Recent Point Source Results from IceCube and Their Implications for the Origin of High-Energy Neutrinos

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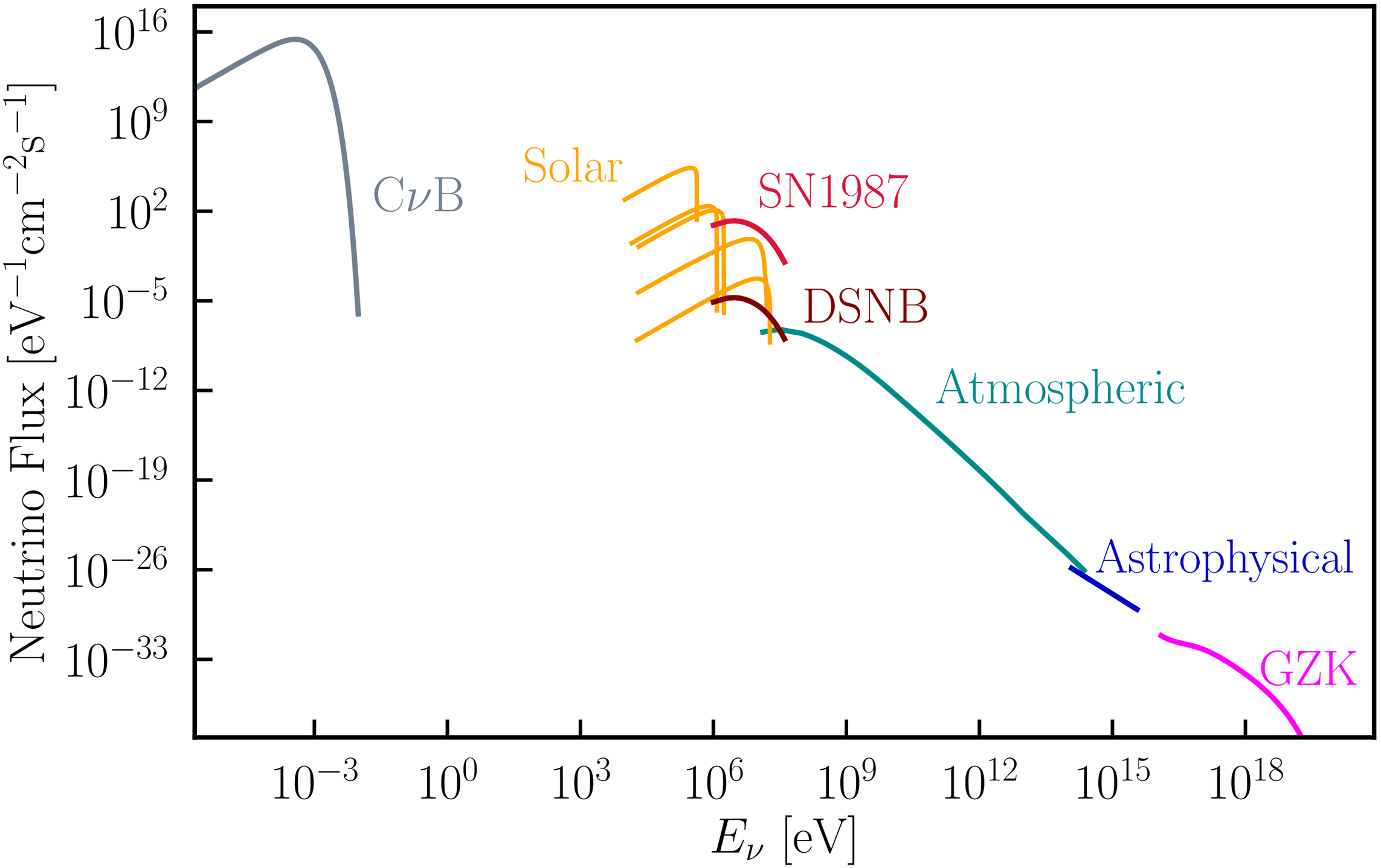
University of Wisconsin
May 2025

UNLV

NCfA

The Universe in Neutrinos



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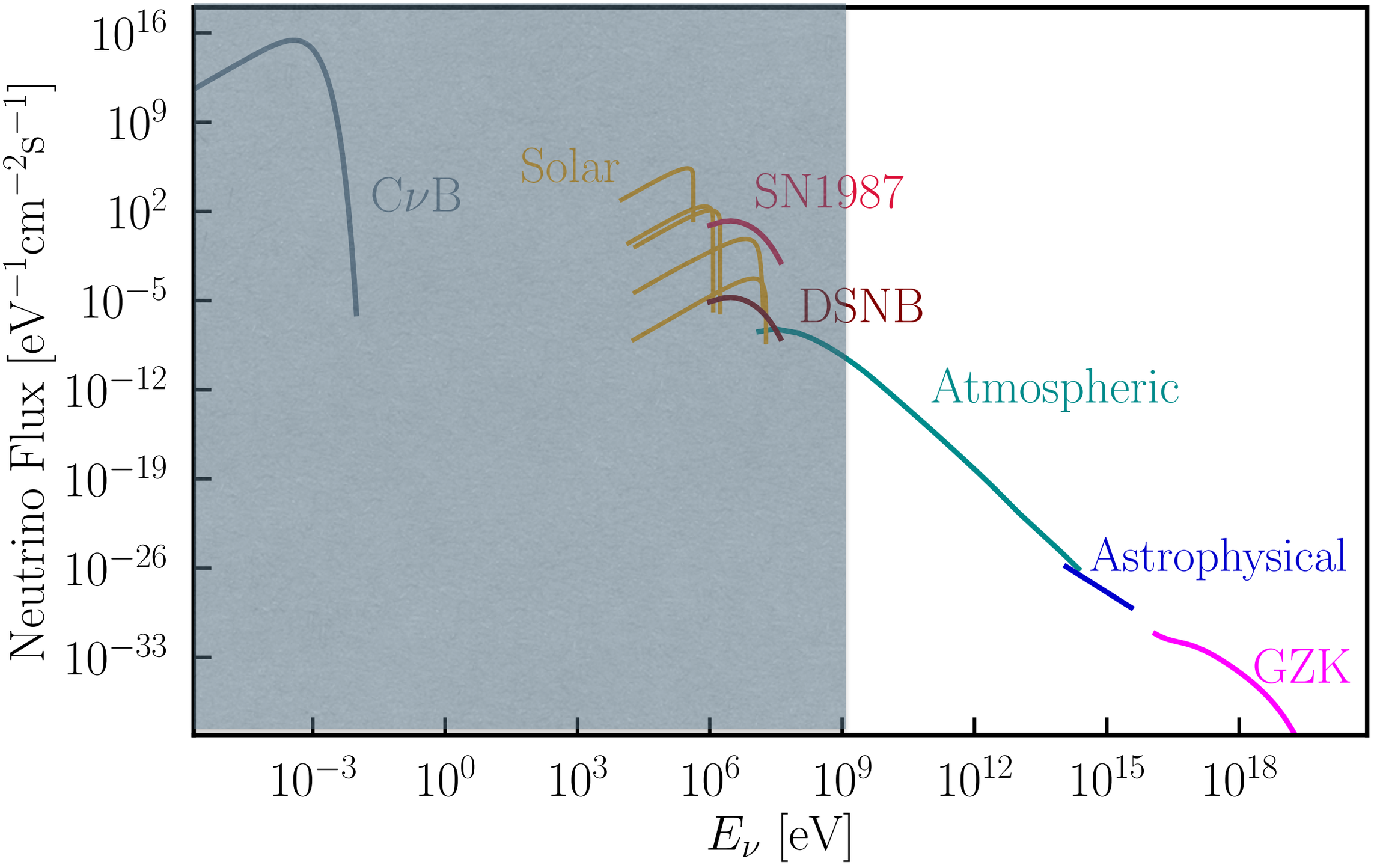

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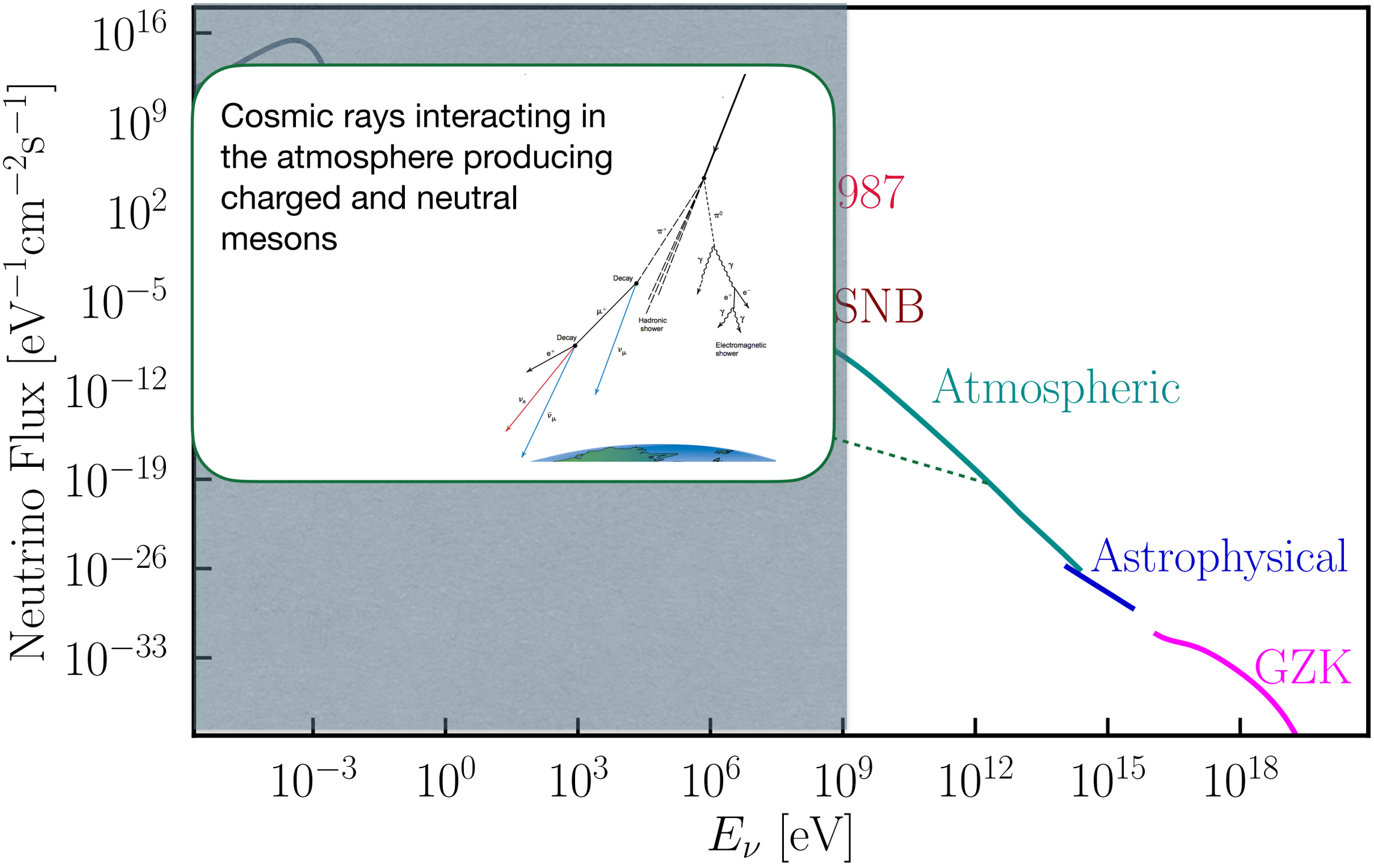

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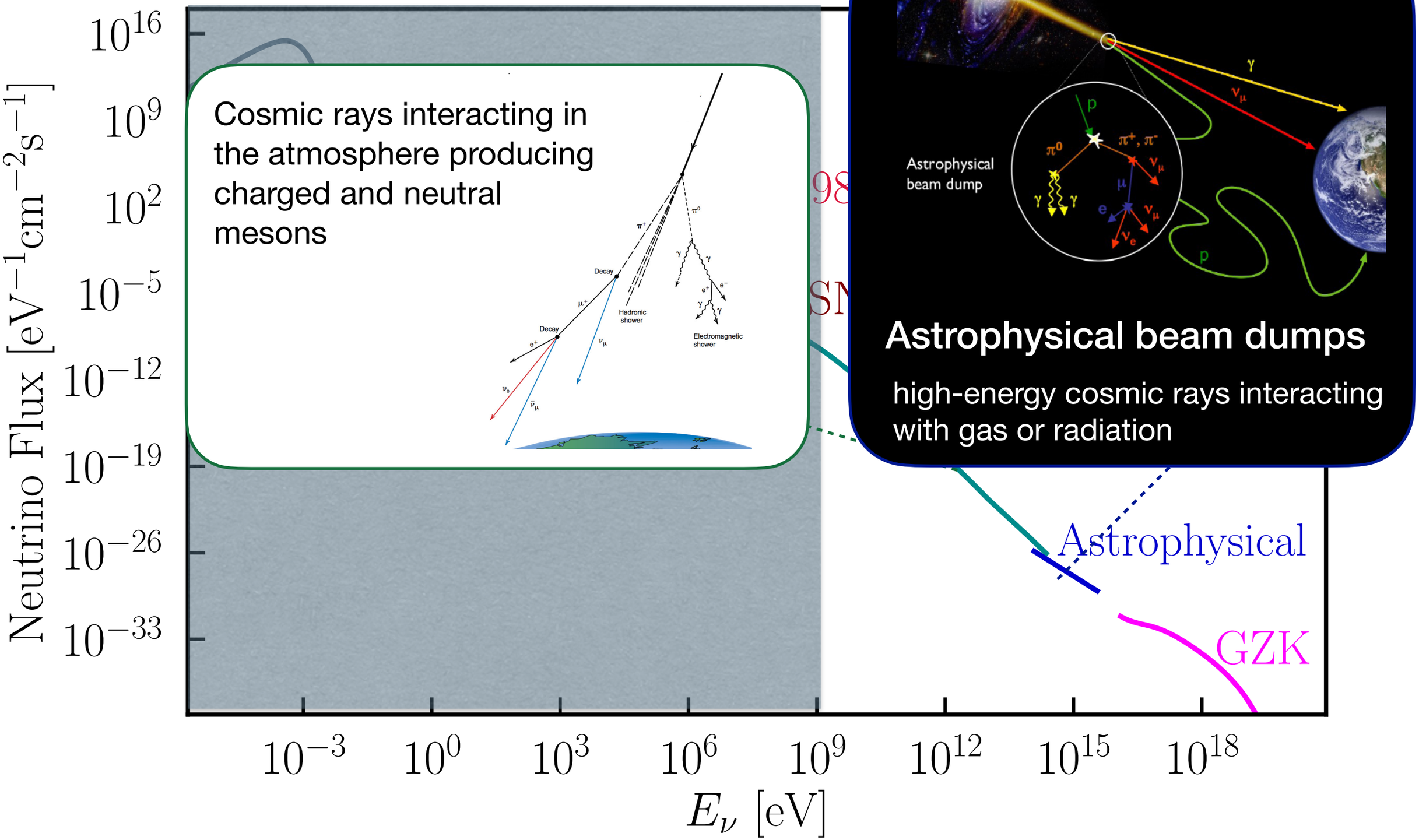
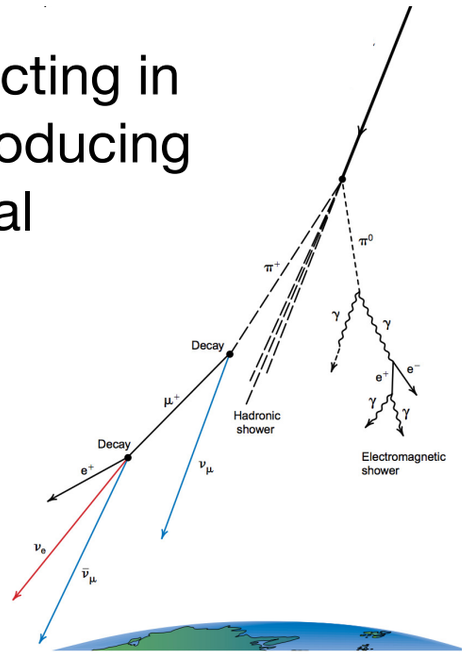
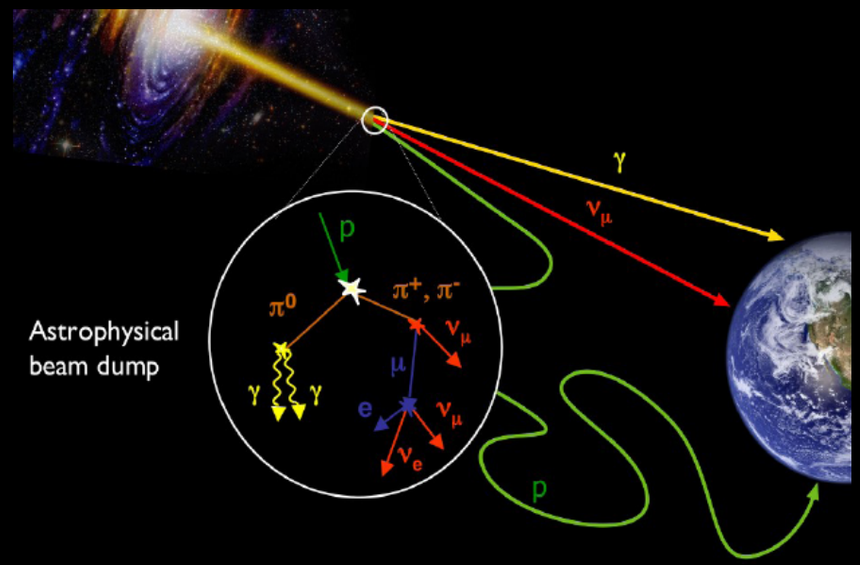


The Universe in Neutrinos

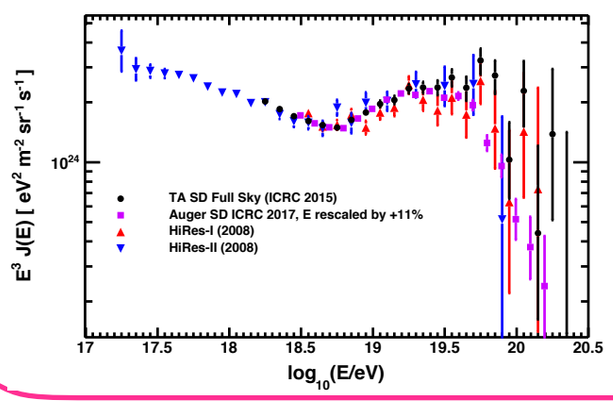
Cosmic rays interacting in the atmosphere producing charged and neutral mesons





Astrophysical beam dumps

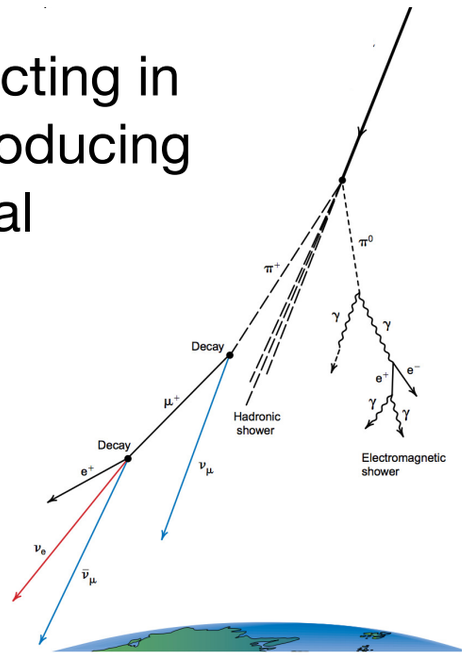
high-energy cosmic rays interacting with gas or radiation

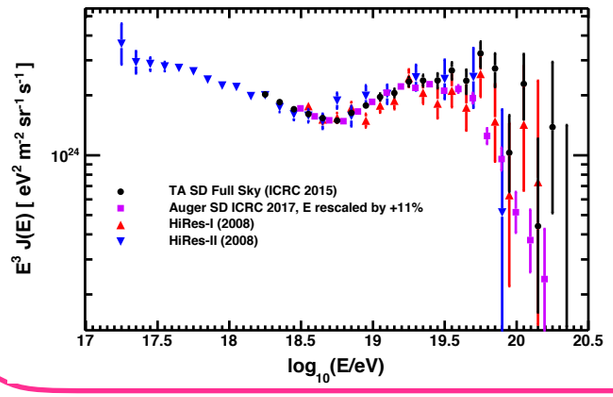


Ultra-high-energy cosmic rays interacting with the Cosmic Microwave Background

The Universe in Neutrinos

Cosmic rays interacting in the atmosphere producing charged and neutral mesons





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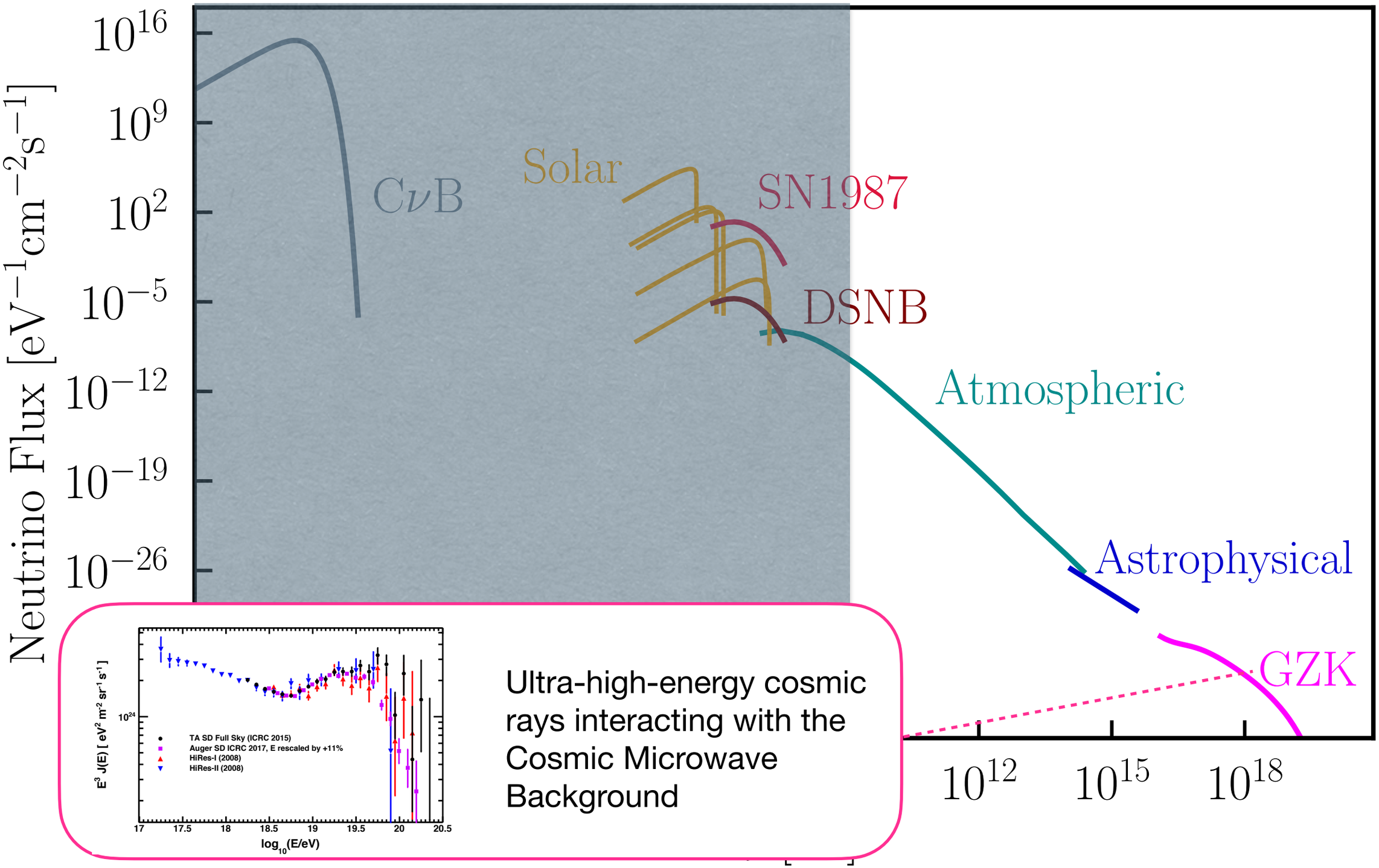

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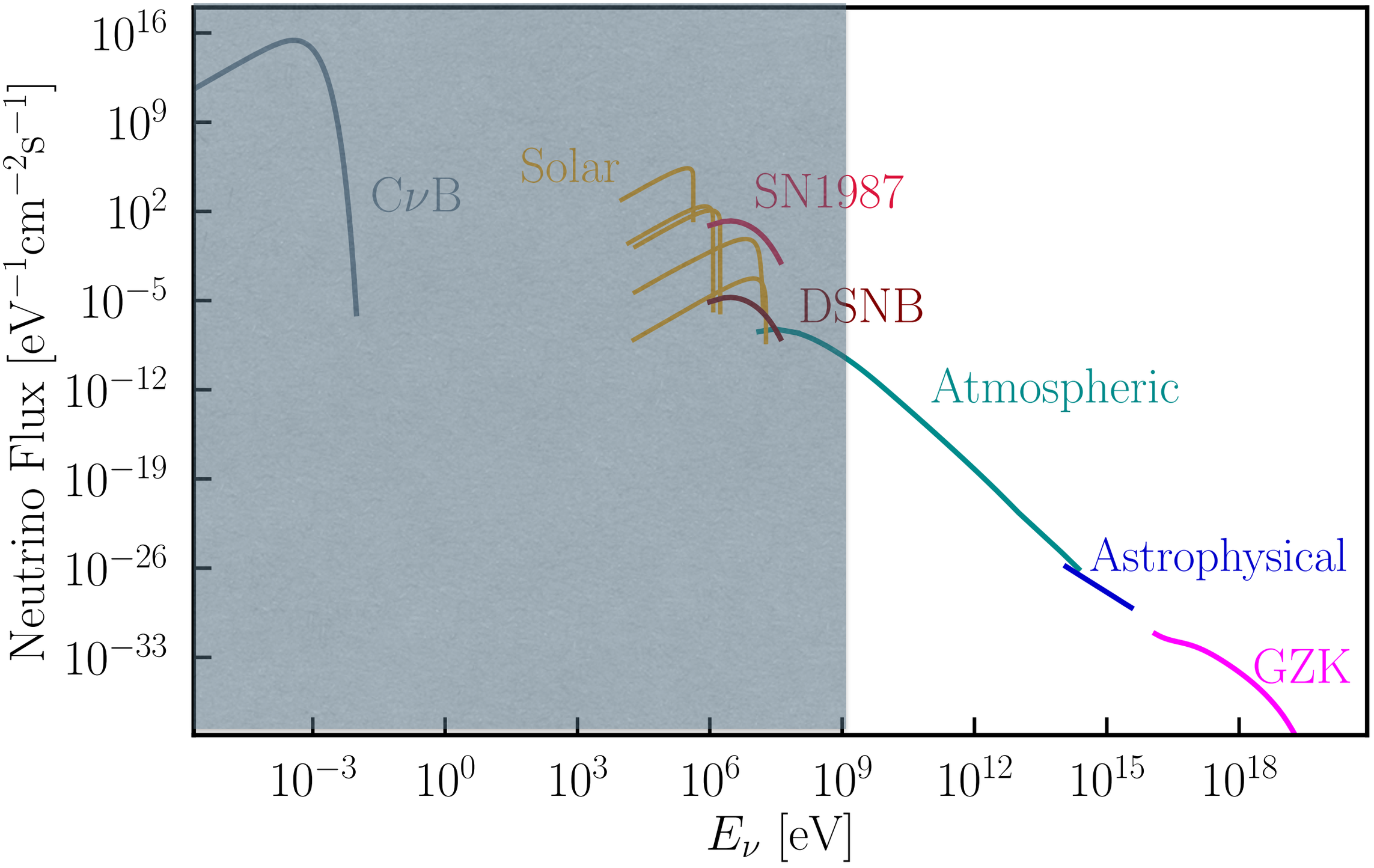

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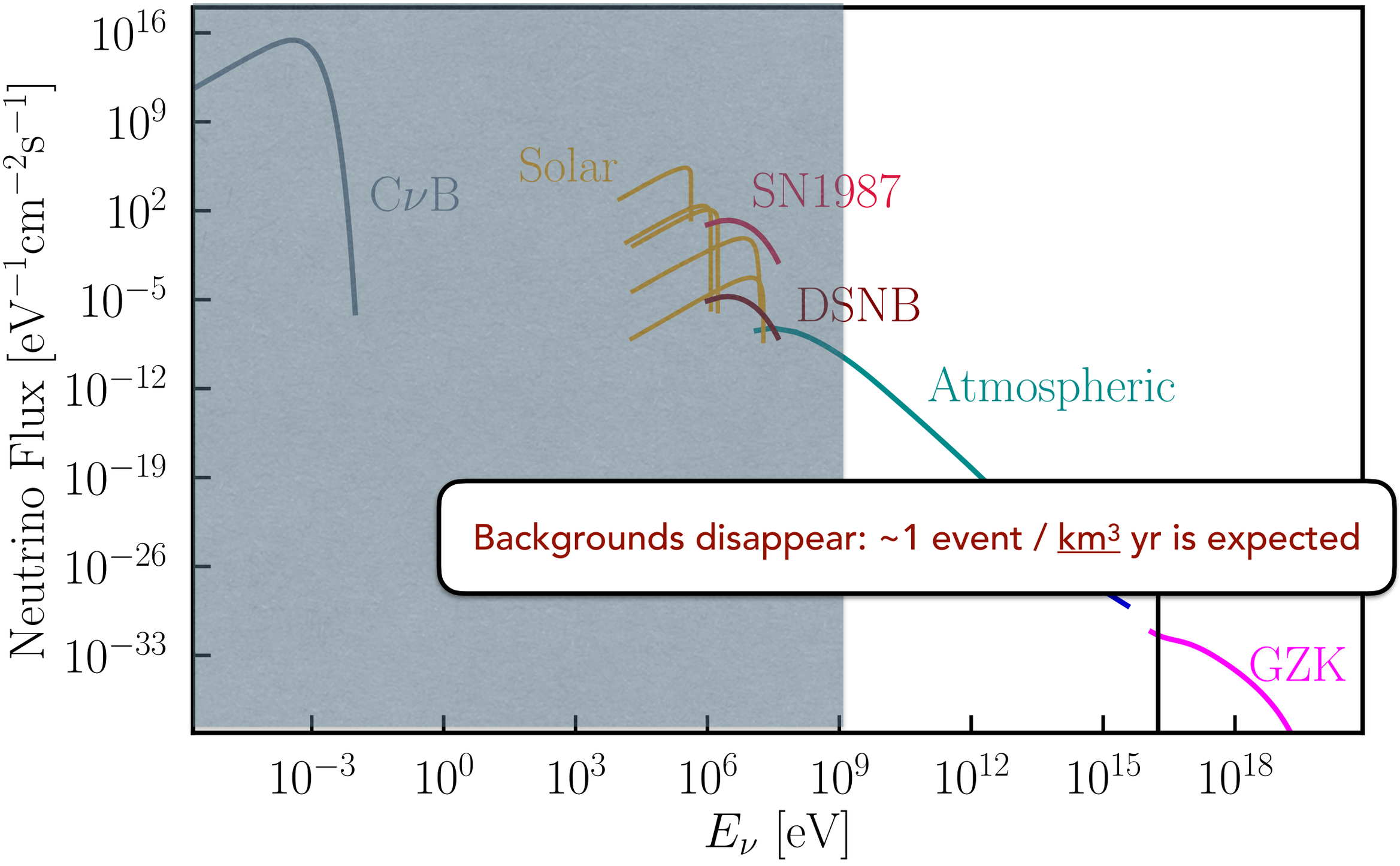
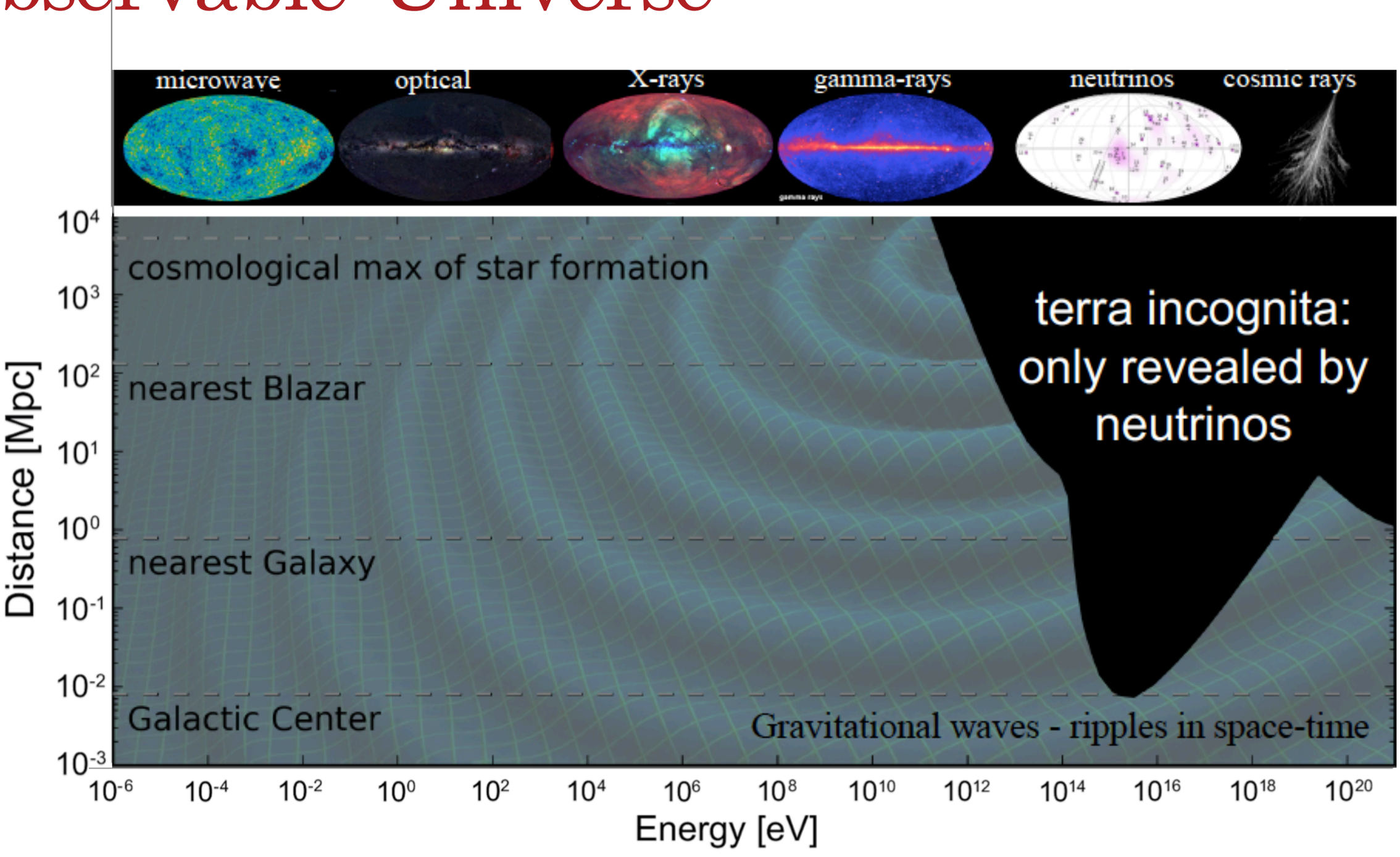


Observable Universe

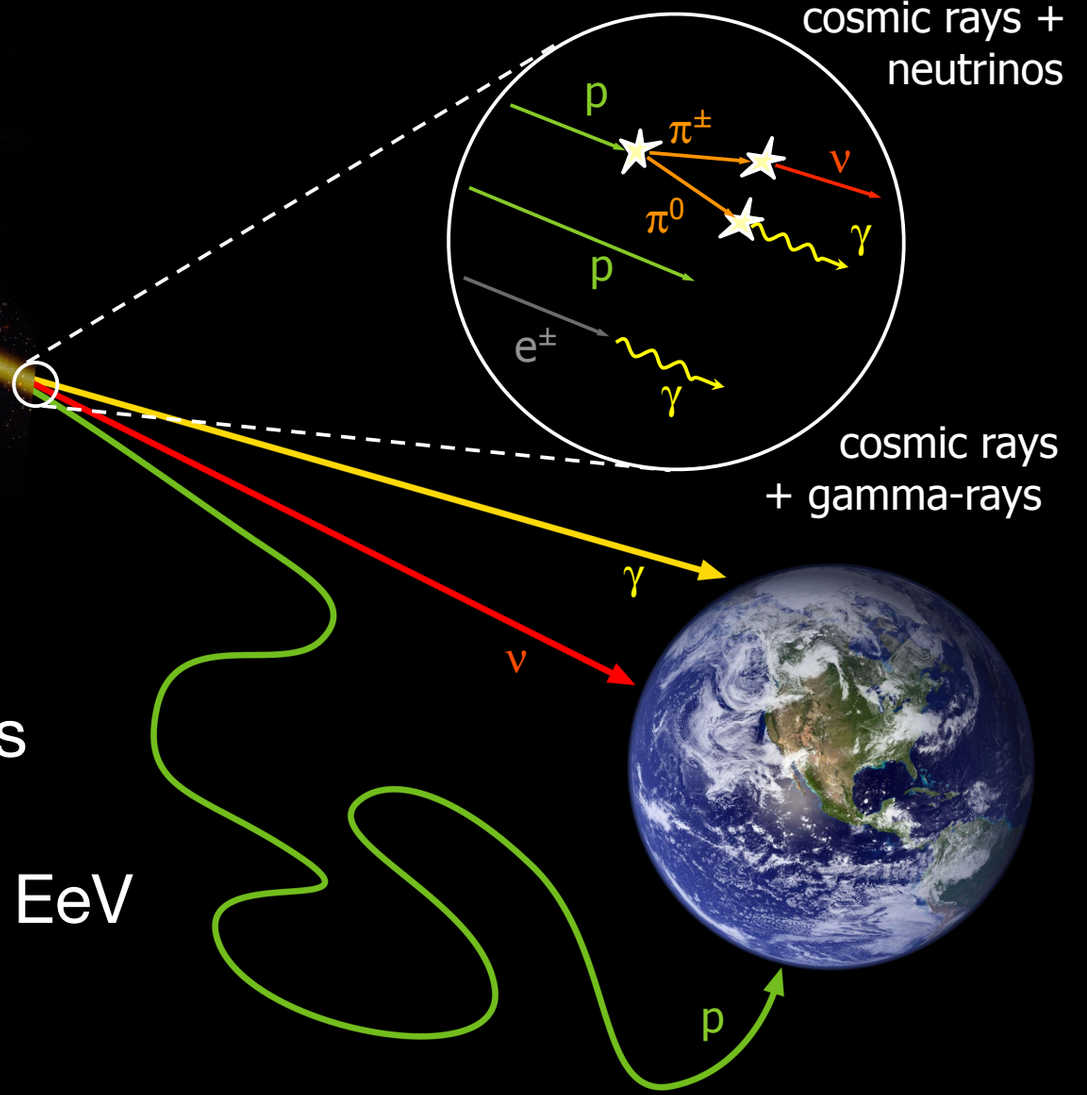


- 20% of the Universe is opaque to the EM spectrum
- non-thermal Universe powered by cosmic accelerators
- probed by gravity waves, neutrinos and cosmic rays

Neutrino Astronomy

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

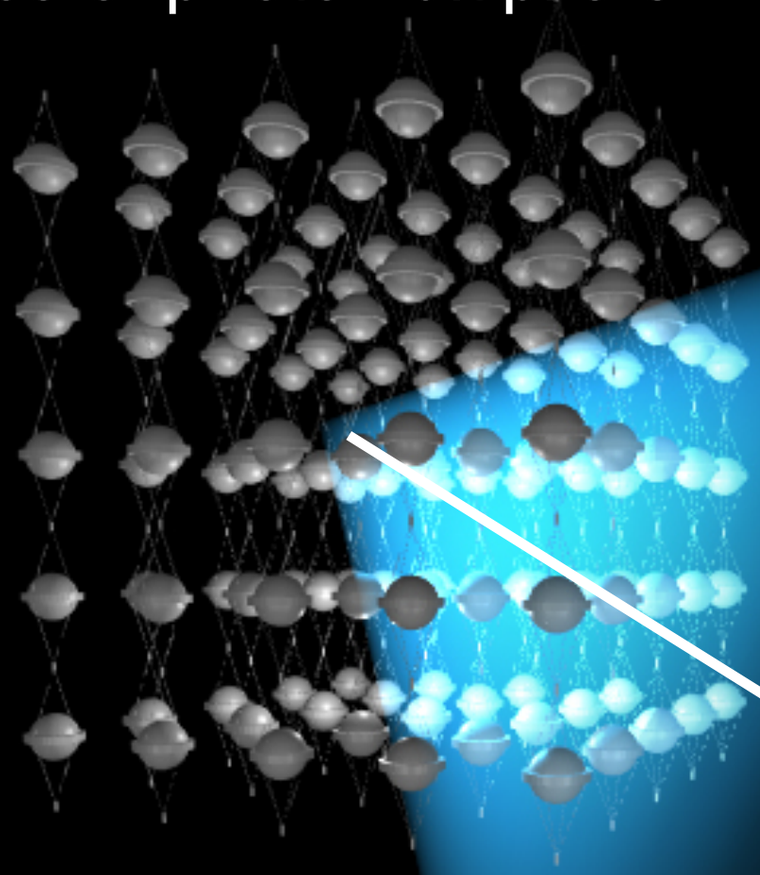
Accelerated CRs interact with gas or radiation in the beam dump and produce charged and neutral pions.



