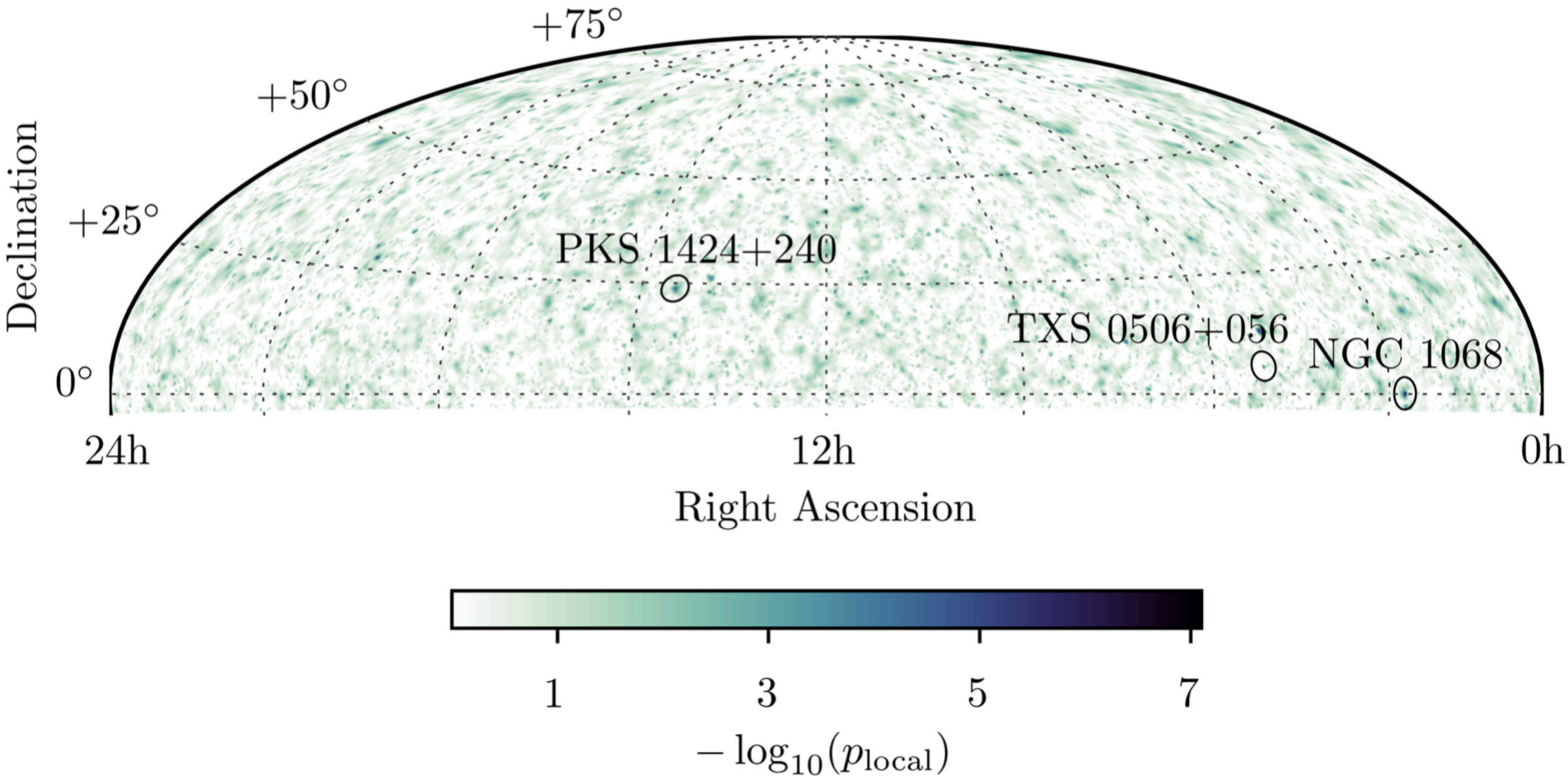
# Multimessenger Characterization of High-Energy Neutrino Emission from the Brightest Neutrino-AGN

**Ali Kheirandish**
University of Nevada, Las Vegas

in collaboration with Jose Carpio & Kohta Murase
*ApJ* 1005 (2026) 1, 61

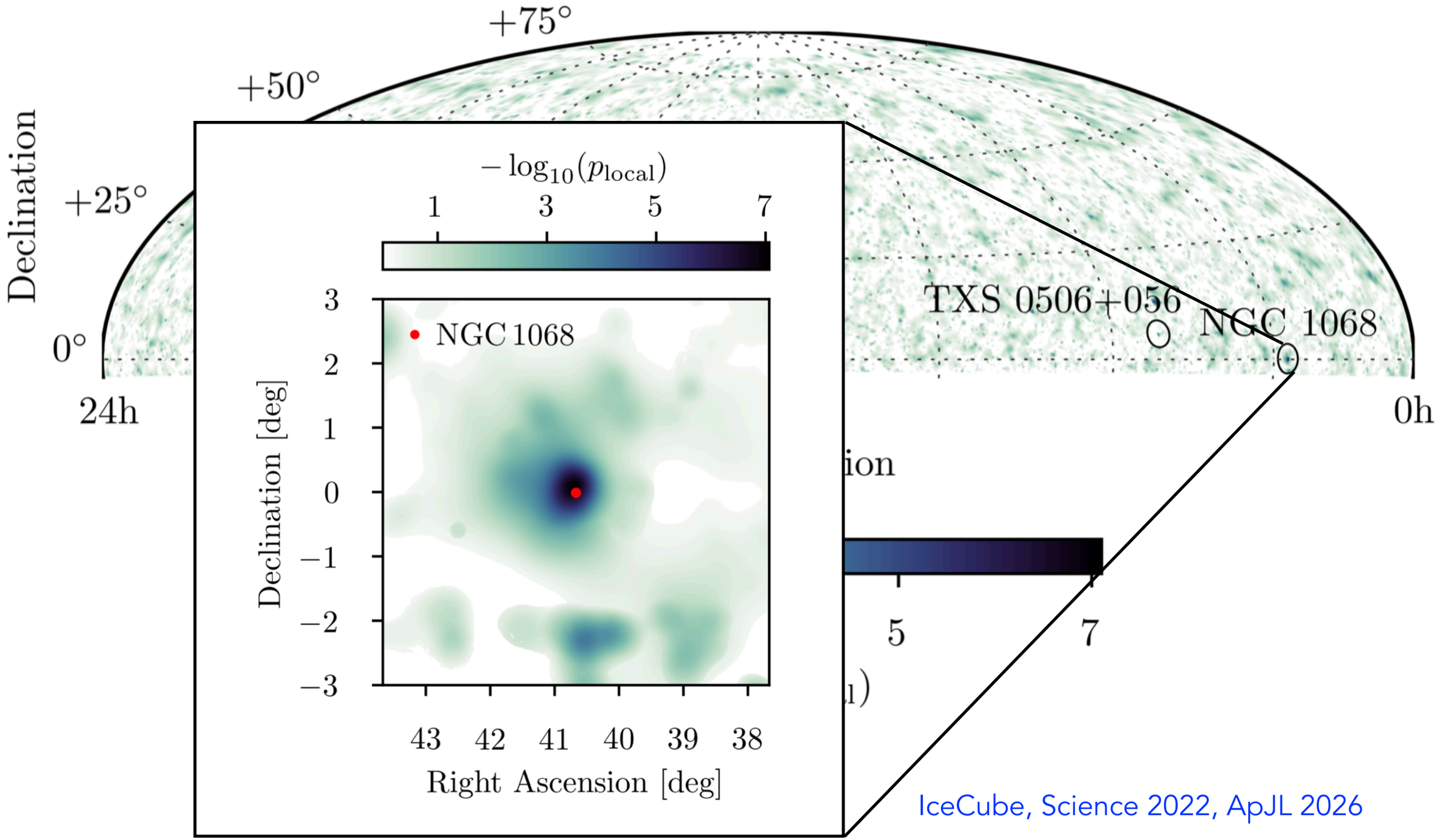
IPA 2026
UW - Madison

# NGC 1068; Brightest Source in Nu Sky




IceCube, Science 2022, ApJL 2026

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IceCube, Science 2022, ApJL 2026

# NGC 1068

Image Credit: NASA, ESA

# NGC 1068

- NGC 1068 is a Seyfert 2 galaxy with a heavily obscured nucleus
- One of the best studied Active Galactic Nuclei (AGN), which played a major role in AGN unification scheme

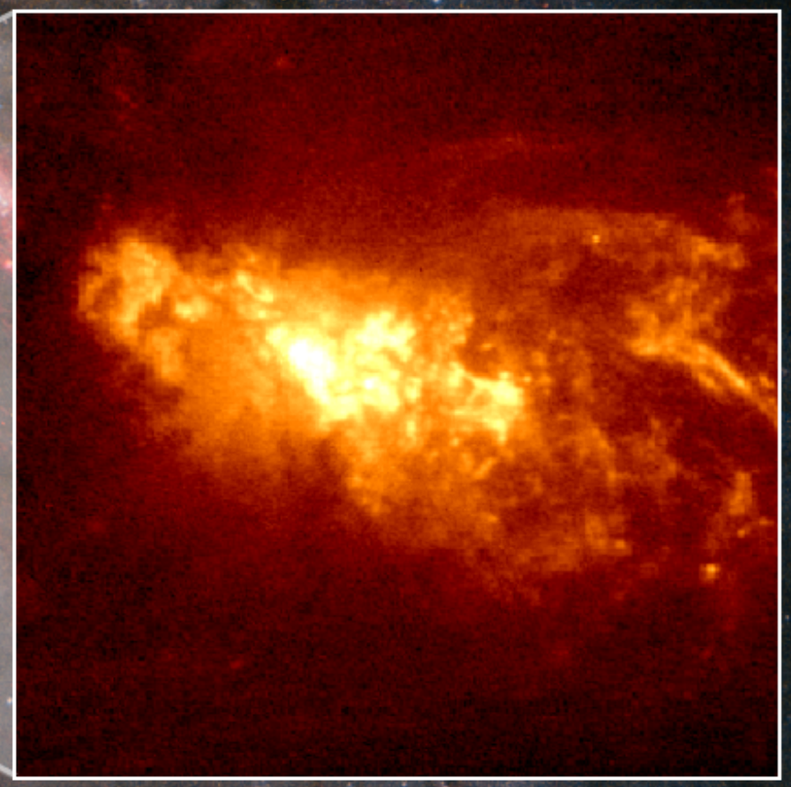
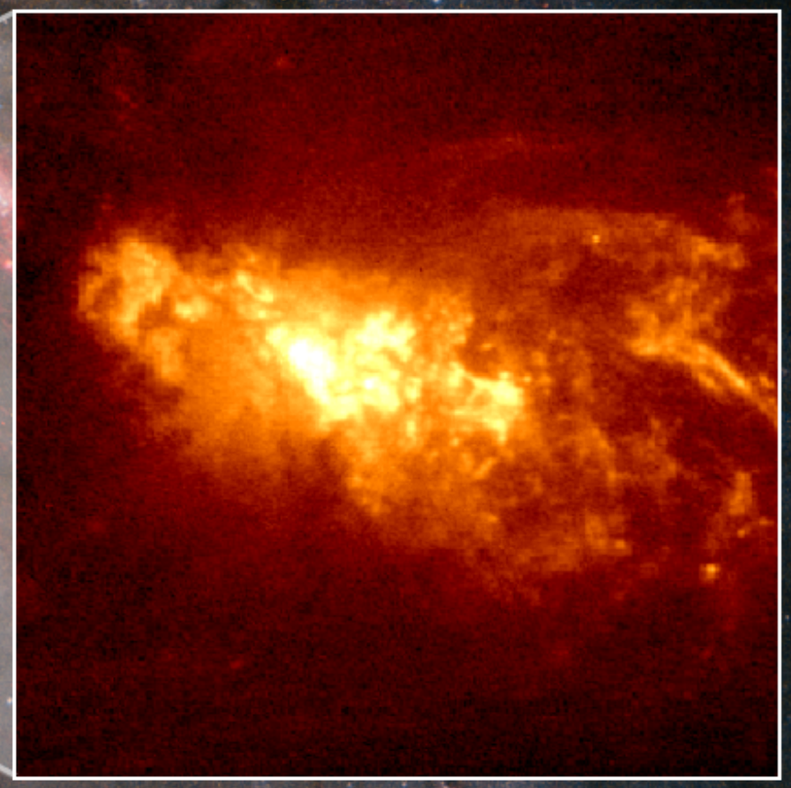


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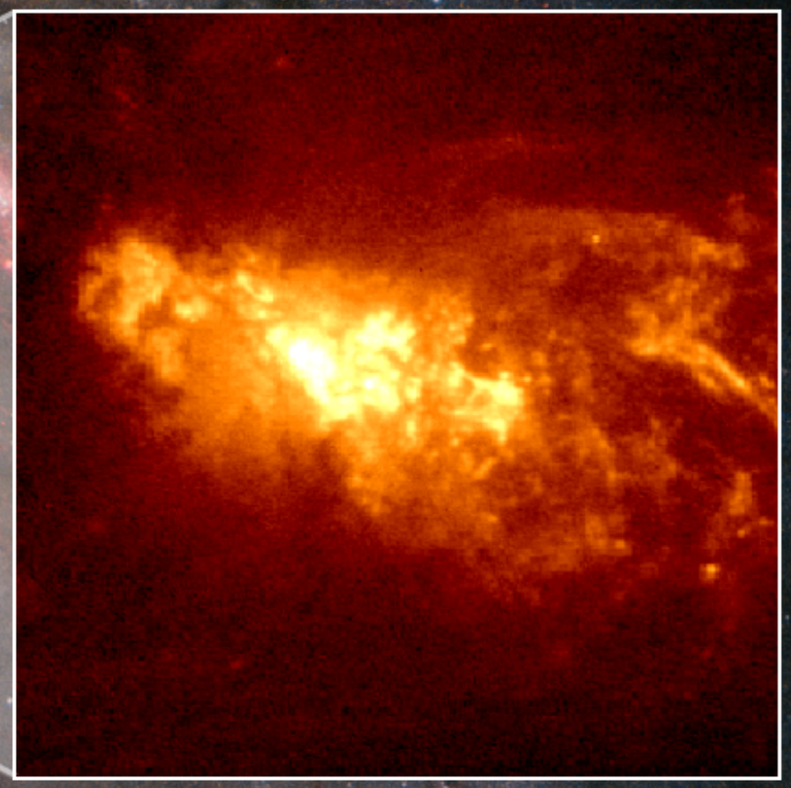


- Compton thick environment with Column density ~ $10^{25}$ $cm^{-2}$
- Bright in X-ray, and high infrared luminosity indicating high level of star formation

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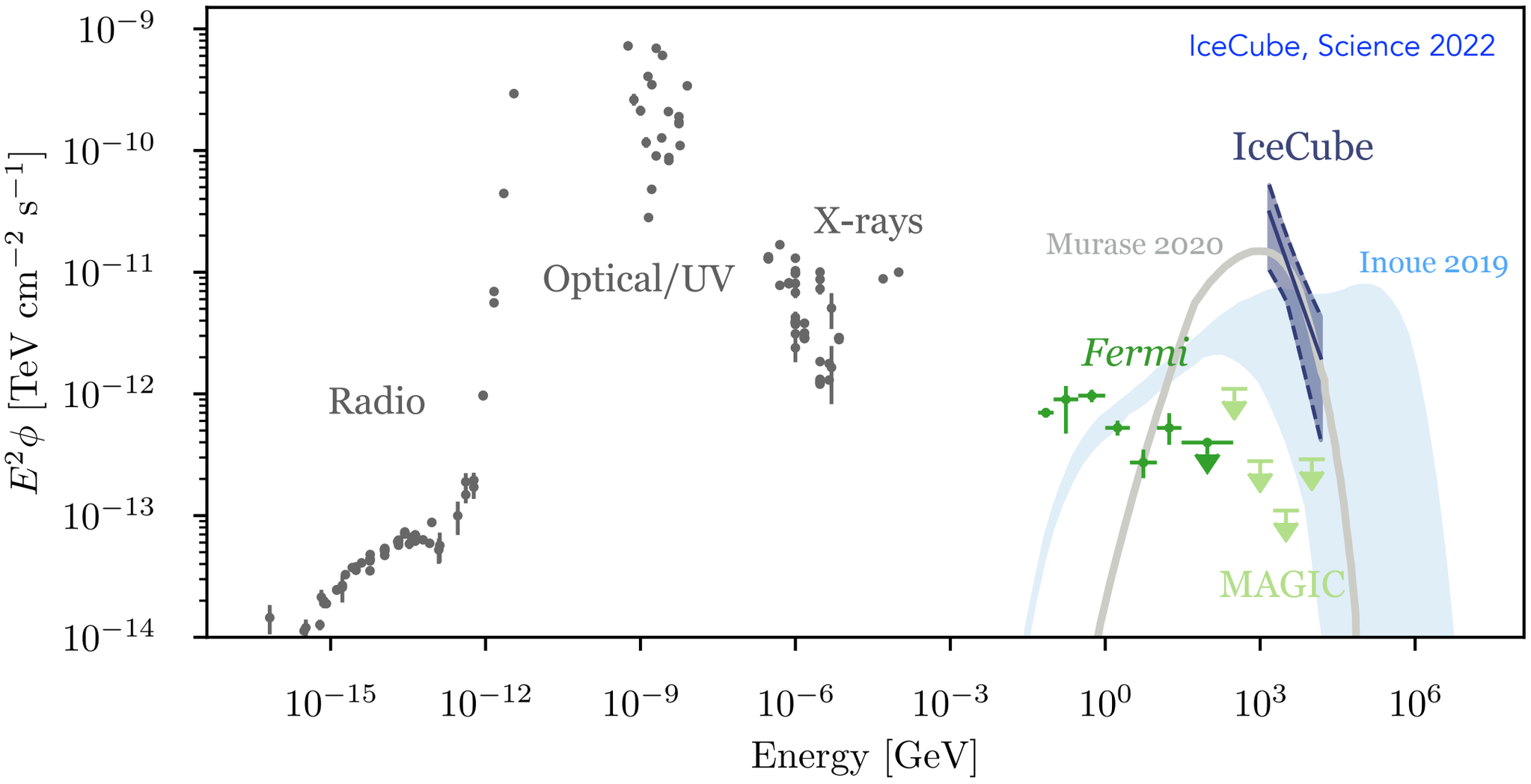
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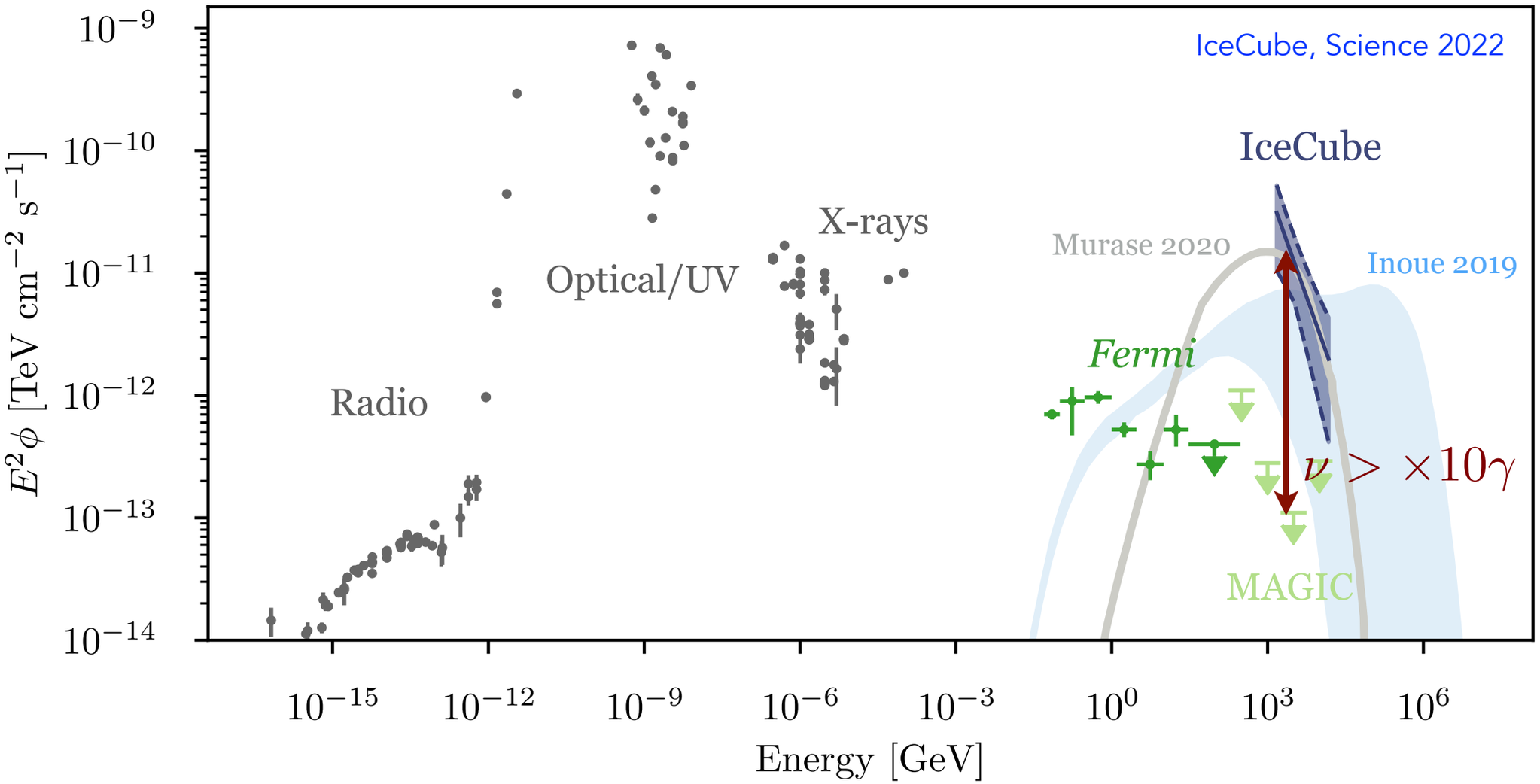
- Compton thick environment with Column density ~ $10^{25}$ $cm^{-2}$
- Bright in X-ray, and high infrared luminosity indicating high level of star formation
    - *Historically considered as a promising cosmic-ray accelerator.*

