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

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The New Era of MM Astroparticle Physics

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VILLUM FONDEN

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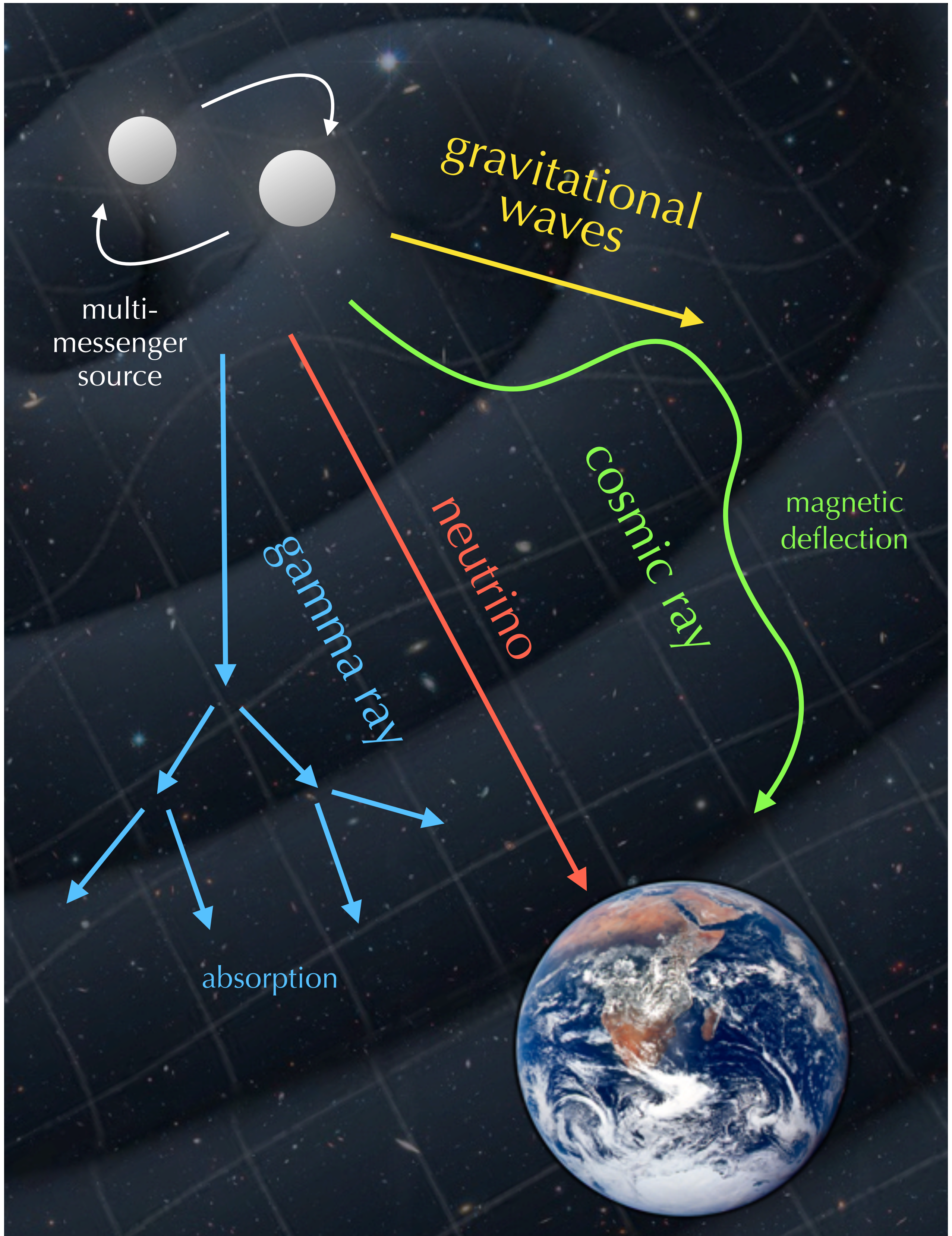
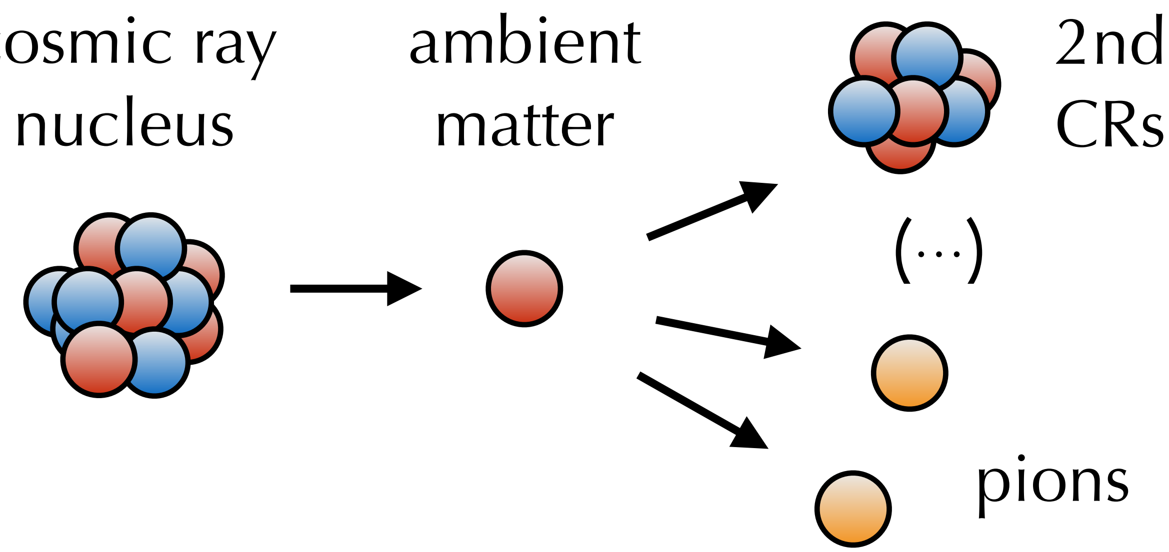
Multi-Messenger Astronomy



Acceleration of **cosmic rays** (CRs) - especially in the aftermath of cataclysmic events, sometimes visible in **gravitational waves** (GW).

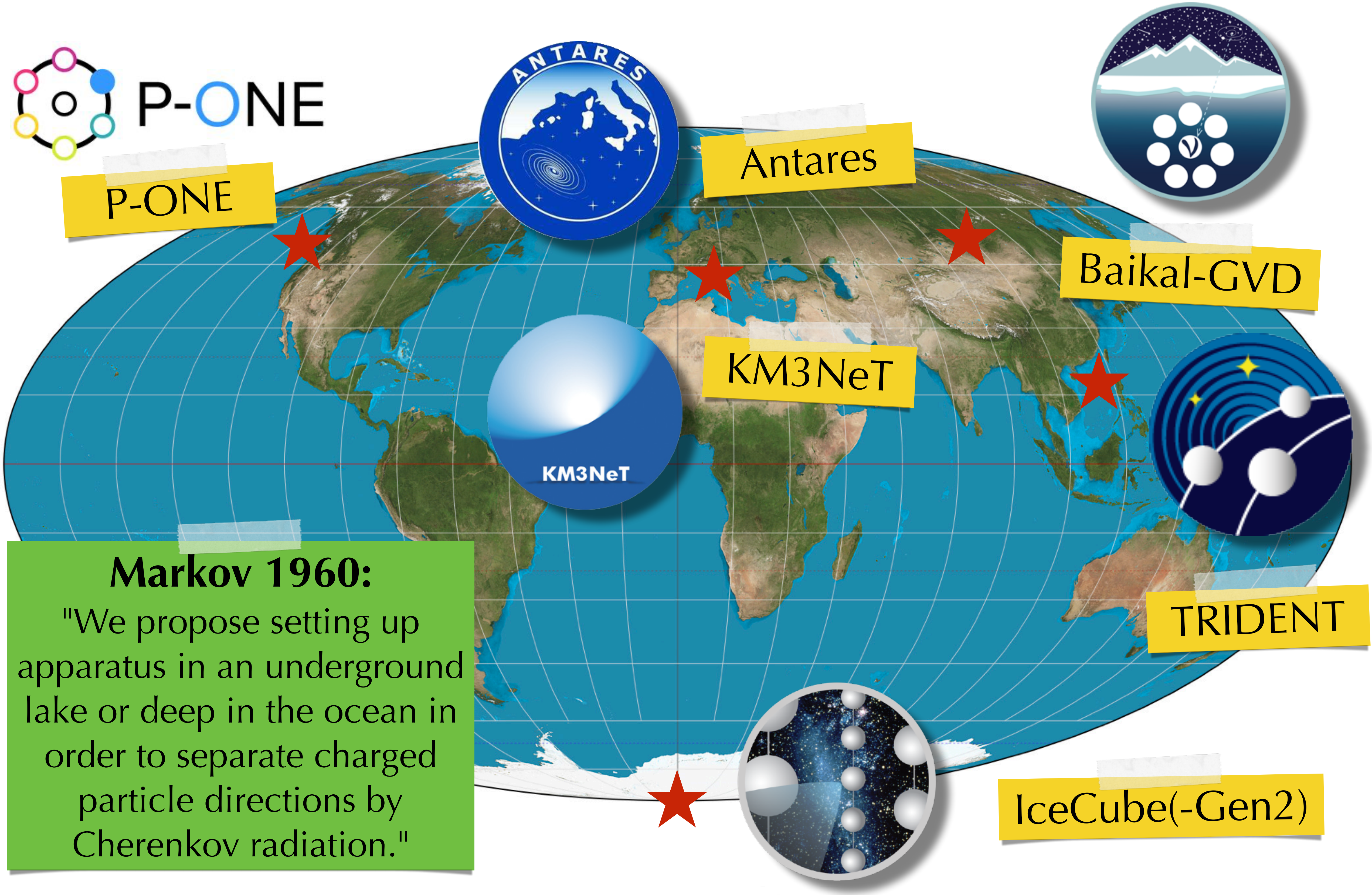


Secondary **neutrinos** and **gamma-rays** from pion decays:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \qquad \pi^0 \rightarrow \gamma + \gamma$$

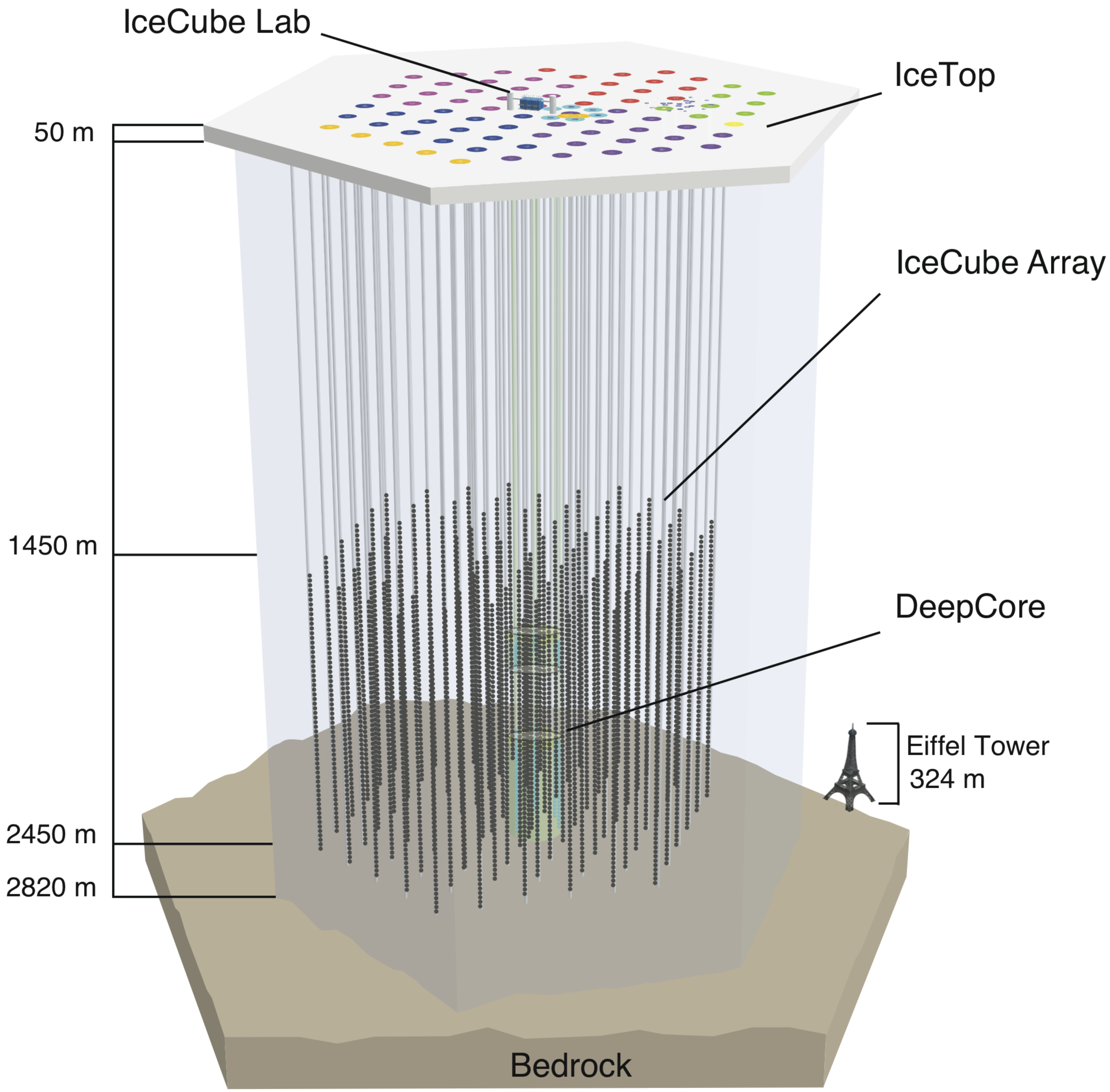
$$\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

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."

IceCube Observatory

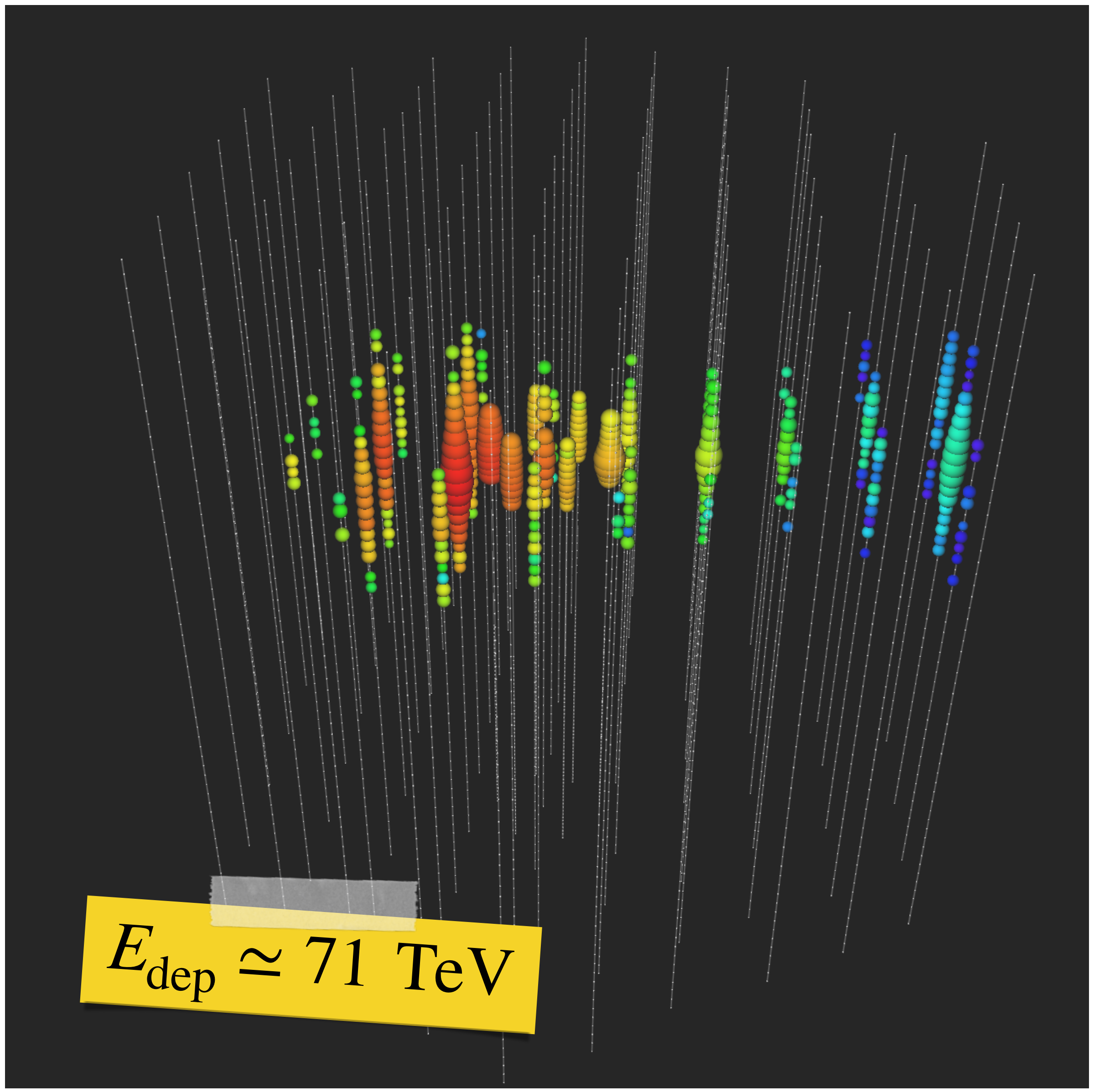


- **Giga-ton optical Cherenkov telescope at the South Pole**
- Collaboration of about 300 scientists at more than 50 international institutions
- 60 digital optical modules (DOMs) attached to strings
- 86 IceCube strings **instrumenting 1 km^3 of clear glacial ice**
- 81 IceTop stations for cosmic ray shower detections

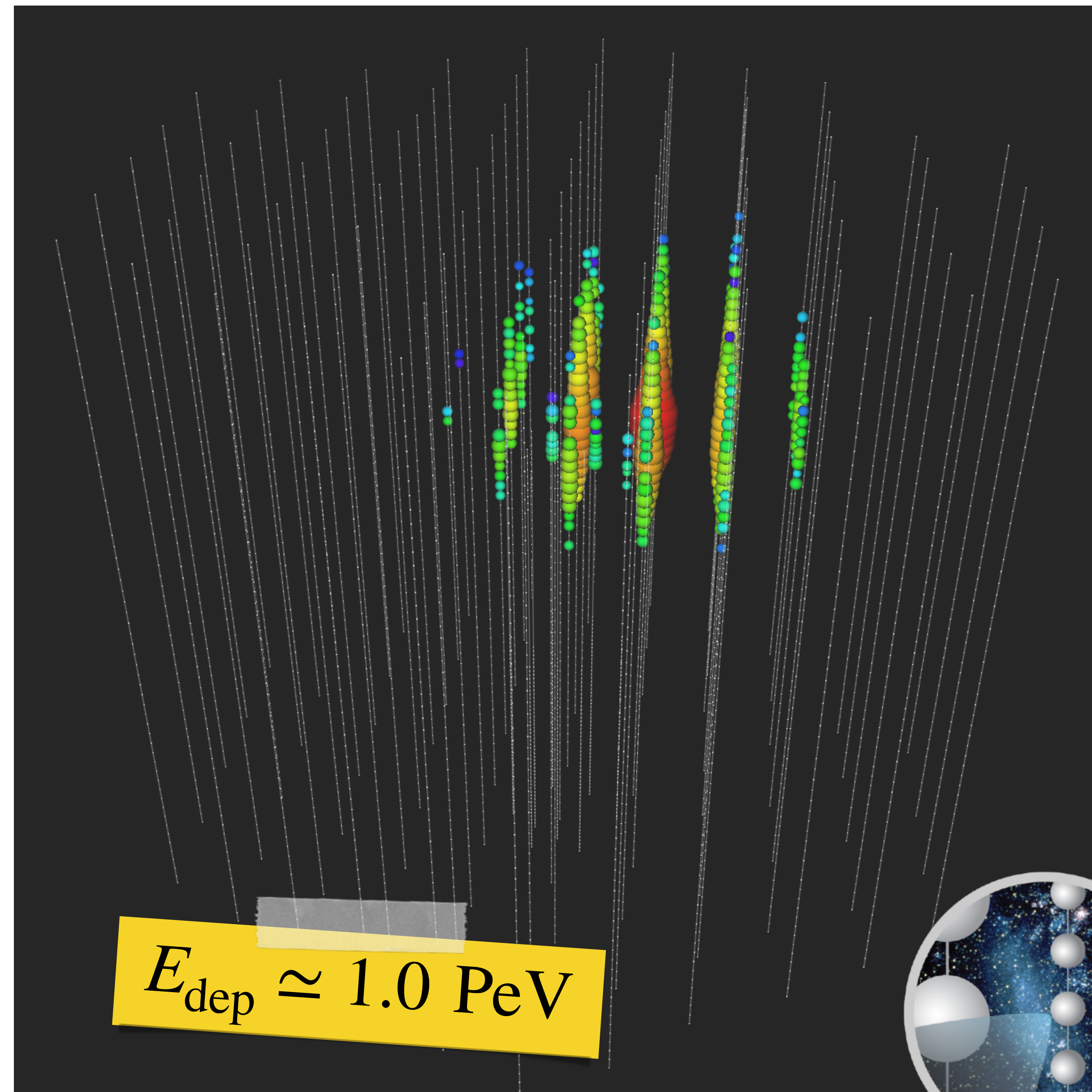
High-Energy Neutrinos

First observation of high-energy astrophysical neutrinos by IceCube in 2013.

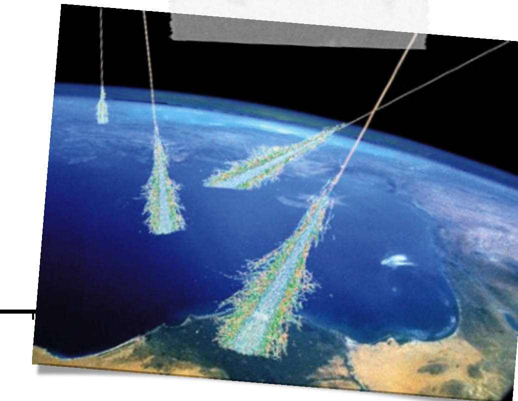
"track event" (*e.g.* ν_μ CC interactions)

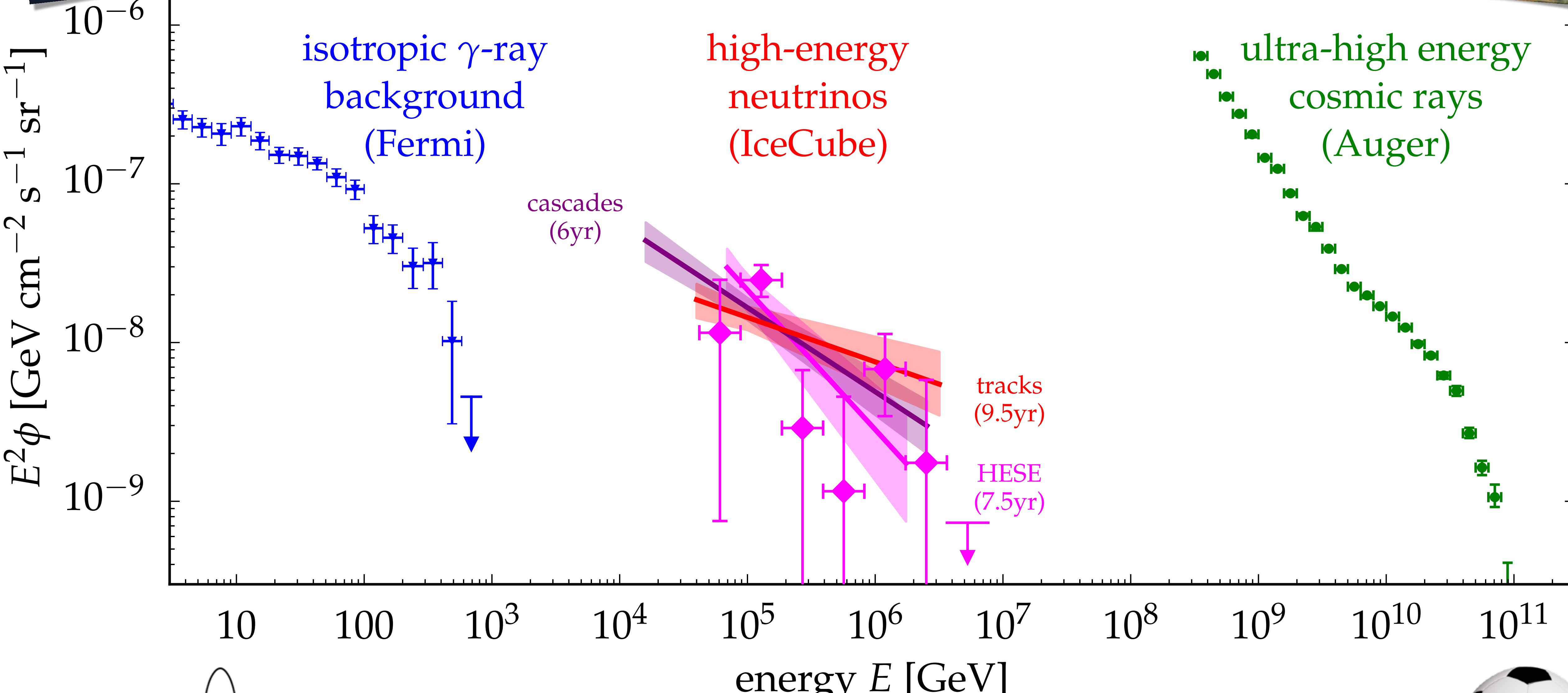


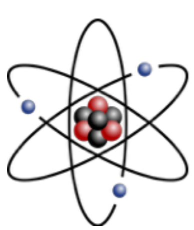
"cascade event" (*e.g.* NC interactions)



(colours indicate arrival time of Cherenkov photons from **early** to **late**)

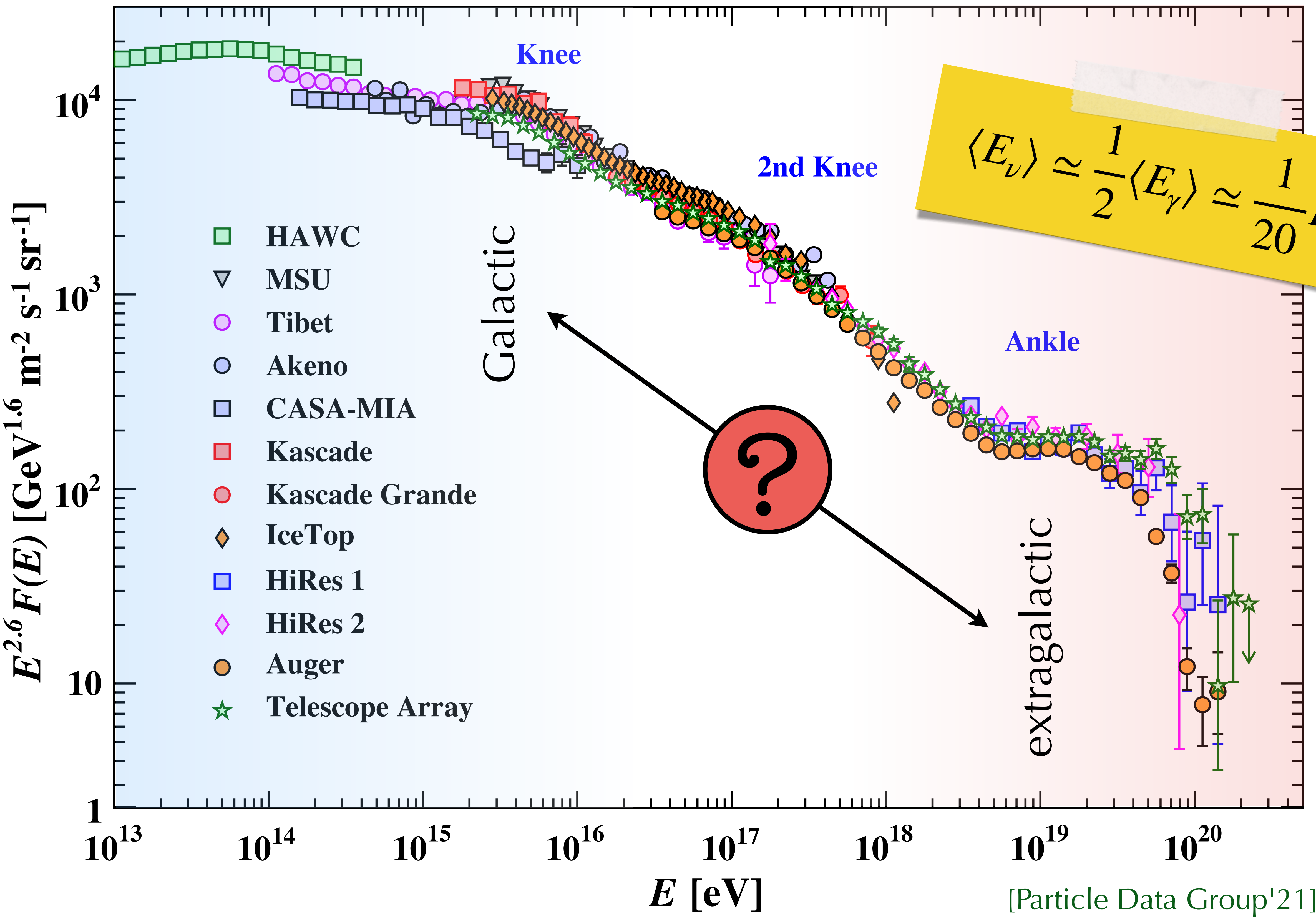






[IceCube, PRL 125 (2020) 12; PoS (ICRC2019) 1017; arXiv:2011.03545]

