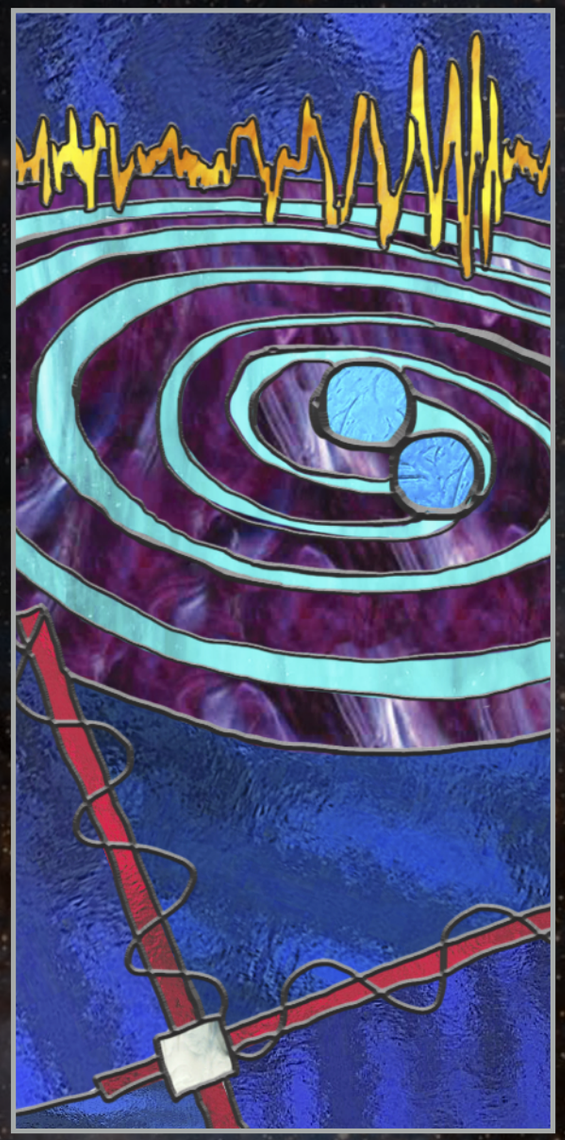
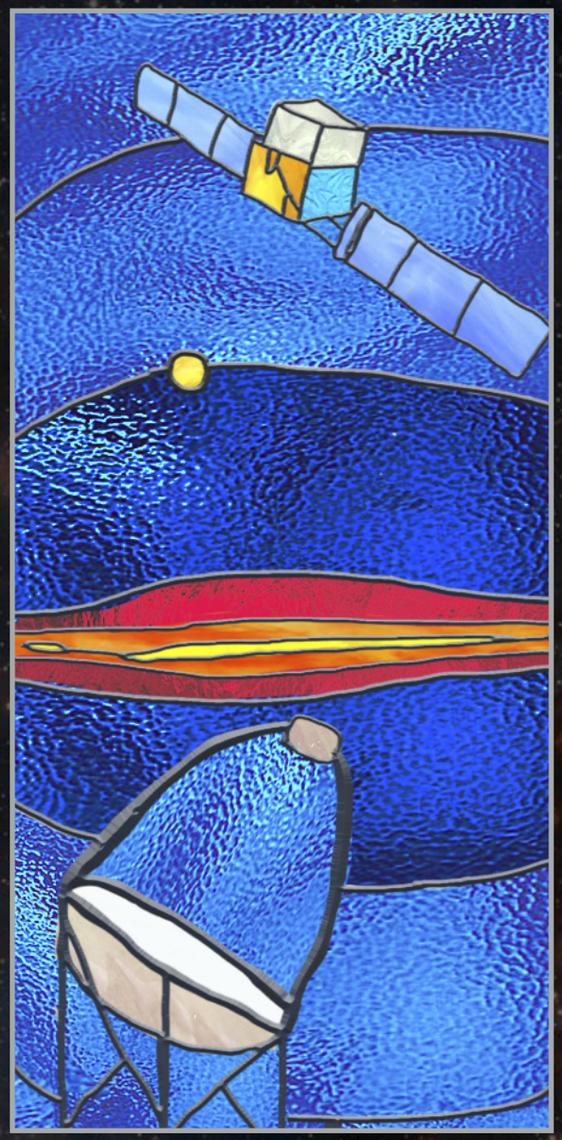




Lecture 3: *Multi-Messenger Astronomy*

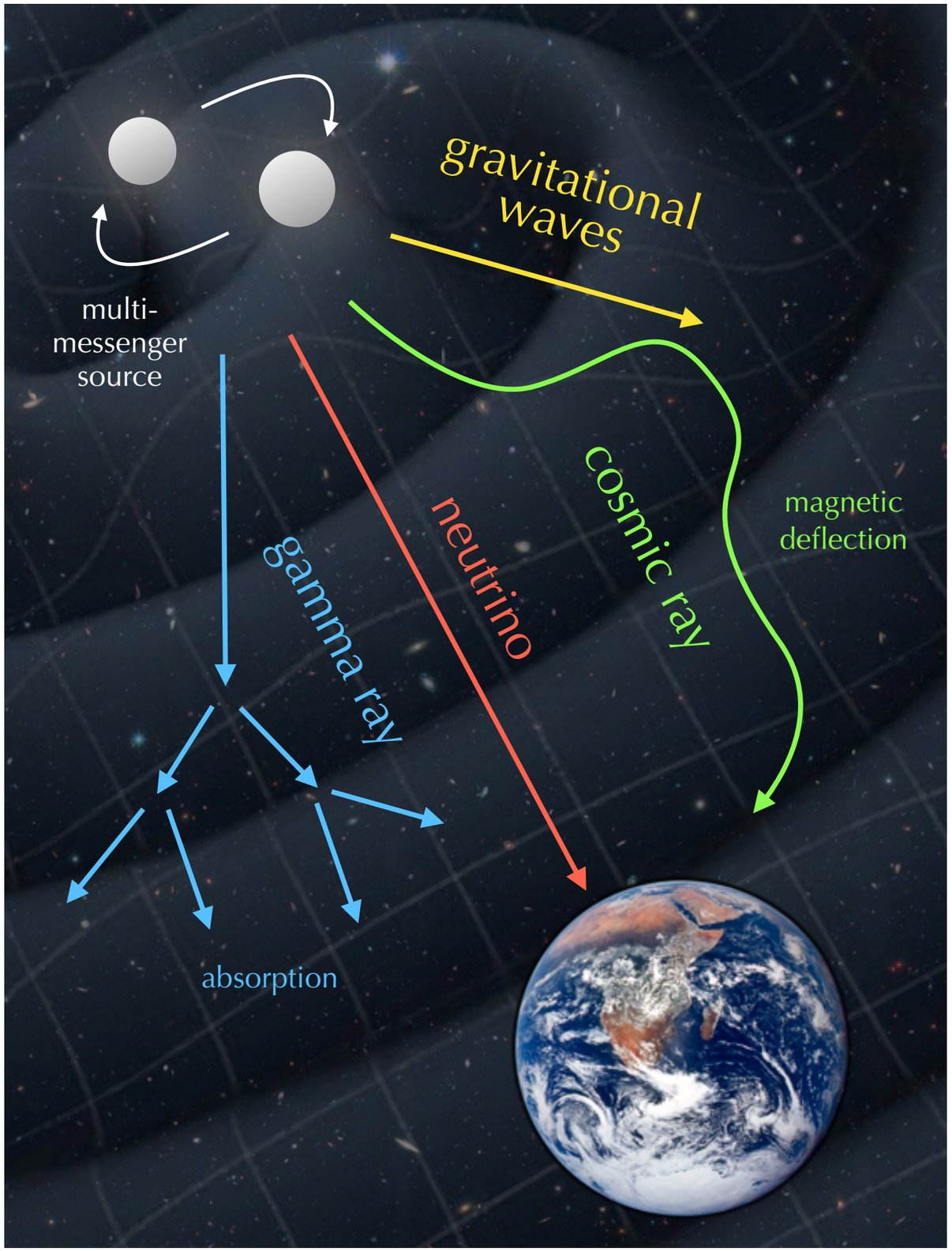
Markus Ahlers
Niels Bohr Institute

2nd UNDARK School 2026

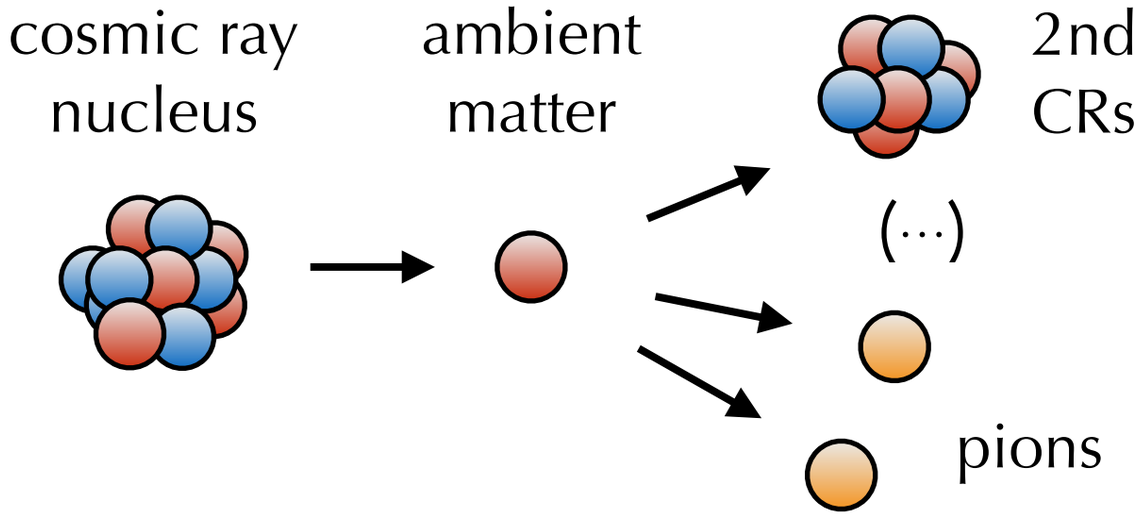
CARLSBERG FOUNDATION

KØBENHAVNS UNIVERSITET

Multi-Messenger Astronomy



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



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:

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

- **Charged-to-neutral pion ratio** K_π:

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

Average Neutrino Energies

- Average energy fraction of pions from CR nucleons:

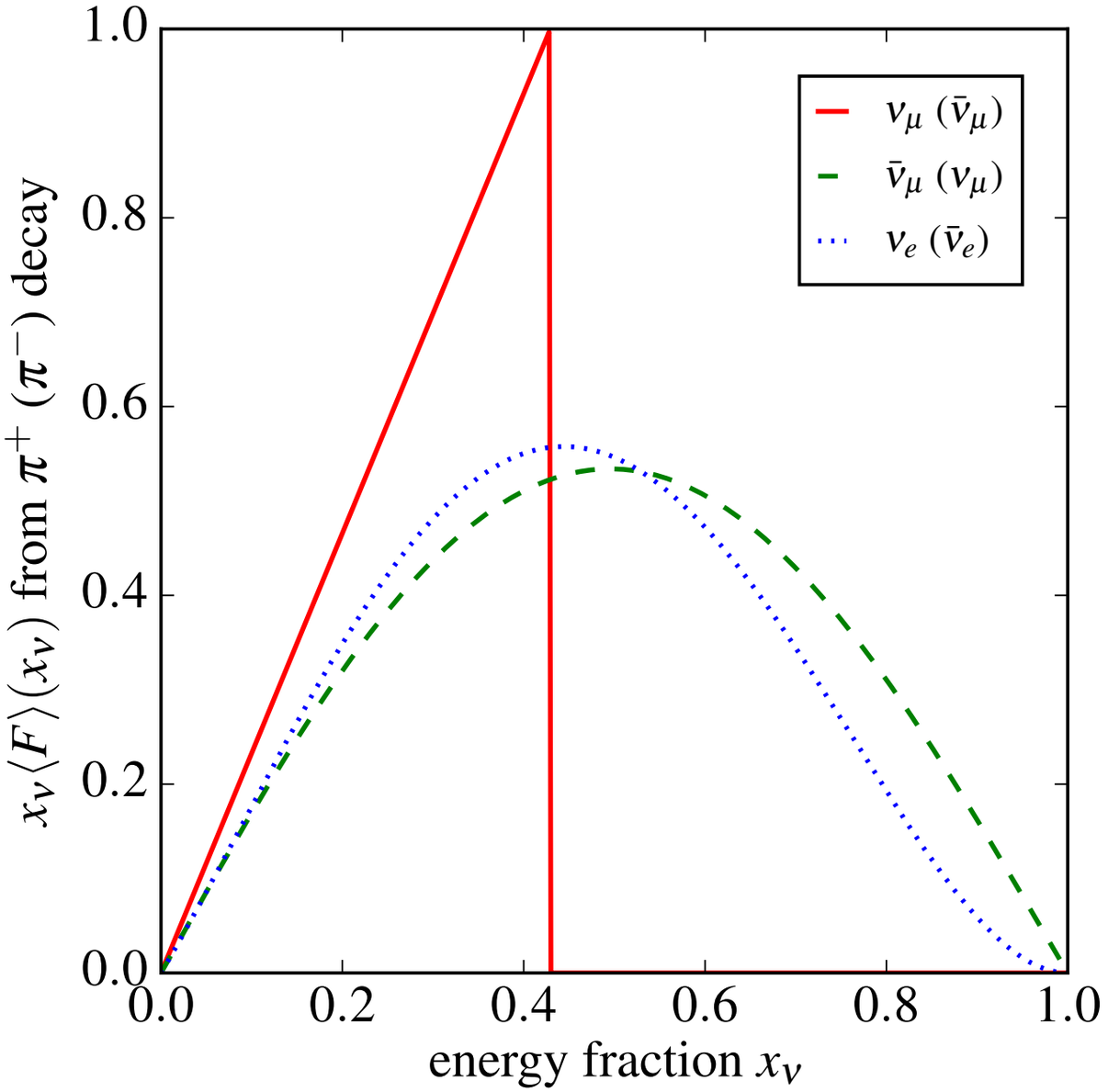
$$\langle x_\pi \rangle = \kappa_\pi \simeq 20\,\%$$

- 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]

$$\pi^+ \to \mu^+ + \nu_\mu$$

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

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:

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

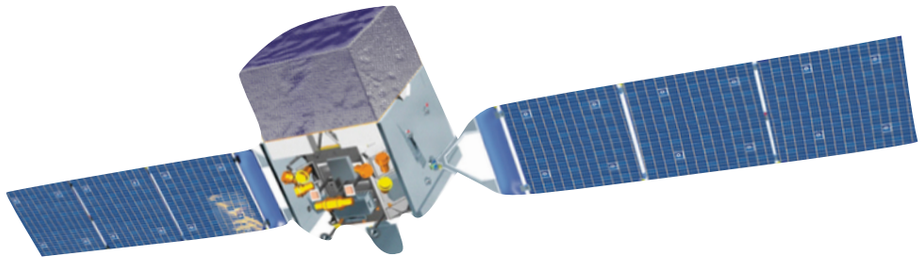
$$\pi^0 \to \gamma + \gamma$$

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

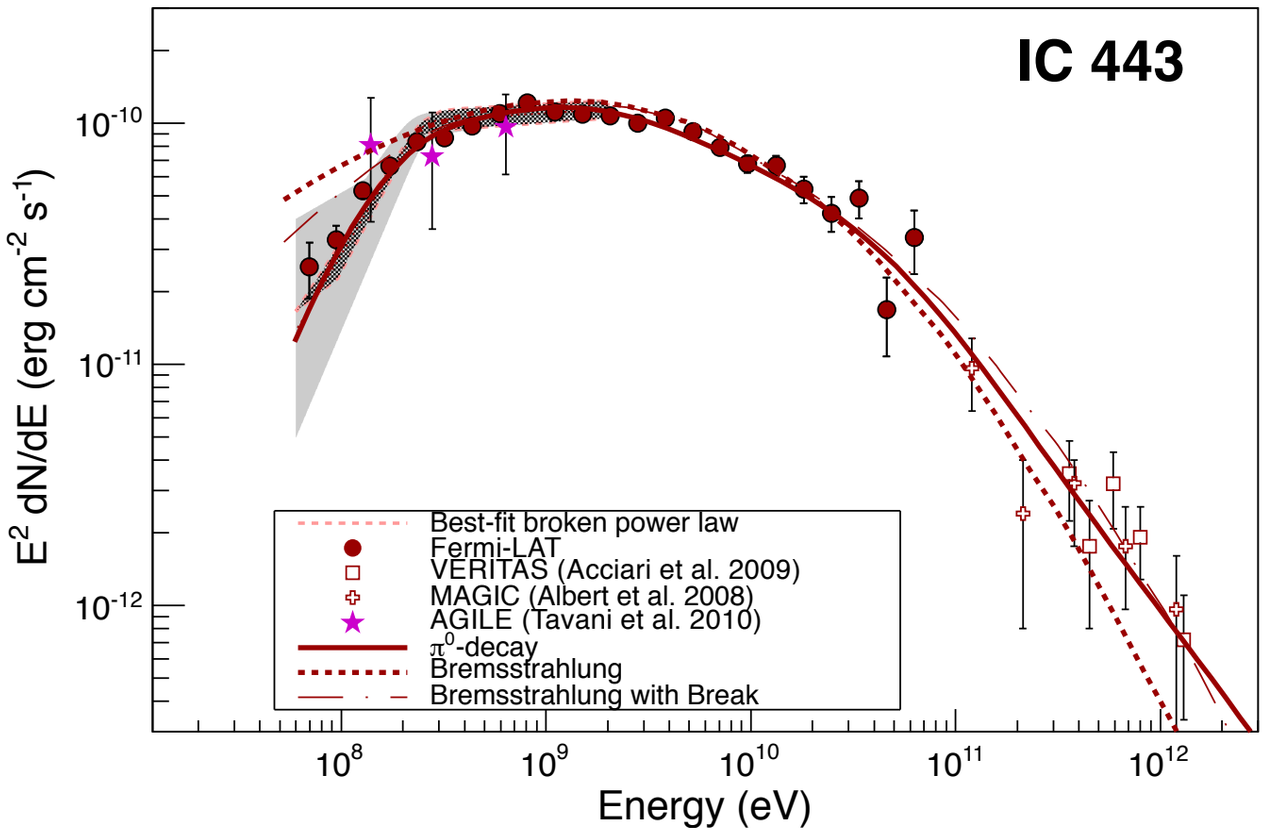
$$\frac{1}{3}\sum_{\alpha} E_\nu^2 Q_{\nu_\alpha}(E_\nu) \simeq \frac{1}{4} K_\pi \left[E_\gamma^2 Q_\gamma(E_\gamma)\right]_{E_\gamma \simeq 2E_\nu}$$

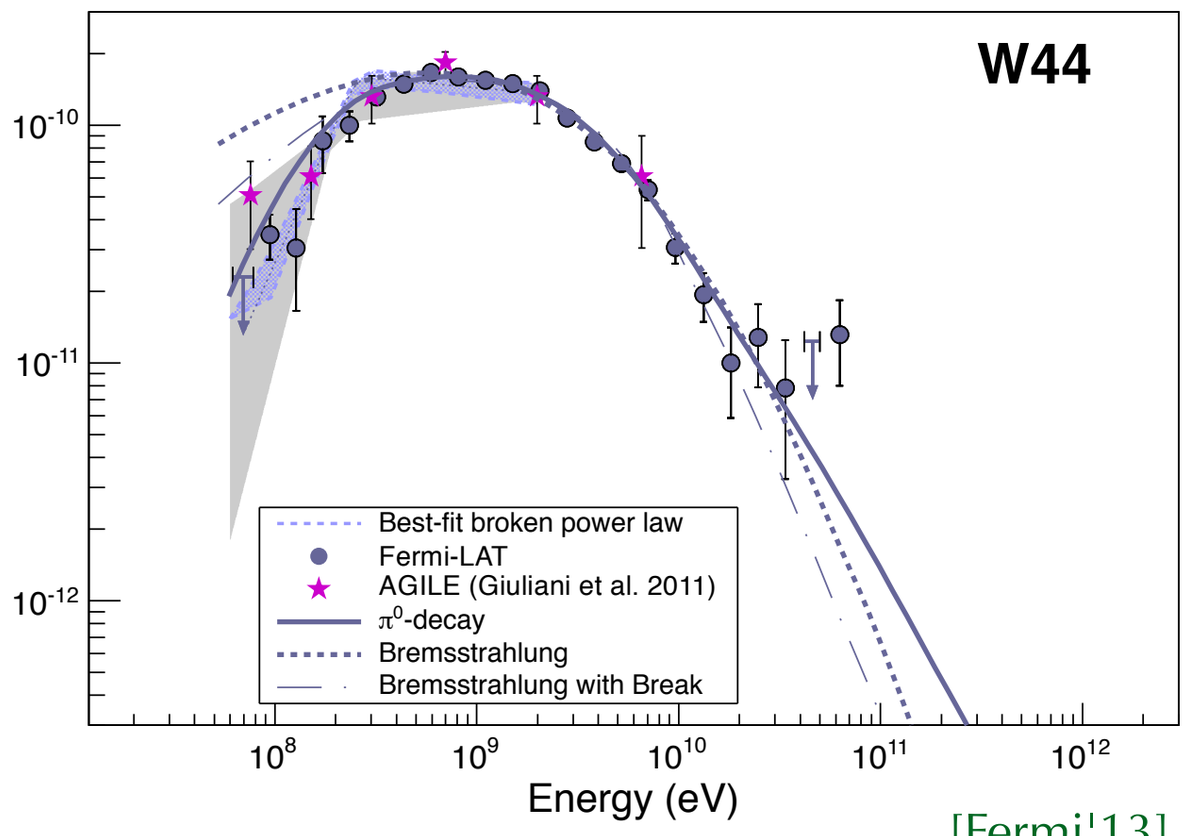
- ***Note:*** Observable γ-ray emission is attenuated in sources and, in particular, in extragalactic background radiation.

Indirect Evidence



gamma-ray spectra observed from two Galactic supernova remnants

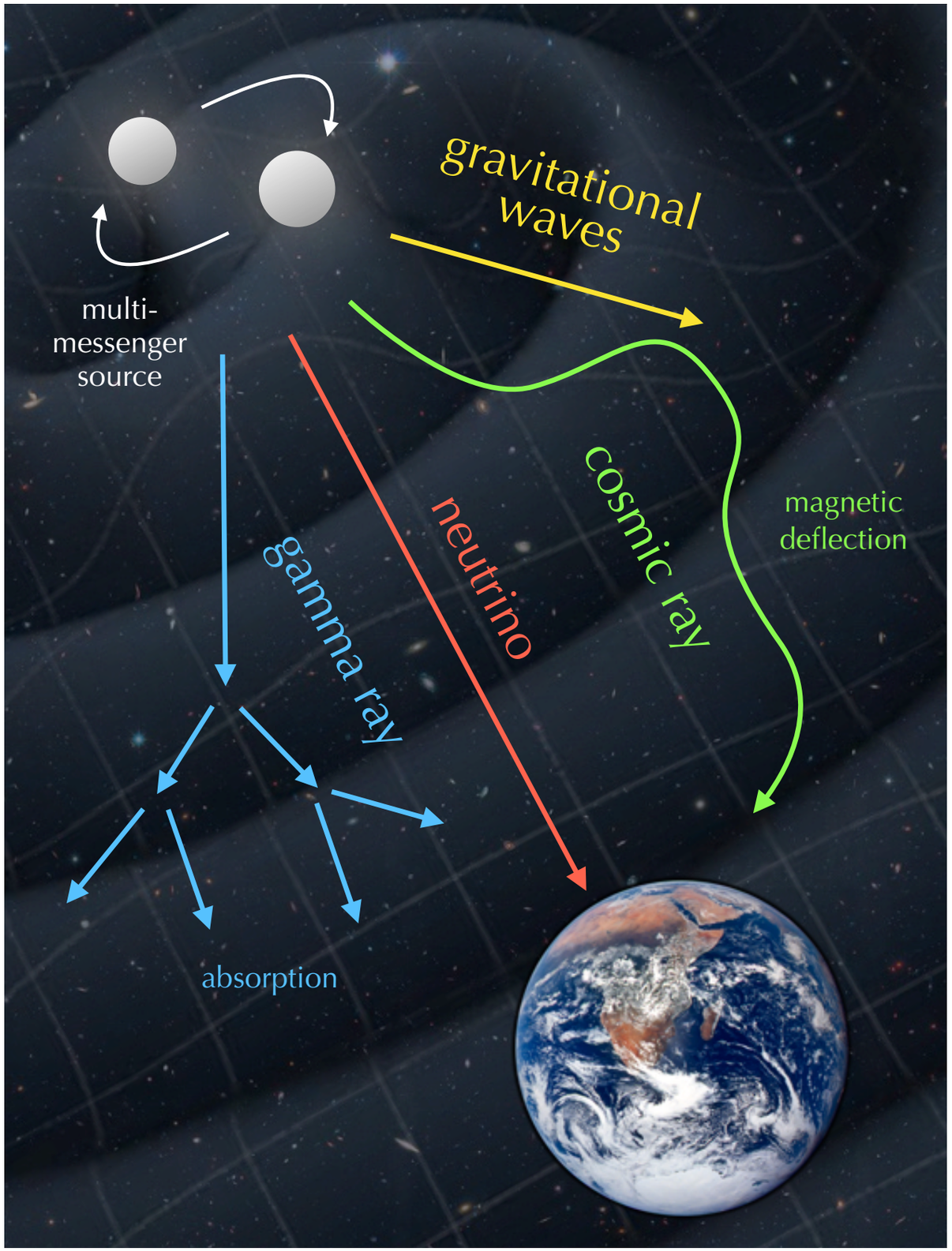




[Fermi'13]

- π^0 production in CR collisions with gas: $p + p \to \pi^0 + X$.
- γ-ray in the rest-frame of the pion takes $E^*_\gamma = m_\pi/2 \simeq 67.5\,\mathrm{MeV}$.
- Kinematics of the interaction produces a break at $E_\gamma \simeq 200\,\mathrm{MeV}$.

Neutrino Astronomy



Unique abilities of **cosmic neutrinos**:

no deflection in magnetic fields
(unlike cosmic rays)

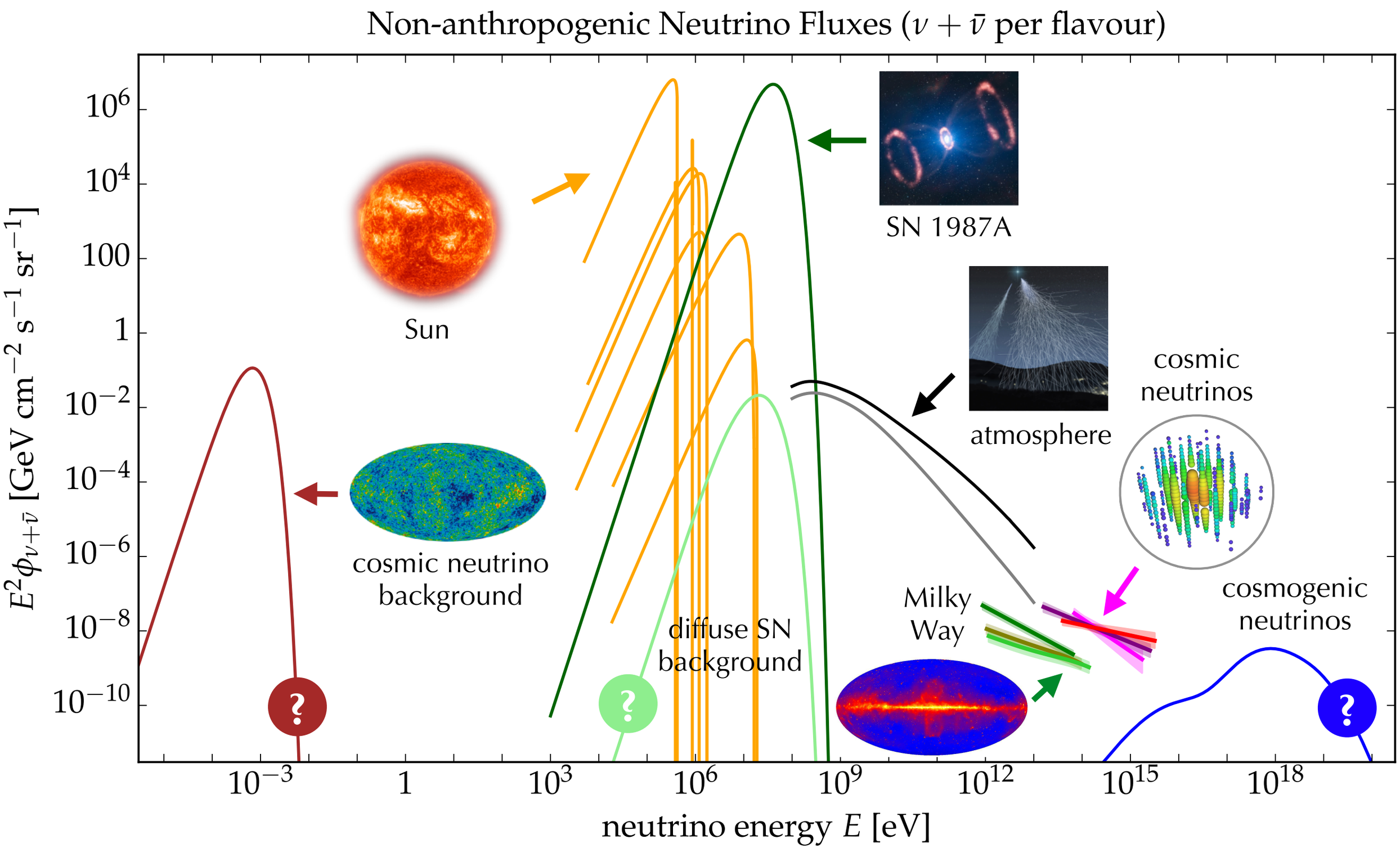
coincident with
photons and gravitational waves

no absorption in cosmic backgrounds
(unlike gamma-rays)

smoking-gun of
unknown sources of cosmic rays

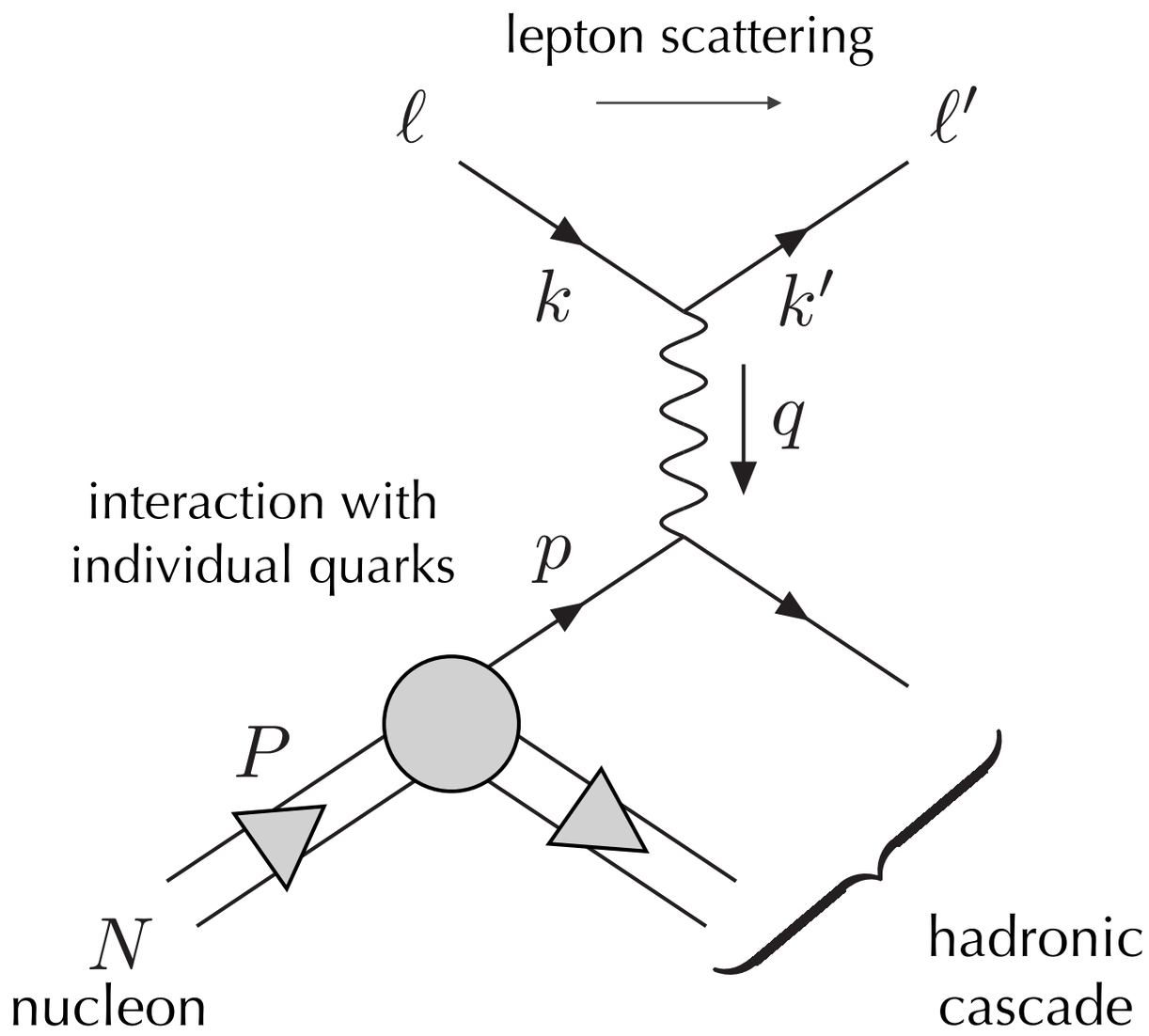
BUT, very difficult to detect!

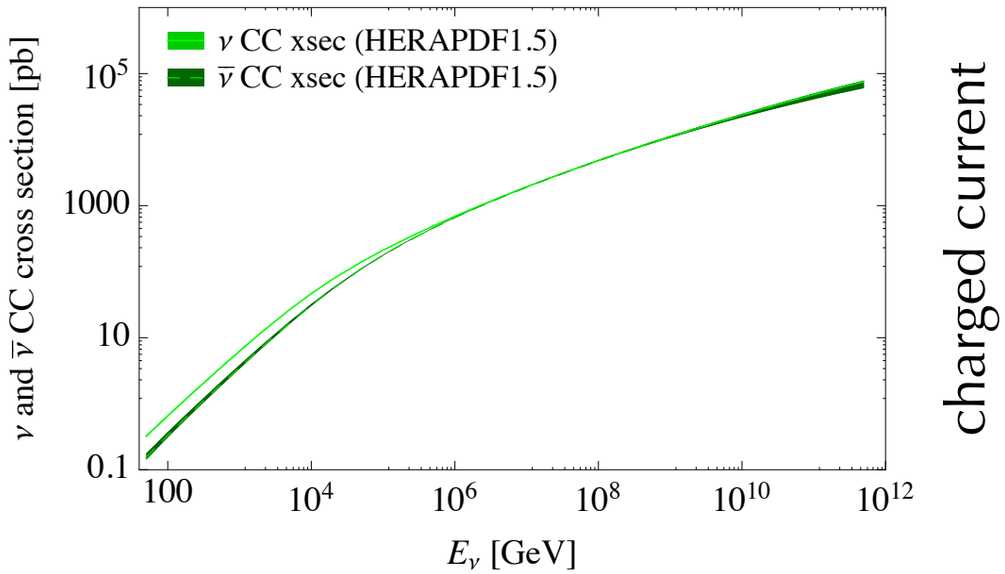
Astrophysical Neutrinos

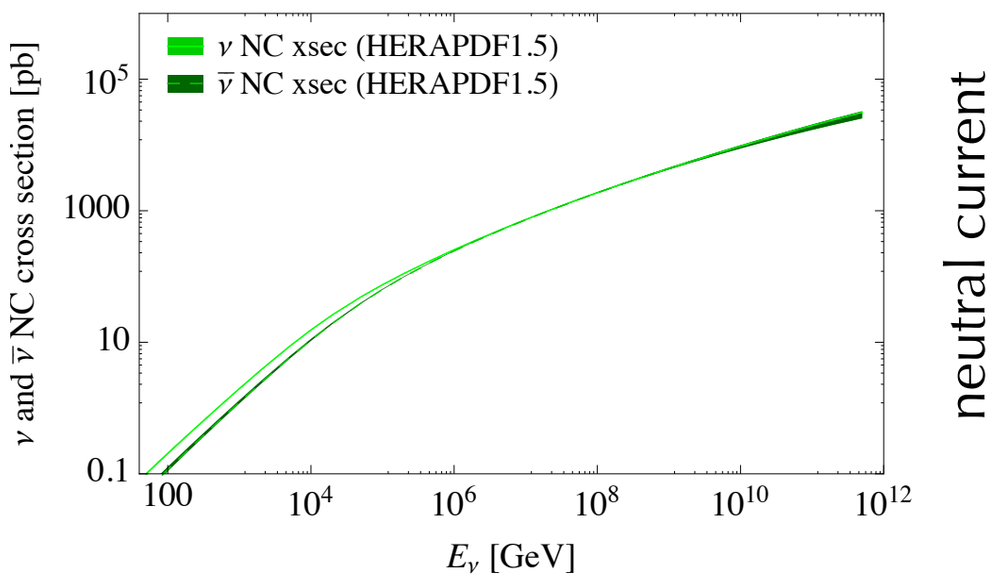


Neutrino Interactions

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

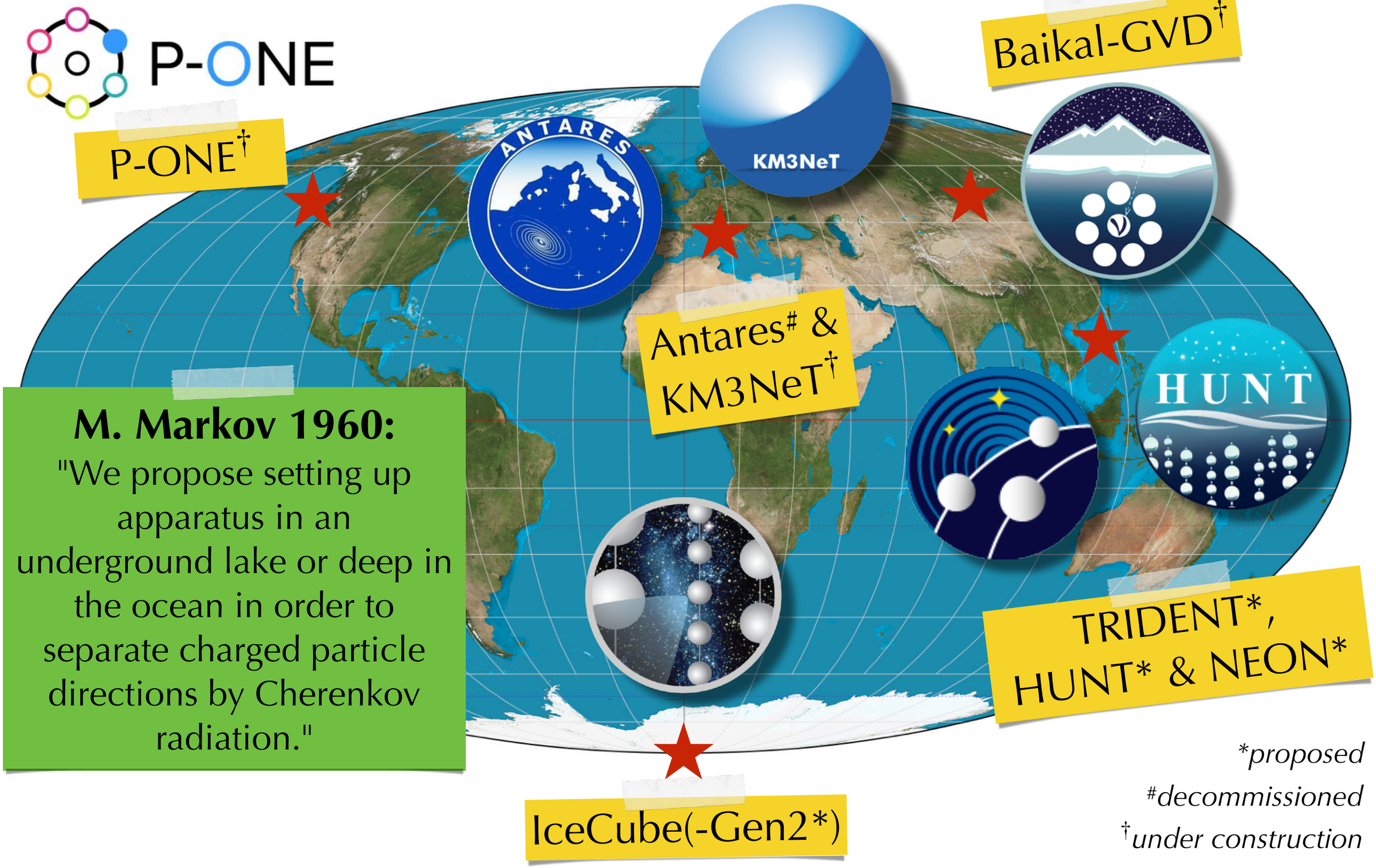
cross section: $\sigma_{\nu\mathrm{p}} \simeq 10^{-8}\sigma_{\mathrm{pp}} \simeq 10^{-33}\mathrm{cm}^2$

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

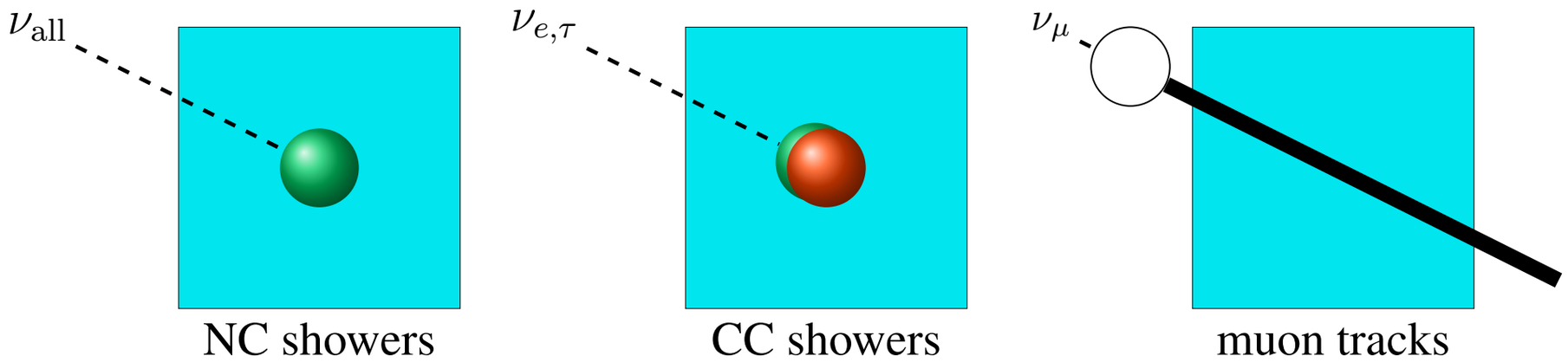


M. Markov 1960:
"We propose setting up apparatus in an underground lake or deep in the ocean in order to separate charged particle directions by Cherenkov radiation."

