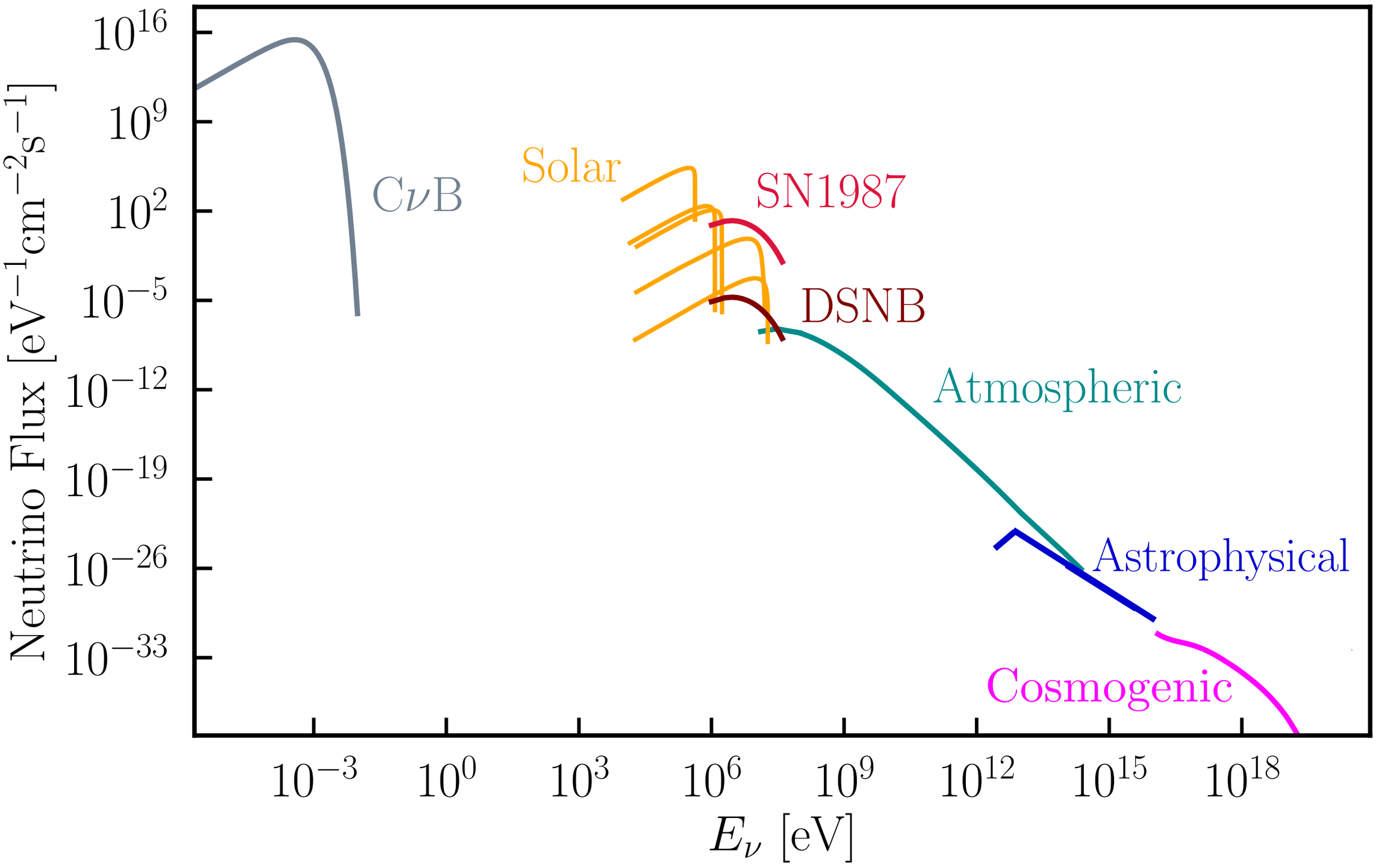
IceCube Astrophysical Neutrinos

Ali Kheirandish
(University of Nevada, Las Vegas)
for the IceCube Collaboration

Neutrino 2026
UC-Irvine

The Universe in Neutrinos



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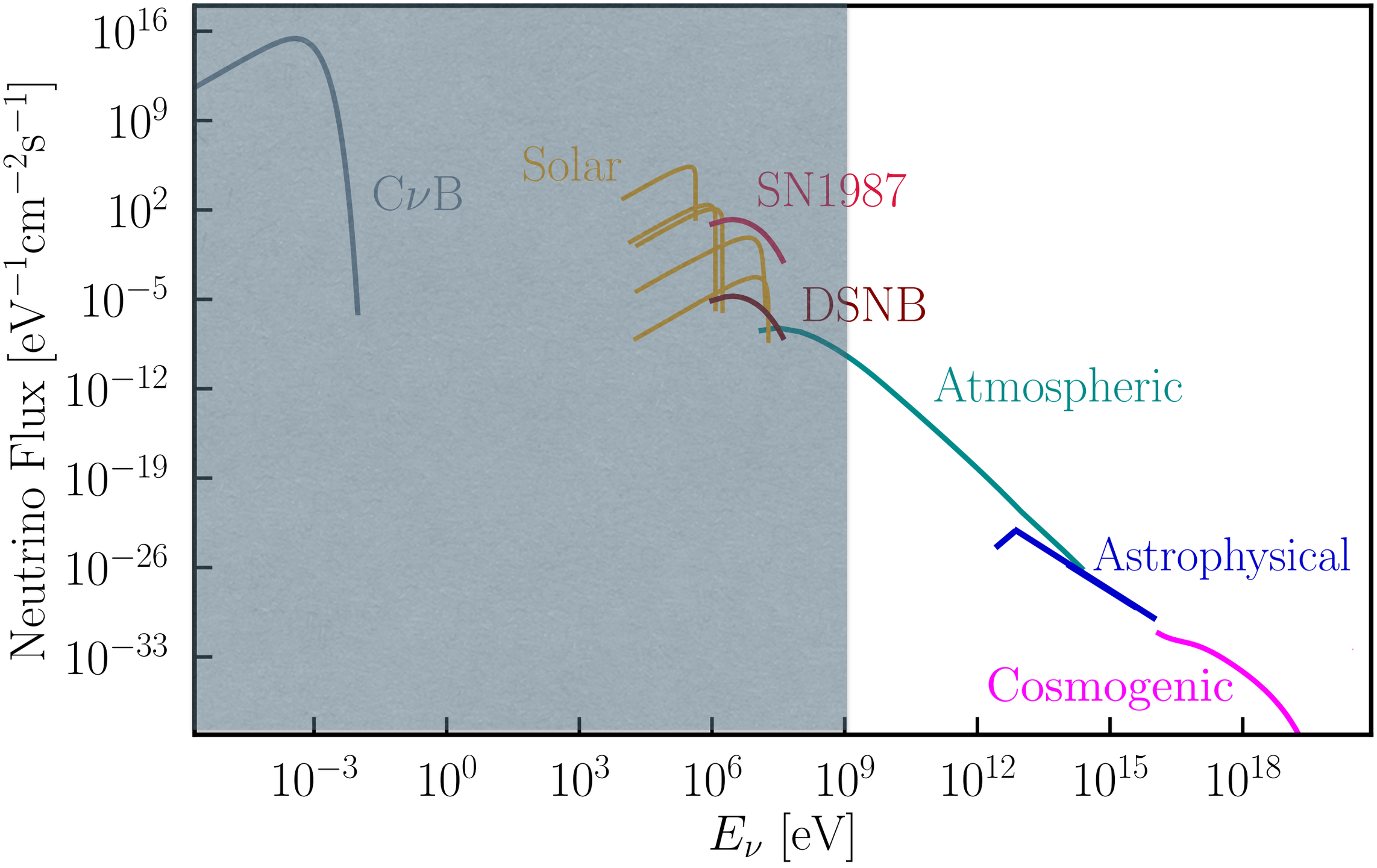

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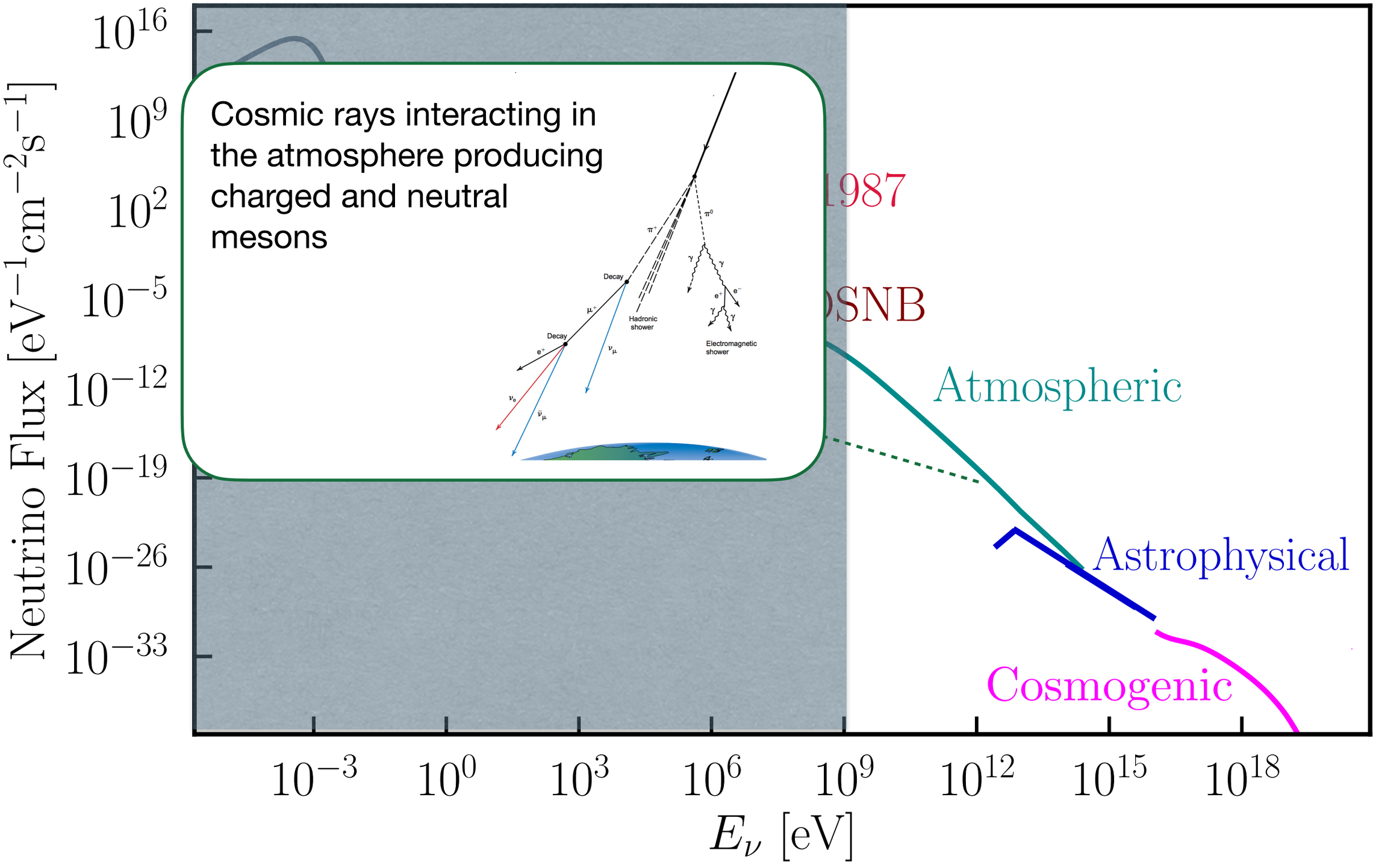

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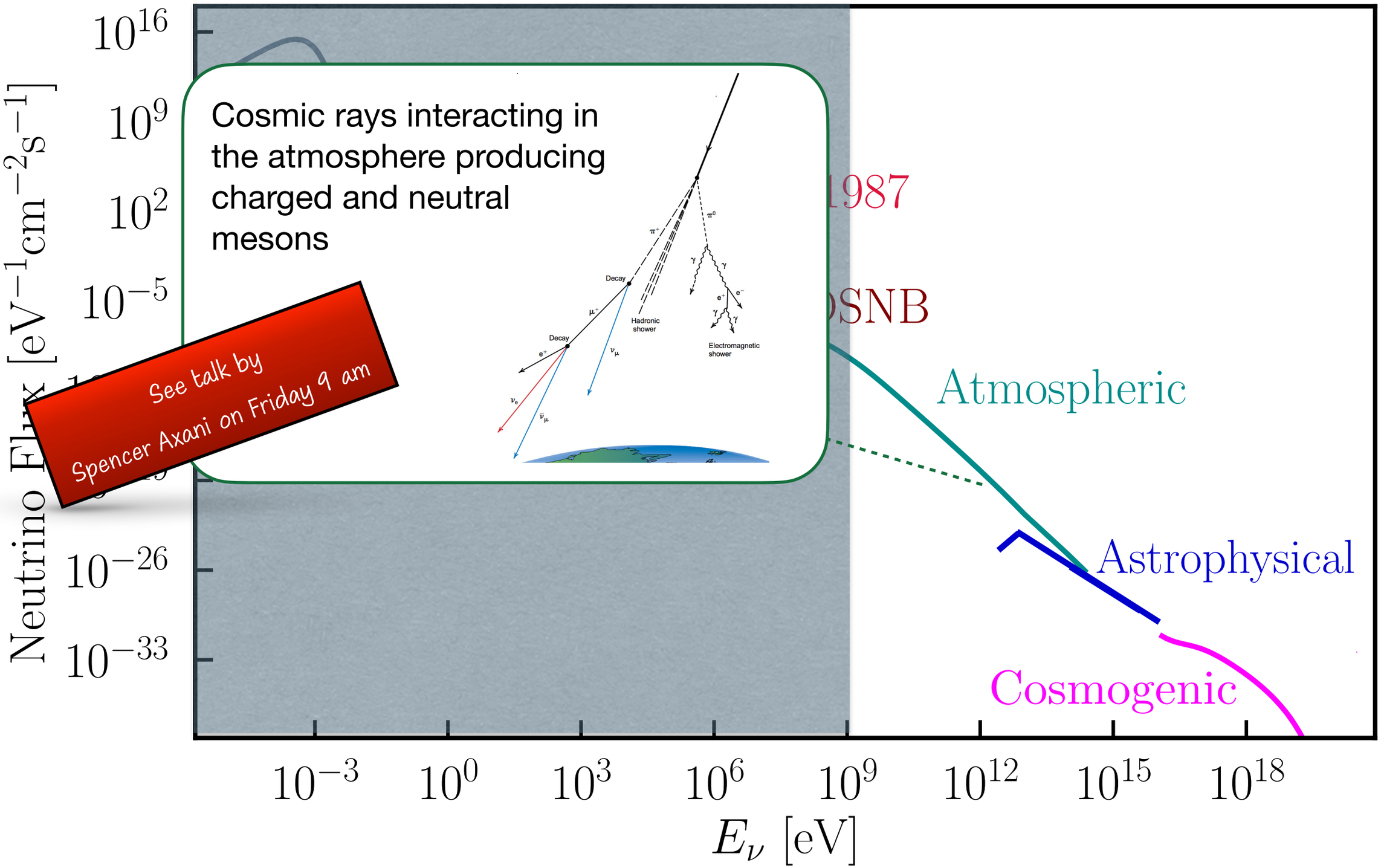
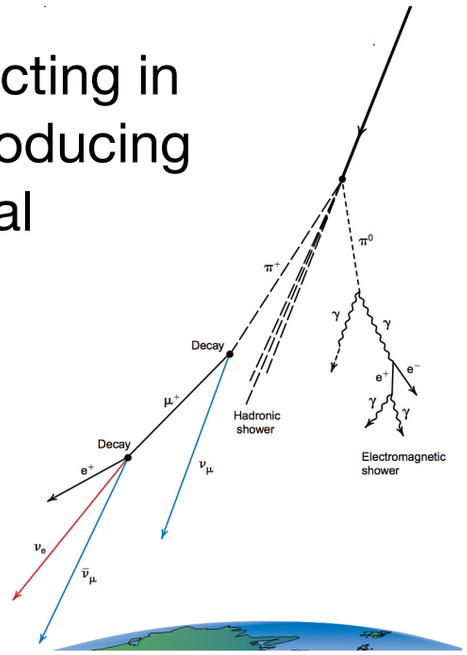
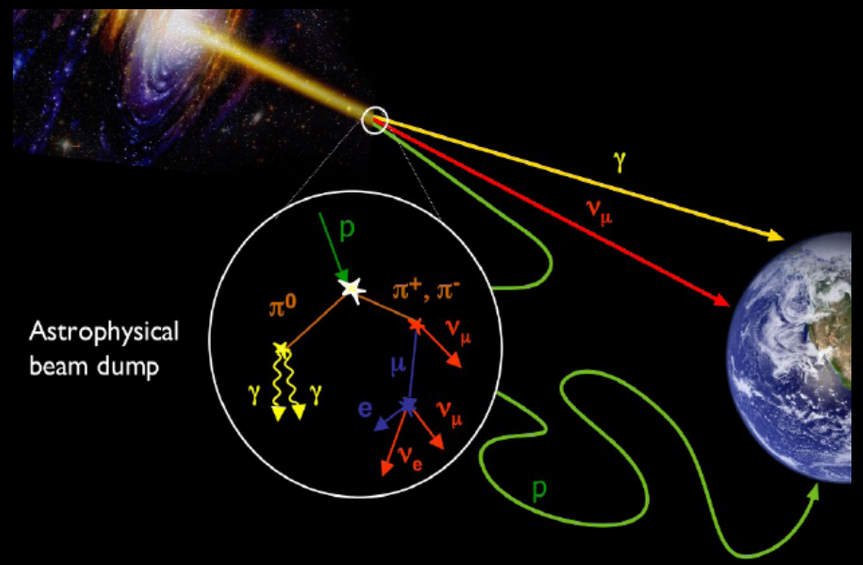


The Universe in Neutrinos

Cosmic rays interacting in the atmosphere producing charged and neutral mesons



See talk by Spencer Axani on Friday 9 am



Astrophysical beam dumps

high-energy cosmic rays interacting with gas or radiation

Astrophysical

Cosmogenic

Neutrino Flux [eV^{-1}cm^{-2}s^{-1}]

10^{16} 10^{9} 10^{2} 10^{-5} 10^{-12} 10^{-19} 10^{-26} 10^{-33}

10^{-3} 10^{0} 10^{3} 10^{6} 10^{9} 10^{12} 10^{15} 10^{18}

E_ν [eV]

The Universe in Neutrinos

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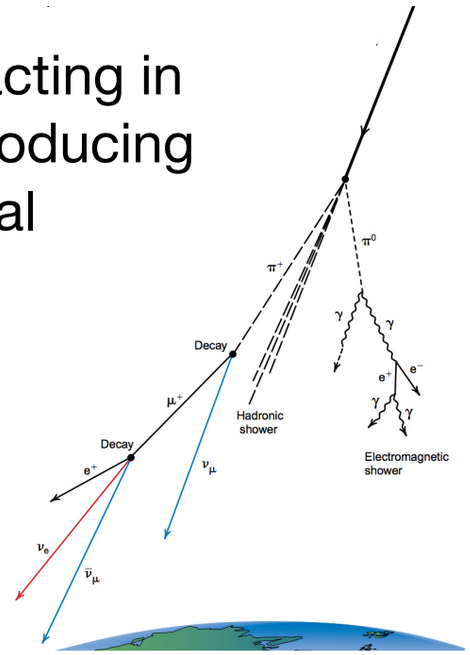

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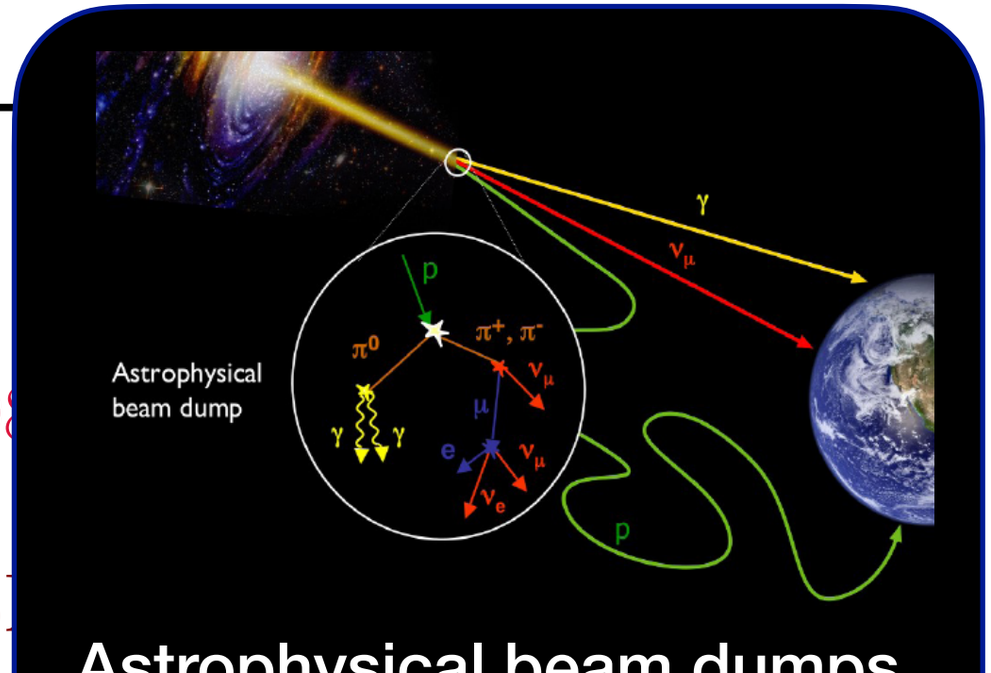

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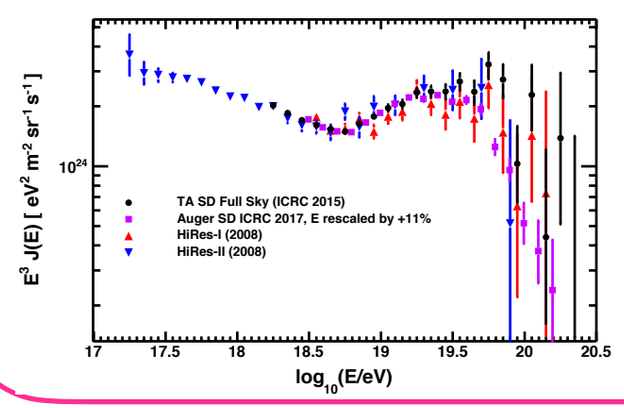
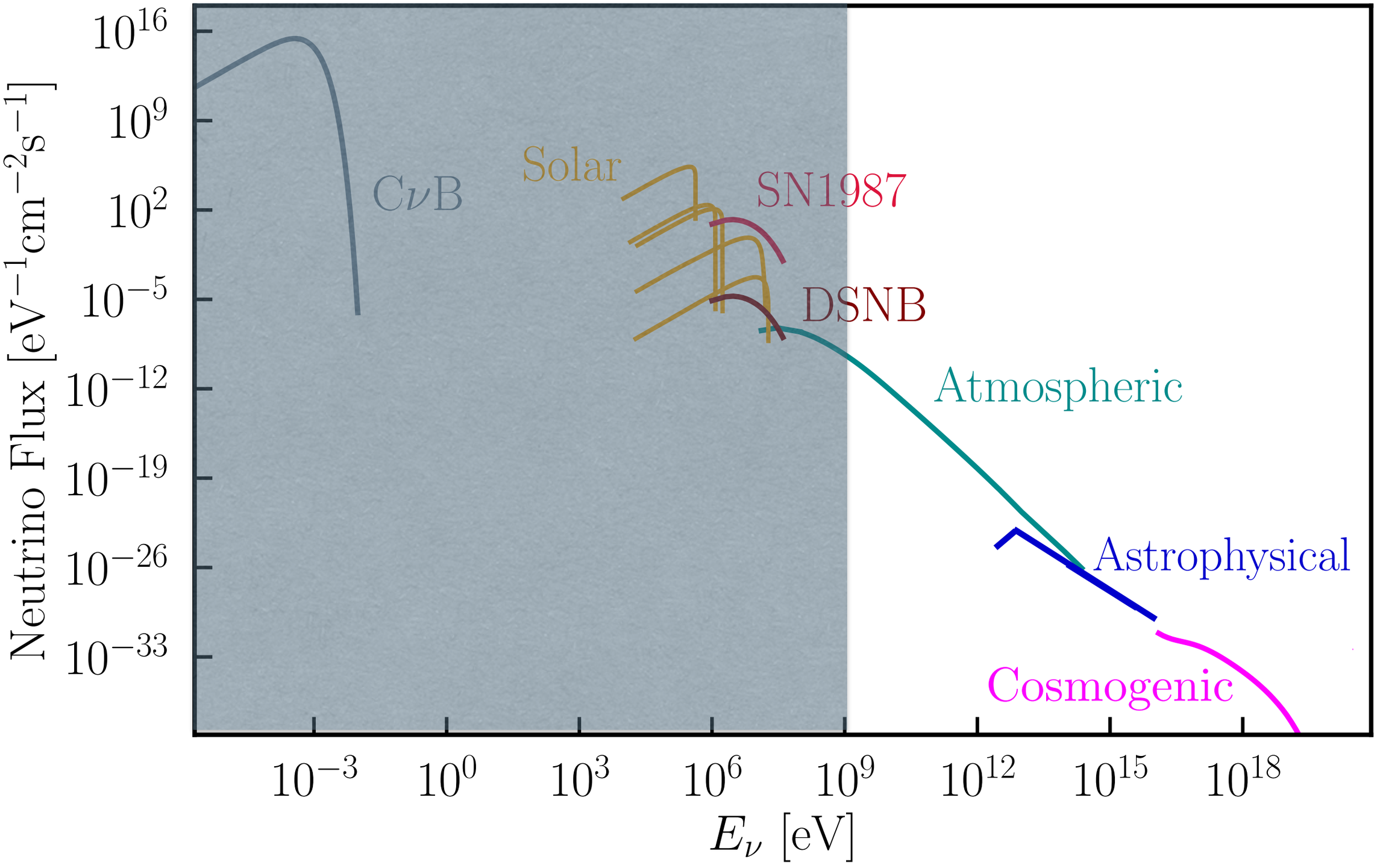


Ultra-high-energy cosmic rays interacting with the Cosmic Microwave Background

The Universe in Neutrinos



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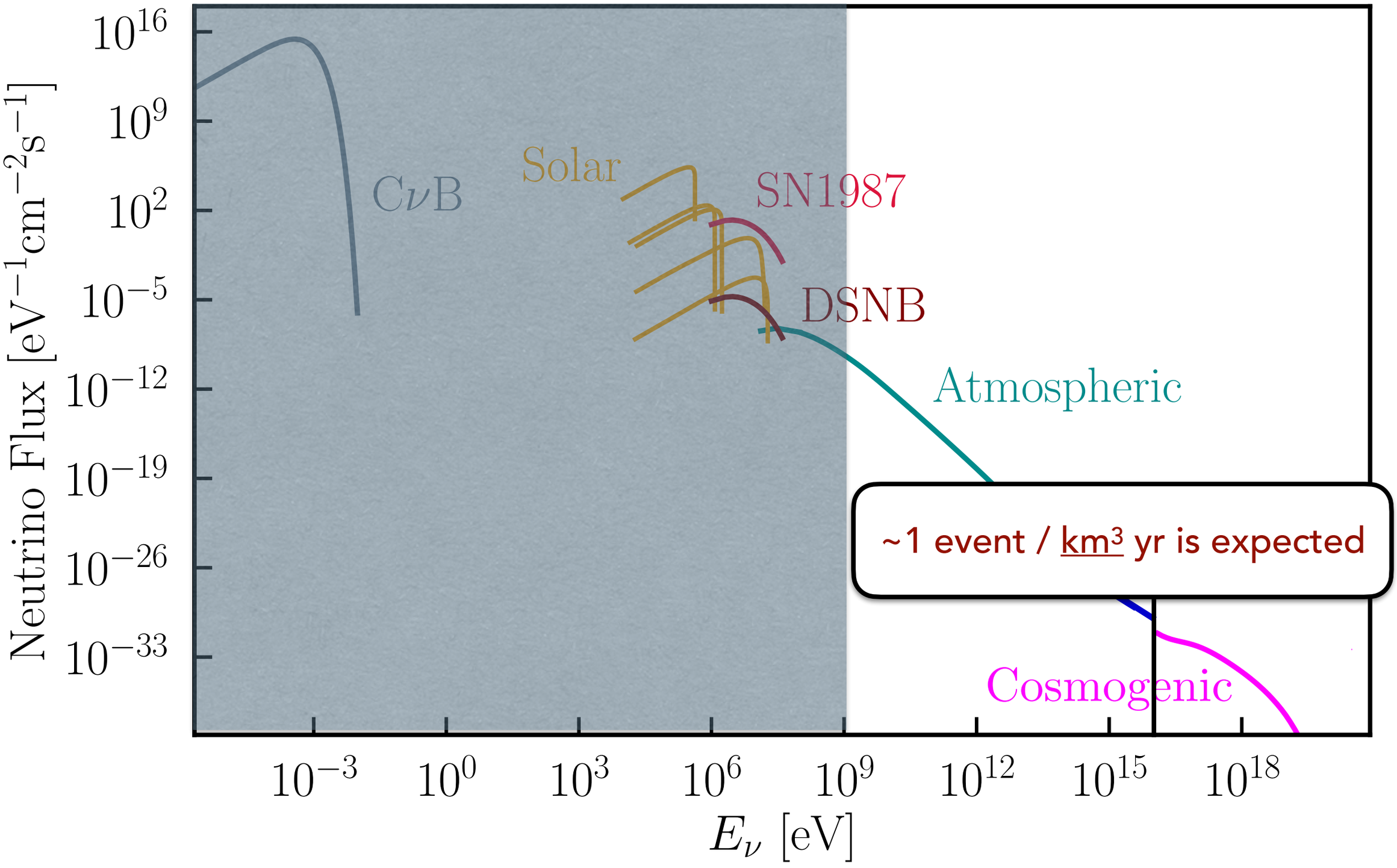
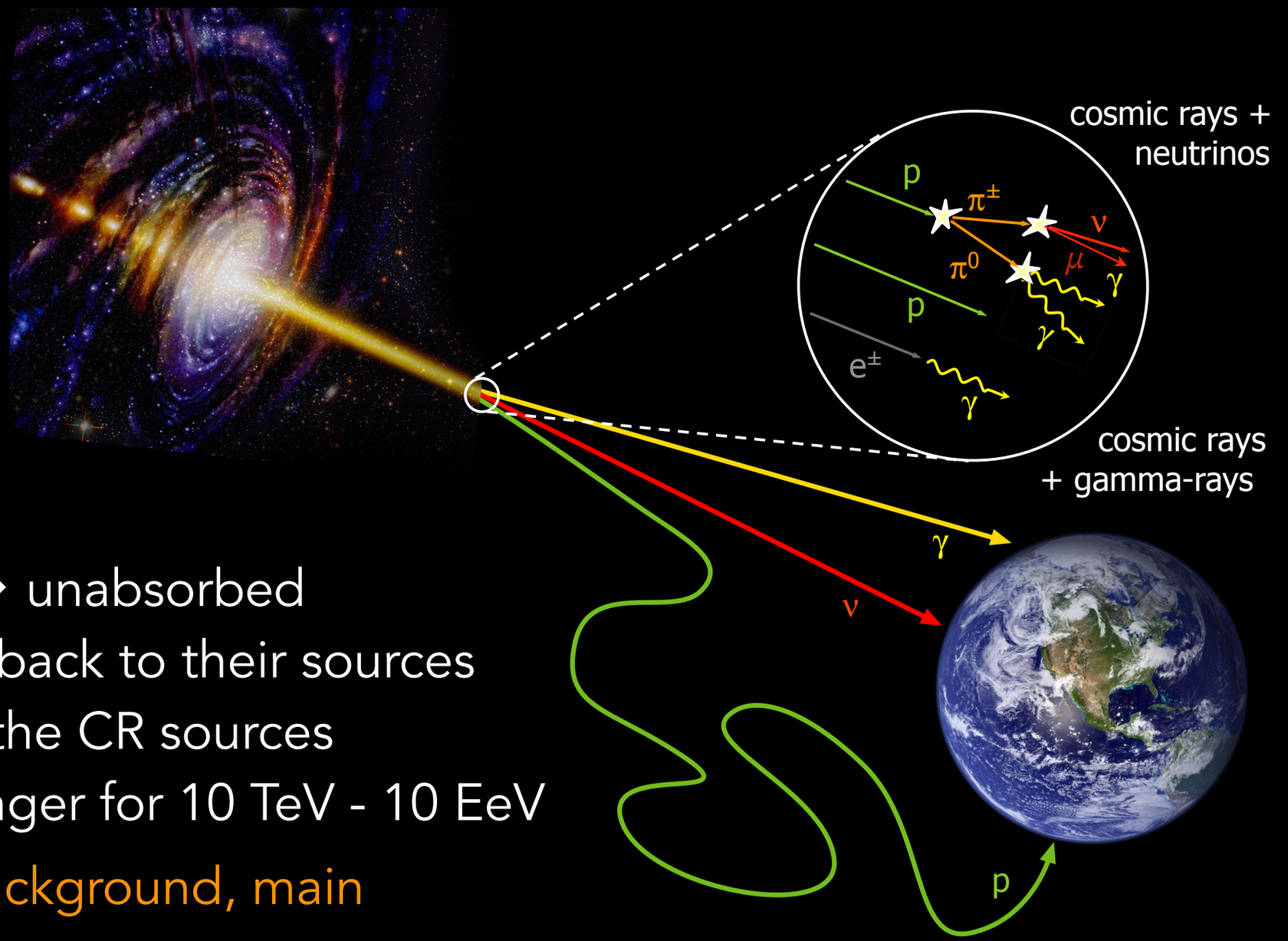


Neutrino Astronomy

- Soon after discovery it was realized neutrinos are ideal cosmic messengers.

Accelerated CRs interact with gas or radiation in the beam dump and produce charged and neutral pions.



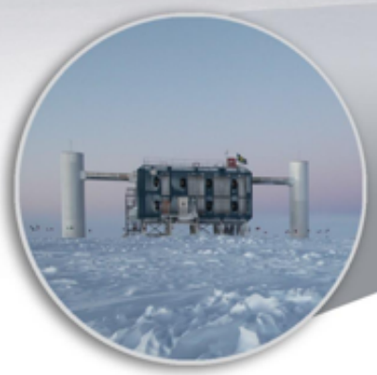
- Neutrinos:
  - ✓ Hardly interact → unabsorbed
  - ✓ Neutral → point back to their sources
  - ✓ Smoking gun of the CR sources
  - ✓ Exclusive messenger for 10 TeV - 10 EeV

Low statistics and large background, main challenges for neutrino astronomy.

