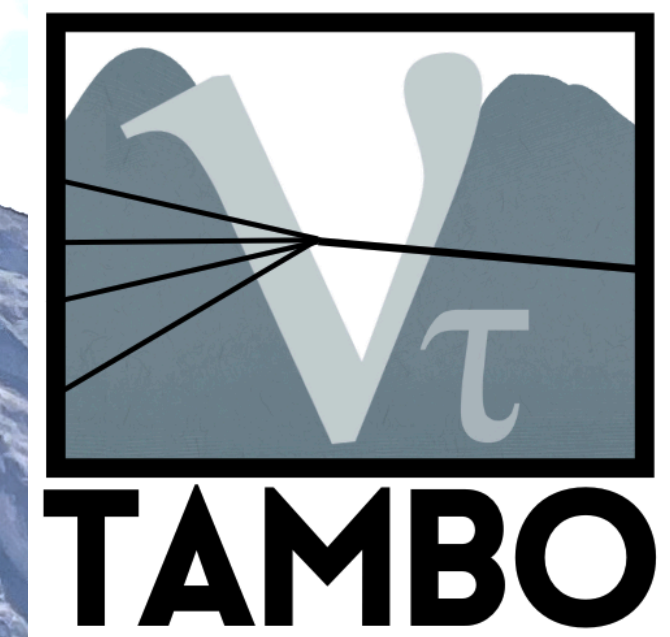




TAMBO: Context and Science

Carlos Argüelles

TAMBO-101, PUCP, Lima, Oct. 20th, 2025



RESEARCH CORPORATION
for SCIENCE ADVANCEMENT



the David
Lucile Packard
FOUNDATION



The Quantum Neutrino

One of the most striking features of neutrinos is their extremely long quantum coherence length.

Flavor measurements of neutrinos so far the only evidence of non-zero neutrino masses

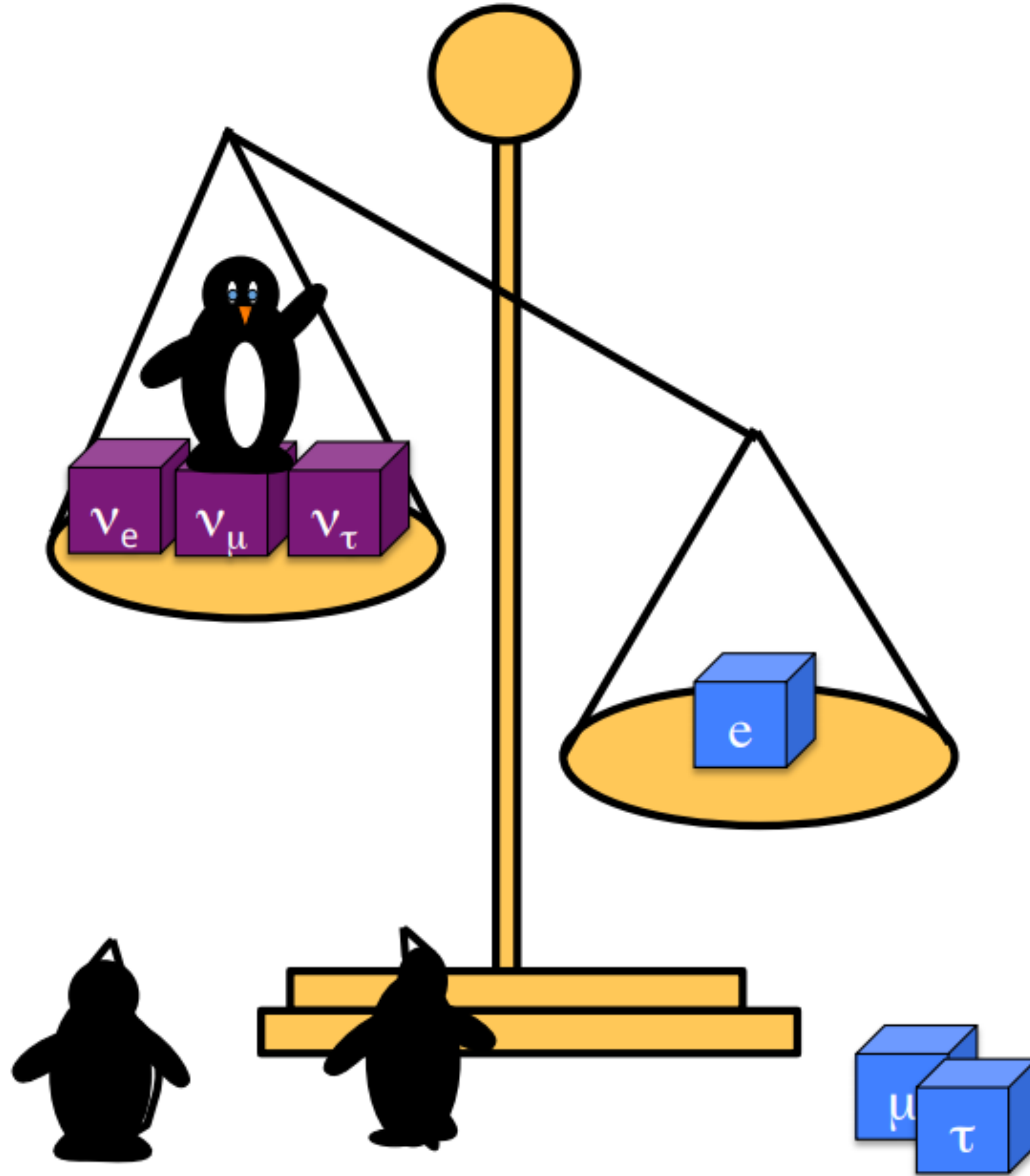
Origin of neutrino masses: a big mystery!

Y. Farzan & A. Y. Smirnov, *Nucl. Phys. B* (2008)

Carlos A. Argüelles —TAMBO101@PUCP

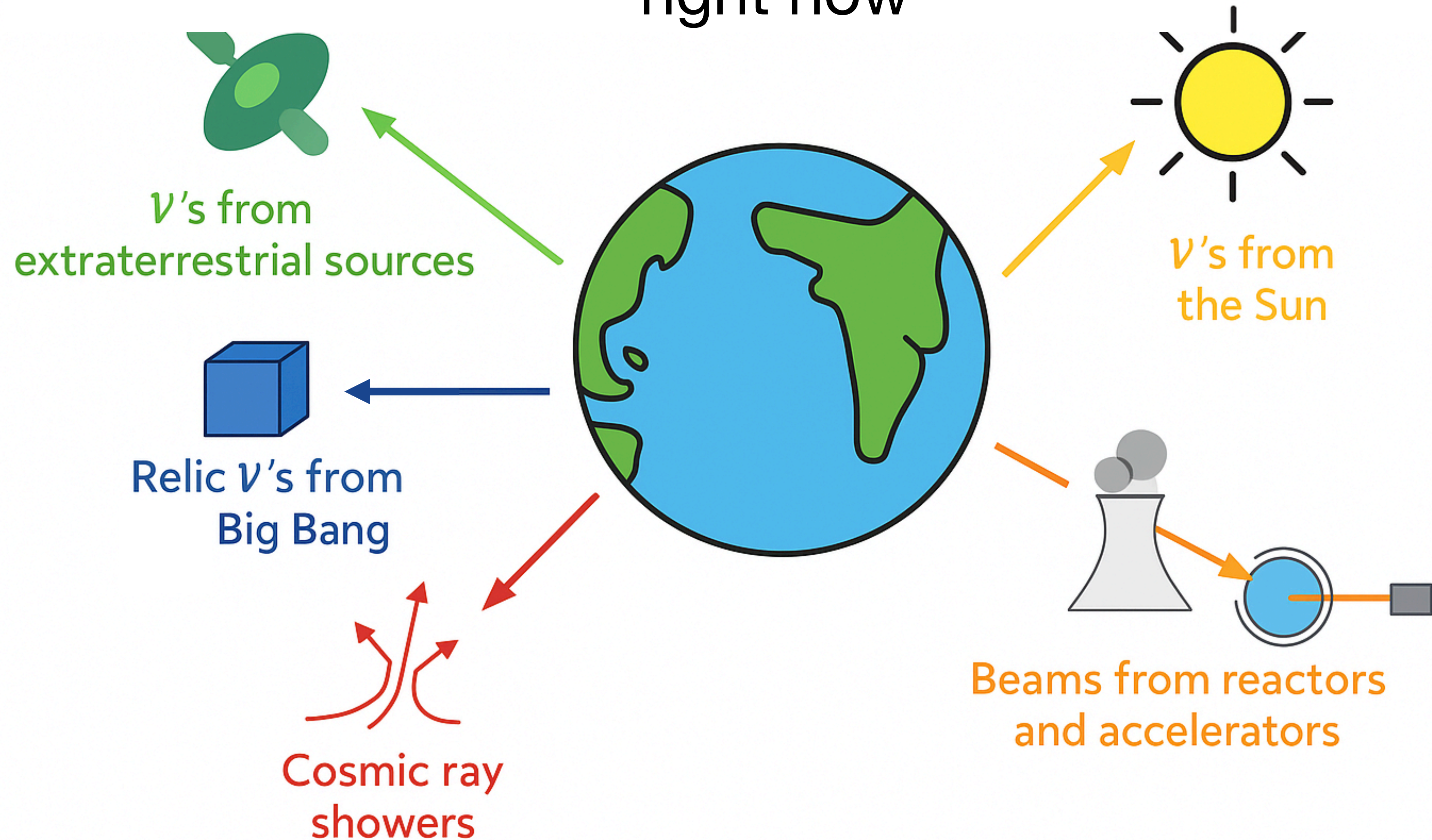


Neutrinos 101



Three
Very
Light
Neutrinos

40 Billion neutrinos are going through your thumbnail right now



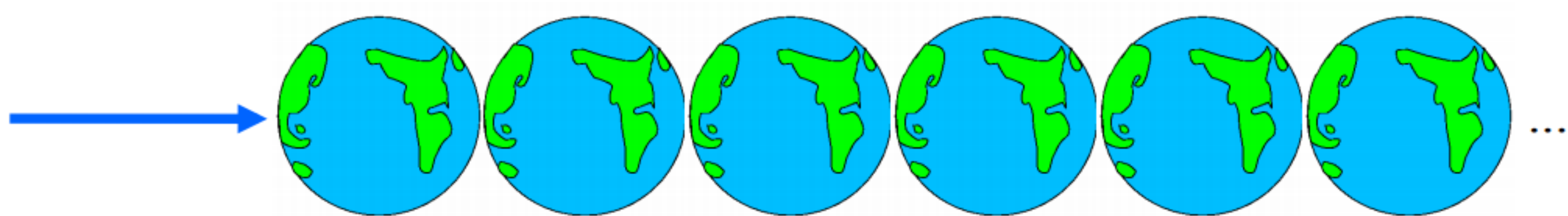
They interact by the **weak** force

Interactions don't happen often!

Solar neutrino cross section $\sim 10^{-43} \text{ cm}^2$

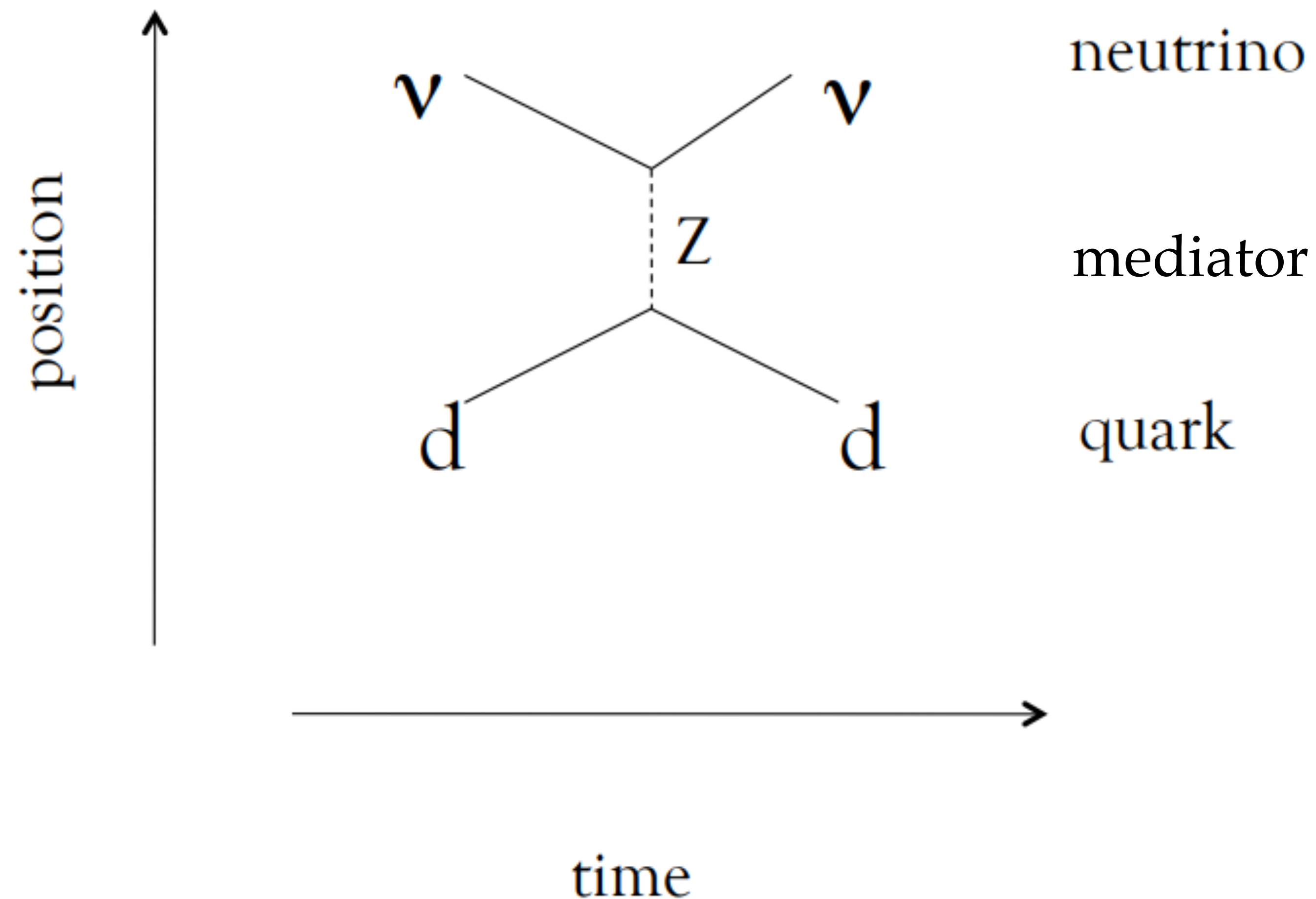
Atmospheric neutrino cross section $\sim 10^{-39} \text{ cm}^2$

Compared to pp fixed target $\sim 10^{-24} \text{ cm}^2$

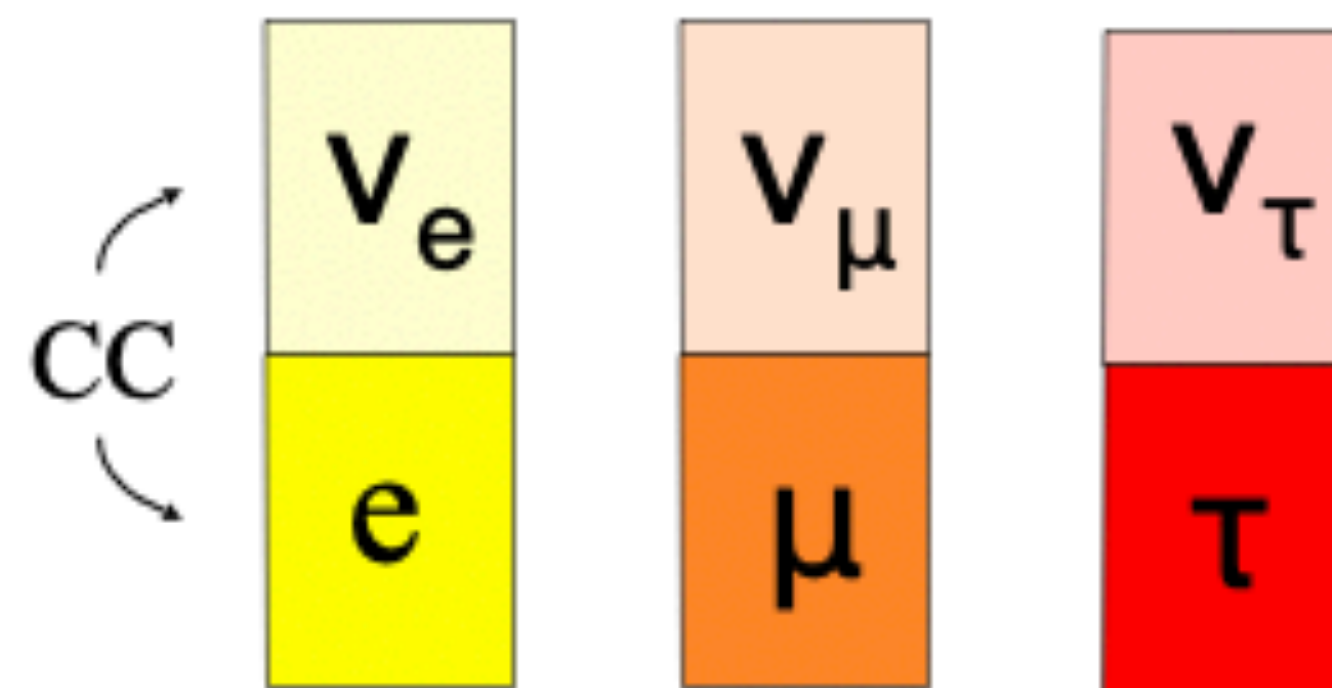
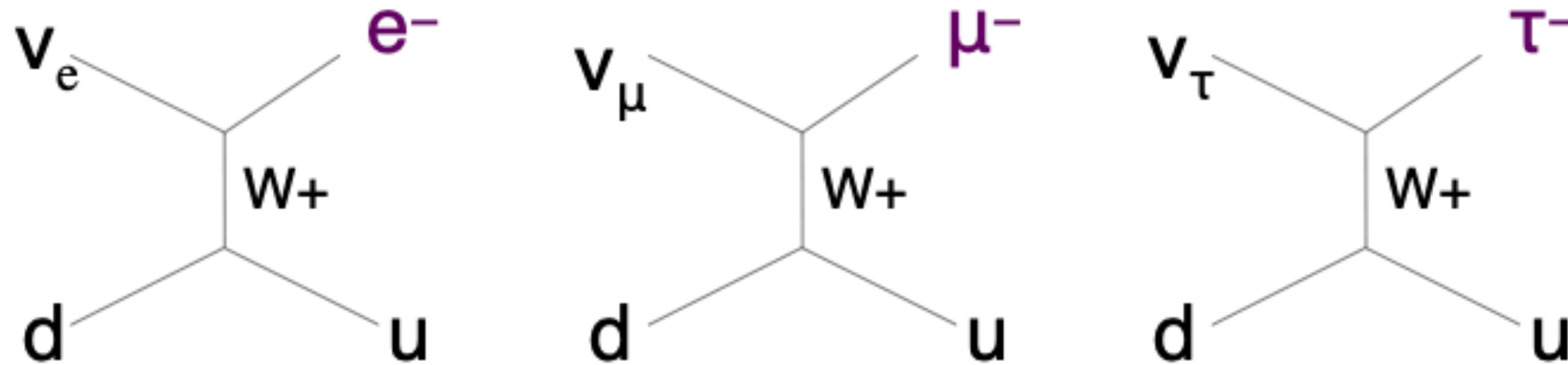


A 100 GeV neutrino produced in the atmosphere has
a good chance of traveling through
> 200 Earth's before interacting at all!

We describe interactions in terms of “exchange particles”



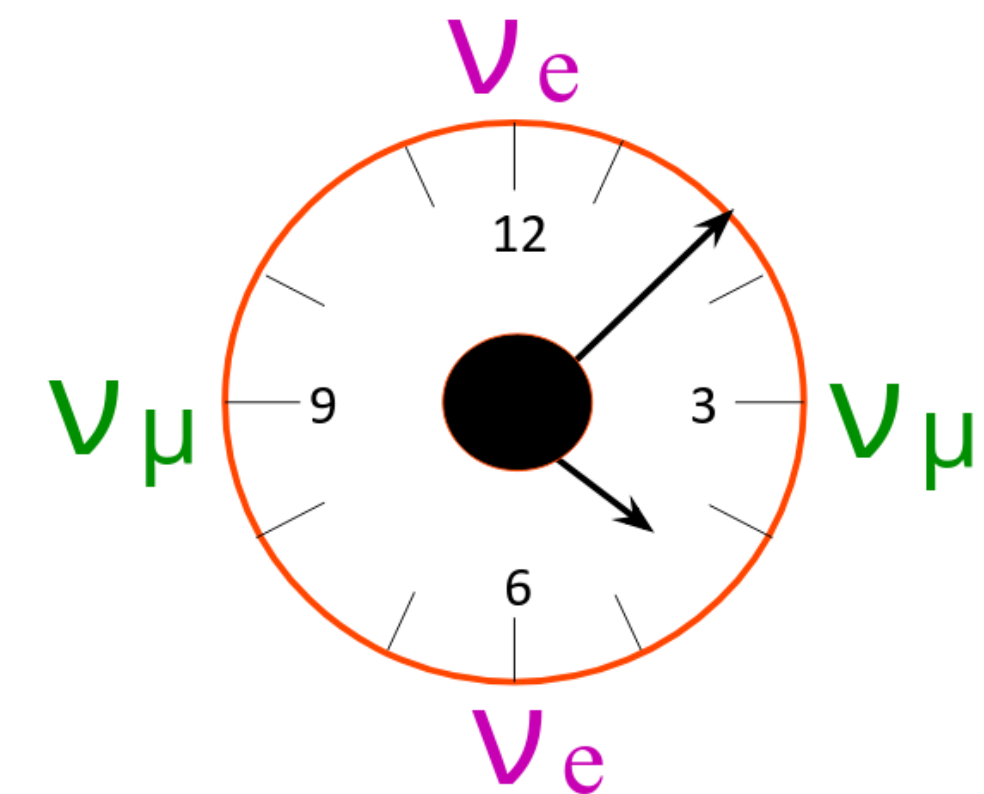
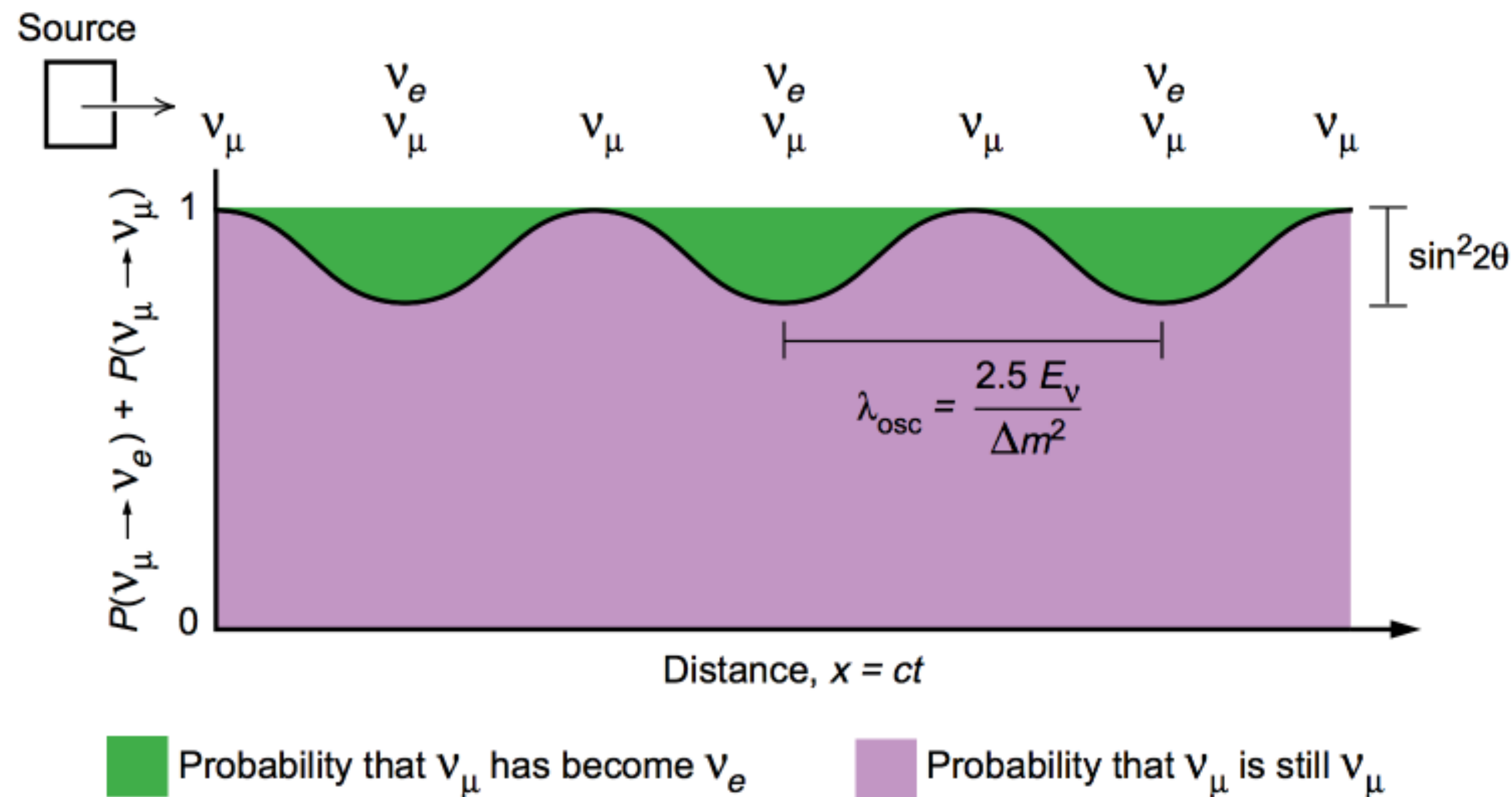
**We use the outgoing particle to classify the neutrino.
We term this neutrino “flavor.”**