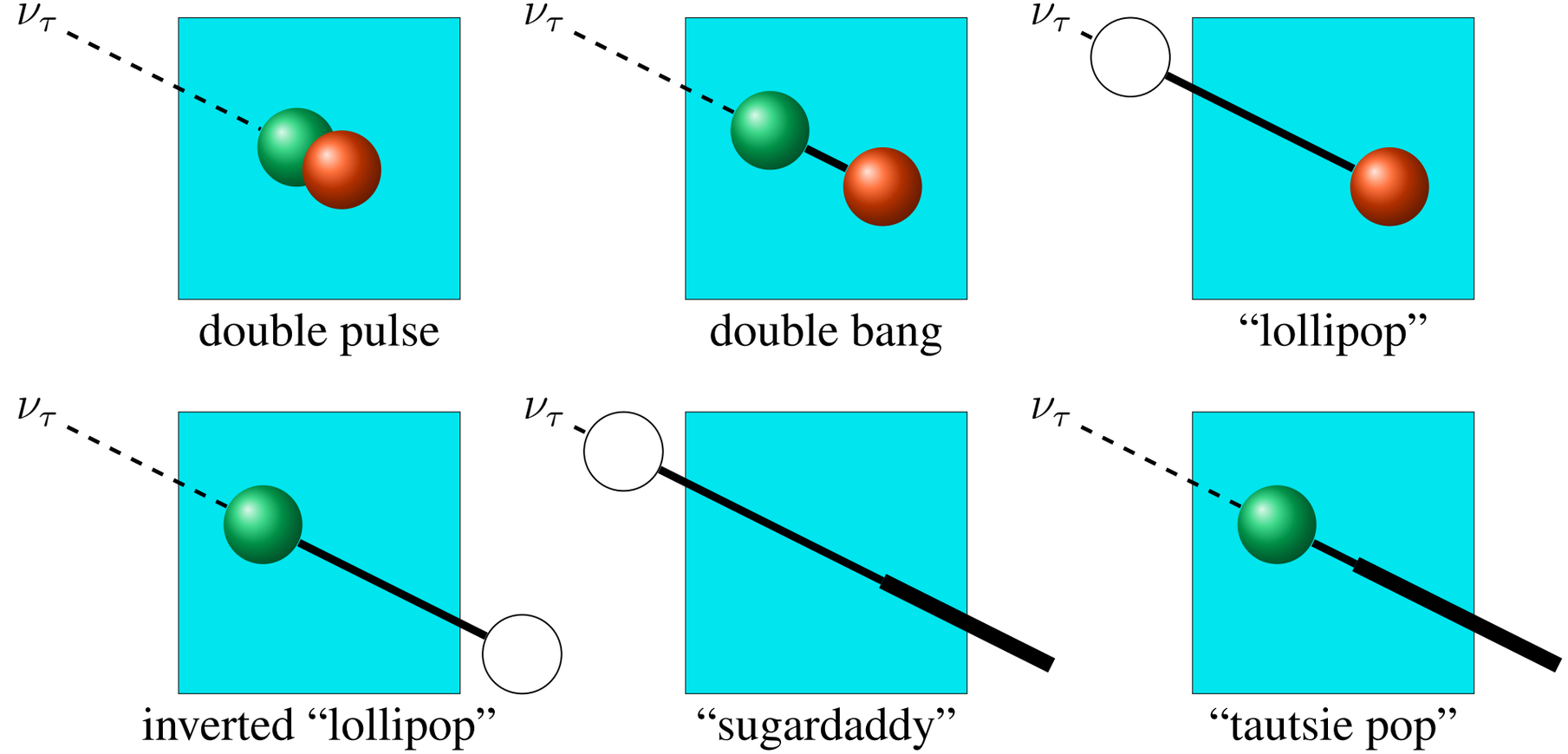
**proposed*
#decommissioned
†under construction

Optical Cherenkov Signals

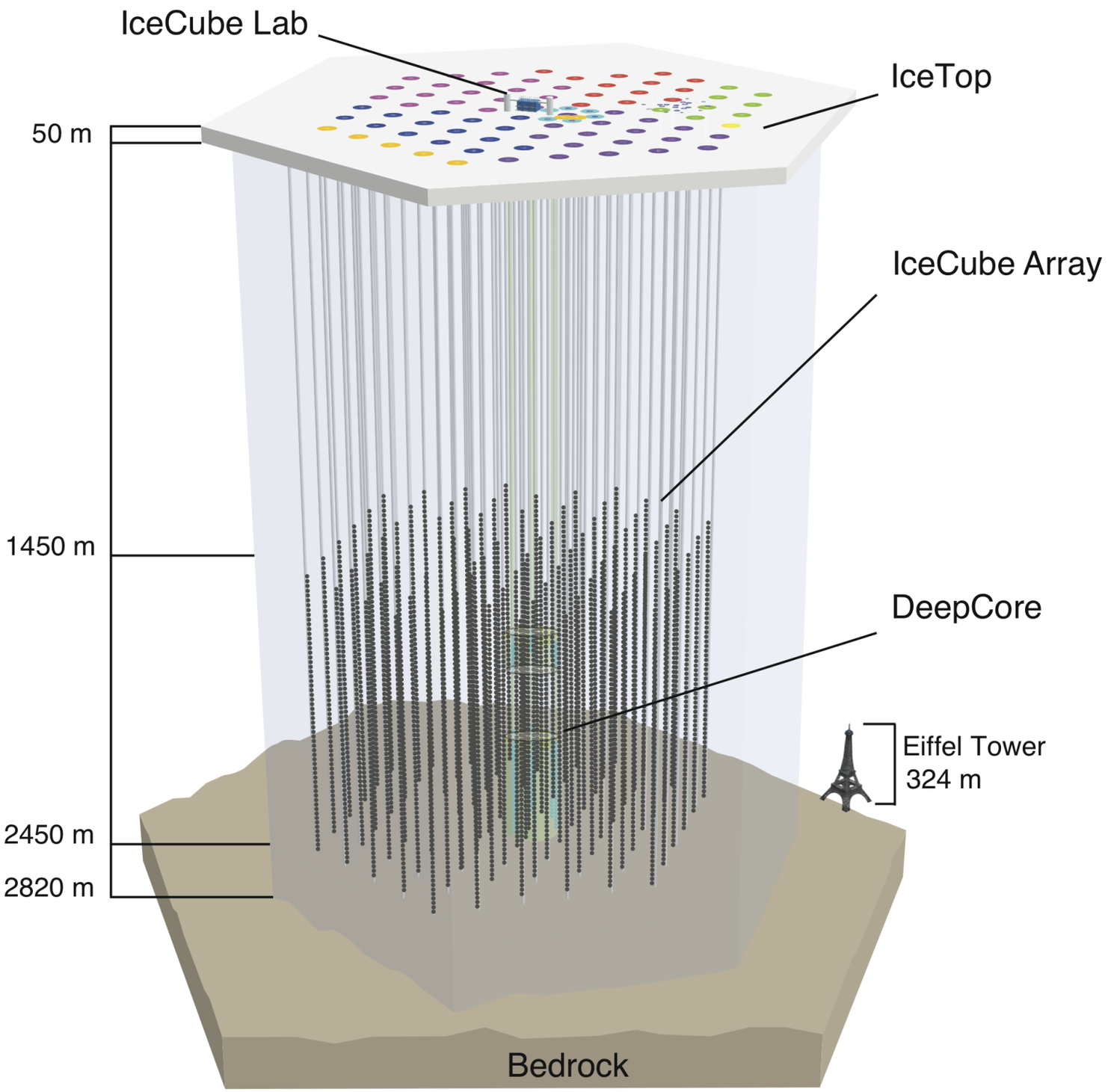
"cascades"
&
"tracks"



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

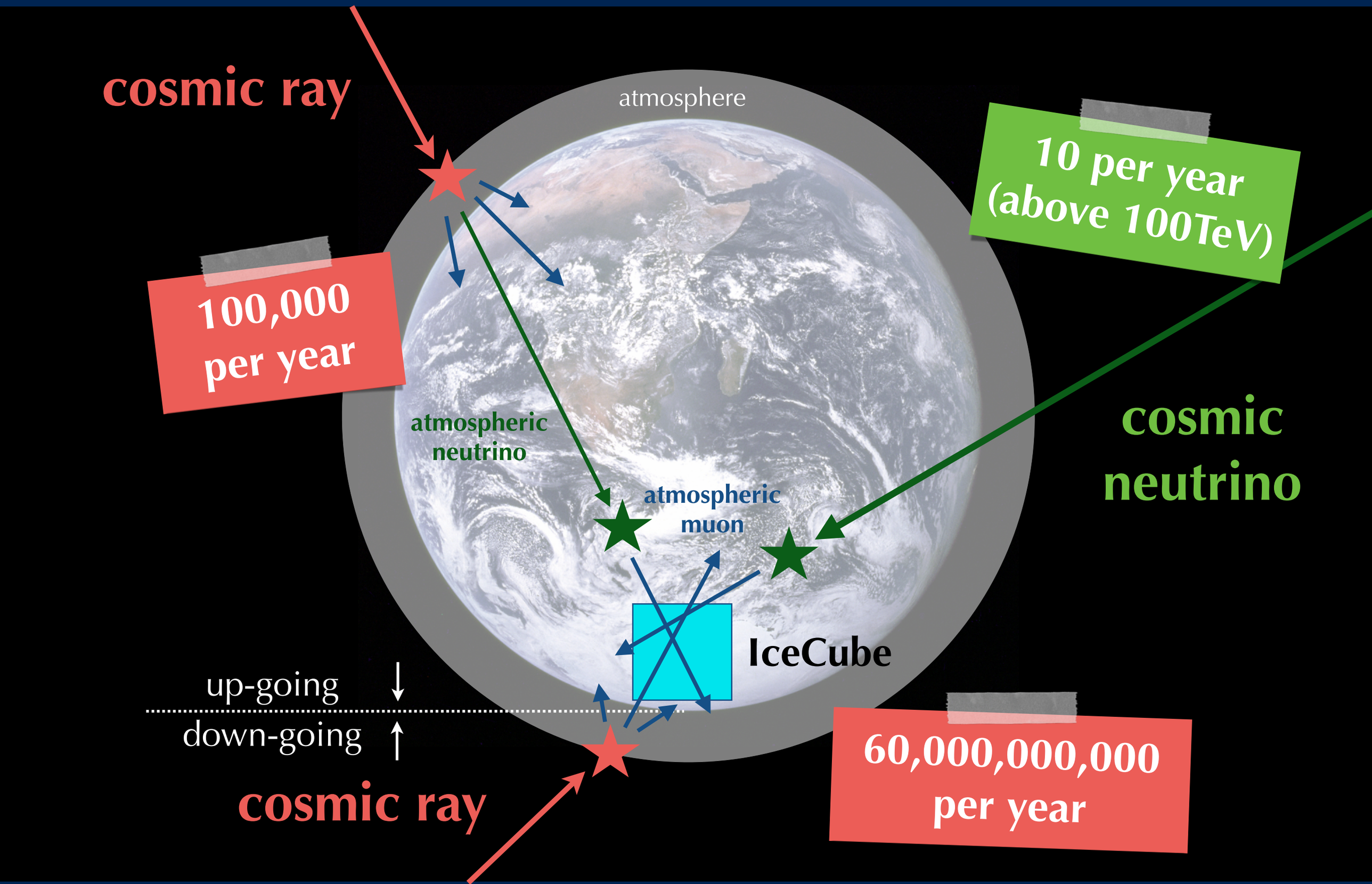
Constant rain of Earth penetrating muons (μ) and neutrinos (ν) from cosmic ray collisions with the atmosphere

$$\pi^- \to \mu^- + \bar{\nu}_\mu \; (\tau \simeq 0.26\text{ns})$$

ν

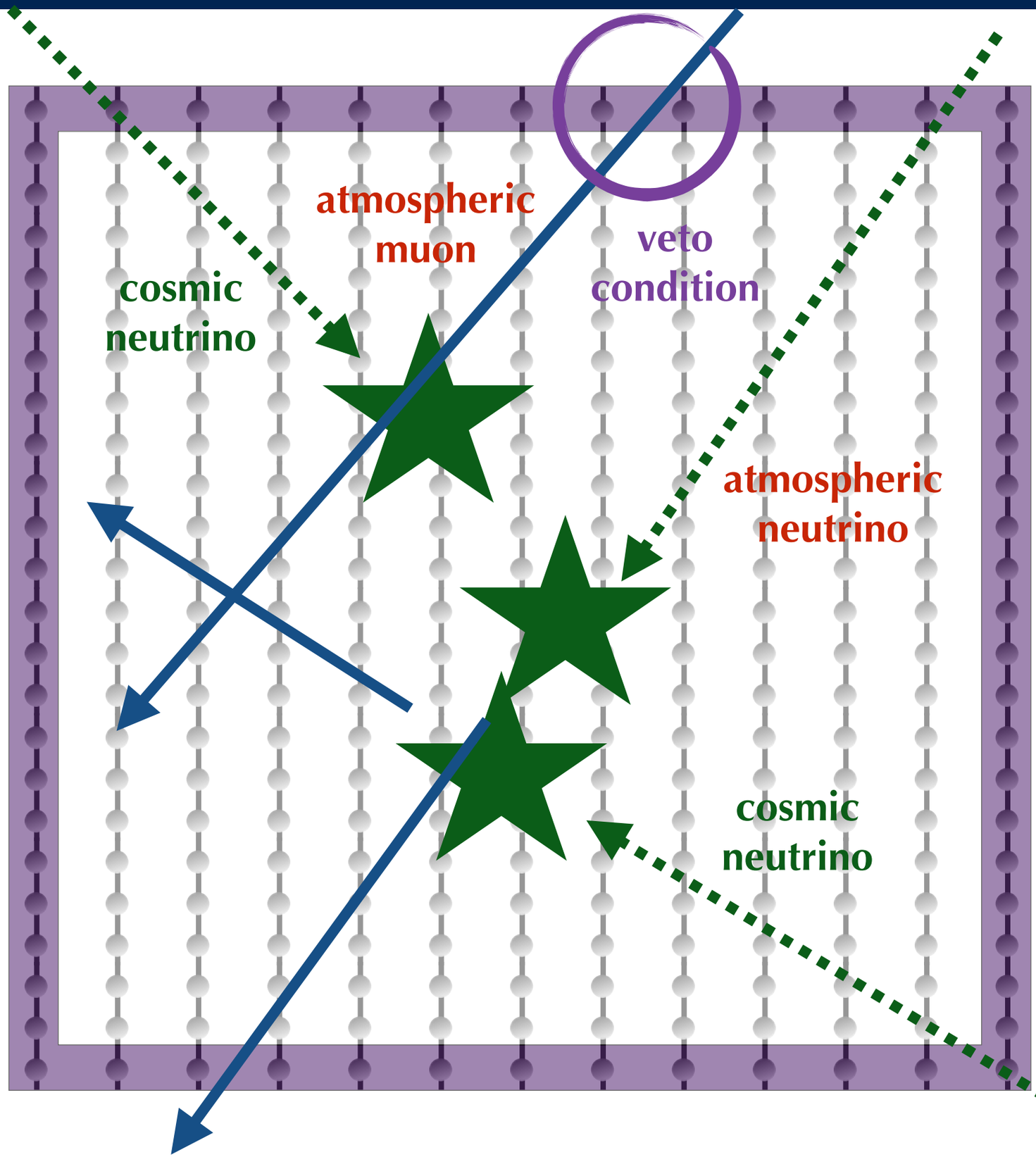
μ

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

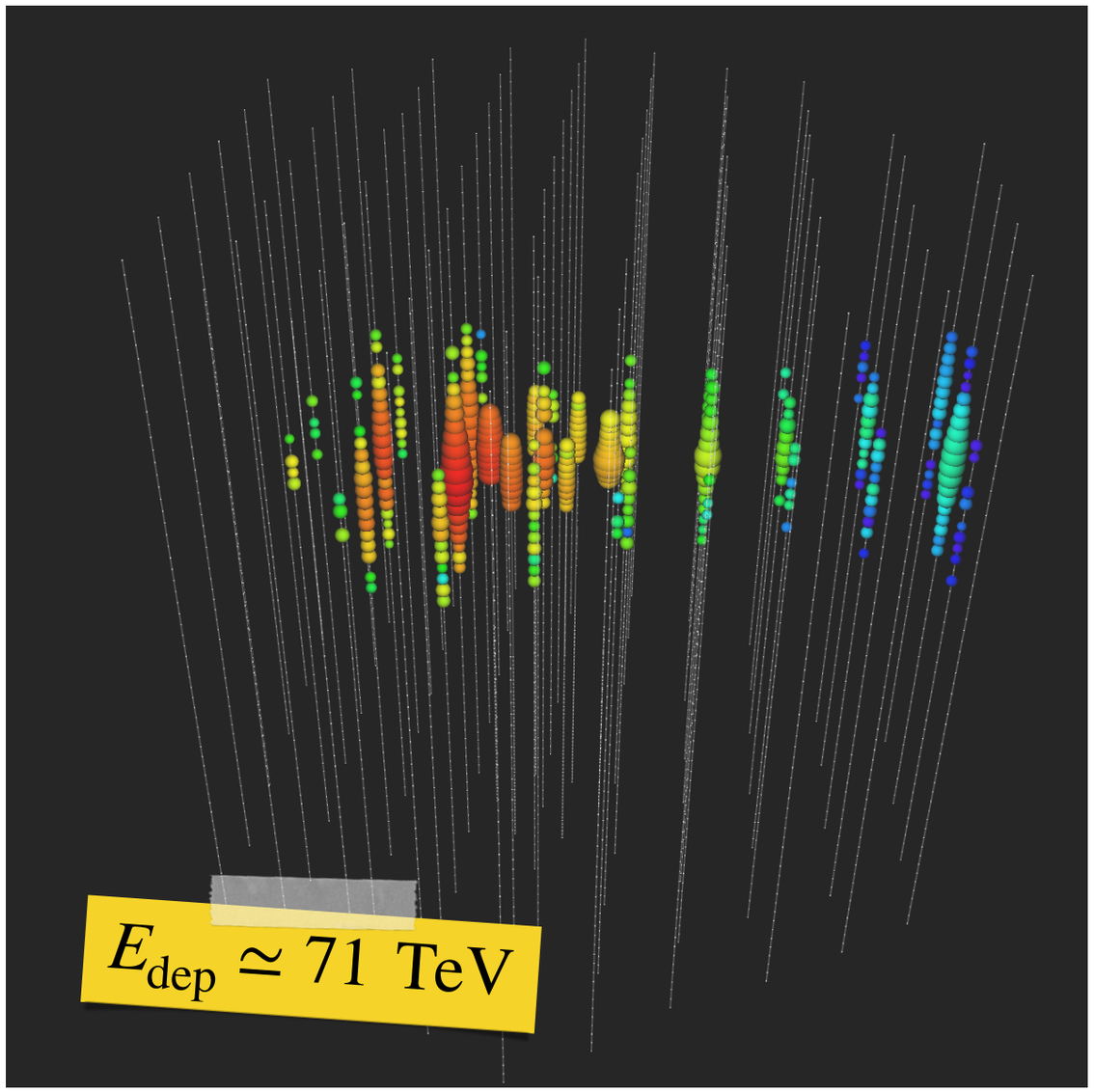


Selected Results in Neutrino Astronomy

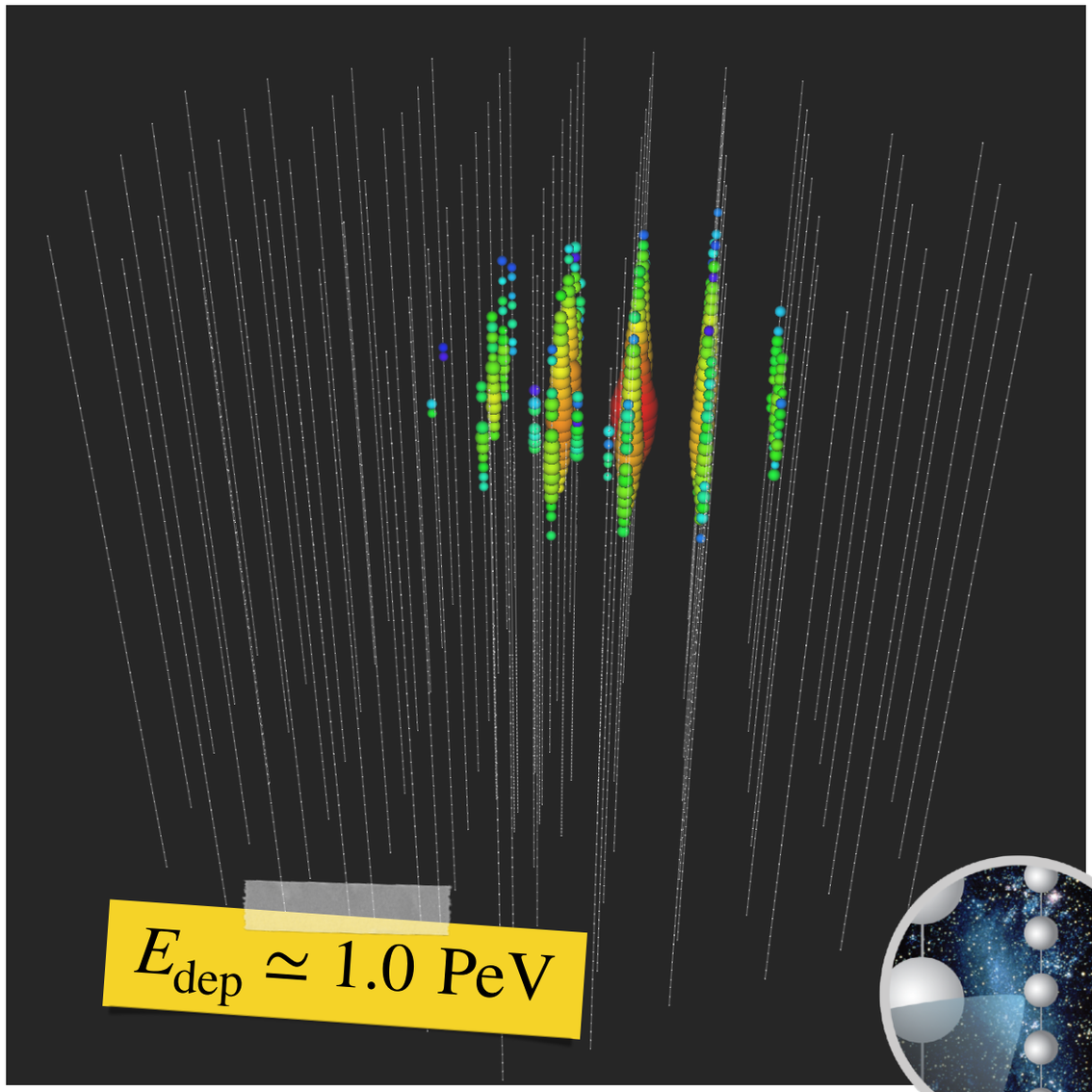
High-Energy Neutrinos

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

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



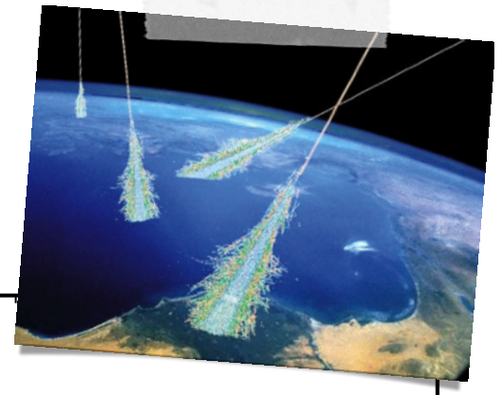
"cascade event" (e.g. NC interactions)

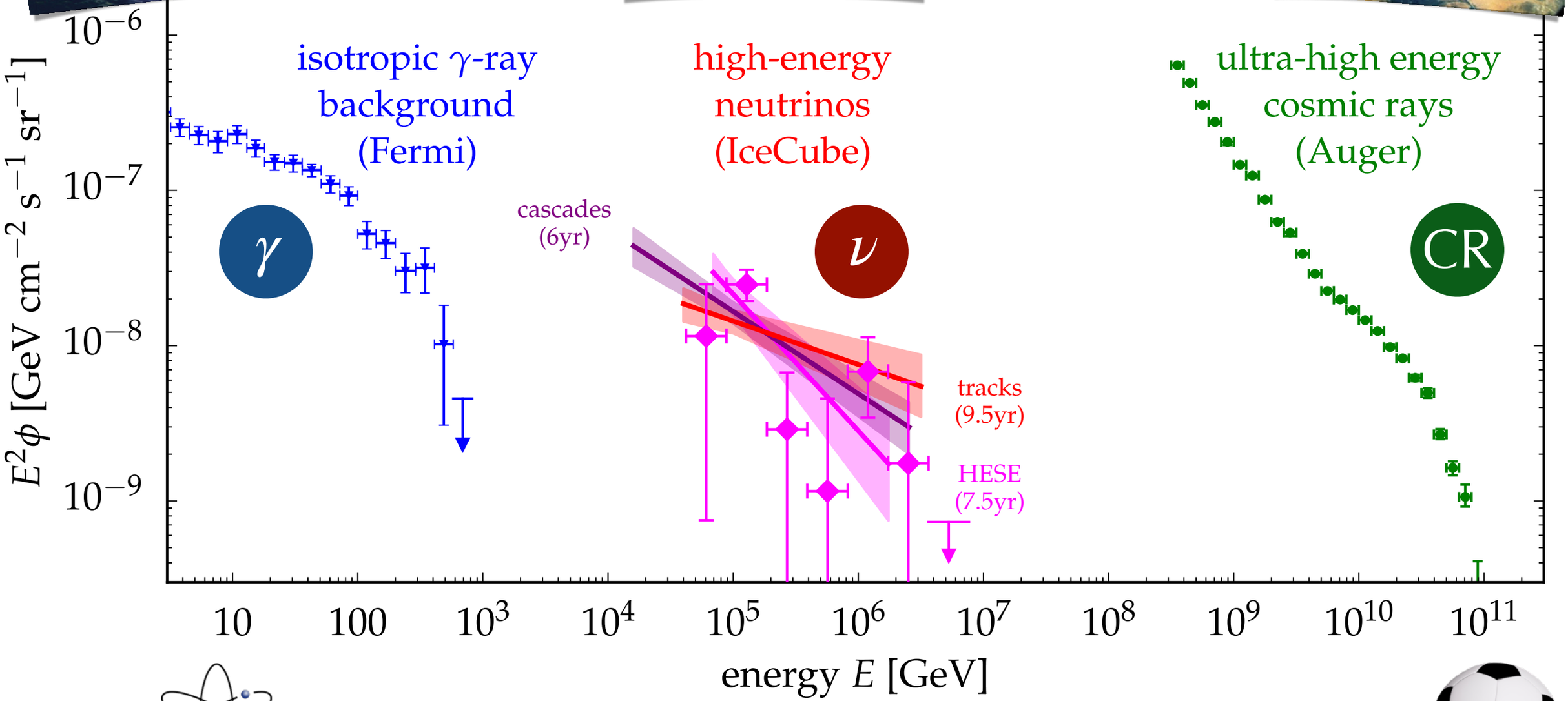


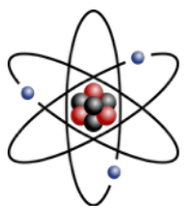
(colours indicate arrival time of Cherenkov photons from **early** to **late**)

ICECUBE

Diffuse TeV-PeV Neutrinos

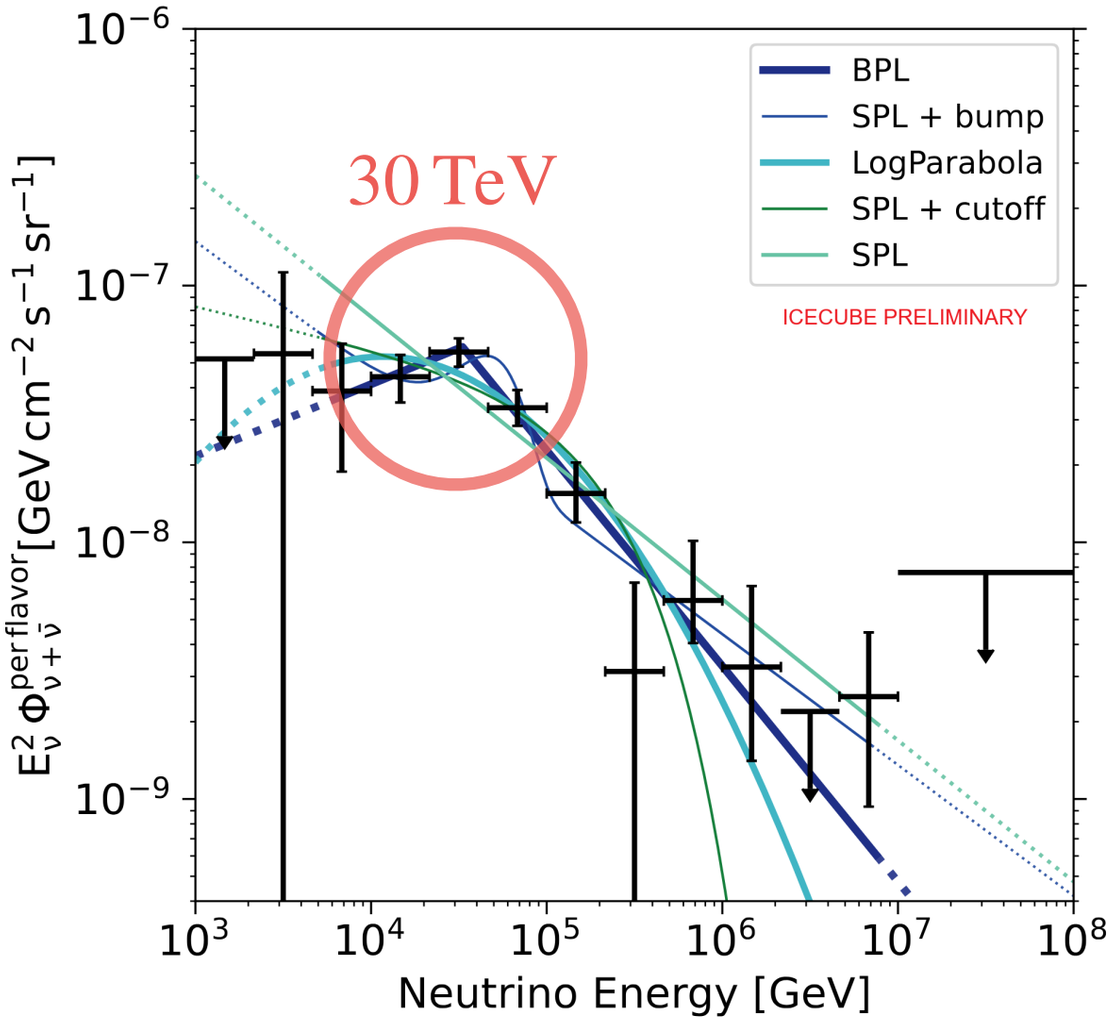


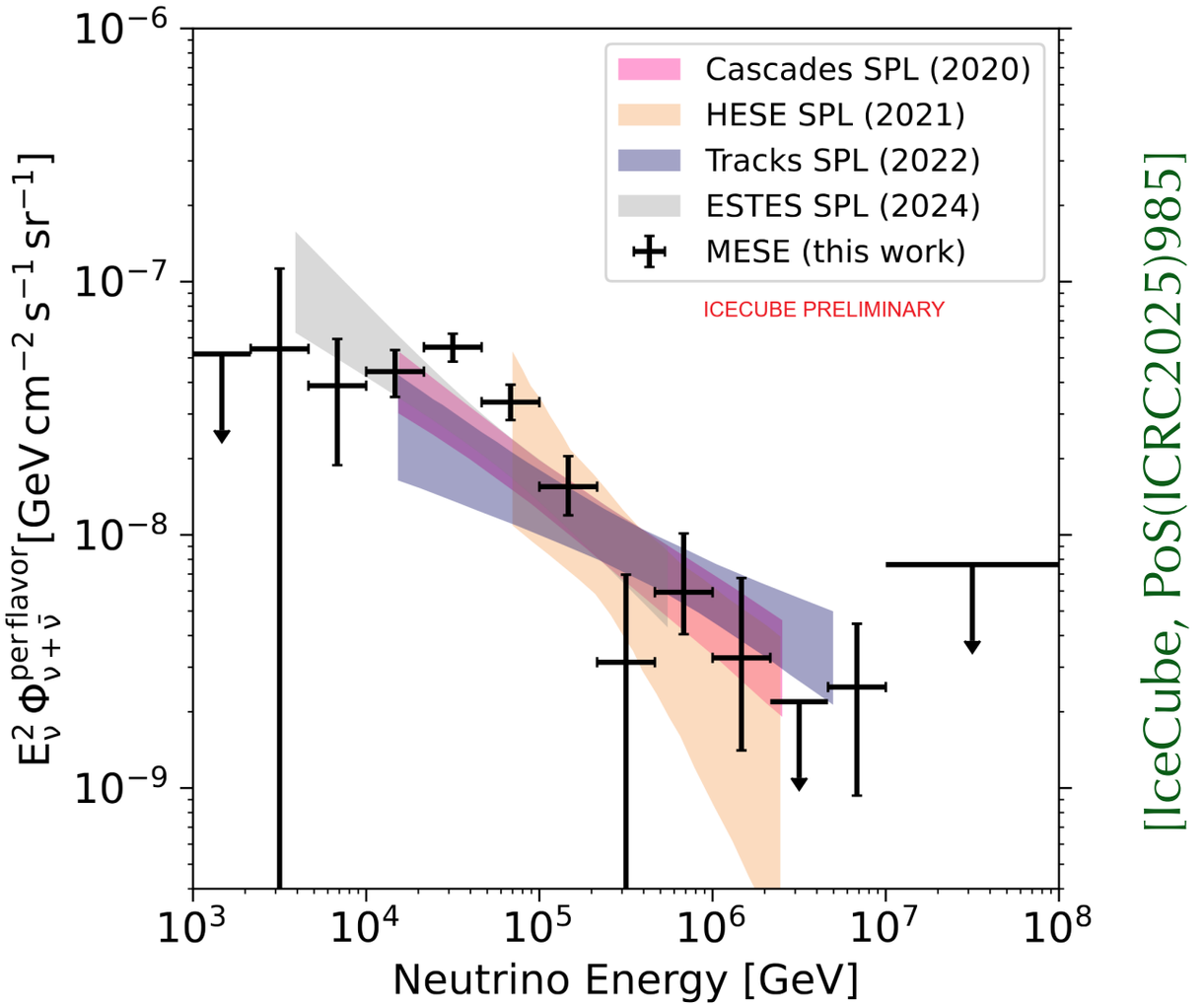




[IceCube, PRL 125 (2020) 12; PoS (ICRC2019) 1017; PRD 104 (2021) 022002]

Diffuse TeV-PeV Neutrinos



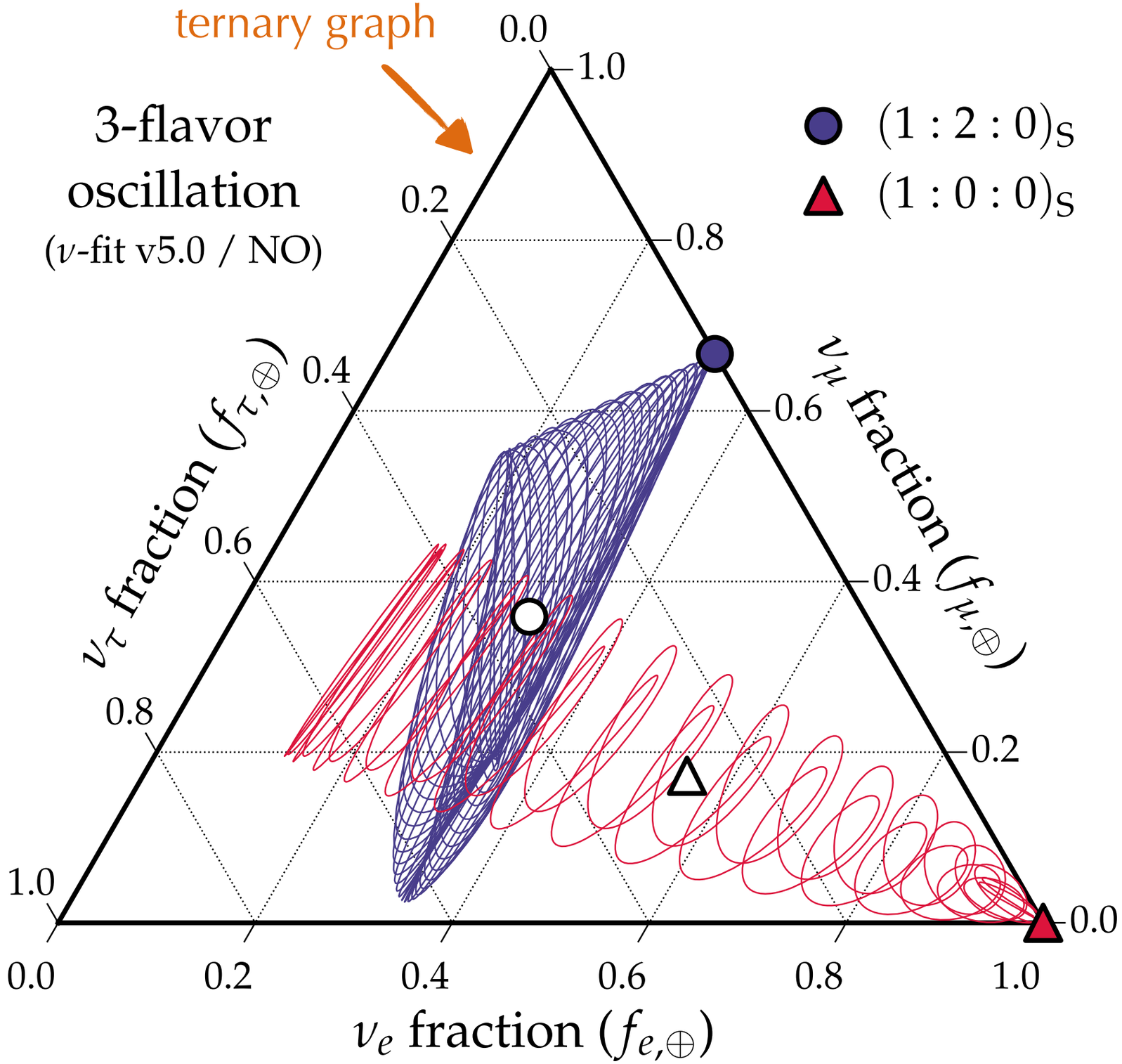


- All-sky neutrino-pure sample (MESE starting events) from 1 TeV to 10 PeV
- Clear evidence for departure from single power law (SPL)
- **Significance:** 4.7σ for broken power law (BPL) with break at 30 TeV

Astrophysical Flavours

ternary graph

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

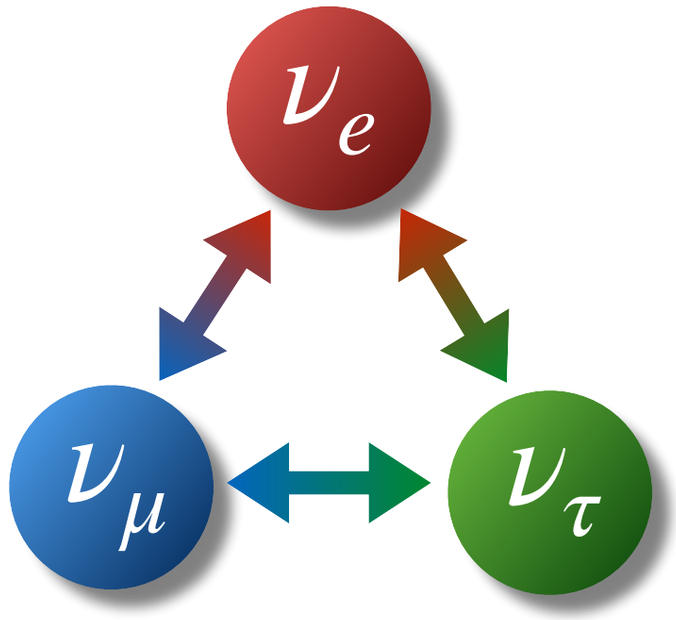


$(1:2:0)_S$

$(1:0:0)_S$

flavour ratios on production

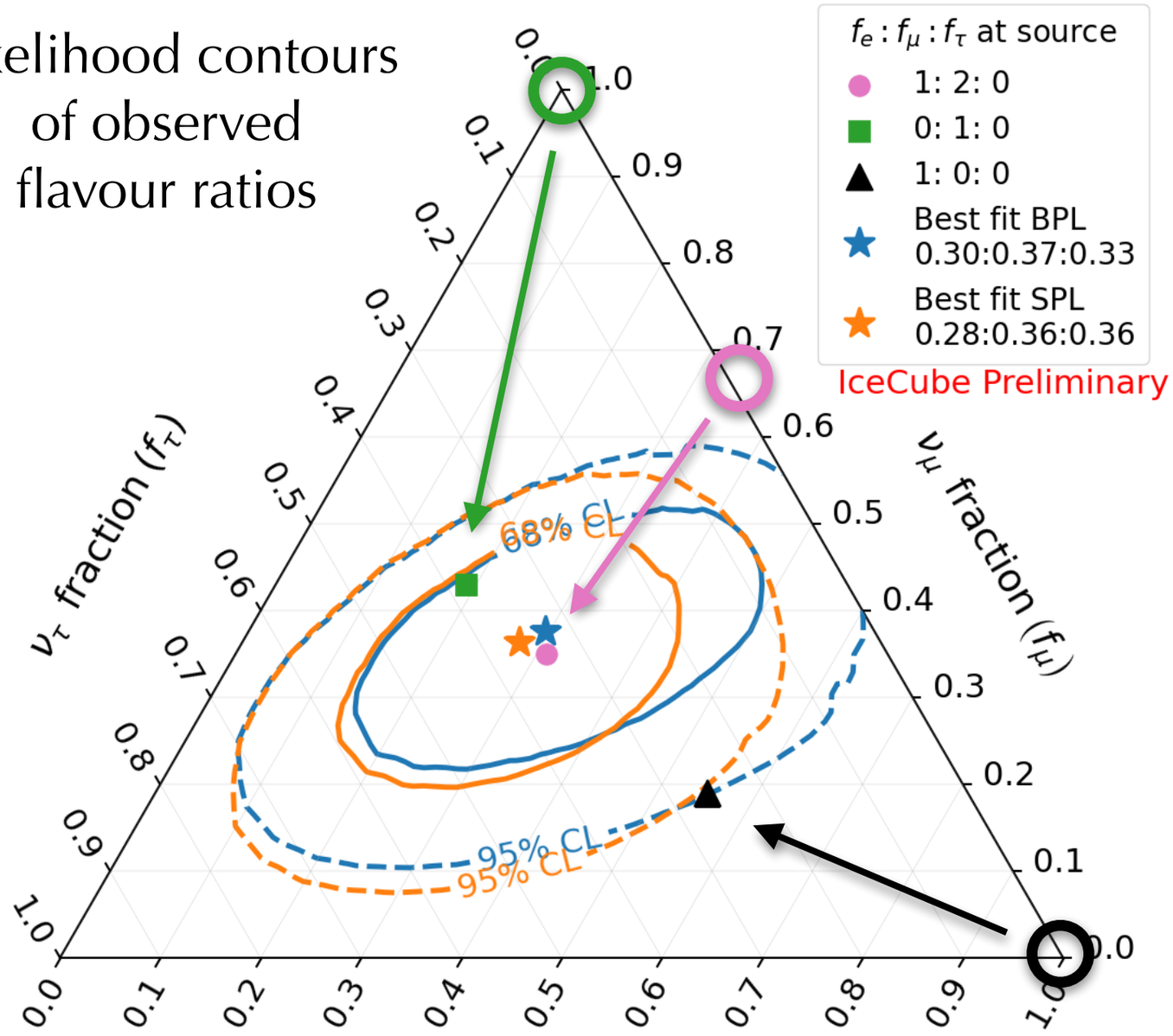
Superposition of flavour and mass states induces oscillations.



