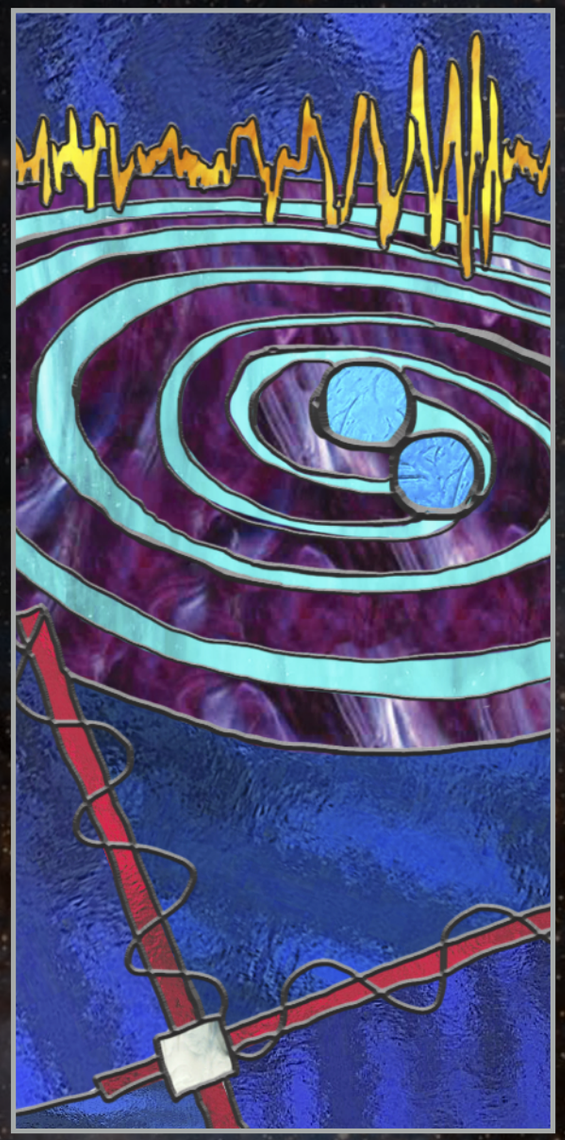
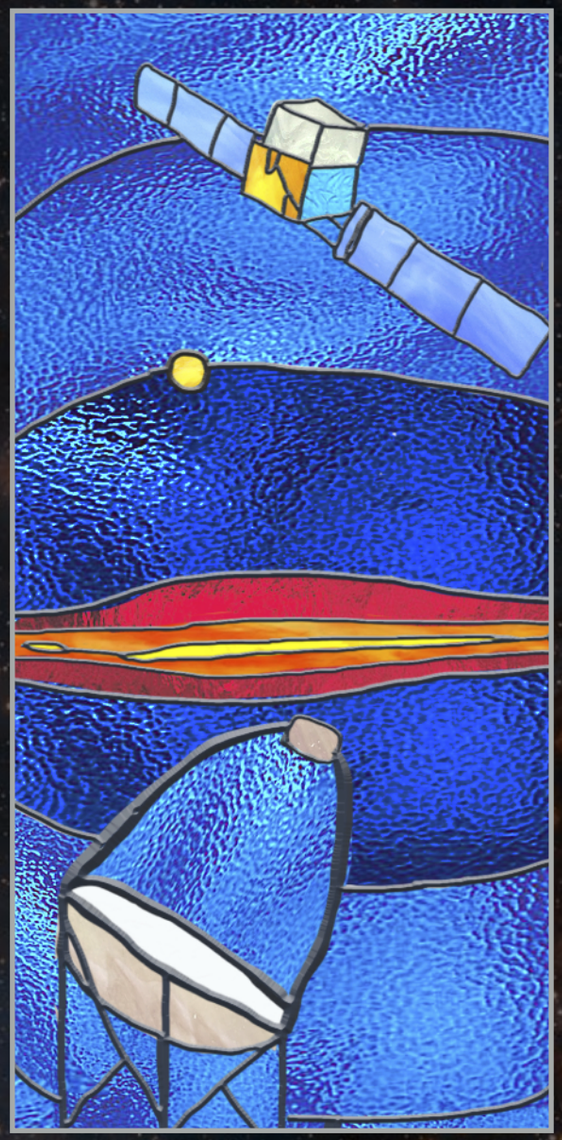




Multi-messenger Astrophysics - Lecture 2

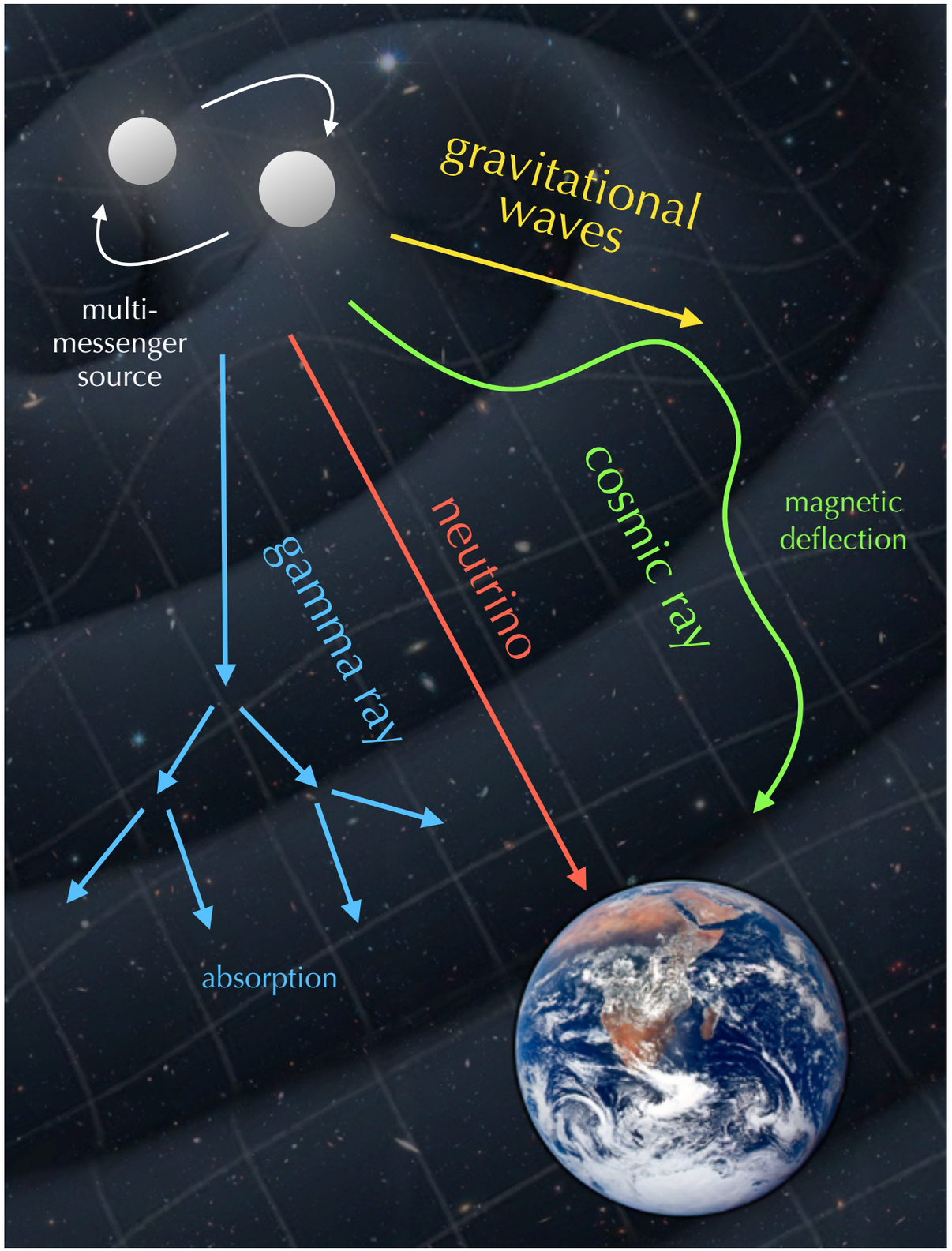
Markus Ahlers
Niels Bohr Institute

ISAPP Paris-Saclay 2026

CARLSBERG FOUNDATION

KØBENHAVNS UNIVERSITET

Neutrino Astronomy



Unique abilities of **cosmic neutrinos**:

no deflection in magnetic fields
(unlike cosmic rays)

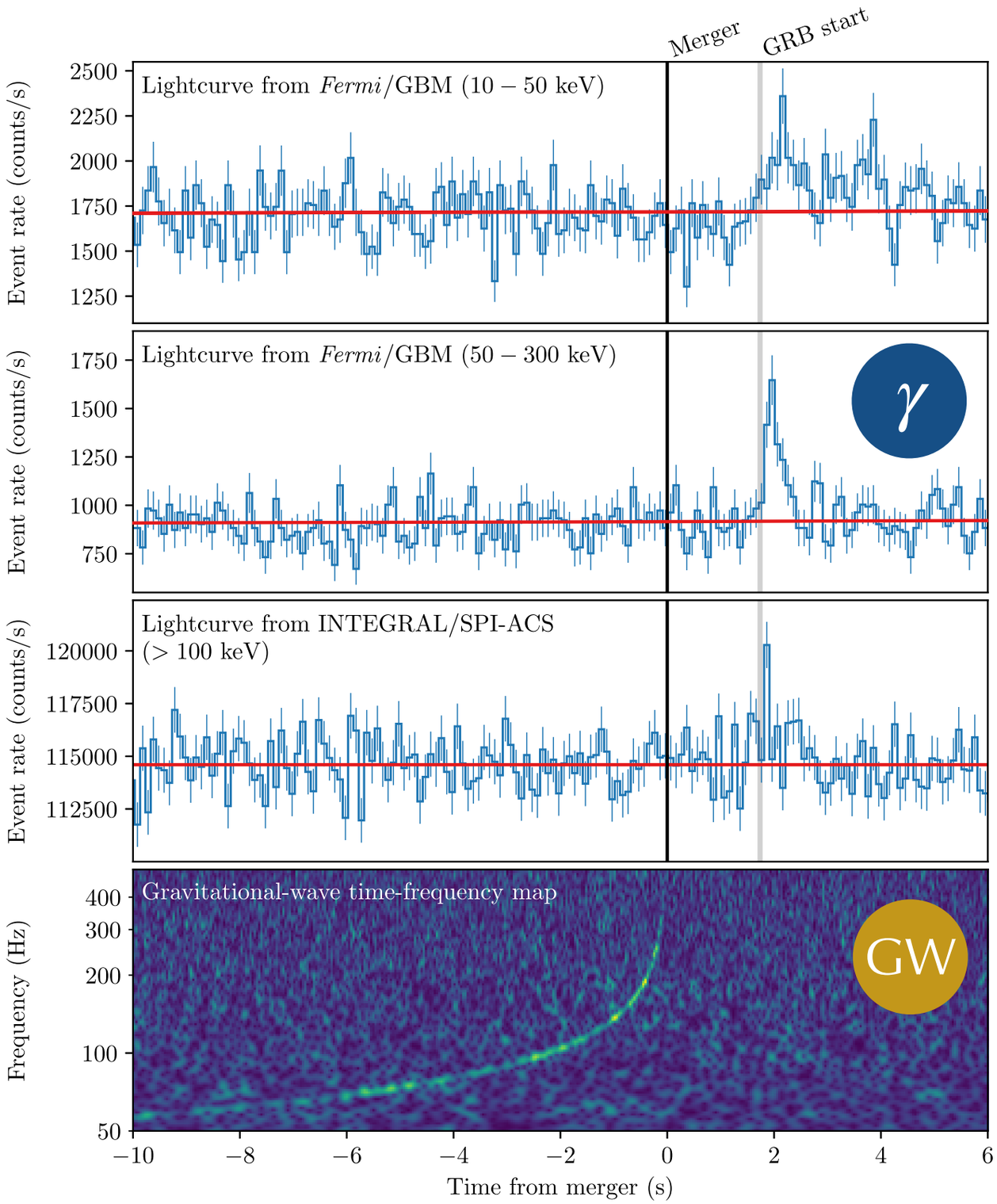
coincident with
photons and gravitational waves

no absorption in cosmic backgrounds
(unlike gamma-rays)

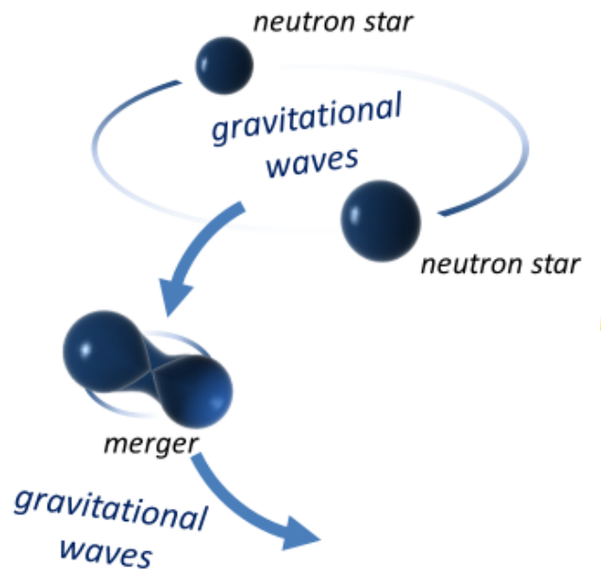
smoking-gun of
unknown sources of cosmic rays

BUT, very difficult to detect!

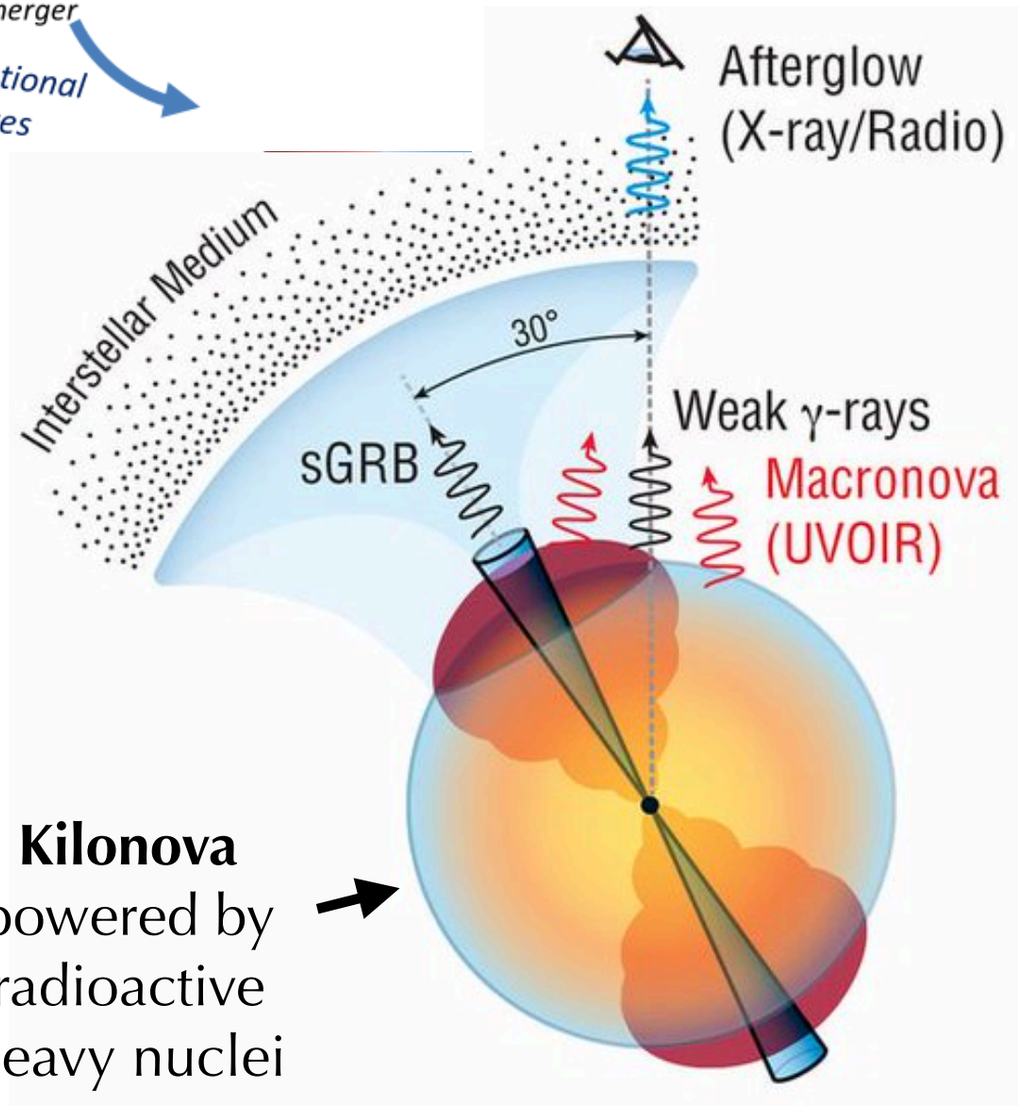
Example: GRB 170817A



[LVD, Fermi & INTEGRAL, **ApJ** 848 (2017) no.2, L13]

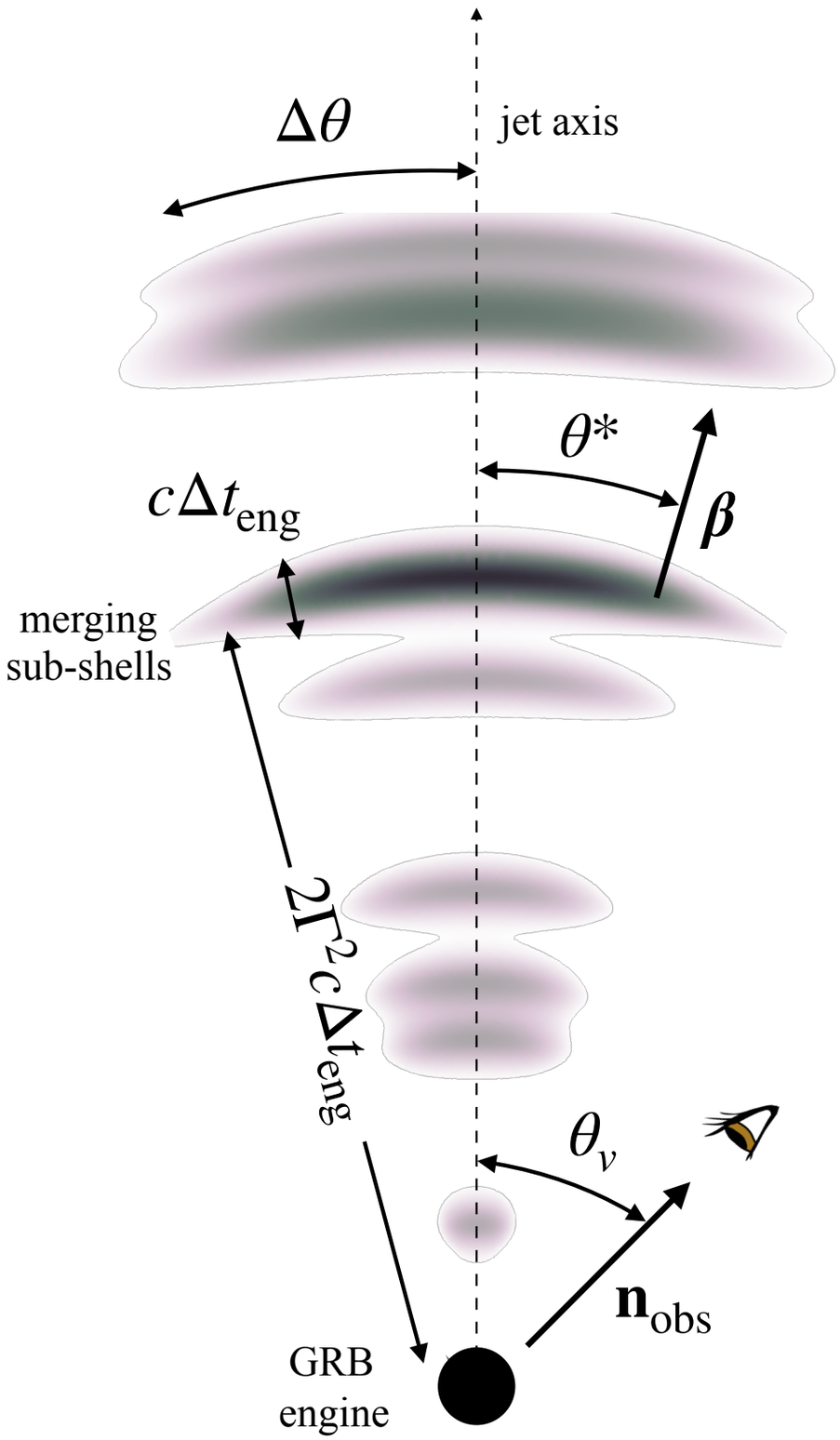


GW 170817
&
GRB 170817A

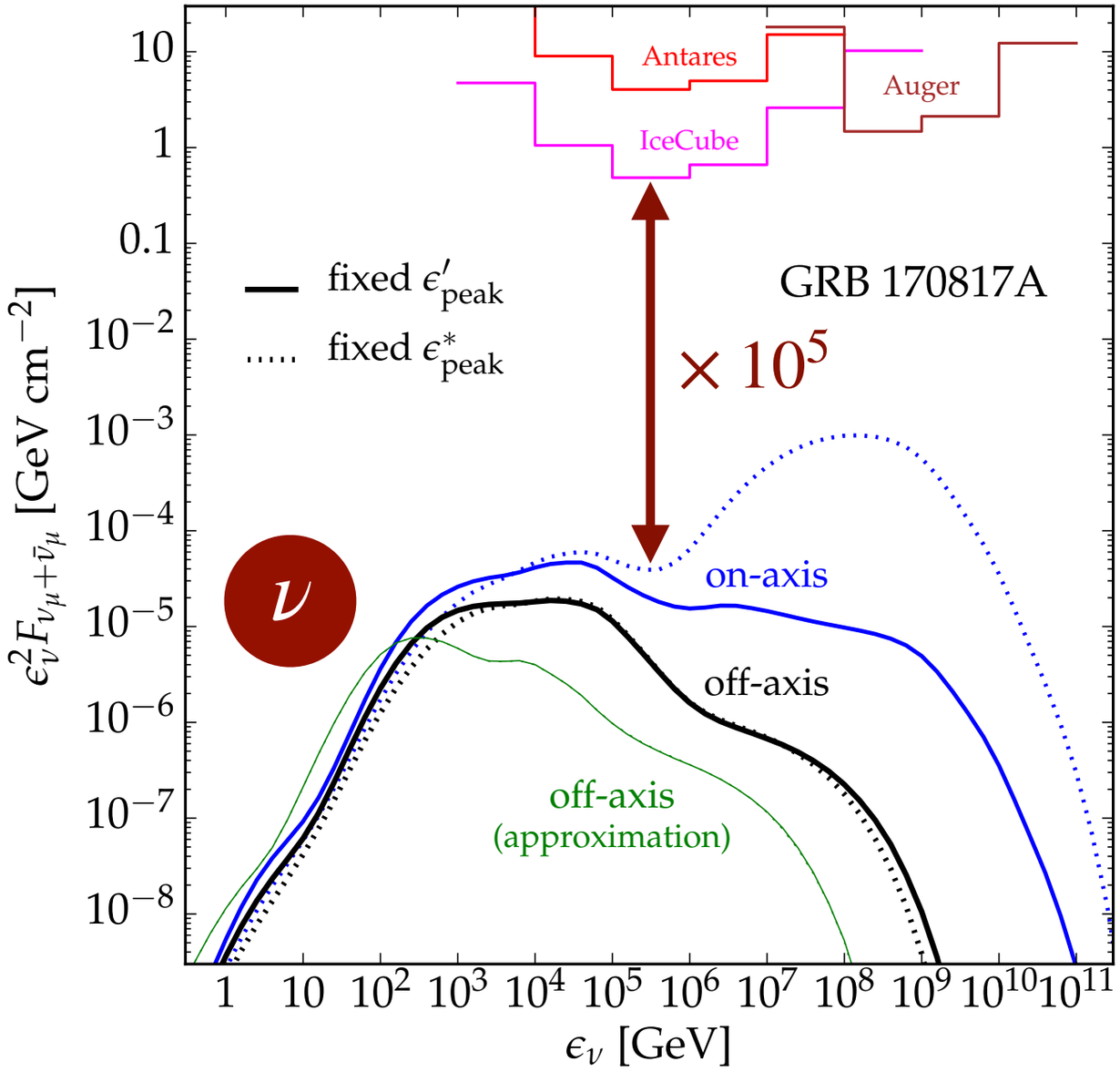


Kilonova
powered by
radioactive
heavy nuclei

Example: GRB 170817A



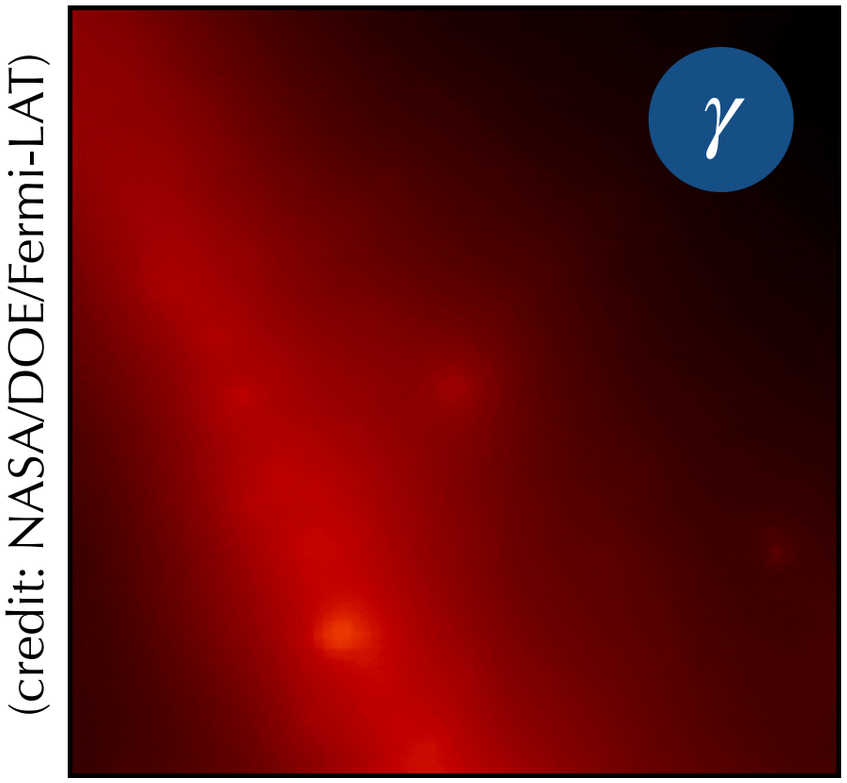
No detection of neutrinos in prompt phase consistent with **off-axis emission.**



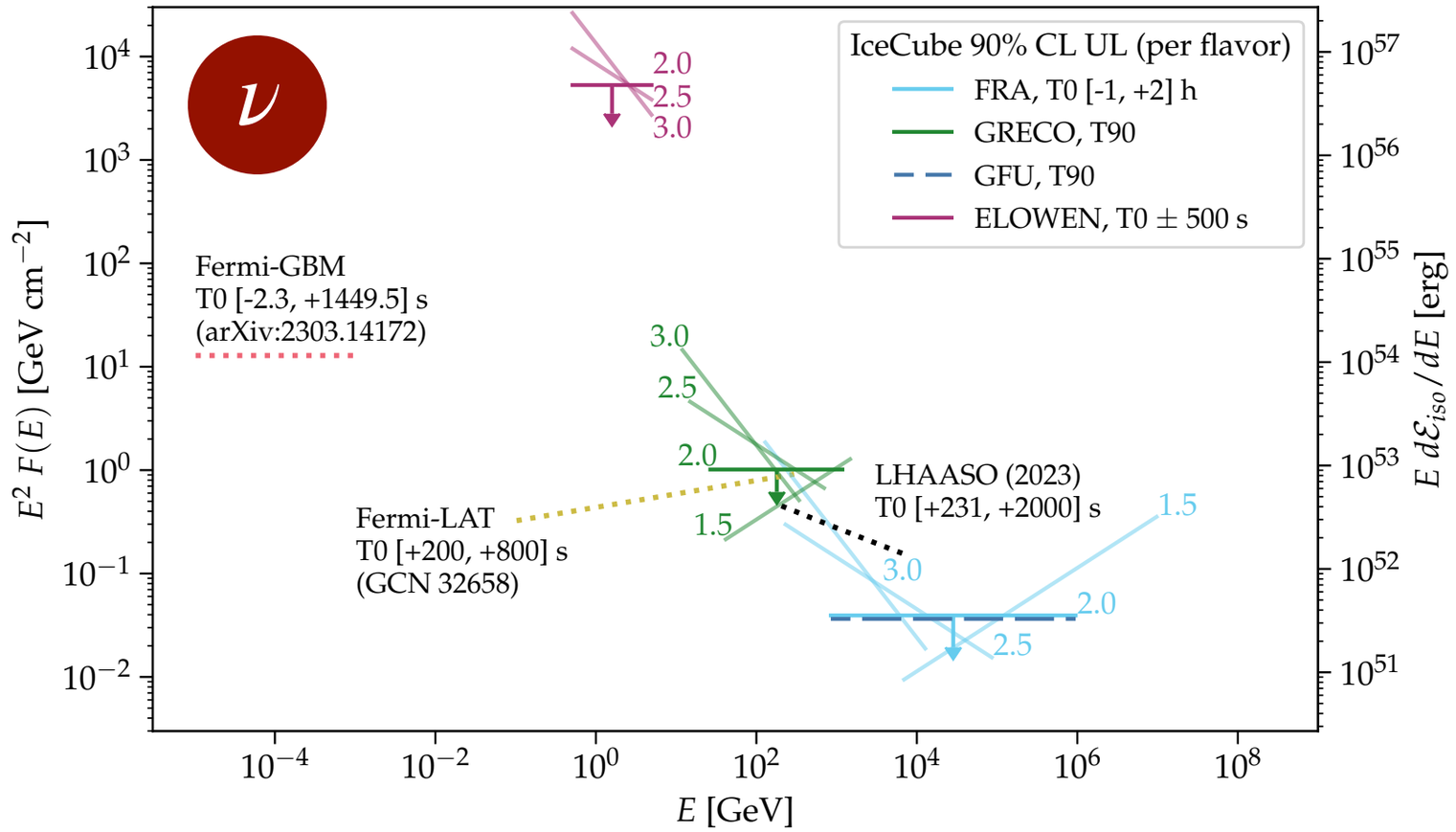
[MA & Halser'19]

Example: GRB 221009A

GRB seen by Fermi-LAT over 10h



Neutrino Upper Limits from IceCube



[γ-ray observations by Fermi **ApJL** 952 (2023) & LHAASO **Science** 9 (2023)]

- "*Brightest-Of-All-Time*" GRB 221009A ($D_L \simeq 740$ Mpc but $E_{\rm iso} \simeq 10^{55}$erg)
- MM observations in ApJL focus issue
- ν predictions for internal shock model

"*Limits on Neutrino Emission from GRB 221009A from MeV to PeV using the IceCube Neutrino Observatory*"

[IceCube **ApJL** 946 (2023)]

[IceCube PoS-ICRC2023-1511]

Average Neutrino Energies

- Average energy fraction of pions from CR nucleons:

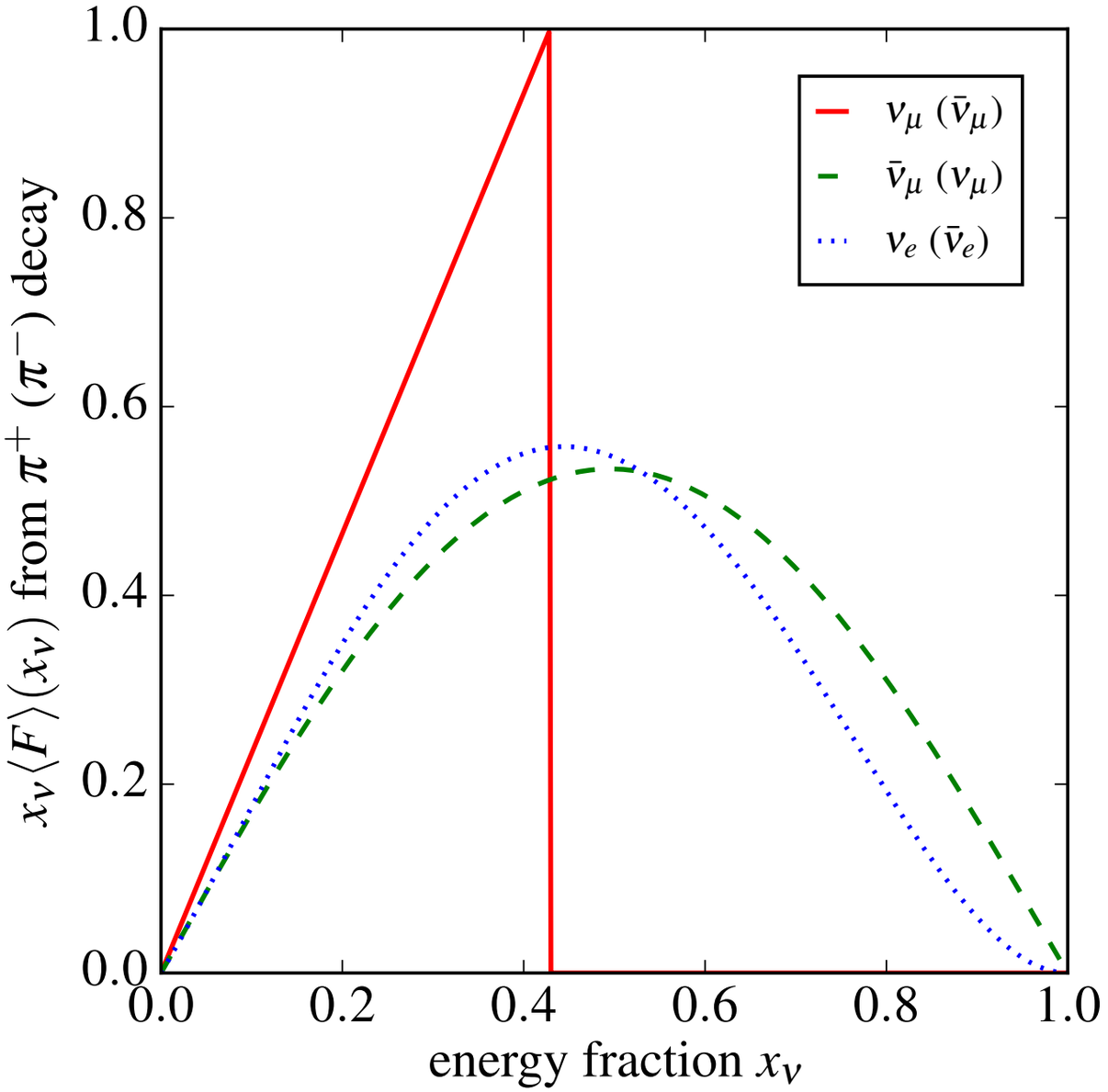
$$\langle x_\pi \rangle = \kappa_\pi \simeq 20\,\%$$

- 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:**

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

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

Gamma-Ray vs. Neutrinos

- **Neutrino emission** from charged pion decay:

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

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

- **Gamma-ray emission** from neutral pion decay:

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

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

- **Multi-messenger relation** between neutrino and γ-ray emission:

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

- ***Note:*** Observable γ-ray emission is attenuated in sources and, in particular, in extragalactic background radiation.

Neutrino Mixing

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix

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

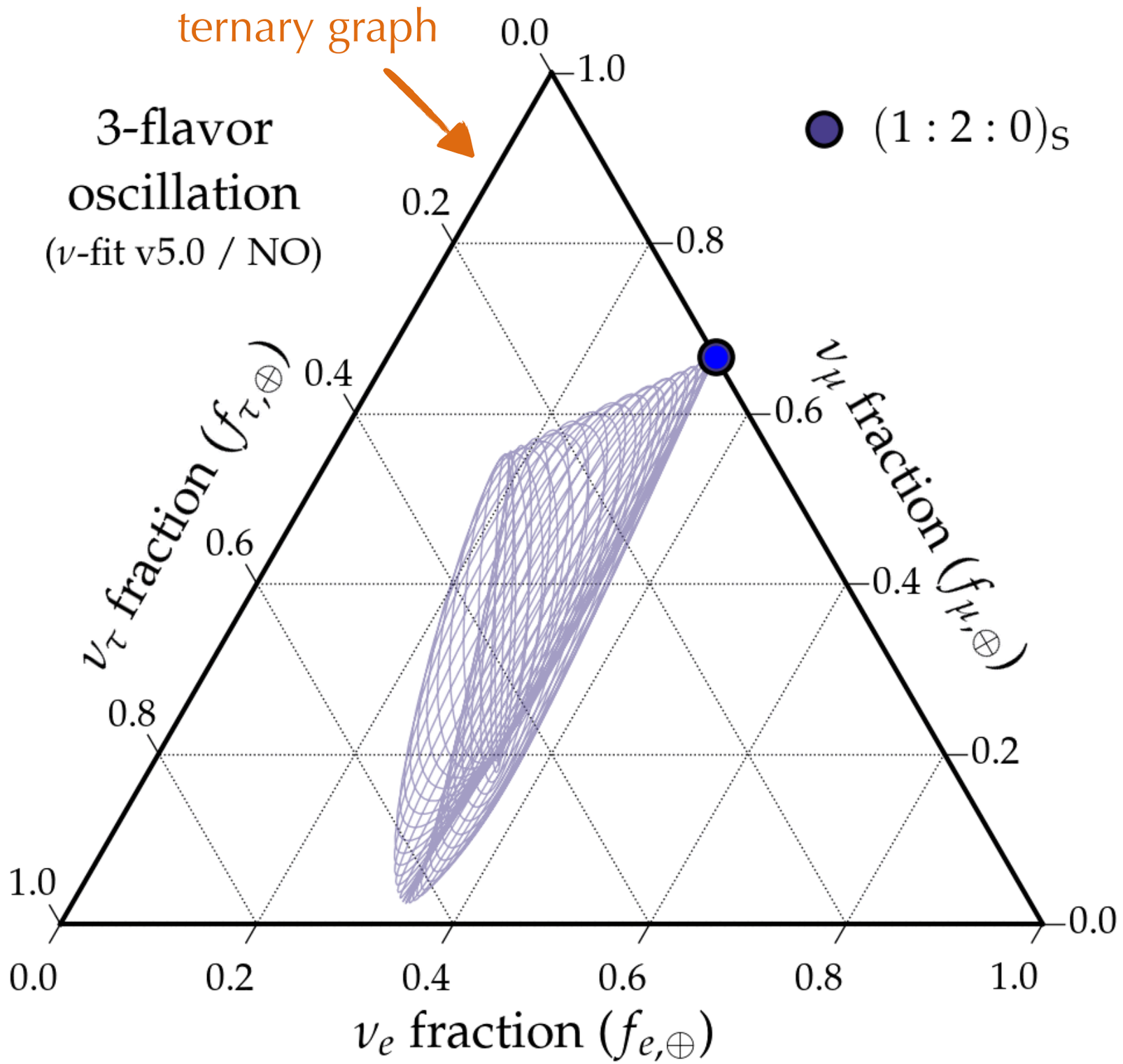
"atmospheric" mixing — ~~CP~~ Dirac phase $\propto \sin\theta_{13}$ — "solar" mixing — ~~CP~~ Majorana phases

flavour transition probability (in vacuum):

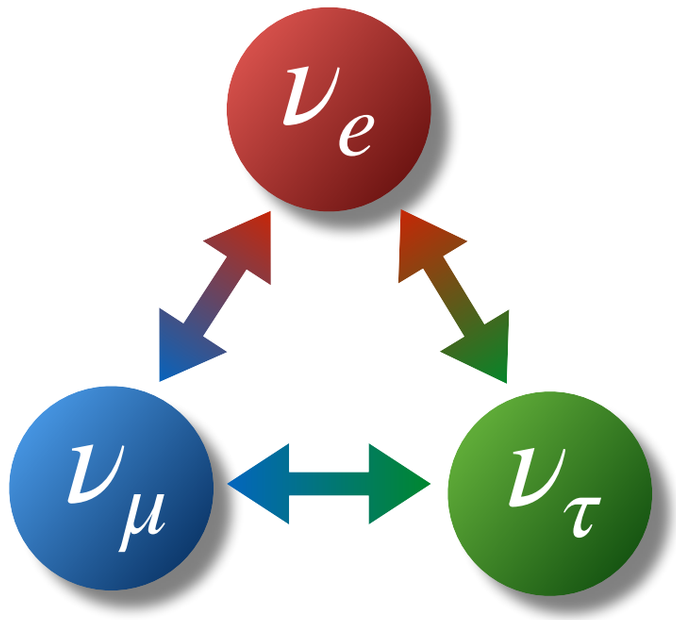
$$P_{\nu_\alpha \to \nu_\beta}(\ell) = \sum_{i=1}^{3}\sum_{j=1}^{3} U_{\alpha i}U^*_{\beta i}U^*_{\alpha j}U_{\beta j} \exp\left(i\frac{\Delta m^2_{ij}\ell}{2E_\nu}\right)$$

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

Astrophysical Flavours



Superposition of flavor and mass states induce oscillations.

