

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New test on ~50% more data

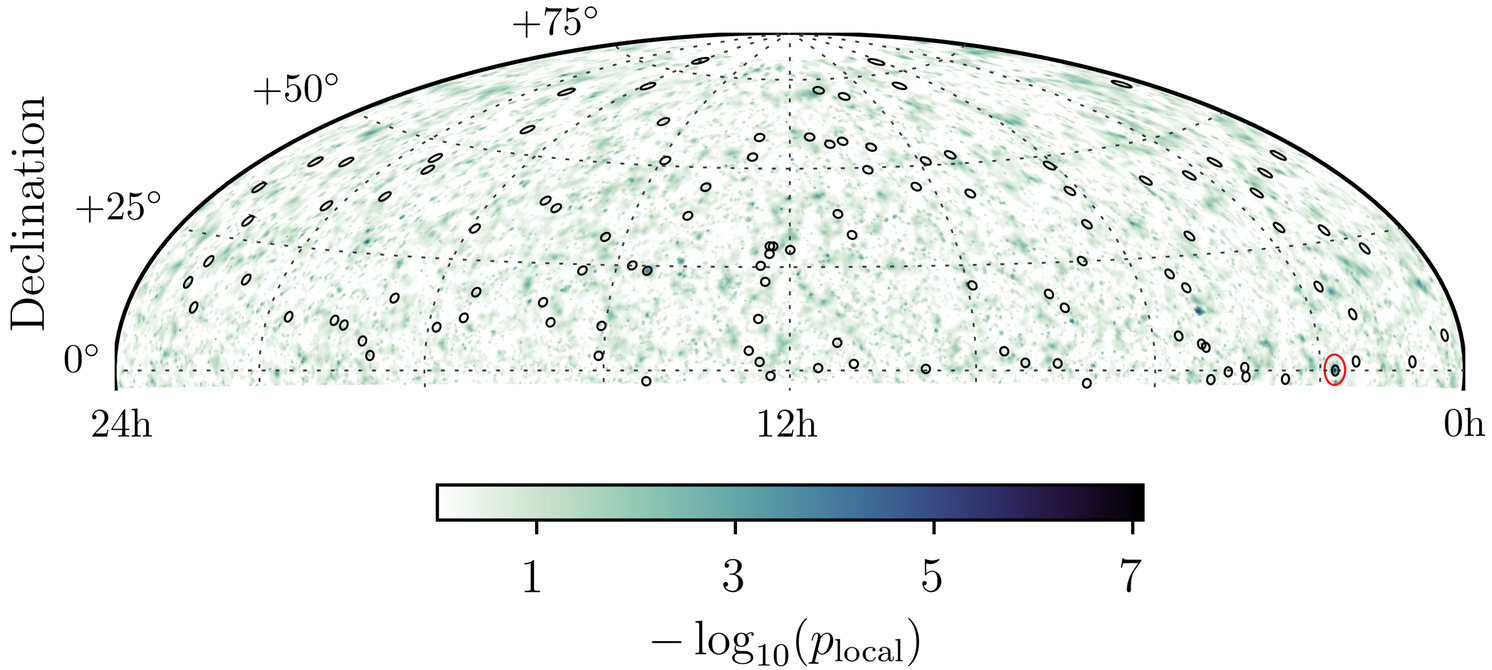
- **13 years** of track-like events (**angular resolution < 1° at E > 1TeV**) from the northern sky.
- **12 years of full detector** configuration with ~99% detector uptime + **1 year of data taken with 79 strings**.
- **~1M events between 100 GeV and ~6 PeV**.

- **New selection of candidate sources** triggered by:
  - observation of neutrinos from NGC 1068,
  - its X-ray brightness.
- **Selected the 47 brightest Seyfert galaxies in 20-50 keV** from the BASS catalog (*Swift*/BAT mission).
  - **Effectively retains nearby, non-blazar AGN with an especially bright corona.**
- Tested for neutrino emission singularly and as a collection of objects.
- Re-test of NGC 1068 as well.

