Technical University of Munich

ICECUBE South Pole Neutrino Observatory

SFB 1258 Neutrinos Dark Matter Messengers

NGC 1068 as a neutrino source

and the emerging class of Seyfert galaxies

Chiara Bellenghi for the IceCube Collaboration

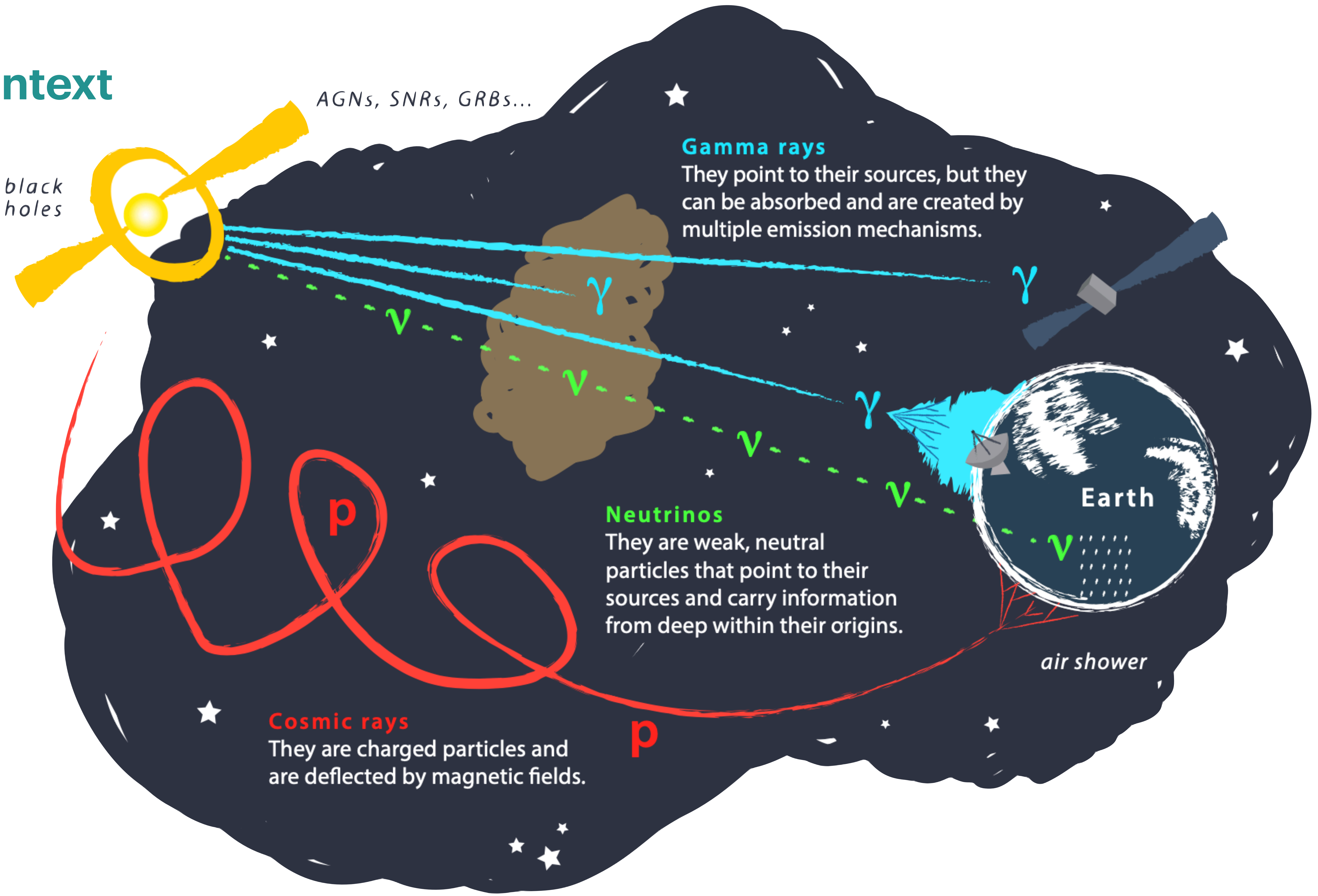
GSSI

The Fourth Gravi-Gamma-Nu Workshop - GSSI, L'Aquila, Italy - 04/10/2023

Neutrinos

In the multimessenger context

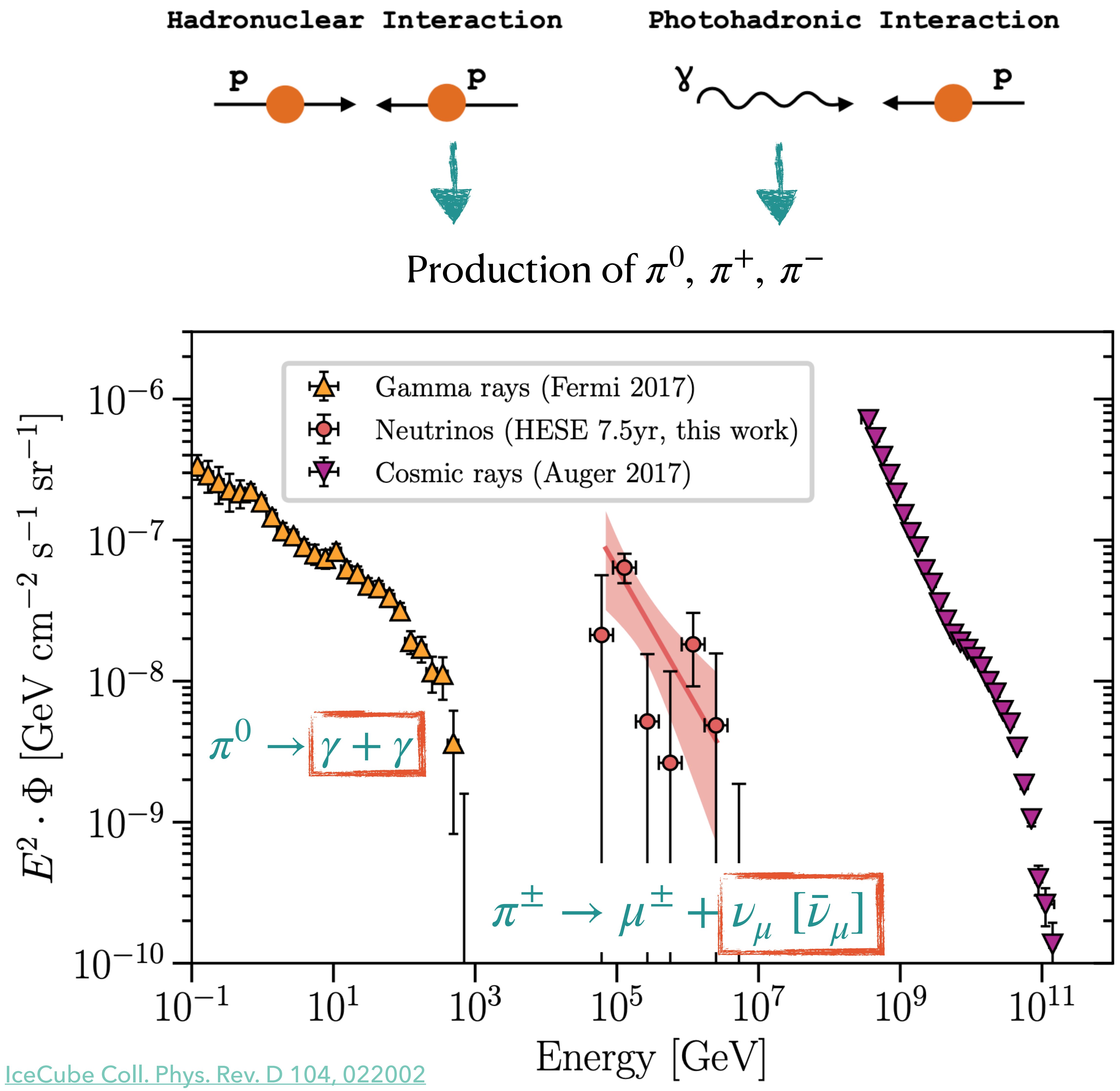
- A cosmic proton accelerator produces both neutrinos and gamma-rays.



Neutrinos

In the multimessenger context

- A cosmic proton accelerator produces both neutrinos and gamma-rays.
- **Simple picture**: we expect to see **similar fluxes of neutrinos and gamma-rays on Earth**.
- The cosmic-ray, neutrino, and gamma-ray backgrounds support this scenario.



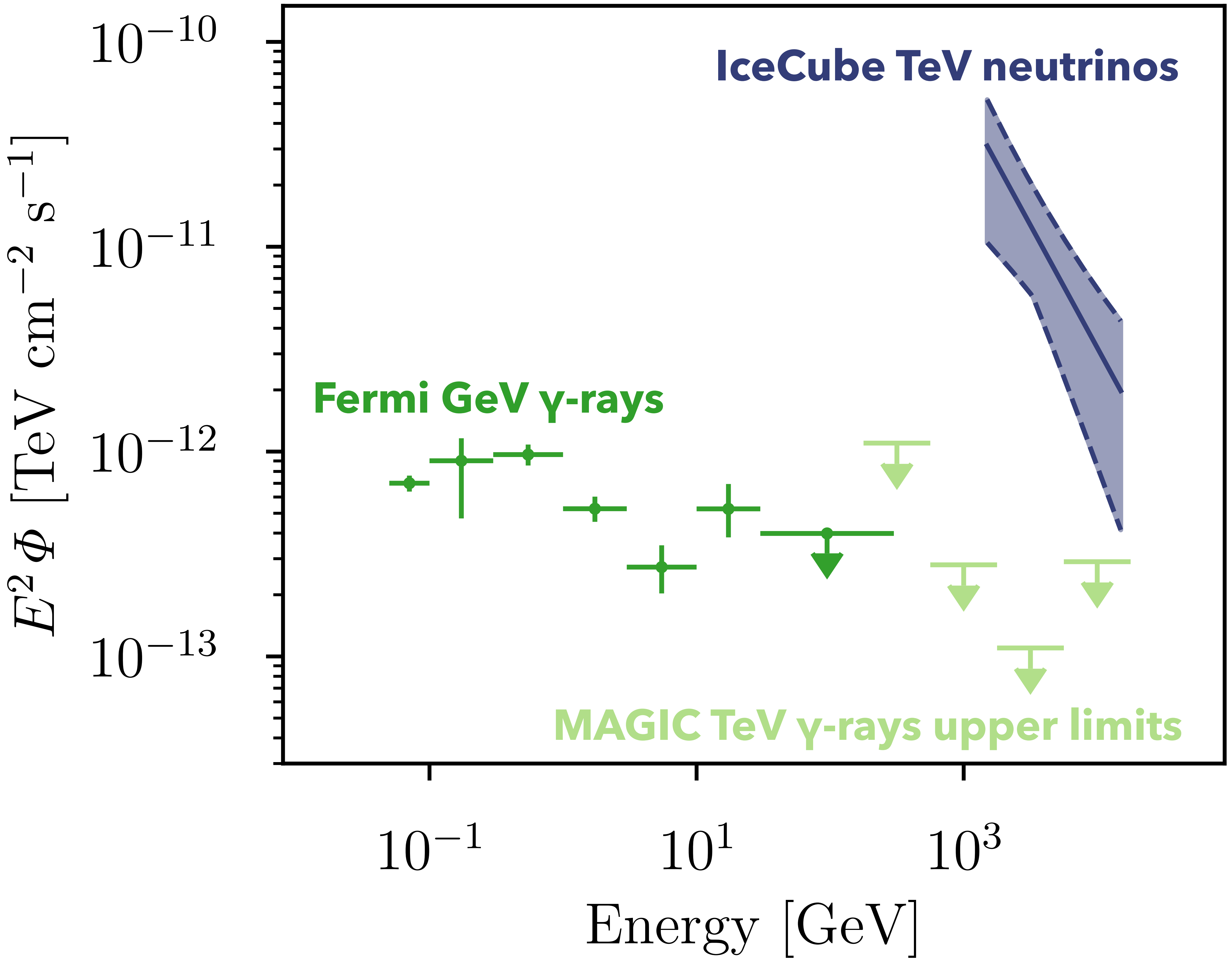
IceCube Coll. Phys. Rev. D 104, 022002

A multimessenger puzzle

Obscured AGN

- November 2022: IceCube publishes **evidence for TeV neutrino emission from the nearby active galaxy NGC 1068.**
- The **GeV γ-ray flux** measured by Fermi is roughly **2 orders of magnitude below the neutrino flux**.
- Upper limits from MAGIC constrain the **TeV γ-ray flux 2 orders of magnitude below the neutrino flux**.
- The neutrino emission from NGC 1068 does not correlate with high-energy γ-rays.

High-energy emission from NGC 1068



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IceCube

A km³ neutrino telescope

- A km3 of antarctic ice at a depth of ~1.5 km.
- 86 strings instrumented with 5160 optical modules.

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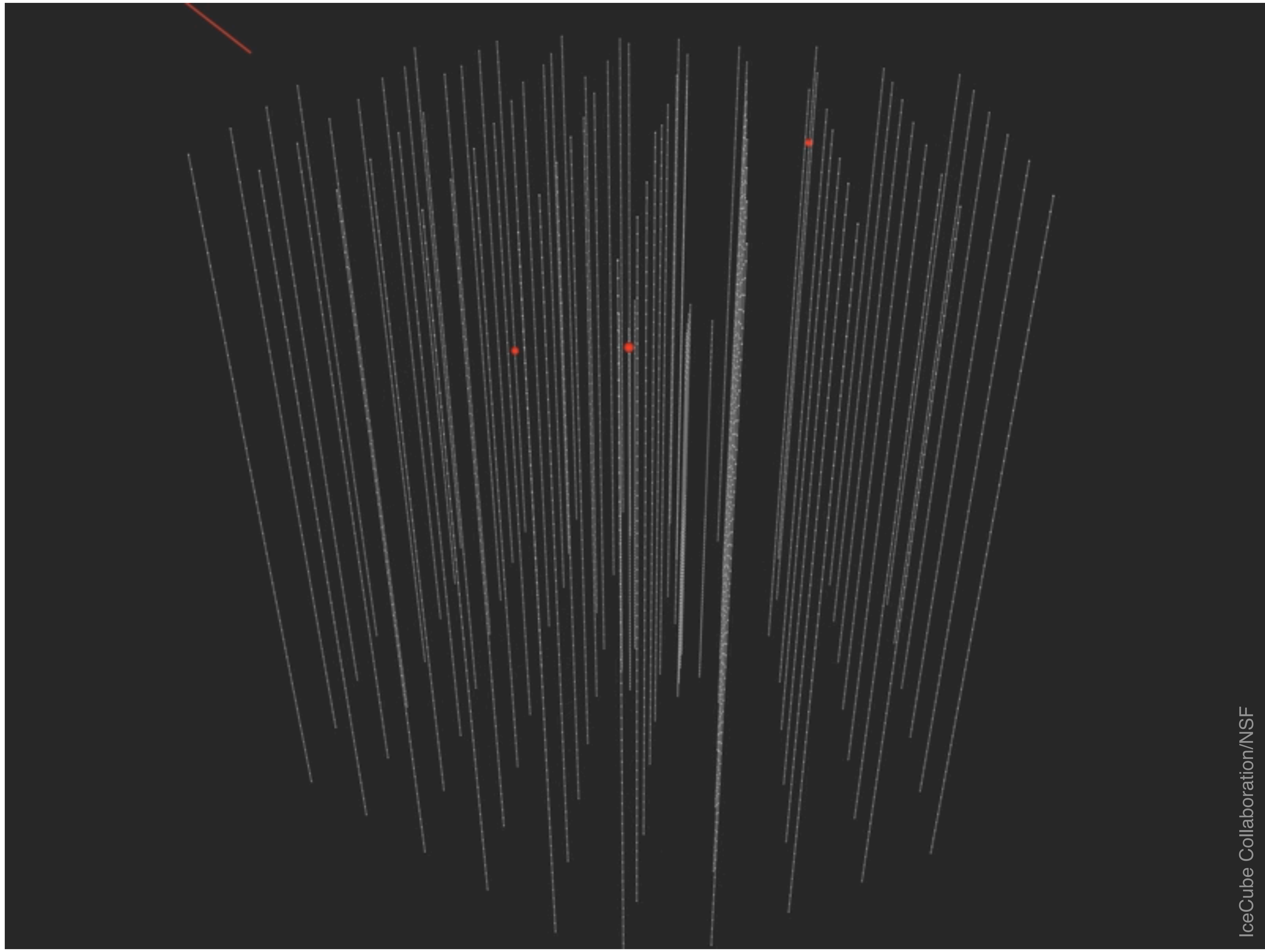
- We reconstruct the original neutrino properties from the deposited light pattern: direction and energy.
- Energies from ~100 GeV to several PeV.