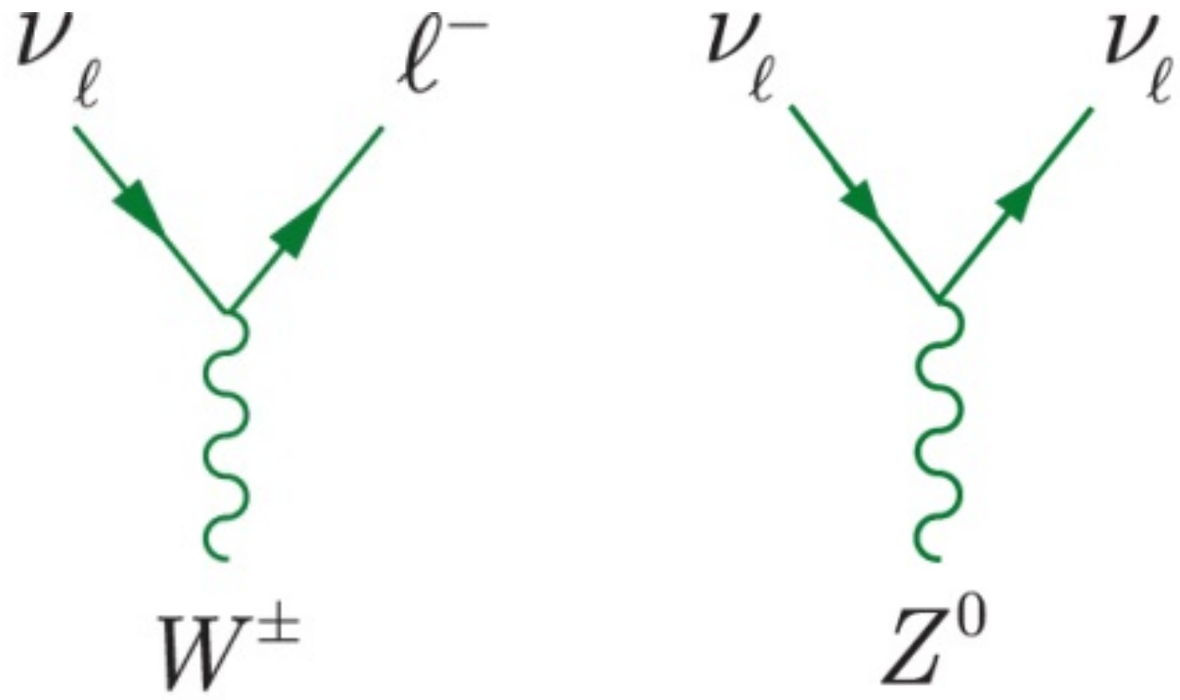


Neutrinos in the Standard Model

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

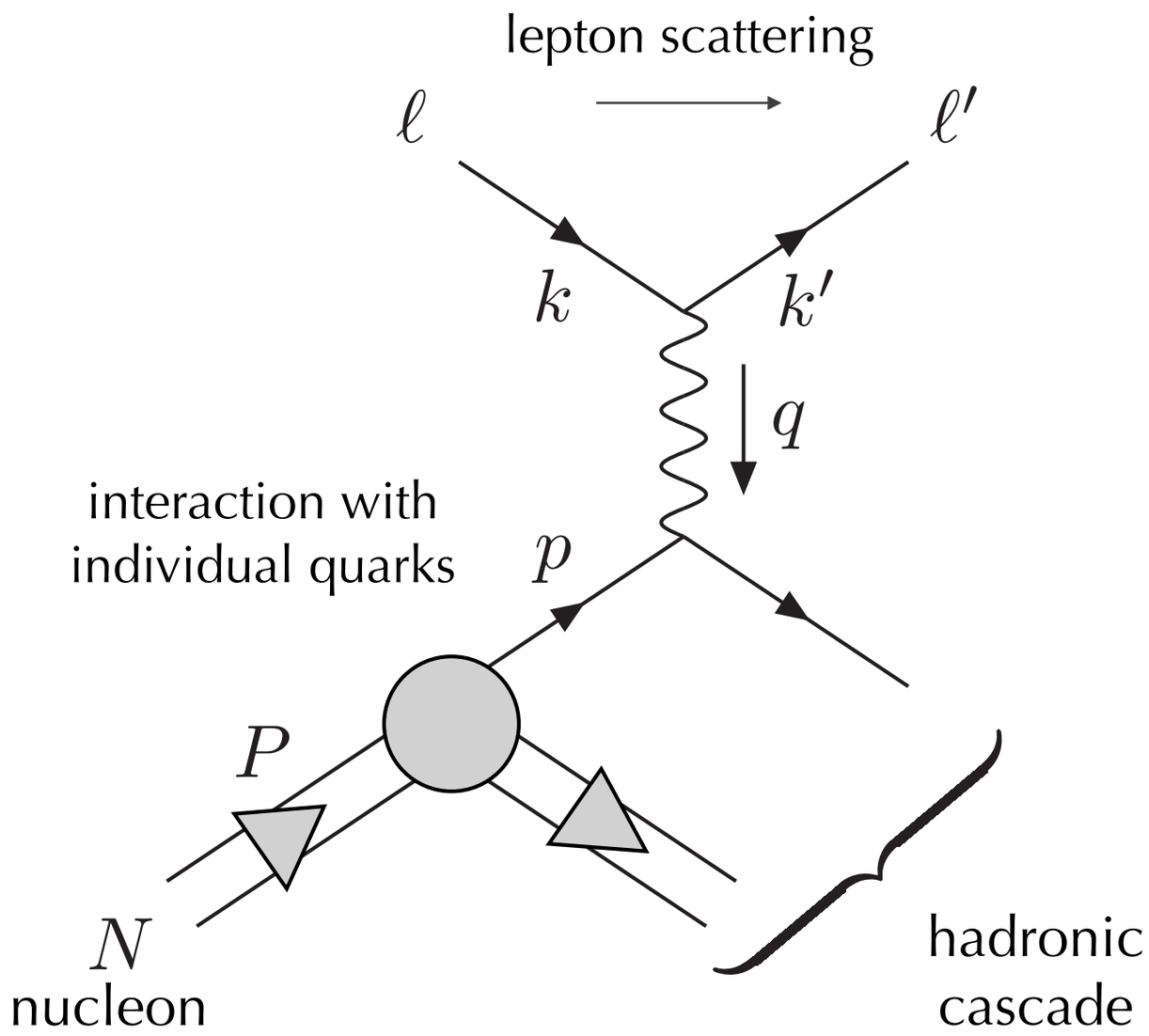
$$\begin{pmatrix}\nu_e\\ e^-\end{pmatrix}_L \quad \begin{pmatrix}\nu_\mu\\ \mu^-\end{pmatrix}_L \quad \begin{pmatrix}\nu_\tau\\ \tau^-\end{pmatrix}_L \quad \begin{pmatrix}e^+\\ \overline{\nu}_e\end{pmatrix}_R \quad \begin{pmatrix}\mu^+\\ \overline{\nu}_\mu\end{pmatrix}_R \quad \begin{pmatrix}\tau^+\\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

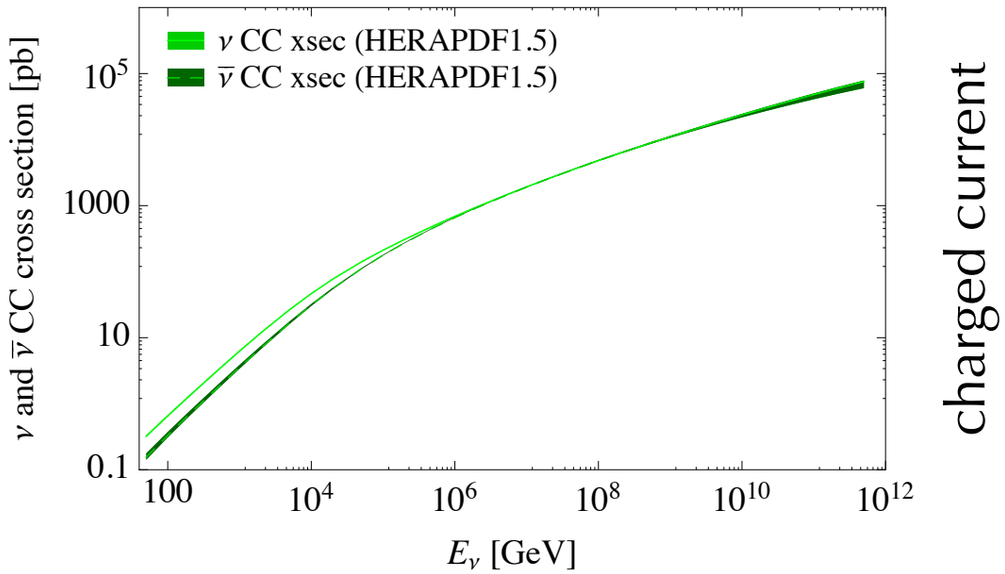
Participate in **charged** (W) **and neutral** (Z) **current** interactions:

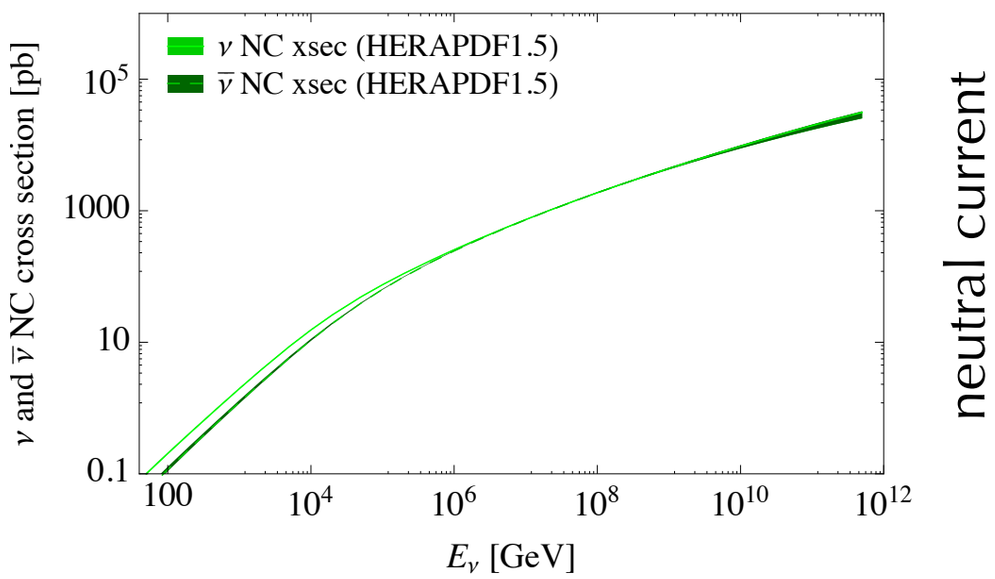


Neutrino Interactions

- 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: $\phi \simeq \frac{10^5}{\mathrm{km^2\,yr}}$

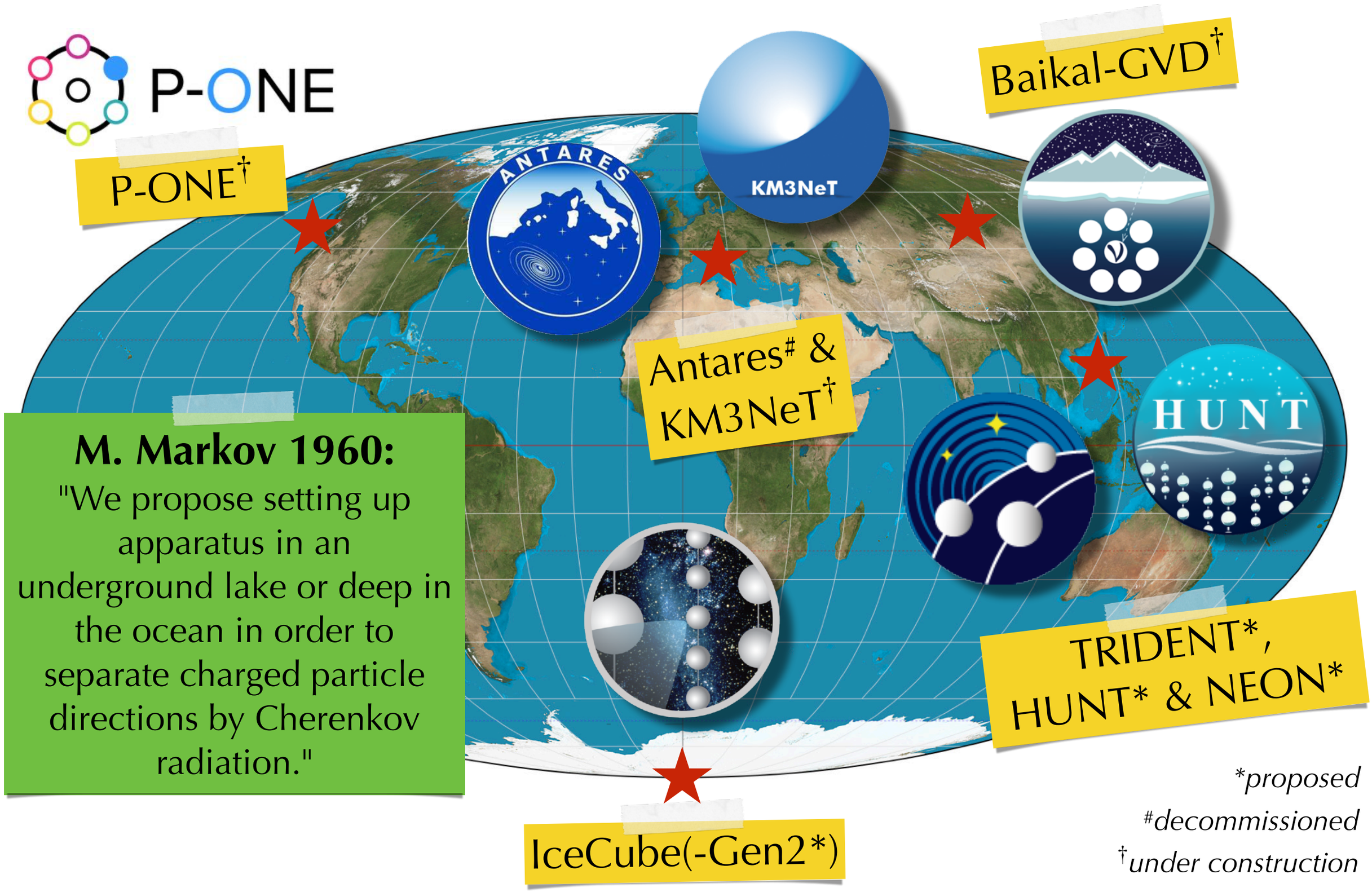
cross section: $\sigma_{\nu\mathrm{p}} \simeq 10^{-8}\sigma_{\mathrm{pp}} \simeq 10^{-33}\mathrm{cm}^2$

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

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

minimum detector size: 1km³

Optical Cherenkov Telescopes

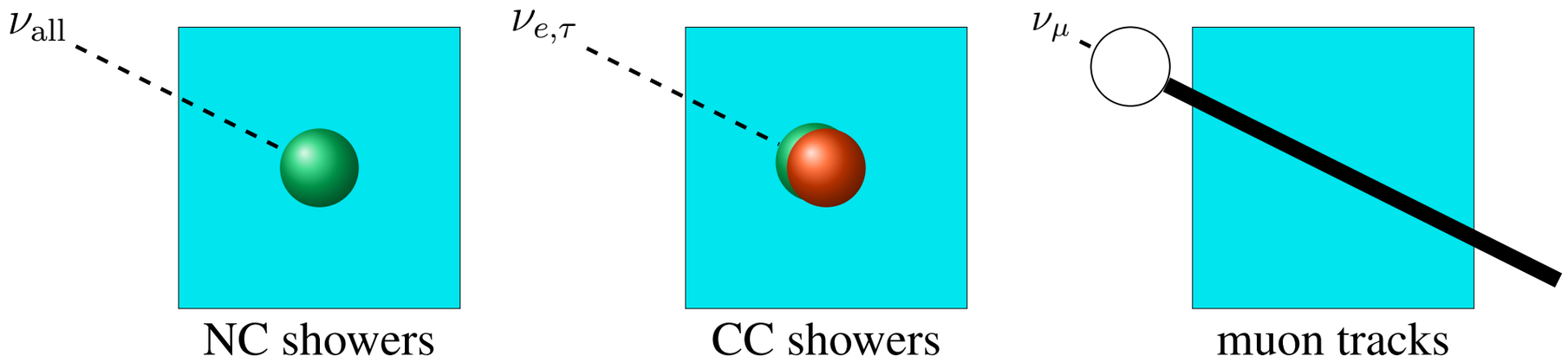


M. Markov 1960:
"We propose setting up apparatus in an underground lake or deep in the ocean in order to separate charged particle directions by Cherenkov radiation."

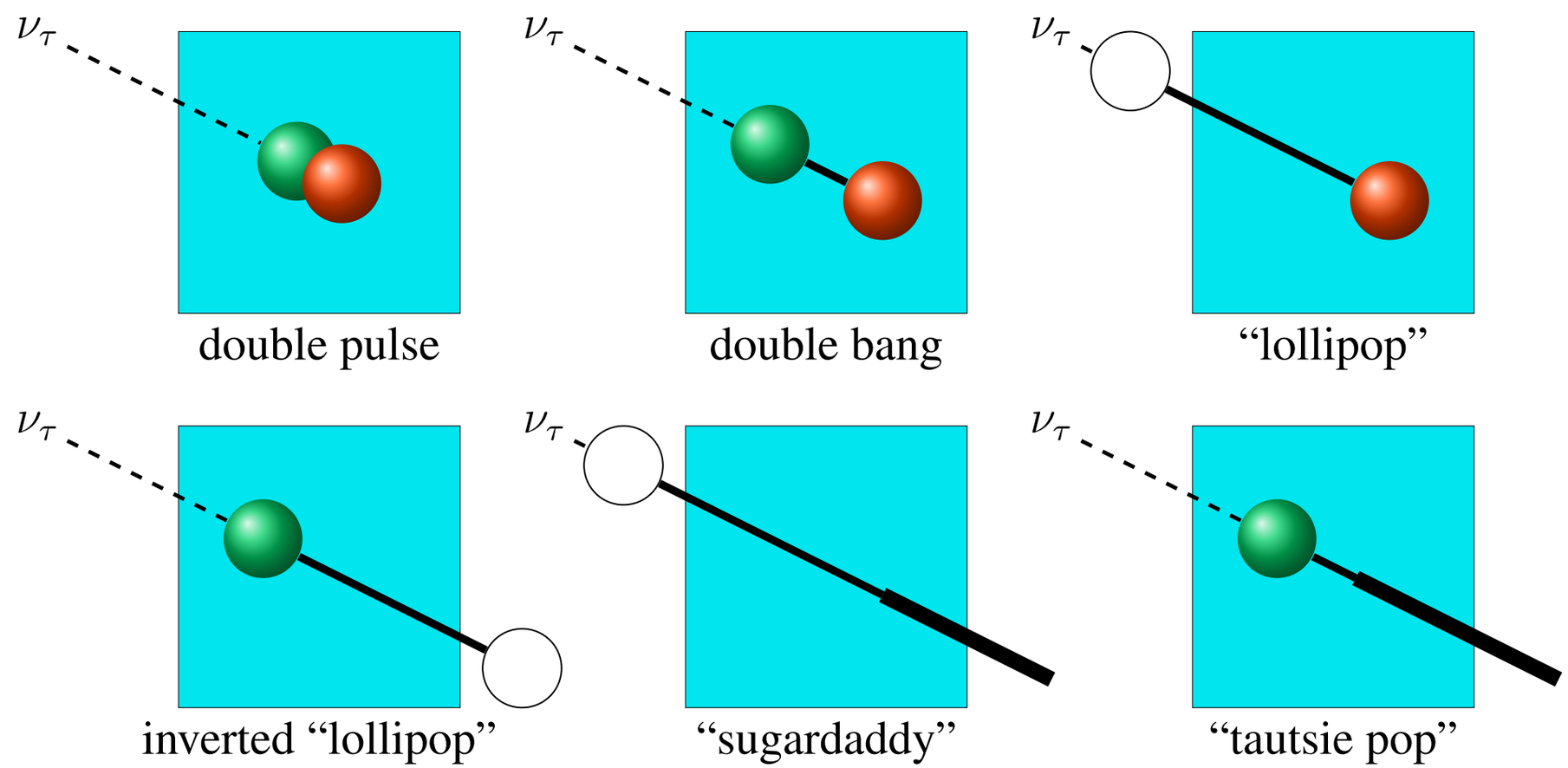
**proposed*
#decommissioned
†under construction

Optical Cherenkov Signals

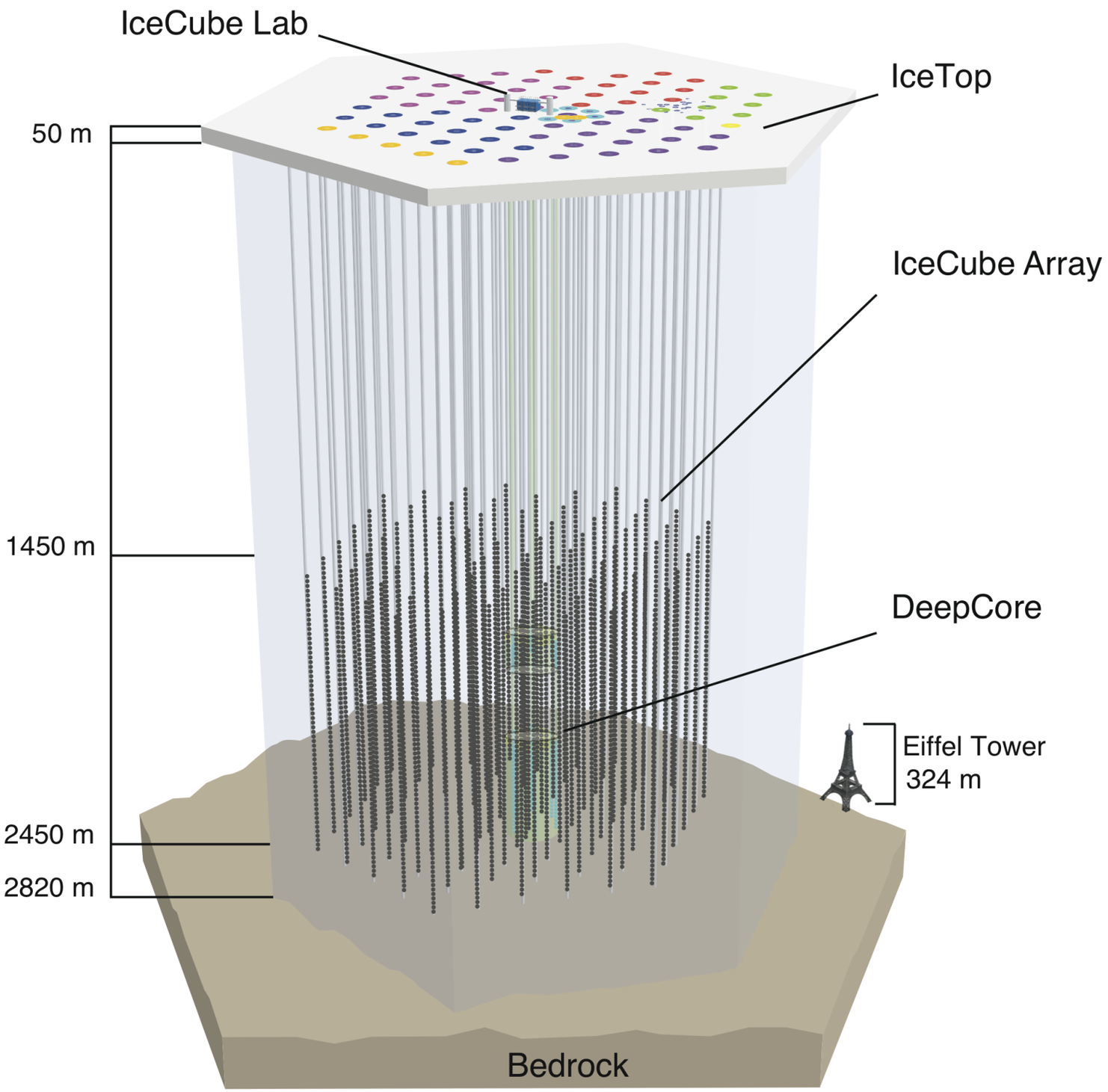
"cascades"
&
"tracks"



rare events
from CC ν_{τ}
interactions

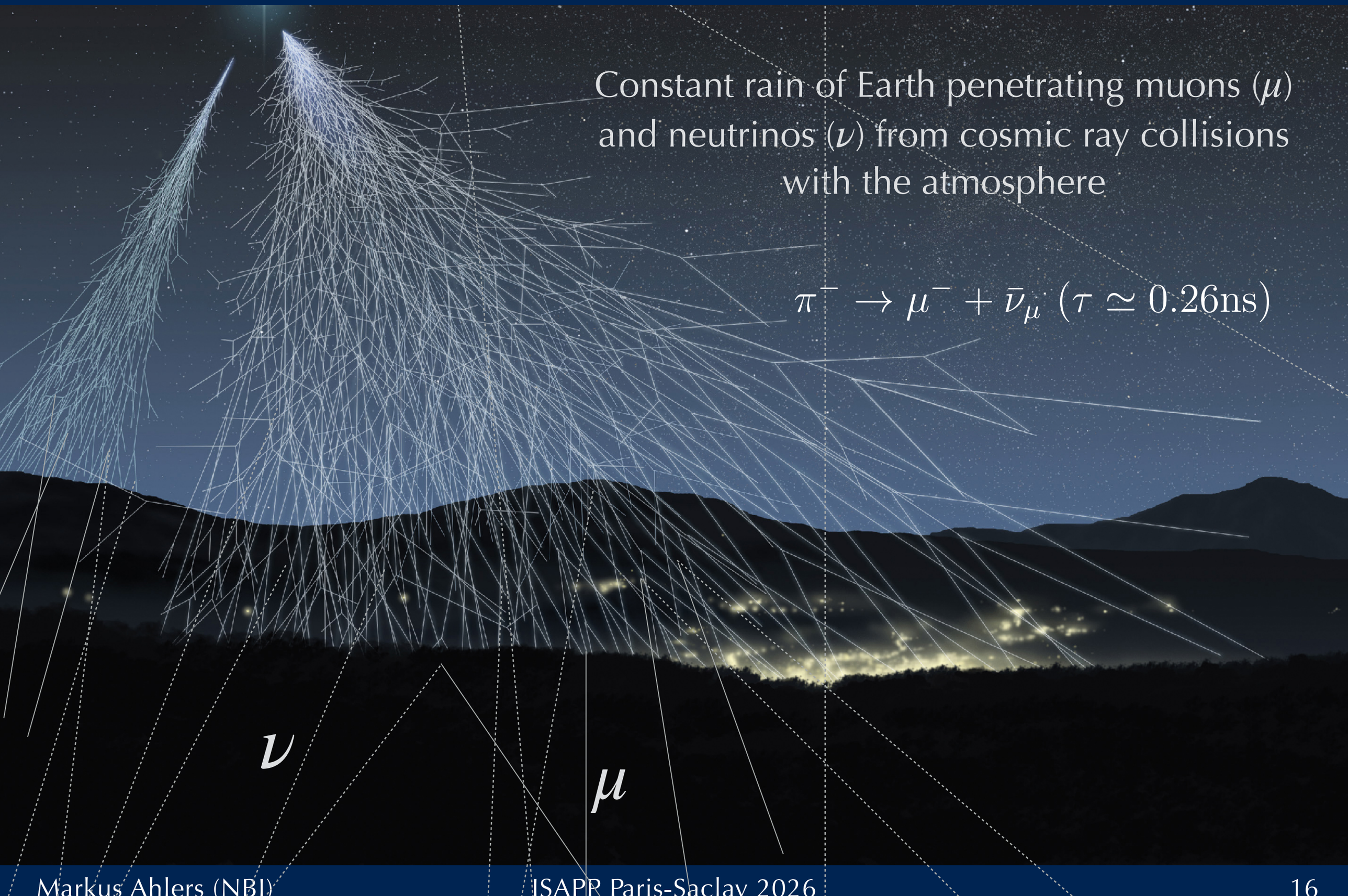


IceCube Observatory

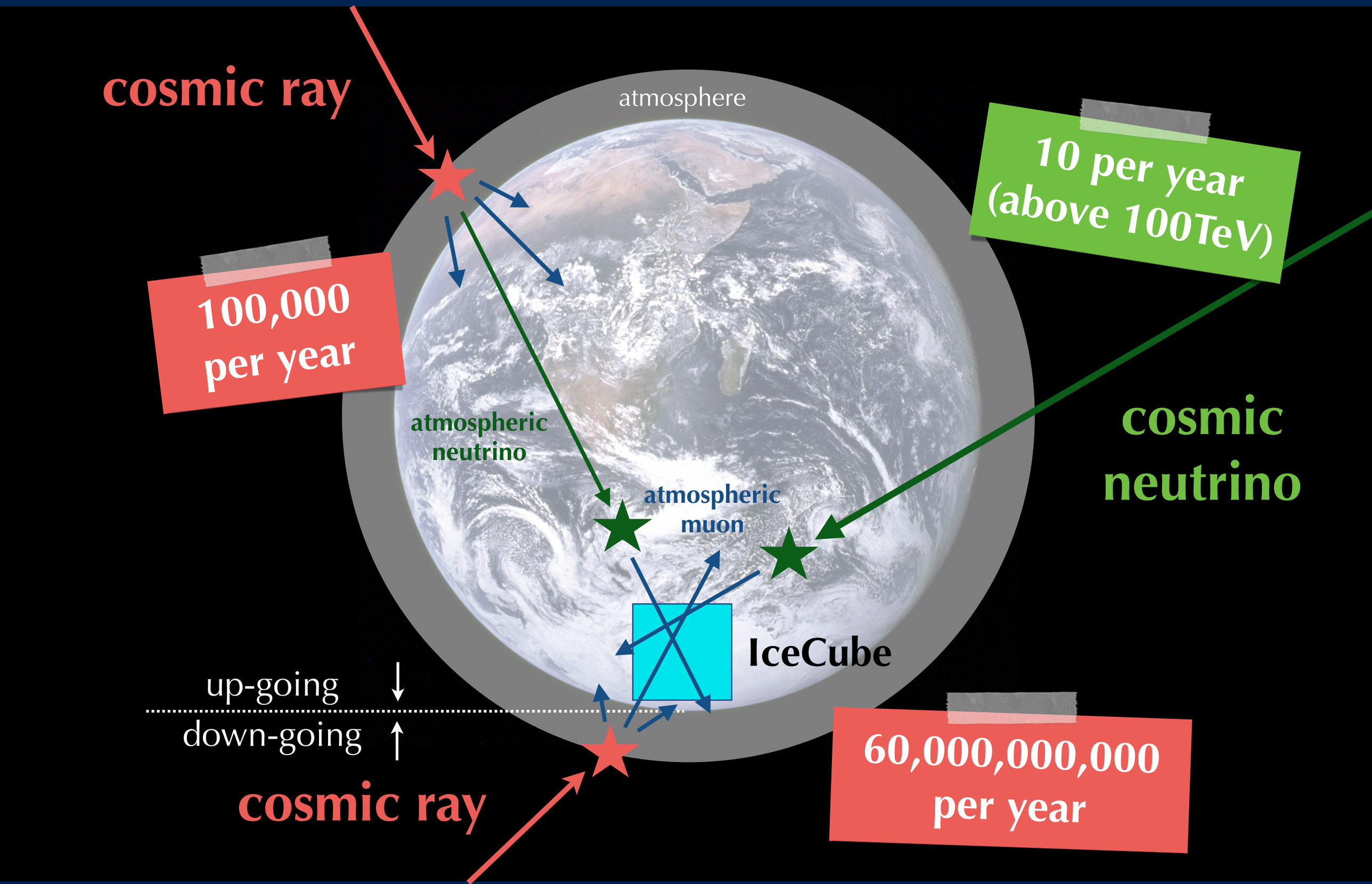


- **Giga-ton optical Cherenkov telescope at the South Pole**
- 86 IceCube strings of 60 DOMs **instrumenting 1 km³ of clear glacial ice**
- 81 IceTop stations for cosmic ray shower detections
- running in full IC86 configuration since 2011
- **>99% detector uptime**
- trigger rate about 2.7 kHz
- about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

Atmospheric Background

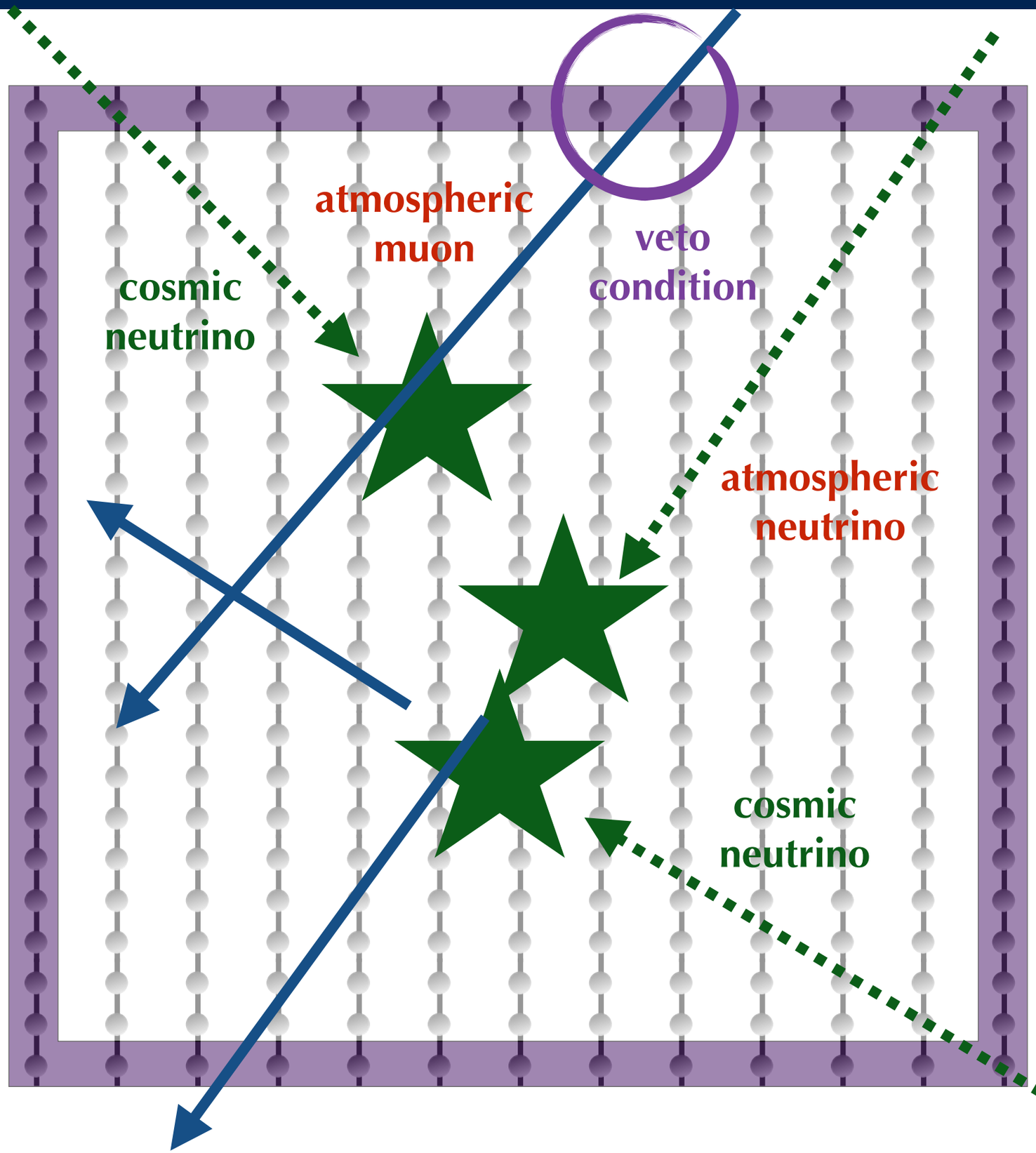


Neutrino Selection I



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



Galactic Cosmic Rays

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

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

- diffusive shock acceleration:

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

- rigidity-dependent escape from Galaxy:

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

★ Neutrino emission from CR interactions with gas

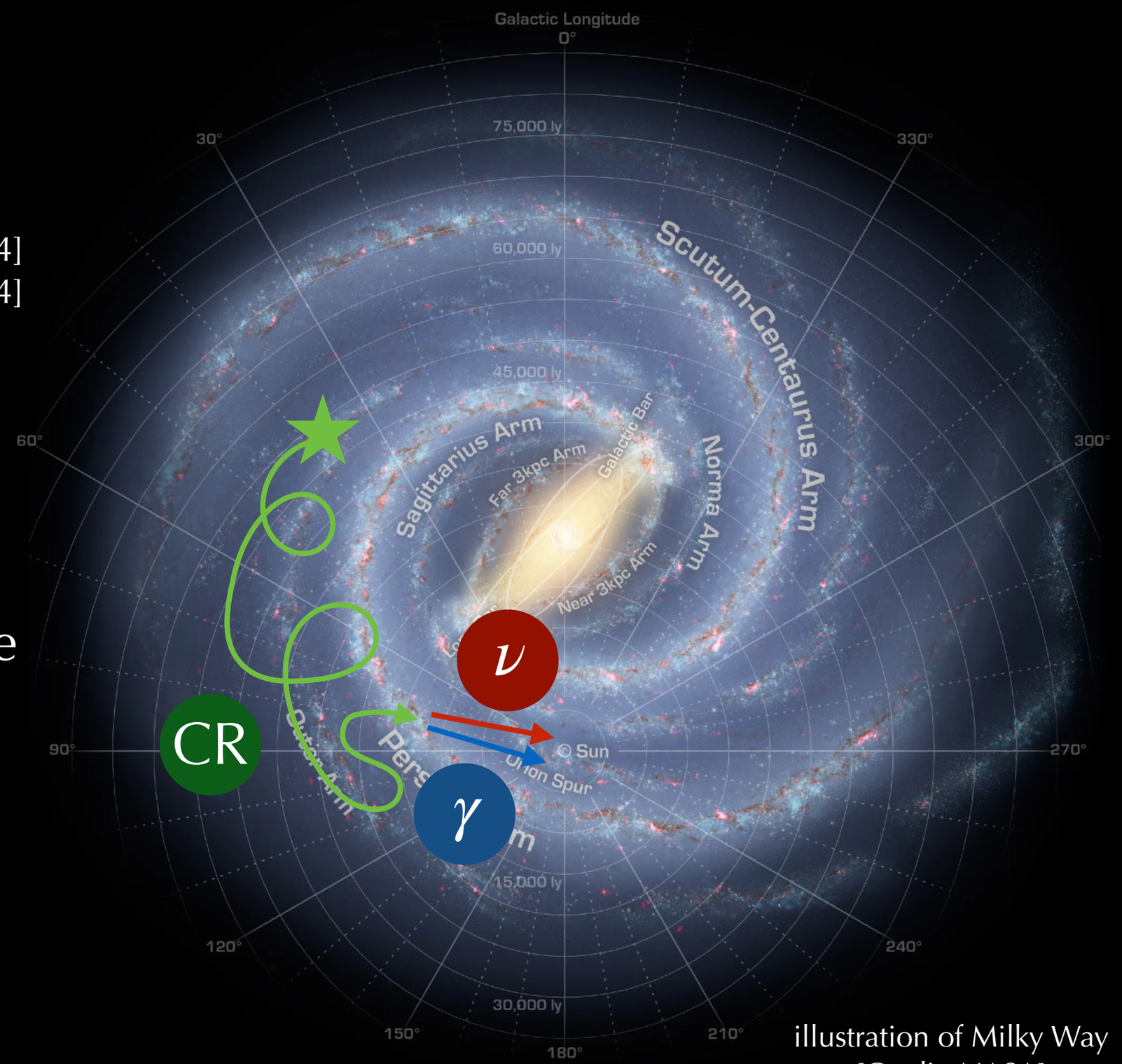
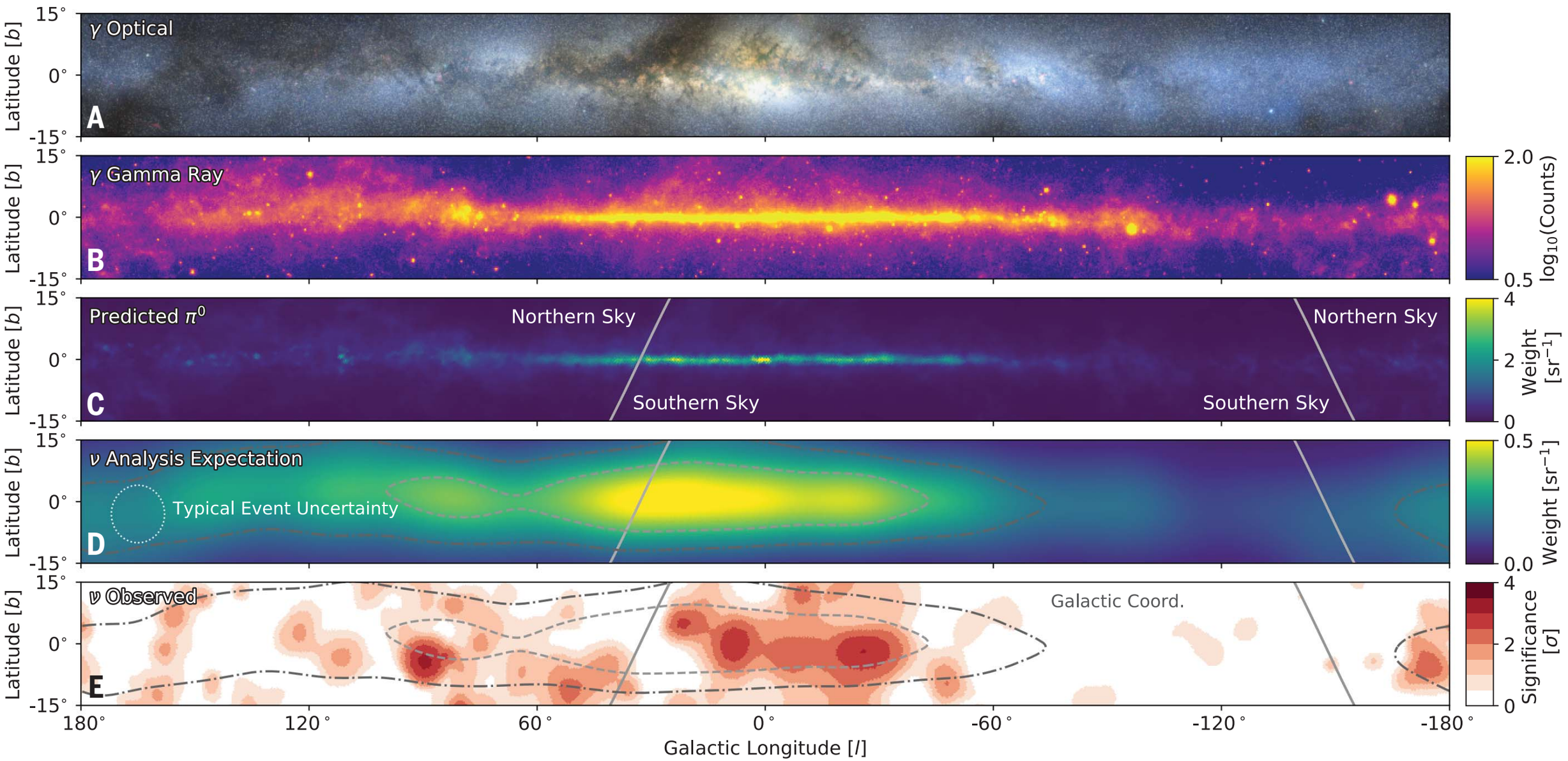


illustration of Milky Way
[Credit: NASA]

Galactic Neutrino Emission

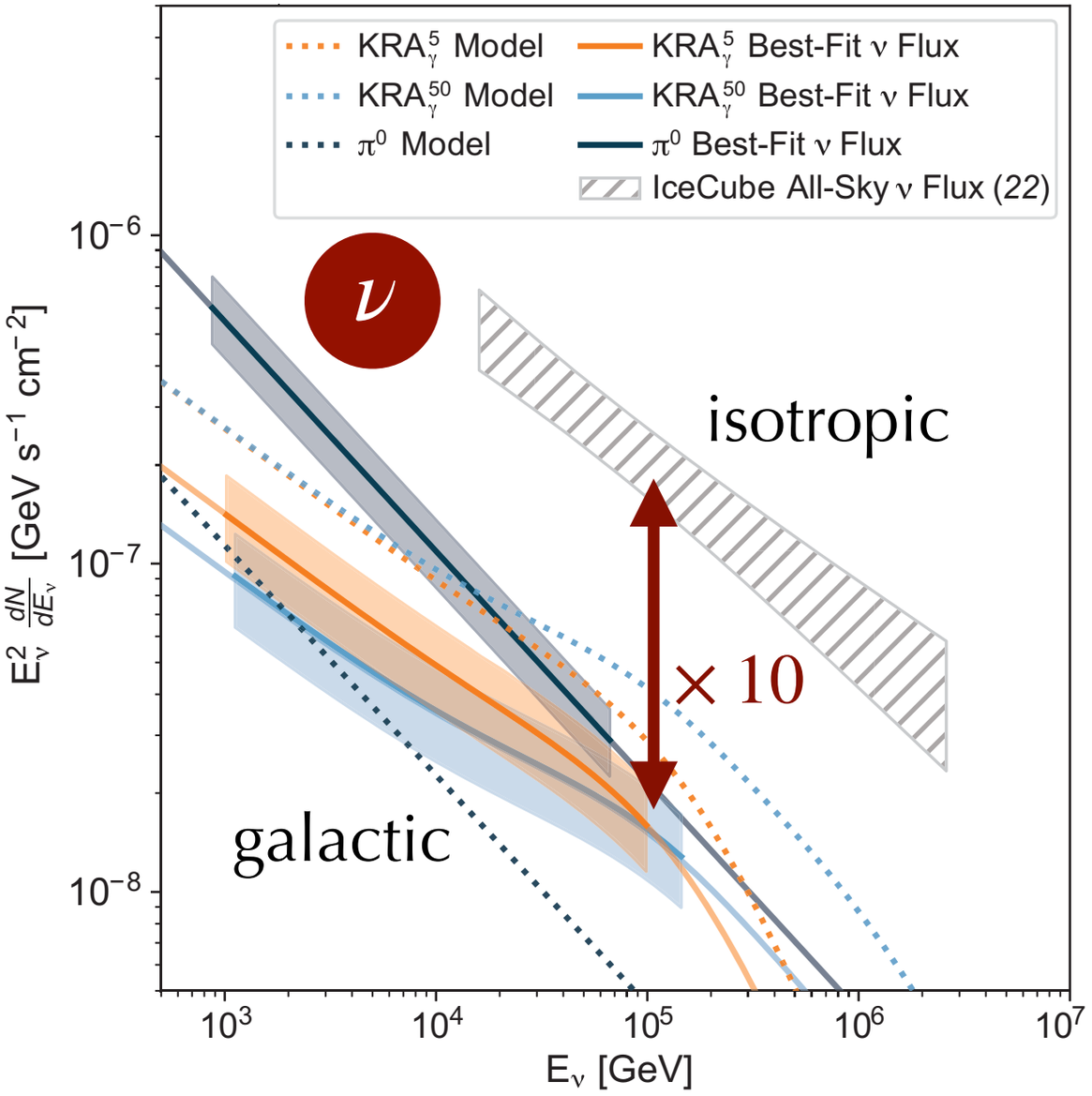
Galactic diffuse ν emission at 4.5σ based on template analysis.



