

Global high-energy and ultra-high-energy neutrino detectors

Mauricio Bustamante

Niels Bohr Institute, University of Copenhagen

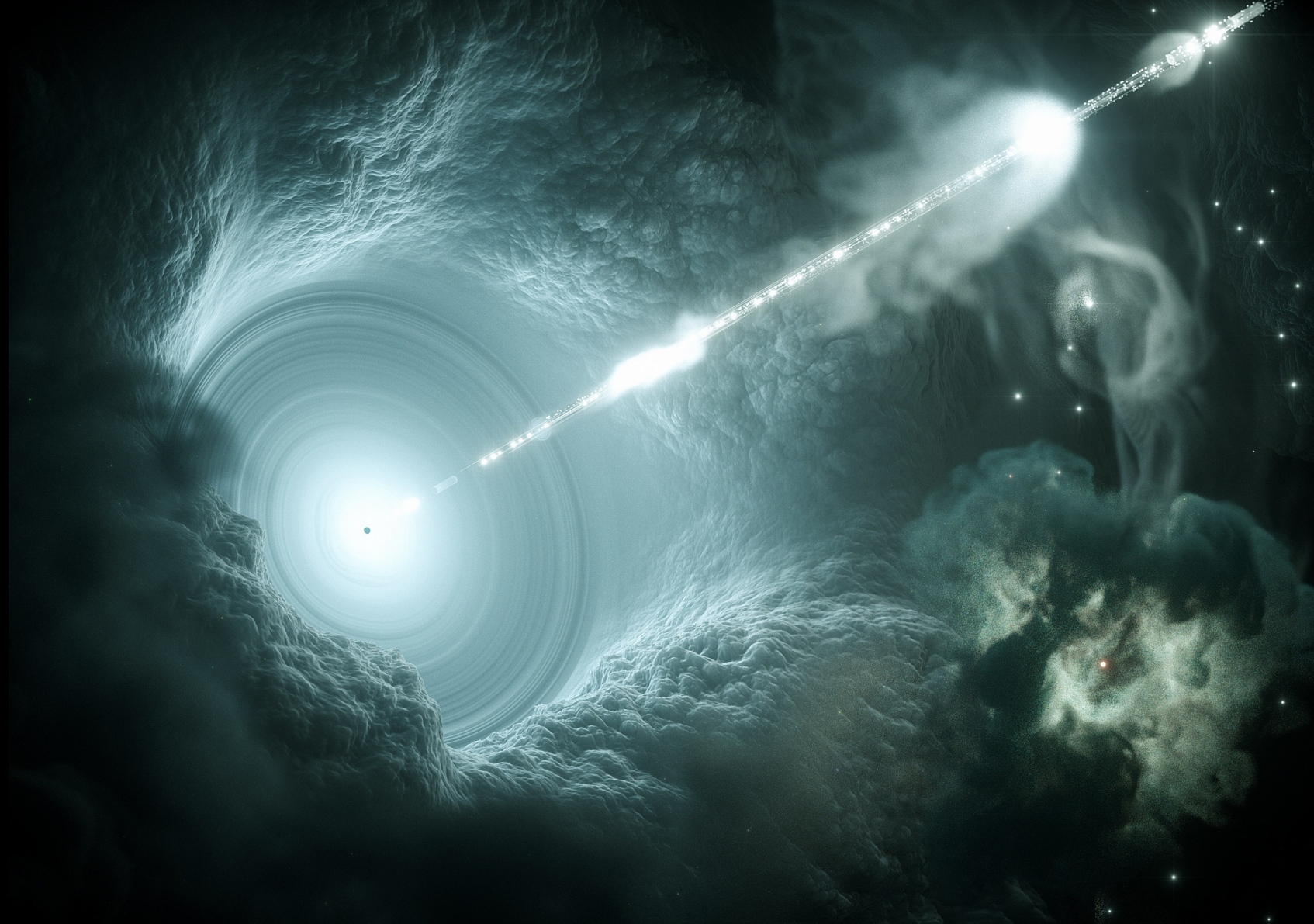
Kavli-IAU Global Coordination Workshop
Görlitz, June 24, 2026

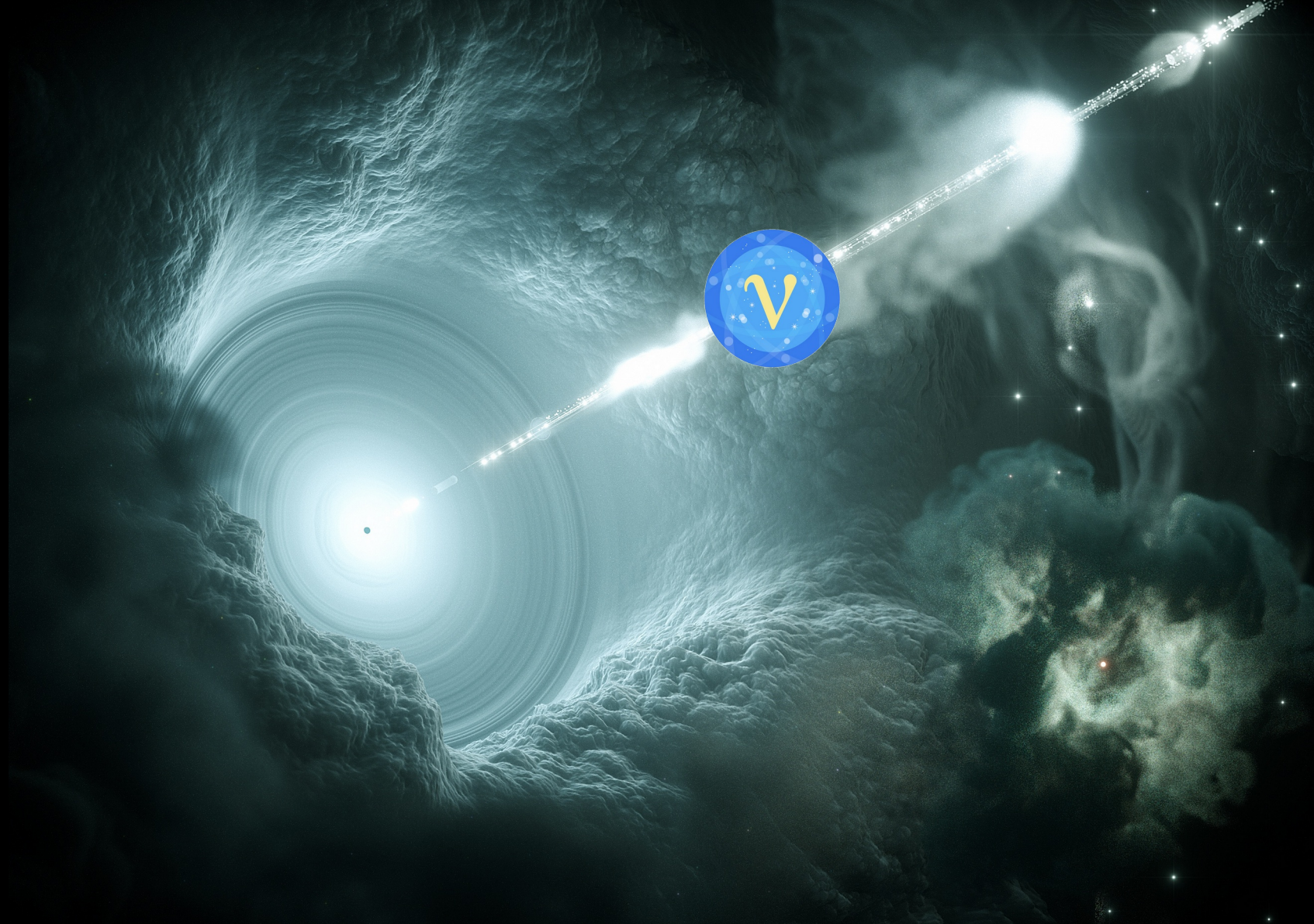
UNIVERSITY OF
COPENHAGEN

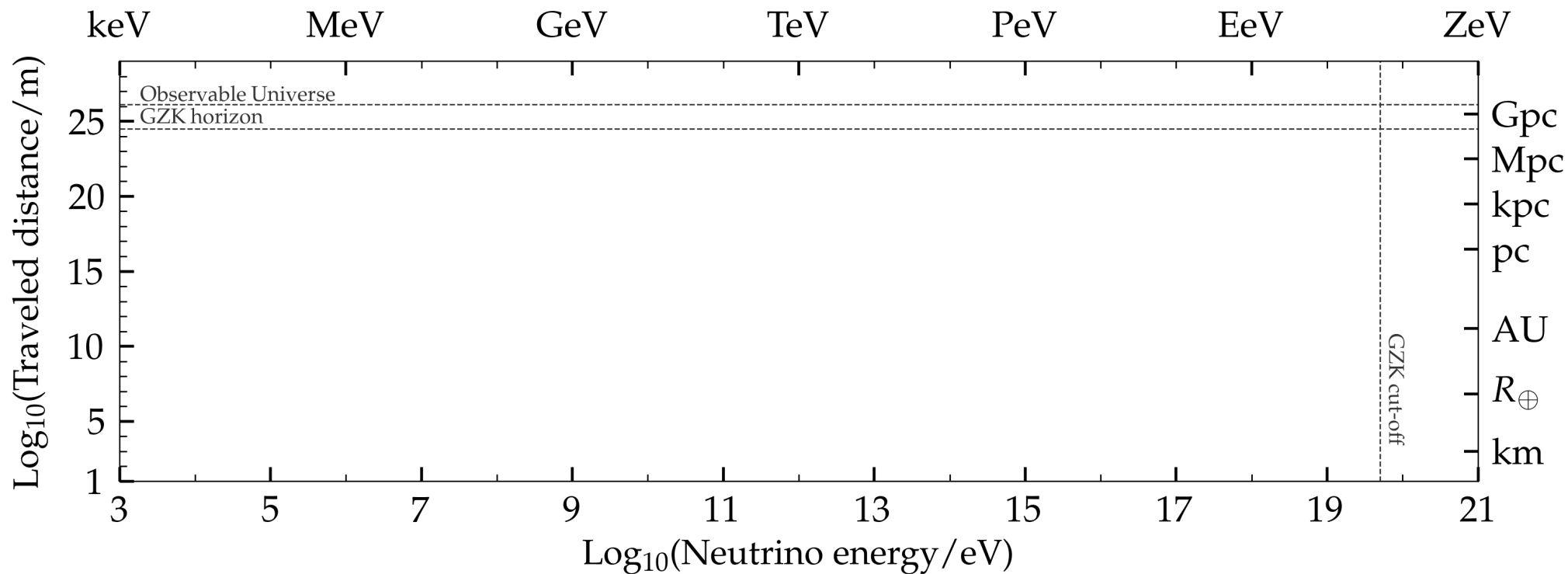


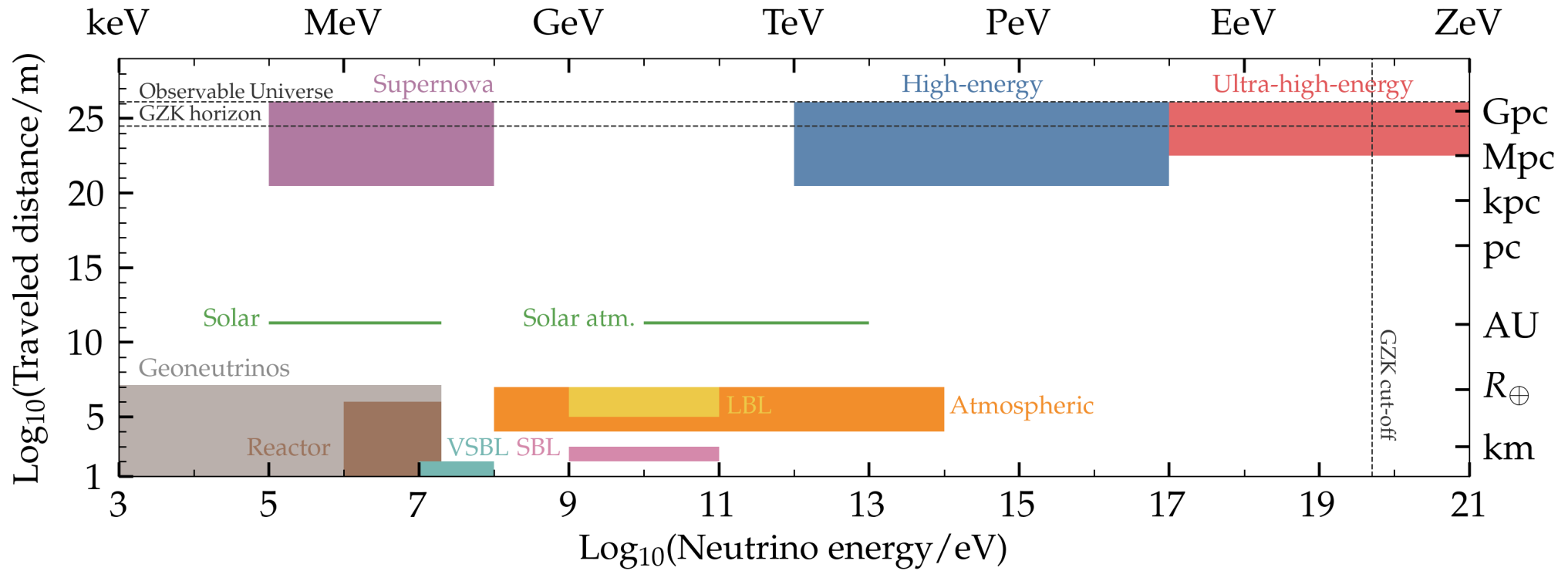
VILLUM FONDEN



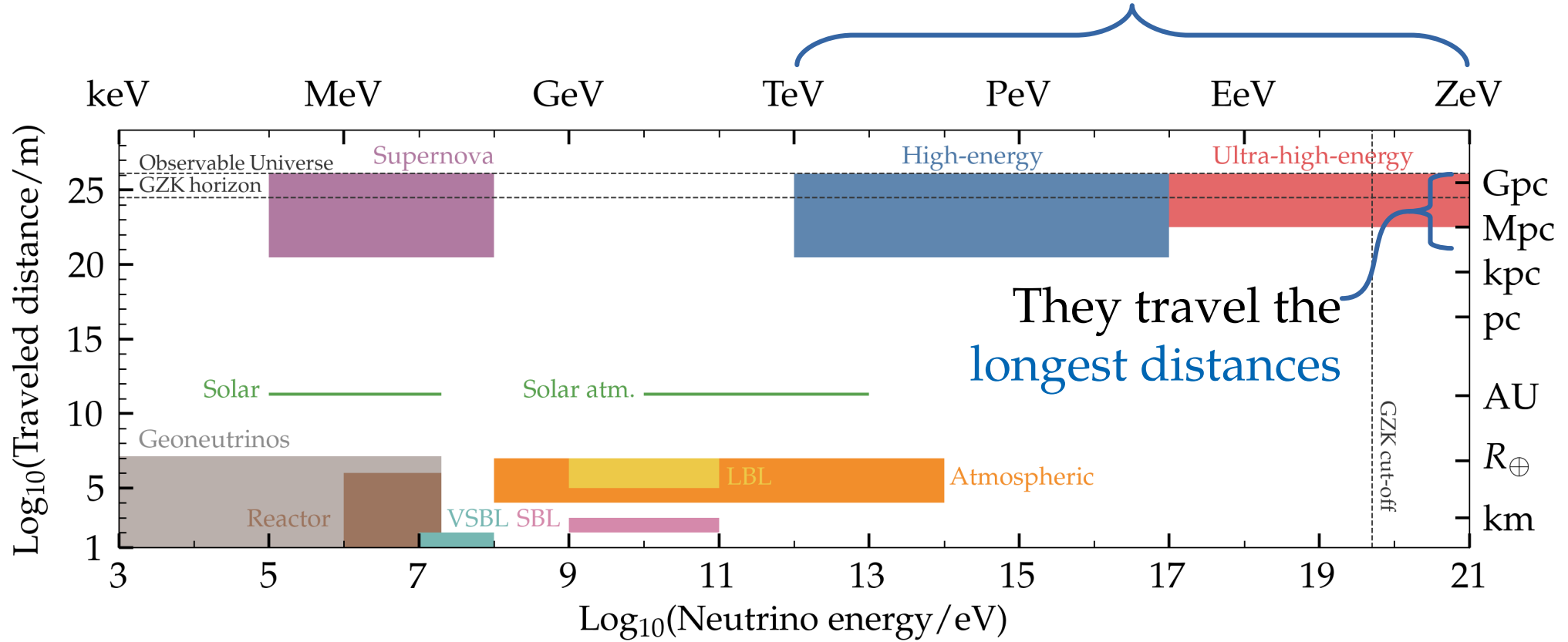


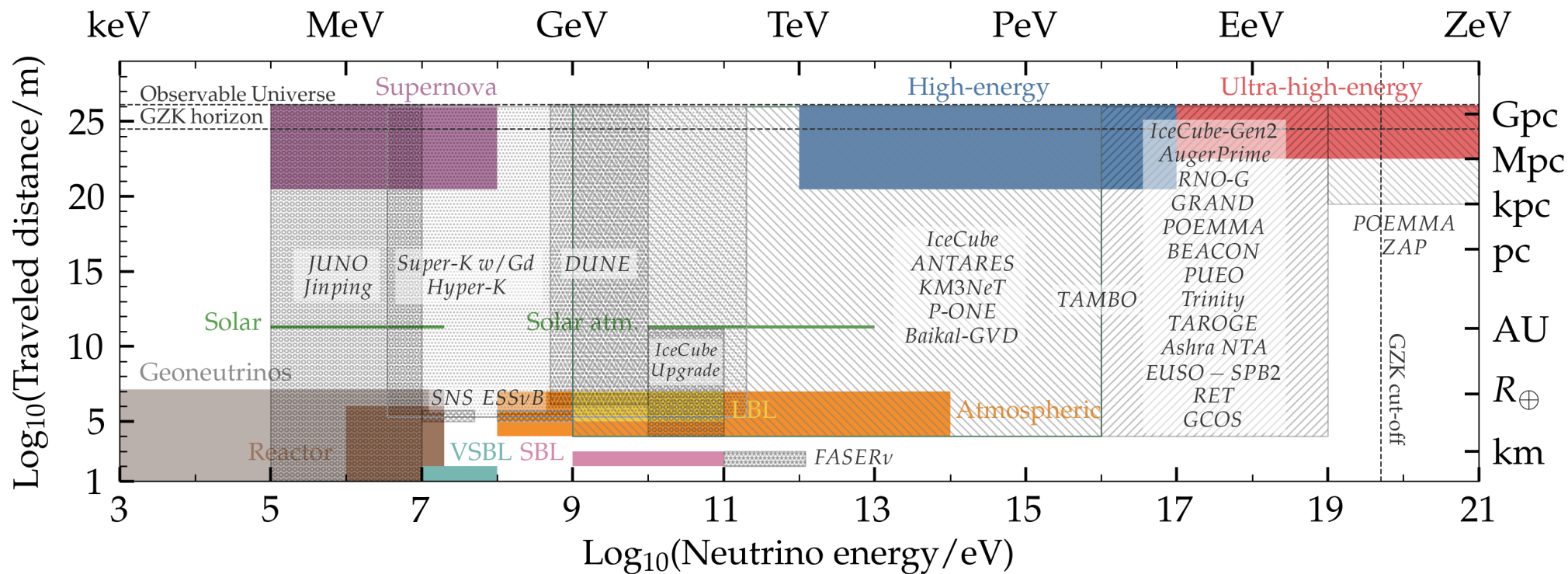


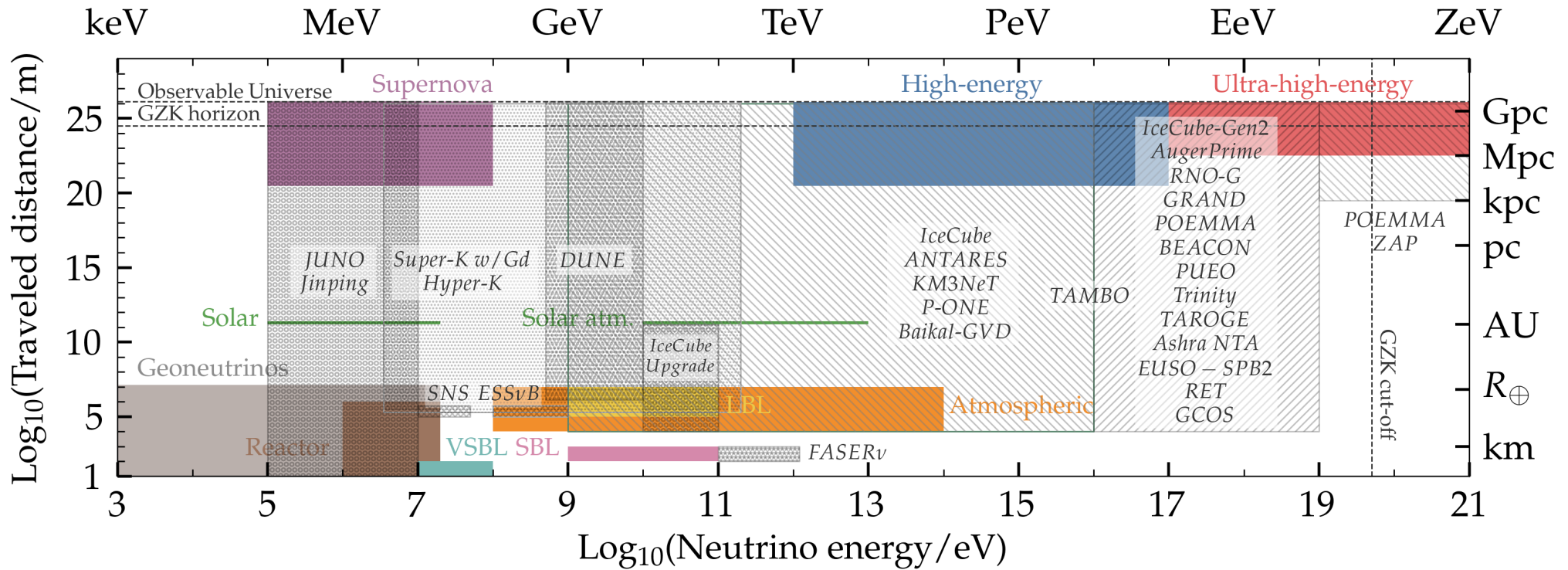




They have the **highest energies**

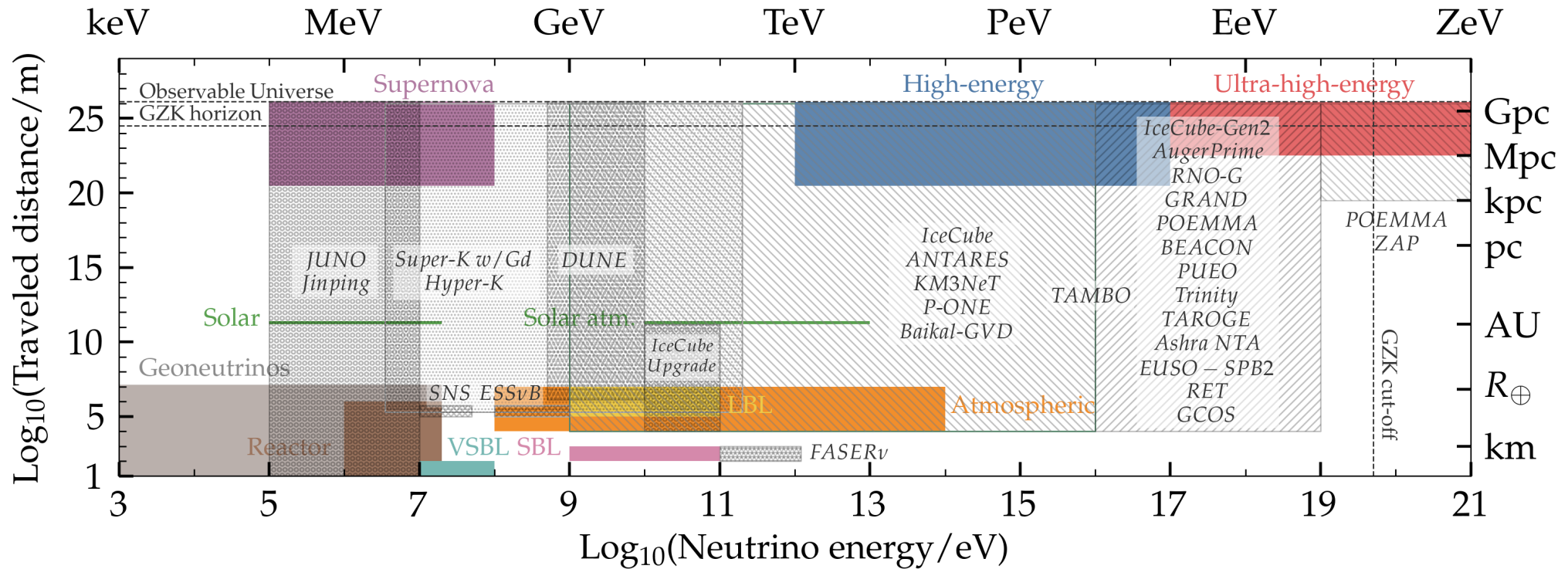






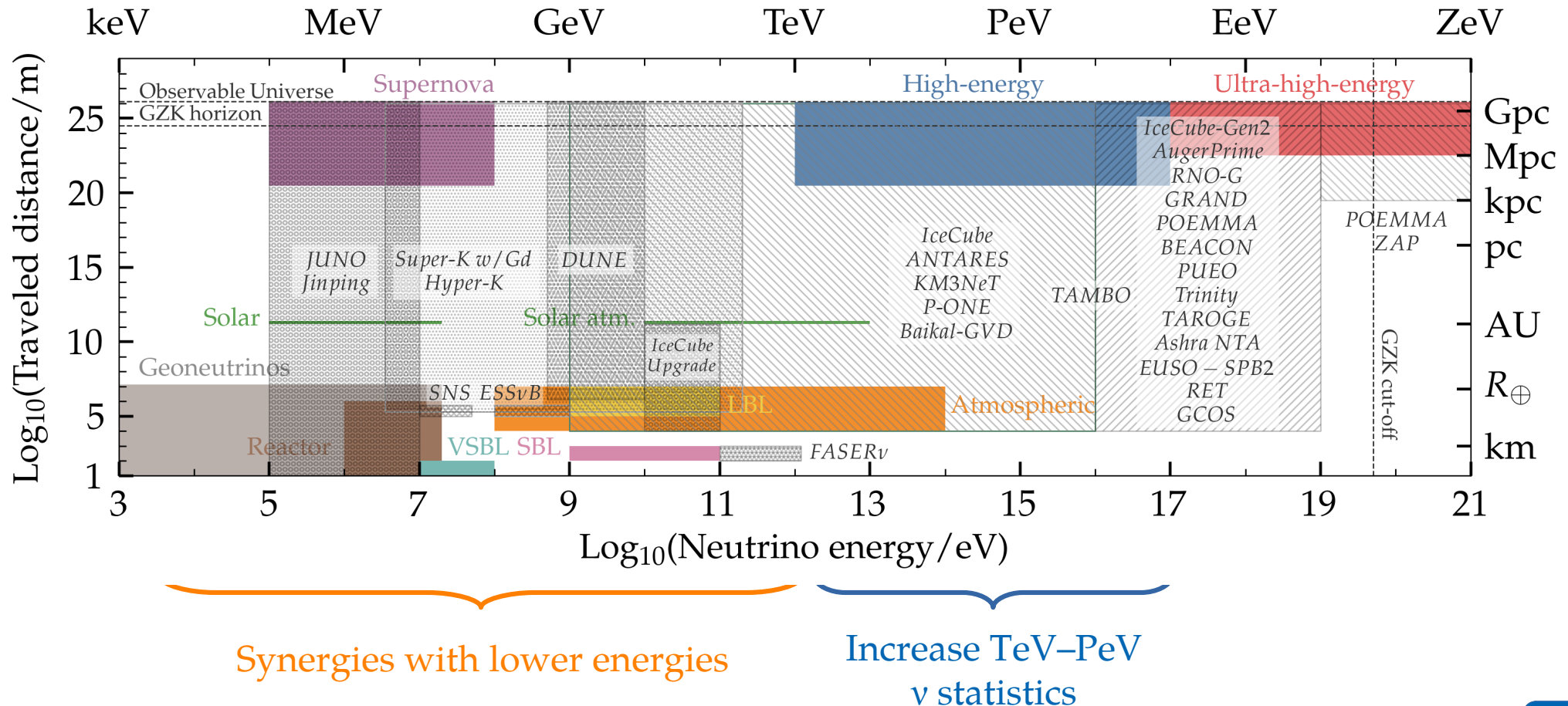
Synergies with lower energies

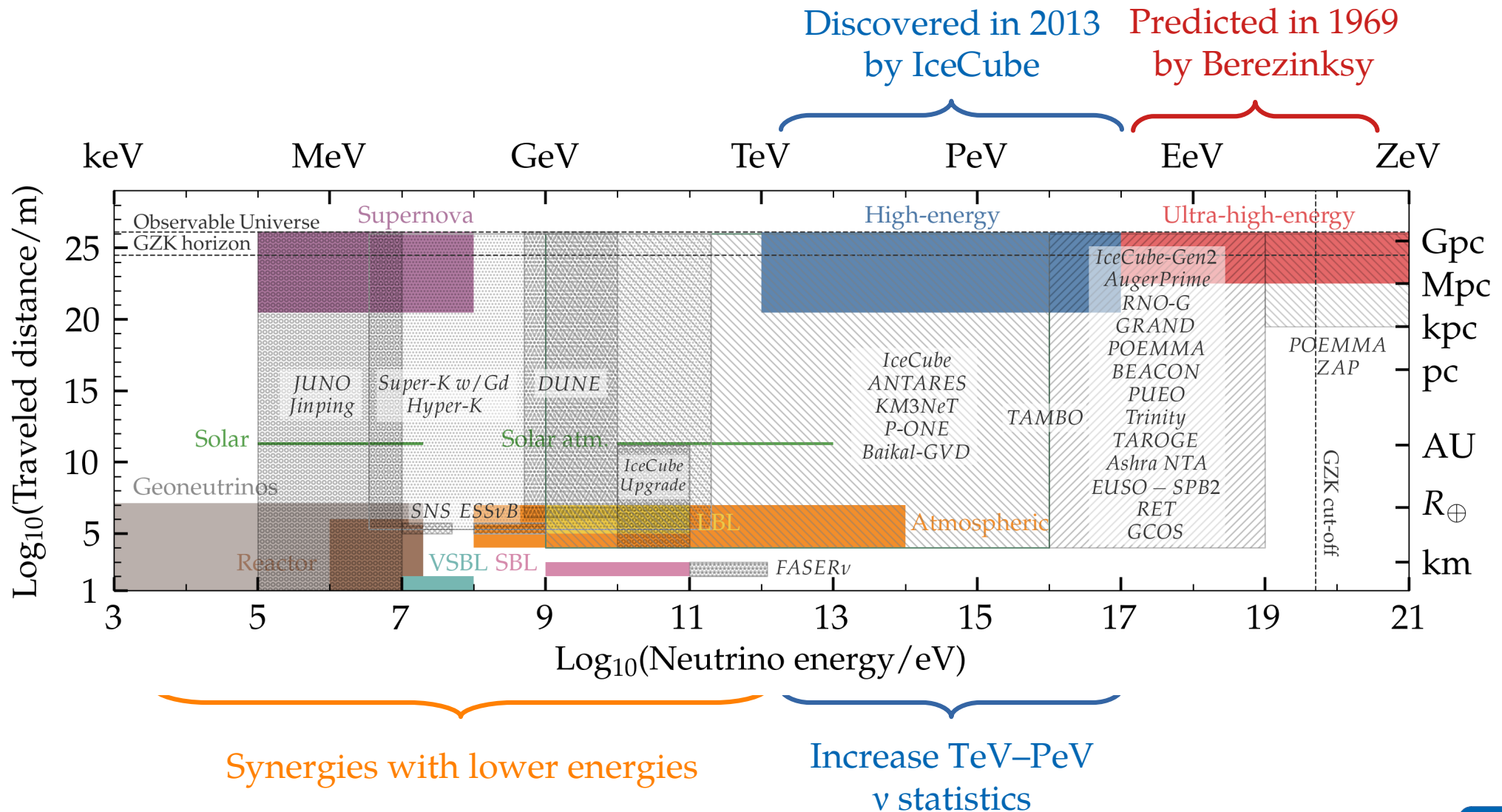
Discovered in 2013
by IceCube

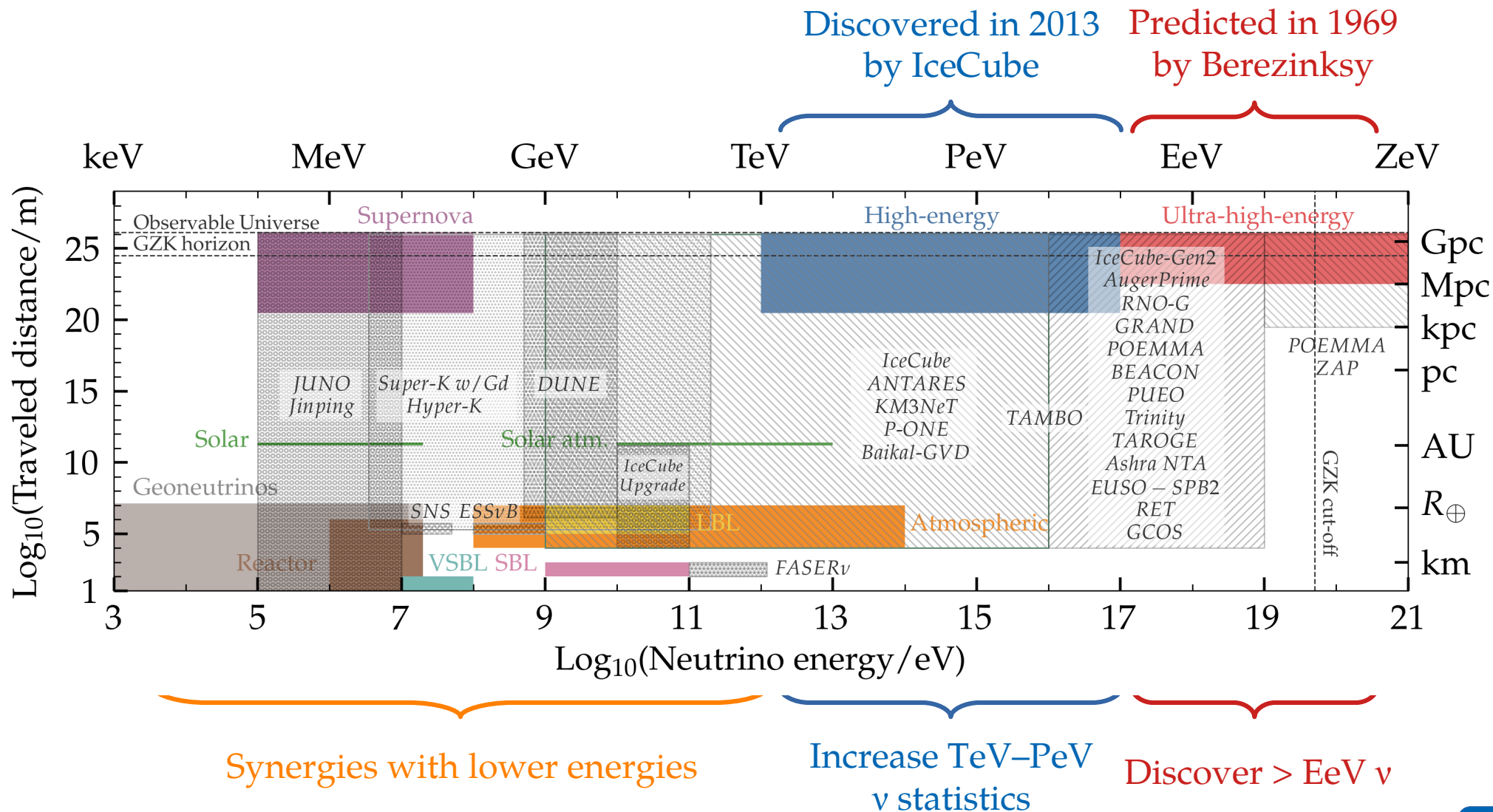


Synergies with lower energies

Discovered in 2013
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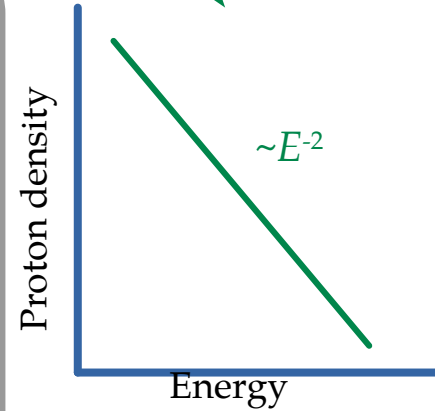
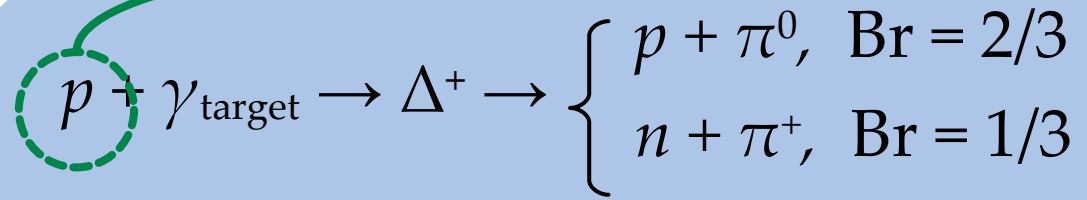
The multi-messenger connection: a simple picture

(or $p + p$)

$$p + \gamma_{\text{target}} \rightarrow \Delta^+ \rightarrow \begin{cases} p + \pi^0, & \text{Br} = 2/3 \\ n + \pi^+, & \text{Br} = 1/3 \end{cases}$$

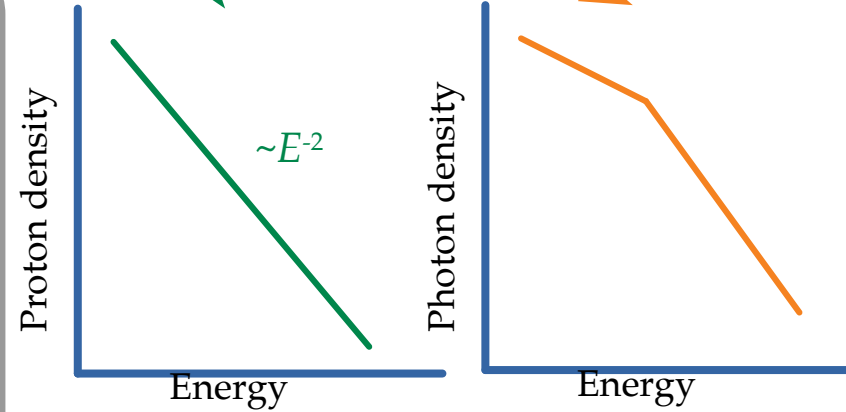
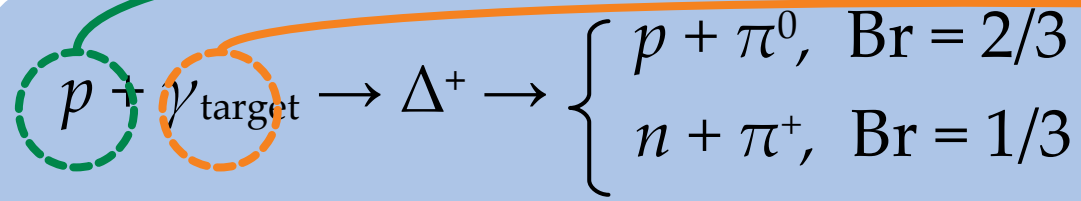
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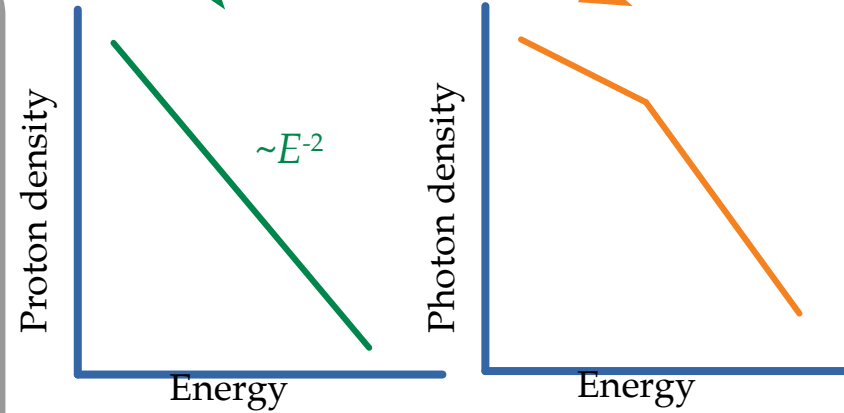
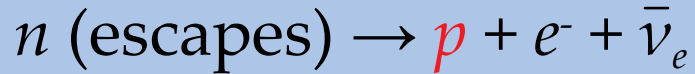
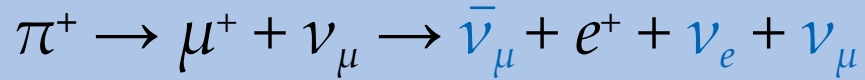
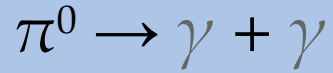
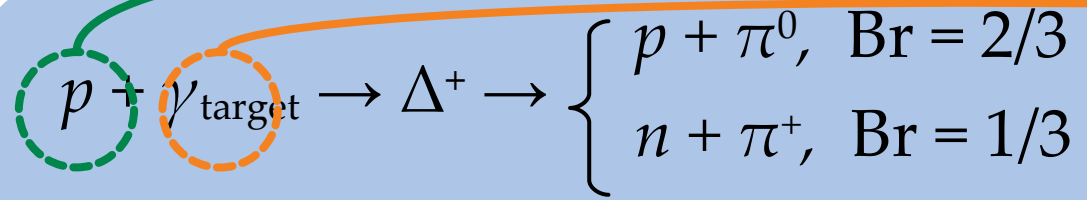
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(or $p + p$)



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The multi-messenger connection: a simple picture

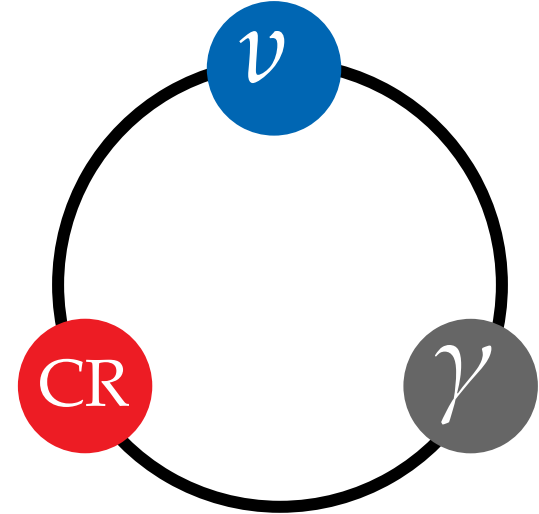
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$$\pi^0 \rightarrow \gamma + \gamma$$

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

$$n \text{ (escapes)} \rightarrow \textcolor{red}{p} + e^- + \bar{\nu}_e$$



Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 10

The multi-messenger connection: a simple picture

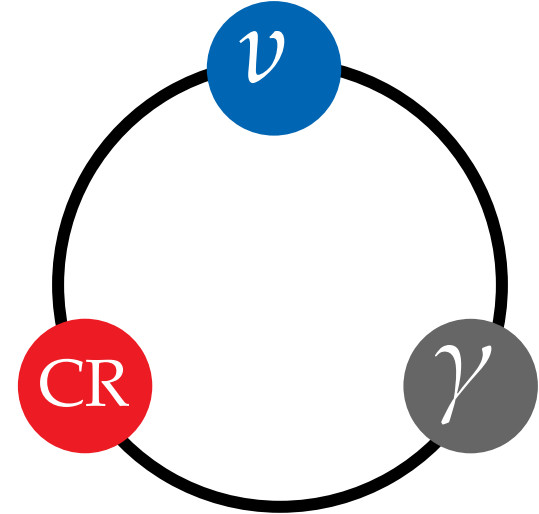
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1 PeV

20 PeV

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Gamma-ray energy = Proton energy / 10

The multi-messenger connection: a simple picture

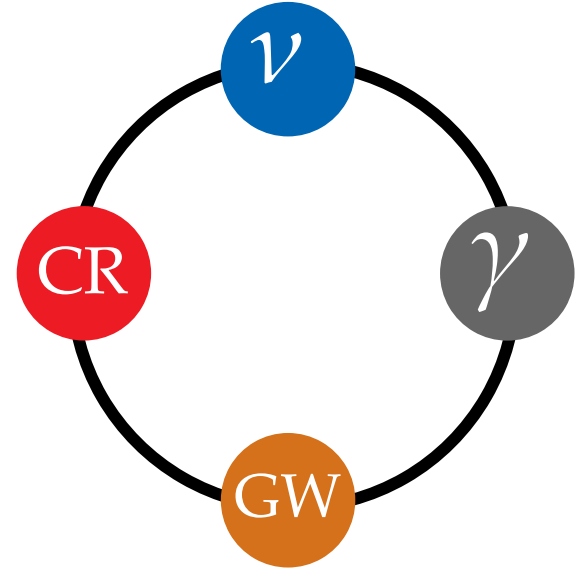
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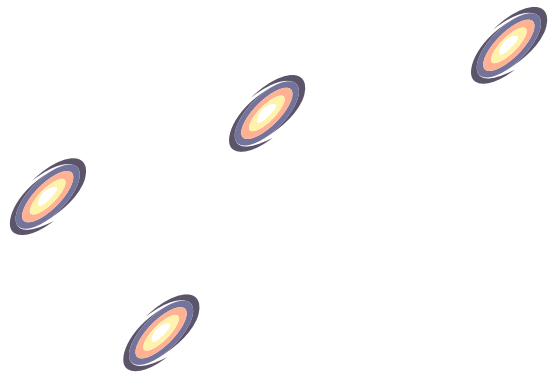
Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 10

Redshift



Note: ν sources can be steady-state or transient



Redshift

$z = 0$

Note: ν sources can be steady-state or transient

MeV γ

Discovered

TeV–PeV ν

“High-energy”

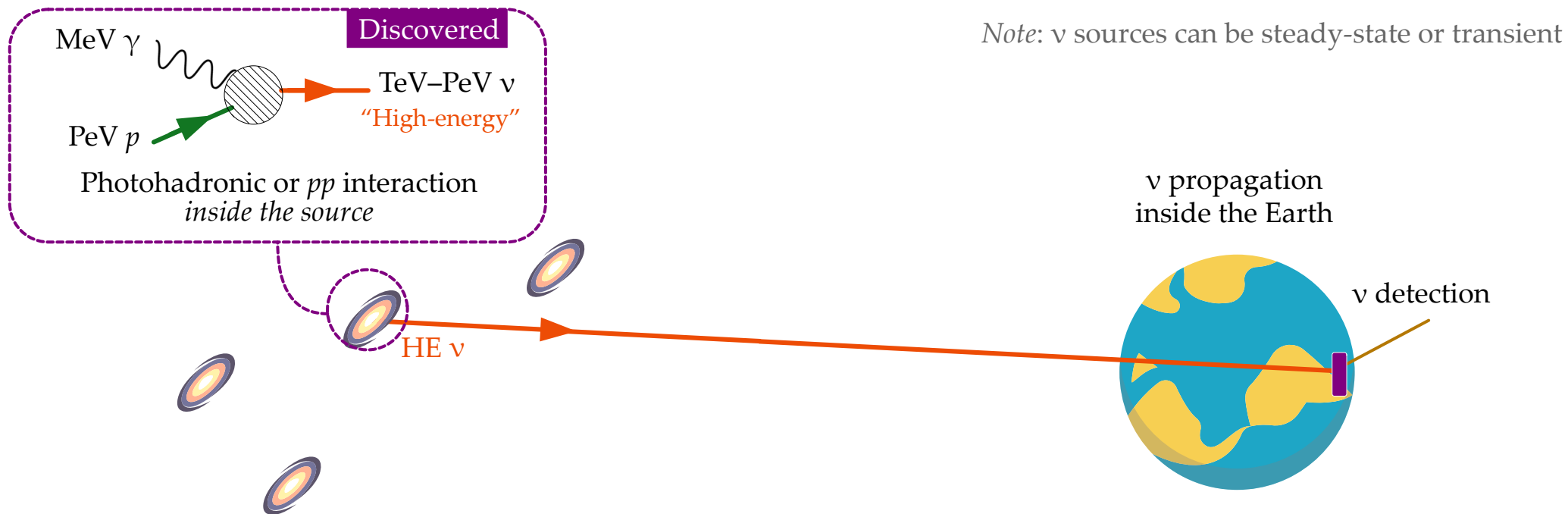
PeV p

Photohadronic or pp interaction
inside the source

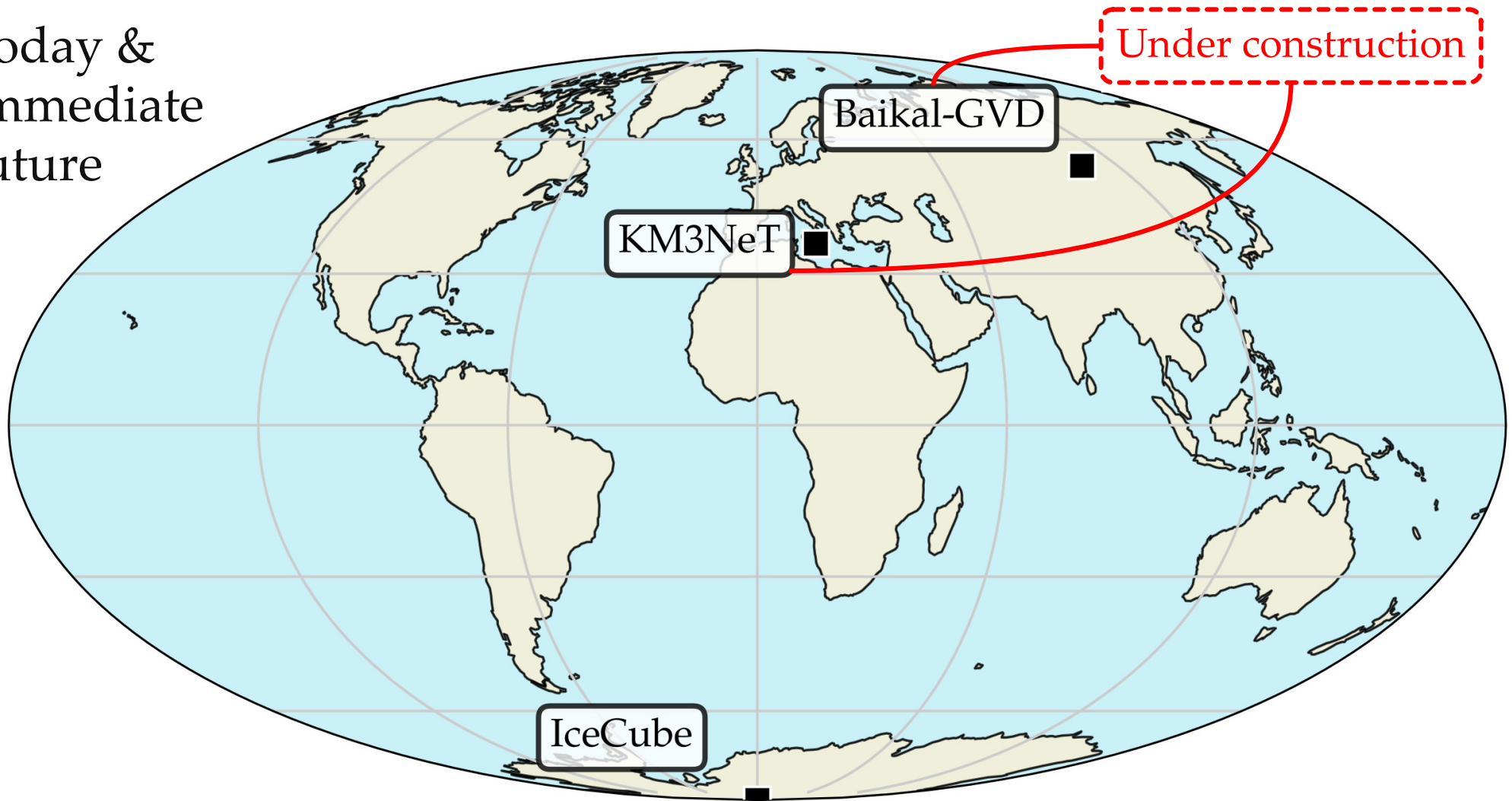
HE ν

ν propagation
inside the Earth

ν detection

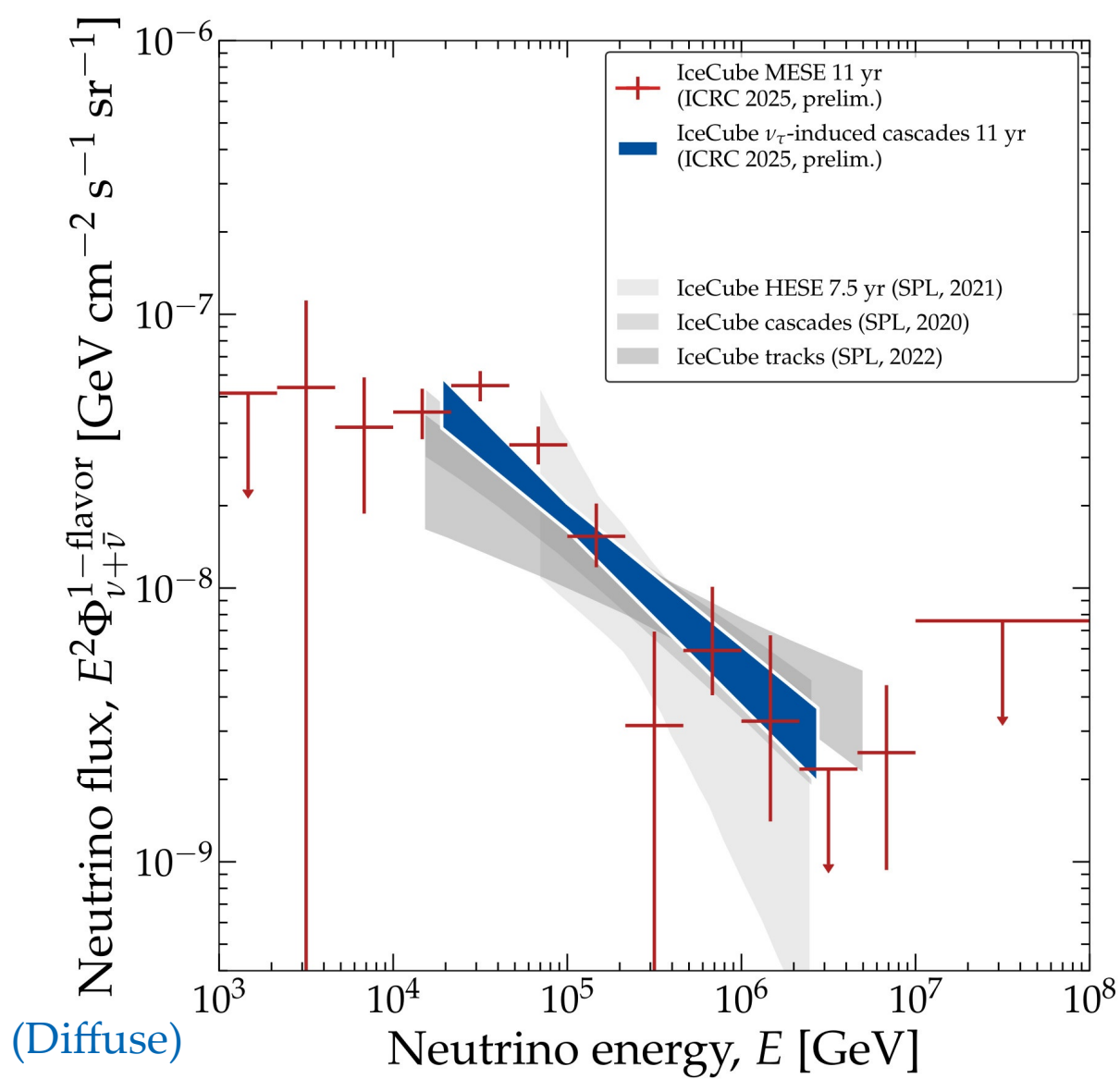


Today &
immediate
future

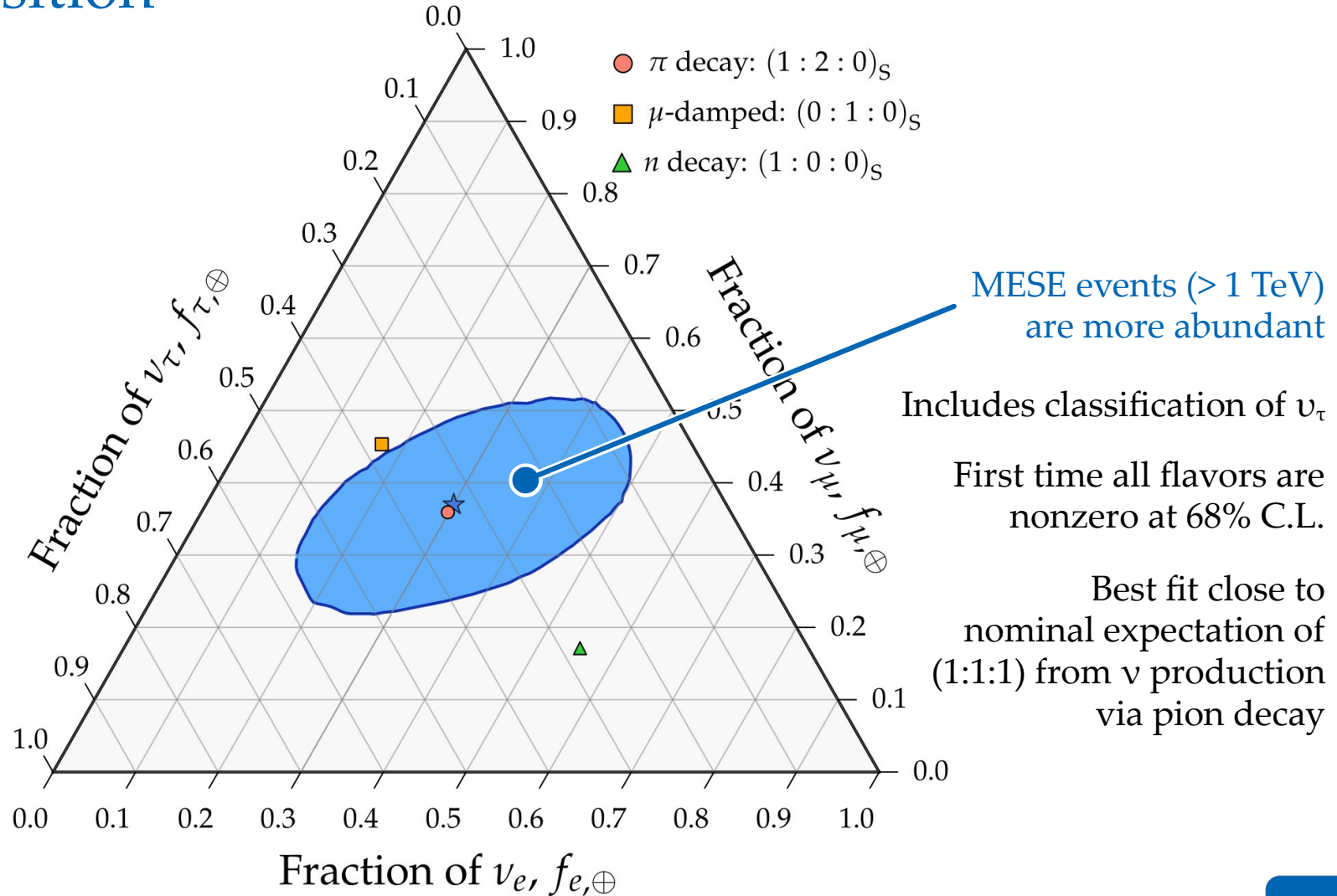


A photograph of the IceCube detector structure in Antarctica. The structure is a large, blue, rectangular building with multiple levels and metal staircases, situated on a snowy, icy landscape. Two large, cylindrical, silver-colored storage tanks are positioned on either side of the main building. The sky is a pale blue, and the ground is covered in snow and ice. The word "IceCube" is overlaid in a large, white, serif font across the center of the image.

IceCube

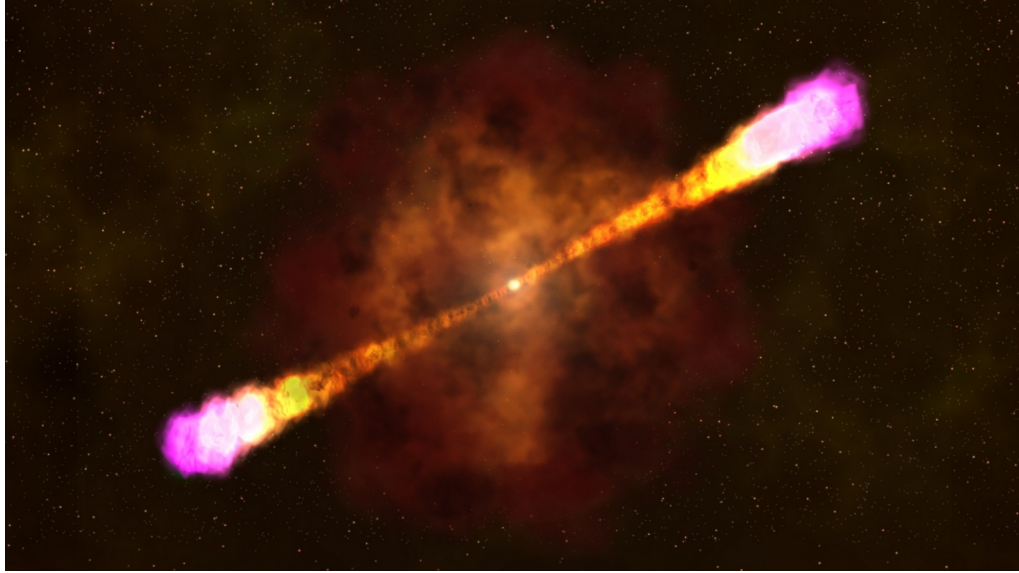


Flavor composition



Gamma-ray bursts and blazars – *not* dominant

Gamma-ray bursts

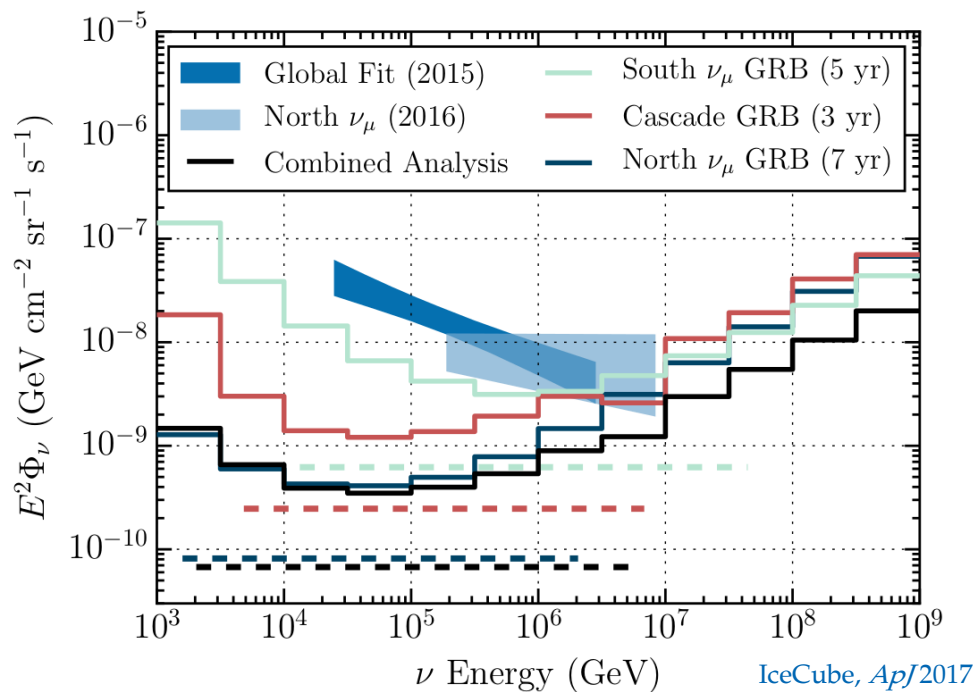


Blazars



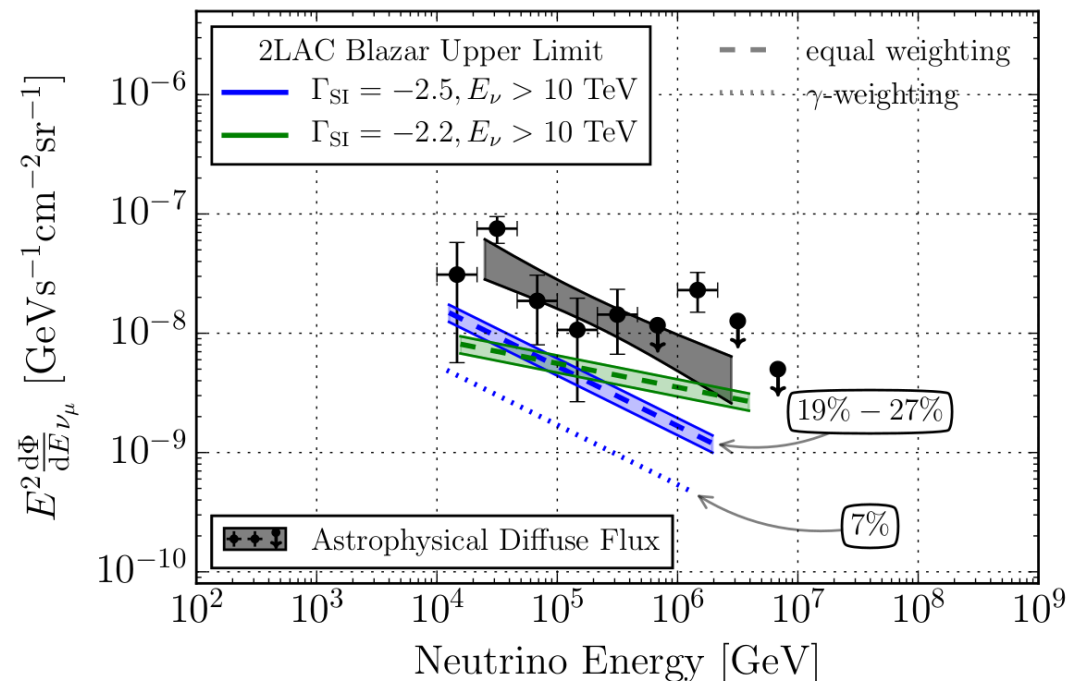
Gamma-ray bursts and blazars – *not* dominant

Gamma-ray bursts



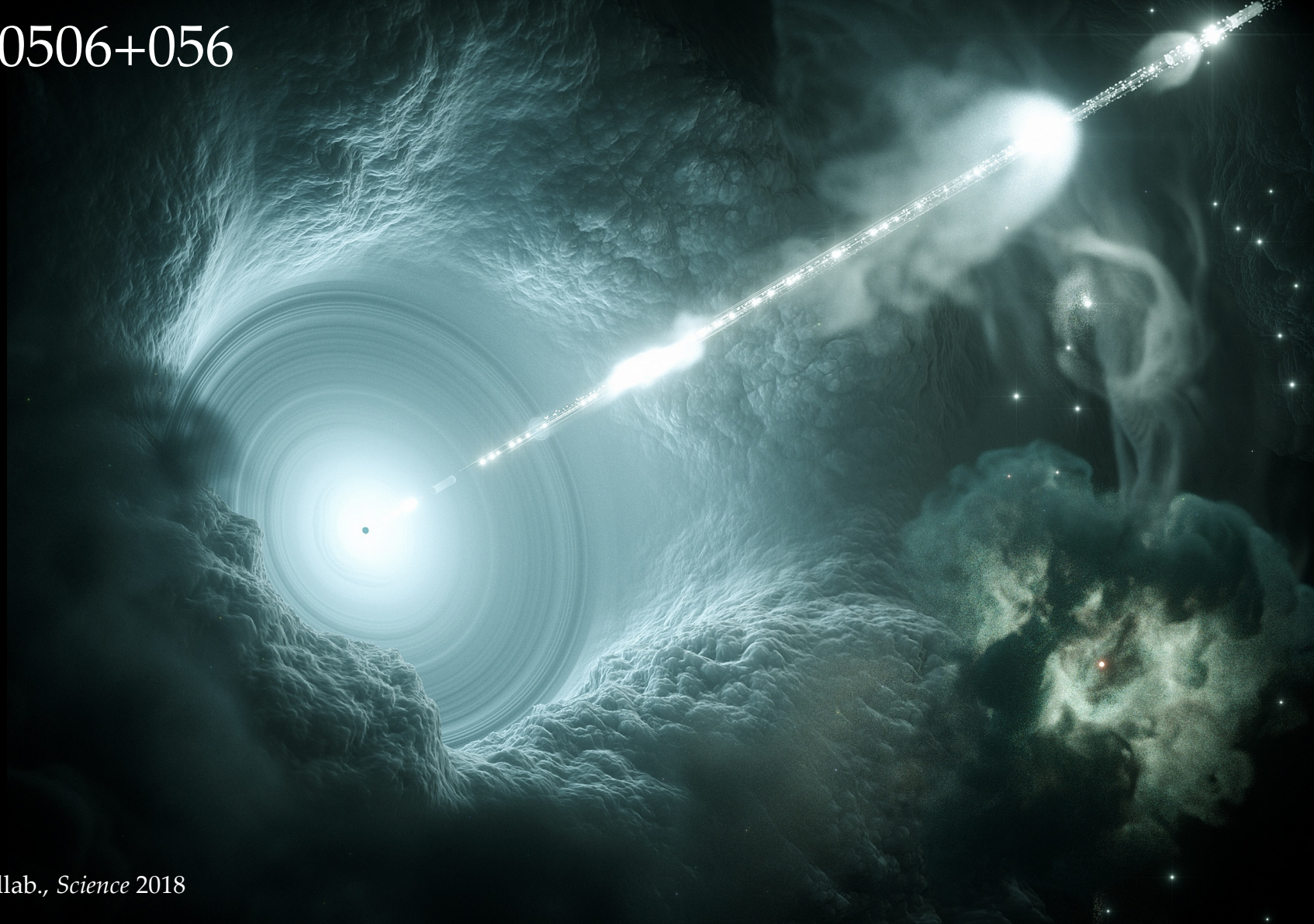
1172 GRBs inspected, no correlation found
< 1% contribution to diffuse flux