Very-High Energy Cosmic Rays

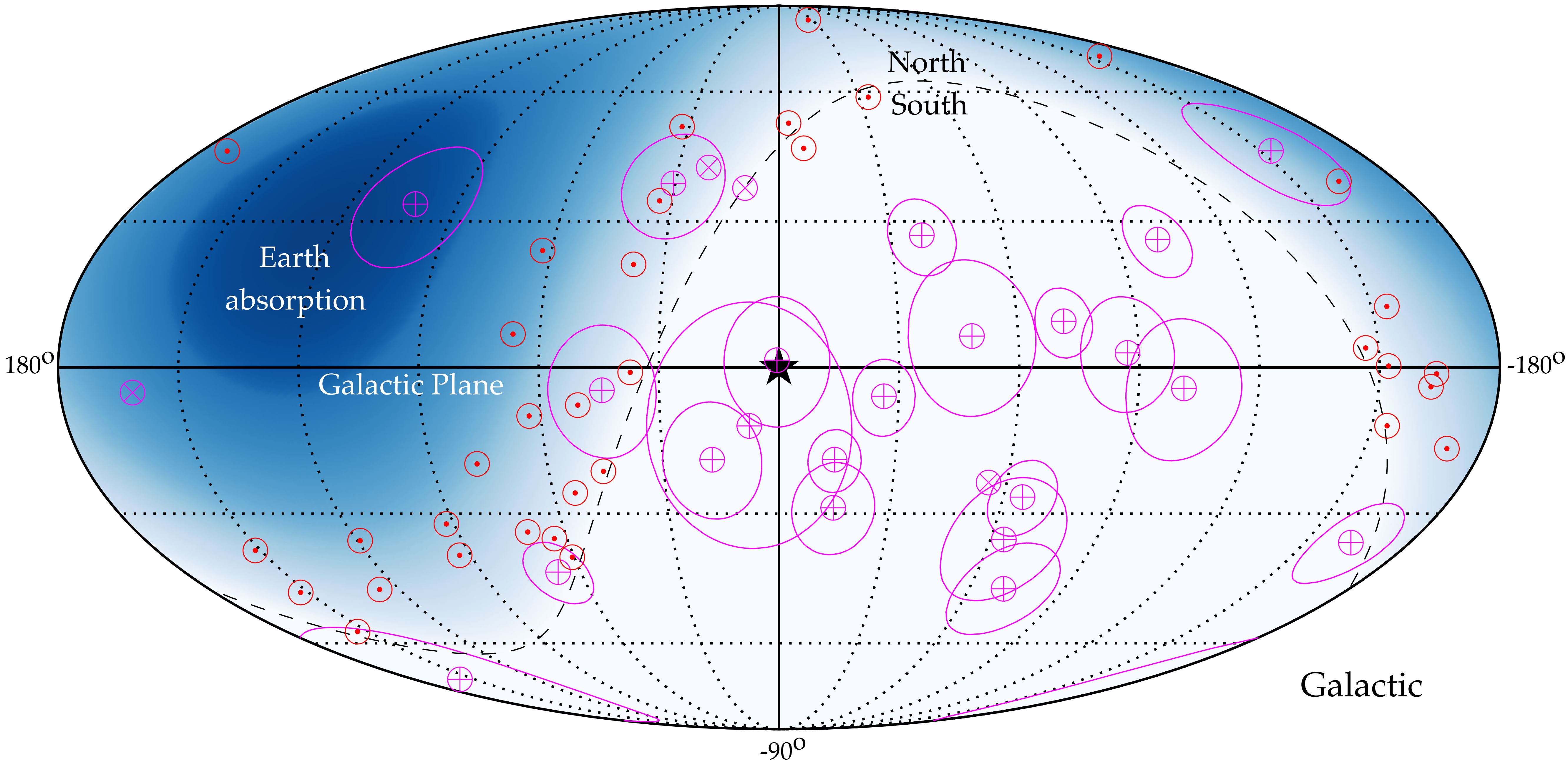


$$\langle E_\nu \rangle \simeq \frac{1}{2}\langle E_\gamma \rangle \simeq \frac{1}{20} E_N$$

[Particle Data Group'21]

Status of Neutrino Astronomy

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



No significant steady or transient emission from known Galactic or extragalactic high-energy sources, but **several interesting candidates.**

Extragalactic Populations

Populations of extragalactic neutrino sources visible as

individual sources

and by

combined isotropic emission.

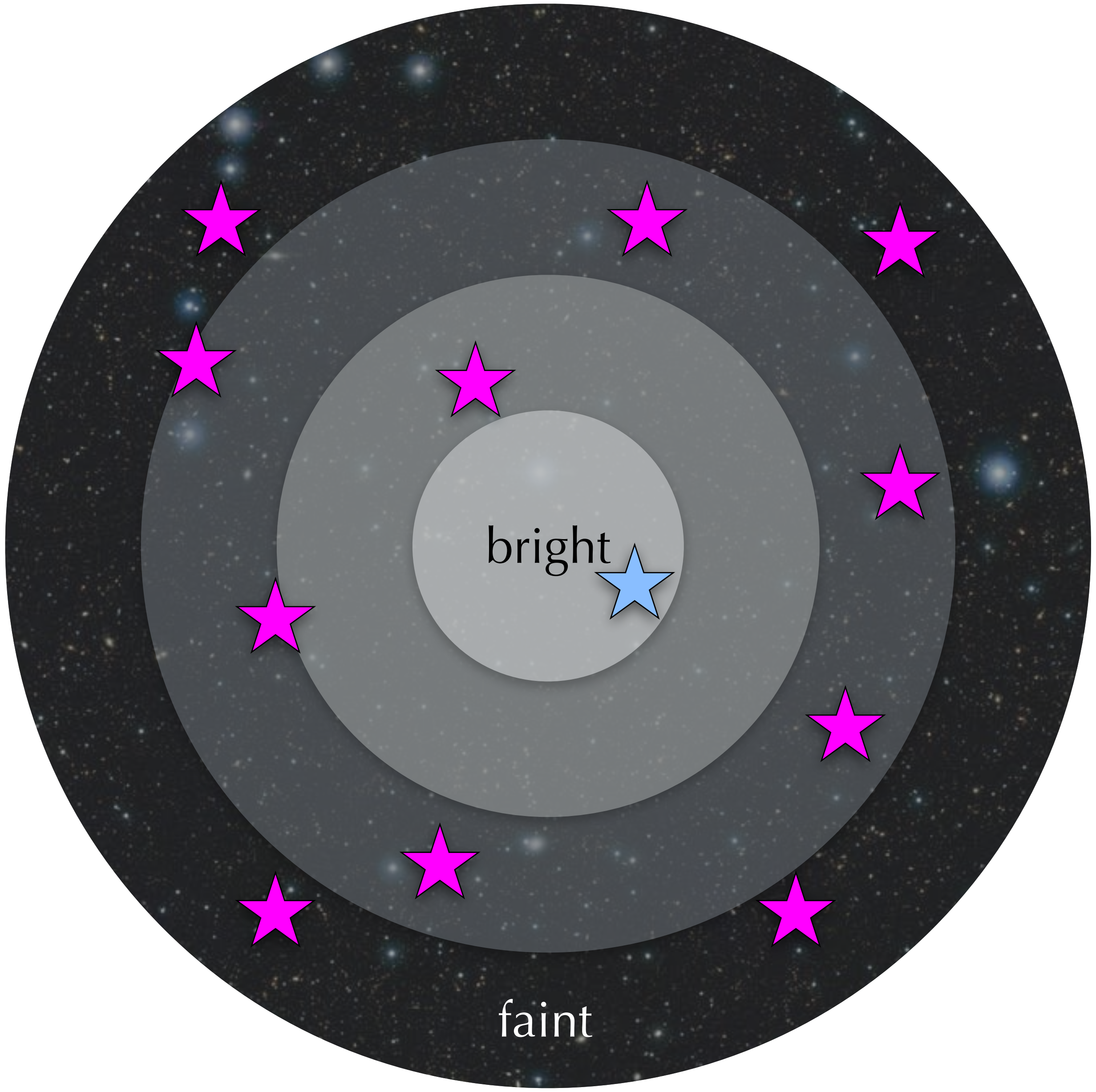
The relative contribution can be parametrized (*to first order*) by the average

local source density $\rho_{\rm eff}$

and

source luminosity L_ν

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



Hubble horizon

Extragalactic Populations

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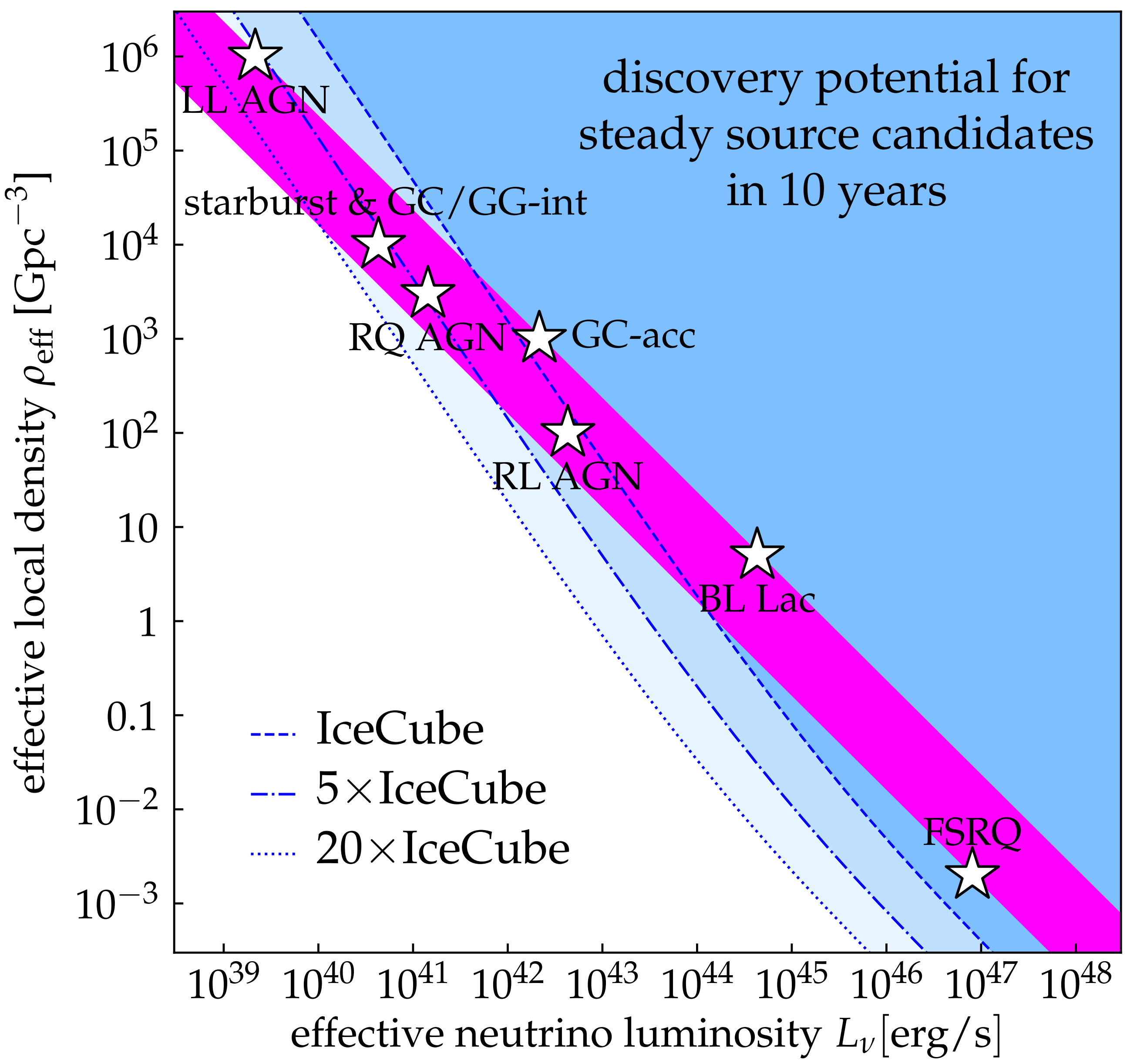
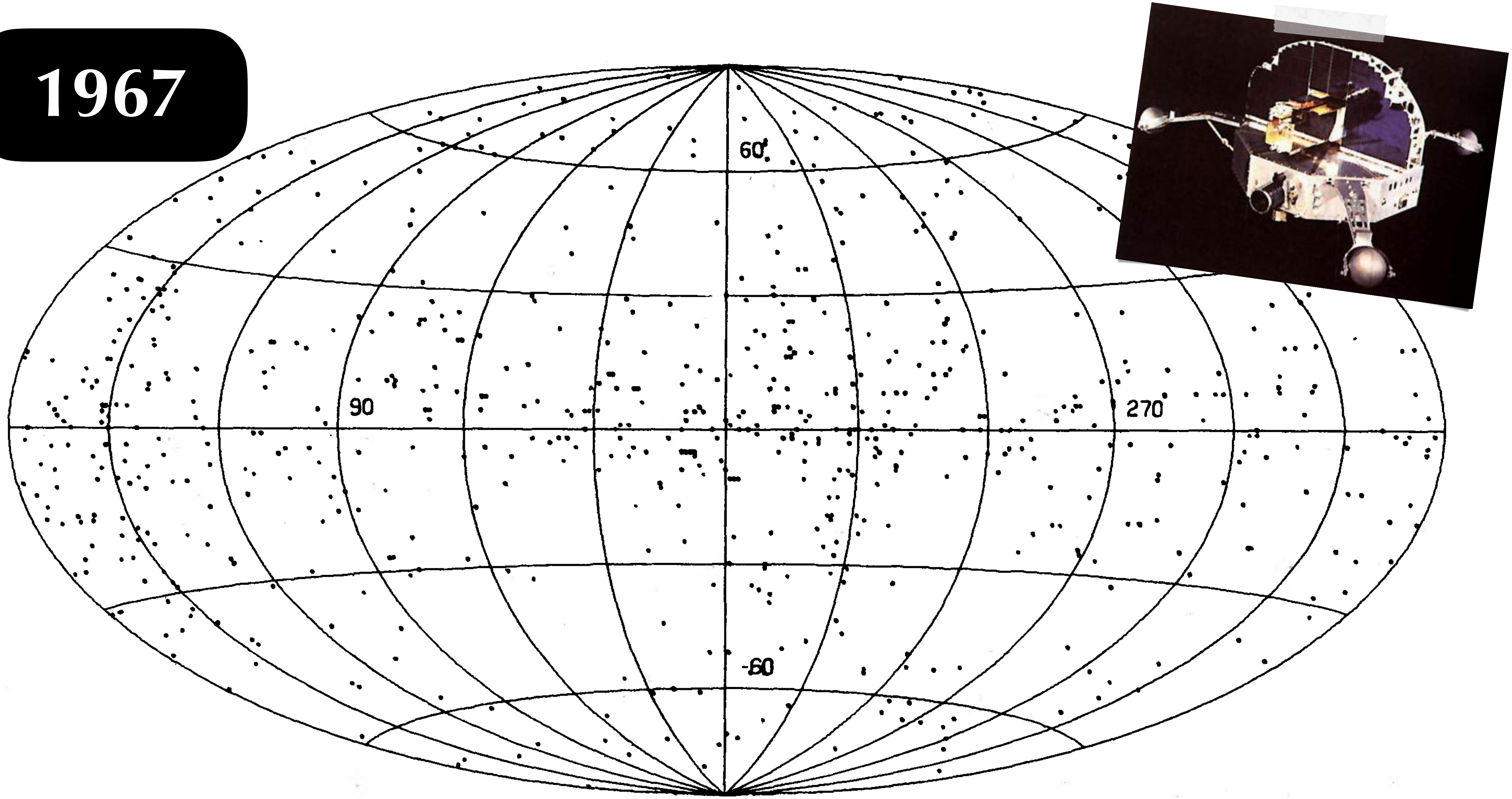


[Ackermann, MA, Anchordoqui, Bustamante *et al.*'19]
[see also Murase & Waxman'16]

Status of Neutrino Astronomy

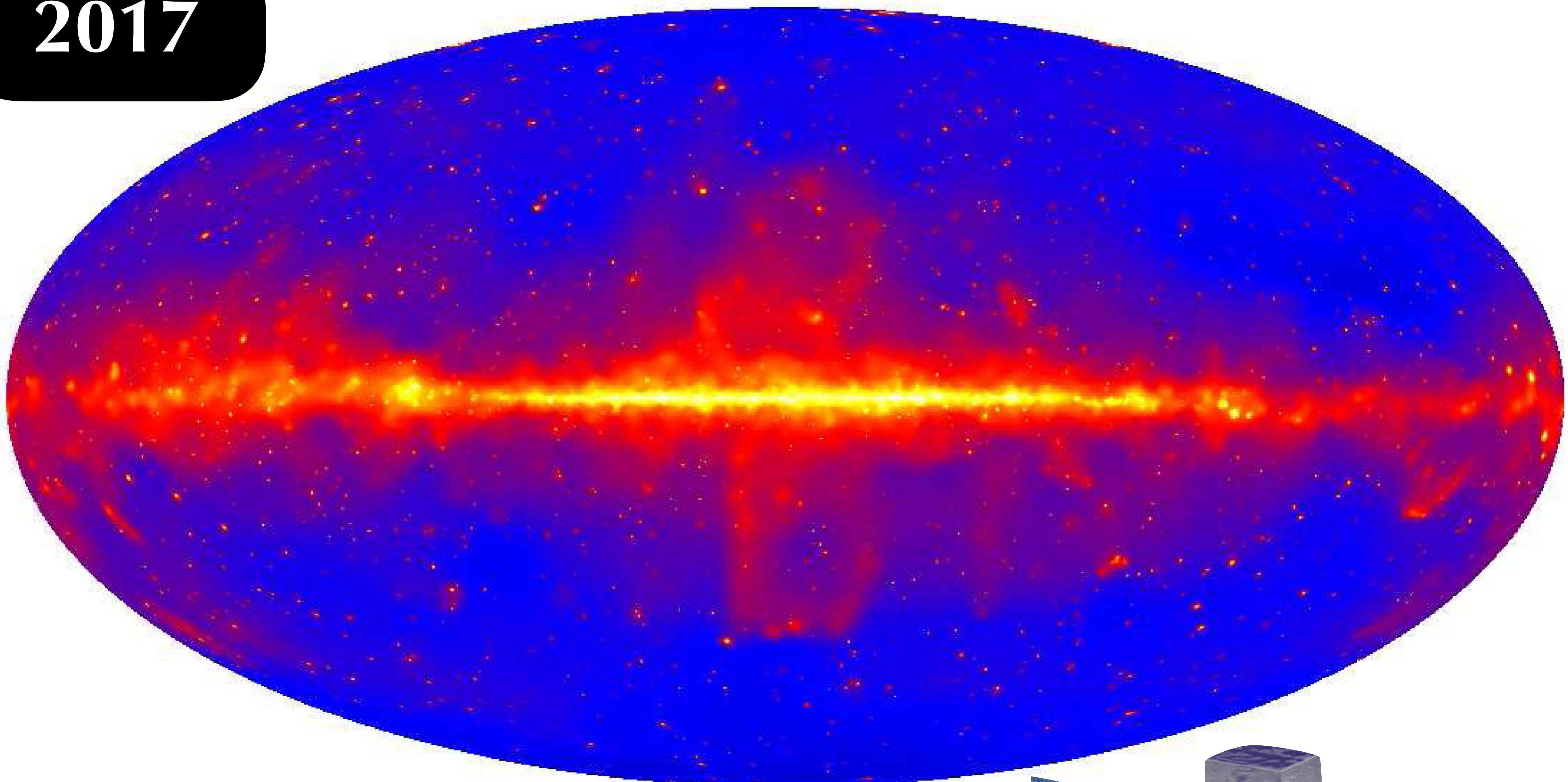
1967



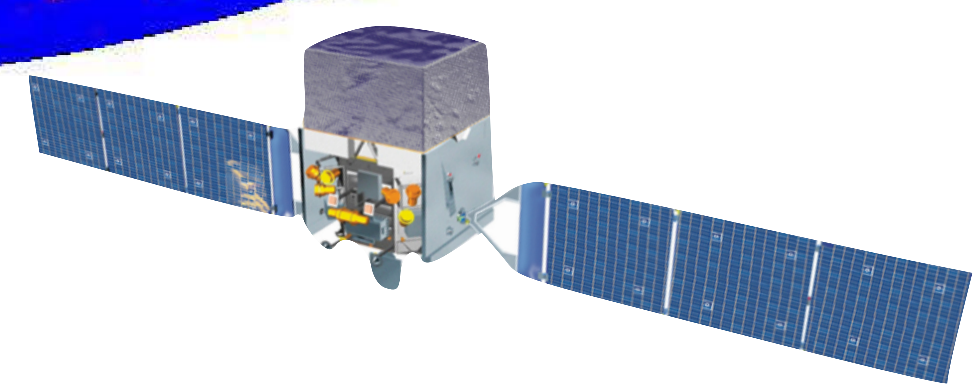
Orbiting Solar Observatory (OSO-3) (Clark & Kraushaar'67)

Status of Neutrino Astronomy

2017



Fermi-LAT gamma-ray count map



Galactic Cosmic Rays

- *Standard paradigm*: Galactic CRs accelerated in supernova remnants
- sufficient power: $\sim 10^{-3} M_\odot$ per 3 SNe per century

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

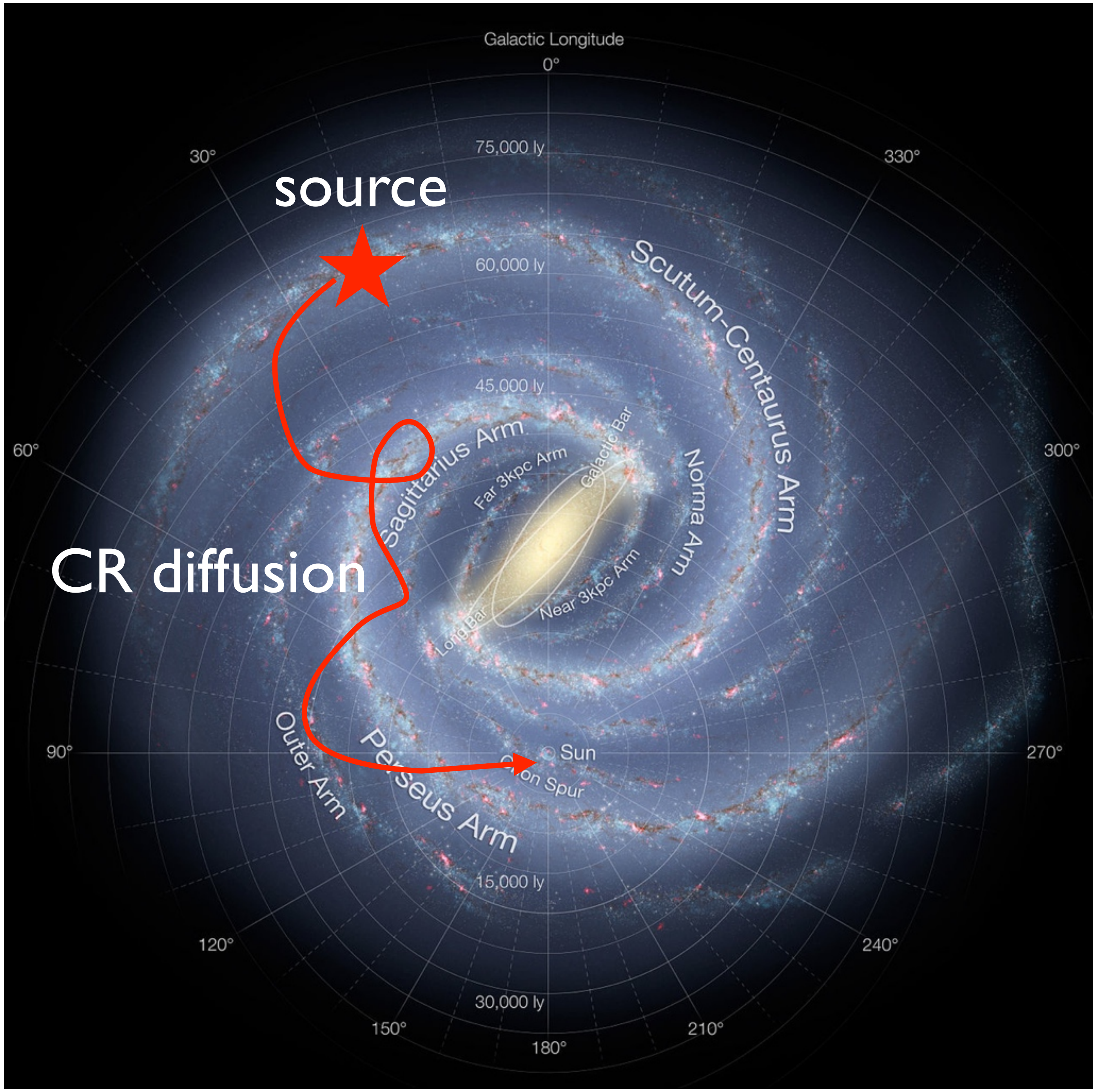
- diffusive shock acceleration:

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

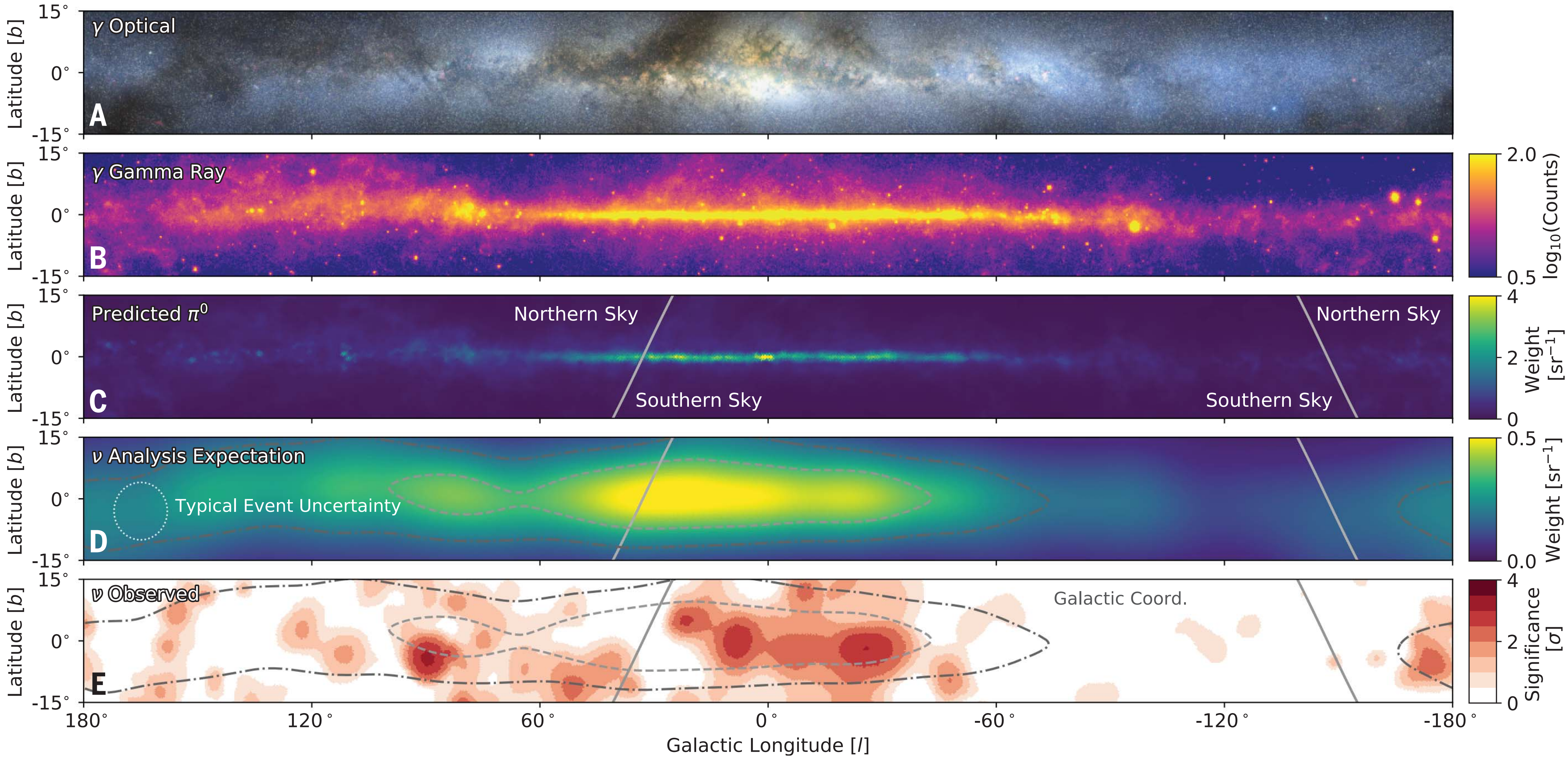
- rigidity-dependent escape from Galaxy:

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

- **hadronic γ & ν emission from interaction with ISM**



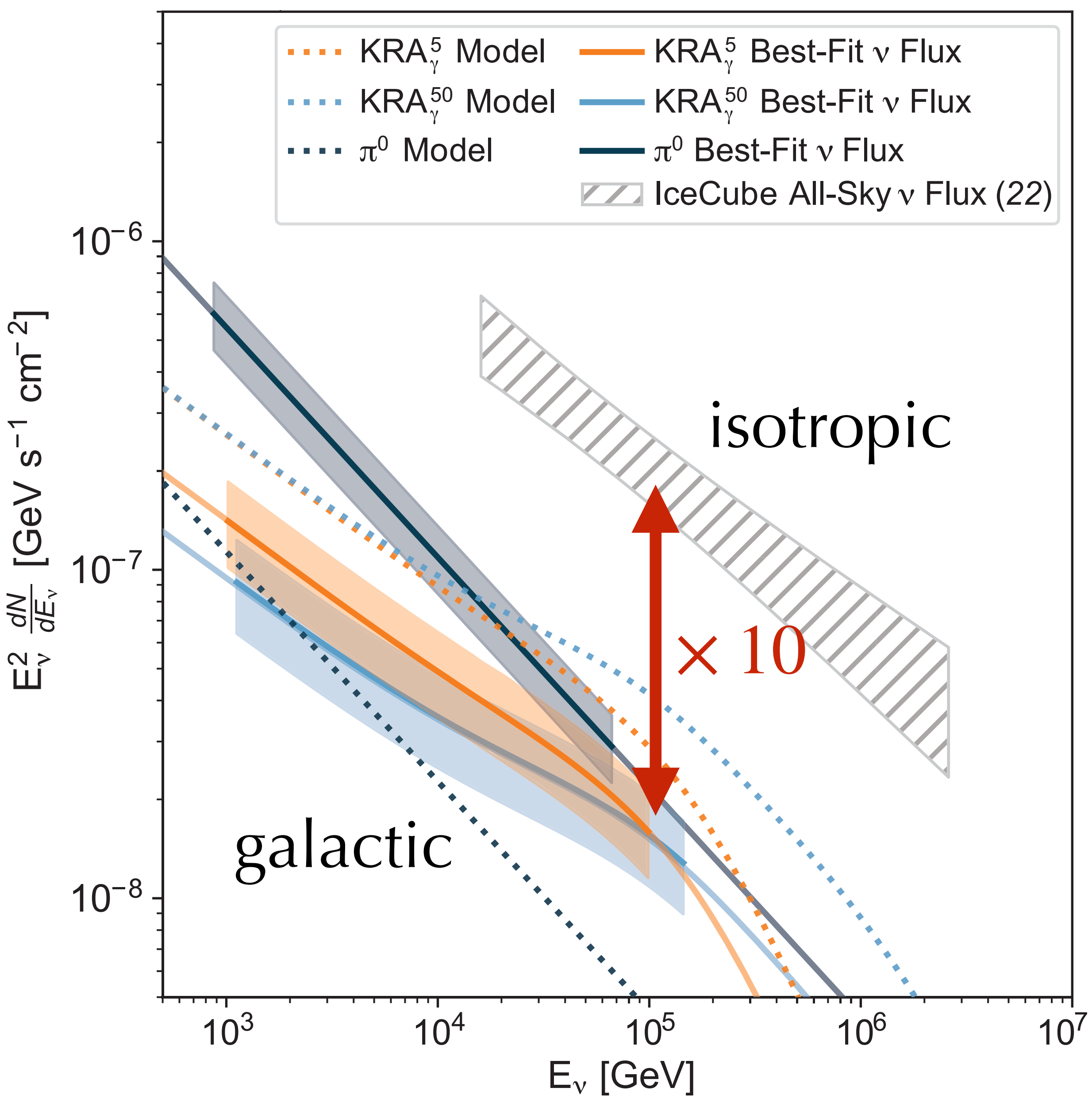
Galactic diffuse ν emission at 4.5σ based on template analysis.



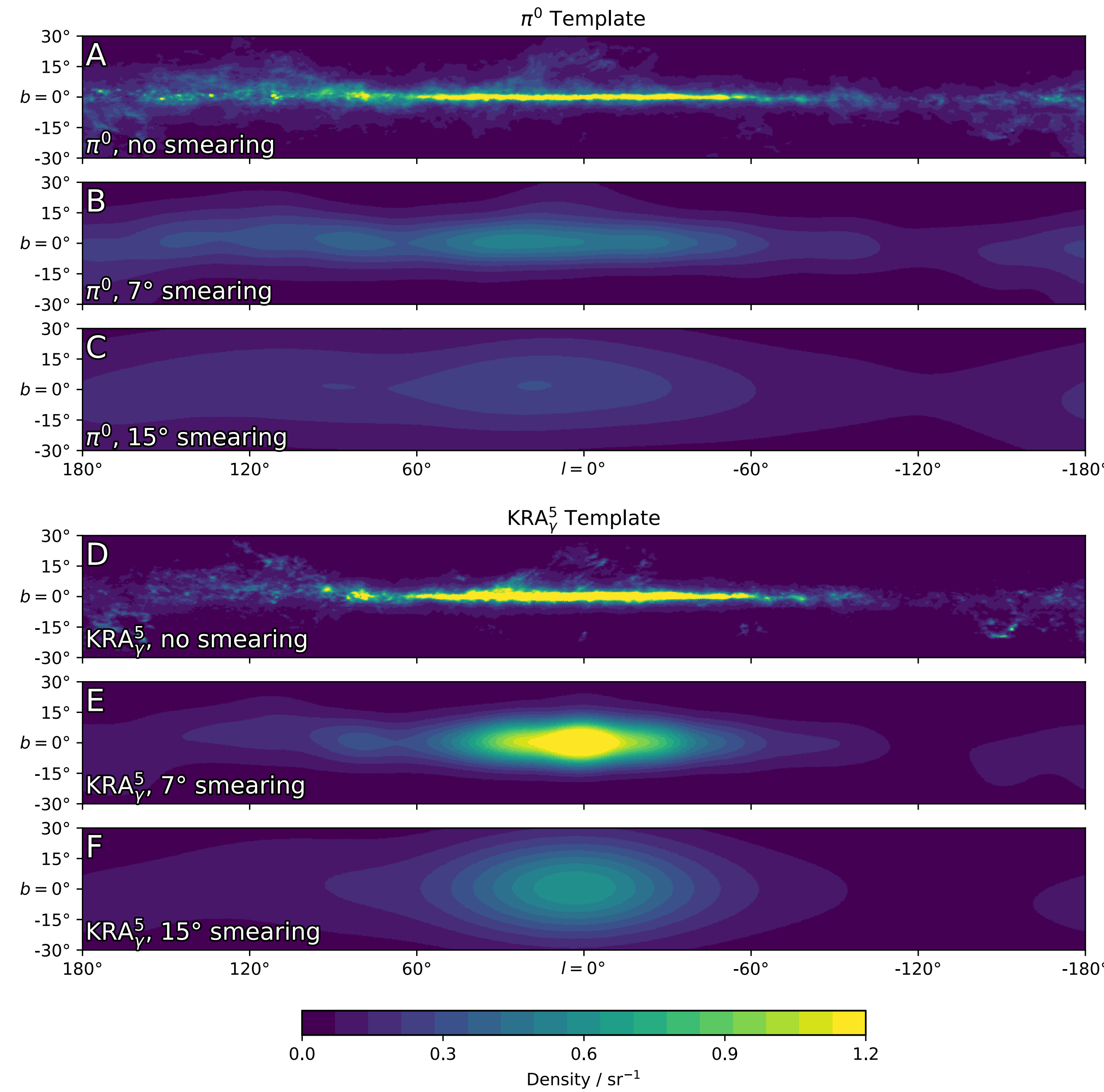
[IceCube **Science** 380 (2023)]

Galactic Neutrino Emission

Best-fit normalization of spectra



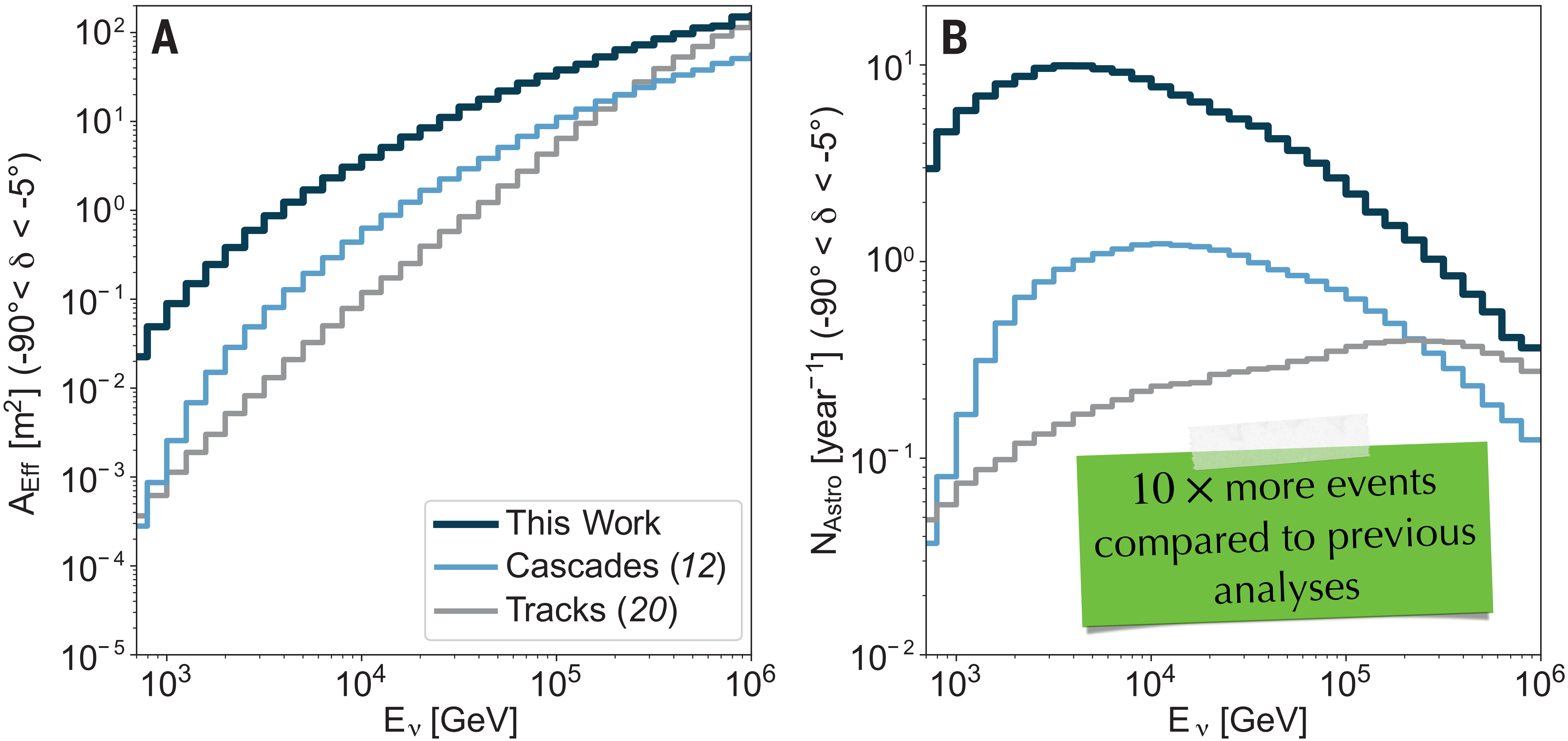
Templates with different resolution



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

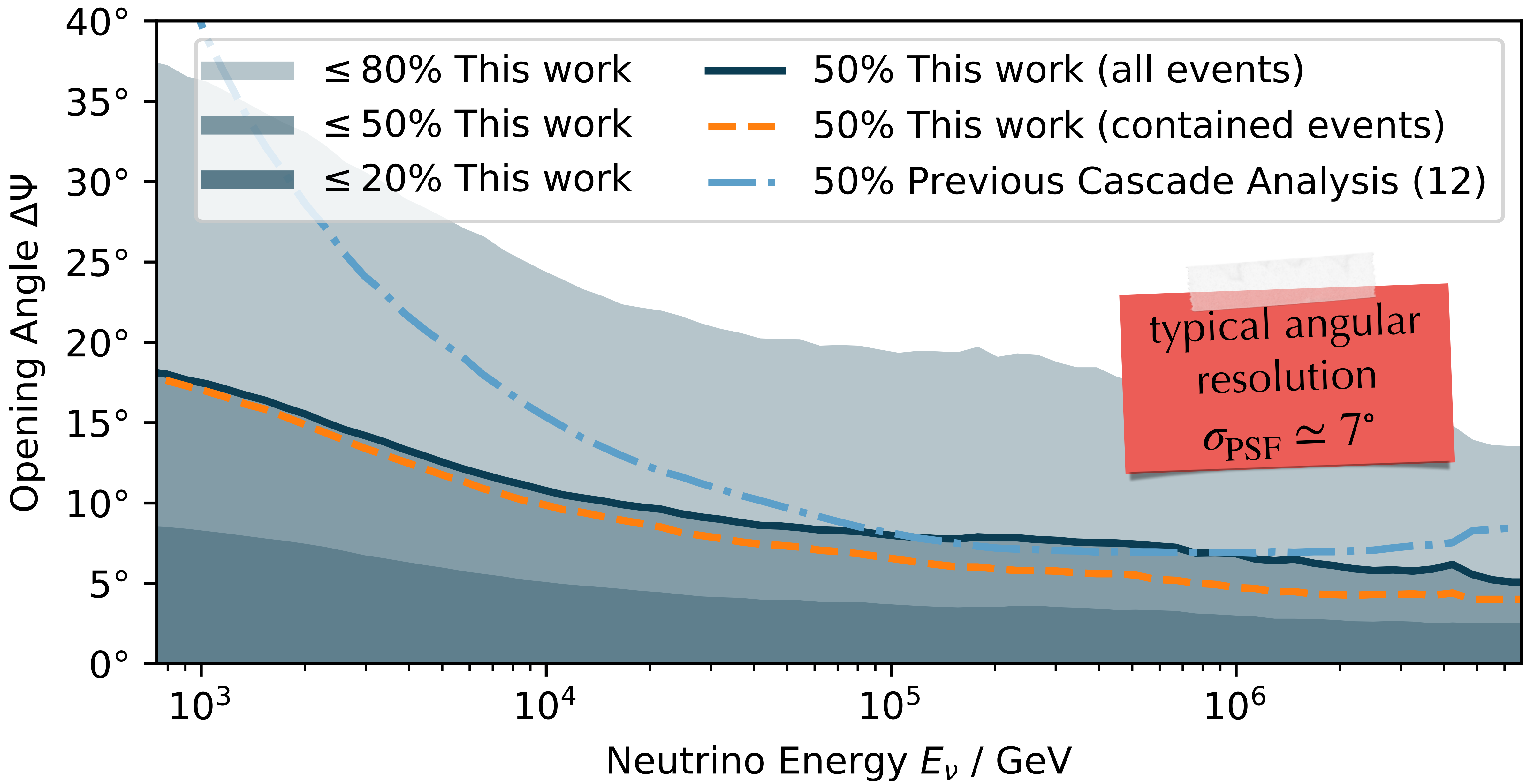
Analysis Sample

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



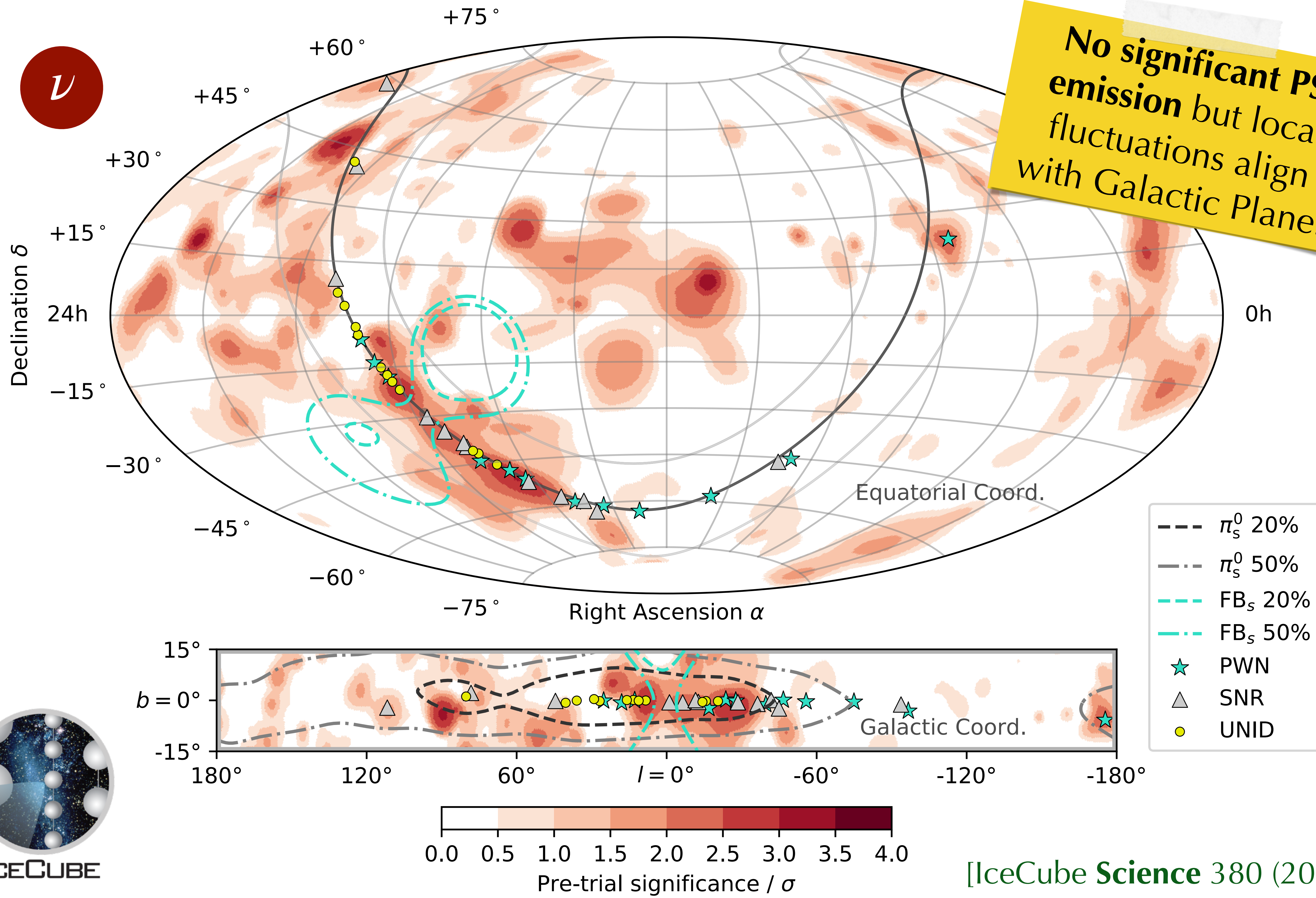
[IceCube **Science** 380 (2023)]

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



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

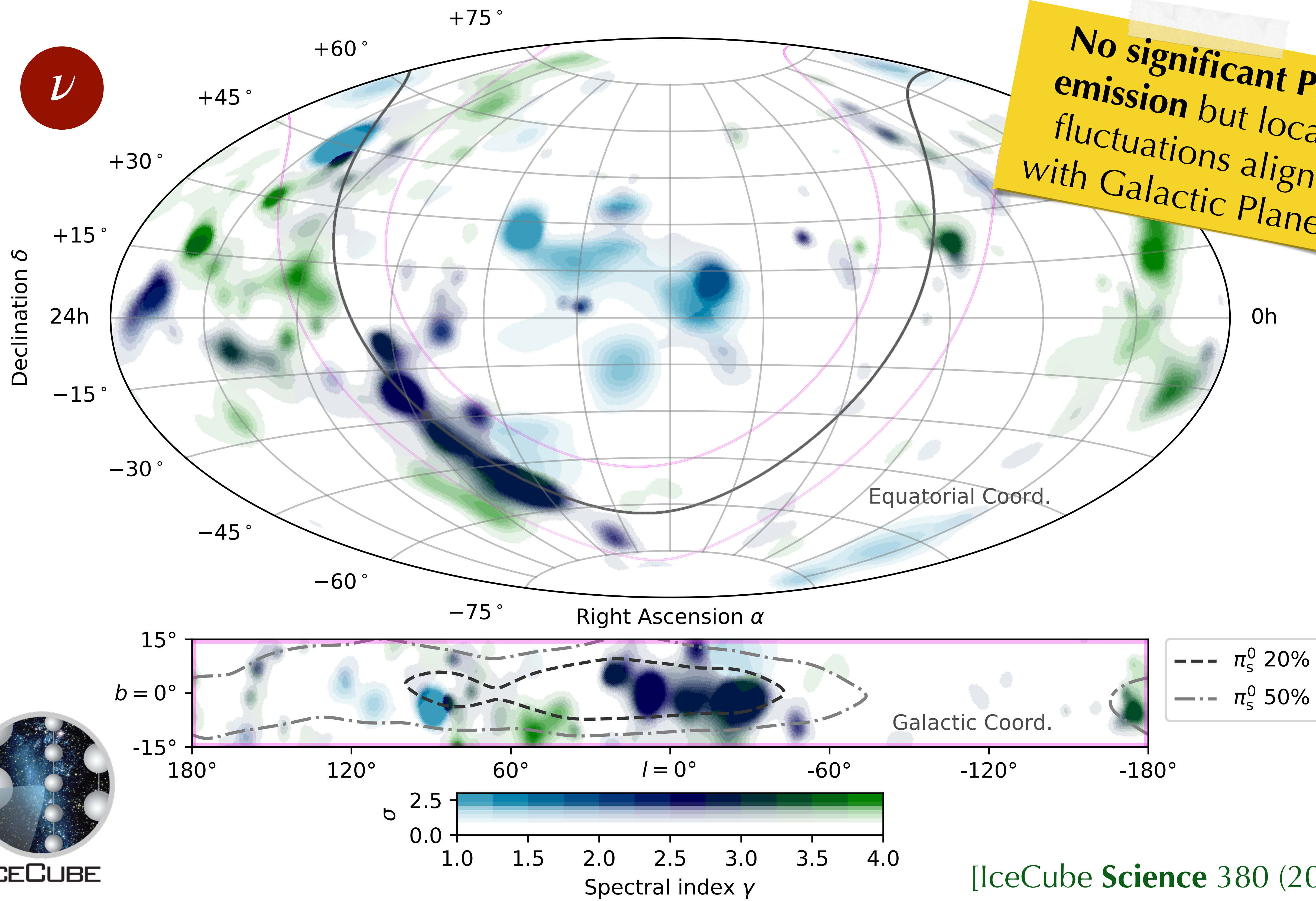
Point-Source Significance Map



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

[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)	

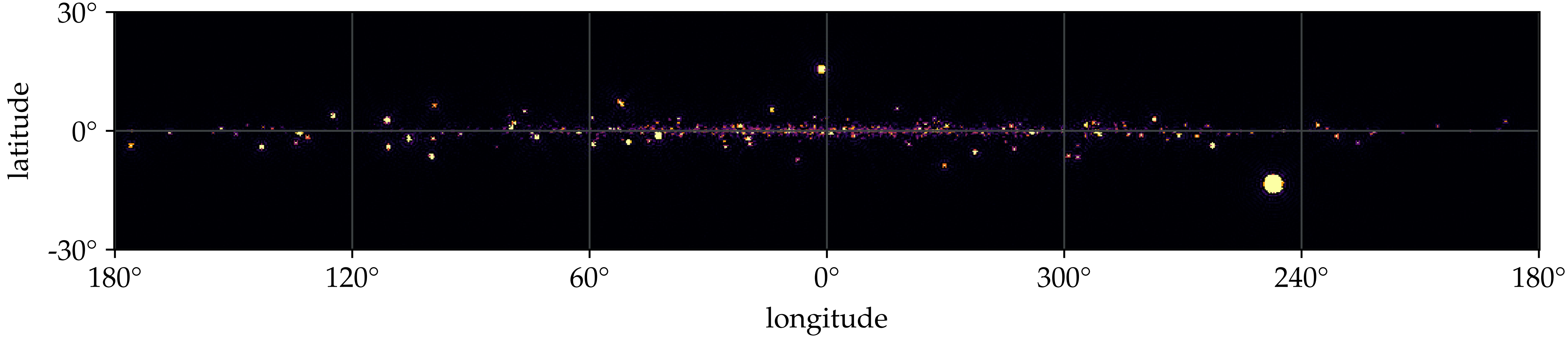
*Significance values that are consistent with the diffuse Galactic plane template search results.

post-trial p-value
template search:
4.5σ

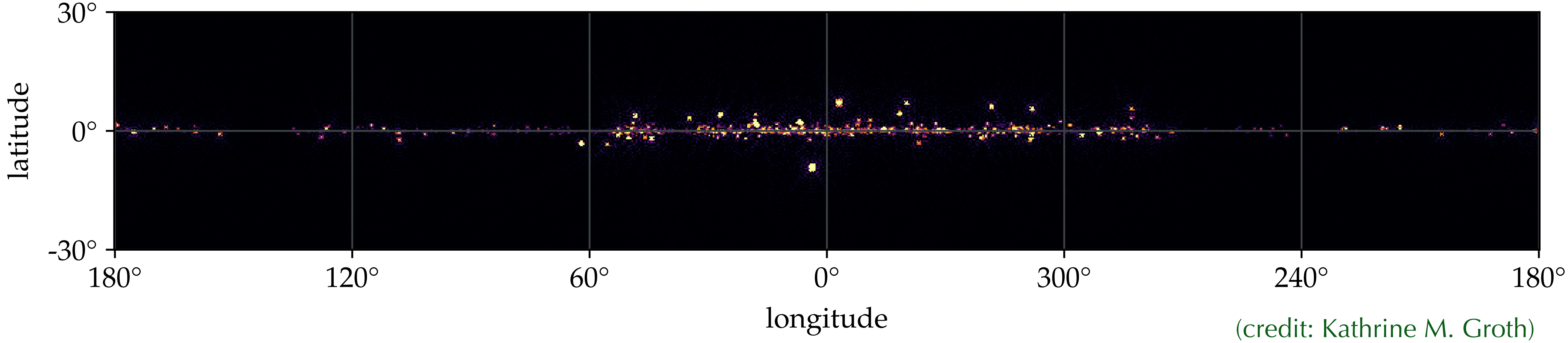
[IceCube **Science** 380 (2023)]

Galactic Neutrino Populations

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



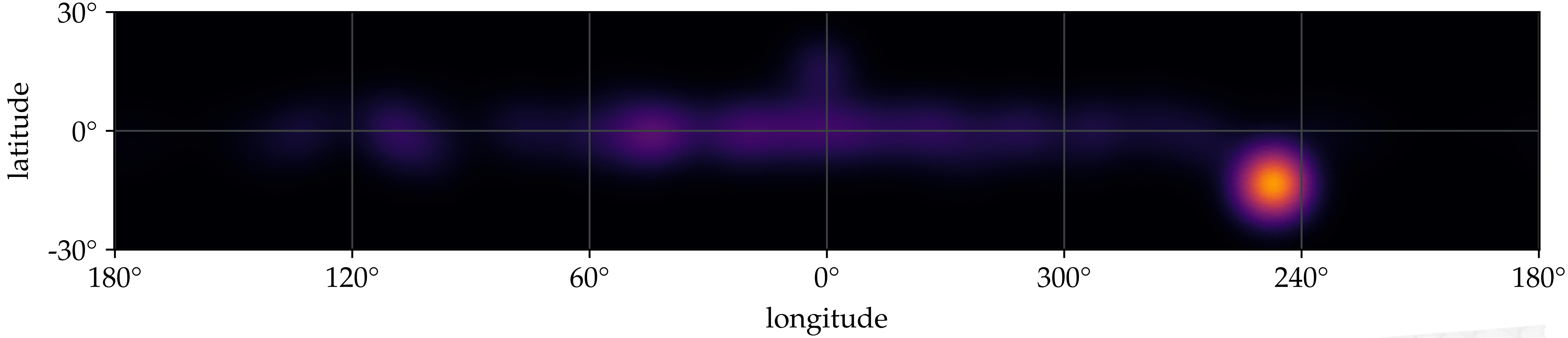
+ modulation with spiral arms



(credit: Kathrine M. Groth)