Astrophysical Flavours

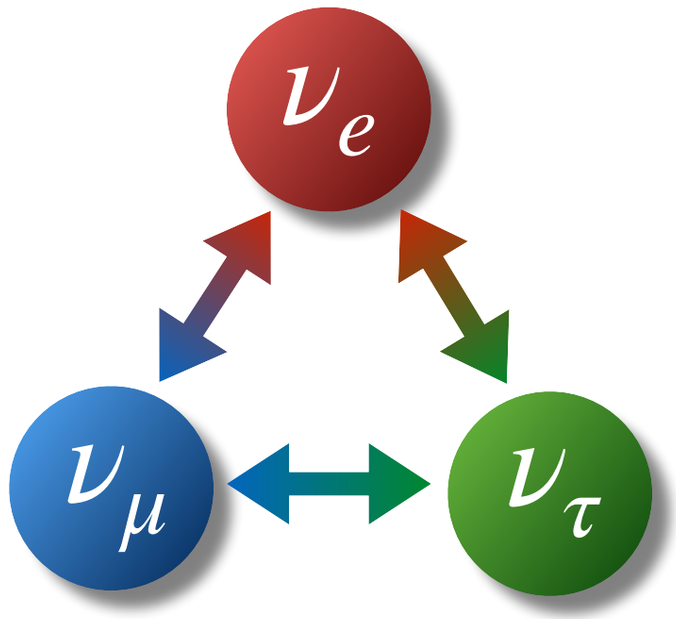
Cosmic neutrinos visible via their oscillation-averaged flavour.

Likelihood contours of observed flavour ratios

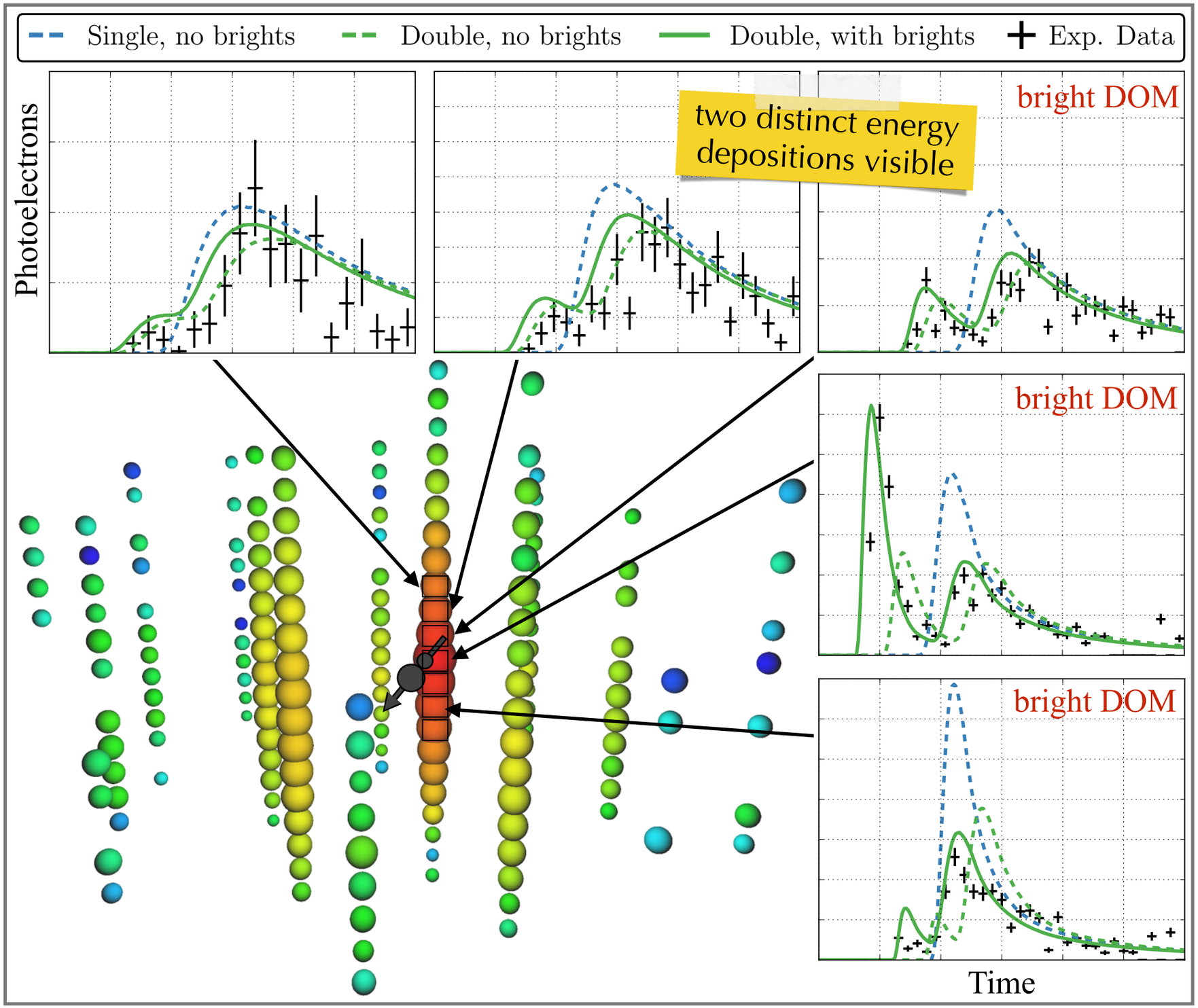


[IceCube, PoS(ICRC2025)983]

Superposition of flavour and mass states induces oscillations.



Astrophysical Flavours



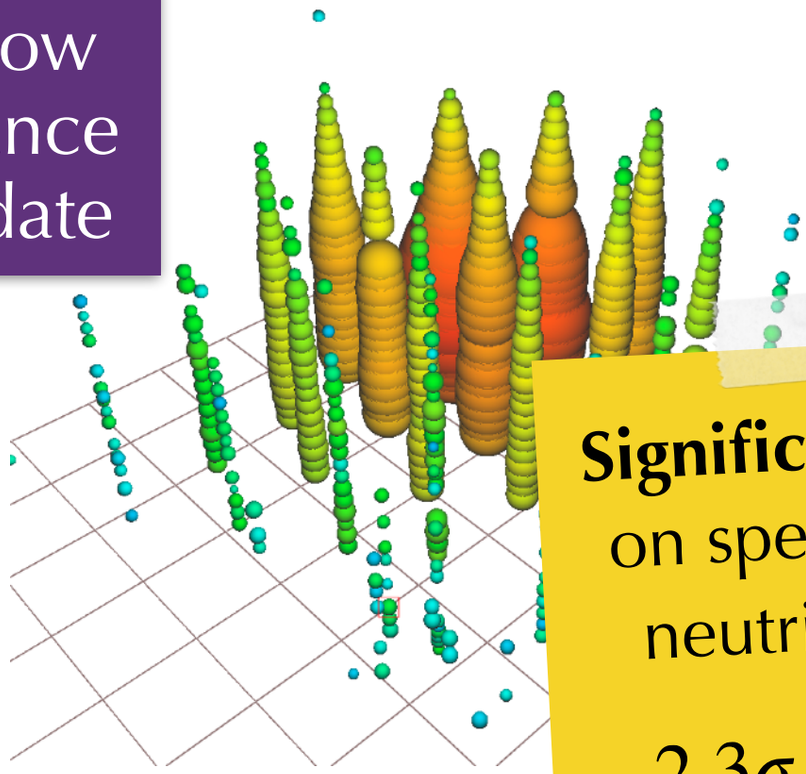
[IceCube, EPJ C (2022) 82]

tau neutrino candidate

- **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



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

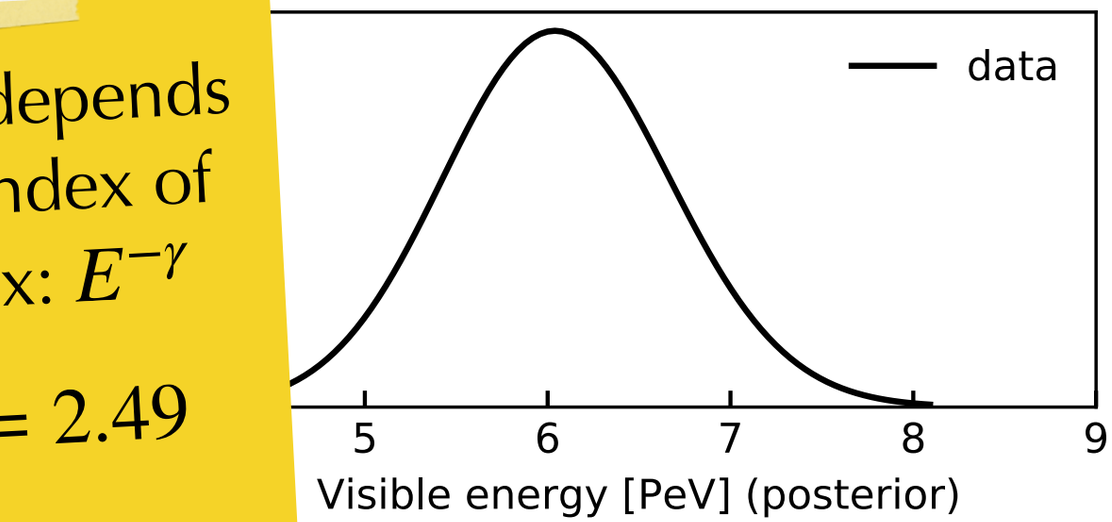
$$\bar{\nu}_e + e^- \to W^- \to X$$

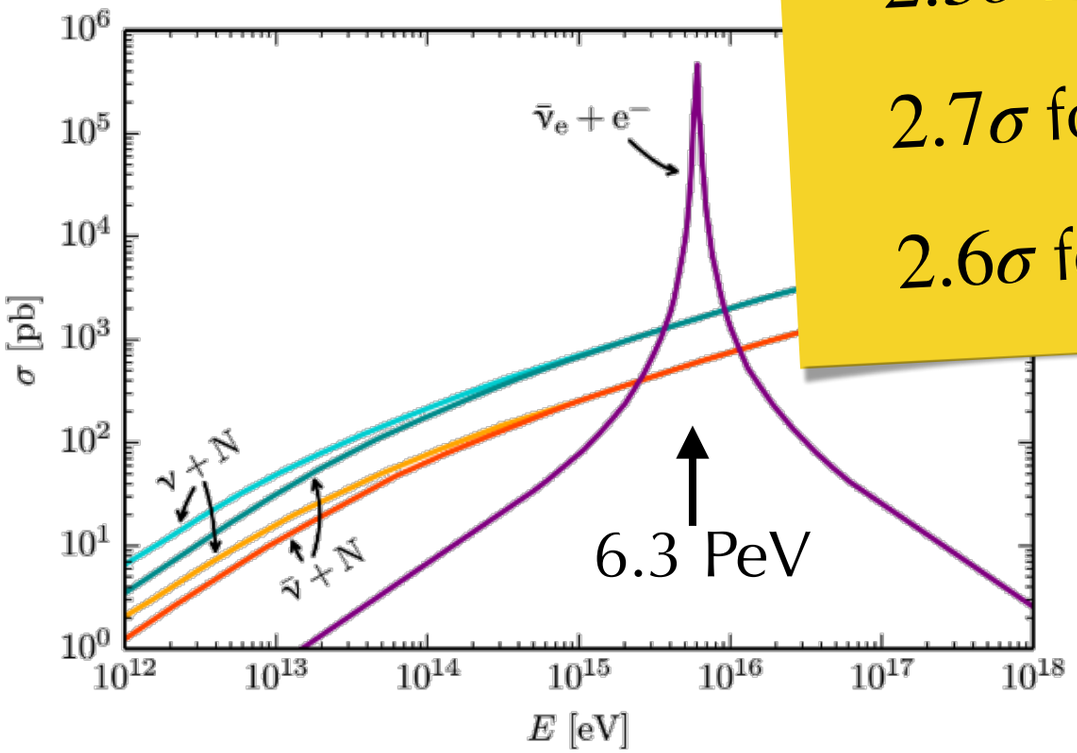
Significance depends on spectral index of neutrino flux: $E^{-\gamma}$

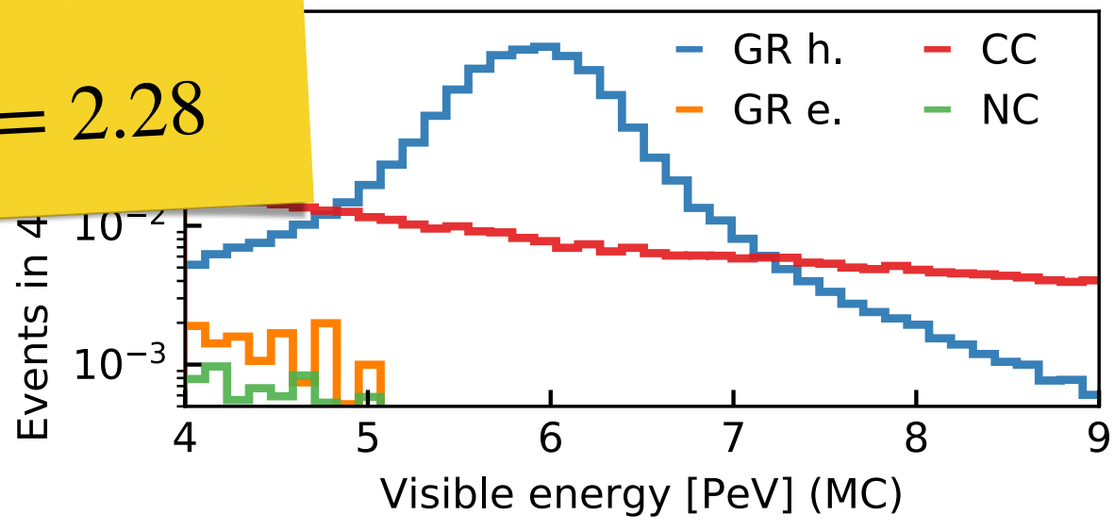
2.3σ for $\gamma = 2.49$

2.7σ for $\gamma = 2.89$

2.6σ for $\gamma = 2.28$

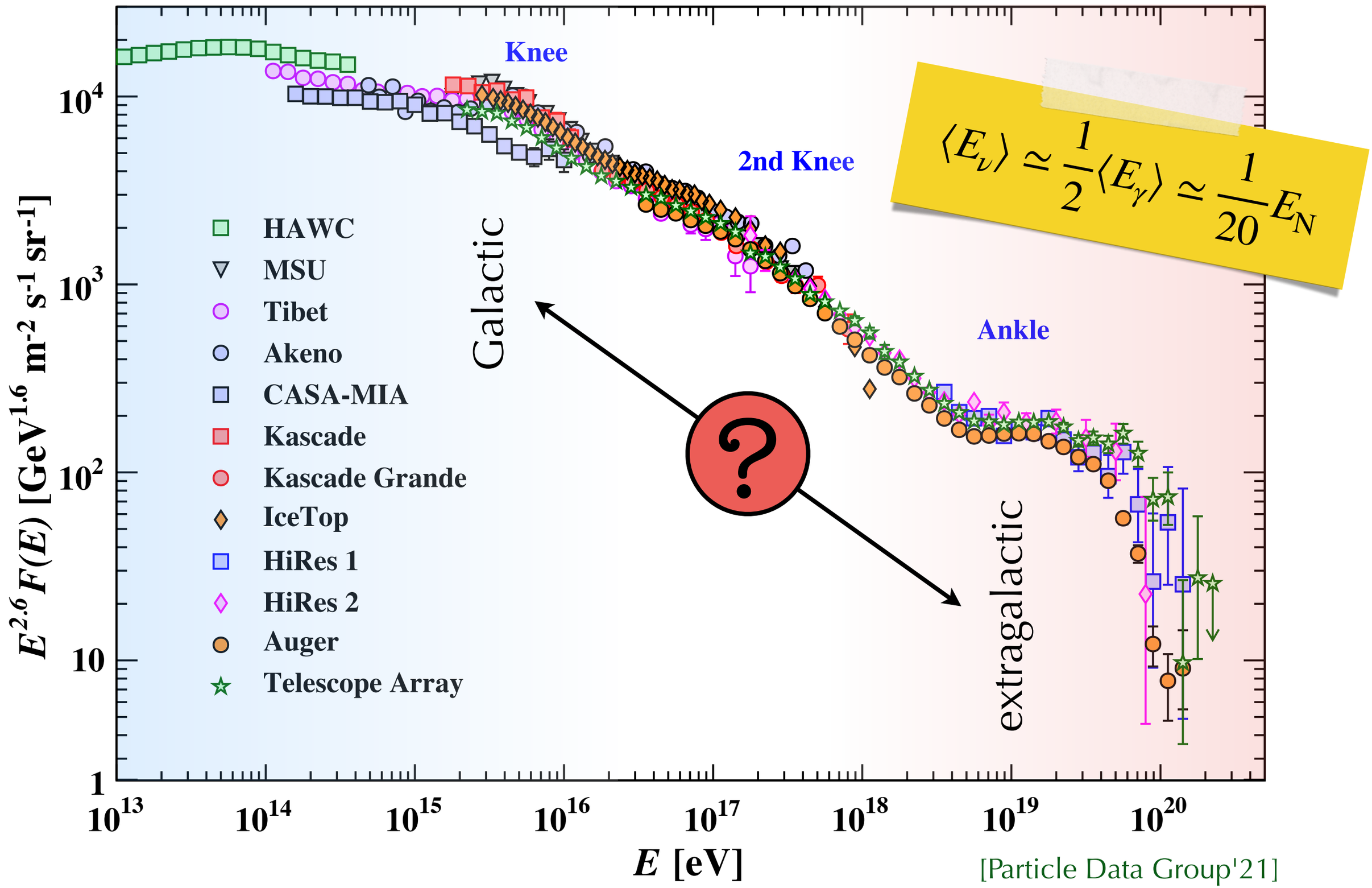






[IceCube, Nature 591 (2021) 220-224]

Very-High Energy Cosmic Rays

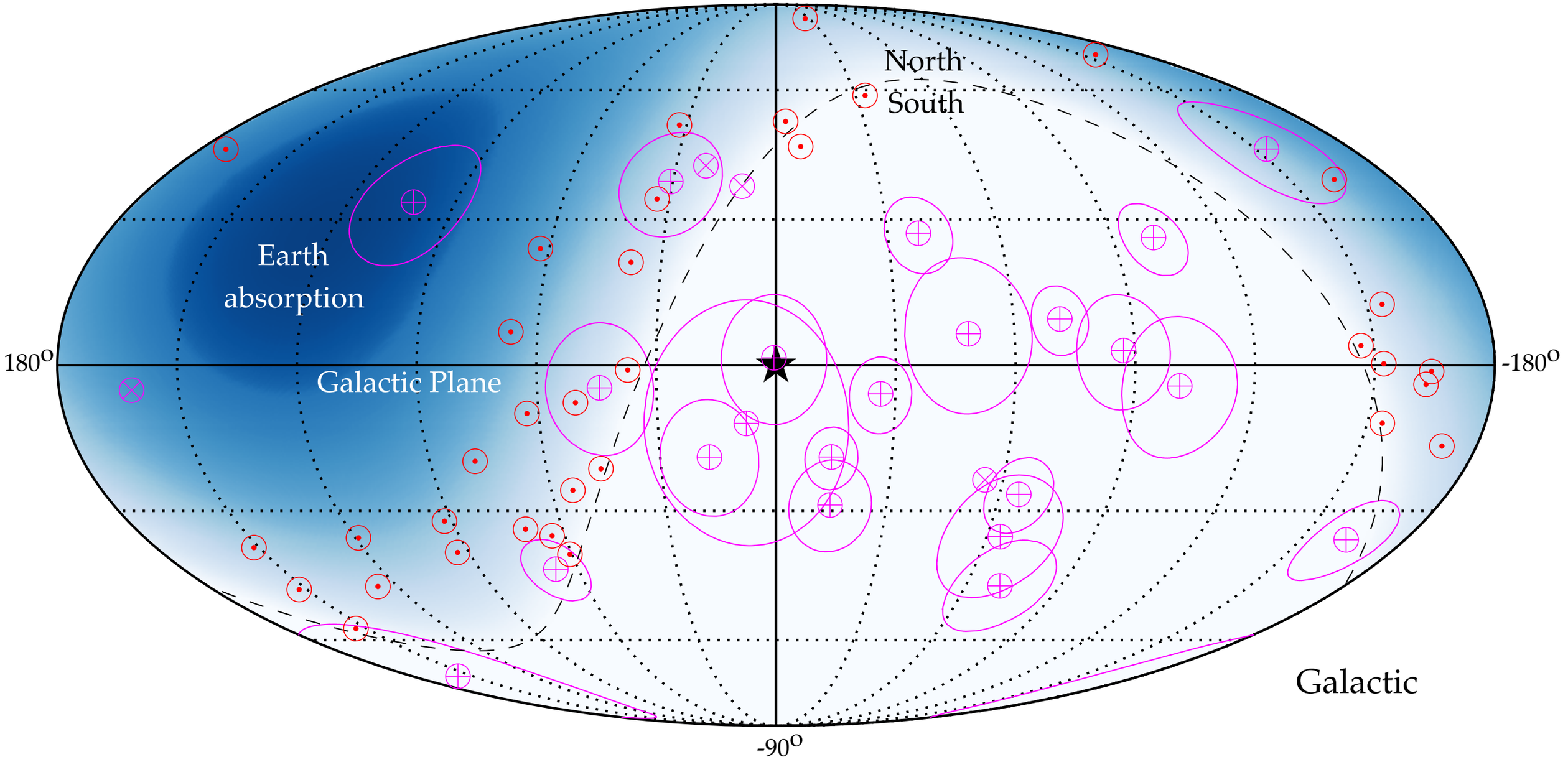


$$\langle E_\nu \rangle \simeq \frac{1}{2}\langle E_\gamma \rangle \simeq \frac{1}{20} E_N$$

[Particle Data Group'21]

Status of Neutrino Astronomy

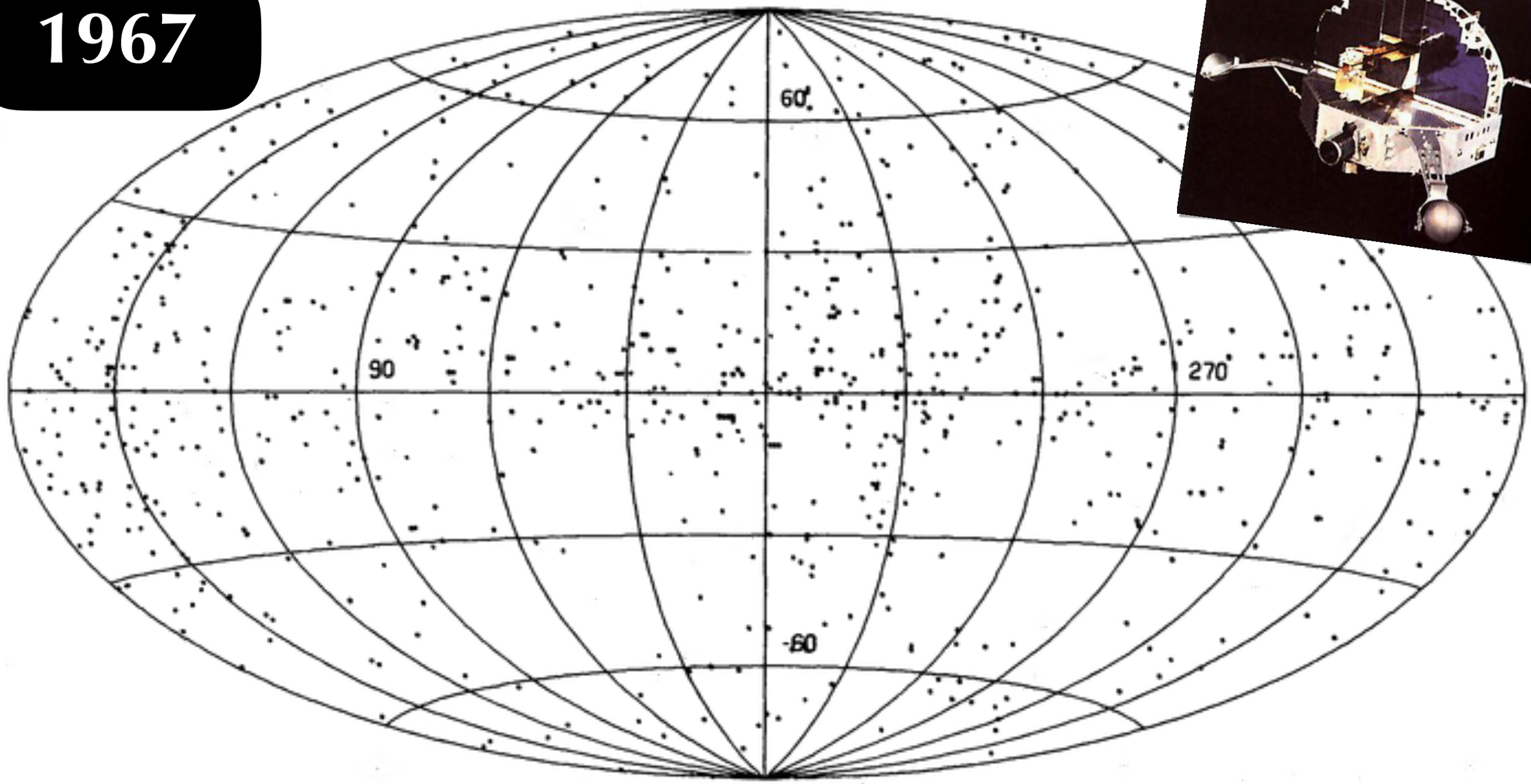
Most energetic neutrino events (HESE 6yr (magenta) & $\nu_\mu + \overline{\nu}_\mu$ 8yr (red))



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

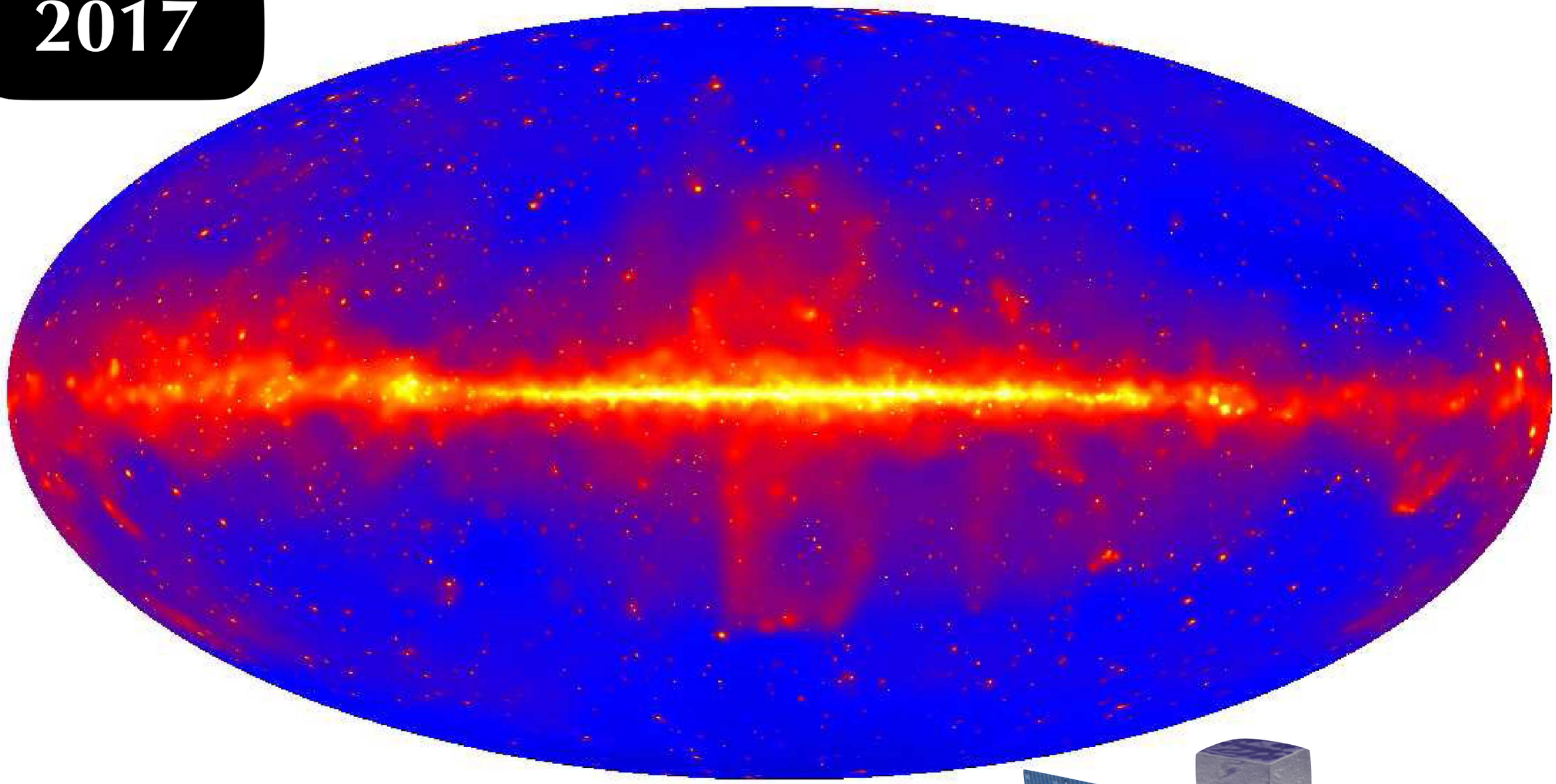
1967



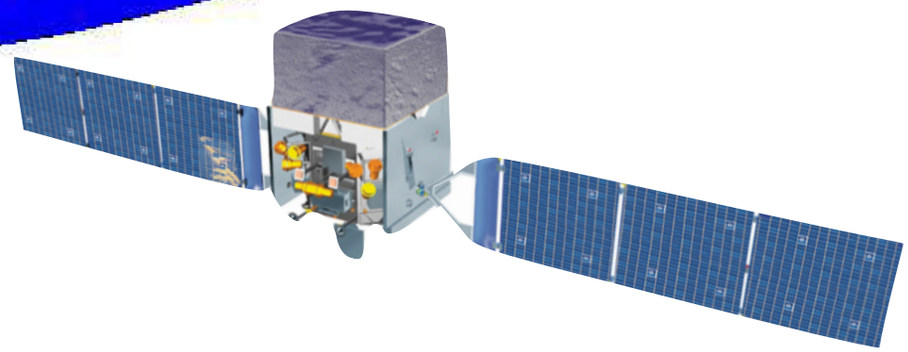
Orbiting Solar Observatory (OSO-3) (Clark & Kraushaar'67)

Status of Neutrino Astronomy

2017



Fermi-LAT gamma-ray count map



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.

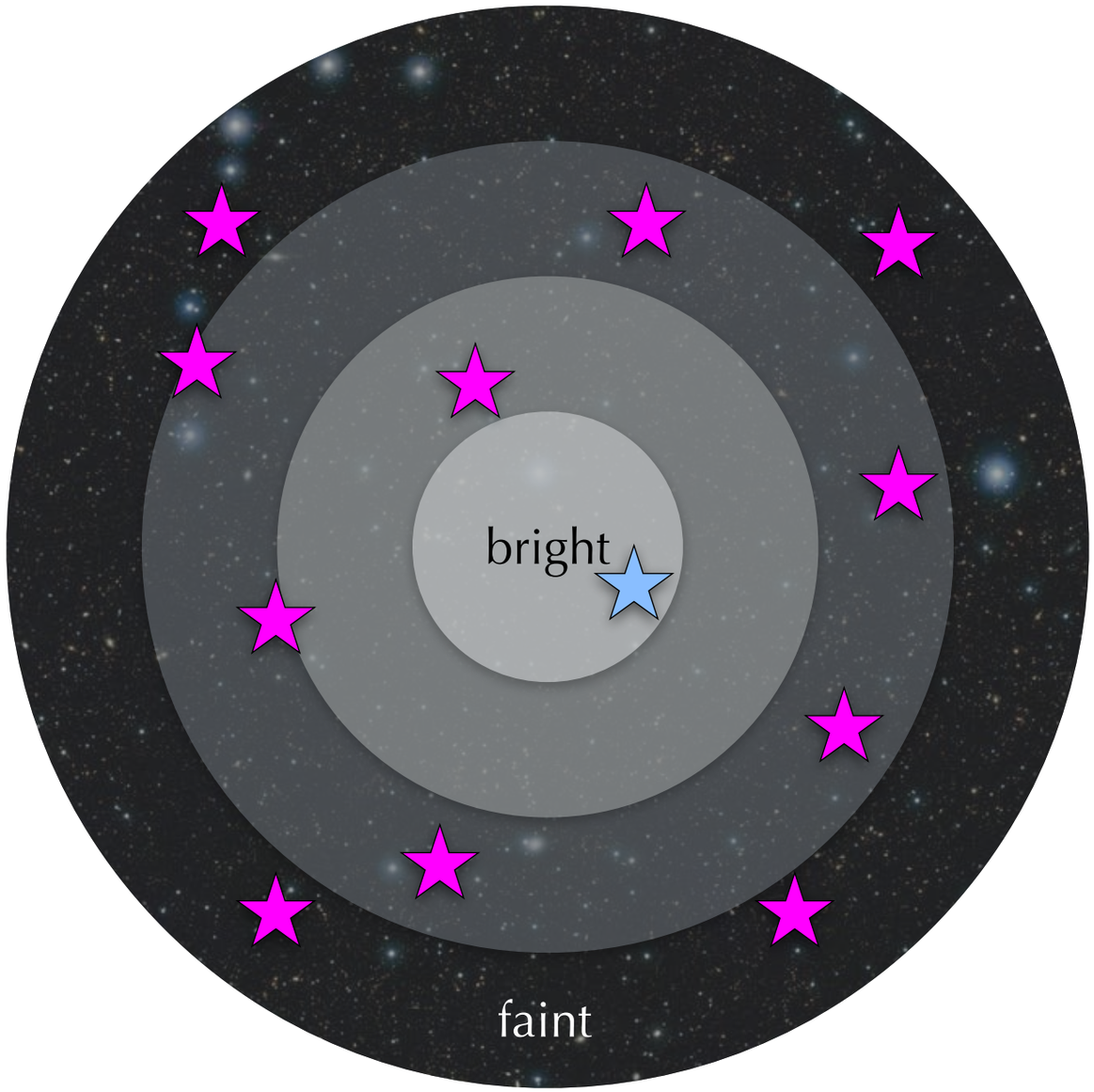
The relative contribution can be parametrized (*to first order*) by the average

local source emissivity $\mathscr{E}_0$

and

source luminosity L_ν

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



Hubble-Lemaître horizon

Extragalactic Populations

Populations of extragalactic neutrino sources visible as

individual sources

and by

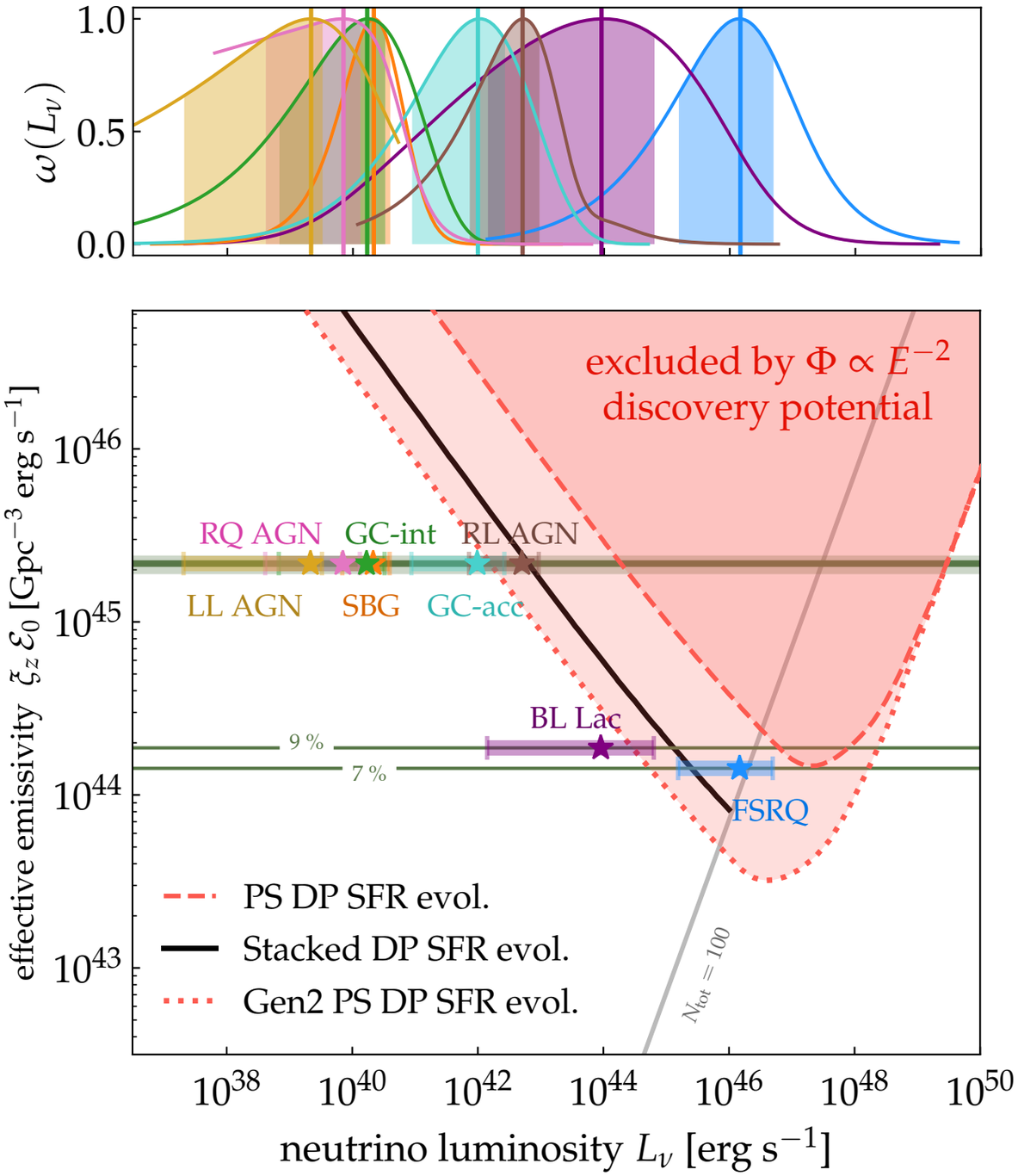
combined isotropic emission.

