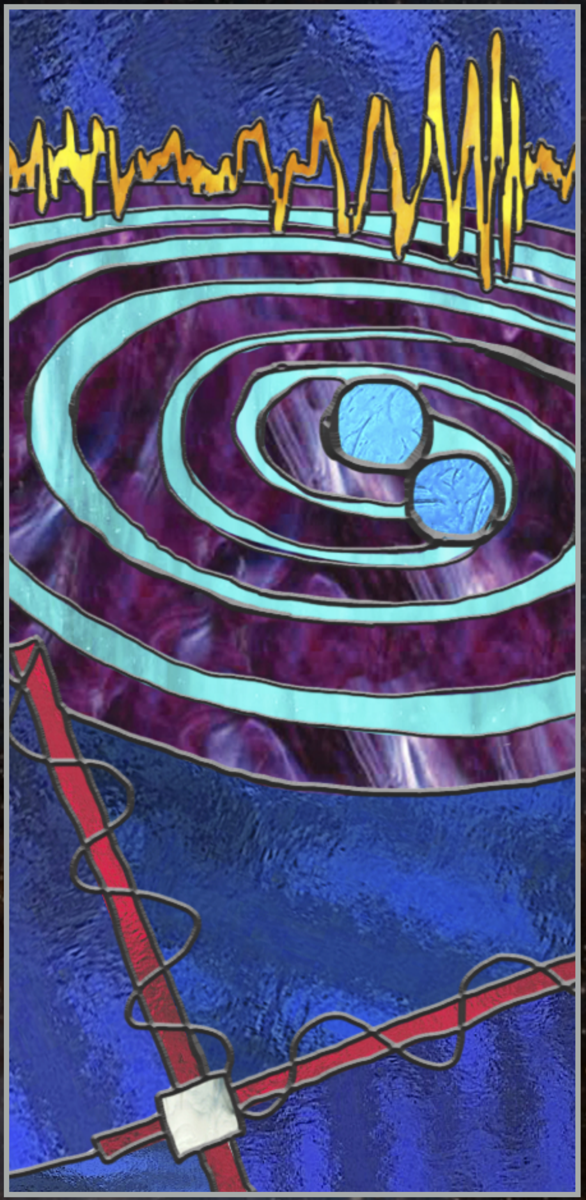
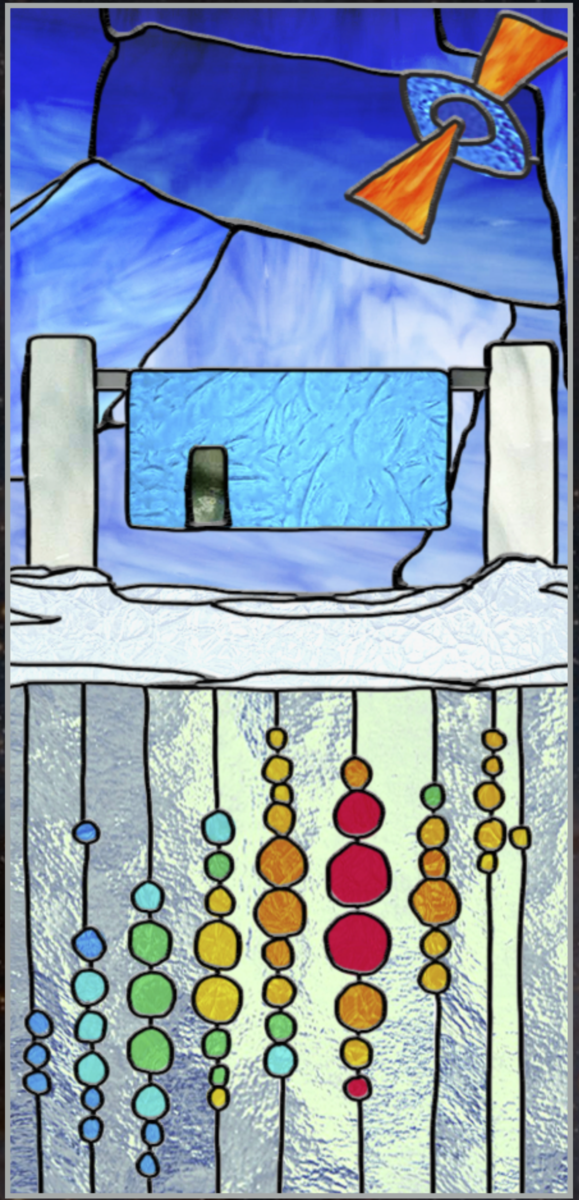
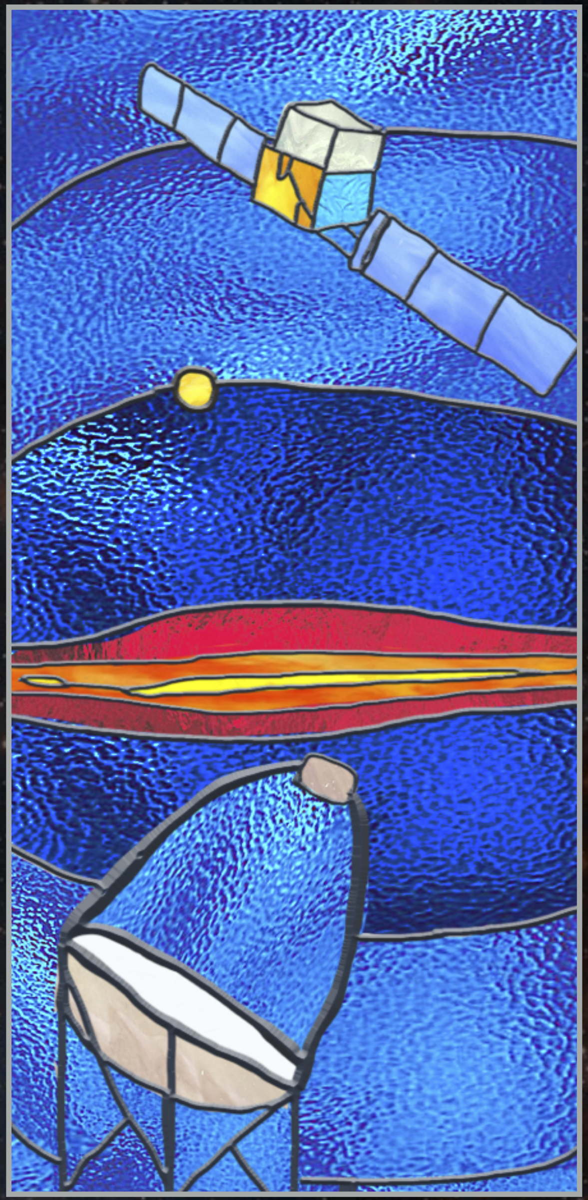






Neutrino Astronomy: Physics, Status & Outlook
Part I

Markus Ahlers
Niels Bohr Institute

Georges Lemaître Chair 2023

VILLUM FONDEN

KØBENHAVNS UNIVERSITET

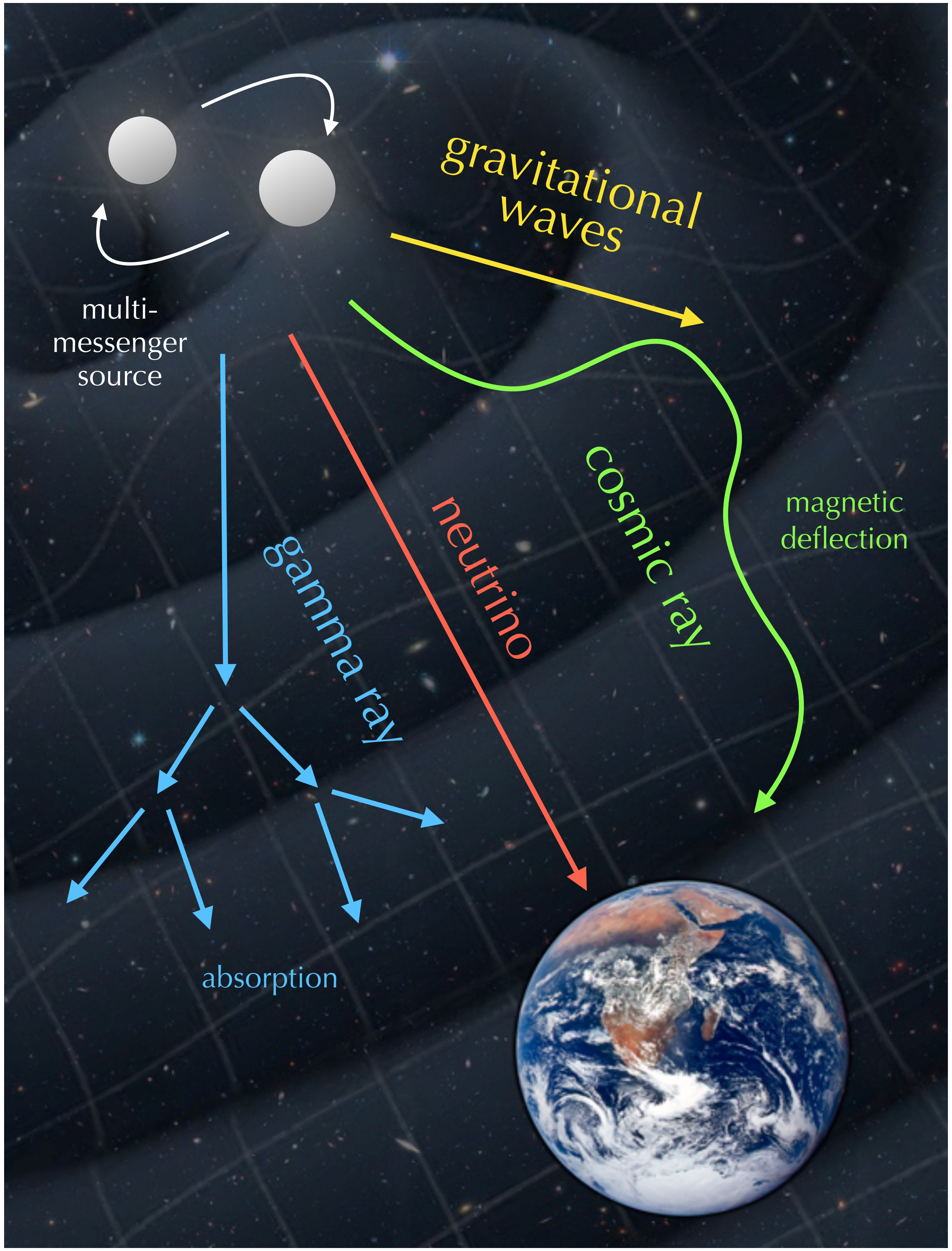
The Elusive Neutrino

- **three neutrino flavours**
- very small masses *(unknown origin)*
- large mixing between flavour and mass states *(unknown mechanism)*
- 2nd most abundant particle in the Universe *(impact on cosmology)*
- **unique probe of high-energy astrophysics**

Standard Model of Particle Physics

(+ Higgs boson)

Neutrino Astronomy



Unique abilities of **cosmic neutrinos**:

no deflection in magnetic fields
(unlike cosmic rays)

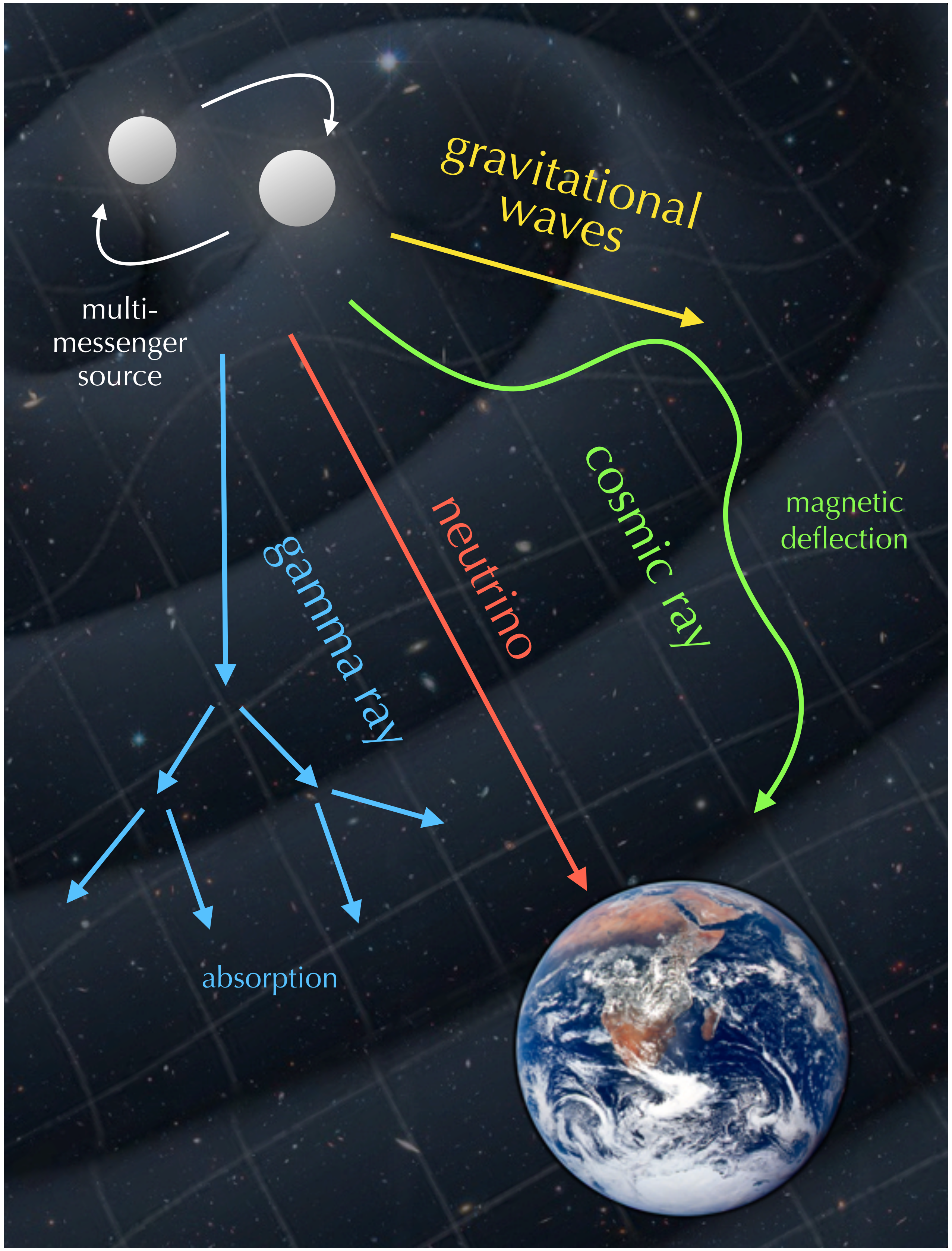
coincident with
photons and gravitational waves

no absorption in cosmic backgrounds
(unlike gamma-rays)

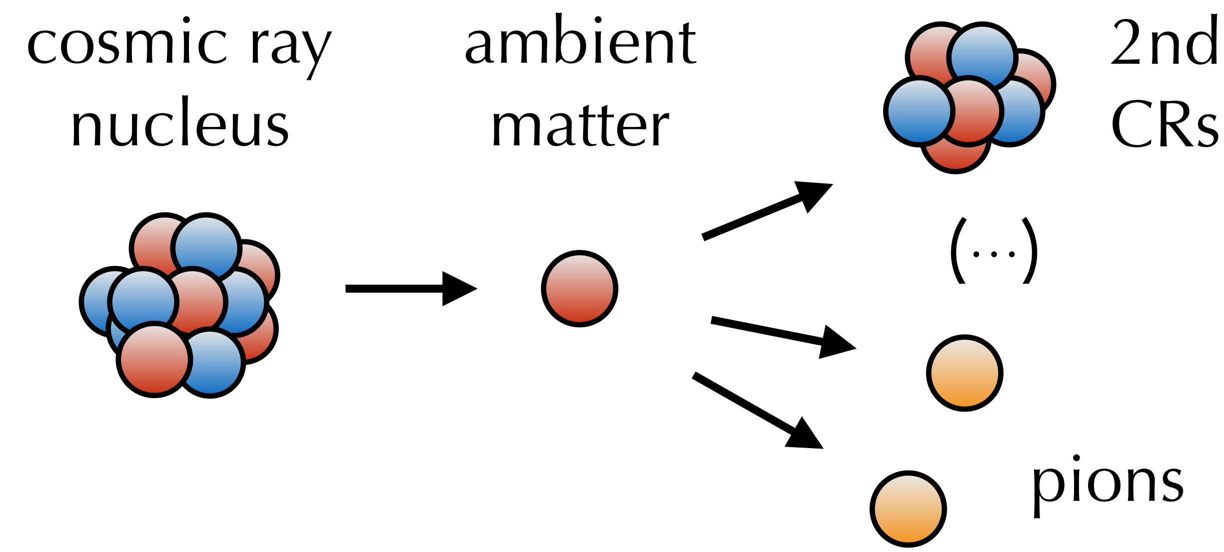
smoking-gun of
unknown sources of cosmic rays

BUT, very difficult to detect!

Multi-Messenger Interfaces



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:

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

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

Pion Production Efficiency

- pion production depend on **target opacity** $\tau = \ell\sigma n$
- "bolometric" **pion production efficiency** (with inelasticity κ):

$$f_\pi = 1 - e^{-\kappa\tau}$$

- inelasticity per pion: $\kappa_\pi = \kappa/\langle N_\pi\rangle \simeq 0.17 - 0.2$
- "bolometric" relation of the production rates Q:

$$E_\pi^2 Q_{\pi^\pm} \simeq \frac{\langle N_{\pi^\pm}\rangle}{\langle N_{\pi^0}\rangle + \langle N_{\pi^\pm}\rangle}\left[f_\pi E_N^2 Q_N(E_N)\right]_{E_N = E_\pi/\kappa_\pi}$$

- with **charged-to-neutral pion ratio** K_π:

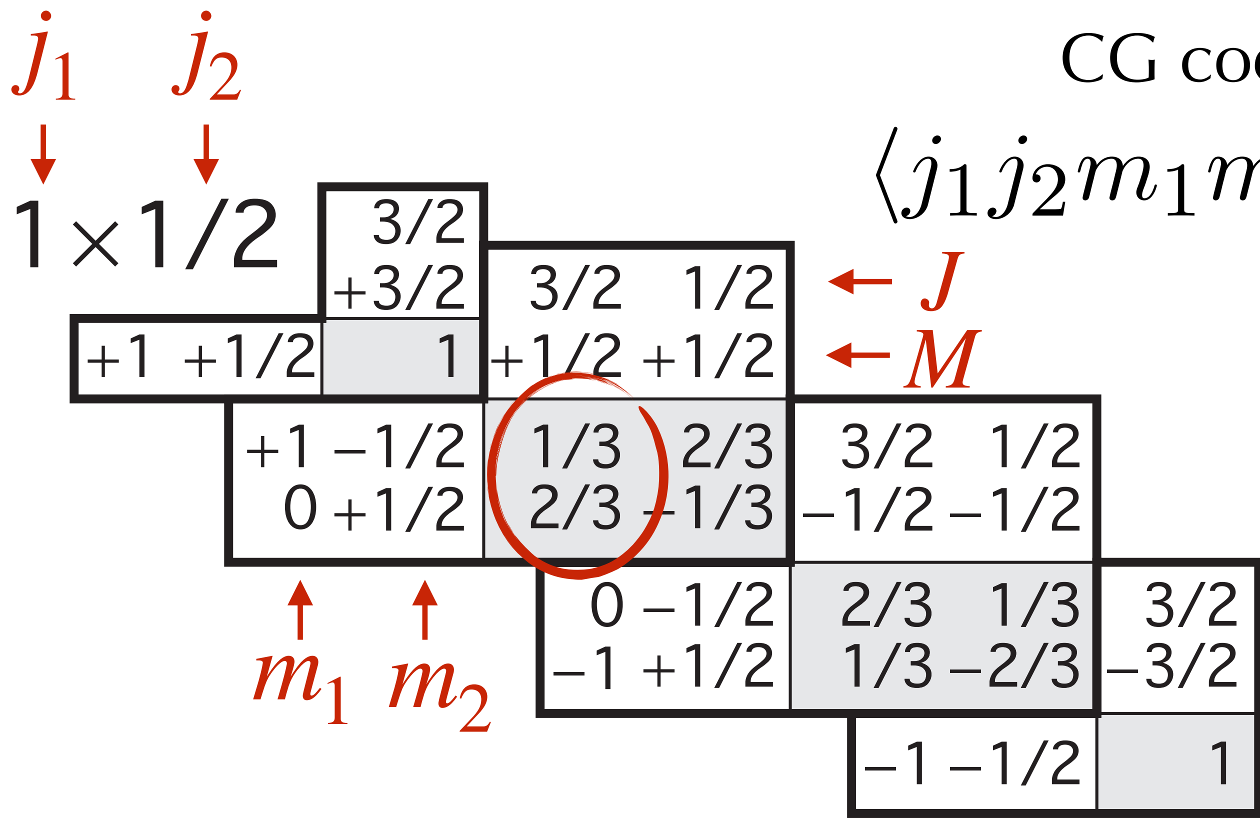
$$E_\pi^2 Q_{\pi^\pm} \simeq \frac{K_\pi}{1+K_\pi}\left[f_\pi E_N^2 Q_N(E_N)\right]_{E_N = E_\pi/\kappa_\pi} \qquad K_\pi = \frac{\langle N_{\pi^\pm}\rangle}{\langle N_{\pi^0}\rangle} = \begin{cases} 2 & \text{pp} \\ 1 & \text{p}\gamma \end{cases}$$

Sidenote: Clebsch-Gordan

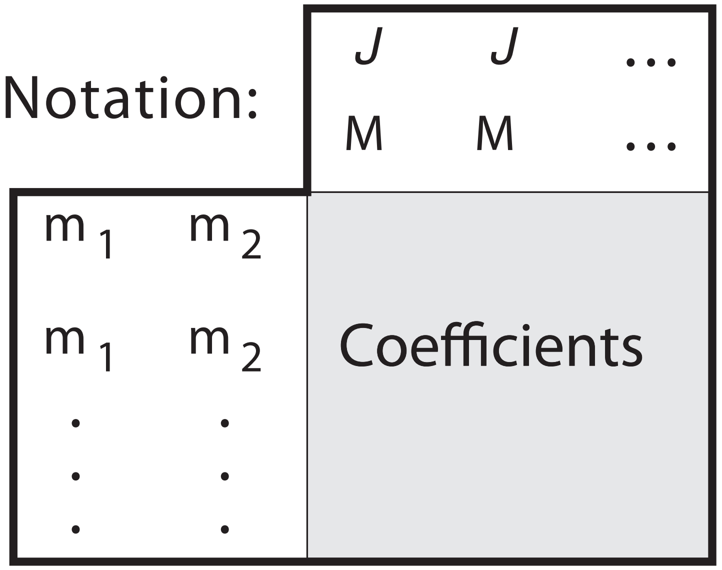
CG coefficients:

$$\langle j_1 j_2 m_1 m_2 | j_1 j_2 J M \rangle$$

from pdg.lbl.gov



Notation:



Note: A square-root sign is to be understood over *every* coefficient, *e.g.*, for $-8/15$ read $-\sqrt{8/15}$.

- **For Δ^+ resonance:** $|j_1, j_2, J, M\rangle = |1{,}1/2{,}3/2{,}1/2\rangle$
  - coefficient for $|j_1, j_2, m_1, m_2\rangle = |1{,}1/2{,}0{,}1/2\rangle$: $\mathrm{Br}(p + \pi^0) = 2/3$
  - coefficient for $|j_1, j_2, m_1, m_2\rangle = |1{,}1/2{,}1, -1/2\rangle$: $\mathrm{Br}(n + \pi^+) = 1/3$

Average Energies

- Average energy fraction of pions from CR nucleons:

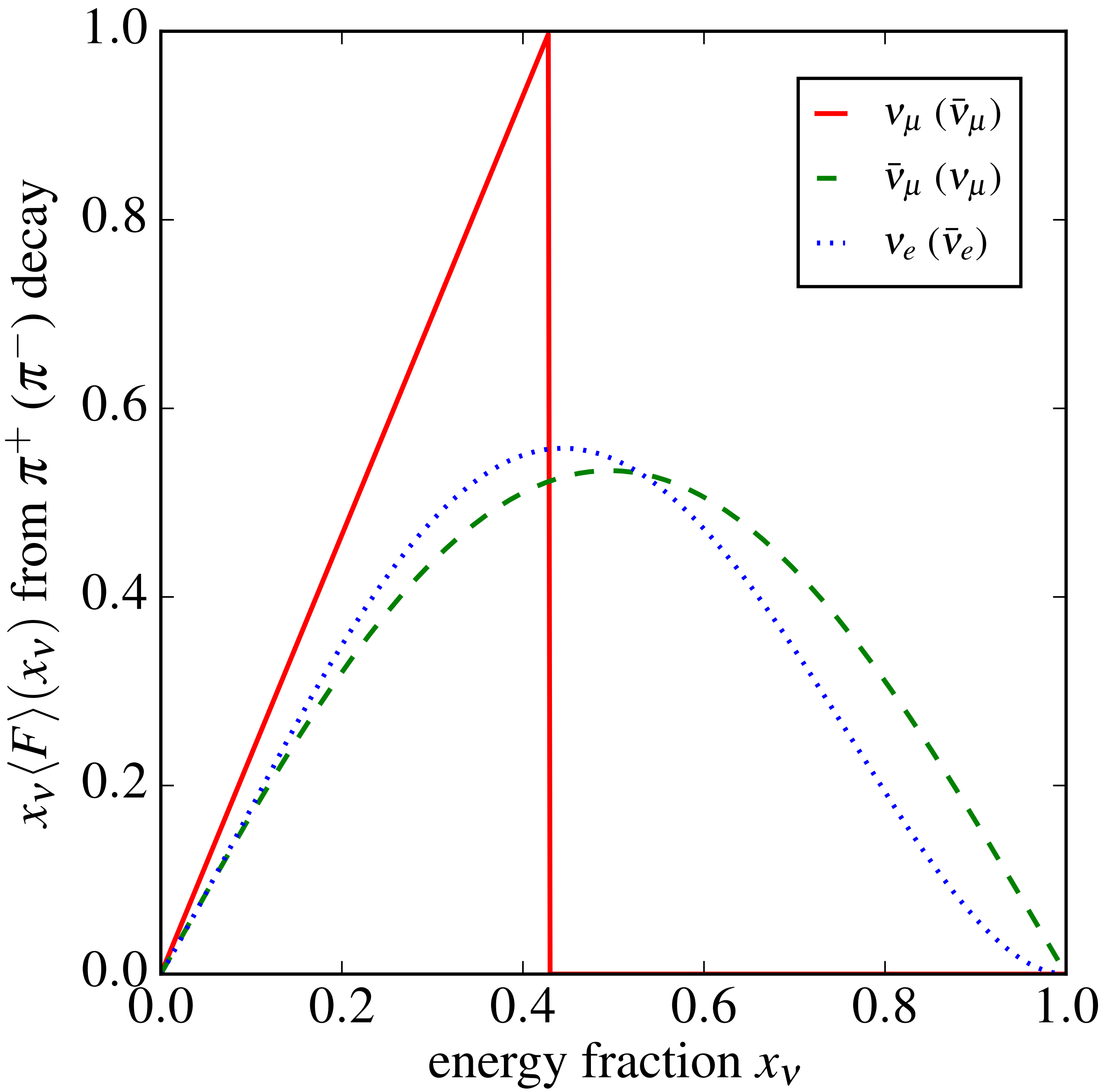
$$\langle x_\pi \rangle = \kappa_\pi \simeq 20\,\%$$

