ICRC 2025 Neutrino Rapporteur

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UNIVERSITY OF COPENHAGEN

VILLUM FONDEN

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Geneva, July 24, 2025

"Now this is not the end.
It is not even the beginning of the end.
But it is, perhaps,
the end of the beginning."

W. Churchill, 1942

1. ## Increased ability to extract physical insight

   Evolved from counting events to sophisticated analyses looking for subtle features

2. ## Intense theoretical interpretation work fueled by data

   More data and higher precision help navigate the theory landscape

3. ## On our way to having multiple km-scale instruments

   IceCube + KM3NeT + Baikal-GBD

4. ## We have broken into a new energy regime

   KM3NeT detected the first ultra-high-energy neutrino

5. ## We have ambitious plans for the short- and mid-term

   More, larger, different neutrino telescopes

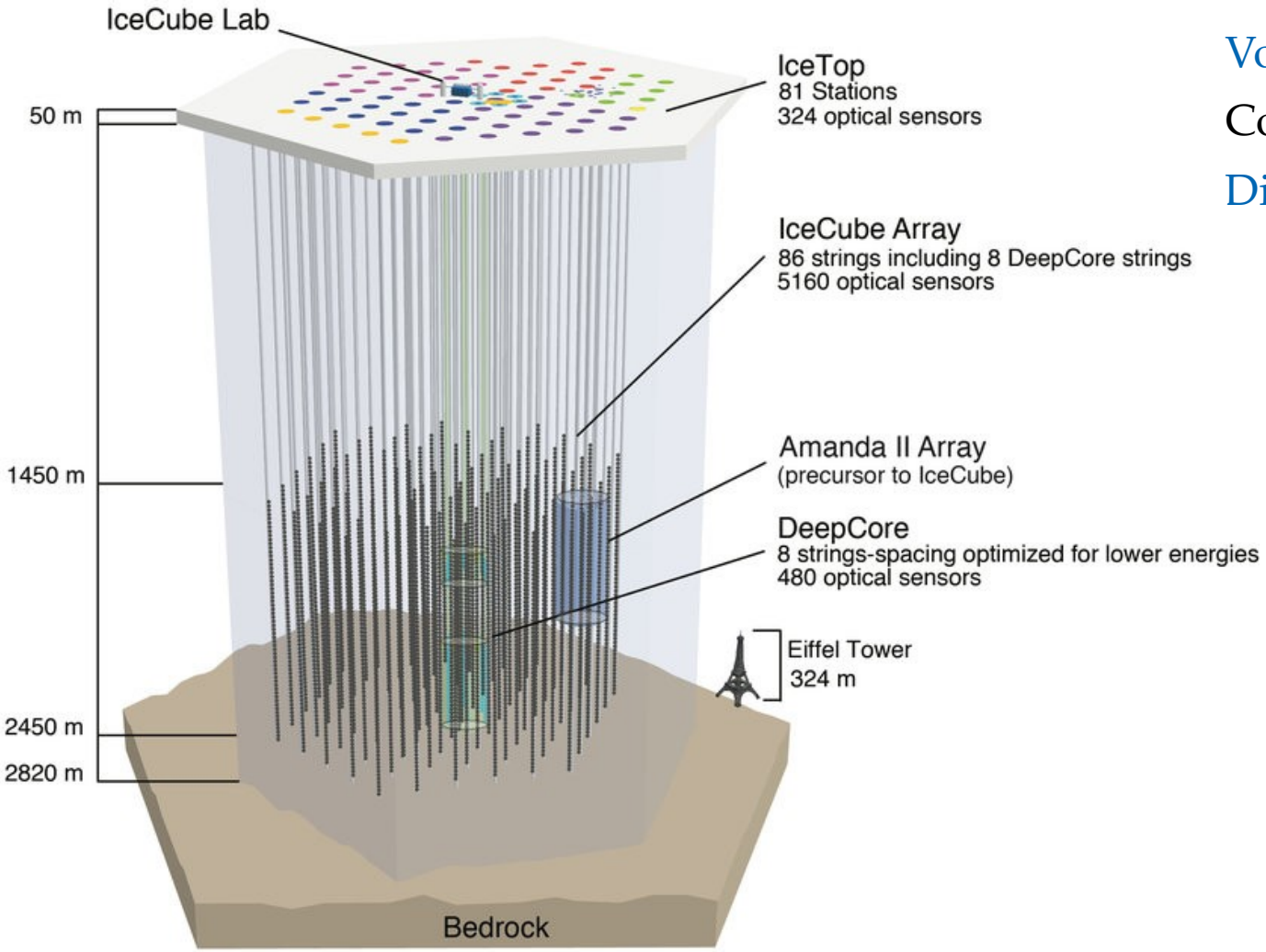
Martin Wolf, IceCube/NSF

Near the South Pole

Volume ~ 1 km^3, 1.5–2.5 km deep

Completed in 2011 (86 strings)

Discovered PeV υ in 2013



Karen Andeen, Matthias Plum, IceCube

IceCube diffuse TeV–PeV υ flux

Using MESE (1 TeV–10 PeV) [new flux points]: V. Basu+ 985
Using contained + uncontained (DNNCascades, WIP): Z. Rechav+ 1154
Unfolding υ_μ spectrum [new flux points, 11 yr]: L. van Rootsellar 1199
PeV flux, combined data sets (WIP) : Y. Yildizci+ 1217
Using tau neutrino-induced cascades [new flux fit, 11 yr]: Z. Chen+ 1011

IceCube source searches

Transient sources, tracks + cascades (WIP): J. Carpio+ 1007
Flaring X-ray binaries, tracks +cascades 13 yr (WIP): A. Kochocki+ 1077
SN2023ixf [new upper limits]: A. Mand+ 1109
Real-time search for gravitational-wave coincidence: Z. Marka+ 1113
Infrared galaxies (WIP): T. Pernice+ 1145
Enhancements from machine learning (WIP): L. Seen+ 1169
GeV–PeV υ recurrent nova T Coronae Borealis (WIP): J. Thwaites+ 1200

IceCube Galactic υ flux

Segmented Galactic Plane (WIP): L. Neste+ 1130
Tracks (starting + thru) + cascades (WIP): J. Hellrung+ 1056 |
J. Osborn+ 1135 |
M. Thiesmeyer+ 1193
Improvement via summary statistics: O. Janik+ 1132

IceCube GeV υ counterparts to high-energy υ

First upper limits, short time-scales: C. Raab+ 1150
Prospects: P. A. S. Myhr+ 1174

IceCube flavor composition

Contained events > 1 TeV (MESE) [new]: A. Balagopal+ 983
High Energy Starting Events > 60 TeV (HESE) [new 12 yr]: N. Lad+ 1198

IceCube Extremely High Energy Events

Diffuse flux > 10 PeV [new upper limit, 12.6 yr]: M. Meier+ 1122
Improvements from machine learning: M. Nakos+ 1127

IceCube alerts

Improved real-time reconstruction (WIP): G. Sommani+ 1184
Real-time track alert catalog IceCat-2 (WIP): A. Zegarelli+ 1224

IceCube neutrino tomography of the Earth

Using υ from 500 GeV to 100 TeV, 11 yr (WIP): A. Y. Wen 1211

IceCube event selection

New DAQ to detect neutron echoes: K. Dutta+ 1030
Northern track selection using GCNN: P. Soldin+ 1183

IceCube detector studies and upgrades

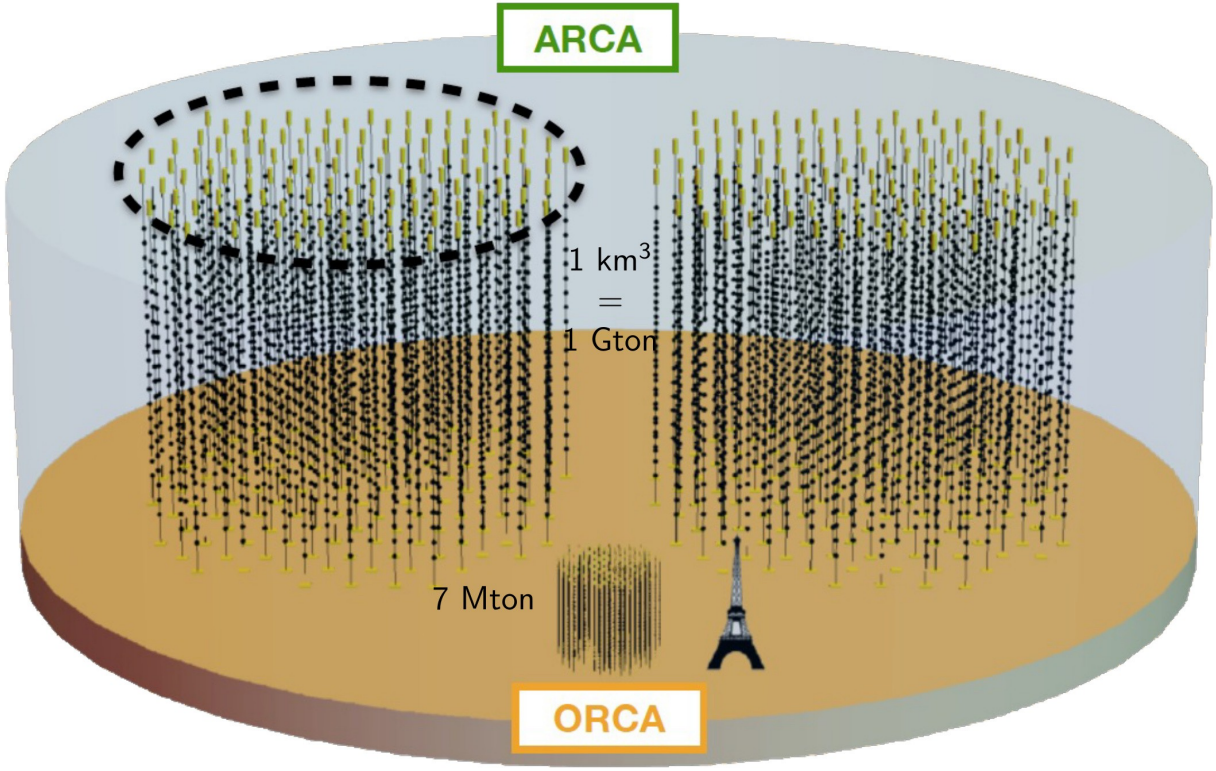
Status of ice model: D. Chirkin+ 1013
Mapping ice stratigraphy: A. Eimer+ 1035

KM3NeT Collab.

Astroparticle Research Mediterranean Sea

[3.5 km deep, Sicily, running since 2015]

Final configuration: > 1 km^3, 230 strings, 4100+ optical modules • **Today:** 33 strings



KM3NeT highlight:
D. Dornic, July 21

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 lines

KM3NeT UHE neutrino

Observation: M. Lamoureux 1018
Source search: M. Marconi+ 1110
Cosmogenic origin: A. Condorelli+ 1111
Galactic origin: M. Breuhaus 997
Blazars: M. Bendahman+ 986 | M. Lincetto+ 1100
Global view: C. Argüelles+ 1117
GRB blastwave: P. A. Sevle Myhr+ 1173

KM3NeT/ARCA: diffuse TeV–PeV υ flux

Today [new limit ARCA6-8-19-21]: V. Tsourapis+ 1196
Full detector: C. Karagiannis+ 1073

KM3NeT source searches

Point & extended [new limit ARCA6-8-19-21]: A. Hejjboer+ 1124
With ANTARES [new limits ARCA6-8-19-21]: B. Caiffi 1002
CMZ & Cygnus OB2: M. Benhassi+ 1039
Galactic gamma-ray sources: V. Parisi+ 1140
Blazar stacking [new limit ARCA6-8-19-21]: F. Carenini+ 1005 | M. R. Musone+ 1125
ULIRG stacking [new limit ARCA6-8-19-21]: A. De Benedittis+ 1023
Low energy, with ORCA: I. Del Rosso+ 1026
CCSNe: S. El Hedri 1037
Real-time alerts: F. Filippini+ 1038
Seyfert stacking [new limit ARCA6-8-19-21]: W. Idrissi Ibnsalih+ 1065
Microquasars: F. Magnani 1108
GRB stacking: J. Palacios González+ 1139

KM3NeT/ARCA: Galactic υ flux

Galactic Ridge [new limit ARCA6-8-19-21]: F. Filippini 1039

KM3NeT prompt atmospheric υ

Sensitivity: Kalaczyński+ 1039

KM3NeT/ORCA neutrino oscillations

First KM3NeT Bayesian: A. Lazo Pedrajas 1092

KM3NeT detector studies and upgrades

Control unit: C. Bozza 993
Junction box: E. Giorgio+ 1043
Online analysis system: M. Mastrodicasa+ 1115
ARCA string calibration: F. Badaracco+ 1116
ARCA time calibration: F. Benfenati Gualandi+ 1137
Acquisition systems: D. Real+ 1152 | D. Real+ 1153
ARCA acoustic positioning: S. Viola+ 1156
ORCA optical water properties: A. Romanov+ 1158