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

local source emissivity $\mathscr{E}_0$

and

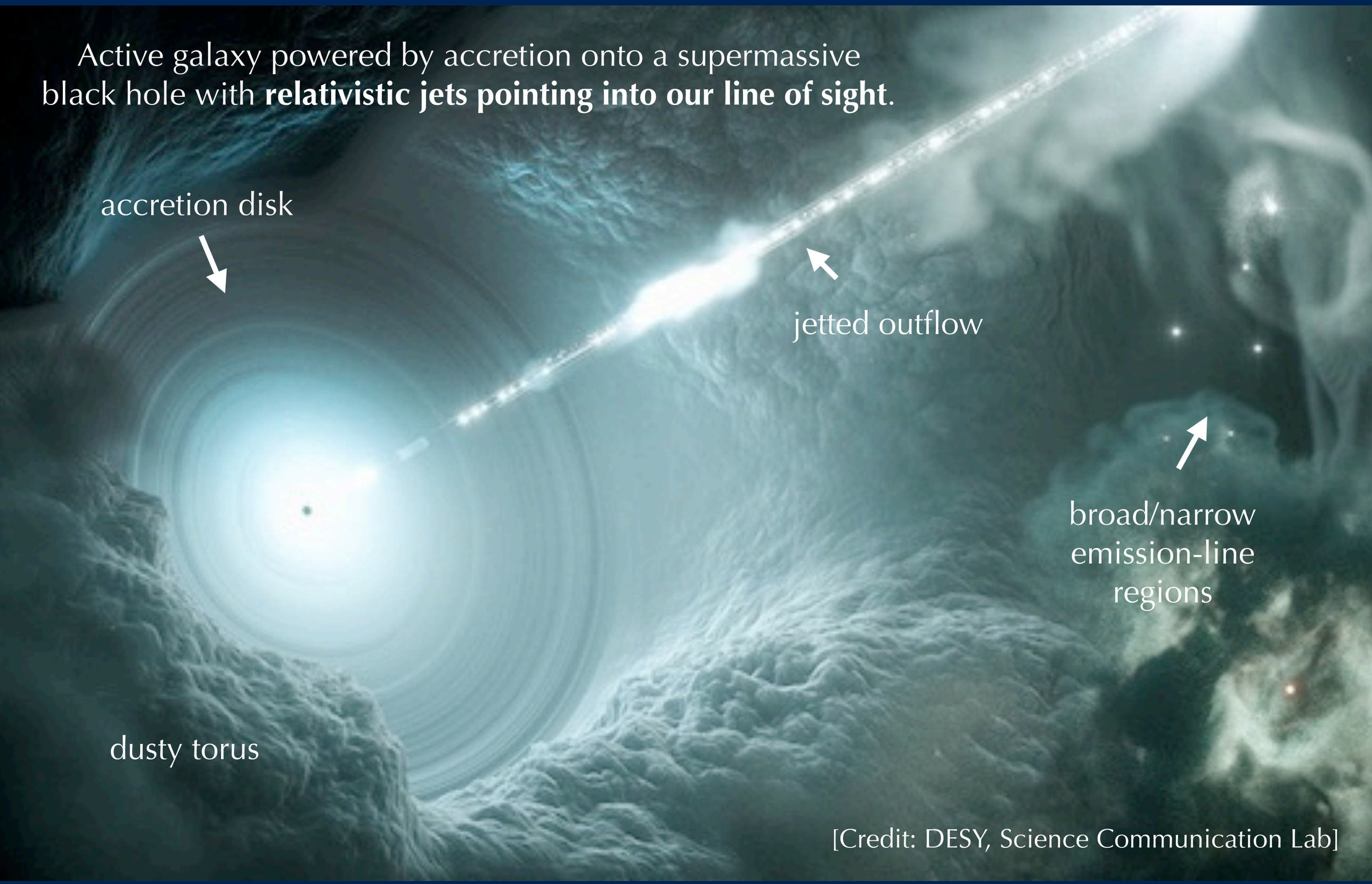
source luminosity L_ν



[Groth & MA'25; see also Murase & Waxman'16; Ackermann, MA, Anchordoqui, Bustamante *et al.*'19]

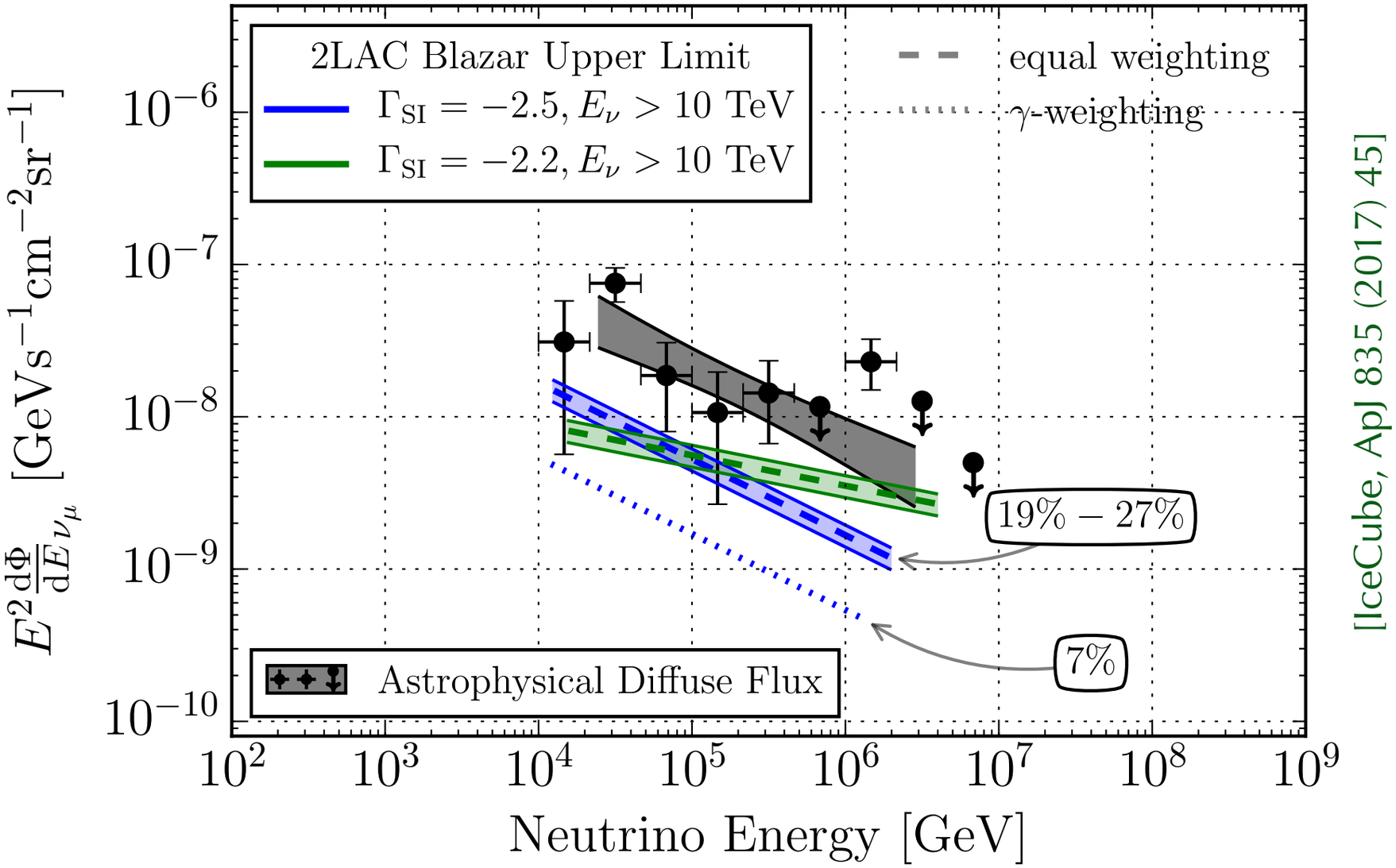
Blazars

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



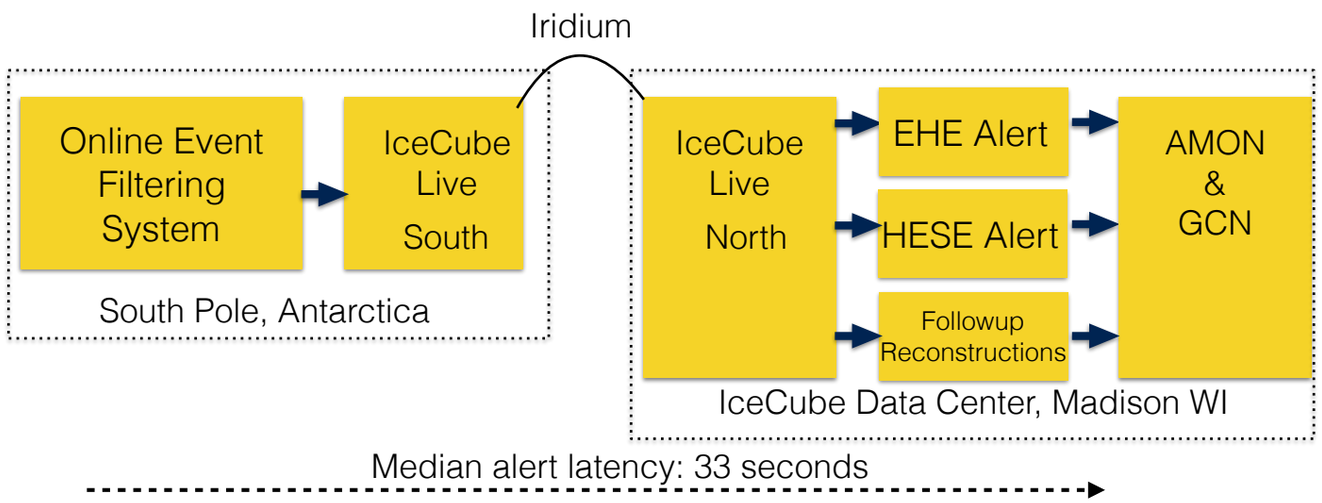
- Combined contribution of Fermi-LAT blazars (2LAC) **below 30%** of the isotropic TeV-PeV neutrino observation. [IceCube, ApJ 835 (2017) 45]
- MeV-detected (1FLE) **below 1%**; "hard" emitters (3FHL) **below 17%**

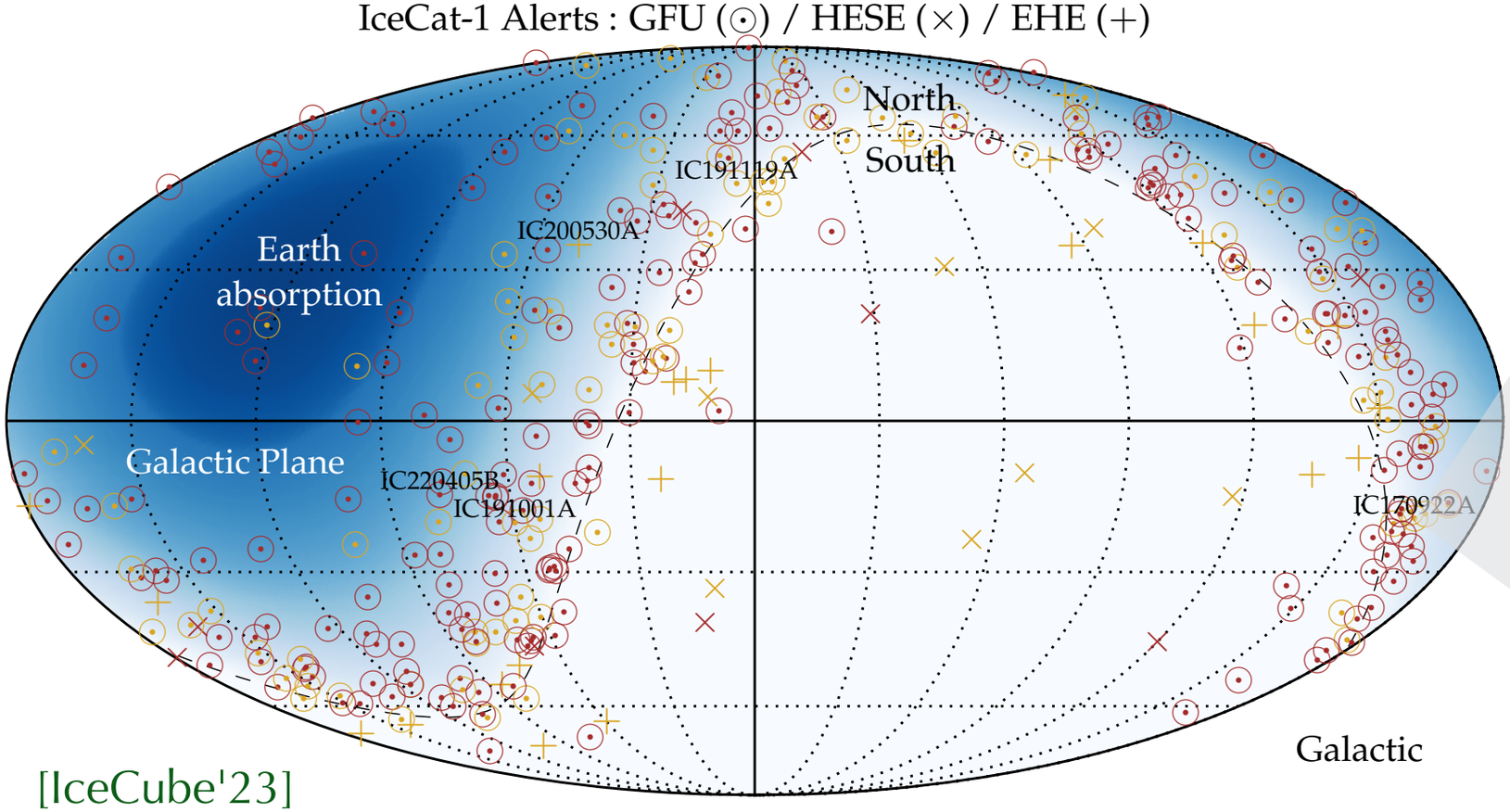
[IceCube, ApJ 938 (2022) 1; PoS ICRC2019 (2020) 916]

Realtime Neutrino Alerts

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

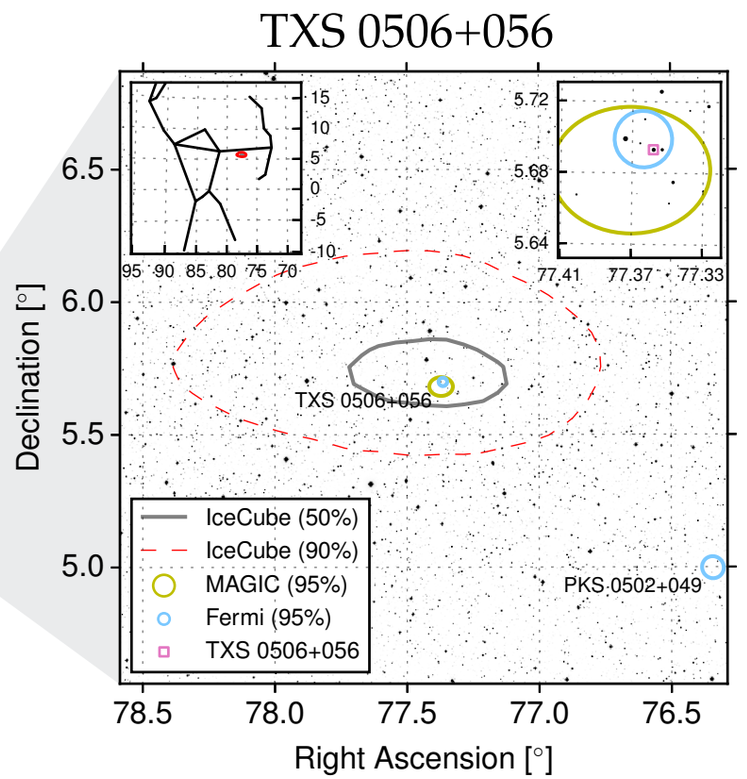
- **Gold alerts:** about **10 per year**
  50% signalness (on average)
- **Bronze alerts:** about **20 per year**
  30% signalness (on average)



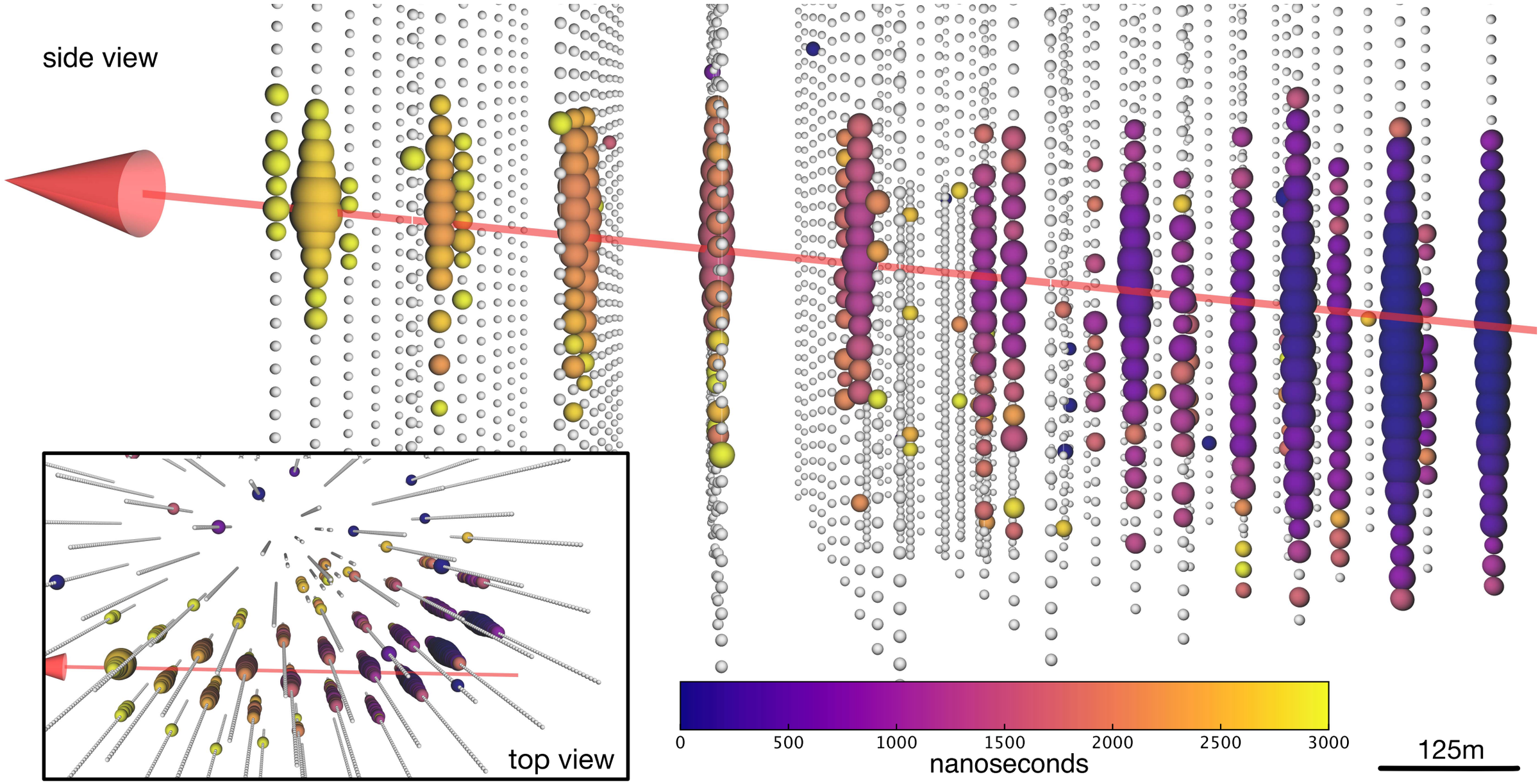


[IceCube'23]

[IceCube, PoS (ICRC2019) 1021]

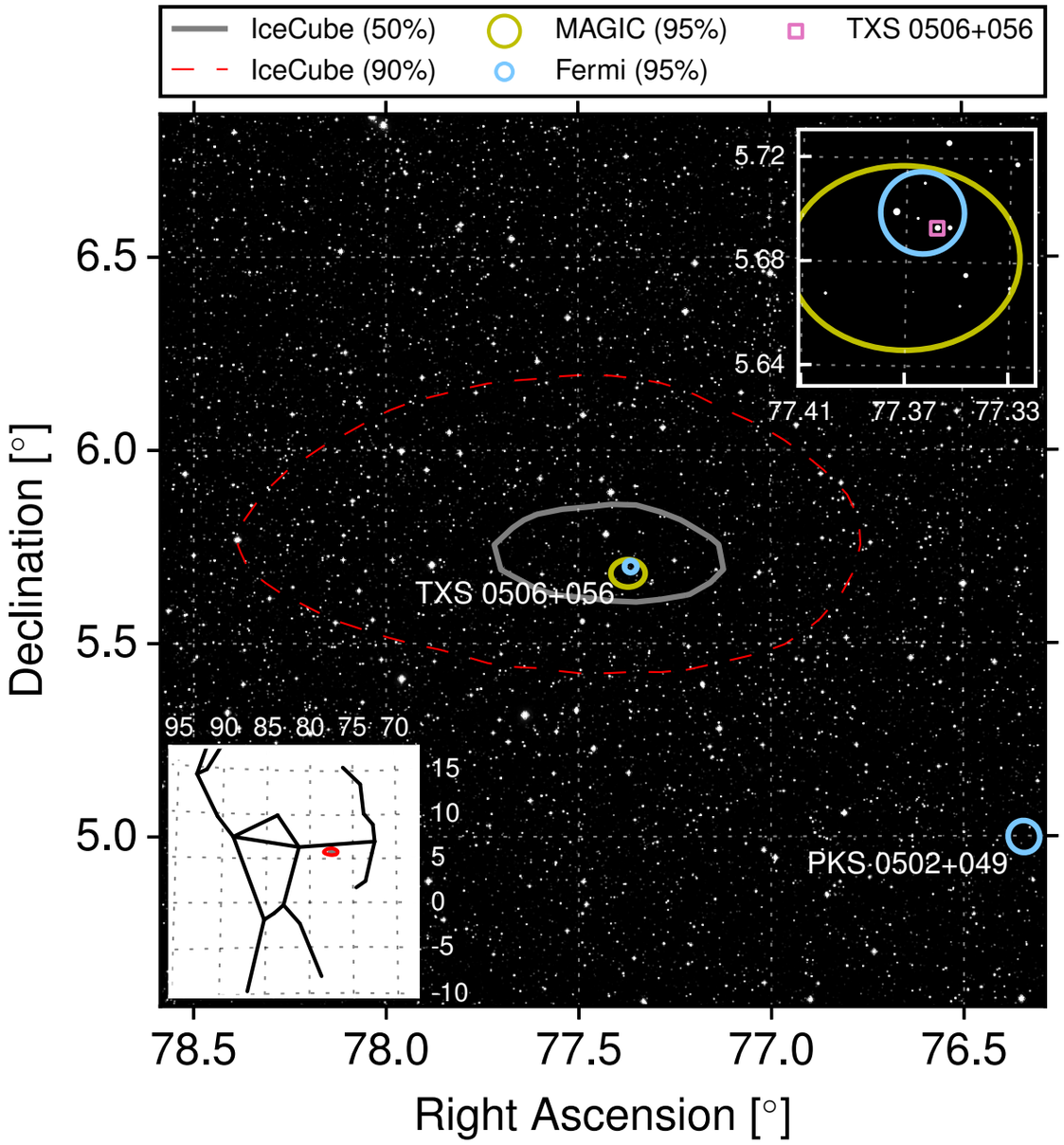


IC-170922A



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

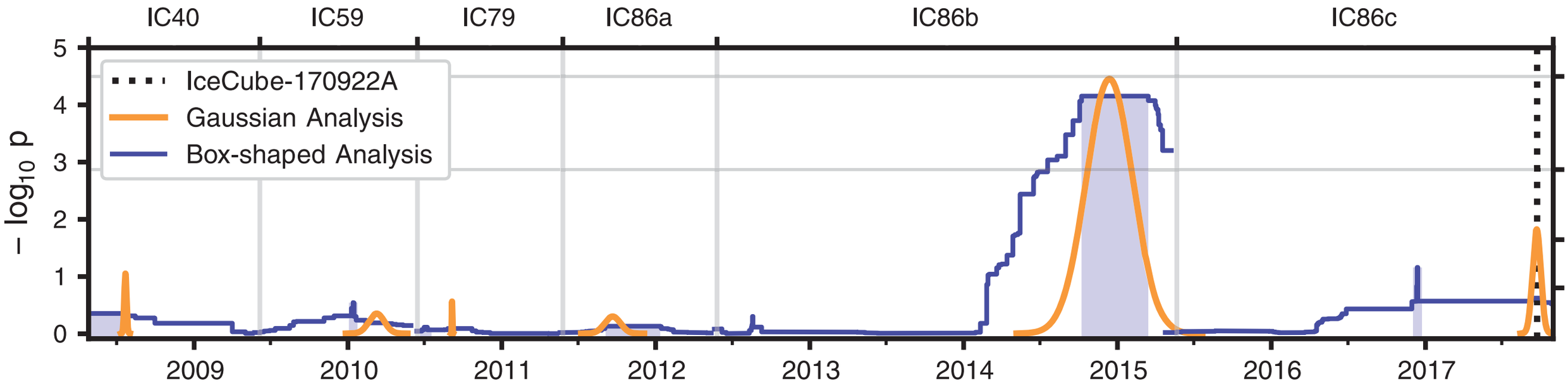
TXS 0506+056



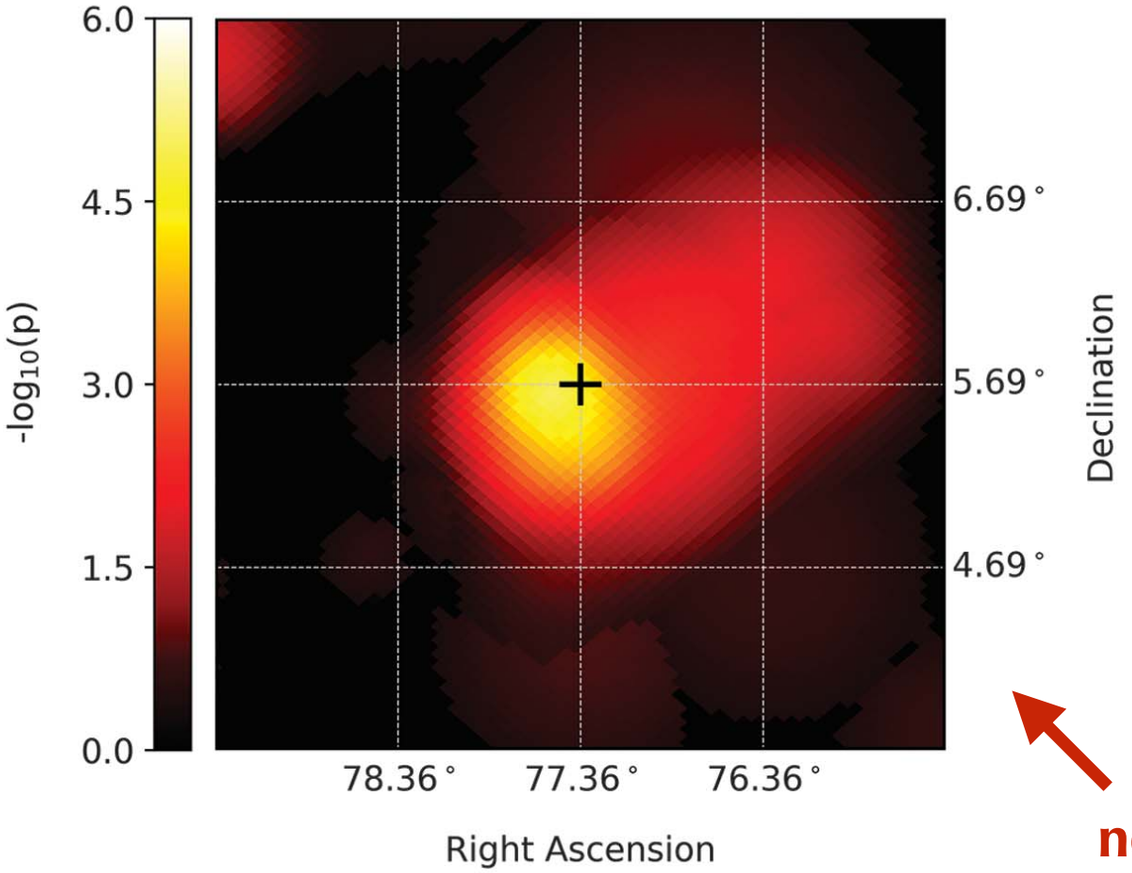
[IceCube++, Science 361 (2018) 6398]

- IC170922A observed in coincident with **flaring blazar TXS 0506+056**.
- Chance correlation can be rejected at the 3σ-level.
- TXS 0506+056 is among the most luminous BL Lac objects in gamma-rays.

Neutrino Flare in 2014/15



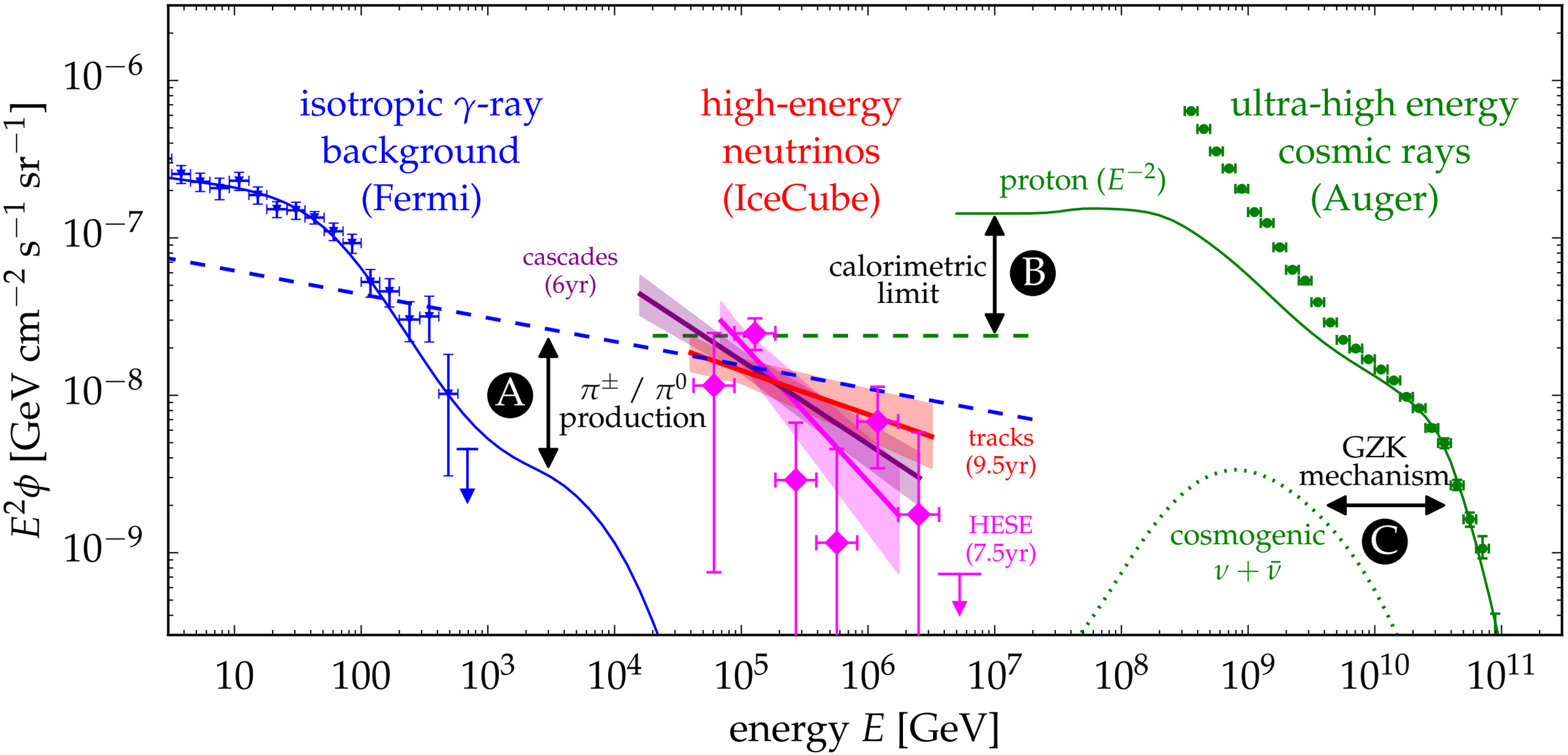
[IceCube, Science 361 (2018) 6398]



- Independent 3.5σ evidence for a **neutrino flare** (13±5 excess events) in 2014/15.
- Neutrino luminosity over 158 days is about **four times that of Fermi-LAT γ-rays**.

neutrino "morphology" of 2014/15 flare

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.

Waxman-Bahcall Limit

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

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

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

$$E_\nu^2\phi_\nu(E_\nu) \simeq f_\pi \underbrace{\frac{\xi_z K_\pi}{1+K_\pi}}_{\mathcal{O}(1)} \underbrace{1.5\times 10^{-8}\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}}_{\text{IceCube diffuse level}}$$

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

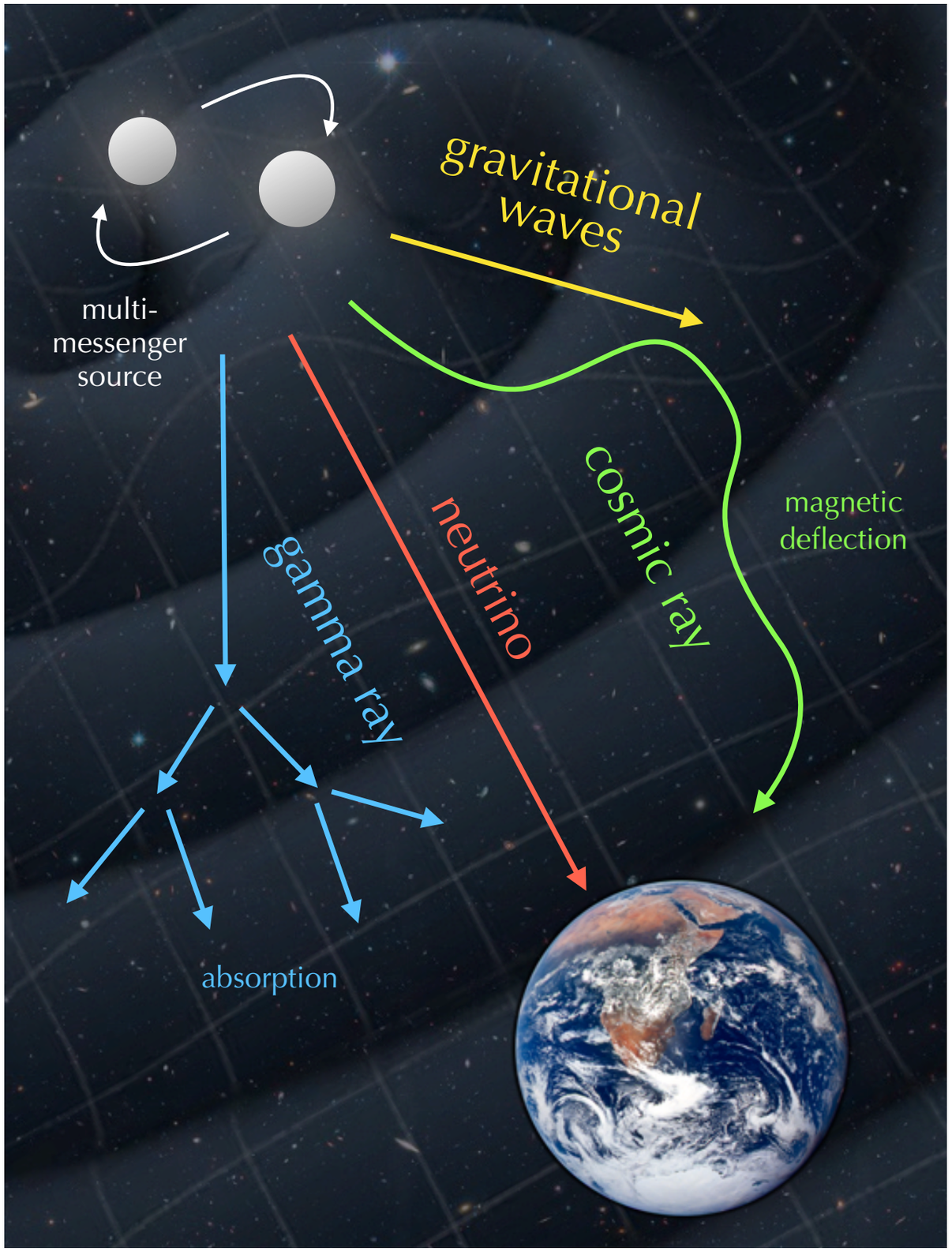
- Similar UHE **nucleon emission rate** density (local minimum at $\Gamma \simeq 2.04$) :

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

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

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

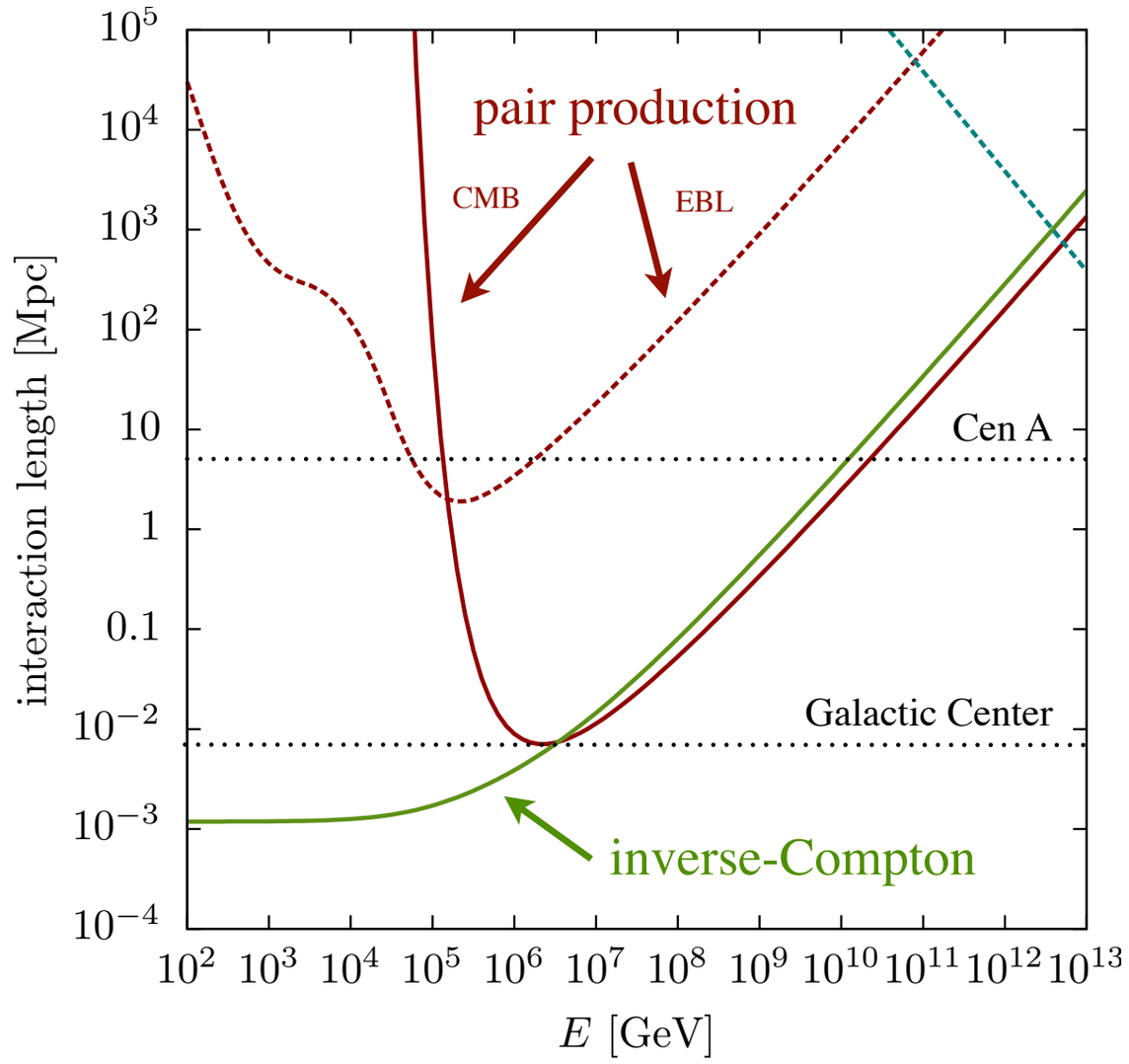
Hadronic Gamma-Rays



EM cascades from interactions in cosmic radiation backgrounds:

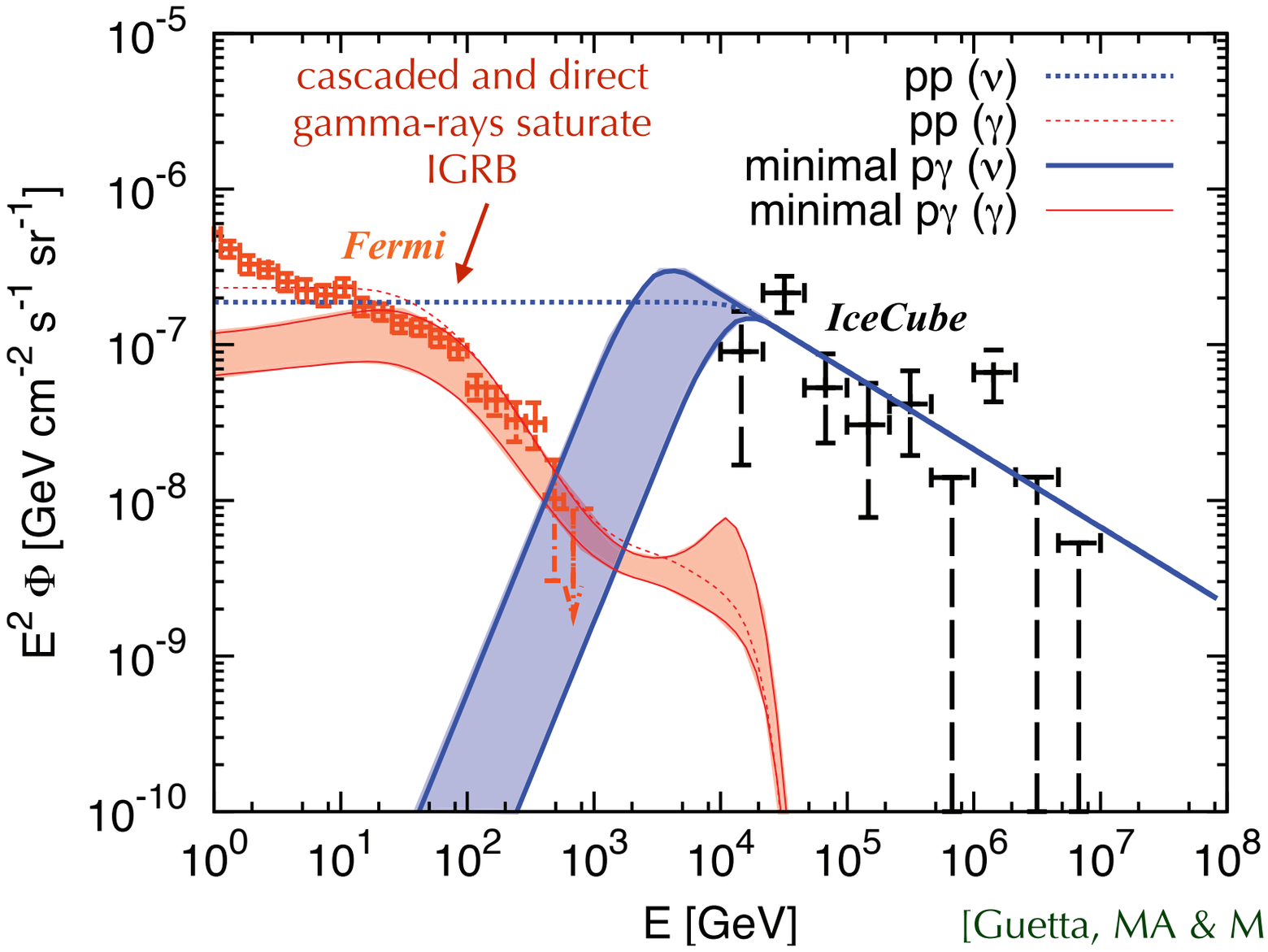
$$\gamma + \gamma_{\rm bg} \to e^+ + e^- \quad \text{(PP)}$$

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



Hadronic Gamma-Rays

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



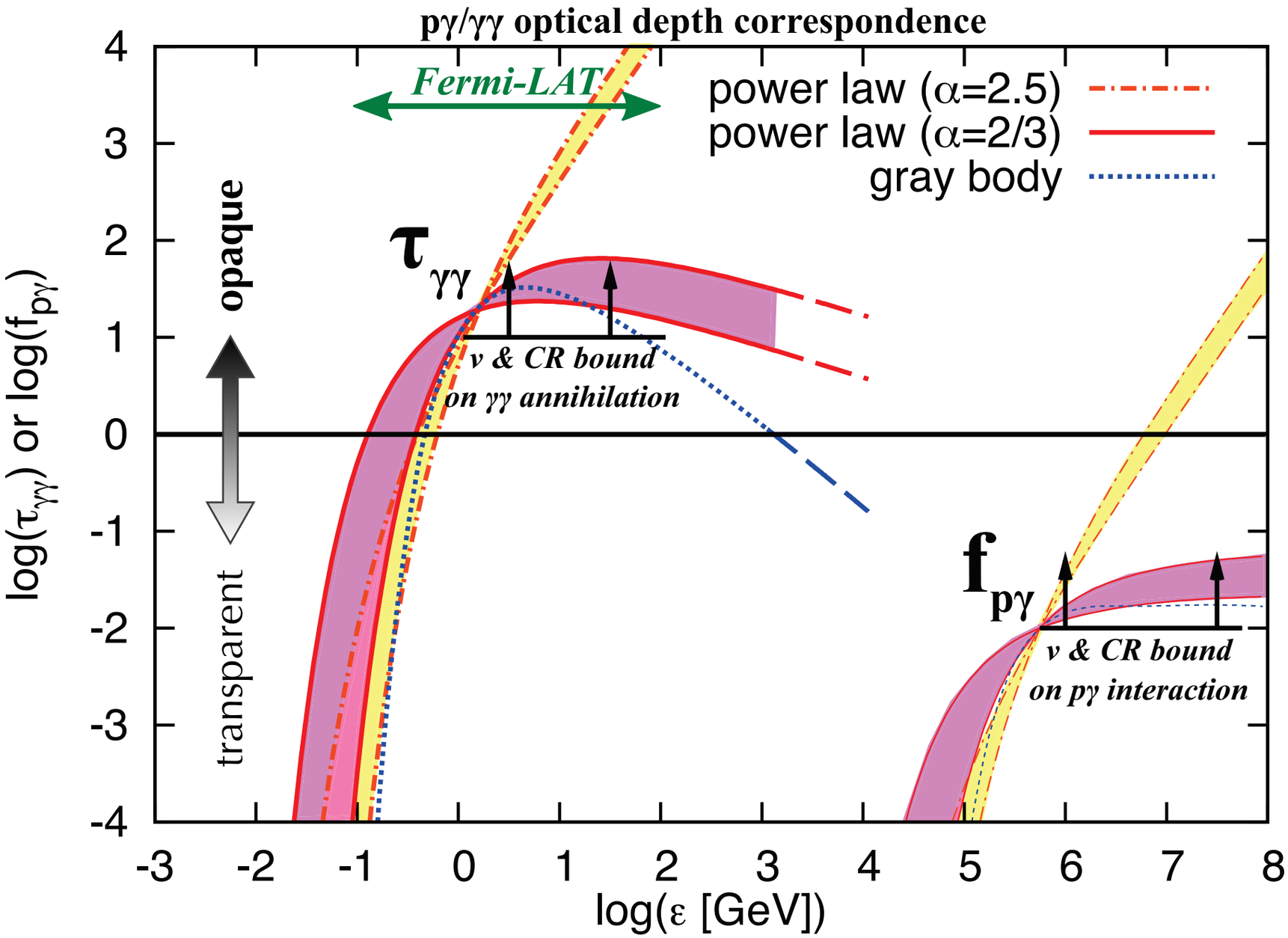
[Guetta, MA & Murase'16]

[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).



