

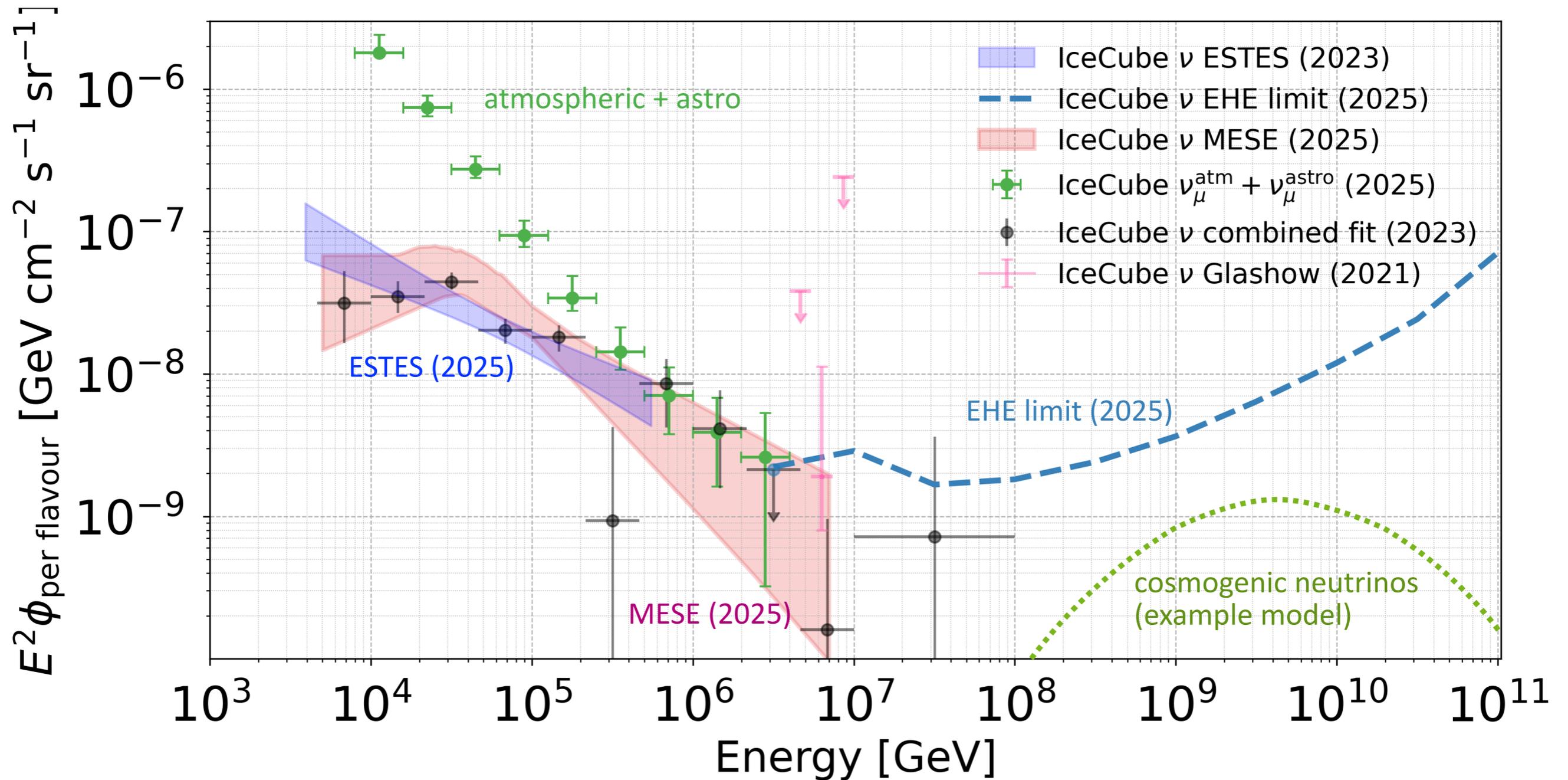
# Neutrino Sources

Ali Kheirandish  
University of Nevada, Las Vegas

4th TDAMM Workshop  
Science & Technology Institute  
October 2025



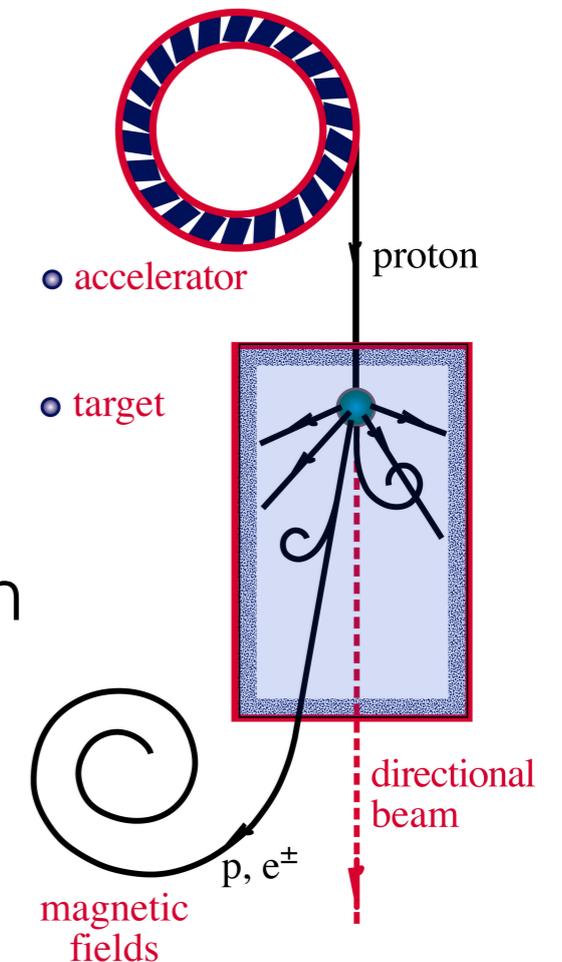
# High-Energy Neutrino Flux



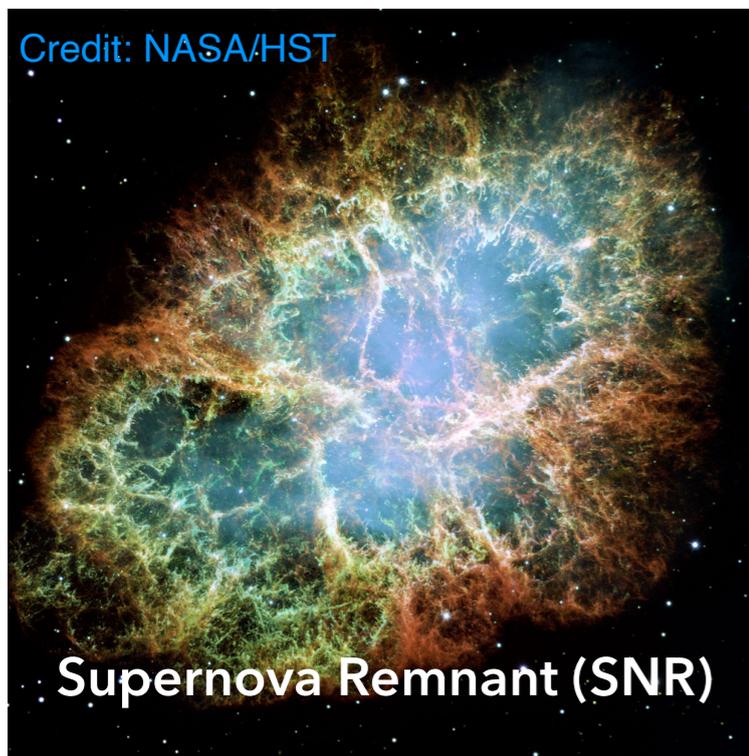
# Possible Sources

Sources of TeV - PeV cosmic neutrinos should

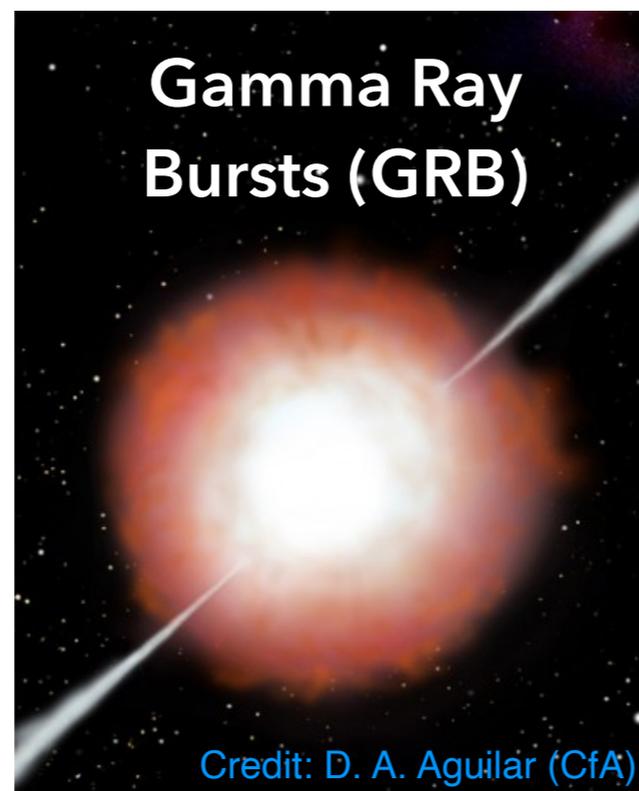
- ▶ Accelerate Cosmic Rays to  $>$  PeV energies
  - ▶▶ sources of VHE & UHE CRs
- ▶ Poses beam dumps that facilitate CR interaction
  - ▶▶ environment that can provide gas and radiation with enough density



Credit: NASA/HST



Gamma Ray  
Bursts (GRB)



Credit: NASA



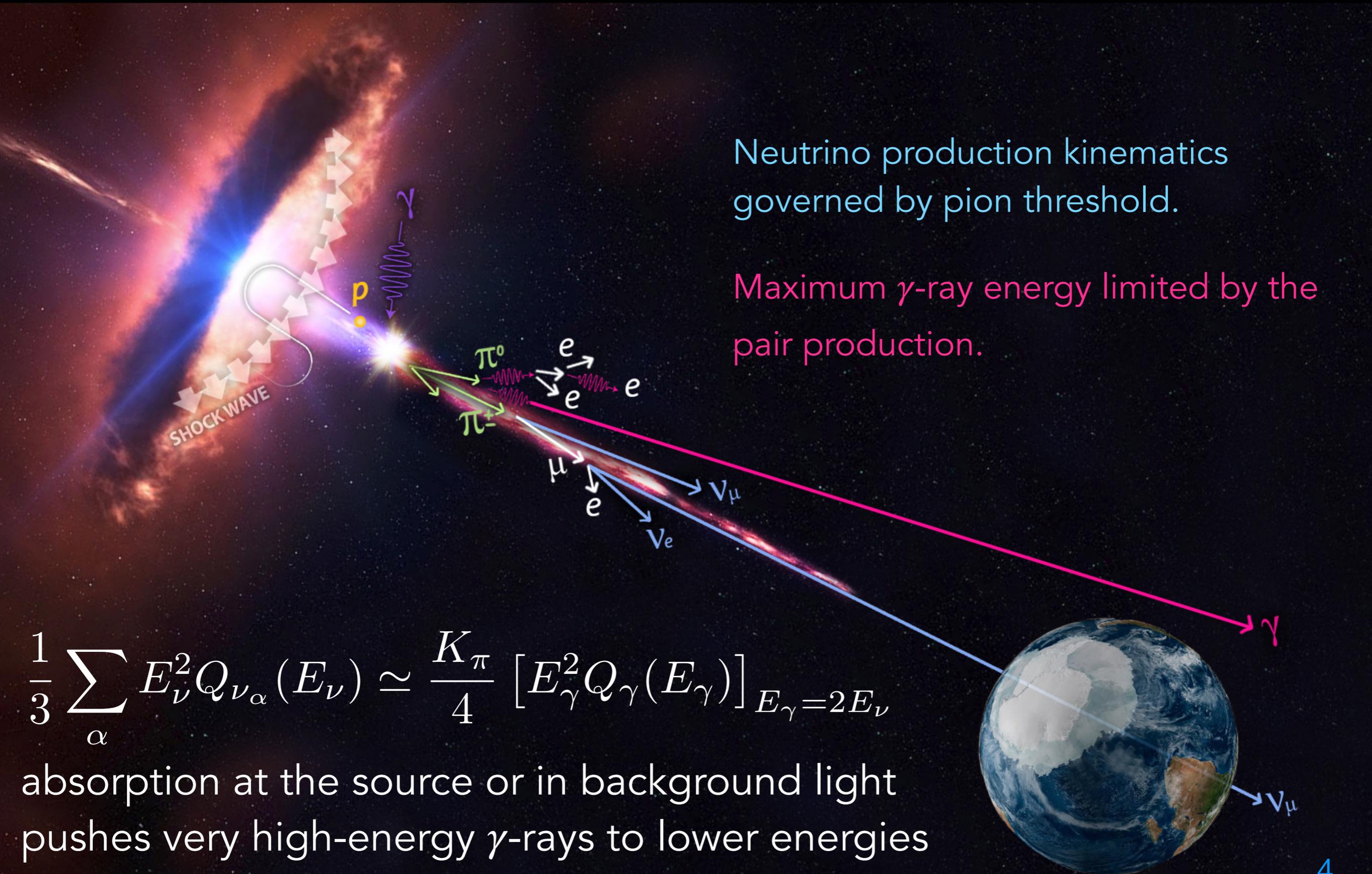
# The Neutrino $\gamma$ -ray Connection

Neutrino production kinematics governed by pion threshold.

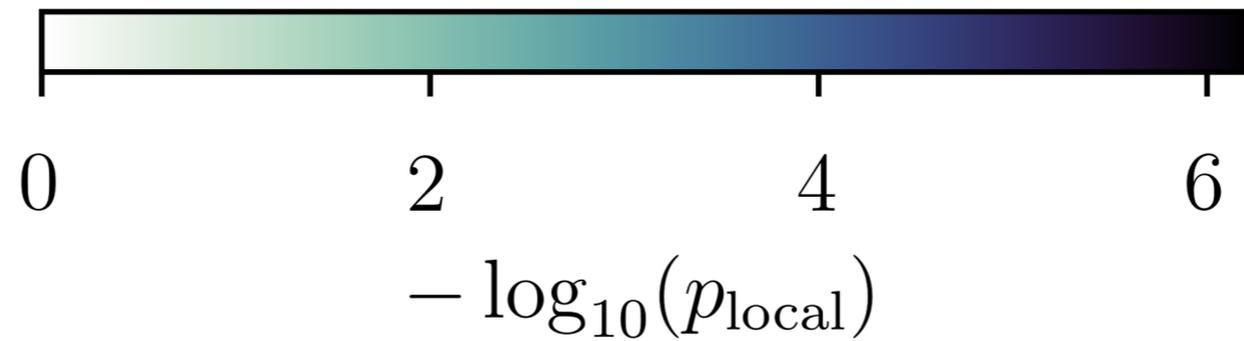
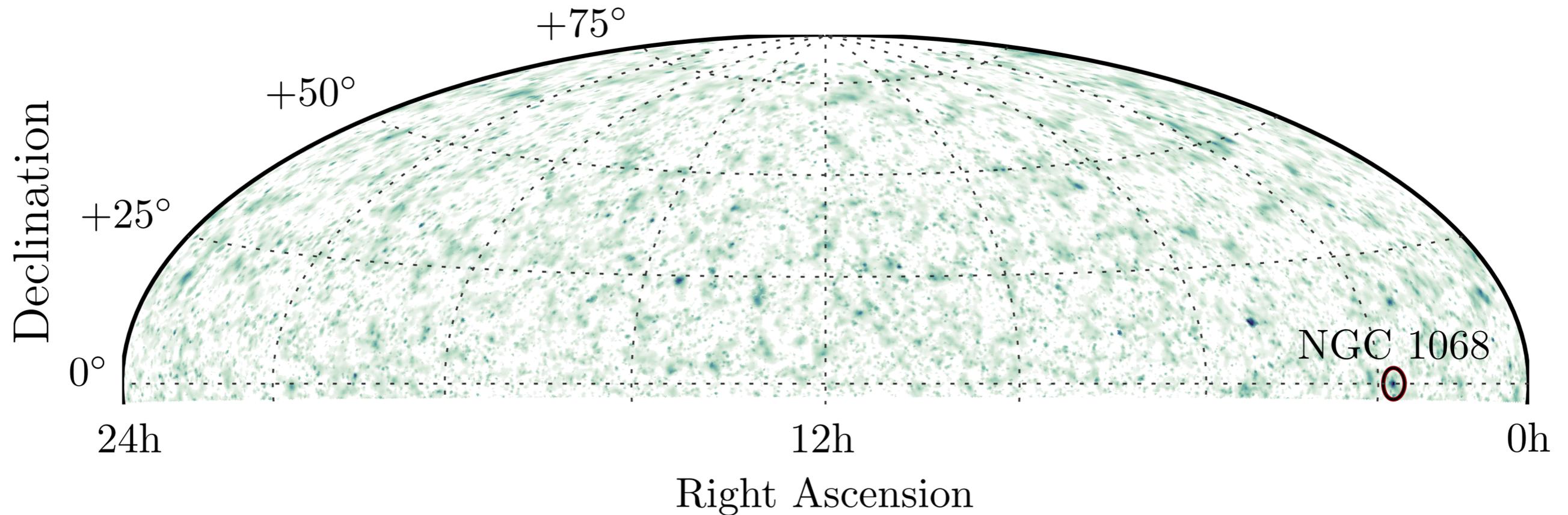
Maximum  $\gamma$ -ray energy limited by the pair production.

$$\frac{1}{3} \sum_{\alpha} E_{\nu}^2 Q_{\nu_{\alpha}}(E_{\nu}) \simeq \frac{K_{\pi}}{4} [E_{\gamma}^2 Q_{\gamma}(E_{\gamma})]_{E_{\gamma}=2E_{\nu}}$$

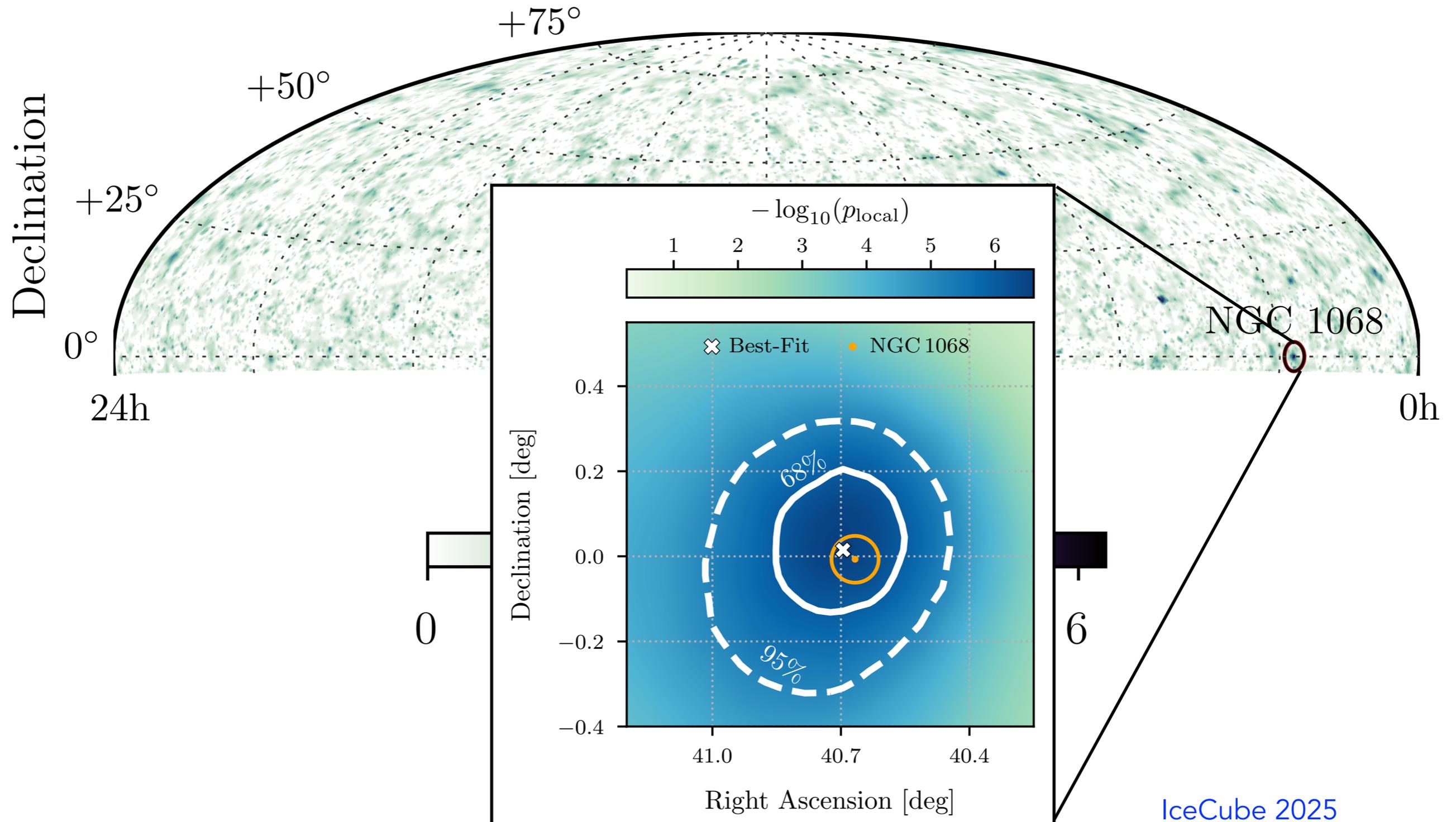
absorption at the source or in background light pushes very high-energy  $\gamma$ -rays to lower energies



# NGC 1068; The 1st Steady Neutrino Source

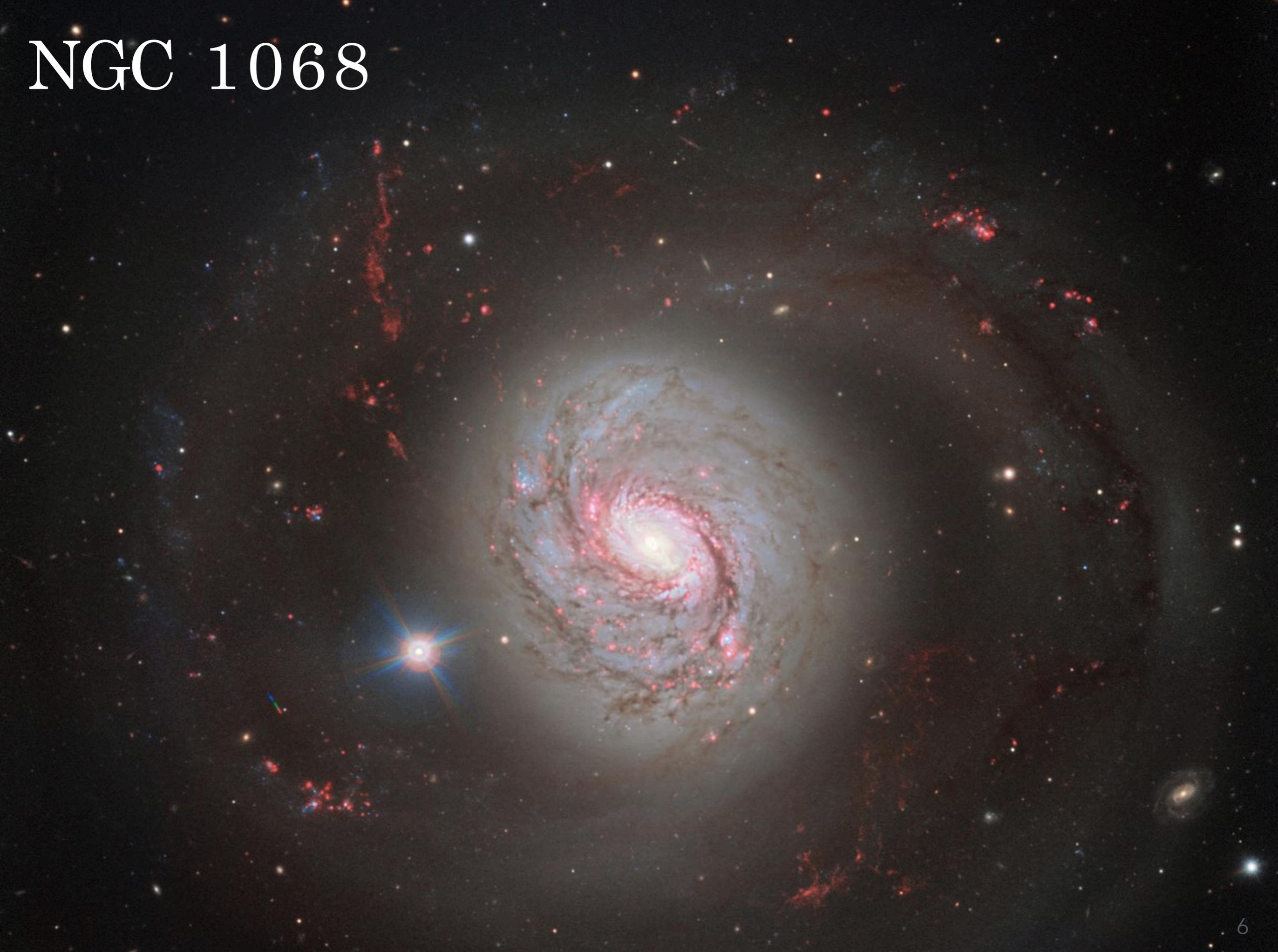


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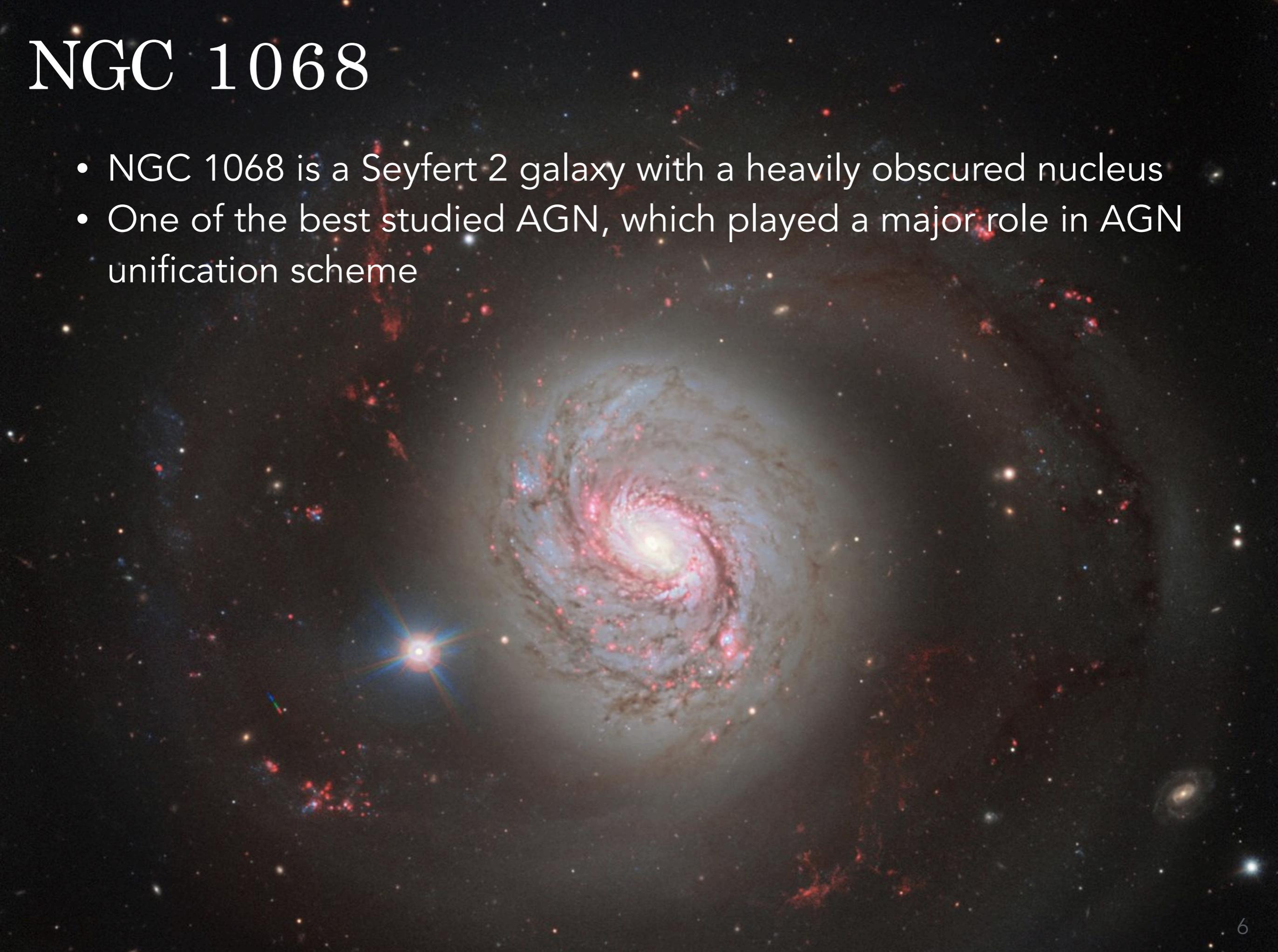
IceCube 2025