# NGC 1068 Spectrum



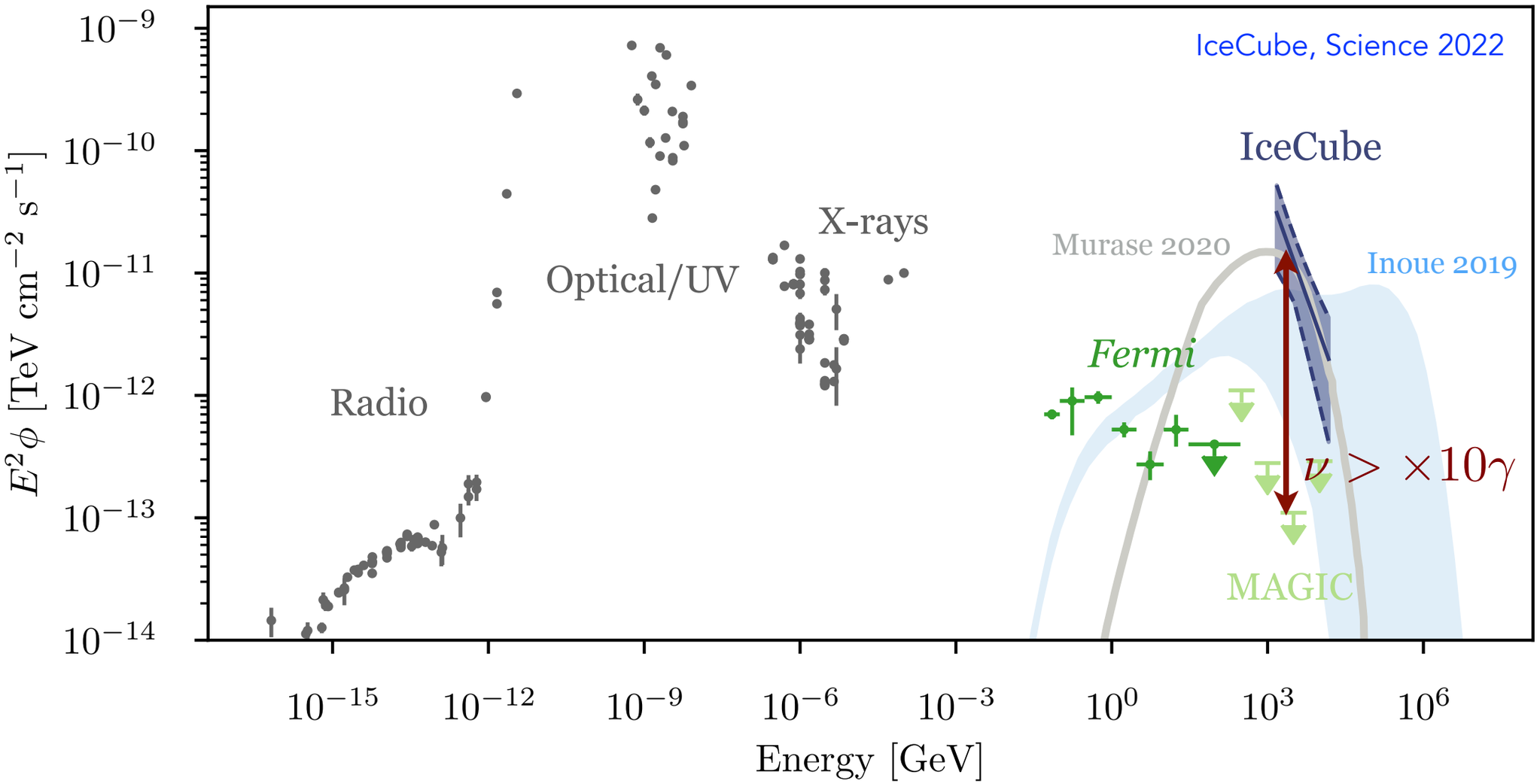

- The neutrino flux much higher than the measured $\gamma$-ray flux.
- Models built on Fermi $\gamma$-ray flux by cannot accommodate the neutrino flux.
- **Obscuring** necessary to absorb the pionic $\gamma$-ray accompanying neutrinos.
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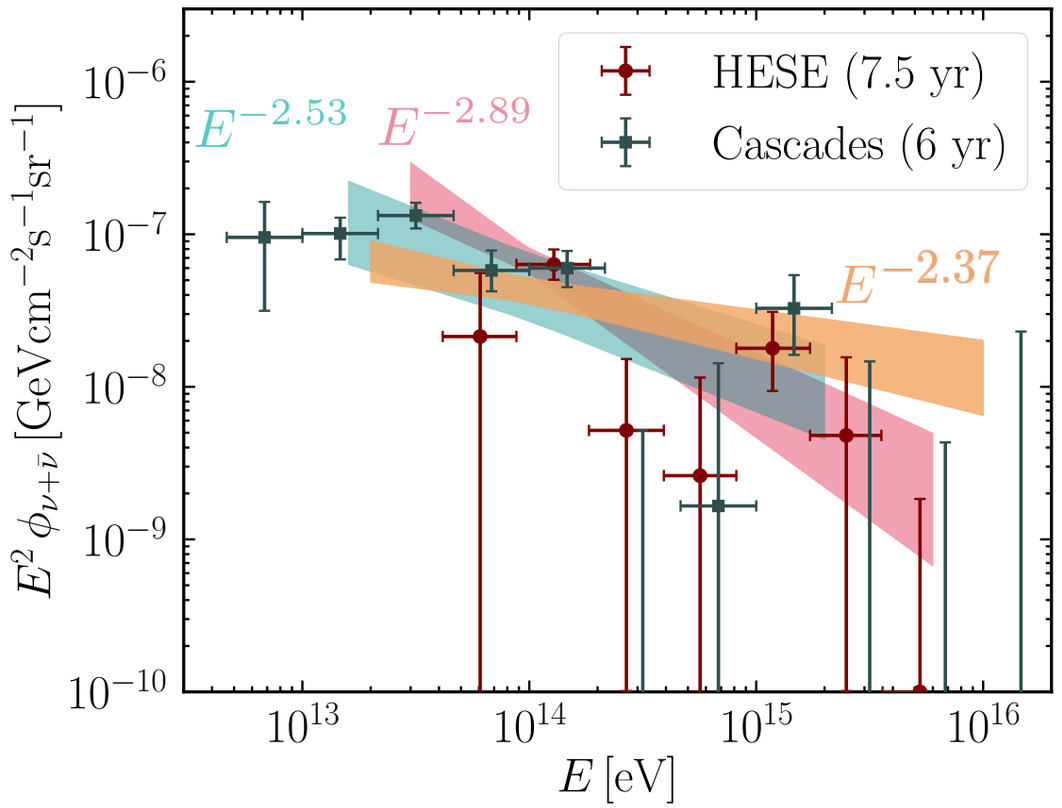


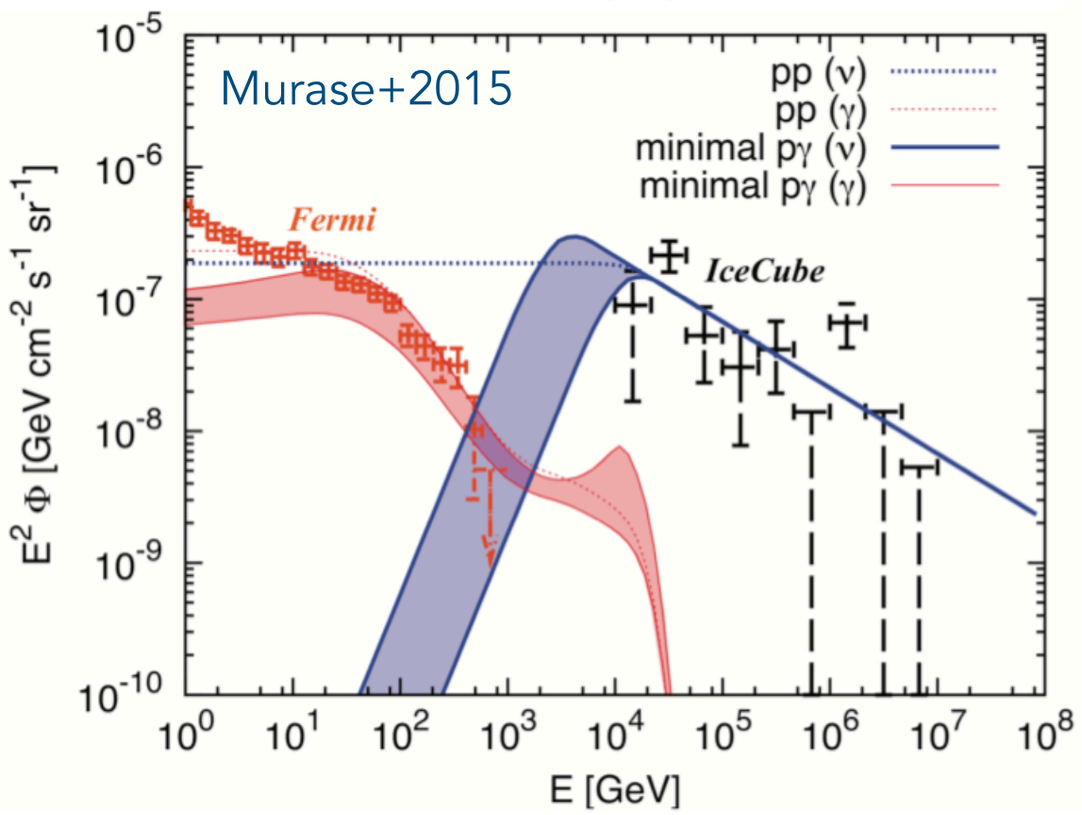

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→ Consistent with the multimessenger picture for the HE cosmic neutrino flux

# Medium-Energy Excess in Neutrino Flux

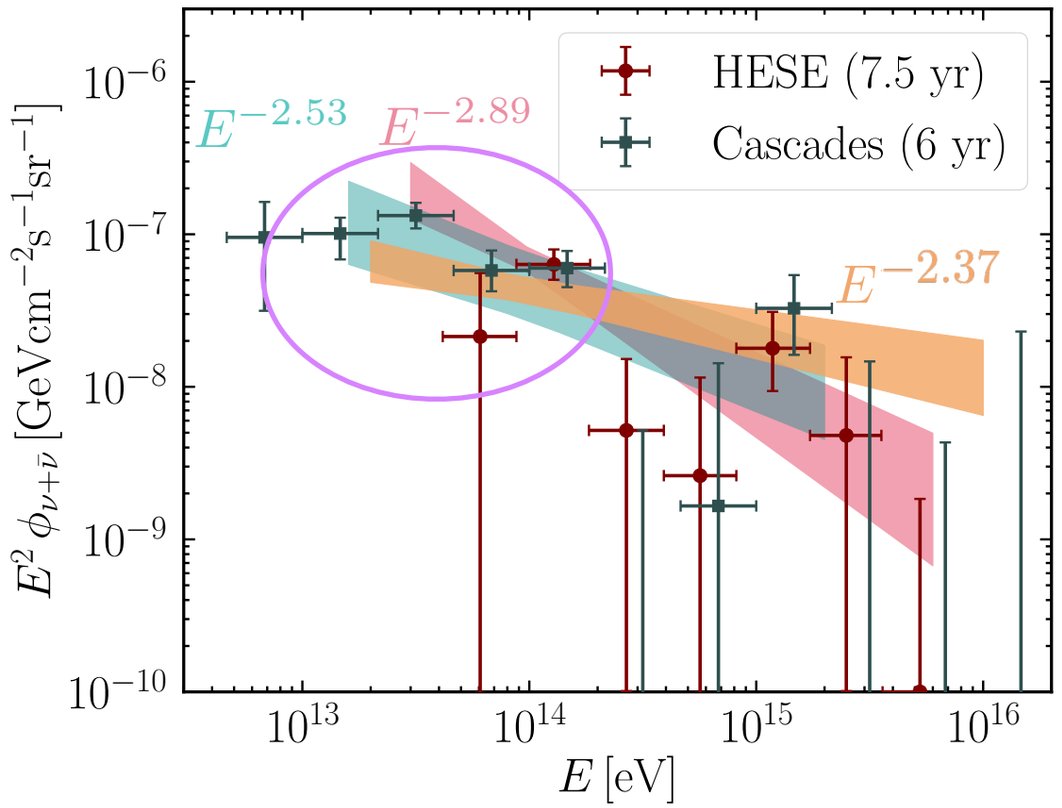
- Different slopes hint at structure in the flux of high-energy cosmic neutrinos.
- The magnitude of the flux at ~10 TeV energies is found to be higher than the flux at >100 TeV energies.
- Multimessenger connection dictates extragalactic sources of the high-energy neutrino flux at medium-energies to be **obscured** to GeV $\gamma$-rays. [Murase+ 2015, Fang+ 2022]
- $\gamma$-ray opaque sources are the dominant contributors to the cosmic neutrino flux.
  - Core of AGN can meet these conditions.

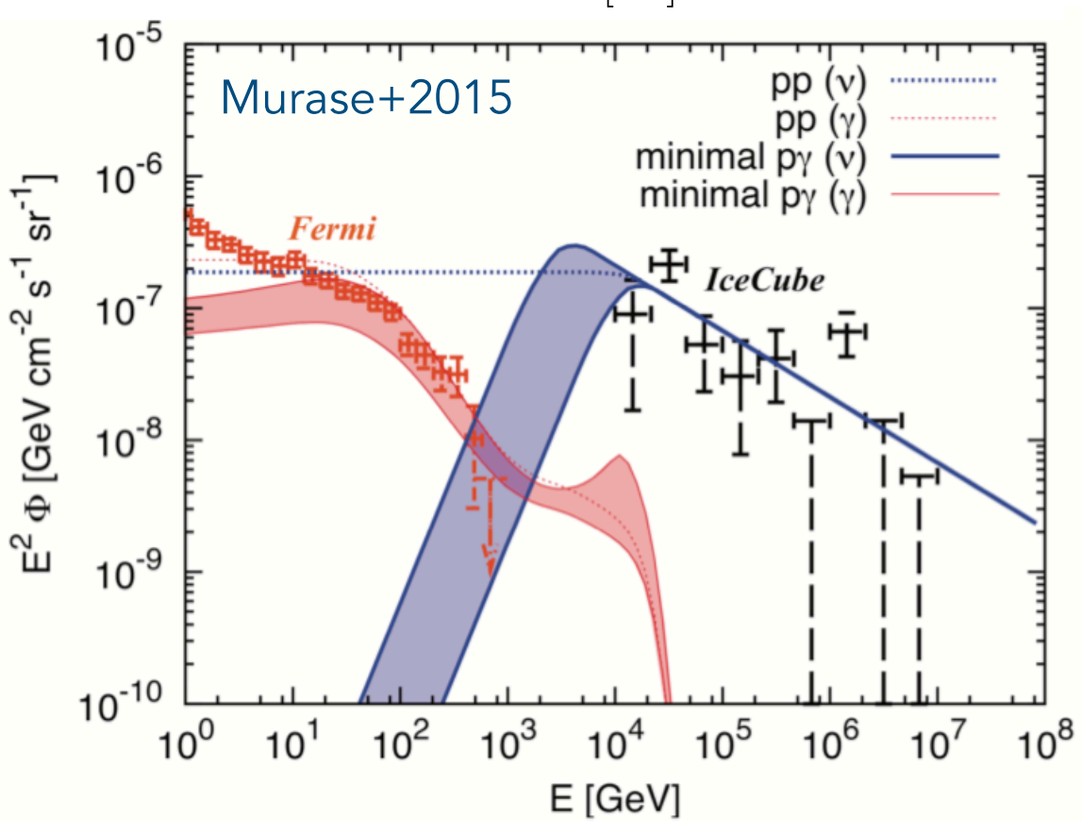


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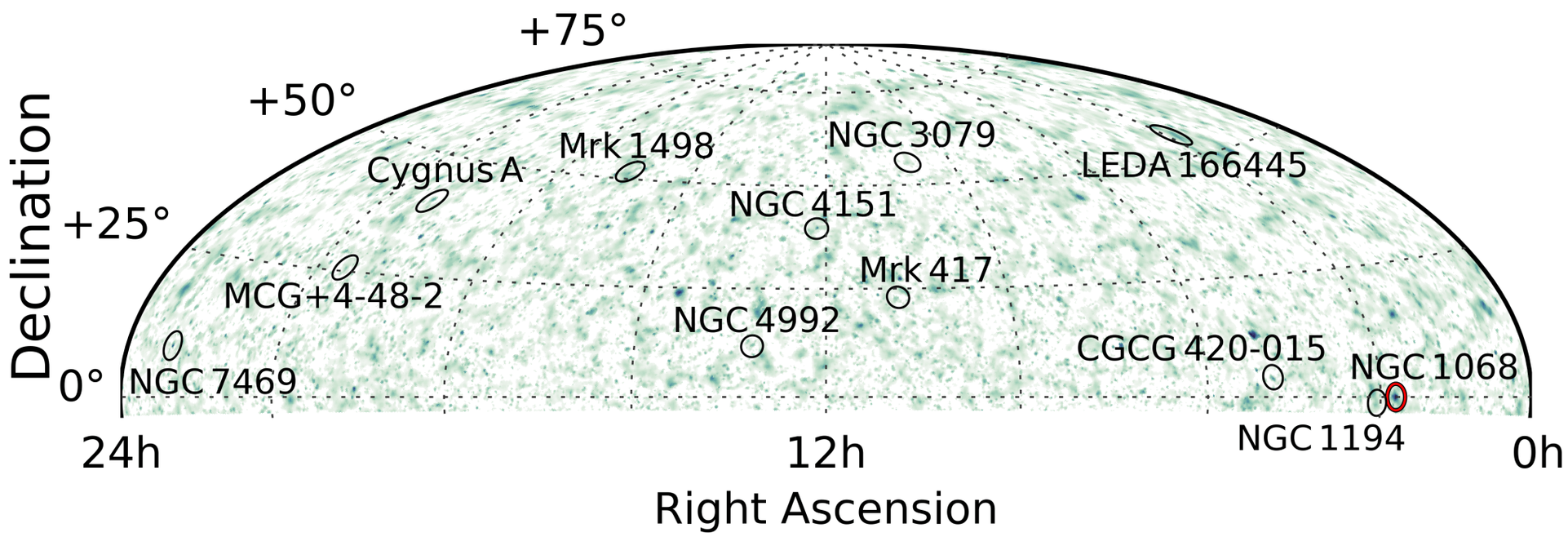