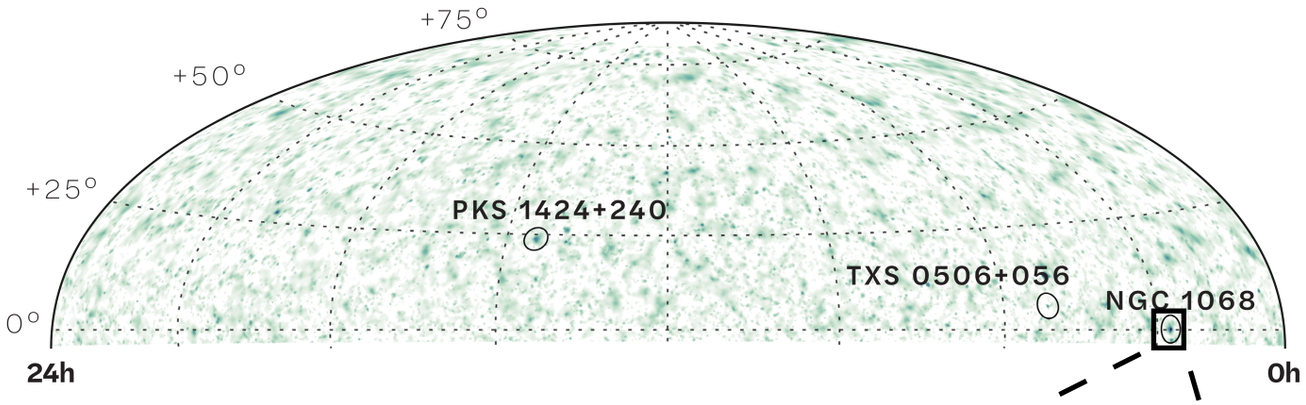
High pion production efficiency implies strong internal **γ-ray absorption in Fermi-LAT energy range:**

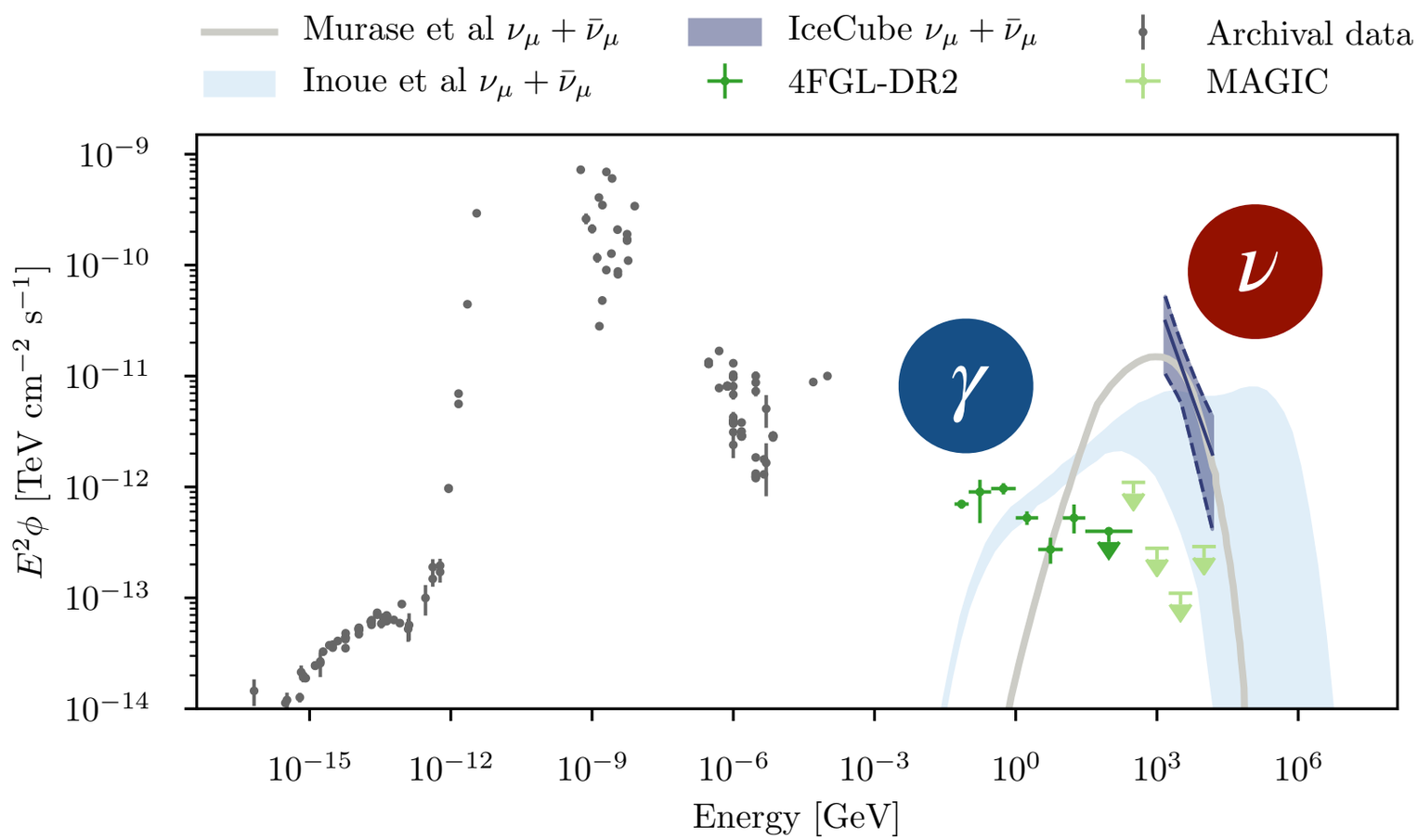
$$\tau_{\gamma\gamma} \simeq 1000\, f_{p\gamma}$$

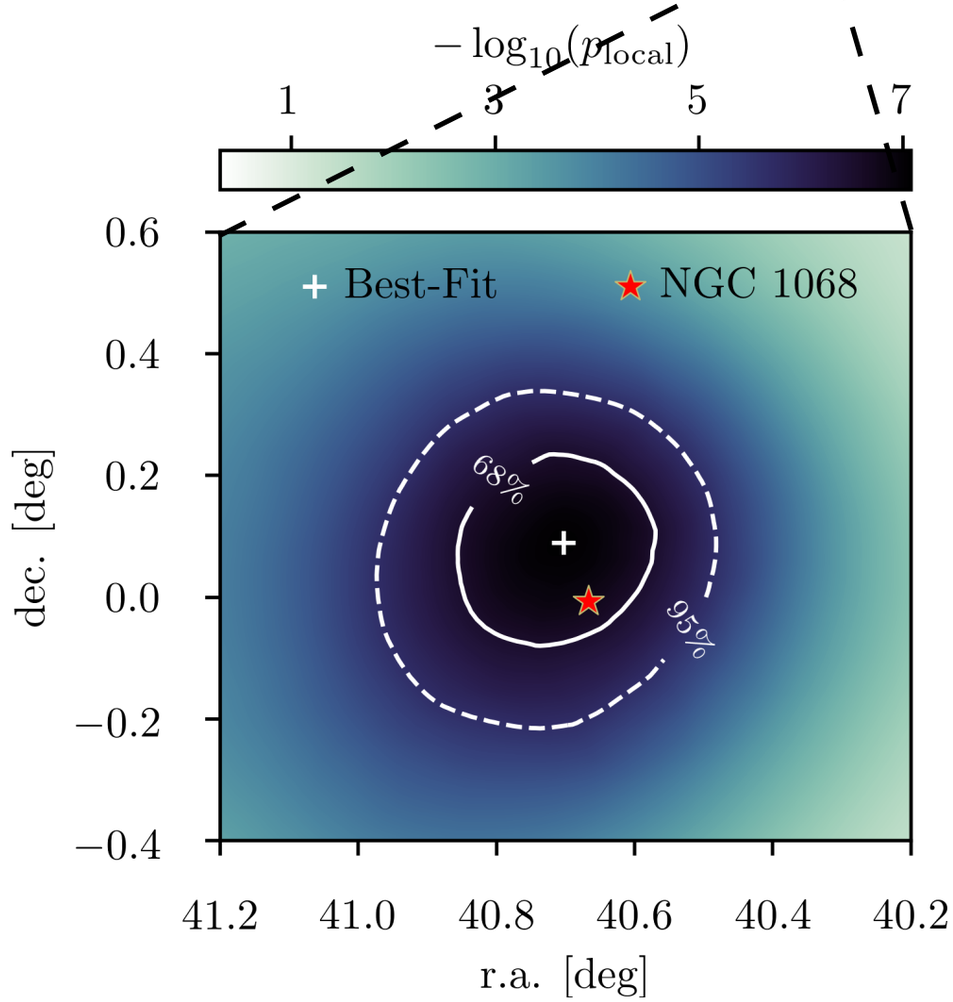
[Guetta, MA & Murase'16]

Excess from NGC 1068

Neutrino excess from Seyfert galaxy **NGC 1068** with a post-trial **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)**]

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

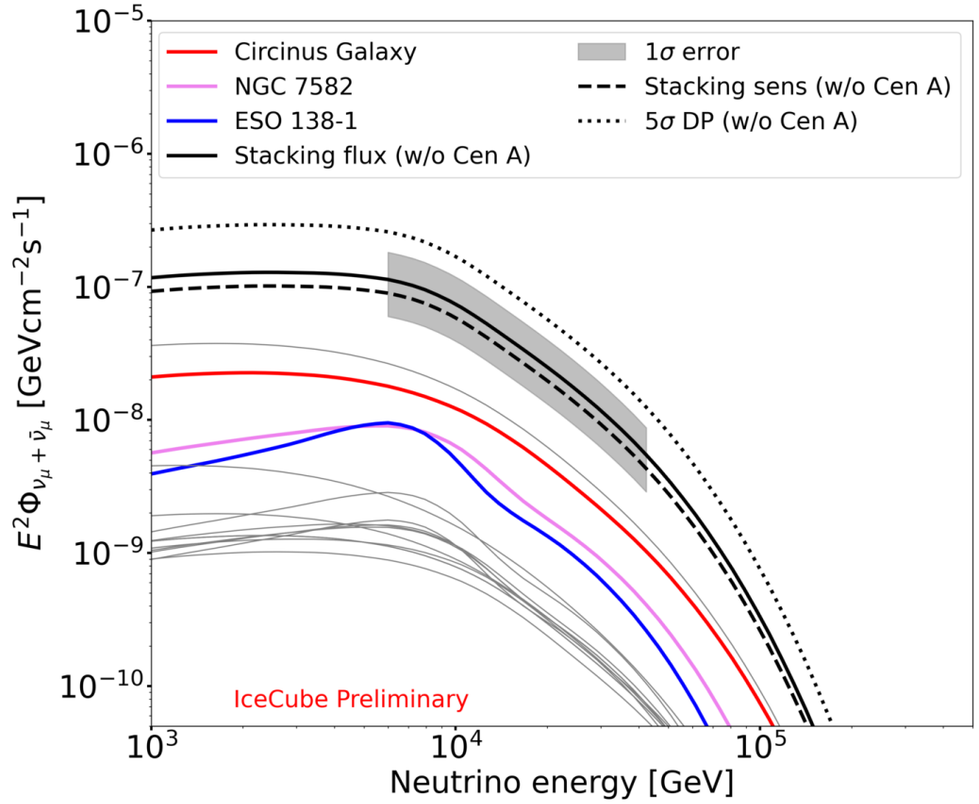
Hidden Cores of AGN

- Evidence (3σ) for neutrino emission of **X-ray bright Seyfert galaxies** in Southern Hemisphere.

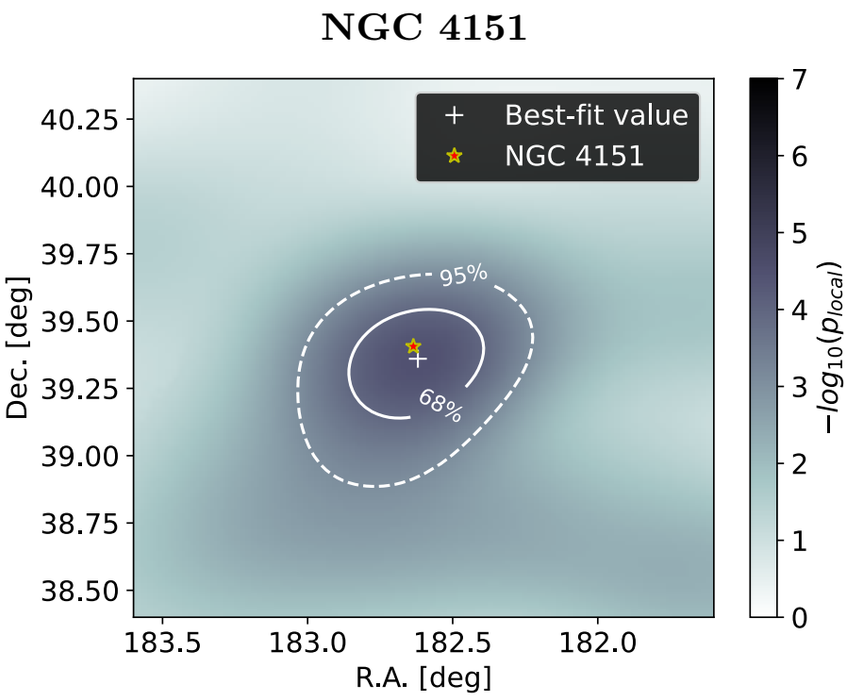
[IceCube, PoS(ICRC2025)1219]
[see also IceCube, ApJ (2025) 981 & ApJ (2025) 988]

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

[IceCube, ApJ (2025) 981]

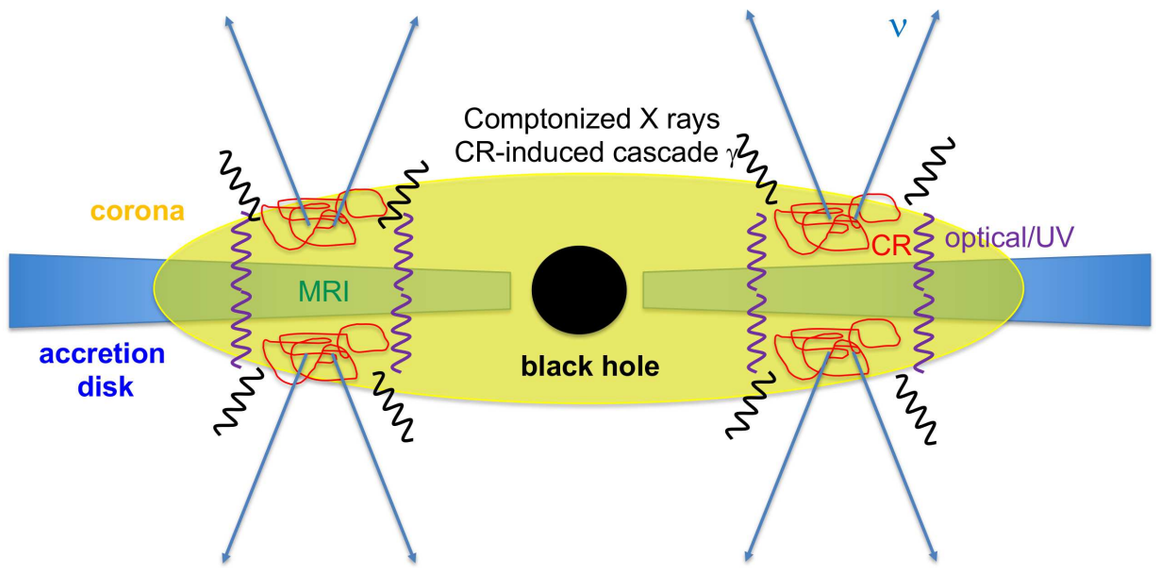


[IceCube, PoS(ICRC2025)1219]



[IceCube, ApJ (2025) 981]

disk-corona model



[Murase, Kimura & Meszaros '20]

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

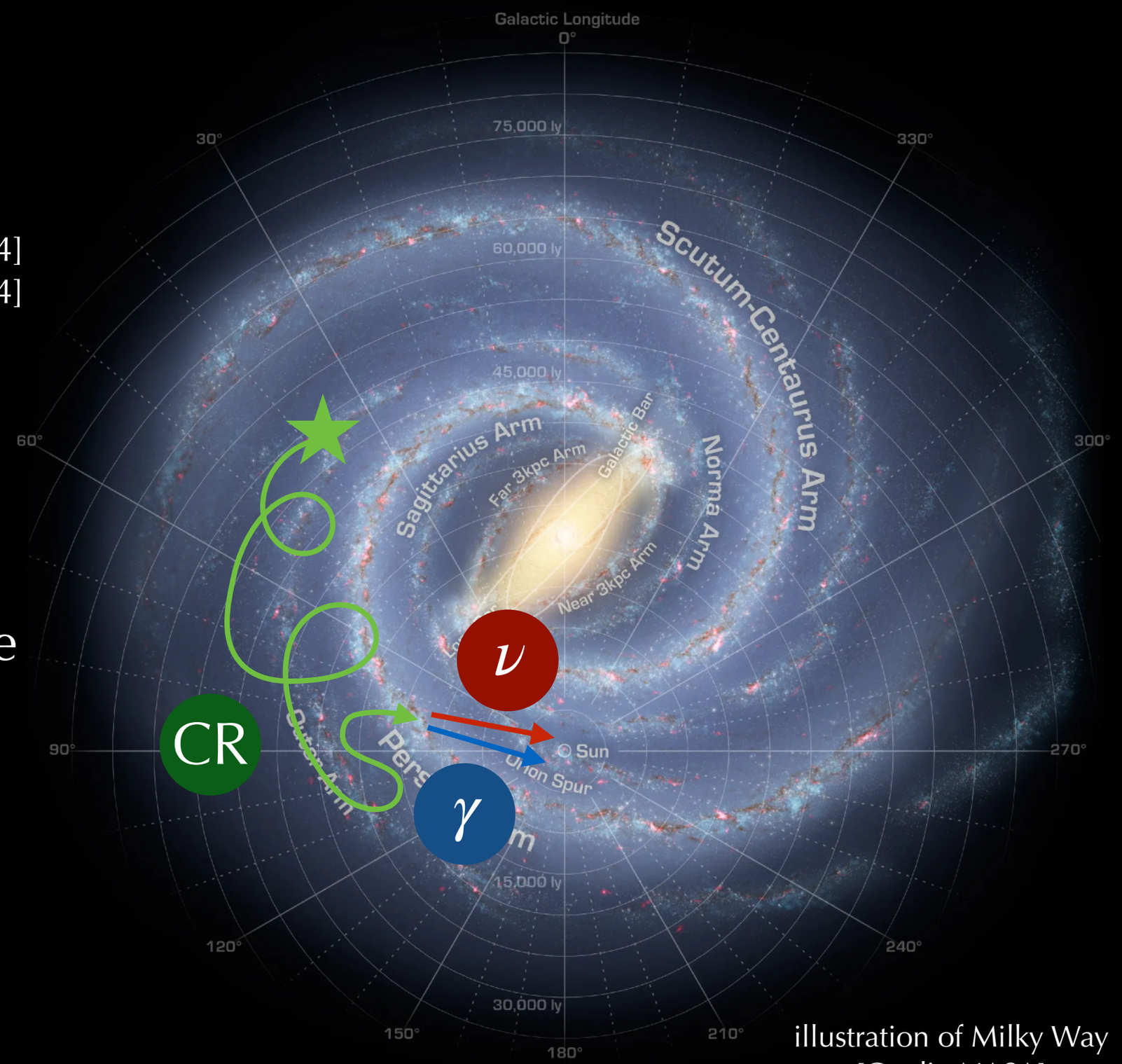
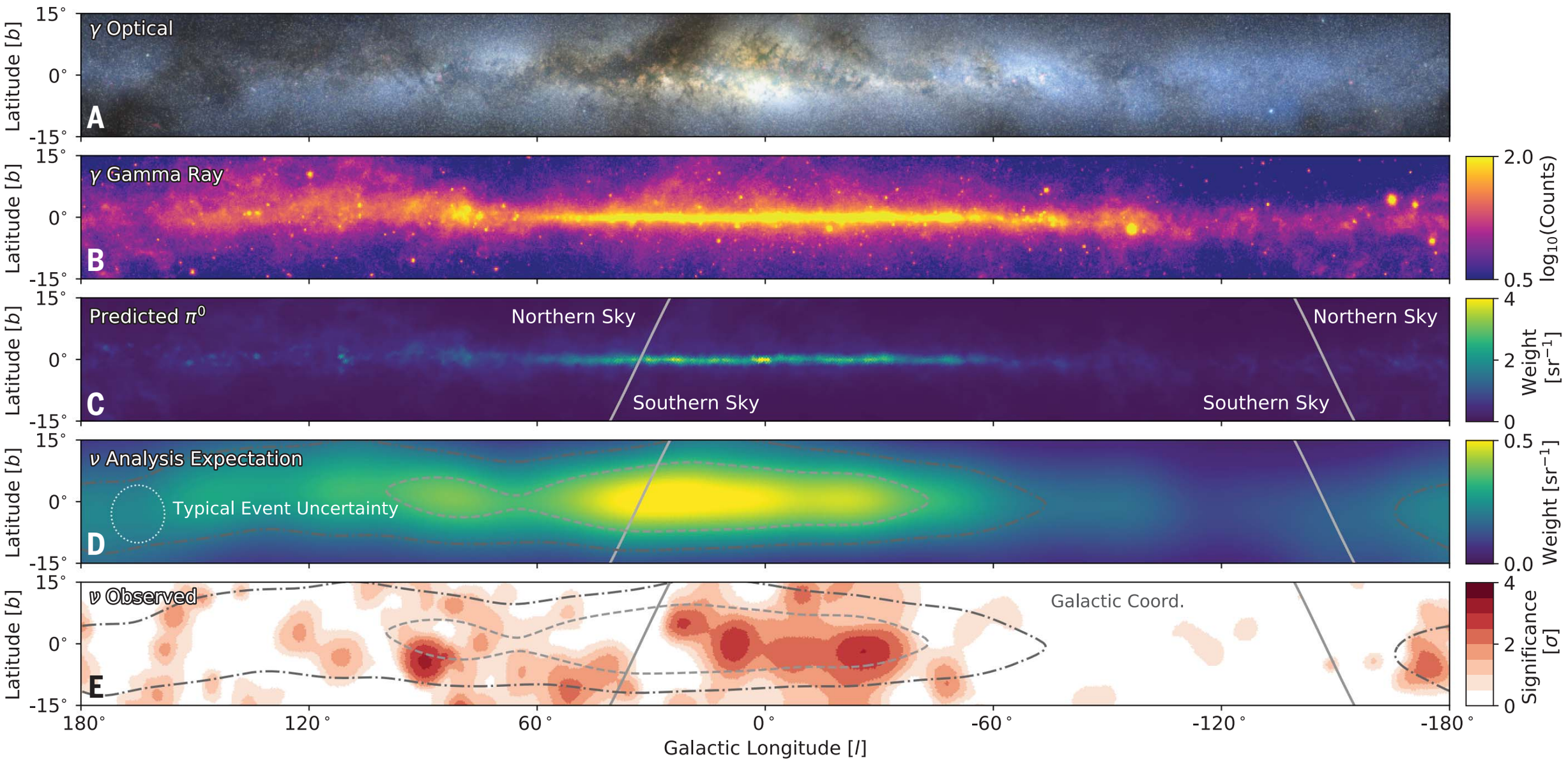


illustration of Milky Way
[Credit: NASA]

Galactic Neutrino Emission

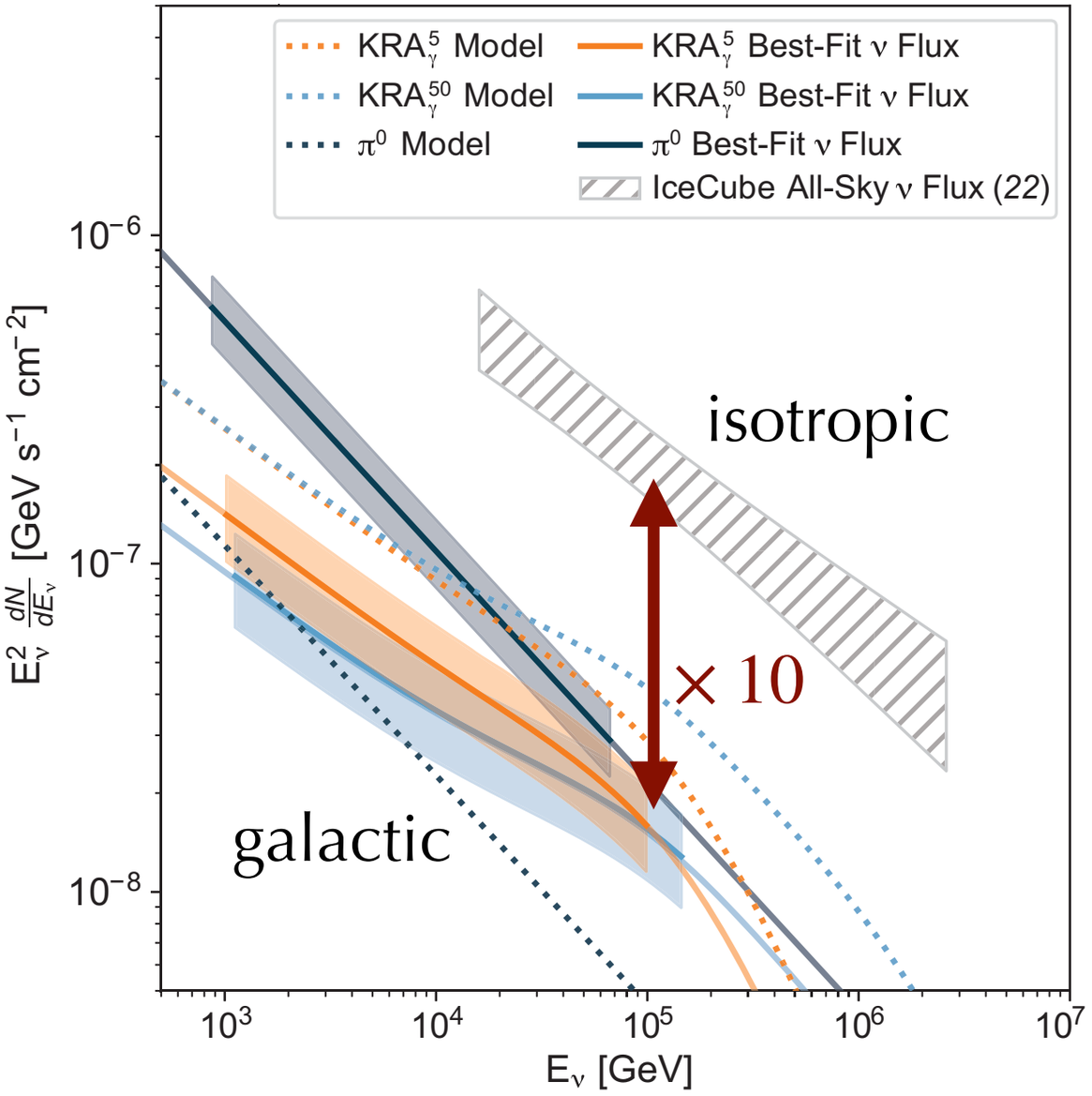
Galactic diffuse ν emission at 4.5σ based on template analysis.



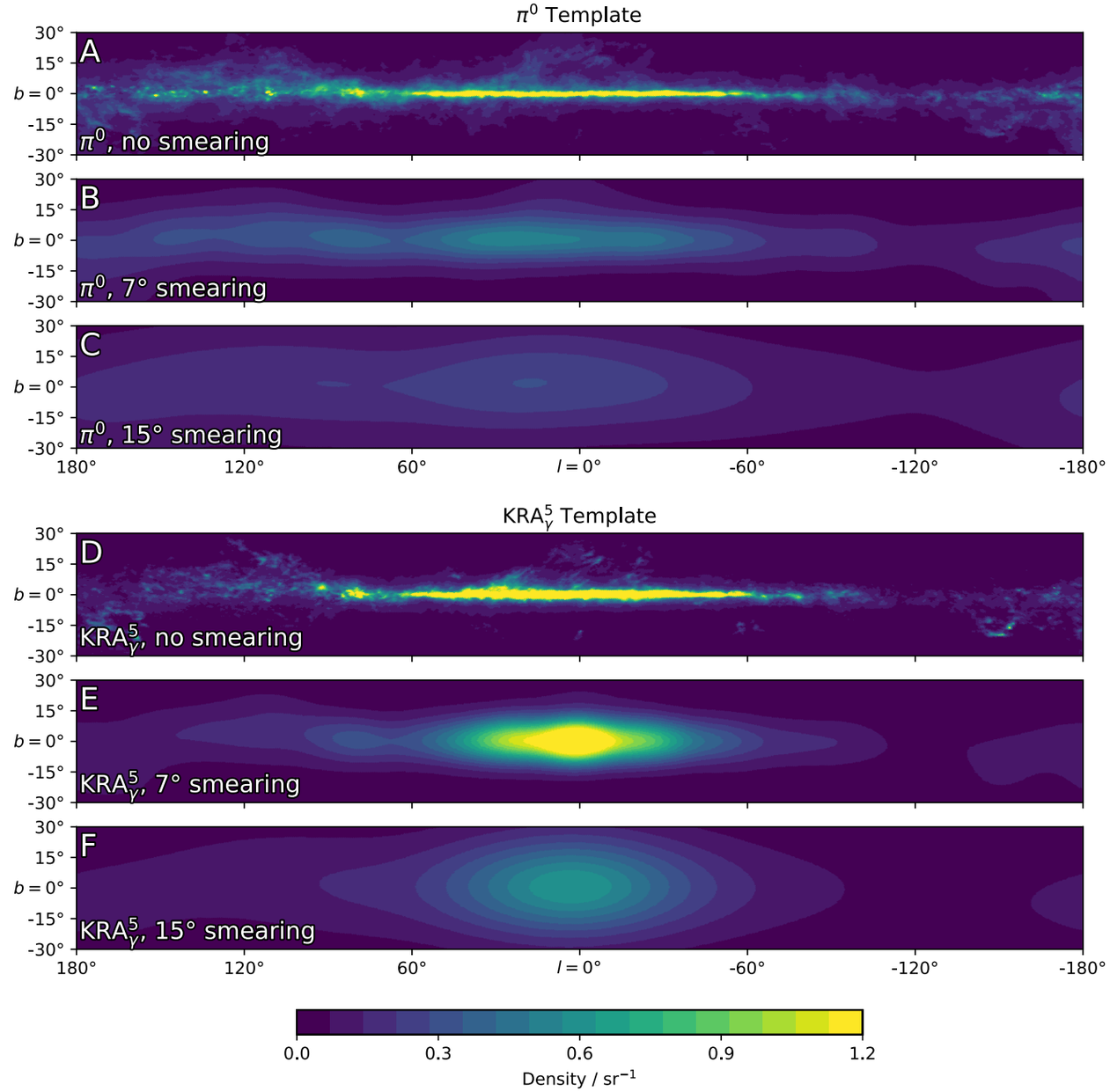
[IceCube **Science** 380 (2023)]

Galactic Neutrino Emission

Best-fit normalization of spectra

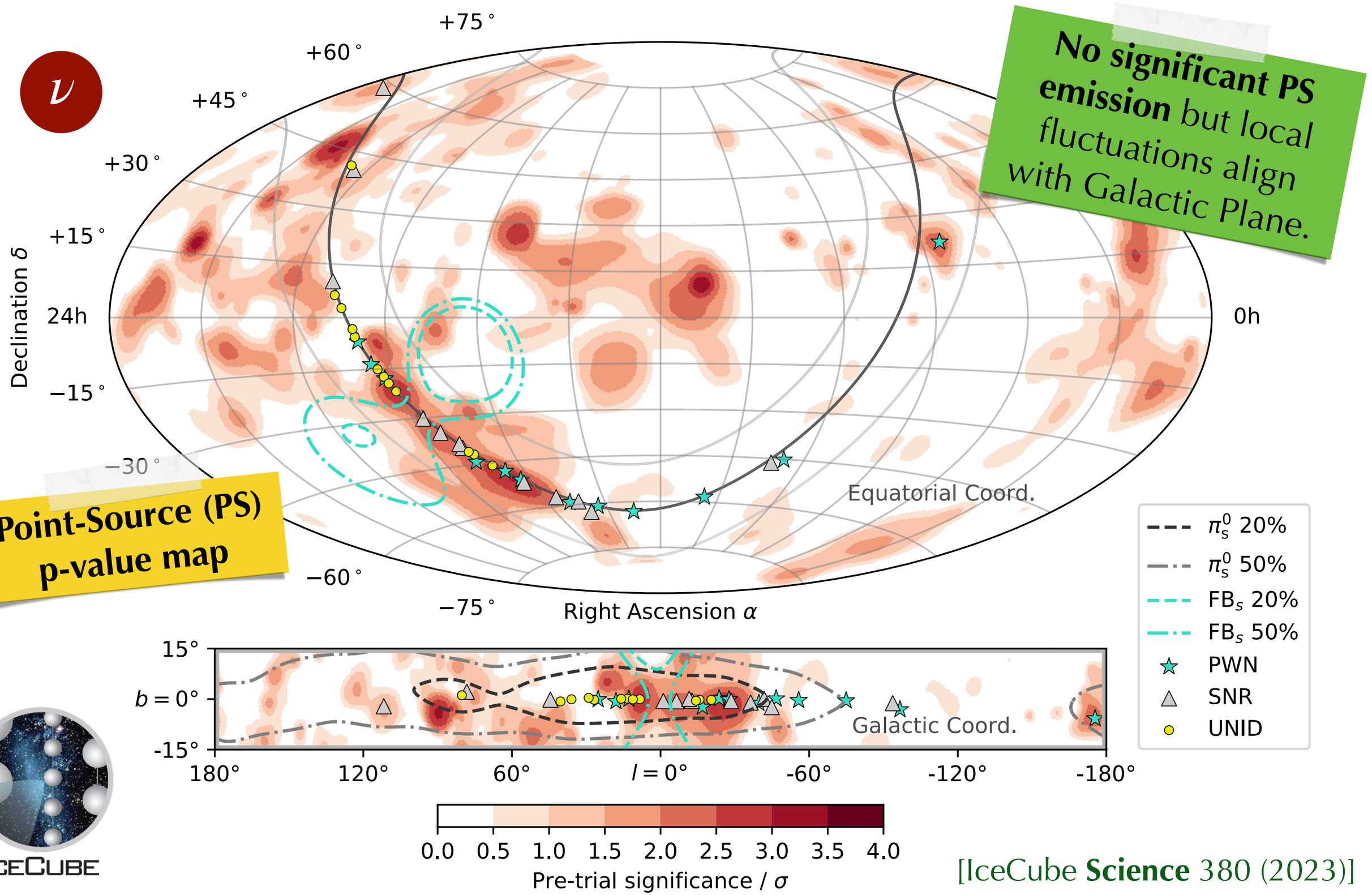


Templates with different resolution



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

Point-Source Significance Map



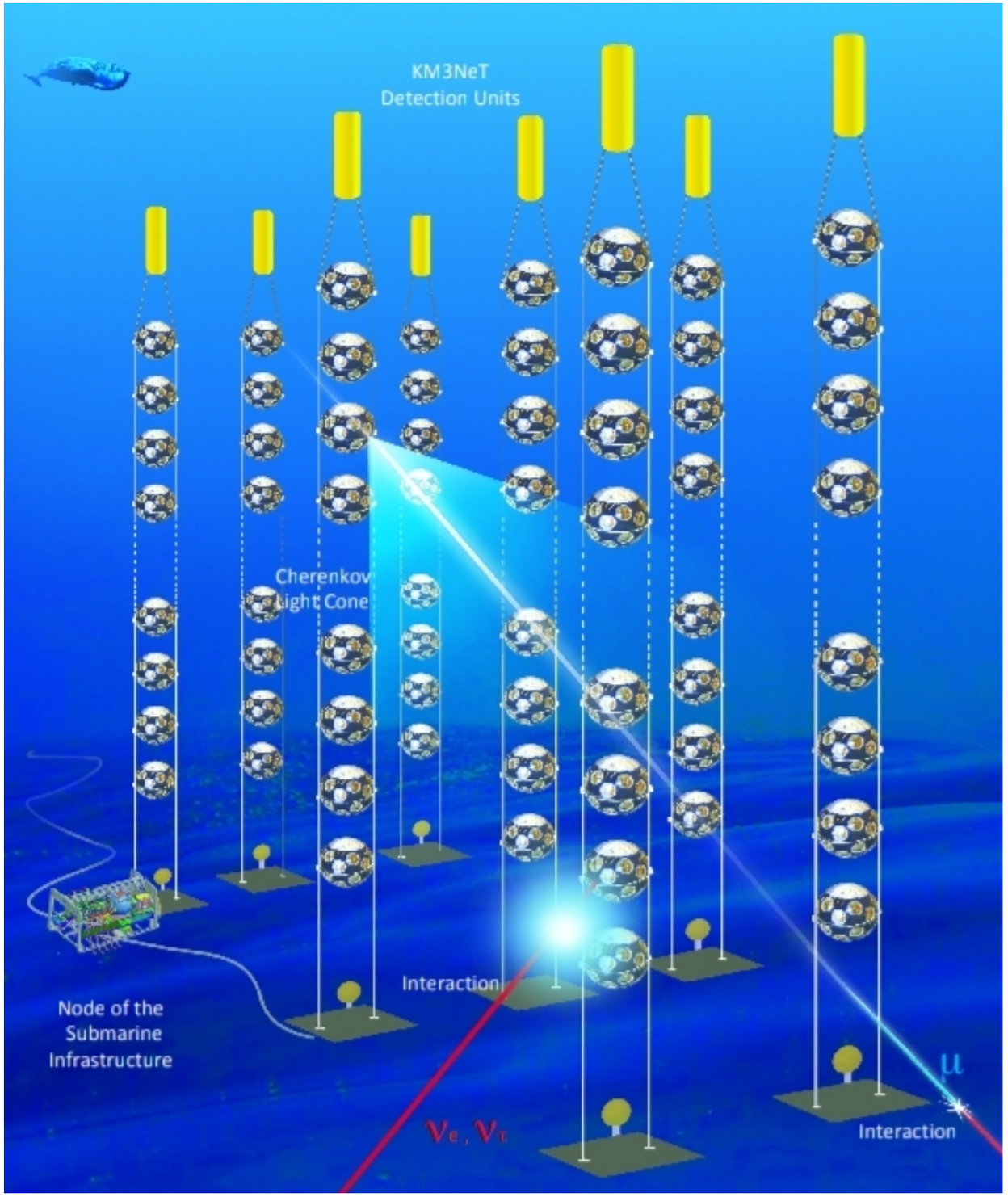
No significant PS emission but local fluctuations align with Galactic Plane.