- Average energy fraction from relativistic pions ($r_\pi = (m_\mu/m_\pi)^2$)

$$\langle x_{\nu_\mu} \rangle = \frac{1 - r_\pi}{2} \simeq 21\,\%$$

$$\langle x_{\bar{\nu}_\mu} \rangle = \frac{3 + 4r_\pi}{20} \simeq 26\,\%$$

$$\langle x_{\nu_e} \rangle = \frac{2 + r_\pi}{10} \simeq 26\,\%$$



- **Approximately:**

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

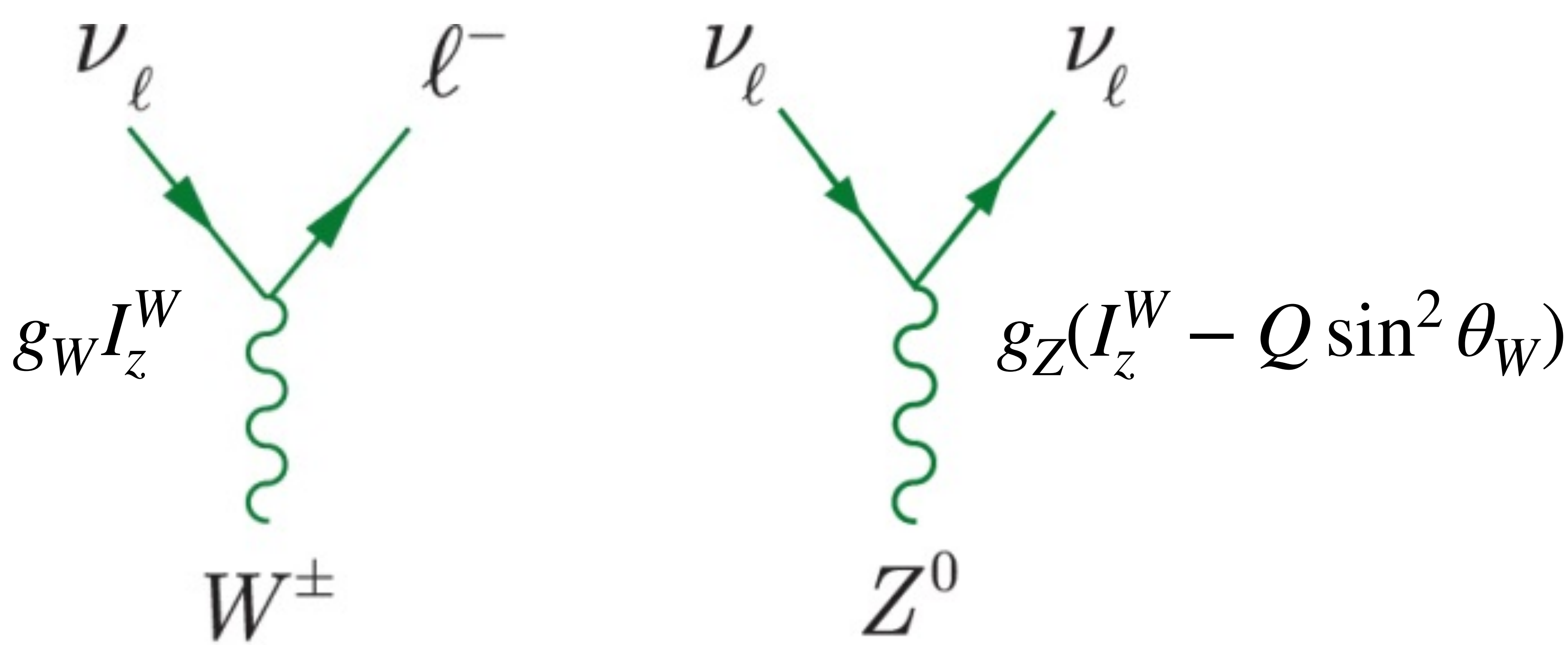
[e.g. Lipari, Lusignoli & Meloni '07]

Neutrinos in the Standard Model

Neutrinos are part of weak isospin doublets and anti-doublets:

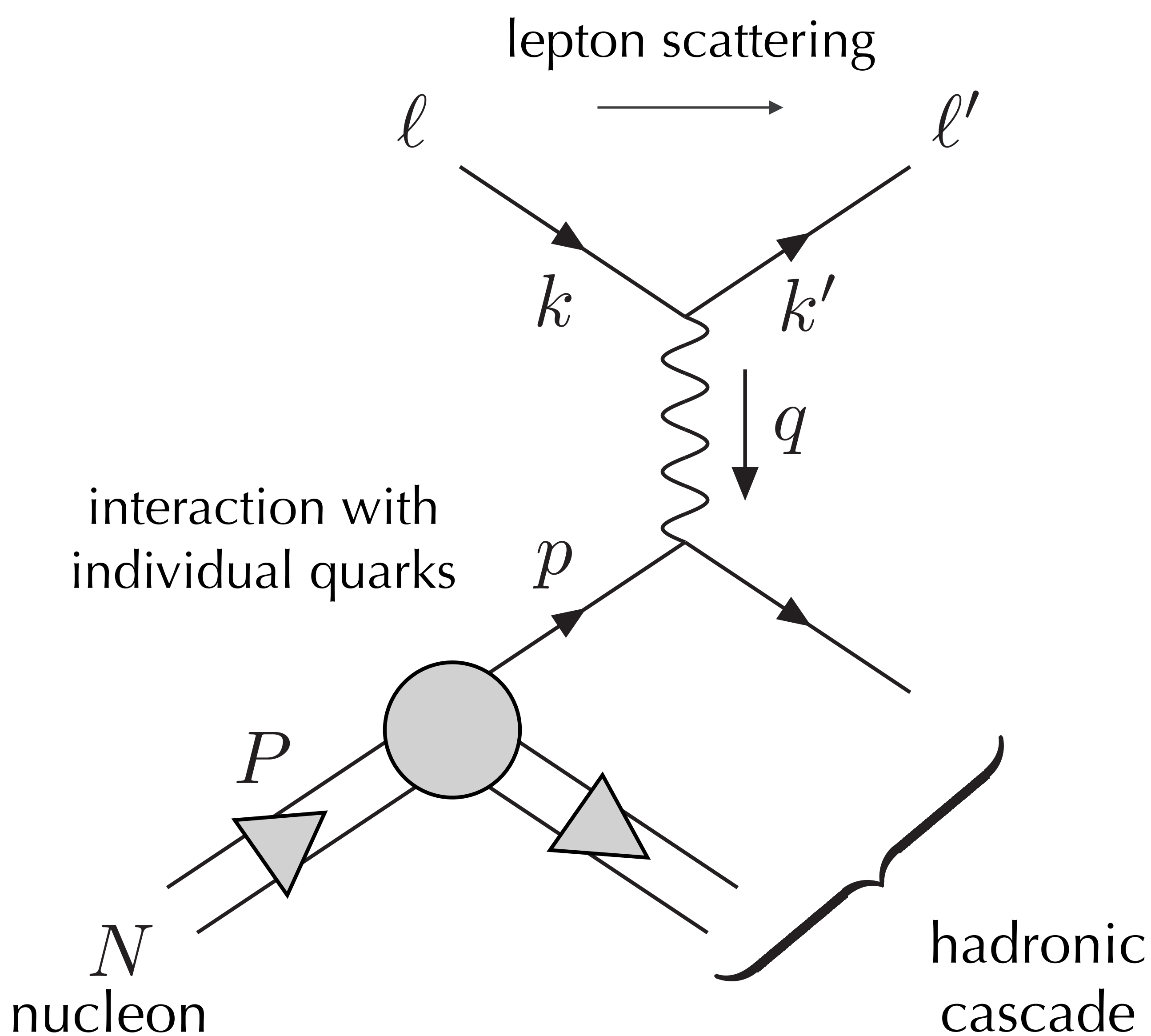
$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L \quad \begin{pmatrix} e^+ \\ \overline{\nu}_e \end{pmatrix}_R \quad \begin{pmatrix} \mu^+ \\ \overline{\nu}_\mu \end{pmatrix}_R \quad \begin{pmatrix} \tau^+ \\ \overline{\nu}_\tau \end{pmatrix}_R$$

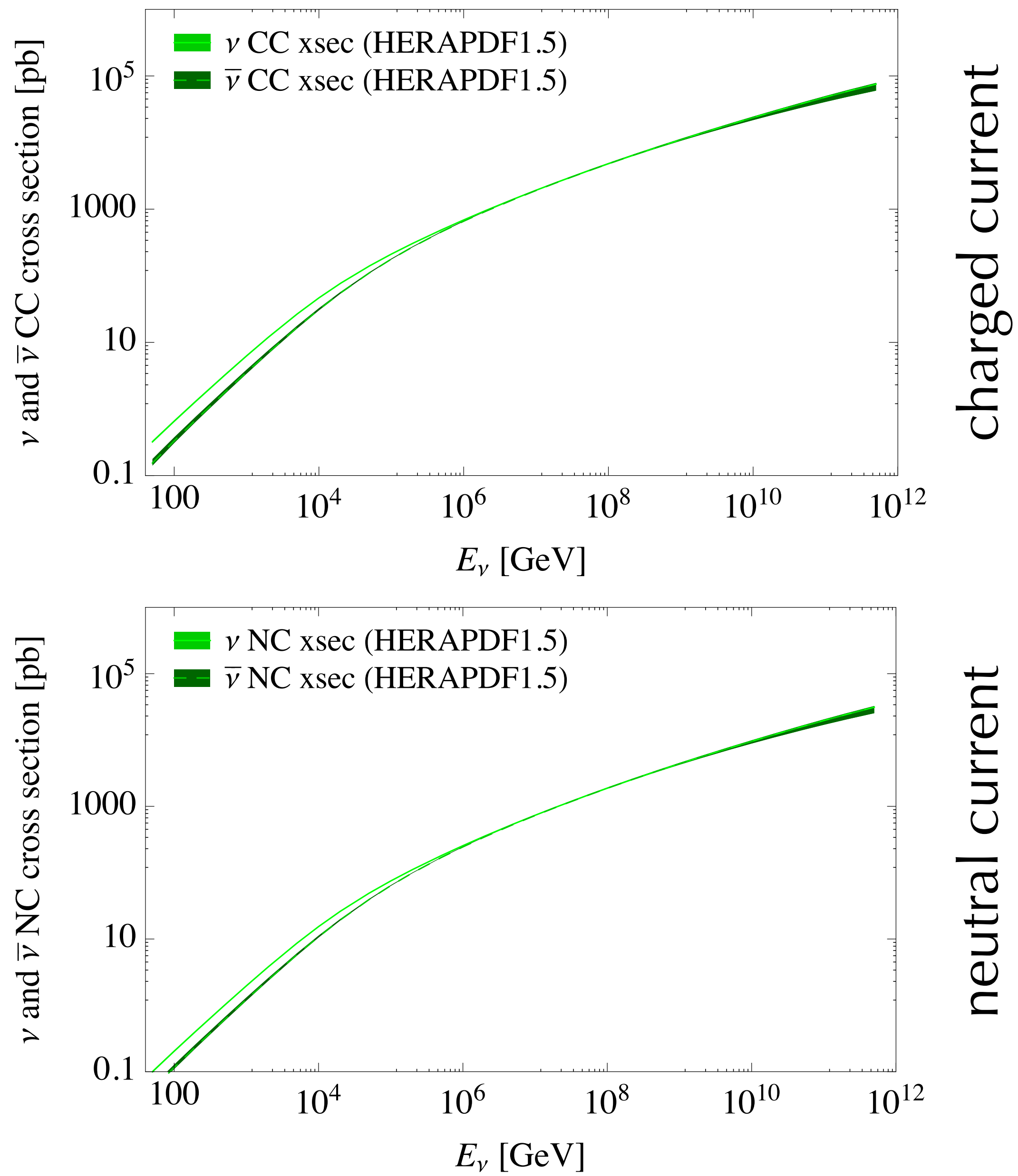
Participate in **charged** (W) **and neutral** (Z) **current** interactions:



Neutrino Interactions

- Low-energy (<10GeV) neutrino interaction with matter in coherent, quasi-elastic or resonant interactions.
- High-energy neutrinos interact with nuclei via **deep inelastic scattering.**





[Cooper-Sarkar, Mertsch & Sarkar'11]

Neutrino Astronomy

Neutrino **charged and neutral current (CC & NC) interactions** are visible by Cherenkov emission of relativistic secondaries in transparent media.

flux of PeV neutrinos: $\phi \simeq \frac{10^5}{\mathrm{km}^2\,\mathrm{yr}}$

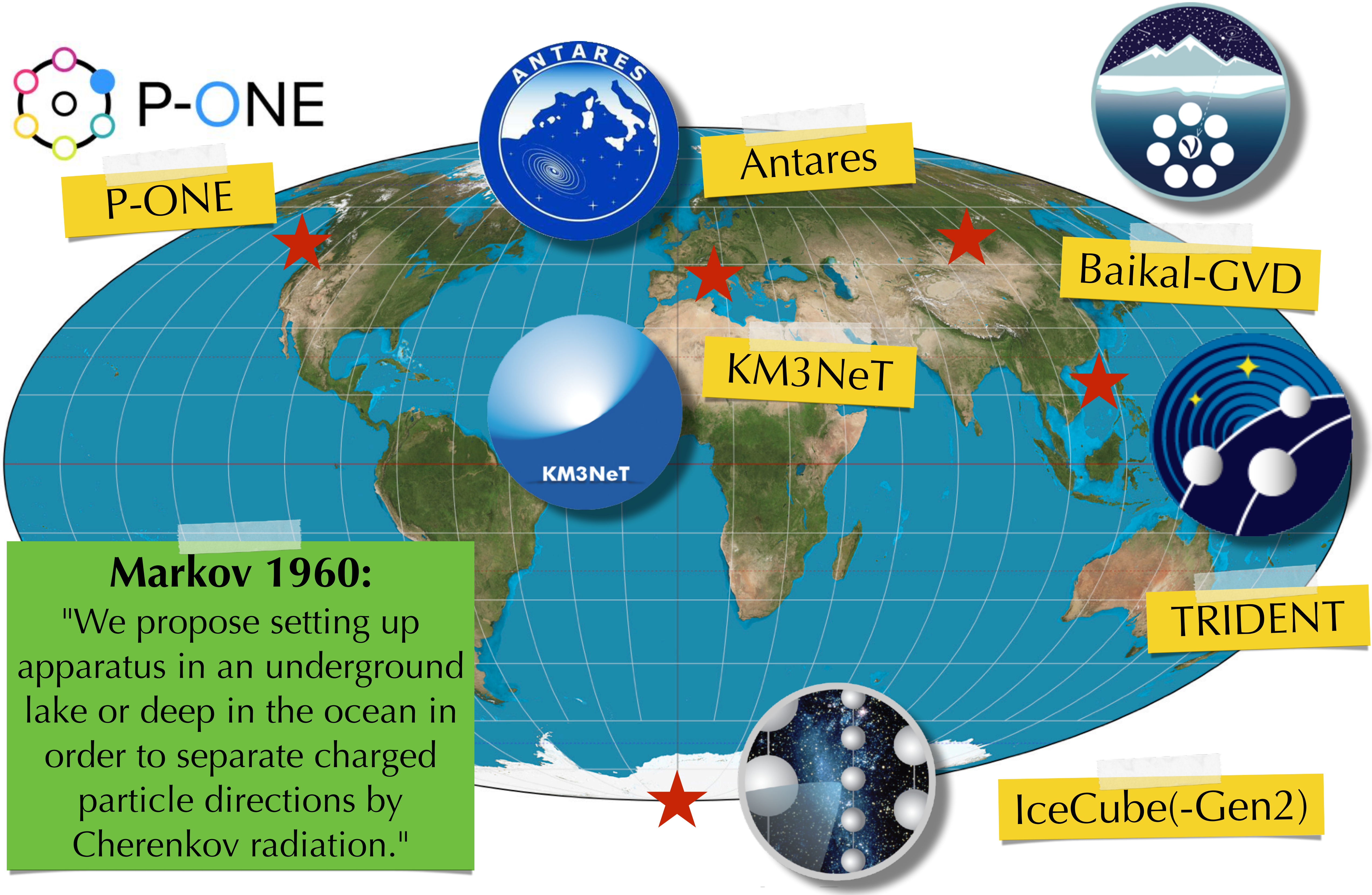
cross section: $\sigma_{\nu\mathrm{p}} \simeq 10^{-8}\sigma_{\mathrm{pp}} \simeq 10^{-33}\mathrm{cm}^2$

targets: $N_{\mathrm{target}} = N_A \times \frac{V}{\mathrm{cm}^3}$

event rate: $N_{\mathrm{events}} = N_{\mathrm{target}} \times \sigma_{\nu\mathrm{p}} \times \phi_\nu = \frac{\mathrm{few}}{\mathrm{km}^3\,\mathrm{yr}}$

minimum detector size: 1km³

Optical Cherenkov Telescopes



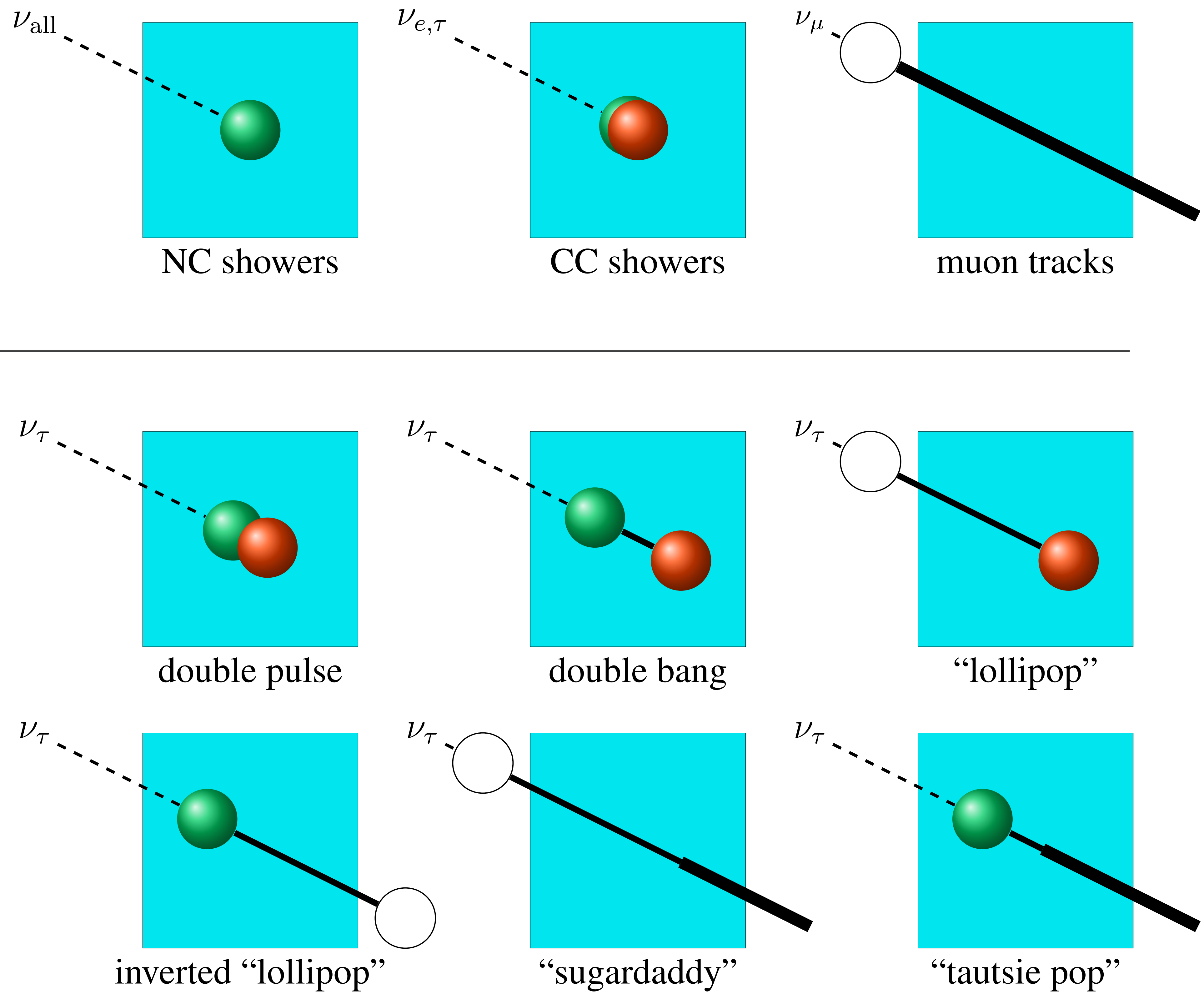
Markov 1960:

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

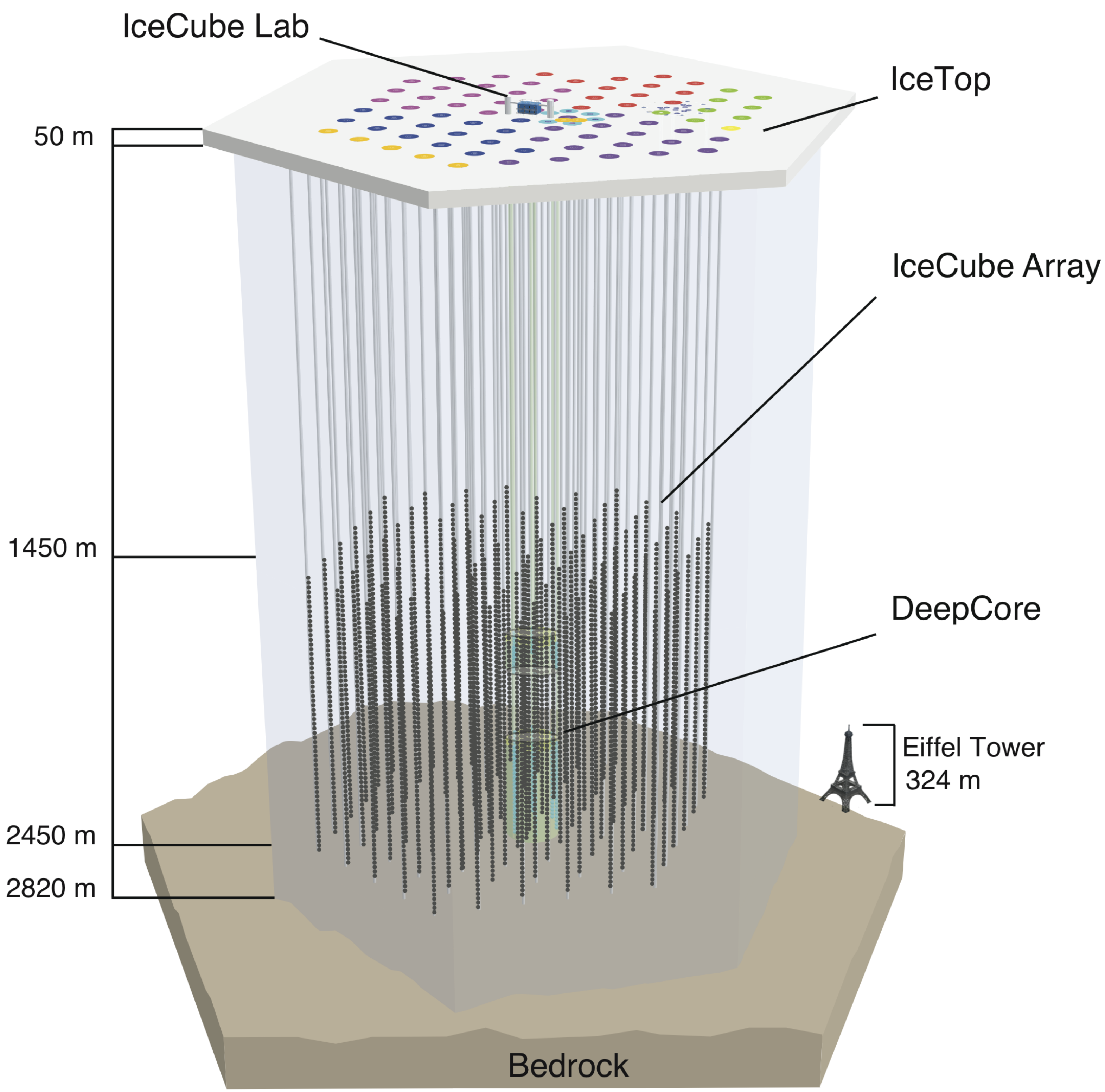
Optical Cherenkov Signals

"cascades"
&
"tracks"