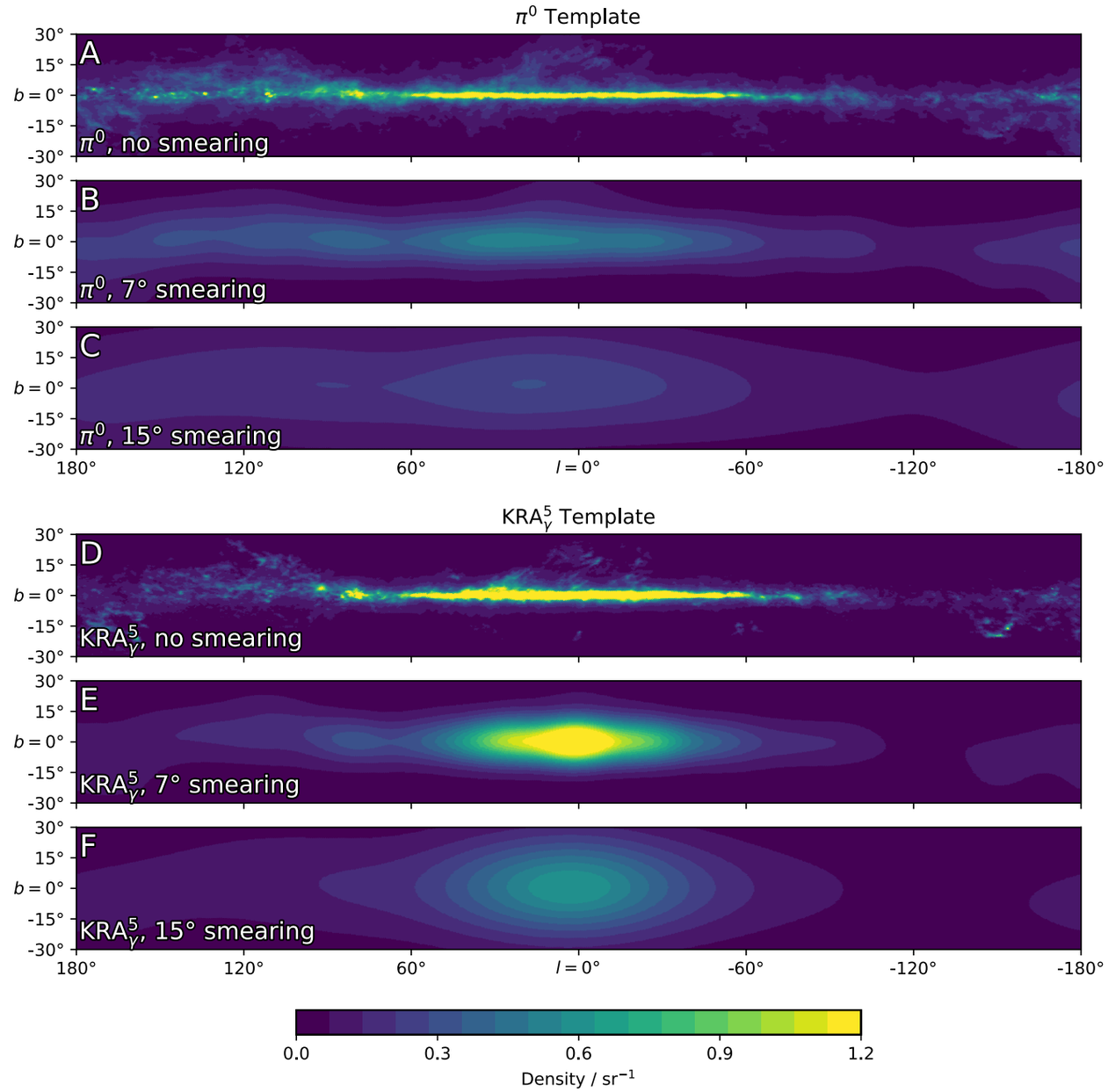
[IceCube, **Science** 380 (2023) 6652; see also IceCube, **PoS** (ICRC2025) 1130 & 1193]

Galactic Neutrino Emission

Best-fit normalization of spectra



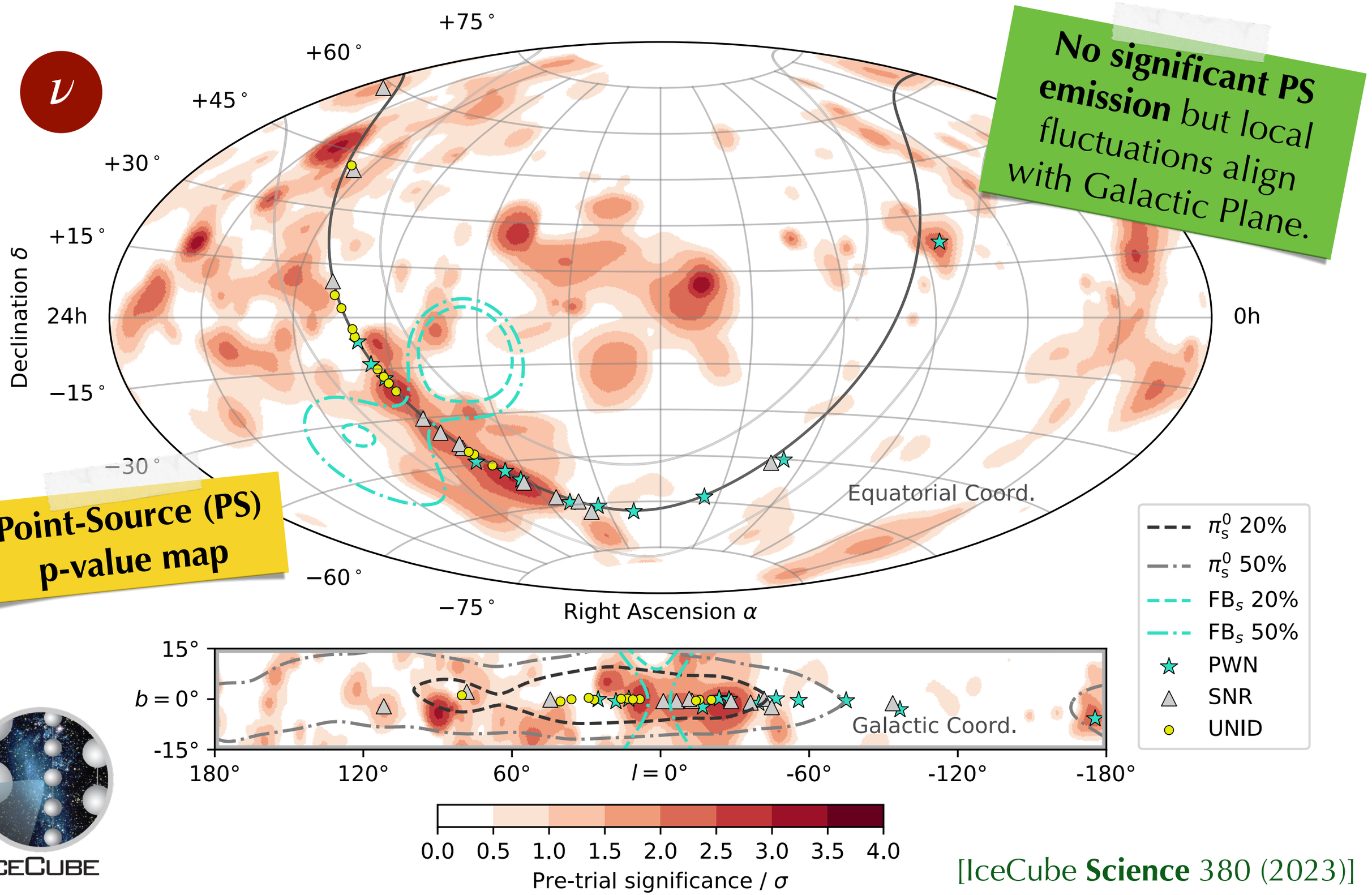
Templates with different resolution



[IceCube **Science** 380 (2023) 6652]

[**templates**: Fermi'12; Gaggero, Grasso, Marinelli, Urbano & Valli '15]

Point-Source Significance Map



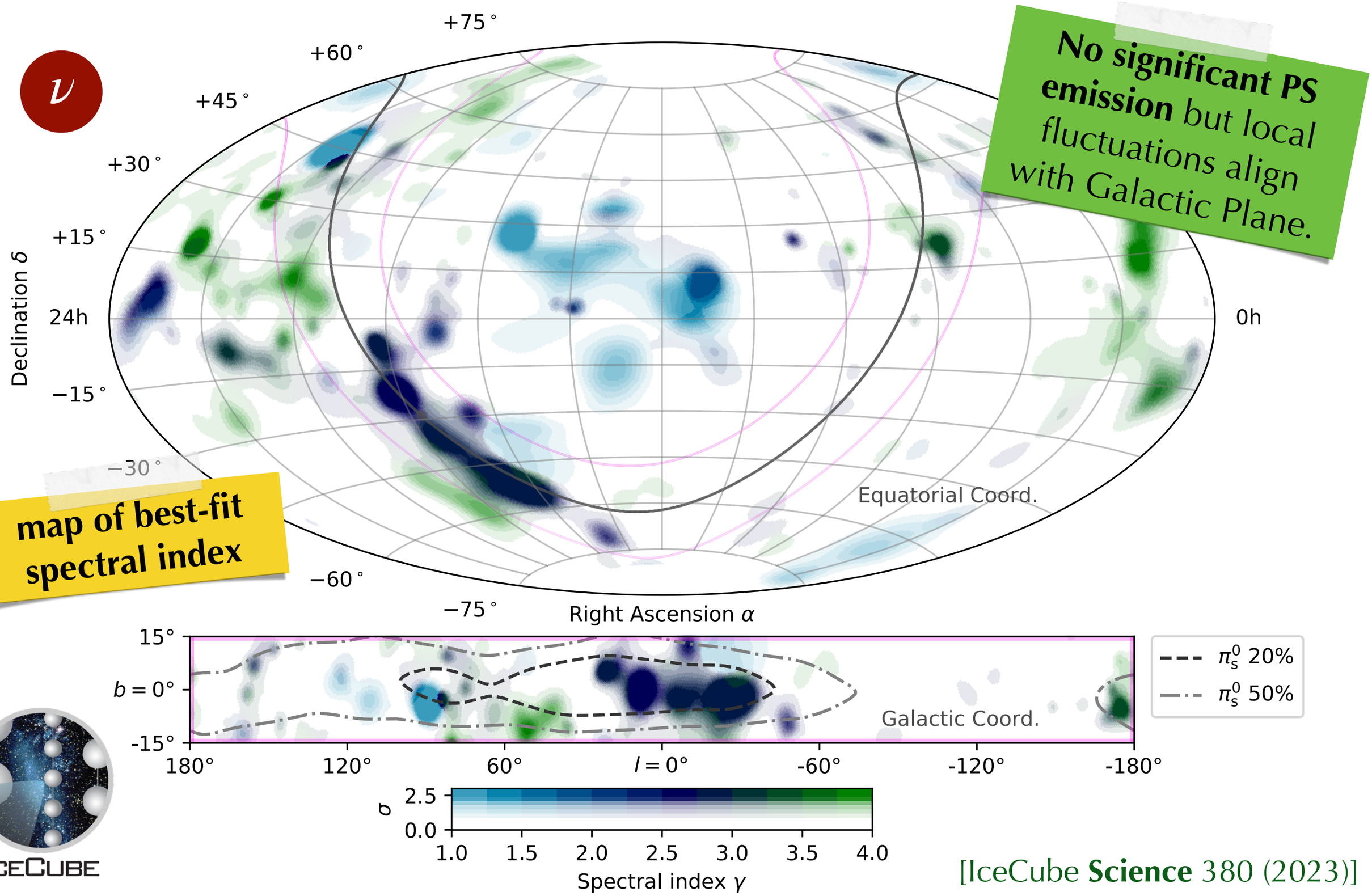
No significant PS emission but local fluctuations align with Galactic Plane.

Point-Source (PS) p-value map

IceCube

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

Point-Source Significance Map



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

map of best-fit spectral index

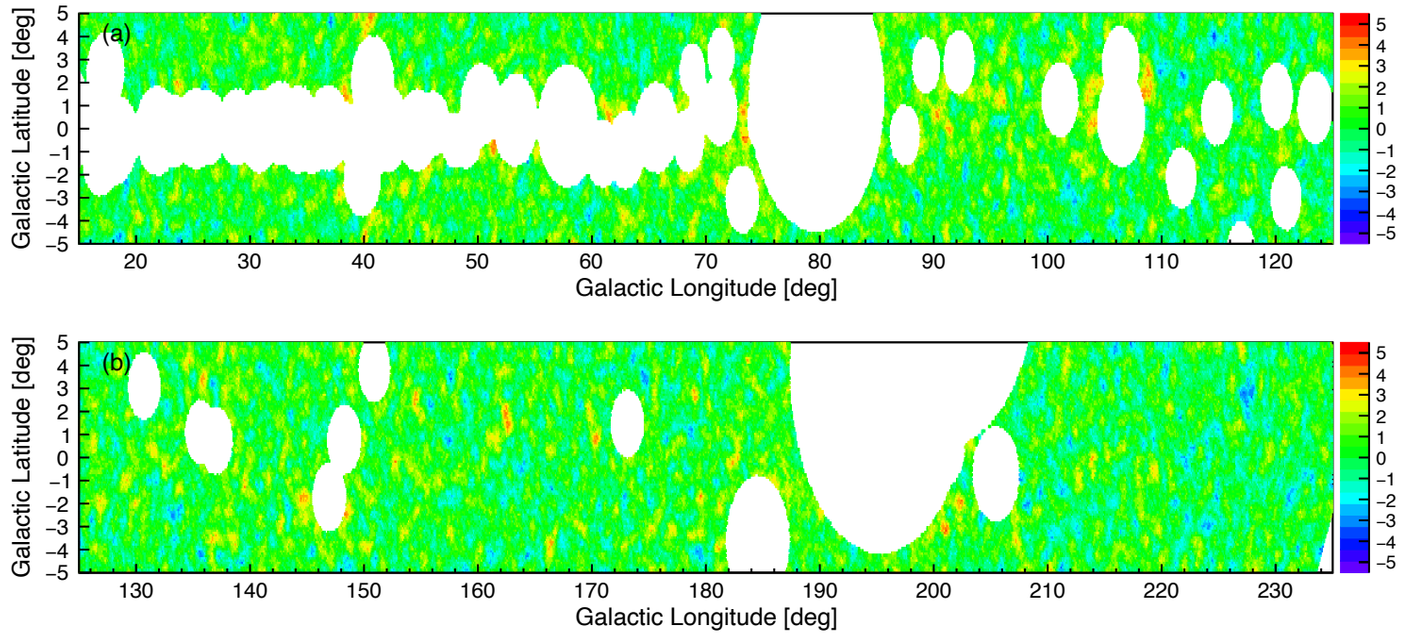
IceCube

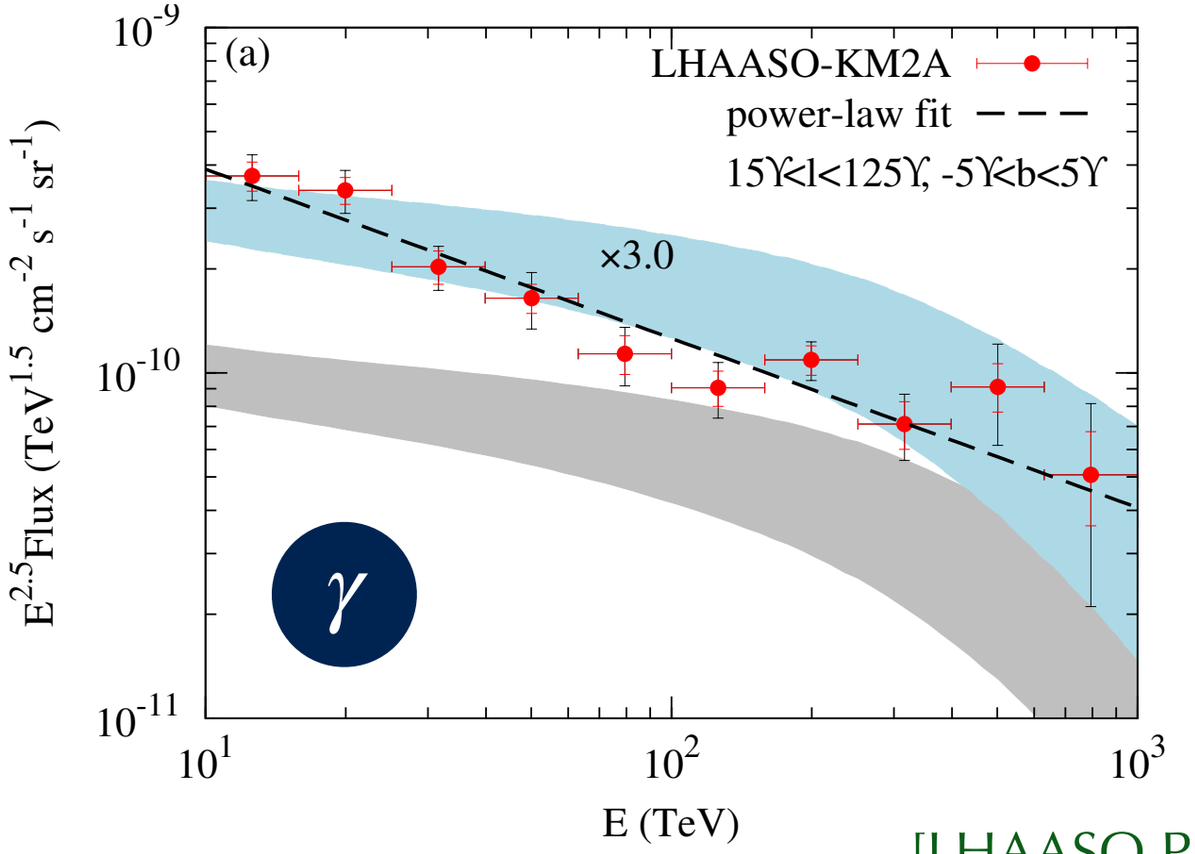
[IceCube **Science** 380 (2023)]

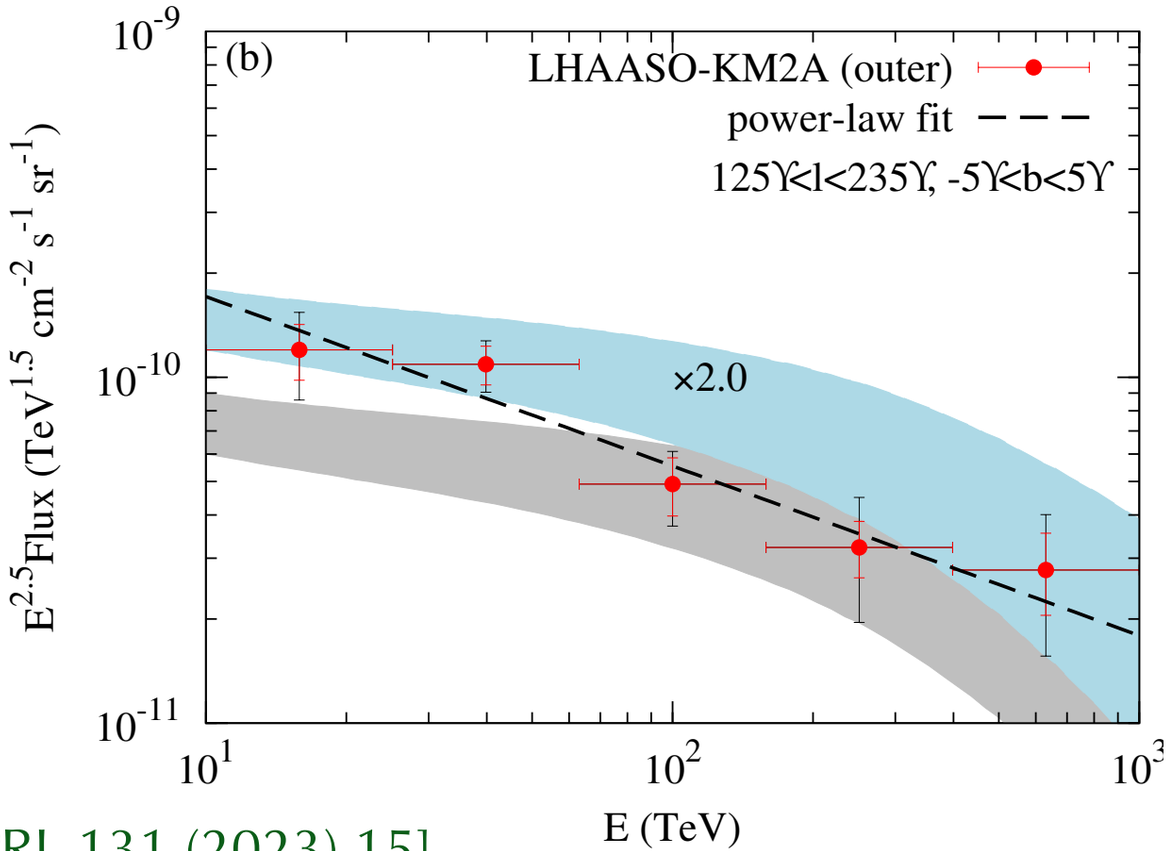
LHAASO Diffuse Emission

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

[LHAASO PRL 131 (2023) 15]



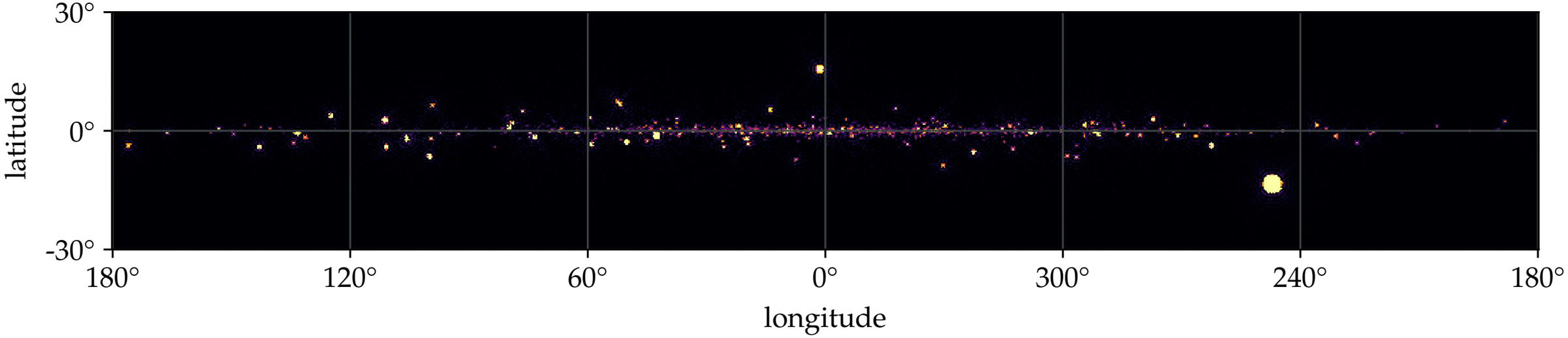




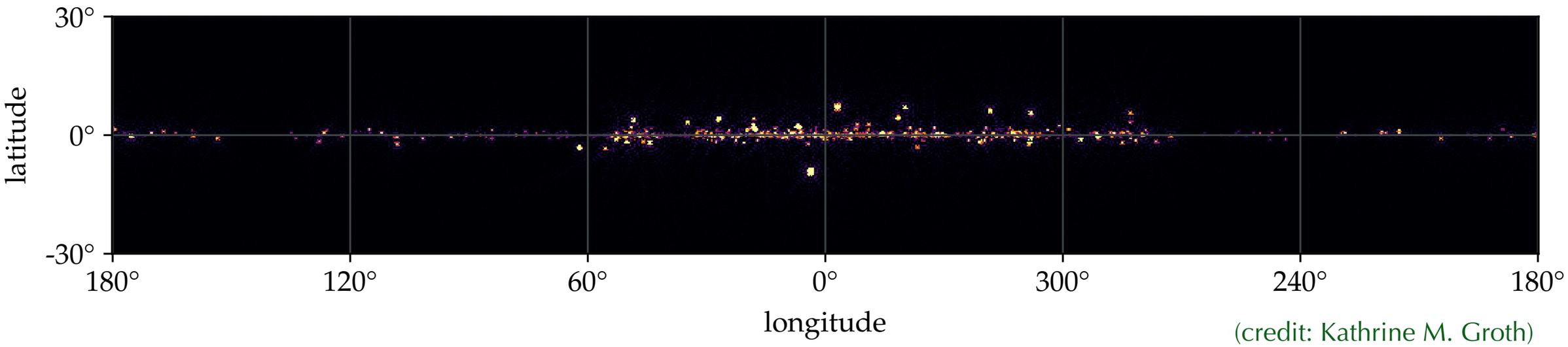
[LHAASO PRL 131 (2023) 15]

Galactic Neutrino Populations

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



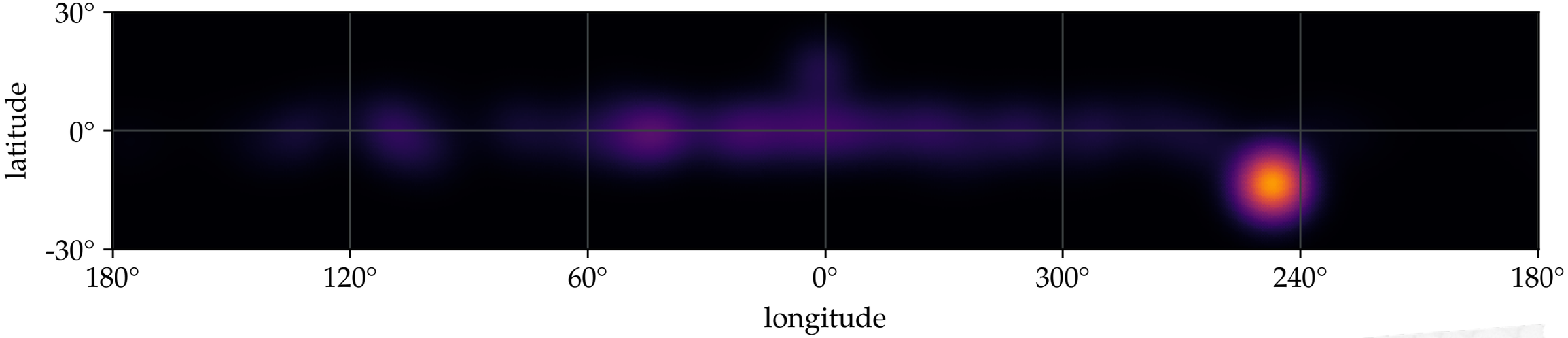
+ modulation with spiral arms



(credit: Kathrine M. Groth)

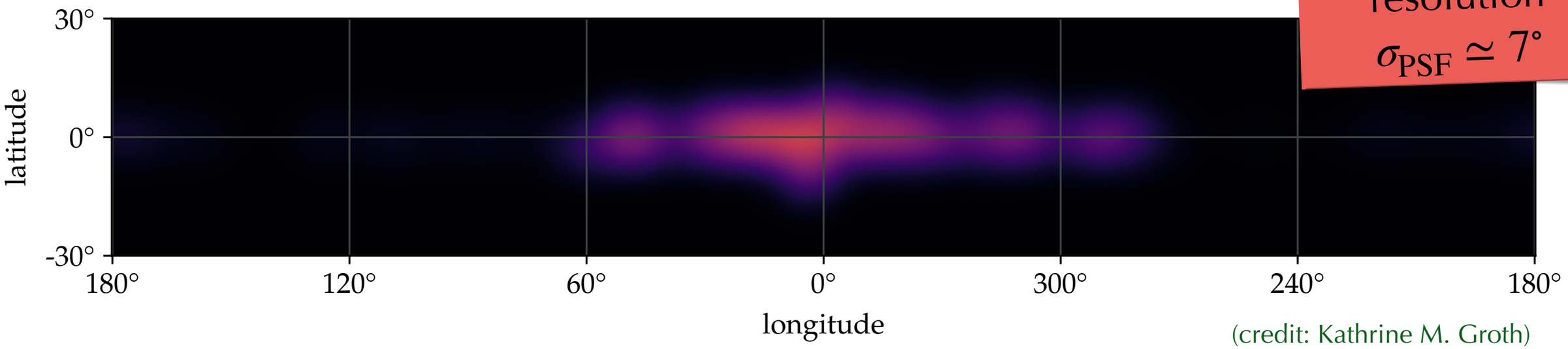
Galactic Neutrino Populations

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



+ modulation with spiral arms

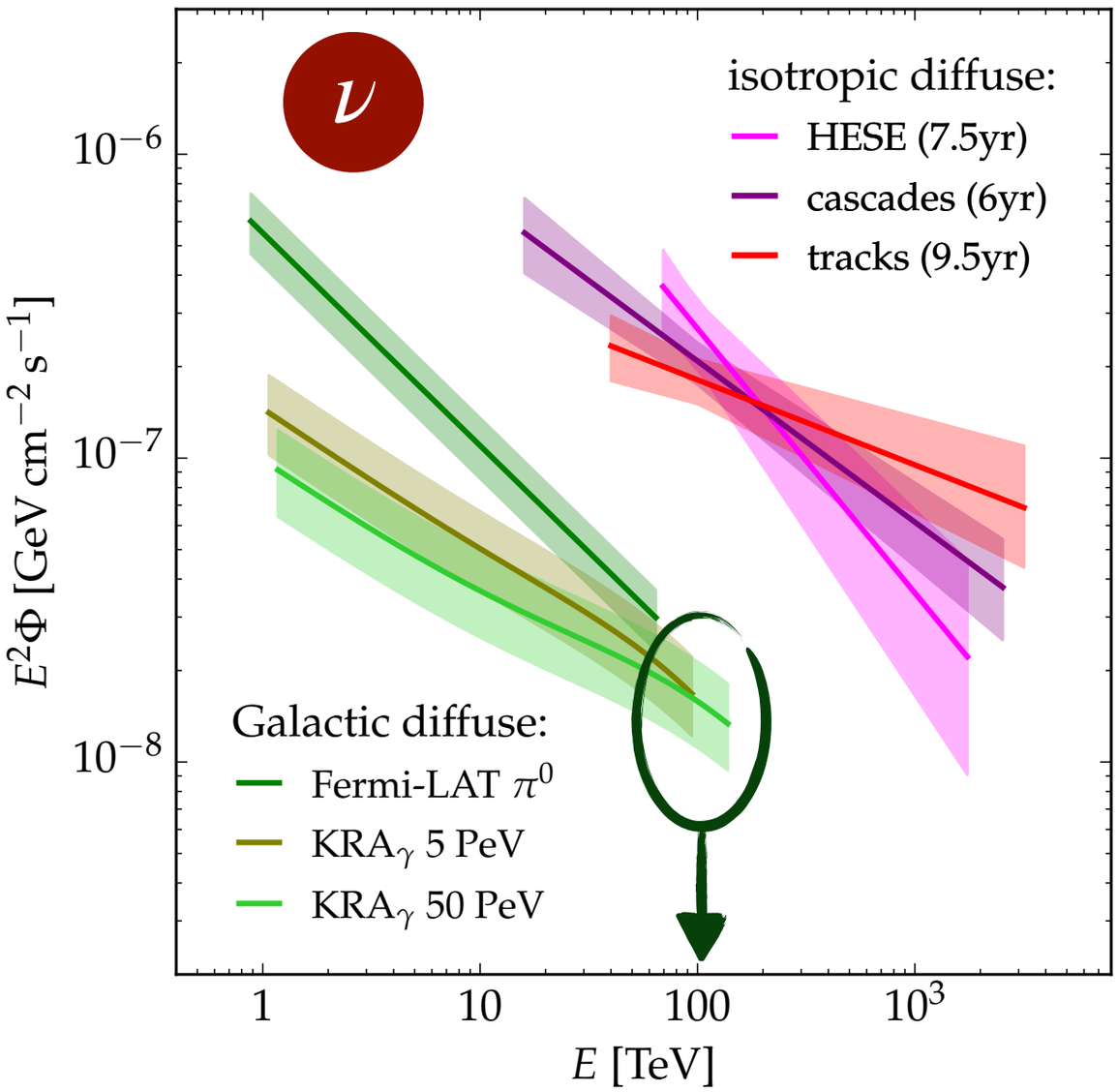
typical angular resolution $\sigma_{\mathrm{PSF}} \simeq 7^\circ$

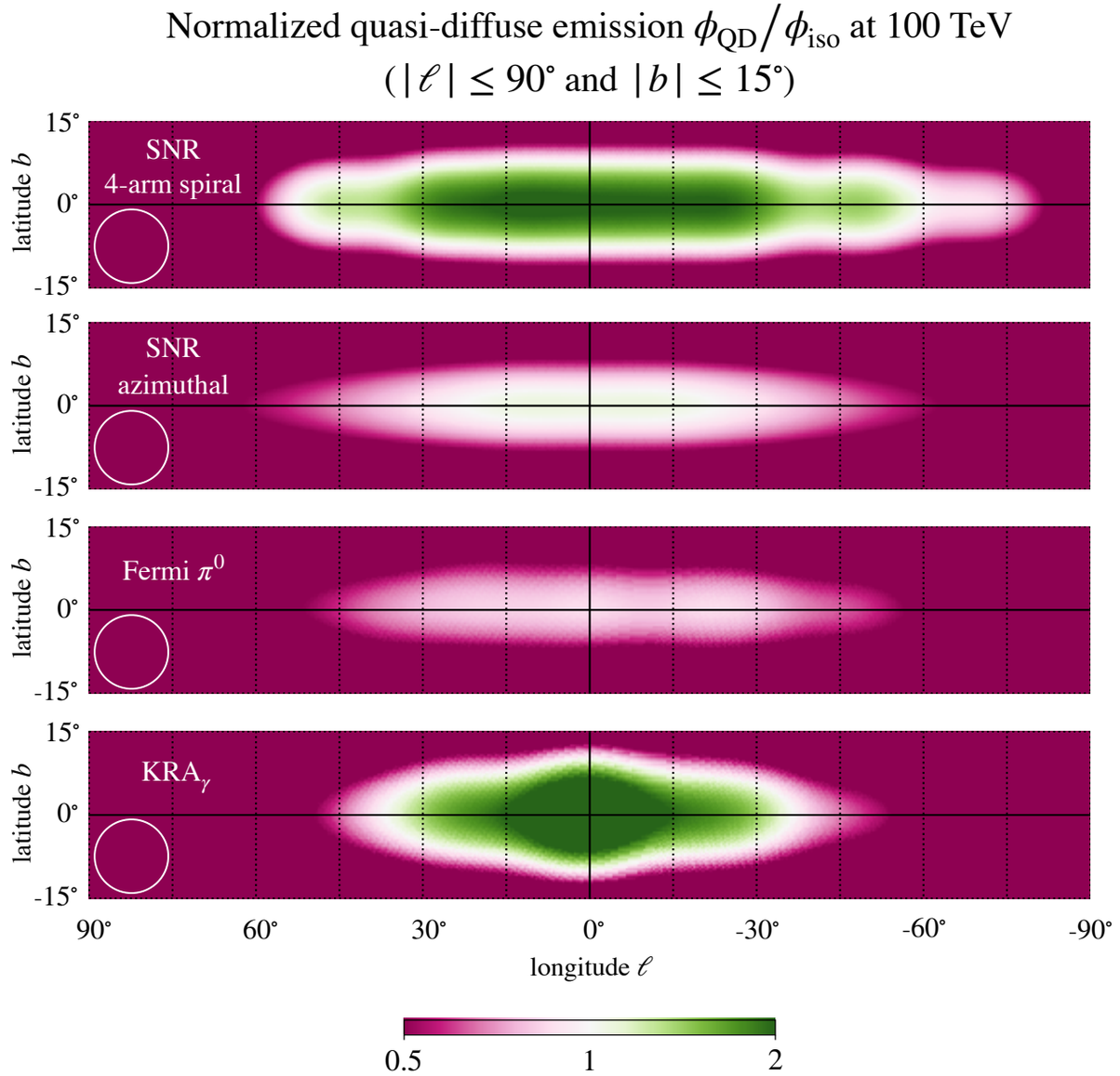


(credit: Kathrine M. Groth)

Hidden Galactic Sources?

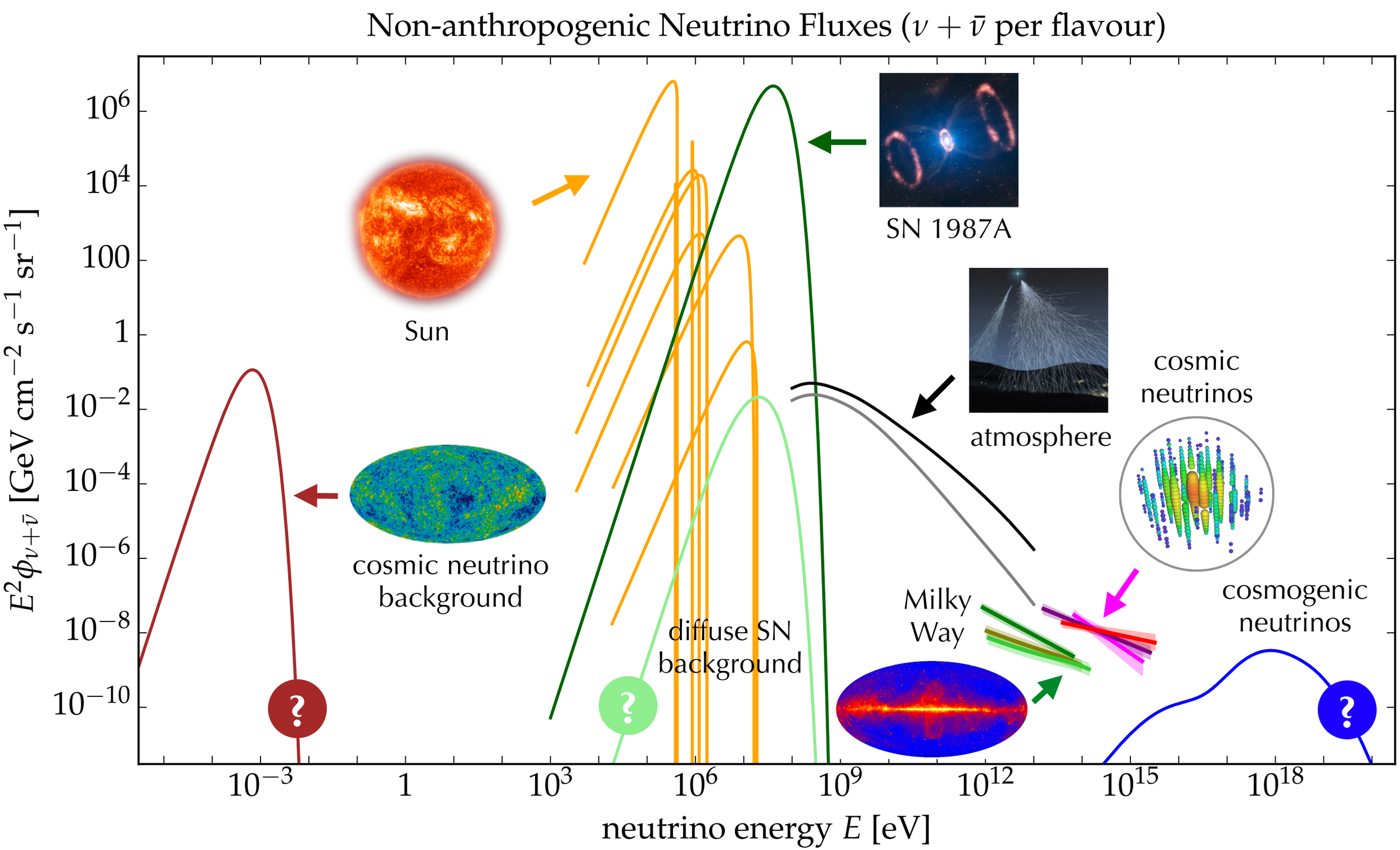
Contribution of neutrino from "freshly" accelerated CRs
most likely to dominate at highest observed energy ($\simeq$ 100TeV).