Point-Source (PS) p-value map

IceCube

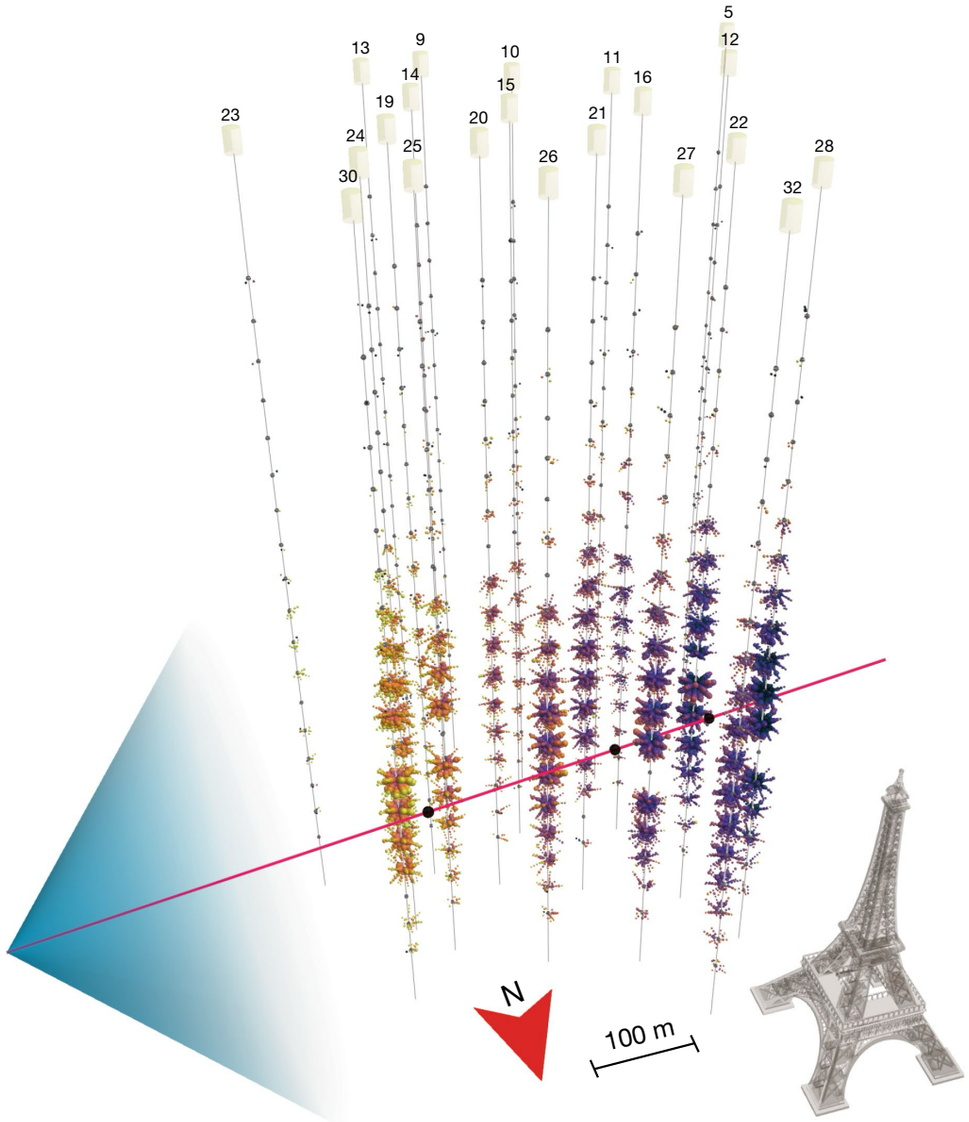
[IceCube **Science** 380 (2023)]

KM3NeT Observatory



- **ARCA :** 2 building blocks of 115 detection units (DUs) each
- **ORCA** : 115 DUs optimized for low-energy (GeV) and oscillation analyses
- *status May 2025* : 33 DUs in ARCA and 28 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

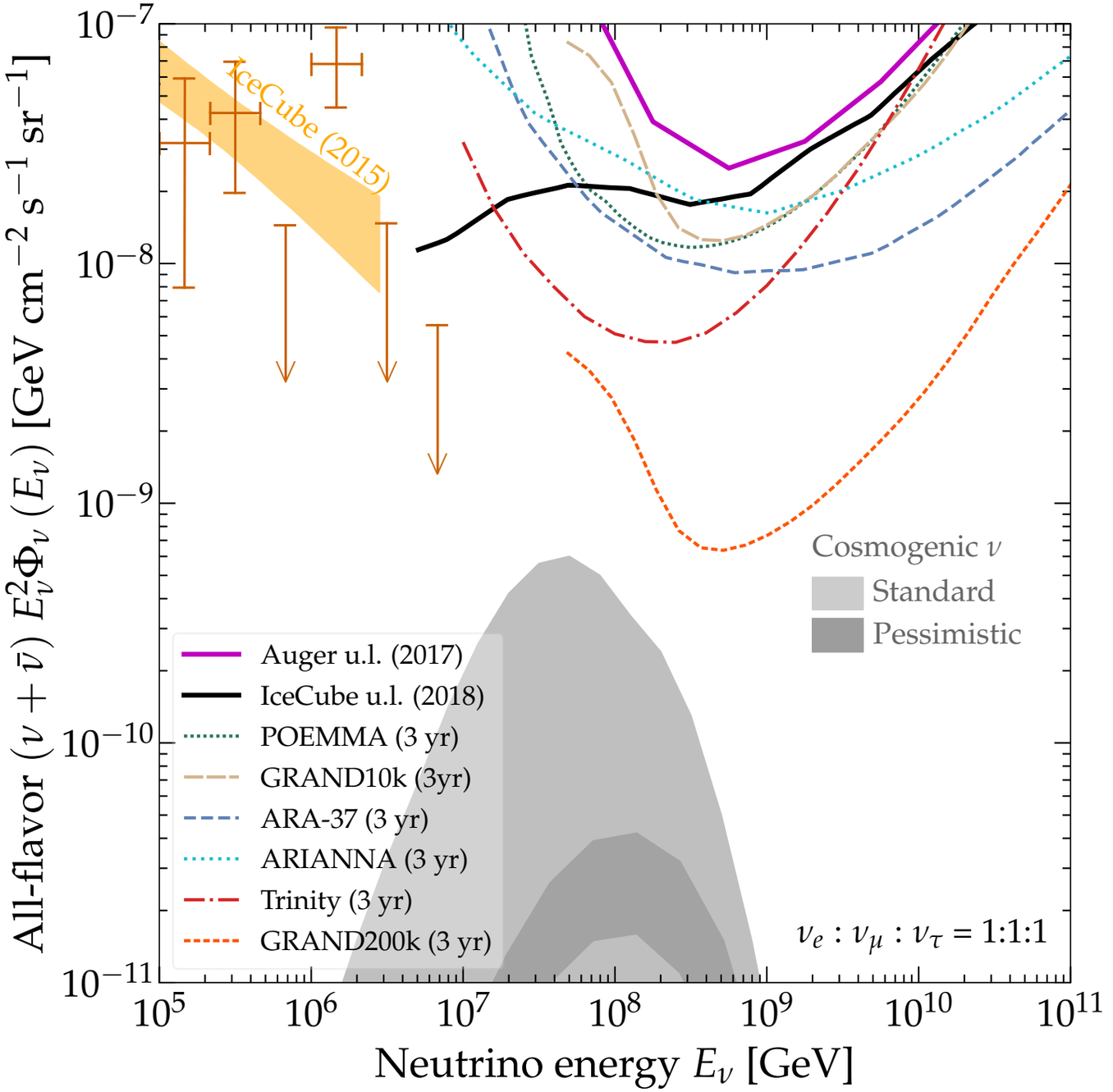
February 13, 2023

- 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; arXiv:2502.08173]

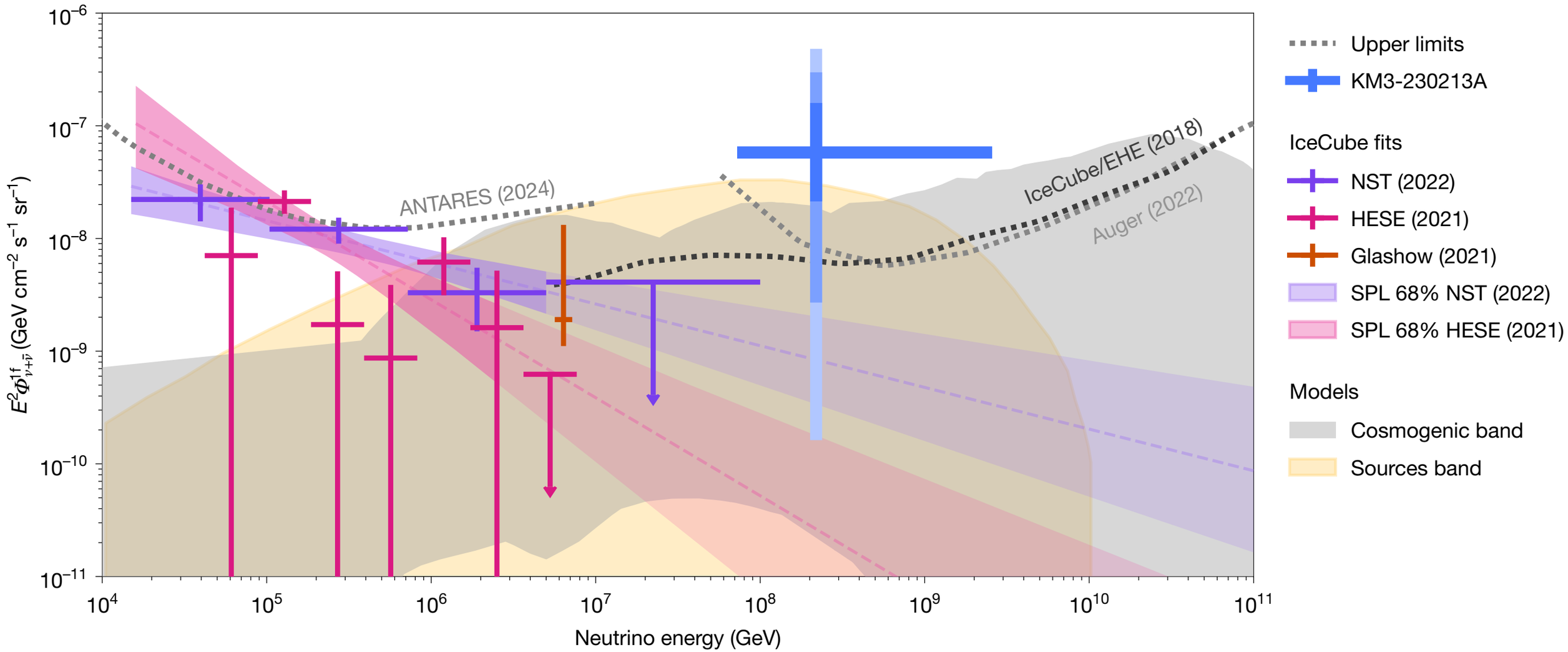
Cosmogenic Neutrinos

- Cosmogenic (GZK) neutrinos produced in UHE CR interactions peak in the EeV energy range.
- Target of proposed in-ice **Askaryan** (ARA & ARIANNA), air shower **Cherenkov** (GRAND) or **fluorescence** (POEMMA & Trinity) detectors.
- Optimistic predictions based on high proton fraction and high maximal energies.
- Absolute flux level serves as **independent measure of UHE CR composition** beyond 40EeV.



[Alves Batista *et al.*'19]

KM3-230213A



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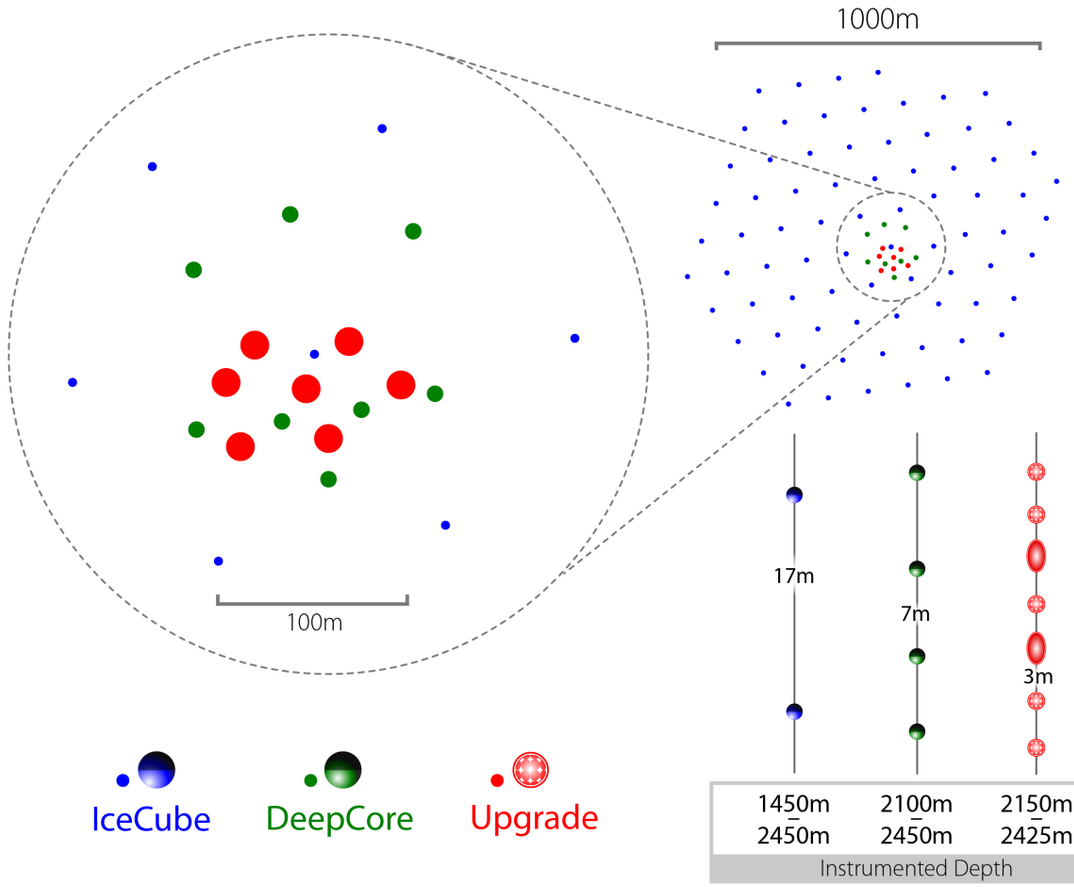
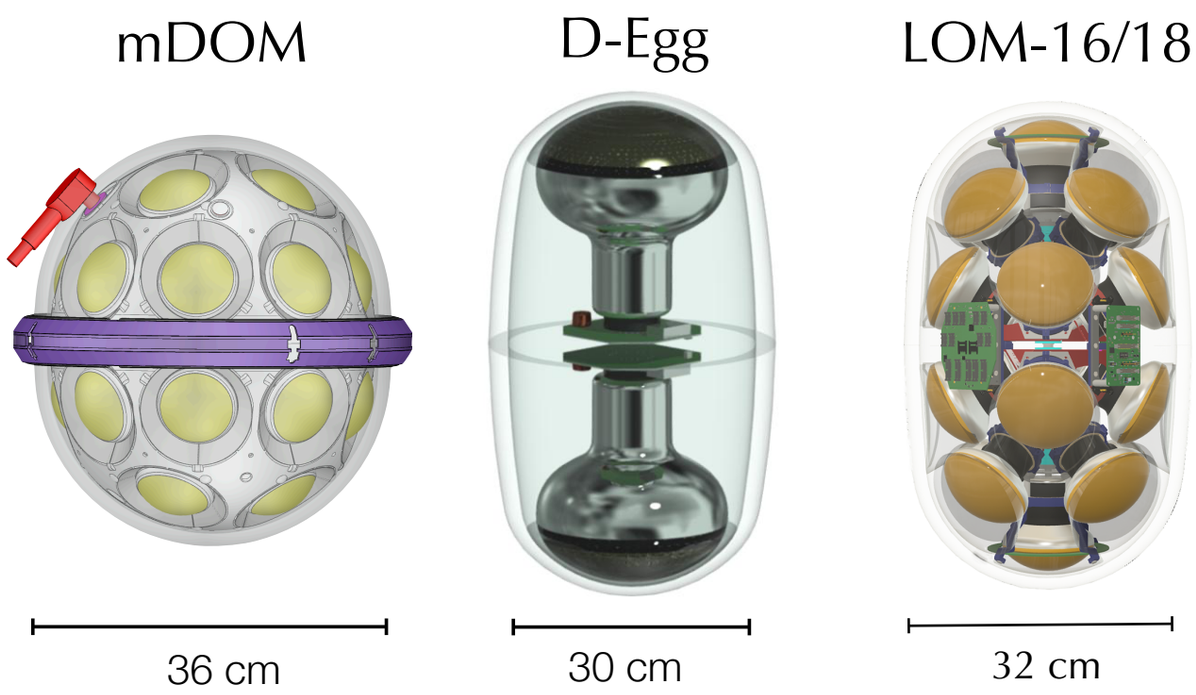
- Flux is in tension with upper limits of IceCube and Auger ($2.5 - 3\sigma$)

[KM3NeT, *Nature* 638 (2025) 8050; arXiv:2502.08173]

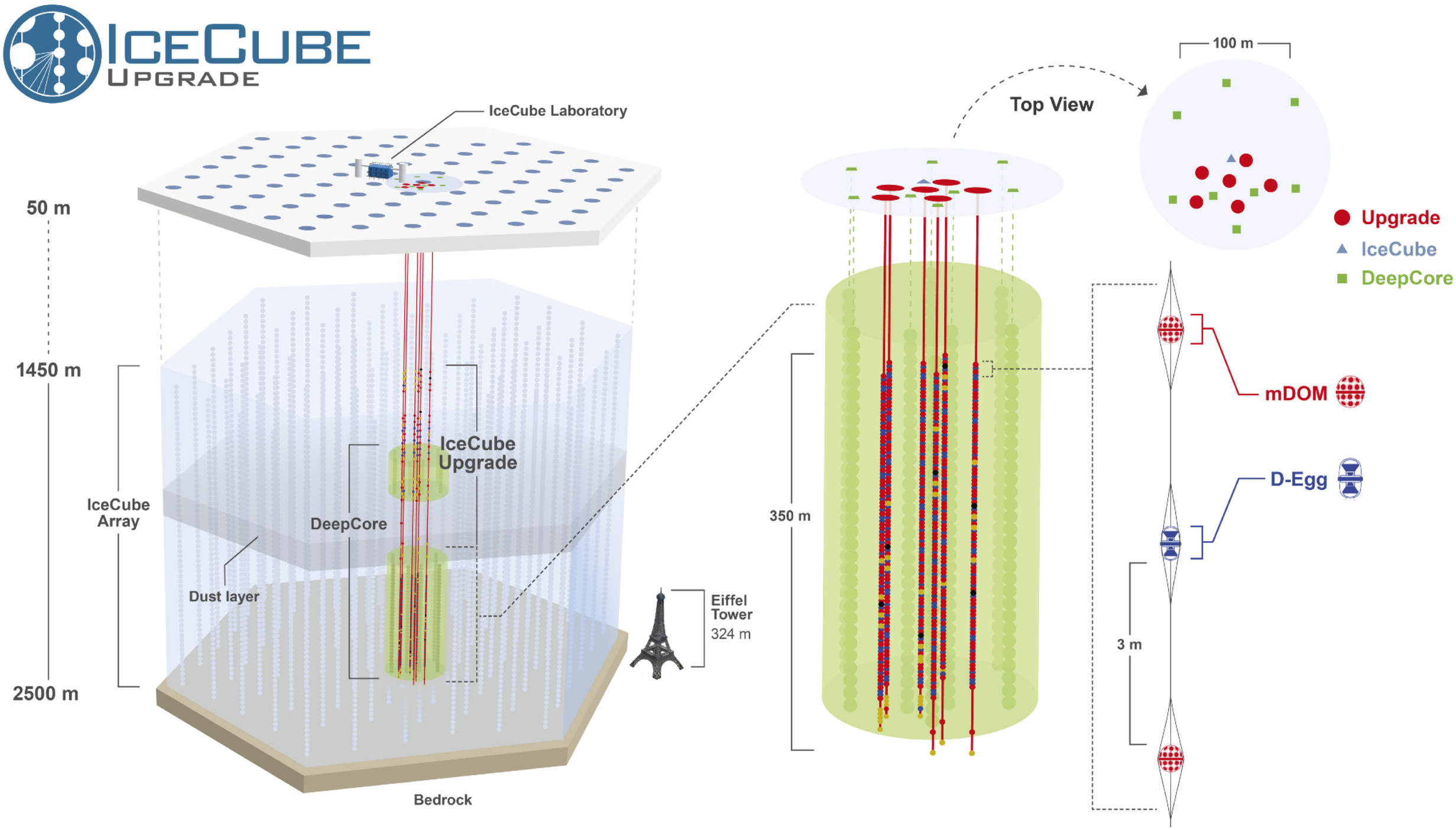
IceCube Upgrade

- *Goal:* 7 **new strings** in the DeepCore region (~20m 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.
- **Deployment finished in February!**



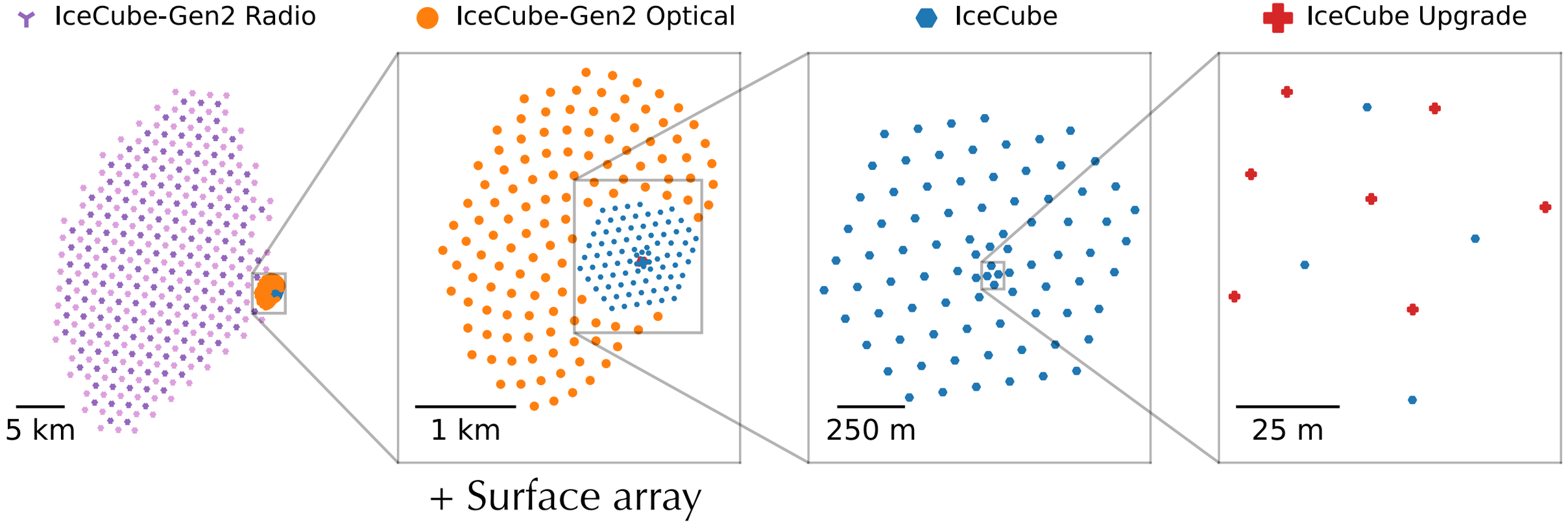


IceCube Upgrade



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 >10 PeV neutrino detection
- *price:* mostly comparable to IceCube-Gen1 when corrected for inflation



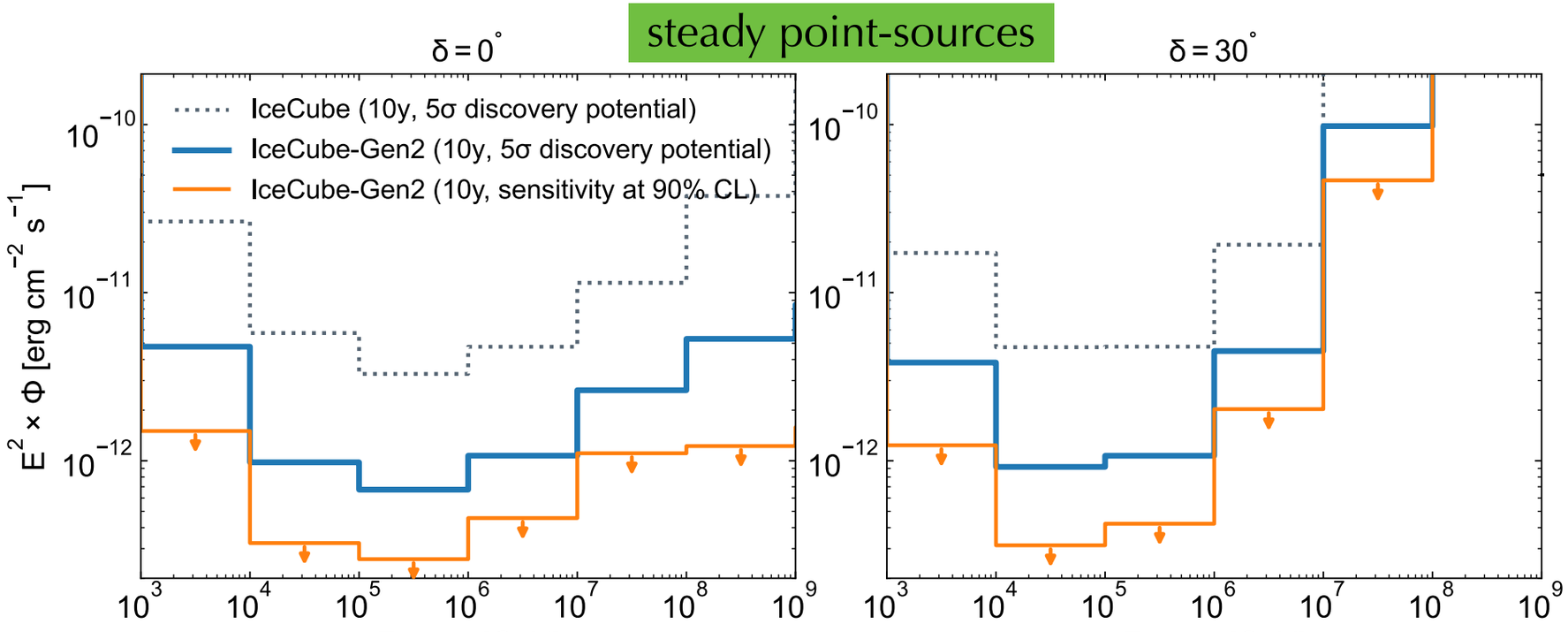
[IceCube-Gen2 *Technical Design Report:* icecube-gen2.wisc.edu/science/publications/tdr/]

Vision: IceCube-Gen2

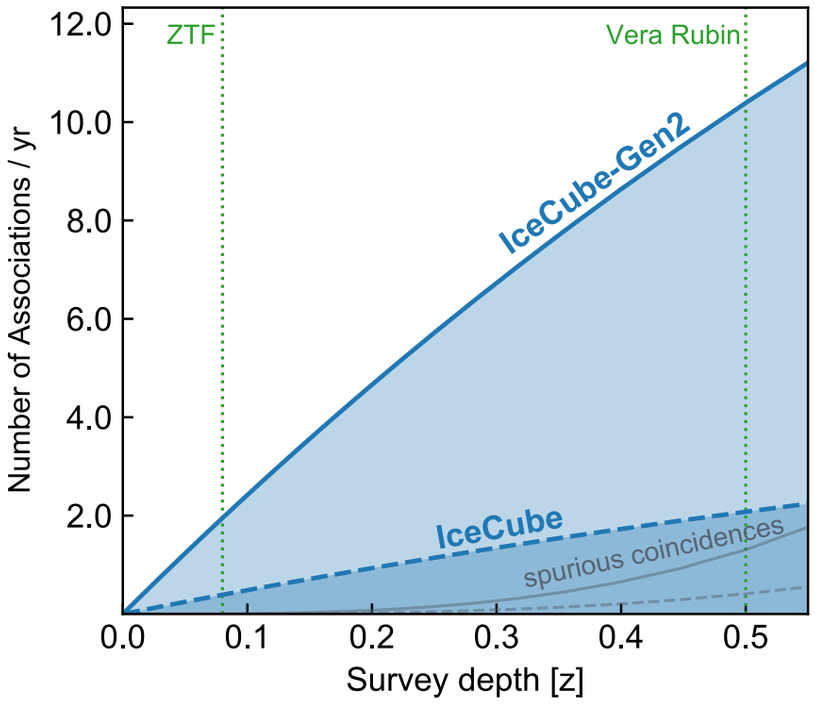
Discovery potentials of IceCube vs. IceCube-Gen2

[IceCube-Gen2 TDR]

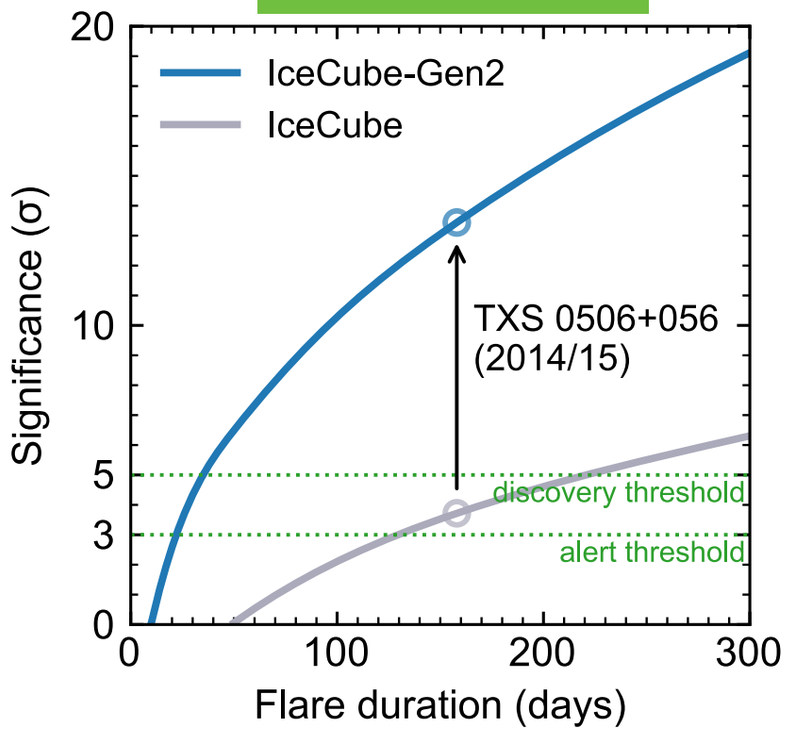
steady point-sources



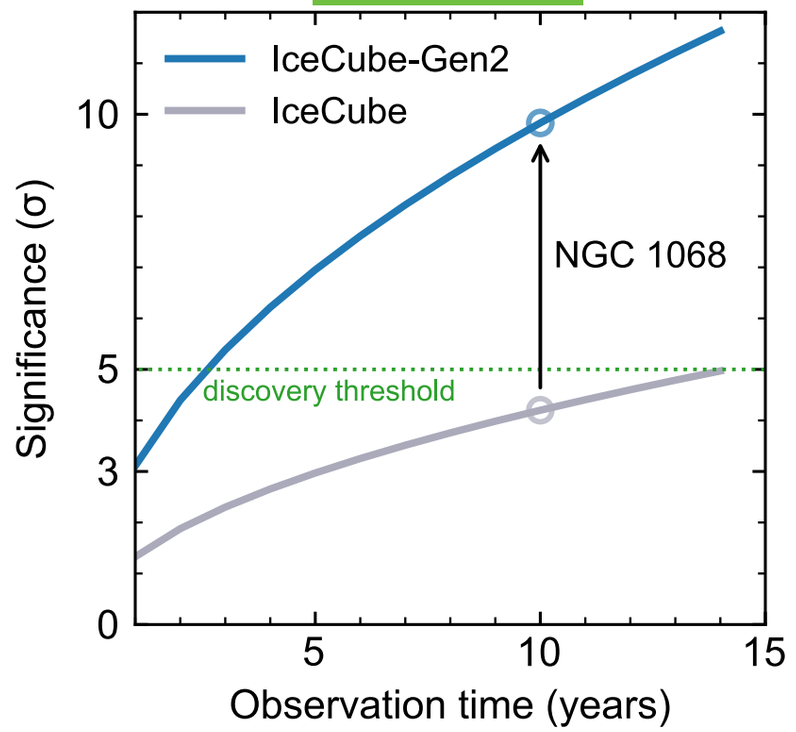
TDEs



TXS 0506+056



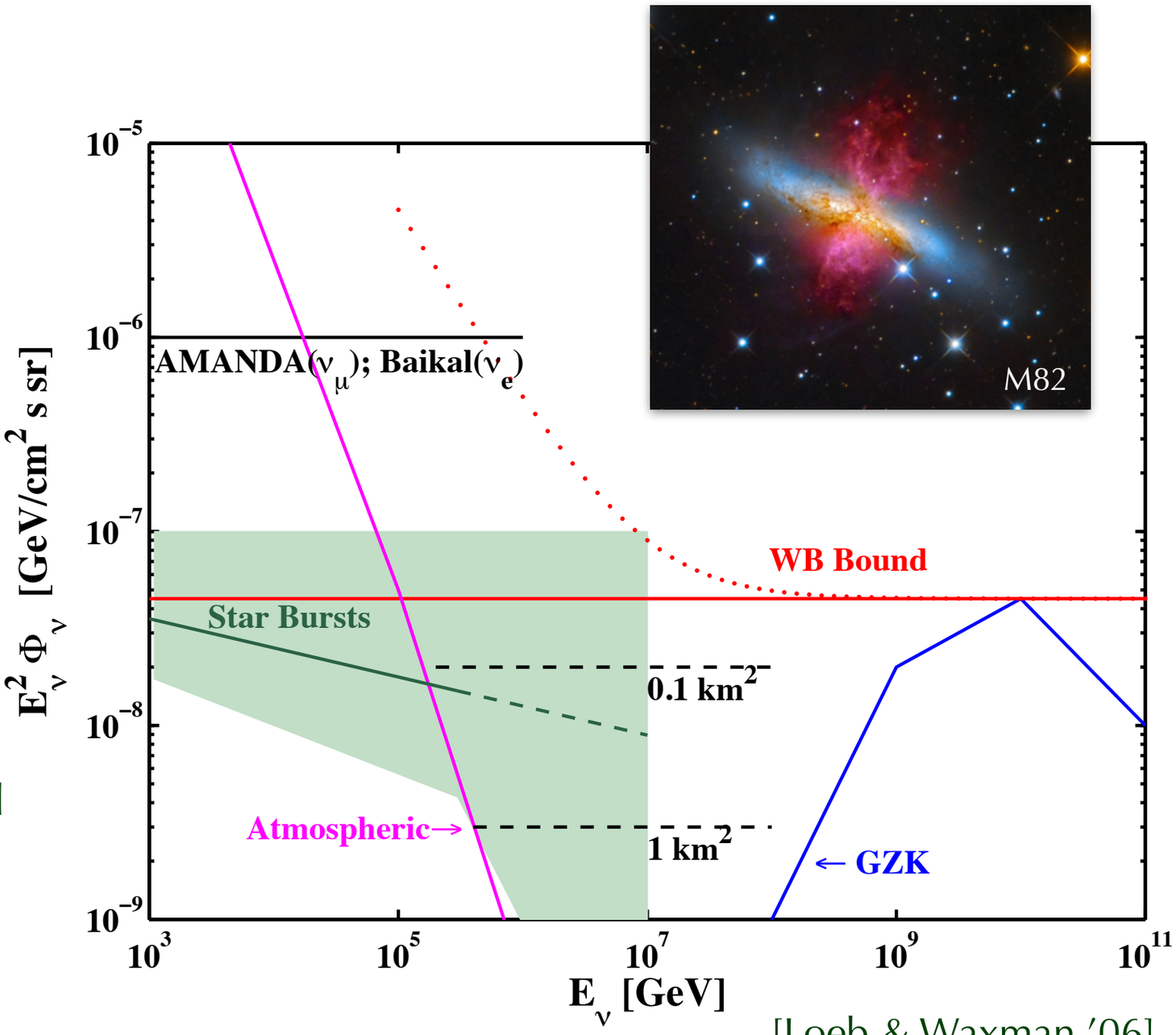
NGC 1068



Backup Slides

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.



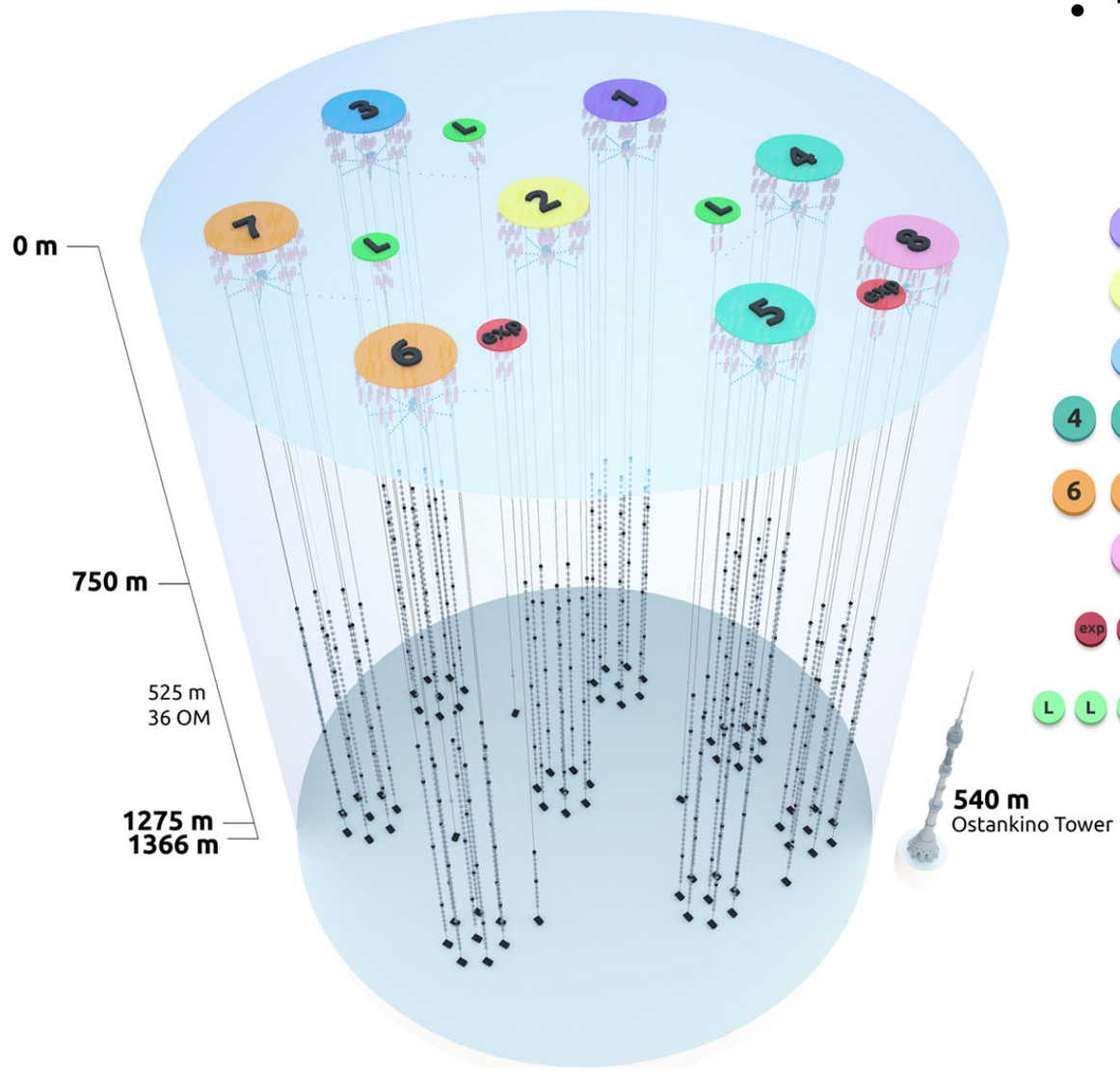
[Loeb & Waxman '06]

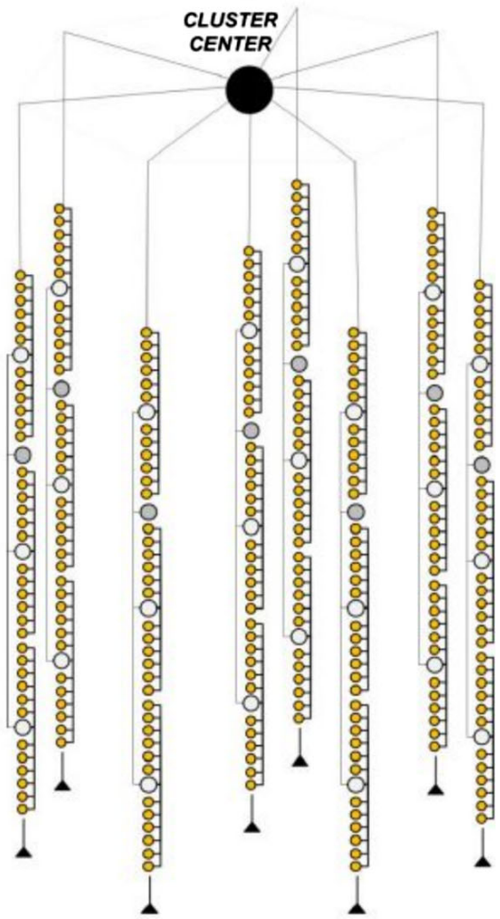
[Romero & Torres'03; Liu, Wang, Inoue, Crocker & Aharonian'14; Tamborra, Ando & Murase'14]
[Palladino, Fedynitch, Rasmussen & Taylor'19; Peretti, Blasi, Aharonian, Morlino & Cristofari'19]
[Ambrosone, Chianese, Fiorillo, Marinelli, Miele & Pisanti'20]

Outlook: Baikal-GVD

BAIKAL-GVD

- **GVD Phase 1:** 8 clusters with 8 strings each were completed in 2021
- **status May 2025: 14 clusters**
- **final goal**: 27 clusters ($\sim 1.4\,\mathrm{km}^3$)

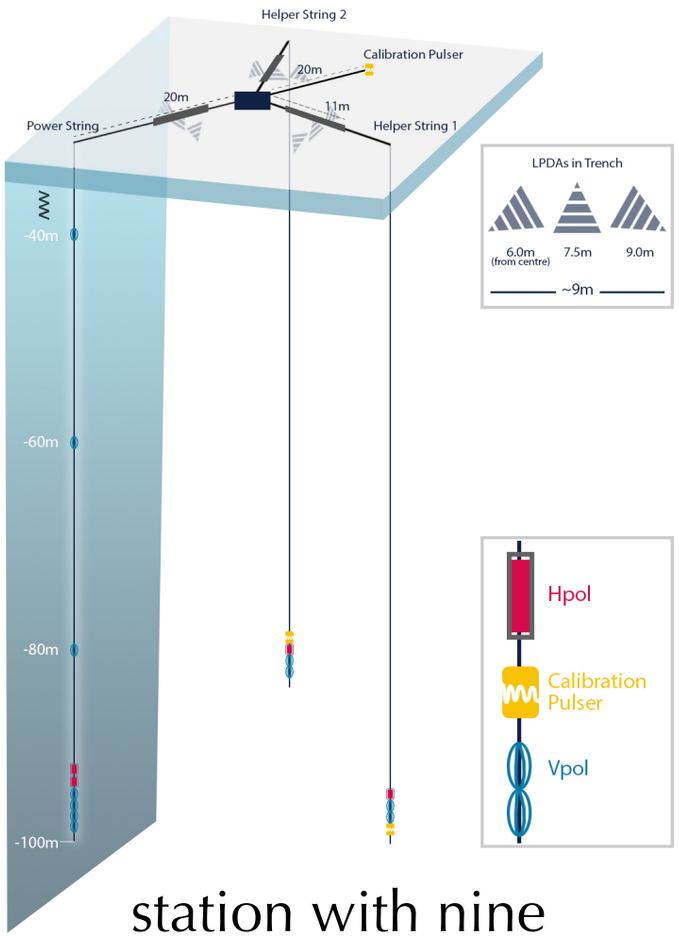




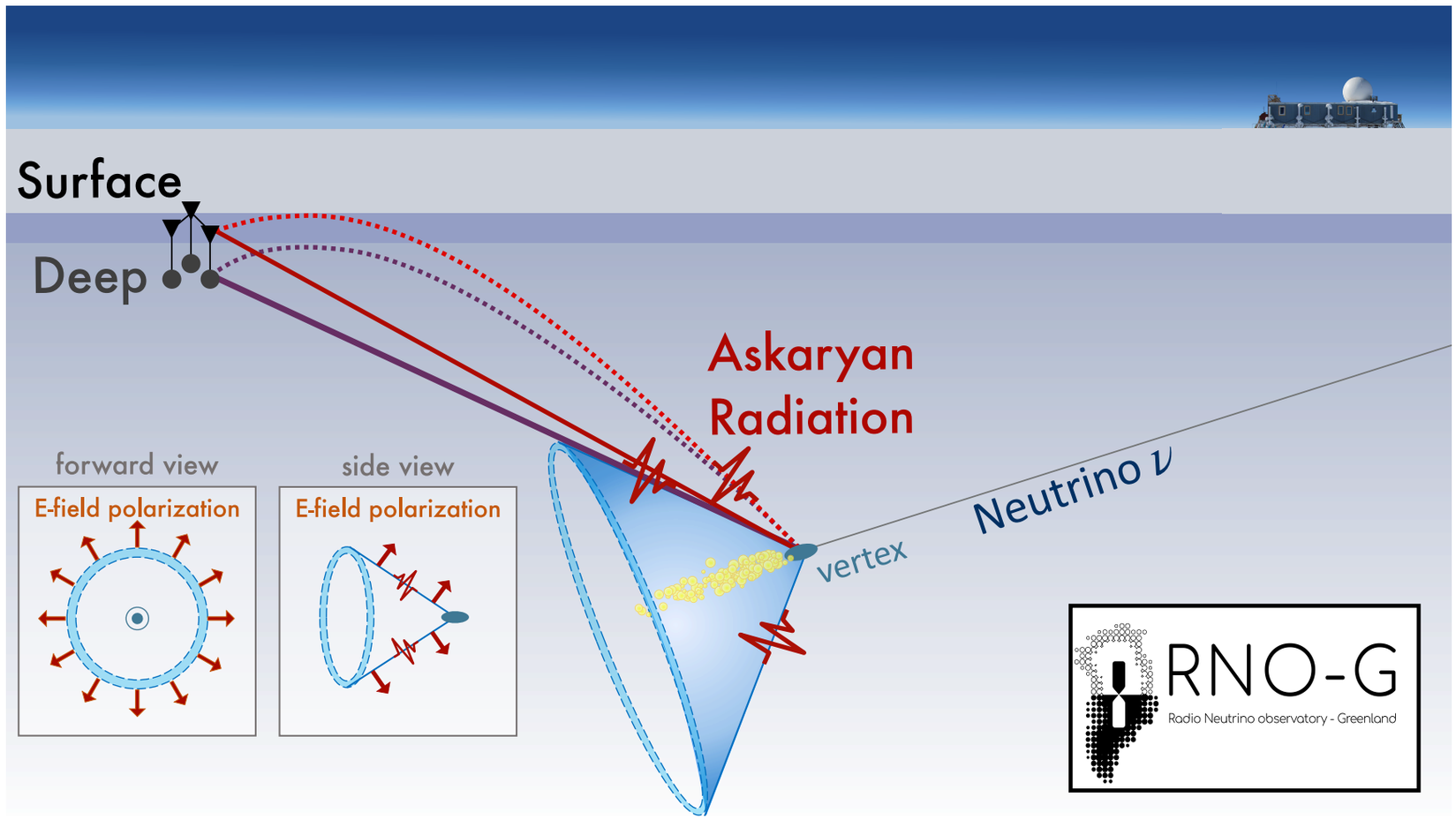
Outlook: RNO-G

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

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

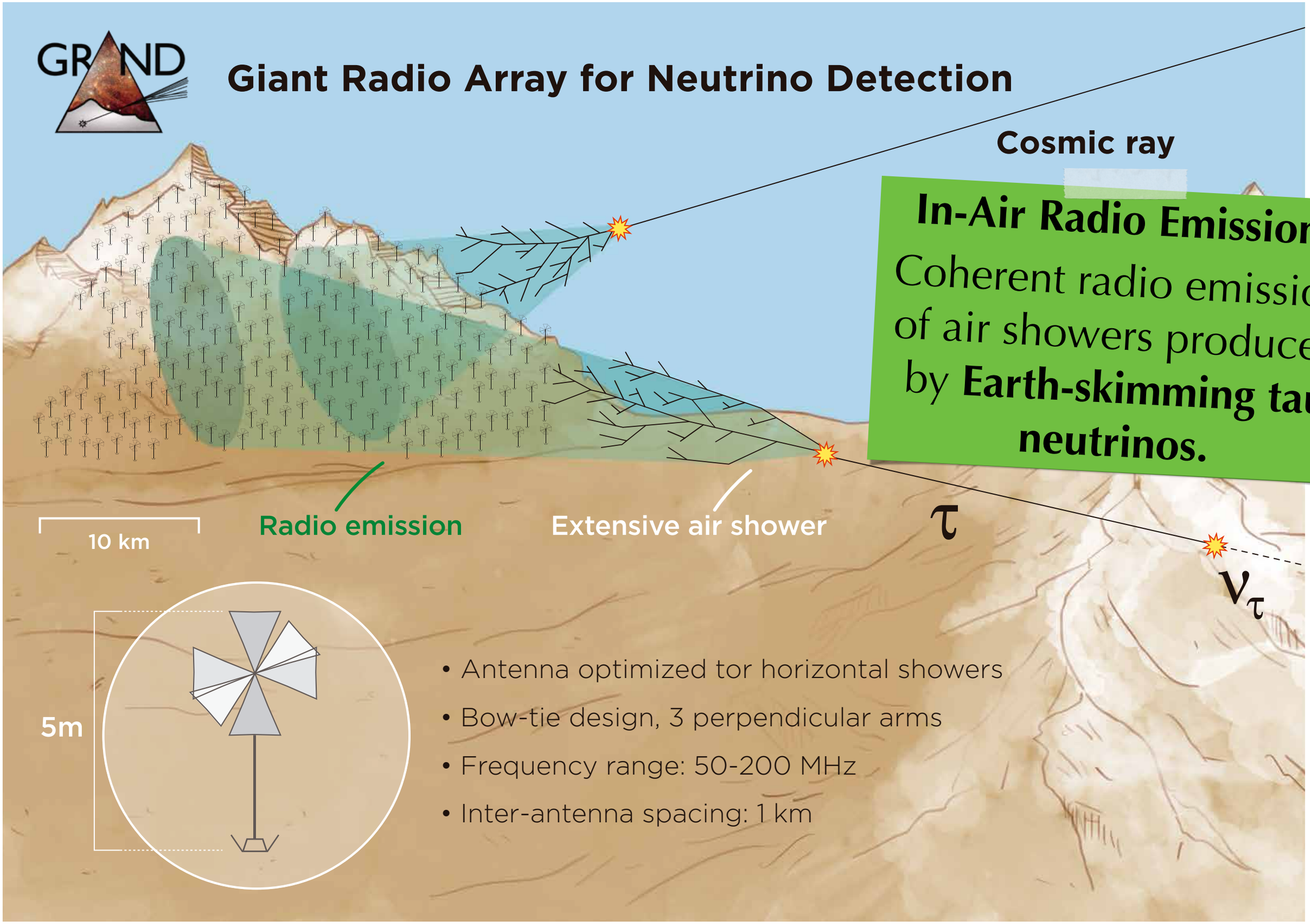


station with nine deep & surface antennas



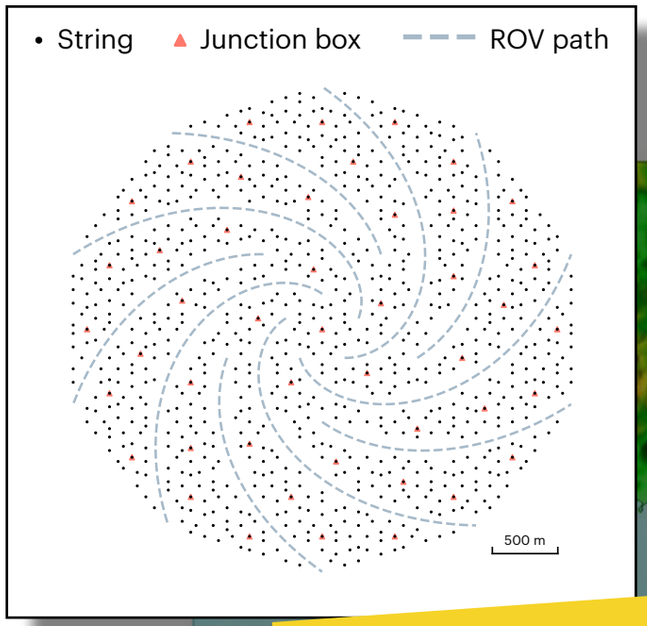
[RNO-G JINST 16 (2021) 3]