Baikal-GVD

JINR

In Lake Baikal, Russia

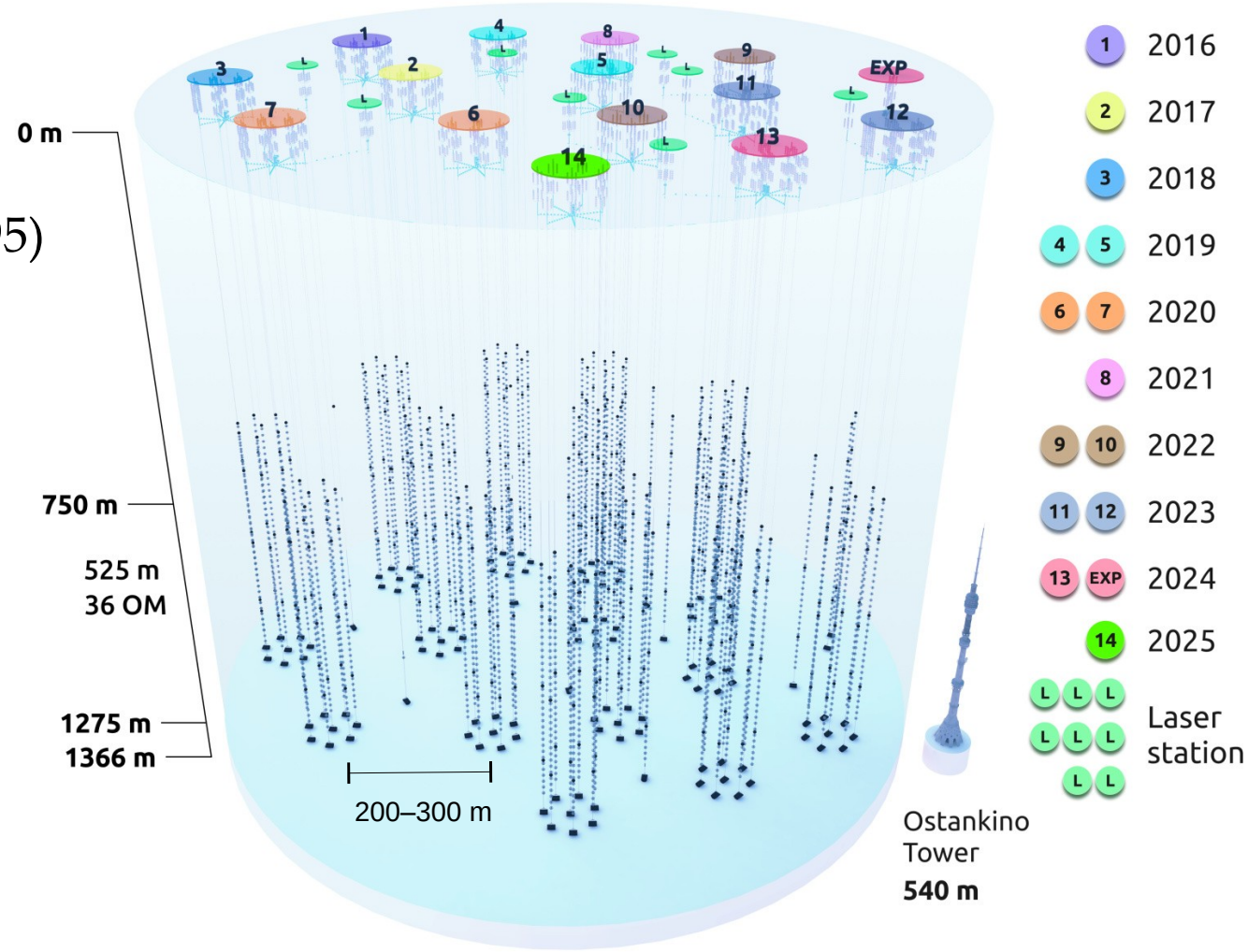
Long-running succession of neutrino telescopes (since 1995)

Depths up to ~1.4 km

Array of clusters of 8 strings

Today:
0.7 km^3, 14 clusters, 4212 OMs

Final configuration (in ~3 yr):
~1 km^3, 90 strings, 6000+ OMs

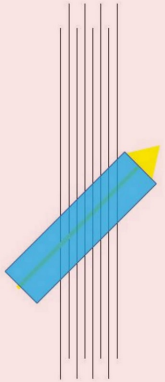


Baikal-GVD overview: G. Safronov, July 19

In use

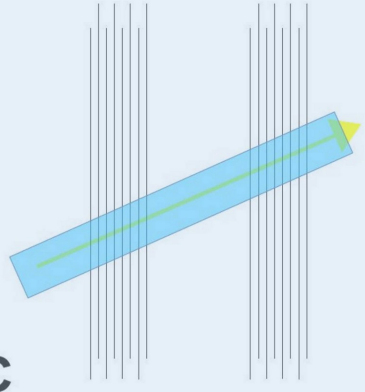
In development

Single-cluster tracks



- Low energy threshold
- Optimal sensitivity to nearly vertical tracks
- 90% of recorded track events

Multi-cluster tracks

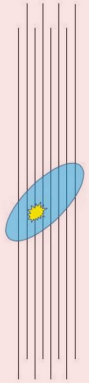


- Moderately low energy threshold
- Optimal sensitivity to inclined tracks
- Best angular resolution

ν_μ CC

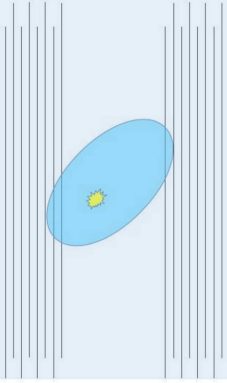
NC, ν_e ν_τ CC

Single-cluster cascades



- High energy threshold
- Good energy resolution
- Relatively rare events

Multi-cluster cascades



- Very high energy threshold
- Excellent energy resolution
- Very rare events

Baikal-GVD overview:
G. Safronov, July 19

Baikal-GVD: diffuse TeV–PeV υ flux

Using 6 yr cascades [detection at 5.1σ]: R. Dvornický+ 1031 [also 2507.01893]
Using tracks (work in progress): G. Safronov+ 1162

Baikal-GVD Galactic υ flux

Using 6 yr cascades, 2.5σ: B. B. Ulzutuev+ 1197

Baikal-GVD source searches

Point sources, using tracks [new limits 5 yr tracks]: G. Safronov+ 1162

Baikal-GVD UHE neutrinos

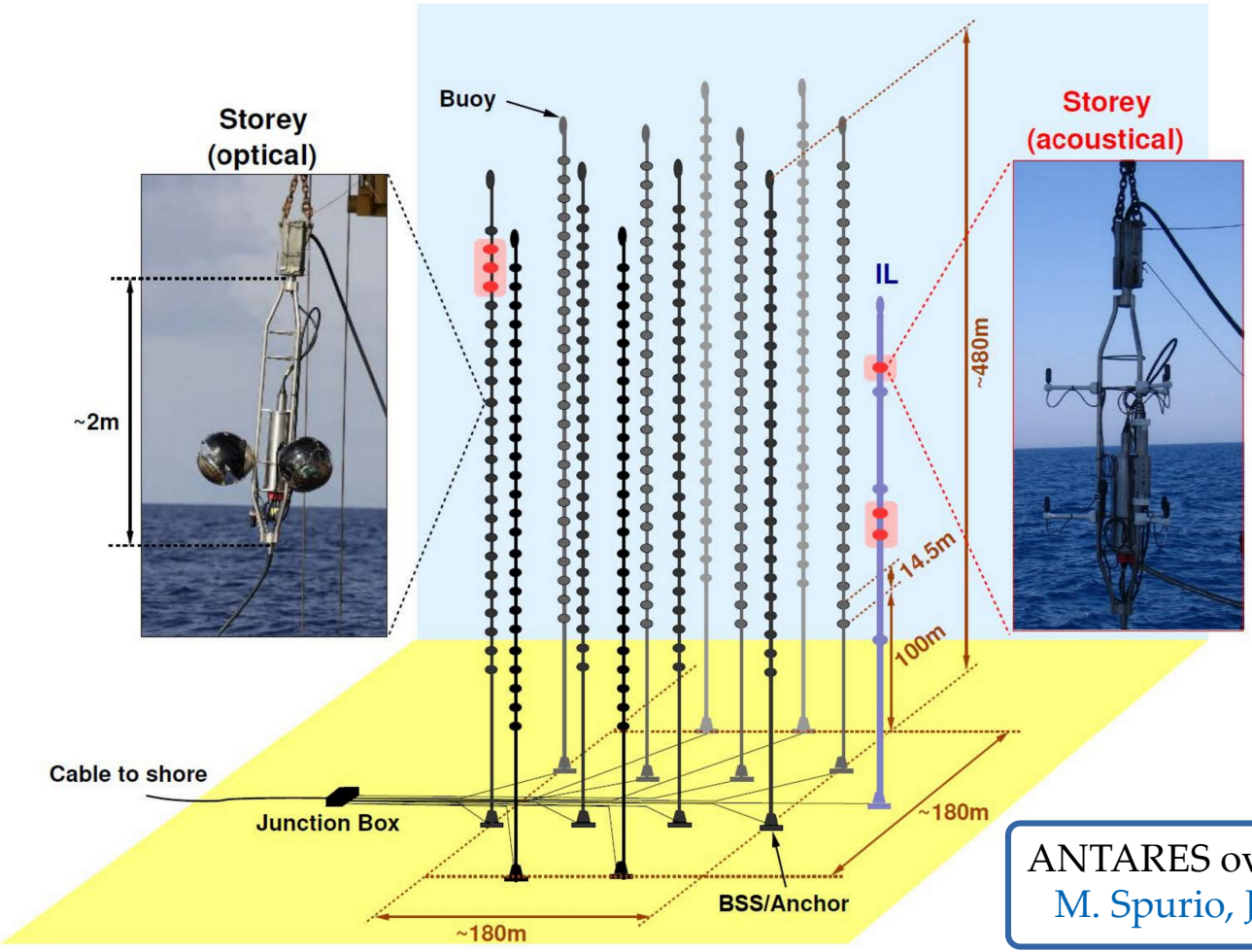
Diffuse flux [new limit 6 yr cascades]: M. N. Sorokovikov 1186

Baikal-GVD detector studies and upgrades

New positioning system: B. A. Shaybonov 1175
Optical water properties: B. A. Shaybonov 1176

ANTARES

KM3NeT Collab.



40 km off of Toulon (ORCA site)

Volume ~ 0.01 km^3, 2.5 km deep

Operated 2008–2022 (12 strings)

Provided invaluable experience for later neutrino telescopes (like AMANDA did in ice!)

Post-decomissioning, provided PMTs for other experiments

ANTARES overview:
M. Spurio, July 17

ANTARES overview

20 years of ANTARES: M. Spurio+ 1187

ANTARES Galactic υ flux

Using tracks and cascades, full data set: T. Cartraud 1009

ANTARES source searches

Point-like and extended, full data set: F. Salesa Greus+ 1191
Neutrino flares, full data set: A. Sánchez Losa+ 1066
Gamma-ray bursts, full data set: M. Scarnera+ 1167

ANTARES BSM search

Magnetic monopoles, full data set: A. Eddymaoui+ 1033

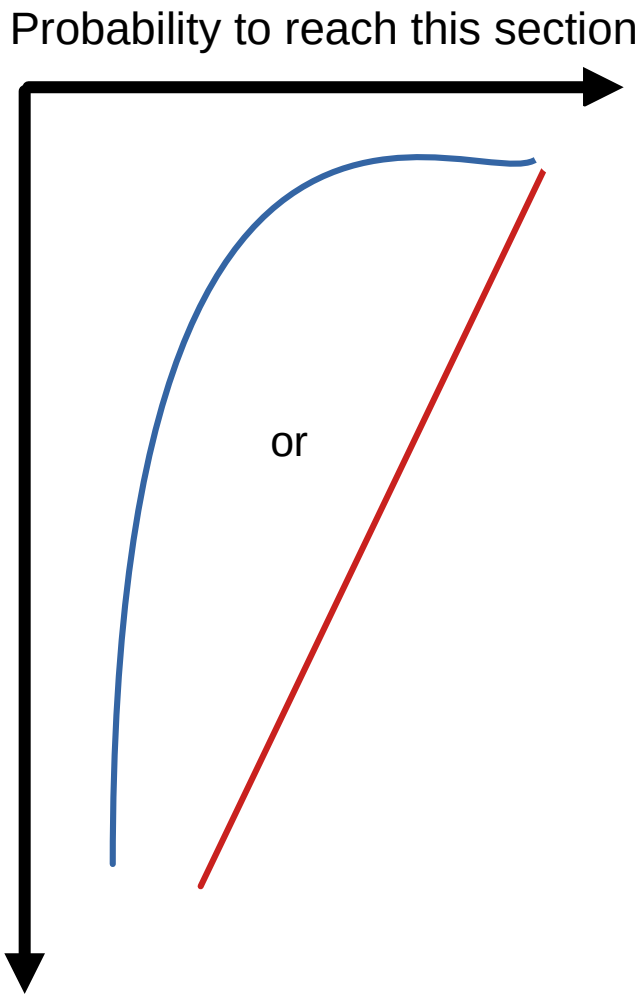
One
The diffuse flux of TeV–PeV neutrinos

Two
Neutrinos from the Milky Way

Three
Neutrino flavor composition

Four
The first neutrino of ultra-high energy

Five
The shape of things to come



One

The diffuse flux of TeV–PeV neutrinos

The multi-messenger connection: a simple picture

(or $p + p$)

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

The multi-messenger connection: a simple picture

(or $p + p$)

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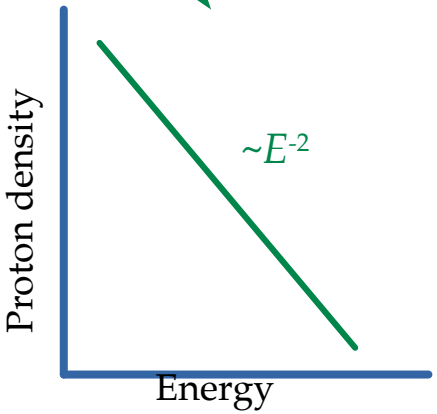