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

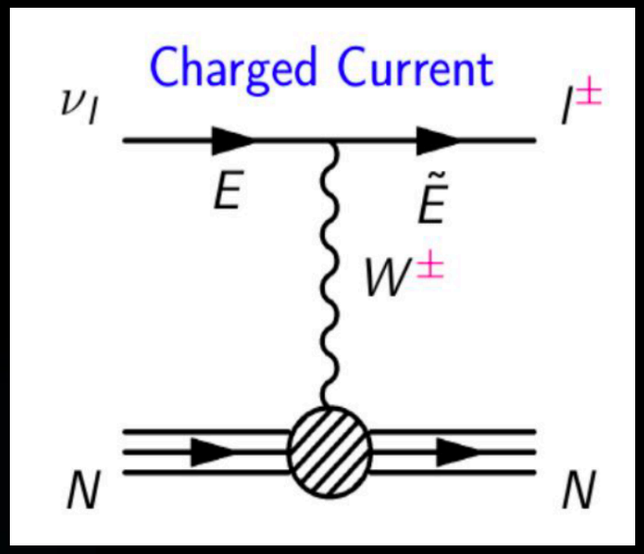
Low statistics and large background, main challenges for neutrino astronomy.

- lattice of photomultipliers



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

charged secondary particles produced as the neutrino interacts with a nucleus

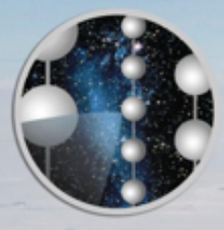


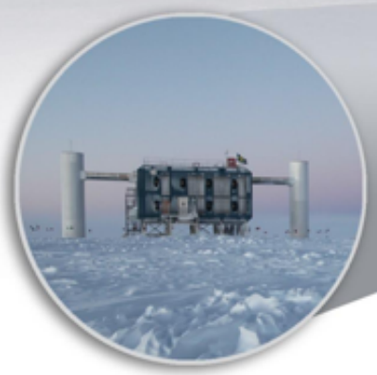
nuclear interaction

neutrino

IceCube: the 1st km³ neutrino telescope

South Pole Neutrino Observatory



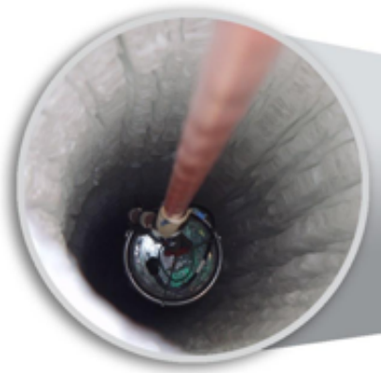


IceCube Laboratory

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

50 m

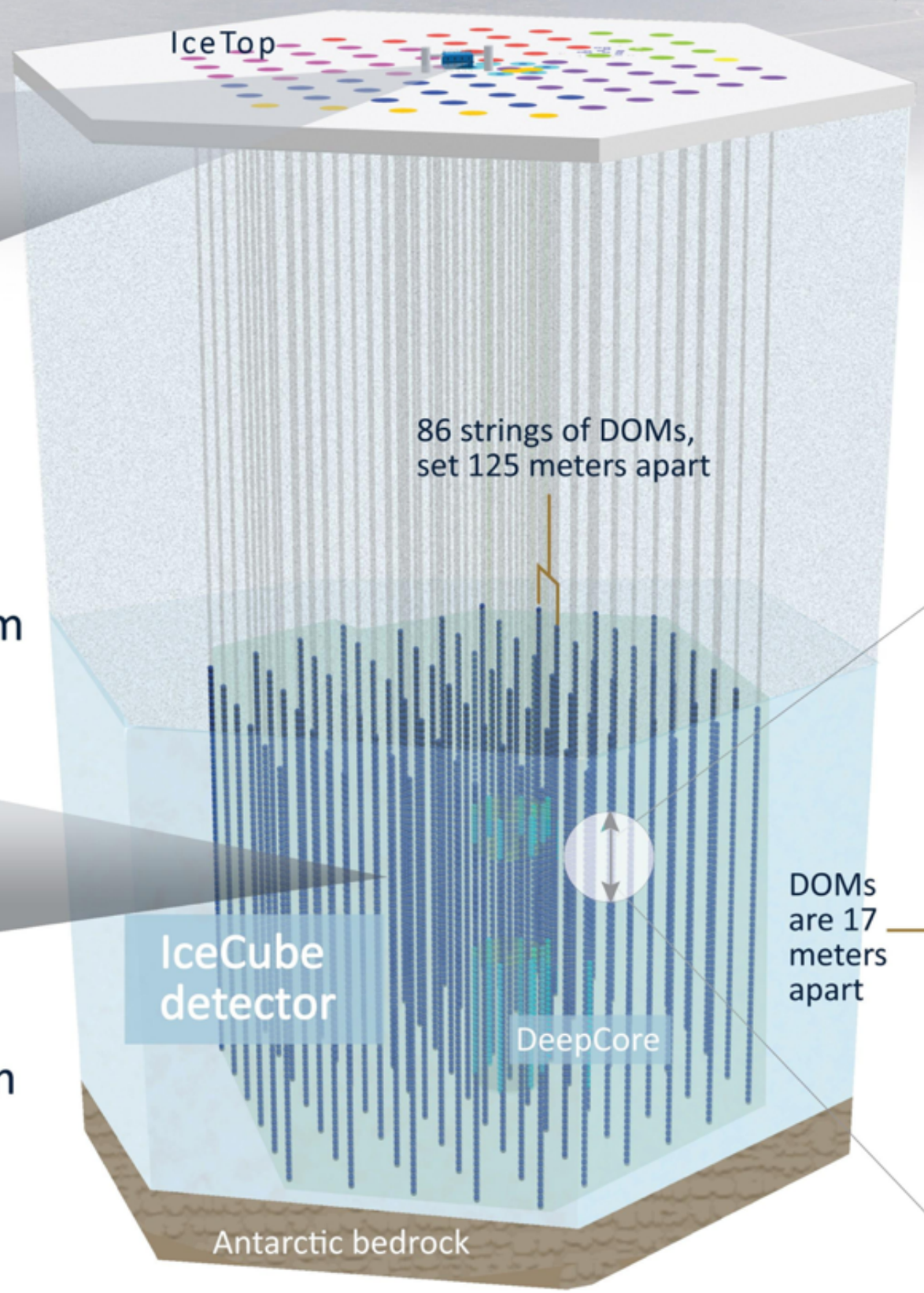
1450 m



Digital Optical Module (DOM)

5,160 DOMs deployed in the ice

2450 m



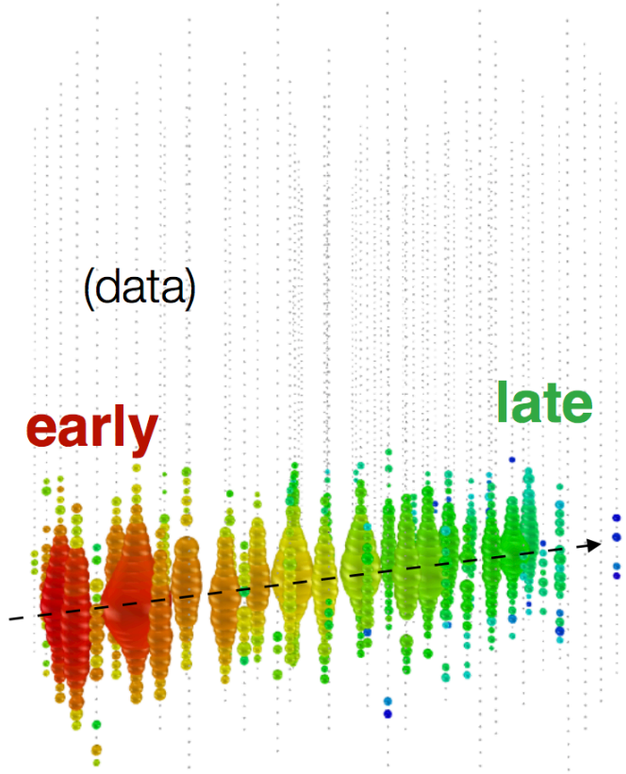
Amundsen–Scott South Pole Station, Antarctica

A National Science Foundation-managed research facility

Detection Principle

High-energy charged particles produce Cherenkov light in the ice.

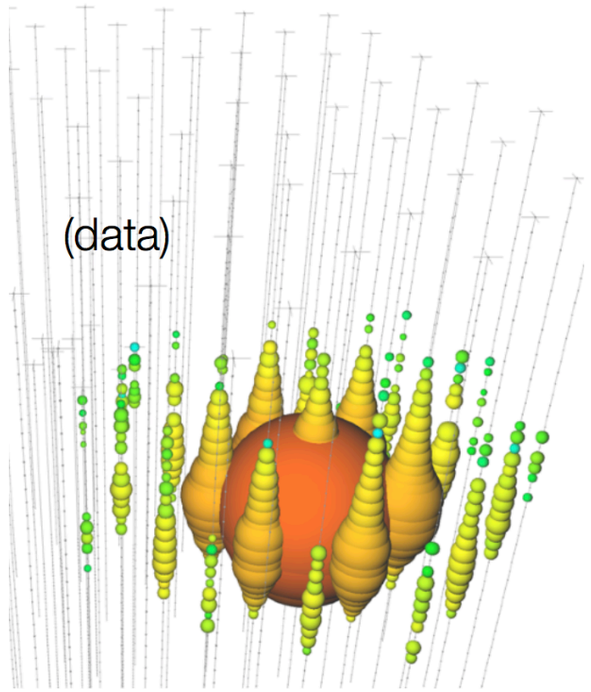
Charged-current ν_μ



Up-going track

Factor of ~2 energy resolution
< 1 degree angular resolution

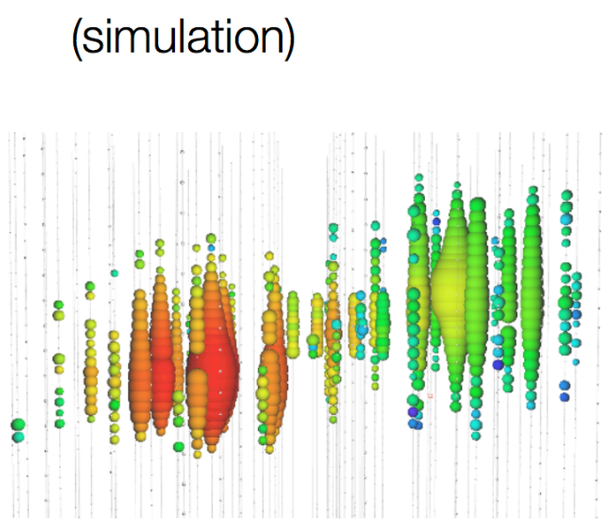
Neutral-current / ν_e



Isolated energy deposition (cascade) with no track

15% deposited energy resolution
10 degree angular resolution (above 100 TeV)

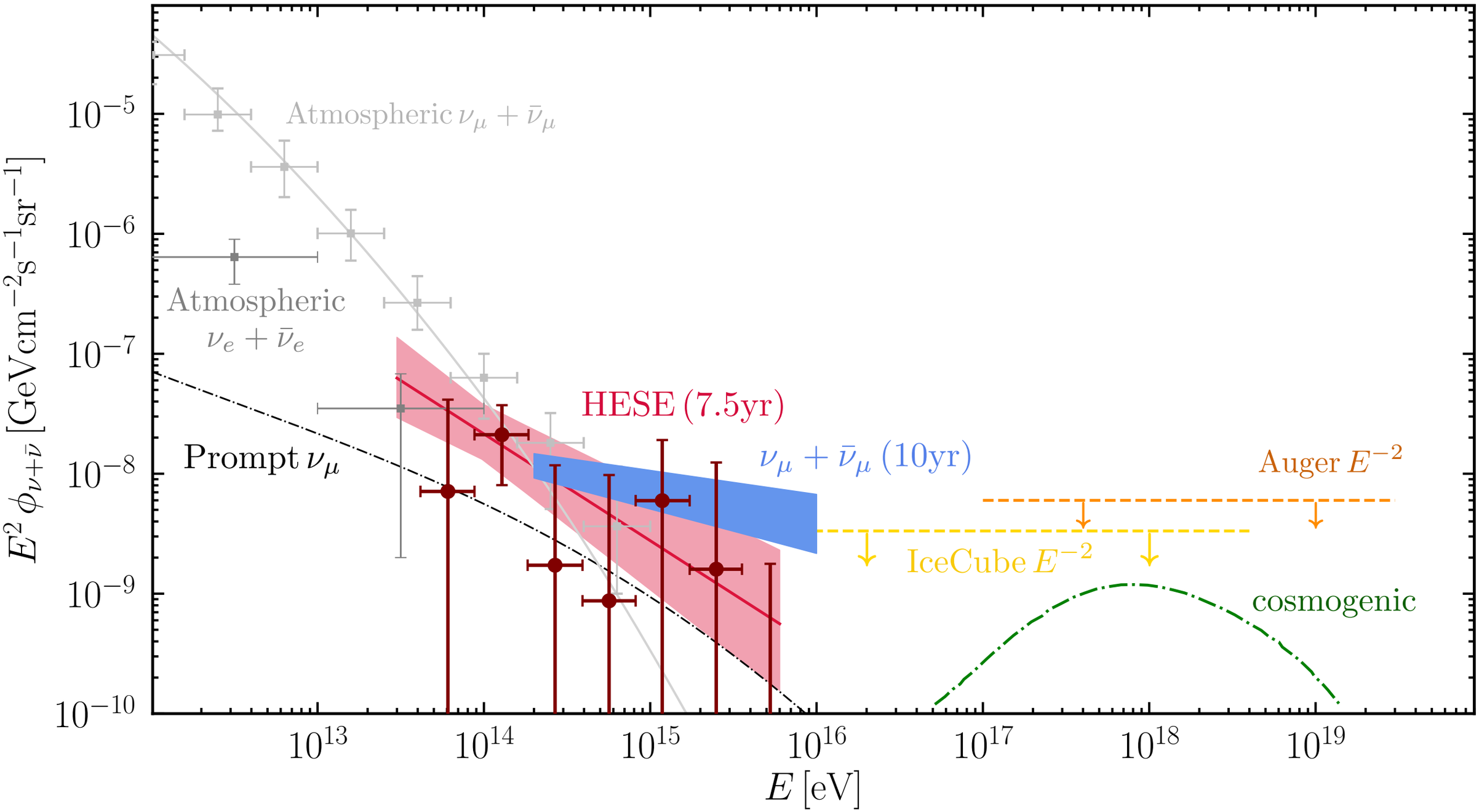
Charged-current ν_τ



Double cascade

(resolvable above ~100 TeV deposited energy)

High-Energy Neutrino Flux



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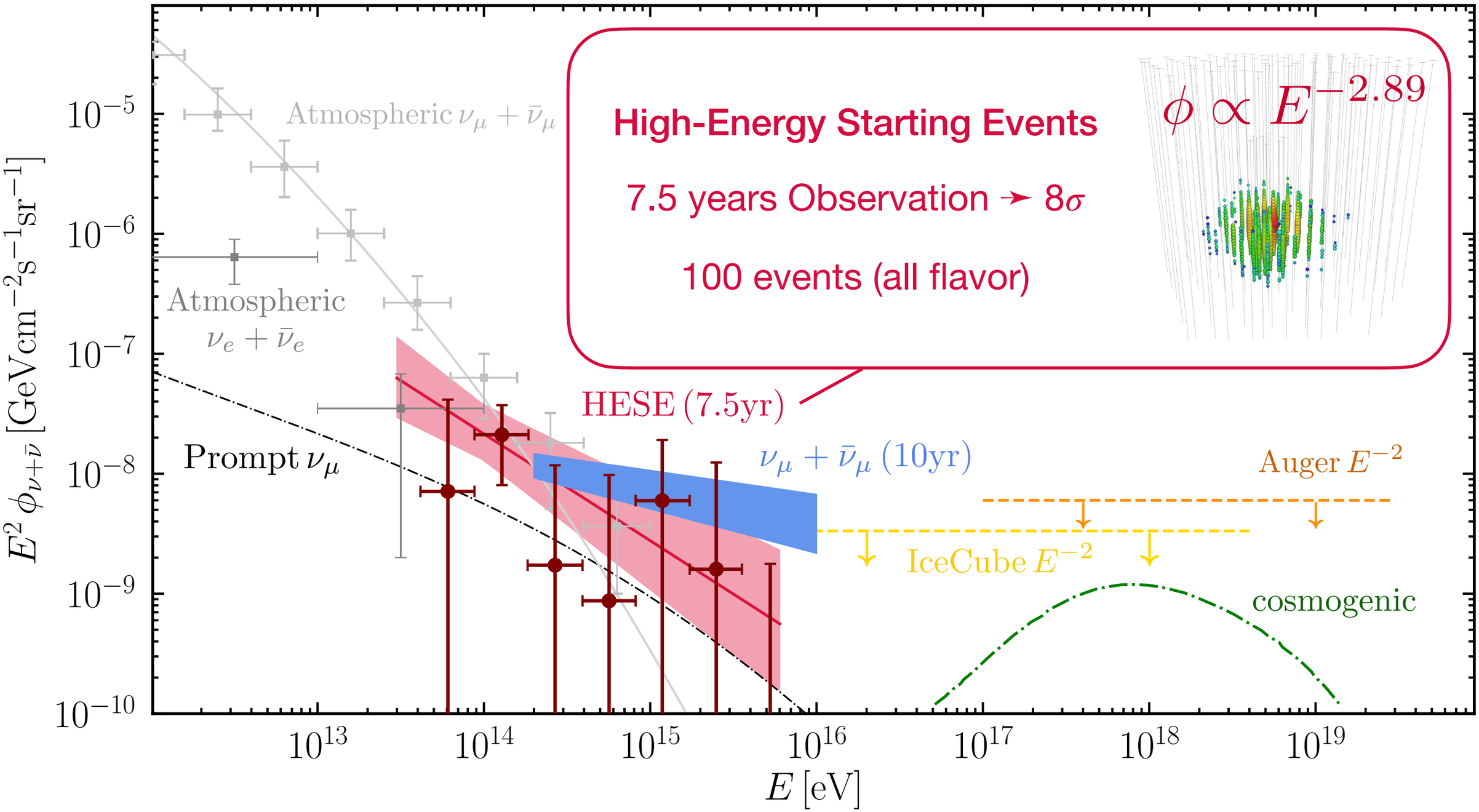

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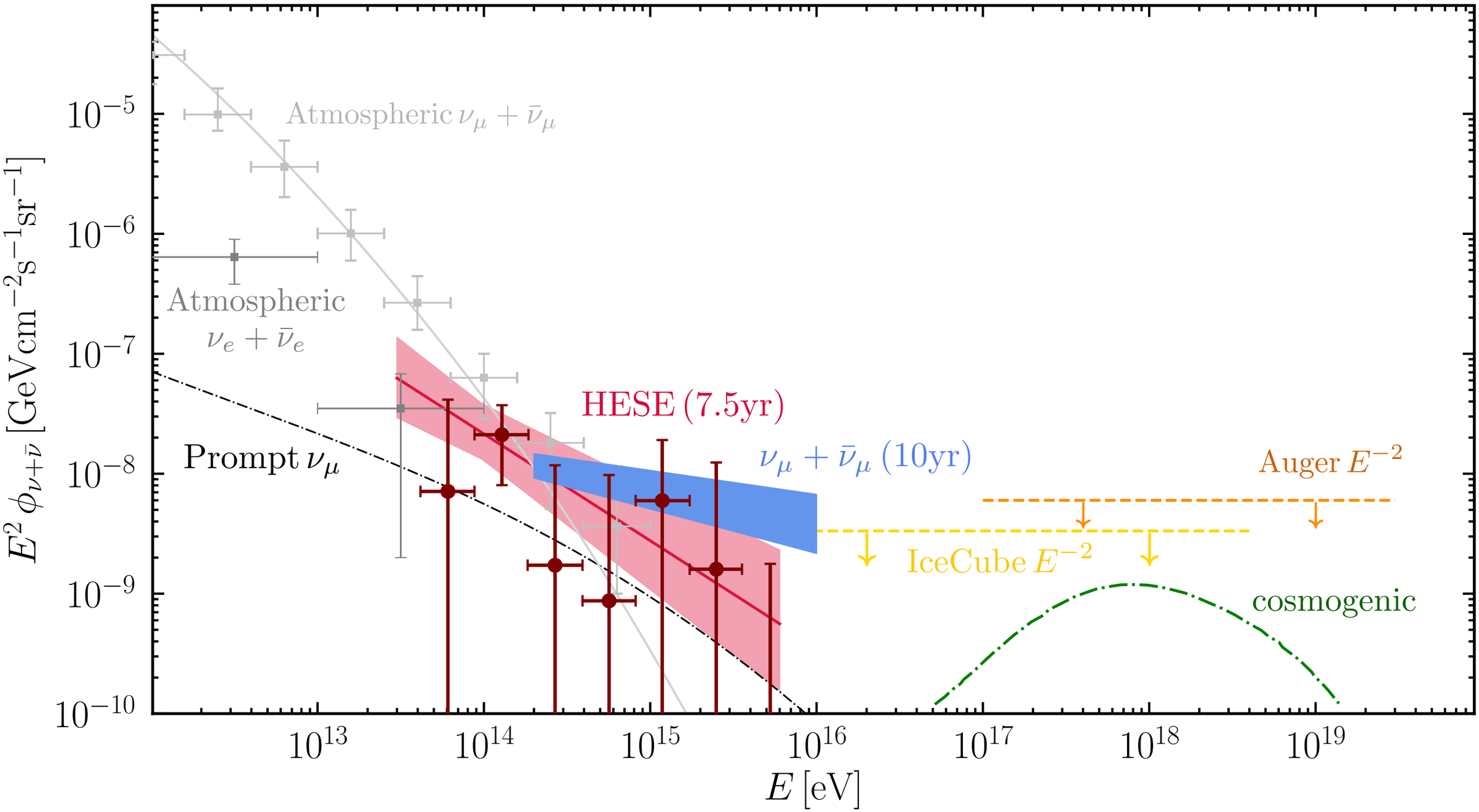

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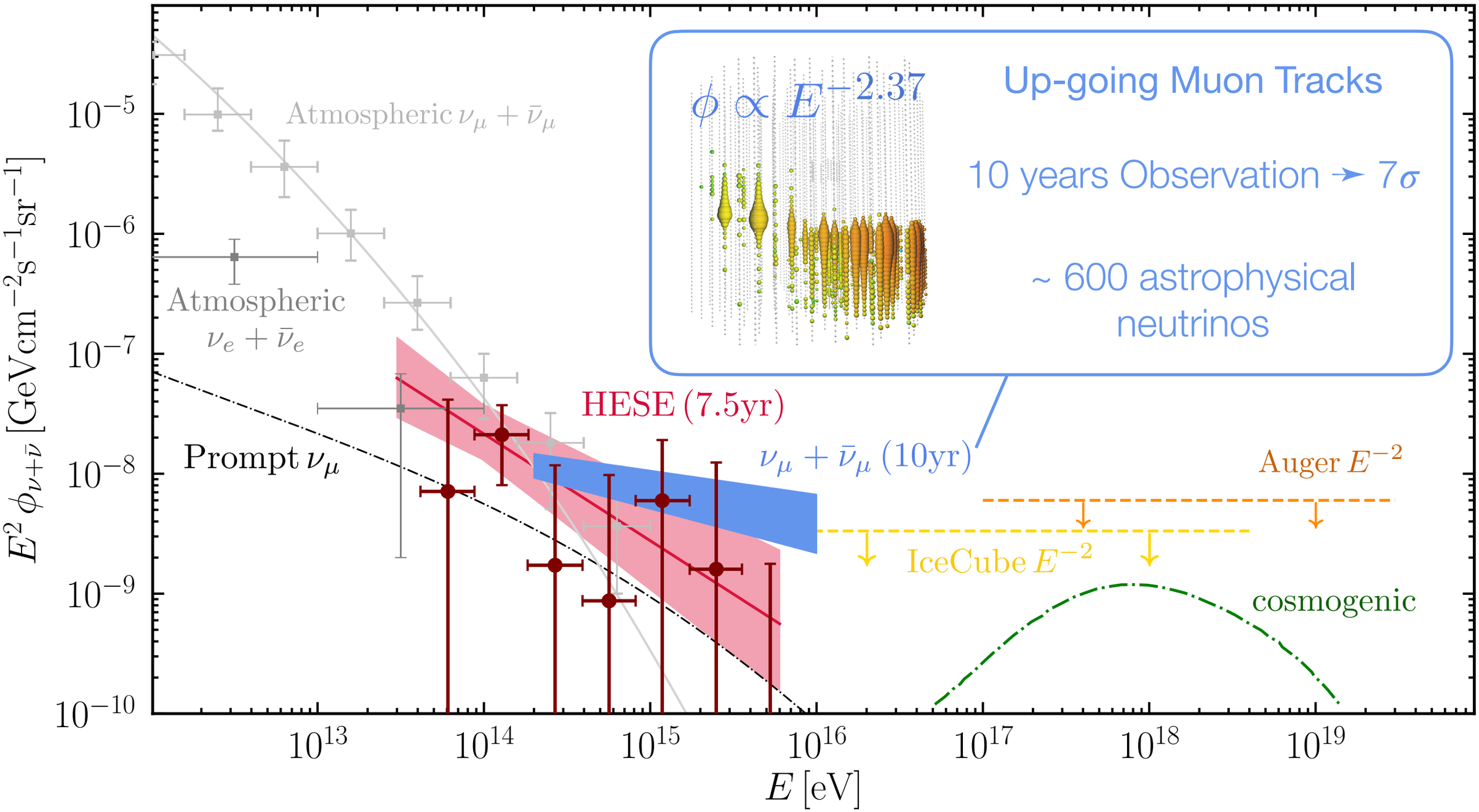

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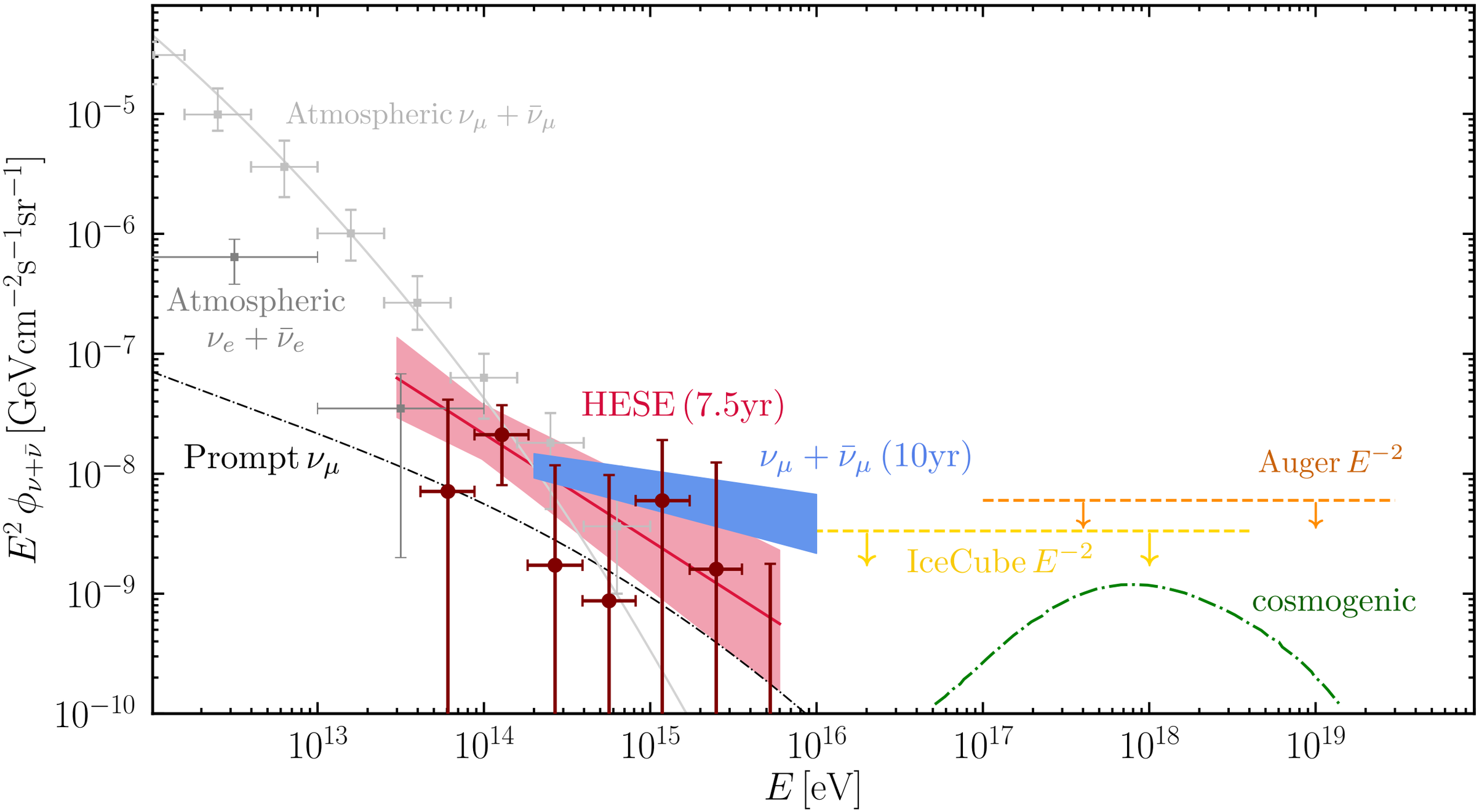

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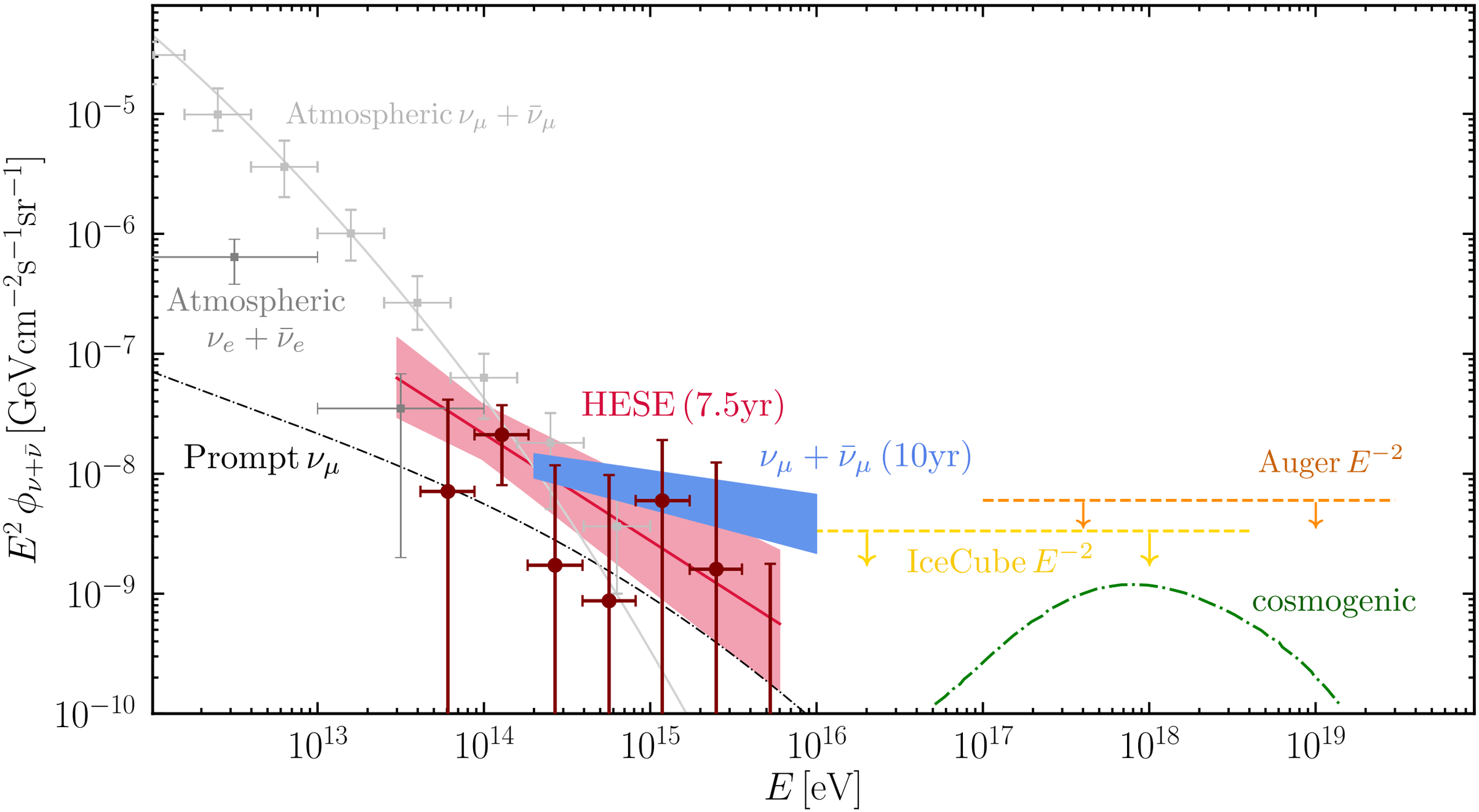
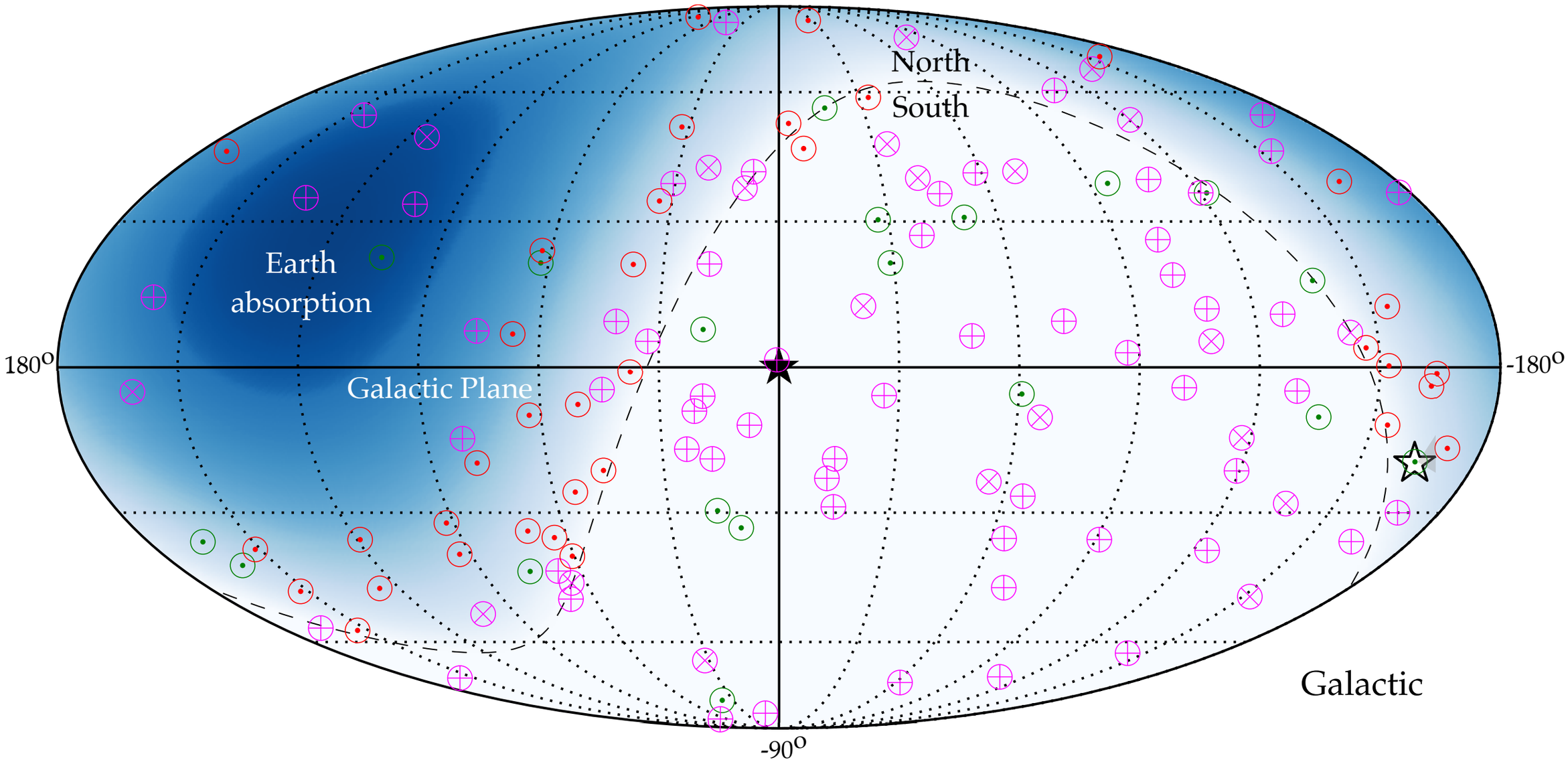


- Fluxes are compatible in common energy range.
- Features in high-energy neutrino flux can point to different source properties.