Neutrinos: nature's chameleons

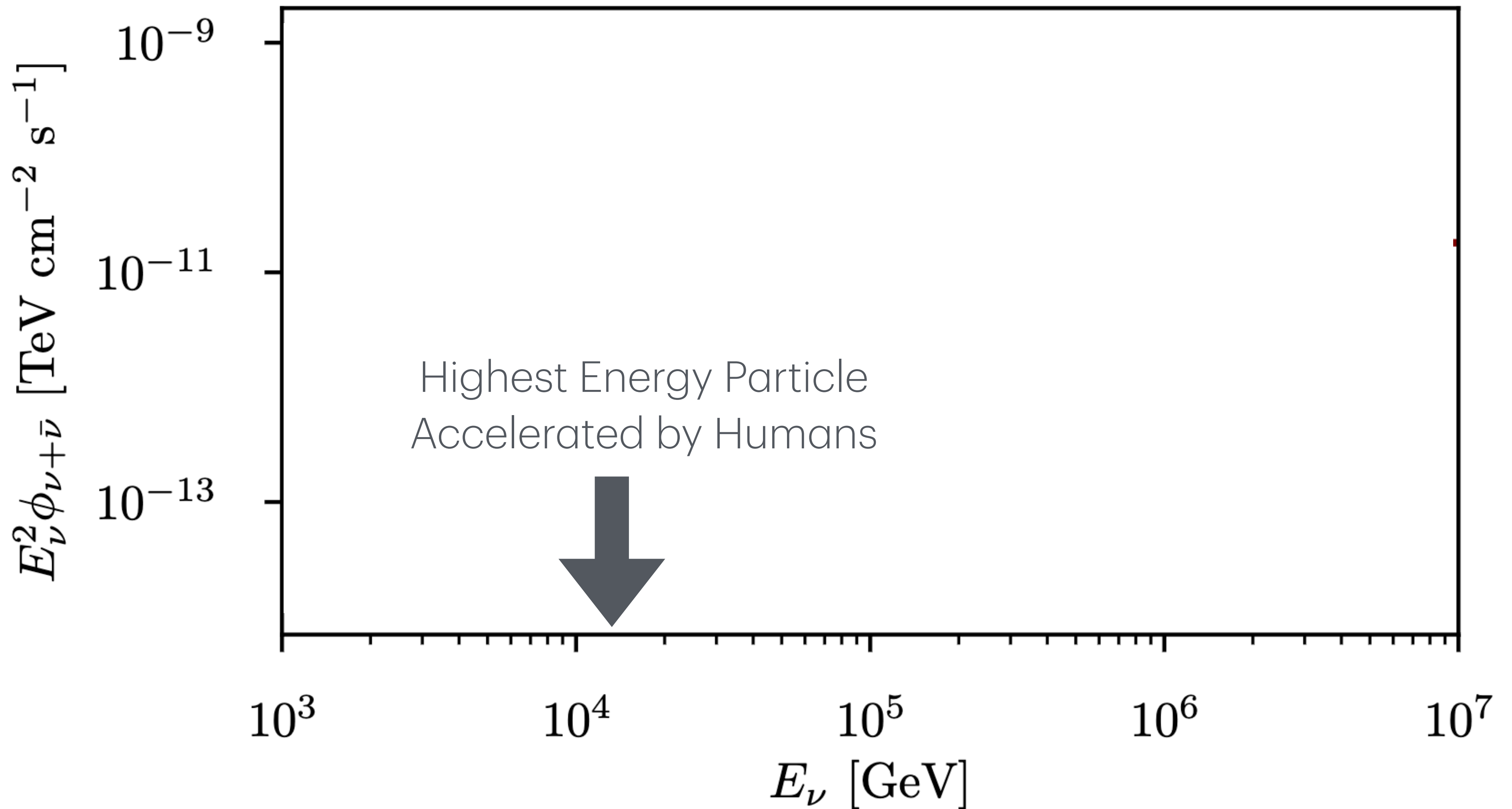
In two generations, the neutrino survival oscillation probability is given by:

$$P(\nu_\alpha \rightarrow \nu_\alpha) = 1 - \sin^2(2\theta) \sin^2 \left(\frac{1.27 \Delta m^2 L}{E} \right)$$

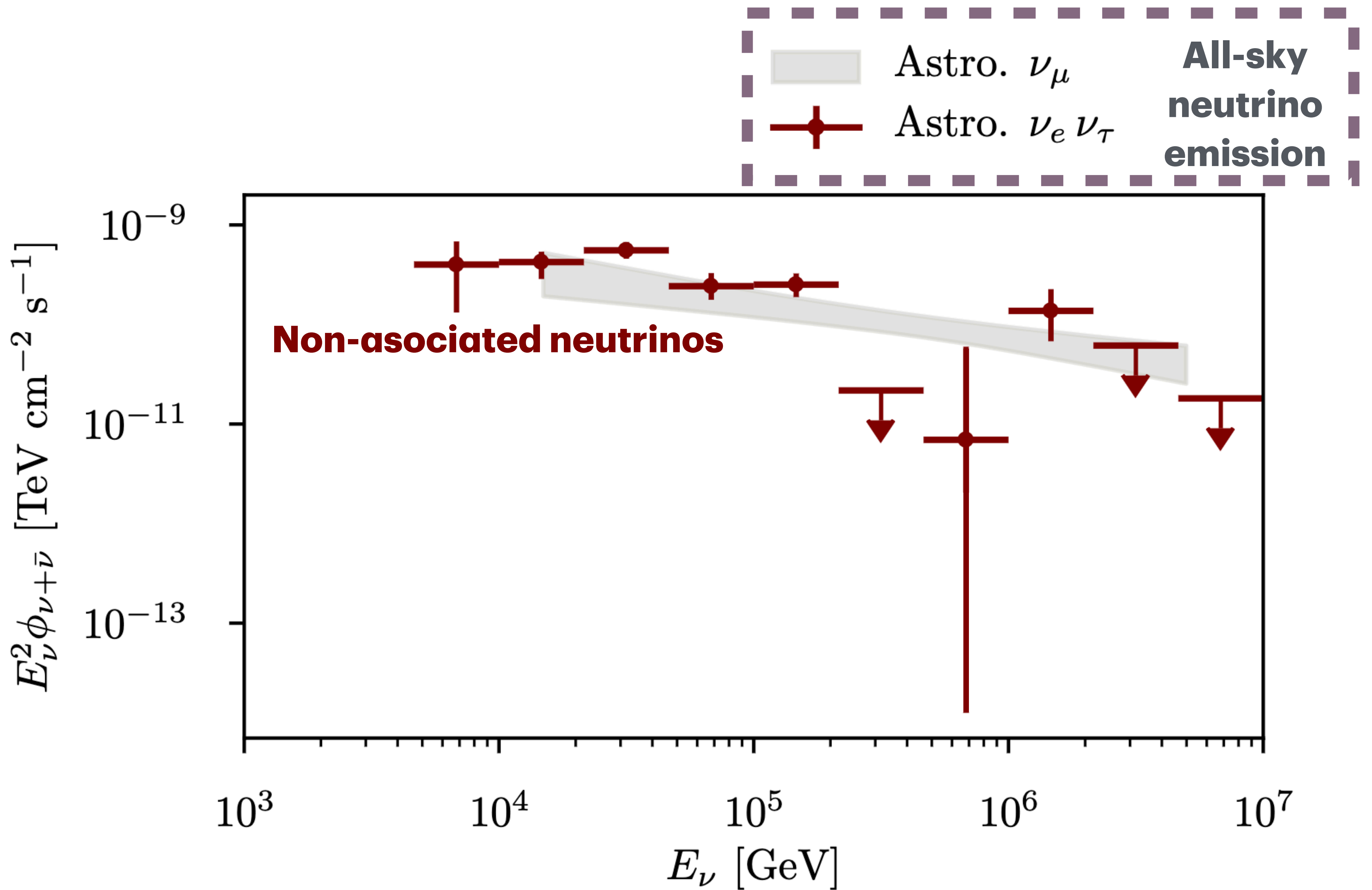


Astrophysical Neutrinos

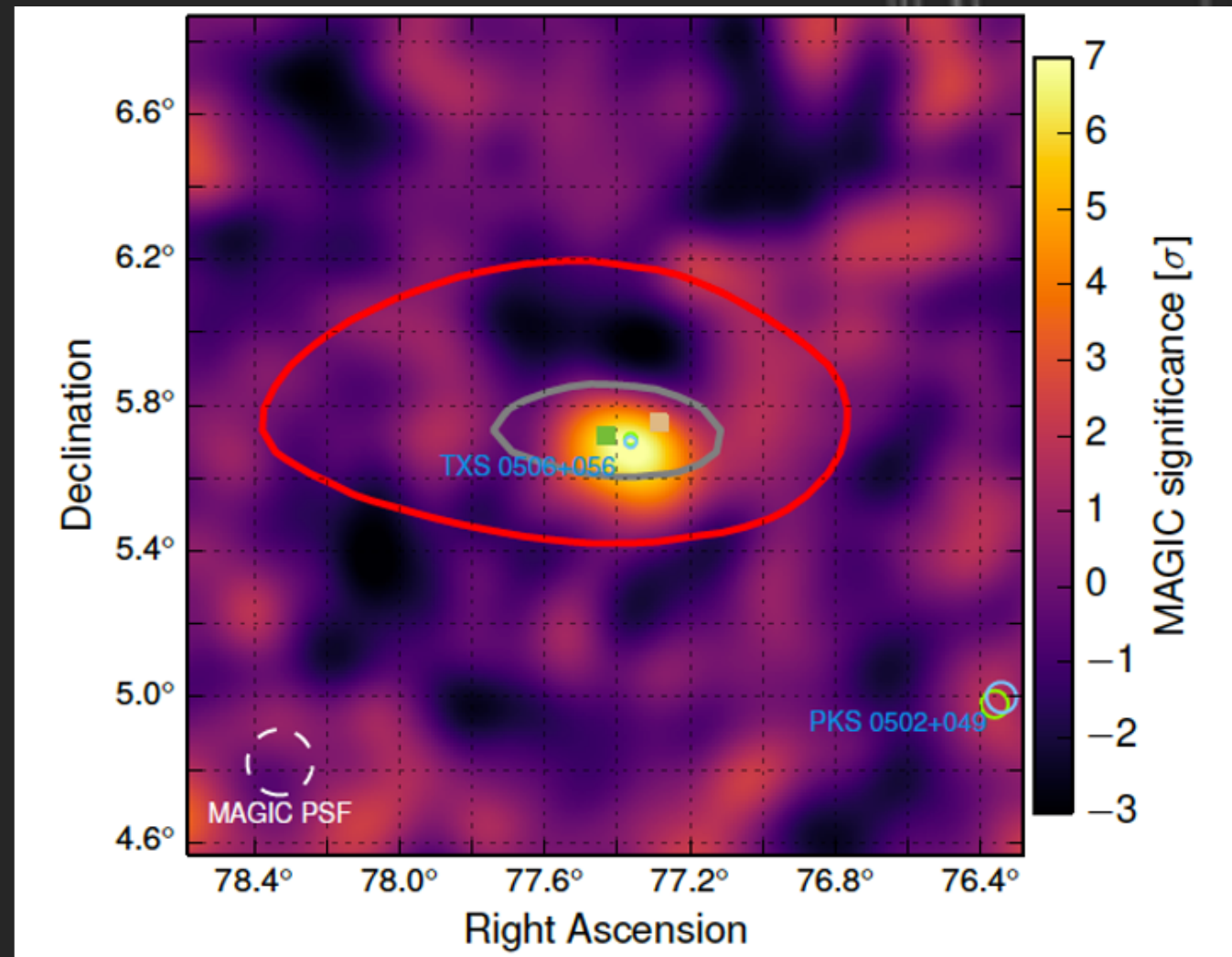
**Intensity of
Neutrino
Emission**



Intensity of Neutrino Emission

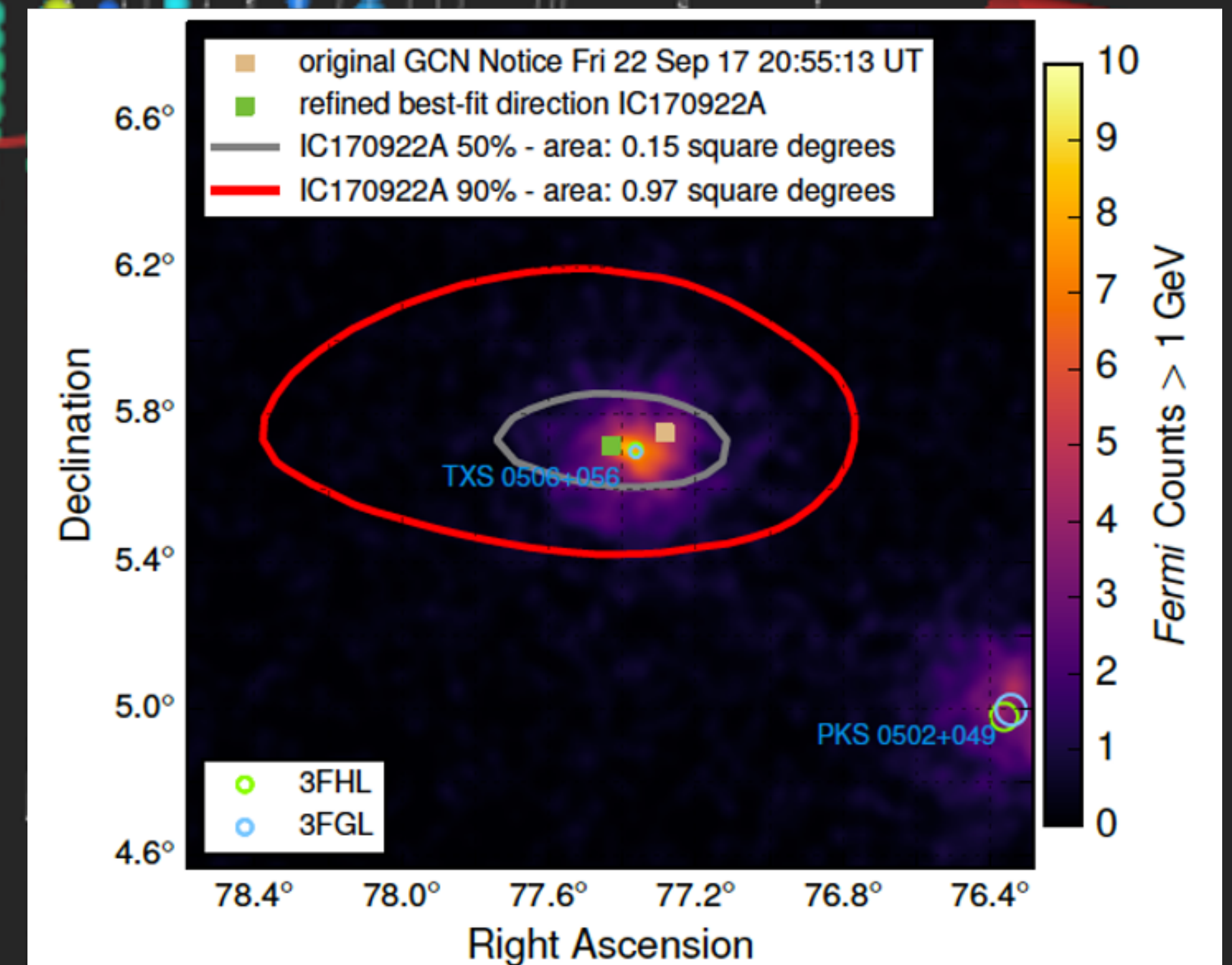


IceCube 170922



MAGIC
detects emission of
> 100 GeV gammas

Fermi
detects a flaring
blazar within 0.1°



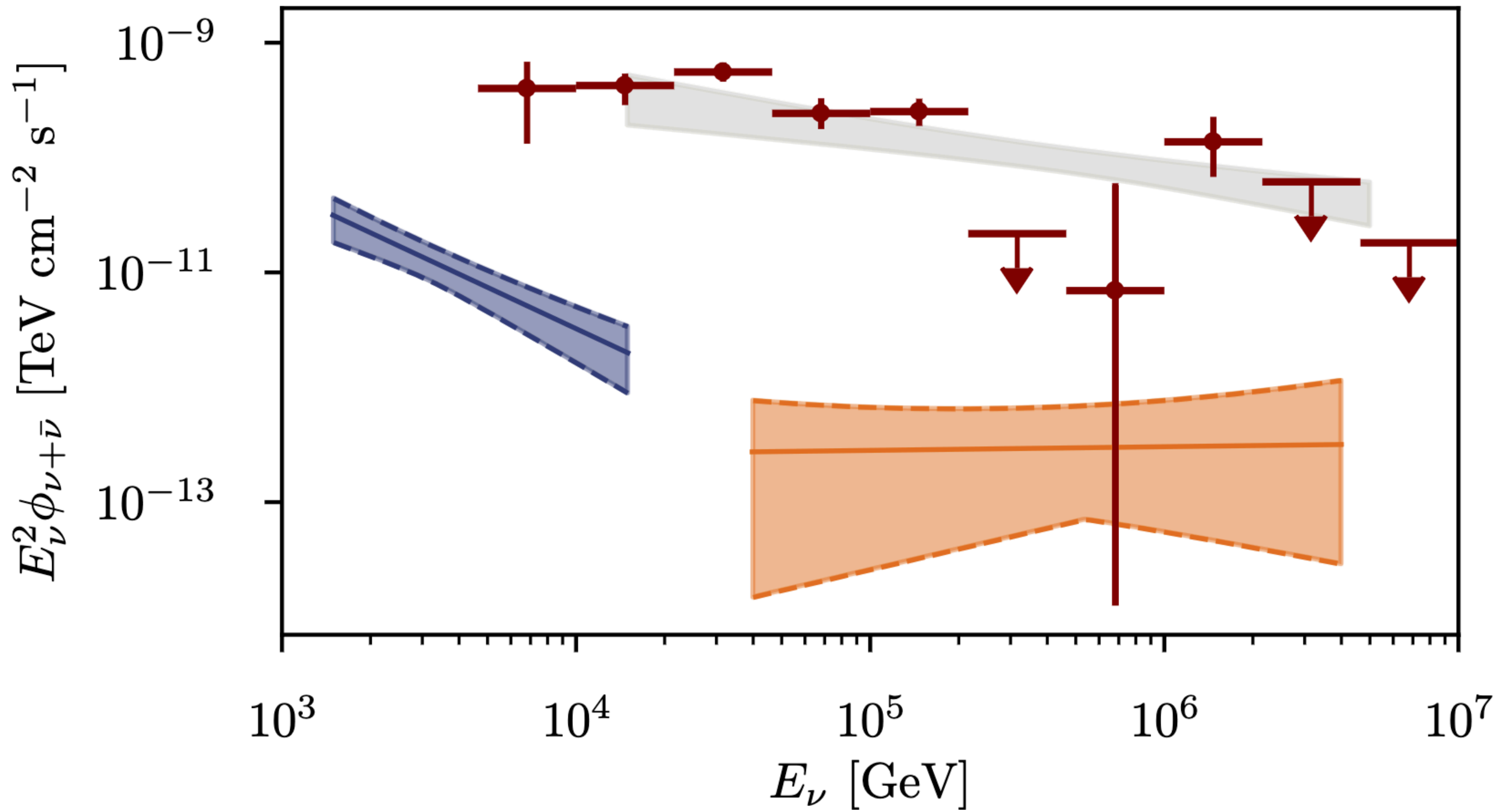
Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

The IceCube Collaboration, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S., *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, *Swift*/*NuSTAR*, VERITAS, and VLA/17B-403 teams*†



“Neutrino emission from the direction of the **blazar TXS 0506+056** prior to the IceCube-170922A alert,” IceCube Collaboration. *Science* 361, 147-151 (2018).