NGC 1068



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



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

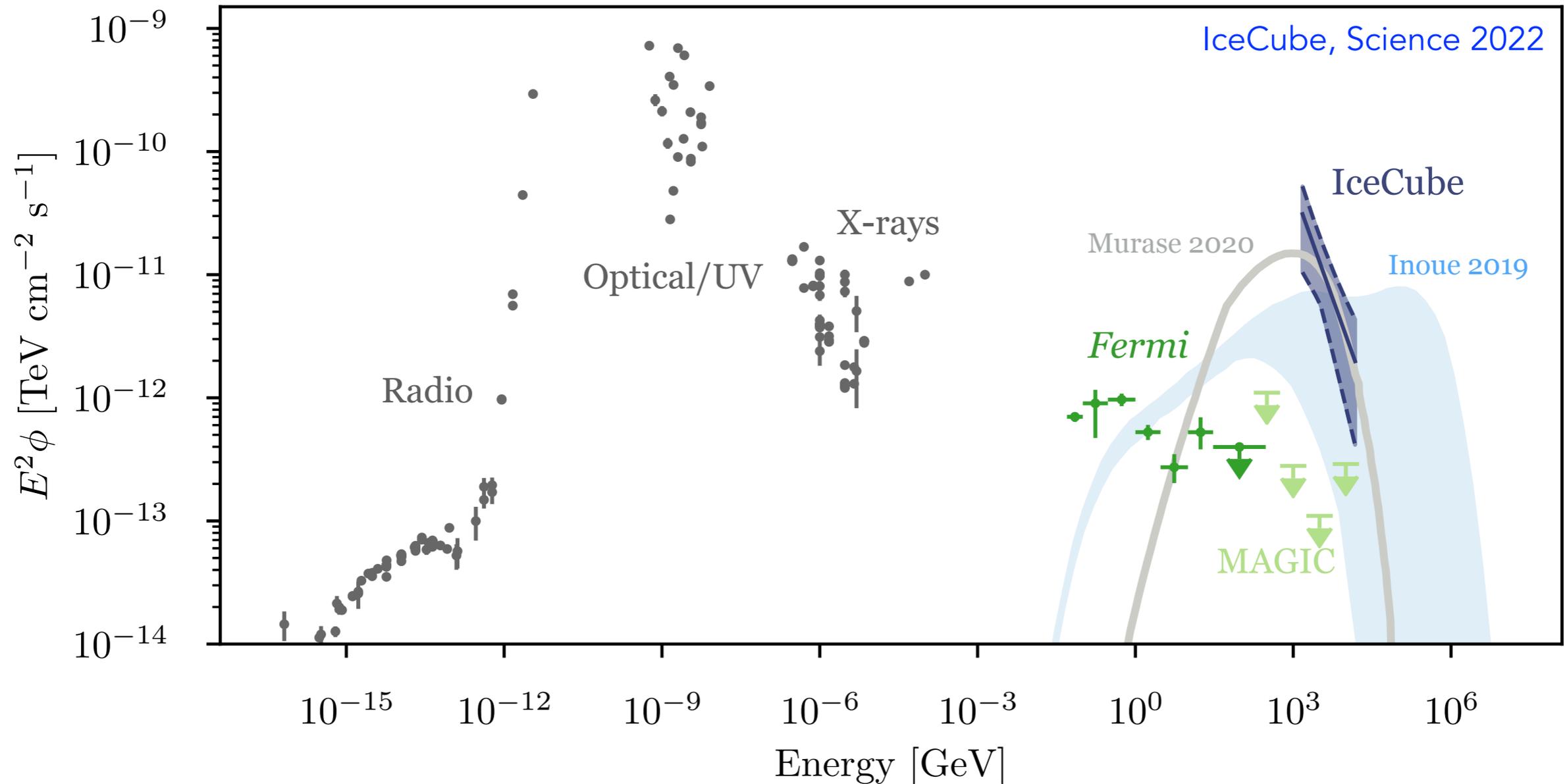
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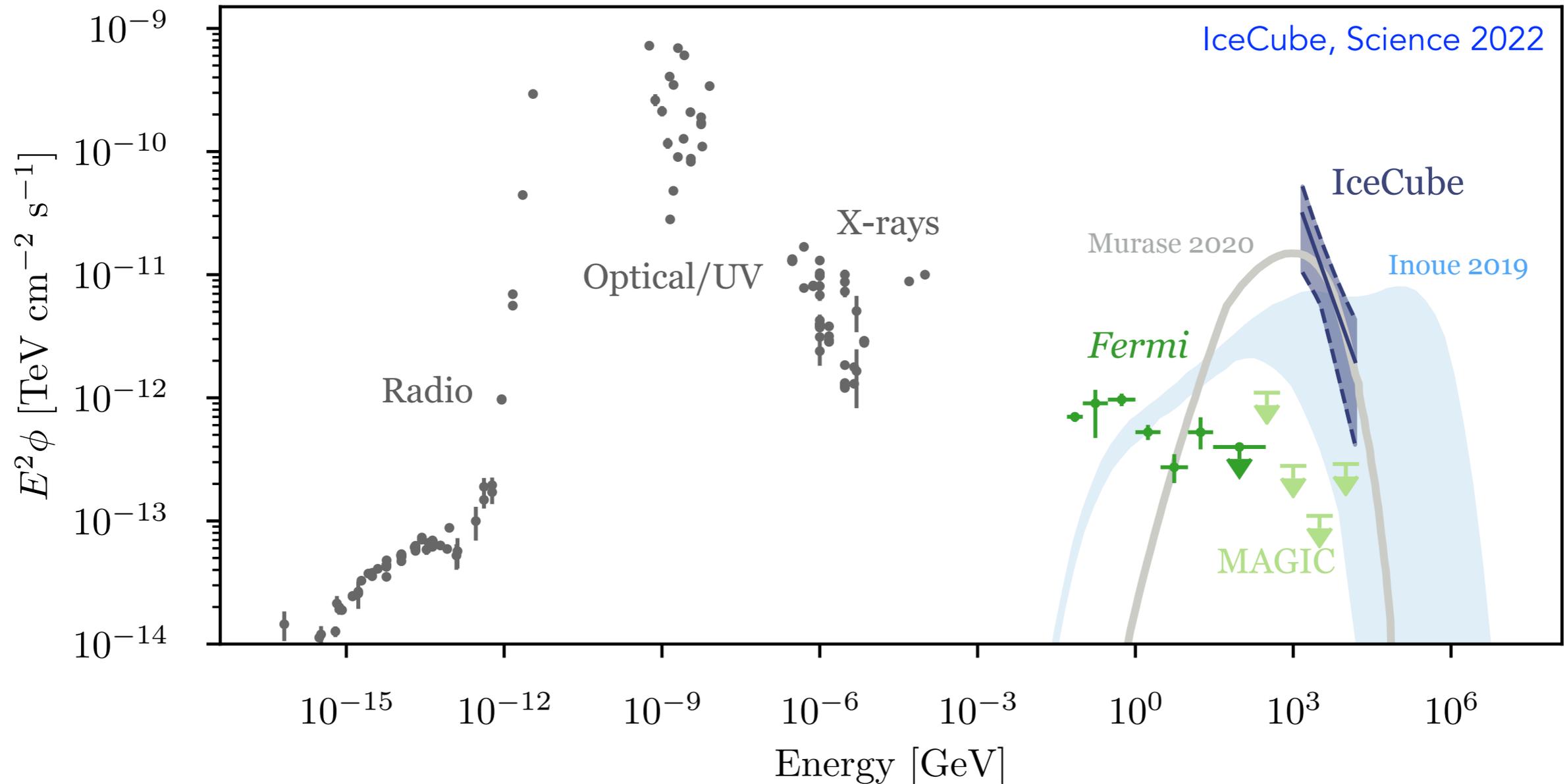
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- Bright in X-ray, and high infrared luminosity indicating high level of star formation
  - ▶ *Historically considered as a promising cosmic-ray accelerator.*

# NGC 1068 Spectrum



- ▶ Models built on Fermi  $\gamma$ -ray flux by cannot accommodate the neutrino flux.
- ▶ **Obscuring** necessary to absorb the pionic  $\gamma$ -ray accompanying neutrinos.
- ▶ The high opacity indicates that the neutrinos are produced in the vicinity of AGN core ( $< 100 R_s$ ) [Murase, ApJL 2022]

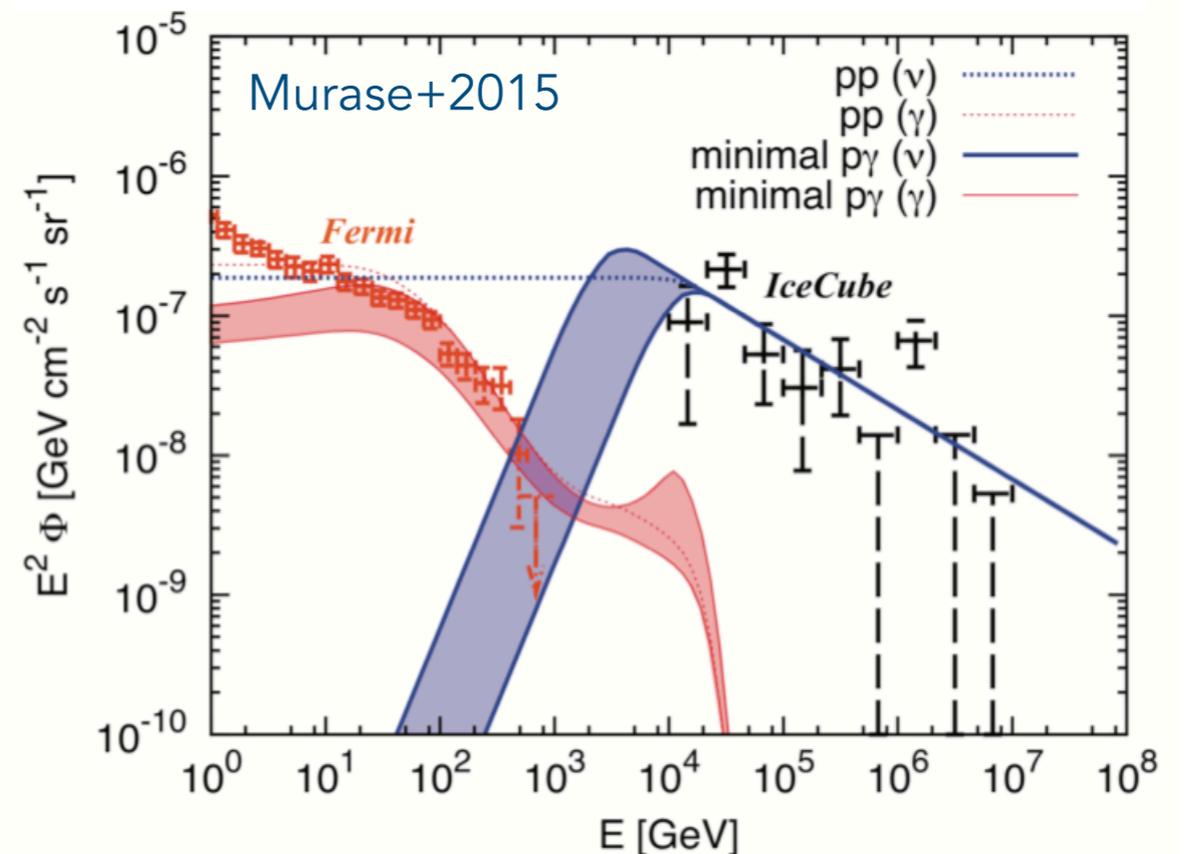
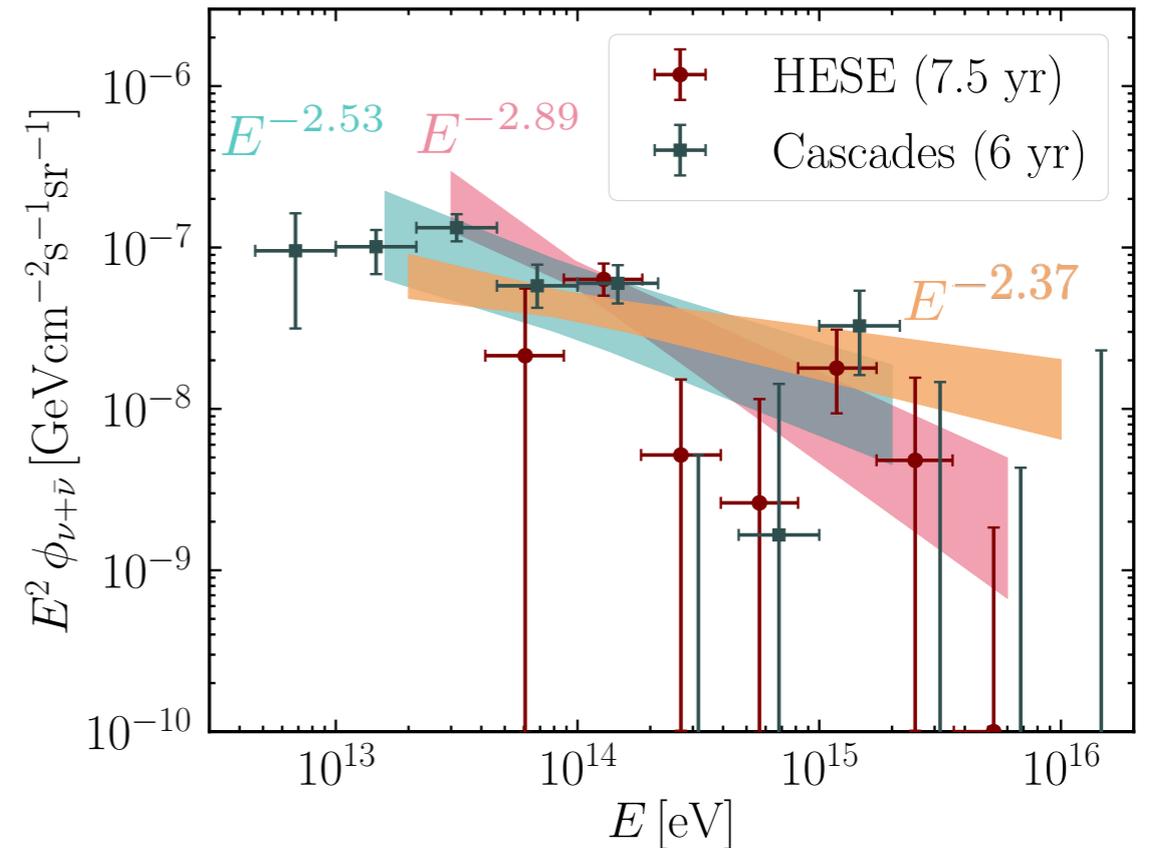
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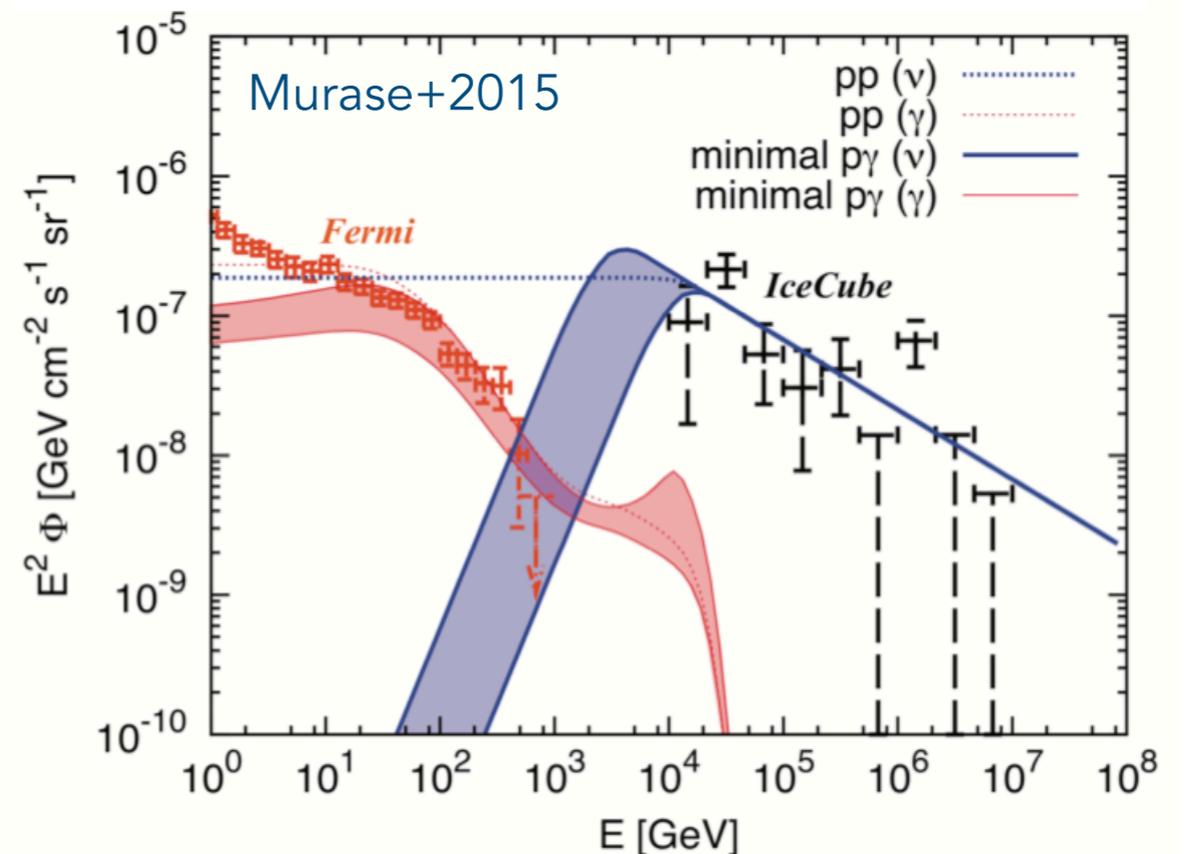
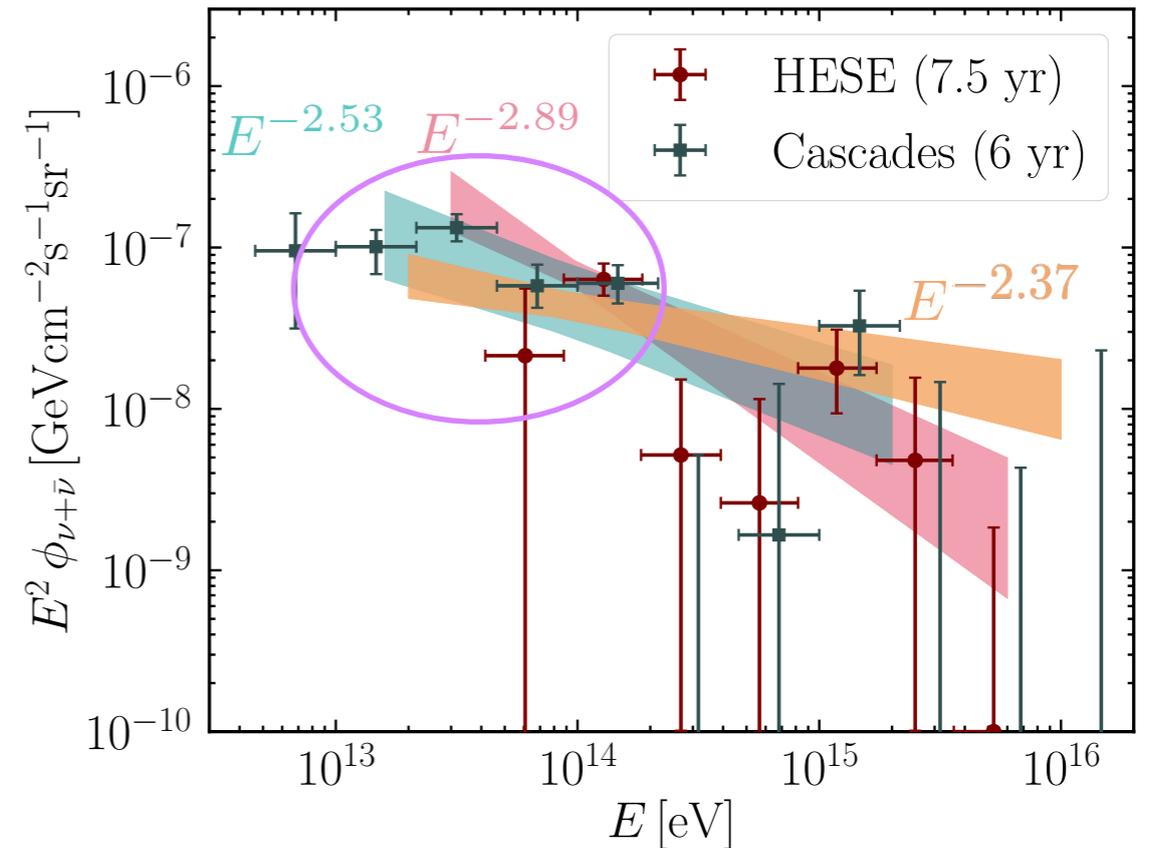
# Medium-Energy Excess in Neutrino Flux

- ▶ Different slopes hint at structure in the flux of high-energy cosmic neutrinos.
- ▶ The magnitude of the flux at  $\sim 10$  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]
  - ▶ Core of AGN can meet these conditions.

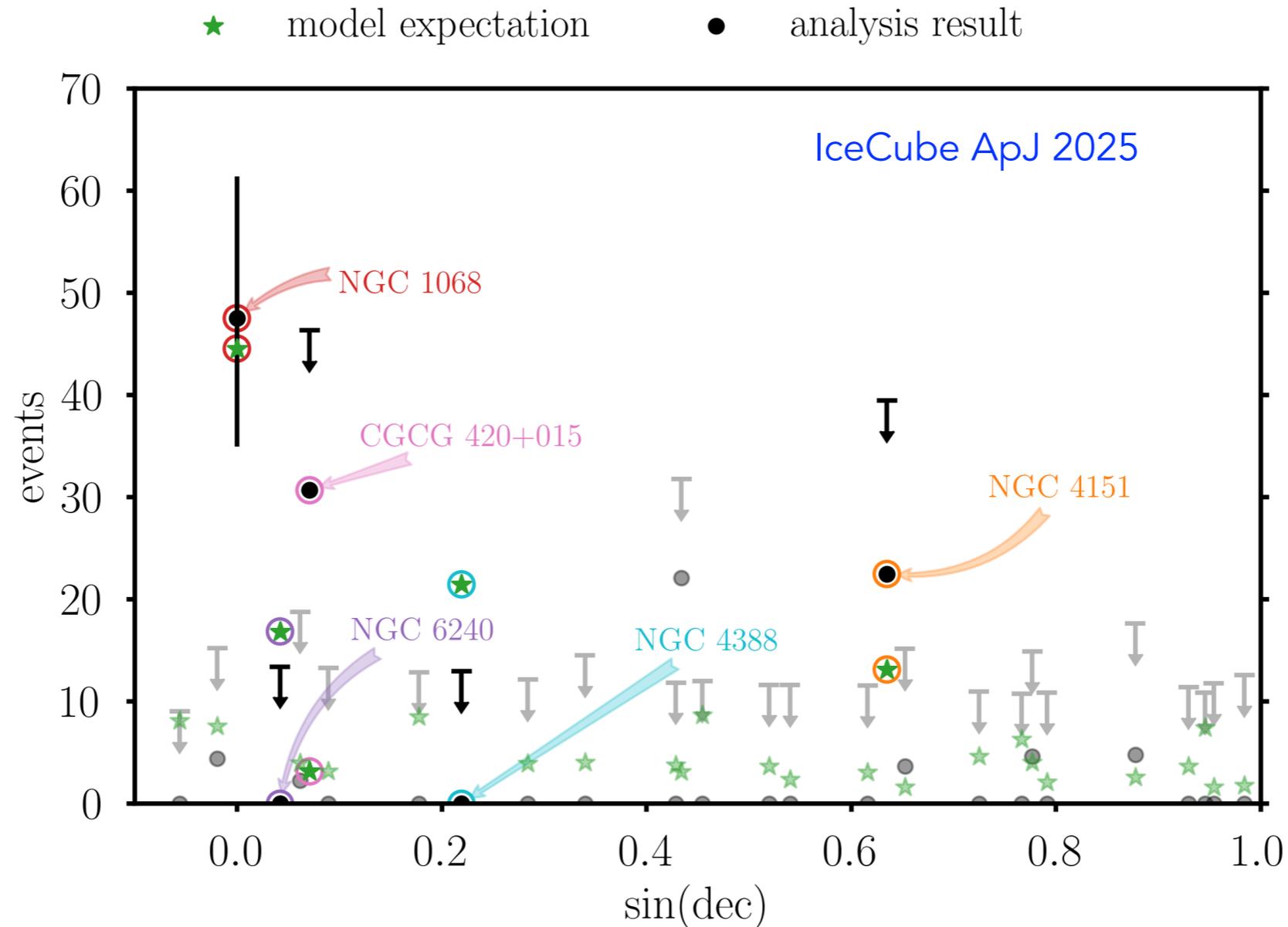


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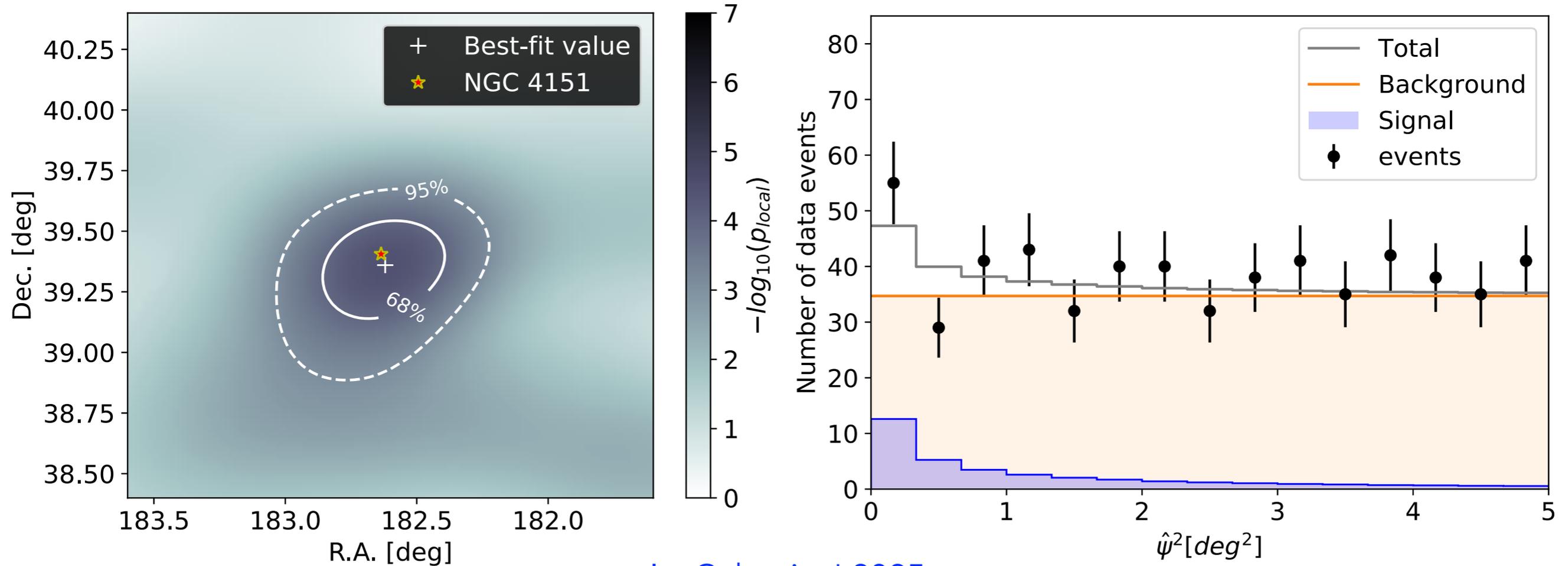


# Neutrinos from Bright Seyferts in Northern Sky



- ▶ Selecting sources based on the intrinsic X-ray flux (as a proxy for neutrino production)
- ▶ Catalog search finds excess in the direction of 2 sources in addition to NGC 1068
  - ▶ Binomial p-value study finds CGCC 420-15 and NGC 4151 at  $2.7\sigma$  (Posterior p-value with NGC 1068 yields  $4\sigma$ )

# NGC 4151



IceCube ApJ 2025

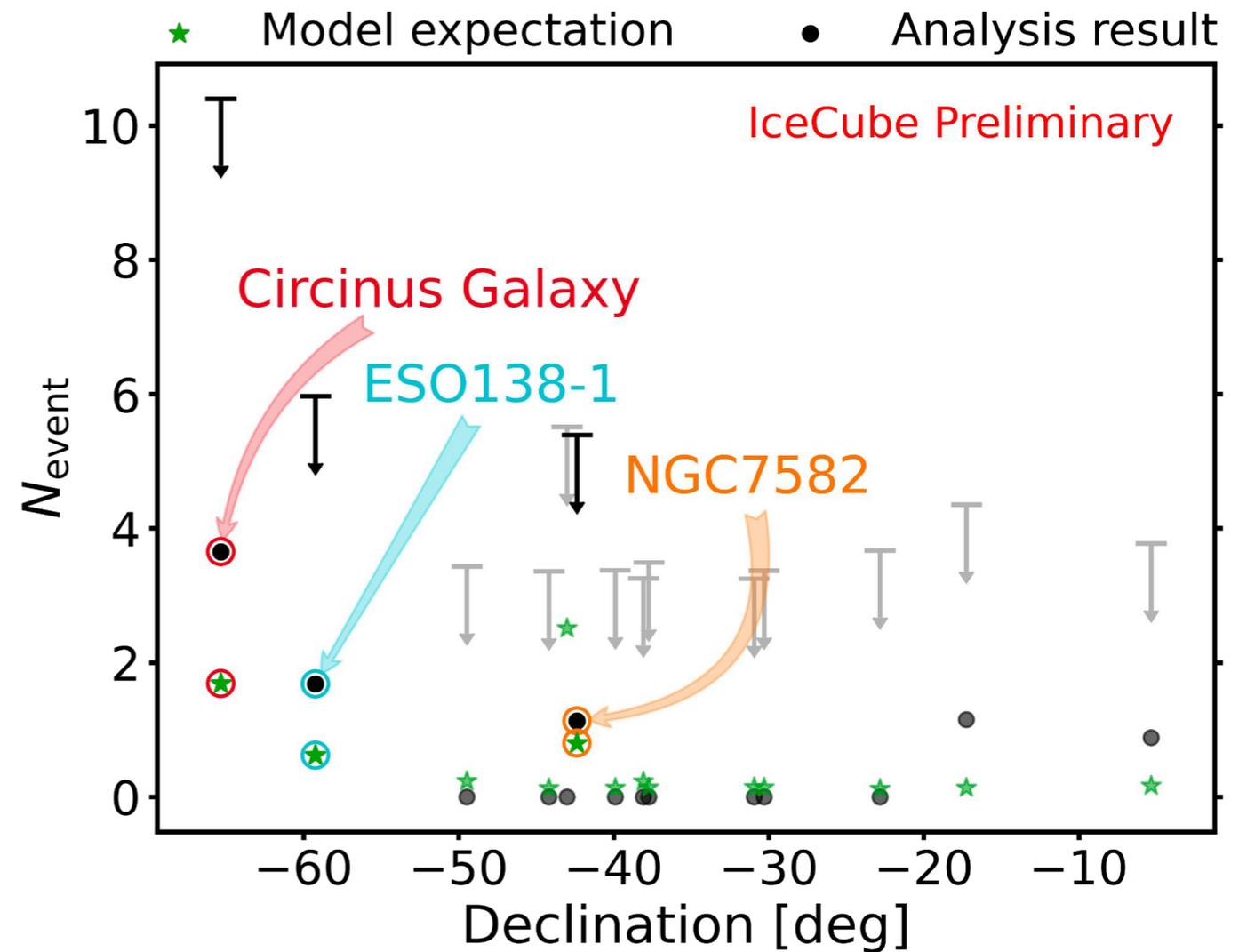
- ▶ NGC 4151 appears at  $2.9\sigma$  (global significance)
- ▶ The second most significant steady source in IceCube

# 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.

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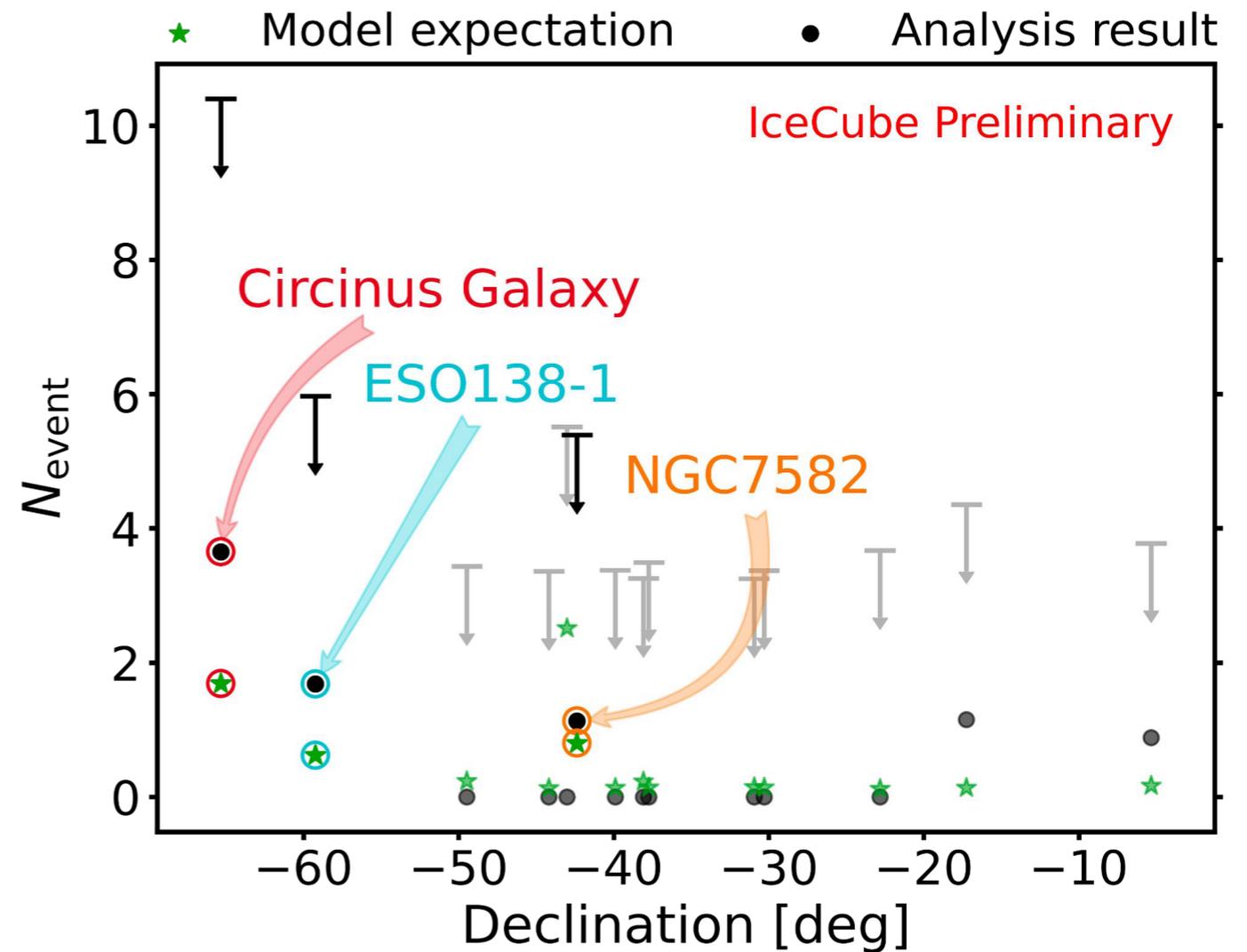
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- Best p-value for the source in the Southern sky:
  - ▶ **Circinus Galaxy**
  - ▶ 3.6 neutrino events at  $2.8\sigma$  local significance ( $1.8\sigma$  post trial)



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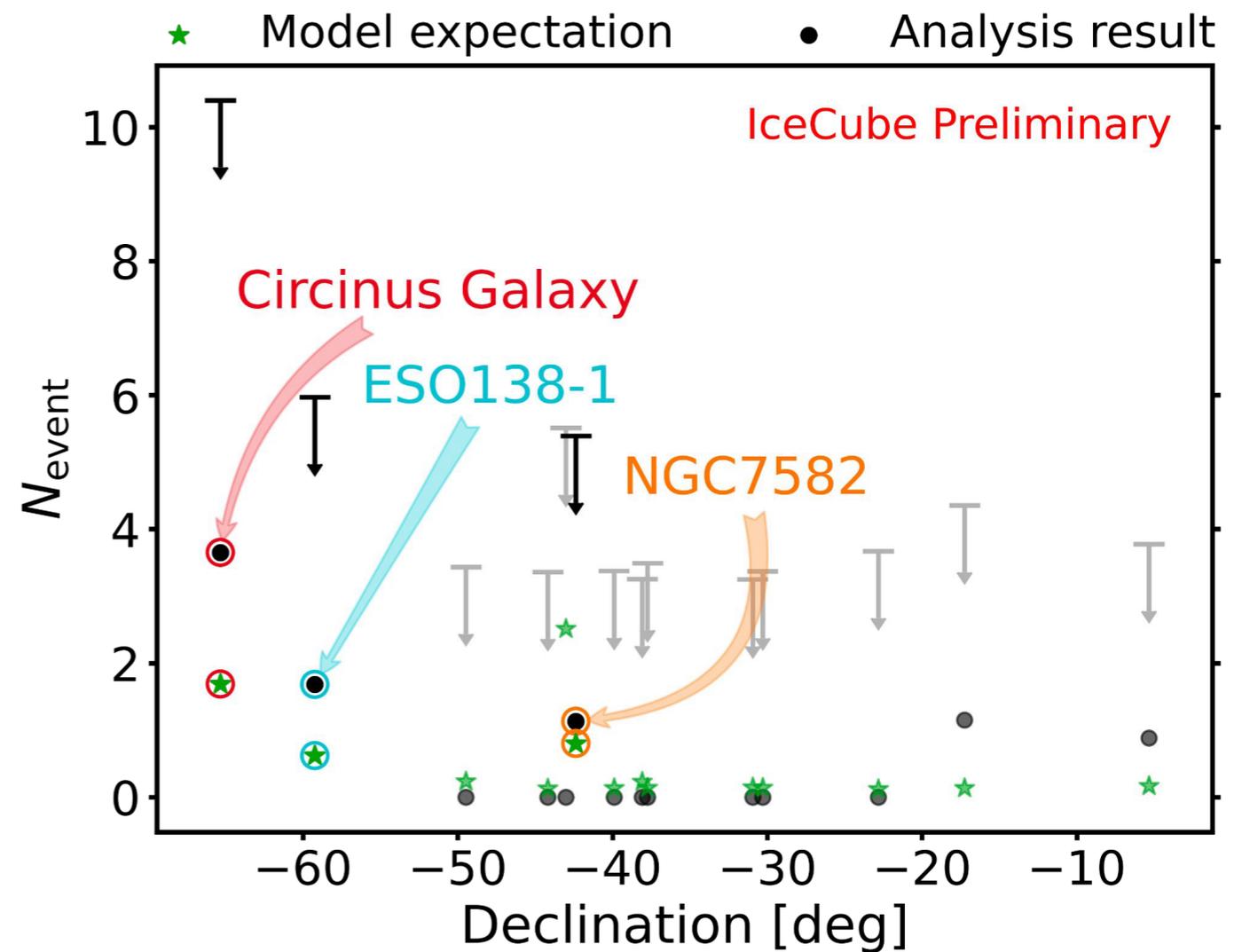
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- ▶ NGC 7582.