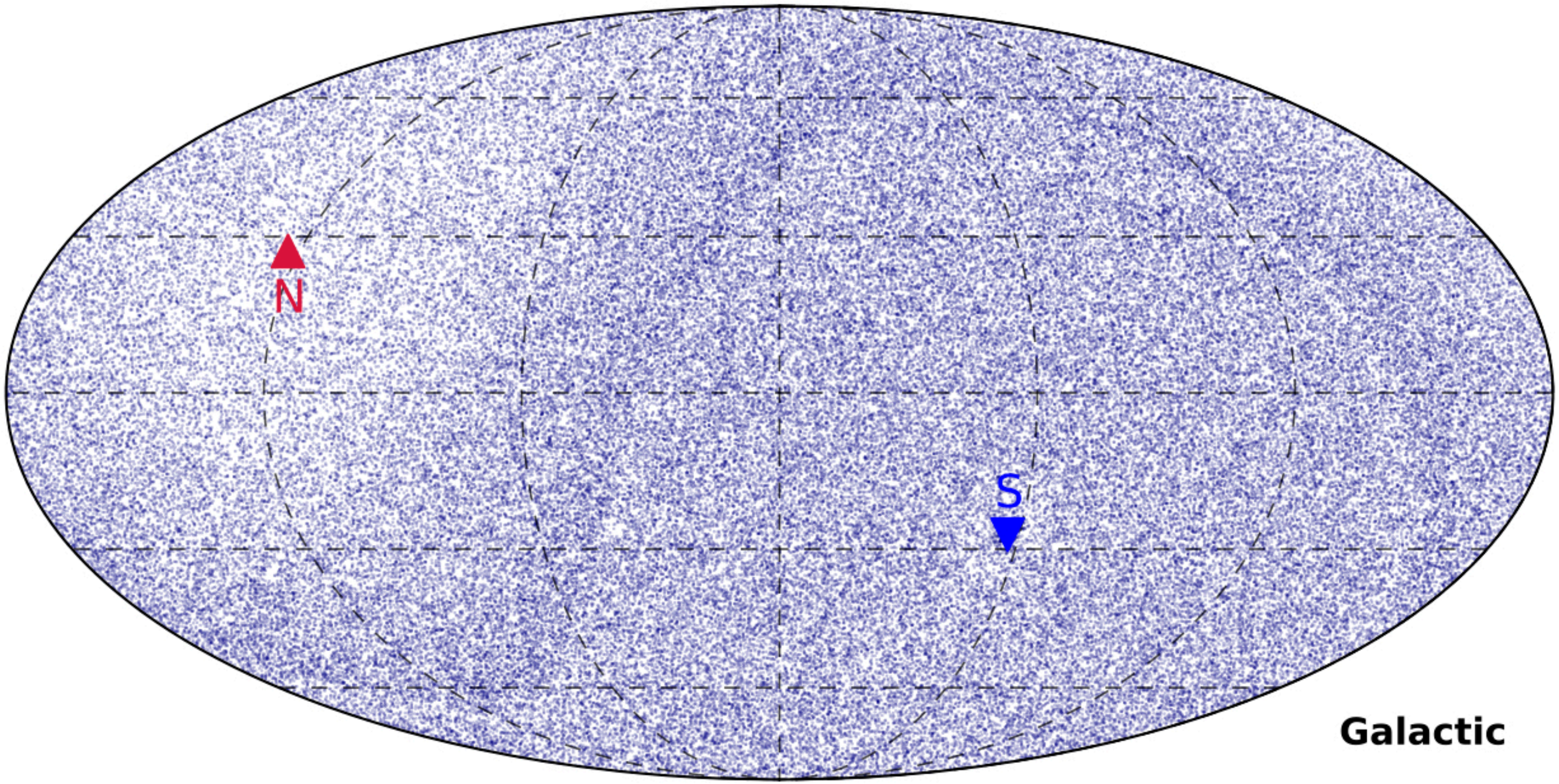
Arrival Direction of the Most Energetic Neutrinos



tracks ⊗ cascades ⊕ alerts ⊙

predominantly extragalactic origin

Spatial Distribution

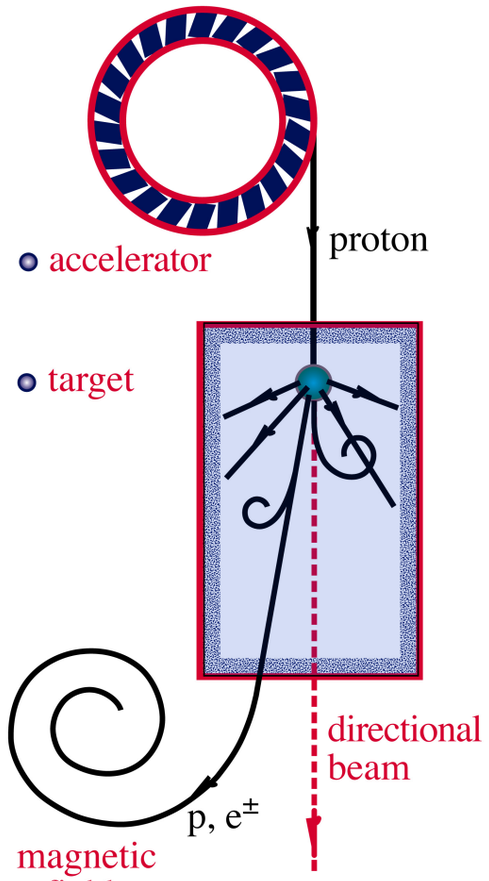


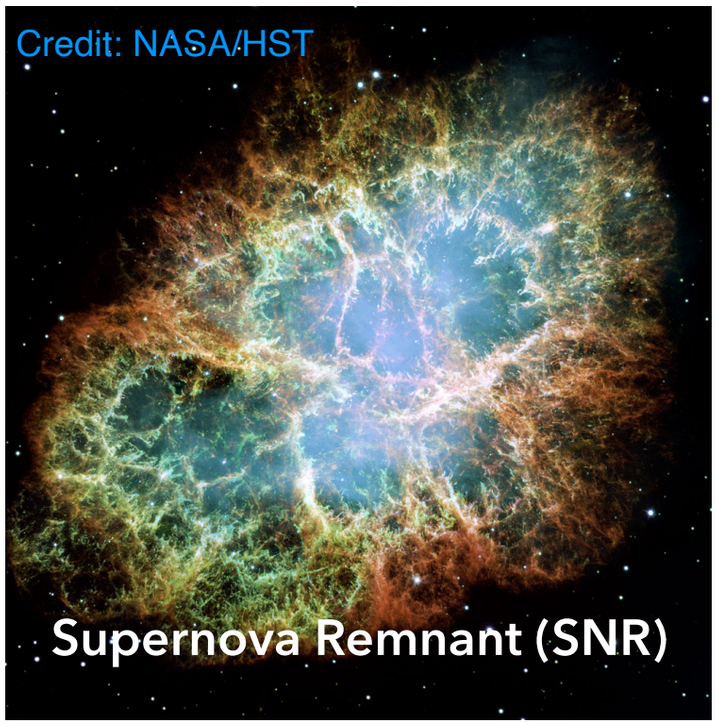
138322 neutrino candidates in one year

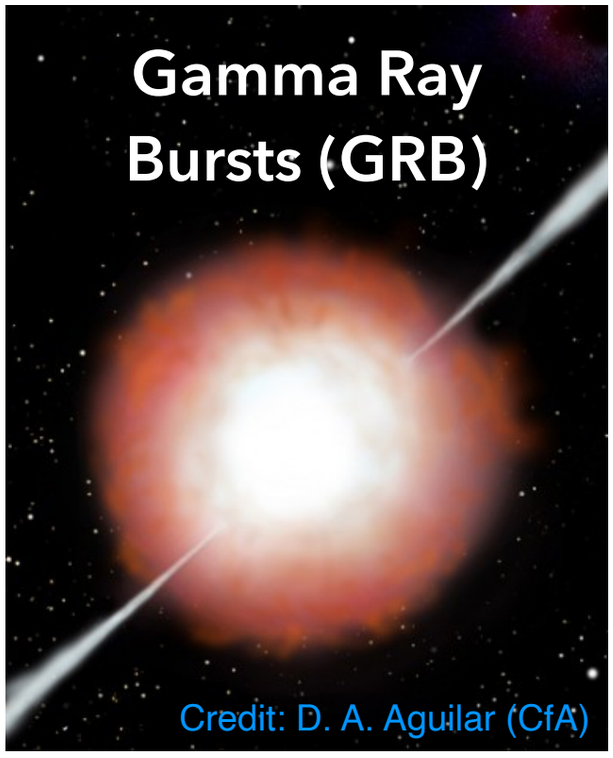
Possible Sources

Sources of TeV - PeV cosmic neutrinos should

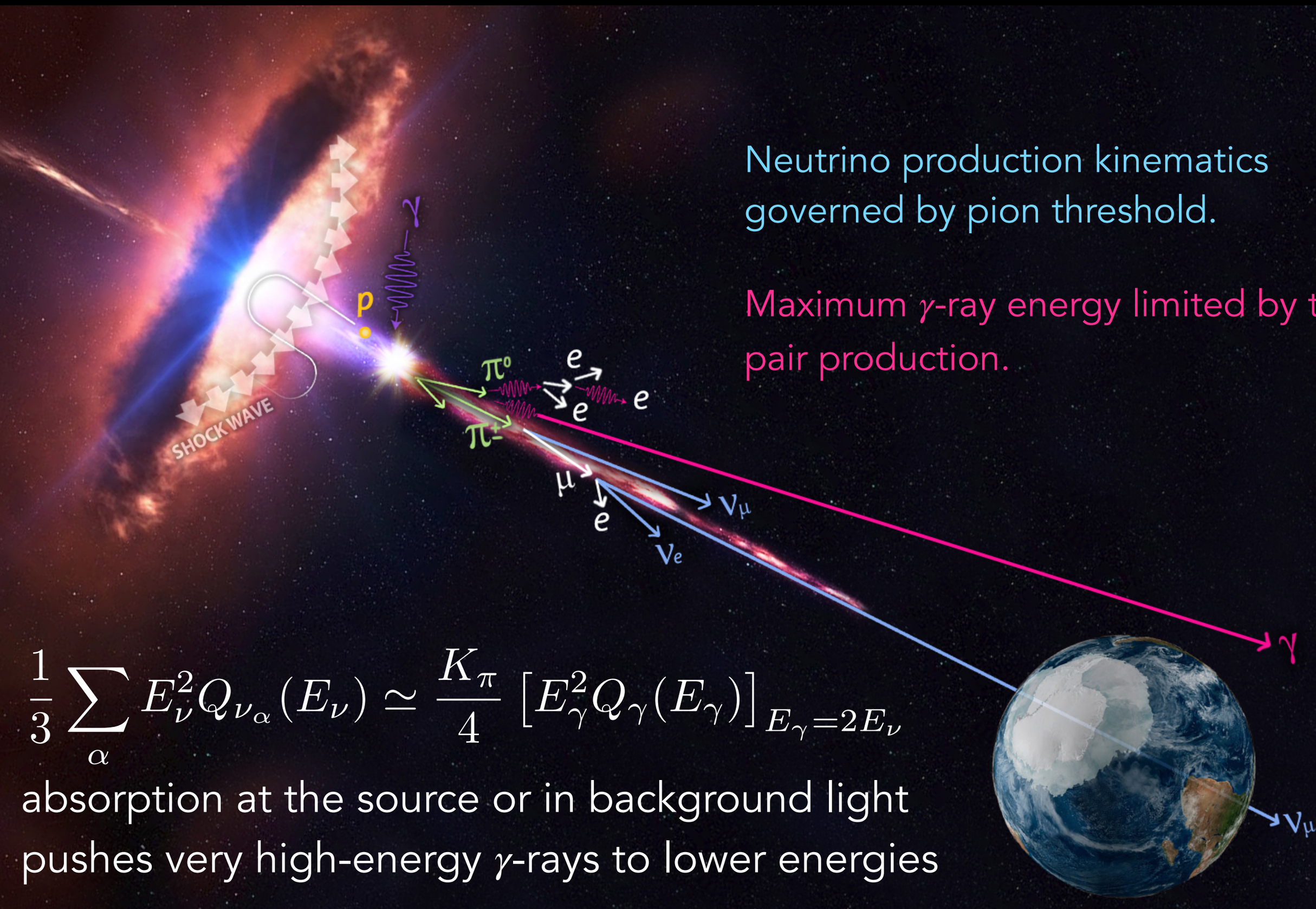
- Accelerate Cosmic Rays to > PeV energies
  - sources of VHE & UHE CRs
- Poses beam dumps that facilitate CR interaction
  - environment that can provide gas and radiation with enough density







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

Point Source Searches

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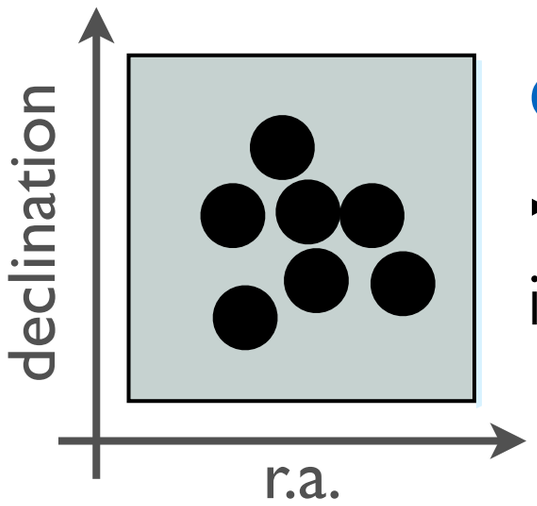

clustering

- Untriggered search

in space & time

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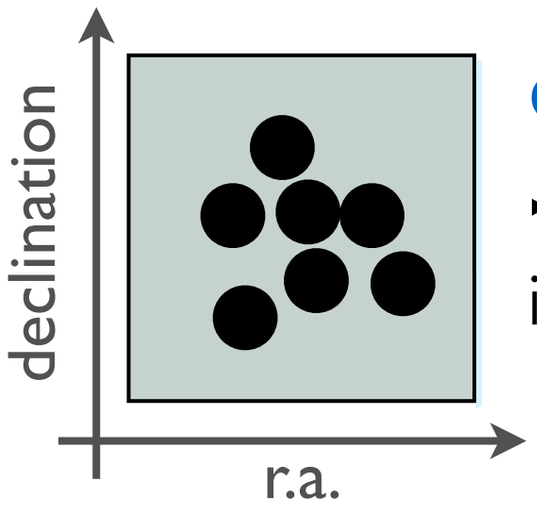

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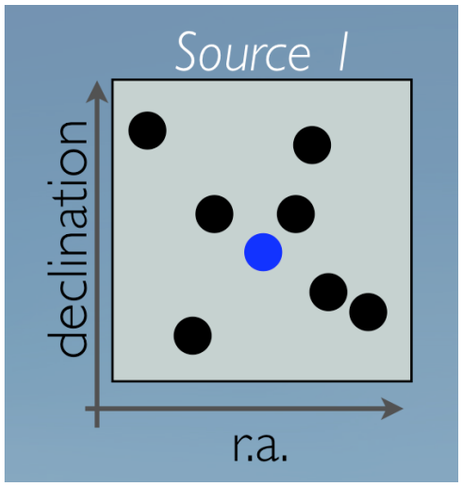

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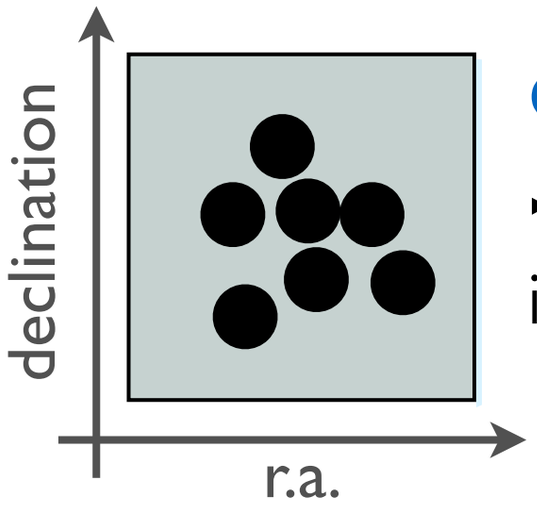

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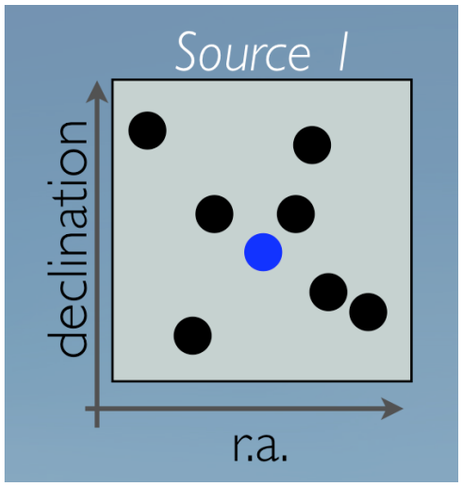
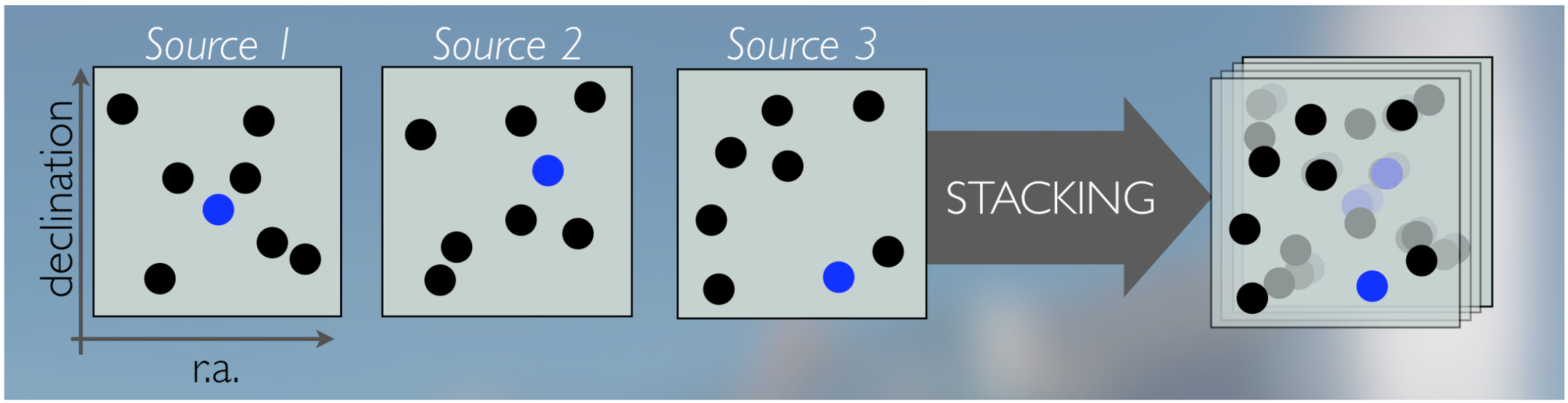
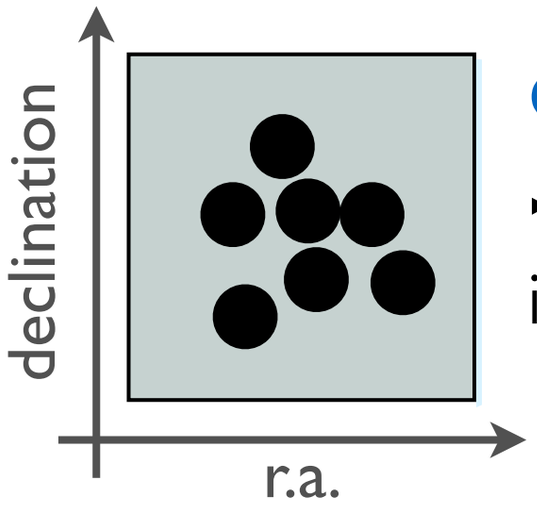




Stacking Search

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

Point Source Searches



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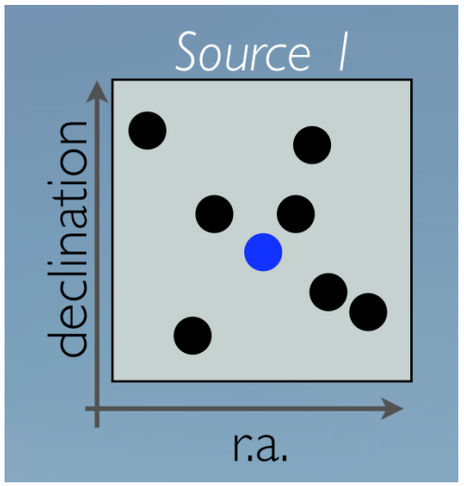

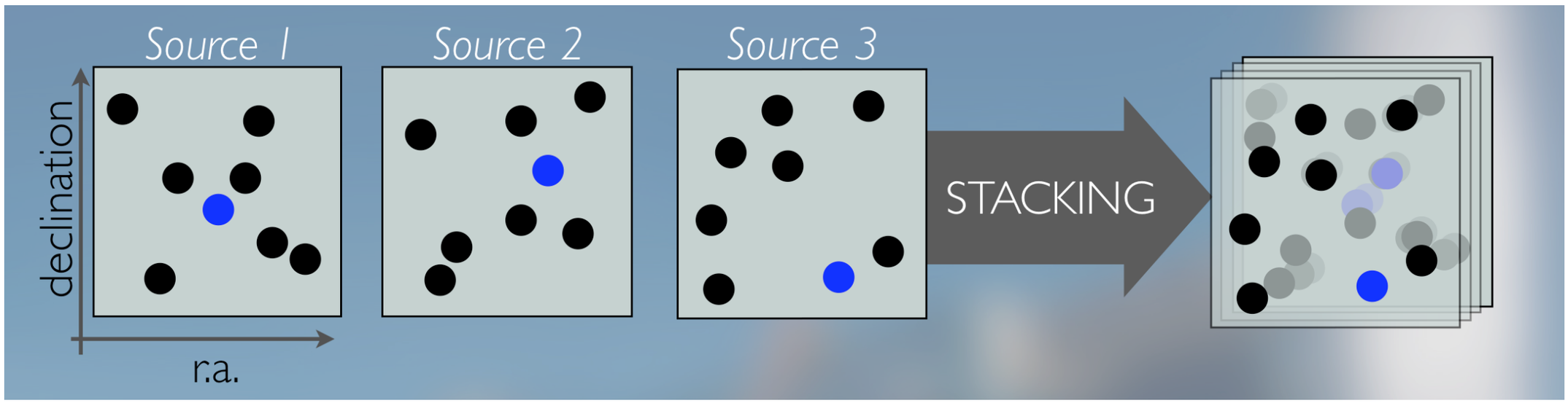

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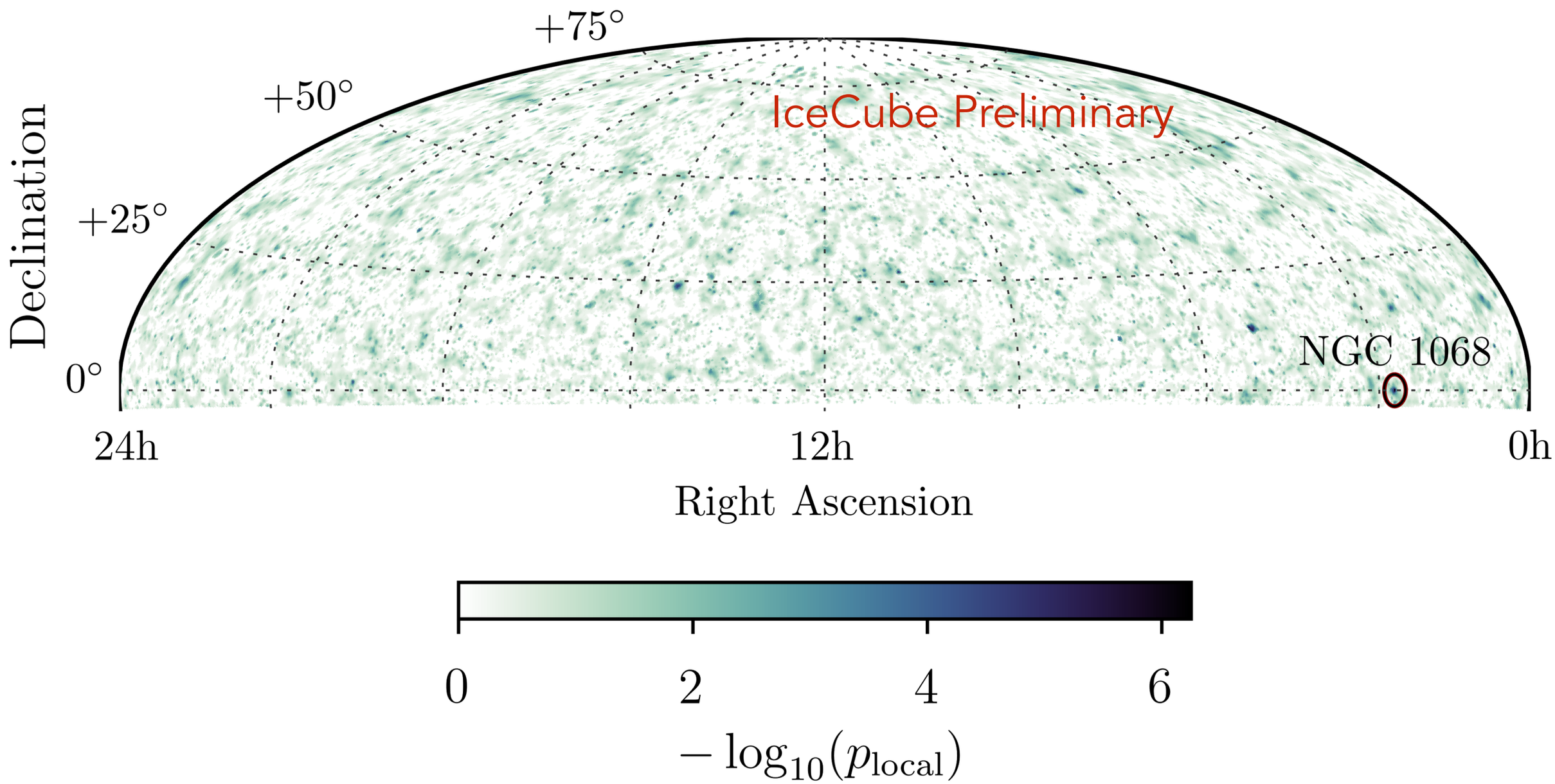
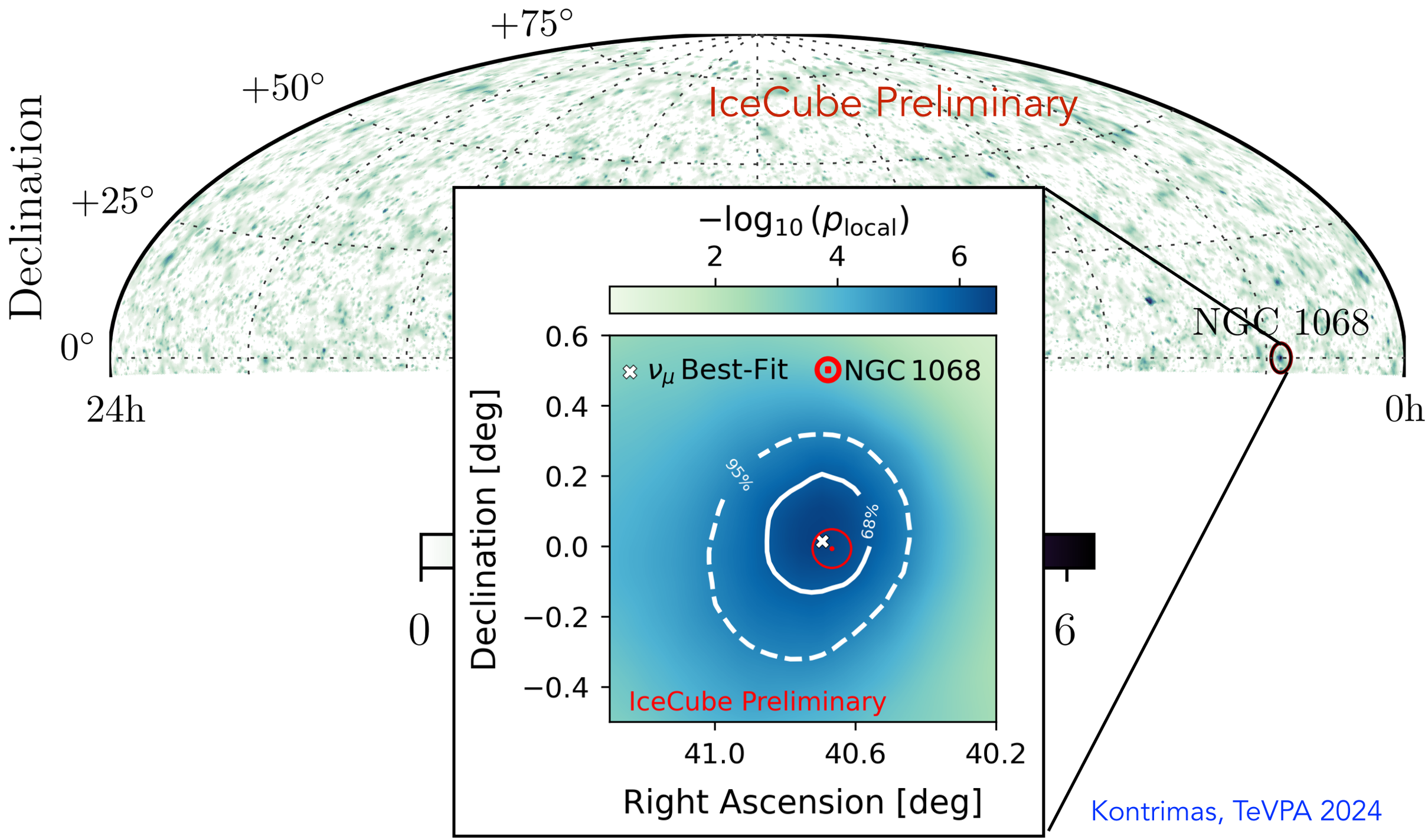
+ 🚨 Realtime analysis and Neutrino alerts!

NGC 1068: The 1st steady Neutrino Source



Kontrimas, TeVPA 2024

NGC 1068; The 1st steady Neutrino Source



Kontrimas, TeVPA 2024

NGC 1068

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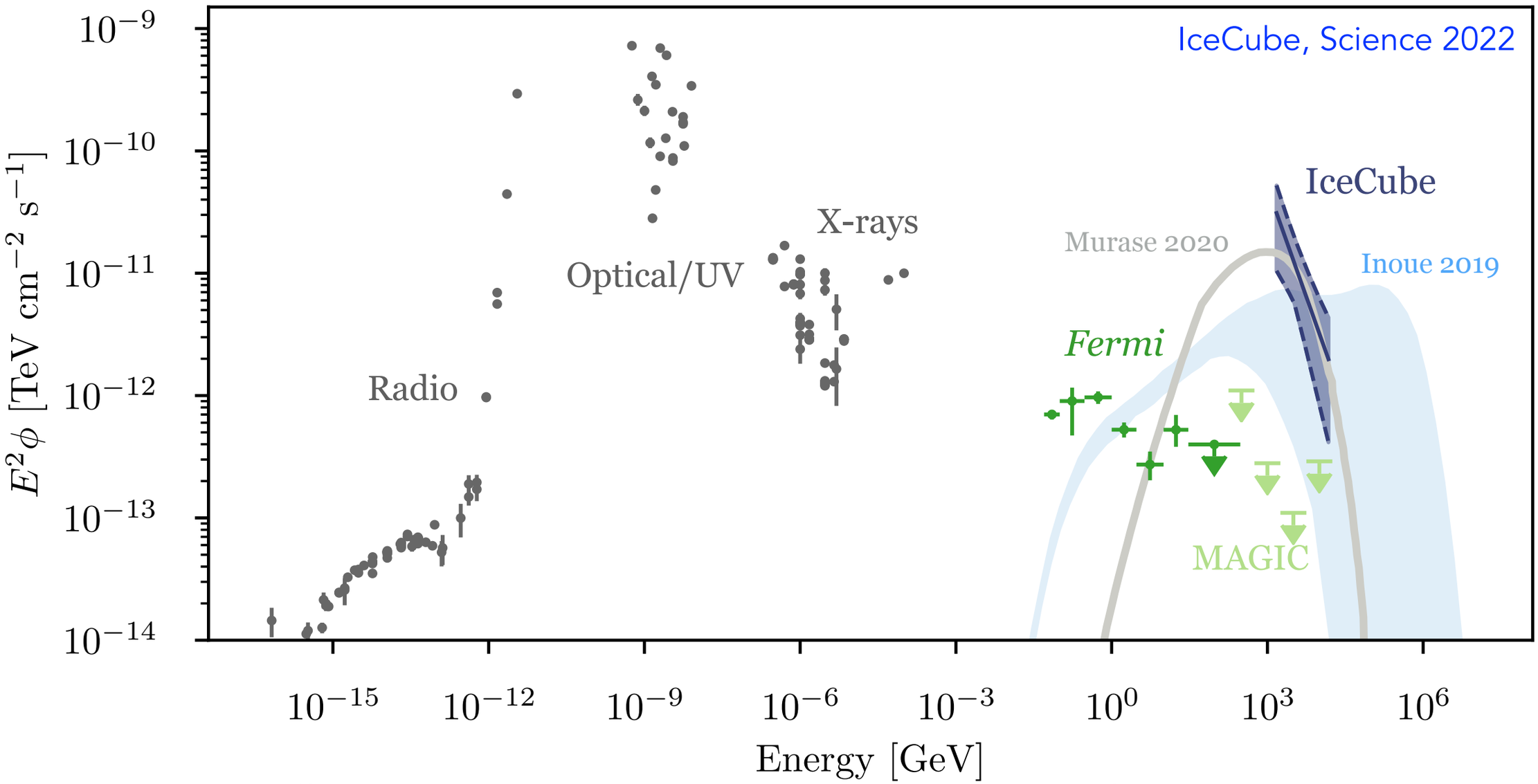
- Compton thick environment with Column density ~ 10^{25} cm^{-2}
- Bright in X-ray, and high infrared luminosity indicating high level of star formation
    - *Historically considered as a promising cosmic-ray accelerator.*

NGC 1068 Spectrum



- The neutrino flux much higher than the observed γ-ray flux by *Fermi*.
- Models built on measured γ-ray flux by *Fermi* 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 the vicinity of AGN core (< 100 R_s) [Murase, ApJL 2022]

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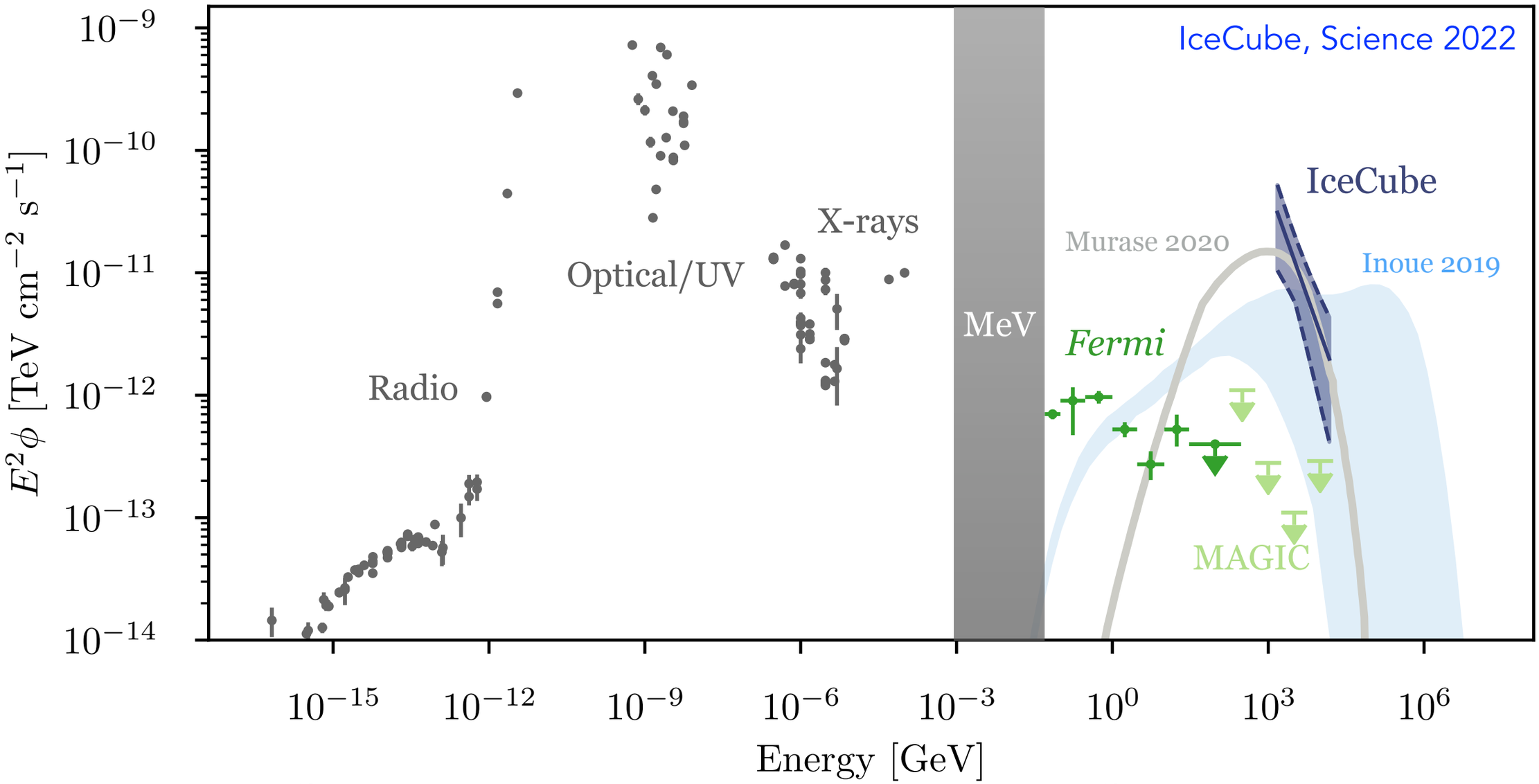

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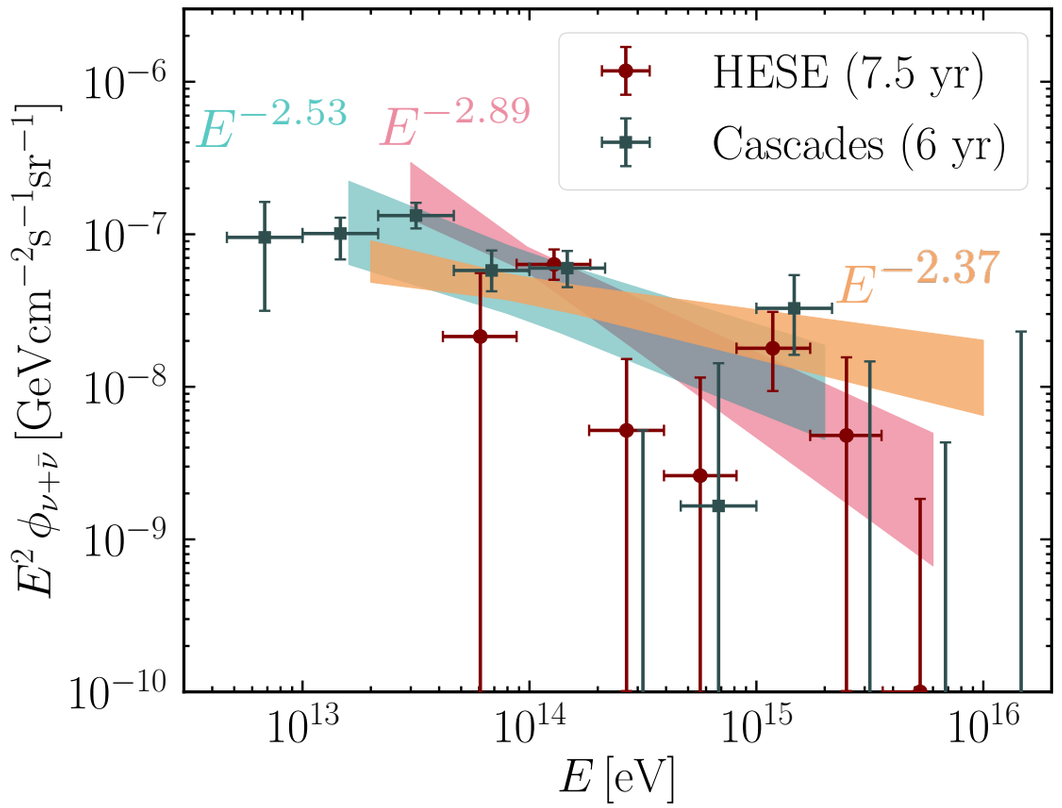
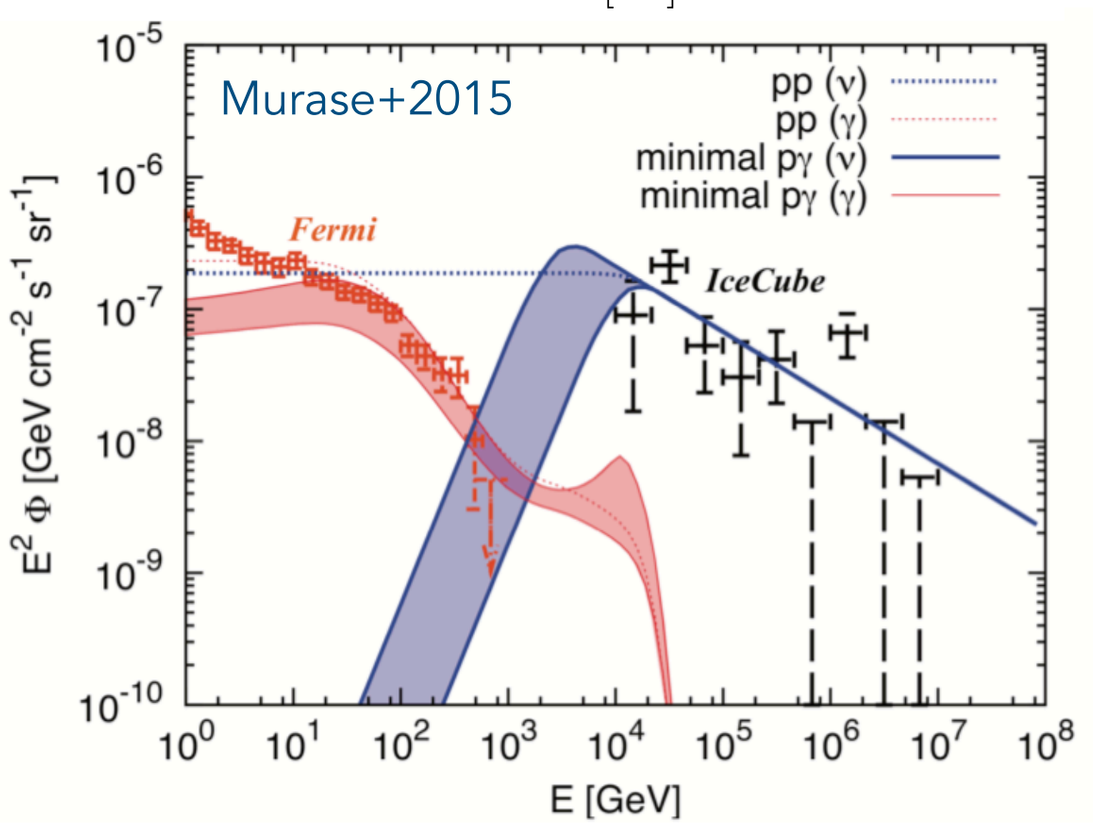
Medium-Energy Excess in Neutrino Flux

- Different slopes hint at structure in the flux of HE 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 HE neutrino flux at medium-energies to be **obscured** to GeV γ-rays. [Murase+ 2015, Fang+ 2022]
- Core of AGN can meet these conditions.