Intensity of Neutrino Emission



Identified Neutrino Sources



Galactic
Neutrinos



NGC 1068



TXS 0506+056



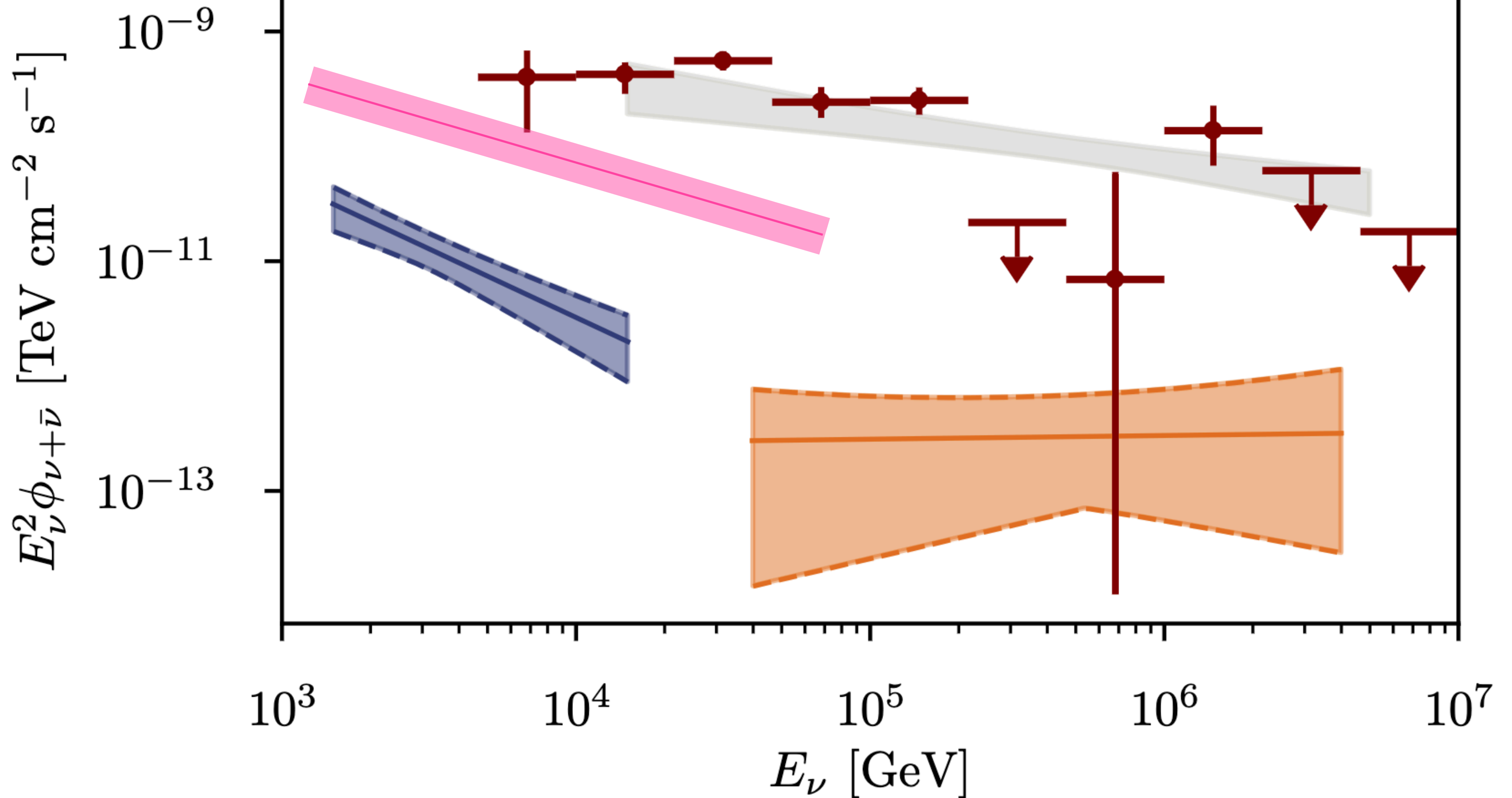
Astro. ν_μ



Astro. $\nu_e \nu_\tau$

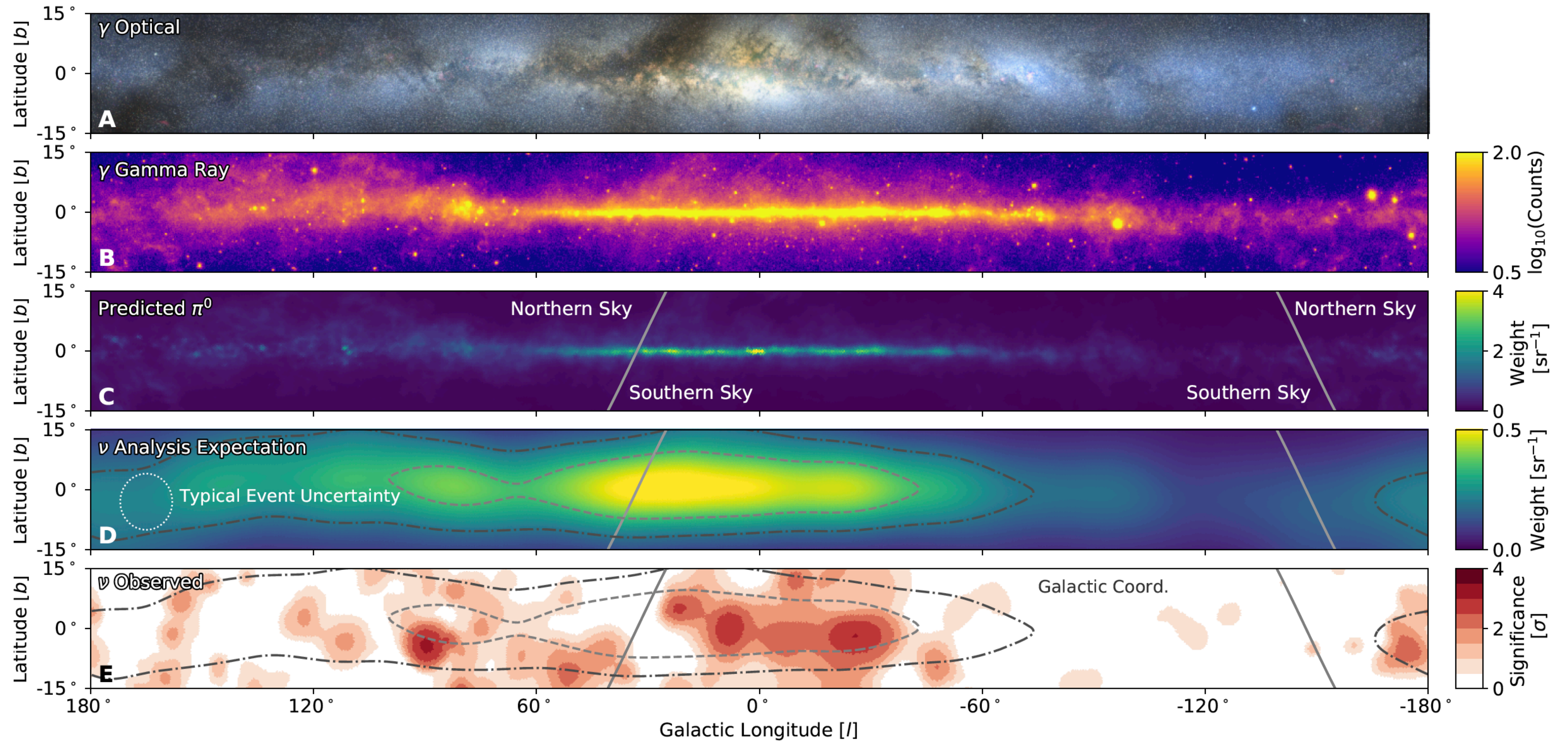
**All-sky
neutrino
emission**

Intensity of Neutrino Emission



Neutrinos from Our Galaxy

IceCube Collaboration, Science, 2023

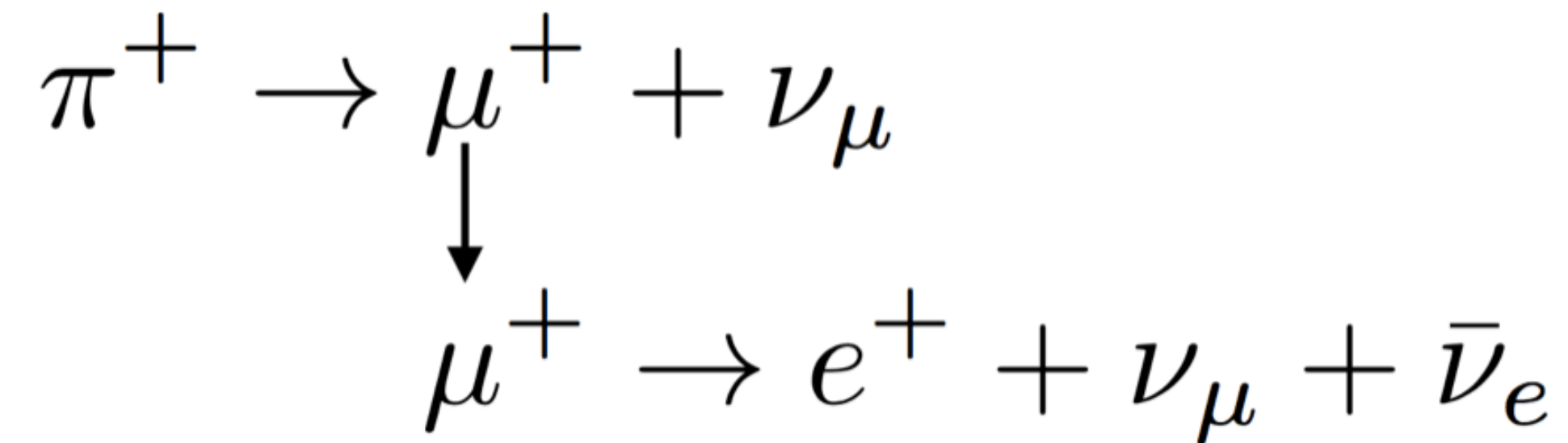


Flavor Composition at Source

(GRBs, AGNs, blazars, pulsars...)

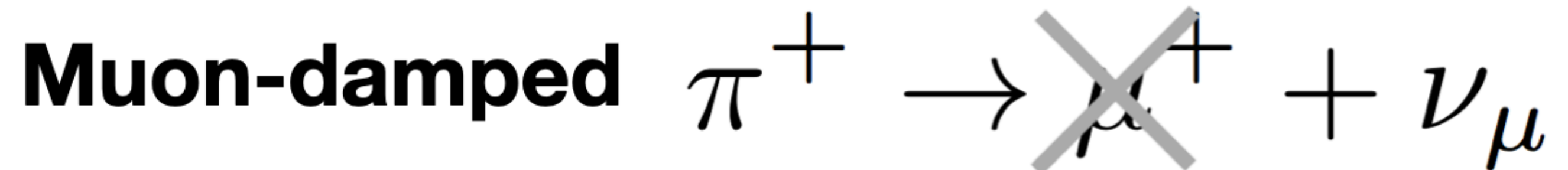
$(\alpha_e : \alpha_\mu : \alpha_\tau)$

Pion



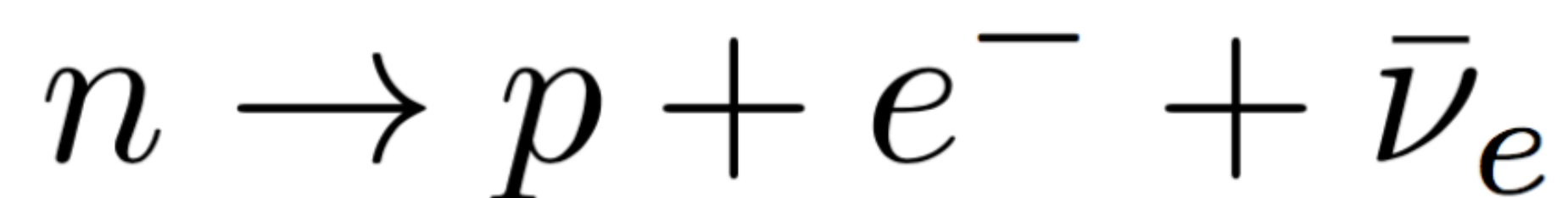
(1:2:0)

Muon-damped



(0:1:0)

Neutron

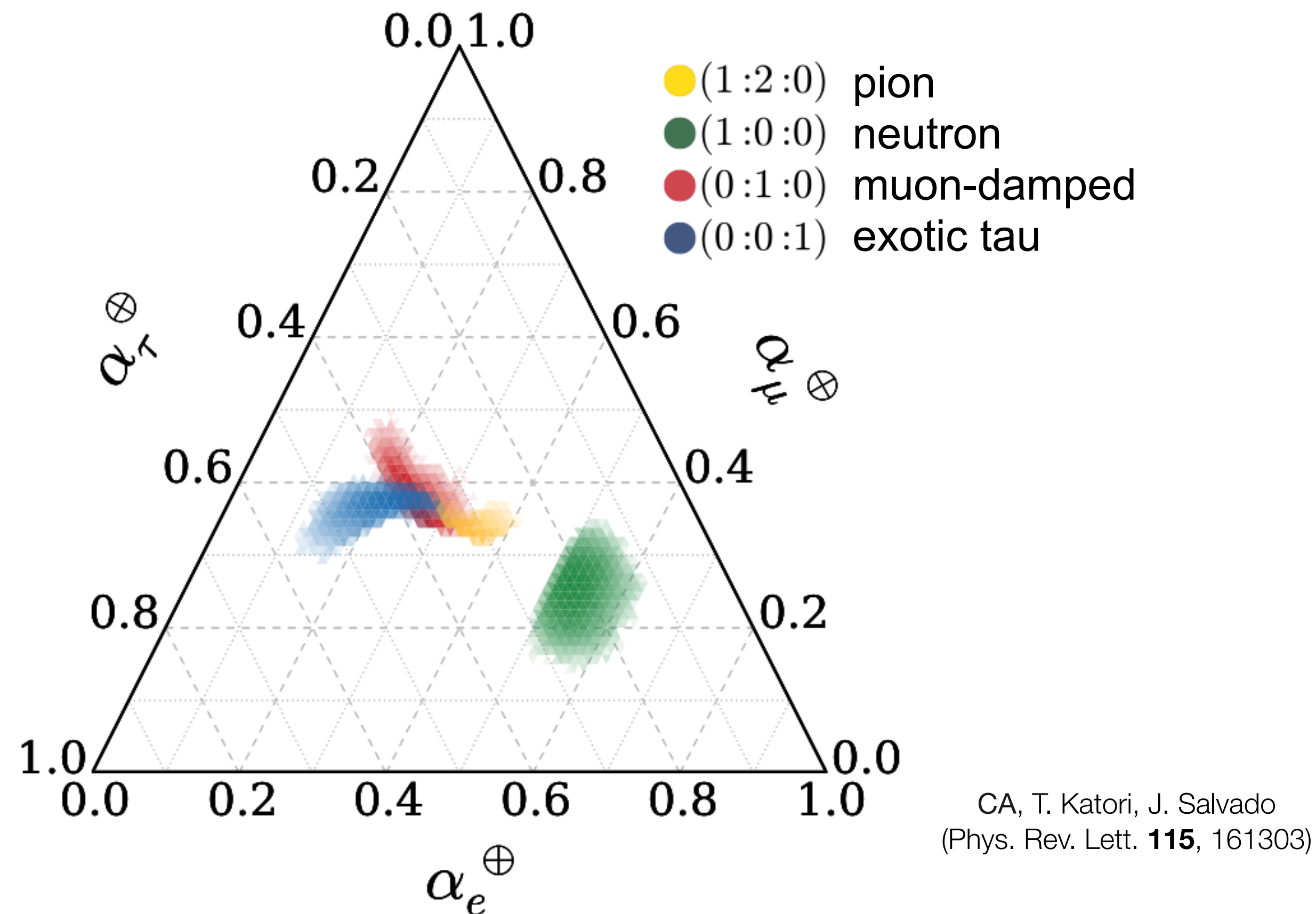


(1:0:0)

No significant tau neutrino production at the source

After Flavor Oscillations: Where Would different sources end up?

Measuring a flavor composition outside of these regions points to new physics!



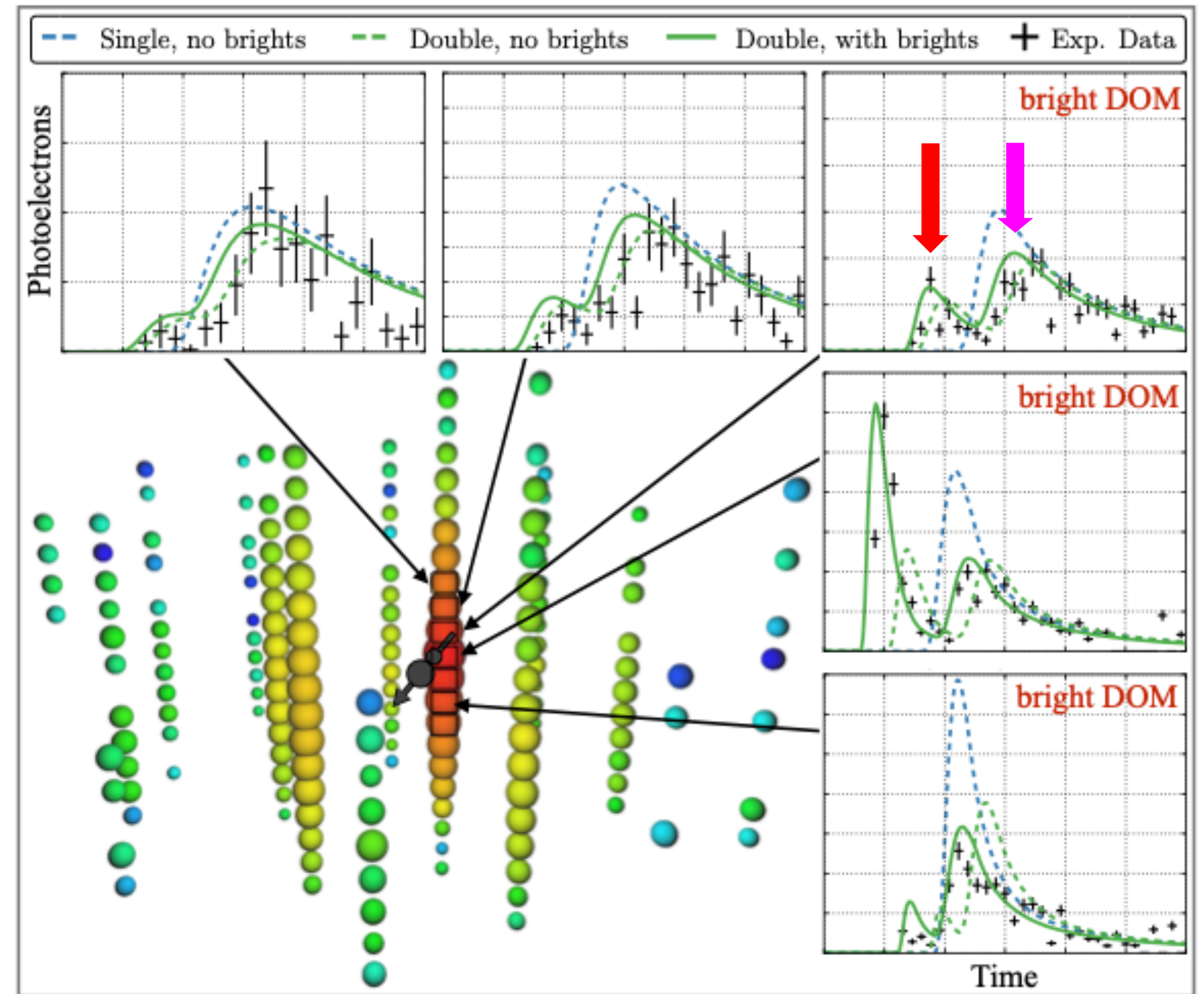
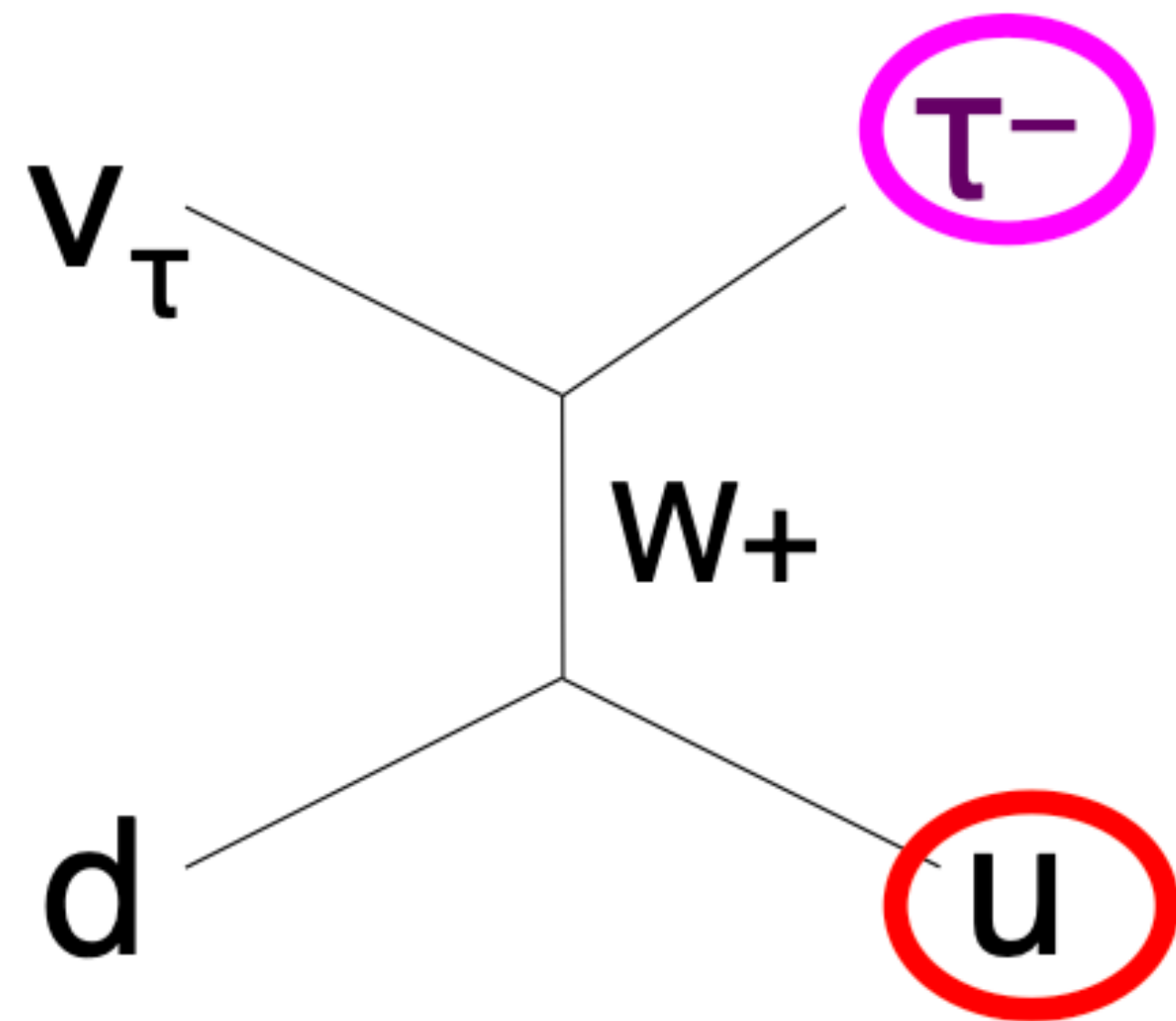
See also Bustamante et al. PRL 115, 161302 (2015); Rasmussen et al. 1707.07684; Palomares-Ruiz 1411.2998; Palladino et al 1502.02923; Bustamante et al 1610.02096; Brdar et al. 1611.04598; Farzan & Palomares-Ruiz 1810.00892; CA et al. 1909.05341; Learned & Pakvasa hep-ph/9405296 ..

Key observation in IceCube: tau neutrinos

Total deposited energy ~ 90 TeV.

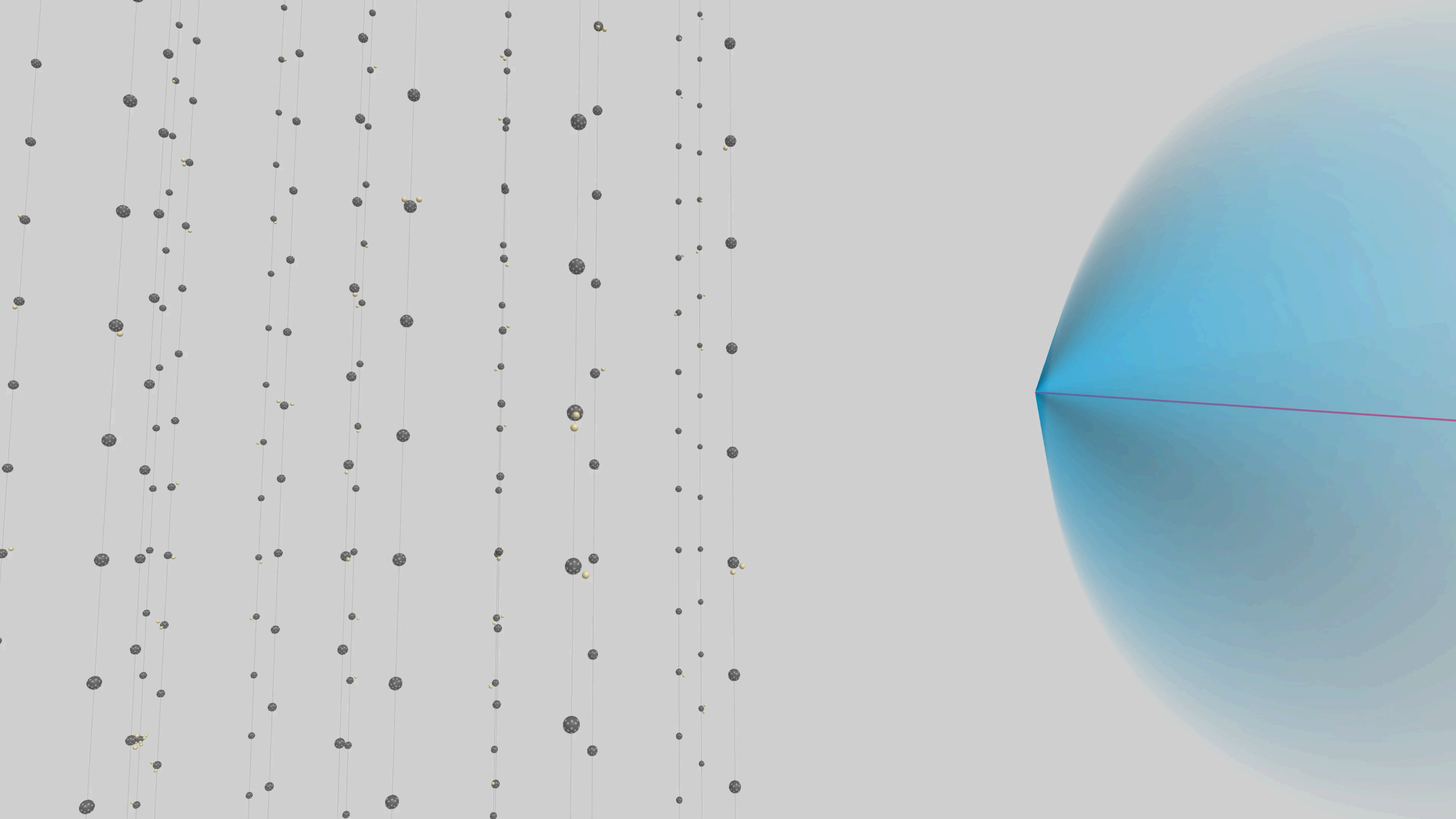
First “bang” in time (shower)

Second “bang” in time (tau decay)



IceCube, Eur. Phys. J. C 82, 1031 (2022); see also IceCube Phys.Rev.Lett. 132 (2024) 15, 151001