Blazars

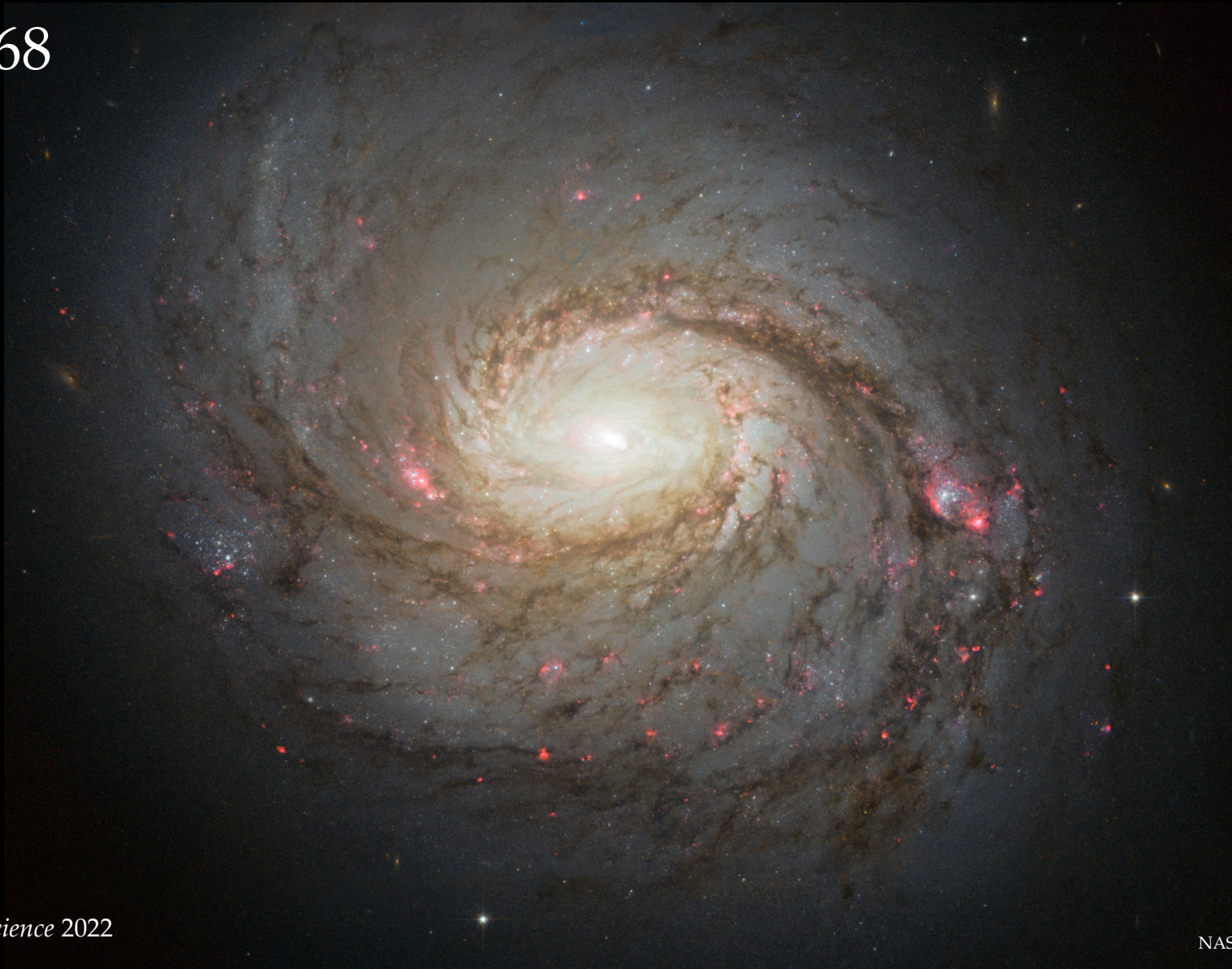


862 blazars inspected, no correlation found
< 27% contribution to diffuse flux

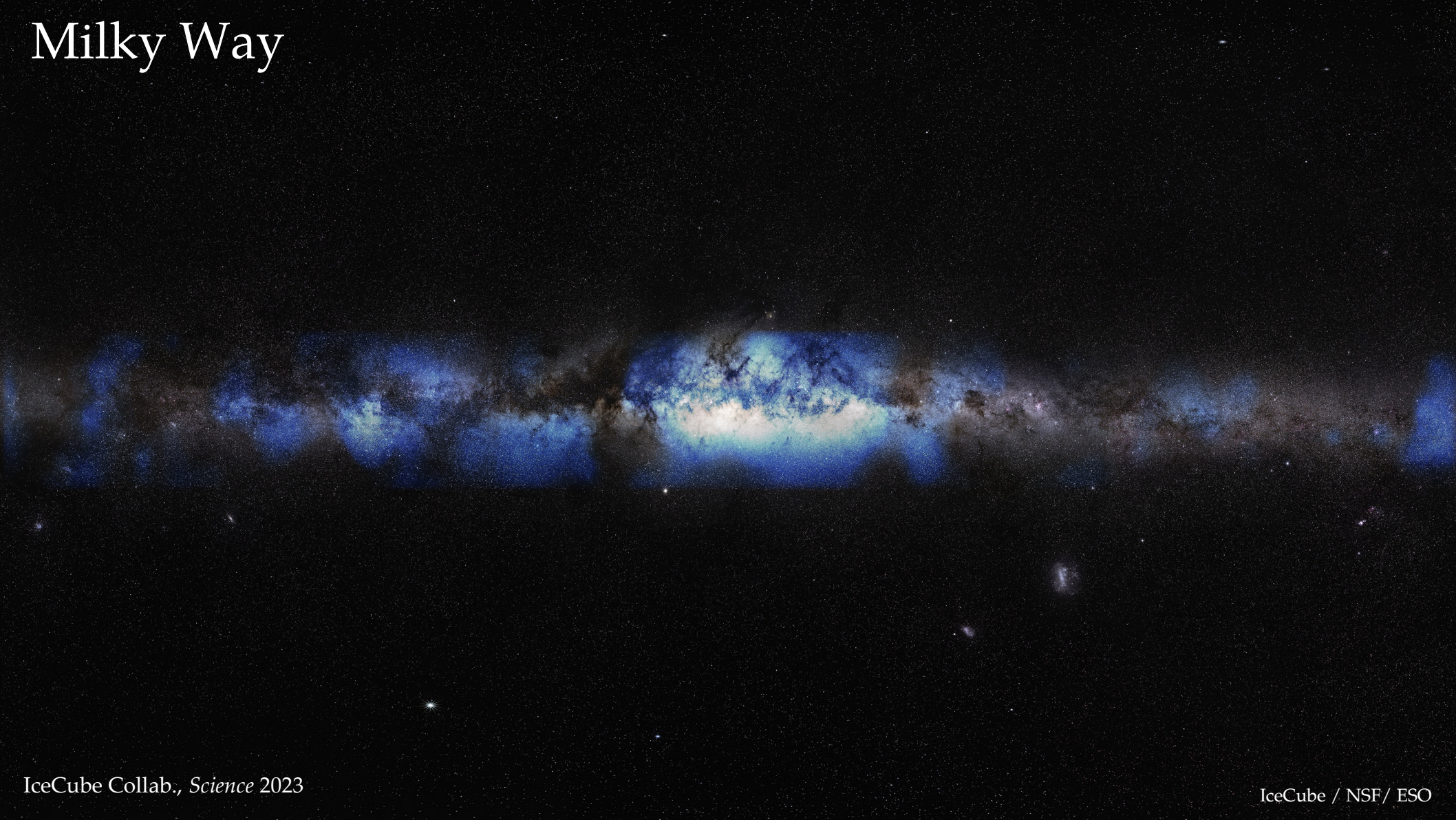
TXS 0506+056

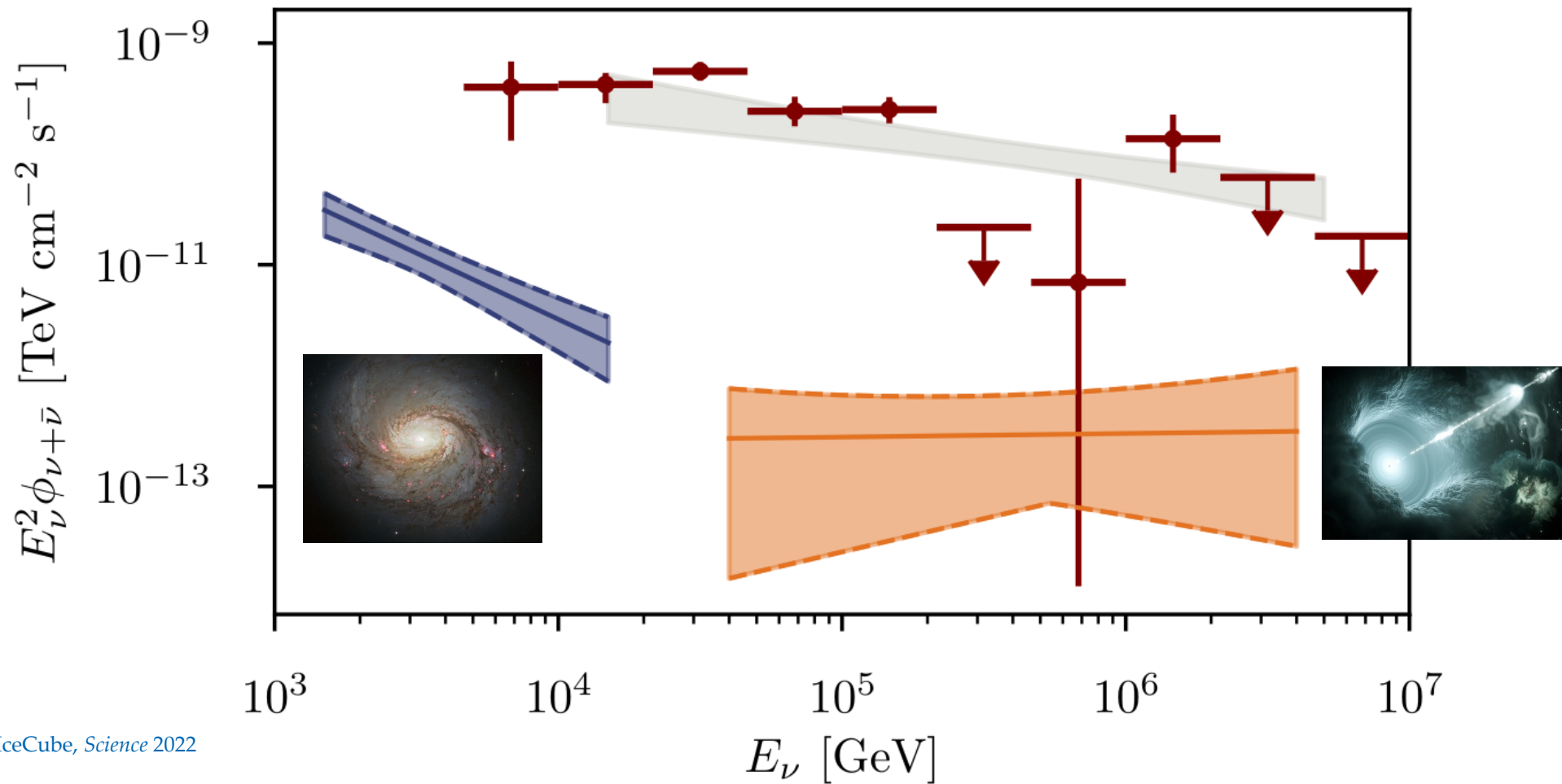


NGC1068



Milky Way

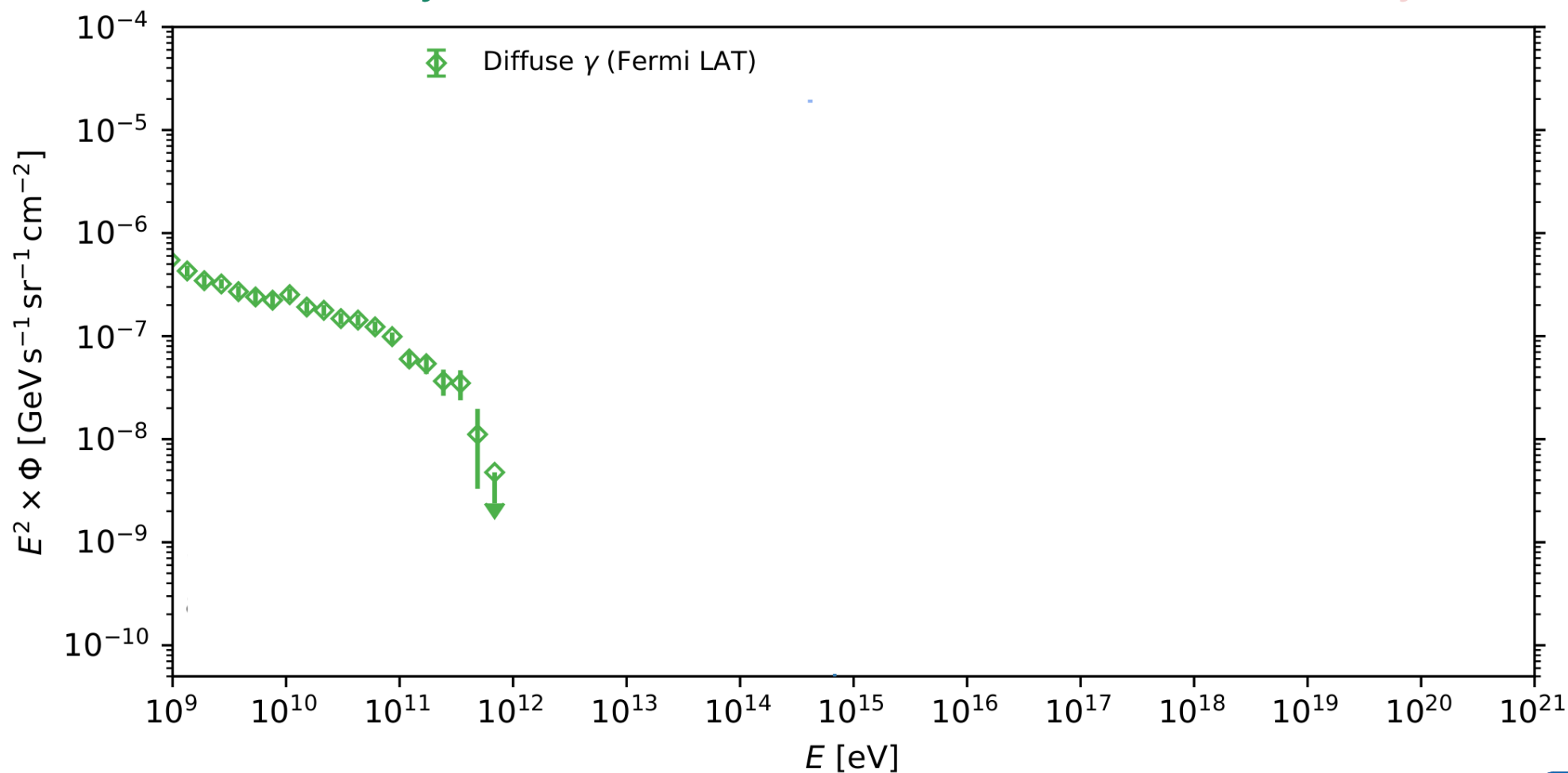




Gamma rays

Neutrinos

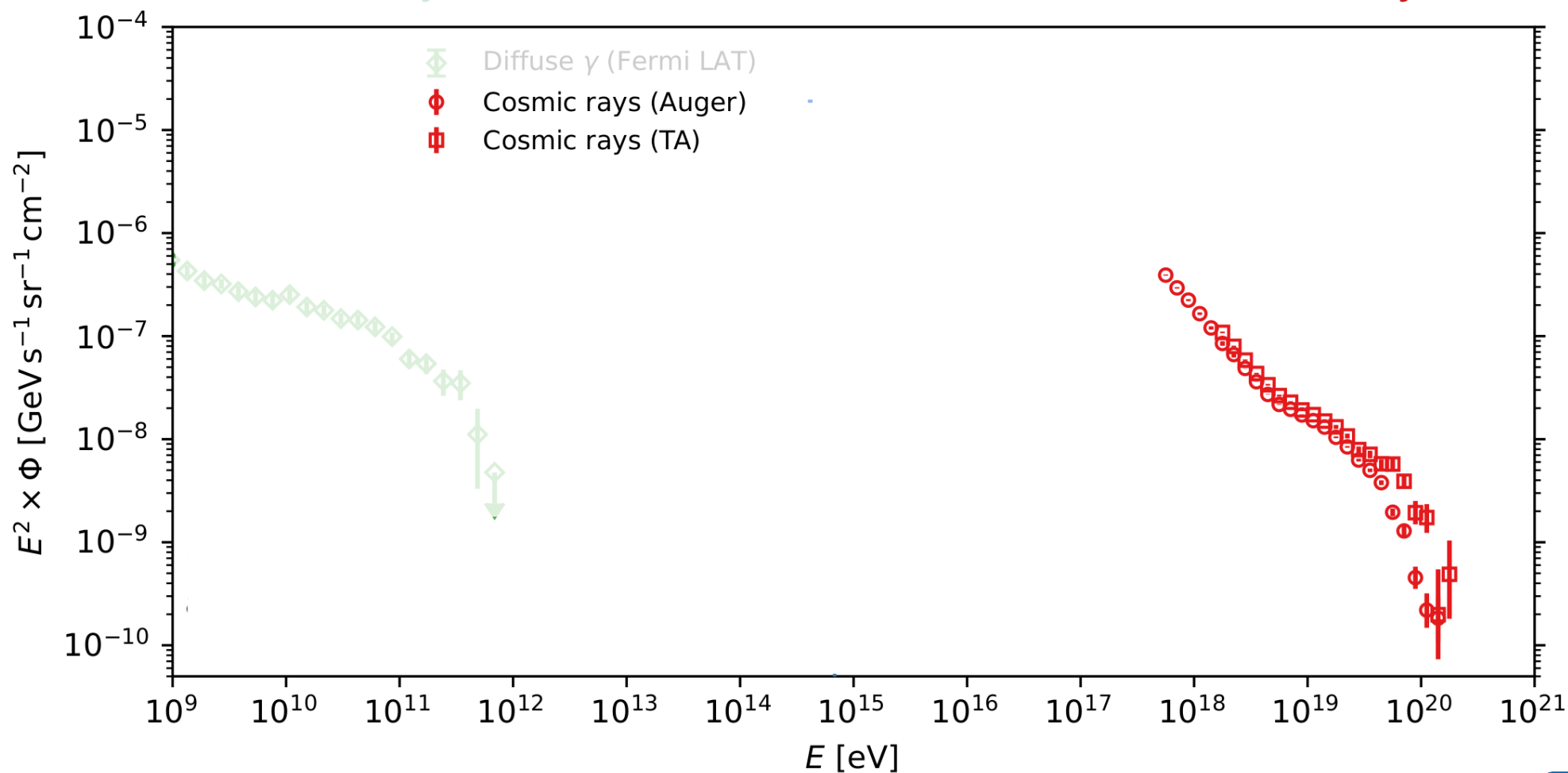
Cosmic rays



Gamma rays

Neutrinos

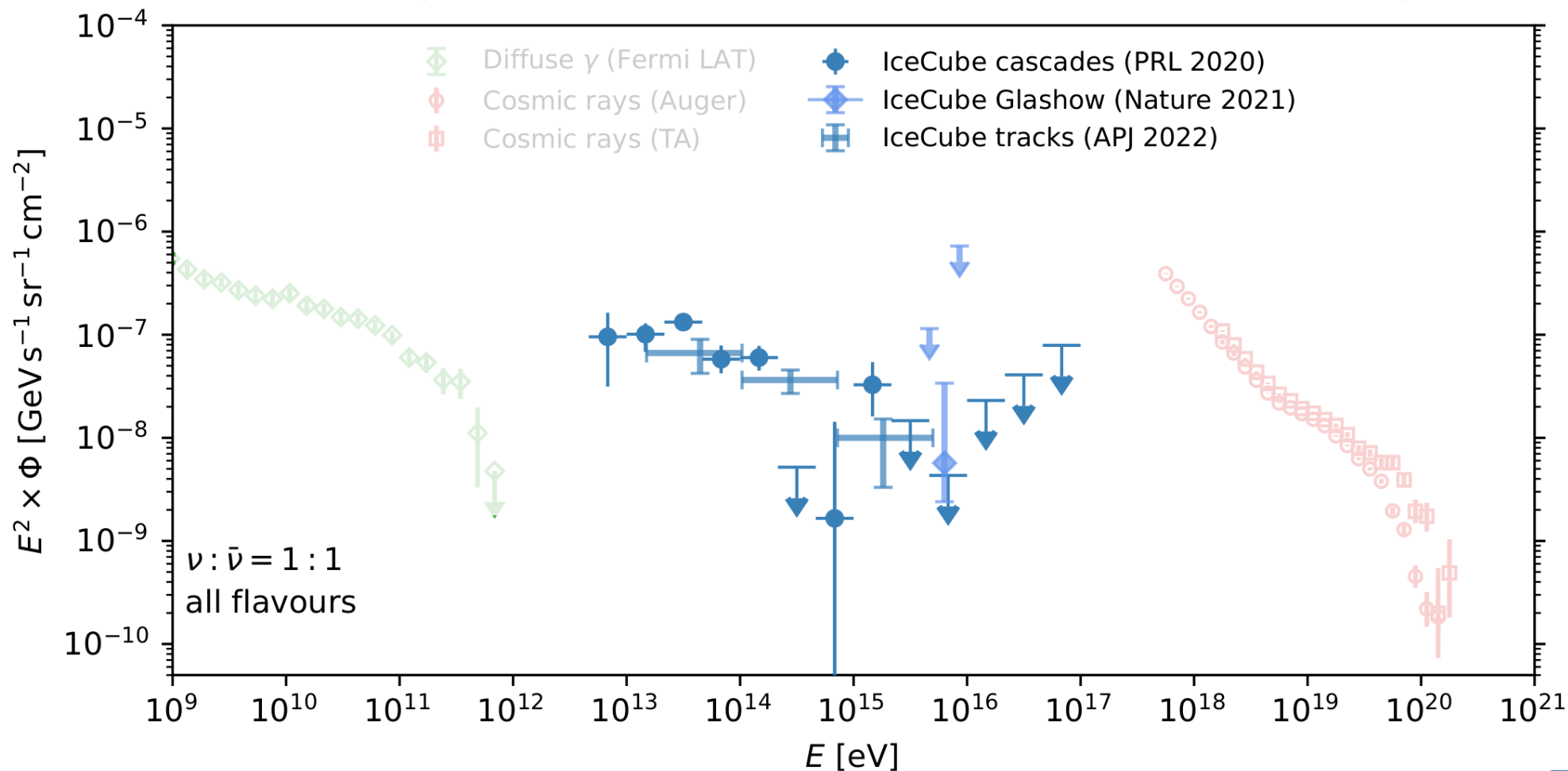
Cosmic rays



Gamma rays

Neutrinos

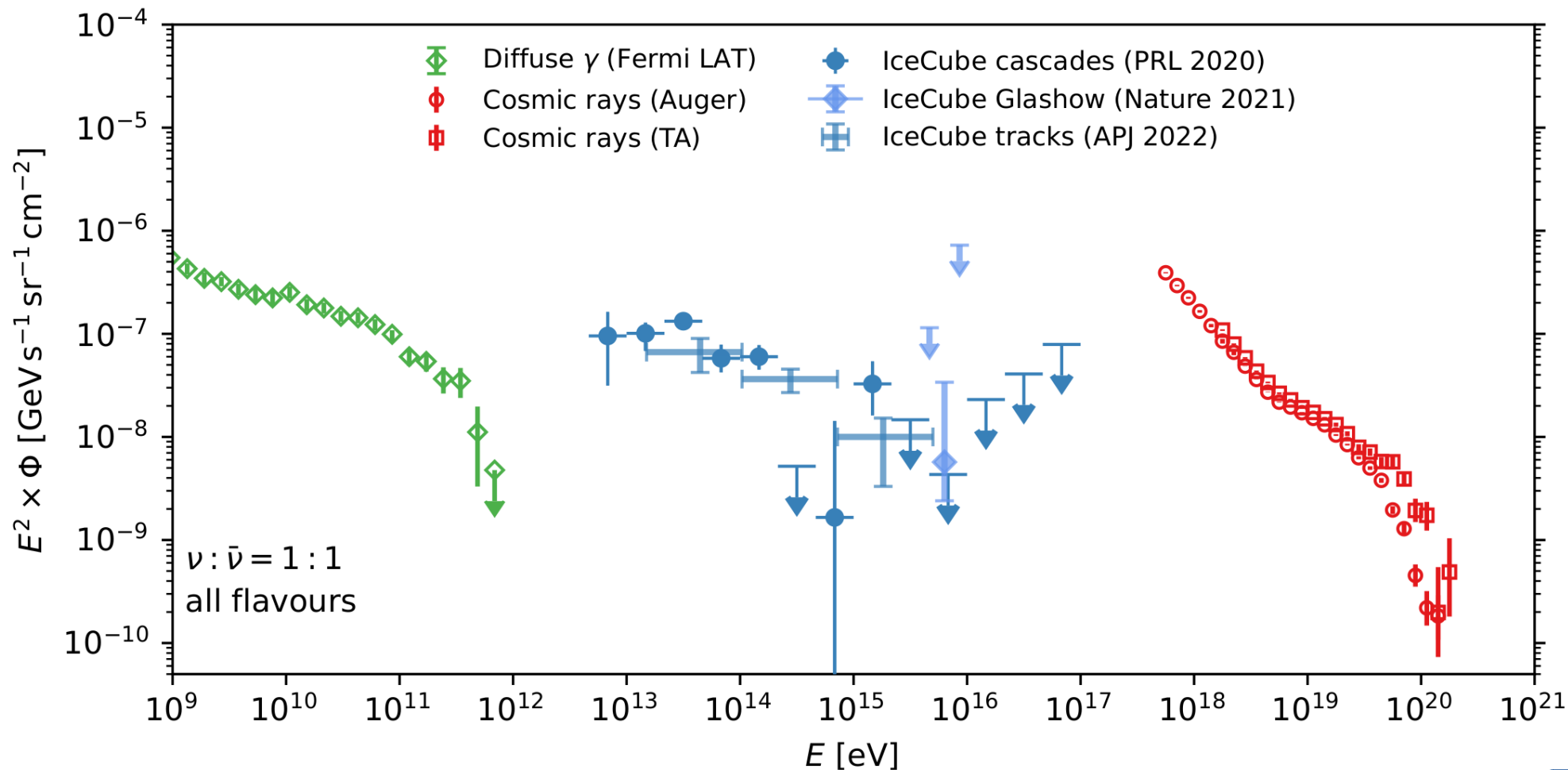
Cosmic rays



Gamma rays

Neutrinos

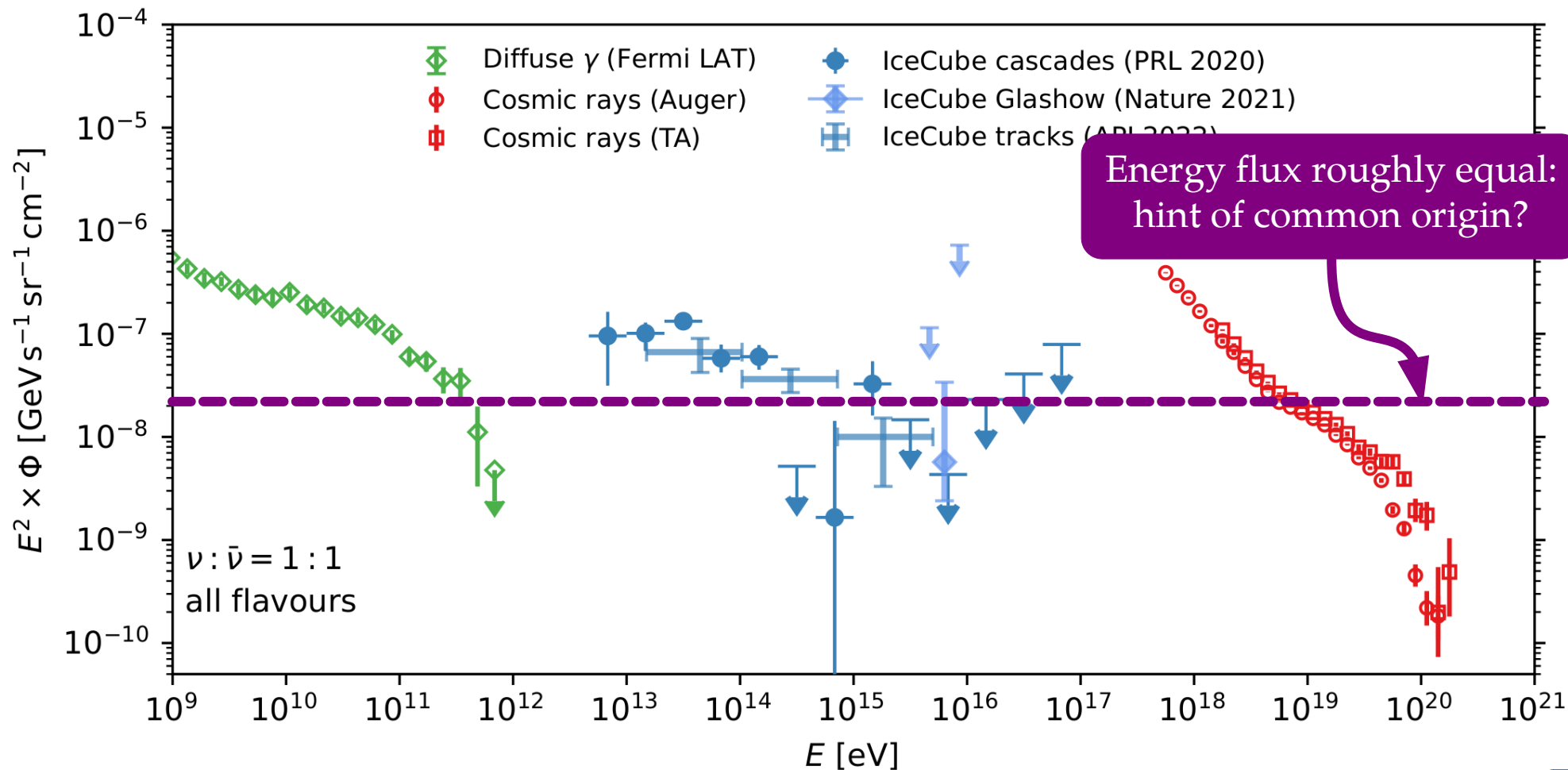
Cosmic rays

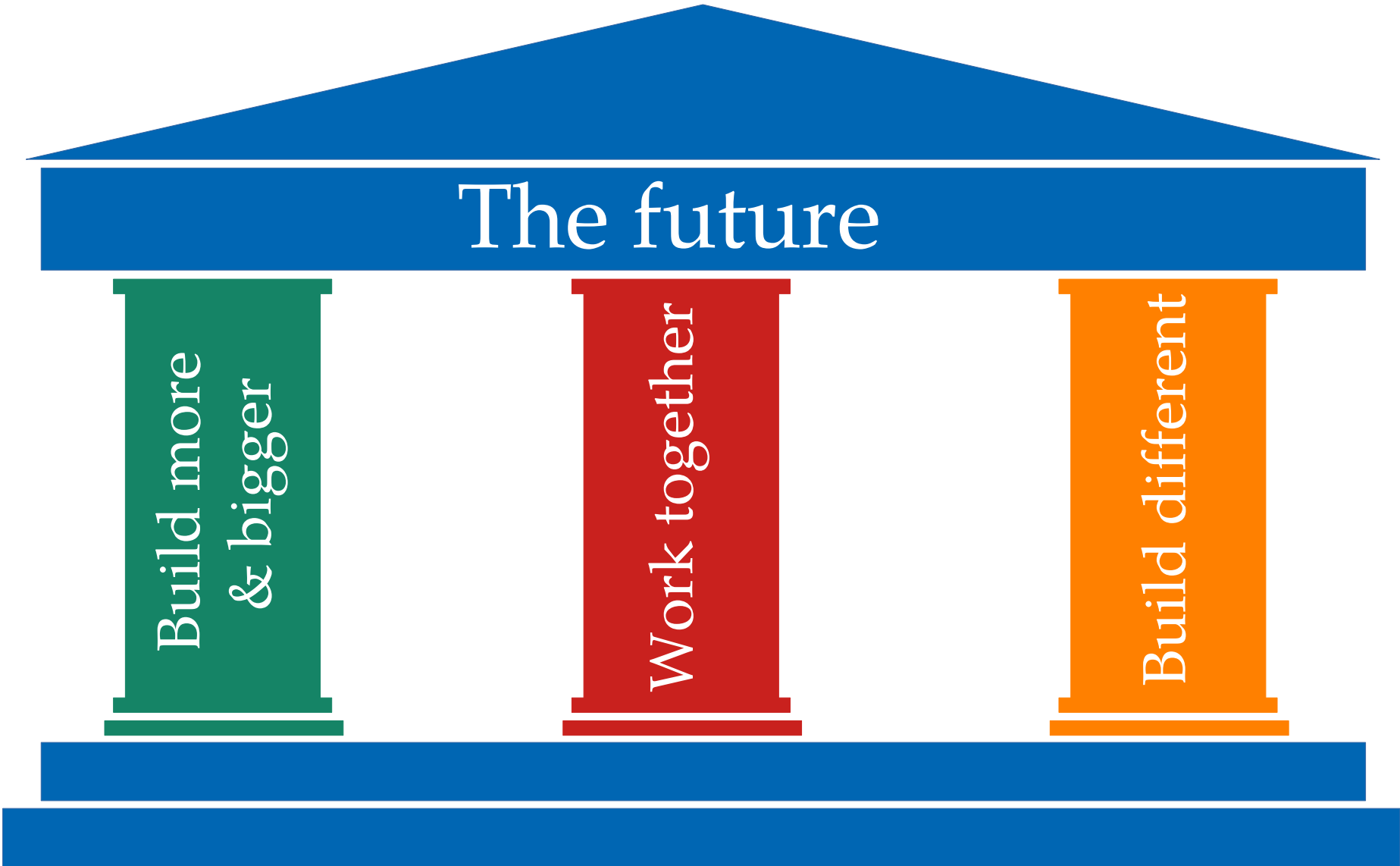


Gamma rays

Neutrinos

Cosmic rays



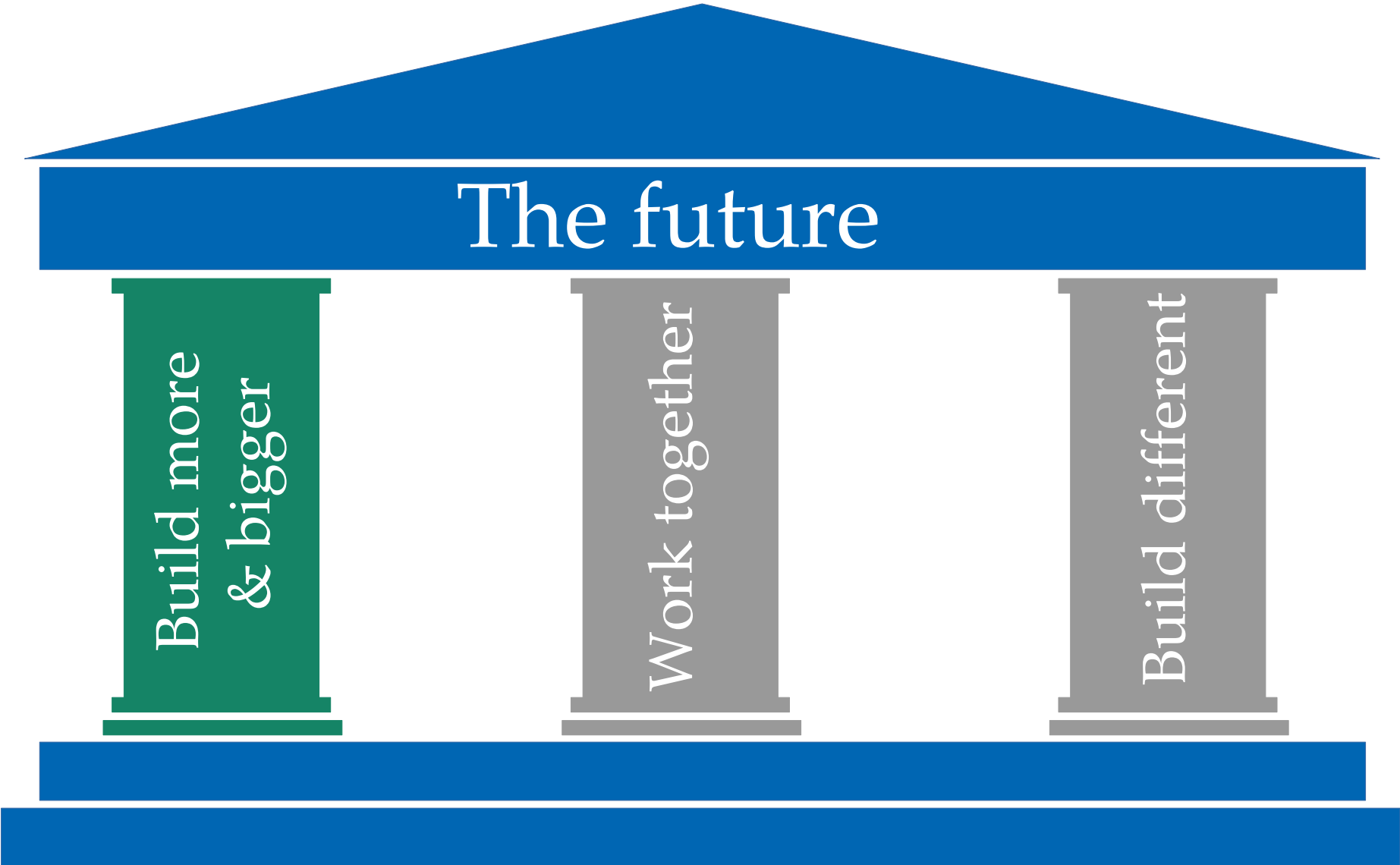


The future

Build more
& bigger

Work together

Build different



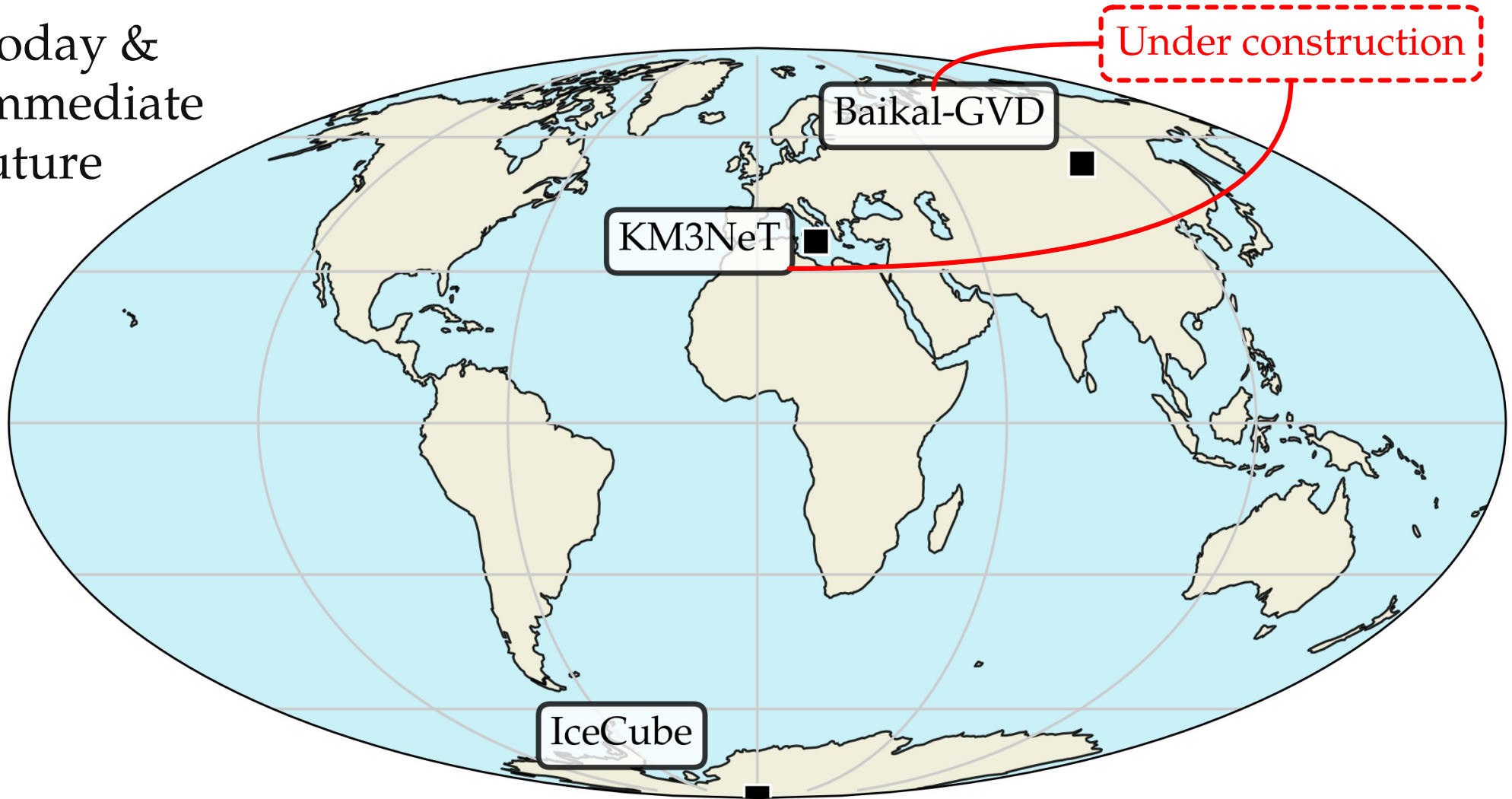
The future

Build more
& bigger

Work together

Build different

Today &
immediate
future



KM3NeT

A 3D rendering of the KM3NeT neutrino detector array. The image shows a vast grid of vertical moorings extending from the sea surface down to the seabed. Each mooring is equipped with numerous small, dark, spherical detector modules. A prominent yellow cylindrical structure is visible on one of the central moorings. On the right side, a large, detailed detector module is shown in close-up, revealing its internal structure and external components. The seabed is visible at the bottom, with various yellow and white structures, likely part of the detector's infrastructure or support vessels. The sky is a clear blue with a bright sun.

The international journal of science / 13 February 2025

nature

COSMIC CATCHER

Deep-sea telescope detects
neutrino with highest
energy ever recorded

Article

Observation of an ultra-high-energy cosmic neutrino with KM3NeT

KM3NeT Collab. *Nature* 638, 376 (2025)

One muon detected with 120^{+110}_{-60} PeV

Inferred neutrino energy: 220^{+570}_{-110} PeV

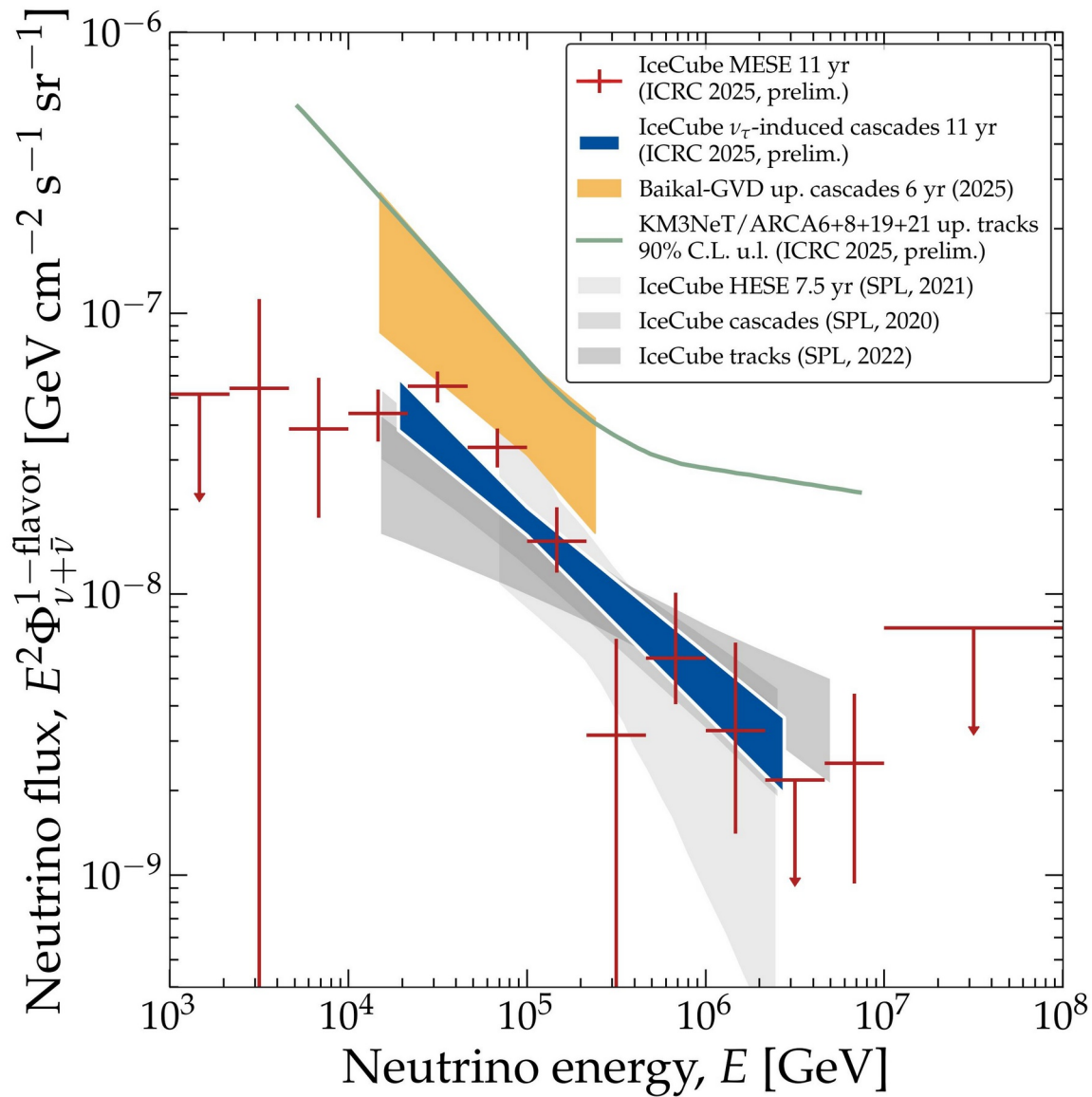
(Assuming E^{-2} spectrum)

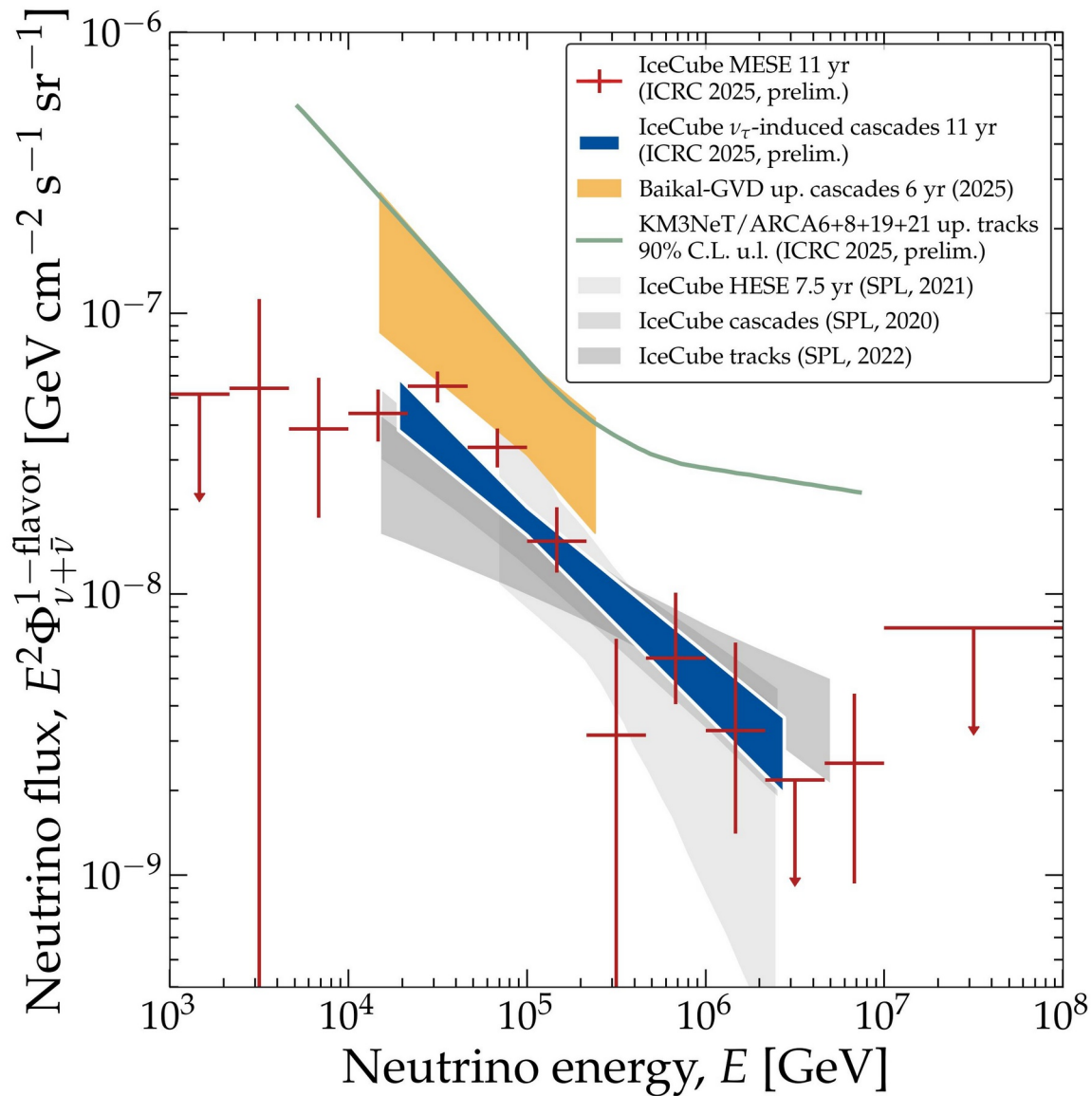
No known source

First ultra-high-energy neutrino
detected, waiting since 1969

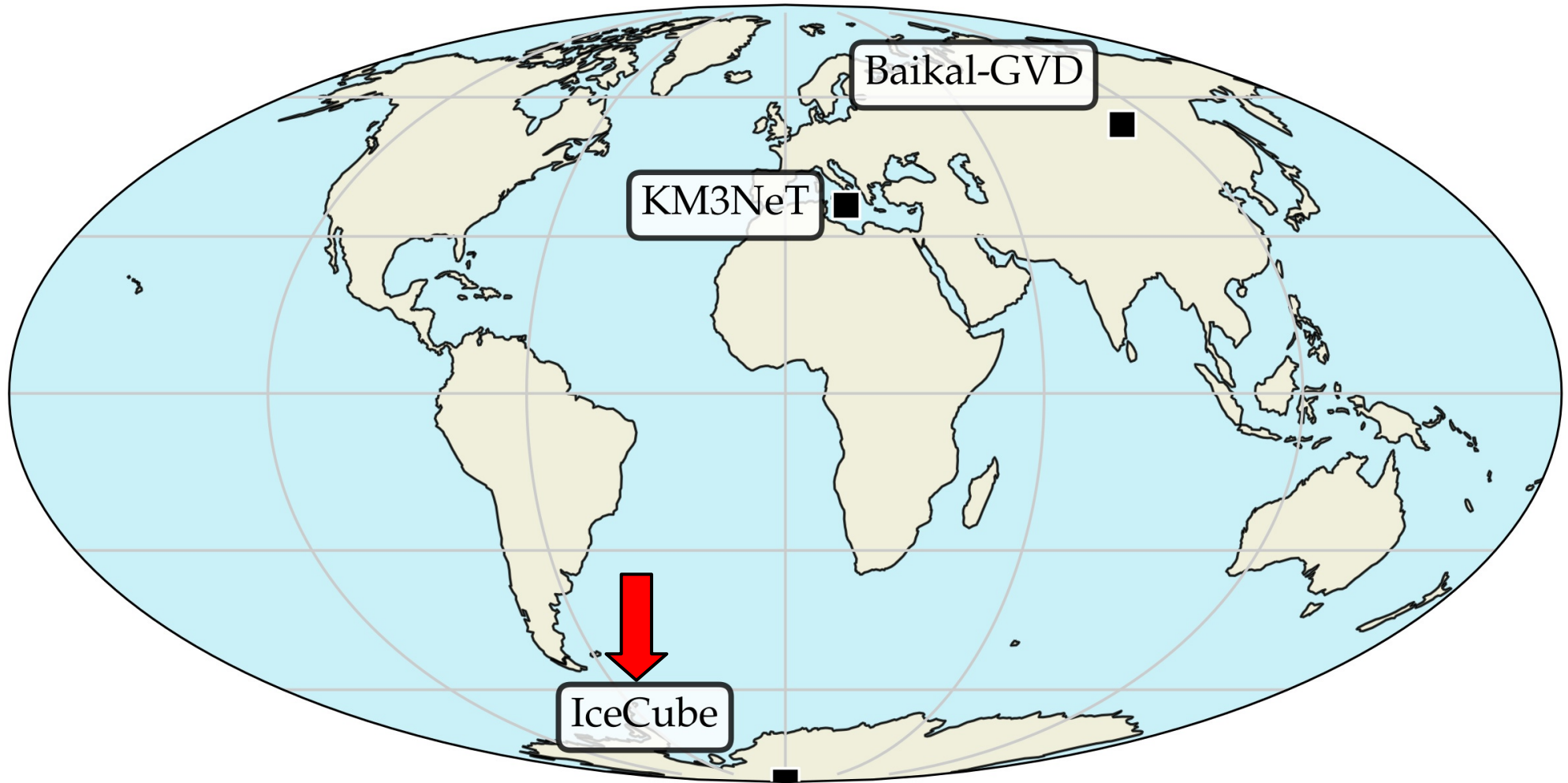


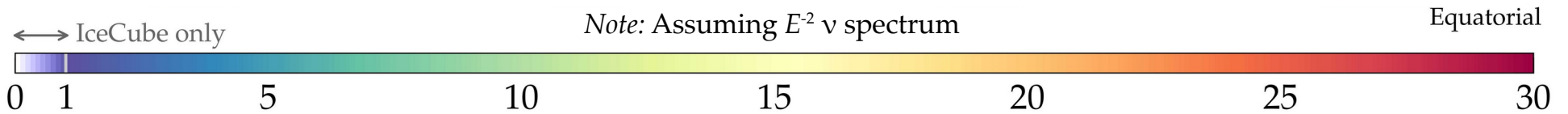
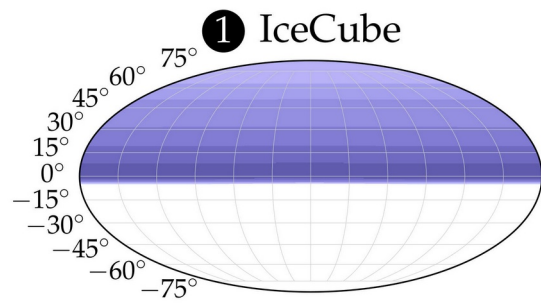
Baikal-GVD



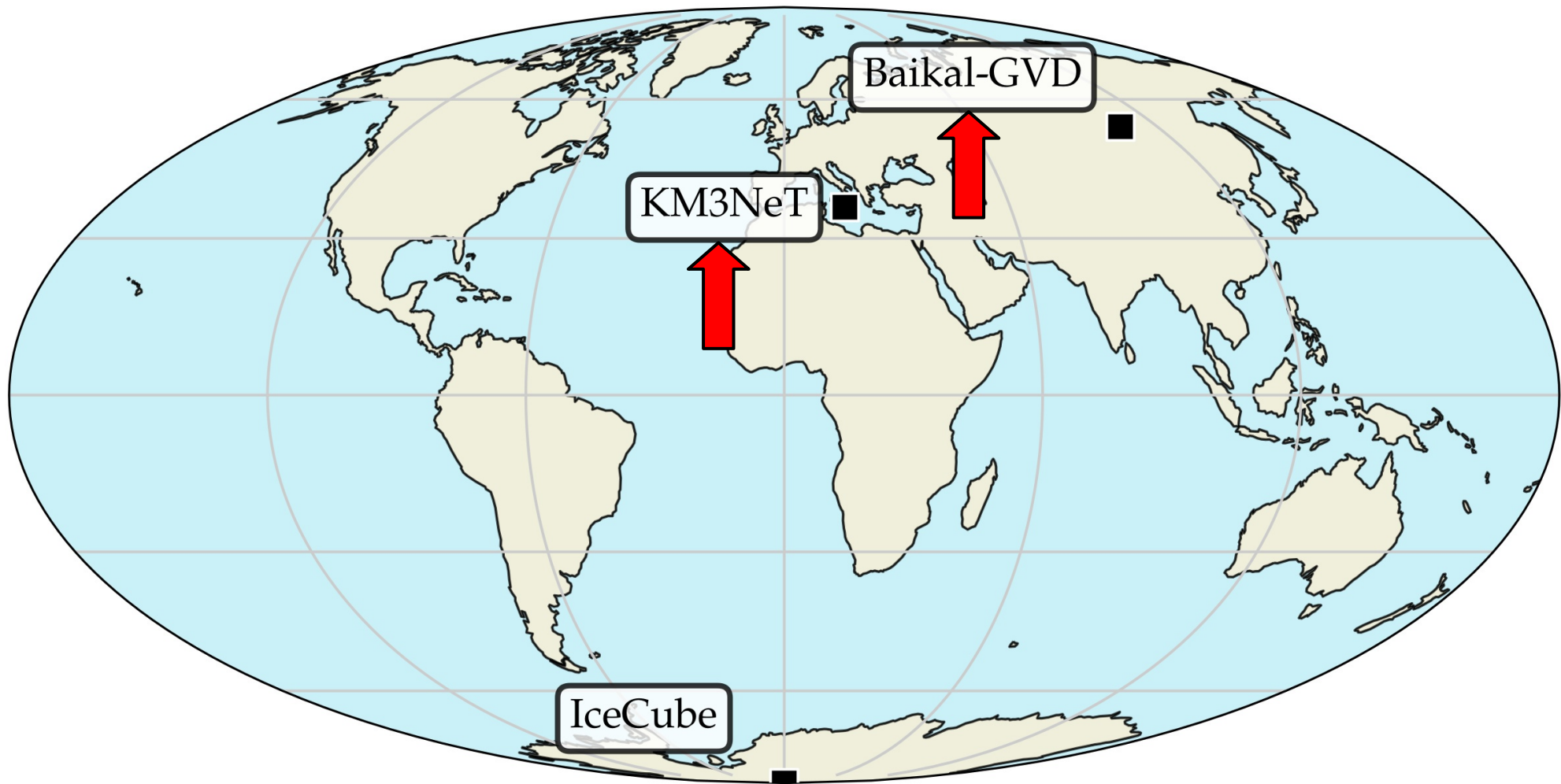


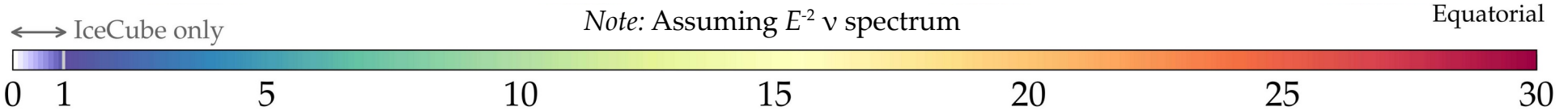
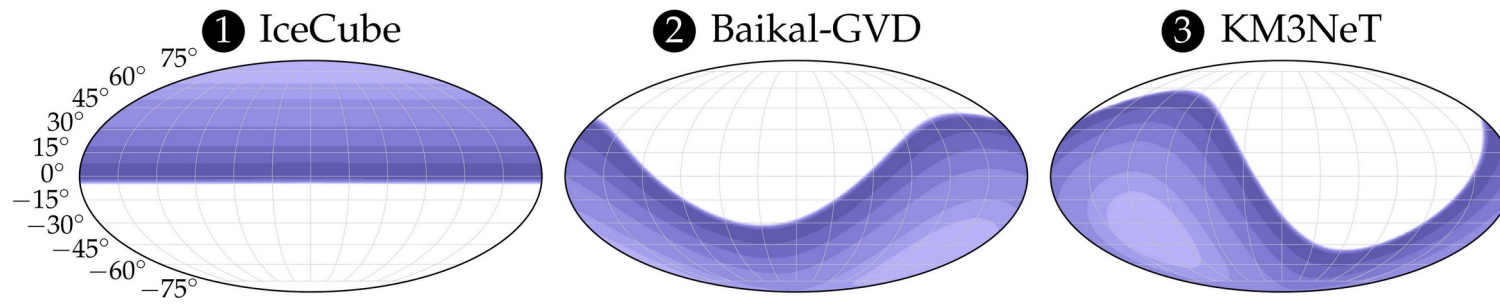
The three existing large neutrino telescopes are independently probing the diffuse flux of TeV–PeV cosmic ν !





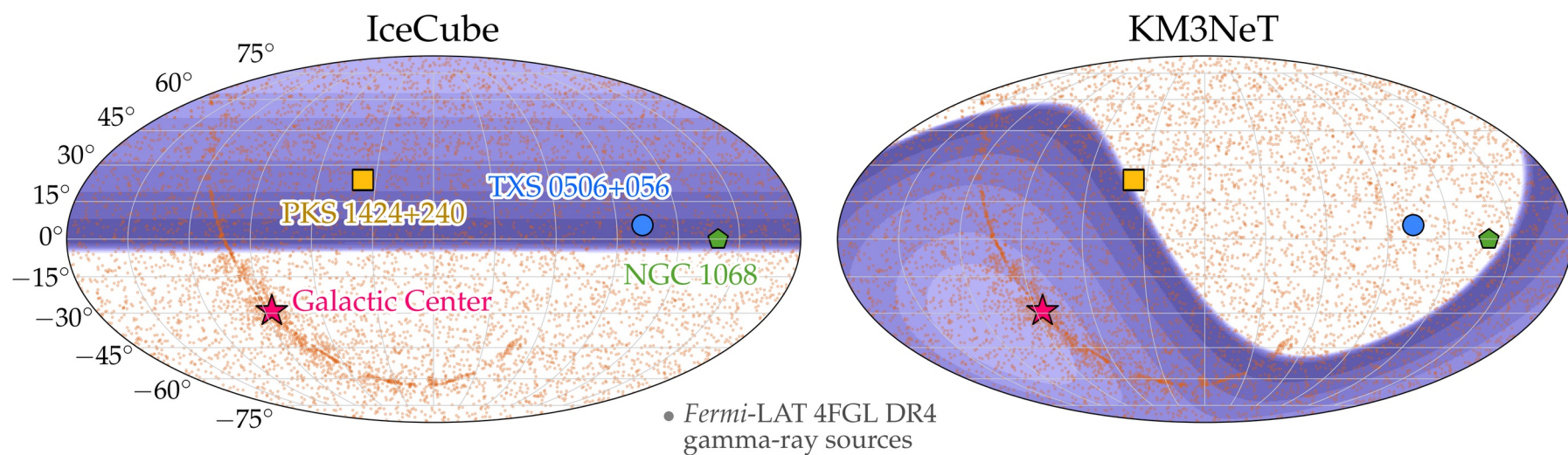
Rate of detected muon tracks relative to IceCube maximum



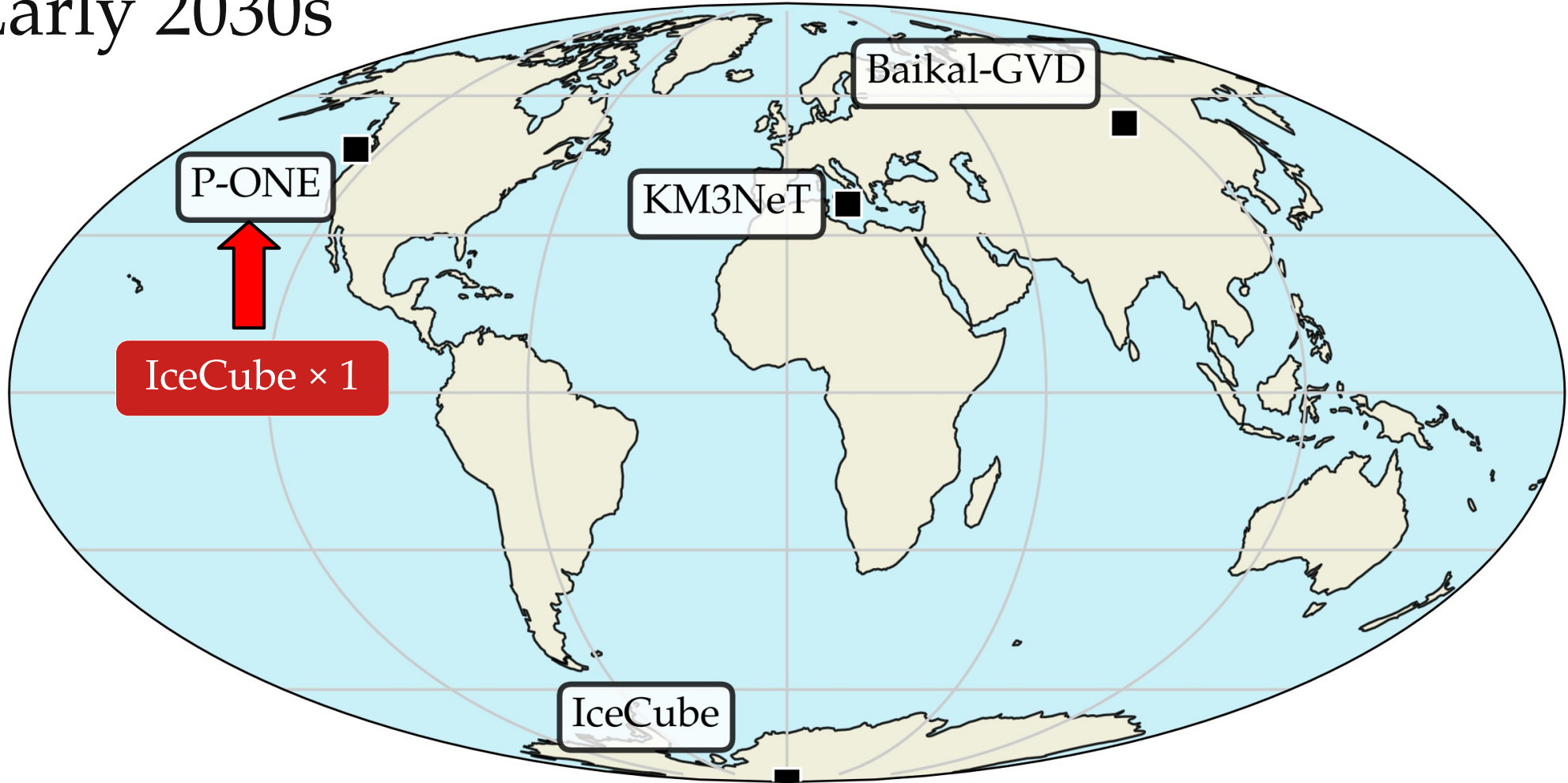


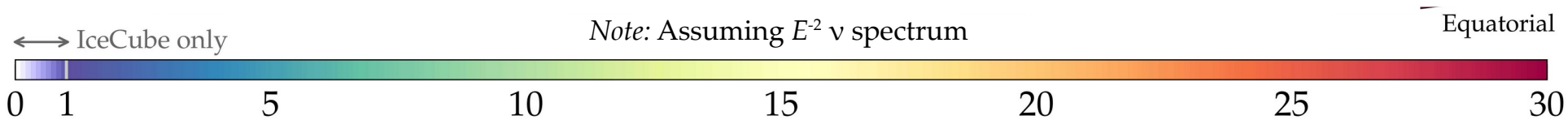
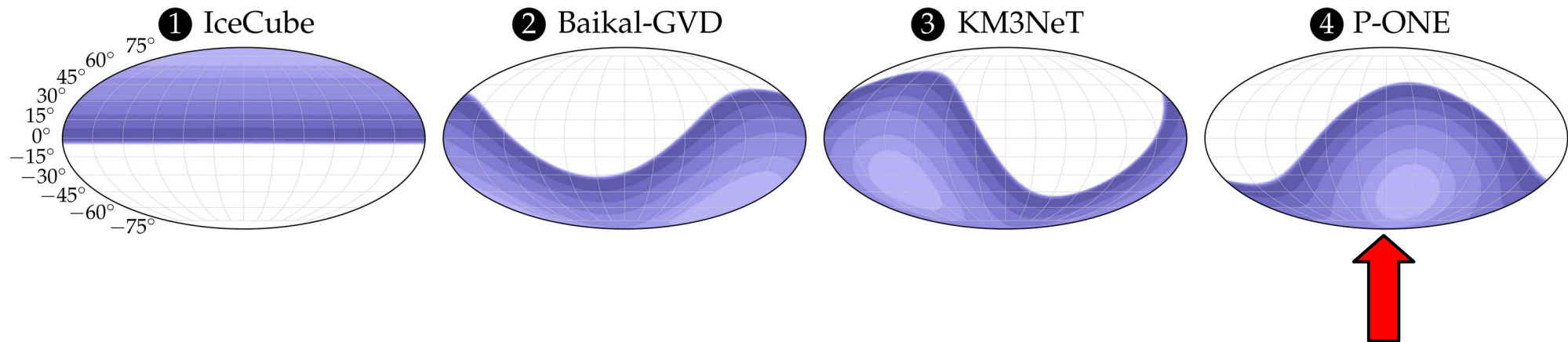
Note: Assuming E^{-2} ν spectrum

Rate of detected muon tracks relative to IceCube maximum



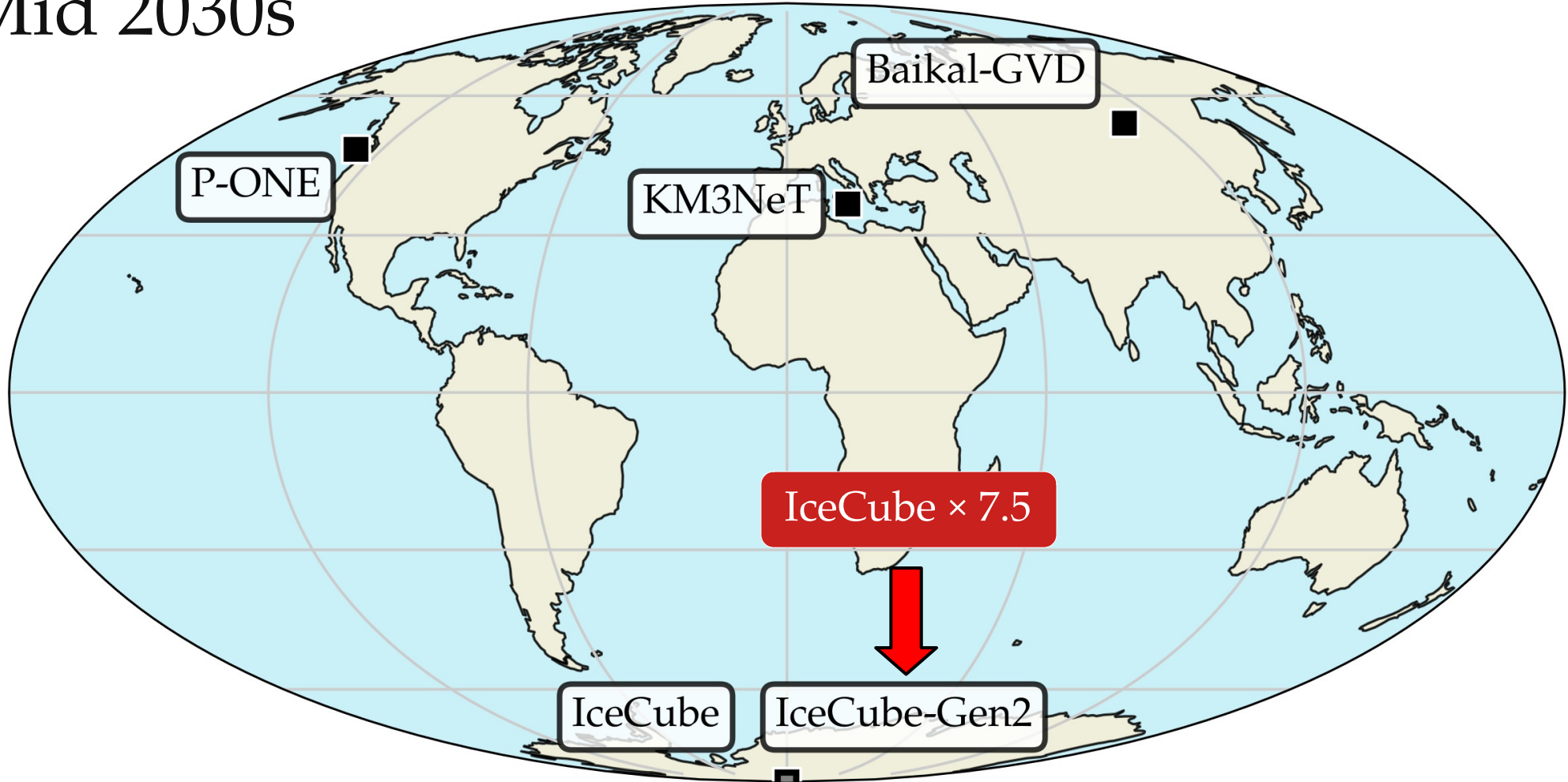
Early 2030s

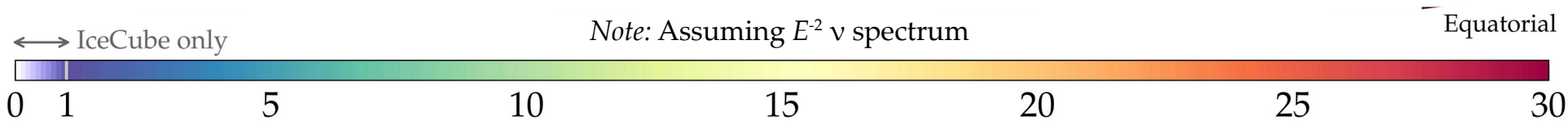
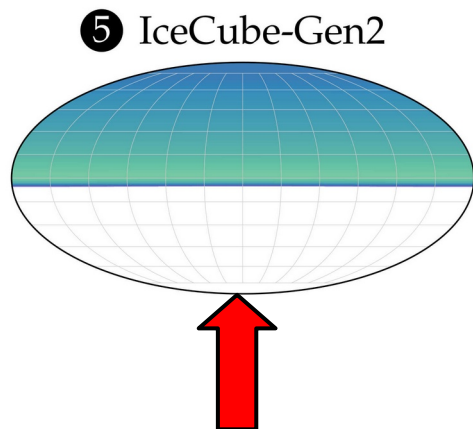
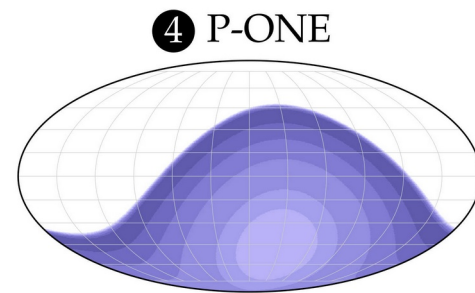
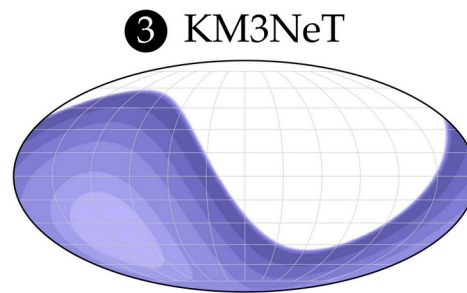
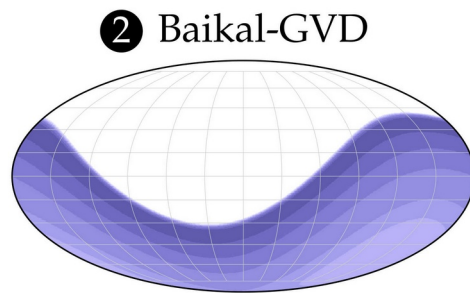
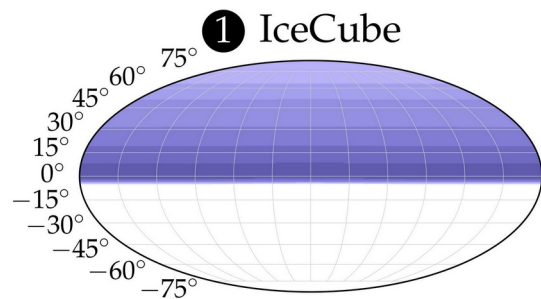




Rate of detected muon tracks relative to IceCube maximum

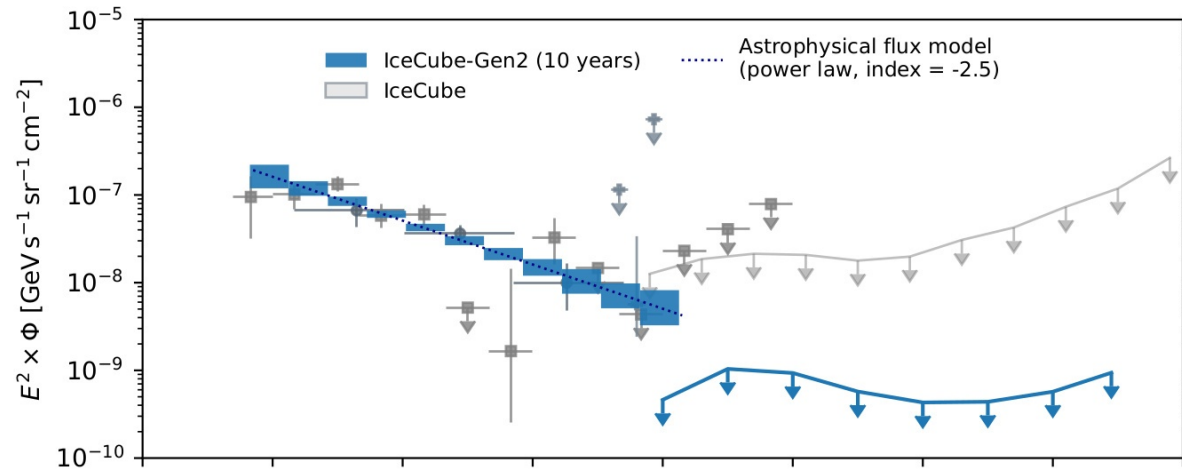
Mid 2030s



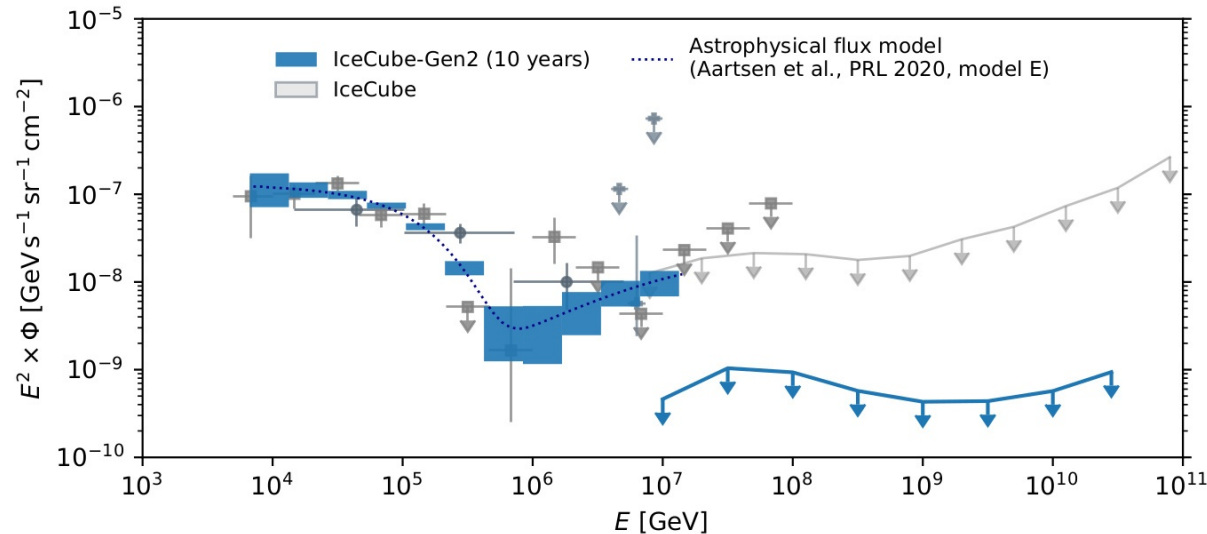


Rate of detected muon tracks relative to IceCube maximum

Measuring the diffuse flux *precisely*

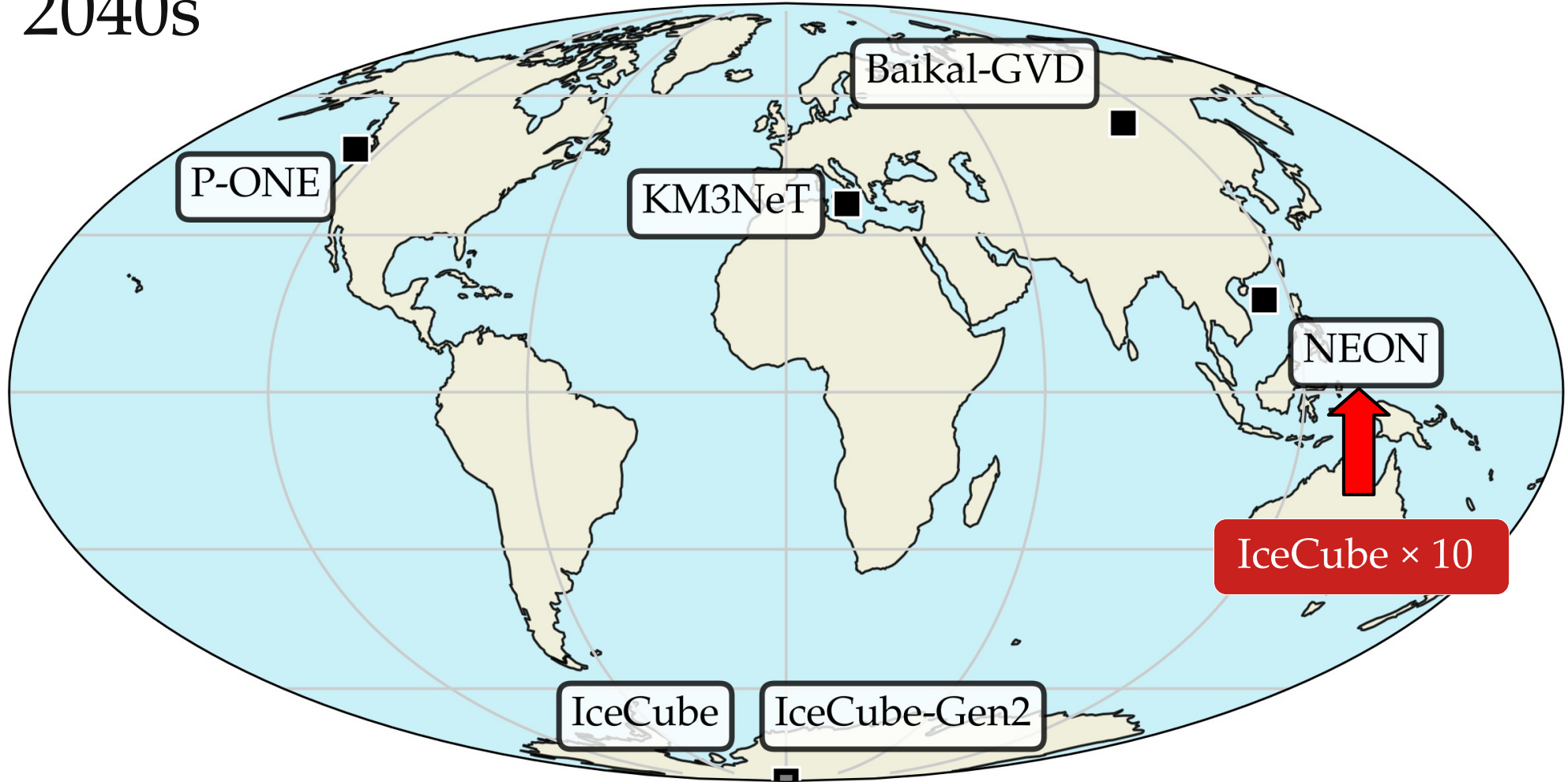


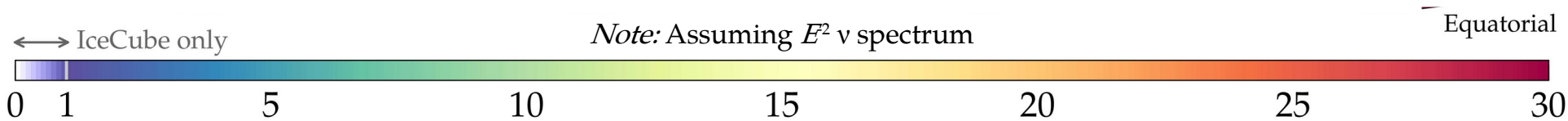
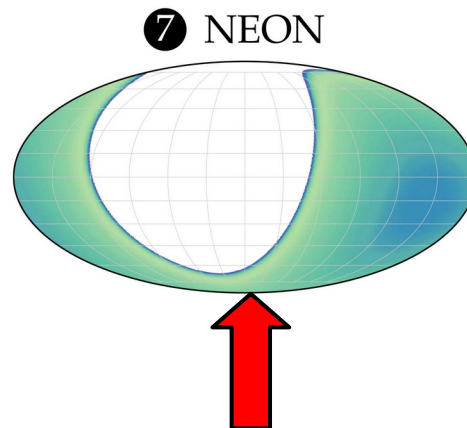
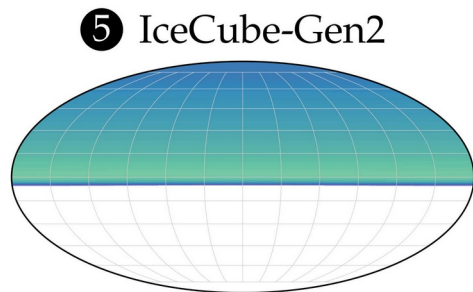
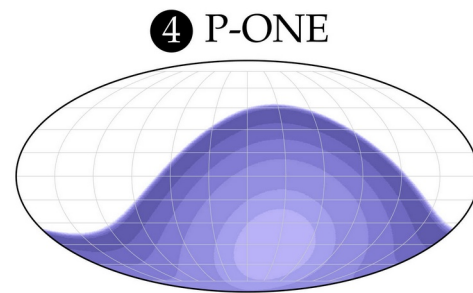
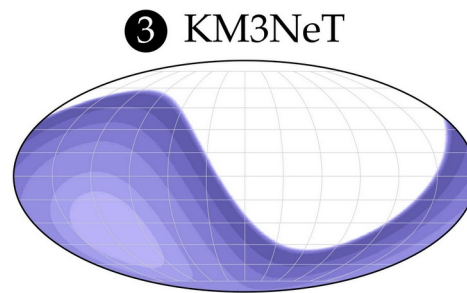
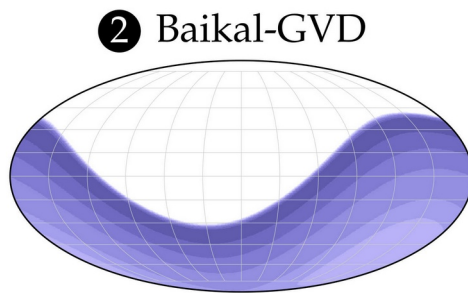
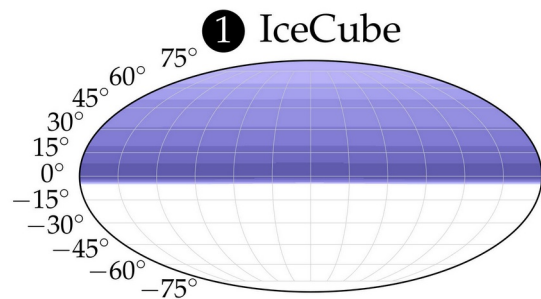
Assuming a power-law ν flux $\propto E^{-2.5}$



