IceCube's Galactic Neutrinos: Diffuse Emission or Hidden Sources?

Markus Ahlers

Niels Bohr Institute, Copenhagen

in collaboration with A. Ambrosone, K. Mørch Groth & E. Peretti

SuGAR, Madison, October 17, 2024

VILLUM FONDEN

KØBENHAVNS UNIVERSITET

Galactic Cosmic Rays

- *Standard paradigm*: Galactic CRs accelerated in supernova remnants

  [Baade & Zwicky'34]
  [Ginzburg & Sirovatskii'64]

- Diffusive shock acceleration:

$$n_{\rm CR} \propto E^{-\Gamma}$$

- Rigidity-dependent escape from Galaxy:

$$n_{\rm CR} \propto E^{-\Gamma-\delta}$$

- Hadronic γ & ν emission from interaction with ISM

  [Stecker'79]
  [Berezinsky, Gaisser, Halzen & Stanev'93]

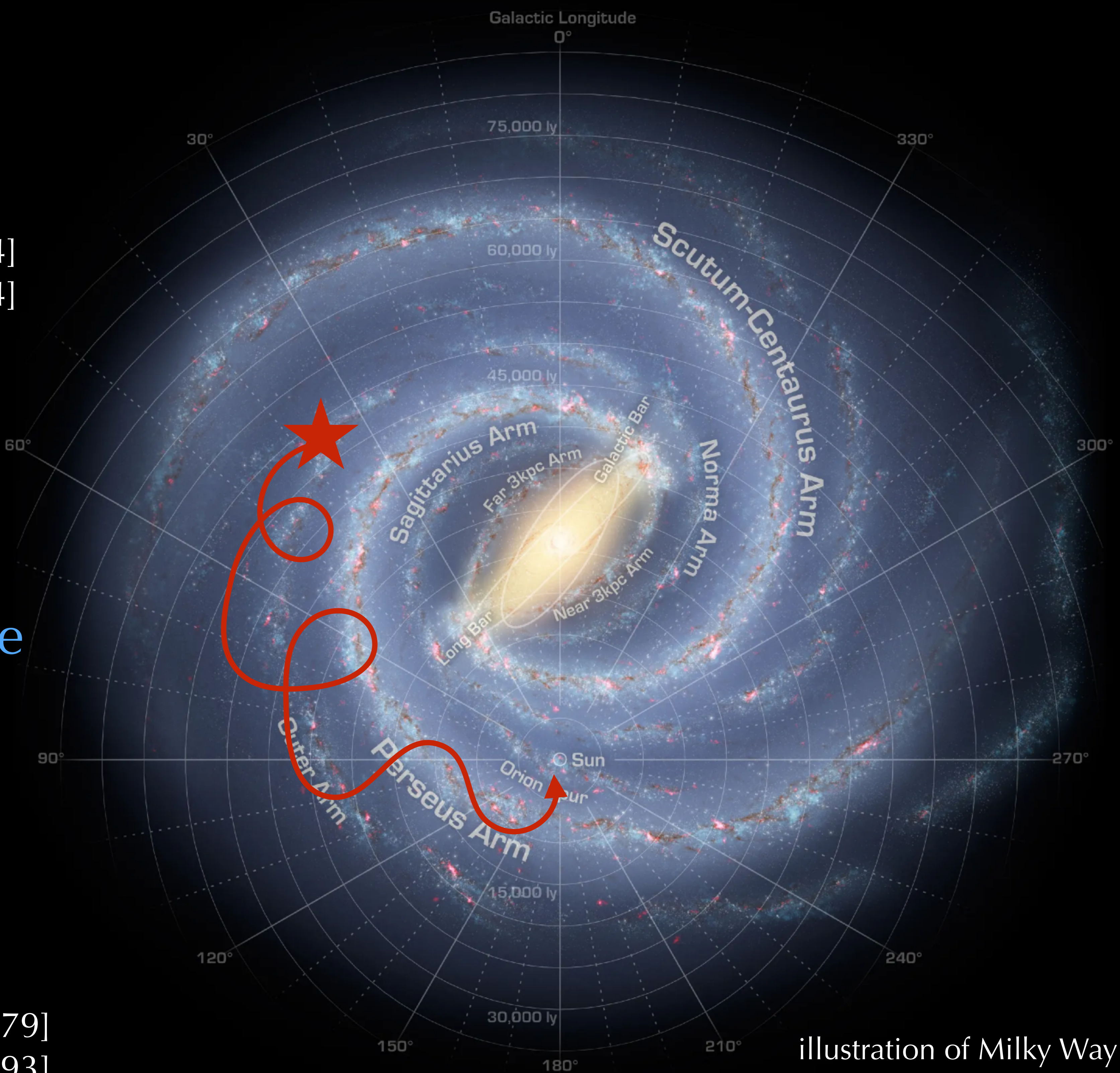
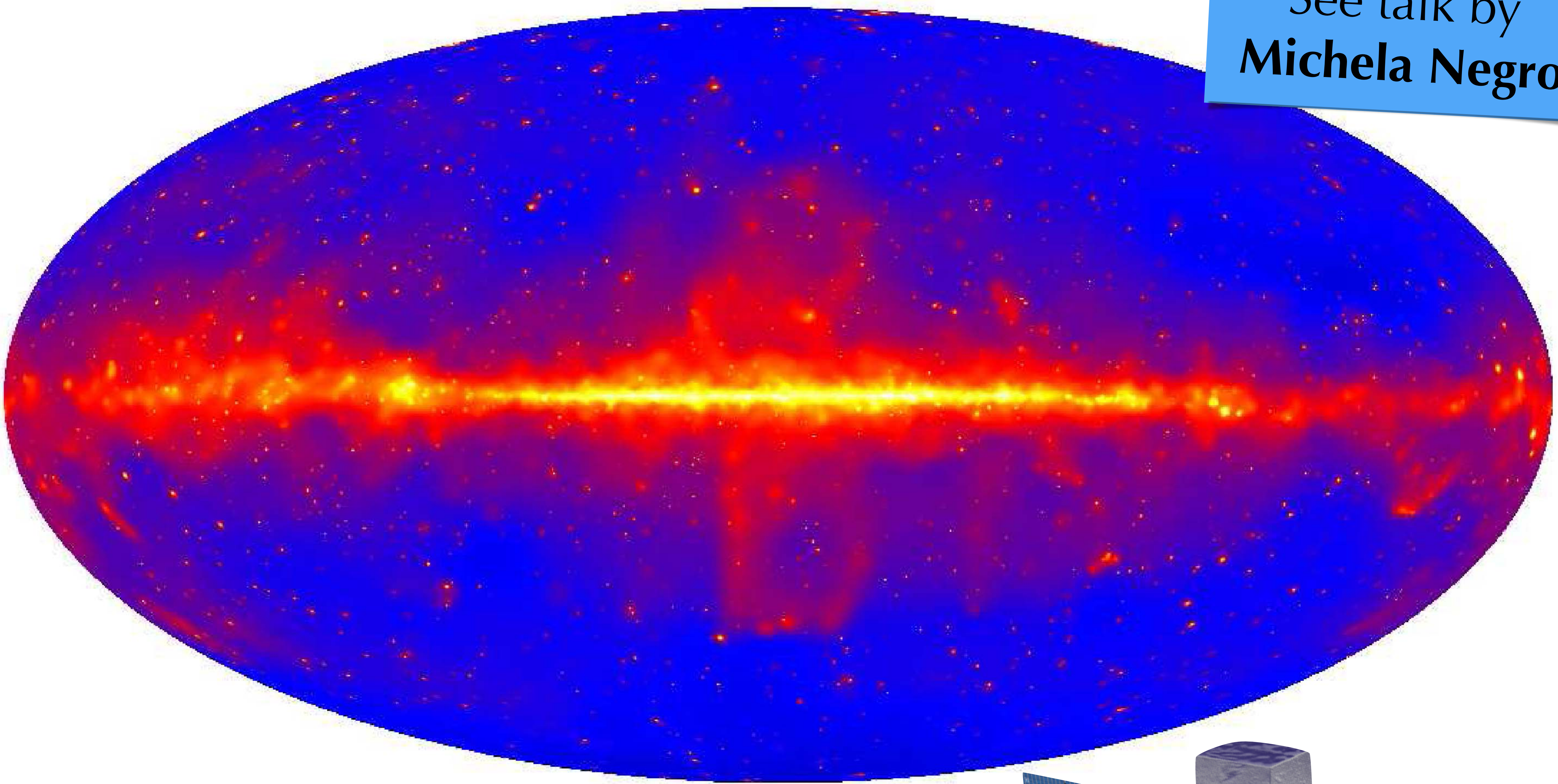


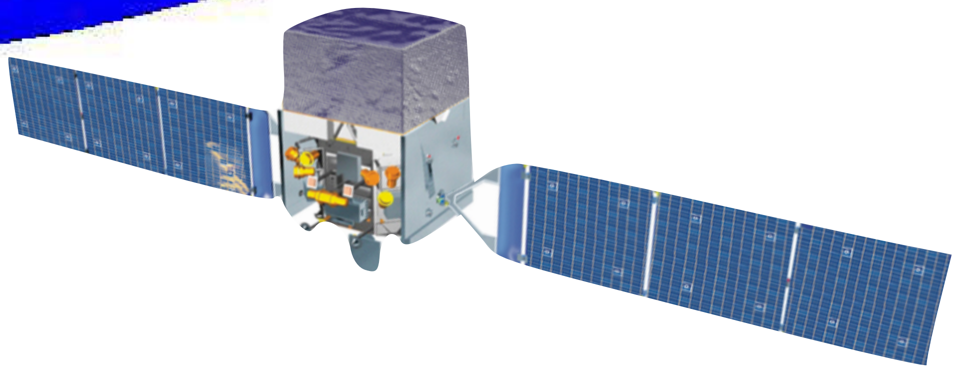
illustration of Milky Way
[Credit: NASA]

Galactic Diffuse γ-ray Emission

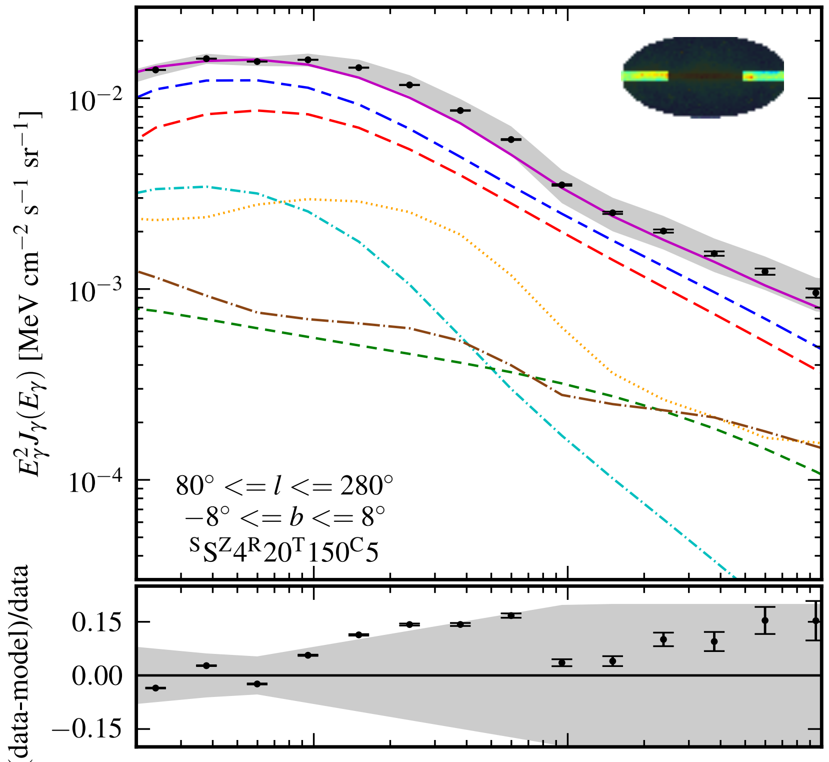


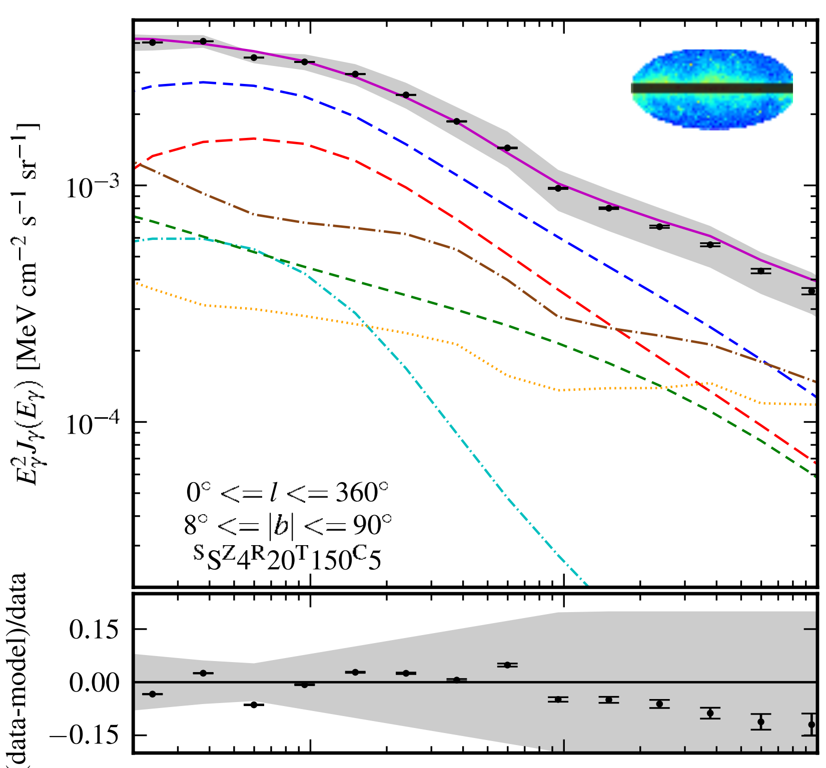
See talk by **Michela Negro**

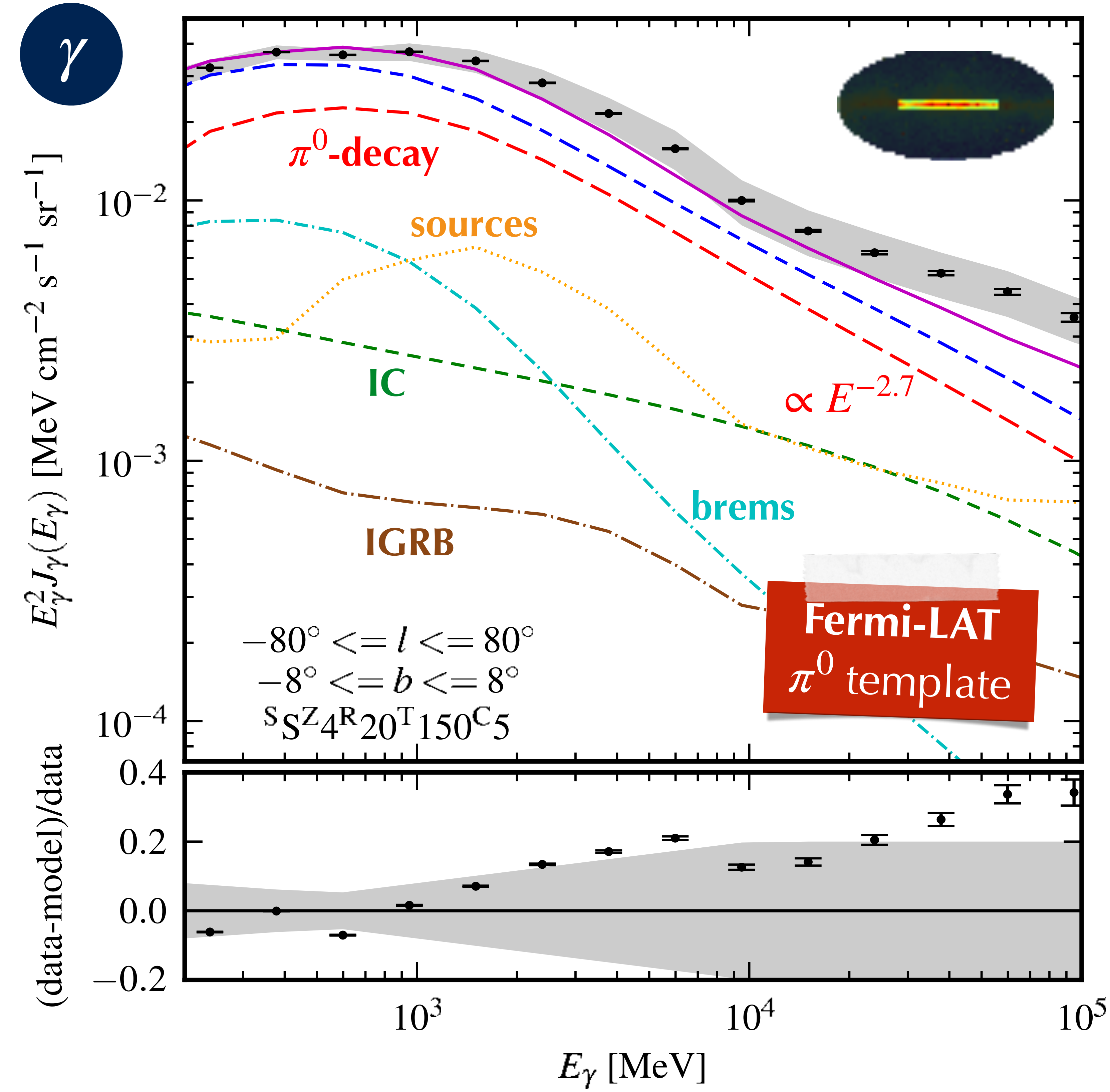
Fermi-LAT γ-ray count map



Galactic Diffuse γ-ray Emission



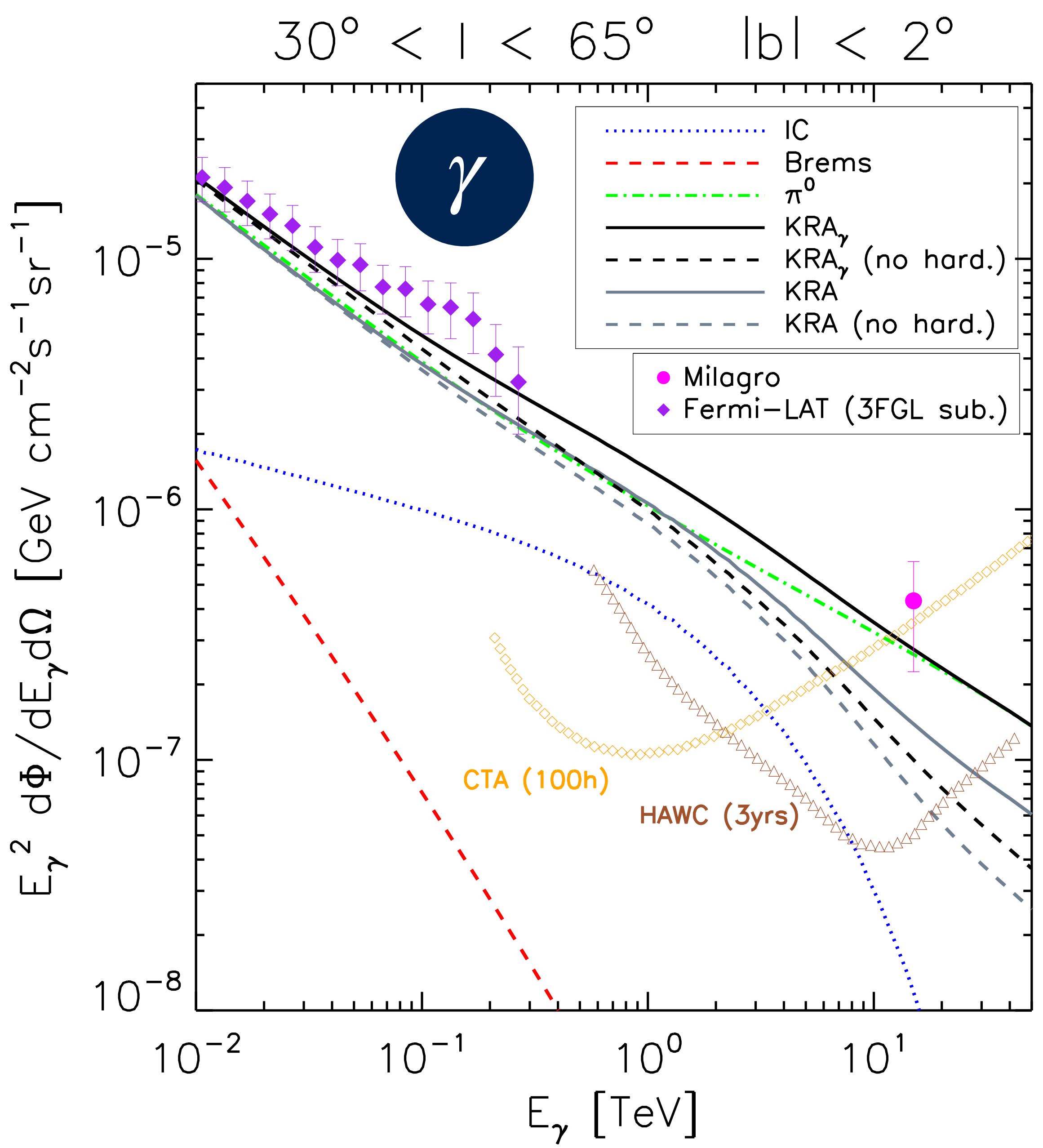


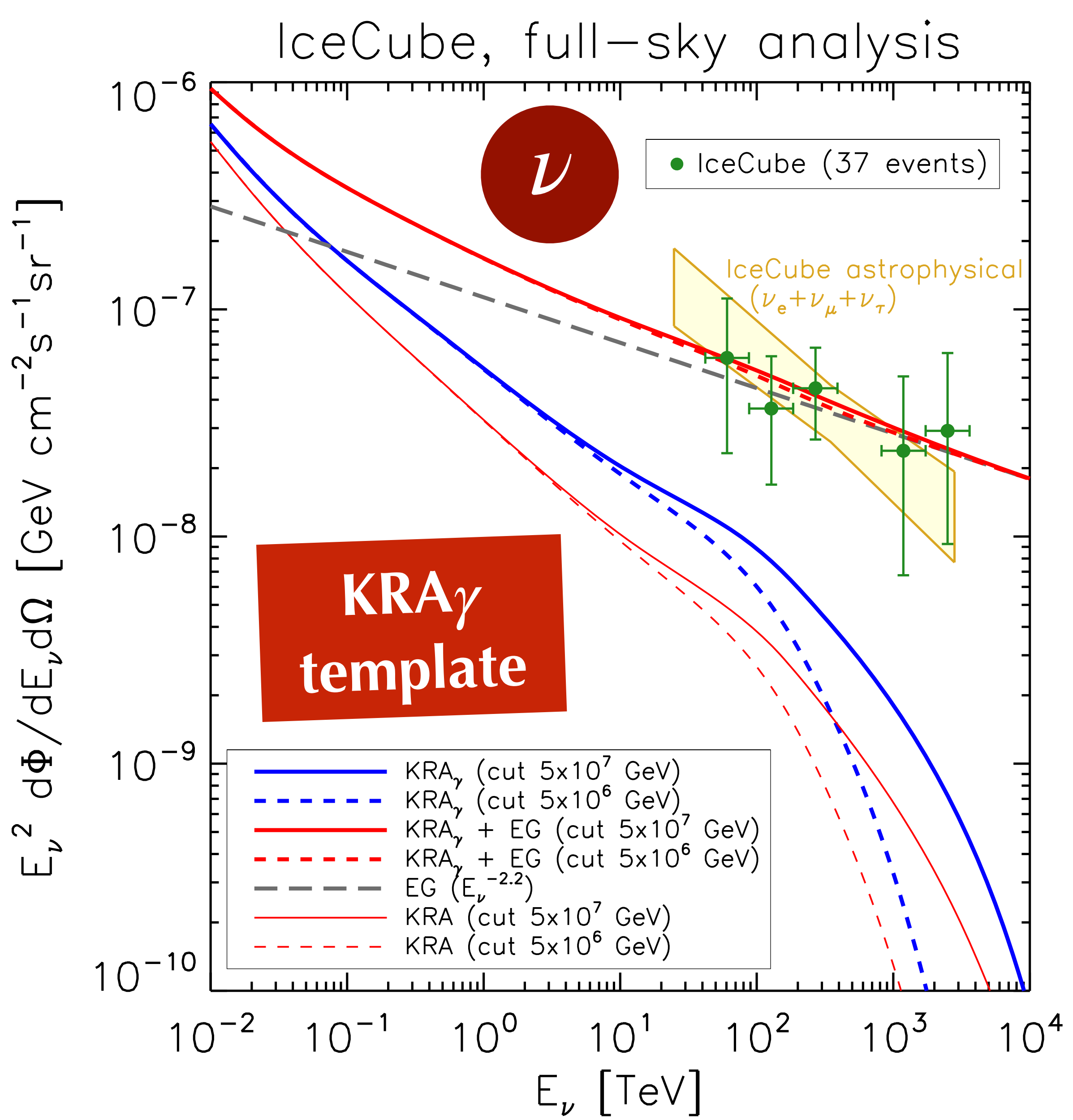


[Fermi-LAT ApJ 750 (2012) 3]

Galactic Diffuse γ-ray Emission

KRAγ model accounts for "anomalously" high γ-ray flux in inner Galaxy by radially dependent diffusion coefficient.



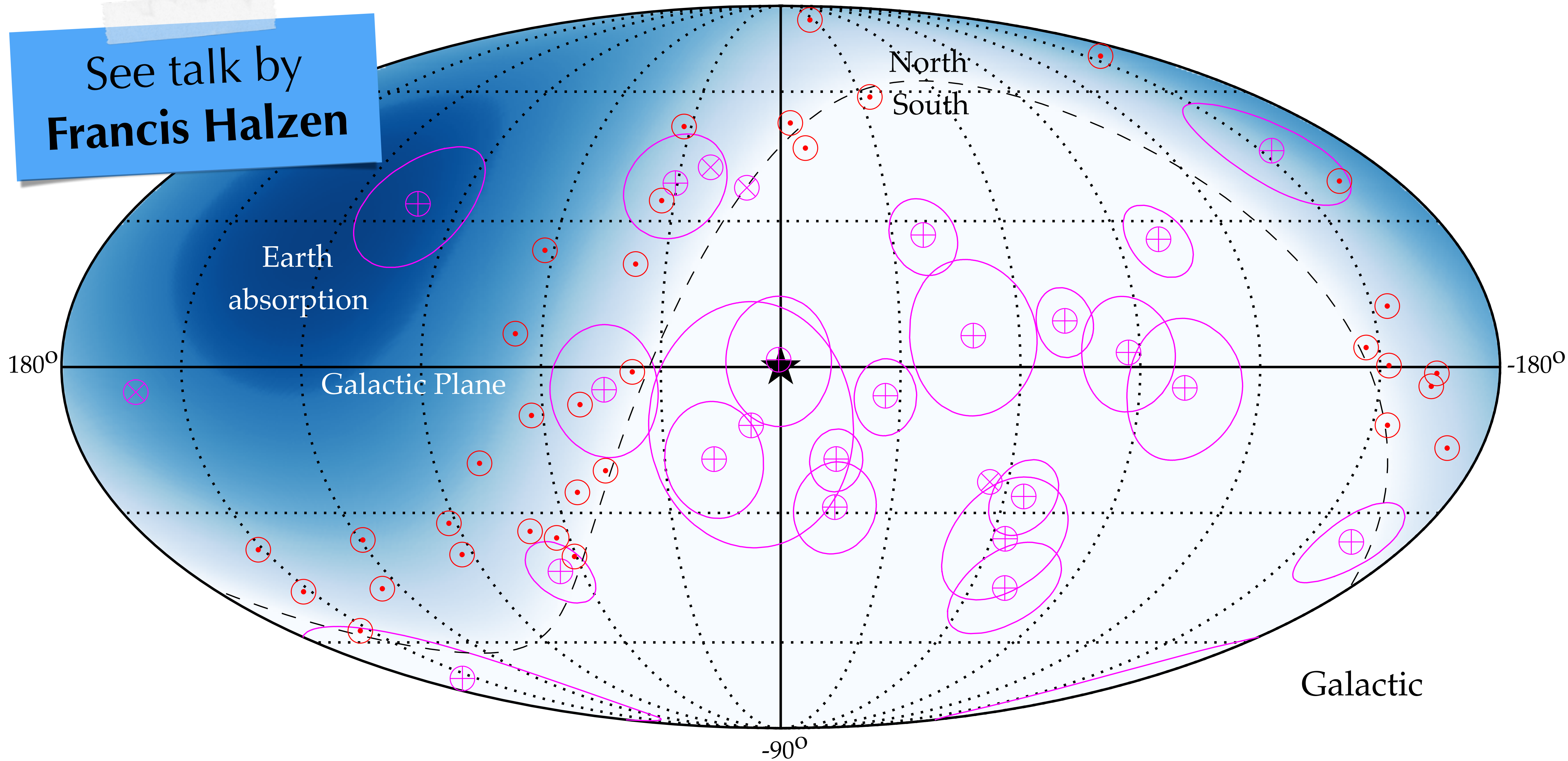


[Gaggero, Grasso, Marinelli, Urbano & Valli '14 & '15]

Diffuse Neutrino Background

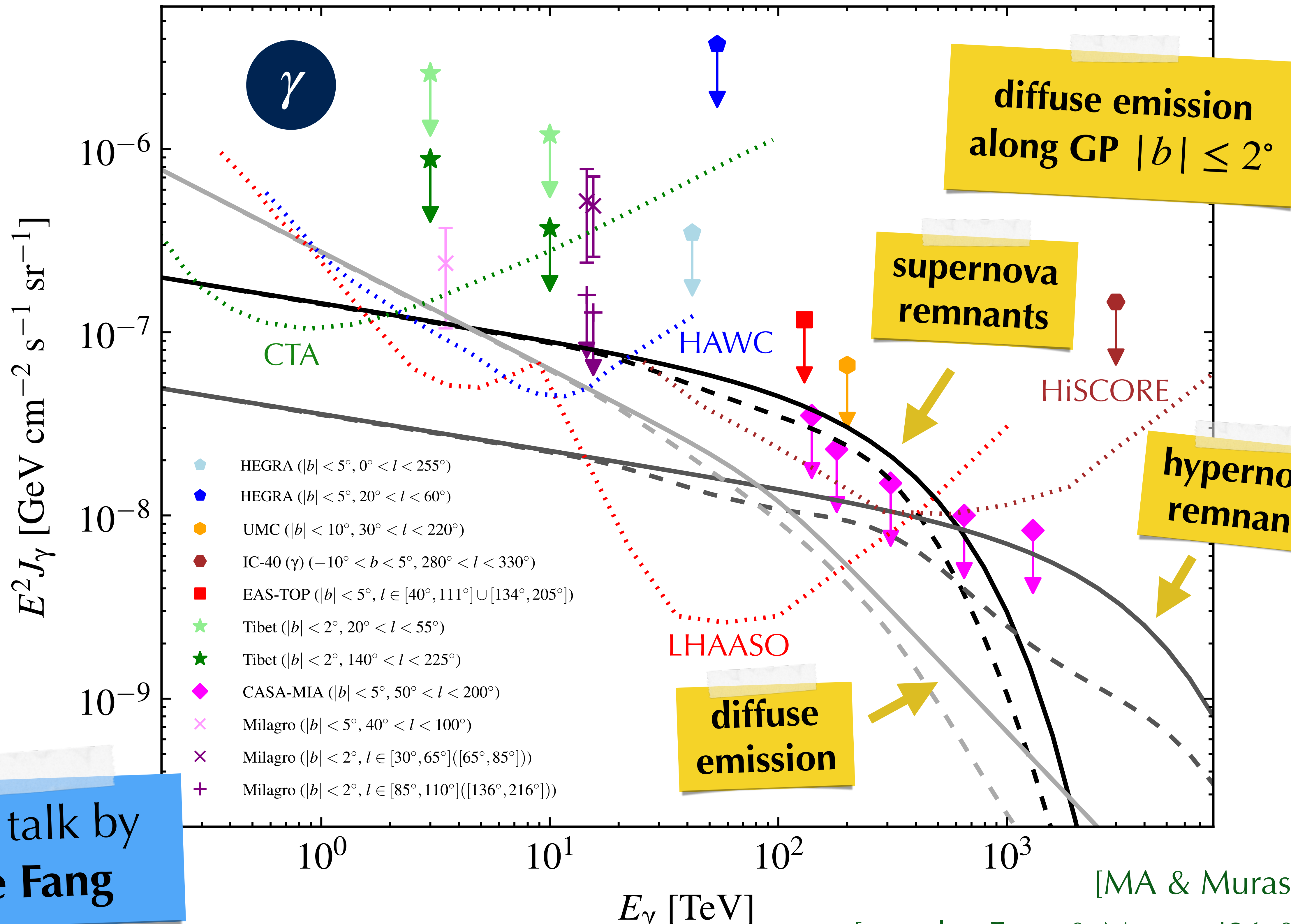
Most energetic neutrino events (HESE 6yr (magenta) & $\nu_\mu + \overline{\nu}_\mu$ 8yr (red))

See talk by **Francis Halzen**



Cosmic neutrino background is dominated by extragalactic sources.
Compelling evidence for ν's from TXS 0506+056 & NGC 1068.