Carlos A. Argüelles — U. Washington, St. Louis, 2025

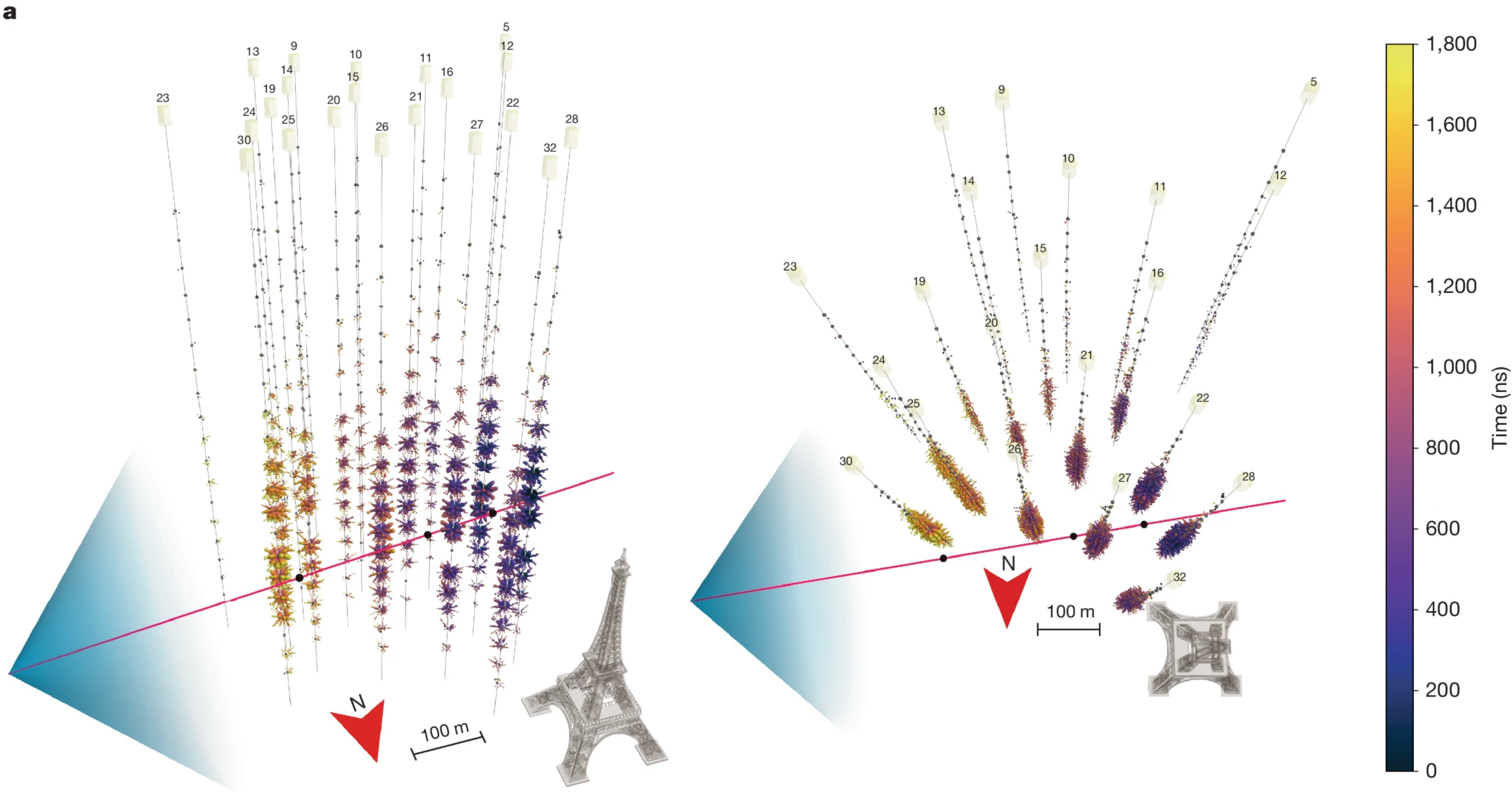


Observation of KM3-230213A

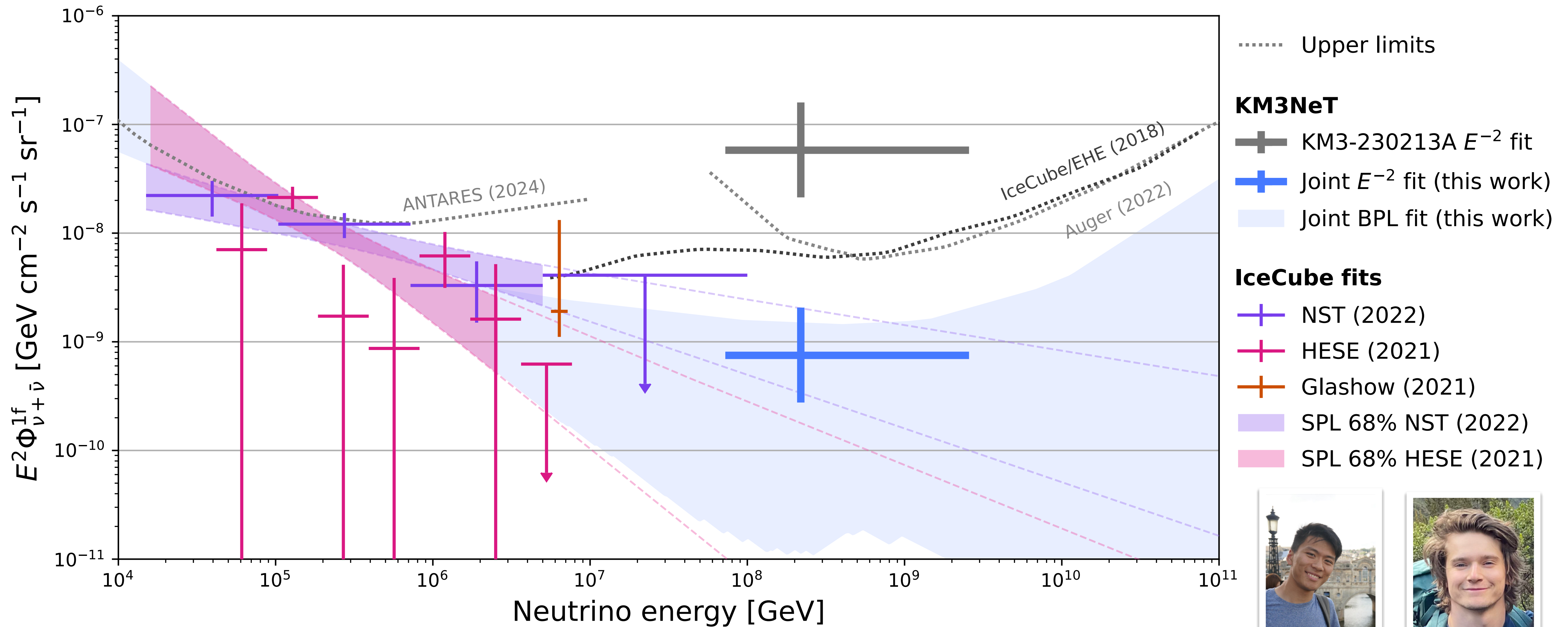


Nature Volume 638 Issue 8050

$$E_{\mu} = 120^{+110}_{-60} \text{ PeV} \implies E_{\nu} \gtrsim 100 \text{ PeV!}$$



KM3-230213A Within the Global Landscape



KM3NeT, *Phys. Rev. X* 15, 031016



Alex Wen



Nick Kamp

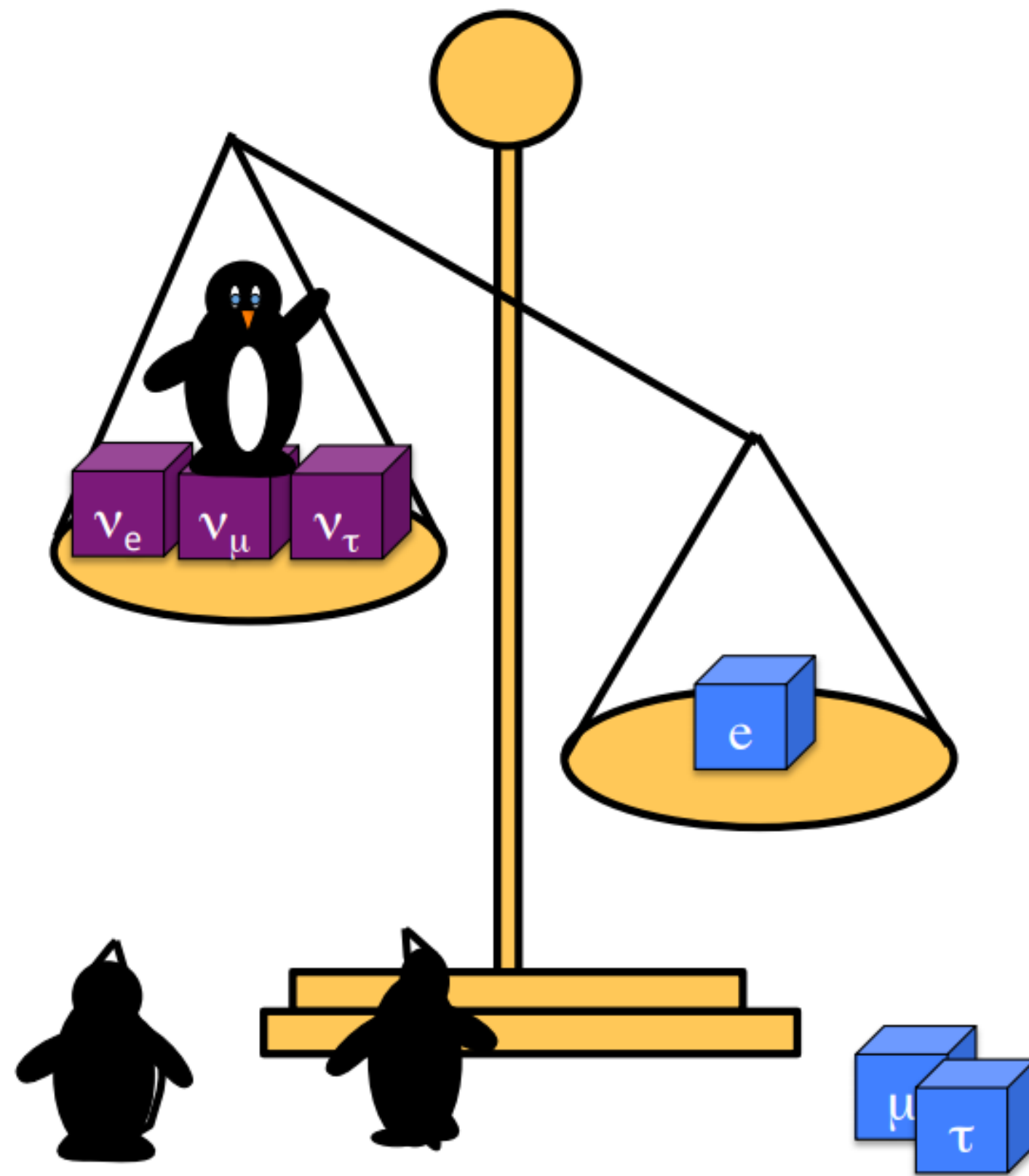
Big Picture Science of TAMBO

- Discovery new astrophysical source
- Understand the Universe neutrino emission in the 1 to 100 PeV energy band
- Study flavor of neutrinos at the highest energies
- Study cosmic rays in new ways
- Your idea!

Particle Physics Motivation

First ideas

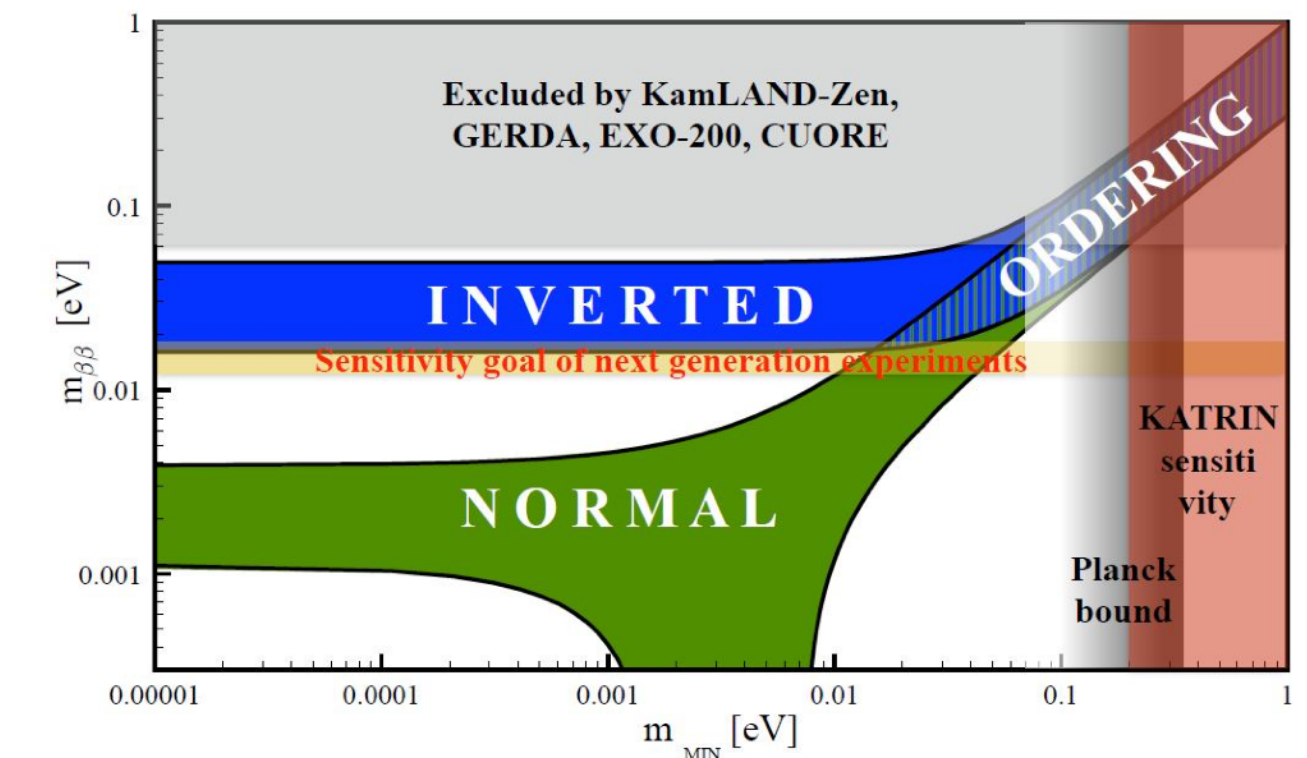
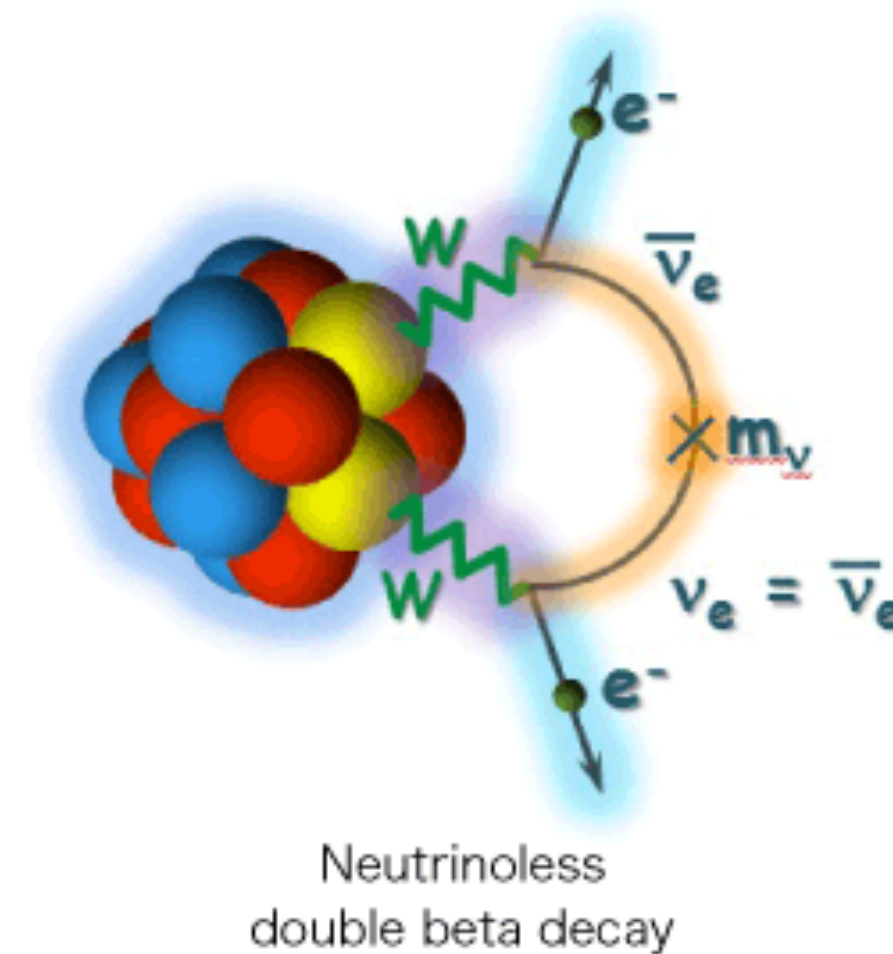
What is the origin of the neutrino mass?



Arkani-Hamed et al, 2007
Ooguri & Vafa, 2017
Gonzalo, Ibañez, Valenzuela, 2021
Vafa, 2024

Majorana

Dirac-like

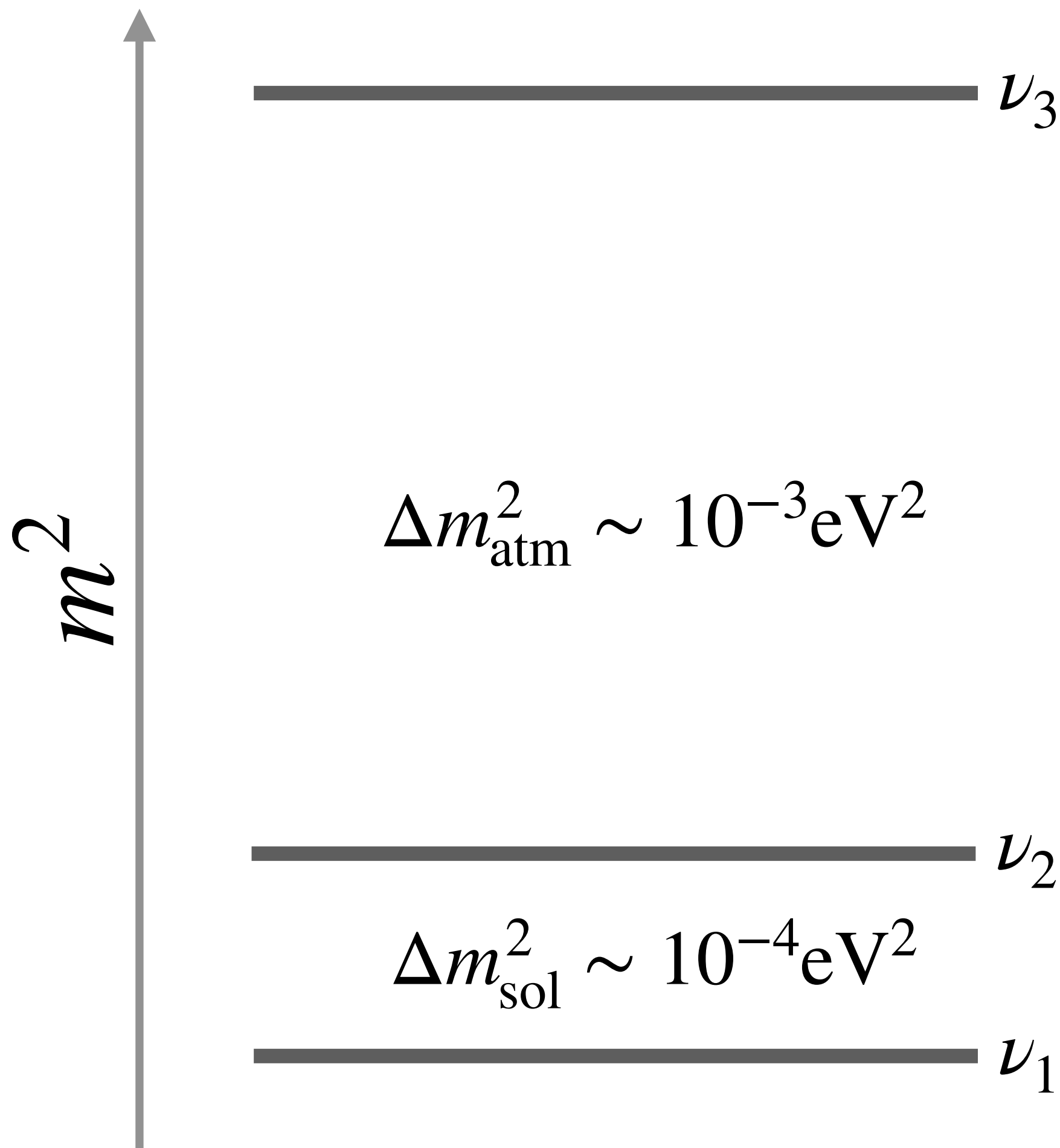


If exactly Dirac: combine measurements from Cosmology or direct neutrino mass measurements and neutrinoless double beta decay.

If Quasi-Dirac: ultra long-baseline neutrino oscillation measurements

Neutrino
telescopes!

The Neutrino Mass Spectra



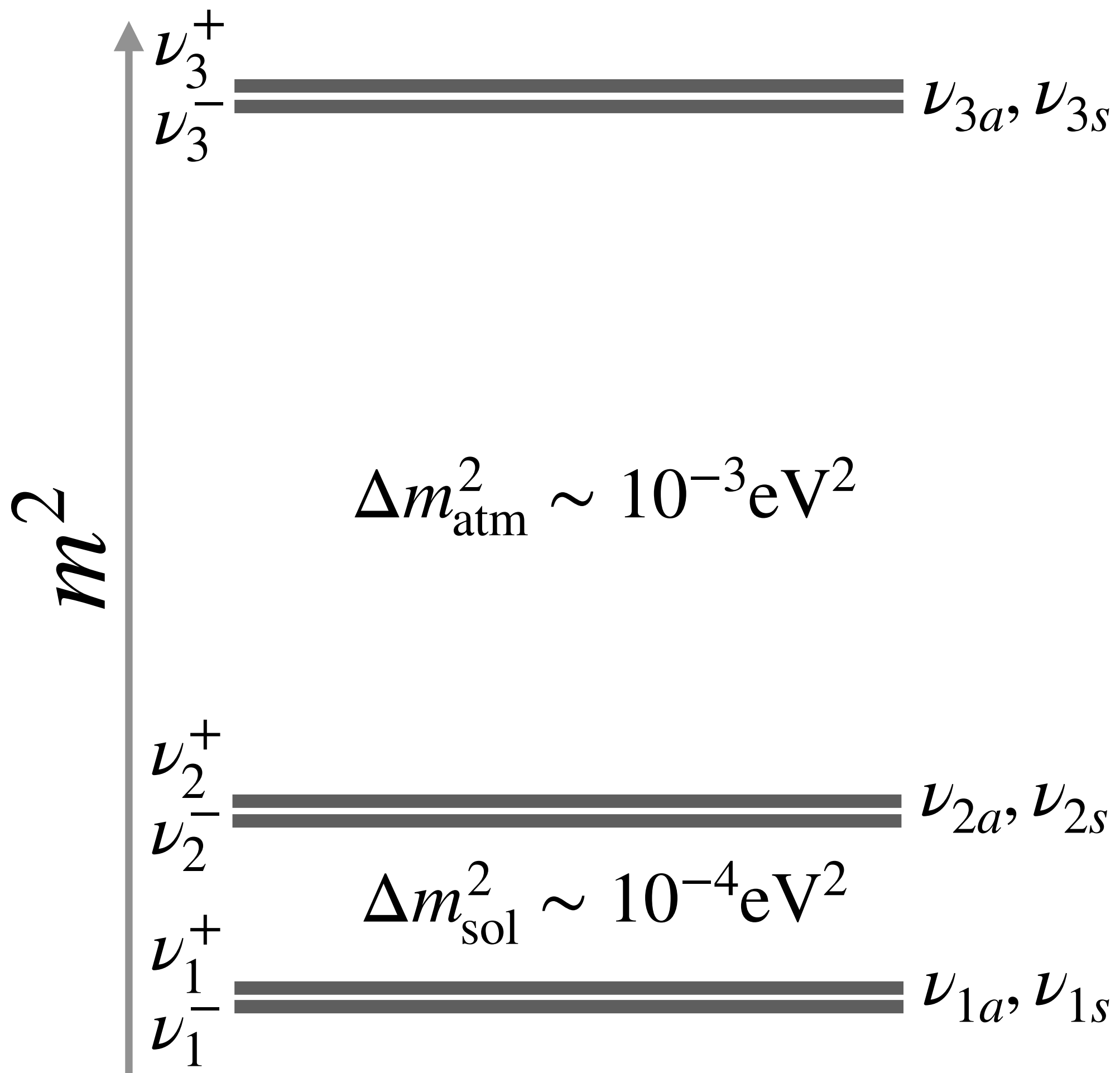
Arkani-Hamed et al, 2007; Ooguri & Vafa, 2017
Gonzalo, Ibañez, Valenzuela, 2021; Vafa, 2024

Recent results from String Theory suggest
that neutrinos are Dirac particles

$$2\mathcal{L}_{\text{mass}} = m_D \overline{N}_R \nu_L + m_D \overline{\nu}_L^C N_R^C + m_R \overline{N}_R^C N_R + \text{h.c.}$$

m_R is unconstrained and connected to
Lepton Number conservation

Neutrino hyperfine mass structure



Hyperfine splitting:

$$\delta m_j^2 \sim 10^{-22} - 10^{-12} \text{eV}^2$$

Oscillations from active to sterile neutrinos

J. W. Valle Phys.Rev.D 28 (1983) 540

Dirac See Saw Scenario: Z. K. Silagadze, *Phys. Atom. Nucl.* 60, 272 (1997); A. S. Joshipura, S. Mohanty, and S. Pakvasa *Phys. Rev. D* 89, 033003 (2014); P.-H. Gu and H.-J. He JCAP 12, 010; E. Ma and R. Srivastava *Phys. Lett. B* 741, 217 (2015); J. W. F. Valle and C. A. Vaquera-Araujo *Phys. Lett. B* 755, 363 (2016); S. Centelles Chuli' a, R. Srivastava, and J. W. F. Valle *Phys. Rev. D* 98, 035009 (2018); Z. G. Berezhiani and R. N. Mohapatra, *Phys. Rev. D* 52, 6607 (1995), ...