Assuming a power-law ν flux with 100-TeV cut-off + $p\gamma$ bump at tens of TeV

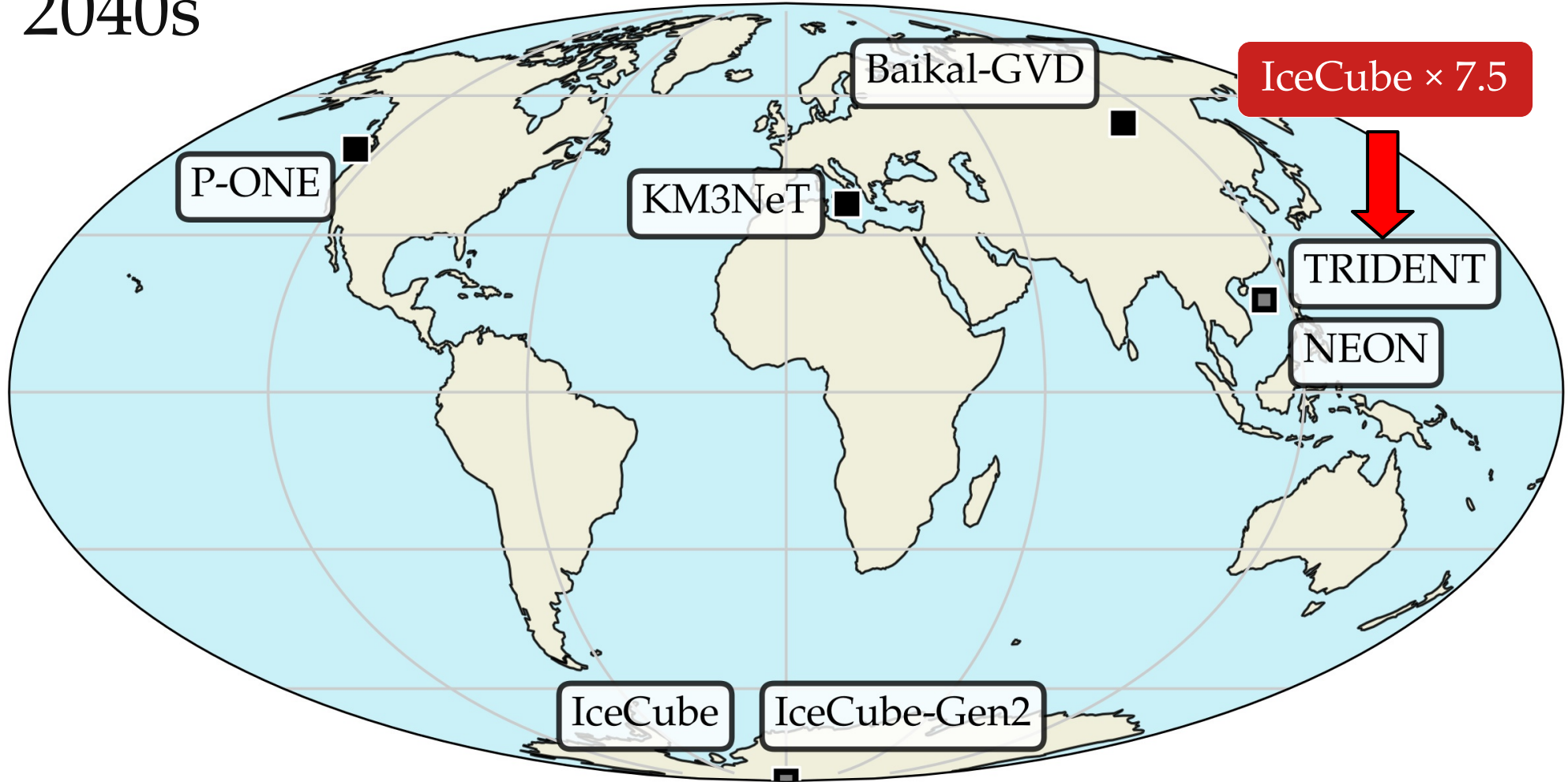
2040s

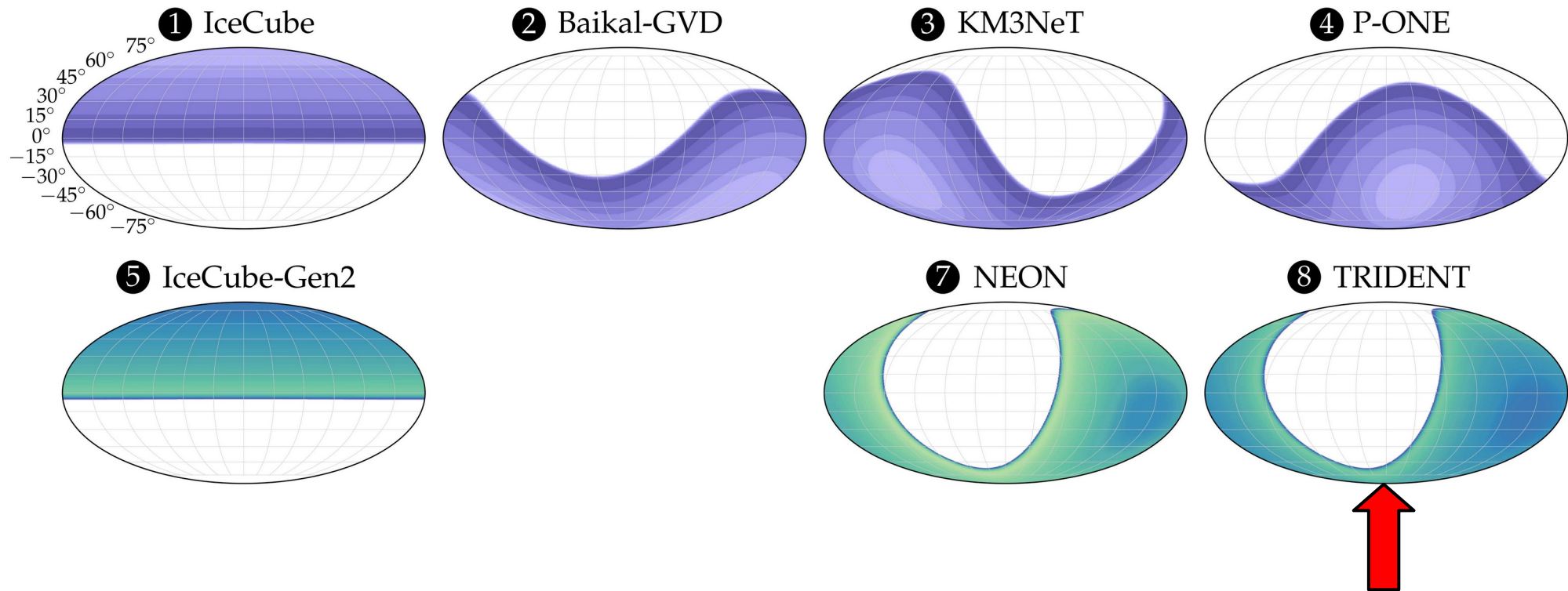




Rate of detected muon tracks relative to IceCube maximum

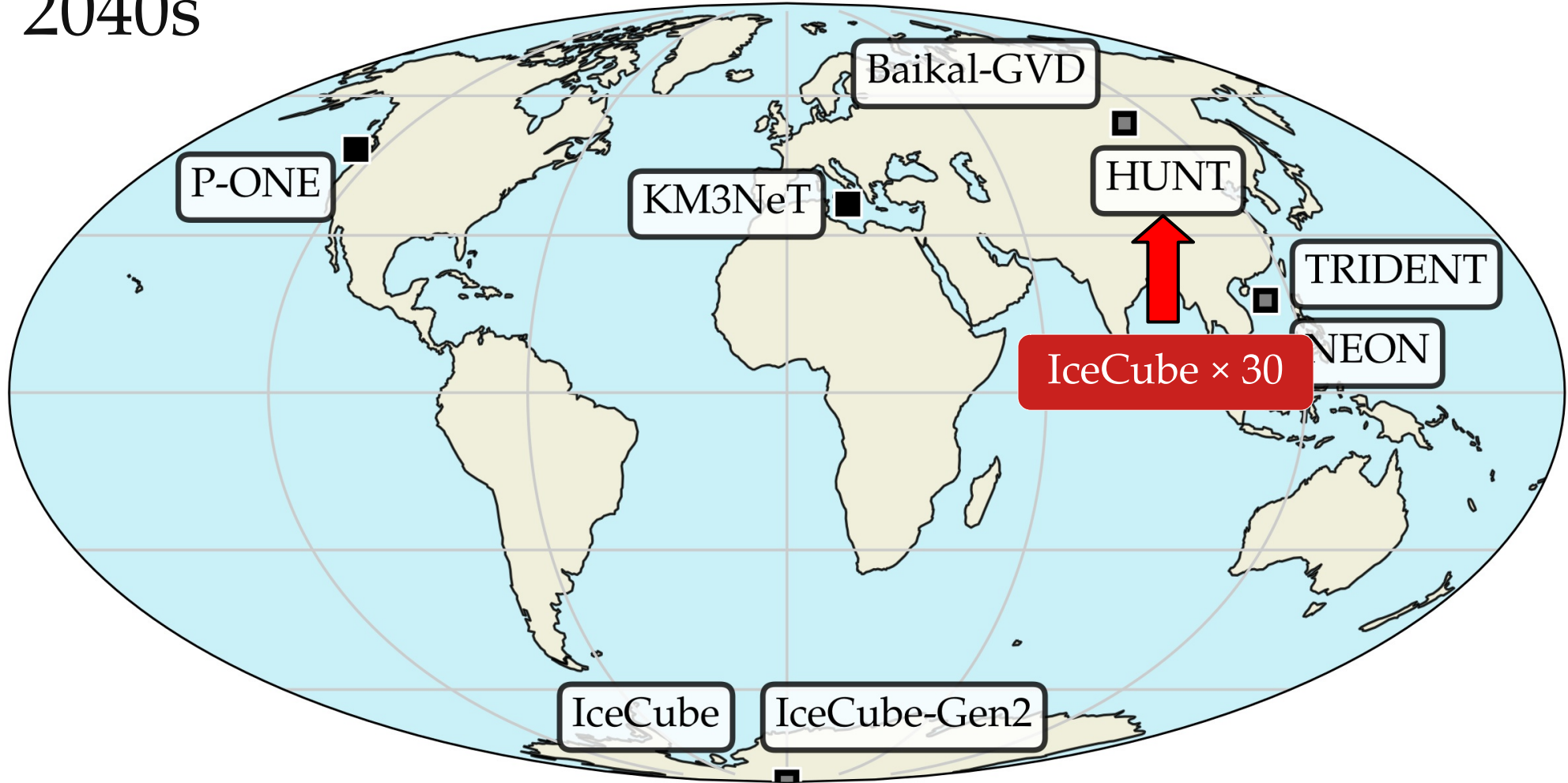
2040s

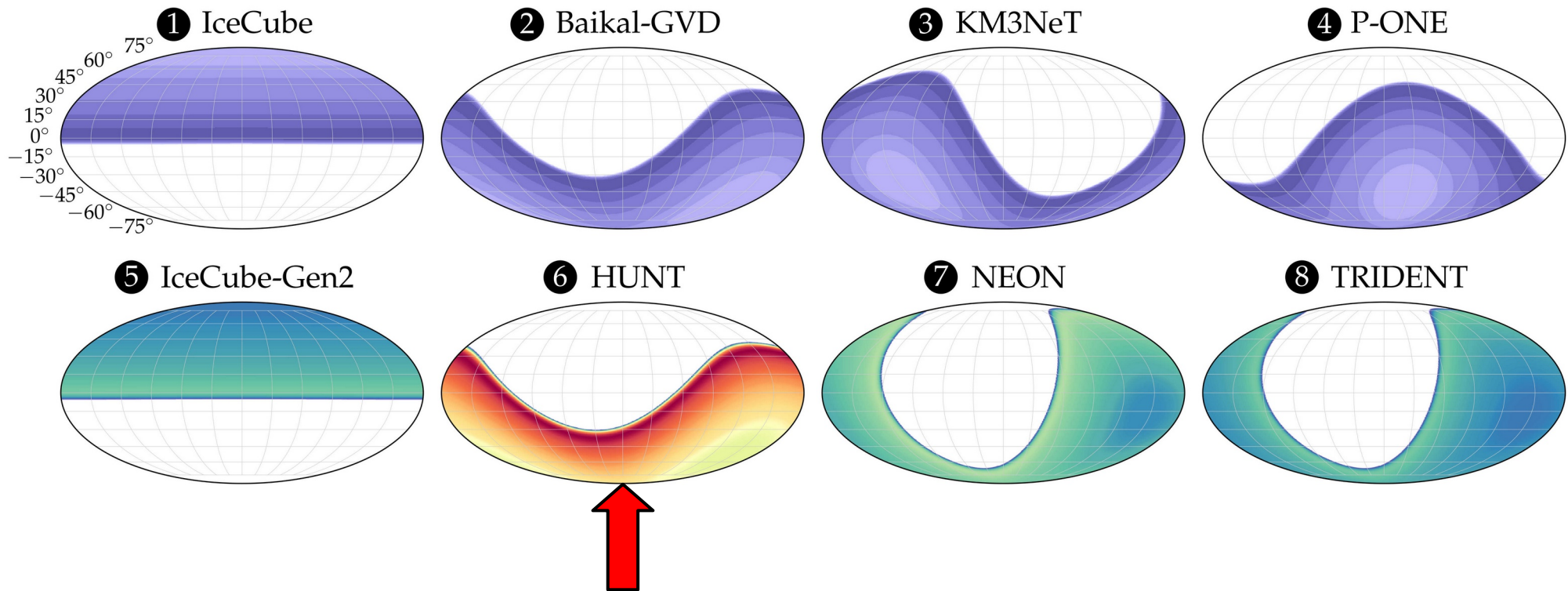




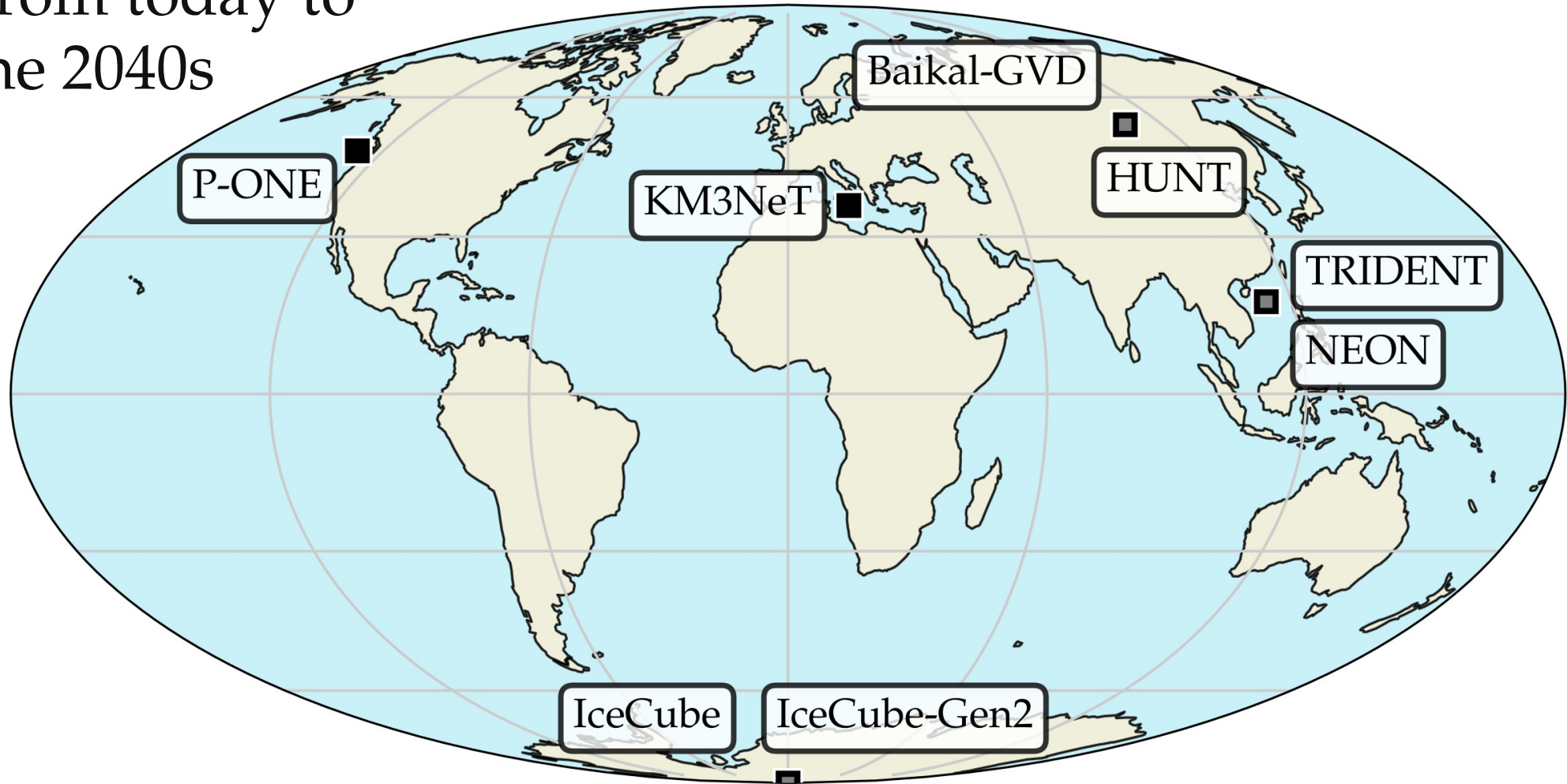
Rate of detected muon tracks relative to IceCube maximum

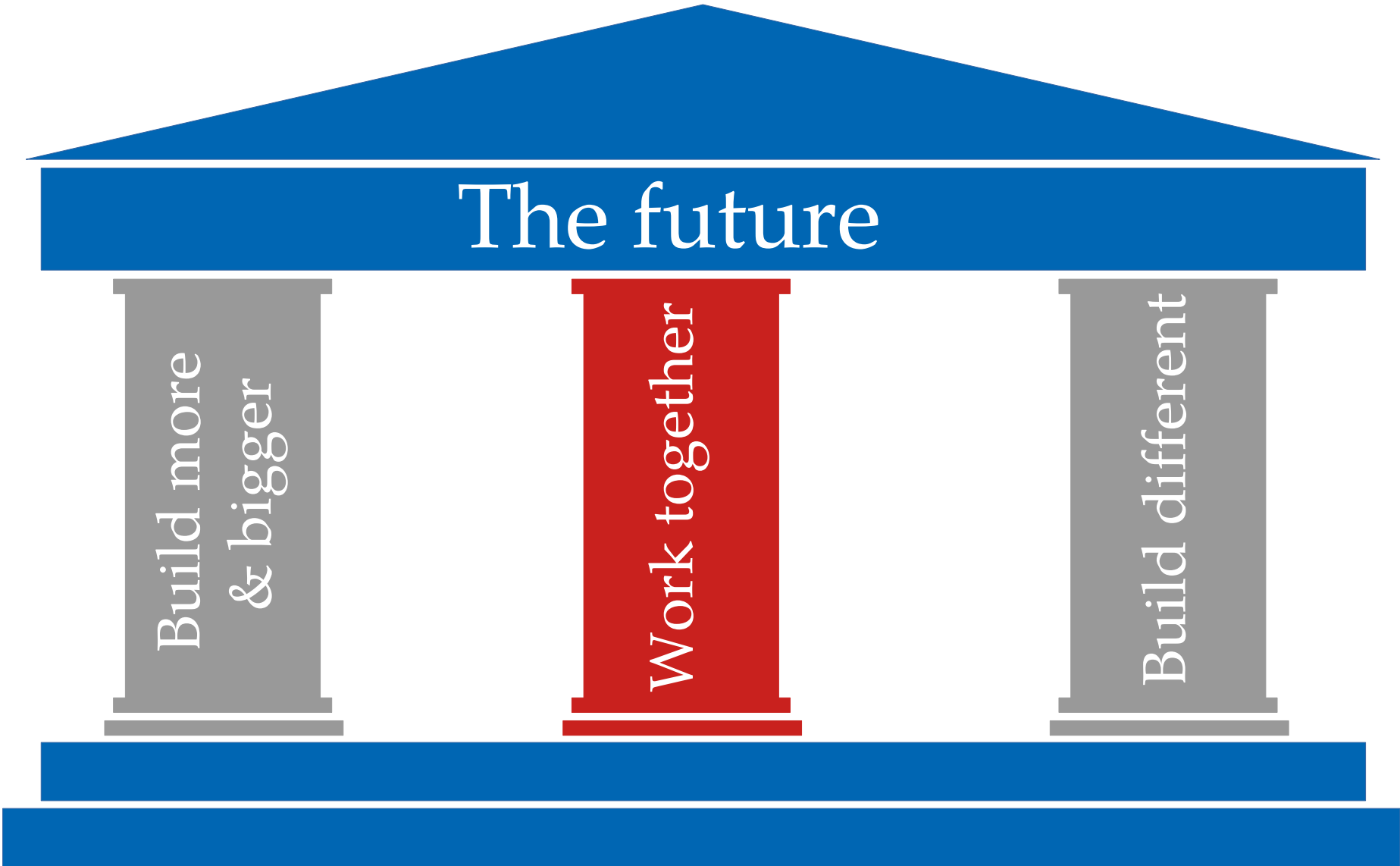
2040s





From today to
the 2040s



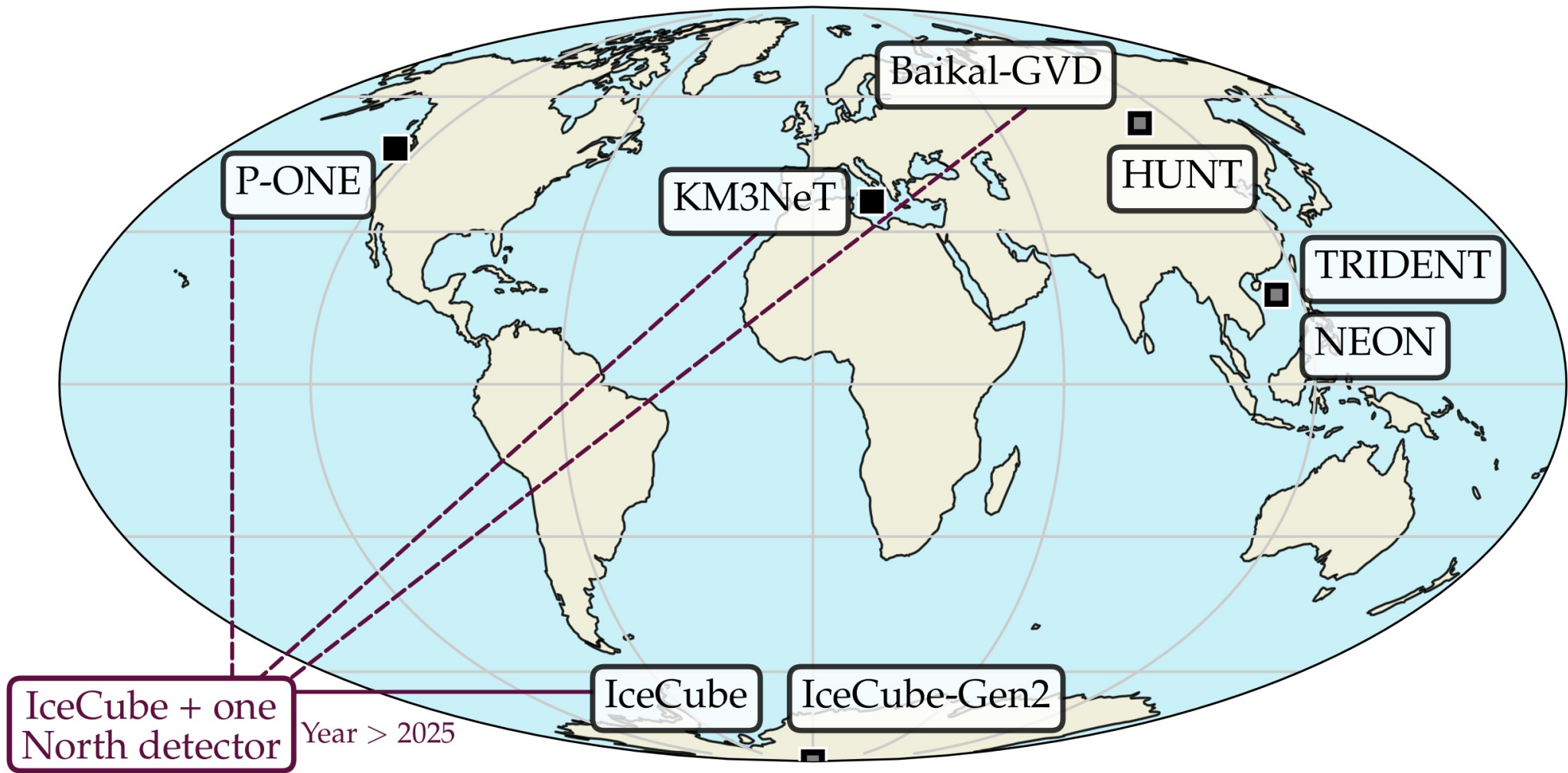


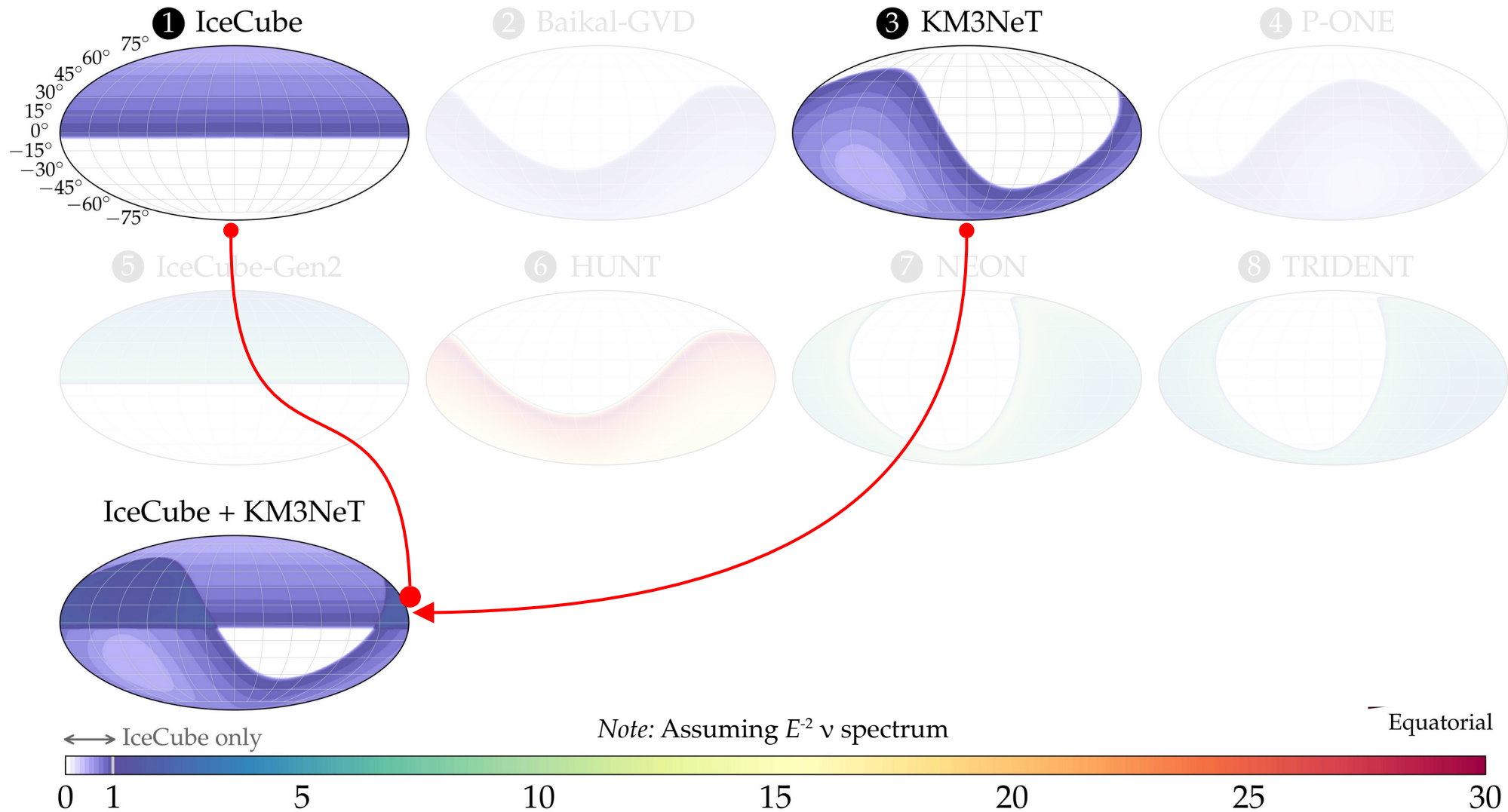
The future

Build more
& bigger

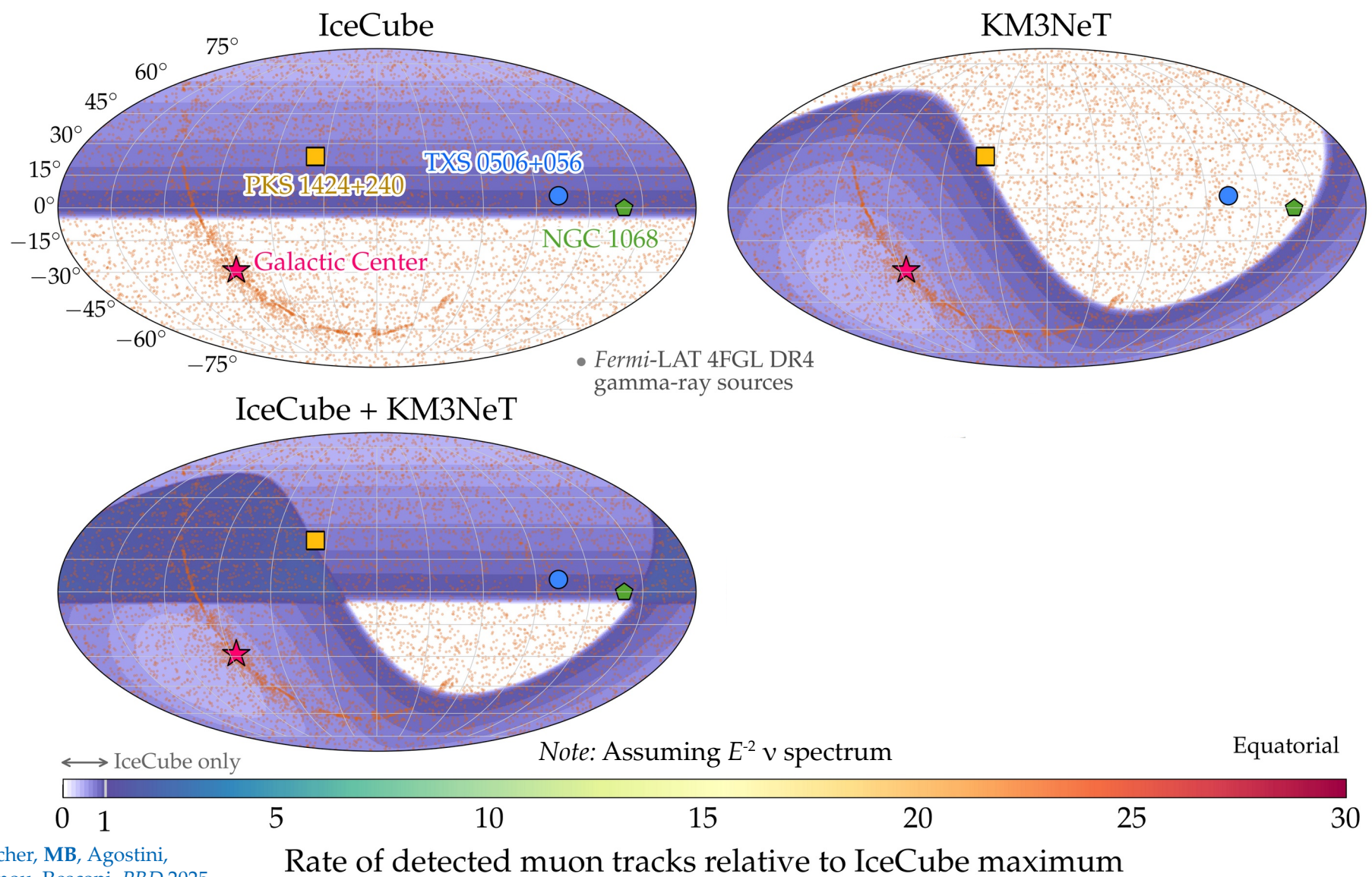
Work together

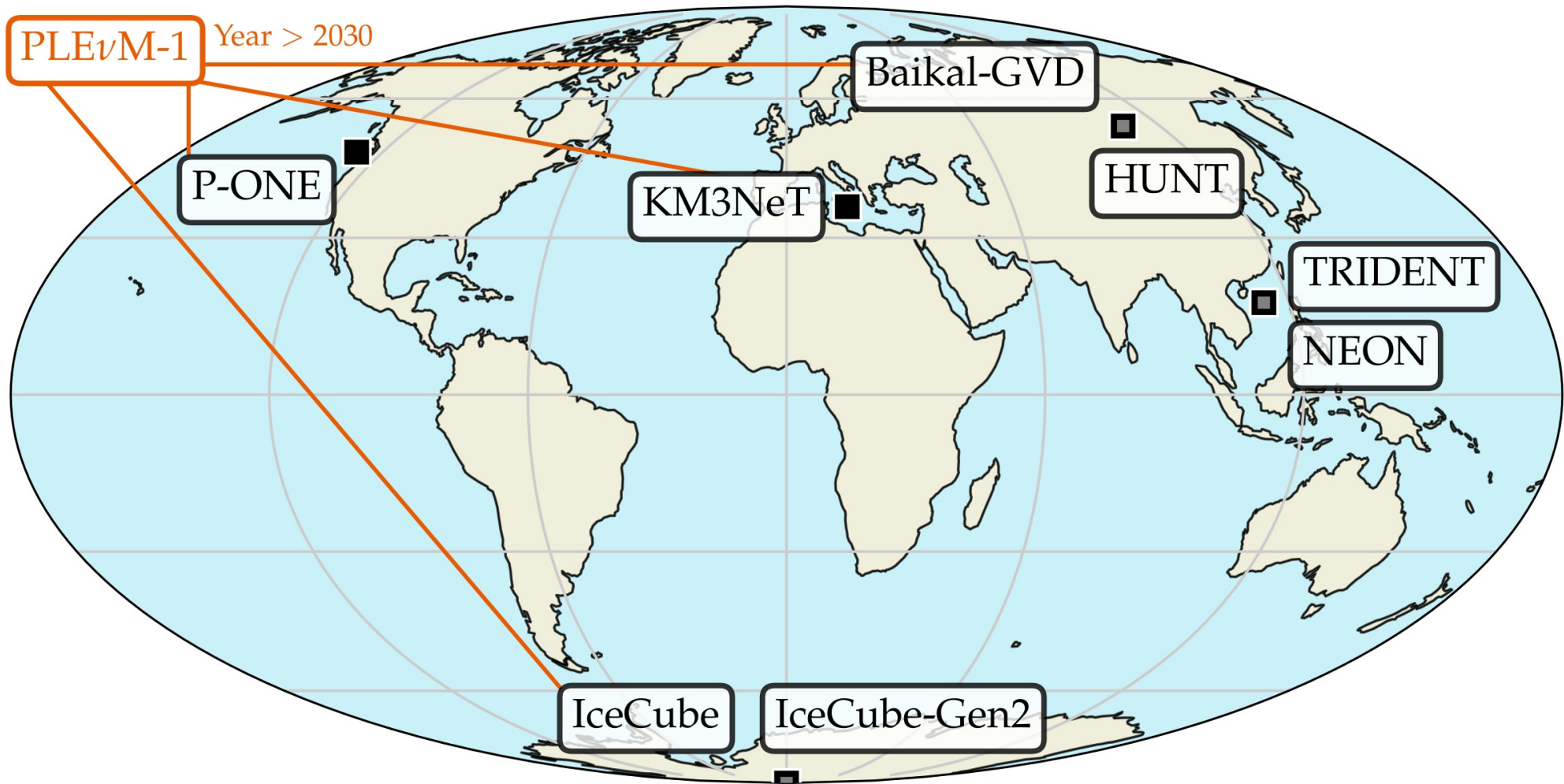
Build different

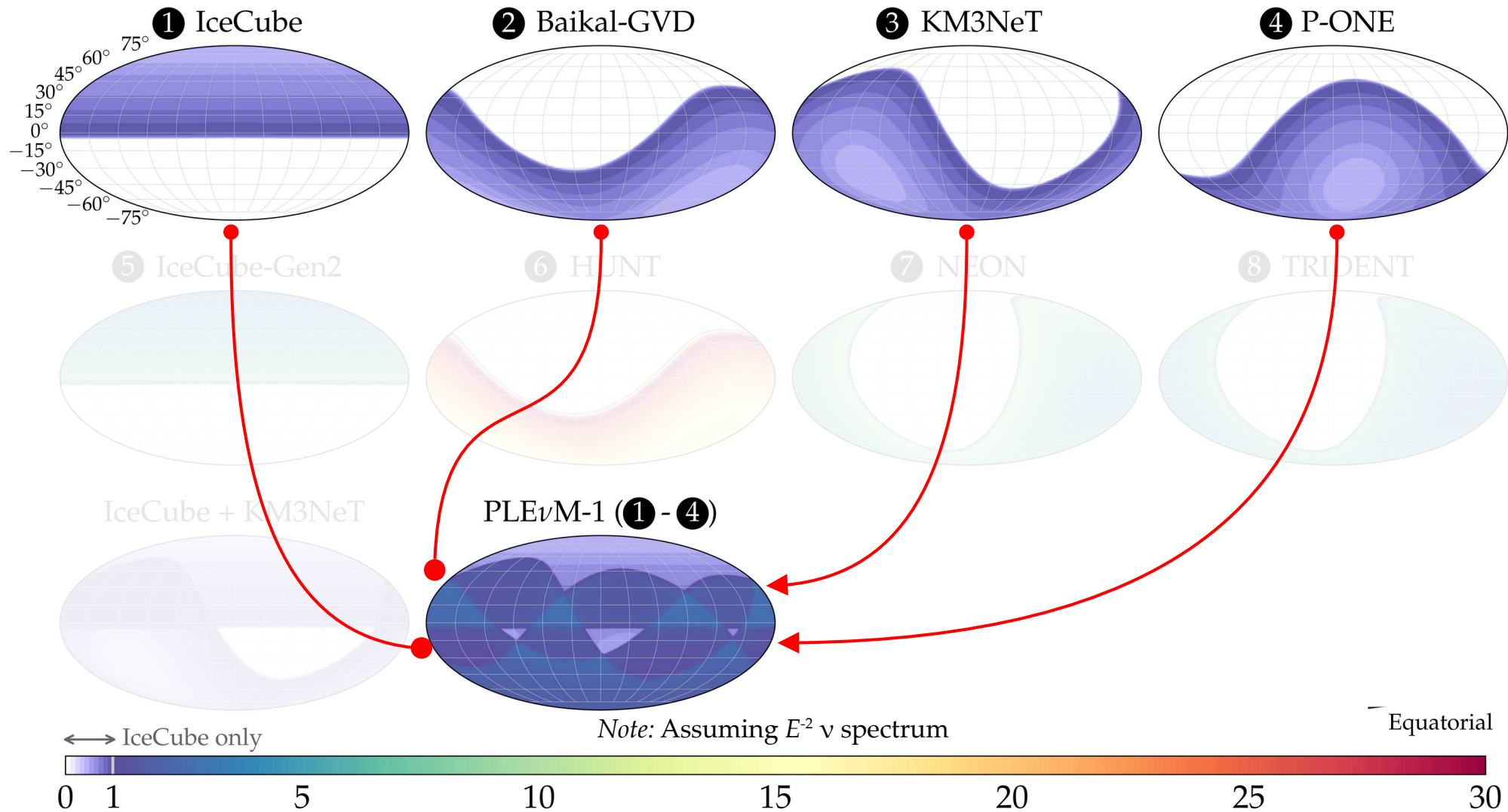


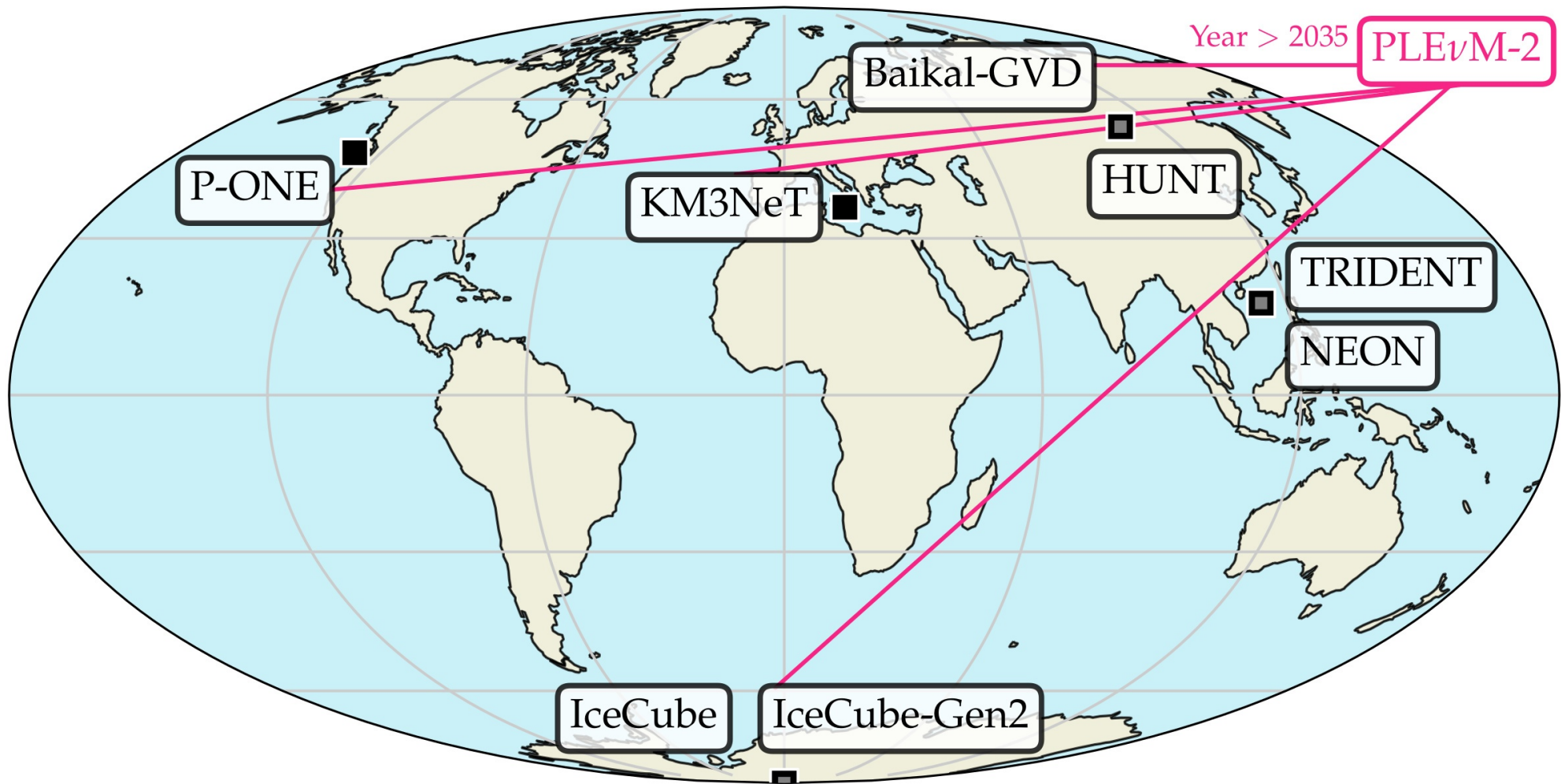


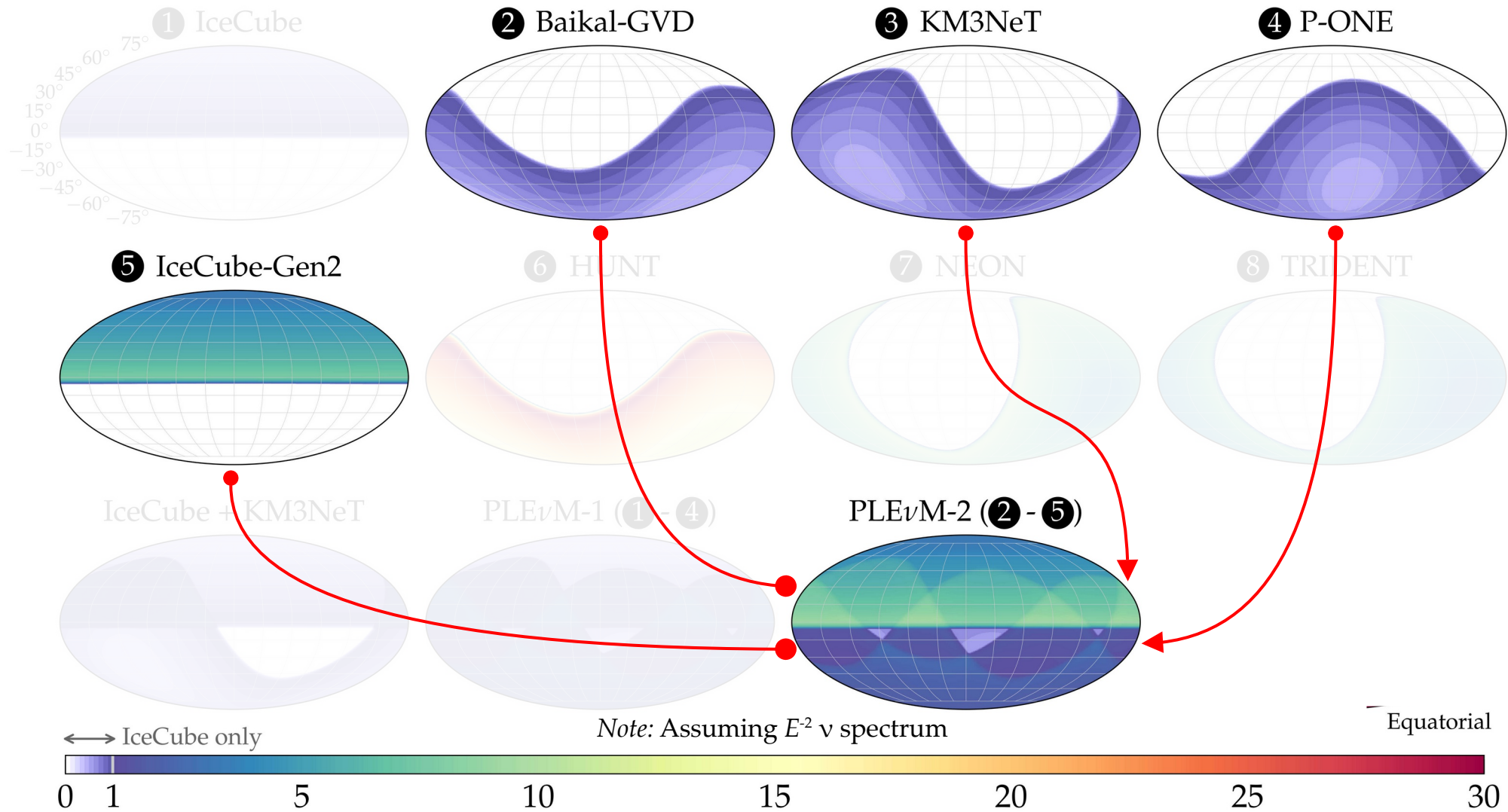
Rate of detected muon tracks relative to IceCube maximum

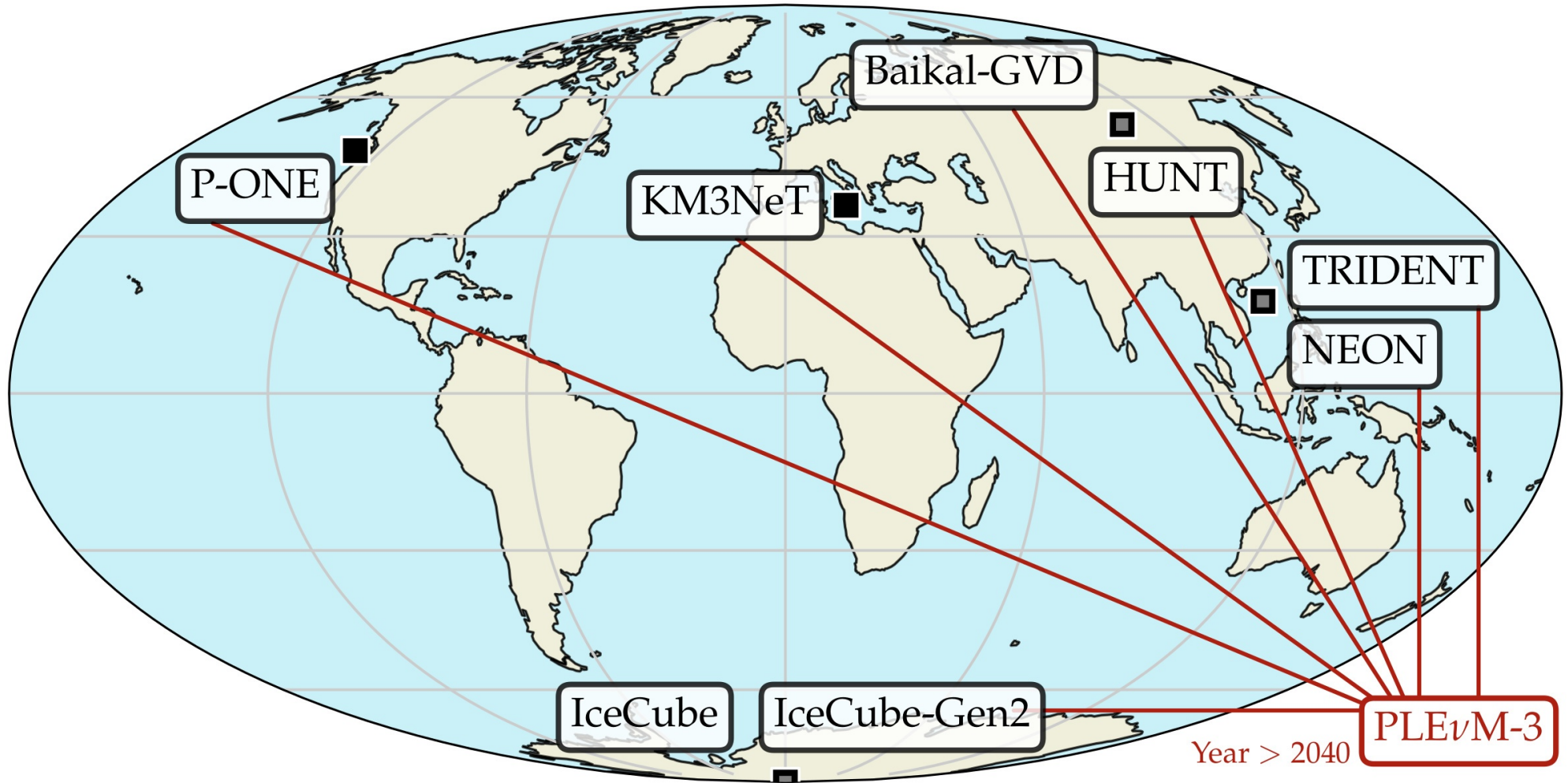


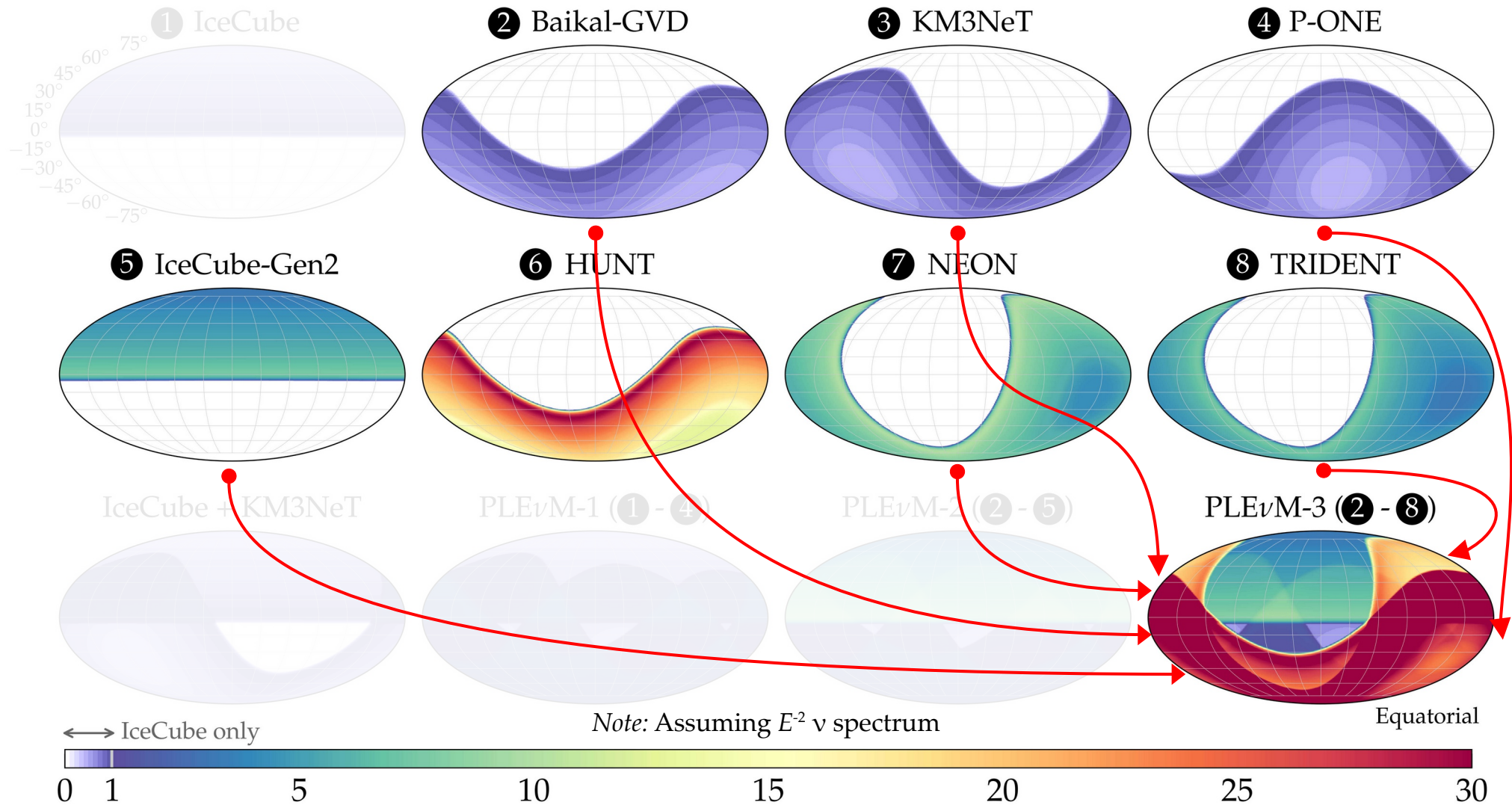


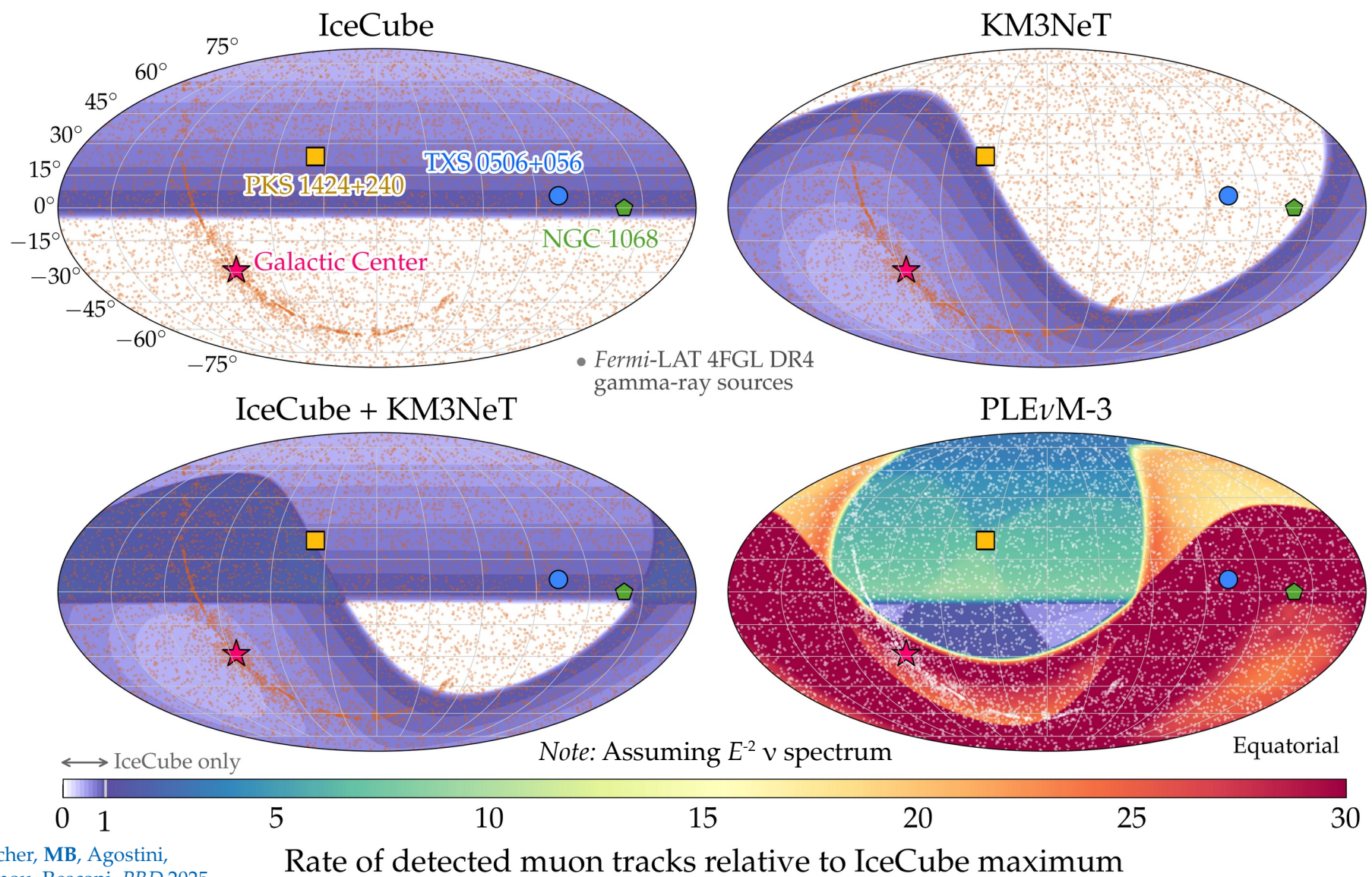


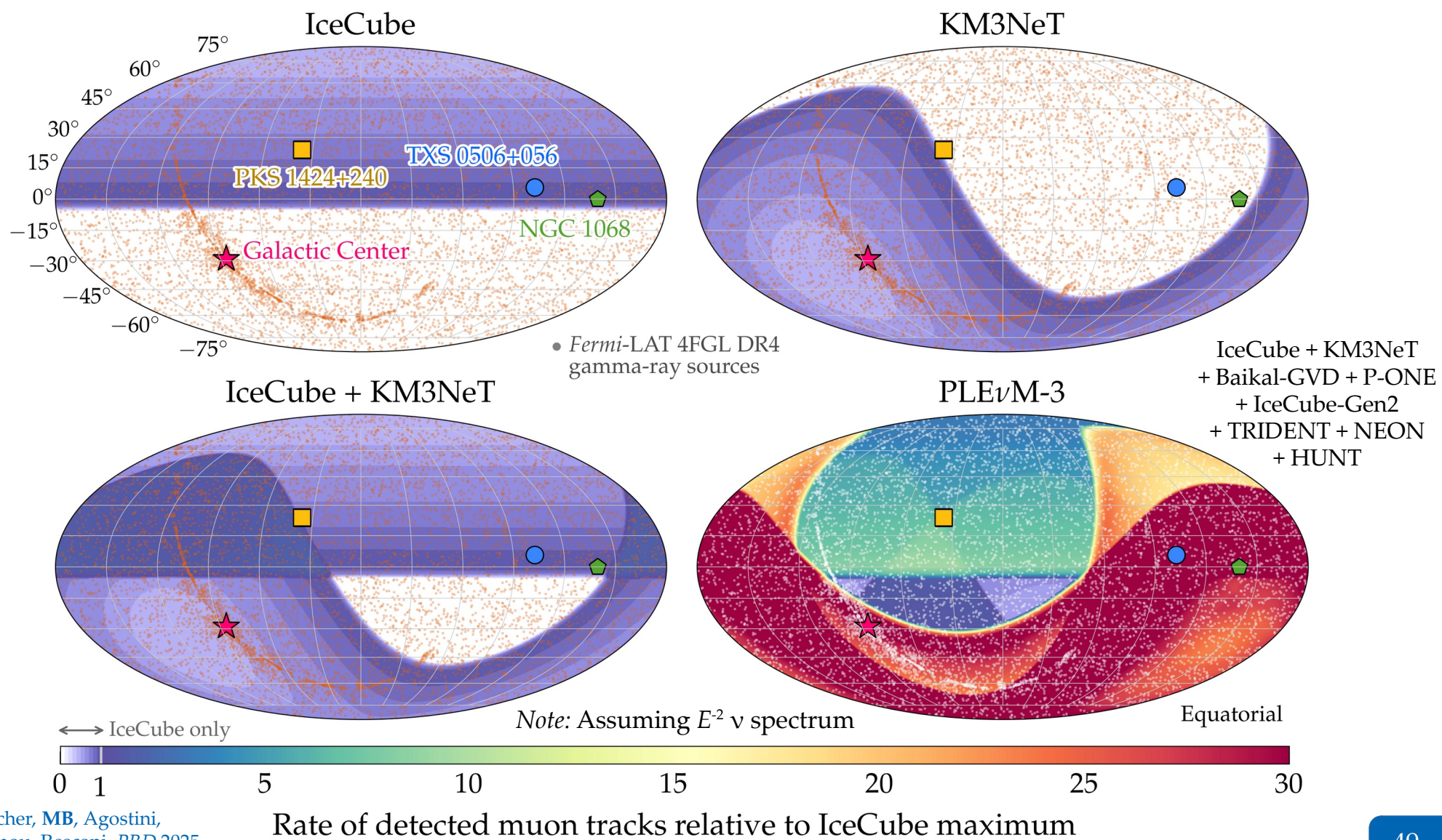


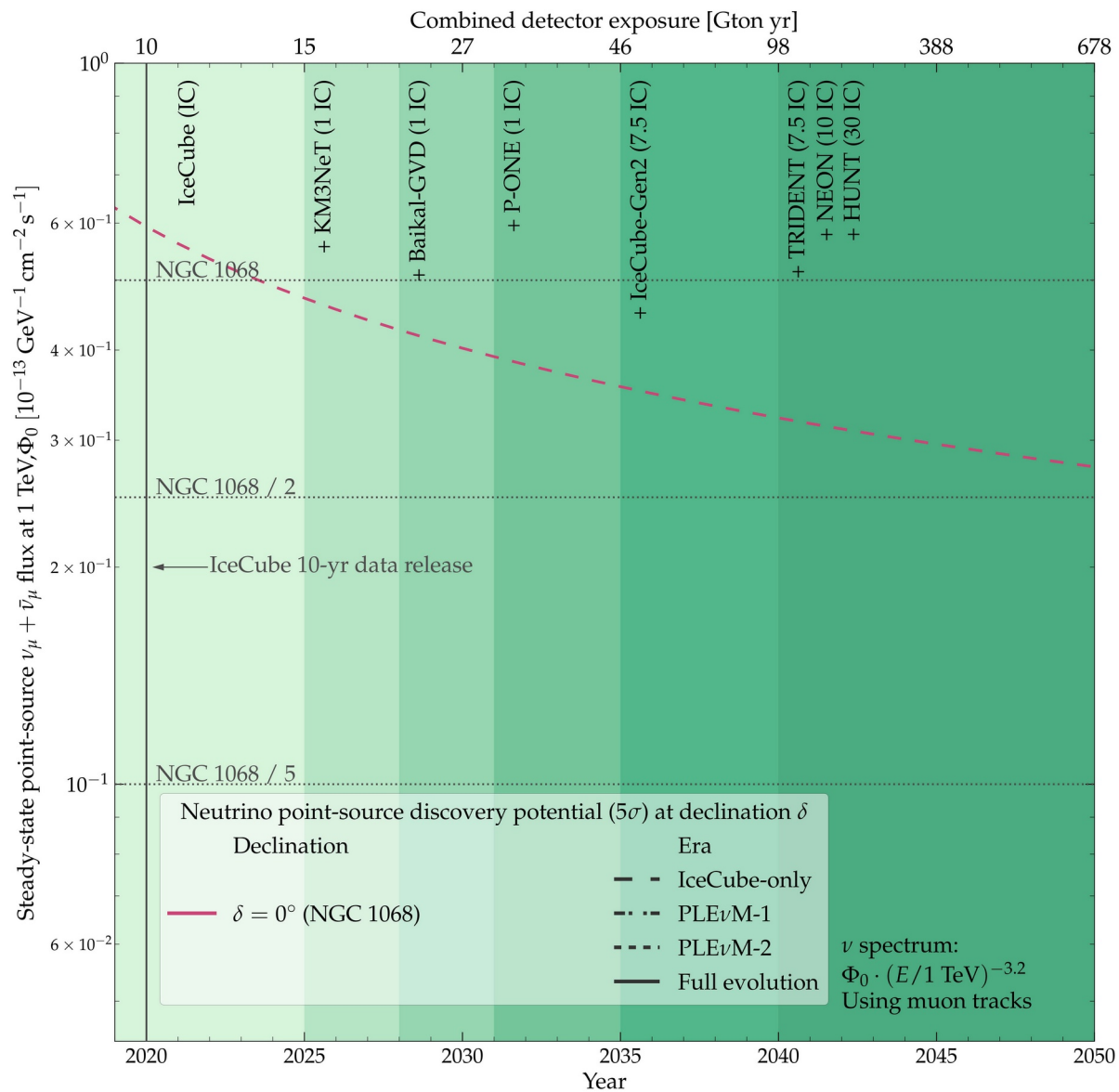


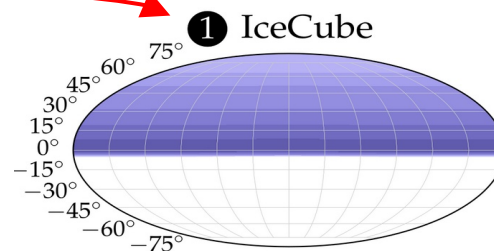
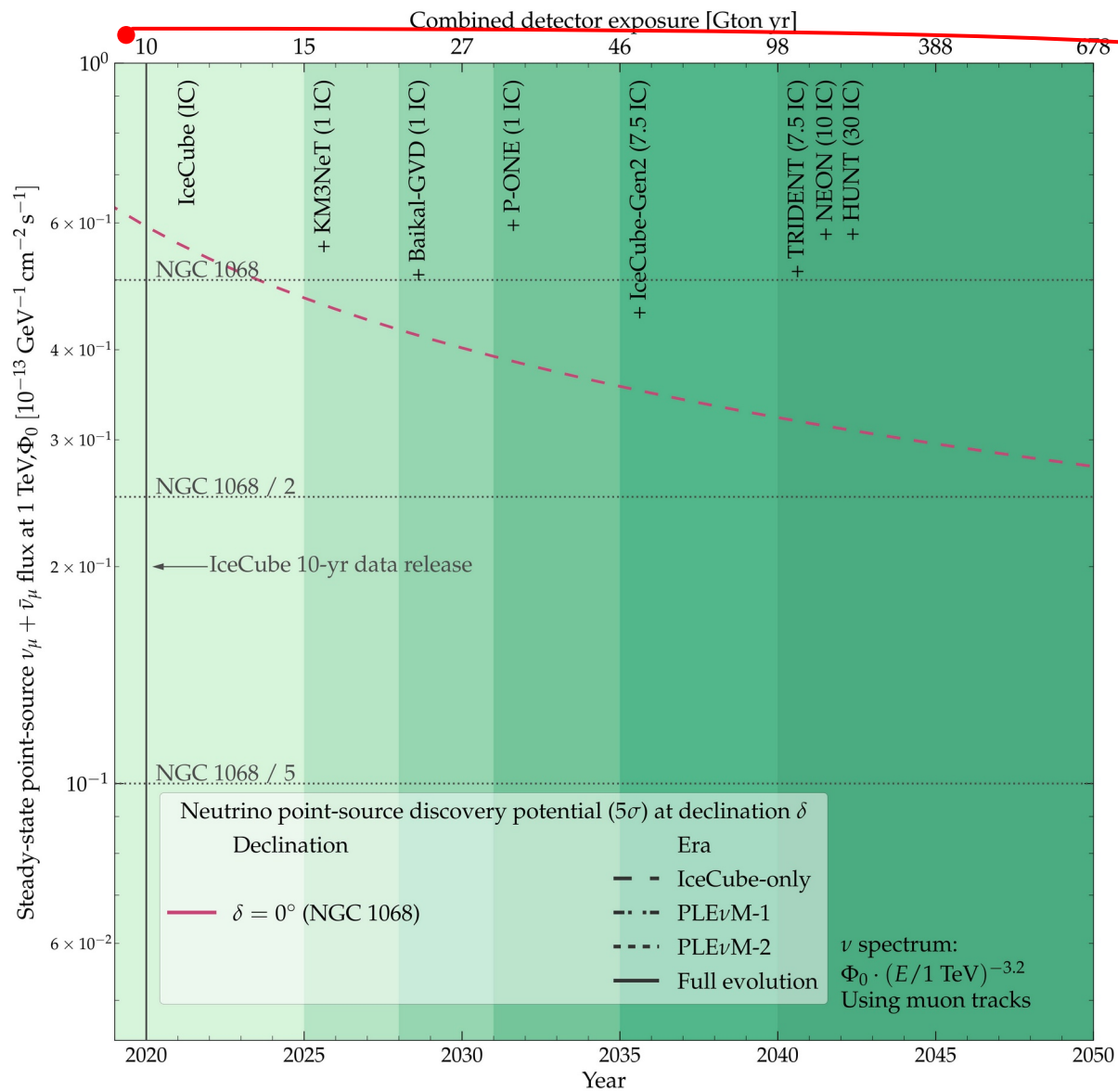