Galactic Quasi-Diffuse Emission

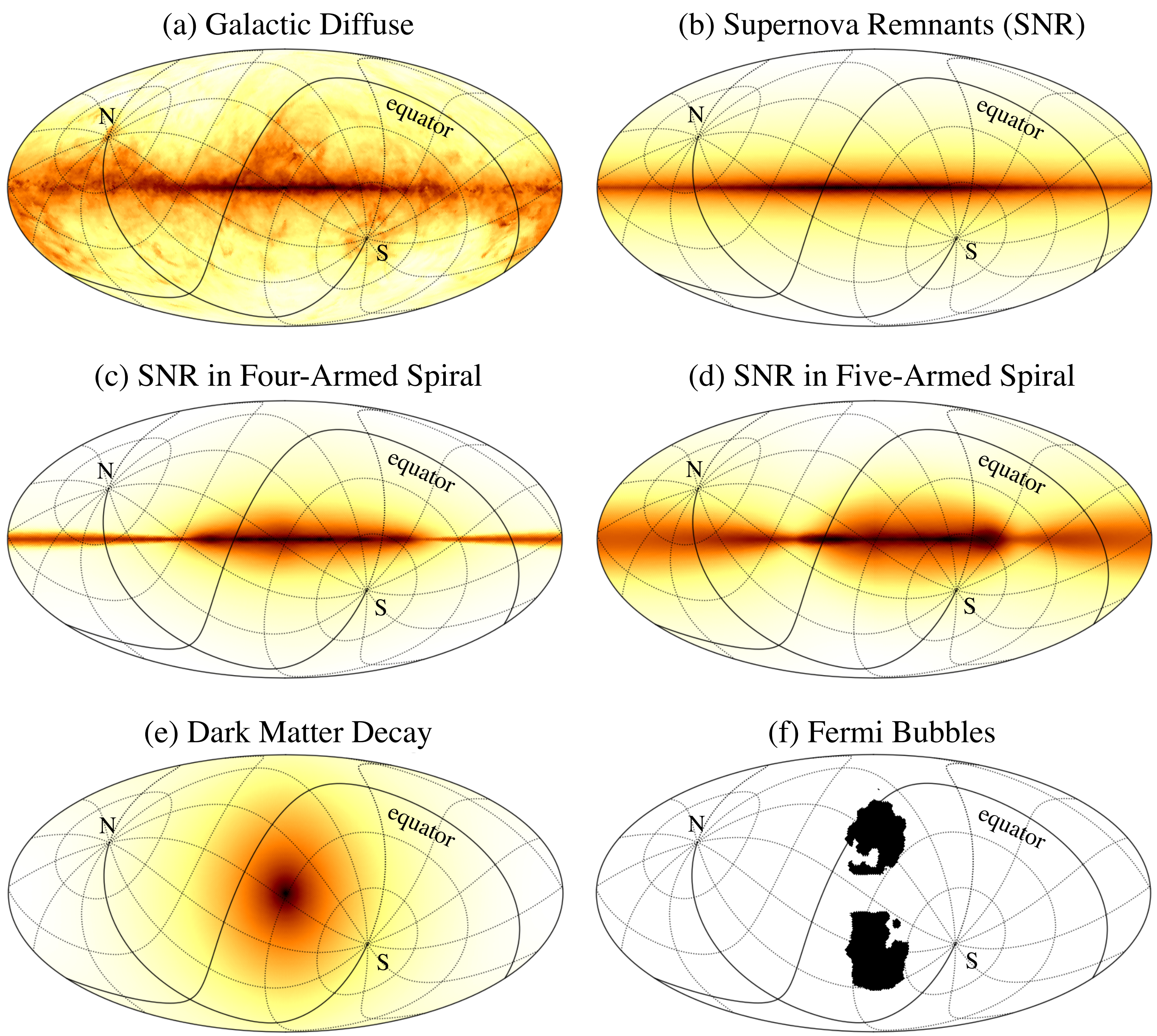


See talk by
Ke Fang

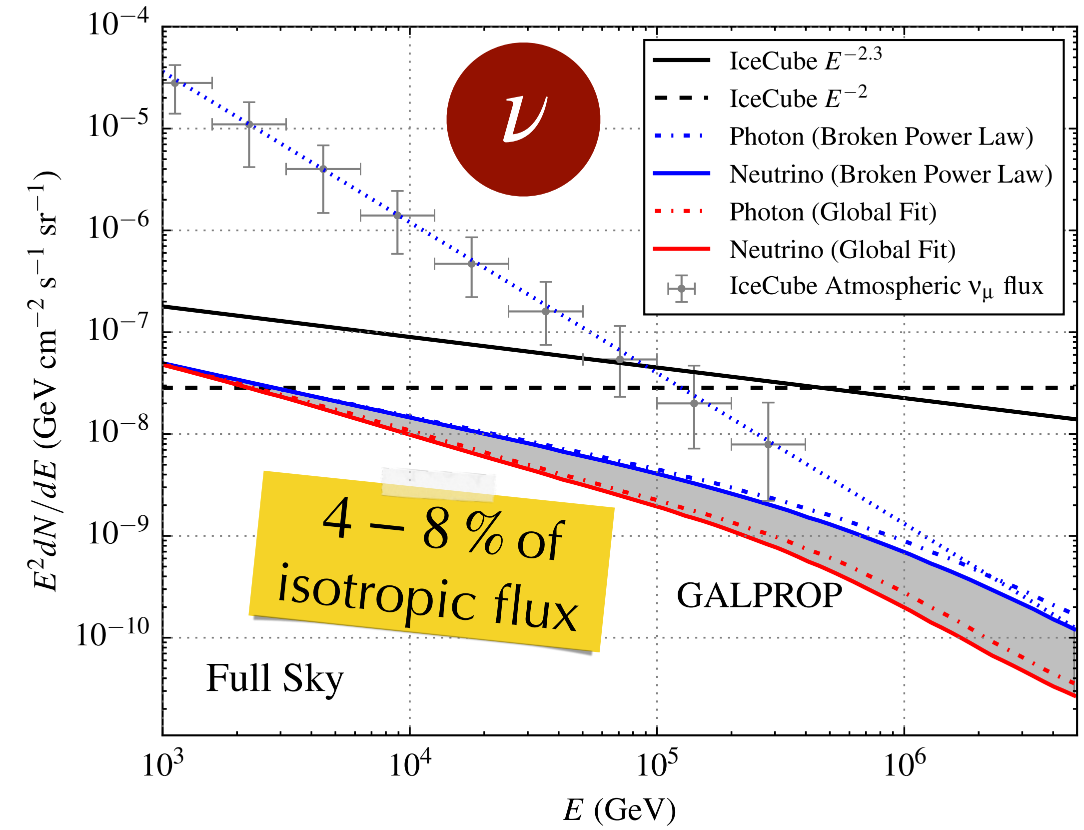
[MA & Murase'13]
[see also Fang & Murase '21 & '23]

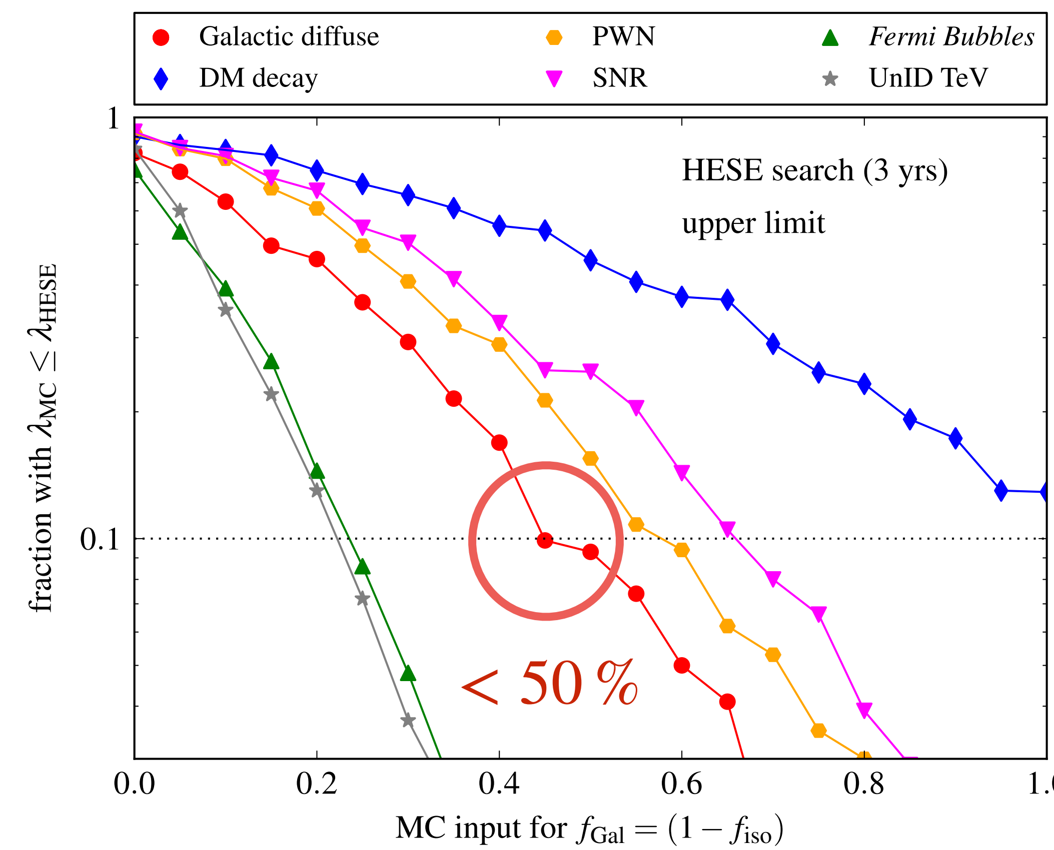
Galactic Quasi-Diffuse Emission

Galactic Emission Templates

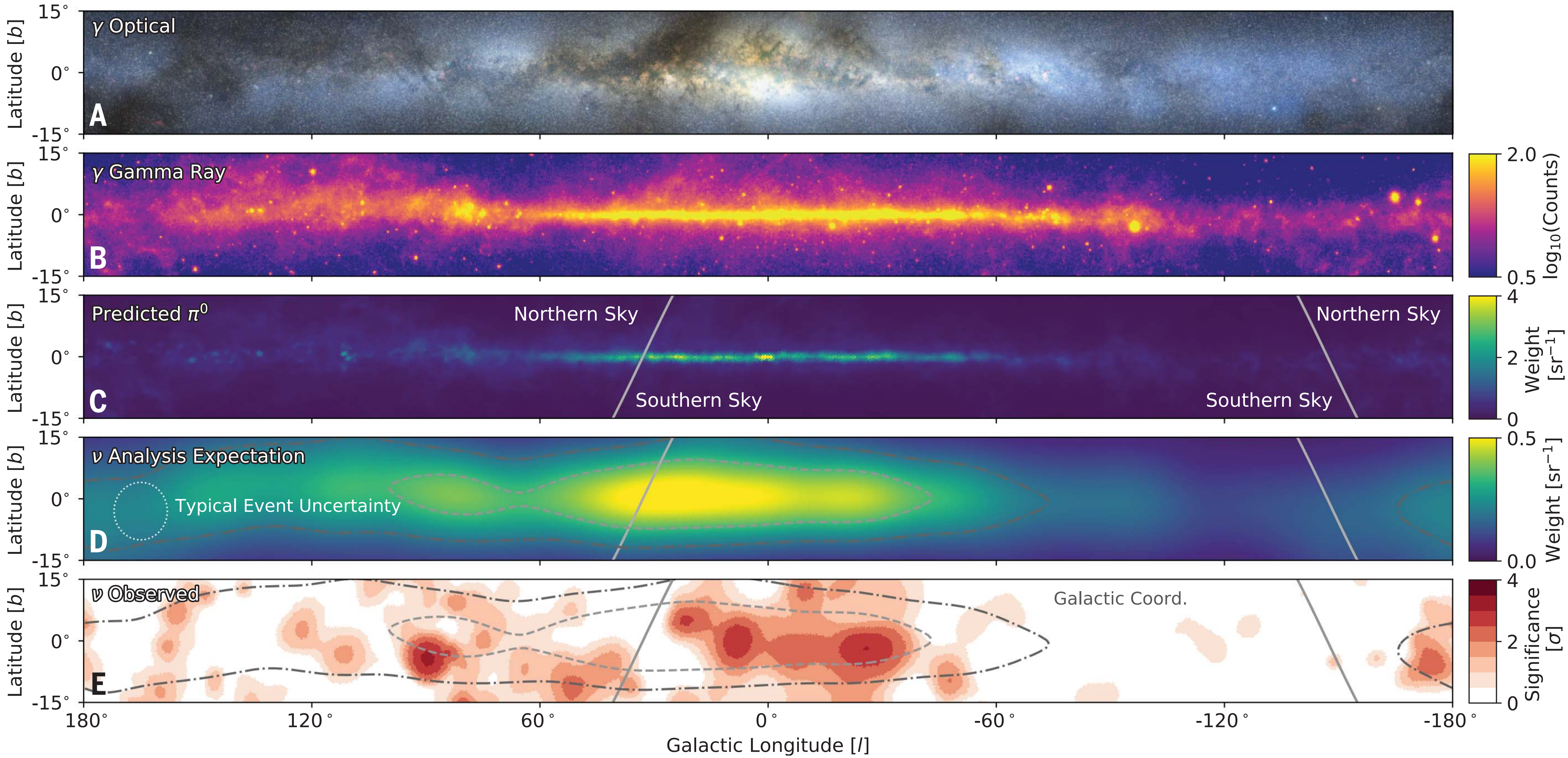


[MA, Bai, Barger & Lu'16]



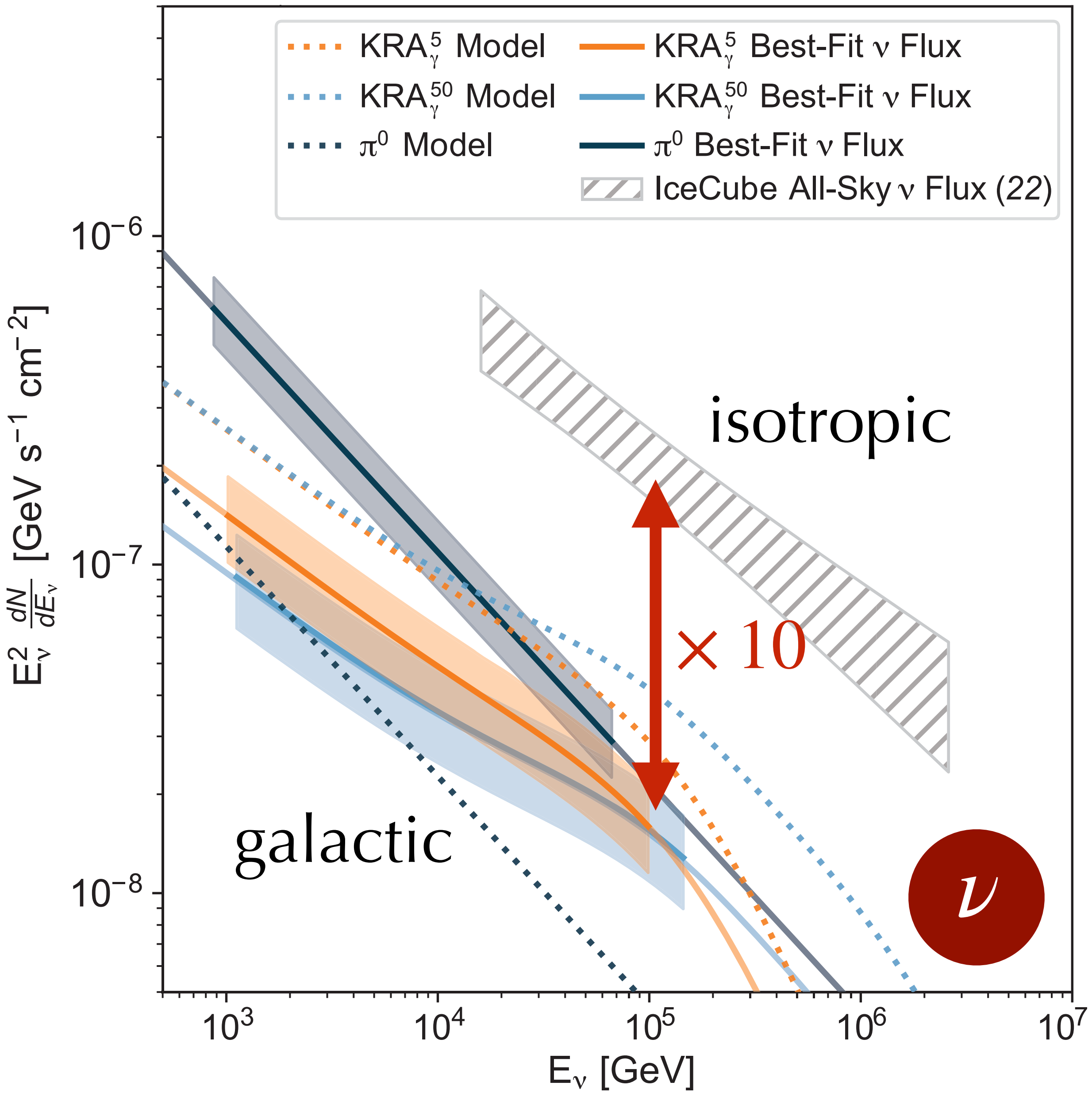


Galactic diffuse ν emission at 4.5σ based on template analysis.

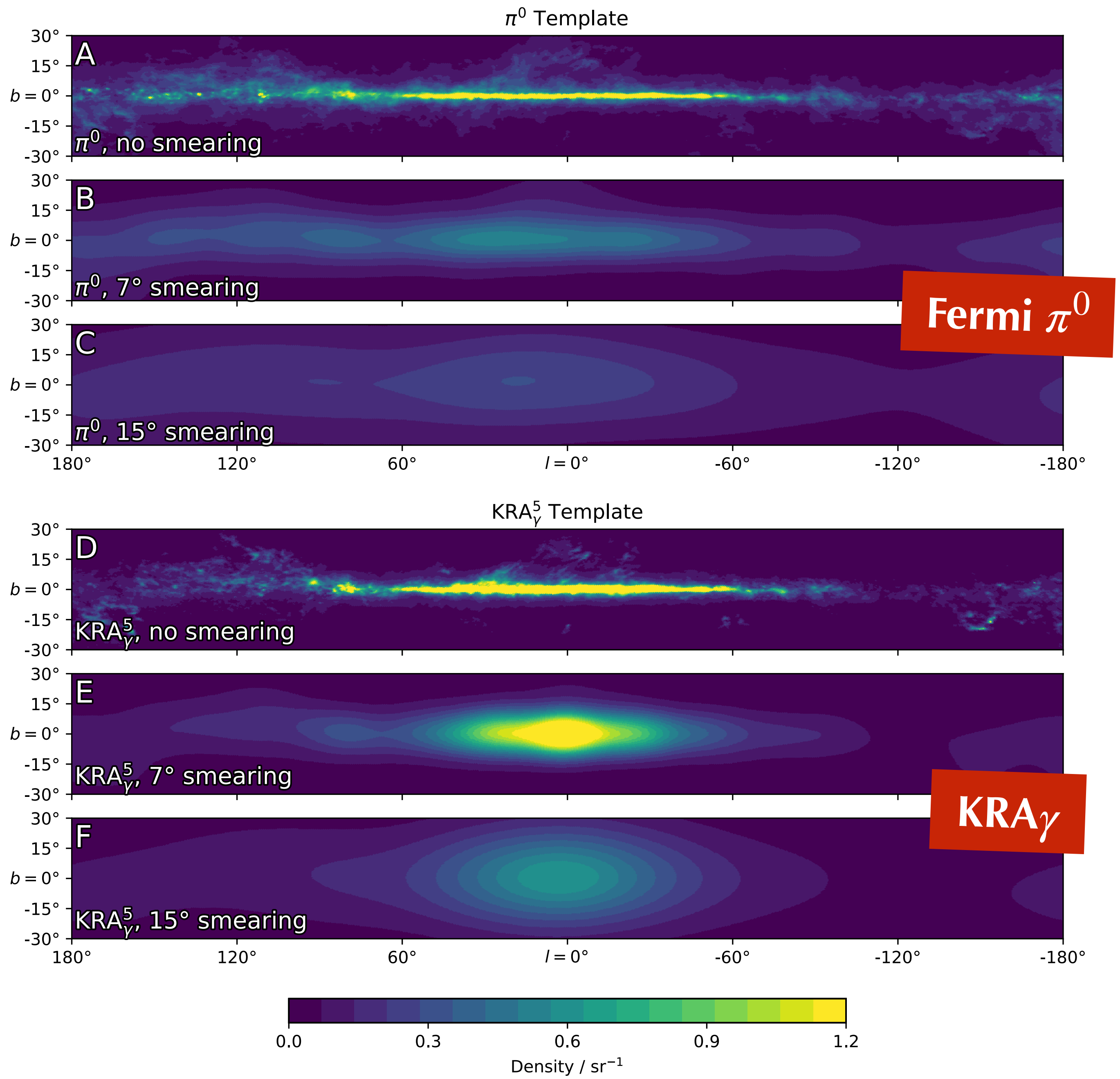


[IceCube **Science** 380 (2023)]

Best-fit normalization of spectra

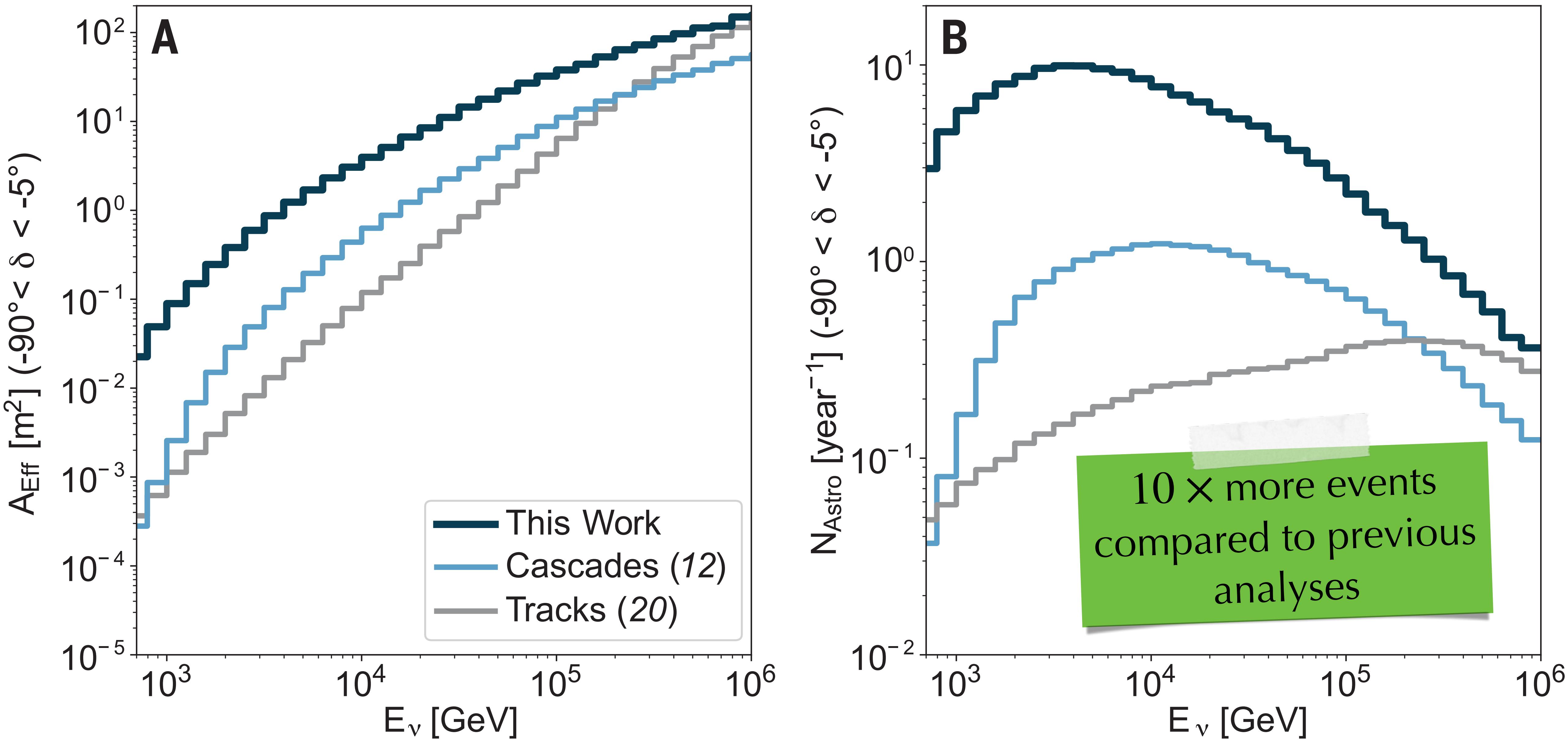


Templates with different resolution



[IceCube **Science** 380 (2023)] [**templates**: Fermi'12; Gaggero, Grasso, Marinelli, Urbano & Valli '15]

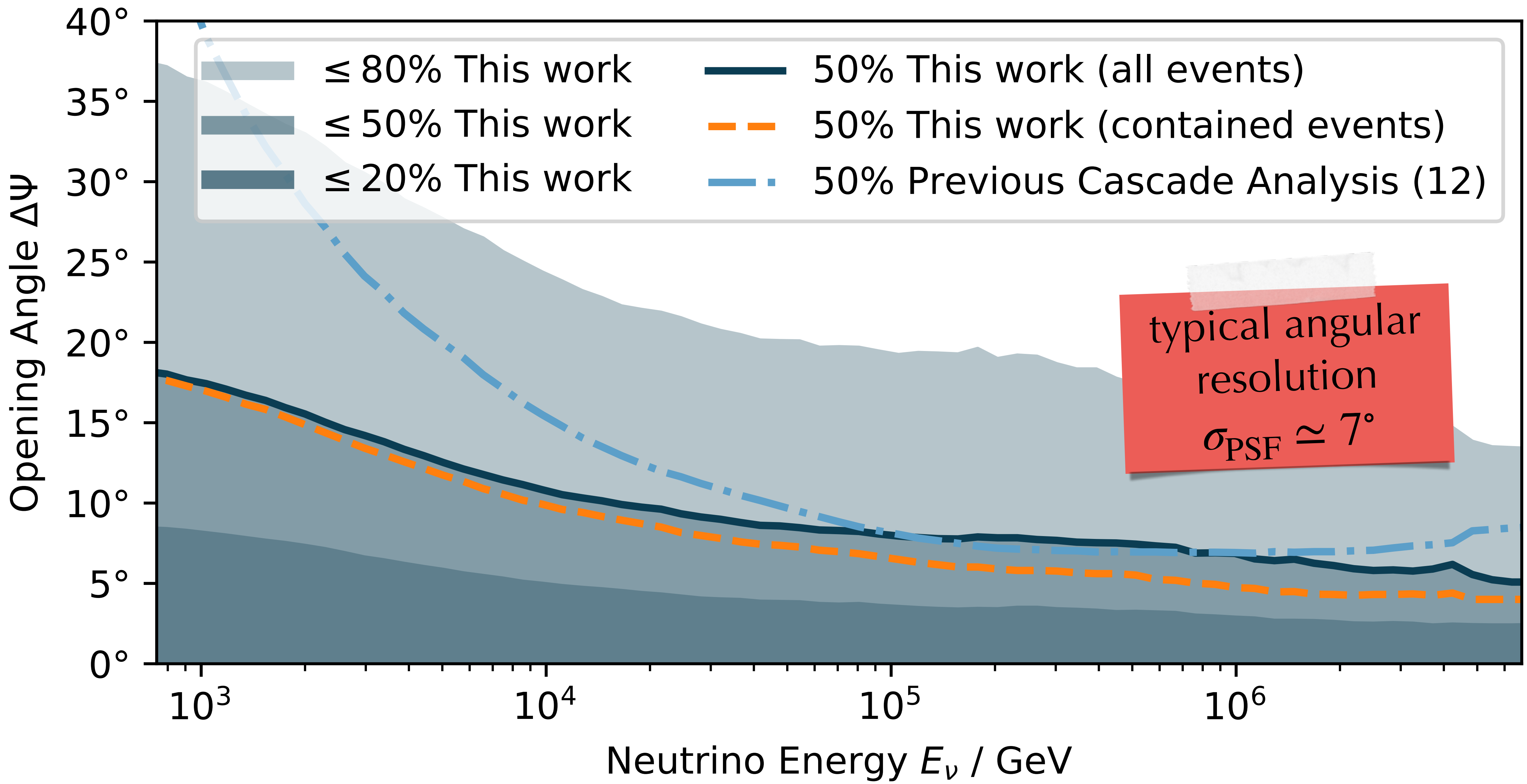
Analysis is based on novel cascade event selection and reconstruction using deep neutral networks (DNNcascade).



[IceCube **Science** 380 (2023)]

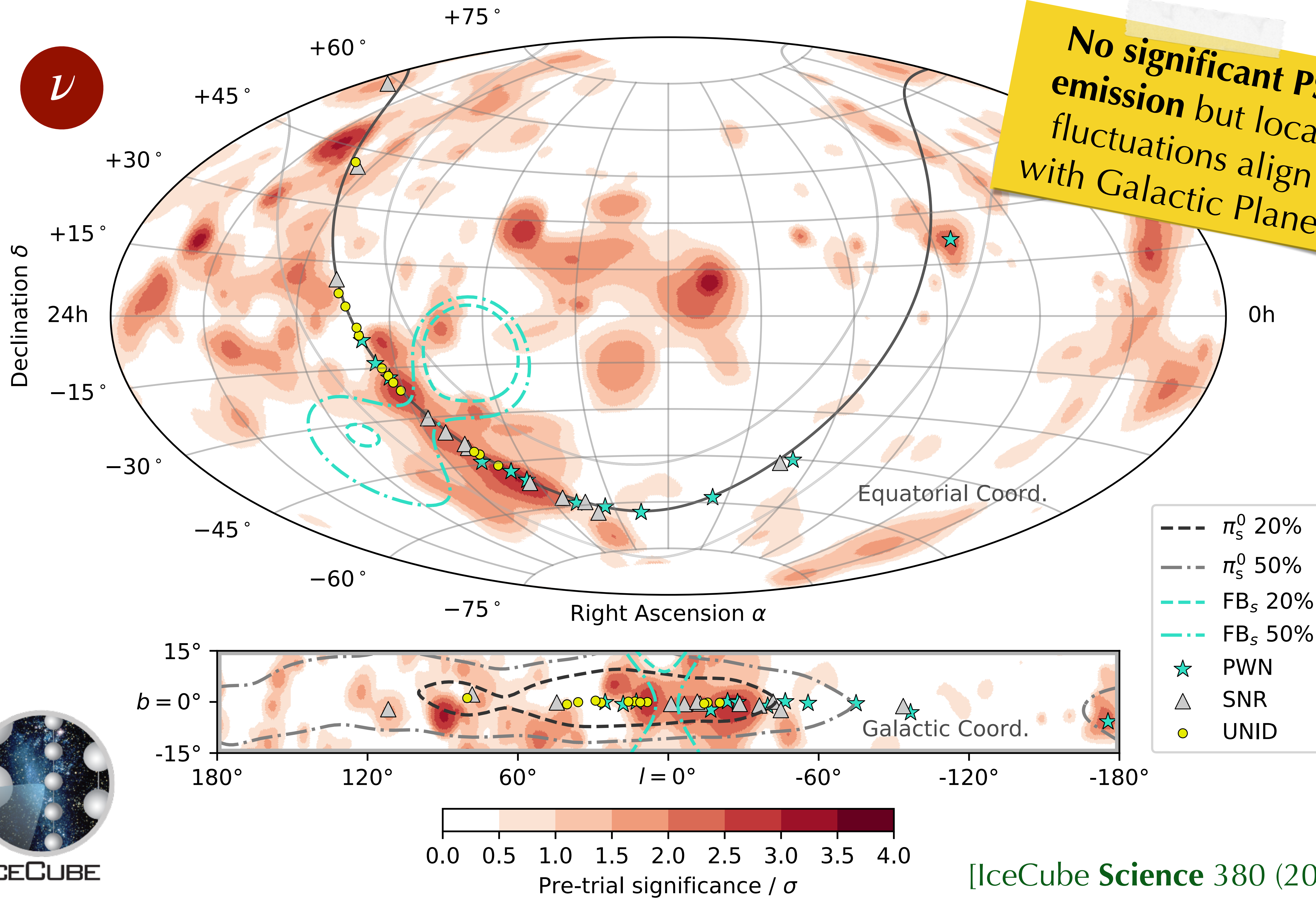
Analysis Sample

Analysis is based on novel cascade event selection and reconstruction using deep neutral networks (DNNcascade).



[IceCube **Science** 380 (2023)]

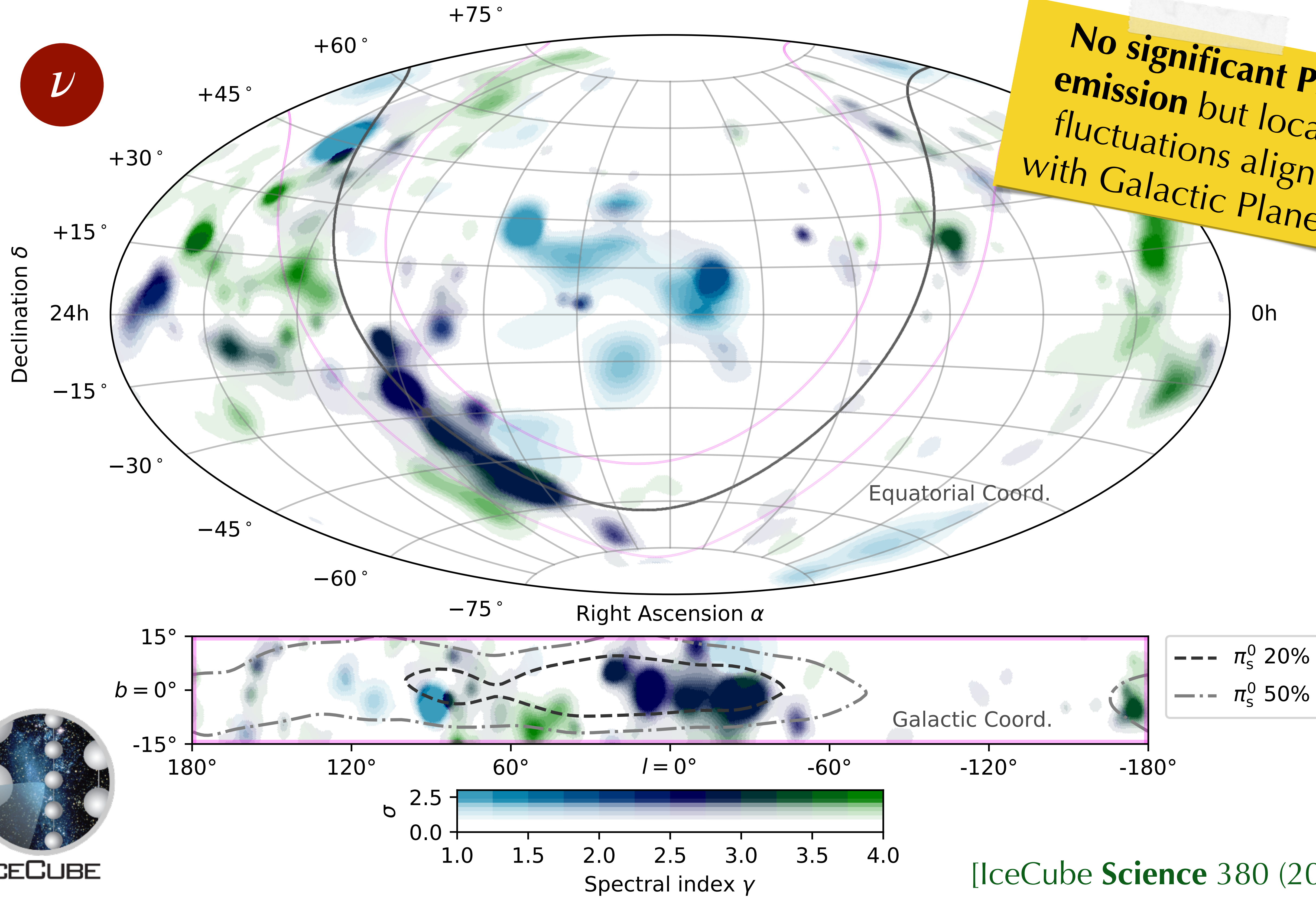
Point-Source Significance Map



No significant PS emission but local fluctuations align with Galactic Plane.

[IceCube **Science** 380 (2023)]

Point-Source Significance Map



No significant PS emission but local fluctuations align with Galactic Plane.