Vision: GRAND



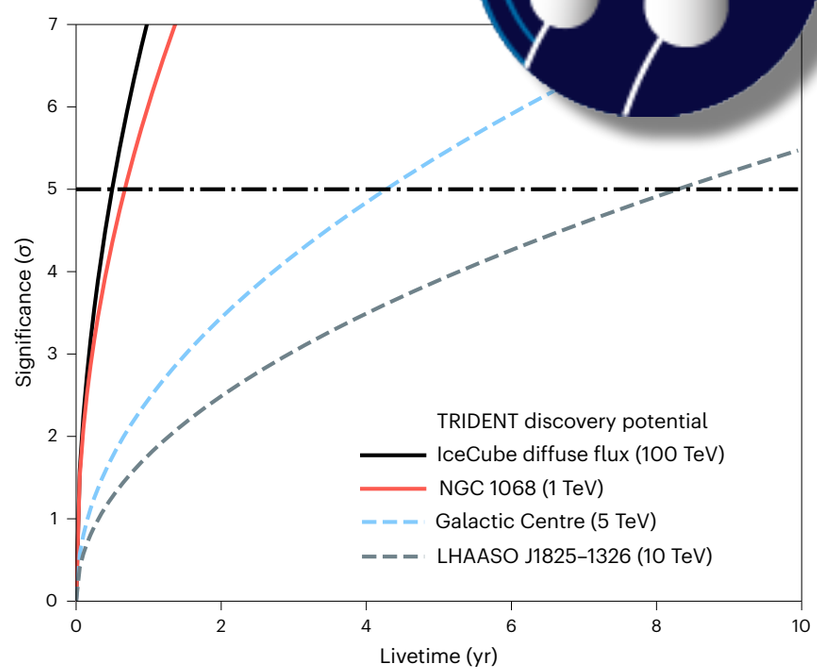
[GRAND SCPMA 63 (2020) 1]

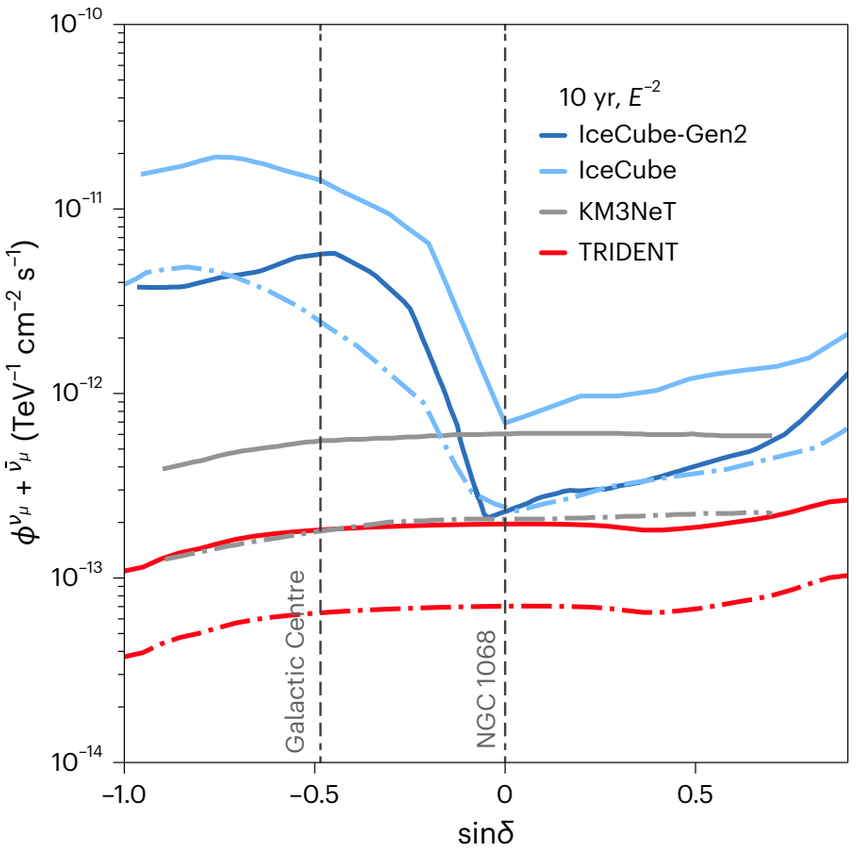
Vision: TRIDENT



South China Sea: 17.4° N
1211 strings with 20 DOMs
instrumented volume: 7.5 km^3

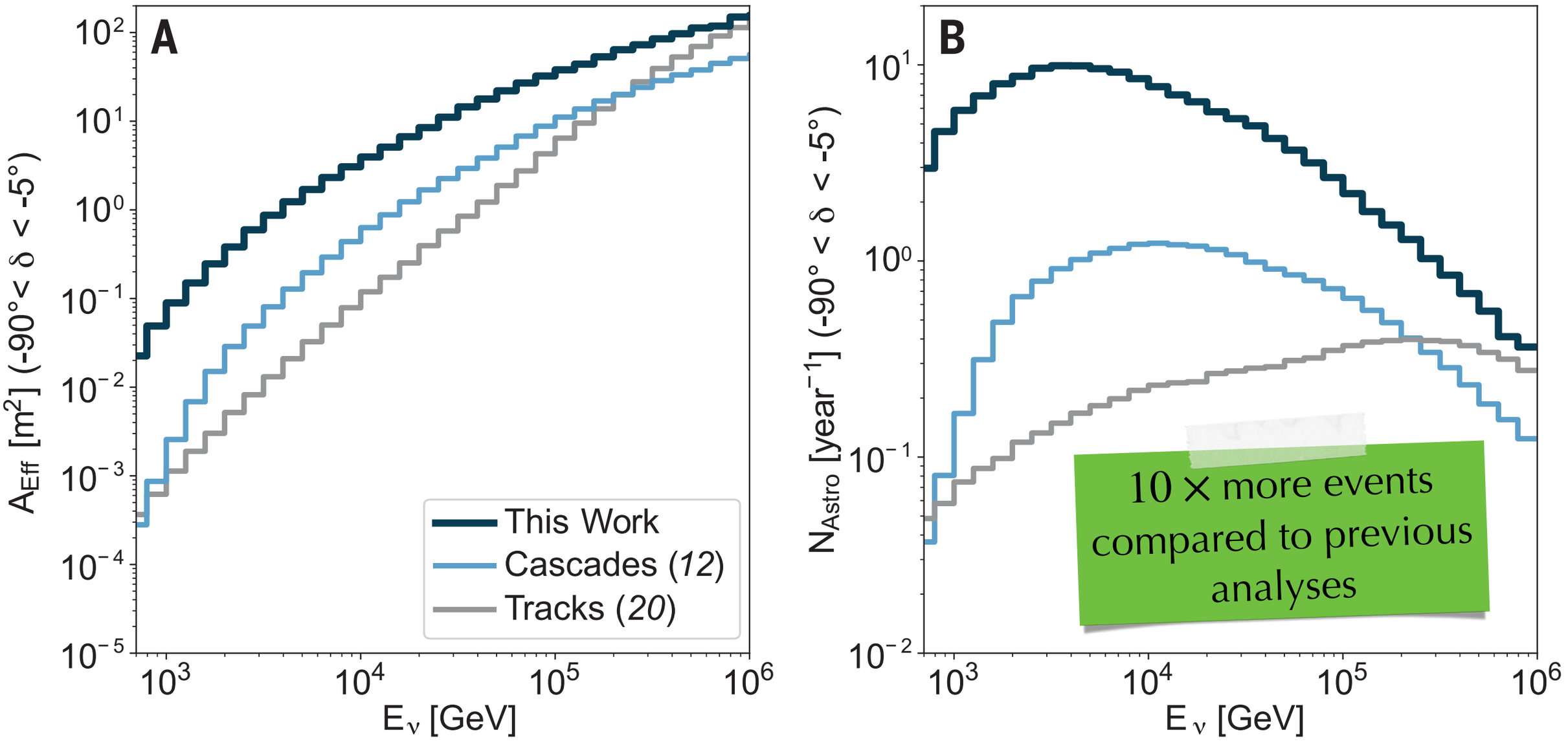
[TRIDENT Nature Astron. 7 (2023) 12]





DNNcascade Sample

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



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

DNNcascade Sample

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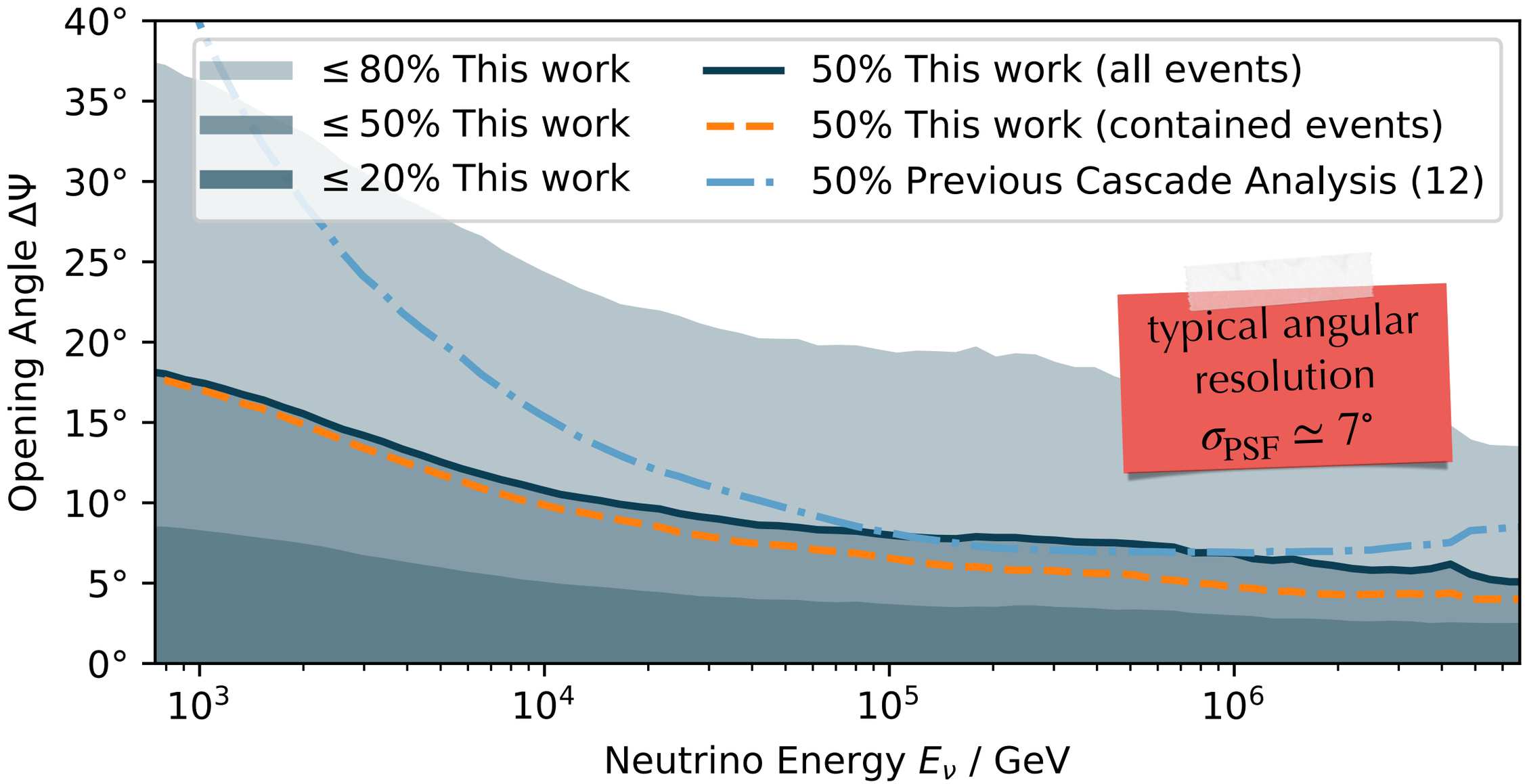
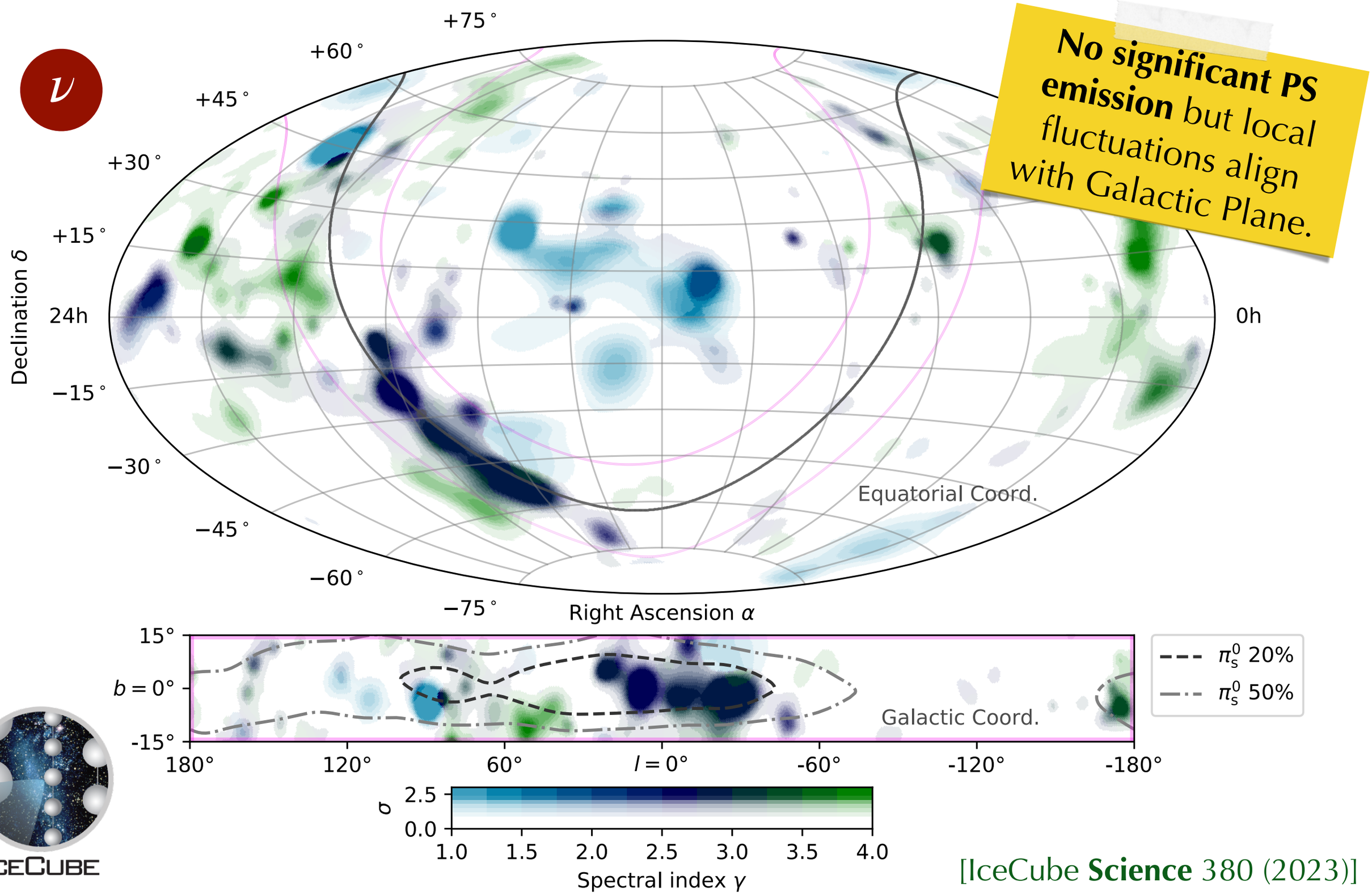


[IceCube **Science** 380 (2023)]

Point-Source Significance Map

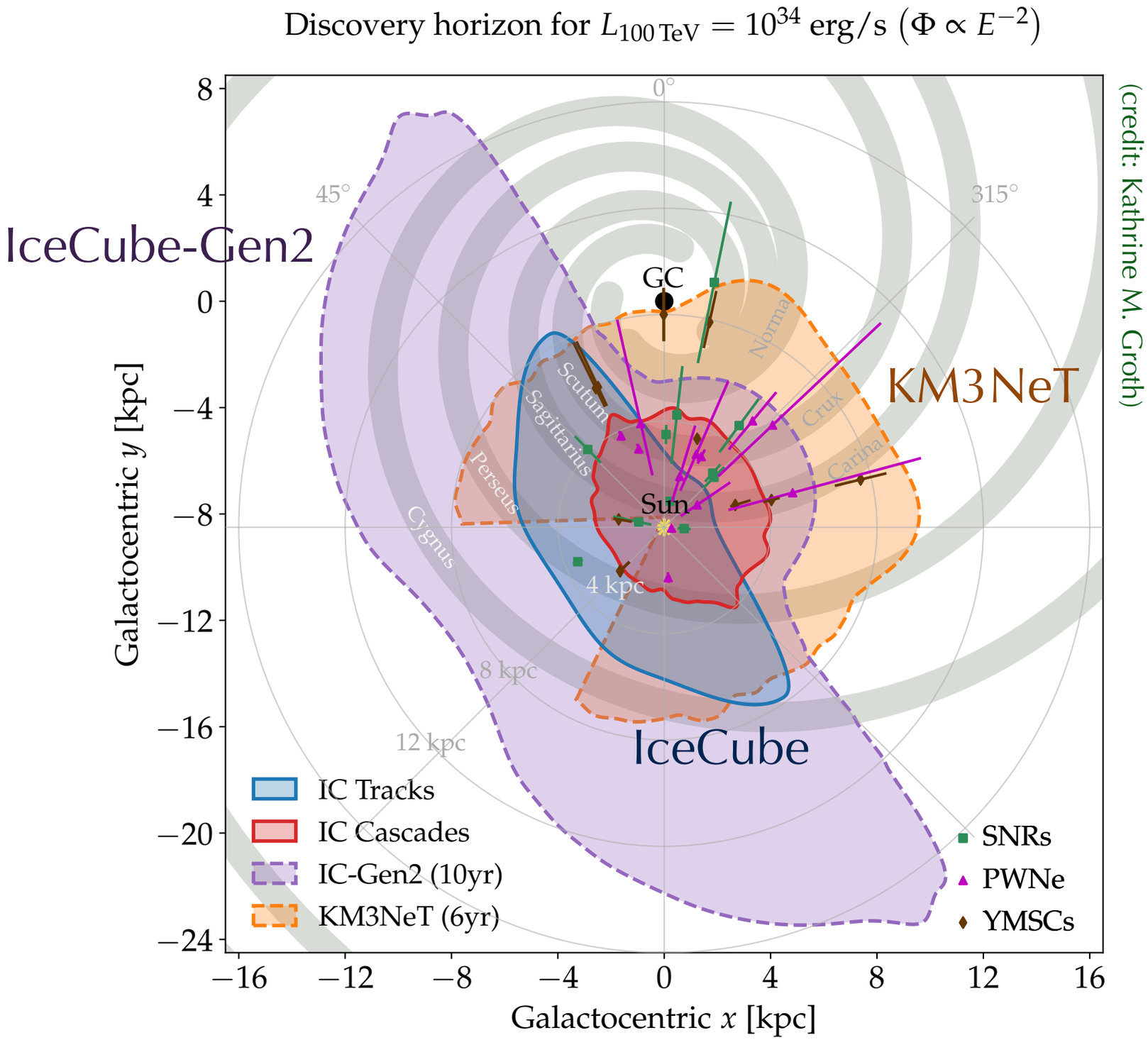


No significant PS emission but local fluctuations align with Galactic Plane.

IceCube

[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

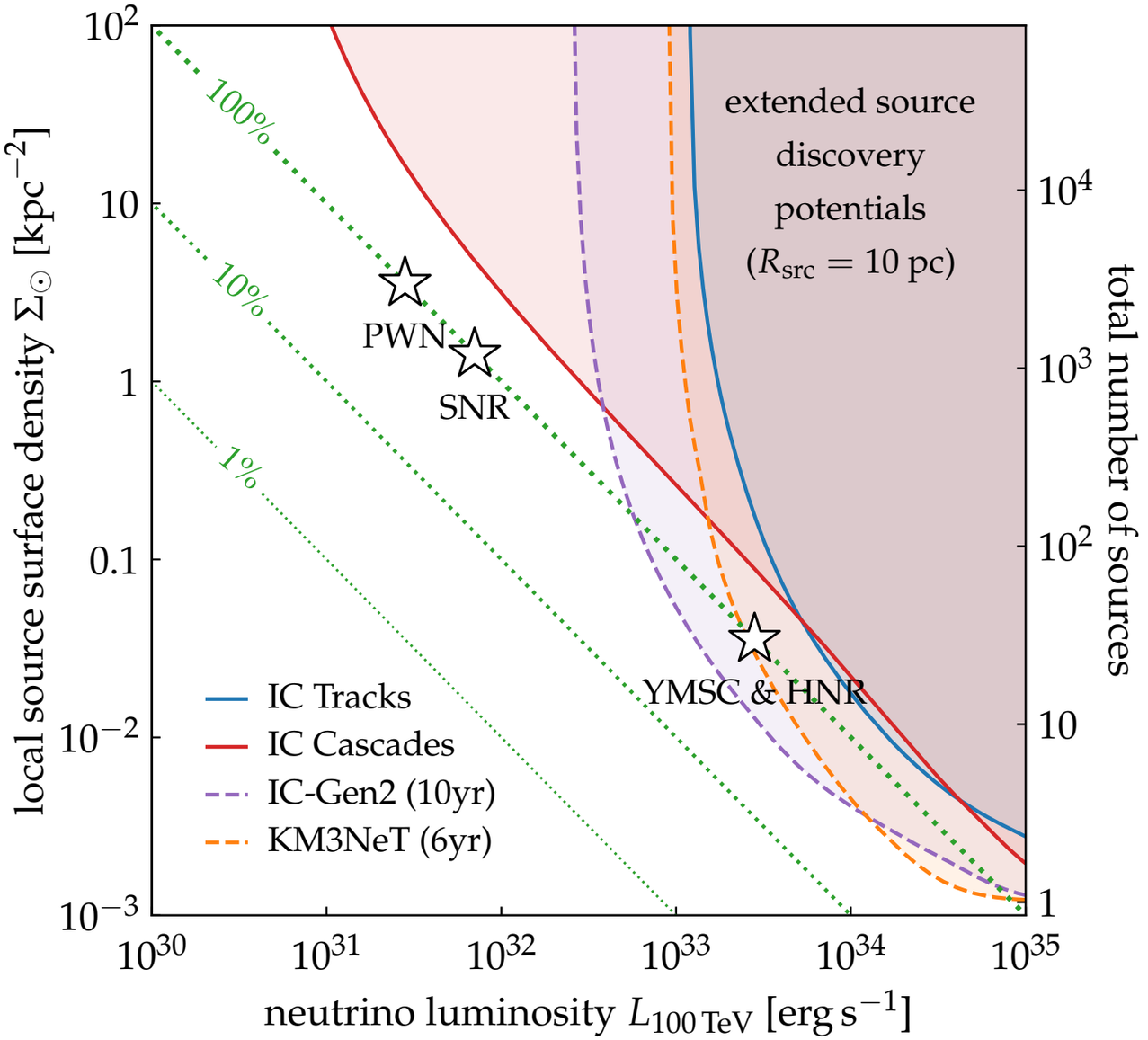
combined isotropic emission.

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

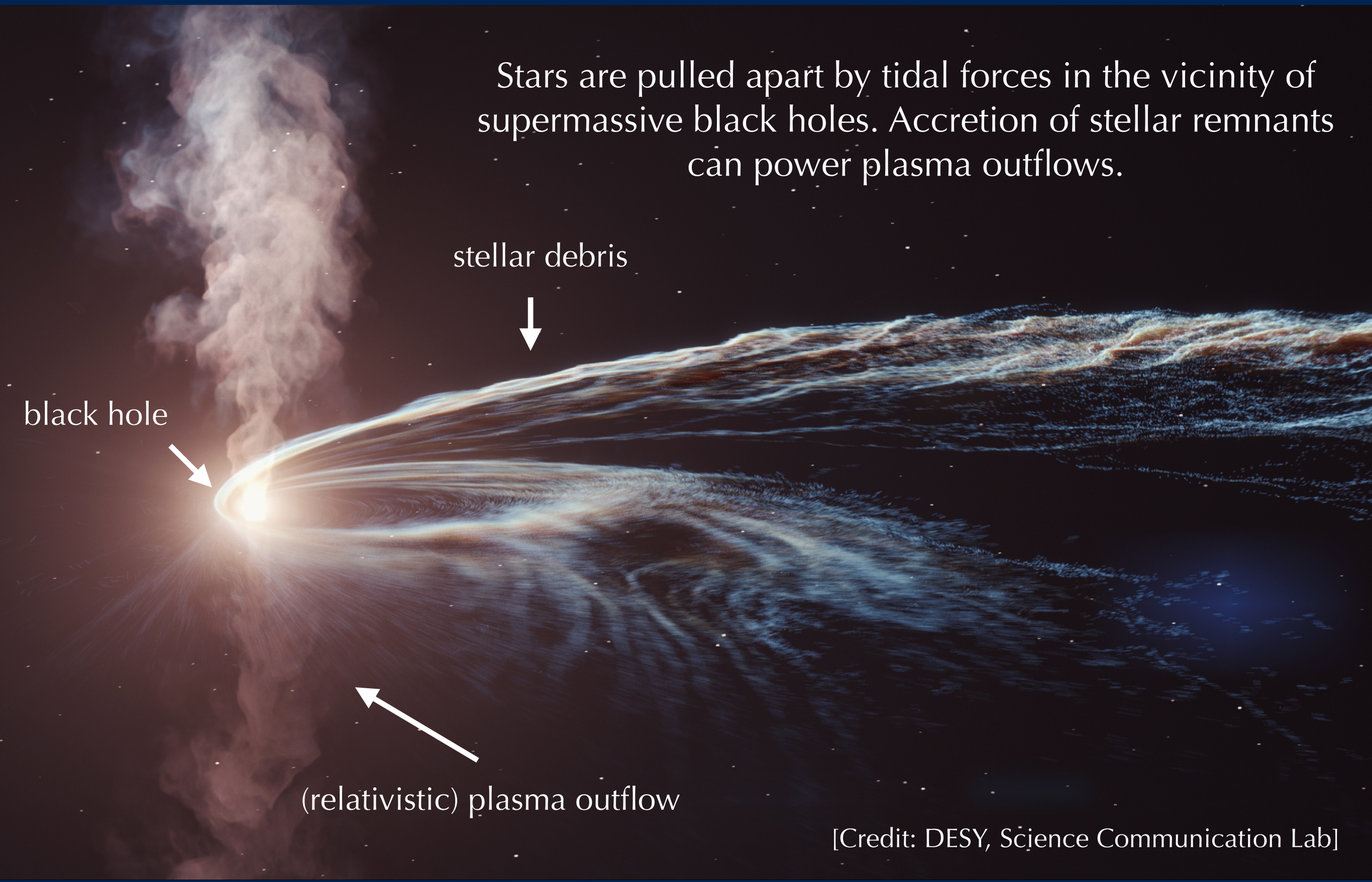
	Flux sensitivity Φ	*P* value	Best-fitting flux Φ
		Diffuse Galactic plane analysis	
π^0	5.98	1.26×10^{-6} (4.71σ)	$21.8^{+5.3}_{-4.9}$
KRA_γ^5	$0.16 \times$ MF	6.13×10^{-6} (4.37σ)	$0.55^{+0.18}_{-0.15} \times$ MF
KRA_γ^{50}	$0.11 \times$ MF	3.72×10^{-5} (3.96σ)	$0.37^{+0.13}_{-0.11} \times$ MF
		Catalog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

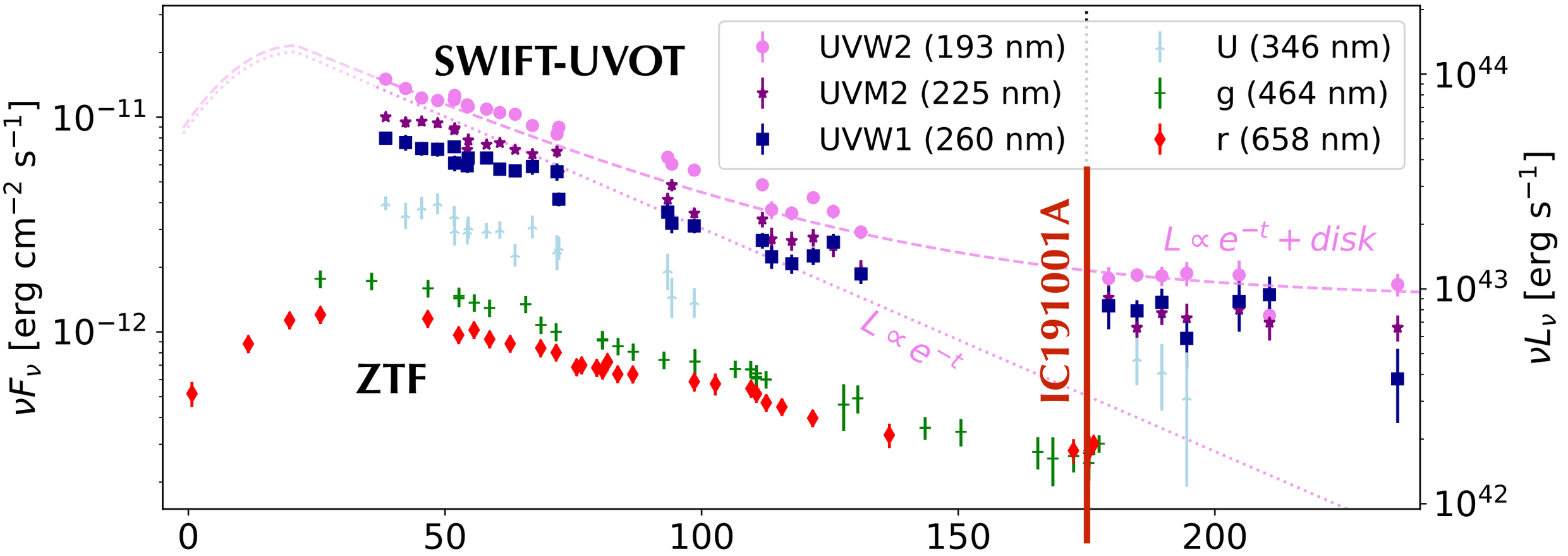
*Significance values that are consistent with the diffuse Galactic plane template search results.

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

Tidal Disruption Events (TDEs)



Tidal Disruption Events (TDEs)

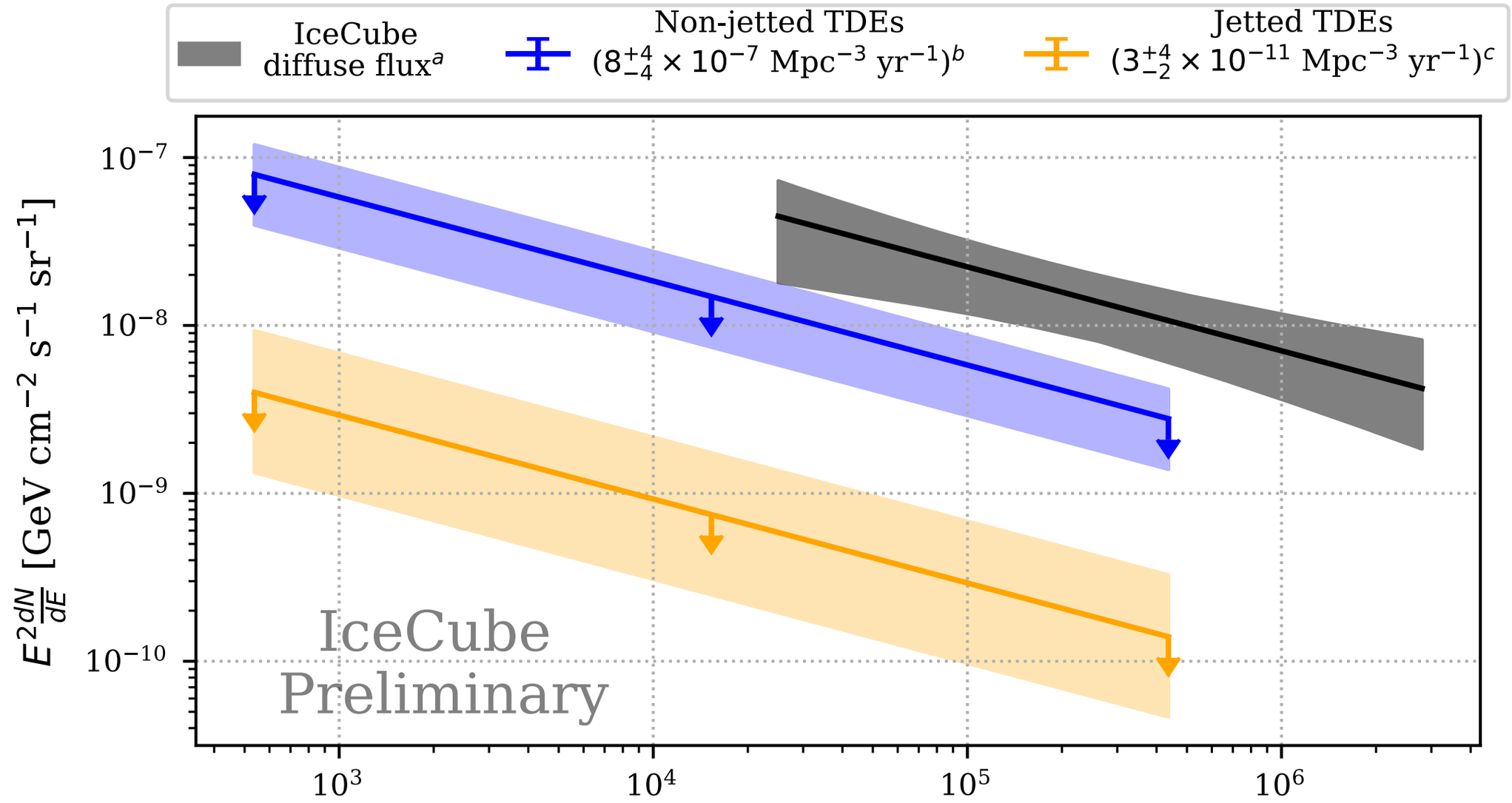


[Stein et al. Nature Astronomy 5 (2021) 5]

- 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.)

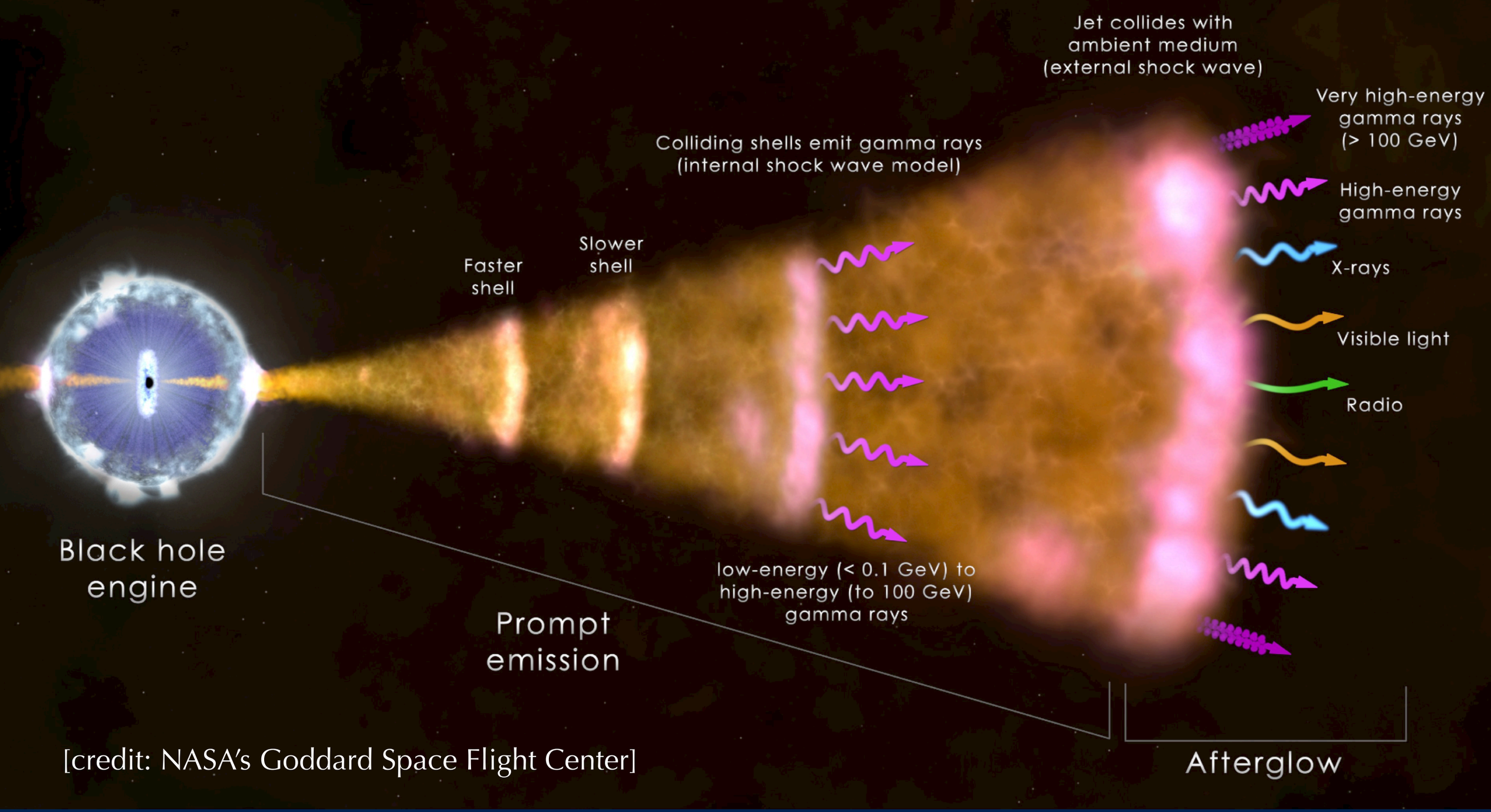
With evolution from Sun et al.[c]

[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.