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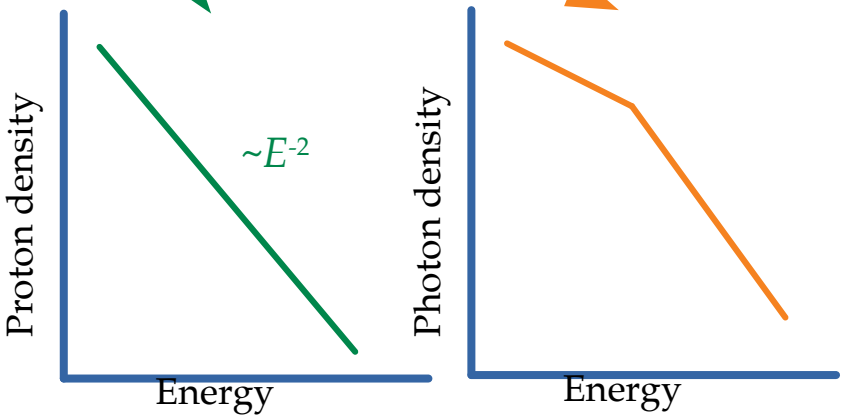

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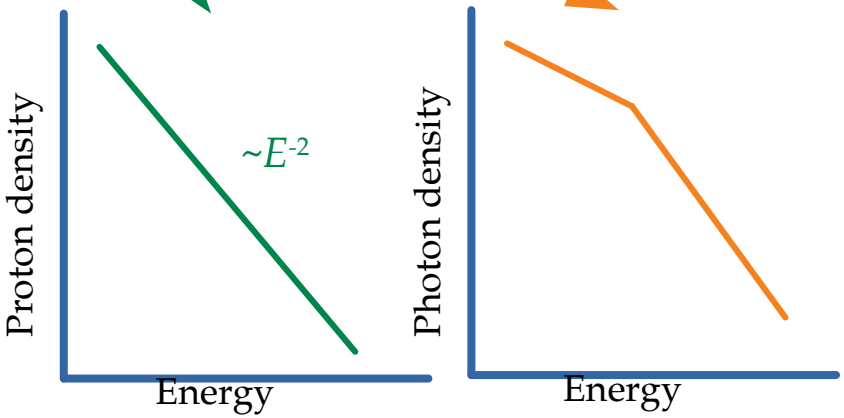
$$\pi^0 \rightarrow \gamma + \gamma$$

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

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



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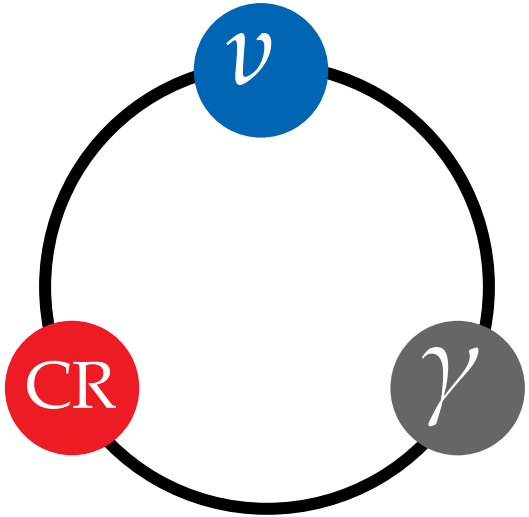

Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 10

The multi-messenger connection: a simple picture

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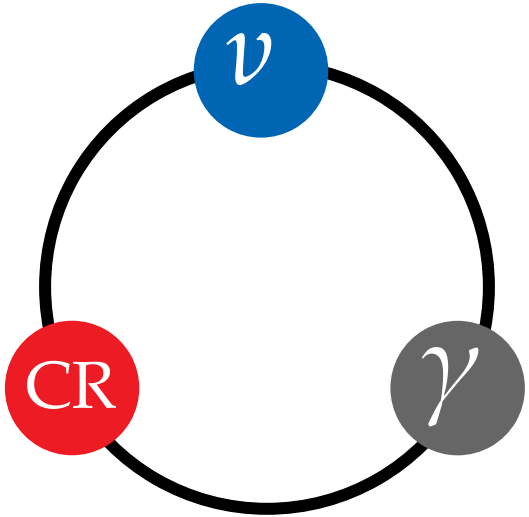

1 PeV 20 PeV

Neutrino energy = Proton energy / 20

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The multi-messenger connection: a simple picture

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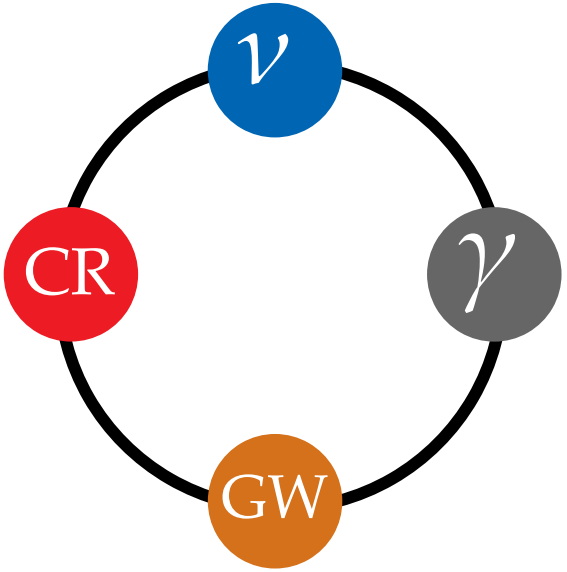

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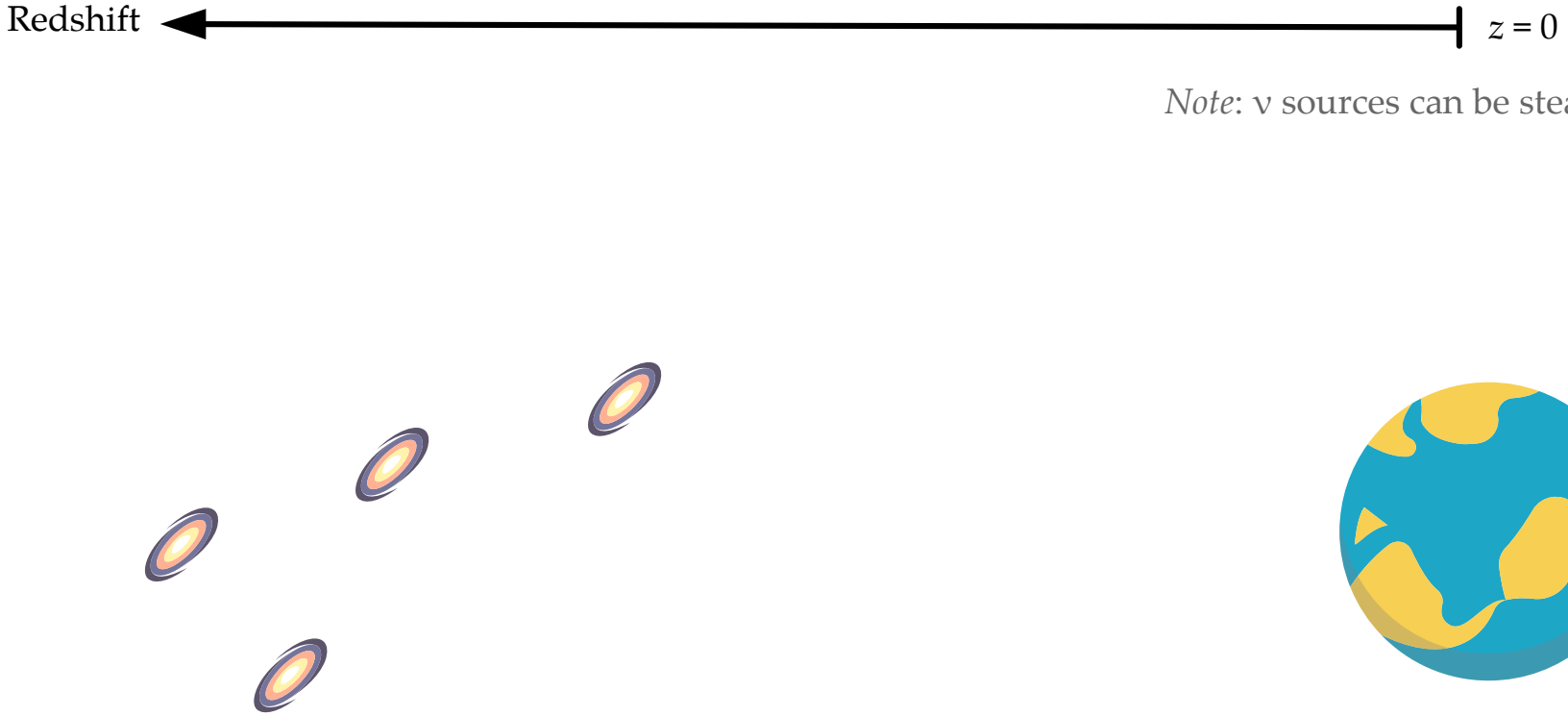
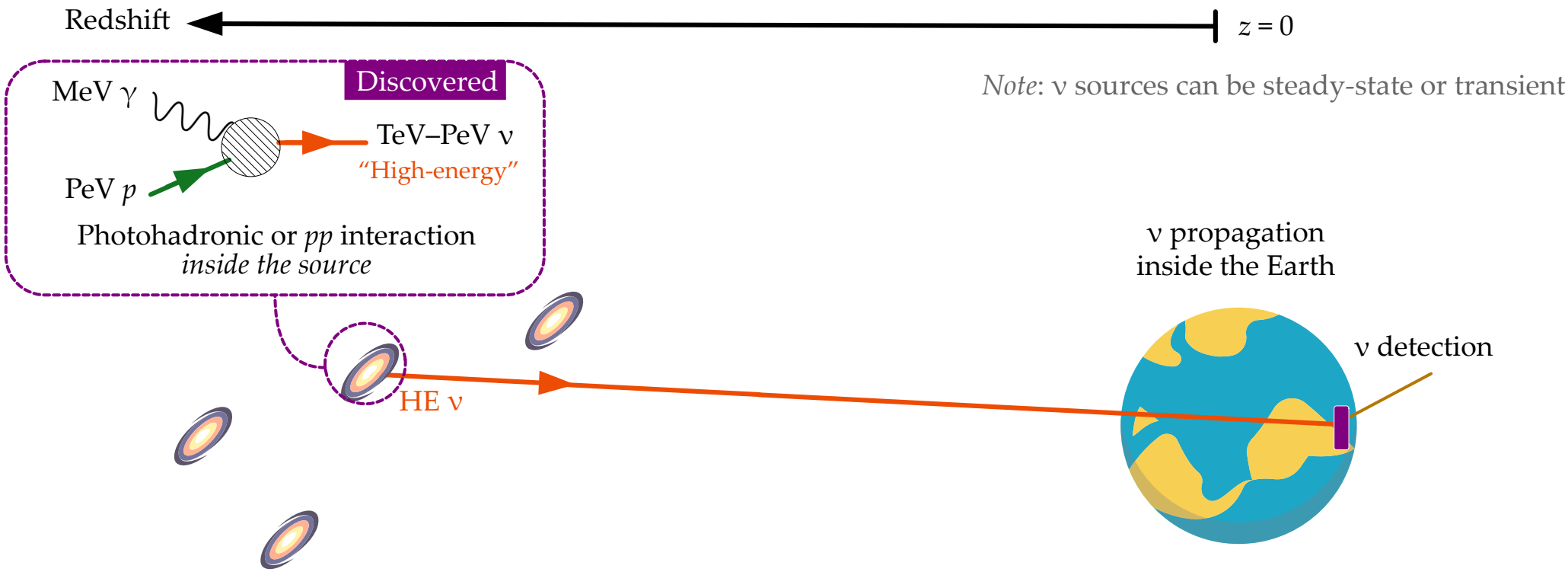


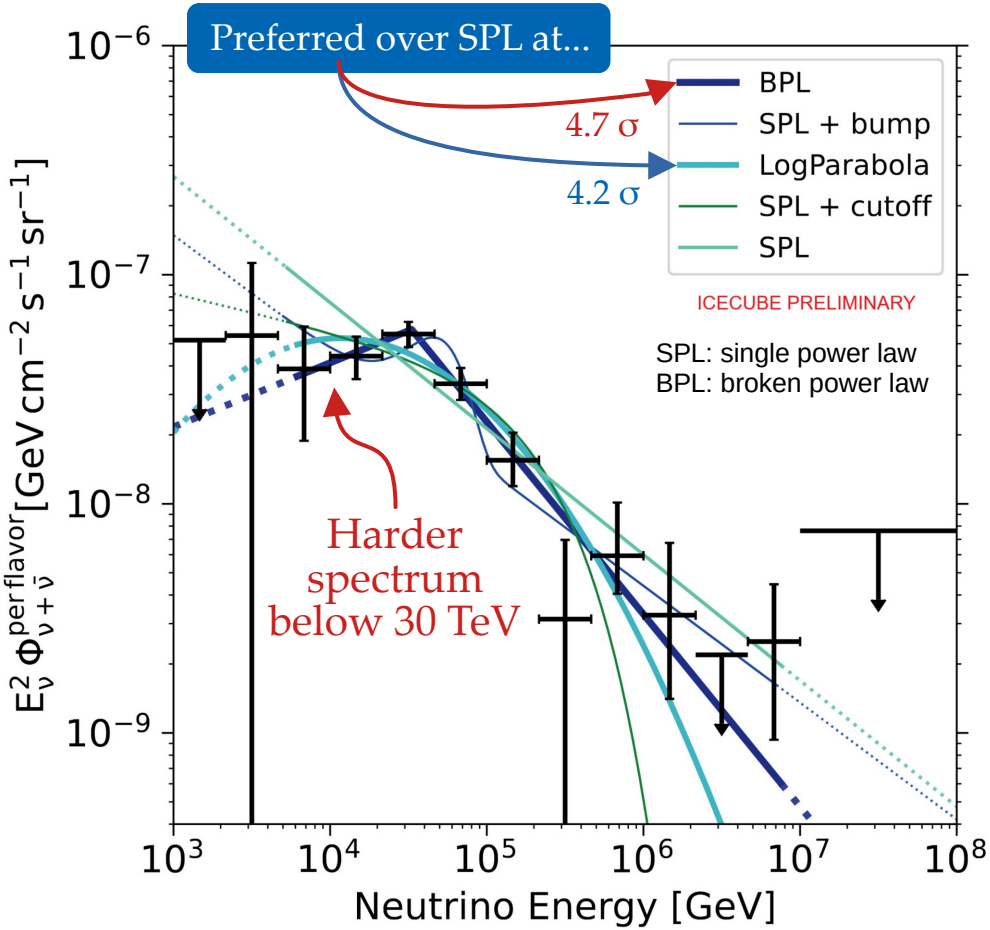
Note: ν sources can be steady-state or transient