[IceCube **Science** 380 (2023)]

Template and Catalog Searches

	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)*	
		Other analyses	
Fermi bubbles		0.06 (1.52σ)	
Source list		0.22 (0.77σ)	
Hotspot (north)		0.28 (0.58σ)	
Hotspot (south)		0.46 (0.10σ)	

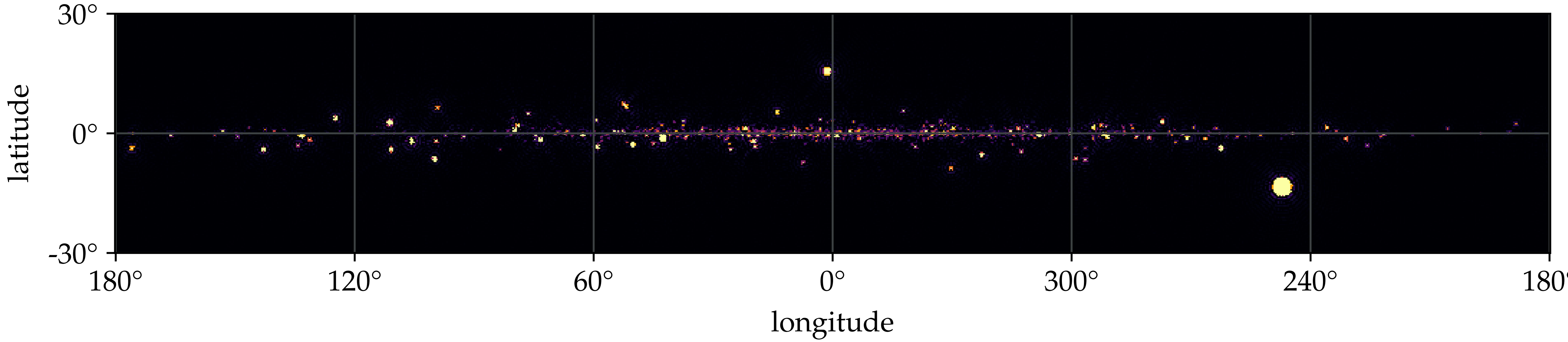
*Significance values that are consistent with the diffuse Galactic plane template search results.

post-trial p-value
template search:
4.5σ

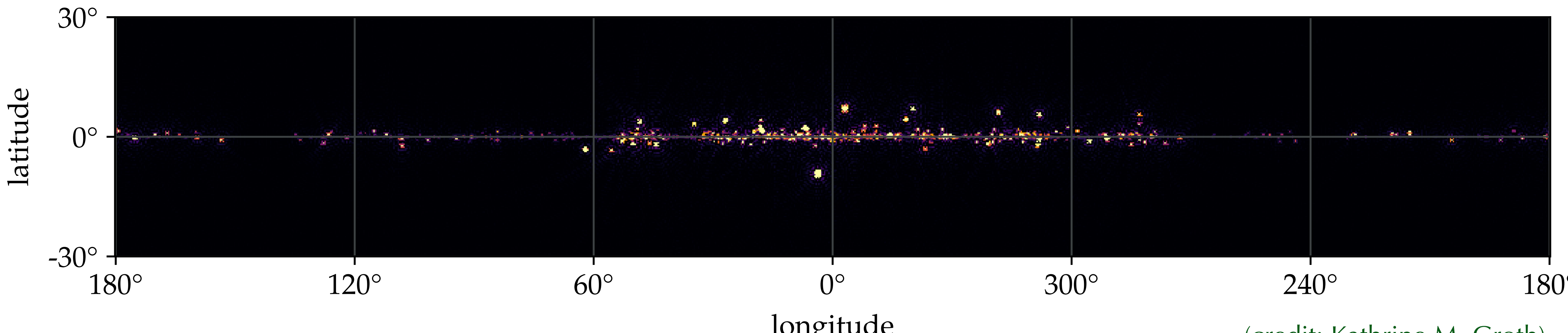
[IceCube **Science** 380 (2023)]

Galactic Neutrino Populations

azimuthally symmetric distribution following SNRs (Case *et al.*)



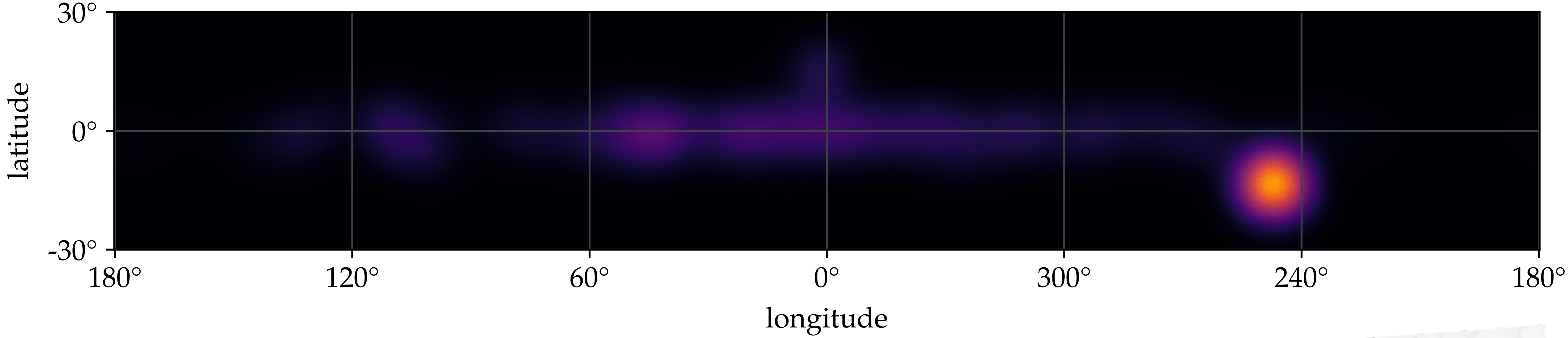
+ modulation with spiral arms



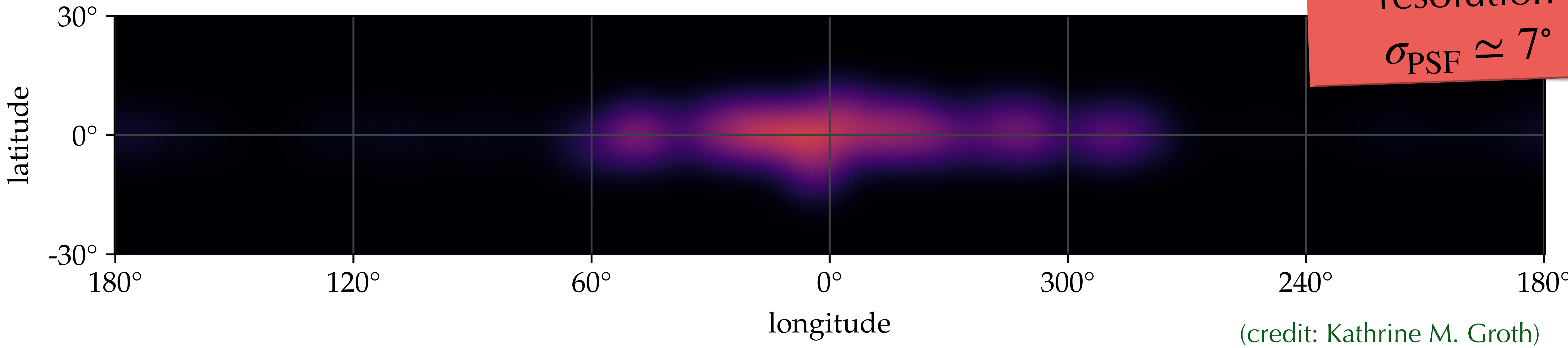
(credit: Kathrine M. Groth)

Galactic Neutrino Populations

azimuthally symmetric distribution following SNRs (Case *et al.*)



+ modulation with spiral arms

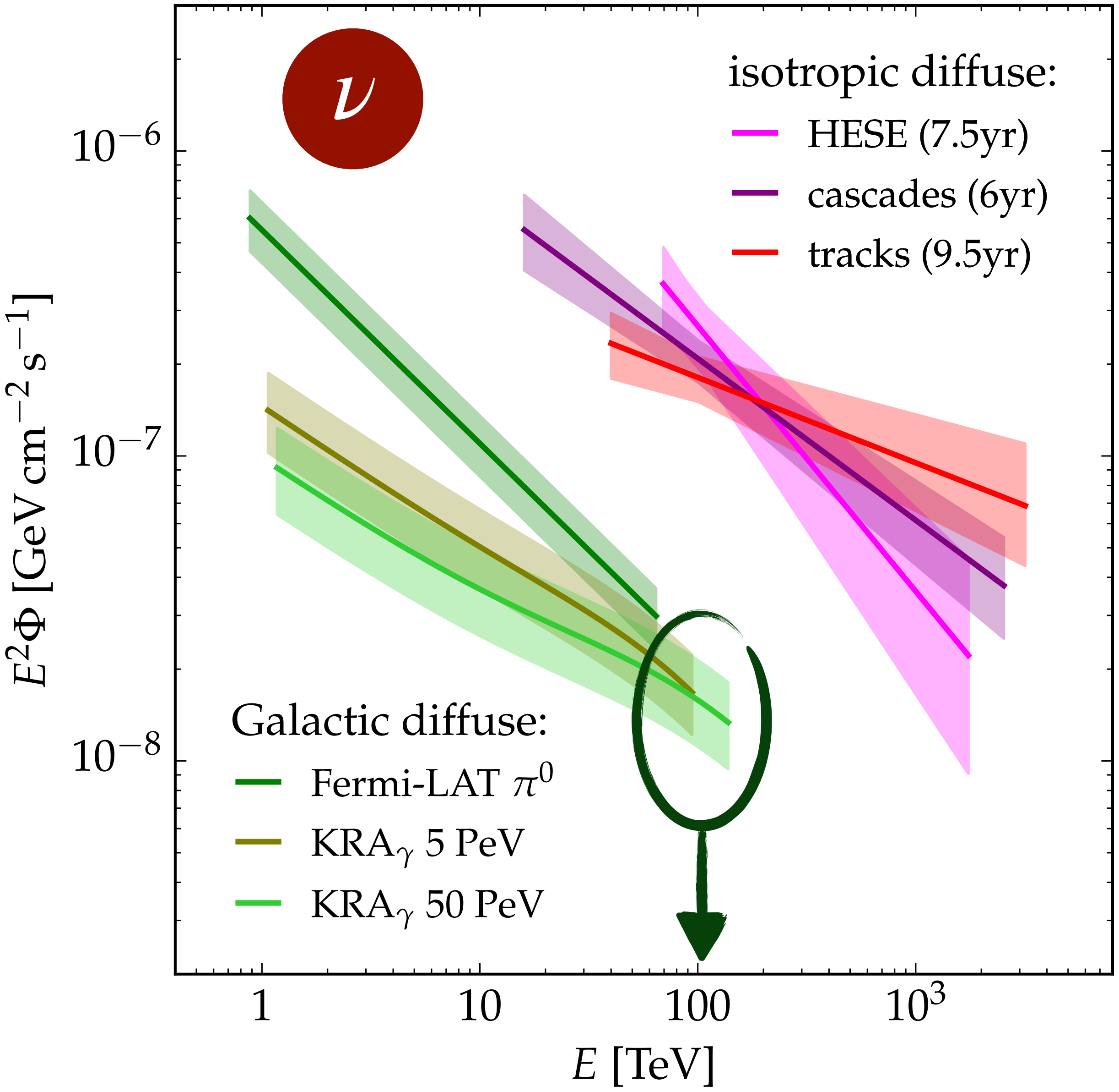


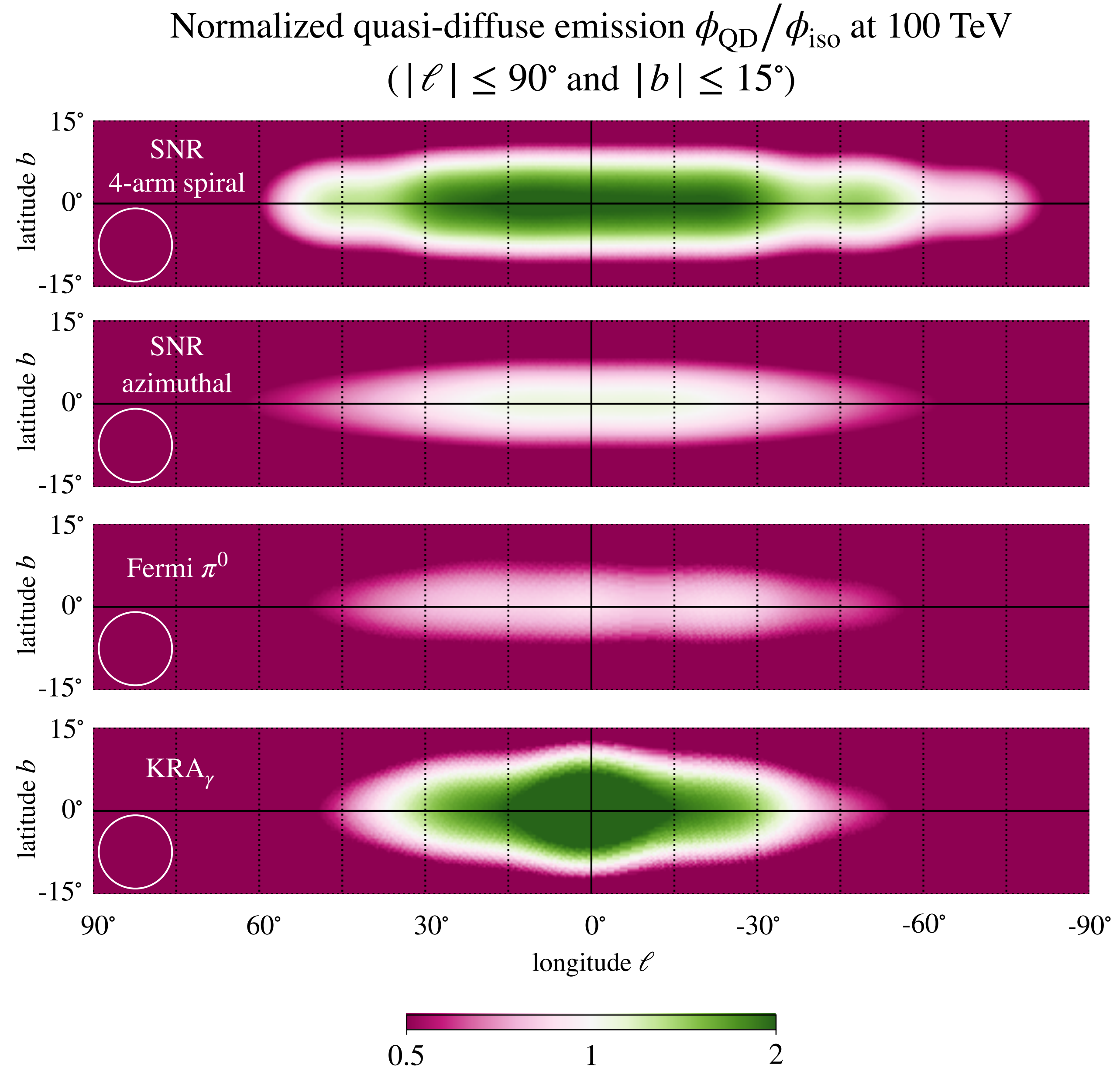
typical angular resolution $\sigma_{\rm PSF} \simeq 7°$

(credit: Kathrine M. Groth)

Hidden Galactic Sources?

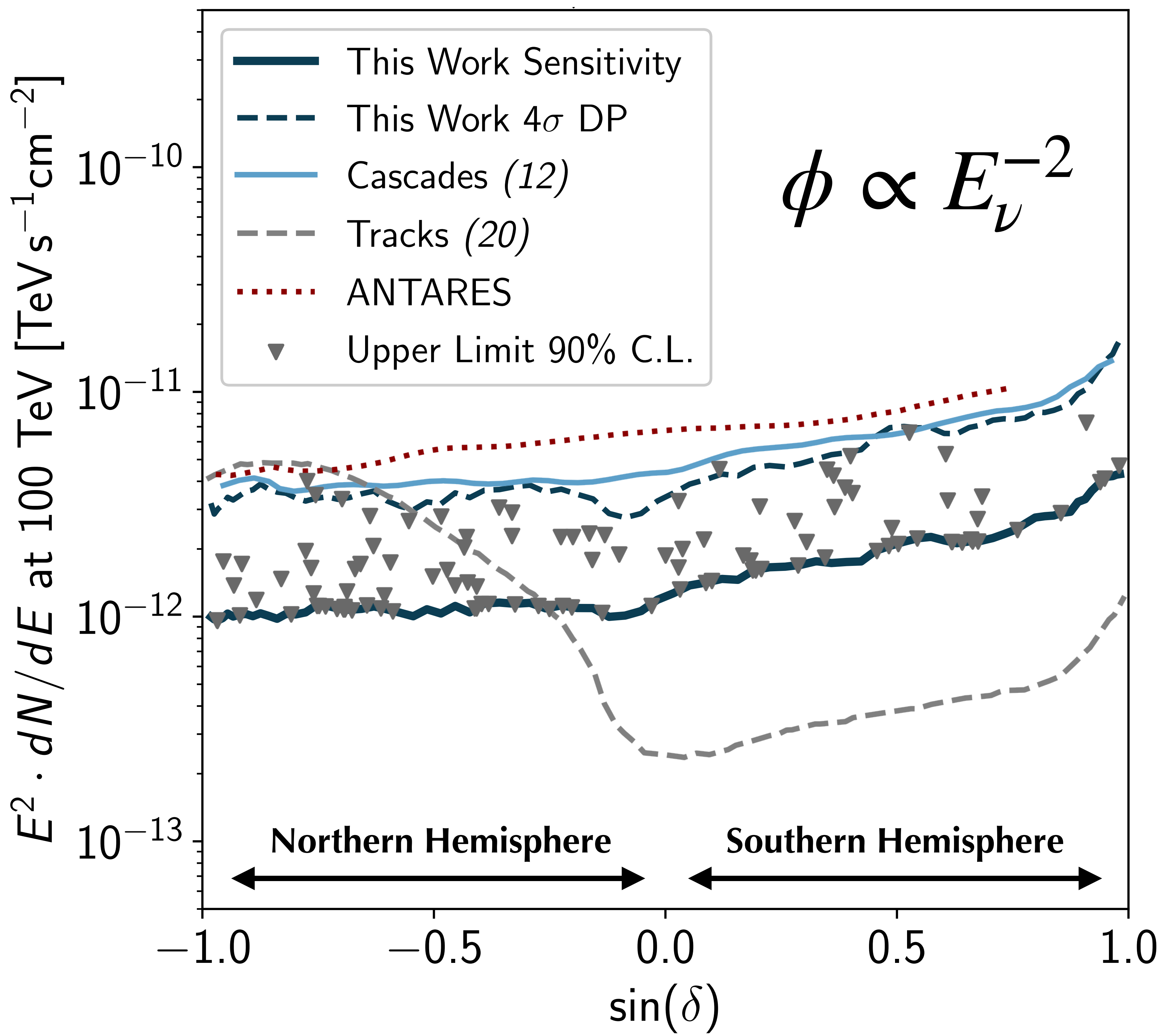
Contribution of neutrino from "freshly" accelerated CRs
most likely to dominate at highest observed energy ($\simeq$ 100TeV).





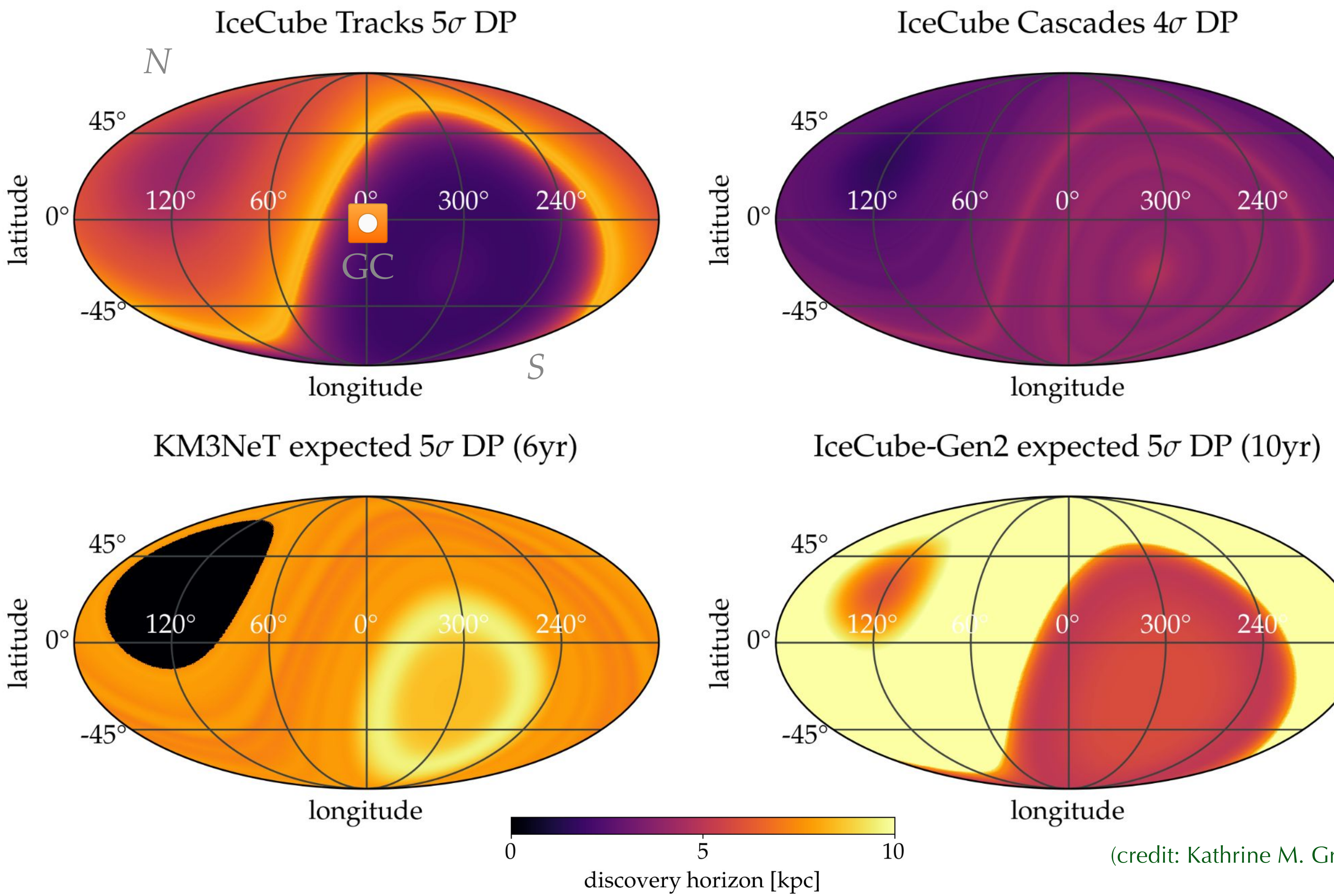
[Ambrosone, Groth, Peretti & MA '23; Desai, Vandenbroucke, Anandagoda, Thwaites & Romfoe '23]

Point-Source Sensitivities



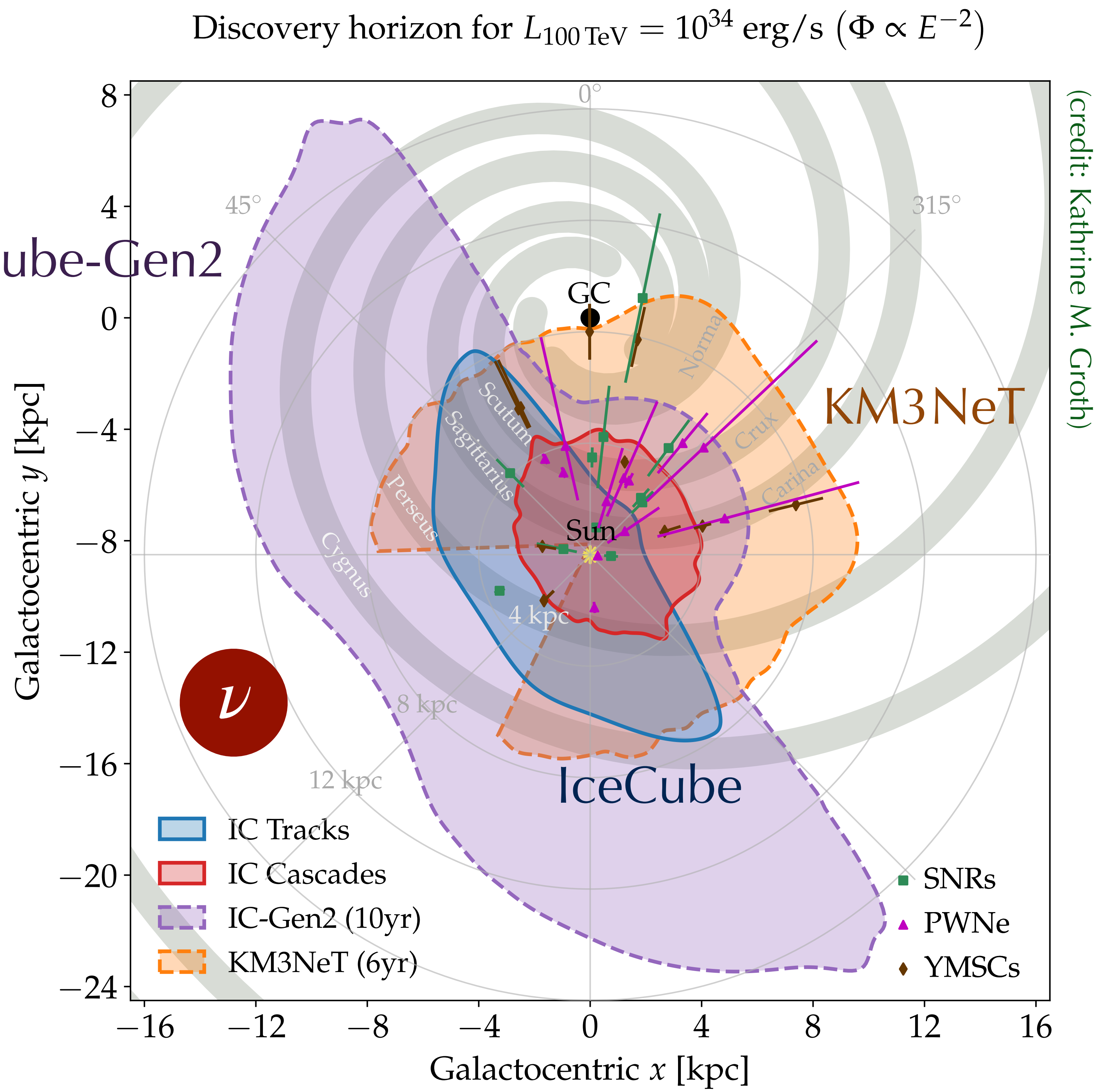
[IceCube **Science** 380 (2023)]

Effective Field of View



(credit: Kathrine M. Groth)

Point-Source Discovery Horizon



[Ambrosone, Groth, Peretti & MA'23]

Point Source vs. Quasi-Diffuse Flux

Populations of galactic neutrino sources visible as

individual sources

and by the

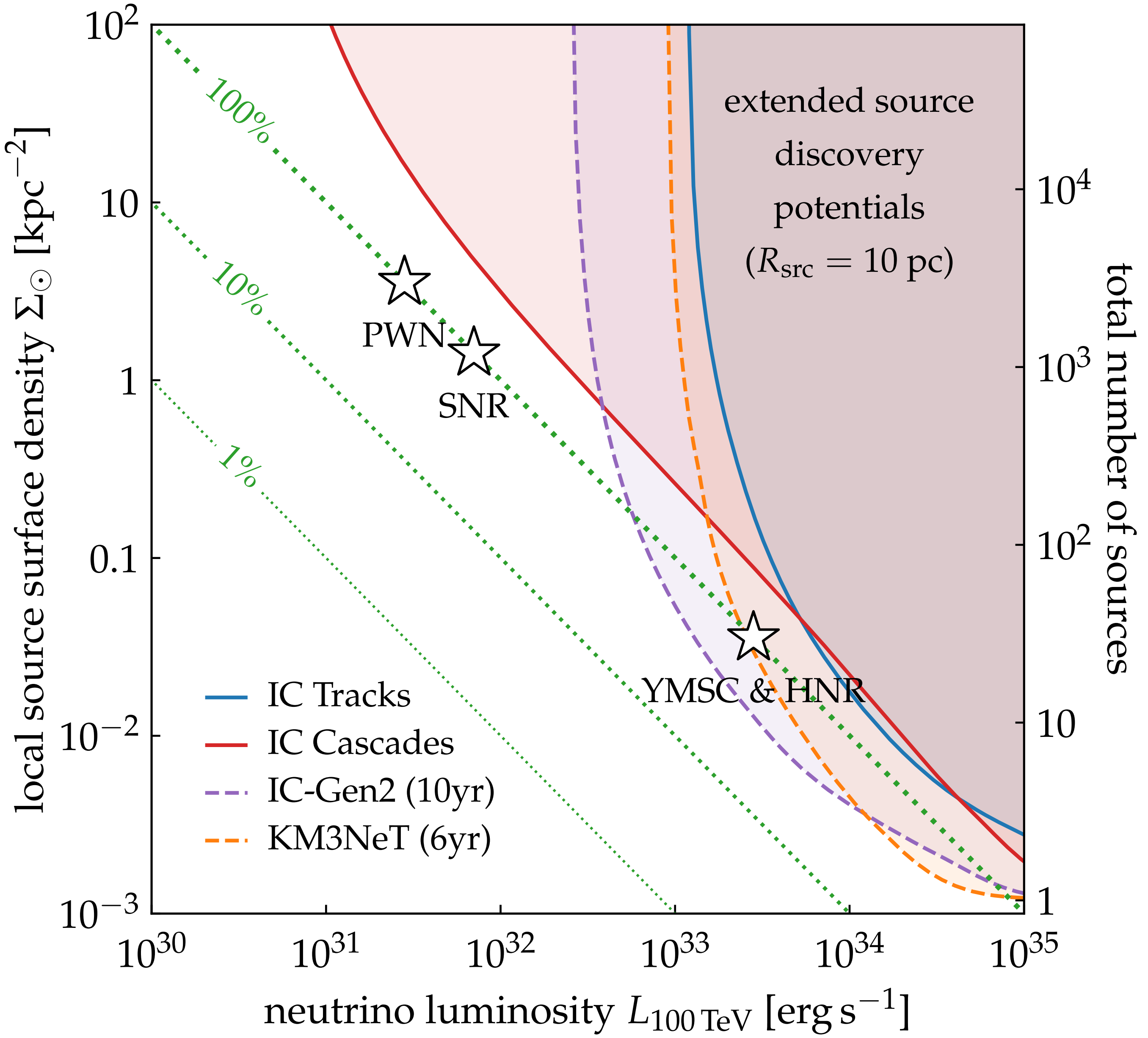
combined isotropic emission.

The relative contribution can be parametrized (*to first order*) by the average

source surface density $\Sigma_\odot$

and

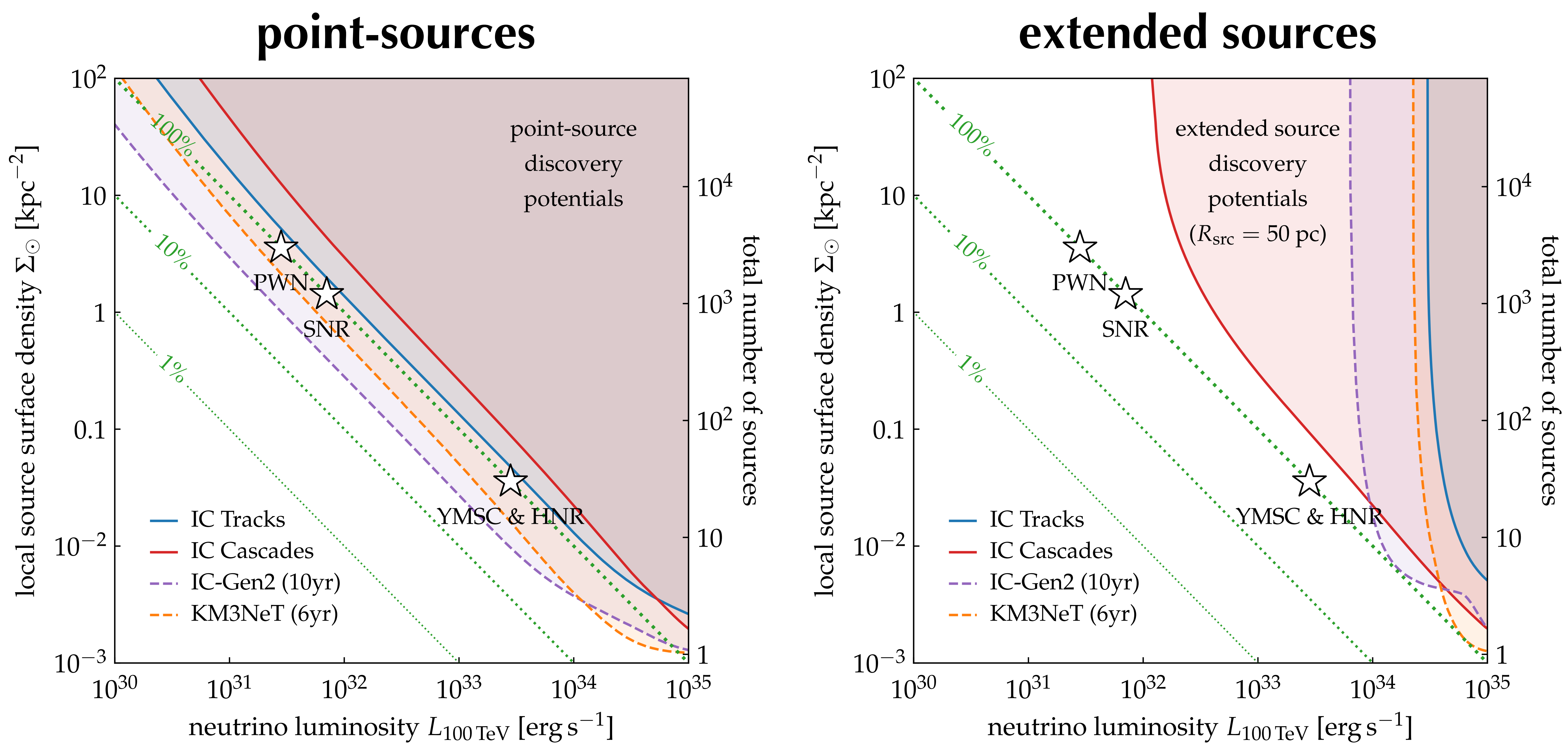
source luminosity $L_{100\mathrm{TeV}}$



[Ambrosone, Groth, Peretti & MA '23]

[see also Desai, Vandenbroucke, Anandagoda, Thwaites & Romfoe '23]