NGC 1068 — Re-measurement

Still the most significant extragalactic source

- Look for neutrino sources from a pre-defined list of objects.
- Selected **110 gamma-ray emitters.**



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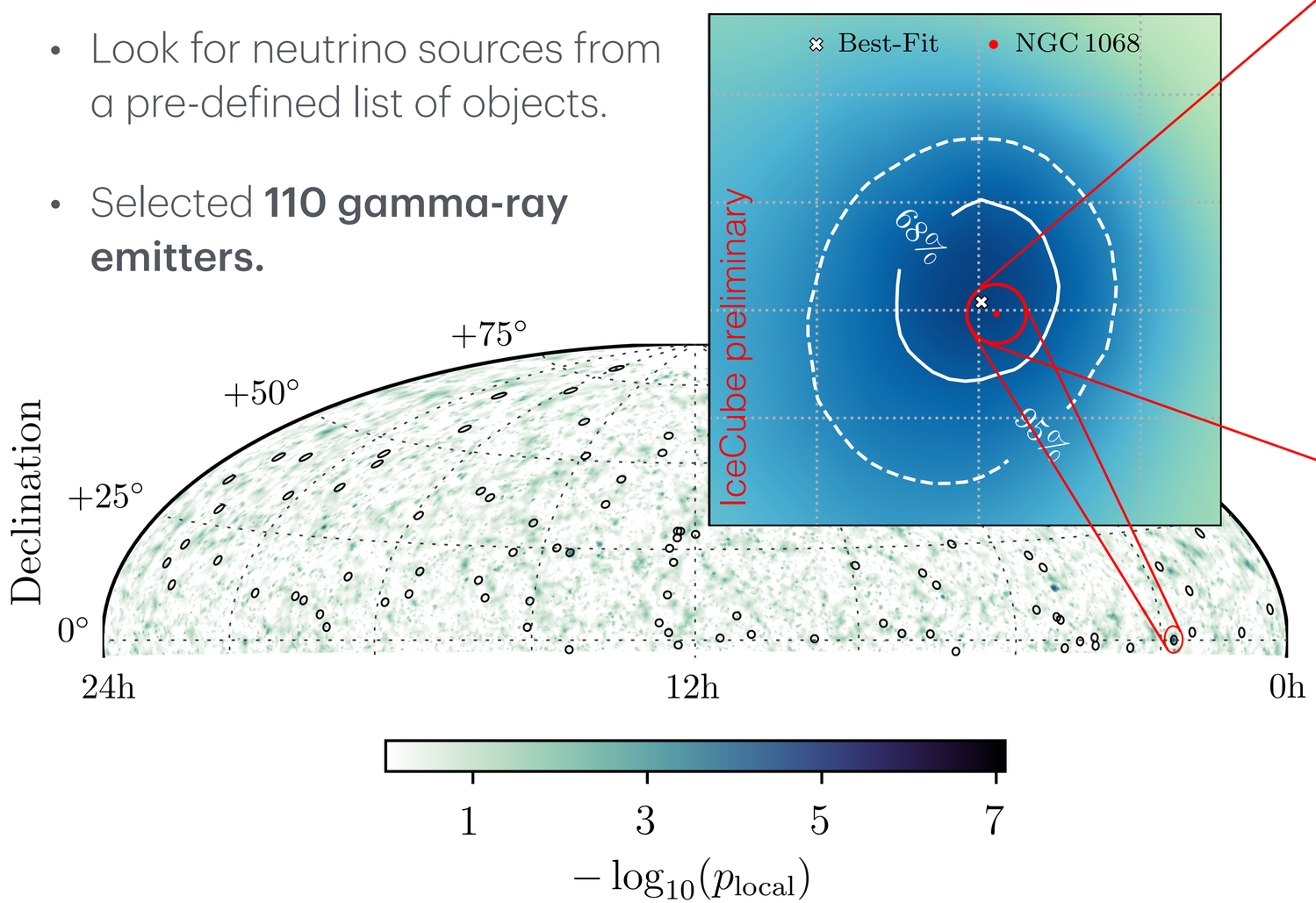
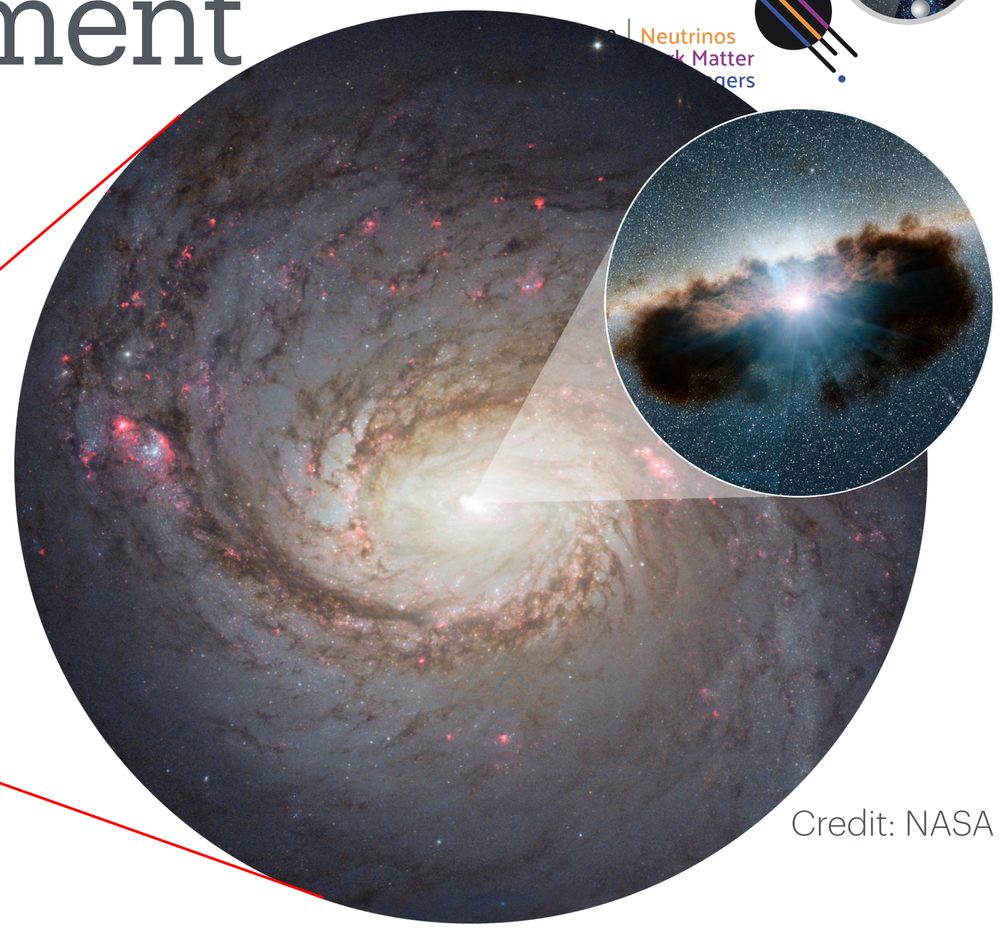