Neutrino Oscillations At Cosmic Scales

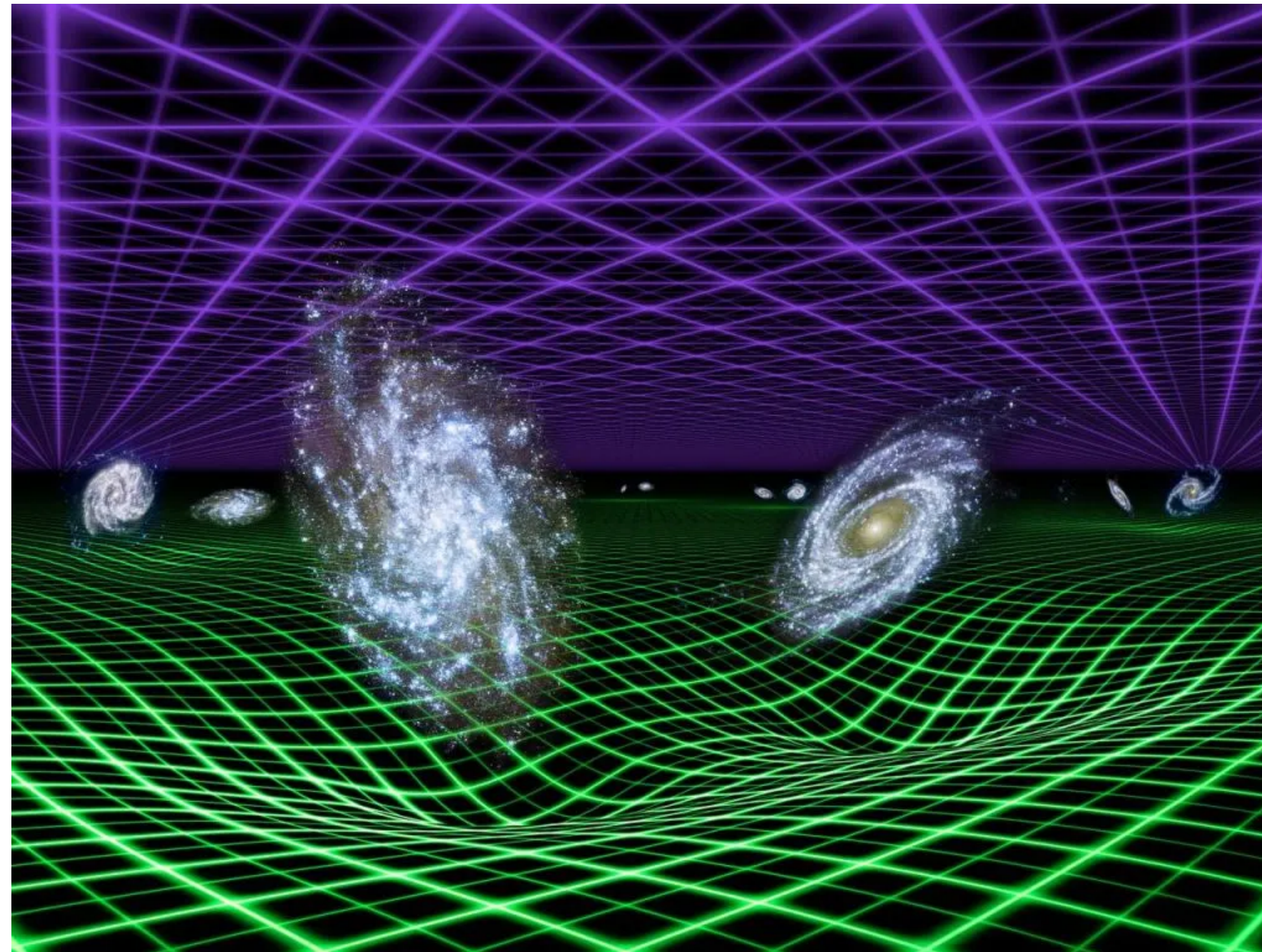
NGC 1068

$$L_{\text{osc}}^{\text{eff}} \sim E / \delta m^2$$



When hyperfine mass structure is present oscillation length at TeV can be Mpc-Gpc!

One of the most important questions in physics



Can we observe low-energy signatures of quantum gravity?

Search Low-Energy Effects of Quantum Gravity via Flavor Morphing

As neutrinos travel from their far away source they can interact with fields in space.

Example: spontaneous Lorentz violation.

Effects expected at the Planck Scale.

Space-time effects

J. Ellis et al arXiv:1807.051550

K. Wang et al. arXiv:2009.05201

Zhang & Ma arXiv:1406.4568

Flavor triangle trajectories in the presence of new physics

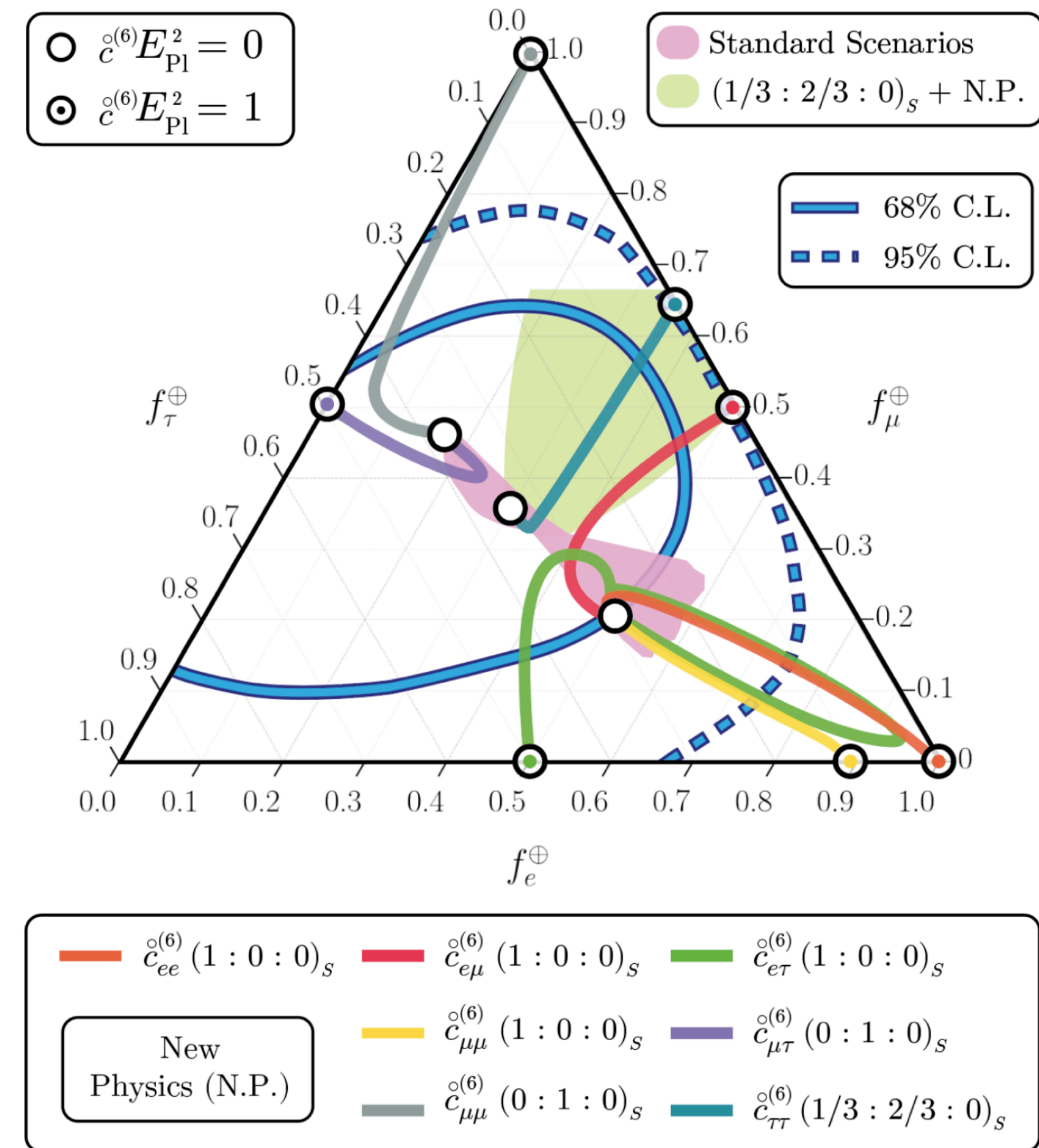
$$H_d = \boxed{\frac{1}{2E} U M^2 U^\dagger} + \boxed{\frac{E^{d-3}}{\Lambda_d} \tilde{U}_d O_d \tilde{U}_d^\dagger}$$

Dimension

Standard Mixing

New Physics Terms

(1 : 2 : 0) pion
 (0 : 1 : 0) neutron
 (1 : 0 : 0) muon-damped



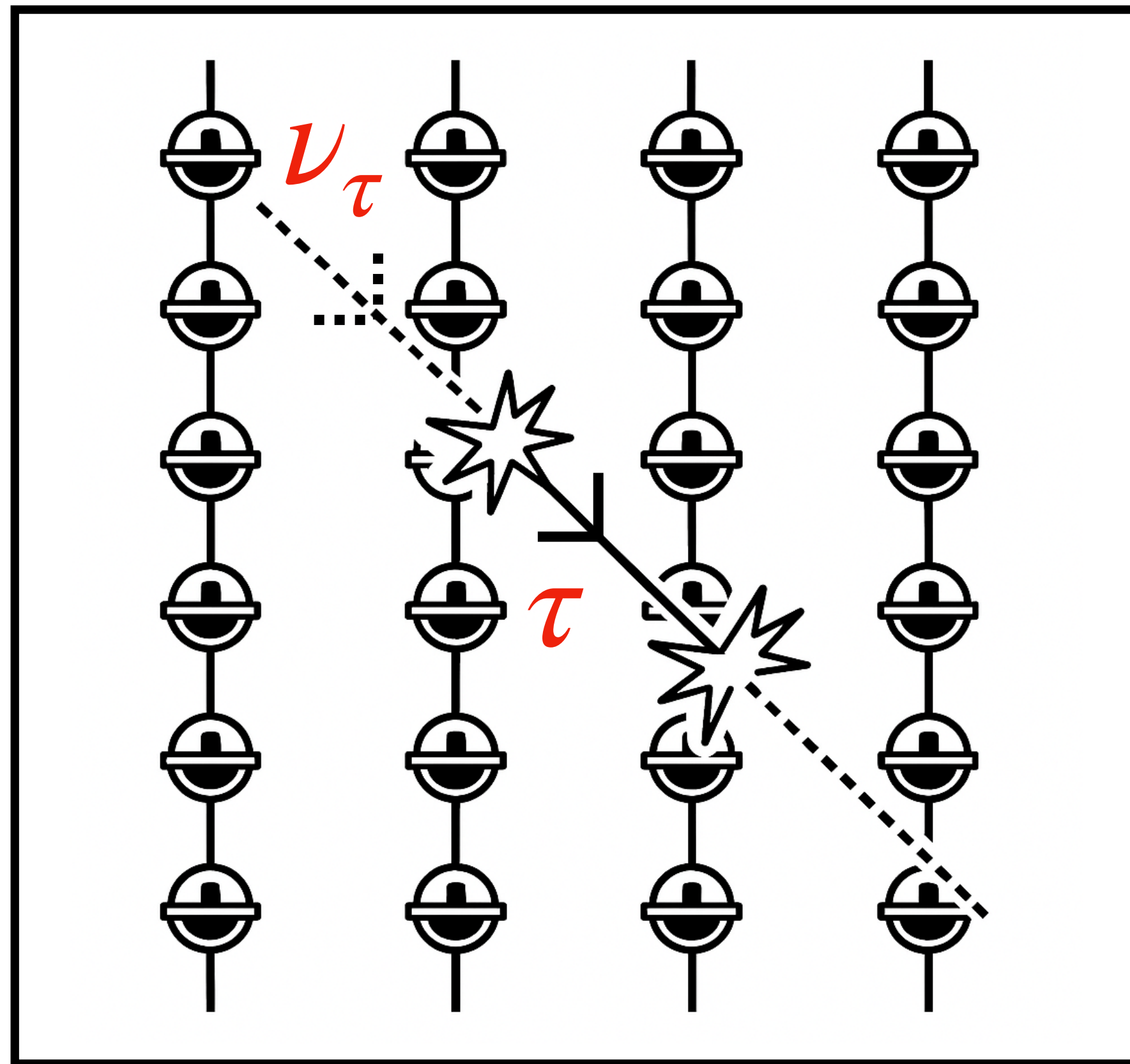
IceCube collaboration *Nature Physics* (2022) arXiv:2111.04654

So taus are important

How do we detect them?

How do we detect high-energy tau neutrinos?

Instrumented volume



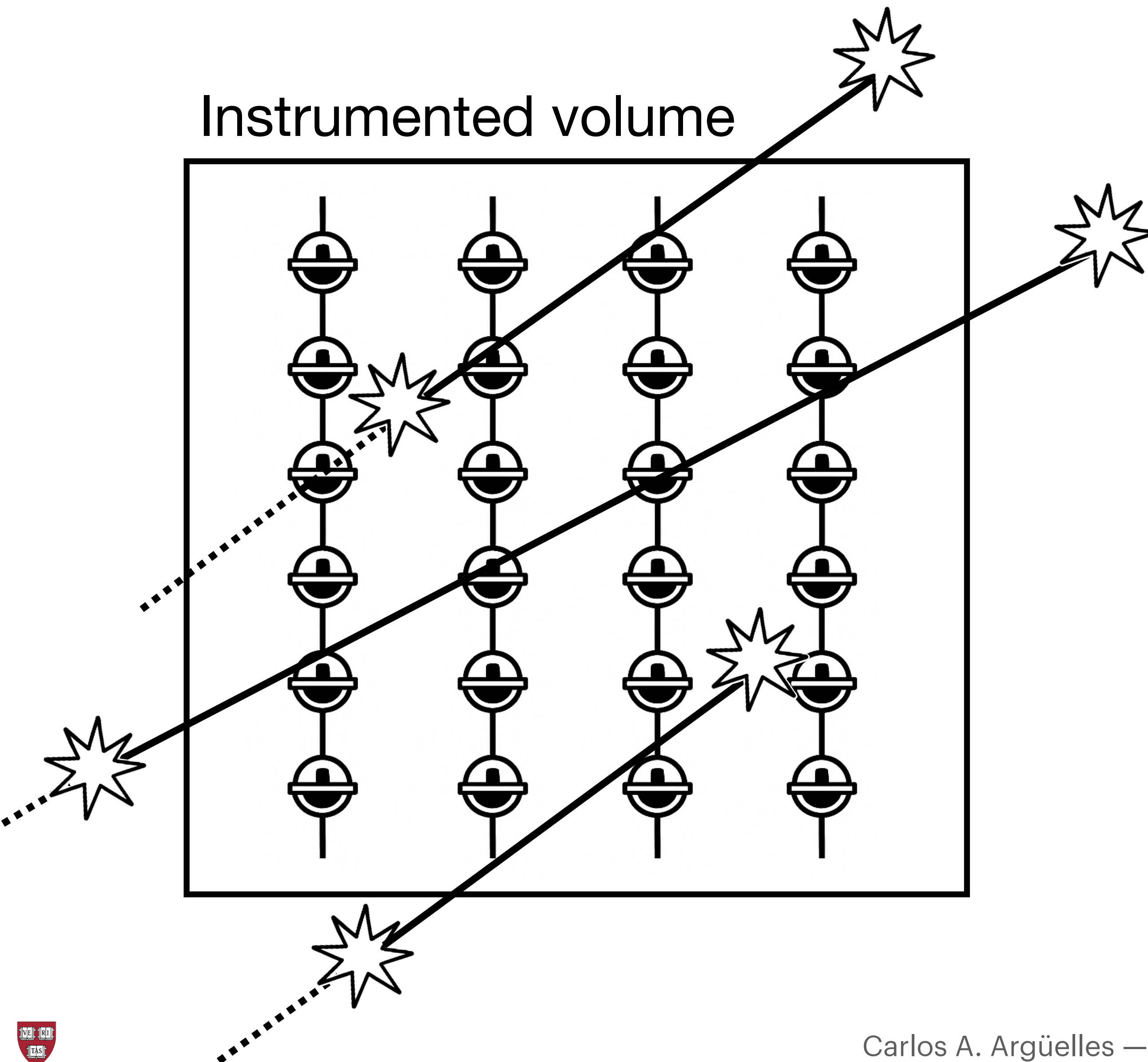
$$N_\tau \sim \sigma_{\nu p} \phi_\nu L_{detector}$$

Identification by separating “bangs”

$$L_\tau \approx 50\text{m} \left(\frac{E}{\text{PeV}} \right)$$

Backgrounds: mis-reco, D-mesons.

How do we detect high-energy tau neutrinos?



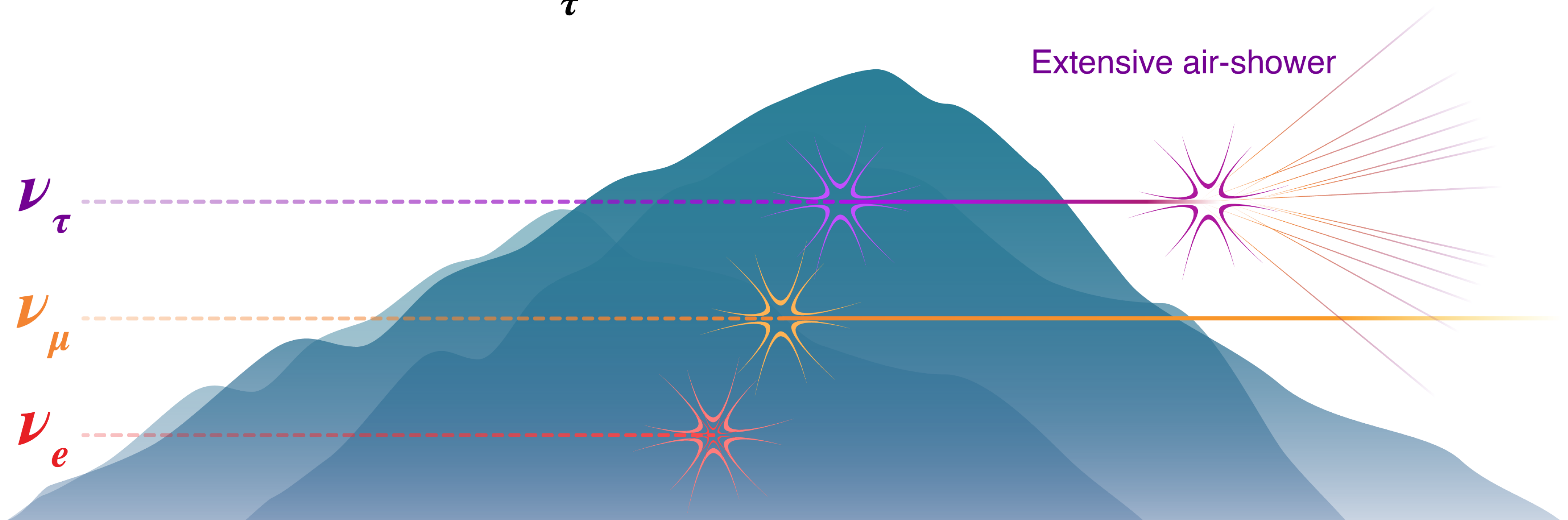
Tau neutrino "double bangs" are increasingly rarer to contain.

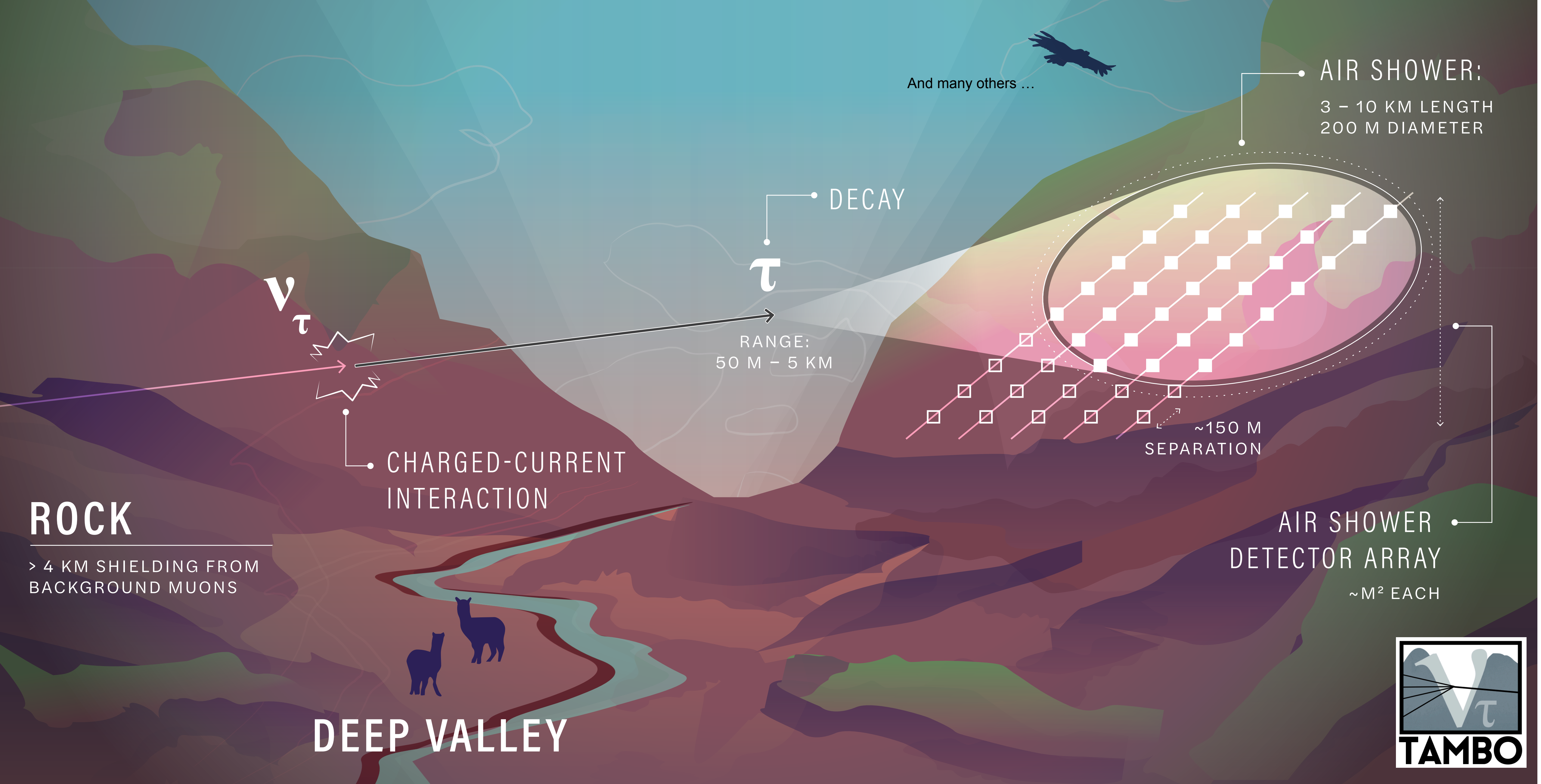
Tau neutrino identification in volumetric detector becomes inefficient.

How do we detect **ultra** high-energy tau neutrinos?

$$N_{\tau} \sim \sigma_{\nu p} \phi_{\nu} L_{\tau}^0 \cdot \frac{E}{m_{\tau}}$$

- High tau purity
- Increasing “efficiency” with energy!





TAU AIR-SHOWER MOUNTAIN-BASED OBSERVATORY (TAMBO)

TAMBO Potential Locations

Canyon	Depth (m)	Width (km)	Location and Notes
Yarlung Tsangpo Canyon	~6000	~5–10	Tibet; extremely deep but very remote.
Cotahuasi Canyon	3535	~3	Peru; deep and accessible.
Colca Canyon	3270	~4–5	Peru; deep and accessible.
Kali Gandaki Gorge	~2500	~5	Nepal; very deep but narrow and remote.
Hells Canyon	~2440	~16	USA (Oregon–Idaho); deepest river gorge in North America with steep walls.
Grand Canyon	~1800	~16	USA (Arizona); massive volume and excellent infrastructure.
Tara River Canyon	~1300	~3	Montenegro/Bosnia; Europe’s deepest.