Point Source vs. Quasi-Diffuse Flux



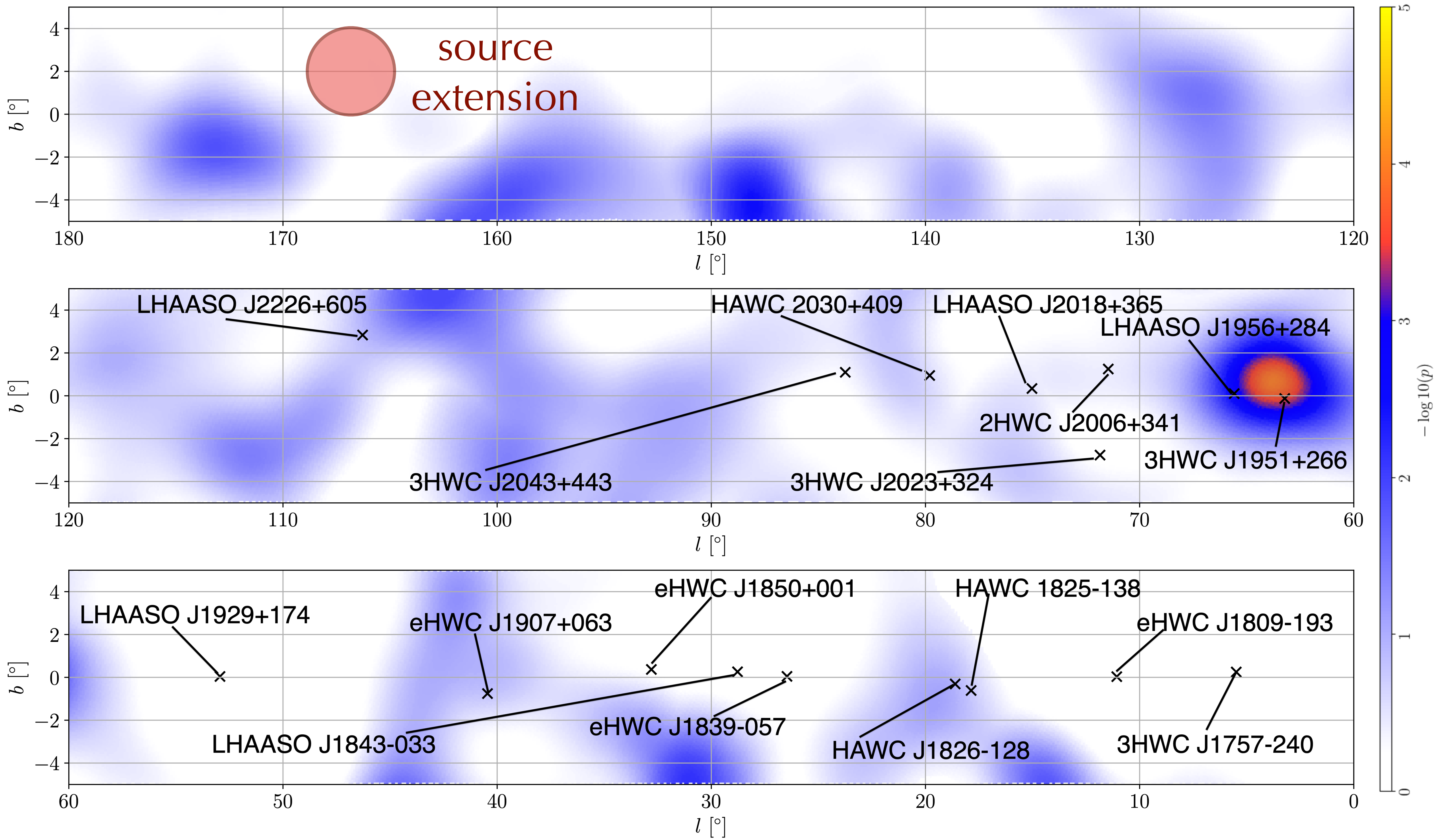
[Ambrosone, Groth, Peretti & MA'23]

sensitivity scaling:

$$\Phi_{\rm DP}(E_\nu, \delta, \sigma_{\rm src}) \simeq \sqrt{\frac{\sigma^2_{\rm PSF} + \sigma^2_{\rm src}}{\sigma^2_{\rm PSF}}}\,\Phi_{\rm DP}(E_\nu, \delta),$$

Extended Source Search

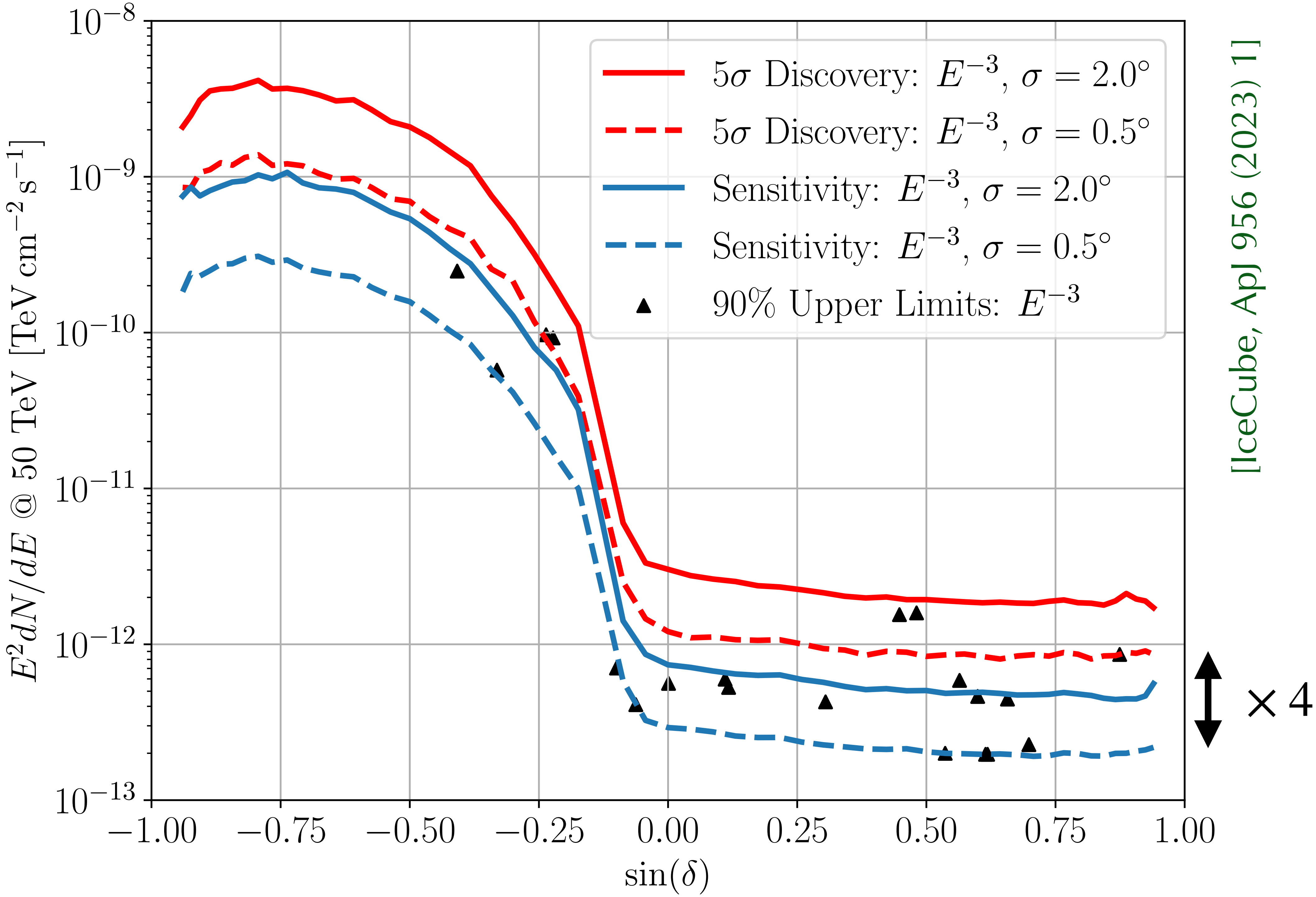
No significant emission from extended Galactic ν sources



[IceCube, ApJ 956 (2023) 1]

Extended Source Search

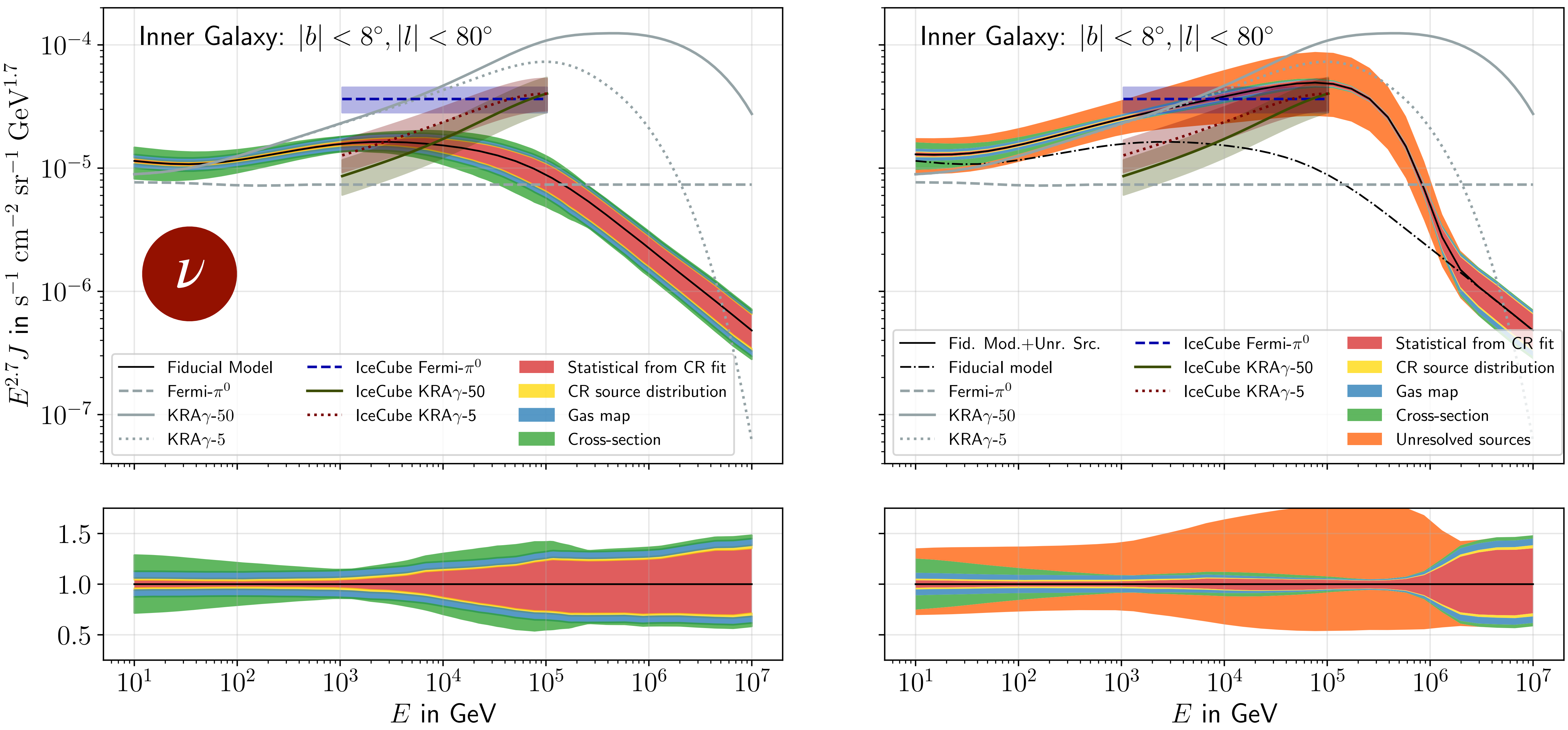
Sensitivity and Upper Limits for ROIs from HAWC & LHAASO



[IceCube, ApJ 956 (2023) 1]

Multi-Messenger Fits

Contribution of unresolved Galactic sources **improve MM fits**.

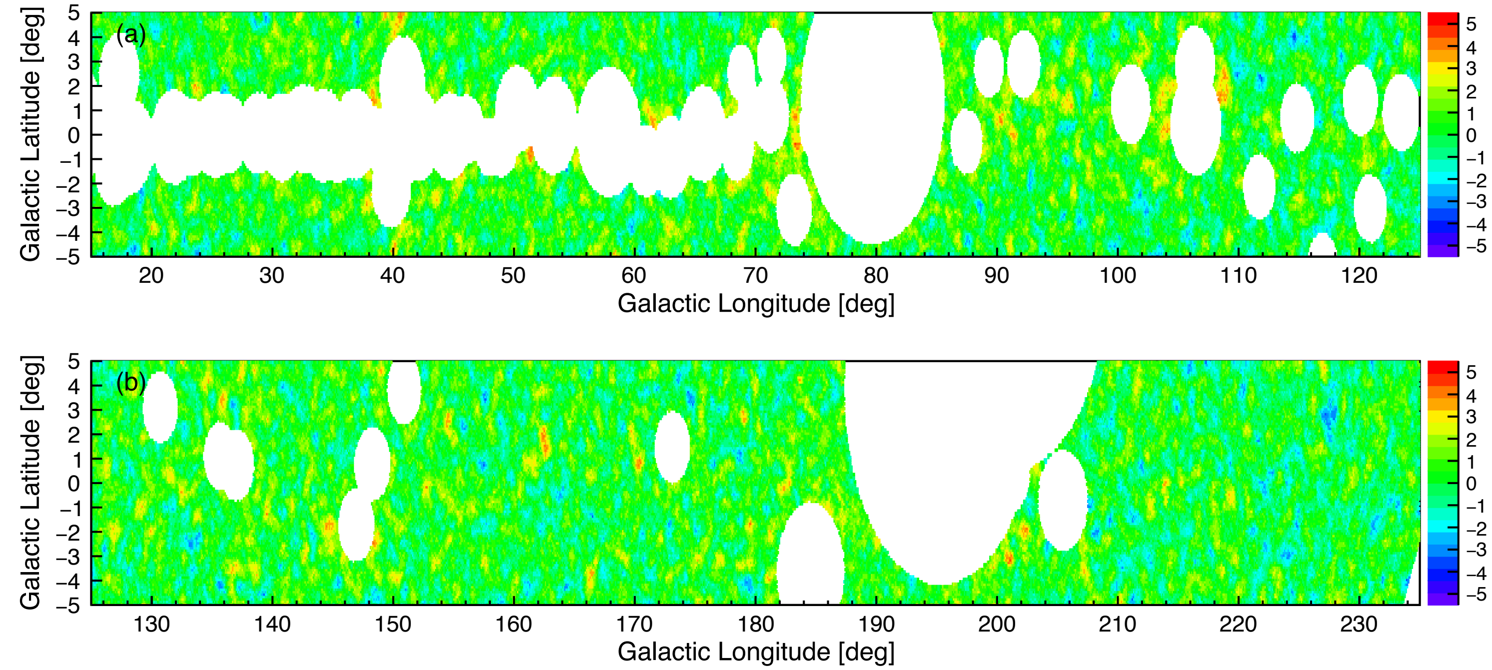


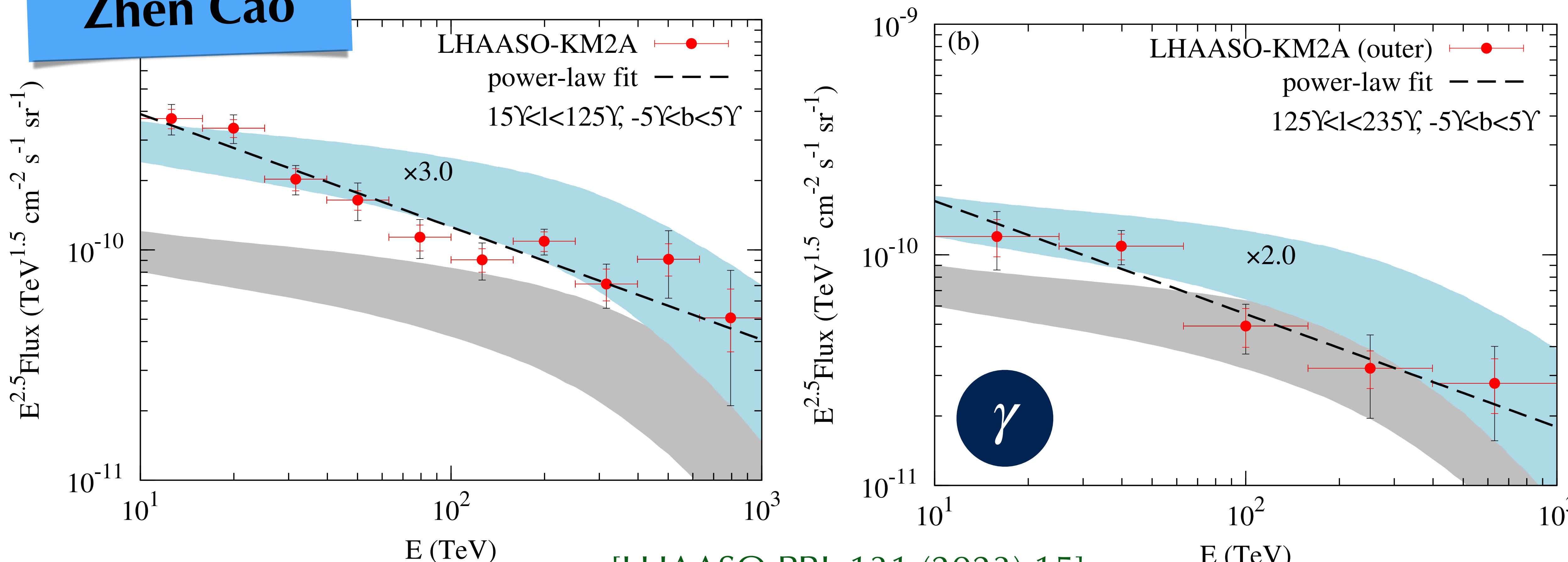
[Schwefer, Mertsch & Wiebusch '23; see also Shao, Lin & Yang'23]

LHAASO Diffuse Emission

LHAASO observes **enhanced 0.1-1 PeV diffuse γ-ray emission** along Galactic Plane.

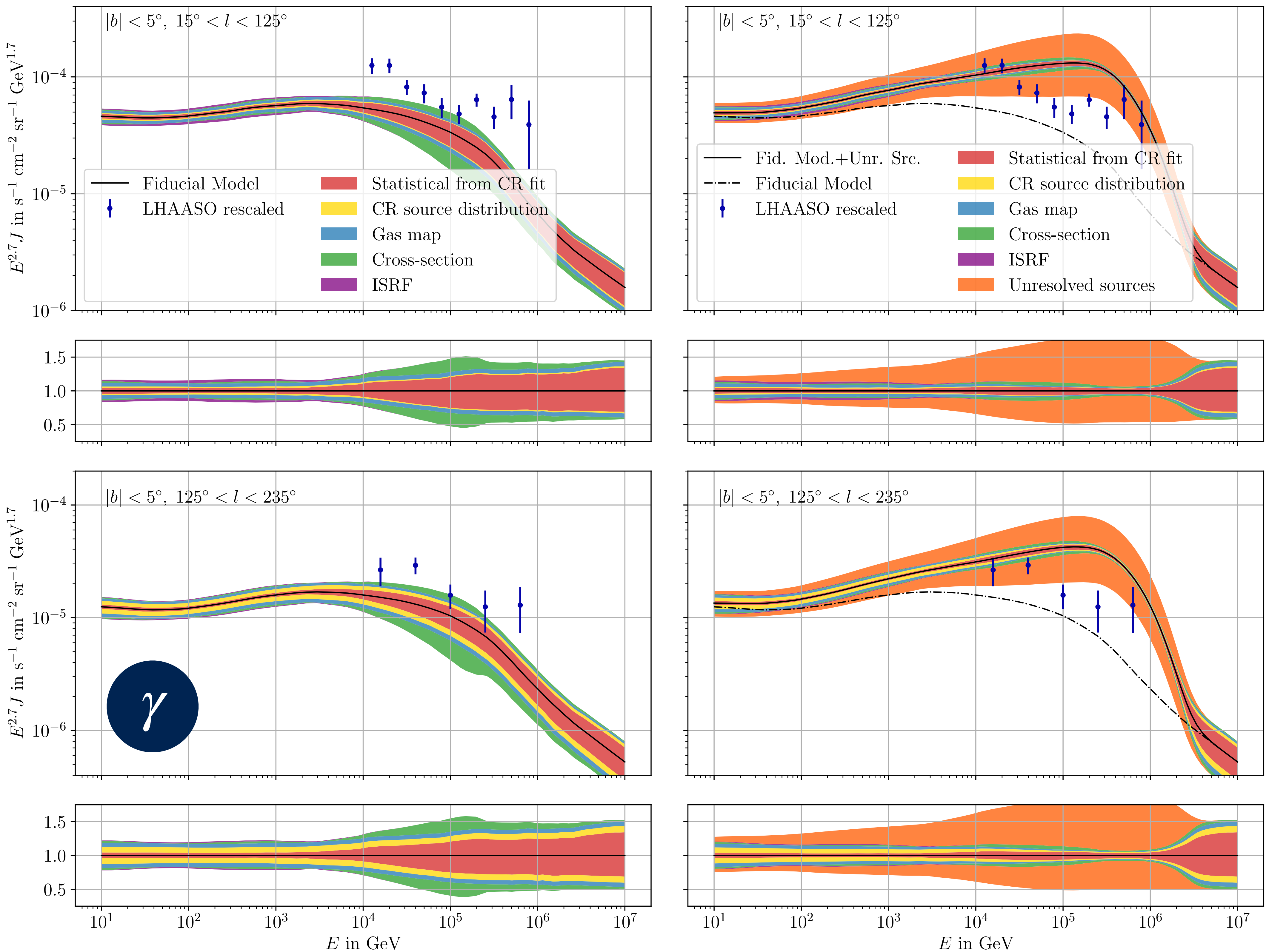
See talk by **Zhen Cao**





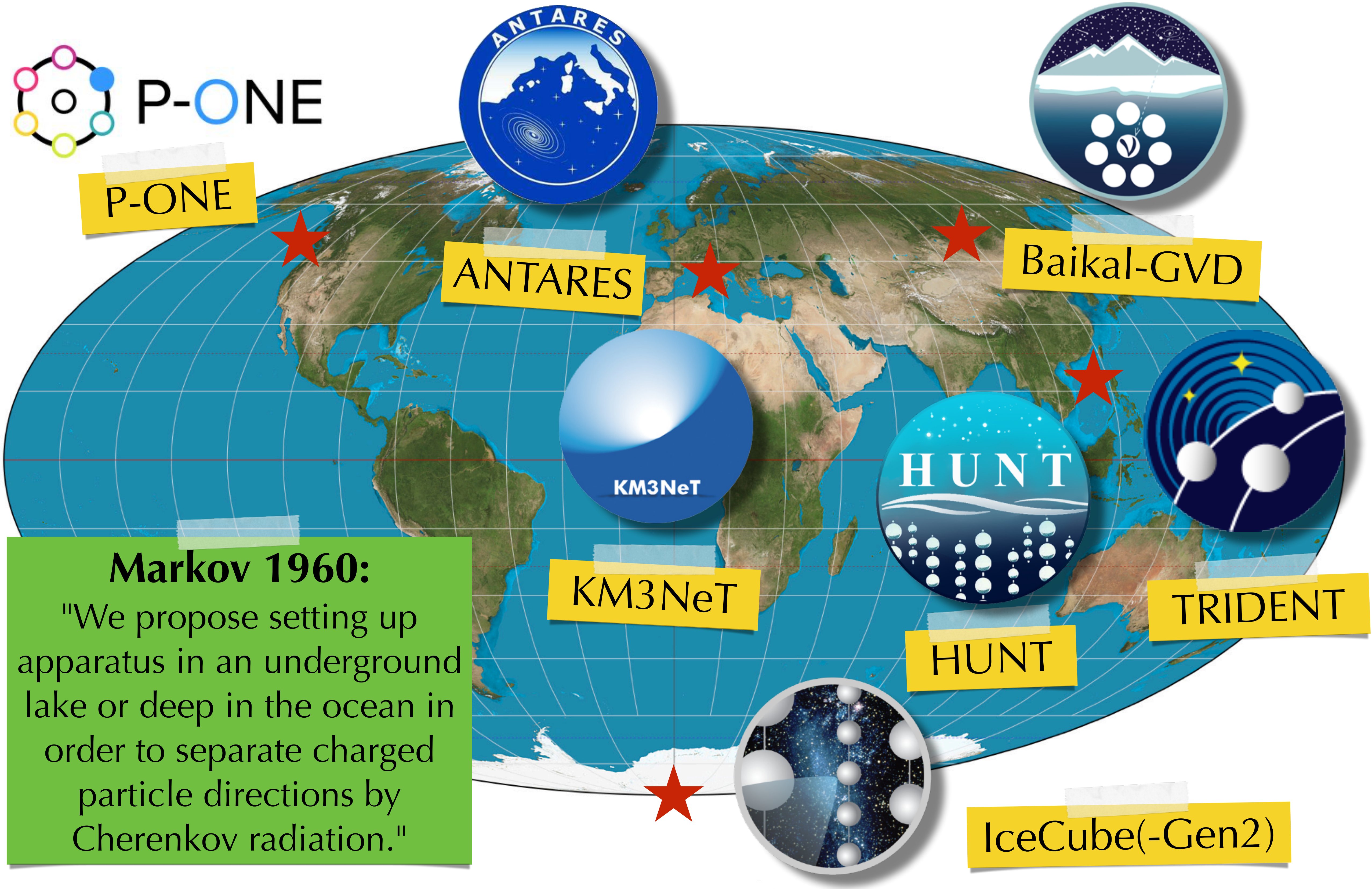
[LHAASO PRL 131 (2023) 15]

Multi-Messenger Fits



[Schwefer, Mertsch & Wiebusch '23]

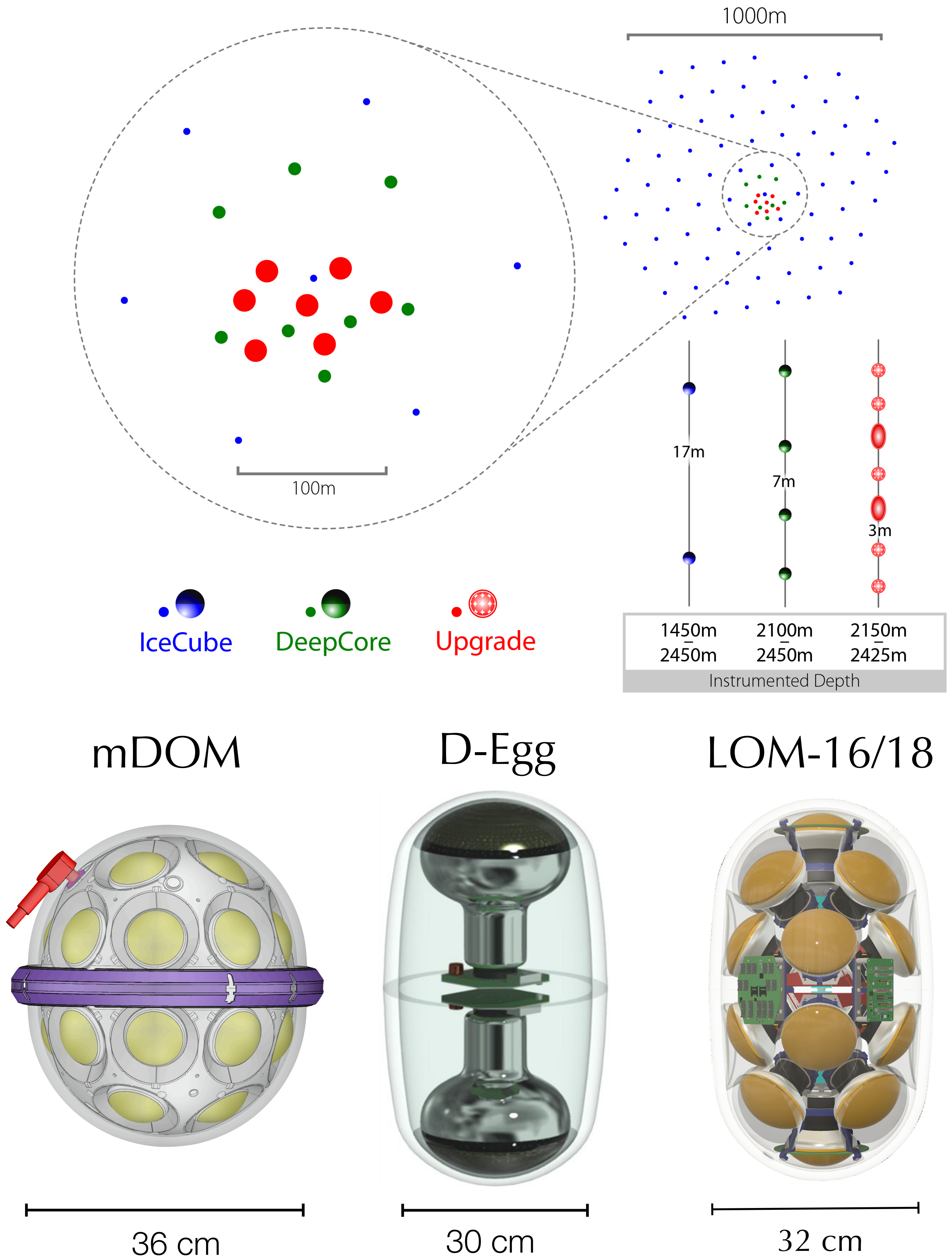
Optical Cherenkov Telescopes



Markov 1960:
"We propose setting up apparatus in an underground lake or deep in the ocean in order to separate charged particle directions by Cherenkov radiation."

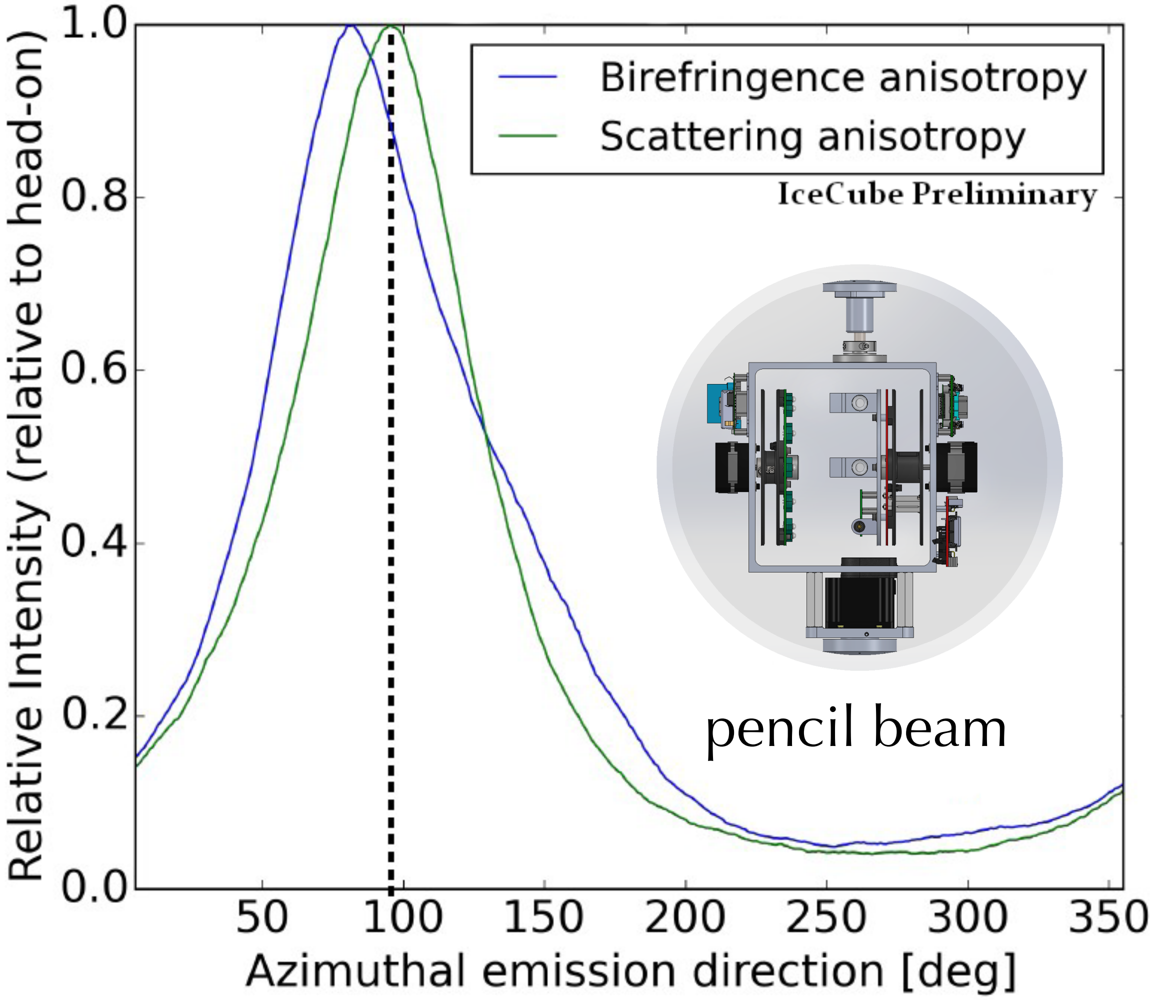
Outlook: IceCube Upgrade

- **7 new strings** in the DeepCore region (~20m inter-string spacing)
- **New sensor designs**, optimized for ease of deployment, light sensitivity & effective area
- **New calibration devices**, incorporating lessons from a decade of IceCube calibration efforts
- In parallel, **IceTop surface enhancements** (scintillators & radio antennas) for CR studies.
- **Scheduled deployment in 2025/26**

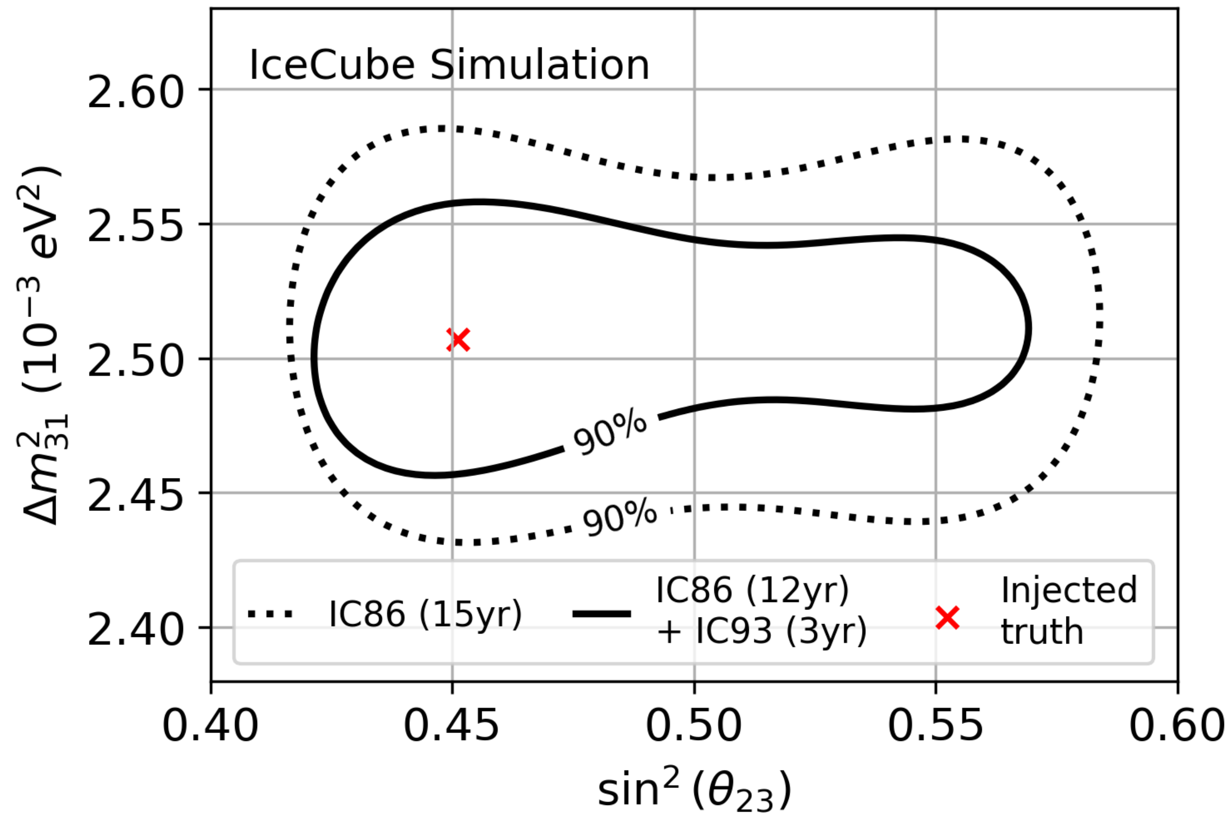


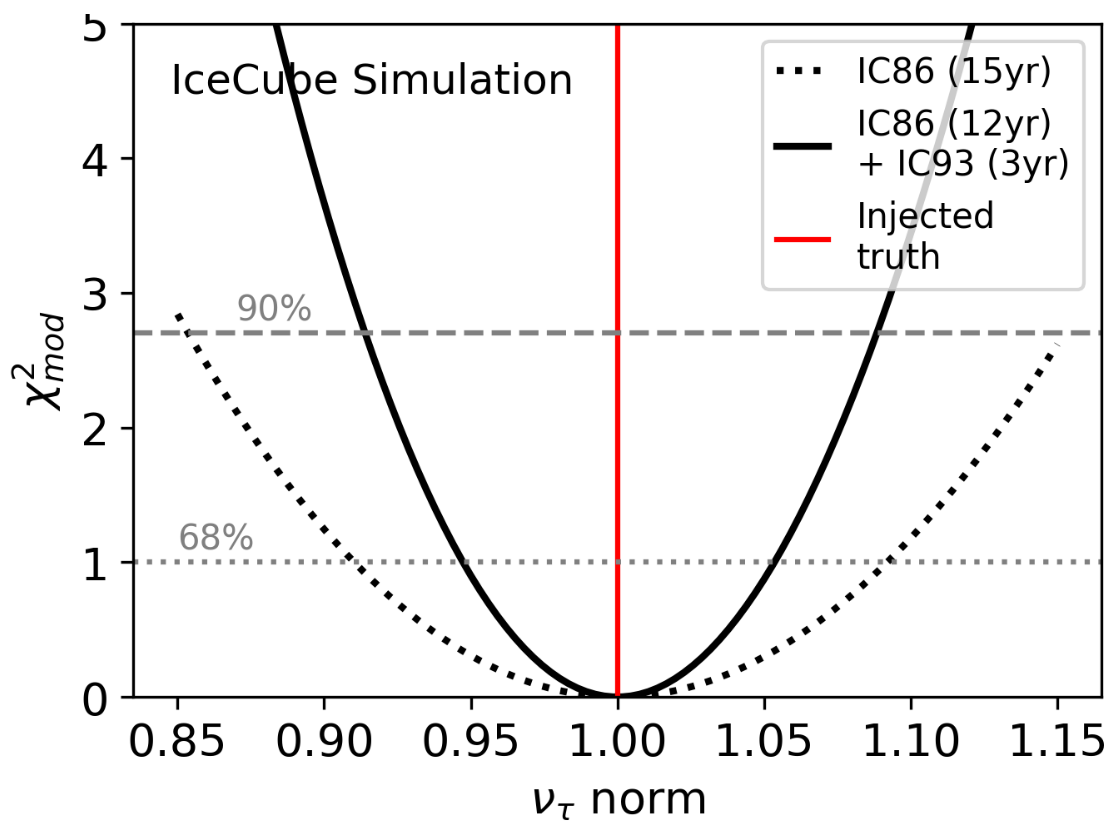
IceCube Upgrade

- **Precision measurement** of atmospheric neutrino oscillations and tau neutrino appearance
- **Improved systematics**, in particular, ice models in event reconstructions