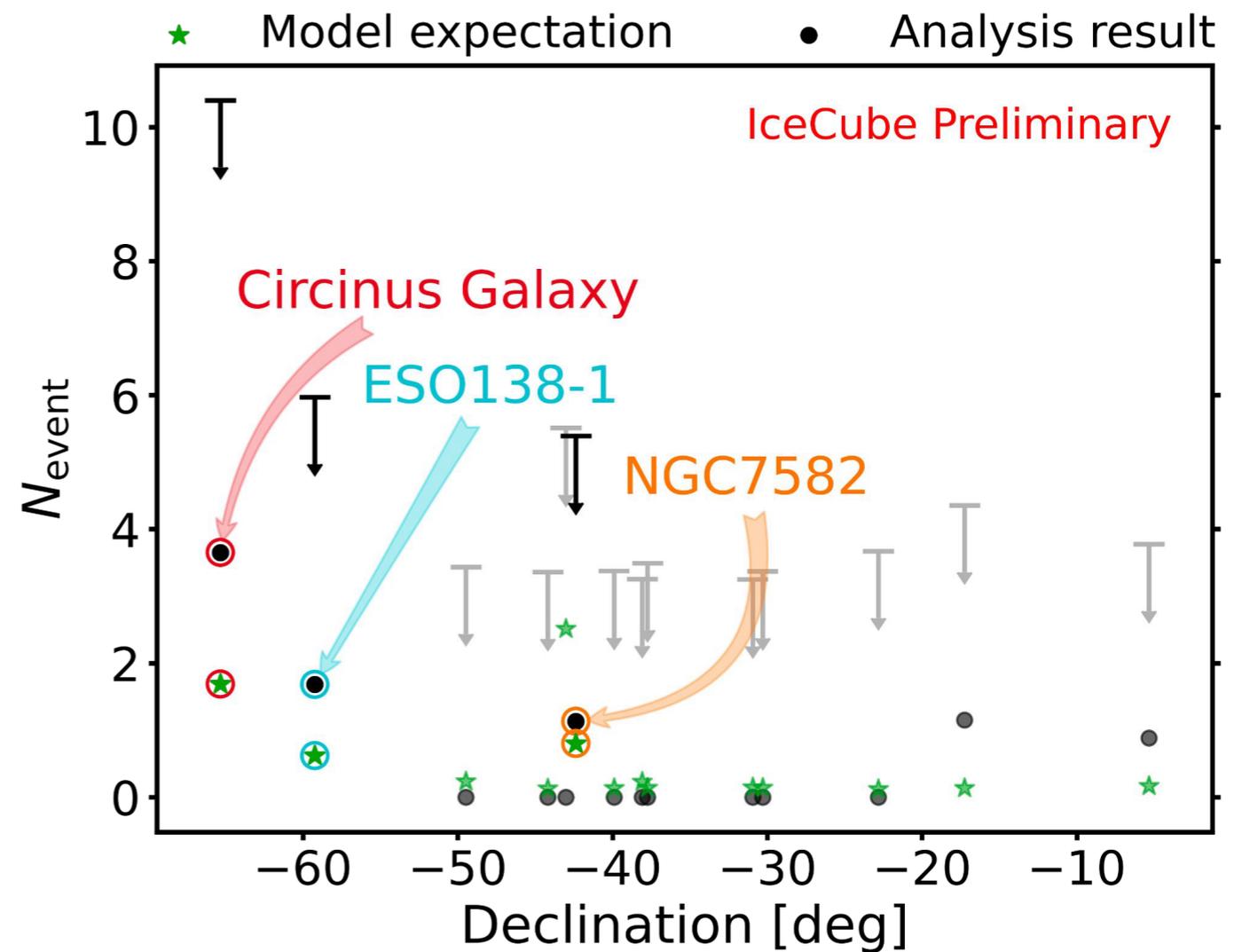


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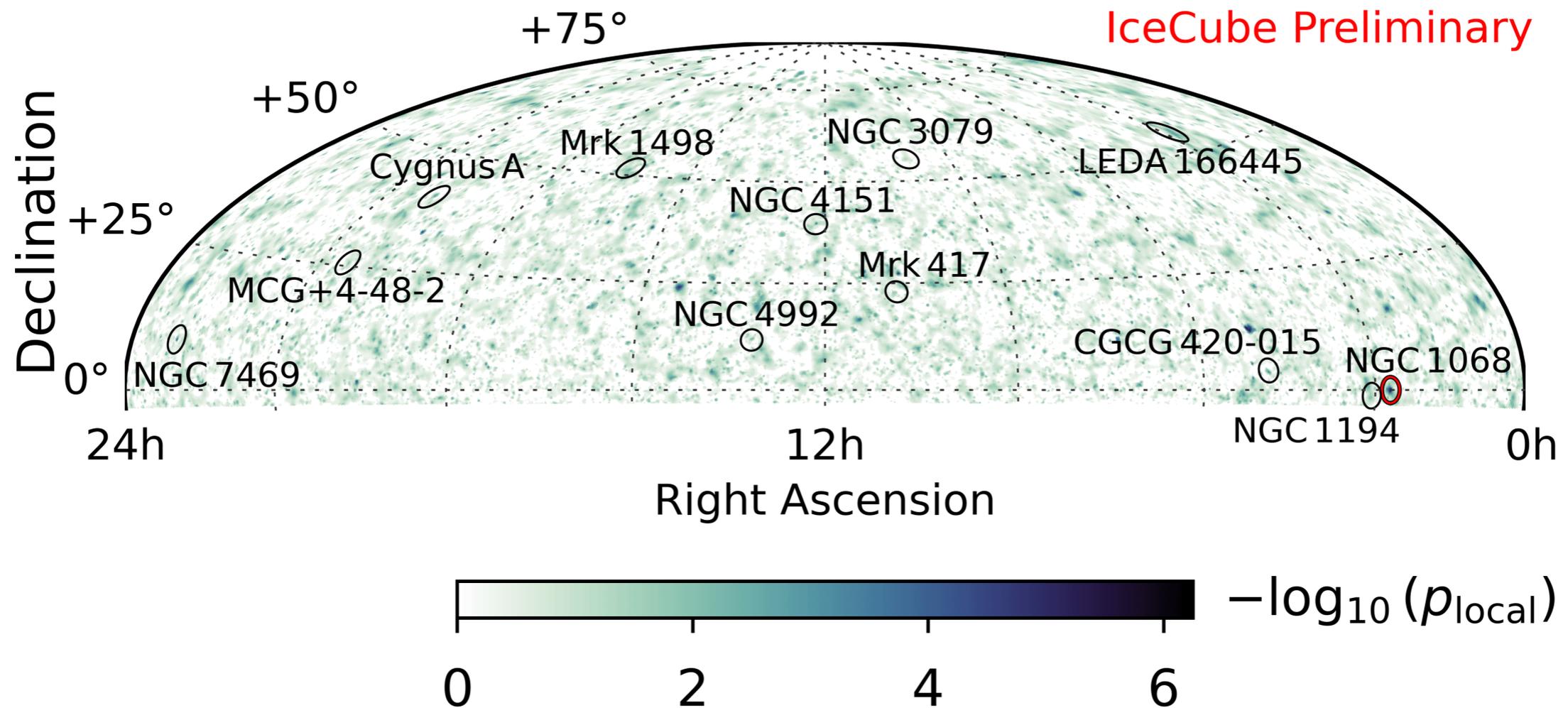
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- Stacking analysis:
  - ▶ **6.7 events at  $3\sigma$**



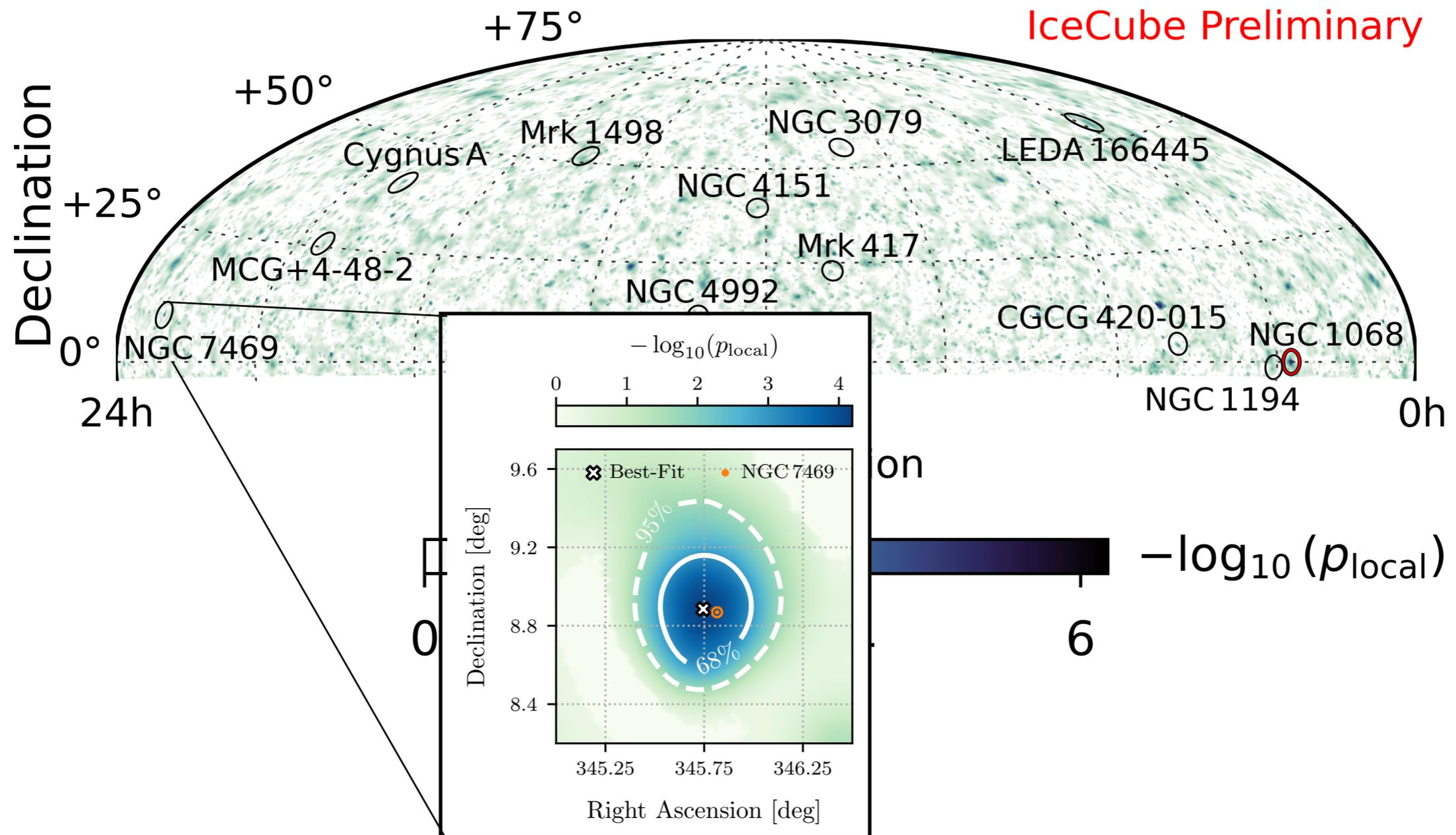
# Extend Northern Sky Search

- ▶ 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)



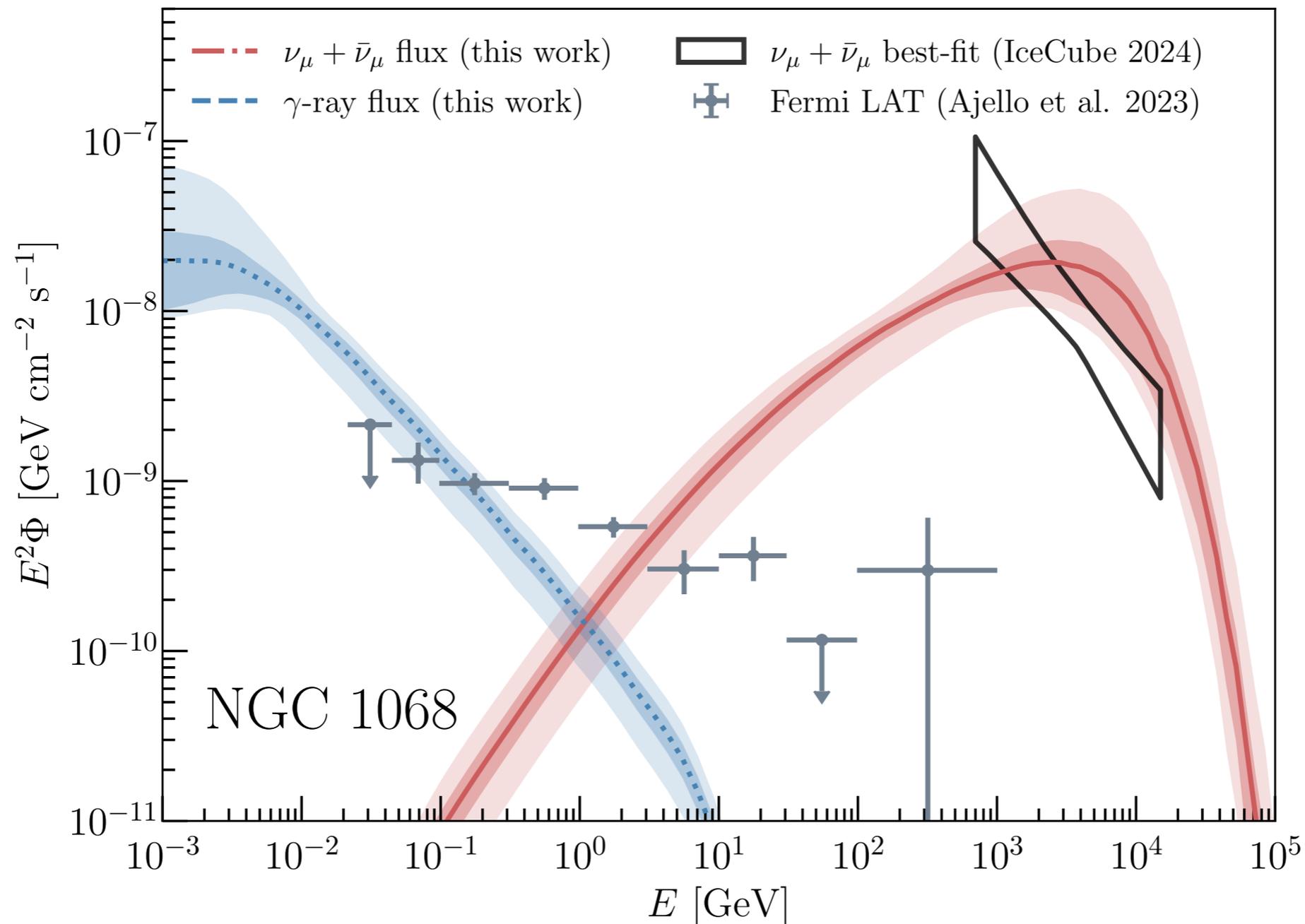
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# Hidden Cores of AGN & MeV Emission

- ▶ MeV measurement is necessary to obtain the complete picture of multimessenger emission from the likely sources of HE neutrinos.

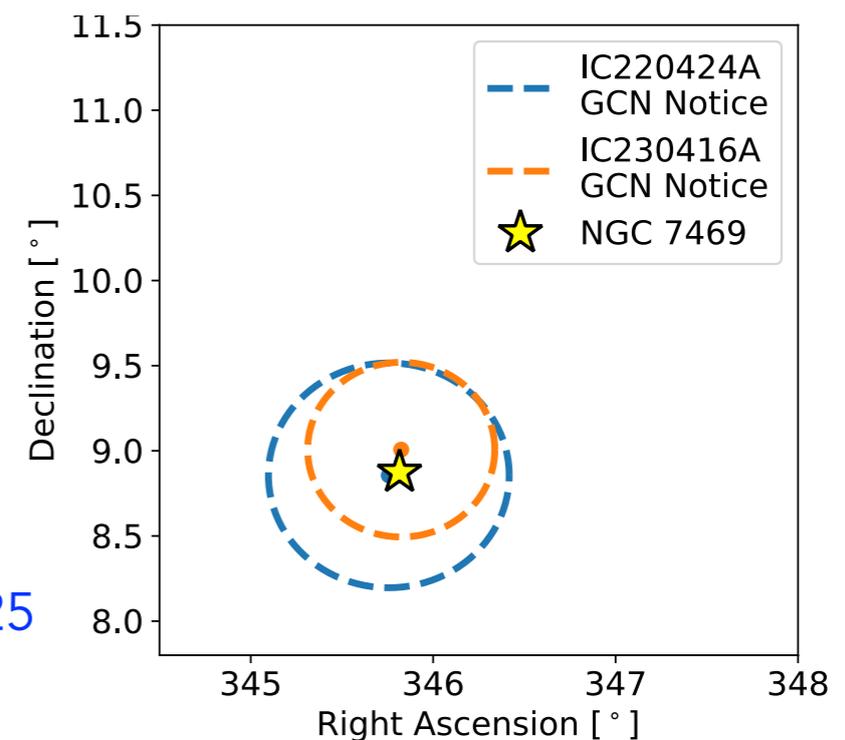
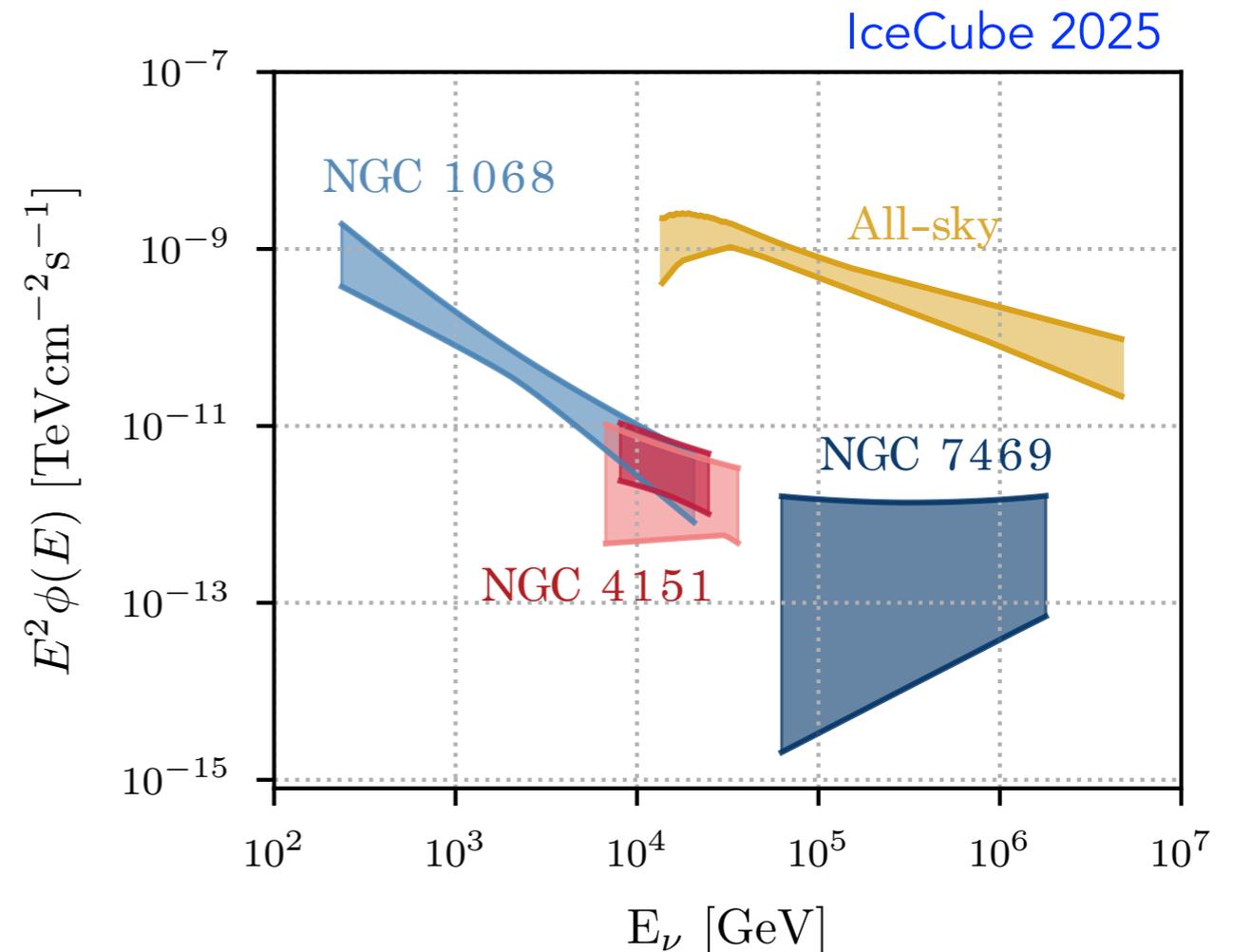


Carpio, **AK**, Murase, *in prep.*

# $\nu$ Emission from Seyfert Galaxies: summary

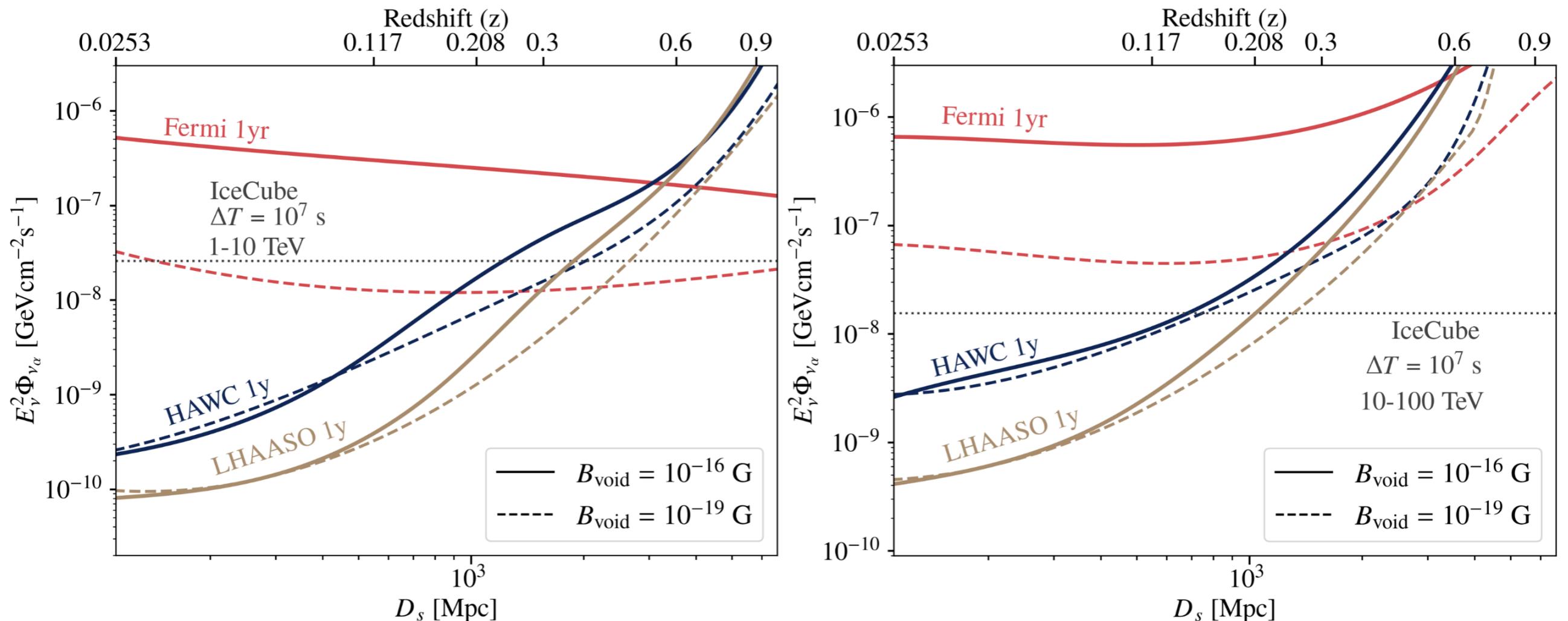
- ▶ Accumulating signal from gamma-ray obscured AGN has been seen in different searches.
- ▶ Not all nearby sources share similar properties of NGC 1068
  - ▶ A subset of sources identified in each search
  - ▶ The nature of neutrino emission is yet to be determined.
  - ▶ Episodic emissions cannot be ruled out.
- ▶▶ NGC 1068 is also identified in time-dependent searches with  $> 1$ yr time window for emission.
- ▶▶ Two alerts associated with NGC 7469, disfavoring background by  $3.3\sigma$ .

Sommani+ 2025



# Horizon for $\nu - \gamma$ correlation

- ▶ TXS 0506+056 remains the only source identified in a flaring  $\gamma$ -ray state.
- ▶ The archival flaring episode is not correlated with enhance  $\gamma$ -ray activity.
- ▶ Additional coincidences with point to  $\gamma$ -ray suppressed state in similar blazars.
- ▶ Possible correlation is highly depend on the absorption in the source and propagation in the EBL.