Redshift
z = 0
Discovered
MeV γ
TeV–PeV ν
"High-energy"
PeV p
Photohadronic or pp interaction
inside the source
Note: ν sources can be steady-state or transient
ν propagation
inside the Earth
ν detection
HE ν

Diffuse TeV–PeV υ flux: **IceCube**

V. Basu, A. Balagopal, A. Karle,
PoS(ICRC2025)985

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



11 yr of Medium Energy Starting Events (MESE)

Cascades (υ_e, υ_μ, υ_τ), tracks (υ_μ), double cascades (υ_τ)

Applied additional selection cuts to remove low-energy atmospheric muons

First time IceCube has resolved structure in the cosmic neutrino spectrum at > 4σ

Features of neutrino production?
Two source populations?
New physics? (E.g., dark-matter decay/annihilation)

SPL b.f.: $\Phi \propto E^{-\gamma}$ ($\gamma = 2.55$)

BPL b.f.: $\Phi \propto \begin{cases} E^{-\gamma_1}, & E < E_b \\ E^{-\gamma_2}, & E > E_b \end{cases}$ ($\gamma_1 = 1.72$, $\gamma_2 = 2.84$, $E_b = 33$ TeV)

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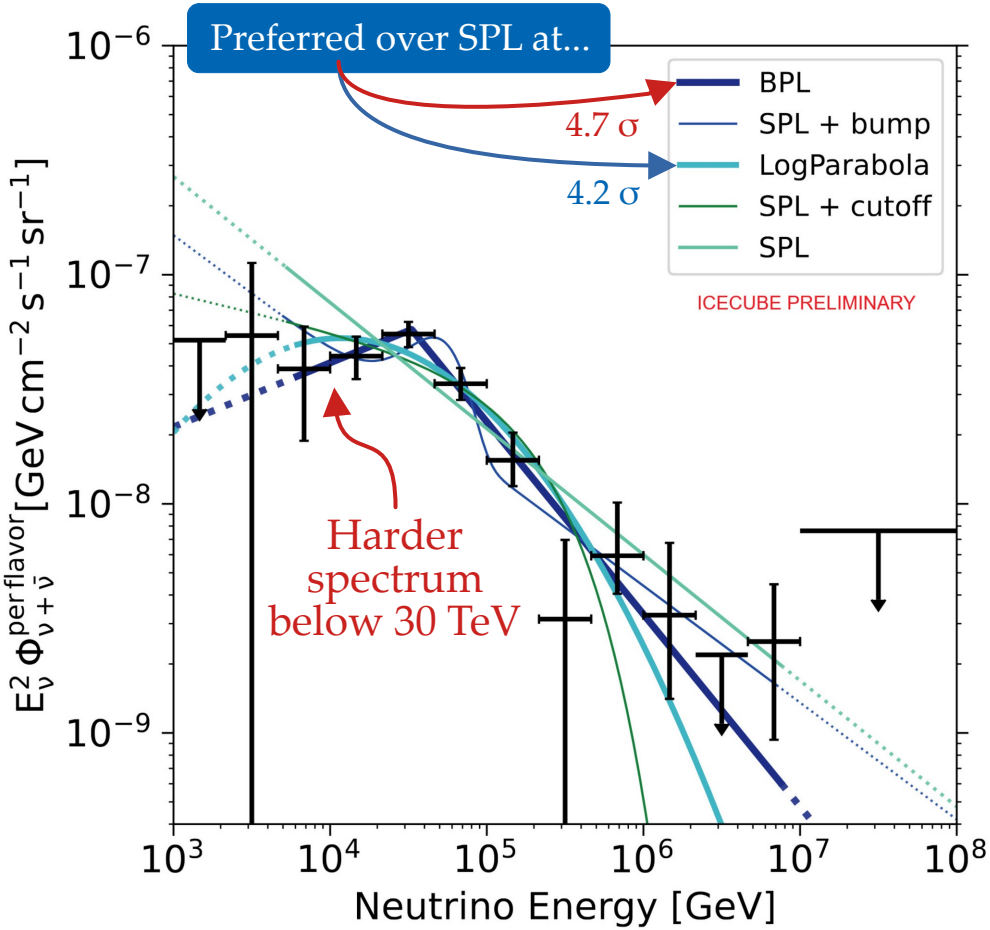
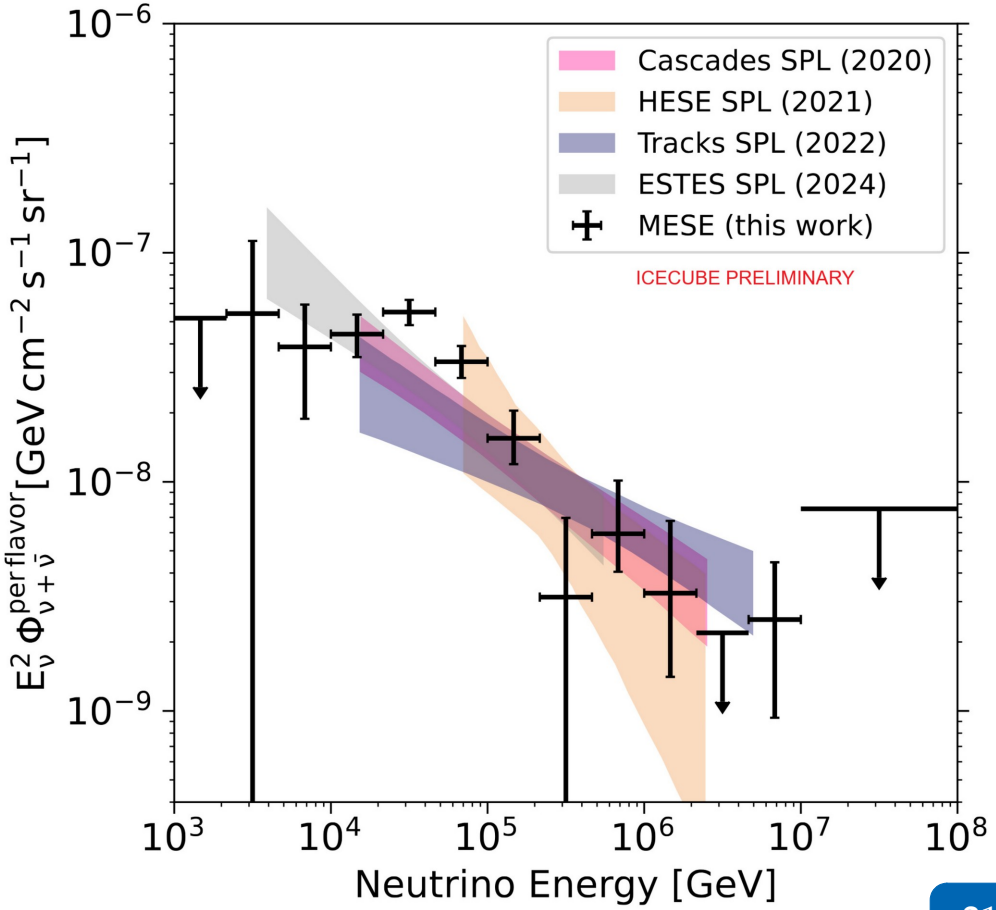
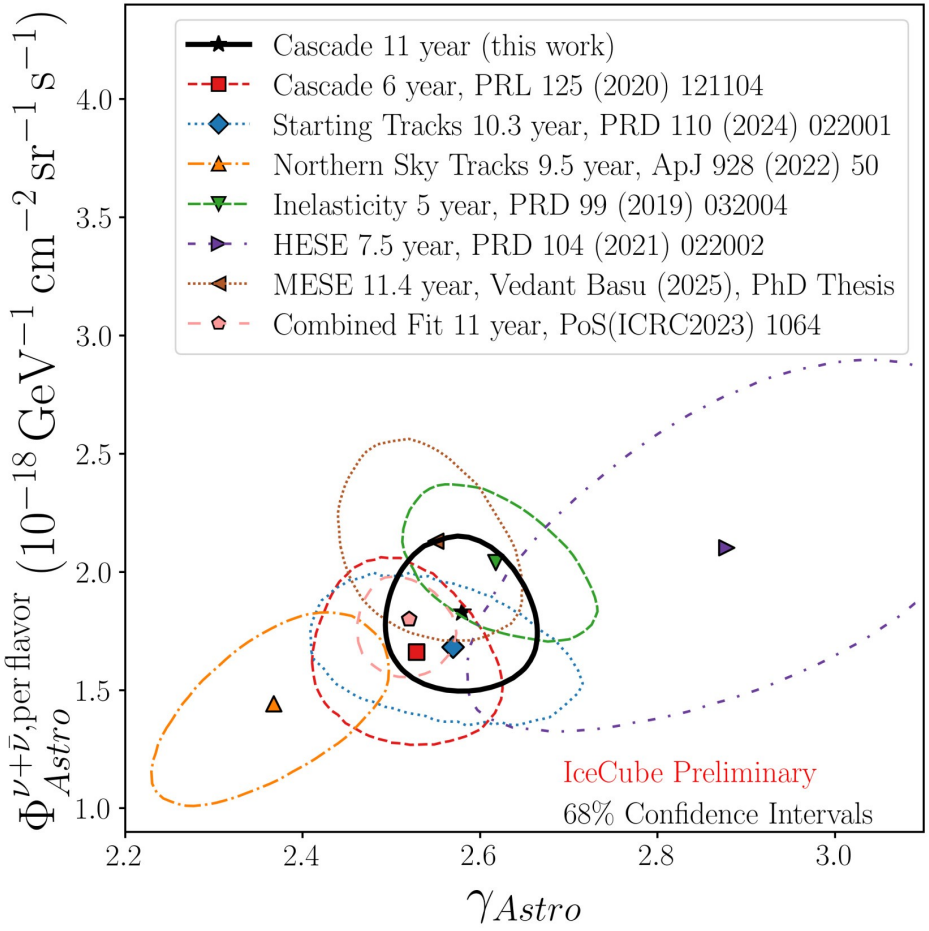


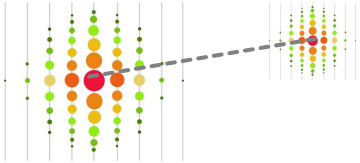


Diffuse TeV–PeV υ flux: **IceCube**

Z. Chen, Z. Zhang, J. Kiryluk (for IceCube)
PoS(ICRC2025)1011

2 – New measurement using cascades at > 10 TeV





11 yr of cascade data

Cascades (υ_e, υ_μ, υ_τ) and double cascades (υ_τ)

Background to double-cascade search:
- υ_e charged-current cascades
- υ_e, υ_μ, υ_τ neutral-current cascades
- υ_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 υ_τ-enriched sample with 90% υ_τ purity

(Great for flavor measurements, see later)

Diffuse TeV–PeV υ flux: **IceCube**

Z. Chen, Z. Zhang, J. Kiryluk (for IceCube)
PoS(ICRC2025)1011

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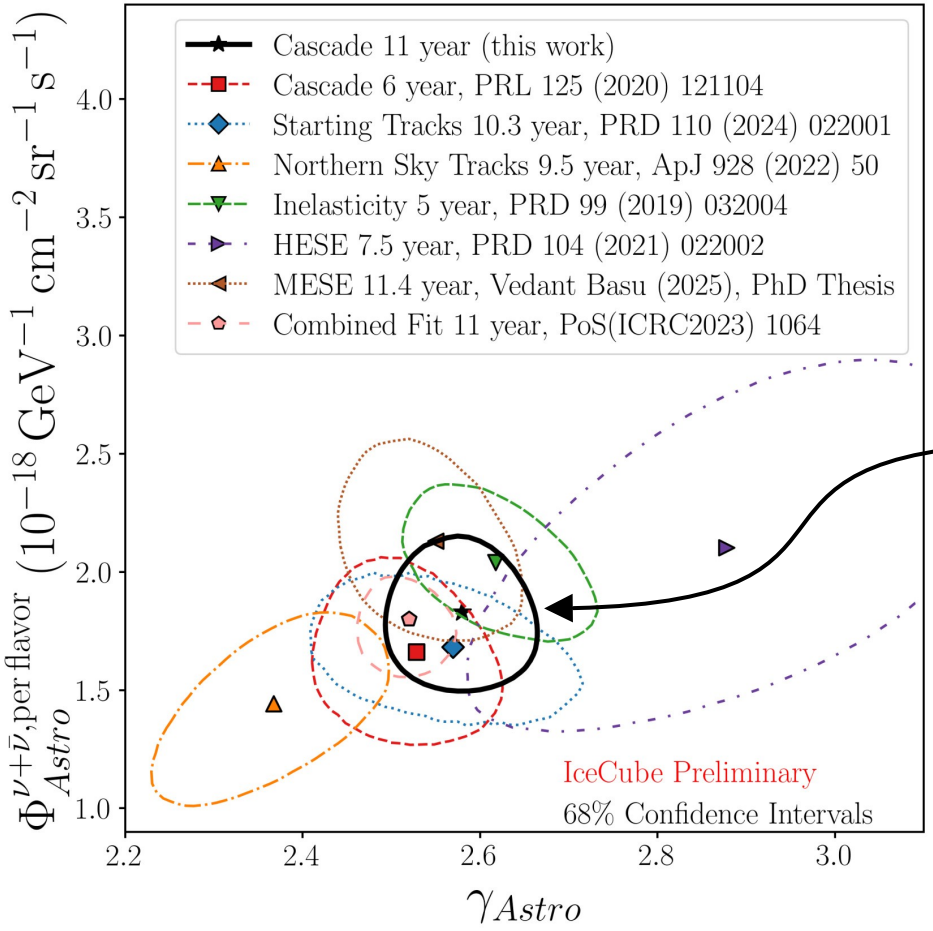