Medium-Energy Excess in Neutrino Flux

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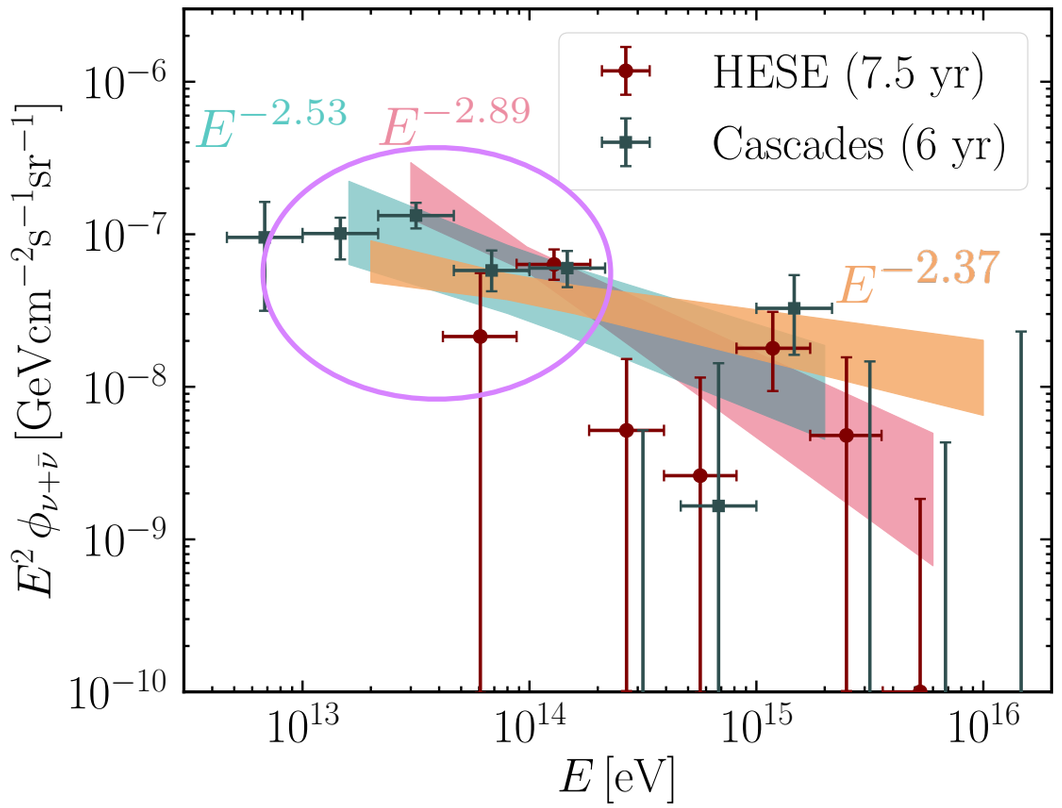

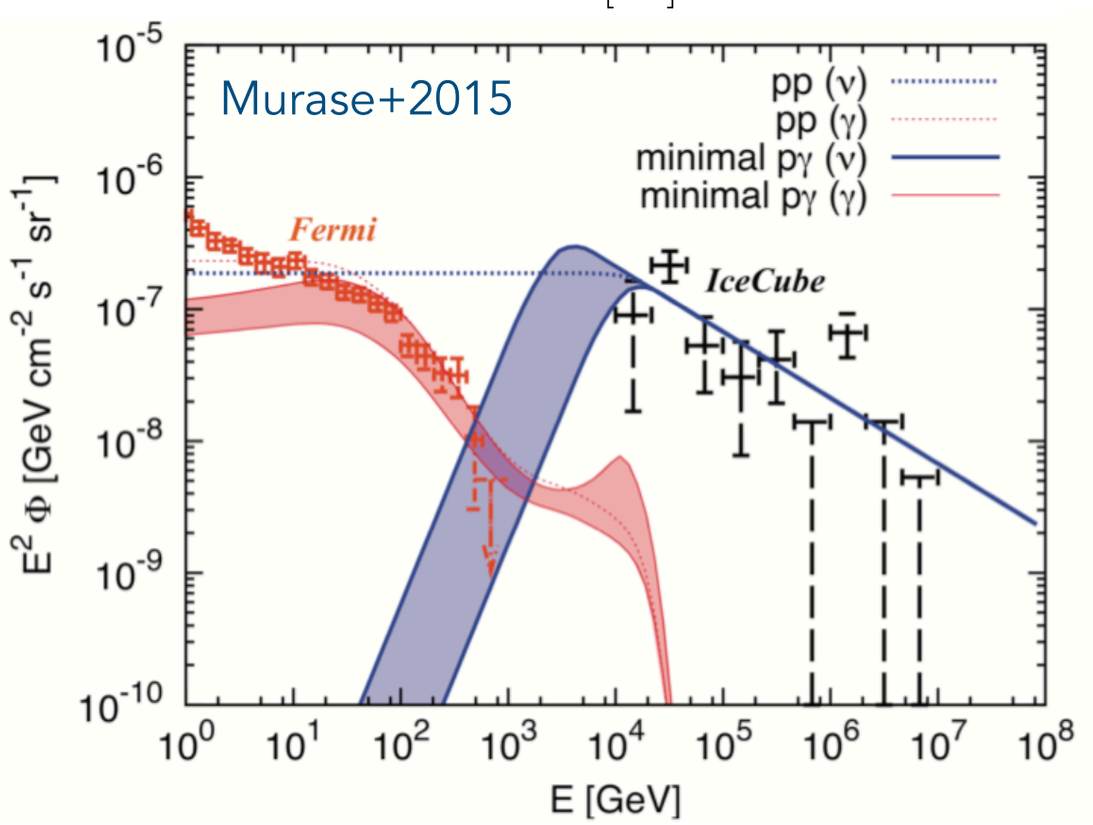

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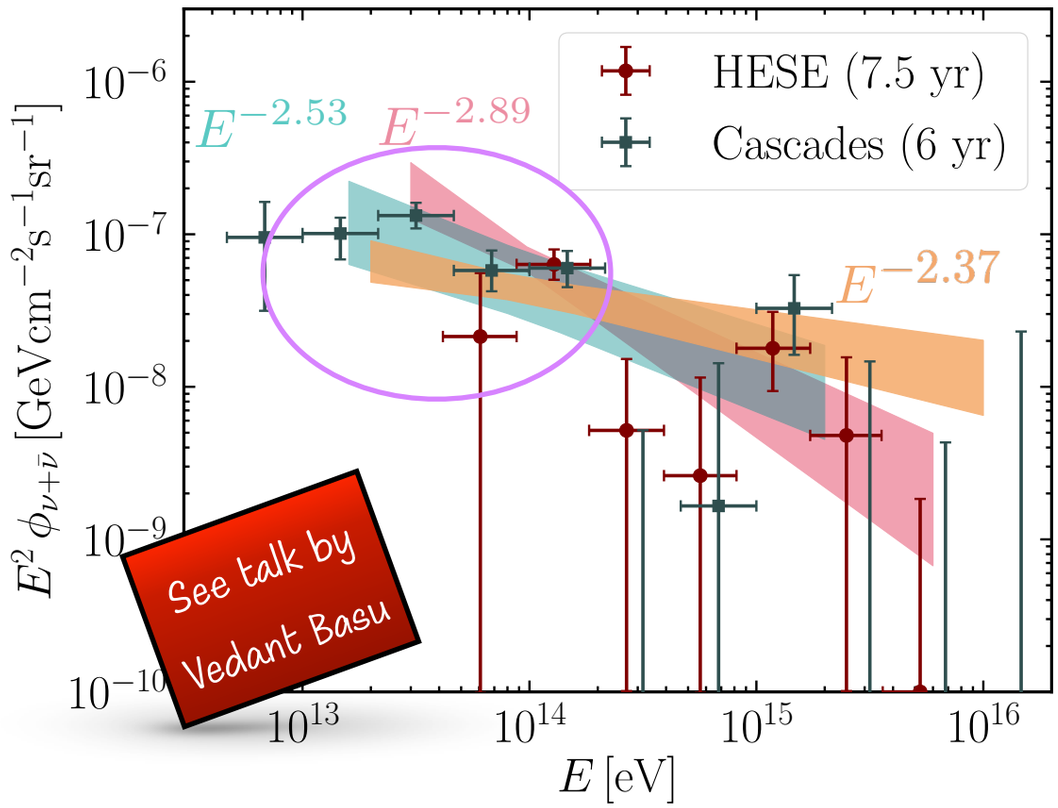

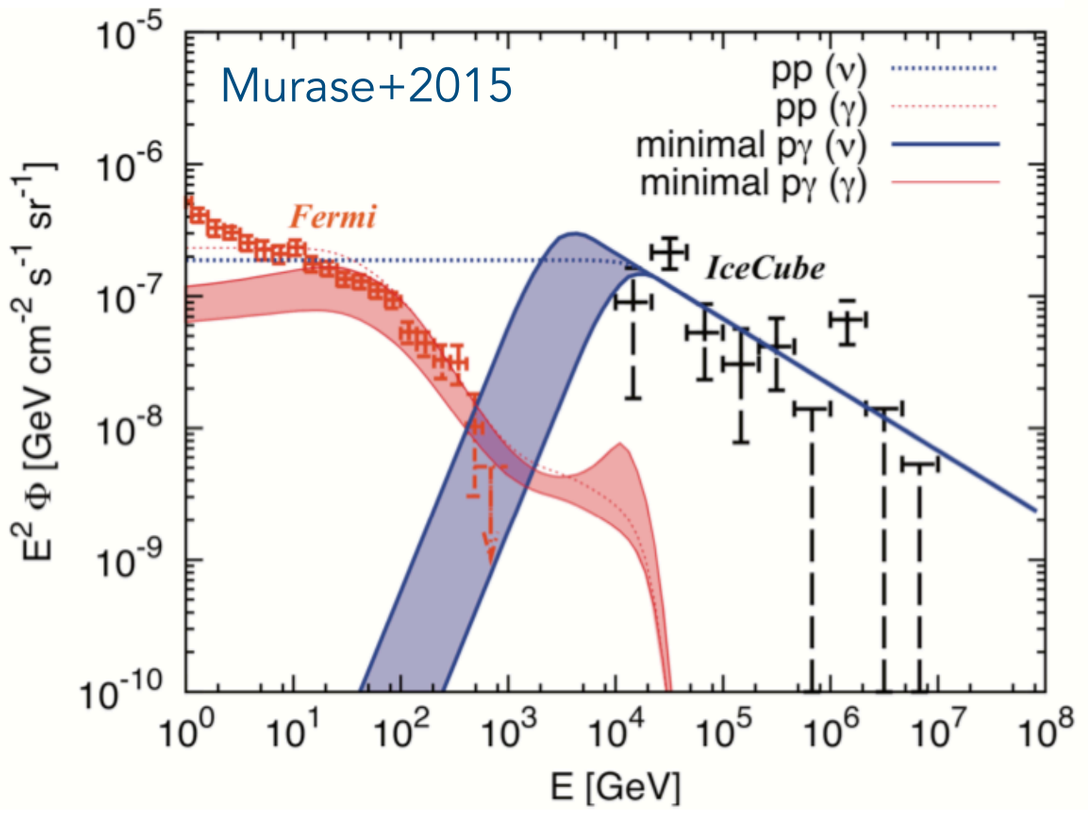

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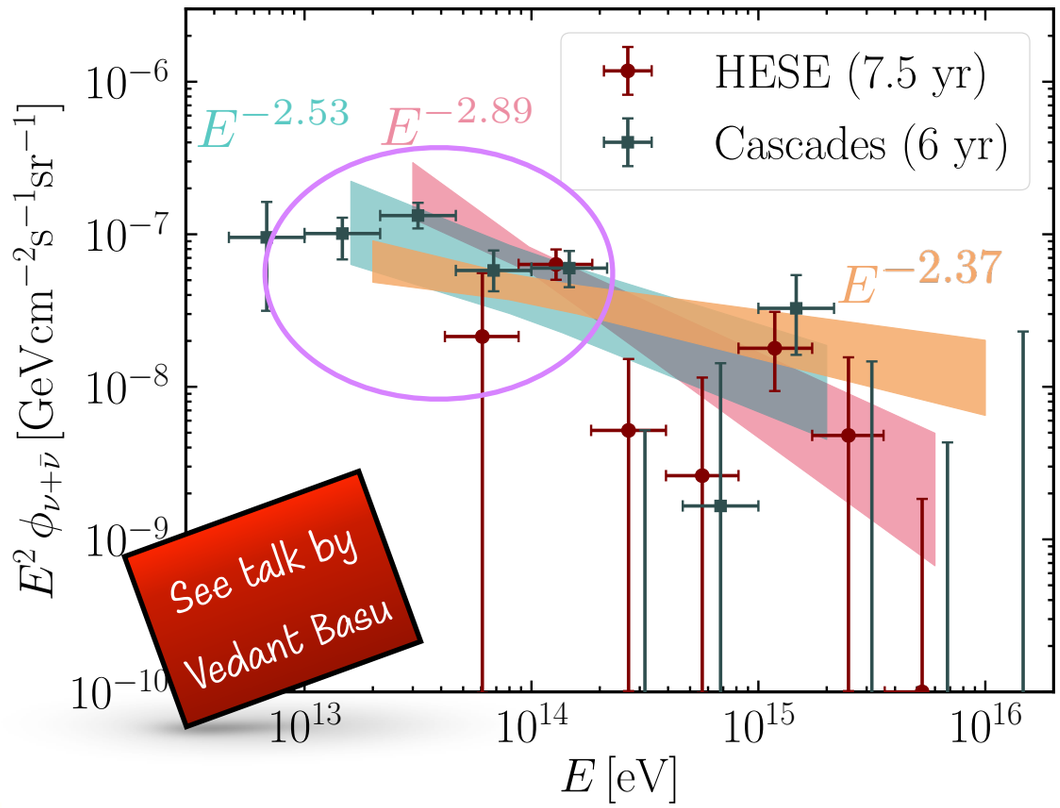

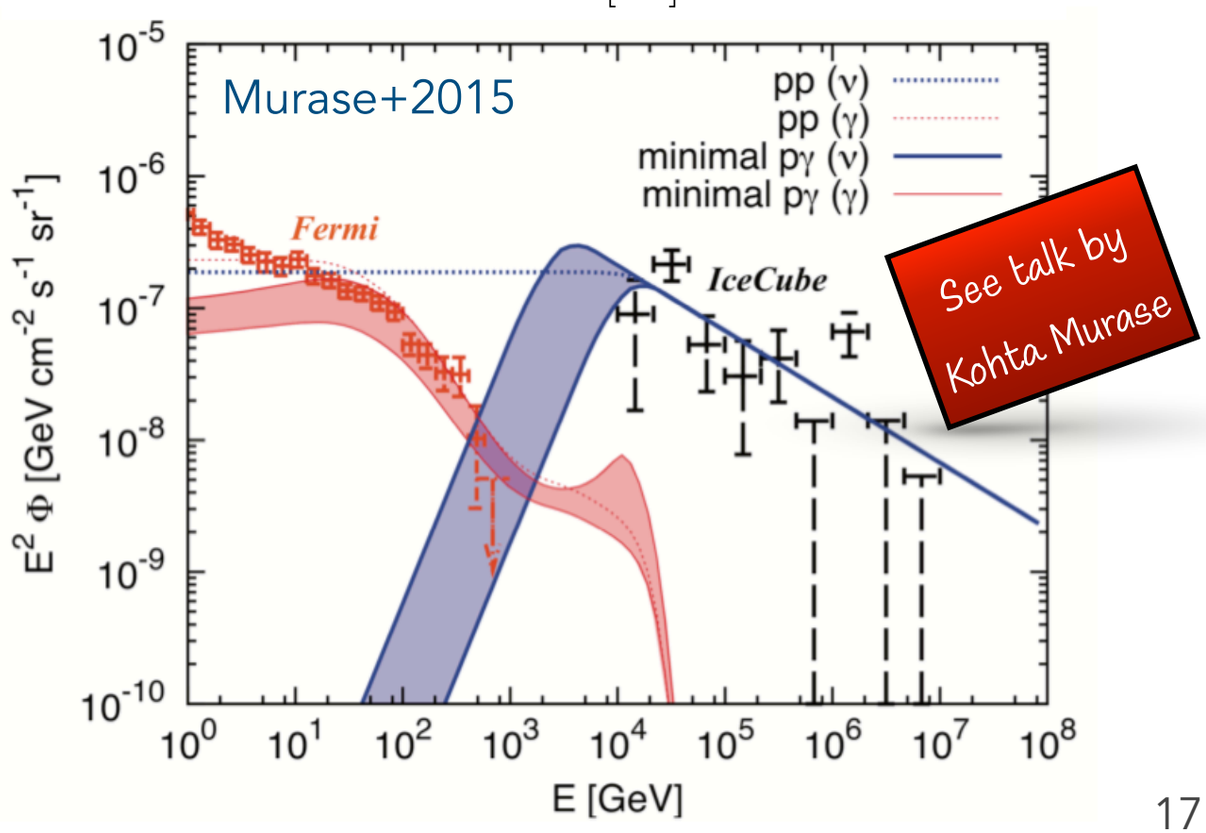

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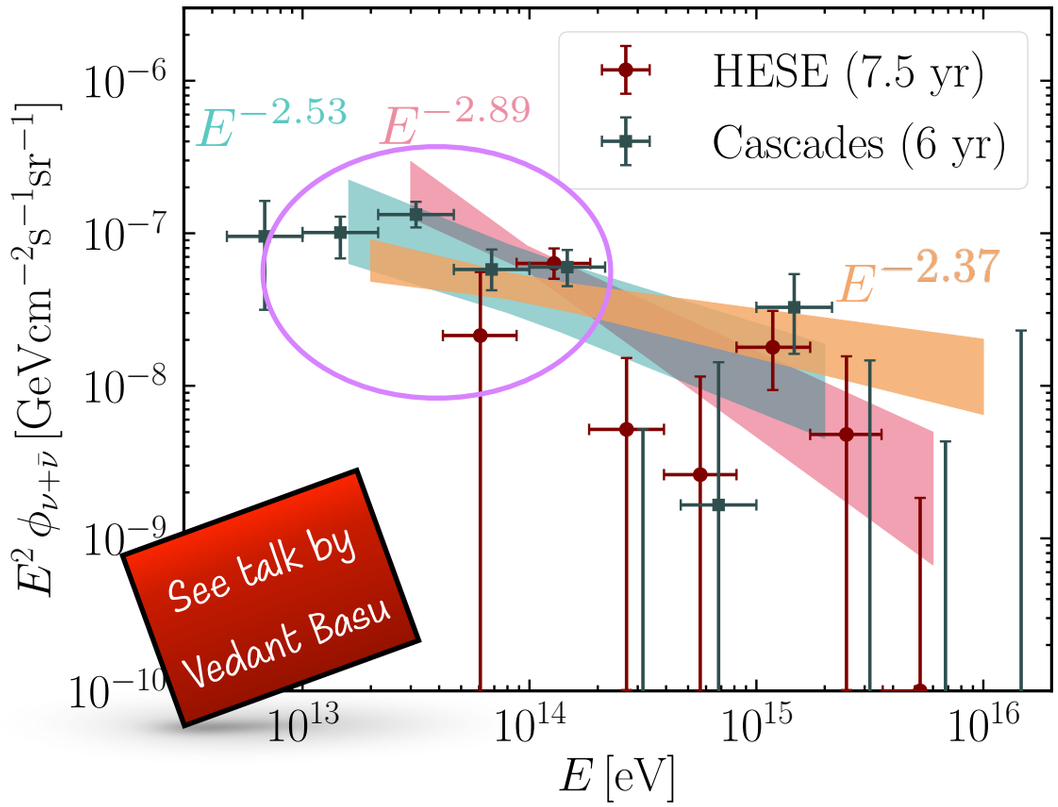

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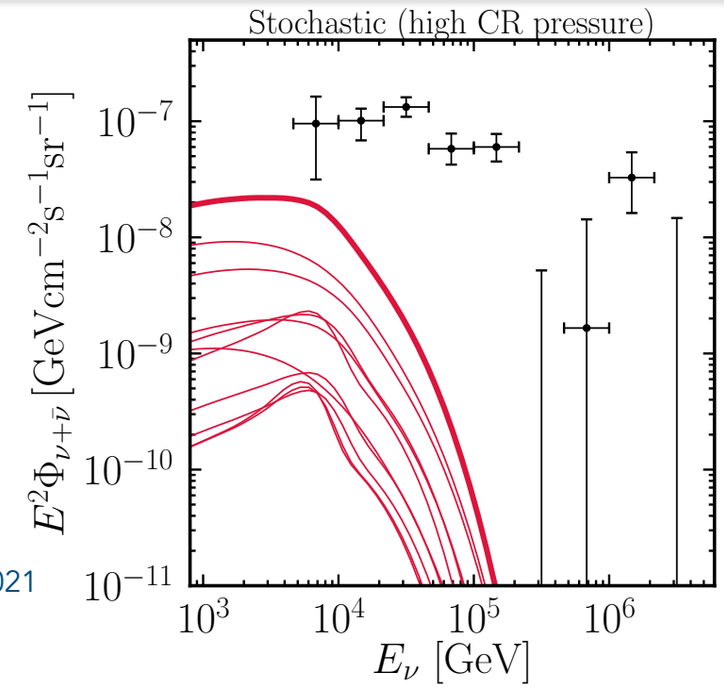
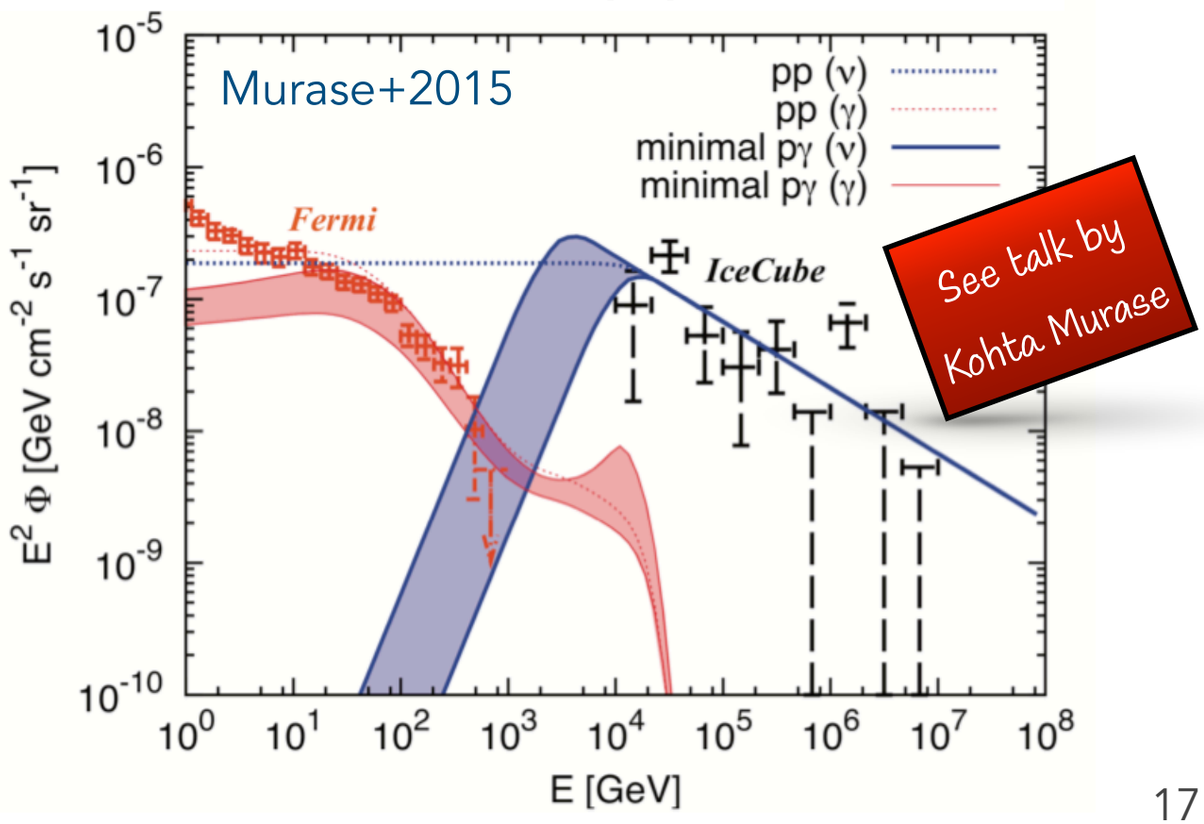
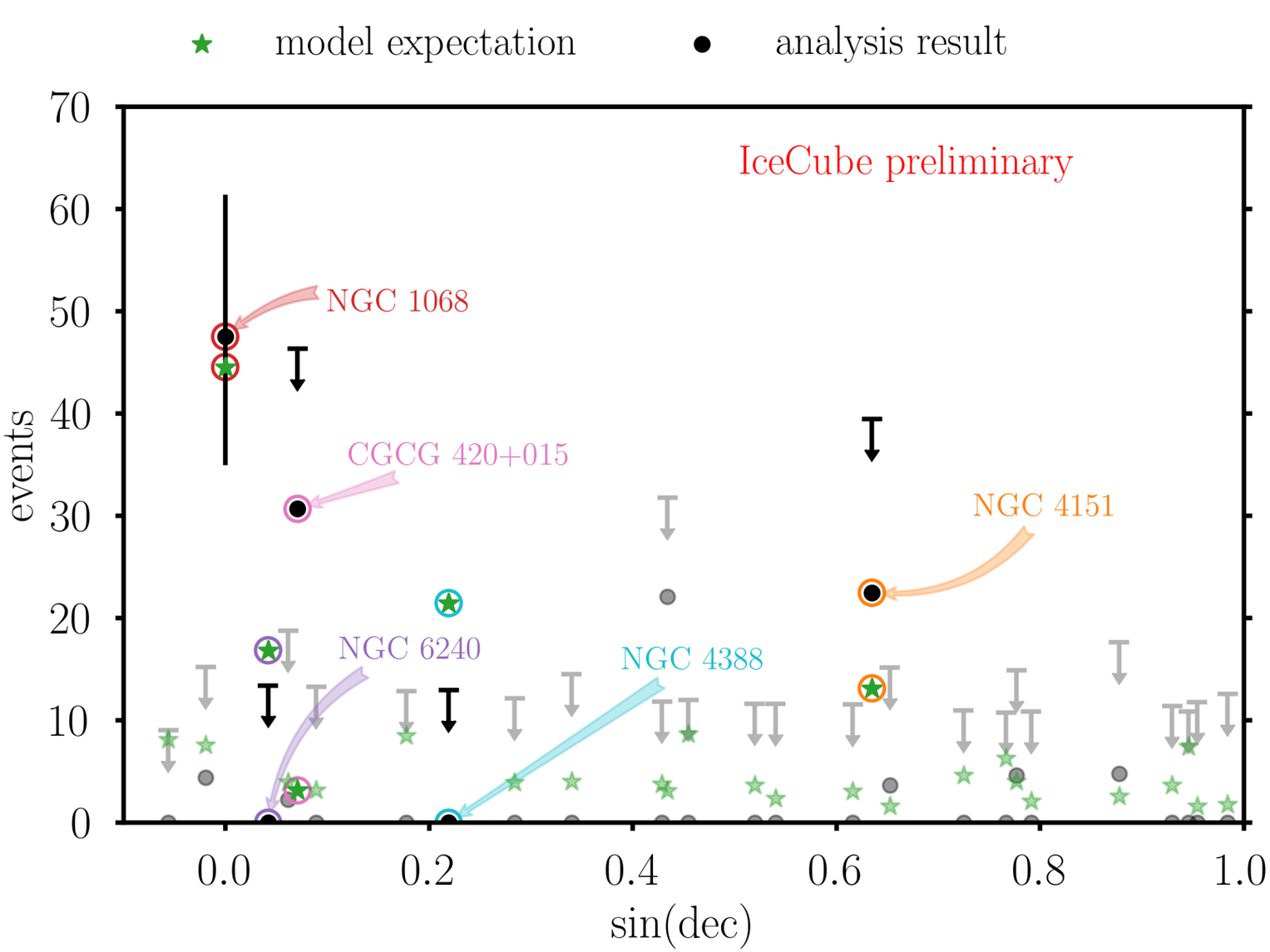
Expected flux from nearby bright seyfert galaxies in disk-corona model compatible with NGC 1068 flux

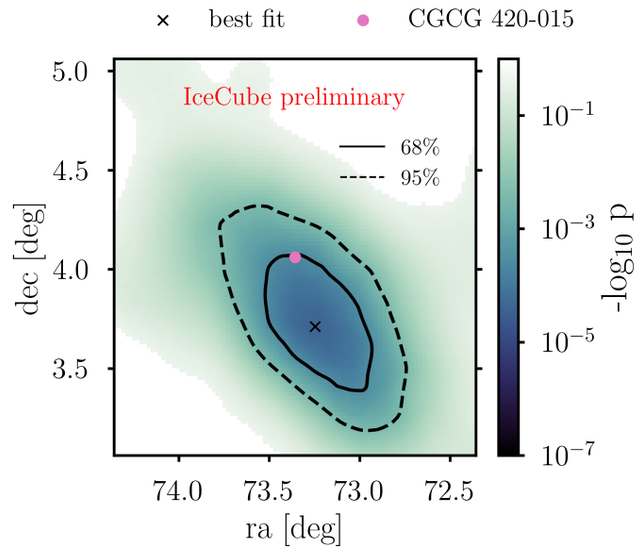
AK, Murase, Kimura, ApJ 2021



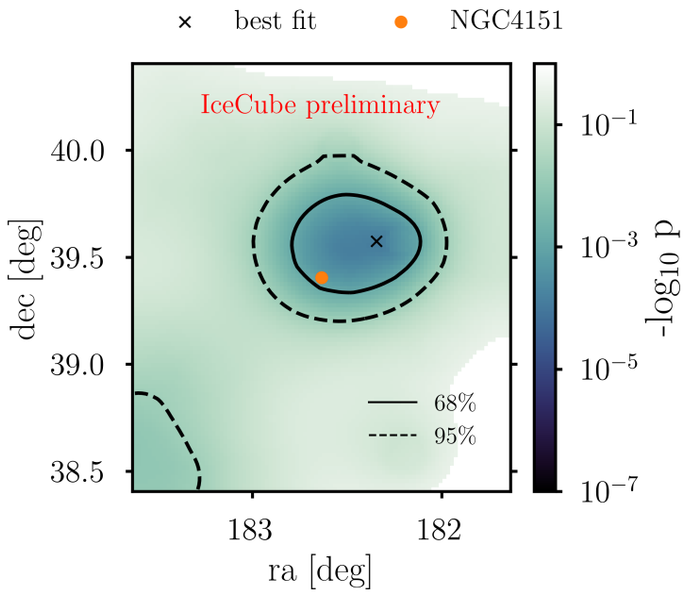


Neutrinos from Bright Seyferts in Northern Sky



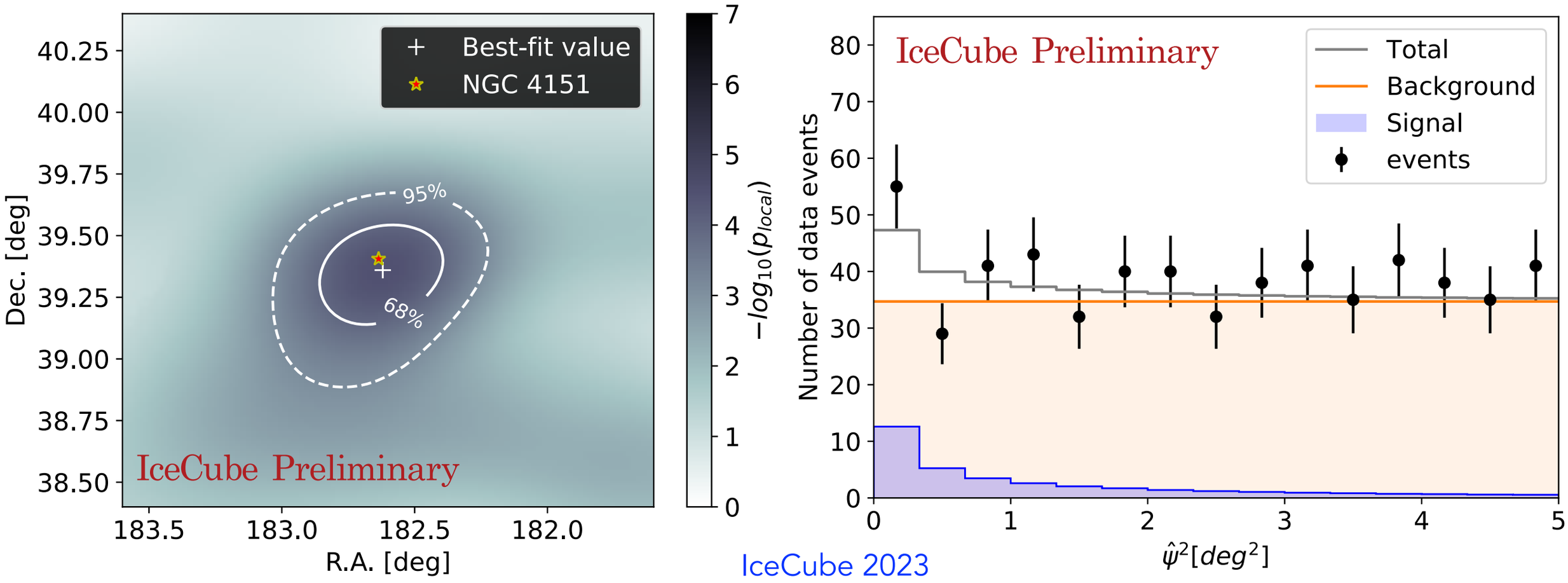


IceCube 2023



- 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 2023

- NGC 4151 appears at 2.9σ (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
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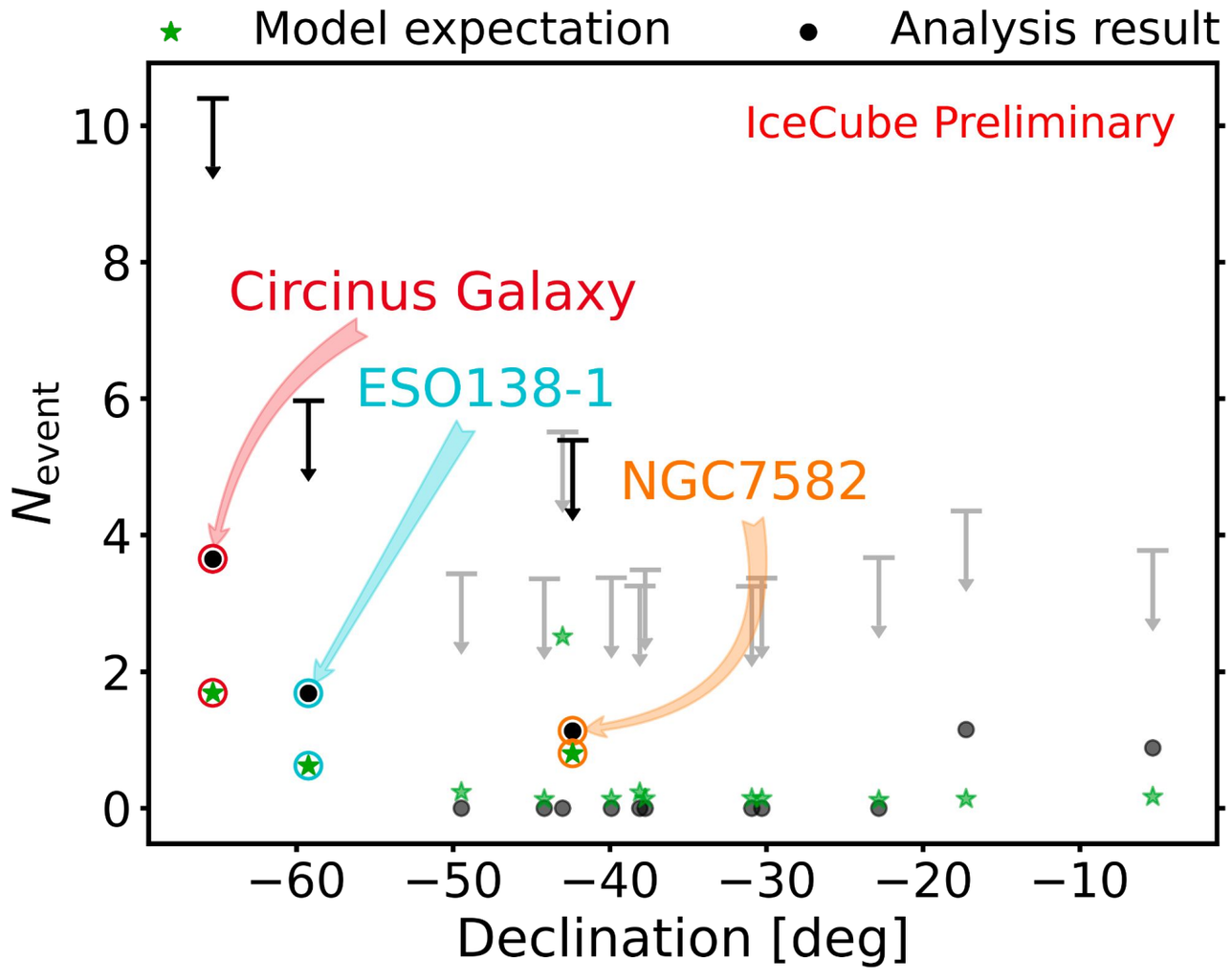