[Ambrosone, Groth, Peretti & MA'23]

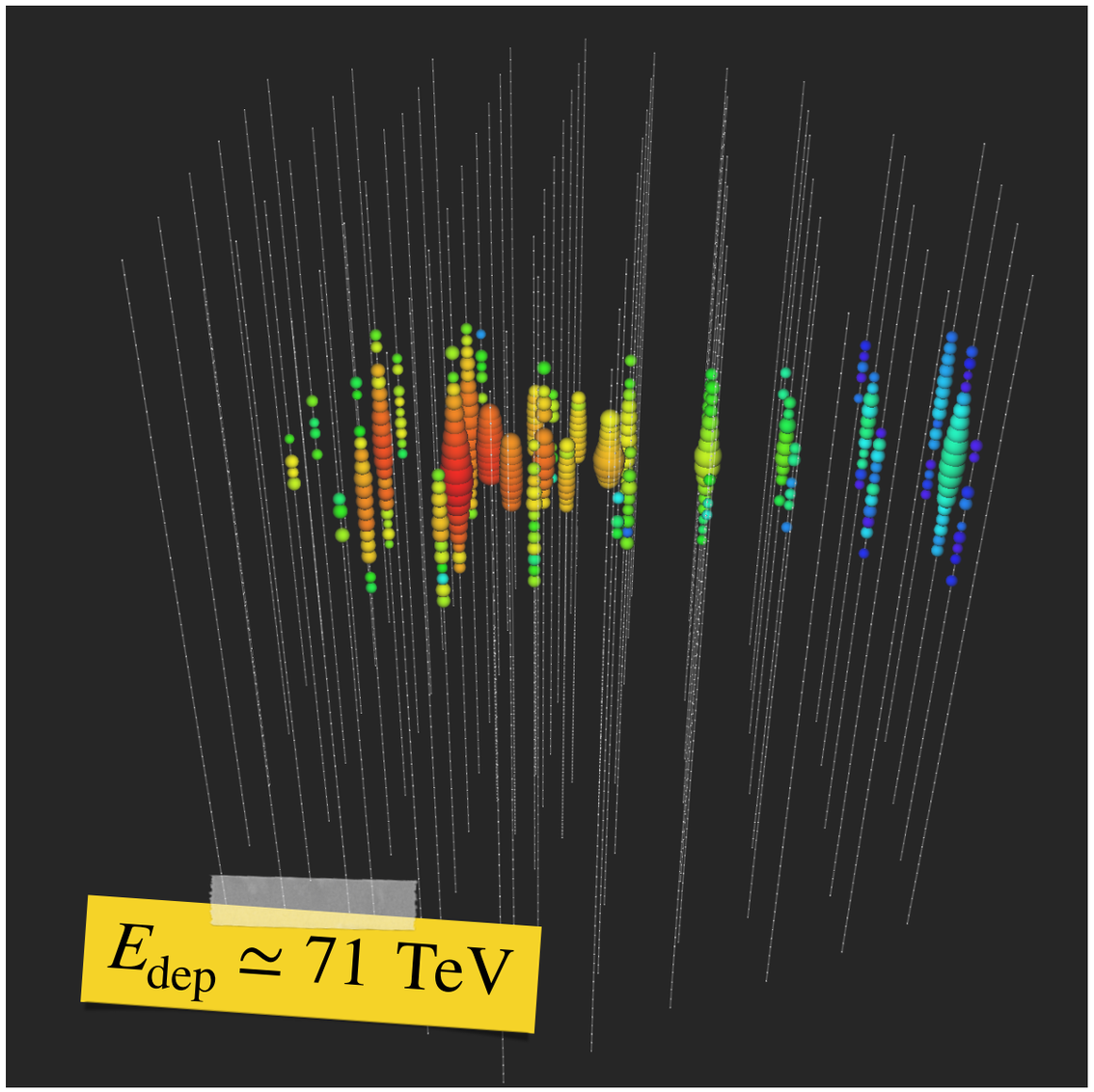
Astrophysical Neutrinos



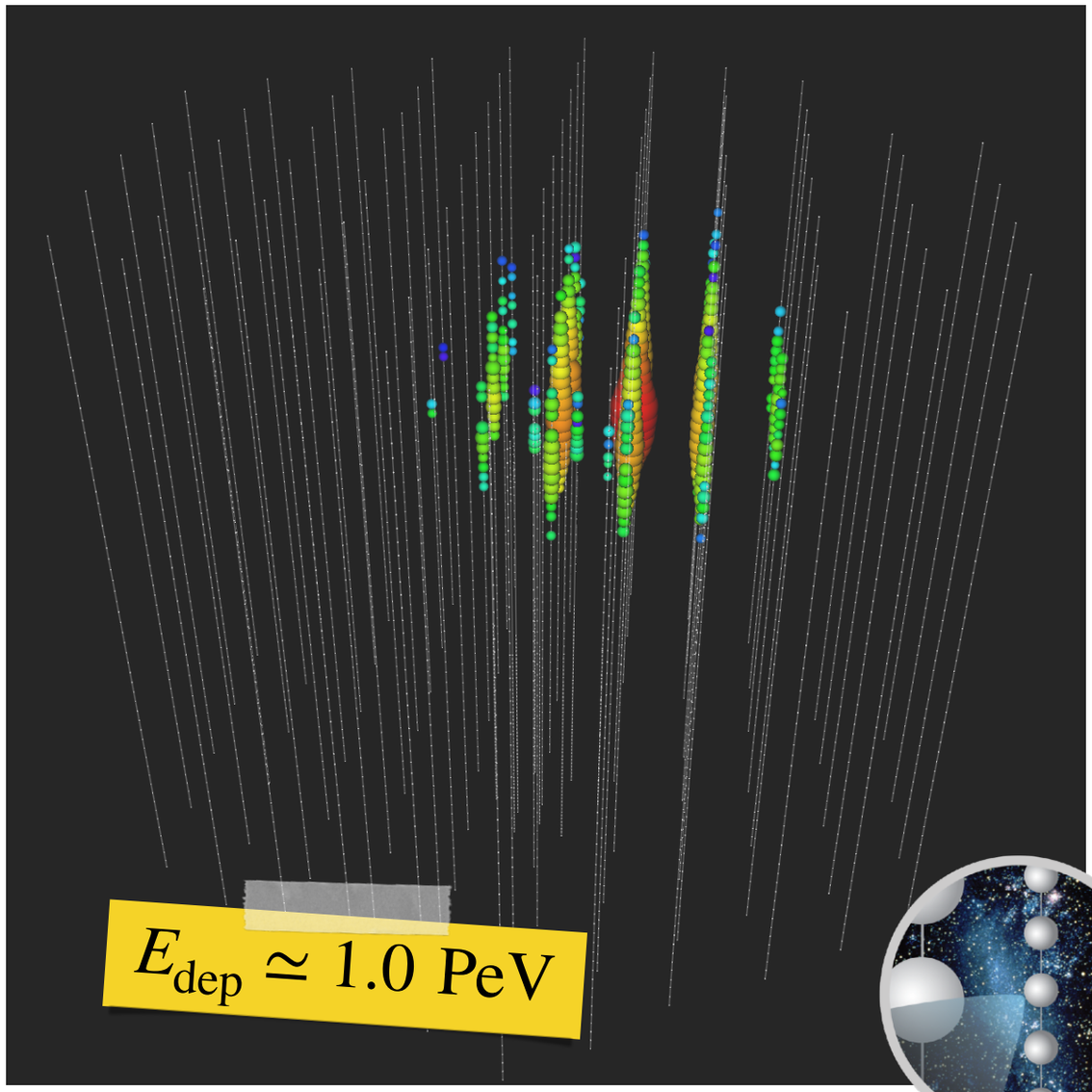
High-Energy Neutrinos

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

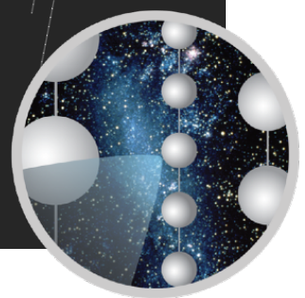
"track event" (e.g. ν_μ CC interactions)



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

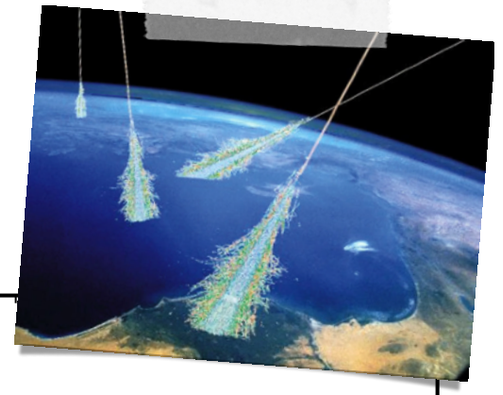


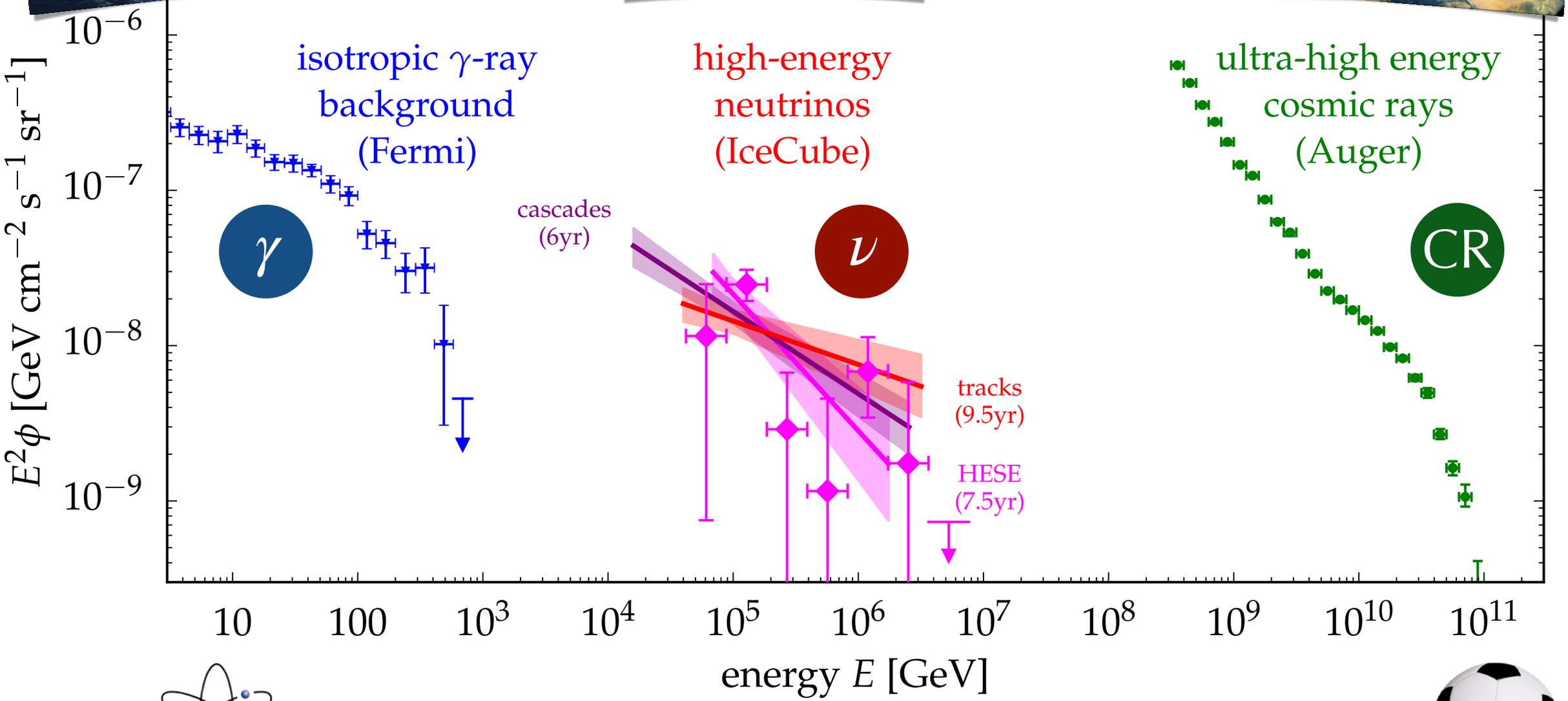
(colours indicate arrival time of Cherenkov photons from **early** to **late**)

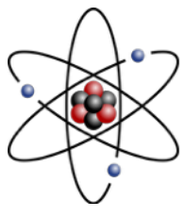


ICECUBE

Diffuse TeV-PeV Neutrinos

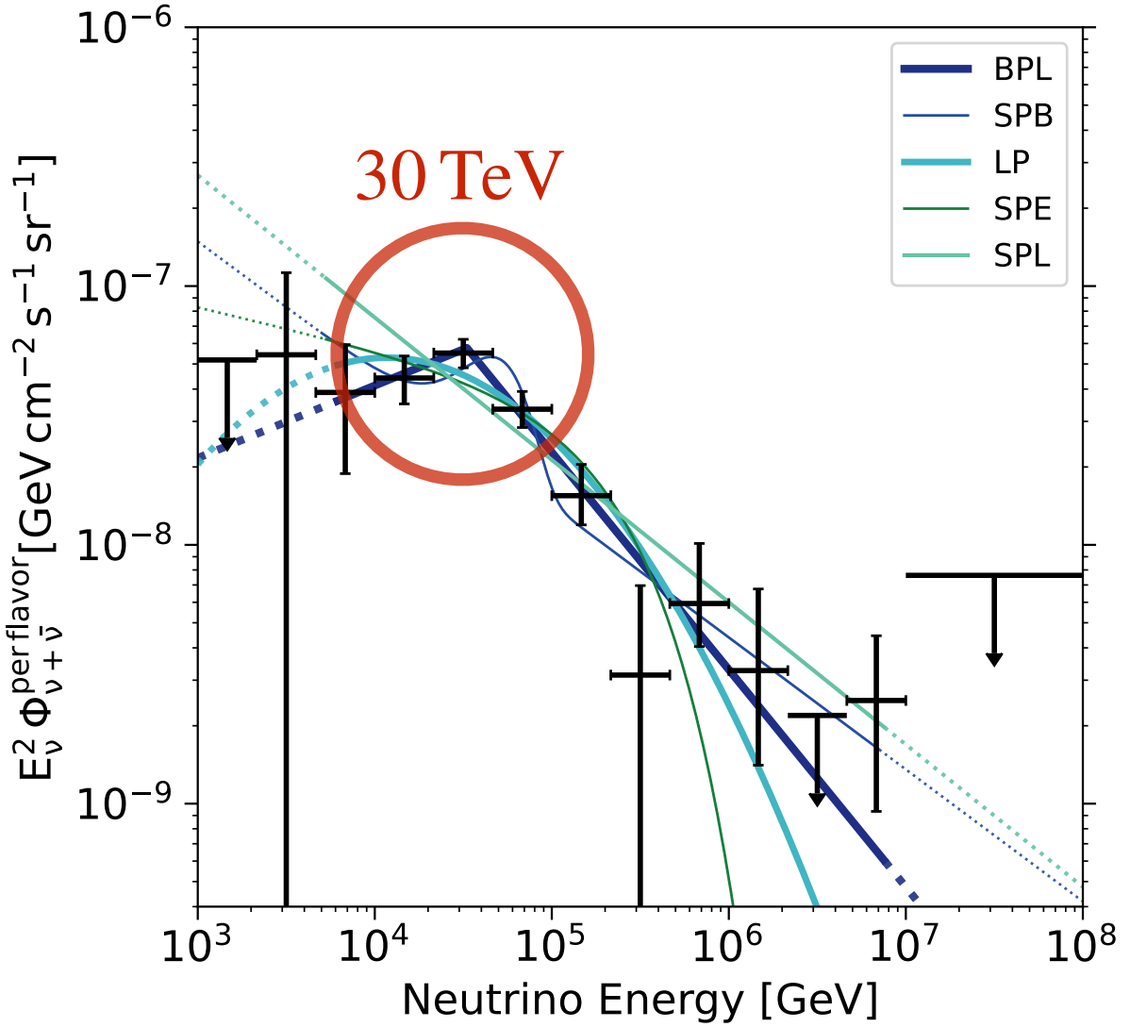


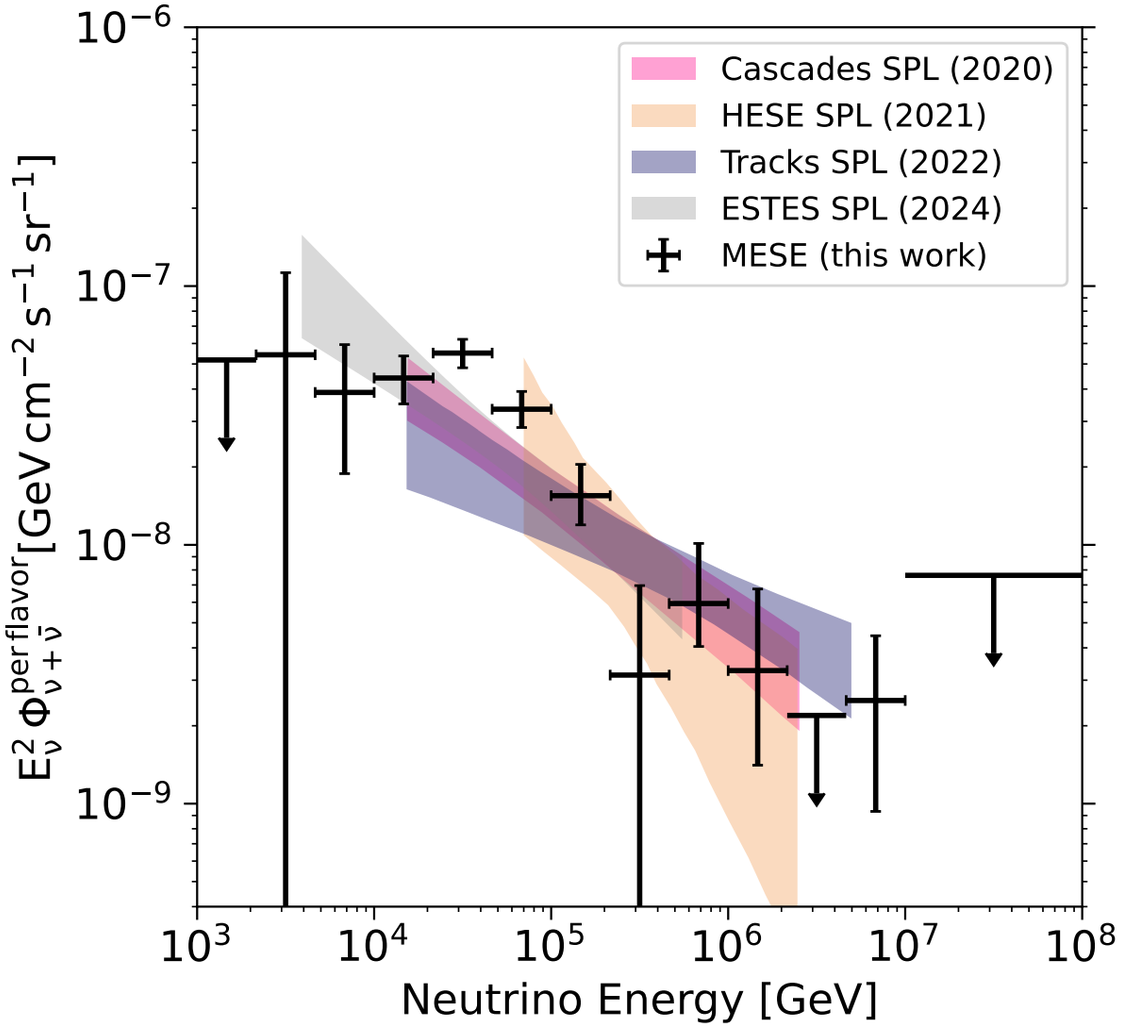




[IceCube, PRL 125 (2020) 12; PoS (ICRC2019) 1017; PRD 104 (2021) 022002]

Diffuse TeV-PeV Neutrinos





[IceCube, **PRD** 113 (2025) 062002]

- All-sky neutrino-pure sample (MESE starting events) from 1 TeV to 10 PeV
- Clear evidence for departure from single power law (SPL)
- **Significance:** $> 4\sigma$ for broken power law (BPL) with **break around 30 TeV**

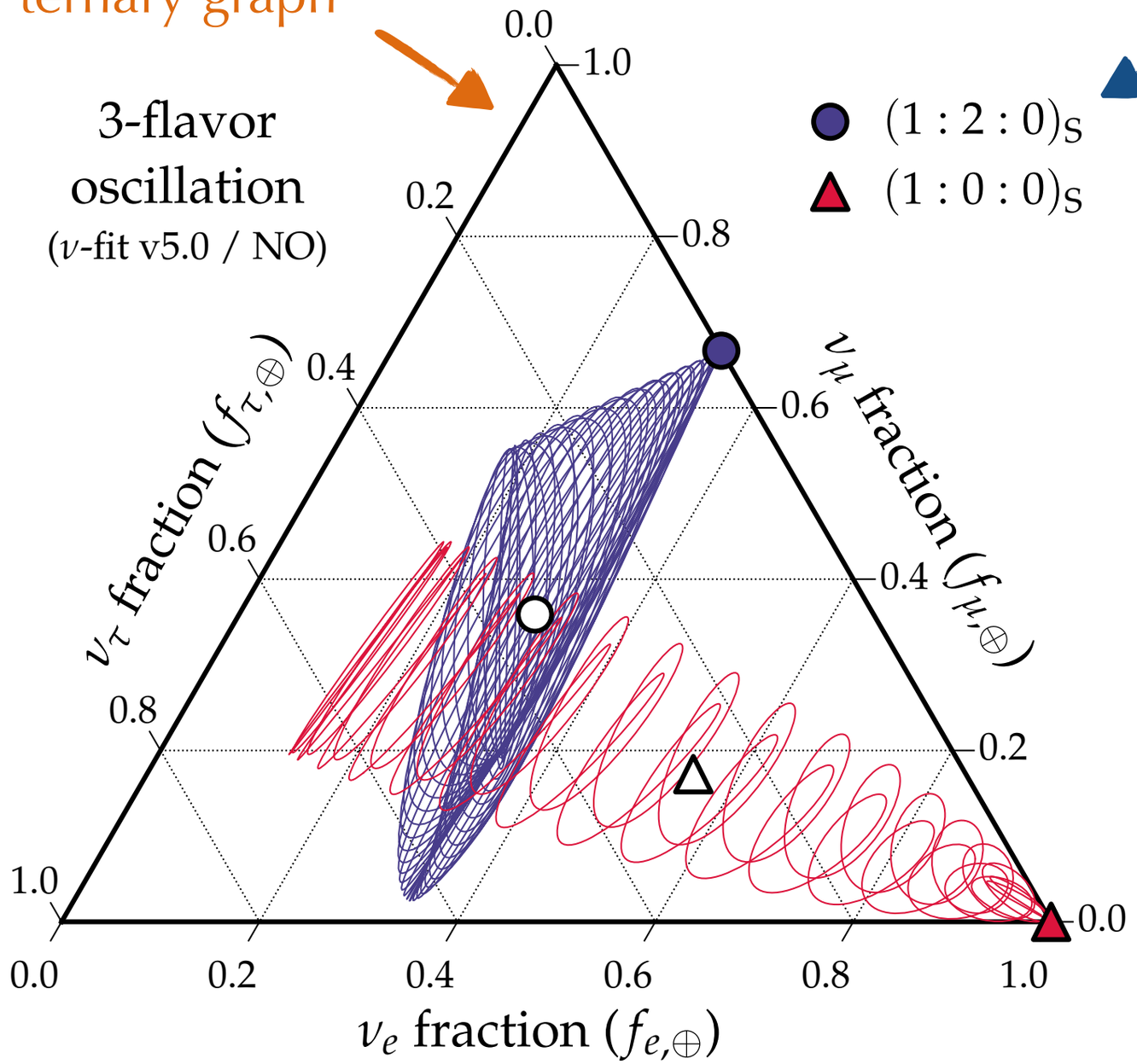
[IceCube, **PRL** 136 (2025) 121002]

Astrophysical Flavours

Cosmic neutrinos visible via their oscillation-averaged flavour.

ternary graph

3-flavor oscillation (ν-fit v5.0 / NO)

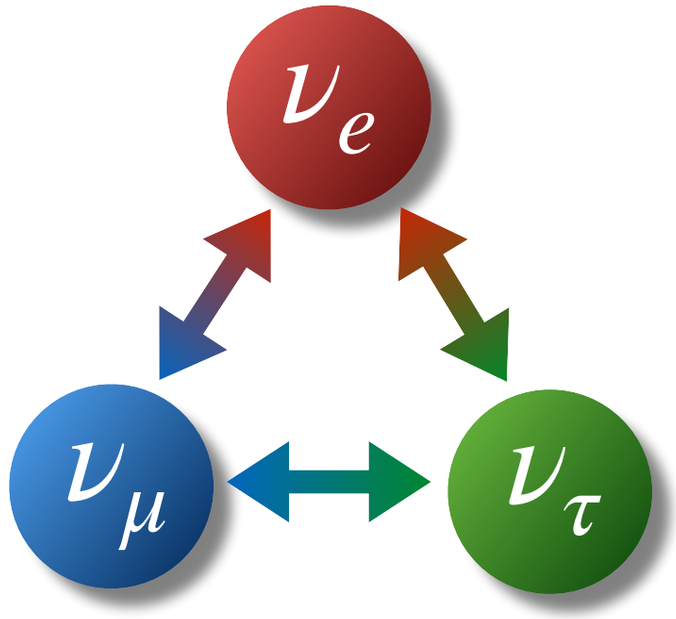


flavour ratio on production

$(1:2:0)_S$

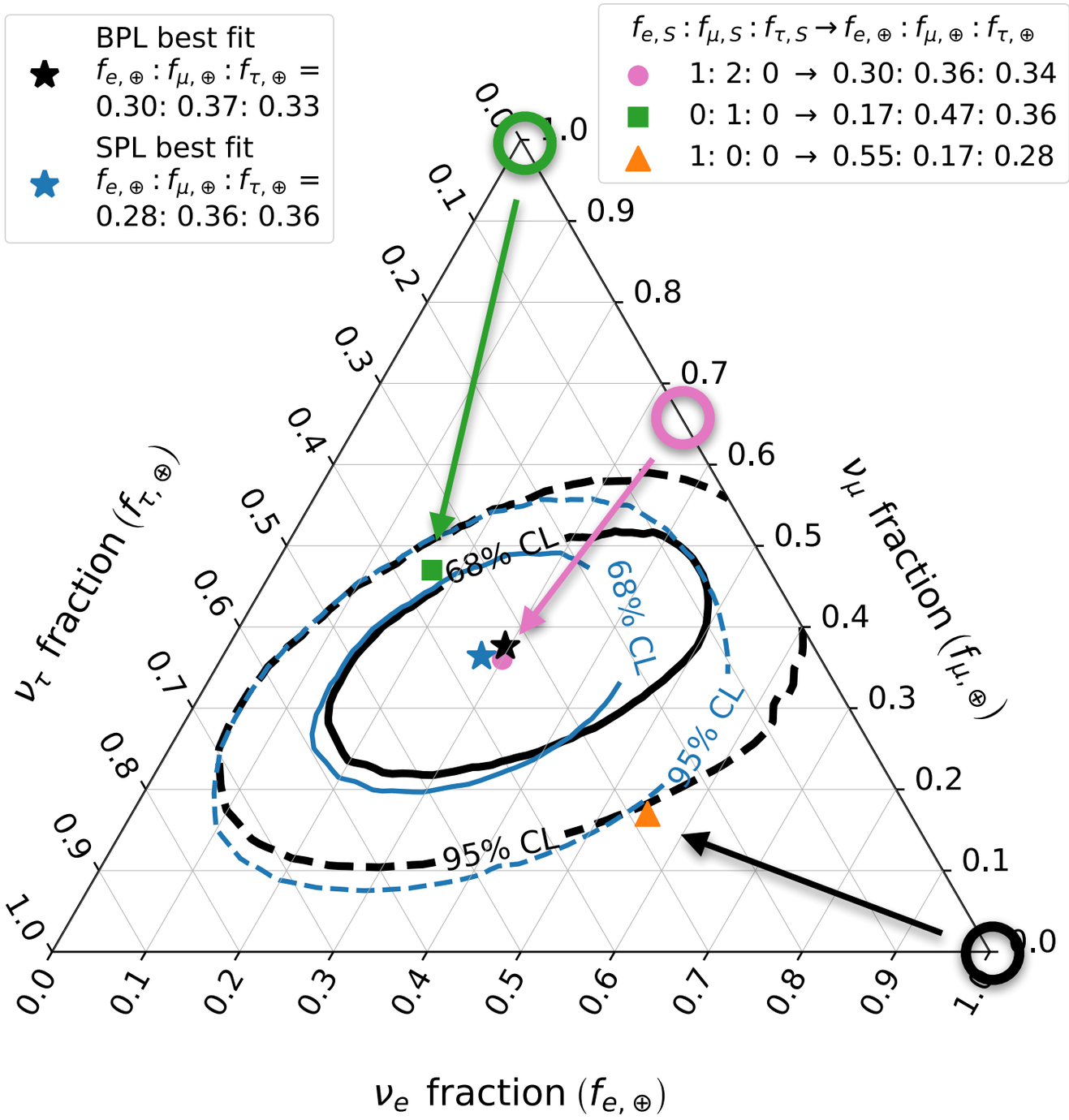
$(1:0:0)_S$

Superposition of flavour and mass states induces oscillations.



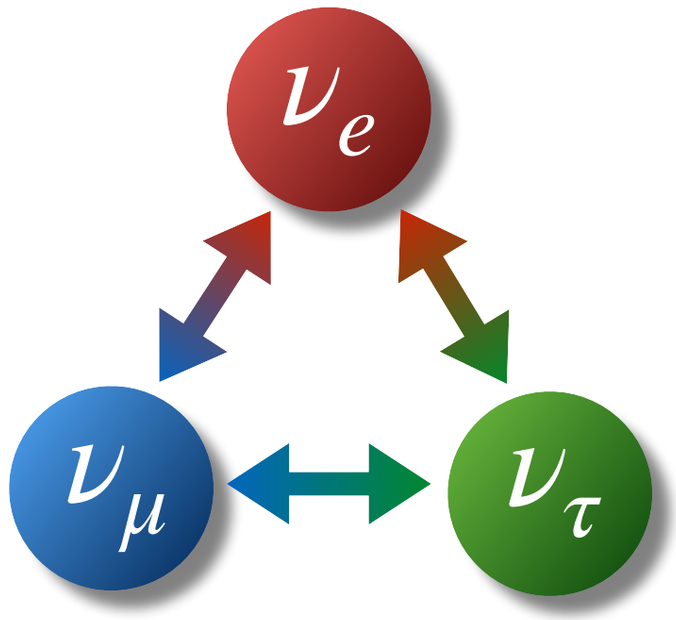
Astrophysical Flavours

Cosmic neutrinos visible via their oscillation-averaged flavour.



[IceCube, **arXiv**:2510.24957, submitted to PRL]
[see also IceCube, **PoS** (ICRC2025) 1011]

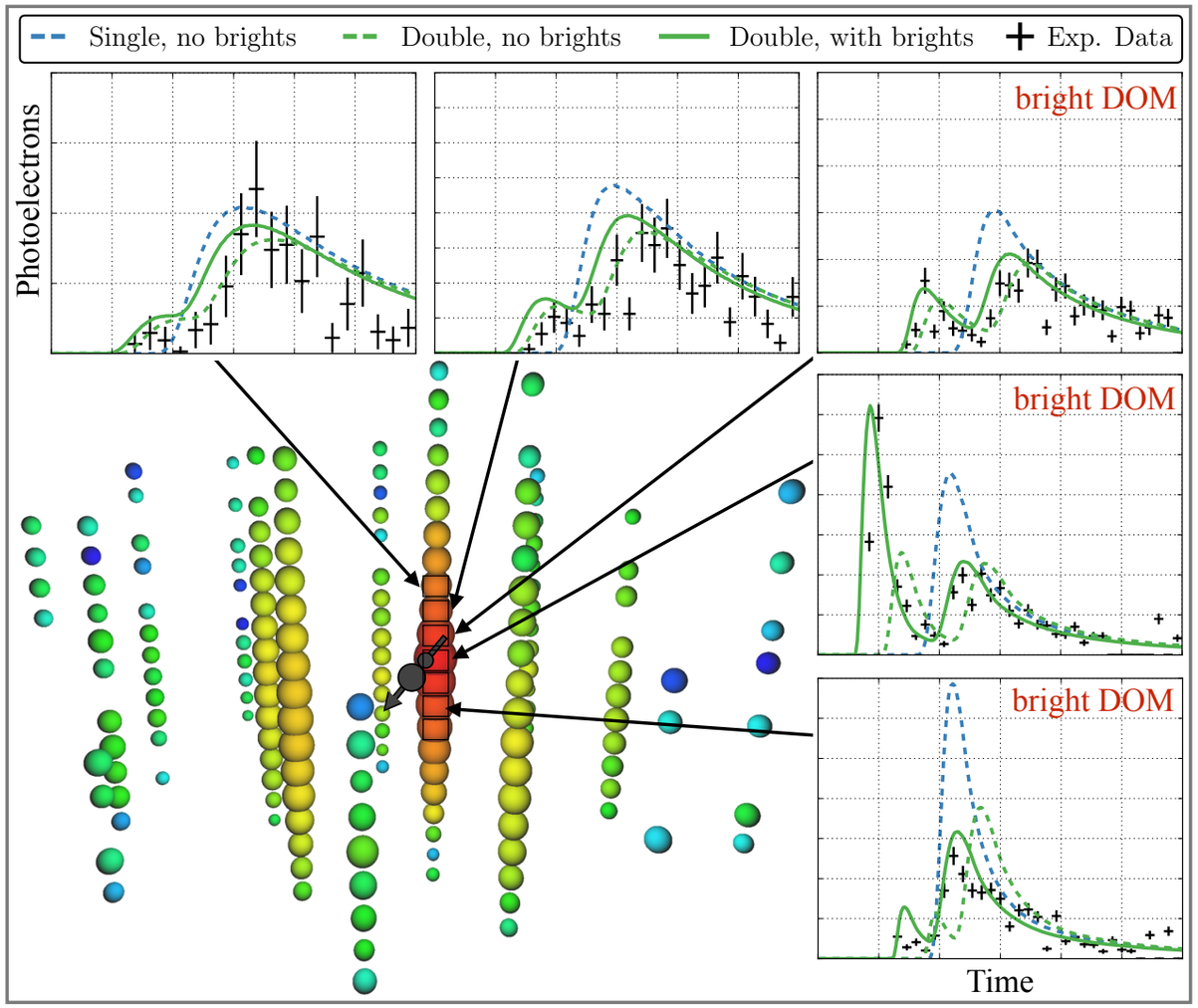
Superposition of flavour and mass states induces oscillations.



Astrophysical ν_τ Searches

Two ν_τ candidates in 7.5yr HESE data (**2.8σ** level) and **seven ν_τ candidates** in 9.7yr data selected for high-Q strings (**5σ** level).

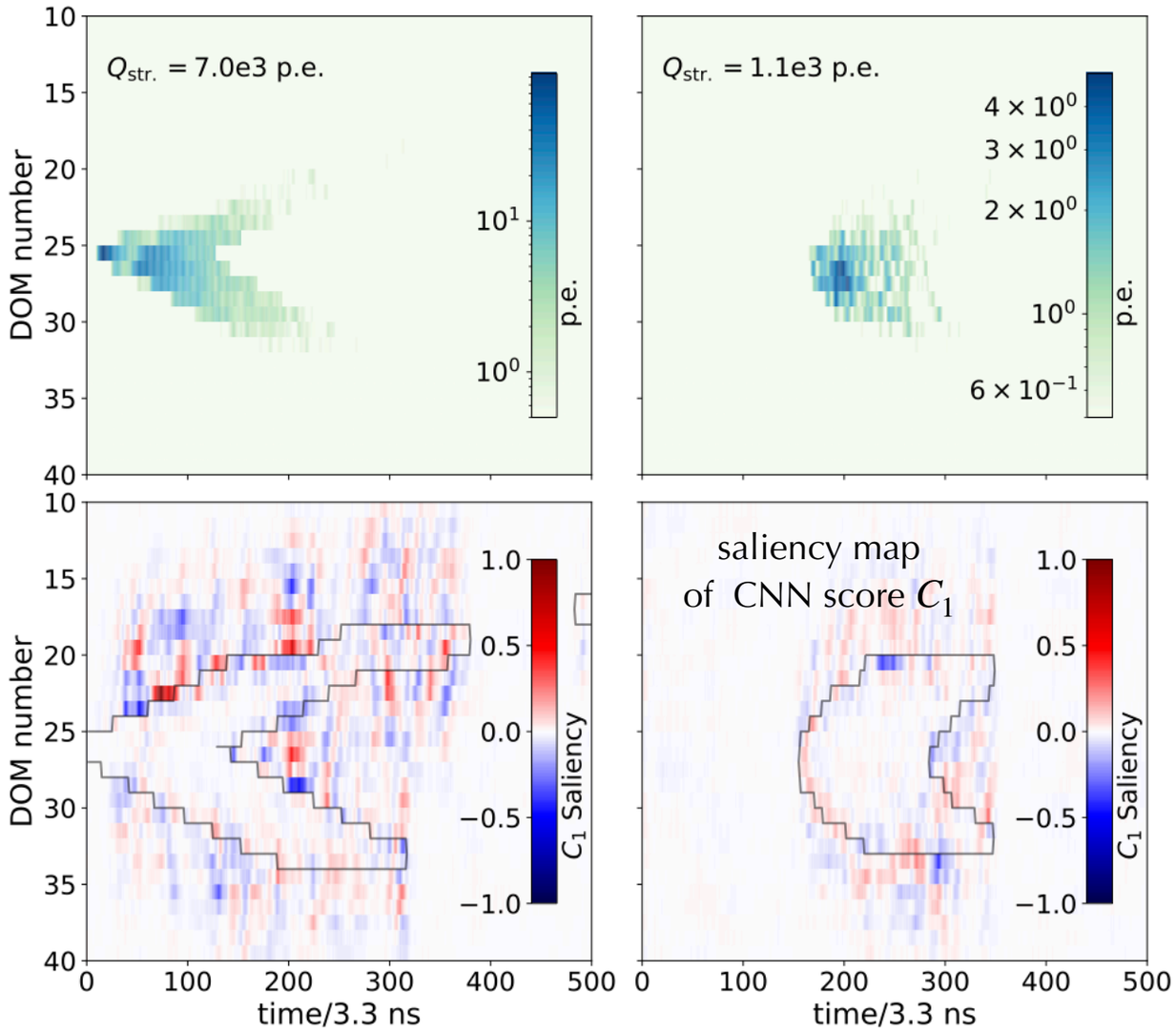
Arrival time of photons in selected DOMs



[IceCube, **EPJ** C 82 (2022) 1031]

brightest string

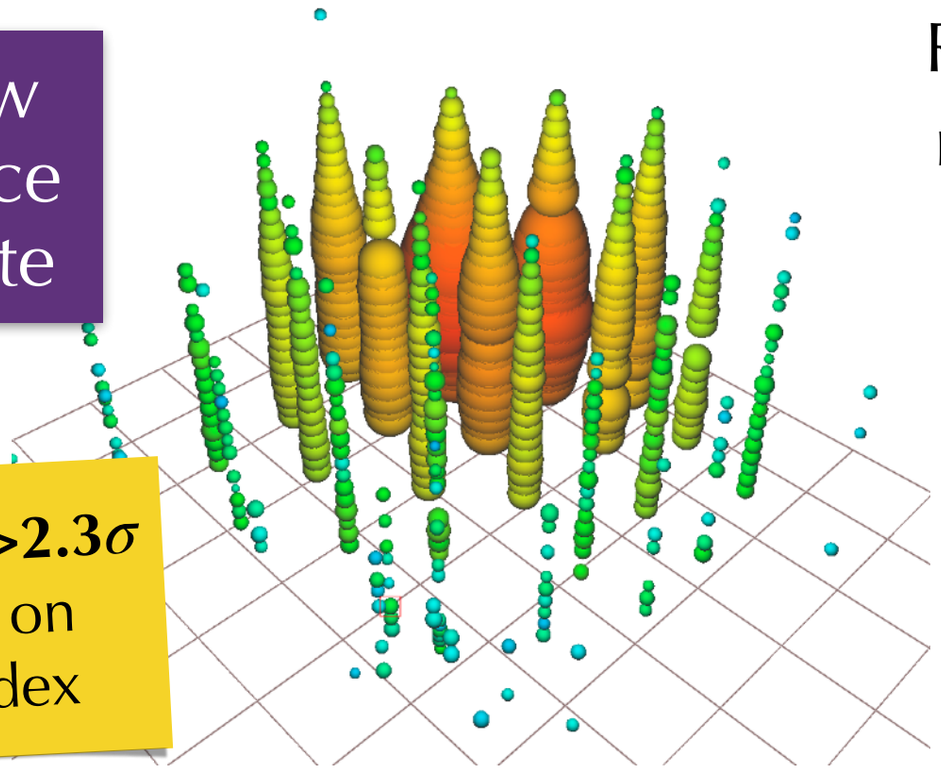
2nd brightest string



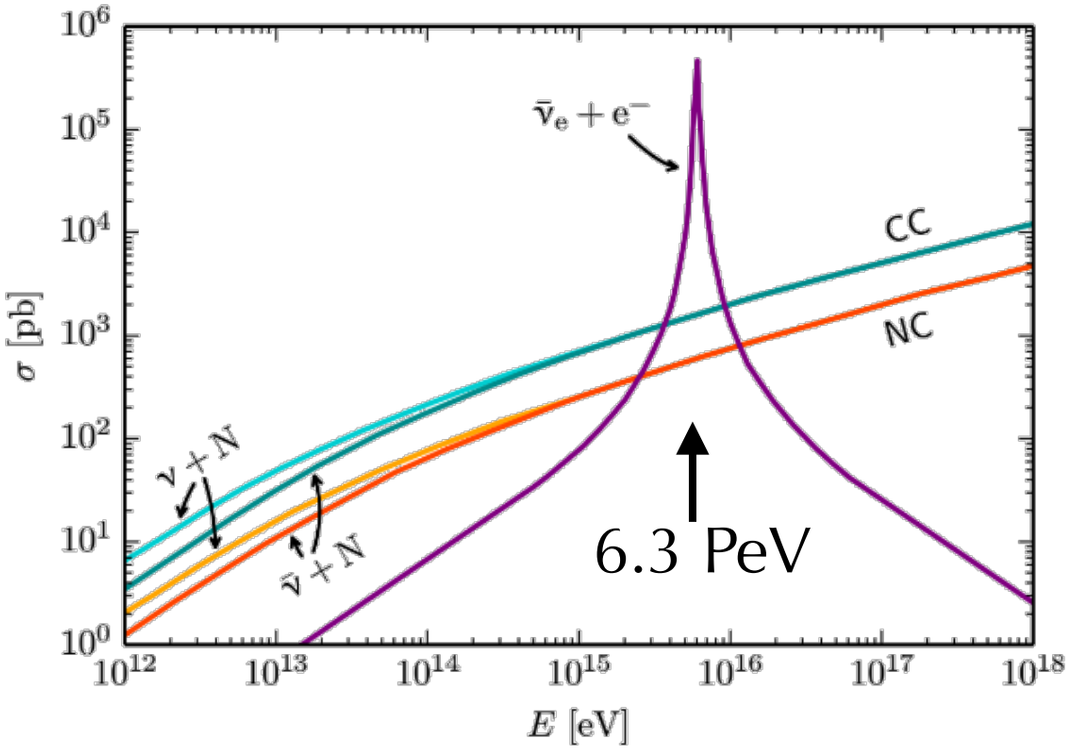
[IceCube, **PRL** 132 (2024) 15]

Glashow Resonance

Glashow resonance candidate

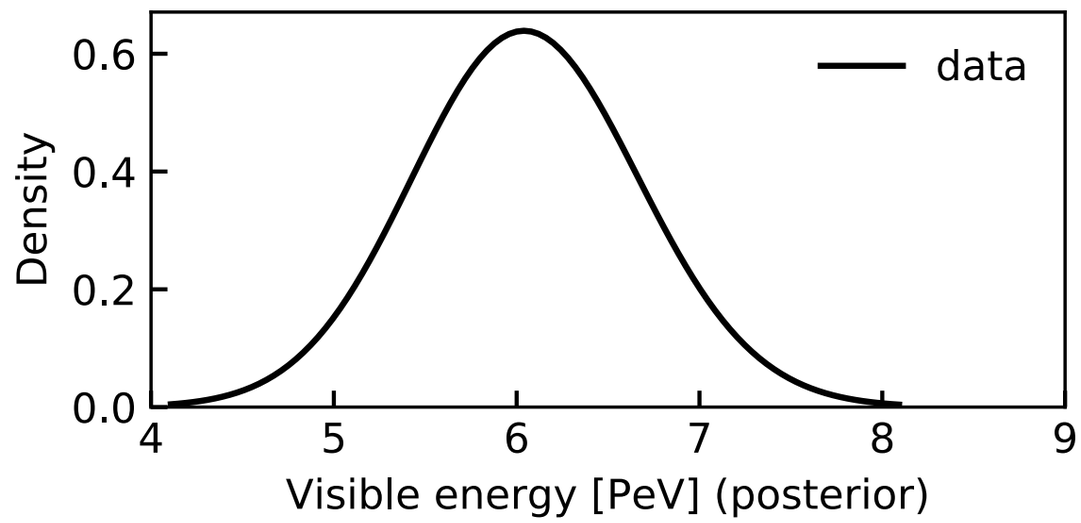


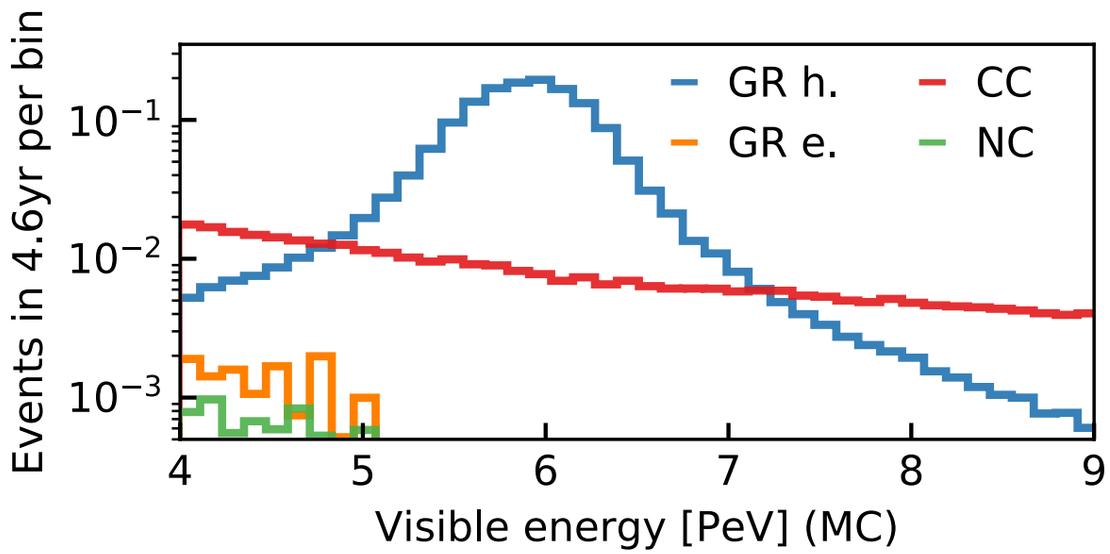
Significance >2.3σ depending on spectral index



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

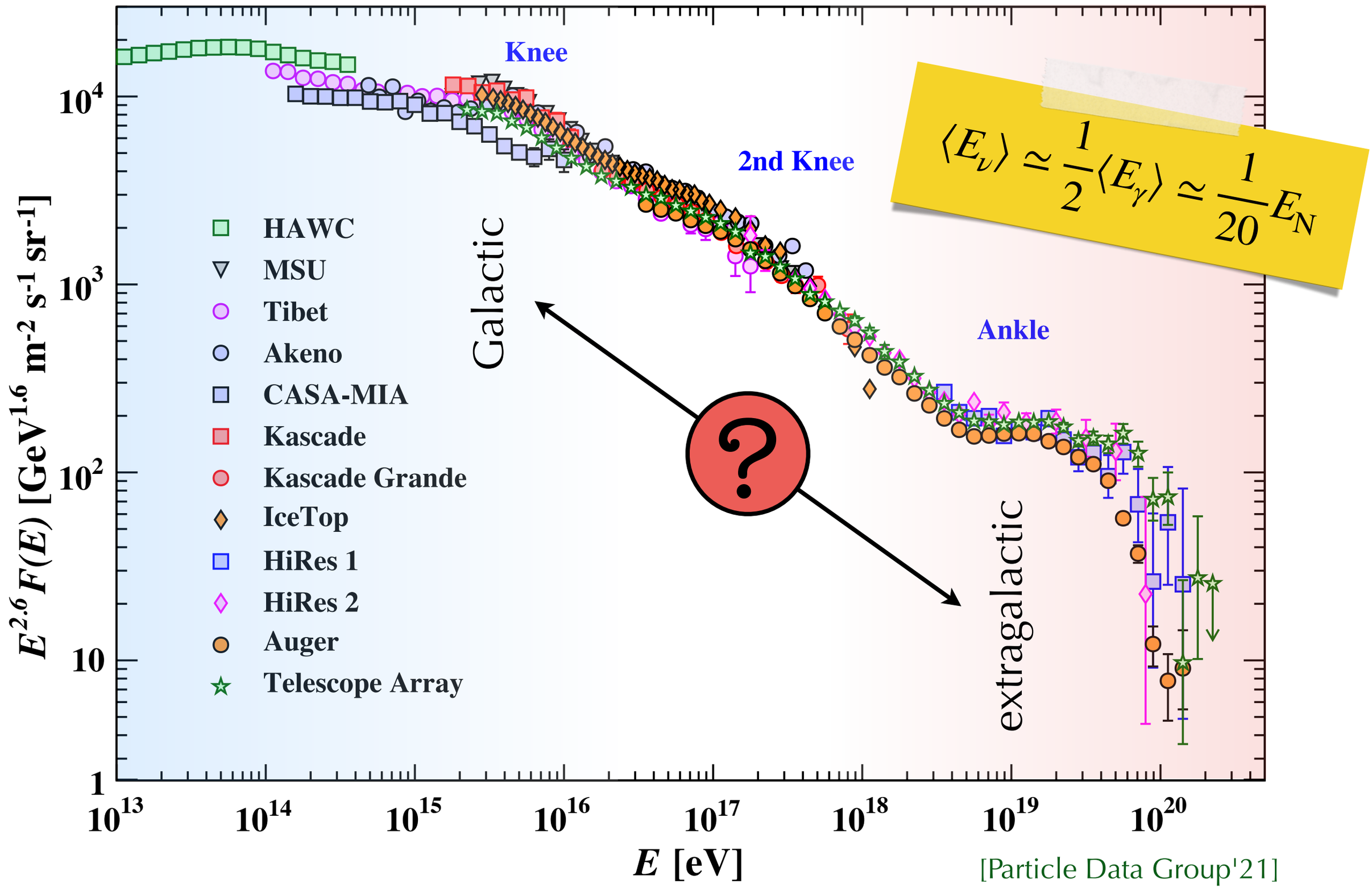
$$\bar{\nu}_e + e^- \rightarrow W^- \rightarrow X$$





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

Very-High Energy Cosmic Rays

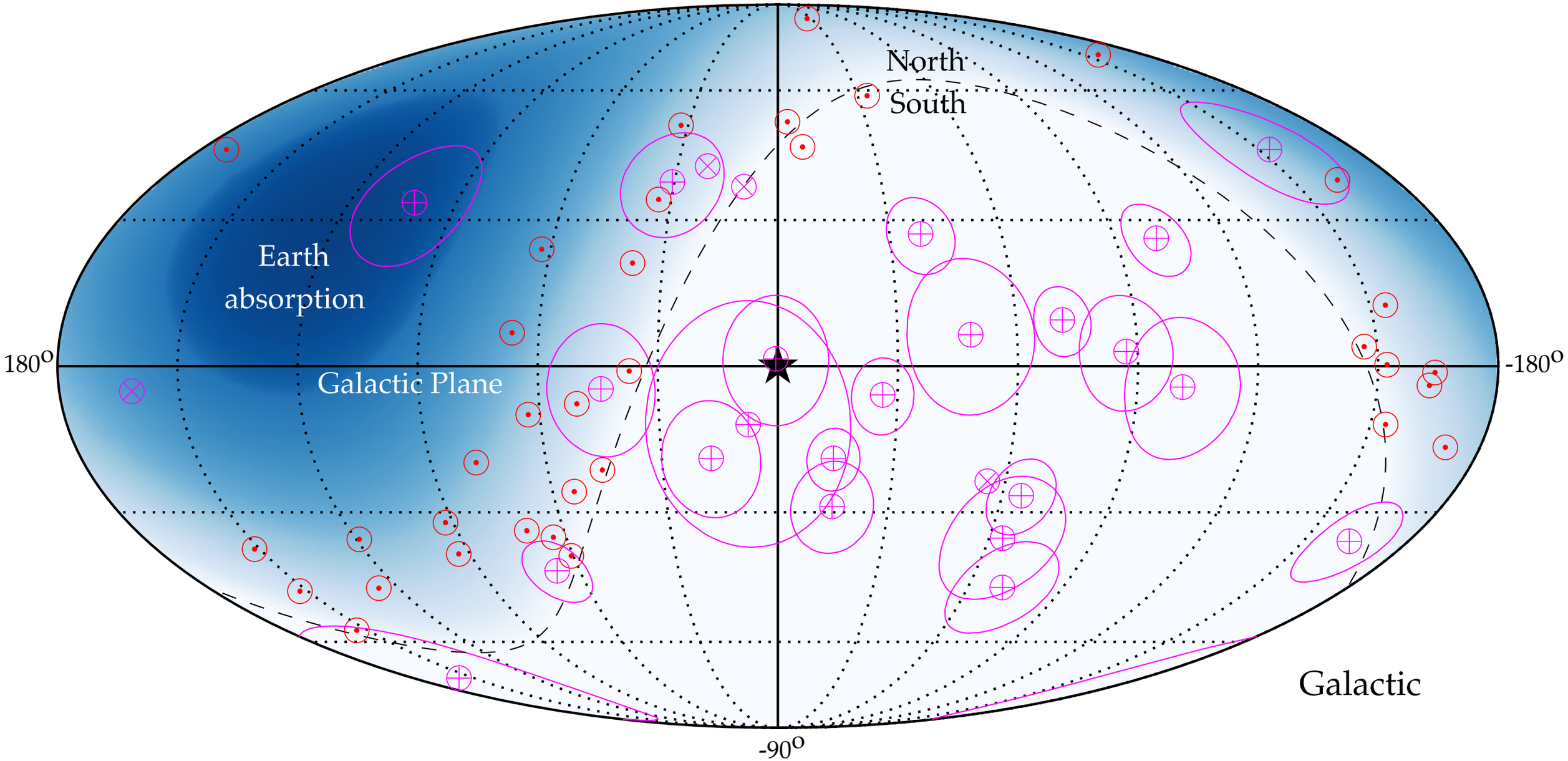


$$\langle E_\nu \rangle \simeq \frac{1}{2}\langle E_\gamma \rangle \simeq \frac{1}{20} E_N$$

[Particle Data Group'21]

Status of Neutrino Astronomy

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



No (5σ) discovery of steady or transient emission from known Galactic or extragalactic high-energy point sources, but **several interesting candidates.**

Status of Neutrino Astronomy

Neutrino sources are hiding in plain sight.