# Neutrino-Bright AGN

- Accumulating evidence for correlation of IceCube neutrinos in the direction of $\gamma$-ray obscured AGN.
  - $3.3\sigma$ excess from ensemble of 11 sources in the Northern Sky (excluding NGS 1068)
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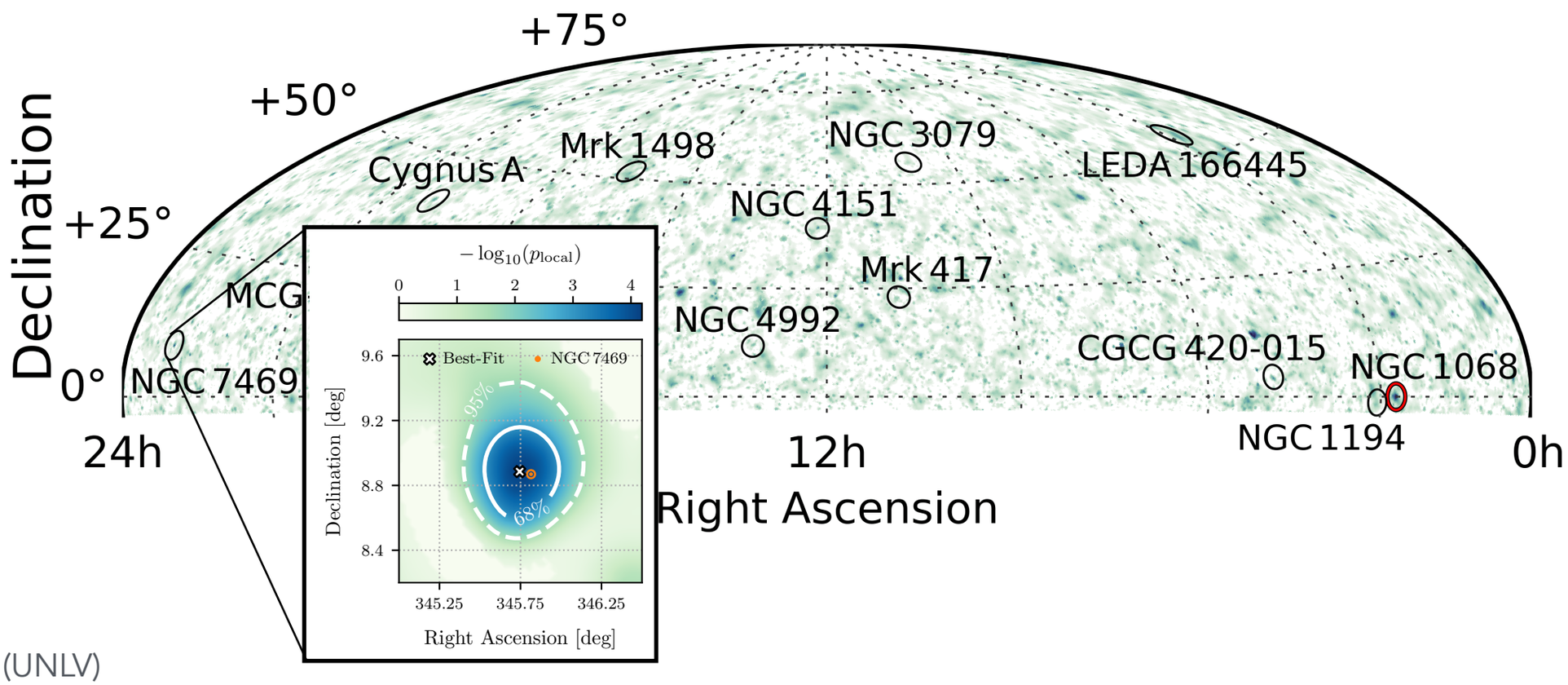
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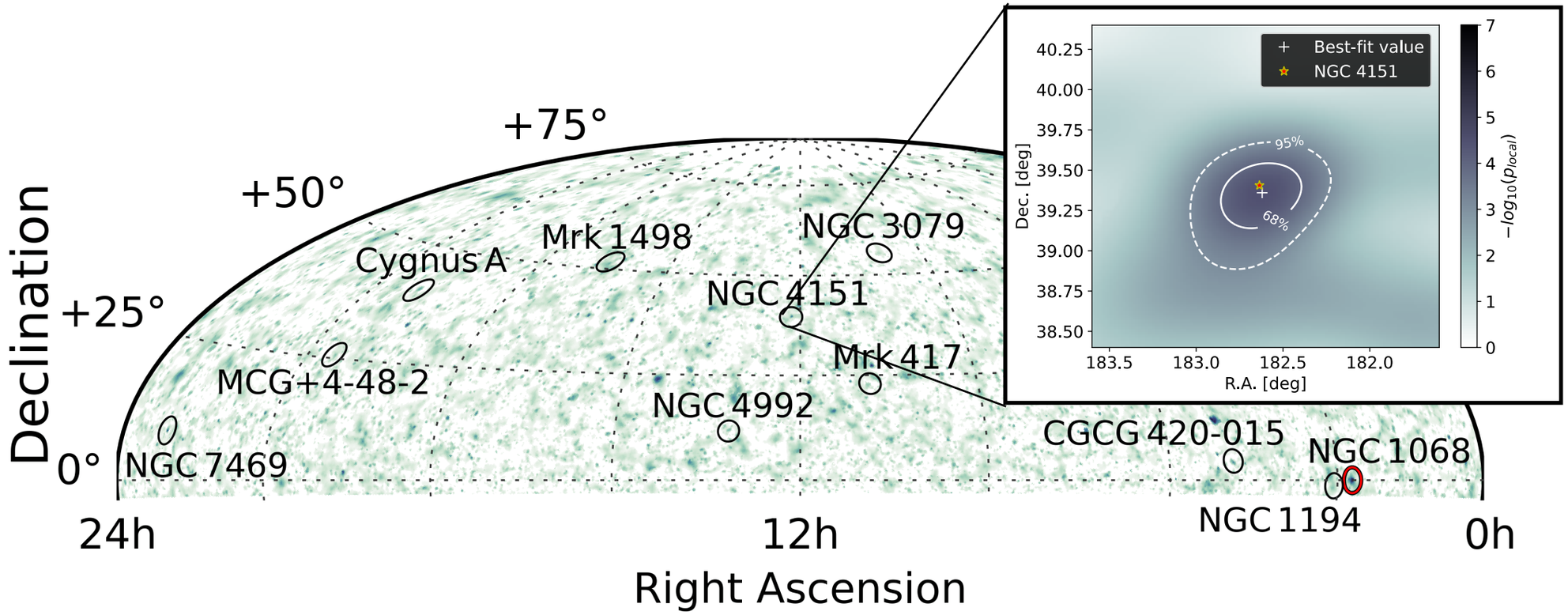
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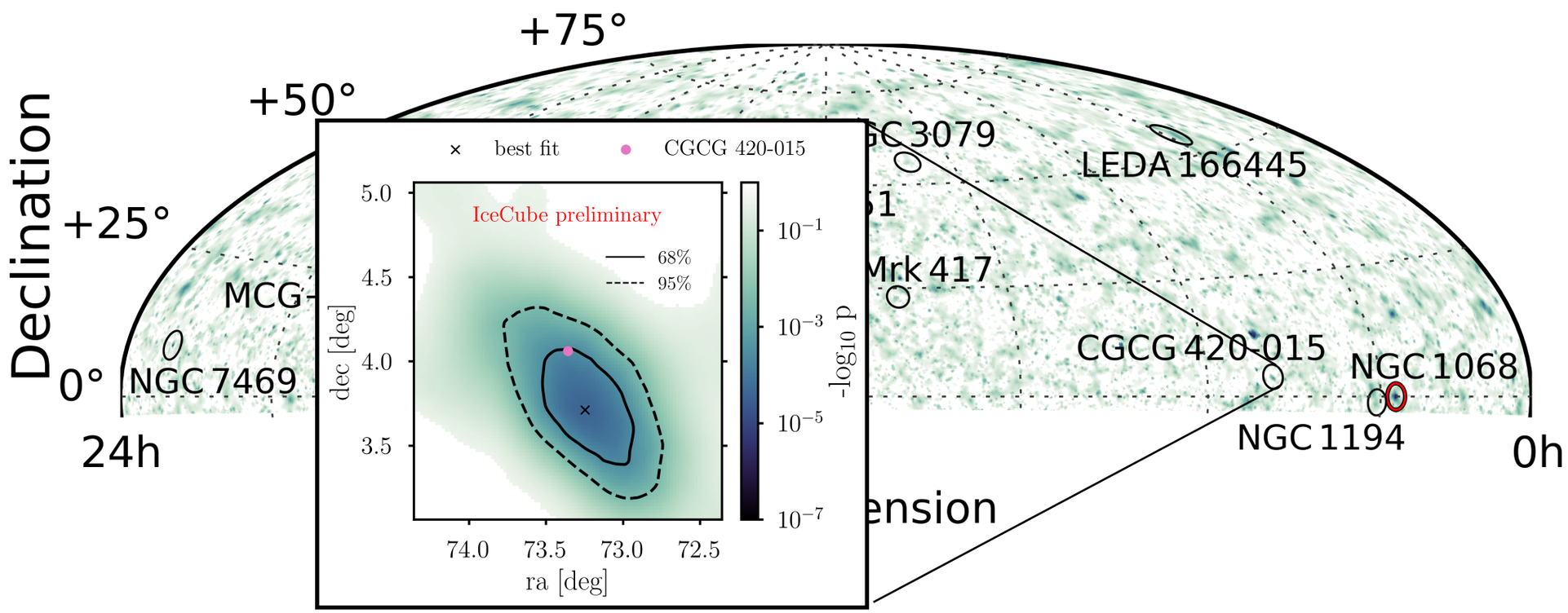
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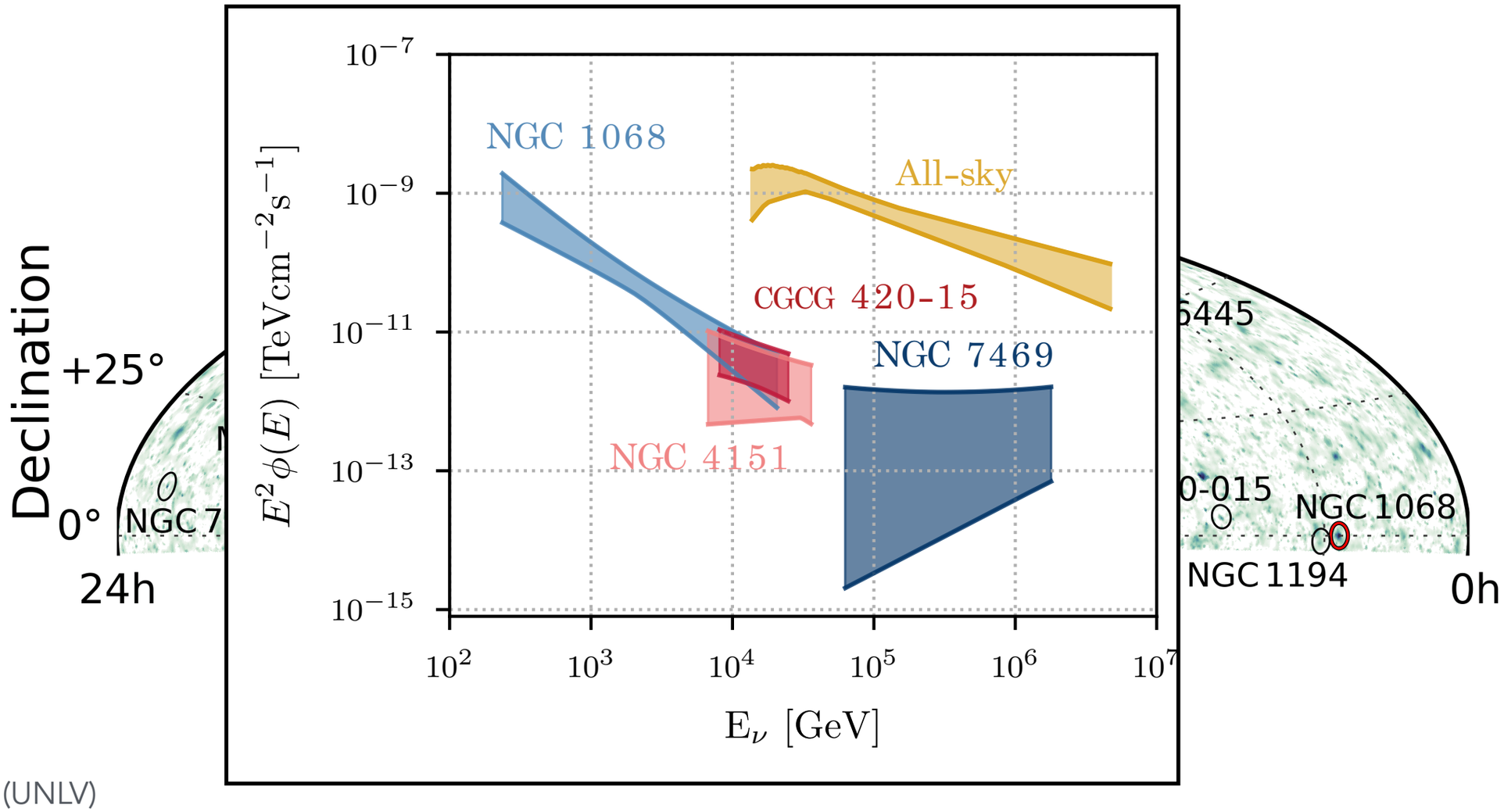
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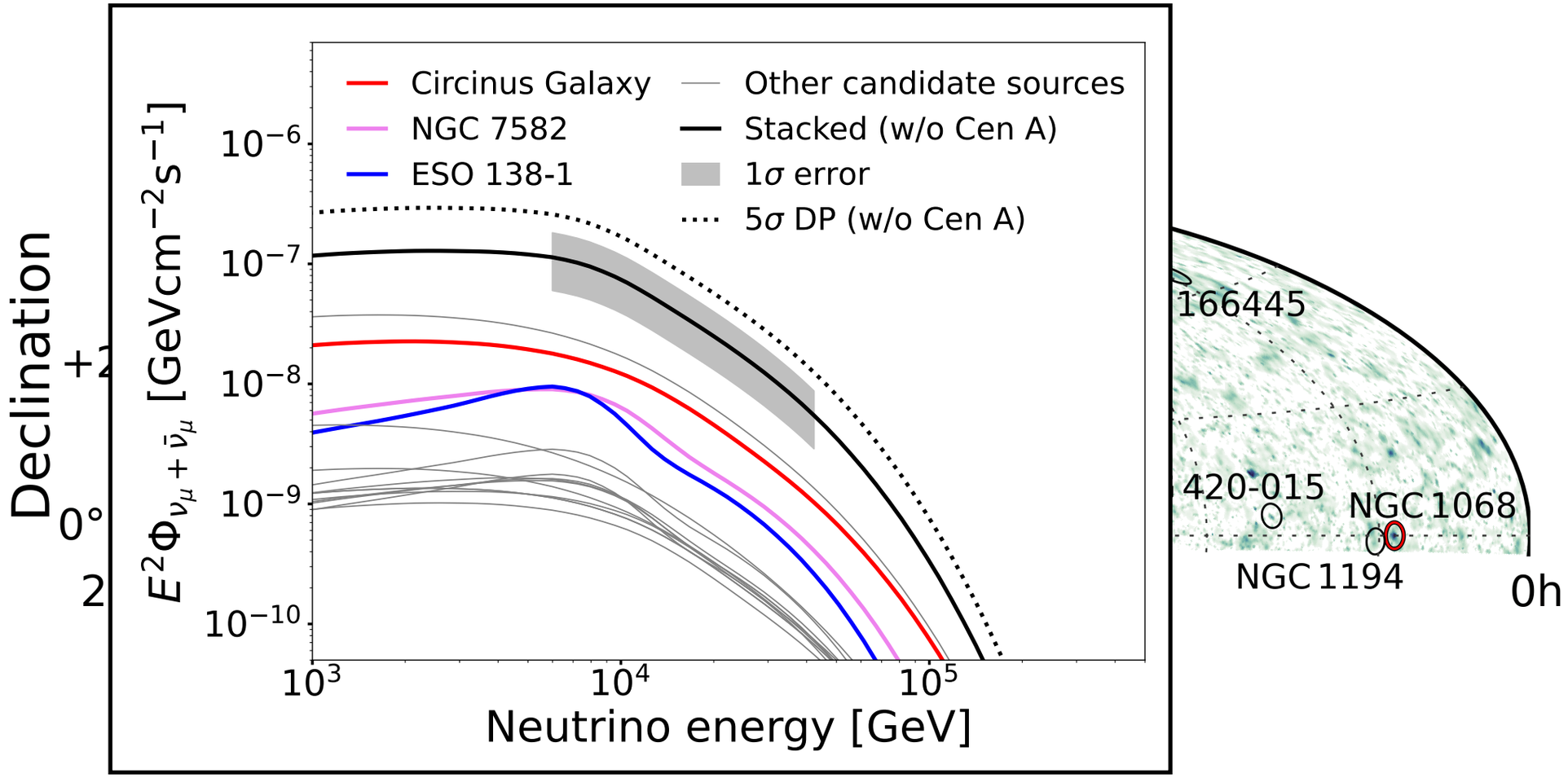
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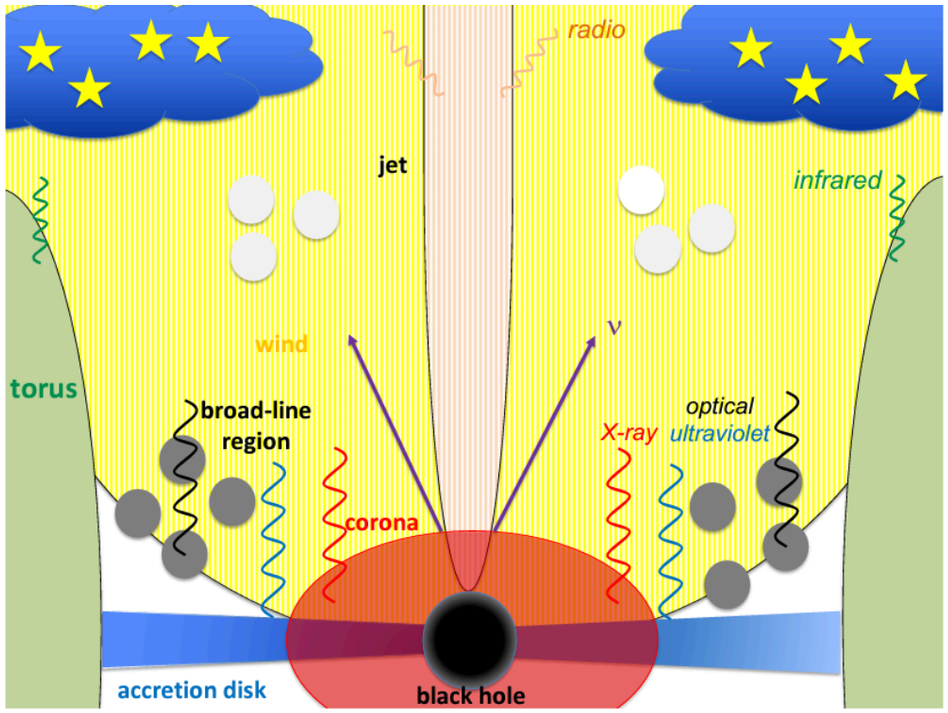


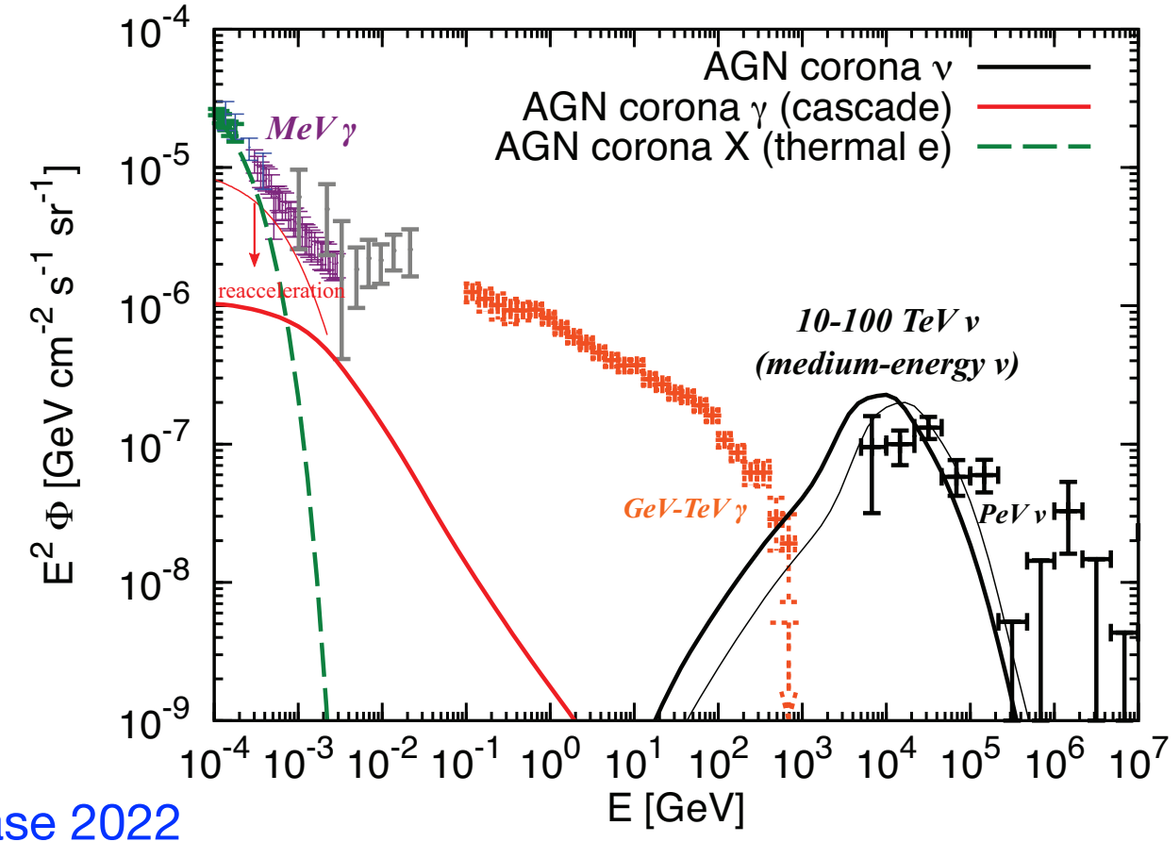
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# Obscured AGNs – The Multimessenger Picture




Murase 2022

**Cosmic ray (CR) acceleration**

Stochastic acceleration in the corona
CR energy cutoff at ~ PeV energies

**Targets**

Coronal X-rays, disk photons, and protons **(main targets for $pp$ and $p\gamma$)**

**Features**

**Non-power law** neutrino spectra

**MeV photons due to the cascade in the source**

# Neutrino and $\gamma$-ray from Magnetically Powered Corona

*Principal Parameters*

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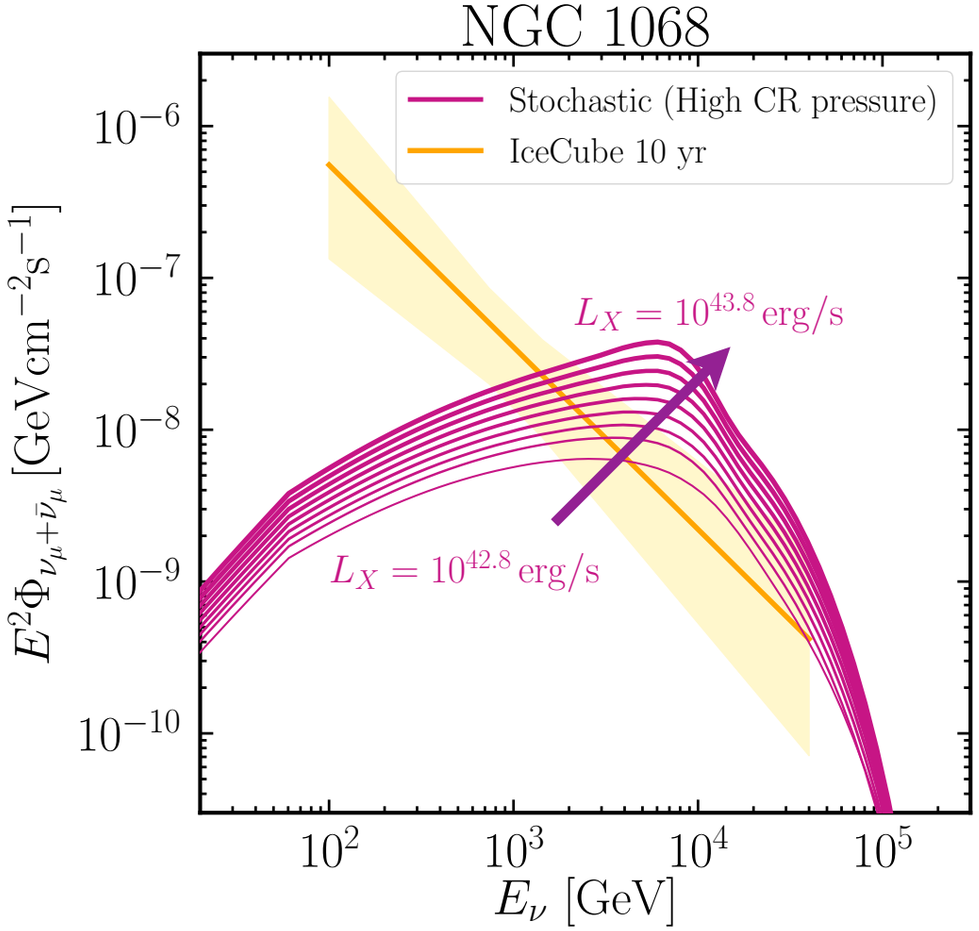
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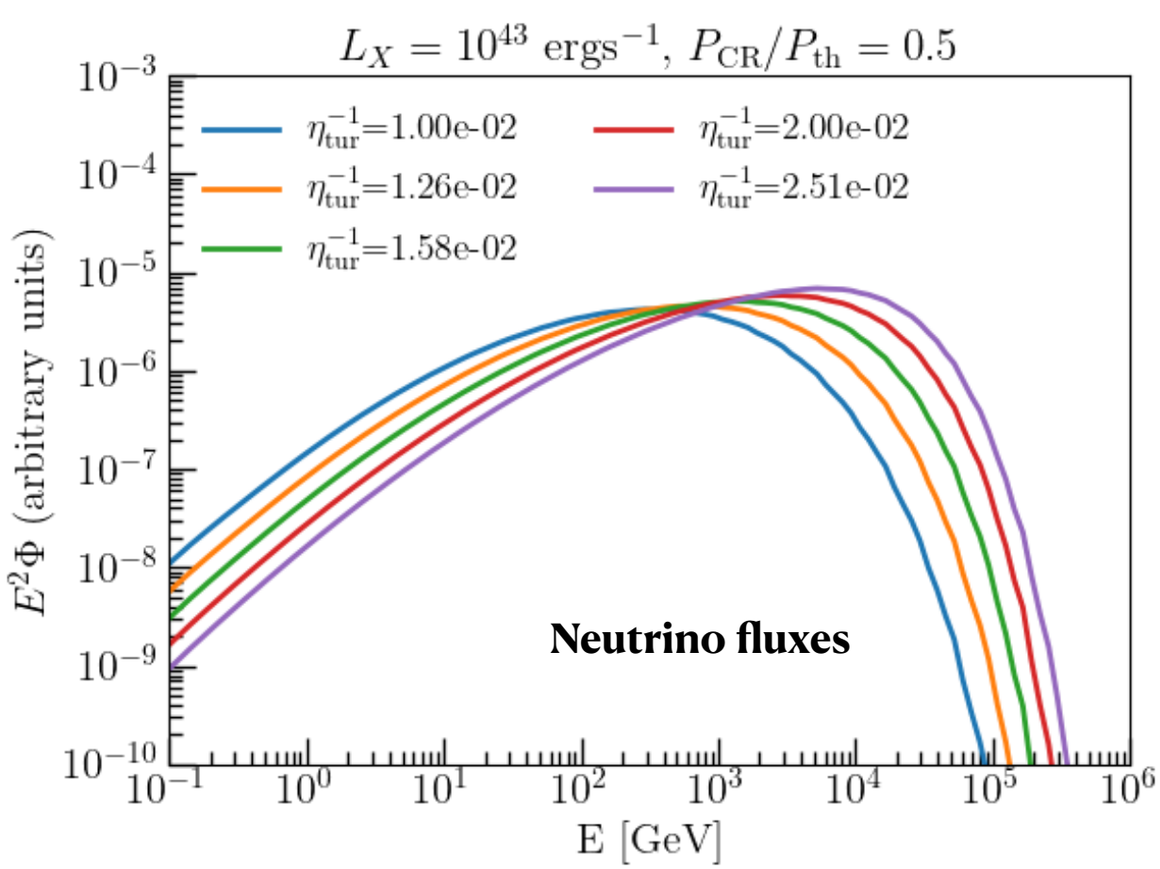
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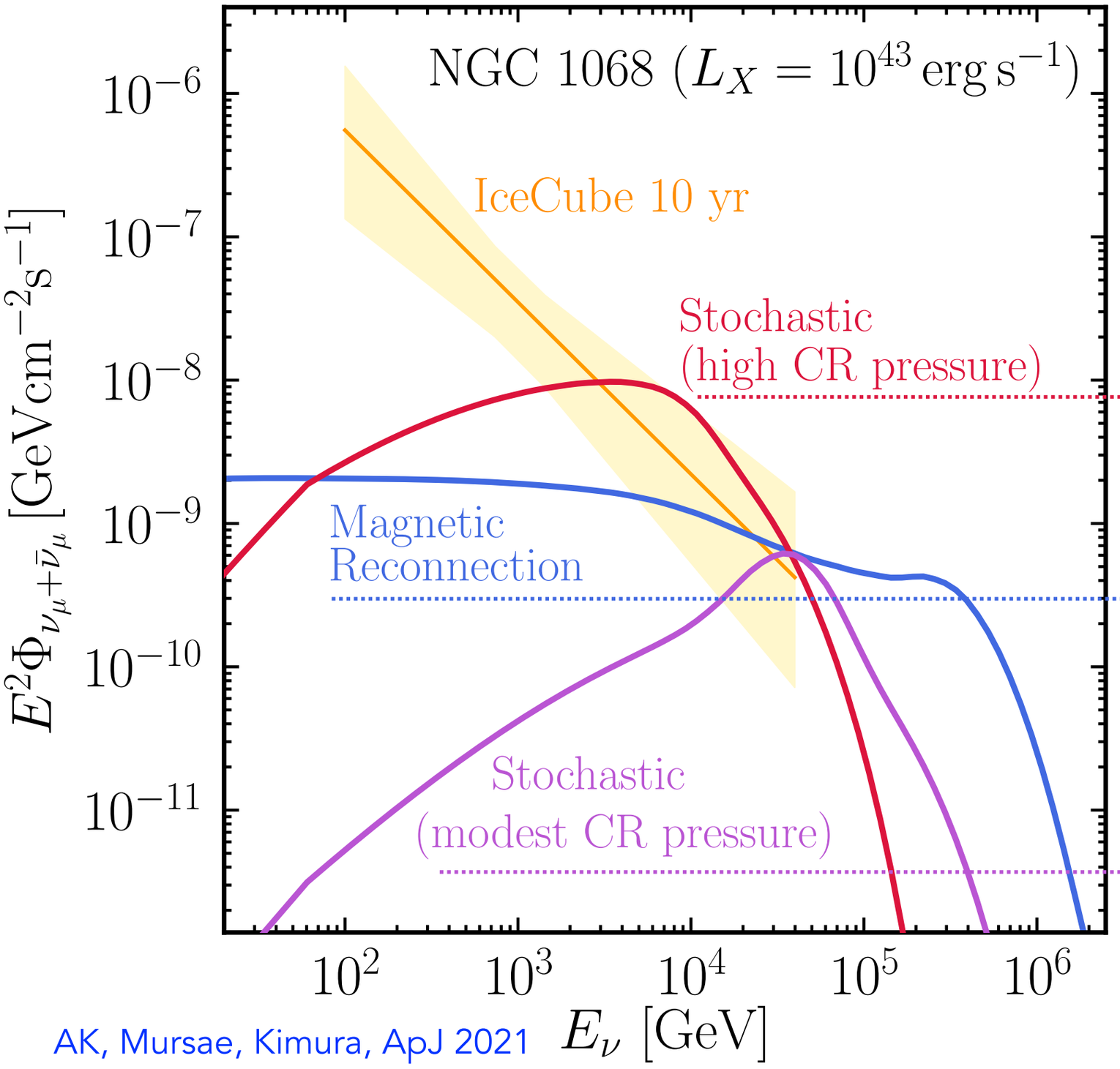
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# NGC 1068 in AGN-Corona Model