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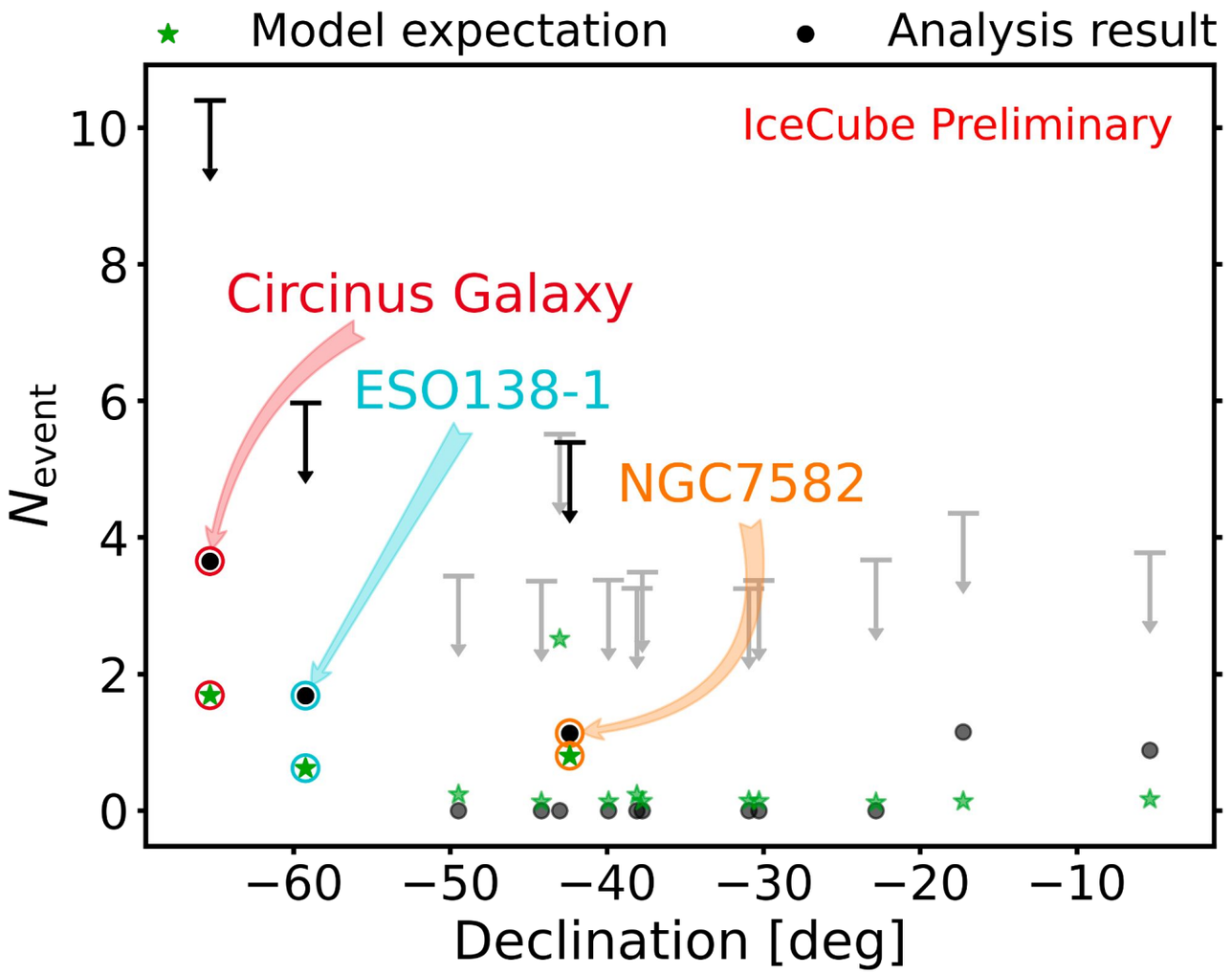
  - 3.6 neutrino events at 2.8σ local significance (1.8σ post trial)



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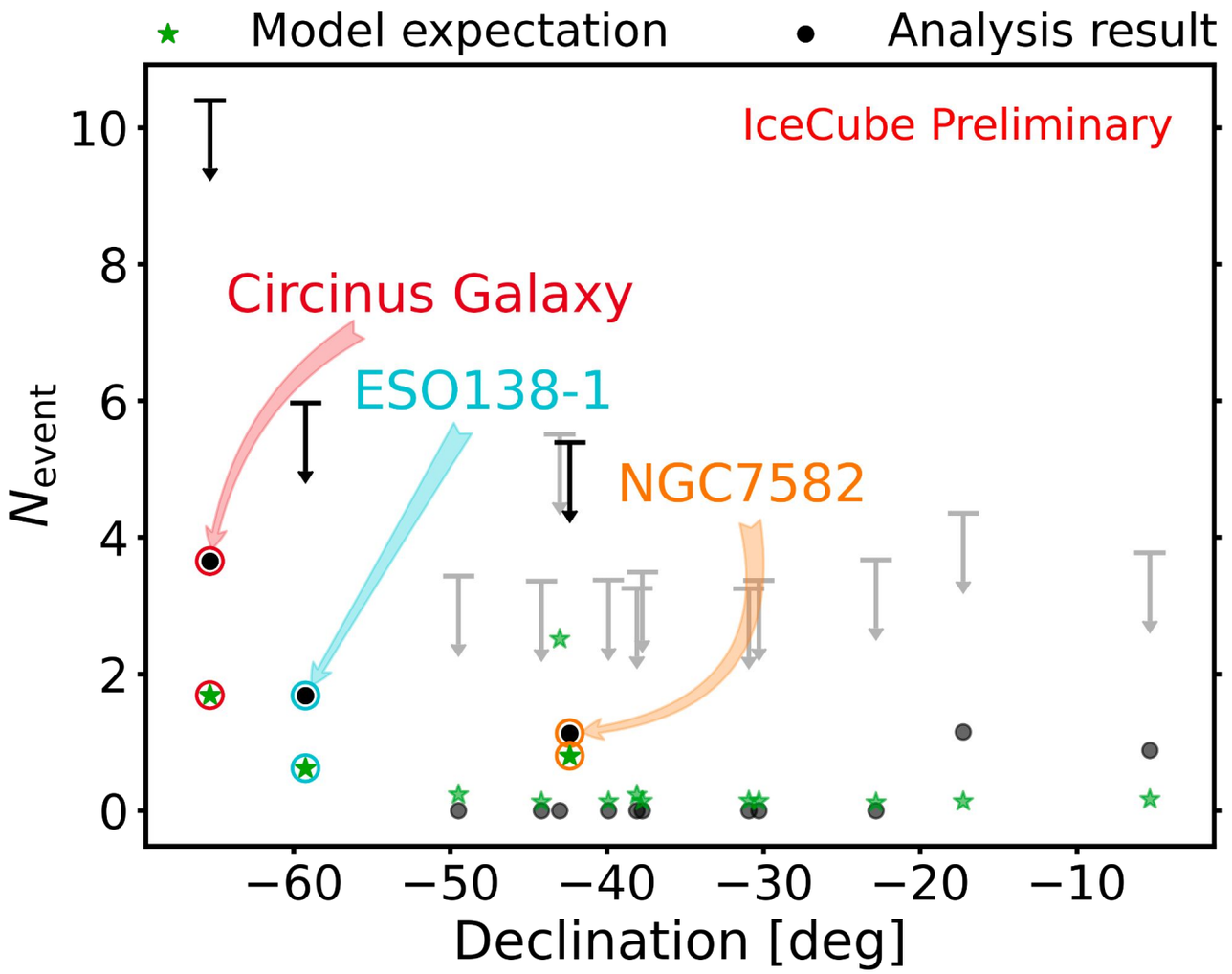

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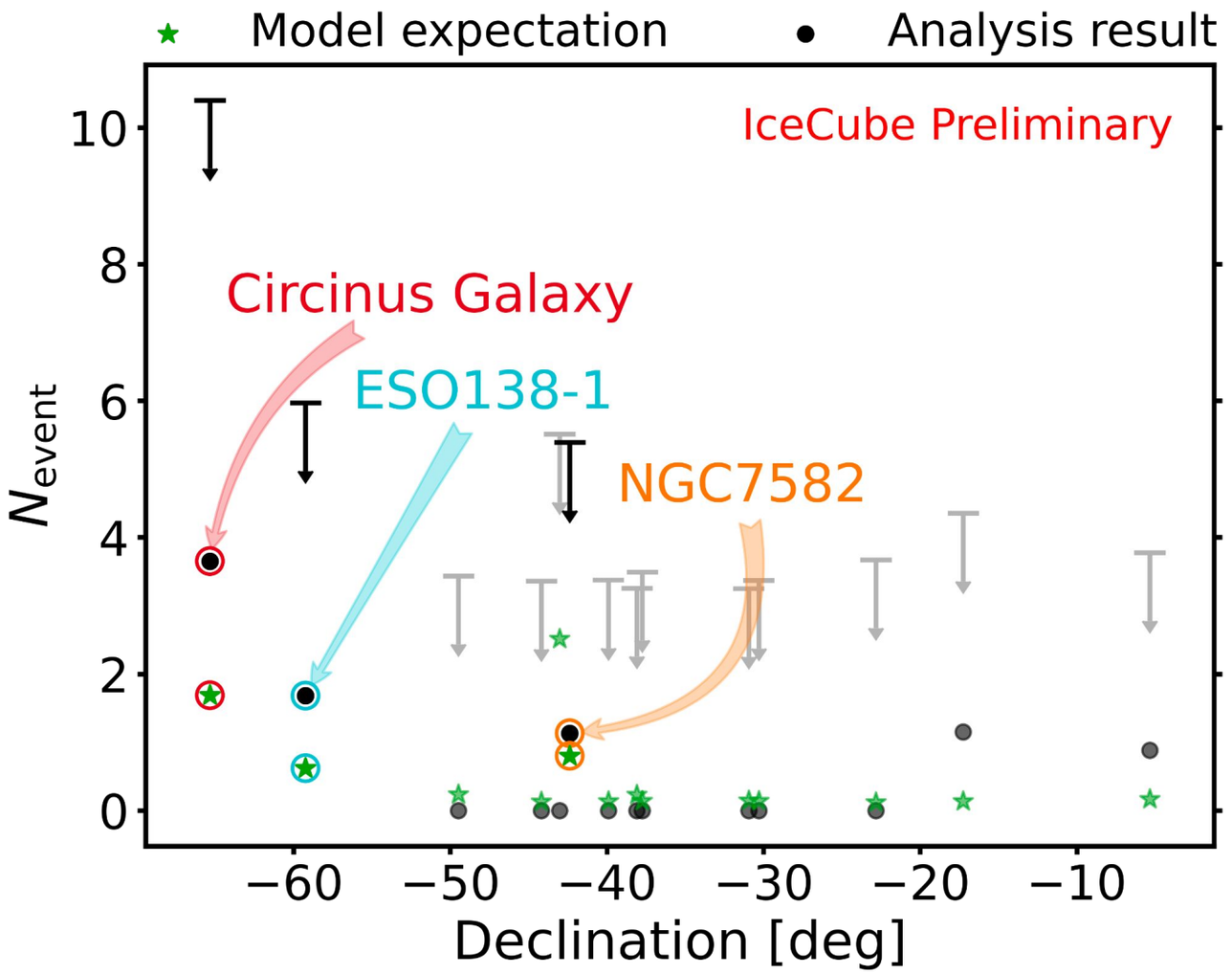
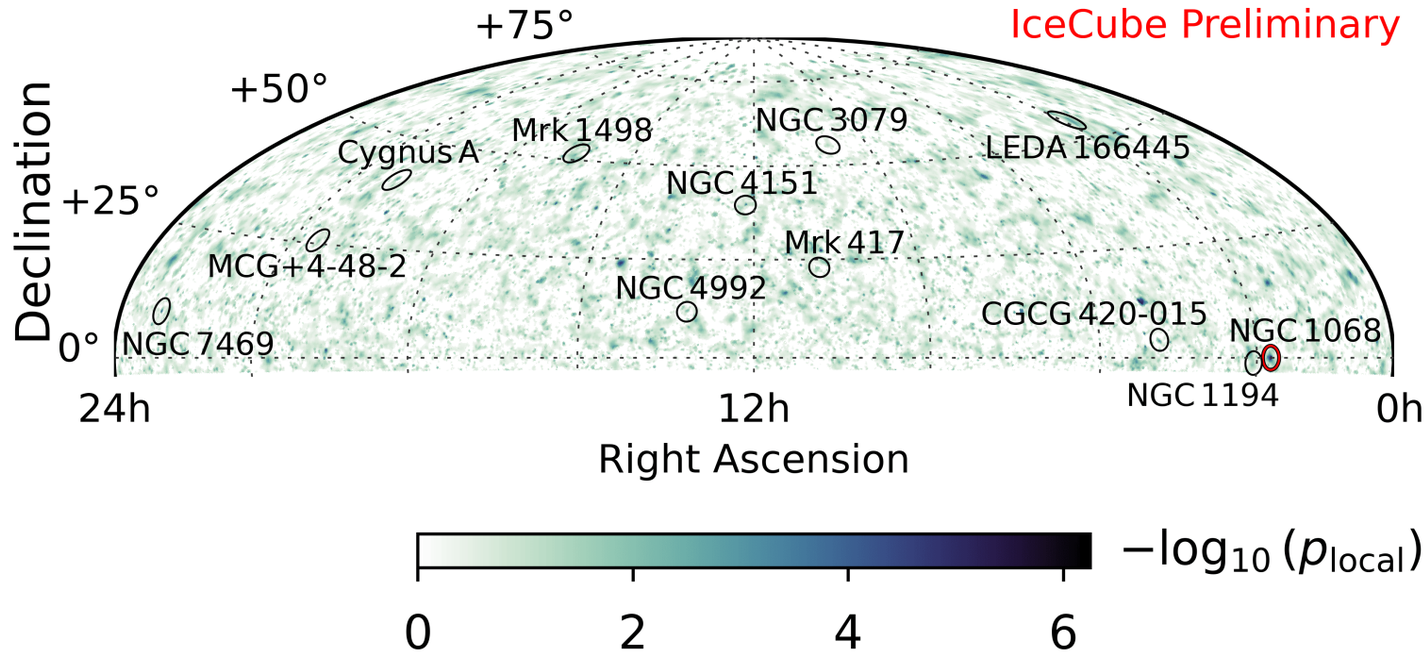
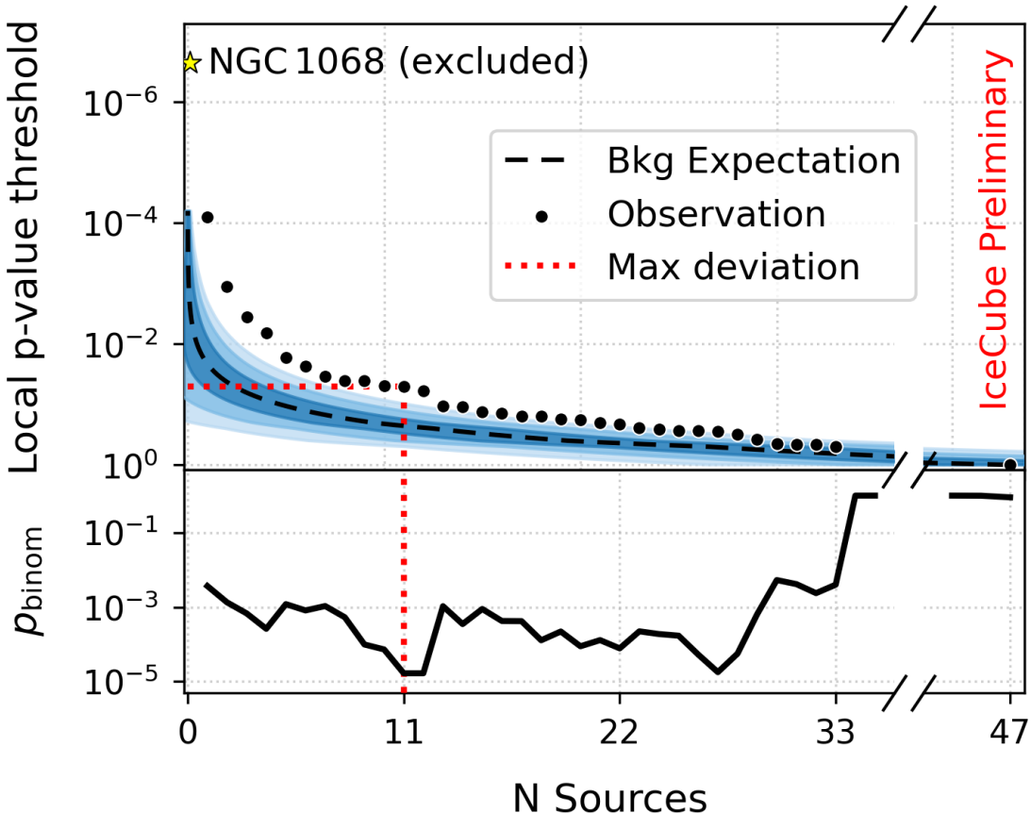
- Stacking analysis:
  - ► 6.7 events at 3σ

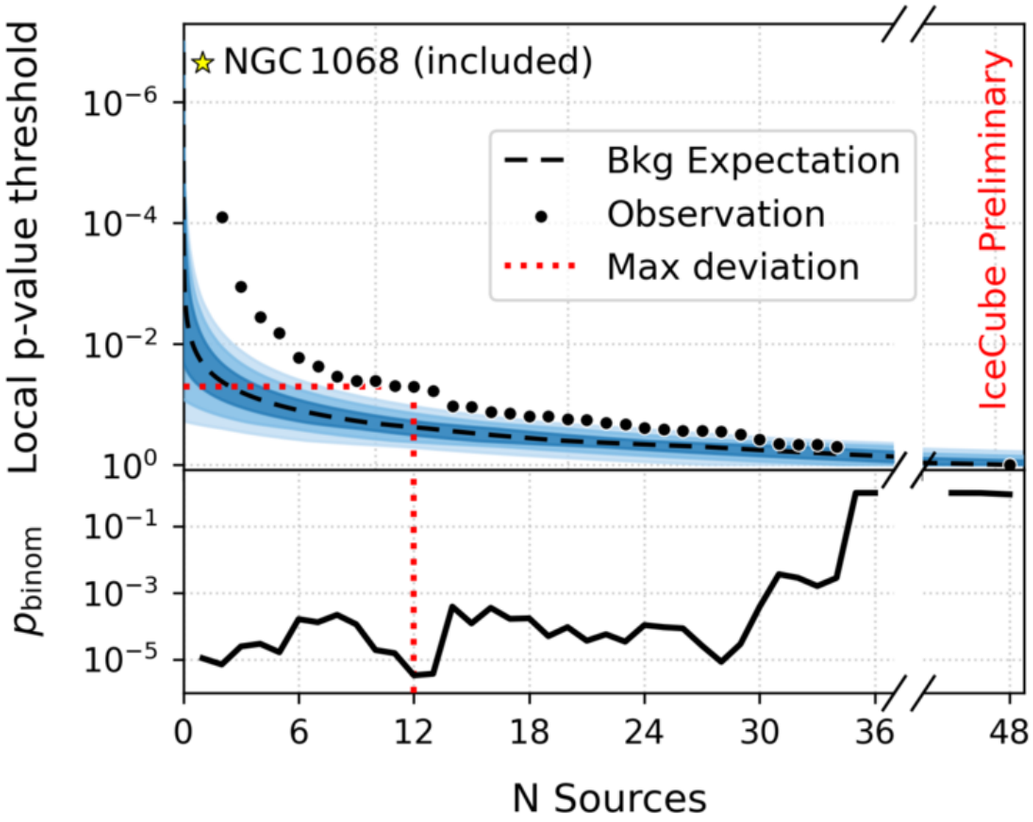


13 yr NT Seyfert Search

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







IceCube Search for Neutrino Emission from Seyfert Galaxies

- 2.9σ ▸ Correlation with Hard X-ray AGN
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  - A subset of sources follow have high CR pressure similar to NGC 1068
  - To find more sources: we need to identify more sources with characteristics similar to NGC 1068 → additional info, other than X-ray intrinsic luminosity is needed to for source selection
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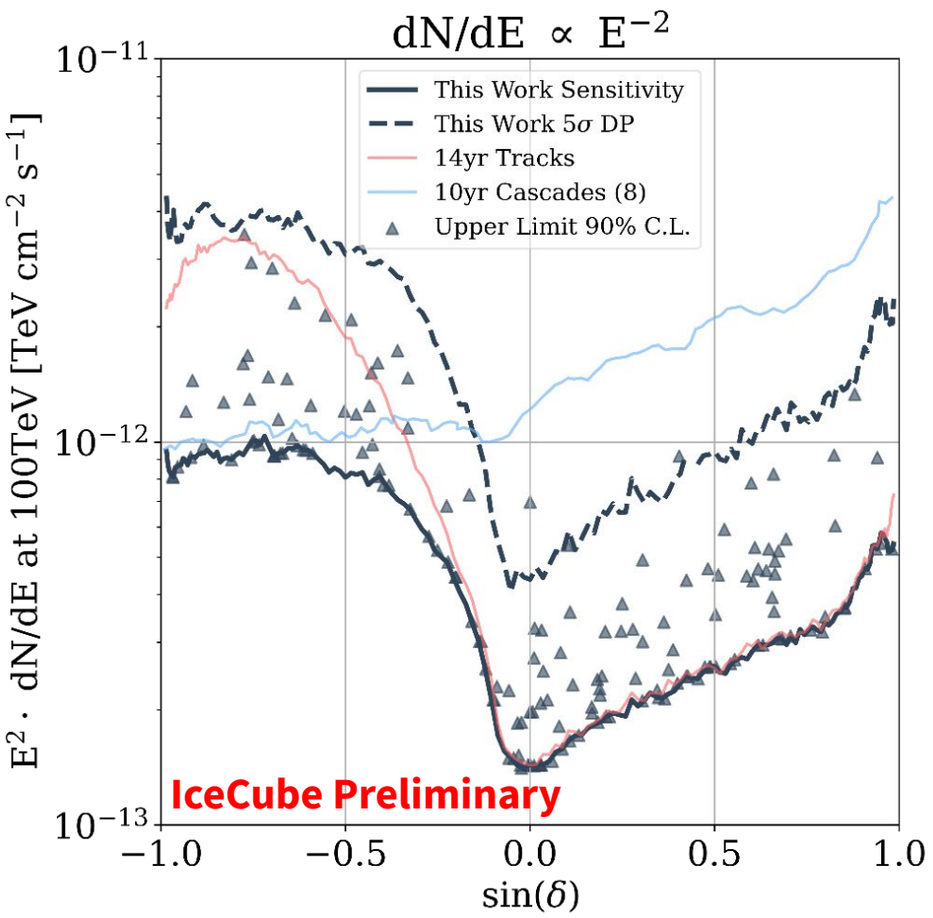
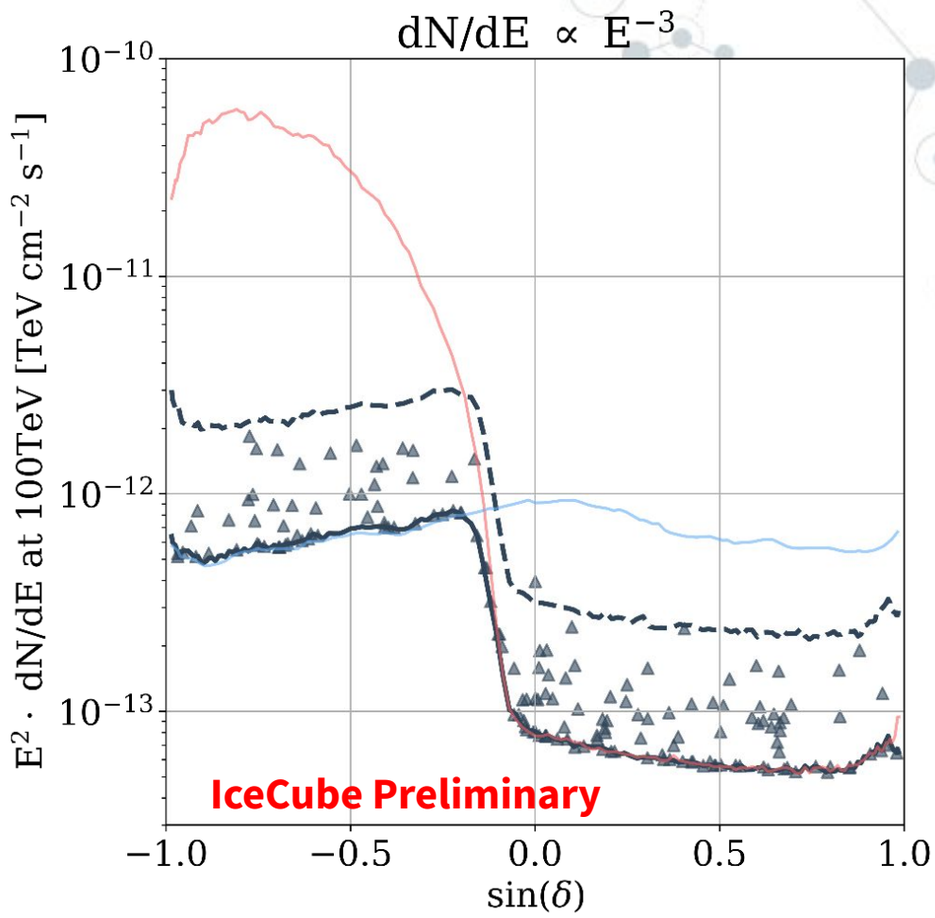
See talk by Kohta Murase

All-flavor Search for Nu Sources





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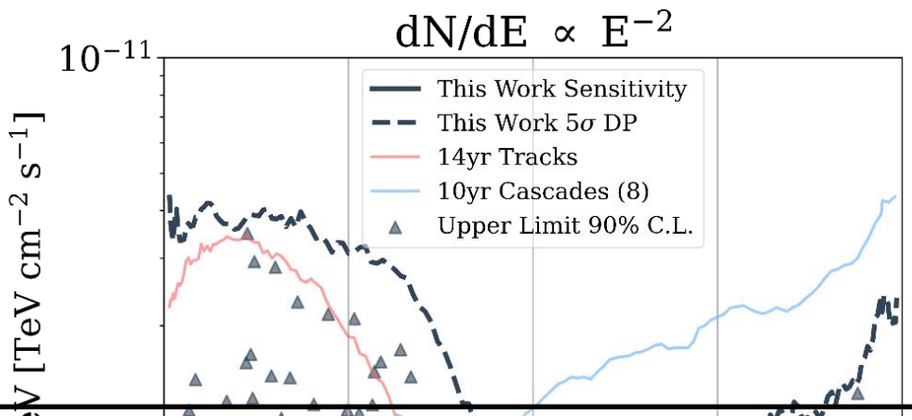
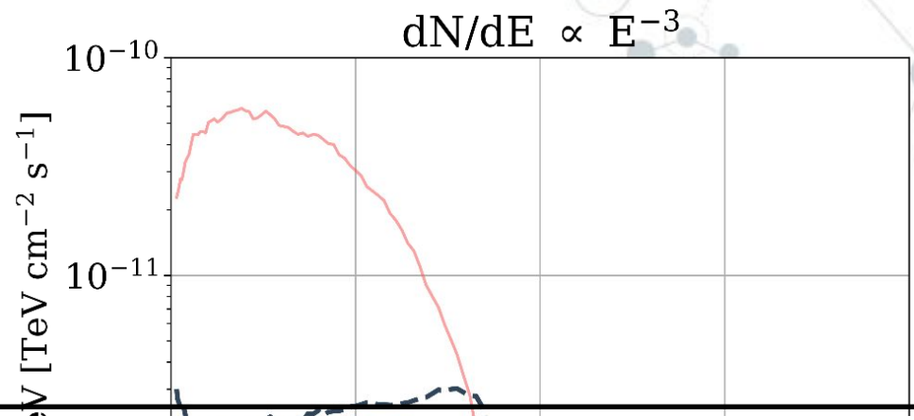
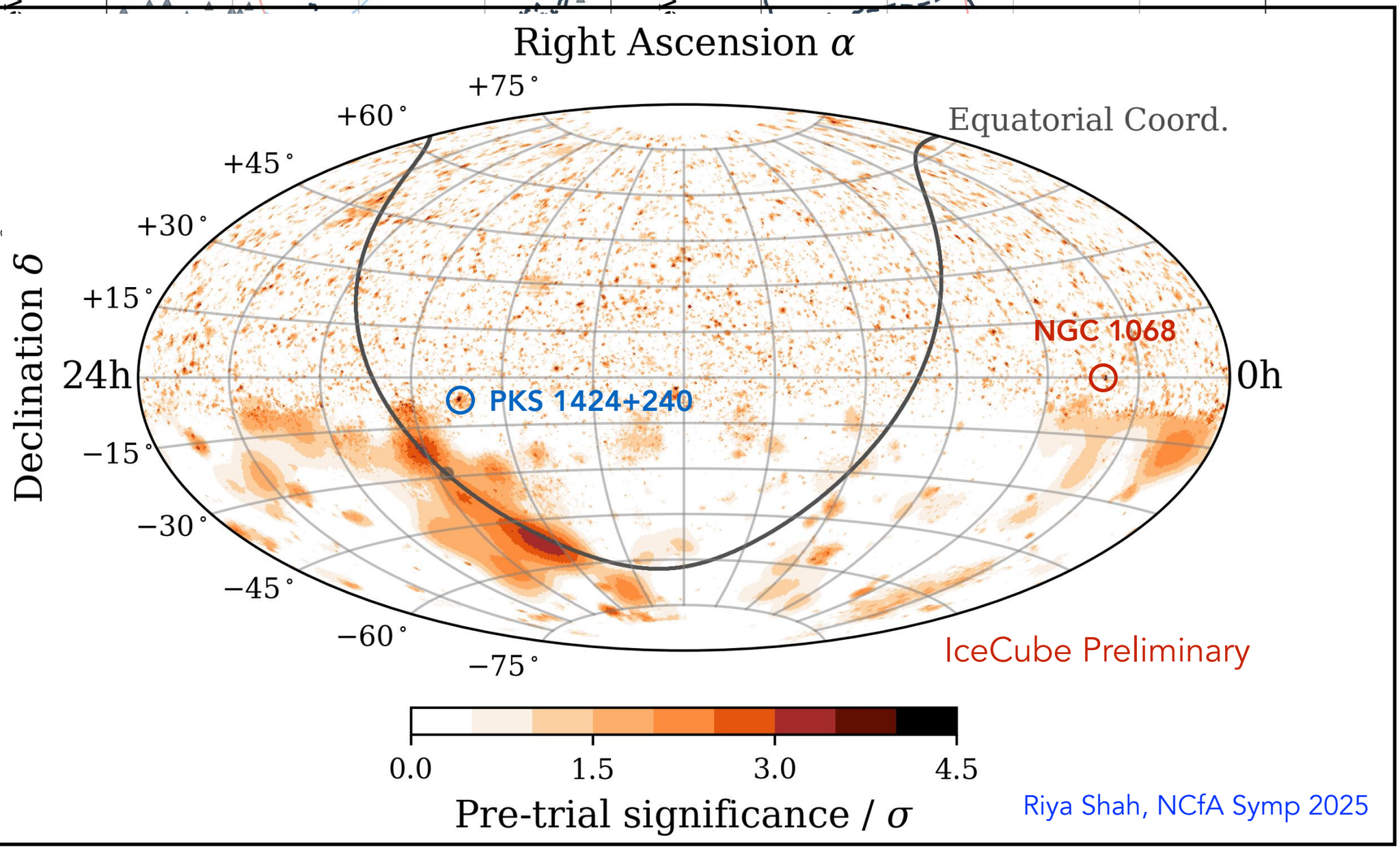
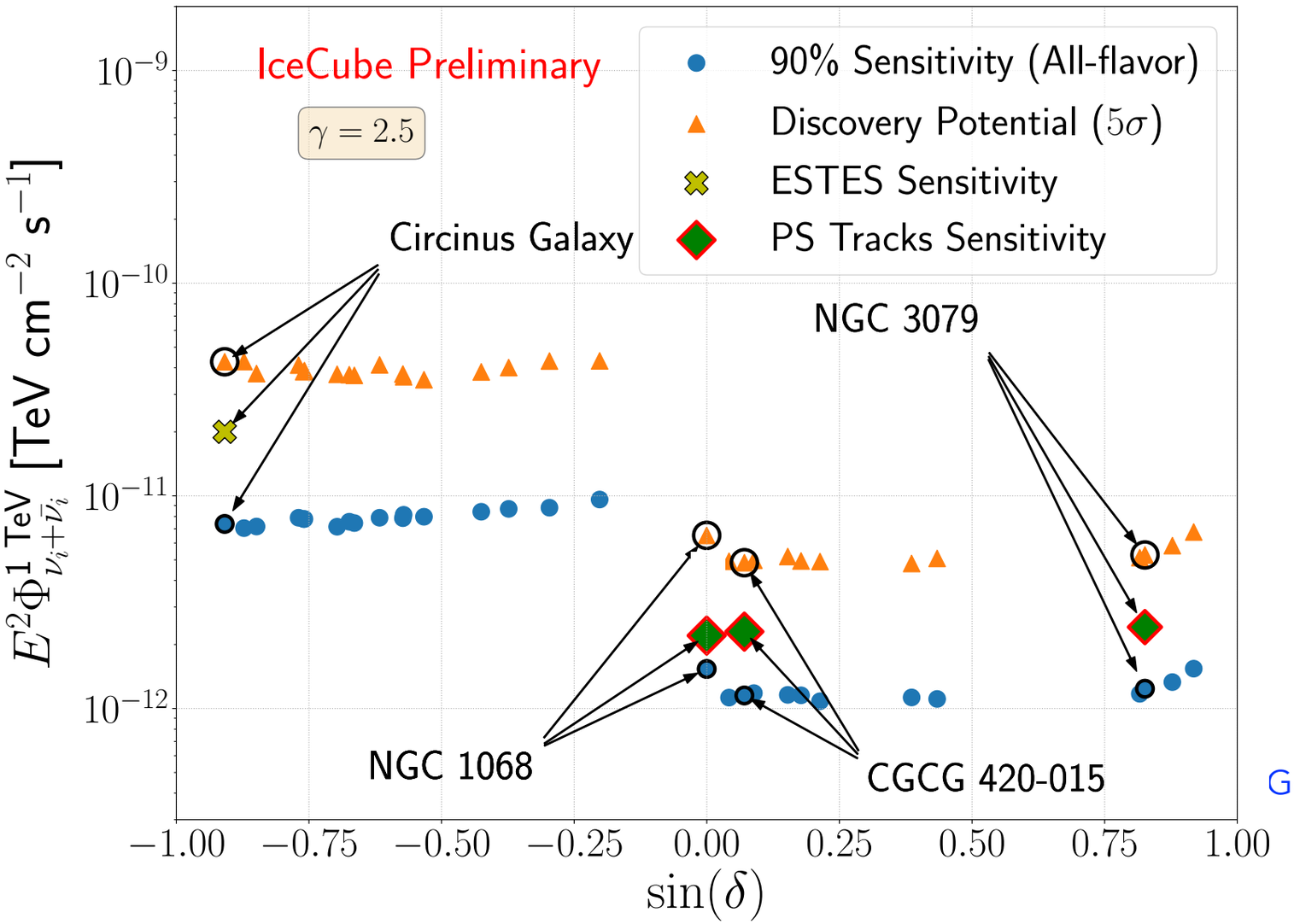