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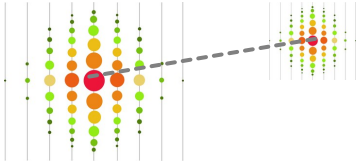


Cascades (υ_e, υ_μ, υ_τ) and double cascades (υ_τ)

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:

$$\Phi_0 = 1.83 \pm 0.21$$
$$\gamma = 2.68 \pm 0.06$$

Diffuse TeV–PeV υ flux: **IceCube**

Z. Chen, Z. Zhang, J. Kiryluk (for IceCube)
PoS(ICRC2025)1011

2 – New measurement using cascades at > 10 TeV

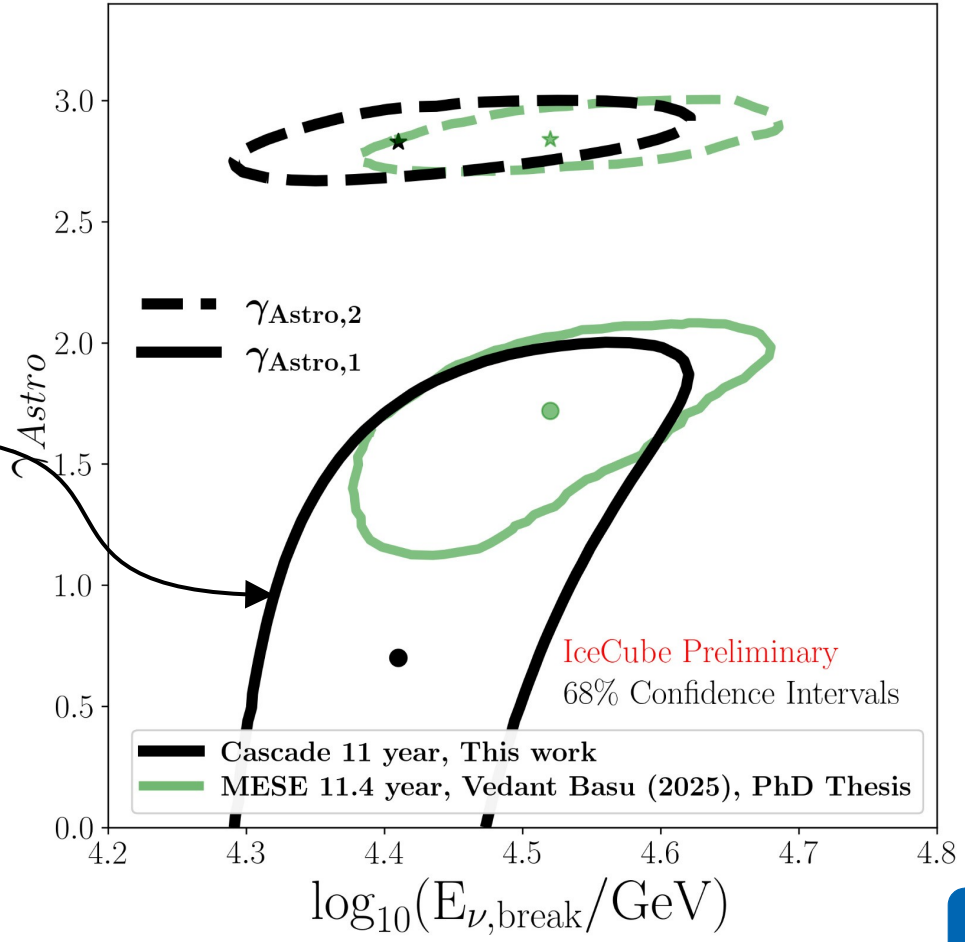
Tried also a broken-power-law fit:

$$\Phi = \Phi_0 \times \begin{cases} \left(\frac{E}{E_b}\right)^{-\gamma_1}, & E < E_\mathrm{b} \\ \left(\frac{E}{E_b}\right)^{-\gamma_2}, & E \geq E_\mathrm{b} \end{cases},$$

but the low-energy branch is only weakly constrained

Best-fit values:

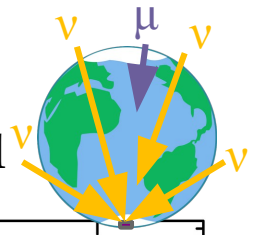
$$\gamma_1 = 0.70^{1.05}_{-0.70}$$
$$\gamma_2 = 2.83 \pm 0.12$$
$$E_\mathrm{b} = 25.7^{+9.0}_{-4.3}\ \mathrm{TeV}$$



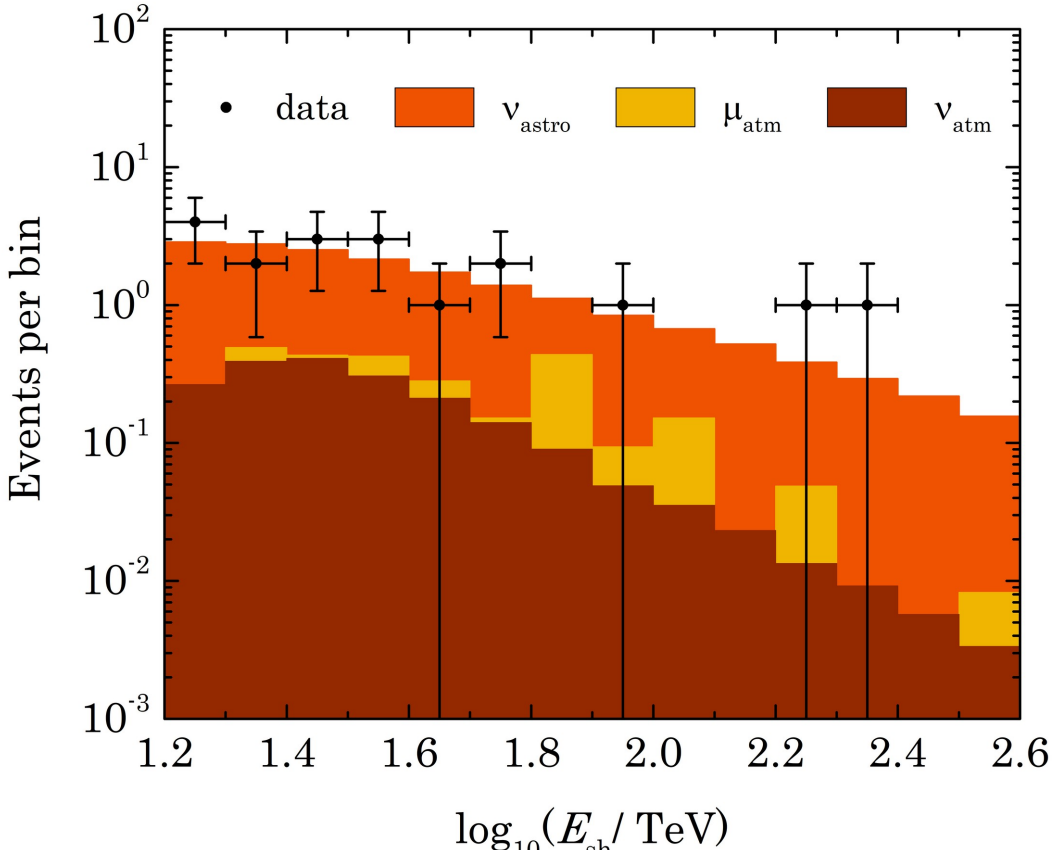
Diffuse TeV–PeV υ flux: **Baikal-GVD**

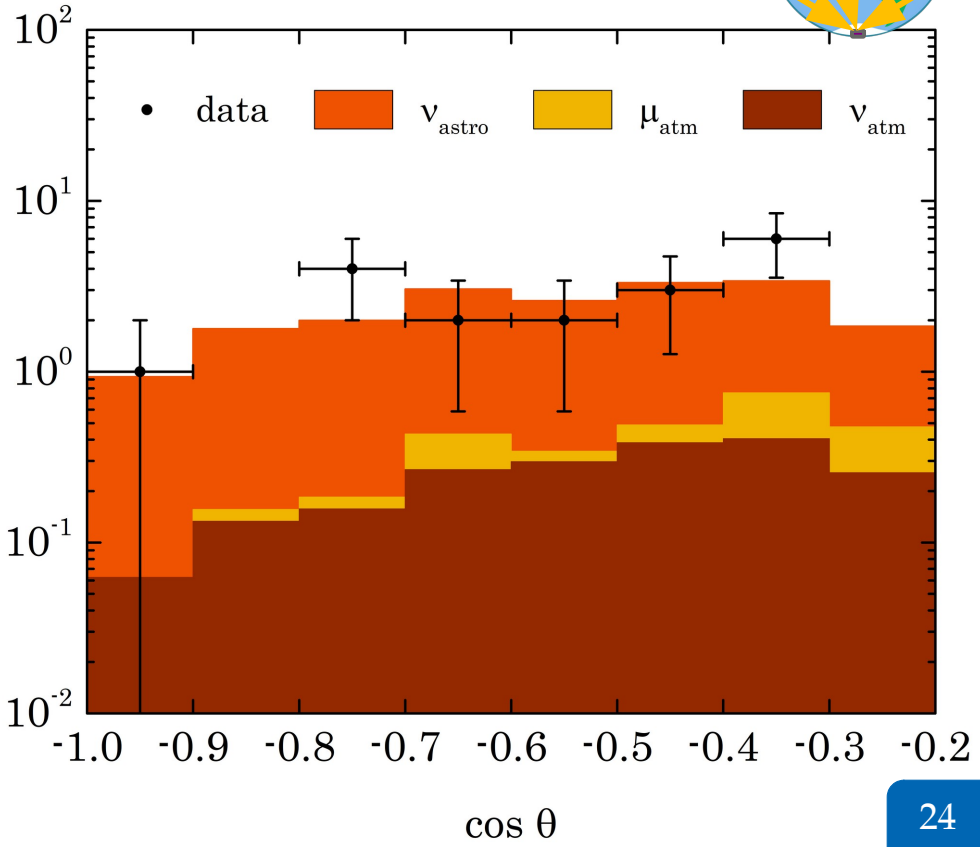
R. Dvornický (for Baikal-GVD)
PoS(ICRC2025)1031
See also arXiv:2507.01893

First independent observation of the diffuse υ flux



6 yr of cascade data (> 10 TeV): 2018–2024
Restricted to upgoing directions to mitigate atmospheric muon background

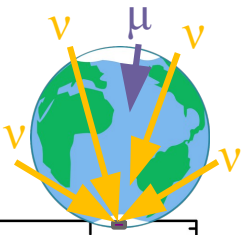




Diffuse TeV–PeV υ flux: **Baikal-GVD**

R. Dvornický (for Baikal-GVD)
PoS(ICRC2025)1031
See also arXiv:2507.01893

First independent observation of the diffuse υ flux



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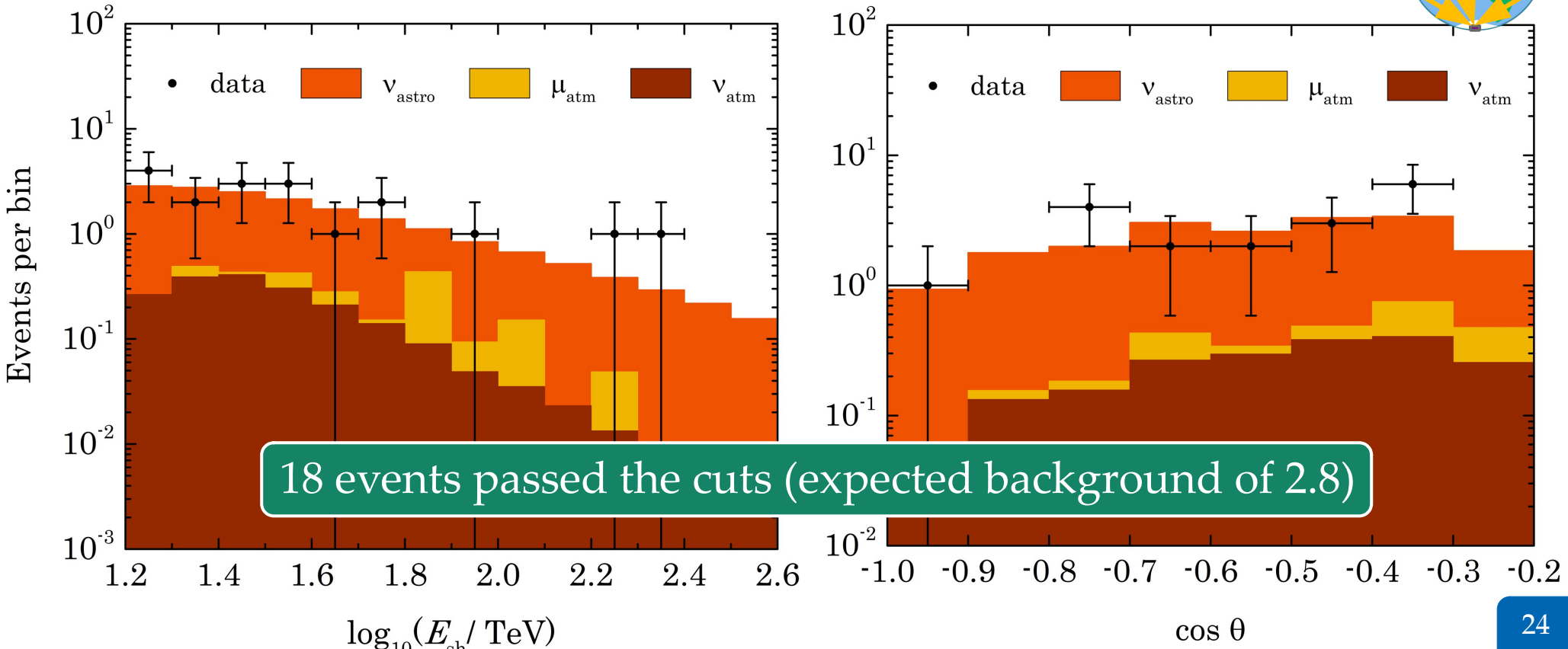