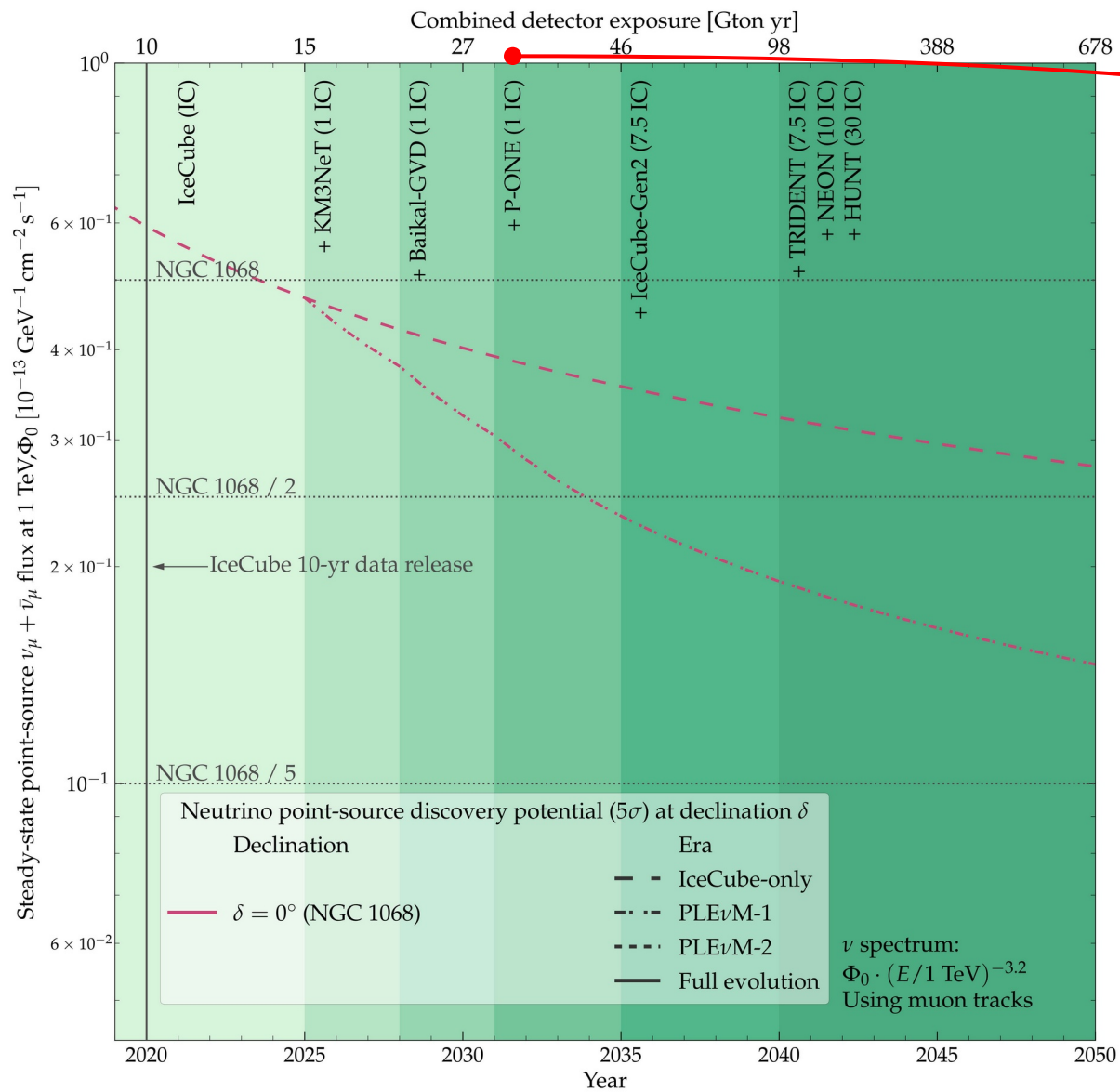




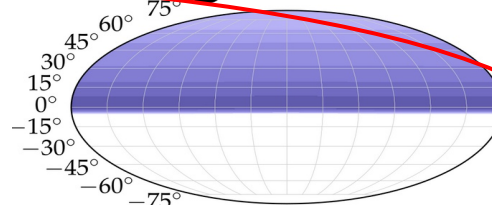




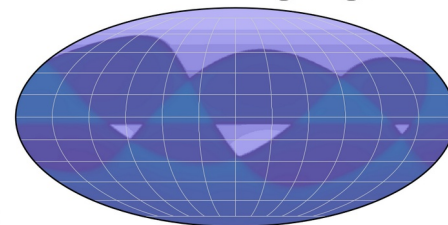




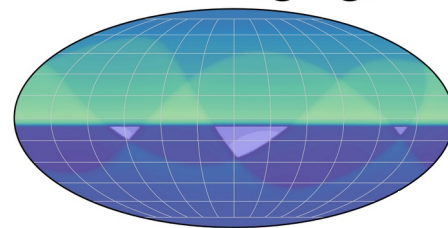
① IceCube



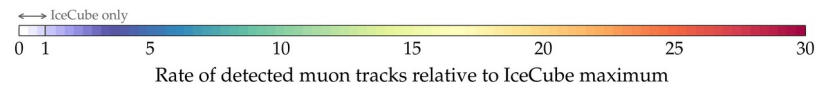
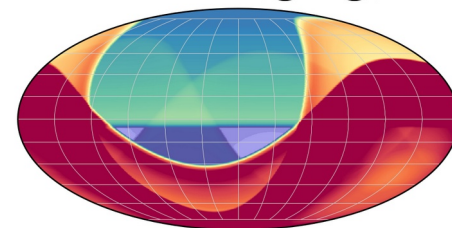
PLE ν M-1 (① - ④)

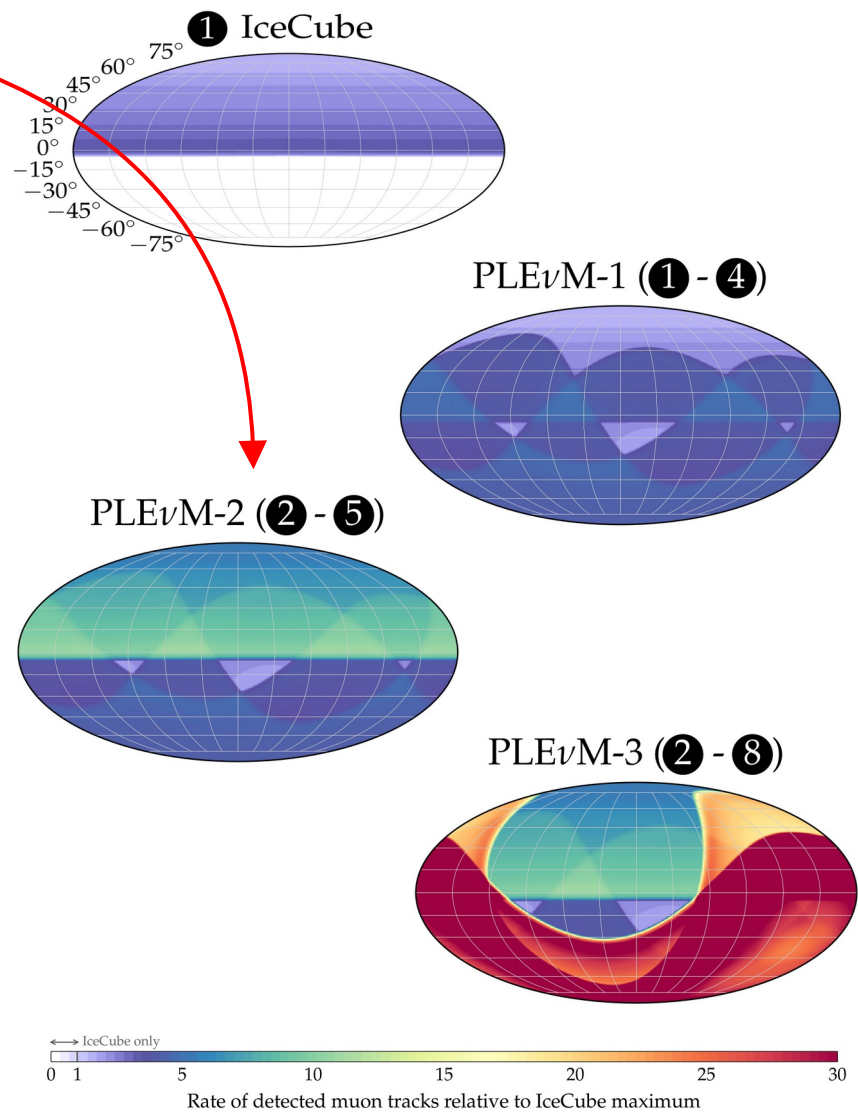
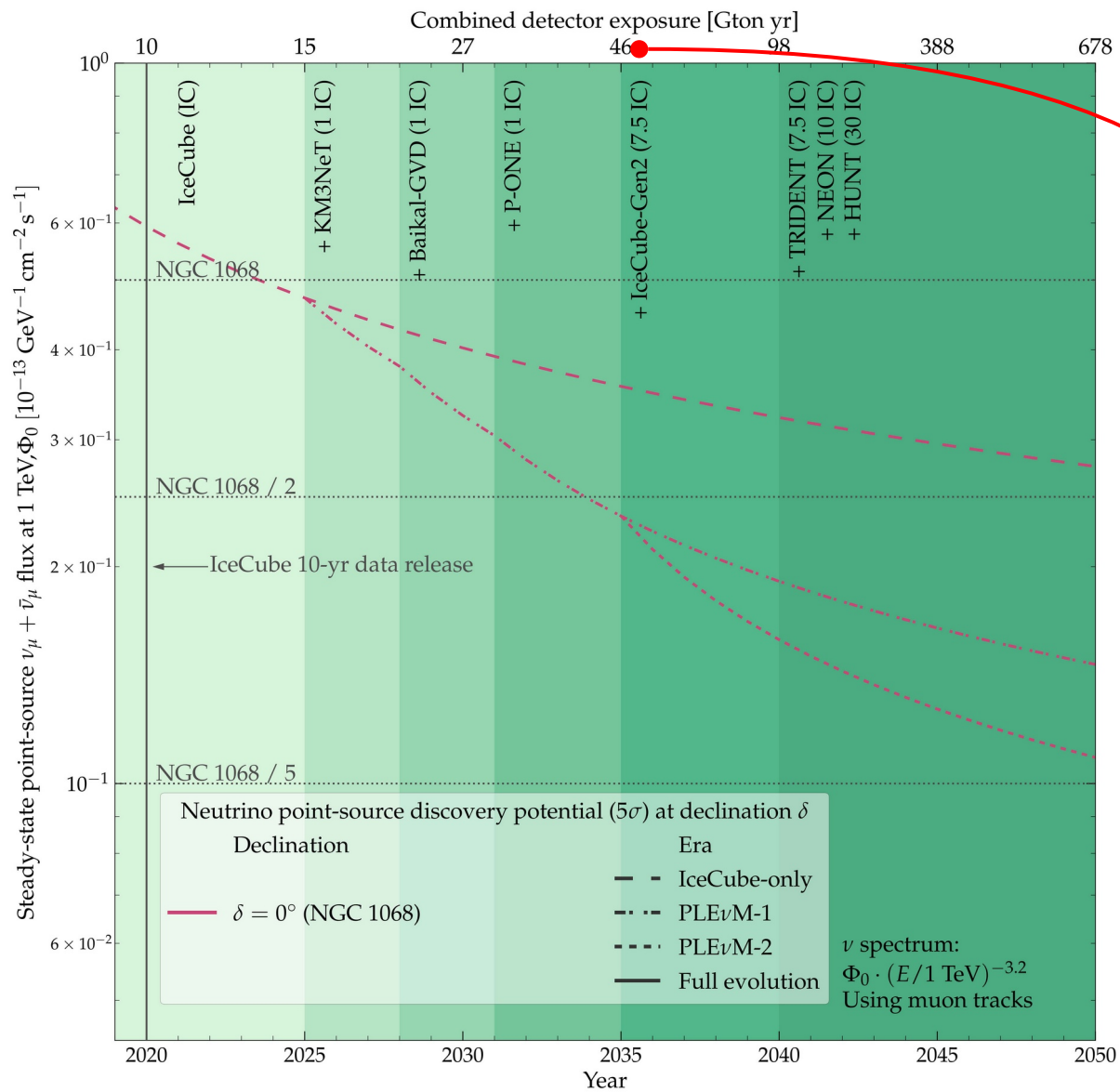


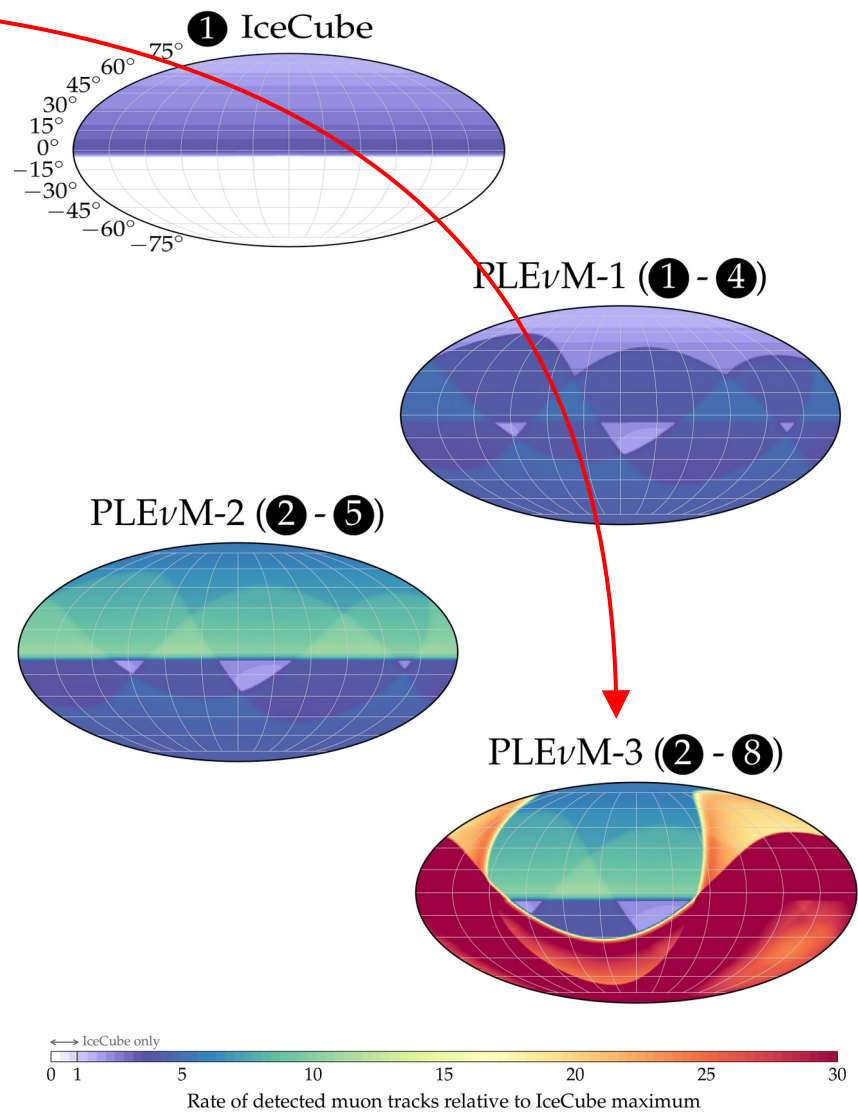
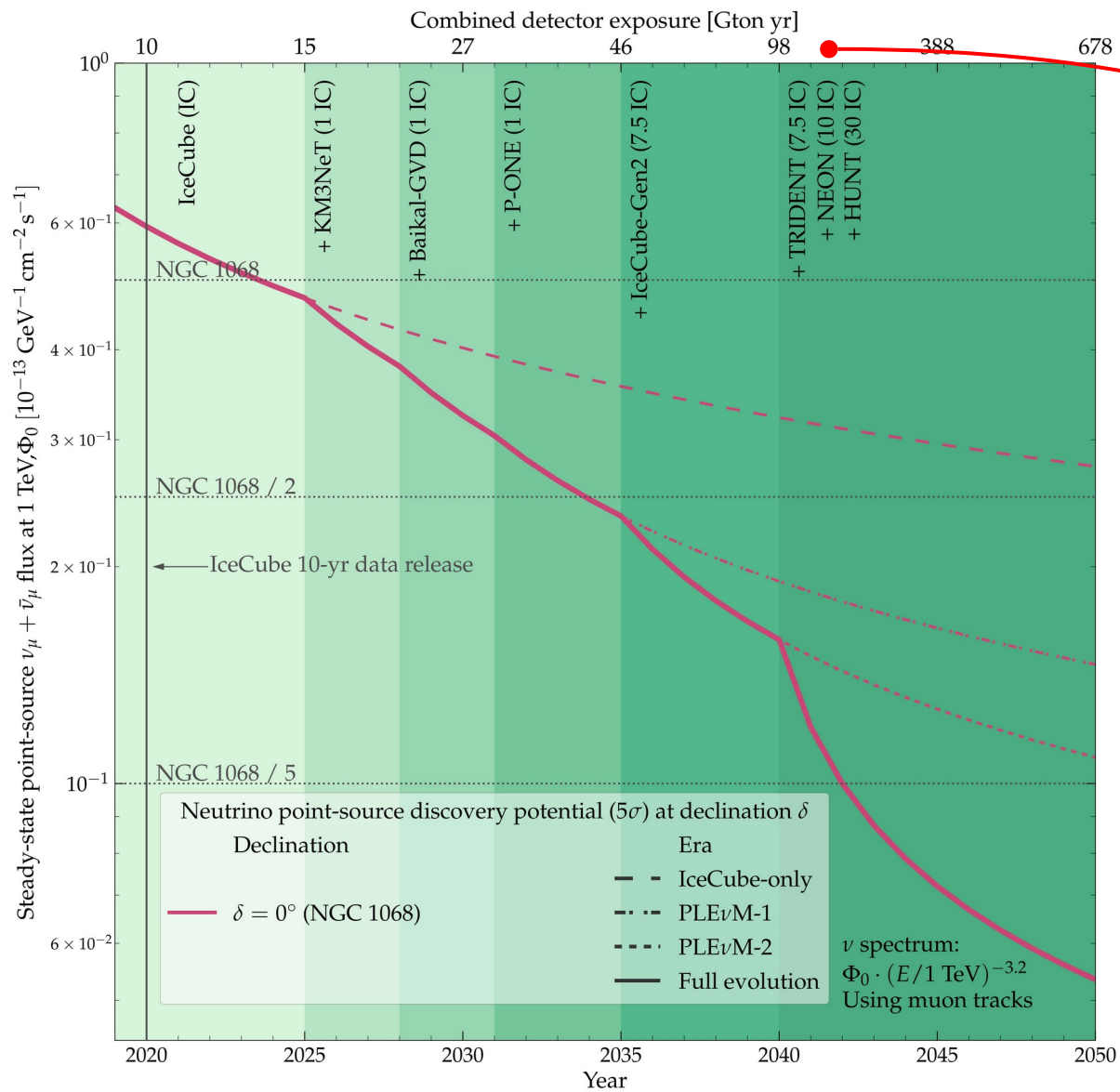
PLE ν M-2 (② - ⑤)

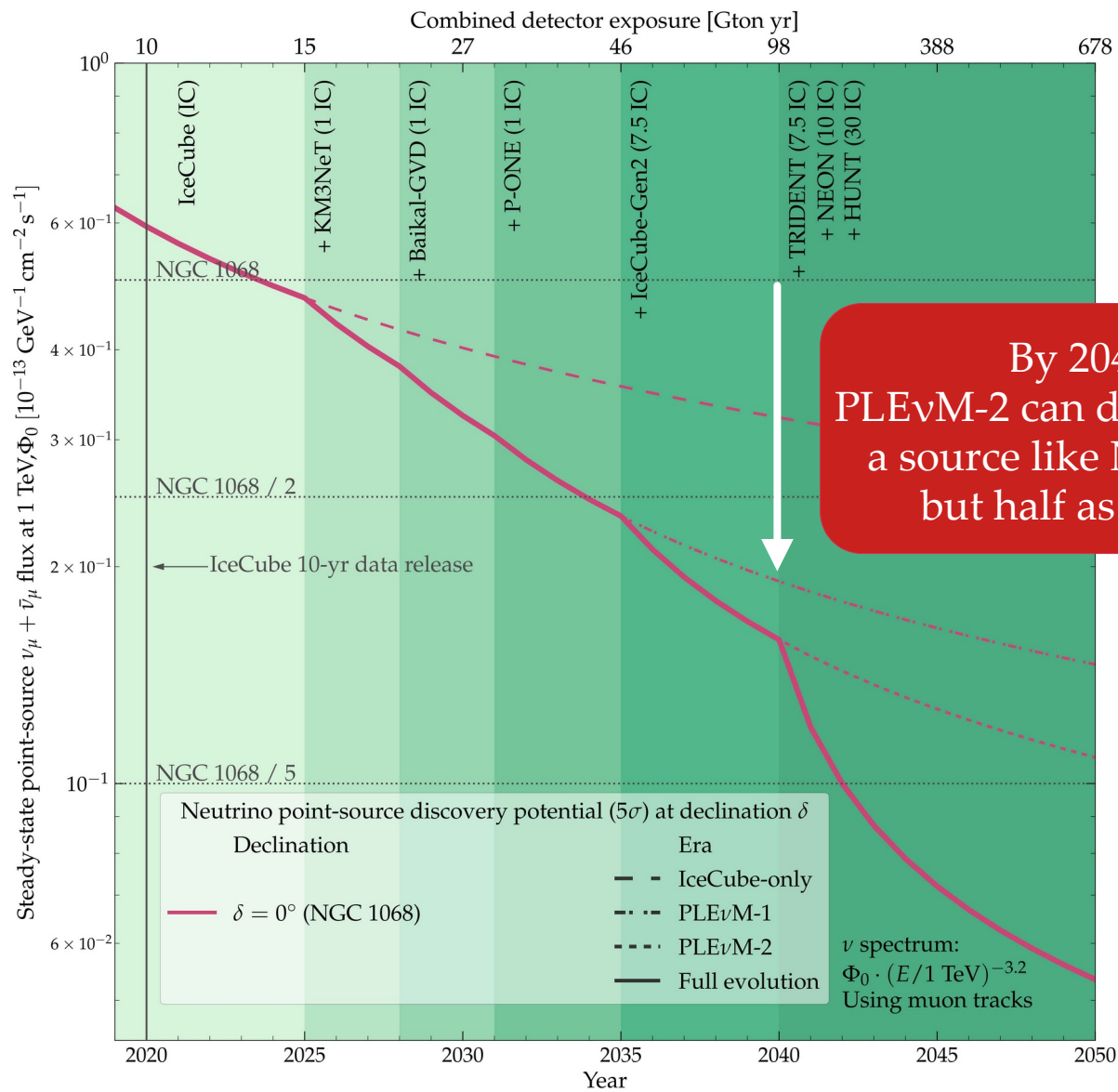


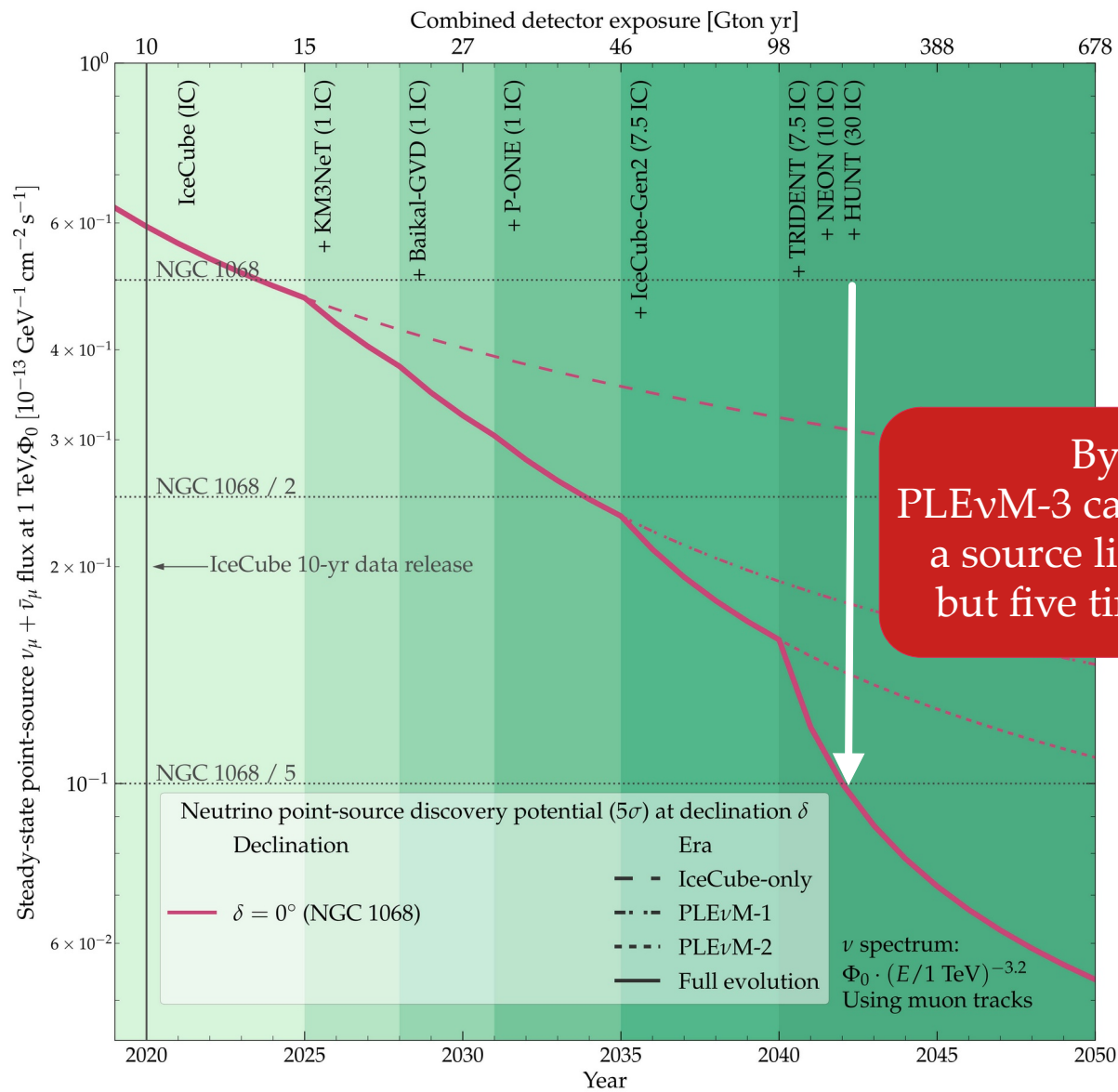
PLE ν M-3 (② - ⑧)

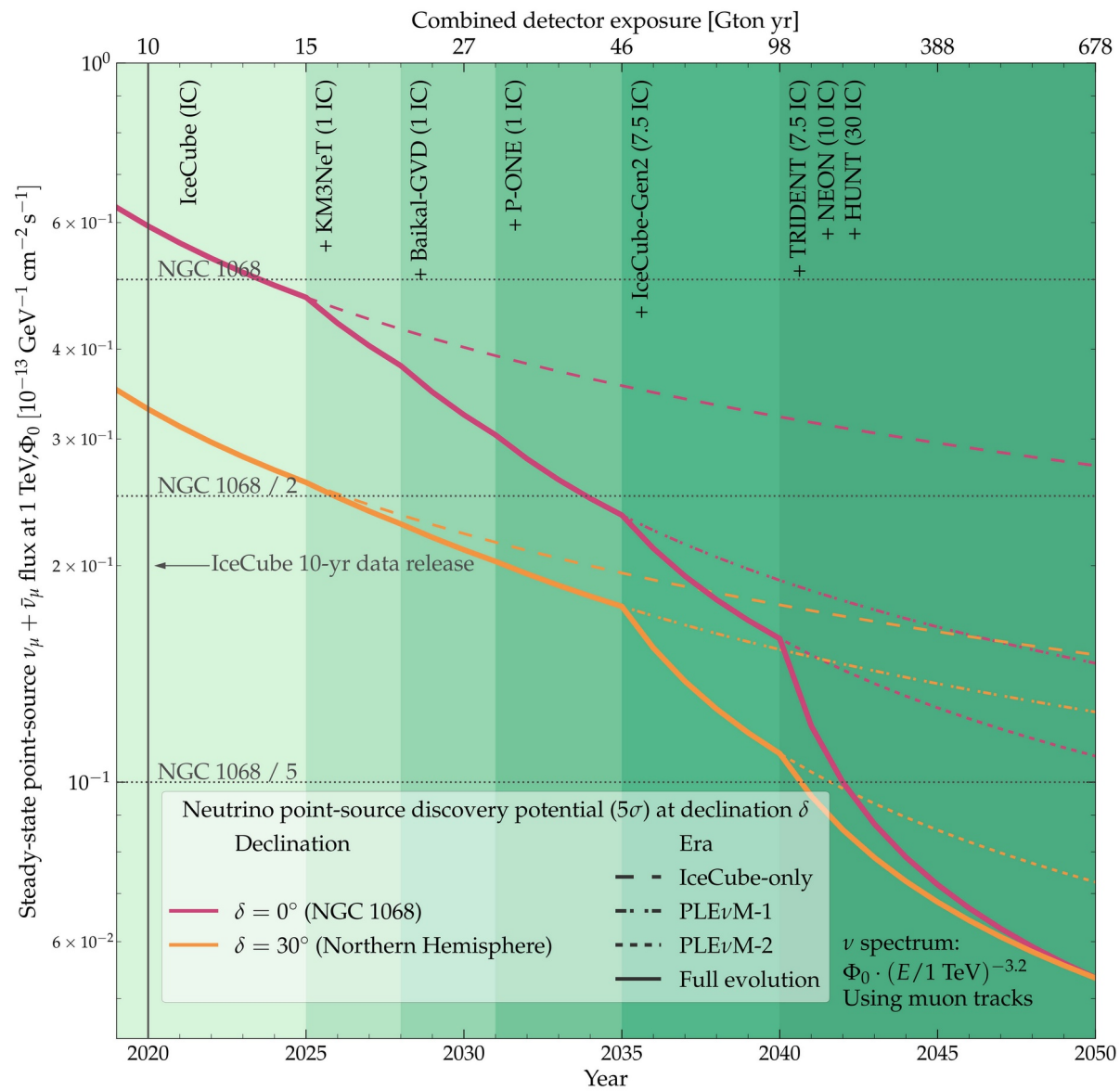


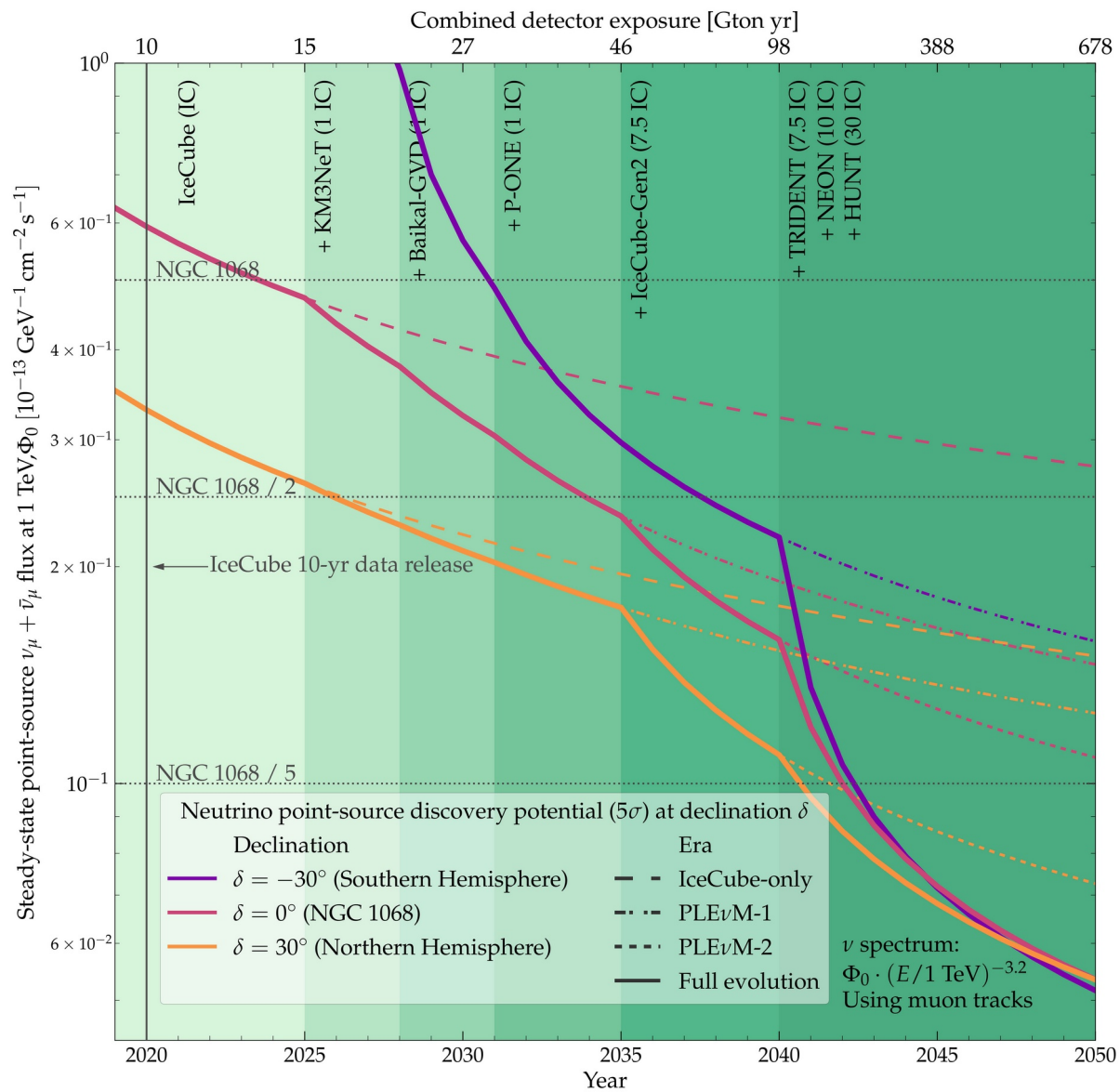


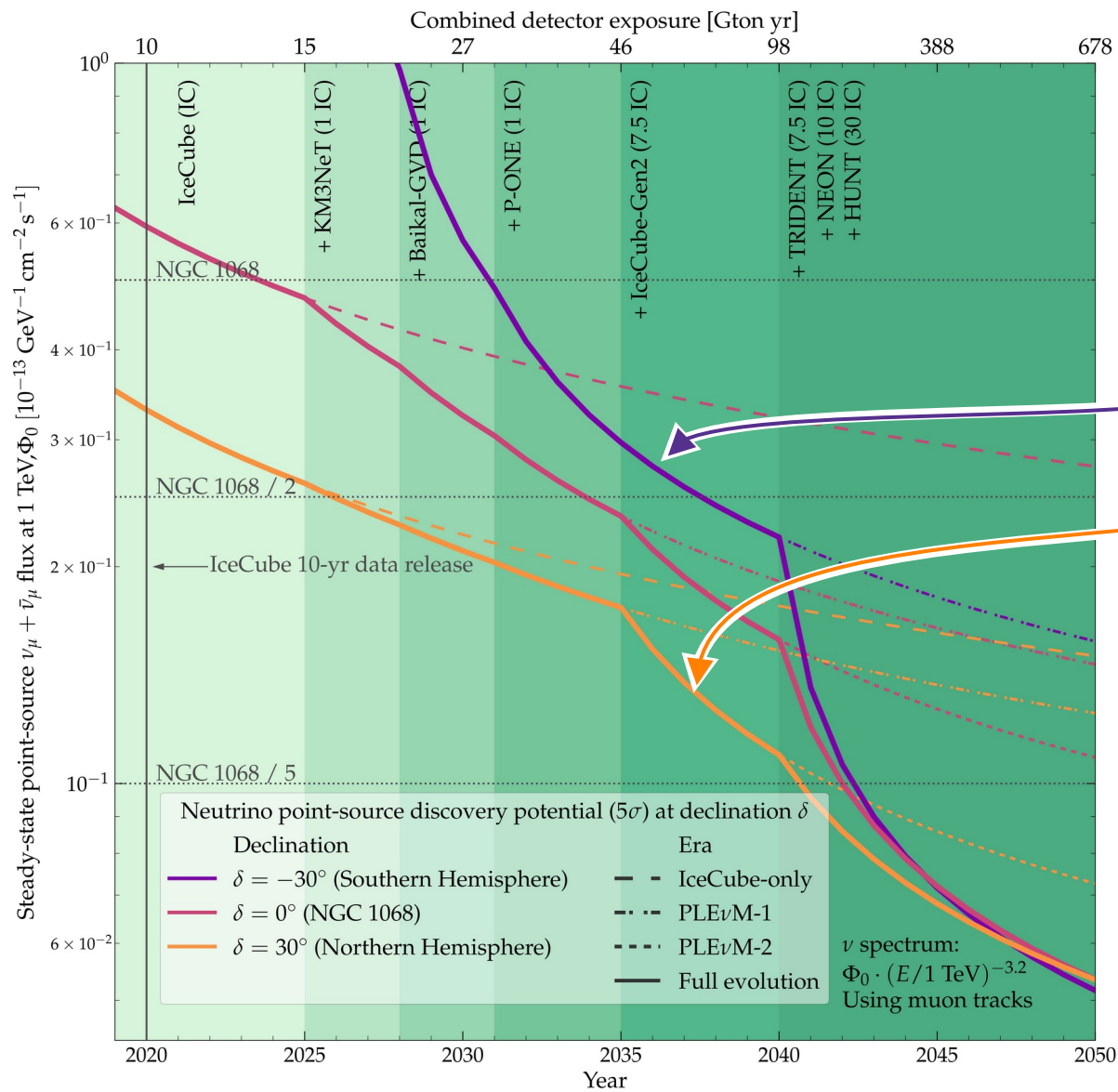


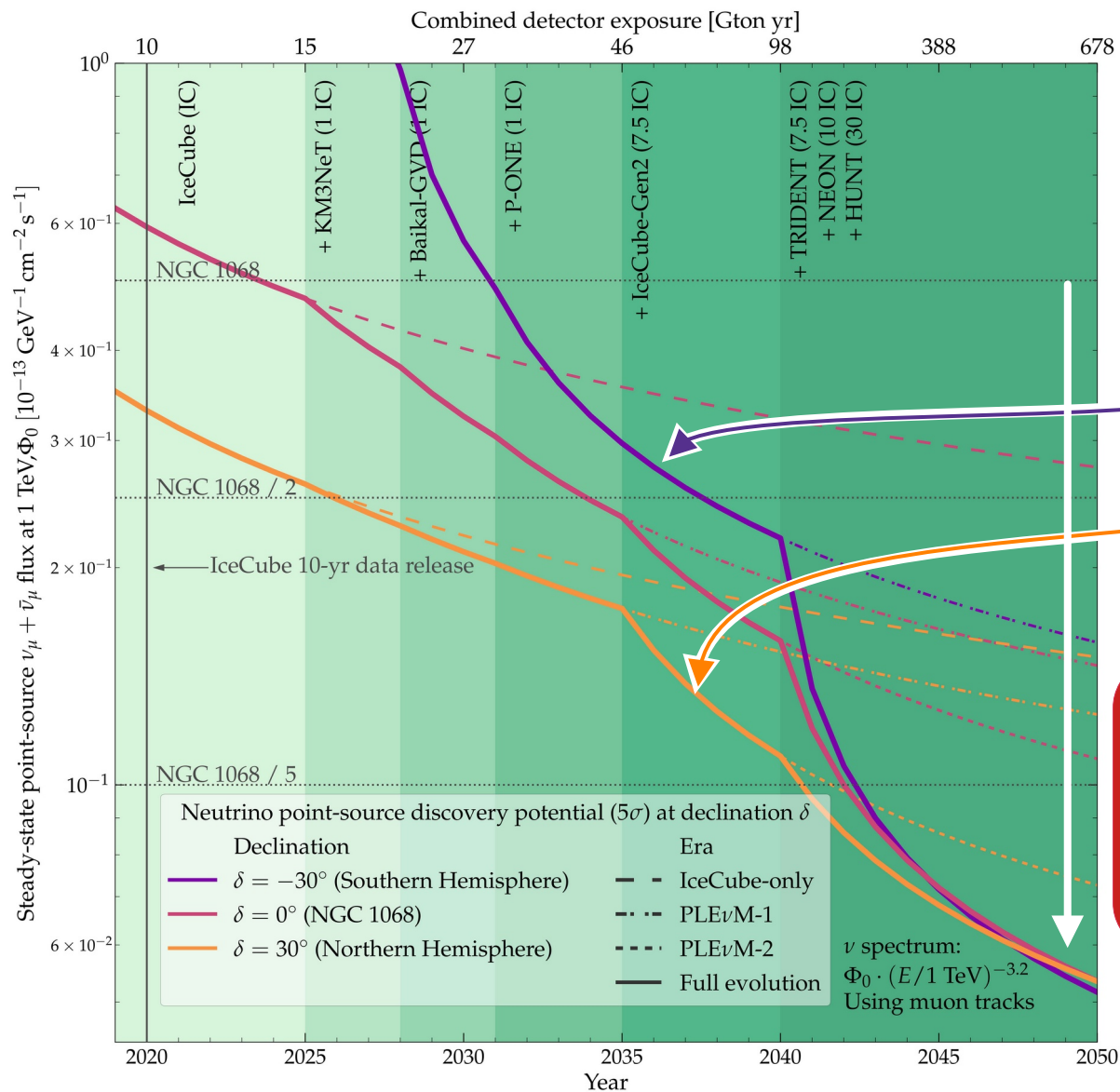






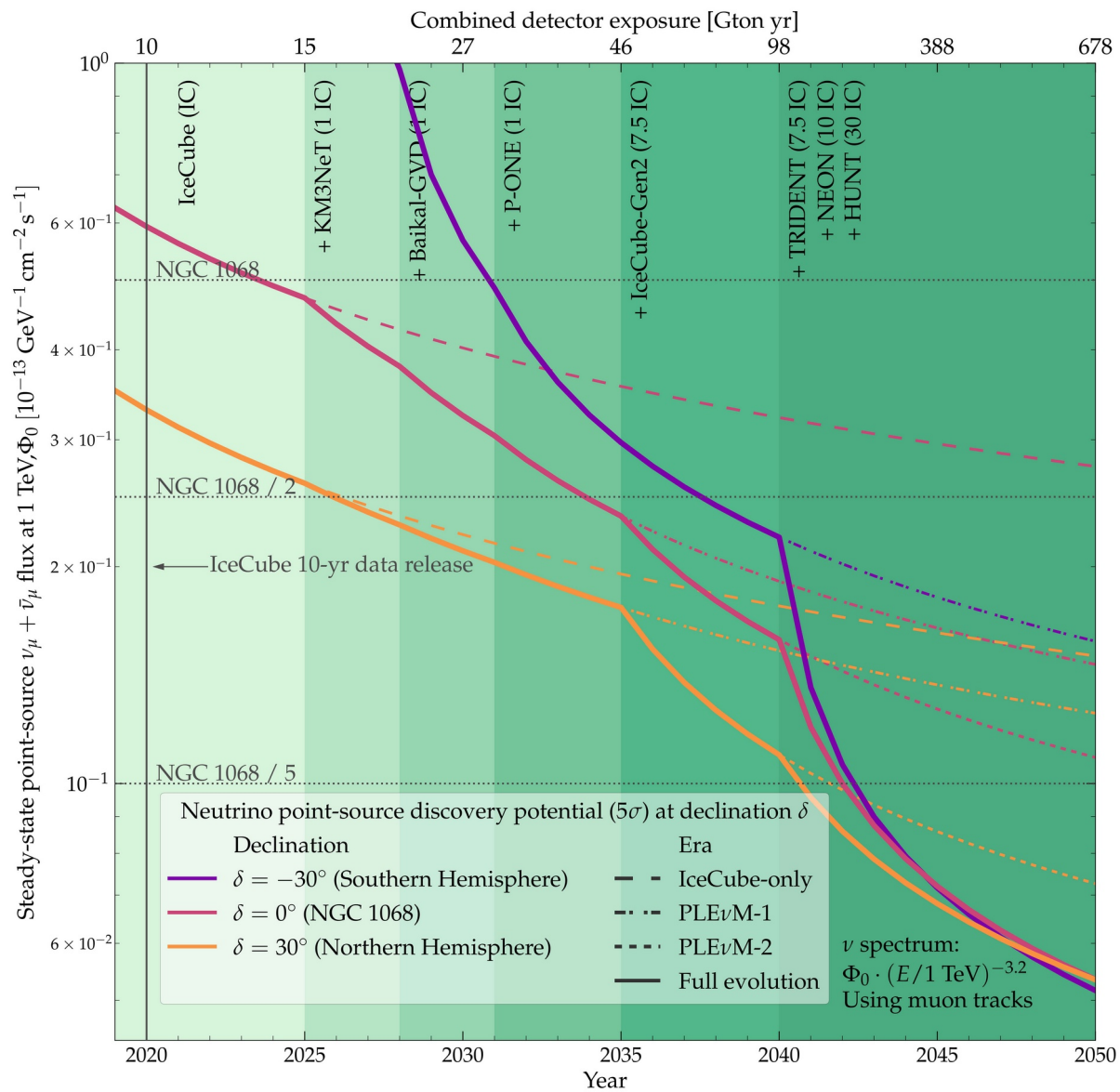


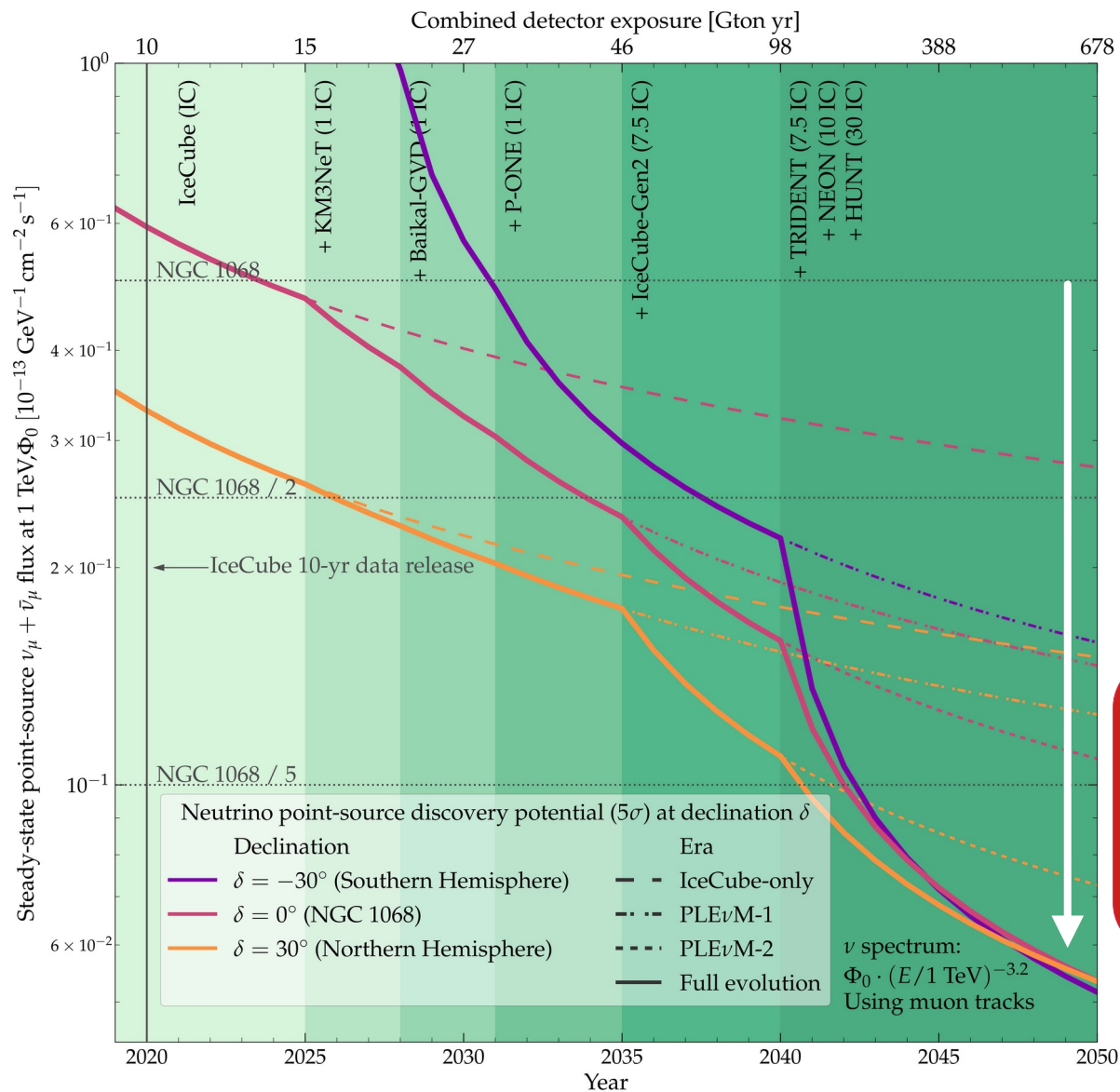




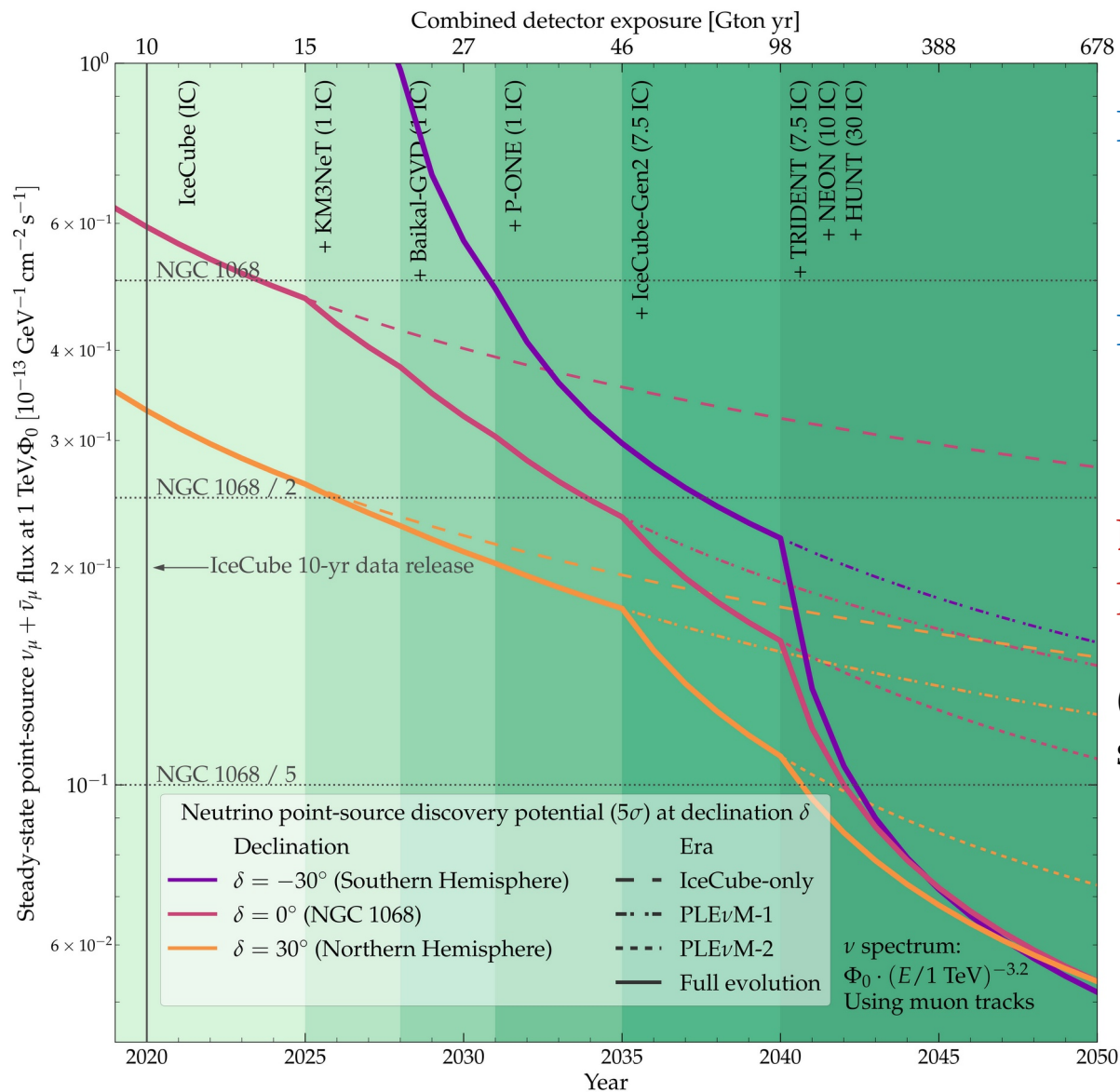
Similar improvement if the source
 is in the
 Southern or Northern Hemispheres

By 2050:
 PLEνM-3 can discover (5σ)
 a source like NGC-1068,
 ten times dimmer,
anywhere in the sky!





By 2050:
 PLEvM-3 can discover (5σ)
 a source like NGC-1068,
 ten times dimmer,
anywhere in the sky!



PLE ν M-1 can detect sources 40% as bright as NGC 1068

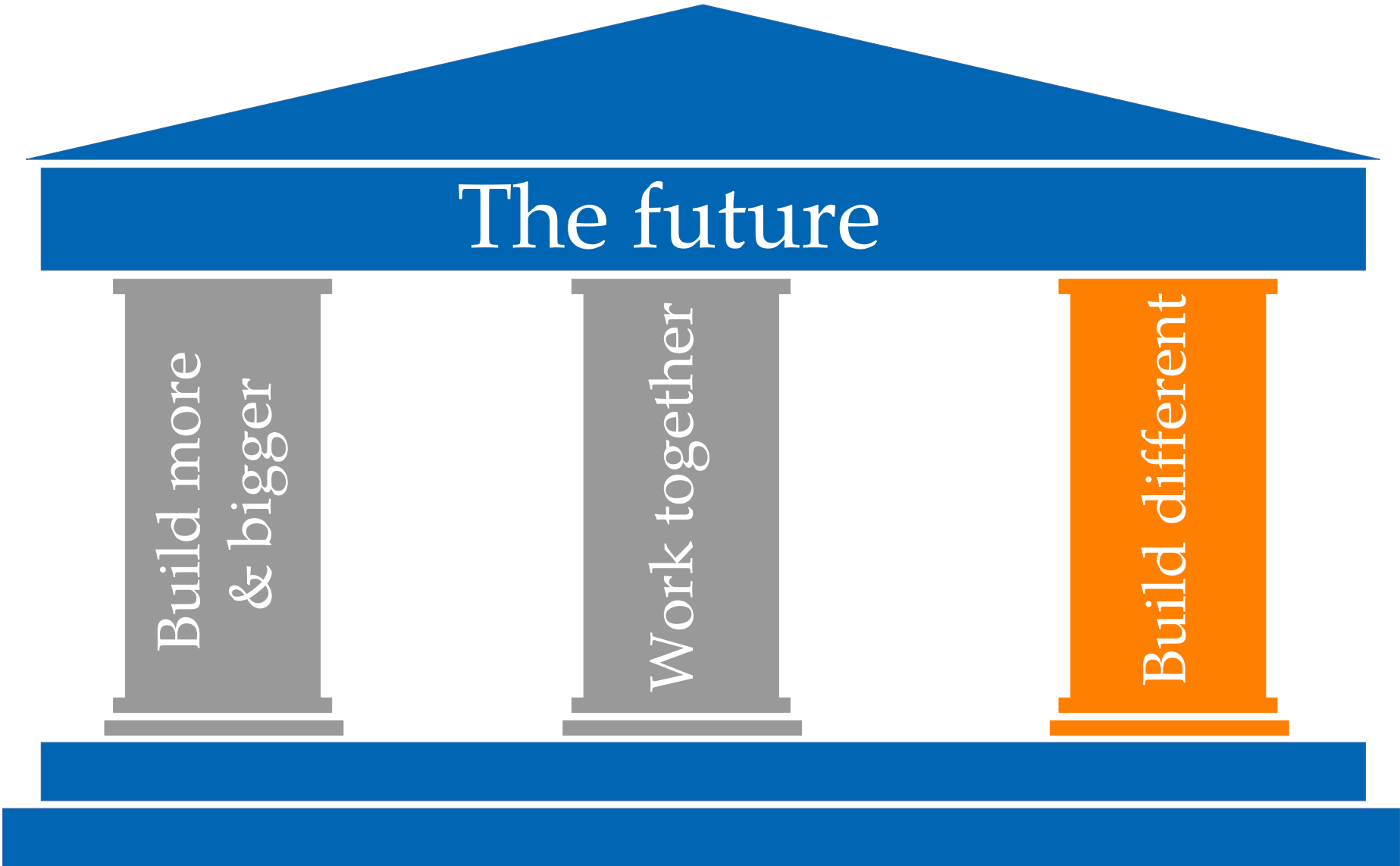
→ 2–6 sources detectable

PLE ν M-2 can detect sources 10% as bright as NGC 1068

→ 10–40 sources detectable

Demanding only 3σ evidence raises prospects by 50%

(Rates depend on choice of local source number density)

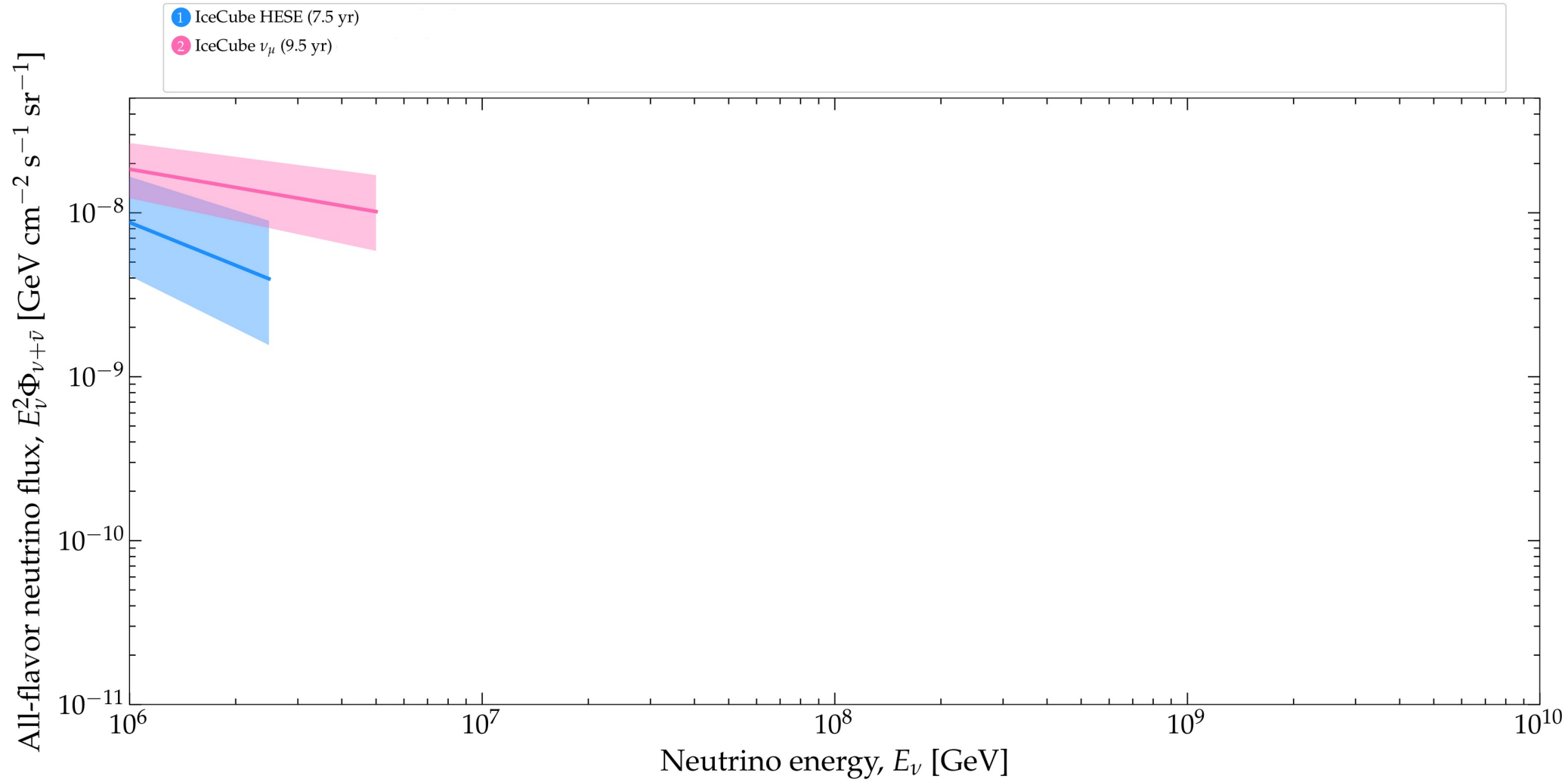


The future

Build more
& bigger

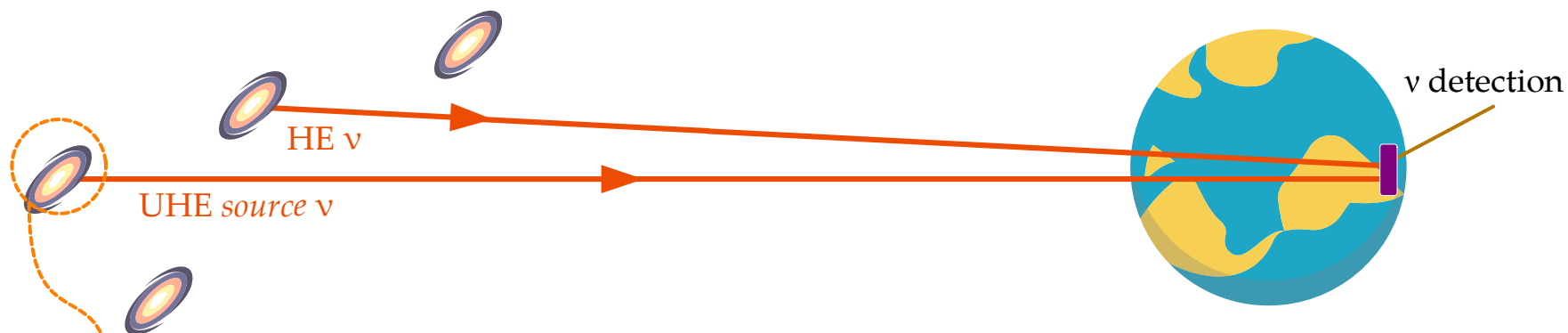
Work together

Build different



Redshift

$z = 0$



meV γ

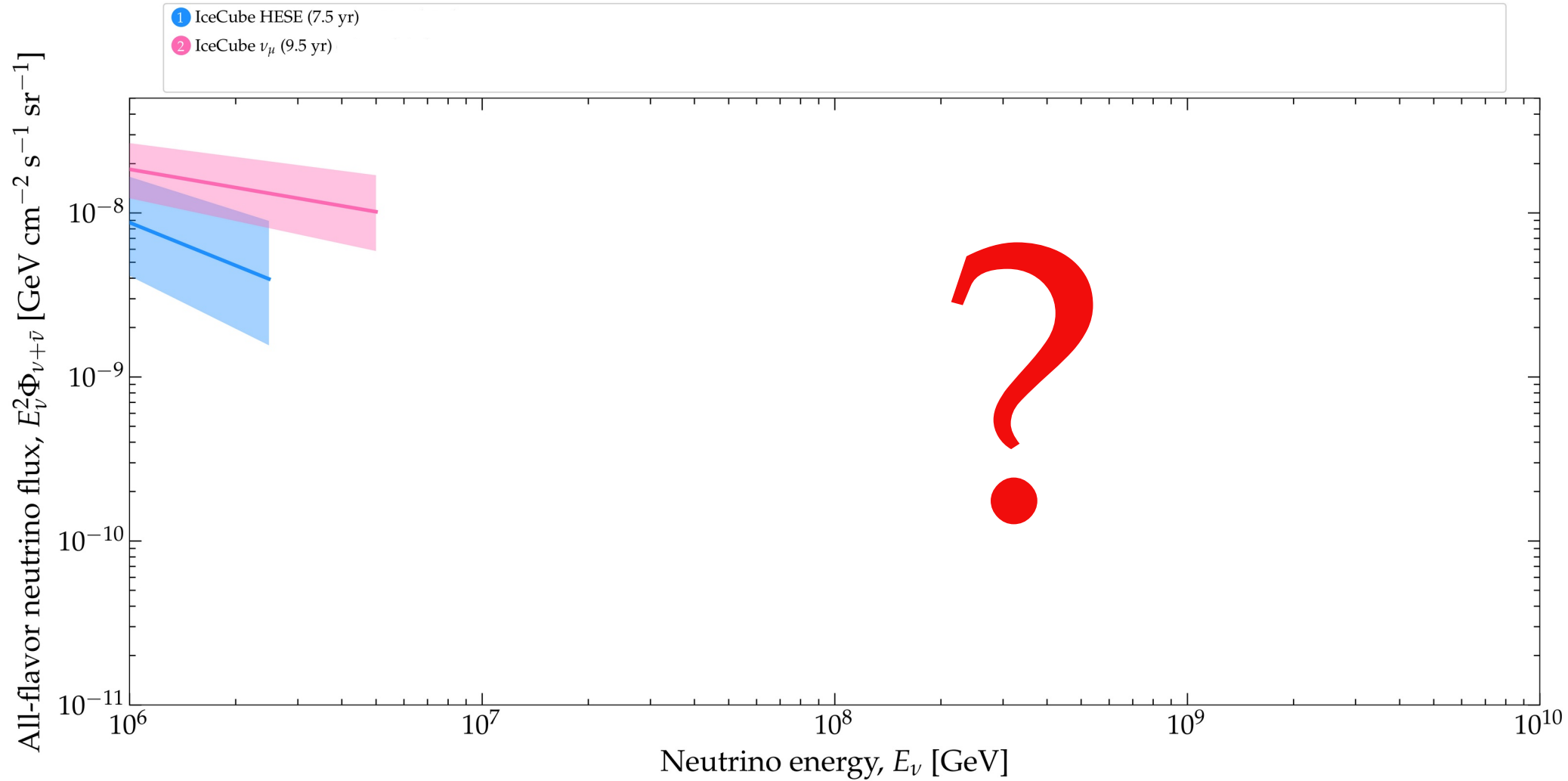
Undiscovered

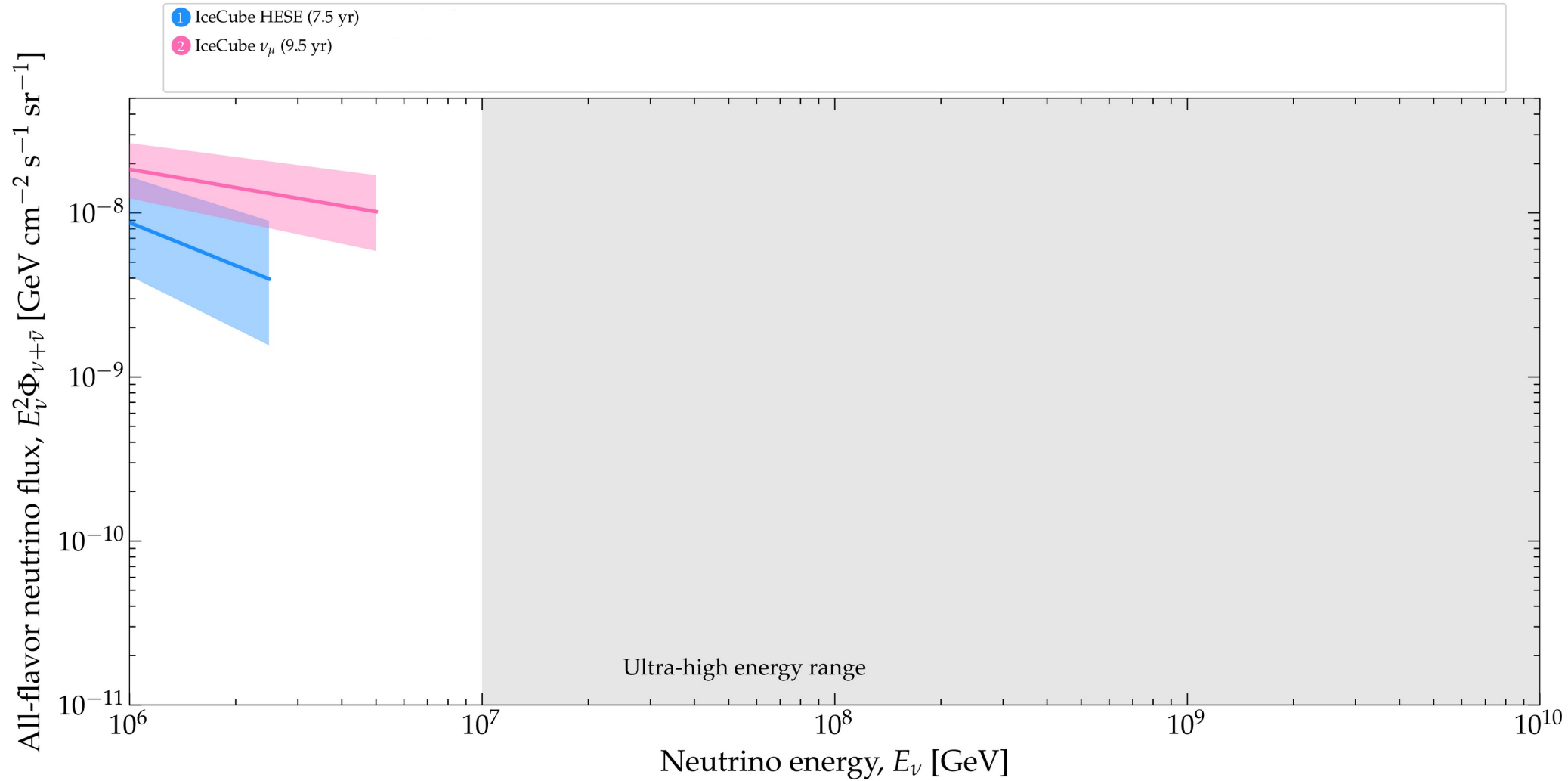
EeV p

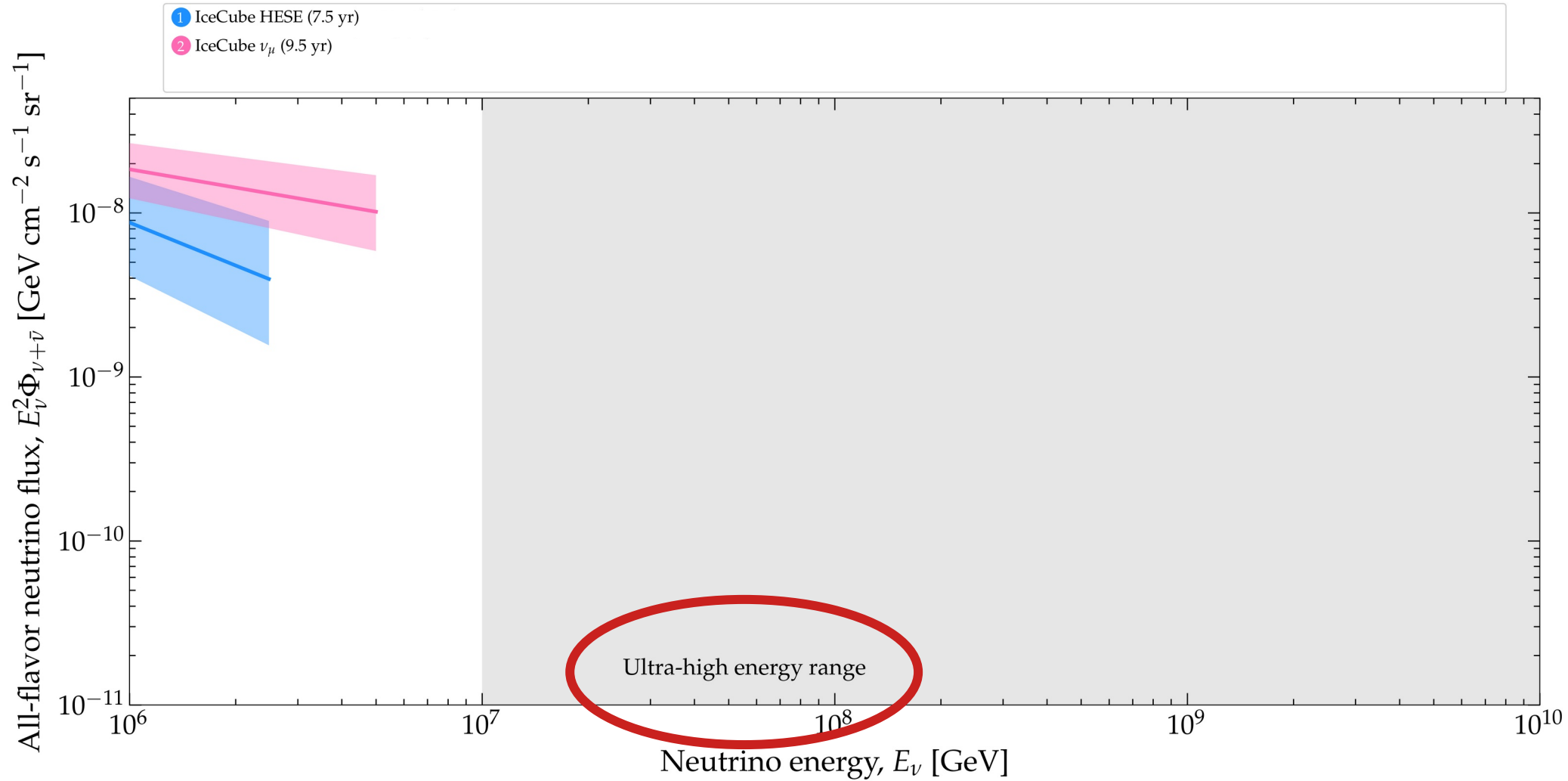
EeV ν

"Ultra-high-energy"

Photohadronic or pp interaction
inside the source



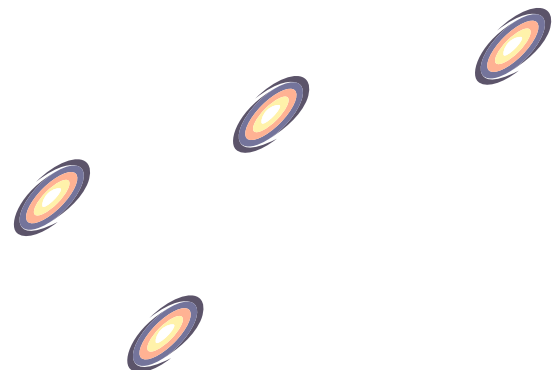




Redshift



$z = 0$



Redshift



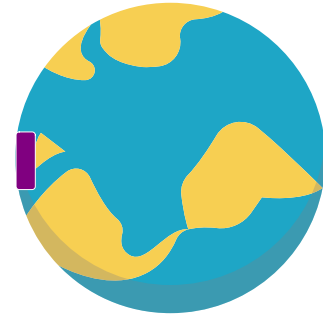
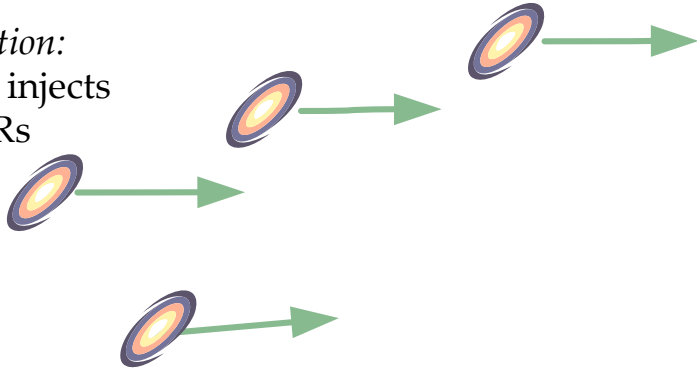
$z = 0$

At production:
Each source injects
UHECRs



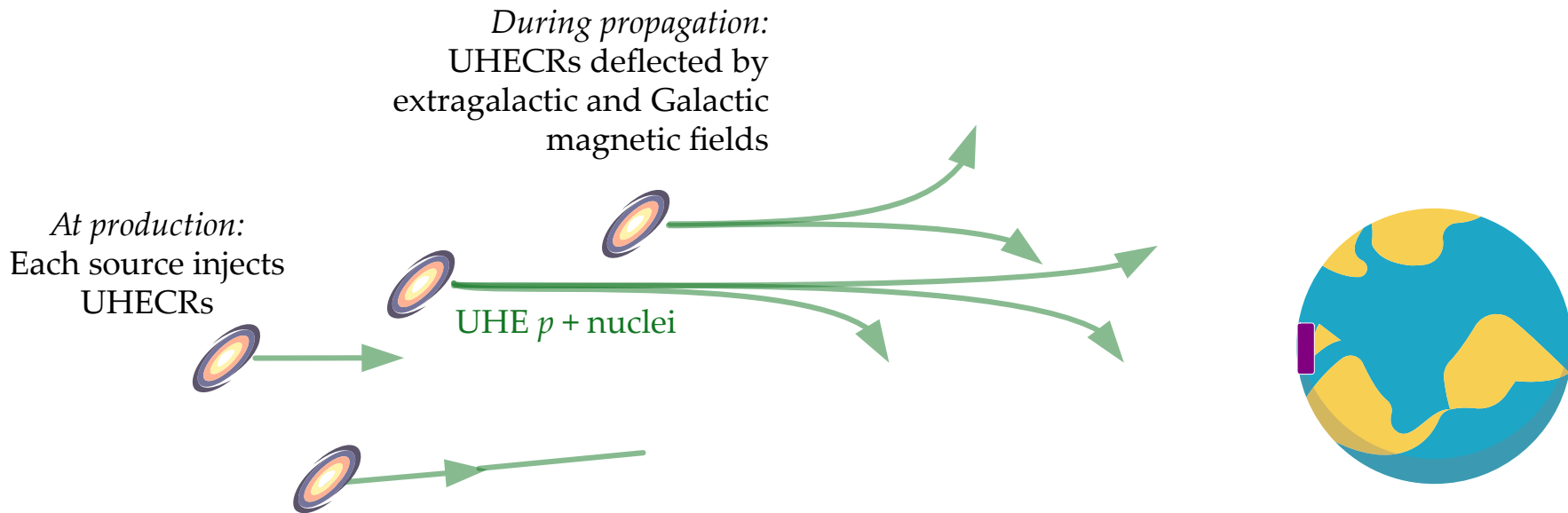
Redshift ← UHECR sources distributed in redshift (e.g., as star-formation rate) $z = 0$

At production:
Each source injects
UHECRs



Redshift ← $z = 0$

UHECR sources distributed in redshift (e.g., as star-formation rate)



Redshift ← $z = 0$

UHECR sources distributed in redshift (e.g., as star-formation rate)

During propagation:
UHECRs deflected by
extragalactic and Galactic
magnetic fields