[IceCube, JINST 16 (2021) 09]



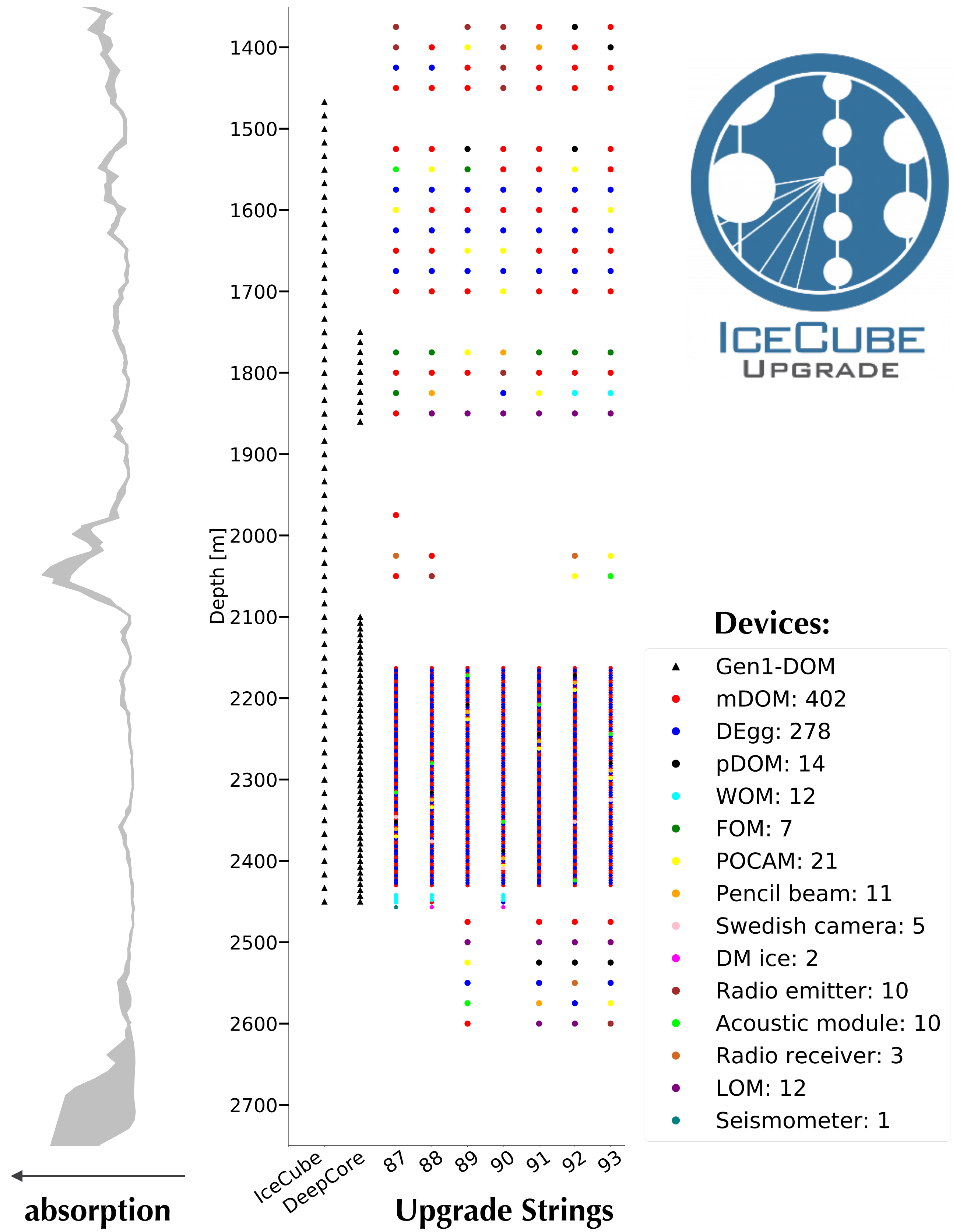


[IceCube, PoS (ICRC2019) 1031]

IceCube Upgrade

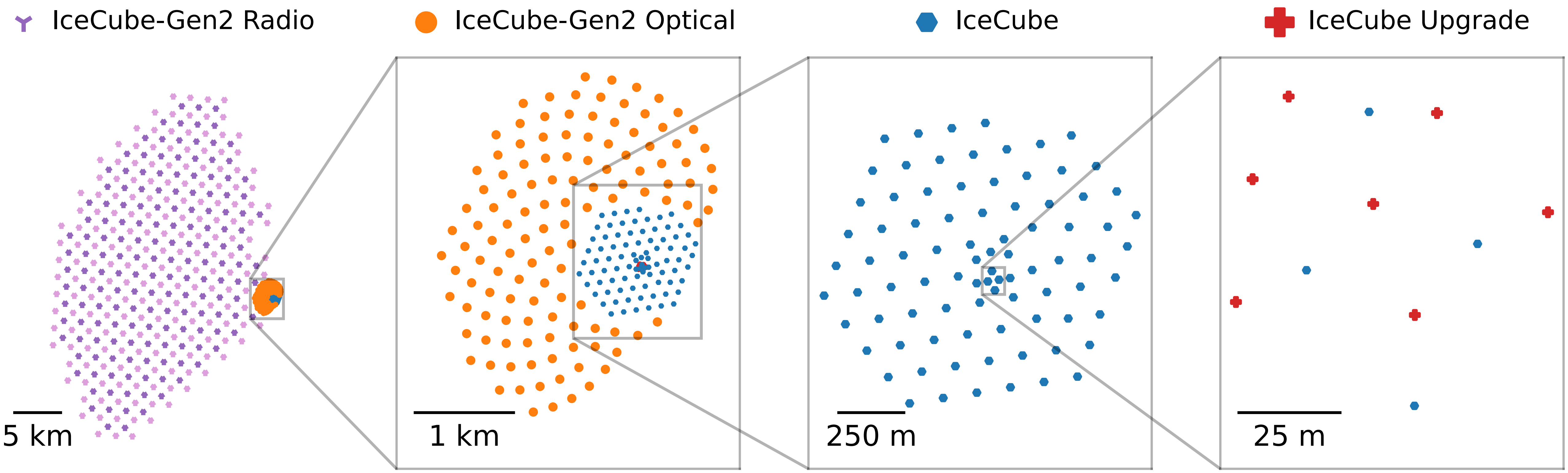
Field Season Schedule

- **2023/24 : Refit**
  - *extensive* refit and upgrade of existing Gen1 equipment
  - set up of Seasonal Equipment Site ("Drill Camp")
- **2024/25 : Commissioning & Test**
  - global integration, commissioning and testing of major subsystems
  - getting system drill-ready
  - surface cable installation and pull into IceCube Lab
- **2025/26 : Drill & Install**
  - drilling and installation of 7 strings



Vision: IceCube-Gen2

- **Multi-component facility** (multi-energy & multi-messenger)
- **In-ice optical Cherenkov array** with 120 strings 240m apart
- **Surface array** (scintillators & radio antennas) for PeV-EeV CRs & veto
- **Askaryan radio array** for >10 PeV neutrino detection
- *price:* mostly comparable to IceCube-Gen1 when corrected for inflation



+ Surface array

[IceCube-Gen2 *Technical Design Report:* icecube-gen2.wisc.edu/science/publications/tdr/]

IceCube-Gen2

- **Technical Design Report** (TDR) available on Gen2 website

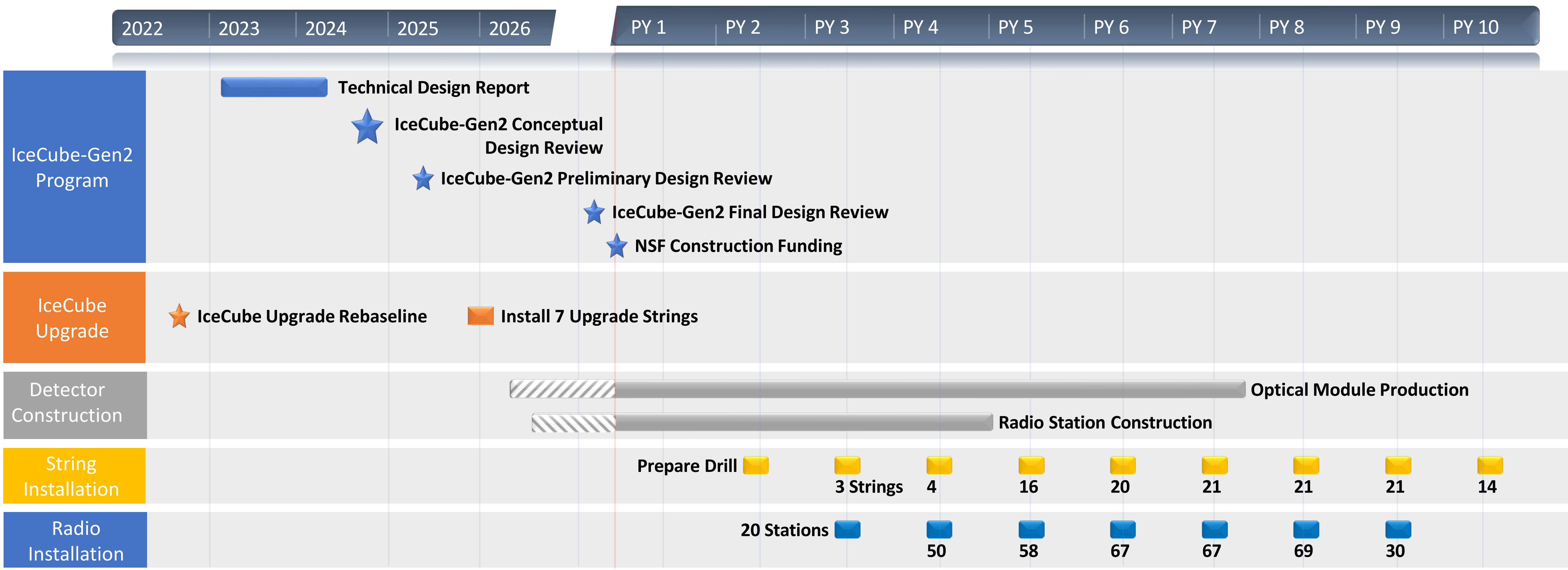
  Part I : *"Science & Design"*

  Part II : *"Detector & Performance"*

  Part III : *"Construction & Logistics"*

  Next goal: Conceptual Design Review

TDR website



Extragalactic Populations

Populations of extragalactic neutrino sources visible as

individual sources

and by

combined isotropic emission.

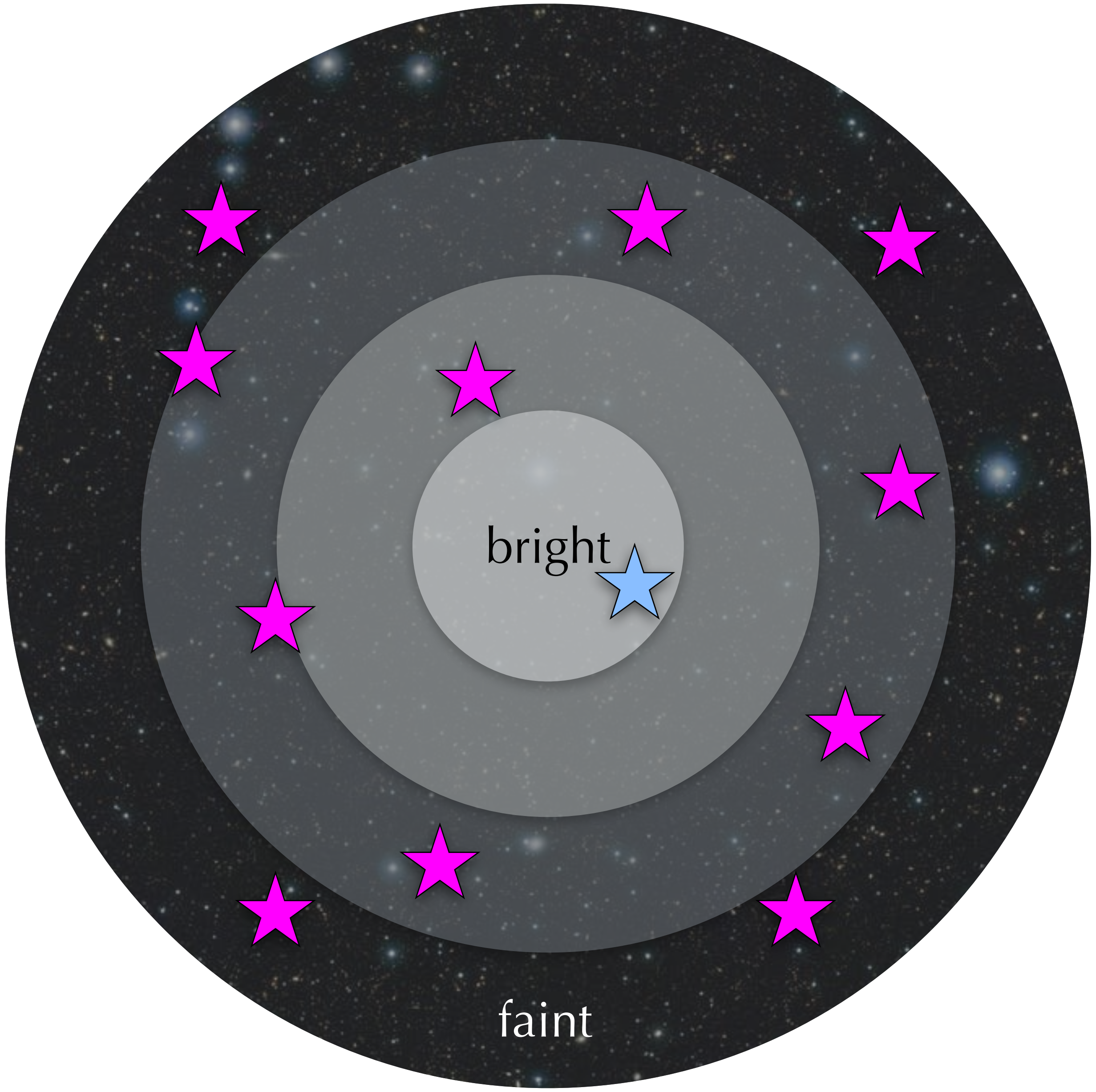
The relative contribution can be parametrized (*to first order*) by the average

local source density

and

source luminosity

"Observable Universe"
with far (faint) and near (bright) sources.



Hubble-Lemaître horizon

Extragalactic Populations

Populations of extragalactic neutrino sources visible as

individual sources

and by

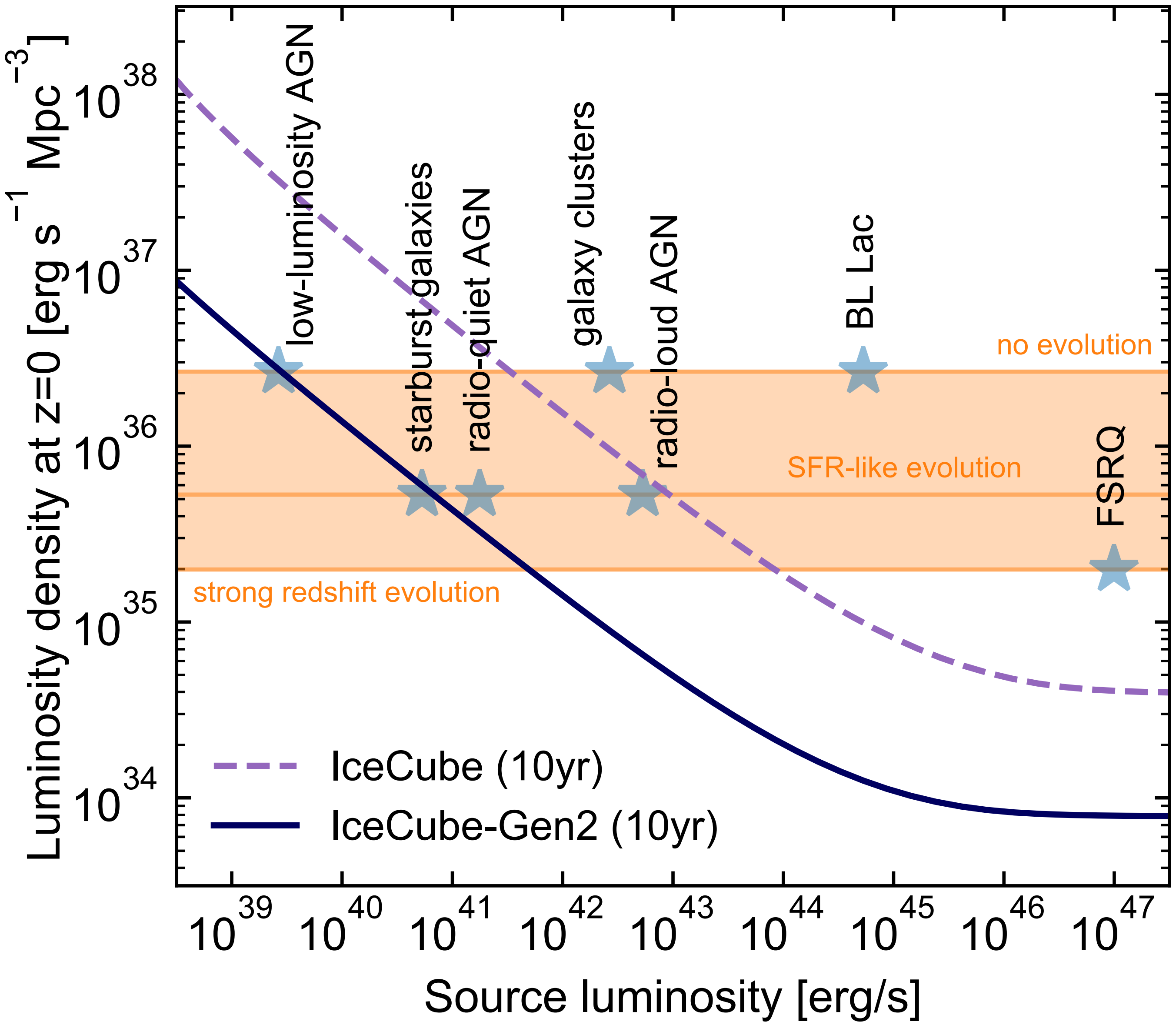
combined isotropic emission.

The relative contribution can be parametrized (*to first order*) by the average

local source density

and

source luminosity



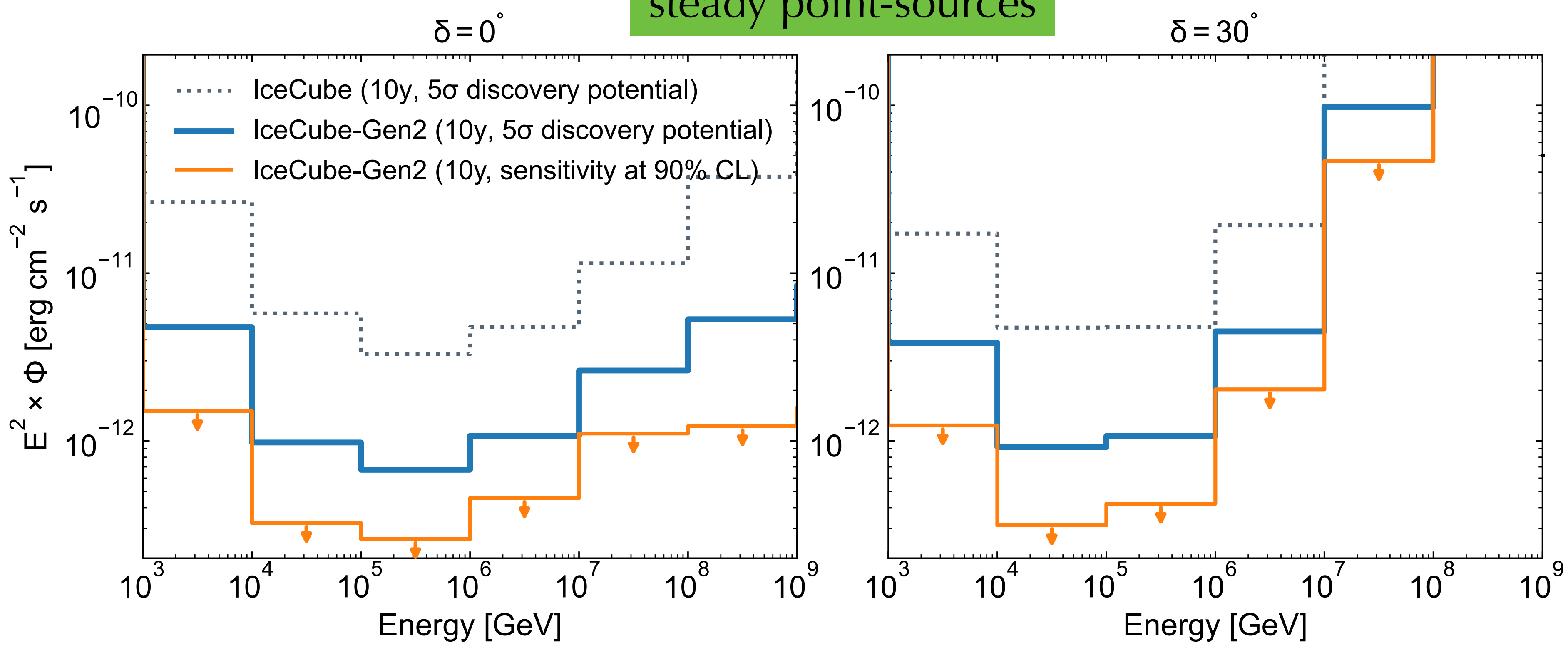
[IceCube-Gen2 TDR]

Discovery Potentials

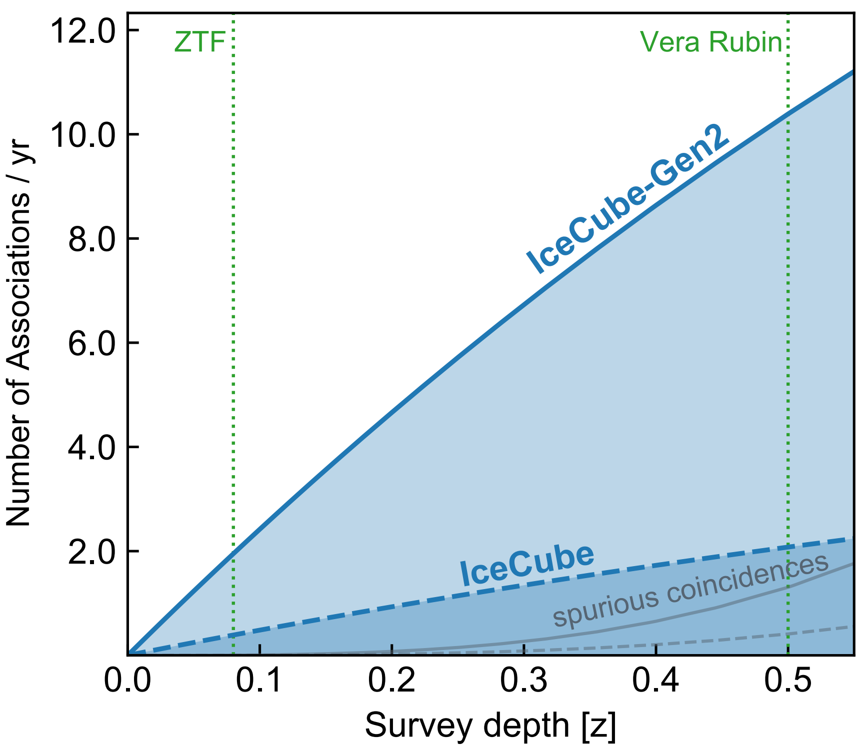
Discovery potentials of **IceCube vs. IceCube-Gen2**

[IceCube-Gen2 TDR]

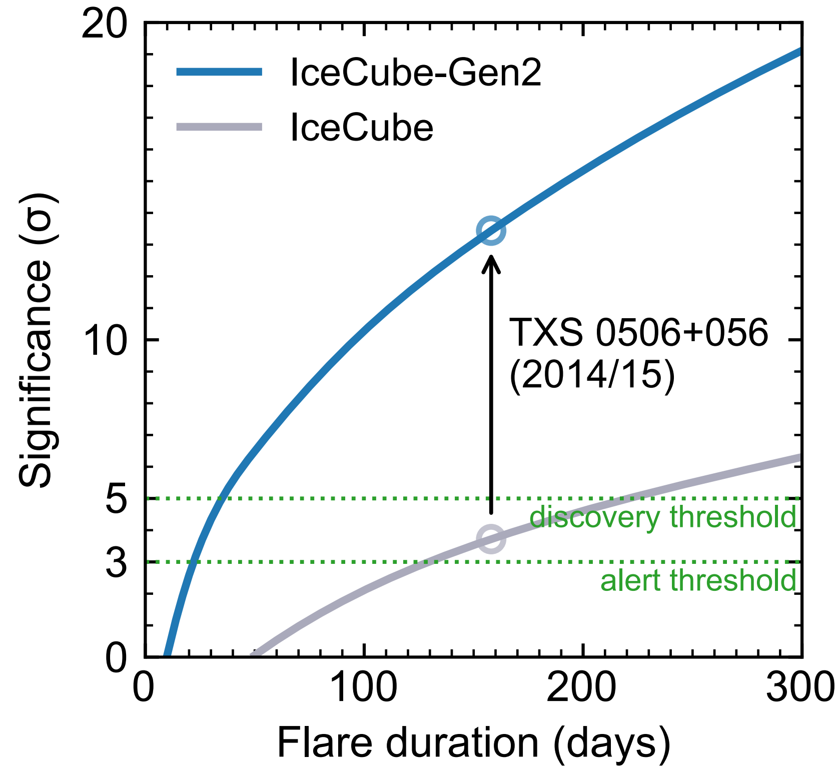
steady point-sources



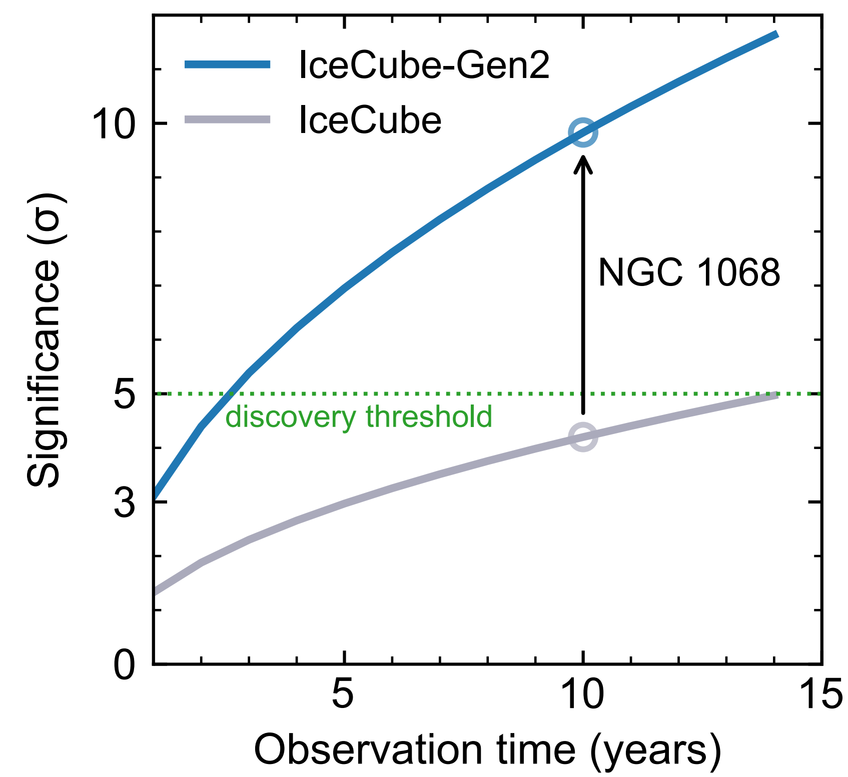
Tidal Disruption Events



TXS 0506+056



NGC 1068

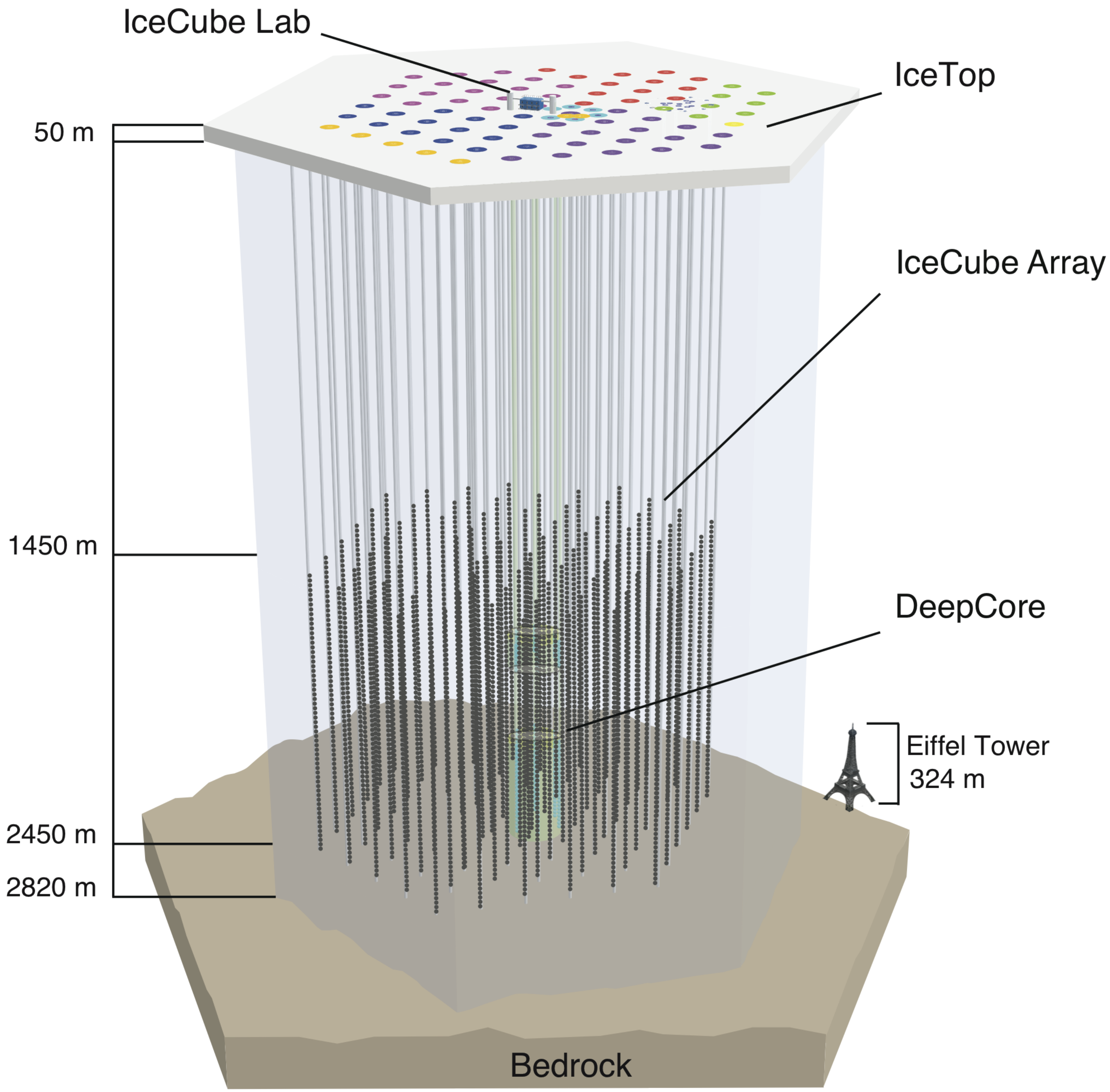


Summary

- **Multi-messenger astronomy** offers a fresh look onto the Universe.
- Neutrino astronomy has reached an important milestone by the discovery of an **isotropic flux of high-energy neutrinos** in 2013.
- So far, **no discovery** of point sources, but some **strong candidates**, in particular, **TXS 0506+056** (2017) and **NGC 1068** (2022).
- Recent observation (4.5σ significance) of neutrino emission of the **Galactic Plane** (2023), consistent with models of **Galactic diffuse emission** from cosmic ray interactions in the interstellar medium.
- Observationally, we **cannot exclude combined emission of PeVatrons**.
- The **new/next generation of neutrino** (KM3NeT, IceCube-Gen2, GRAND, ...) **and γ-ray observatories** (LHAASO, CTA, SWGO, ...) will help to decipher Galactic PeVatrons.