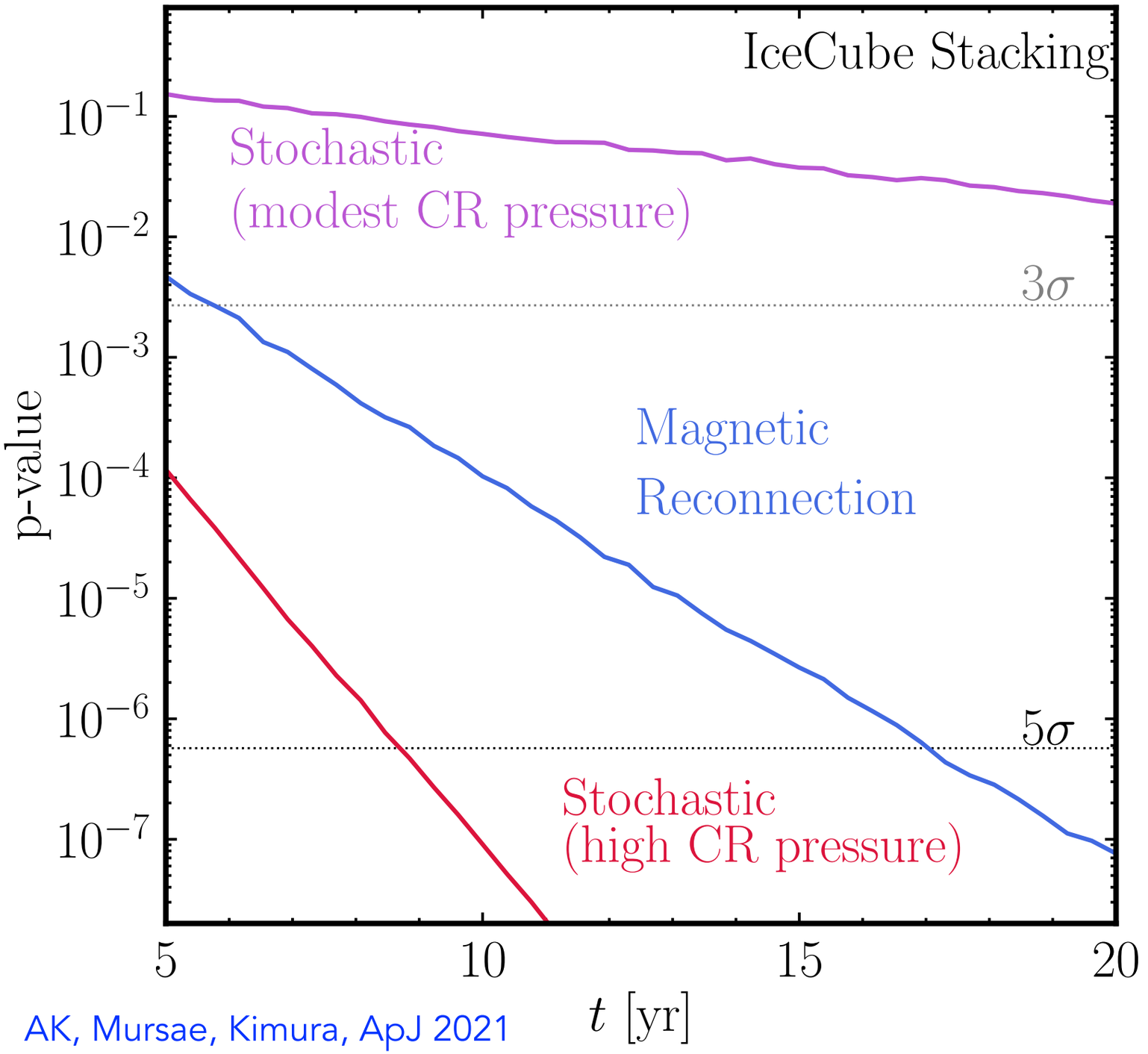

$P_{\rm CR} = 50\% P_{\rm th}$
$\eta_{\rm tur} = 50$

$P_{\rm CR} = 50\% P_{\rm th}$
$\eta_{\rm acc} = 10^4$

$P_{\rm CR} = 0.8\% P_{\rm th}$
$\eta_{\rm tur} = 10$

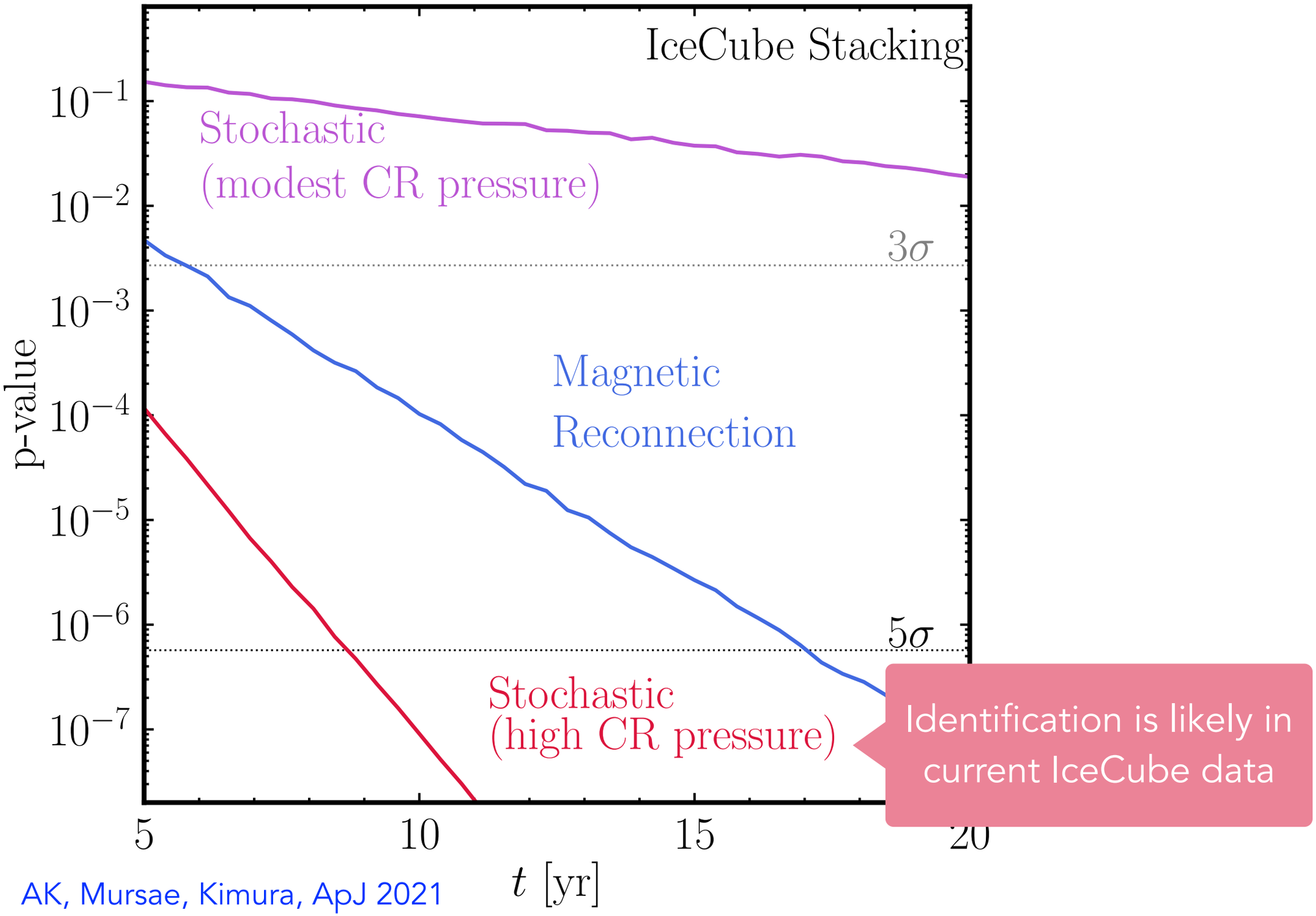
AK, Mursae, Kimura, ApJ 2021

# Bright Seyfert Galaxies: IceCube Prospects



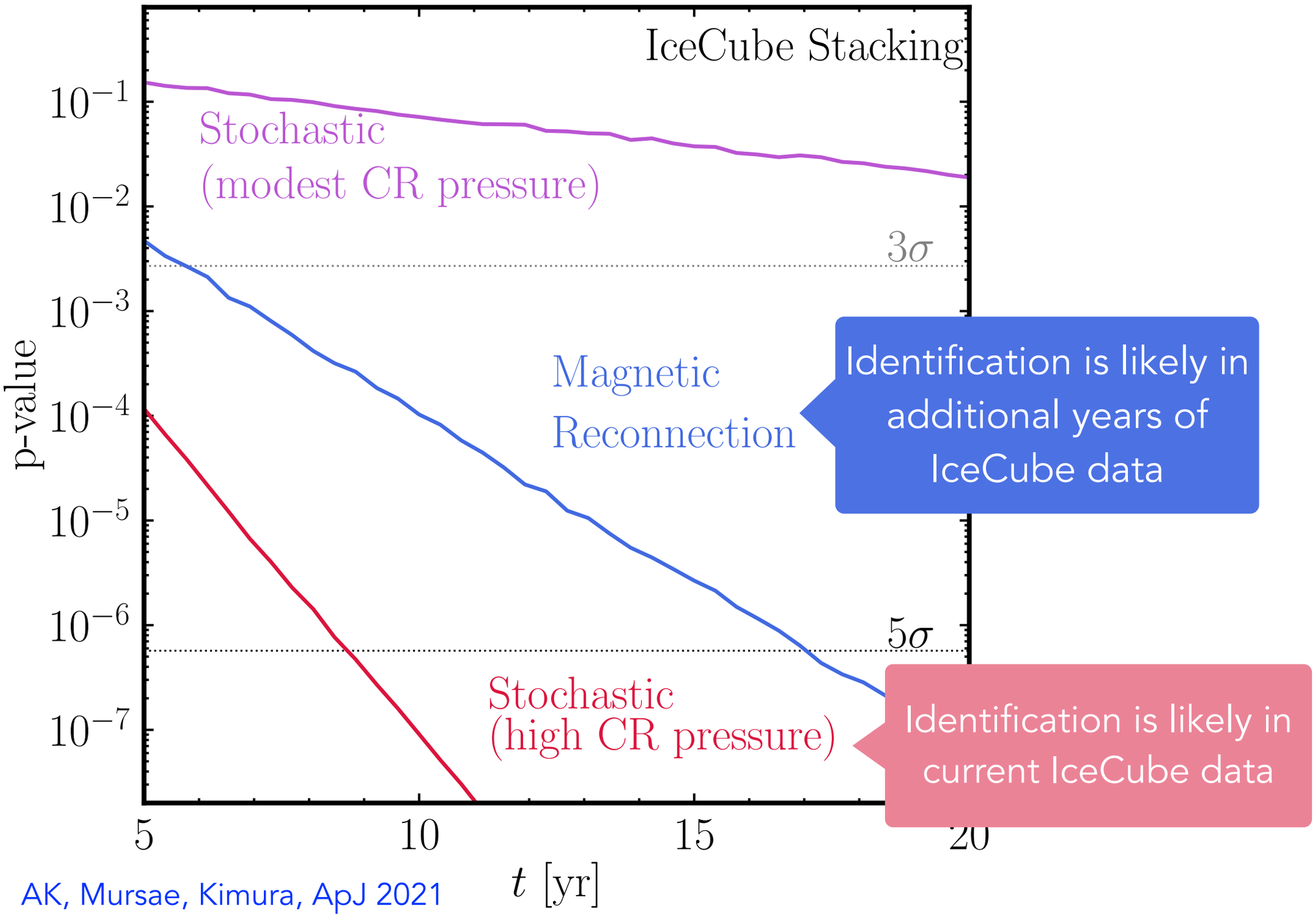

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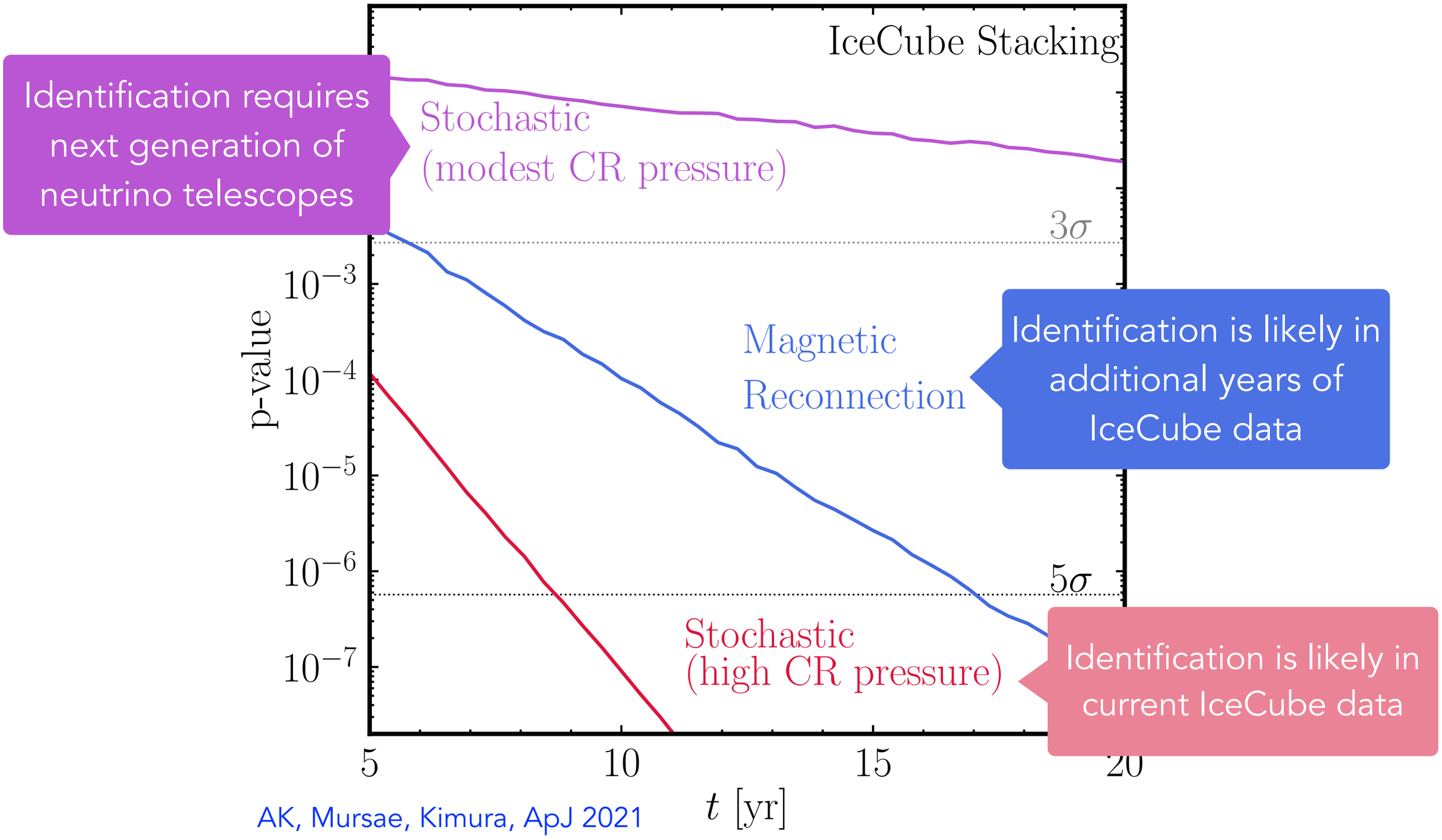



Identification is likely in additional years of IceCube data

Identification is likely in current IceCube data

AK, Mursae, Kimura, ApJ 2021

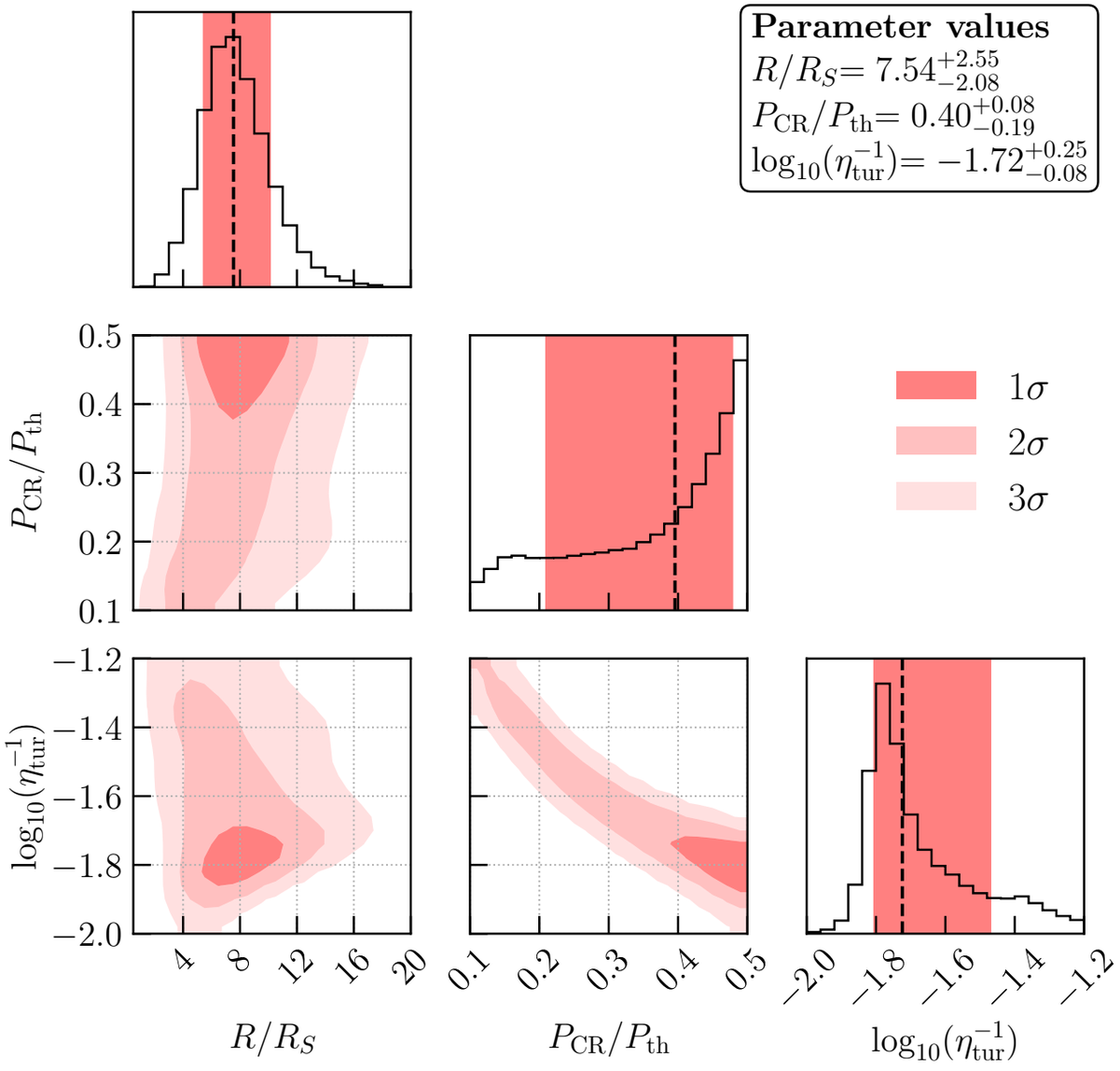
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AK, Mursae, Kimura, ApJ 2021

# NGC 1068

$$M_{\rm BH} = 1.8 \times 10^7 M_\odot \; — \; L_x = 3 \times 10^{43} \text{ erg s}^{-1}$$



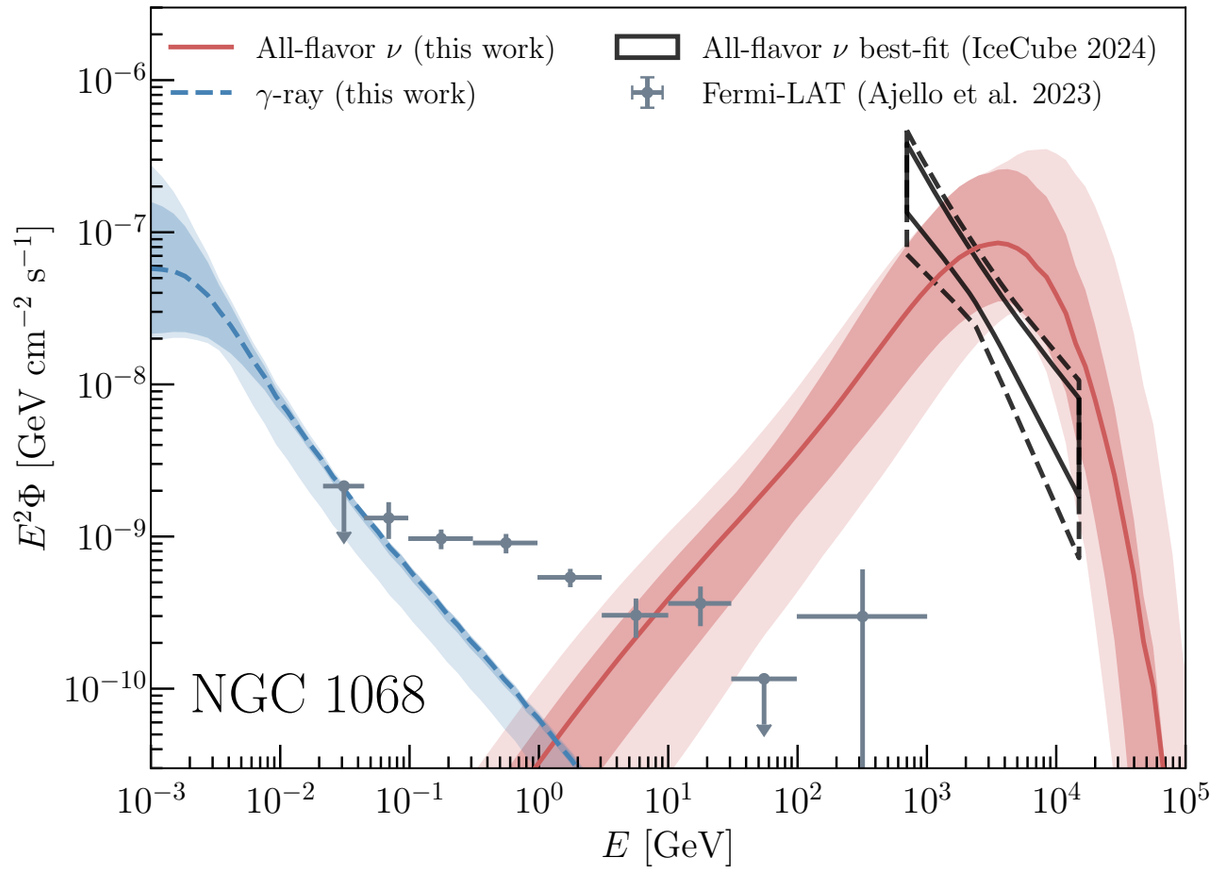

**Parameter values**

$R/R_S = 7.54^{+2.55}_{-2.08}$

$P_{\rm CR}/P_{\rm th} = 0.40^{+0.08}_{-0.19}$

$\log_{10}(\eta_{\rm tur}^{-1}) = -1.72^{+0.25}_{-0.08}$

- Near maximal pressure ratio
- $R \sim 7R_S$



# NGC 4151

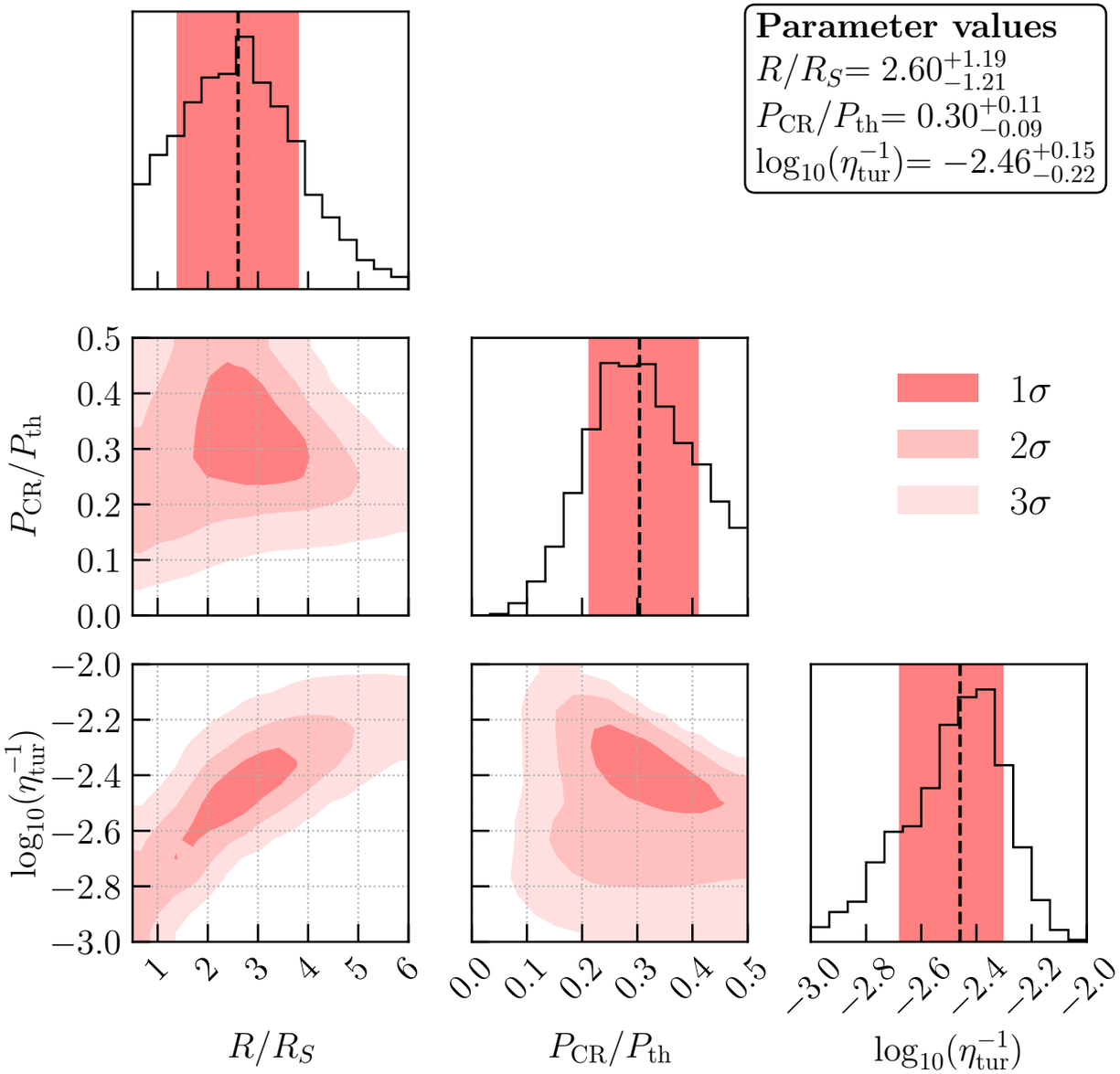
$M_{\rm BH} = 1.7 \times 10^7 M_\odot$ — $L_x = 2.6 \times 10^{42}$ erg s$^{-1}$