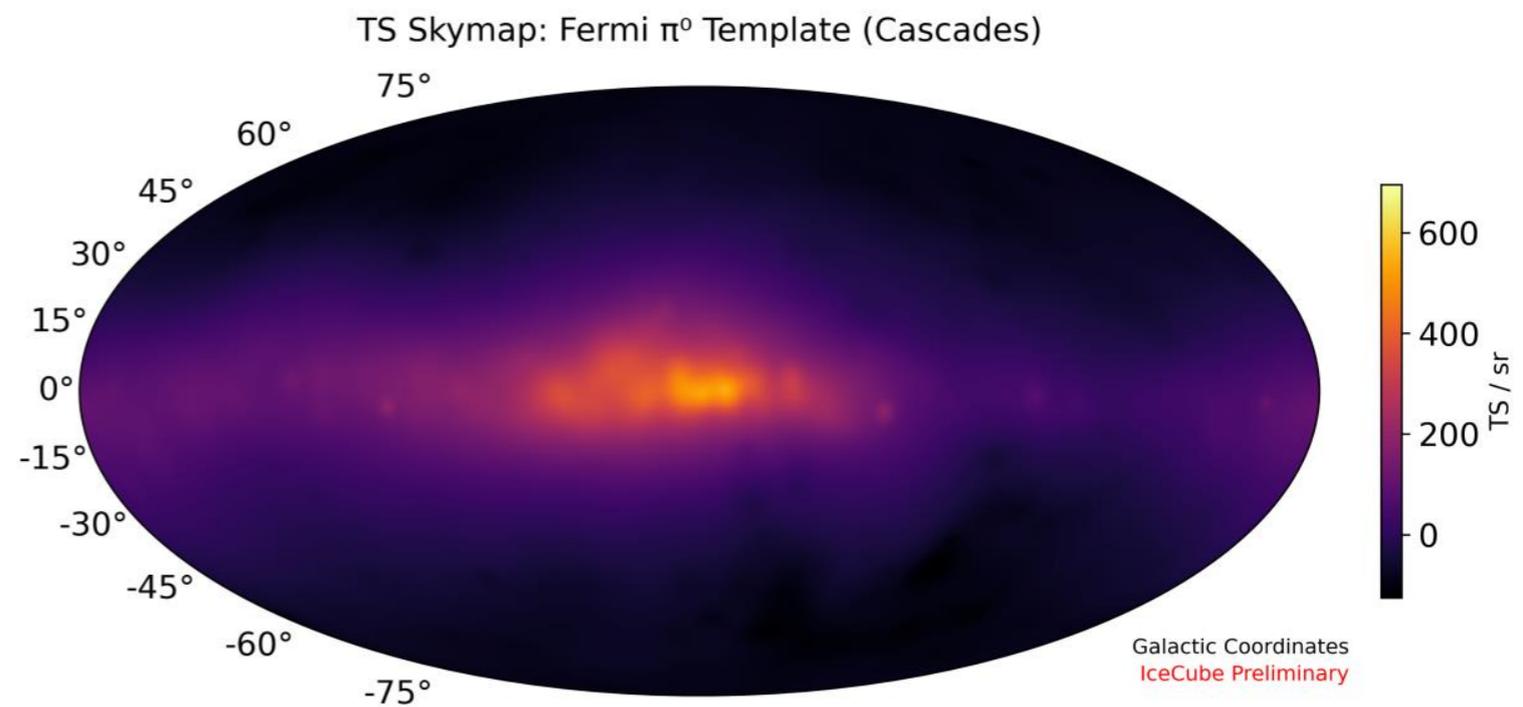
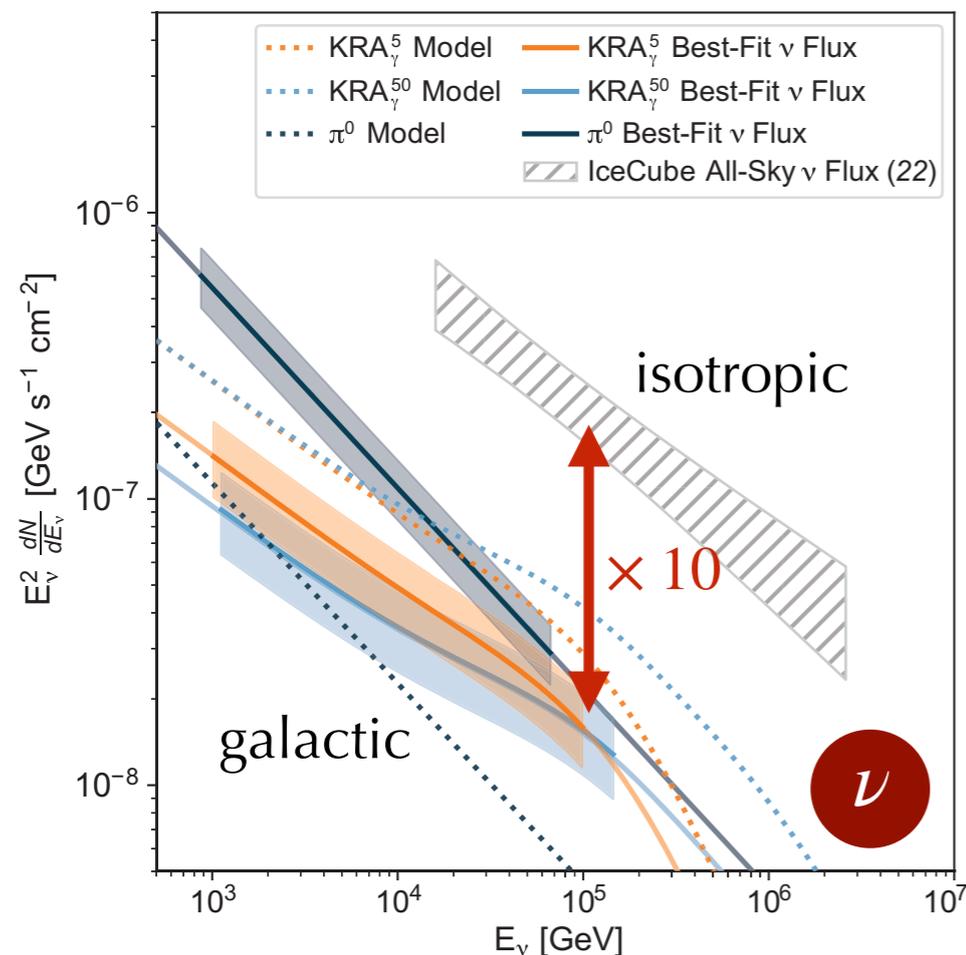
Ding, Carpio, AK, in prep.

# Galactic Neutrino Flux

Cascades boost IceCube sensitivity to extended emission in the Southern sky.

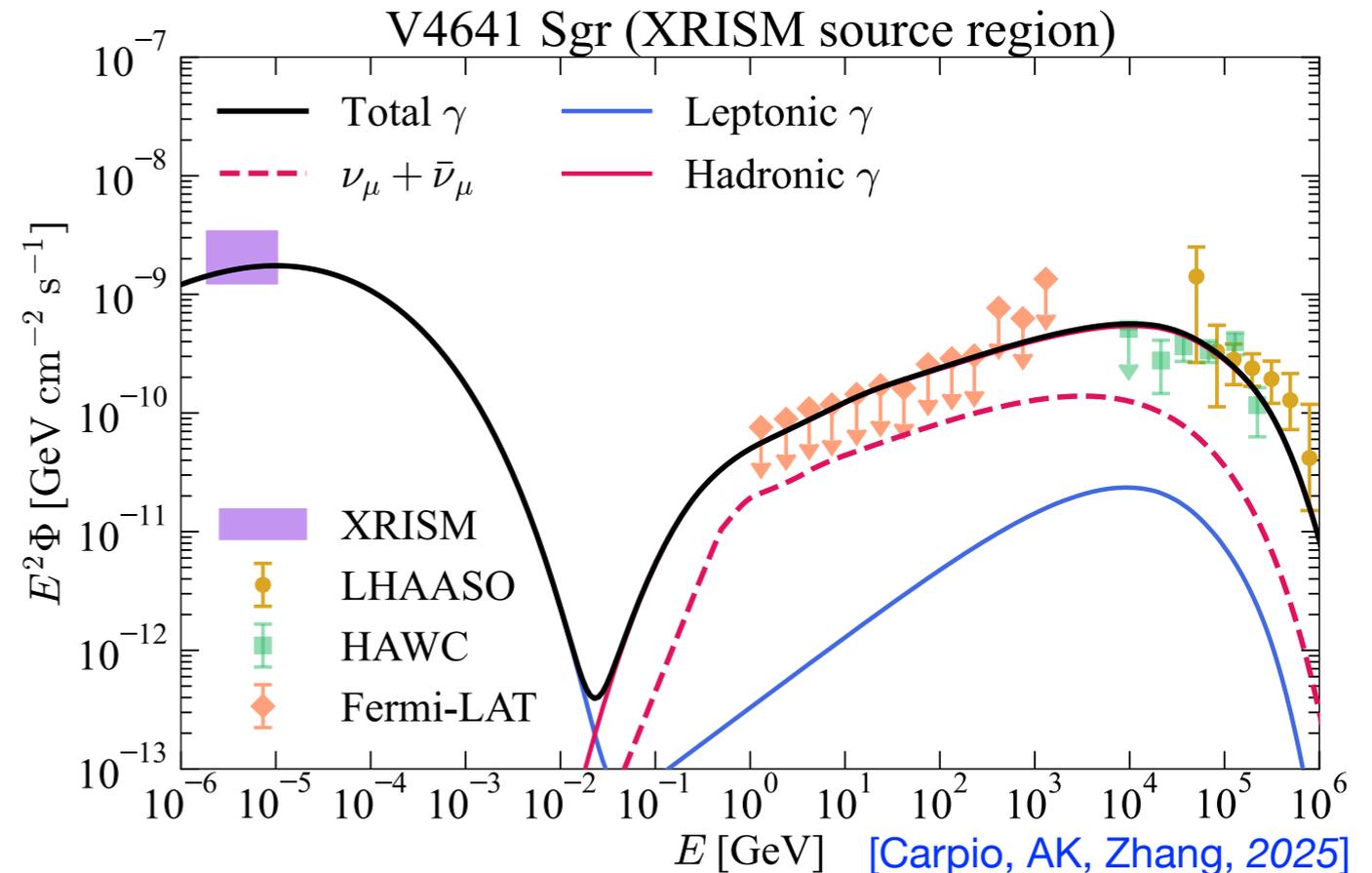
**10 years of data identified Galactic component at  $4.5\sigma$**

- ▶ New analysis with additional years find  $> 5\sigma$  emission
- ▶ rejecting no Galactic component hypothesis but cannot distinguish models
- ▶ The nature of Galactic neutrinos (source vs diffuse) remains an open question



# VHE emission from X-ray Binaries

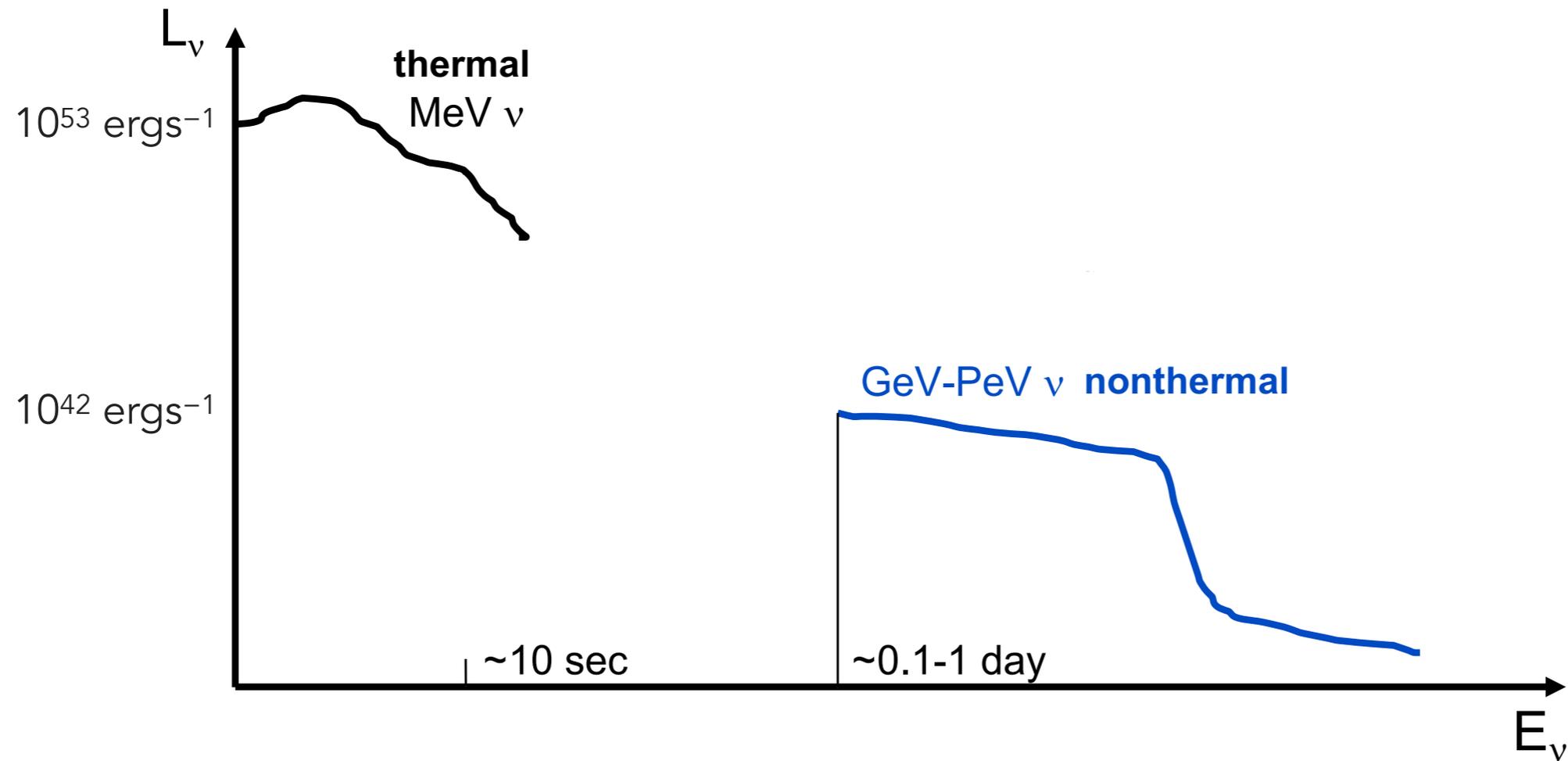
- ▶ Newly identified VHE emission from binaries have prompt them as a prominent target.
- ▶ Hadrons play a major role in the  $\gamma$ -ray emission from these sources.
- ▶ The level of flux not high enough to be identified in current experiments.
- ▶ X-ray measurements are crucial for understanding the emission and time-dependent searches.
- ▶ Strongest excess so far in time-dependent search for binaries was correlated with with V404 Cyg X-ray outburst.
- ▶ Cygnus X-3 stands out in time-integrated search.



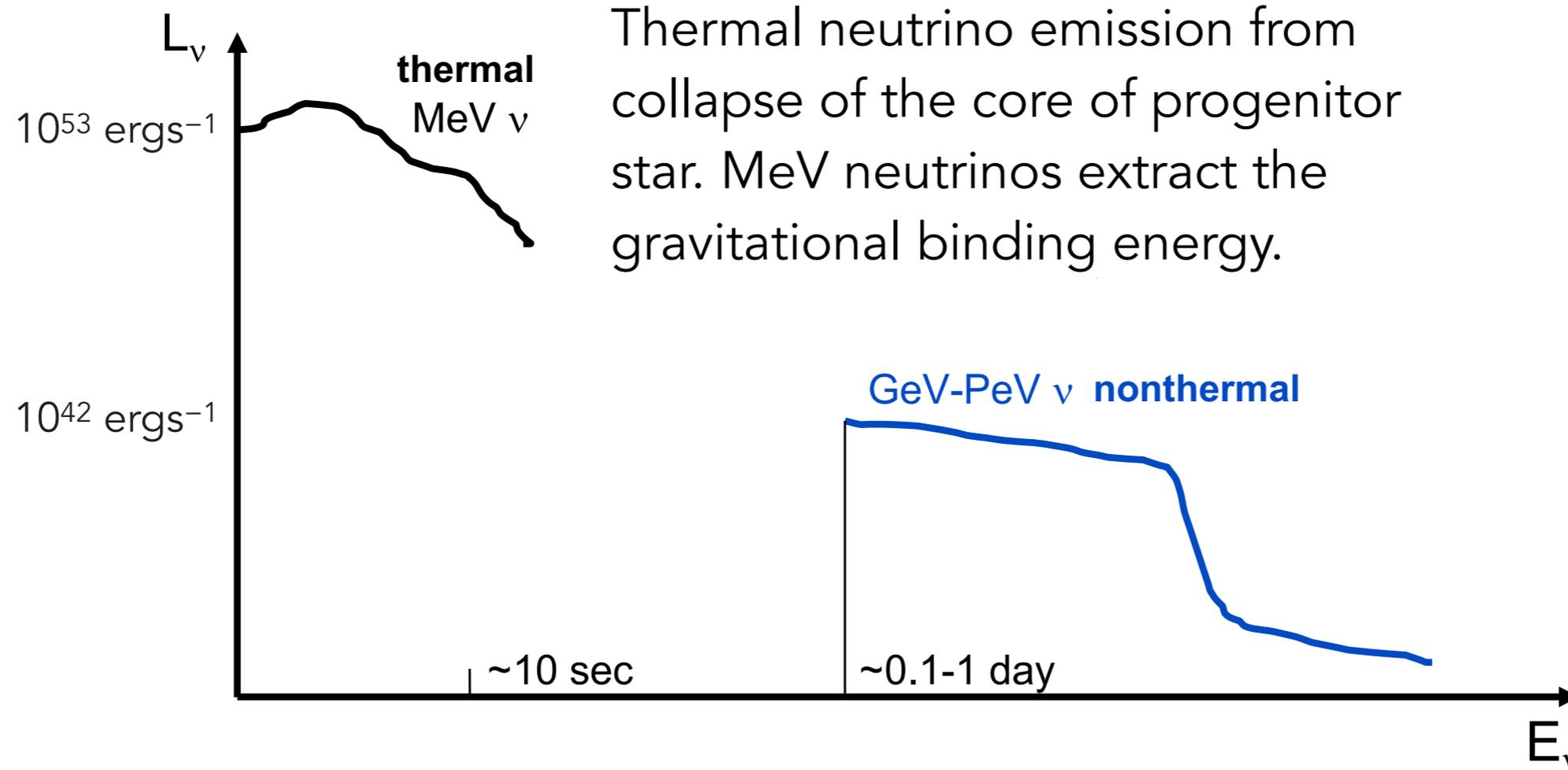
Analysis	Source	TS	$\hat{n}_s$	$\hat{\gamma}$	$p$ -value
Periodic	V635 Cas	9.07	50.5	4	0.25 (0.0052)
Flare	V404 Cyg	8.28	5.4	4	0.75 (0.014)
Time-integrated	Cyg X-3	6.81	44.6	3.25	0.036 (0.009)

IceCube 2022

# Neutrinos from Core Collapse Supernovae

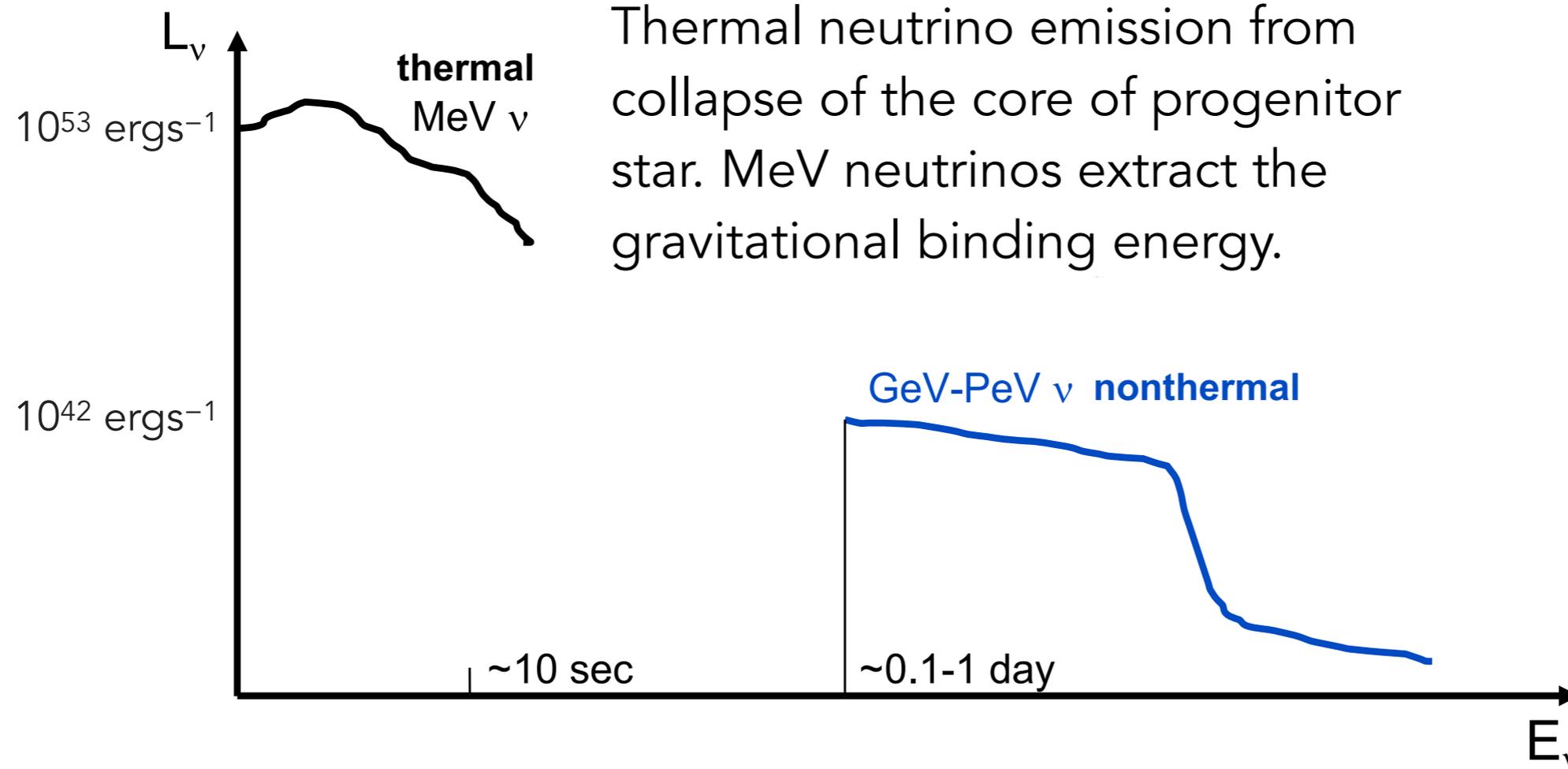


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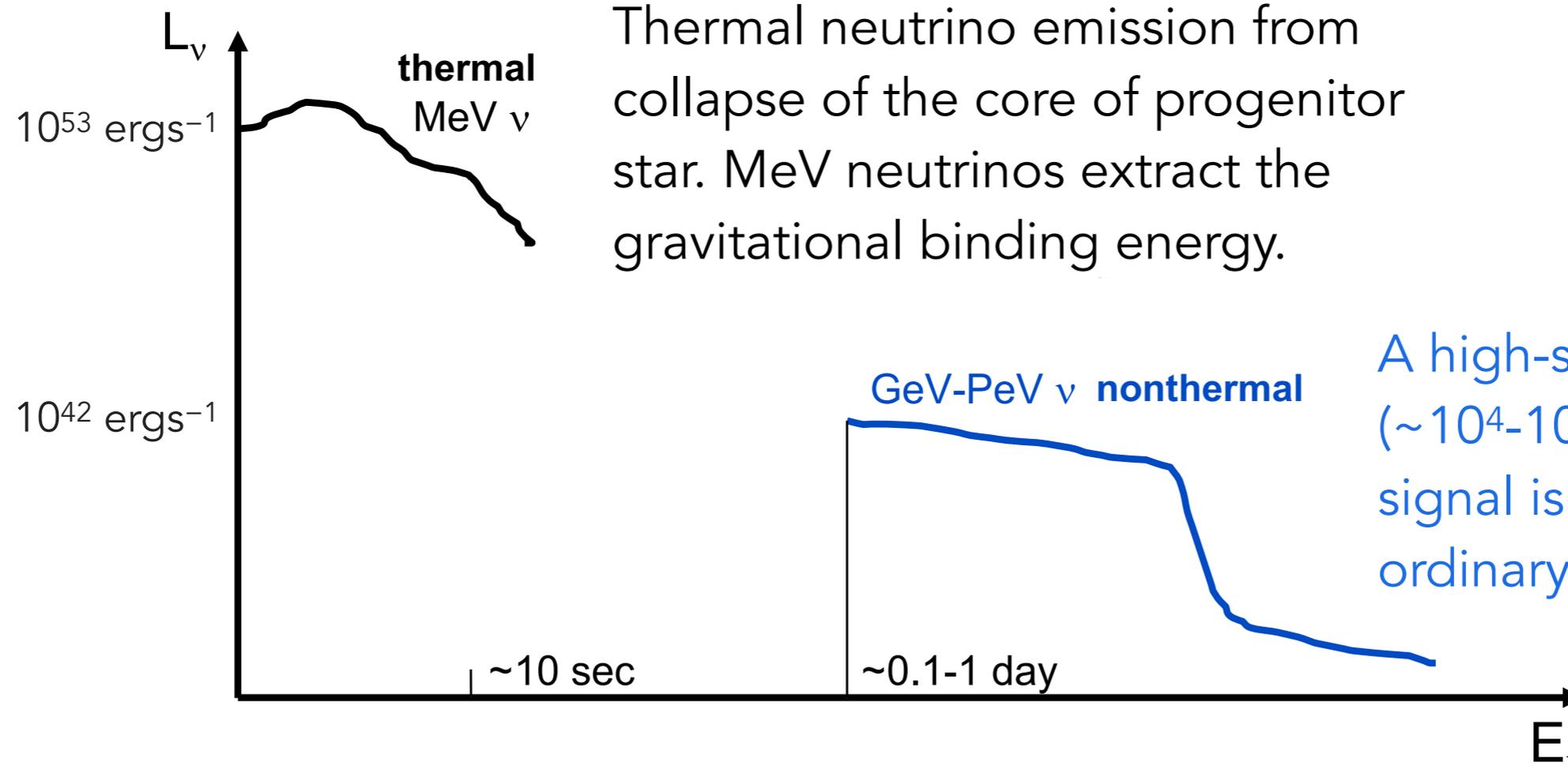
Thermal neutrino emission from collapse of the core of progenitor star. MeV neutrinos extract the gravitational binding energy.

# Neutrinos from Core Collapse Supernovae



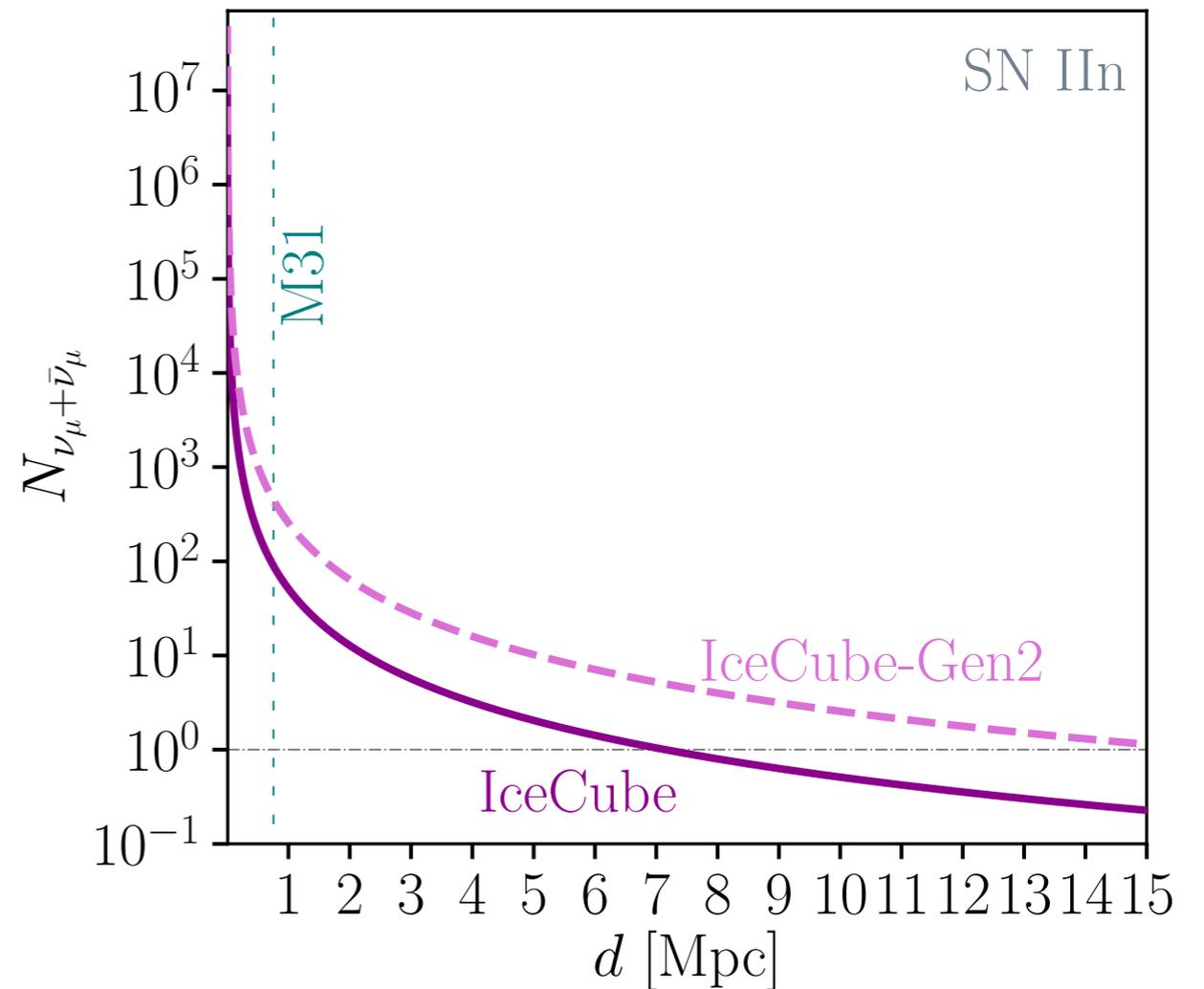
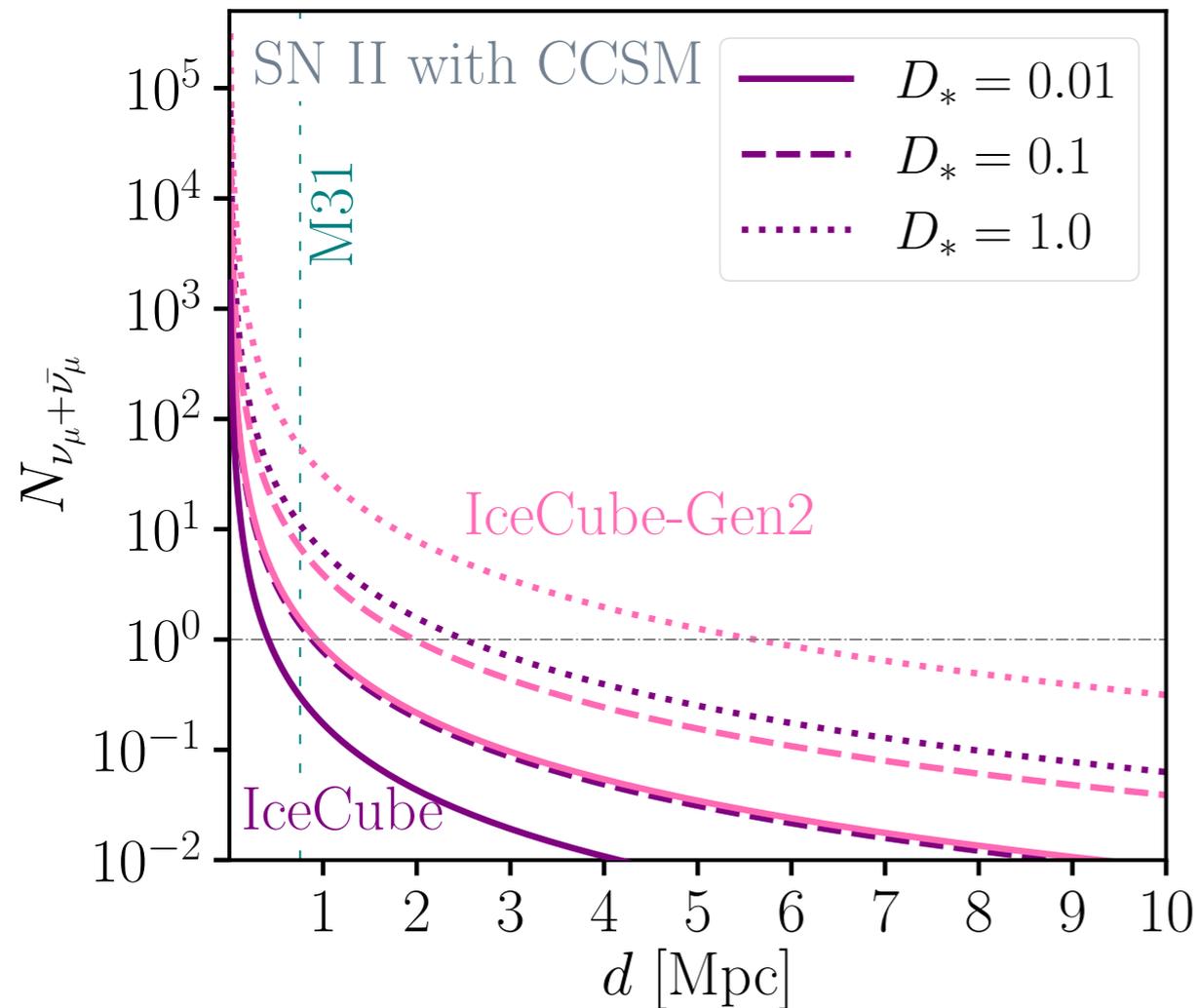
- Observation of extragalactic SNe showed rapid significant mass loss in SN progenitor which leads to shock interaction with dense circumstellar material (CSM).
  - ▶ Shock interaction with CSM results in production of HE neutrinos!