Backup Slides

IceCube Observatory

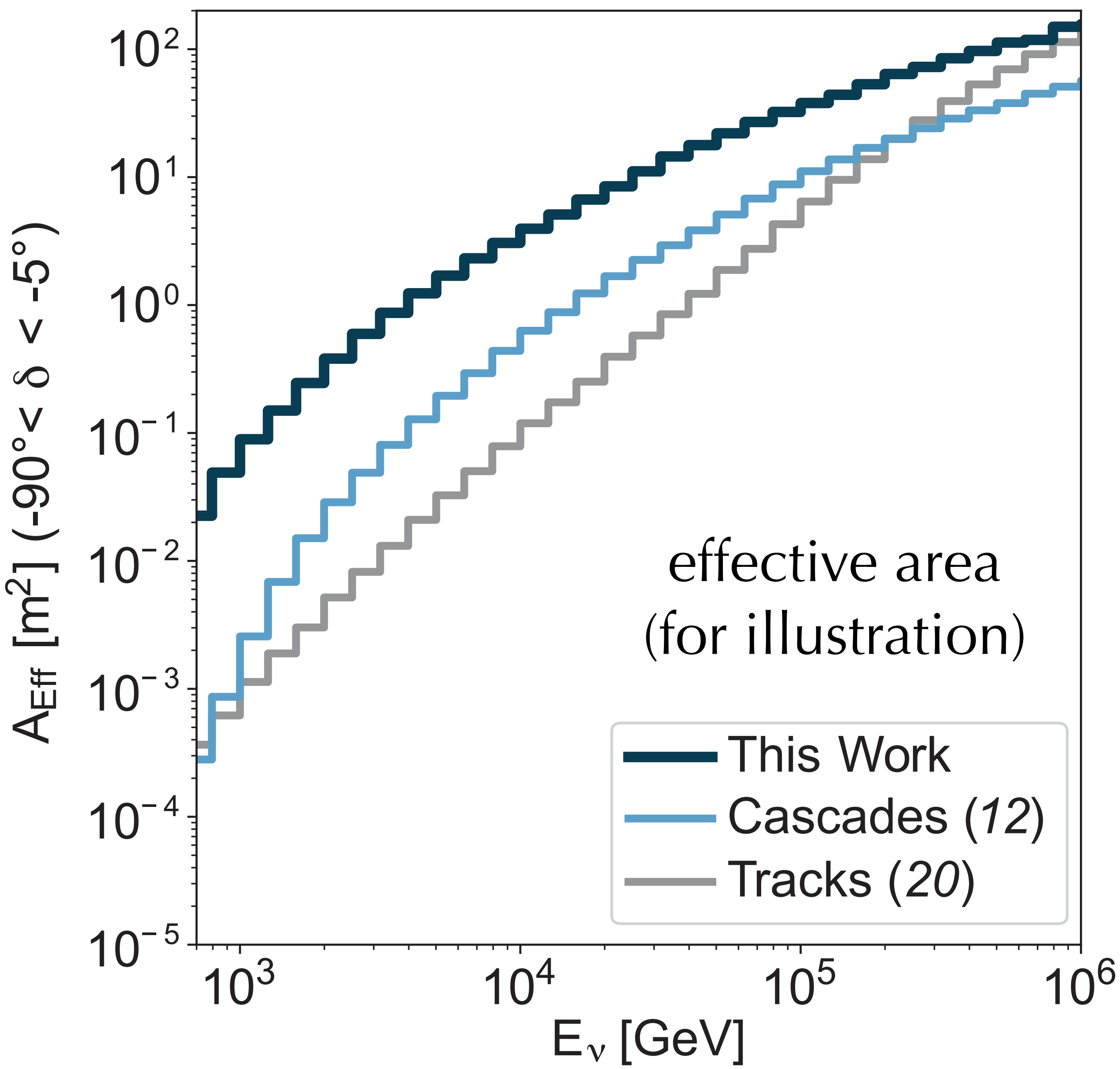


- **Giga-ton optical Cherenkov telescope at the South Pole**
- 86 IceCube strings of 60 DOMs **instrumenting 1 km³ of clear glacial ice**
- 81 IceTop stations for cosmic ray shower detections
- running in full IC86 configuration since 2011
- **>99% detector uptime**
- trigger rate about 2.7 kHz
- about 100 GB/day data transferred via satellite


58 institutions
14 countries
350+ authors
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 Wuppertal
Westfälische Wilhelms-Universität Münster
ITALY
University of Padova
JAPAN
Chiba University
NEW ZEALAND
University of Canterbury
REPUBLIC OF KOREA
Chung-Ang University
Sungkyunkwan University
SWEDEN
Stockholms universitet
Uppsala universitet
SWITZERLAND
Université de Genève
TAIWAN
Academia Sinica
UNITED KINGDOM
University of Oxford
UNITED STATES
Columbia University
Drexel University
Georgia Institute of Technology
Harvard University
Lawrence Berkeley National Lab
Loyola University Chicago
Marquette University
Massachusetts Institute of Technology
Mercer University
Michigan State University
Ohio State University
Pennsylvania State University
South Dakota School of Mines and Technology
Southern University and A&M College
Stony Brook University
University of Alabama
University of Alaska Anchorage
University of California, Berkeley
University of California, Irvine
University of Delaware
University of Kansas
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

DNNcascade Sample

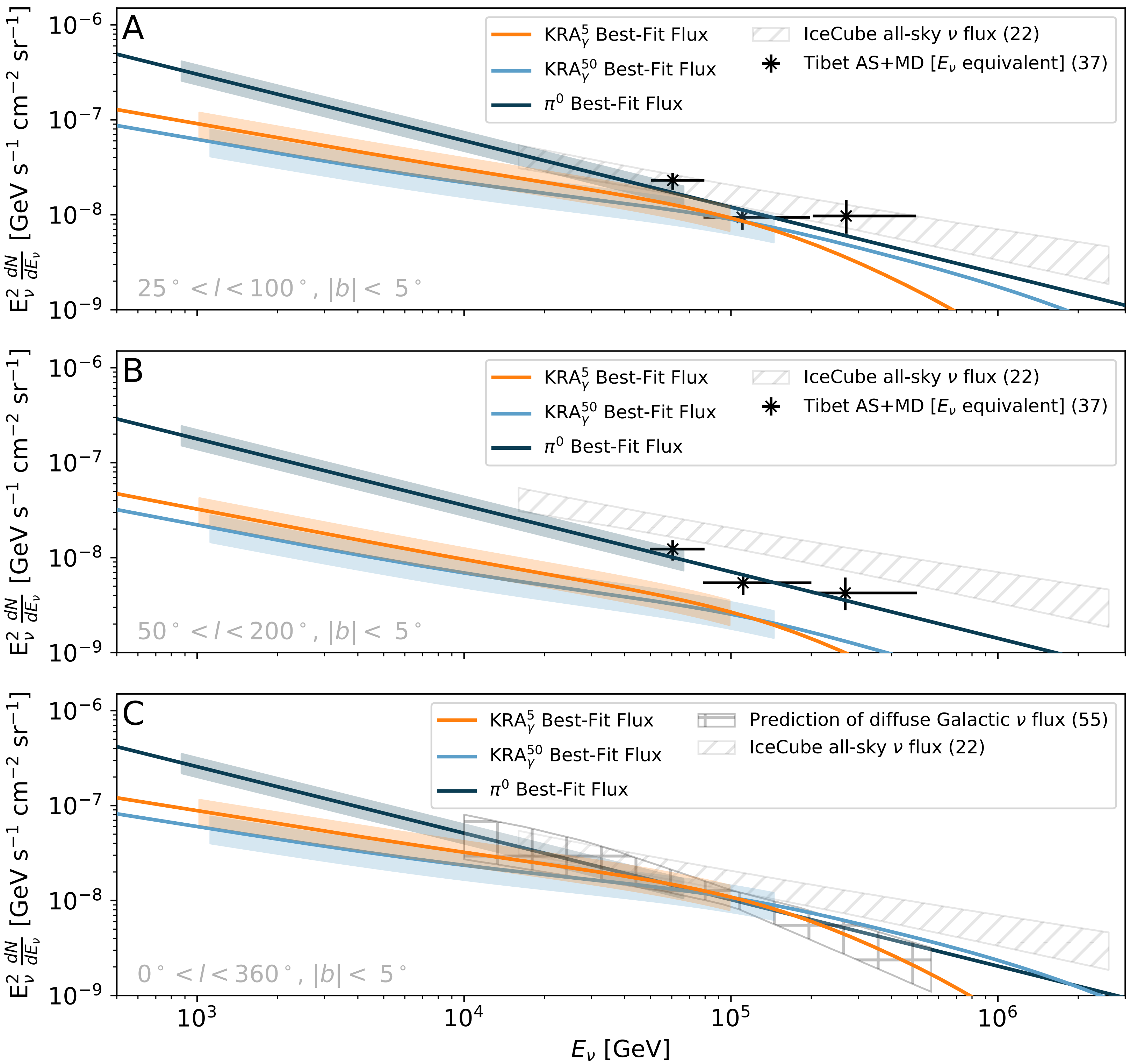
Analysis is based on novel cascade event selection and reconstruction using deep neutral networks (DNNcascade).



- **59,592 events** over period May'11 - May'21
- retains about **20 times more events** compared to previous cascade analysis [IceCube, ApJ 886 (2019) 12]
- expected composition:
  - ⋆ 87% atmospheric ν
  - ⋆ 6% atmospheric μ
  - ⋆ 7% astrophysical ν

[IceCube, Science 380 (2023)]

VHE Galactic Gamma-Rays



[IceCube **Science** 380 (2023)]

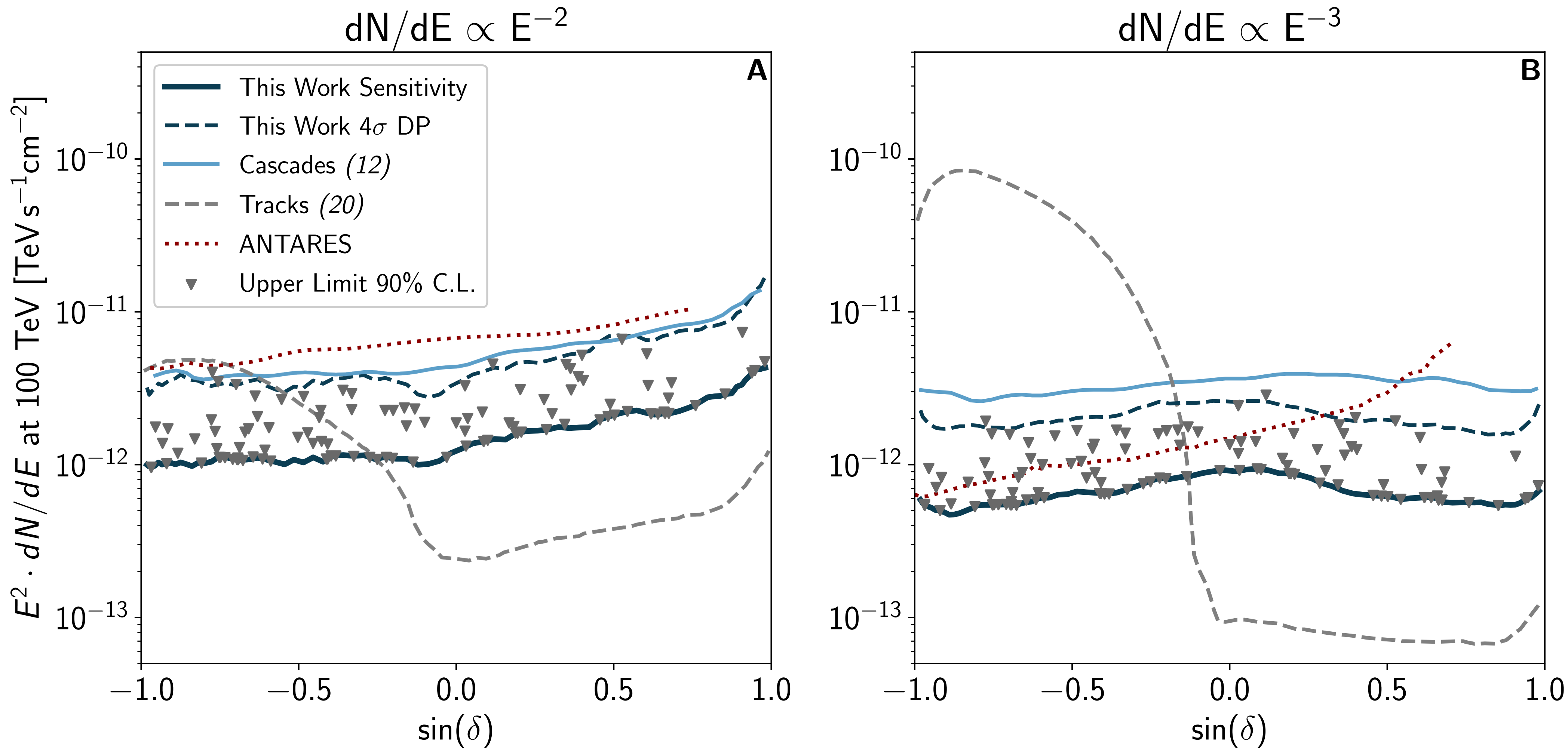
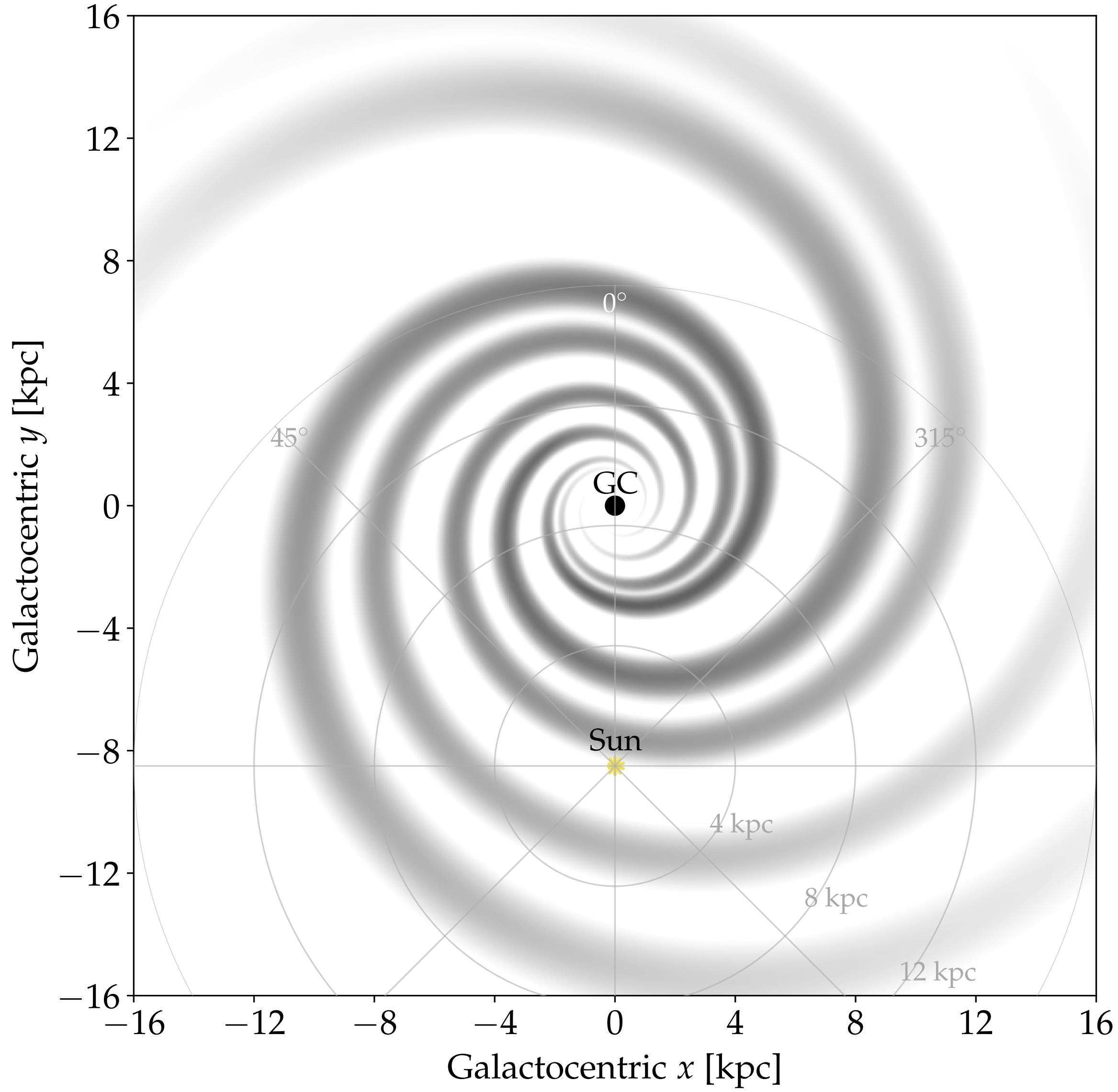


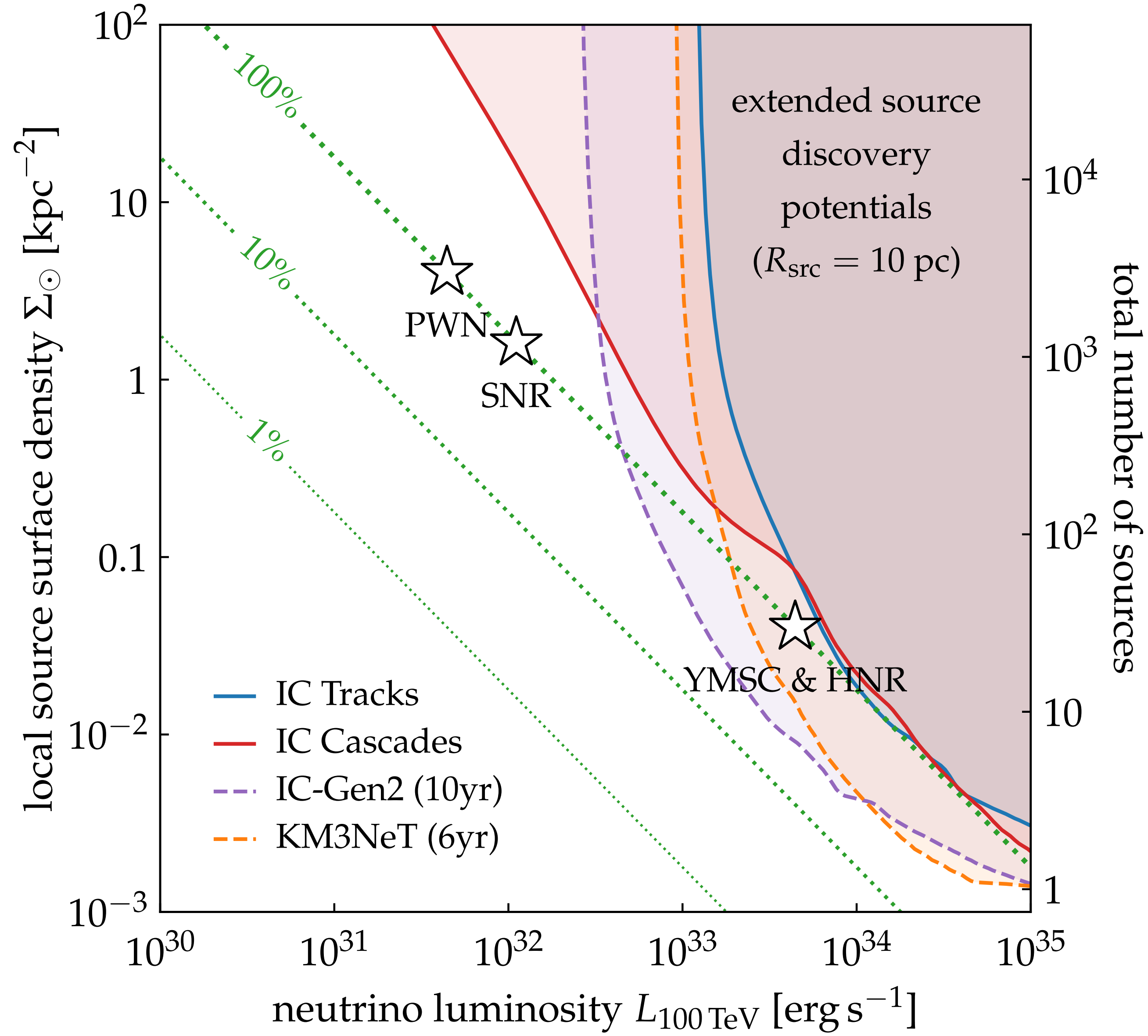
Figure S12: **Source list sensitivity and upper limits** Sensitivity to sources emitting an E^{-2} spectrum (A) and E^{-3} spectrum (B) for each data set. Individual sources in the source catalog are shown with their 90% confidence level (CL) upper limits assuming an E^{-2} (A) and E^{-3} (B) emission spectra. ANTARES results are for E^{-2} (*61*) and E^{-3} (*62*) sensitivities. We also show previous results from IceCube tracks (*20*) and cascades (*12*). Also shown in the 4σ discovery potential (DP) for this work. All results are consistent with background.

[IceCube **Science** 380 (2023)]

Non-Azimuthal Distributions

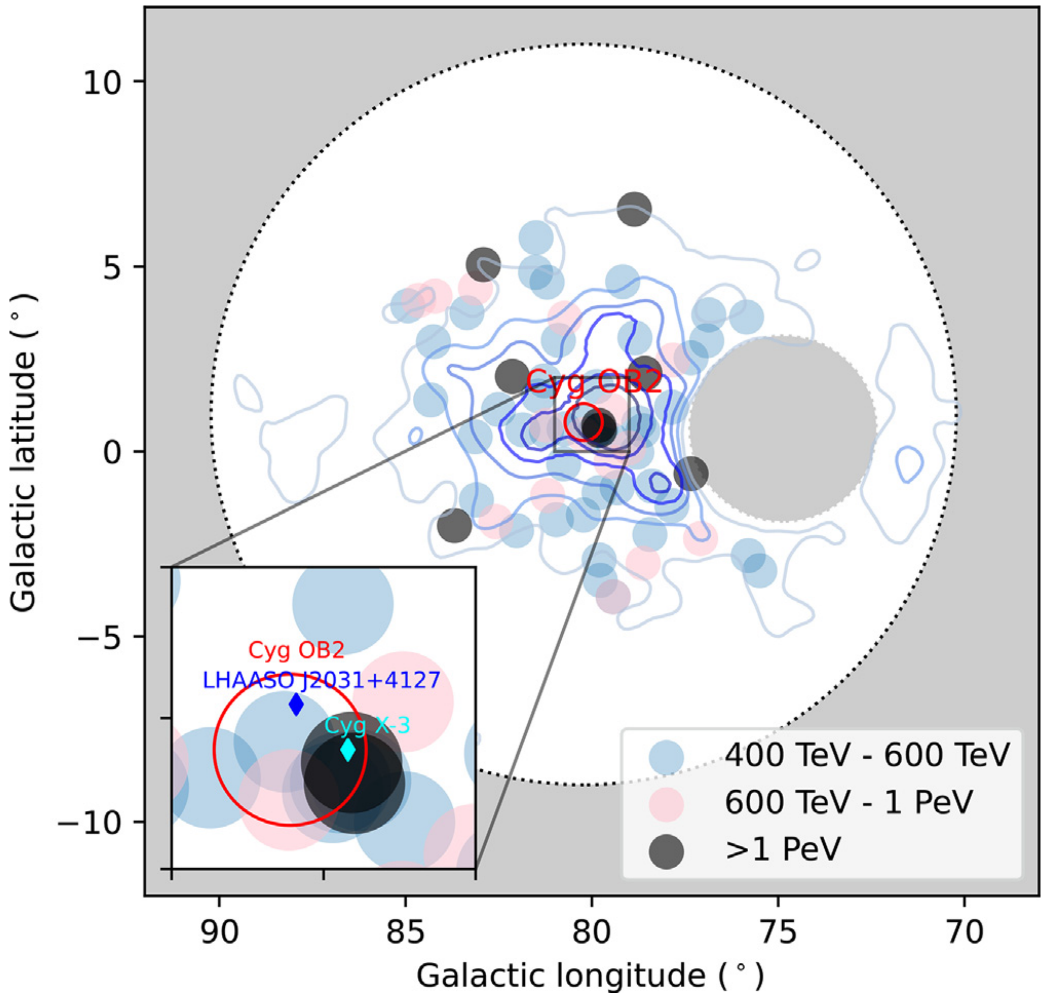
Galactic arm structure has only little impact on conclusions drawn from idealized azimuthally symmetric distributions.

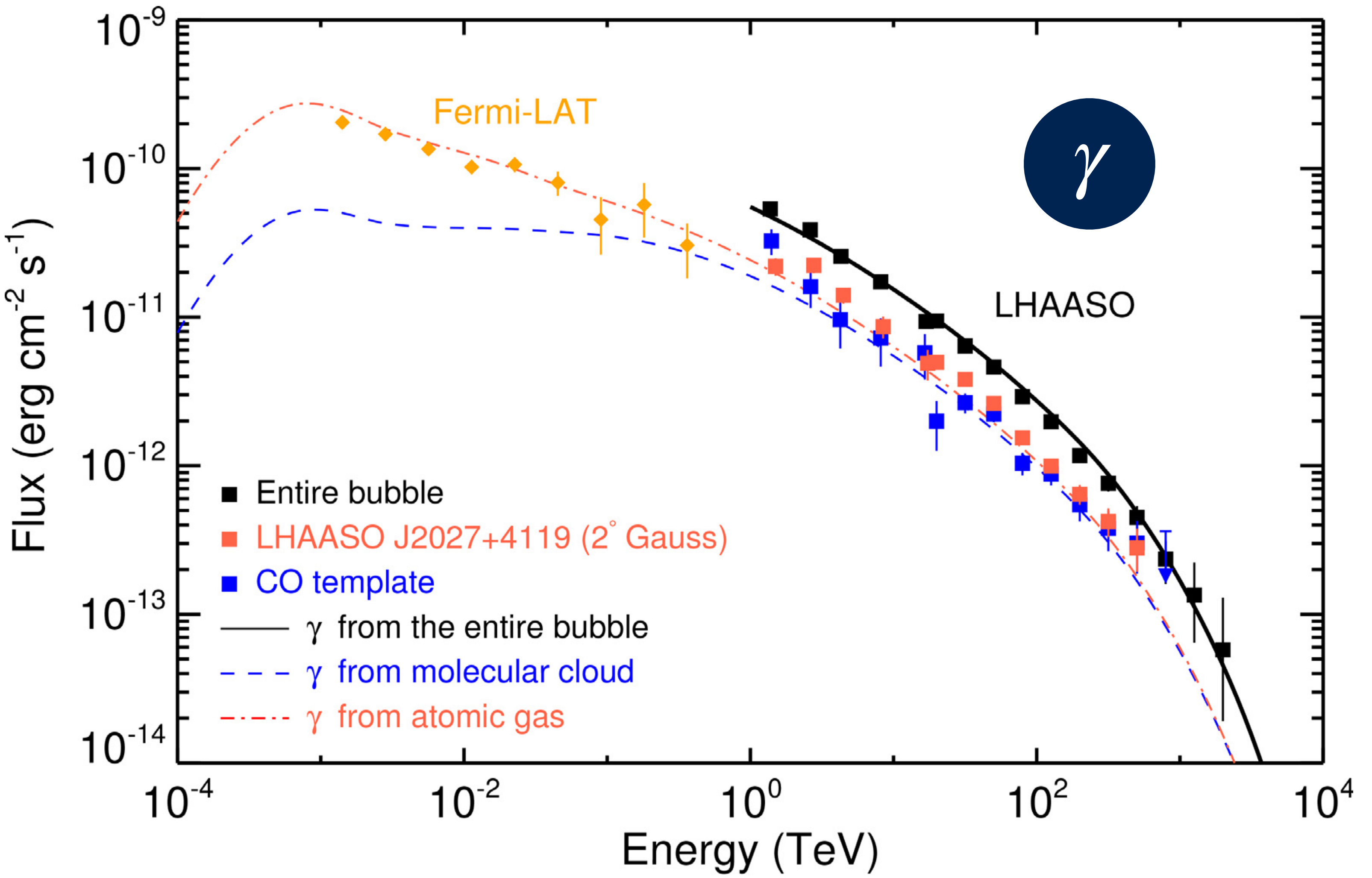




[Ambrosone, Groth, Peretti & MA'23]

Cygnus Region





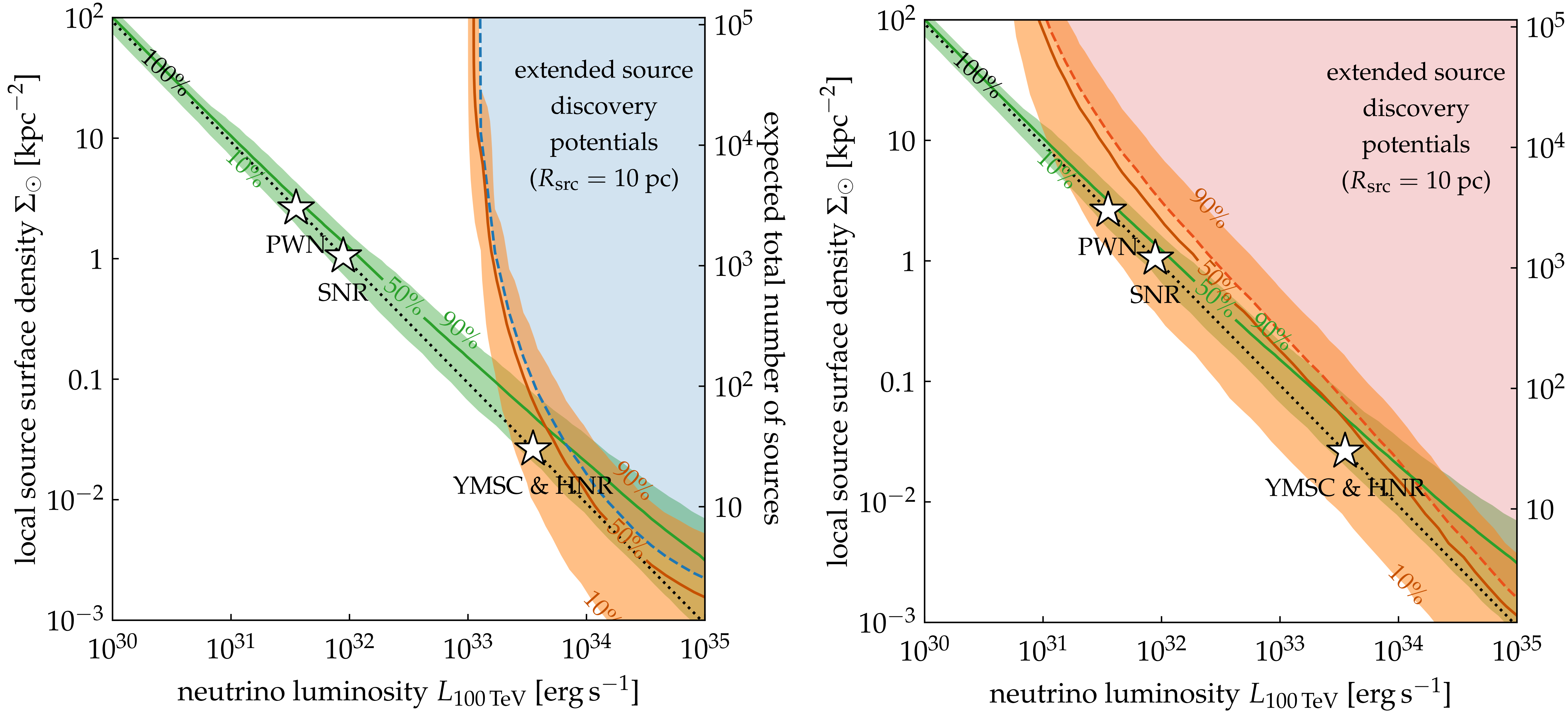
- LHAASO observes extended γ-ray emission from Cygnus region.

[LHAASO, Sci.Bull. 69 (2024) 4 '23]

- Soft spectrum ($\Gamma \simeq 2.7$) with "hot spots" correlated to molecular clouds.
- Emission reaches PeV, indicating CR PeVatron(s) in the central region.

Ensemble Fluctuations

Rare sources can have significant ensemble fluctuations that may improve visibility in neutrino telescopes.