IceCube Collaboration/NSF

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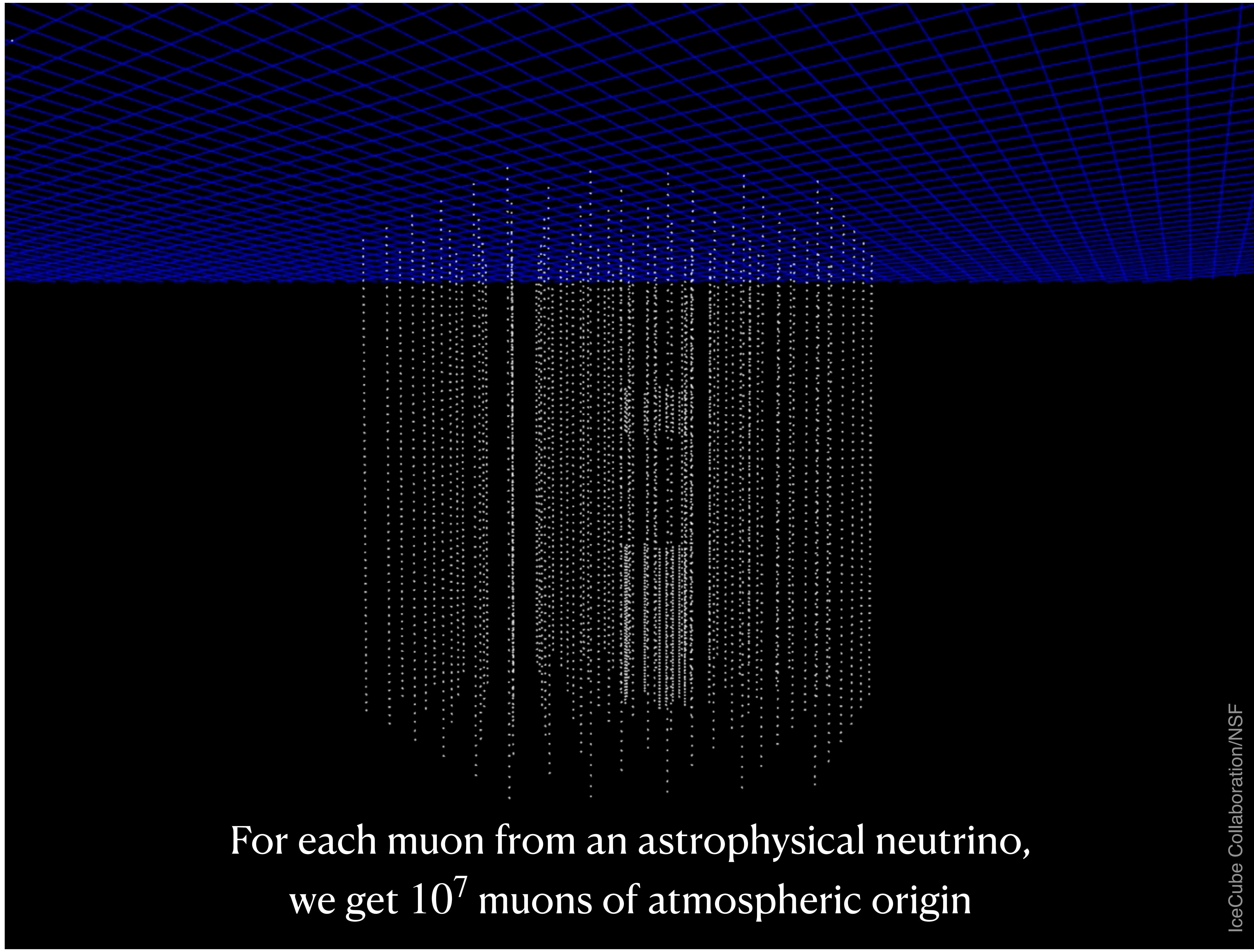
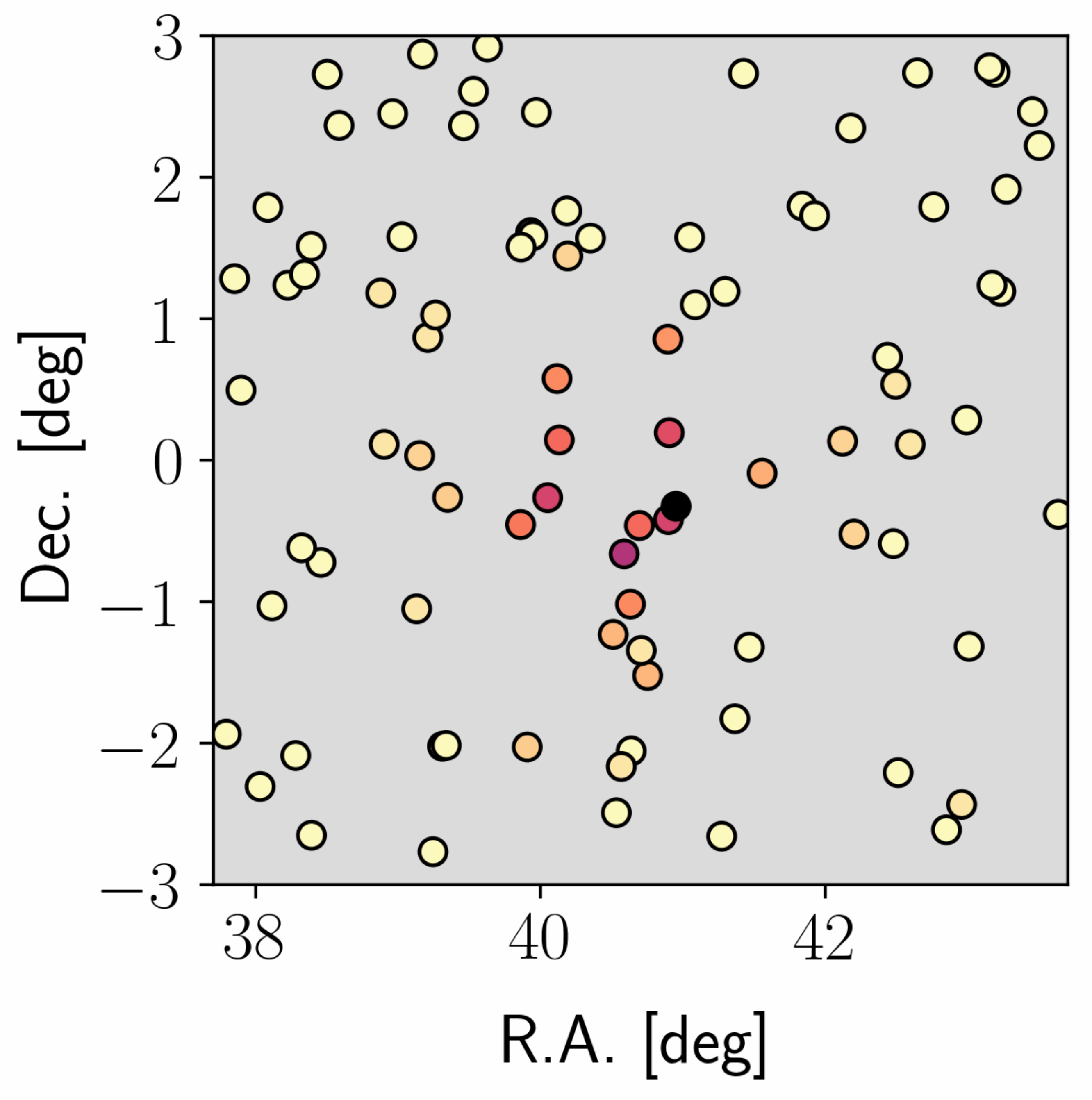


Searching for neutrino sources

aka, looking for a needle in a haystack

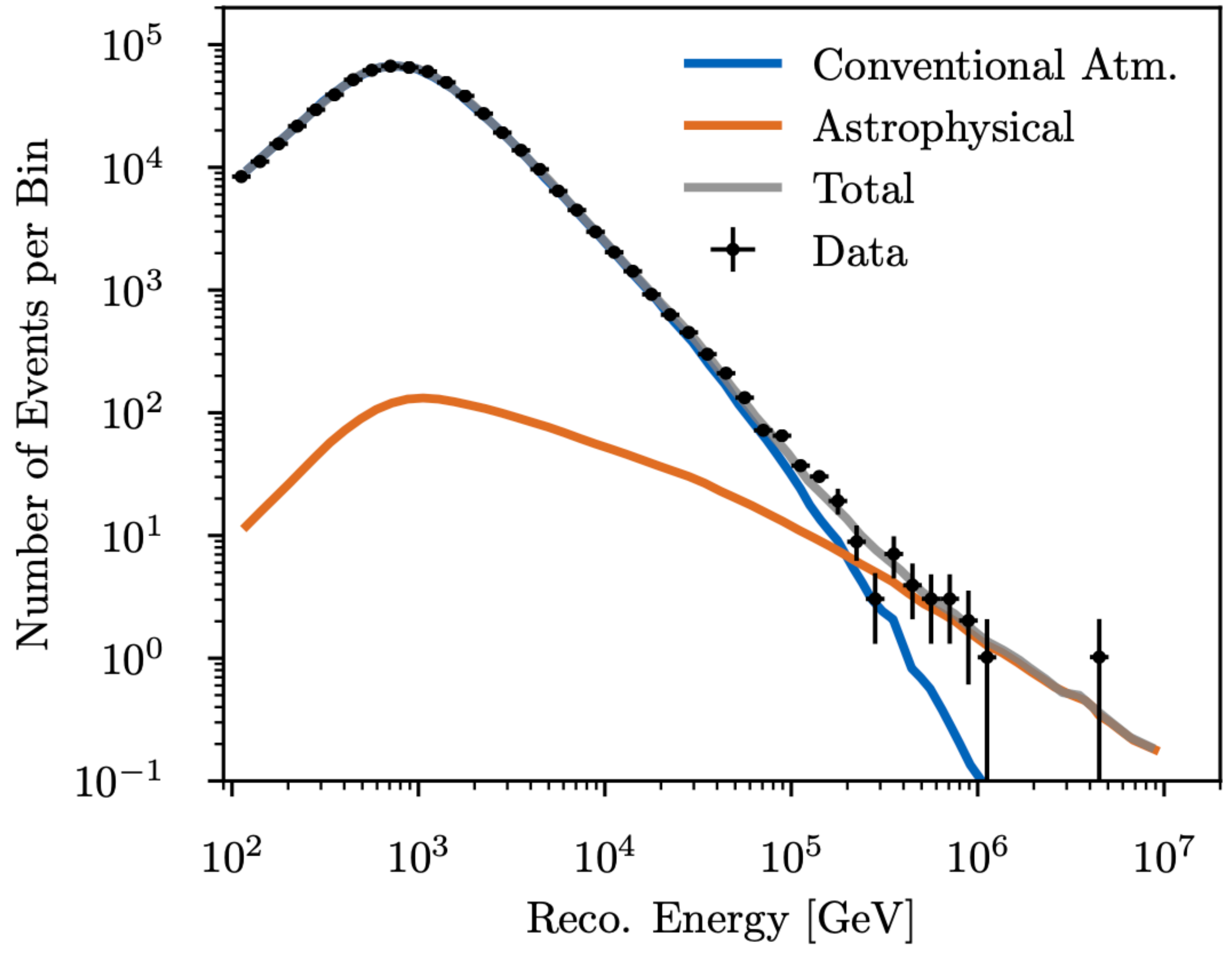
Accumulation of events around NGC 1068 over 9 years.



Color scale = S/B

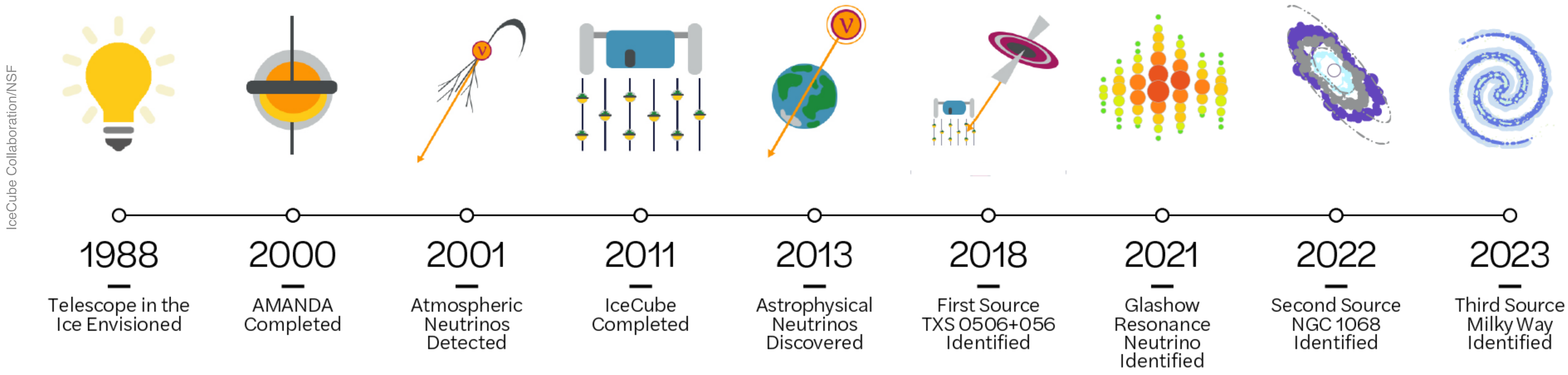
- Use the maximum likelihood ratio method to search for **clustering** of events around the source.
- Include the **energy information** to increase the sensitivity to a potential signal.

Energy distribution in the Northern sky



A little history

Searching for neutrino sources for two decades



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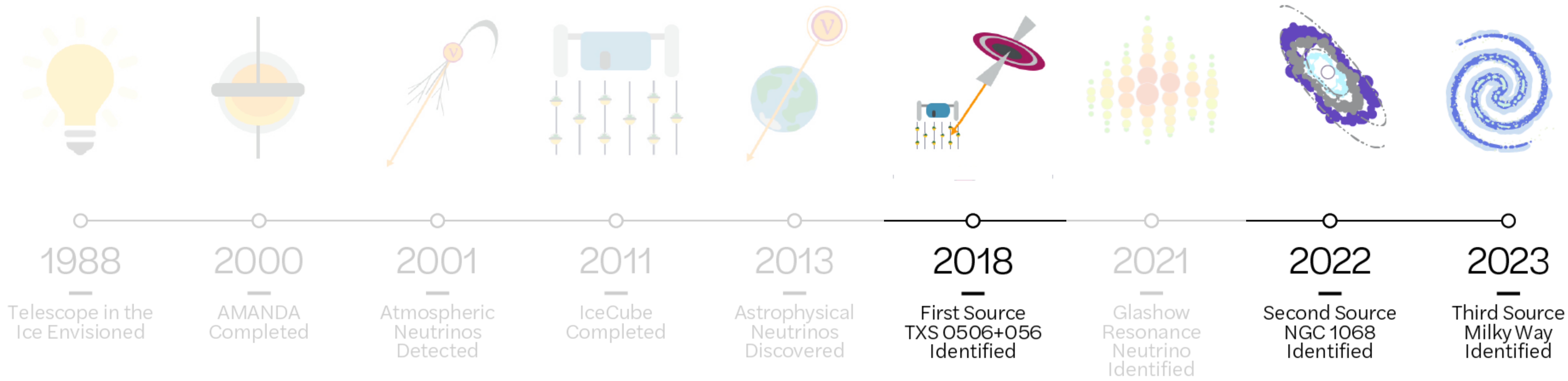
A non-jetted AGN



IceCube Collaboration/NSF

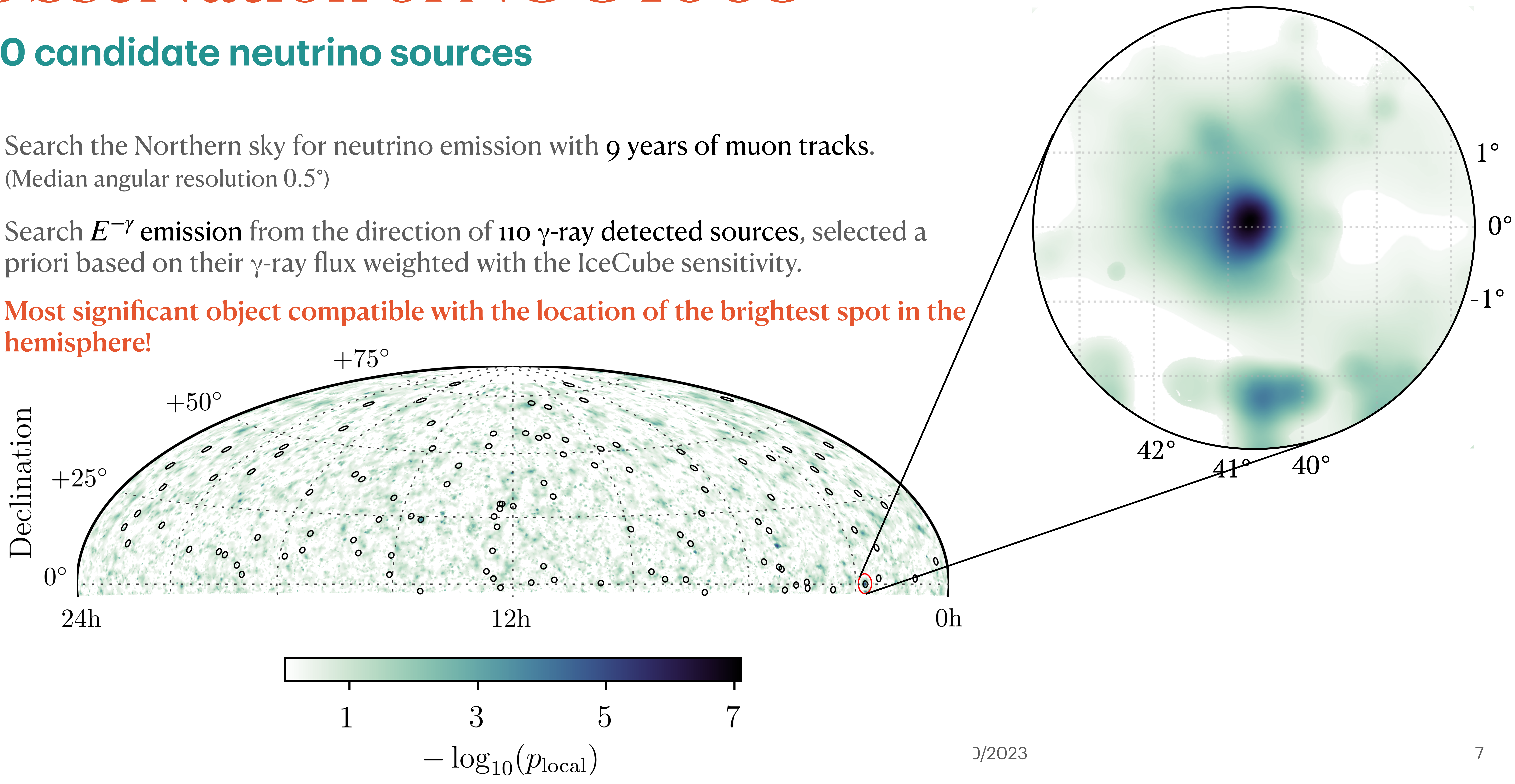
A flaring blazar, jetted AGN

Our own non-active galaxy!