rare events
from CC ν_τ
interactions

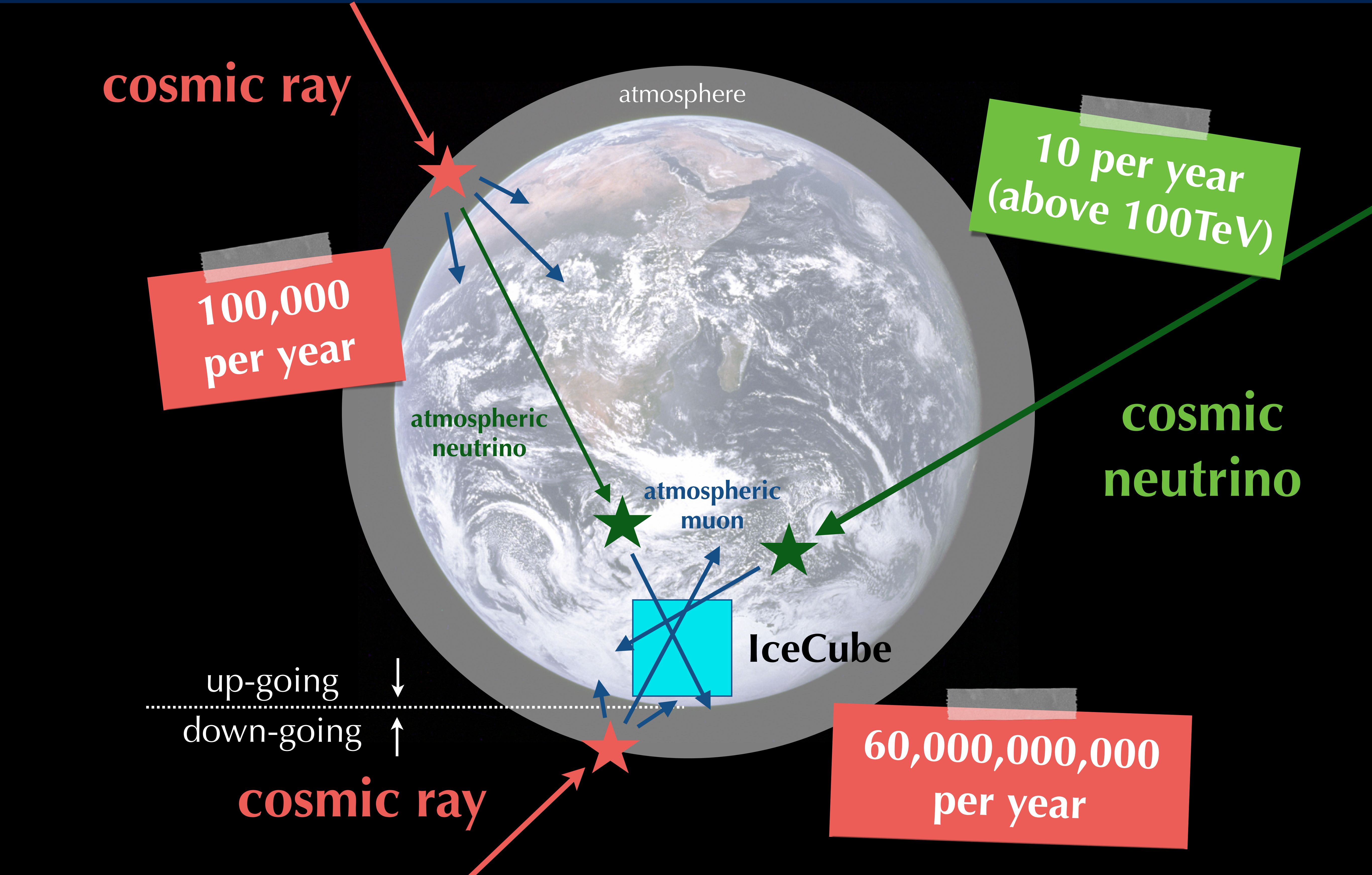


IceCube Observatory



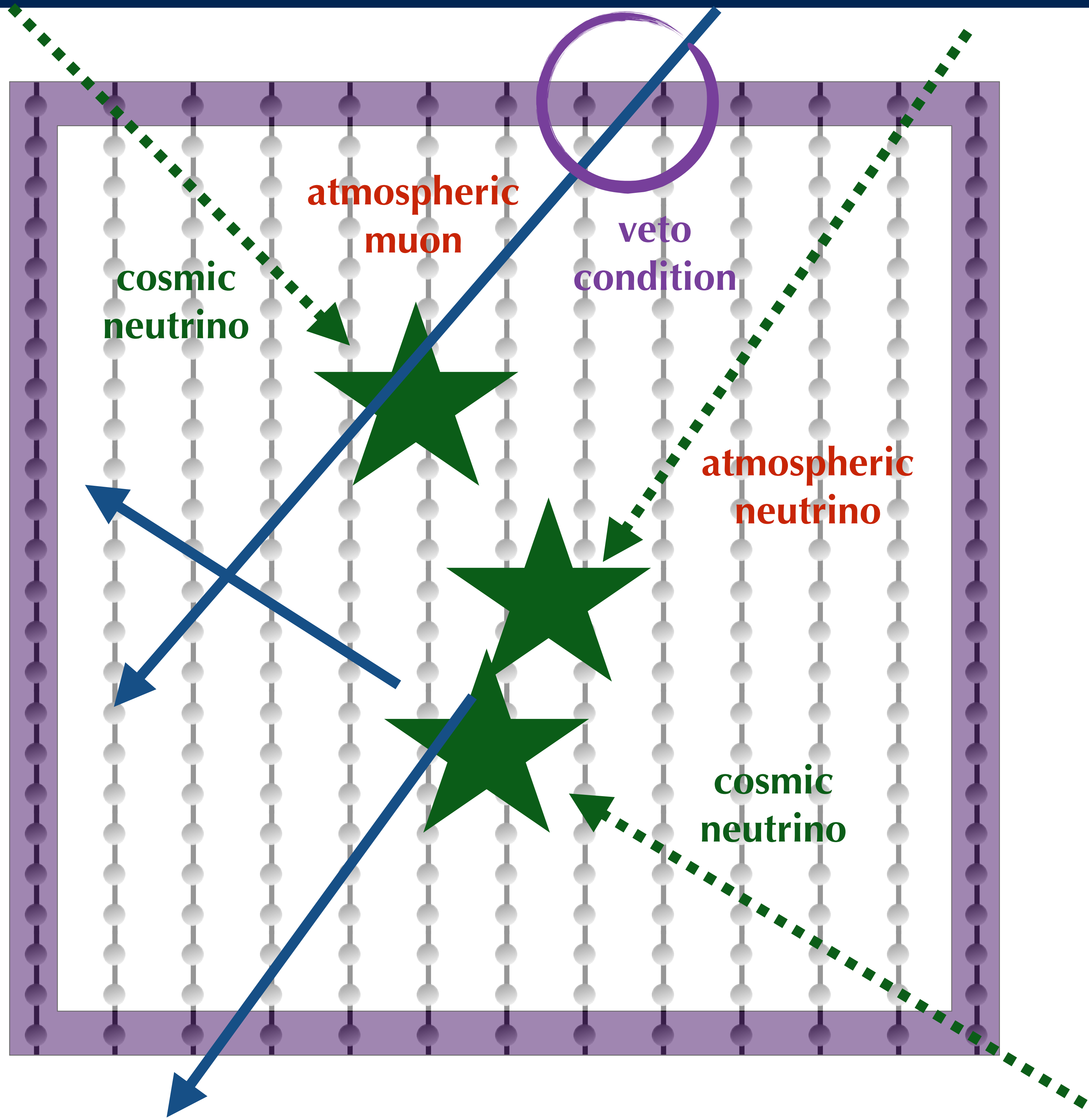
- **Giga-ton optical Cherenkov telescope at the South Pole**
- Collaboration of about 300 scientists at more than 50 international institutions
- 60 digital optical modules (DOMs) attached to strings
- 86 IceCube strings **instrumenting 1 km³ of clear glacial ice**
- 81 IceTop stations for cosmic ray shower detections

Neutrino Selection I



Neutrino Selection II

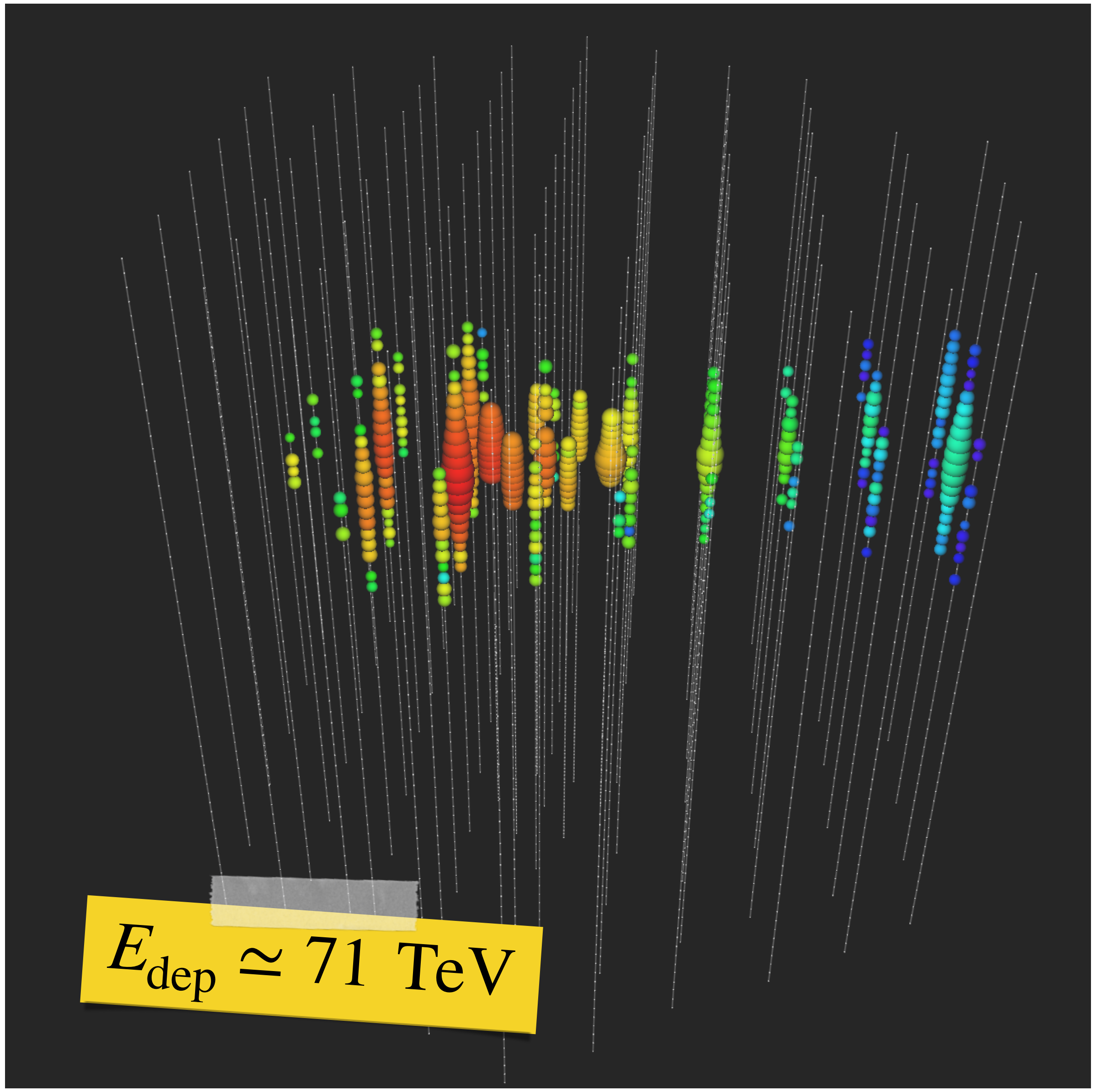
- Outer layer of optical modules used as virtual **veto region.**
- **Atmospheric muons** pass through veto from above.
- **Atmospheric neutrinos** coincidence with atmospheric muons.
- **Cosmic neutrino** events can start inside the fiducial volume.
- **High-Energy Starting Event** (HESE) analysis



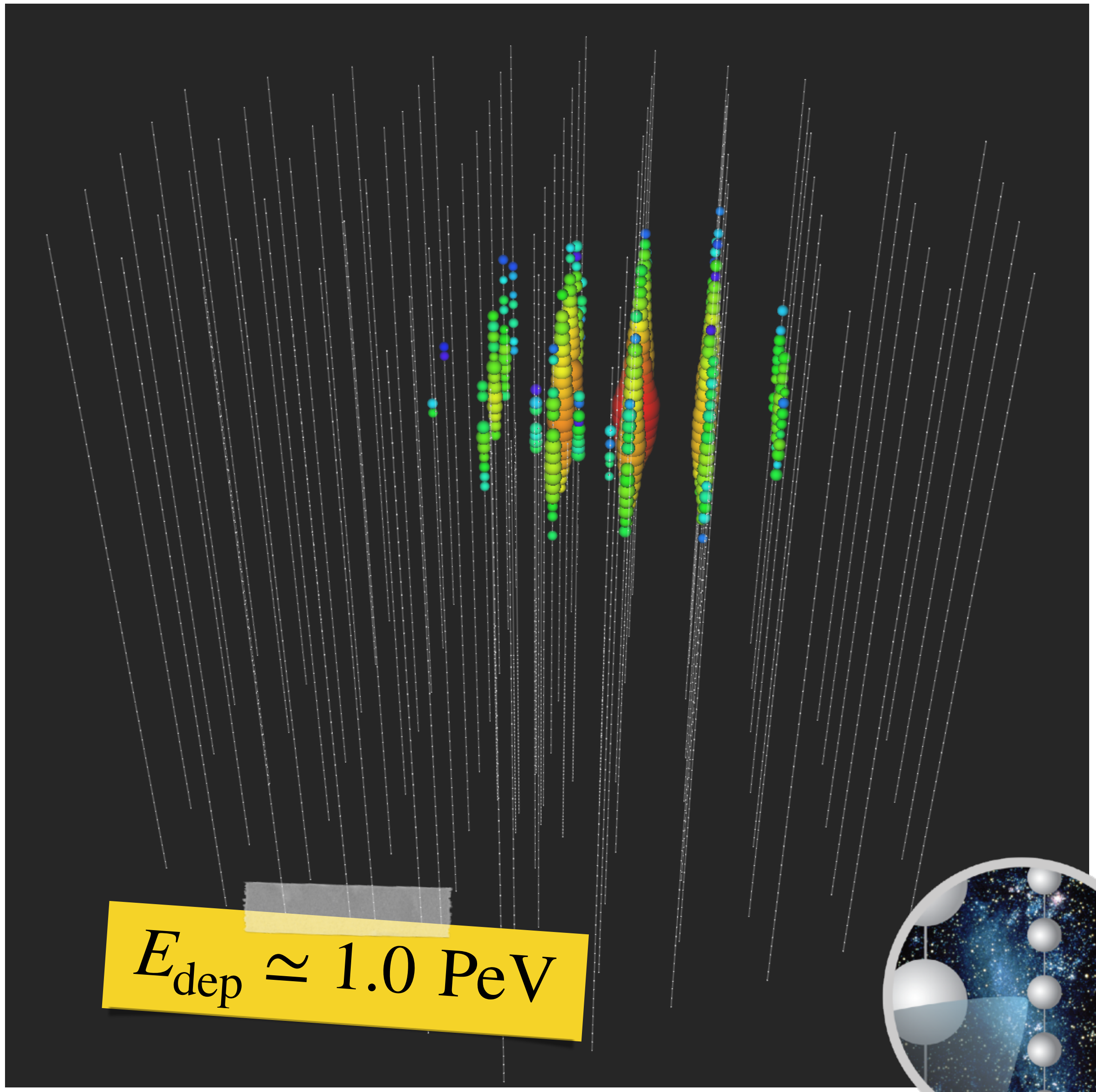
High-Energy Neutrinos

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

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

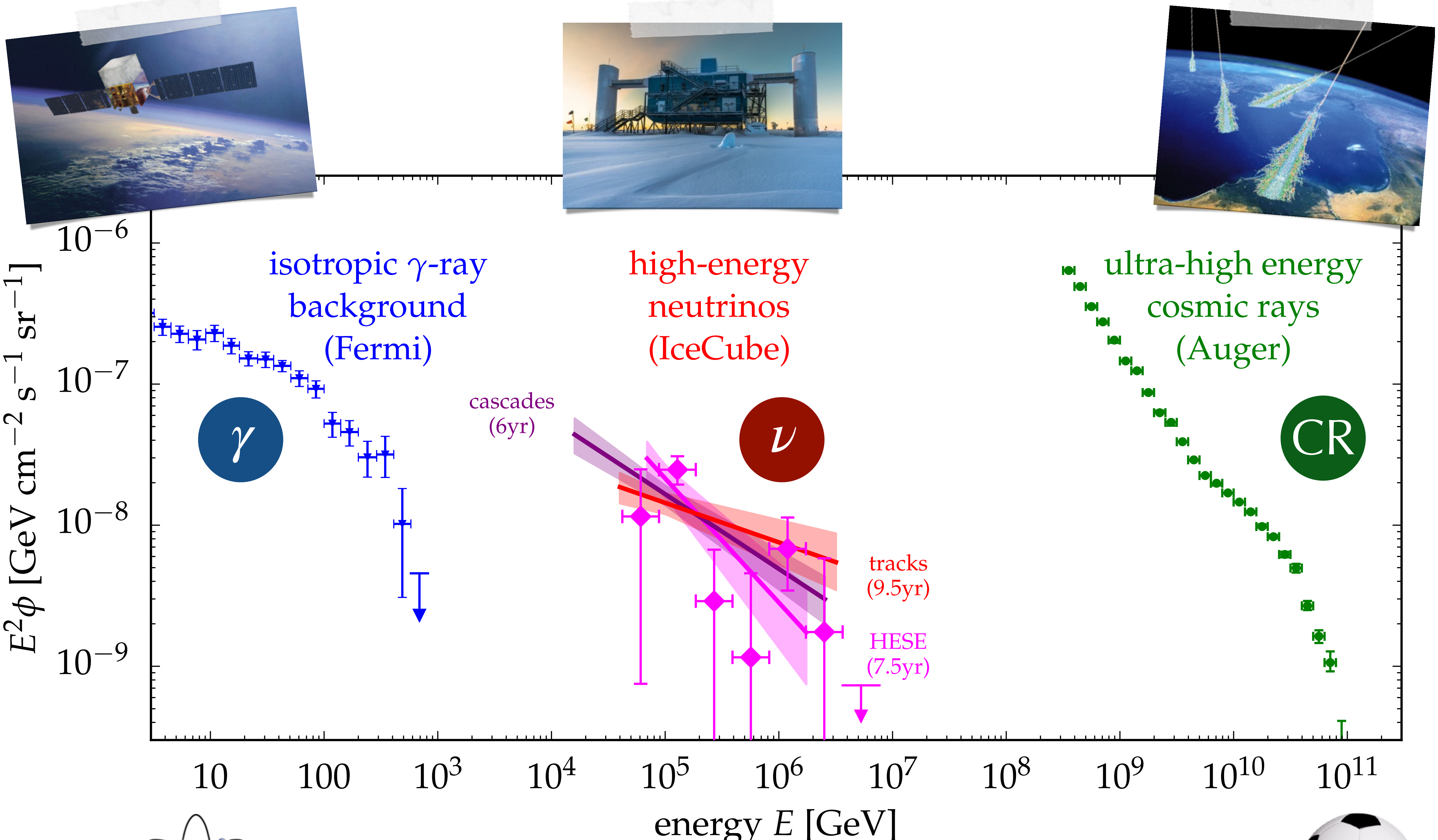


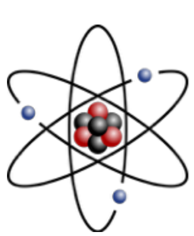
"cascade event" (e.g. NC interactions)



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

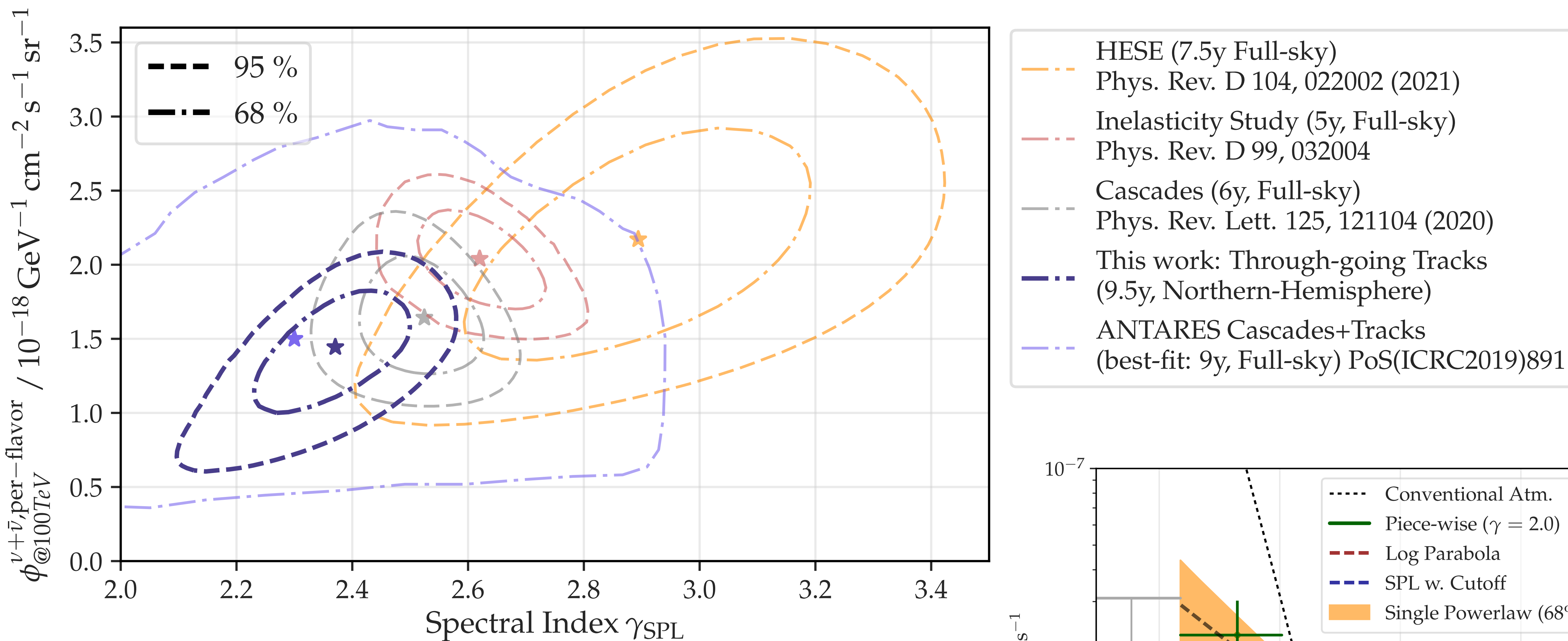
Diffuse TeV-PeV Neutrinos





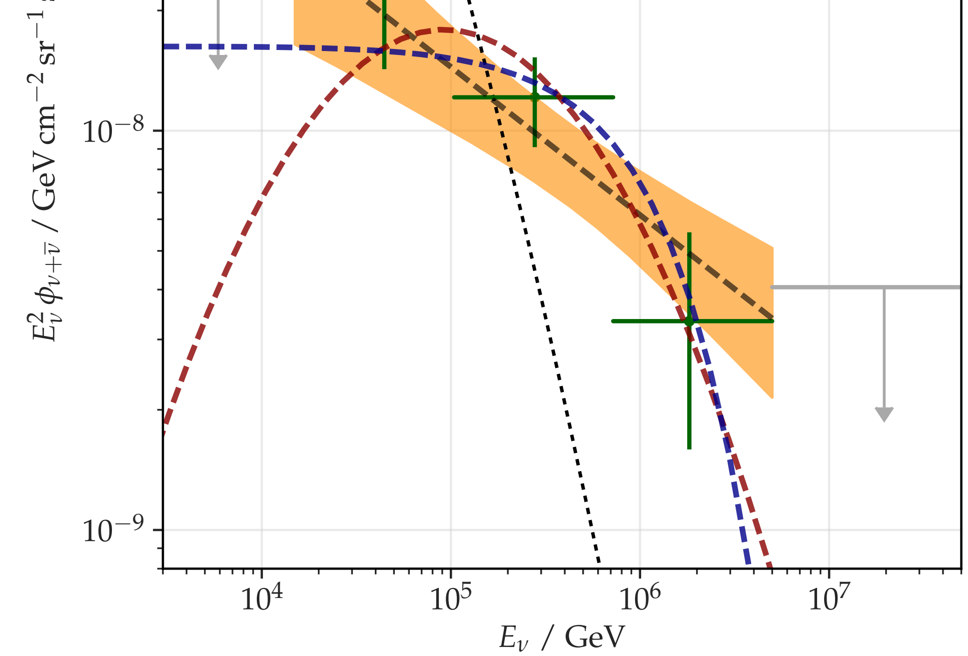
[IceCube, PRL 125 (2020) 12; PoS (ICRC2019) 1017; arXiv:2011.03545]

Isotropic Diffuse Flux

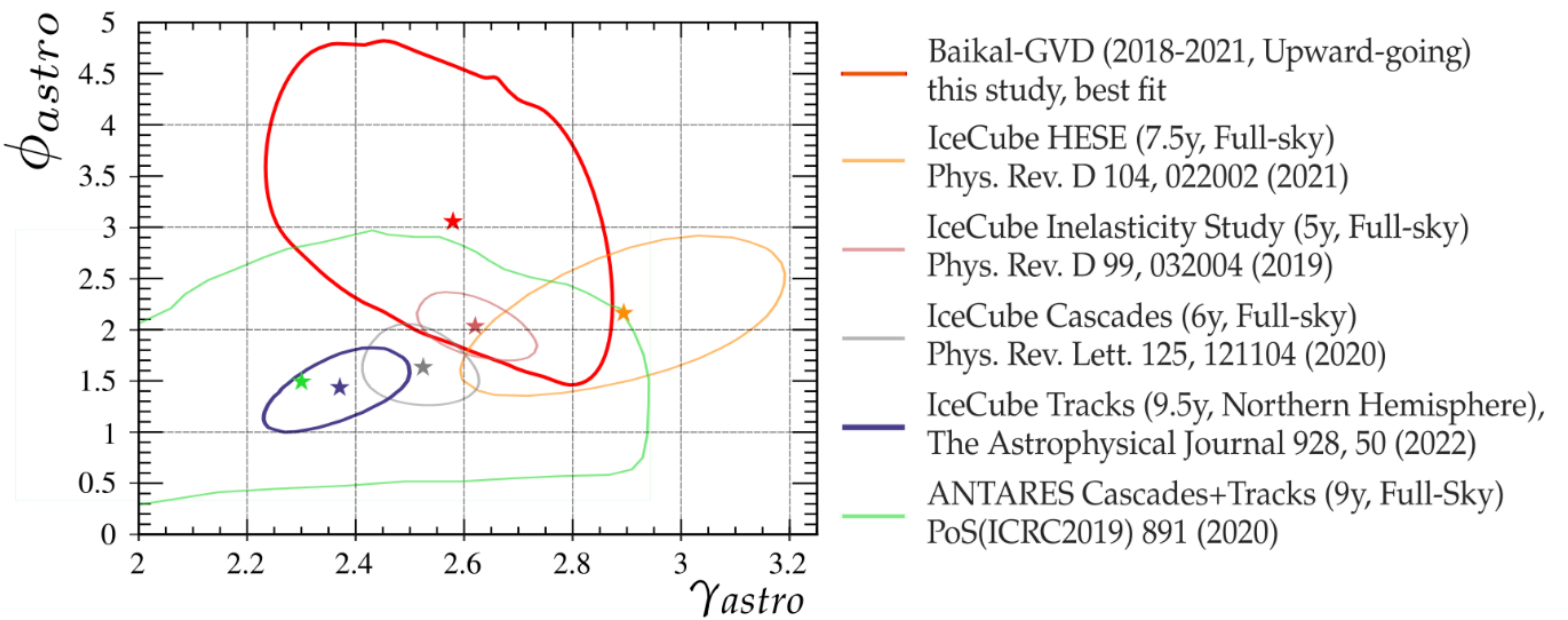


[IceCube, ApJ (2022) 928]

- Diffuse flux agrees across analyses (within their overlapping energy regions).
- However, mild tensions though for a "vanilla" single power-law flux.