IceCube

South Pole Neutrino Observatory

50 m



IceCube Laboratory

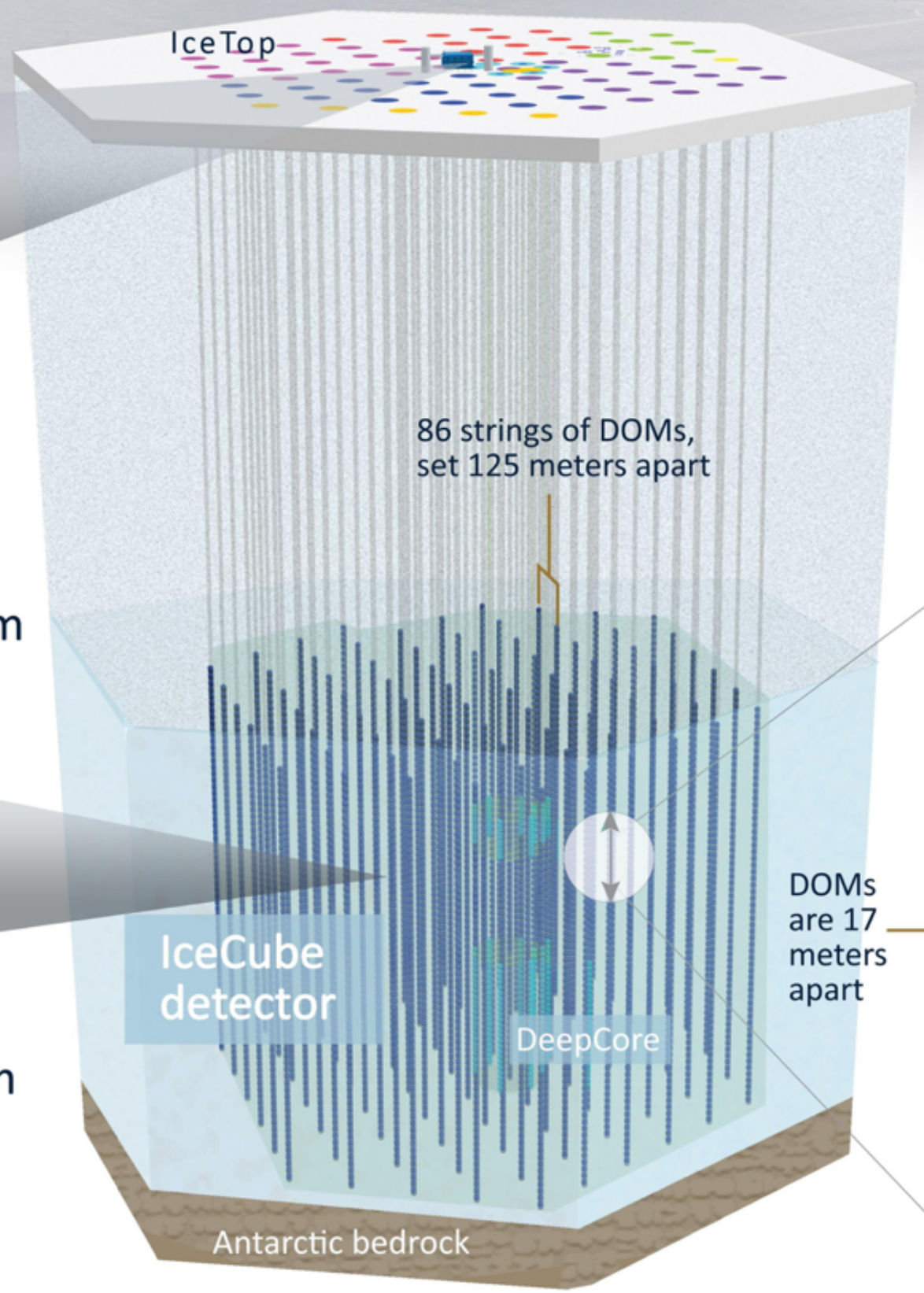
Data is collected here and sent by satellite to the data warehouse at UW–Madison

1450 m

Digital Optical Module (DOM)

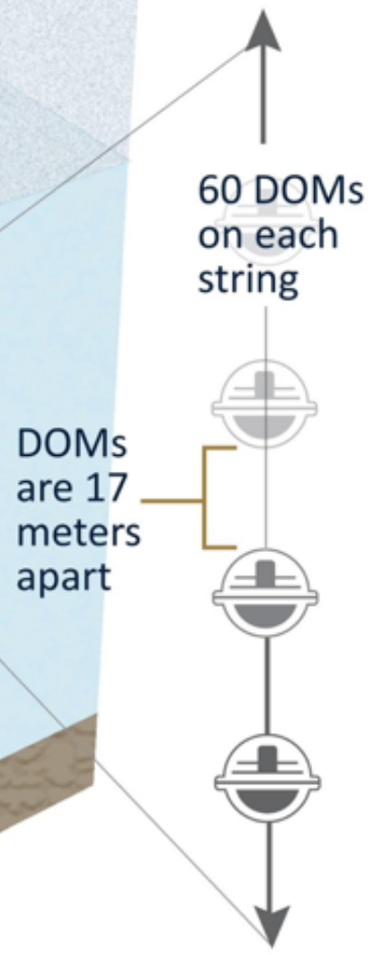
5,160 DOMs deployed in the ice

2450 m

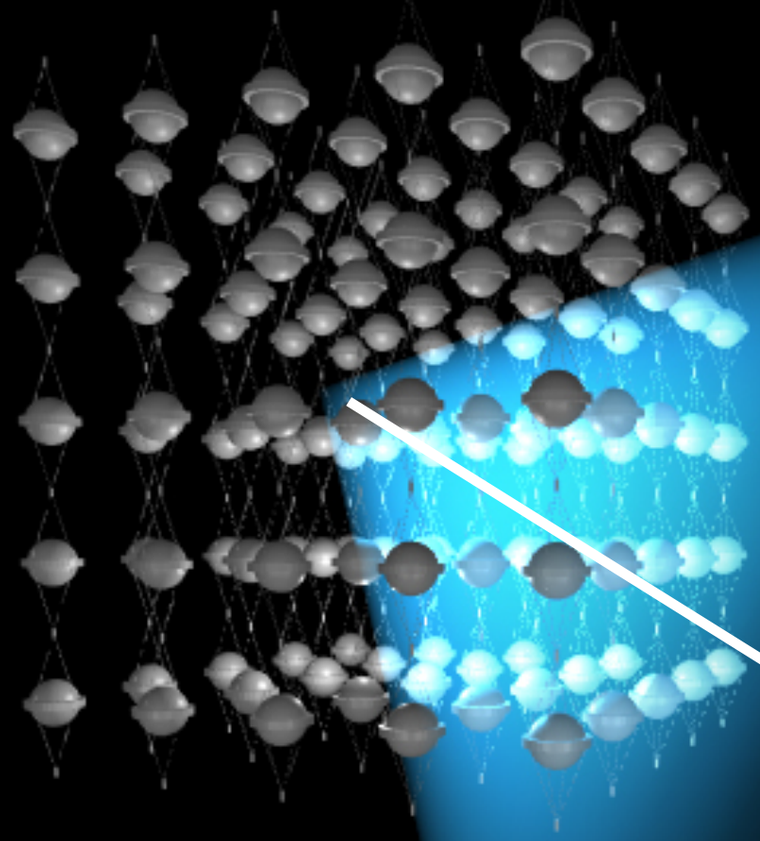


Amundsen–Scott South Pole Station, Antarctica

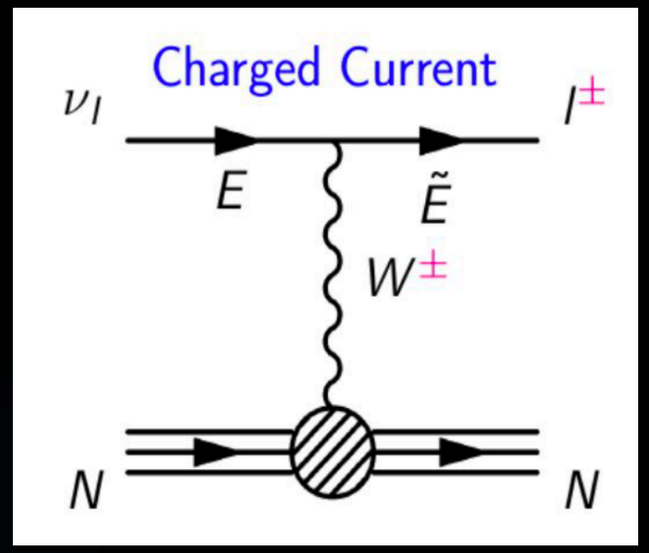
A National Science Foundation-managed research facility



- lattice of photomultipliers



charged secondary particles produced as the neutrino interacts with a nucleus

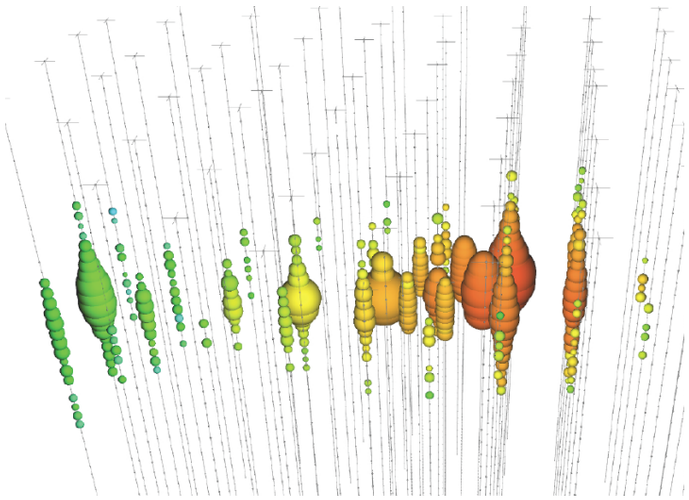


High-energy charged particles, traveling faster than light in ice or water, produce ***Cherenkov* light** in the ice.

neutrino

Event Morphologies

Charged-current ν_μ

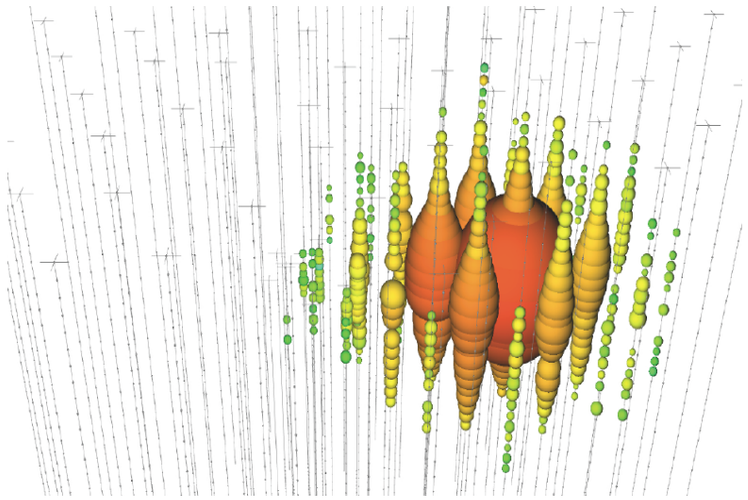


Tracks

Good (0.2–1 degree) angular resolution

Factor of two muon energy resolution

Neutral-current / ν_e

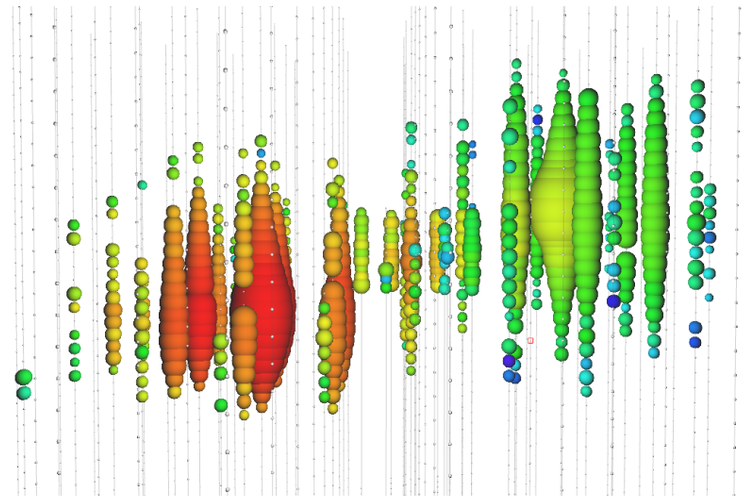


Cascades

Good (15%) energy resolution

> 4 degrees angular resolution

Charged-current ν_τ

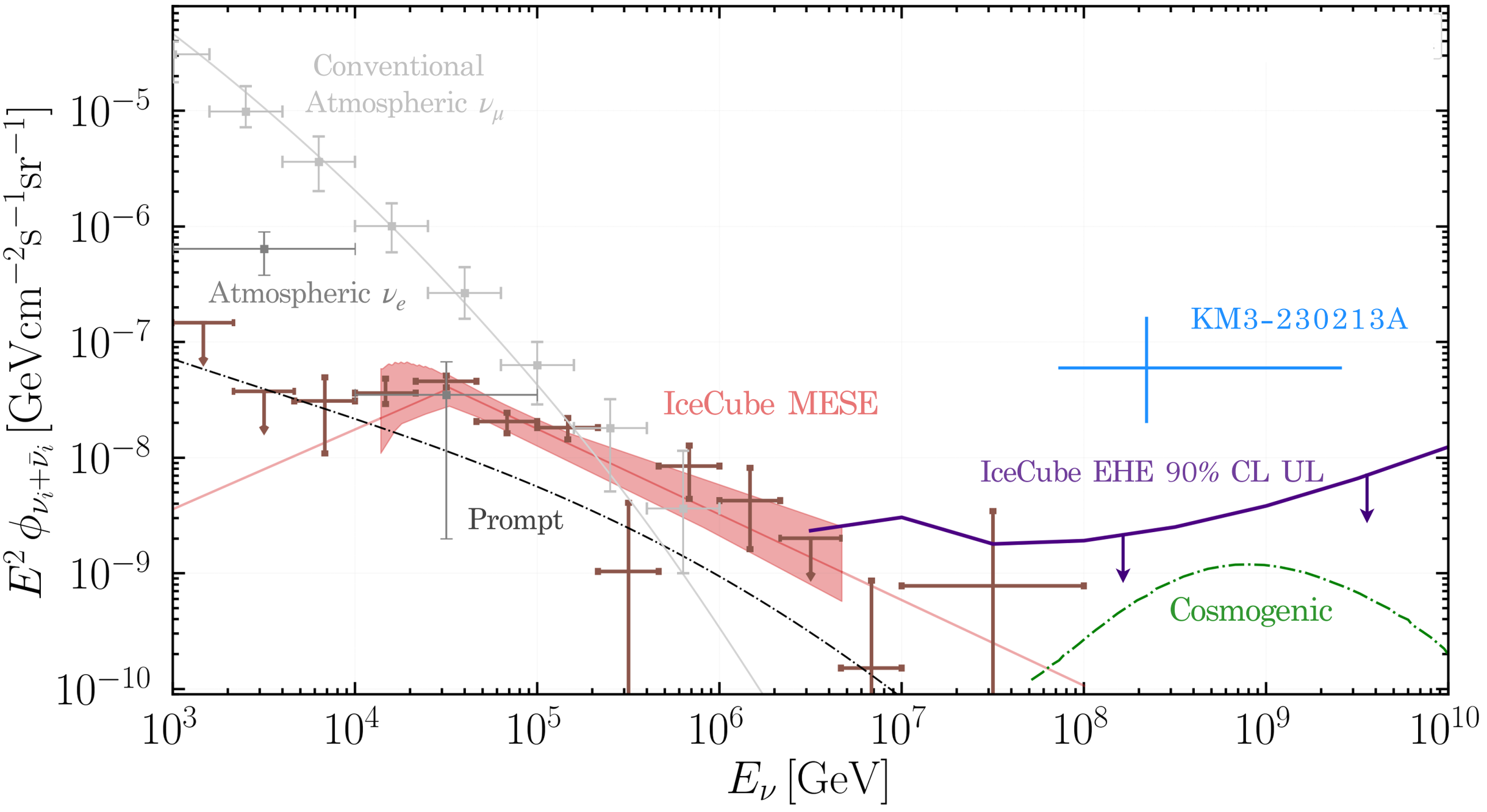


Double Cascades

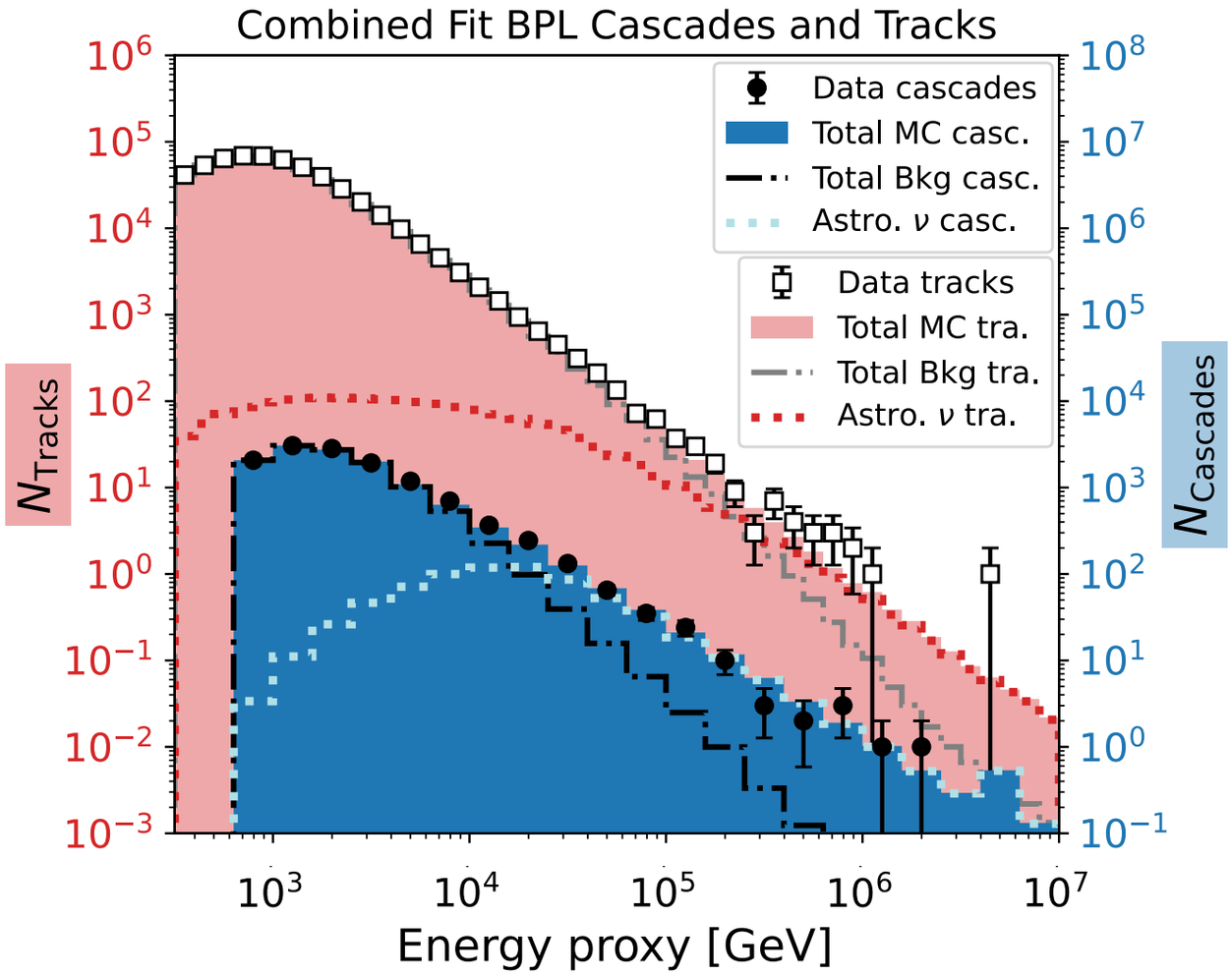
Resolvable at high energies

High purity (i.e., astrophysicalness)

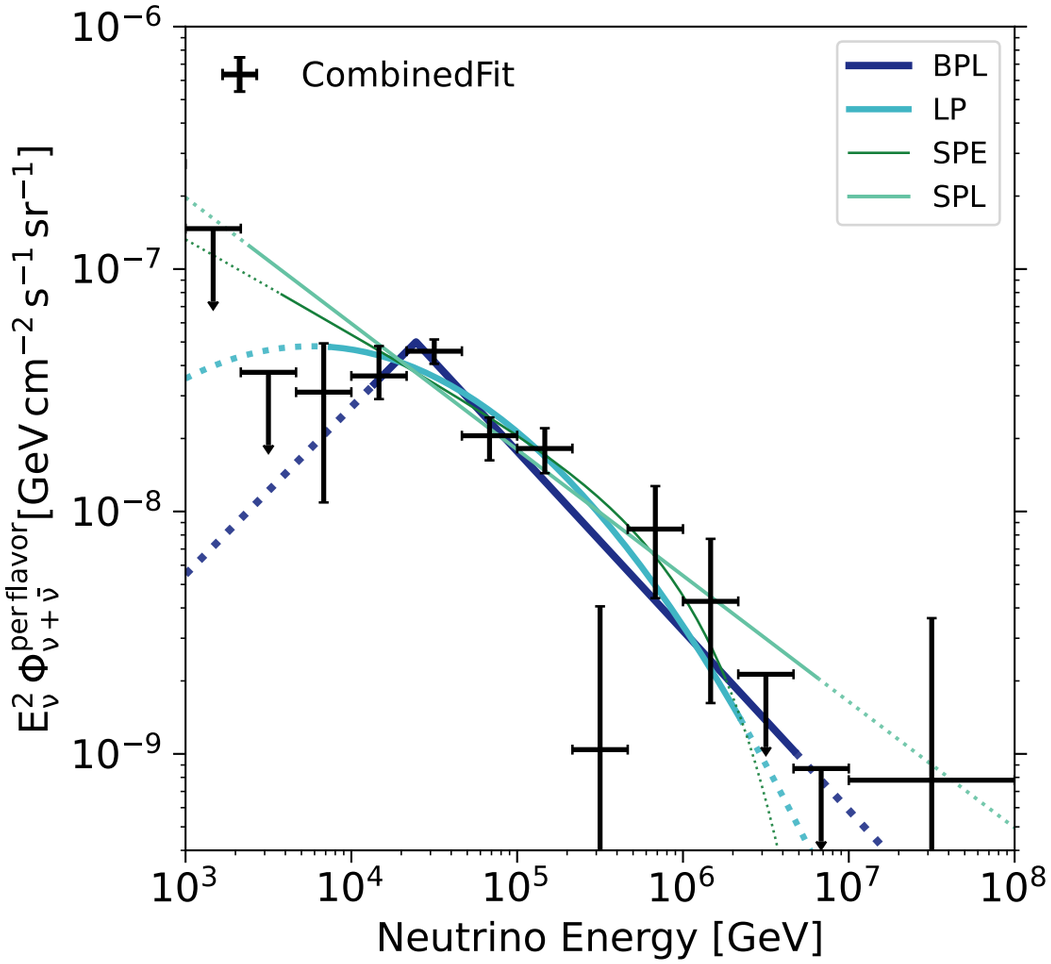
High-Energy Neutrino Flux



Evidence for Spectral Break



IceCube PRL 2026



IceCube PRD 2026

- Combined analysis of Medium Energy Starting Events (MESE) and Combined Track and Cascade data show departure from single power law (SPL) at 4σ
  - Spectral break at ~ 30 TeV

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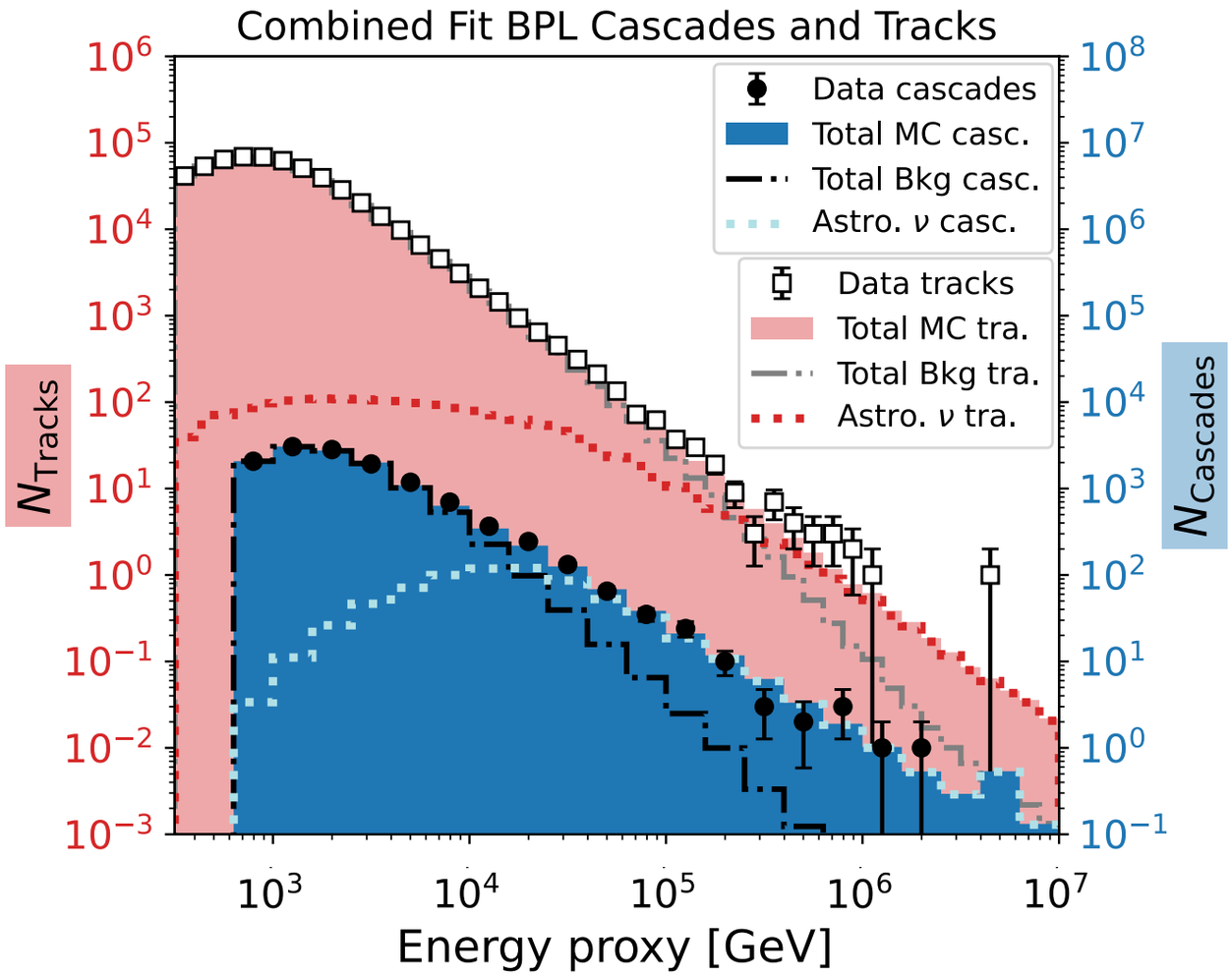

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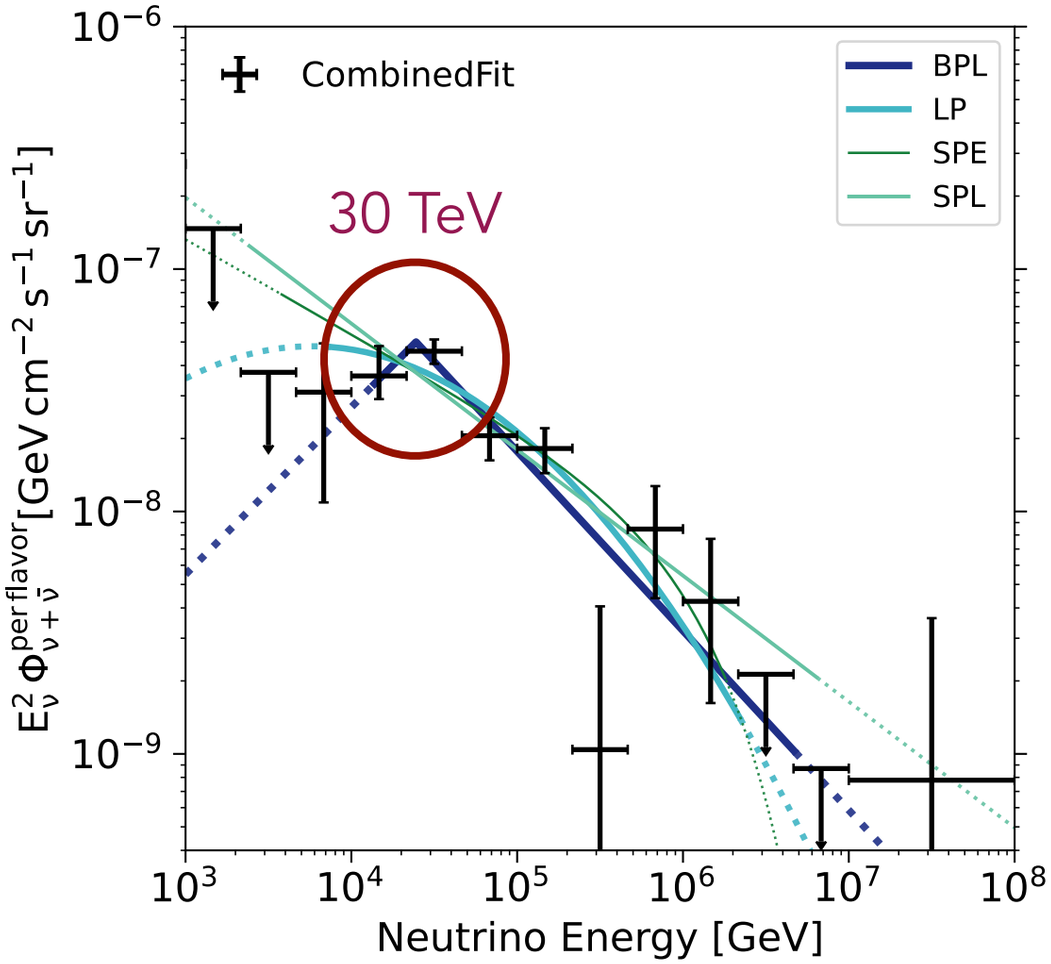

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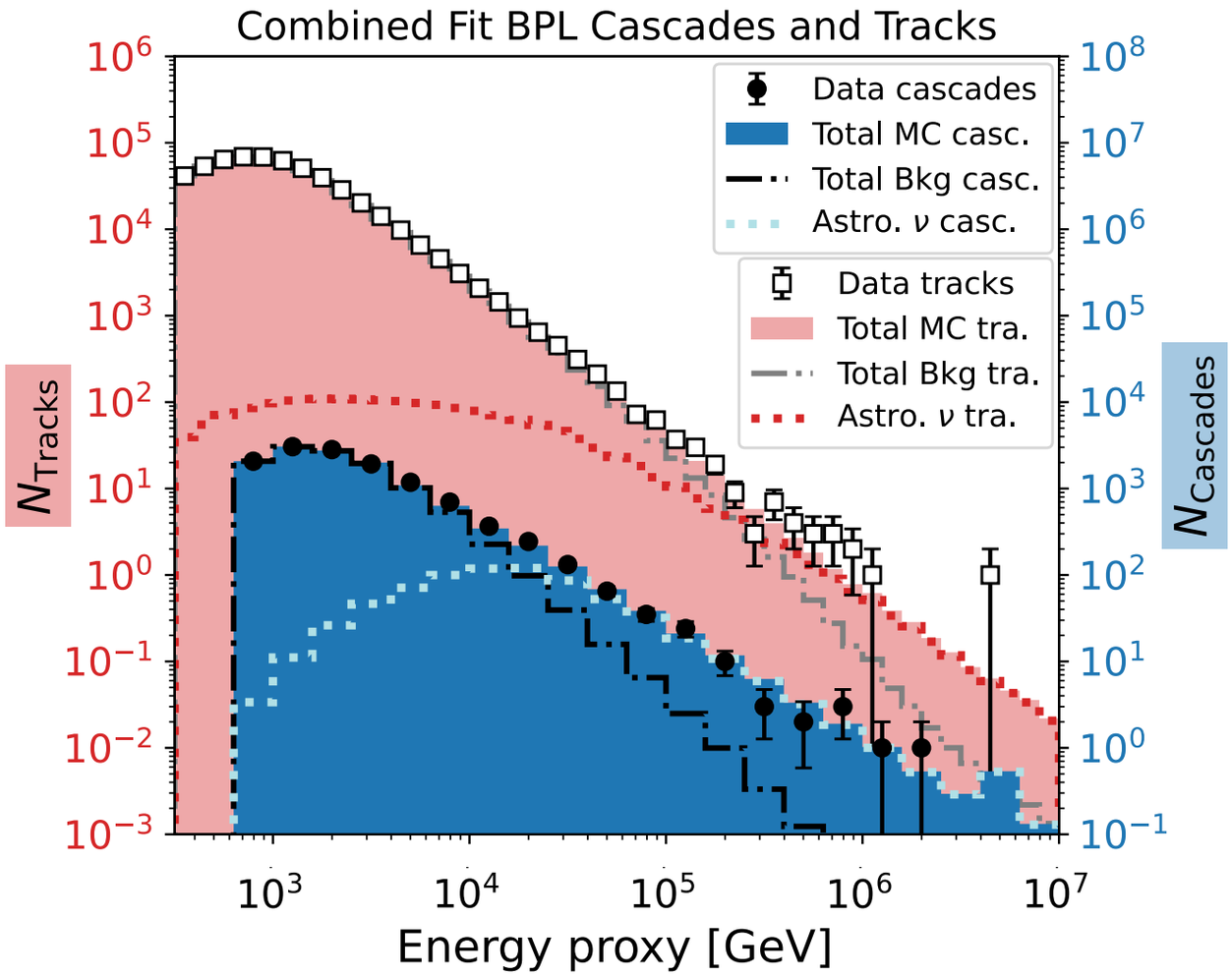

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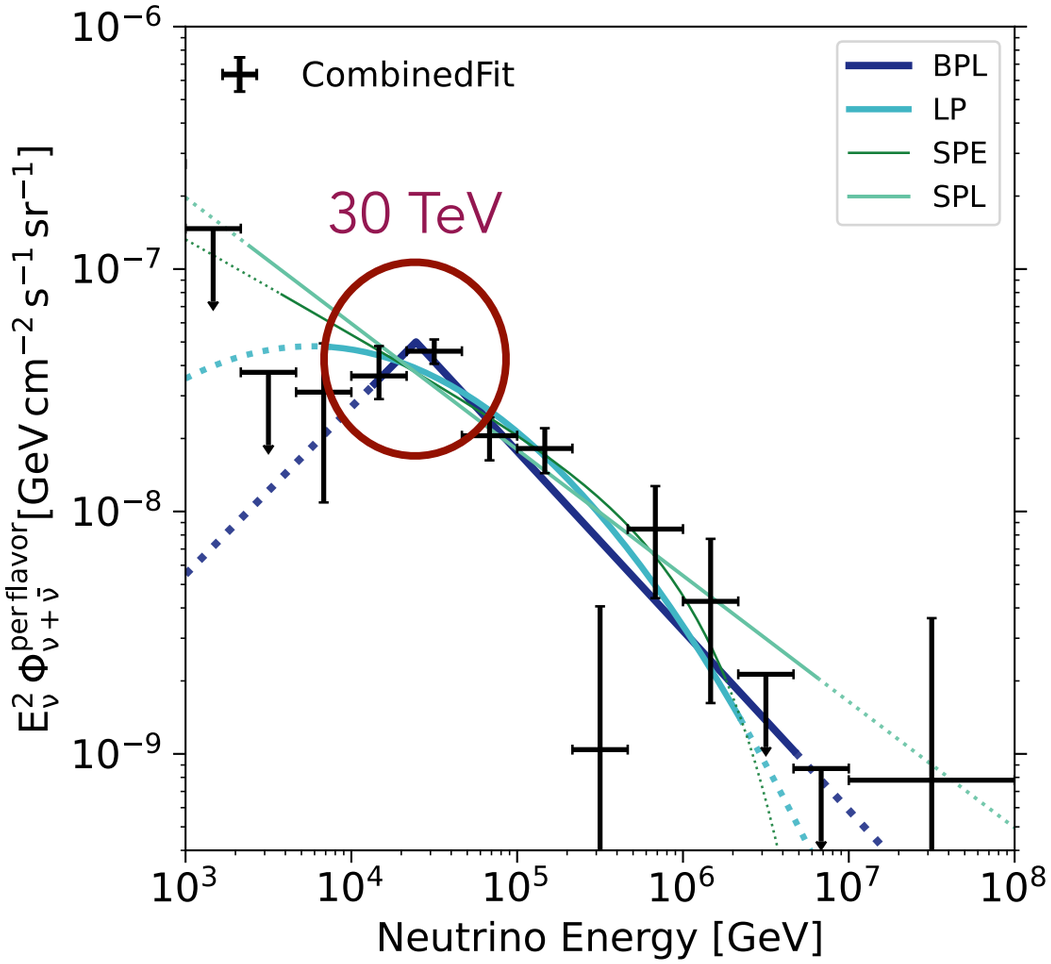