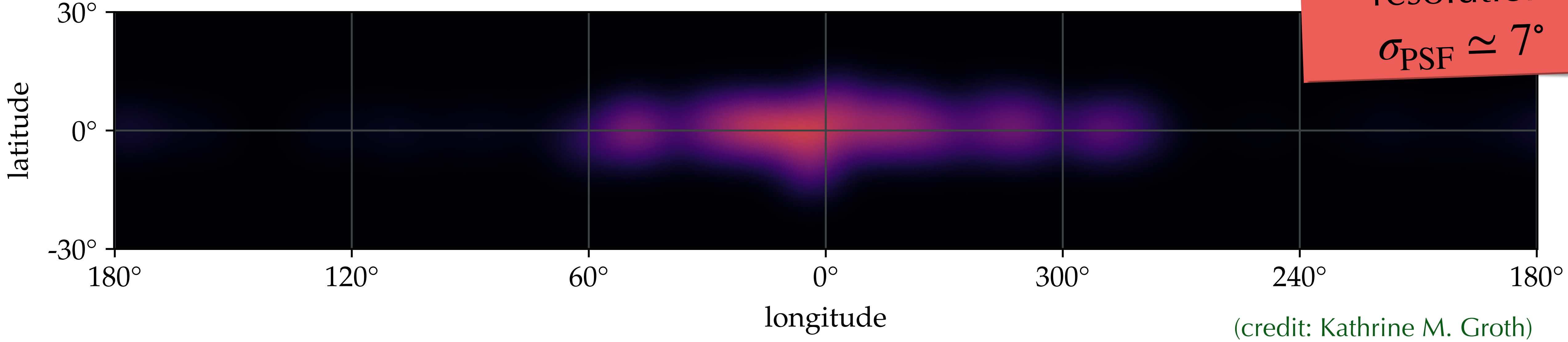
Galactic Neutrino Populations

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



+ modulation with spiral arms

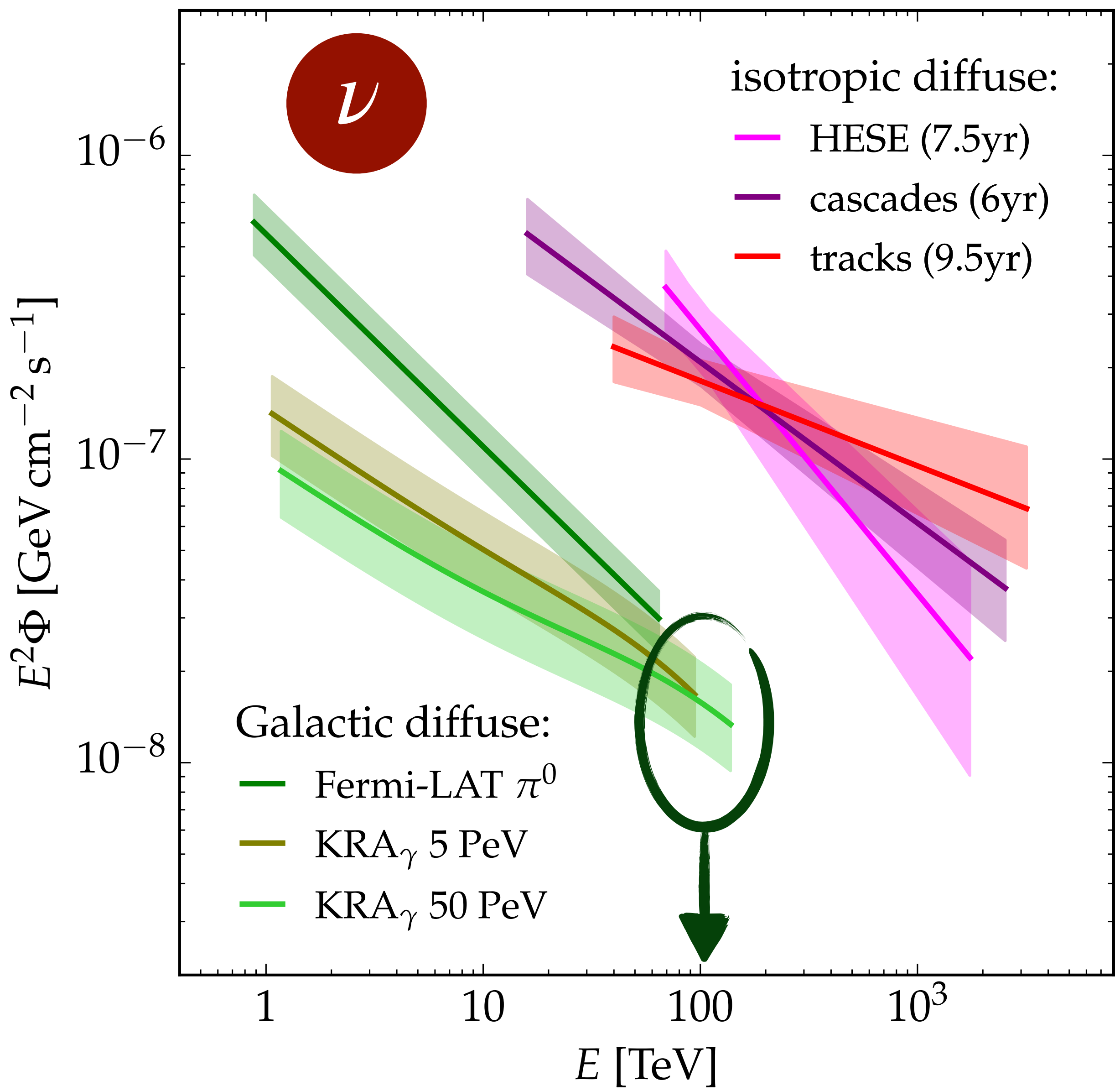
typical angular resolution $\sigma_{\rm PSF} \simeq 7°$

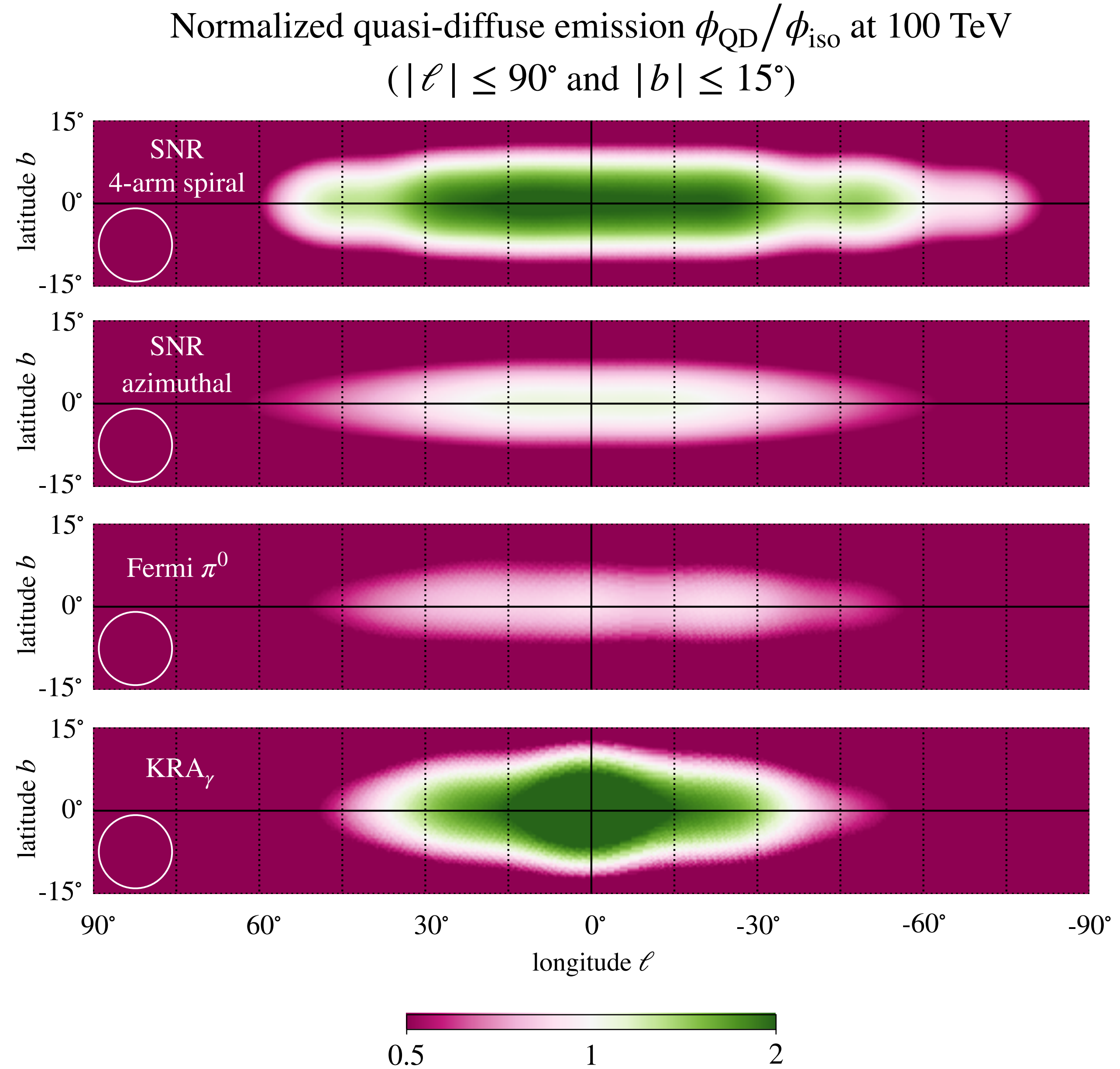


(credit: Kathrine M. Groth)

Hidden Galactic Sources?

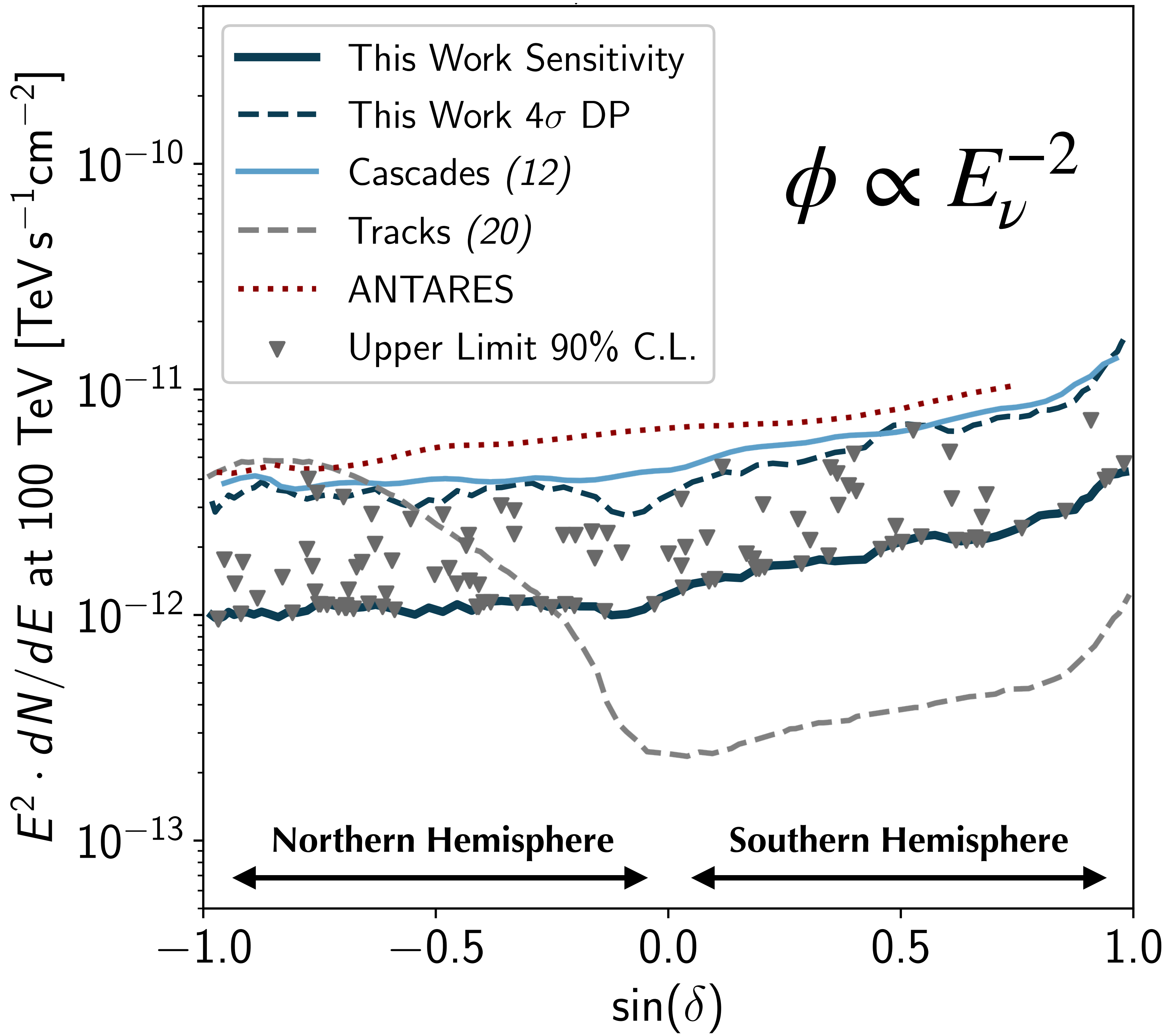
Contribution of neutrino from "freshly" accelerated CRs most likely to dominate at highest observed energy ($\simeq$ 100TeV).





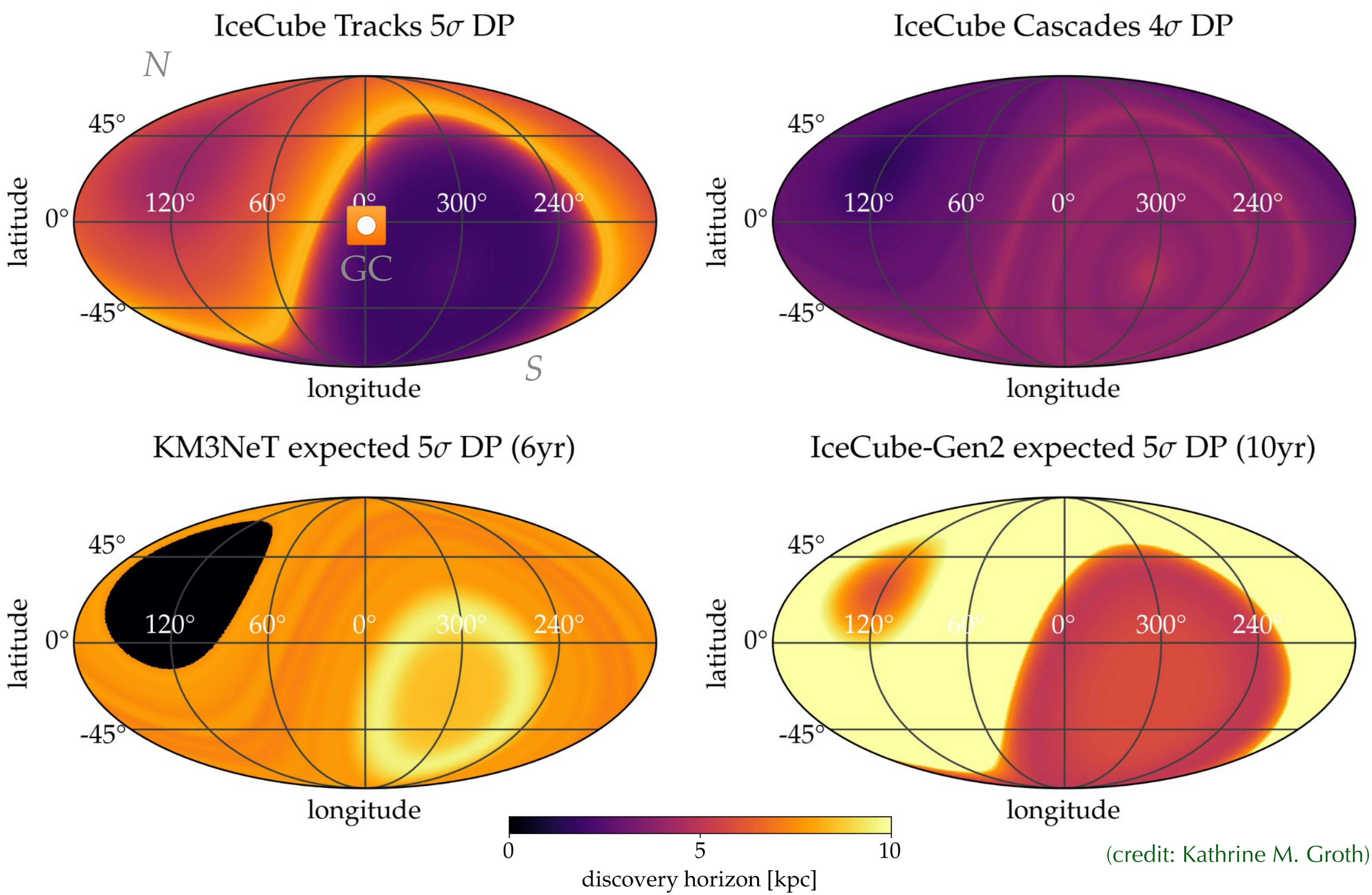
[Ambrosone, Groth, Peretti & MA'23]

Point-Source Sensitivities



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

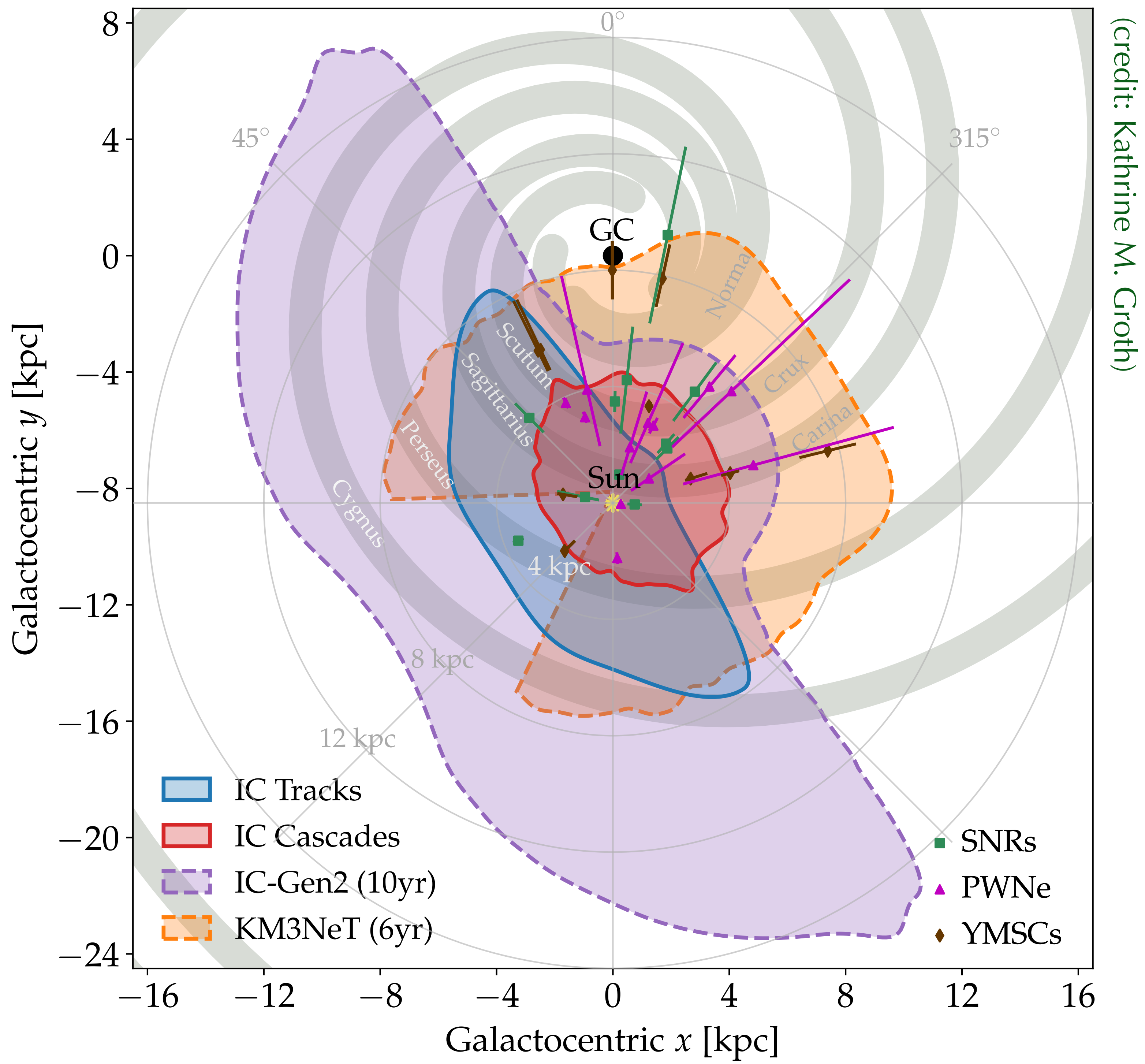
Effective Field of View



(credit: Kathrine M. Groth)

Point-Source Discovery Horizon

Discovery horizon for $L_{100\,\mathrm{TeV}} = 10^{34}$ erg/s $(\Phi \propto E^{-2})$



[Ambrosone, Groth, Peretti & MA'23]

Point Source vs. Quasi-Diffuse Flux

Populations of galactic neutrino sources visible as

individual sources

and by the

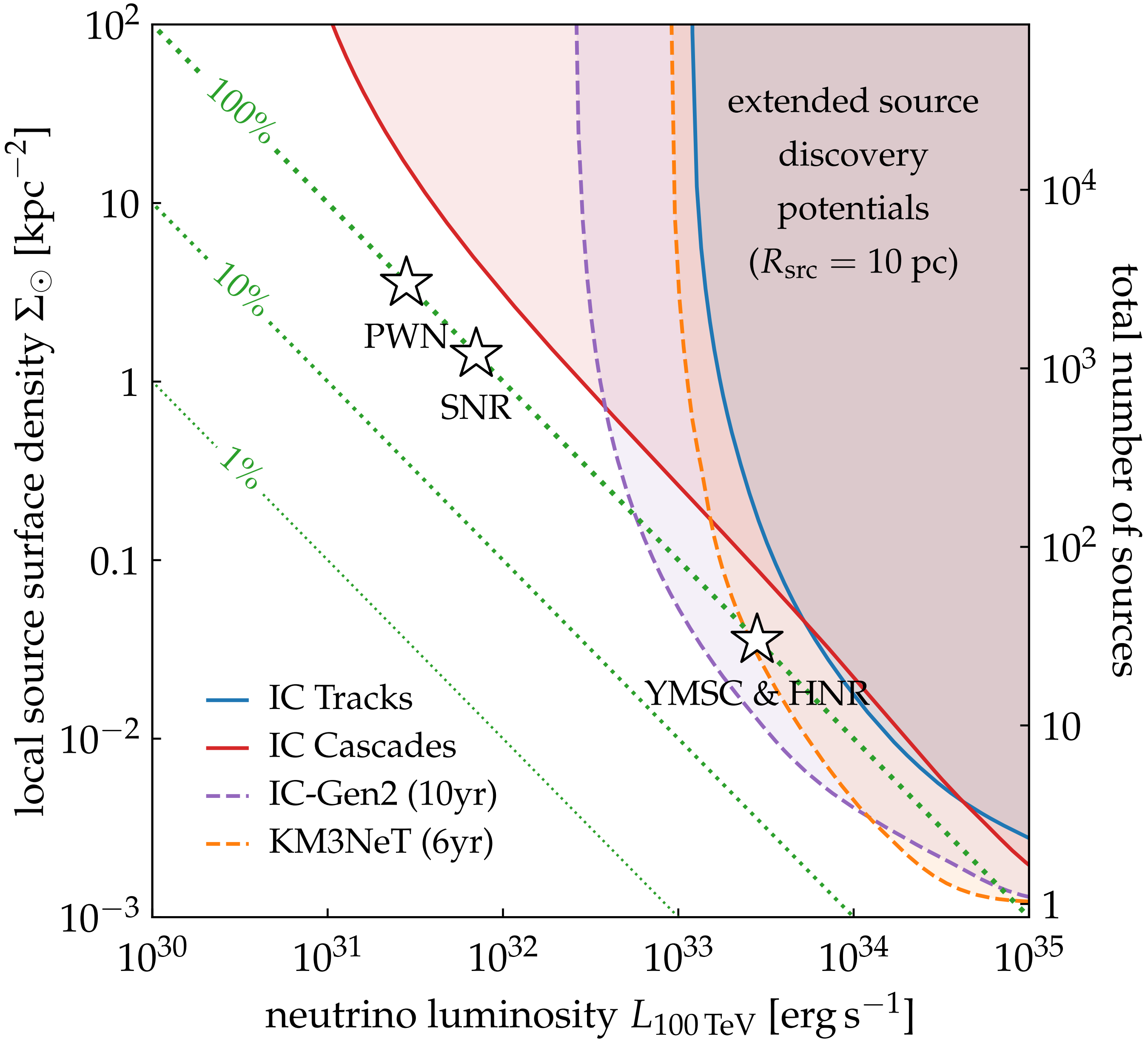
combined isotropic emission.