18 events passed the cuts (expected background of 2.8)

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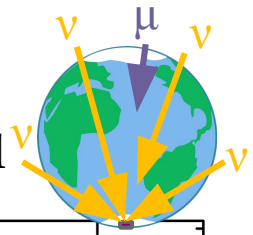

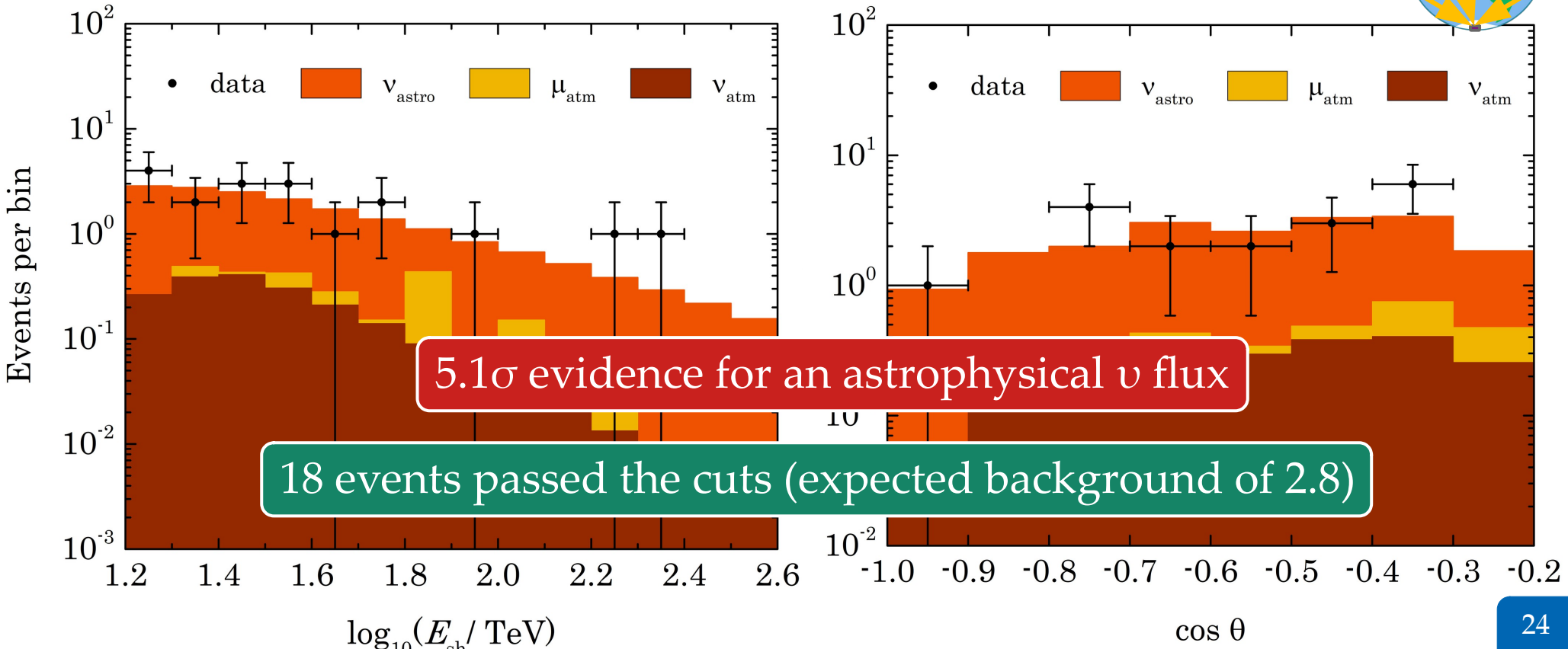

5.1σ evidence for an astrophysical υ flux

18 events passed the cuts (expected background of 2.8)

Diffuse TeV–PeV υ flux: **Baikal-GVD**

R. Dvornický (for Baikal-GVD)
PoS(ICRC2025)1031
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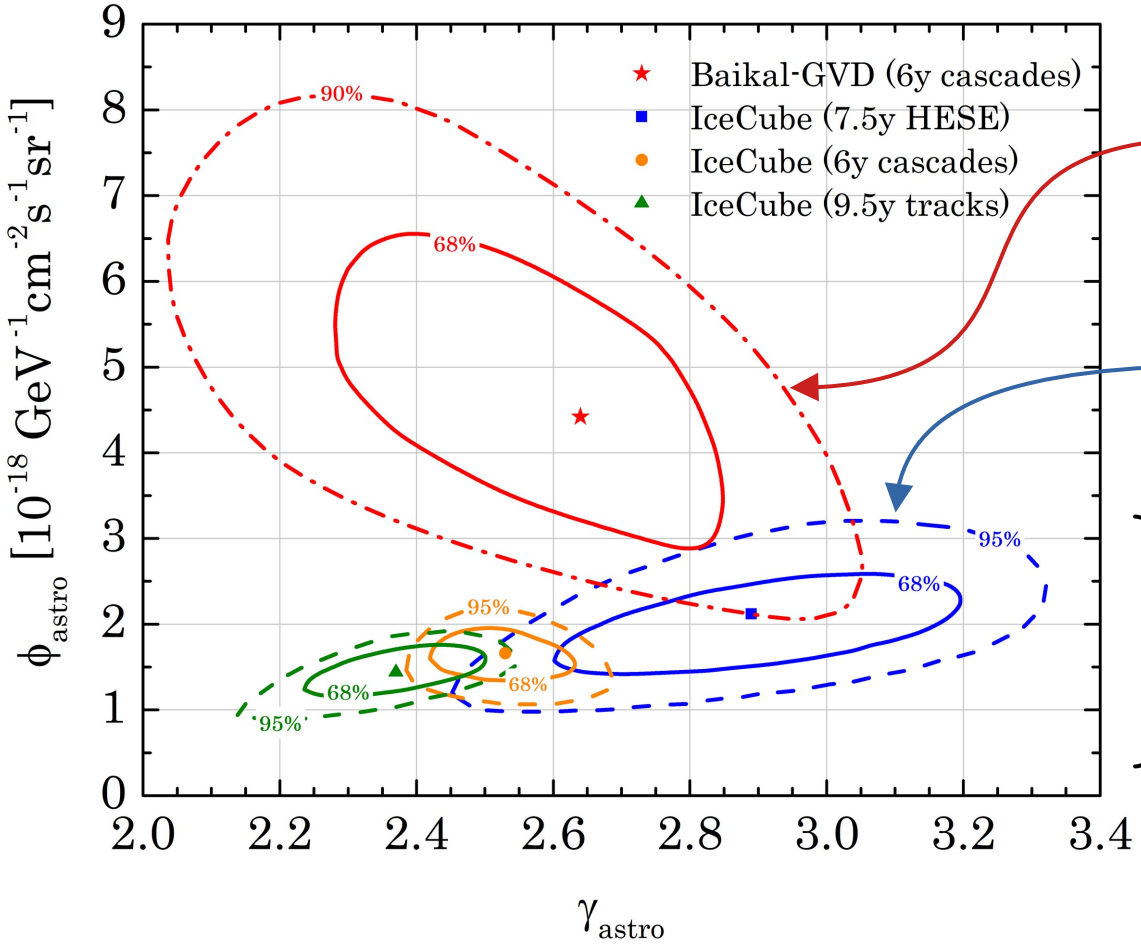


Single-power-law fit to Baikal-GVD data

Baikal-GVD results compatible (~90% C.L.) with IceCube HESE (dominated by cascades > 60 TeV)

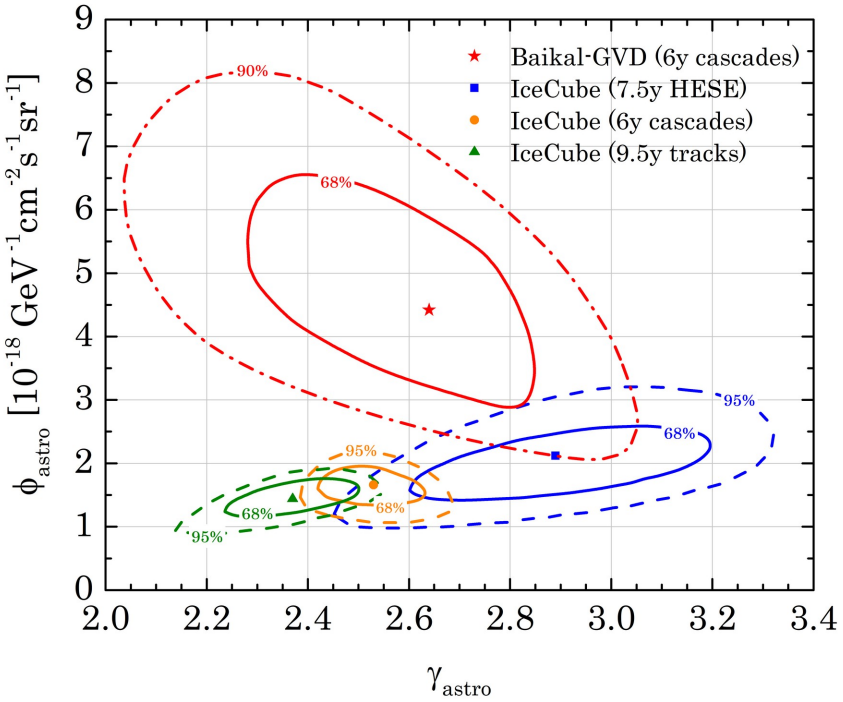
⚠️ Tension with other IceCube results
(possible reasons: systematics, υ sky anostropies, etc.)