Riya Shah, NCfA Symp 2025

All flavor search for nu from Compton Thick AGN

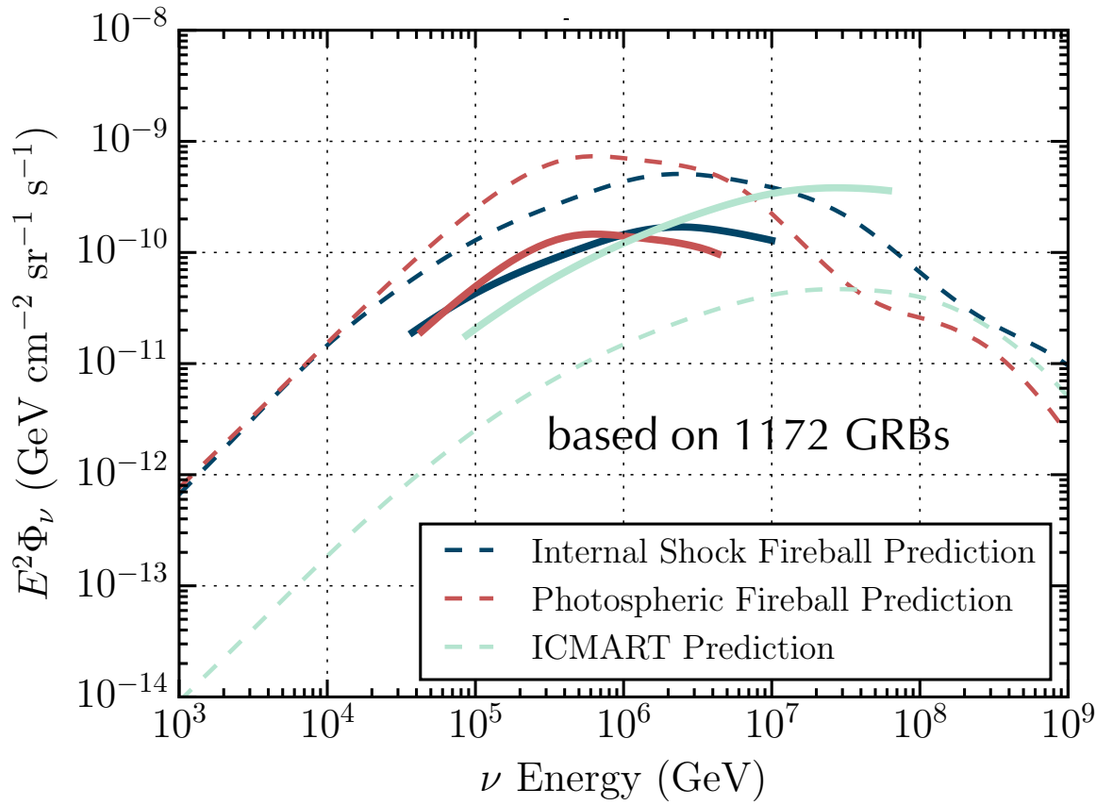


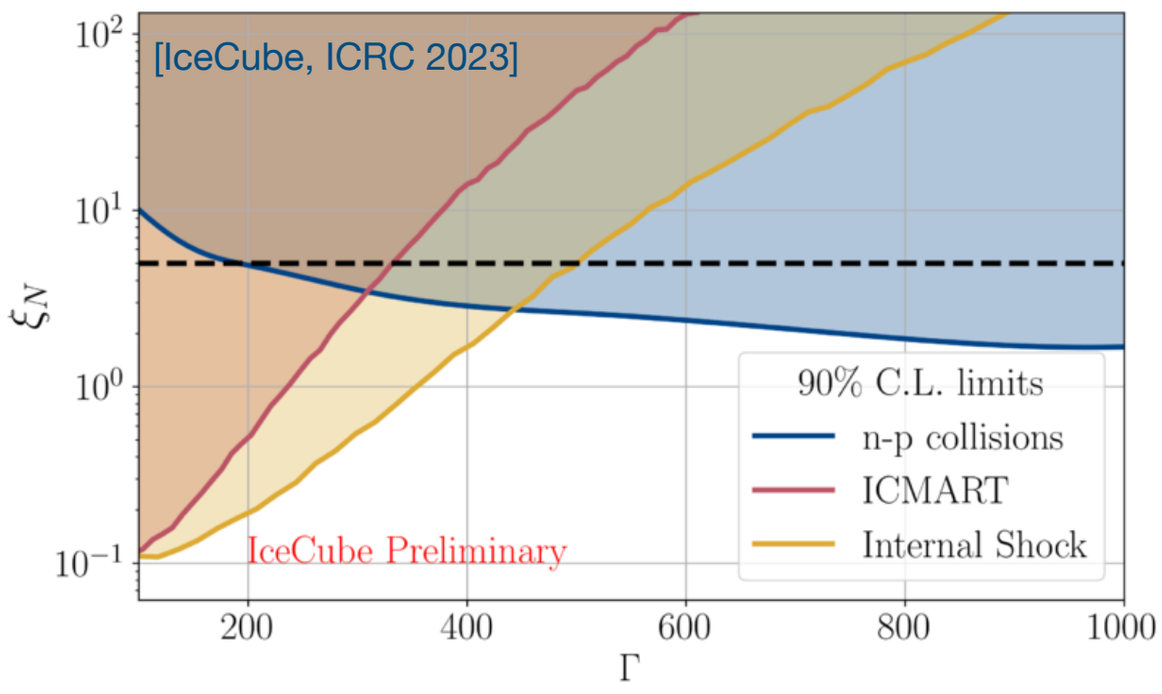
Goswami, NCfA Symp 2025

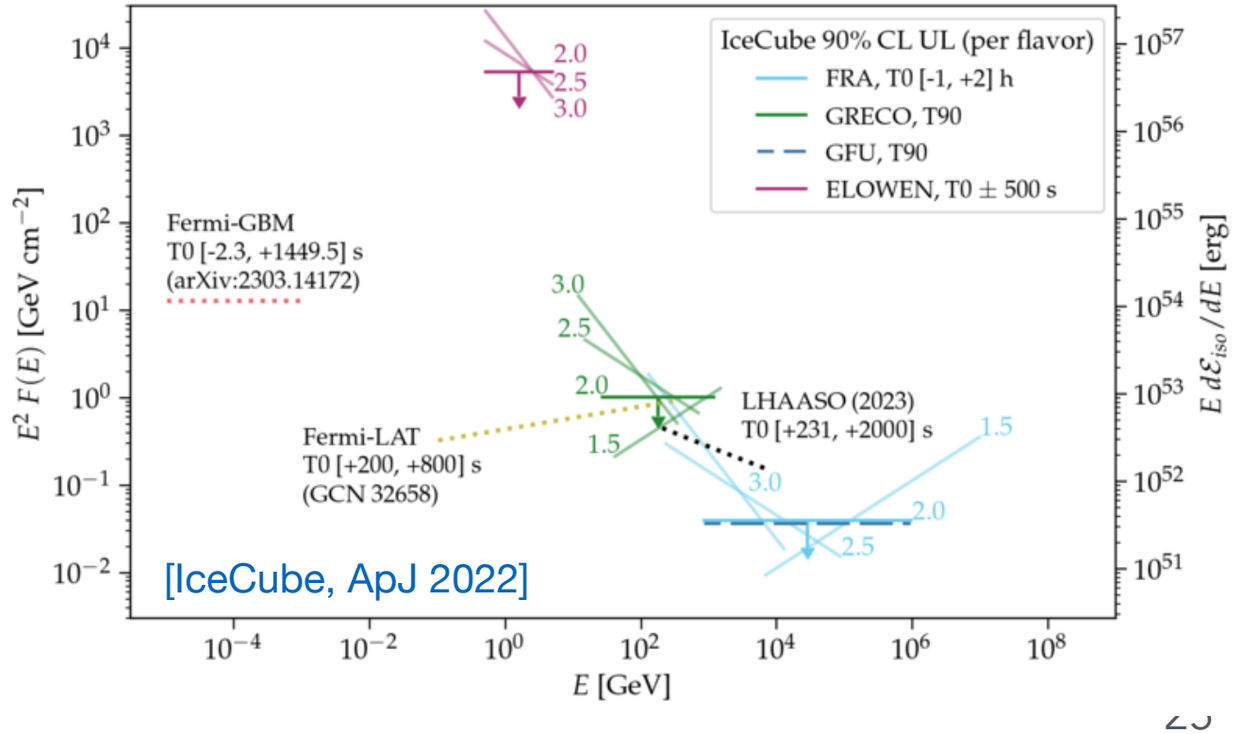
- **All flavor** search by combining DNNCascade (12 yr), Northern Tracks (13 yr), and ESTES (~10 yr)
  - *Obtaining the best accessible all-sky sensitivity*
- Using the most up-to-date and comprehensive study of obscured AGN cores

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

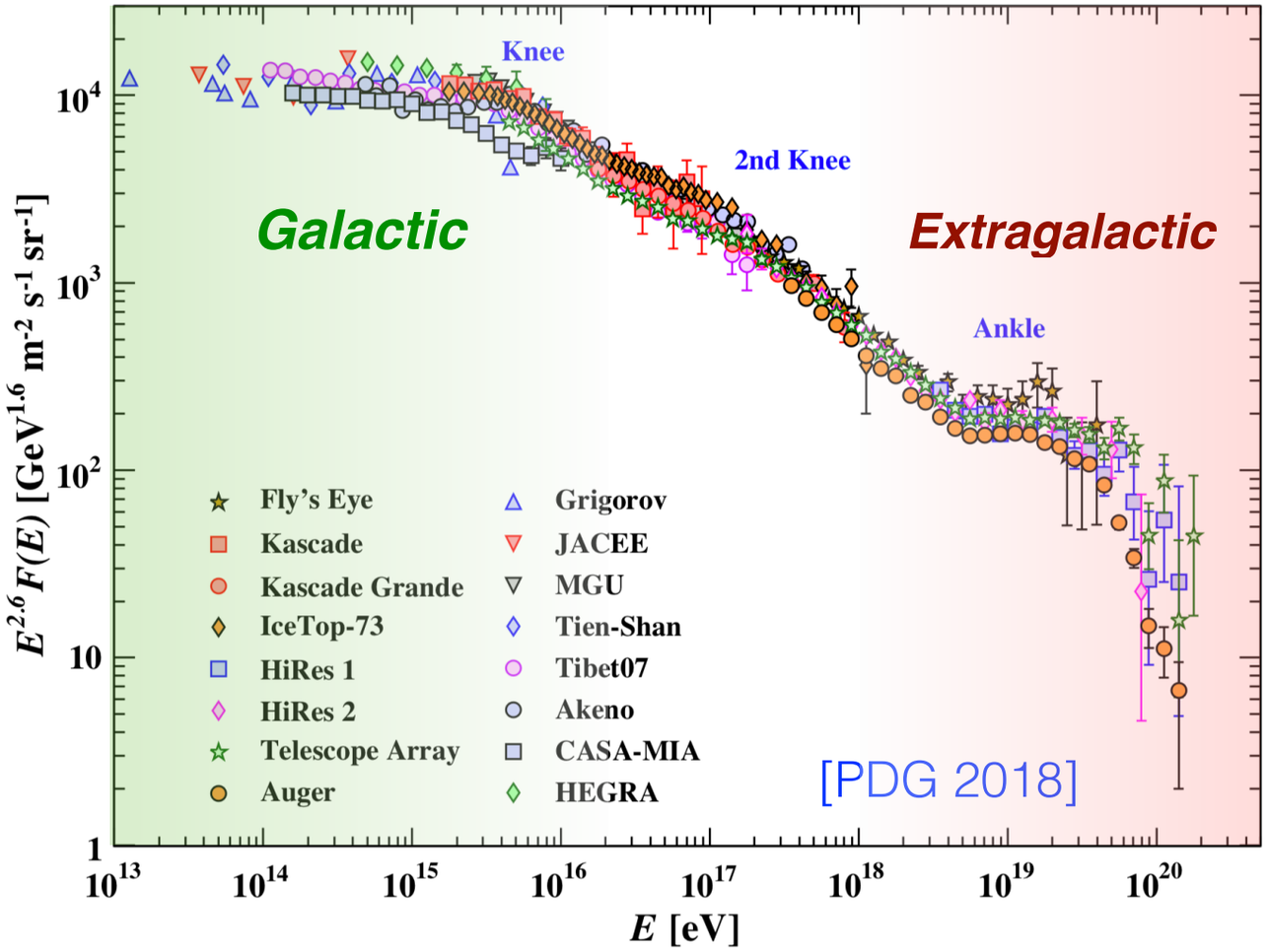


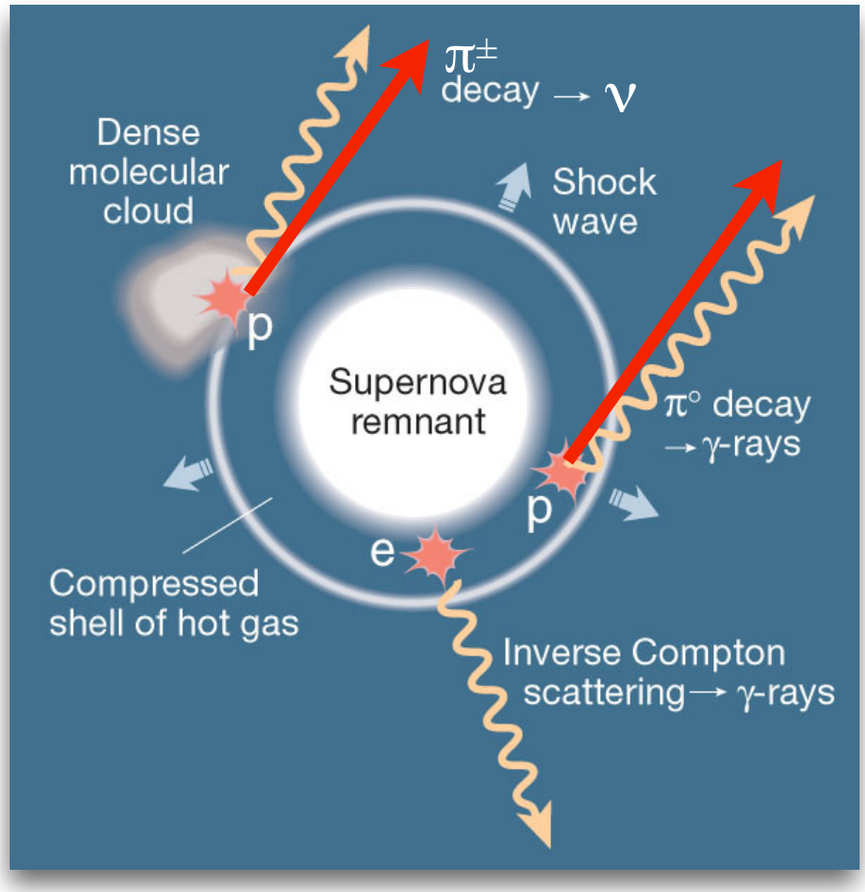




Galactic Cosmic Ray Accelerators

- The search for Galactic cosmic neutrino sources concentrates on the search for "Pevatrons" which have the required energetics to produce cosmic rays up to the knee in the spectrum.
- ``Pevatrons" will produce pionic γ-rays whose spectrum extends to several hundred TeV without cut-off.
- Supernova remnant meet such condition.
- TeV γ-rays should be accompanied by TeV neutrinos, observable at IceCube.

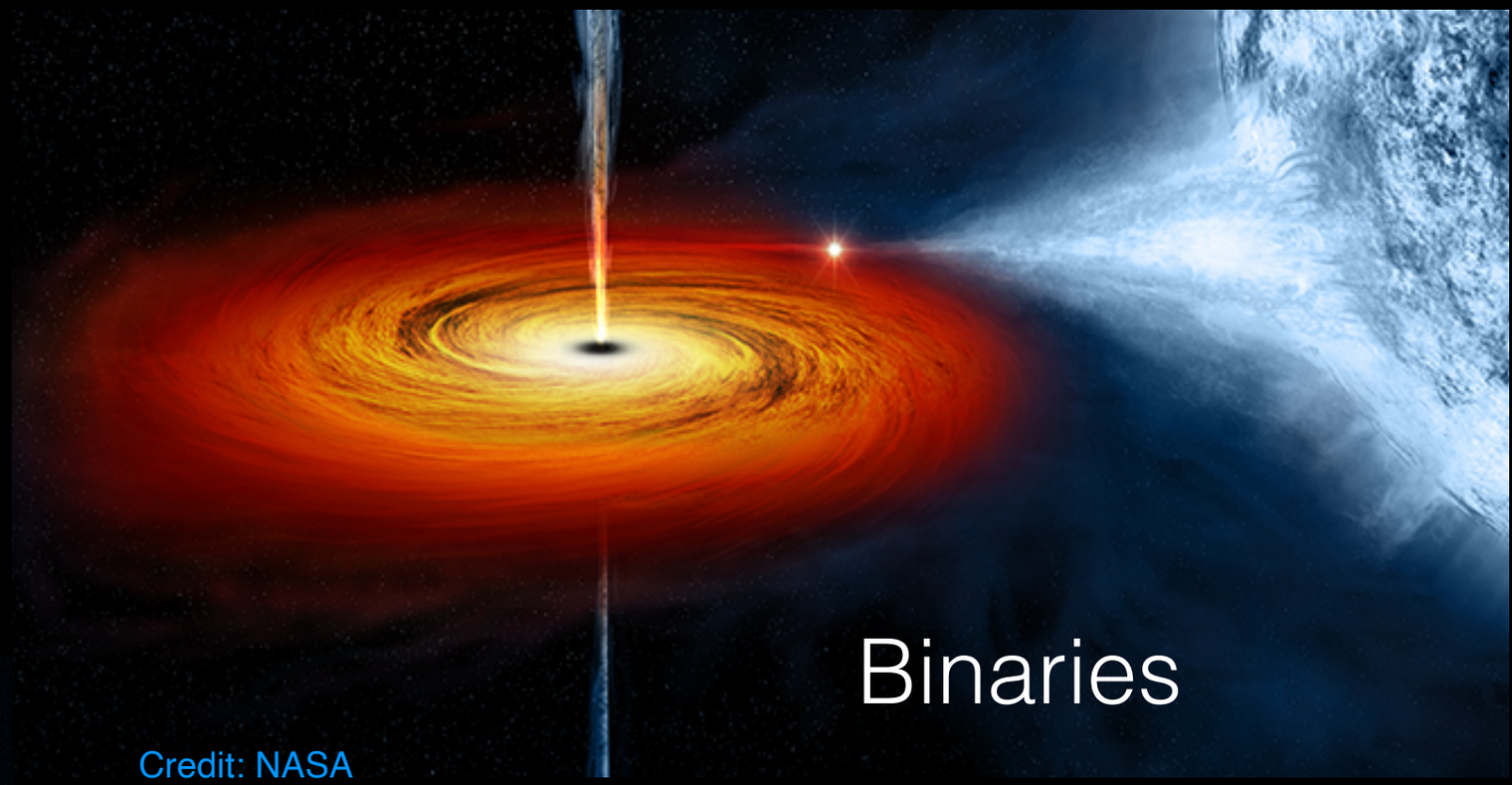




Potential Galactic Sources

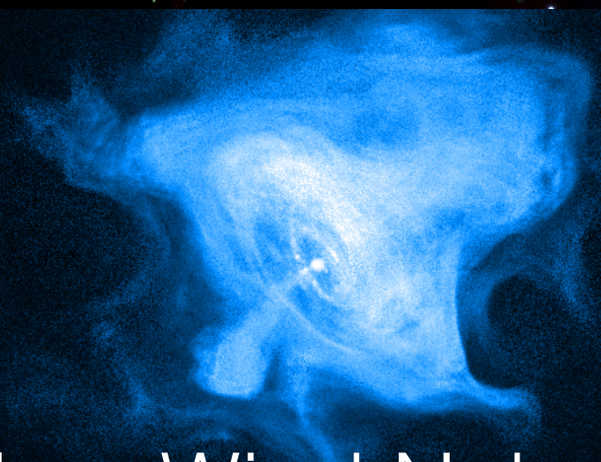
Supernova Remnants

Credit: ESA/Hubble



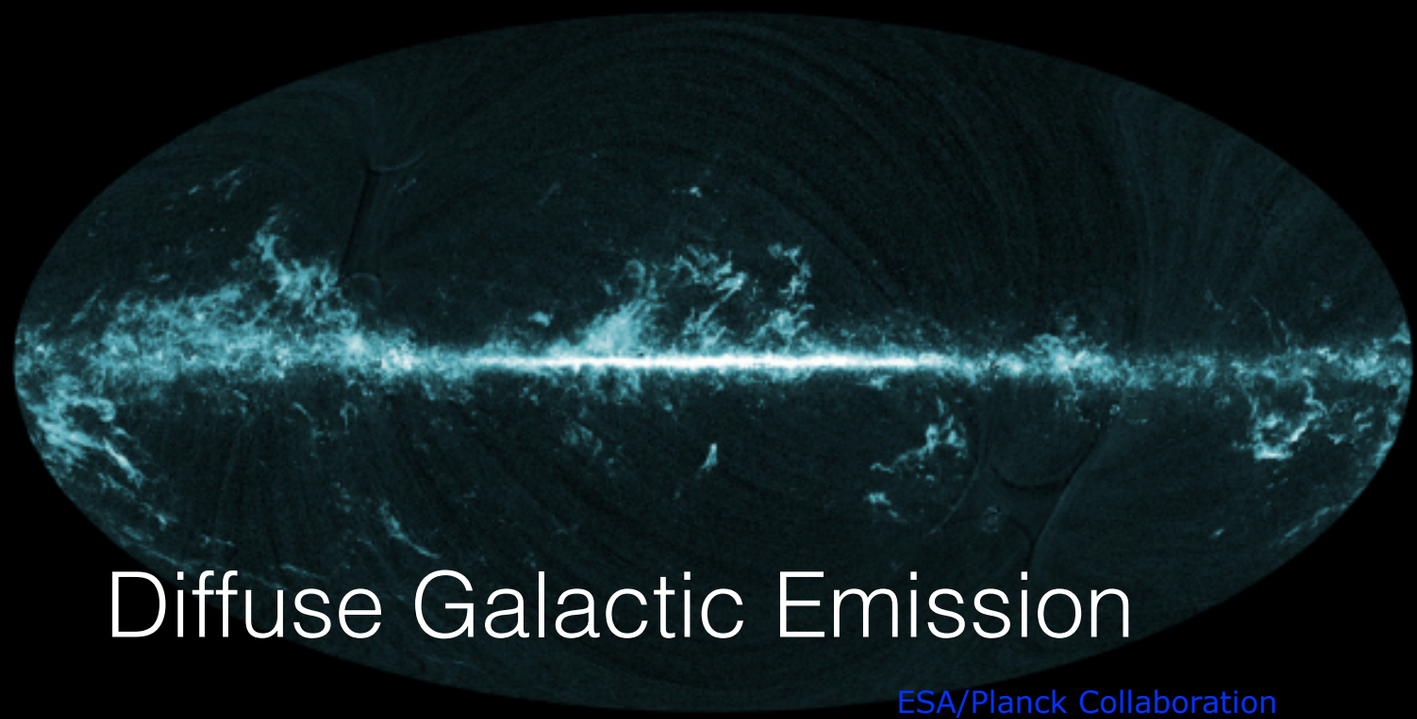
Binaries

Credit: NASA



Pulsar Wind Nebulae

Credit: NASA/CXC/SAO



Diffuse Galactic Emission

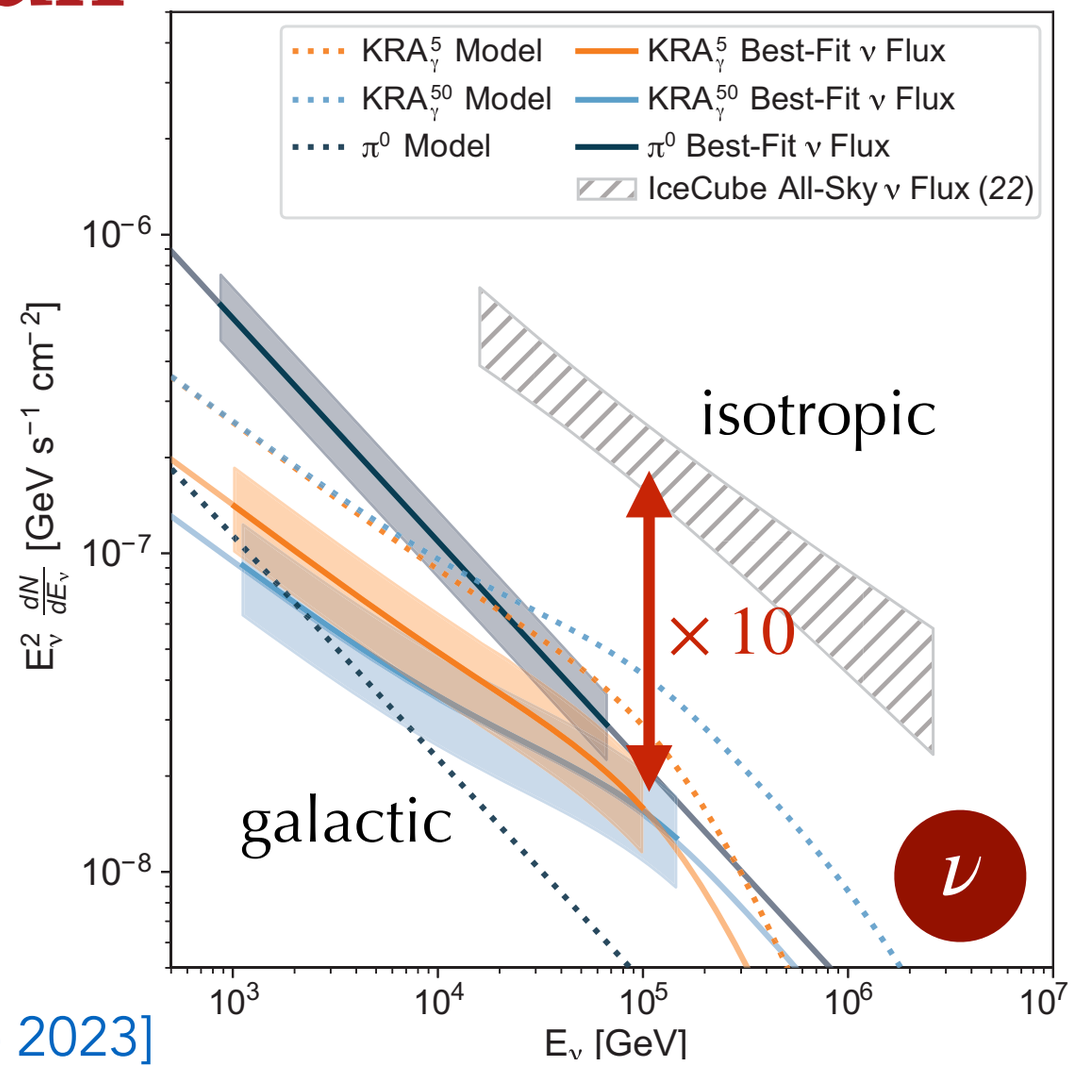
ESA/Planck Collaboration

Galactic Neutrino Flux

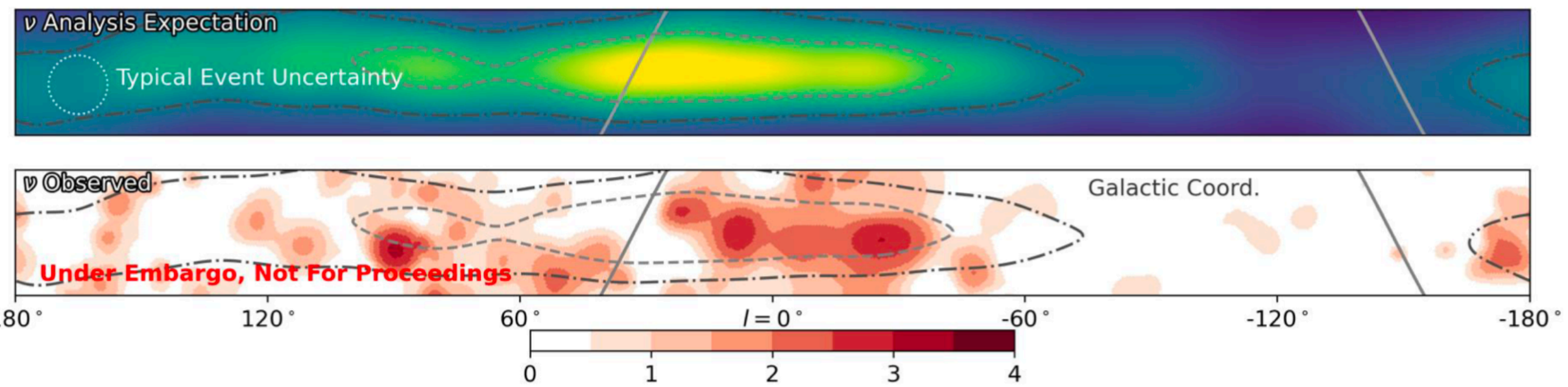
Cascades boost IceCube sensitivity to extended emission in the Southern sky.

10 years of data identified Galactic component at <u>4.5σ</u>

- rejecting no Galactic component hypothesis



[IceCube, Science 2023]



The source of Galactic neutrinos?

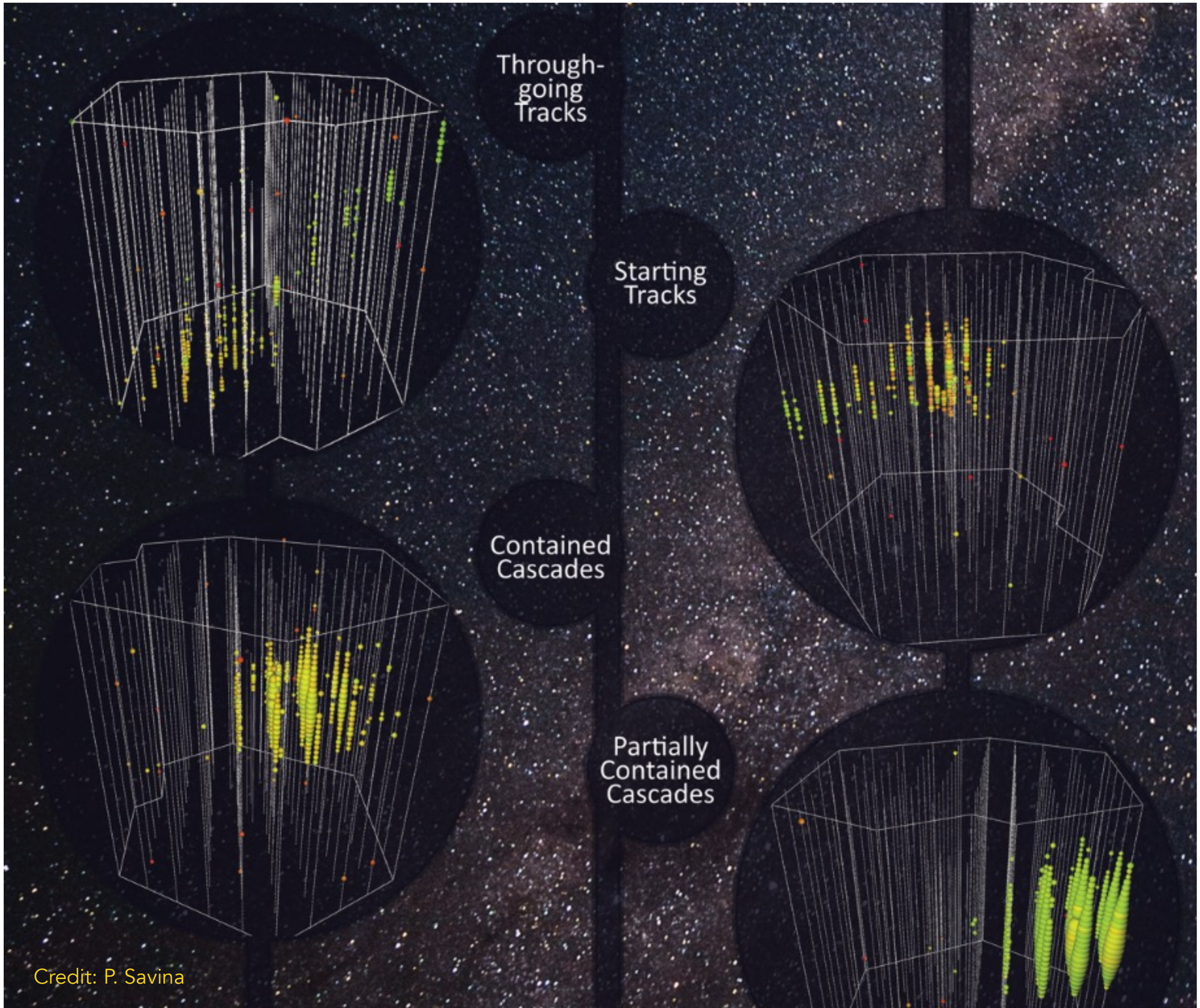
	Flux sensitivity Φ	*P* value	Best-fitting flux Φ
Diffuse Galactic plane analysis			
π^0	5.98	1.26×10^{-6} (4.71σ)	$21.8^{+5.3}_{-4.9}$
KRA_γ^5	0.16 × MF	6.13×10^{-6} (4.37σ)	$0.55^{+0.18}_{-0.15} \times$ MF
KRA_γ^{50}	0.11 × MF	3.72×10^{-5} (3.96σ)	$0.37^{+0.13}_{-0.11} \times$ MF
Catalog stacking analysis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

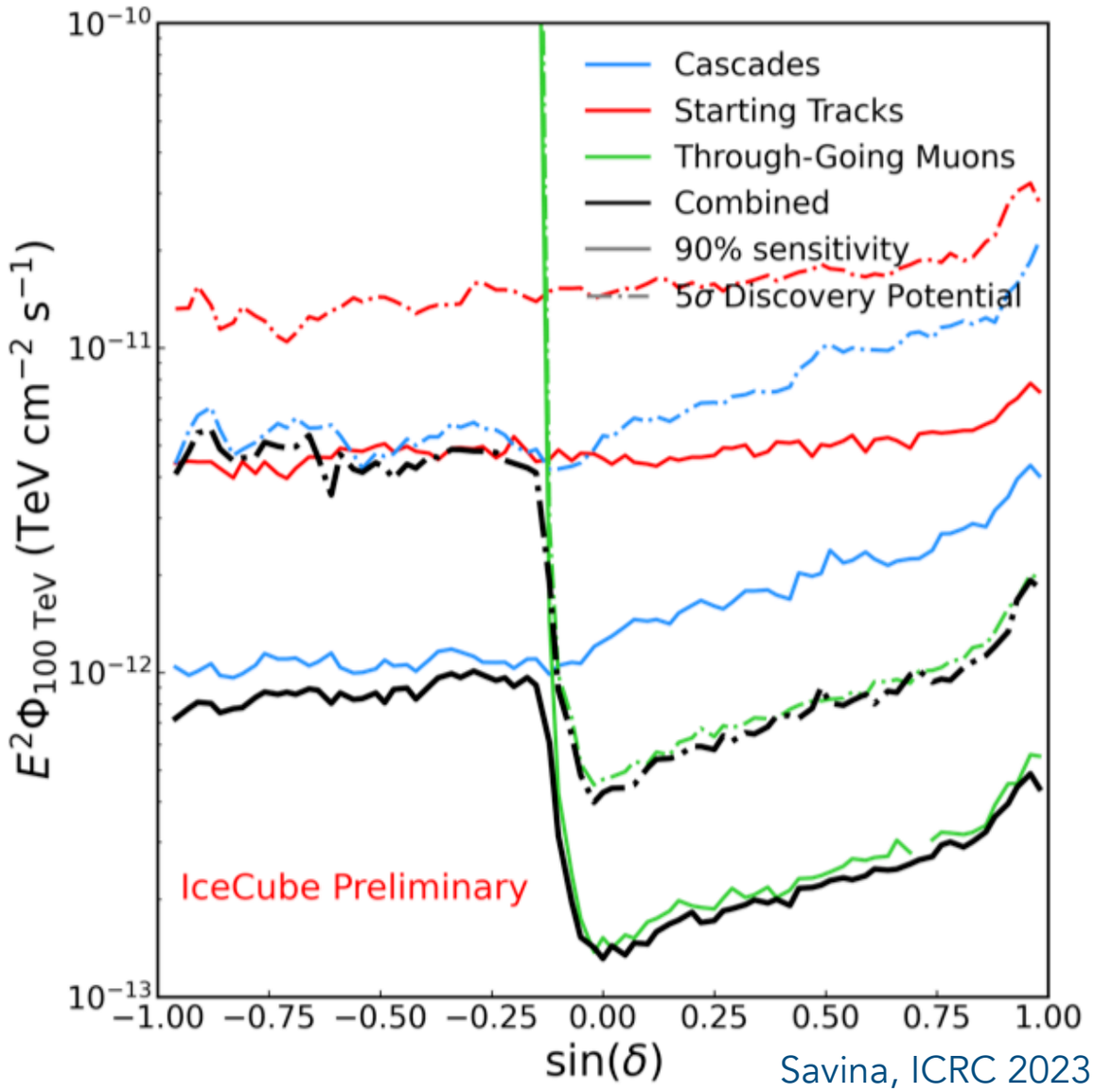
Coming Up: combined dataset searches



Credit: P. Savina

Coming Up: combined dataset searches

- Multi-flavor sensitivity: time-integrated searches



Savina, ICRC 2023

Credit: P. Savina

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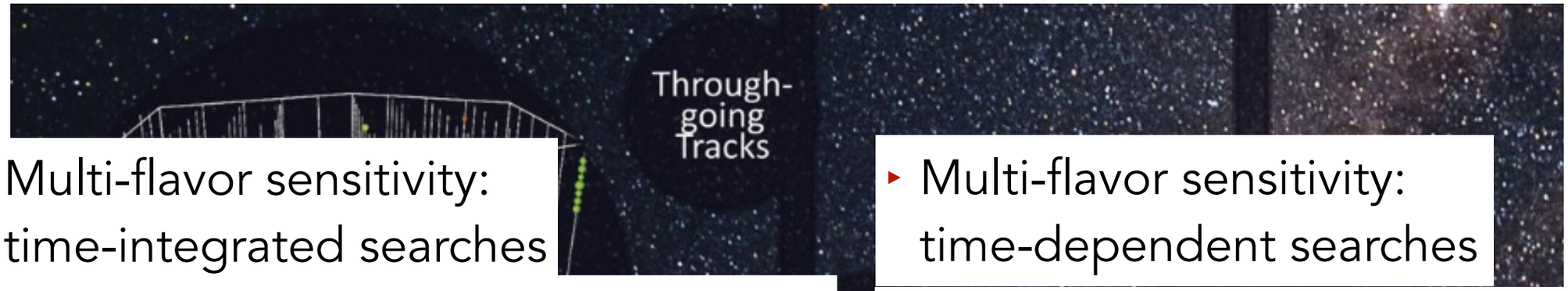