Observation of NGC 1068

110 candidate neutrino sources

- Search the Northern sky for neutrino emission with 9 years of muon tracks. (Median angular resolution 0.5°)
- Search $E^{-\gamma}$ emission from the direction of 110 γ-ray detected sources, selected a priori based on their γ-ray flux weighted with the IceCube sensitivity.
- **Most significant object compatible with the location of the brightest spot in the hemisphere!**



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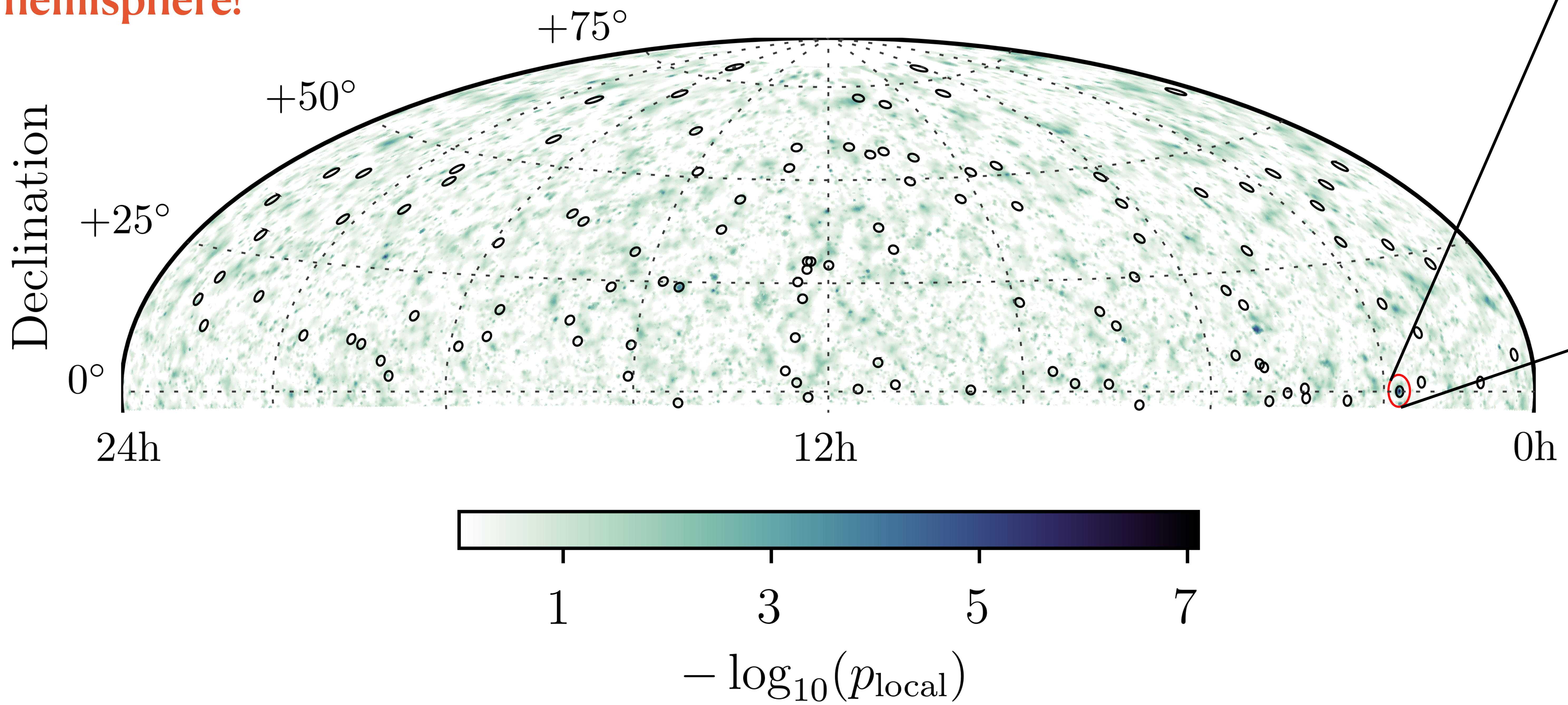

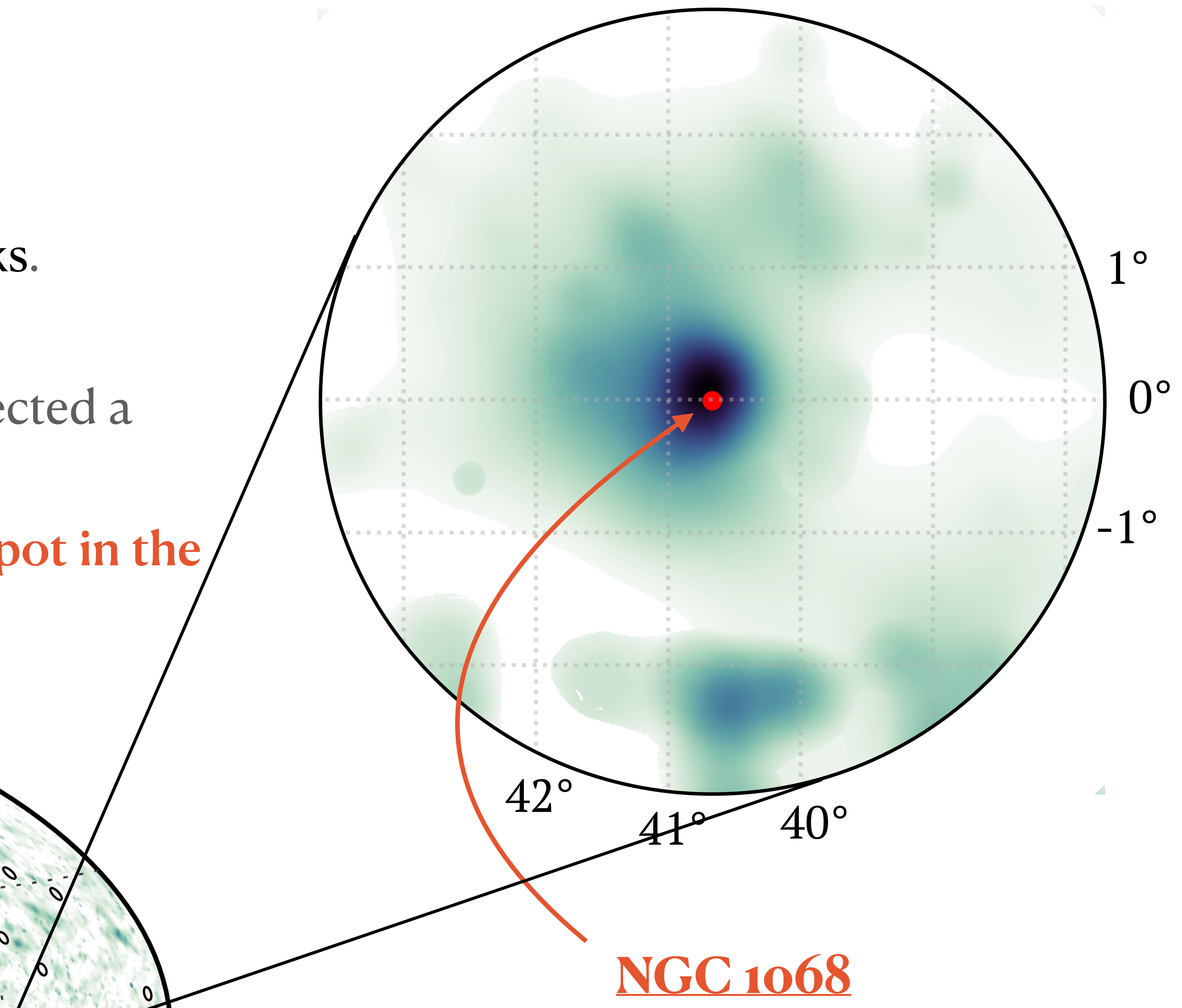

- R.A. 40.67° and Dec. −0.01°
- Mean # of signal events $\hat{n}_s = 79^{+22}_{-20}$
- Spectral index $\hat{\gamma} = 3.2 \pm 0.2$

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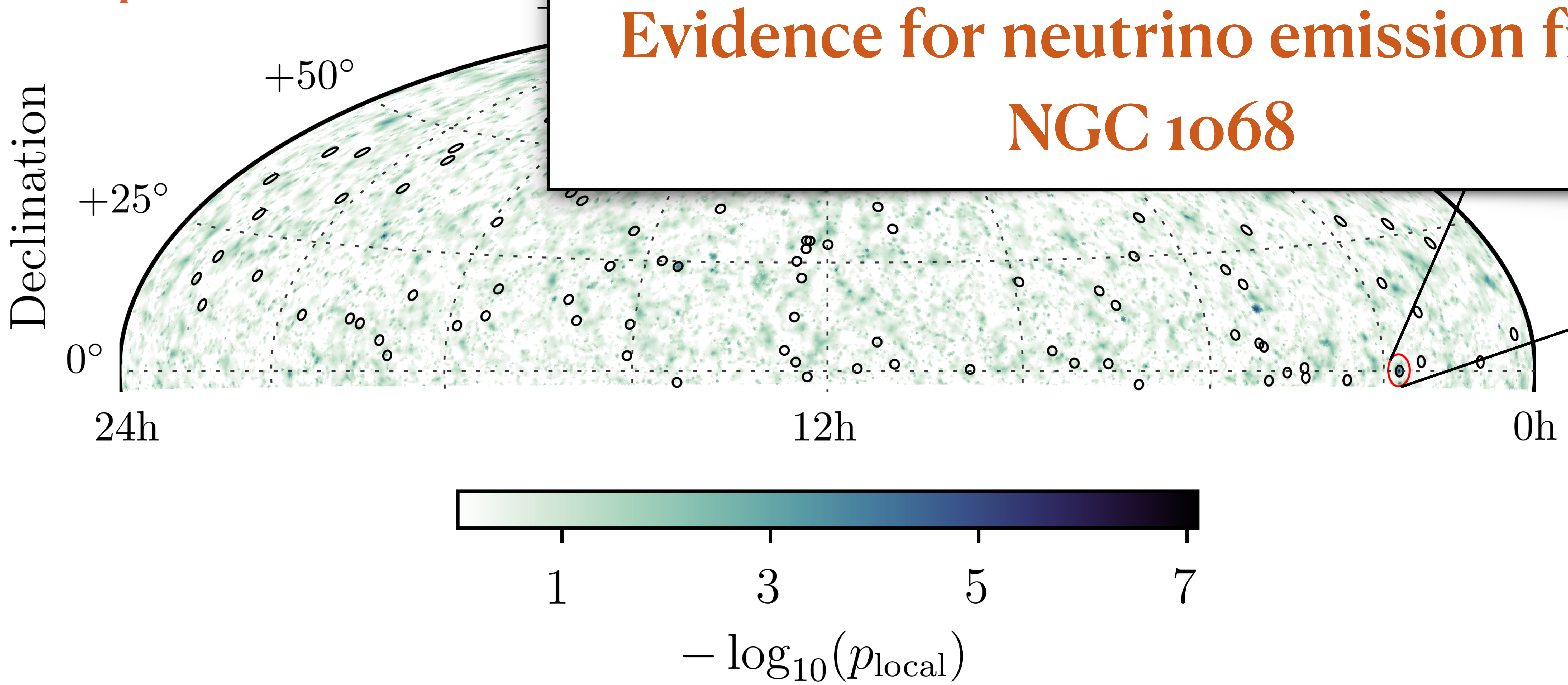
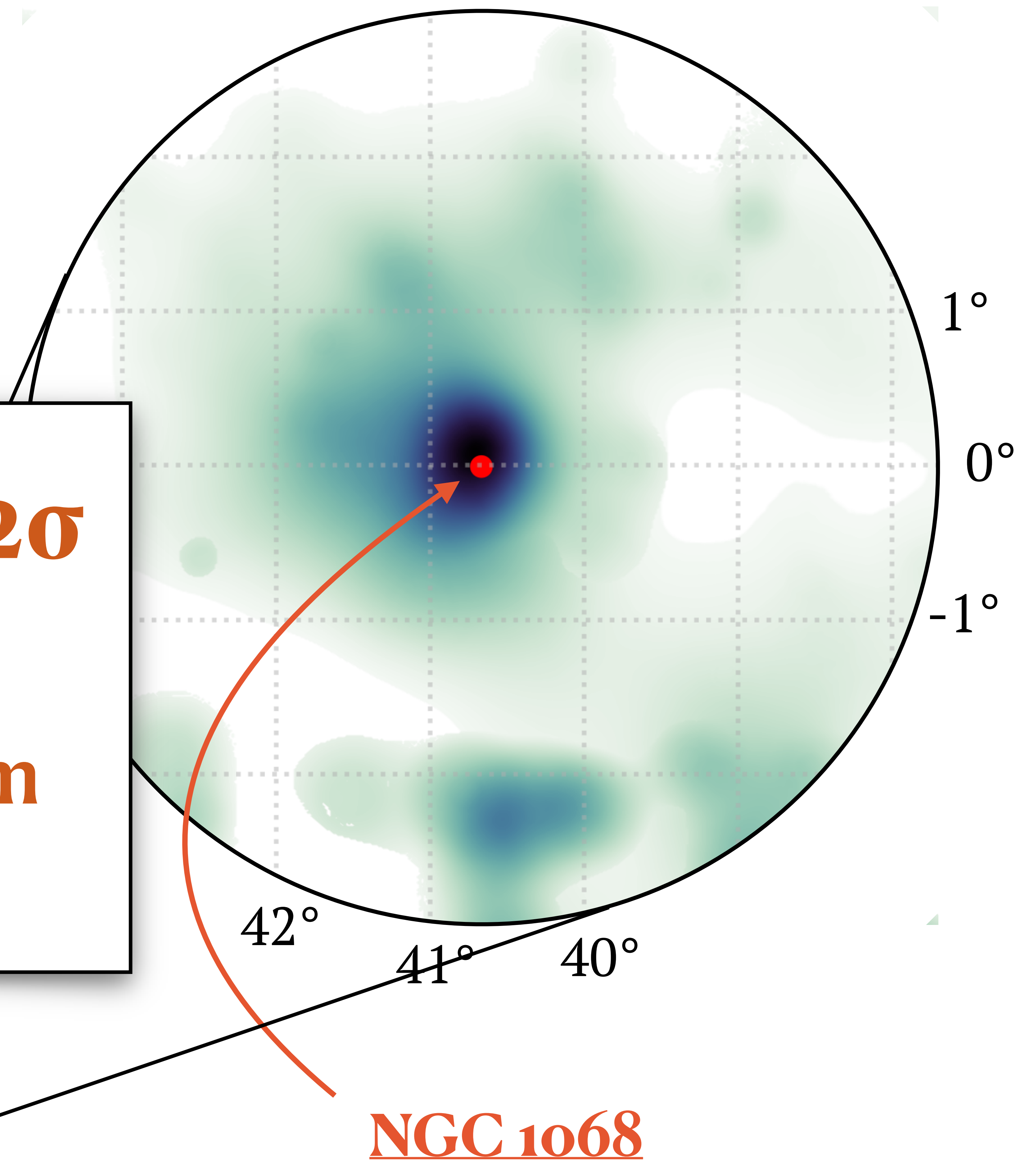
Global significance of the excess: 4.2σ