At production:
Each source injects
UHECRs

UHE $p + \text{nuclei}$

CMB/EBL γ

e^+, e^-

EeV p

Lower-energy p

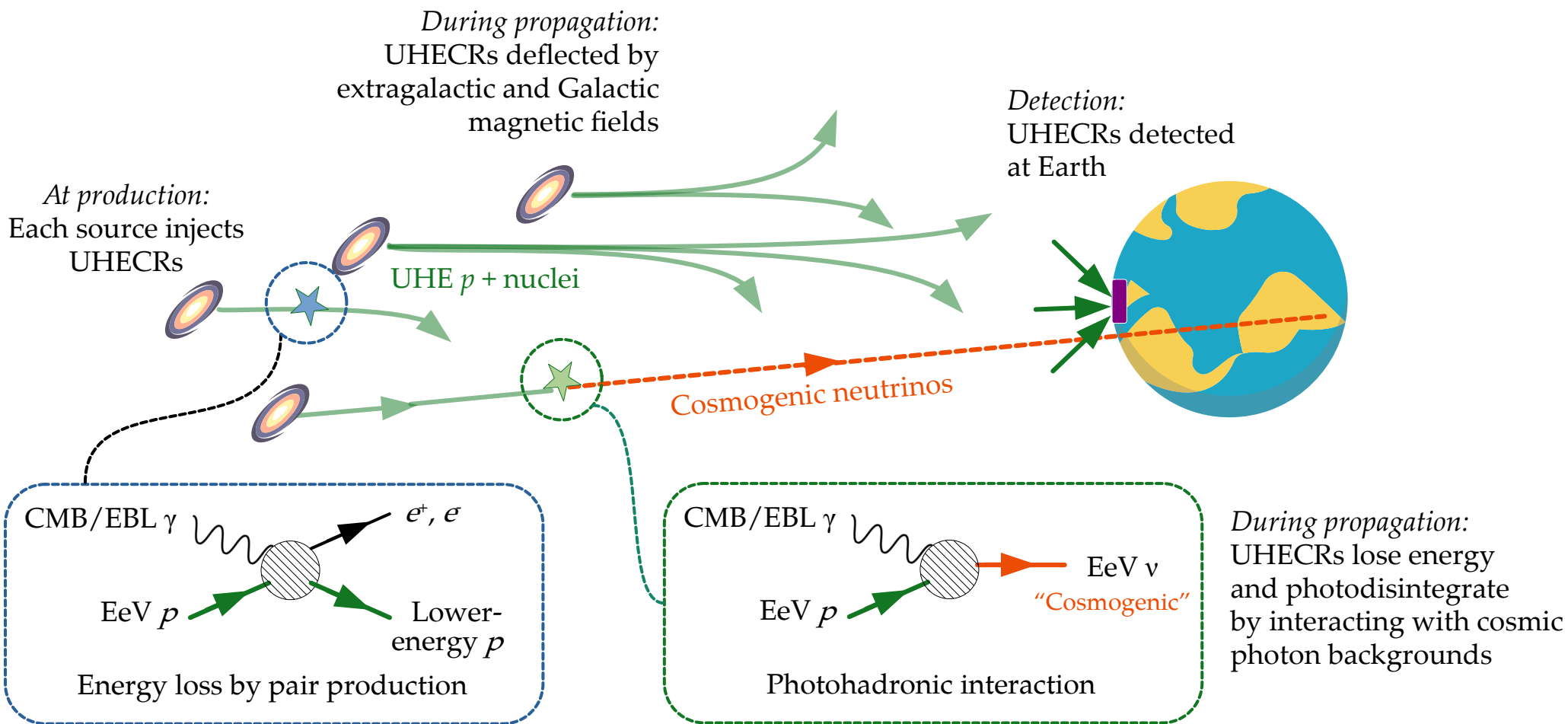
Energy loss by pair production

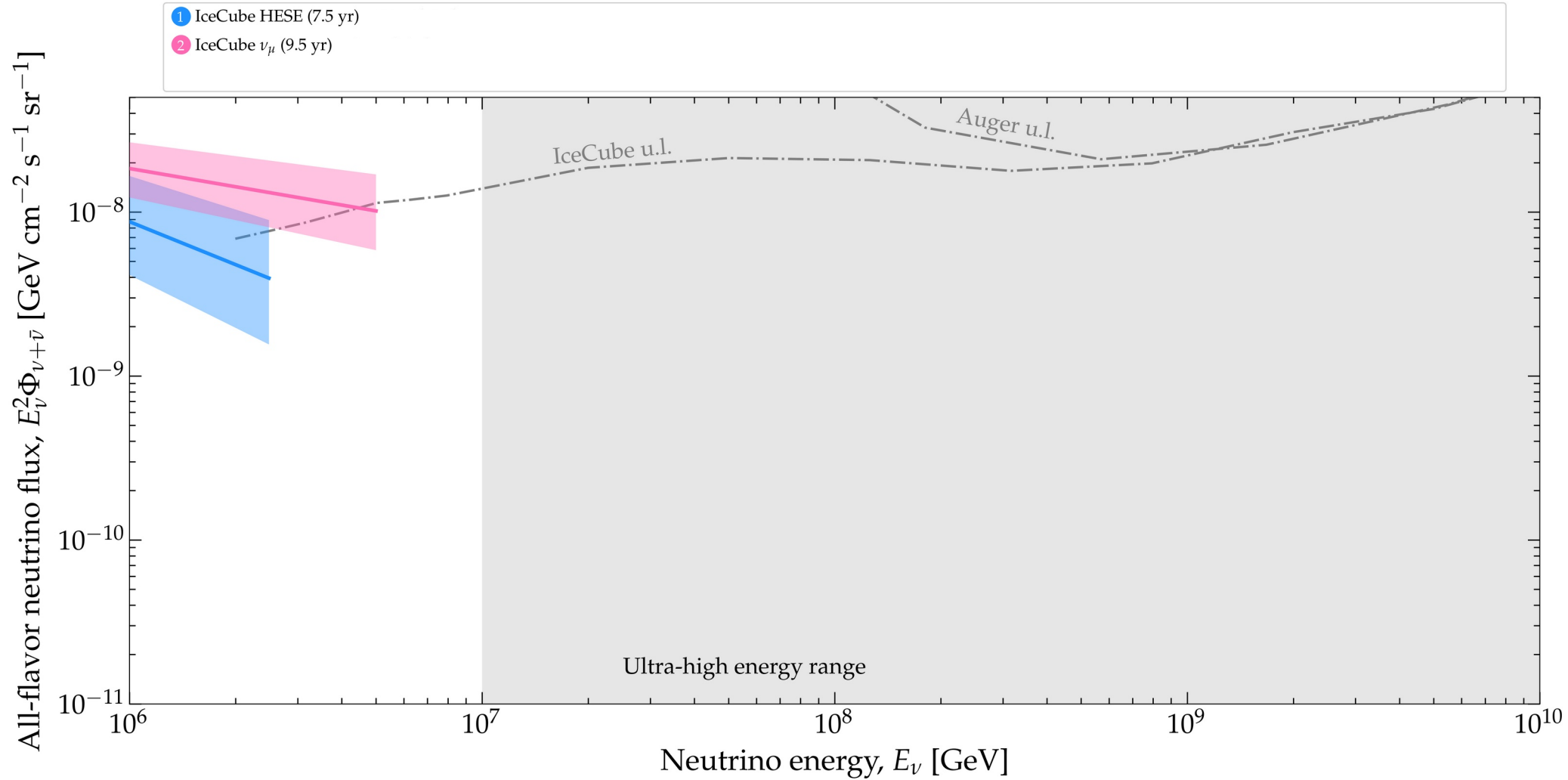


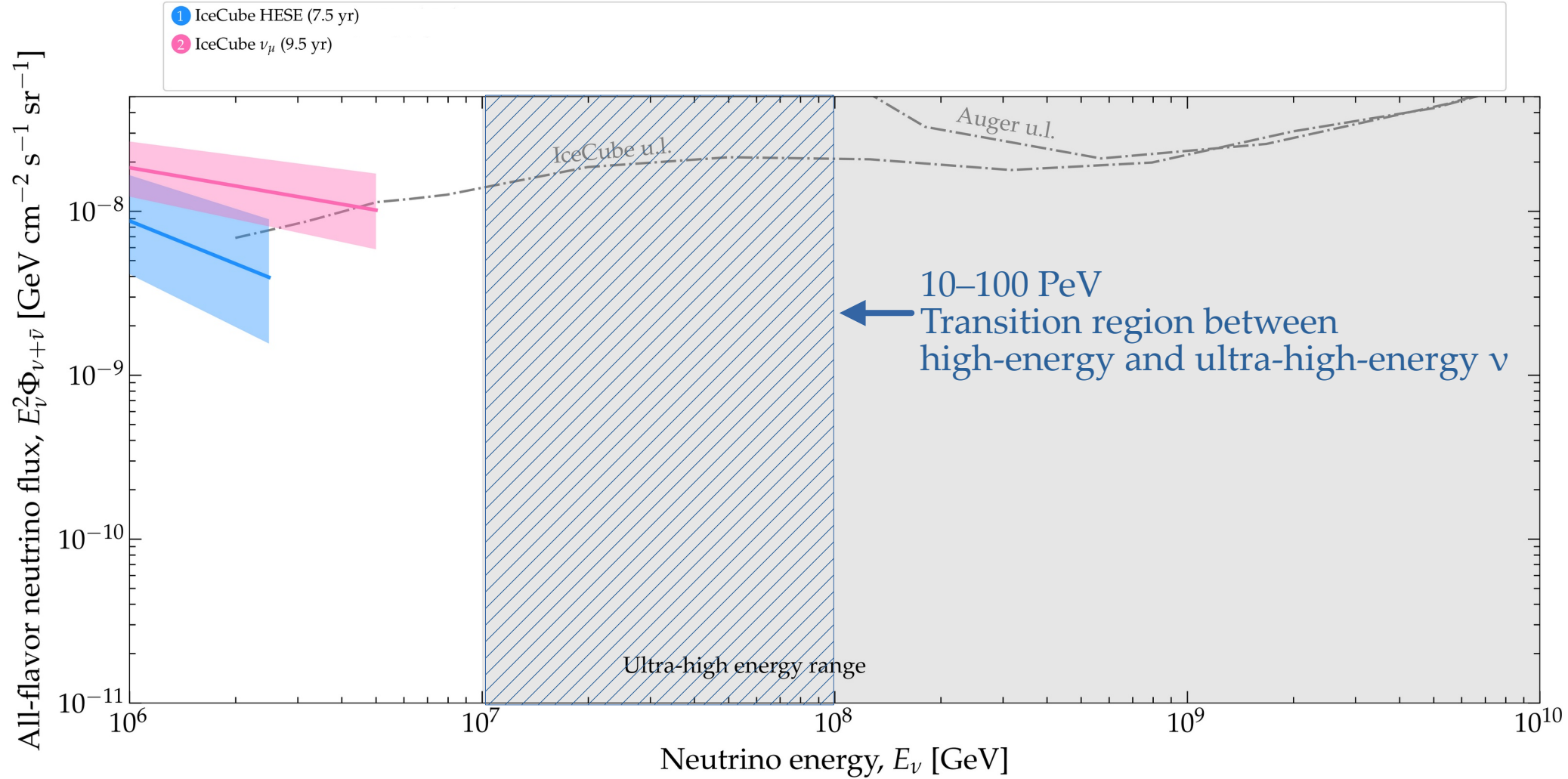
During propagation:
UHECRs lose energy
and photodisintegrate
by interacting with cosmic
photon backgrounds

Redshift $\longleftarrow$ $\longrightarrow$ $z = 0$

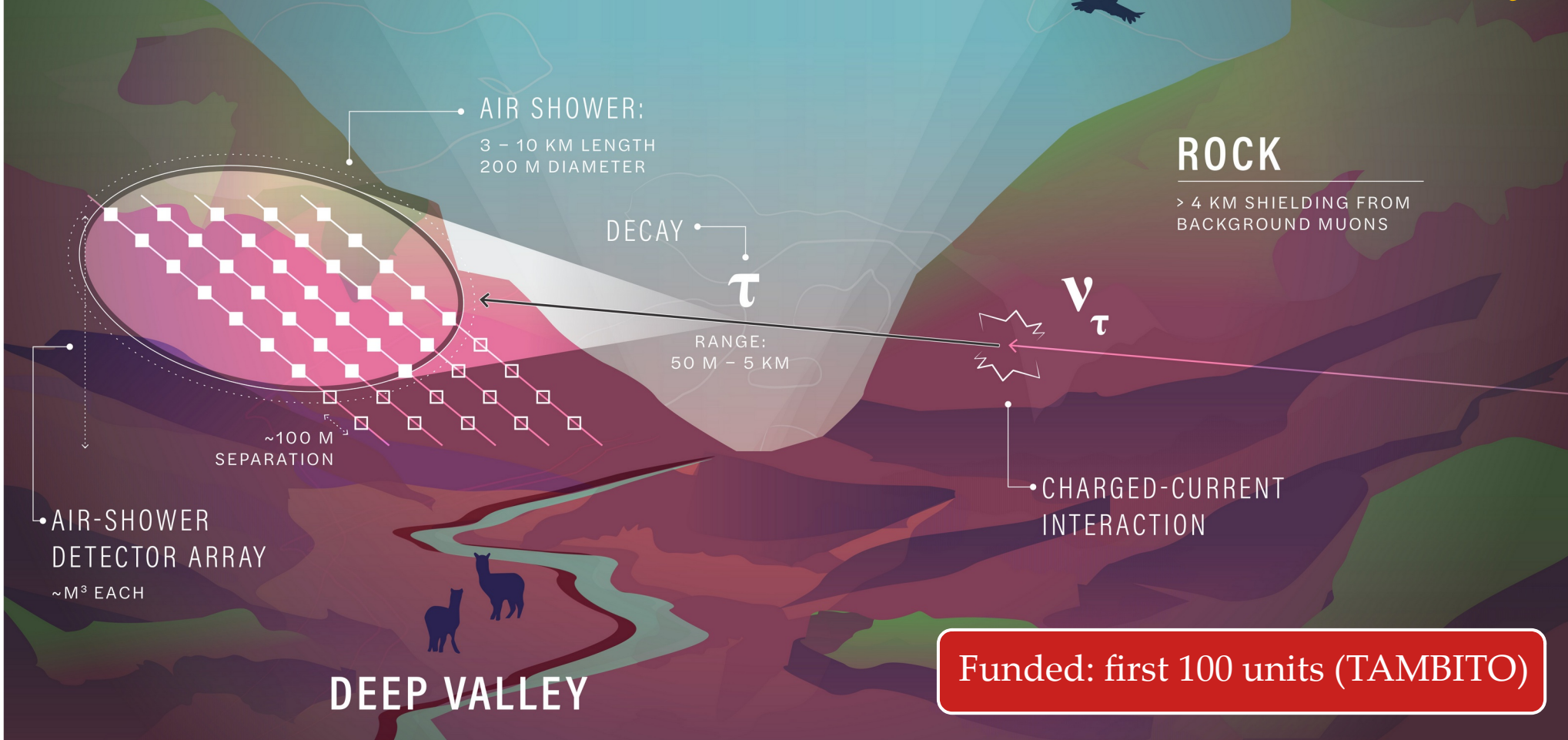
UHECR sources distributed in redshift (e.g., as star-formation rate)







TAMBO: the Tau Air-Shower Mountain-Based Observatory

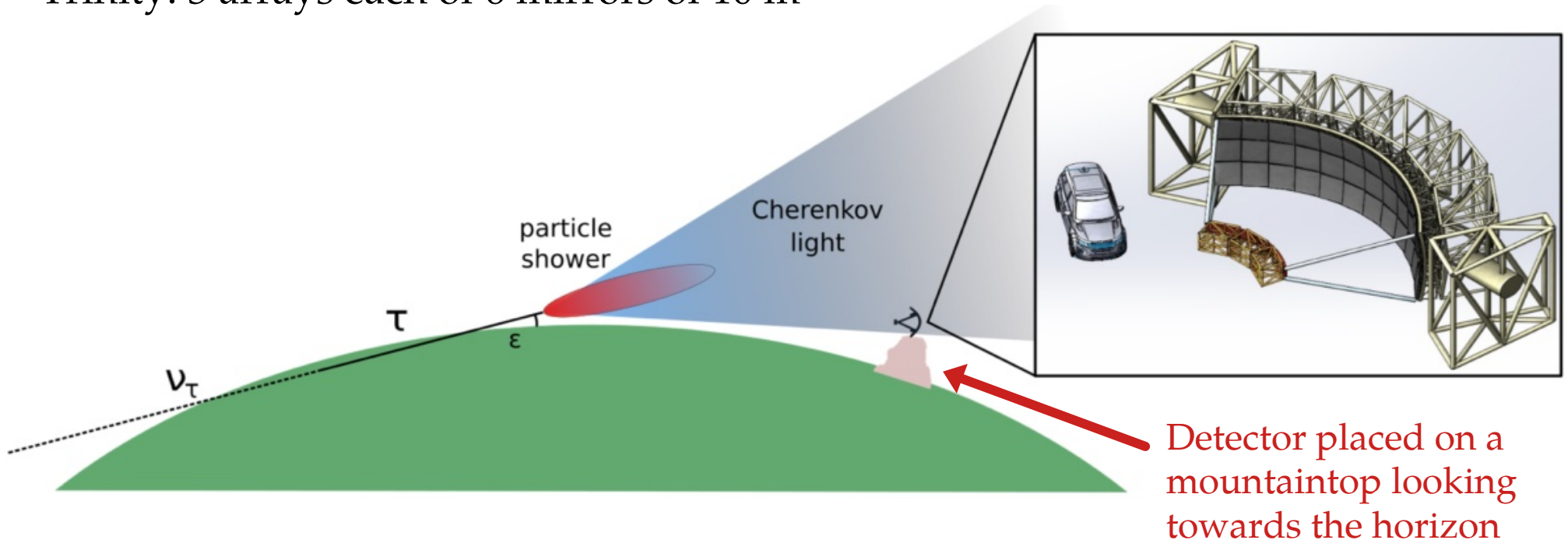


Trinity

Atmospheric Cherenkov imaging applied to PeV neutrinos

Pioneered by MAGIC (pointing at Atlantic), ASHRA, and NTA (Mauna Kea)

Trinity: 3 arrays each of 6 mirrors of 10 m²

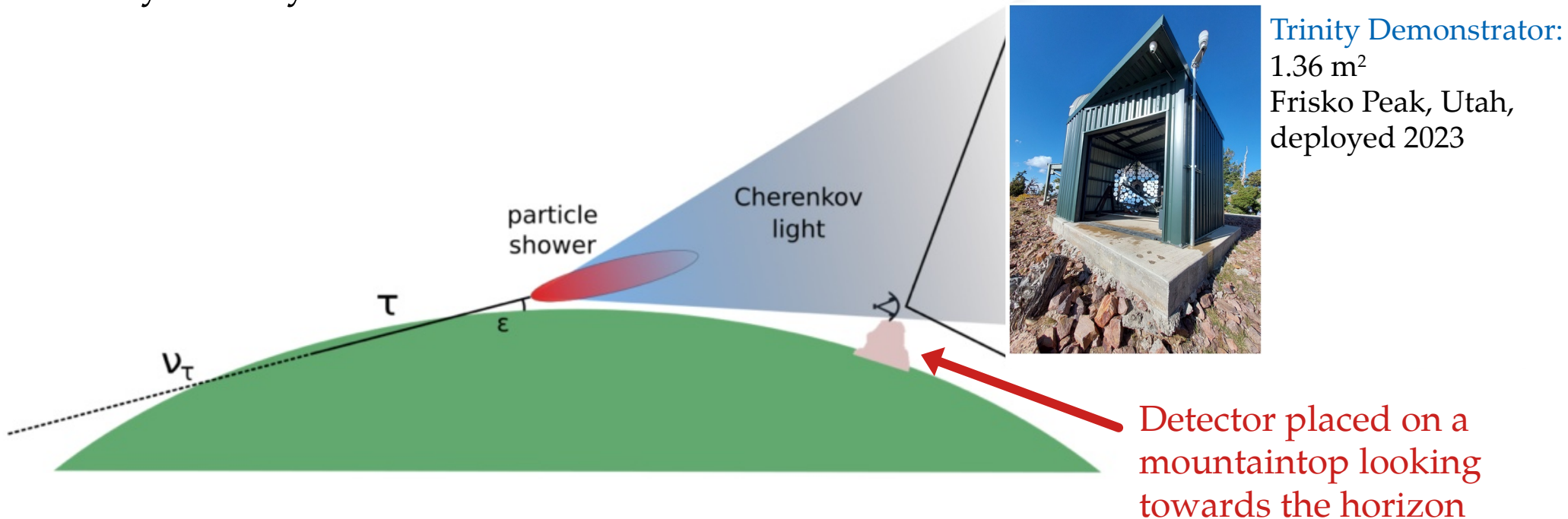


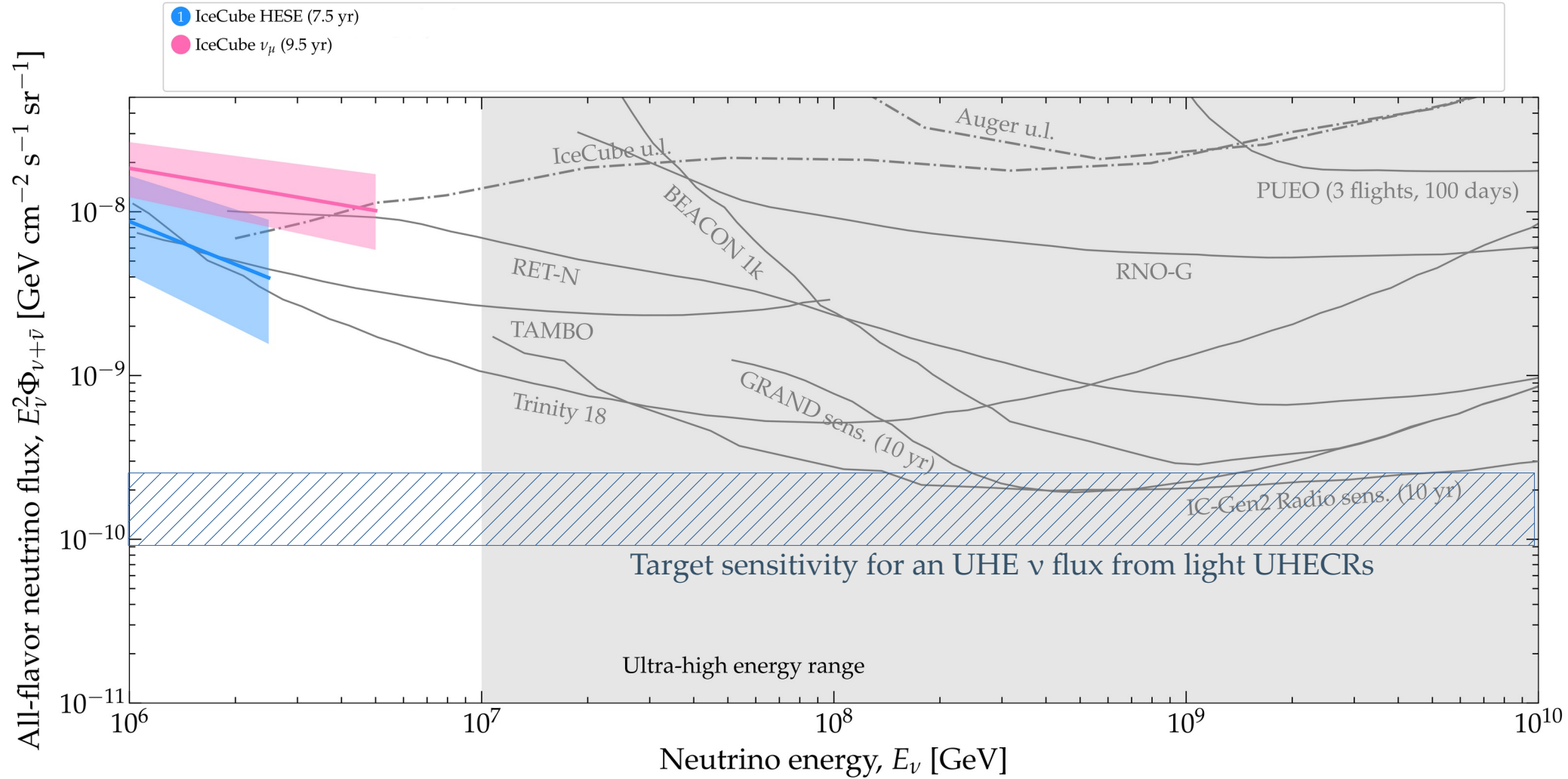
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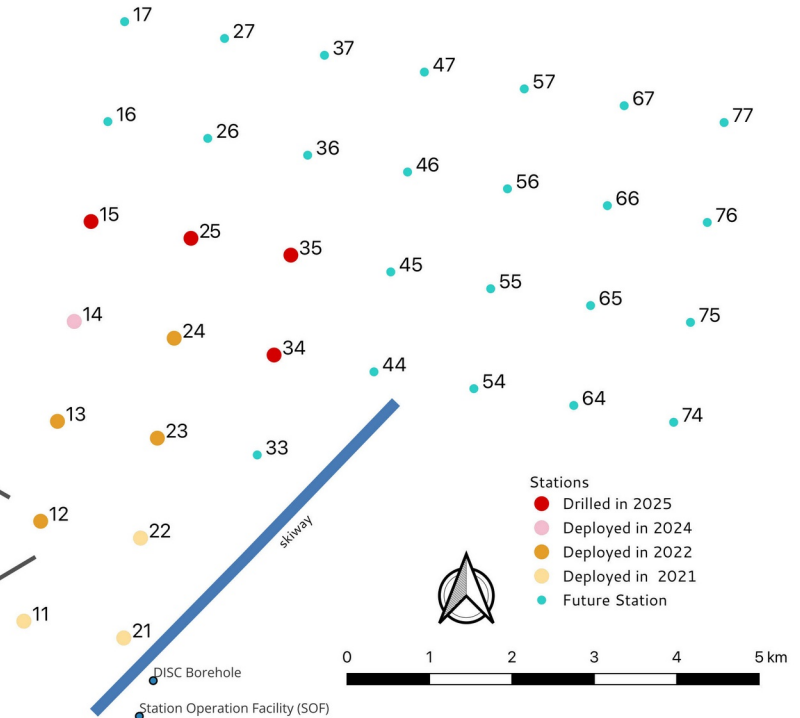
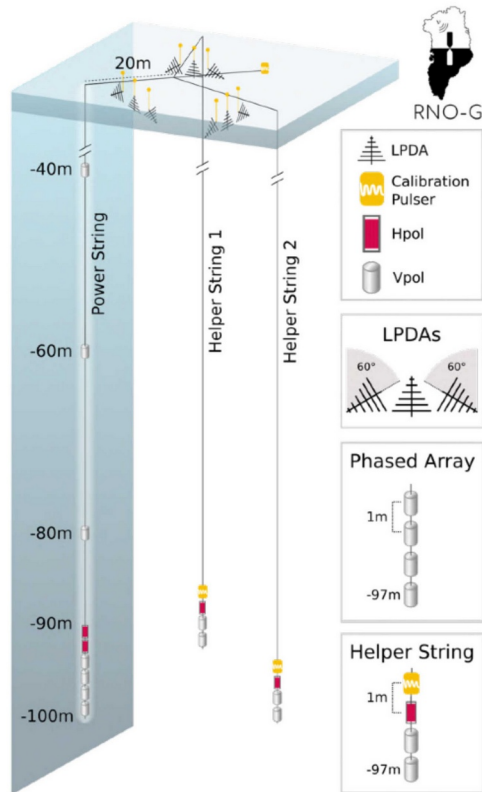


RNO-G: Radio Neutrino Observatory - Greenland

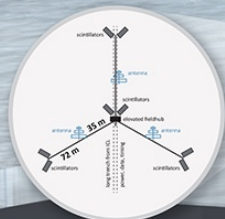
In construction

35 in-ice radio stations planned

ARA + ARIANNA experience



- 8 stations operational (Apr - Oct), Wind-power tested
- 4 additional stations drilled (as of today)



Cosmic Ray Surface Array

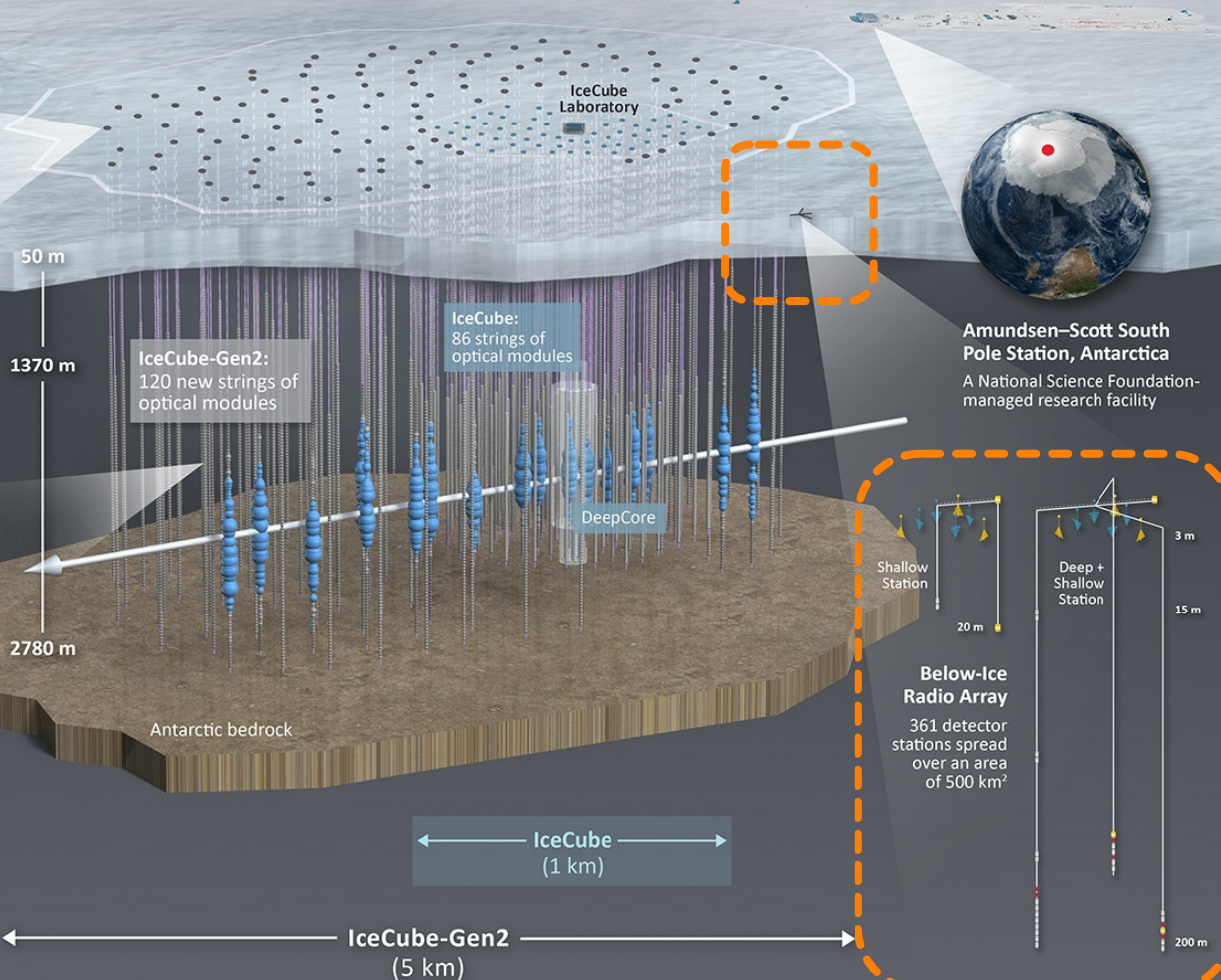
An air shower array that sits on top of the optical array
One surface station installed above each optical string



IceCube-Gen2 Optical Module

4x the sensitivity of IceCube's modules
9,600 new optical modules in total to be deployed in the ice

80 modules on each string, spaced 17 meters apart

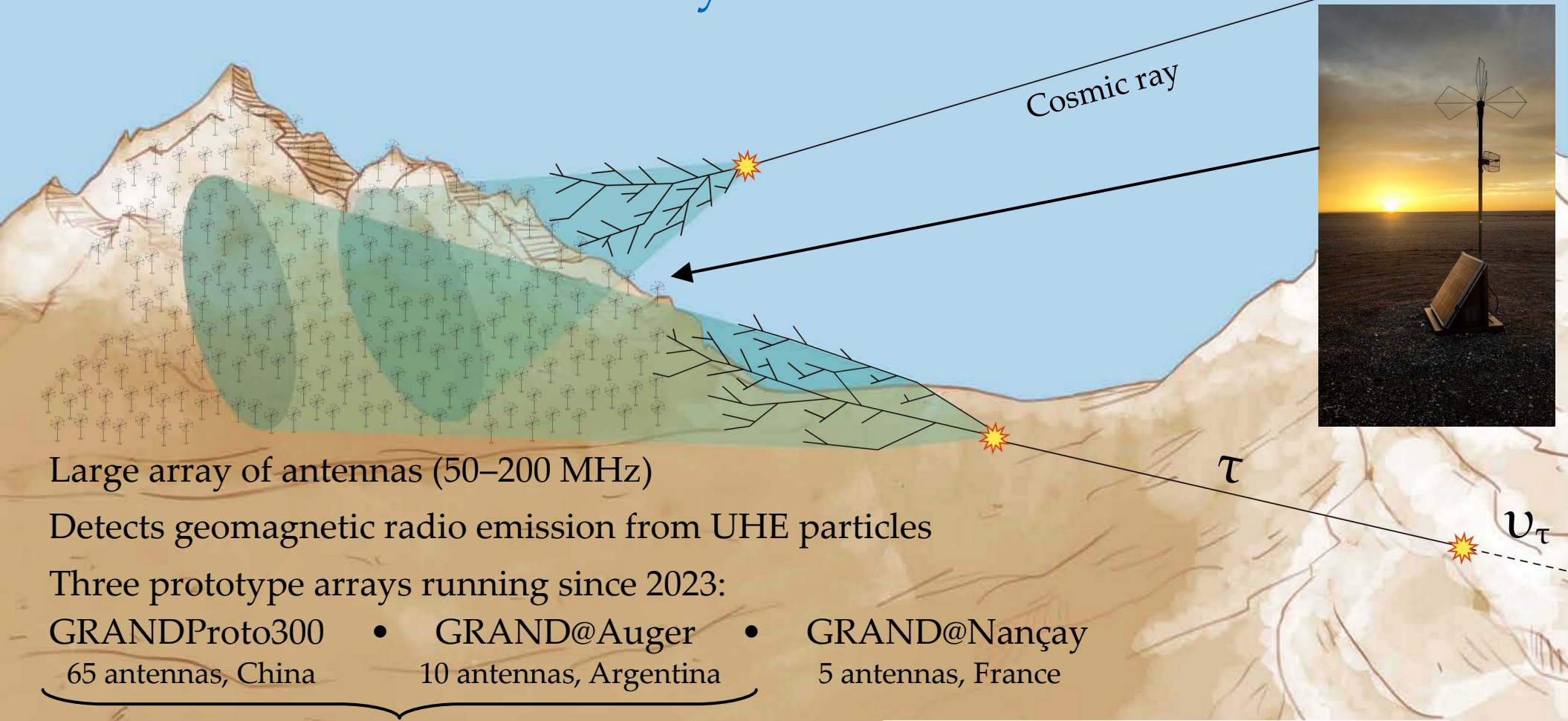


High-energy
IceCube successor

Radio array:
> 100 PeV ν
Askaryan radiation
~310 stations
~500 km²

~100× rate of EeV ν
vs. IceCube

GRAND: Giant Radio Array for Neutrino Detection

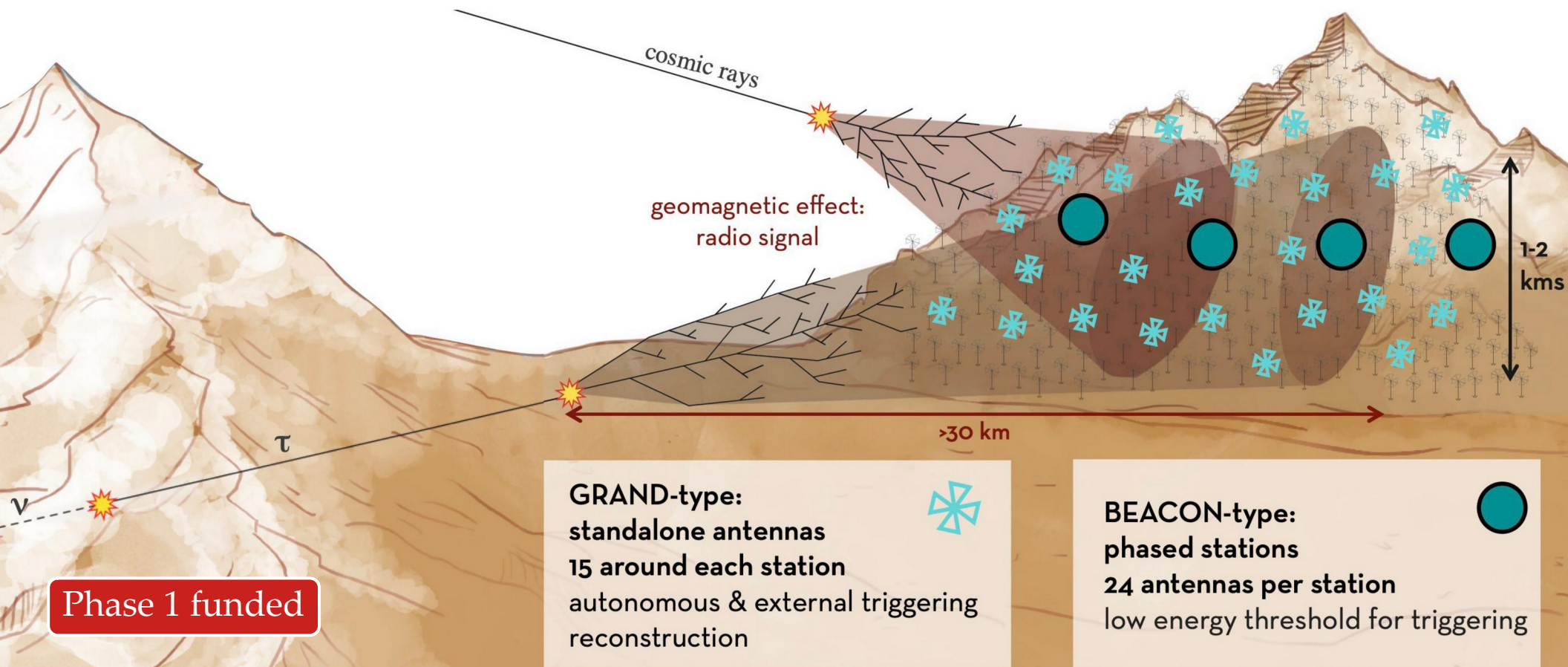


First cosmic-ray candidates shown at ICRC 2025

Funded: extension to 300 antennas

HERON: Hybrid Elevated Radio Observatory for Neutrinos

BEACON phased-array stations (low-SNR detection) + GRAND antennas (self-triggering)



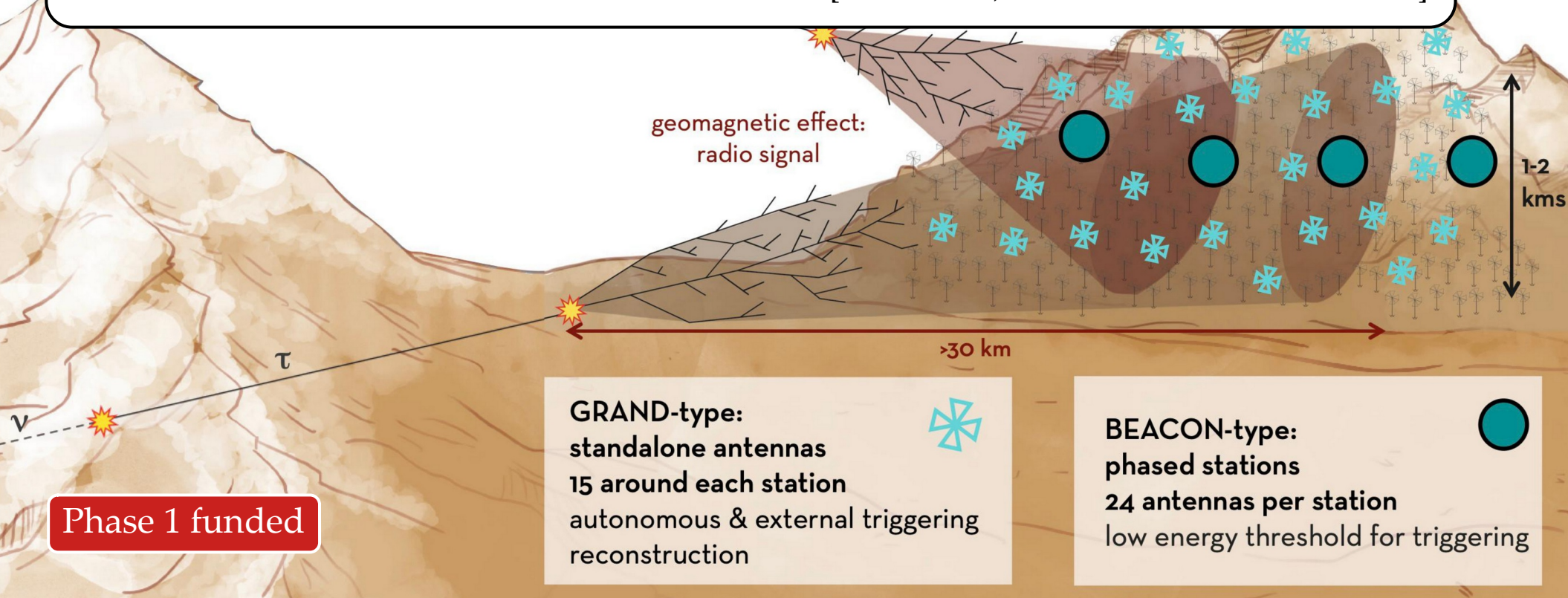
HERON: Hybrid Elevated Radio Observatory for Neutrinos

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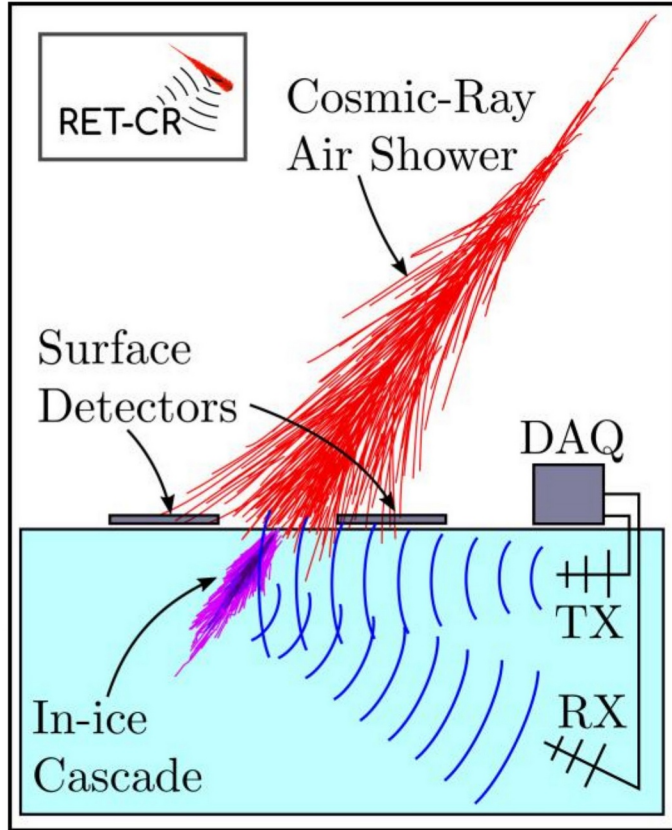
Narrow field of view, high sensitivity:

Phase 1: 24 BEACON stations + 360 GRAND antennas [$\approx$ GRAND10k sens. for point sources]

Phase 2: 200 BEACON stations + 3k GRAND antennas [$\approx$ GRAND, IC-Gen2 sens. for diffuse flux]



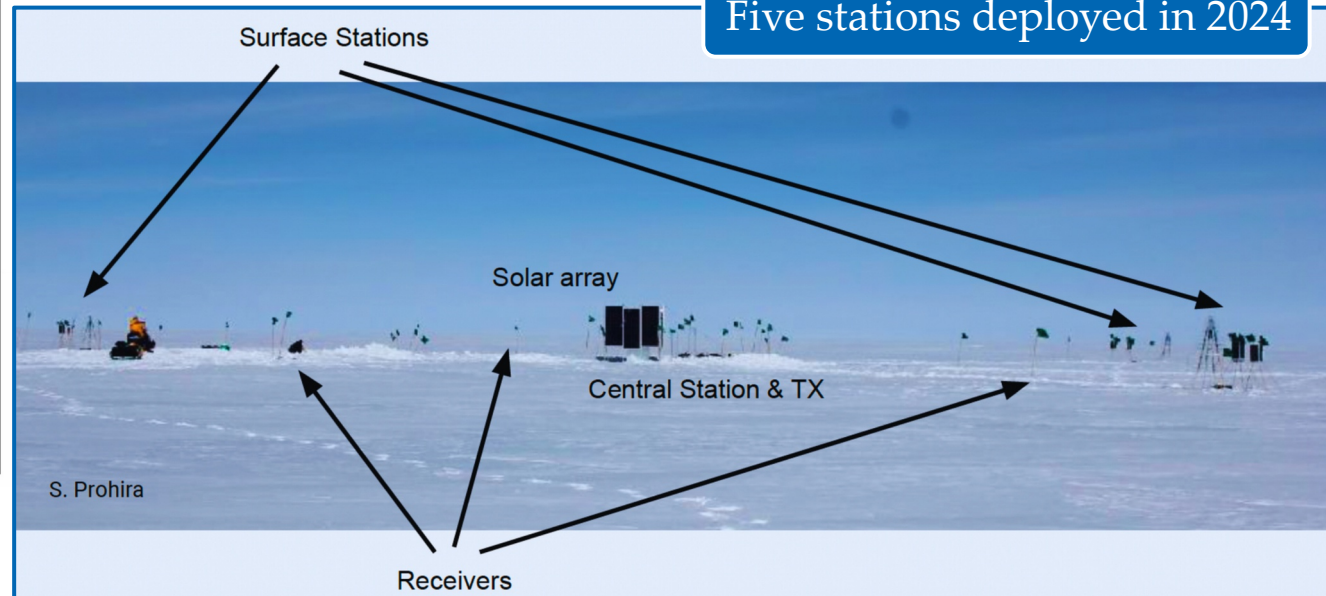
RET: Radar Echo Telescope



Detect the ionization trail made by in-ice high-energy particle showers via active radar sounding

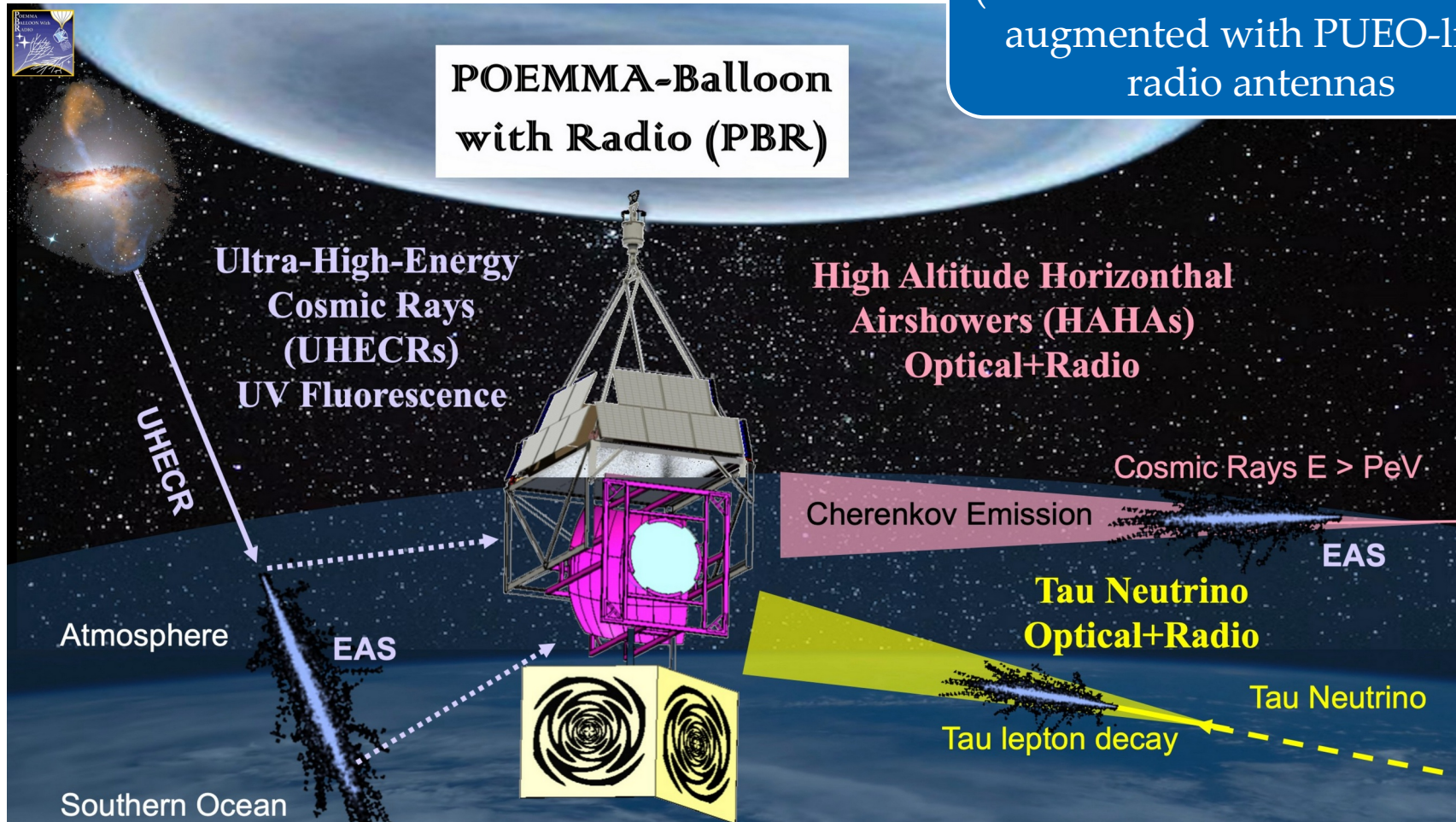
Today: RET-CR to detect cosmic rays, proof of principle

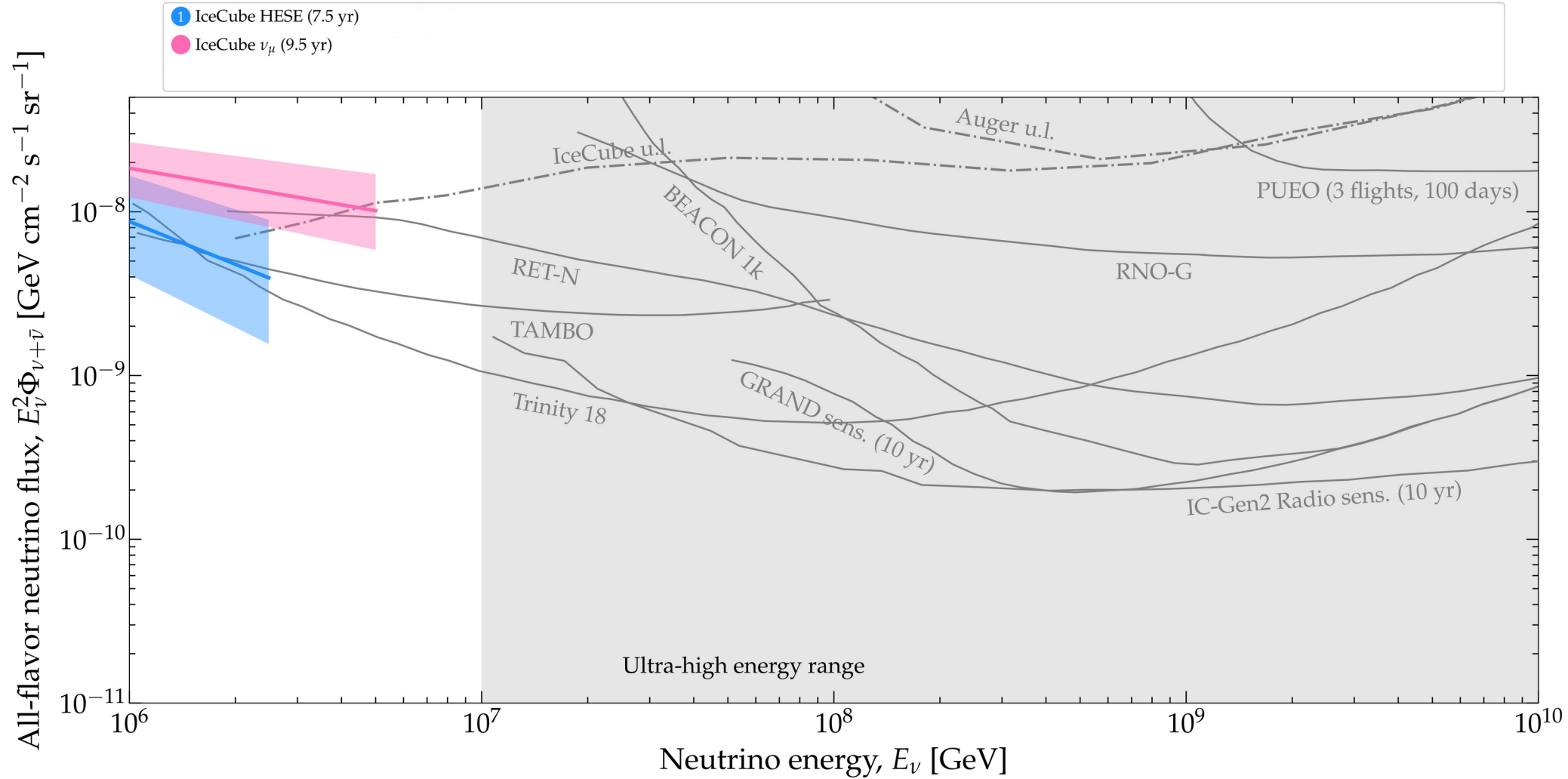
Future: RET-N to detect neutrinos

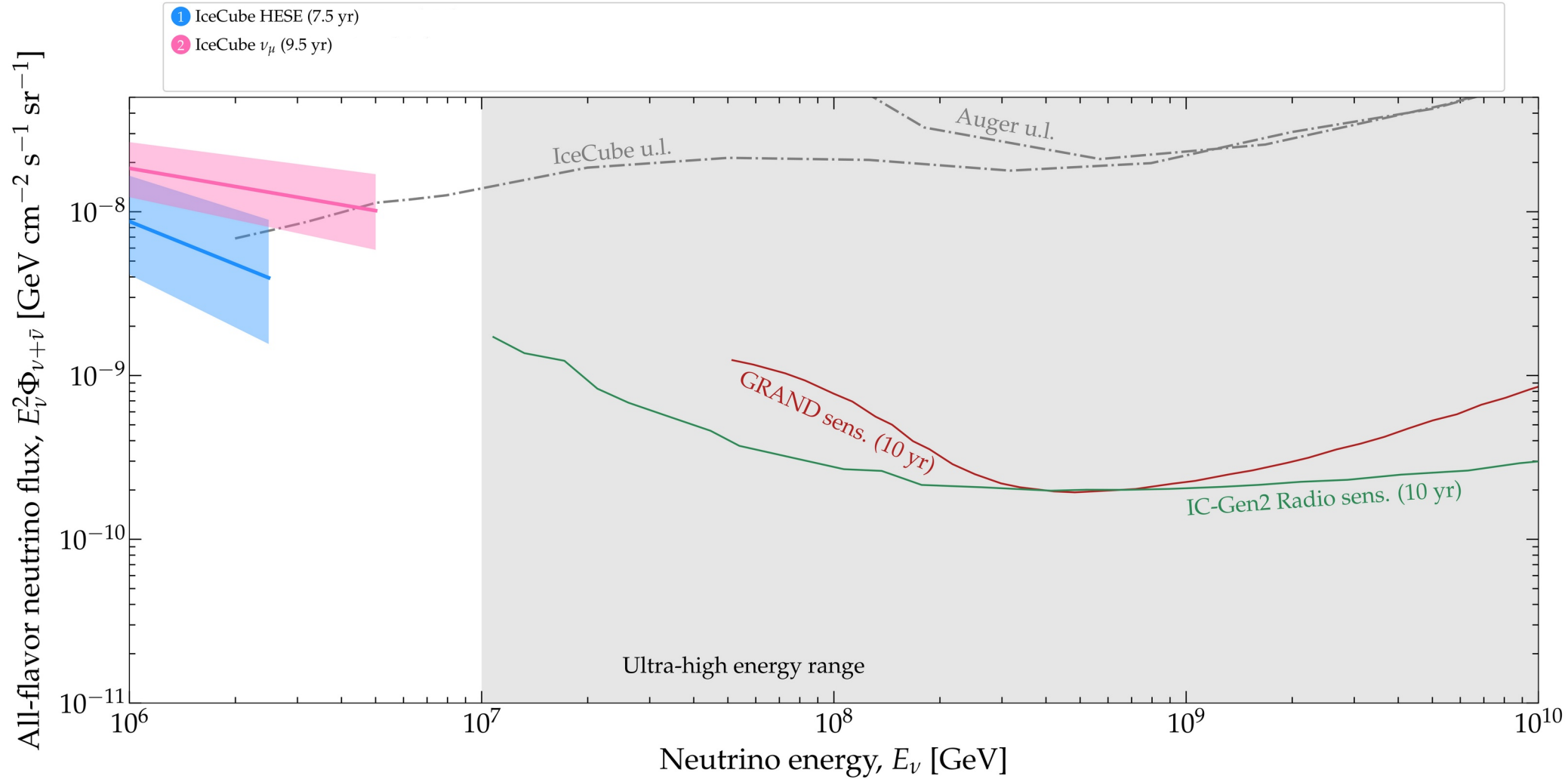


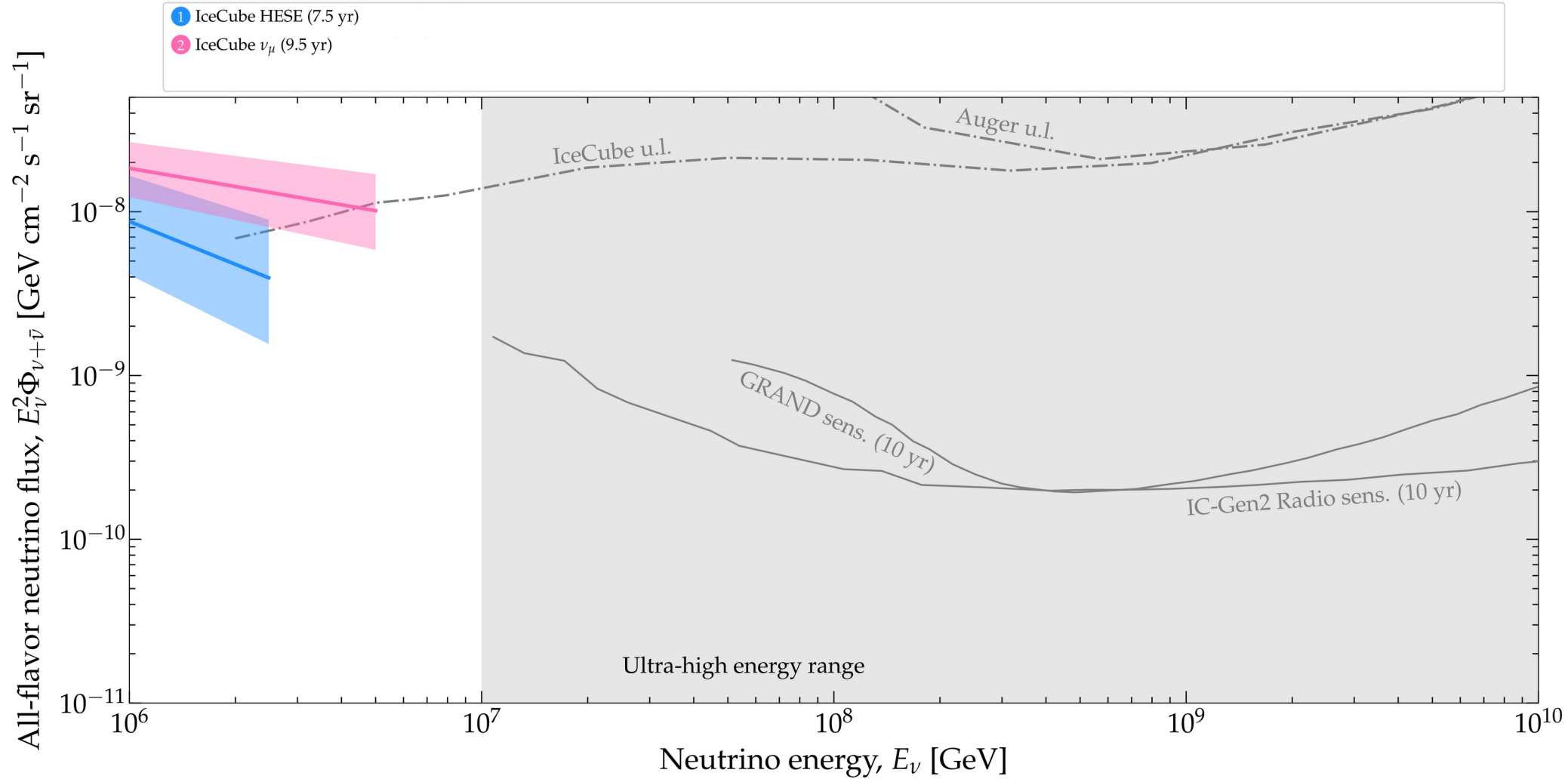
PBR: POEMMA-Balloon with Radio

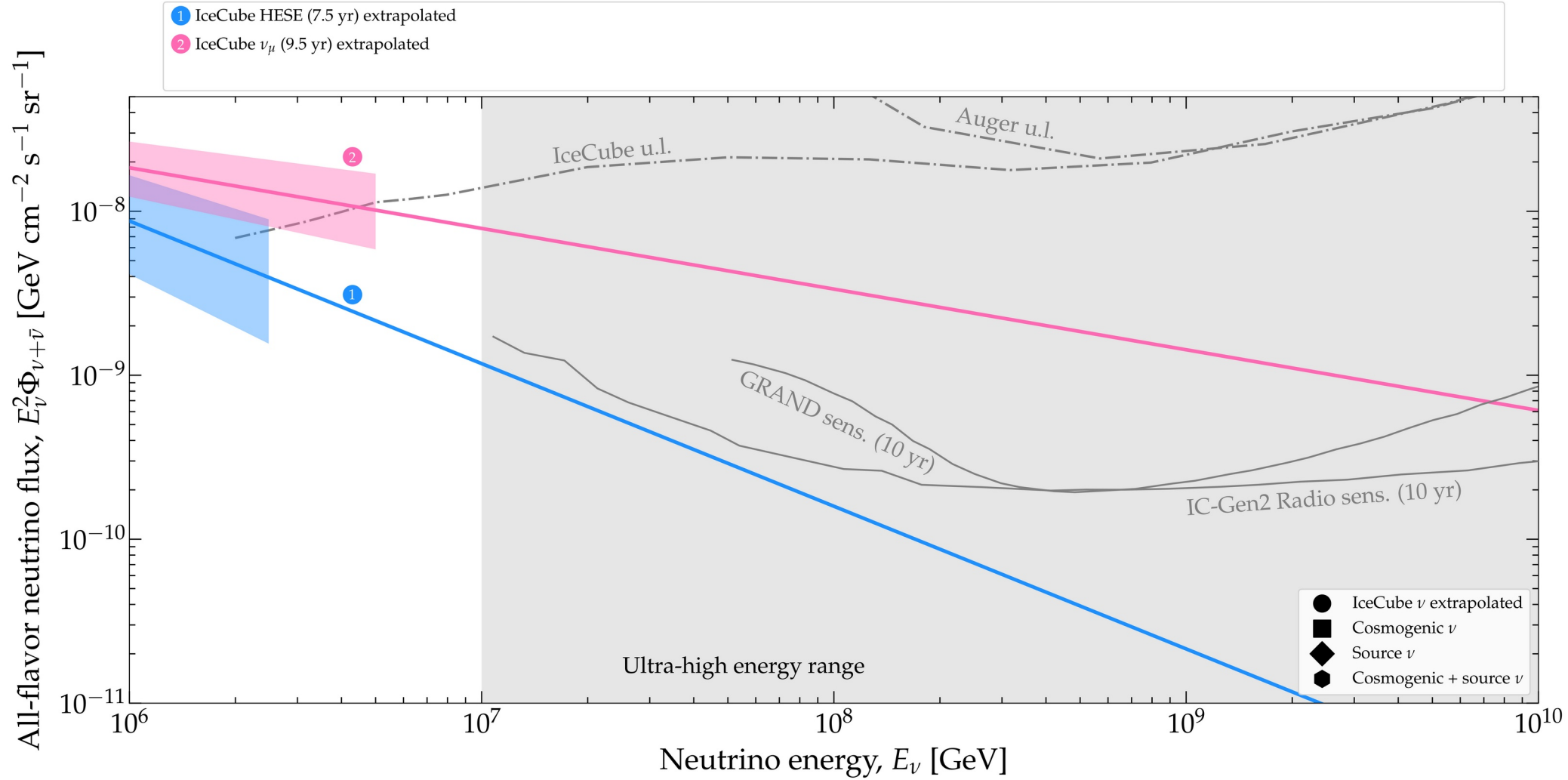
EUSO-SPB design
(UV fluorescence + Cherenkov),
augmented with PUEO-like
radio antennas