[Credit: John Beacom, CCAPP]

Extragalactic Populations

Populations of extragalactic neutrino sources visible as

individual sources

and by

combined isotropic emission.

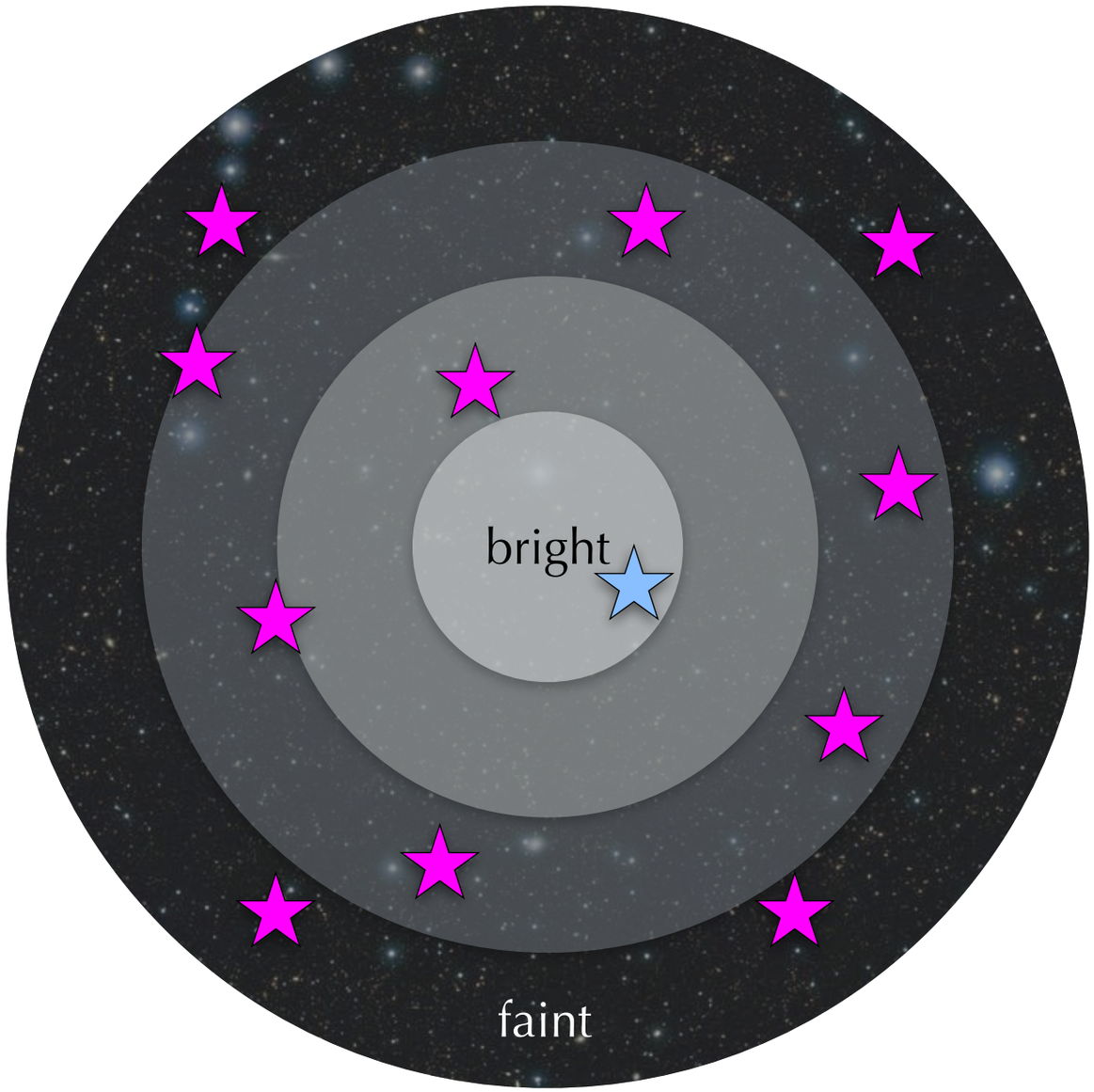
The relative contribution can be parametrized (*to first order*) by the average

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

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and by

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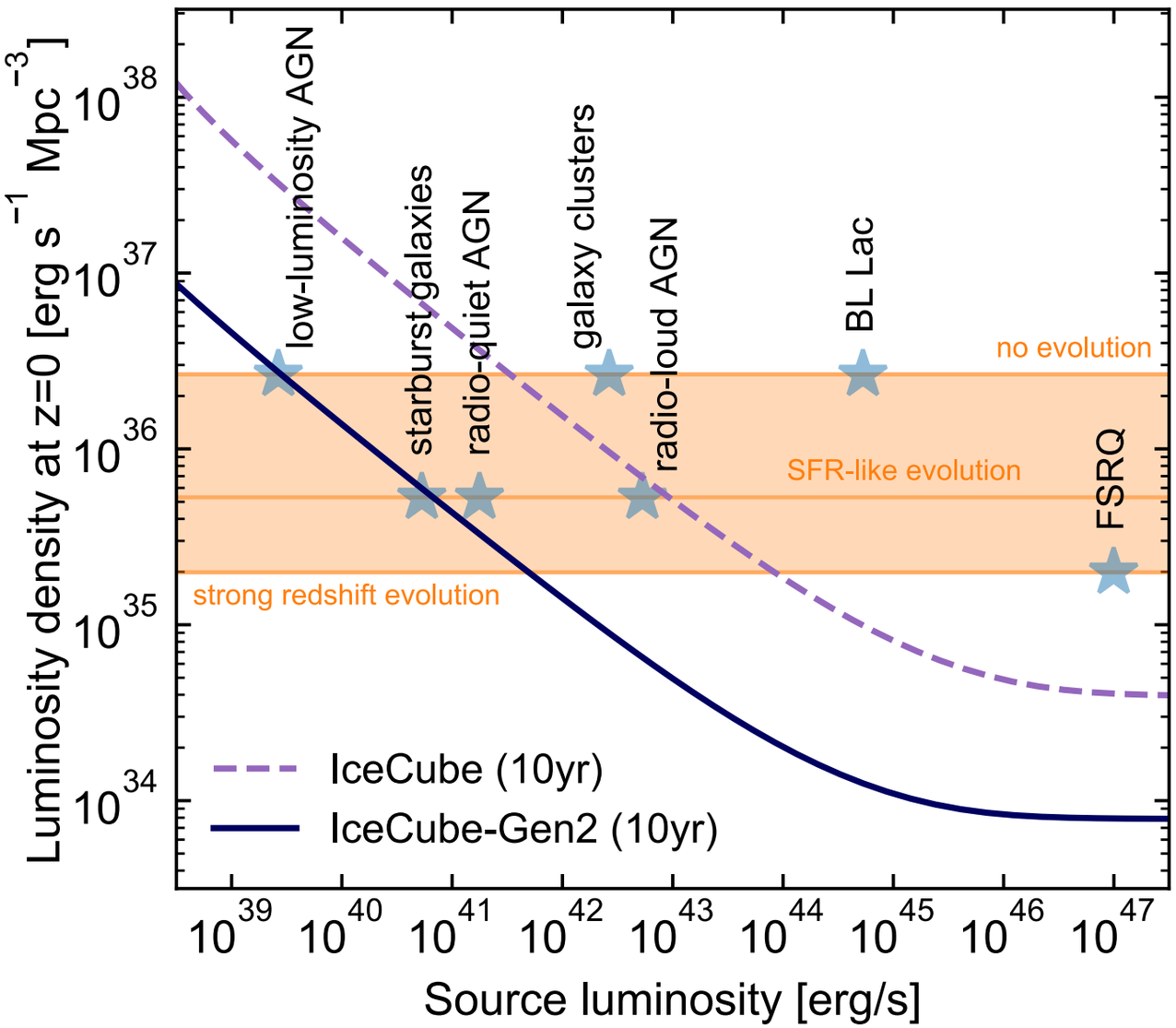
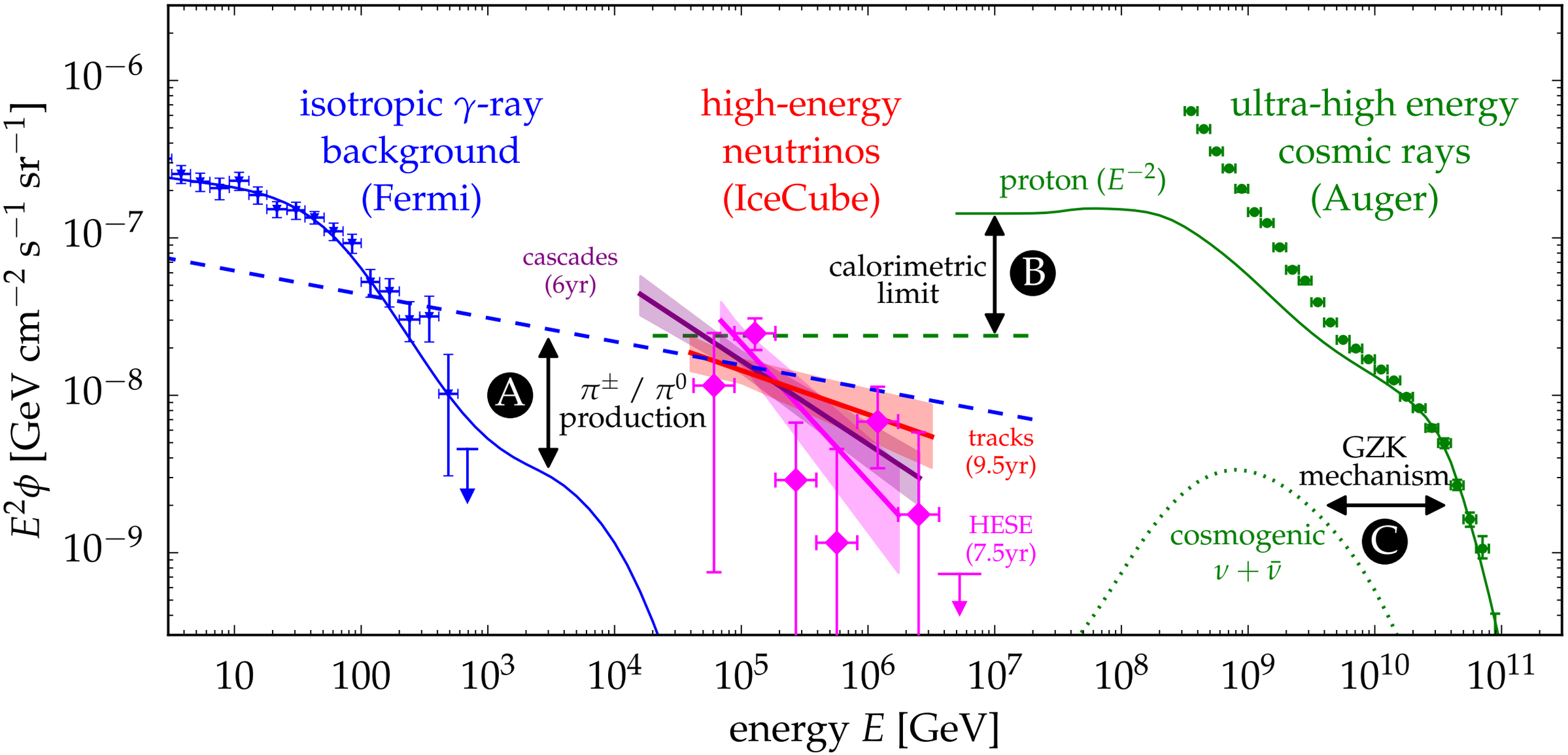


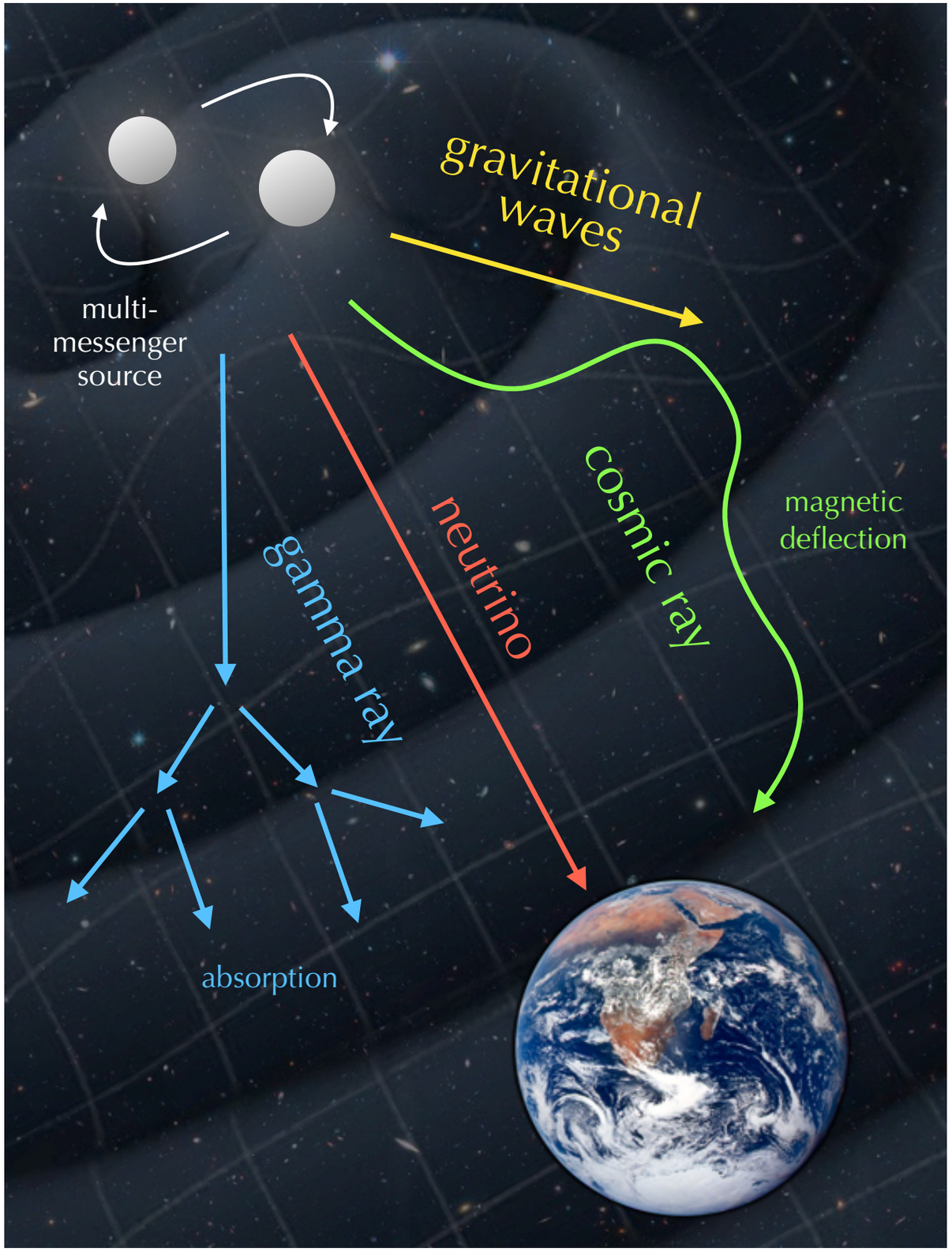
[IceCube-Gen2 *Technical Design Report* **(TDR)**]
icecube-gen2.wisc.edu/science/publications/tdr

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.

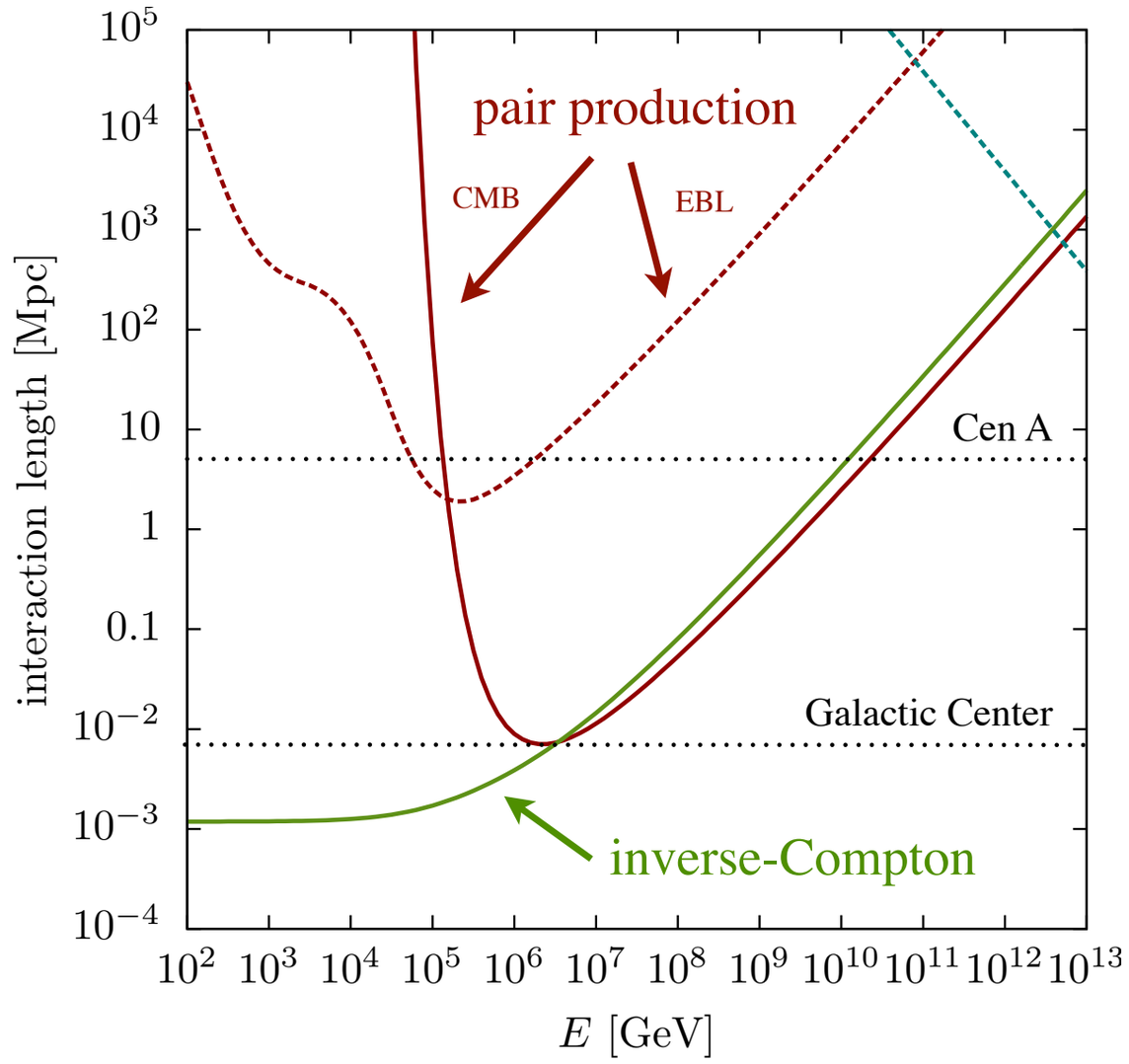
Hadronic Gamma-Rays



EM cascades from interactions in cosmic radiation backgrounds:

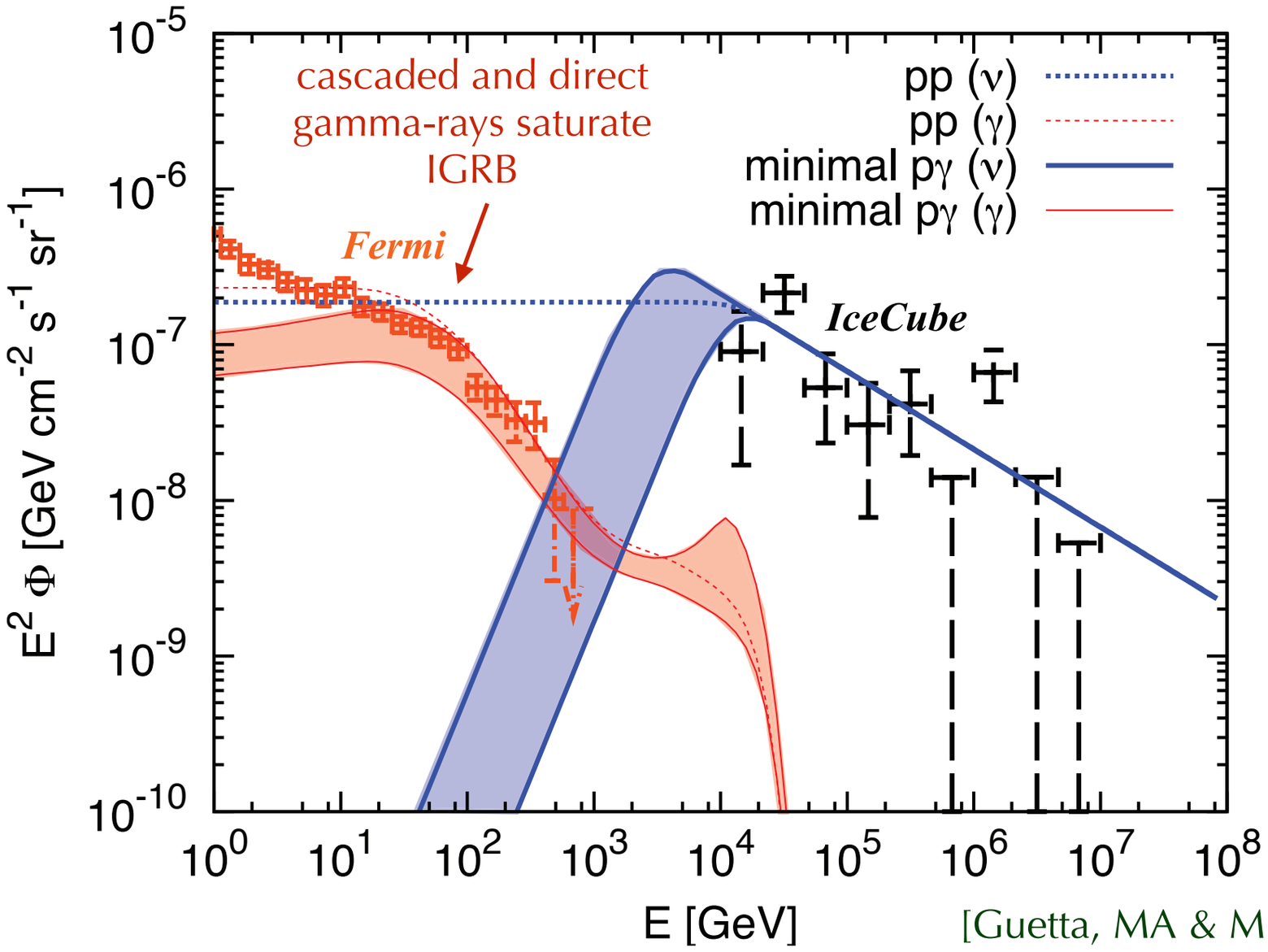
$$\gamma + \gamma_{\rm bg} \to e^+ + e^- \quad \text{(PP)}$$

$$e^\pm + \gamma_{\rm bg} \to e^\pm + \gamma \quad \text{(ICS)}$$



Hadronic Gamma-Rays

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



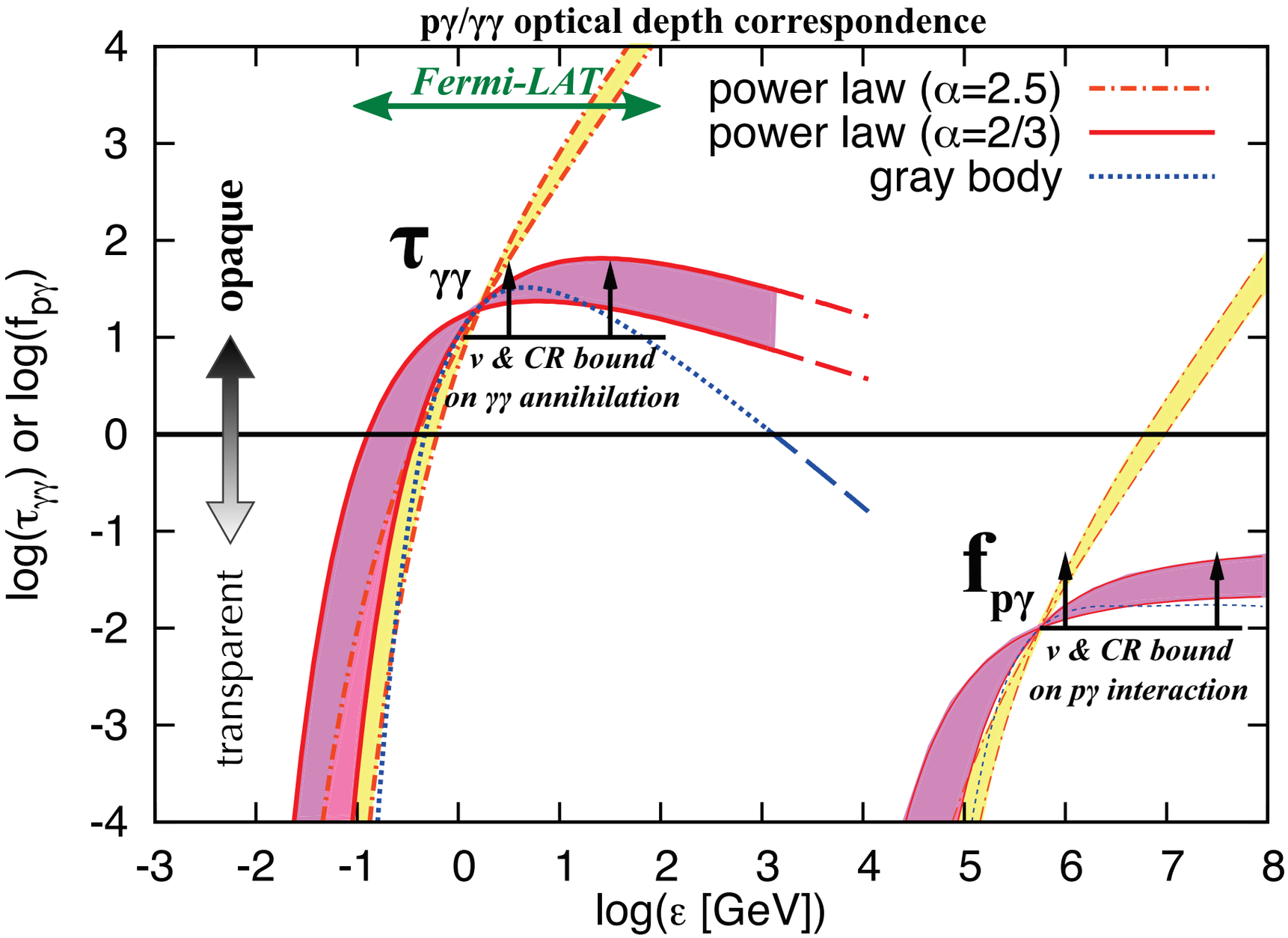
[Guetta, MA & Murase'16]

[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]

Waxman-Bahcall Limit

- UHE CR **proton emission rate** density: [e.g. MA & Halzen'12]

$$[E_p^2 Q_p(E_p)]_{10^{19.5}\mathrm{eV}} \simeq 8\times10^{43}\mathrm{erg\,Mpc^{-3}\,yr^{-1}}$$

- Neutrino flux can be estimated as (ξ_z : redshift evolution factor) :

$$E_\nu^2\phi_\nu(E_\nu) \simeq f_\pi \underbrace{\frac{\xi_z K_\pi}{1+K_\pi}}_{\mathcal{O}(1)} \underbrace{1.5\times10^{-8}\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}}_{\text{IceCube diffuse level}}$$

- Limited by **pion production efficiency**: $f_\pi \lesssim 1$ [Waxman & Bahcall'98]

- Similar UHE **nucleon emission rate** density (local minimum at $\Gamma \simeq 2.04$) :

$$[E_N^2 Q_N(E_N)]_{10^{19.5}\mathrm{eV}} \simeq 2.2\times10^{43}\mathrm{erg\,Mpc^{-3}\,yr^{-1}}$$

[Auger'16; see also Jiang, Zhang & Murase'20]

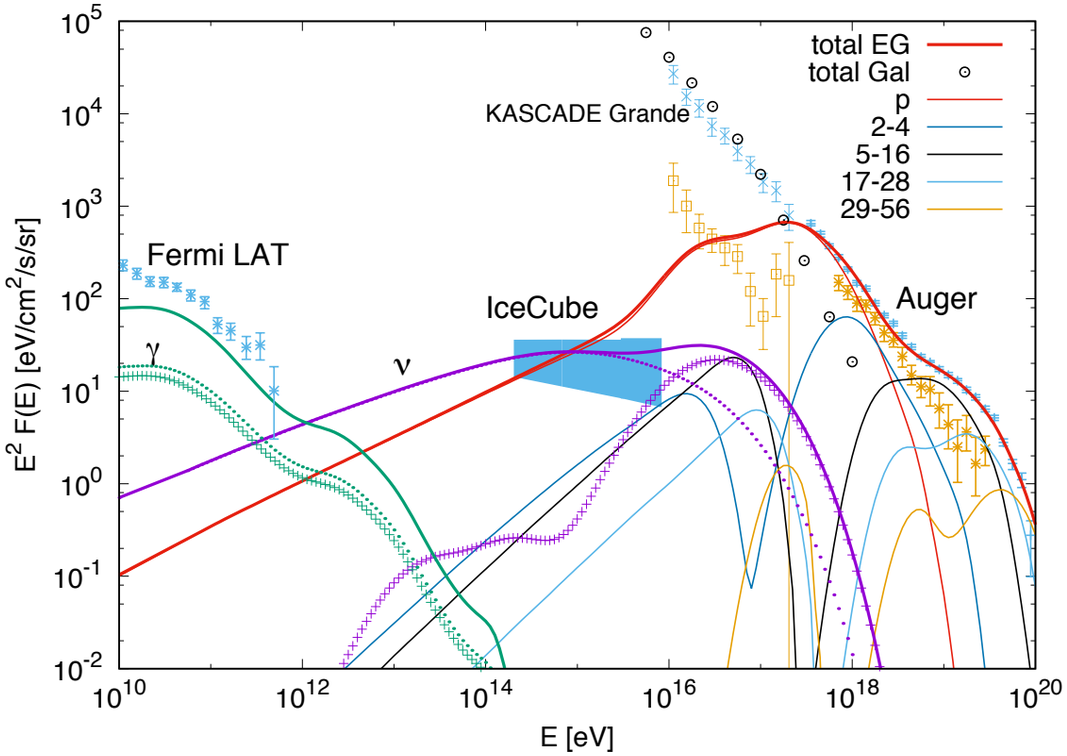
- **Competition** between pion production efficiency (*dense target*) and CR acceleration efficiency (*thin target*).

Cosmic Ray Calorimeters

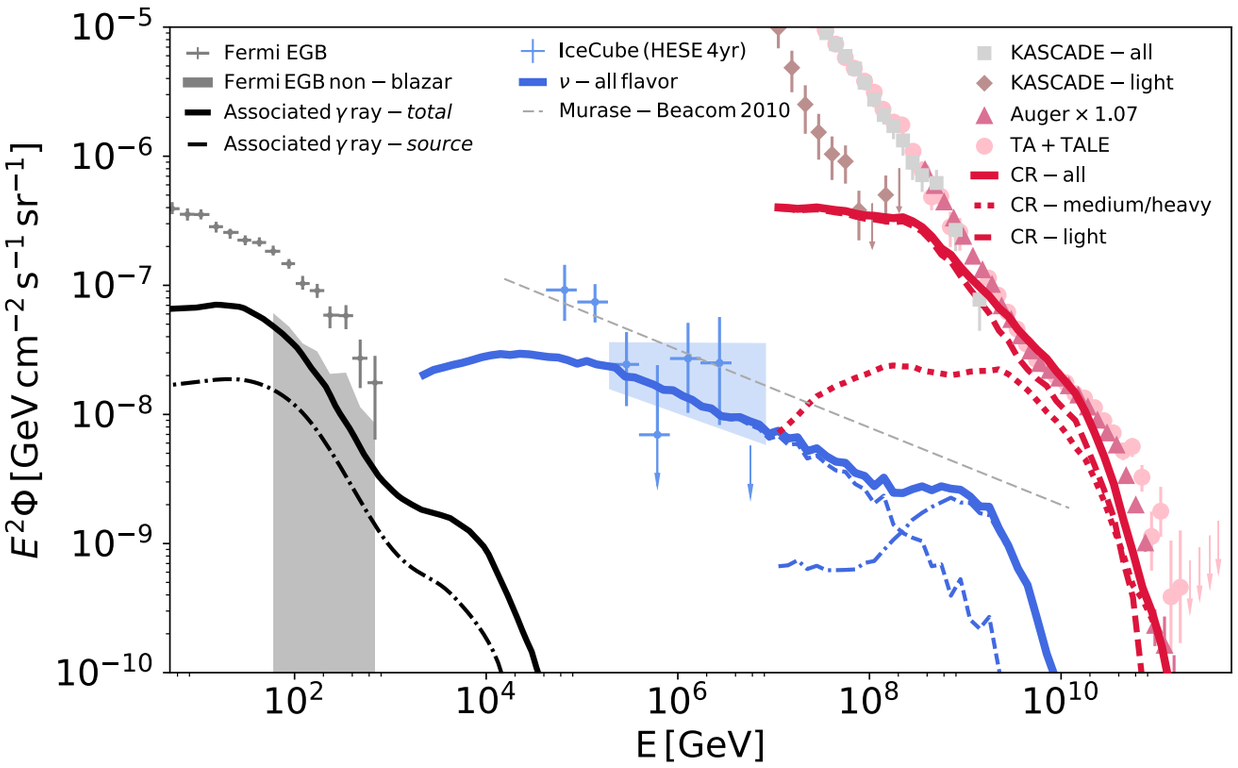
- Competing requirements for efficient CR acceleration and subsequent interaction can be accommodated in **multi-zone models**.
- Magnetic confinement in CR calorimeters, such as **starburst galaxies**, could provide a unified origin of UHE CRs and TeV–PeV neutrinos.

[Loeb & Waxman '06]

- "*Grand Unification*" of UHE CRs, γ-rays and neutrinos?



[Kachelriess, Kalashev, Ostapchenko & Semikoz'17]



[Fang & Murase'17]

UHE CR-Neutrino Correlations?

- Unified source models are tested by joint neutrino & CR analyses by **ANTARES, Auger, IceCube & TA**.
  [PoS (ICRC2019) 842]

- So far, no significant correlations have been identified.

- ***Principal challenge:*** Only 5% of observed TeV-PeV neutrinos are expected to correlate with UHE CRs.