**Parameter values**

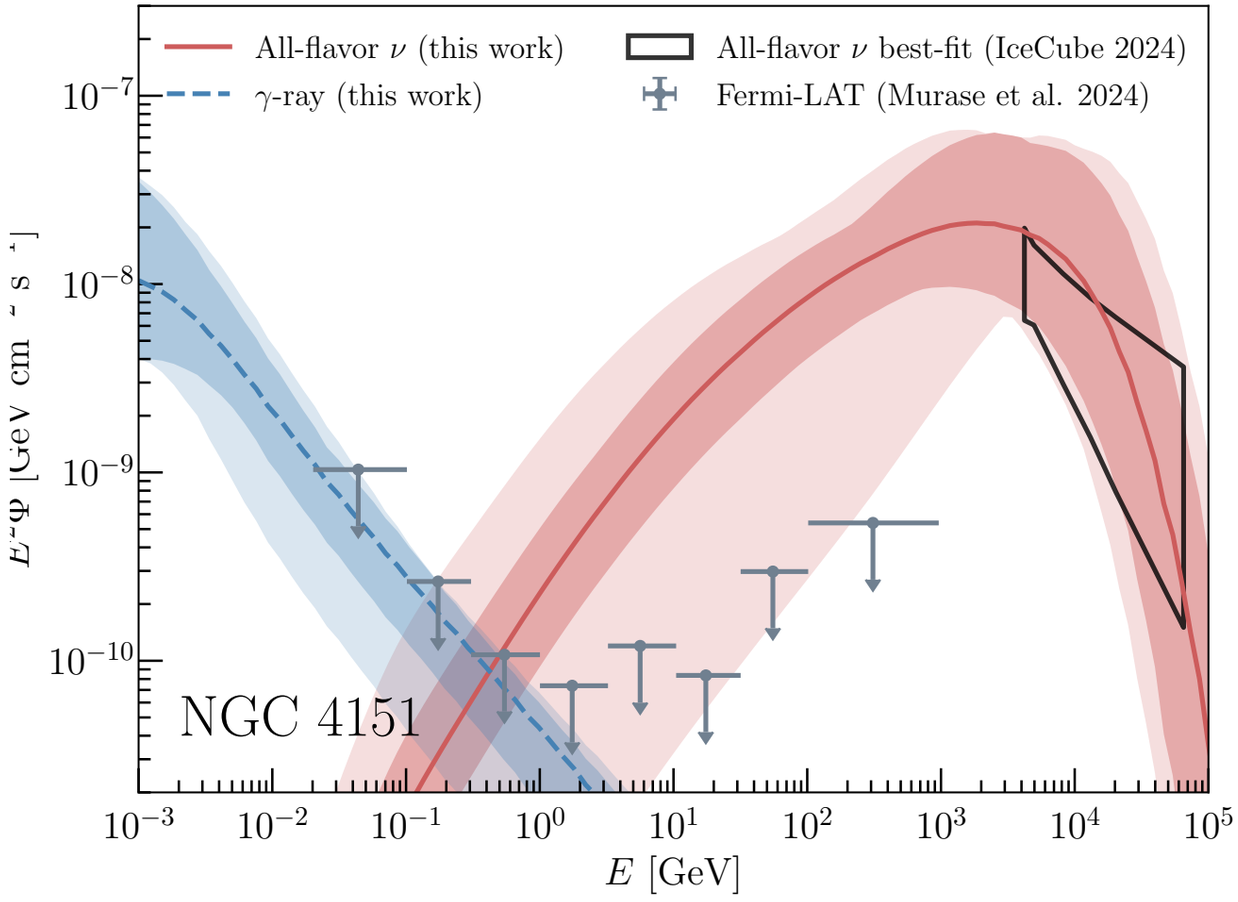
$R/R_S = 2.60^{+1.19}_{-1.21}$

$P_{\rm CR}/P_{\rm th} = 0.30^{+0.11}_{-0.09}$

$\log_{10}(\eta_{\rm tur}^{-1}) = -2.46^{+0.15}_{-0.22}$

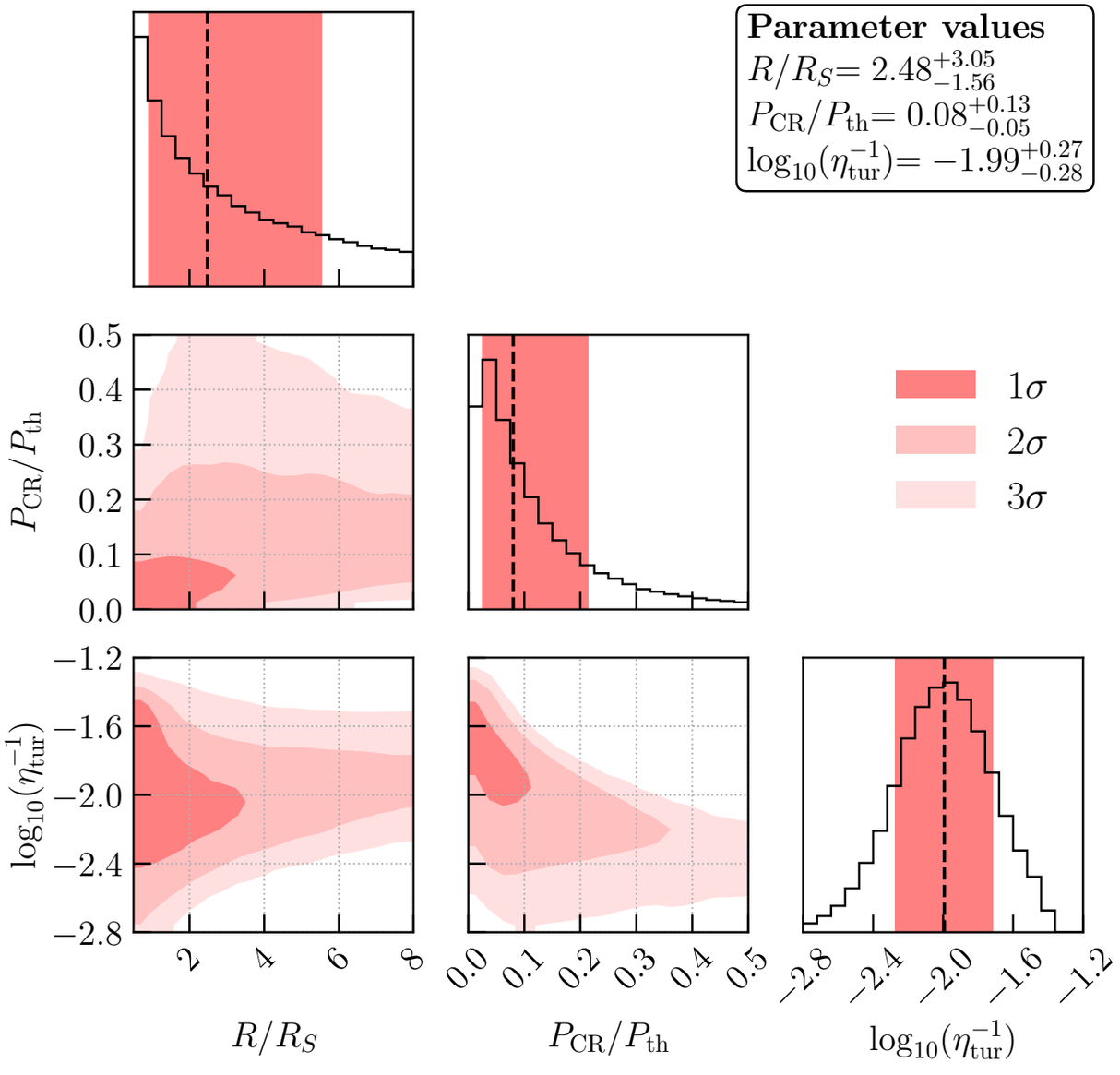



- High CR, but below the maximal value
- $R \lesssim 2R_S$ (smaller radius)



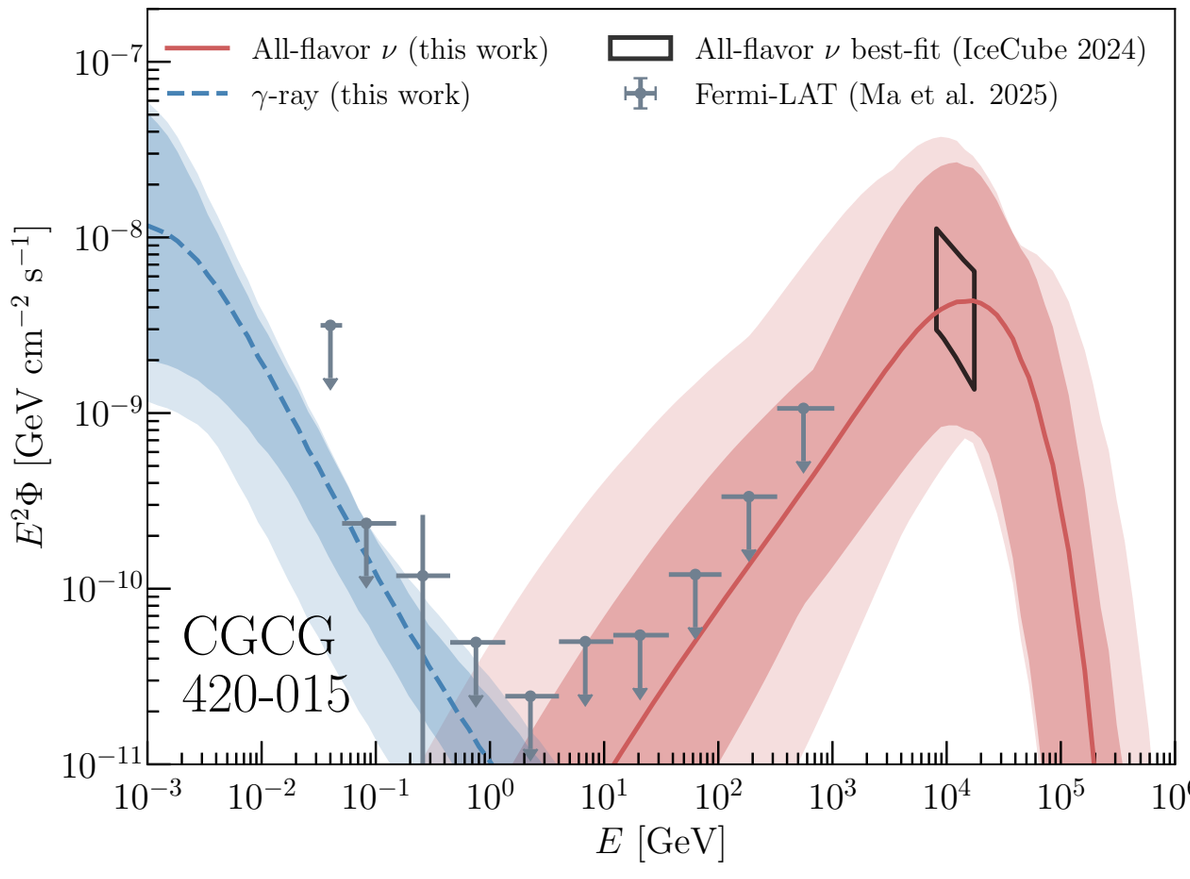
# CGCG 420-015

$M_{BH} = 2.0 \times 10^8 M_\odot$ – $L_x = 7.1 \times 10^{43}$ erg s$^{-1}$



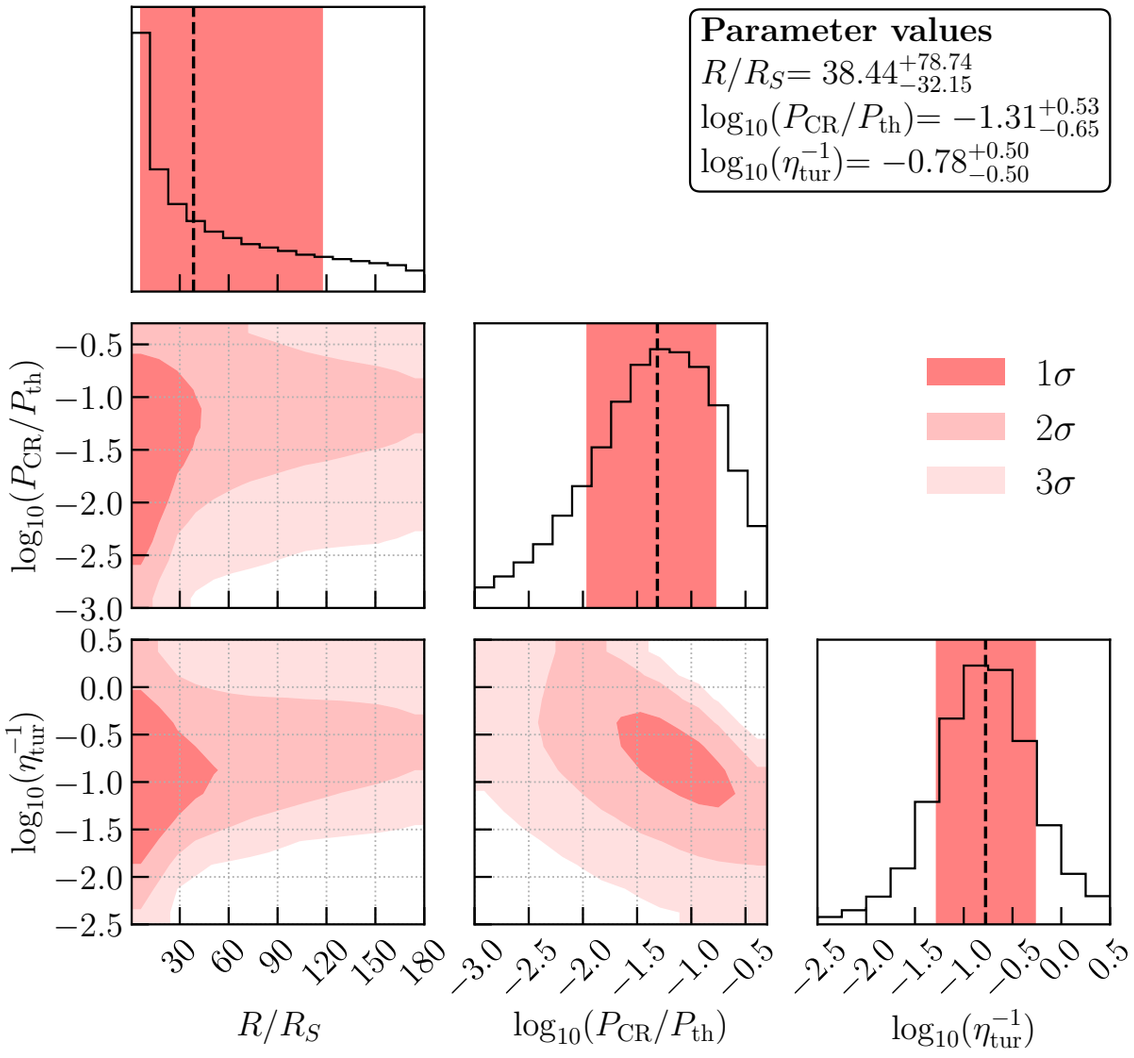

**Parameter values**
$R/R_S = 2.48^{+3.05}_{-1.56}$
$P_{\rm CR}/P_{\rm th} = 0.08^{+0.13}_{-0.05}$
$\log_{10}(\eta_{\rm tur}^{-1}) = -1.99^{+0.27}_{-0.28}$

- A more moderate pressure ratio
- $R \sim 2R_S$ (smaller radius)

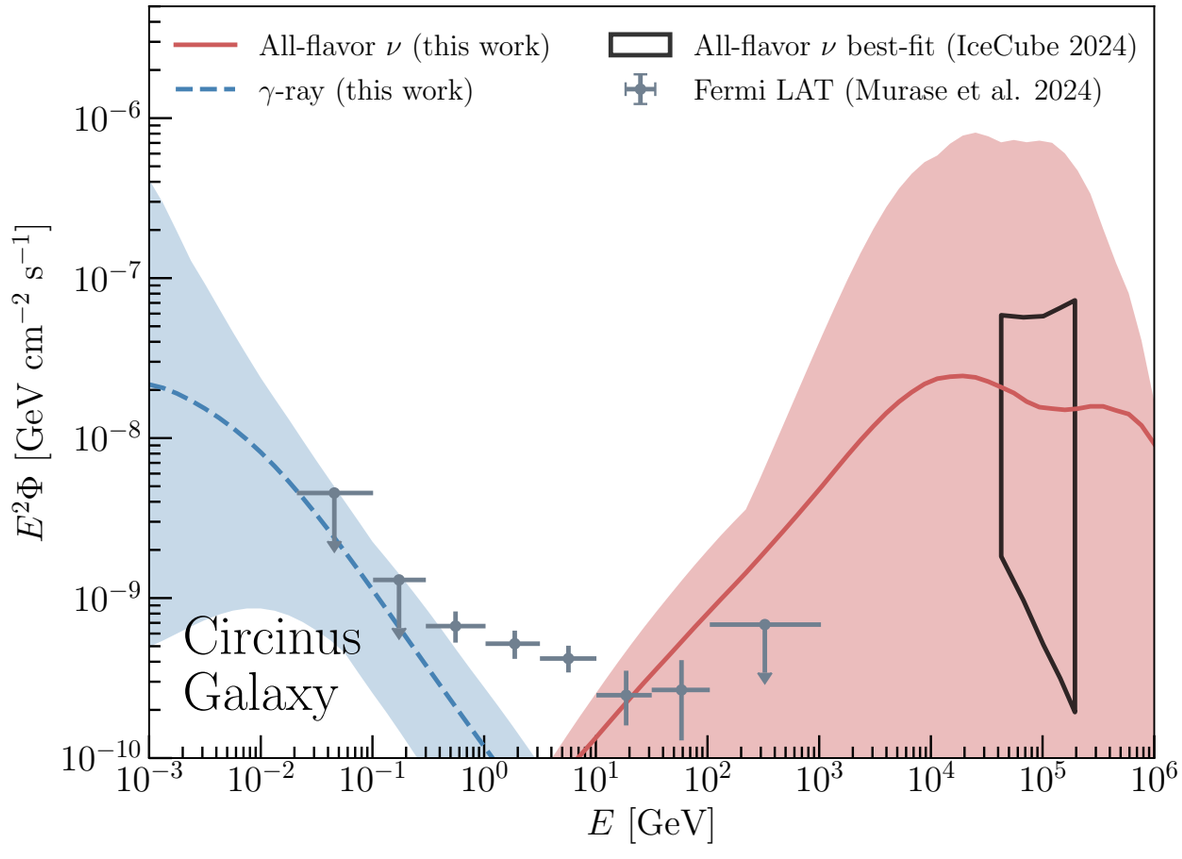


# Circinus Galaxy

$$M_{BH} = 1.7 \times 10^6 M_\odot - L_x = 3.1 \times 10^{42}\ \text{erg s}^{-1}$$

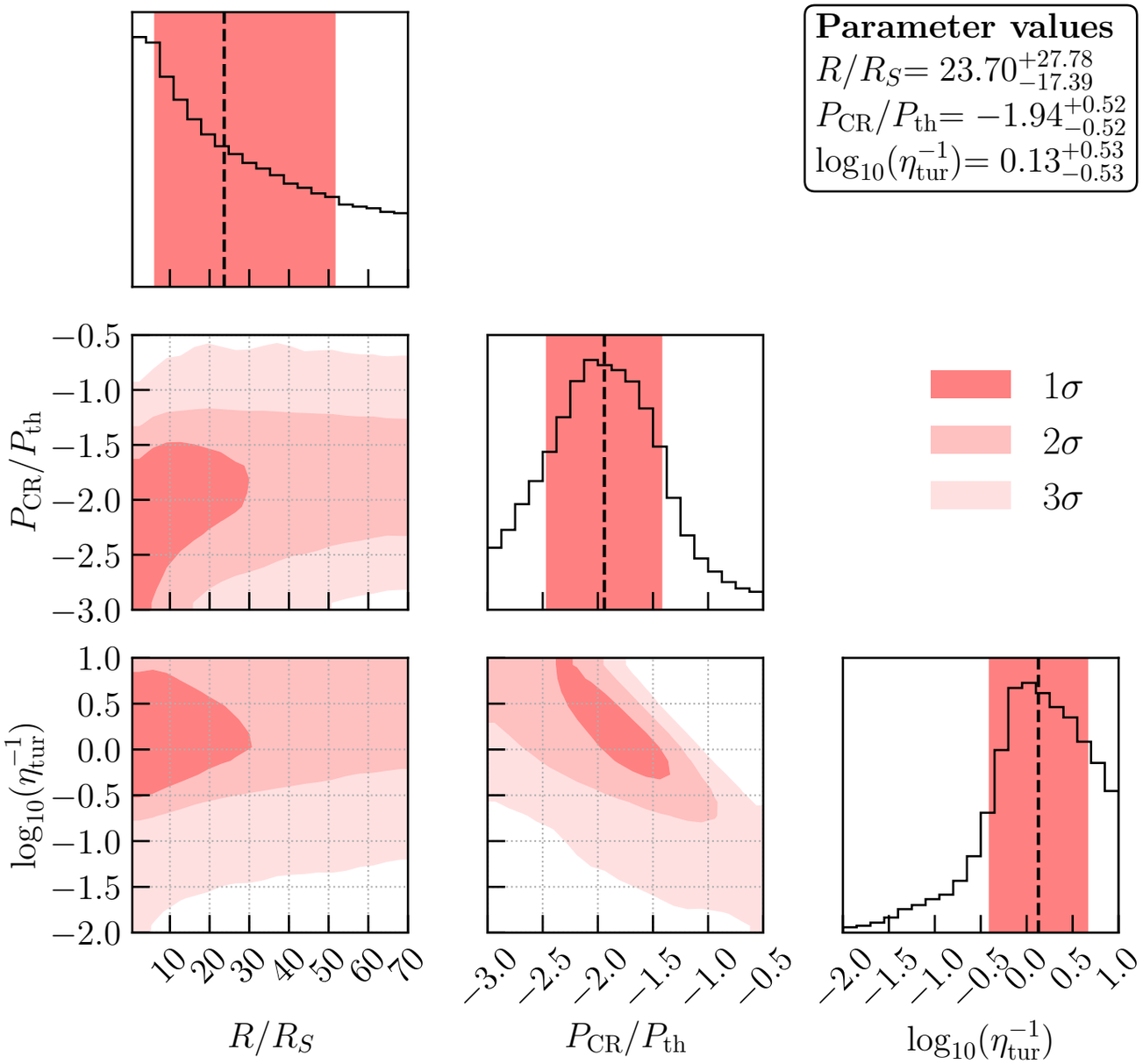



- A more moderate pressure ratio
- $R \sim 38 R_S$ (larger radius)