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

source surface density $\Sigma_\odot$

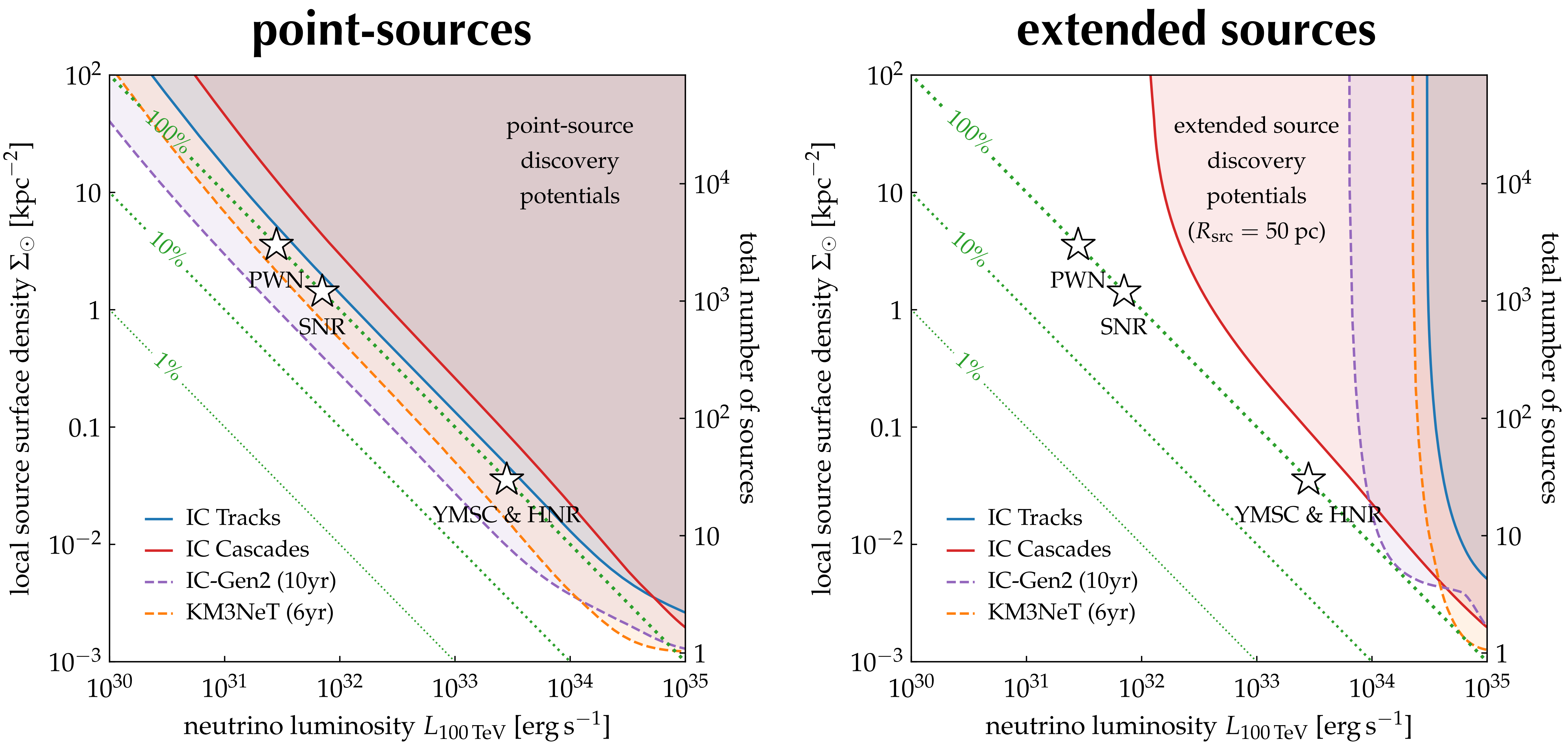
and

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



[Ambrosone, Groth, Peretti & MA'23]

Point Source vs. Quasi-Diffuse Flux

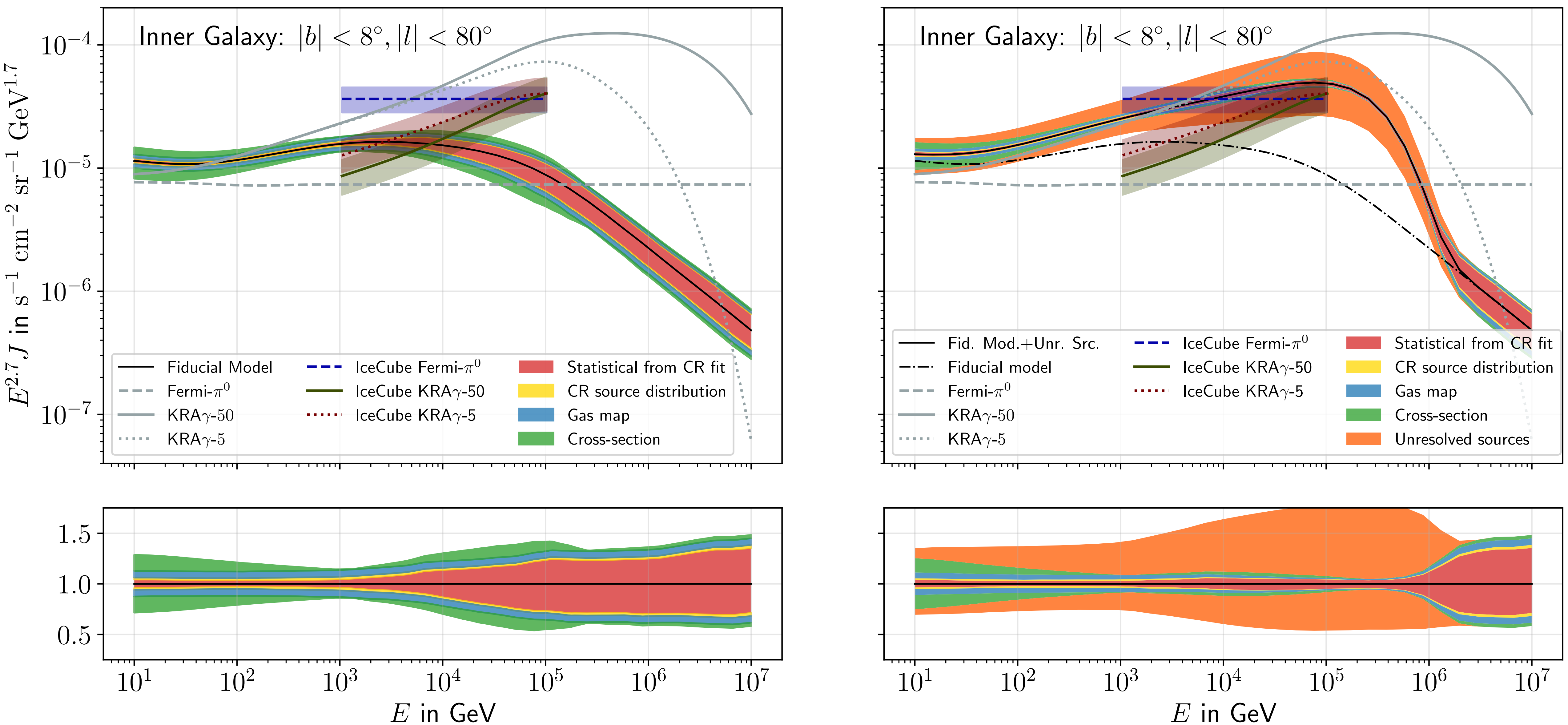


[Ambrosone, Groth, Peretti & MA'23]

sensitivity scaling:

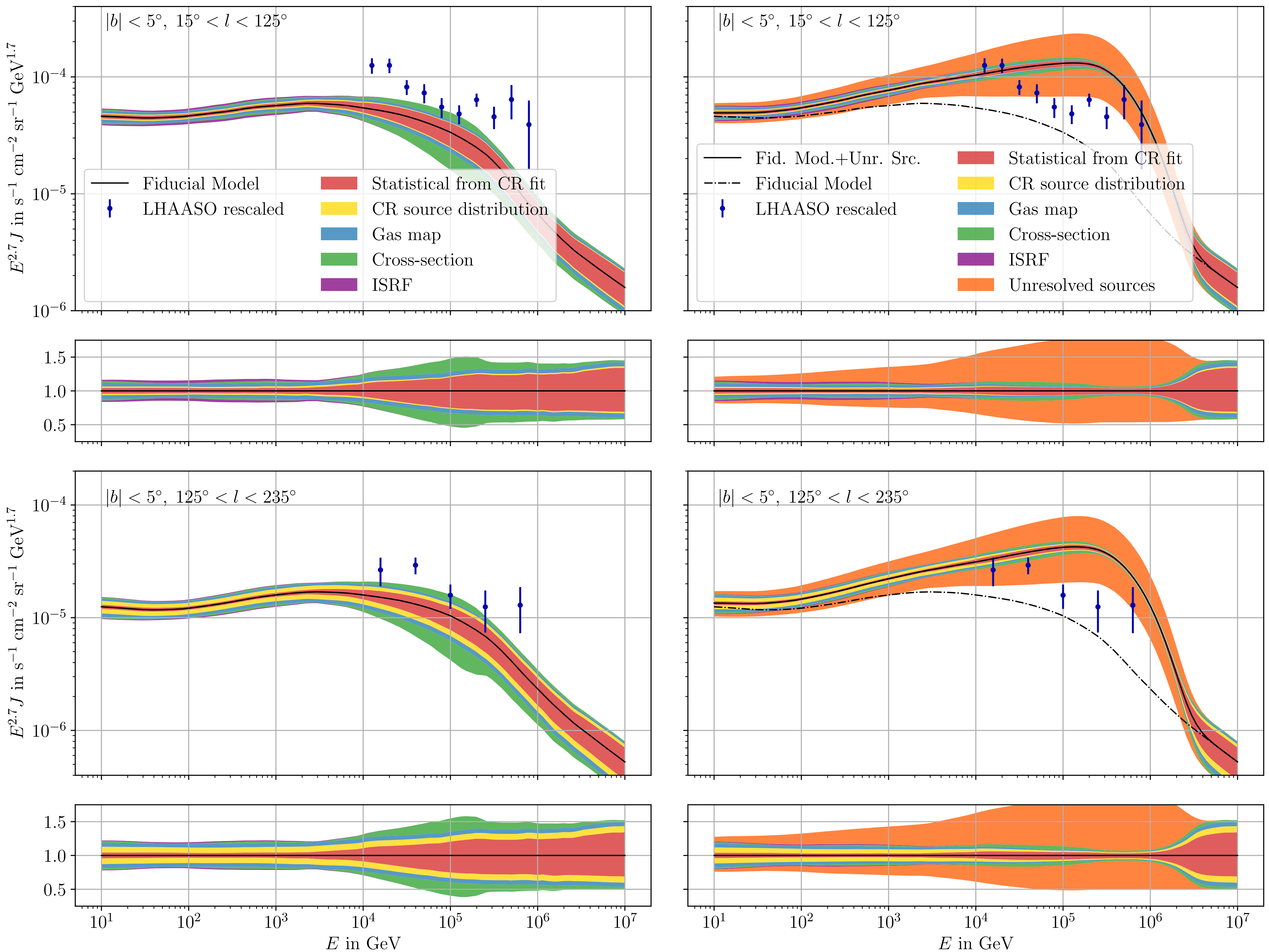
$$\Phi_{\rm DP}(E_\nu, \delta, \sigma_{\rm src}) \simeq \sqrt{\frac{\sigma^2_{\rm PSF} + \sigma^2_{\rm src}}{\sigma^2_{\rm PSF}}}\,\Phi_{\rm DP}(E_\nu, \delta),$$

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



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

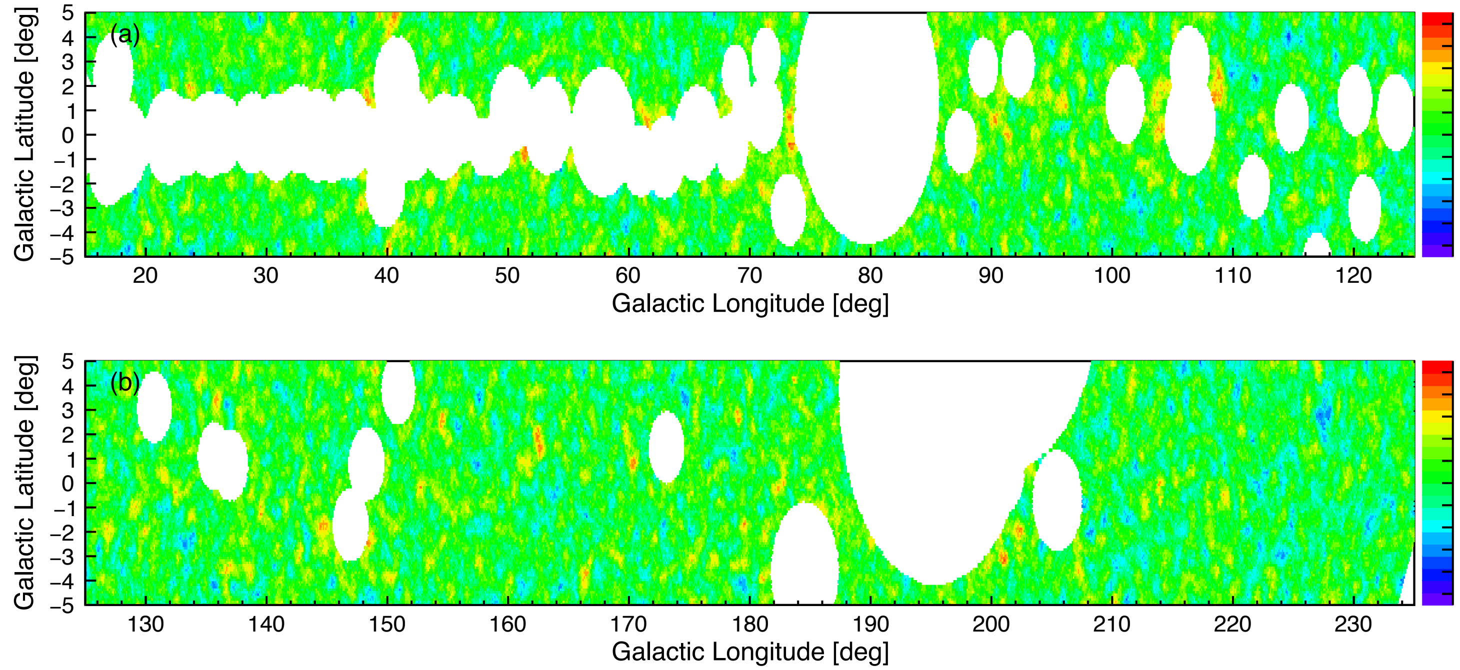
Multi-Messenger Fits



[Schwefer, Mertsch & Wiebusch '23]

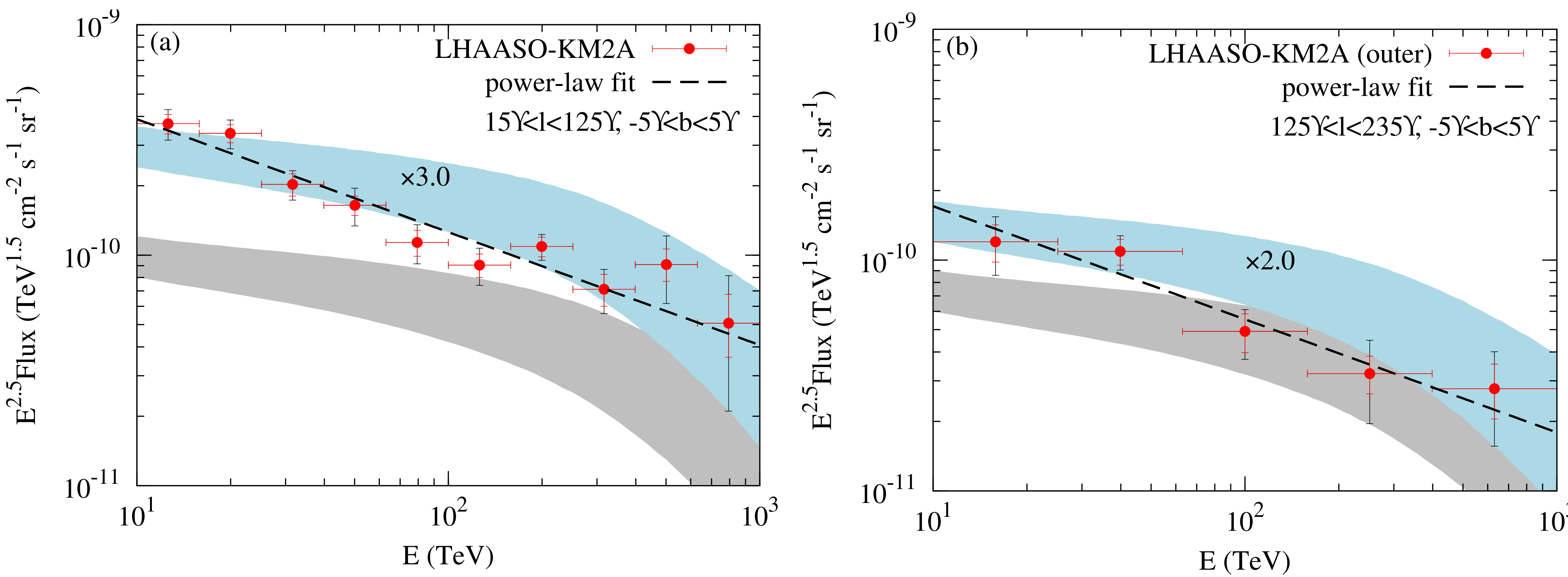
γ

Multi-Messenger Fits



γ

[LHAASO '23]

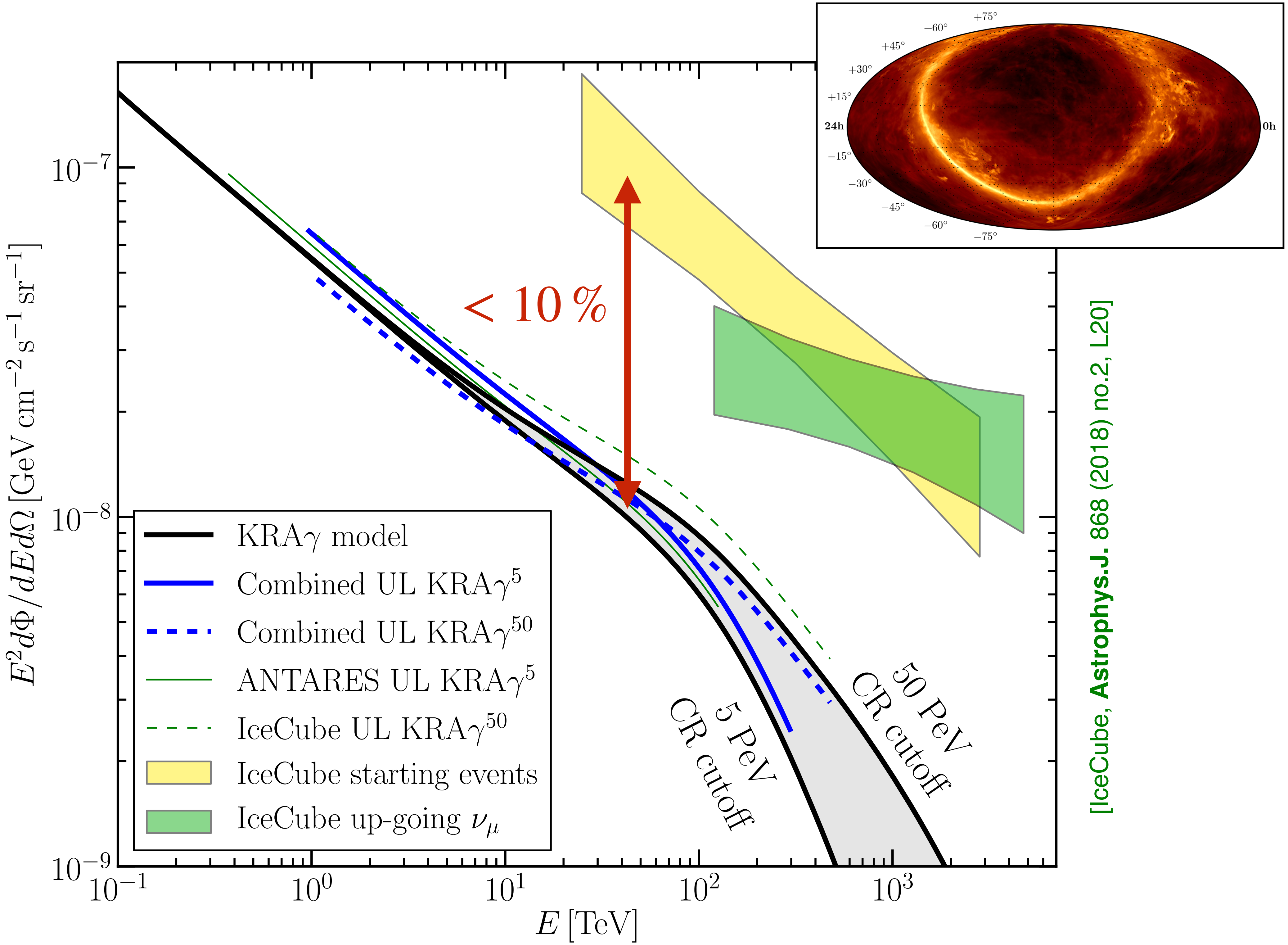


Summary

- **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

Galactic Neutrino Emission

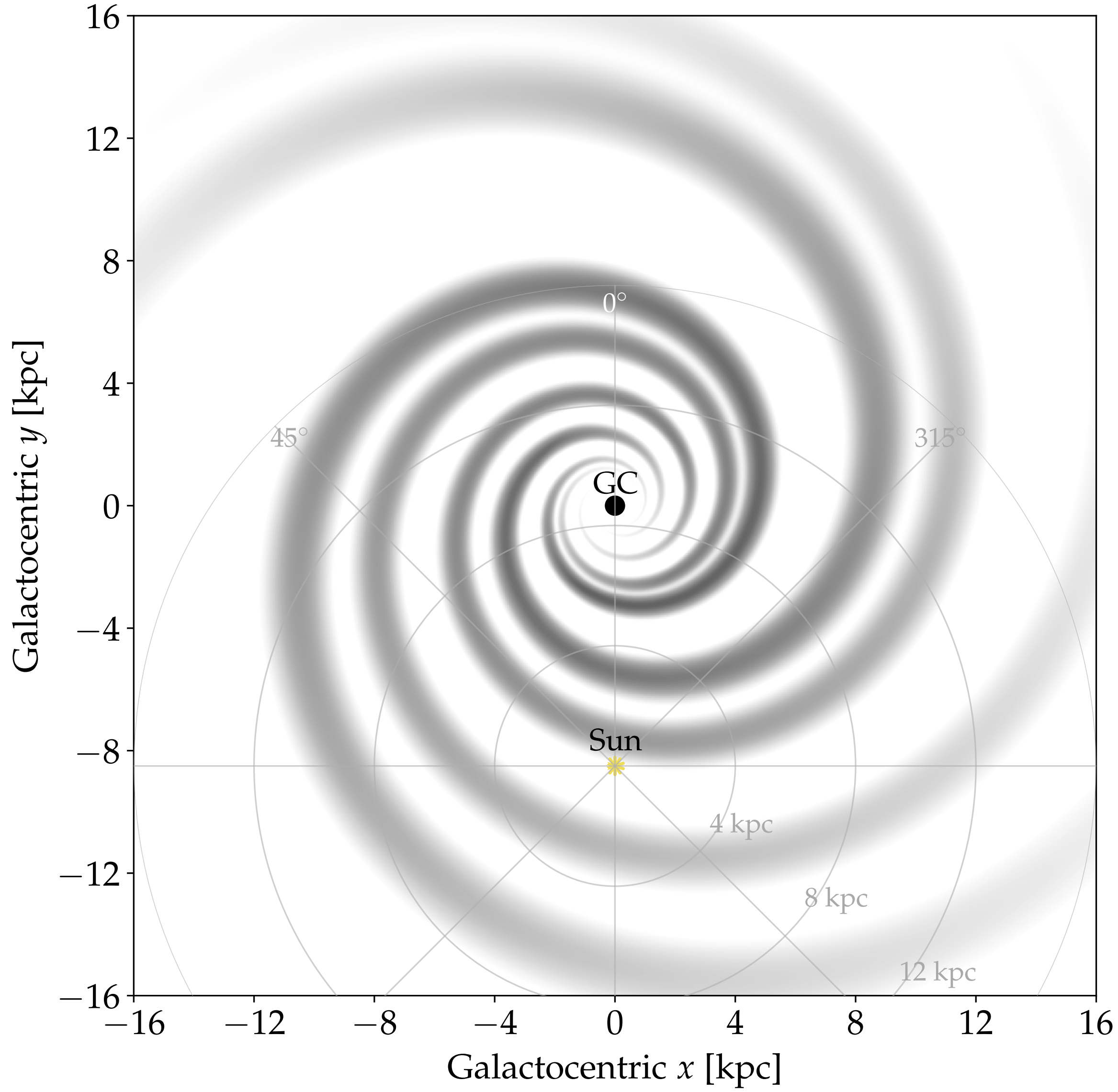


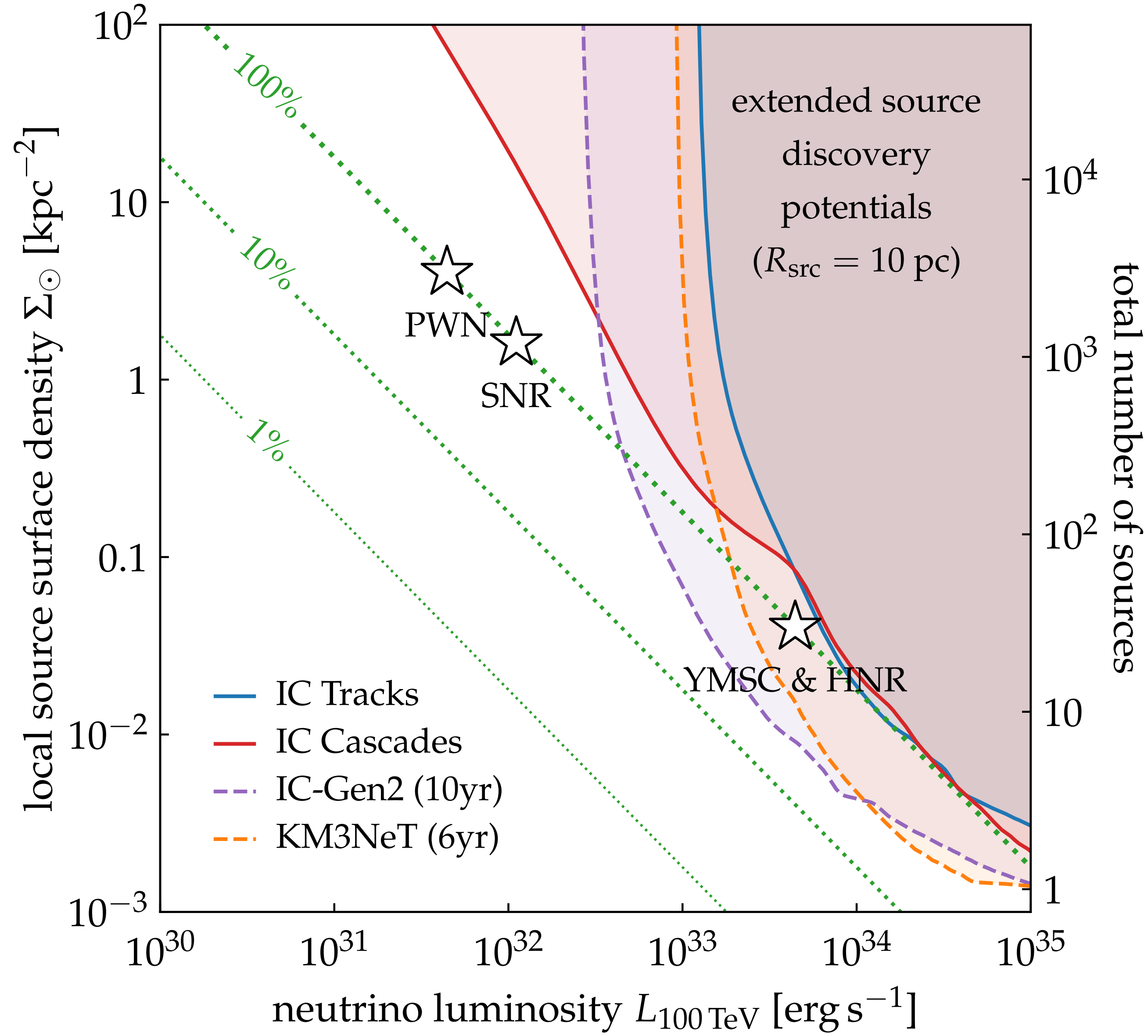
[IceCube, **Astrophys.J.** 868 (2018) no.2, L20]

Contribution of Galactic diffuse emission at 10TeV-PeV is subdominant.