Location will determine sky coverage, detection efficiency, and background rejection

In what follows I will show results for the Colca Valley Location

The final location of TAMBO is still under consideration and will be decided based on a combination of scientific, logistical, and societal considerations

Humanities can help make physics greener, J de Swart, AC Thresher, CA Argüelles, *Nature Reviews Physics* 6 (7), 404-405

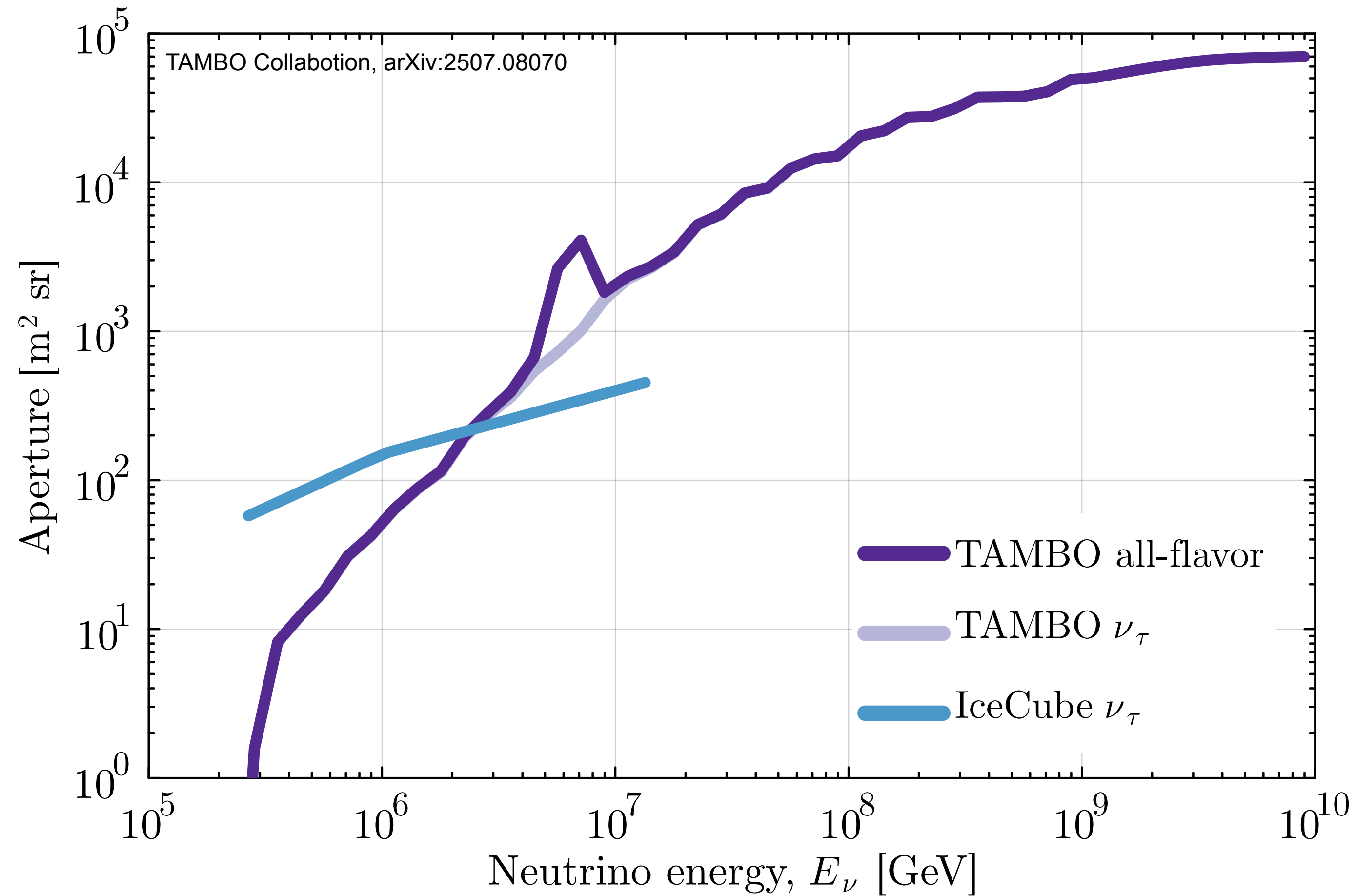
TAMBO Collabotio**n**, arXiv:2507.08070

Carlos A. Argüelles —TAMBO101@PUCP

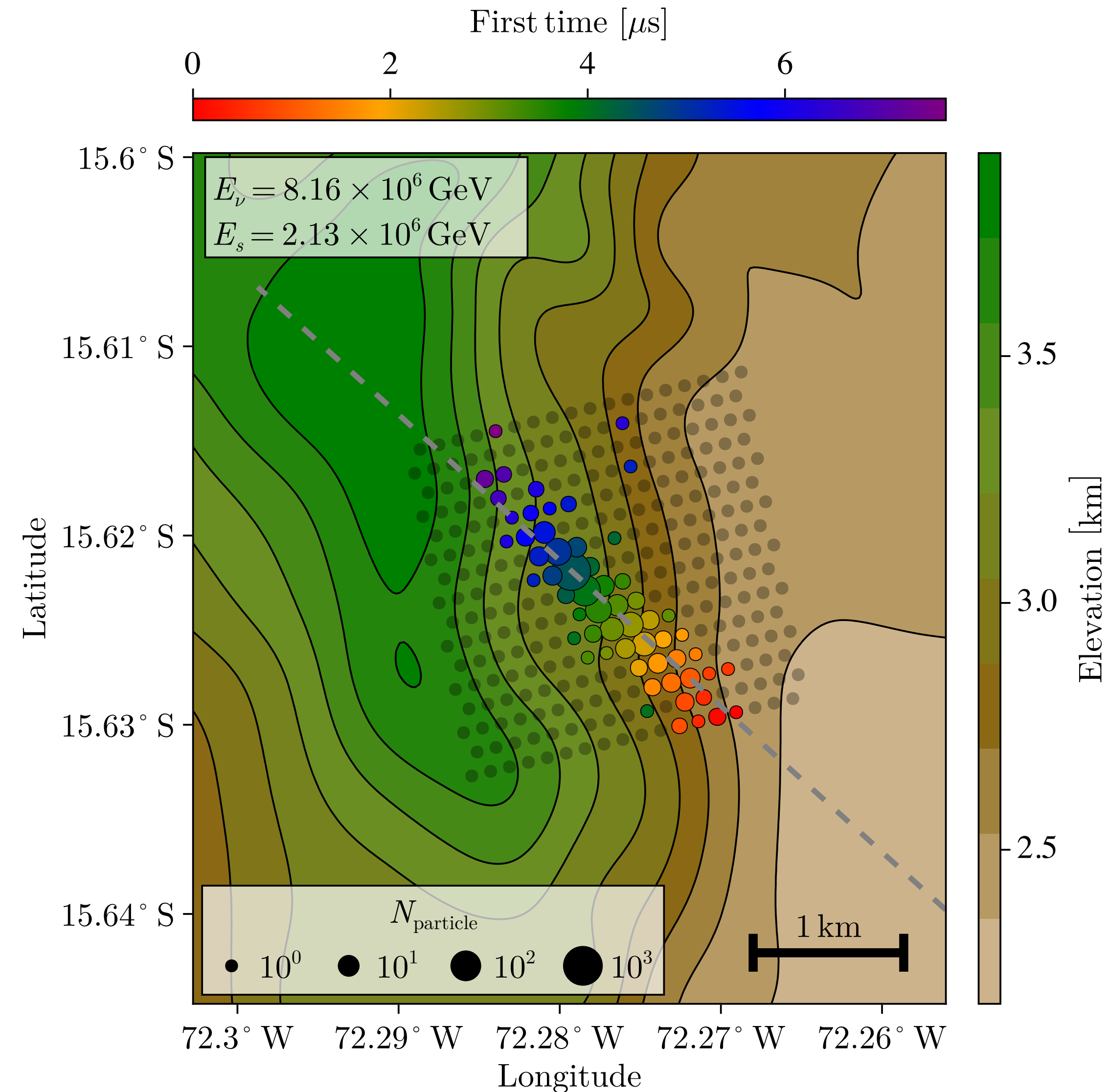


TAMBO Expectation

Design goal: Aim to go as low as possible in energy: 1 PeV to 100 PeV range

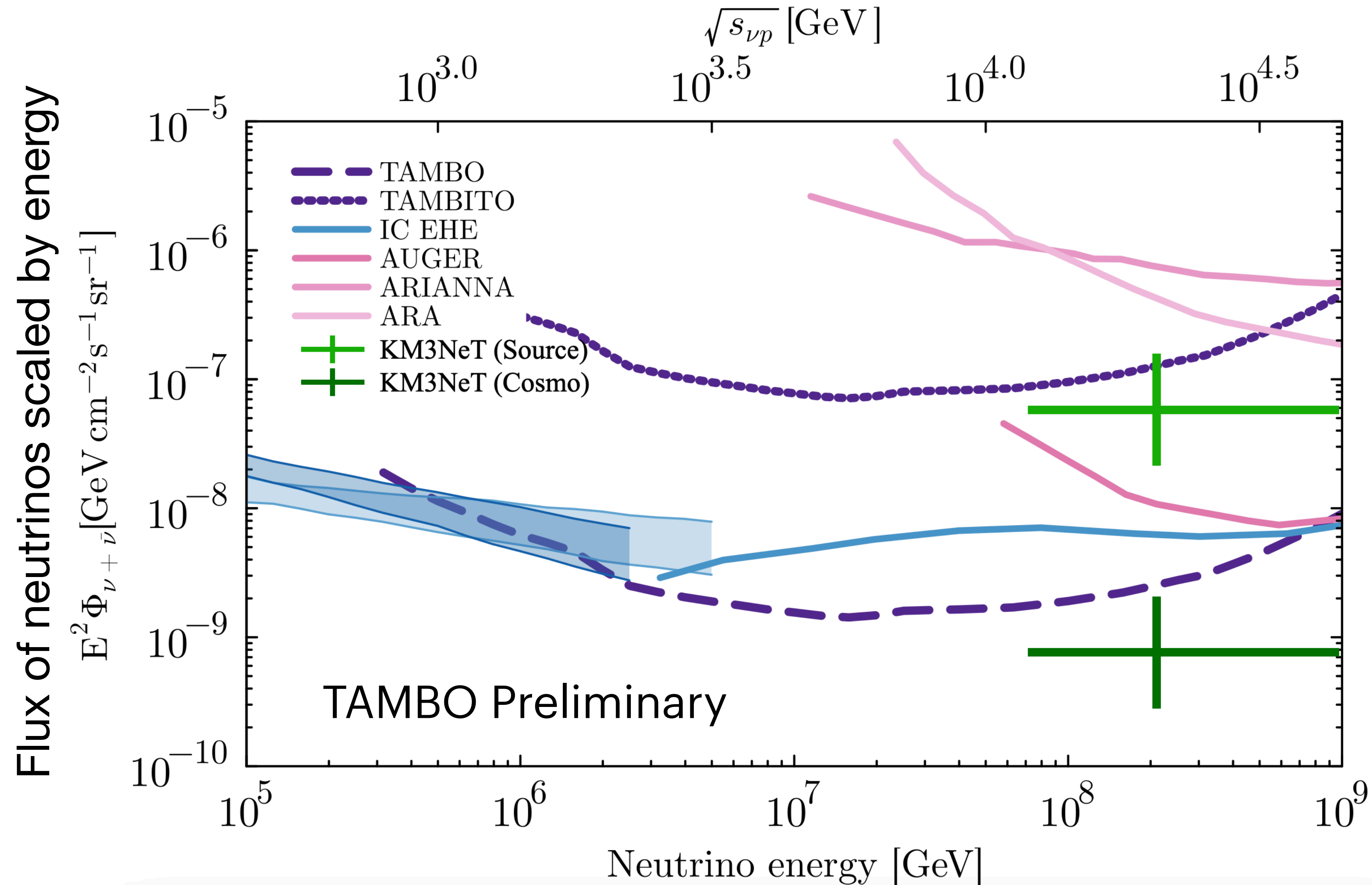


With ~ 5000 modules we have IceCube-EHE comparable or greater effective areas

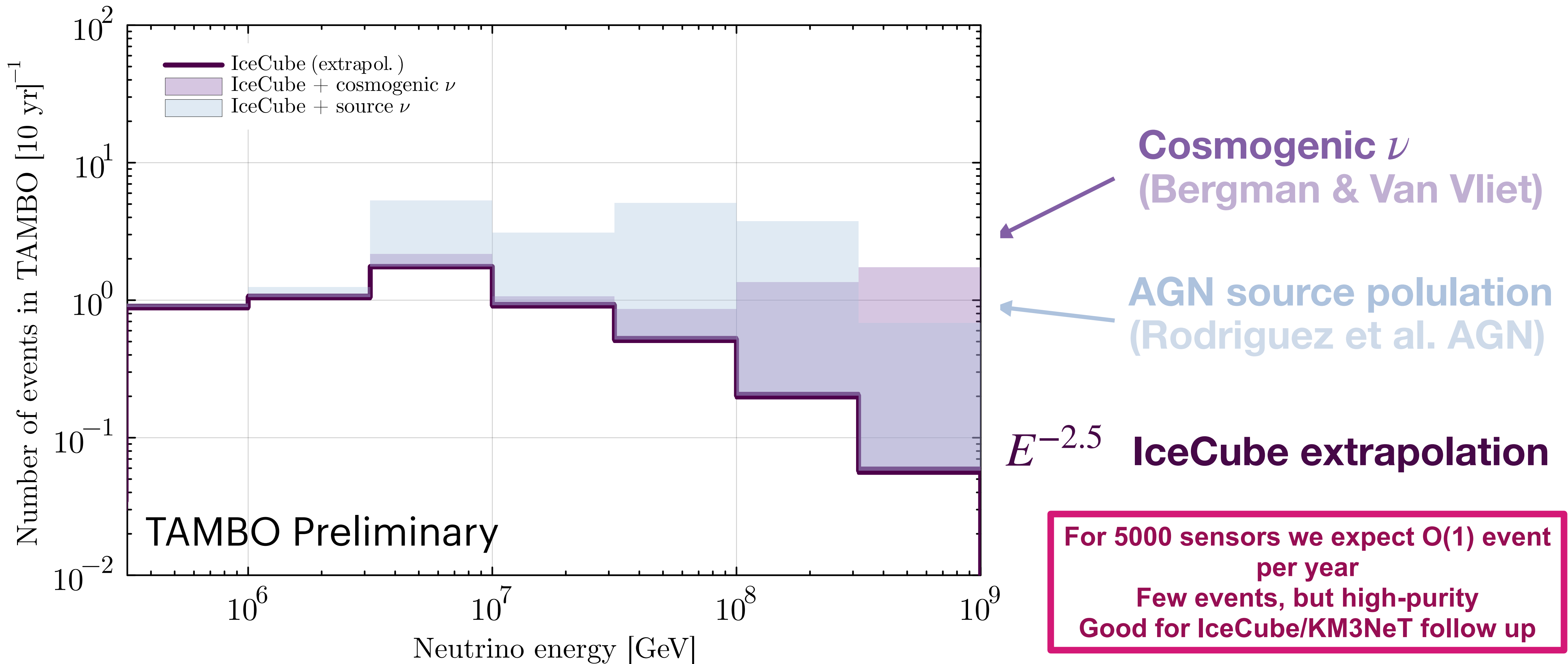


TAMBO Collabotio, arXiv:2507.08070

Expected reach of TAMBO



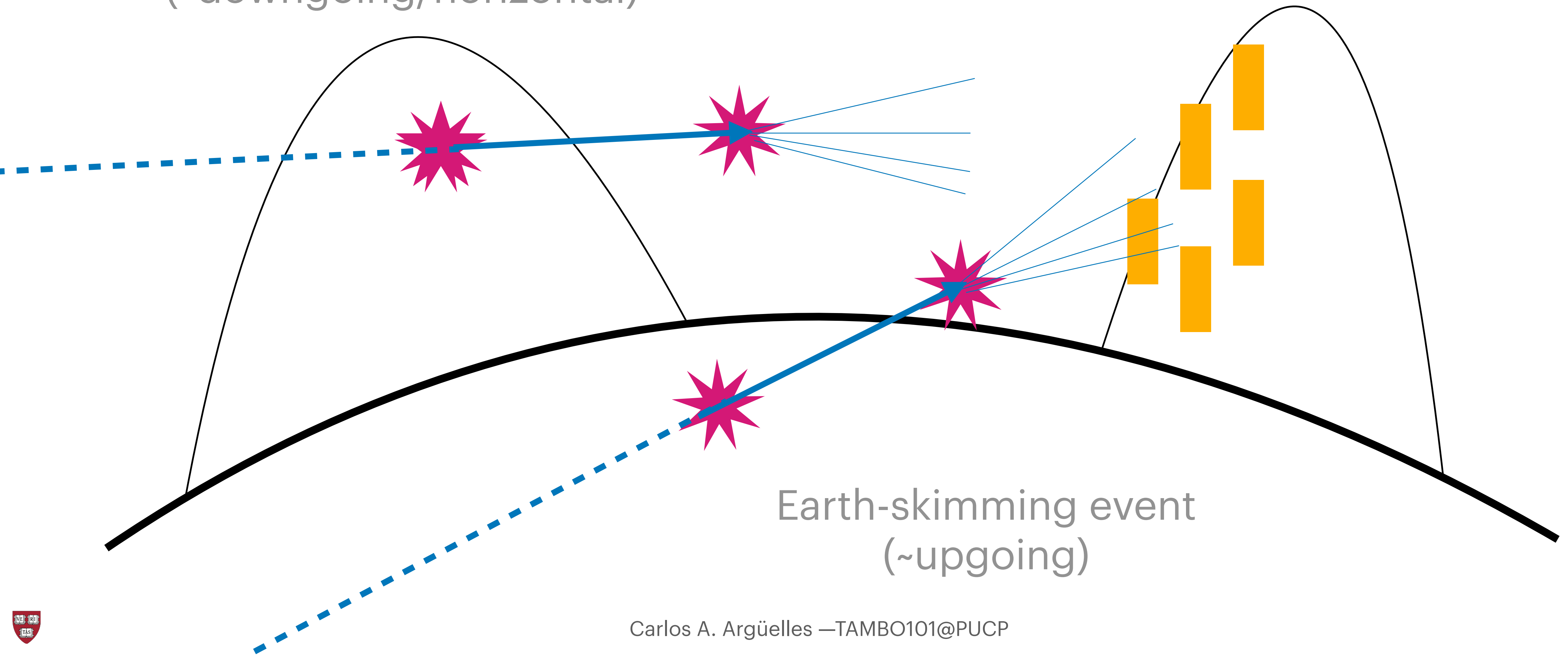
Expected rates at TAMBO given unknown-origin IceCube flux



Events in TAMBO

**not to scale*

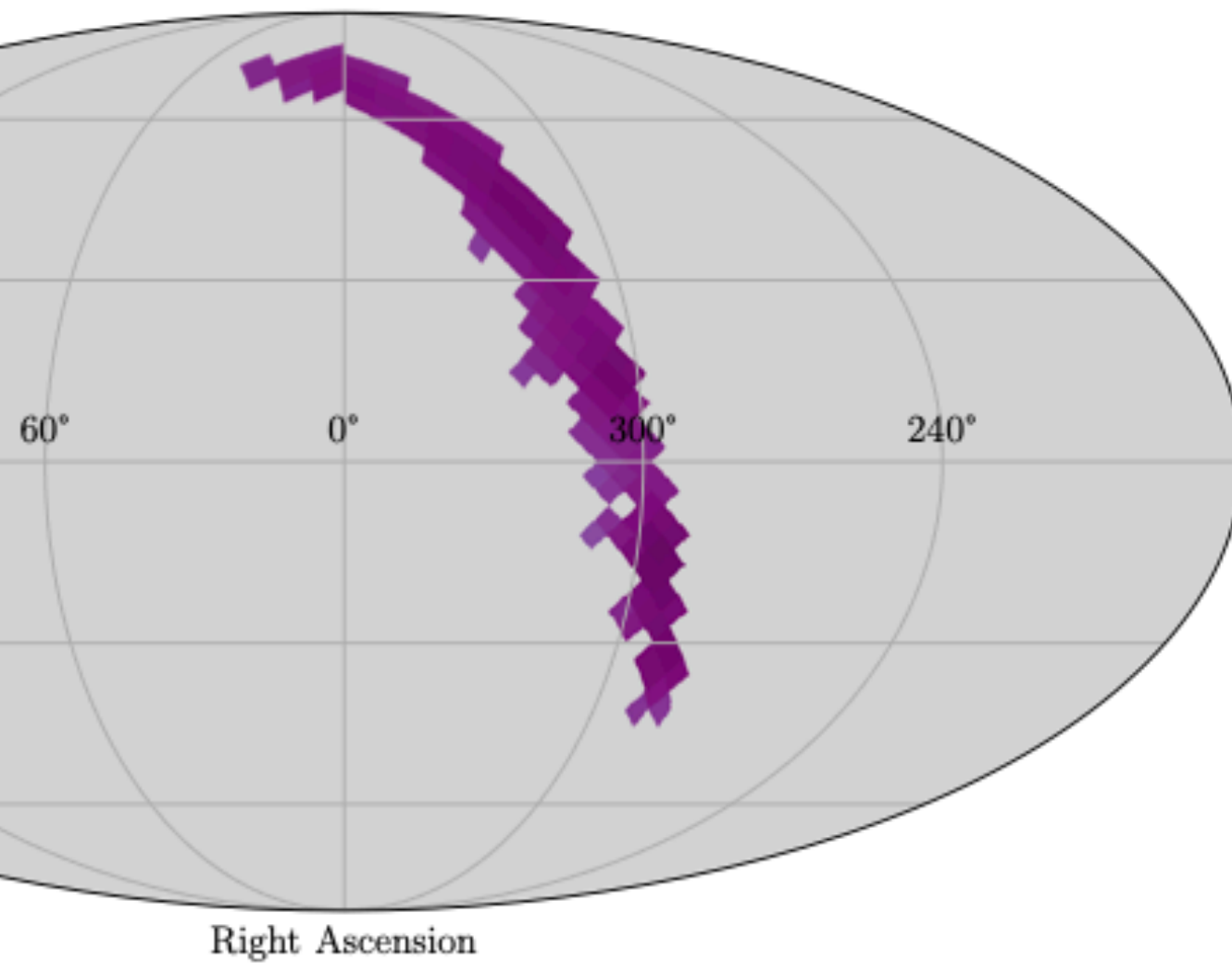
Mountain-through-going event
(~downgoing/horizontal)



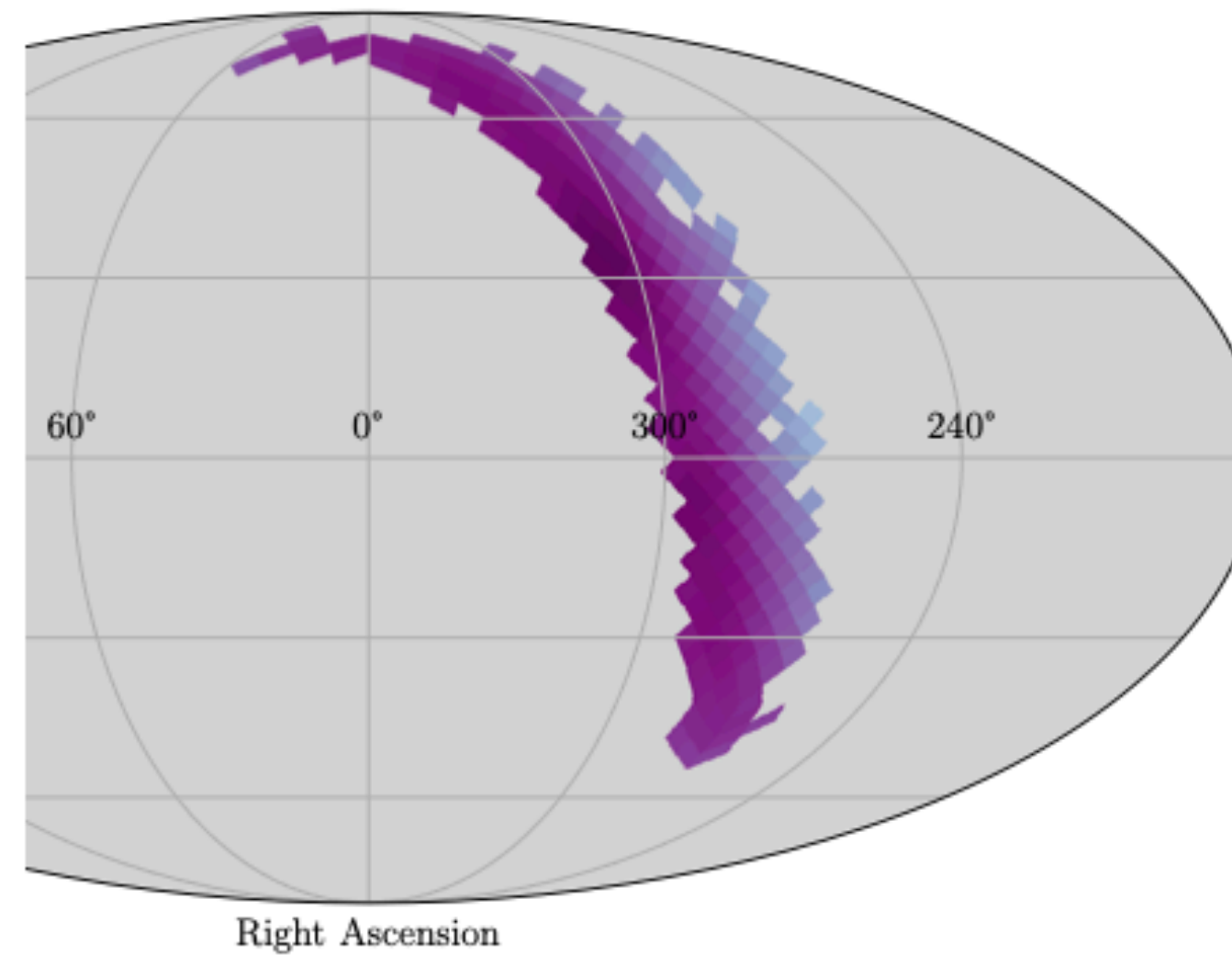
Earth-skimming event
(~upgoing)