Evidence for neutrino emission from NGC 1068





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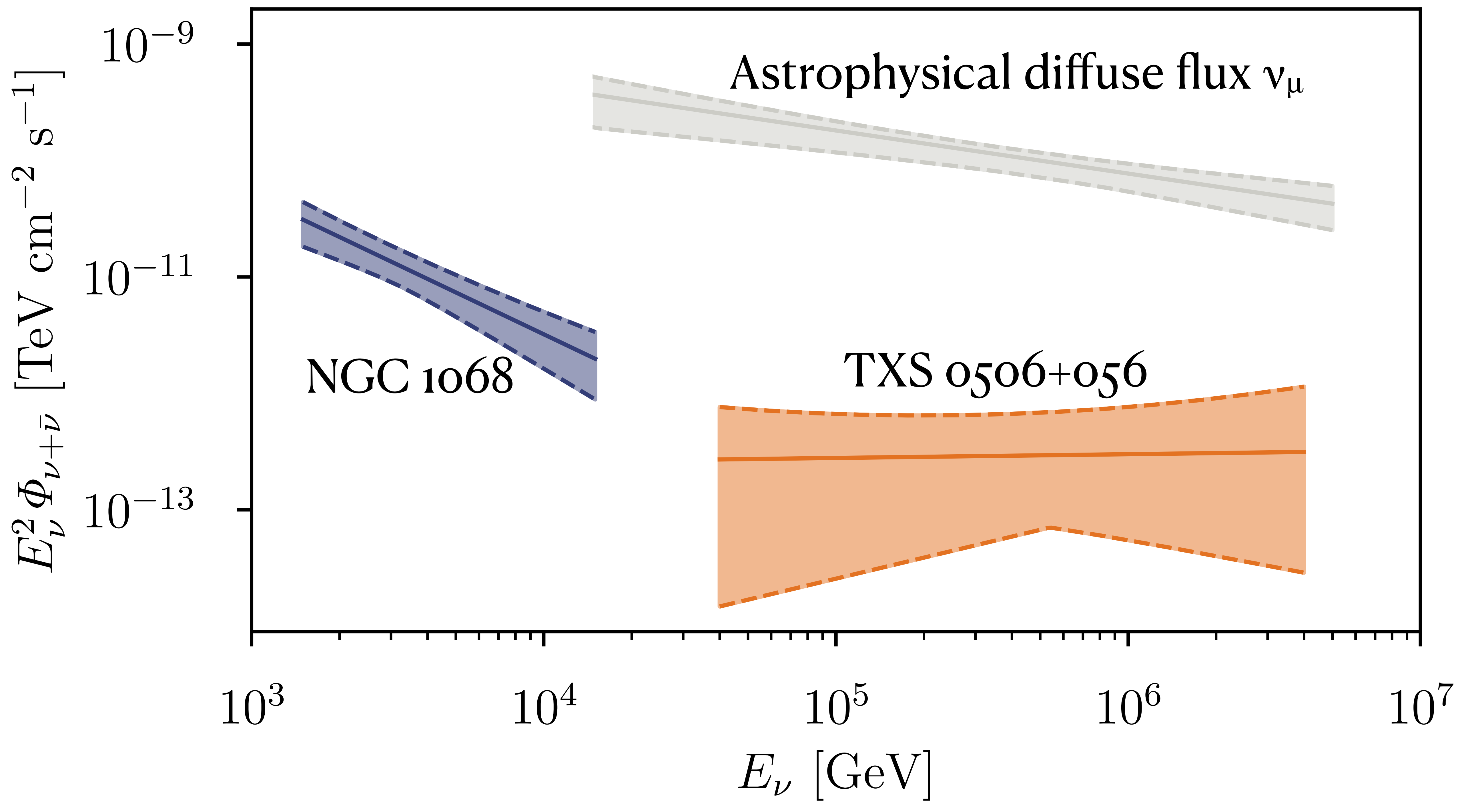
NGC 1068 neutrinos

Less than 1% of the the diffuse background

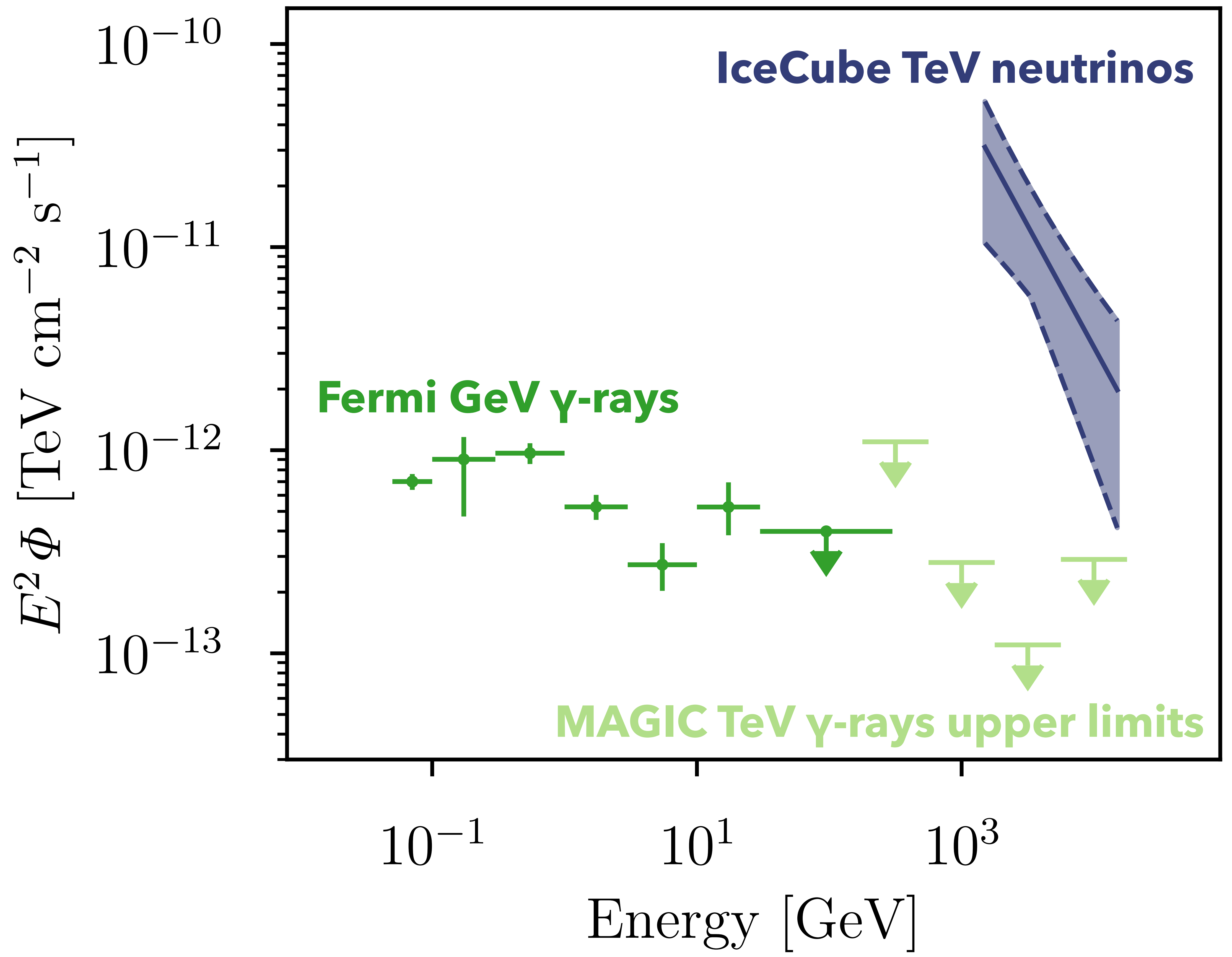
- TXS 0506+056 and NGC 1068 extragalactic contribution is ~1% of the total astrophysical diffuse neutrino background each.
- **AGN may produce the primary component of the high-energy neutrino background.**
- Not only blazars. Non-jetted AGN may be other sources of high-energy neutrinos.
- More sources from the same population?
- More populations? **More NGC1068-like objects?**



NGC 1068 gamma-rays

Flux $\mathcal{O}(100)$ times smaller than the neutrino flux

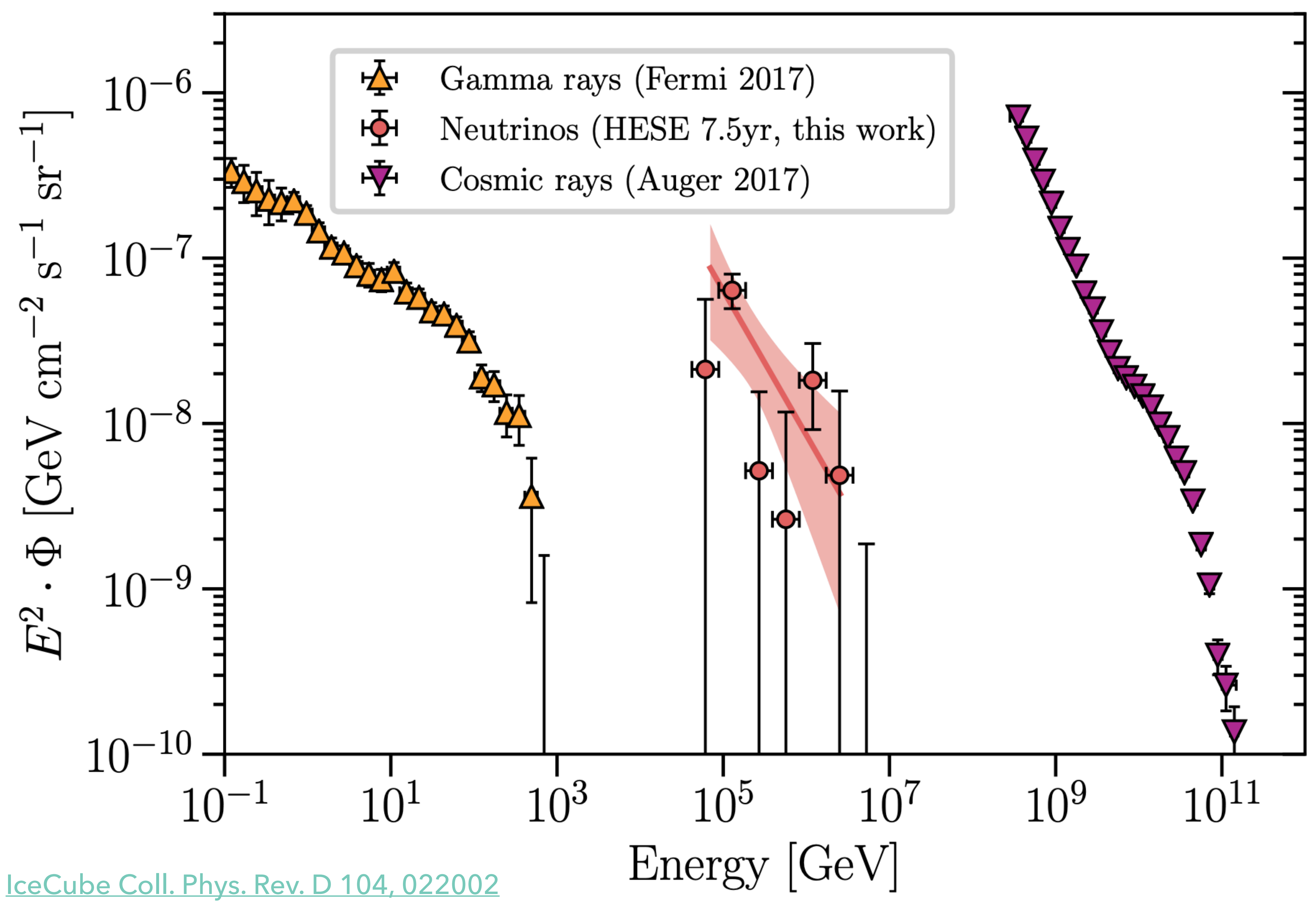
- **The neutrino flux outshines the γ-ray one!**
- γ-rays must be absorbed. But they should also reappear somewhere at lower energies. MeV excess from NCG 1068? Currently missing MeV telescope: untestable.
- Where is the Fermi flux produced? Are neutrinos and γ-rays coming from different sources within the galaxy?



Hidden sources

The medium energy neutrino flux

- NGC 1068 is not breaking the big multimessenger picture.
- The measured neutrino flux at medium energies (~ 30 TeV) is an order of magnitude greater than the flux at > 100 TeV) (Aartsen et al. Phys. Rev. Lett., 125, 121104)
- **The sources producing the TeV neutrino flux need to be opaque to GeV-TeV γ-rays** to not exceed the γ-ray background measured by Fermi.



IceCube Coll. Phys. Rev. D 104, 022002

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 ~10^7 - 10^8 M_{sol}.
- Intrinsically the brightest Seyfert in the X-ray band.

Hidden sources

Re-inventing the wheel

- "There are several classes of galaxies with compact nuclei and huge energy output from these nuclei […]. Seyferts of class 2, however, are so heavily obscured by dust and gas that their non-thermal nature is not established. It is shown that neutrino astronomy would help ascertain the nature of class 2 Seyferts."

NEUTRINOS AS A PROBE FOR THE NATURE OF

AND PROCESSES IN ACTIVE GALACTIC NUCLEI

R. Silberberg and M. M. Shapiro
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Washington, D. C. 20375, U.S.A.

ICRC PoS from 1979!

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§9. Hidden sources

In the example of a massive black hole in a cocoon we encountered a model of a hidden source: an object which contains particles accelerated to high energies, but is not seen in high-energy electromagnetic radiation (X-ray and (or) gamma-ray radiation).

Hidden sources

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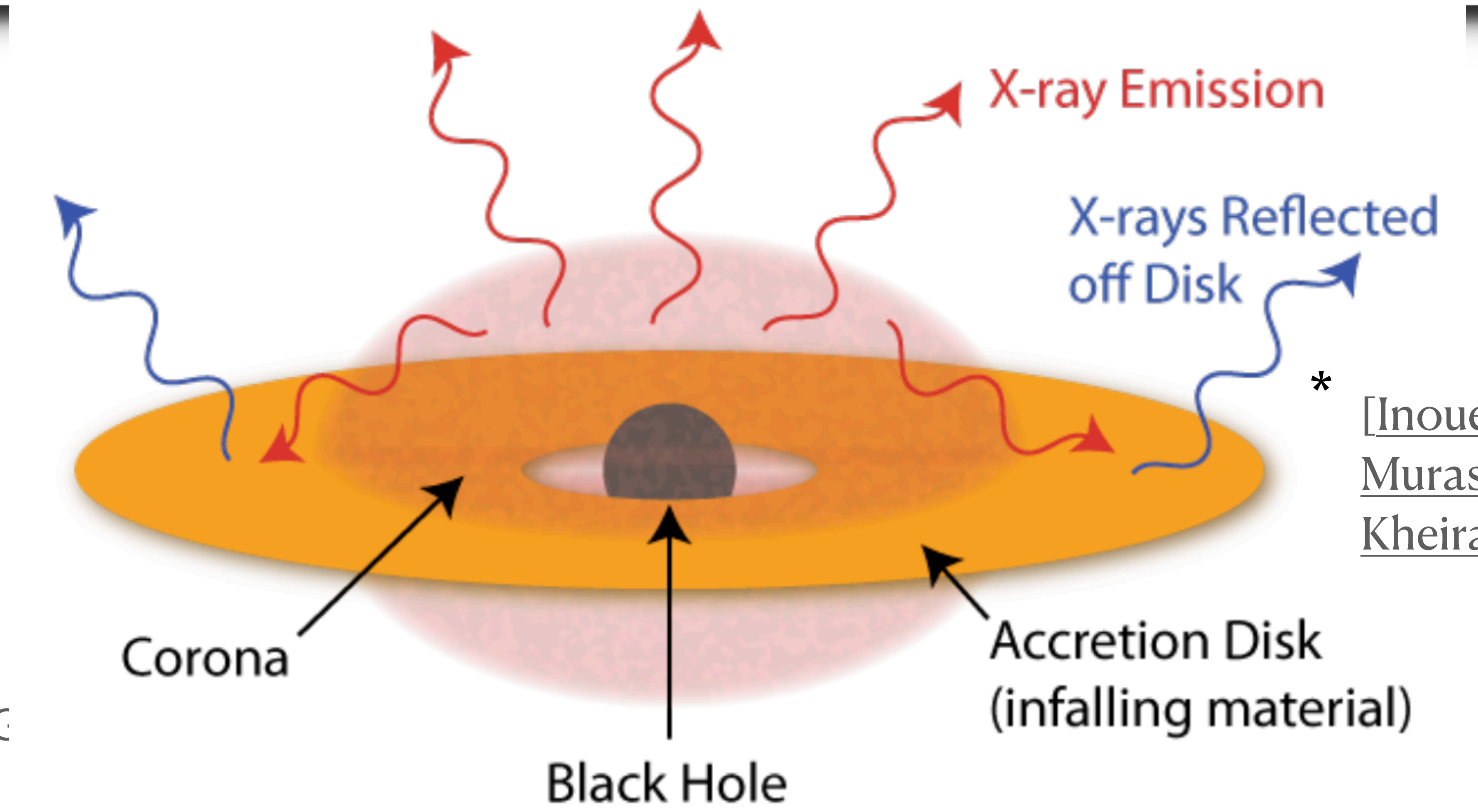
- Disk-Corona Model: a very dense, hot, turbulent region in the vicinity of the BH offers a suitable target for neutrino production and γ-ray absorption at the same time.