Isotropic Diffuse Flux



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

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

Neutrino Mixing

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\frac{\alpha_1}{2}} & 0 & 0 \\ 0 & e^{i\frac{\alpha_2}{2}} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

"atmospheric" mixing

~~CP~~ Dirac phase $\propto \sin\theta_{13}$

"solar" mixing

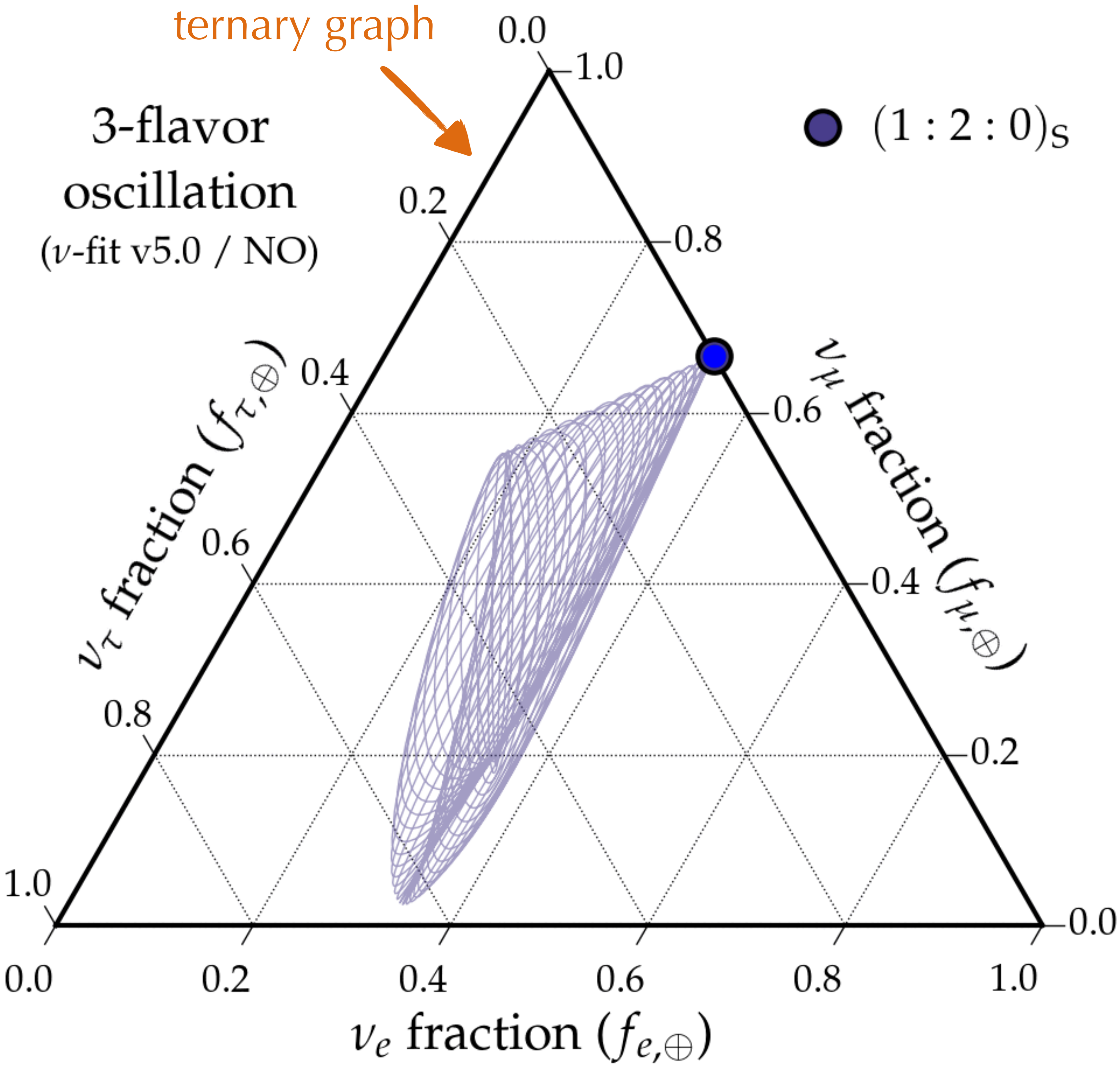
~~CP~~ Majorana phases

flavour transition probability (in vacuum):

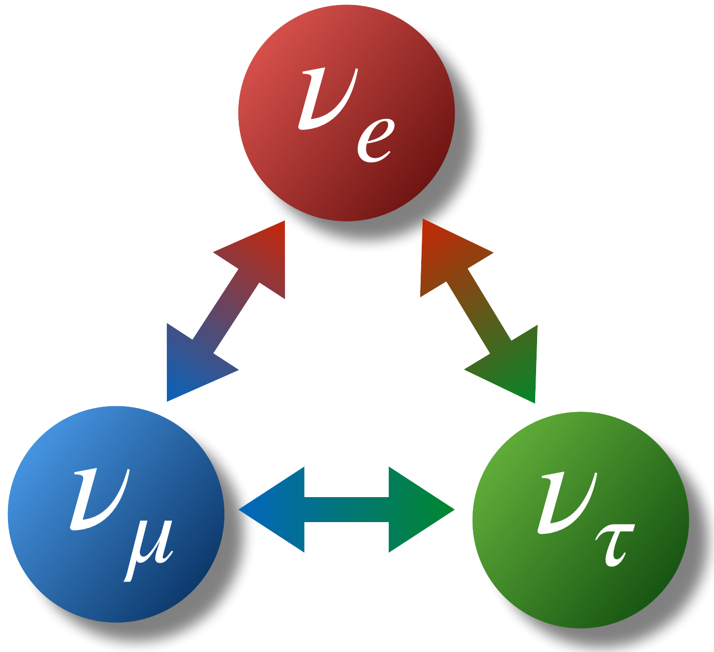
$$P_{\nu_\alpha \to \nu_\beta}(\ell) = \sum_{i=1}^{3} \sum_{j=1}^{3} U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j} \exp\left(i \frac{\Delta m^2_{ij} \ell}{2E_\nu} \right)$$

notation: $c_{ij} \equiv \cos\theta_{ij}$ & $s_{ij} \equiv \sin\theta_{ij}$ & $\Delta m^2_{ij} \equiv m_i^2 - m_j^2$

Astrophysical Flavours



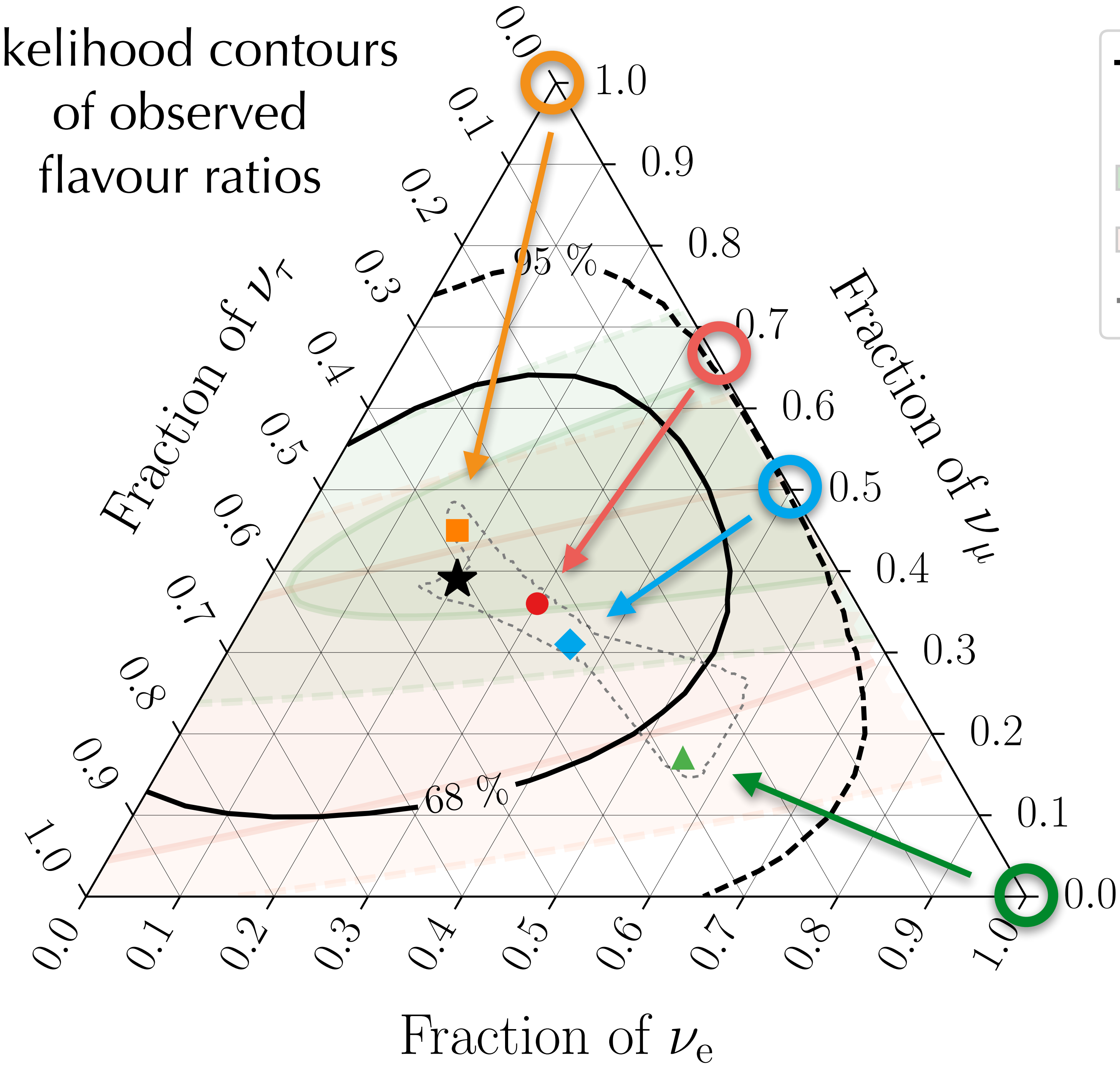
Superposition of flavor and mass states induce oscillations.



Astrophysical Flavours

Cosmic neutrinos visible via their oscillation-averaged flavour.

Likelihood contours of observed flavour ratios



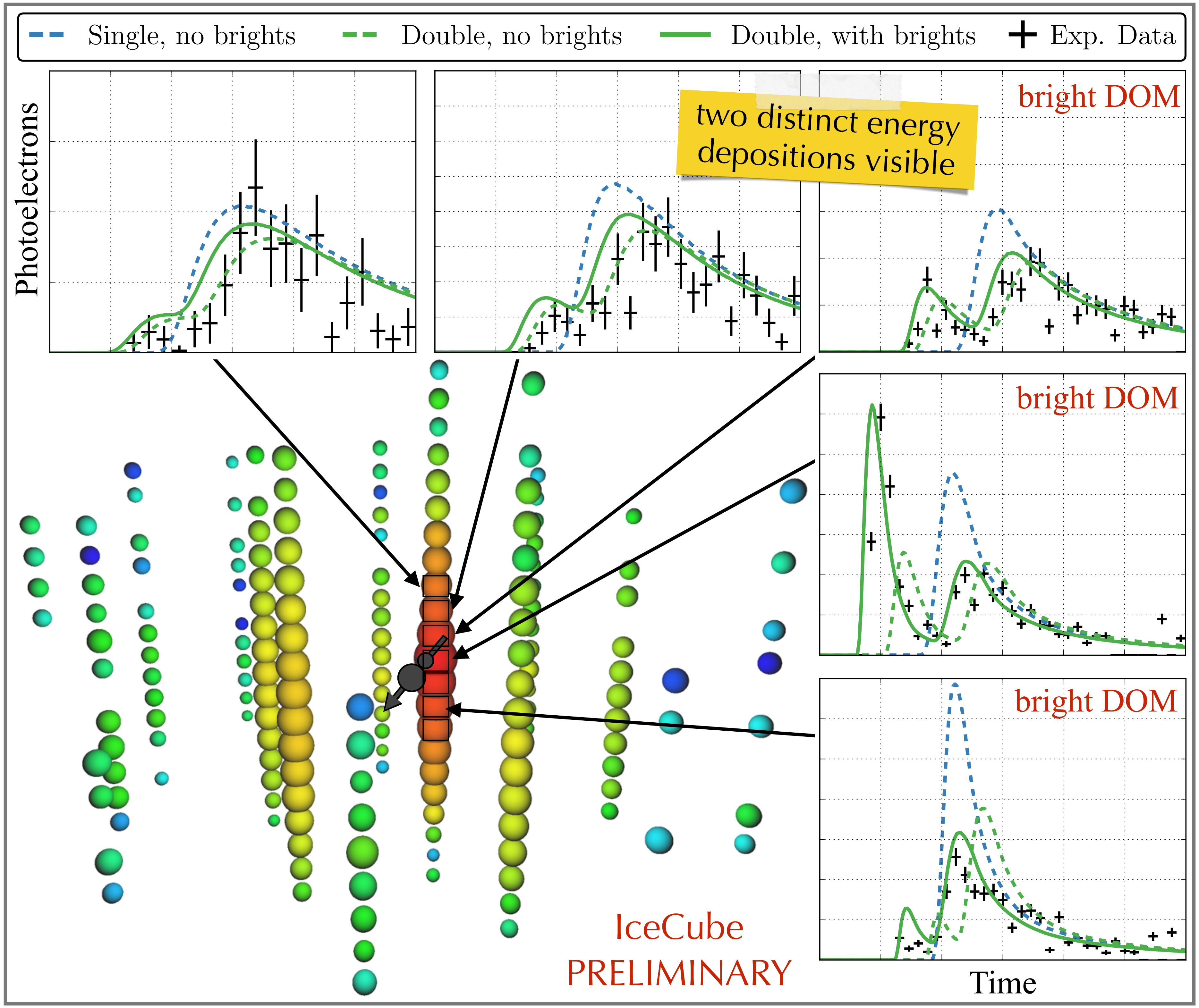
- HESE with ternary topology ID
- ★ Best fit: 0.20 : 0.39 : 0.42
- Global Fit (IceCube, APJ 2015)
- Inelasticity (IceCube, PRD 2019)
- 3ν-mixing 3σ allowed region

$\nu_e : \nu_\mu : \nu_\tau$ at source $\to$ on Earth:

■ (orange)	0:1:0 $\to$ 0.17 : 0.45 : 0.37
● (red)	1:2:0 $\to$ 0.30 : 0.36 : 0.34
▲ (green)	1:0:0 $\to$ 0.55 : 0.17 : 0.28
◆ (blue)	1:1:0 $\to$ 0.36 : 0.31 : 0.33

[IceCube, Eur. Phys. J. C 82, 1031 (2022)]

Astrophysical Flavours



[IceCube, arXiv:2011.03561]

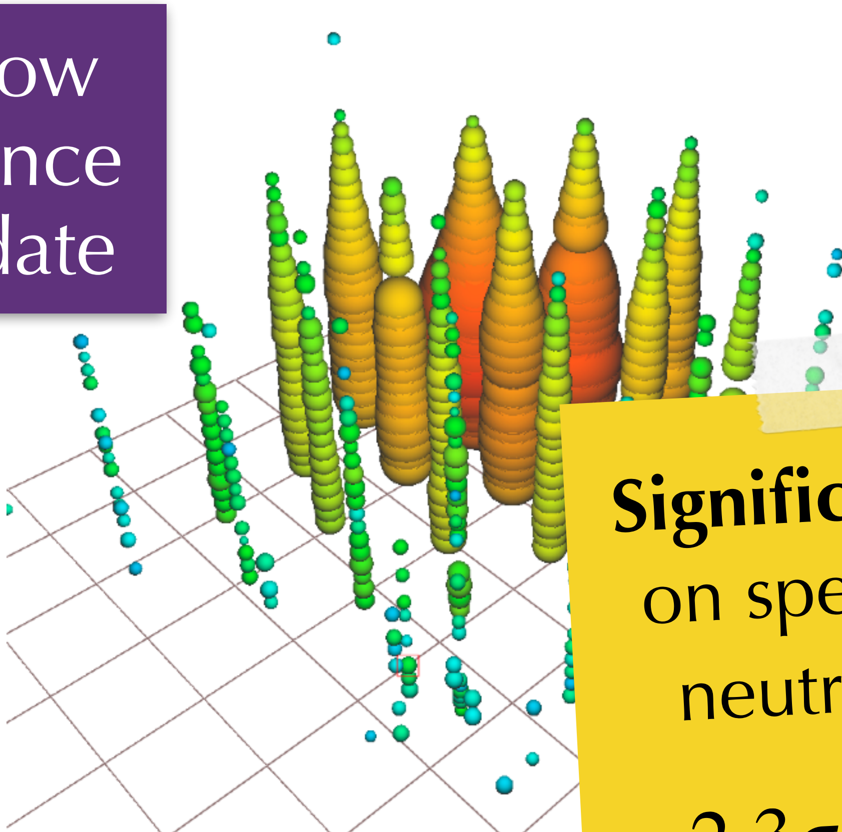
tau neutrino candidate

ICECUBE

- **Tau neutrino** charged current interactions can produce delayed hadronic cascades from tau decays.
- Arrival time of Cherenkov photons is visible in individual DOMs.

Astrophysical Flavours

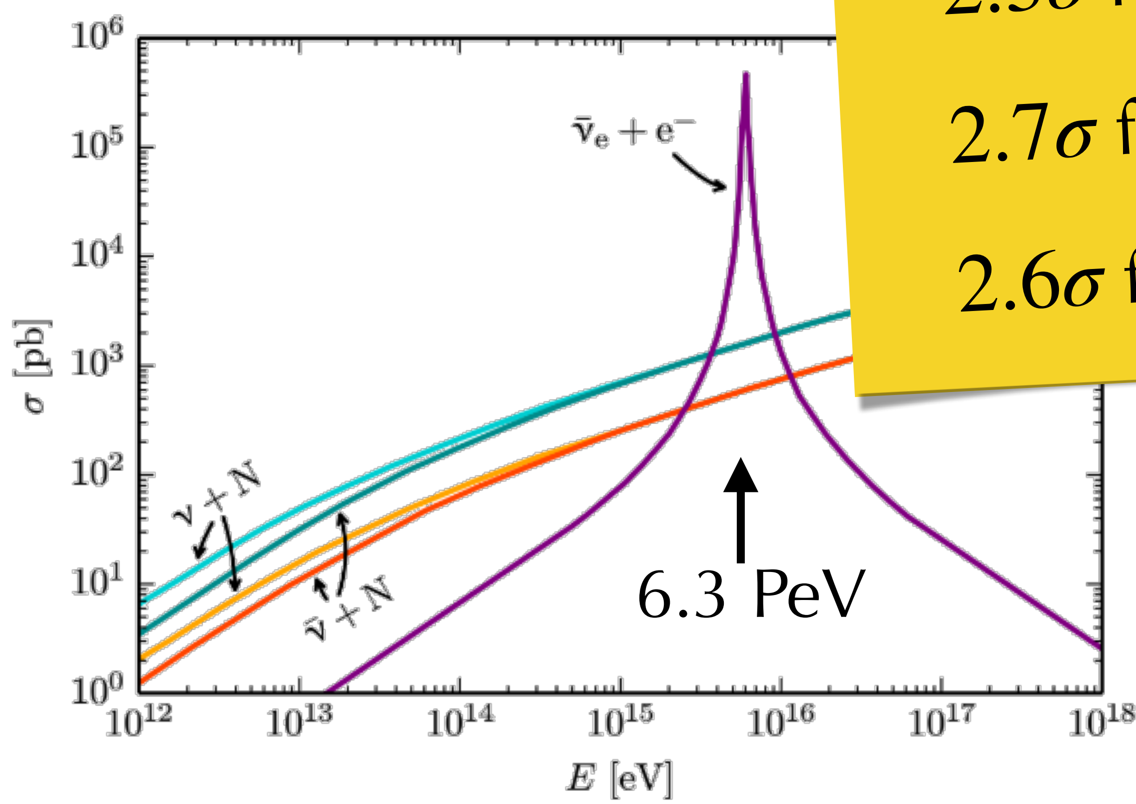
Glashow resonance candidate



ICECUBE

Resonant interaction of **electron anti-neutrinos** with electrons at 6.3PeV:

$$\bar{\nu}_e + e^- \rightarrow W^- \rightarrow X$$

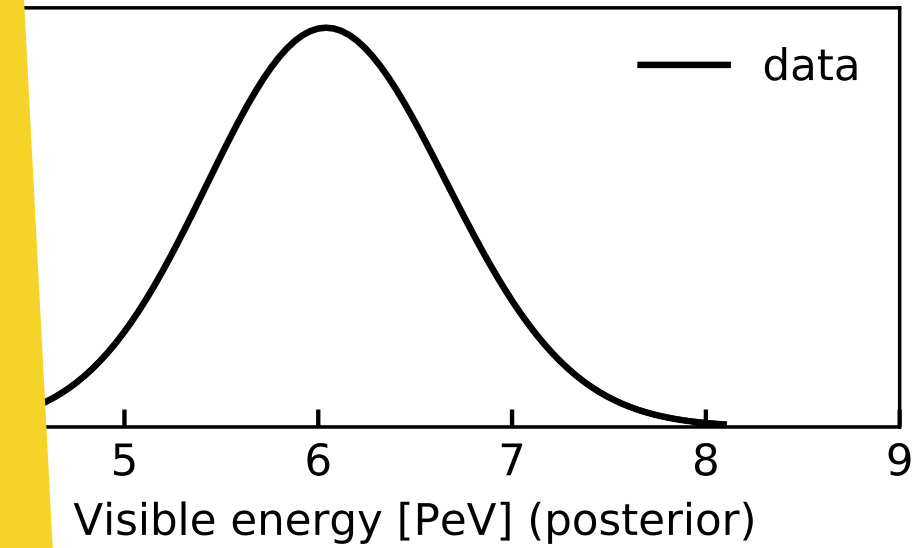


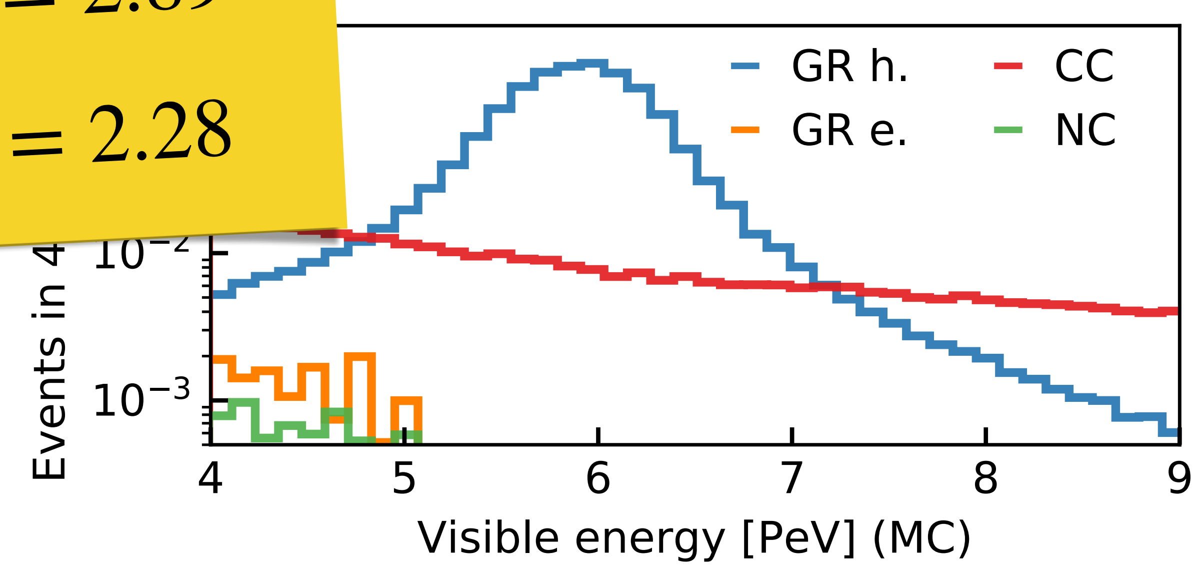
Significance depends on spectral index of neutrino flux: $E^{-\gamma}$

2.3σ for $\gamma = 2.49$

2.7σ for $\gamma = 2.89$

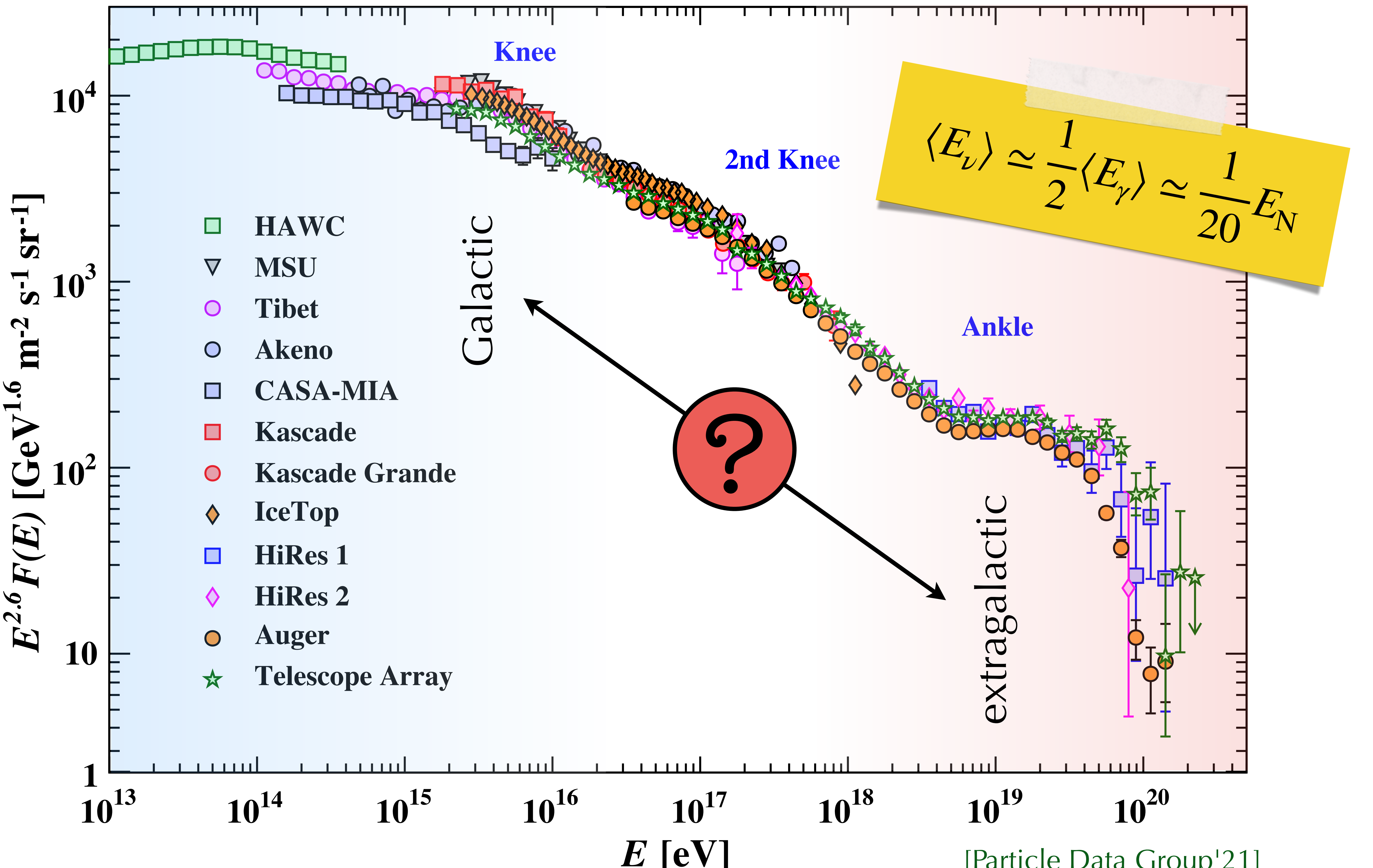
2.6σ for $\gamma = 2.28$





[IceCube, Nature 591 (2021) 220-224]

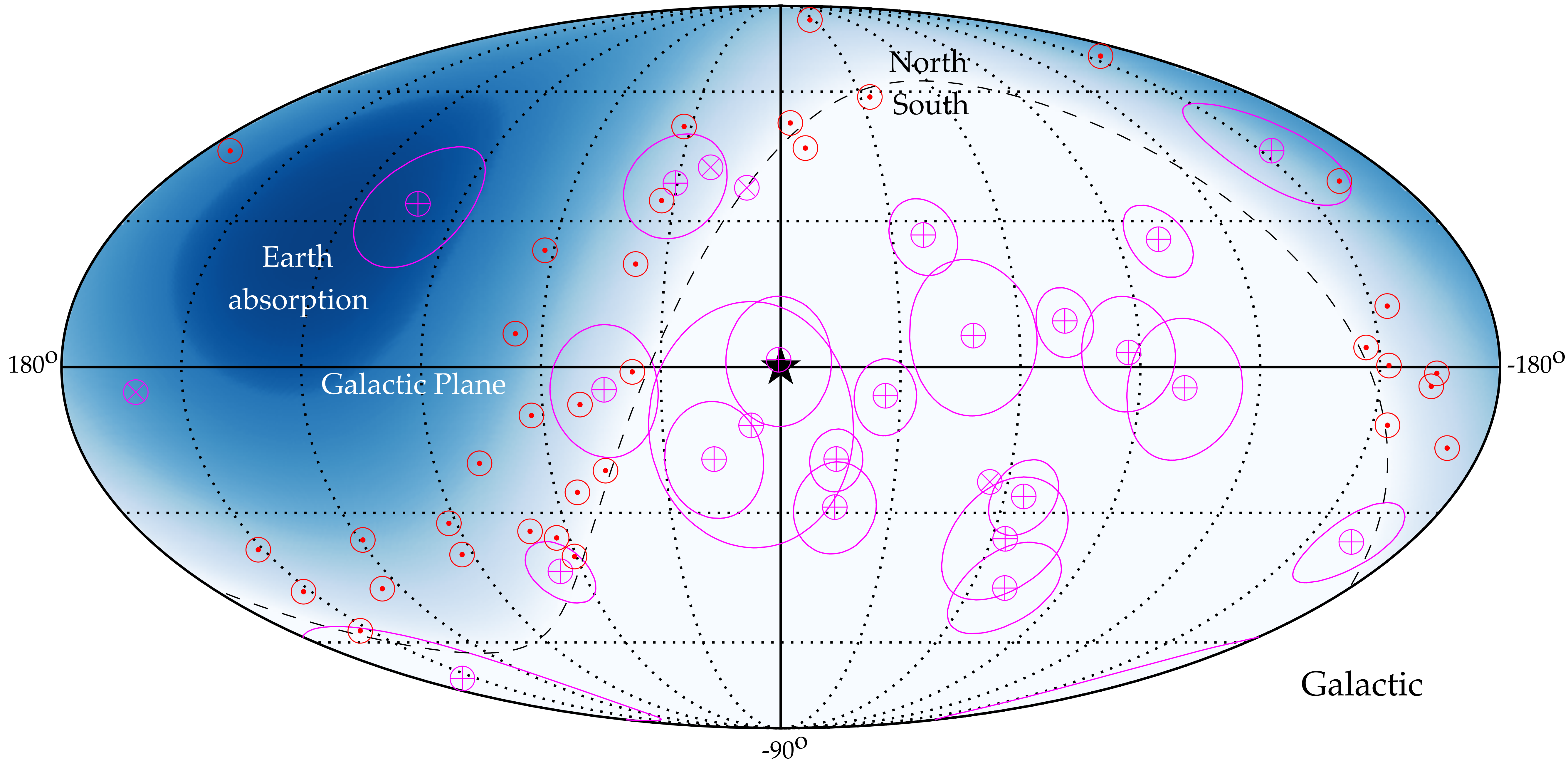
Very-High Energy Cosmic Rays



[Particle Data Group'21]