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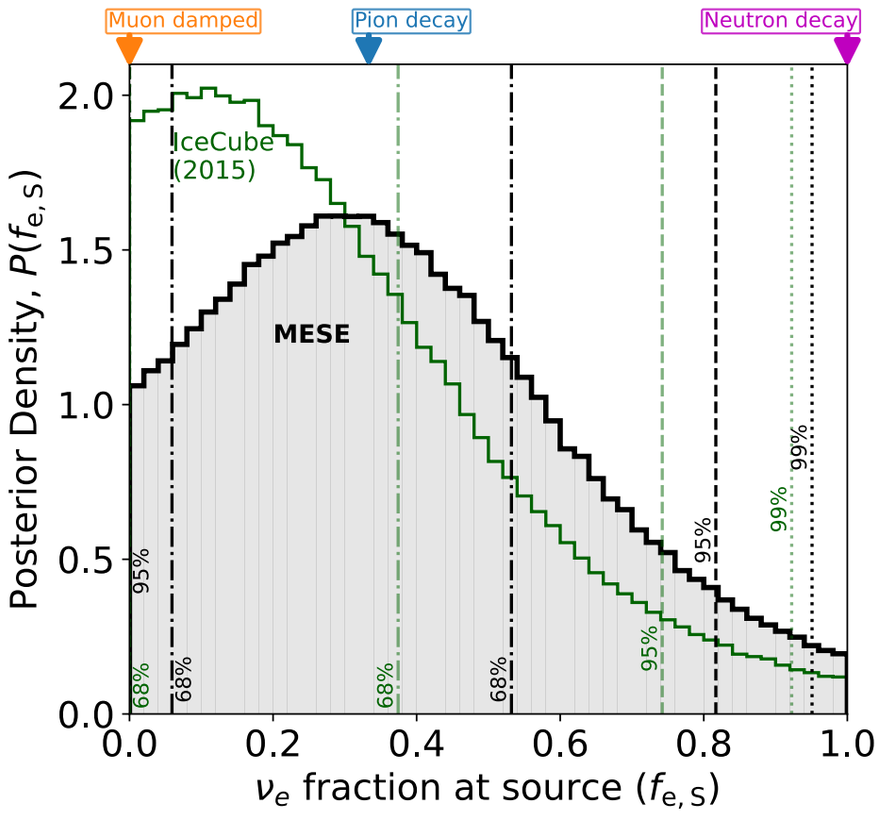
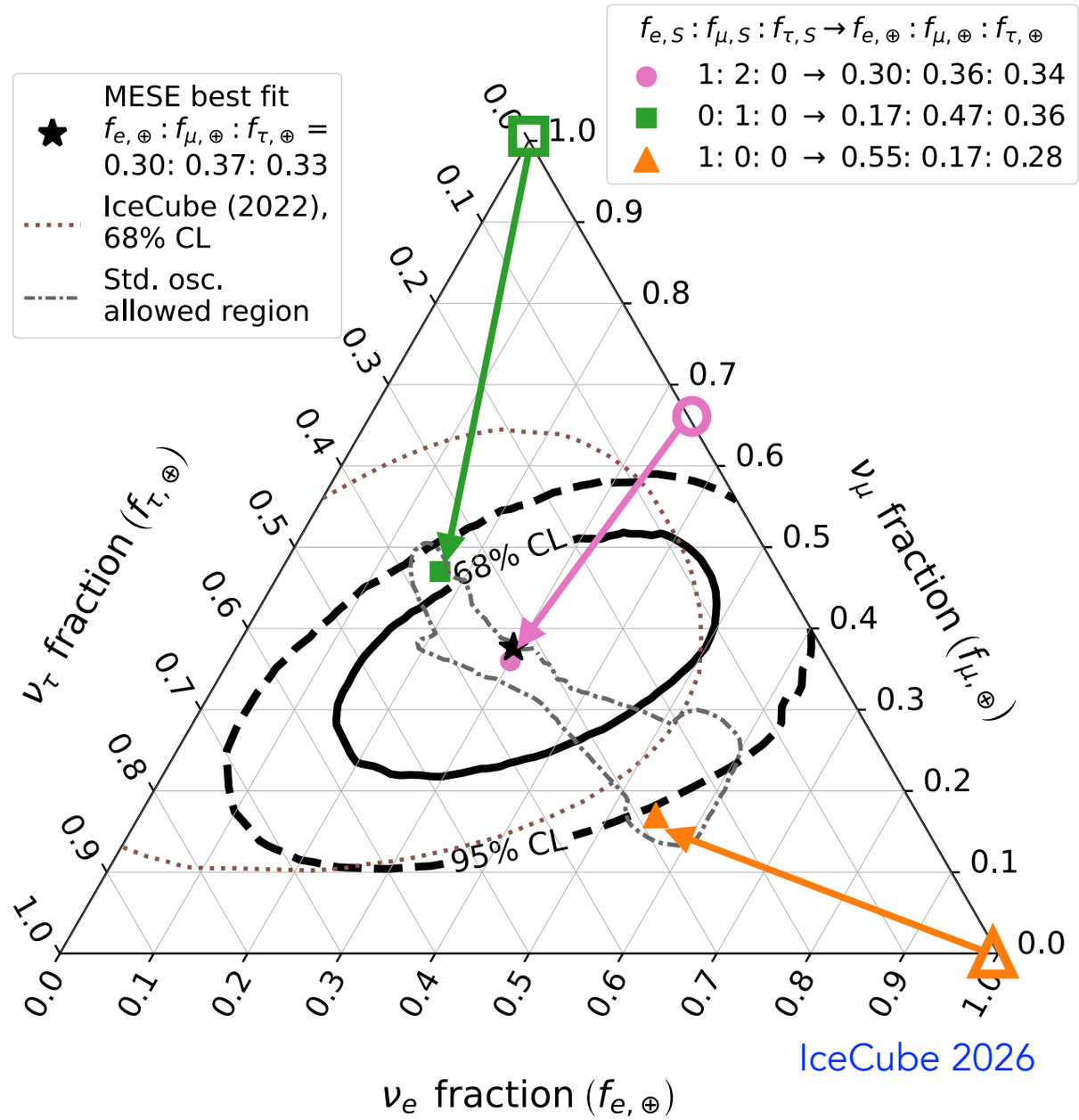
  - Spectral break at ~ 30 TeV

See poster by Aswathi Balagopal

Cosmic Neutrinos Flavor Composition

- Neutrino oscillation modifies the flavor composition of neutrinos after their production.
- 11.4 yr MESE: 5 TeV - 10 PeV
- All flavor analysis with improved double cascades identification above 30 TeV.
- Best fit very close to the nominal expectation of ~(1:1:1) from π decay.
- 1st time all flavors are nonzero at 68% C.L





→ *Neutron decay rejected at ~ 4 sigma (posteriori)*

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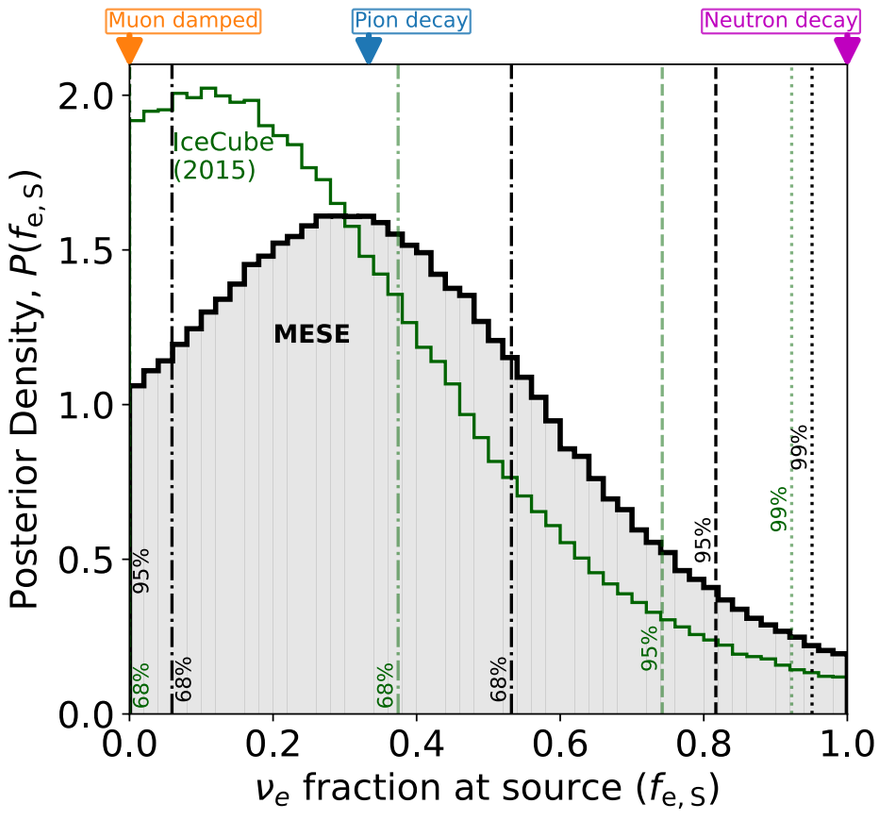
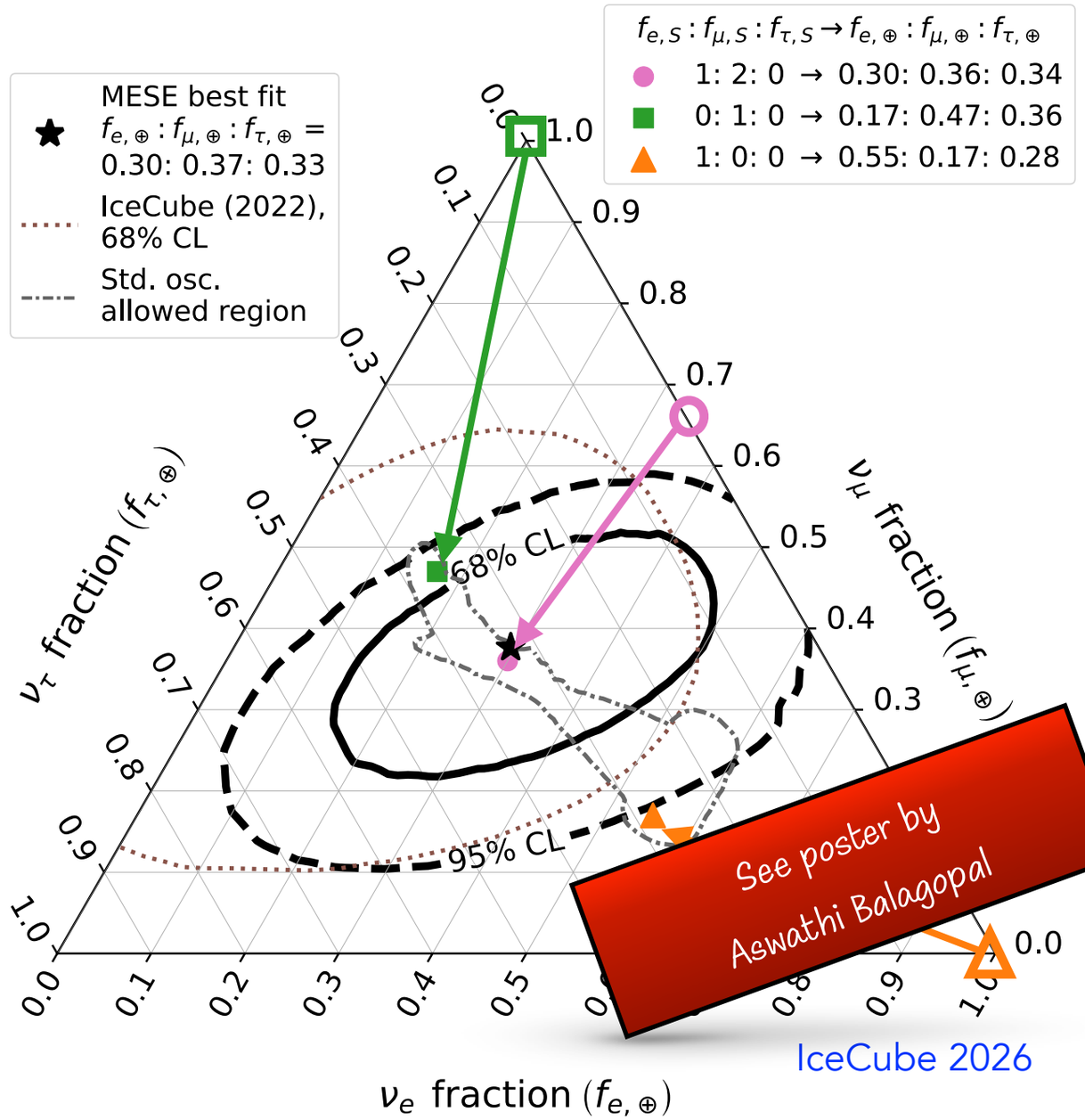
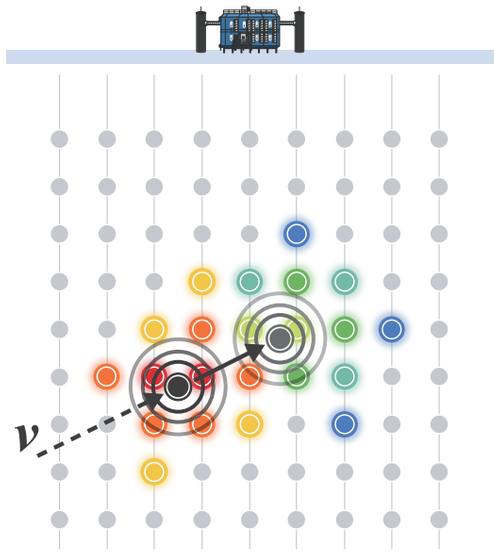




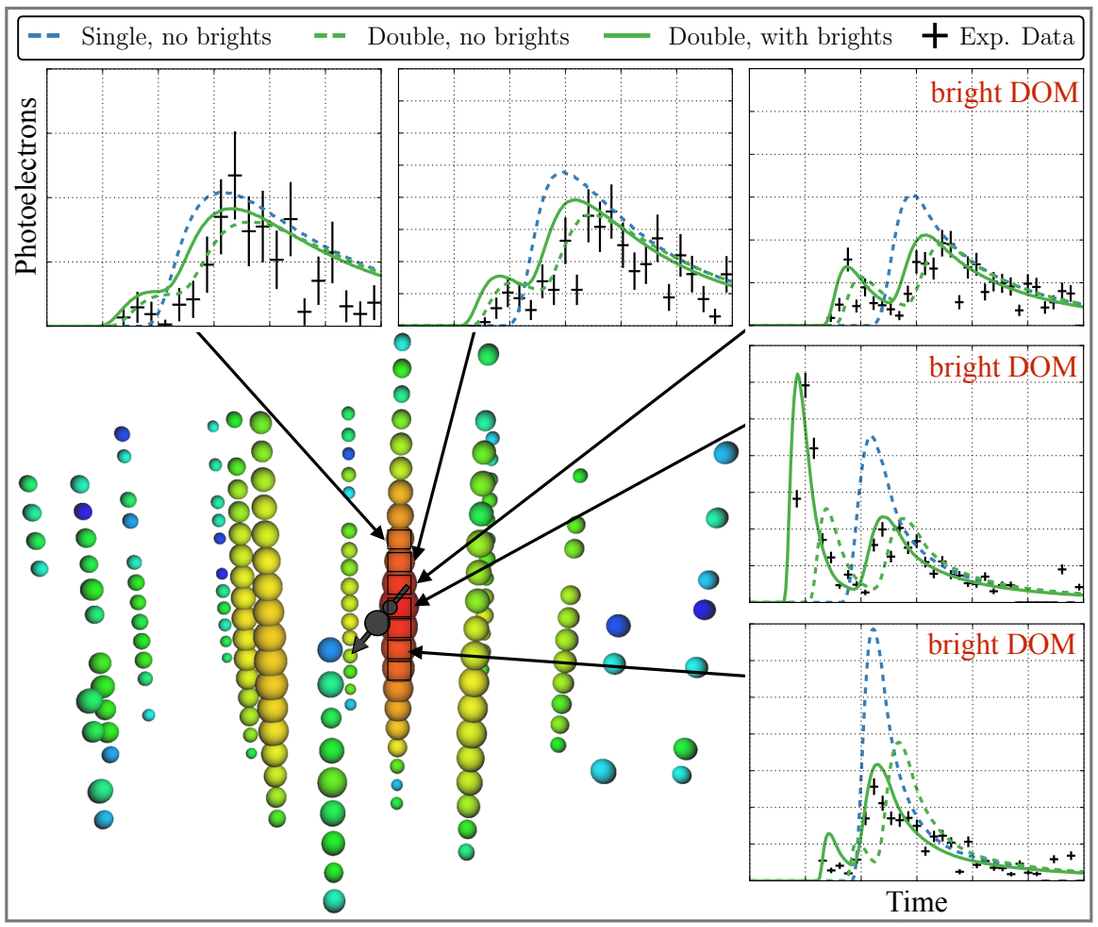
→ *Neutron decay rejected at ~ 4 sigma (posteriori)*

Tau Neutrinos

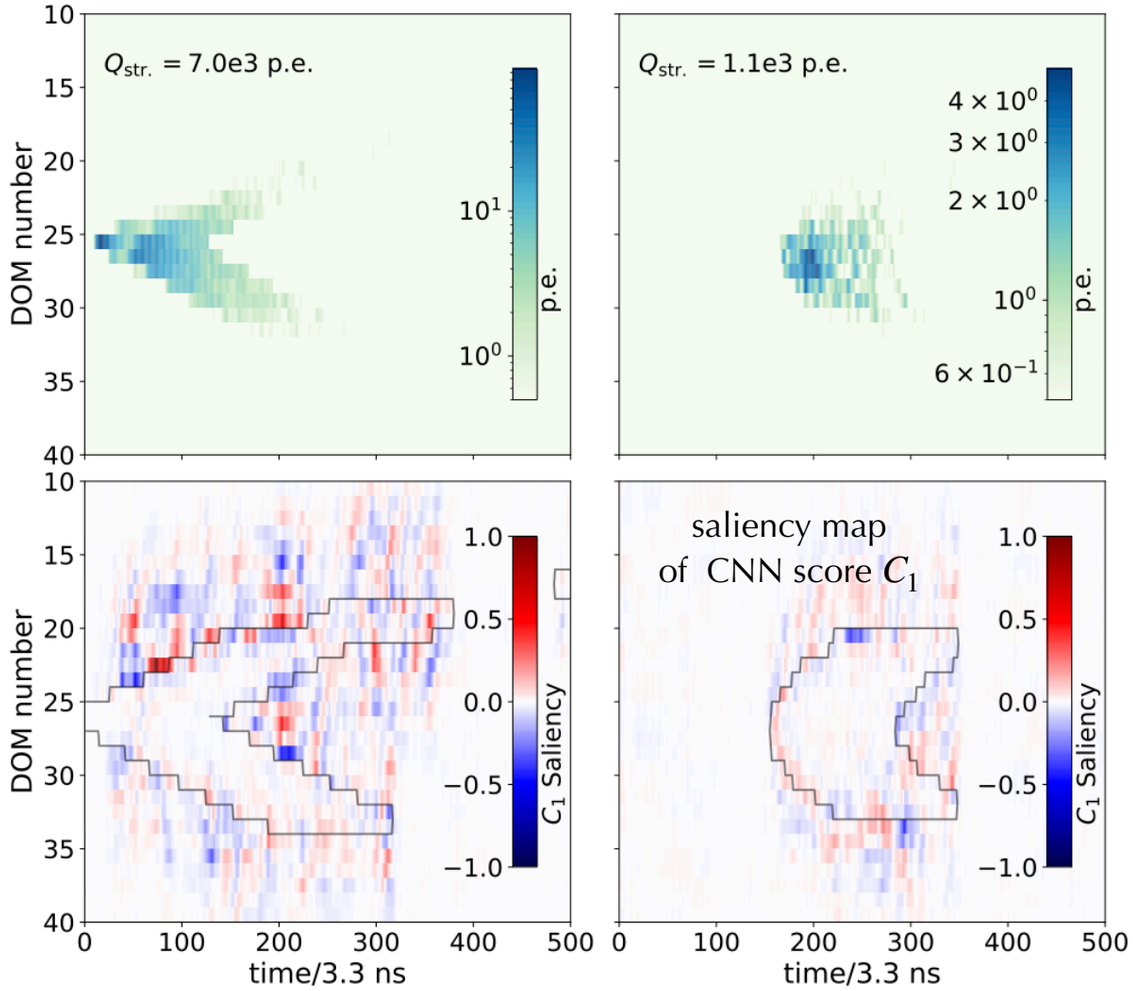
- Identified through double cascade signature
  - 2 candidates in 7.5 years of High Energy Starting Events (HESE) ➛ 2.8σ
  - 7 candidates in 10 years of data selected for high-Q strings via machine learning ➛ 5σ
  - 9 candidates in 11.4 years of MESE (70% purity)



IceCube PRL 2024

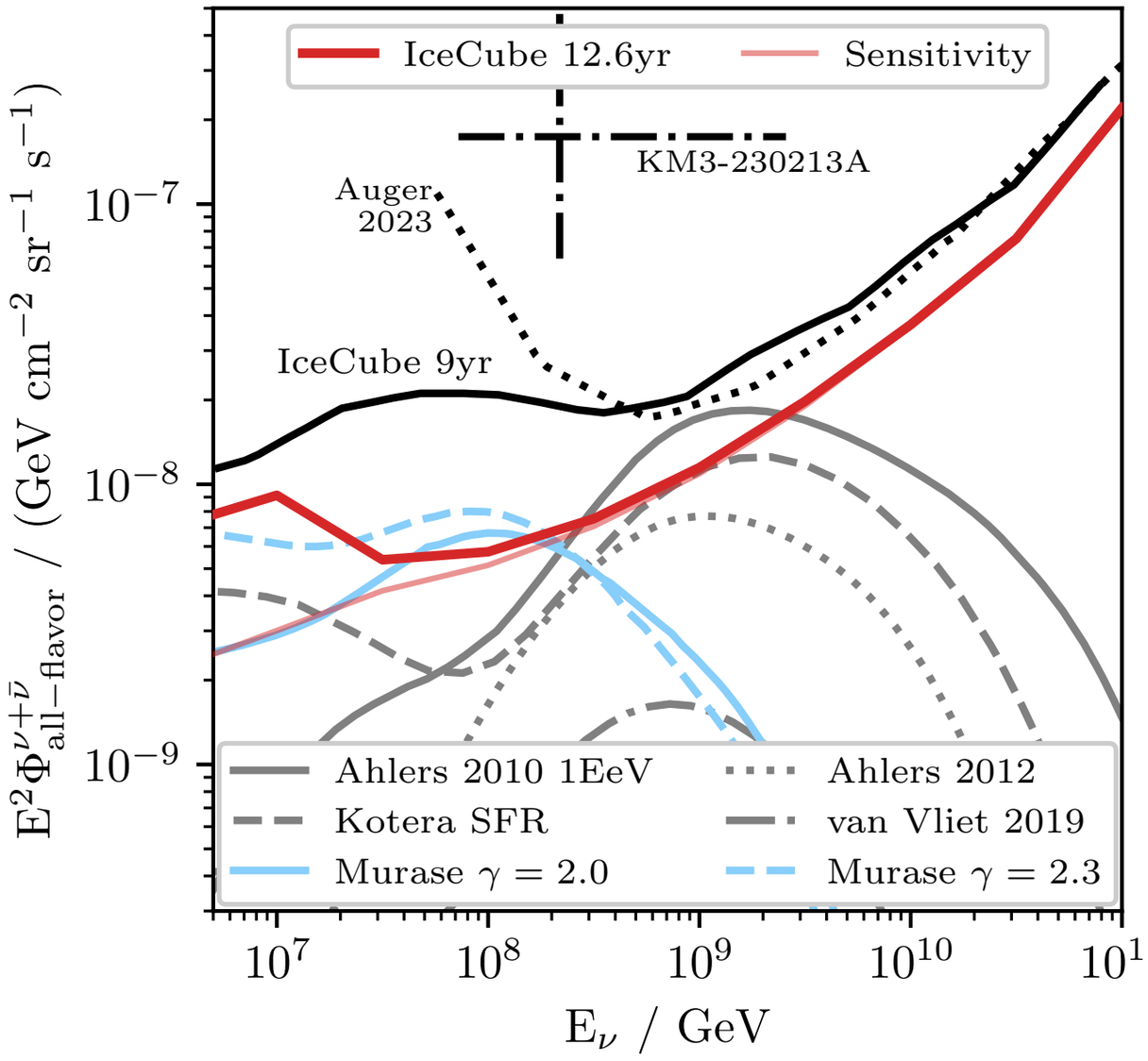


IceCube Eur. Phys. J. 2022



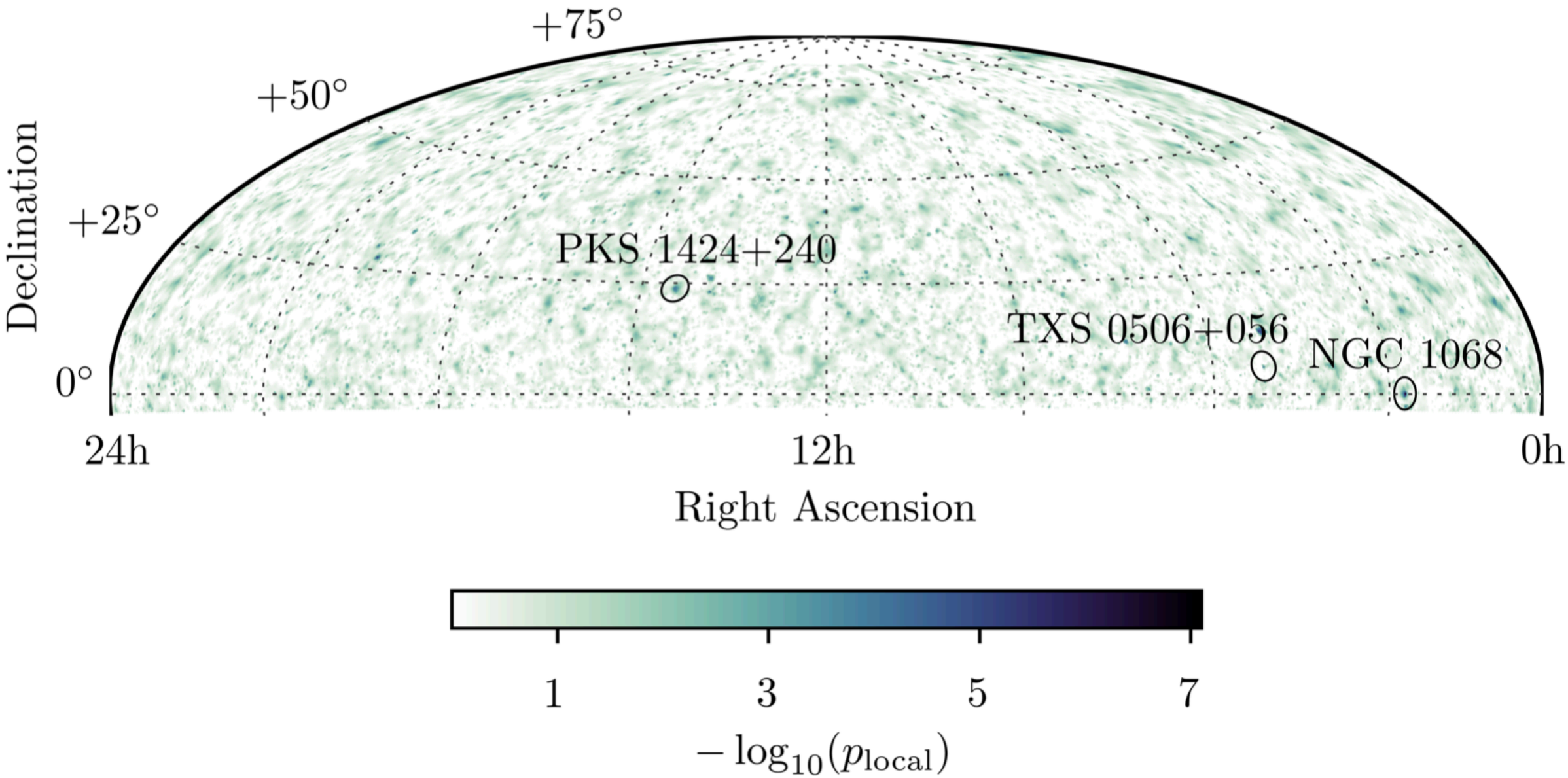
Cosmogenic Neutrinos

- Cosmogenic neutrinos are produced via interaction of UHE CRs with the background radiation
- The Spectrum is expected to peak at EeV energies
- The expectations depend on the composition of the UHE CRs:
  - Optimistic: high proton fraction
- Improved IceCube UL constrains the proton fraction beyond 30 EeV
- KM3-230213A UHE event and IceCube's non-observation yield a 3σ tension



IceCube, PRL 2025

NGC 1068; Brightest Source in Nu Sky



IceCube, Science 2022, ApJL 2026

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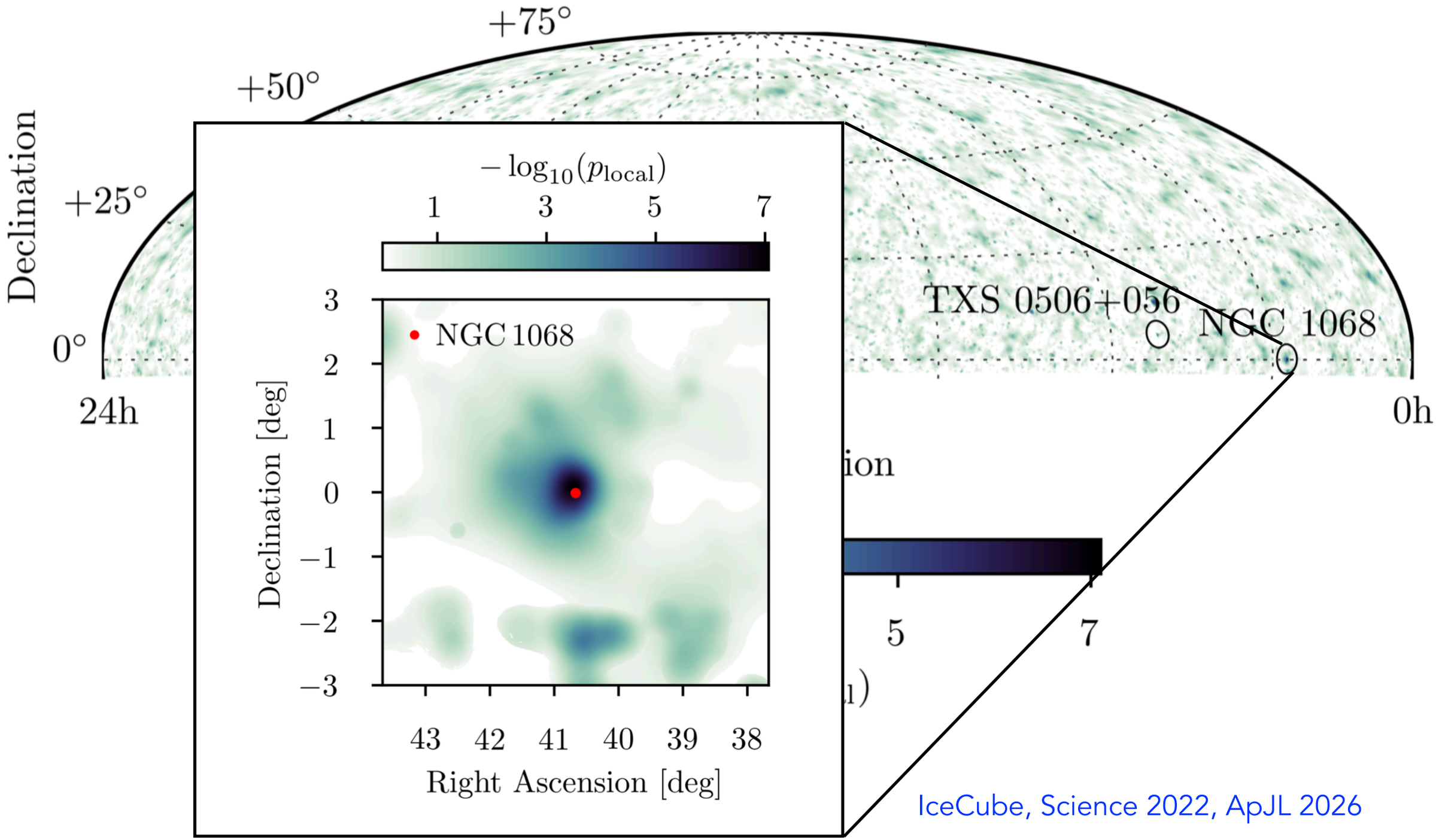

IceCube, Science 2022, ApJL 2026

NGC 1068

Image Credit: NASA, ESA

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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

Image Credit: NASA, ESA

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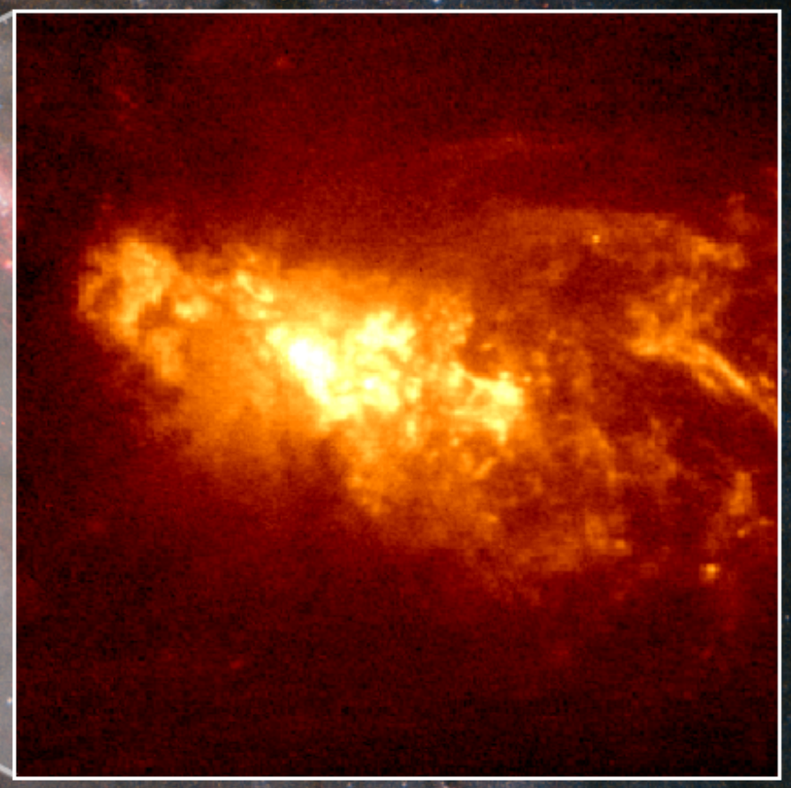

- Compton thick environment with Column density ~ 10^{25} cm^{-2}
- Bright in X-ray, and high infrared luminosity indicating high level of star formation