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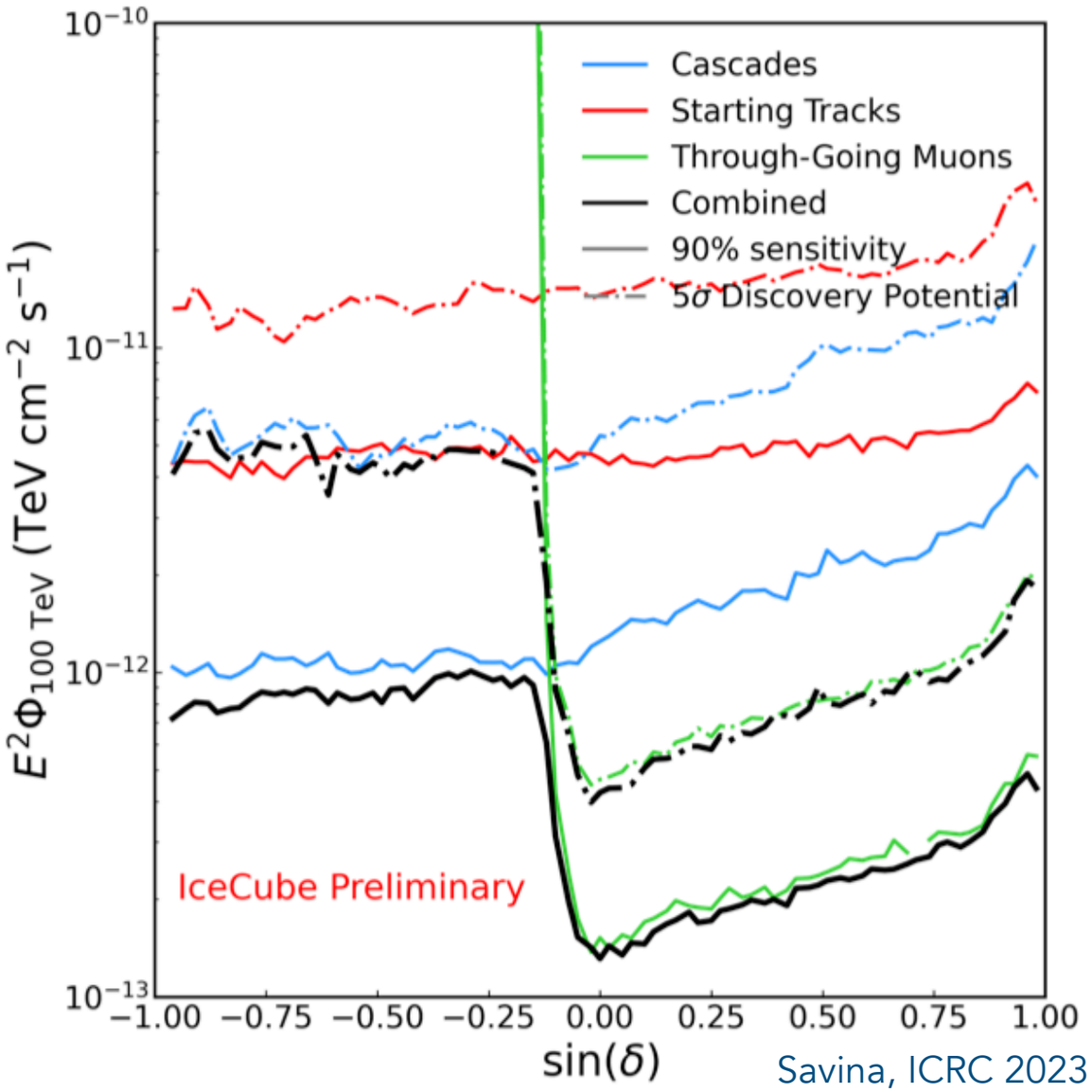
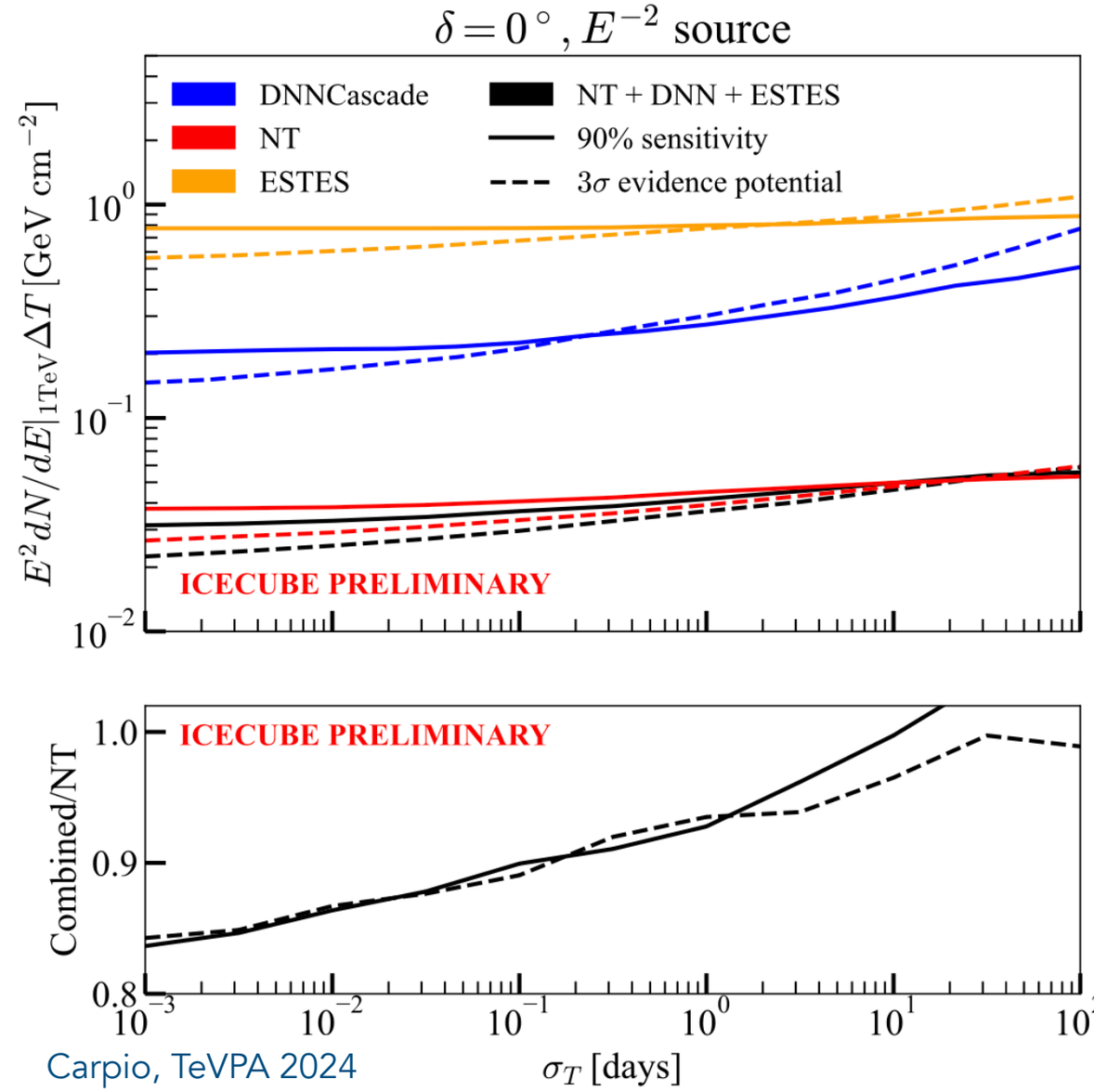


Savina, ICRC 2023

- Multi-flavor sensitivity: time-dependent searches

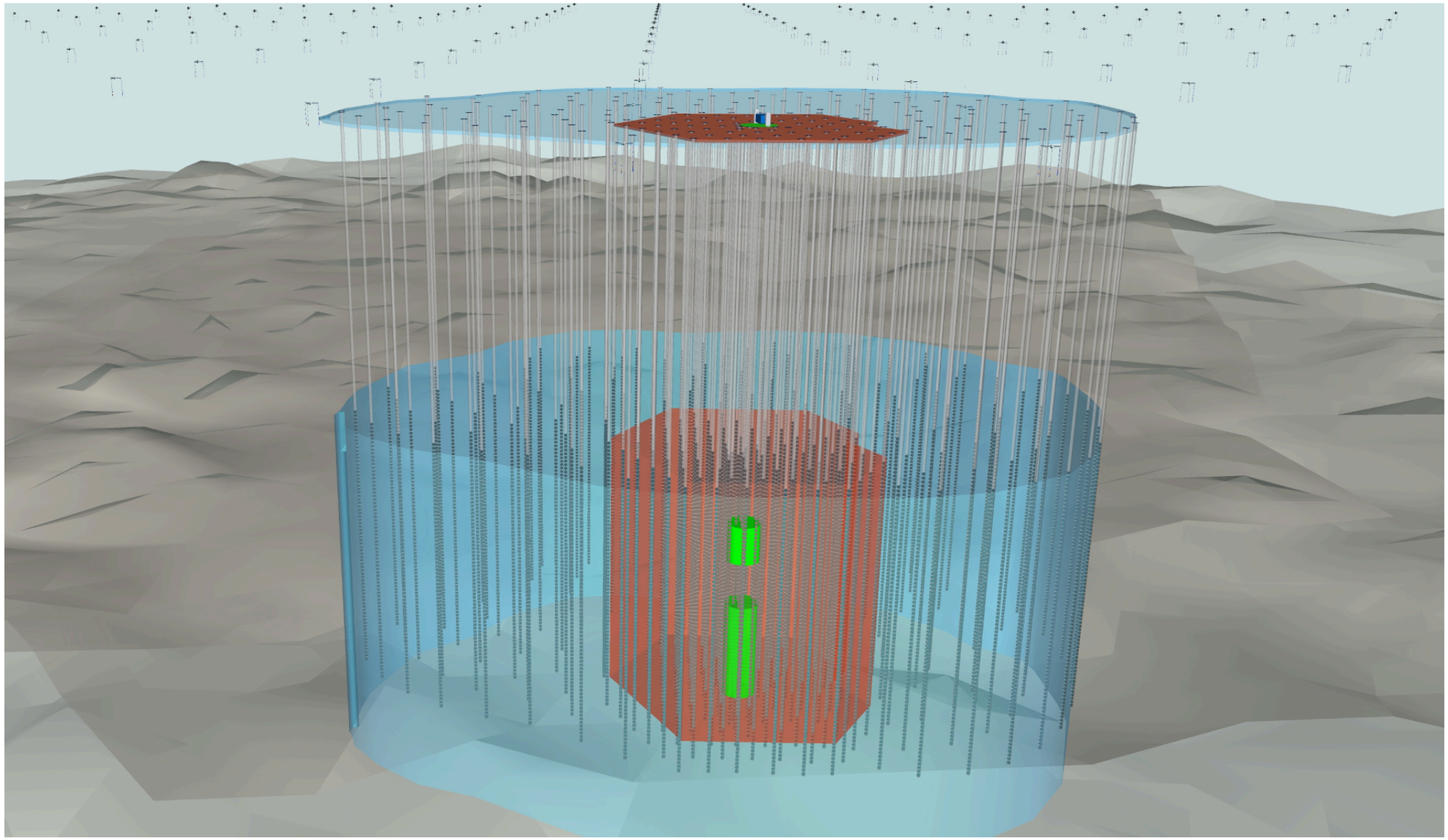


Carpio, TeVPA 2024

Credit: P. Savina

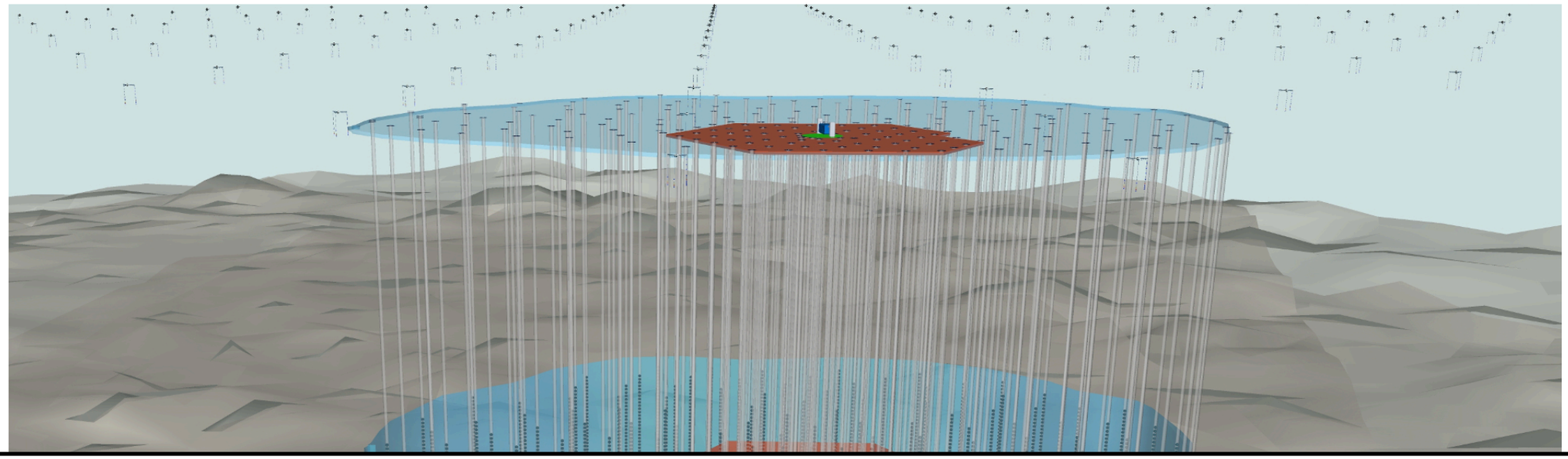
IceCube-Gen2

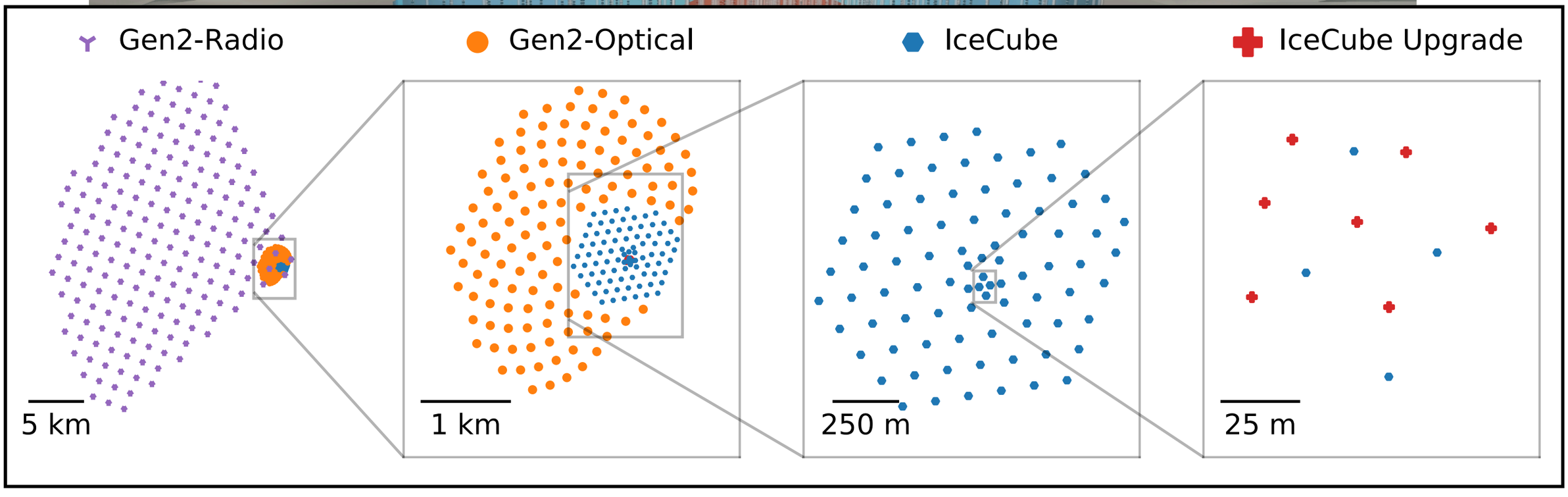
Near 10 times larger, reaching to energies of EeV



IceCube-Gen2

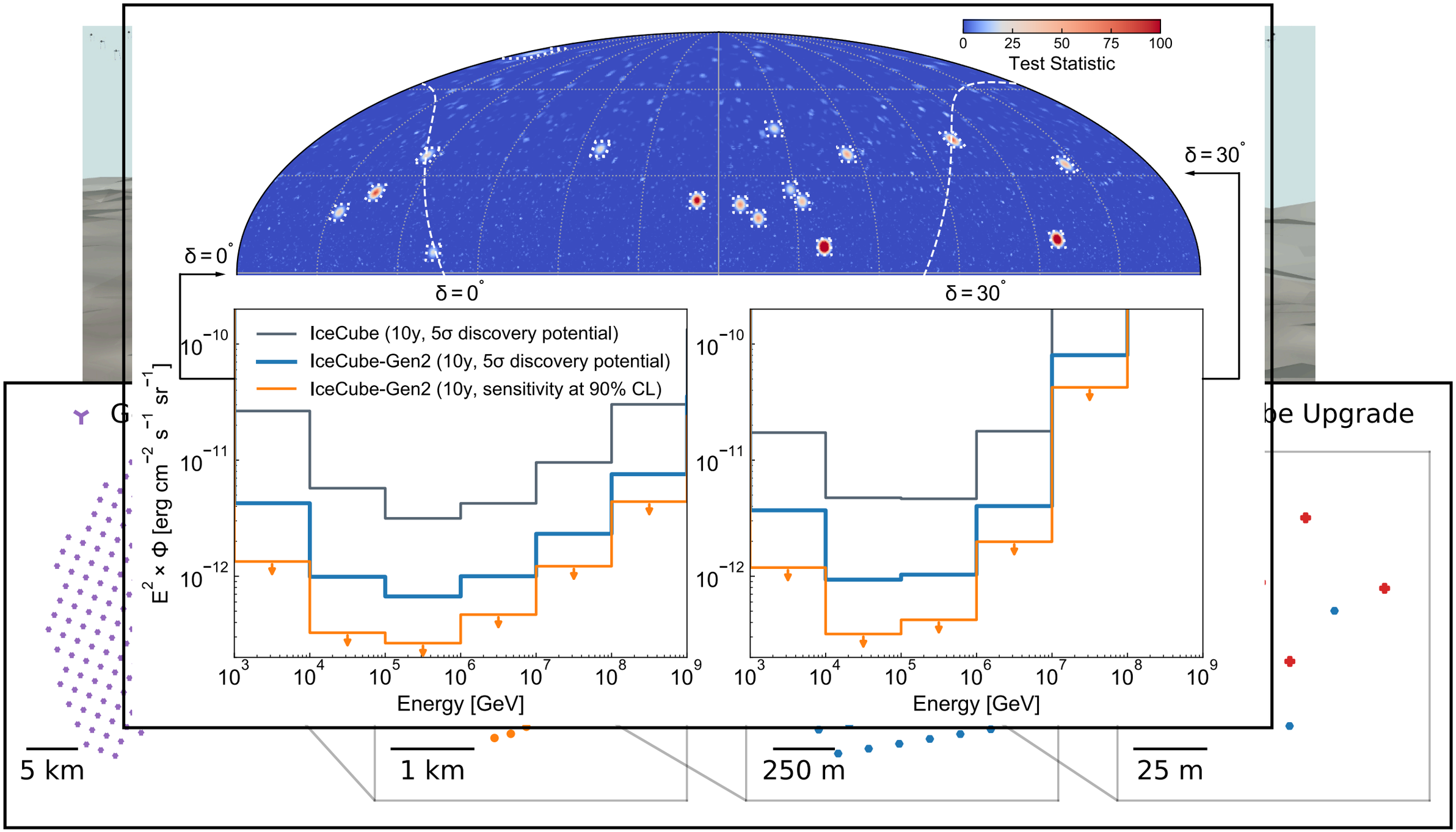
Near 10 times larger, reaching to energies of EeV





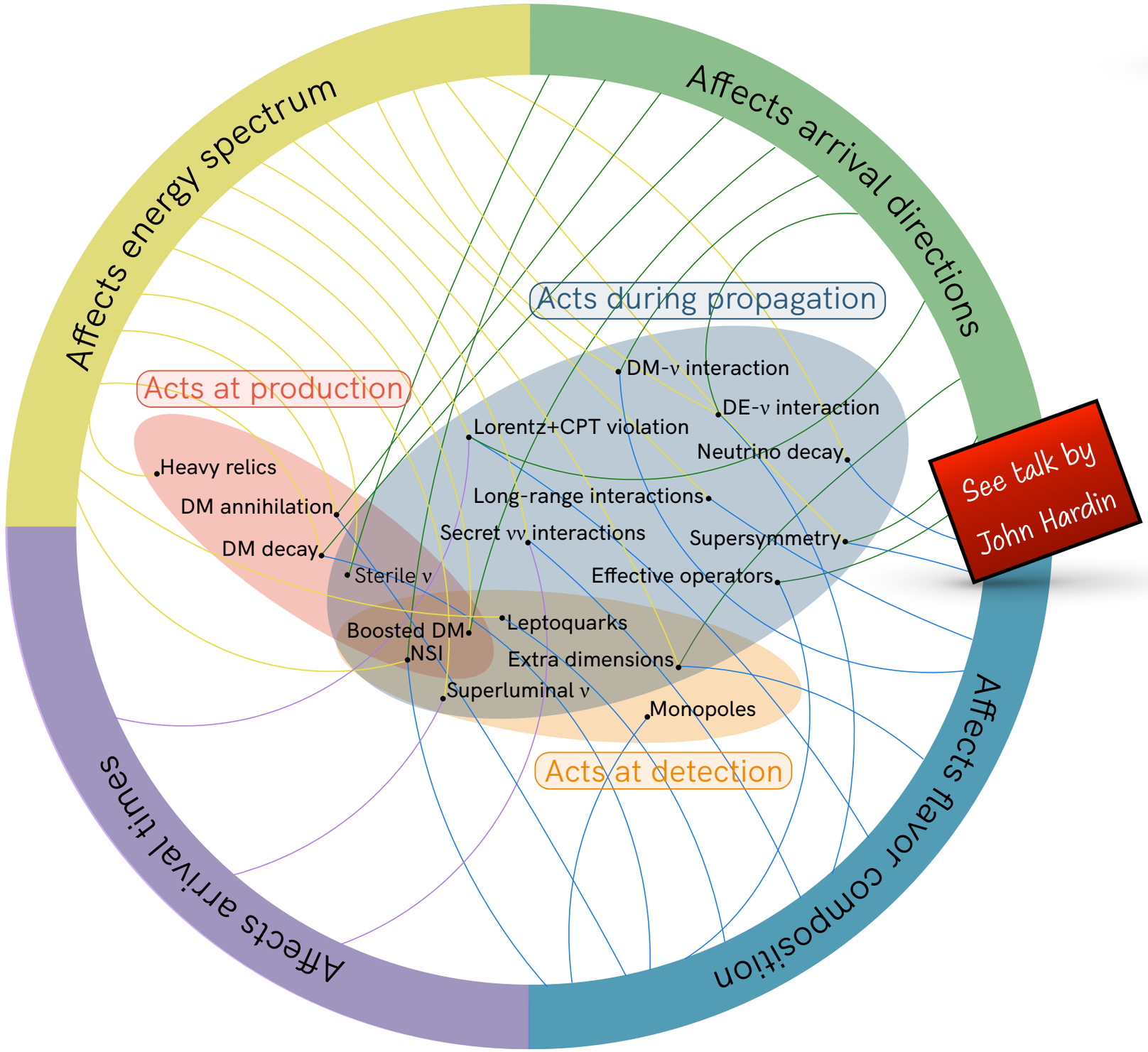
IceCube-Gen2

Near 10 times larger, reaching to energies of EeV



New Physics and HE Cosmic Neutrinos

See talk by Mehr Un Nisa



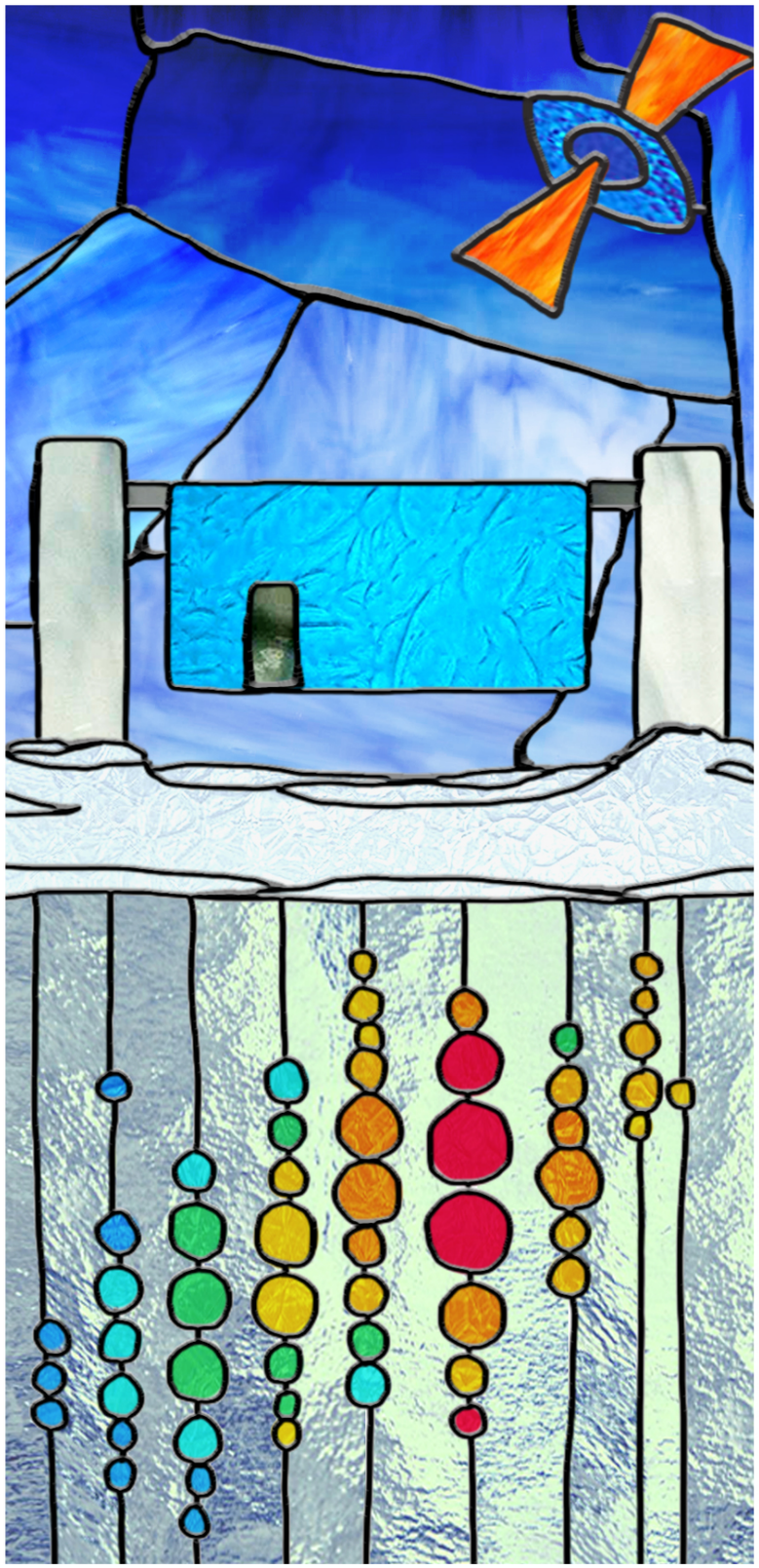
See talk by John Hardin

[Argüelles, Bustamante, **AK,** Palomares-Ruis, Vincent, 2019]

Summary

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

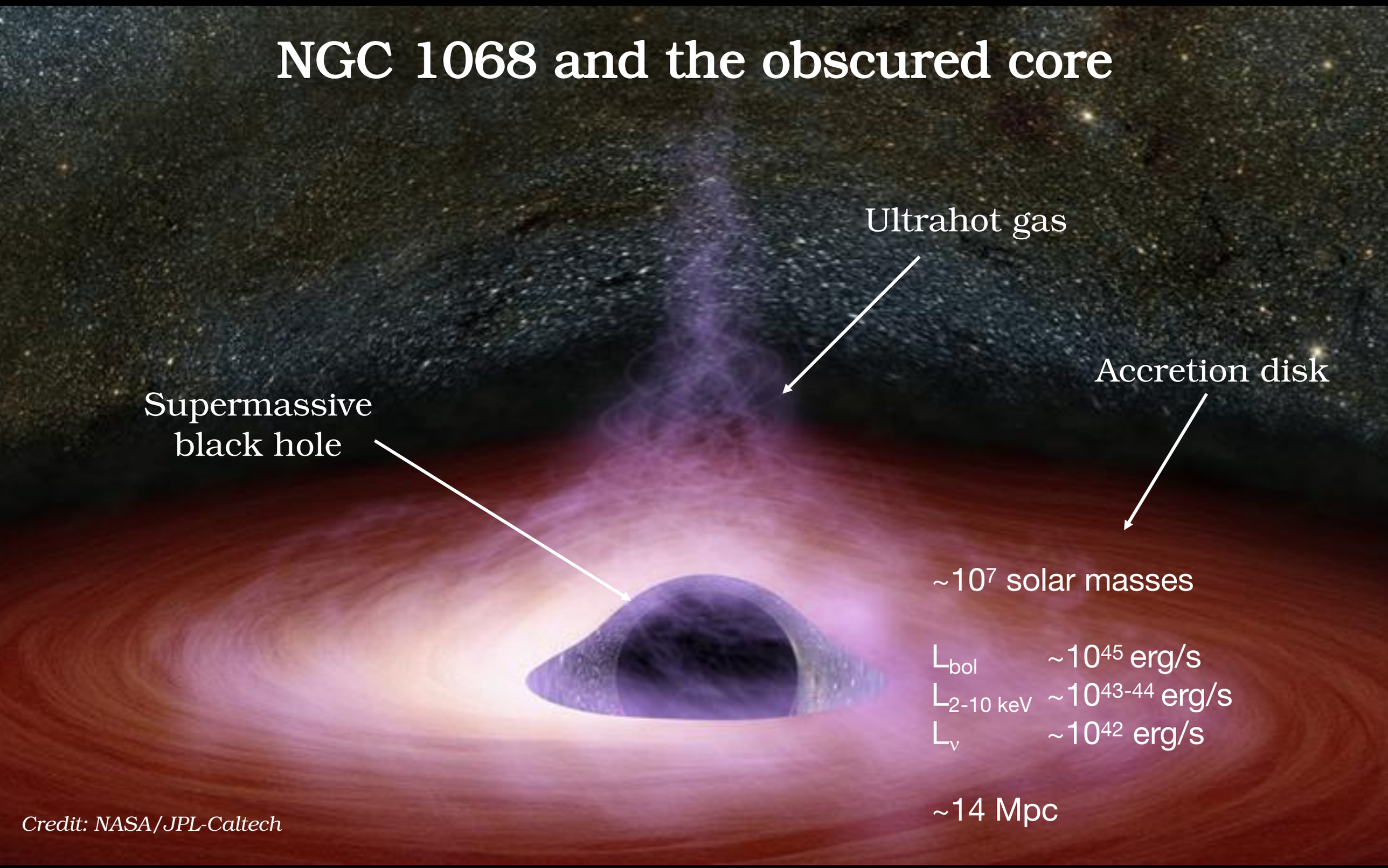
- Early indications points to AGN as primary source of high-energy cosmic neutrinos.
- Features in the measured cosmic neutrino flux point to different population of sources
- Mutlimessenger paradigm indicates that sources of HE cosmic neutrinos are opaque to VHE gamma-rays
- NGC 1068 is strongest extragalactic source in IceCube
- Galactic neutrinos have opened a new front in particle astrophysics with neutrinos.
- Additional years of data and improved analyses will bring more insight to the nature of emission from AGN and the Galactic neutrino emission.



Thanks!

Back up Slides

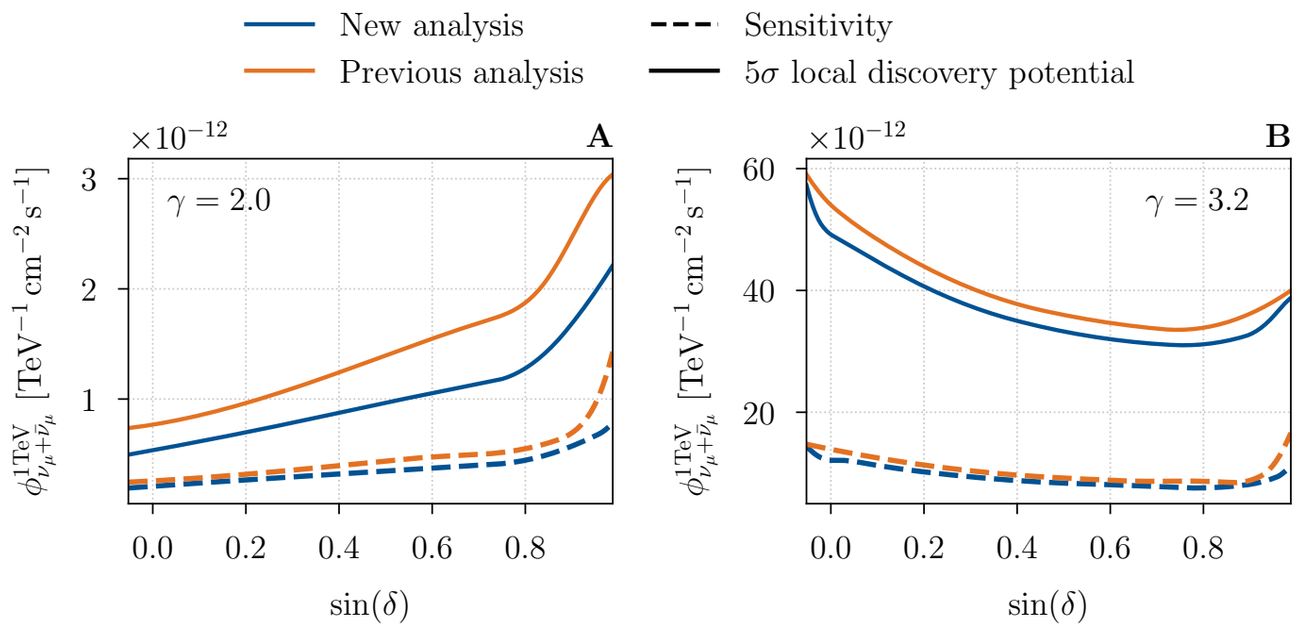
NGC 1068 and the obscured core



Credit: NASA/JPL-Caltech

IceCube 2022 Point Source Search

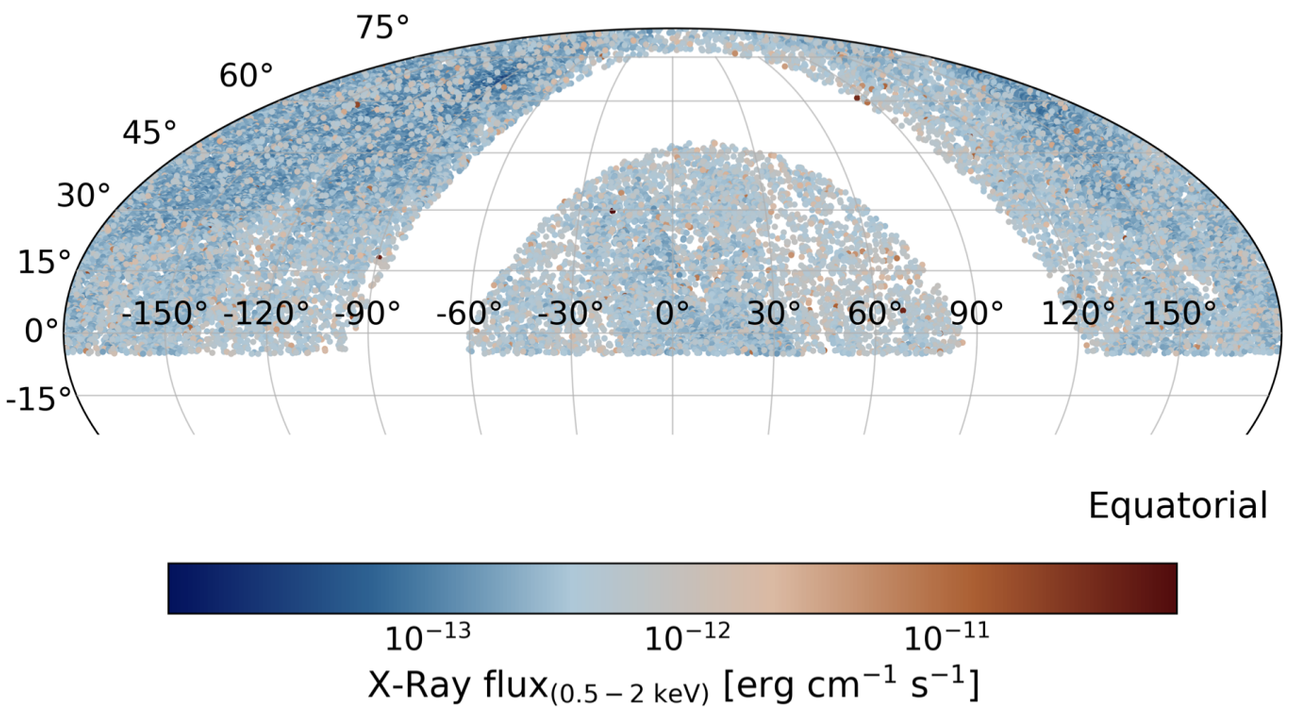
- Search for neutrino emission from the Northern Hemisphere using throughgoing tracks (NorthenTracks)
- Un-triggered Search (all sky scan) identifying the hottest point in the Northern Sky
- Source Catalog search, analyzing 110 sources identified from gamma ray sources
- Source selection identical to previous analysis (10 yr ps track [IceCube, PRL 2020])
- improved detector geometry and calibration (each PMT calibrated individually), muon angular resolution, and energy reconstruction

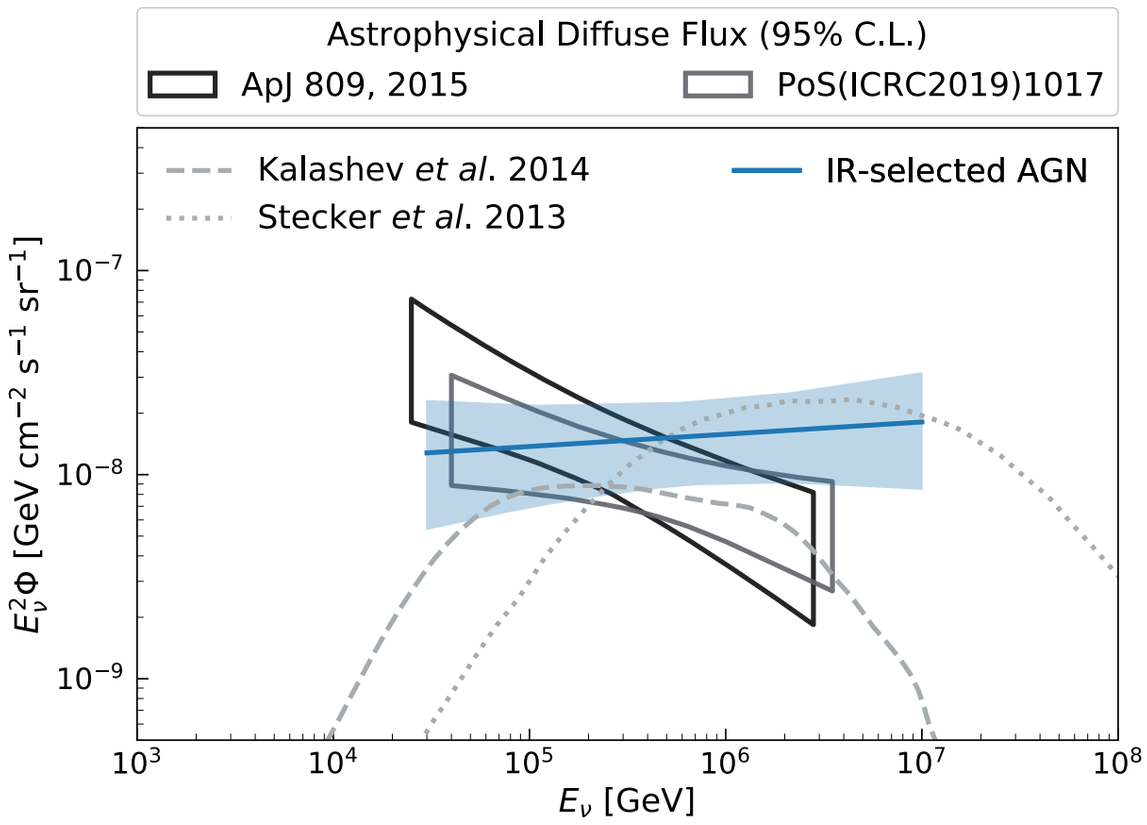


Source Name	Source Type	α [°]	δ [°]	$\hat{n}_s$	$\hat{\gamma}$	$-\log_{10} p_{\text{local}}$	$\Phi_{90\%}$
NGC 1068	SBG/AGN	40.67	-0.01	79	3.2	7.0 (5.2 σ)	9.6
PKS 1424+240	BLL	216.76	23.80	77	3.5	4.0 (3.7 σ)	11.4
TXS 0506+056	BLL/FSRQ	77.36	5.70	5	2.0	3.6 (3.5 σ)	7.5
PKS 0019+058	BLL	5.64	6.13	1	2.4	0.4 (0.2 σ)	2.6
1ES 0033+595 (*)	BLL	8.98	59.83	0	4.3	0.0 (0.0 σ)	5.0
M 31	GAL	10.82	41.24	13	3.3	0.8 (1.0 σ)	6.2
4C +01.02	FSRQ	17.17	1.58	0	4.3	0.0 (0.0 σ)	2.1
S2 0109+22	BLL	18.03	22.75	10	2.8	0.7 (0.8 σ)	4.8
B3 0133+388	BLL	24.14	39.10	0	4.3	0.0 (0.0 σ)	3.8
TXS 0141+268	BLL	26.15	27.09	0	4.3	0.0 (0.0 σ)	3.2
MITG J021114+1051	BLL	32.81	10.86	0	4.3	0.0 (0.0 σ)	2.6
PKS 0215+015	FSRQ	34.46	1.73	2	3.9	0.2 (0.0 σ)	1.9
B2 0218+357	FSRQ	35.28	35.94	8	4.3	0.4 (0.2 σ)	4.1
3C 66A	BLL	35.67	43.04	0	4.3	0.0 (0.0 σ)	3.9
4C +28.07	FSRQ	39.47	28.80	3	2.9	0.3 (0.0 σ)	3.4
PKS 0235+164	BLL	39.67	16.62	5	3.9	0.3 (0.0 σ)	2.8
NGC 1275	RDG	49.96	41.51	8	3.0	0.5 (0.5 σ)	5.1
PKS 0336-01	FSRQ	54.88	-1.78	4	4.3	0.3 (0.1 σ)	2.1
PKS 0420-01	FSRQ	65.83	-1.33	0	4.3	0.0 (0.0 σ)	2.0
4C +41.11 (*)	BLL	65.98	41.83	0	4.3	0.0 (0.0 σ)	3.9
PKS 0422+00	BLL	66.19	0.60	0	4.3	0.0 (0.0 σ)	2.1
MG2 J043337+2905	BLL	68.41	29.10	0	4.3	0.0 (0.0 σ)	3.4
PKS 0440-00	FSRQ	70.66	-0.30	1	2.7	0.3 (0.0 σ)	2.0
S3 0458-02	FSRQ	75.30	-1.97	9	4.3	0.5 (0.4 σ)	2.4
PKS 0502+049	FSRQ	76.34	5.00	0	4.3	0.0 (0.0 σ)	2.3

[IceCube, Science 2022]

AGN Core Stacking





[IceCube, PRD 2022]

- Searching for correlation of HE neutrinos with core of AGN with soft X-rays as the proxy. Motivated by neutrino production related to AGN accretion and RIAFS [Stecker+ 2013, Kalashev+2014 & Kimura+2015].
- Selecting sources based on X-ray, IR, and Radio observations.
- IceCube finds a **2.6σ excess** for 32,249 AGN selected by their IR emission.