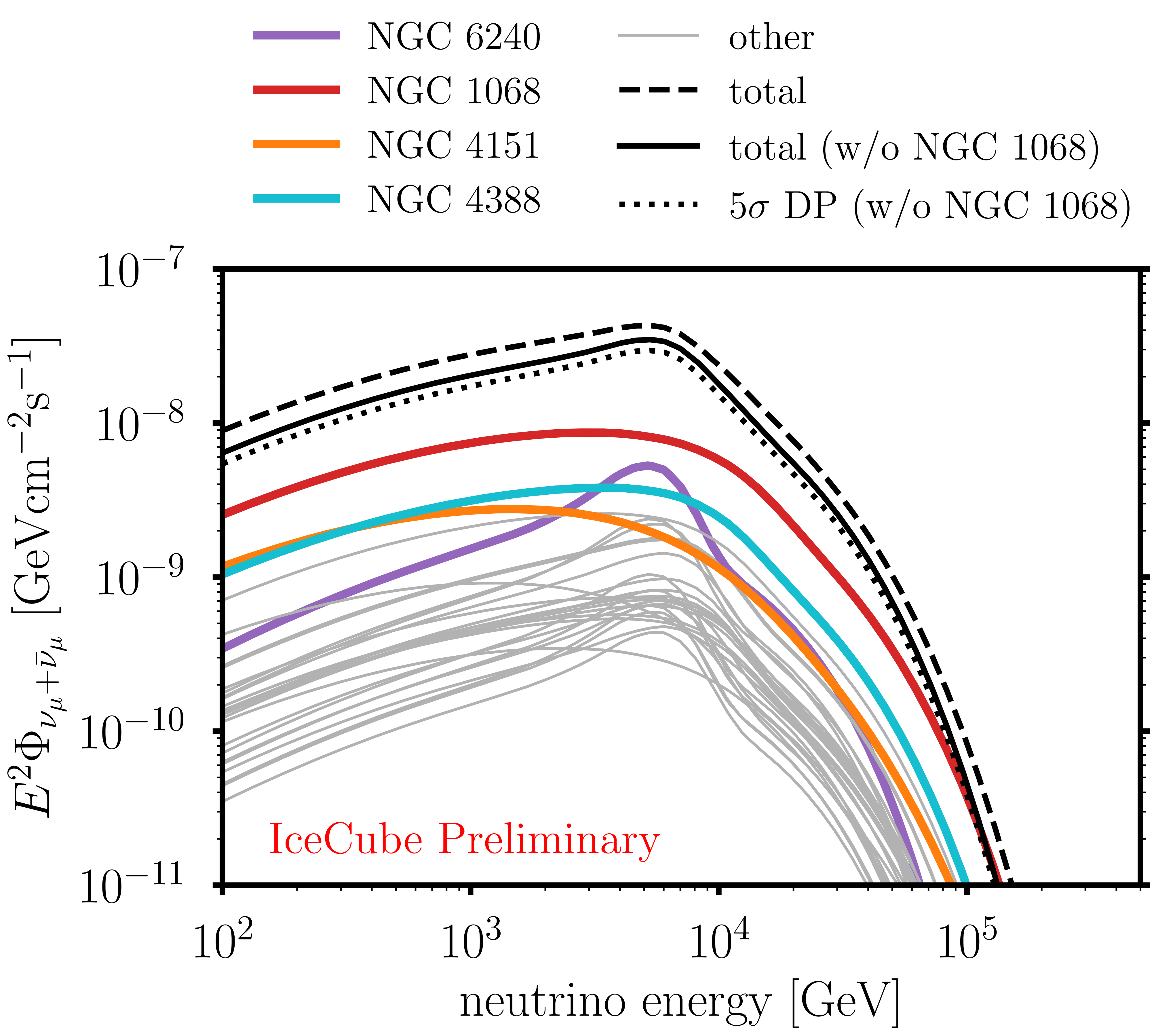
* [Inoue et al 2020 ApJL 891 L33, Murase et al 2020 PRL 125, 011101, Kheirandish et al 2021 ApJ 922 45, …]

Neutrinos from Seyfert galaxies

In the Northern sky of IceCube

- **Are other X-ray bright Seyferts emitting neutrinos too?**
- Select "bright" sources with intrinsic X-ray flux (2-10 keV from BASS - Ricci et al. 2017) at least 10% of that of NGC 1068 → 28 sources (including NGC 1068).
- Catalog search: **unbroken power-law** energy spectrum.
- Catalog and stacking searches: **disk-corona model in the optimistic high-pressure scenario** (Kheirandish et al. 2021)
  - Flux shape determined by L_X.
  - Normalization changes with the CR pressure.
  - All other parameters fixed to NGC 1068.

Disk-corona model expectation



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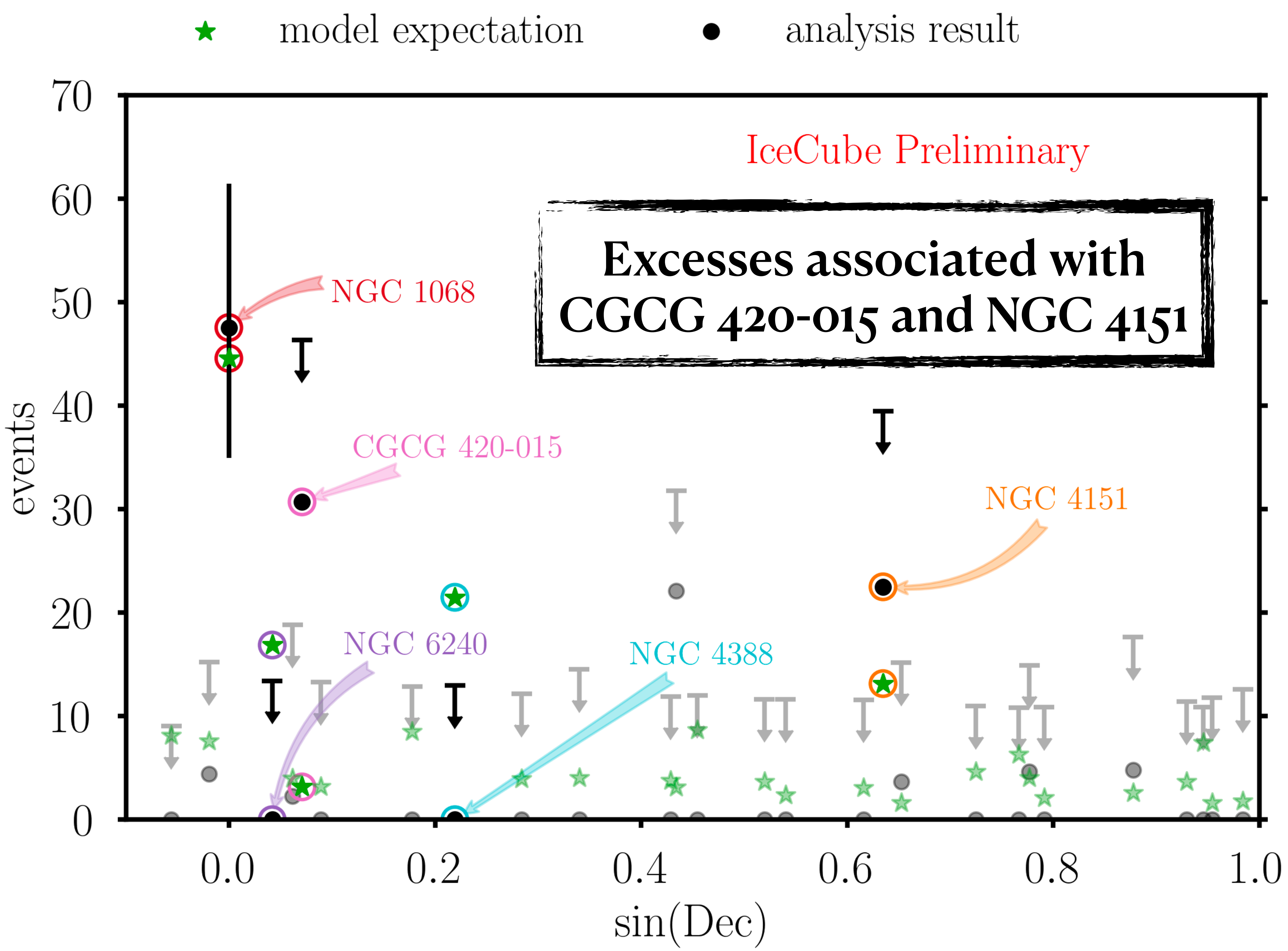

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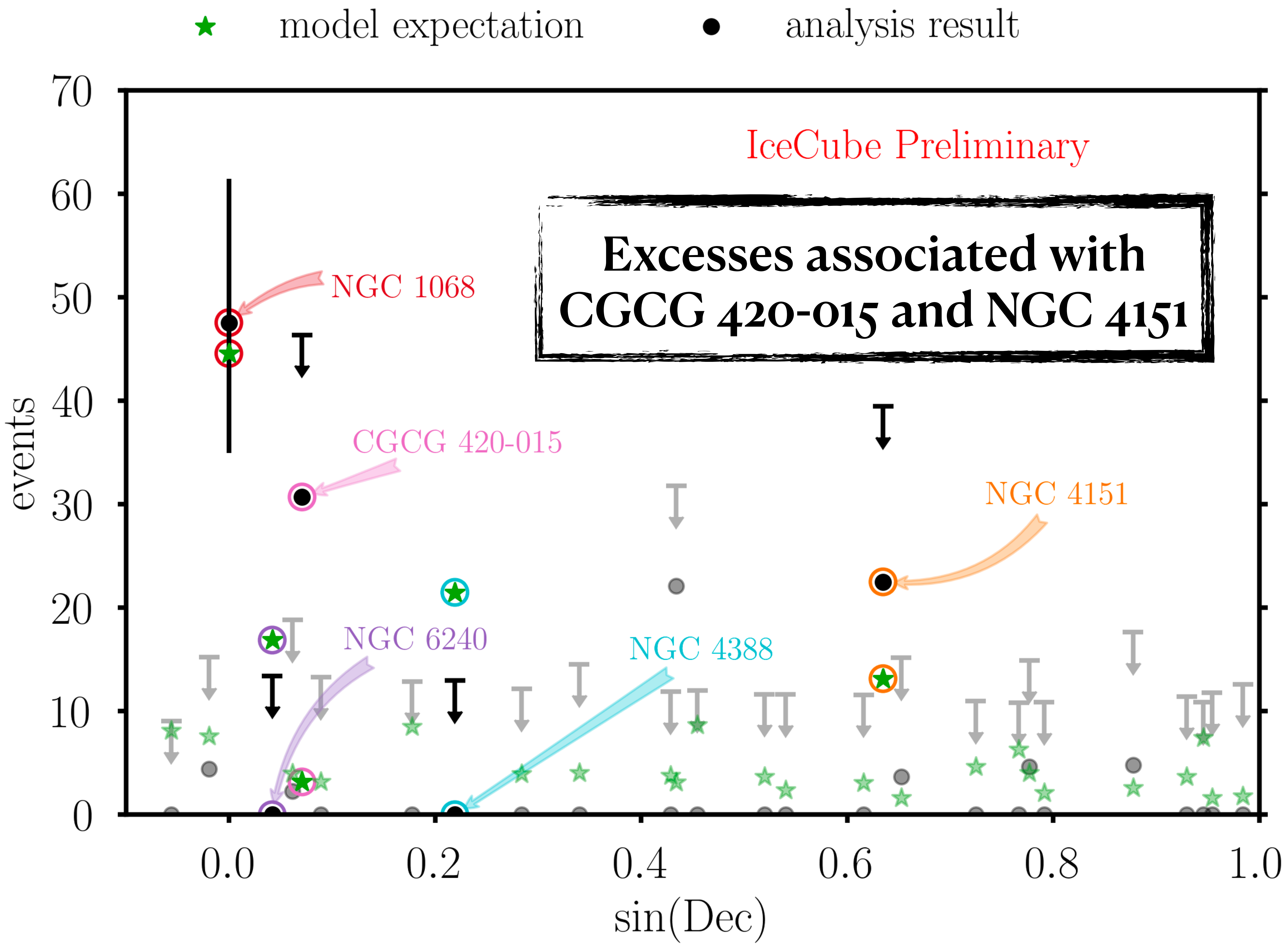
- Catalog search: 2.3σ from CGCG 420-015 assuming the disk-corona model.
- Binomial test: 2.7σ emission from 2/27 sources in the disk-corona model.
- Stacking search: Non significant result.



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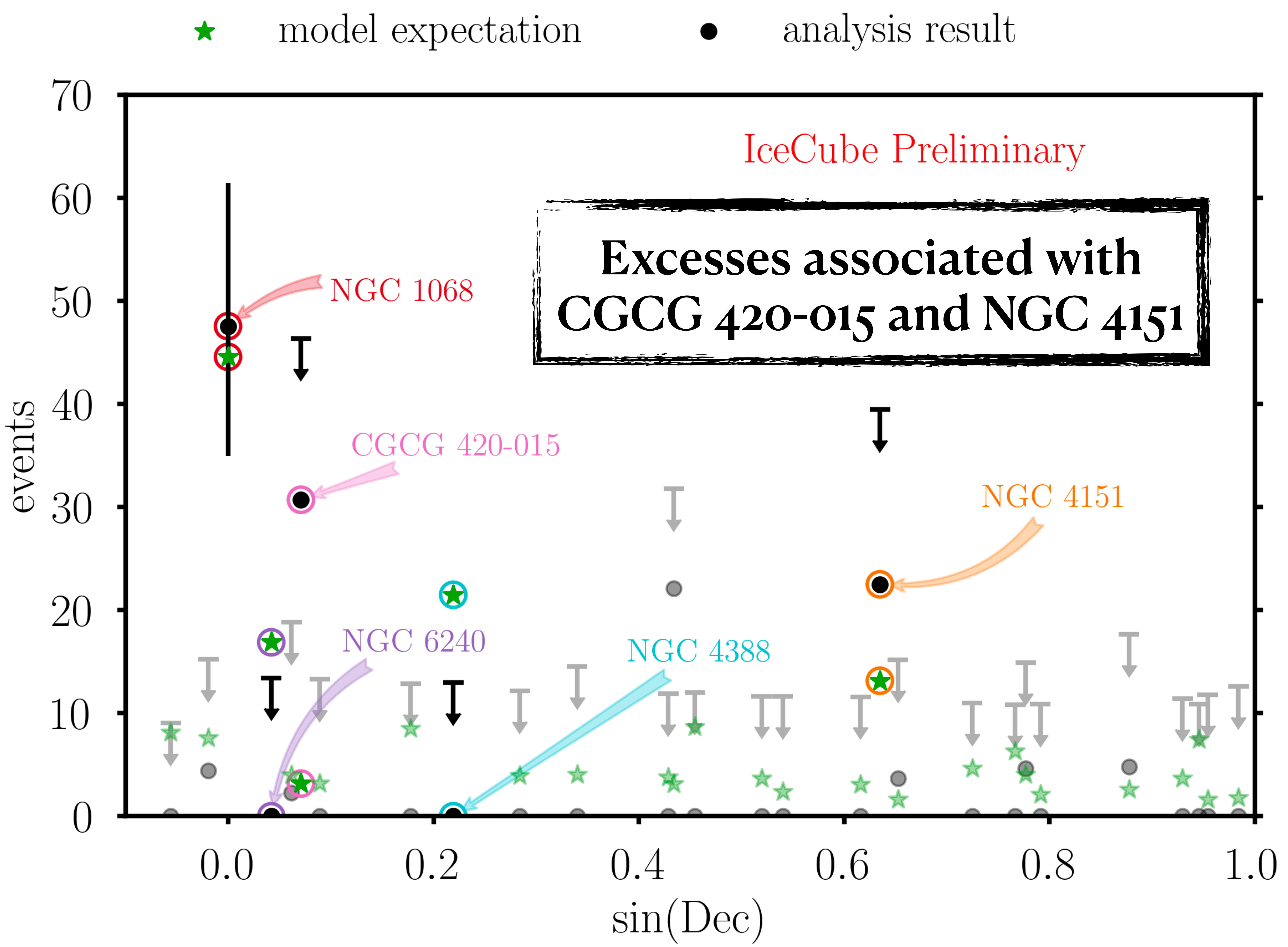