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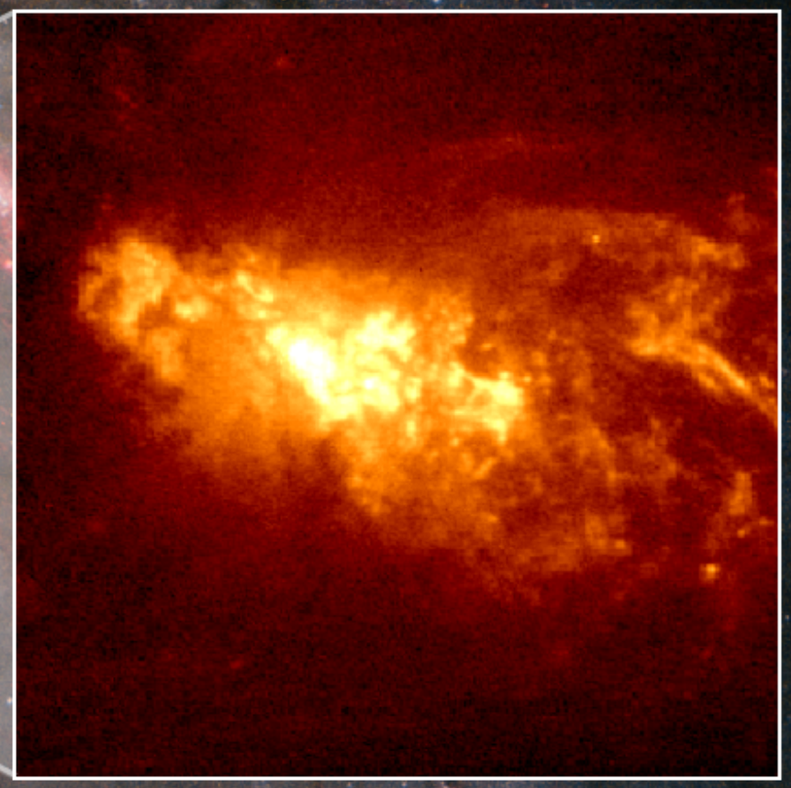
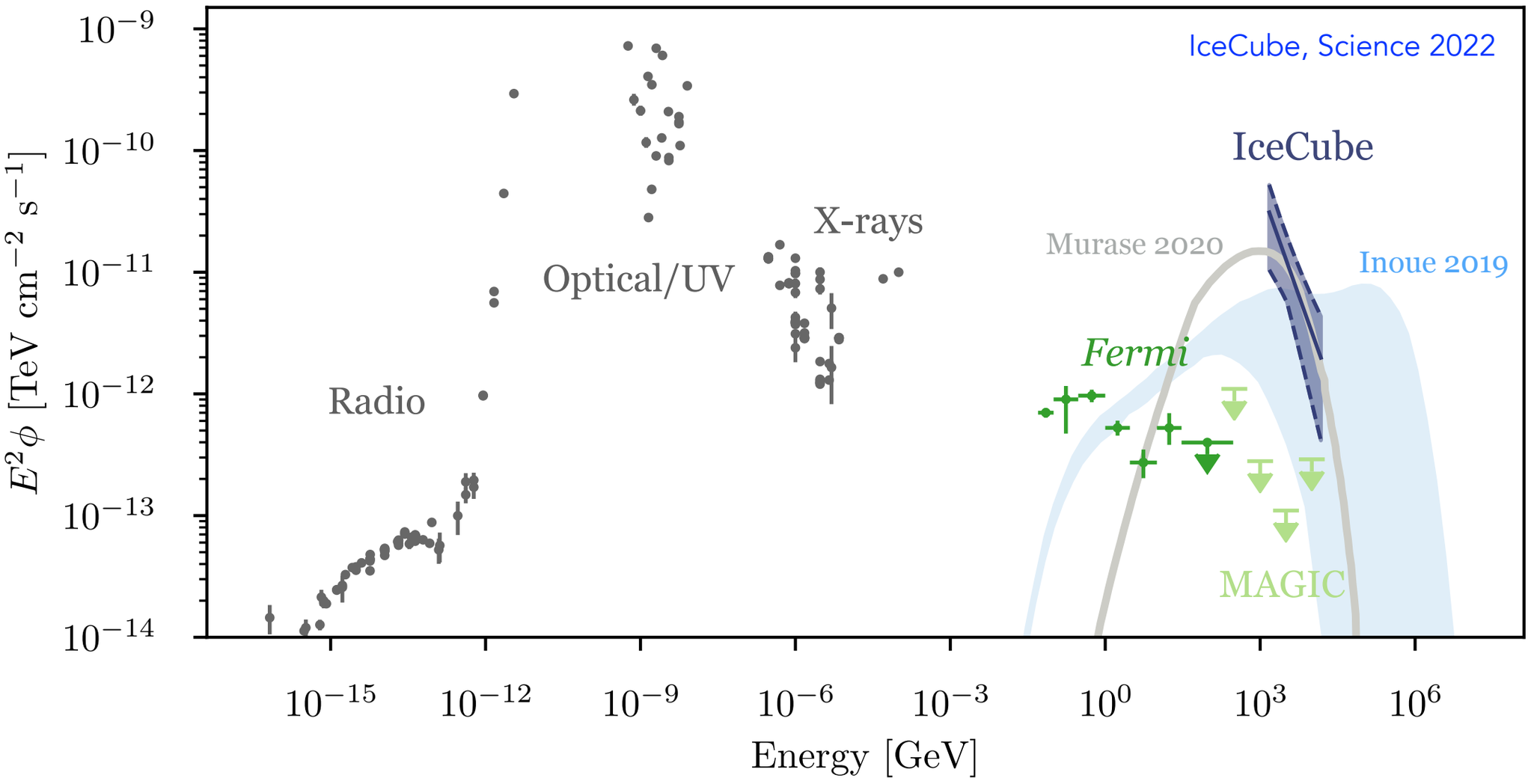
- One of the best studied Active Galactic Nuclei (AGN), which played a major role in AGN unification scheme



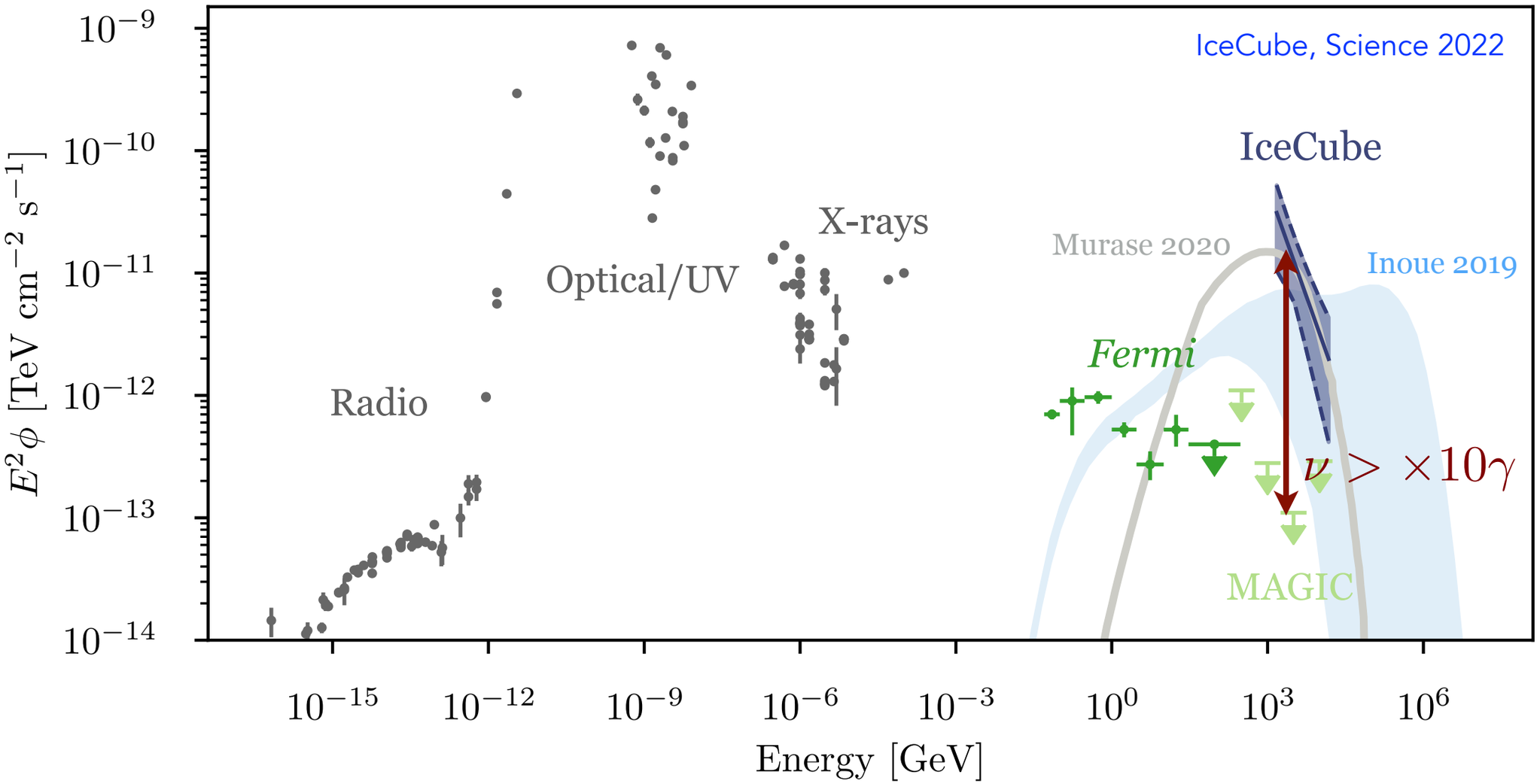
- Compton thick environment with Column density ~ 10^{25} cm^{-2}
- Bright in X-ray, and high infrared luminosity indicating high level of star formation
    - *Historically considered as a promising cosmic-ray accelerator.*

NGC 1068 Spectrum



- The neutrino flux much higher than the measured γ-ray flux.
- Models built on Fermi γ-ray flux by cannot accommodate the neutrino flux.
- **Obscuring** necessary to absorb the pionic γ-ray accompanying neutrinos.
- The high opacity indicates that the neutrinos are produced in dense environment in the vicinity of AGN core (< 100 R_s)

NGC 1068 Spectrum



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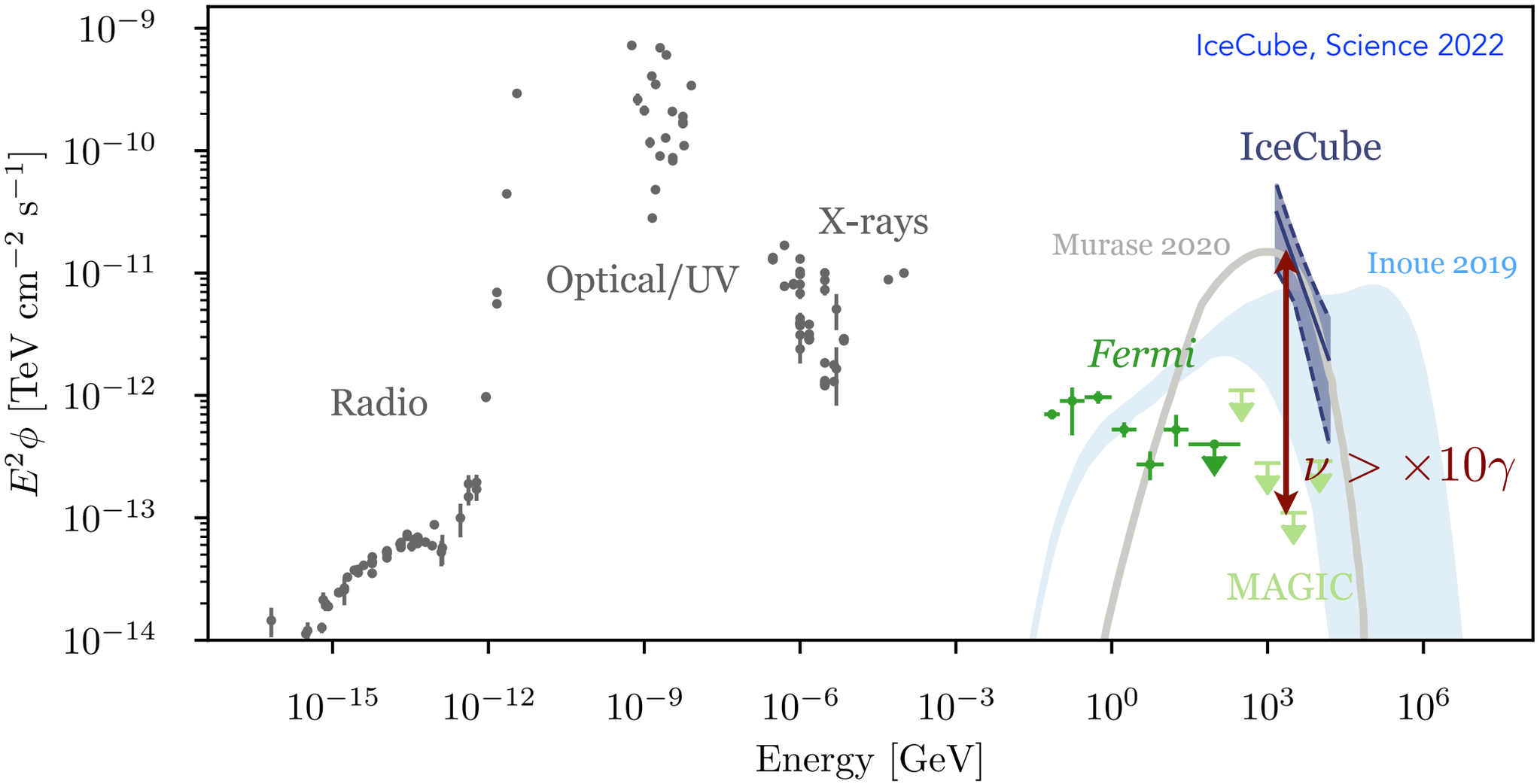

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→ Consistent with the multimessenger picture for the HE cosmic neutrino flux

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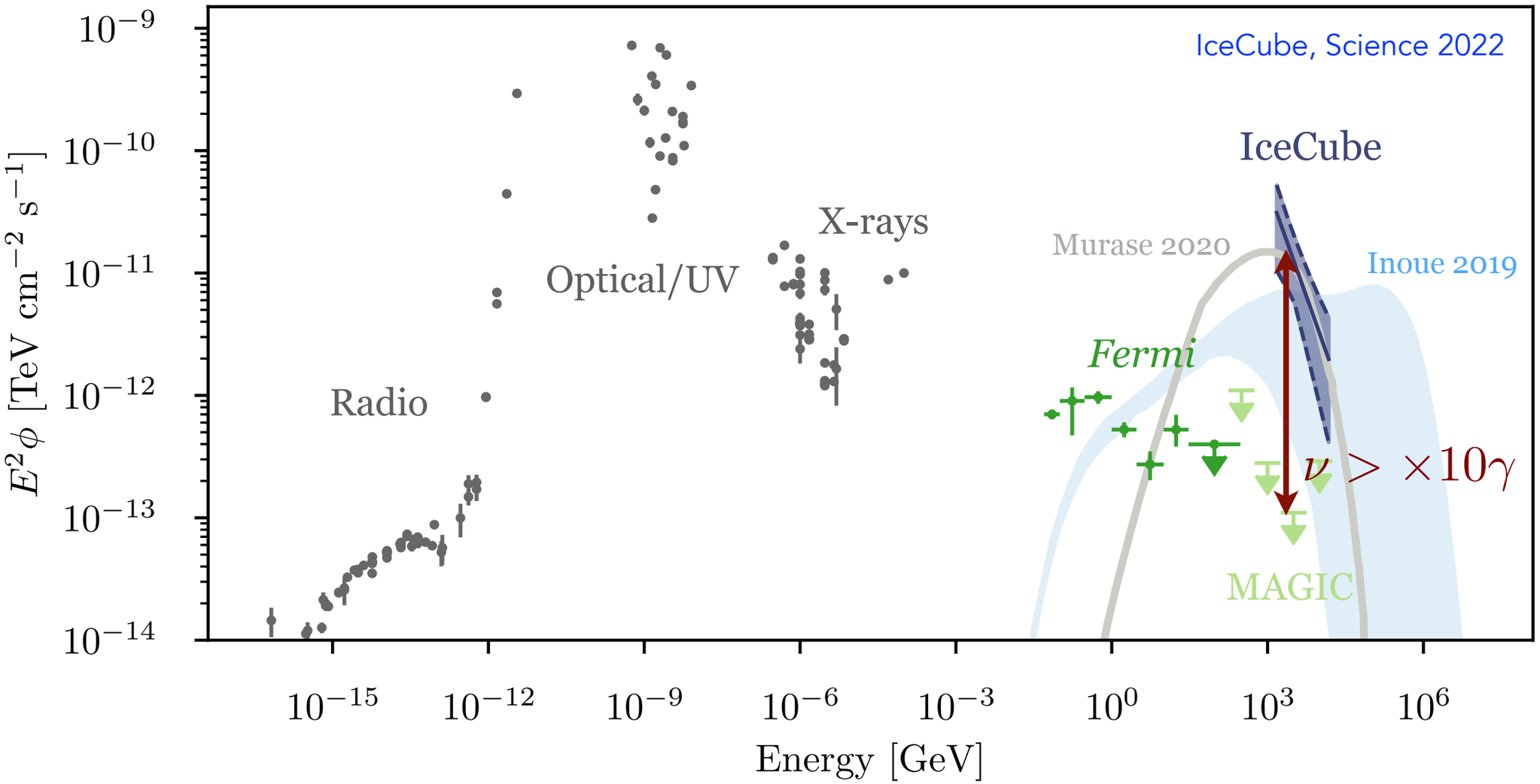

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See talk by Kohta Murase on Thursday 12 pm

Neutrino-Bright AGN

- Accumulating evidence for correlation of IceCube neutrinos in the direction of γ-ray obscured AGN.
  - 3.3σ excess from ensemble of 11 sources in the Northern Sky (excluding NGS 1068)
  - 2.9σ excess from the direction of NGC 4151
  - 3.0σ excess in the stacking search in the Southern sky

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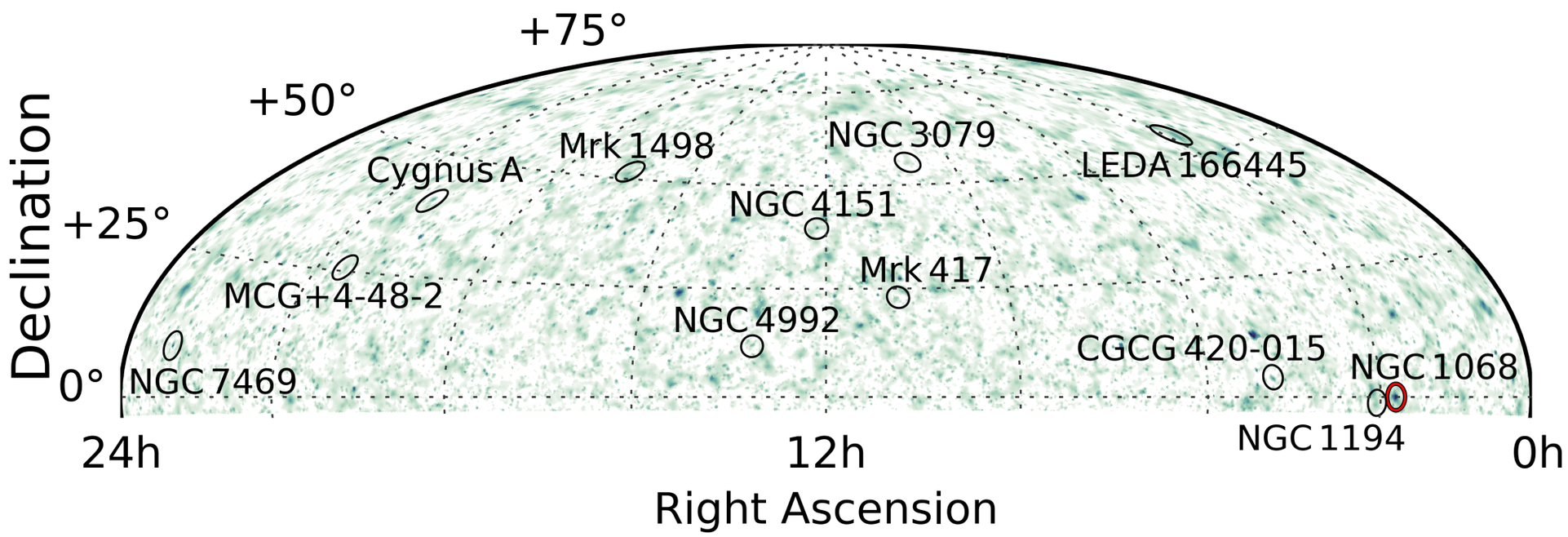

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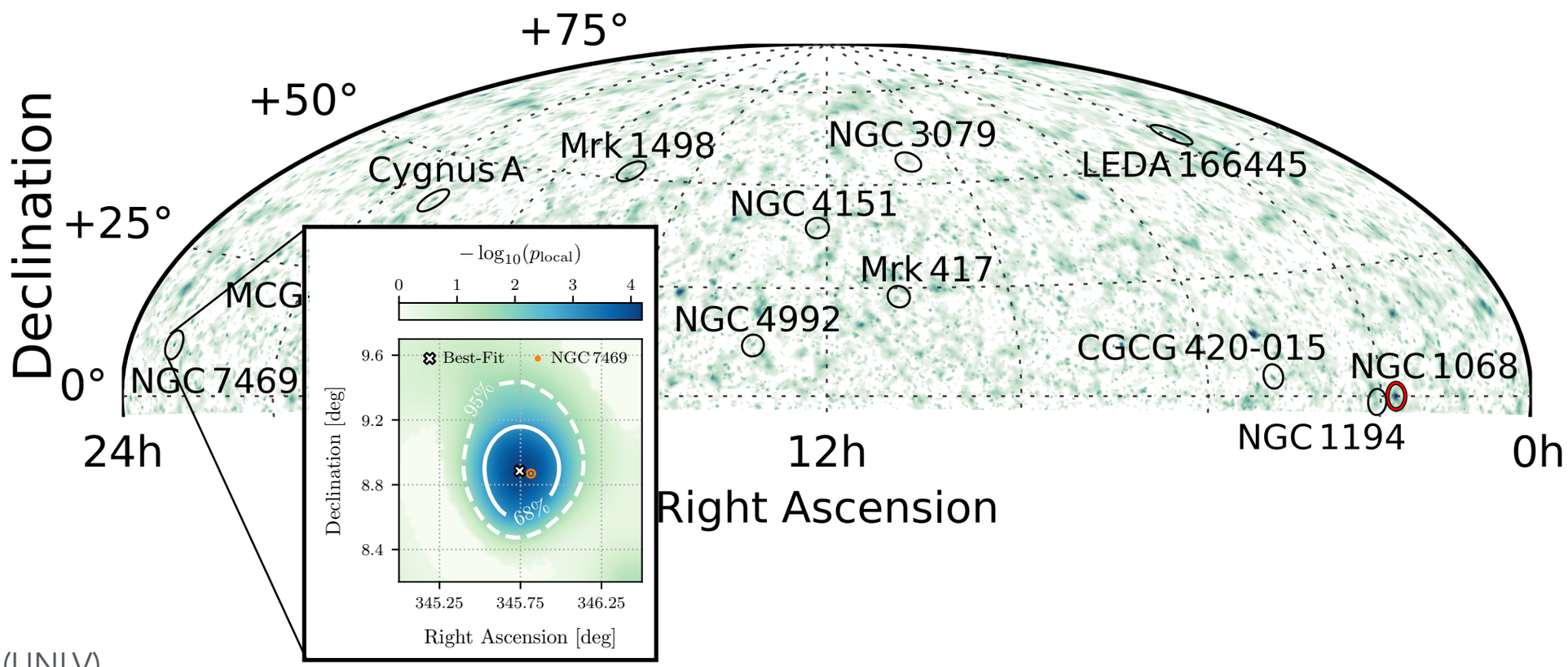

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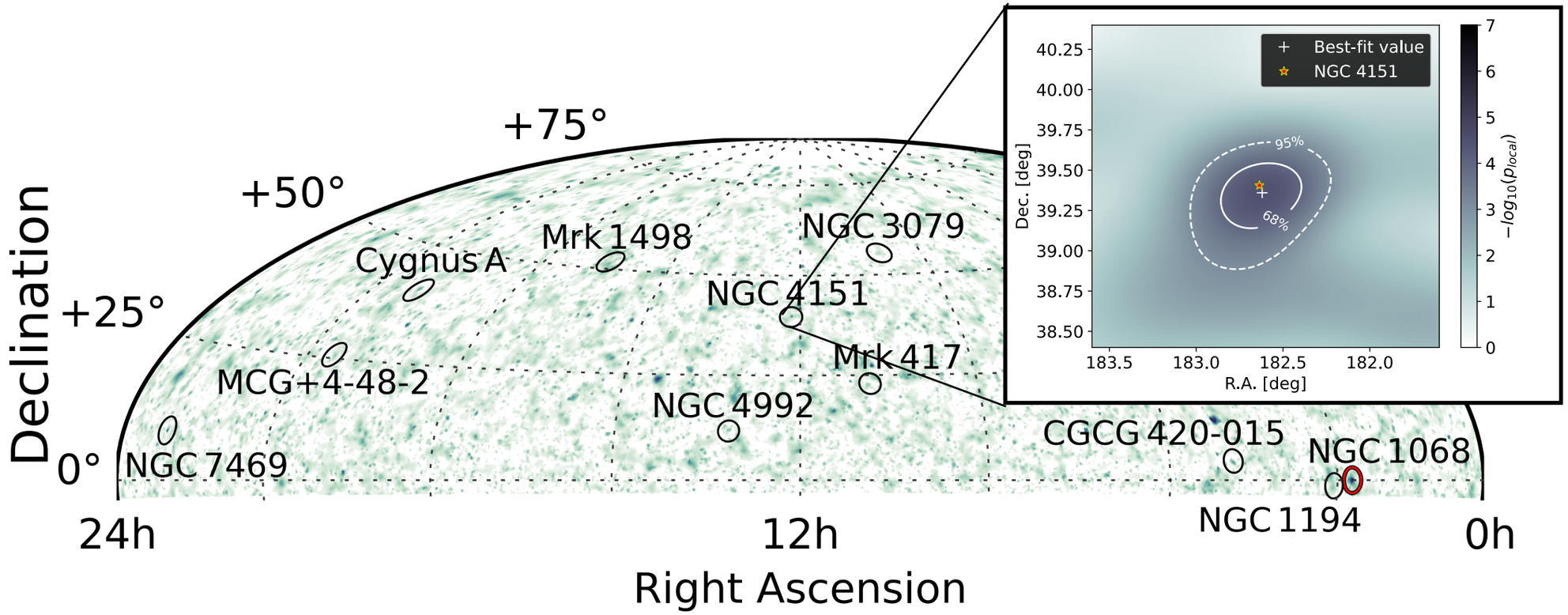
- Accumulating evidence for correlation of IceCube neutrinos in the direction of γ-ray obscured AGN.
  - 3.3σ excess from ensemble of 11 sources in the Northern Sky (excluding NGS 1068)
  - 2.9σ excess from the direction of NGC 4151
  - 3.0σ excess in the stacking search in the Southern sky



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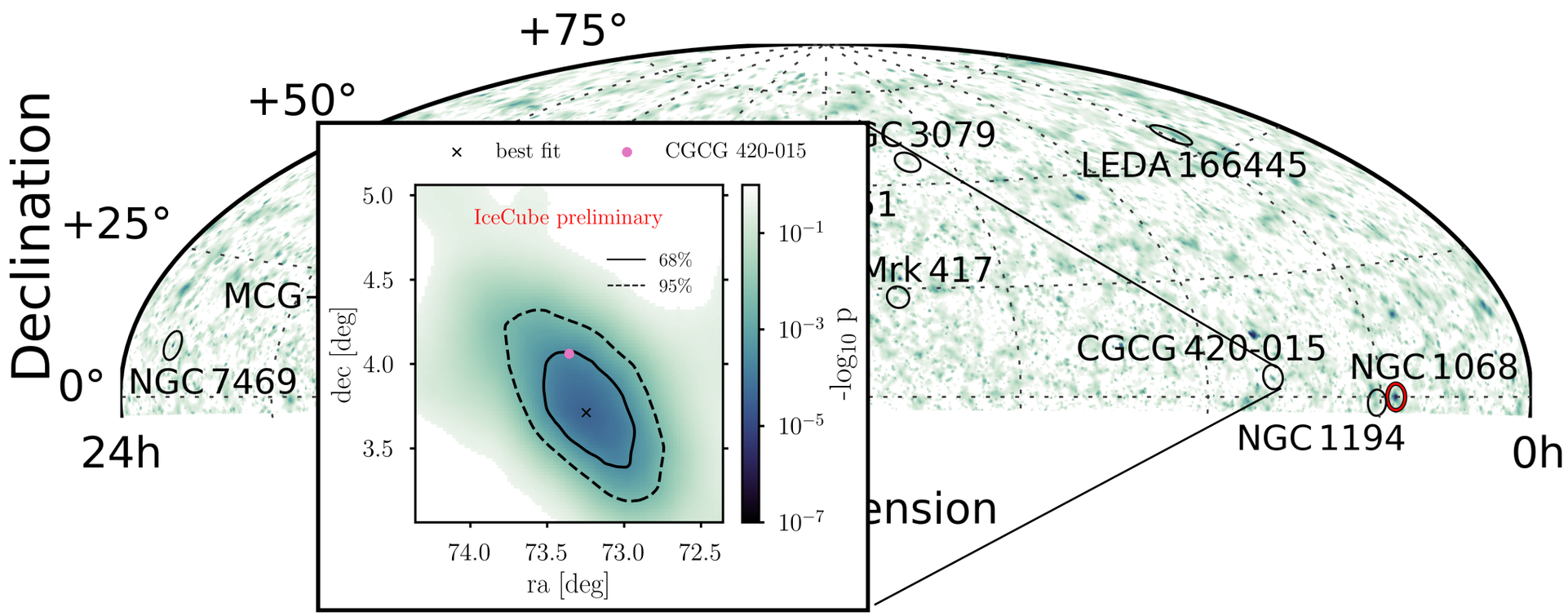

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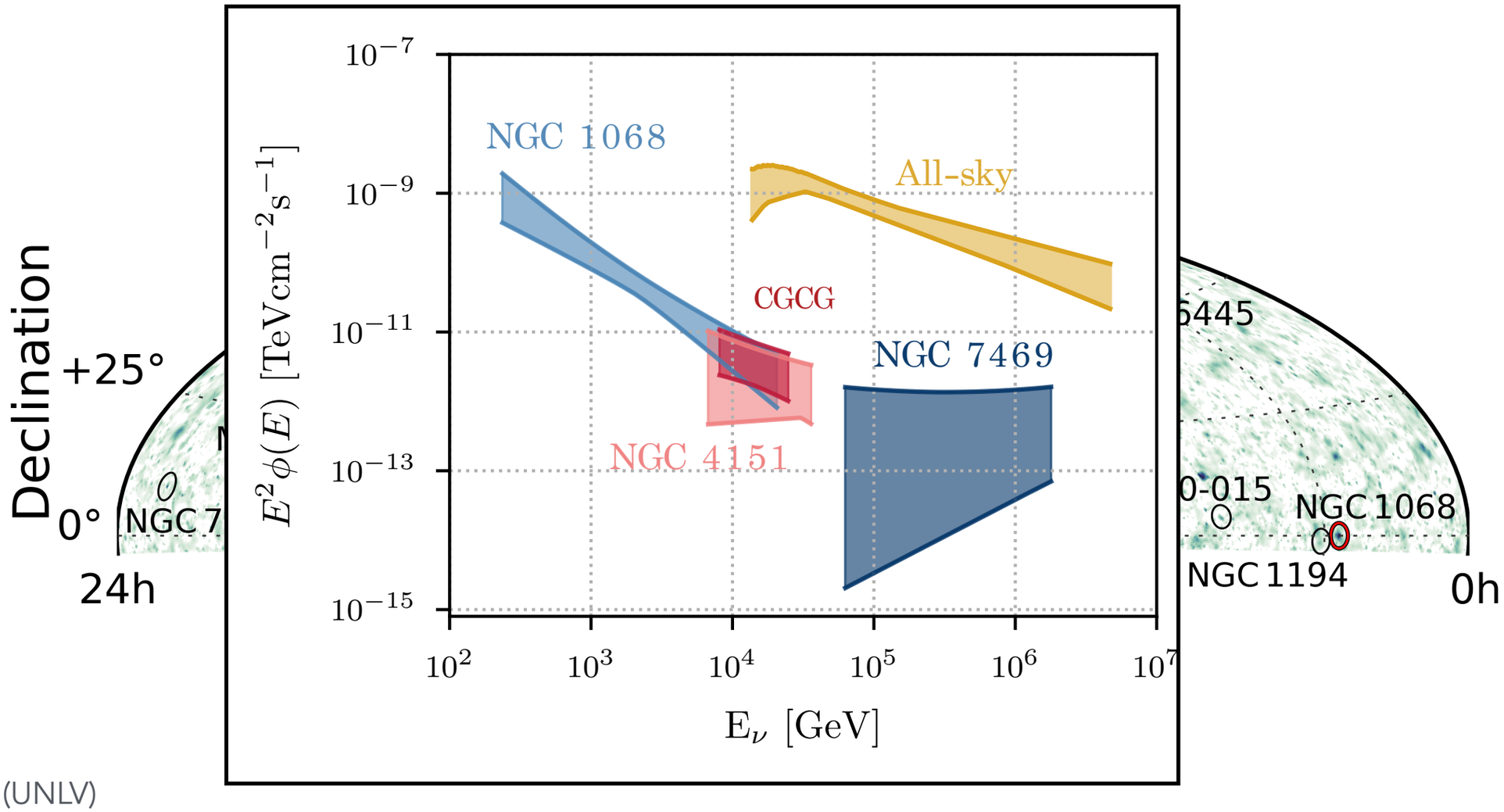

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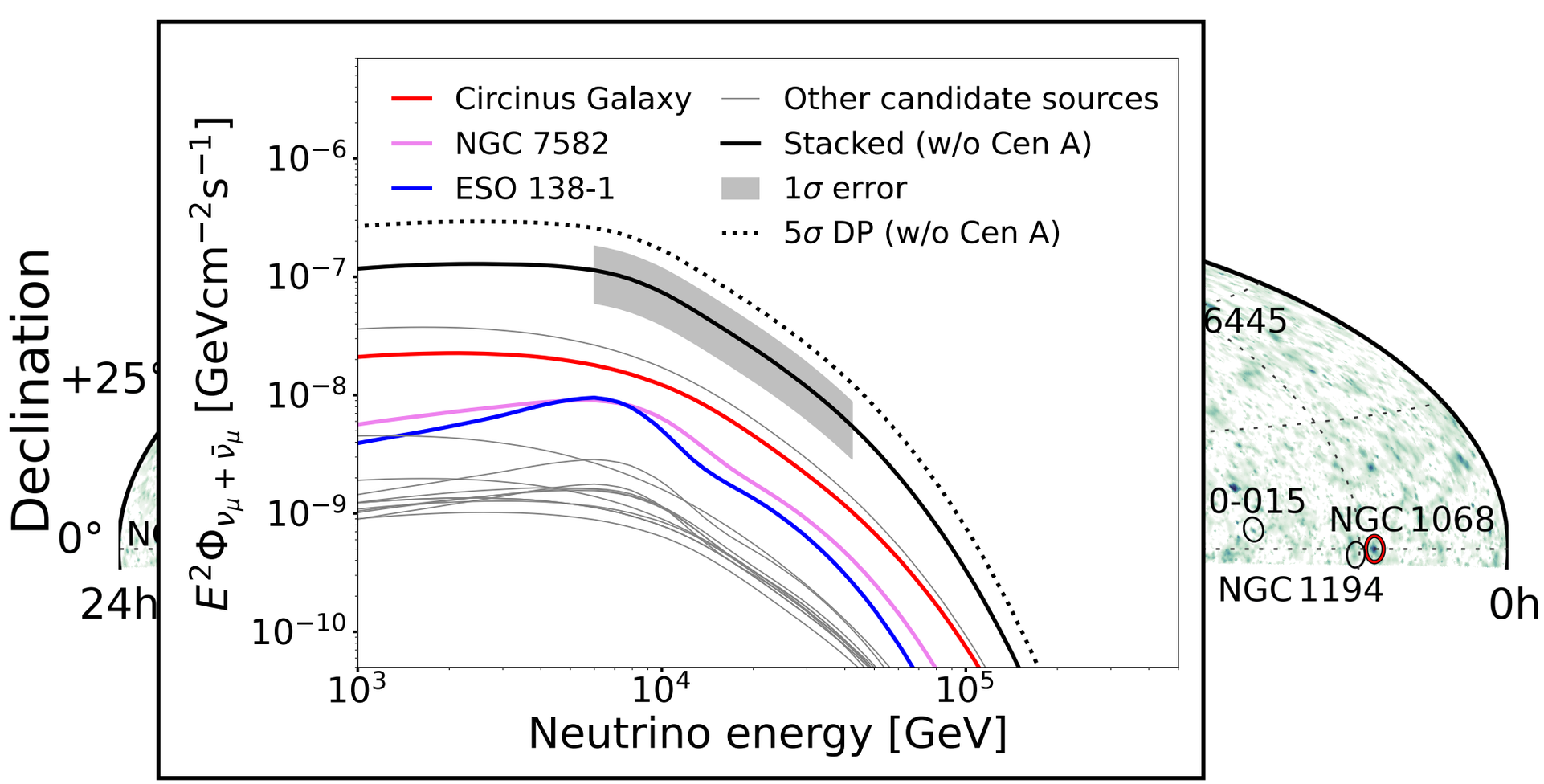