Status of Neutrino Astronomy

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

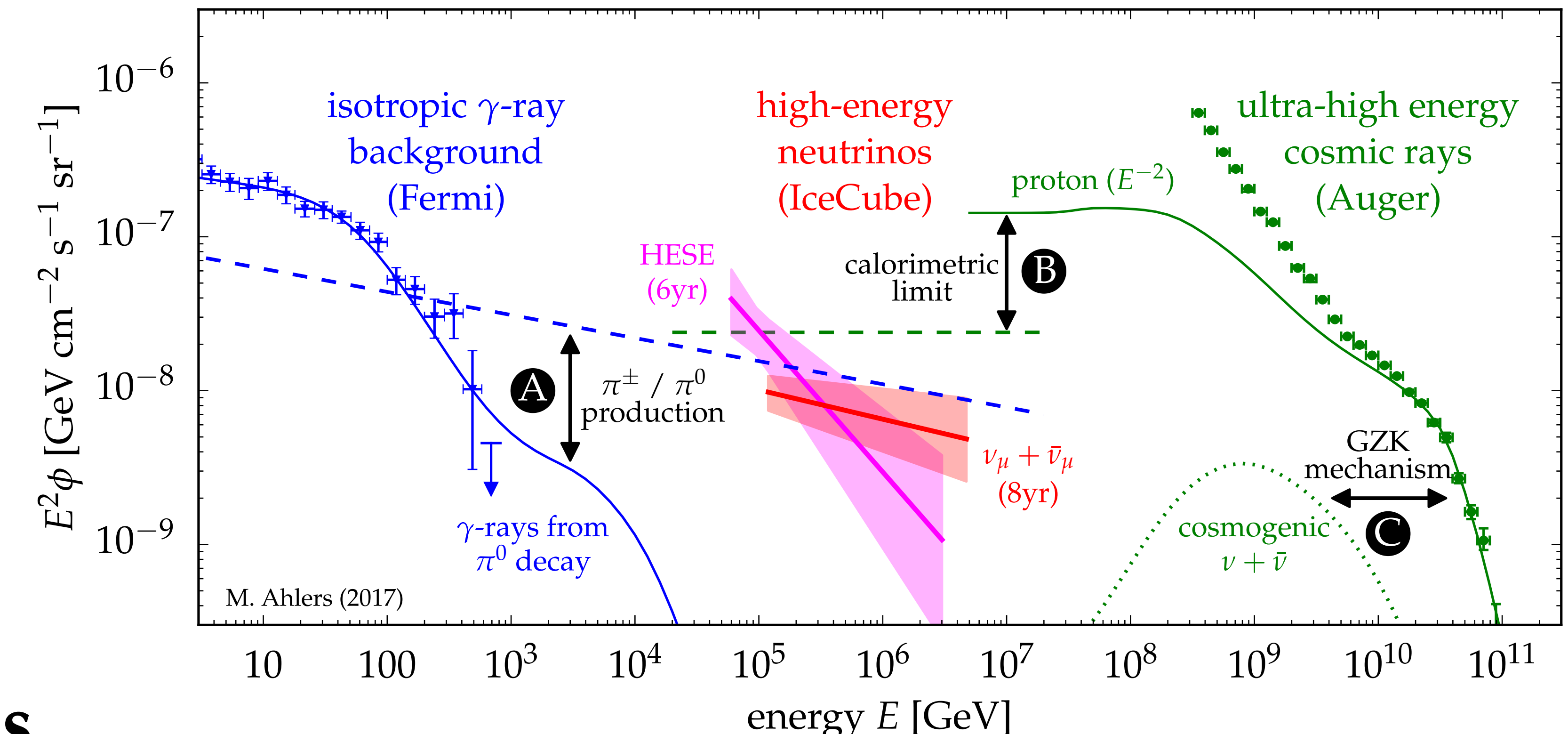


No significant steady or transient emission from known Galactic or extragalactic high-energy sources, but **several interesting candidates.**

Status of Neutrino Astronomy

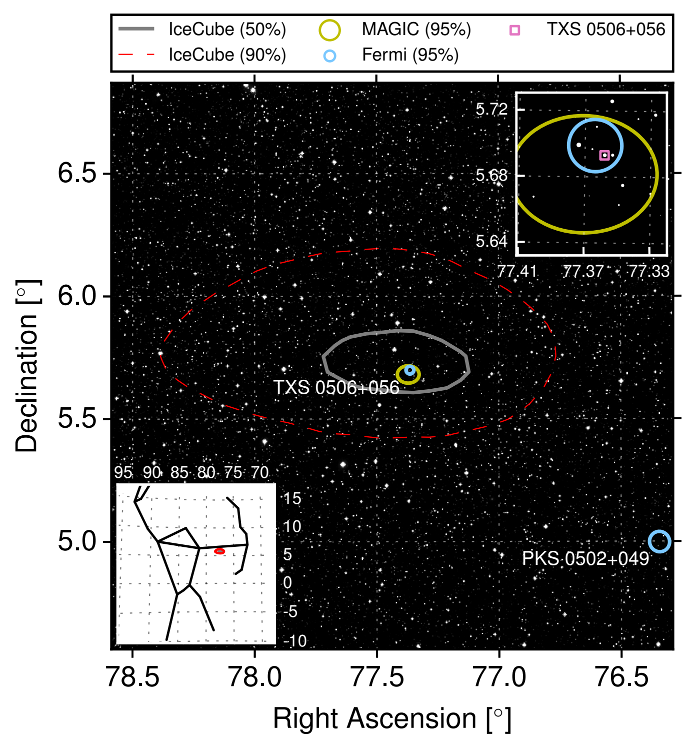
- **High neutrino intensity** compared to other cosmic backgrounds.
- **Open questions**:
  - ⋆ origin?
  - ⋆ spectral features?
  - ⋆ consistent MM emission?
- **Some strong indications for individual sources:**
  - ⋆ blazar TXS 0506+056
  - ⋆ Seyfert II galaxy NGC 1068
  - ⋆ Galactic plane
- **Many interesting (but weak) correlations** with other candidate sources.

multi-messenger interfaces



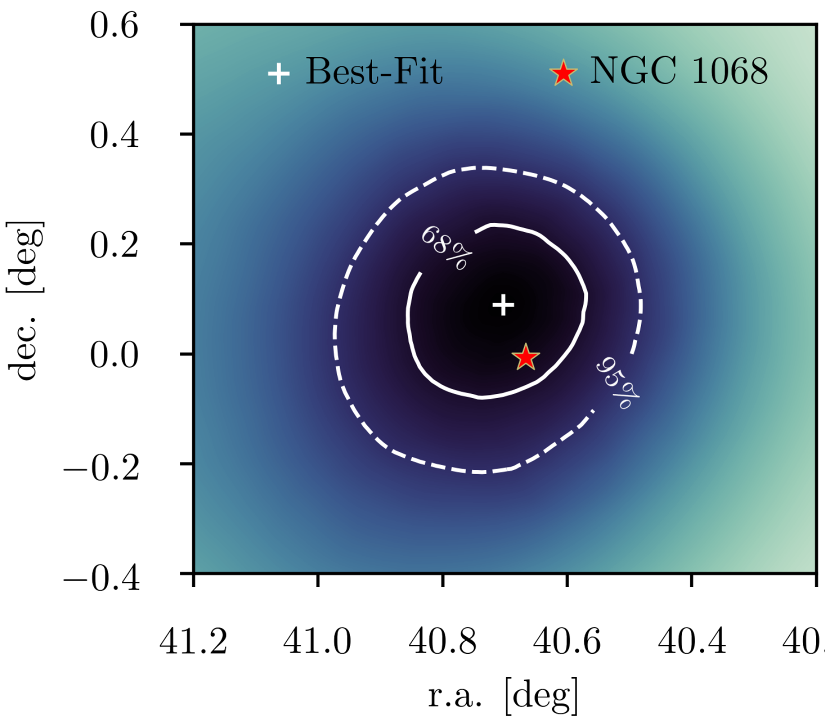
[MA & Halzen, **PPNP** 102 (2018)]

TXS 0506+056



[IceCube, **Science** 361 (2018)]

NGC 1068



[IceCube, **Science** 378 (2022)]

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:

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

- Interaction of CRs with interstellar medium creates hadronic γ & ν emission.

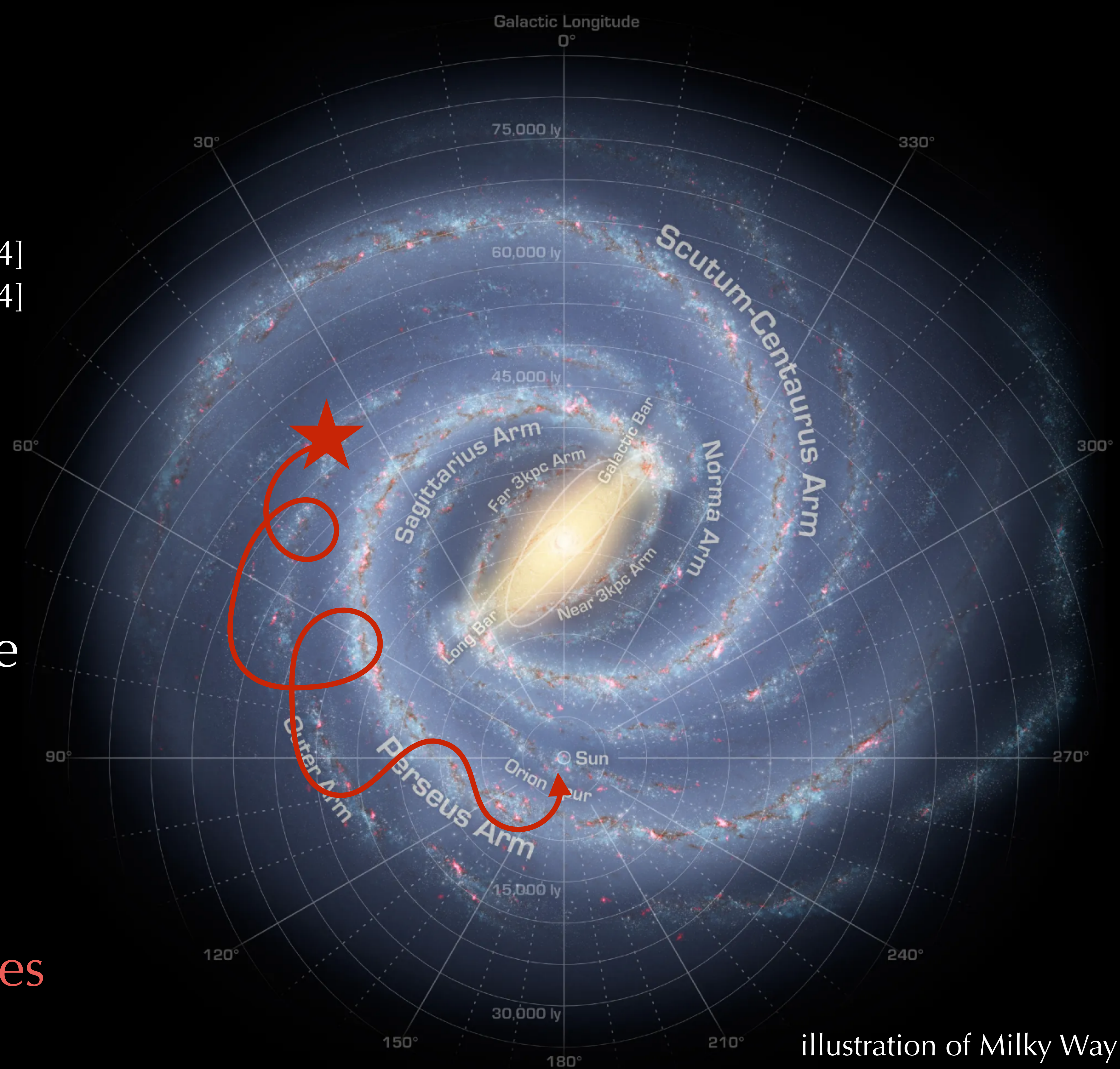


illustration of Milky Way
[Credit: NASA]

Gamma-Ray vs. Neutrinos

- neutrino emission from charged pion decay:

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

$$\pi^+ \to \mu^+ + \nu_\mu$$
$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$

- γ-ray emission from neutral pion decay:

$$\frac{1}{2} E_\gamma Q_\gamma(E_\nu) \simeq \left[E_\pi Q_{\pi^0}(E_\pi)\right]_{E_\pi \simeq 2E_\gamma}$$

$$\pi^0 \to \gamma + \gamma$$

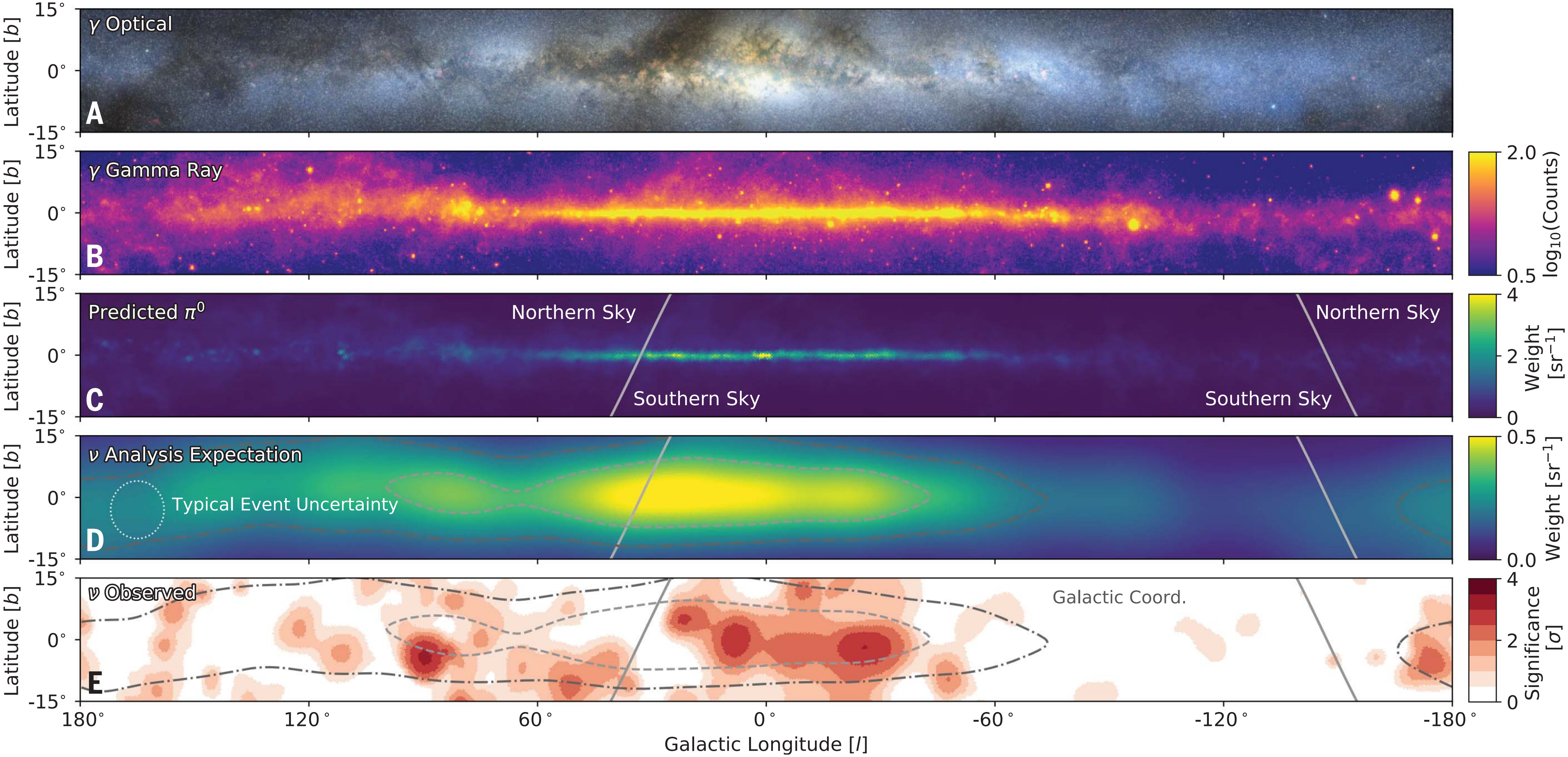
- **intrinsic relation** between neutrino and γ-ray emission:

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

- observable γ-ray emission is attenuated in sources and, in particular, in extragalactic background radiation.

Galactic Neutrino Emission

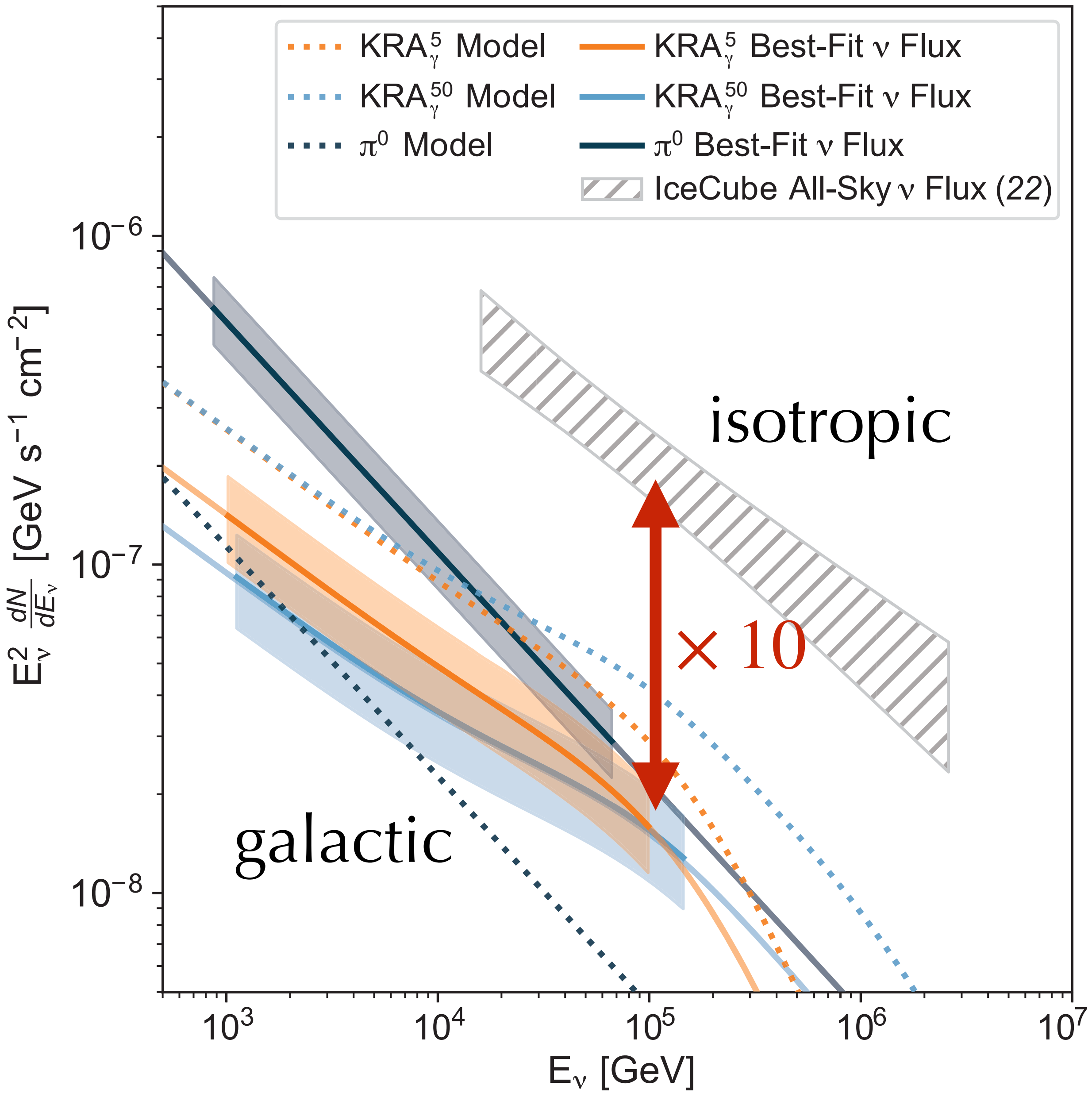
Galactic diffuse ν emission at 4.5σ based on template analysis.



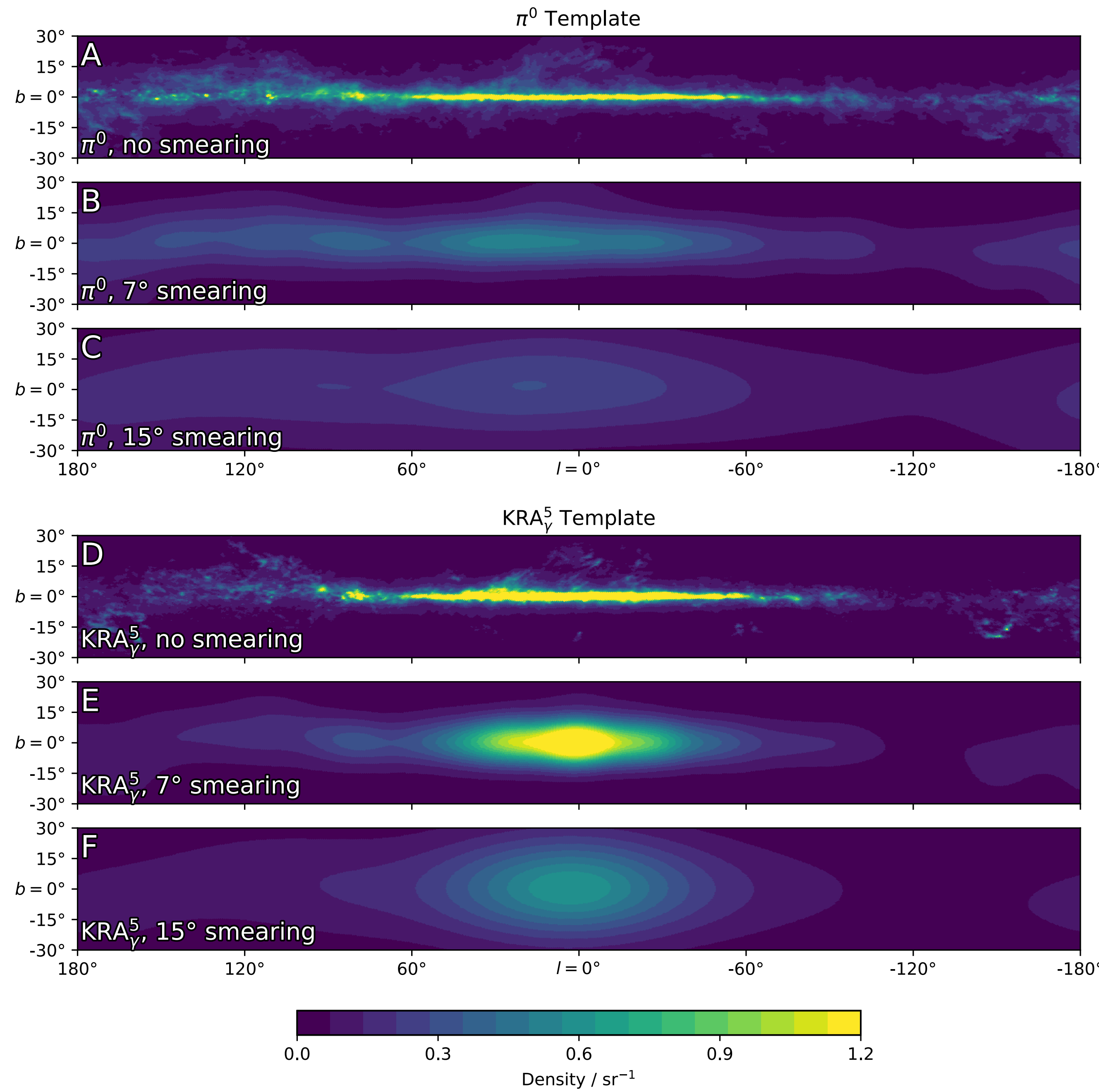
[IceCube **Science** 380 (2023)]