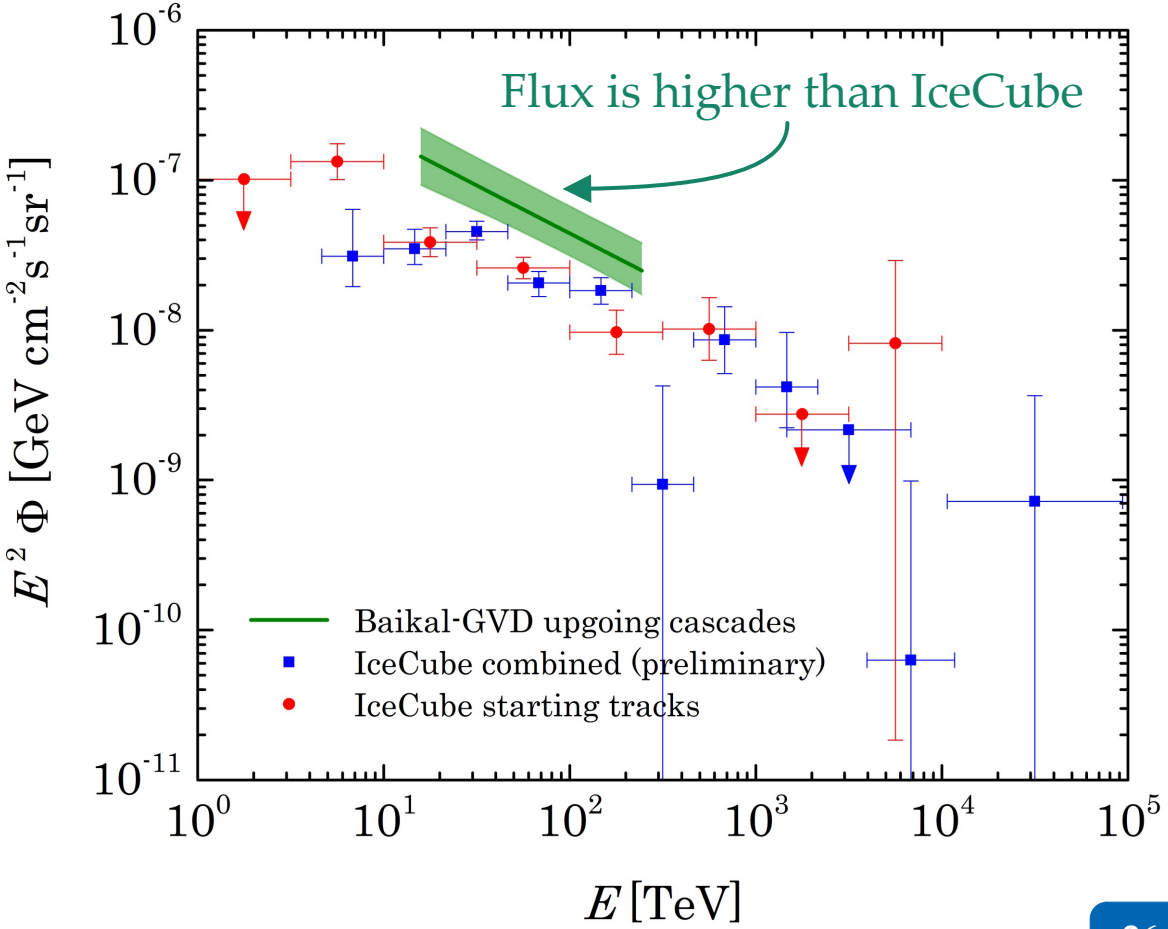
Fits to different IceCube data sets

Diffuse TeV–PeV υ flux: **Baikal-GVD**

R. Dvornický (for Baikal-GVD)
PoS(ICRC2025)1031
See also arXiv:2507.01893

First independent observation of the diffuse υ flux

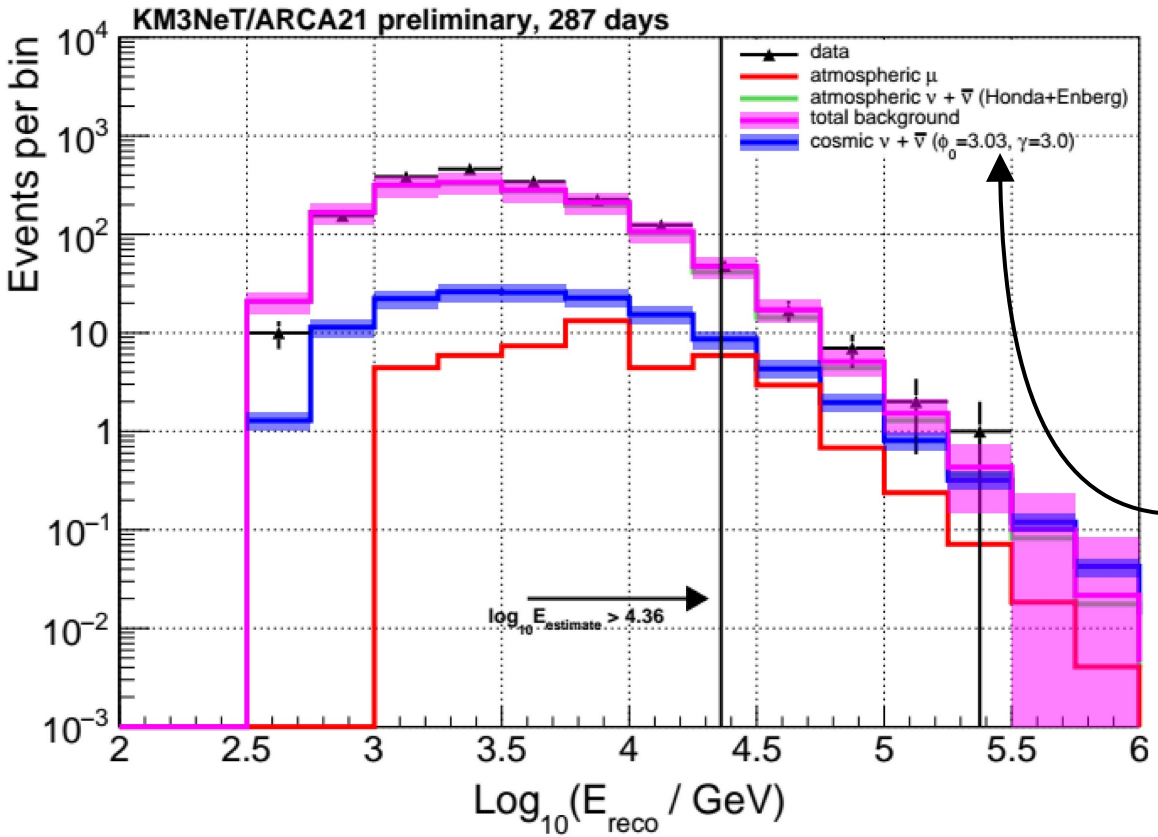




Diffuse TeV–PeV υ flux: **KM3NeT**

V. Tsourapis, E. Drakopoulou, L. Kalousis,
C. Markou, A. Sinopoulou, E. Tzamariudaki (for KM3NeT)
PoS(ICRC2025)1196

First upper limit from ARCA



640 days of ARCA6+8+19+21 (2021–2023)

Uses upgoing tracks to mitigate atmospheric muon background

Uses Bayesian approach
(frequentist also available)

Best-fit values (single power law):

$$\Phi_0 = 3.03 \times 10^{-18}\ \mathrm{GeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}$$

$$\gamma = 3.0$$

Insufficient evidence for a measurement

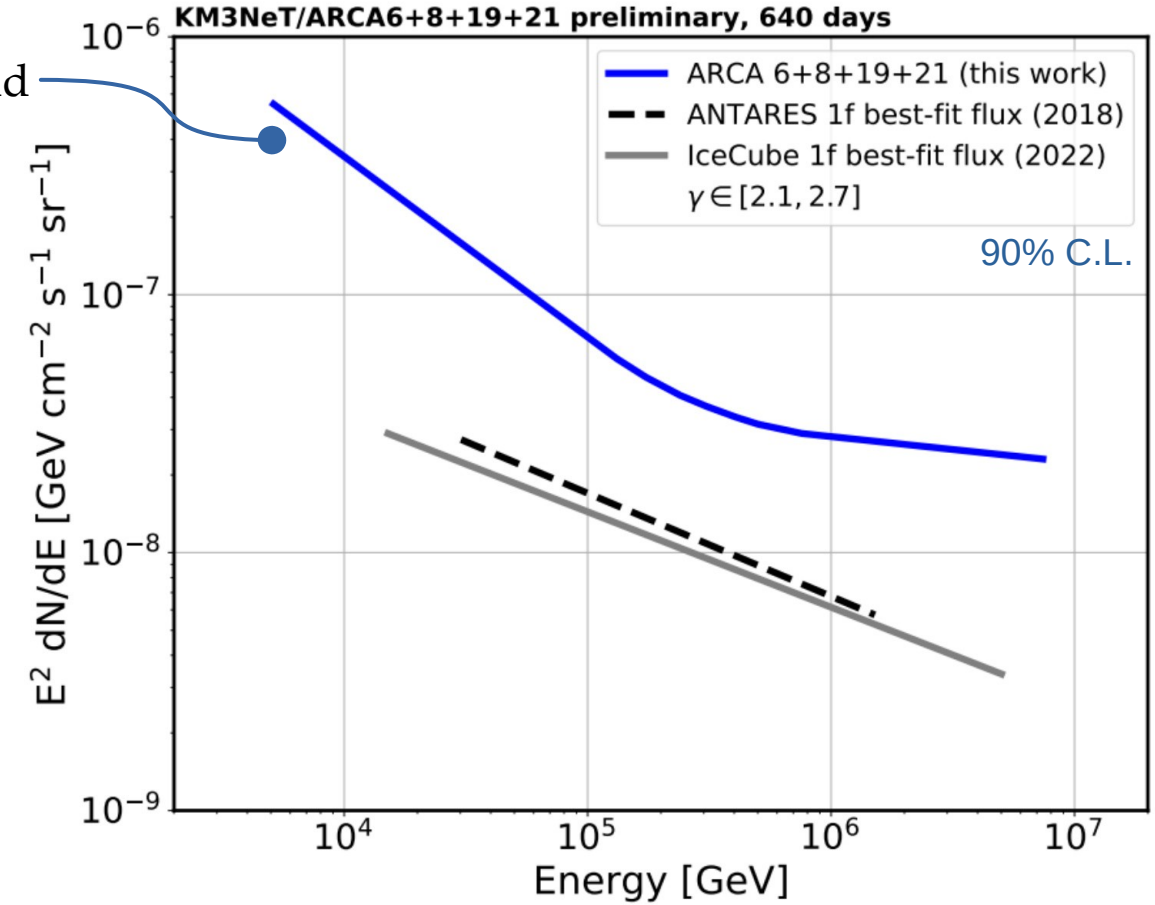
Simulations – atm. μ: 45.8 • atm. υ: 1466.9 • cosmic υ: 140.7 *vs.* Data – 1780