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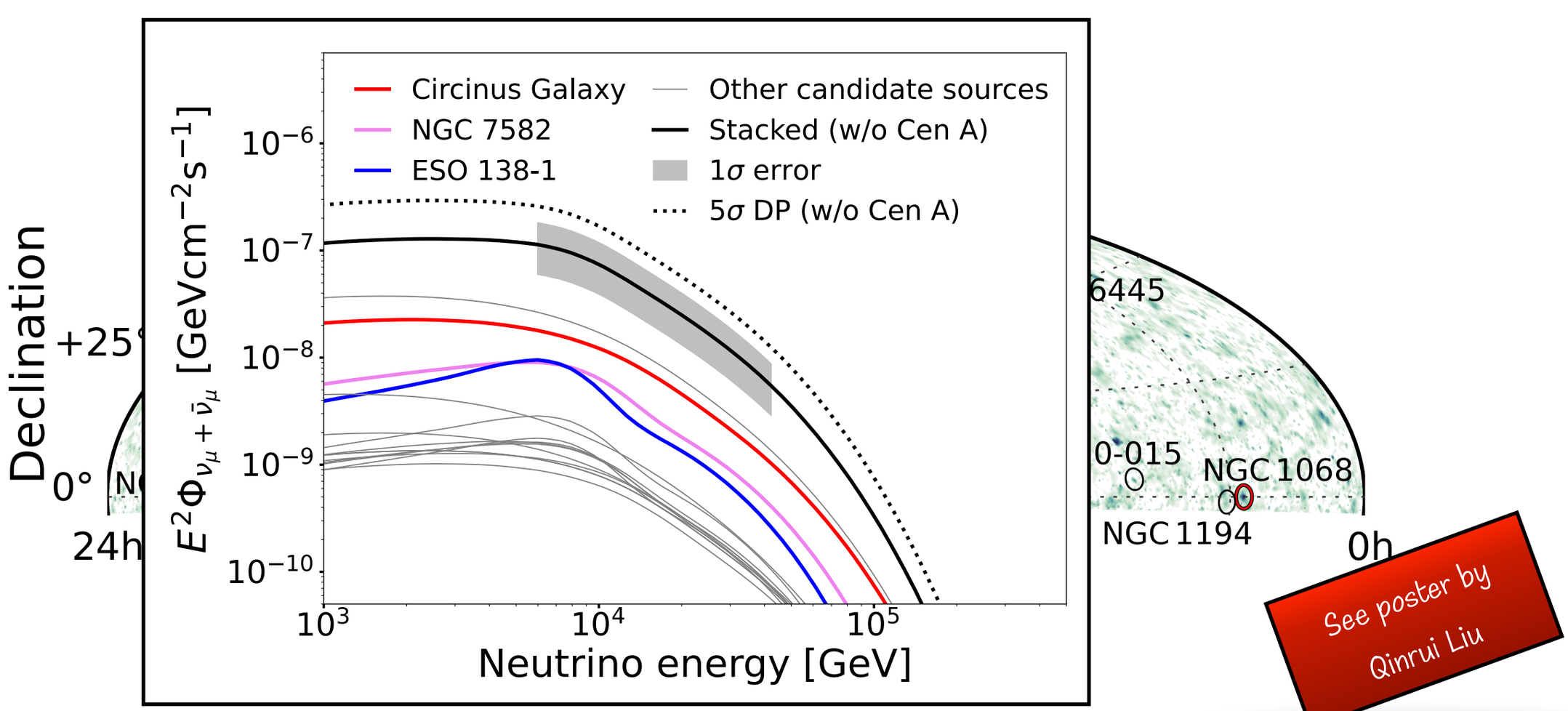
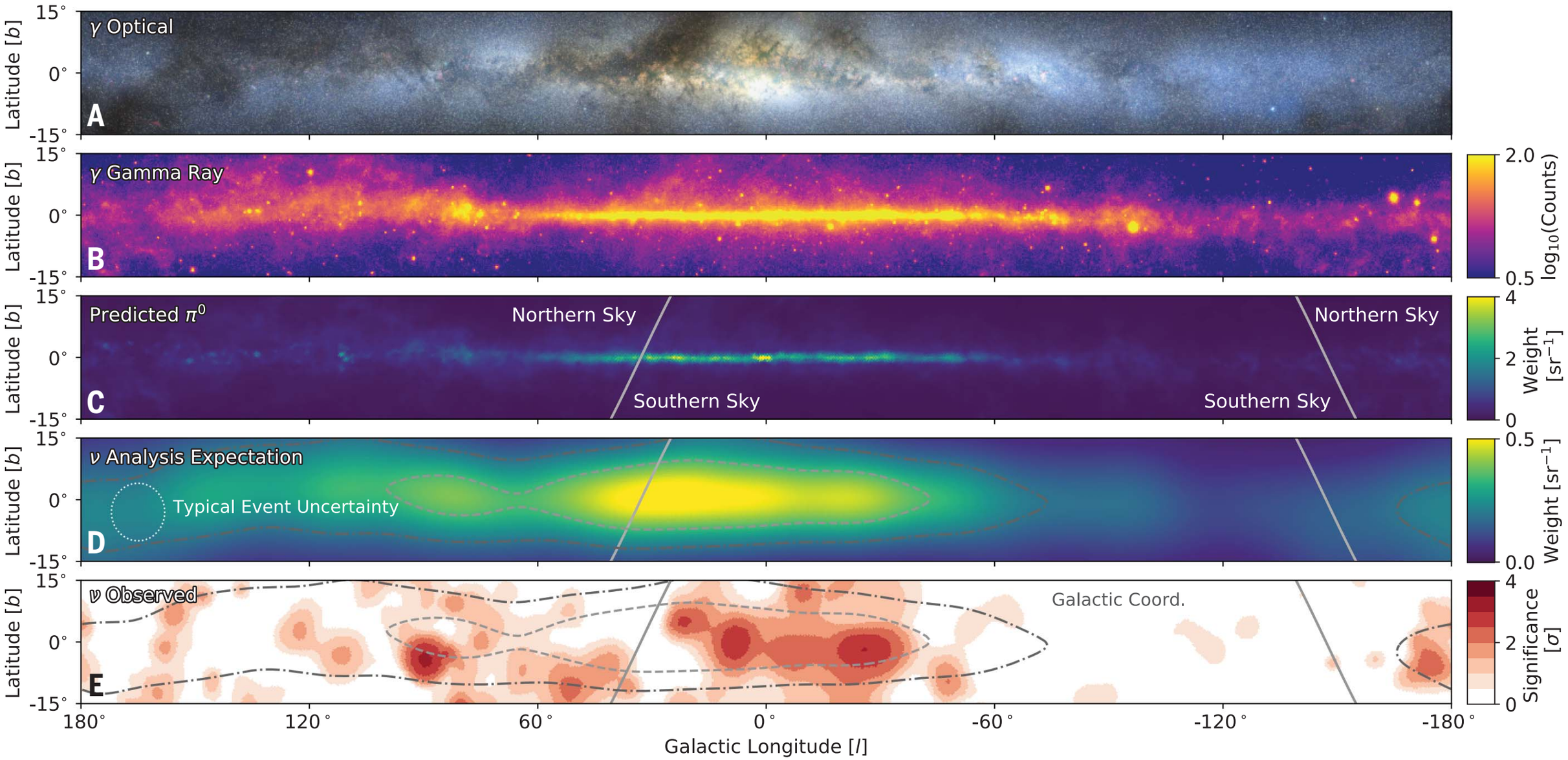


See poster by Qinrui Liu

Galactic Neutrino Emission

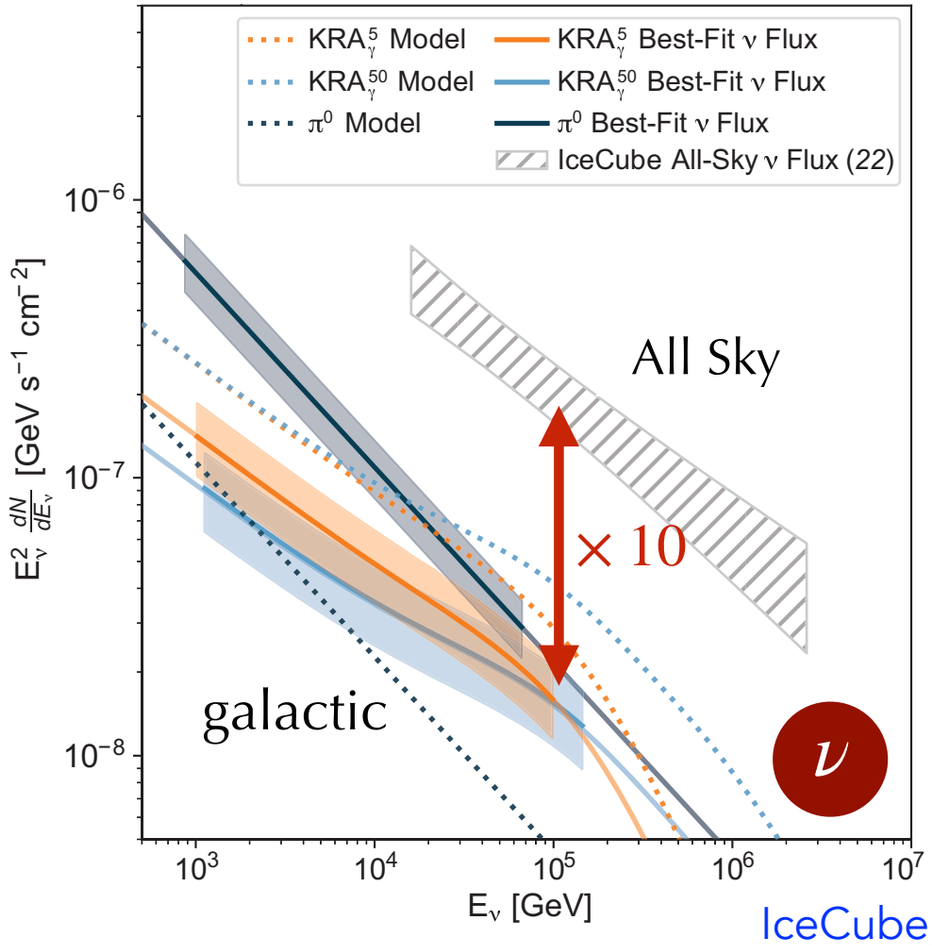


10 years of cascade data identified neutrino emission from the Milky Way at 4.5σ

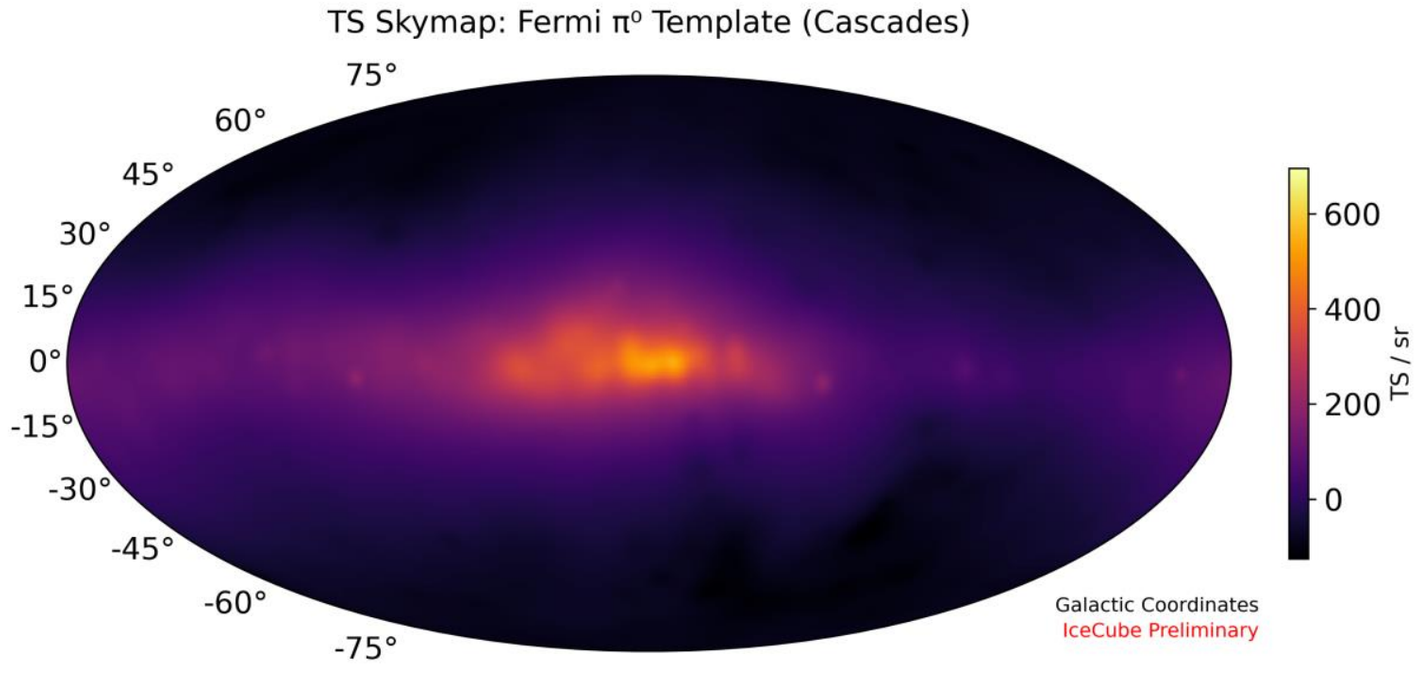
Galactic Neutrino Emission

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

- New analysis with additional years, combined dataset, and improved systematics rejects the no Galactic hypothesis at > 5σ significance
- Current analyses reject no Galactic component hypothesis but cannot distinguish between models
- The nature of Galactic neutrinos (source vs diffuse) remains an open question



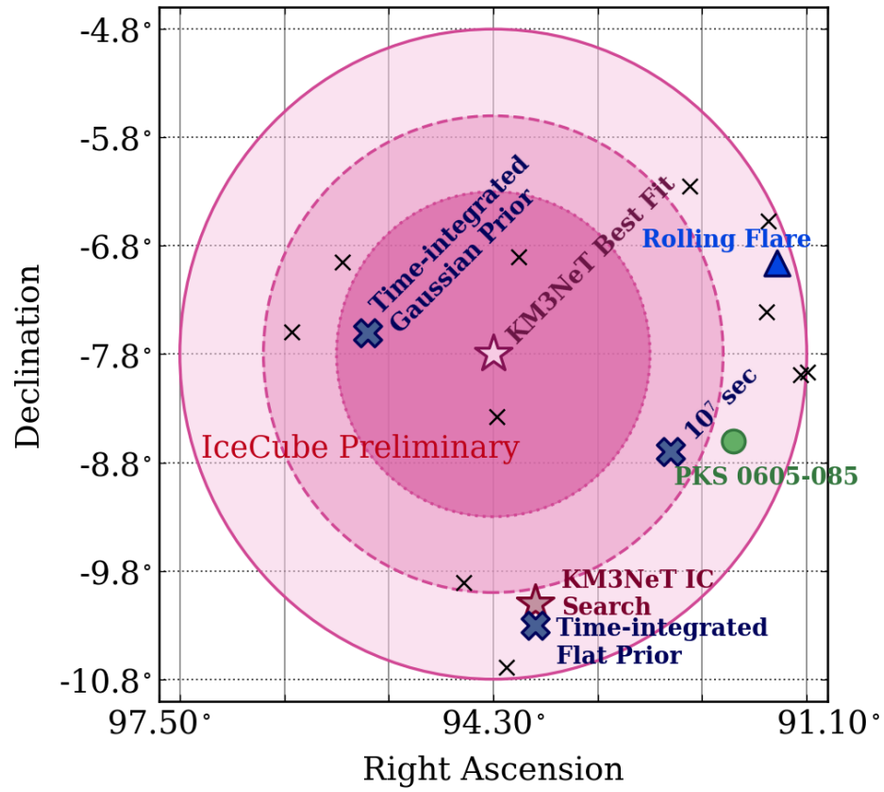
IceCube, Science 2023

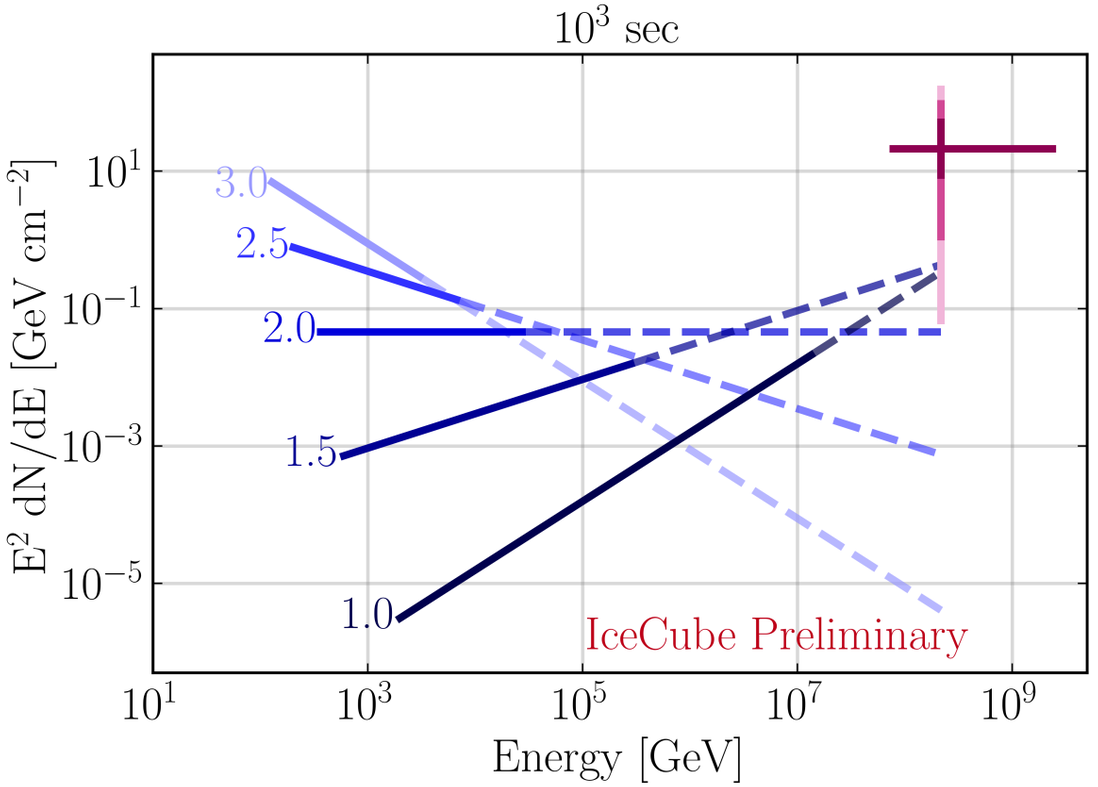


M. Thiesmeyer , ICRC 2025

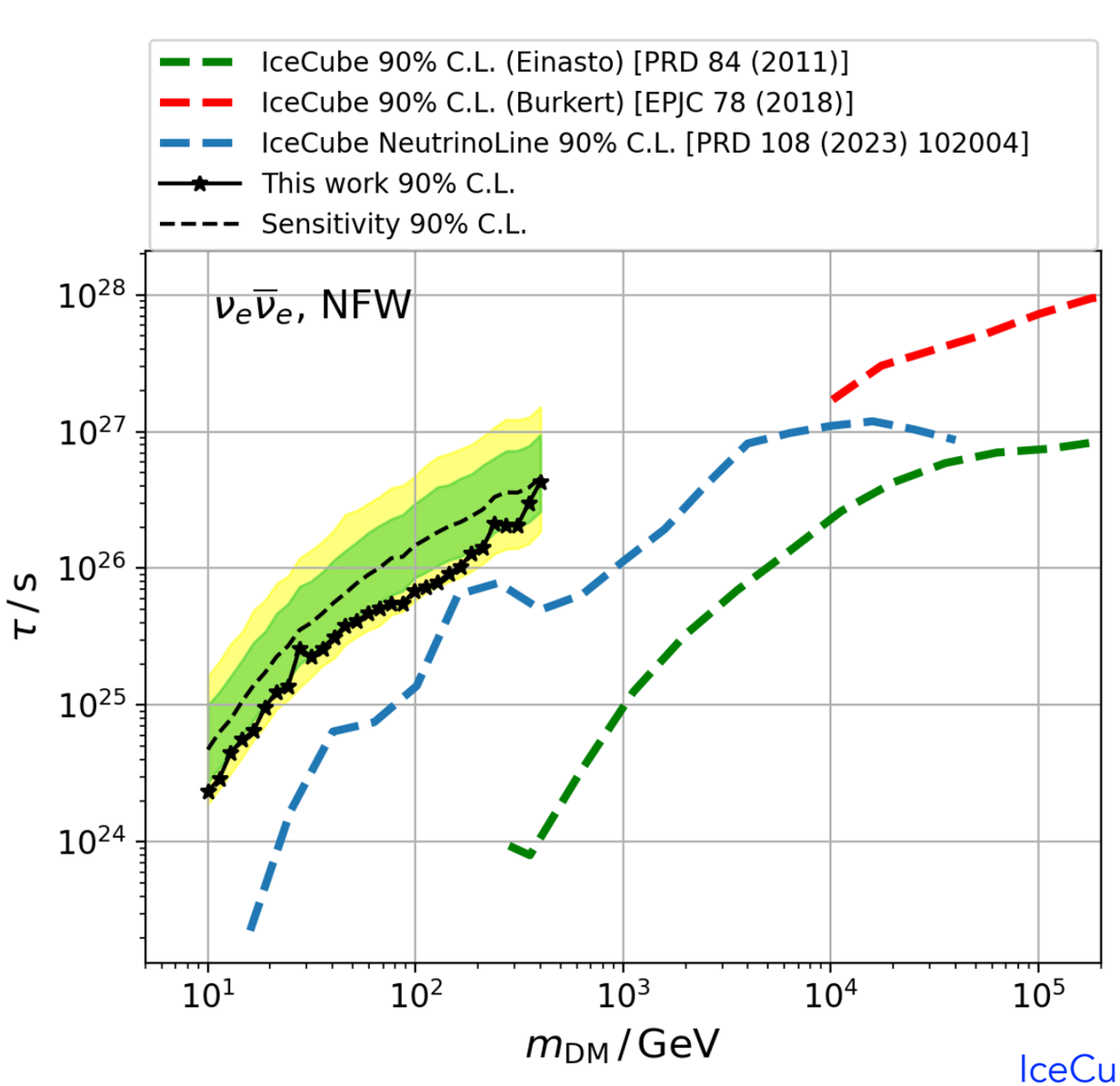
KM3-230213A Archival Follow Up

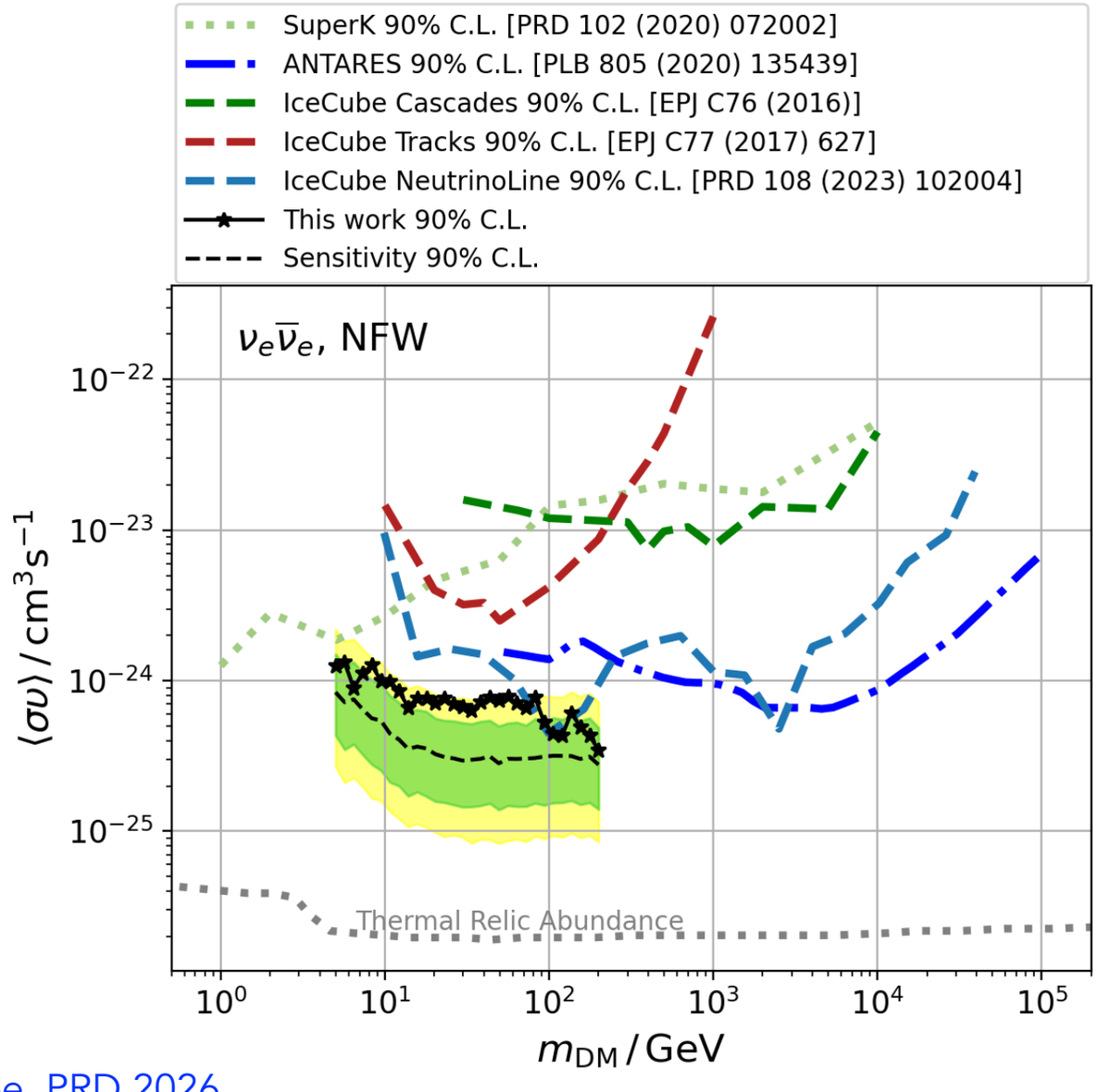
- Searching for transient and steady emission from the direction of KM3-230213A using ~15 years of tracks and 12 years of cascade data
- Three analyses:
  - Prompt search with expanding time-window
    - Rolling flare
    - Realtime monitoring
- No significant excess identified.
  - constraining the hypothesis of a source counterpart with emission extended to lower energies, especially prompt short duration emission





Indirect Dark Matter Search

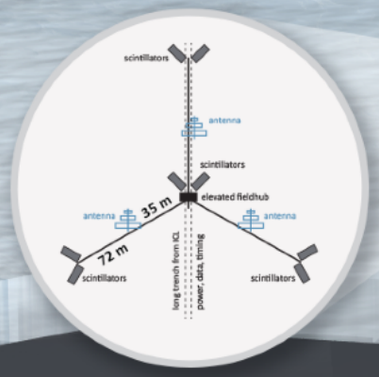




IceCube, PRD 2026

- Constraining GeV scale dark matter decay or annihilation from the Galactic center

IceCube GEN2



Cosmic Ray Surface Array

An air shower array that sits on top of the optical array

One surface station installed above each optical string

IceCube-Gen2 Optical Module

4x the sensitivity of IceCube's modules

9,600 new optical modules in total to be deployed in the ice

80 modules on each string, spaced 17 meters apart

IceCube Laboratory

50 m

1370 m

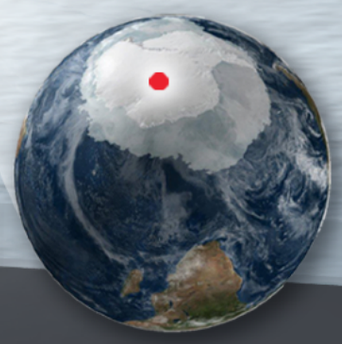
IceCube-Gen2: 120 new strings of optical modules

IceCube: 86 strings of optical modules

DeepCore

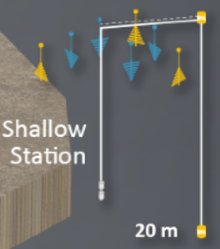
2780 m

Antarctic bedrock



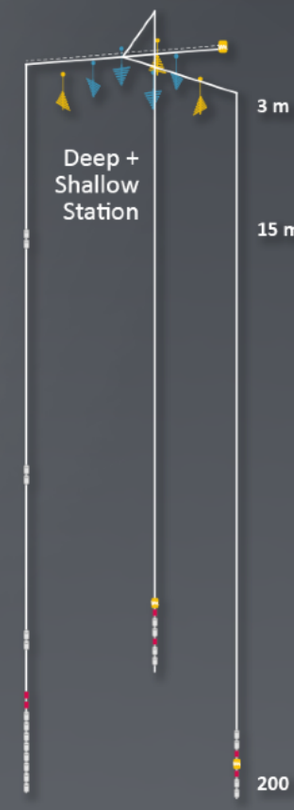
Amundsen–Scott South Pole Station, Antarctica

A National Science Foundation-managed research facility



Below-Ice Radio Array

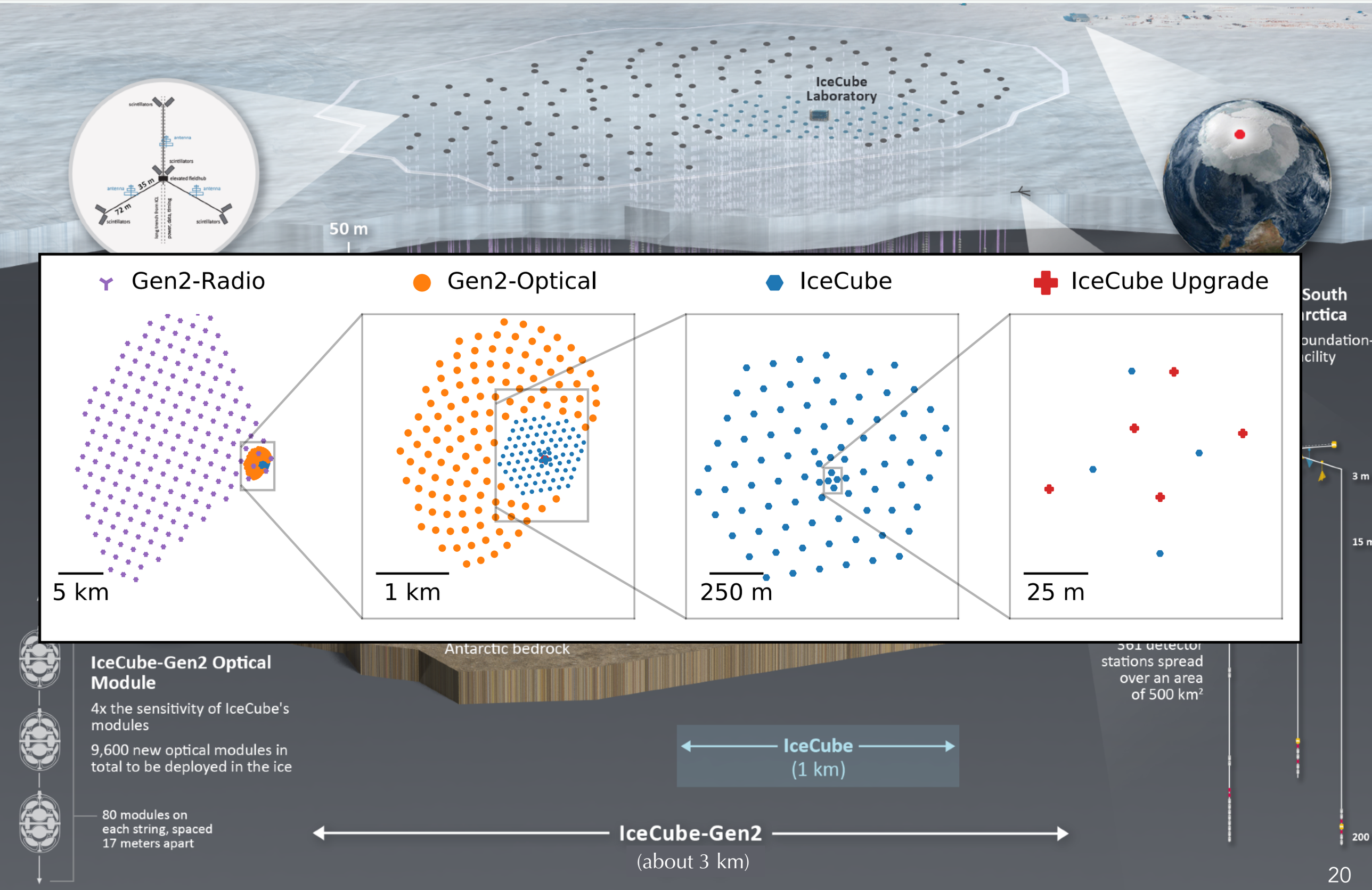
361 detector stations spread over an area of 500 km²



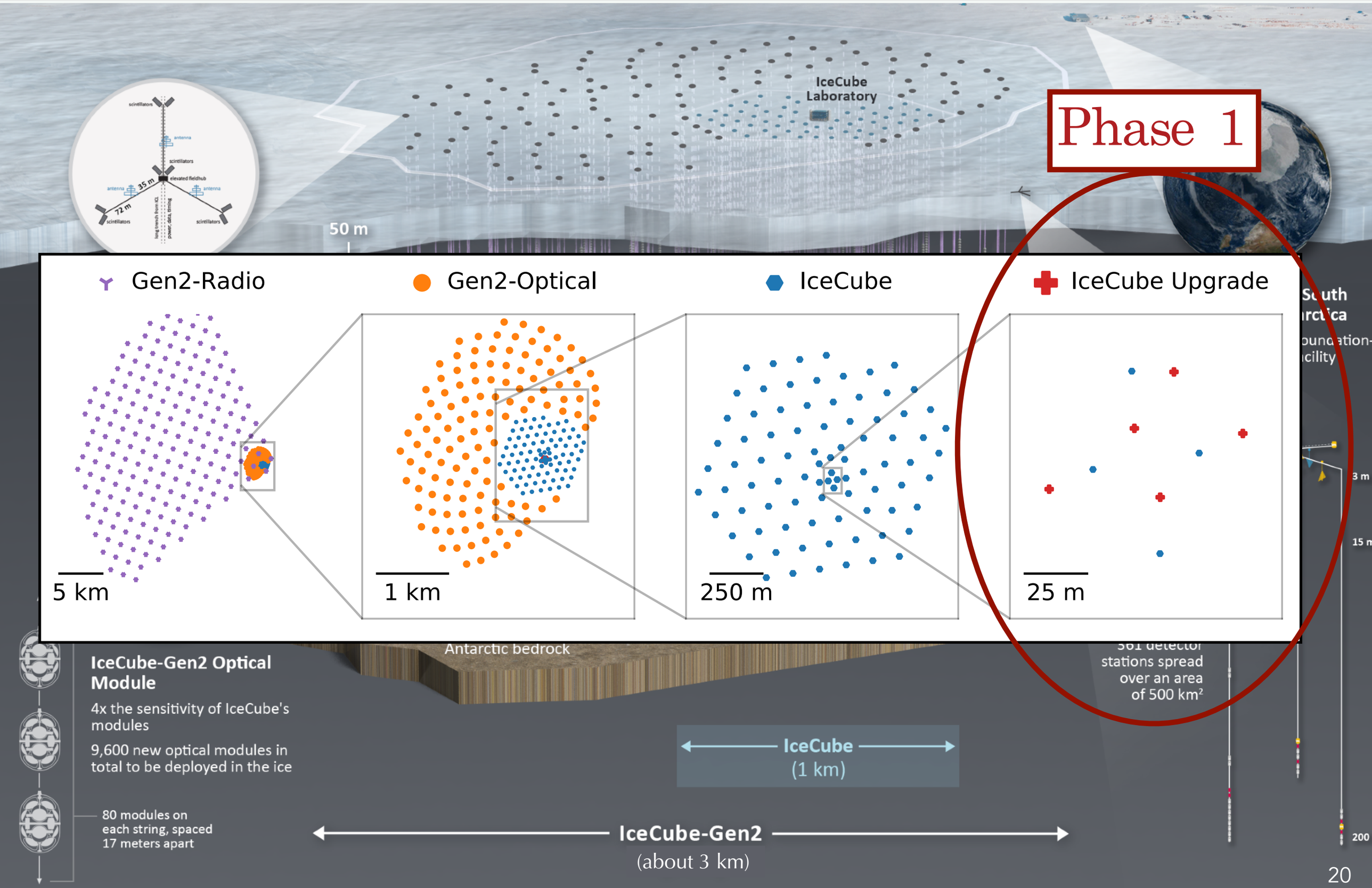
IceCube (1 km)

IceCube-Gen2 (about 3 km)