Galactic Neutrino Emission

Best-fit normalization of spectra

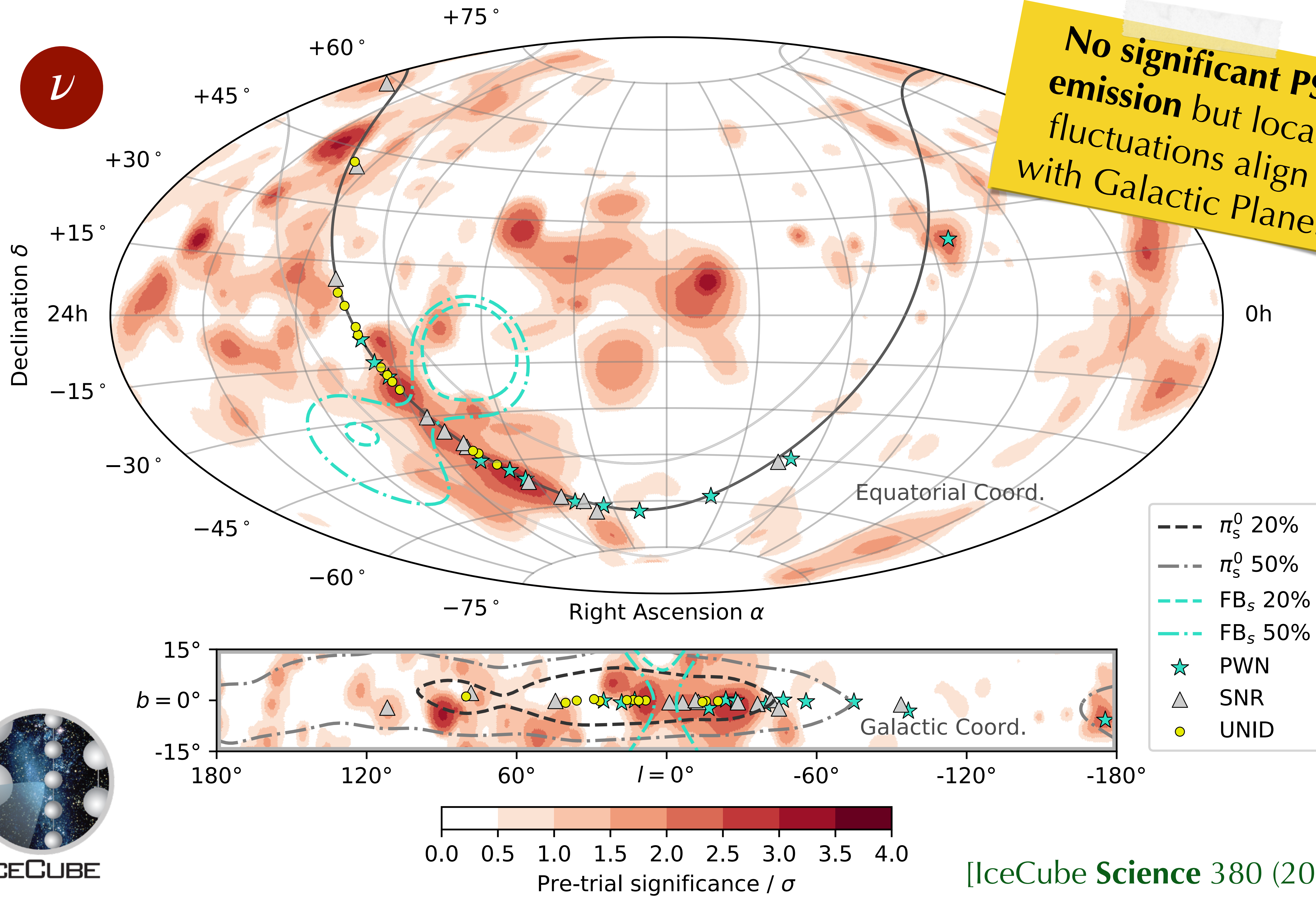


Templates with different resolution



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

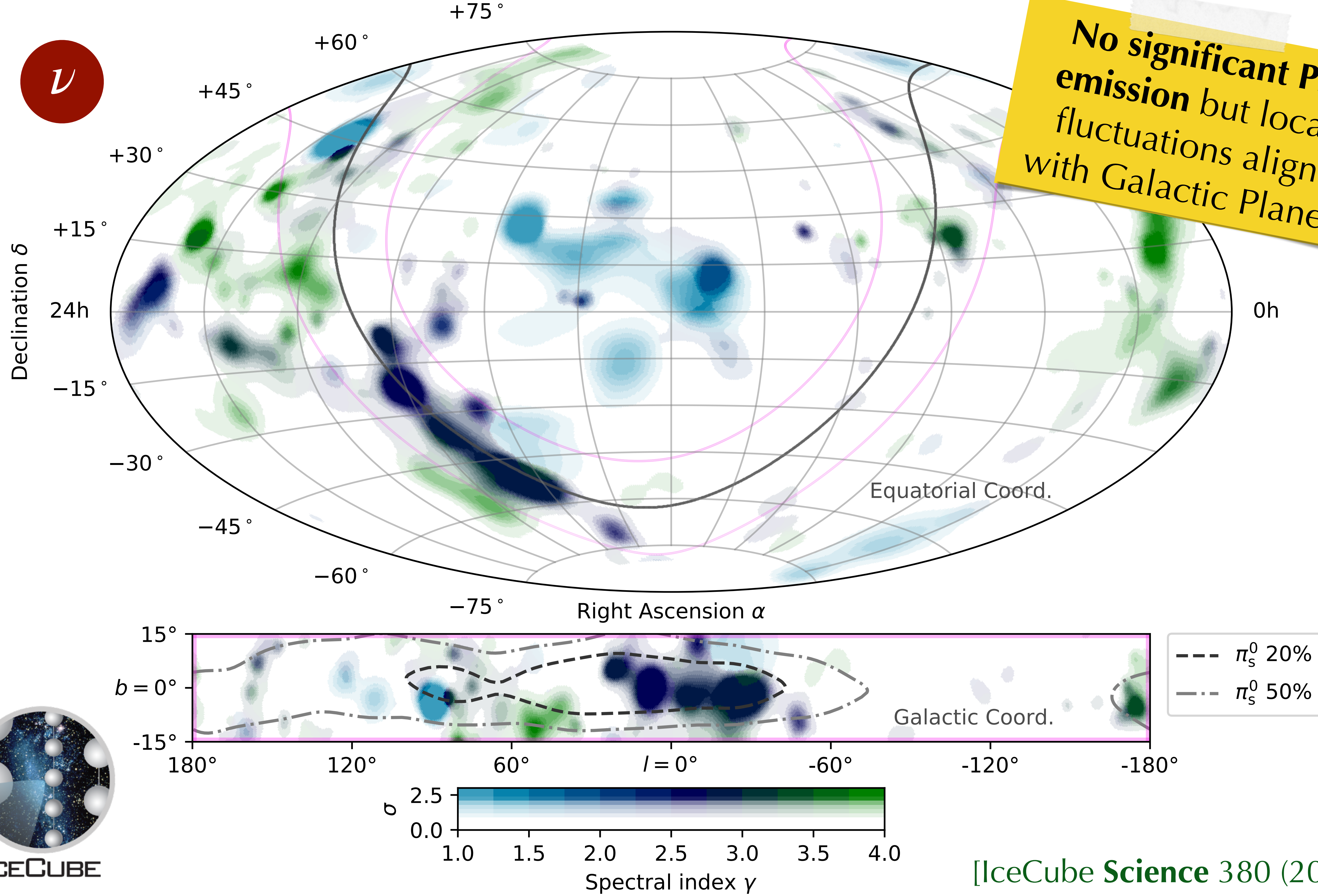
Point-Source Significance Map



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

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

Point-Source Significance Map



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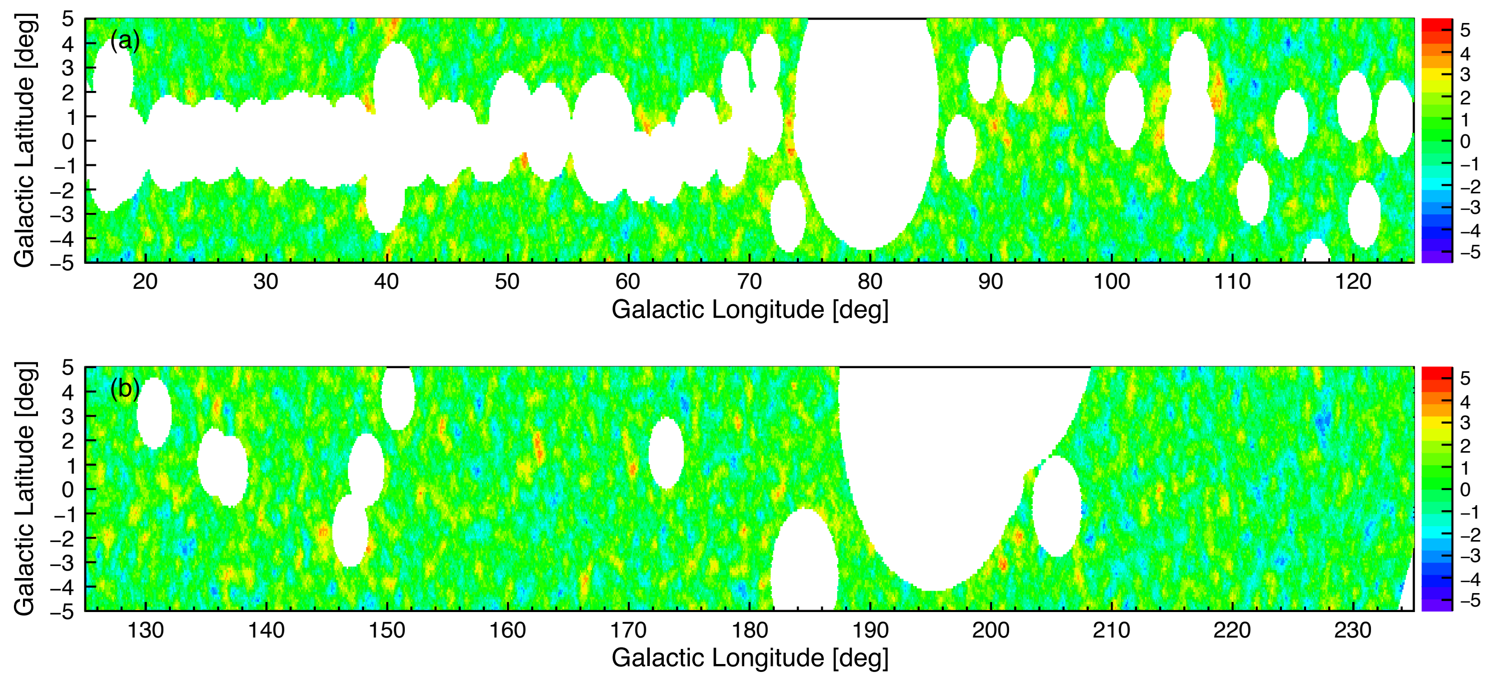
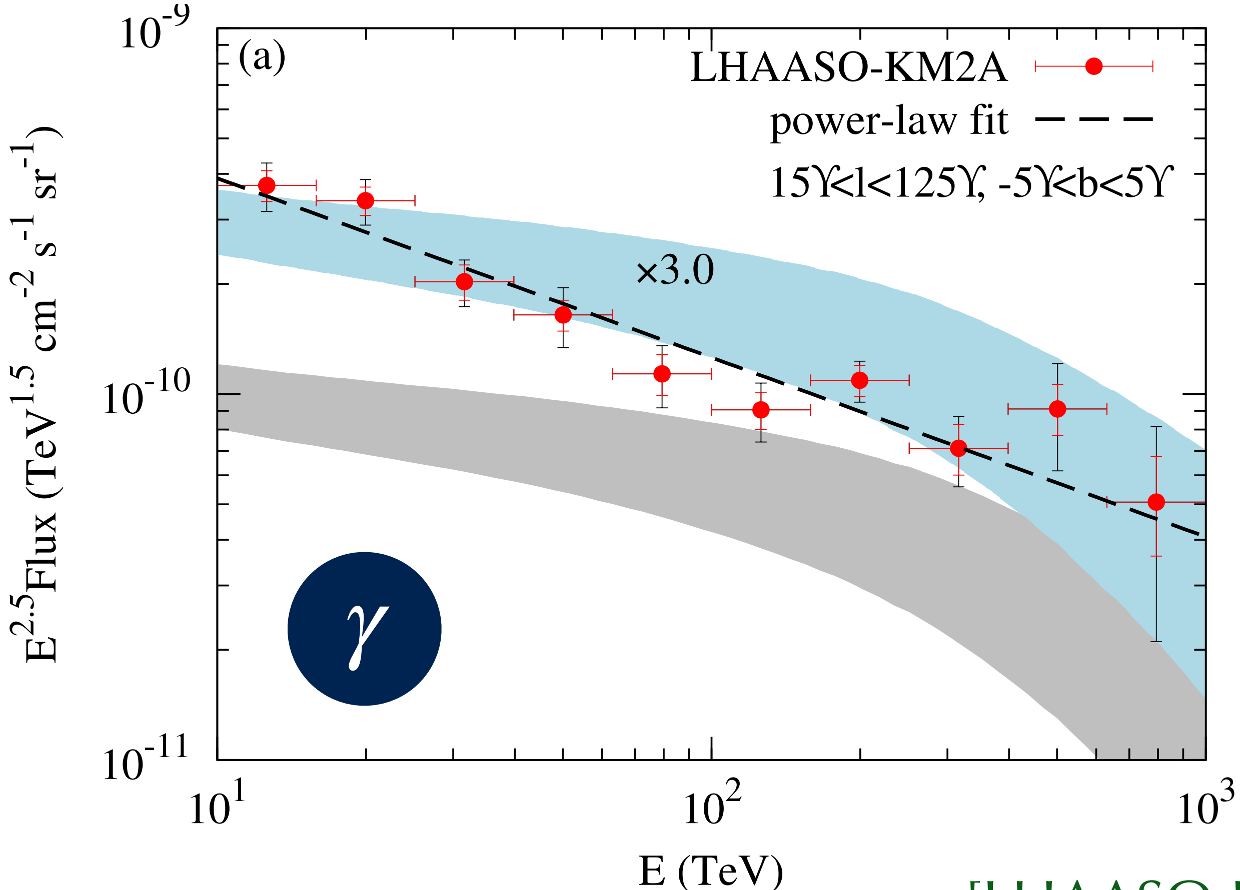
[IceCube **Science** 380 (2023)]

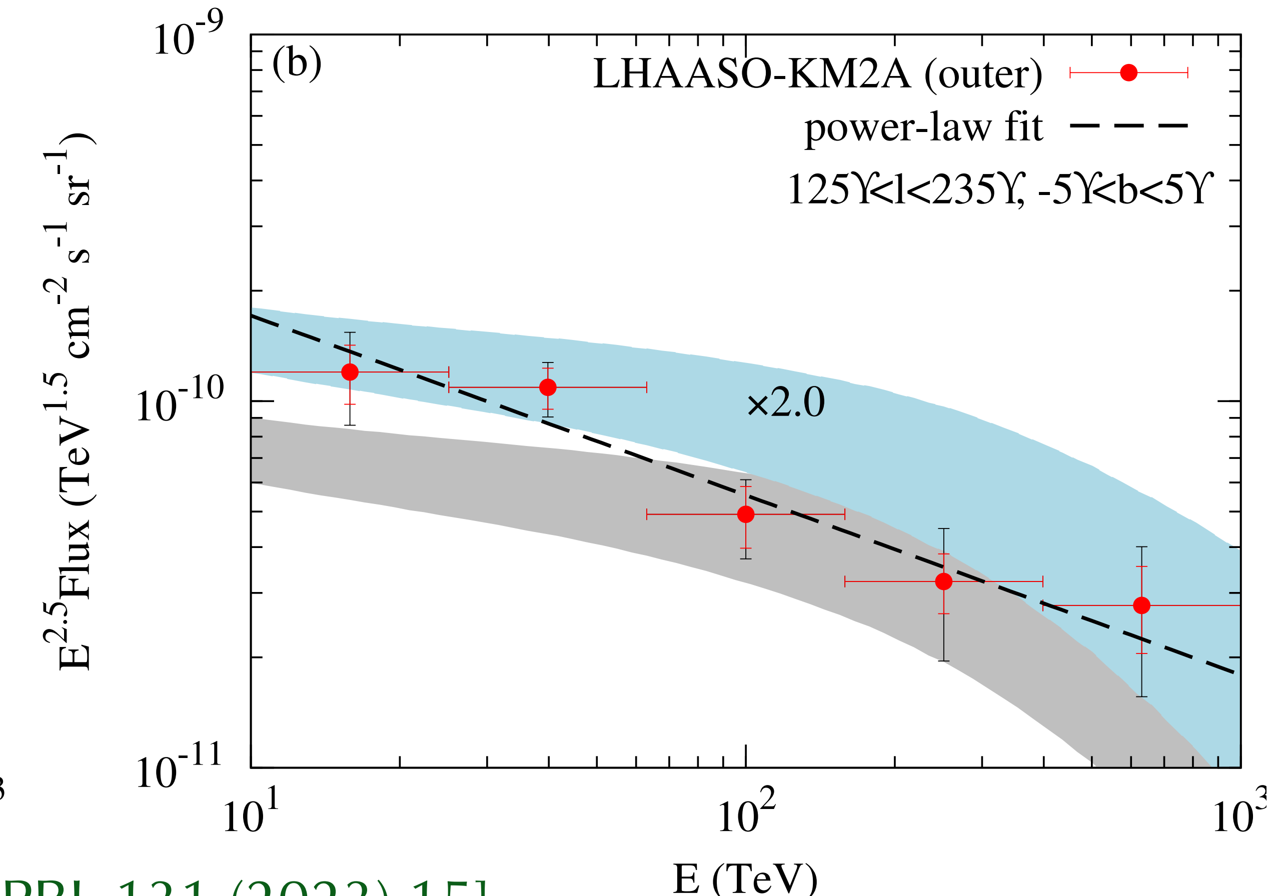
LHAASO Diffuse Emission

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

[LHAASO PRL 131 (2023) 15]



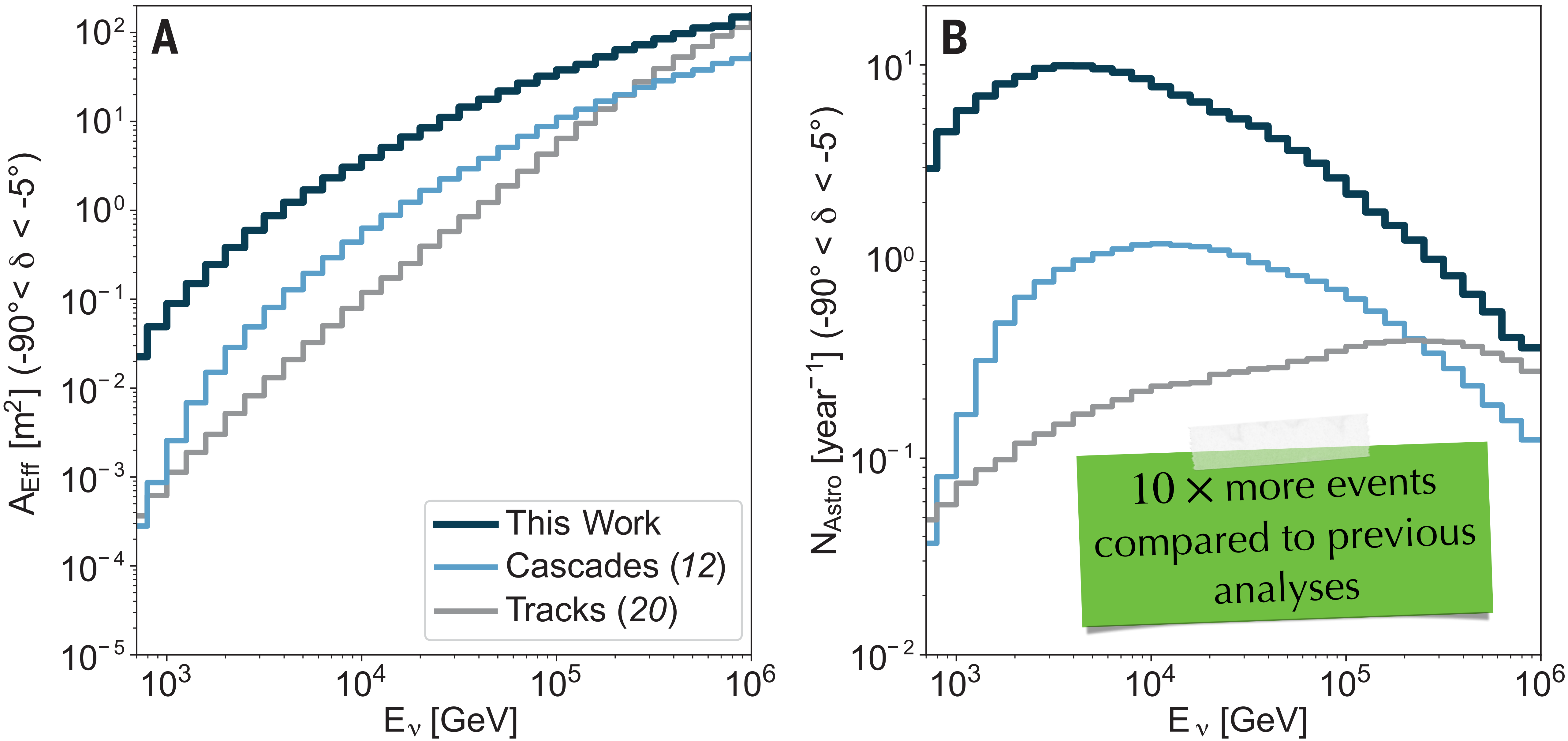




[LHAASO PRL 131 (2023) 15]

Analysis Sample

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



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

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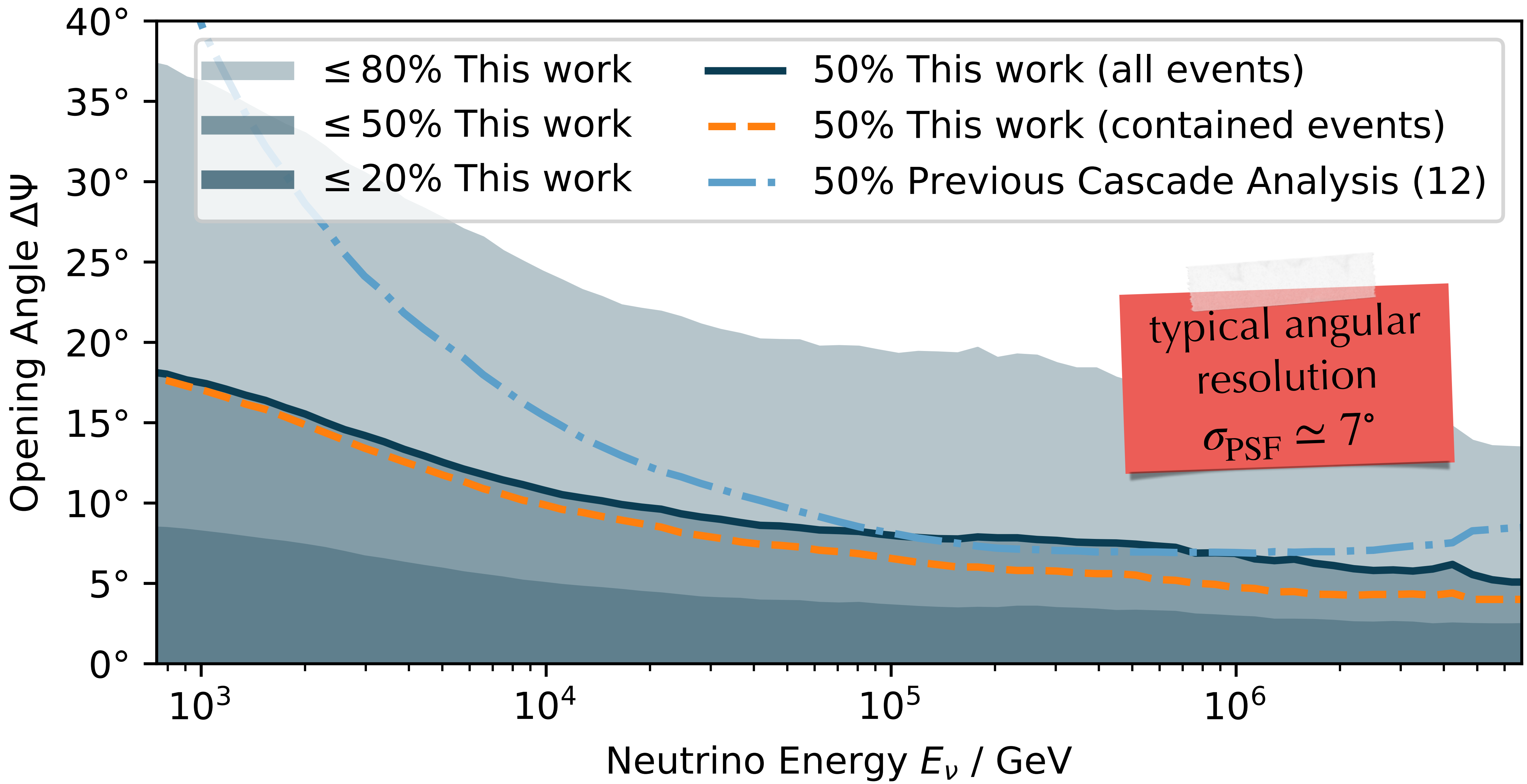


[IceCube **Science** 380 (2023)]

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	$0.16 \times$ MF	6.13×10^{-6} (4.37σ)	$0.55^{+0.18}_{-0.15} \times$ MF
KRA_γ^{50}	$0.11 \times$ MF	3.72×10^{-5} (3.96σ)	$0.37^{+0.13}_{-0.11} \times$ MF
	Catalog stacking analysis		
SNR		5.90×10^{-4} (3.24σ)*	
PWN		5.93×10^{-4} (3.24σ)*	
UNID		3.39×10^{-4} (3.40σ)*	
	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)	

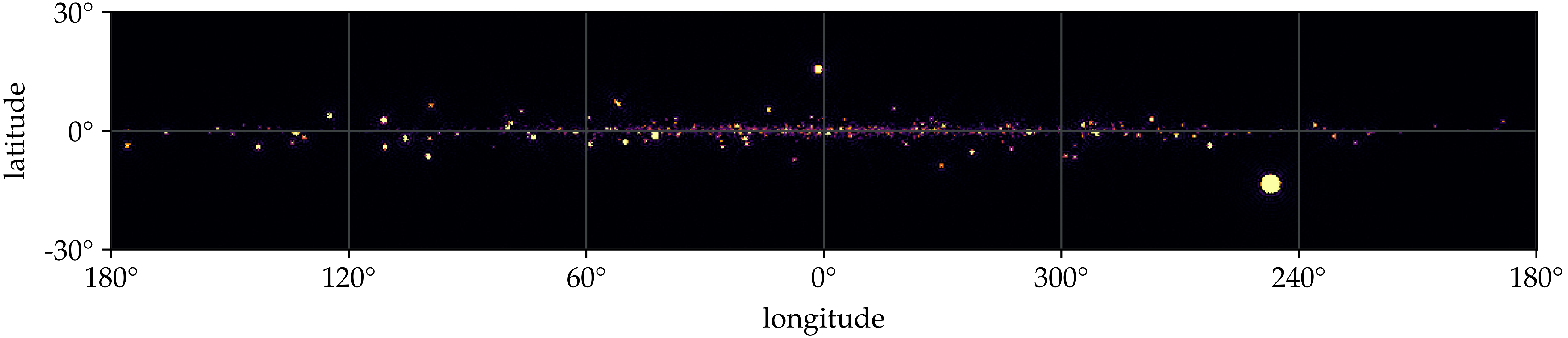
*Significance values that are consistent with the diffuse Galactic plane template search results.

post-trial p-value
template search:
4.5σ

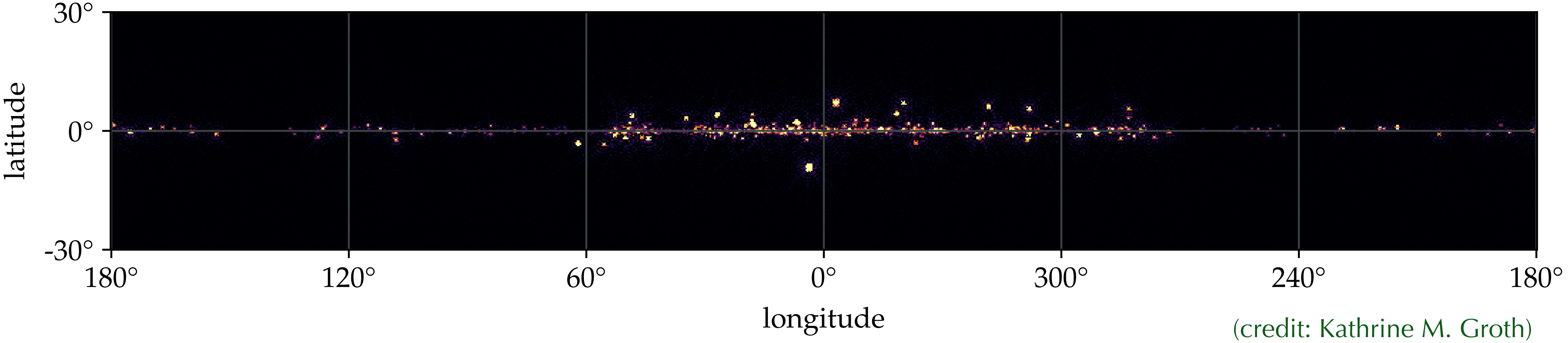
[IceCube **Science** 380 (2023)]

Galactic Neutrino Populations

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



+ modulation with spiral arms



(credit: Kathrine M. Groth)