Non-Azimuthal Distributions

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

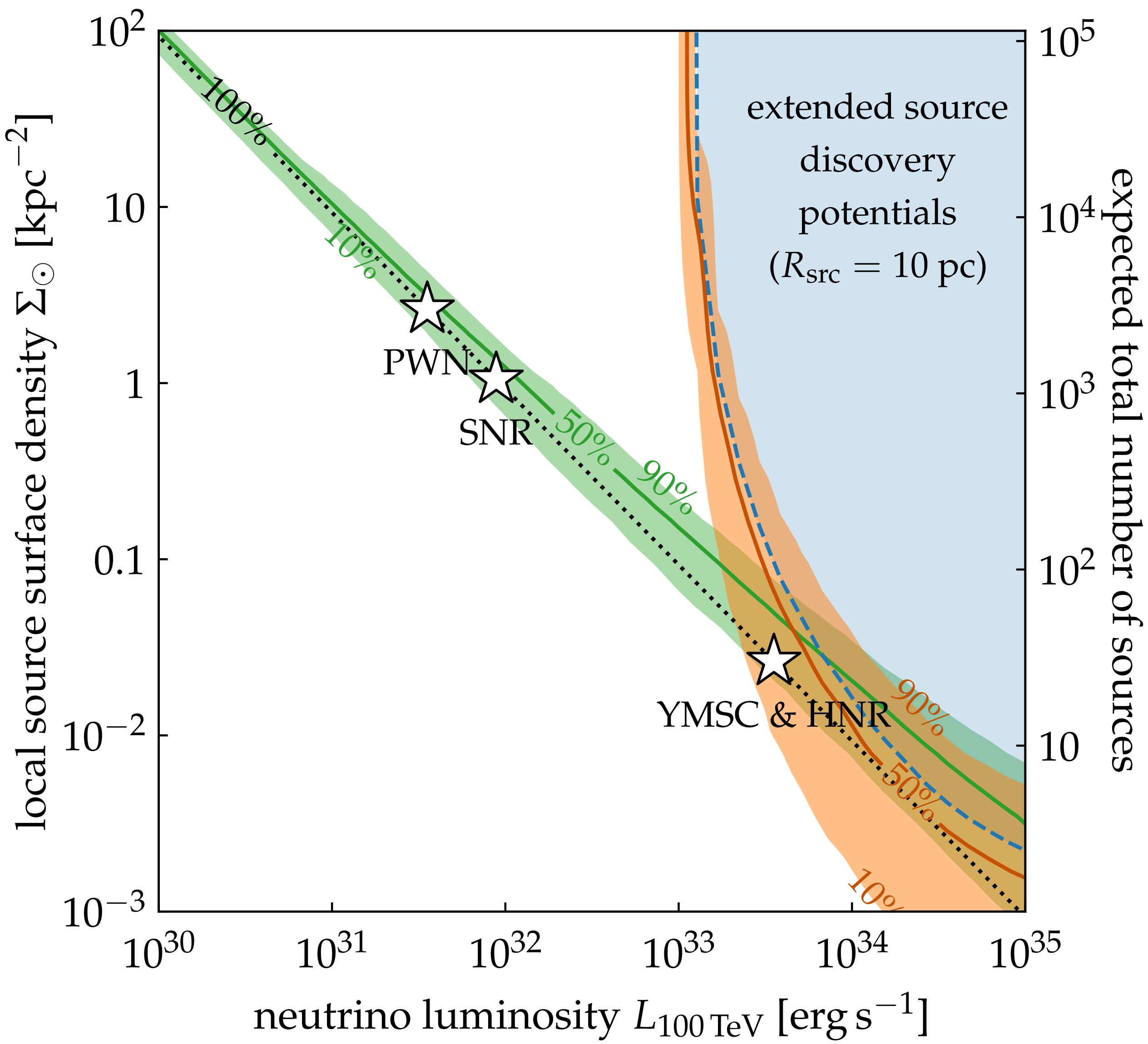


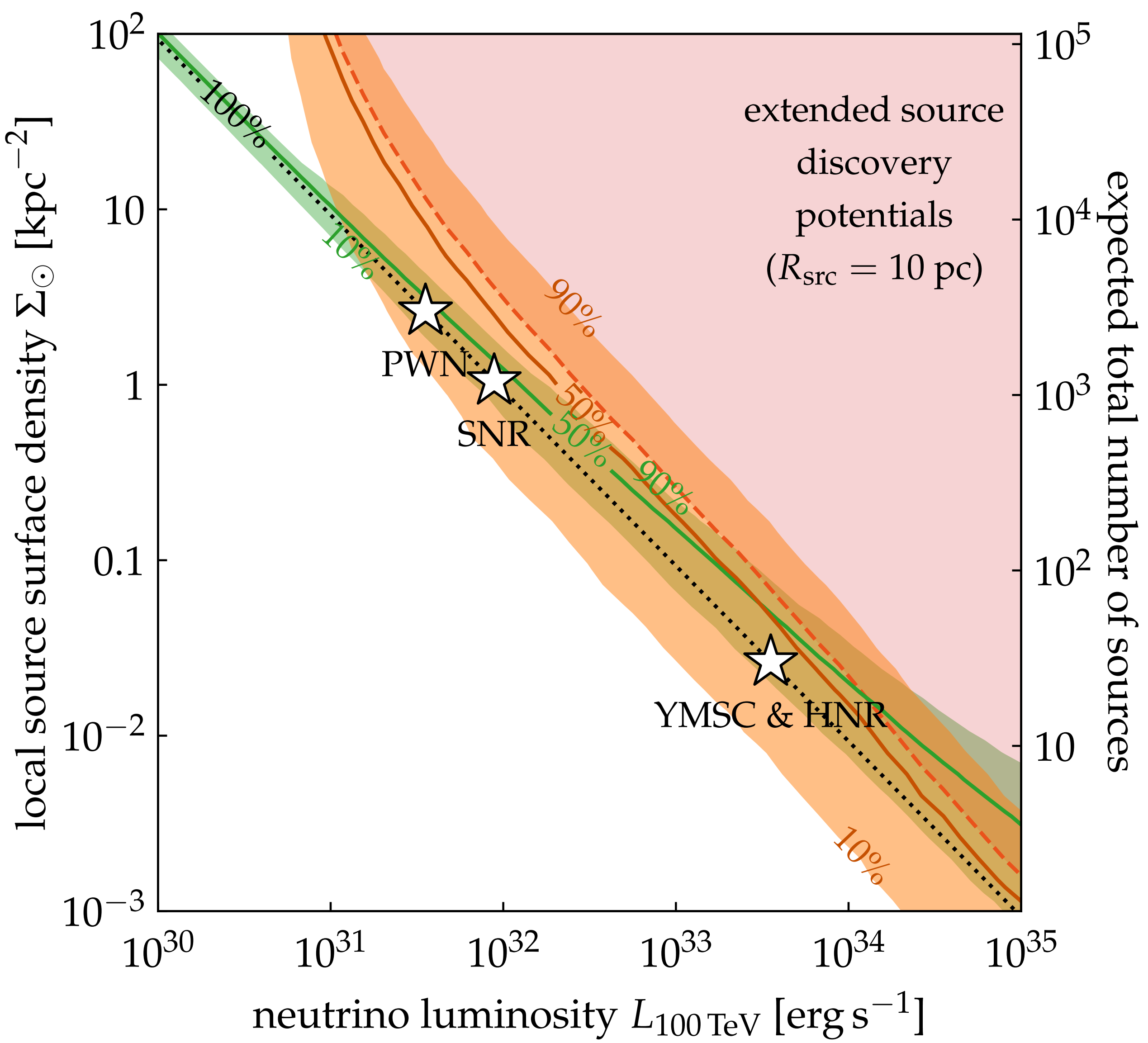


[Ambrosone, Groth, Peretti & MA'23]

Ensemble Fluctuations

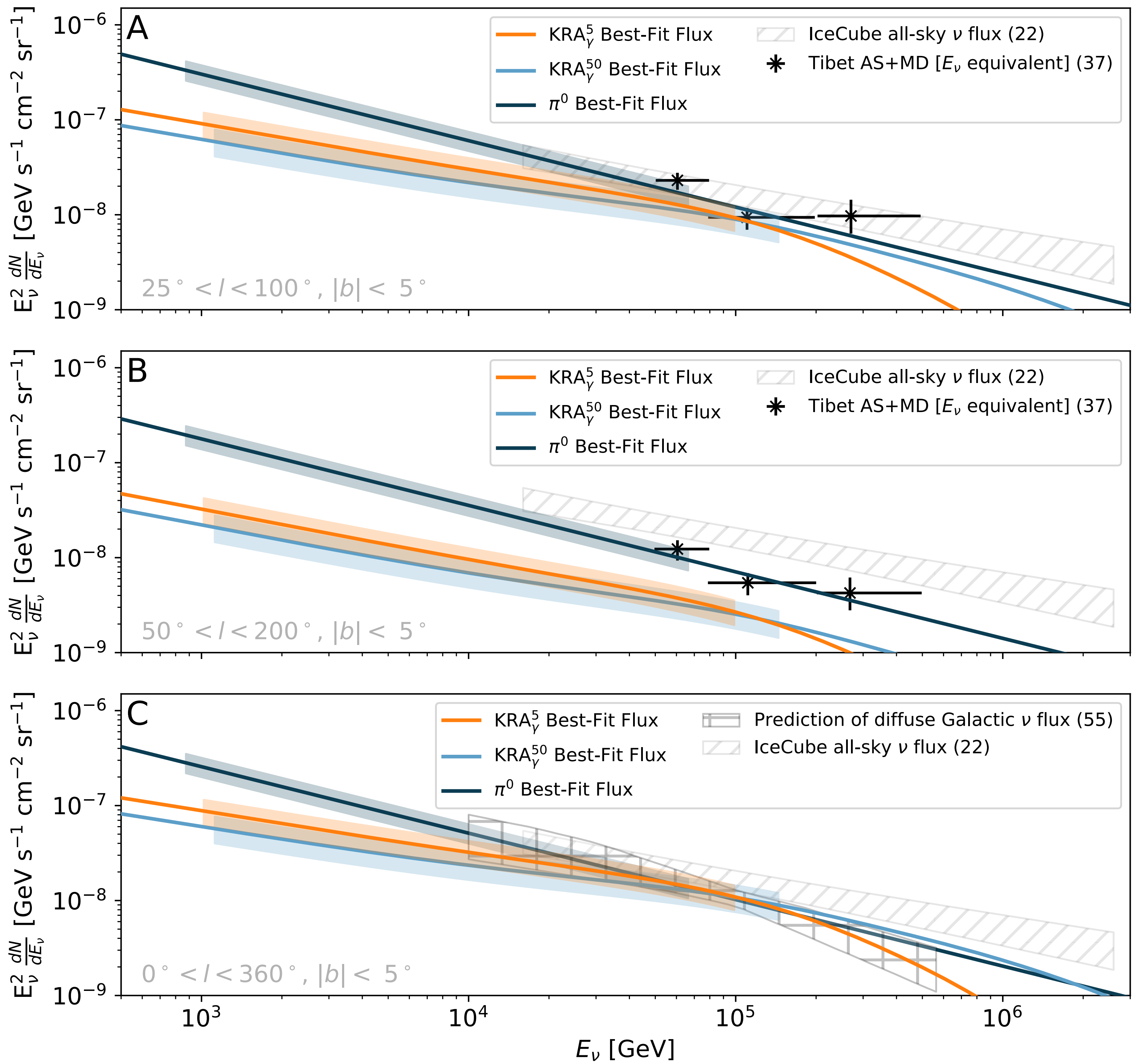
Rare sources can have significant ensemble fluctuations that may improve visibility in neutrino telescopes.





[Groth & MA in preparation]

VHE Galactic Gamma-Rays



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

Point Source Sensitivities

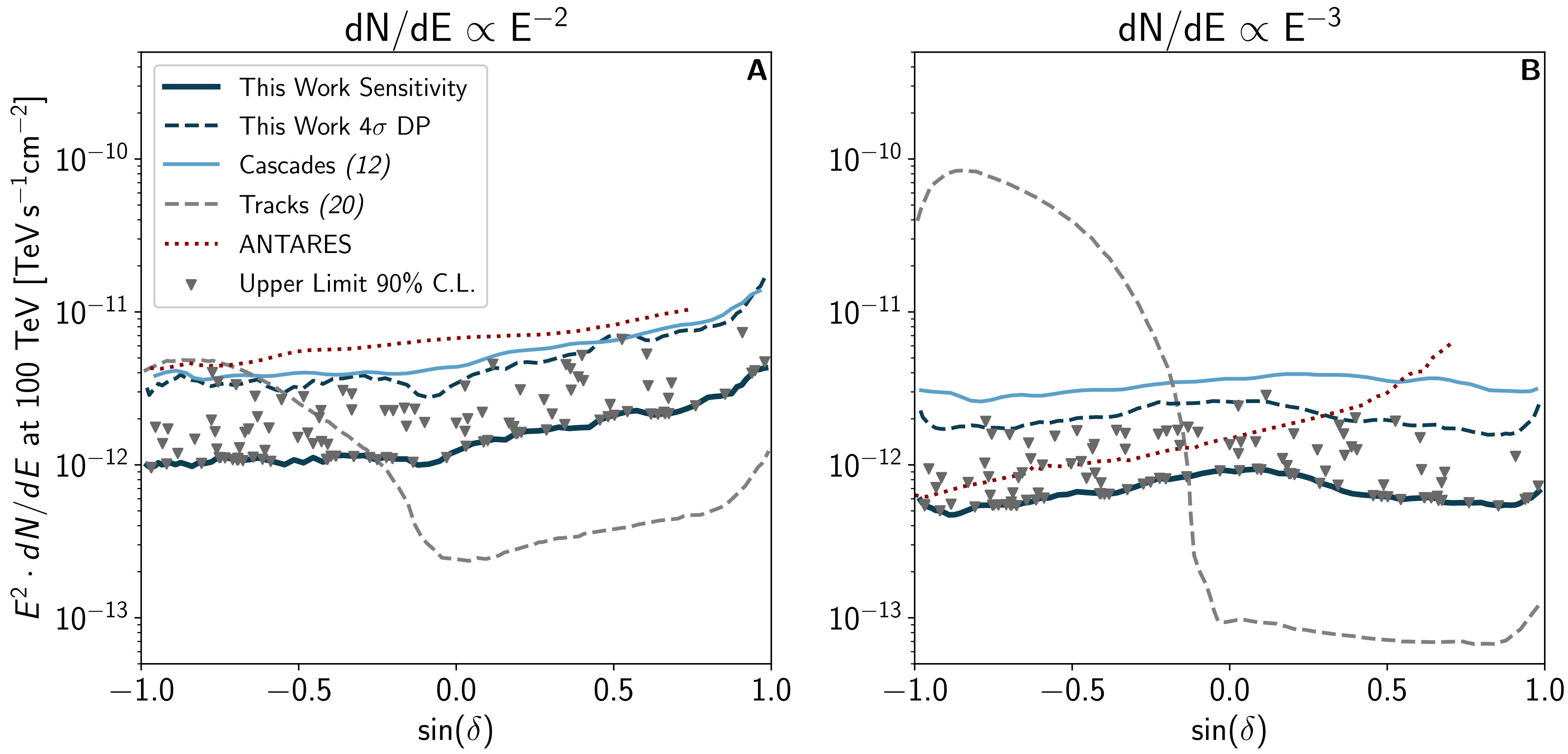
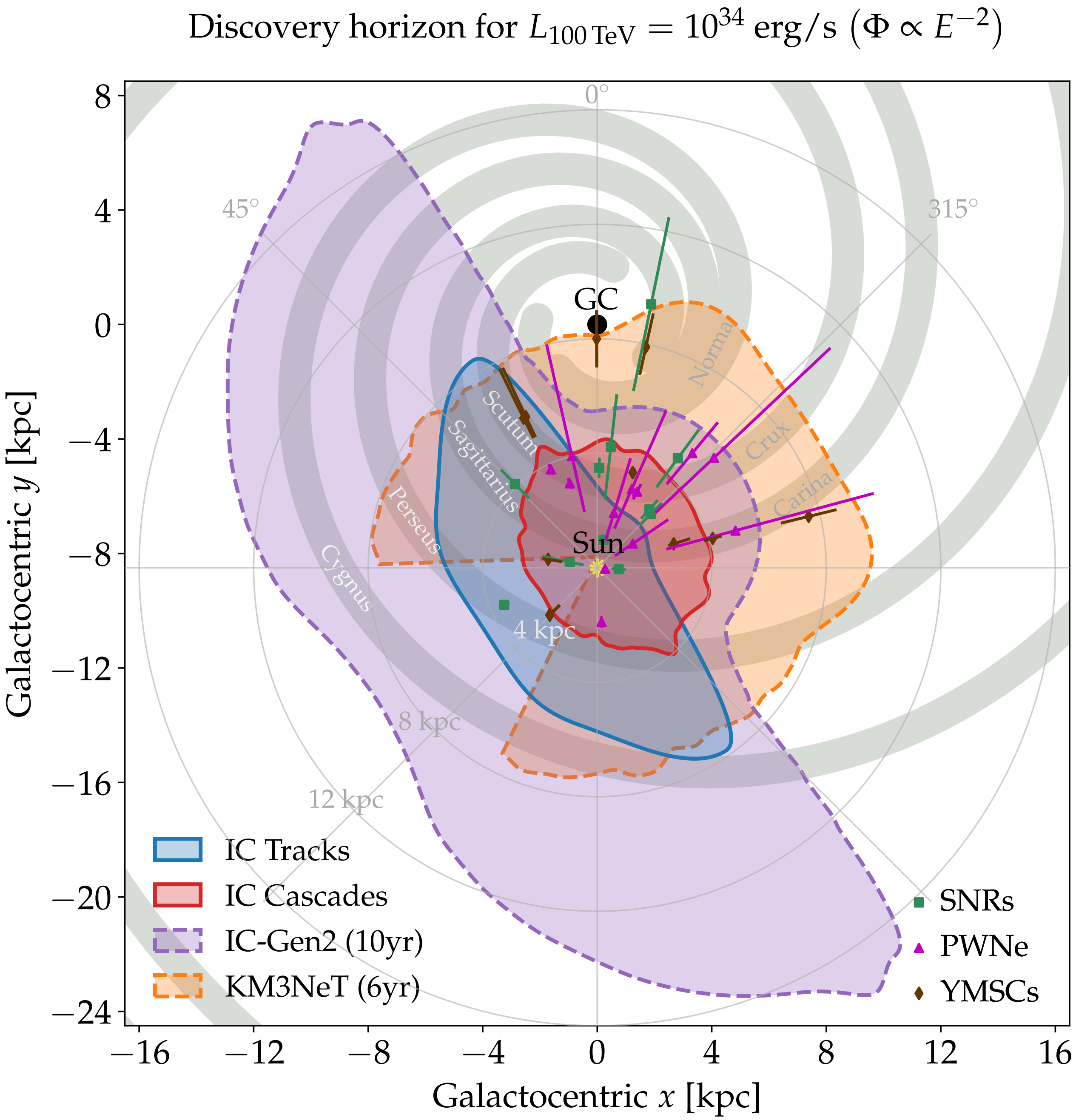


Figure S12: **Source list sensitivity and upper limits** Sensitivity to sources emitting an E^{-2} spectrum (A) and E^{-3} spectrum (B) for each data set. Individual sources in the source catalog are shown with their 90% confidence level (CL) upper limits assuming an E^{-2} (A) and E^{-3} (B) emission 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.

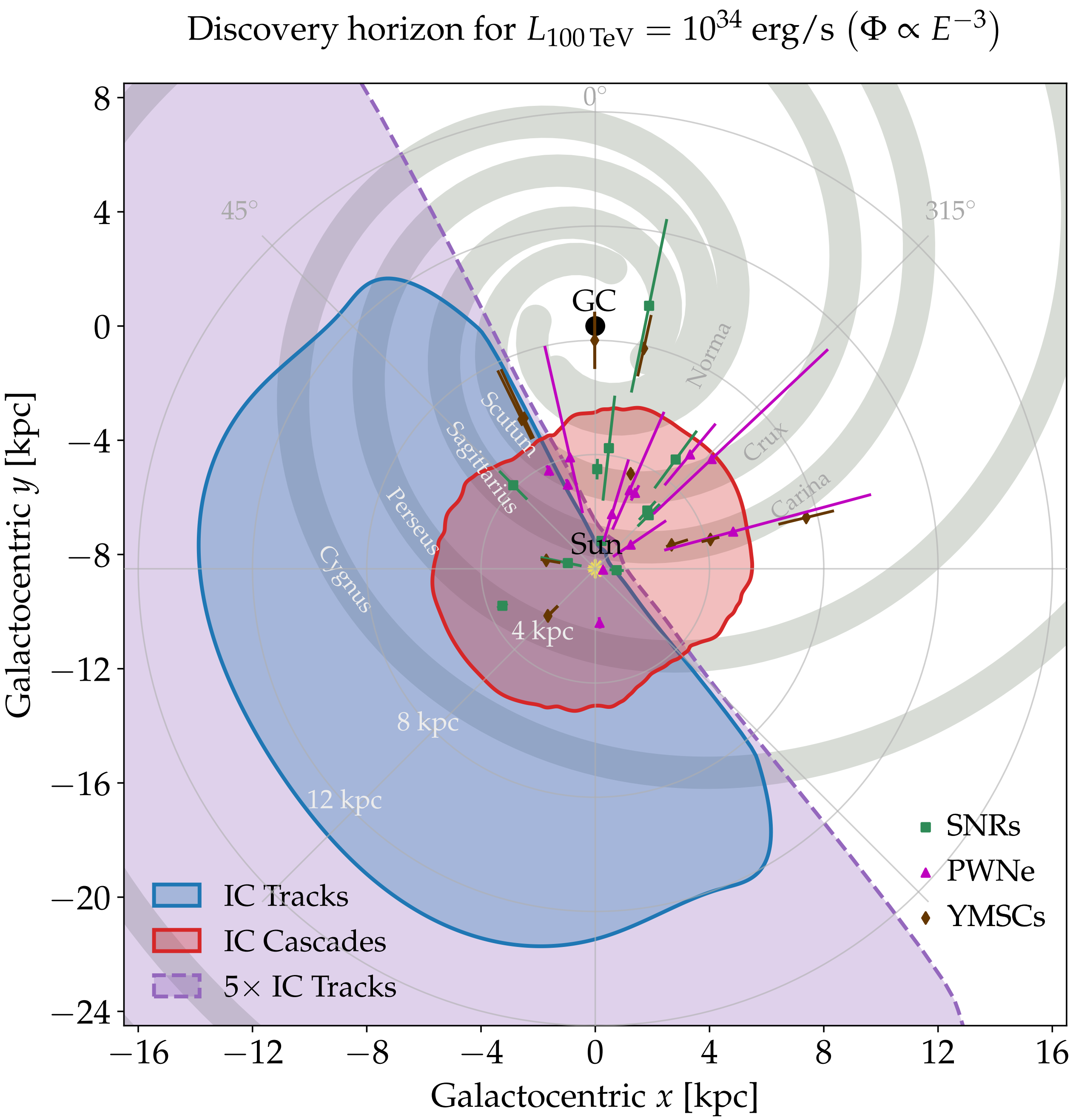
[IceCube **Science** 380 (2023)]

Point Source Sensitivities

E^{-2}

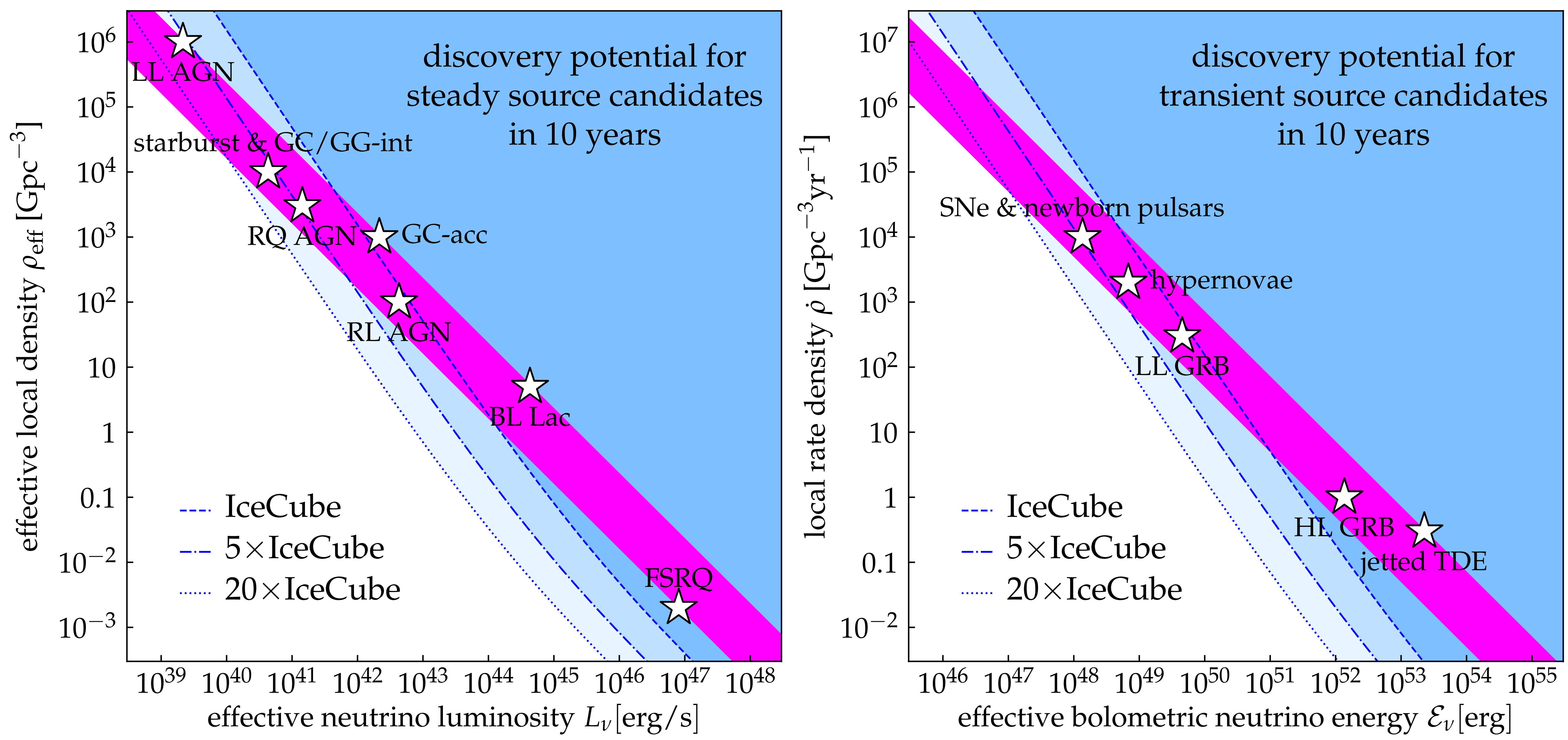


E^{-3}



[Ambrosone, Groth, Peretti & MA'23]

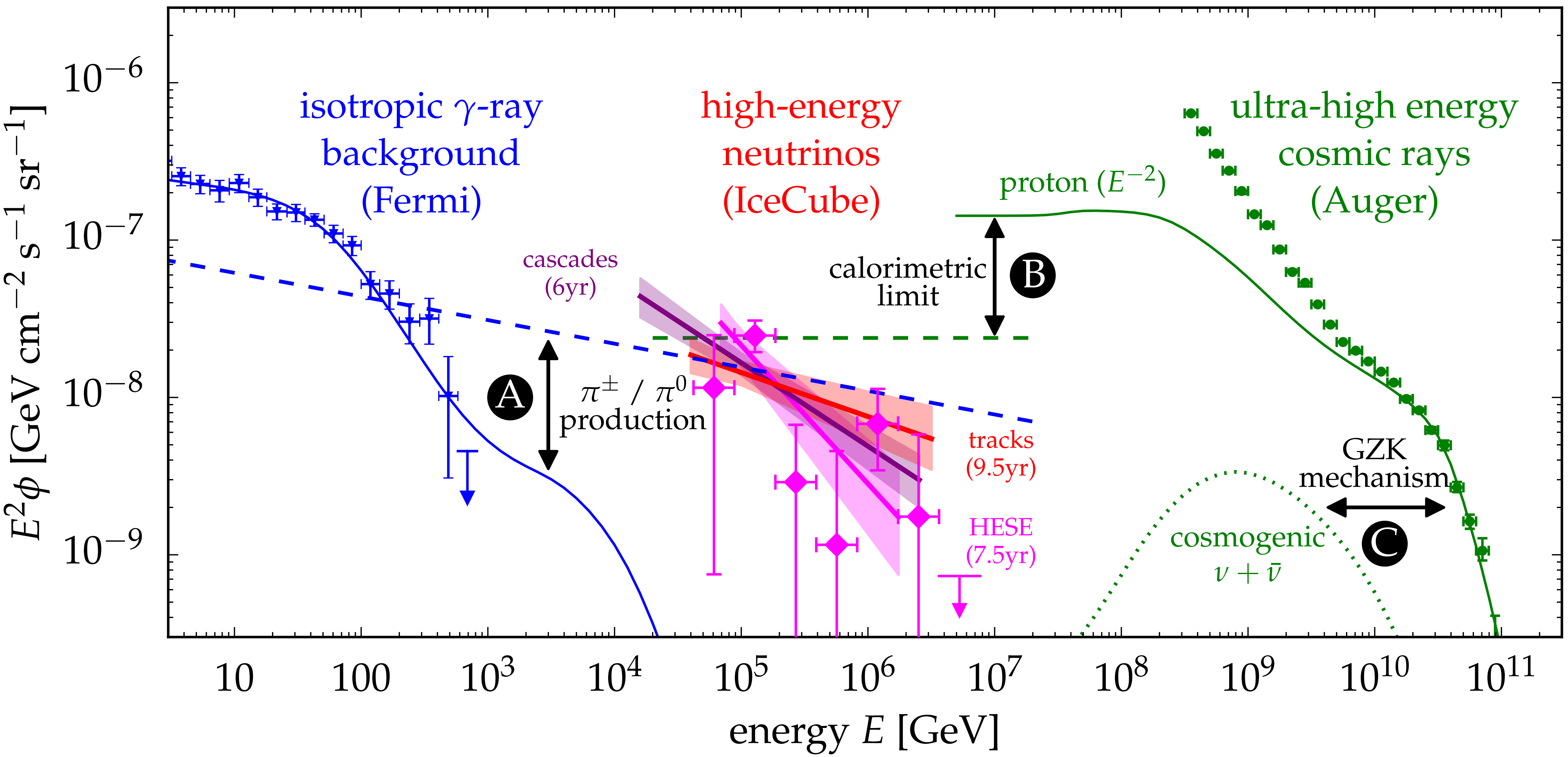
Point Source vs. Diffuse Flux



[Murase & Waxman'16; Ackermann *et al.'19*]

Rare sources - blazars, HL GRBs or jetted TDEs - can not be the dominant sources of TeV-PeV neutrino emission (magenta band).

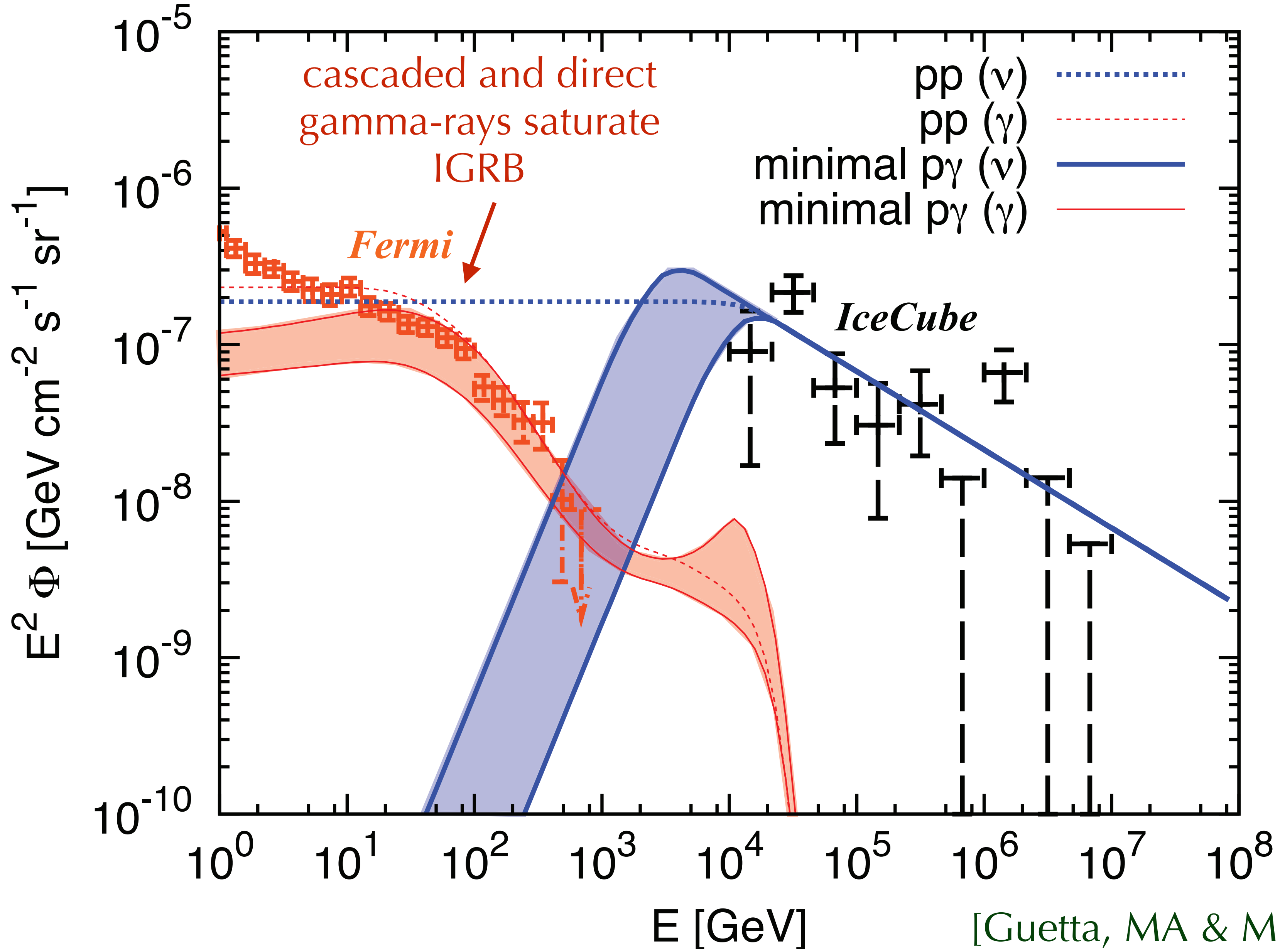
Multi-Messenger Interfaces



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.