IceCube Gen2

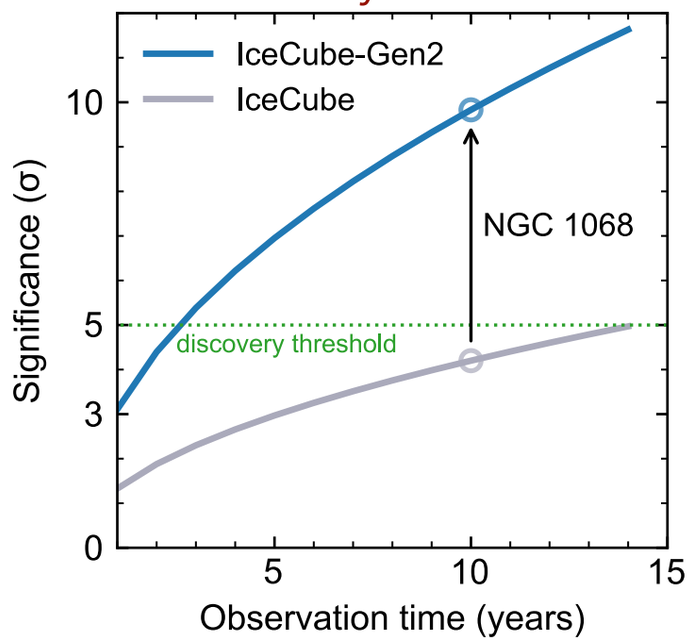


IceCube Gen2

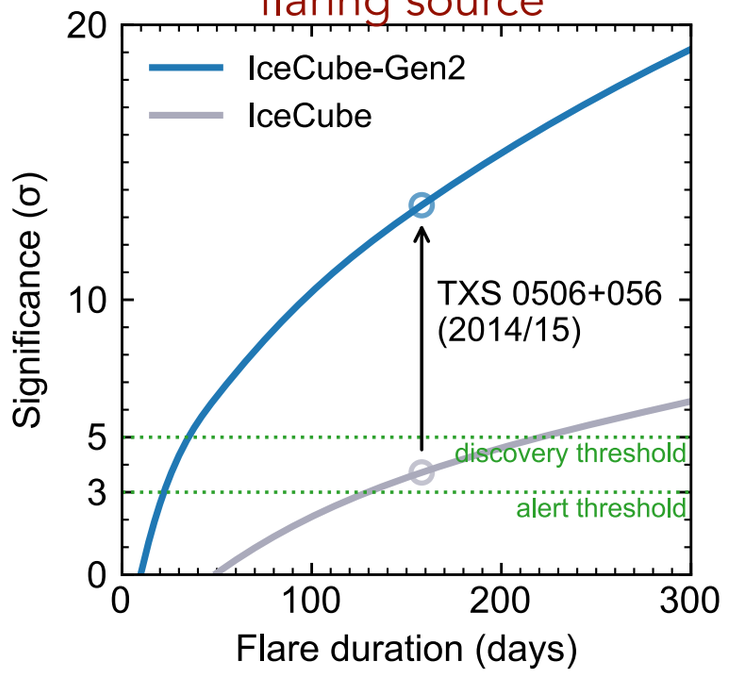


IceCube-Gen2: Source Identification

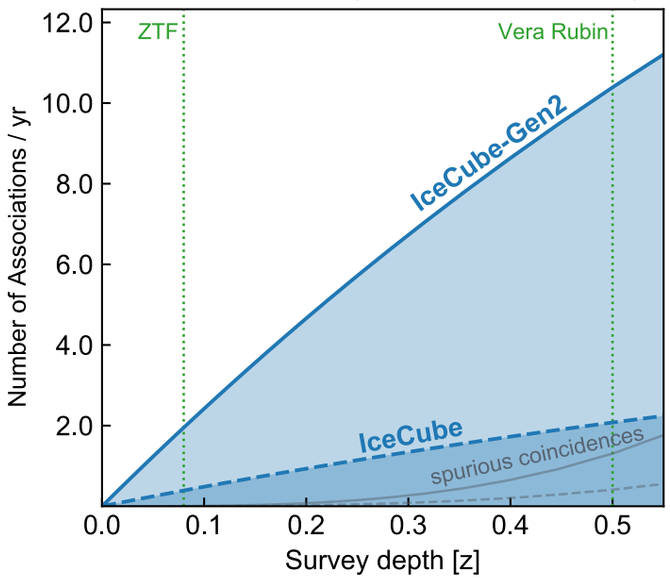
steady source



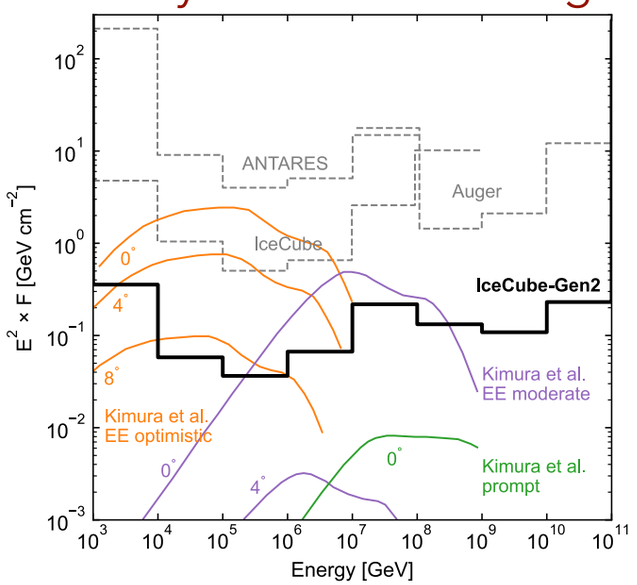
flaring source



transients (time-domain)

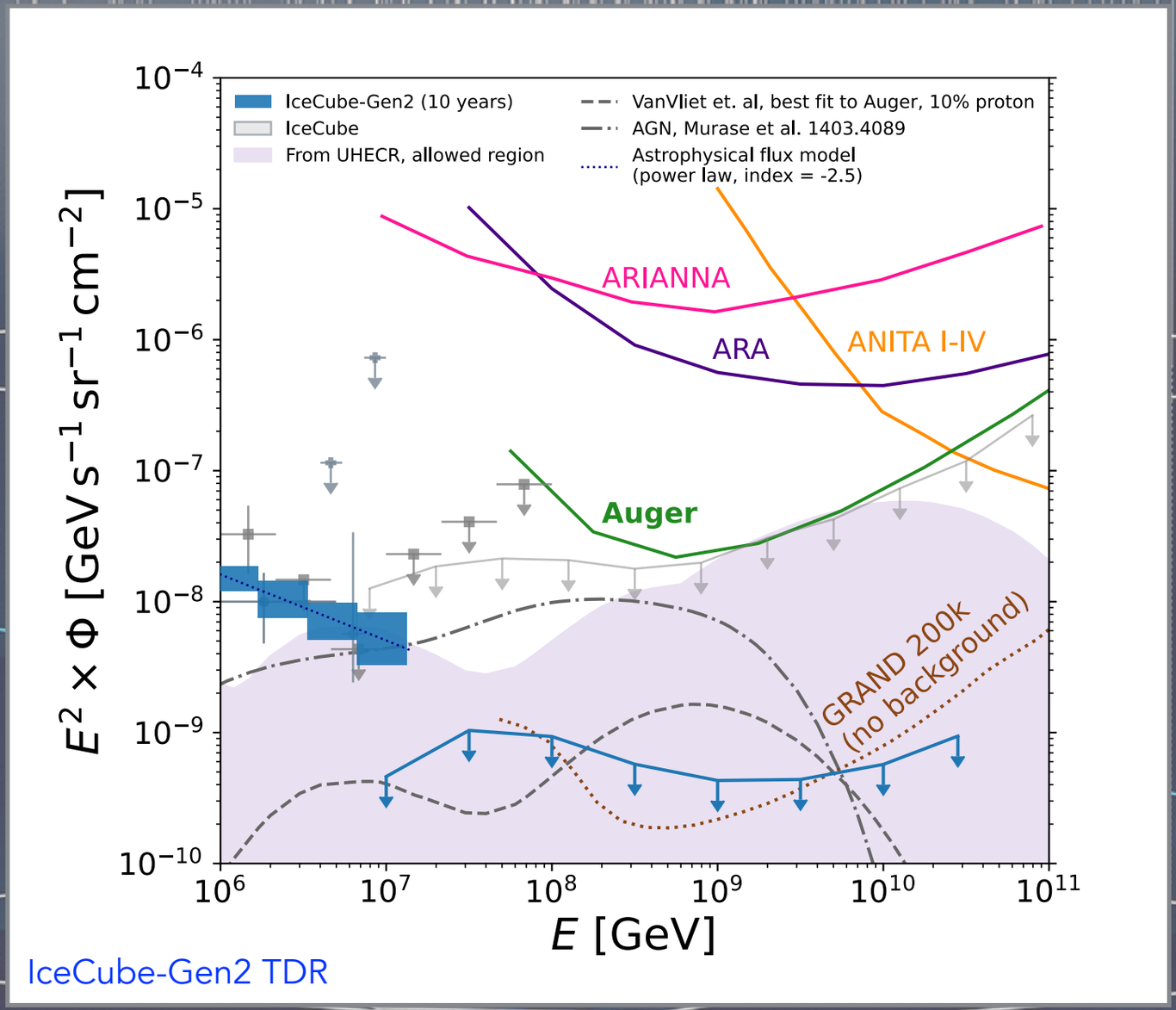


binary neutron star merger



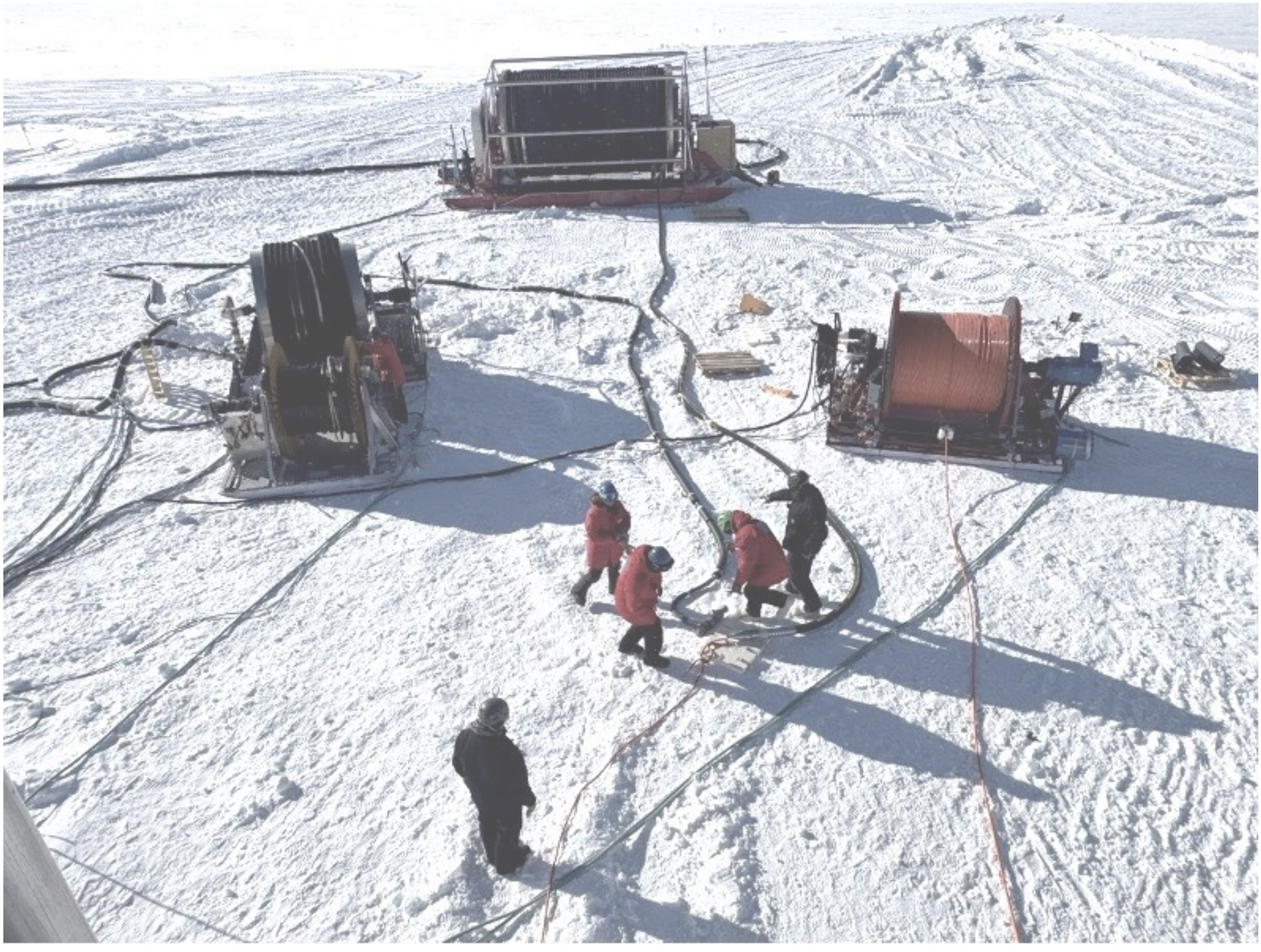
IceCube-Gen2 TDR

IceCube-Gen2: Cosmogenic Neutrinos

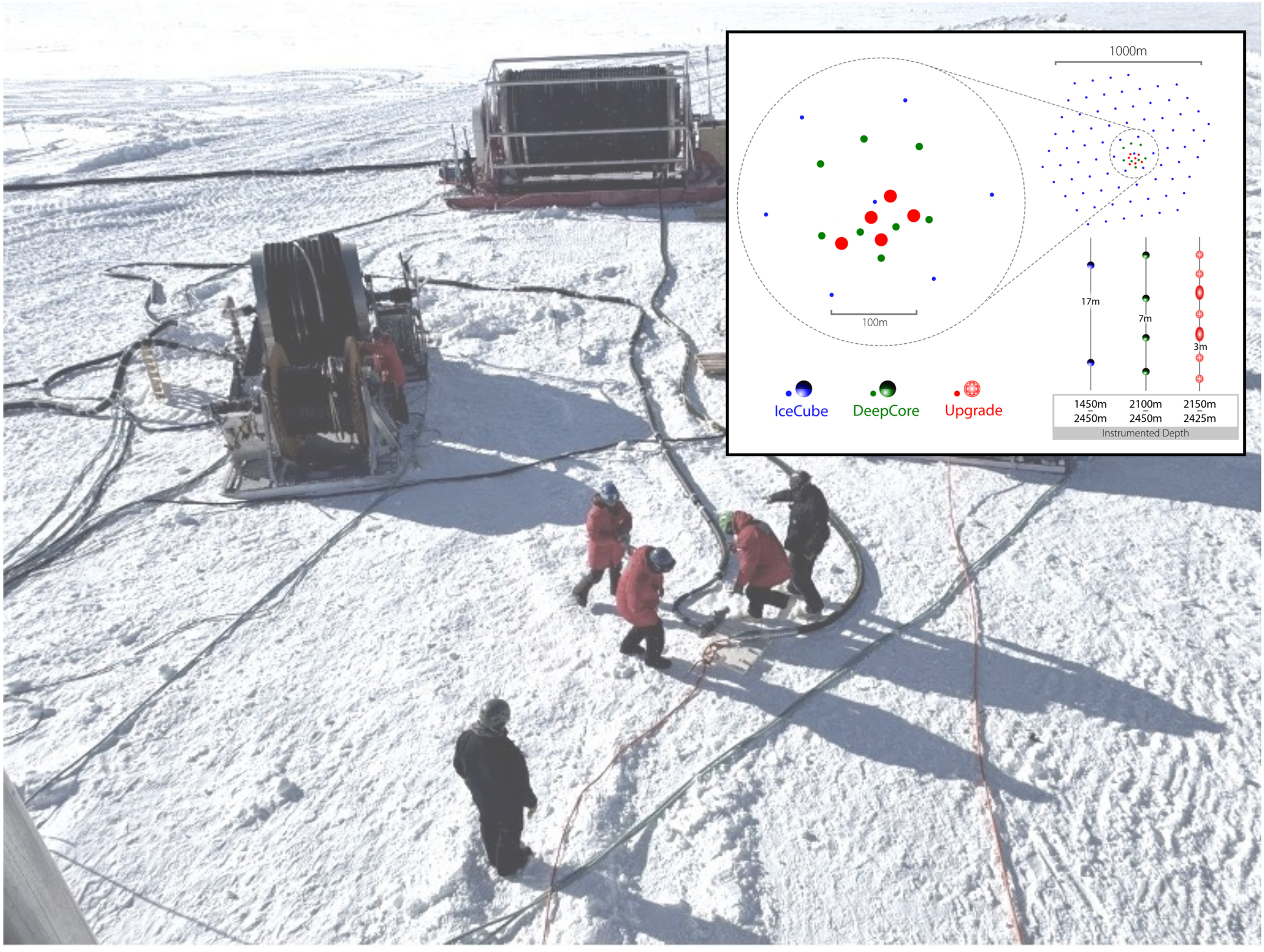


IceCube-Gen2 TDR

IceCube-Upgrade

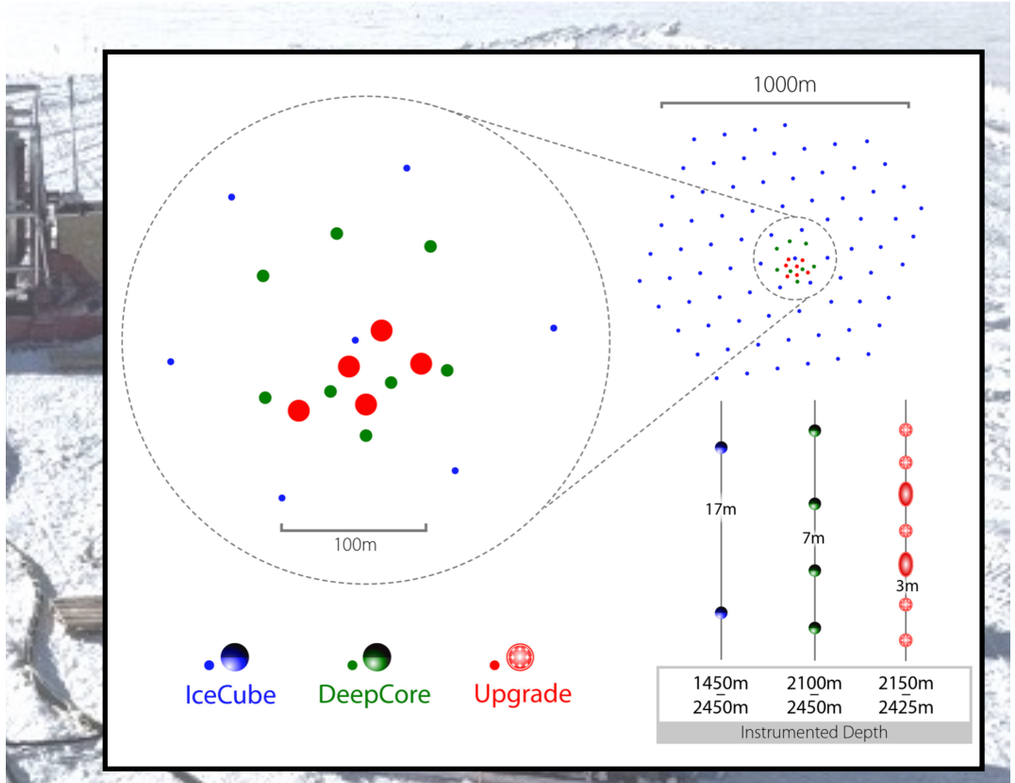


IceCube-Upgrade



IceCube-Upgrade

- 5 new strings deployed within DeepCore
- Equipped with new calibration devices and new sensor designs offering
  - Boosting sensitivity at lower energies
  - Better understanding of the systematics
- Establish R&D pathway towards IceCube-Gen2



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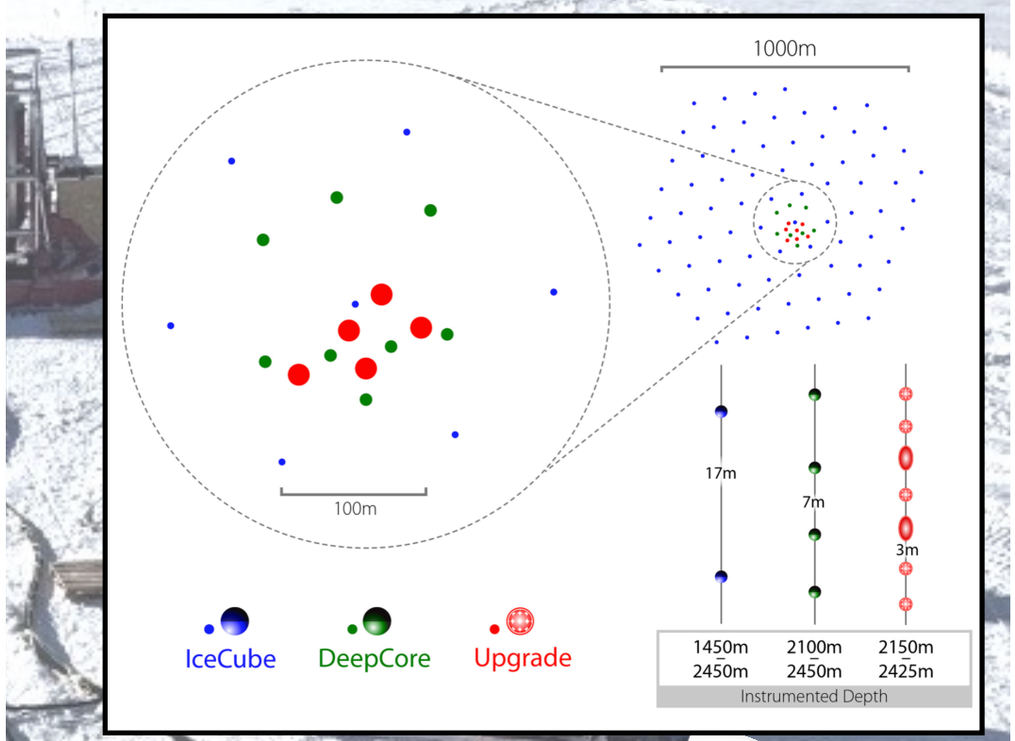

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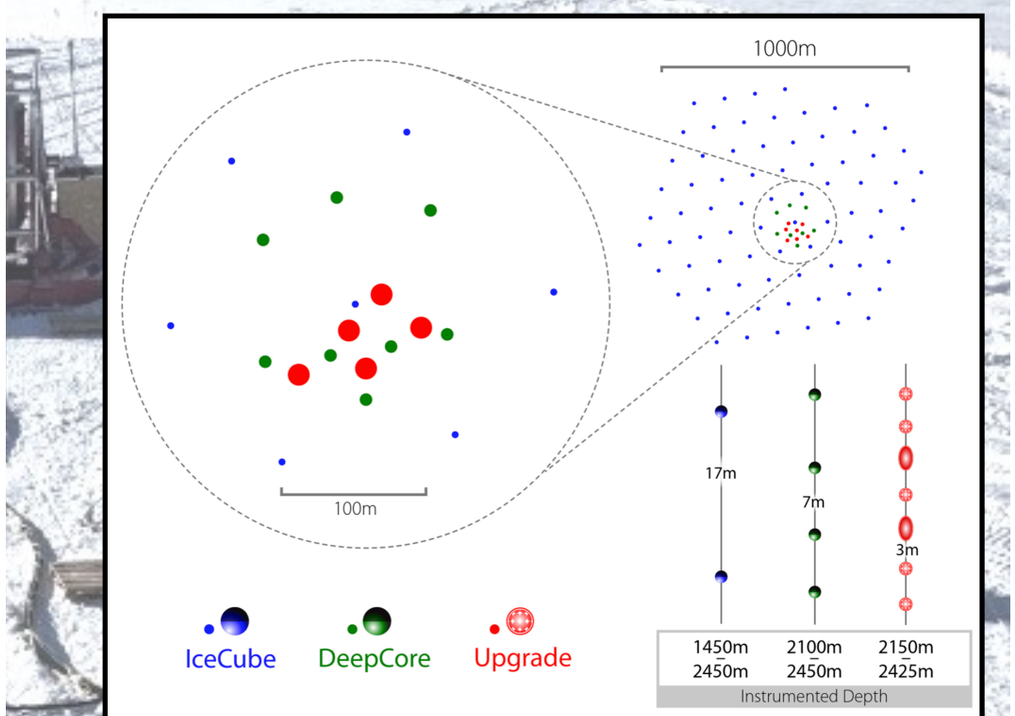

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See poster by Carsten Rott

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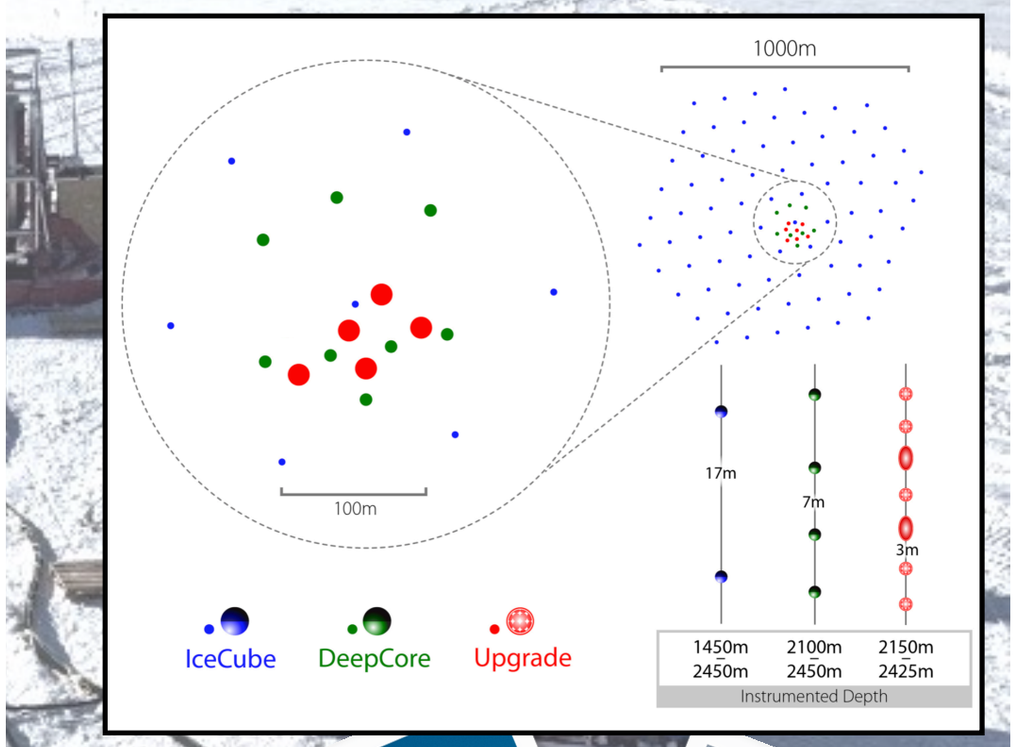

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See poster by Carsten Rott

See talk by Spencer Axani

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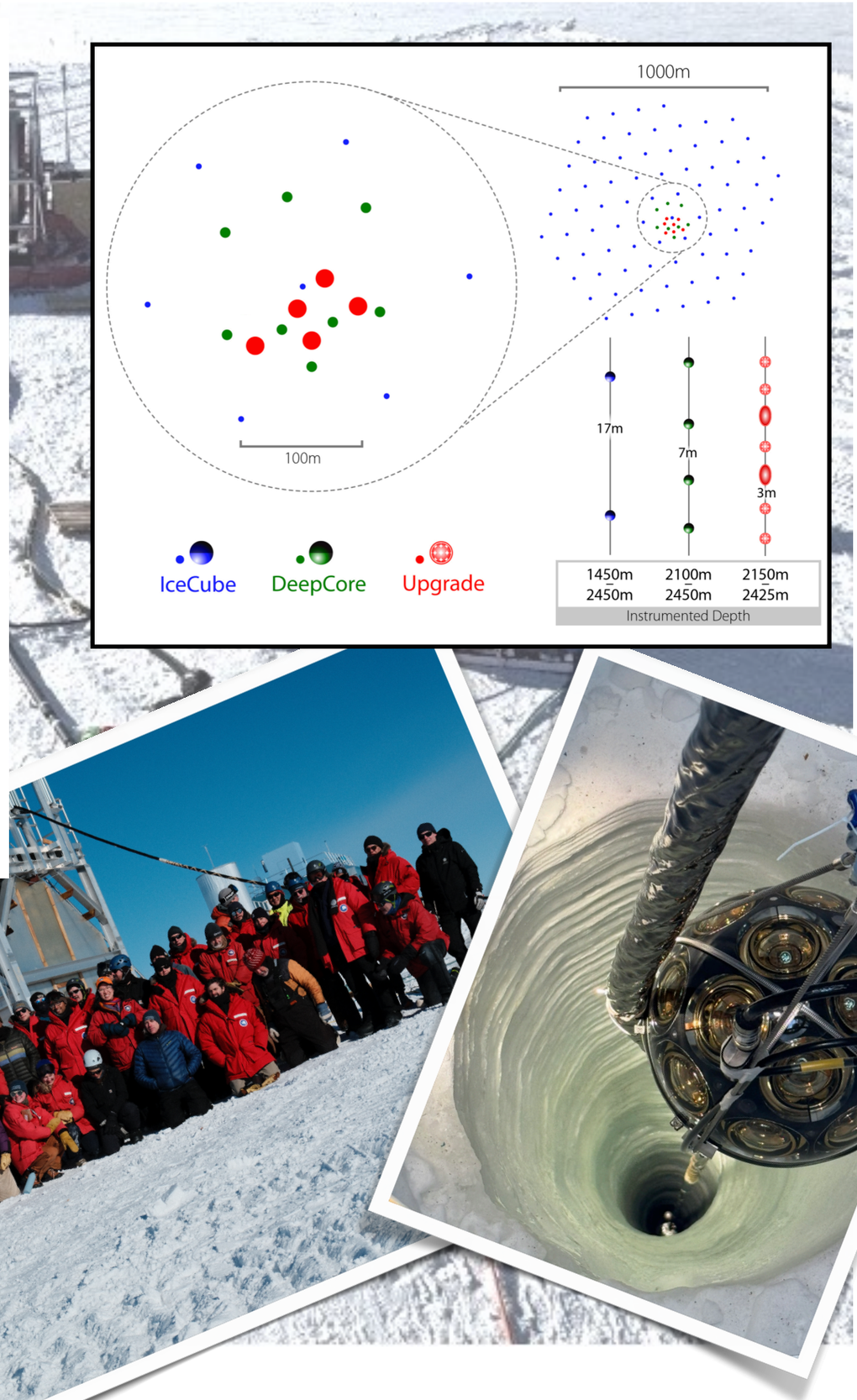
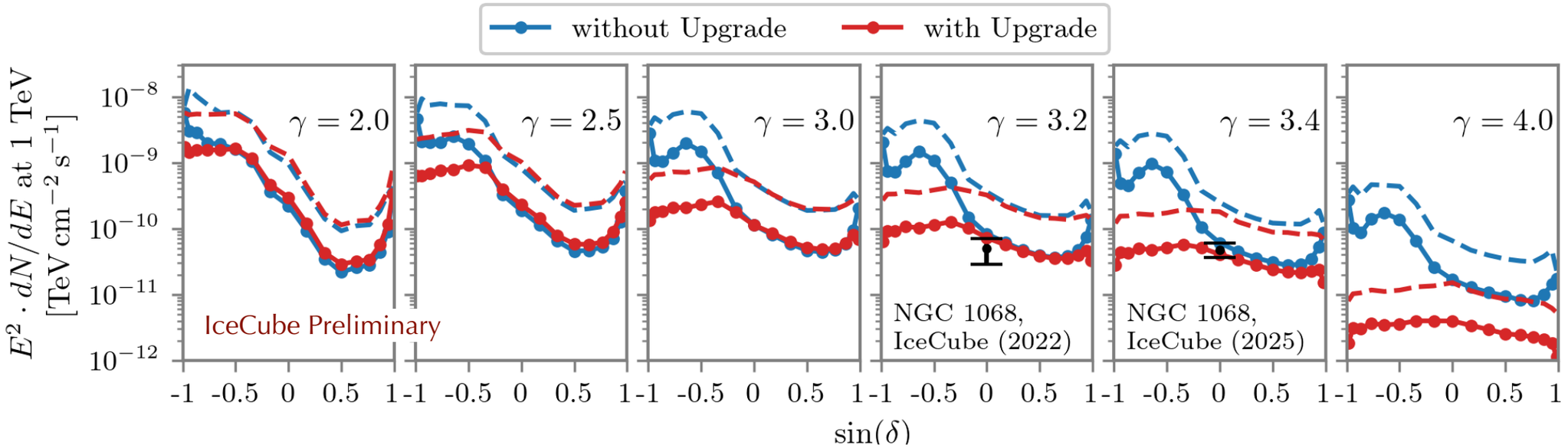


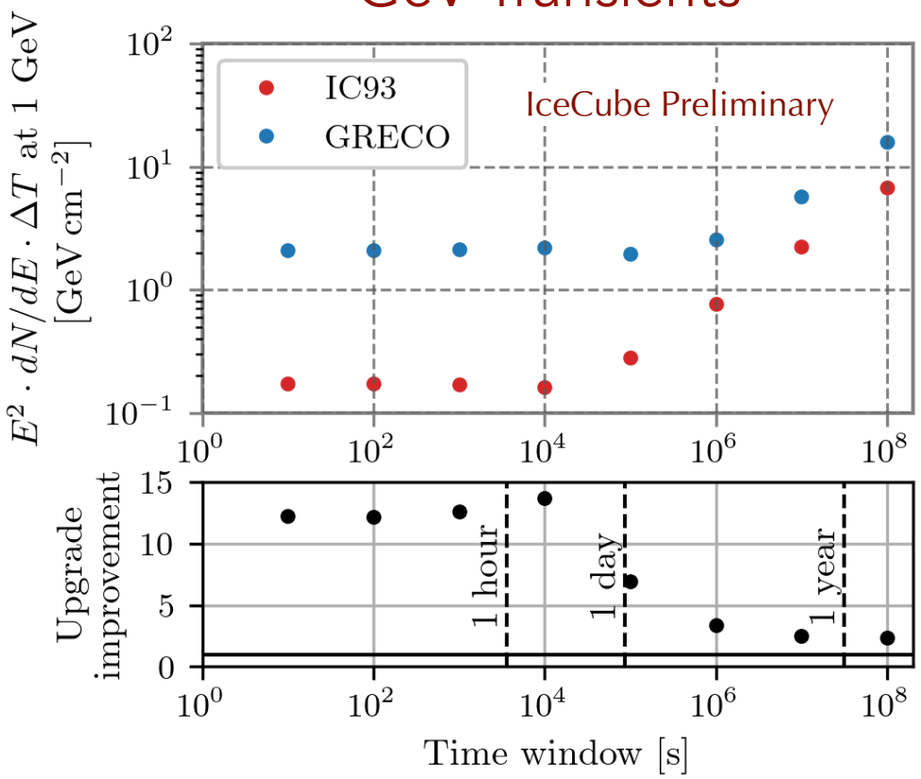
IceCube-Upgrade

- Expected improvements for astrophysical searches

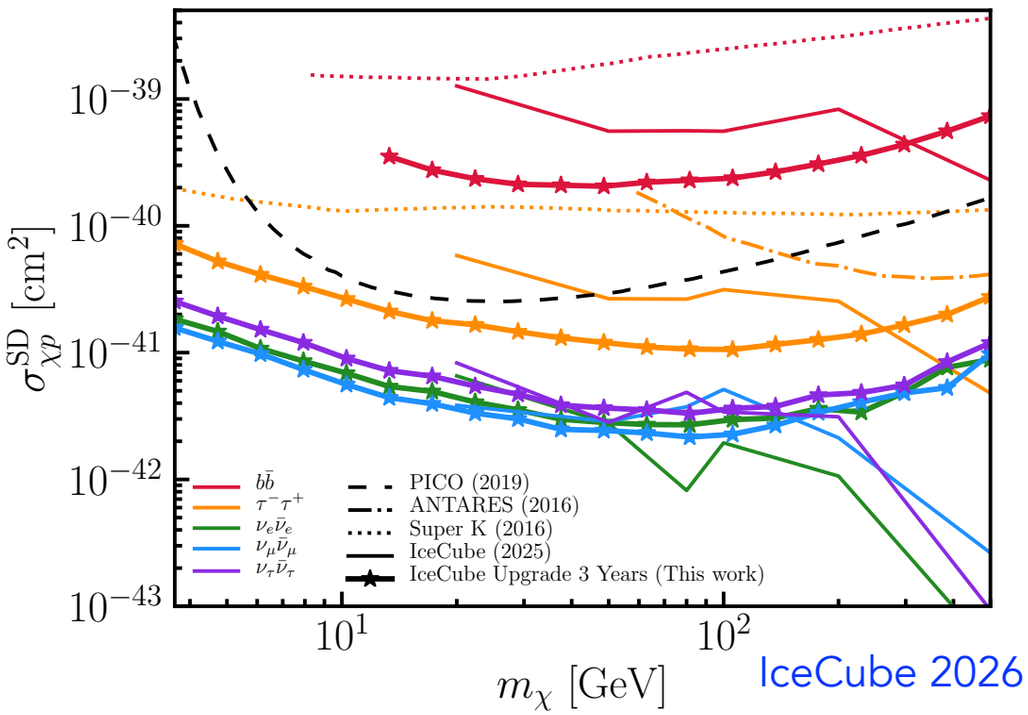
- Neutrino Sources



- GeV Transients



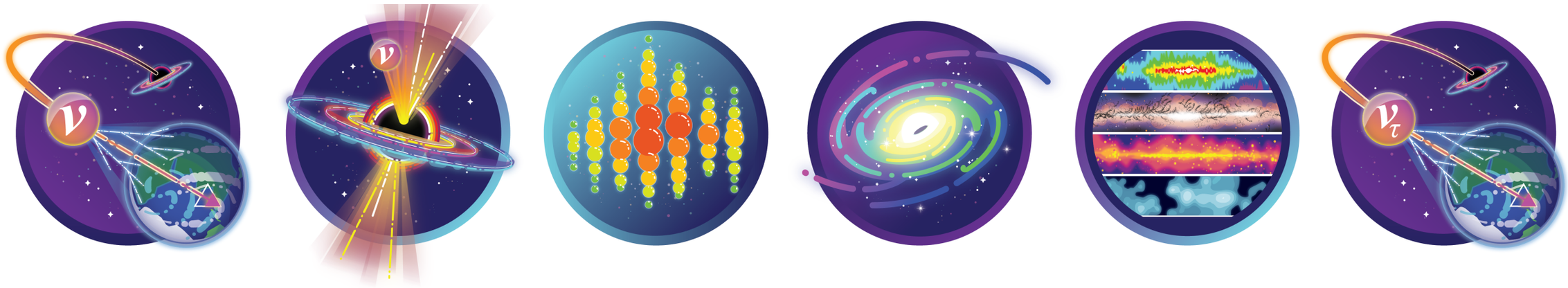
- WIMP



Summary & Outlook

- After a decade of observation, signs of anisotropy have emerged in IceCube data.
- Early indications points to obscured AGN as primary source of extragalactic high-energy cosmic neutrino flux.
- Evidence for features in the cosmic neutrino spectrum brings information about their nature and production mechanism.
- Observation of neutrinos from the Milky Way shows hadronic origin of γ-ray emission and offers new multimessenger opportunities at TeV energies.
- Identifying of the origin of HE cosmic neutrinos provides new opportunities in understanding dark matter and physics beyond the Standard Model.
- IceCube-Upgrade is complete and offers a better systematics for the detector.