Northern Seyferts Results

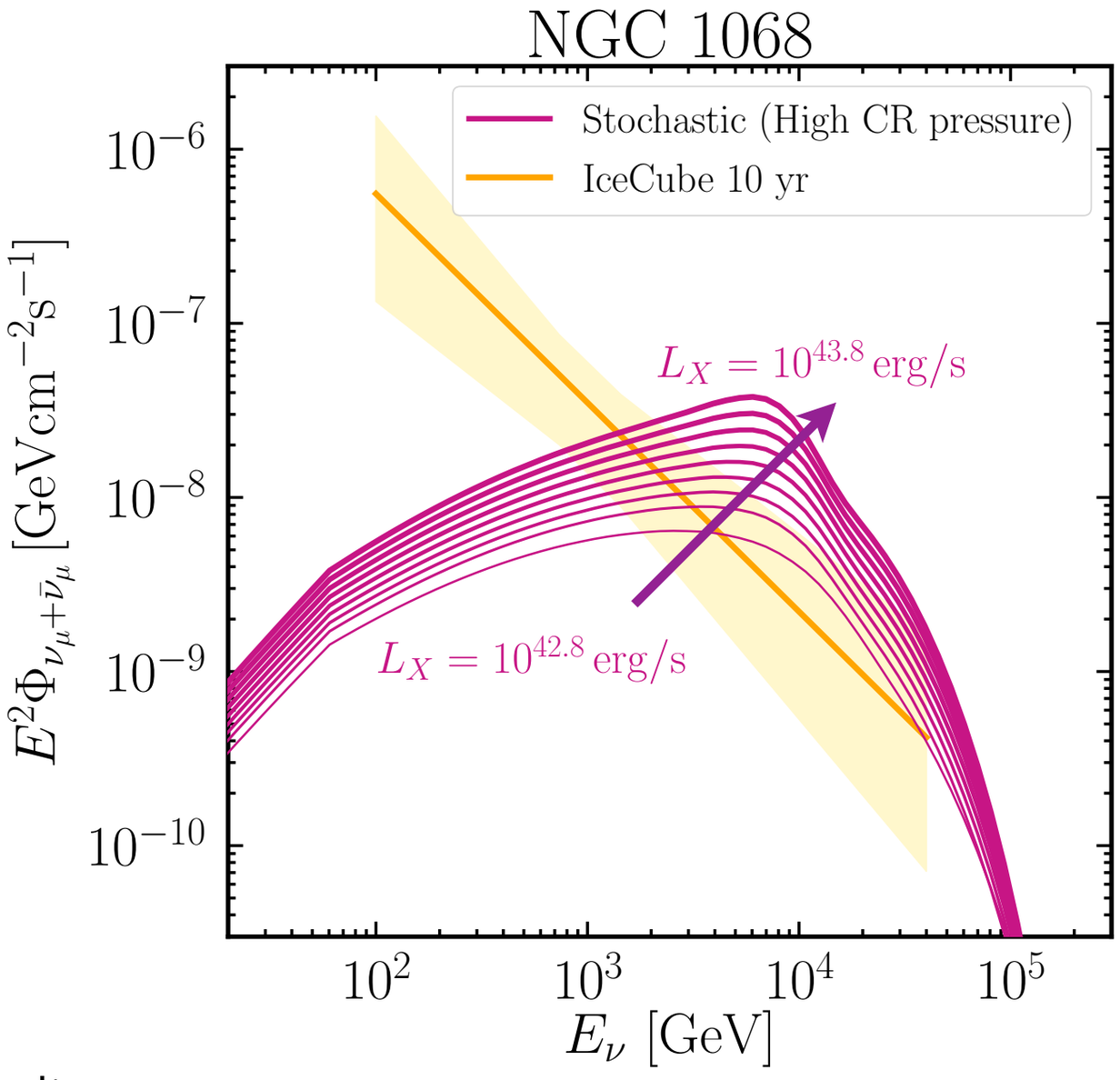
	spectral model	$n_{\rm exp}$	TS	$\hat{n}_{\rm s}$	$\hat{\gamma}$	$p_{\rm local}$	$p_{\rm global}$	$n_{\rm UL}$
Stacking Searches								
Stacking (excl.)	disk-corona	154.0	0.1	5	–	$2.4 \times 10^{-1}\,(0.7\,\sigma)$	$2.4 \times 10^{-1}\,(0.7\,\sigma)$	51.1
Stacking (incl.) $^{(*)}$	disk-corona	199.0	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 $^{(*)}$	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 $^{(*)}$	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 ($n_{\rm exp}$) 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).

Neutrino flux & X-ray Measurements

- The high level of column density for NGC 1068 makes measuring the intrinsic X-ray luminosity challenging.
  - Estimated intrinsic X-ray luminosity carry large uncertainties.

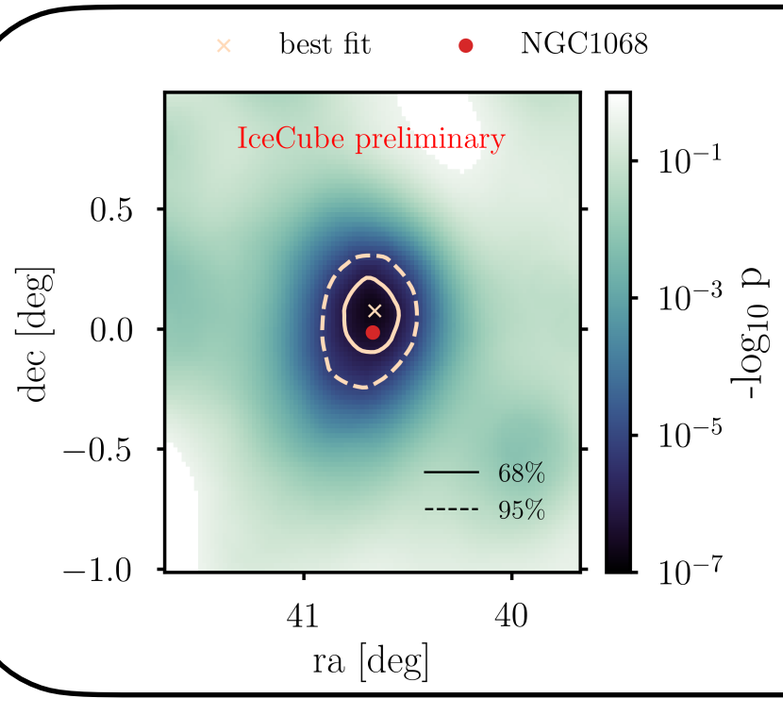
- NuSTAR and XMM-Newton monitoring campaigns have reported $L_X \simeq 7^{+7}_{-4} \times 10^{43}\mathrm{erg/s}$ [Marinucci+2015]

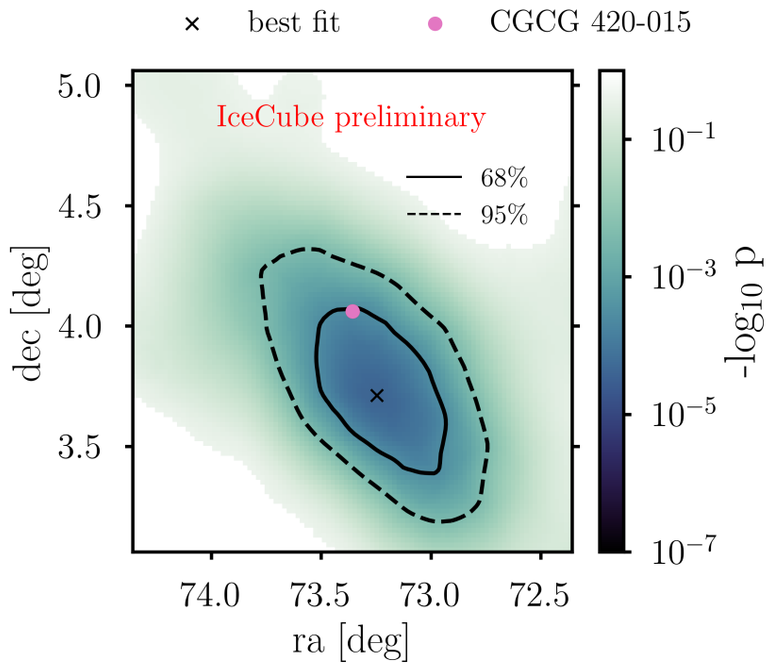


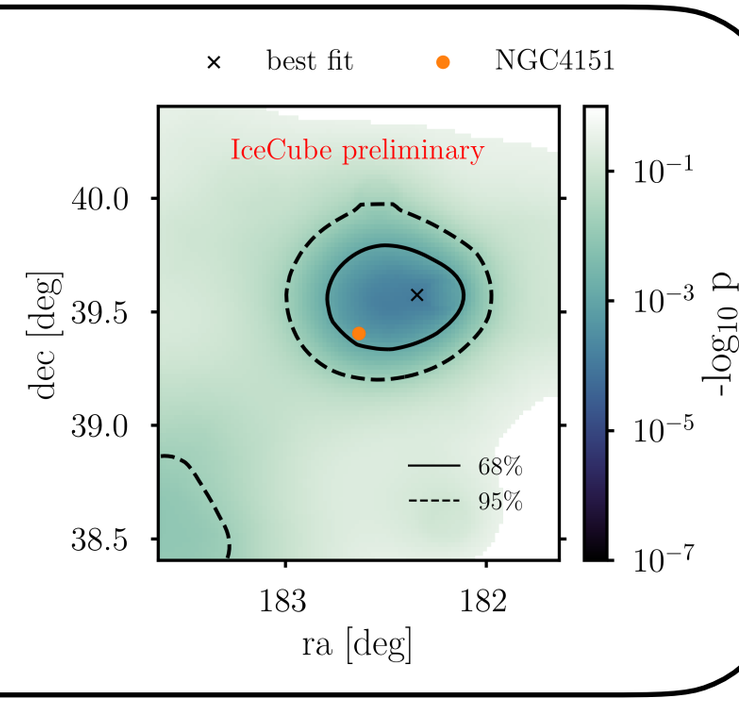
- The uncertainty is entangled with the discrepancy in measured distance for nearby sources.

Power-Law vs Model Fit Sky Maps

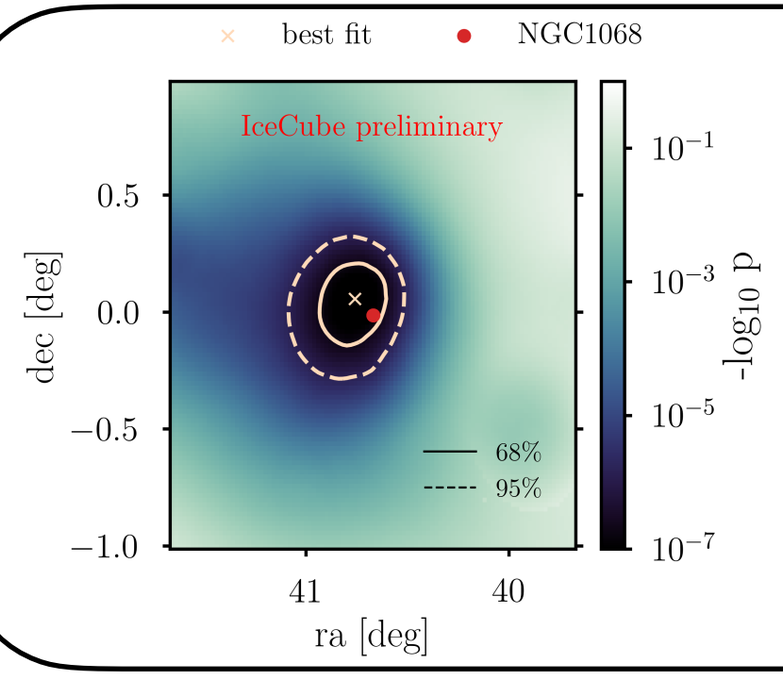
Disk Corona Model

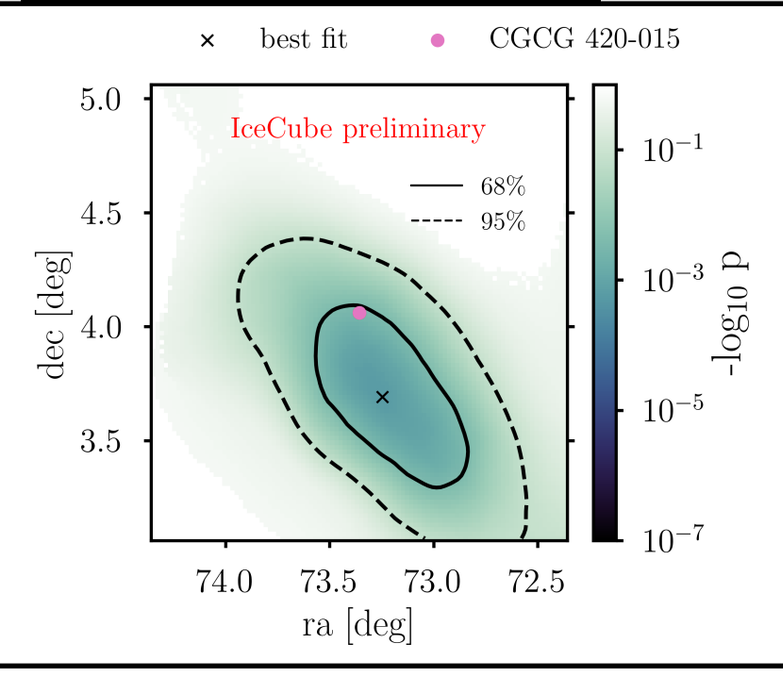


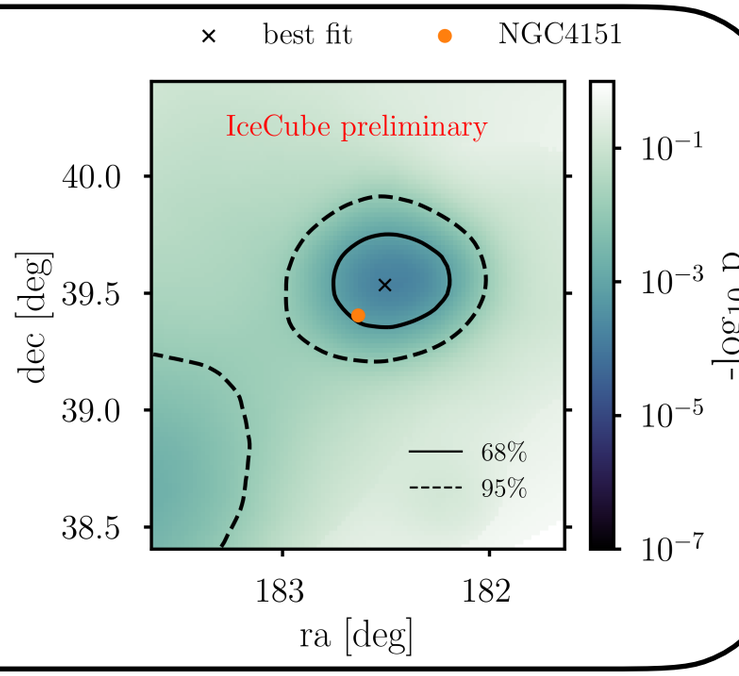




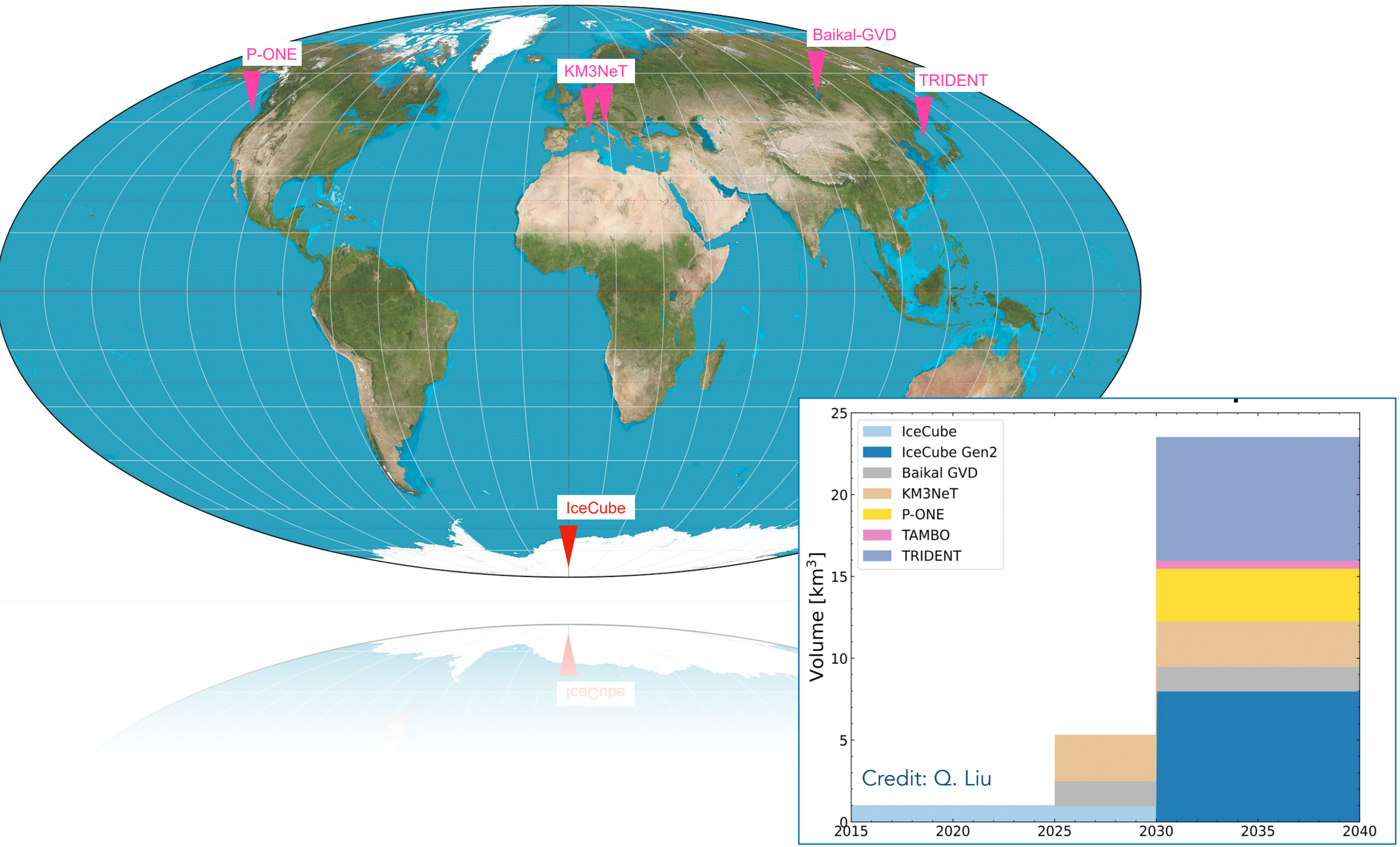
Power-Law





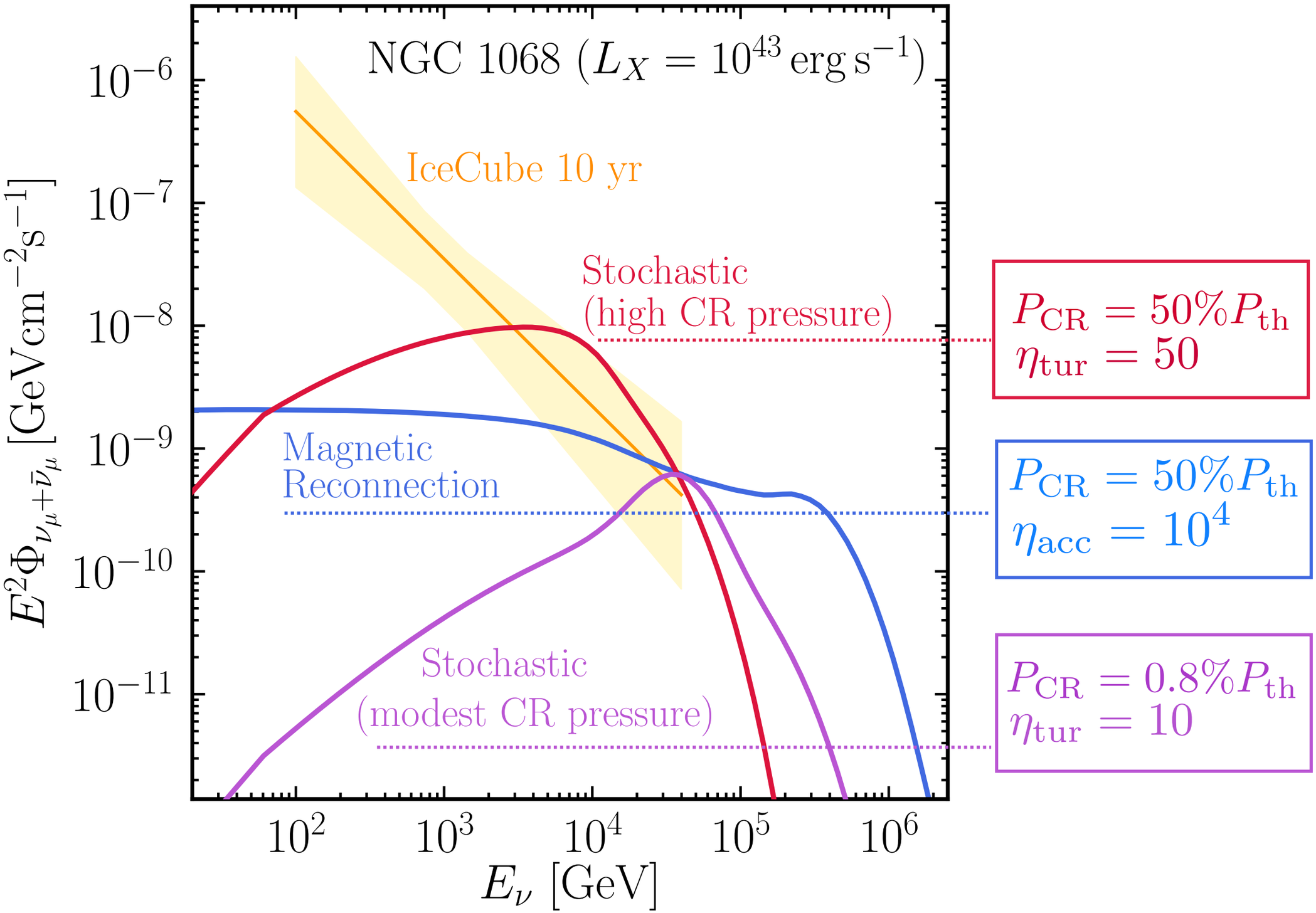


Neutrino Astronomy Landscape



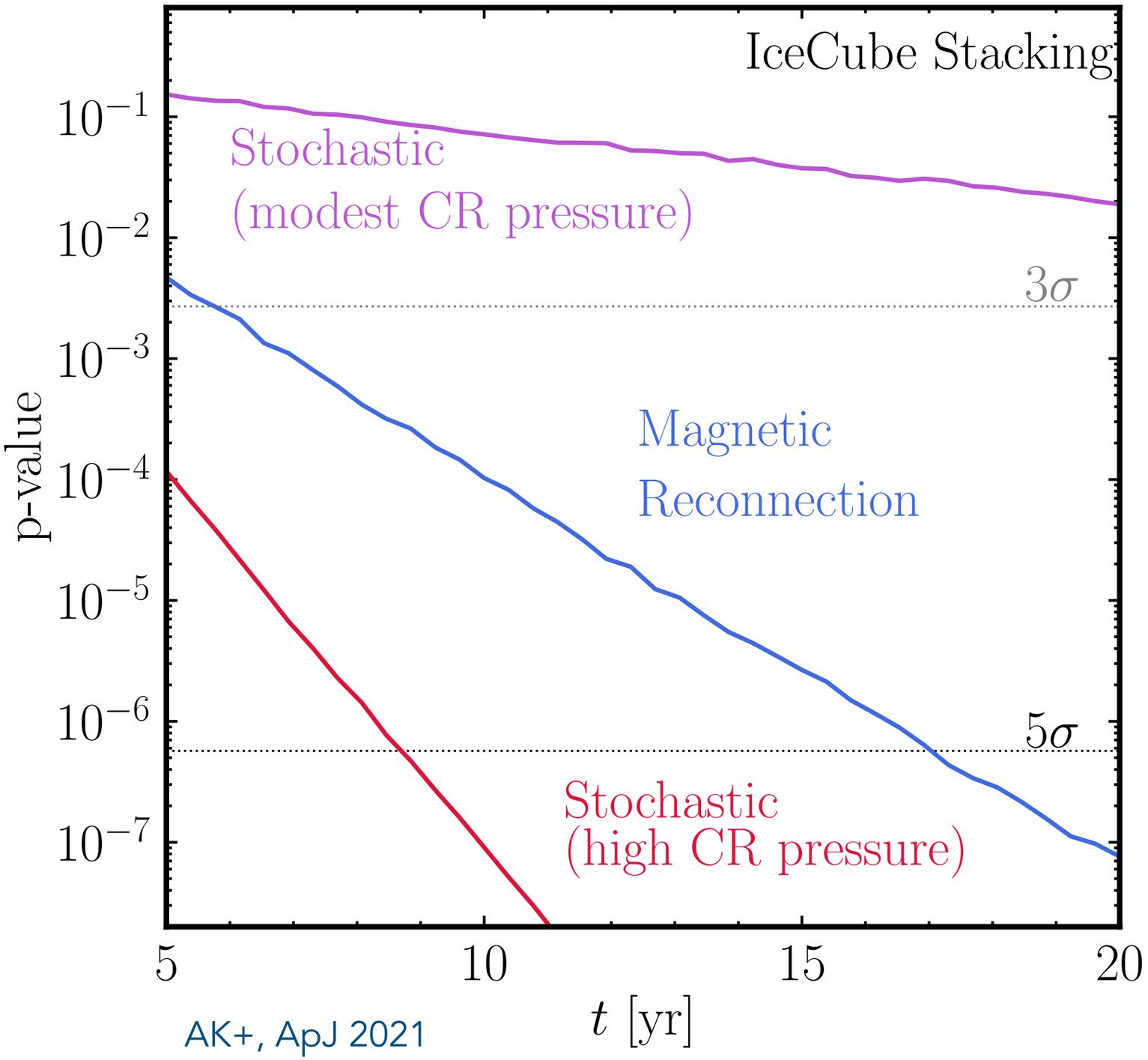
NGC 1068 in AGN-Corona Model

Adopting parameters compatible with IceCube 10 year source search



AK, Murase, Kimura, ApJ 2021

Bright Seyfert Galaxies: IceCube Prospects



AK+, ApJ 2021

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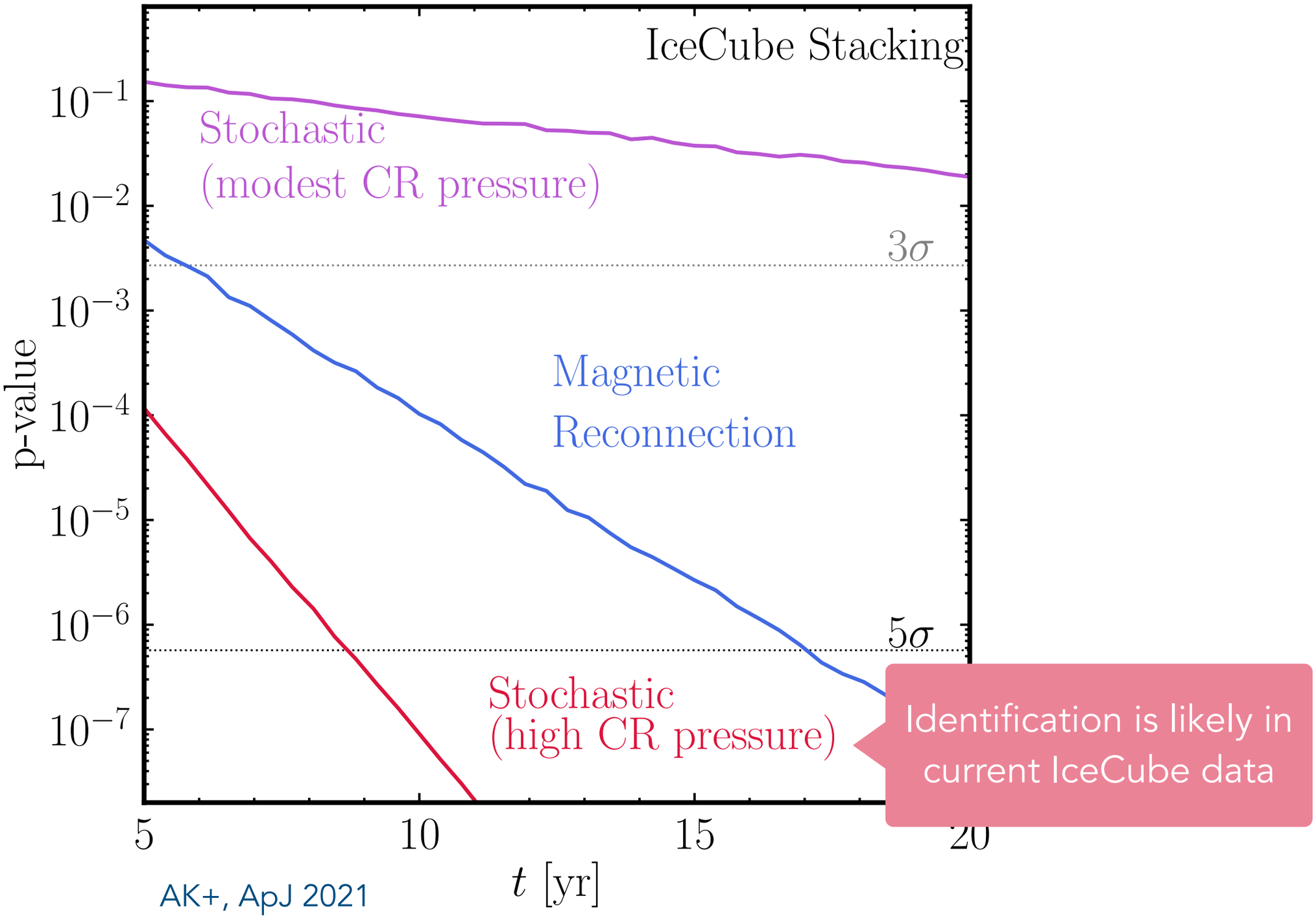

AK+, ApJ 2021

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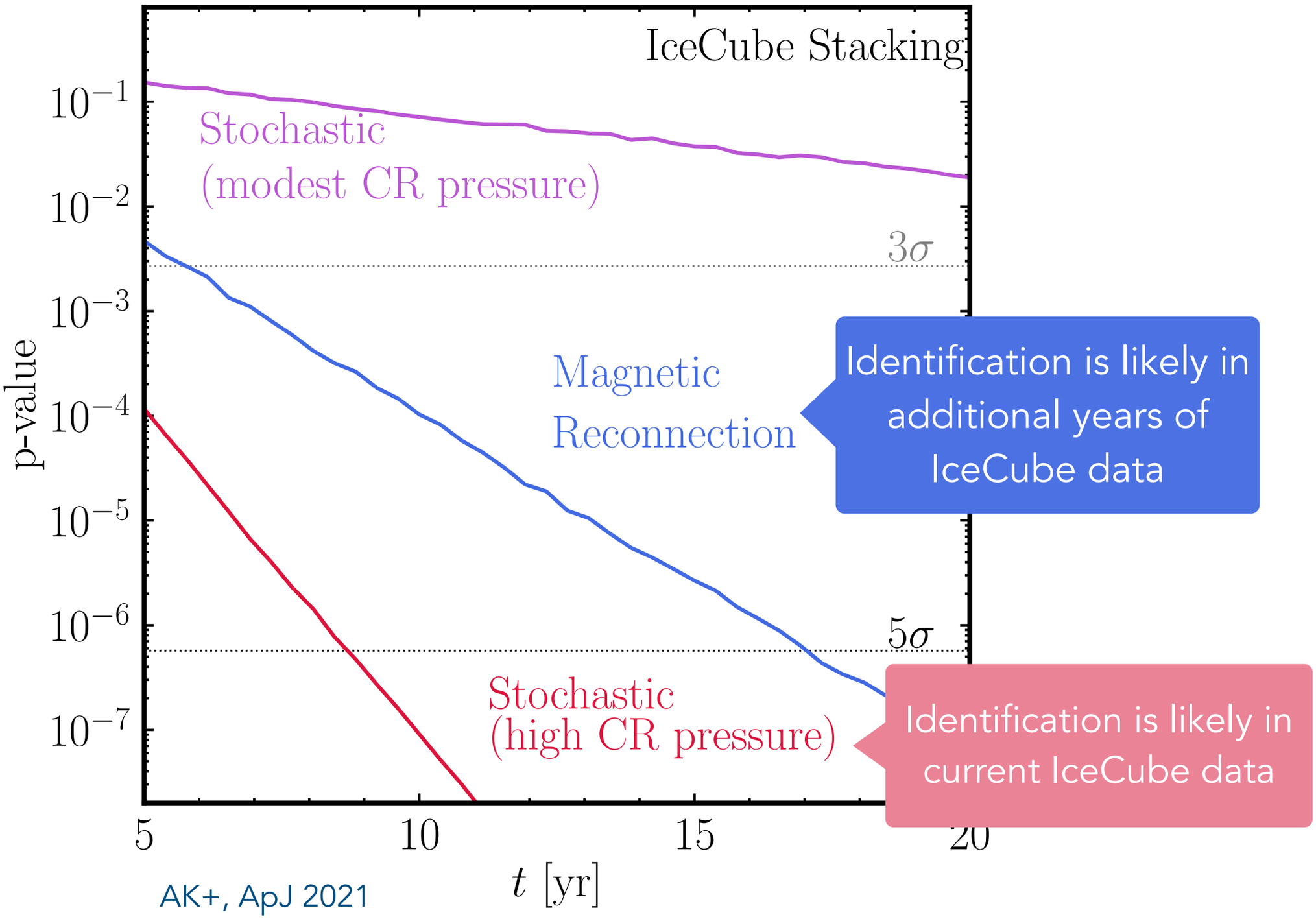

AK+, ApJ 2021

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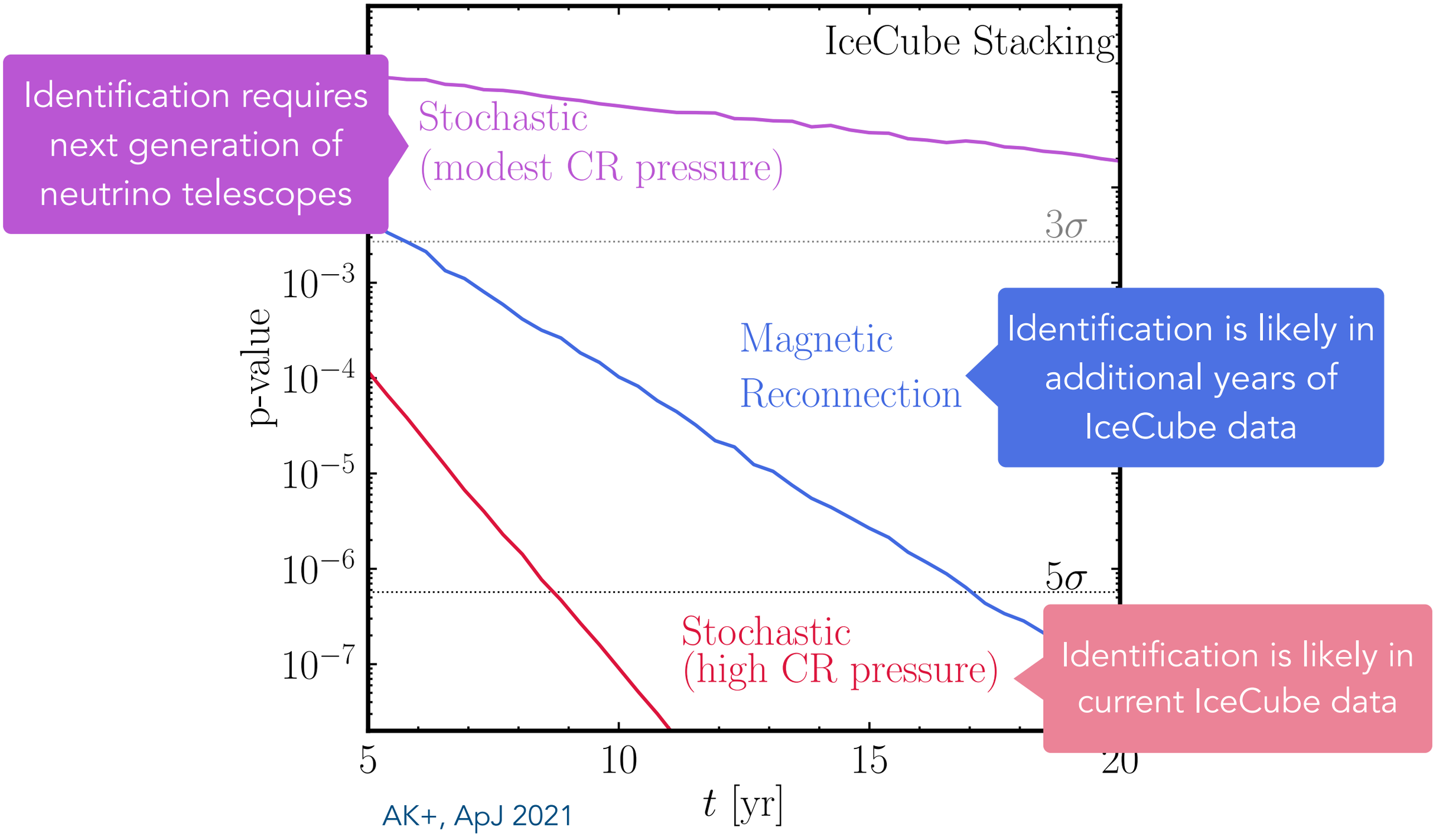

AK+, ApJ 2021