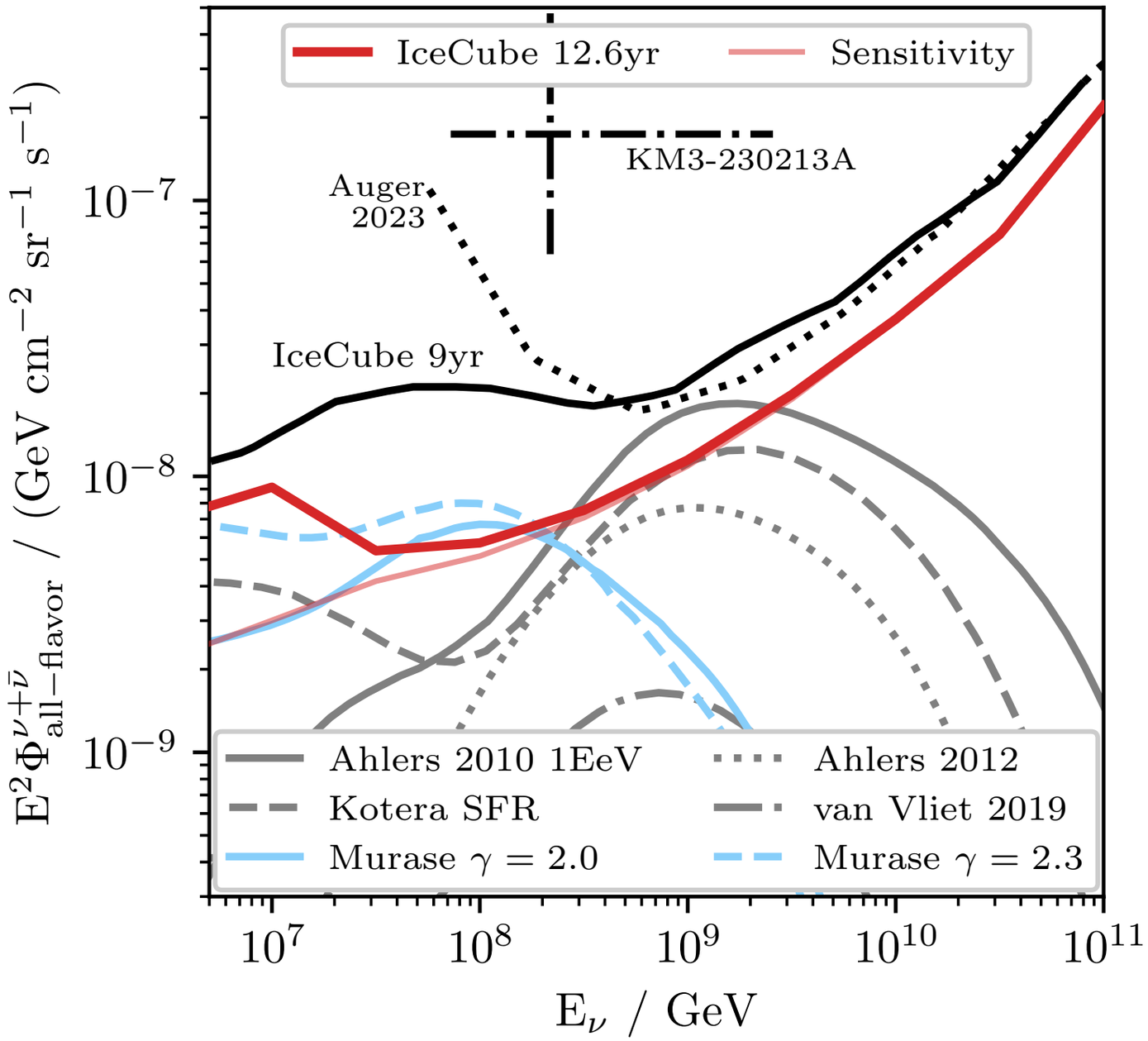
$$\frac{\lambda_{\mathrm{GZK}}}{\lambda_{\mathrm{Hubble}}} \sim 5\,\%$$

"Observable Universe"
in neutrinos and UHE CRs

Hubble horizon

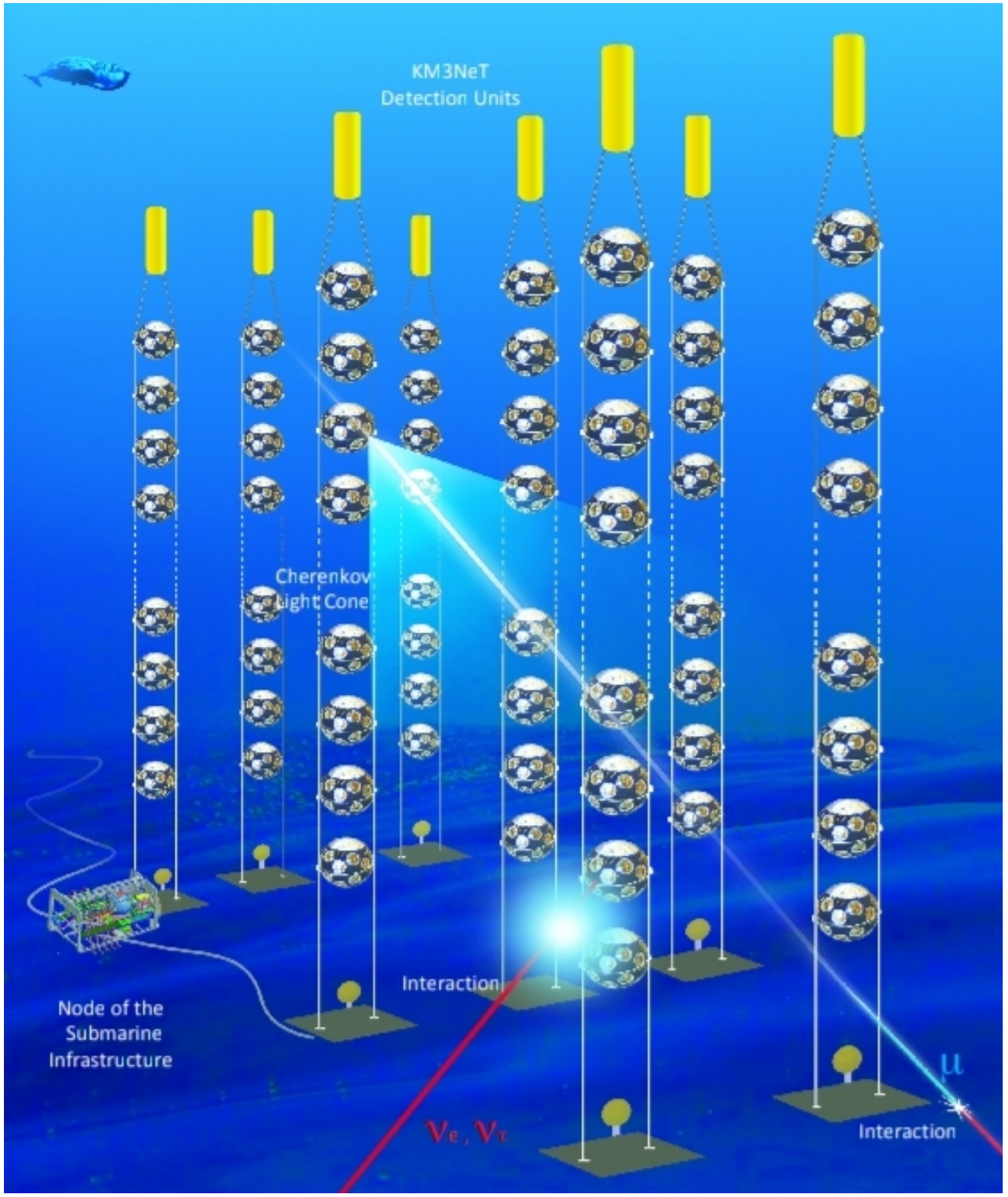
Cosmogenic Neutrinos

- Cosmogenic neutrinos produced in UHE CR interactions peak in the EeV energy range.
- Optimistic predictions based on high proton fraction and high maximal energies.
- **Proton fraction** of UHE CRs above 30 EeV **limited to 70%** (90% CL) for source evolution following star-formation rate.
- **Tension** between IceCube's non-observation and **KM3-230213A** (about 200 PeV) at **3σ level**.



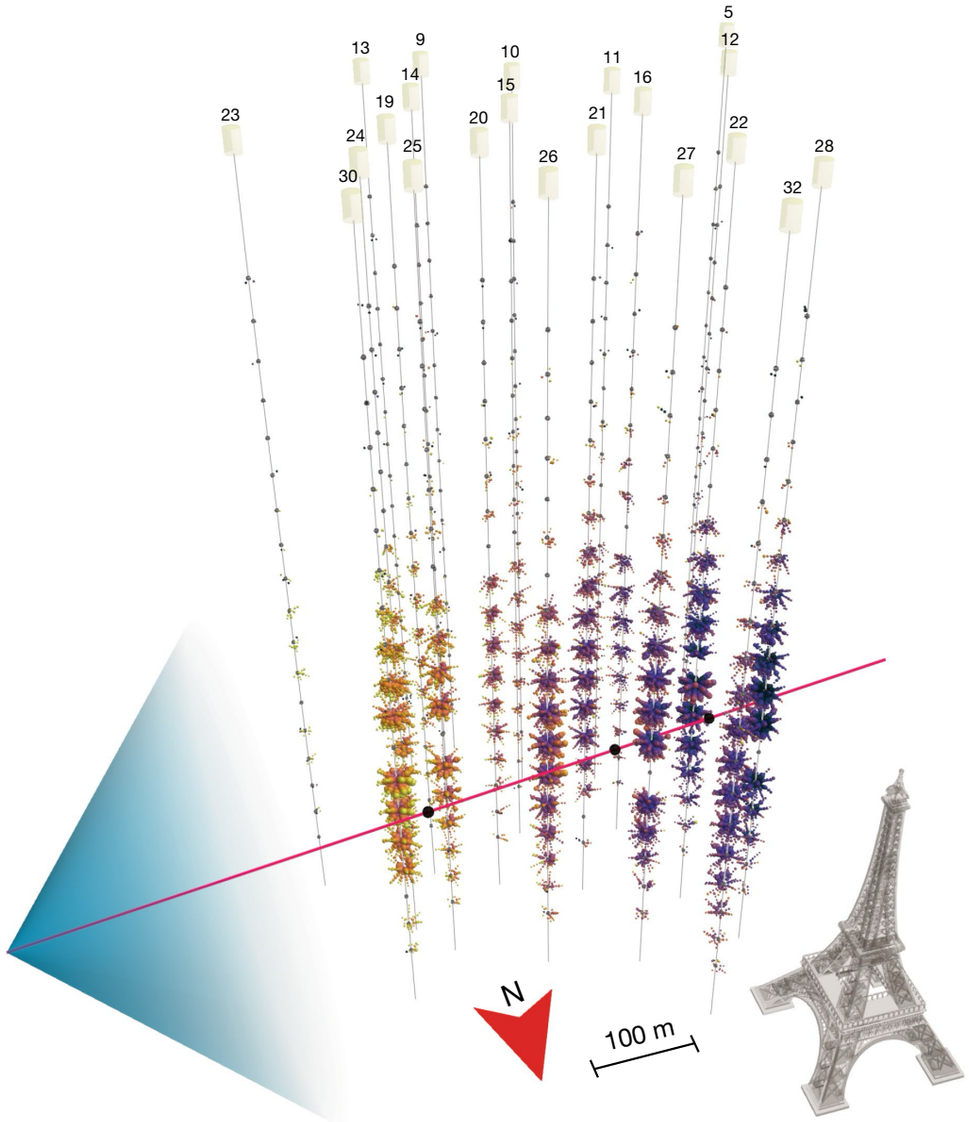
[IceCube, **PRL** 1325 (2025) 3]

KM3NeT Observatory



- **ARCA :** 2 building blocks with 198 detection units (DUs)
- **ORCA** : 108 DUs optimized for low-energy (GeV) and oscillation analyses
- *status June 2026* : 51 DUs in ARCA and 38 DUs in ORCA
- **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.

KM3-230213A



ARCA-21

February 13, 2023

120 PeV muon reaching ARCA-21 from 0.6° above the horizon

For $E_{\nu_\mu}^{-2}$-flux, corresponds to 72 PeV – 2.6 EeV neutrino (90% C.L.)

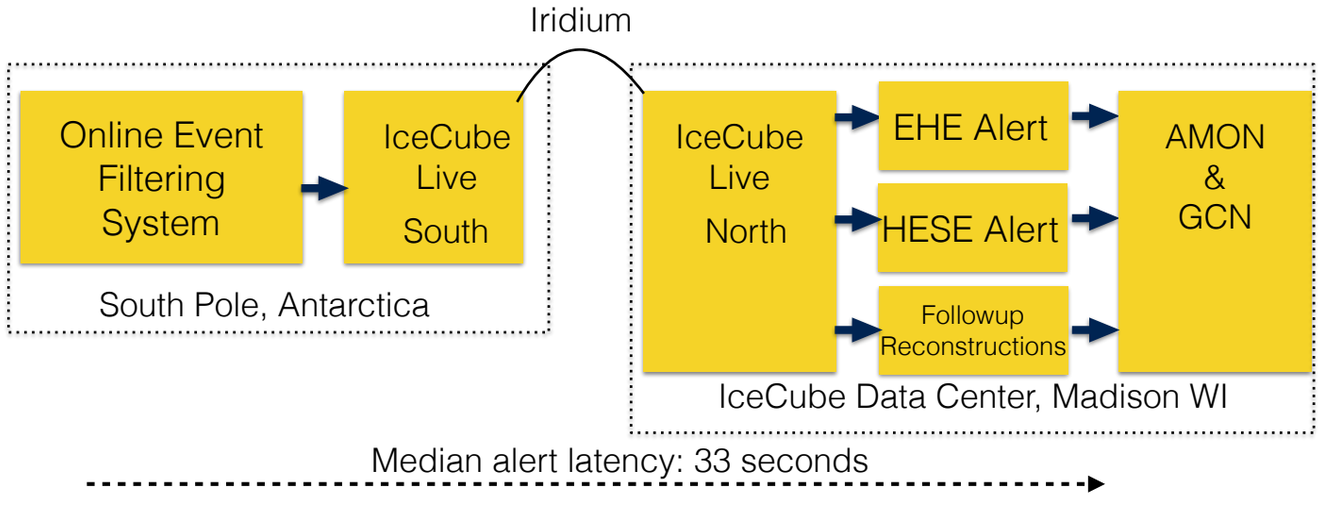
Flux is in tension with upper limits of IceCube and Auger ($2.5 - 3\sigma$)

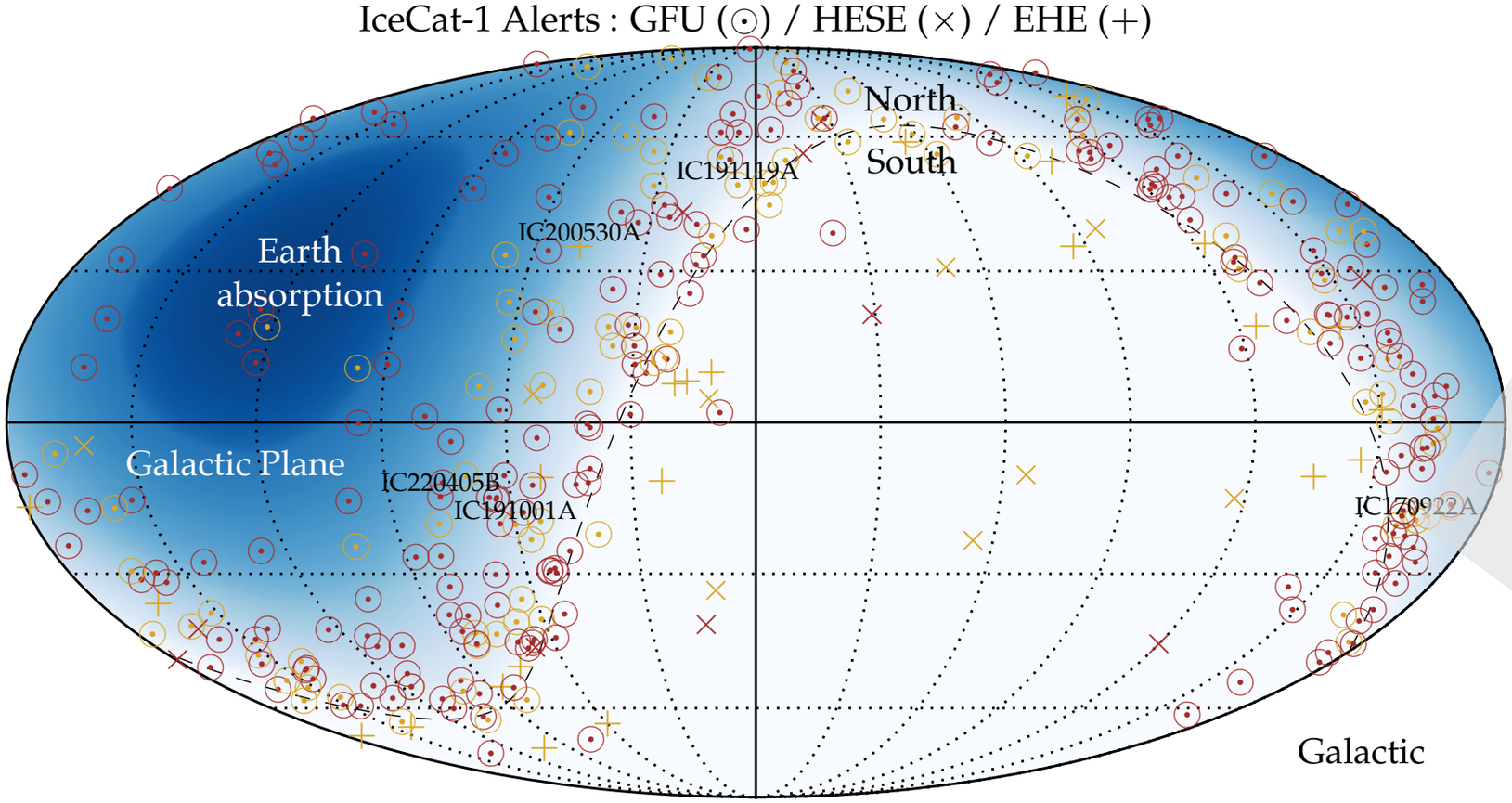
[KM3NeT, *Nature* 638 (2025) 8050; PRX 15 (2025) 3]

Realtime Neutrino Alerts

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

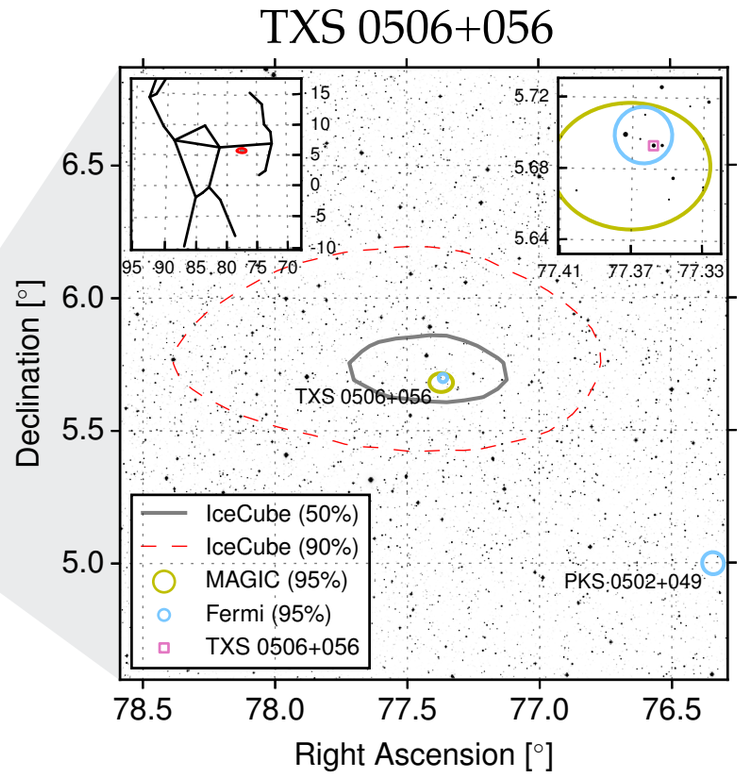
- **Gold alerts:** about **10 per year**
  50% signalness (on average)
- **Bronze alerts:** about **20 per year**
  30% signalness (on average)



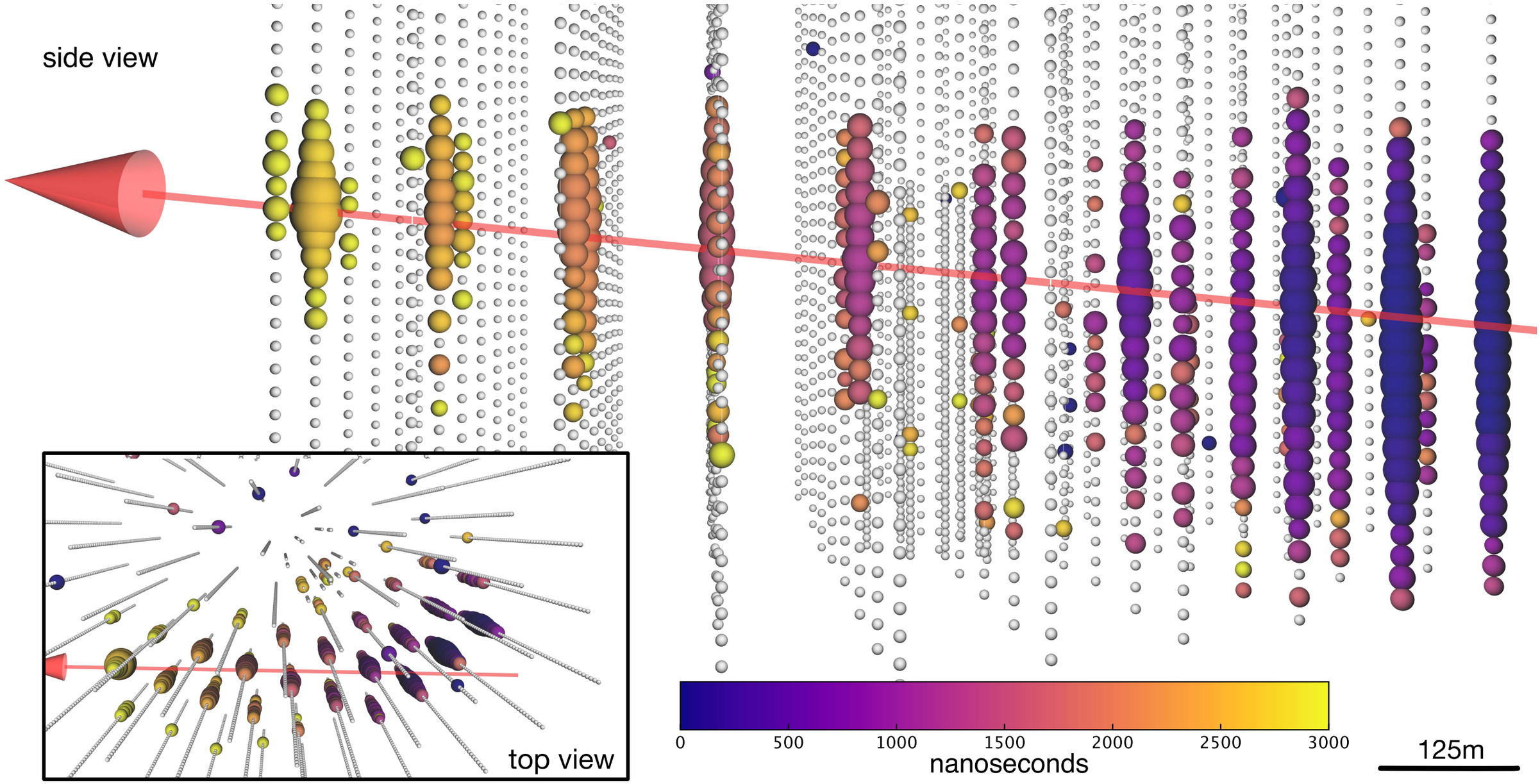


[IceCube, **ApJS** 269 (2023) 1; see also **PoS** (ICRC2025) 1224]

[IceCube, **PoS** (ICRC2019) 1021]

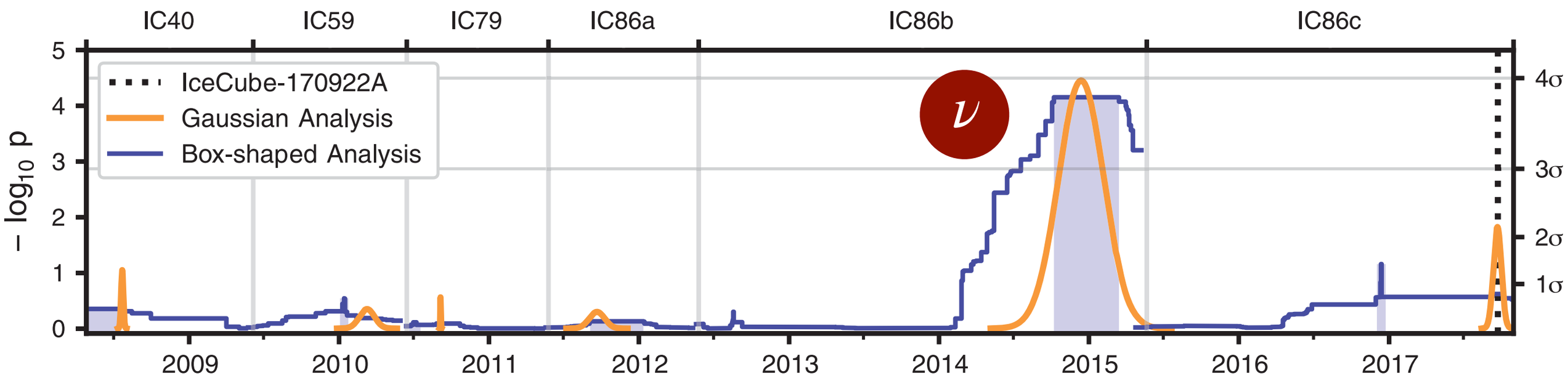


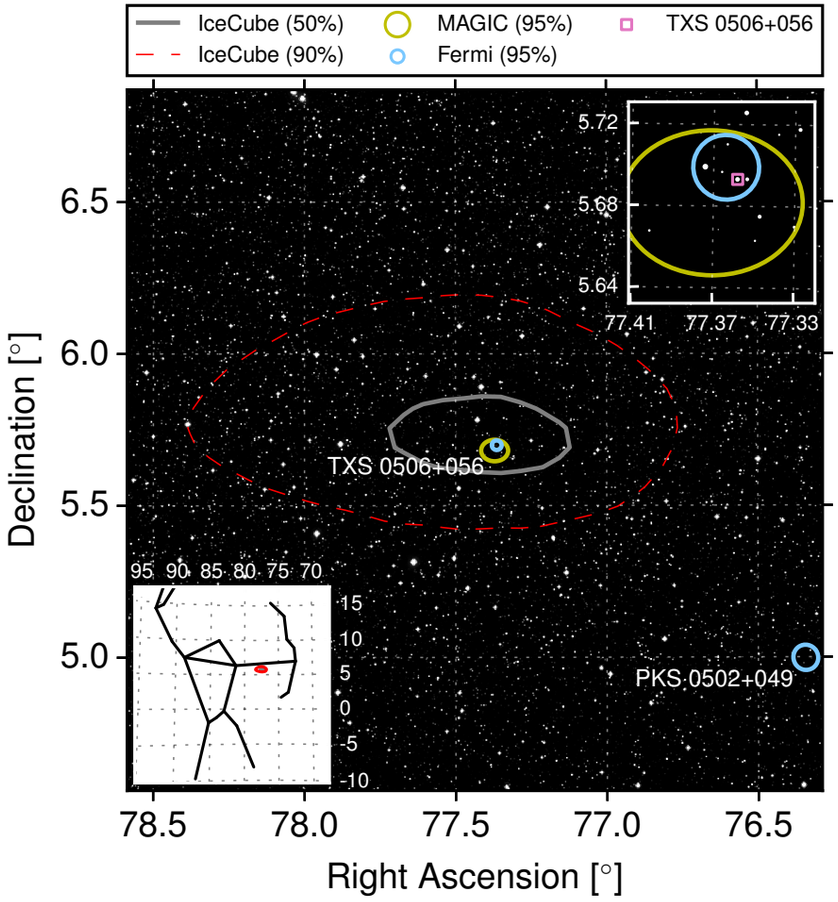
Neutrino Alert IC-170922A



up-going muon track (5.7° below horizon) observed September 22, 2017
best-fit neutrino energy is about 300 TeV

Neutrino Blazar: TXS 0506+056





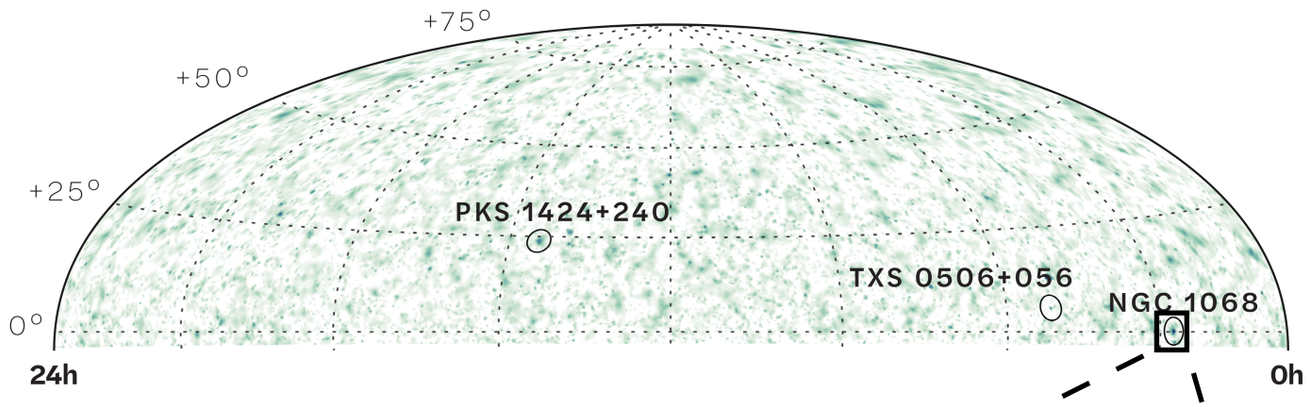
- Chance correlation of **IC-170922A** coincident with **flaring blazar in 2017** rejected at 3σ-level.
  [IceCube, **Science** 361 (2018) 6398, eaat1378]
- Independent 3.5σ evidence for a **neutrino flare in 2014/15** (13±5 excess events).
  [IceCube, **Science** 361 (2018) 6398, 147]
- Neutrino luminosity over 158 days is about **four times that of Fermi-LAT γ-rays**.

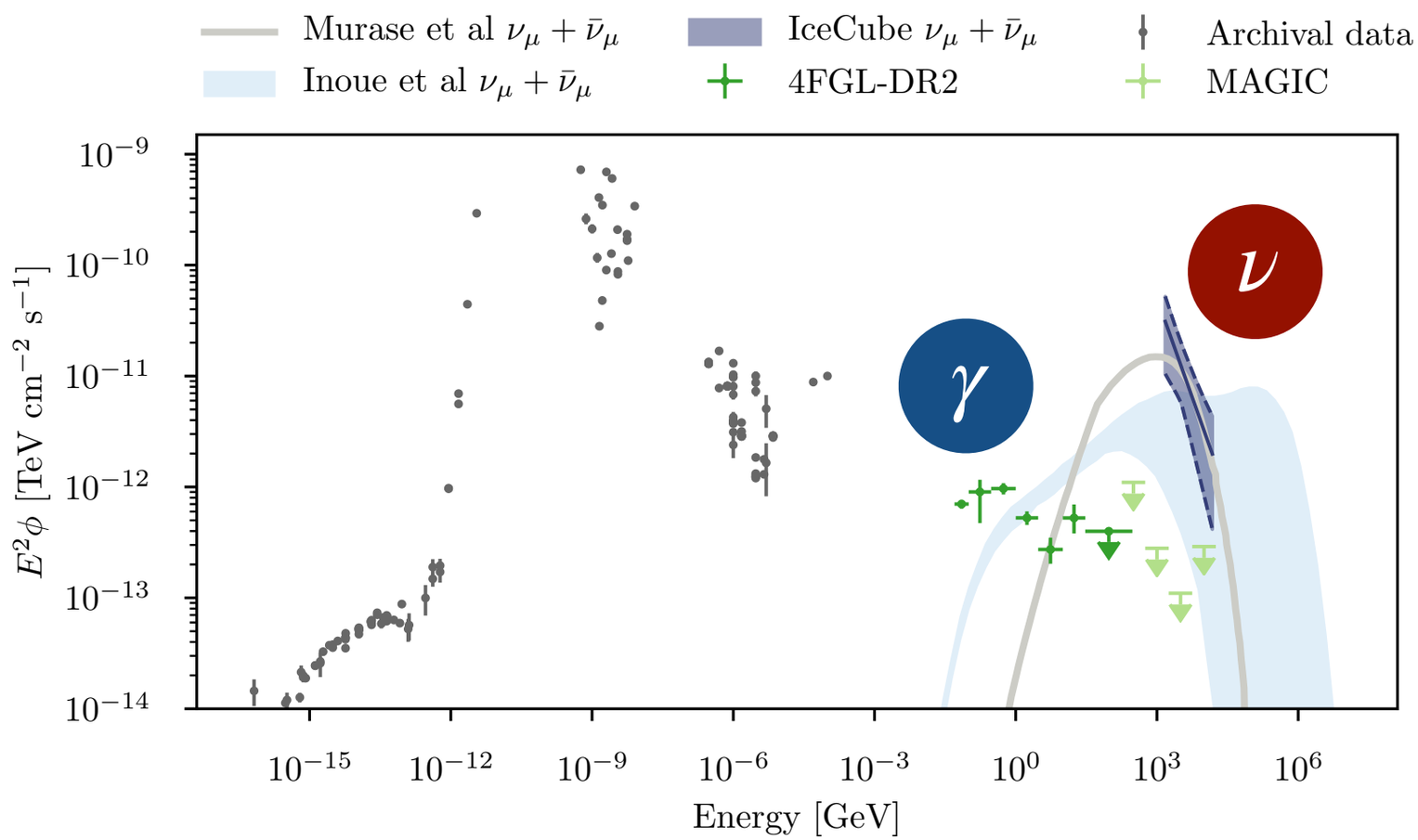
Neutrino AGN: NGC 1068

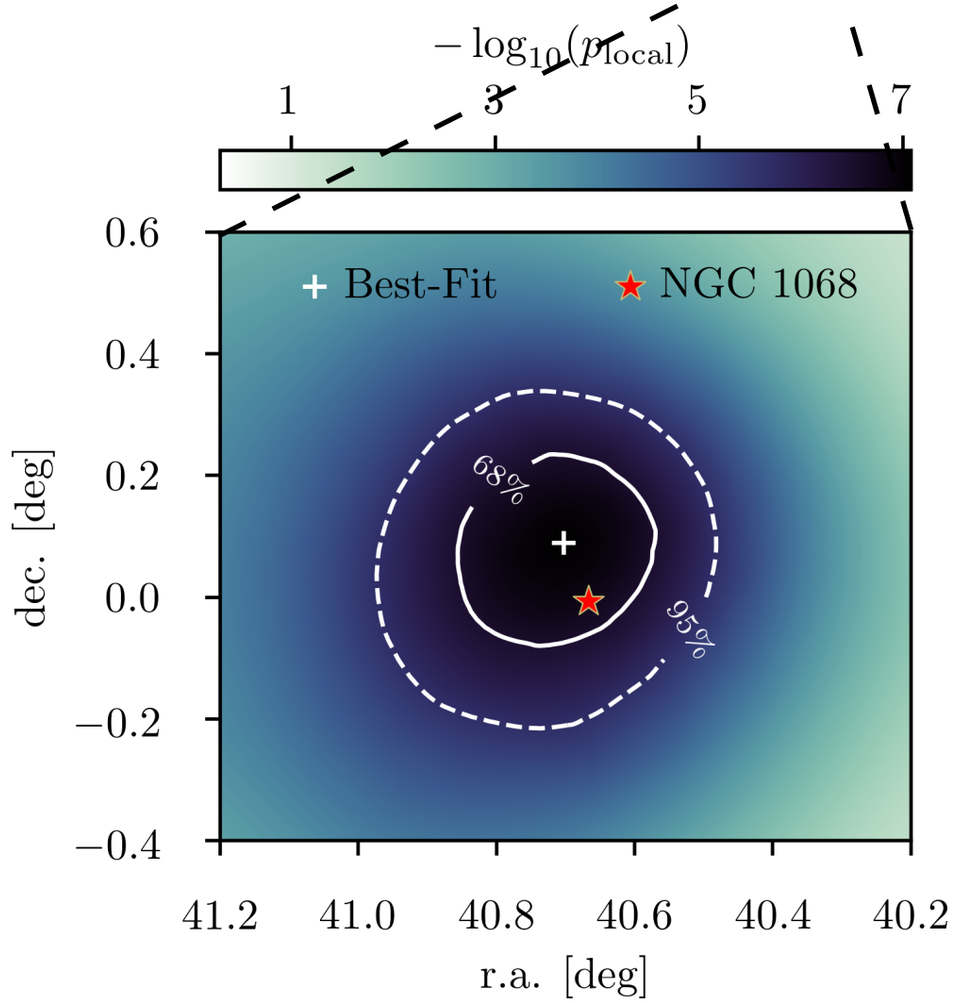
Neutrino excess from Seyfert galaxy **NGC 1068** with a post-trial **significance of 4.2σ**

(trial-corrected for 110 sources)

[IceCube, **Science** 378 (2022) 6619]







[see also IceCube, **PRL** 124 (2020) 5 **(2.9σ)**; **ApJ** 995 (2025) 1 **(3.5σ); ApJL** 1000 (2026) 1 **(4.0σ)**]

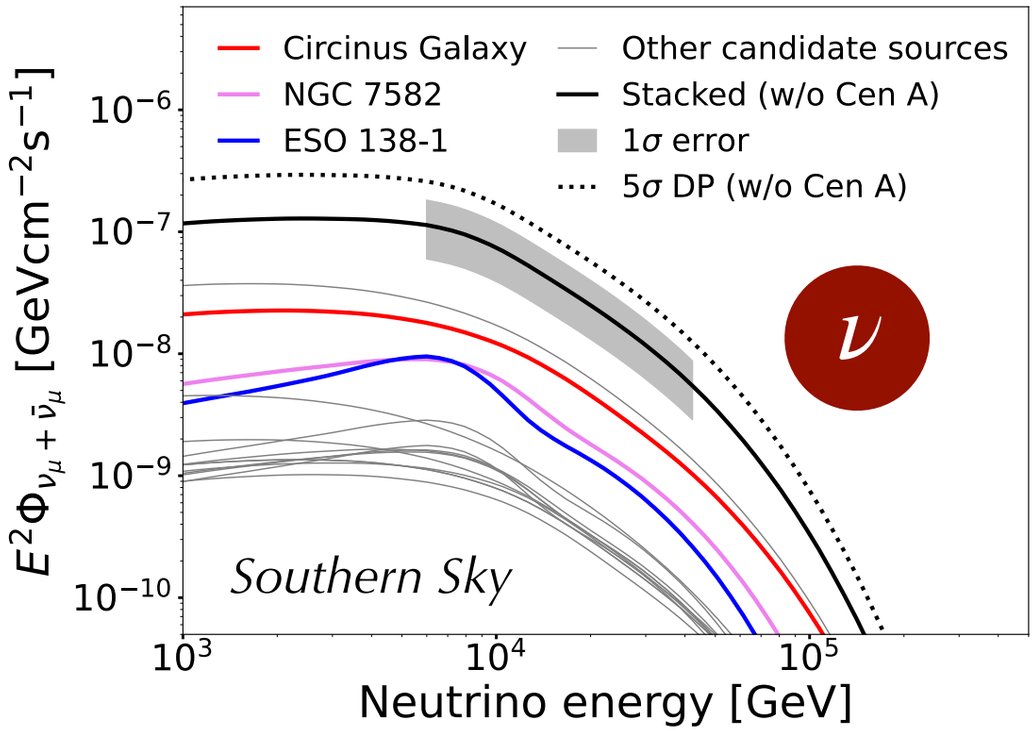
[model predictions by Murase, Kimura & Meszaros '20; Inoue, Khangulyan & Doi '20]

Hidden Cores of Seyfert Galaxies

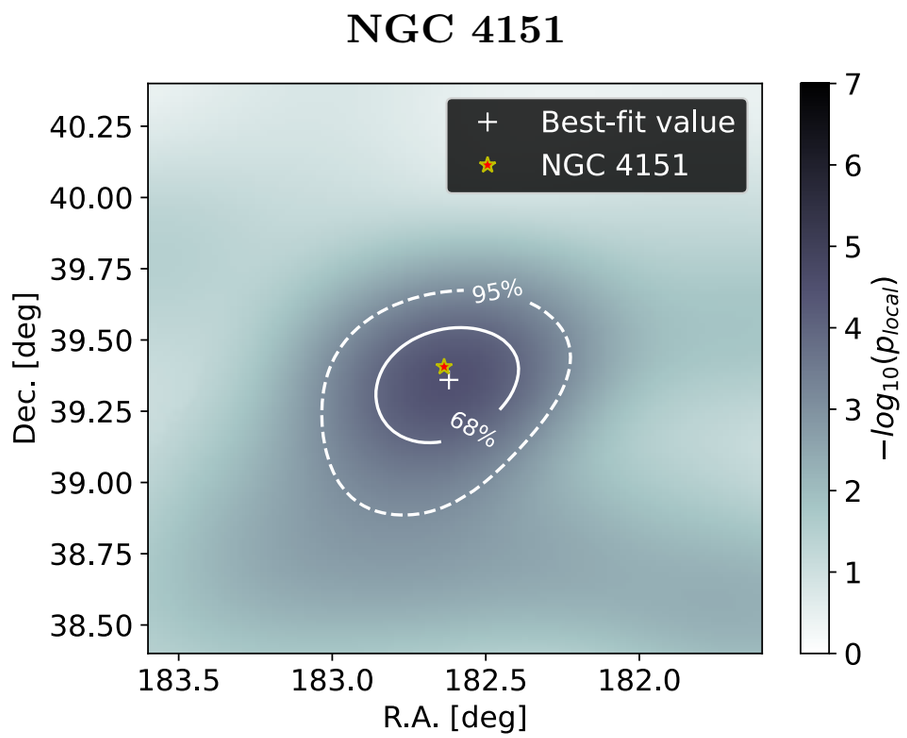
Evidence **(3σ)** for neutrino emission of **X-ray bright Seyfert galaxies**
(*Southern Sky*: 14 / *Northern Sky*: 11)

[IceCube, **ApJL** 1000 (2026) 1 & 2]
[see also IceCube, **ApJ** 981 (2025) 2; **ApJ** 988 (2025) 1]

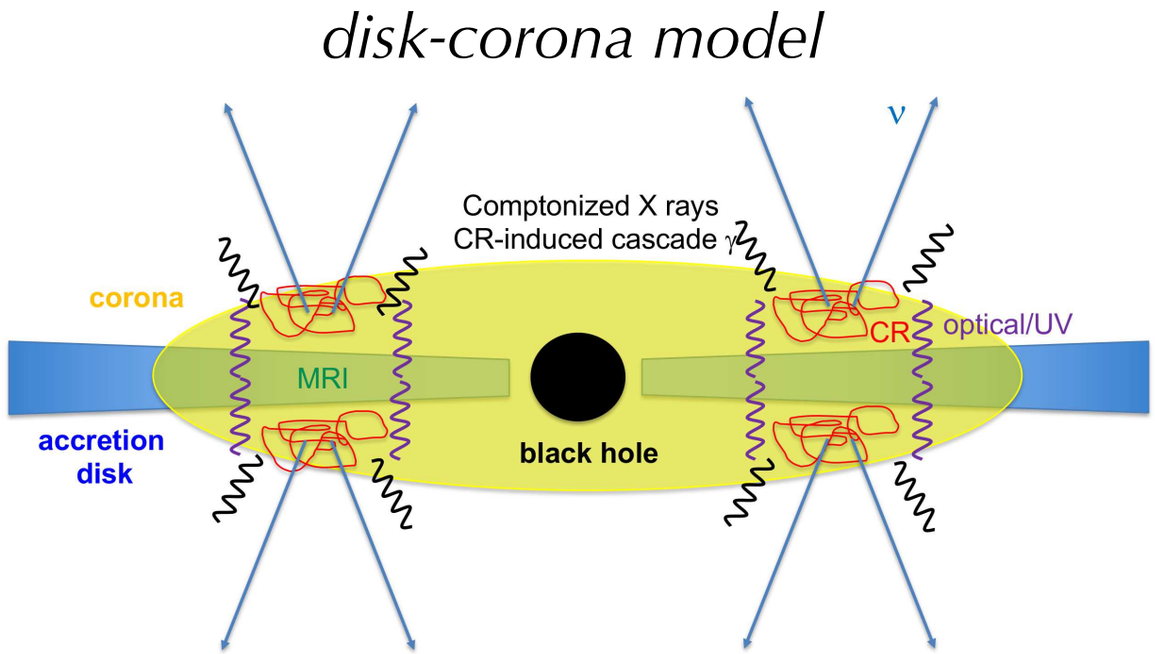
Neutrino excess from direction of Seyfert galaxy **NGC 4151** with post-trial **significance 2.9σ**.