A Decade of HE Neutrino Astrophysics with IceCube



2013
ASTROPHYSICAL NEUTRINOS
DISCOVERED

2018
BLAZAR TXS 0506+056
NEUTRINO EMISSION IDENTIFIED

2021
GLASHOW RESONANCE
NEUTRINO IDENTIFIED

2022
ACTIVE GALAXY NGC 1068
NEUTRINO EMISSION IDENTIFIED

2023
MILKY WAY
NEUTRINO EMISSION IDENTIFIED

2024
ASTROPHYSICAL TAU NEUTRINOS
IDENTIFIED

The IceCube Collaboration

Uppsala University, May 2025

Thanks!

Back up Slides

THE ICECUBE COLLABORATION

AUSTRALIA
University of Adelaide

BELGIUM
UCLouvain
Université libre de Bruxelles
Universiteit Gent
Vrije Universiteit Brussel

CANADA
Queen's University
Simon Fraser University
University of Alberta–Edmonton

DENMARK
University of Copenhagen

GERMANY
Deutsches Elektronen-Synchrotron
ECAP, Universität Erlangen-Nürnberg
Humboldt–Universität zu Berlin
Karlsruhe Institute of Technology
Ruhr-Universität Bochum
RWTH Aachen University
Technische Universität Dortmund
Technische Universität München
Universität Mainz
Universität Münster
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ITALY
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University of Canterbury

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Pennsylvania State University
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University of Maryland
University of Nevada, Las Vegas
University of Rochester
University of Utah
University of Wisconsin–Madison
University of Wisconsin–River Falls
Yale University

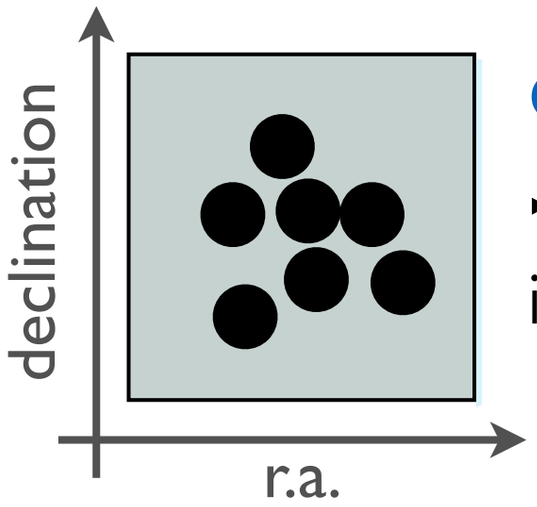
FUNDING AGENCIES

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education and Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Japan Society for the Promotion of Science (JSPS)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

IceCube Neutrino Observatory

icecube.wisc.edu

Point Source Searches

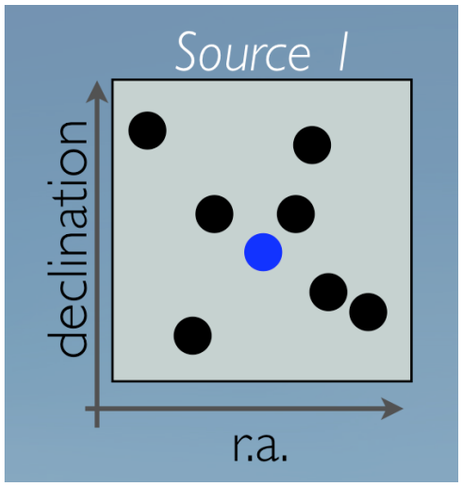


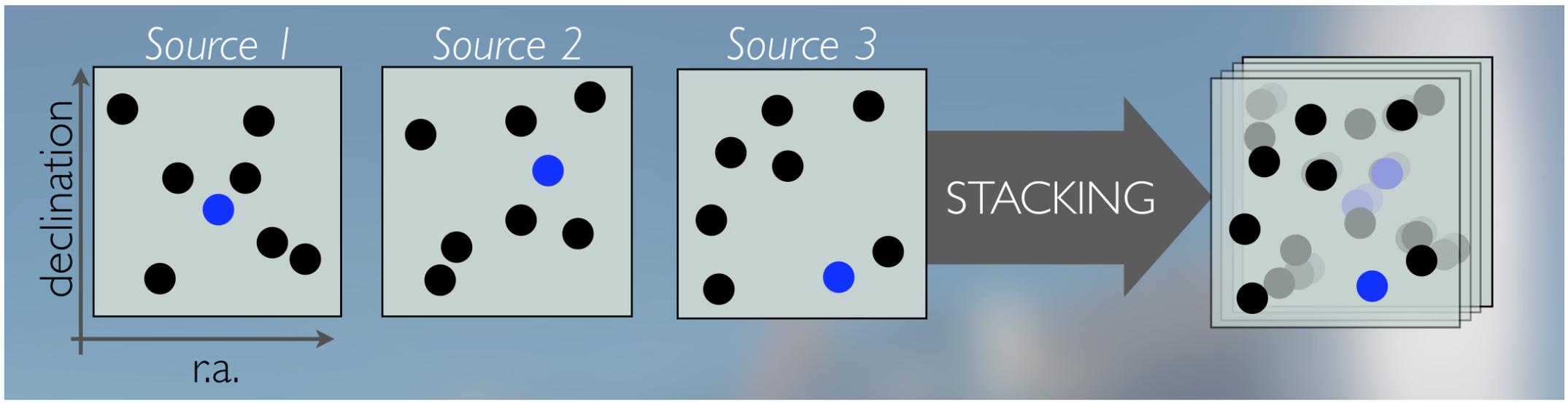
clustering

- Untriggered search in space & time

source search

- Triggered search for pre-identified locations



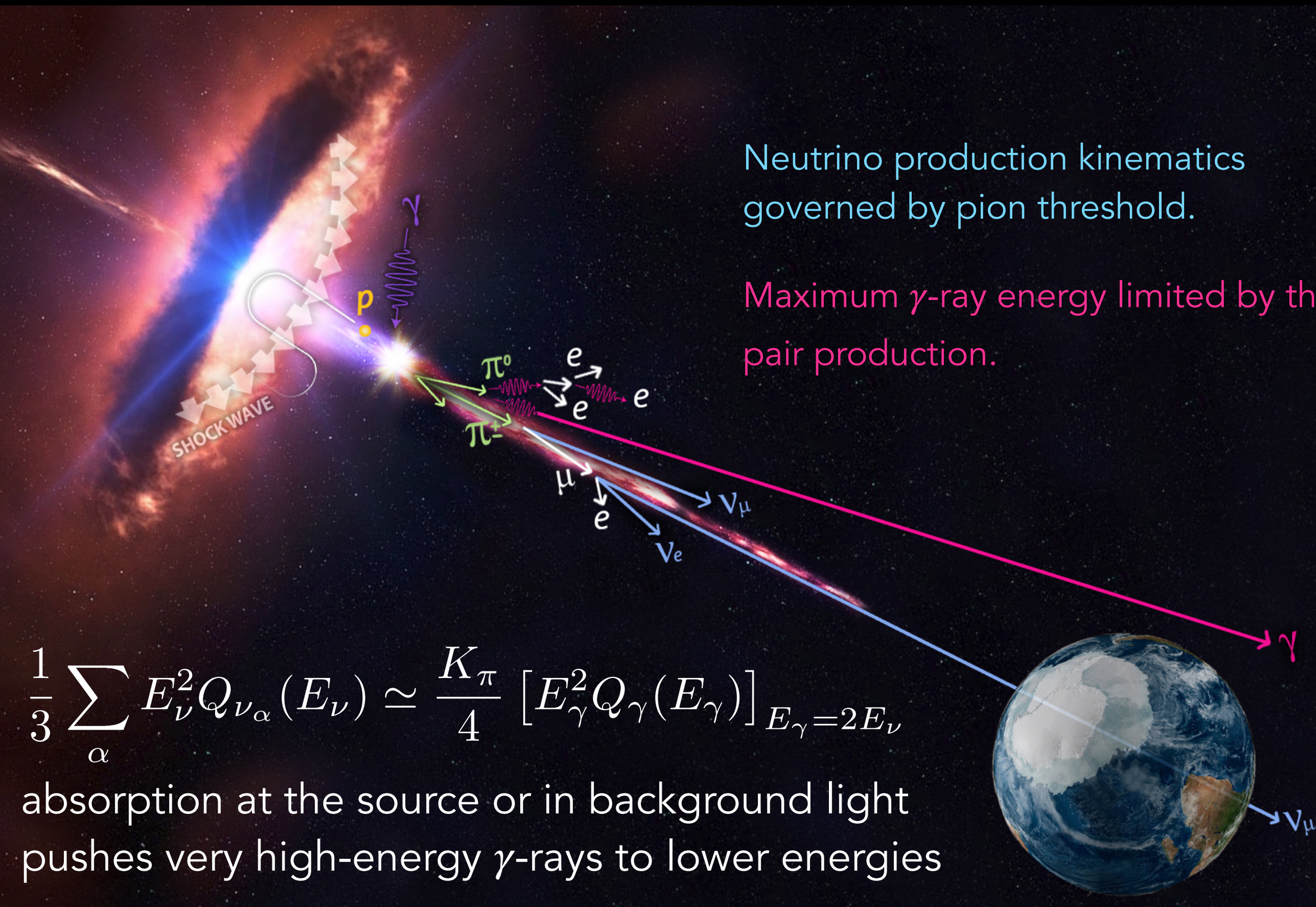


Stacking Search

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

+ 🚨 Realtime analysis and Neutrino alerts!

The Neutrino γ-ray Connection



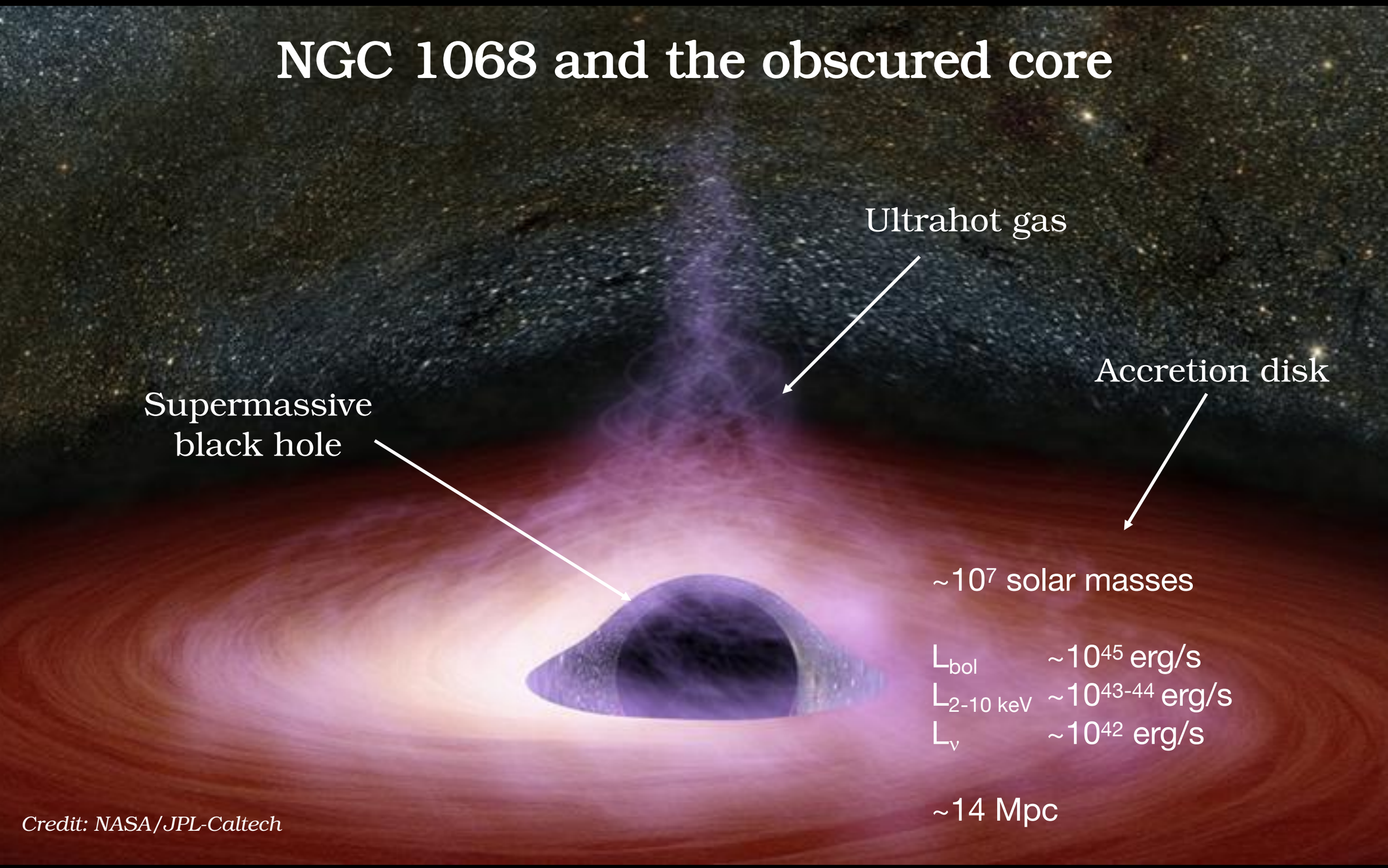
Neutrino production kinematics governed by pion threshold.

Maximum γ-ray energy limited by the pair production.

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

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

NGC 1068 and the obscured core



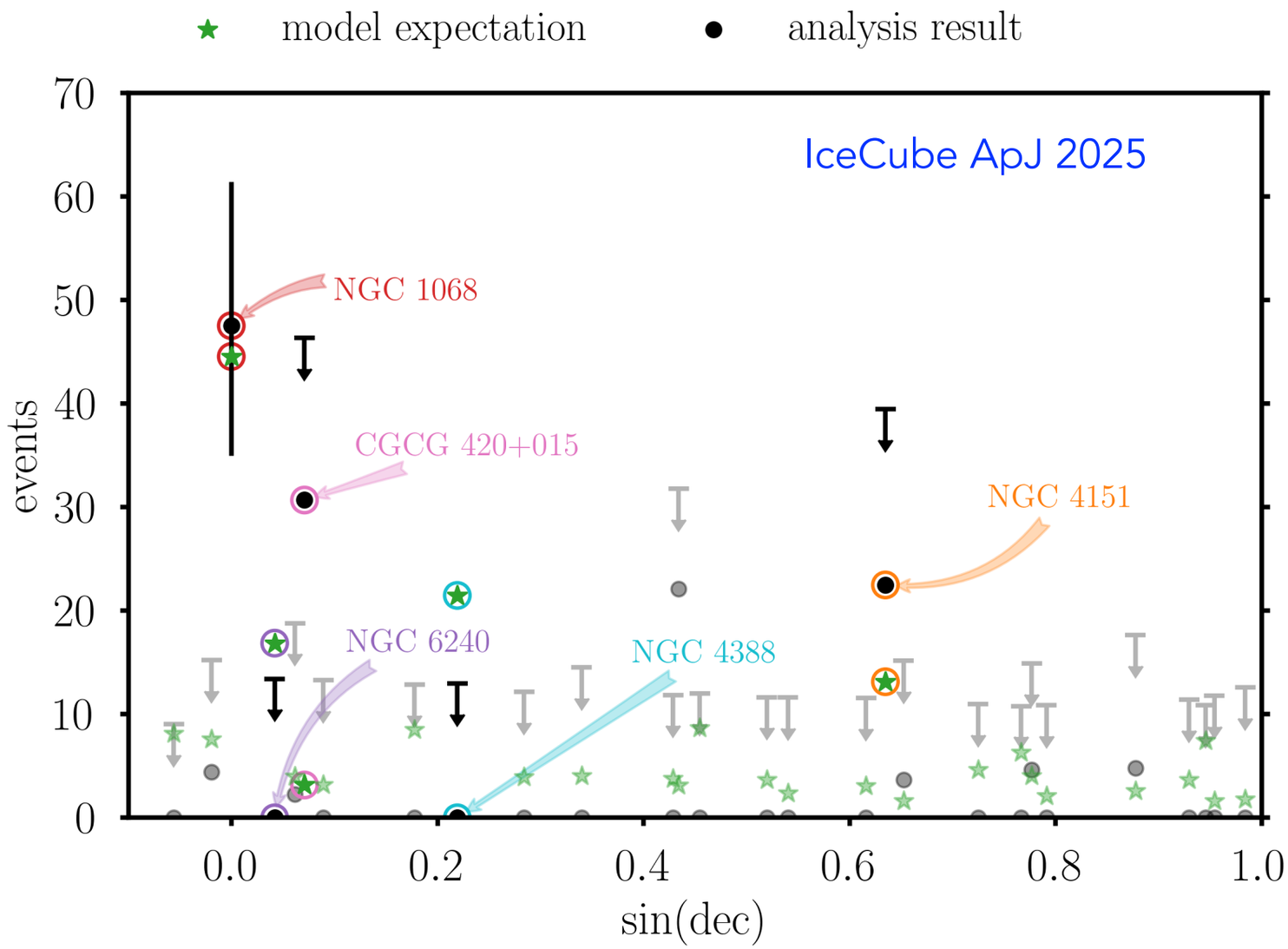
Credit: NASA/JPL-Caltech

Northern Seyferts Results

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

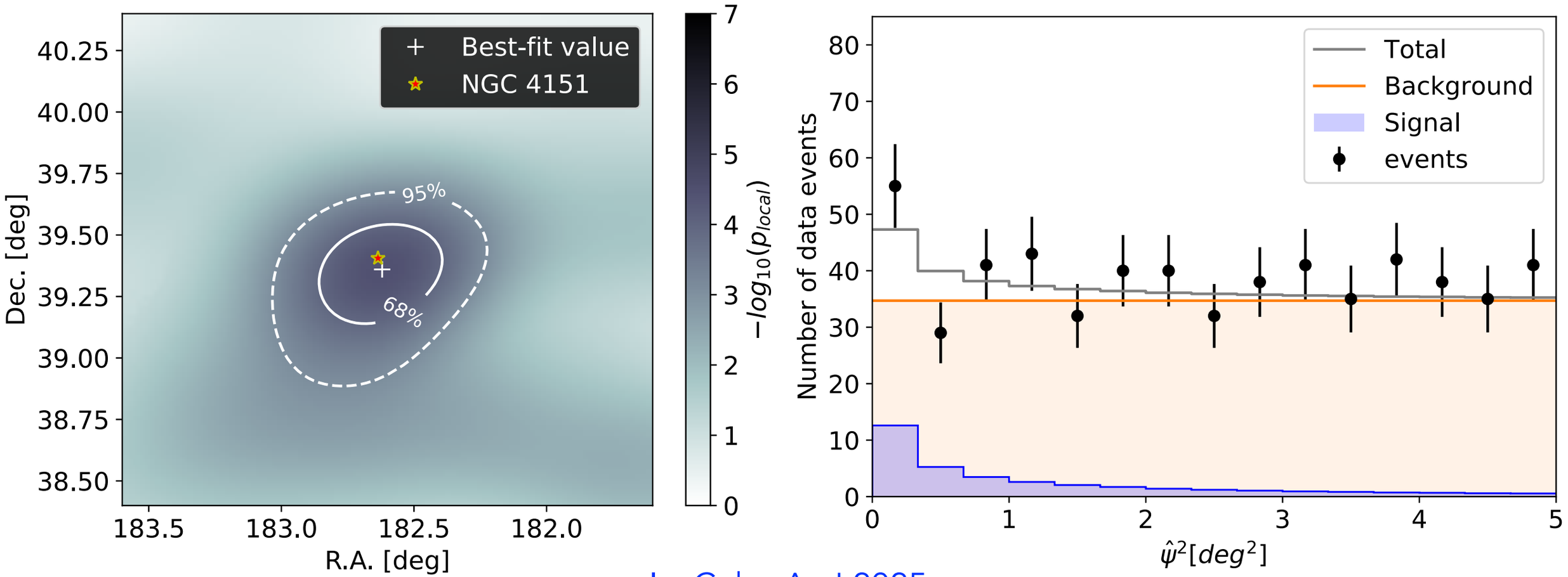
NOTE—Results for the stacking search and selected results from two catalog searches, Catalog Search 1: disk-corona model; and Catalog Search 2: power-law model. Best-fitted TS, $\hat{n}_s$, local (pre-trial) and global (post-trial) p-values, and corresponding significances are shown. For the disk-corona model analysis, expected numbers of events ($n_{\rm exp}$) are listed and for the power-law analysis, best-fitted spectral indices $\hat{\gamma}$ are listed. $n_{\rm UL}$ 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 $^{(*)}$ 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).

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 2.7σ *(Posterior p-value with NGC 1068 yields* 4σ*)*

NGC 4151



IceCube ApJ 2025

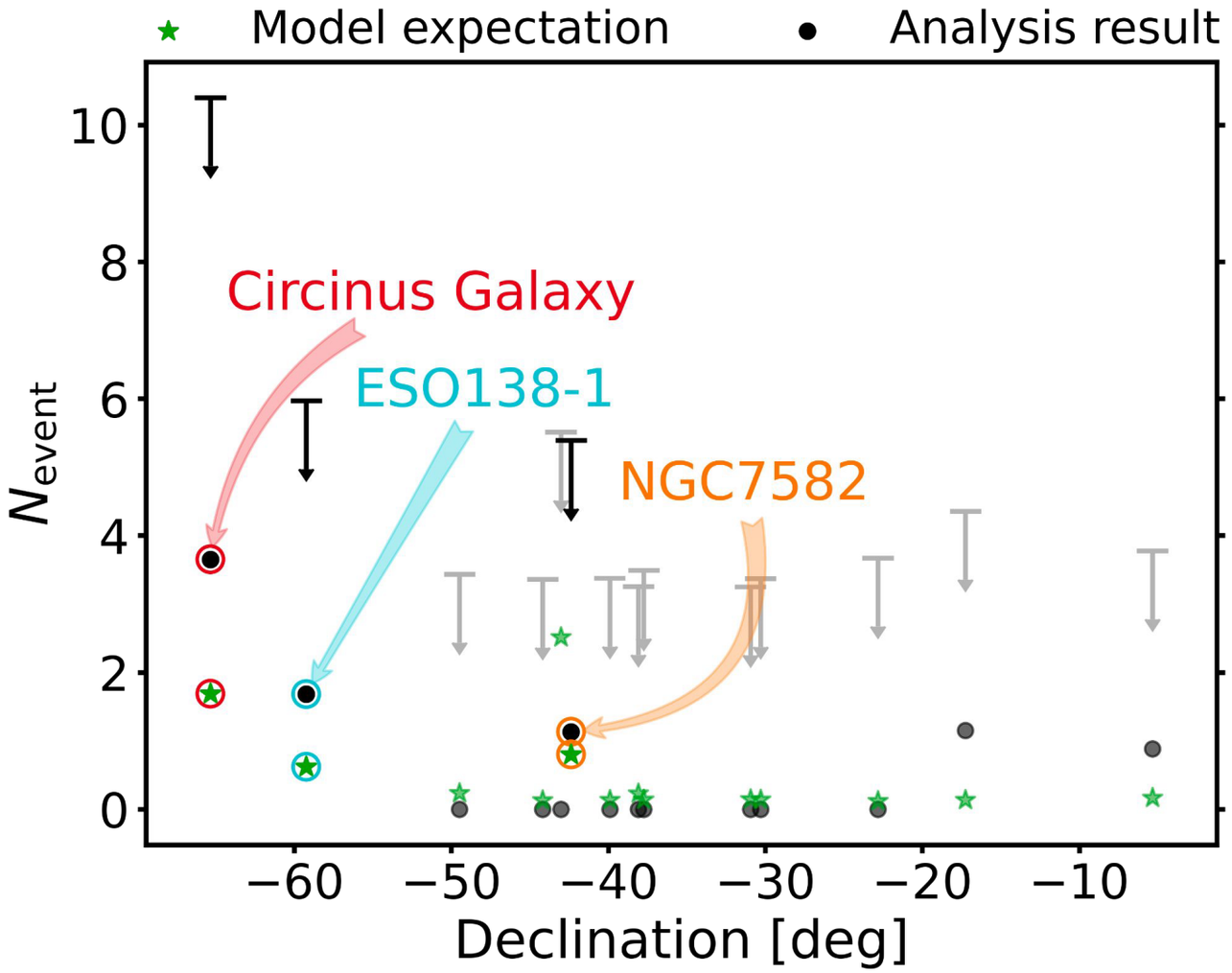
- NGC 4151 appears at 2.9σ (global significance)
- The second most significant steady source in IceCube

Neutrinos from Seyferts in 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 2.8σ local significance (1.8σ post trial)
- 2 additional sources with excess:
  - ESO 138-1
  - NGC 7582.

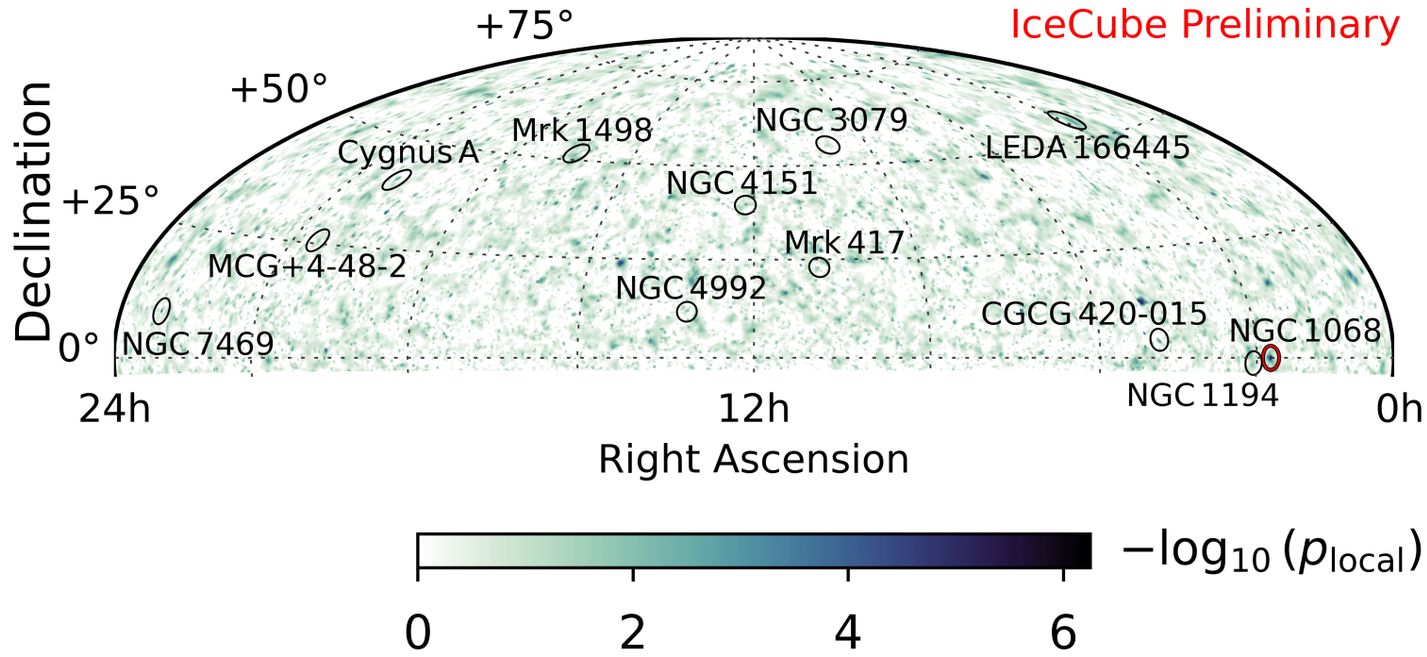
- Stacking analysis:
  - ► 6.7 events at 3σ

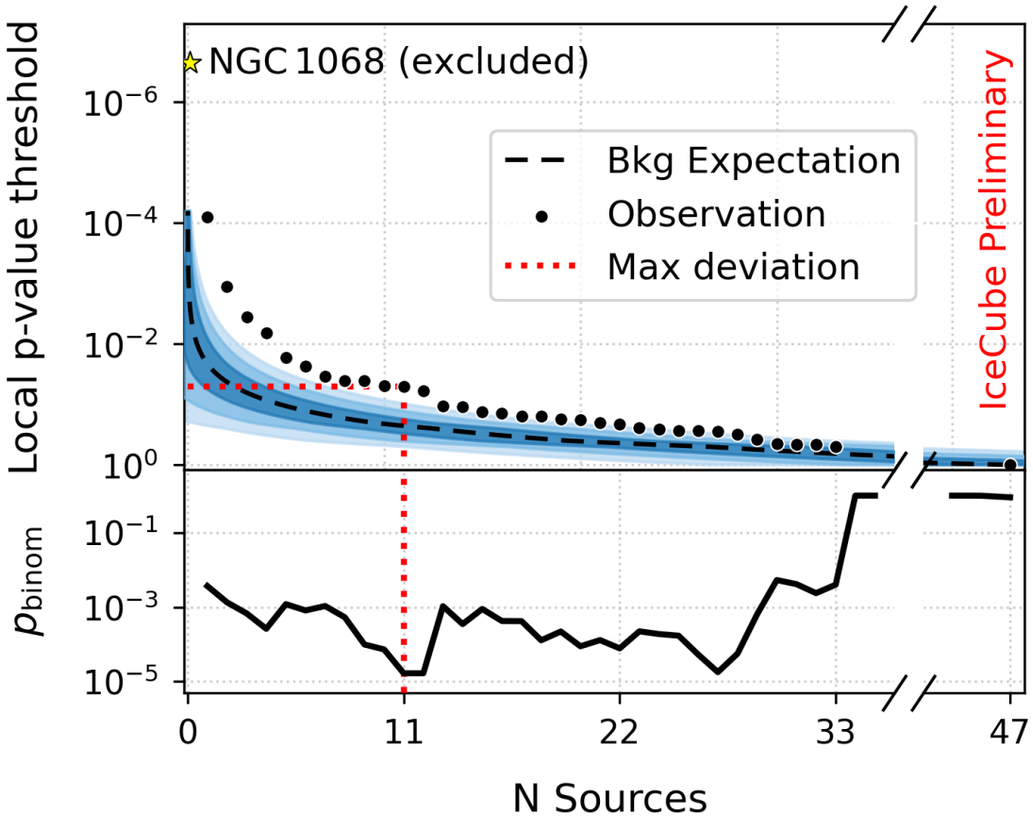


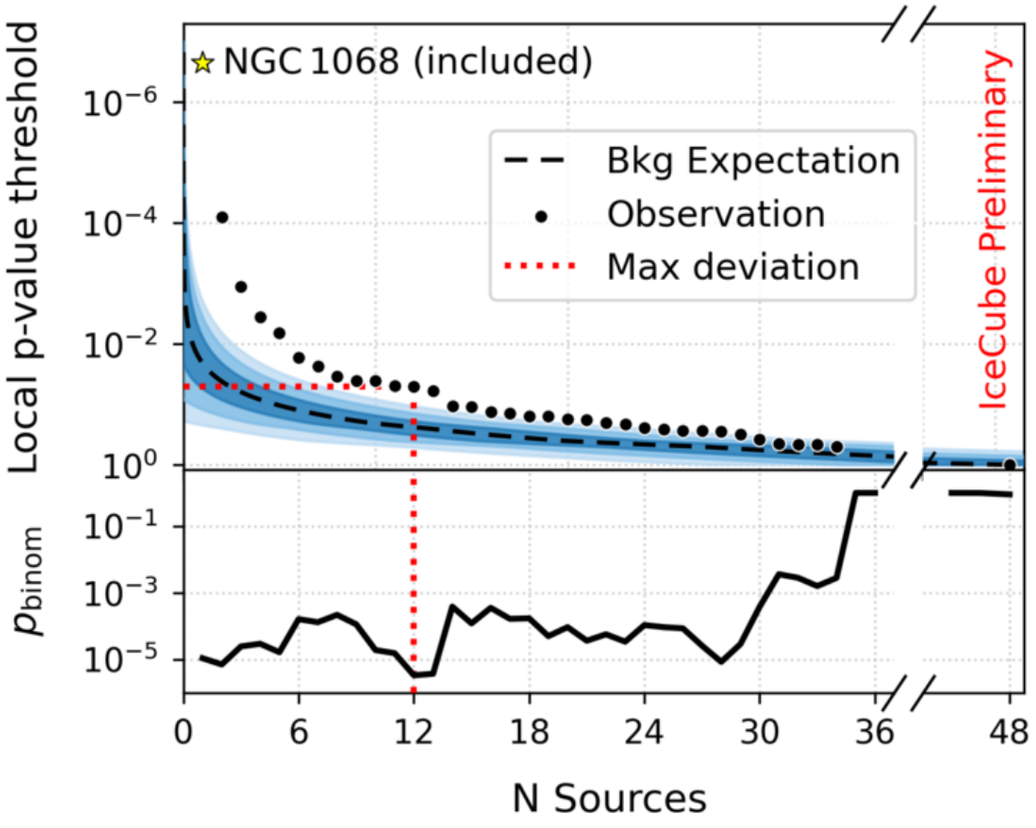
IceCube ApJL 2025

Extend Northern Sky Search

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



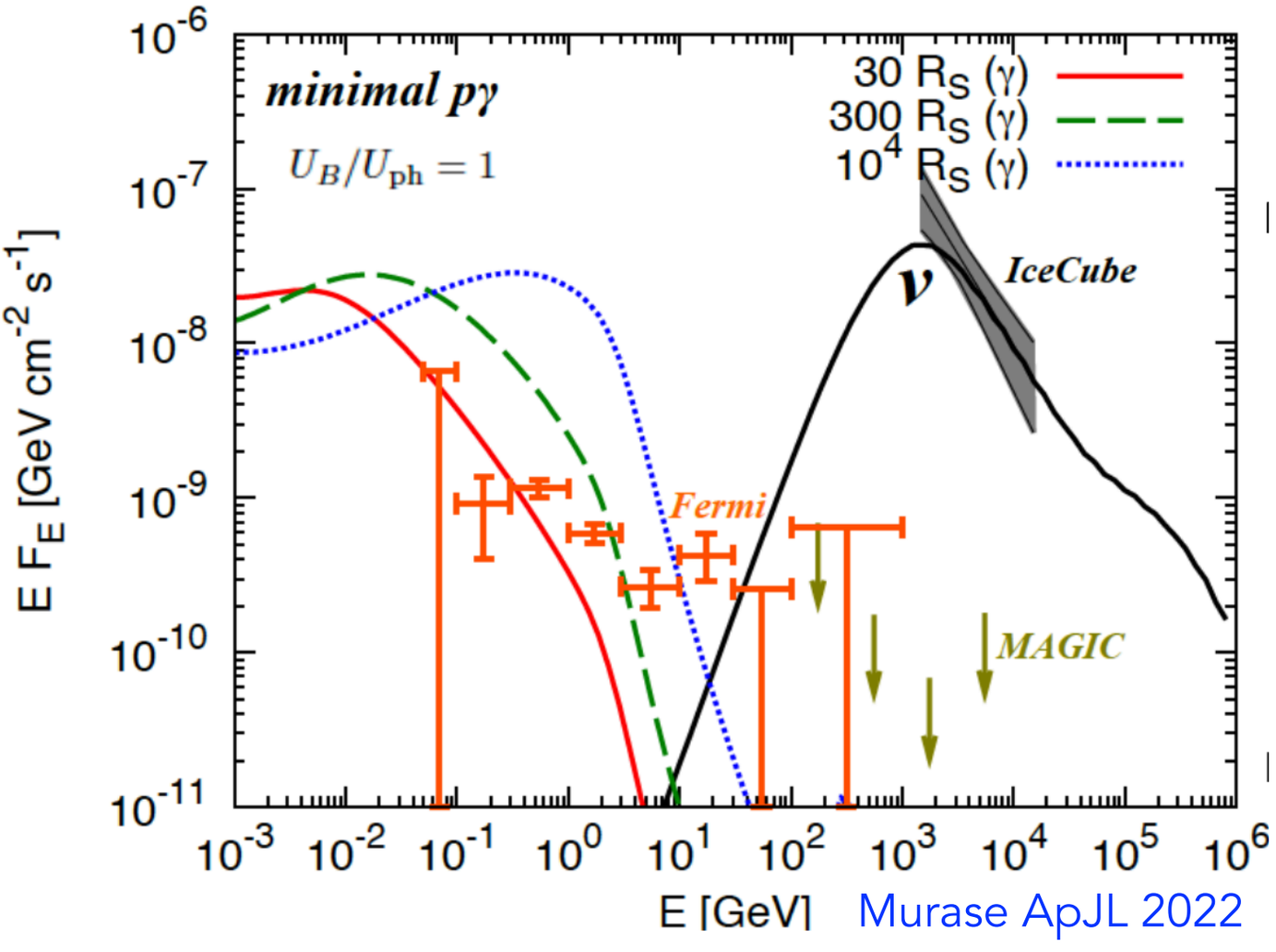




Hidden Cores of AGN

- Being **obscured** to GeV γ-rays restricts the size of emission region in AGN.
- For γ-rays in Fermi range, the optical depth is