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# HE Neutrino Emission from CCSNe



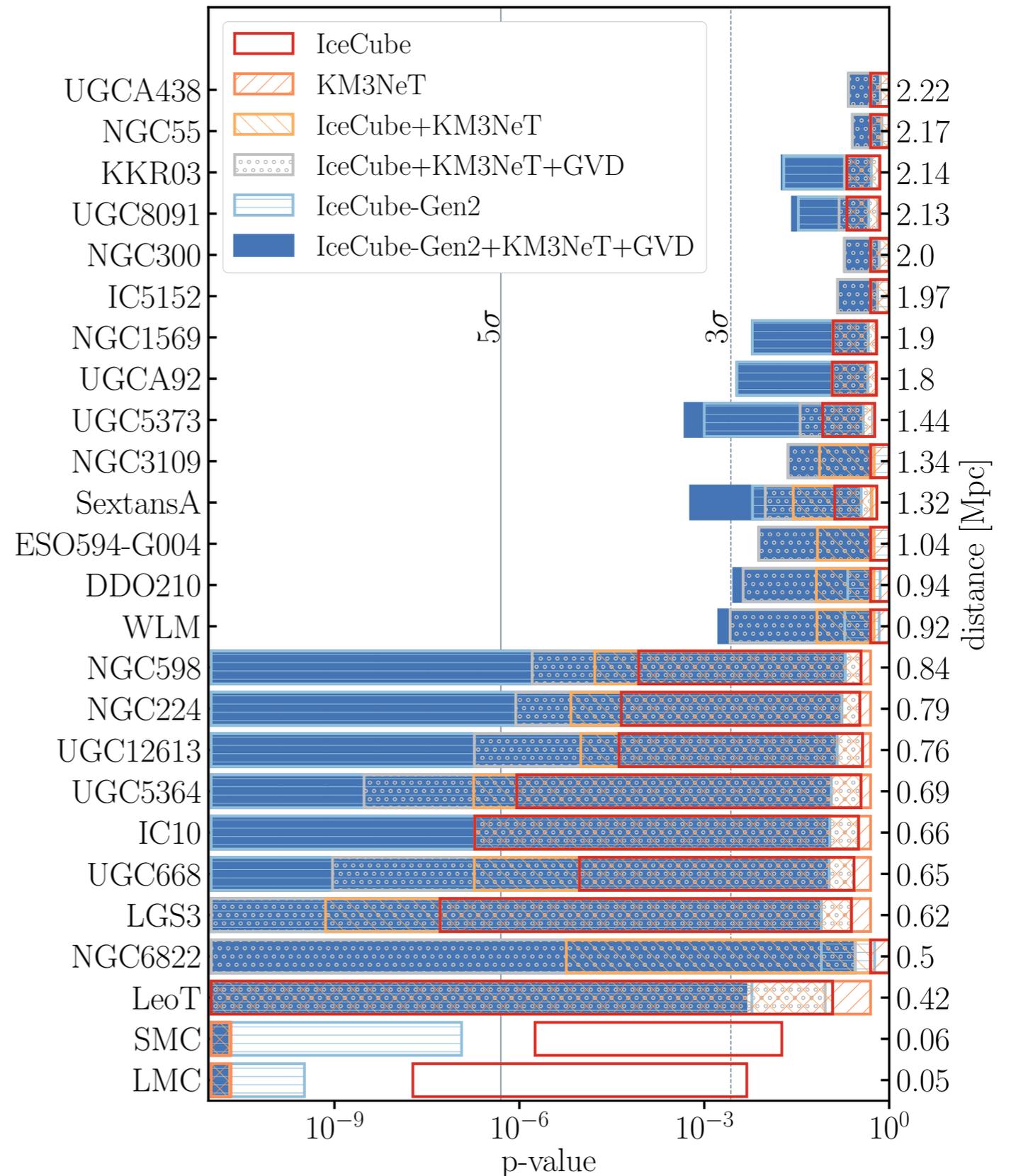
AK & Murase ApJL 2023

- ▶ Occurrence of SNe inside Milky Way would overwhelm neutrino telescopes with  $> 10^7$  neutrinos within a year.
- ▶ The horizon for observation of neutrinos from SNe extends beyond our Galaxy.

# HE Neutrinos from SN II with CCSM in Local Galaxies

AK & Murase ApJL 2023

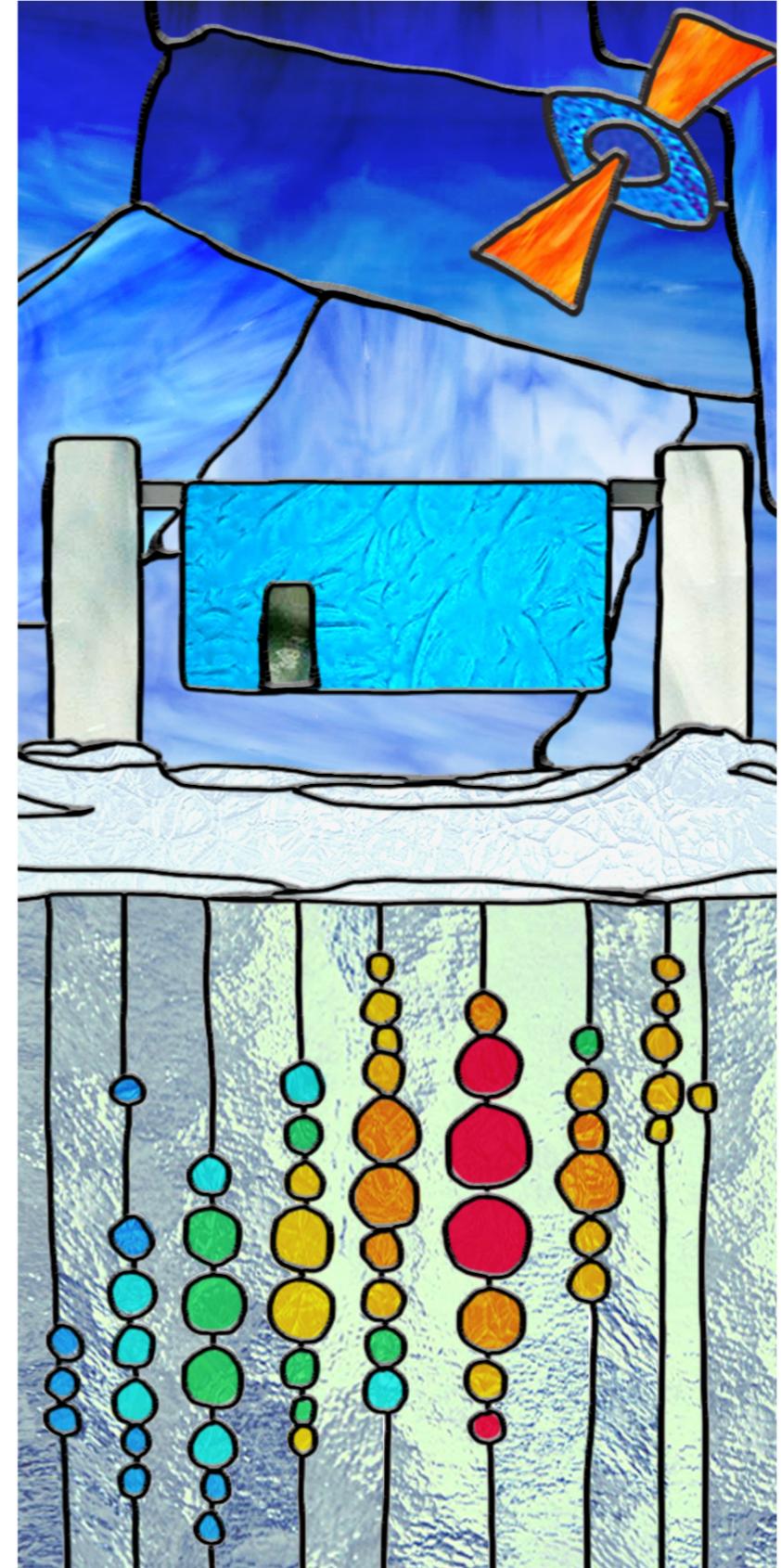
- ▶ HE neutrinos from close by sources (e.g., LMC & SMC) can be identified in current detectors.
- ▶ Next generation of neutrino telescopes will push the horizon for identification of HE neutrinos from CCSM SNe to more than 2 Mpc.
- ▶ Combined with MW observation, they offer a unique opportunity to understand CR acceleration.



# Outlook

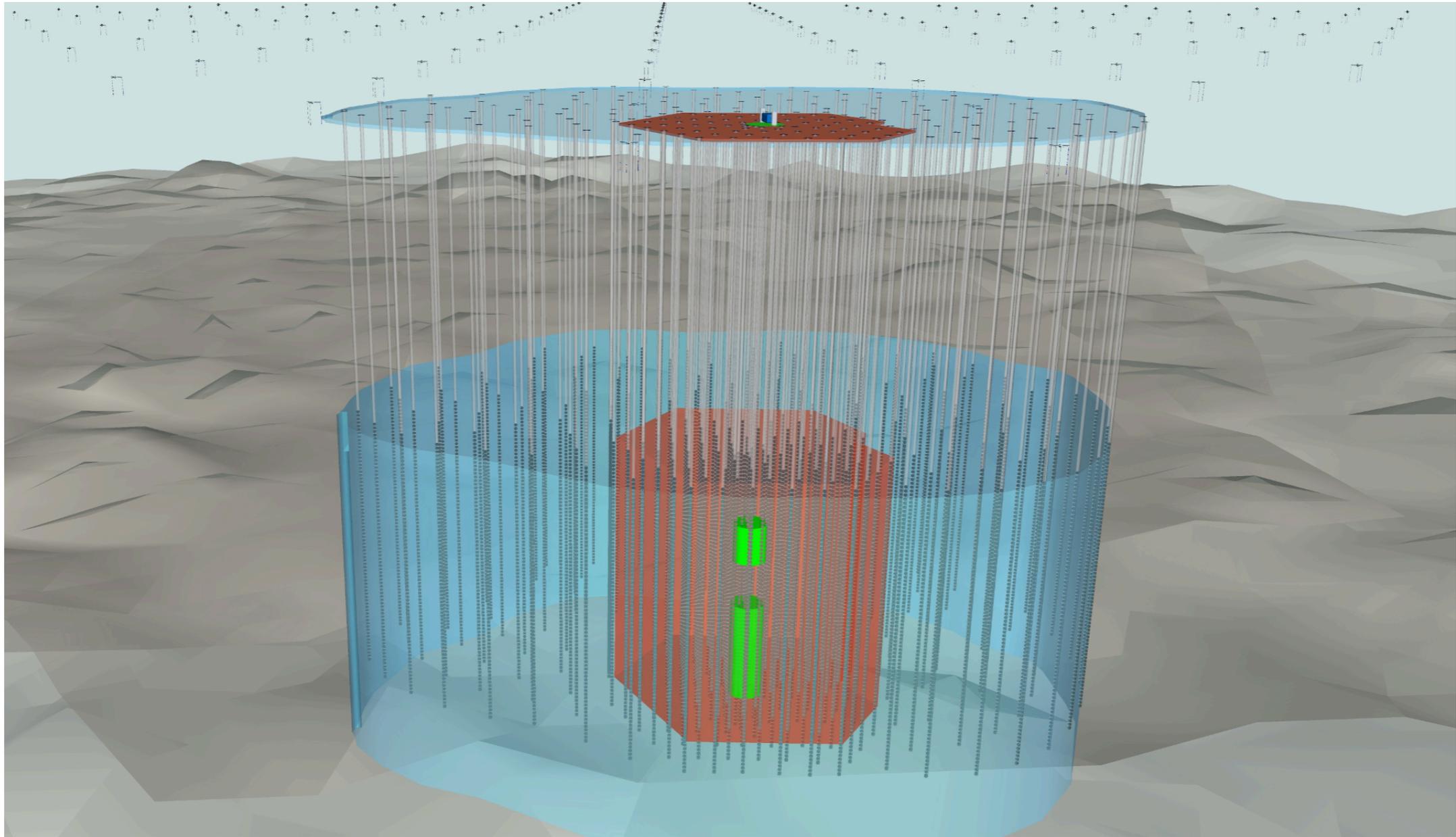
After a decade of observation, signs of anisotropy have emerged in IceCube data.

- ▶ Early indications points to AGN as primary source of high-energy cosmic neutrinos.
- ▶ Features in the measured cosmic neutrino flux point to different population of sources
- ▶ Triggered searches will boost neutrino telescopes ability to identify sources
- ▶ New opportunities emerge with UHE neutrino candidates, midscale telescope probing PeV emission, and neutrino emission prediction in the GeV range



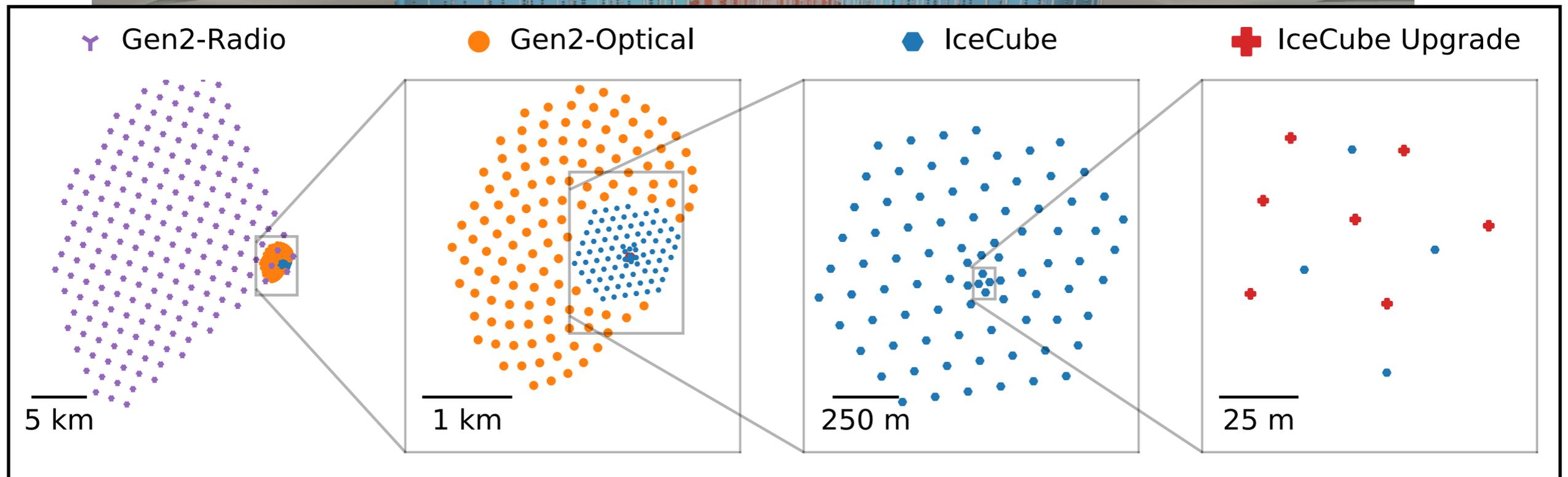
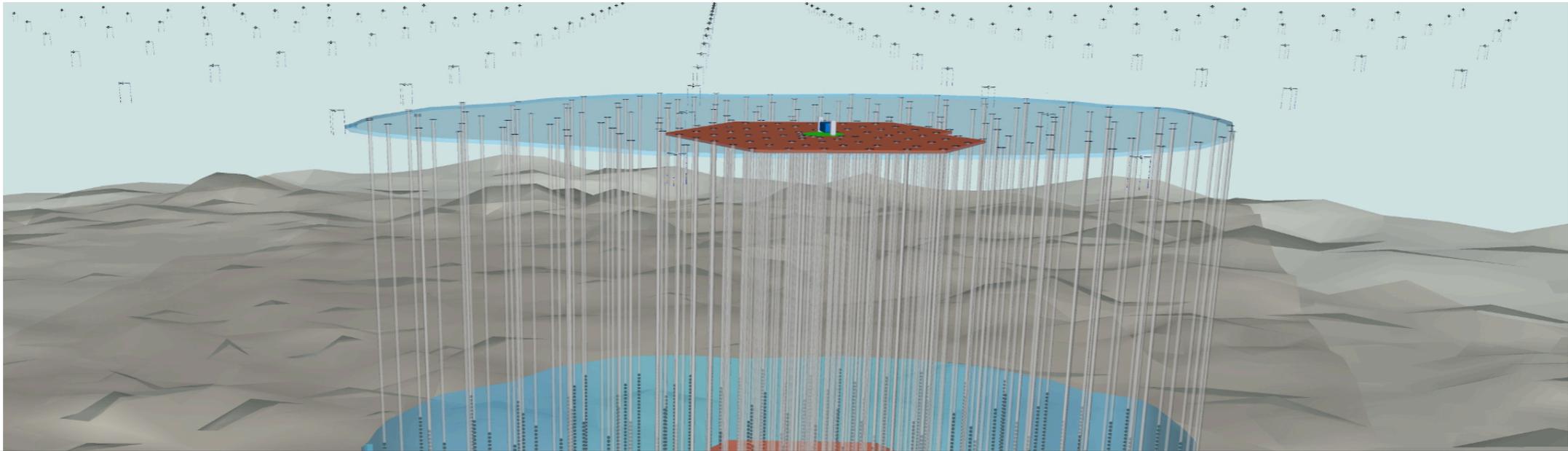
# IceCube-Gen2

Near 10 times larger, reaching to energies of EeV



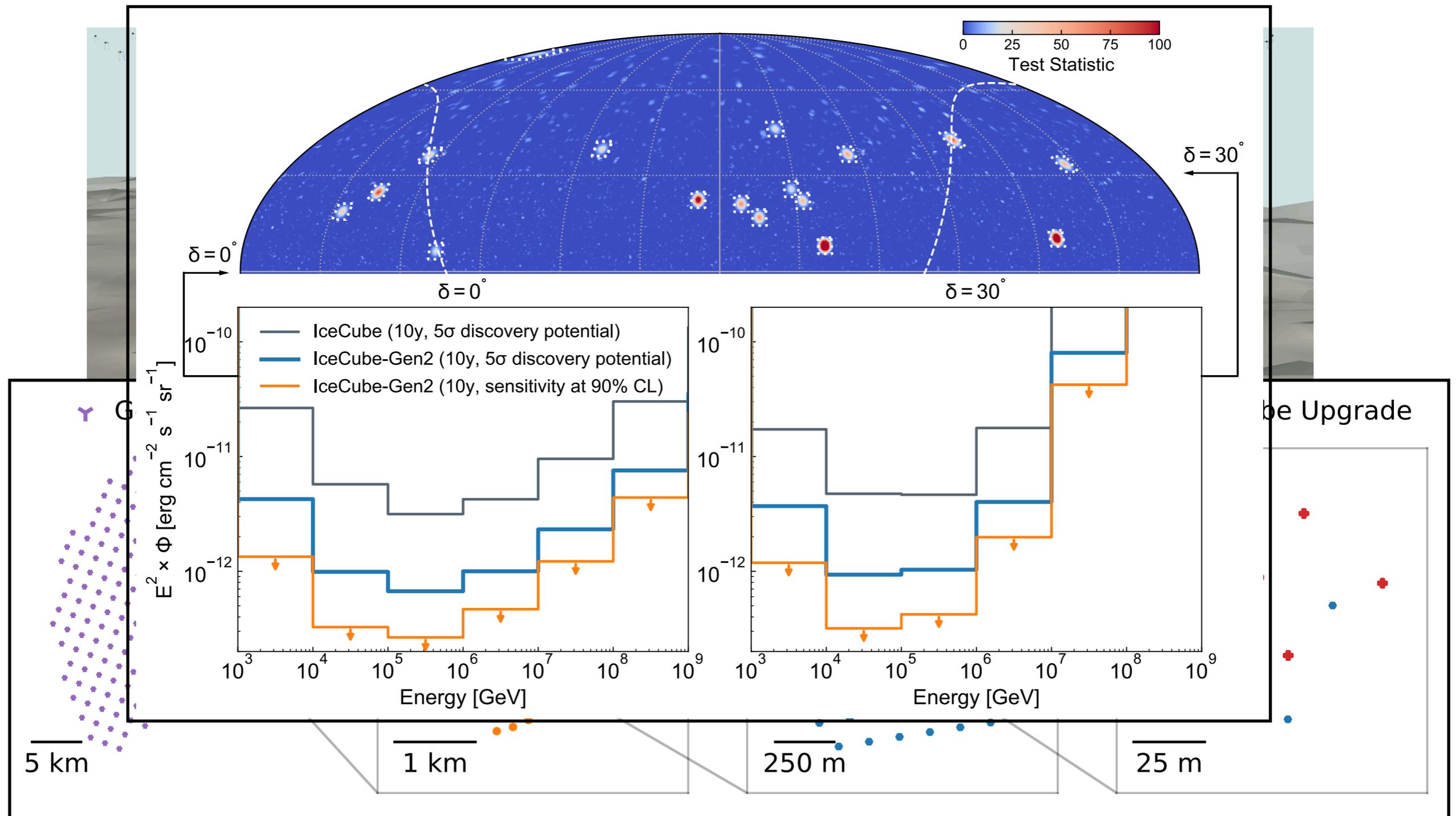
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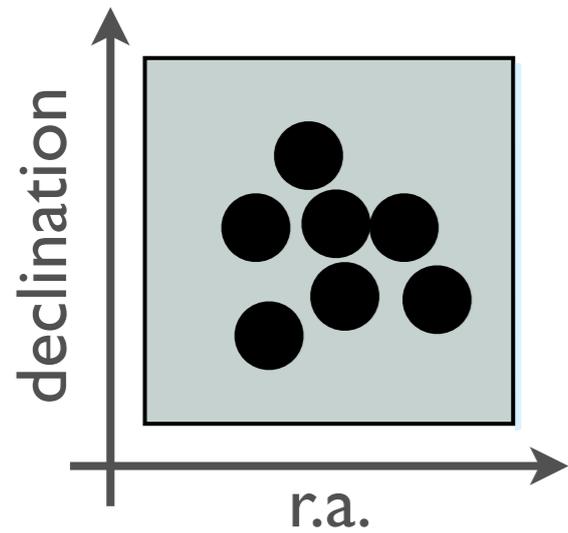


*Thanks!*

*Back up Slides*

# Point Source Searches

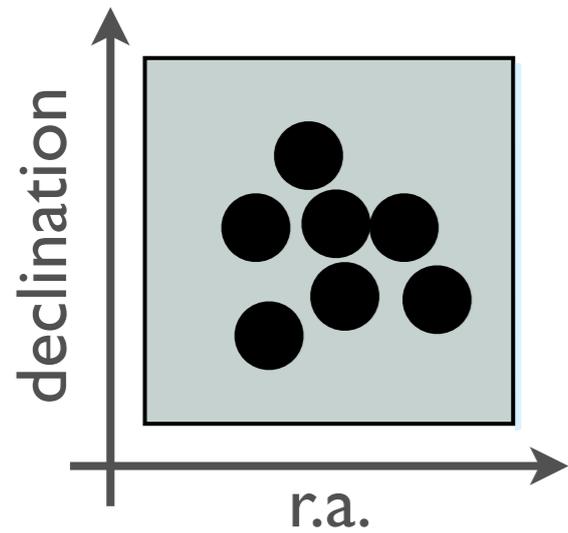
# Point Source Searches



clustering

- Untriggered search in space & time

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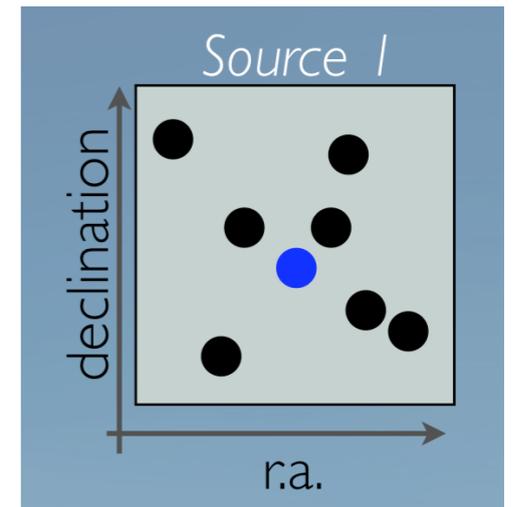


## clustering

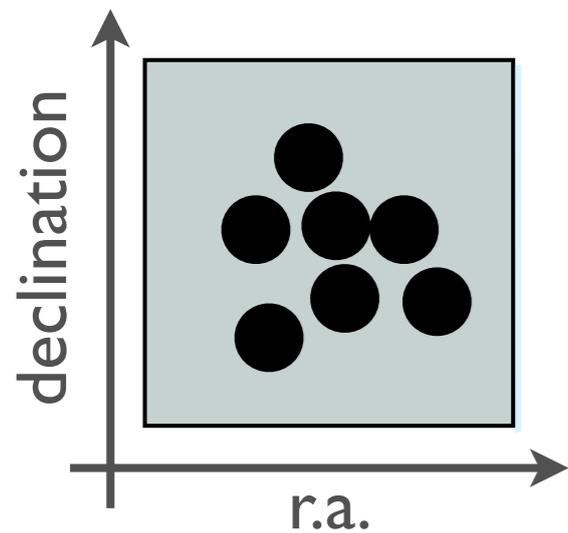
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## source search

- Triggered search for pre-identified locations



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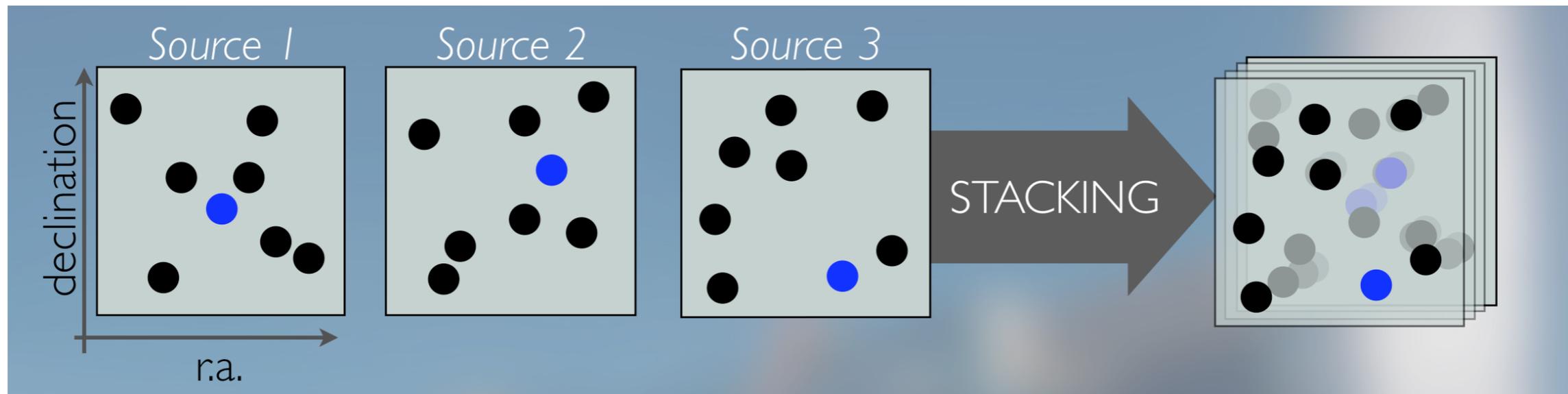
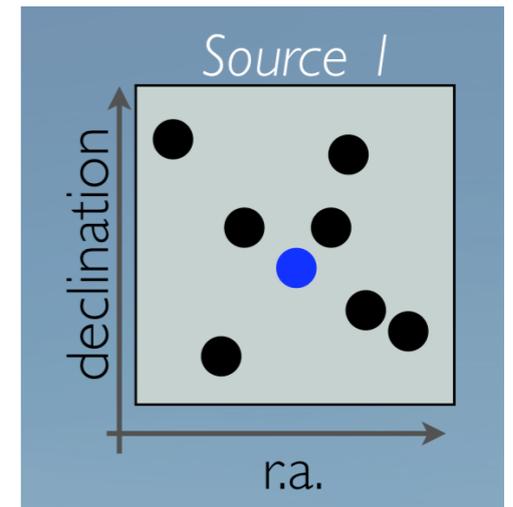


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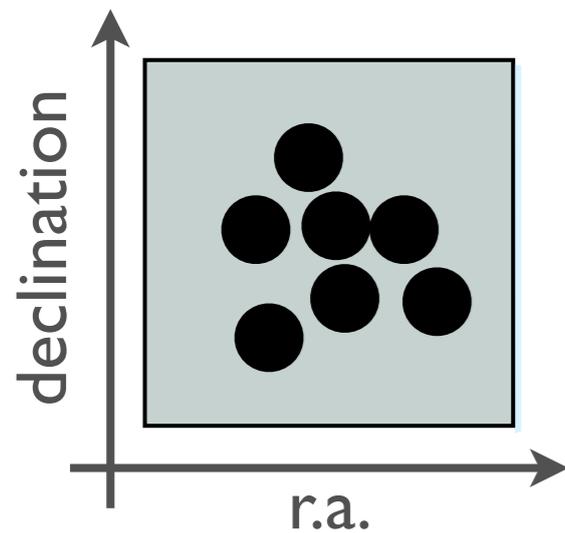
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## Stacking Search

- Search for collective neutrino emission from a catalog/class of sources

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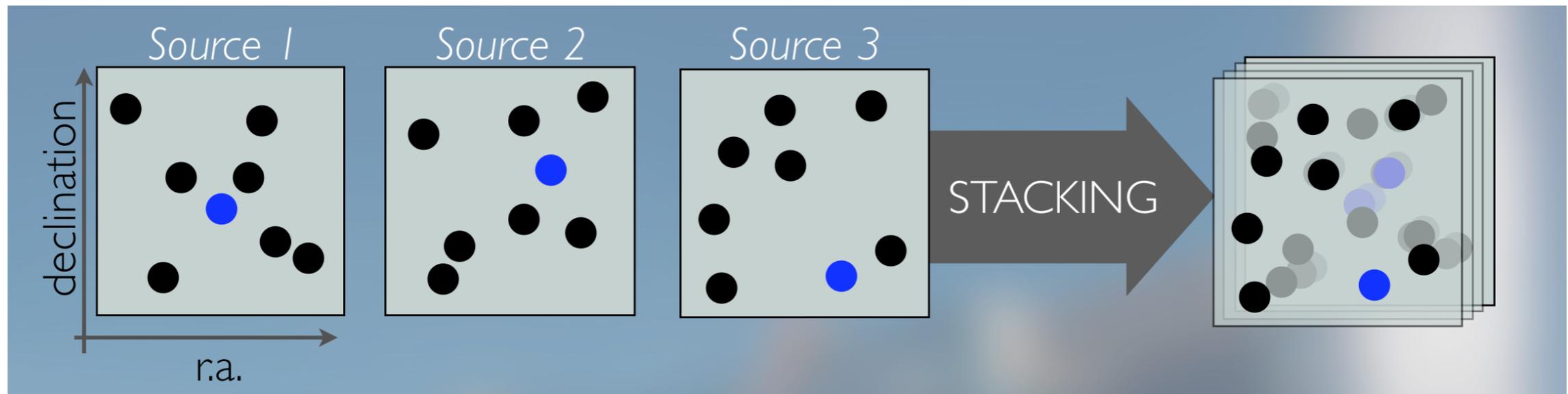
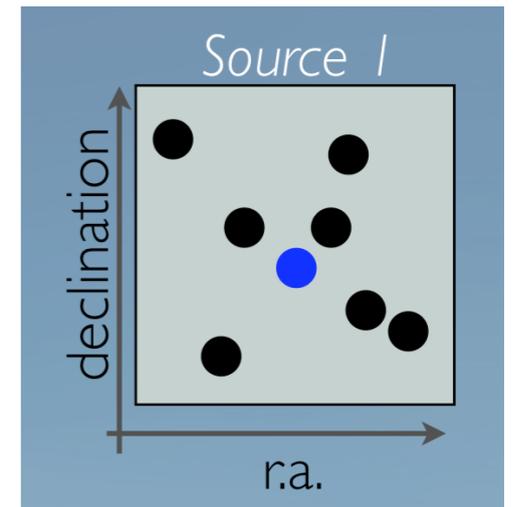