# NGC 7469

$M_{BH} = 9 \times 10^6 M_\odot$ – $L_x = 1.5 \times 10^{43}$ erg s$^{-1}$



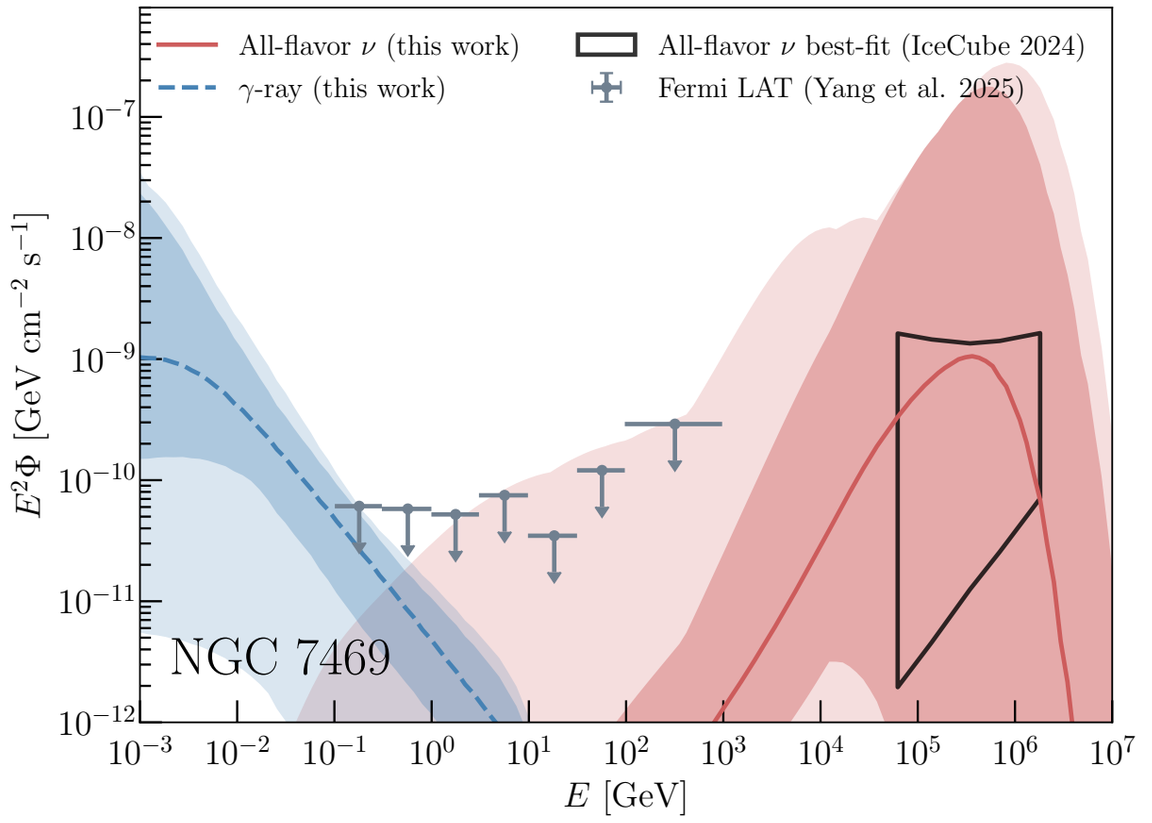

**Parameter values**

$R/R_S = 23.70^{+27.78}_{-17.39}$

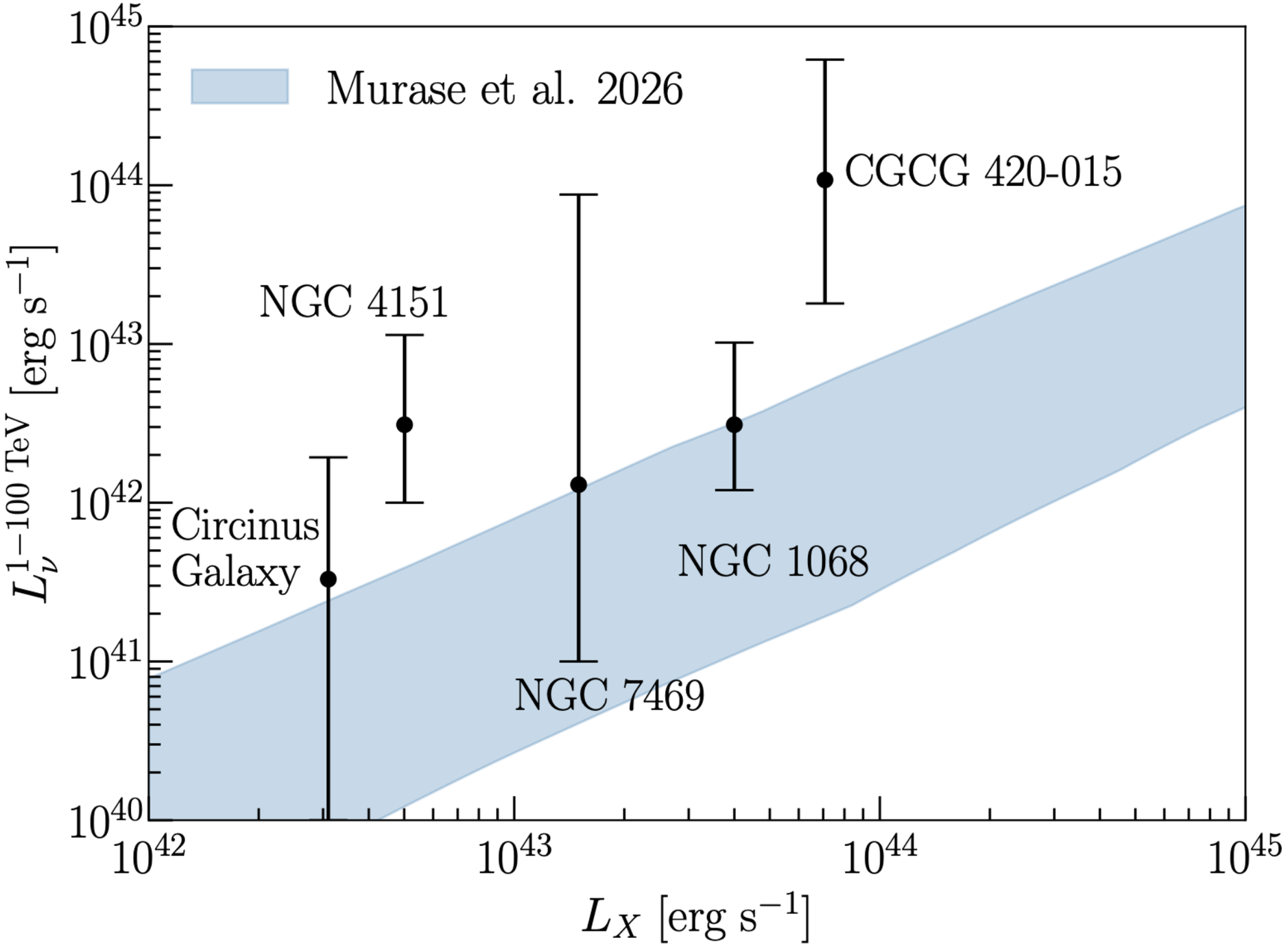
$P_{\rm CR}/P_{\rm th} = -1.94^{+0.52}_{-0.52}$

$\log_{10}(\eta_{\rm tur}^{-1}) = 0.13^{+0.53}_{-0.53}$

- A more moderate pressure ratio
- $R \sim 23 R_S$ (smaller radius)



# Emerging X-ray – Neutrino Connection




Carpio, AK, Murase, ApJ 2026

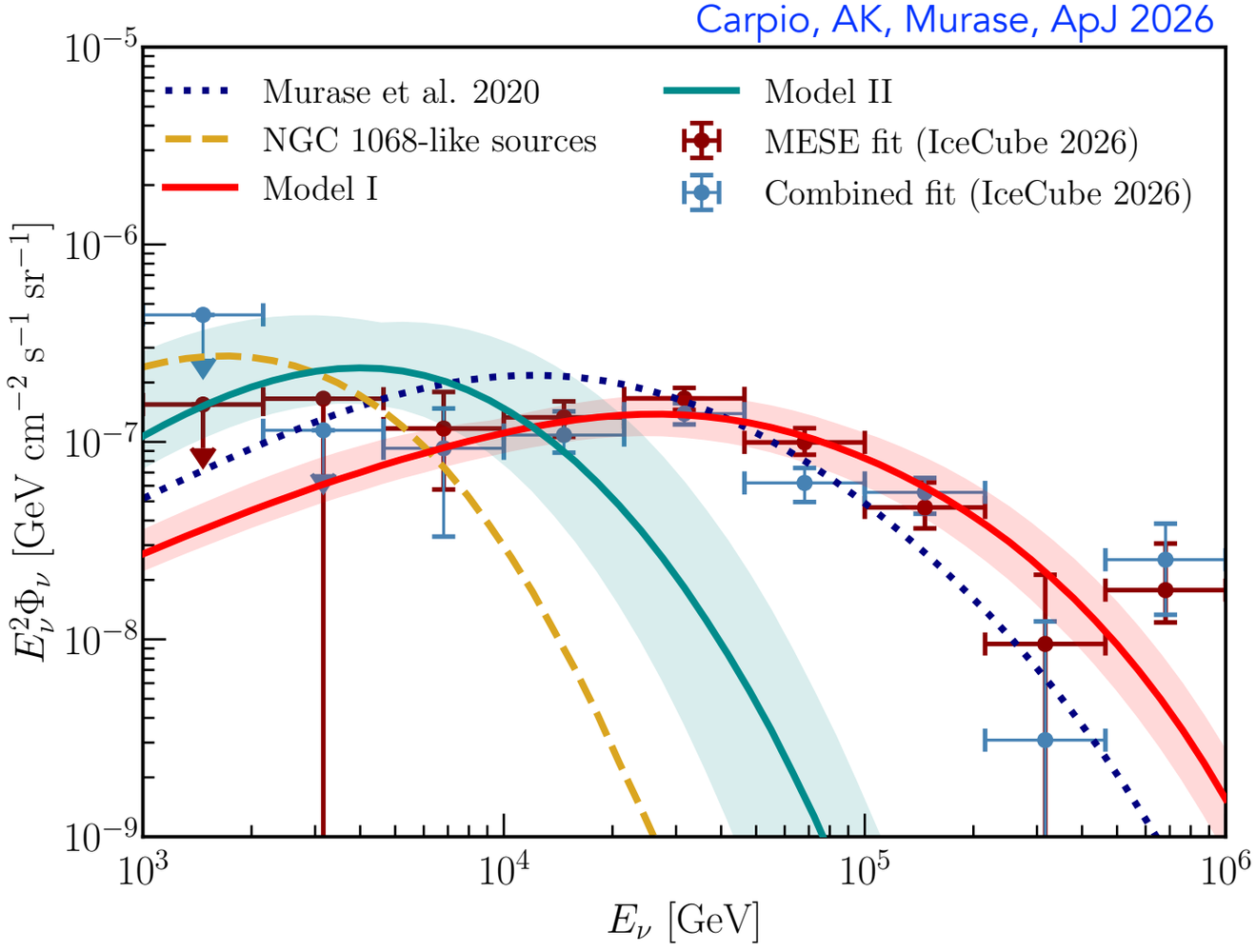
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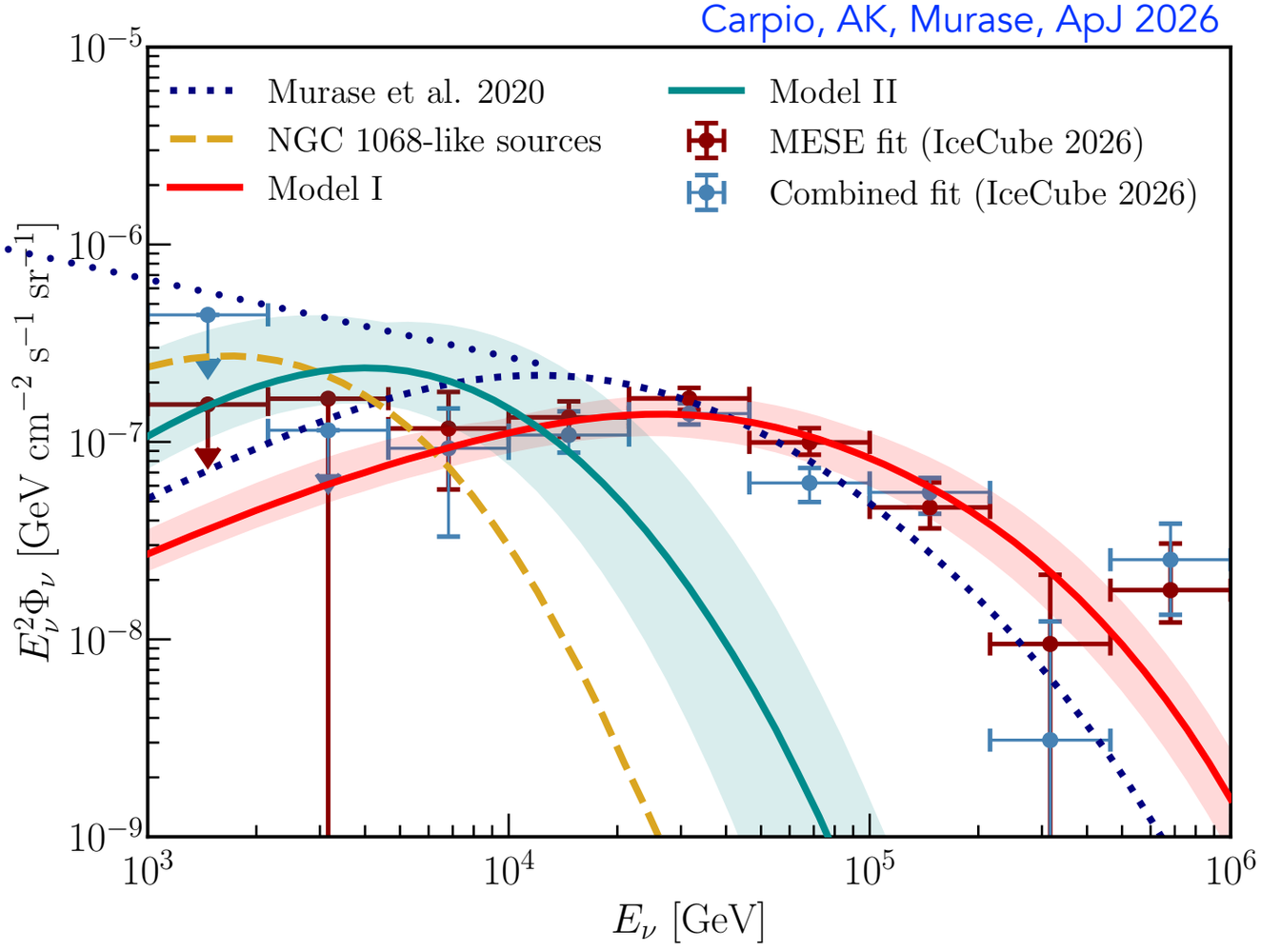


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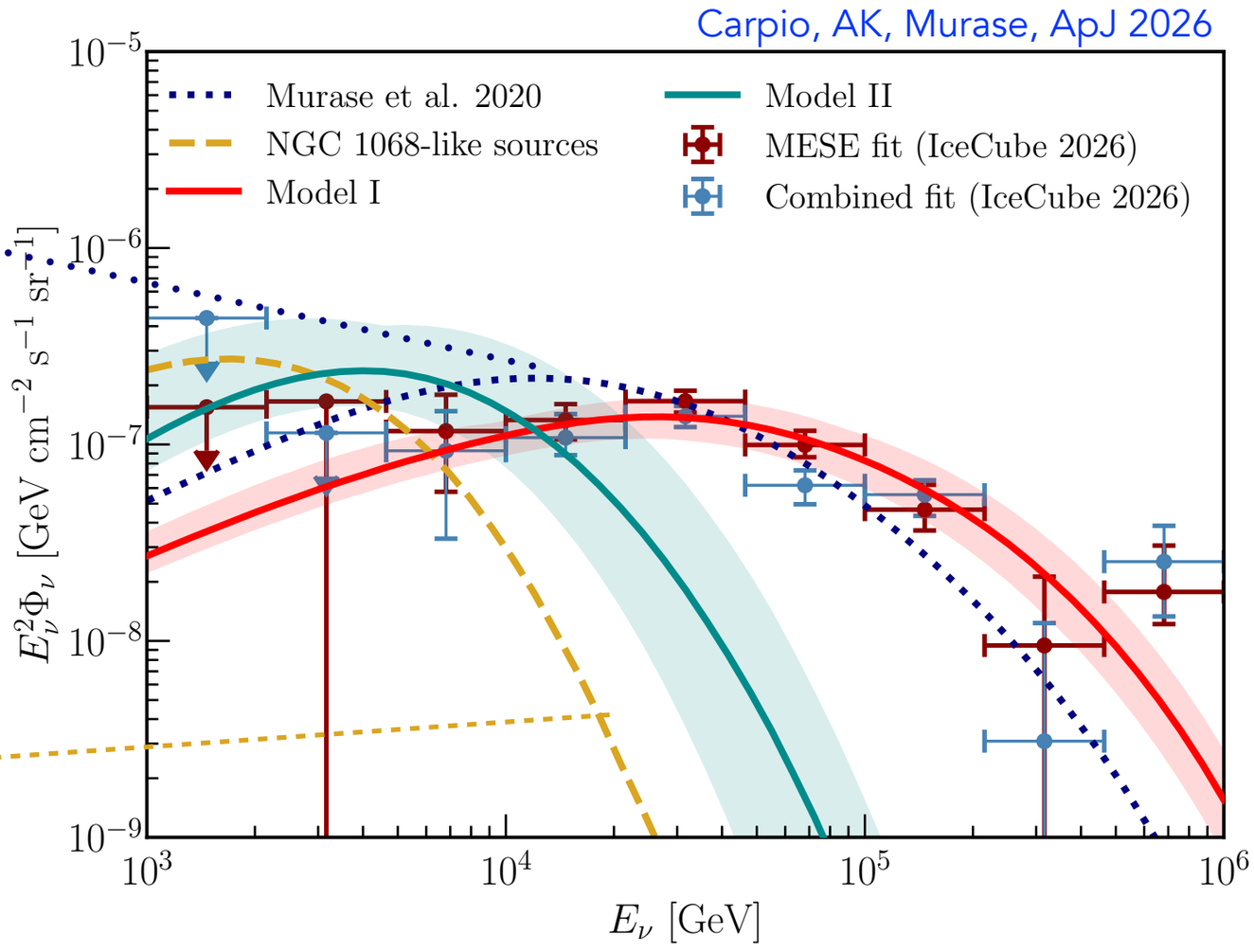
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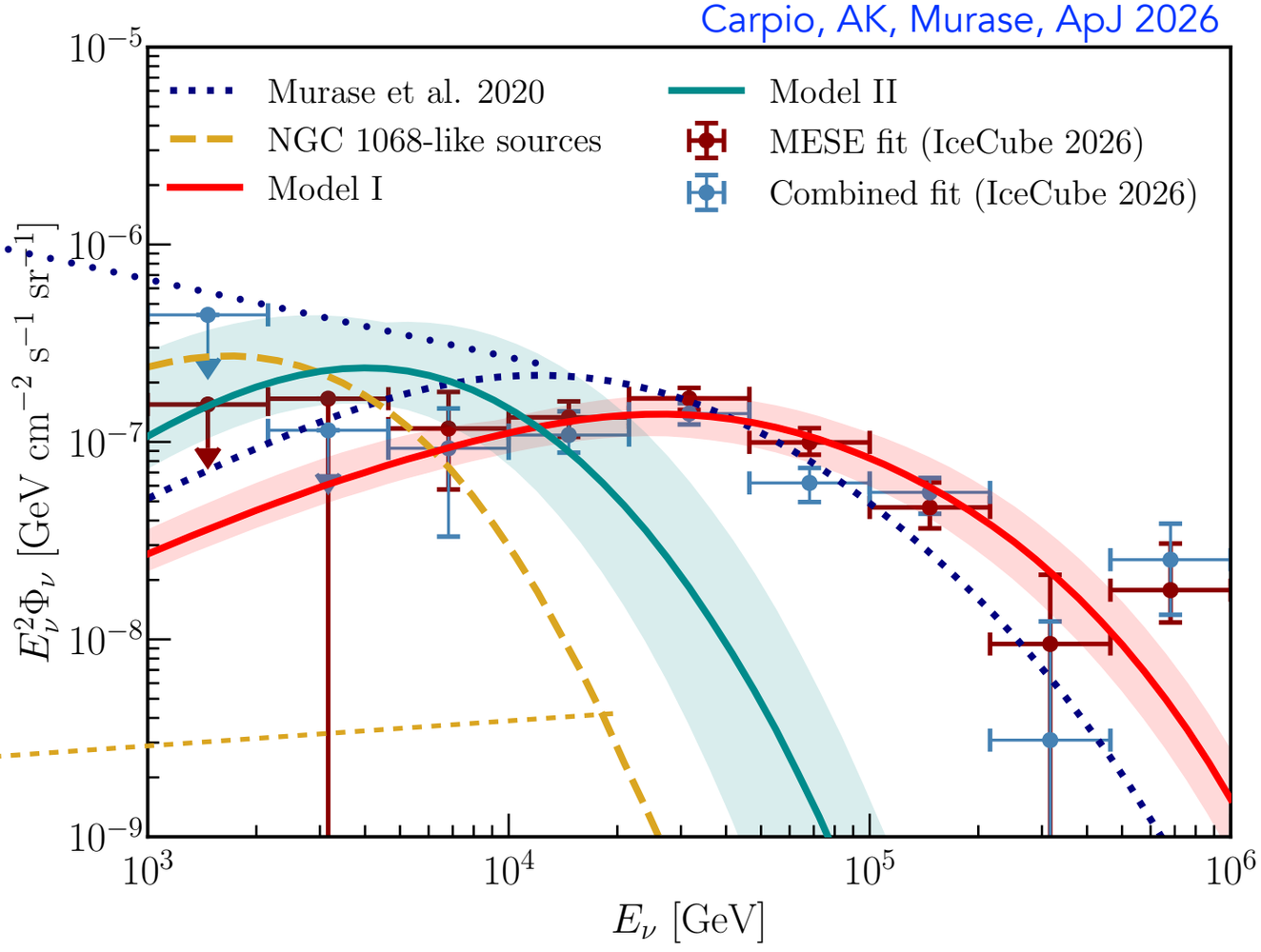
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Assume X-ray Luminosity function [Ueda et al 2014]