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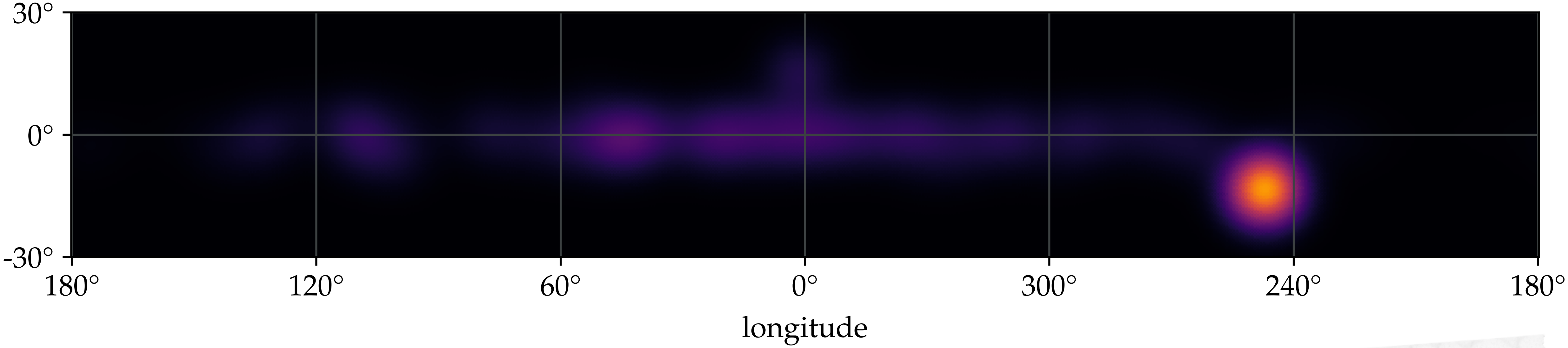

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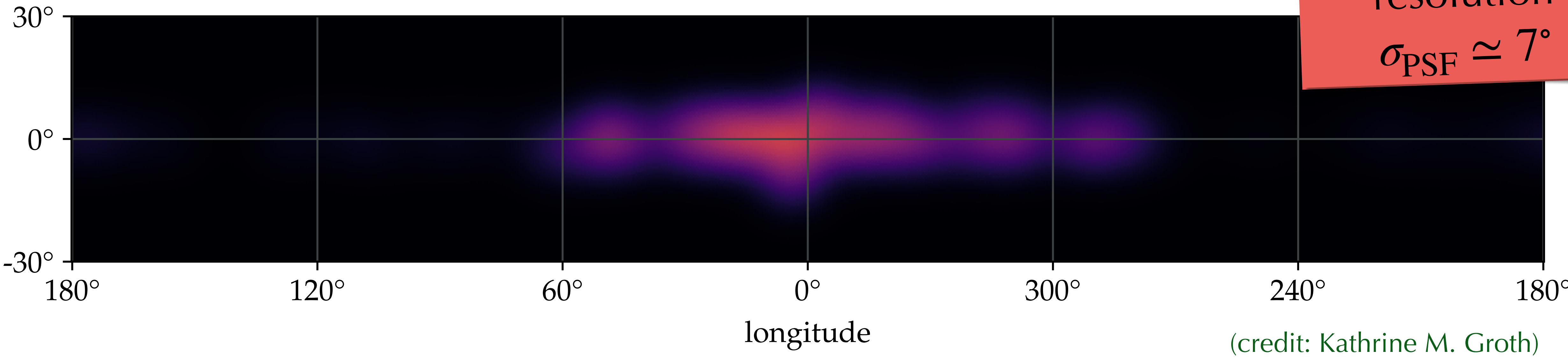
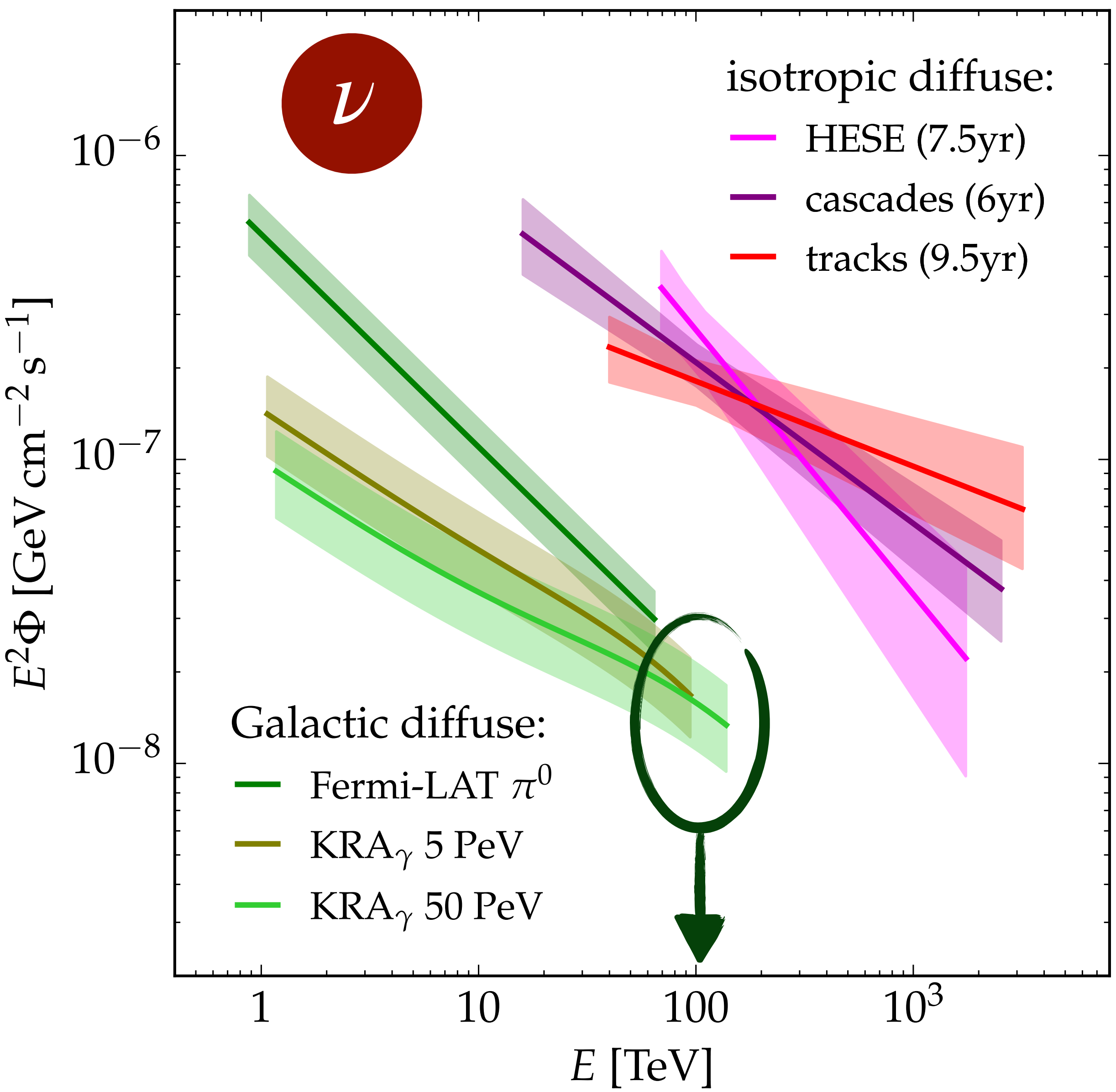


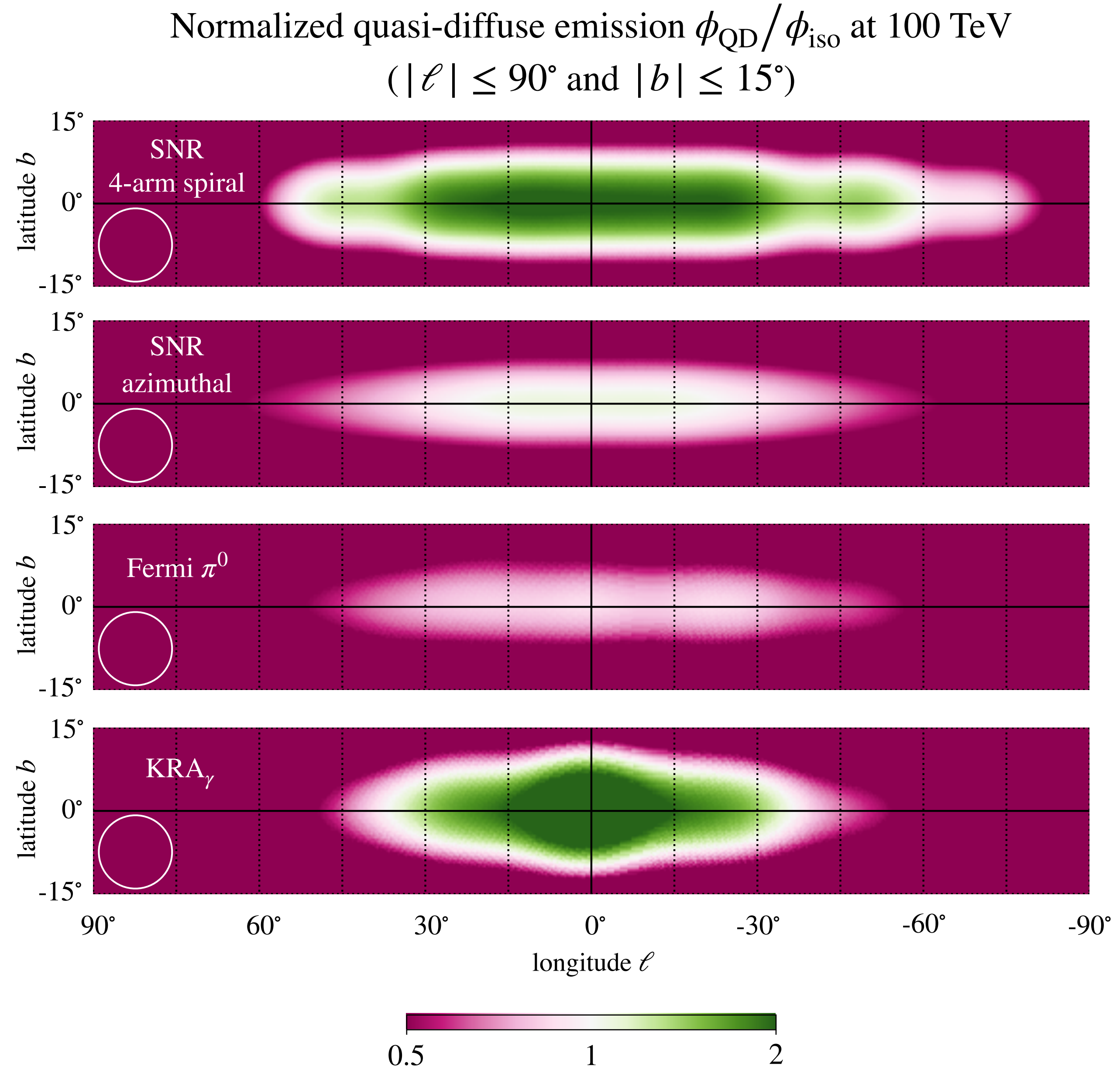
typical angular resolution $\sigma_{\rm PSF} \simeq 7^\circ$

(credit: Kathrine M. Groth)

Hidden Galactic Sources?

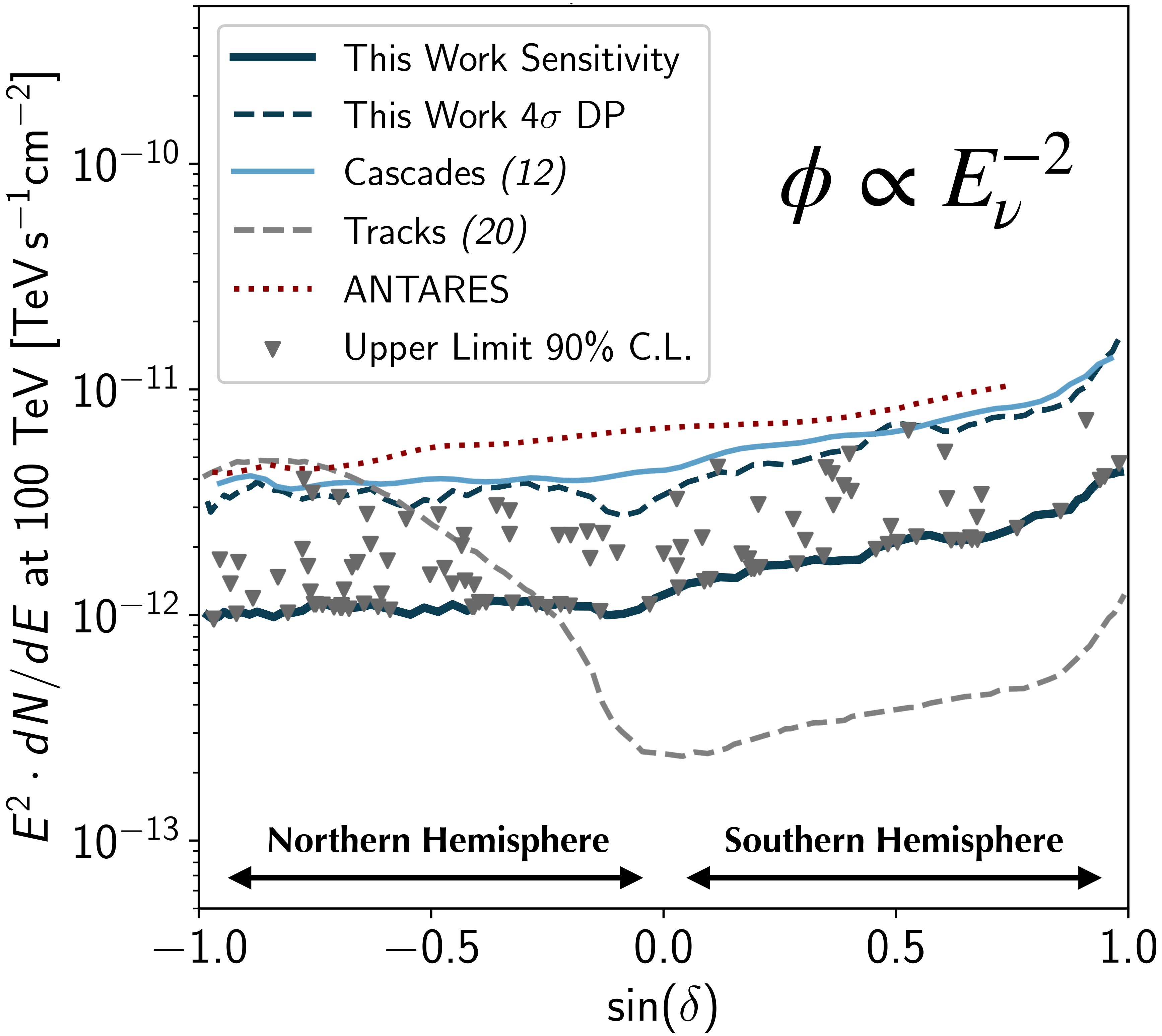
Contribution of neutrino from "freshly" accelerated CRs most likely to dominate at highest observed energy ($\simeq$ 100TeV).





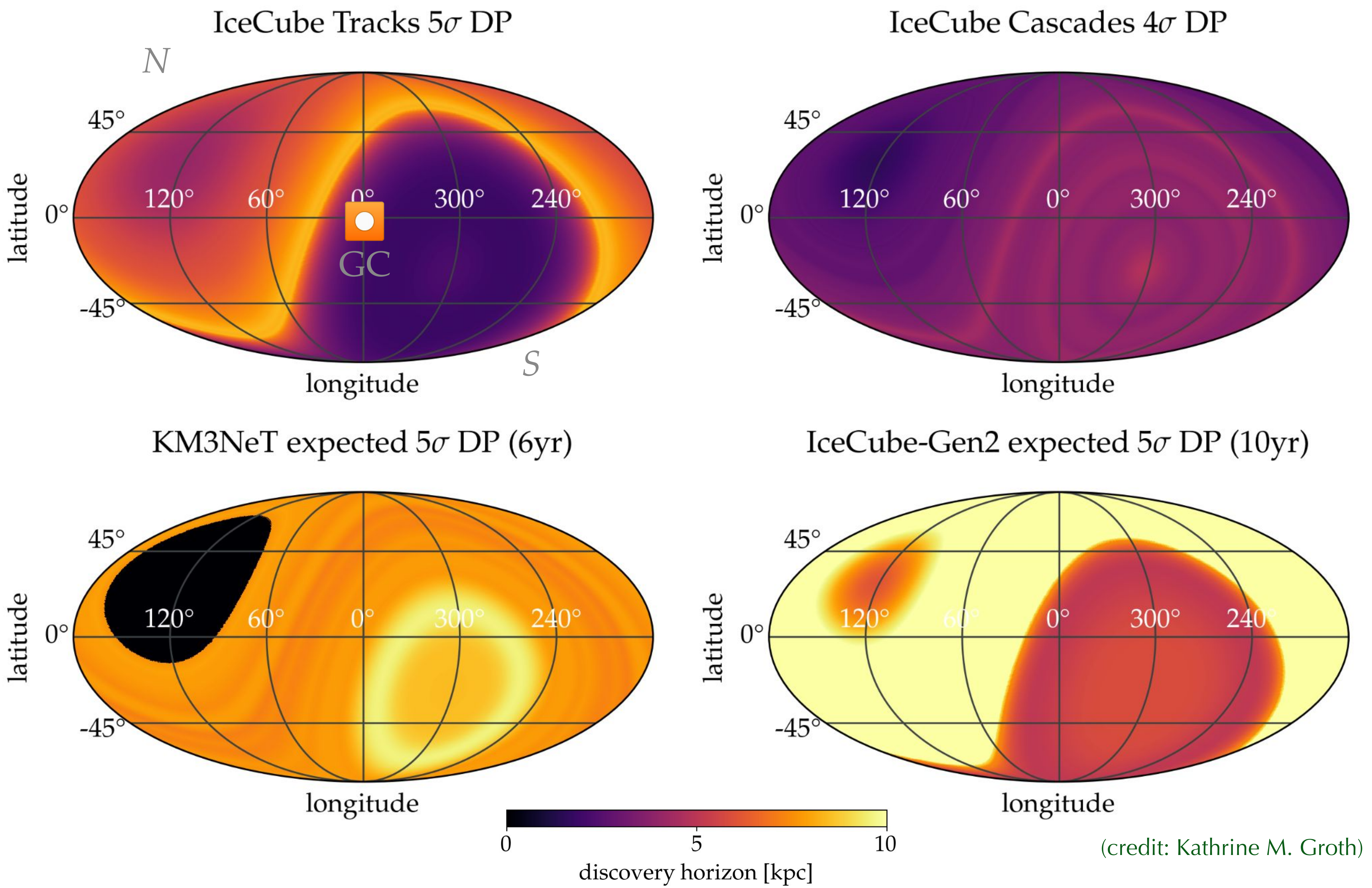
[Ambrosone, Groth, Peretti & MA'23]

Point-Source Sensitivities



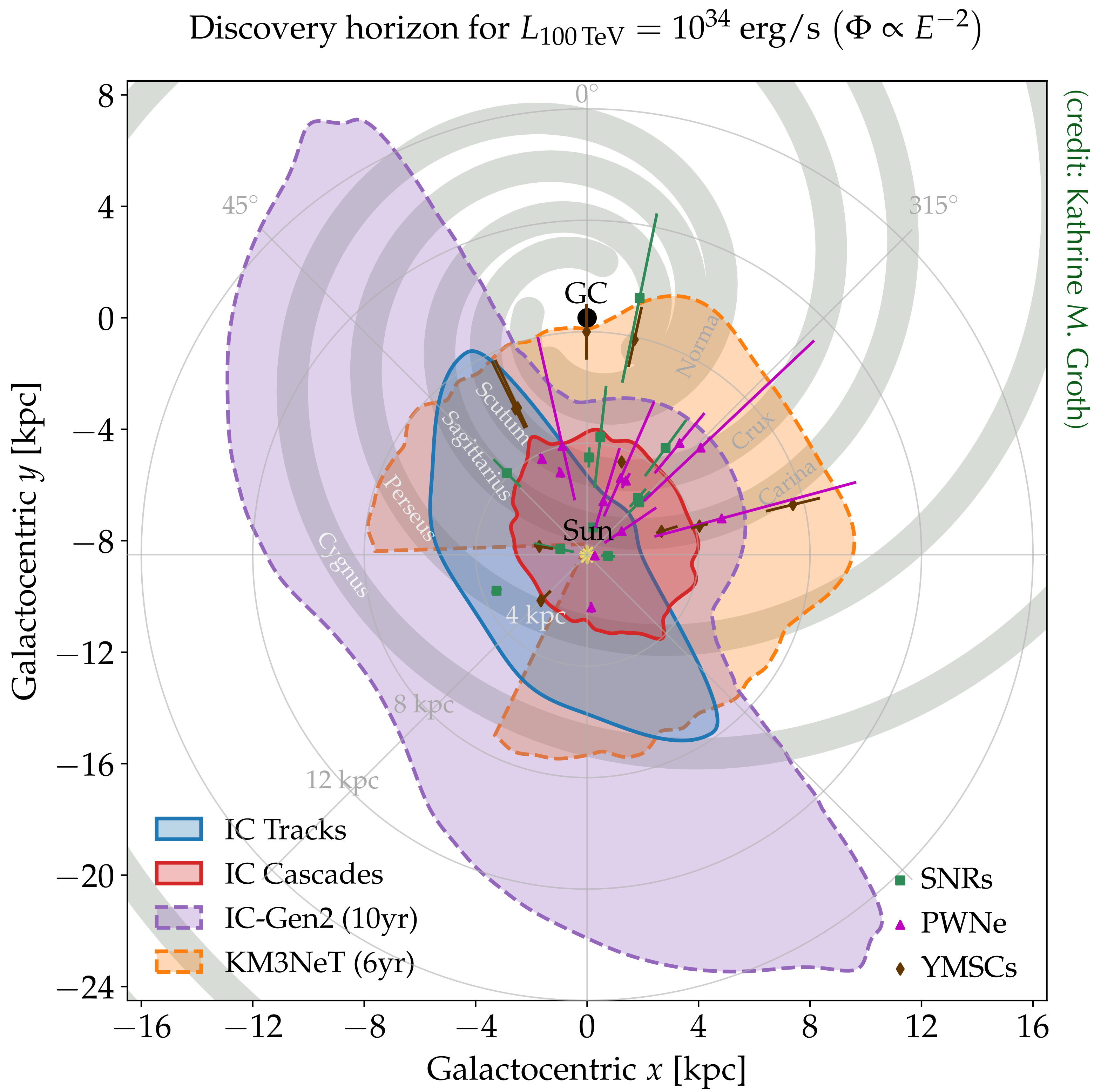
[IceCube **Science** 380 (2023)]

Effective Field of View



(credit: Kathrine M. Groth)

Point-Source Discovery Horizon



[Ambrosone, Groth, Peretti & MA'23]

Point Source vs. Quasi-Diffuse Flux

Populations of galactic neutrino sources visible as

individual sources

and by the

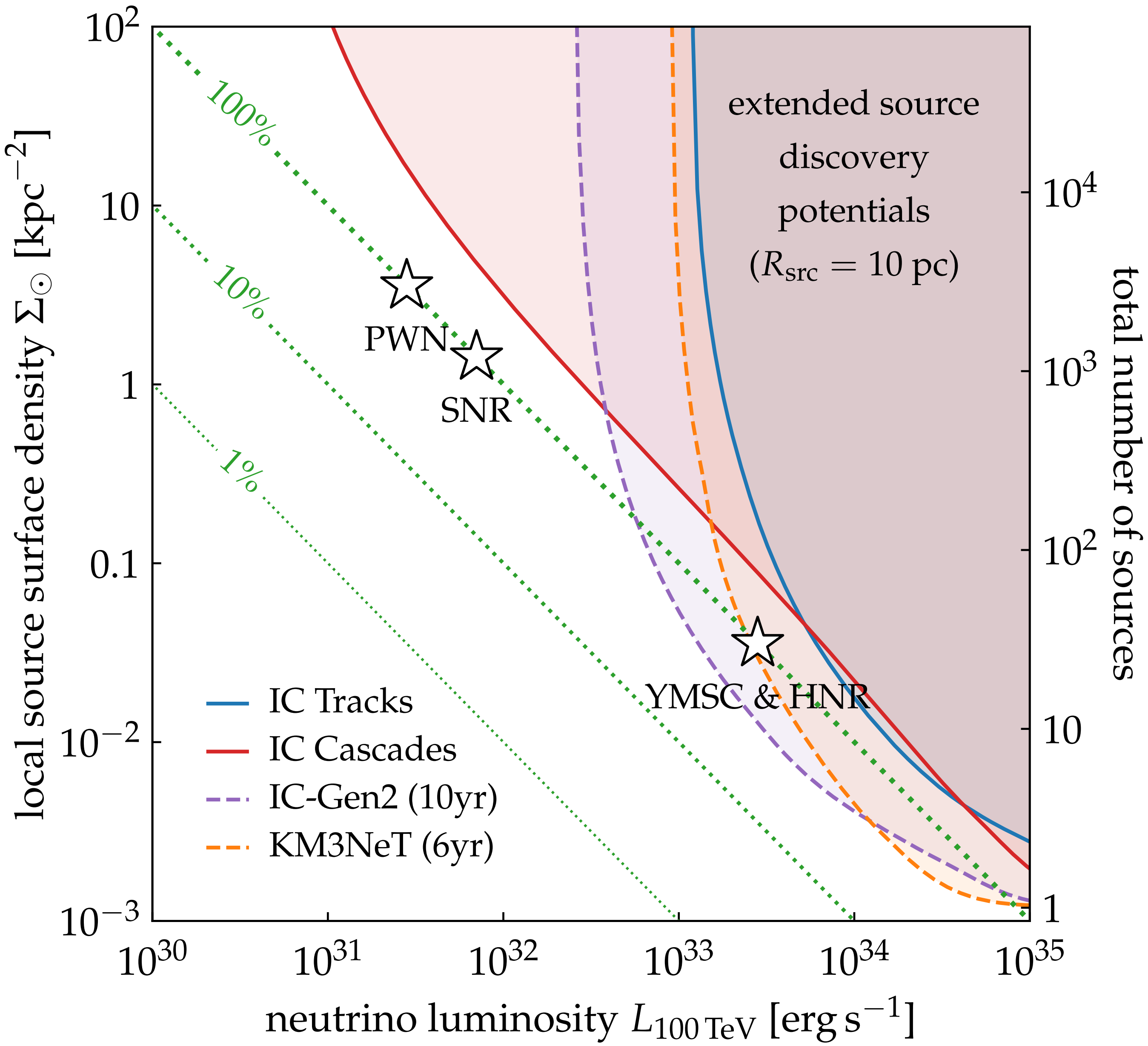
combined isotropic emission.