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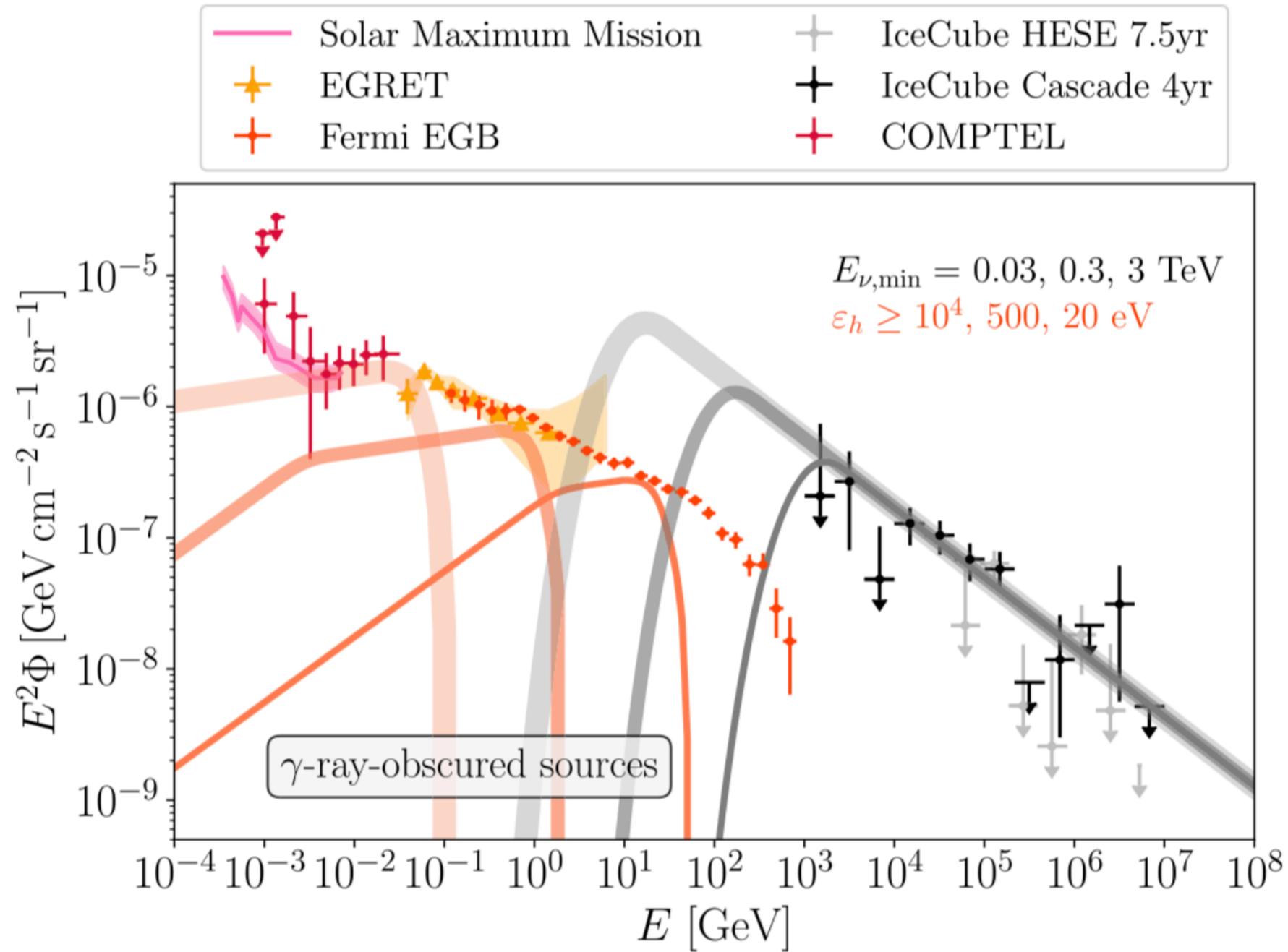


## Stacking Search

- ▶ Search for collective neutrino emission from a catalog/class of sources

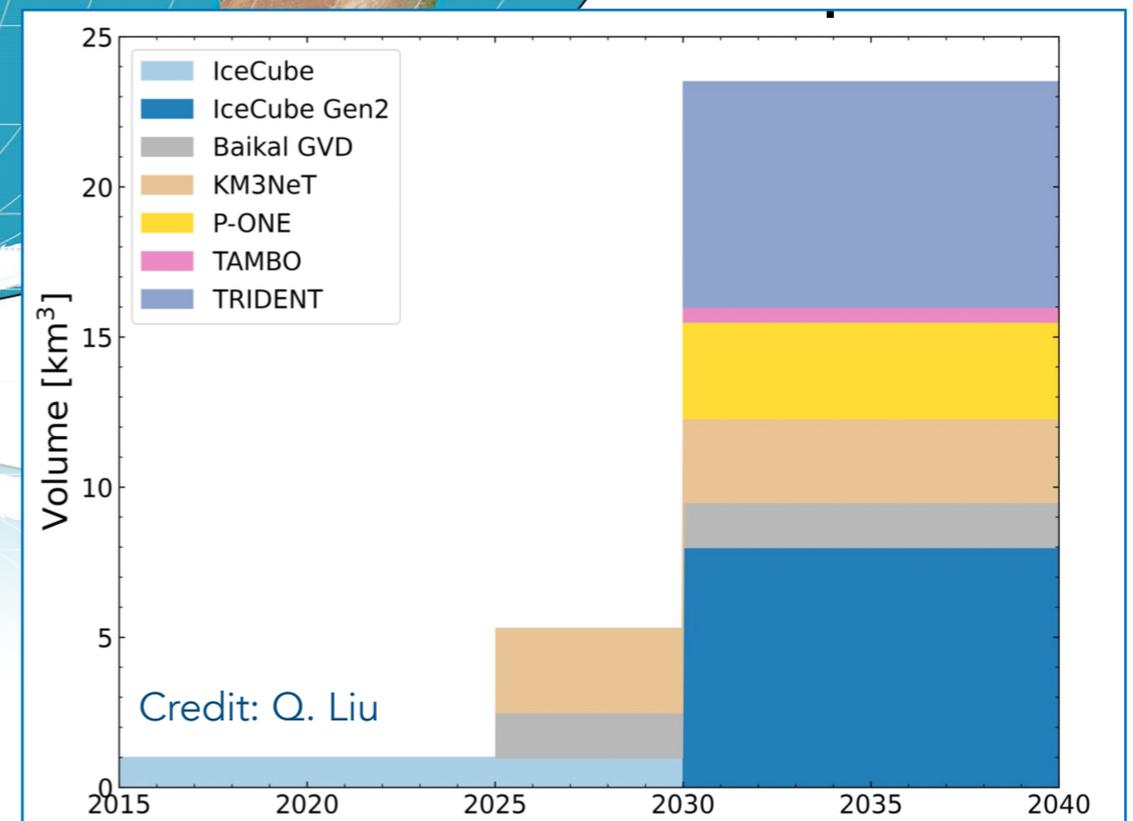
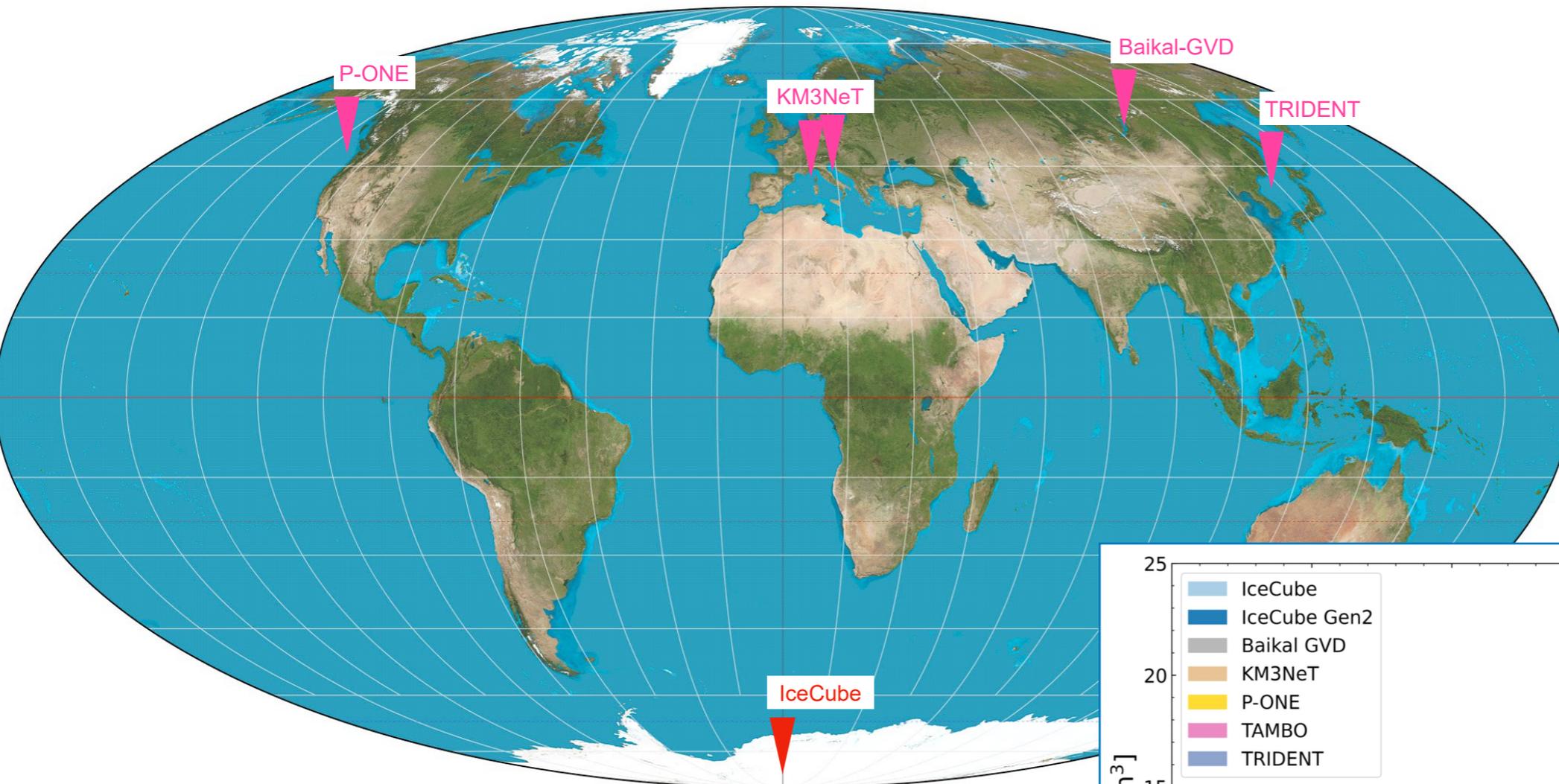
+  *Realtime analysis and Neutrino alerts!*

# Gamma-ray Obscured Sources

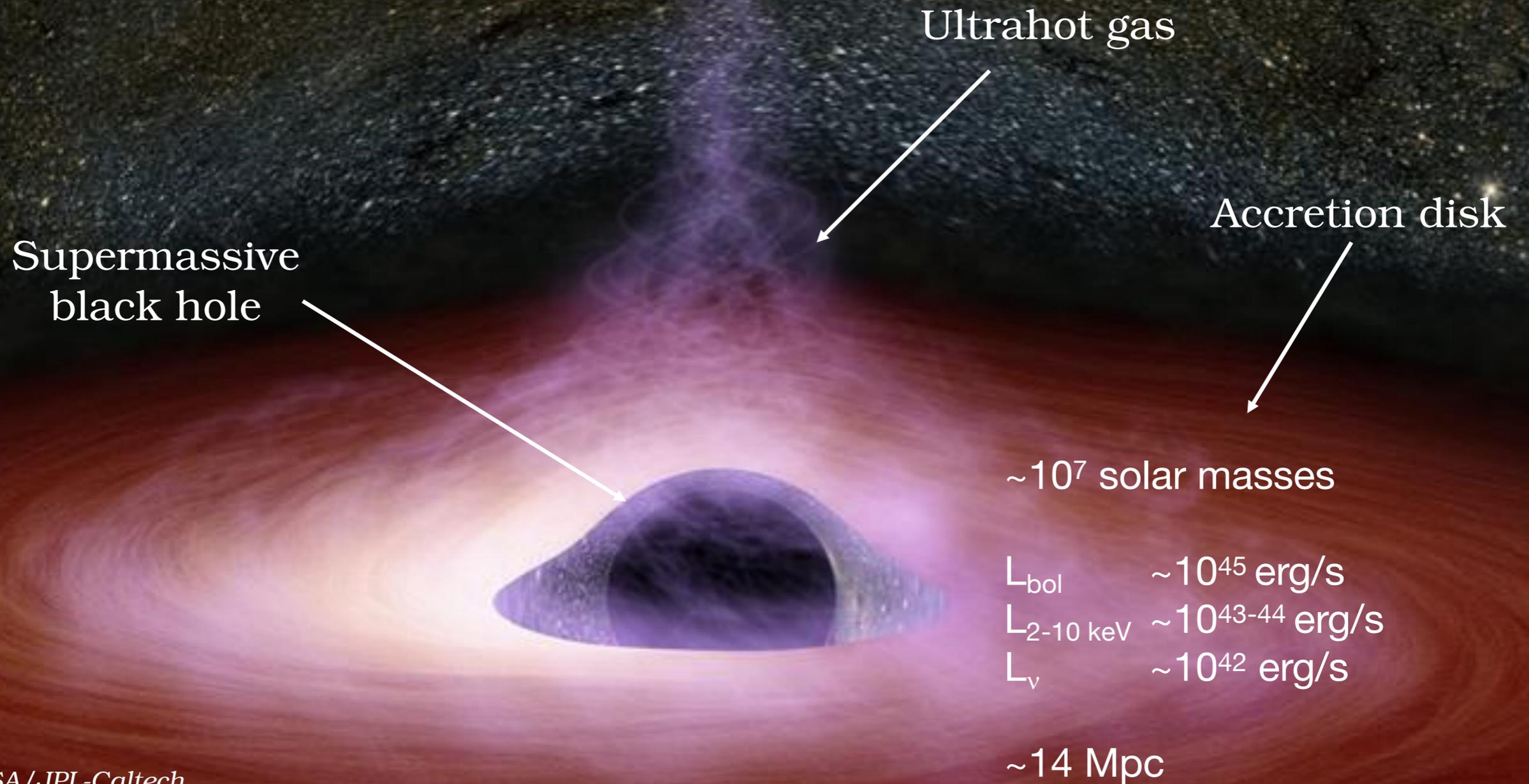


[Fang, Gallagher, Halzen ApJ 2022]

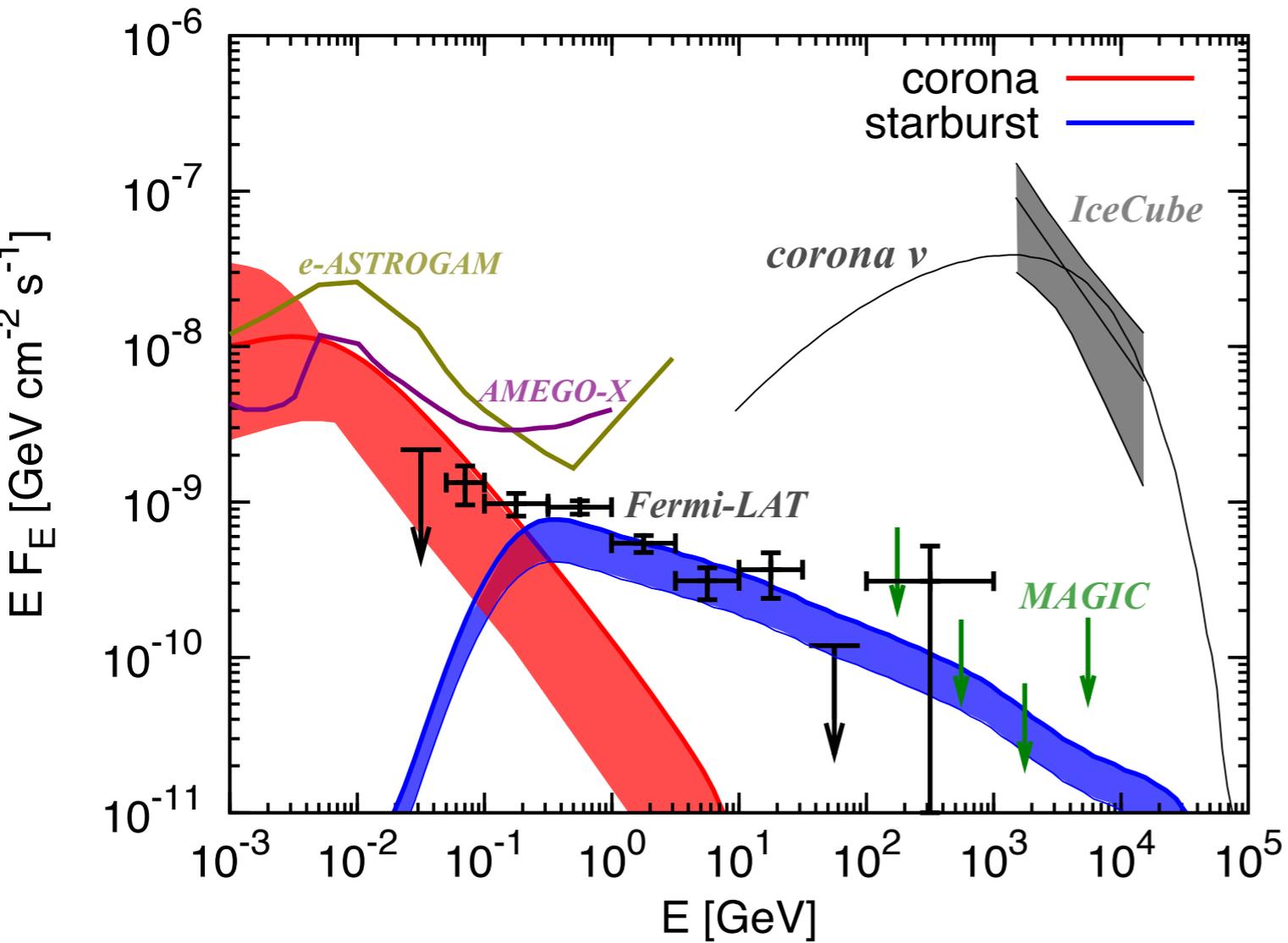
# Neutrino Astronomy Landscape



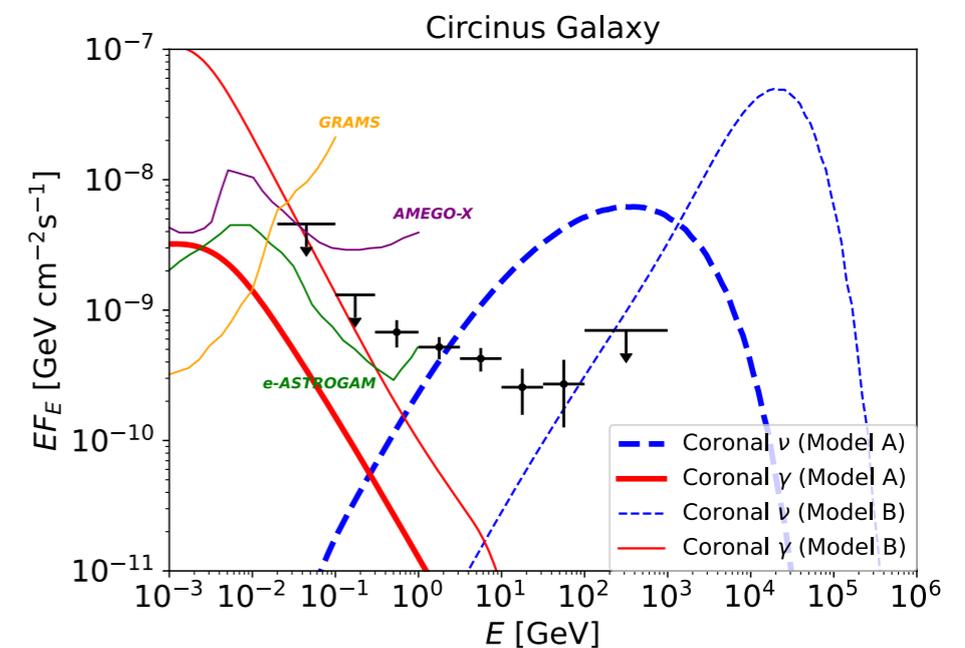
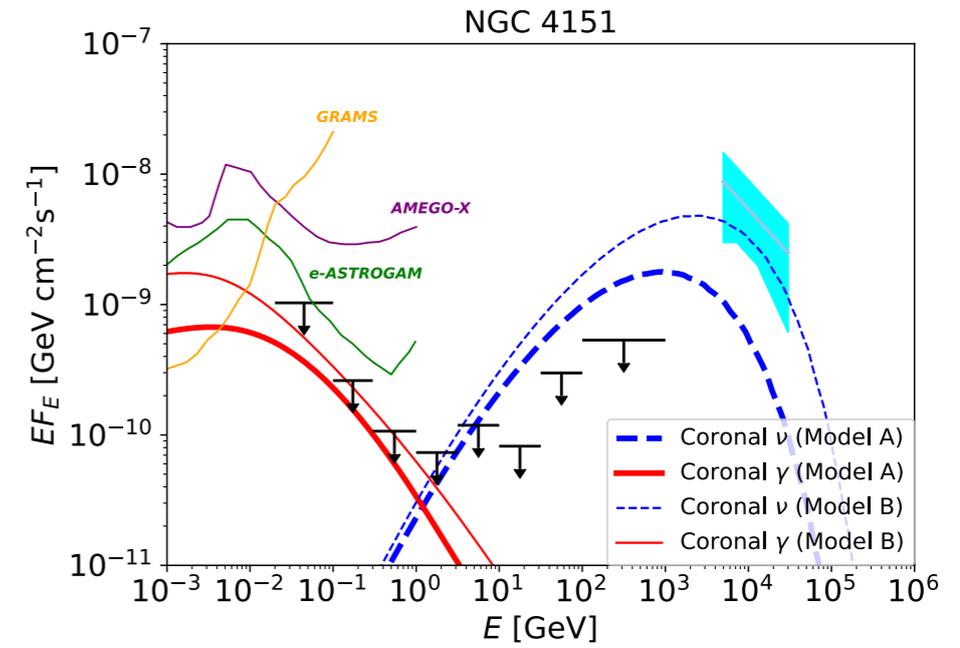
# NGC 1068 and the obscured core



# Hidden Cores of AGN & MeV Emission



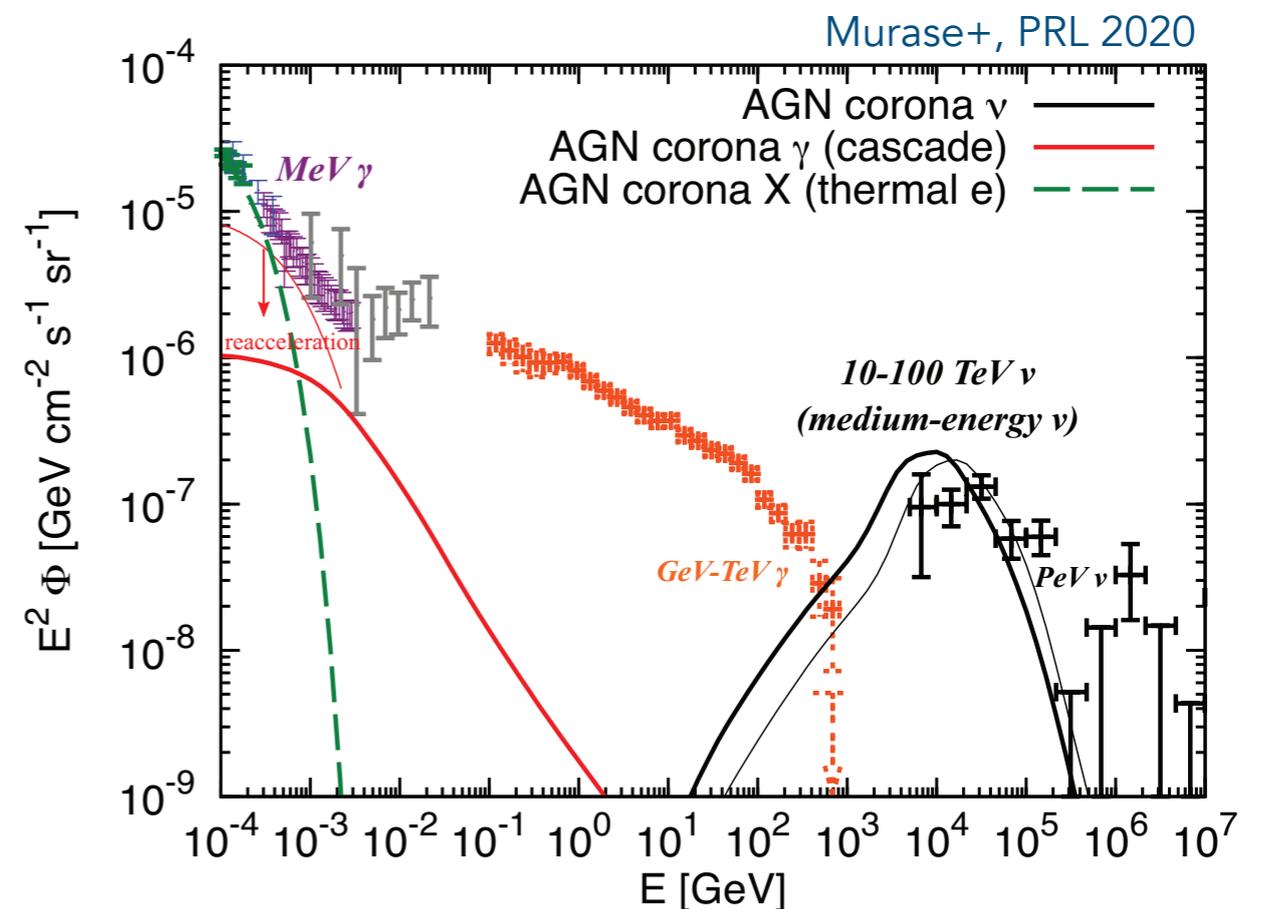
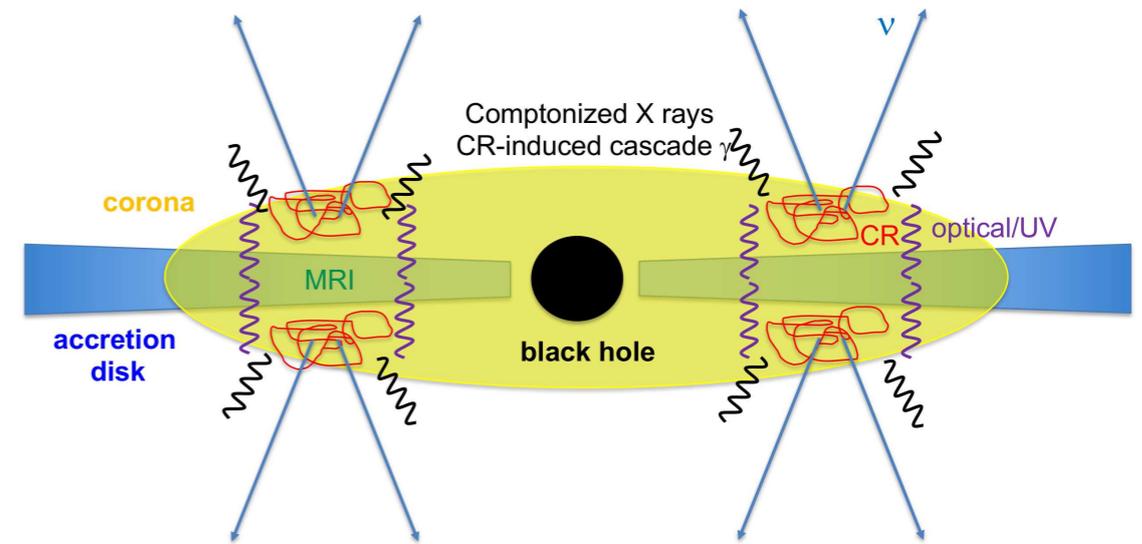
Murase+, ApJL 2023, Ajello+ 2023



- ▶ MeV measurement is necessary to obtain the complete picture of multimessenger emission from the likely sources of HE neutrinos.

# Neutrino Production in Disk-Corona Model

- **Cores** of the active galactic nuclei (AGN), which are optically thick for GeV-TeV  $\gamma$ -rays are one of the best candidates as the source of the high-energy neutrinos.
- In **Seyfert galaxies**, accretion dynamics and magnetic dissipation will form a magnetized **corona** above the disk.
- The **disk-corona** model for high-energy neutrino emission from the core of AGNs can successfully accommodate the flux of cosmic neutrinos at medium energies in the 10-100 TeV range.