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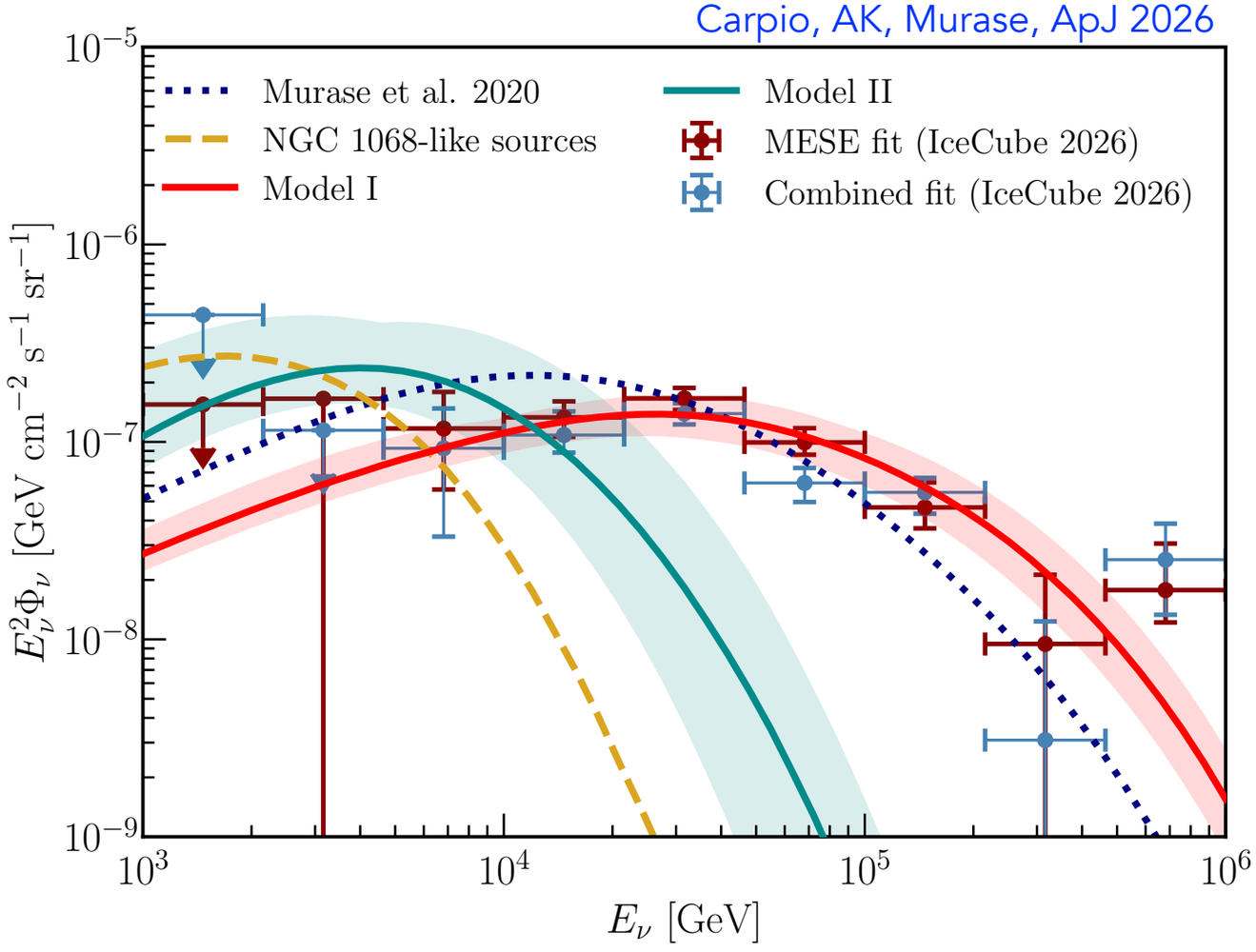
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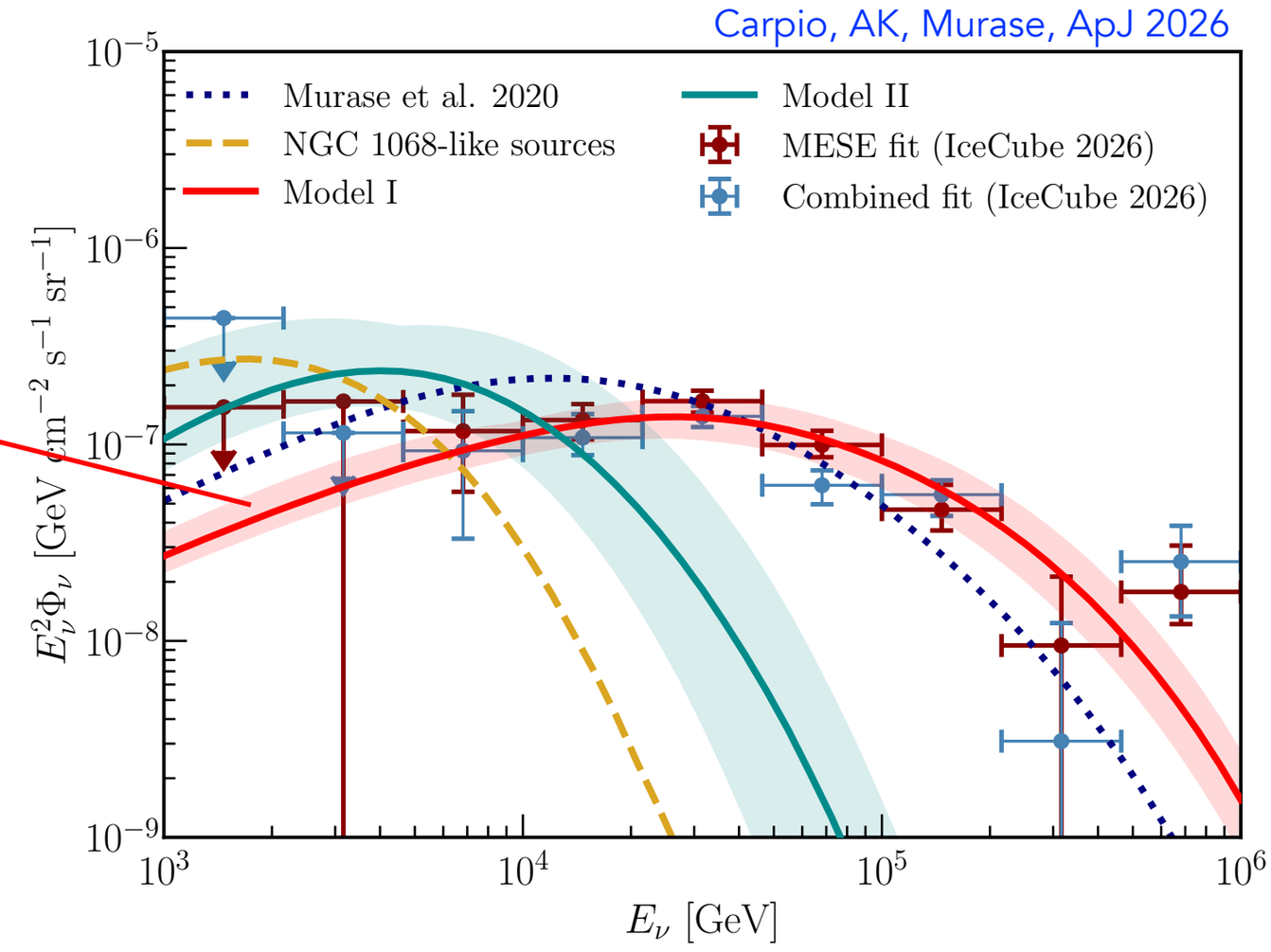


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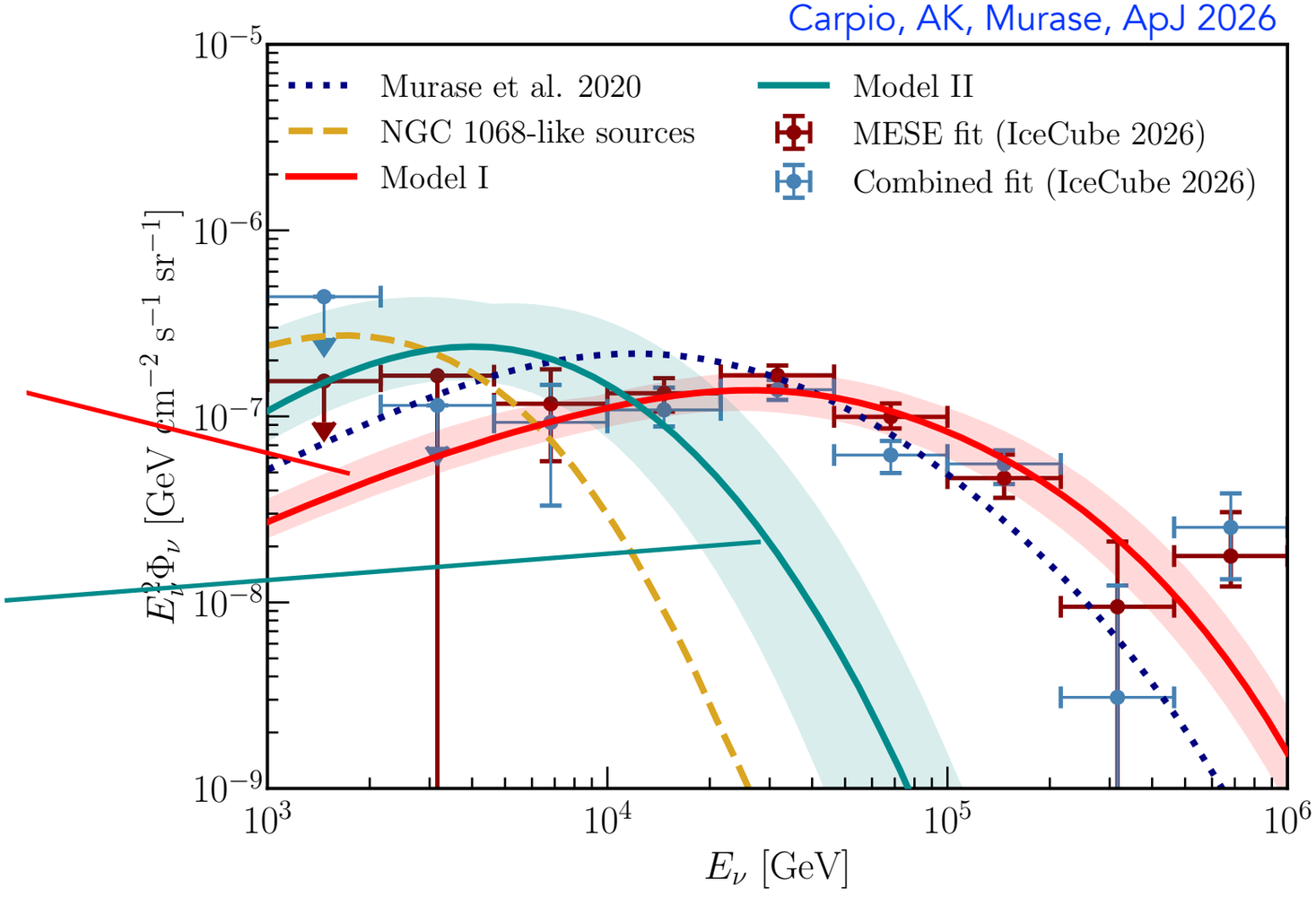
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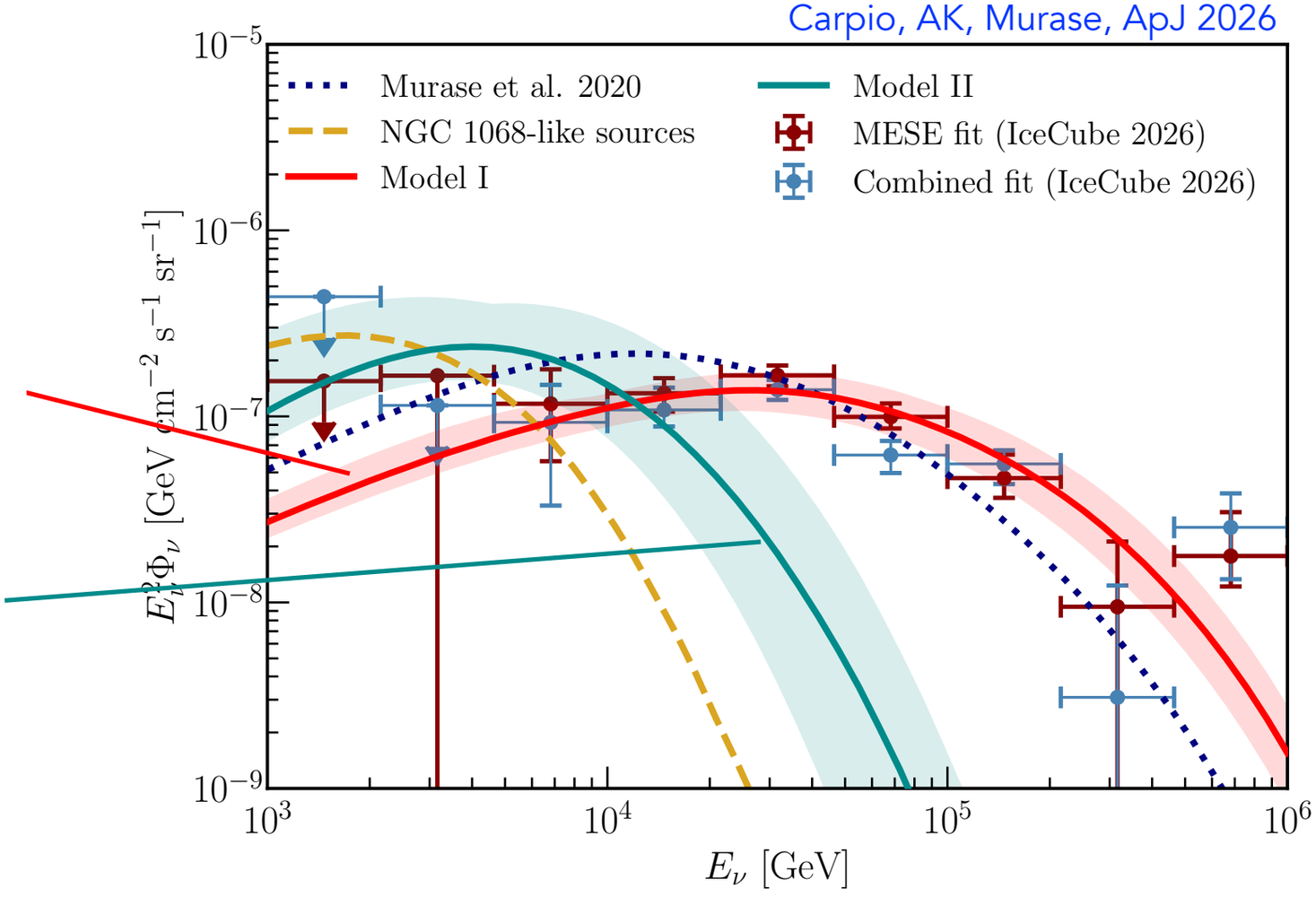
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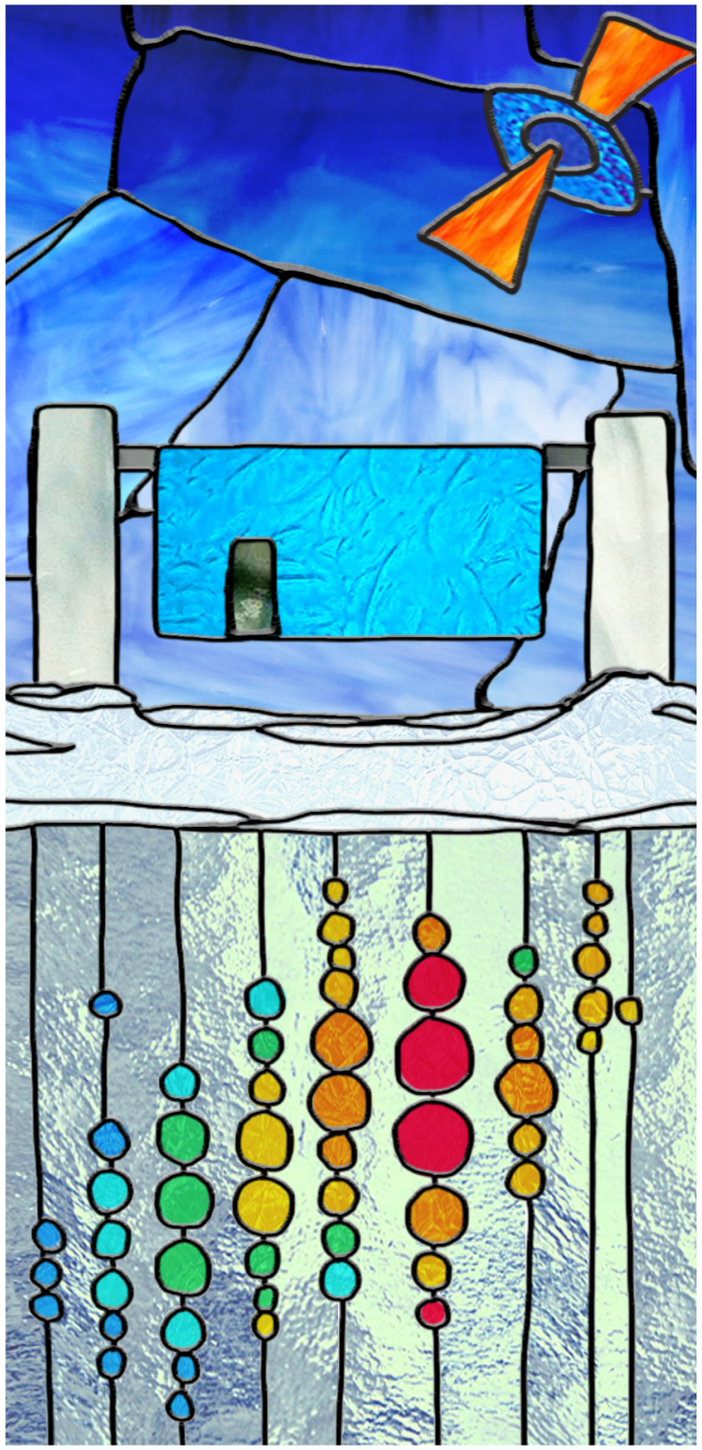
Fitting for the luminosity function

Carpio, AK, Murase, ApJ 2026



# Summary

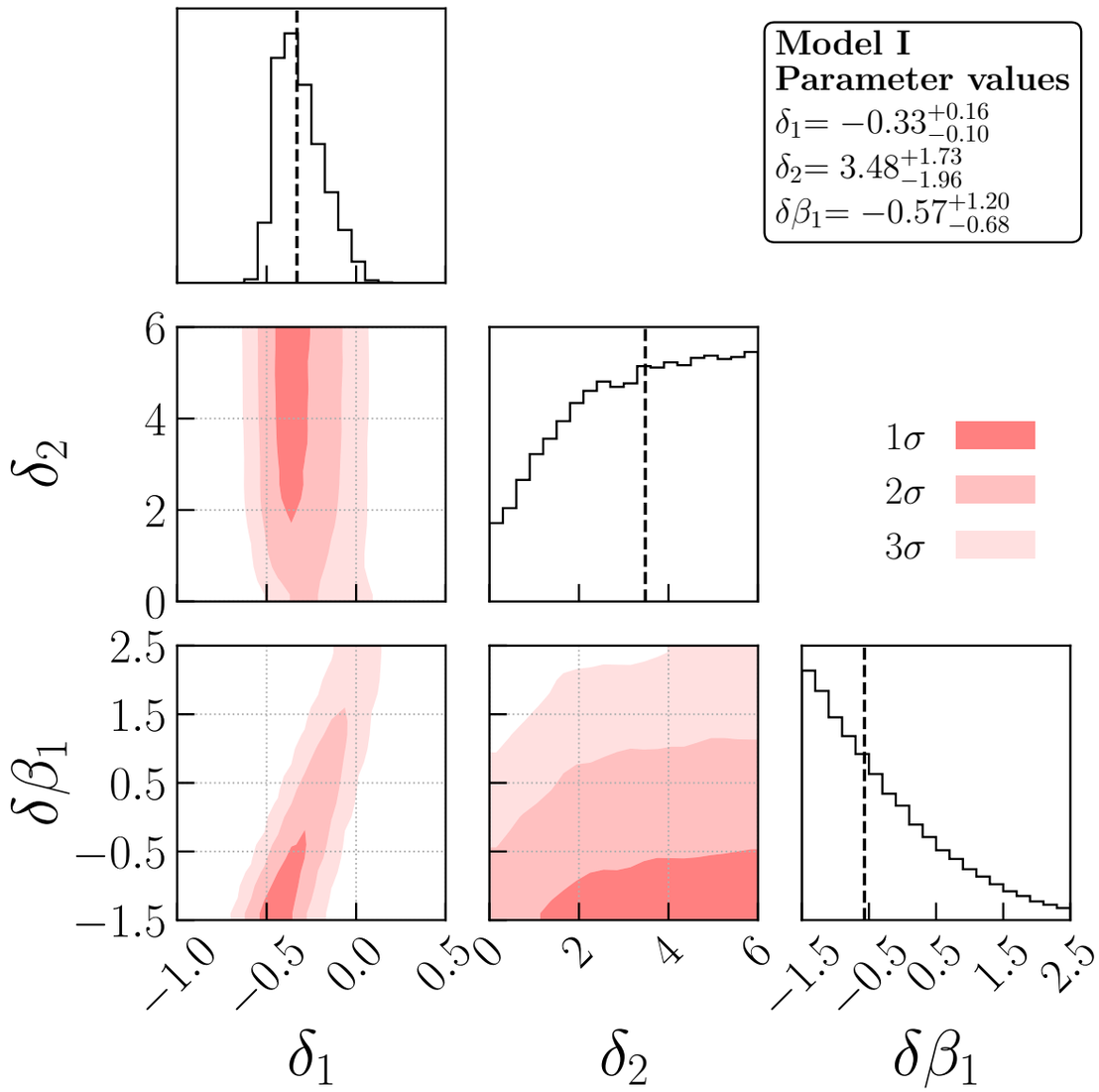
- Growing evidence supports the idea of AGN as the primary sources of HE cosmic neutrinos.
- The high-level of neutrino flux at 30 TeV points to dense environments as the site of neutrino production.
- Multimessenger connection requires $\gamma$-ray hidden $\nu$ sources
  - NGC 1068 and other source candidates fit this criteria.
  - This offers a unique probe of non-thermal phenomena
    - MeV observations are critical to identify the sources.

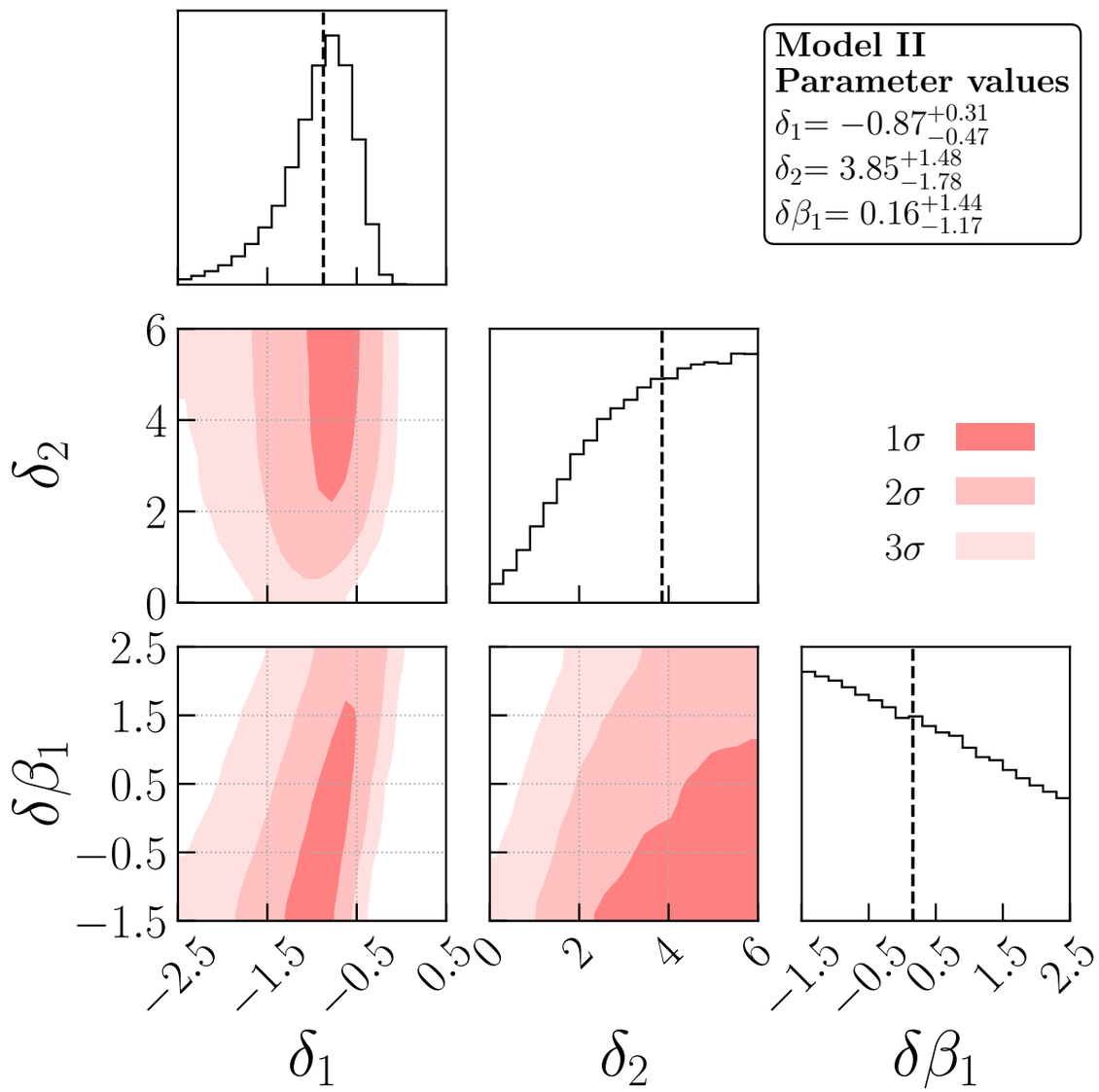


*Thanks!*

# *Back up Slides*

# Luminosity Function Scan



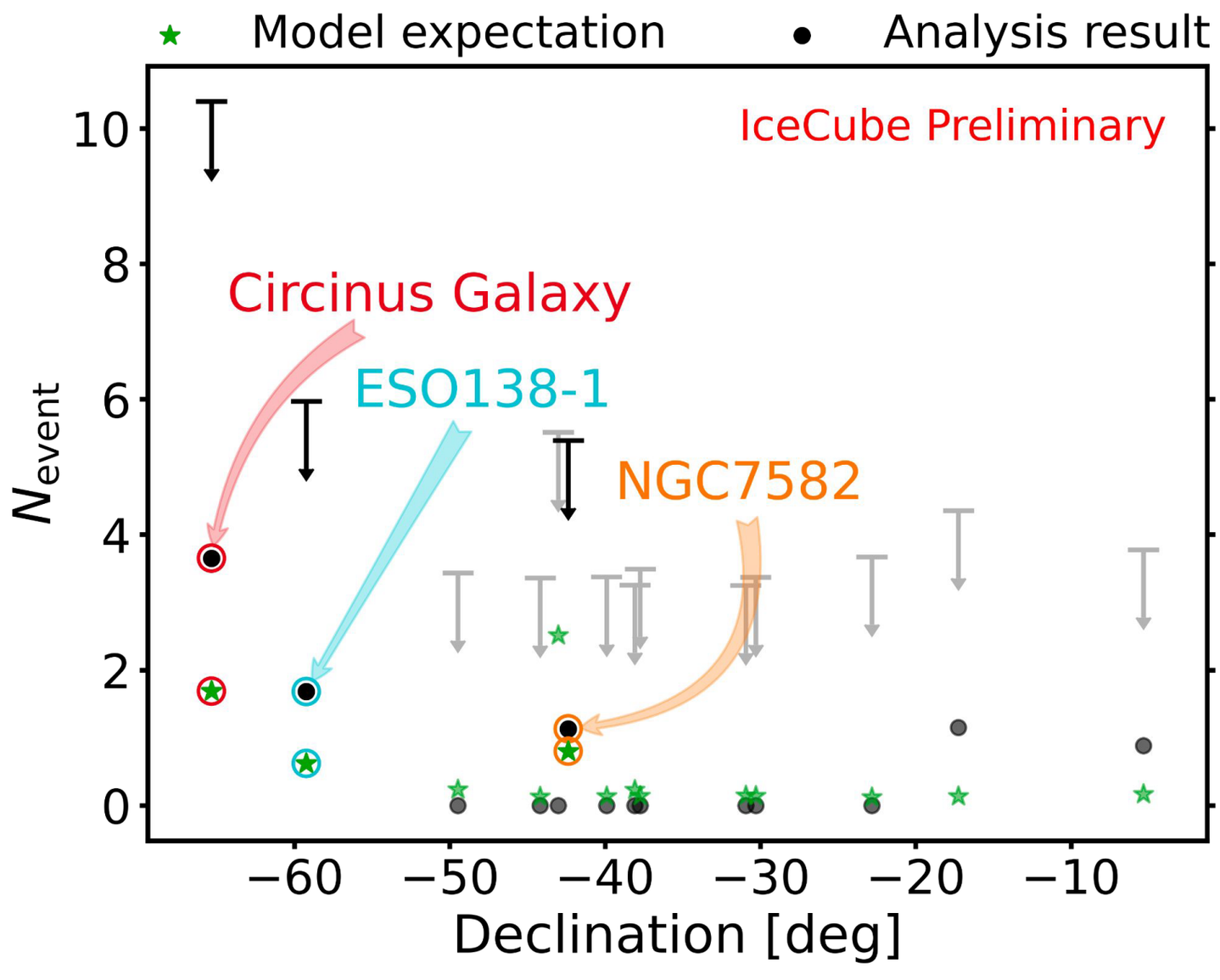
# Results from the Southern Sky

- The majority of bright nearby Seyfert galaxies are in the Southern Hemisphere
- IceCube has **sufficient sensitivity** with Enhanced Starting Events to search for emission from prominent sources in the Southern Hemisphere.