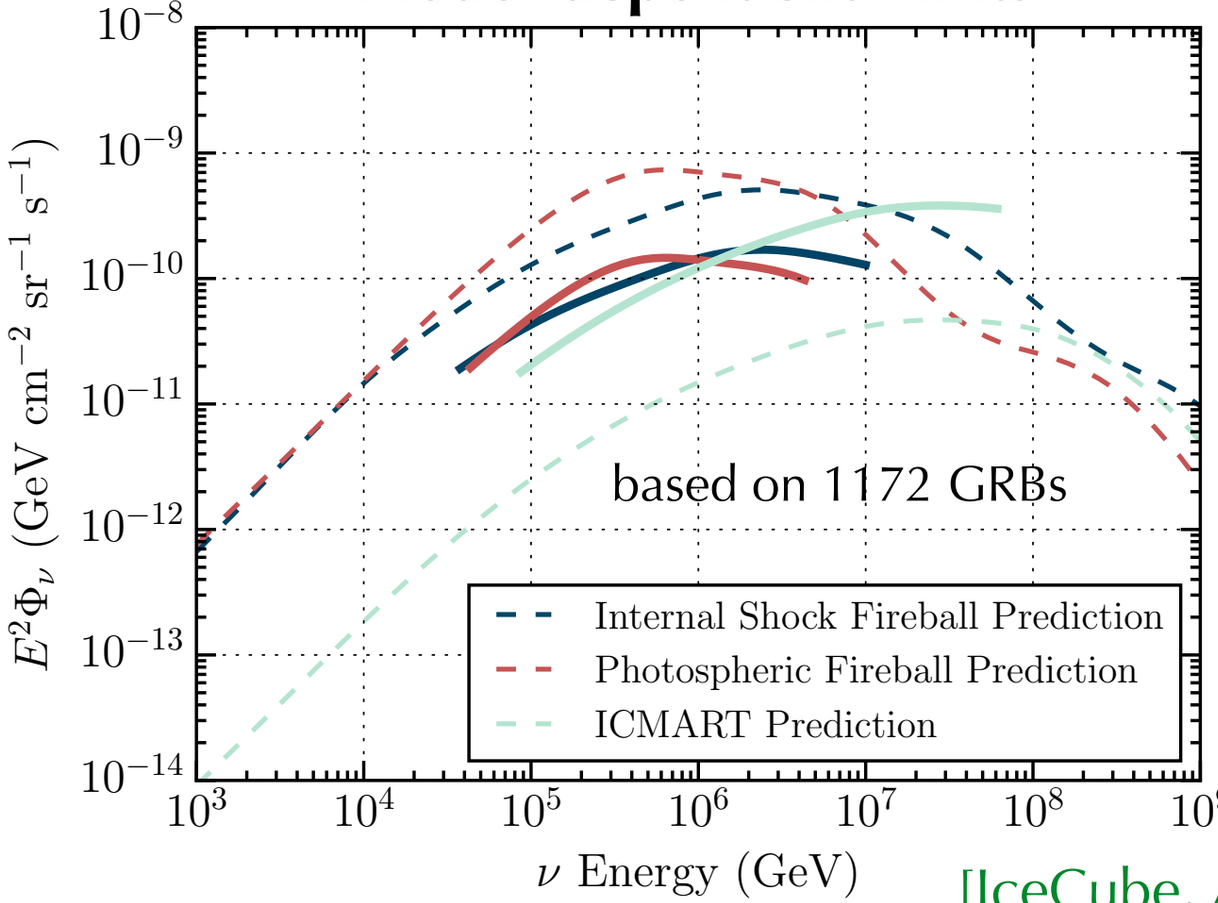


[credit: NASA's Goddard Space Flight Center]

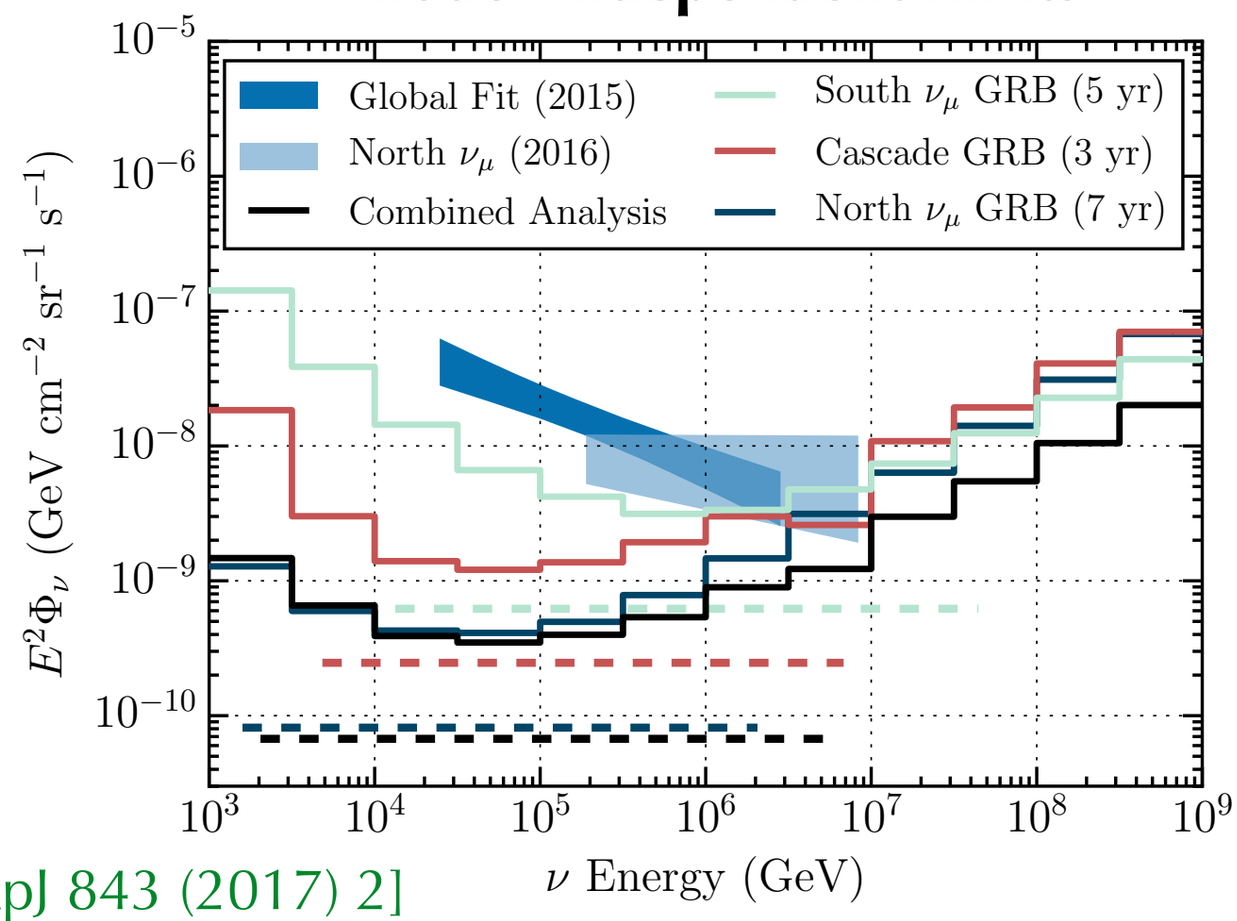
GRB Neutrino Limits

- 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

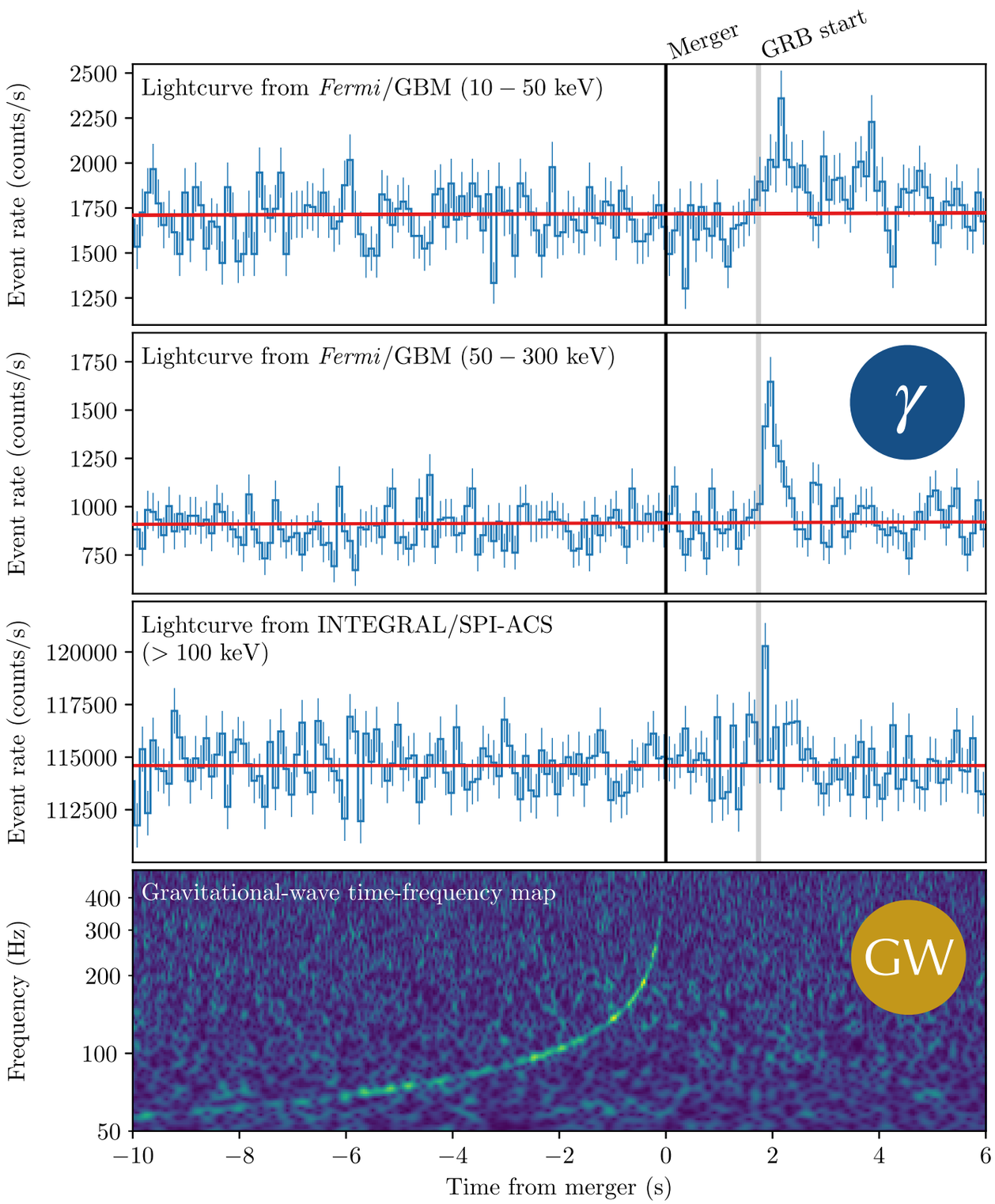


model-independent limits

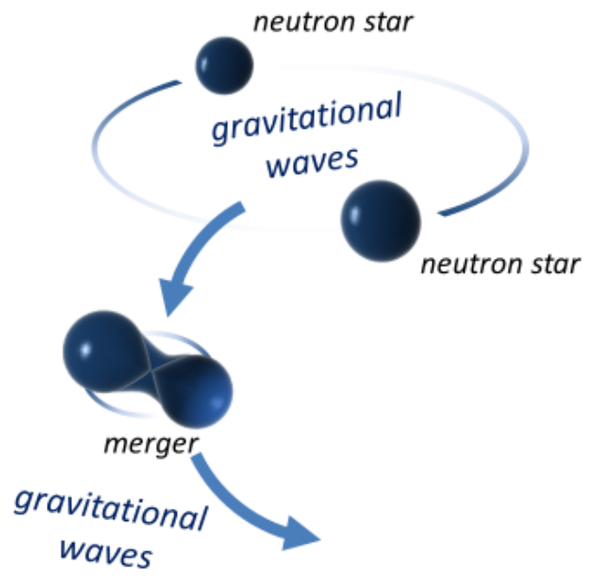


[IceCube, ApJ 843 (2017) 2]

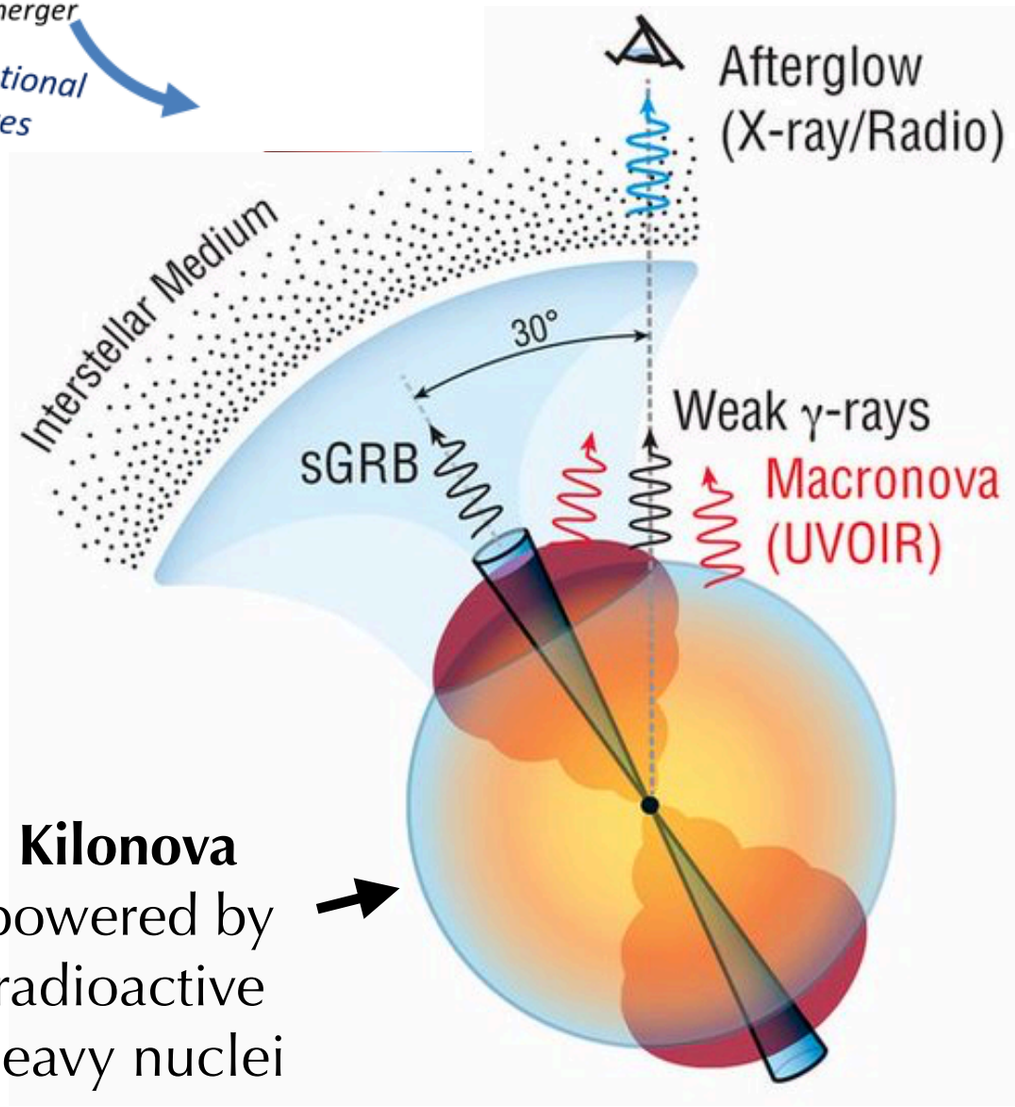
GRBs and Gravitational Waves



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

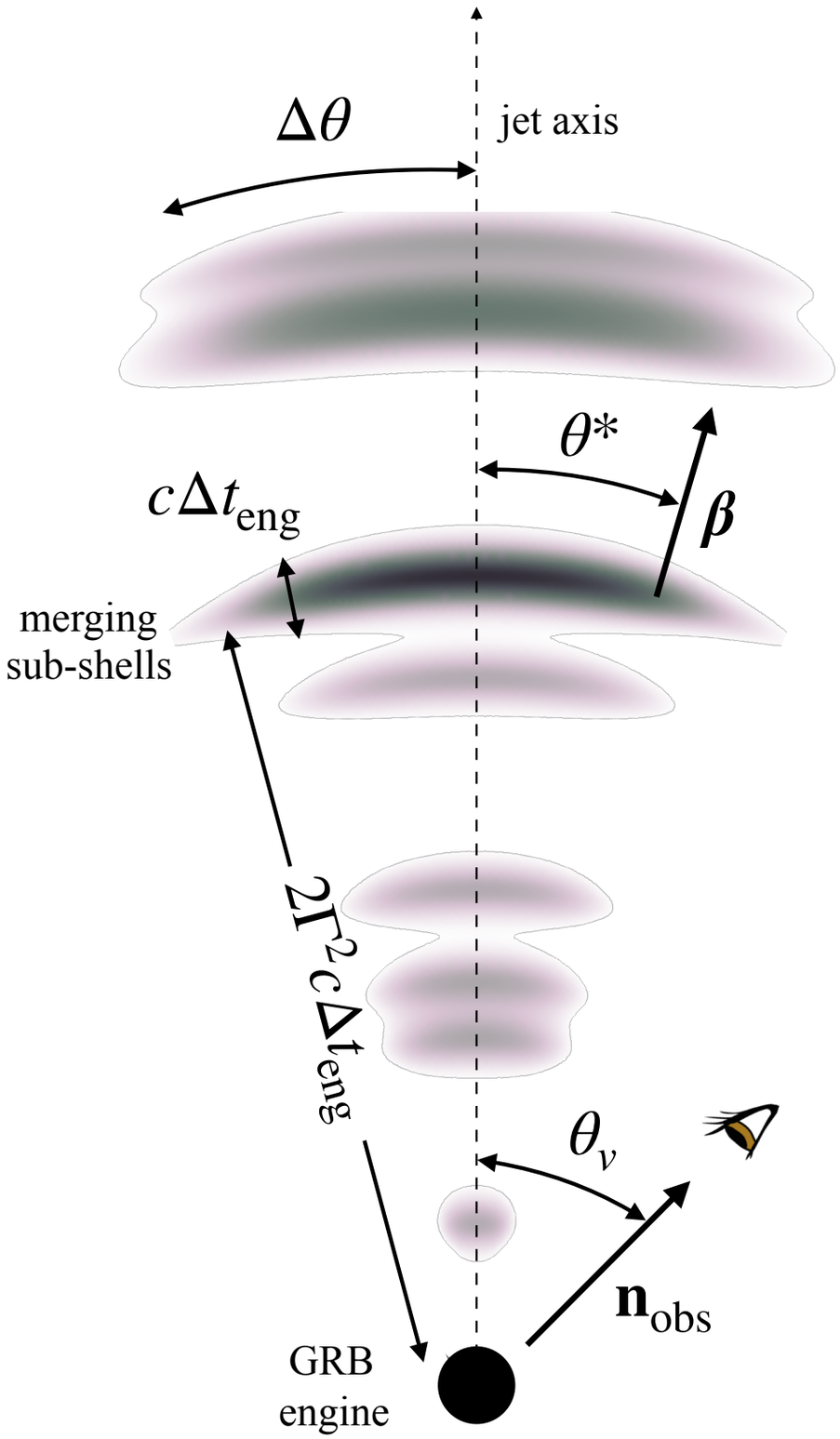


GW 170817
&
GRB 170817A

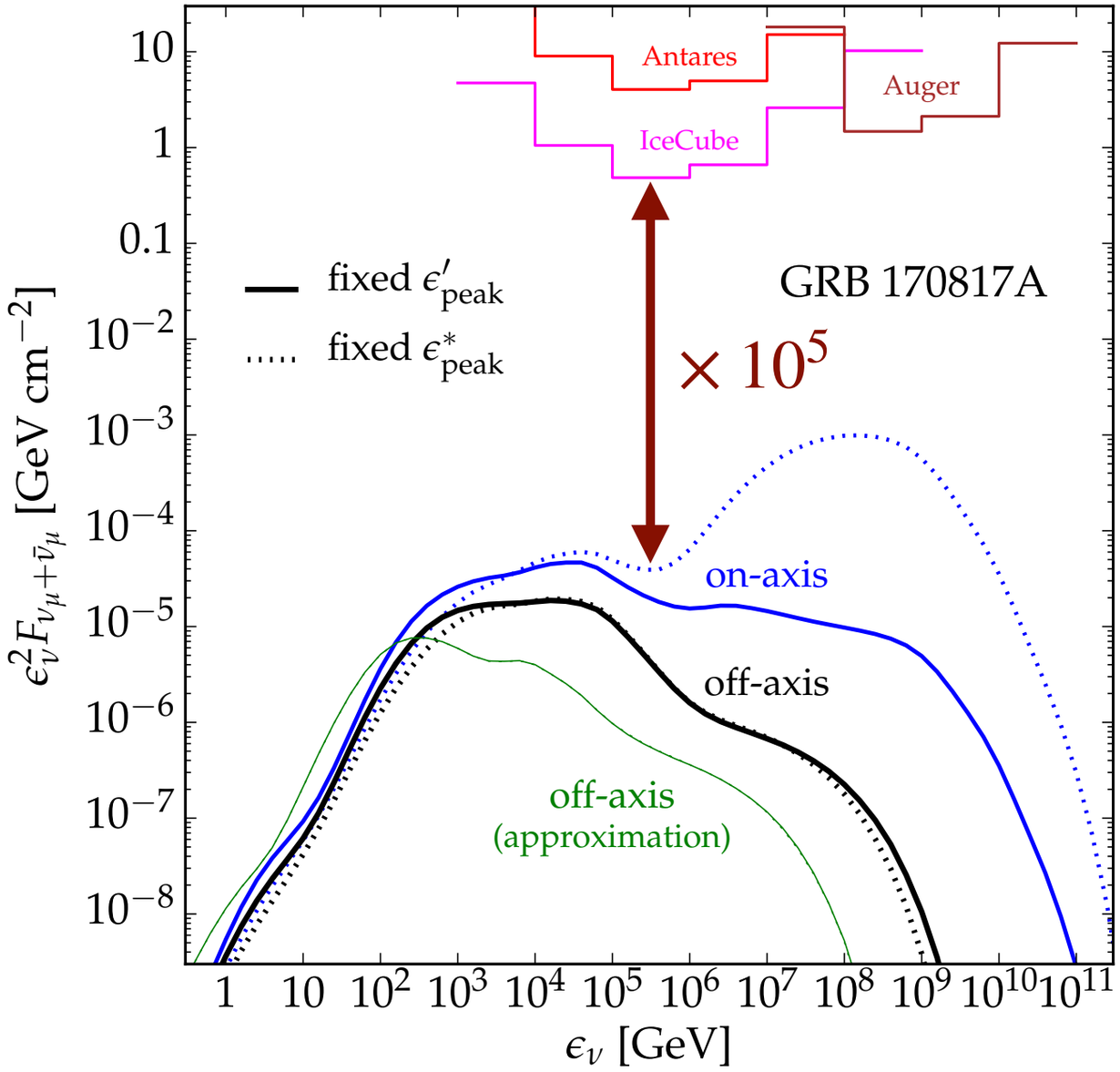


Kilonova
powered by
radioactive
heavy nuclei

GRB 170817A - Neutrino Limits



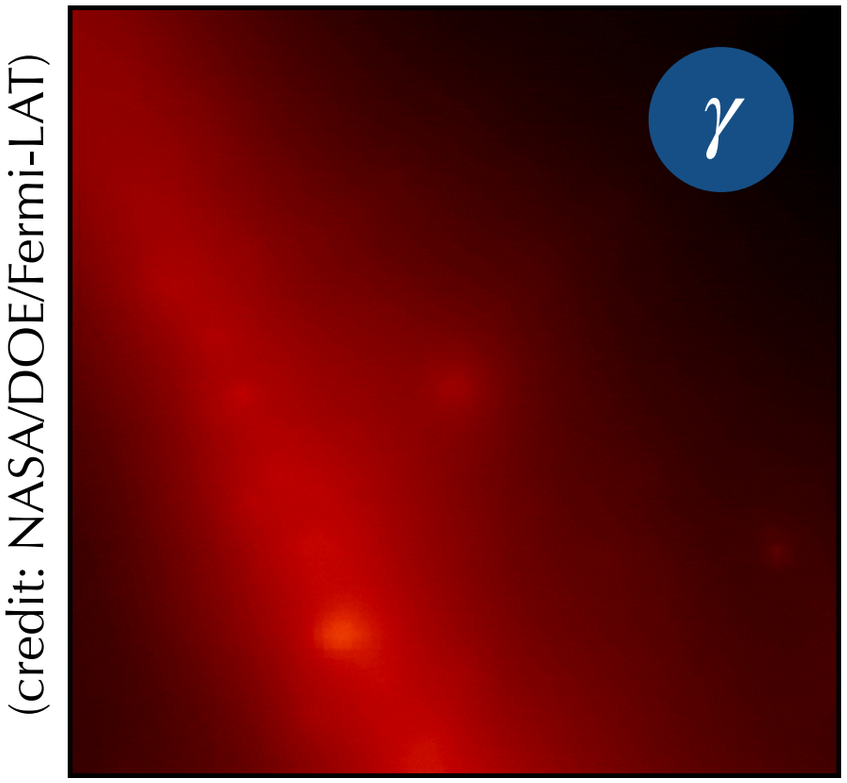
No detection of neutrinos in prompt phase consistent with **off-axis emission.**



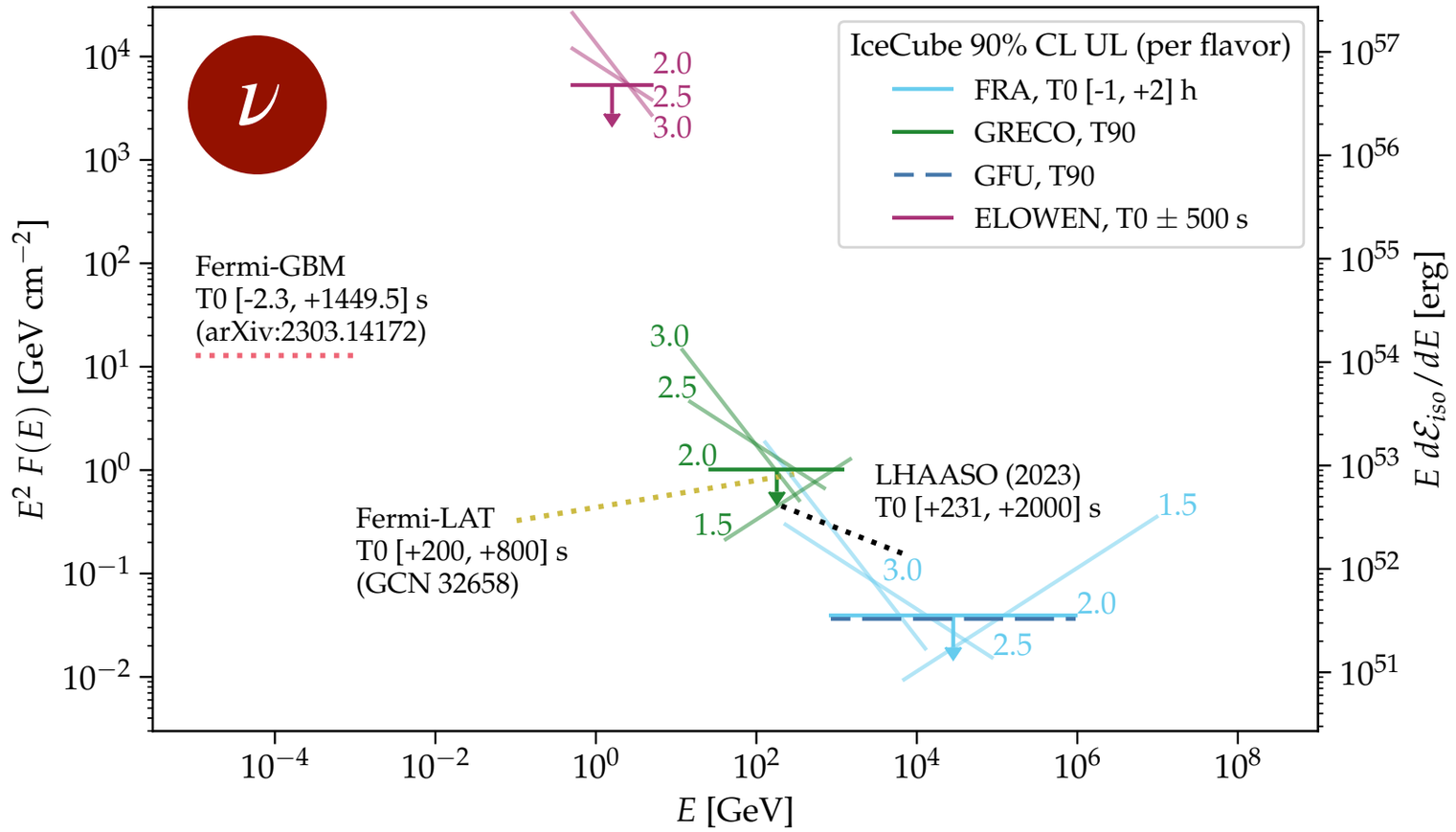
[MA & Halser'19]

GRB 221009A - The "BOAT"

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

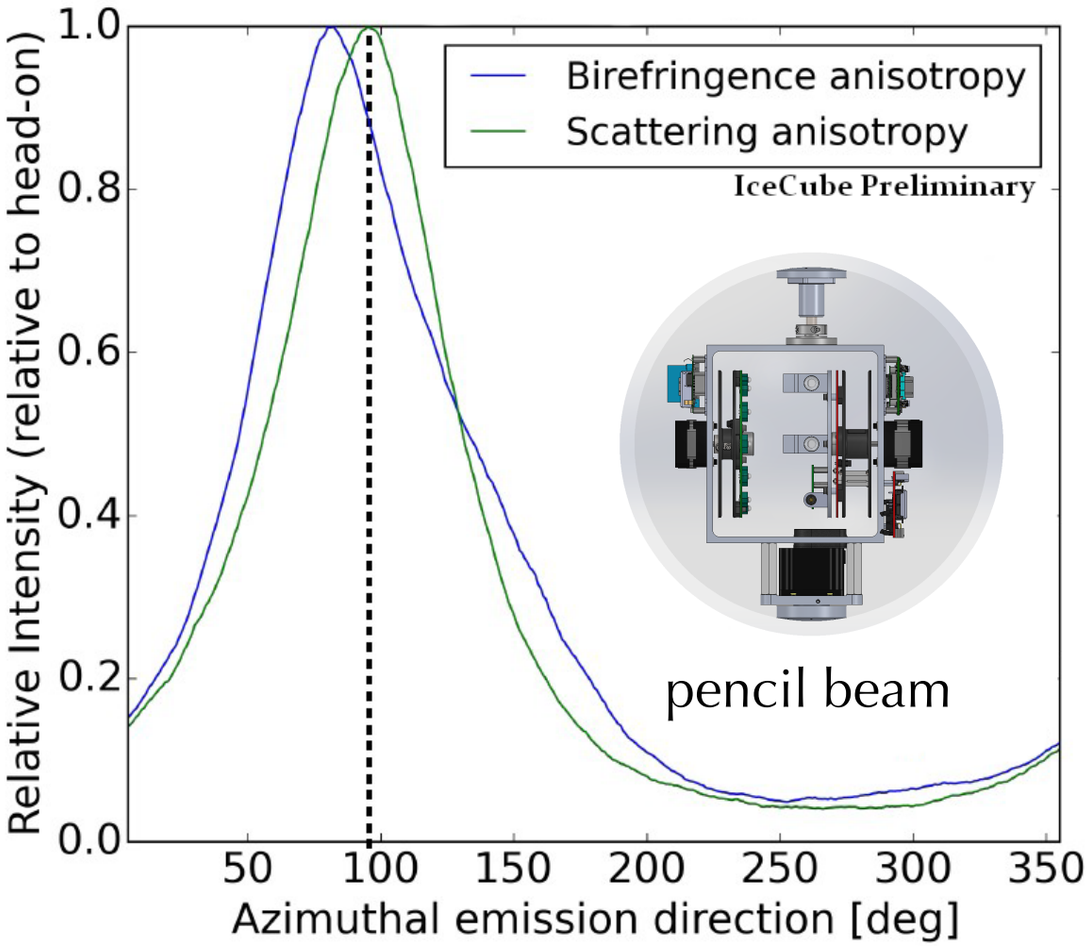
"*Limits on Neutrino Emission from GRB 221009A from MeV to PeV using the IceCube Neutrino Observatory*"

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

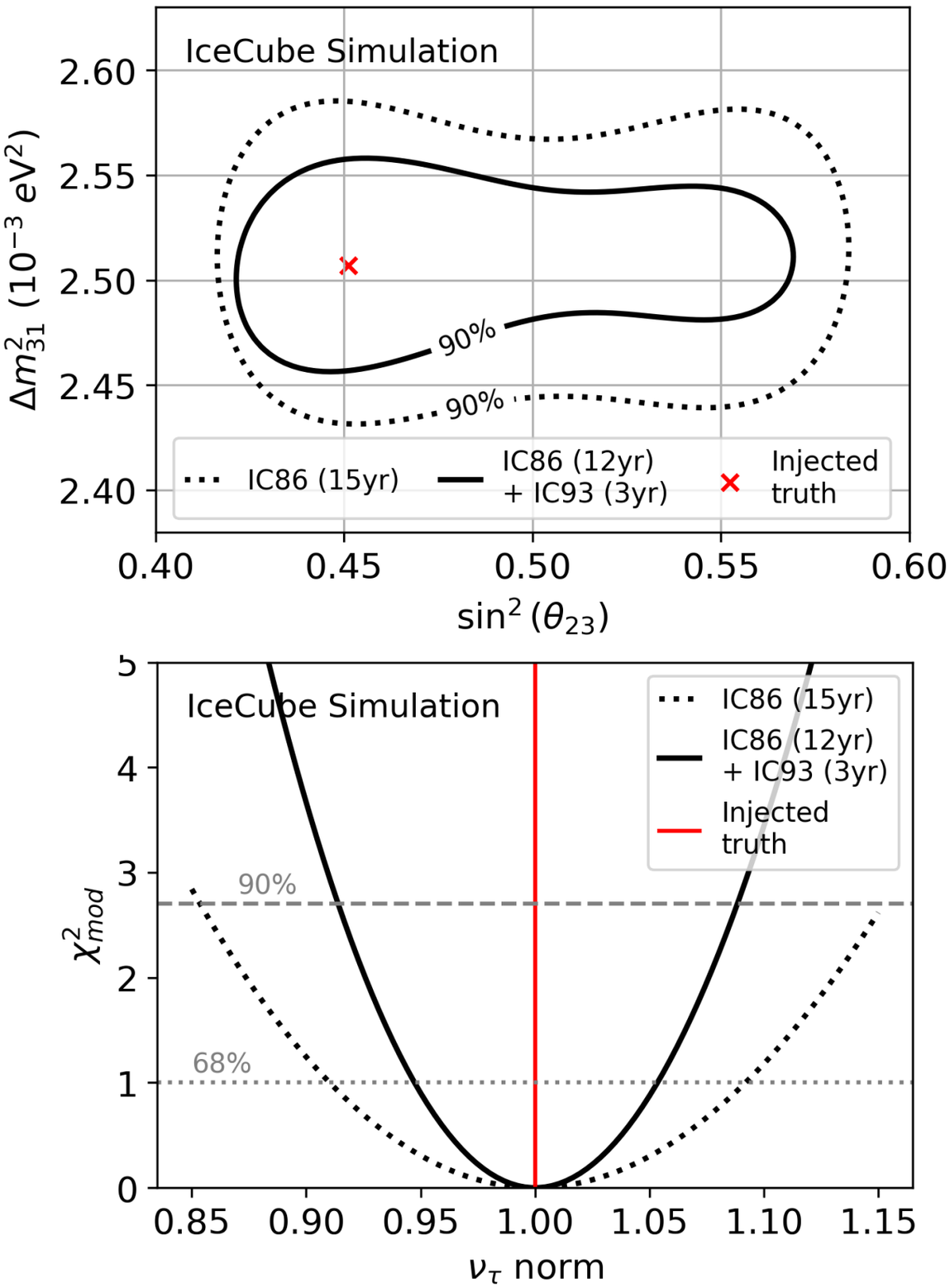
[IceCube PoS-ICRC2023-1511]

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]

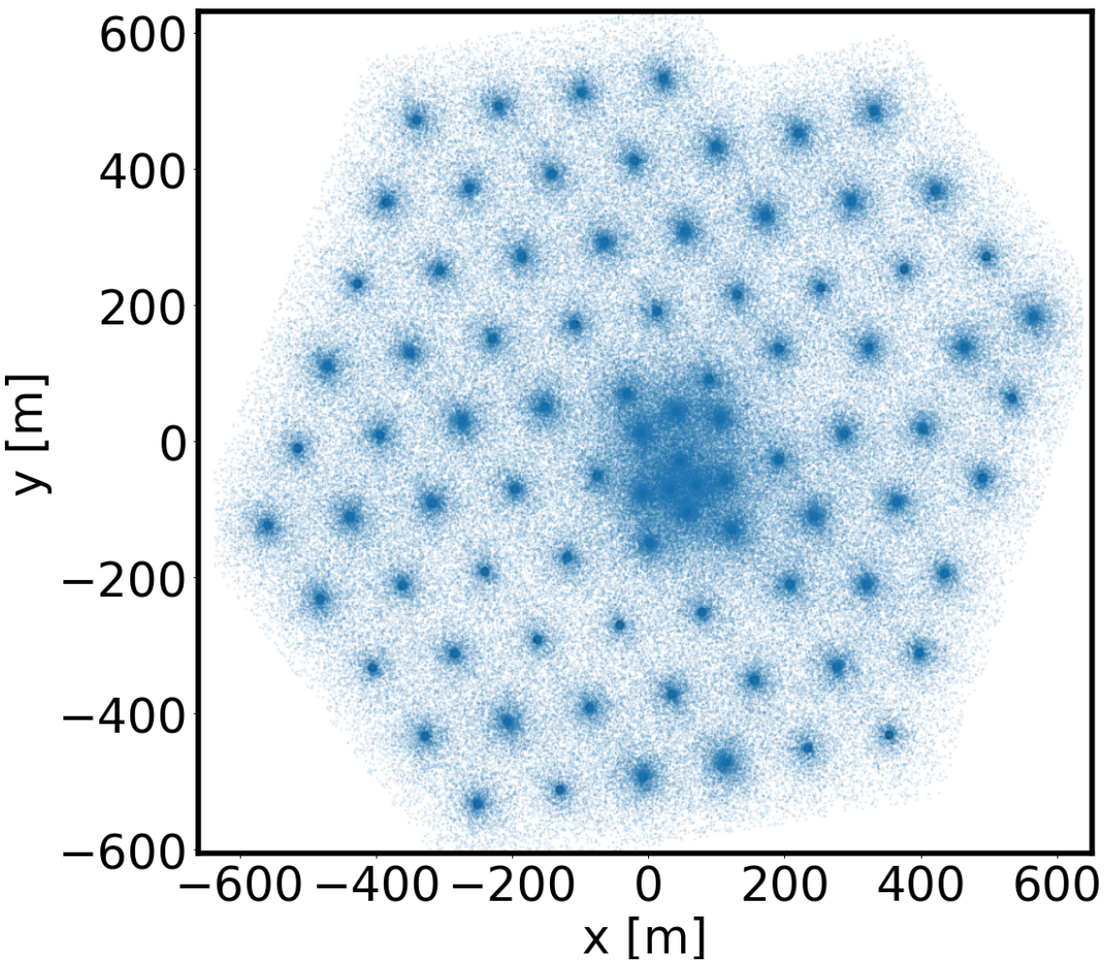


[IceCube, PoS (ICRC2019) 1031]

Supernovae in IceCube

Inverse β-decay

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



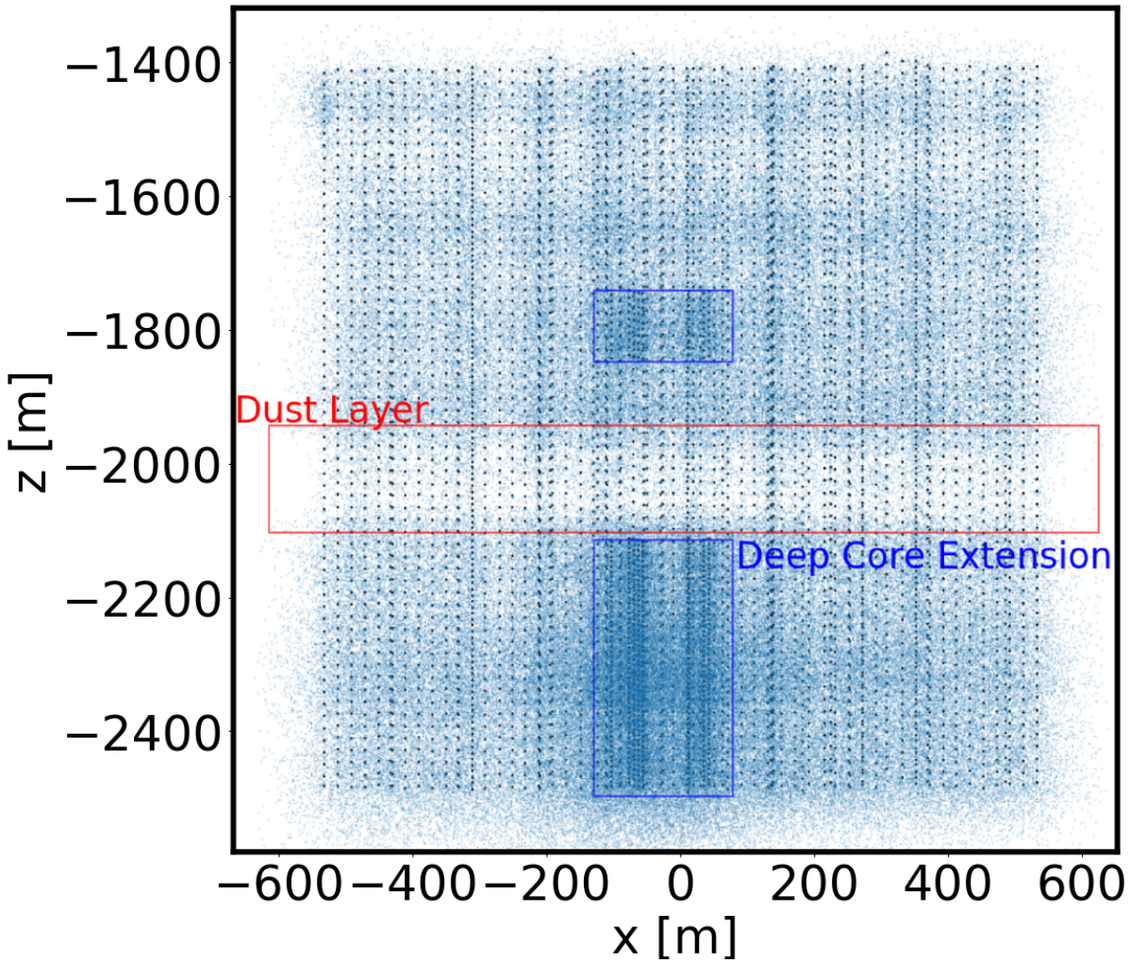


Figure 1: Top and side view of $\sim 3.4 \times 10^5$ simulated supernova ν interaction vertices registered by IceCube DOMs. The dust layer between -1950 m and -2050 m and the denser DeepCore subarray are clearly visible.

[IceCube, PoS (ICRC2019) 1177]

Core-Collapse Supernovae