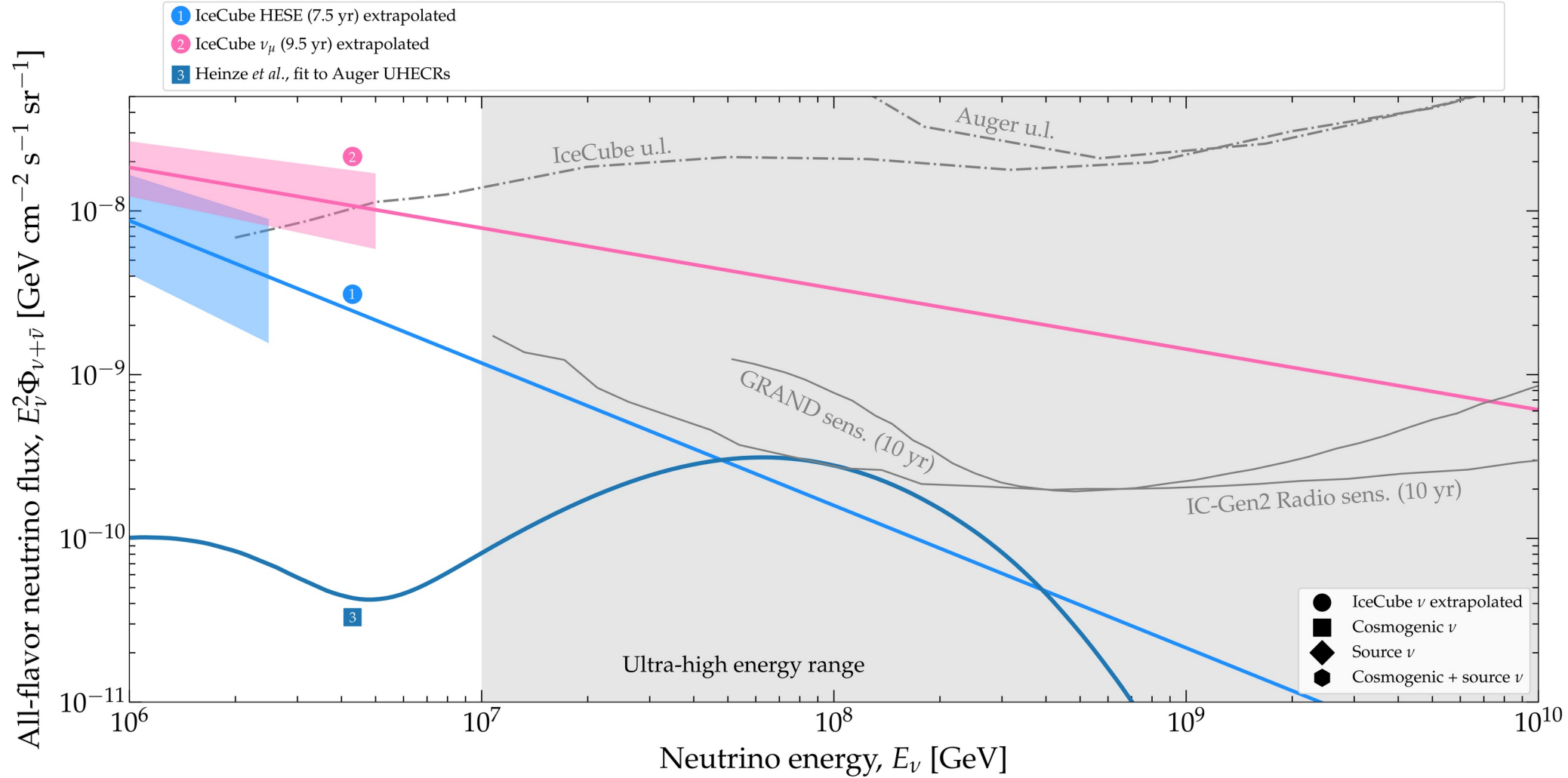


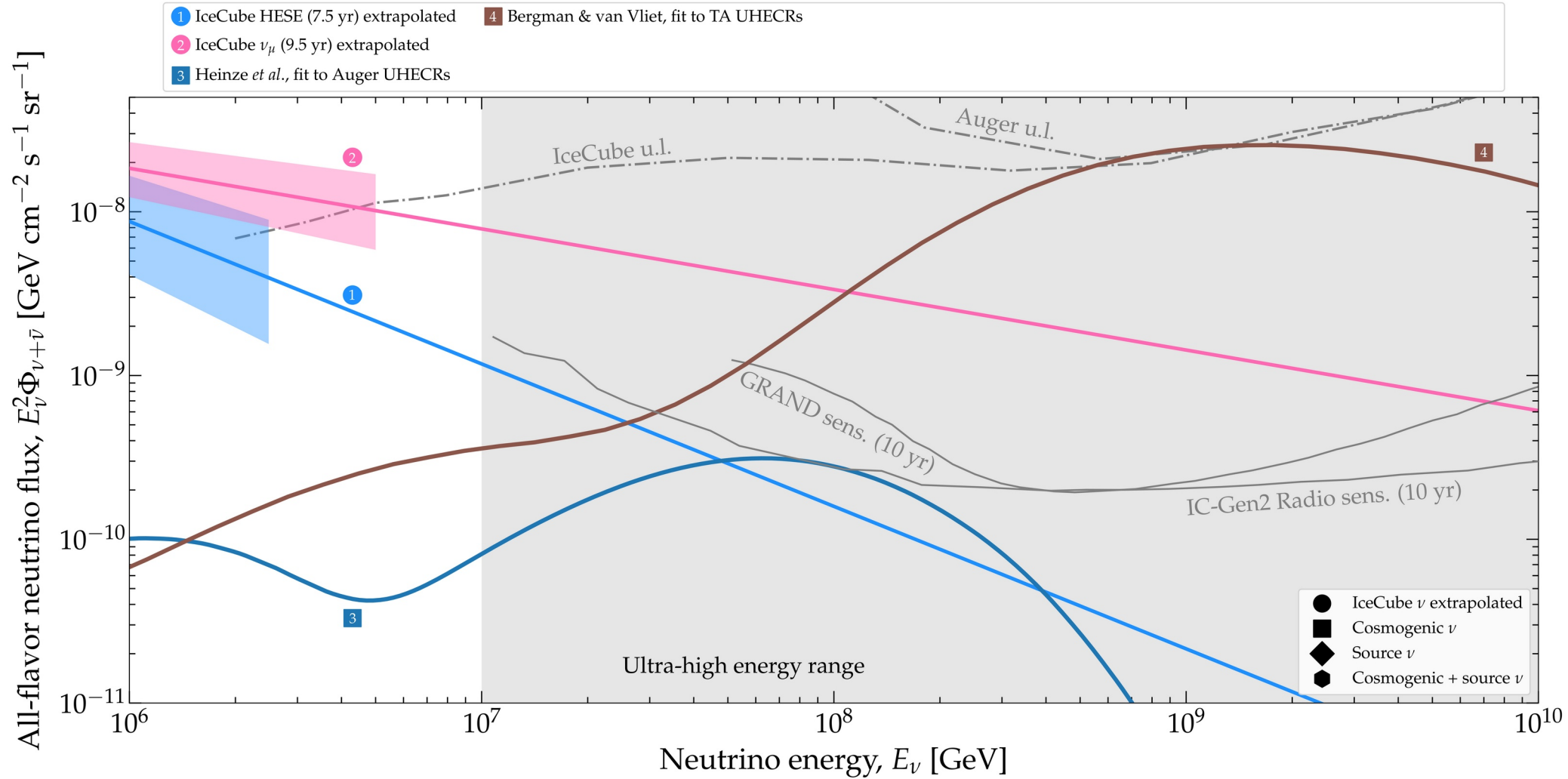


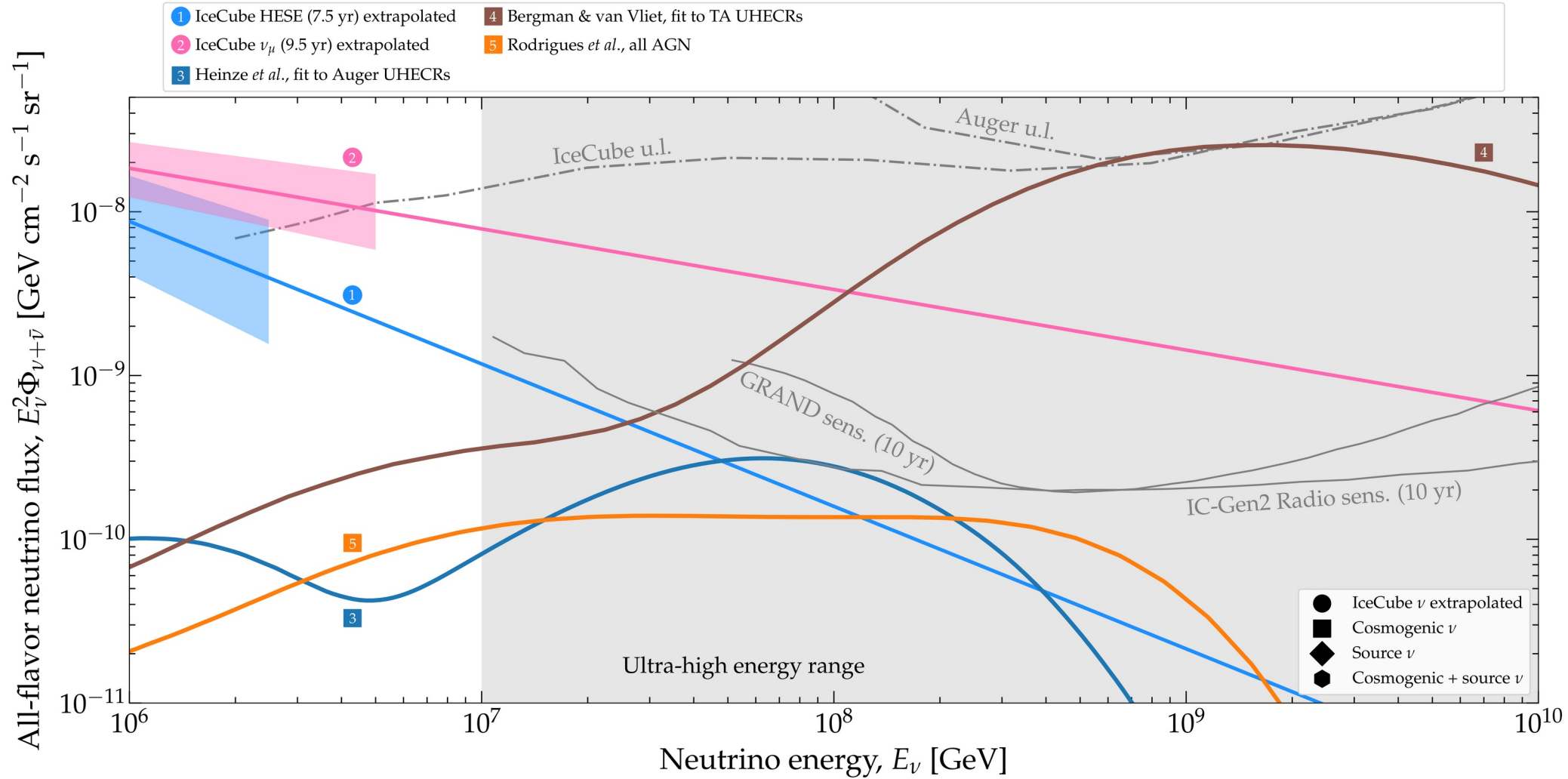


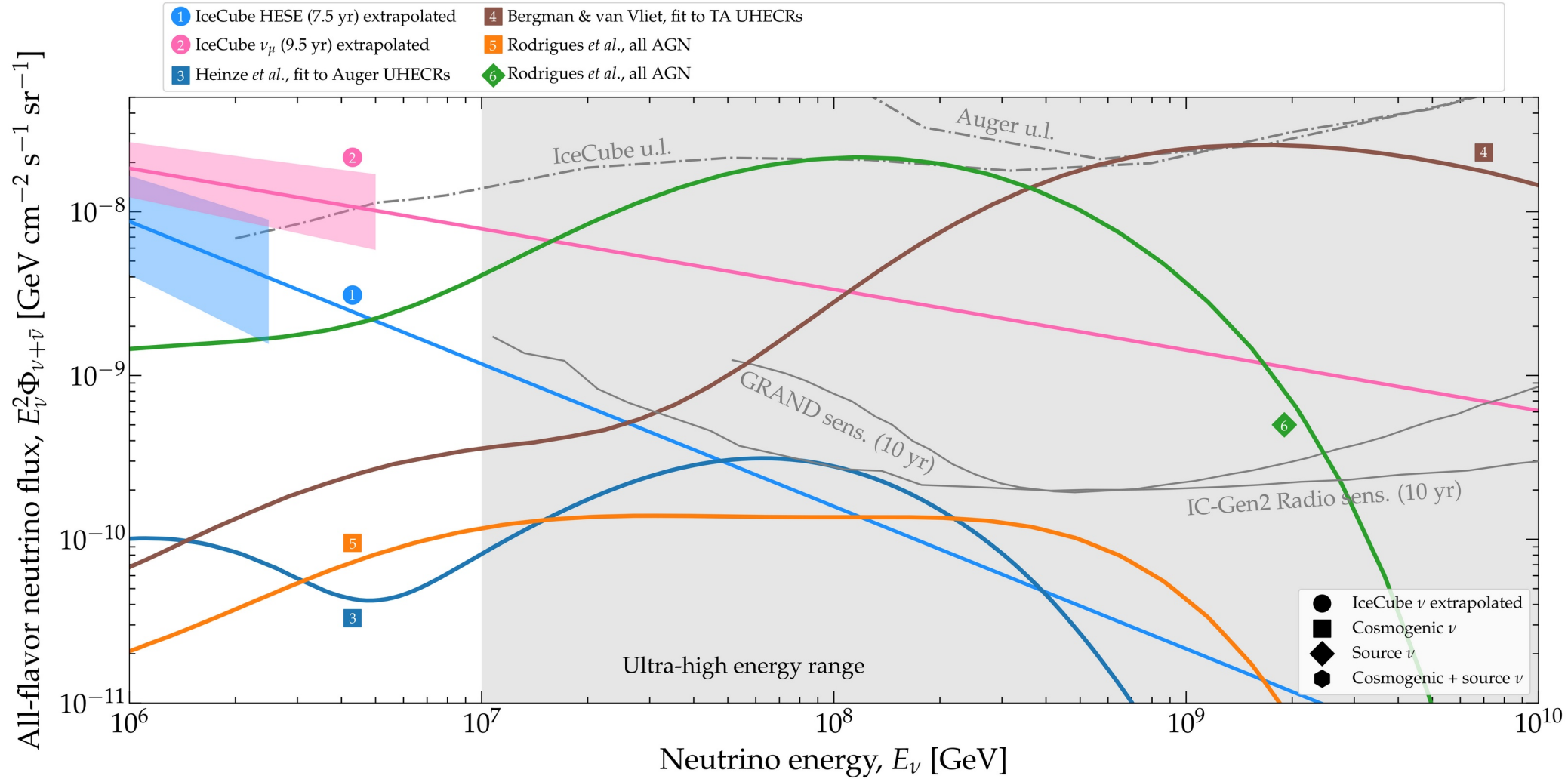


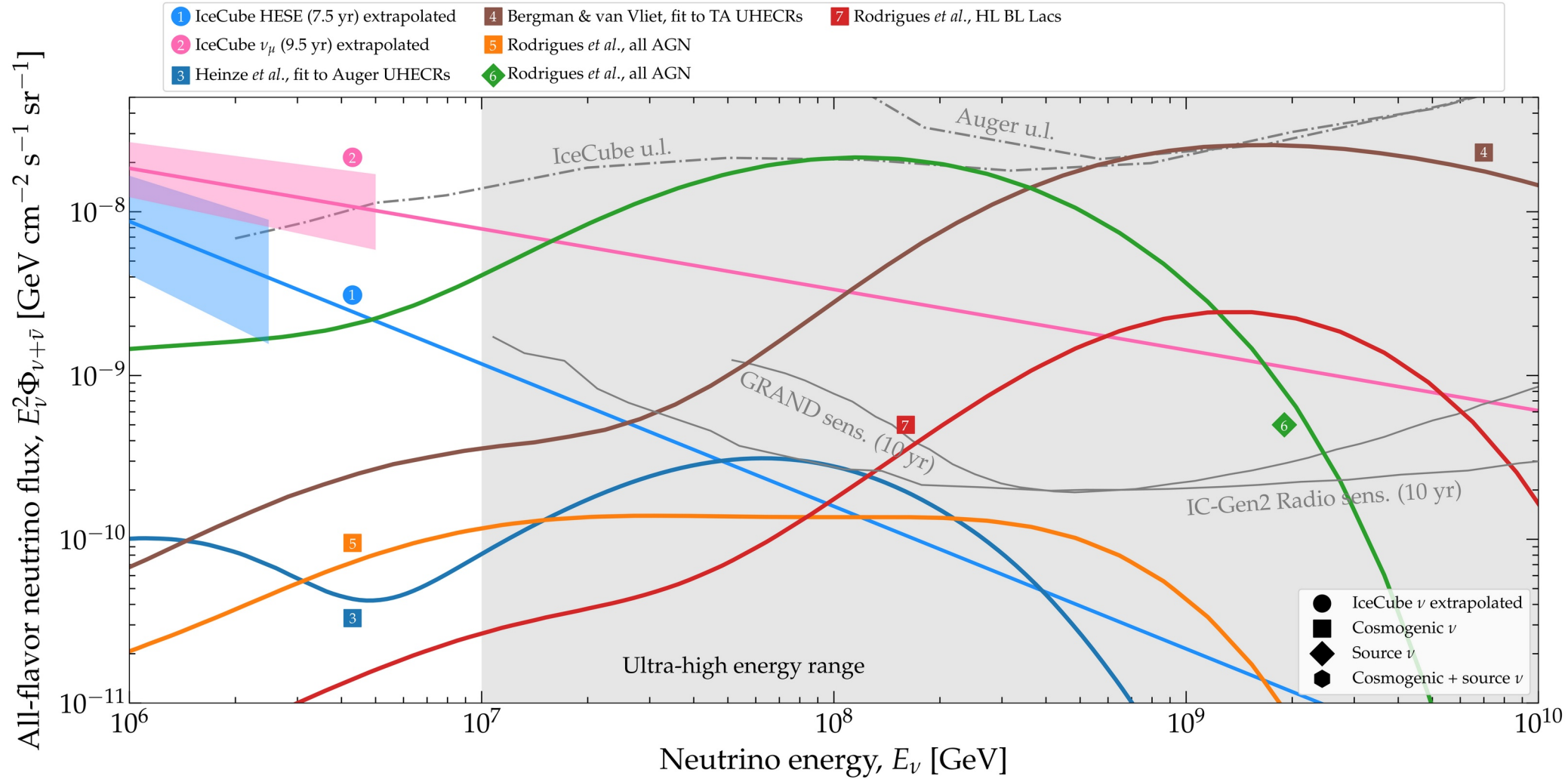


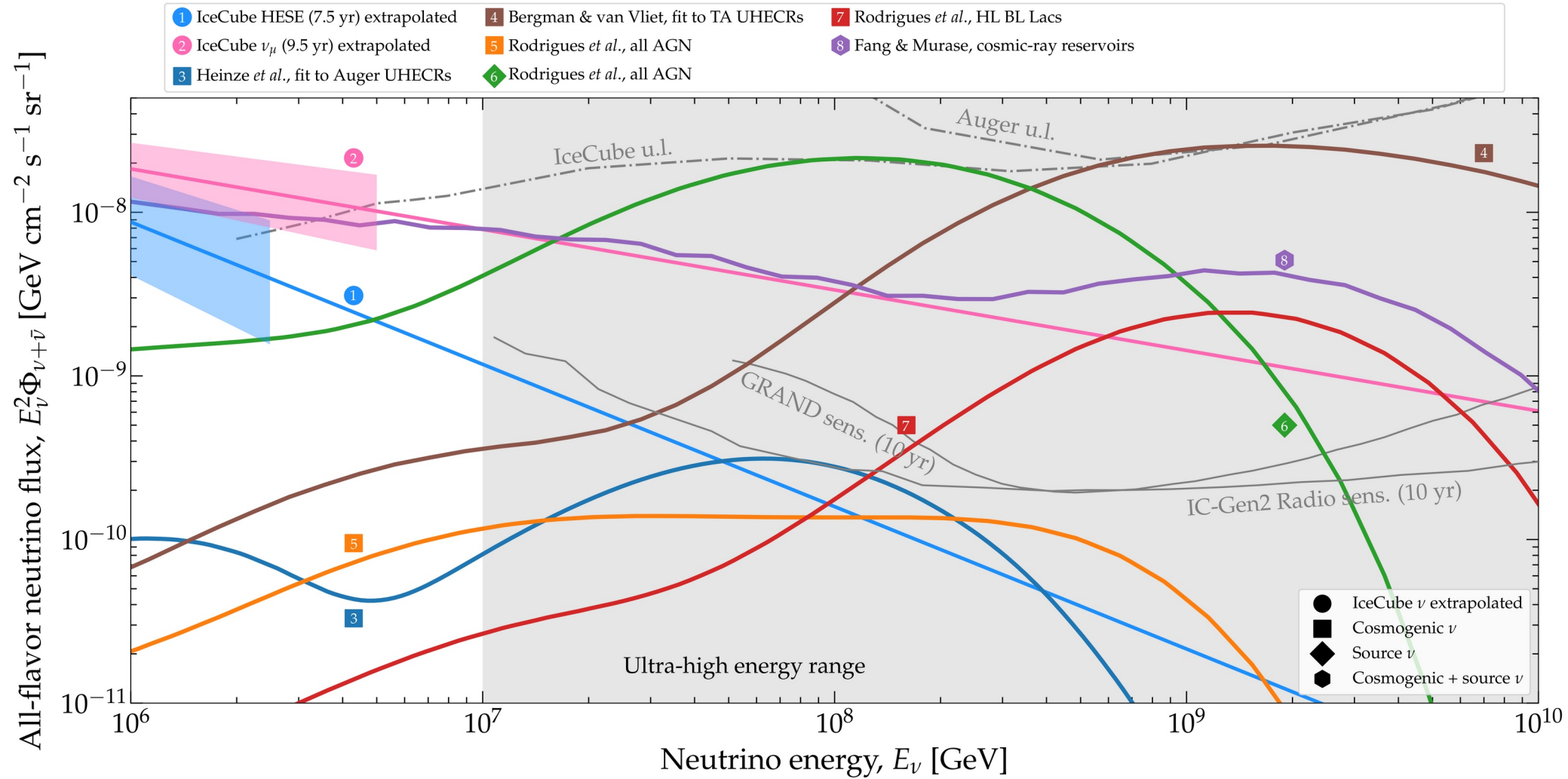


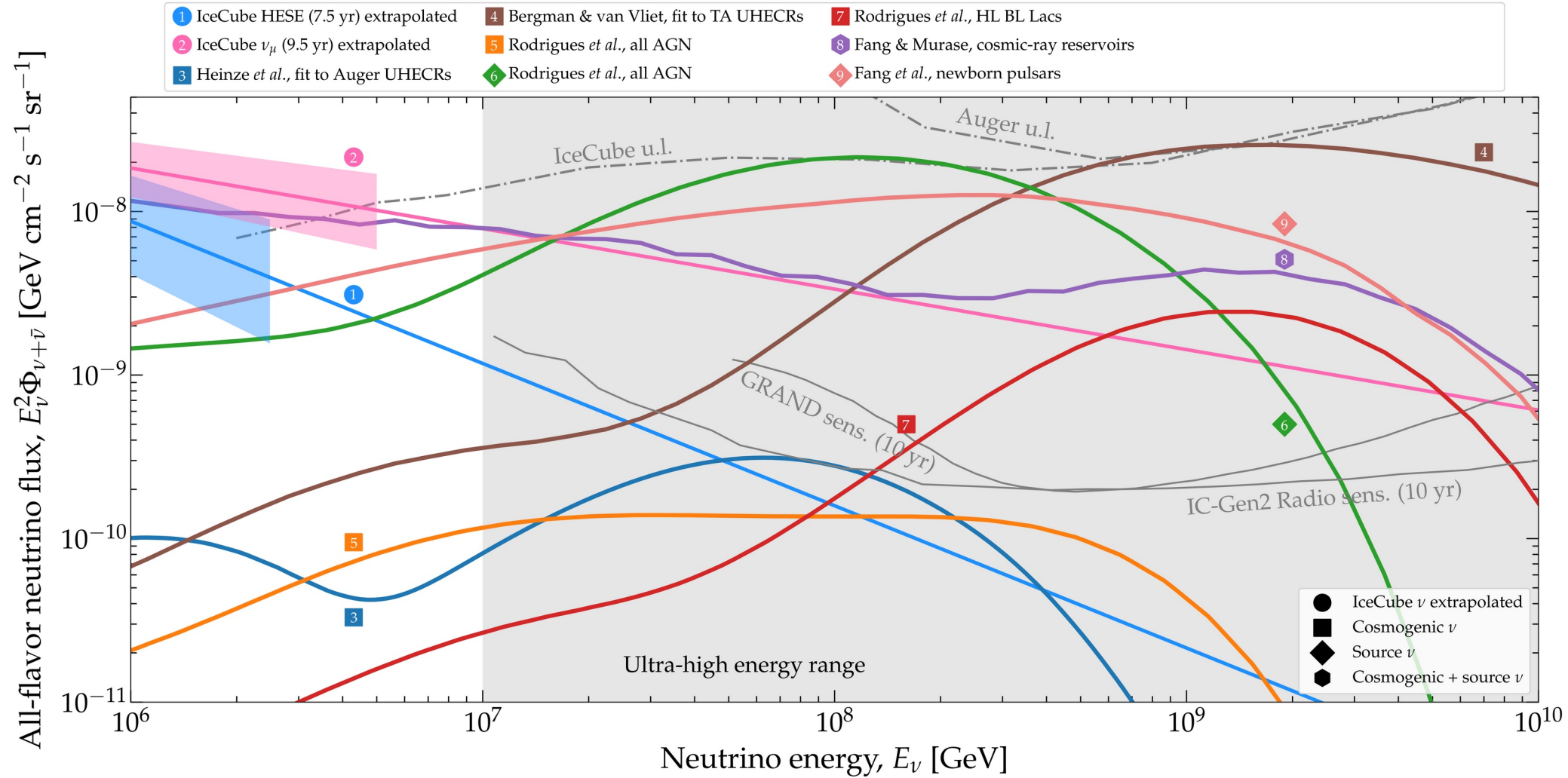


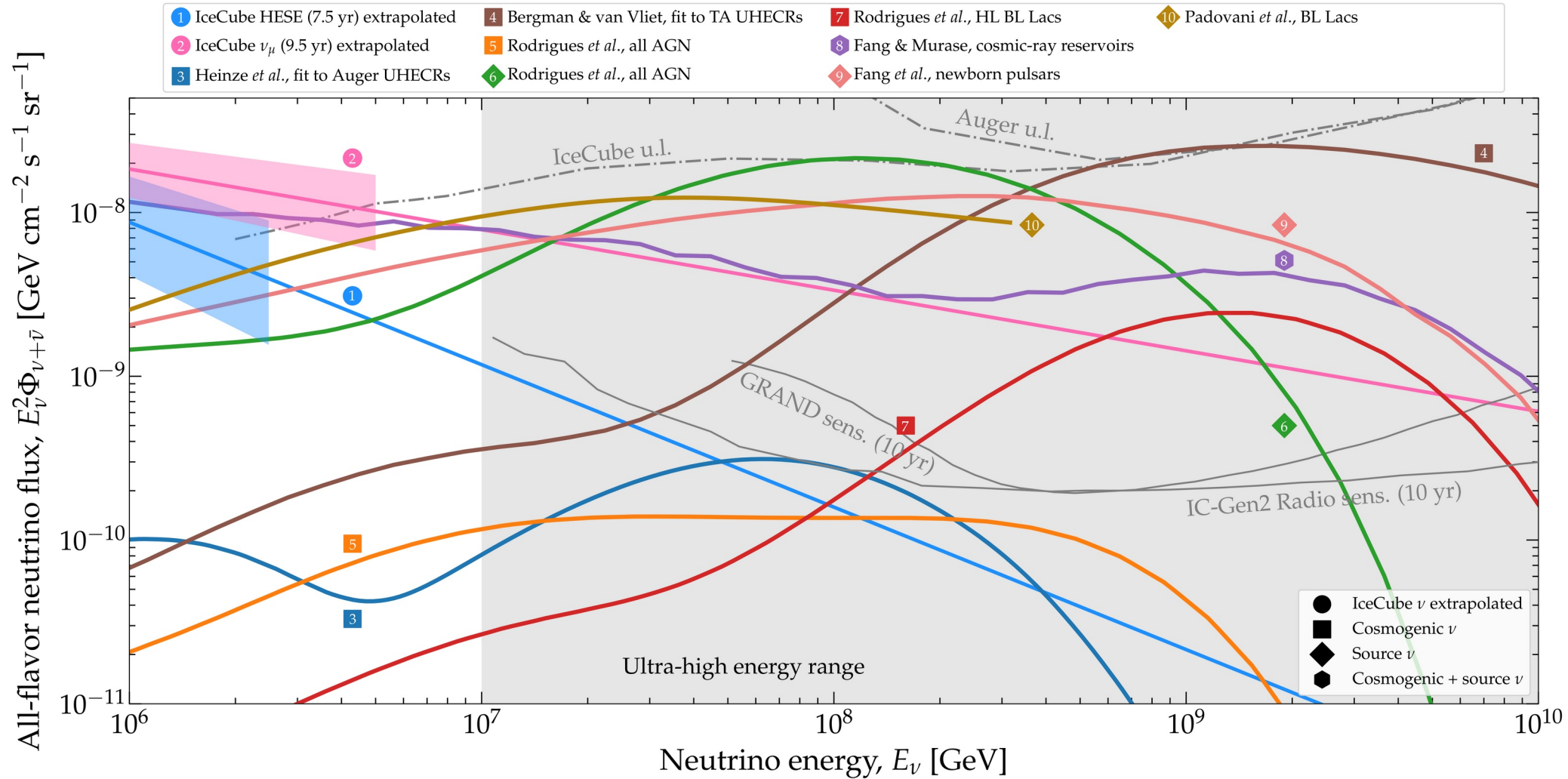


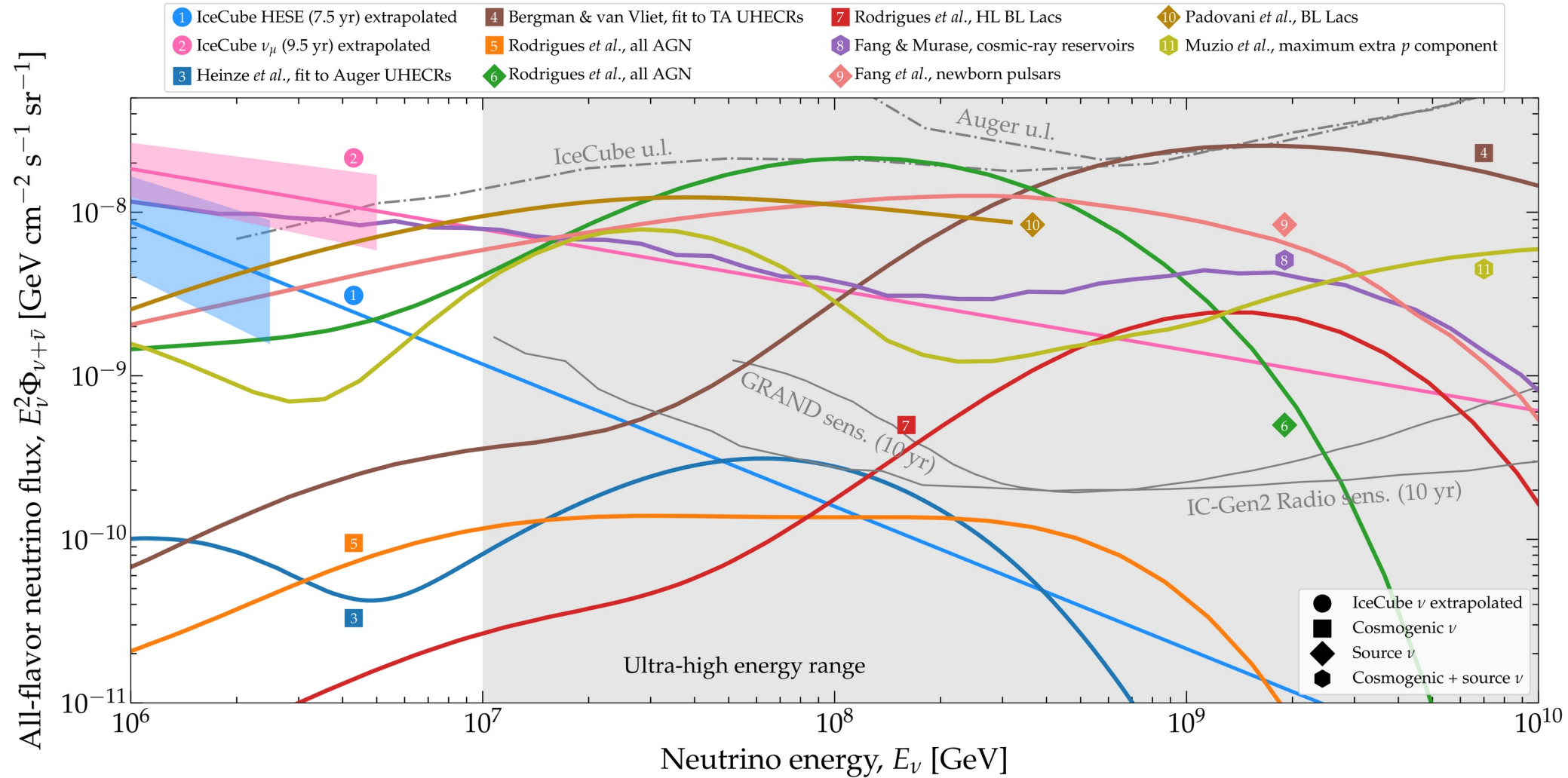


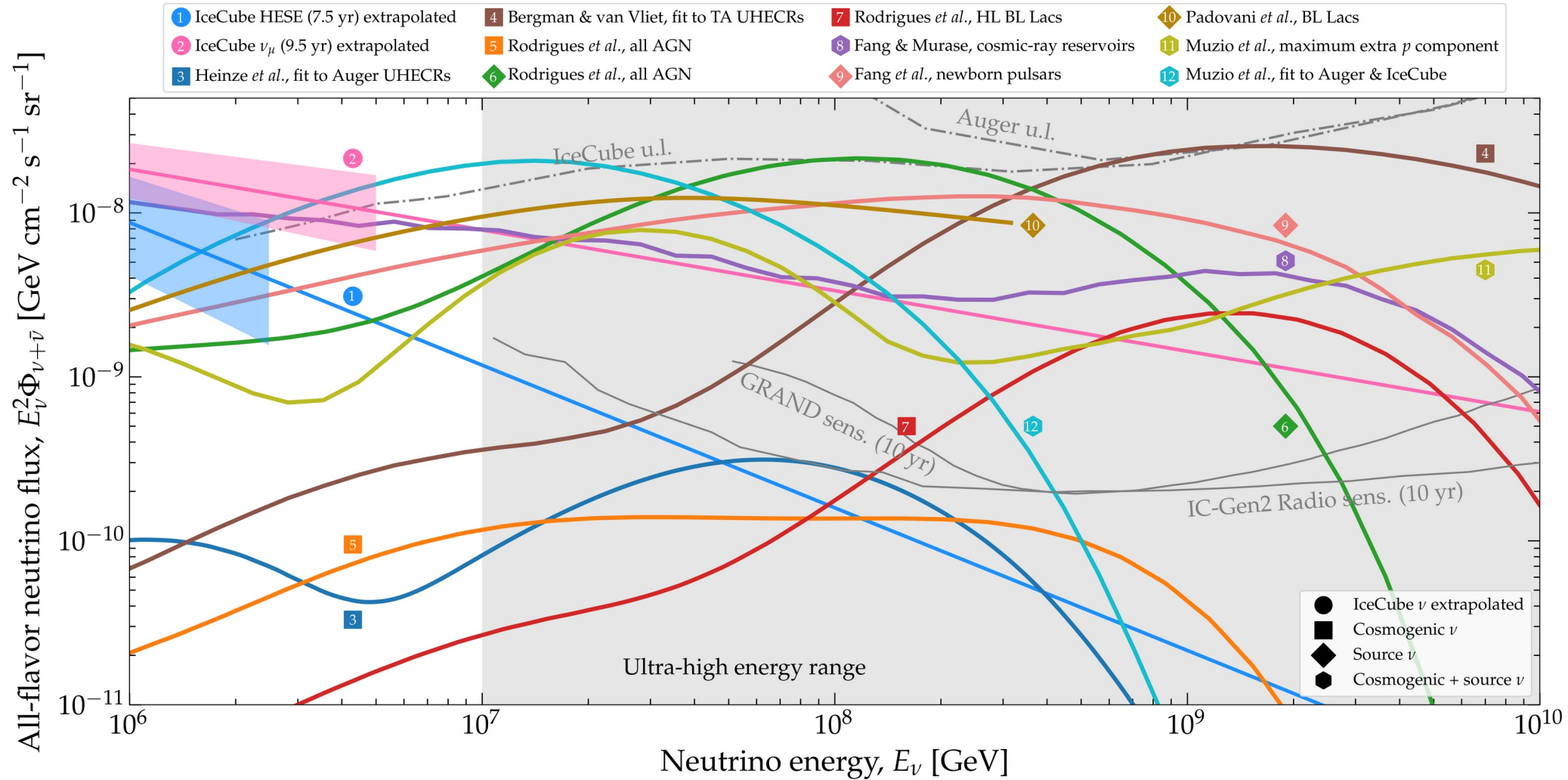


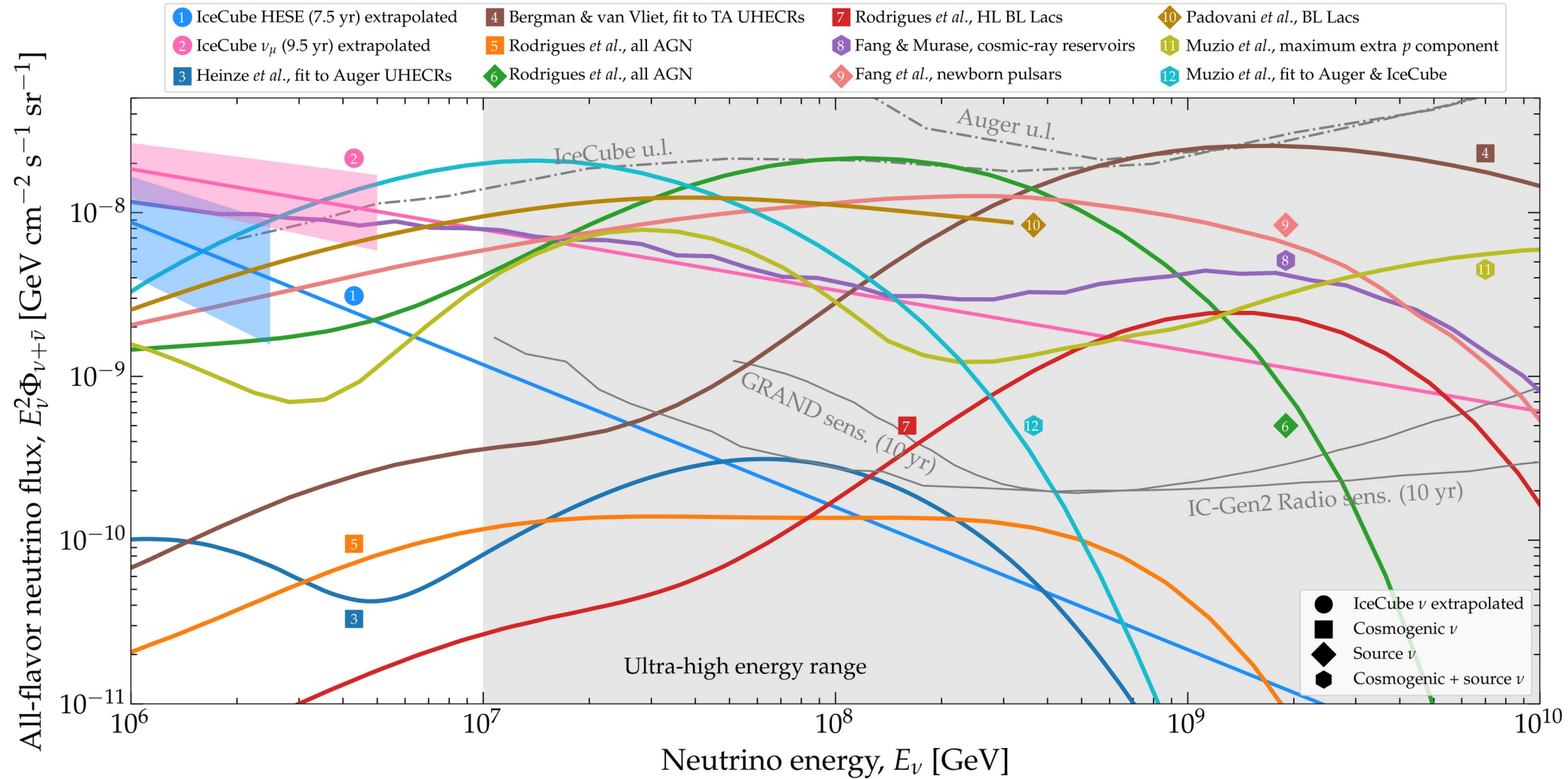




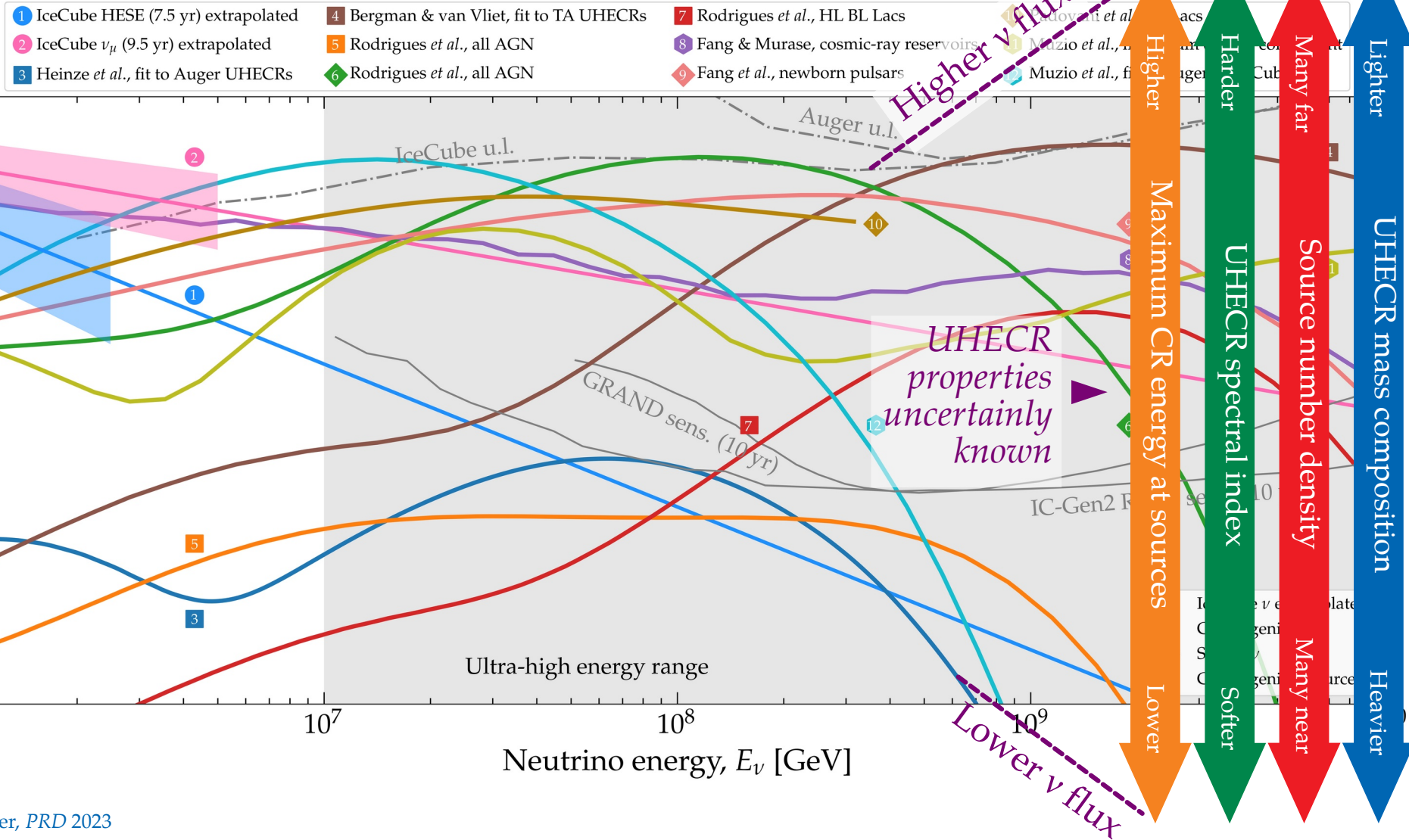


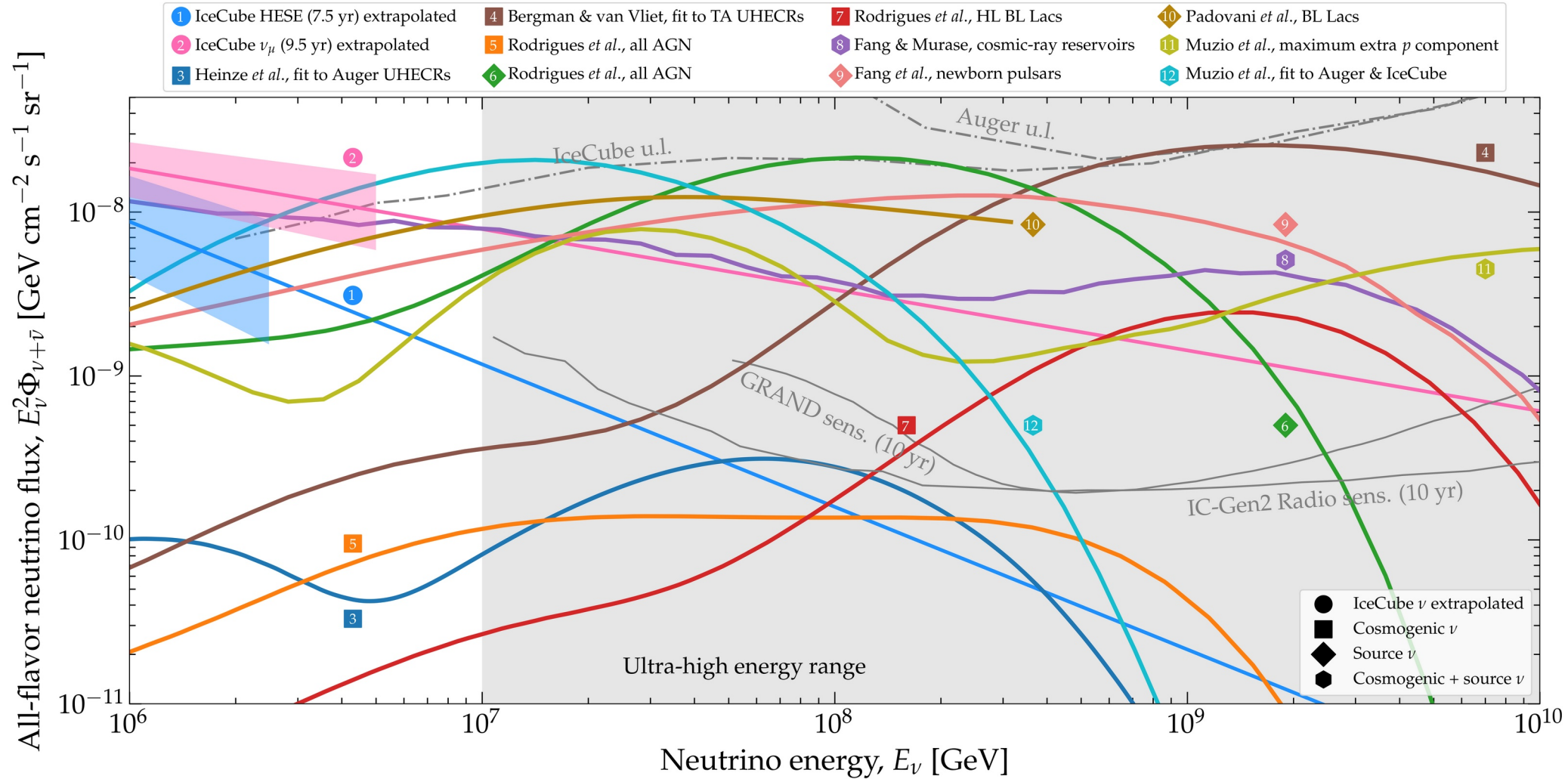






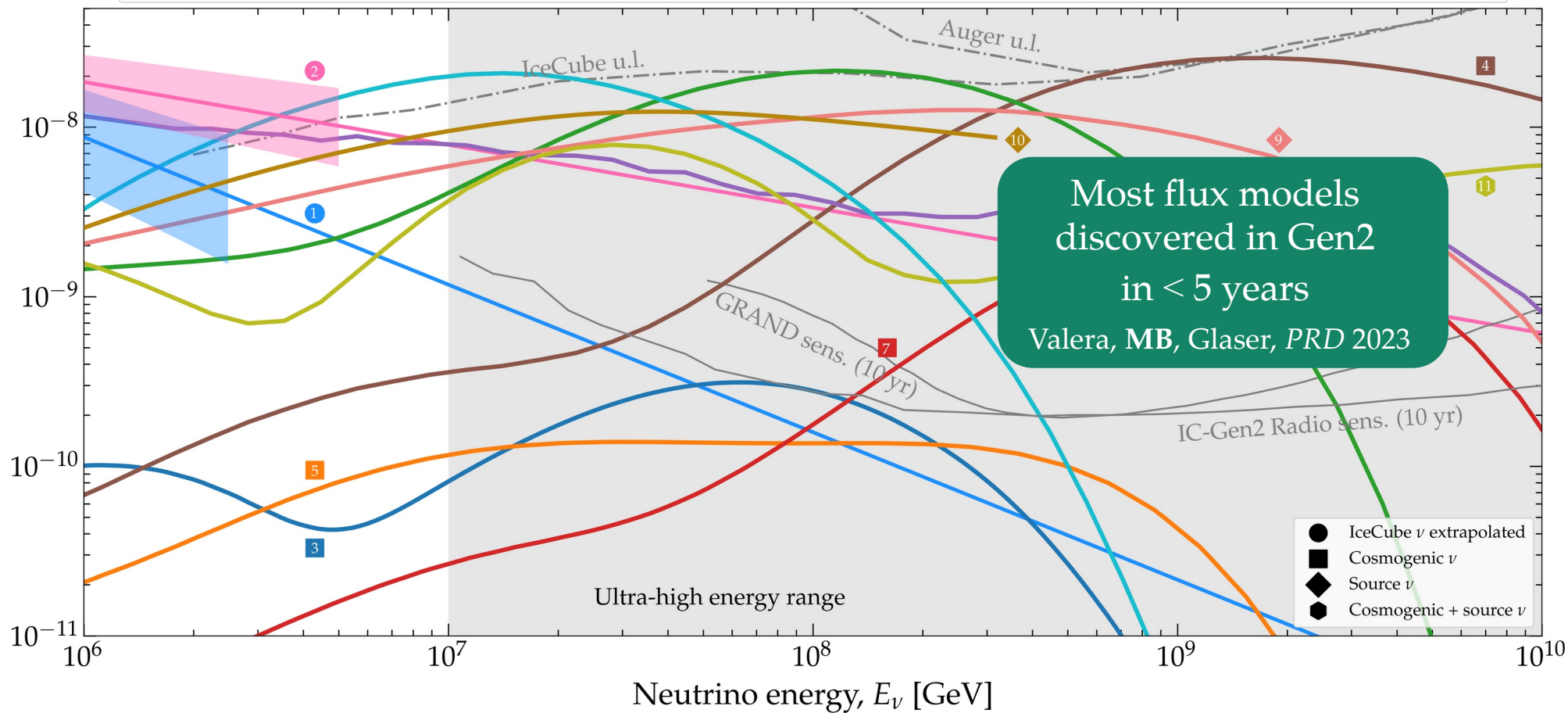
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [$\text{GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$]

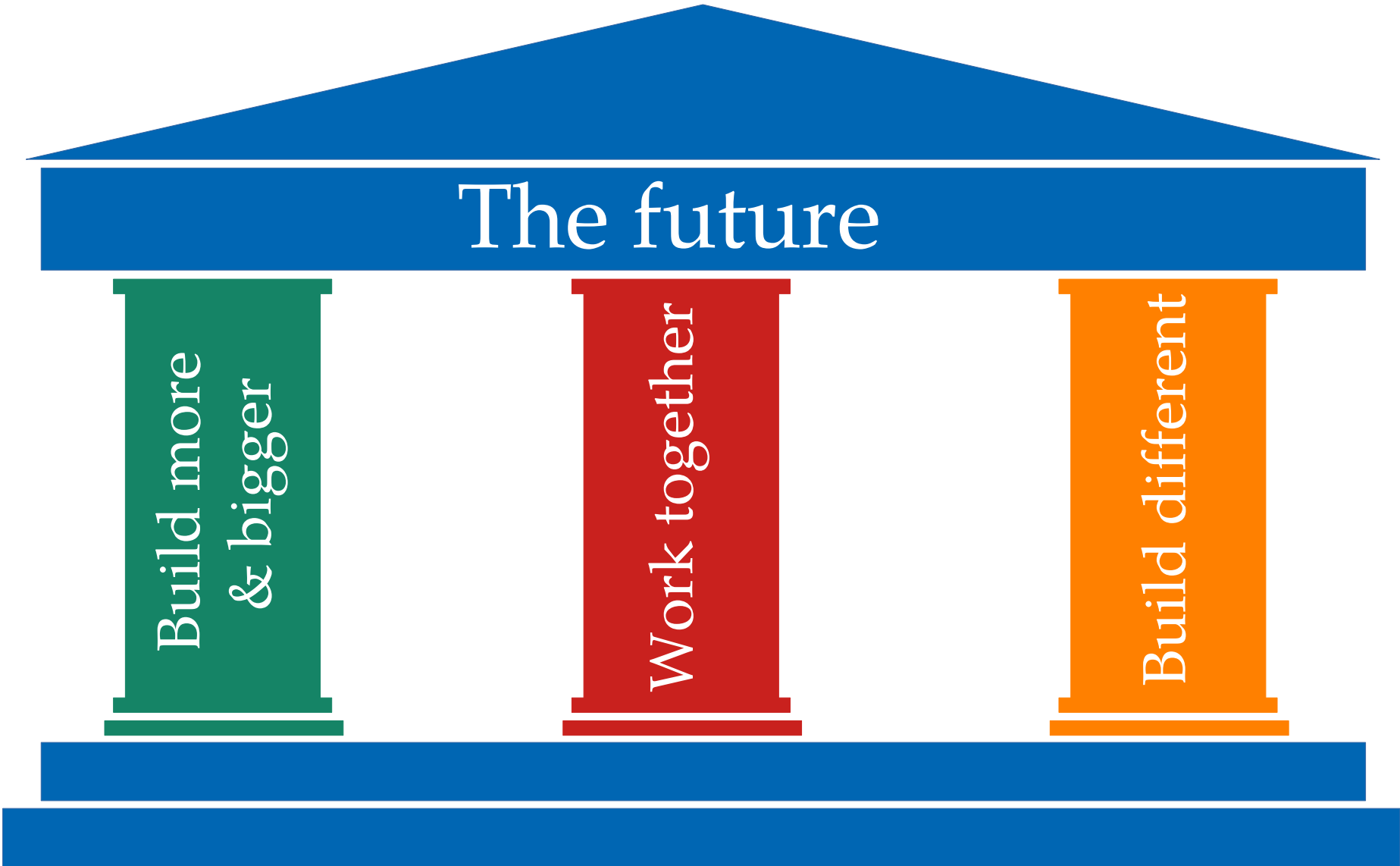




All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [$\text{GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$]

- | | | | |
|--|---|--|--|
| 1 IceCube HESE (7.5 yr) extrapolated | 4 Bergman & van Vliet, fit to TA UHECRs | 7 Rodrigues <i>et al.</i> , HL BL Lacs | 10 Padovani <i>et al.</i> , BL Lacs |
| 2 IceCube ν_μ (9.5 yr) extrapolated | 5 Rodrigues <i>et al.</i> , all AGN | 8 Fang & Murase, cosmic-ray reservoirs | 11 Muzio <i>et al.</i> , maximum extra p component |
| 3 Heinze <i>et al.</i> , fit to Auger UHECRs | 6 Rodrigues <i>et al.</i> , all AGN | 9 Fang <i>et al.</i> , newborn pulsars | 12 Muzio <i>et al.</i> , fit to Auger & IceCube |





The future

Build more
& bigger

Work together

Build different

Open questions that call for cooperation

What rate of transient ν sources is IceCube + KM3NeT + Baikal-GVD sensitive to?

[How about the future global neutrino network, a la PLE ν UM?]

What are the dominant steady-state sources of high-energy neutrinos?

[Are they Seyferts, like NGC 1068?]

What e.m. observations would help find or understand neutrino sources?

[Do we need new instruments or are the ones we have enough?]

Are the sources of TeV–PeV neutrinos also the sources of UHECRs?

[What UHECR and neutrino detection rate and precision would we need to test this?]

What are the diffuse flux and sources of ultra-high-energy neutrinos (> 100 PeV)?

[What do we learn from this?]

Is there new physics to be discovered in TeV–EeV neutrinos?

[Modified neutrino oscillations? New neutrino interactions? Dark matter? Broken symmetries?]

Thank you!

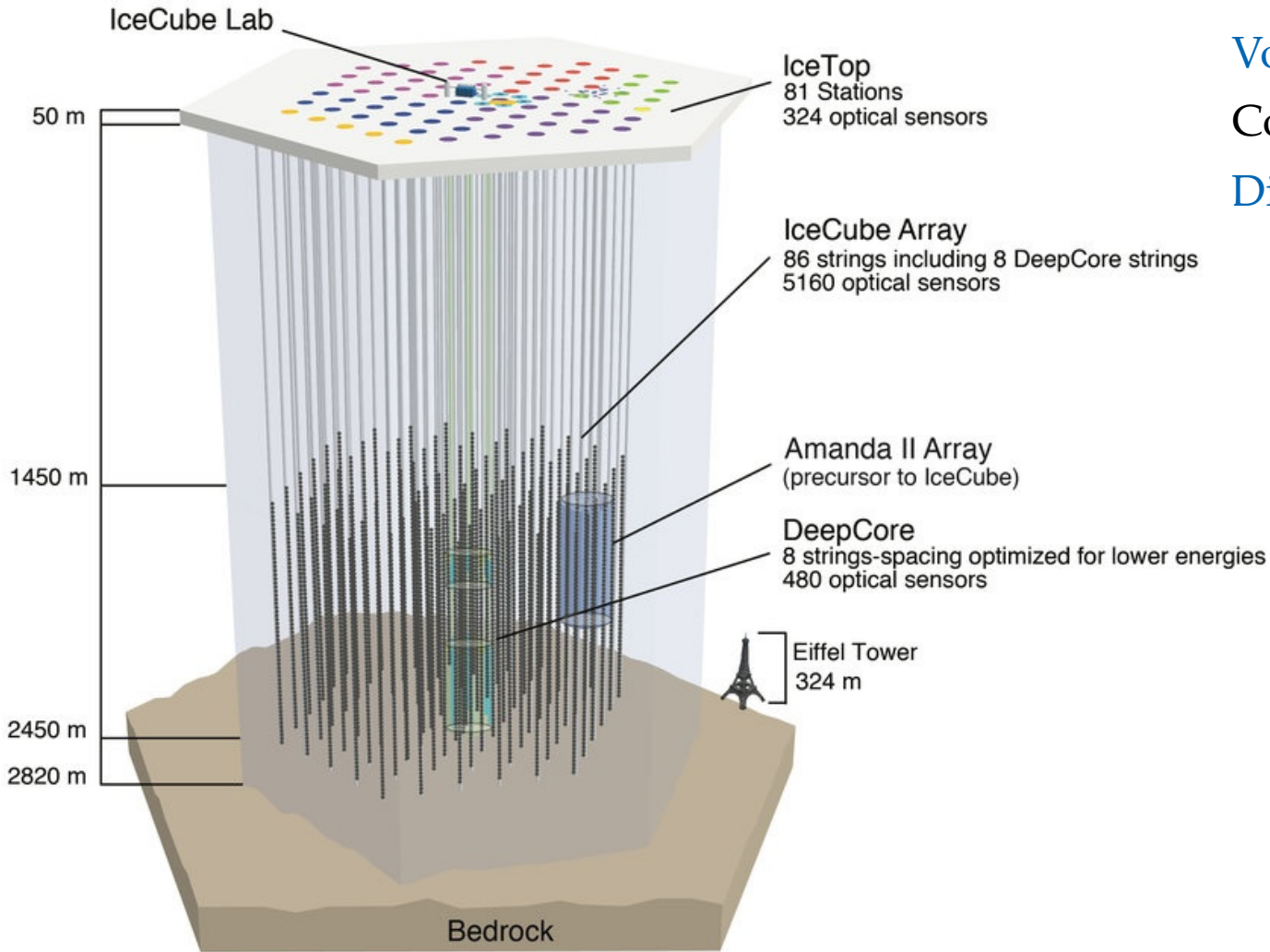
Backup slides

Near the South Pole

Volume $\sim 1 \text{ km}^3$, 1.5–2.5 km deep

Completed in 2011 (86 strings)

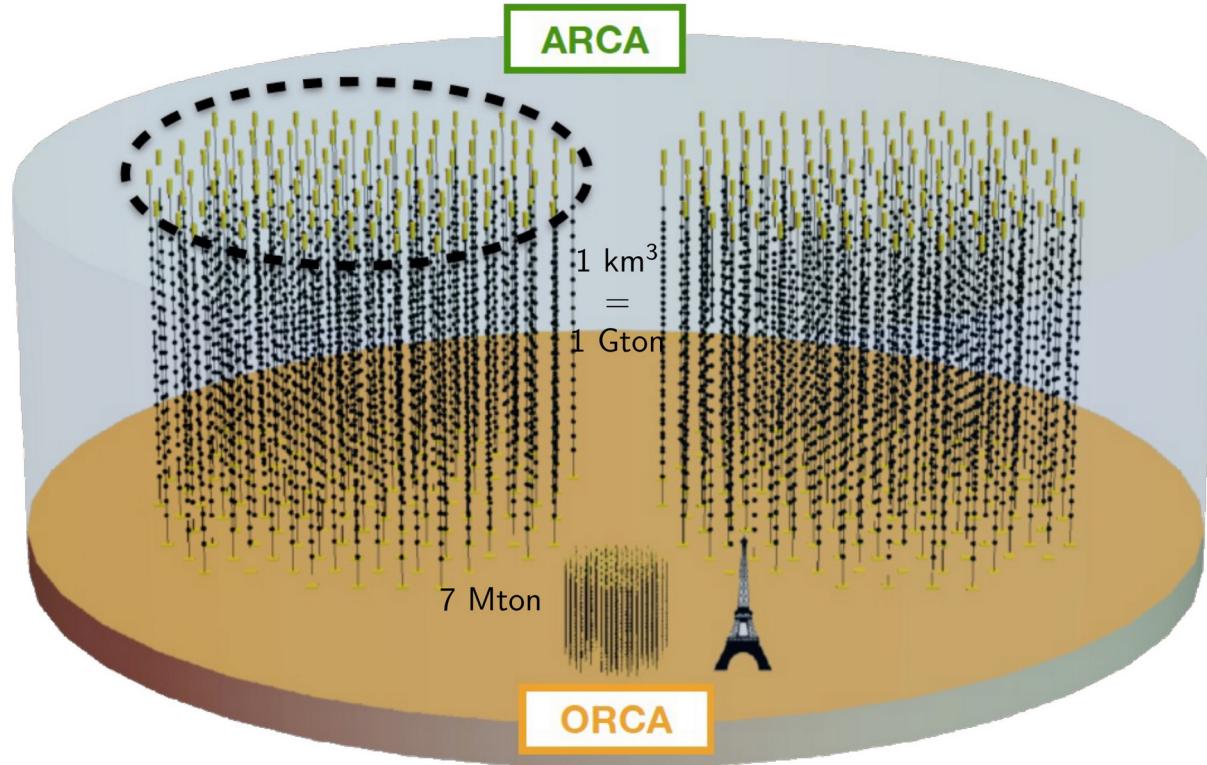
Discovered PeV ν in 2013



Astroparticle Research Mediterranean Sea

[3.5 km deep, Sicily, running since 2015]

Final configuration: $> 1 \text{ km}^3$, 230 strings, 4100+ optical modules • **Today:** 51 strings



Oscillation Research with Cosmics in the Abyss

2.5 km deep, Toulon, running since 2017

Final configuration: 1 km^3 , 115 strings, 2070 optical modules • **Today:** 28 strings

In Lake Baikal, Russia

Long-running succession of
neutrino telescopes (since 1995)

Depths up to ~1.4 km

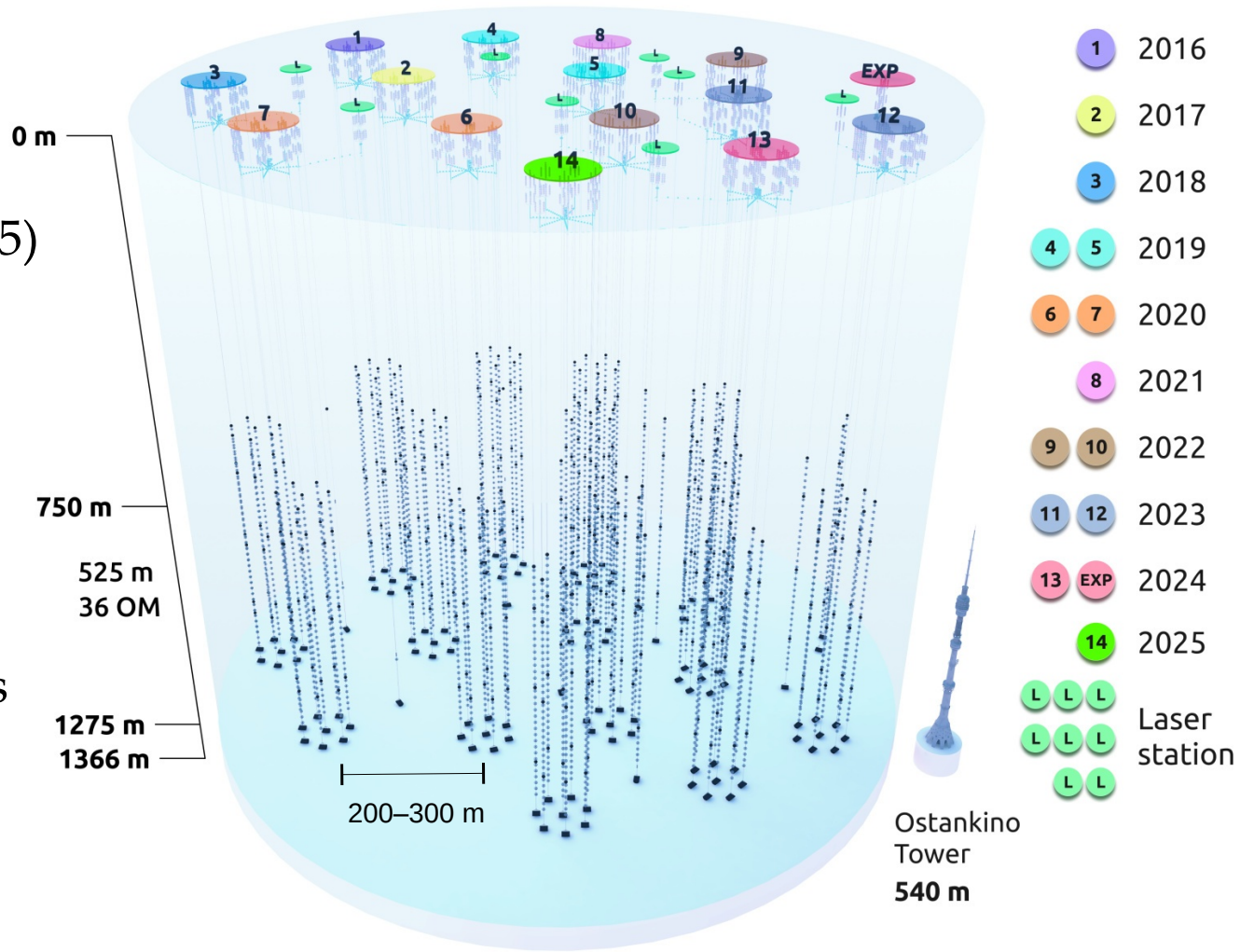
Array of clusters of 8 strings

Today:

~0.7 km³, 14 clusters, 4212 OMs

Final configuration (in ~3 yr):

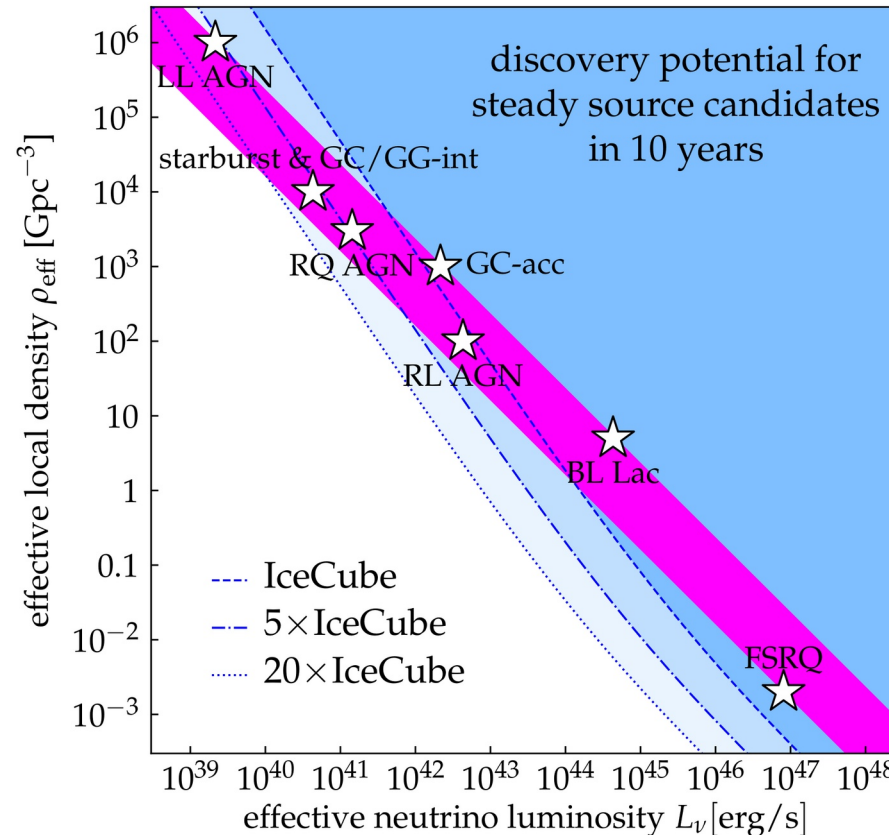
~1 km³, 90 strings, 6000+ OMs



Source discovery potential: today and in the future

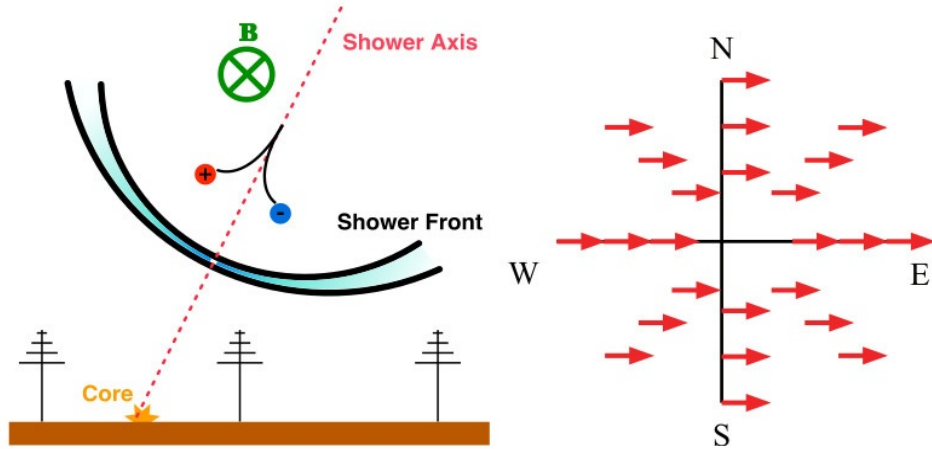
■ Accounts for the observed diffuse ν flux (lower/upper edge: rapid/no redshift evolution)

Closest source with $E^2 \phi_{\nu_\mu + \bar{\nu}_\mu} = 10^{-9} \text{ GeV cm}^{-2} \text{ s}^{-1}$



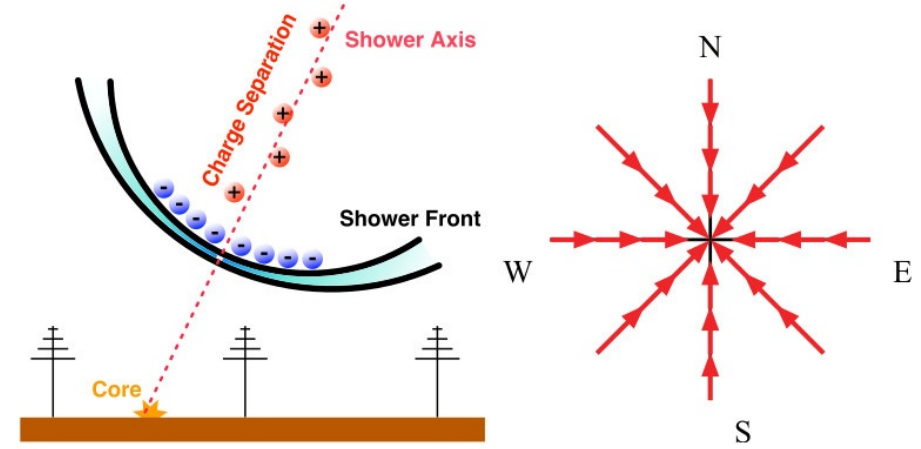
Radio emission: geomagnetic and Askaryan

Geomagnetic



- ▶ Time-varying transverse current
- ▶ Linearly polarized parallel to Lorentz force
- ▶ Dominant in air showers

Askaryan



- ▶ Time-varying negative-charge ~20% excess
- ▶ Linearly polarized towards axis
- ▶ Sub-dominant in air showers

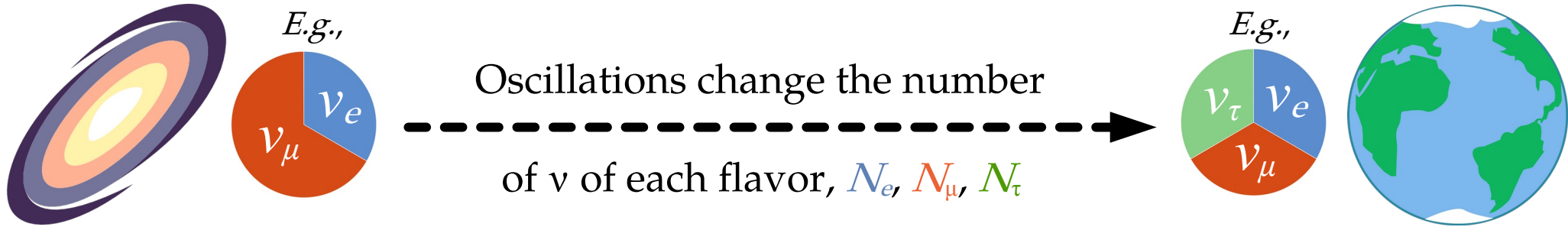
Figures by H. Schoorlemmer and K. D. de Vries

Precision in flavor

Astrophysical sources

Earth

Up to a few Gpc



Different production mechanisms yield different flavor ratios:

$$(f_{e,S}, f_{\mu,S}, f_{\tau,S}) \equiv (N_{e,S}, N_{\mu,S}, N_{\tau,S}) / N_{\text{tot}}$$

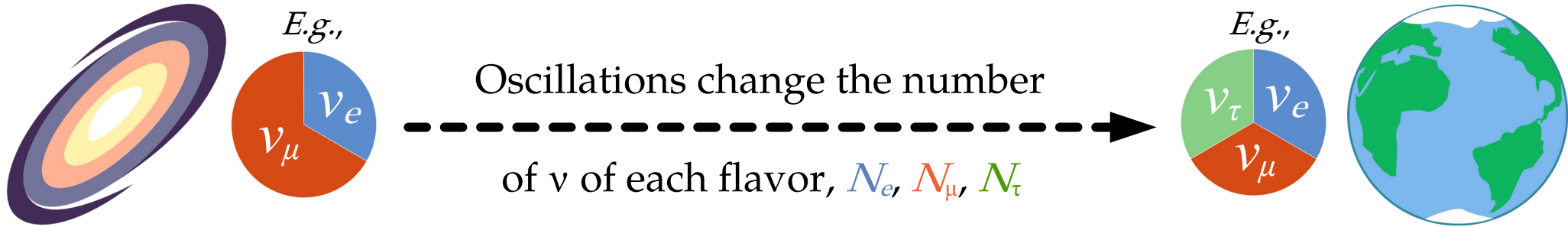
Flavor ratios at Earth ($\alpha = e, \mu, \tau$):

$$f_{\alpha,\oplus} = \sum_{\beta=e,\mu,\tau} P_{\nu_\beta \rightarrow \nu_\alpha} f_{\beta,S}$$

Astrophysical sources

Earth

Up to a few Gpc



Different production mechanisms yield different flavor ratios:

$$(f_{e,S}, f_{\mu,S}, f_{\tau,S}) \equiv (N_{e,S}, N_{\mu,S}, N_{\tau,S}) / N_{\text{tot}}$$

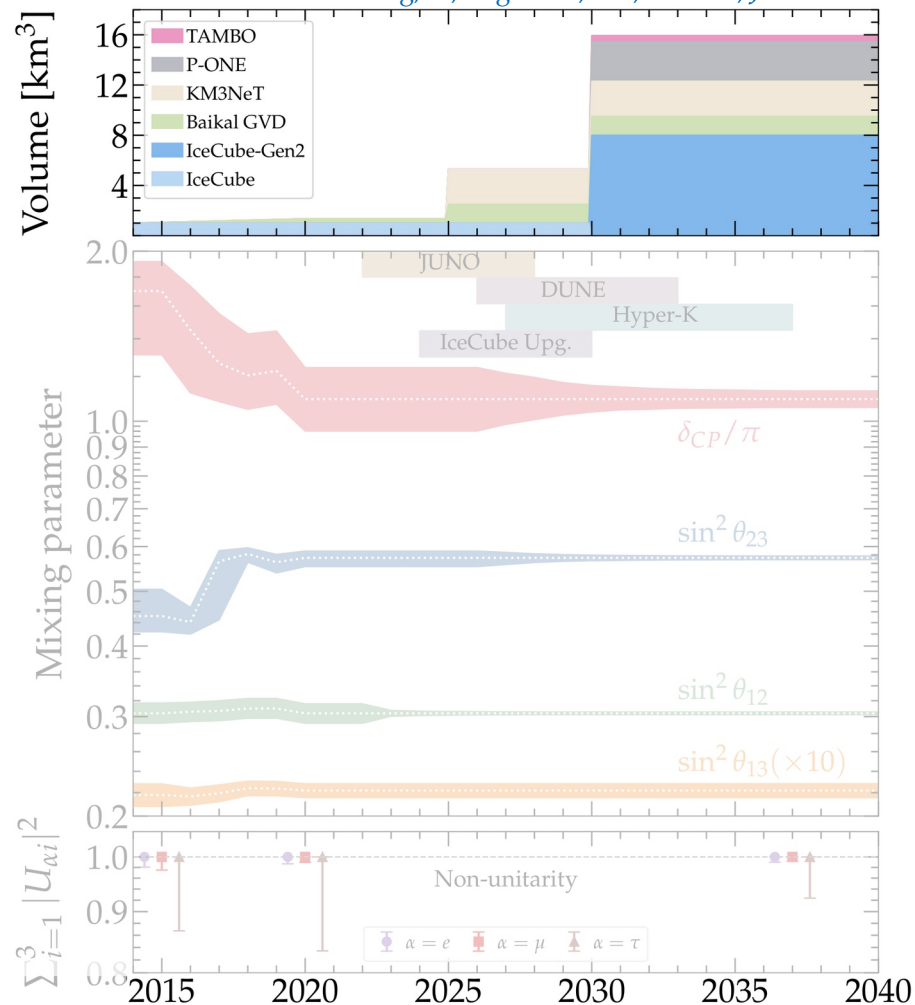
Flavor ratios at Earth ($\alpha = e, \mu, \tau$):

$$f_{\alpha,\oplus} = \sum_{\beta=e,\mu,\tau} P_{\nu_\beta \rightarrow \nu_\alpha} f_{\beta,S}$$

Standard oscillations
or
new physics

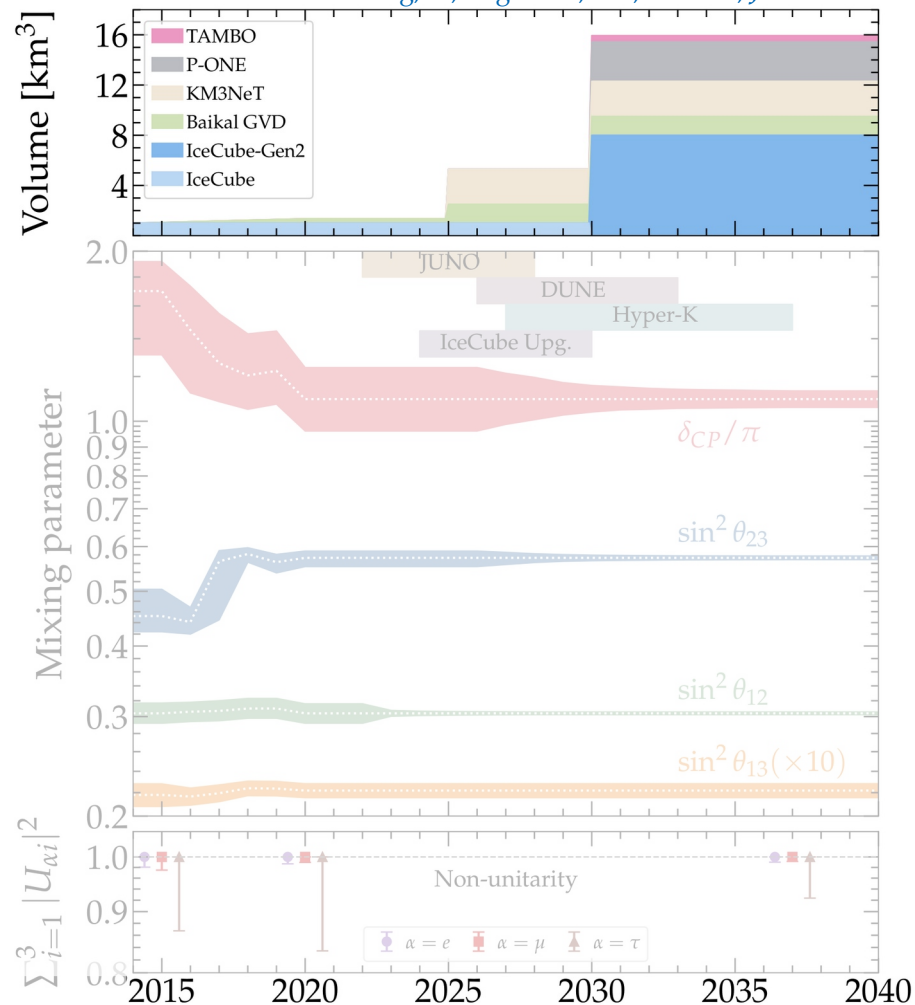
Measuring flavor composition: 2015–2040

Song, Li, Argüelles, MB, Vincent, *JCAP*2021



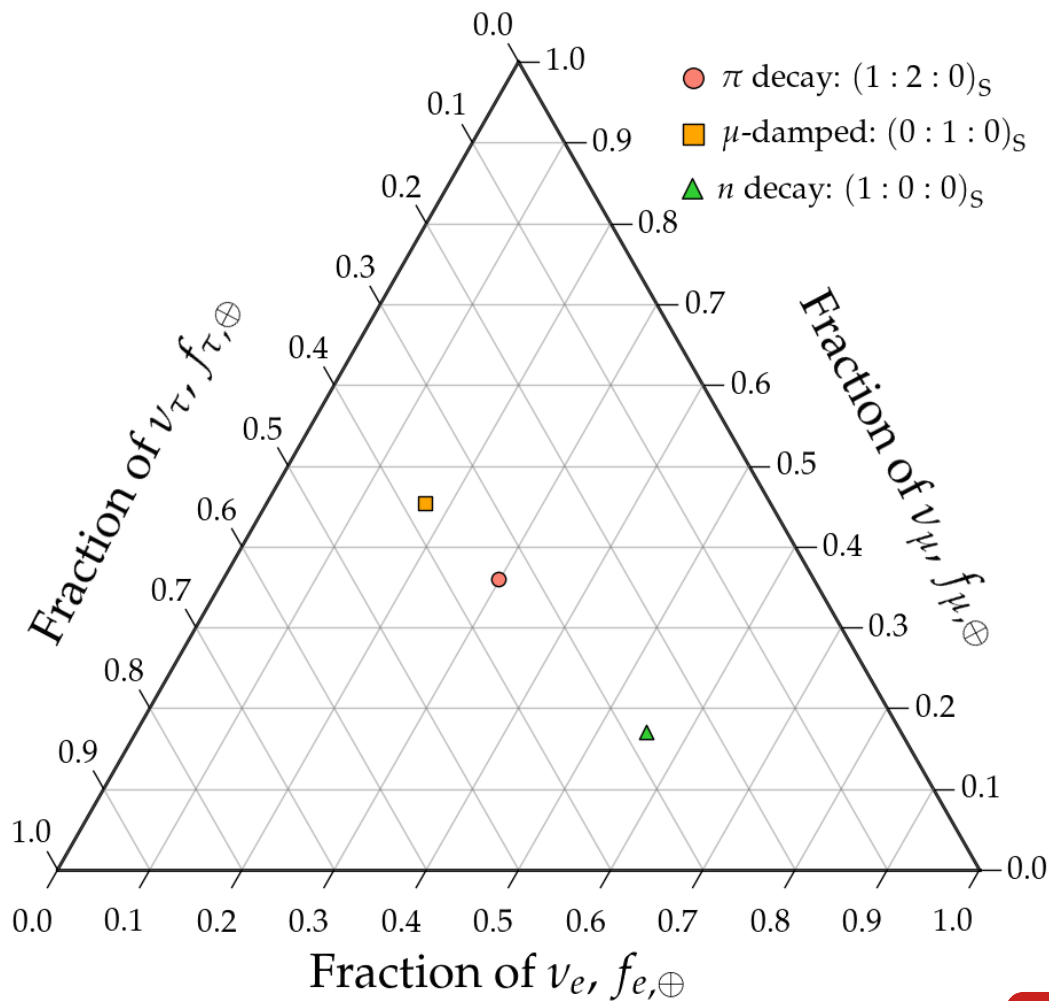
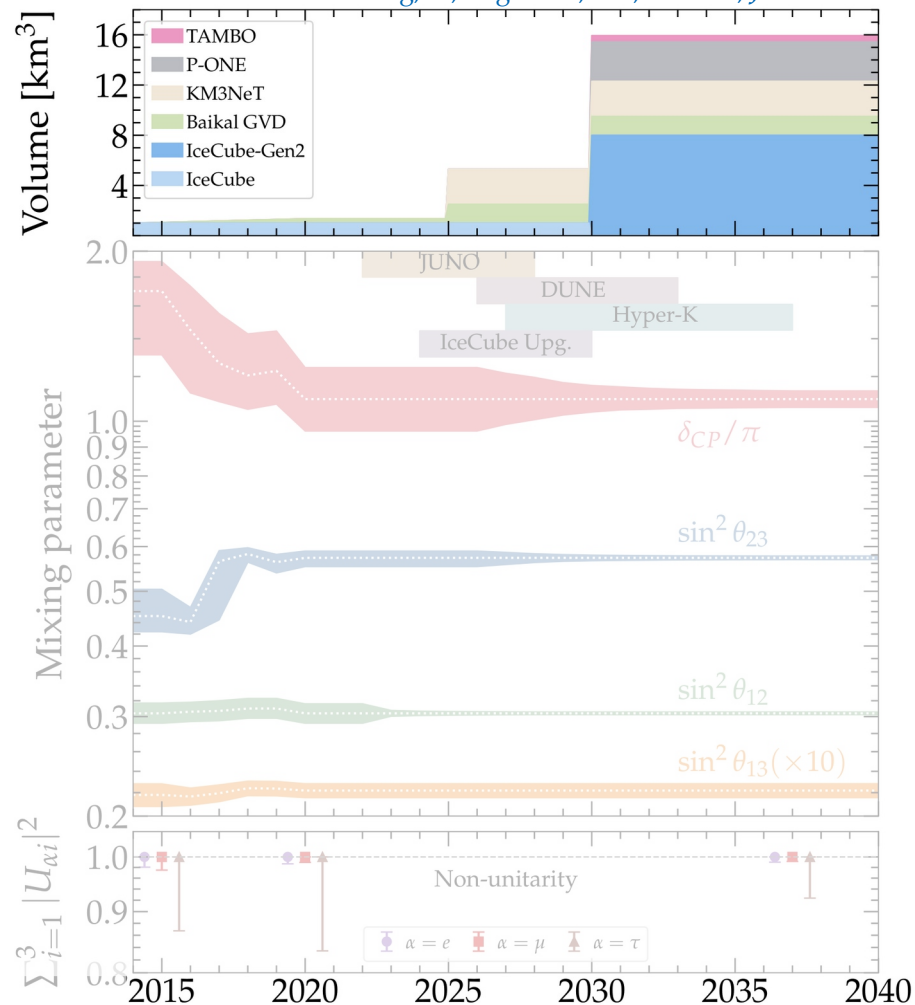
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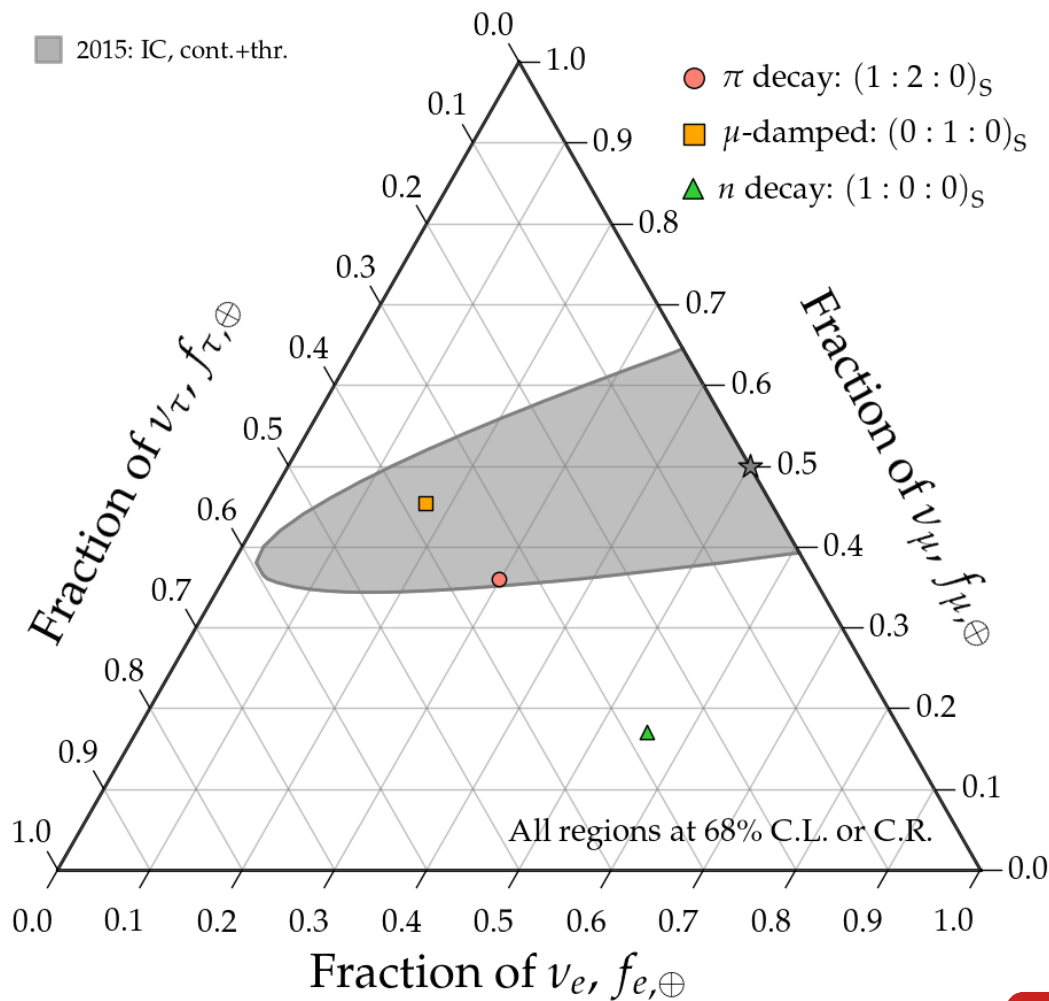
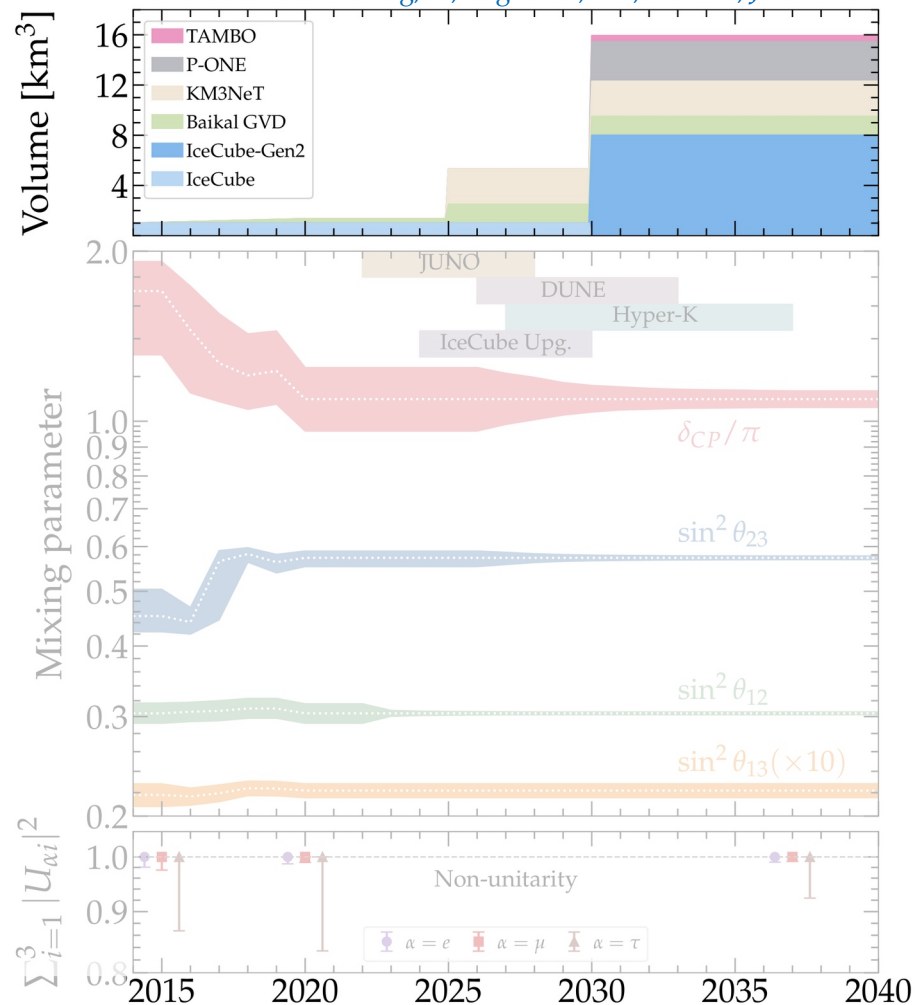
Measuring flavor composition: 2015–2040