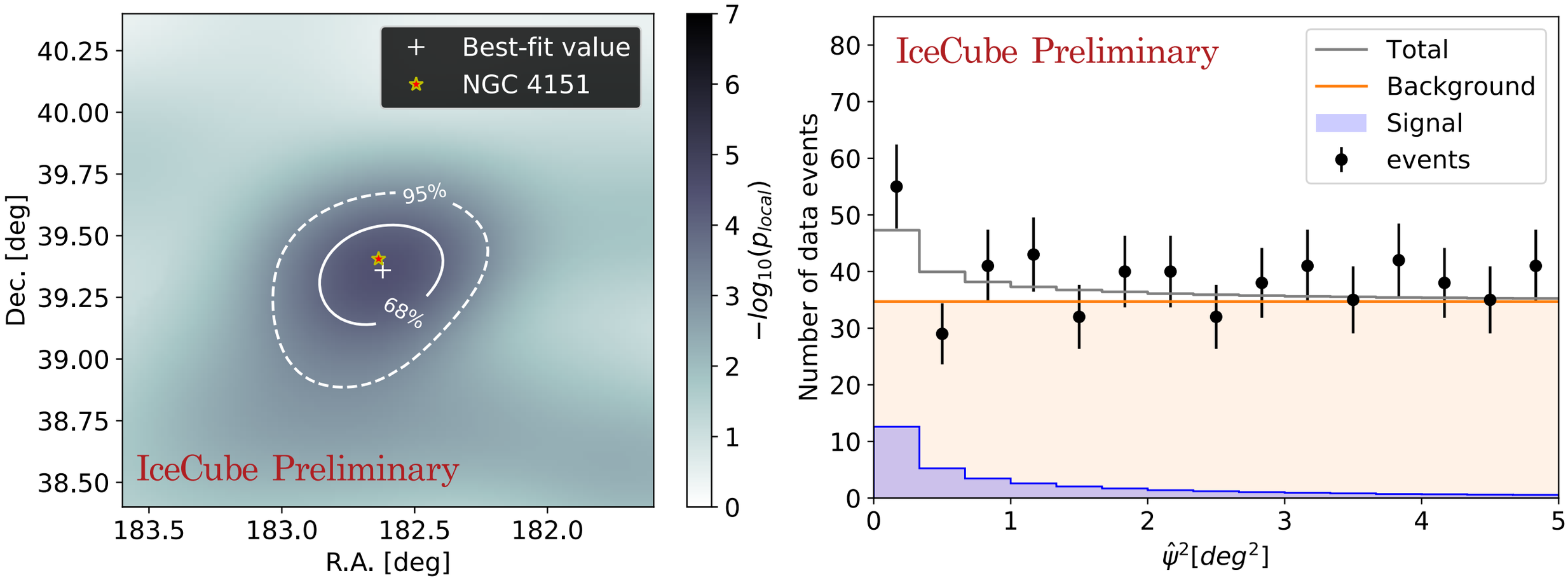
- Best p-value for the source in the Southern sky:
  - ***Circinus Galaxy***
  - 3.6 neutrino events at $2.8\sigma$ local significance ($1.8\sigma$ post trial)

- 2 additional sources with excess:
  - ESO 138-1
  - NGC 7582.

- Stacking analysis:
  - ► 6.7 events at $3\sigma$



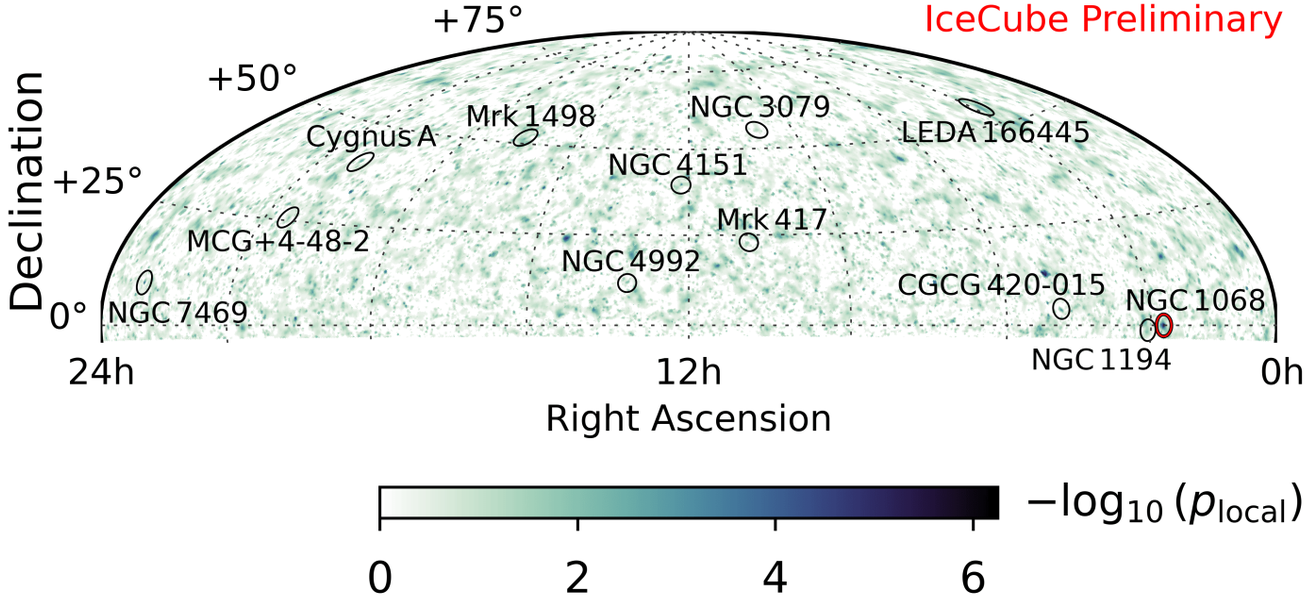
# NGC 4151 — $2.9\sigma$

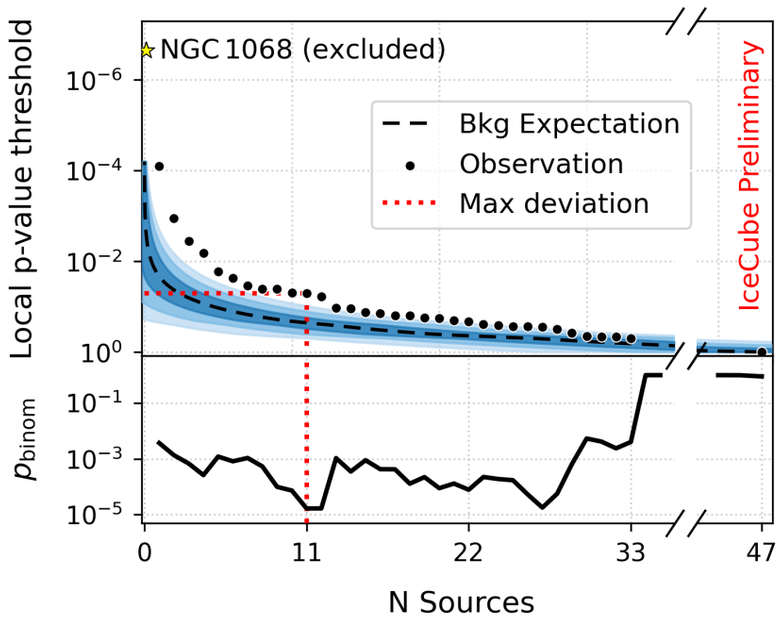


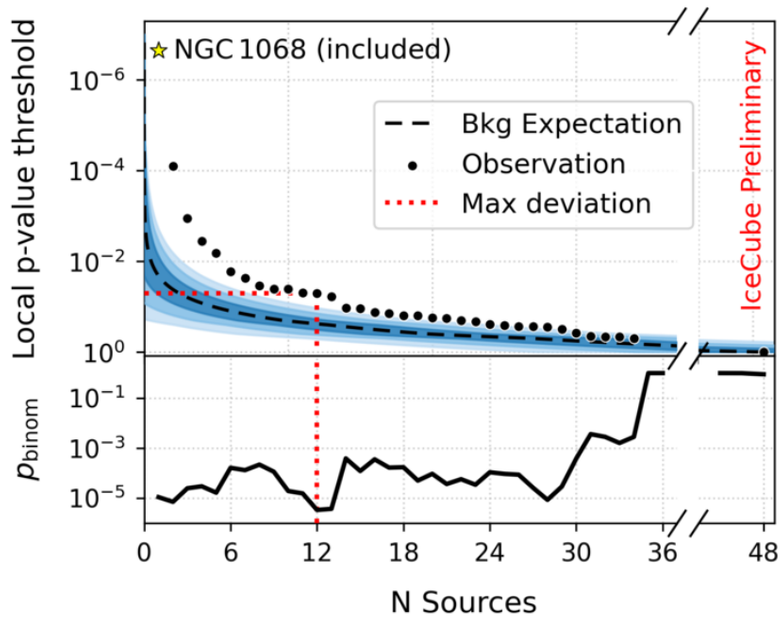

- NGC 4151 appears at $2.9\sigma$ (global significance)
- The second most significant steady source in IceCube

# 13 yr NT Seyfert Search

- Tested 47 bright seyfert galaxies in the Northern Hemisphere
- 11 sources are found in the binomial p-value test at $3.3\sigma$ (excluding NGC 1068)




T. Kontrimas
TeVPA 2024

# Neutrino and $\gamma$-ray from Magnetically Powered Corona

*Principal Parameters*

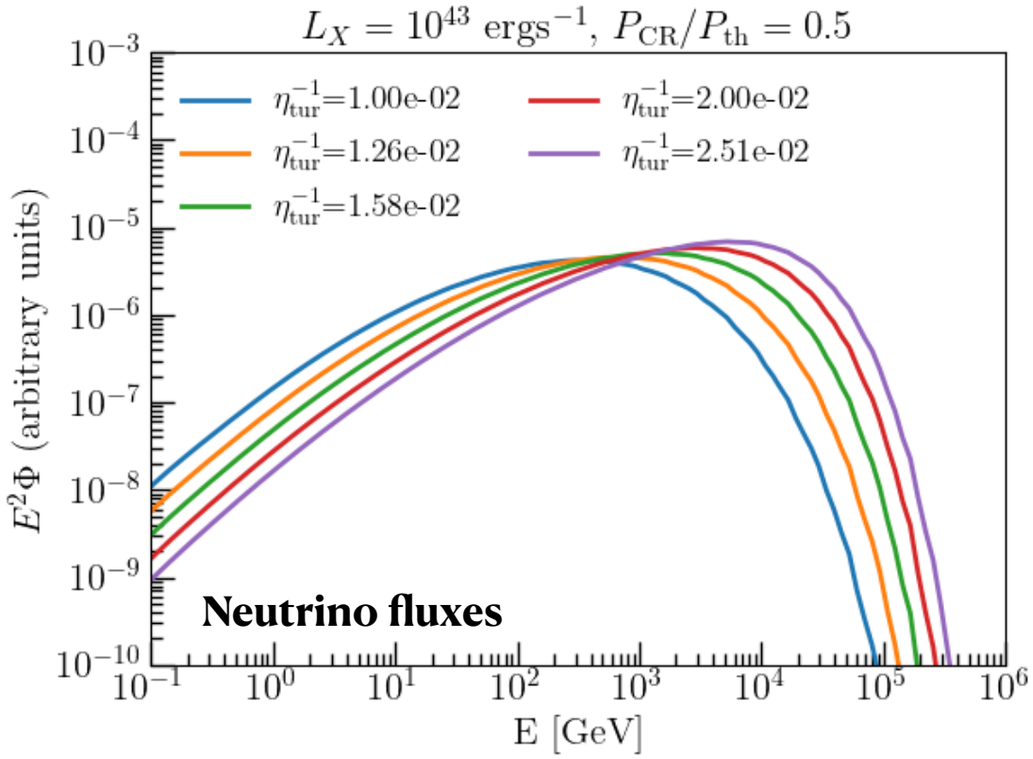
Turbulence strength $\eta_{\rm tur}$ → Determines **maximum** CR energy

$\eta_{\rm tur} \propto t_{\rm acc}$, where $t_{\rm acc}$ is the CR acceleration time

Large $\eta_{\rm tur}^{-1}$ (short $t_{\rm acc}$) require **shorter cooling times** to prevent efficient acceleration

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Proton energy **cutoff** occurs at higher energies



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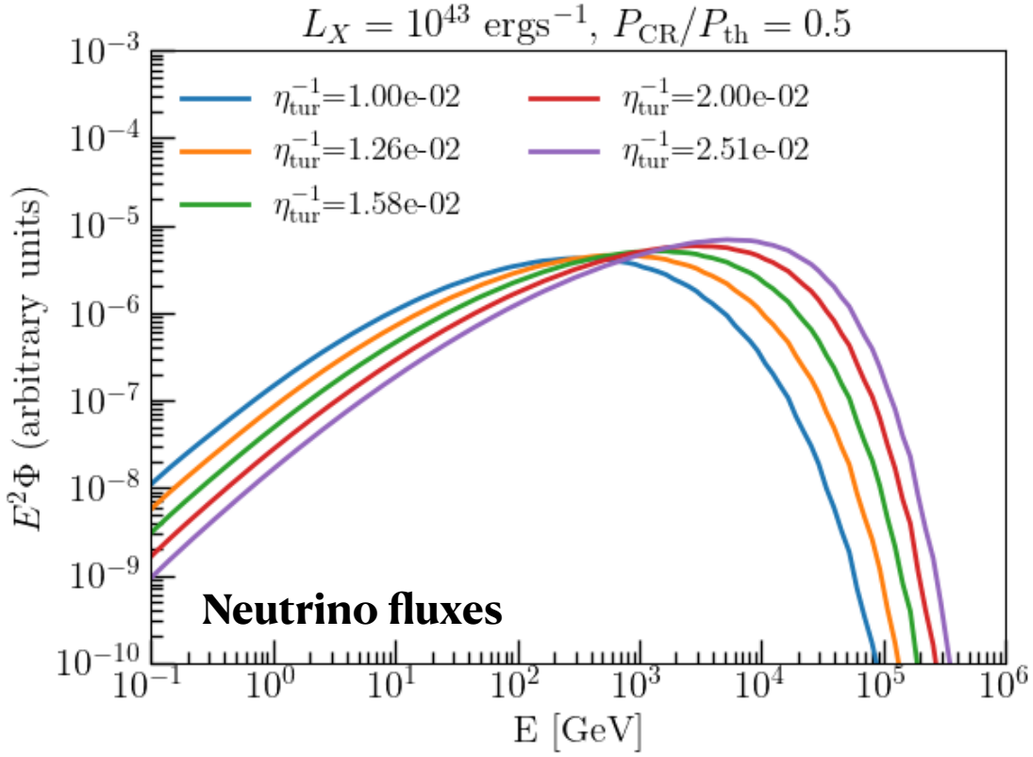
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Emission radius → Determines injection spectra and optical depths

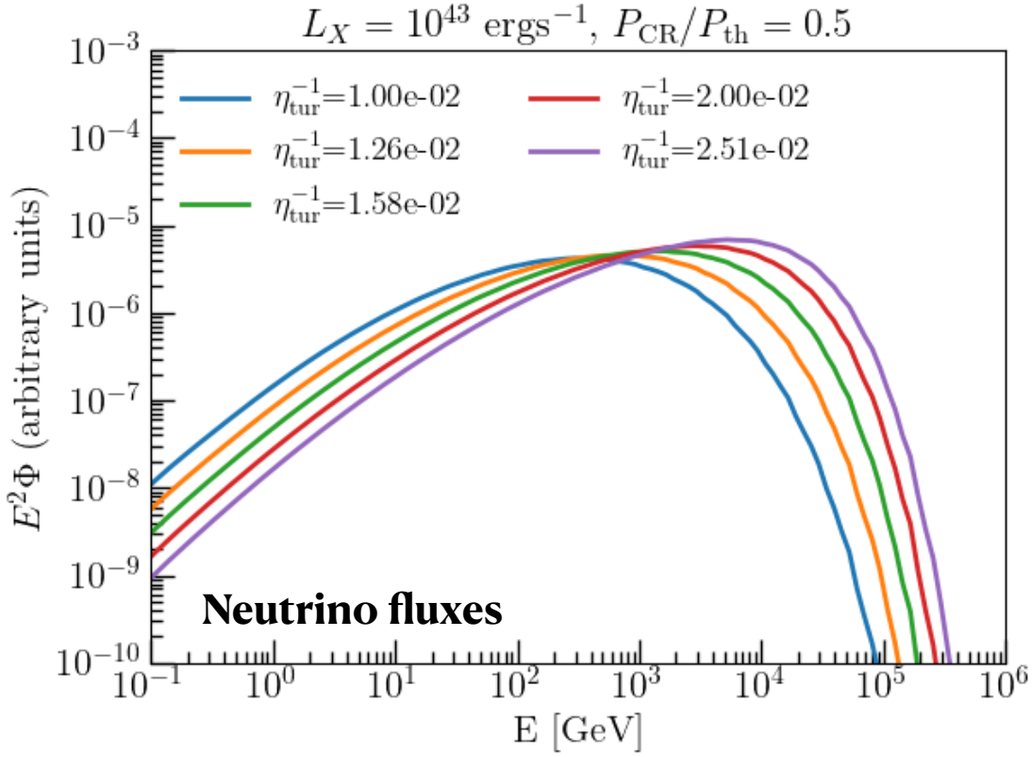
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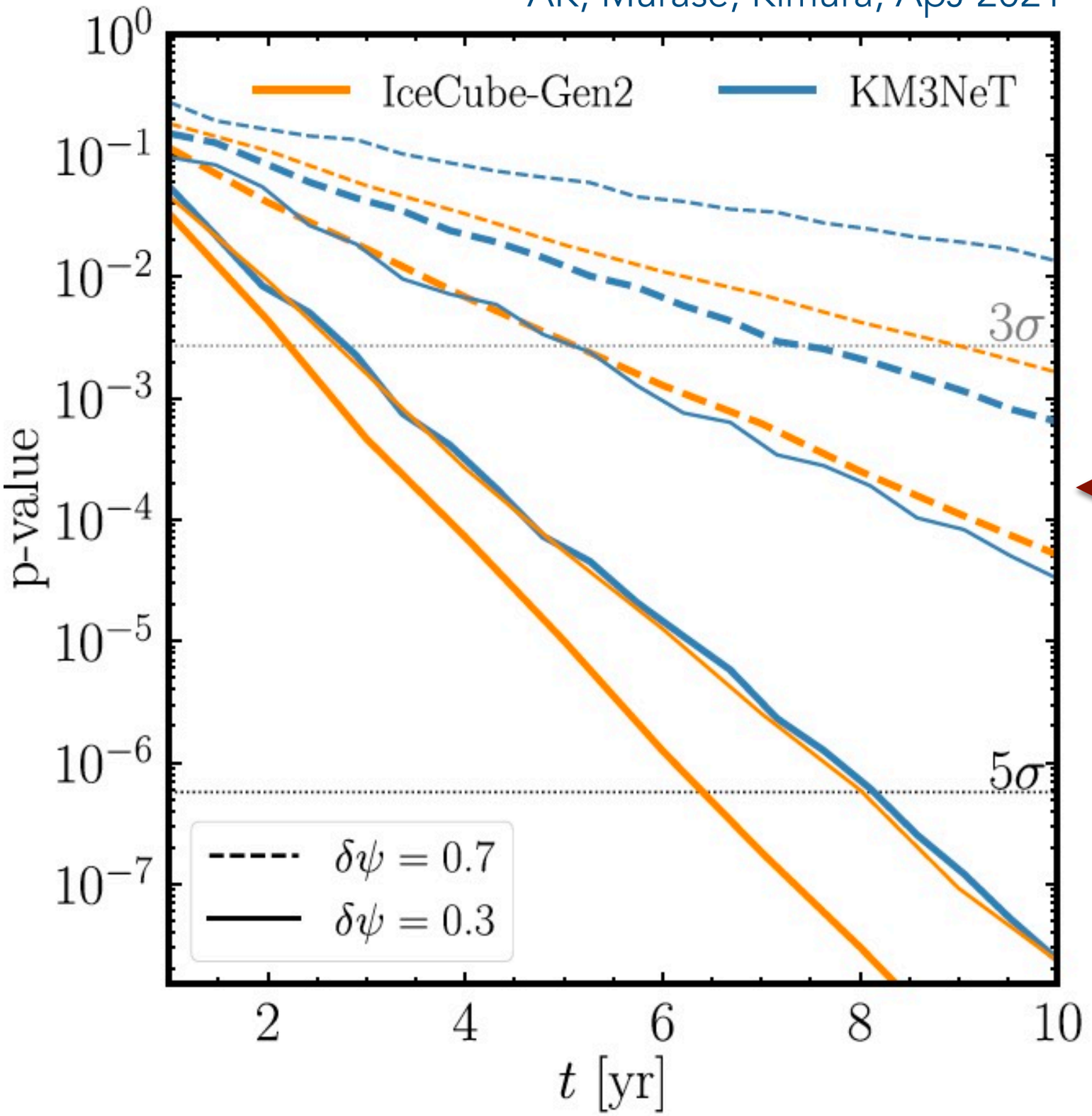
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# Prospects for future experiments

AK, Murase, Kimura, ApJ 2021




Modest CR Pressure Scenario