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]

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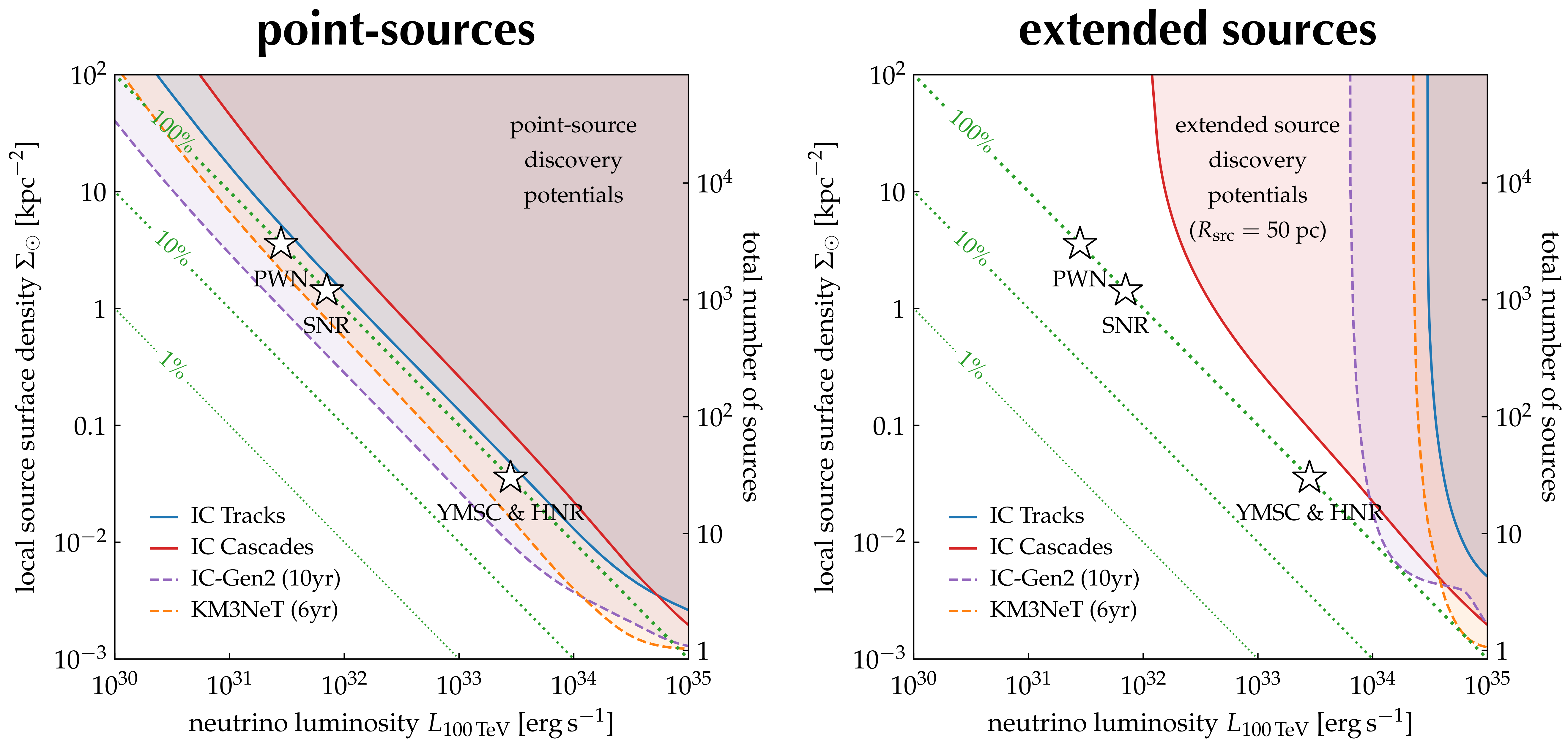


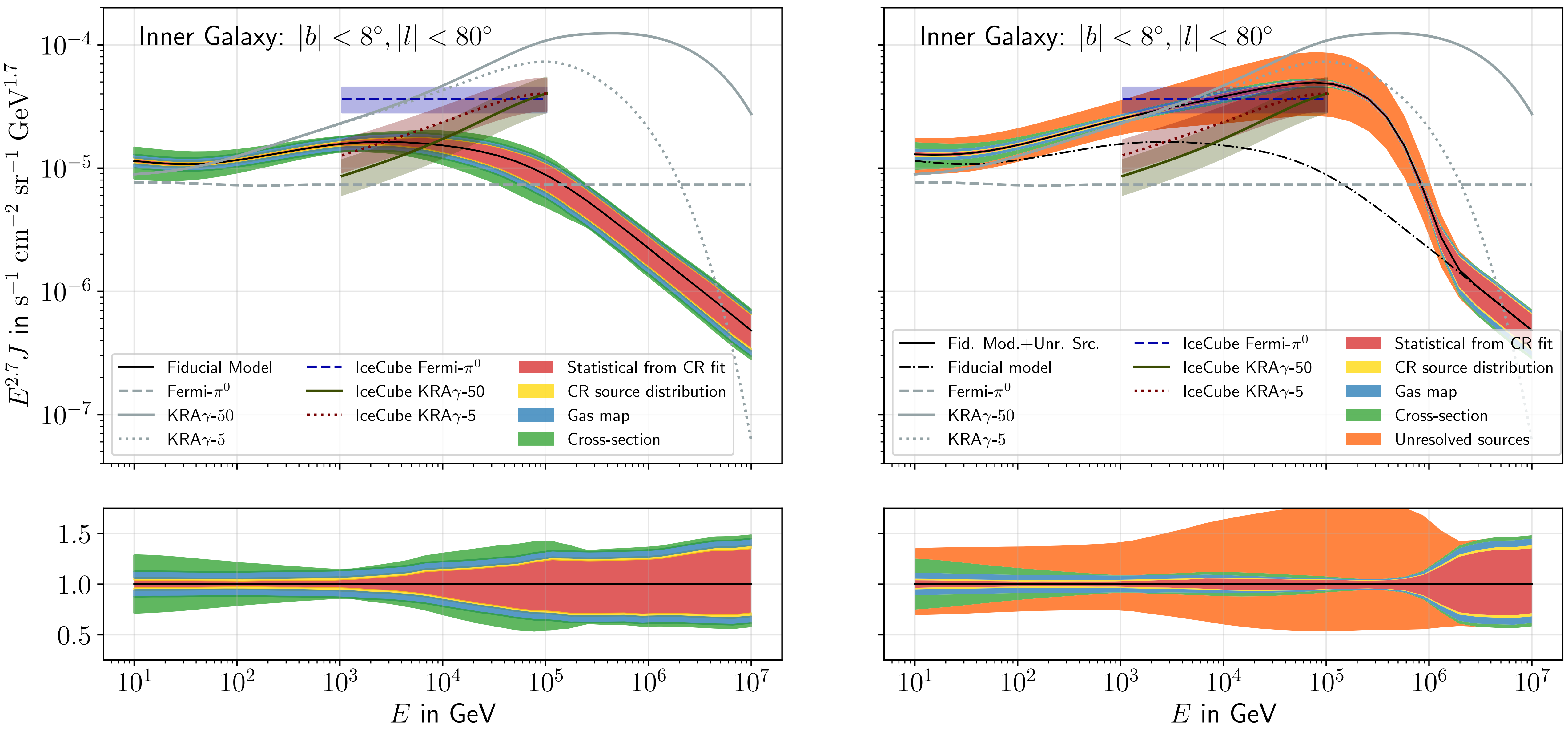
[Ambrosone, Groth, Peretti & MA'23]

sensitivity scaling:

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

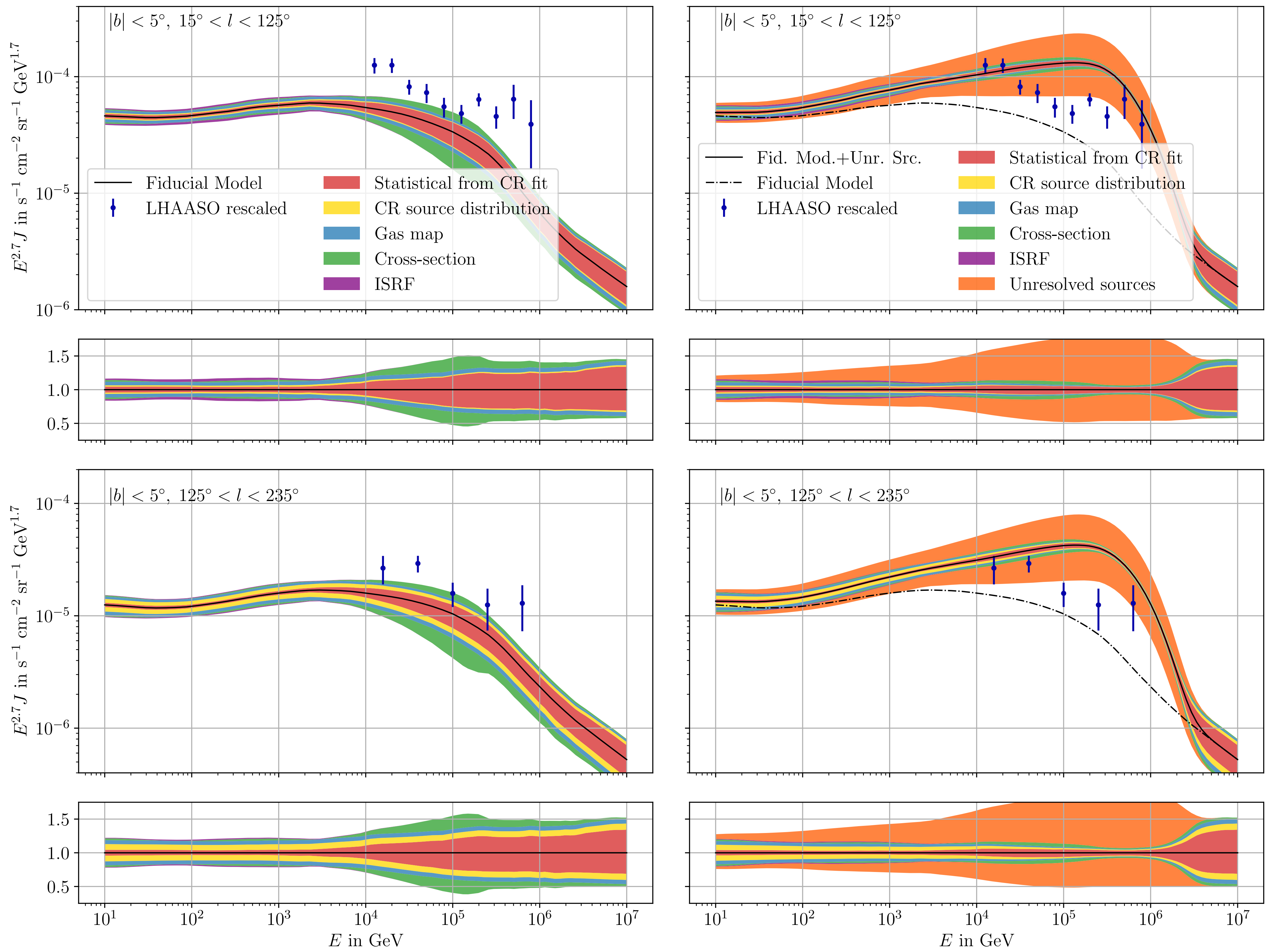
Multi-Messenger Fits

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

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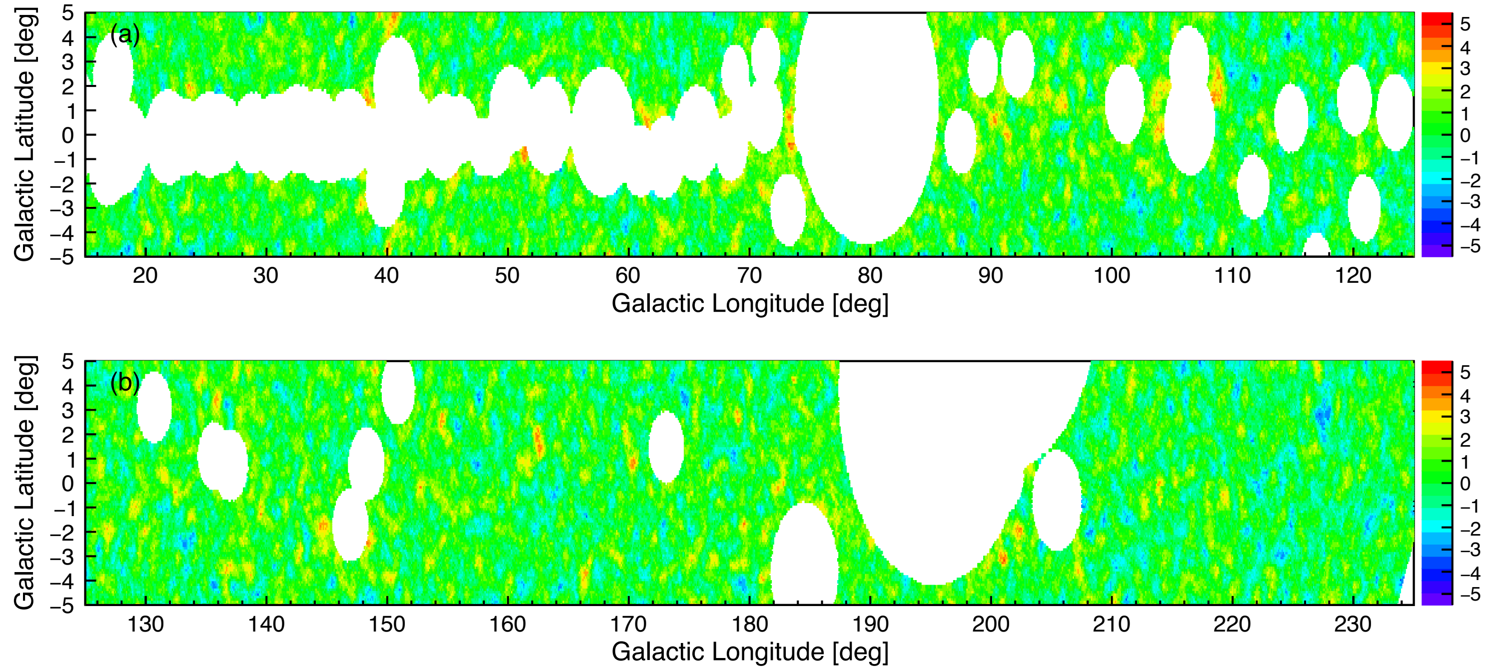
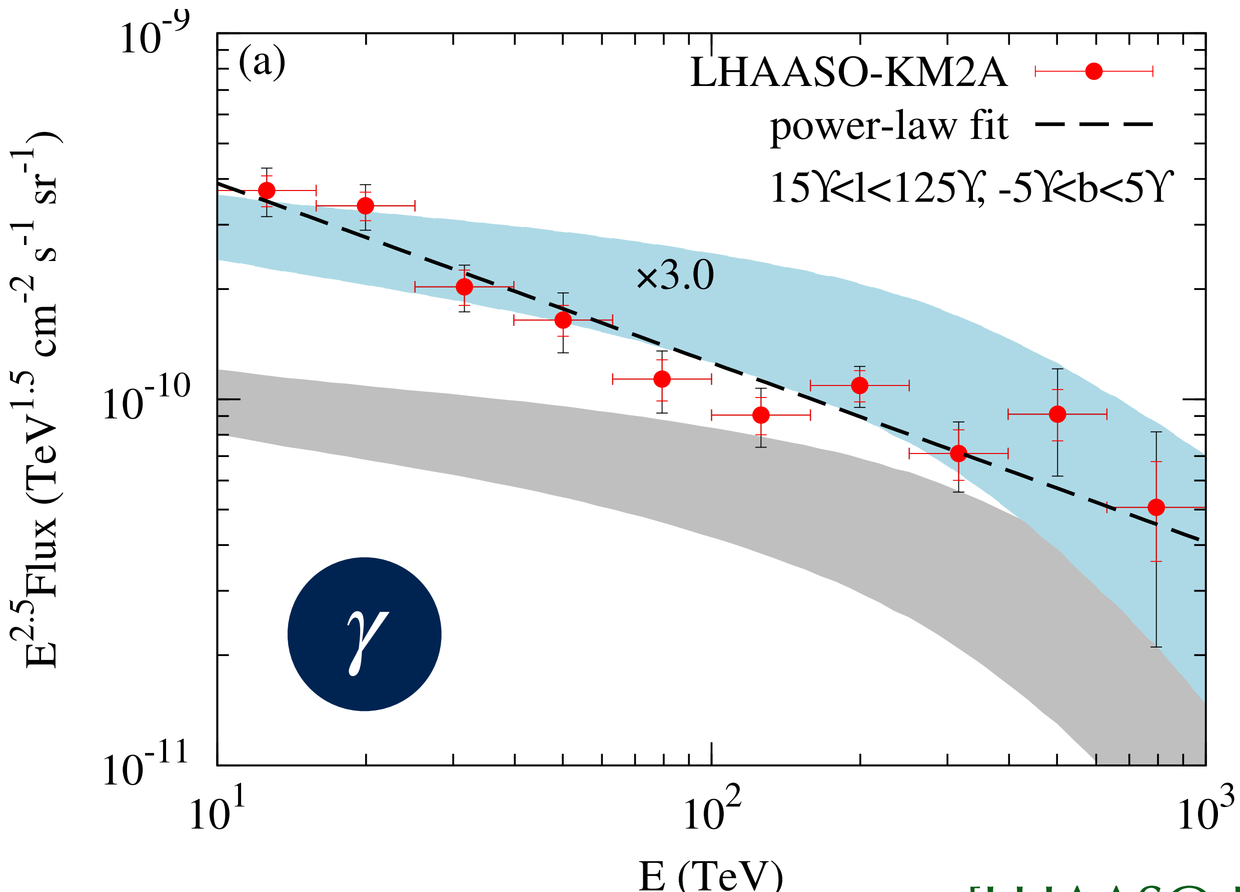
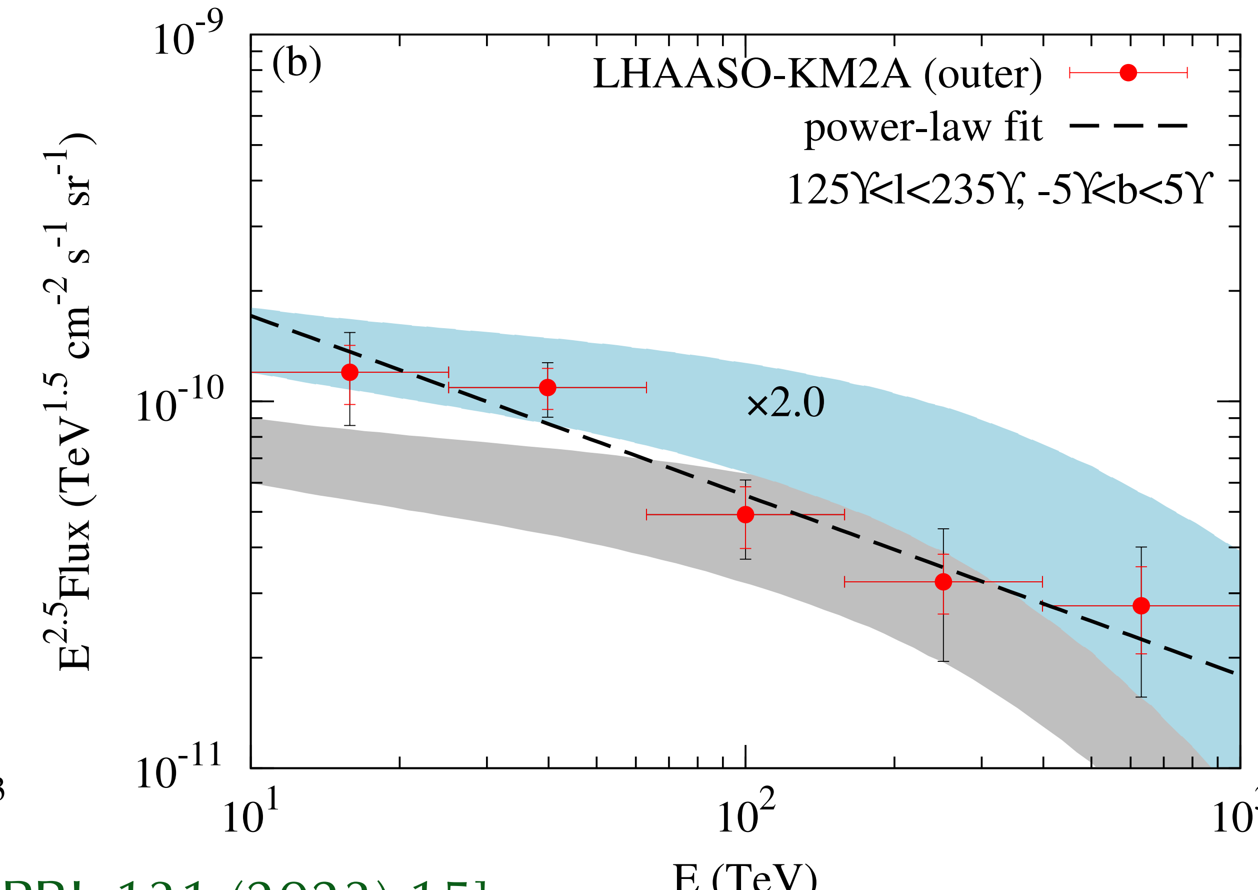
[LHAASO PRL 131 (2023) 15]

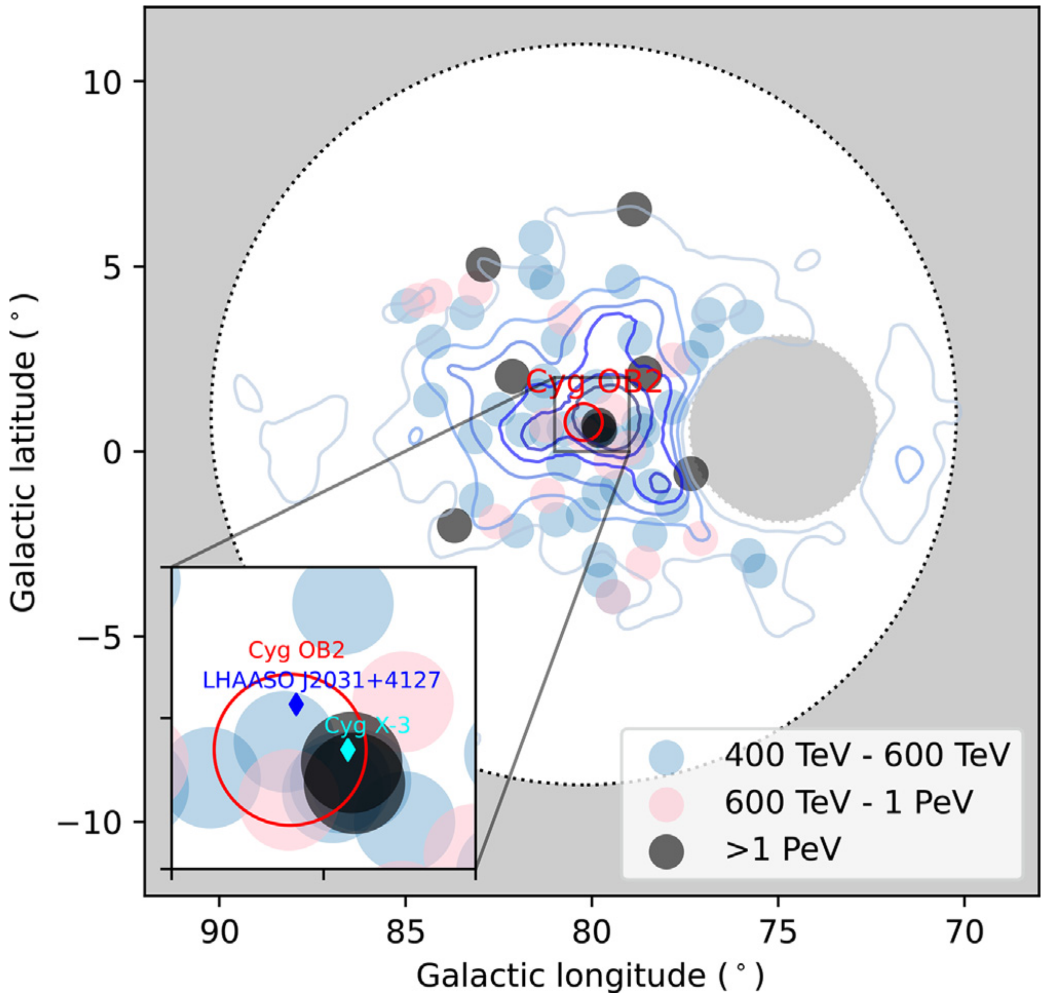


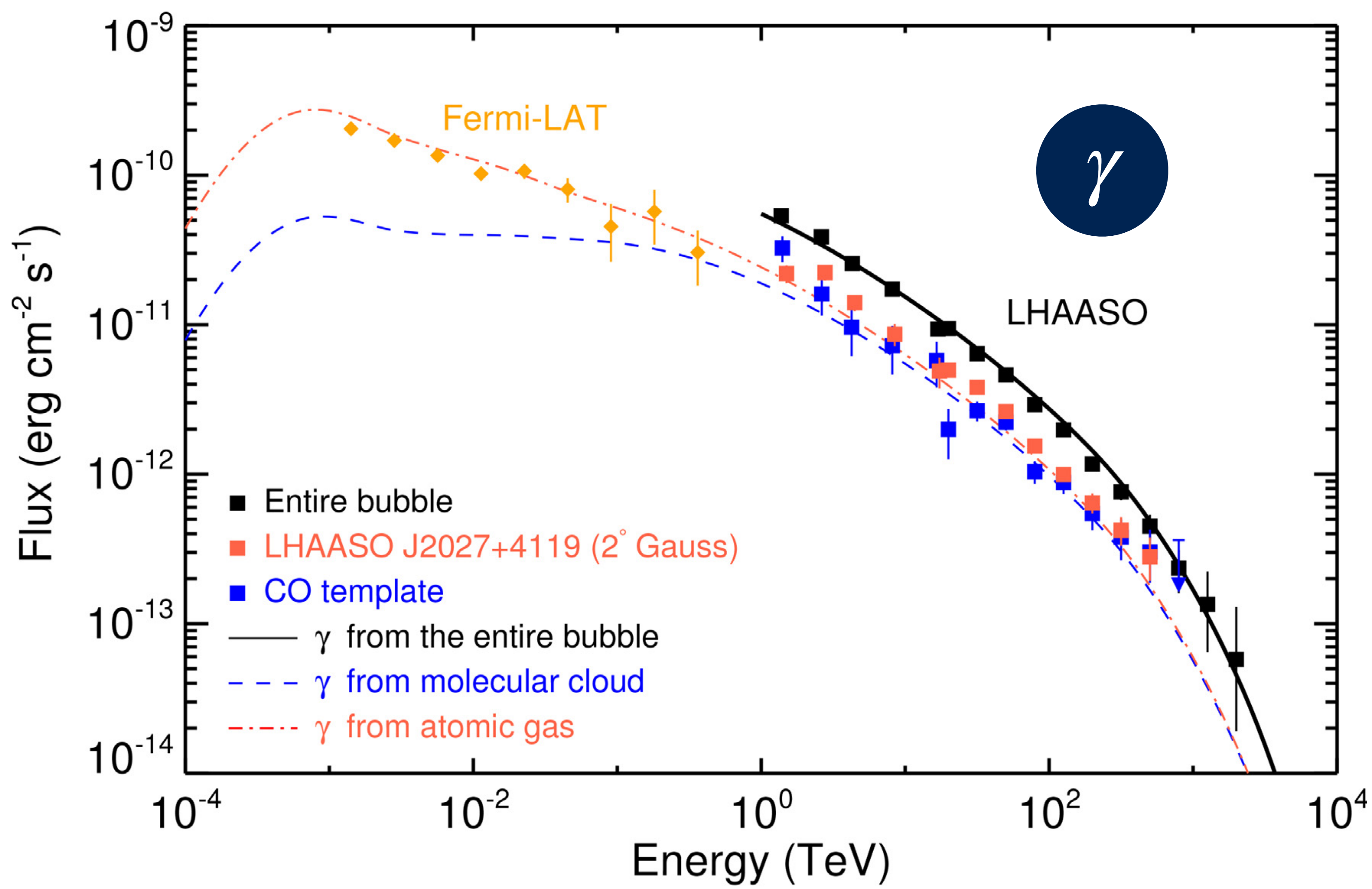




[LHAASO PRL 131 (2023) 15]

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.