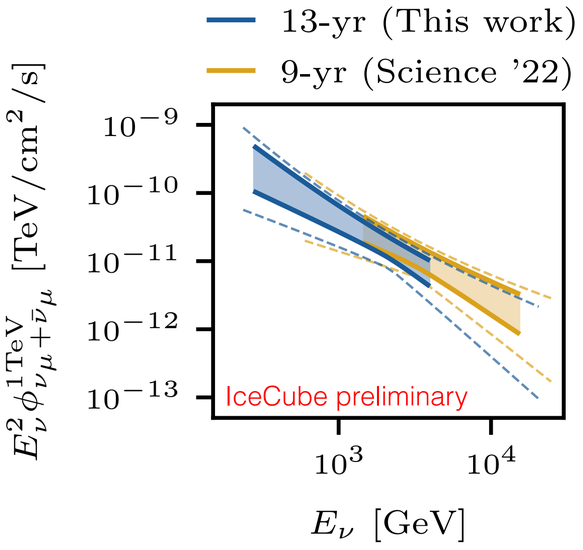


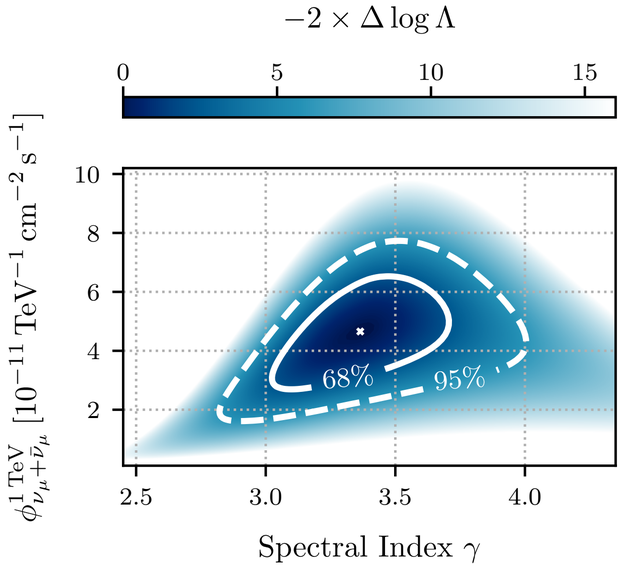
Credit: NASA

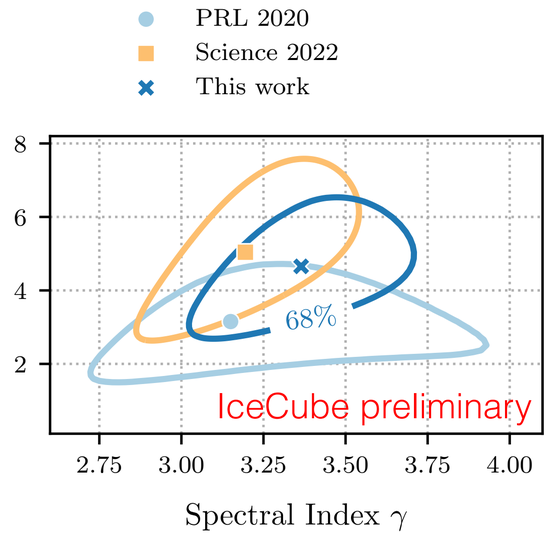
- Most significant emission at **4σ**.
- **0.04° away from the hottest spot** (previously 0.11° but same within stats).

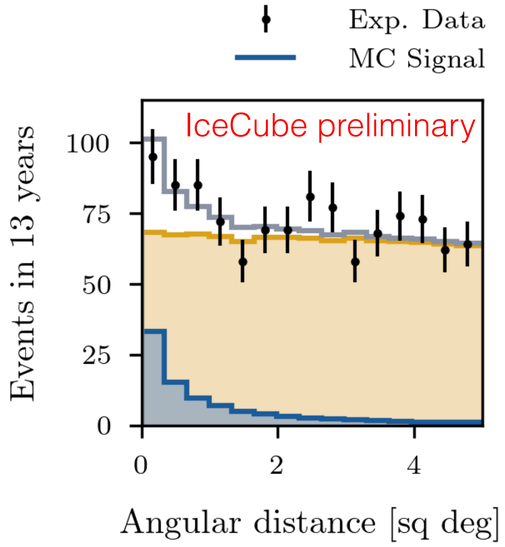
NGC 1068 — Re-measurement

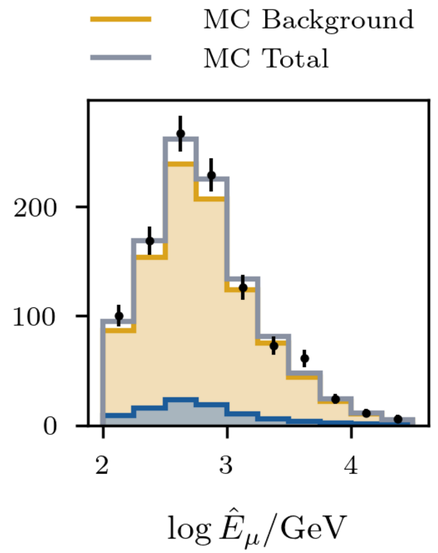
- Flux compatible with previous measurements within 1σ (stat.)
- The energy spectrum shifts to lower energies. Close to the lower energy boundary of the sample.