[IceCube, **ApJL** 1000 (2026) 2]



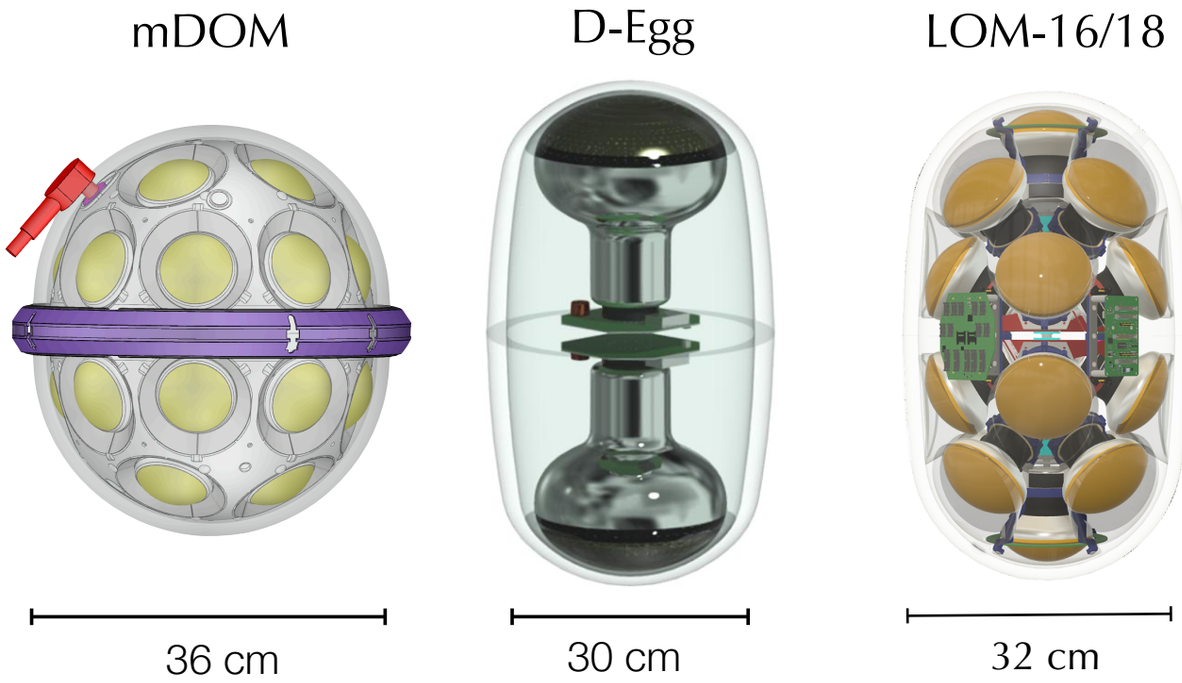
[IceCube, **ApJ** 981 (2025)]

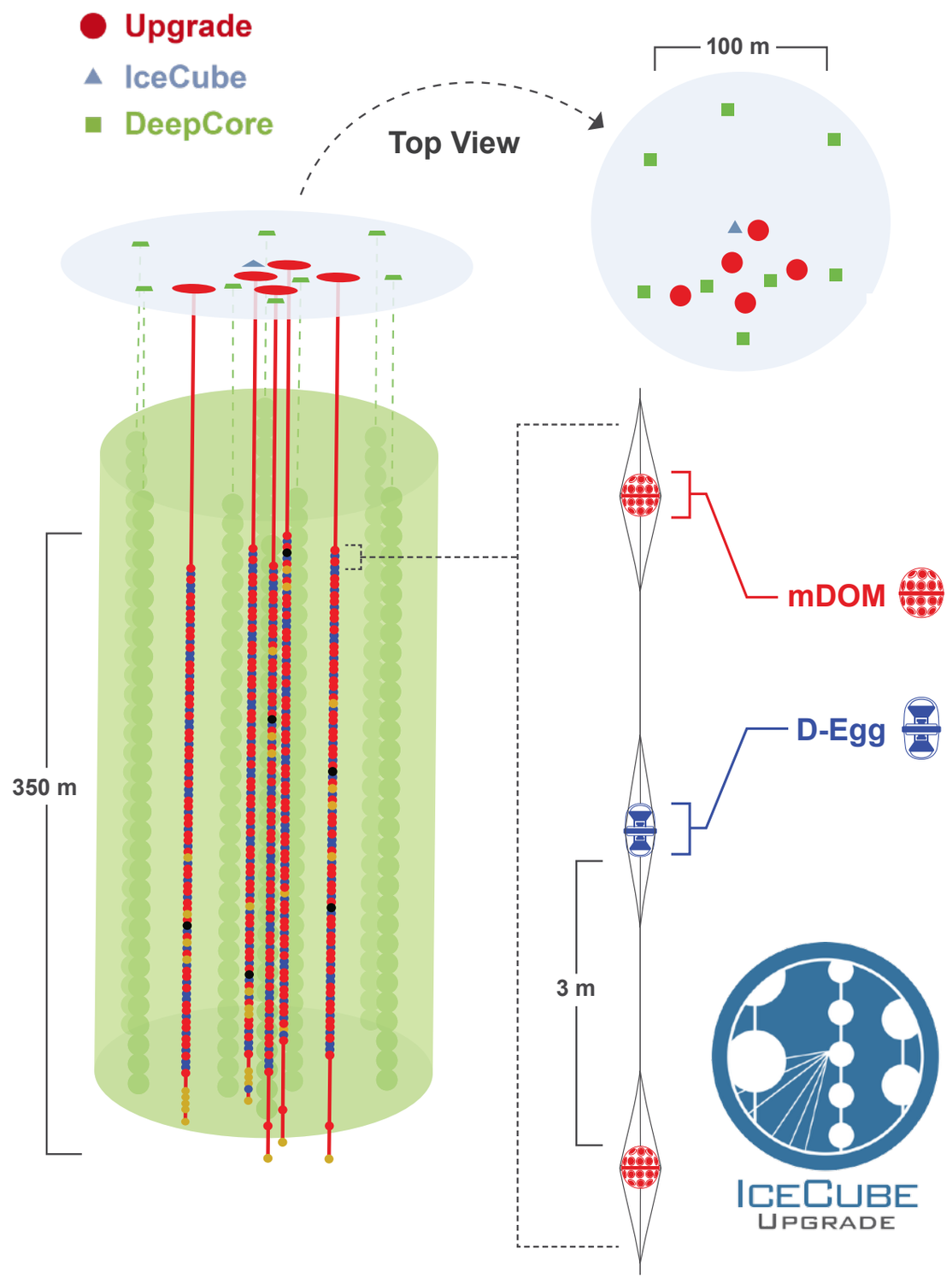


[Murase, Kimura & Meszaros '20]

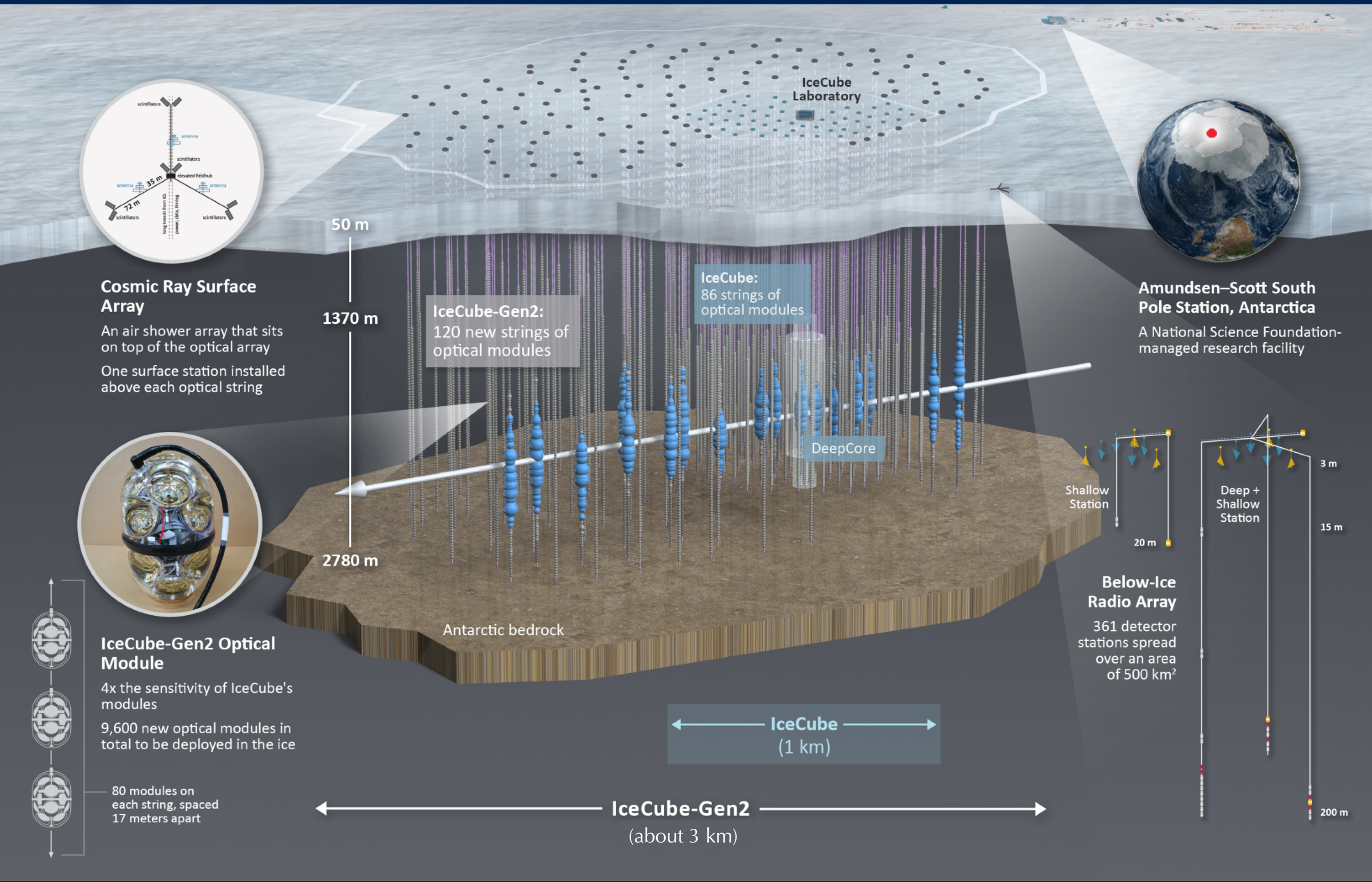
IceCube Upgrade

- *IC-Upgrade:* **5 new strings** in the DeepCore region (~20m spacing).
- **New calibration devices** incorporating lessons from a decade of IceCube calibration efforts.
- **New sensor designs**, optimized for ease of deployment, light sensitivity & effective area.





Vision: IceCube-Gen2



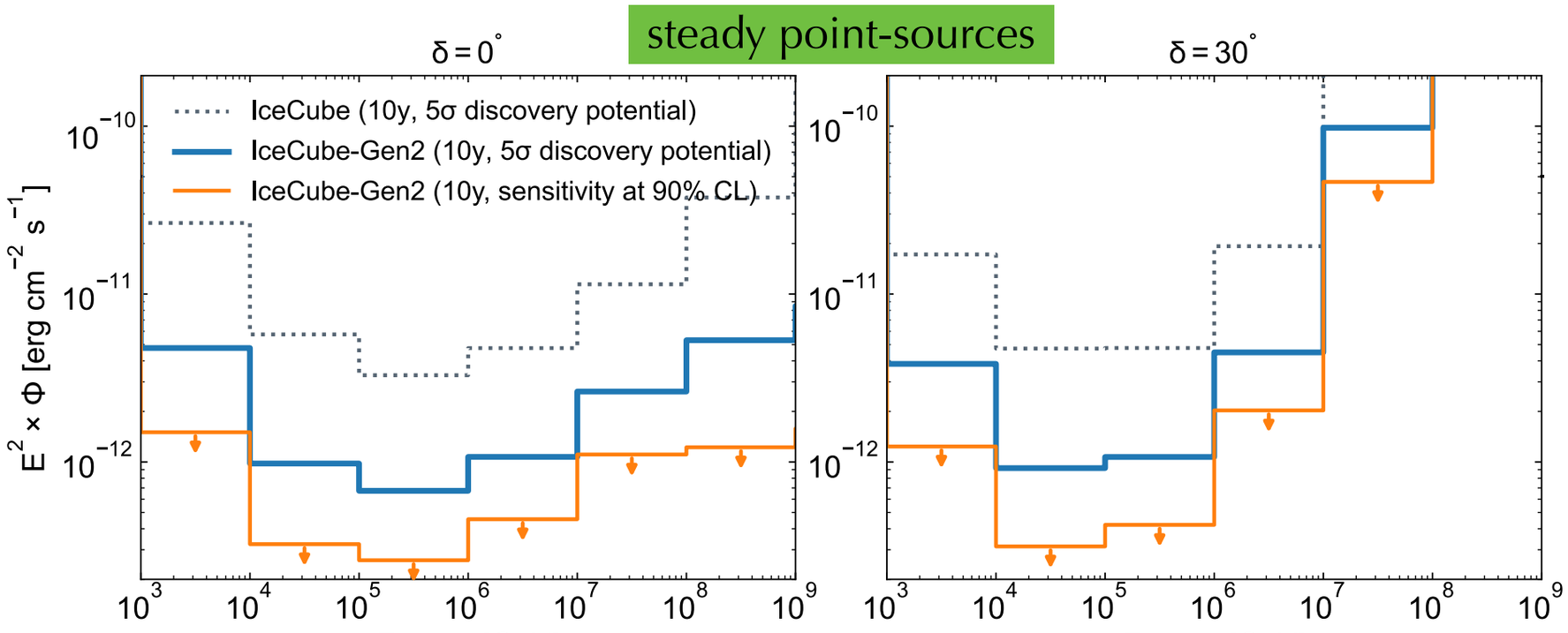
Vision: IceCube-Gen2

IceCube GEN2

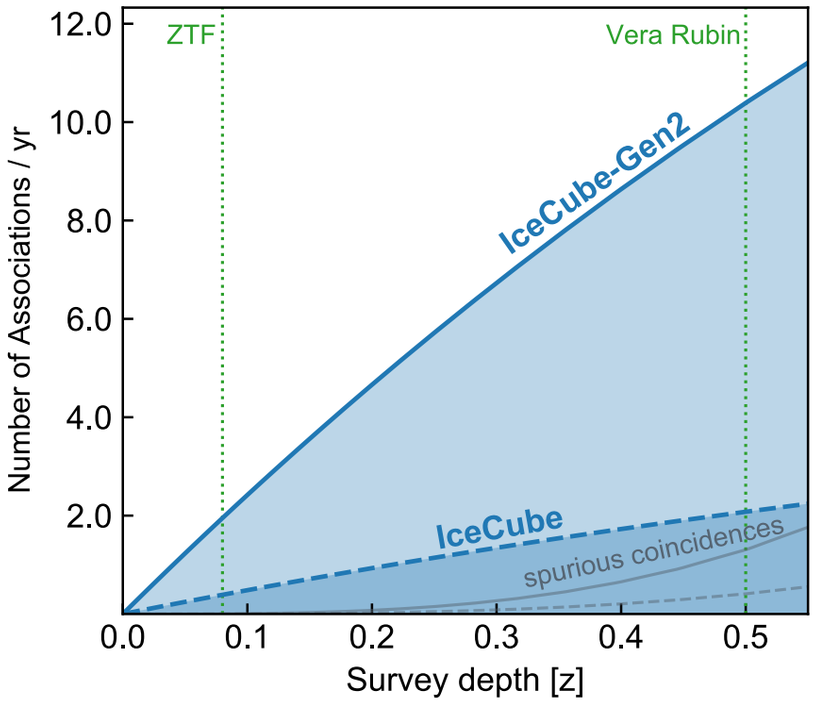
Discovery potentials of IceCube vs. IceCube-Gen2

[IceCube-Gen2 TDR]

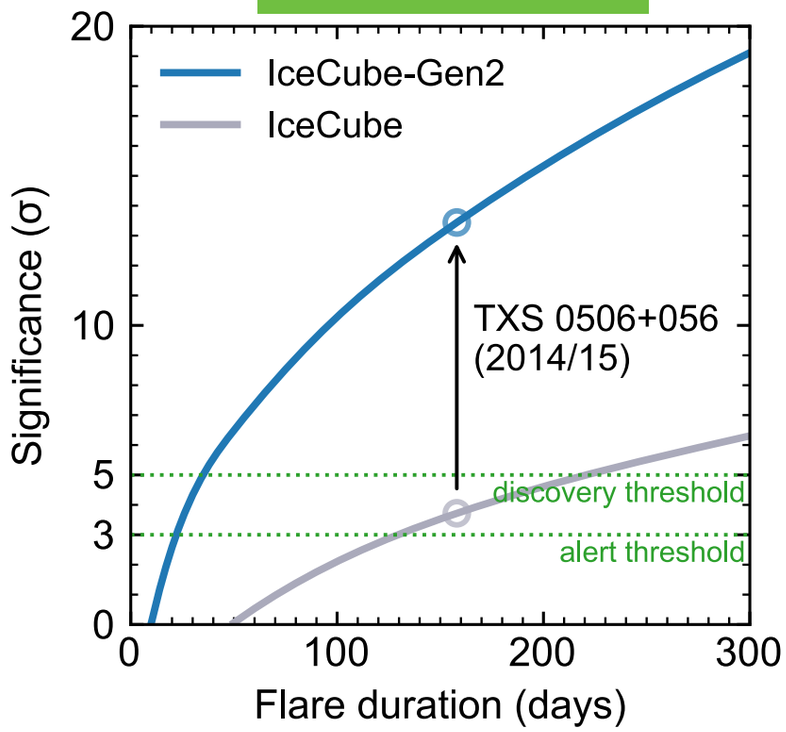
steady point-sources



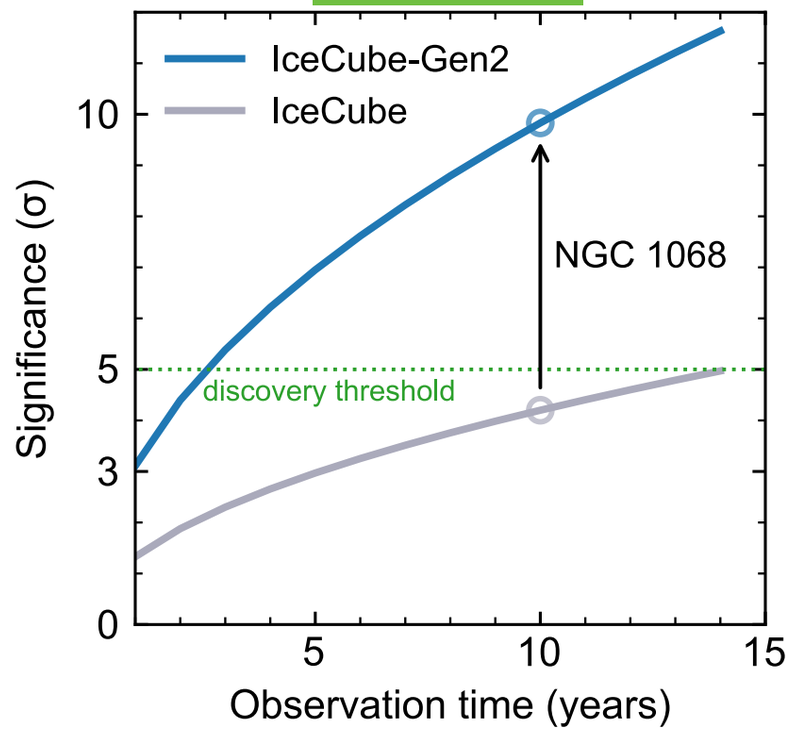
TDEs



TXS 0506+056



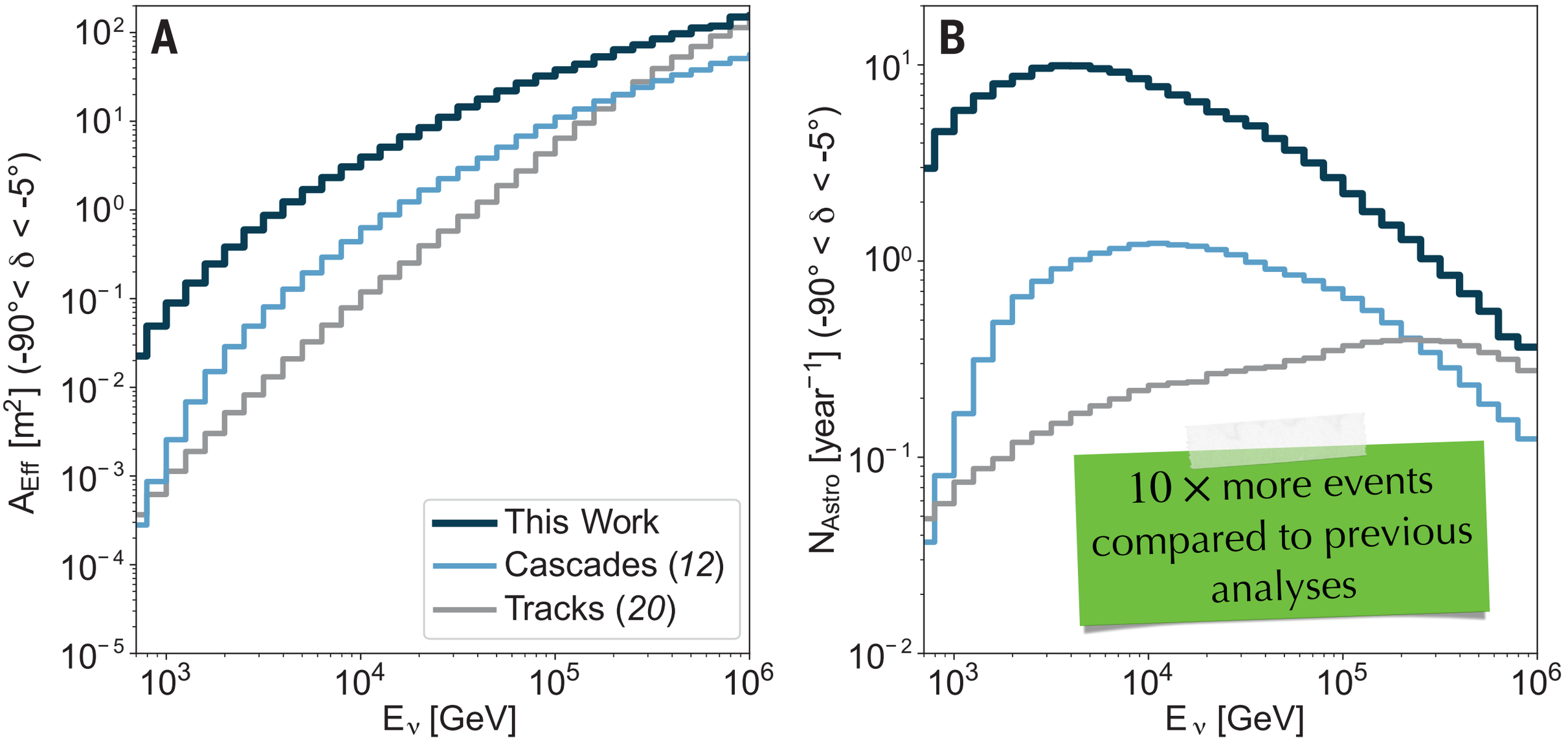
NGC 1068



Backup Slides

DNNcascade Sample

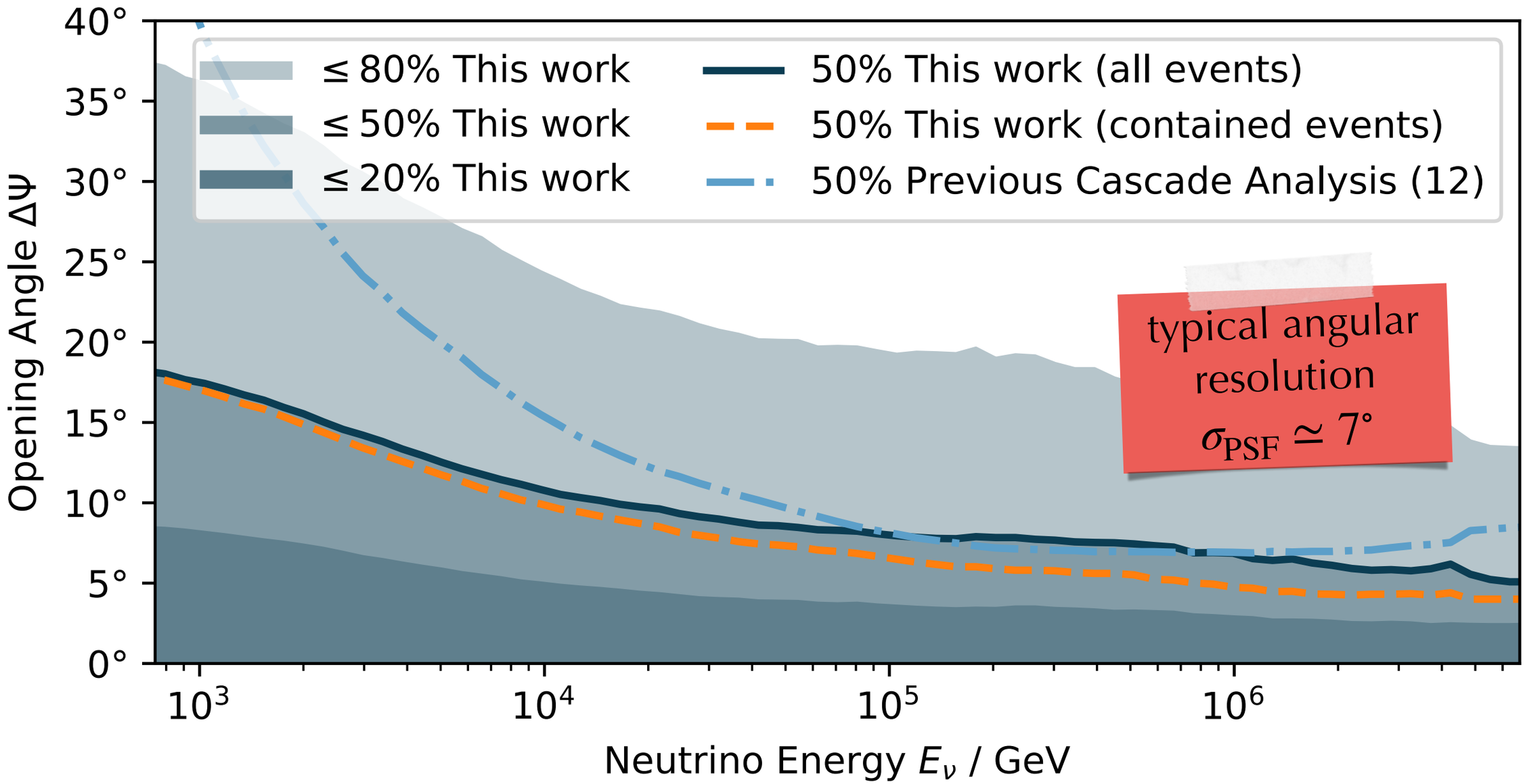
Analysis is based on novel cascade event selection and reconstruction using deep neutral networks (DNNcascade).



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

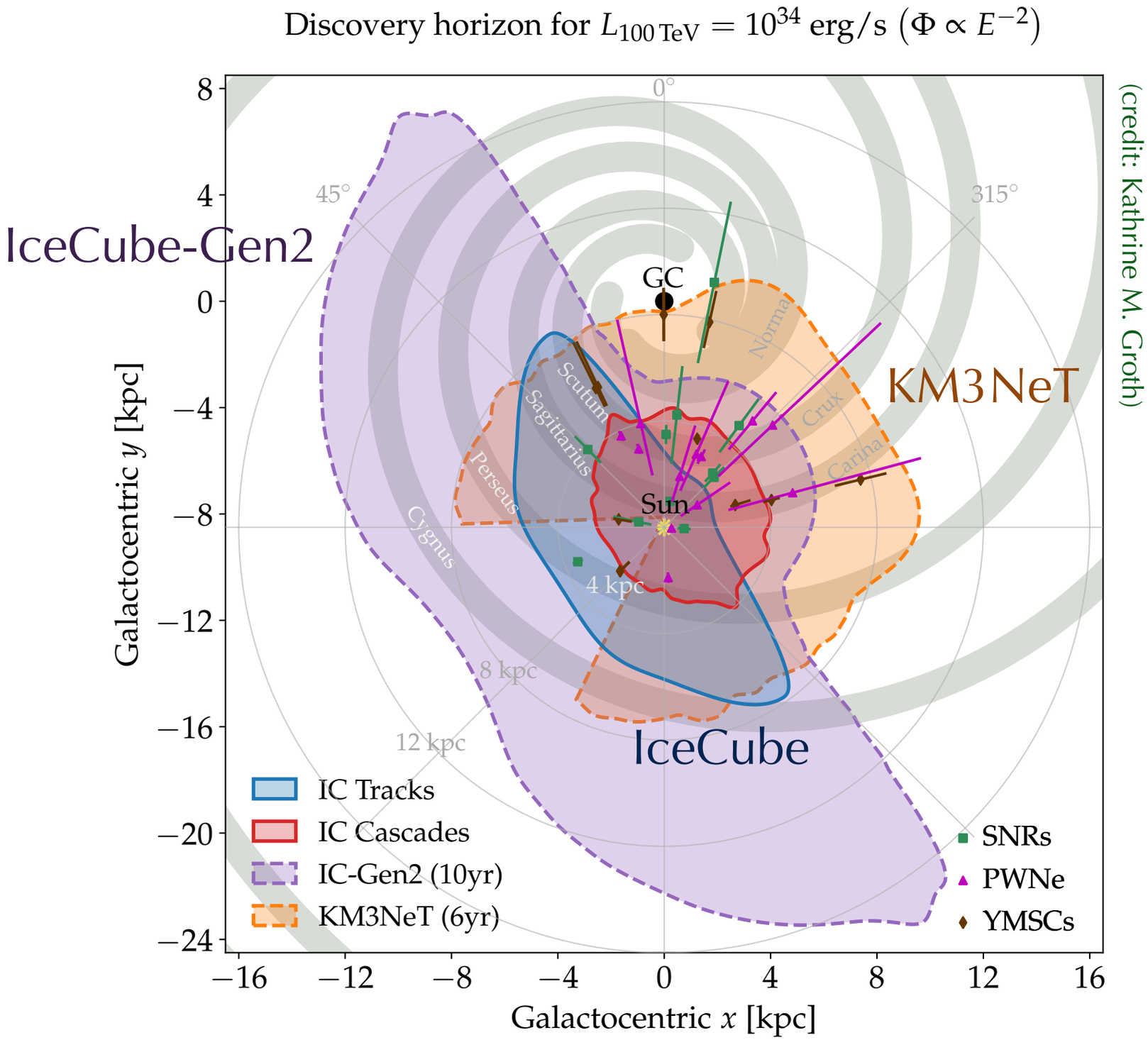
DNNcascade Sample

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



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

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

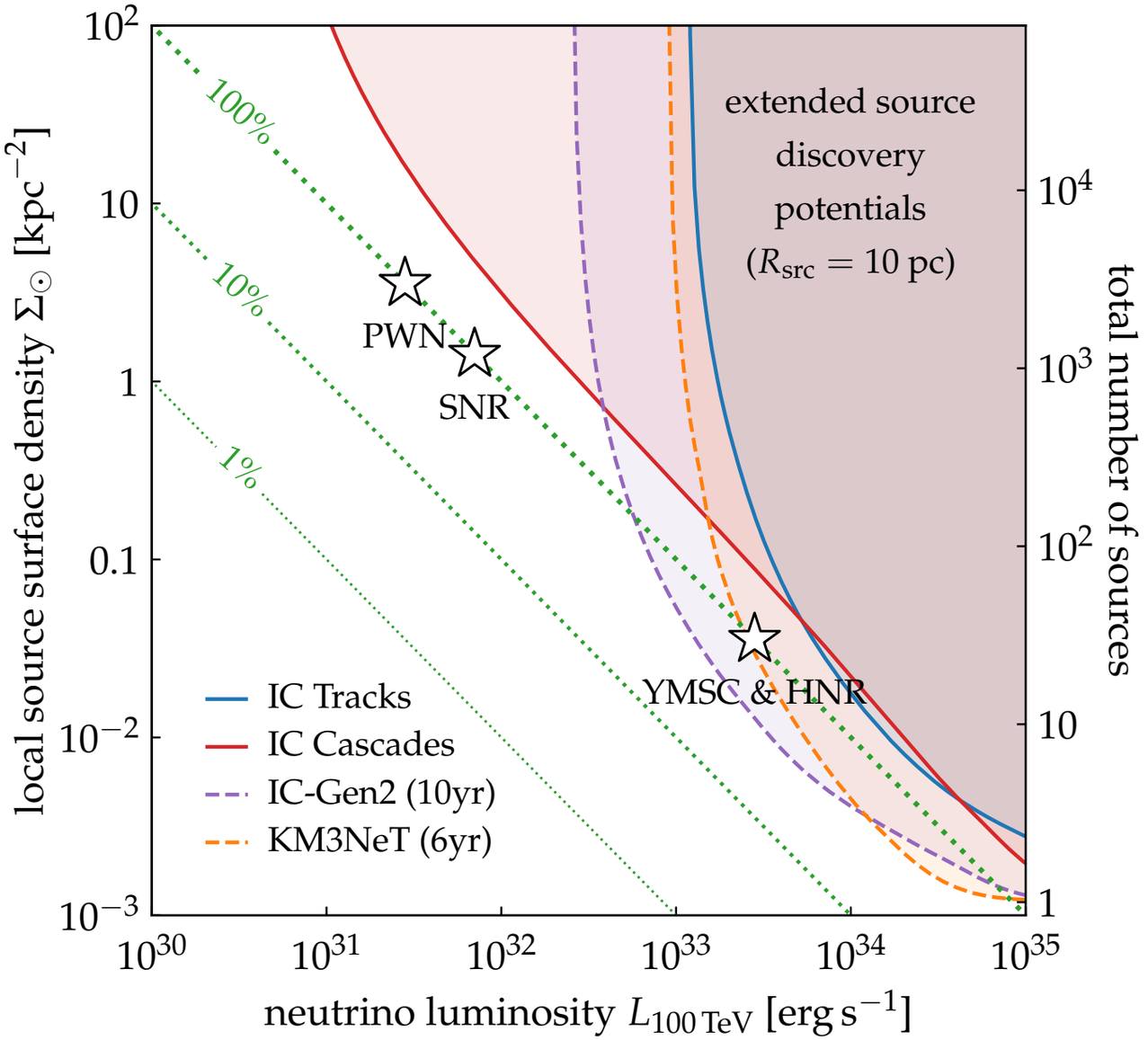
combined isotropic emission.

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]

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)	

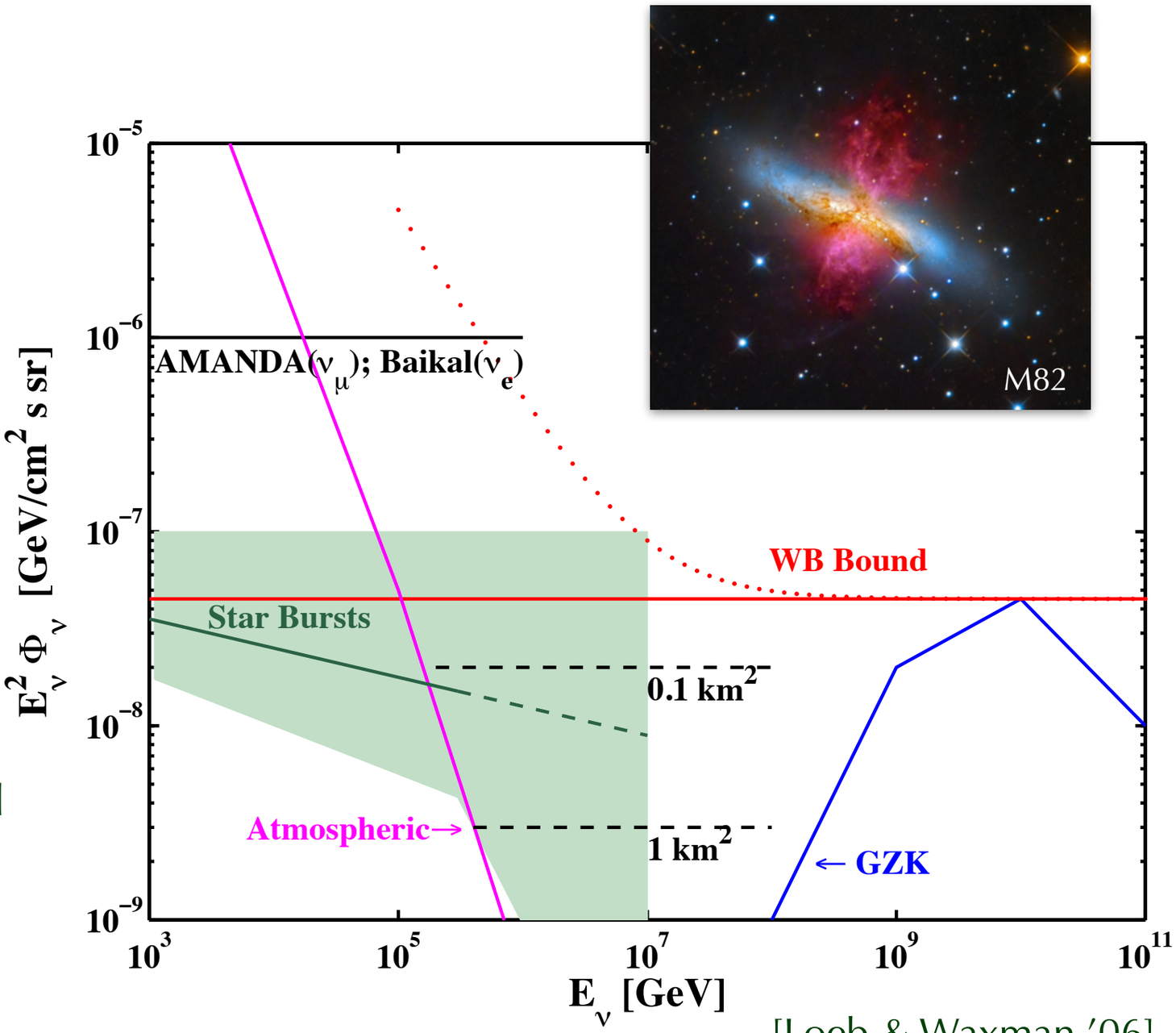
post-trial p-value
template search:
4.5σ

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

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

Starburst Galaxies

- High rate of **star formation** and SN explosions enhances (UHE) CR production.
- Low-energy cosmic rays remain magnetically confined and eventually collide in **dense environment**.
- In time, efficient **conversion of CR energy density into γ-rays and neutrinos**. [Loeb & Waxman '06]
- Power-law neutrino spectra with high-energy softening from CR leakage and/or acceleration.



[Loeb & Waxman '06]

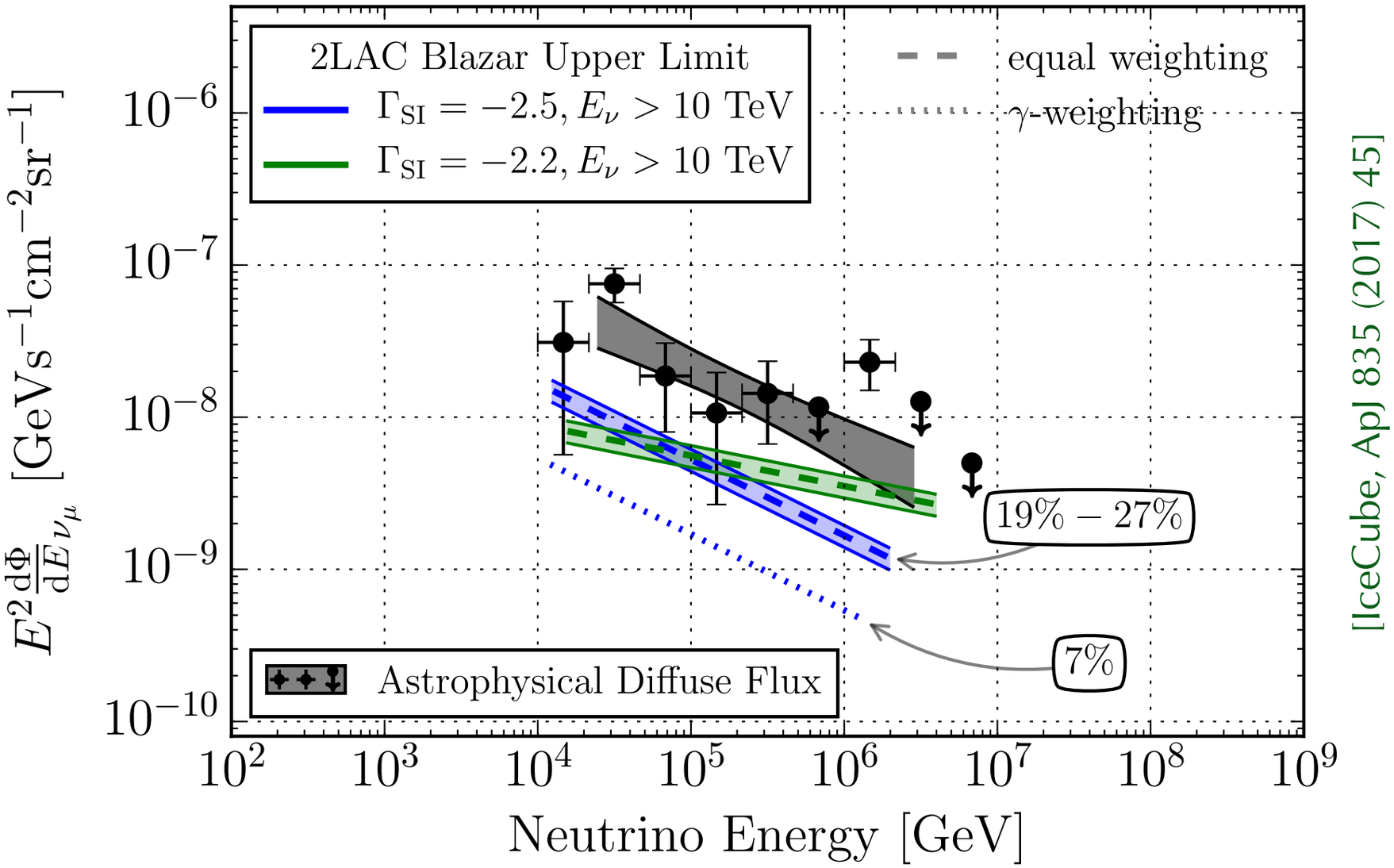
[Romero & Torres'03; Liu, Wang, Inoue, Crocker & Aharonian'14; Tamborra, Ando & Murase'14]
[Palladino, Fedynitch, Rasmussen & Taylor'19; Peretti, Blasi, Aharonian, Morlino & Cristofari'19]
[Ambrosone, Chianese, Fiorillo, Marinelli, Miele & Pisanti'20]

Blazars

Active galaxy powered by accretion onto a supermassive black hole with **relativistic jets pointing into our line of sight**.

[Credit: DESY, Science Communication Lab]

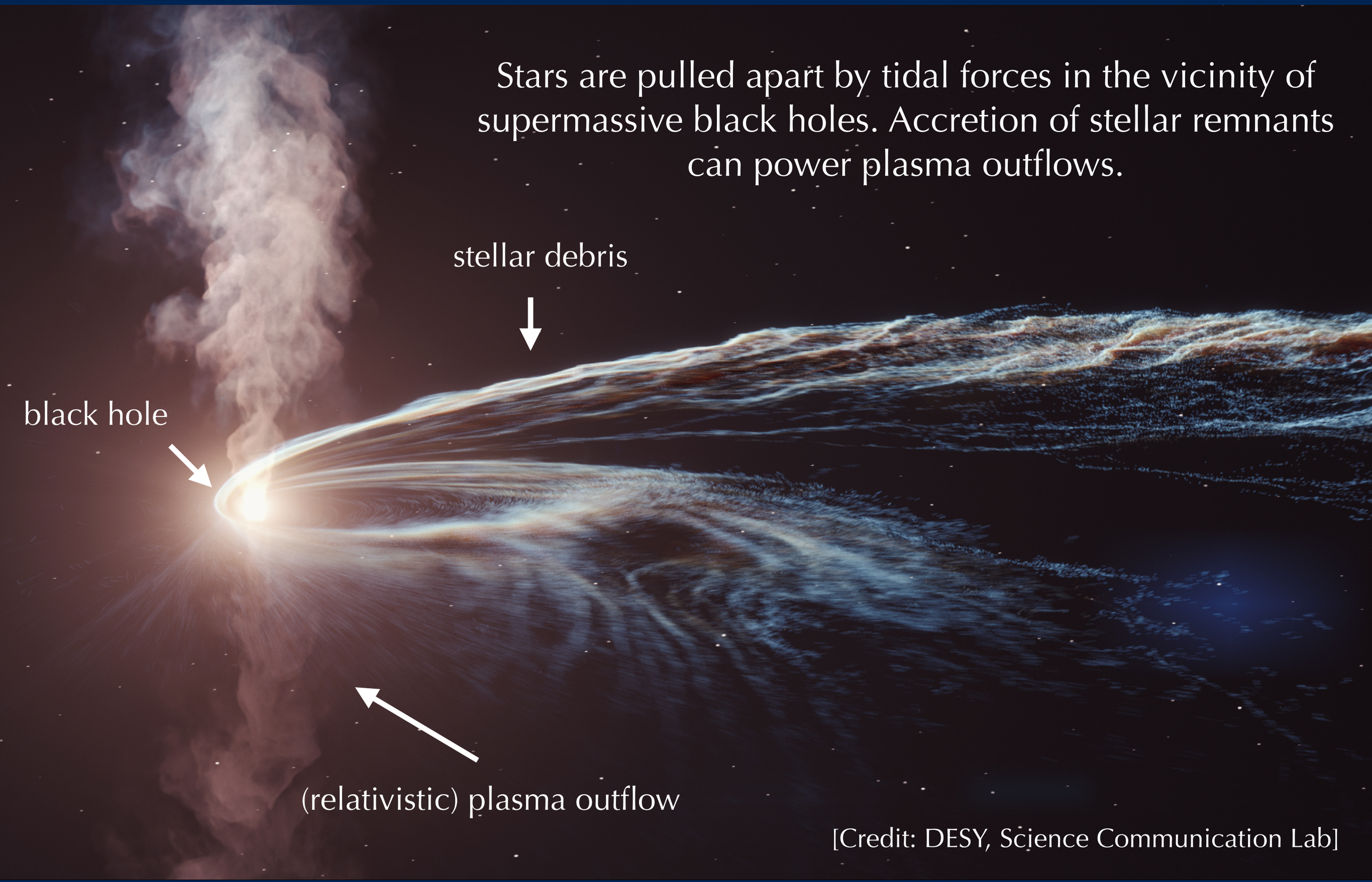
Fermi-LAT Blazar Stacking



- Combined contribution of Fermi-LAT blazars (2LAC) **below 30%** of the isotropic TeV-PeV neutrino observation. [IceCube, ApJ 835 (2017) 45]
- MeV-detected (1FLE) **below 1%**; "hard" emitters (3FHL) **below 17%** [IceCube, ApJ 938 (2022) 1; PoS ICRC2019 (2020) 916]

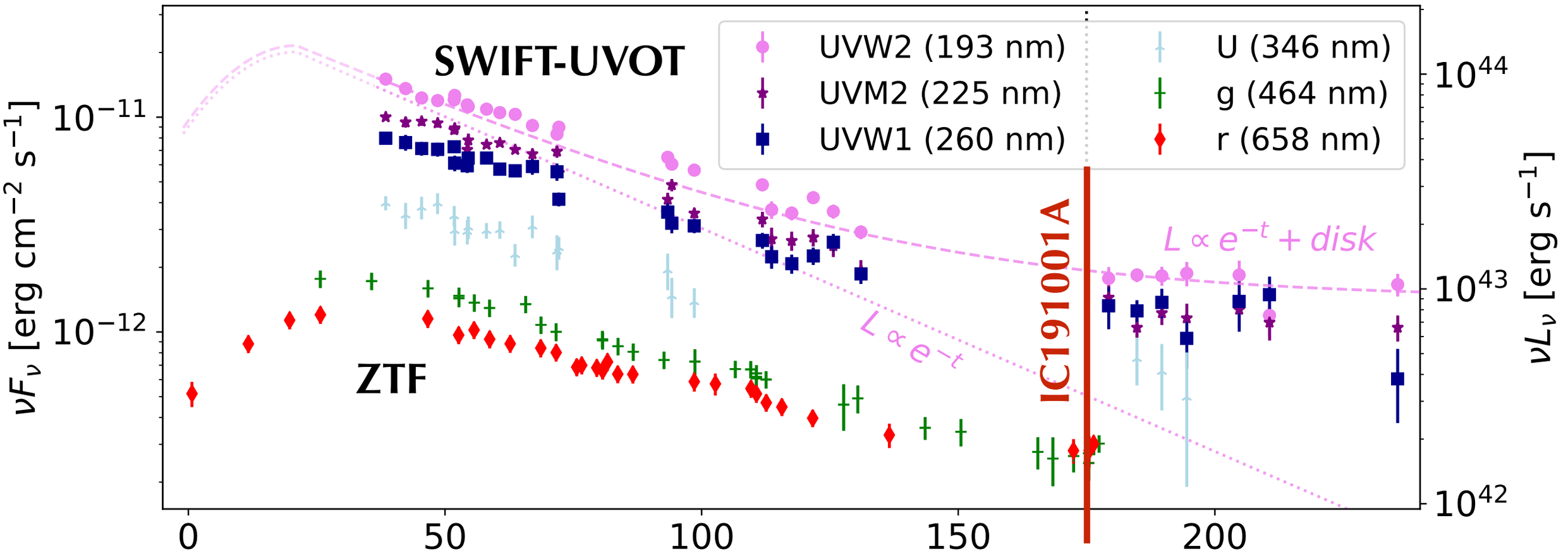
Tidal Disruption Events (TDEs)

Stars are pulled apart by tidal forces in the vicinity of supermassive black holes. Accretion of stellar remnants can power plasma outflows.