Song, Li, Argüelles, MB, Vincent, JCAP2021



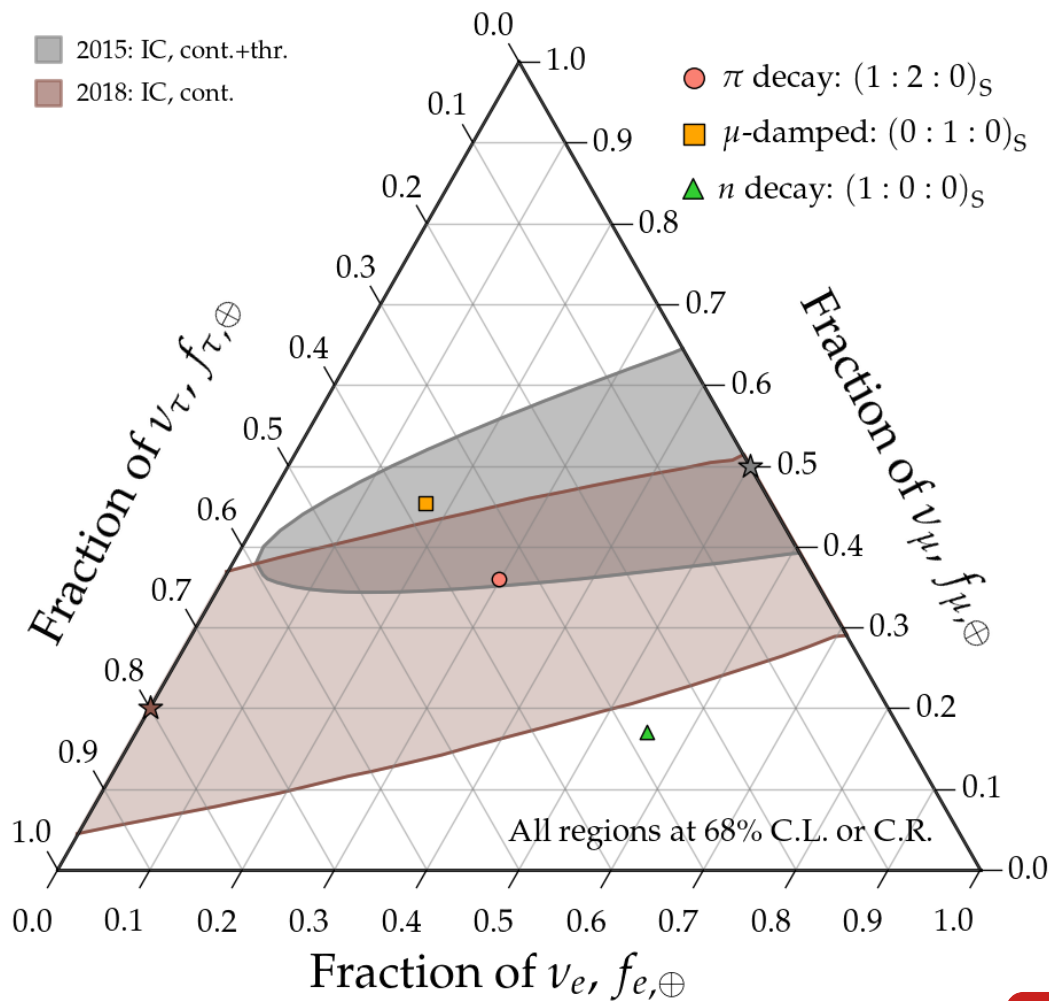
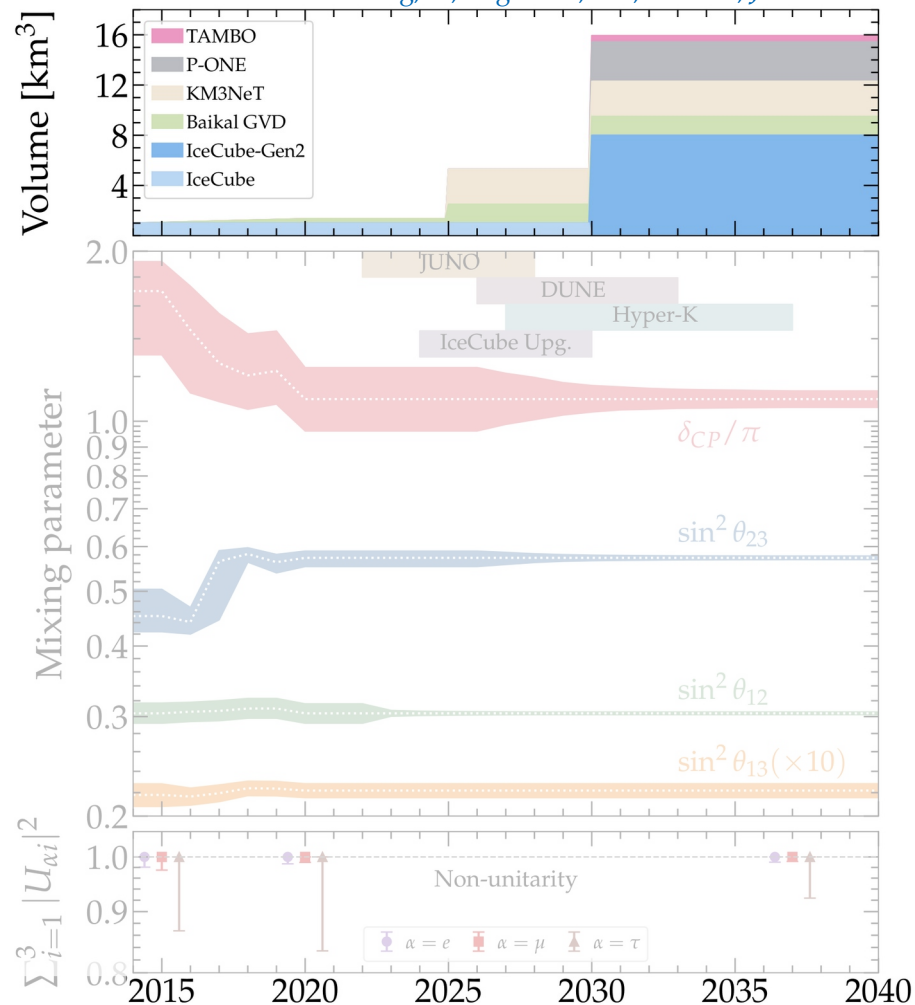
Measuring flavor composition: 2015–2040

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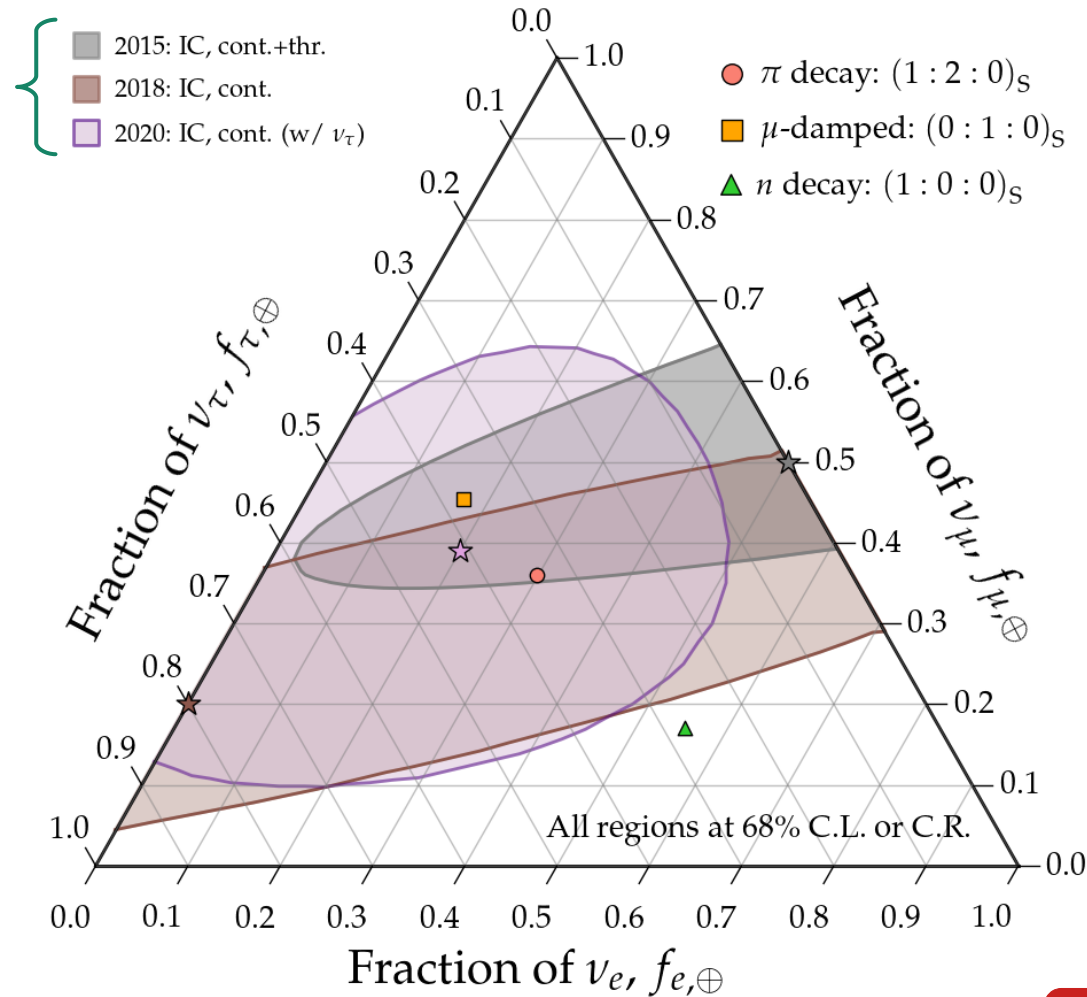
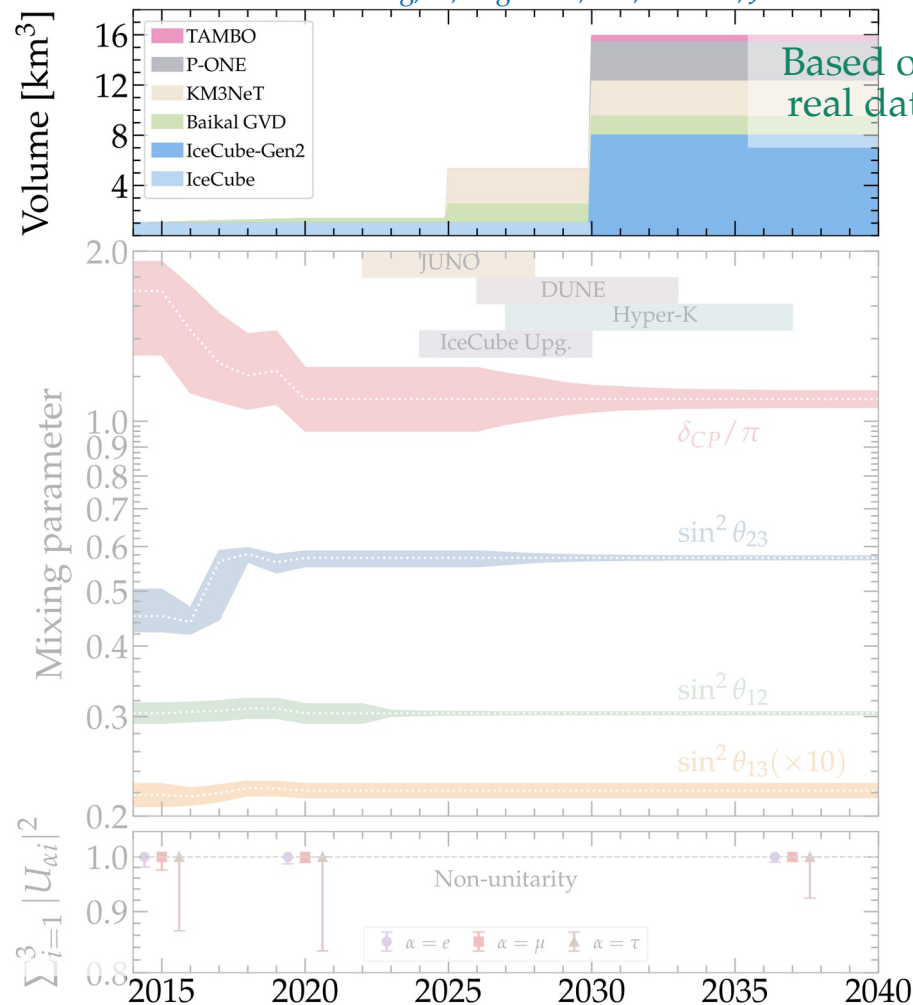
Measuring flavor composition: 2015–2040

Song, Li, Argüelles, MB, Vincent, JCAP2021



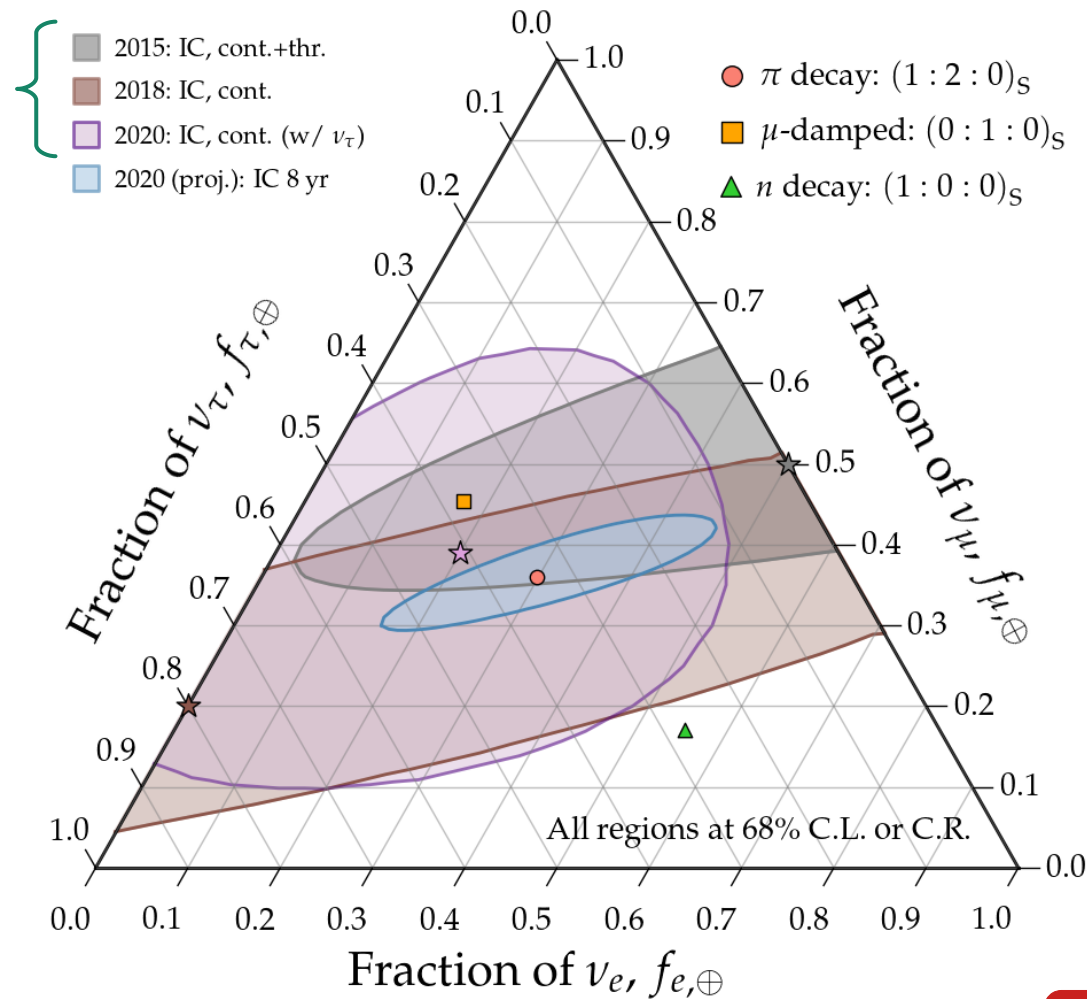
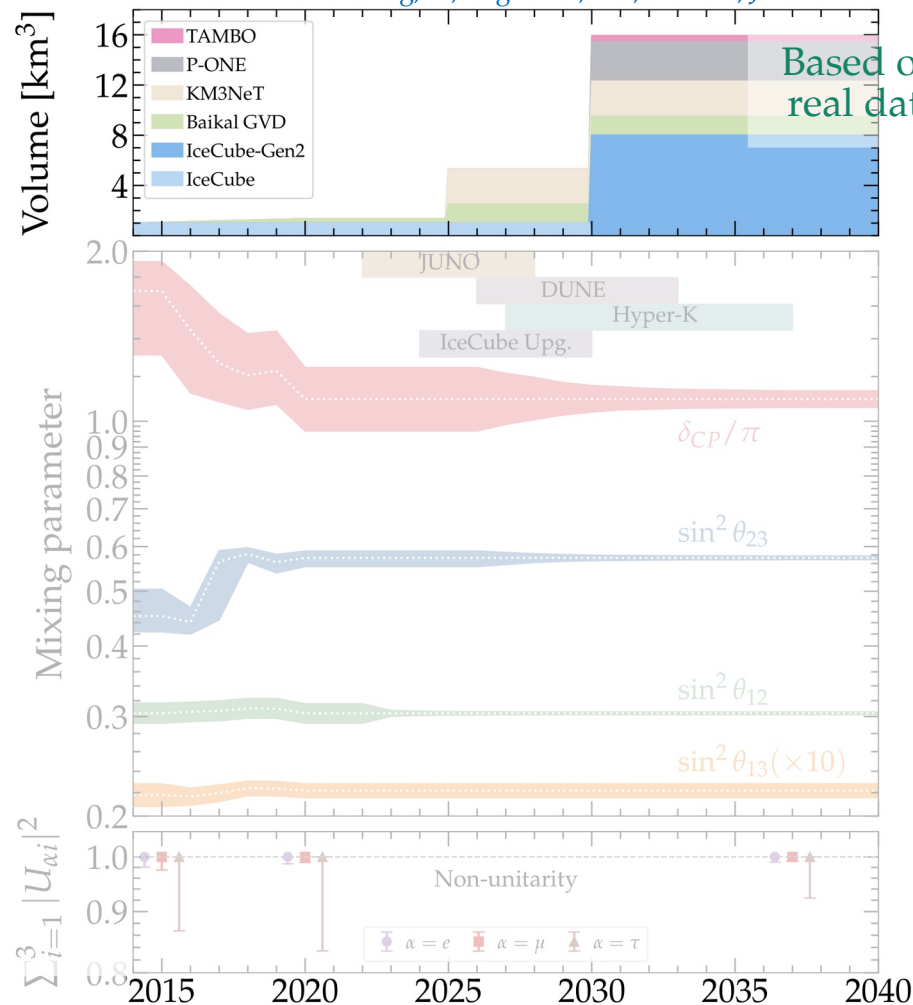
Measuring flavor composition: 2015–2040

Song, Li, Argüelles, MB, Vincent, JCAP2021



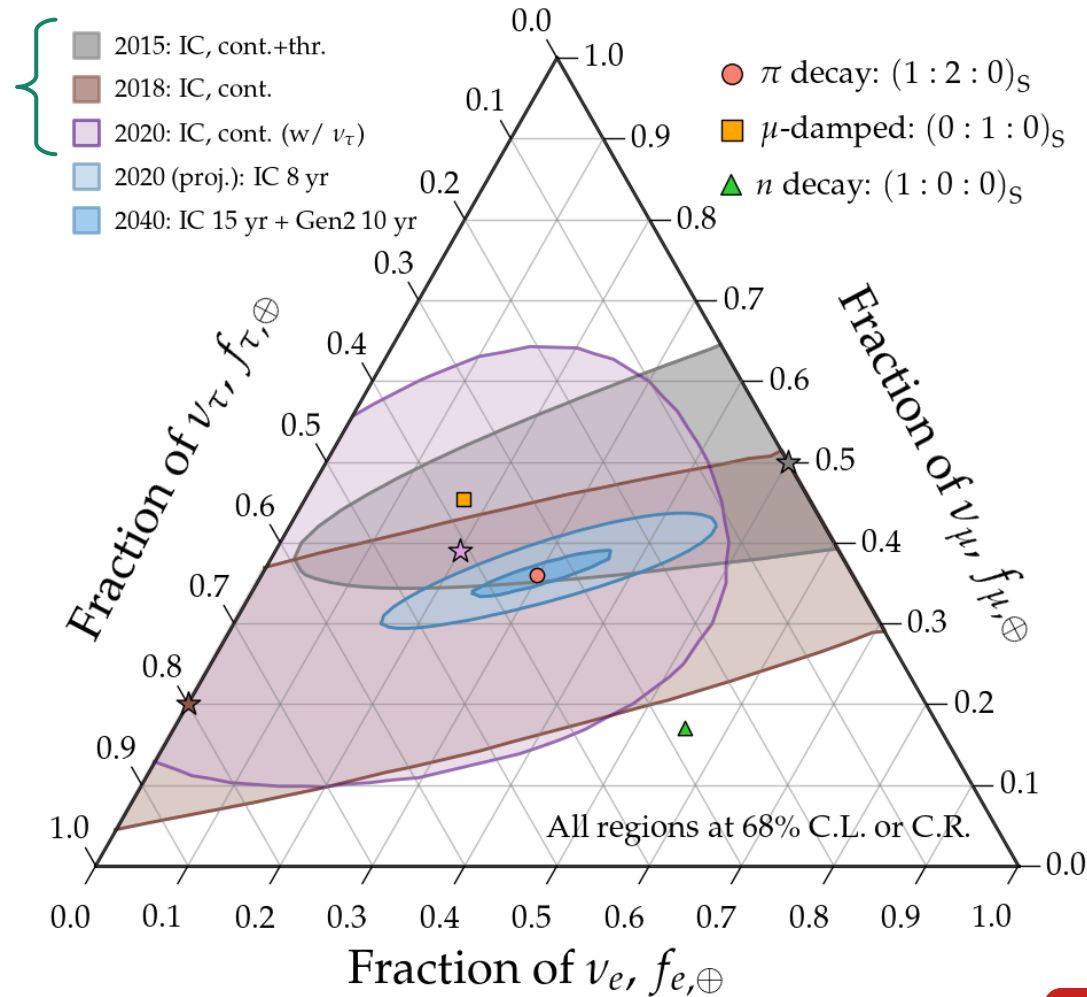
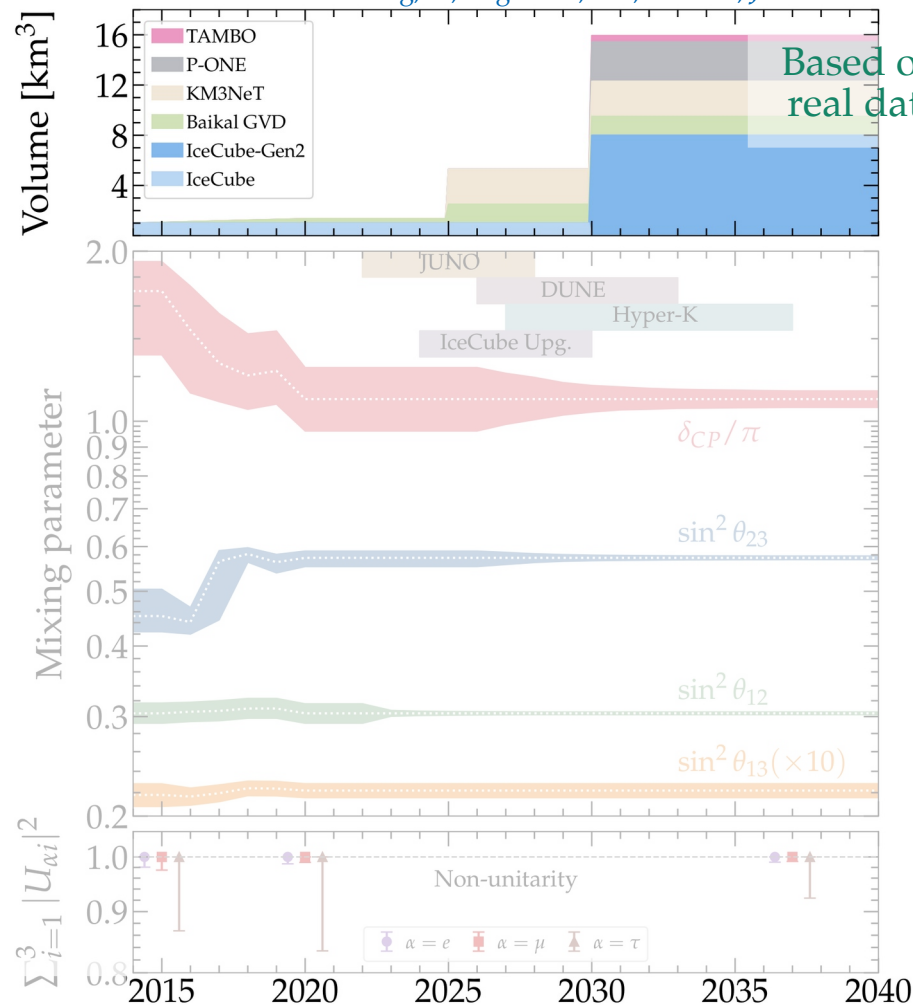
Measuring flavor composition: 2015–2040

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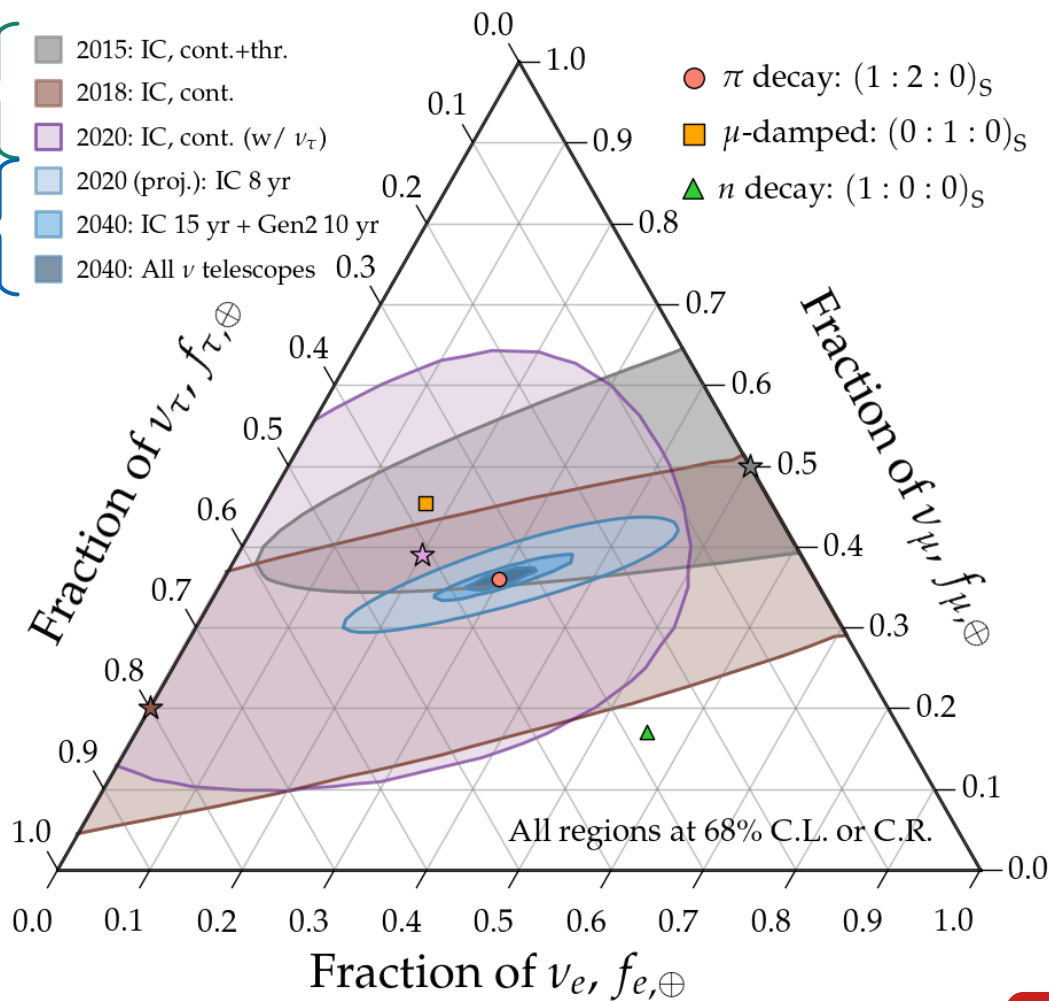
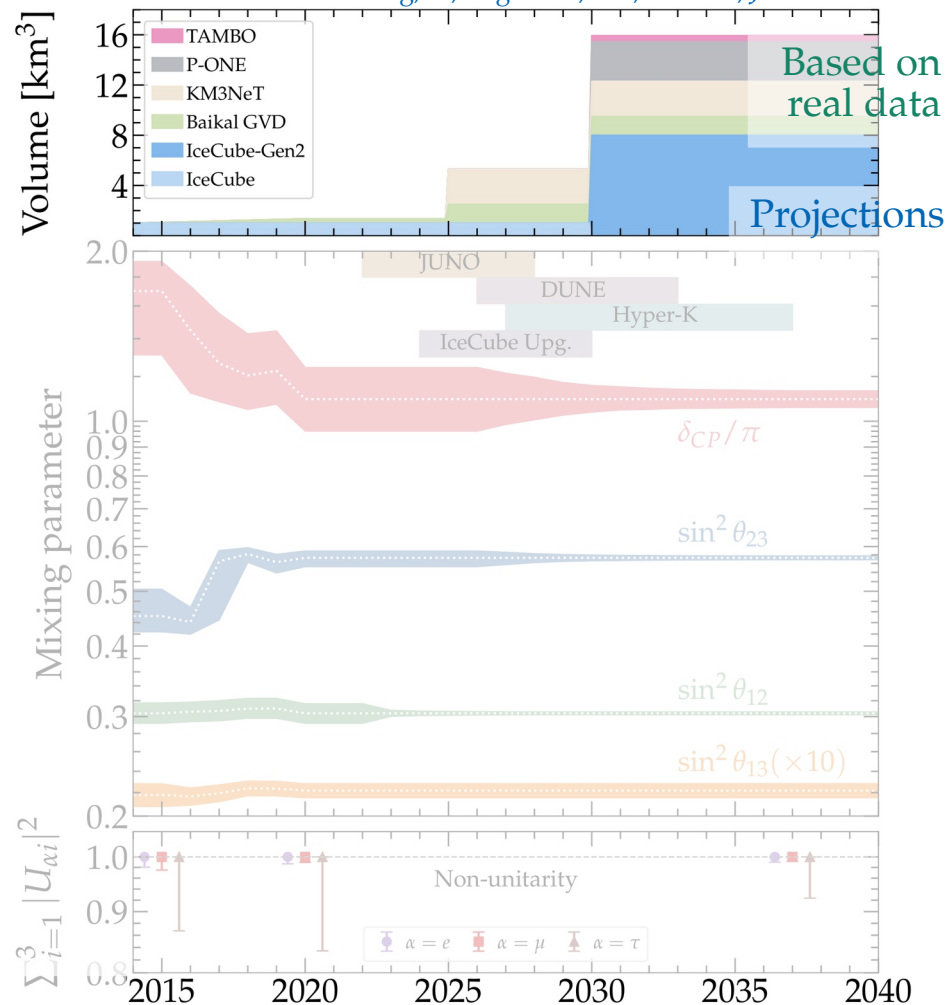
Measuring flavor composition: 2015–2040

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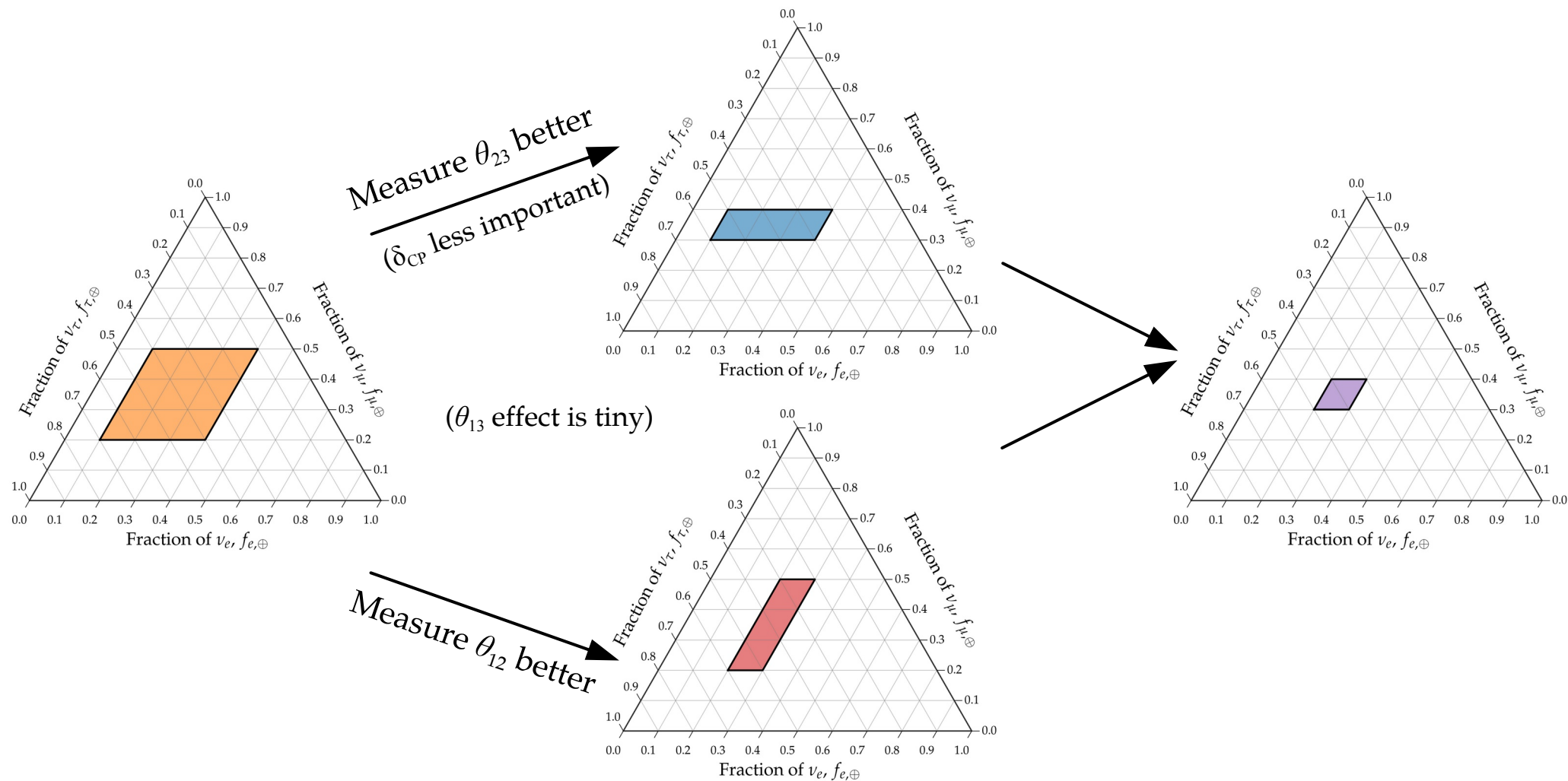


Measuring flavor composition: 2015–2040

Song, Li, Argüelles, MB, Vincent, JCAP2021



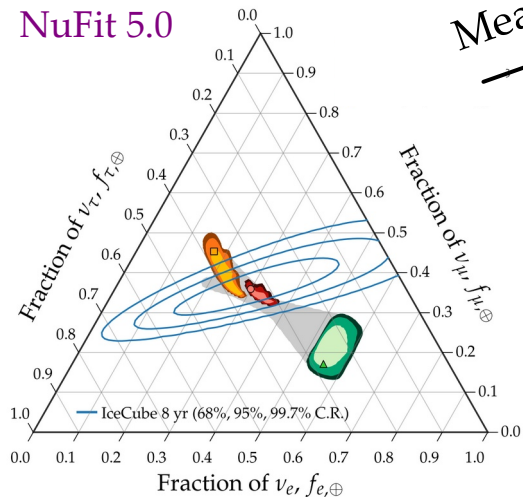
How knowing the mixing parameters better helps



How knowing the mixing parameters better helps

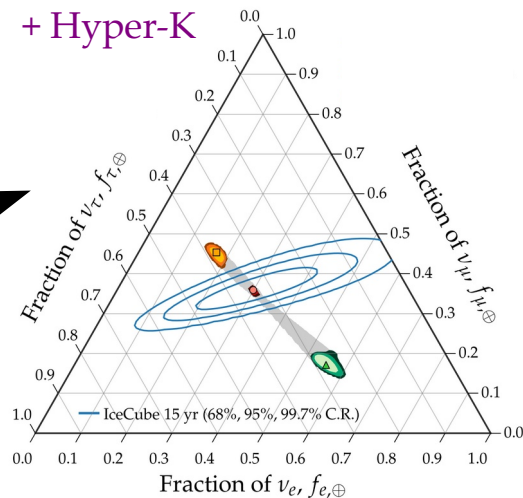
2020

NuFit 5.0

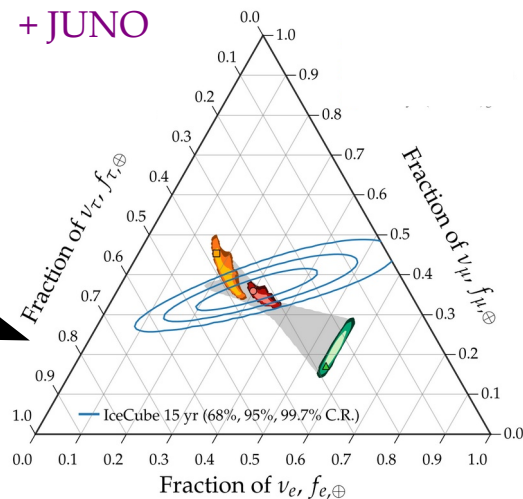


Measure θ_{23} better

+ Hyper-K



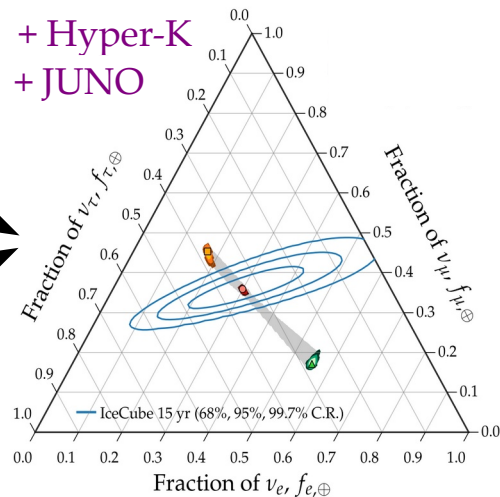
+ JUNO



Measure θ_{12} better

~2030

+ Hyper-K
+ JUNO

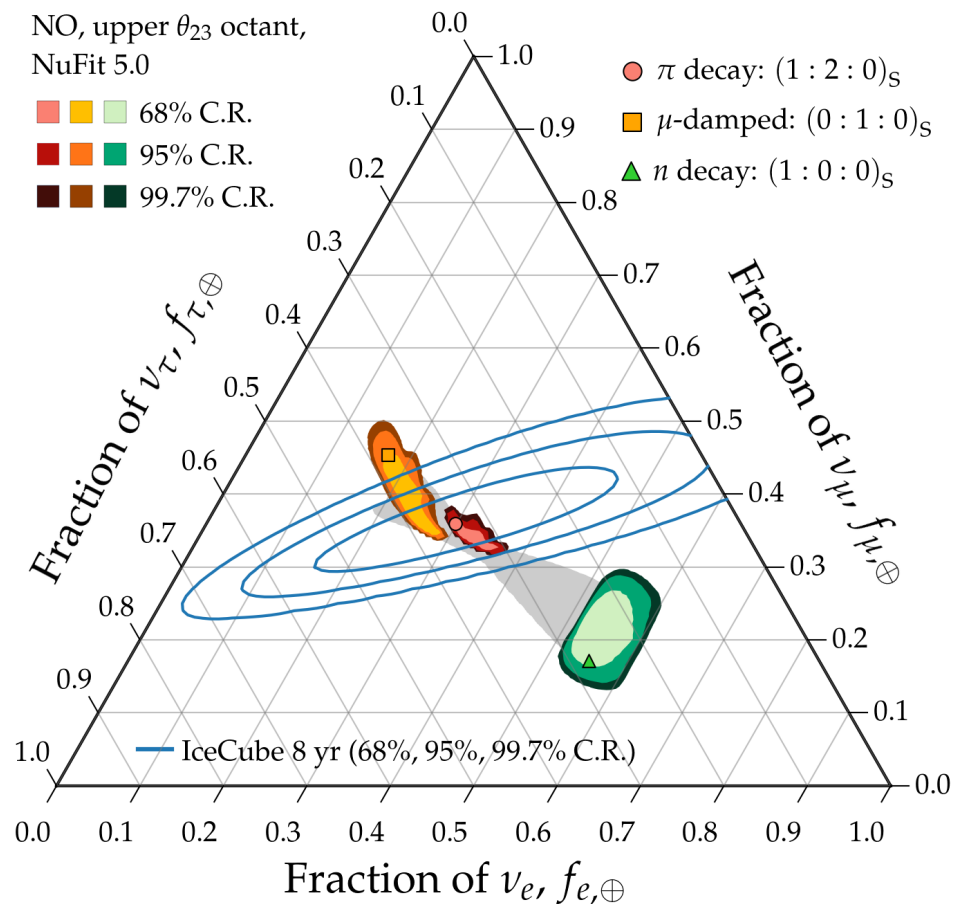


In our results:
JUNO + Hyper-K + DUNE

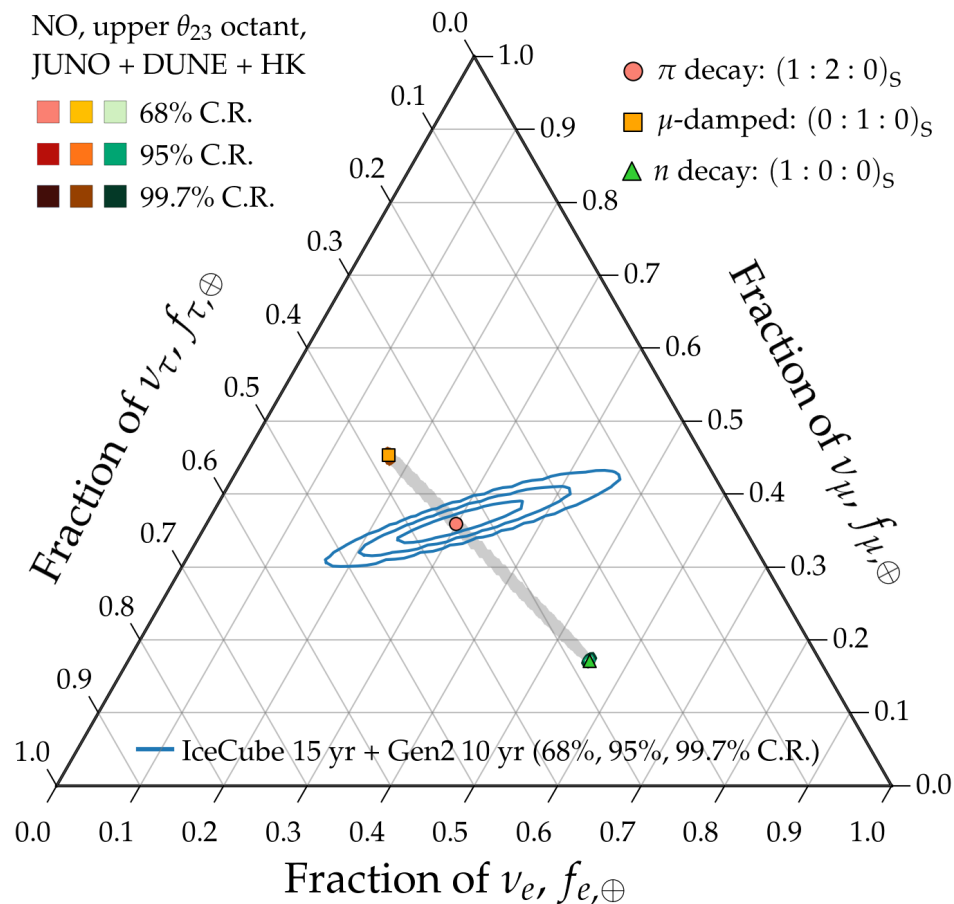
Marginal improvement til 2040

Theoretically palatable regions: 2020 $\rightarrow$ 2040

2020



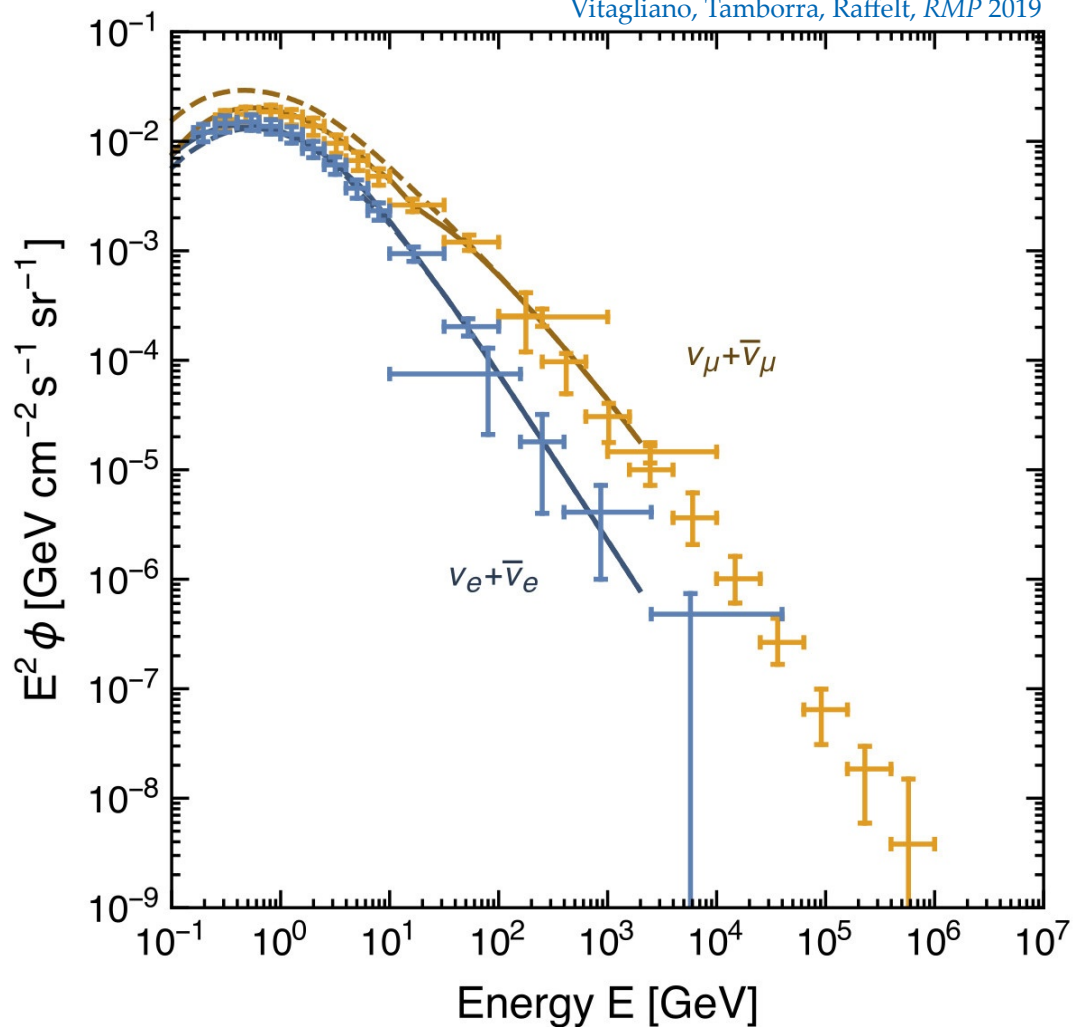
2040



Neutrinos from the Milky Way

Neutrinos from the Galaxy

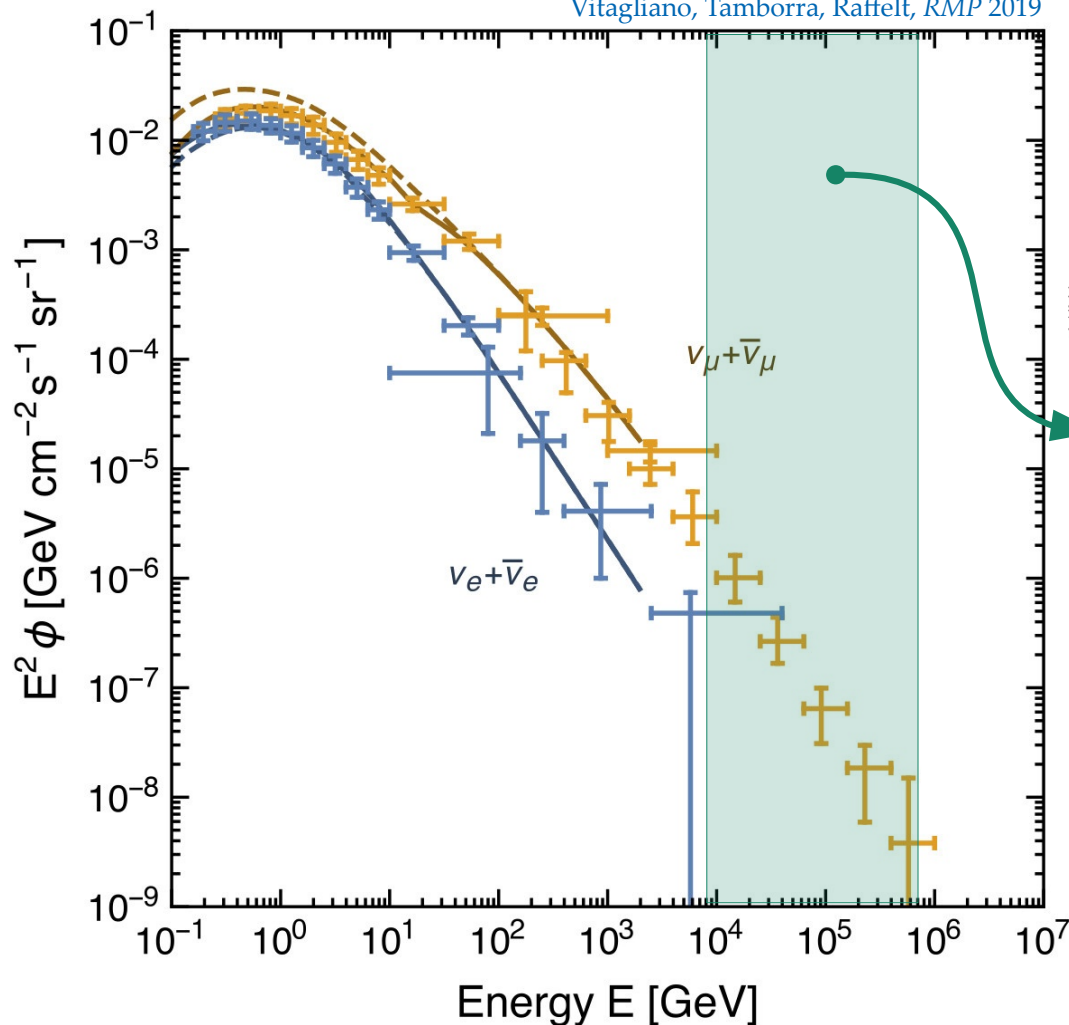
Vitagliano, Tamborra, Raffelt, *RMP* 2019



See also: [Beacom & Candia, JCAP 2004](#)

Neutrinos from the Galaxy

Vitagliano, Tamborra, Raffelt, *RMP* 2019

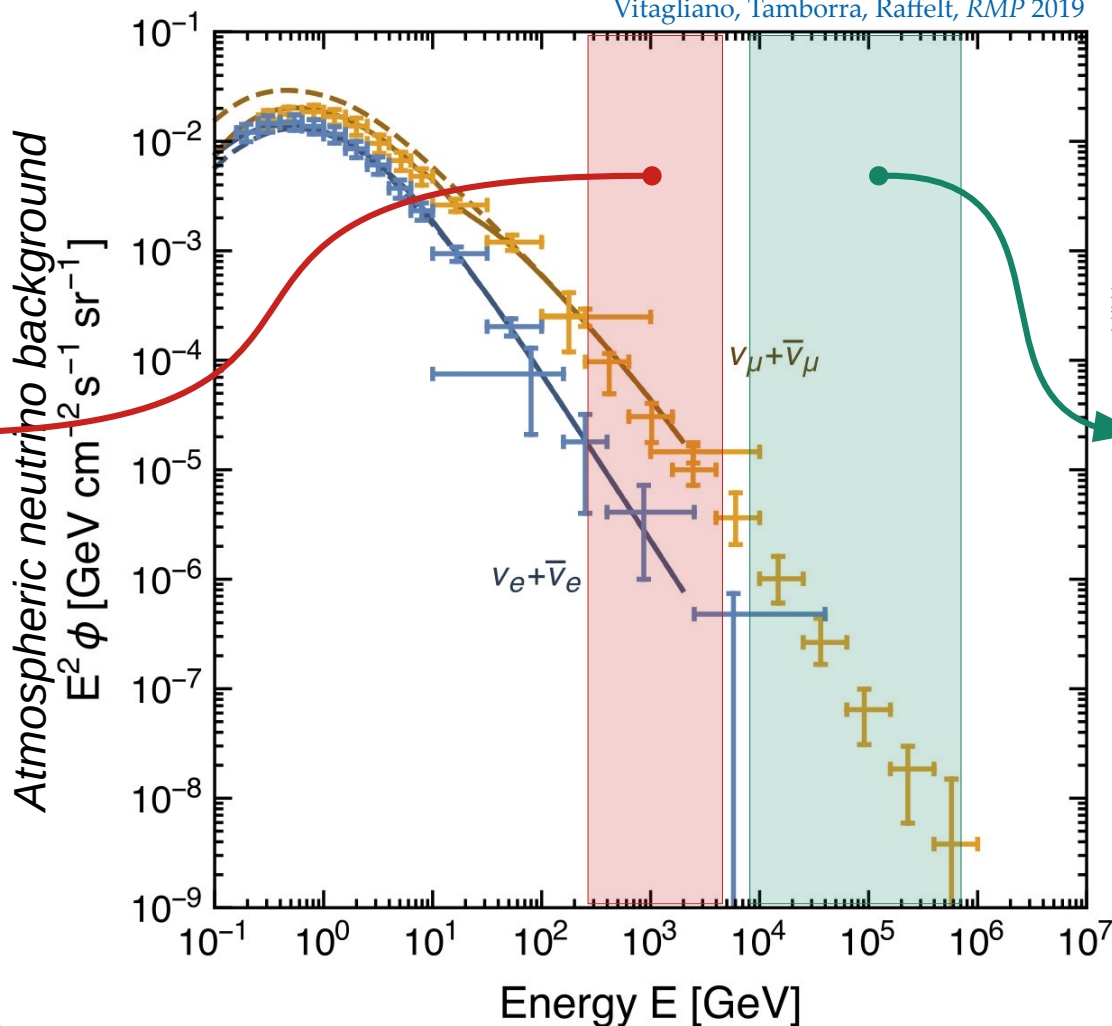


Search for >10 -TeV
astrophysical ν

- Use *muon tracks*
- Pointing accuracy: $\sim 1^\circ$
- Atm. bg. is mostly ν_μ
- Self-veto screens for atm. muons to cut ν bg.

Neutrinos from the Galaxy

Vitagliano, Tamborra, Raffelt, *RMP* 2019



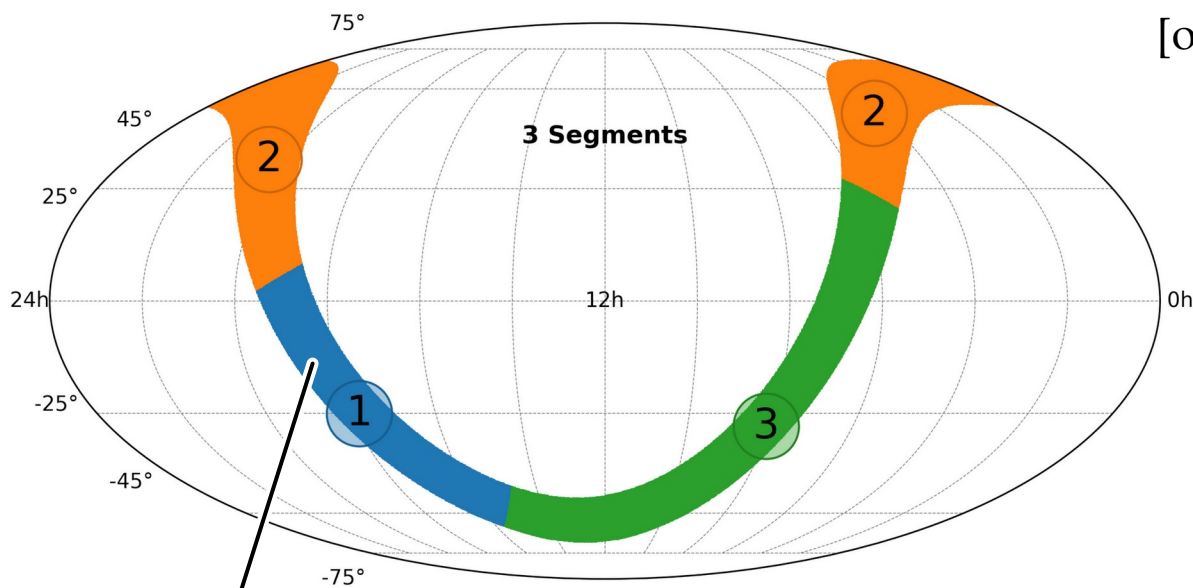
Search for **TeV**
astrophysical ν

Search for **>10-TeV**
astrophysical ν

- ▶ But GP ν are TeV
- ▶ Use **cascades**
- ▶ Atm. ν_e bg. $10\times$ lower
- ▶ Bg.-to-signal: $10^8:1$
- ▶ *Deep learning retains 20 times more events, $2\times$ better angular res.*

- ▶ Use *muon tracks*
- ▶ Pointing accuracy: $\sim 1^\circ$
- ▶ Atm. bg. is mostly ν_μ
- ▶ Self-veto screens for atm. muons to cut ν bg.