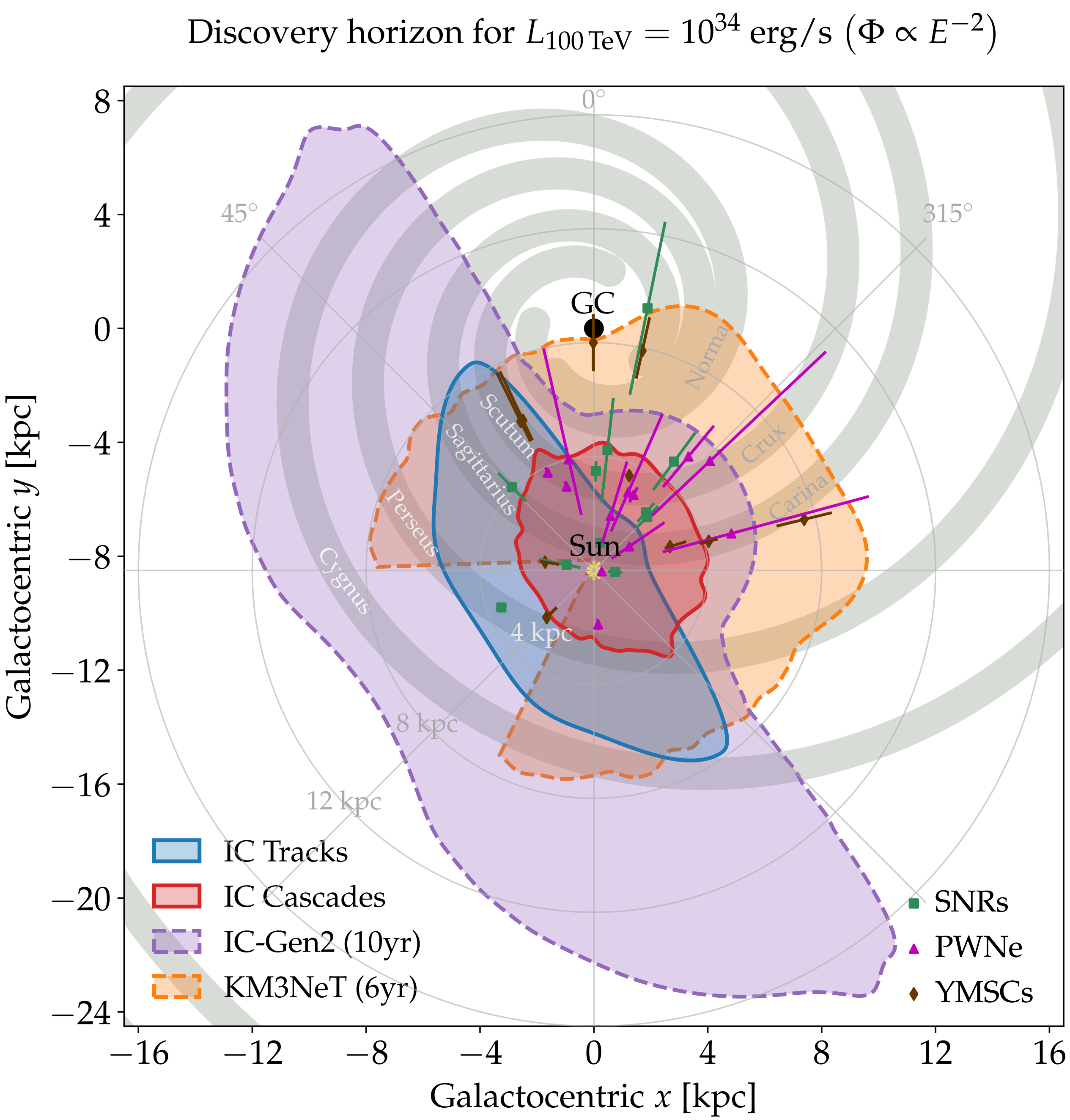


[Groth & MA in preparation]

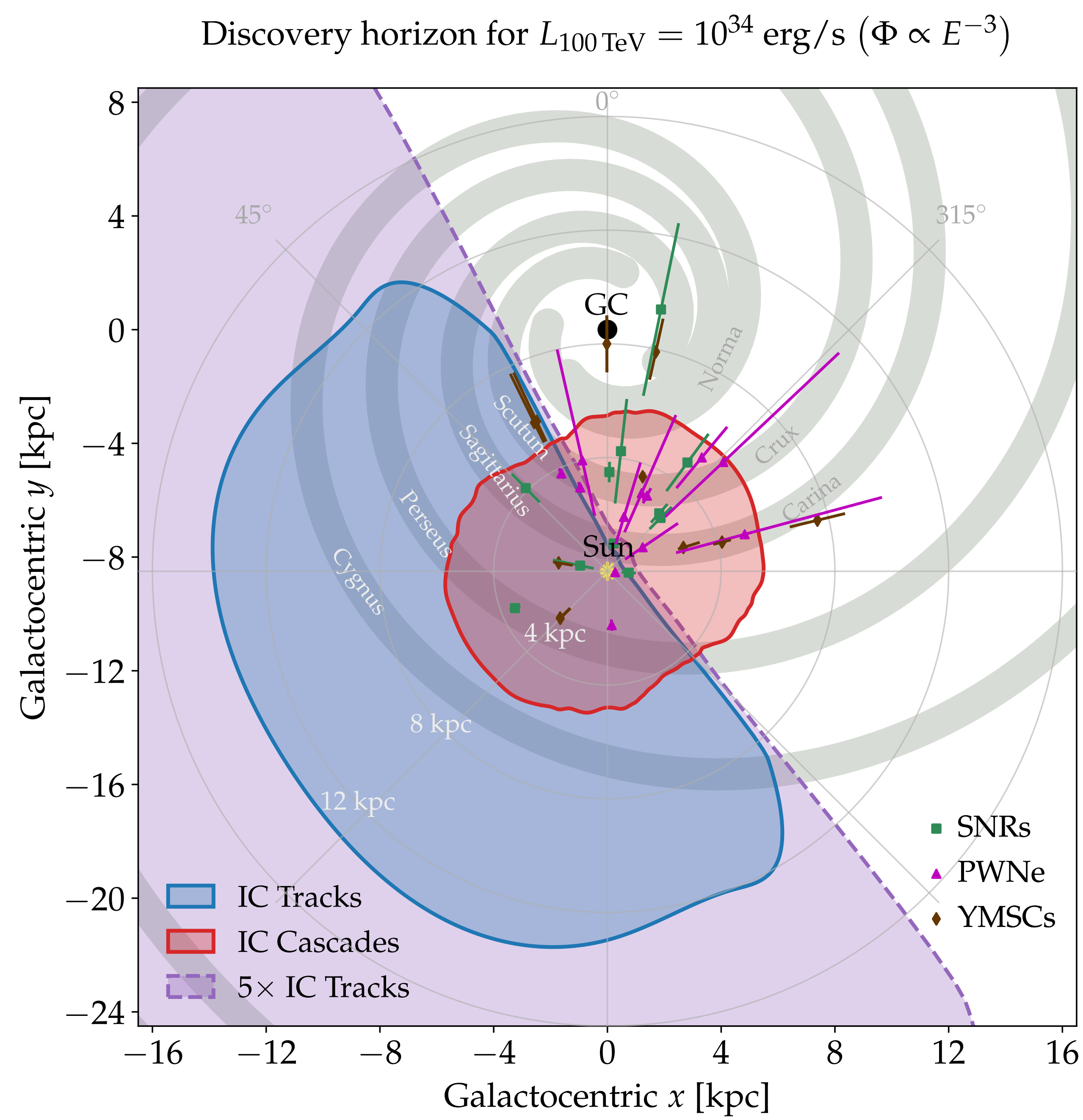
[see also Desai, Vandenbroucke, Anandagoda, Thwaites & Romfoe '23]

Point Source Sensitivities

E^{-2}

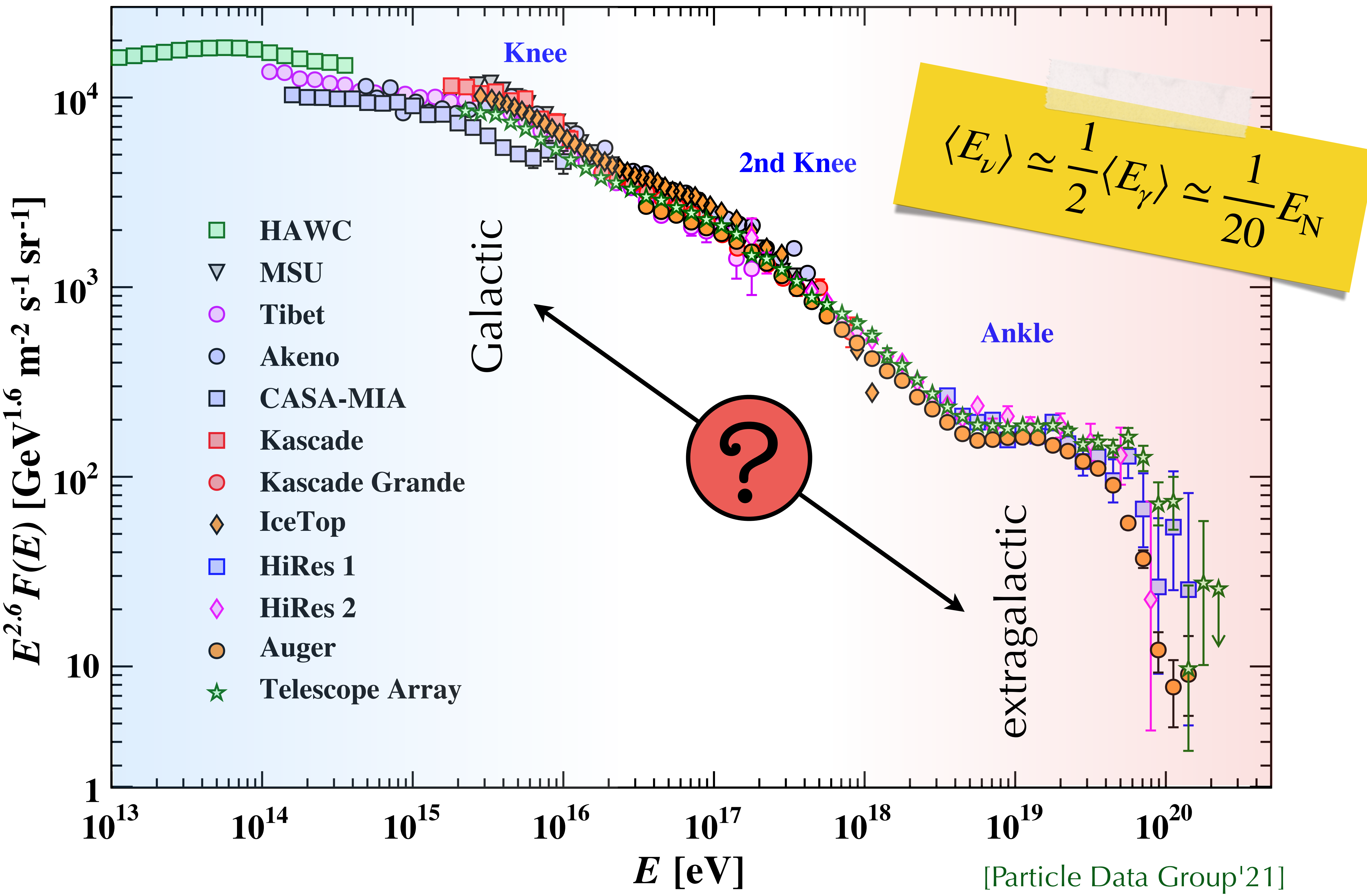


E^{-3}



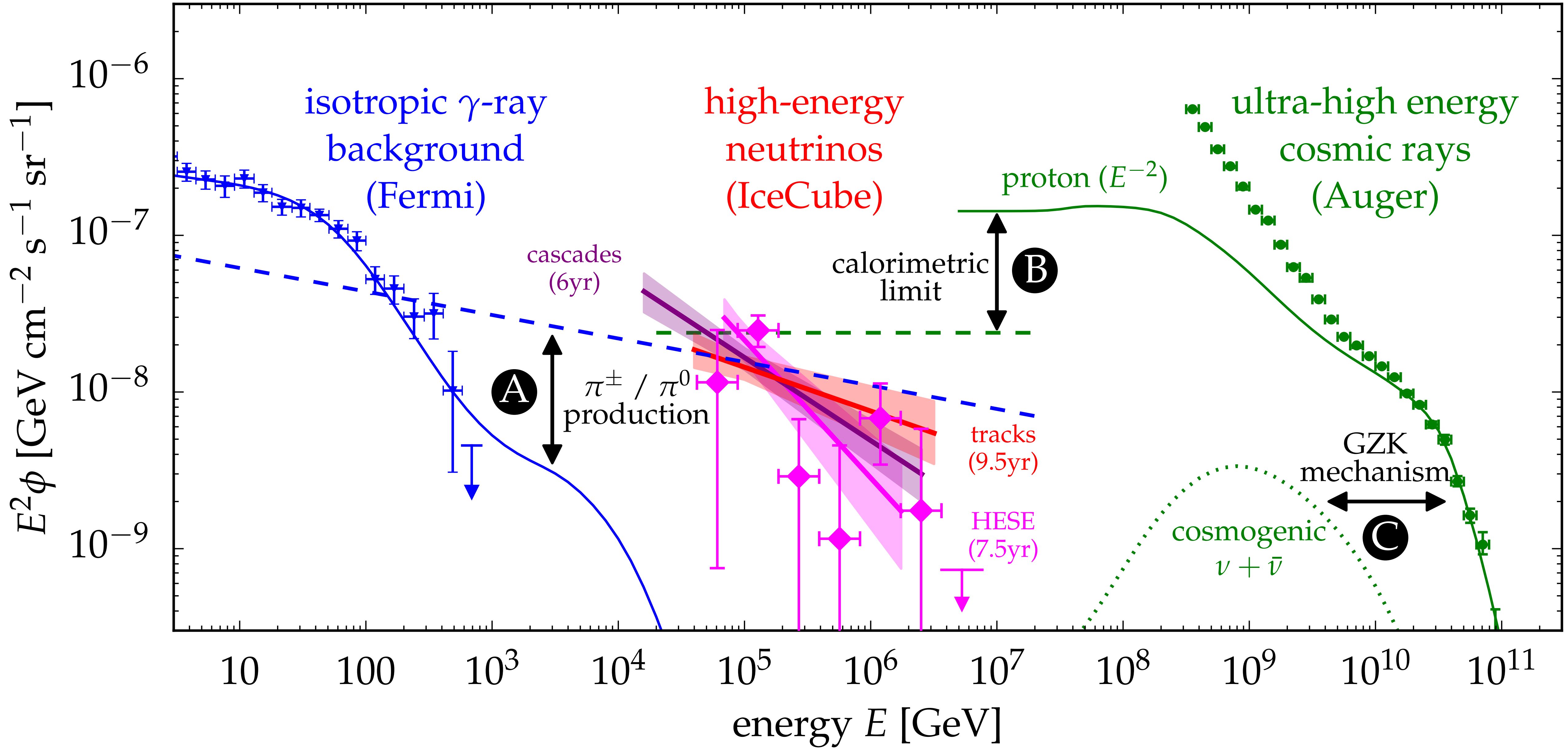
[Ambrosone, Groth, Peretti & MA'23]

Very-High Energy Cosmic Rays



[Particle Data Group'21]

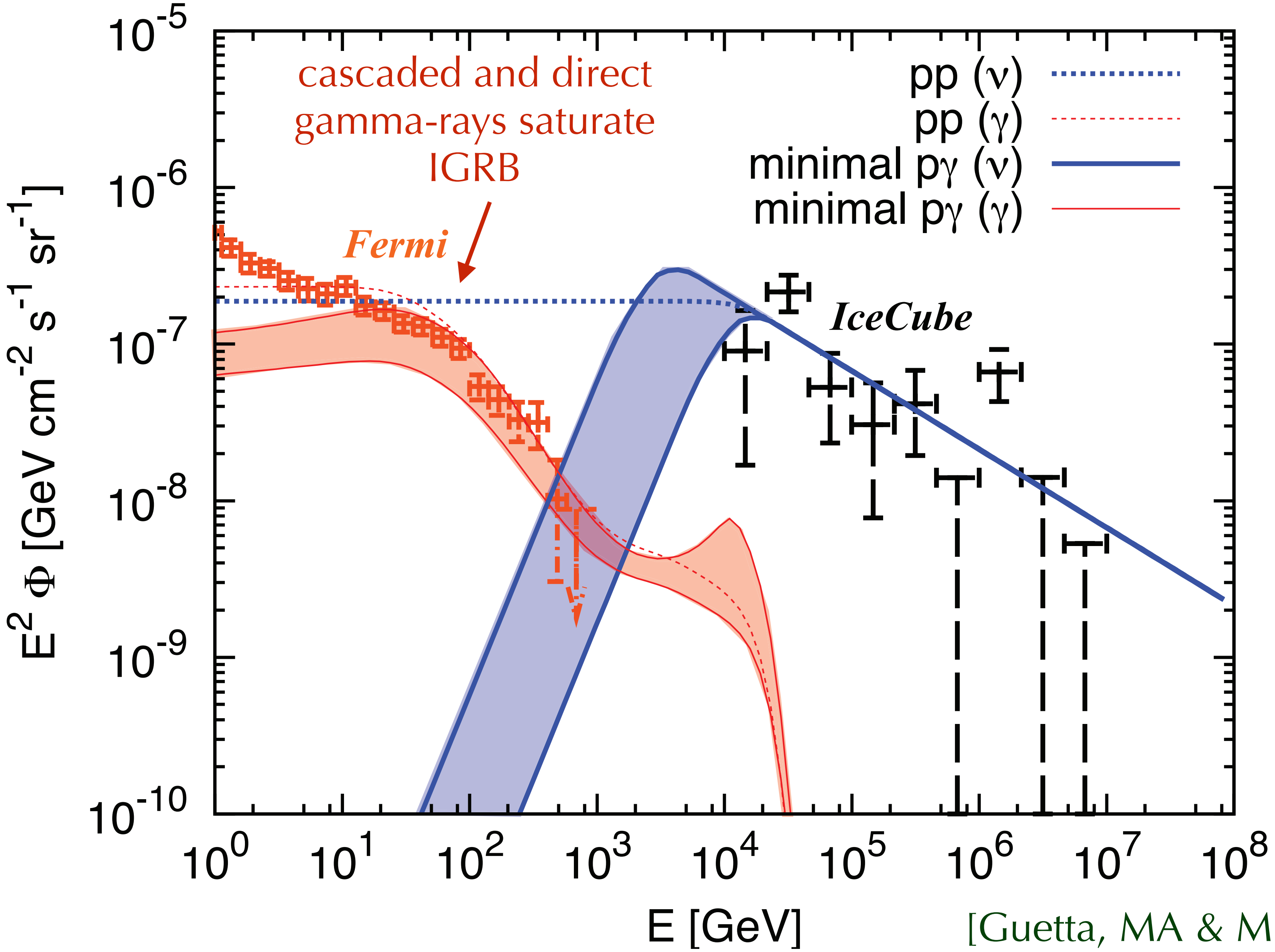
Multi-Messenger Interfaces



The high intensity of the neutrino flux compared to that of γ-rays and cosmic rays offers many interesting multi-messenger interfaces.

Hadronic Gamma-Rays

Neutrino production via cosmic ray interactions with gas (pp) or radiation (pγ) saturate the isotropic diffuse gamma-ray background.



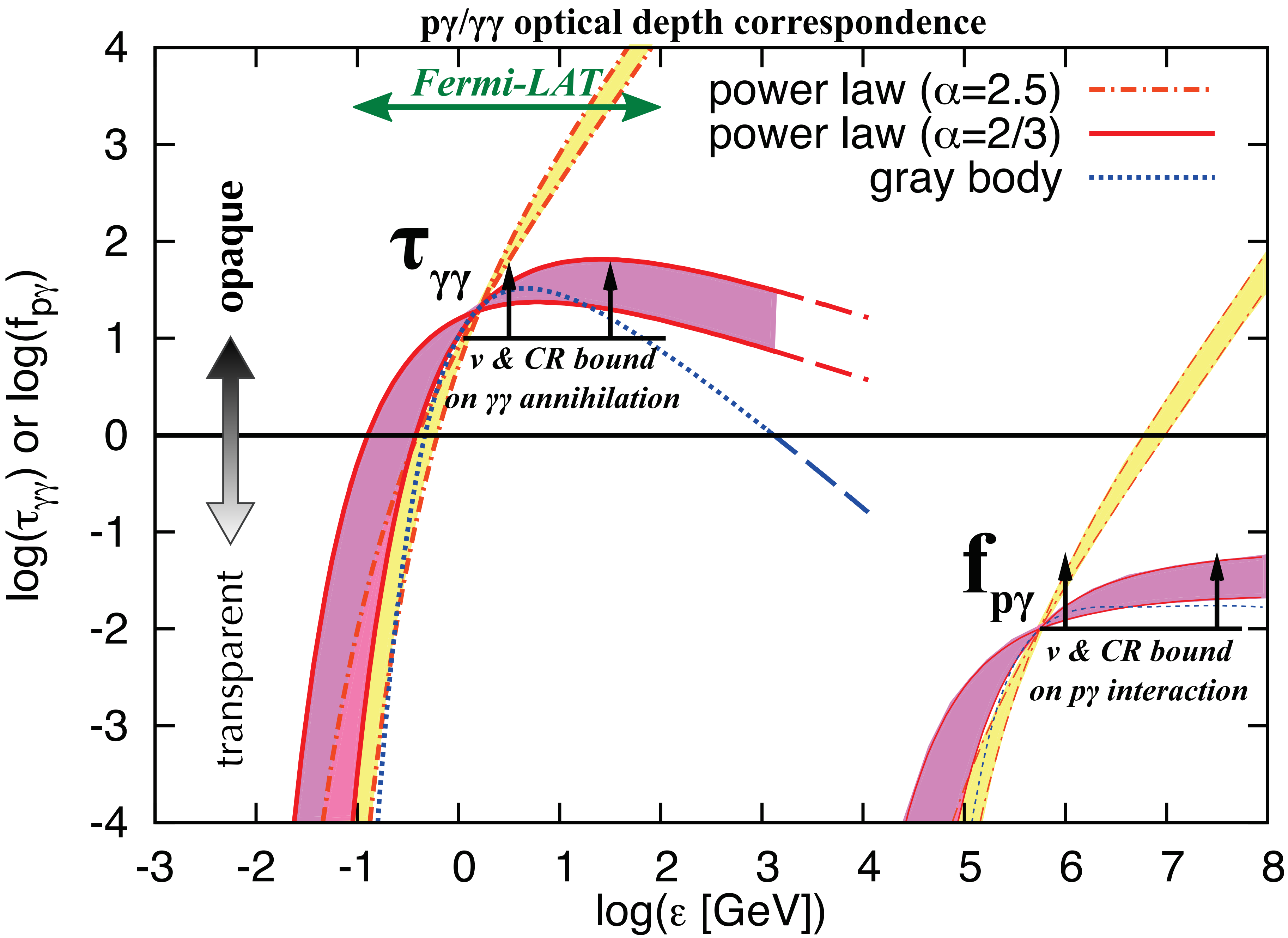
[Guetta, MA & Murase'16]

[see also Murase, MA & Lacki'13; Tamborra, Ando & Murase'14; Ando, Tamborra & Zandanel'15]

[Bechtol, MA, Ajello, Di Mauro & Vandenbrouke'15; Palladino, Fedynitch, Rasmussen & Taylor'19]

Hidden Sources?

Efficient production of 10 TeV neutrinos in pγ scenarios require sources with **strong X-ray backgrounds** (e.g. AGN core models).

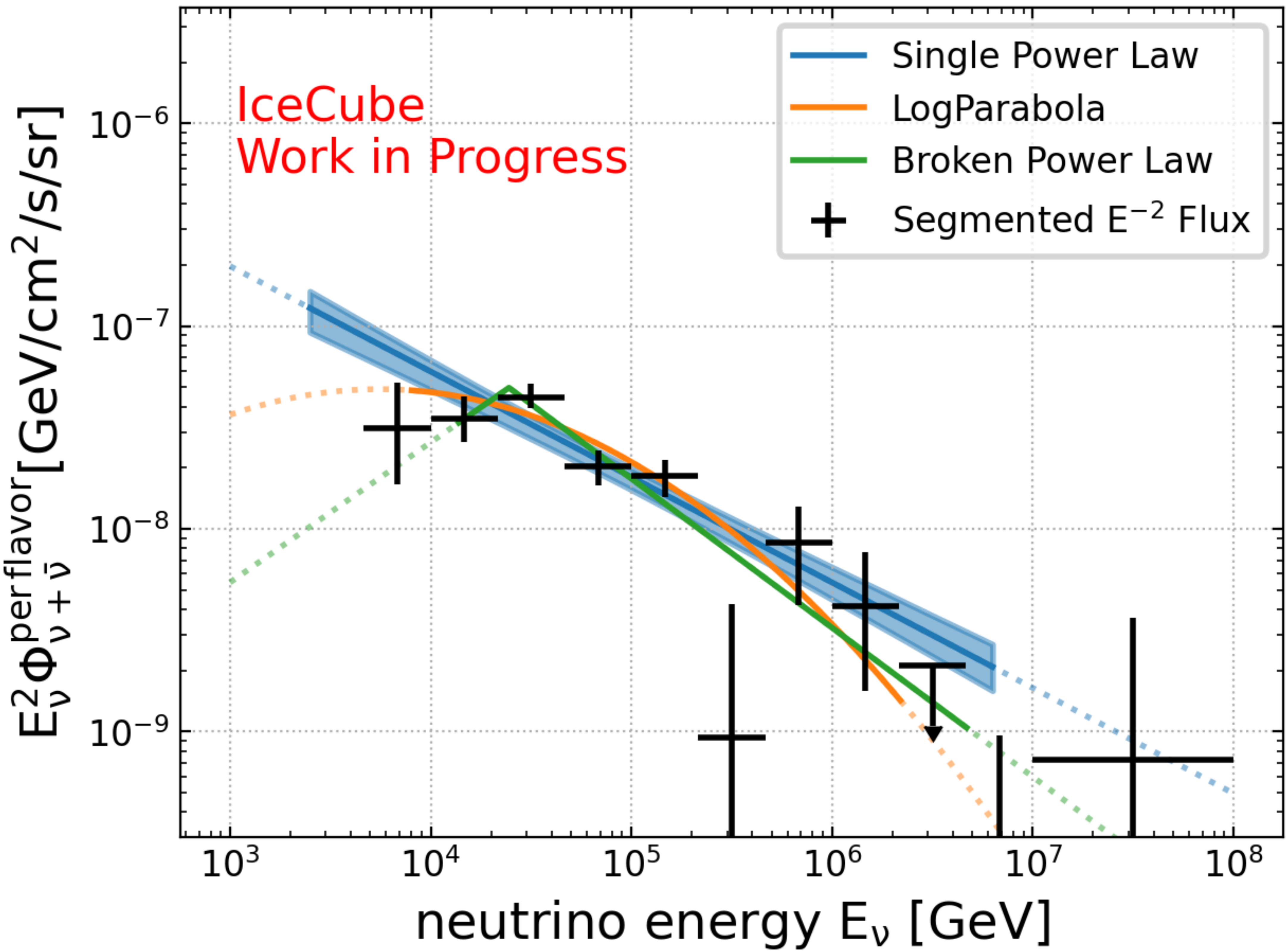


High pion production efficiency implies strong internal ***γ*-ray absorption in Fermi-LAT energy range:**

$$\tau_{\gamma\gamma} \simeq 1000 f_{p\gamma}$$

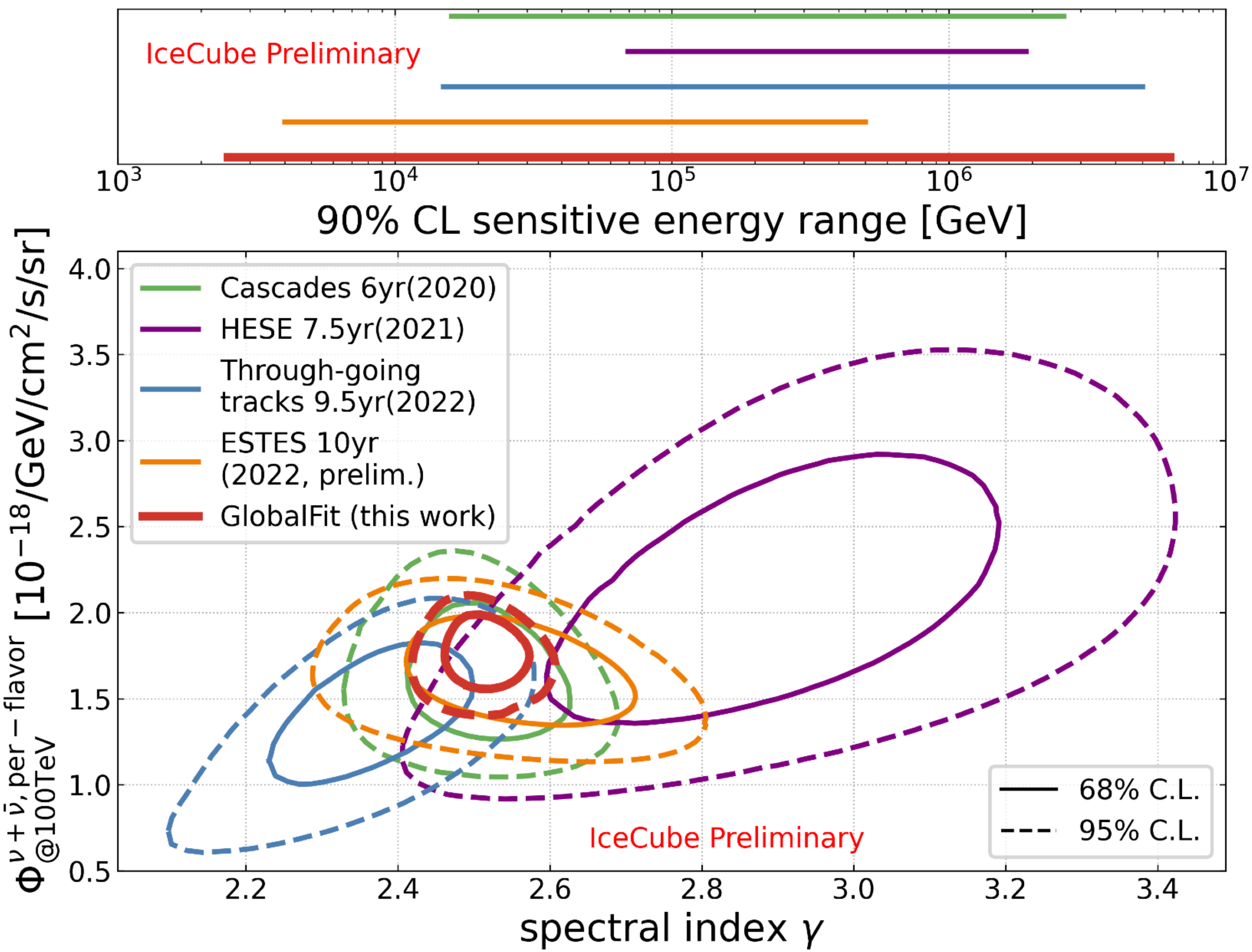
[Guetta, MA & Murase'16]

Global Diffuse Fit



[IceCube, PoS (ICRC2023) 1064]

Diffuse Flux Fits



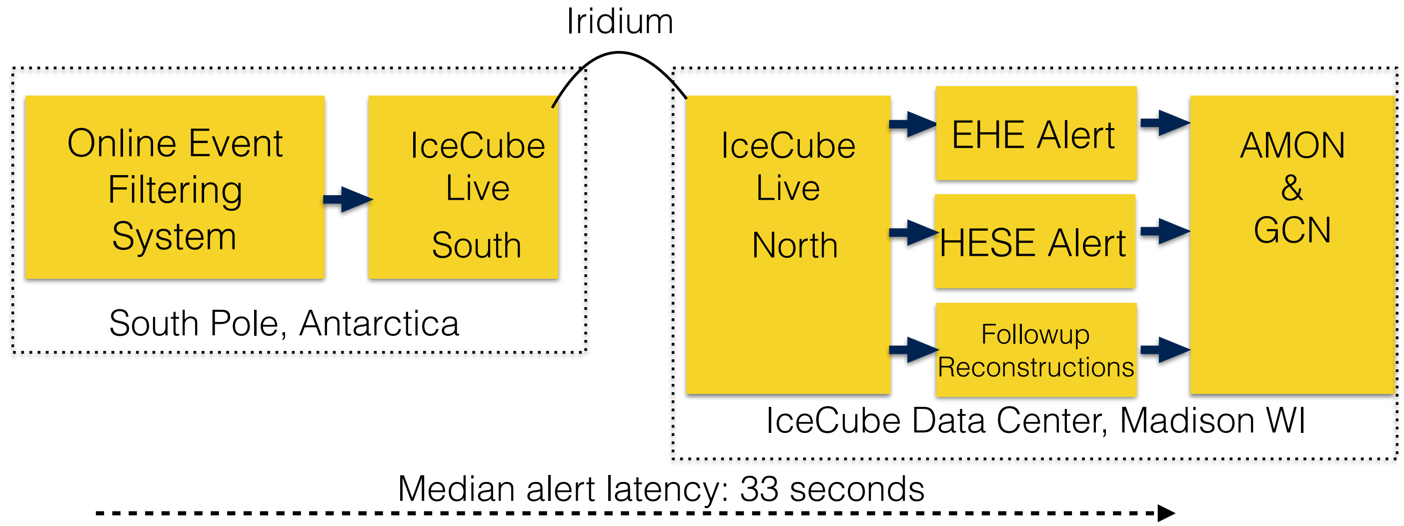
[IceCube, PoS (ICRC2023) 1064]

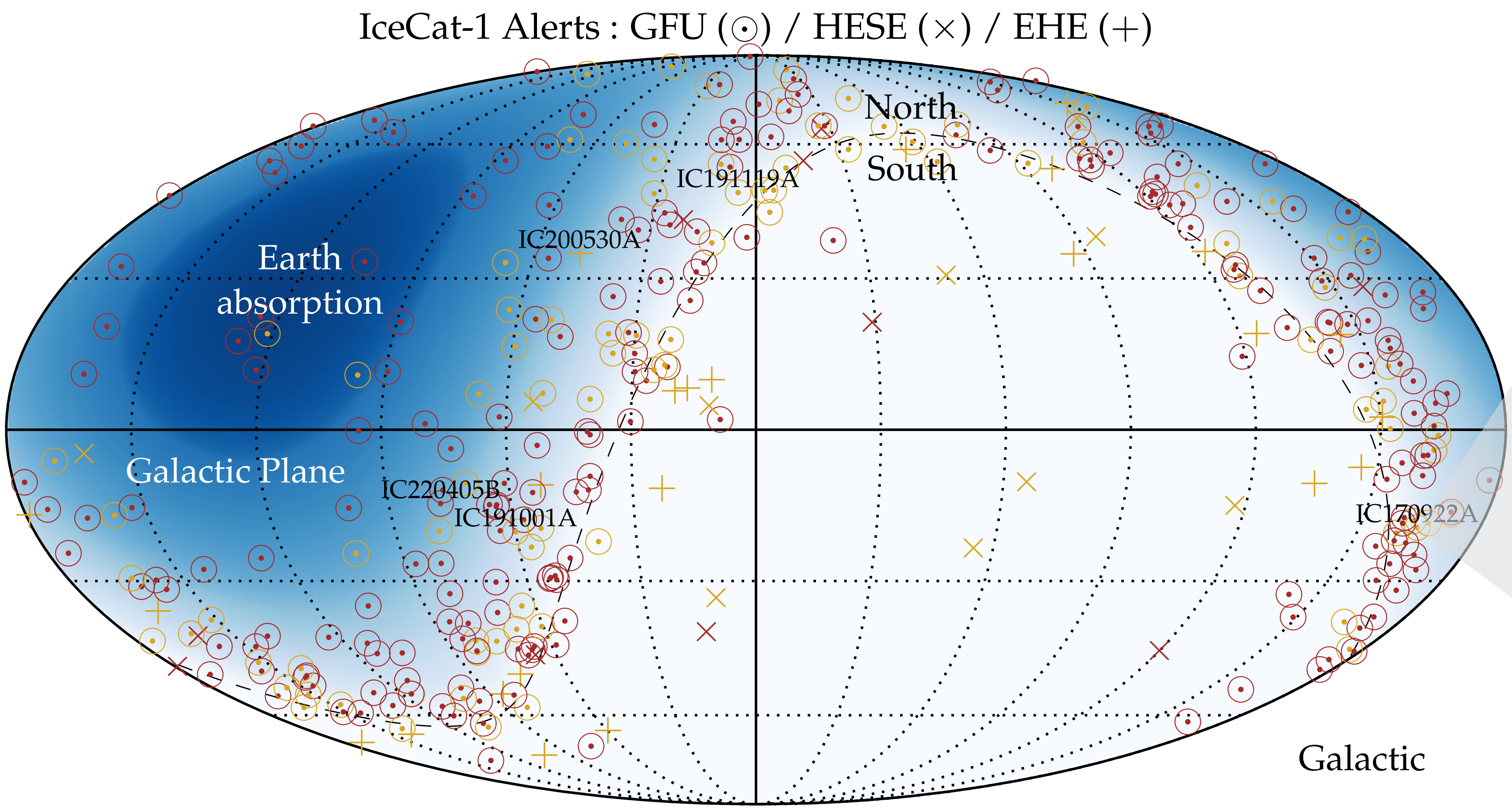
Realtime Neutrino Alerts

Low-latency (<1min) **public neutrino alert system** established in April 2016.