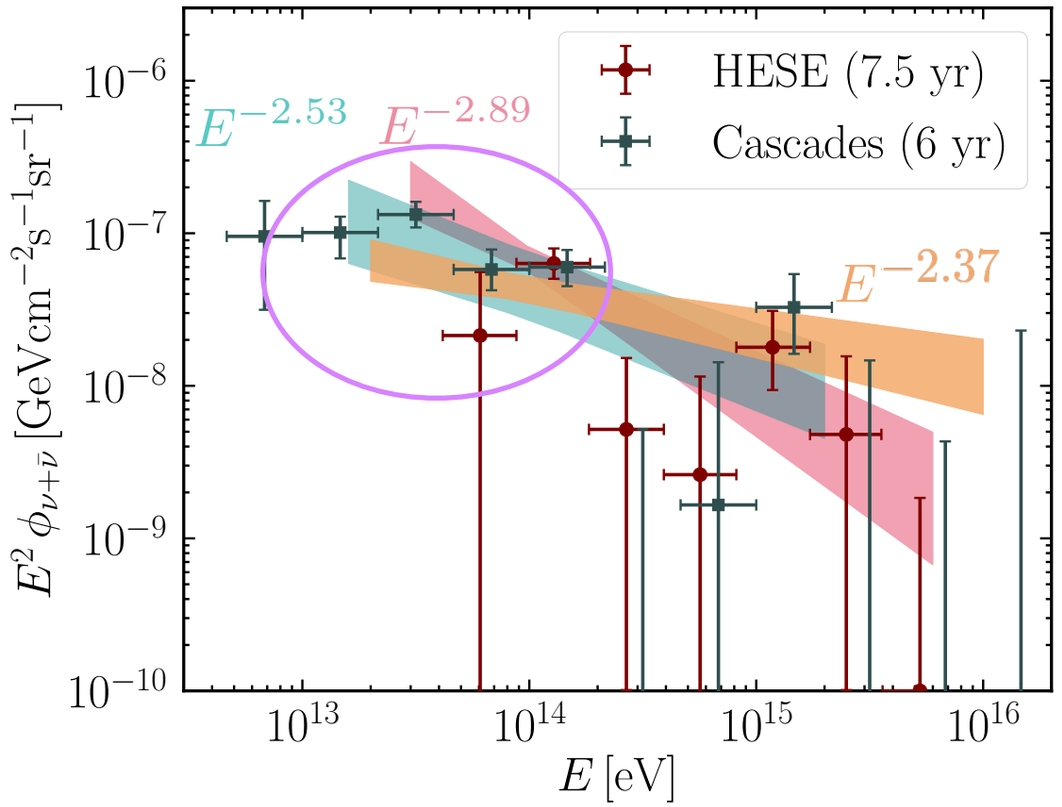
$$\tau_{\gamma\gamma} \sim \left(\frac{1}{4\pi}\right)\left(\frac{\sigma_{\gamma\gamma}}{R}\right)\left(\frac{L_X}{m_e c^3}\right)\left(\frac{\varepsilon_\gamma}{m_e c^2}\right) \gtrsim 10$$



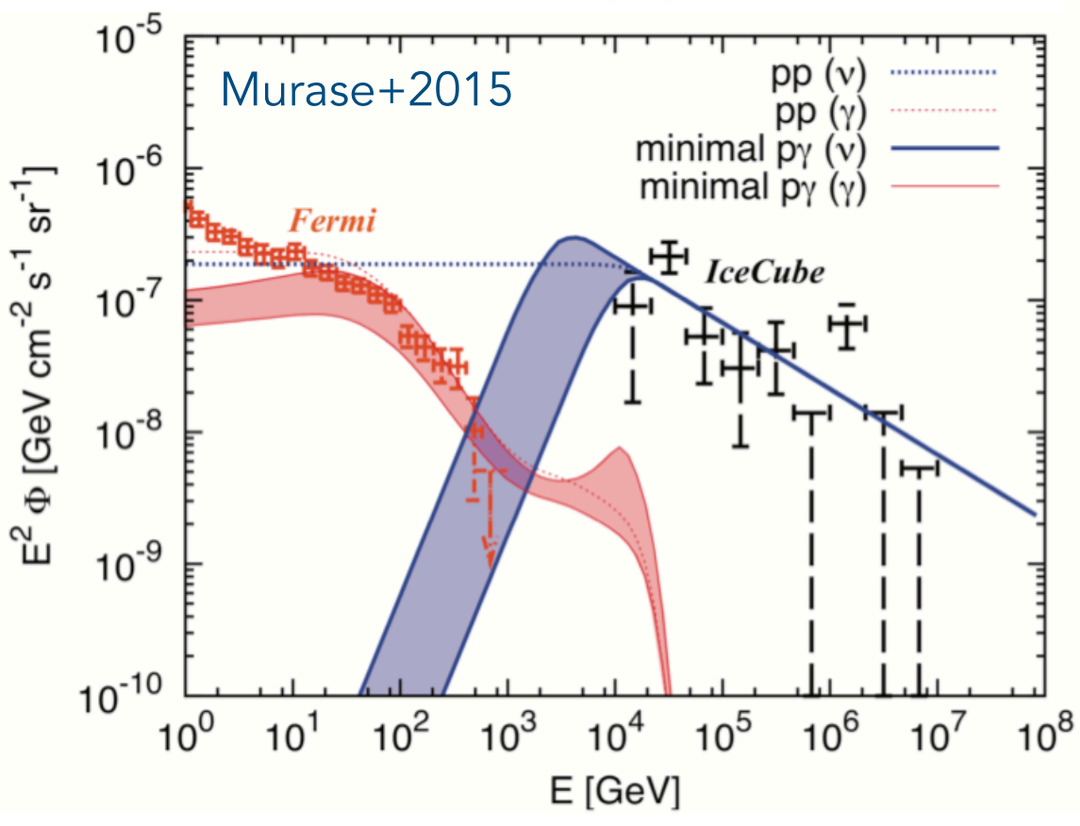
- Considering the EM Cascade:
  $R < (10\text{-}30)\ R_S$
- Efficient photohadronic neutrino production requires
  $R < (30\text{-}100)\ R_S$

Medium-Energy Excess in Neutrino Flux

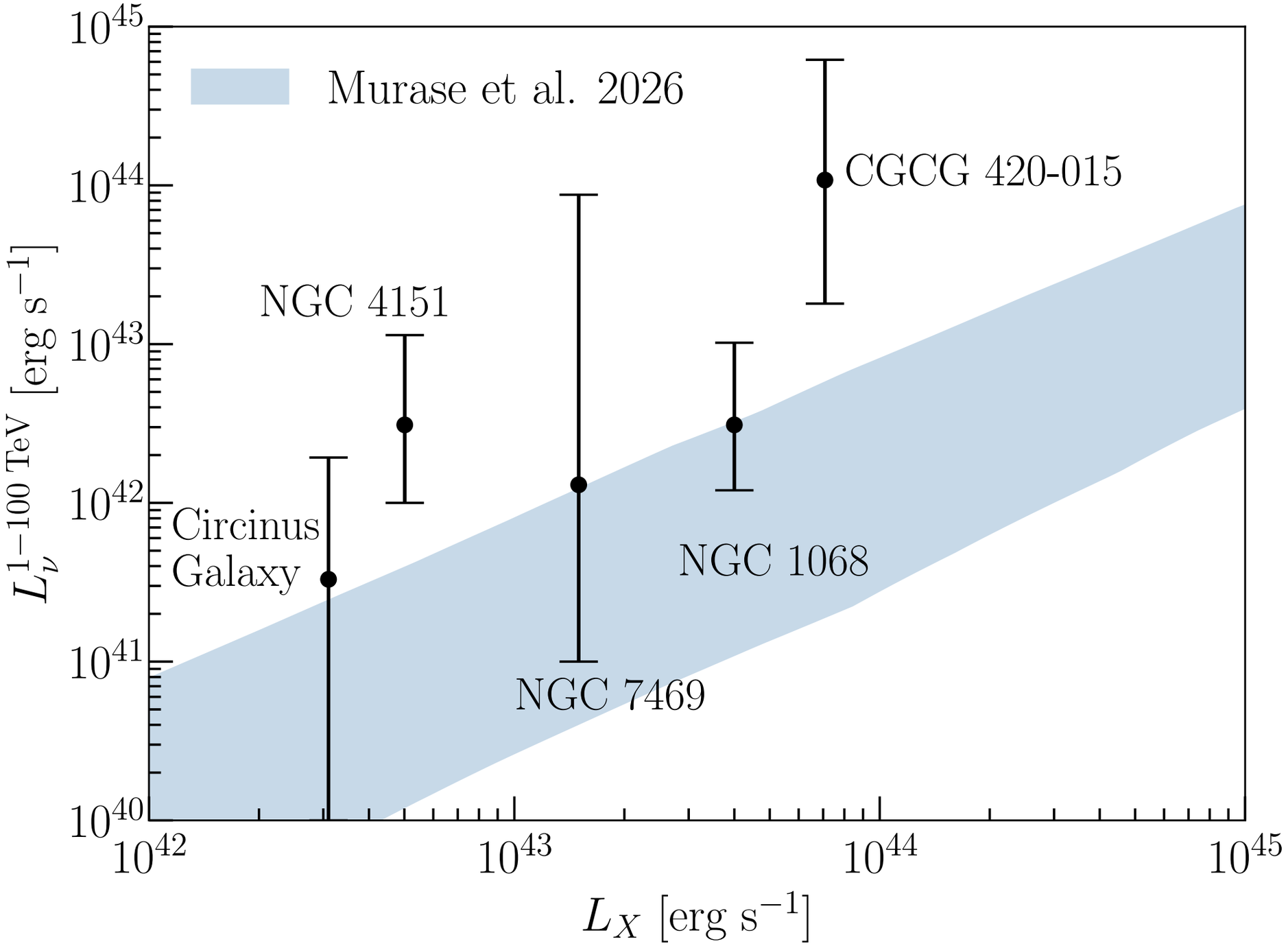
- Different slopes hint at structure in the flux of high-energy cosmic neutrinos.
- The magnitude of the flux at ~10 TeV energies is found to be higher than the flux at >100 TeV energies.



- Multimessenger connection dictates extragalactic sources of the high-energy neutrino flux at medium-energies to be **obscured** to GeV γ-rays. [Murase+ 2015, Fang+ 2022]
  - Core of AGN can meet these conditions.



Emerging X-ray – Neutrino Connection



Carpio, **AK**, Murase, 2026

The source of Galactic neutrinos?

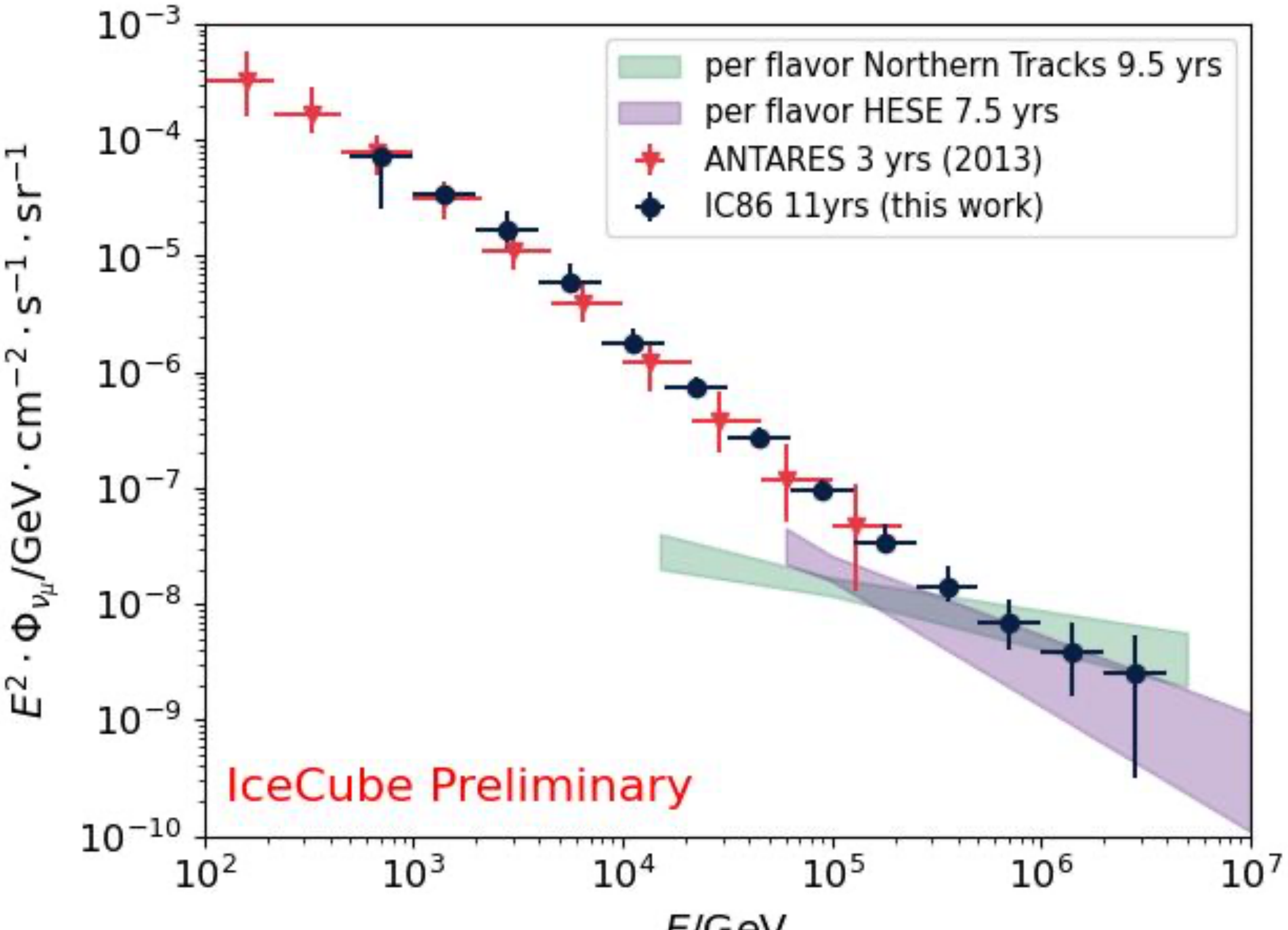
	Flux sensitivity Φ	*P* value	Best-fitting flux Φ
	Diffuse Galactic plane analysis		
π^0	5.98	1.26×10^{-6} (4.71σ)	$21.8^{+5.3}_{-4.9}$
KRA_γ^5	$0.16 \times$ MF	6.13×10^{-6} (4.37σ)	$0.55^{+0.18}_{-0.15} \times$ MF
KRA_γ^{50}	$0.11 \times$ MF	3.72×10^{-5} (3.96σ)	$0.37^{+0.13}_{-0.11} \times$ MF
	Catalog stacking analysis		
SNR		5.90×10^{-4} (3.24σ)*	
PWN		5.93×10^{-4} (3.24σ)*	
UNID		3.39×10^{-4} (3.40σ)*	

[IceCube, Science 2023]

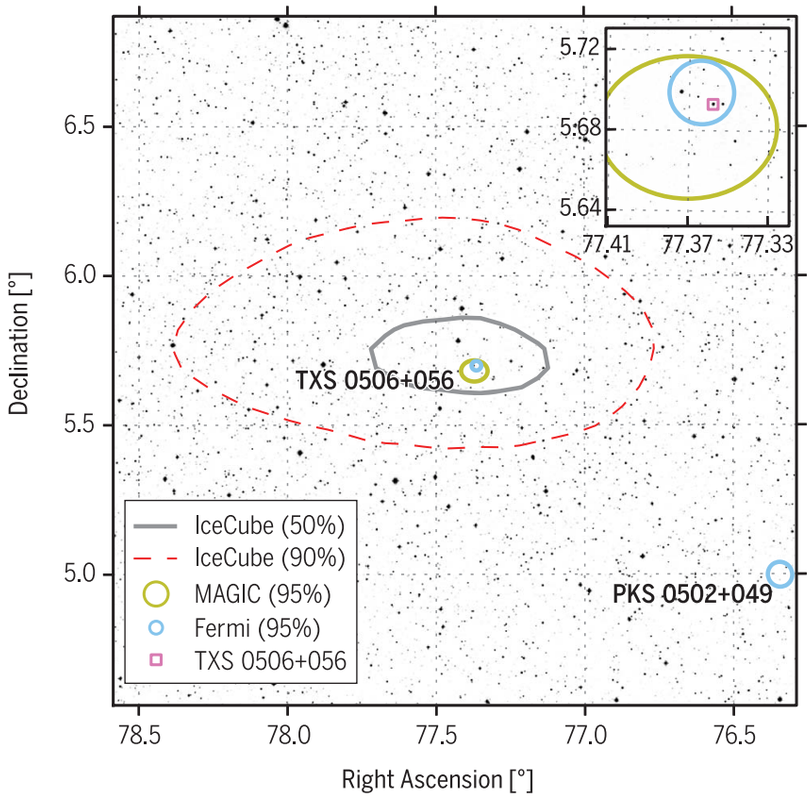
The nature of the Galactic HE neutrino emission is yet to be understood.

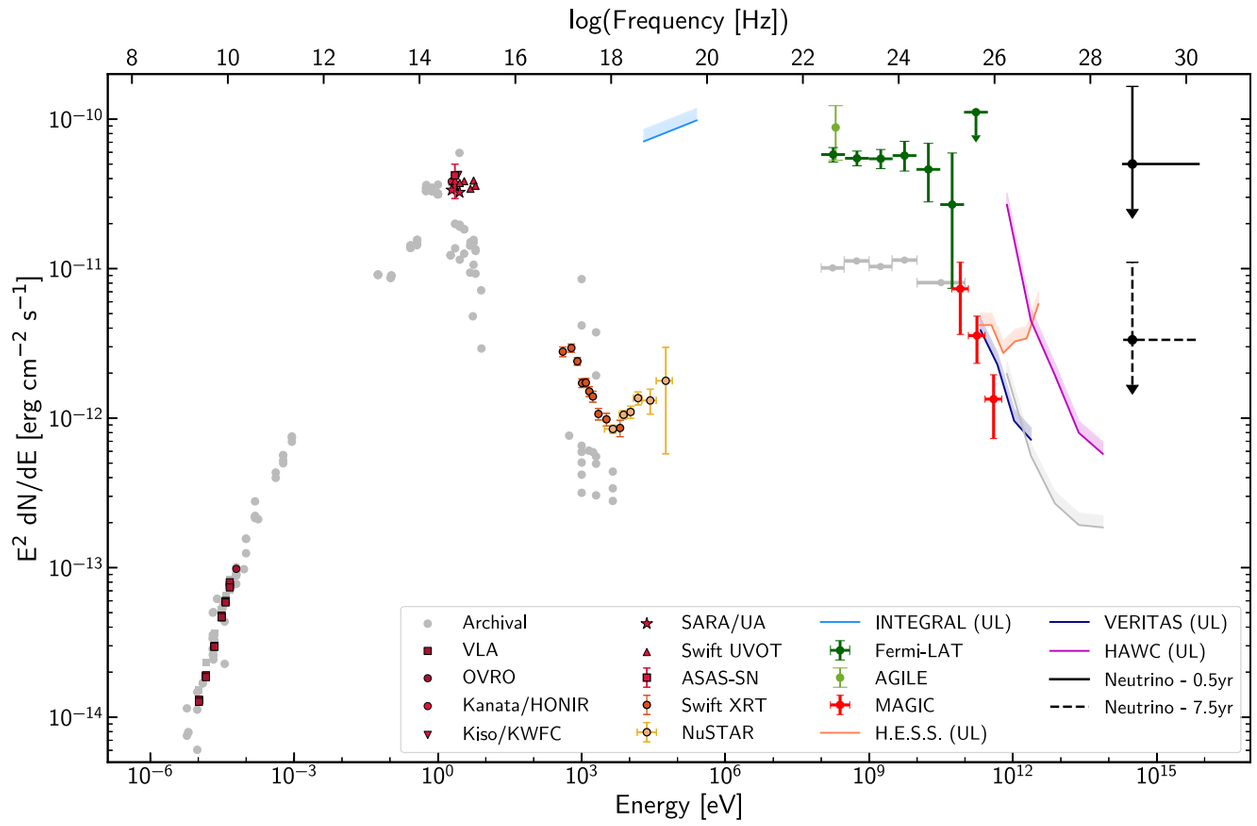
Catalog searches significance is consistent with the template searches.

Unfolded Muon Neutrino Flux



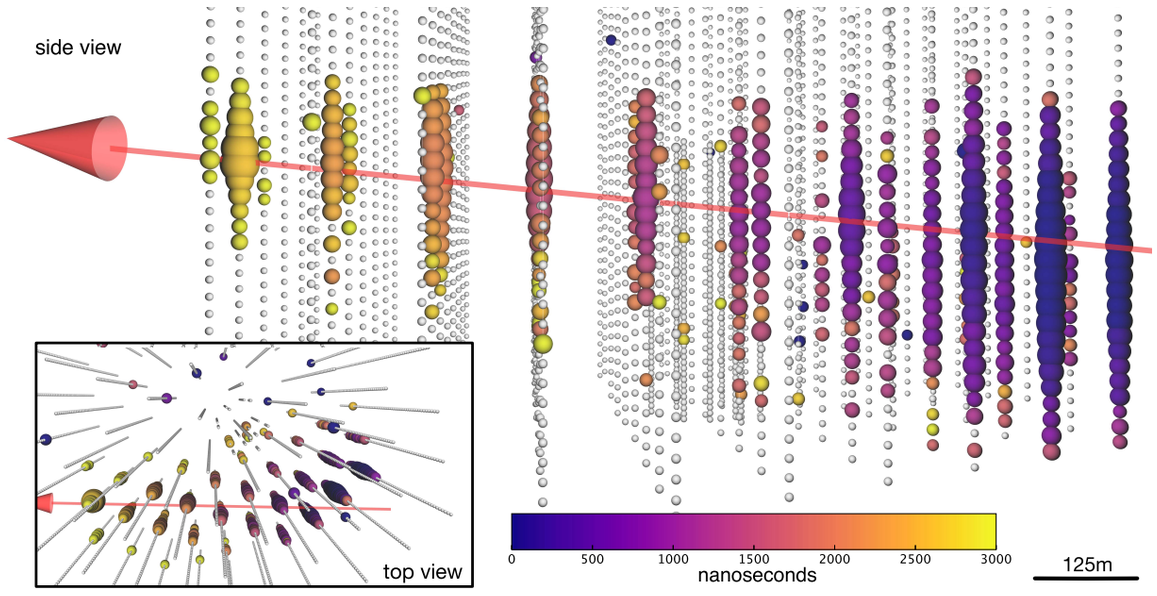
TXS 0506+056



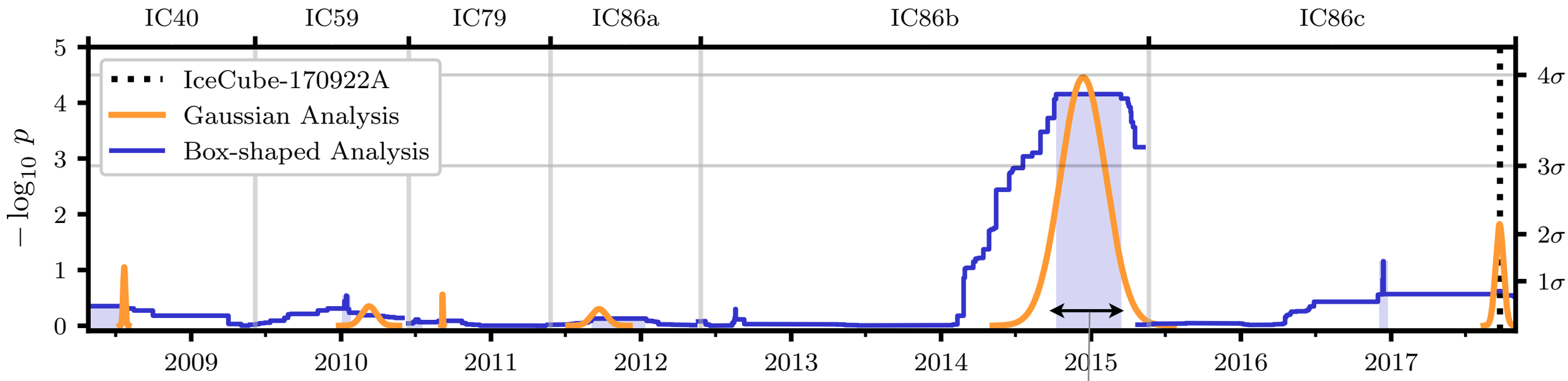


- Up-going track observed on September 22, 2017 from 5.7° below horizon with best fit neutrino energy of ~300 TeV for E^{-2} Spectrum.
- Coincidence with enhanced γ-ray activity, chance correlation rejected at the level of 3σ.

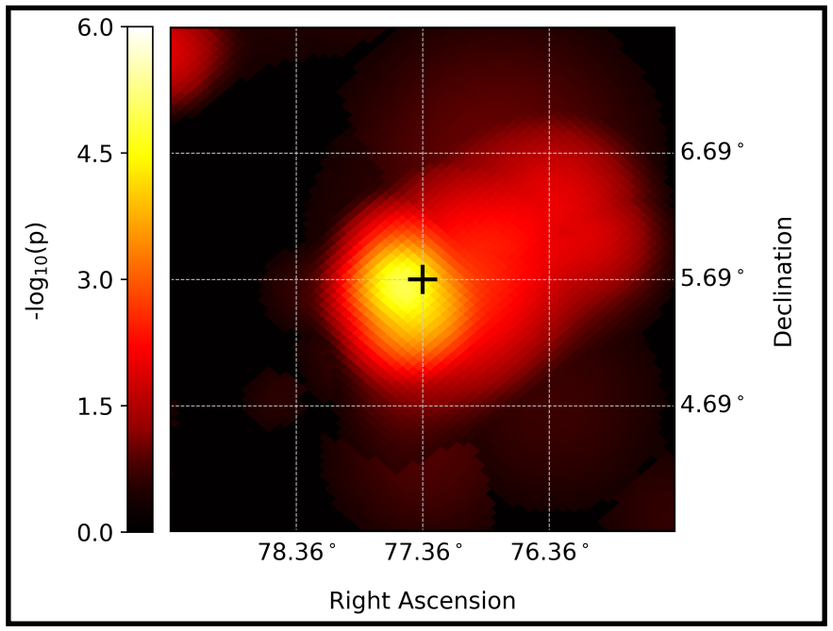
[IceCube+, Science 2018]



Neutrino Flare in 2014-15



[IceCube, Science 2018]

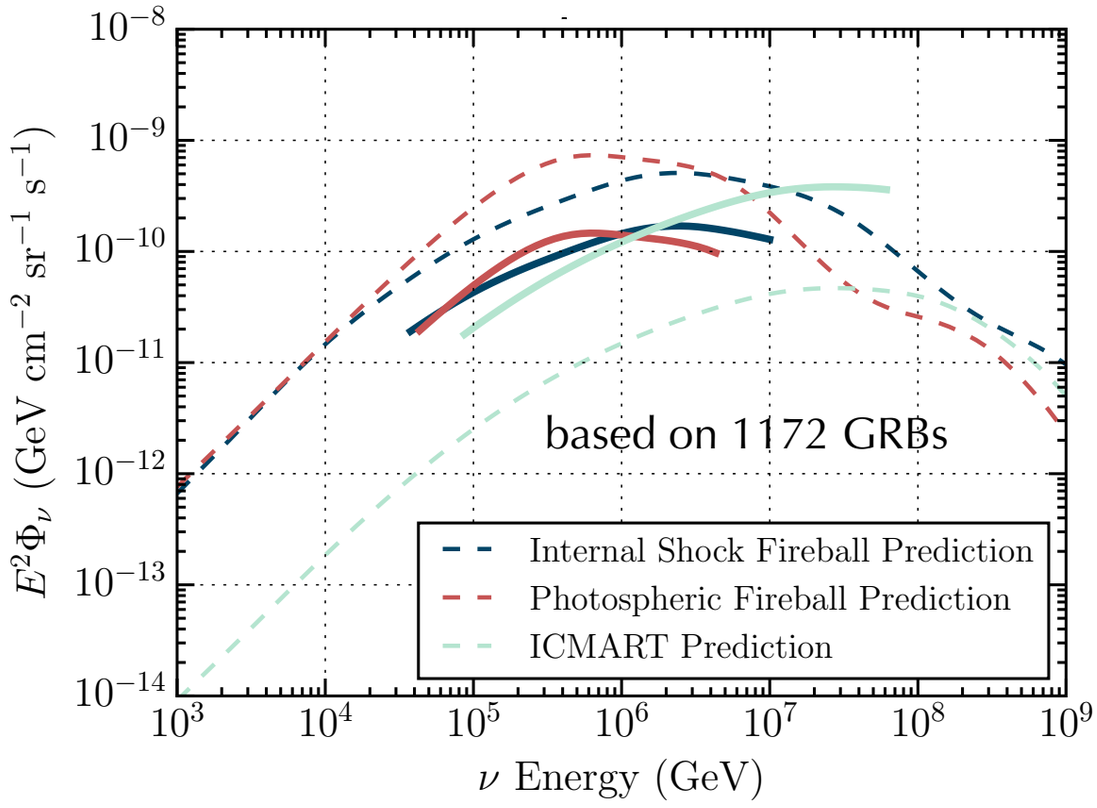


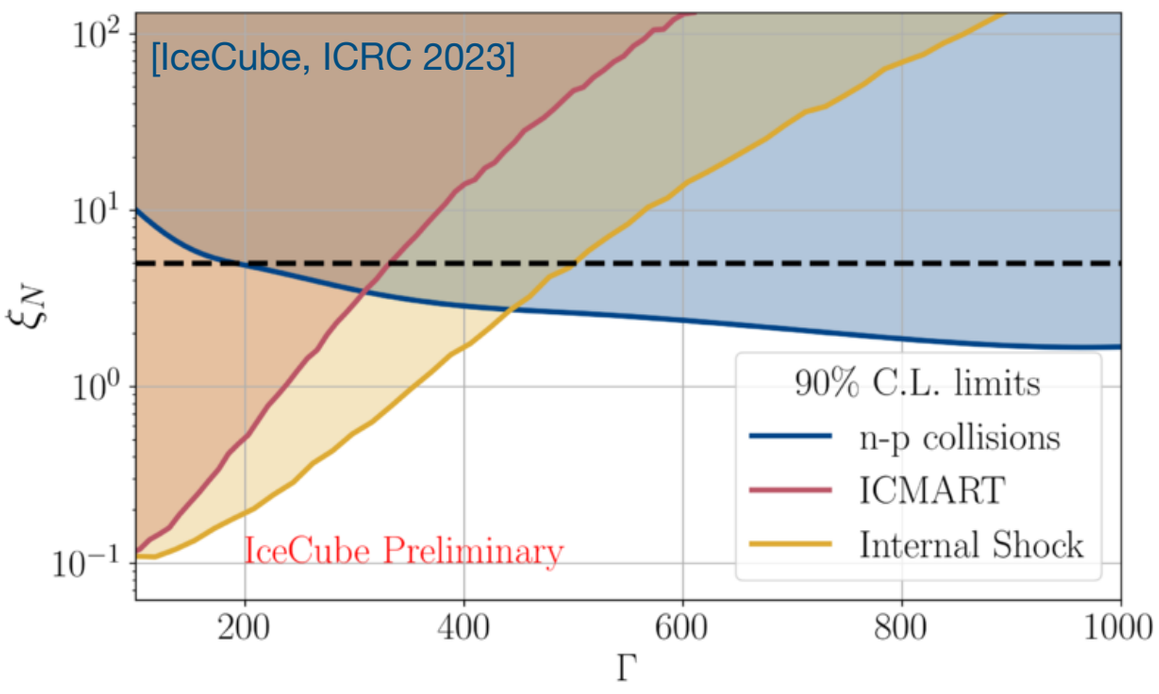
13±5 signal events rejecting background hypothesis at 3.5σ

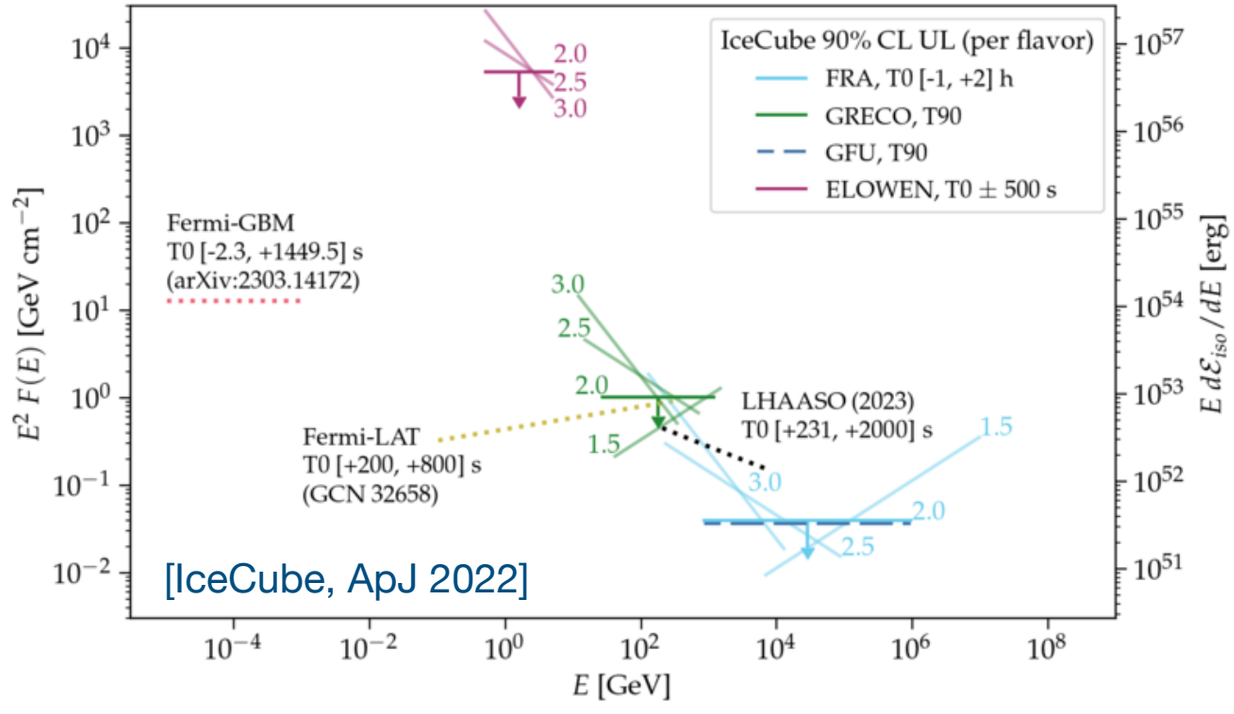
- Remains the most significant observed transient
- Not accompanied by a gamma-ray flare

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







IceCube-Gen2

Near 10 times larger, reaching to energies of EeV