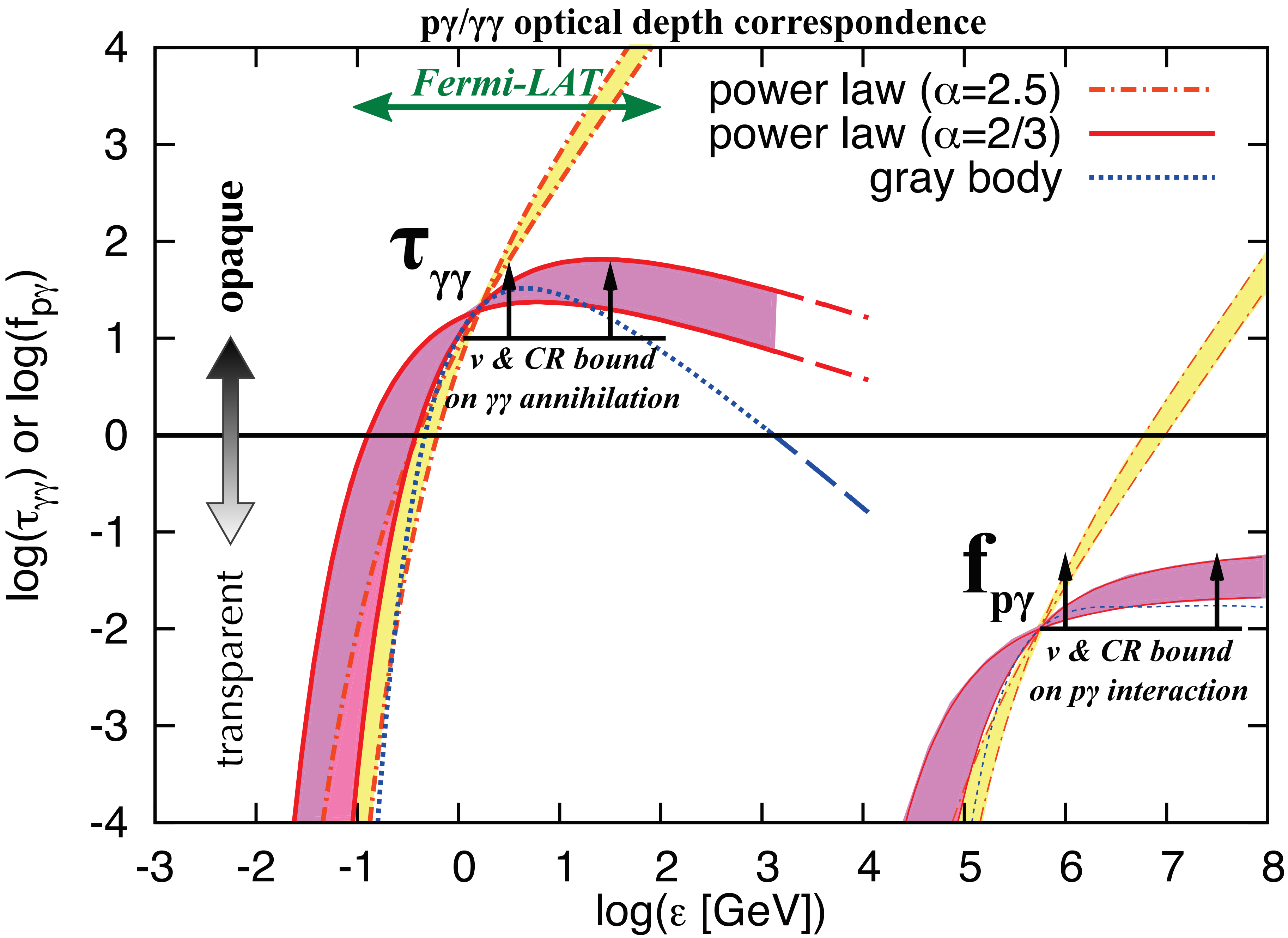
[Guetta, MA & Murase'16]

[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 $p\gamma$ scenarios require sources with **strong X-ray backgrounds** (e.g. AGN core models).

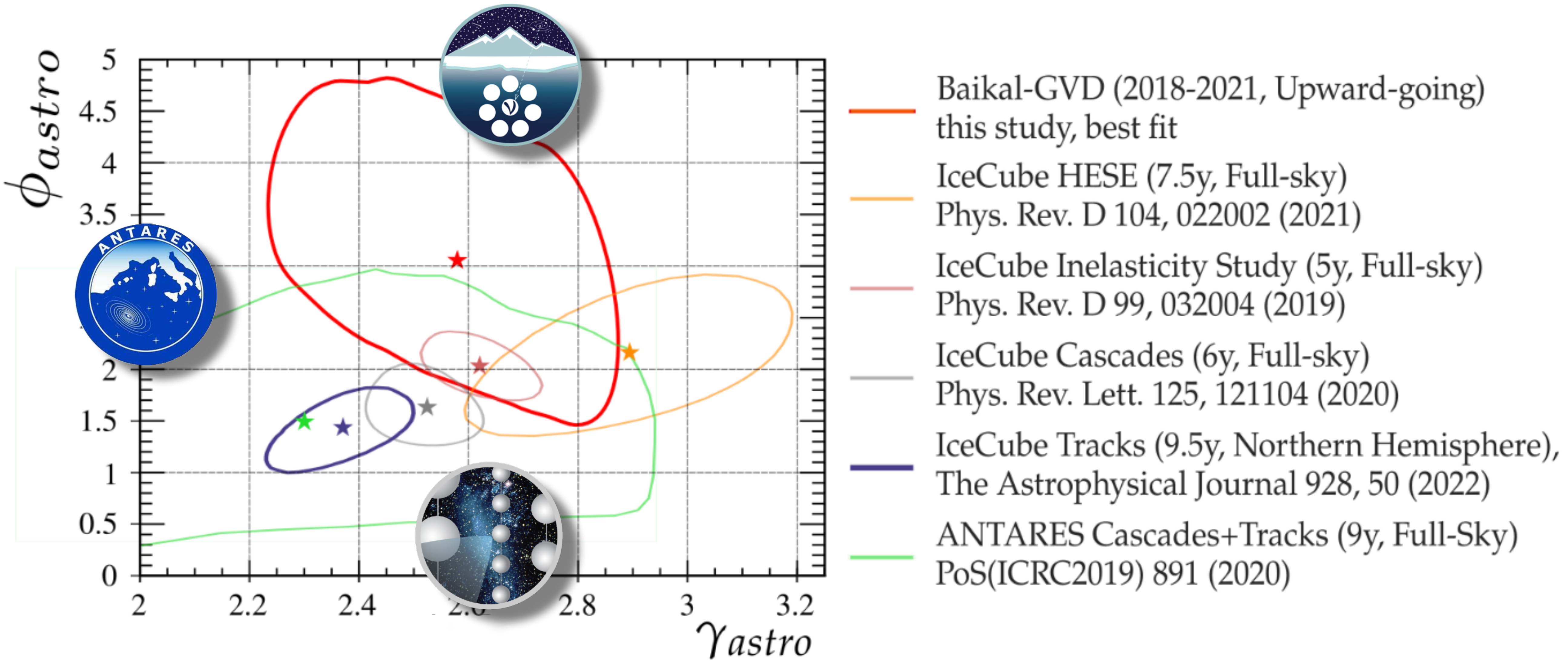


High pion production efficiency implies strong internal ***γ*-ray absorption in Fermi-LAT energy range:**

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

[Guetta, MA & Murase'16]

Isotropic Diffuse Flux



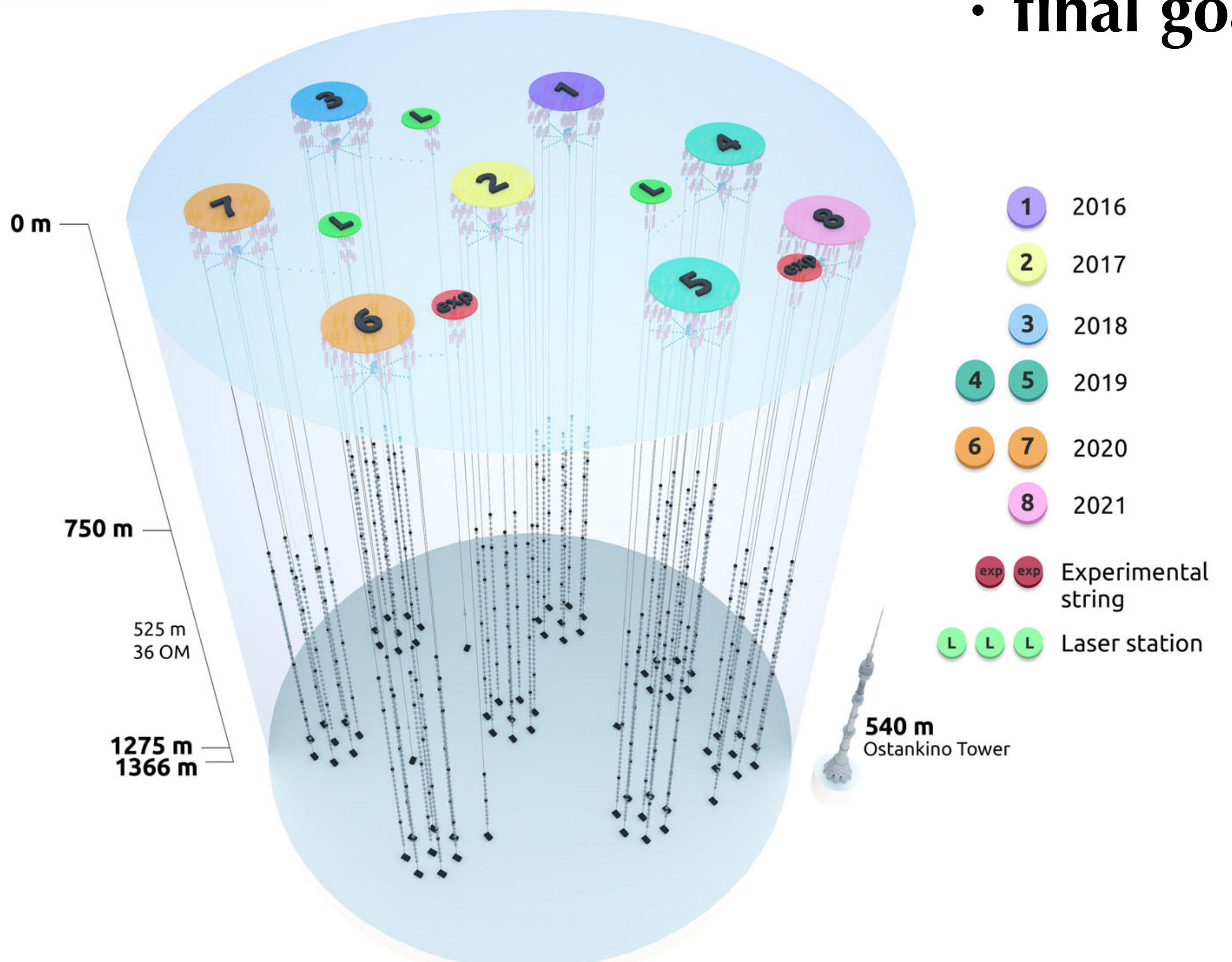
[ANTARES, PoS (ICRC2019) 891 & PoS (ICRC2021) 1121; Baikal-GVD, arXiv:2210.01650]

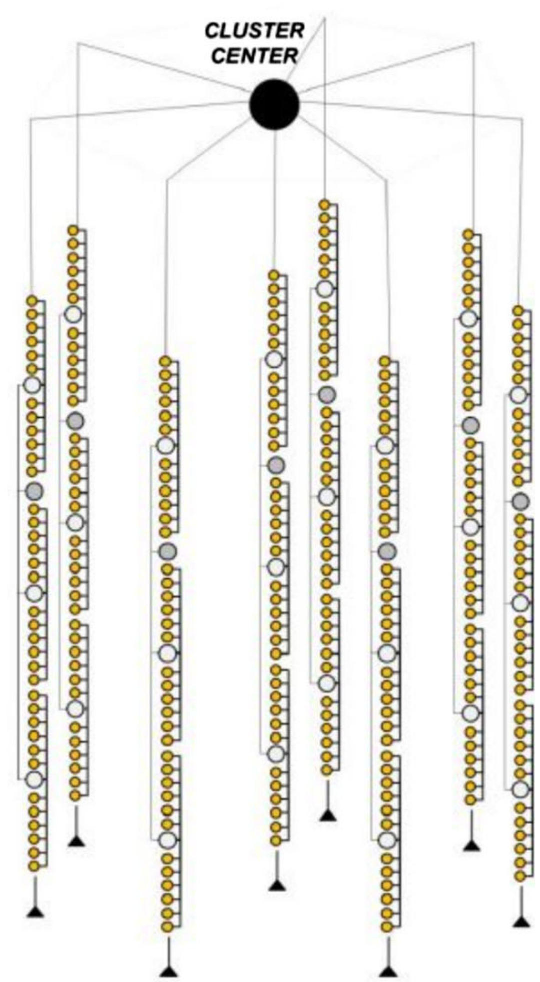
- Independent probe of diffuse flux by ANTARES/KM3NeT and Baikal-GVD.
- Complementary field of view allows to decipher anisotropies, e.g. by Galactic diffuse emission.

Outlook: Baikal-GVD

BAIKAL-GVD

- **GVD Phase 1:** 8 clusters with 8 strings each were completed in 2021
- **status April 2023: 11(+1) clusters**
- **final goal**: 27 clusters ($\sim 1.4\,\mathrm{km}^3$)

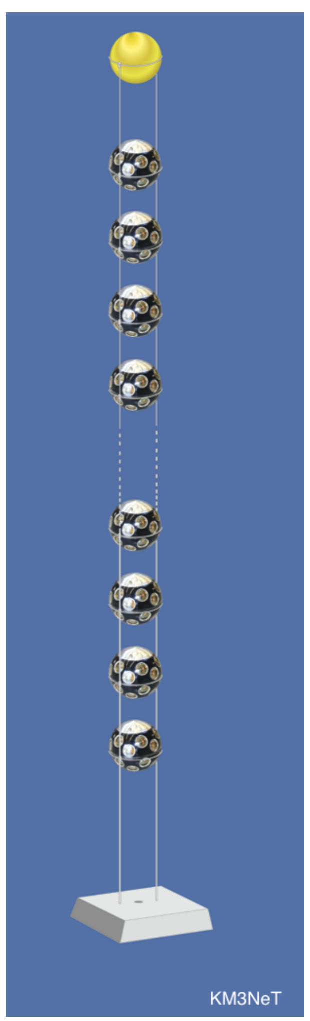


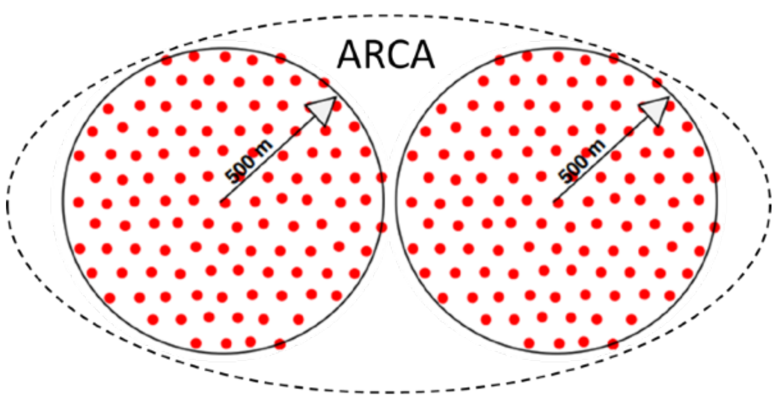


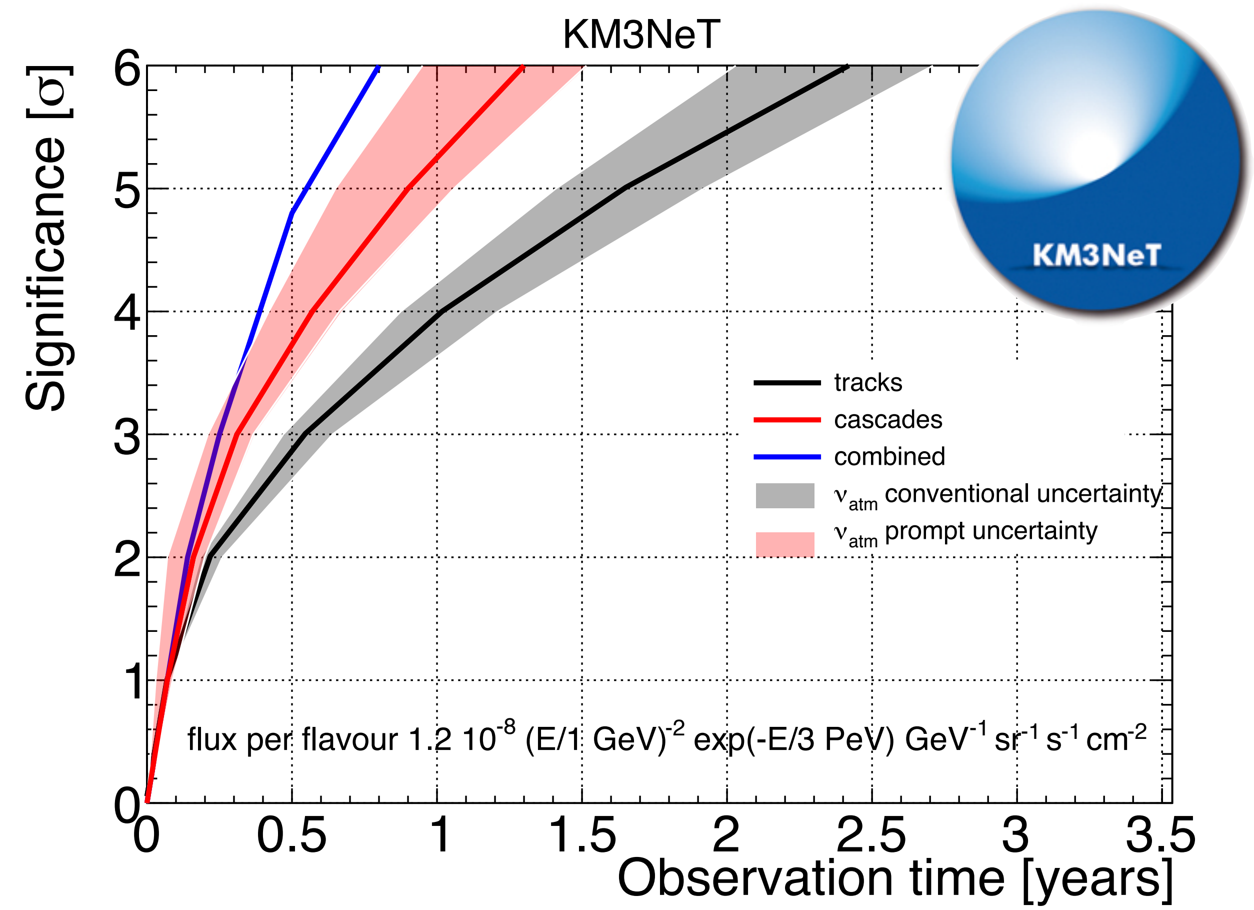
Outlook: KM3NeT/ARCA

- **ARCA :** 2 building blocks of 115 detection units (DUs)
- **status April 2023: 21 (ARCA) DUs**
- **ORCA** : optimized for low-energy (GeV) and oscillation analyses

detection unit with multi-PMT DOMs



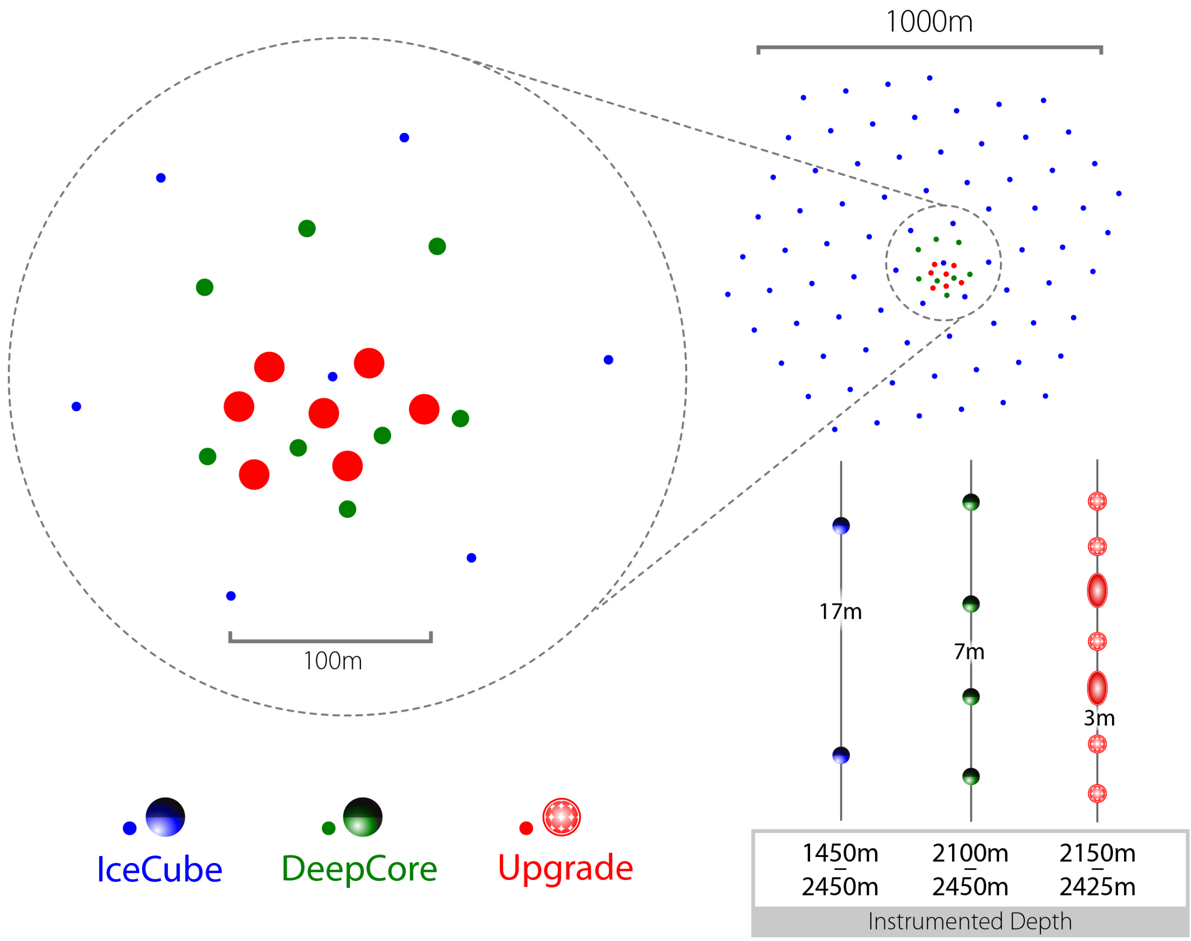


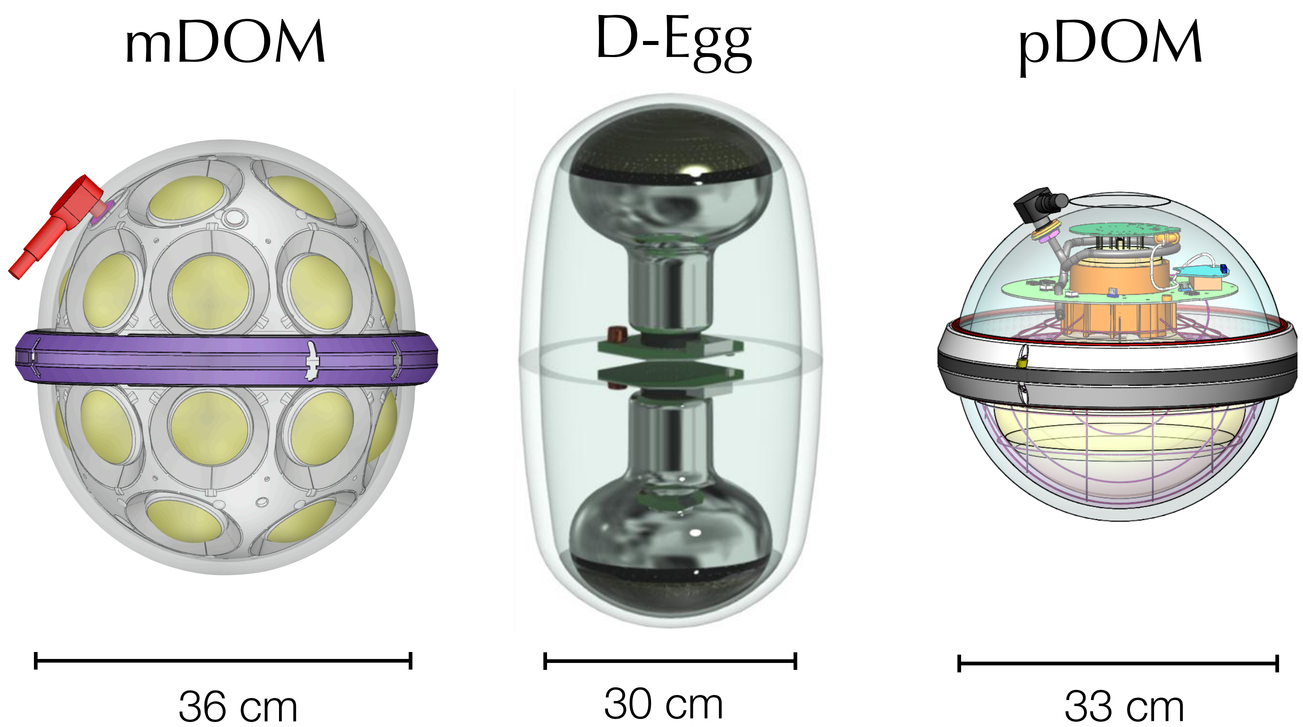


- **Improved angular resolution** for water Cherenkov emission.
- 5σ discovery of **diffuse flux** with full ARCA within one year
- **Complementary field of view** ideal for the study of point sources.