[Credit: DESY, Science Communication Lab]

Tidal Disruption Events (TDEs)

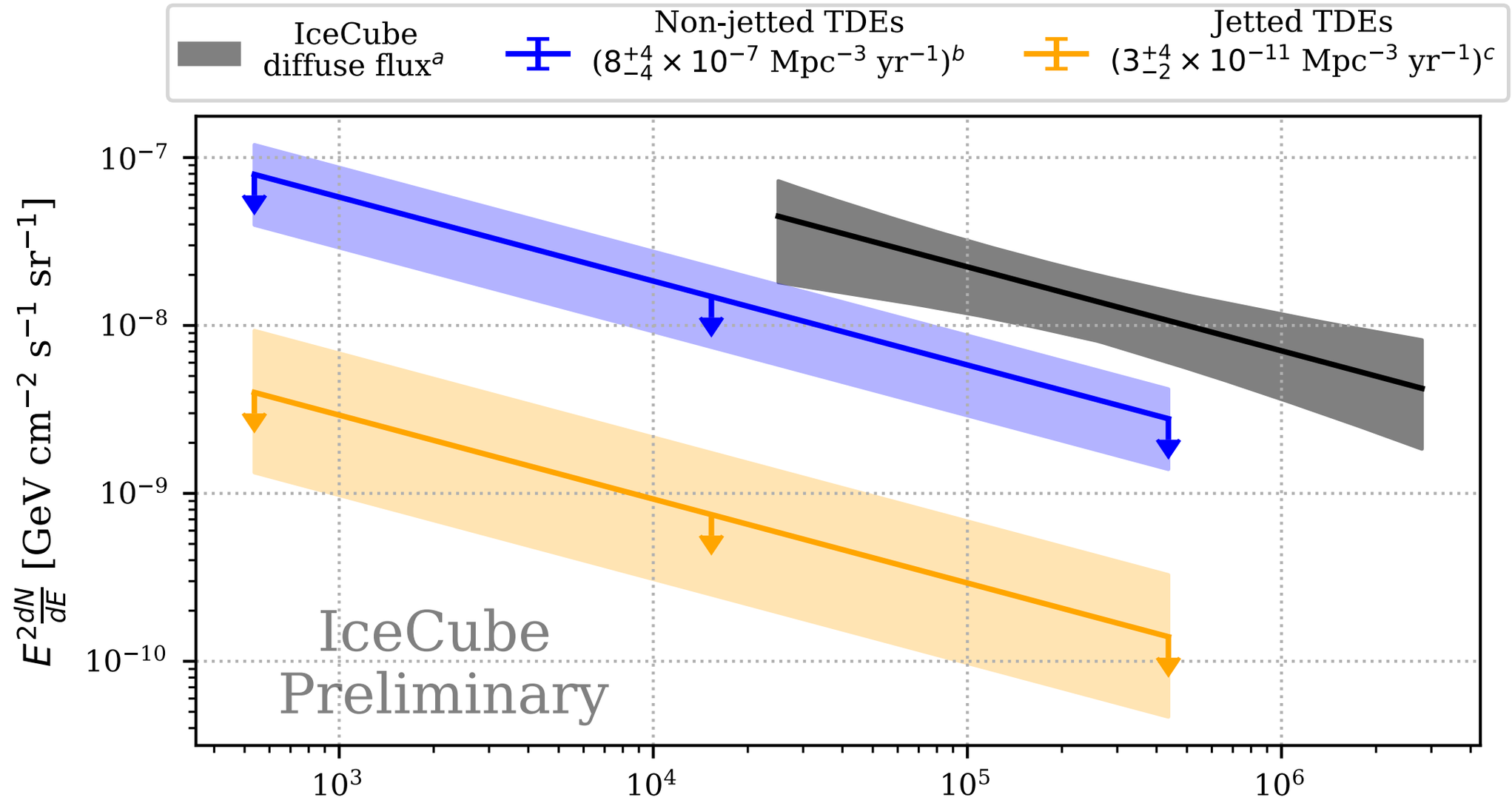


[Stein et al. Nature Astronomy 5 (2021) 5]

- Association of alert IC191001A with radio-load TDE AT2019dsg
- Chance for random correlation of TDEs and IceCube alerts is 0.5%.
- Other associations with TDE candidates, *e.g.* IC200530A & AT2019fdr.

[Reusch et al. PRL 128 (2022) 221101; Walter & Lunardini ApJ 948 (2023) 1]

TDE Neutrino Limits



a: 2015ApJ...809...98A (IceCube Collab.)
b: 2018ApJ...852...72V (van Velzen)
c: 2015ApJ...812...33S (Sun et al.)

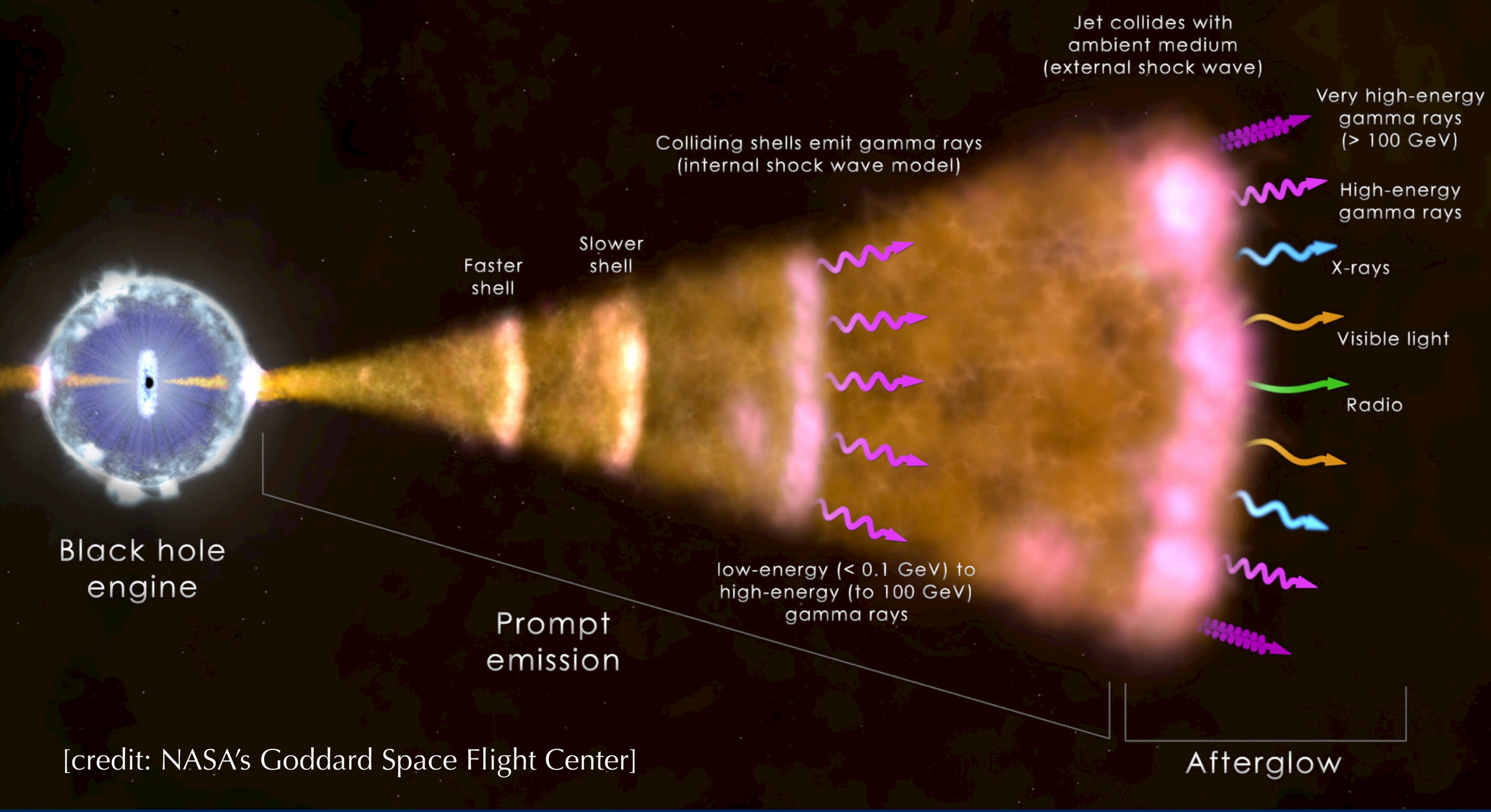
With evolution from Sun et al.[c]

[IceCube, PoS (ICRC2019) 1016]

Limits derived based on stacking of 3 jetted and 13 non-jetted TDEs.
Contribution to diffuse flux **below 2%** and **below 26%**, respectively.

Gamma-Ray Bursts

High-energy neutrino emission is predicted by cosmic ray interactions with radiation at various stages of the GRB evolution.

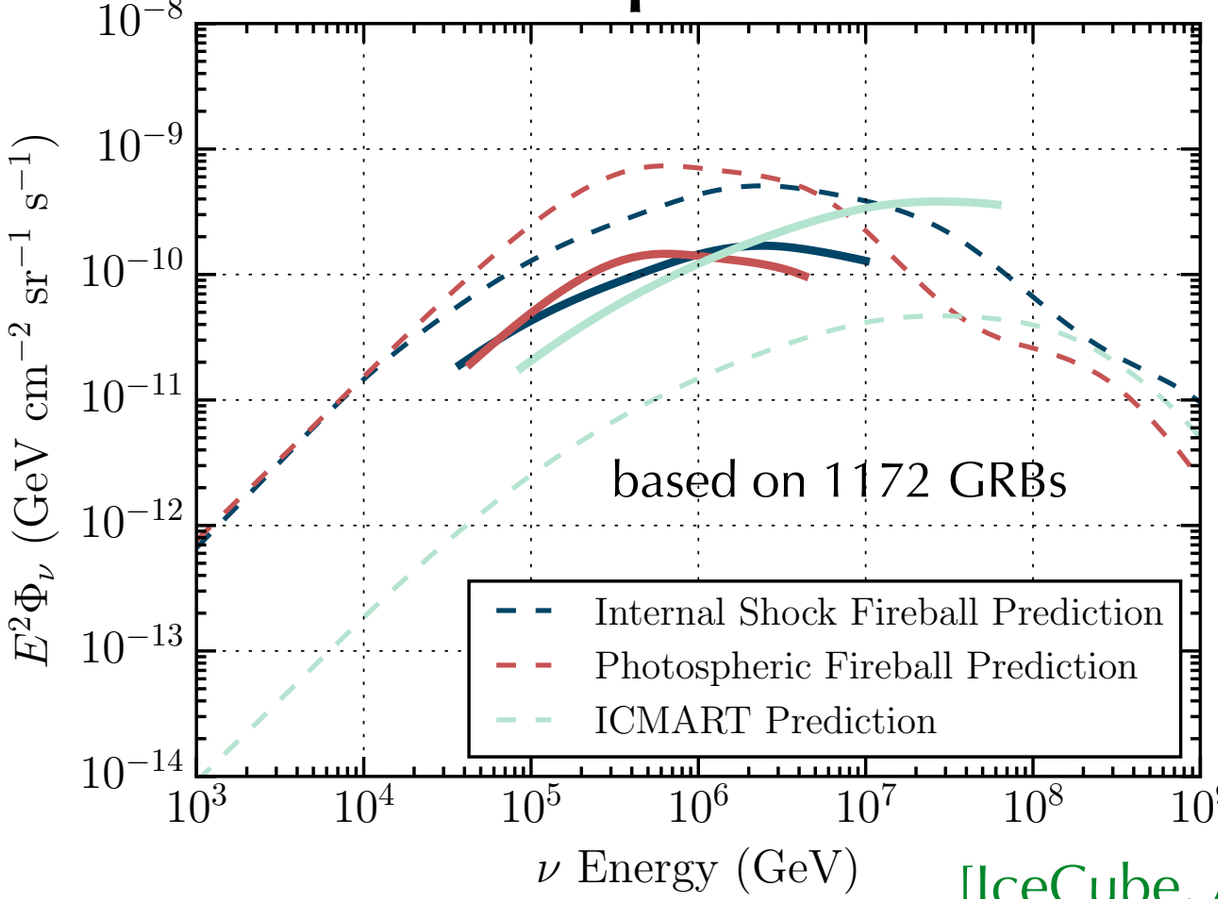


[credit: NASA's Goddard Space Flight Center]

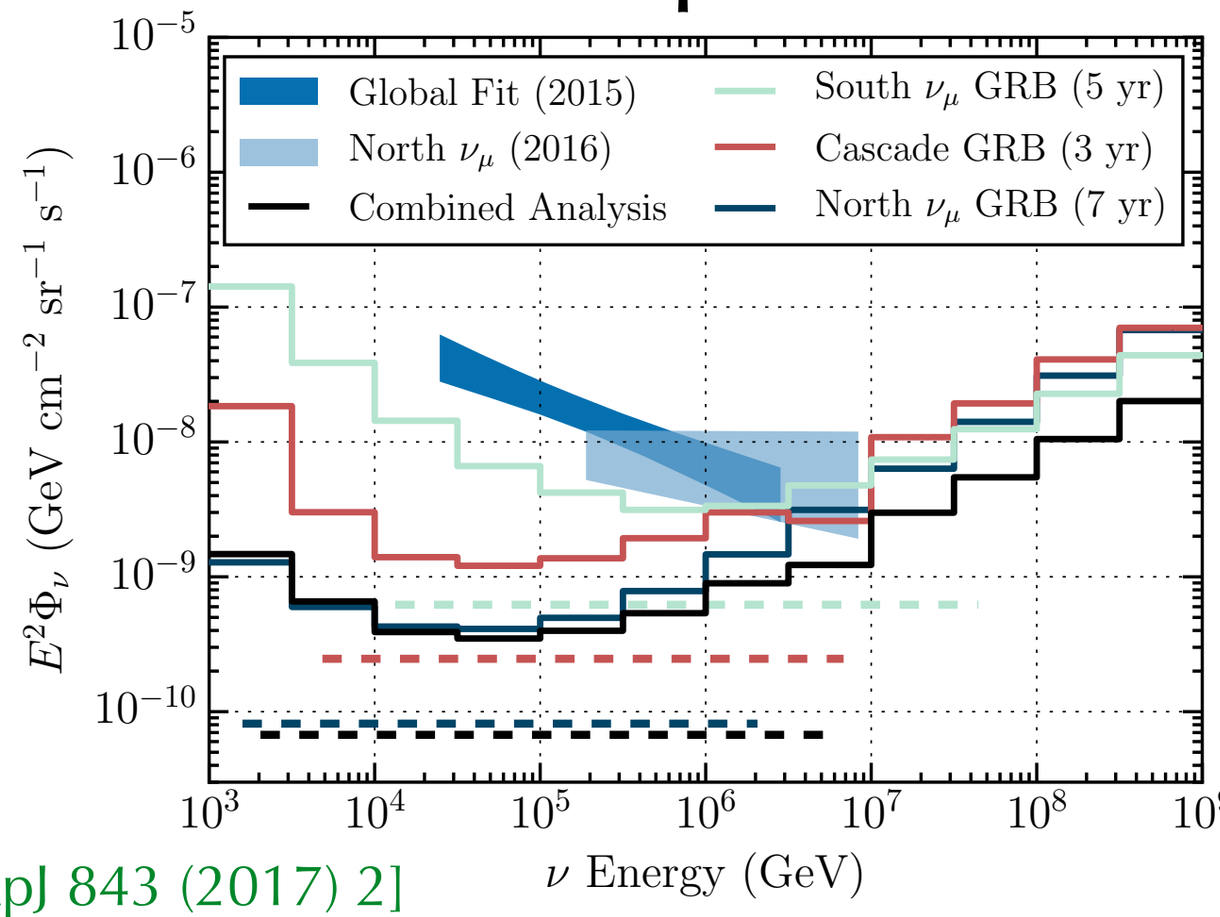
GRB Neutrino Limits

- IceCube routinely follows up on γ-ray bursts. [IceCube, ApJ 843 (2017) 2]
- Search is most sensitive to "prompt" (<100s) neutrino emission. [Waxman & Bahcall '97]
- Contribution to diffuse flux **below 1%** for "prompt" phase and **below 27%** for neutrino emission within 3h. [IceCube, ApJ 939 (2022) 2]

model-dependent limits



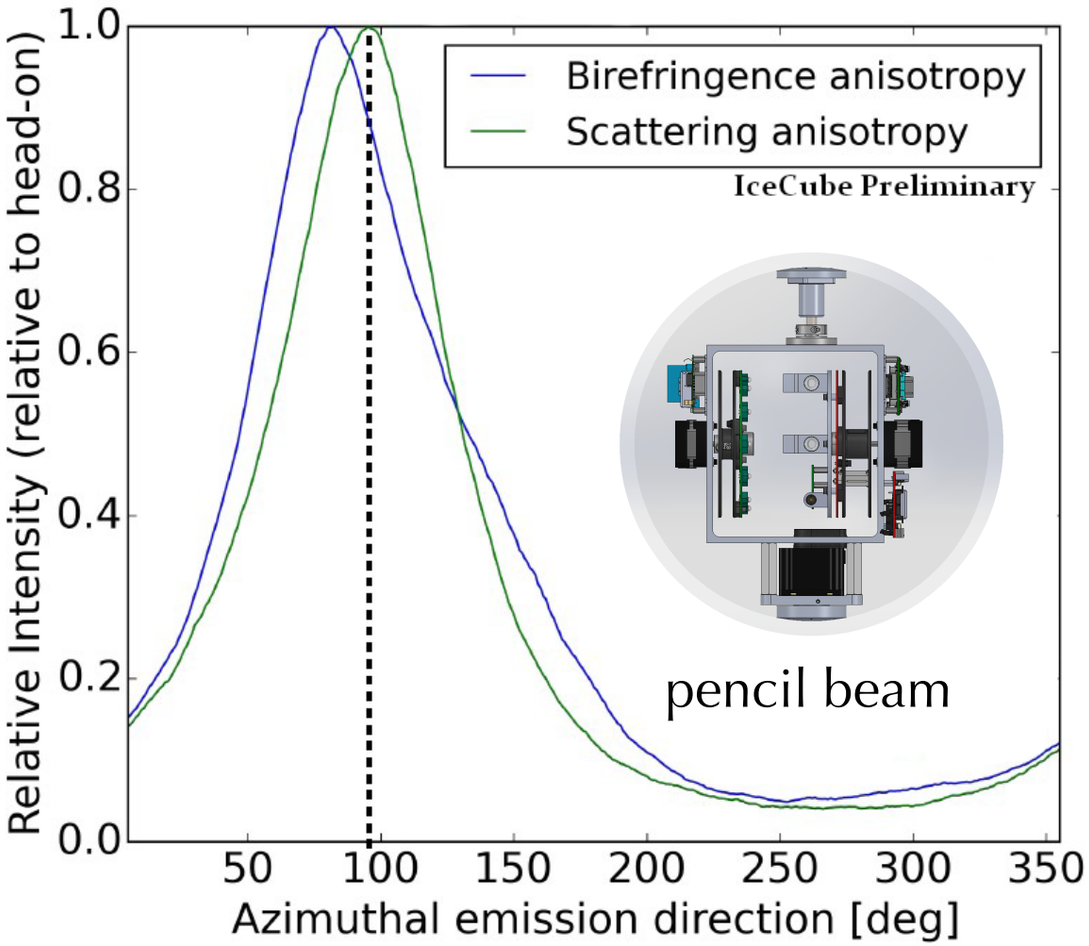
model-independent limits



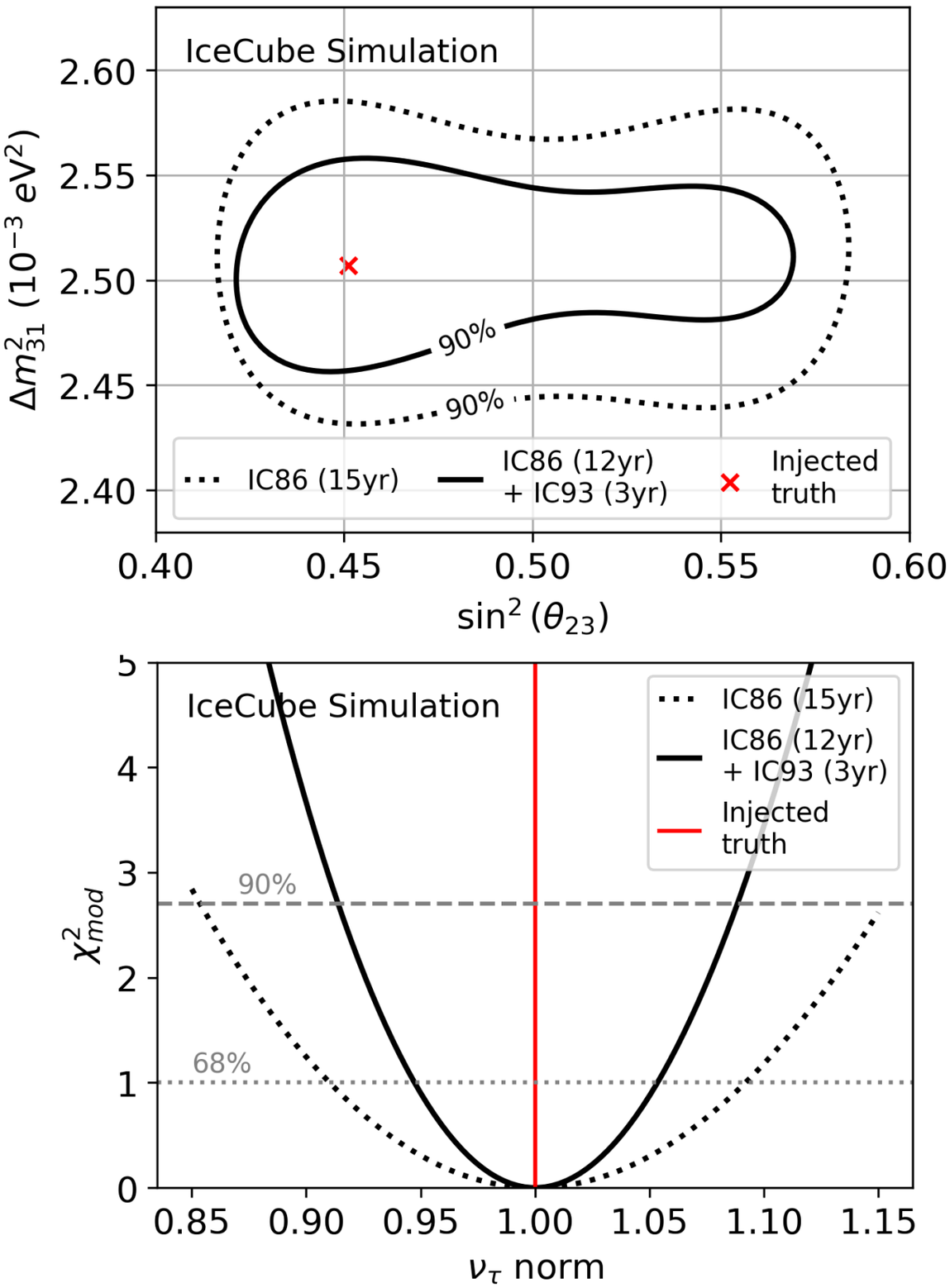
[IceCube, ApJ 843 (2017) 2]

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]

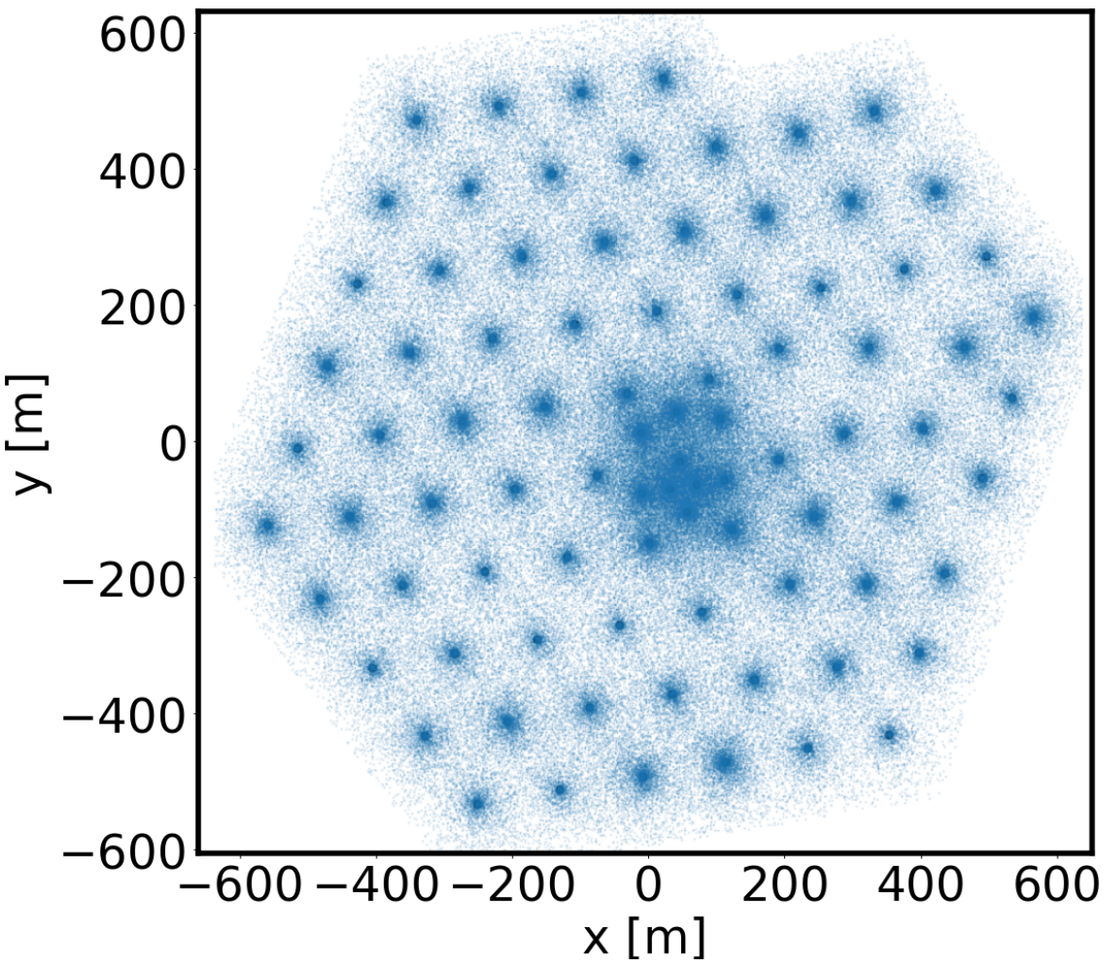


[IceCube, PoS (ICRC2019) 1031]

Supernovae in IceCube

Inverse β-decay

$$\bar{\nu}_e + p \rightarrow e^+ + n$$



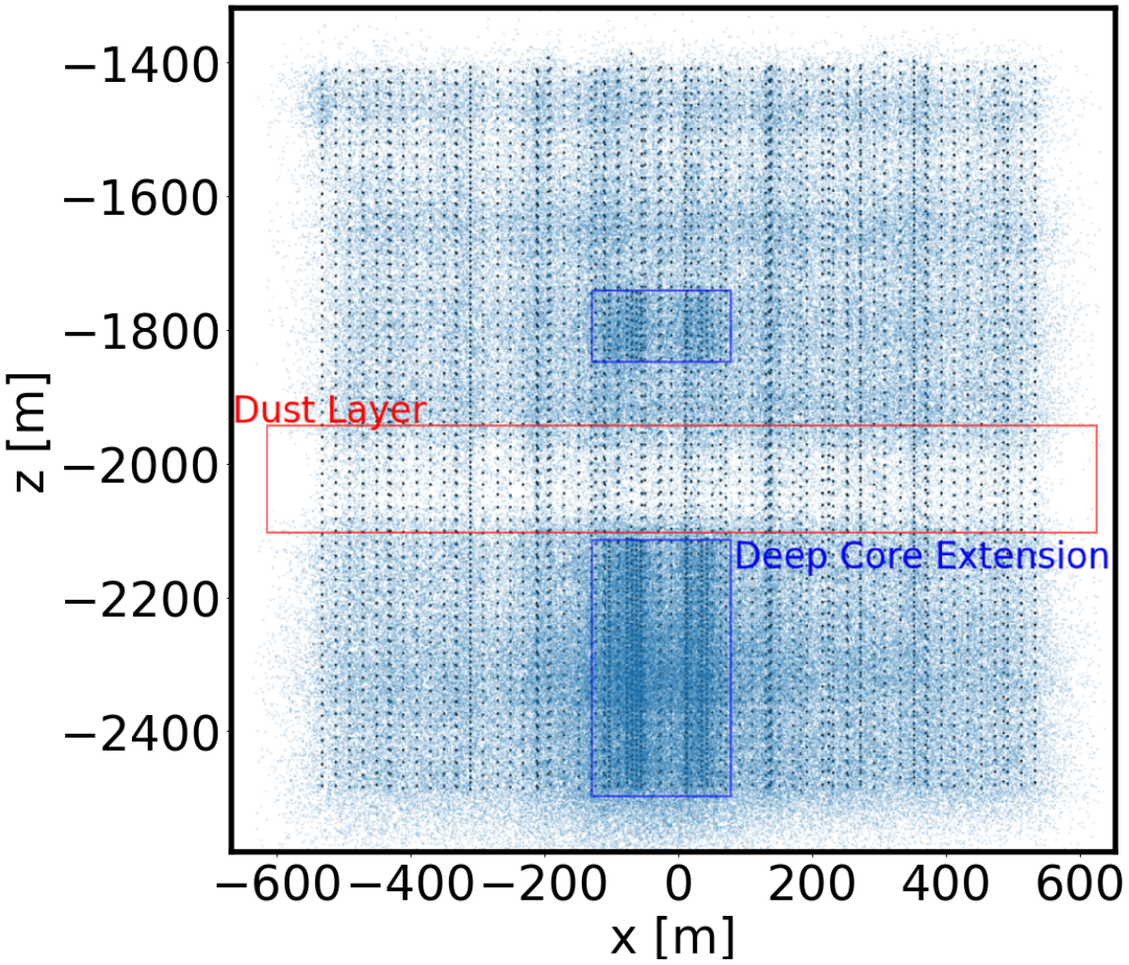
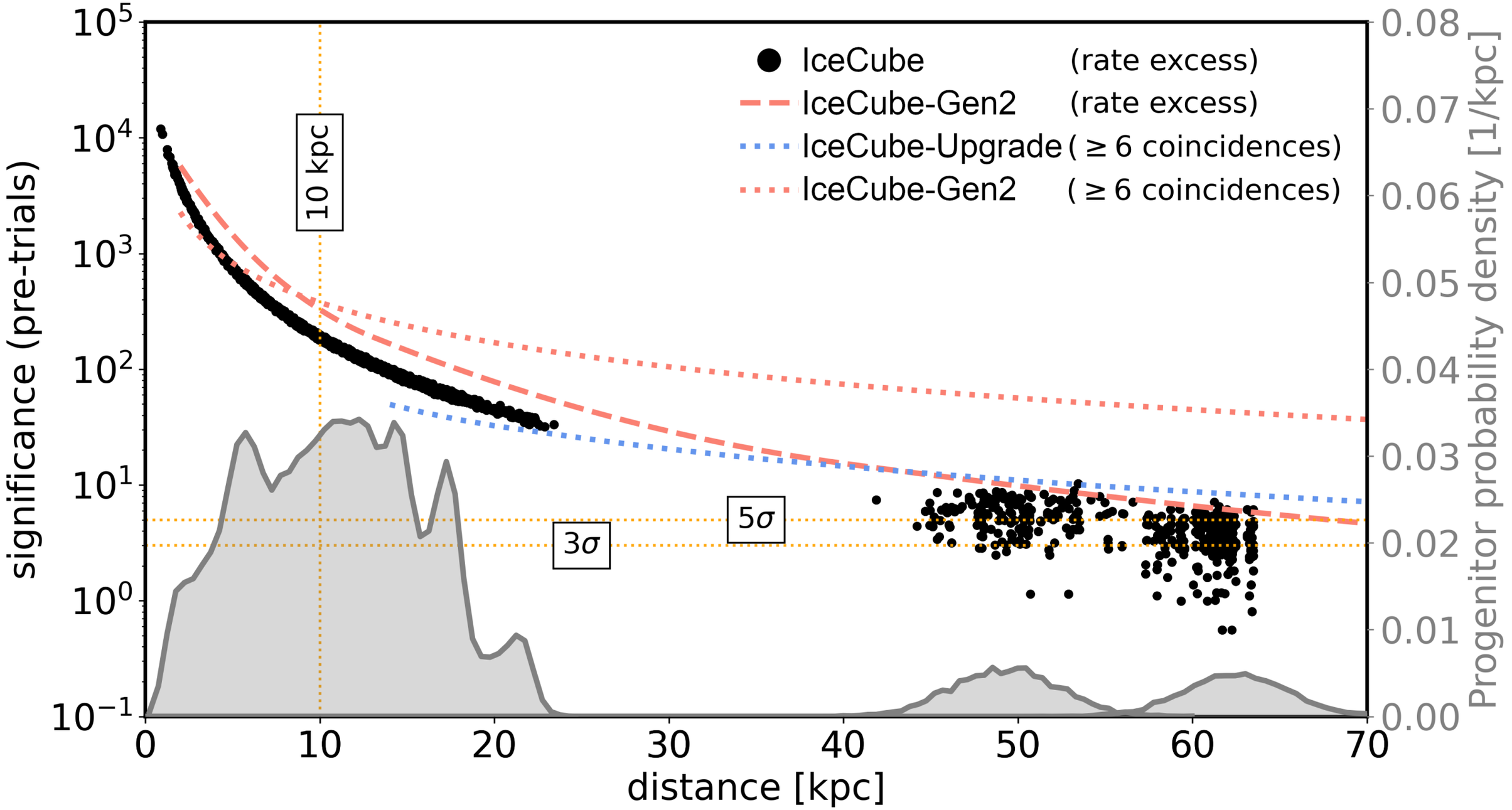


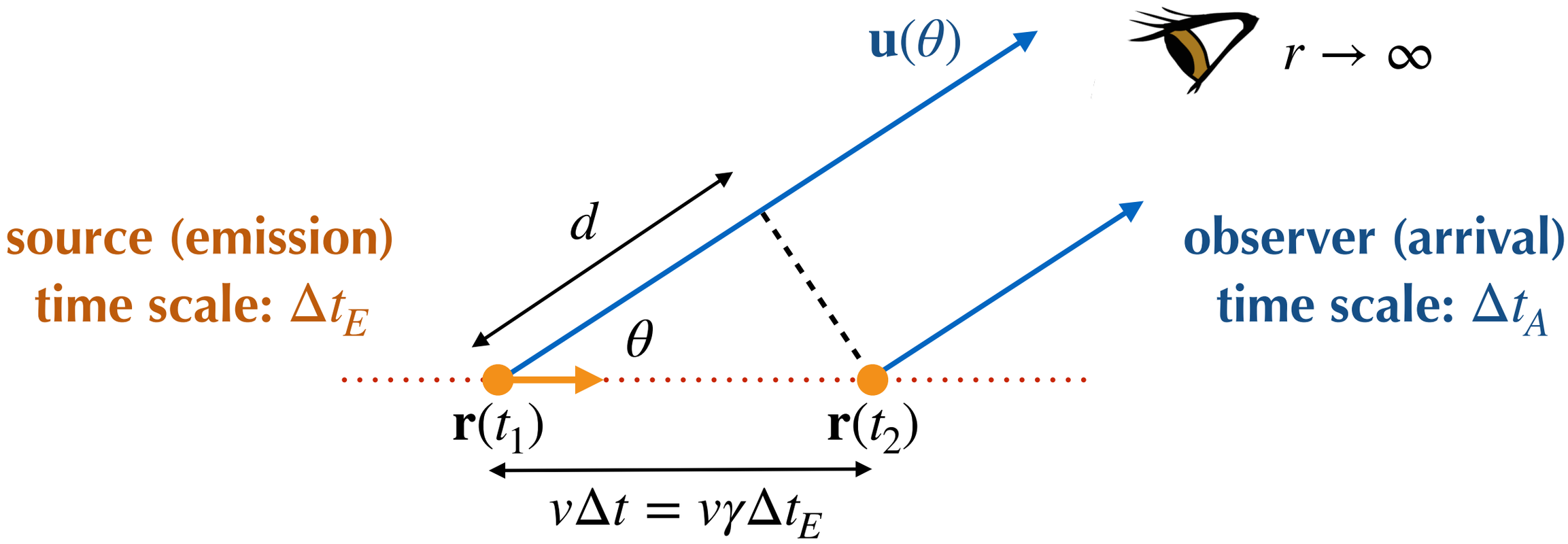
Figure 1: Top and side view of $\sim 3.4 \times 10^5$ simulated supernova ν interaction vertices registered by IceCube DOMs. The dust layer between -1950 m and -2050 m and the denser DeepCore subarray are clearly visible.

[IceCube, PoS (ICRC2019) 1177]

Core-Collapse Supernovae



Relativistic Doppler Effect



$$\Delta t_A = \Delta t - \frac{d}{c} = \Delta t - \frac{v}{c}\cos\theta\Delta t = \frac{\Delta t_E}{\delta(\beta,\theta)}$$

Doppler factor: $\delta(\beta,\theta) \equiv \dfrac{1}{\gamma(1-\beta\cos\theta)}$

Relativistic Doppler Effect

- Transformation of **(angular) frequencies and energies**:

$$\omega_A = \delta(\beta, \theta)\omega_E$$

- Transformation of **velocity u(θ)**:

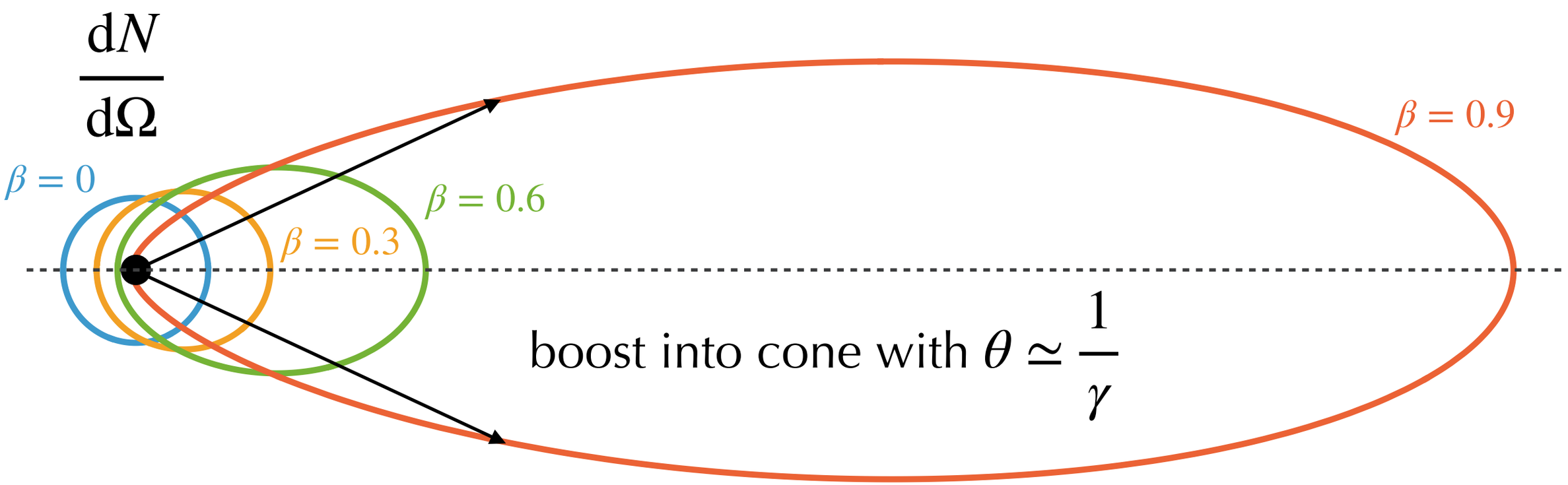
$$\Delta x_{\parallel} = \gamma(\Delta x'_{\parallel} + \beta c \Delta t') \qquad c\Delta t = \gamma(c\Delta t' + \beta \Delta x'_{\parallel})$$

$$u_{\parallel} = \frac{\Delta x_{\parallel}}{\Delta t} = \frac{u'_{\parallel} + v}{1 + v u'_{\parallel}/c^2} \quad \rightarrow \quad \cos\theta = \frac{\cos\theta' + \beta}{1 + \beta\cos\theta'}$$

- Gives us relation between **observation and emission angles**:

$$\frac{\mathrm{d}\cos\theta}{\mathrm{d}\cos\theta'} = \delta^2(-\beta, \theta') = \frac{1}{\delta^2(\beta, \theta)}$$

Doppler-Boosted Emission



consider isotropic emission in **rest frame**: $\dfrac{\mathrm{d}N}{\mathrm{d}\Omega'} = \dfrac{1}{4\pi}$

emission in **observer frame**: $\dfrac{\mathrm{d}N}{\mathrm{d}\Omega} = \dfrac{\mathrm{d}N}{\mathrm{d}\Omega'}\dfrac{\mathrm{d}\Omega'}{\mathrm{d}\Omega} = \dfrac{\delta^2(\beta,\theta)}{4\pi}$