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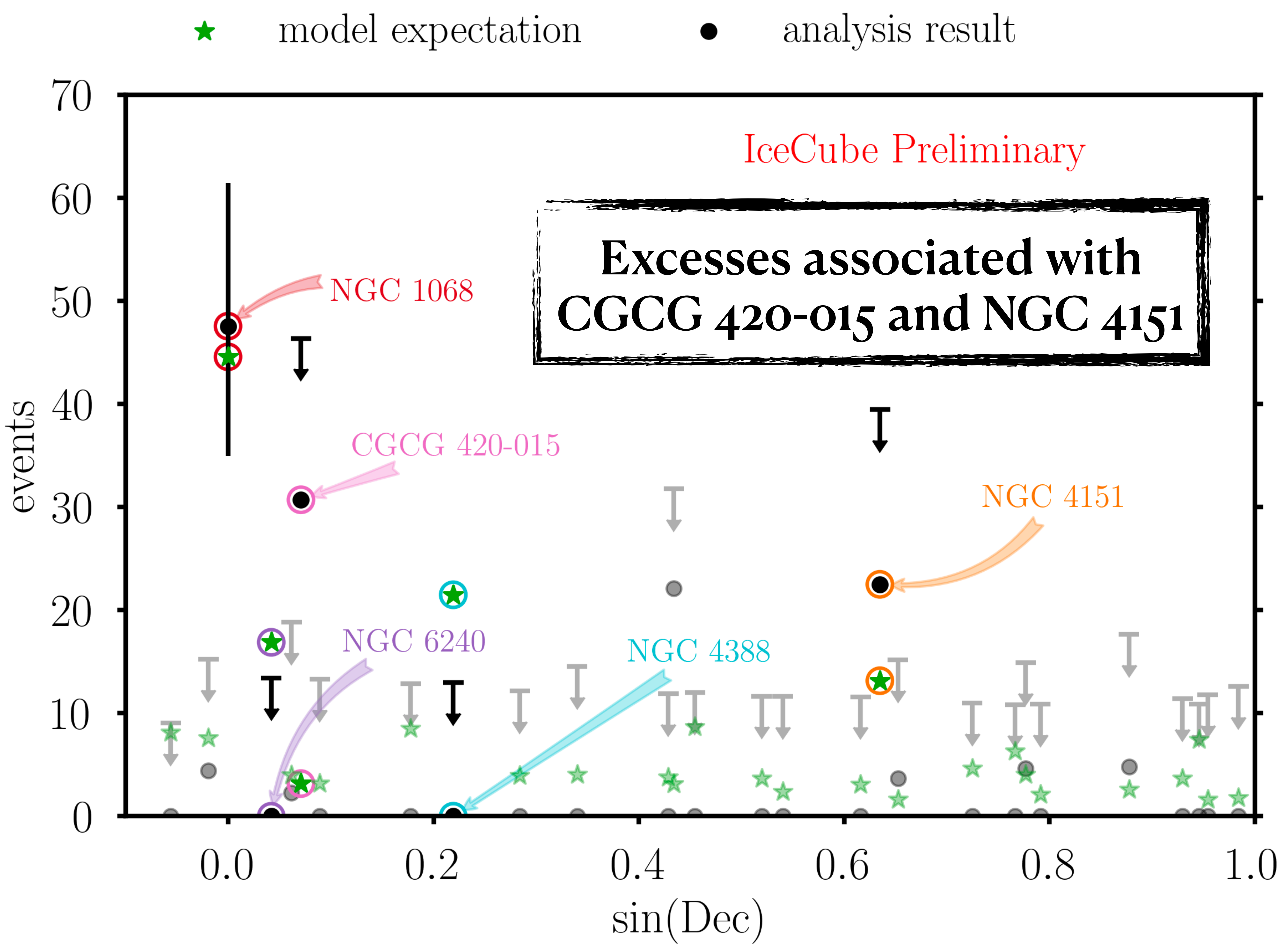
- **The model parameters that fit NGC 1068 don't describe most sources in the catalog.**
- However, **IceCube can find sources similar to NGC 1068!**



Neutrinos from Seyfert galaxies

Updated measurement of NGC 1068

- With ~1.5 more years of data, the emission from NGC 1068 has been measured again.
- The result is compatible with steady neutrino emission from this source: mean number of events in the detector increases from 79 to 94.

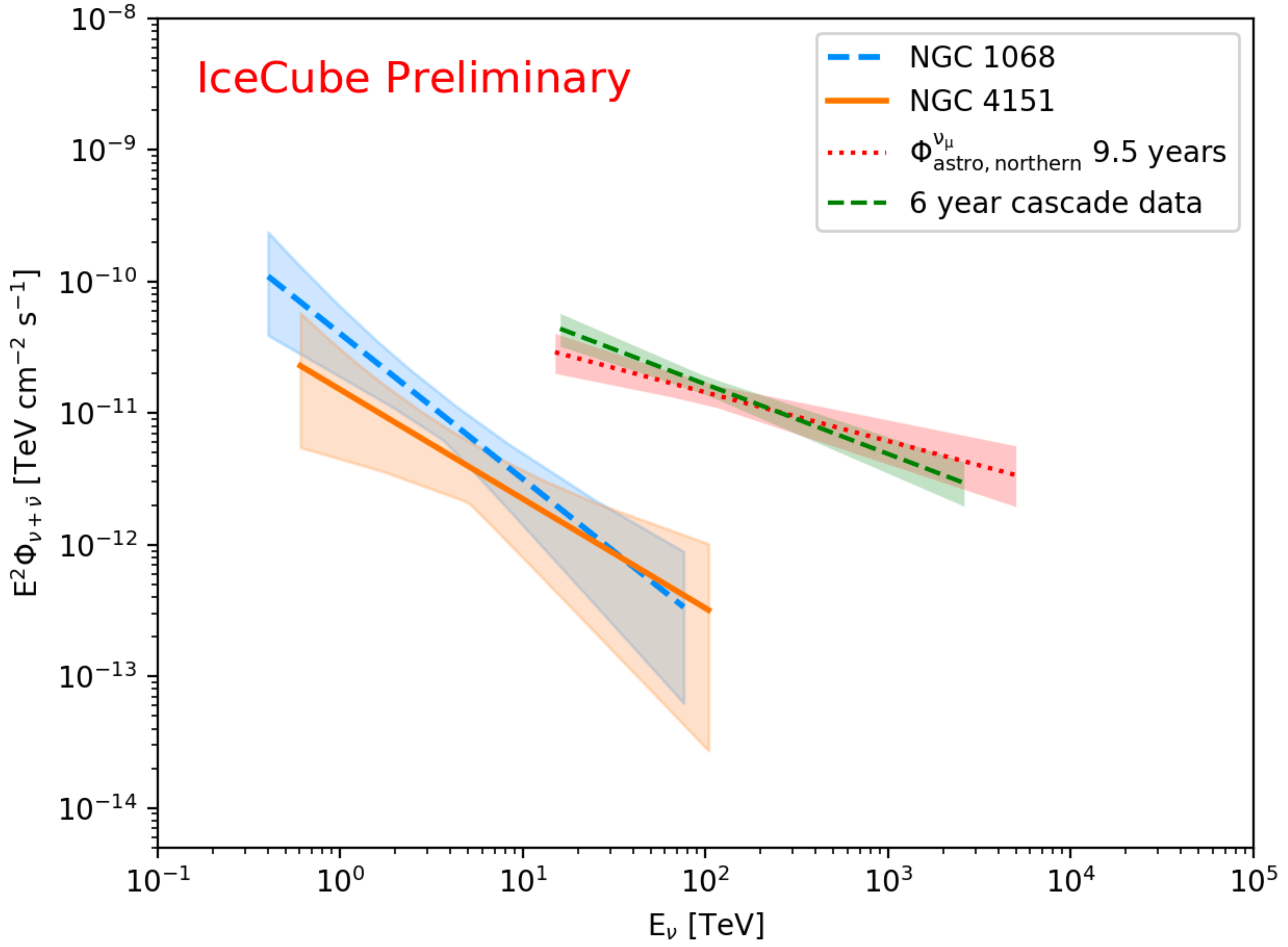
	spectral model	n_{exp}	TS	$\hat{n}_s$	$\hat{\gamma}$	p_{local}
NGC 1068 (*)	power-law	–	29.5	94	3.3	8.0×10^{-8} $(5.2\,\sigma)$

- We can correct the pre-trial significance for the same number of trials used before. A slight increase in the global significance is observed: 4.2σ → 4.3σ .

Neutrinos from hard X-ray AGN

NGC 4151

- **Can we identify AGN where γ-rays produced with the neutrinos cascade to hard X-rays?**
- 836 AGN sources from the BASS catalog (14-195 keV)
  - 104 blazars
  - 732 non-blazar (731 Seyferts, 1 uncertain)
- Stacking analysis assuming power-law spectral emission and with L_X-based weights: No significant result for any source classification.
- Catalog search: sub-select 43 sources (including NGC 1068) based on IceCube's sensitivity. Excess from NGC 4151 at 2.9σ.

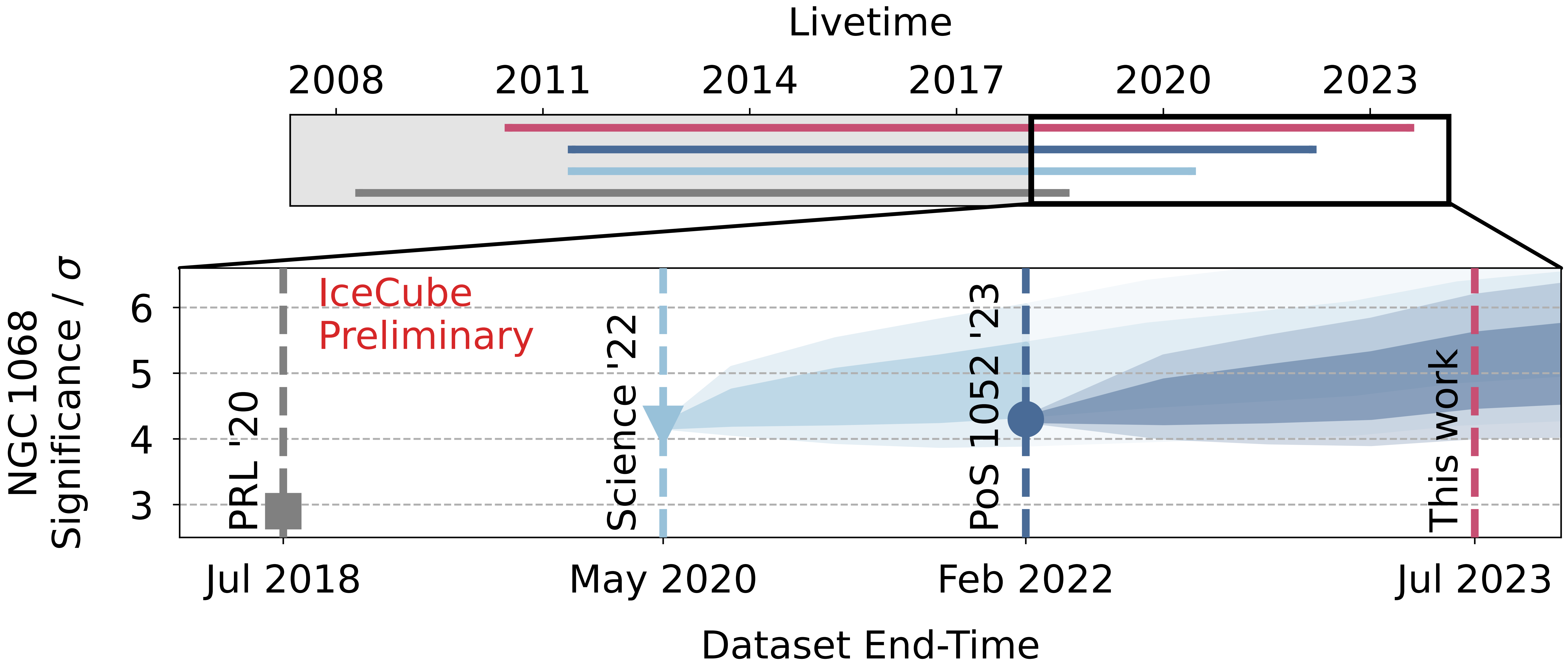


ALERT: This analysis uses a different dataset compared to the Seyfert analysis. They aren't directly comparable.

Happening soon!

Update the Northern sky scan with 4 more years of IceCube data

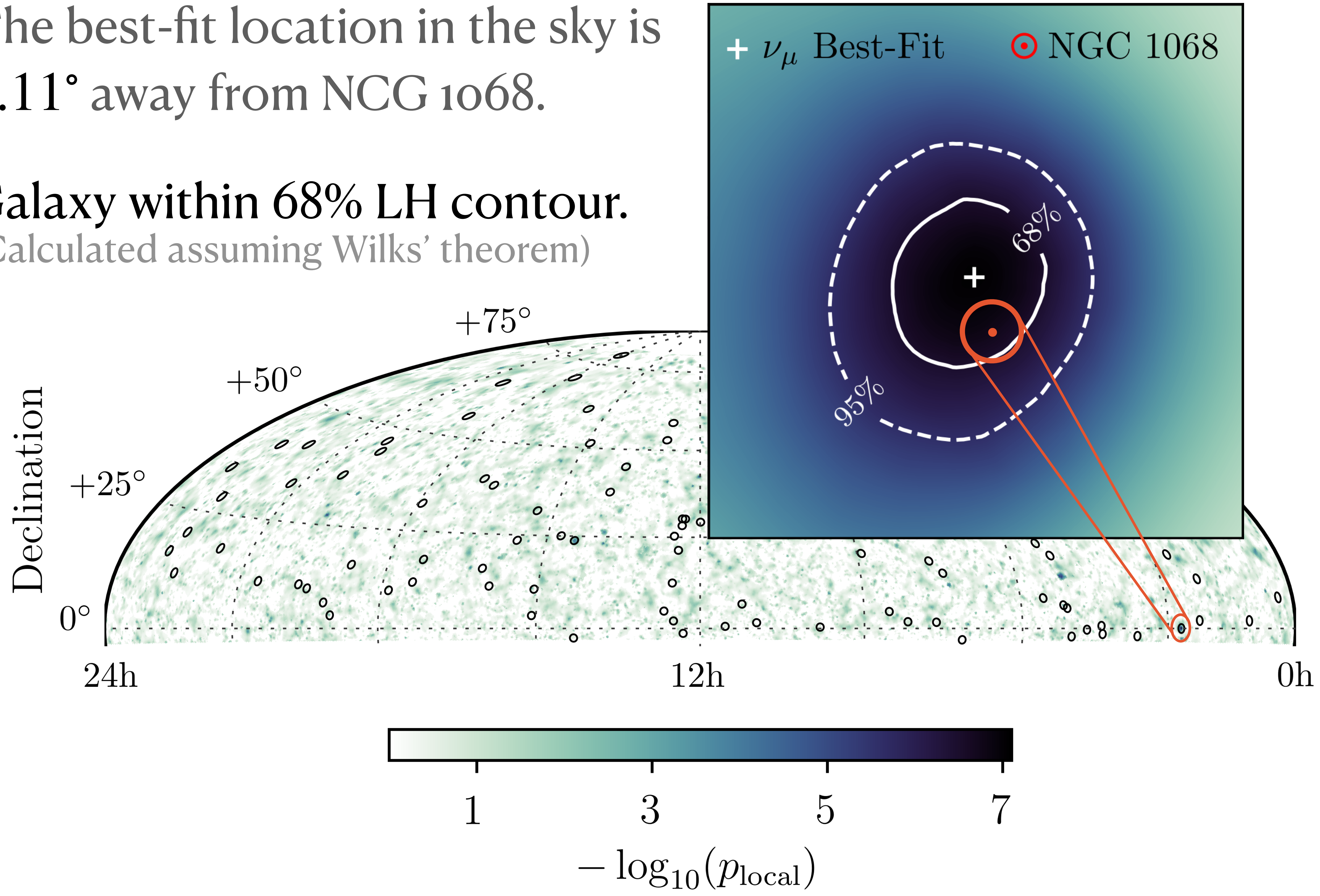
- Preparing an update to the **Northern sky scan using 4 more years of data**.
- **20% — 30% improvement in discovery potential** across the entire sky.
- According to the most recent measurement of the neutrino flux from NGC 1068 and assuming steady neutrino emission, we expect the **significance of the brightest Seyfert to fall between 4.5σ and 5.5σ (68% C.L.)**.