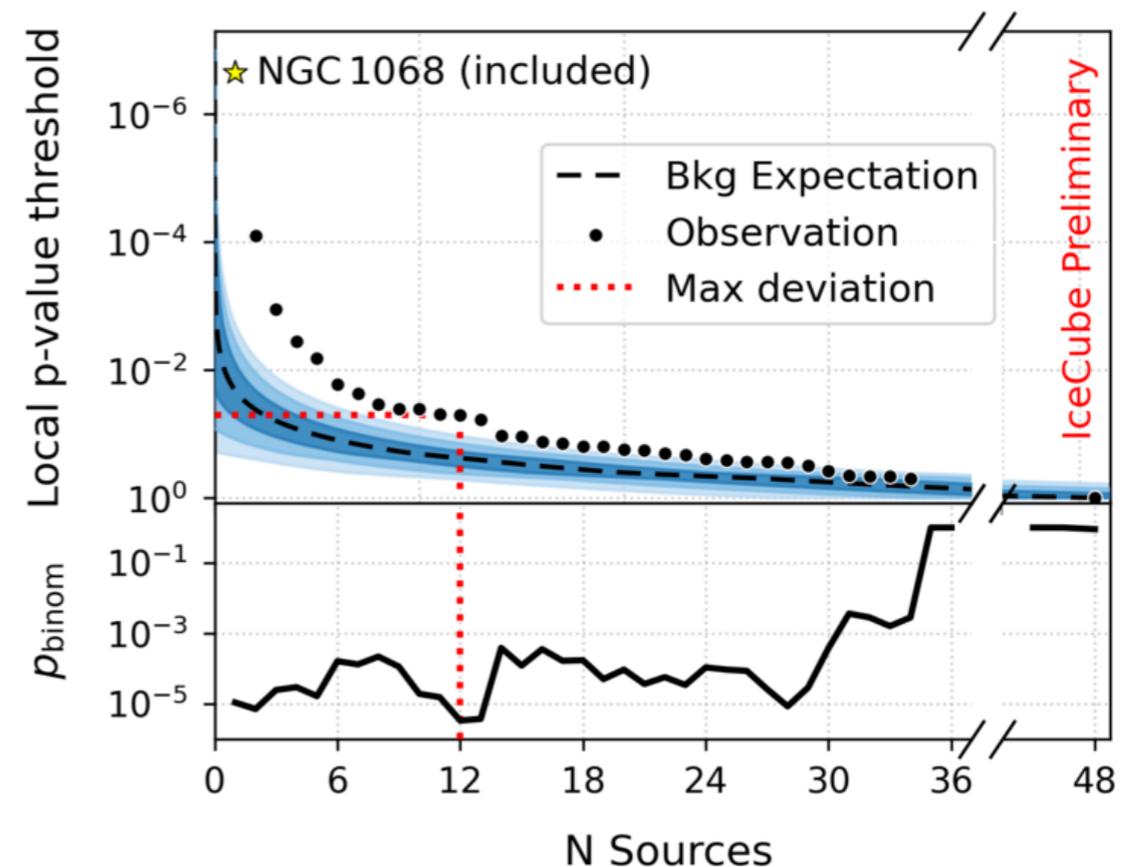
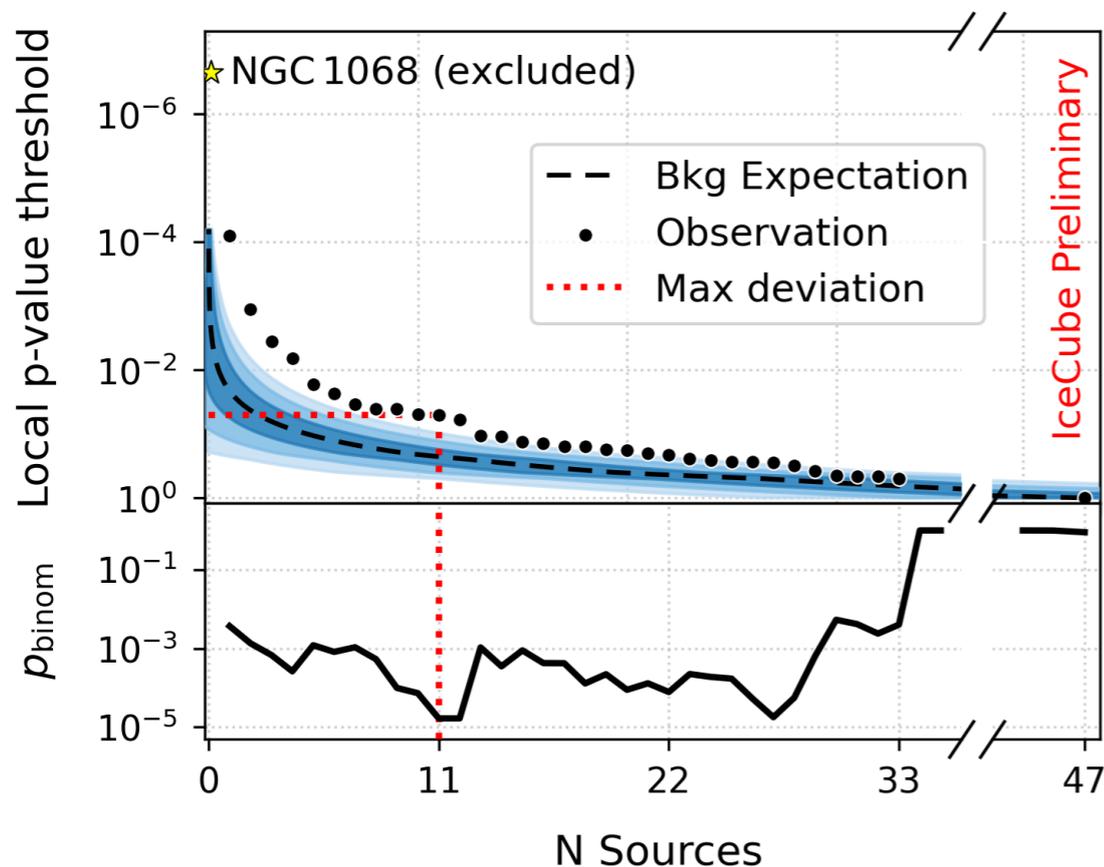
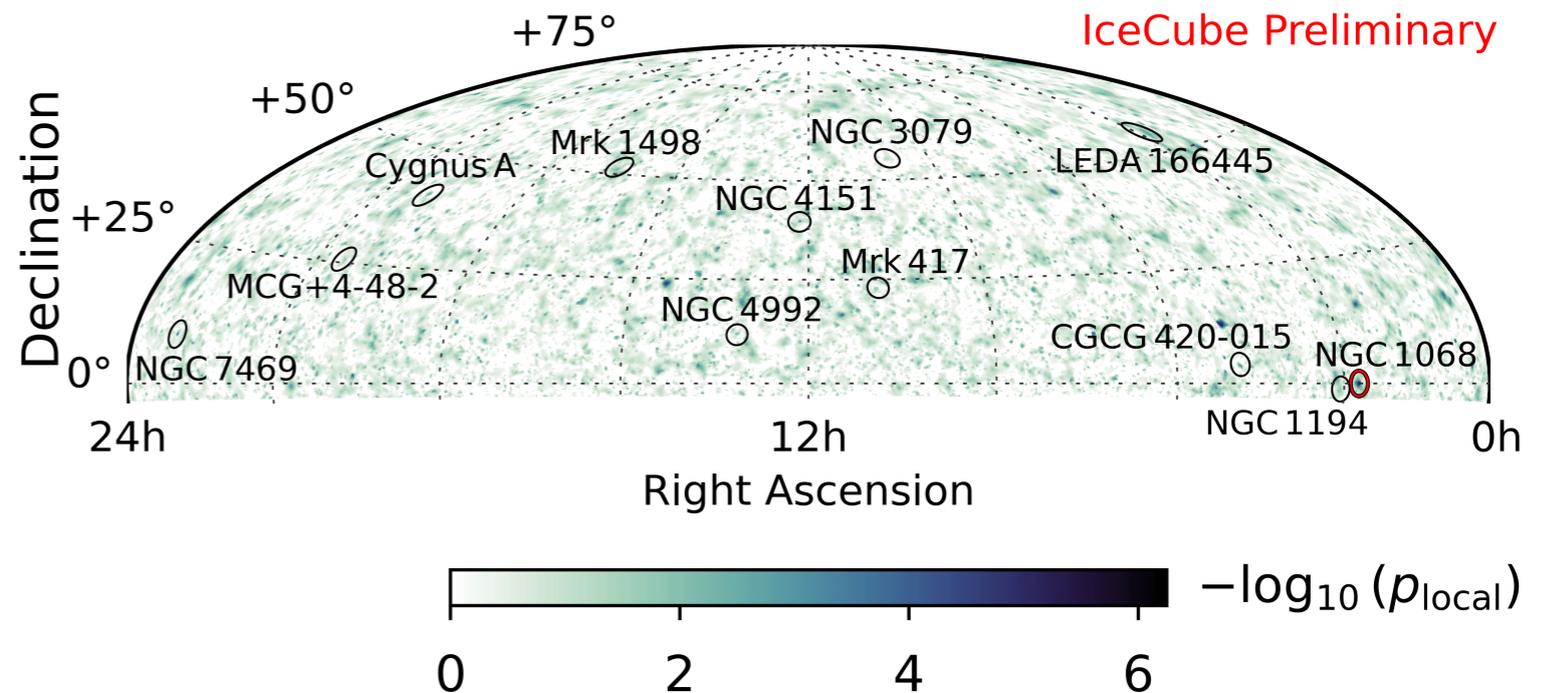
# Northern Seyferts Results

	spectral model	$n_{\text{exp}}$	TS	$\hat{n}_s$	$\hat{\gamma}$	$p_{\text{local}}$	$p_{\text{global}}$	$n_{\text{UL}}$
Stacking Searches								
Stacking (excl.)	disk-corona	154.0	0.1	5	—	$2.4 \times 10^{-1}$ (0.7 $\sigma$ )	$2.4 \times 10^{-1}$ (0.7 $\sigma$ )	51.1
Stacking (incl.) <sup>(*)</sup>	disk-corona	199.0	11.2	77	—	$1.1 \times 10^{-4}$ (3.7 $\sigma$ )	—	128.0
Catalog Search 1								
CGCG 420-015	disk-corona	3.2	11.0	31	—	$2.4 \times 10^{-4}$ (3.5 $\sigma$ )	$6.5 \times 10^{-3}$ (2.5 $\sigma$ )	46.4
NGC 4151	disk-corona	13.1	9.0	23	—	$6.4 \times 10^{-4}$ (3.2 $\sigma$ )	—	39.5
NGC 1068 <sup>(*)</sup>	disk-corona	44.6	23.4	48	—	$3.0 \times 10^{-7}$ (5.0 $\sigma$ )	—	61.4
Catalog Search 2								
NGC 4151	power-law	—	7.4	30	2.7	$6.4 \times 10^{-4}$ (3.2 $\sigma$ )	$1.7 \times 10^{-2}$ (2.1 $\sigma$ )	61.4
CGCG 420-015	power-law	—	9.2	35	2.8	$3.0 \times 10^{-3}$ (2.7 $\sigma$ )	—	62.1
NGC 1068 <sup>(*)</sup>	power-law	—	29.5	94	3.3	$8.0 \times 10^{-8}$ (5.2 $\sigma$ )	—	94.9

NOTE—Results for the stacking search and selected results from two catalog searches, Catalog Search 1: disk-corona model; and Catalog Search 2: power-law model. Best-fitted TS,  $\hat{n}_s$ , local (pre-trial) and global (post-trial)  $p$ -values, and corresponding significances are shown. For the disk-corona model analysis, expected numbers of events ( $n_{\text{exp}}$ ) are listed and for the power-law analysis, best-fitted spectral indices  $\hat{\gamma}$  are listed.  $n_{\text{UL}}$  column shows the 90% upper limits of the numbers of signal events. Upper limits assuming power-law spectra are given assuming  $E^{-3}$ . Results marked with <sup>(\*)</sup> are provided for completeness but are not used to compute final significances because evidence for neutrino emission from NGC 1068 was known prior to this work (Abbasi et al. 2022a; Aartsen et al. 2020c).

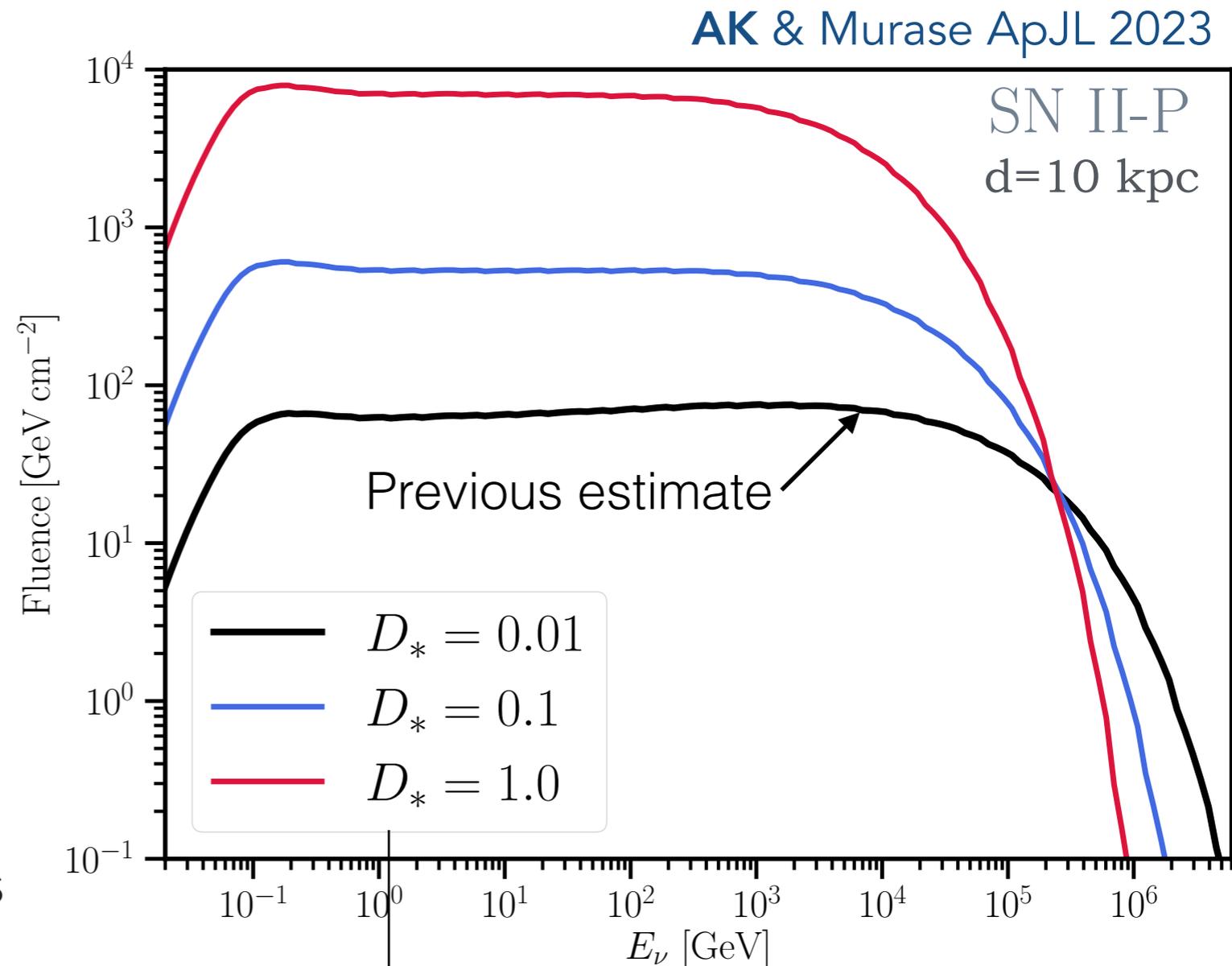
# Extend Northern Sky Search

- ▶ 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)



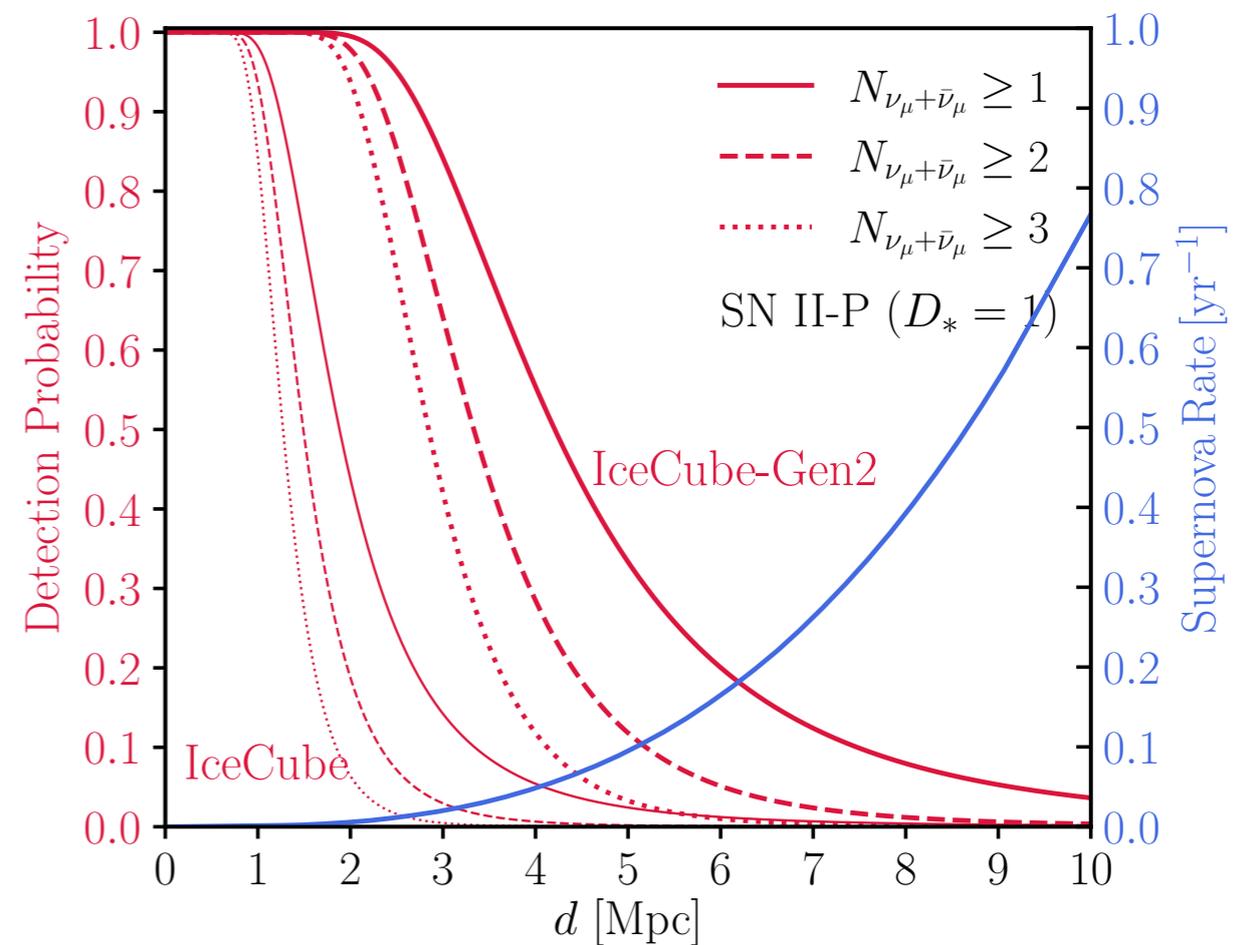
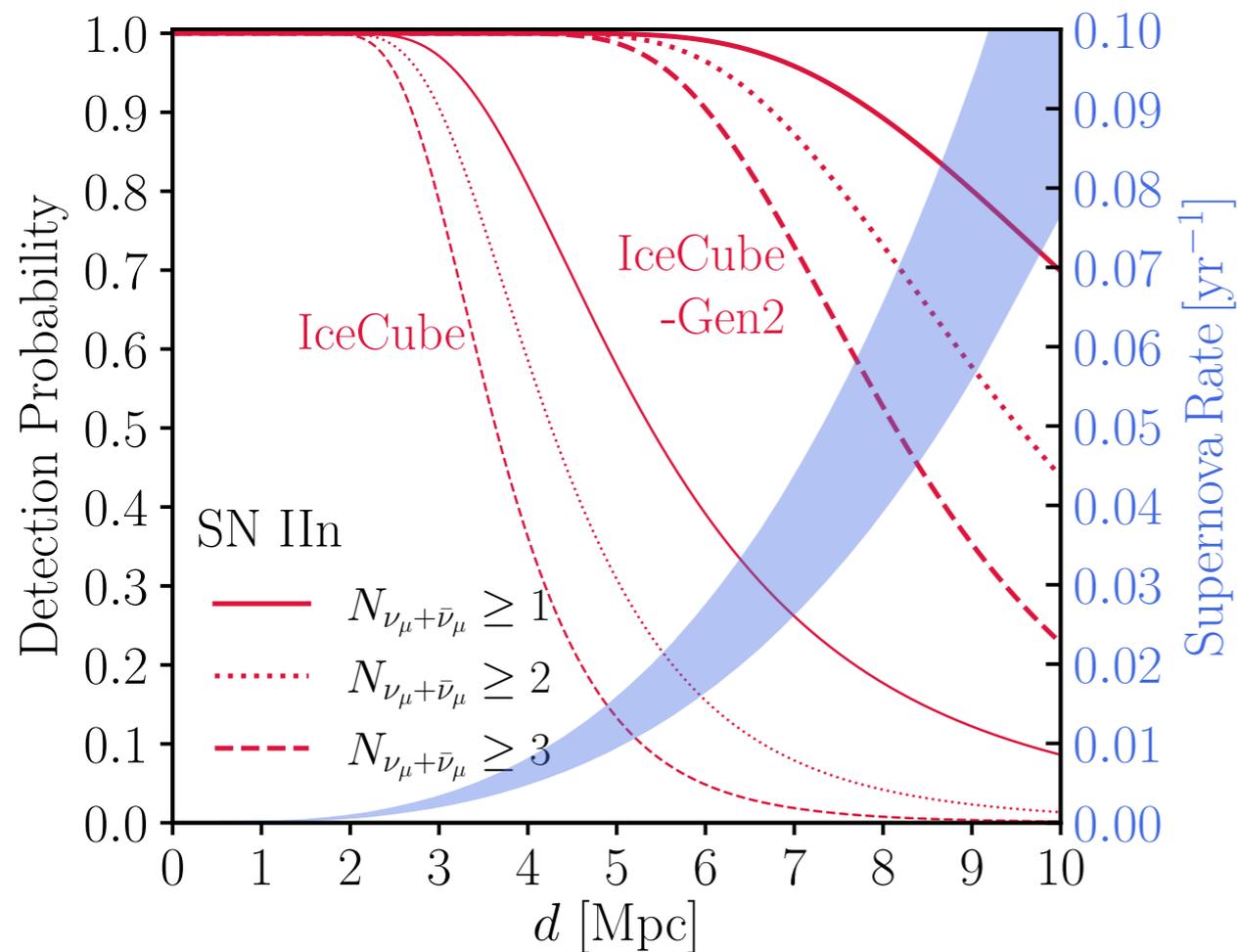
# HE Neutrinos from SN II with CCSM

- SN II-P is the most common type of core-collapse SN
- Progenitors are Red Super Giants.
- The level of the neutrino emission is generally lower than SN IIc but the higher rate increases the chance for observation.
- Recent observations suggests more efficient neutrino production [MOROZOVA+2018].
  - ▶ *Observation is more likely!*



$D^*$  parameterizes mass loss rate and wind velocity and is directly correlated with neutrino emission.

# HE Neutrinos from CCSNe



AK & Murase ApJL 2023

The next generation of neutrino telescopes will extend the horizon for observation of multiple neutrinos from extragalactic SN IIn.

# The source of Galactic neutrinos?

	Flux sensitivity $\Phi$	<i>P</i> value	Best-fitting flux $\Phi$
<i>Diffuse Galactic plane analysis</i>			
$\pi^0$	5.98	$1.26 \times 10^{-6}$ (4.71 $\sigma$ )	$21.8^{+5.3}_{-4.9}$
$\text{KRA}_{\gamma}^5$	$0.16 \times \text{MF}$	$6.13 \times 10^{-6}$ (4.37 $\sigma$ )	$0.55^{+0.18}_{-0.15} \times \text{MF}$
$\text{KRA}_{\gamma}^{50}$	$0.11 \times \text{MF}$	$3.72 \times 10^{-5}$ (3.96 $\sigma$ )	$0.37^{+0.13}_{-0.11} \times \text{MF}$
<i>Catalog stacking analysis</i>			
SNR		$5.90 \times 10^{-4}$ (3.24 $\sigma$ )*	
PWN		$5.93 \times 10^{-4}$ (3.24 $\sigma$ )*	
UNID		$3.39 \times 10^{-4}$ (3.40 $\sigma$ )*	

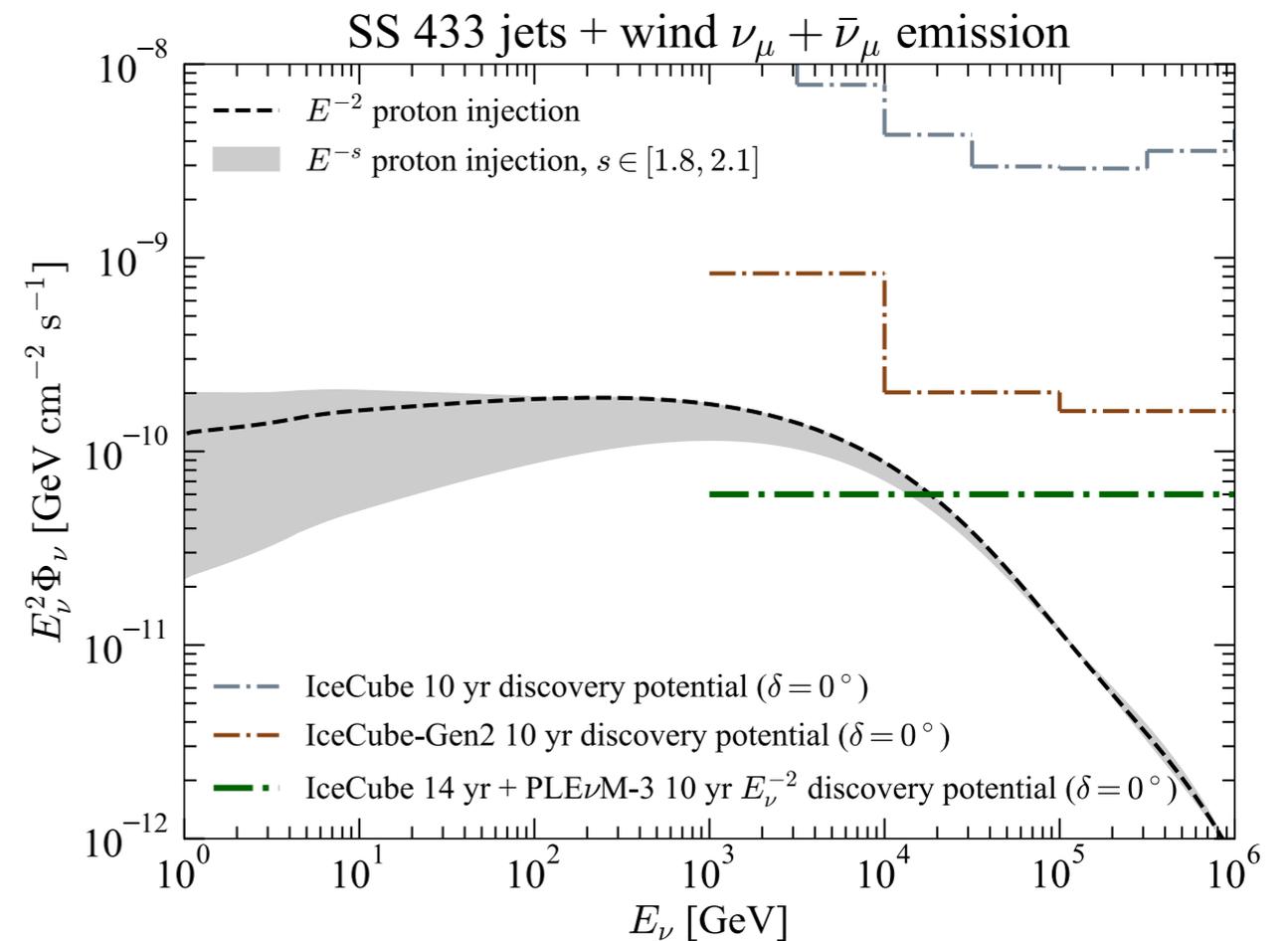
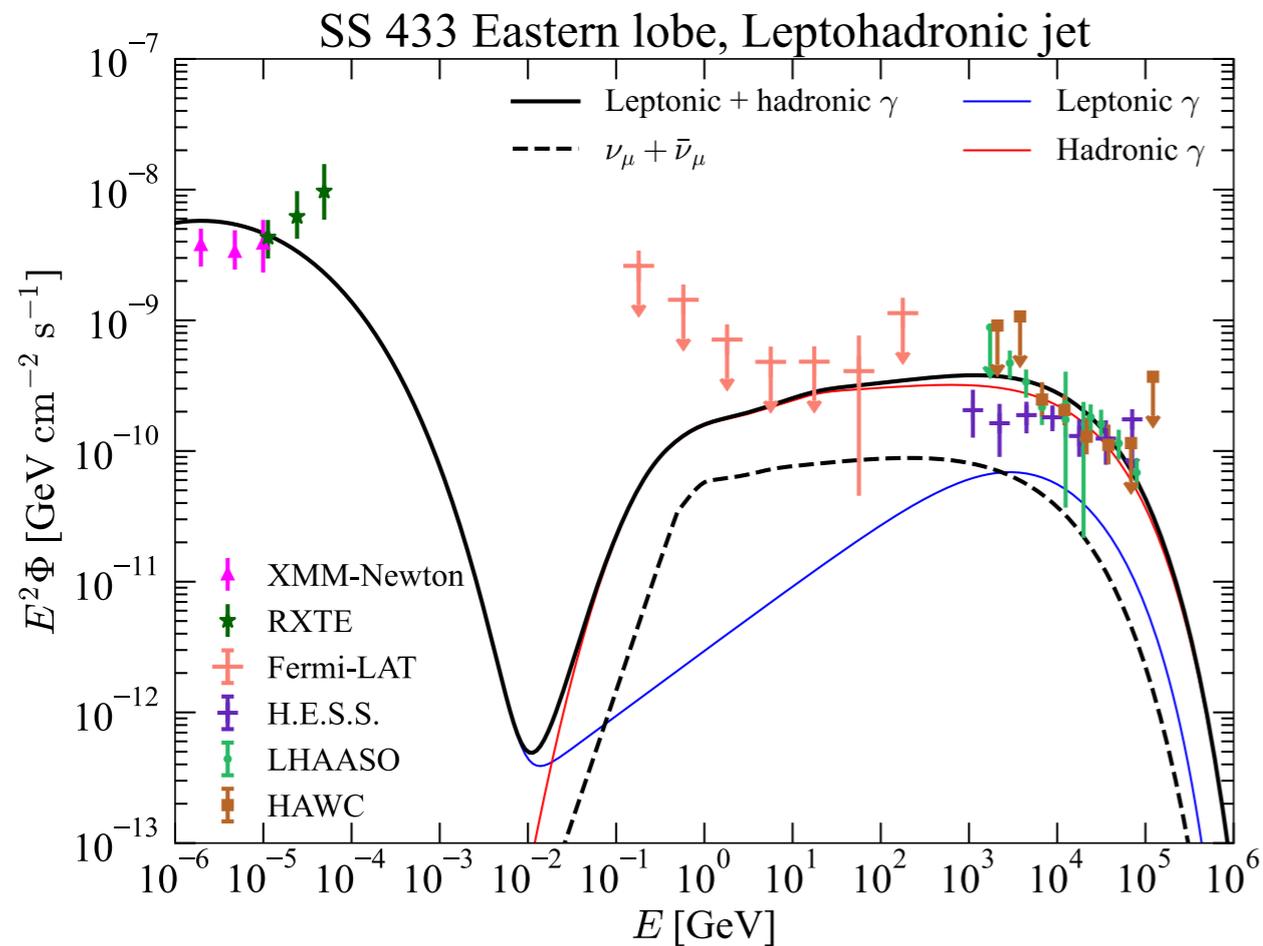
[IceCube, Science 2023]

The nature of the Galactic HE neutrino emission is yet to be understood.

Catalog searches significance is consistent with the template searches.