Outlook: IceCube Upgrade

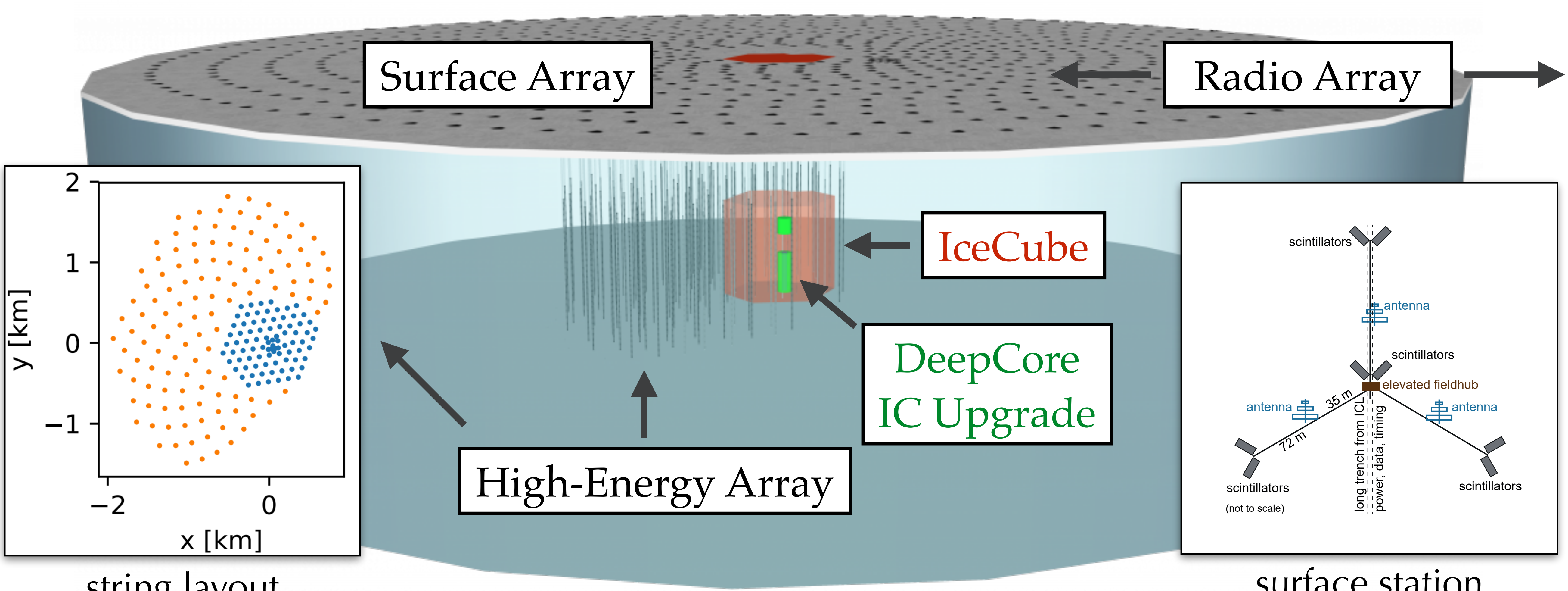
- **7 new strings** in the DeepCore region (~20m inter-string spacing)
- **New sensor designs**, optimized for ease of deployment, light sensitivity & effective area
- **New calibration devices**, incorporating lessons from a decade of IceCube calibration efforts
- In parallel, **IceTop surface enhancements**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





Vision: IceCube-Gen2

- **Multi-component facility** (low- and high-energy & multi-messenger)
- **In-ice optical Cherenkov array** with 120 strings and 240m spacing
- **Surface array** (scintillators & radio antennas) for PeV-EeV CRs & veto
- **Askaryan radio array** for >10PeV neutrino detection

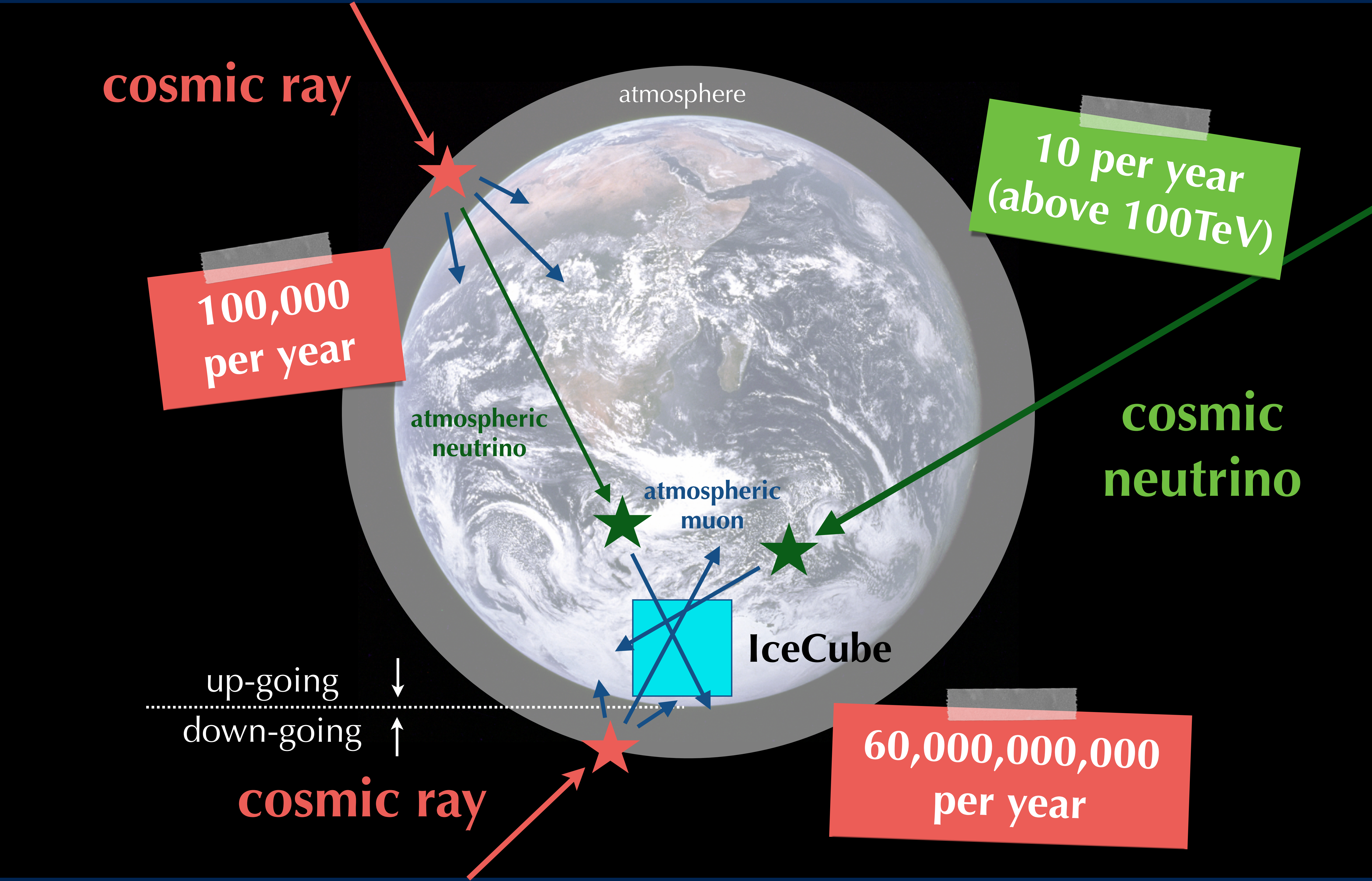


string layout

surface station

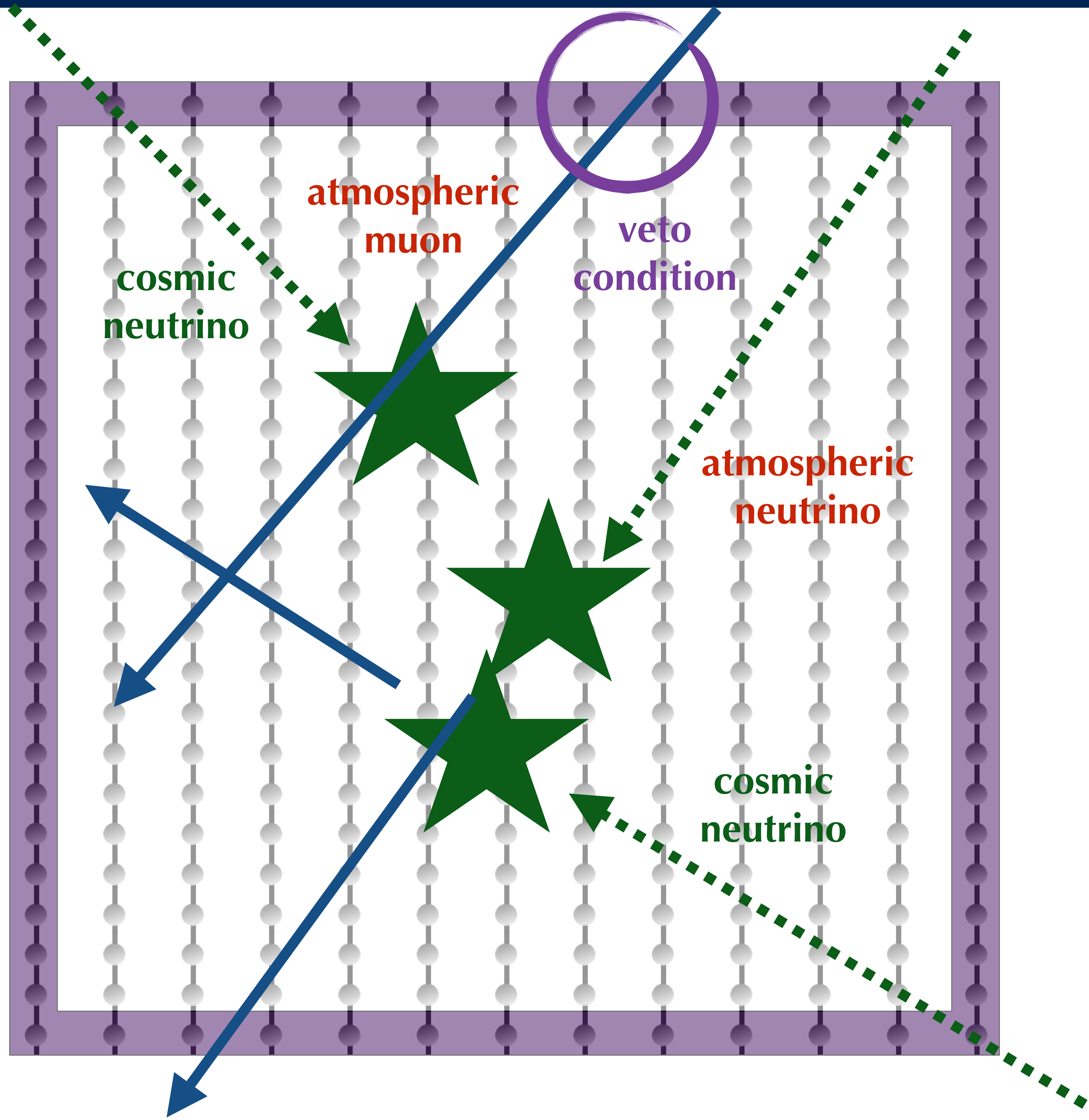
[IceCube-Gen2 *Technical Design Report:* icecube-gen2.wisc.edu/science/publications/tdr/]

Neutrino Selection I



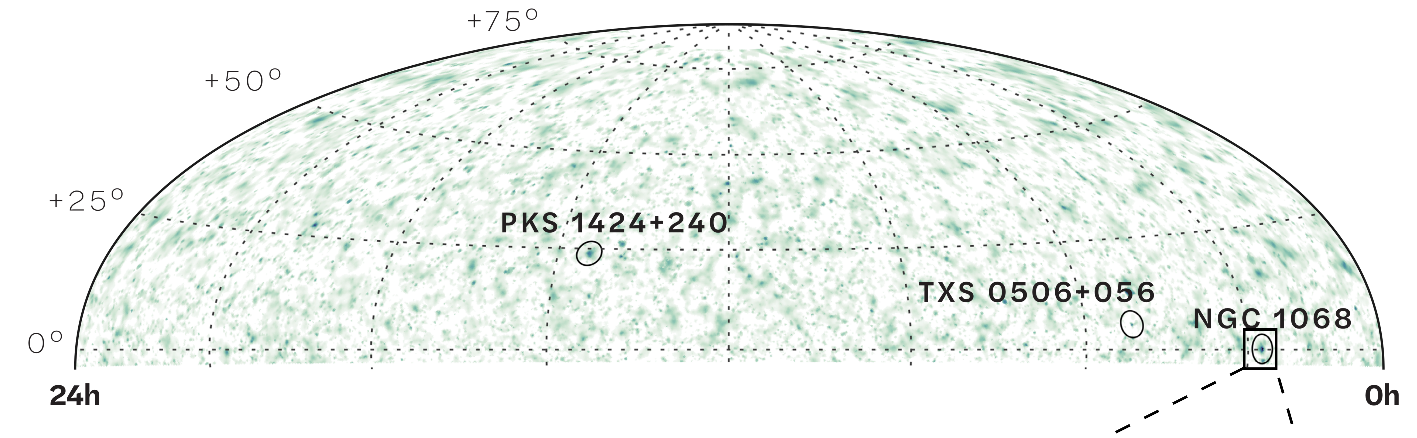
Neutrino Selection II

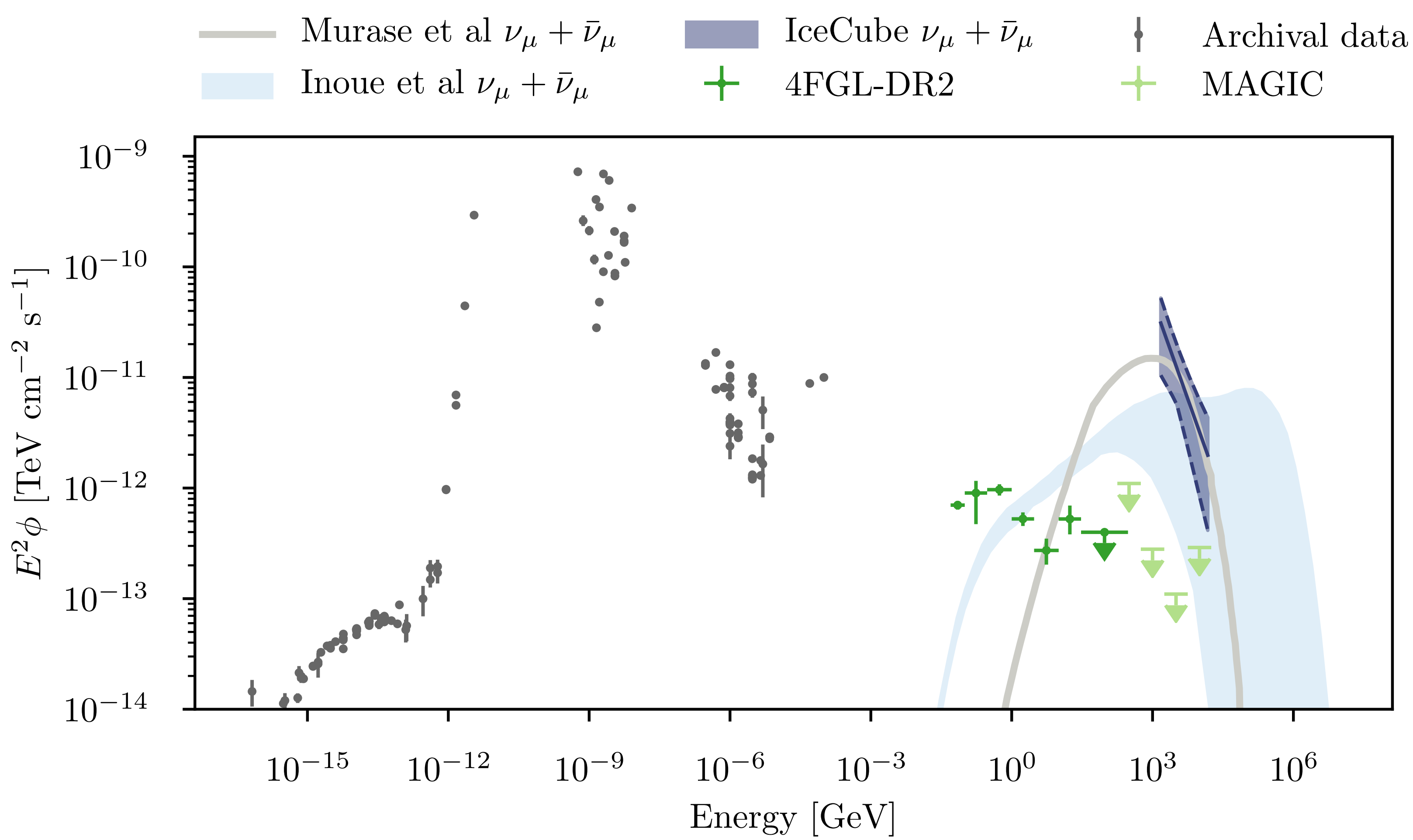
- Outer layer of optical modules used as virtual **veto region.**
- **Atmospheric muons** pass through veto from above.
- **Atmospheric neutrinos** coincidence with atmospheric muons.
- **Cosmic neutrino** events can start inside the fiducial volume.
- **High-Energy Starting Event** (HESE) analysis

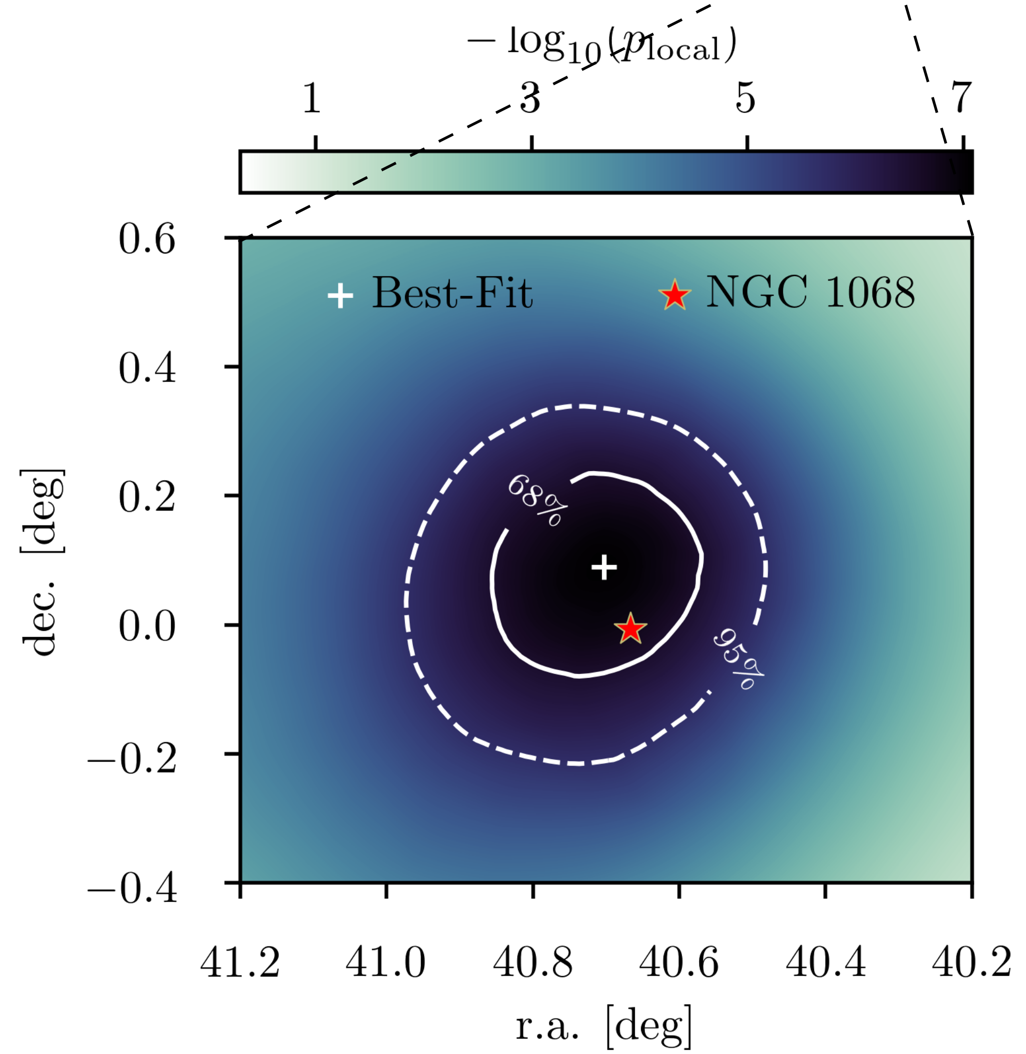


Excess from NGC 1068

Northern hot spot in the vicinity of Seyfert II galaxy **NGC 1068** has now a **significance of 4.2σ** *(trial-corrected for 110 sources)*.

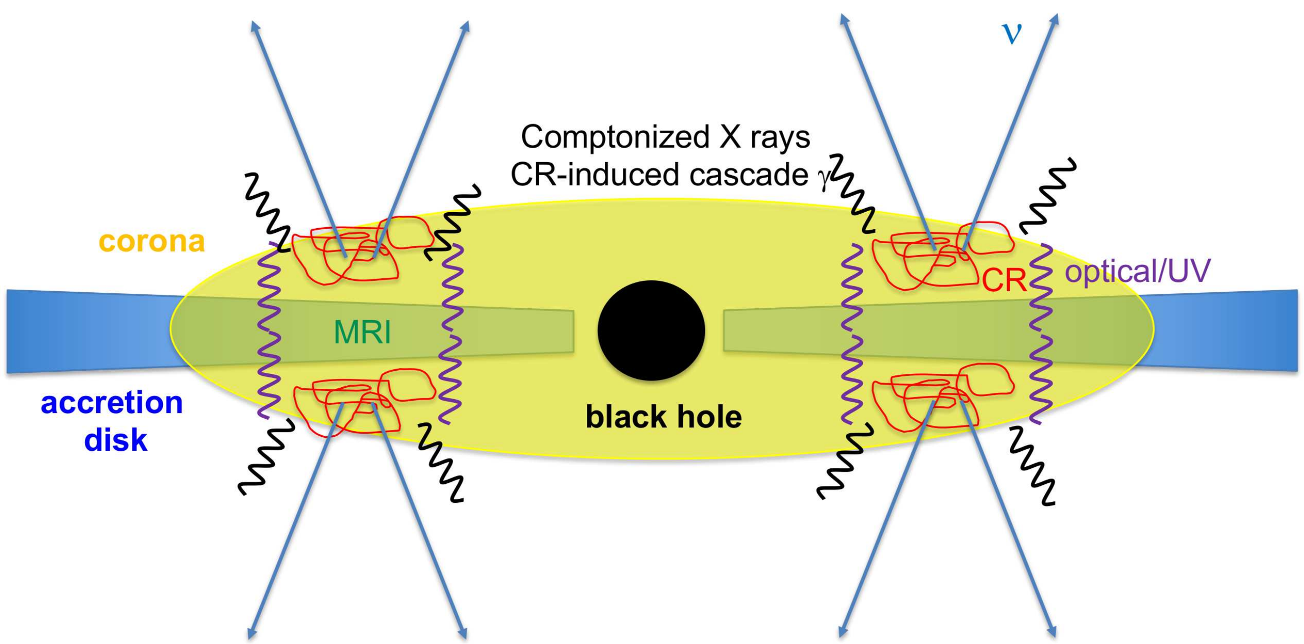




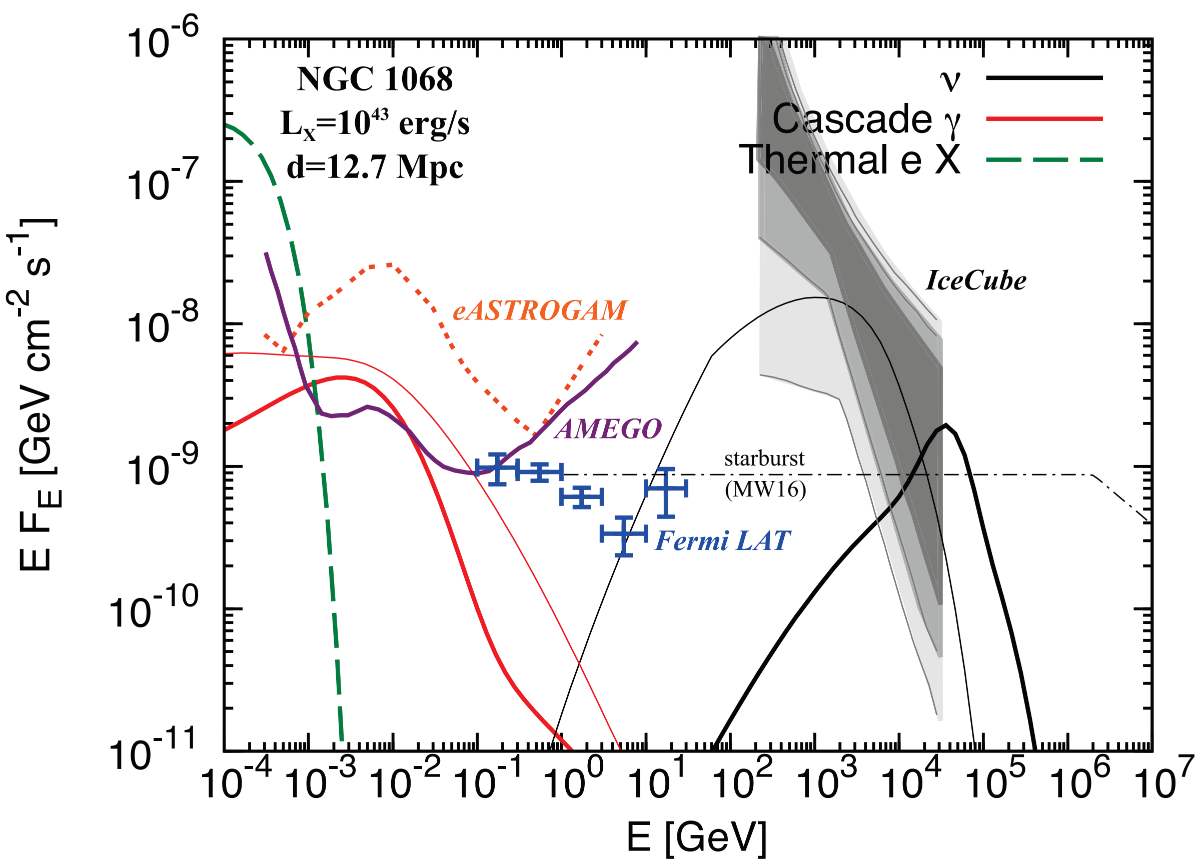


[IceCube, PRL 124 (2020) 5 **(2.9σ post-trial)**; Science 378 (2022) 6619 **(4.2σ post-trial)**]

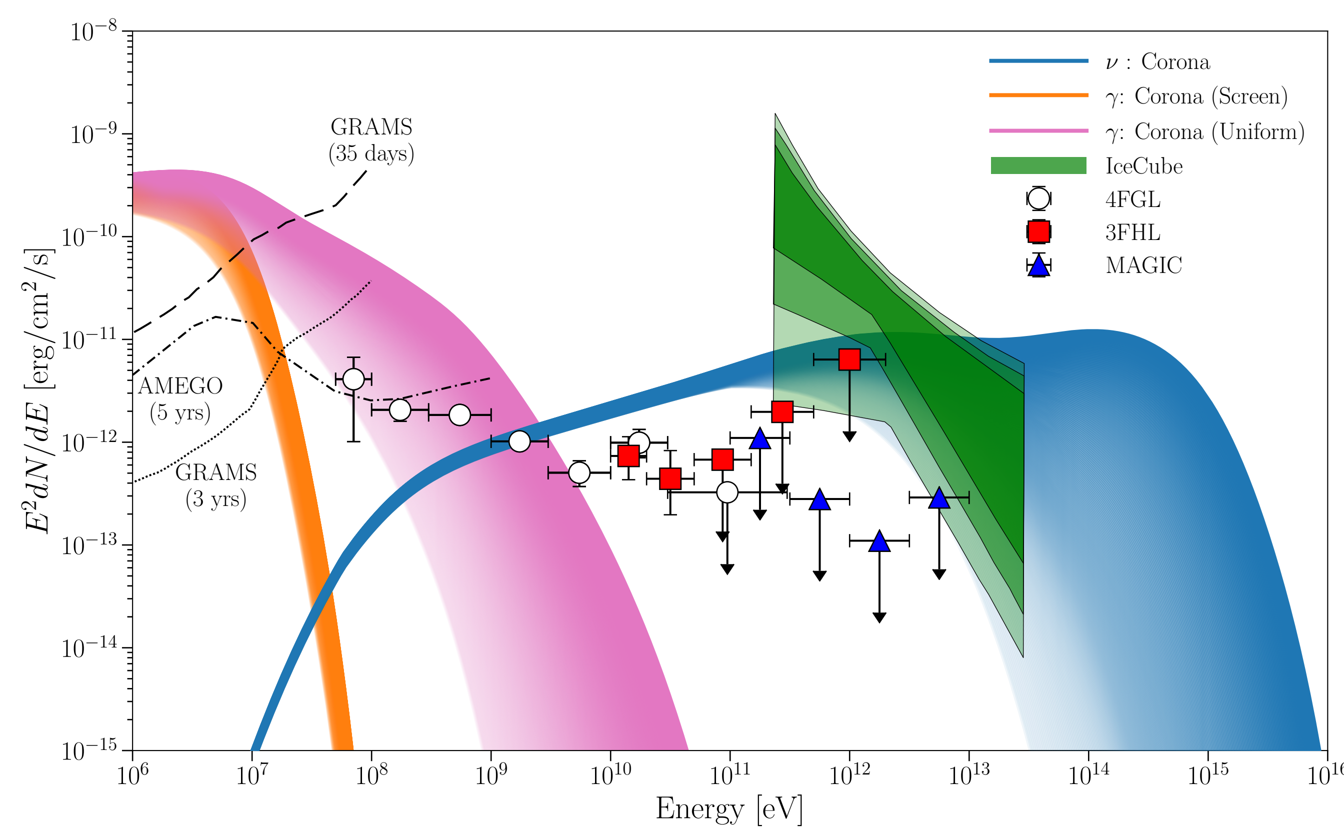
Excess from NGC 1068



- **Soft spectrum** ($\gamma = 3.2 \pm 0.2$) within 1.5-15 TeV indicates peak or cutoff in ν emission.
- Effective **absorption** of accompanying γ-rays in X-ray photons of **AGN corona.**



[Murase, Kimura & Meszaros '20]



[Inoue, Khangulyan & Doi '20]