- ✦ **Gold alerts:** about **10 per year**
  50% signalness (on average)

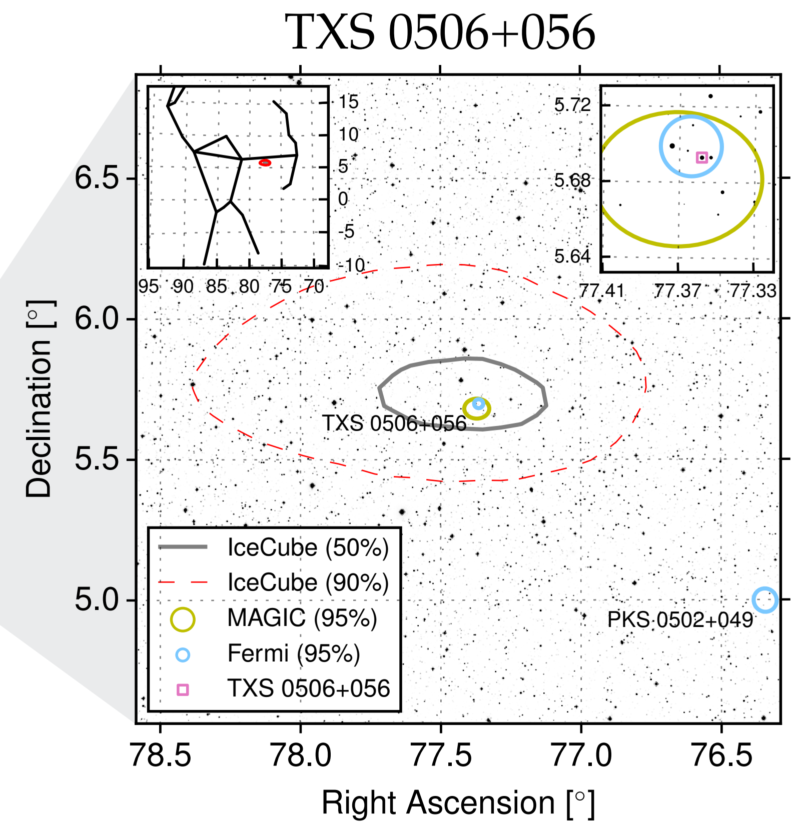
- ✦ **Bronze alerts:** about **20 per year**
  30% signalness (on average)





[IceCube, ApJS 269 (2023) 1]

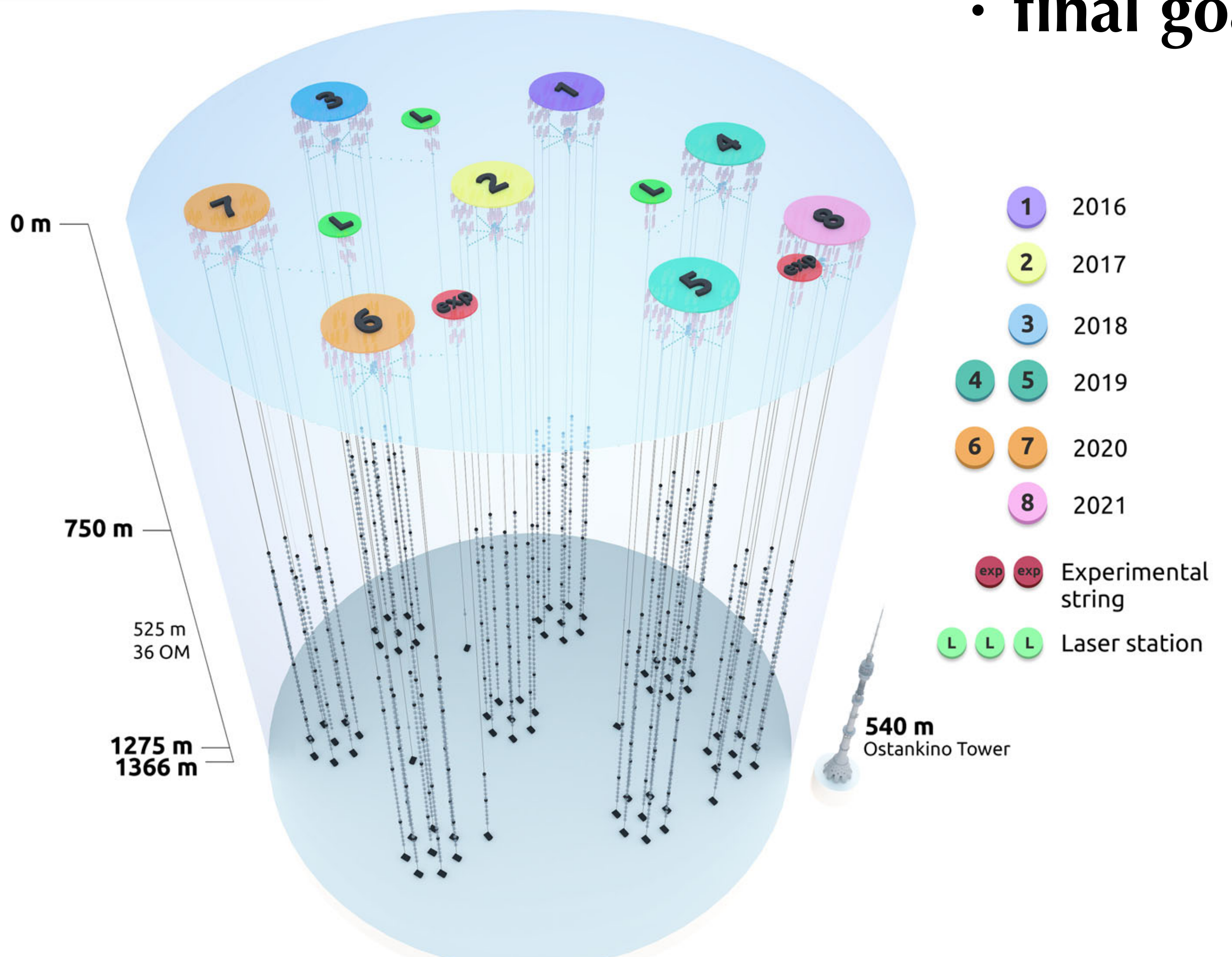
[IceCube, PoS (ICRC2019) 1021]

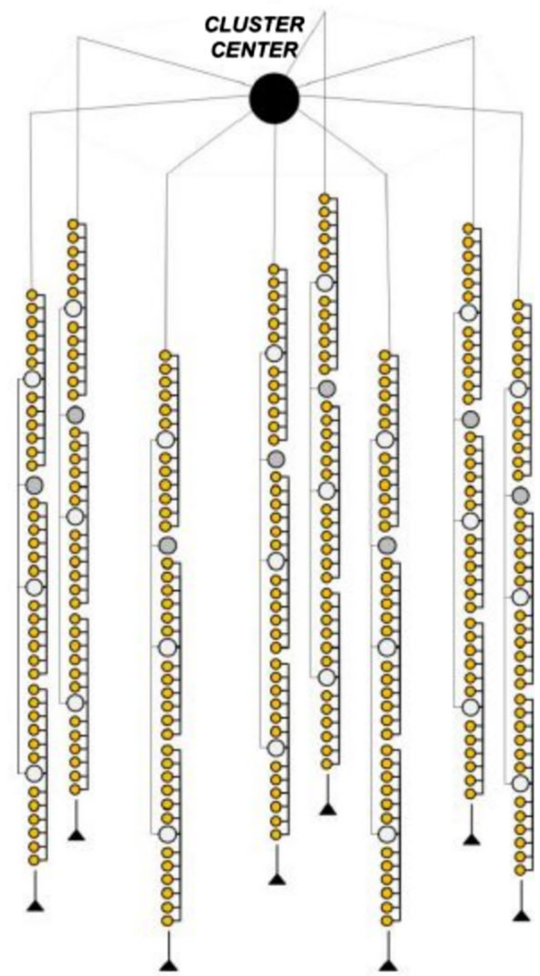


Outlook: Baikal-GVD

BAIKAL-GVD

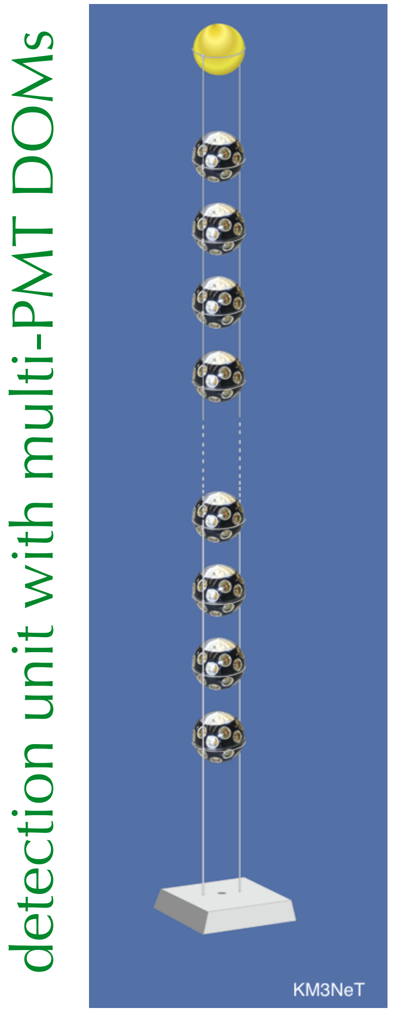
- **GVD Phase 1:** 8 clusters with 8 strings each were completed in 2021
- **status March 2024: 11(+1) clusters**
- **final goal**: 27 clusters ($\sim 1.4\,\mathrm{km}^3$)

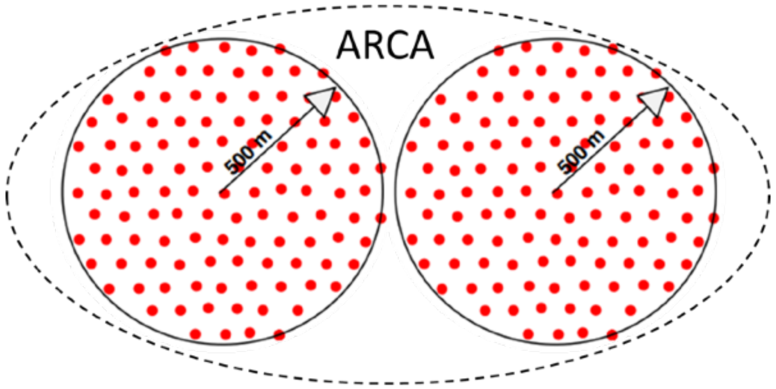


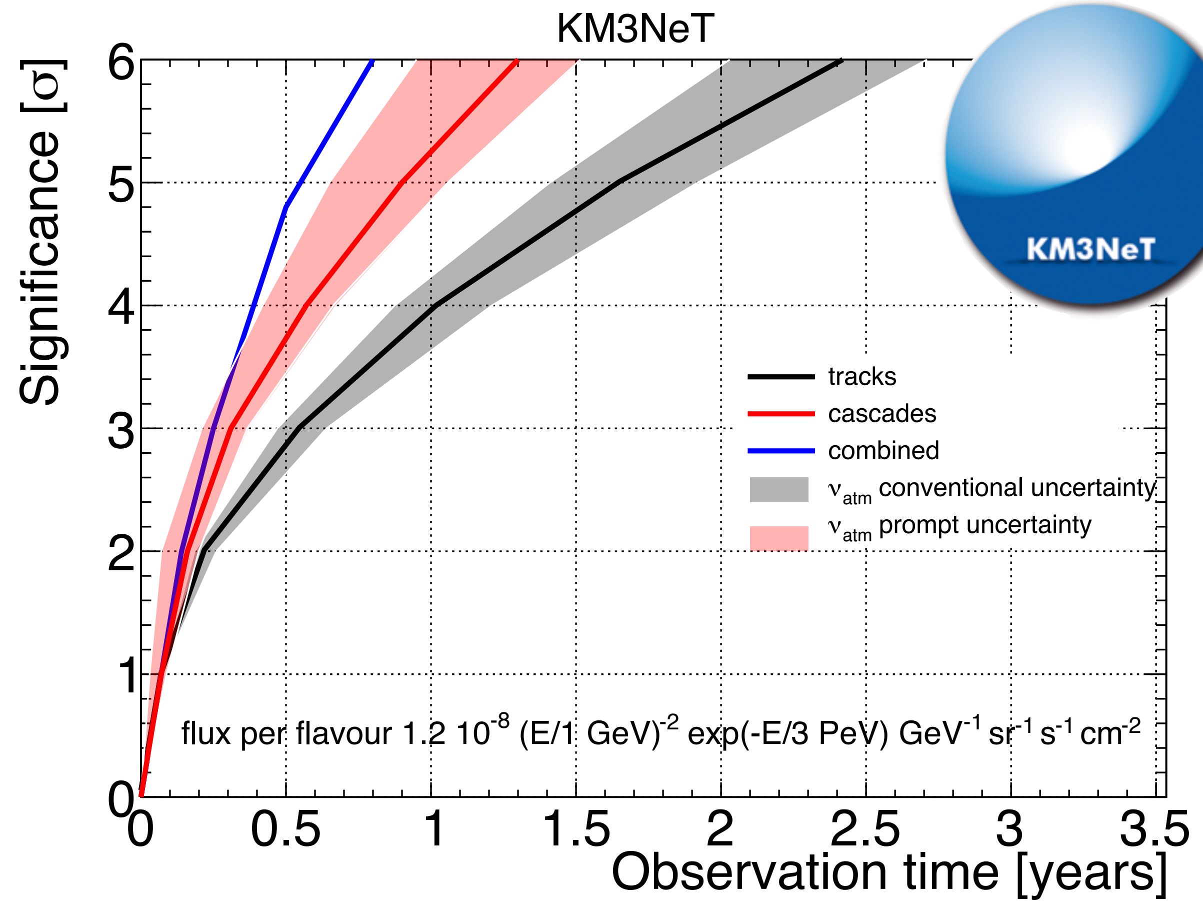


Outlook: KM3NeT/ARCA

- **ARCA :** 2 building blocks of 115 detection units (DUs)
- **status March 2024: 28 (ARCA) DUs**
- **ORCA** : optimized for low-energy (GeV) and oscillation analyses





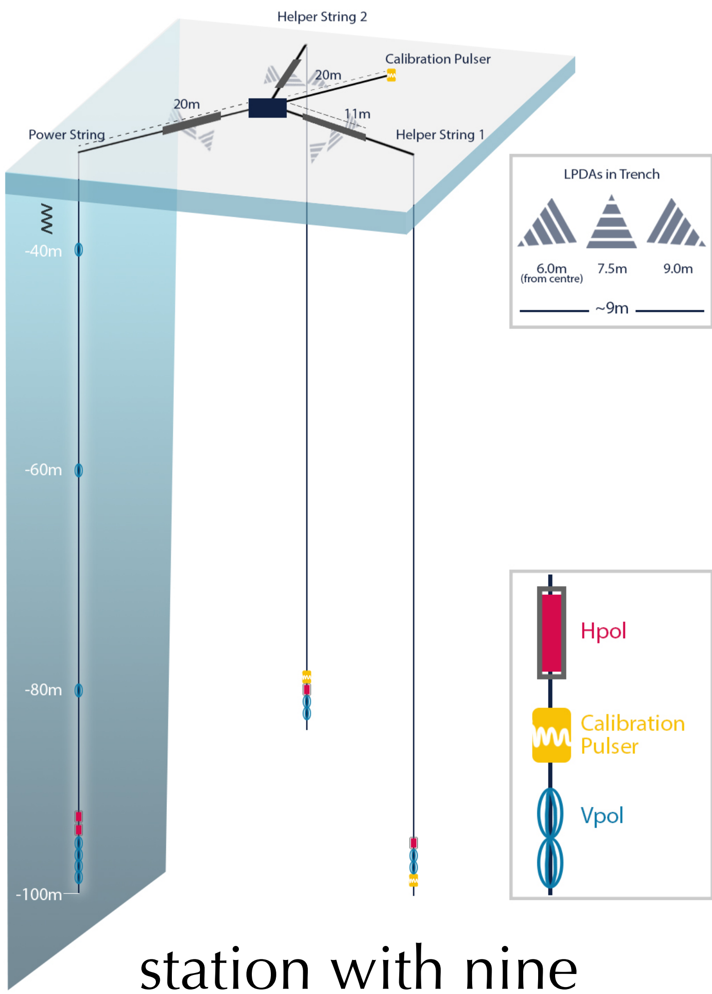


- **Improved angular resolution** for water Cherenkov emission.
- 5σ discovery of **diffuse flux** with full ARCA within one year
- **Complementary field of view** ideal for the study of point sources.

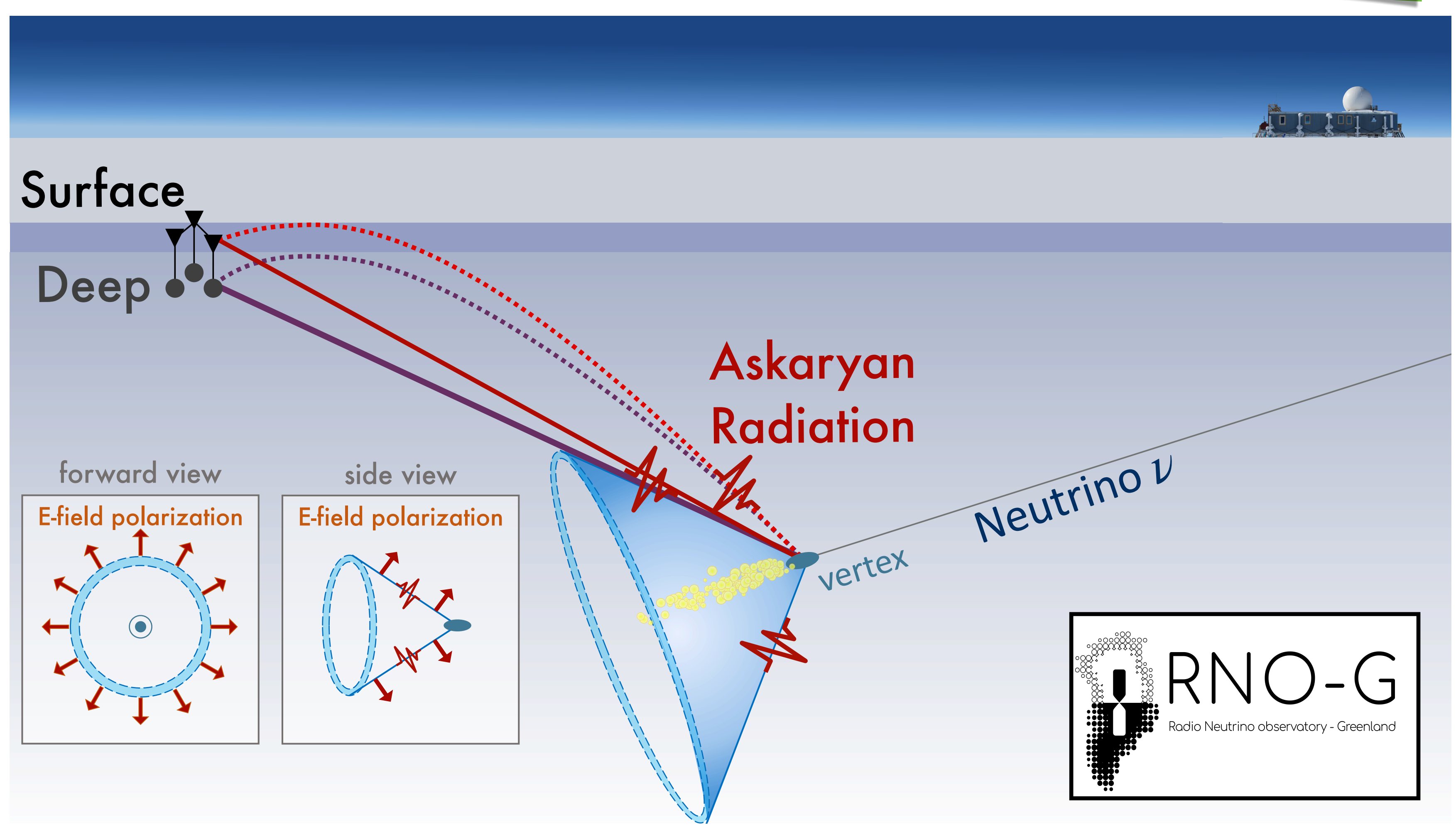
Outlook: RNO-G

- Detection principle of **ANITA, ARA & ARIANNA** (Antarctica)
- **Under construction:** Radio Neutrino Observatory-Greenland (**RNO-G)**
- **status March 2024:** 7 of 35 stations deployed

Askaryan effect:
Neutrino emission above 10 PeV can be observed via **coherent radio emission of showers** in radio-transparent media.

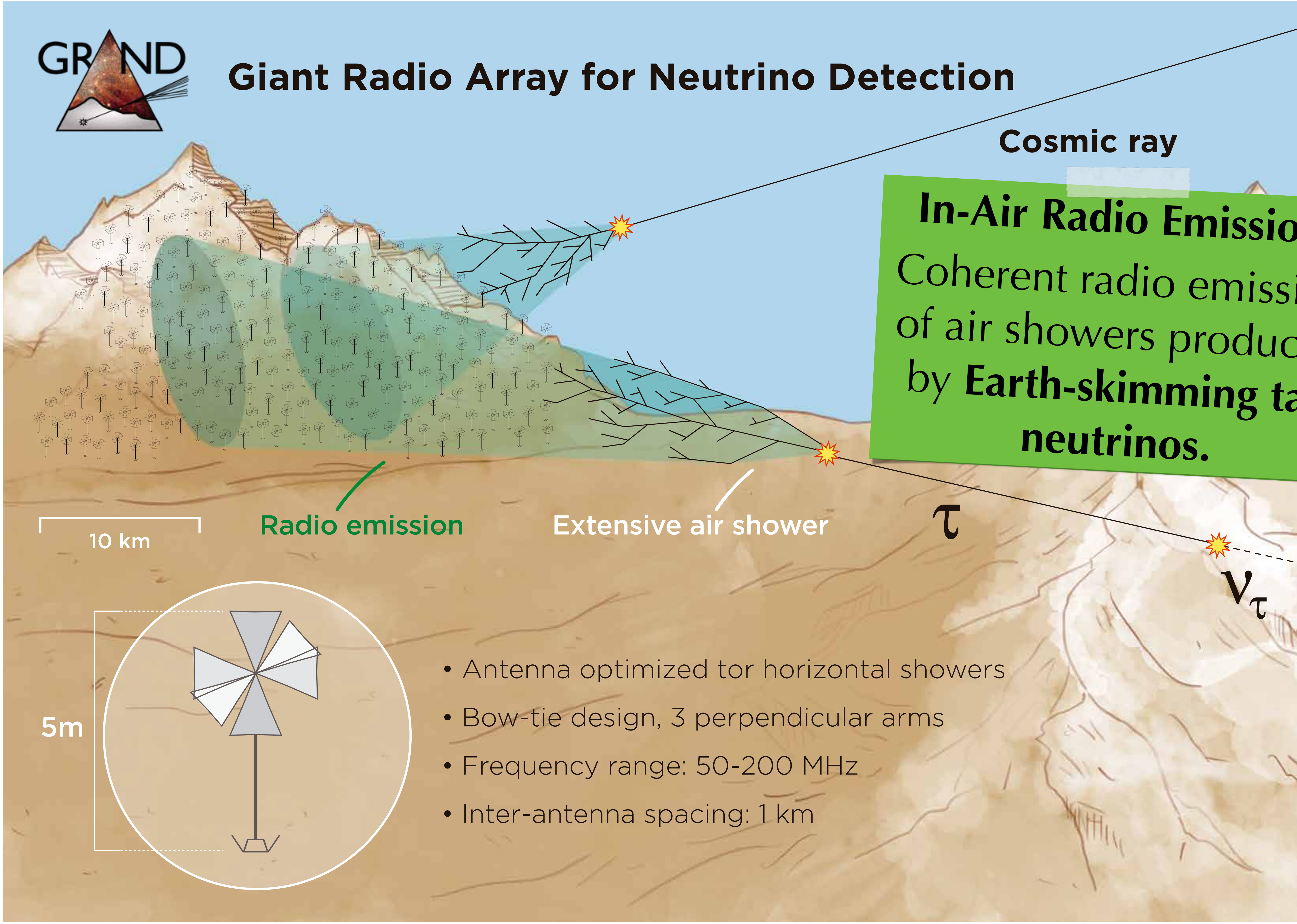


station with nine deep & surface antennas



[RNO-G JINST 16 (2021) 3]

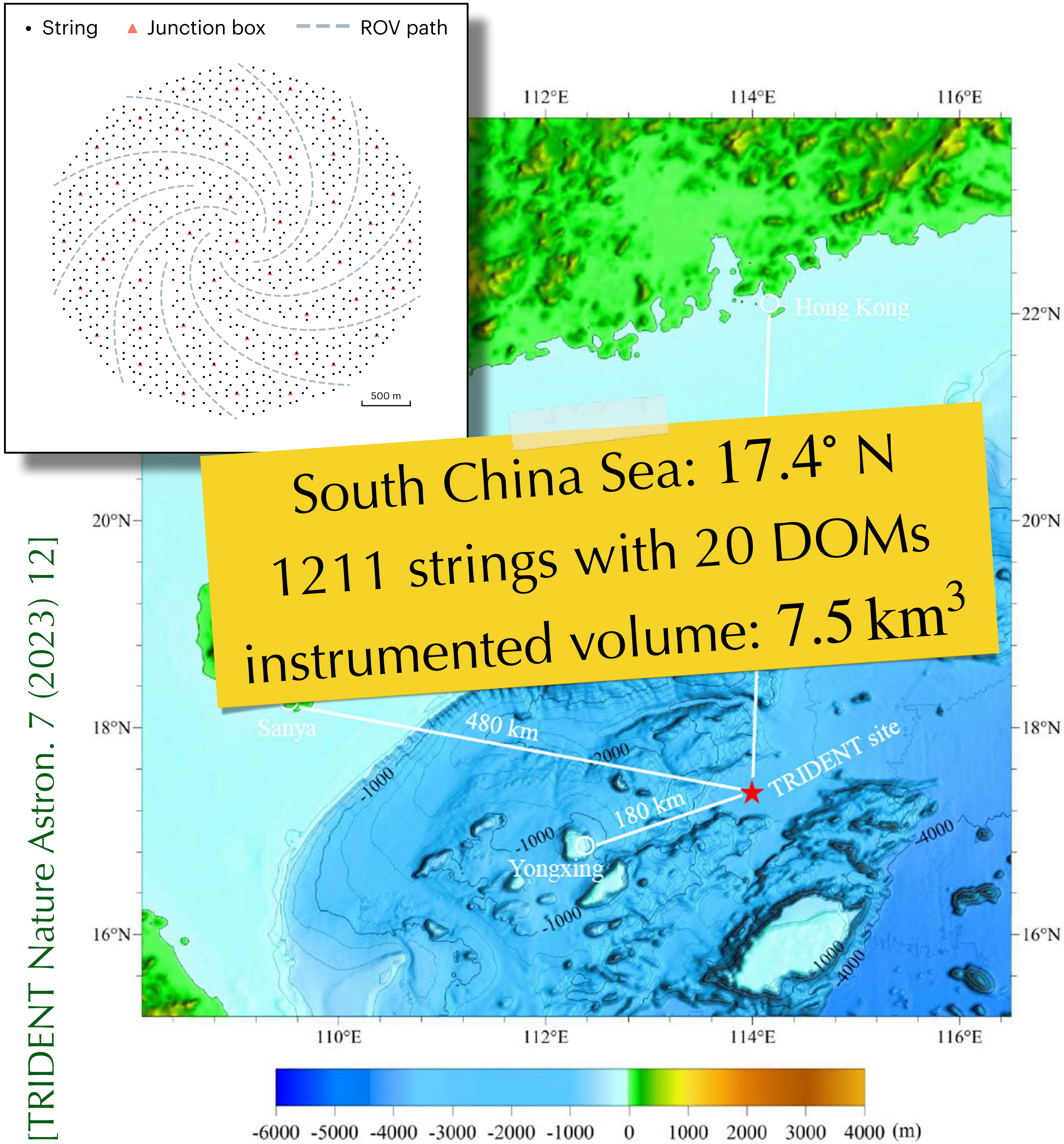
Vision: GRAND



In-Air Radio Emission:
Coherent radio emission of air showers produced by **Earth-skimming tau neutrinos.**

[GRAND SCPMA 63 (2020) 1]

Vision: TRIDENT

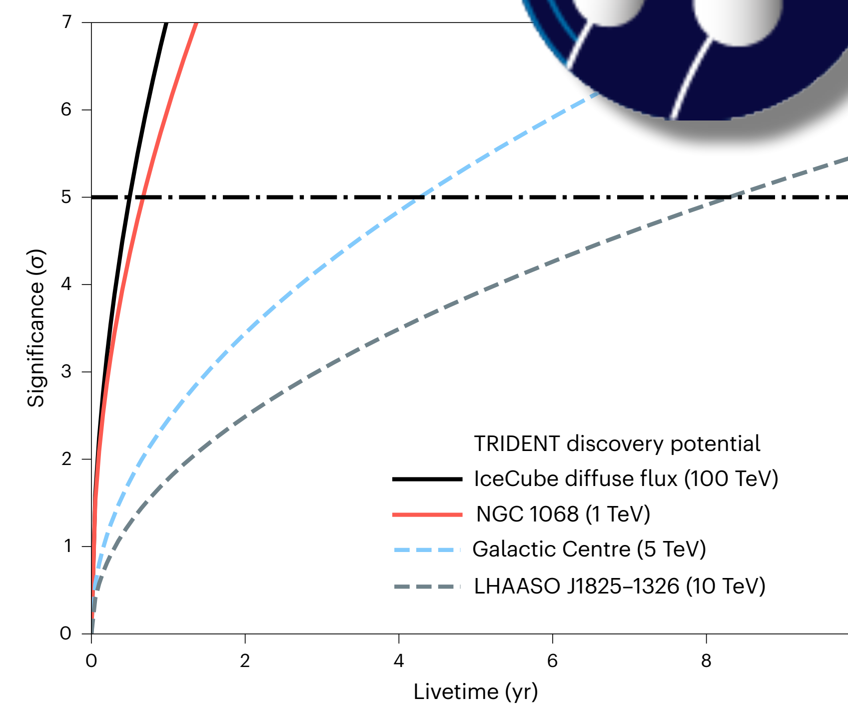


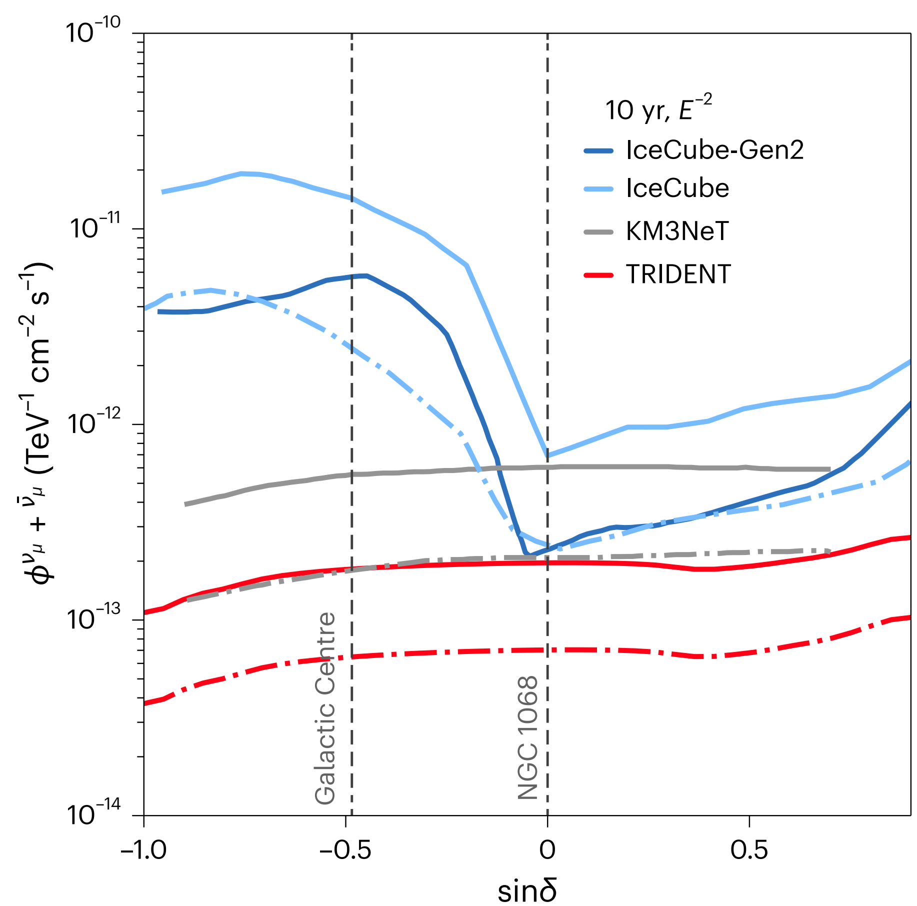
South China Sea: 17.4° N

1211 strings with 20 DOMs

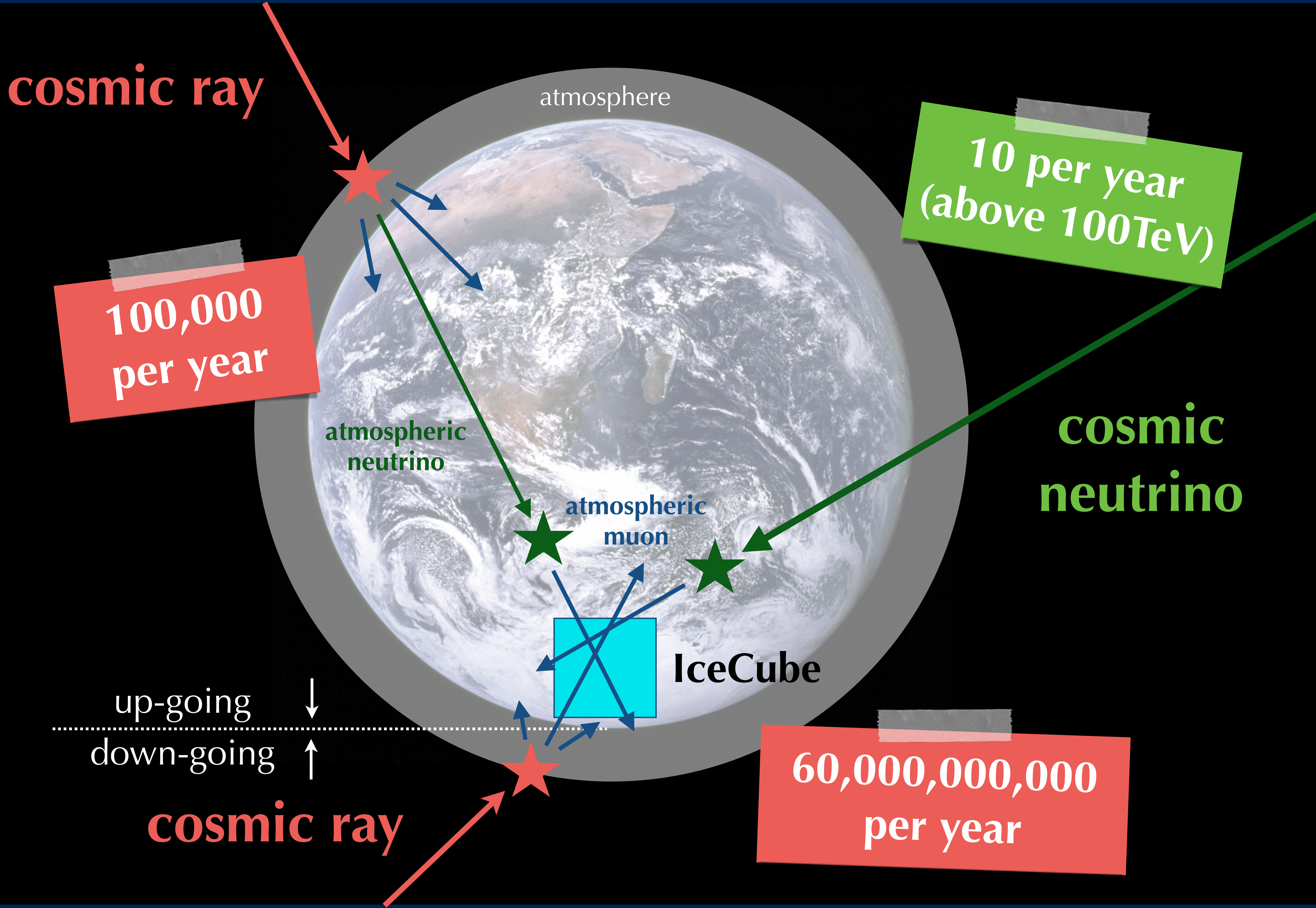
instrumented volume: 7.5 km^3

[TRIDENT Nature Astron. 7 (2023) 12]





Neutrino Selection I



Neutrino Selection II

- Outer layer of optical modules used as virtual **veto region.**
- **Atmospheric muons** pass through veto from above.
- **Atmospheric neutrinos** coincidence with atmospheric muons.
- **Cosmic neutrino** events can start inside the fiducial volume.
- **High-Energy Starting Event** (HESE) analysis