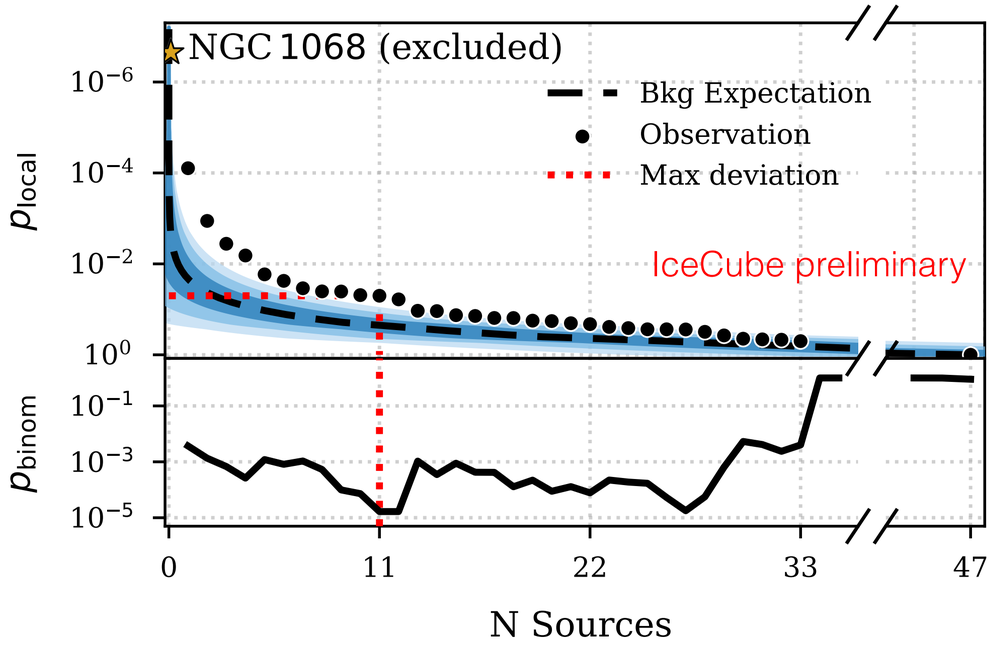


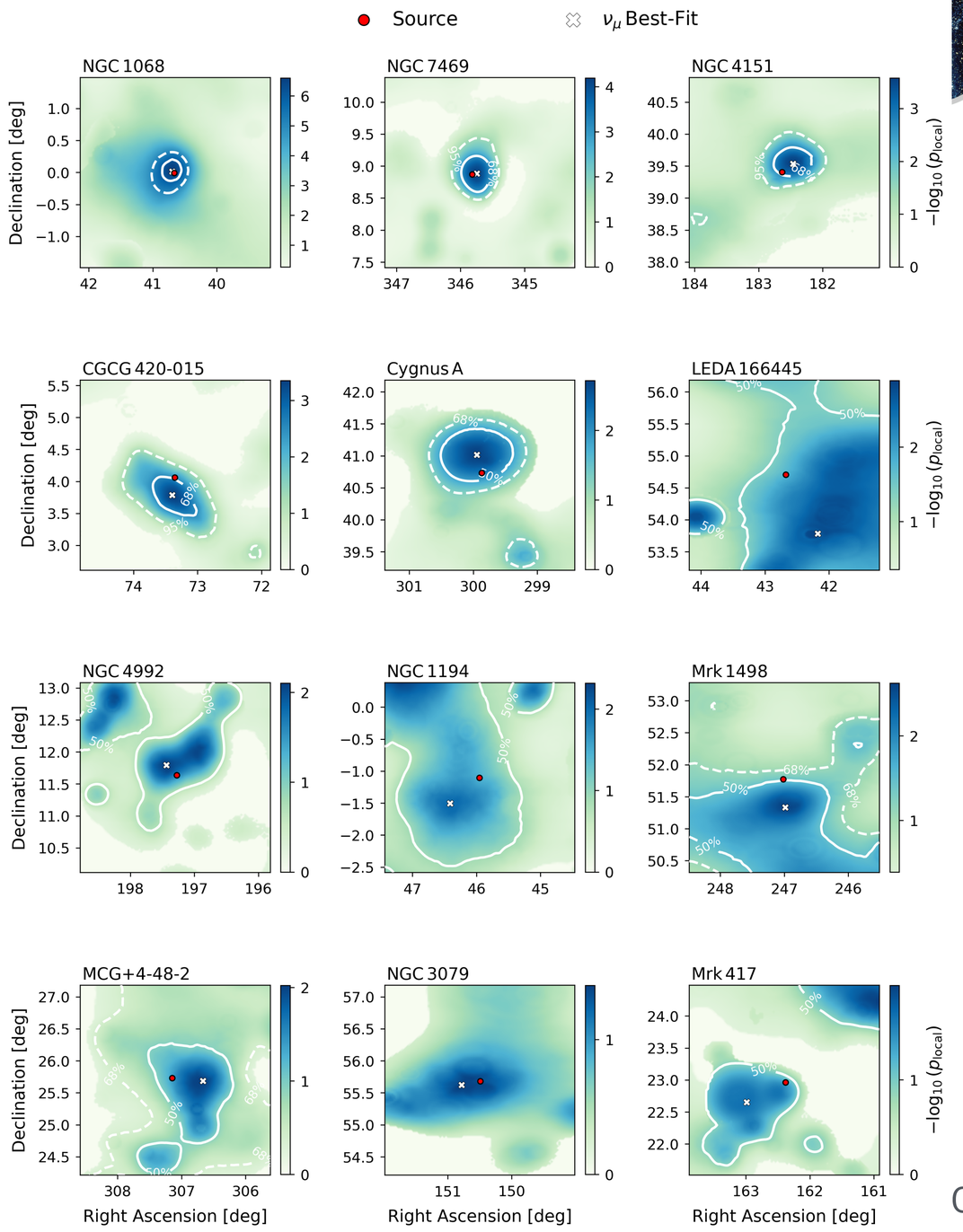




Cumulative excess from X-ray-bright AGN

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





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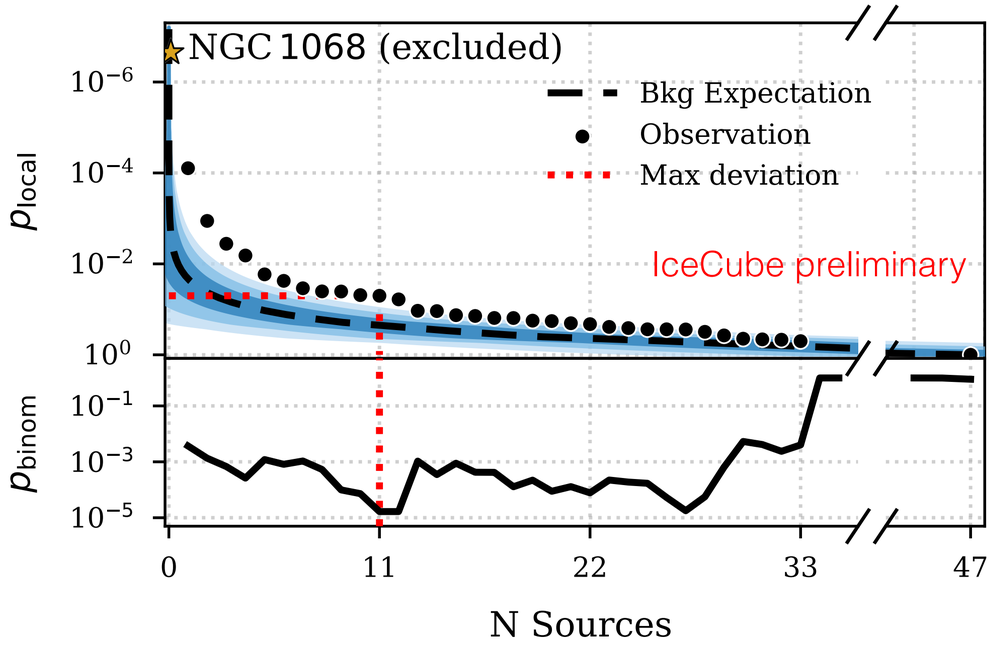
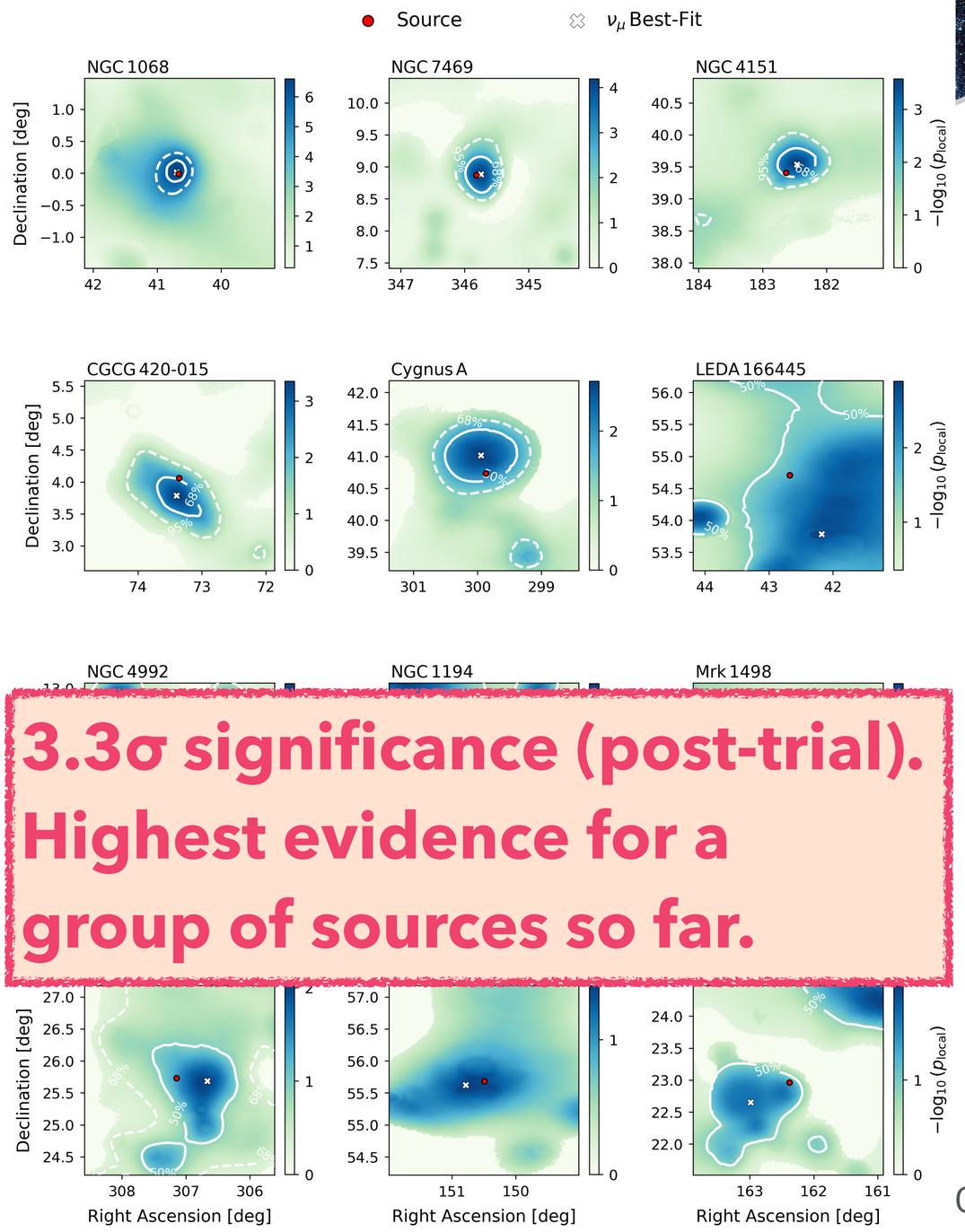
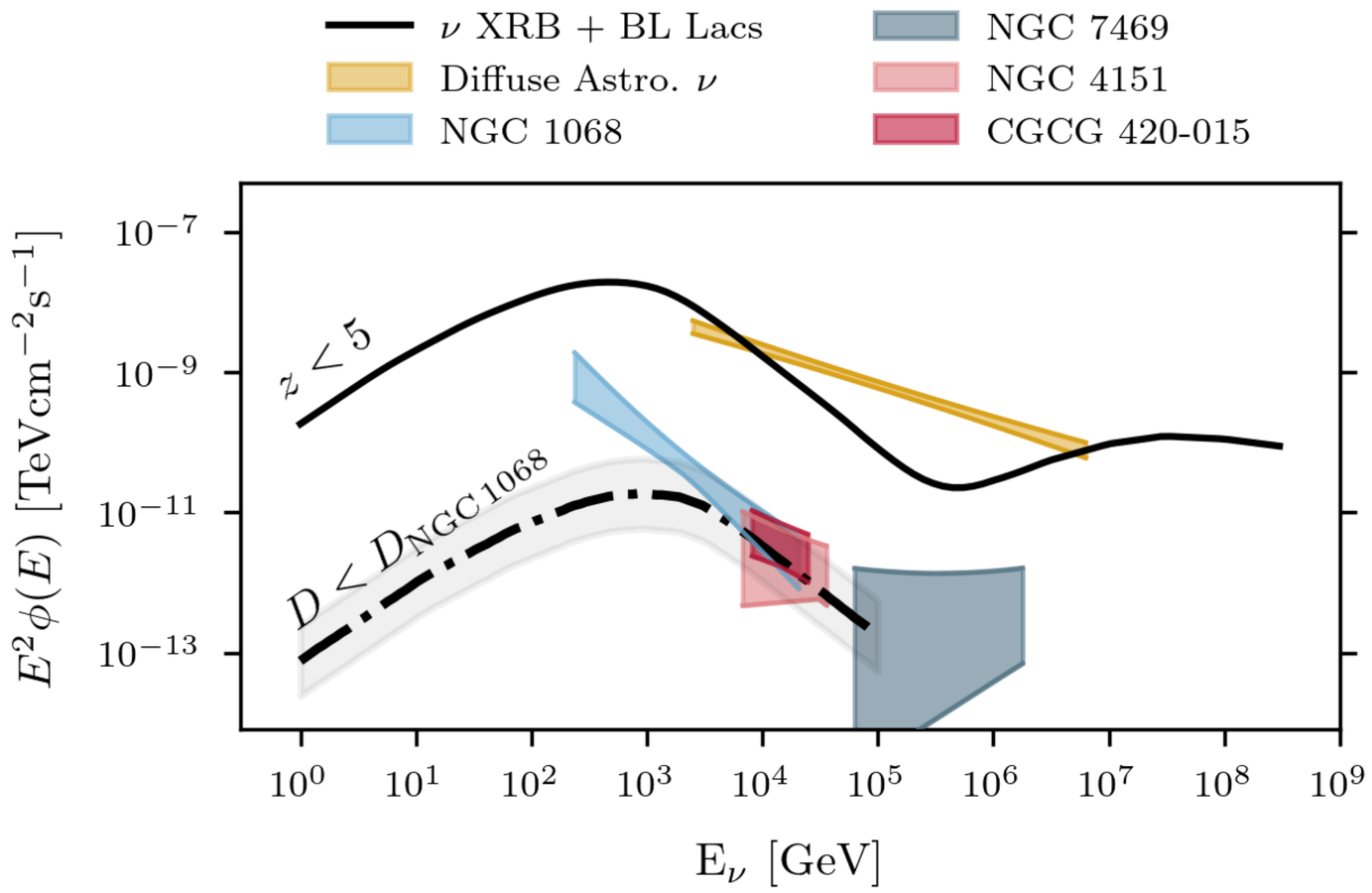




3.3σ significance (post-trial). Highest evidence for a group of sources so far.

Back to the population

And our simplified assumptions



- **NGC7469 already challenges our simple assumption** that X-ray-bright non-blazar AGN and blazars are well separated in the energy spectrum.
- The X/ν ratios not constant.
  → anchoring the population to NGC1068's ratio oversimplifies reality.
- Update to the paper as soon as the IceCube paper is published — WIP.

Conclusion: a paradigm shift

From gamma rays to X-rays as neutrino tracers in AGN

- Neutrinos from the **blazar TXS 0506+056 —> γ-rays and neutrinos correlated in observations**.
- Neutrinos from **NGC 1068 —> γ-ray-obscured AGN that is X-ray bright**.
- **Additional excesses** from X-ray-bright, non-blazar, AGN.
  - Recently, **binomial evidence at 3.3σ from a population of hard X-ray AGN**.
- Recent studies challenge the neutrino—γ-ray correlation for blazars, speculating that neutrinos are produced in the AGN core, while gamma-rays come from the jet (https://arxiv.org/abs/2411.14598).
- A **planetary neutrino monitoring system** with IceCube, KM3NeT, P-ONE, GVD, Trident, … will provide the additional sensitivity we need to confirm or discard the evidence provided by IceCube.