The neutrino production region

We need higher resolution

- The best-fit location in the sky is 0.11° away from NCG 1068.
- Galaxy within 68% LH contour.
  (Calculated assuming Wilks' theorem)



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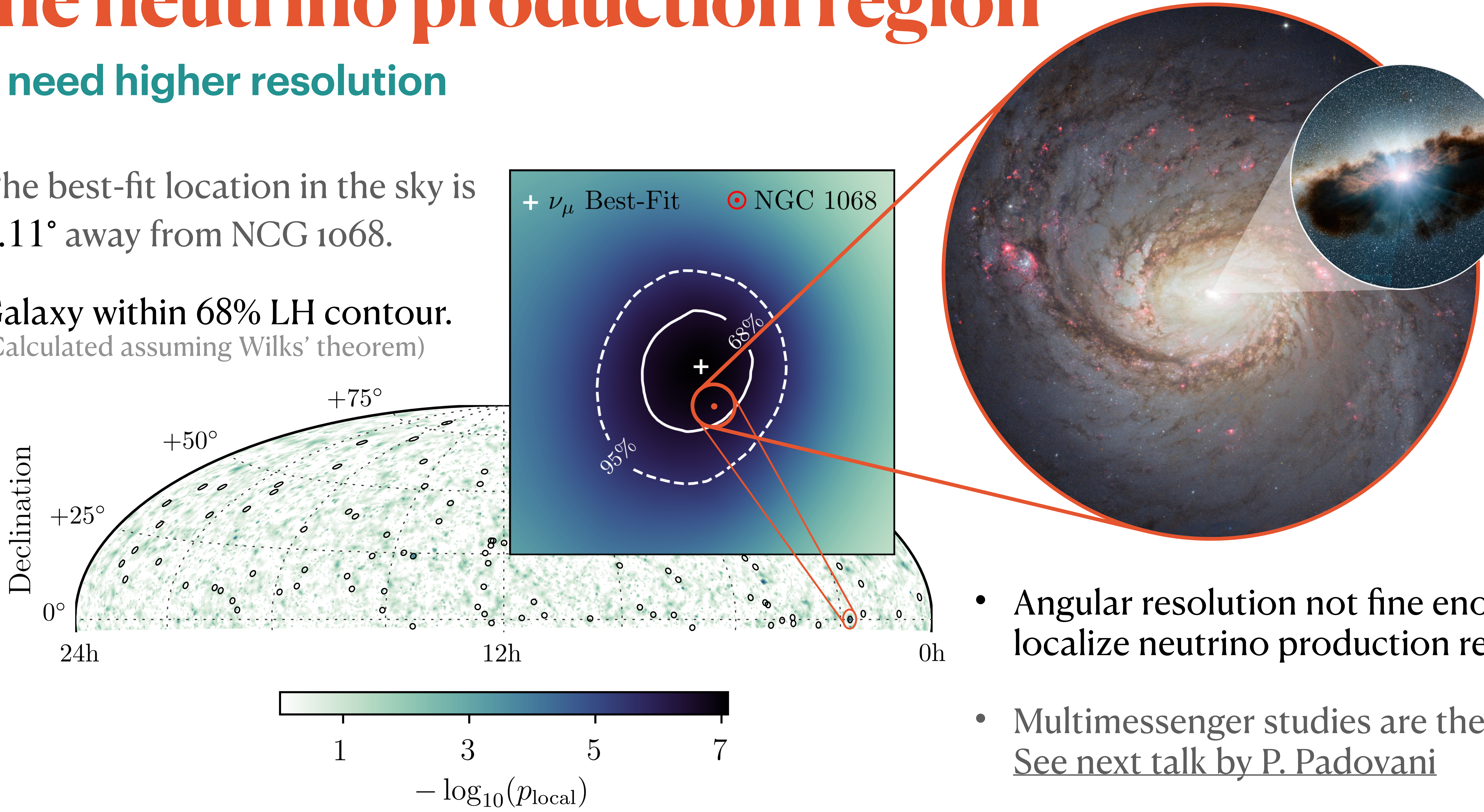


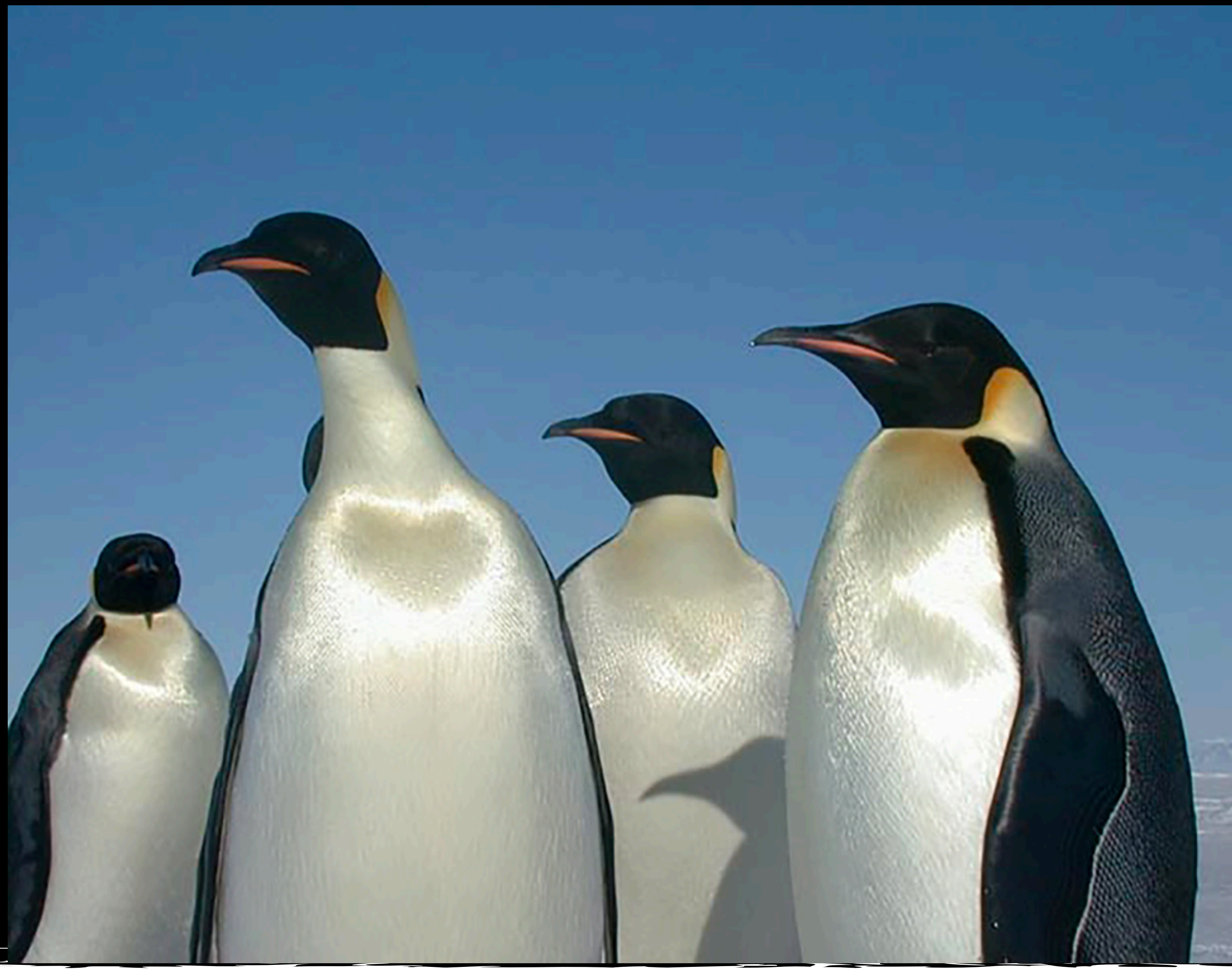
- Angular resolution not fine enough to localize neutrino production region(s).
- Multimessenger studies are the key!
  See next talk by P. Padovani

In summary

We are learning something new

- The Seyfert 2 NGC 1068 is the brightest source in the Northern sky of IceCube: currently at 4.3σ.
- The neutrino flux outshines the γ-ray flux by over an order of magnitude: hidden neutrino source!
- A dense, hot, turbulent "corona" close to the BH can provide efficient ν production and γ-ray opacity.
- IceCube can identify other AGN that seem to be similar to NGC 1068:
  - CGCG 420-015 and NGC 4151 at 2.7σ from a search for neutrino emission from bright X-ray Seyferts
  - NGC 4151 at 2.9σ from a search for neutrino emission from hard X-ray AGN (all-sky).

IceCube can't resolve what region in the galaxy produces neutrinos.
We need to look at the multimessenger picture! (see next talk!)



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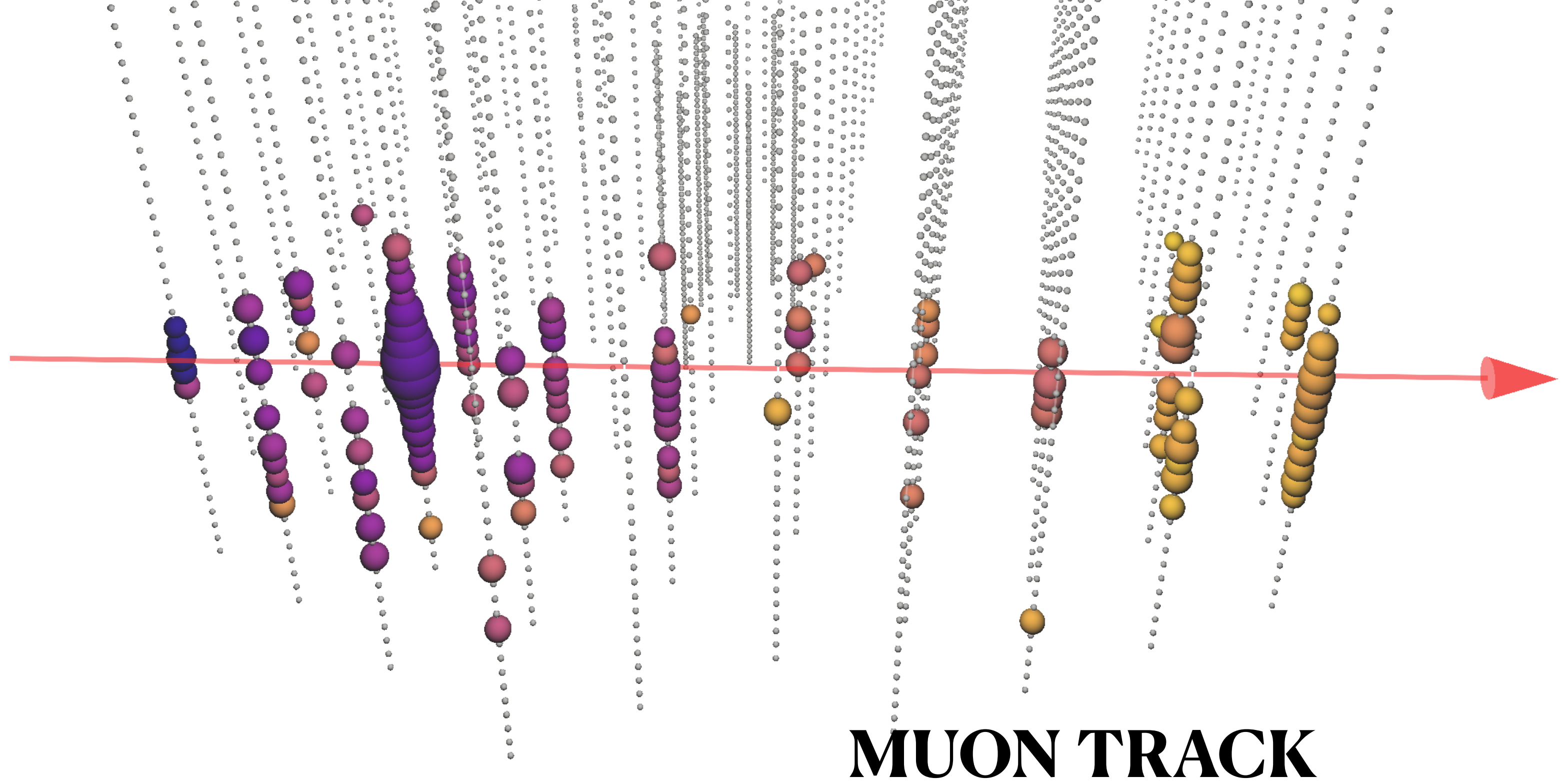
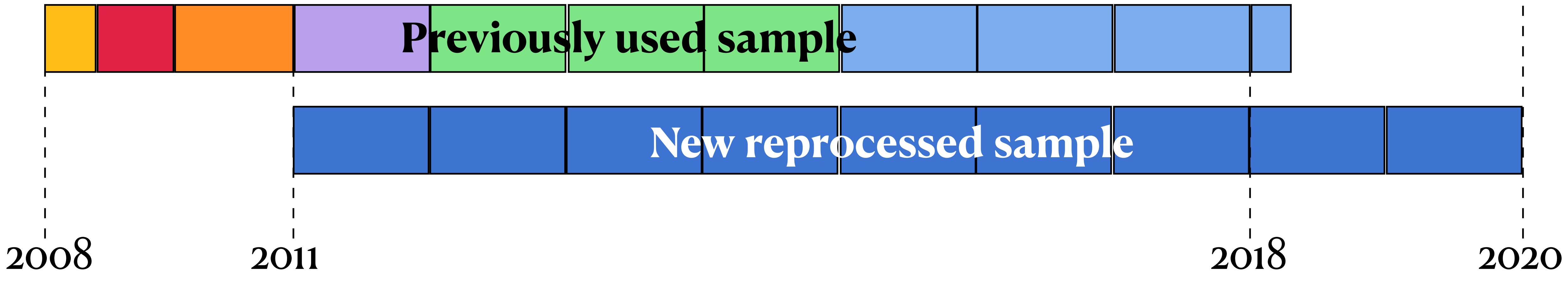
Backup

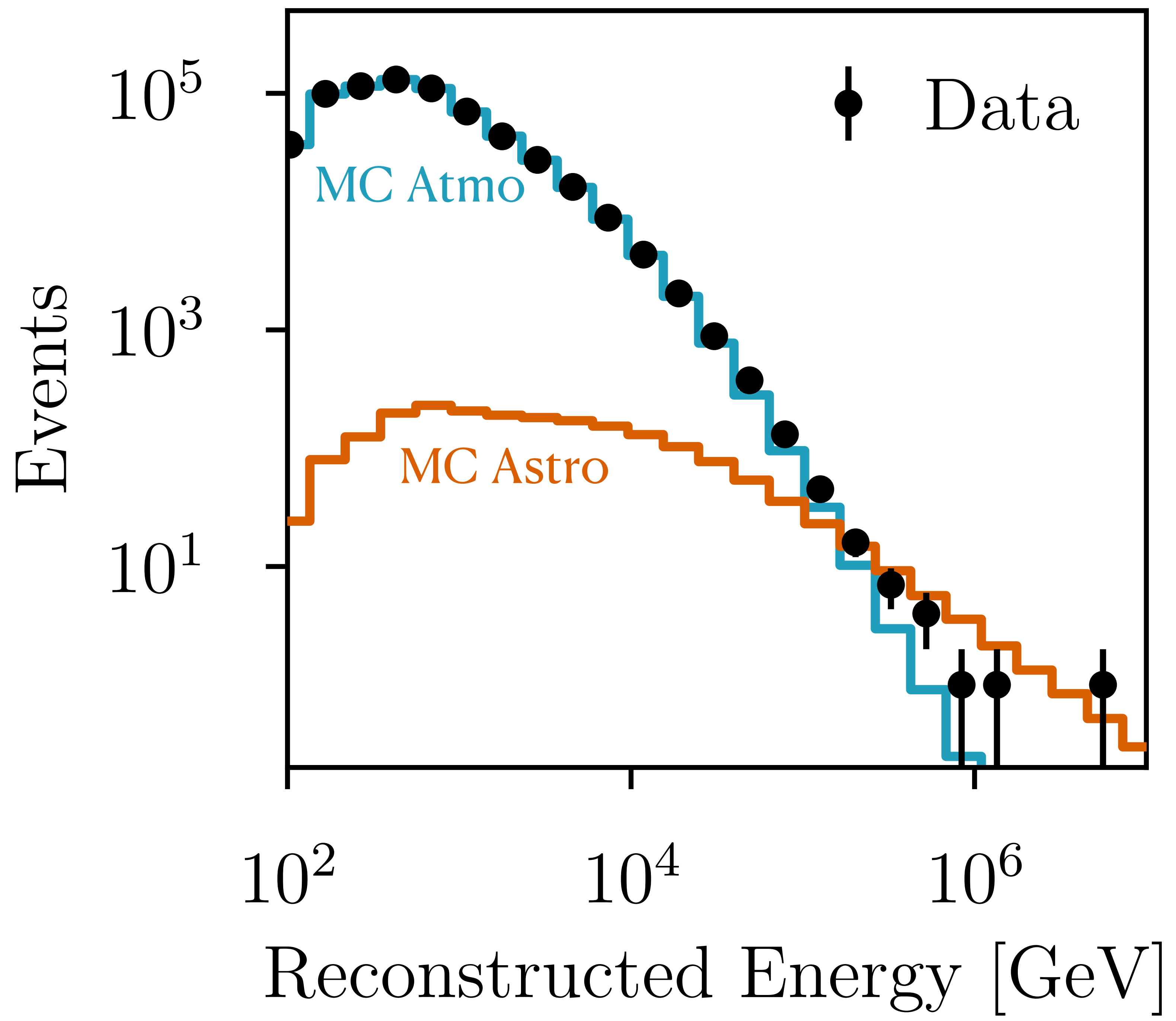
Improved point-source analysis

Dataset and detector calibration



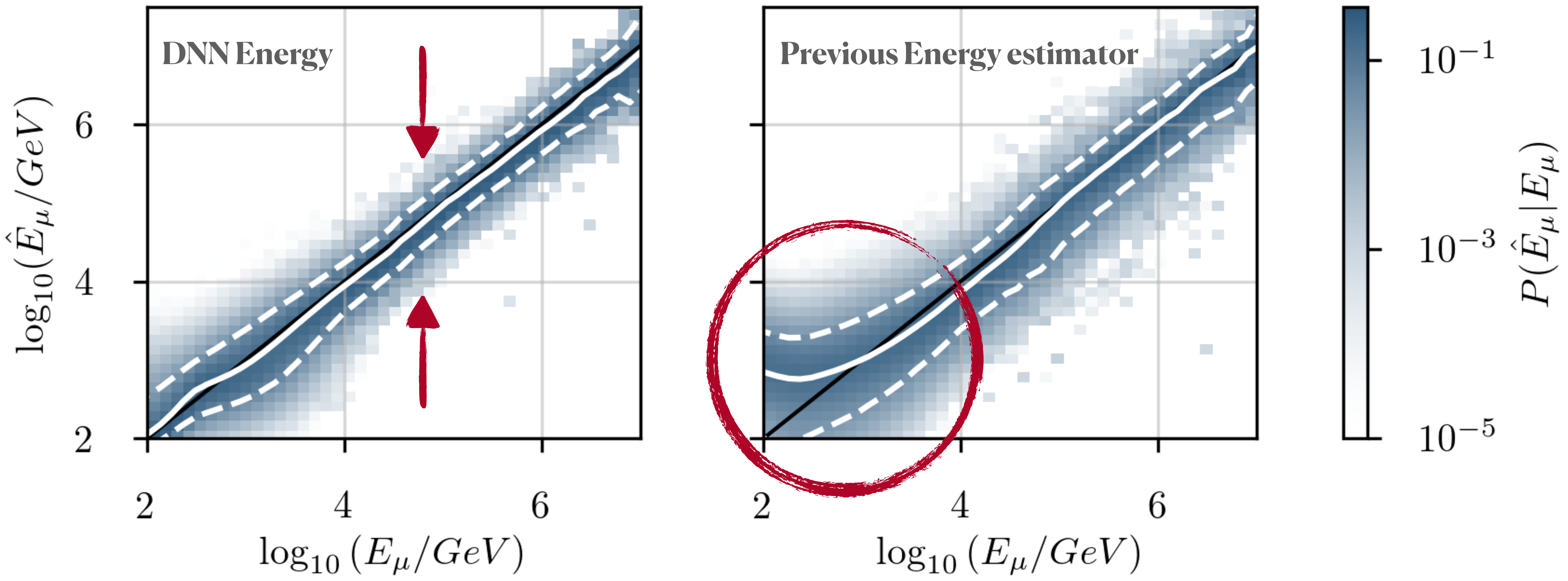
- **9 years** of track-like events (angular resolution < 1° at E > 1TeV) from the **northern sky** (atmospheric muon background suppressed).
- Data-taking in **full detector** configuration with **~99% detector uptime**.
- **~670'000 events between 100 GeV and 6 PeV.**
- **Improved and homogeneous detector calibration and data processing.**