Improvements **without** template fitting



Divide the Galactic Plane into 3 generic segments
[other segmentation schemes, too (*e.g.*, 2, 6)]

Same cascade sample as 2023 discovery

Same unbinned maximum likelihood
... but now segmented

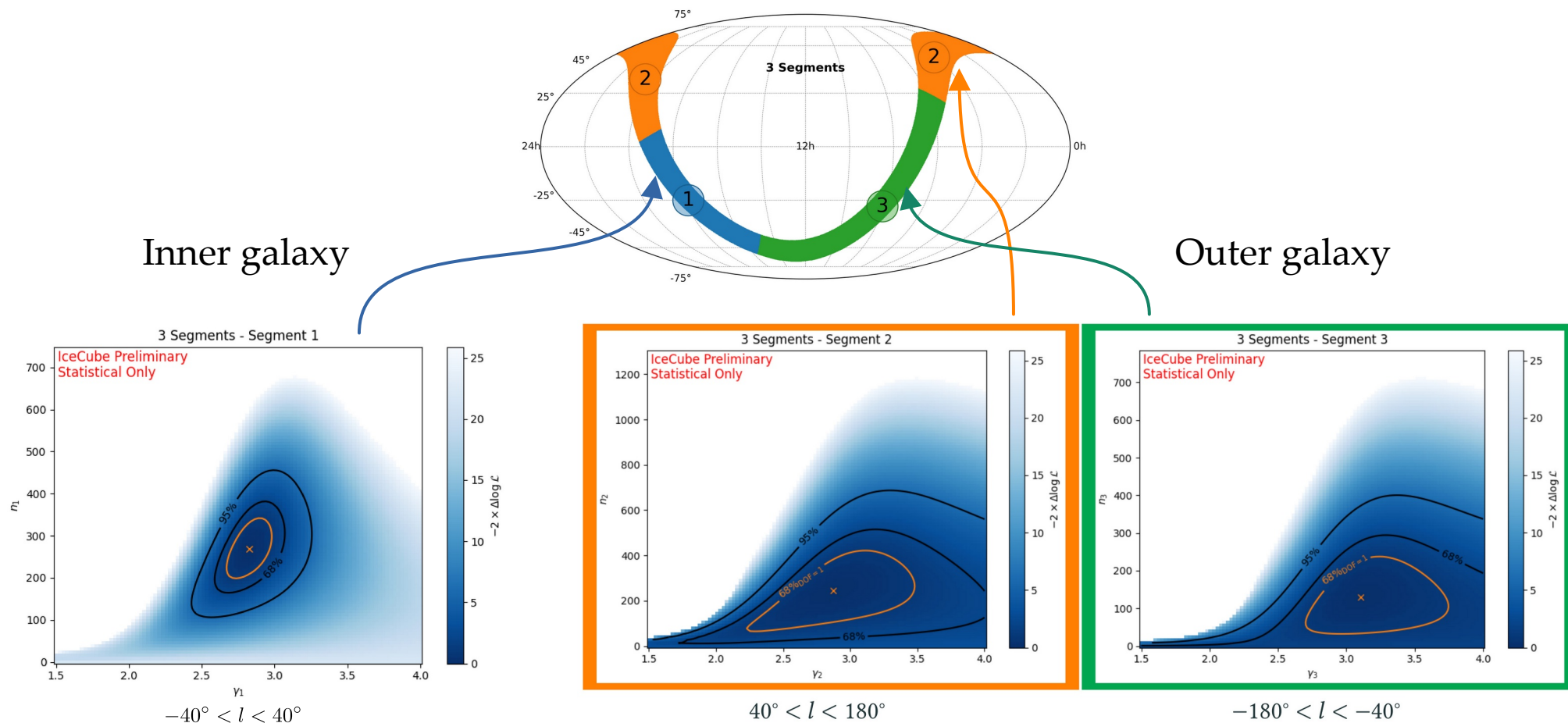
In each segment: single power law
Fit flux normalization and spectral index

Note: No systematics yet

Neutrinos from the Galaxy: IceCube

L. NESTE, M. HÜNNEFELD, C. FINLEY
PoS(ICRC2025)1130 • Talk July 21

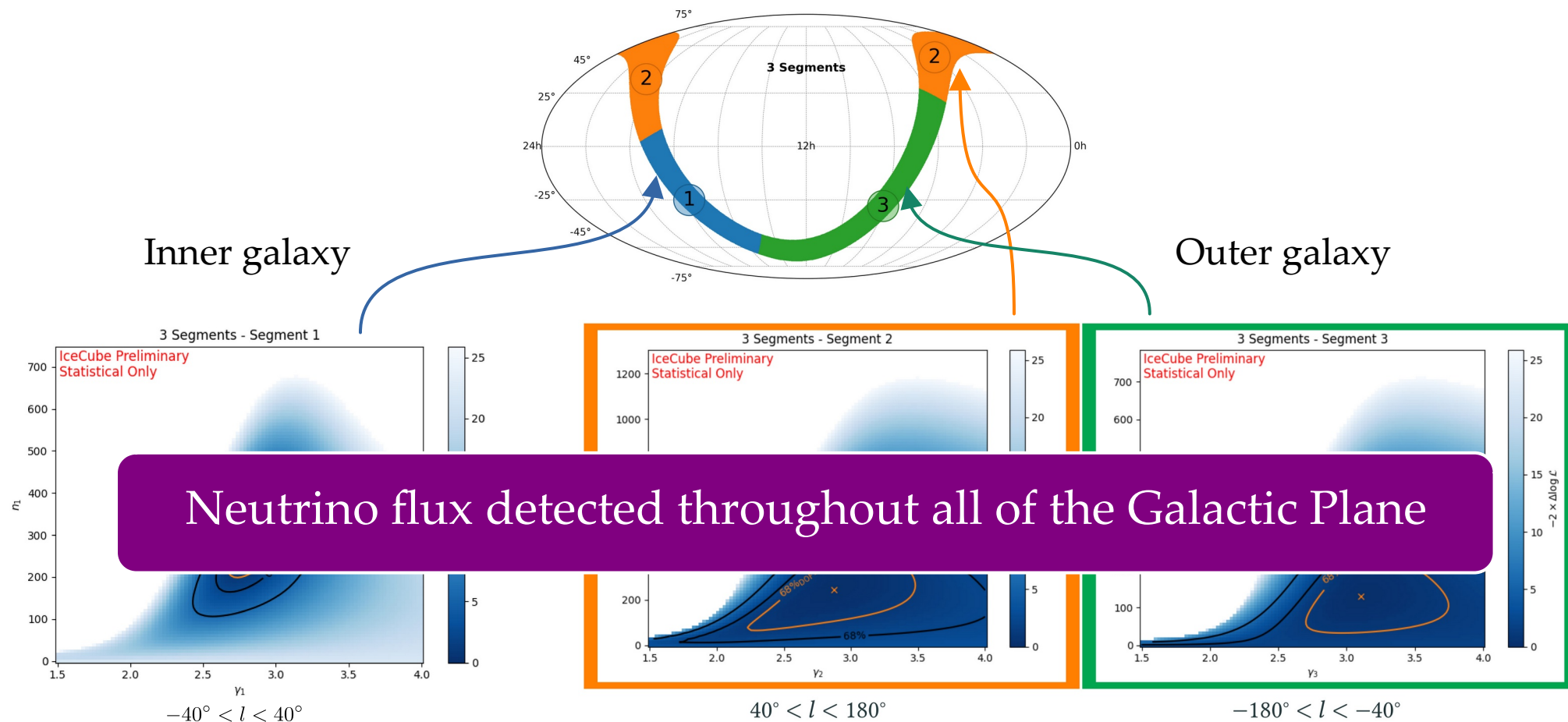
Improvements **without** template fitting



Neutrinos from the Galaxy: IceCube

L. NESTE, M. HÜNNEFELD, C. FINLEY
PoS(ICRC2025)1130 • Talk July 21

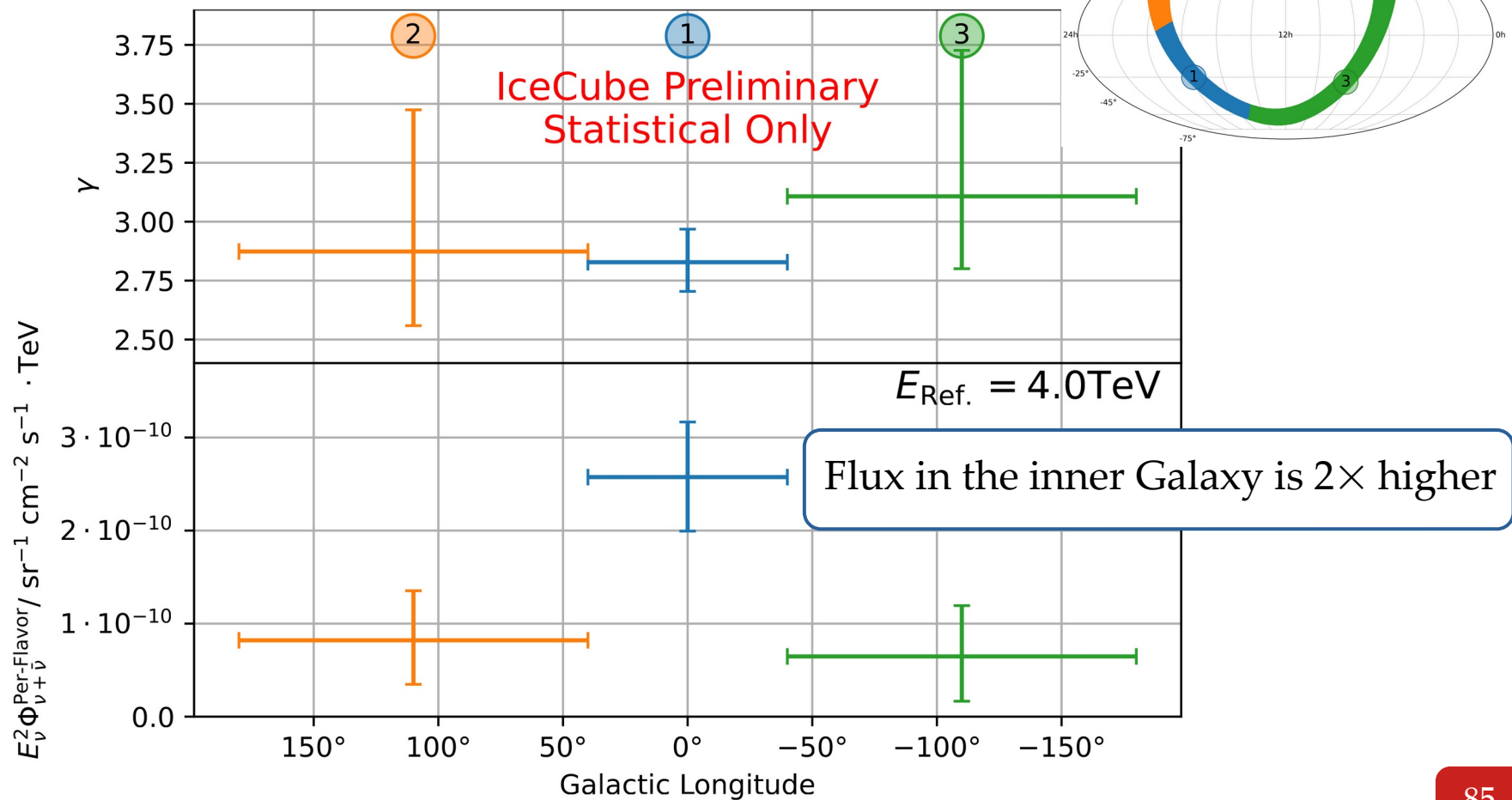
Improvements **without** template fitting



Neutrinos from the Galaxy: IceCube

L. NESTE, M. HÜNNEFELD, C. FINLEY
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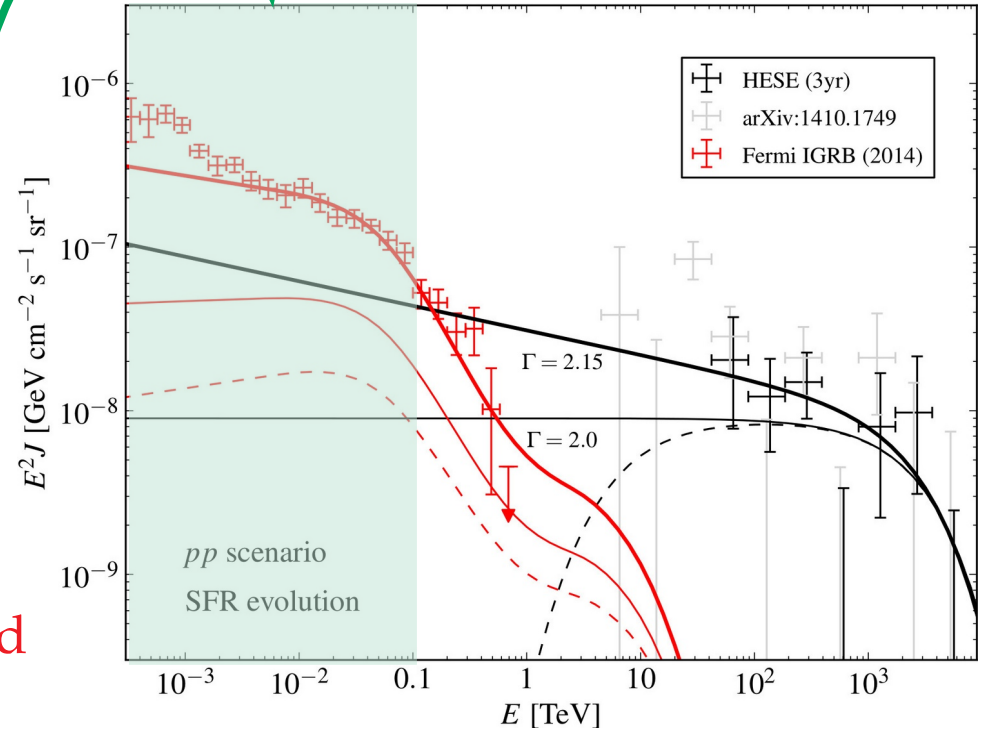
Improvements **without** template fitting



Constraints from the gamma-ray background

- ▶ Production via *pp*: ν and gamma-ray spectra follow the CR spectrum E^Γ
- ▶ Gamma-ray interactions on the CMB make them pile up at GeV
- ▶ *Fermi* gamma-ray background is not exceeded only if $\Gamma < 2.2$
- ▶ But IceCube found $\Gamma = 2.5\text{--}2.7$
- ▶ Therefore, production via *pp* is disfavored between 10–100 TeV

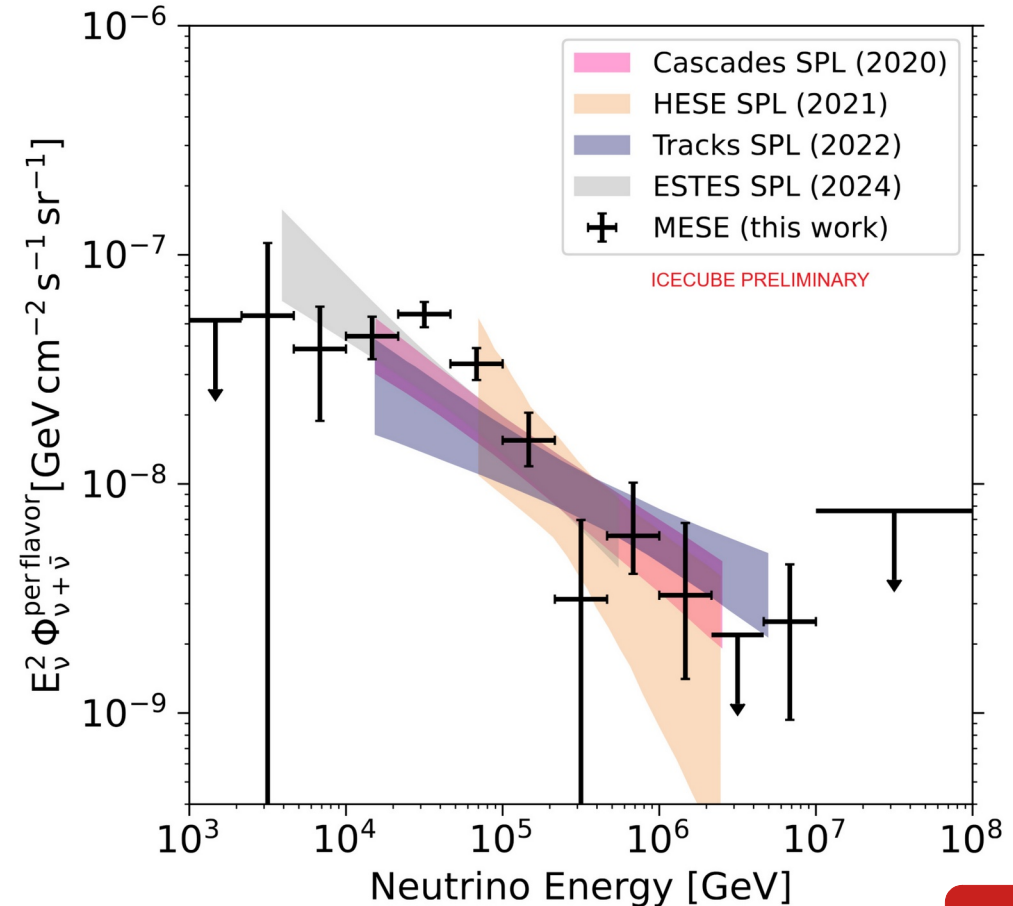
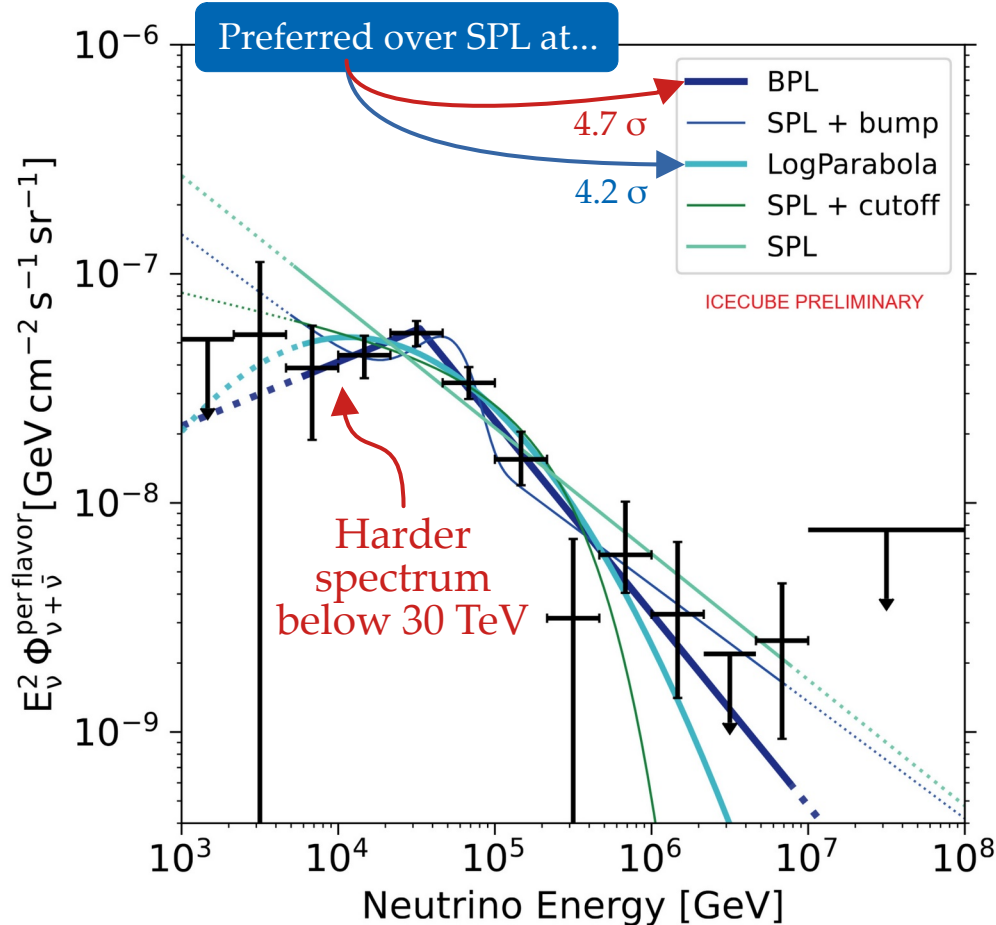
Murase, Ahlers, Lacki, *PRD* 2013



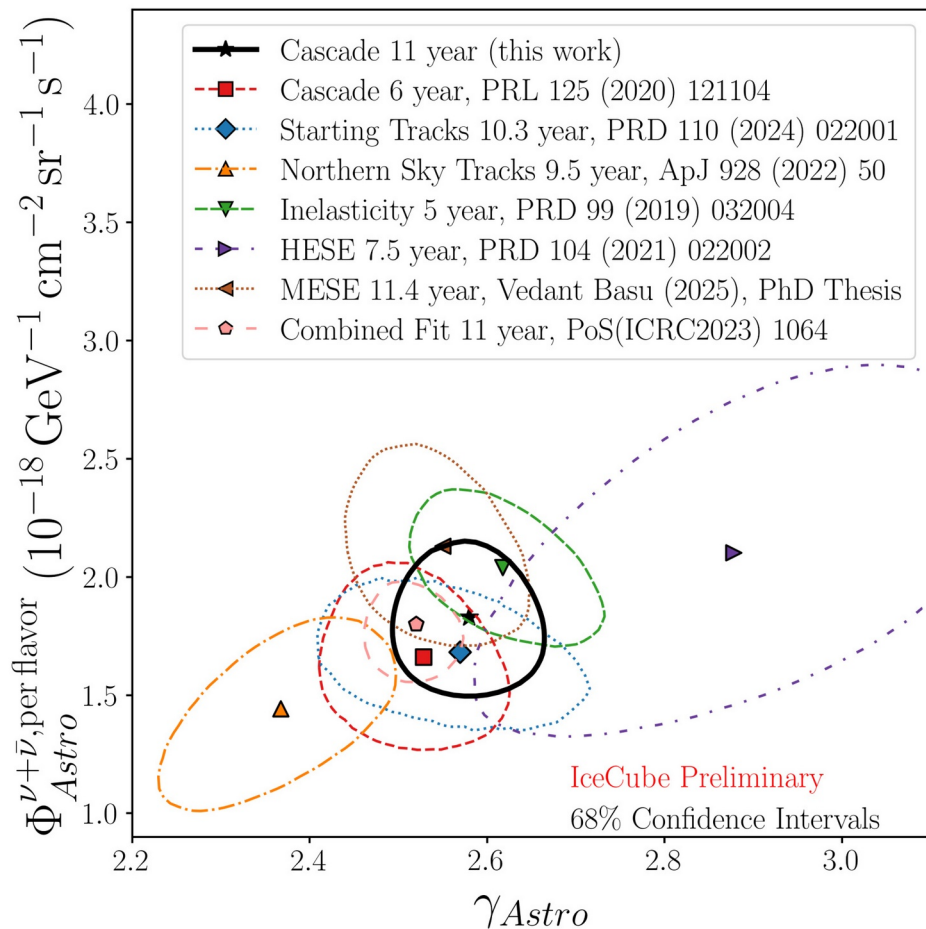
Diffuse ν flux:
beyond the power law

Diffuse TeV–PeV ν flux: IceCube

1 – New all-flavor flux measurement at 1 TeV–10 PeV



2 – New measurement using cascades at > 10 TeV



11 yr of cascade data

Cascades (ν_e, ν_μ, ν_τ) and double cascades (ν_τ)

Background to double-cascade search:

ν_e charged-current cascades

ν_e, ν_μ, ν_τ neutral-current cascades

ν_μ starting tracks

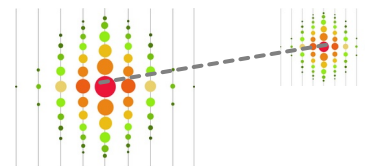
Extra cuts to find double cascades (+ self-veto):

total energy $> 10^{4.5}$ GeV

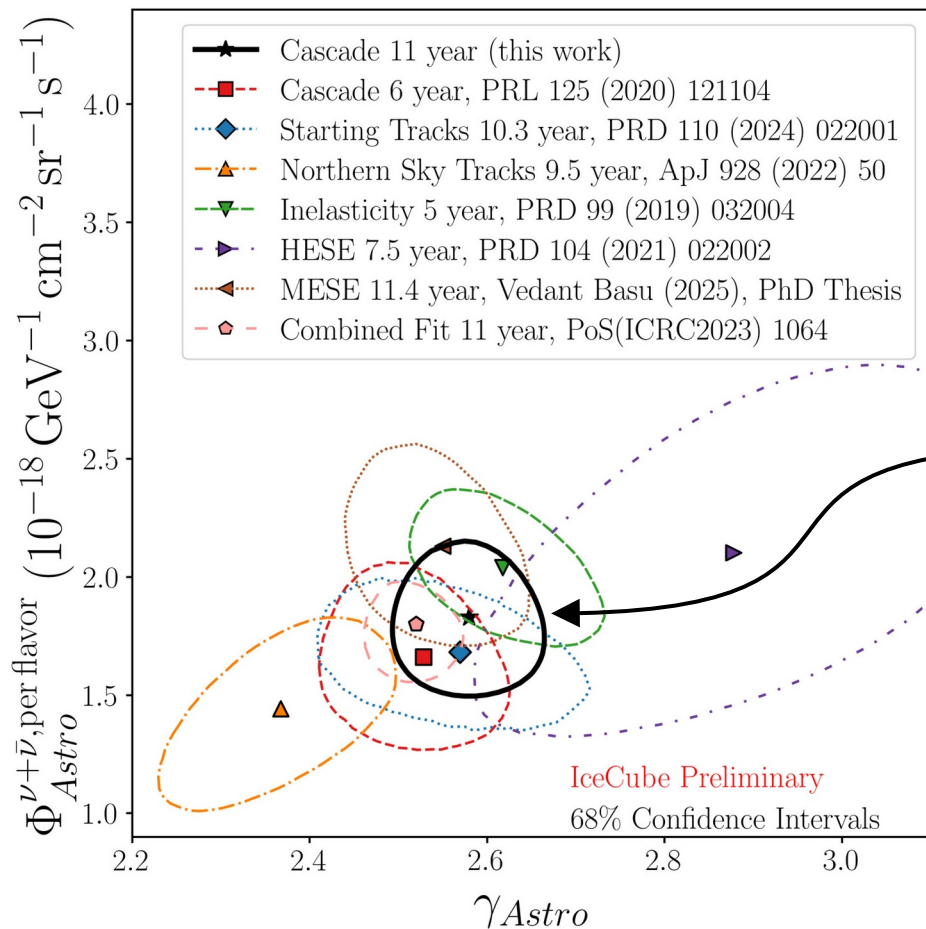
inter-cascade length > 10 m

energy asymmetry

Produce ν_τ -enriched sample with 90% ν_τ purity
(Great for flavor measurements, see later)

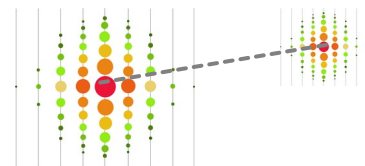


2 – New measurement using cascades at > 10 TeV



11 yr of cascade data

Cascades (ν_e, ν_μ, ν_τ) and double cascades (ν_τ)



Single-power-law (SPL) fit to data,

$$\Phi = \Phi_0 \times \left(\frac{E}{100 \text{ TeV}} \right)^{-\gamma},$$

agrees with previous results

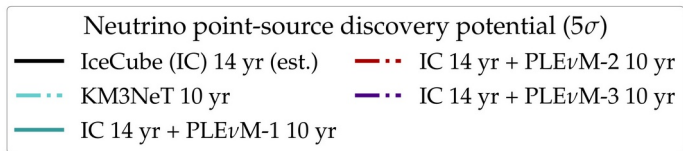
Best-fit values:

$$\Phi_0 = 1.83 \pm 0.21$$

$$\gamma = 2.68 \pm 0.06$$

PLEvM

Discovery (5σ) of a steady-state point source



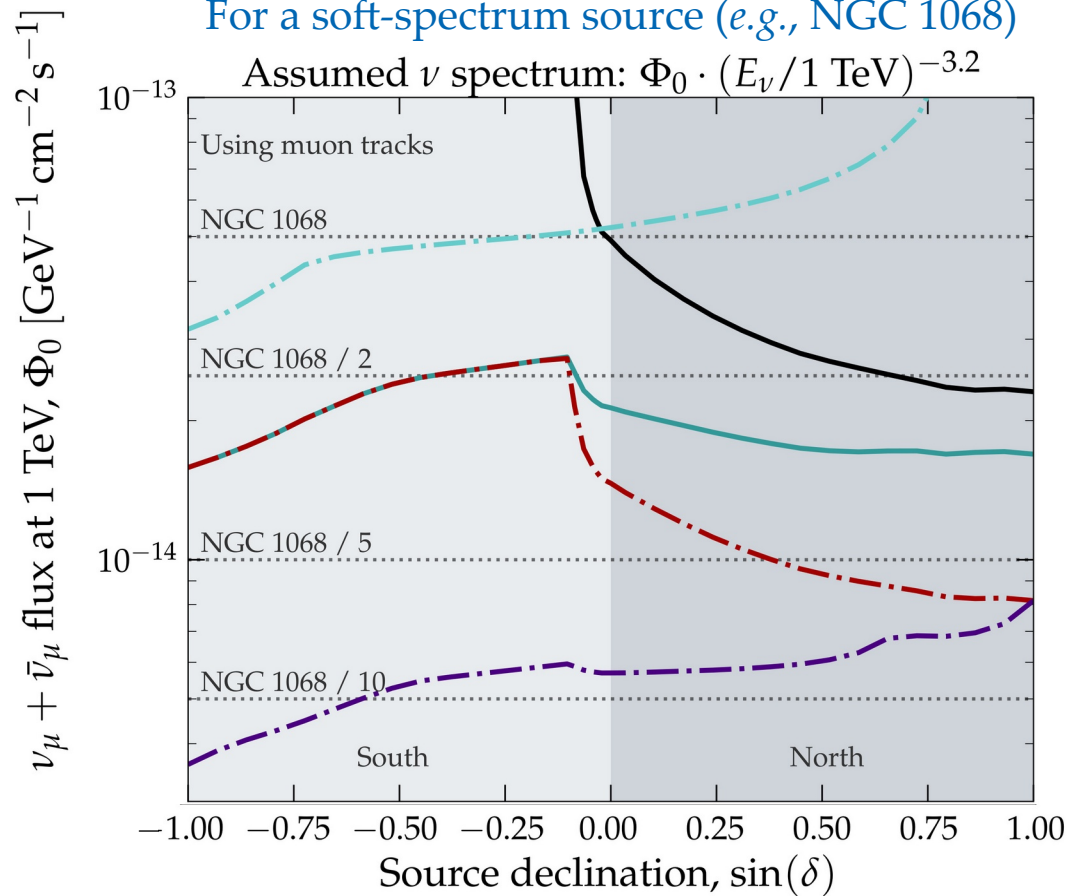
PLEνM-1: IceCube + Baikal-GVD + KM3NeT + P-ONE

PLEνM-2: IceCube-Gen2 + Baikal-GVD + KM3NeT + P-ONE

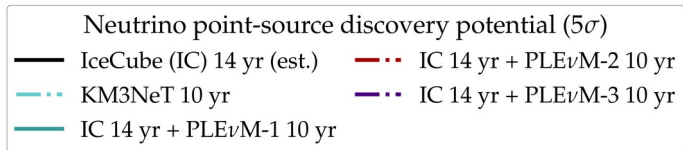
PLEνM-3: PLEνM-2 + HUNT + TRIDENT + NEON

For a soft-spectrum source (*e.g.*, NGC 1068)

Assumed ν spectrum: $\Phi_0 \cdot (E_\nu/1 \text{ TeV})^{-3.2}$



Discovery (5σ) of a steady-state point source



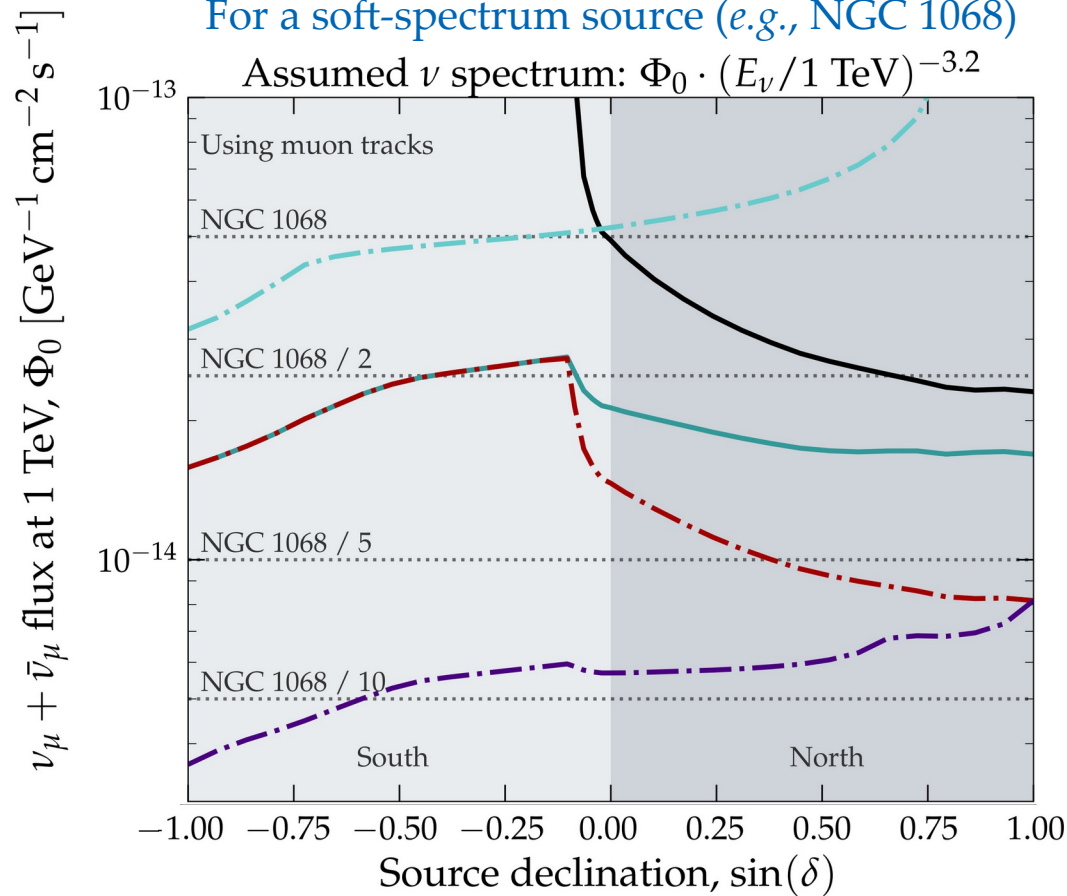
PLE ν M-1: IceCube + Baikal-GVD + KM3NeT + P-ONE

PLE ν M-2: IceCube-Gen2 + Baikal-GVD + KM3NeT + P-ONE

PLE ν M-3: PLE ν M-2 + HUNT + TRIDENT + NEON

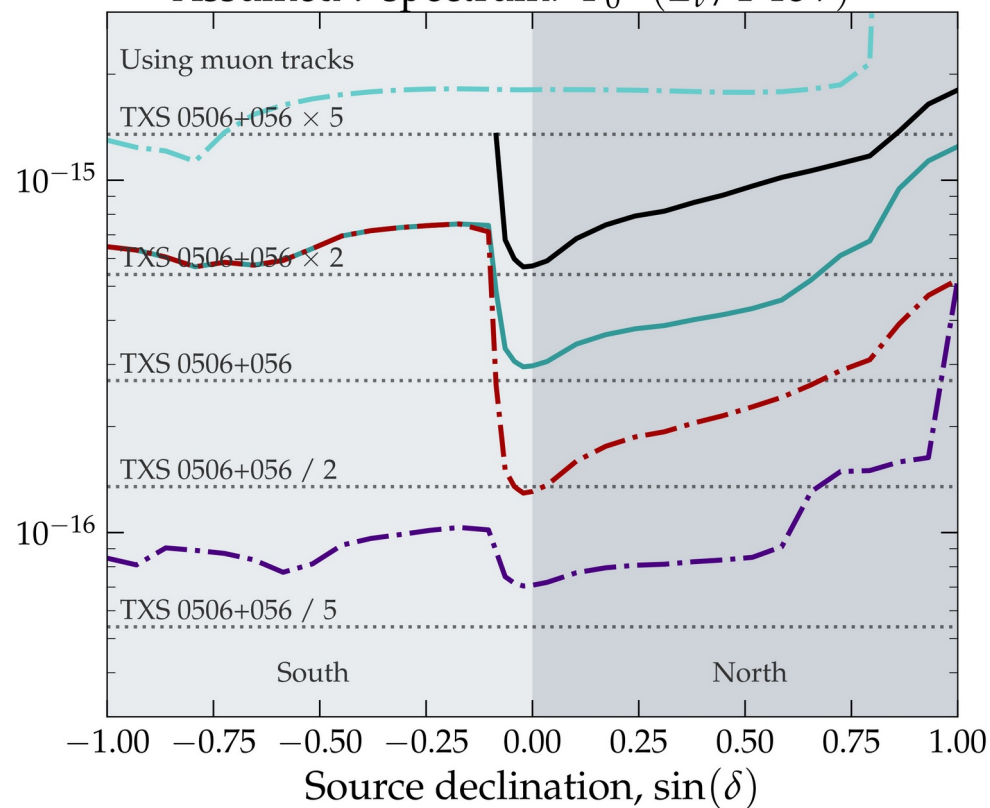
For a soft-spectrum source (*e.g.*, NGC 1068)

Assumed ν spectrum: $\Phi_0 \cdot (E_\nu/1 \text{ TeV})^{-3.2}$



For a hard-spectrum source (*e.g.*, TXS 0506+056)

Assumed ν spectrum: $\Phi_0 \cdot (E_\nu/1 \text{ TeV})^{-2}$



How many more sources?

Redshift evolution of number density of sources follows star-formation rate

All sources have identical luminosity

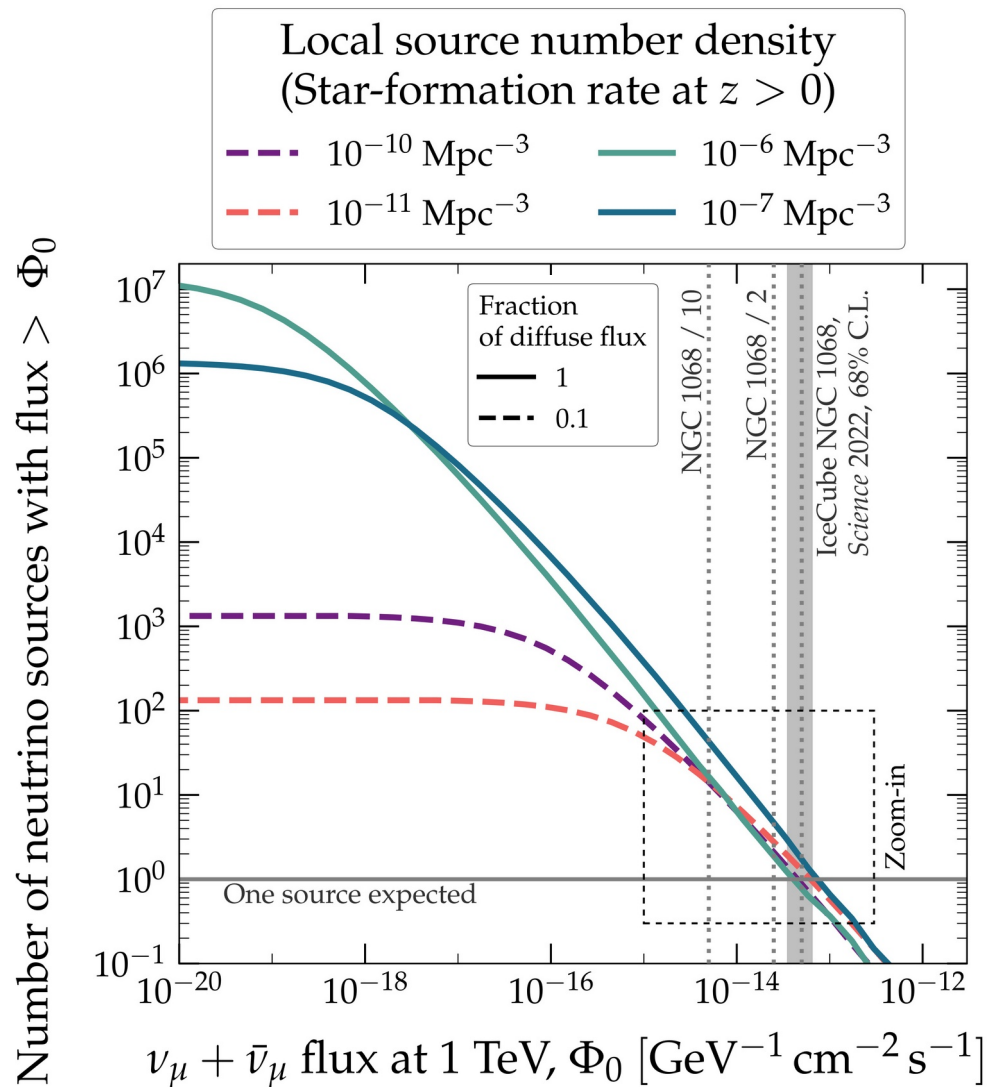
PLEvM-1 can detect sources 40% as bright as NGC 1068

→ 2–6 sources

PLEvM-2 can detect sources 10% as bright as NGC 1068

→ 10–40 sources

Demanding only 3σ evidence raises prospects by 50%

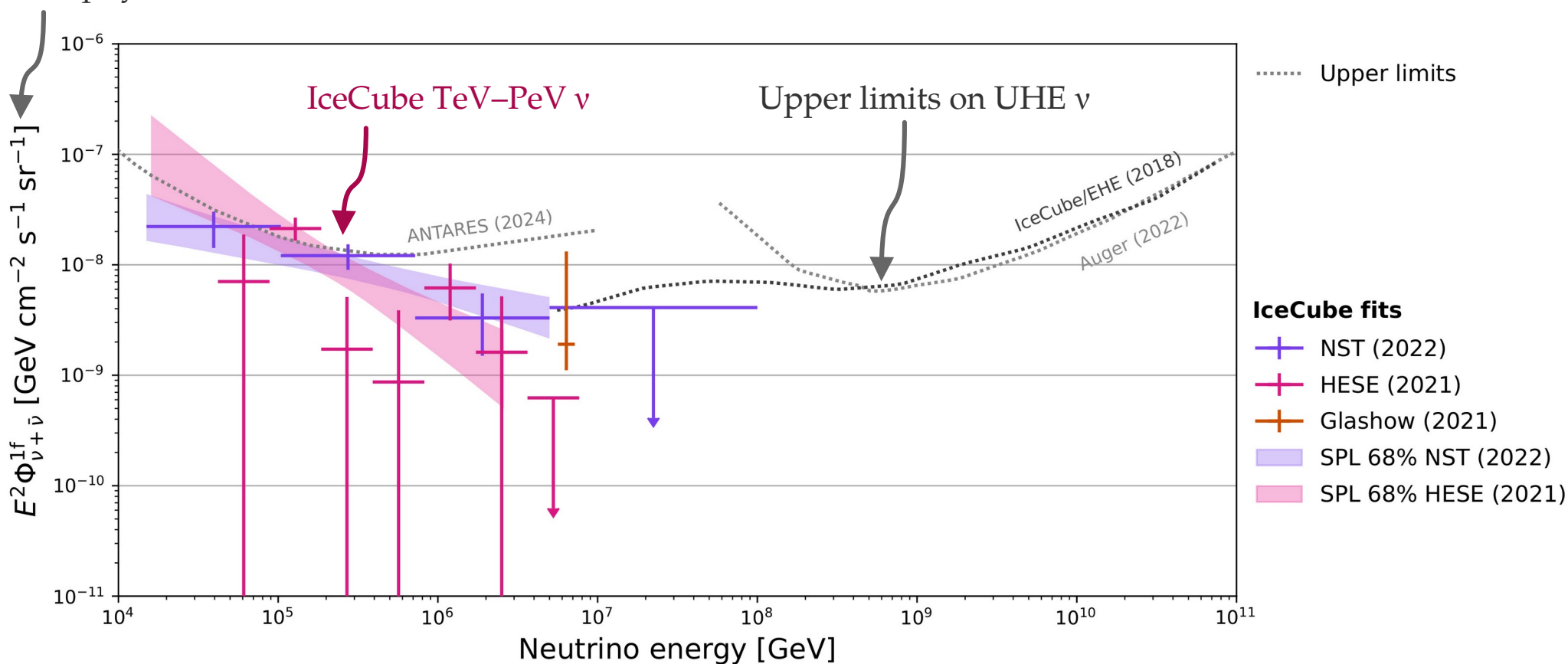


KM3NeT

UHE neutrino

KM3NeT *vs.* IceCube & Auger

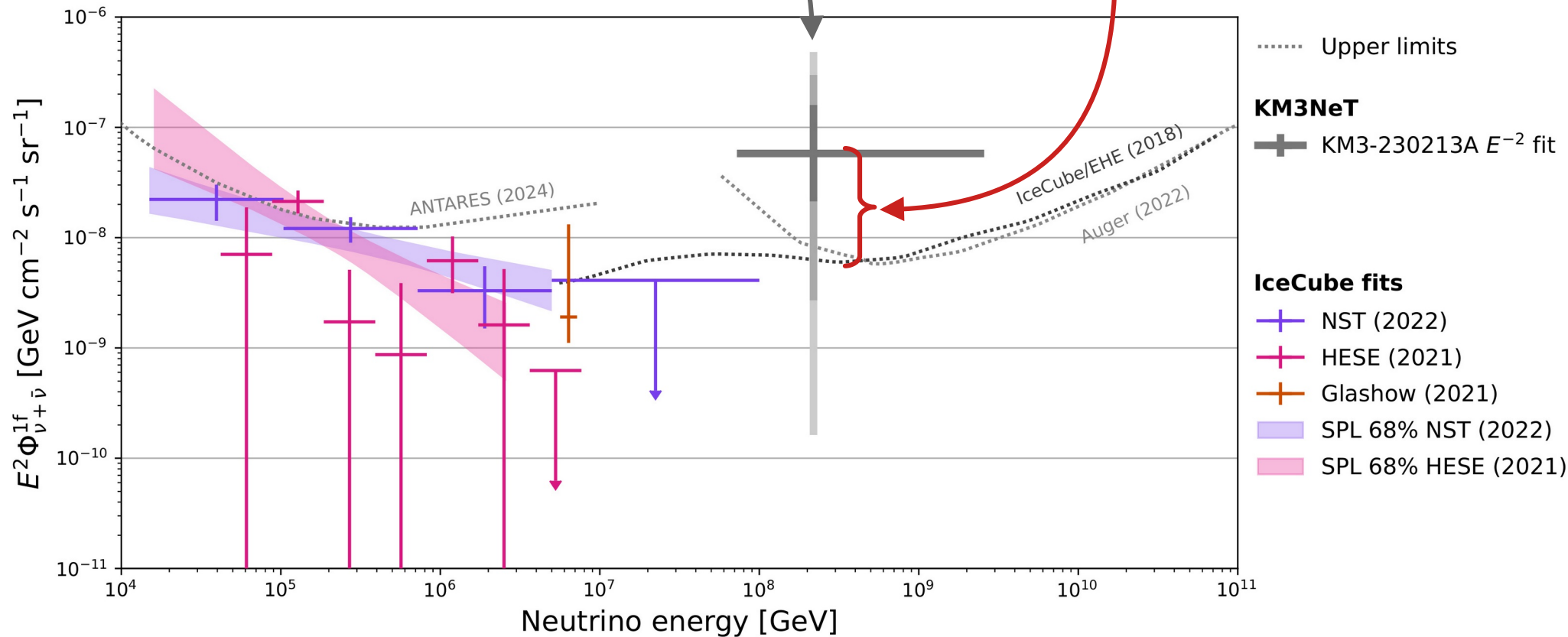
Diffuse flux of high-energy
astrophysical ν



KM3NeT vs. IceCube & Auger

UHE ν flux inferred from KM3NeT event
when considered by itself

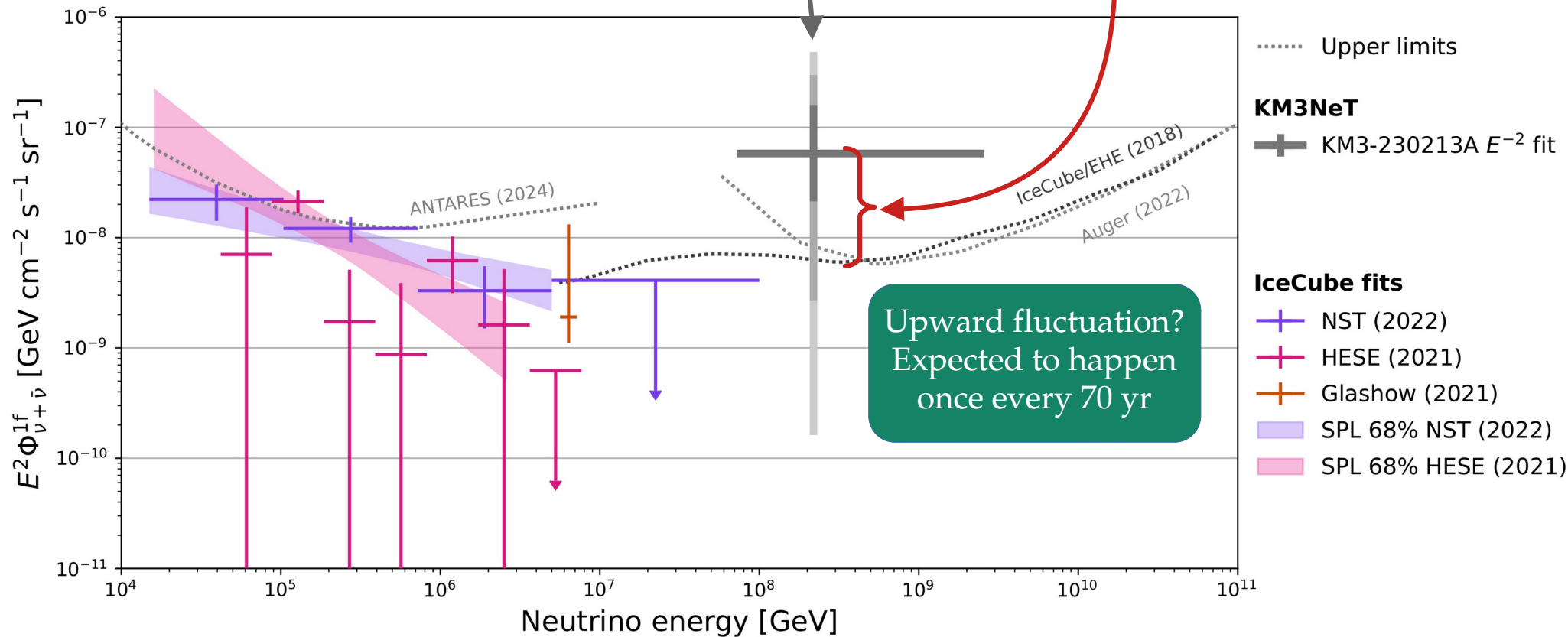
Flux is above upper limits!



KM3NeT vs. IceCube & Auger

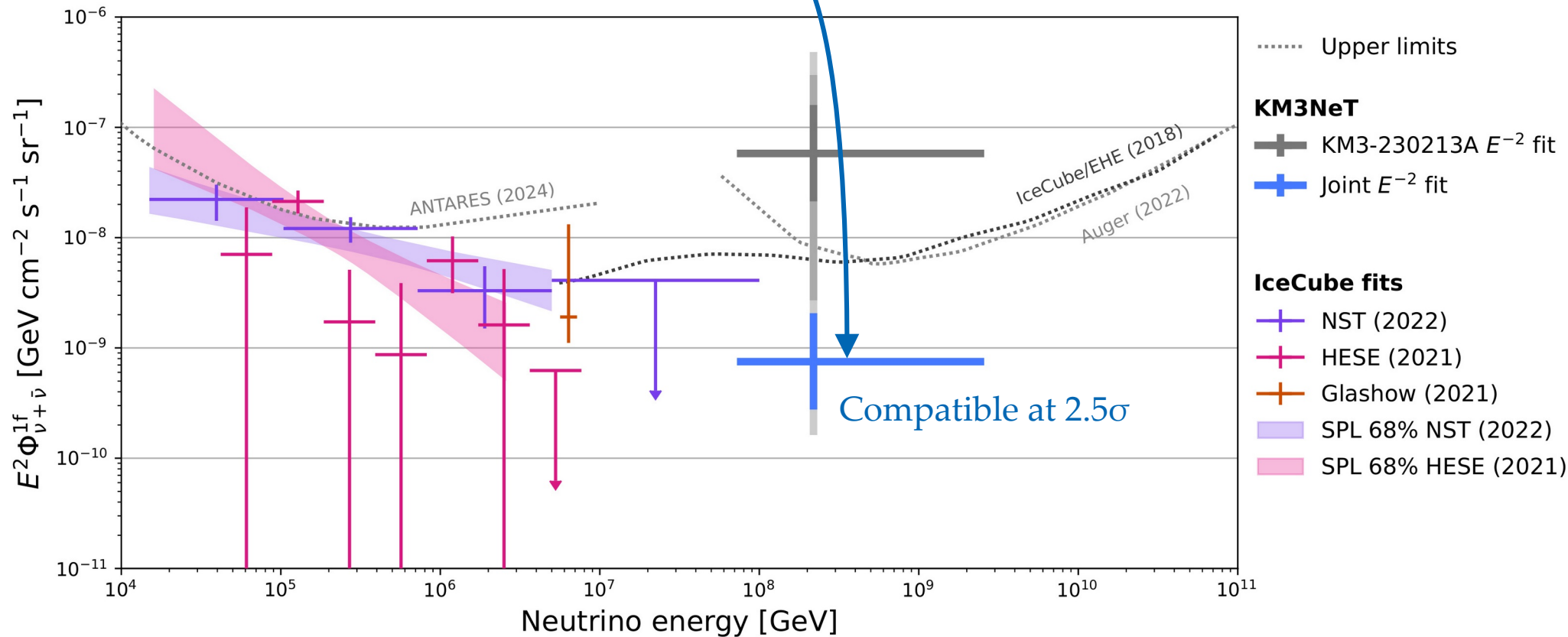
UHE ν flux inferred from KM3NeT event
when considered by itself

Flux is above upper limits!



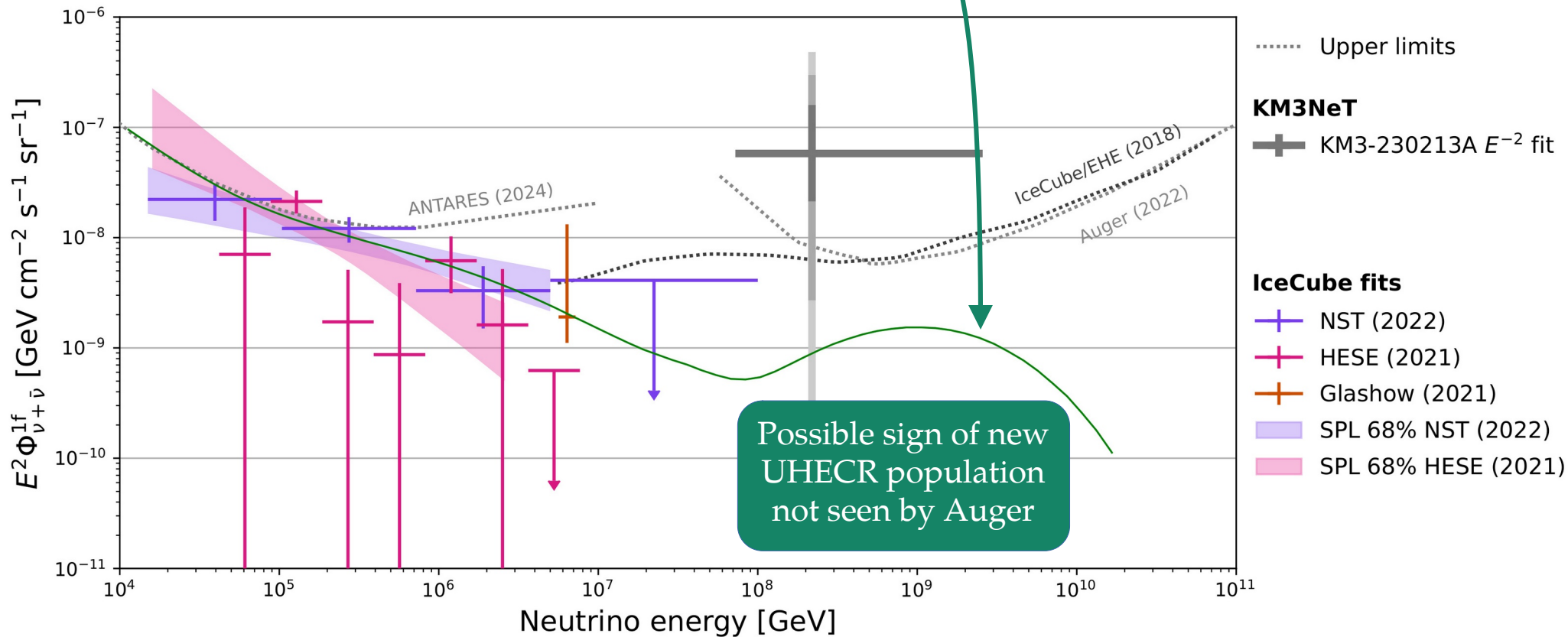
KM3NeT vs. IceCube & Auger

UHE ν flux inferred when considering non-observation by IceCube & Auger



Joint neutrino + cosmic-ray interpretation

Joint fit to IceCube and KM3NeT ν data + Auger UHECR data
(Assuming 100 PeV for KM3-230213A)



Pushing ν physics
to the cosmic frontier

Fundamental physics with high-energy cosmic neutrinos

Numerous new ν physics effects grow as $\sim \kappa_n \cdot E^n \cdot L$

If BSM effects are comparable in size to SM effects, then we can probe

$$\kappa_n \sim 10^{-47} \left(\frac{E}{\text{PeV}} \right)^{-n} \left(\frac{L}{\text{Gpc}} \right)^{-1} \text{PeV}^{1-n}$$

With 1-PeV ν : $\kappa_2 \sim 10^{-47} \text{PeV}^{-1}$

With 100-PeV ν : $\kappa_2 \sim 10^{-51} \text{PeV}^{-1}$



Orders-of-magnitude improvement

Fundamental physics with high-energy cosmic neutrinos

Numerous new ν physics effects grow as $\sim \kappa_n \cdot E^n \cdot L$ $\left\{ \begin{array}{l} \text{E.g.,} \\ n = -1: \text{neutrino decay} \\ n = 0: \text{CPT-odd Lorentz violation} \\ n = +1: \text{CPT-even Lorentz violation} \end{array} \right.$

If BSM effects are comparable in size to SM effects, then we can probe

$$\kappa_n \sim 10^{-47} \left(\frac{E}{\text{PeV}} \right)^{-n} \left(\frac{L}{\text{Gpc}} \right)^{-1} \text{PeV}^{1-n}$$

With 1-PeV ν : $\kappa_2 \sim 10^{-47} \text{PeV}^{-1}$

With 100-PeV ν : $\kappa_2 \sim 10^{-51} \text{PeV}^{-1}$

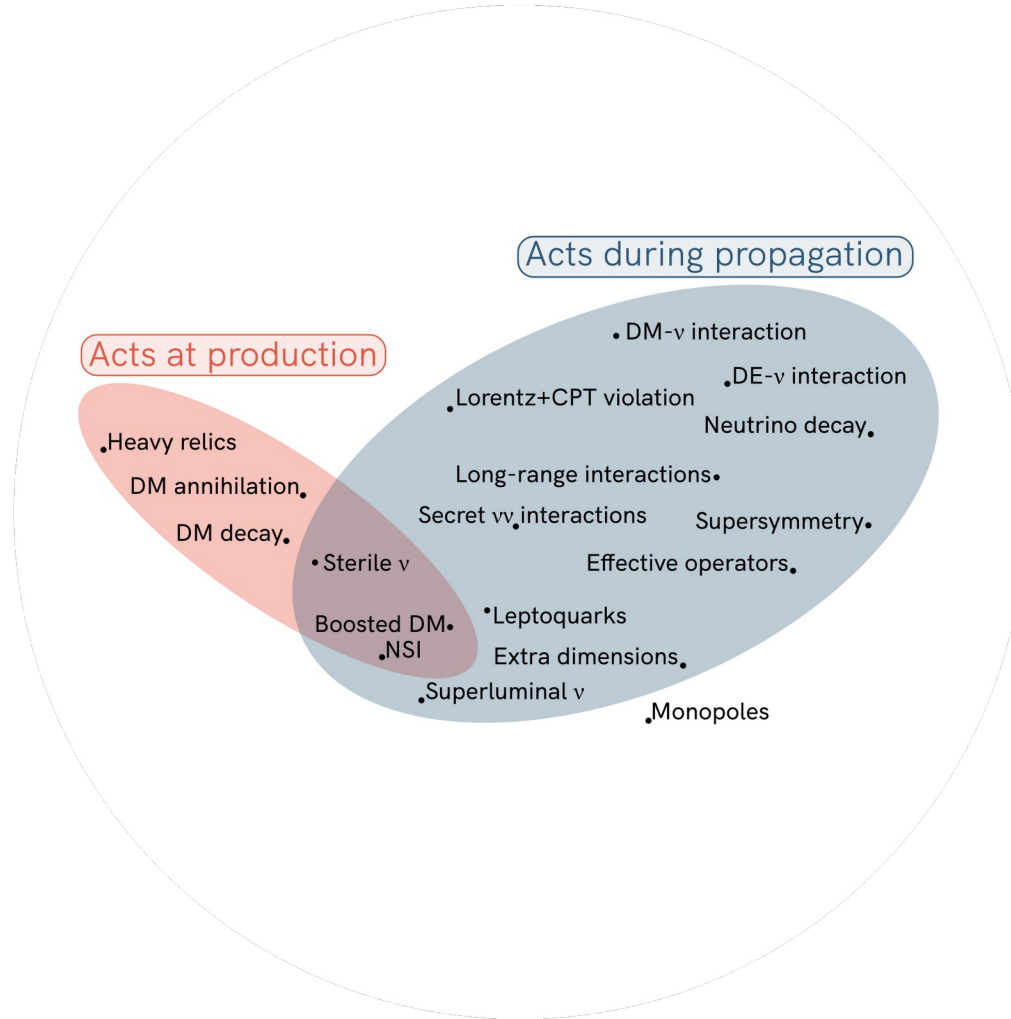
Orders-of-magnitude improvement



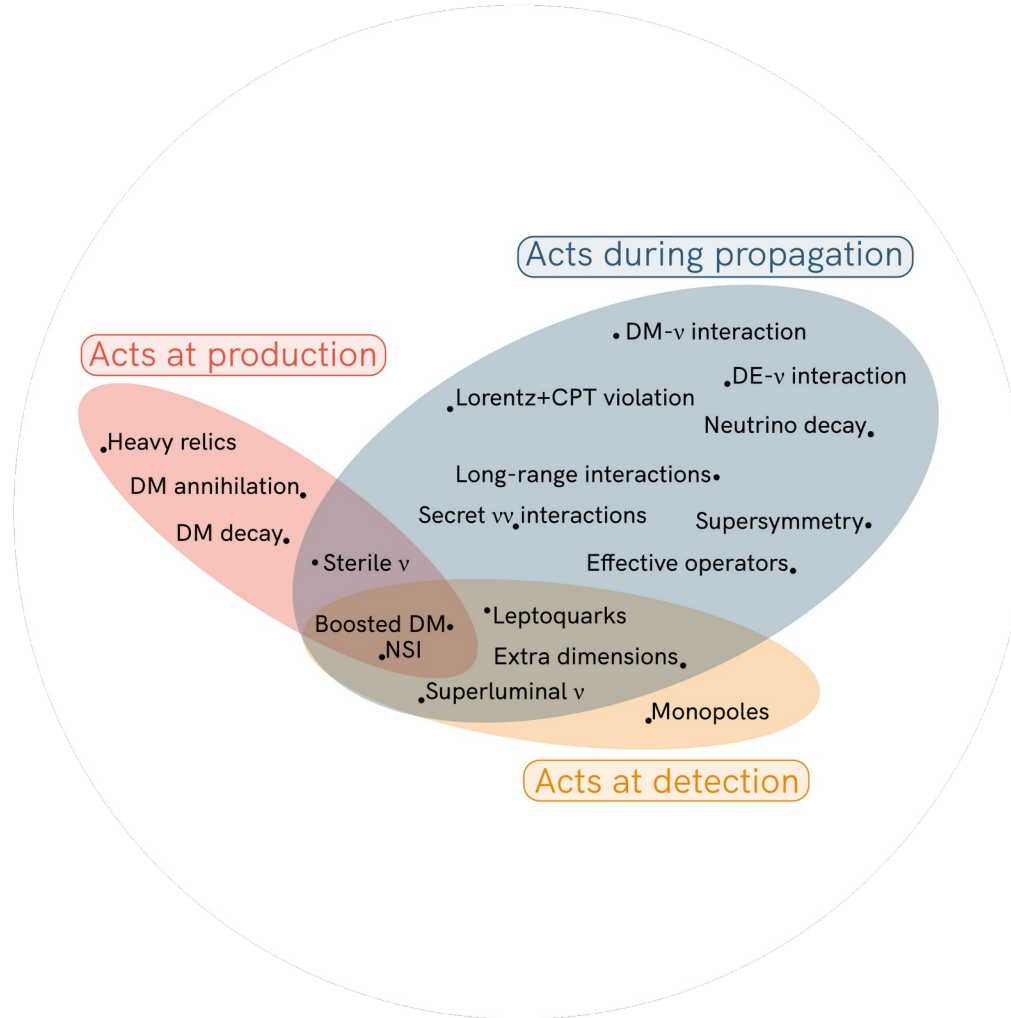
Note: Not an exhaustive list



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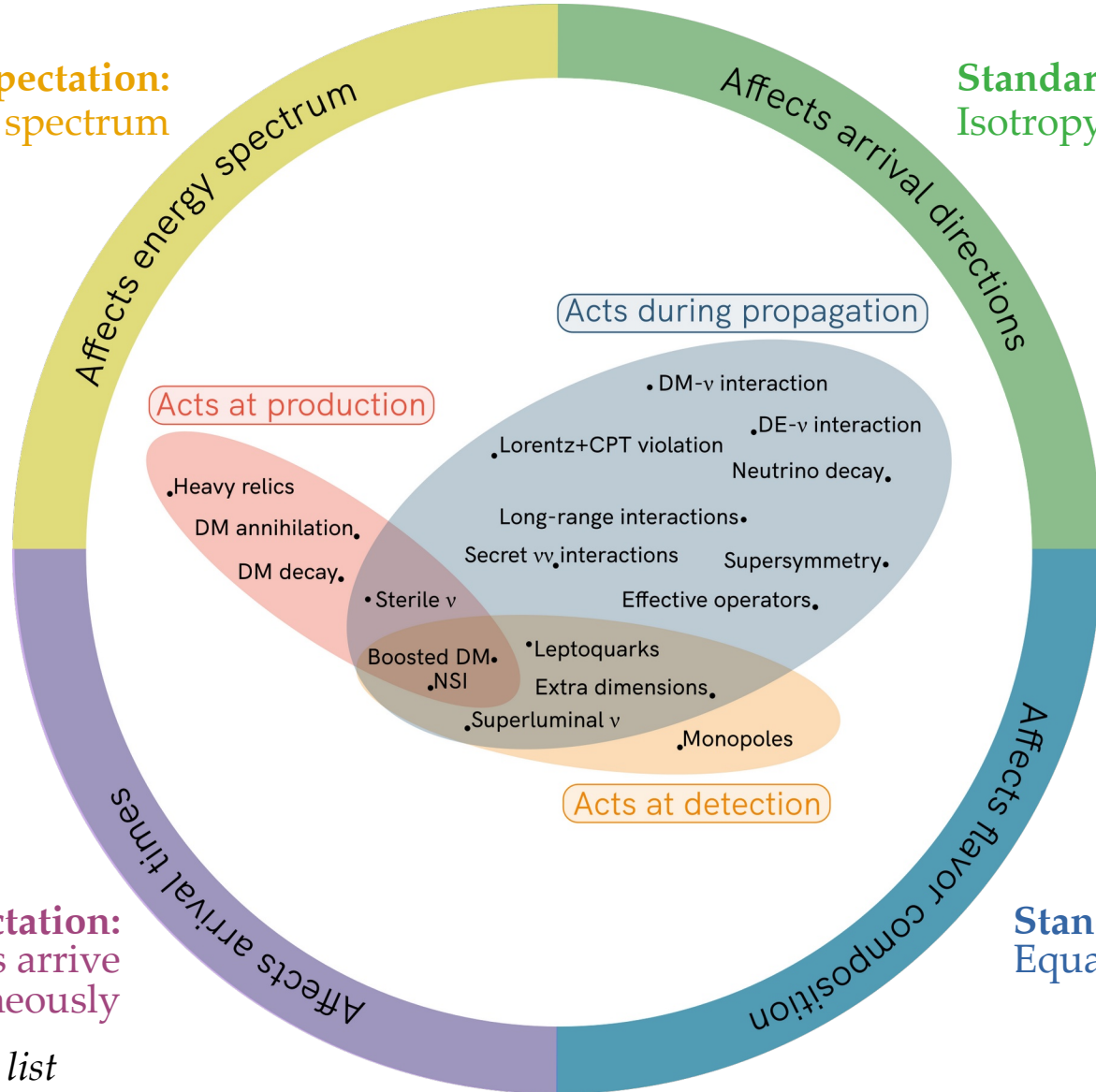
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Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



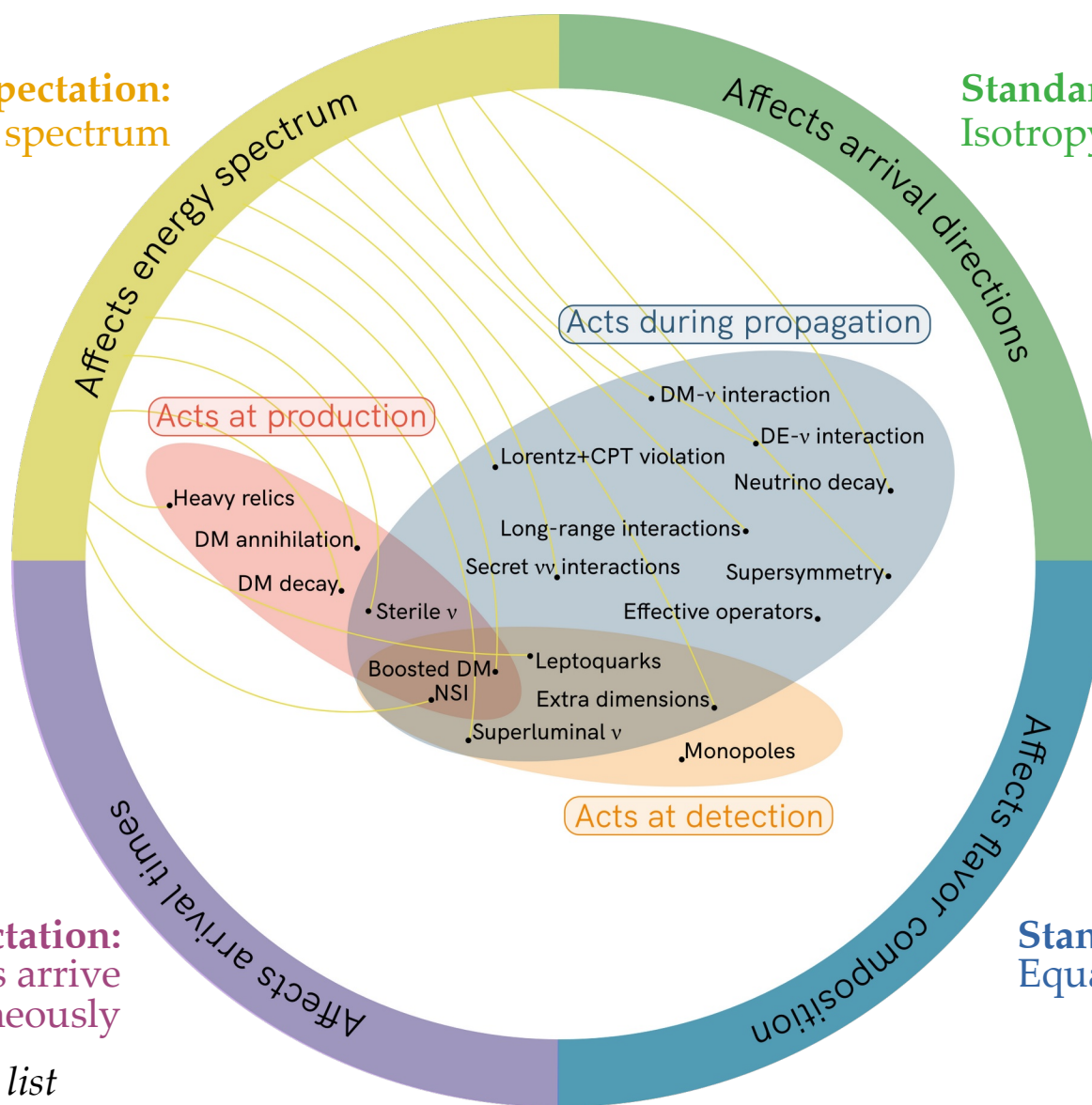
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Equal number of ν_e, ν_μ, ν_τ

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 ν and γ from transients arrive simultaneously

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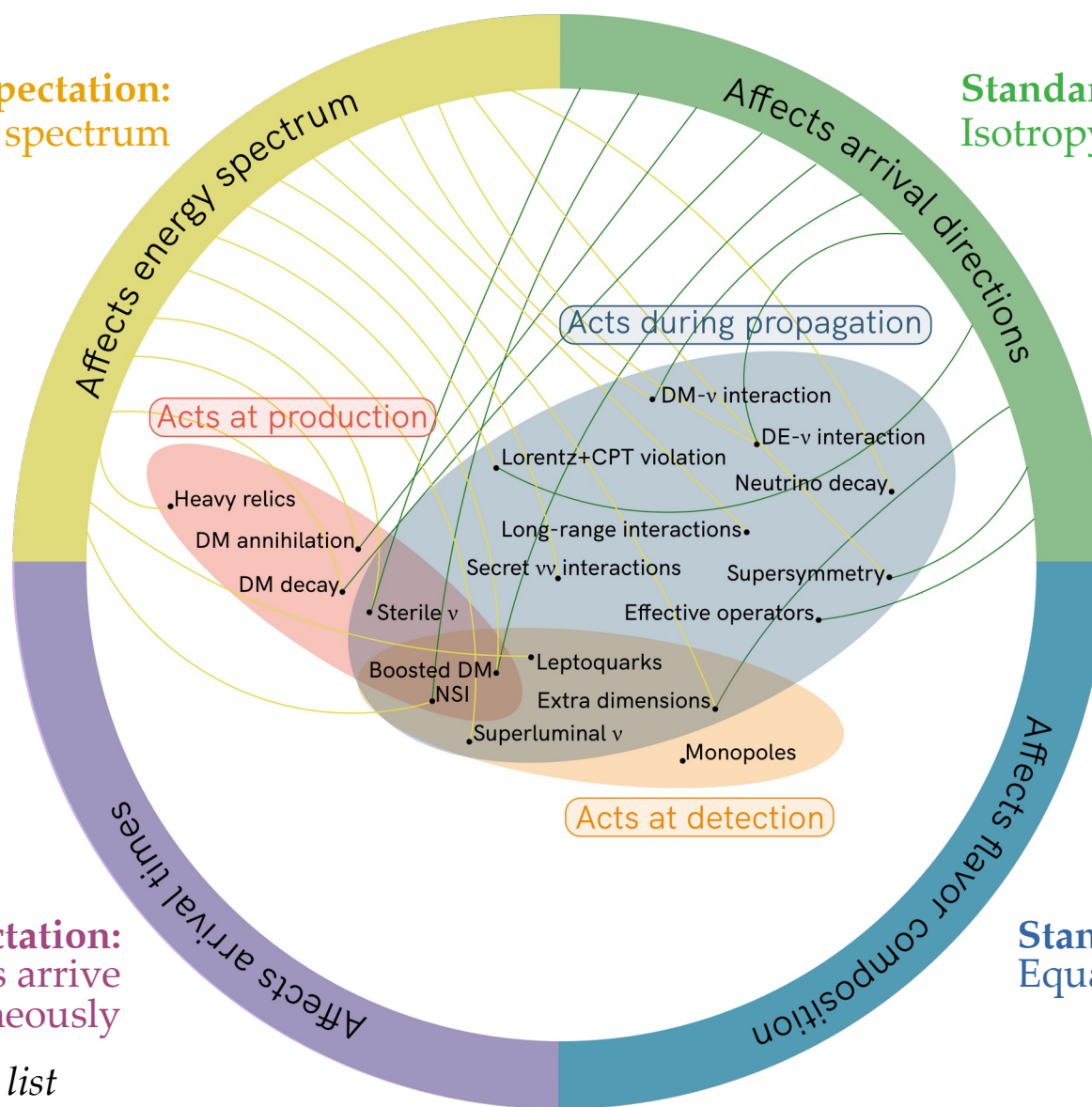
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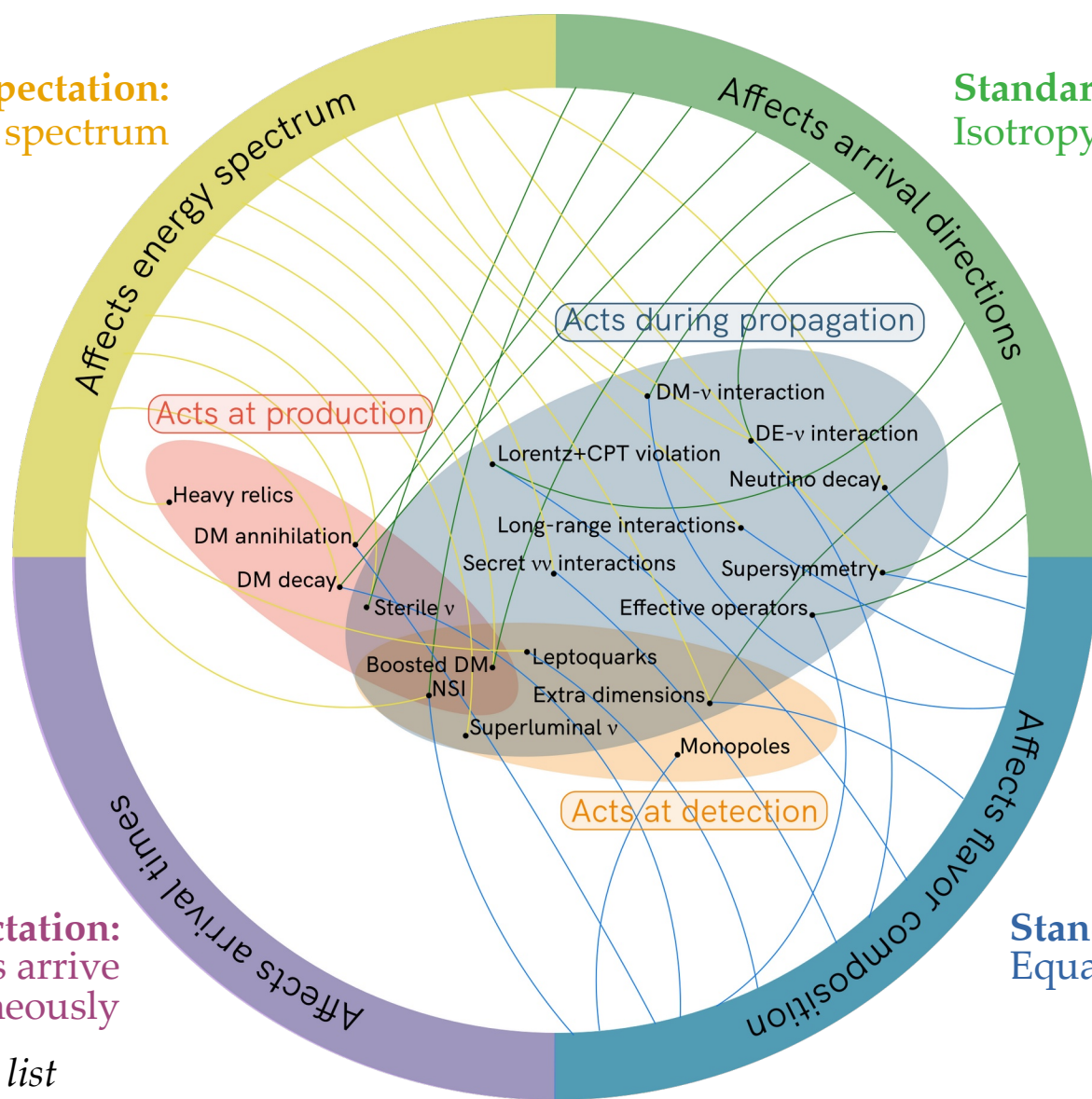
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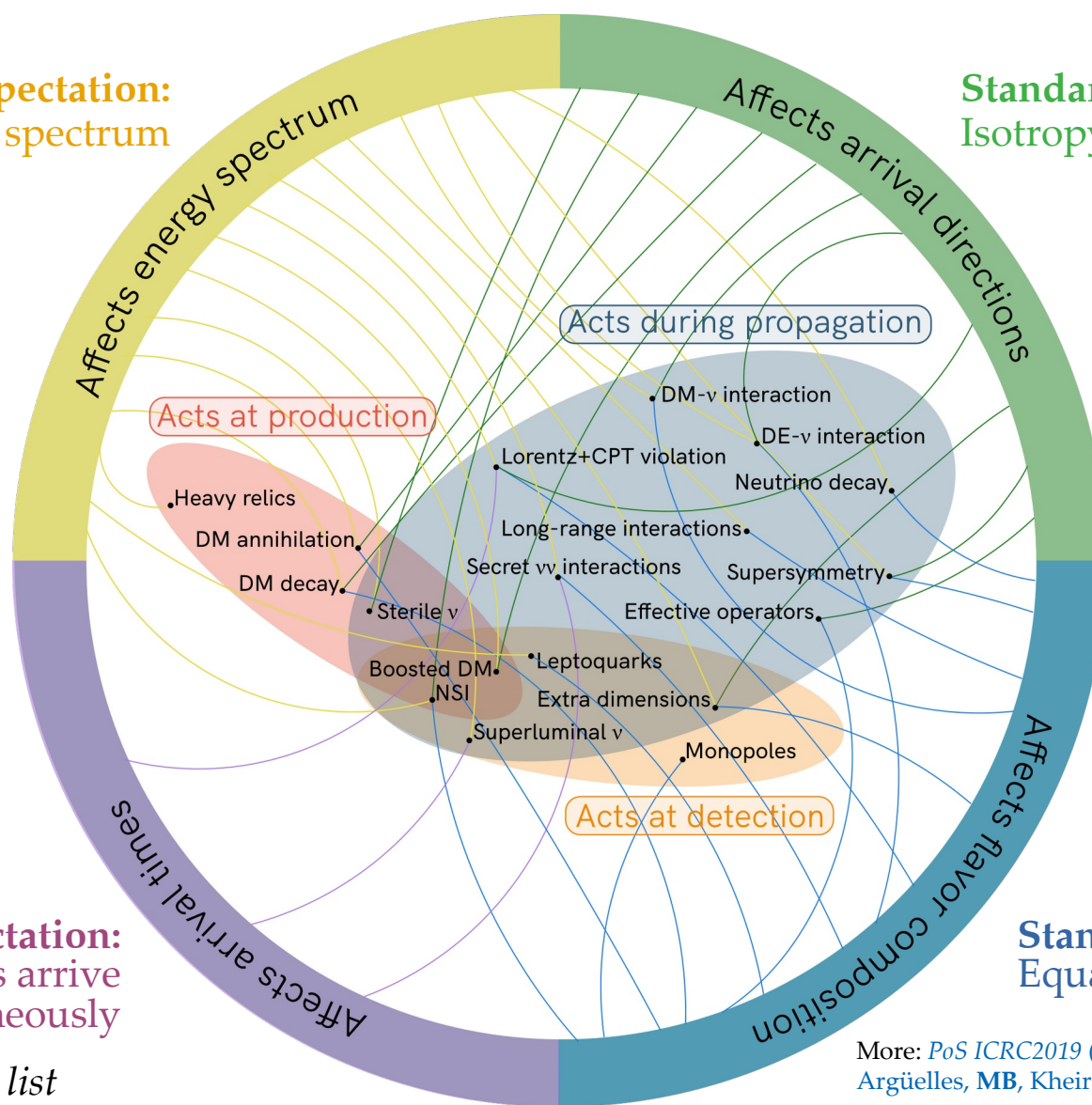
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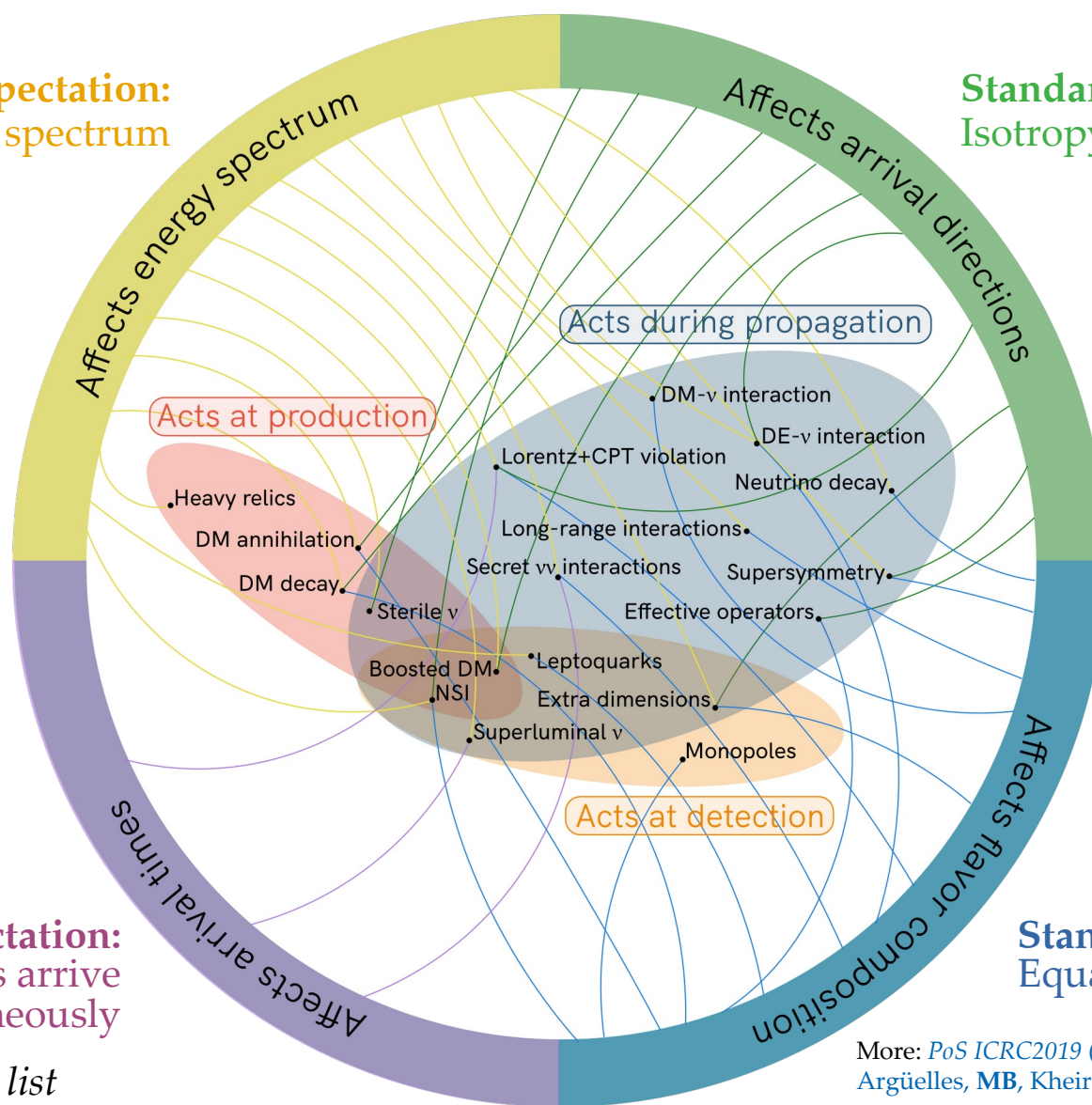
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More: *PoS ICRC2019 (1907.08690)*
Argüelles, MB, Kheirandish, Palomares-Ruiz, Salvadó, Vincent

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