TAMBO Instantaneous Aperture

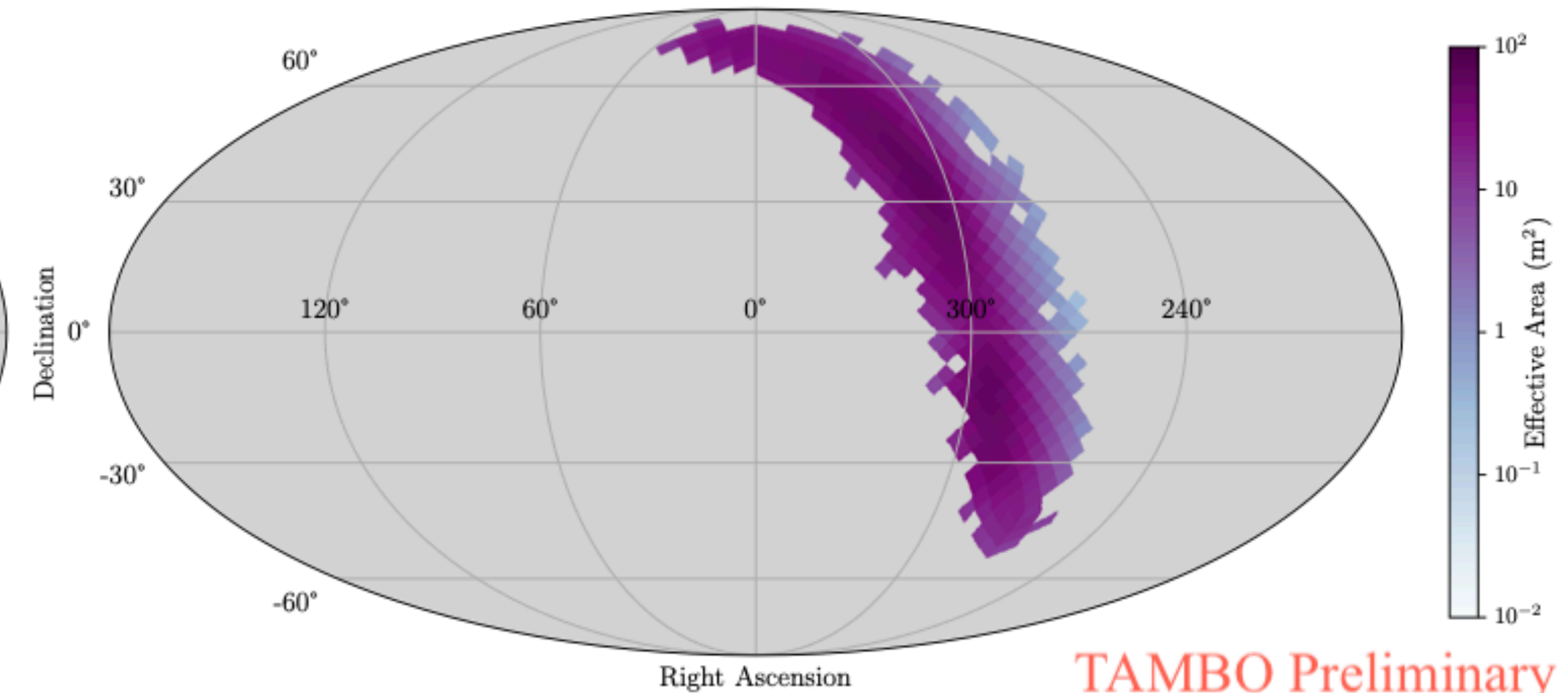
Downgoing



Upgoing



Full Acceptance

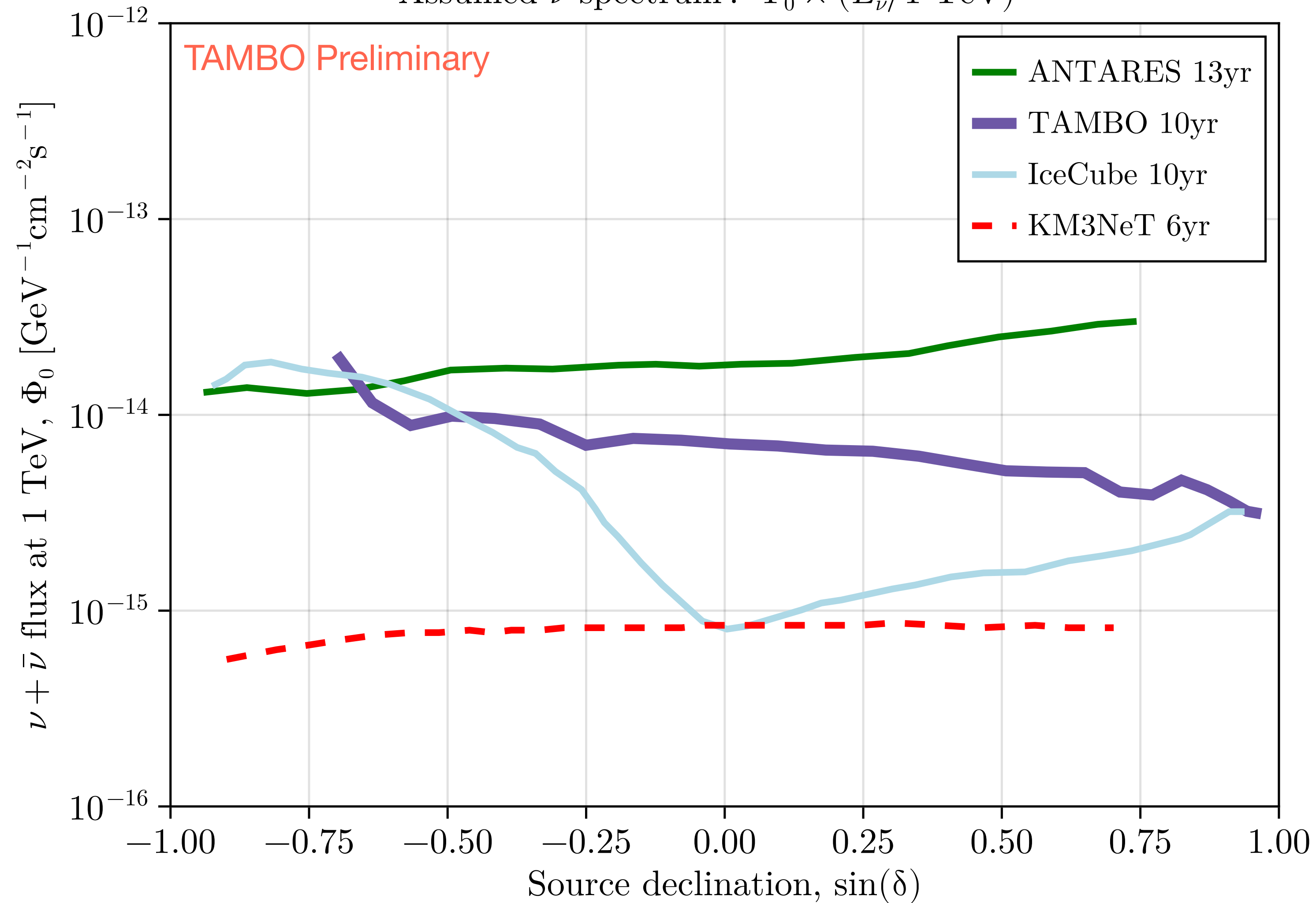


The unique mountain geometry increases acceptance by ~50%, compared to Earth-skimming only.

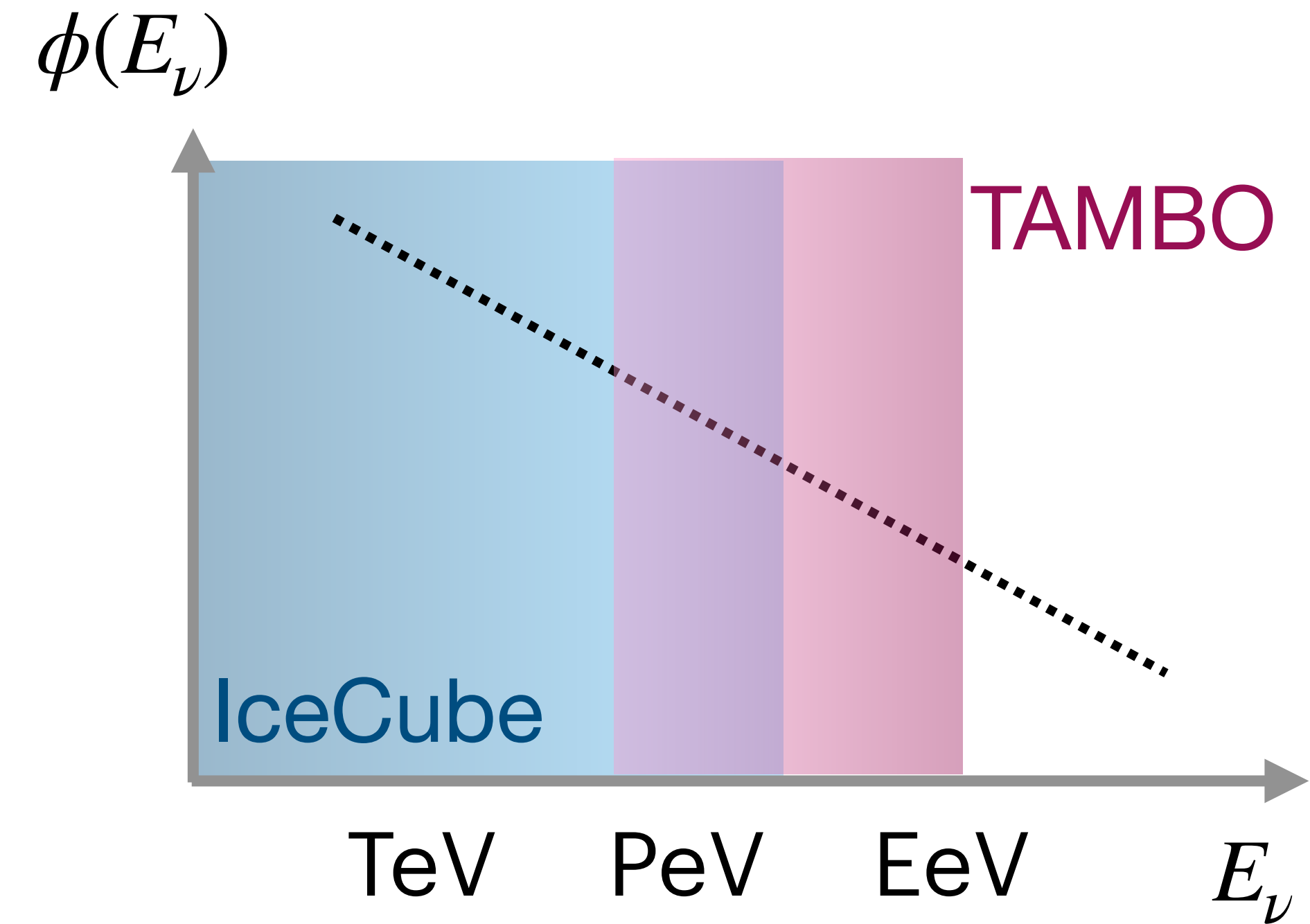


Sensitivity to unbroken, power-law sources

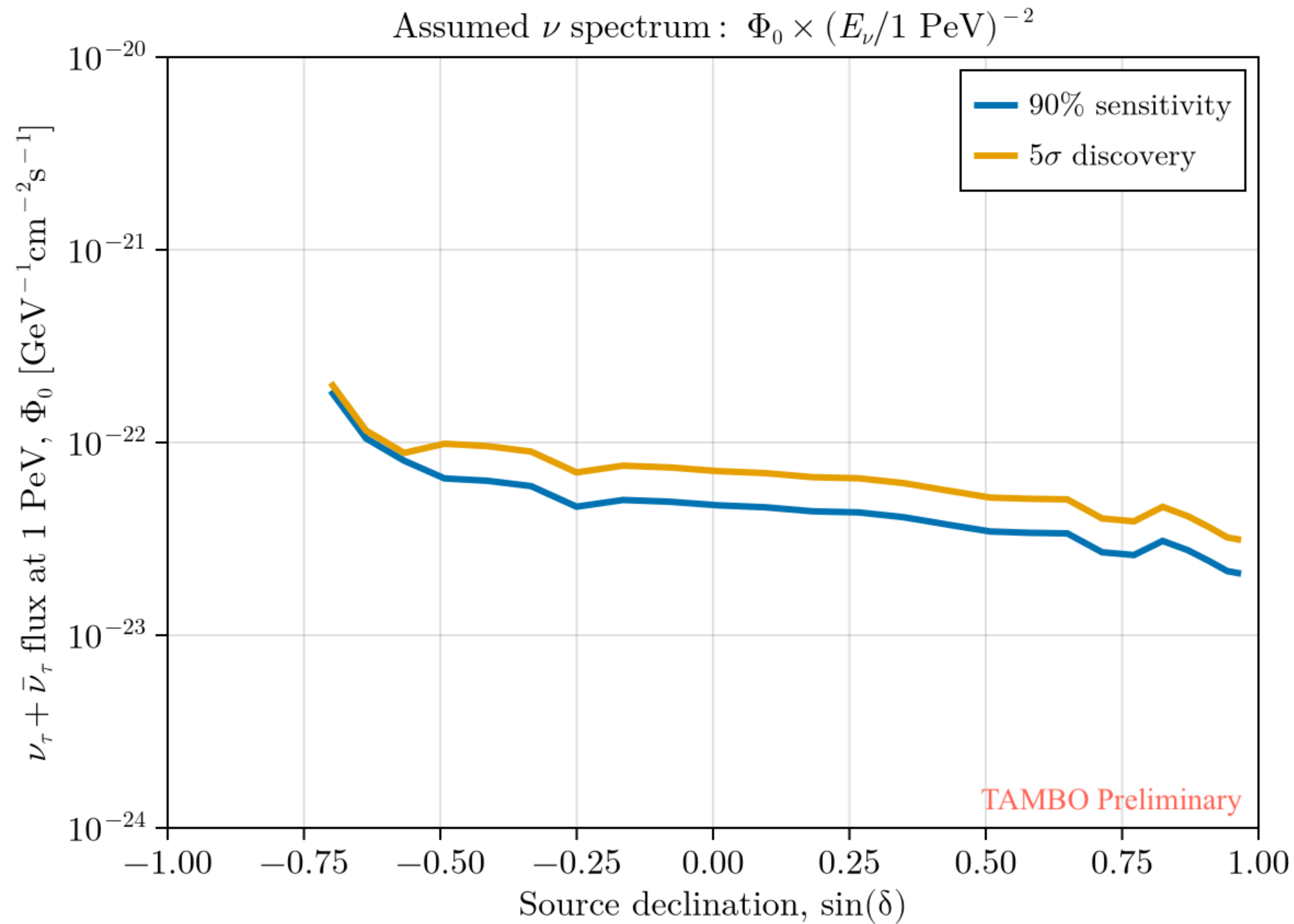
Assumed ν spectrum: $\Phi_0 \times (E_\nu/1 \text{ TeV})^{-2}$



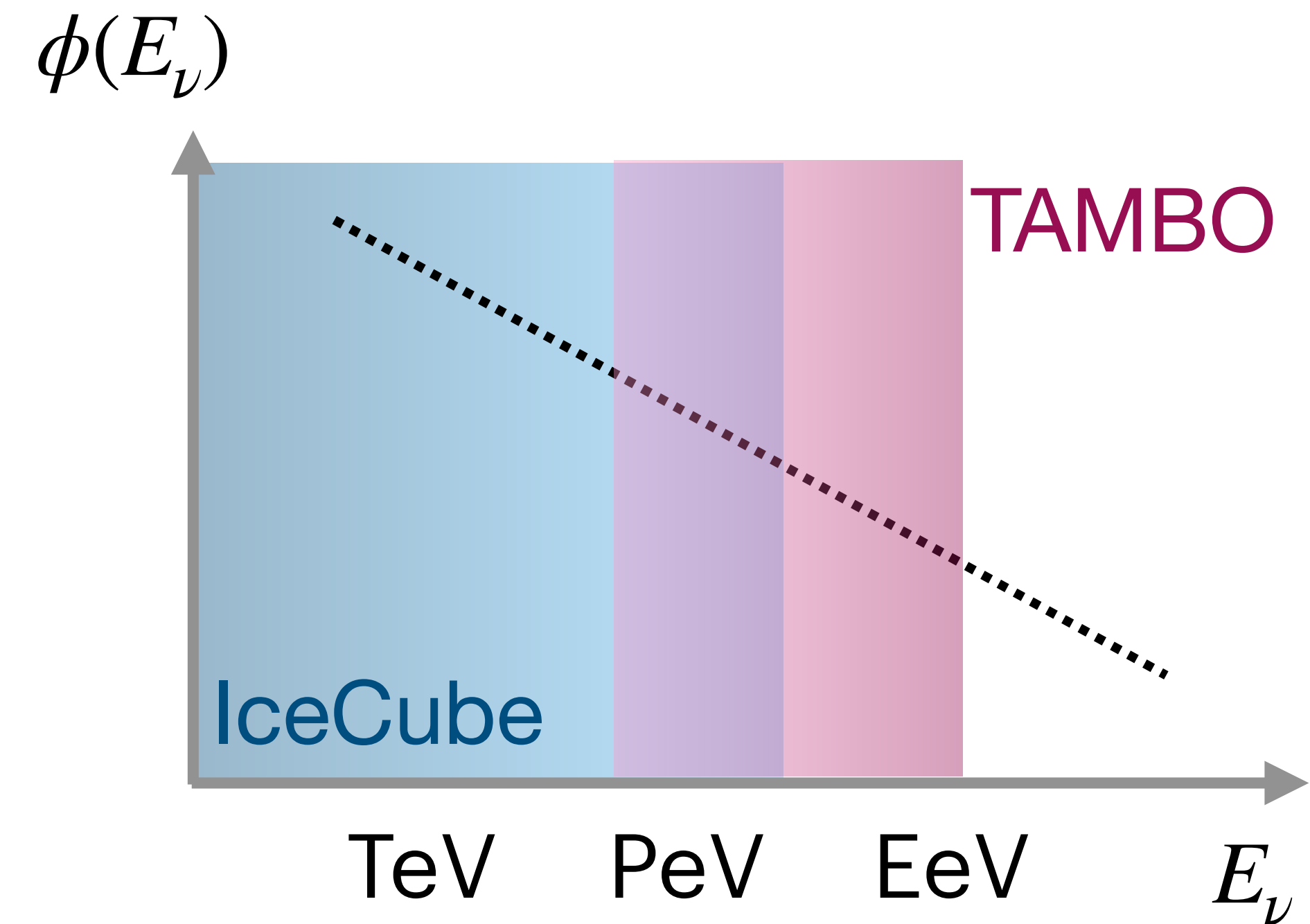
Source sensitivity comparable to other experiments.



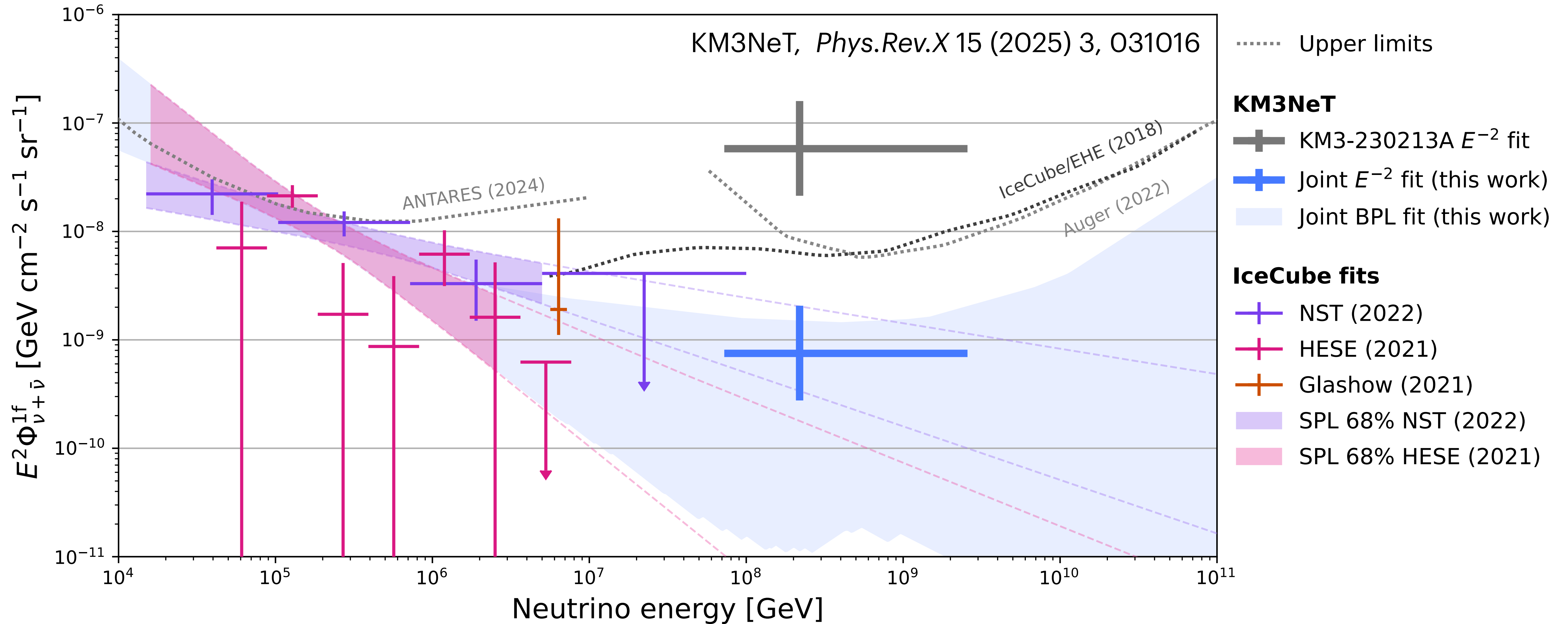
Sensitivity to unbroken, power-law sources



Source sensitivity at $\sim > \text{PeV}$ energies



Interesting Things Maybe Happening at Very-High-Energies

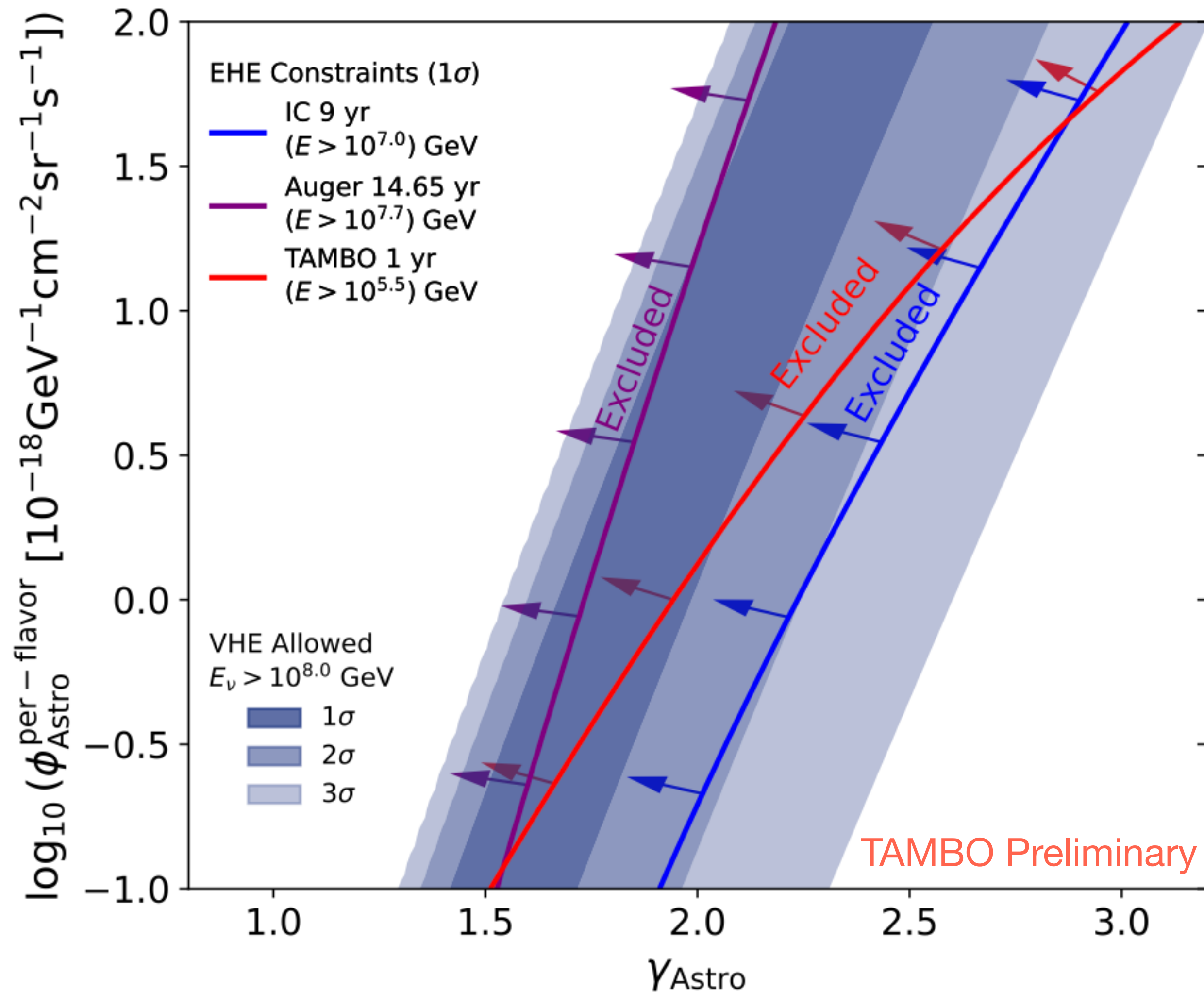


See also KM3NeT, *Nature* 638 (2025); IceCube, *Phys.Rev. Let*, *arXiv:2502.01963*

E_ν



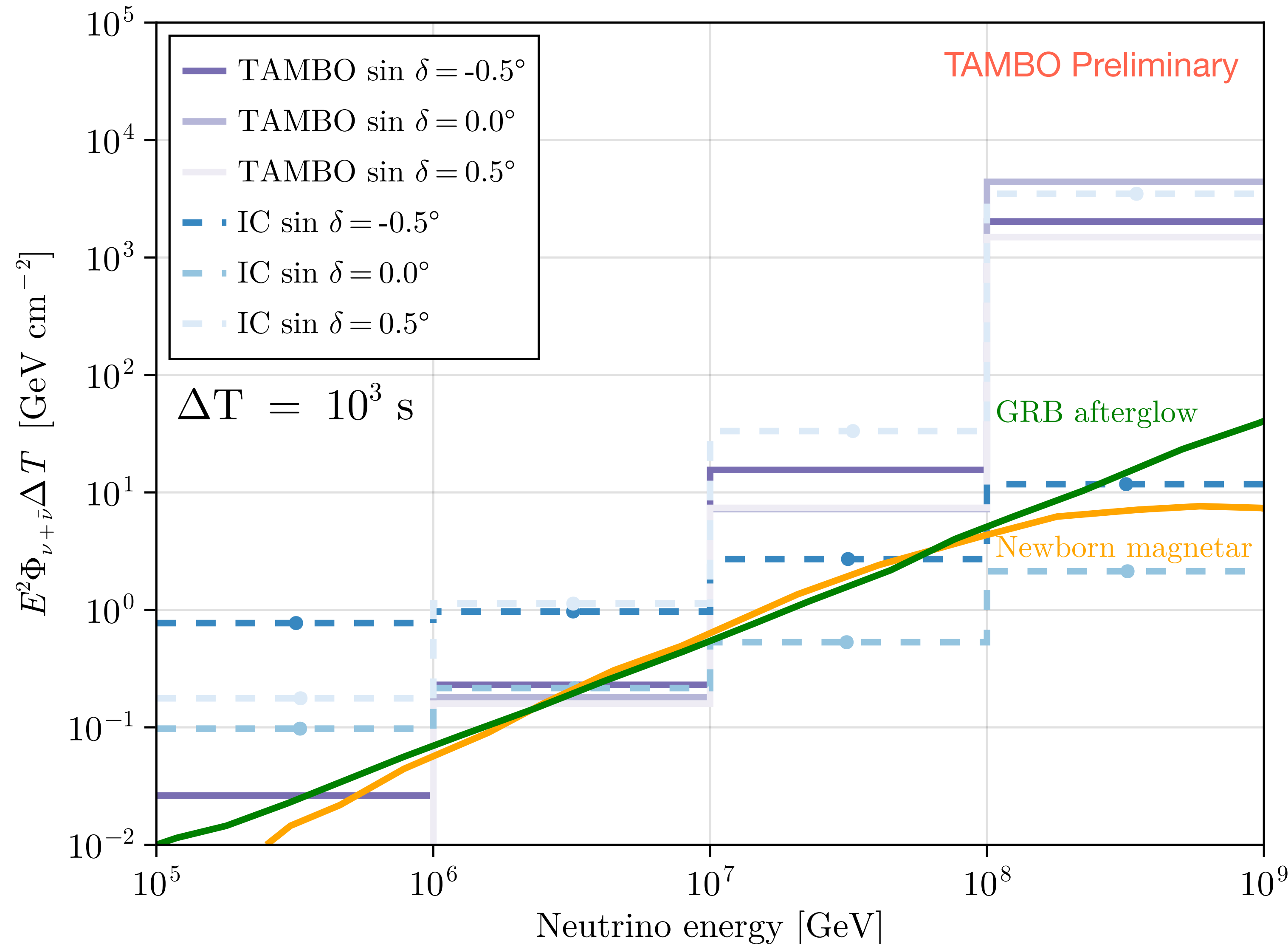
Sensitivity to very-high-energy component



Assuming all-sky neutrino emission, aka diffuse.