Improved point-source analysis

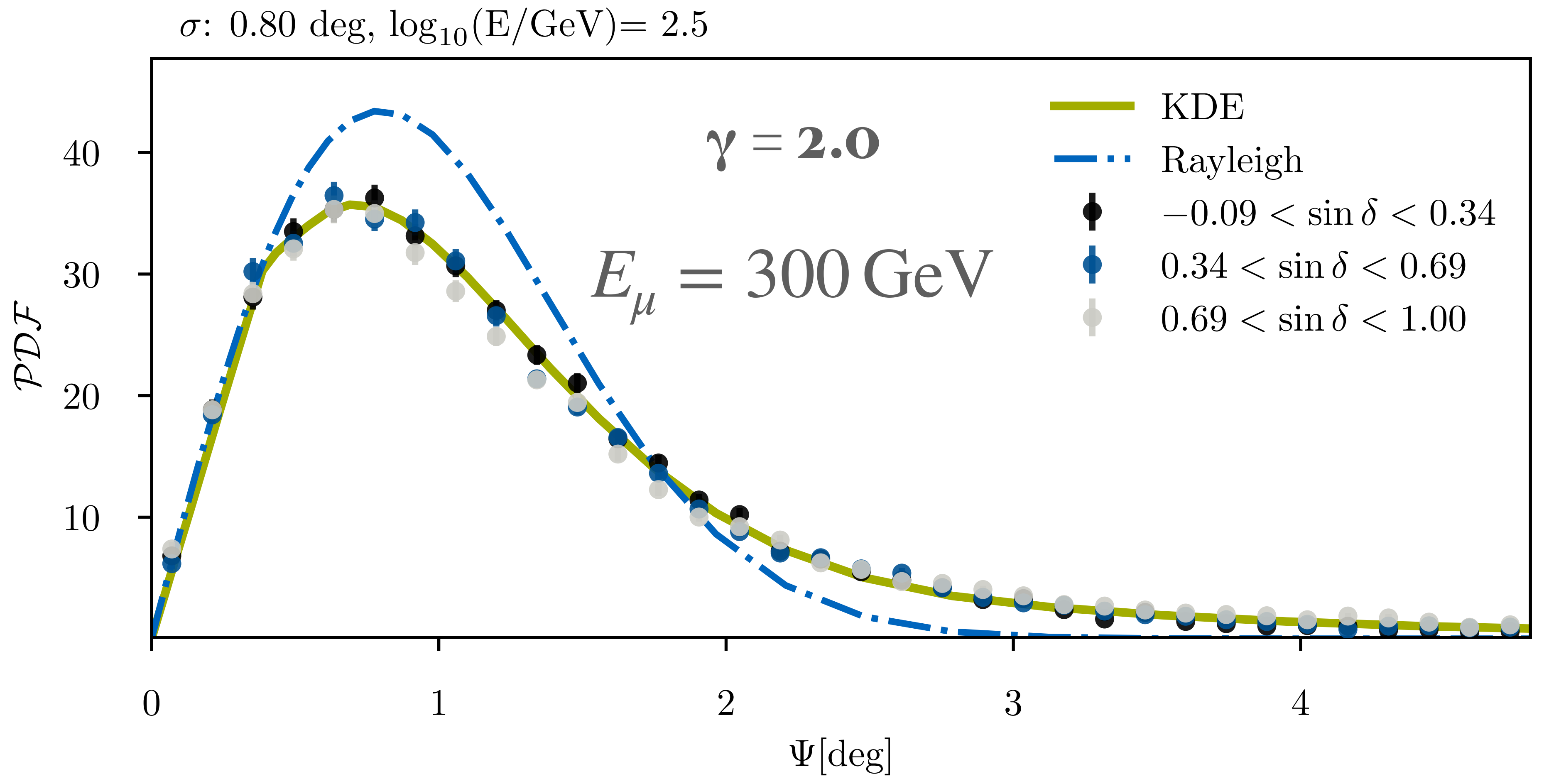
New reconstructions using machine learning techniques

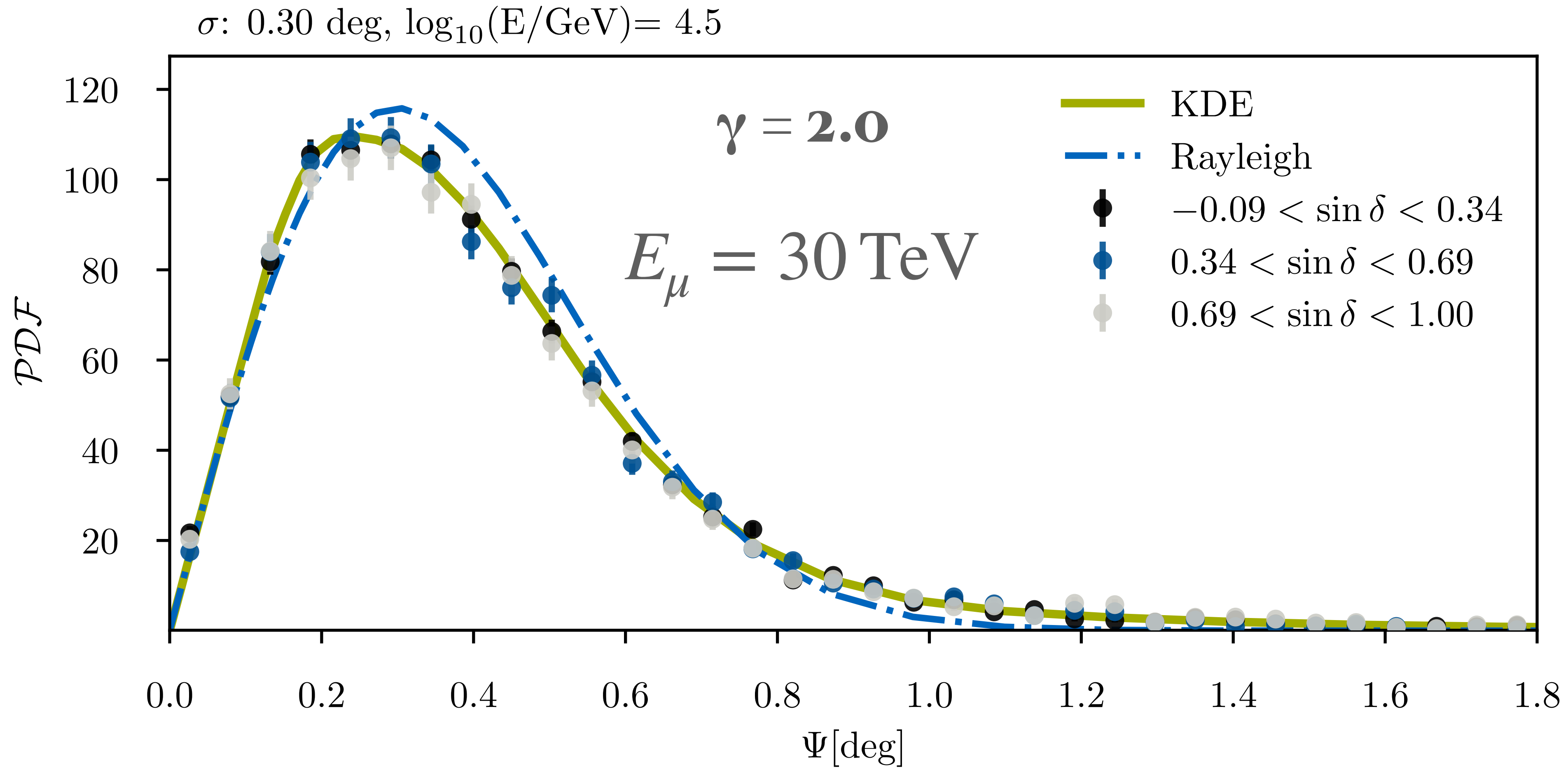


- **Deep Neural Network energy estimator:**
  - Improves resolution by >30% above 10 TeV.
  - Resolves muon energy degeneracy below 1 TeV.
- Produces **better background-signal separation**, especially at low energies.

Improved point-source analysis

Modeling the PSF from the simulations





Previously used analytic approximation: $f^{spatial}_{Gaus} = \frac{1}{2\pi\sigma} e^{-\frac{\Psi^2}{2\sigma^2}}$

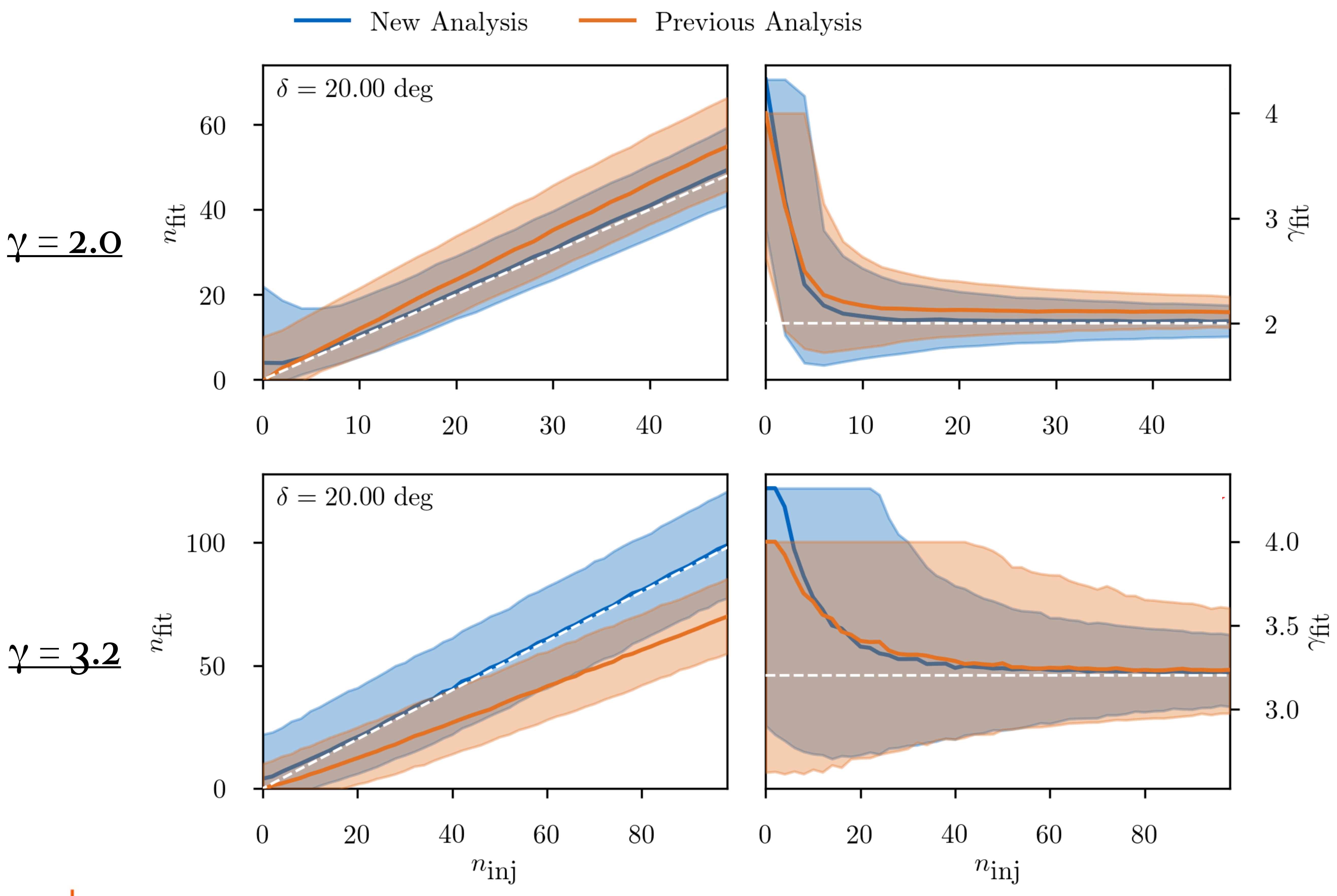
- Previously used: Rayleigh (1D-projection of 2D Gauss) doesn't describe our simulations properly, especially for low energy events!

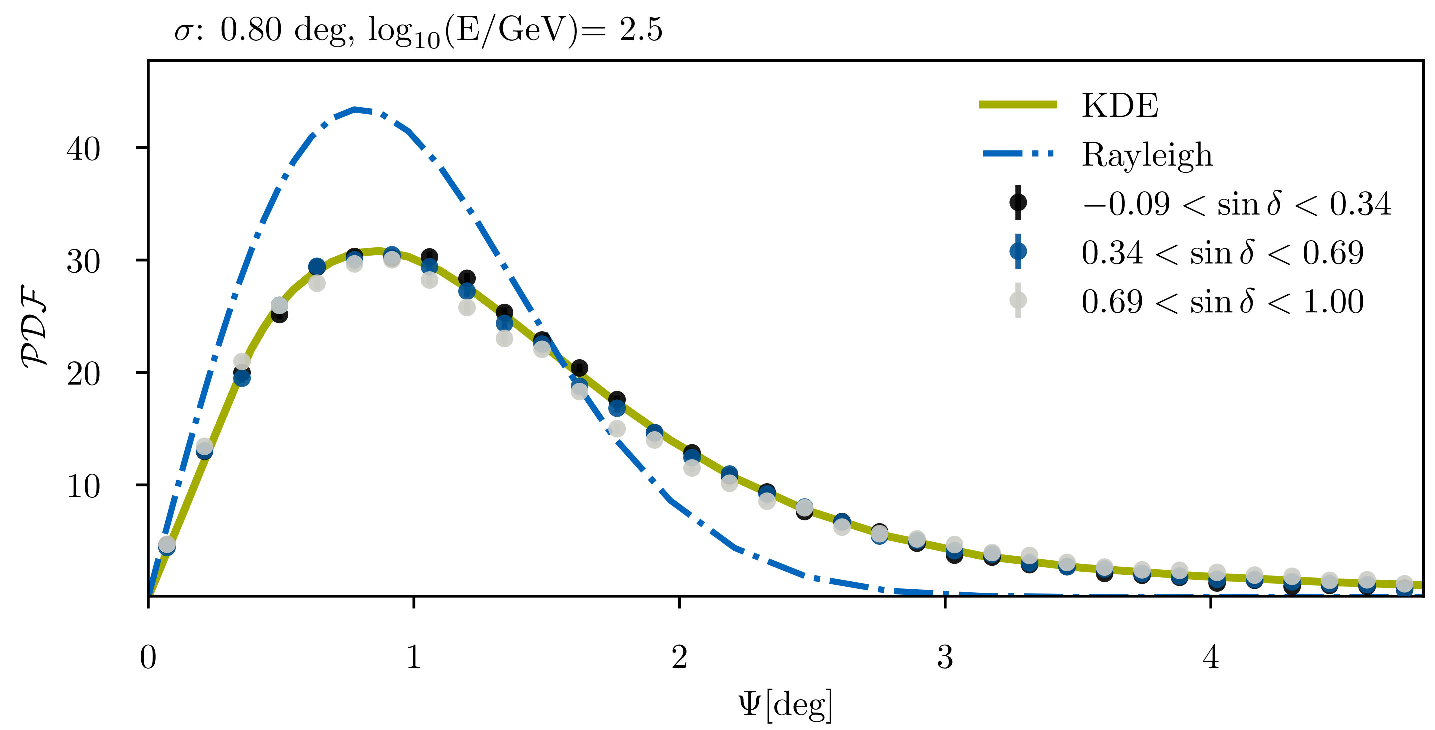
New MC-based construction: $f^{spatial}_{KDE} = \frac{1}{2\pi \sin\psi} f_s(\psi \mid E_\mu, \sigma, \gamma)$

- Numerical non-parametric construction of the PDFs based on MC using Kernel Density Estimation (KDE).

Improved point-source analysis

Robust and reliable characterization of the source flux





- Unbiased estimates of the MLE, thanks to a precise description of the PDFs.
- Soft spectra: the coverage of the long tail of the pdf recovers many low-energy events.
- The improved energy estimation produces better-constrained soft spectral indices.
- **Overall, the new analysis can reliably characterize the source spectral emission!**