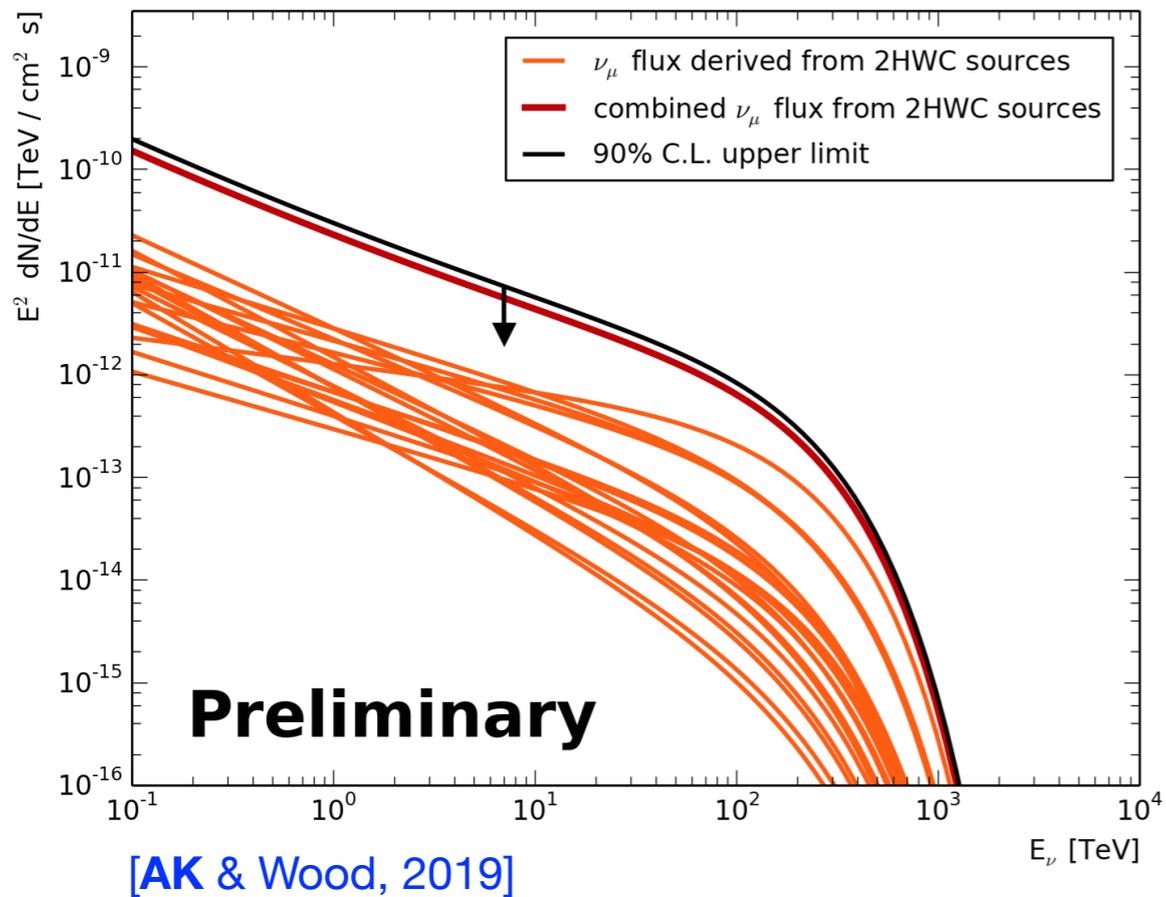
# VHE Emission from X-ray binaries

[Carpio, AK, Zhang, 2025]

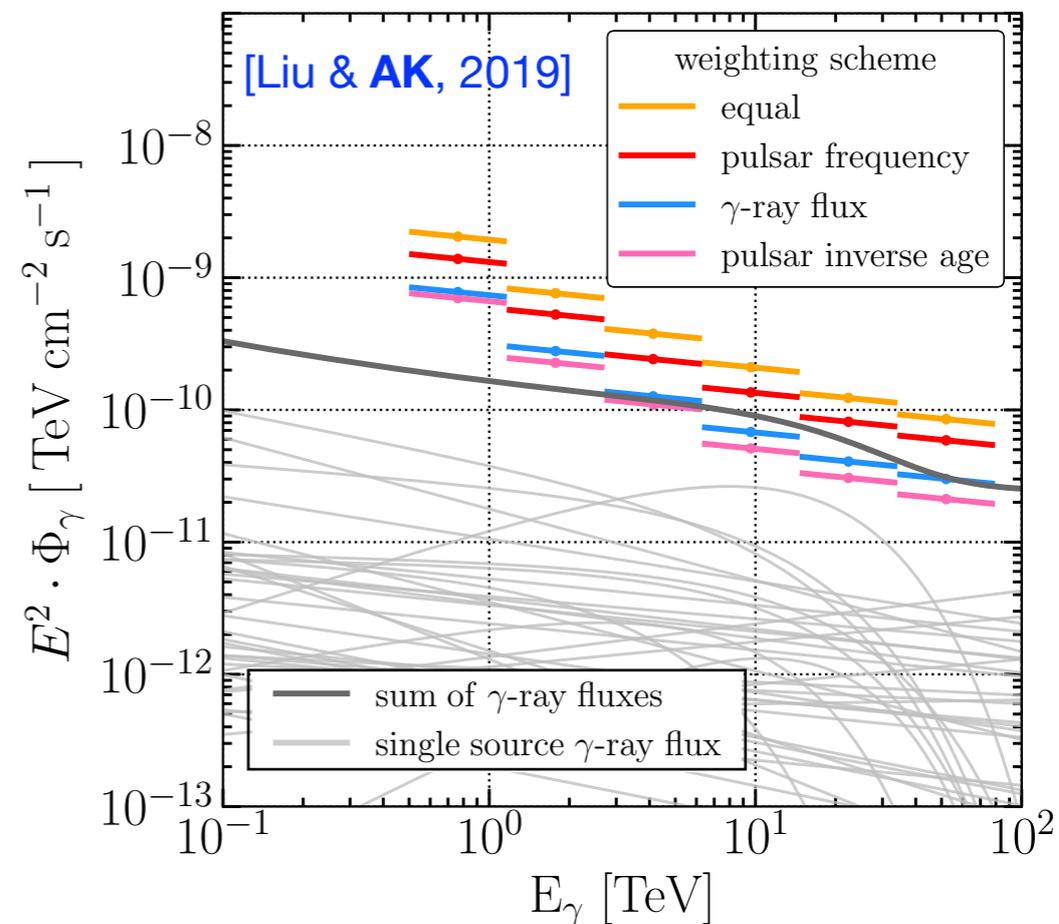


- ▶ Hadrons play a major role in the  $\gamma$ -ray emission from these sources.
- ▶ The level of flux not high enough to be identified in current experiments.

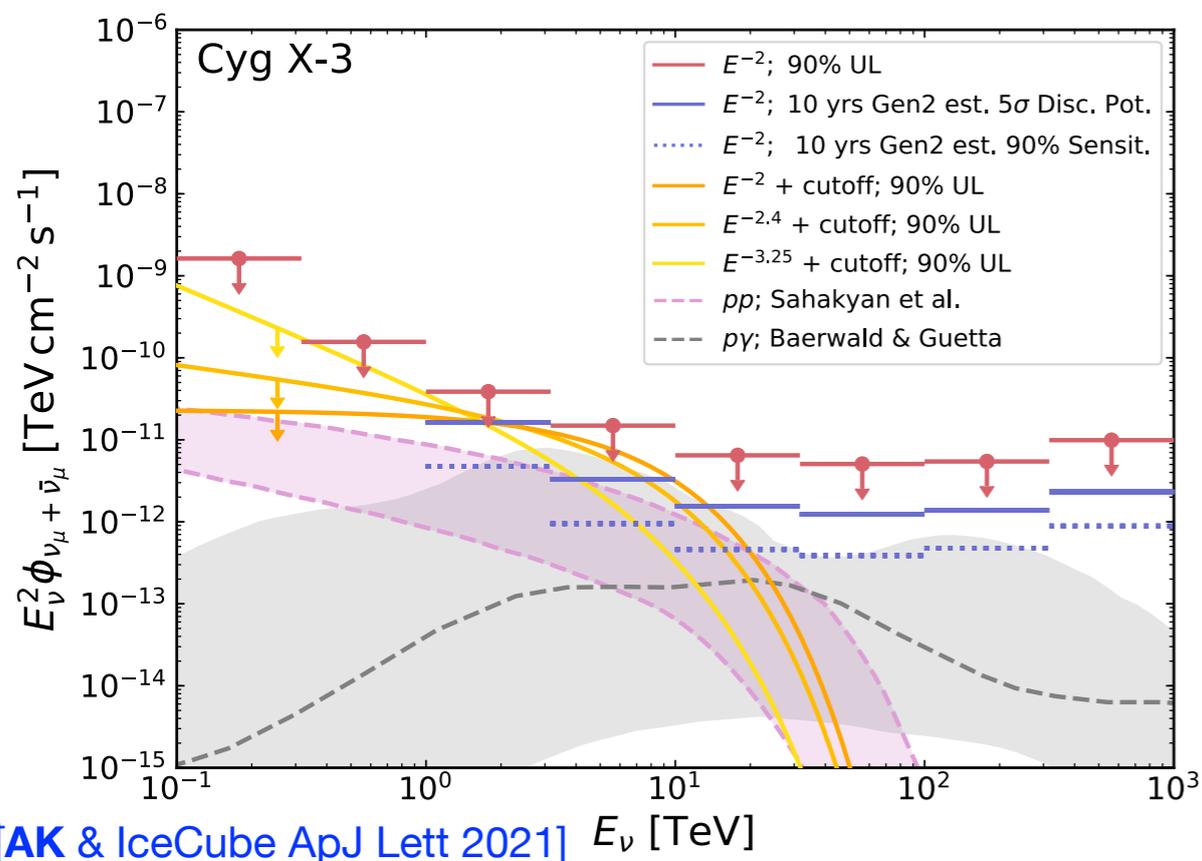
# Supernova Remnants



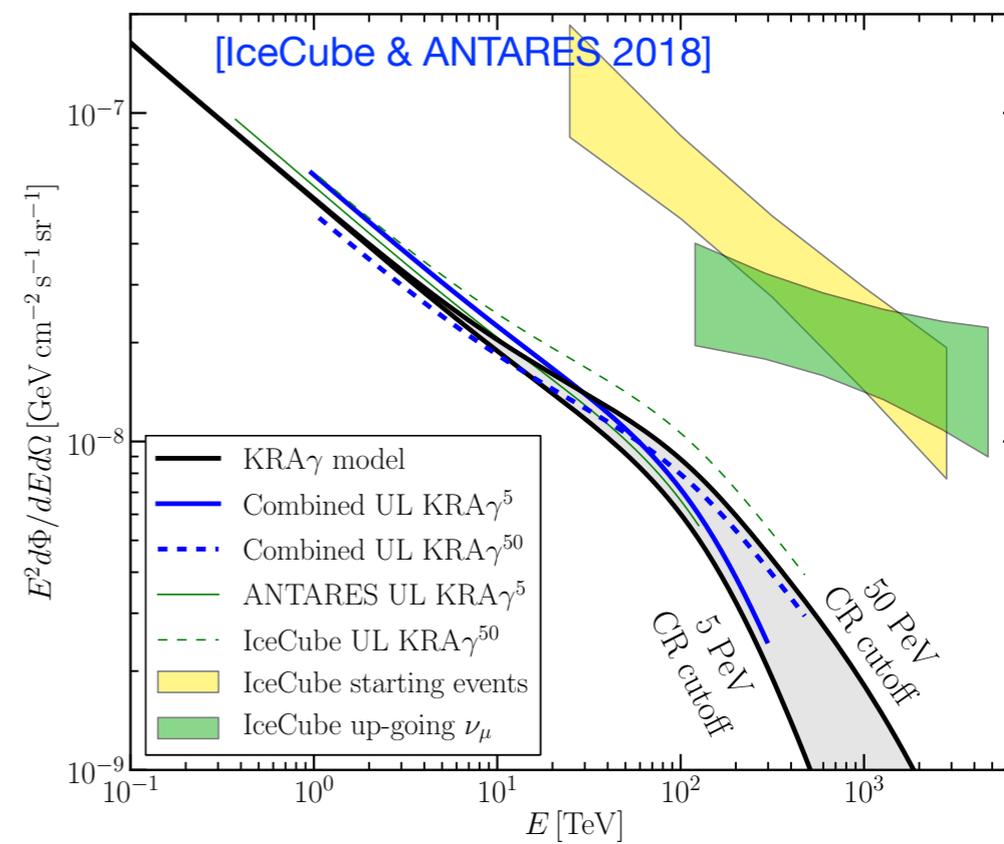
# Pulsar Wind Nebulae



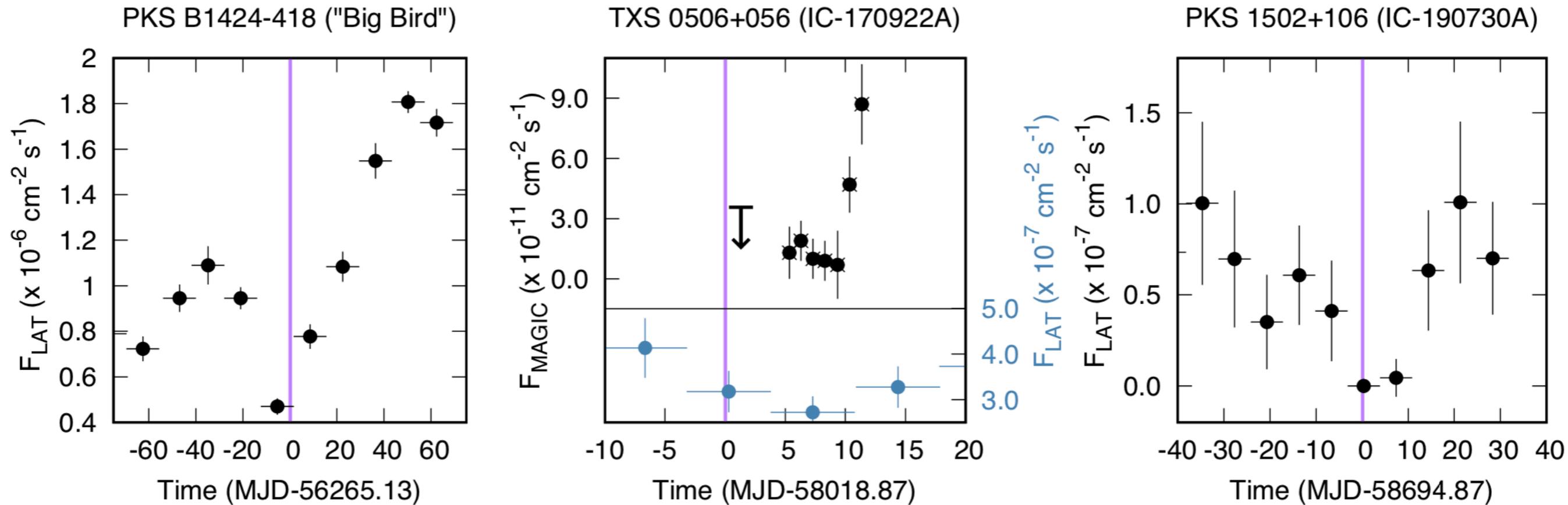
# Binaries



# Diffuse Galactic Emission



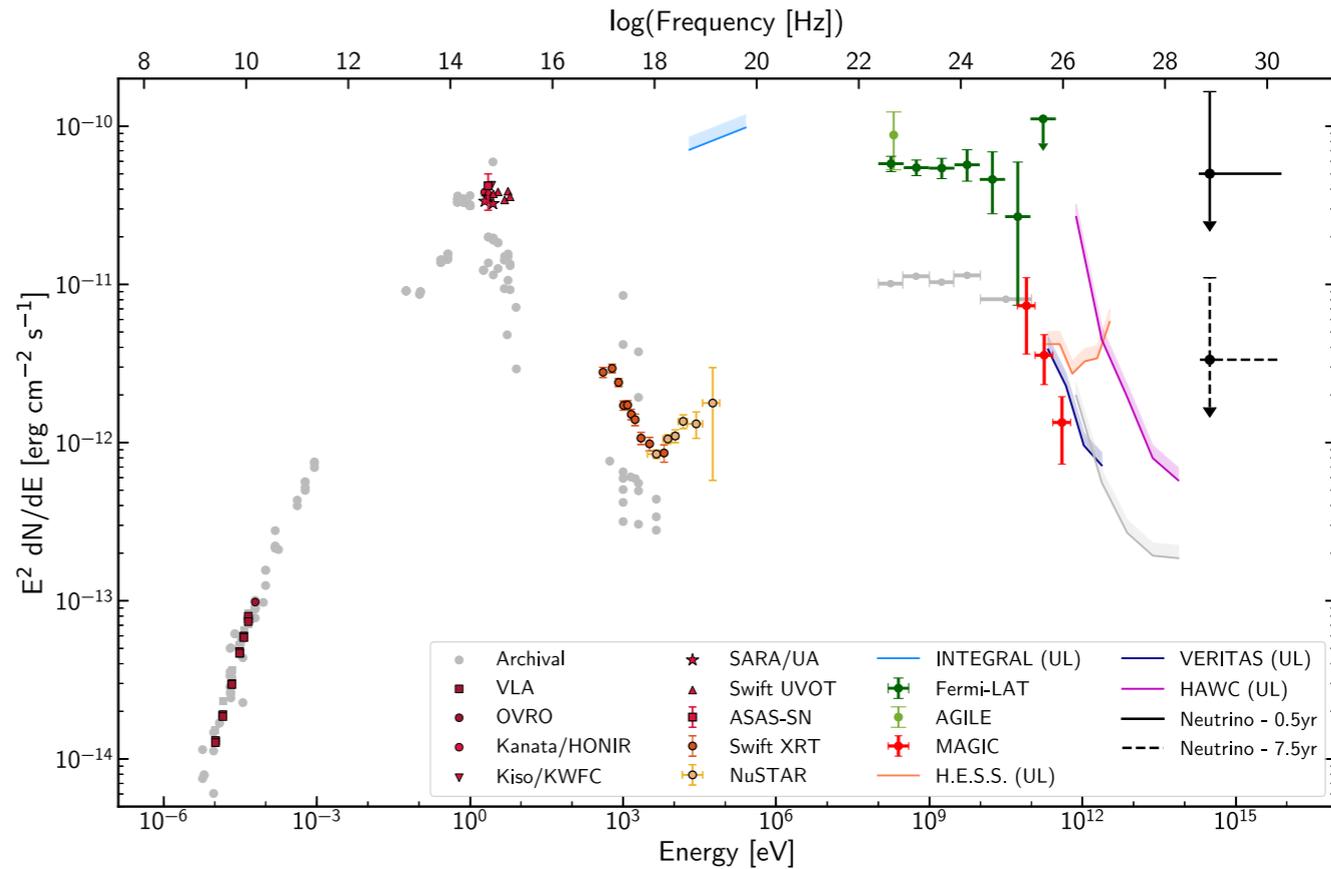
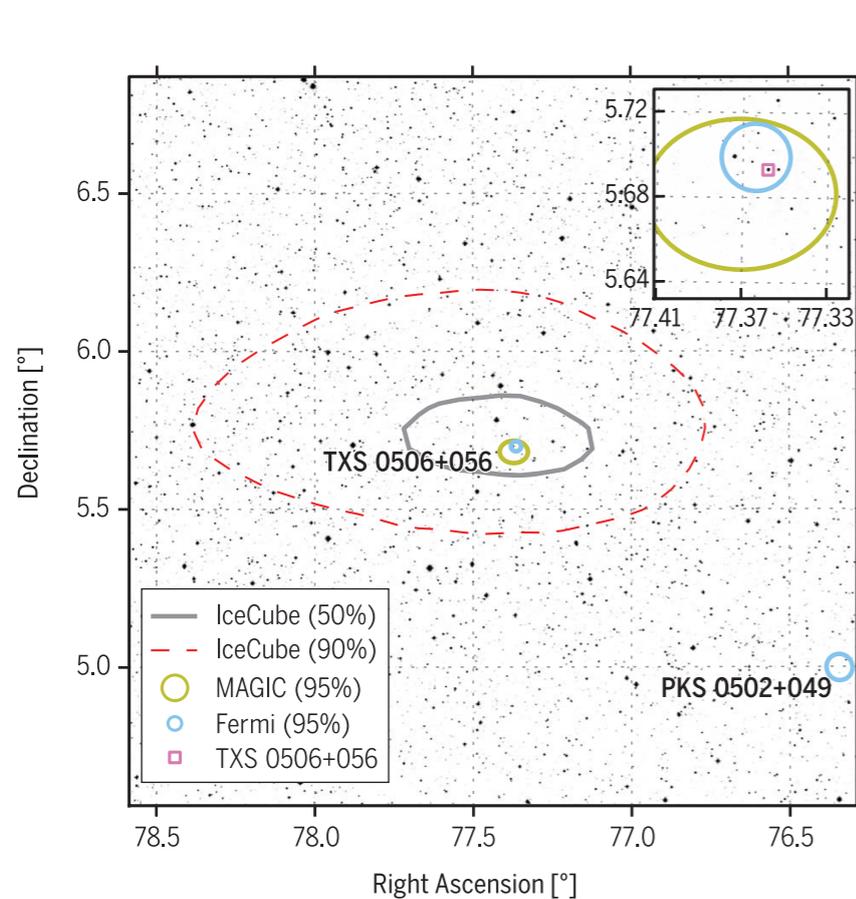
# Emerging Feature: $\gamma$ -ray Suppression



[Kun+ 2021]

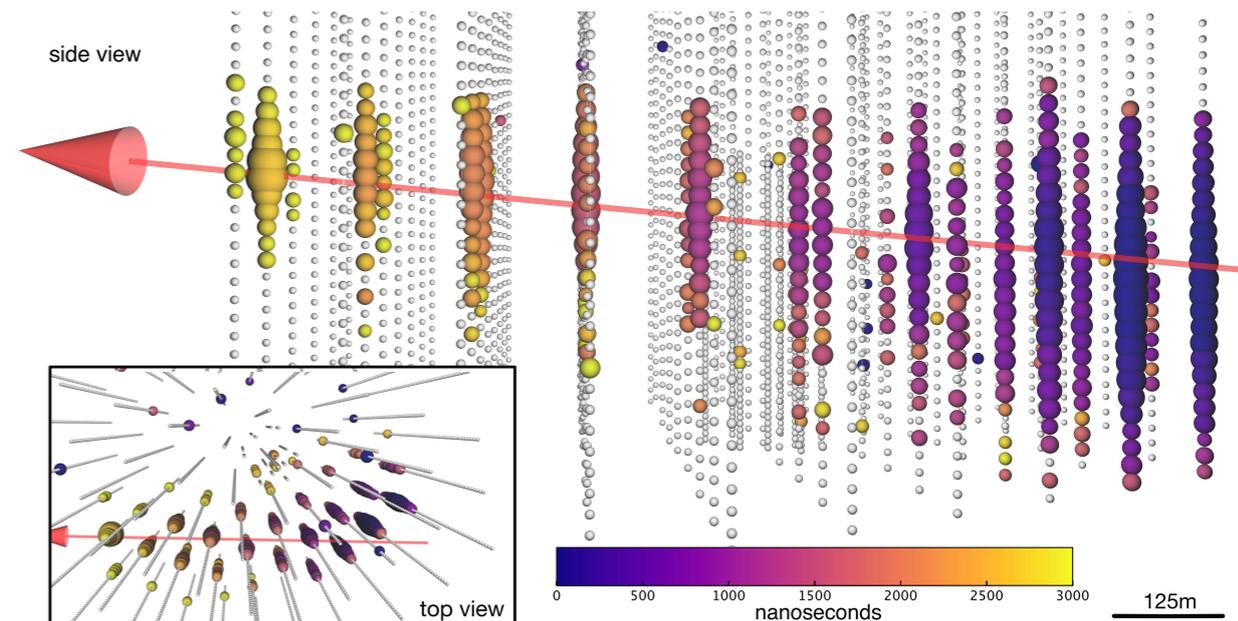
Sources found to be in quiet mode in  $\gamma$ -rays at the time of a high-energy neutrino alert detection.

# TXS 0506+056



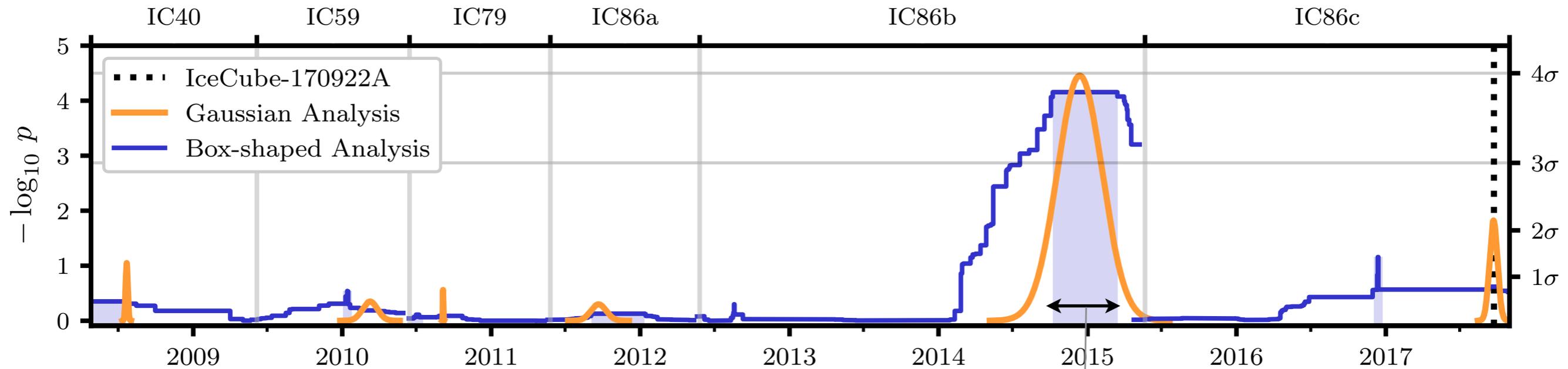
- ▶ Up-going track observed on September 22, 2017 from  $5.7^\circ$  below horizon with best fit neutrino energy of  $\sim 300$  TeV for  $E^{-2}$  Spectrum.
- ▶ Coincidence with enhanced  $\gamma$ -ray activity, chance correlation rejected at the level of  $3\sigma$ .

[IceCube+, Science 2018]

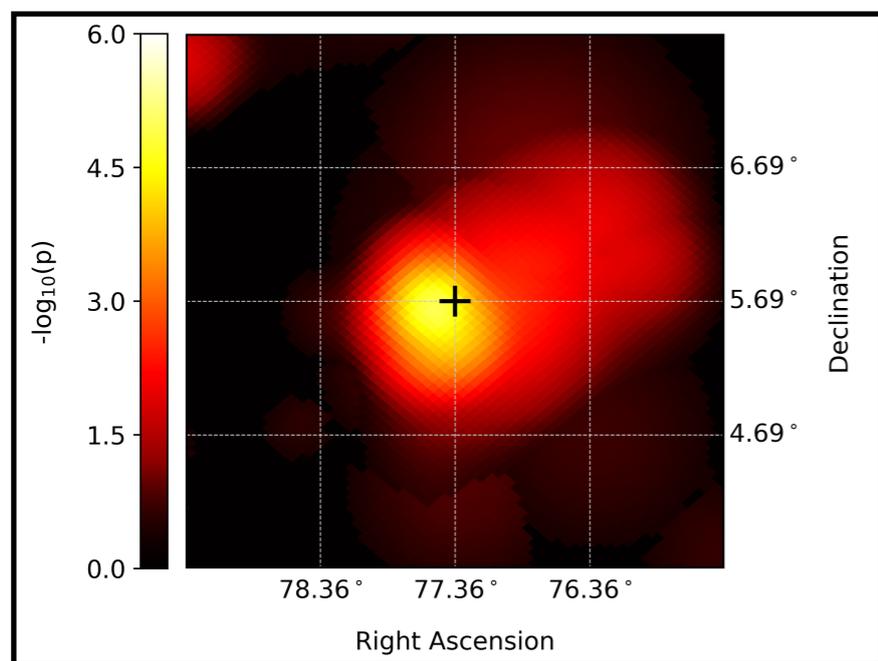


# Neutrino Flare in 2014-15

**Time-dependent search** in the direction of TXS 0506+056 revealed a neutrino flare in December 2014.



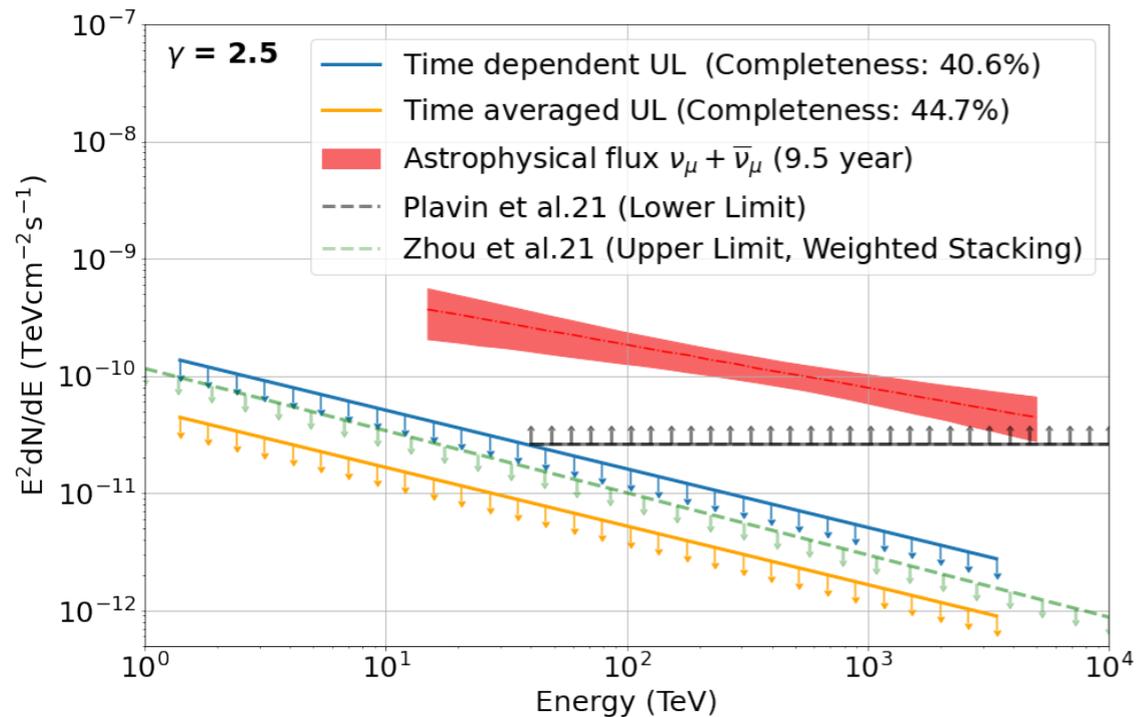
[IceCube, Science 2018]



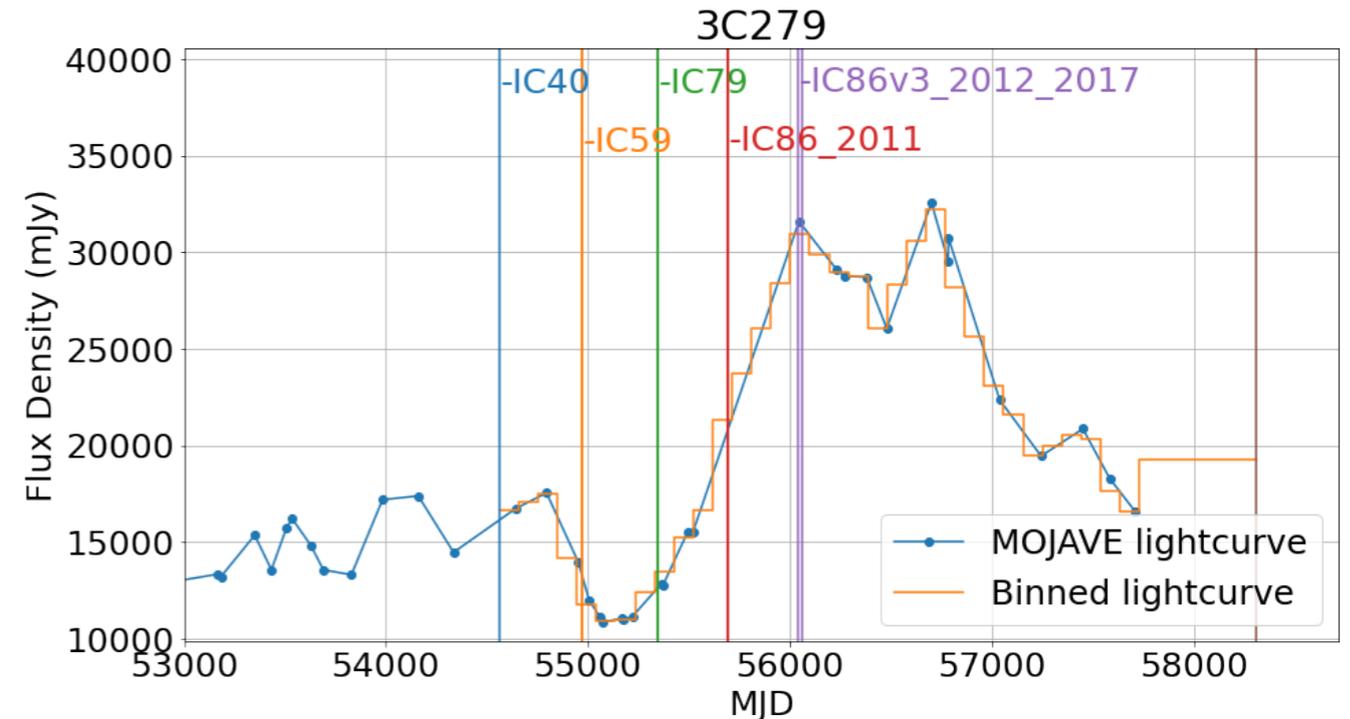
$13 \pm 5$  signal events rejecting background hypothesis at  $3.5\sigma$

- ▶ Remains the most significant observed transient
- ▶ Not accompanied by a gamma-ray flare

# Radio Loud AGN



[IceCube 2024]



- ▶ Testing correlation of HE neutrinos with MOJAVE sample of 437 AGNs in the 15 GHz band
  - ▶▶ **Time-Integrated search:** Using time-average radio flux from each source as proxy in the stacking analysis
  - ▶▶ **Time-dependent search:** Using radio light curves as proxy for the neutrino emission from each source
- ▶ IceCube analysis constrains the neutrino emission from radio bright sources to the total neutrino flux if neutrino emission is directly correlated to the radio emission

# Gamma Ray Bursts (MeV-PeV)

- ▶ IceCube has continuously searched for neutrino emission from GRBs
- ▶ Prompt emission is constrained, less than a percent of IceCube flux would come from prompt GRB emission
- ▶ IceCube follow up on GRB 221009A (brightest of all time) provided strongest limit on the neutrino emission and baryon loading factor