TAMBO can provide insights into the KM3NeT detection.

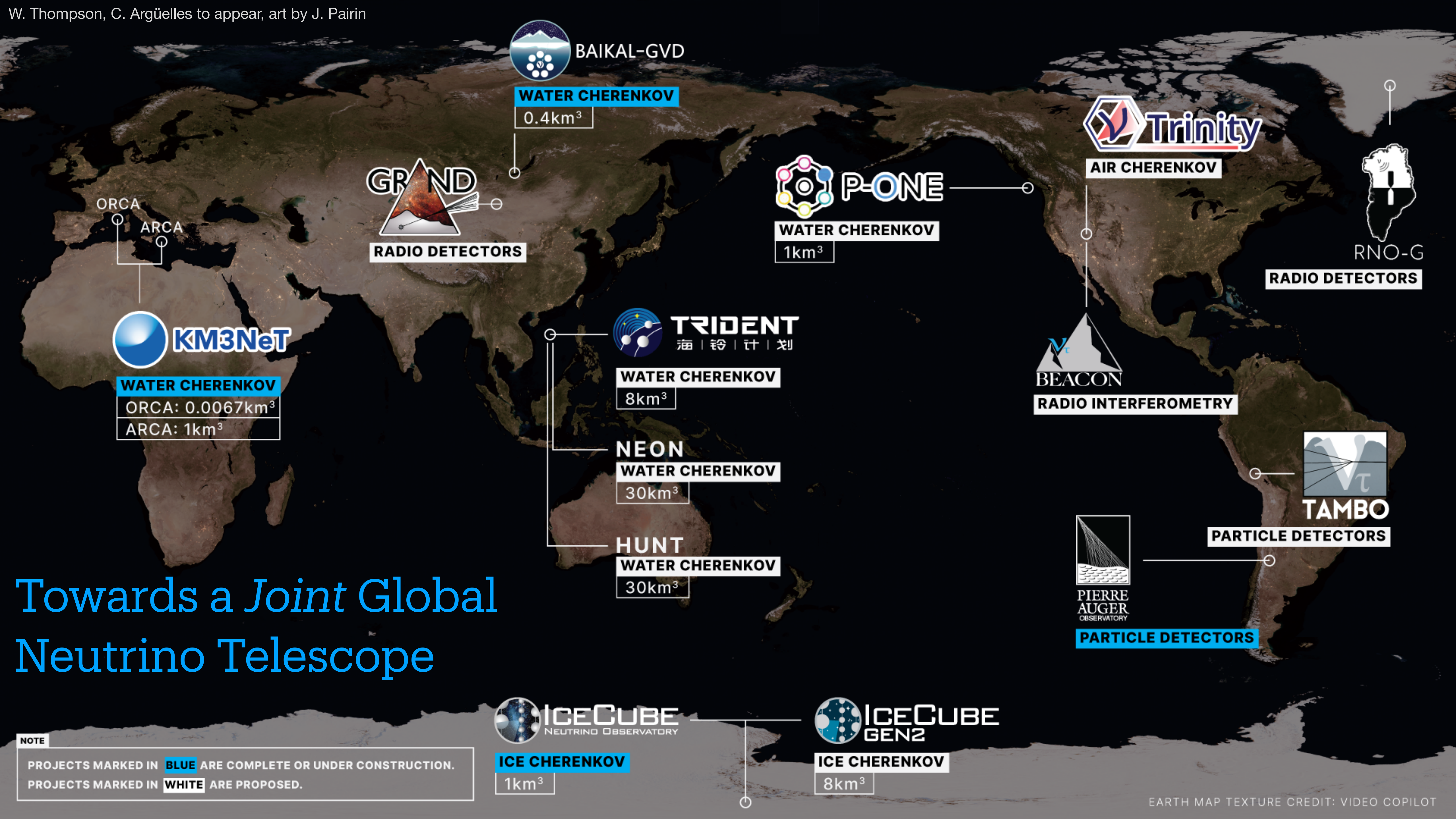
Sensitivity to very-high-energy transients



Sensitivity to very-high-energy transients comparable or better than IceCube, depending on declination.

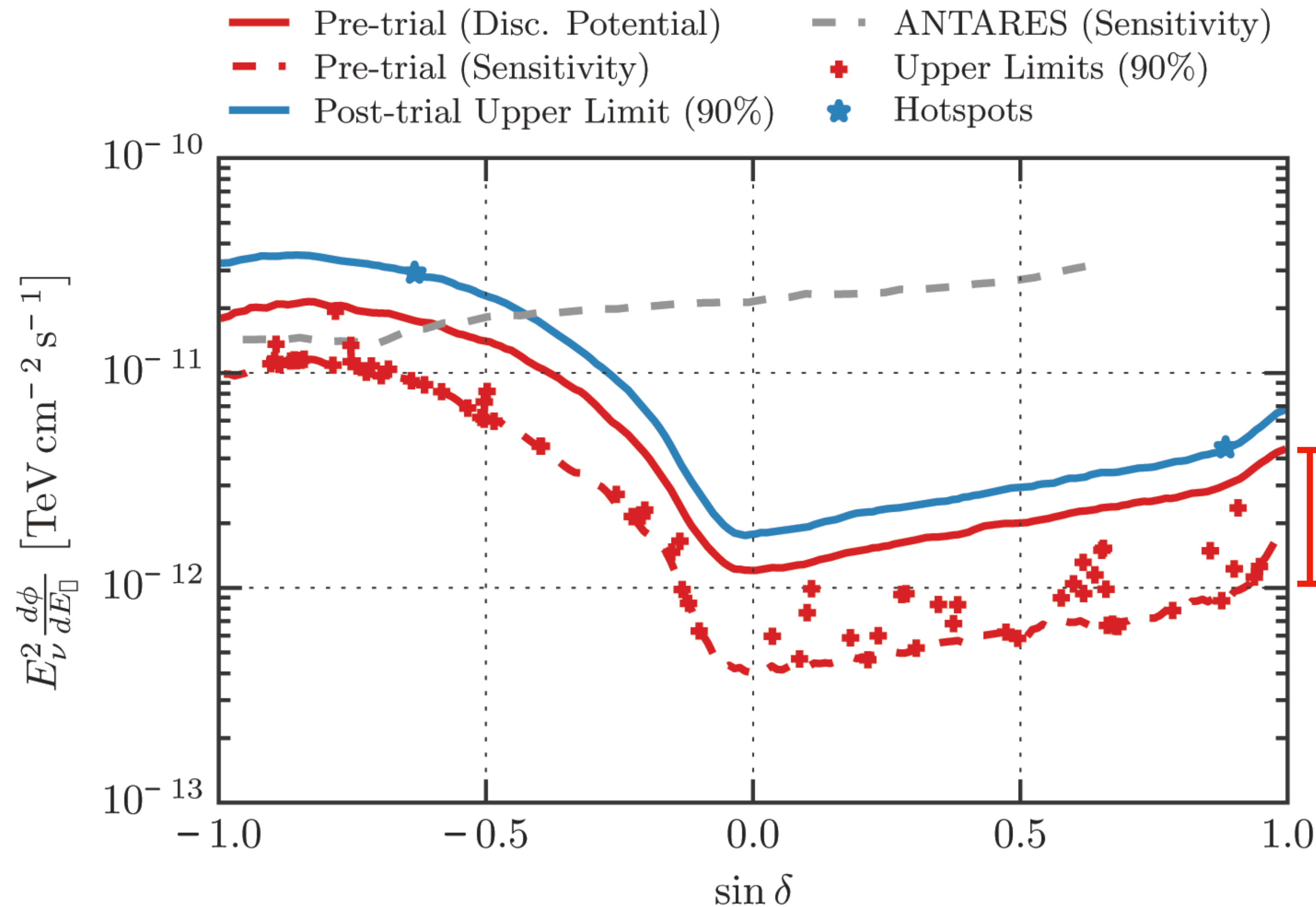
Newborn magnetar: J. A. Carpio, *Phys. Rev. D* 102, 103001 (2020)

GRB Afterglow: K. Murase, *Phys. Rev. D* 76, 123001 (2007)



Towards a *Joint Global* Neutrino Telescope

TAMBO as a *Viewfinder*: Overcoming trials



Neutrino telescopes all-sky searches are penalized by large trial factors.

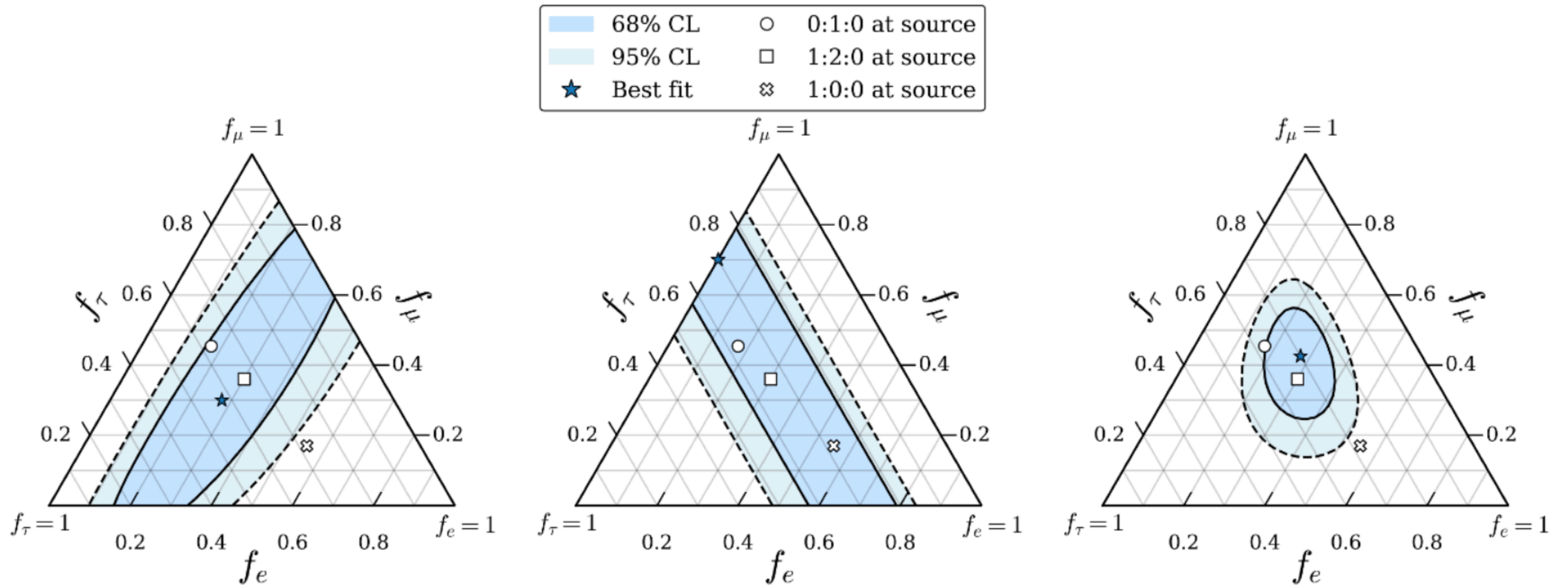
$$\sim 445,000 \text{ trials} \Rightarrow 19.8 \frac{\text{trials}}{\text{.}^2}$$

TAMBO very-high astrophysical purity can narrow search location.

IceCube, *Astrophys. J.*, 835 (2017) no. 2, 151

Flavor Combinations

Alba Burgos, CA, W. Thompson, to appear



No TAMBO

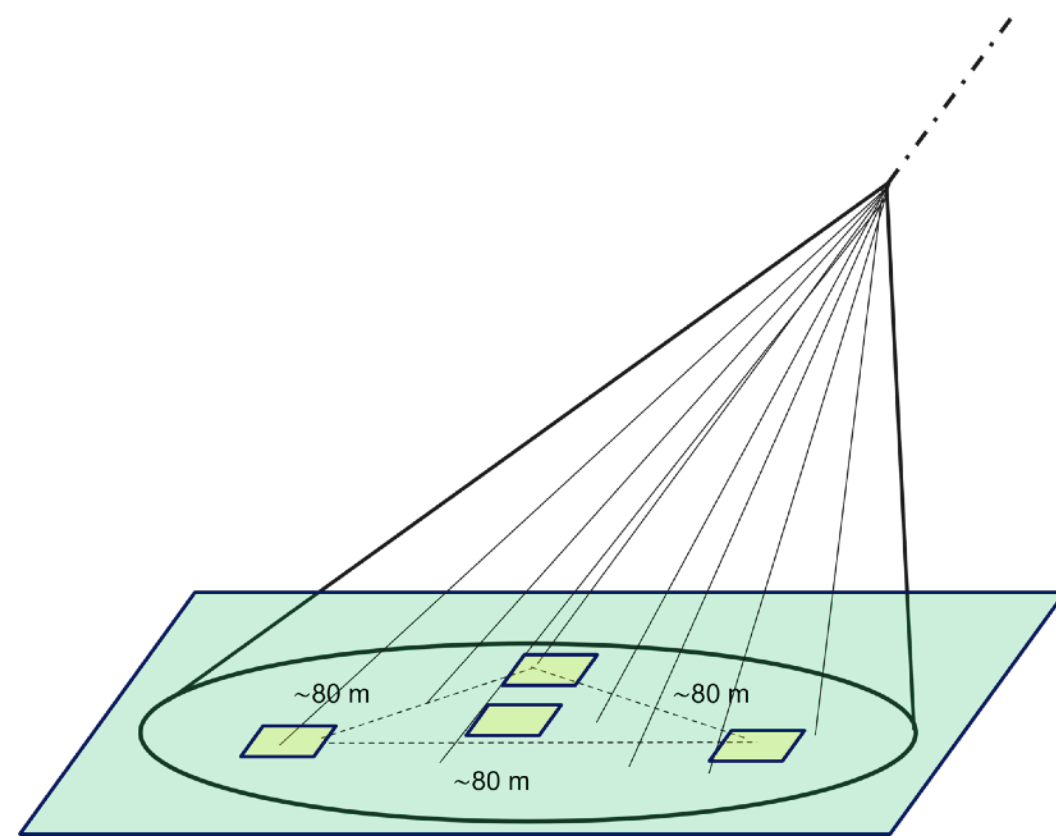
~TAMBO-only

Together

Status of TAMBO

Today

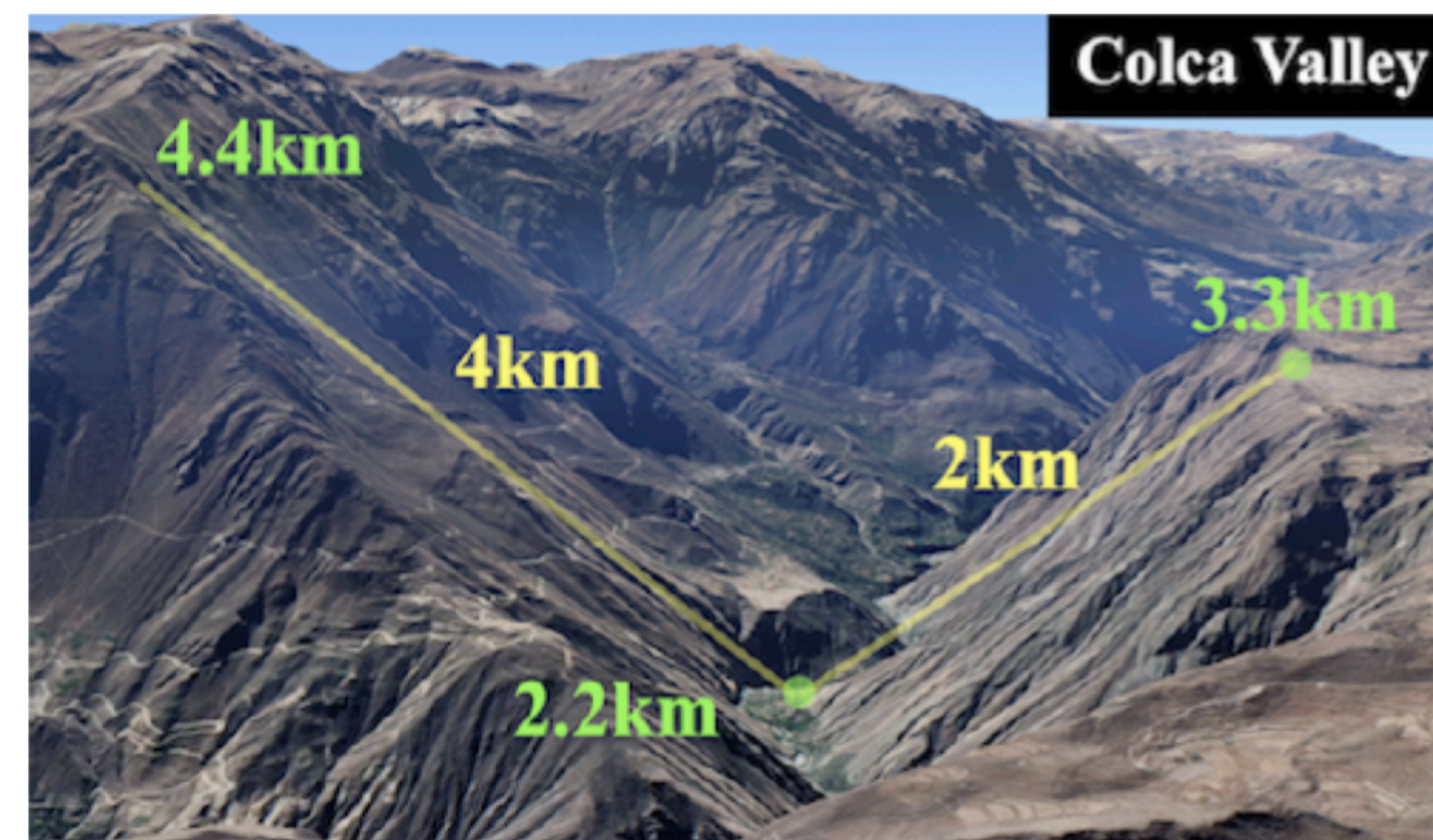
TAMBO-4



Small test array
Electronics, detector
prototypes

2025-2028

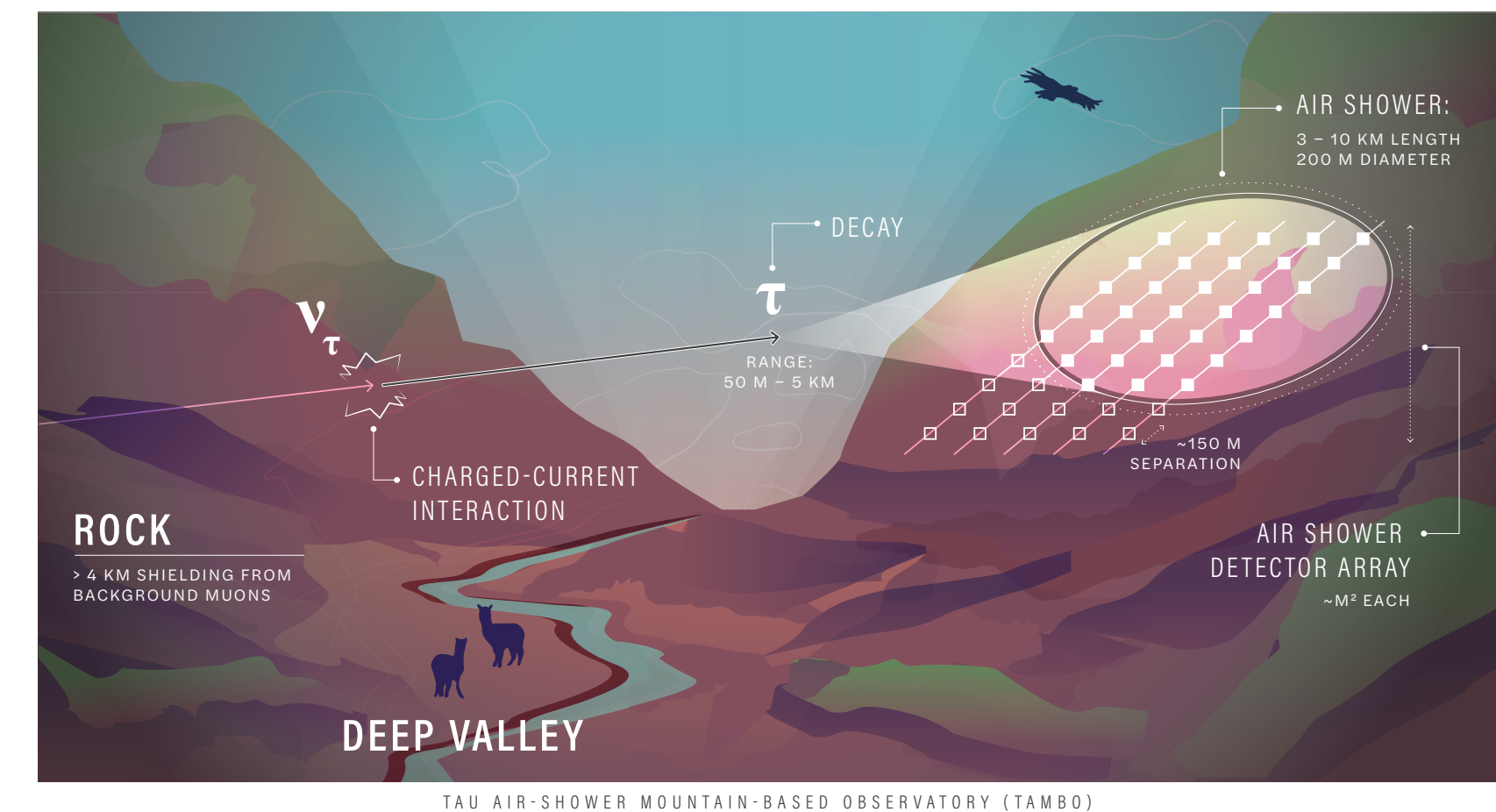
TAMBO-100
(aka TAMBITO)



Pilot array
Deployment techniques,
background, and social science

2028 - ...

TAMBO-5k



Array capable of detecting O(1)
neutrinos per year in the PeV to
100 PeV energy range

End

Looking forward for a productive discussion about TAMBO science!