Diffuse TeV–PeV υ flux: **KM3NeT**

V. Tsourapis, E. Drakopoulou, L. Kalousis,
C. Markou, A. Sinopoulou, E. Tzamariudaki (for KM3NeT)
PoS(ICRC2025)1196

First upper limit from ARCA

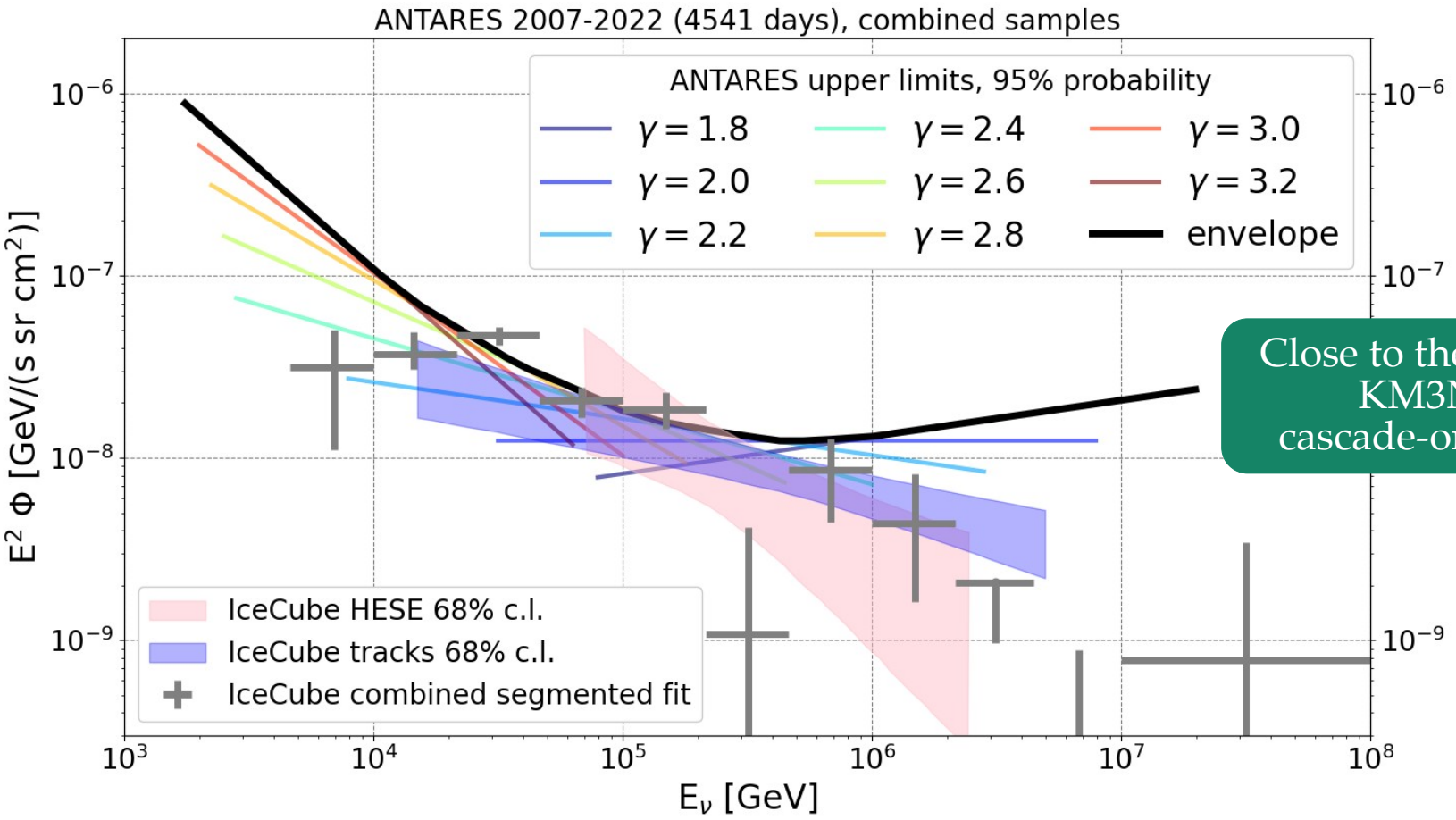
Place upper limit instead



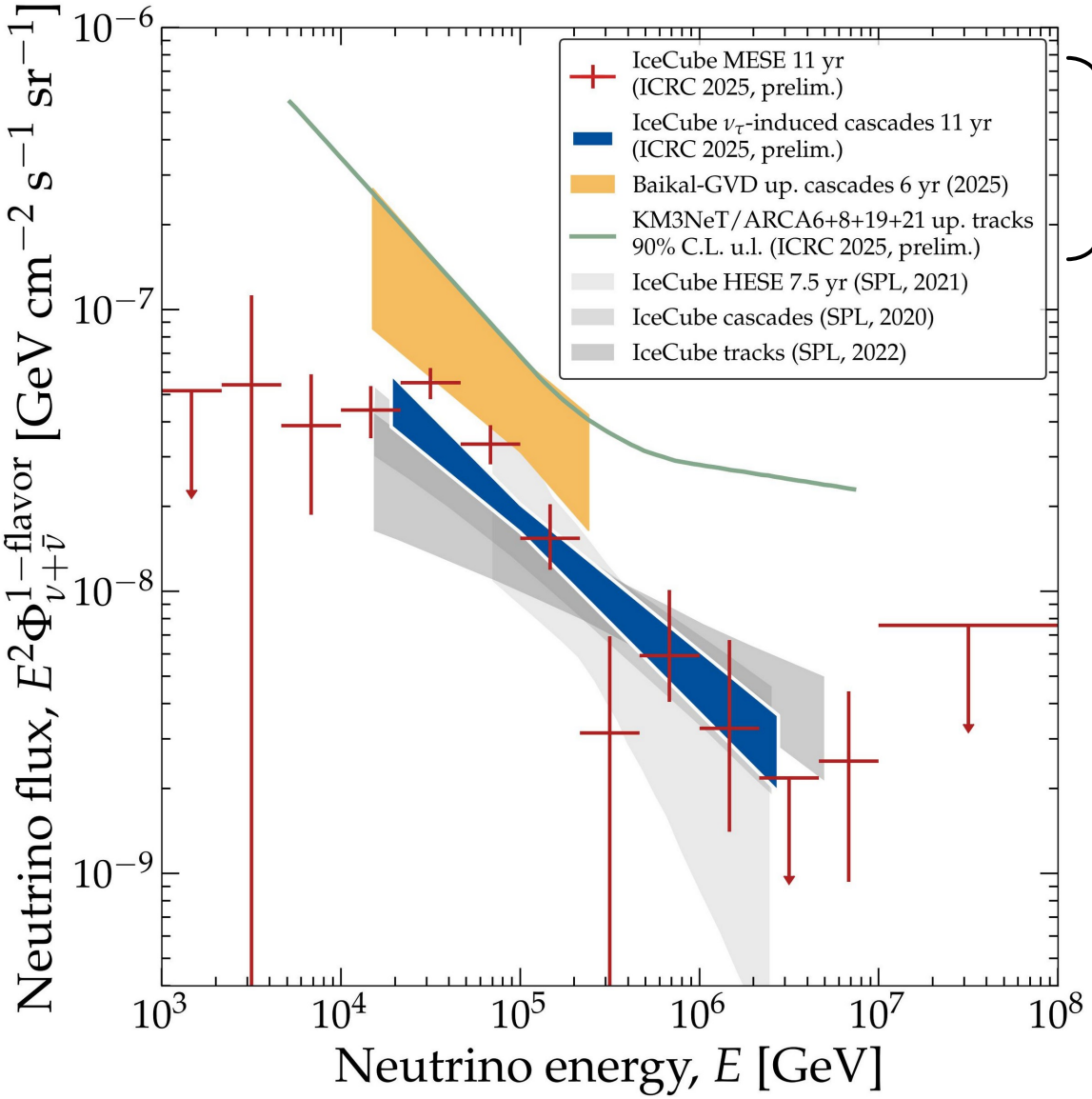
Diffuse TeV–PeV υ flux: **ANTARES**

M. Spurio, S. Navas (for ANTARES)
PoS(ICRC2025)1187
See also *JCAP* 08, 038 (2024) [arXiv:2407.00328]

Upper limit using full legacy data from ANTARES

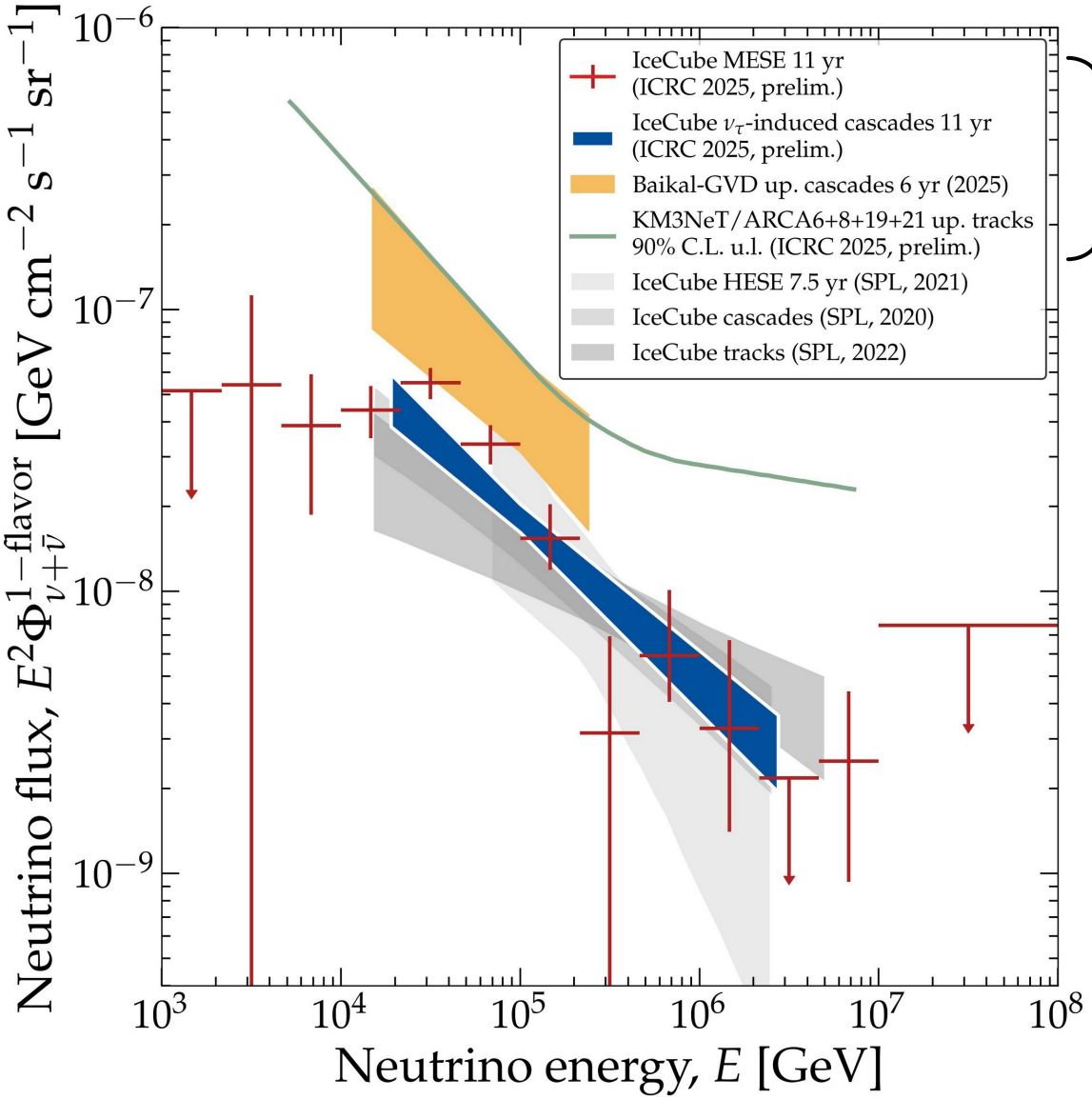


Close to the 640-day KM3NeT cascade-only limit



New in 2025

Thanks to Aswathi Balagopal for providing the butterflies!

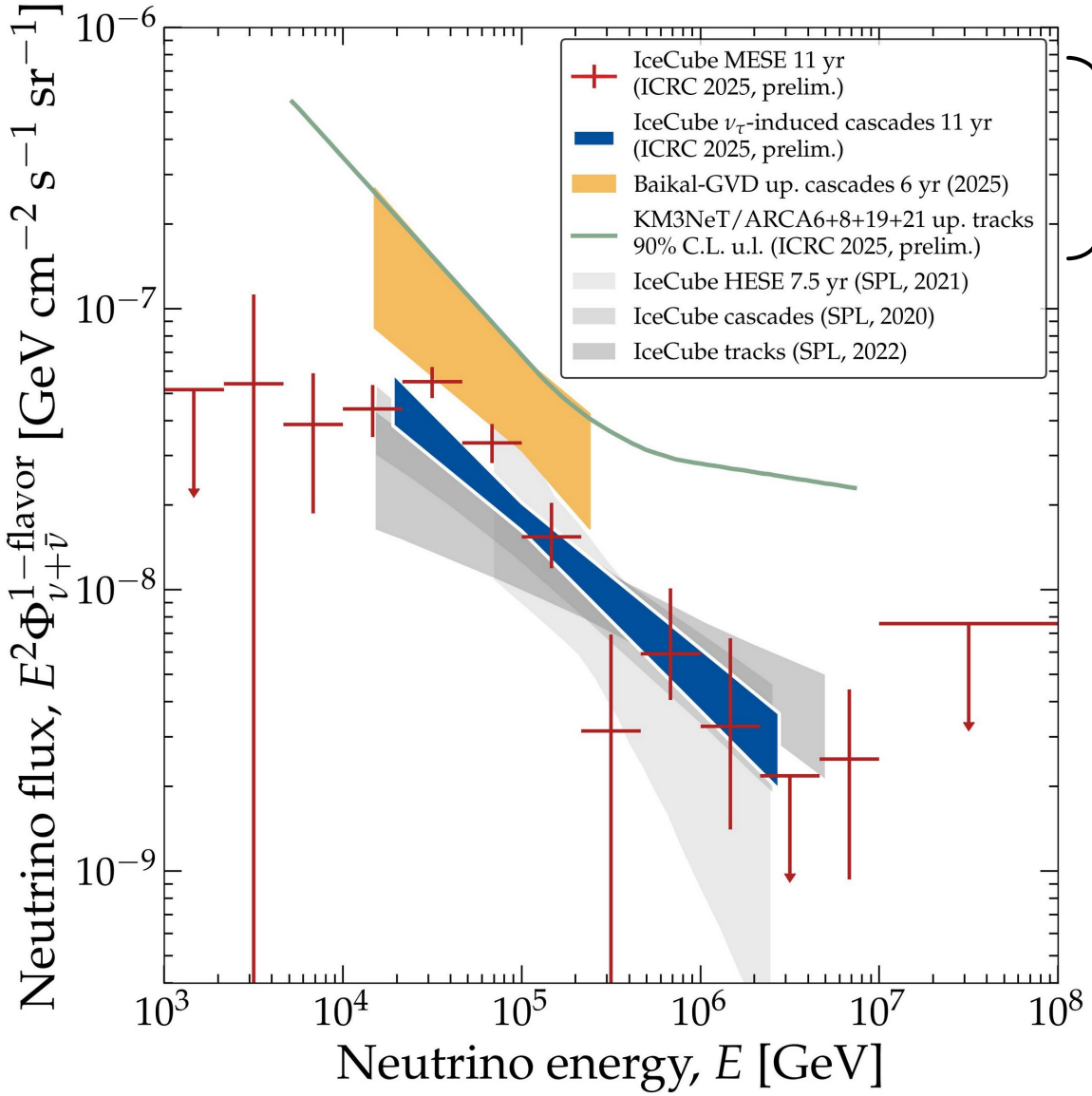


New in 2025

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

Thanks to Aswathi Balagopal for providing the butterflies!

And IceCube is finding structure in the energy spectrum



New in 2025

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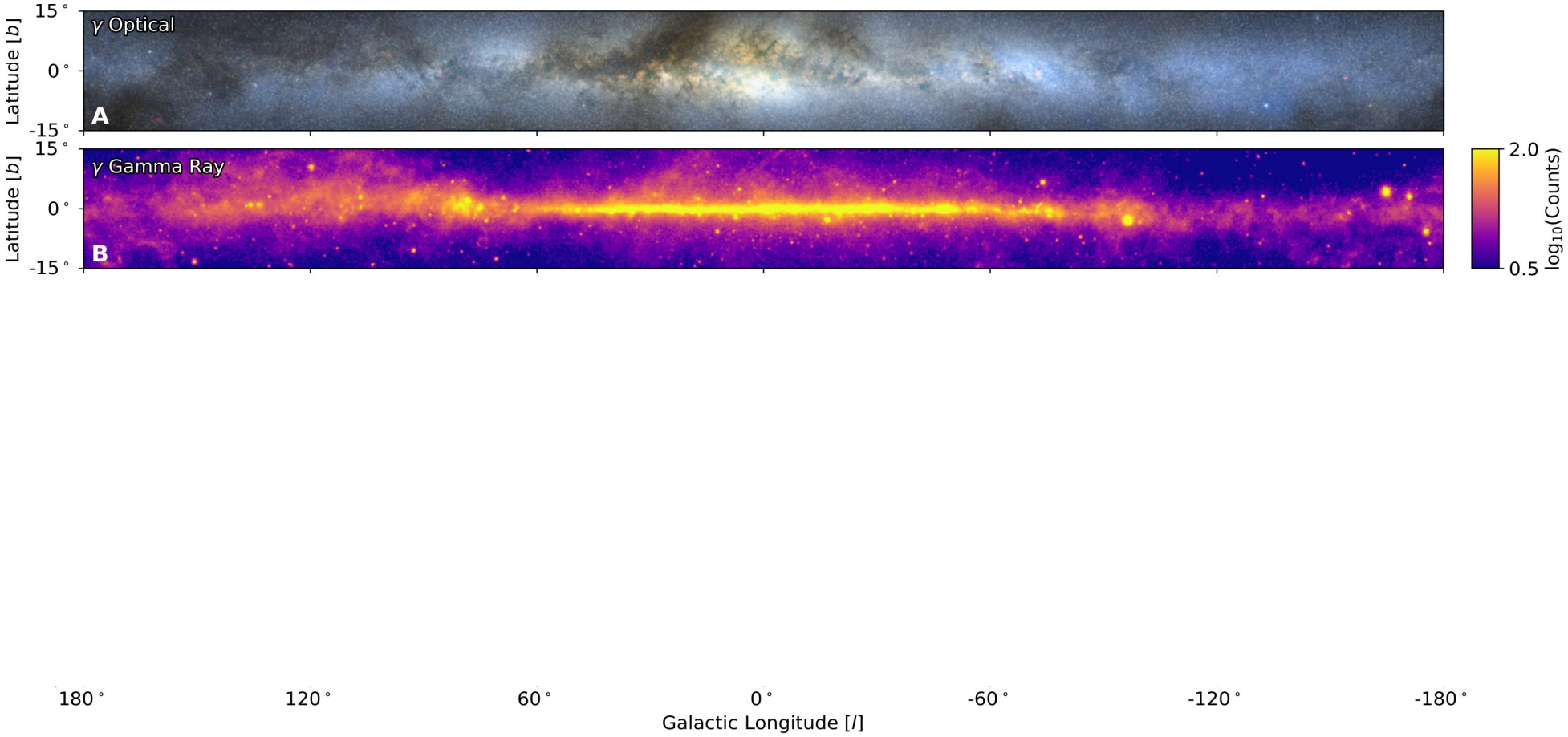
Thanks to Aswathi Balagopal for providing the butterflies!

Two

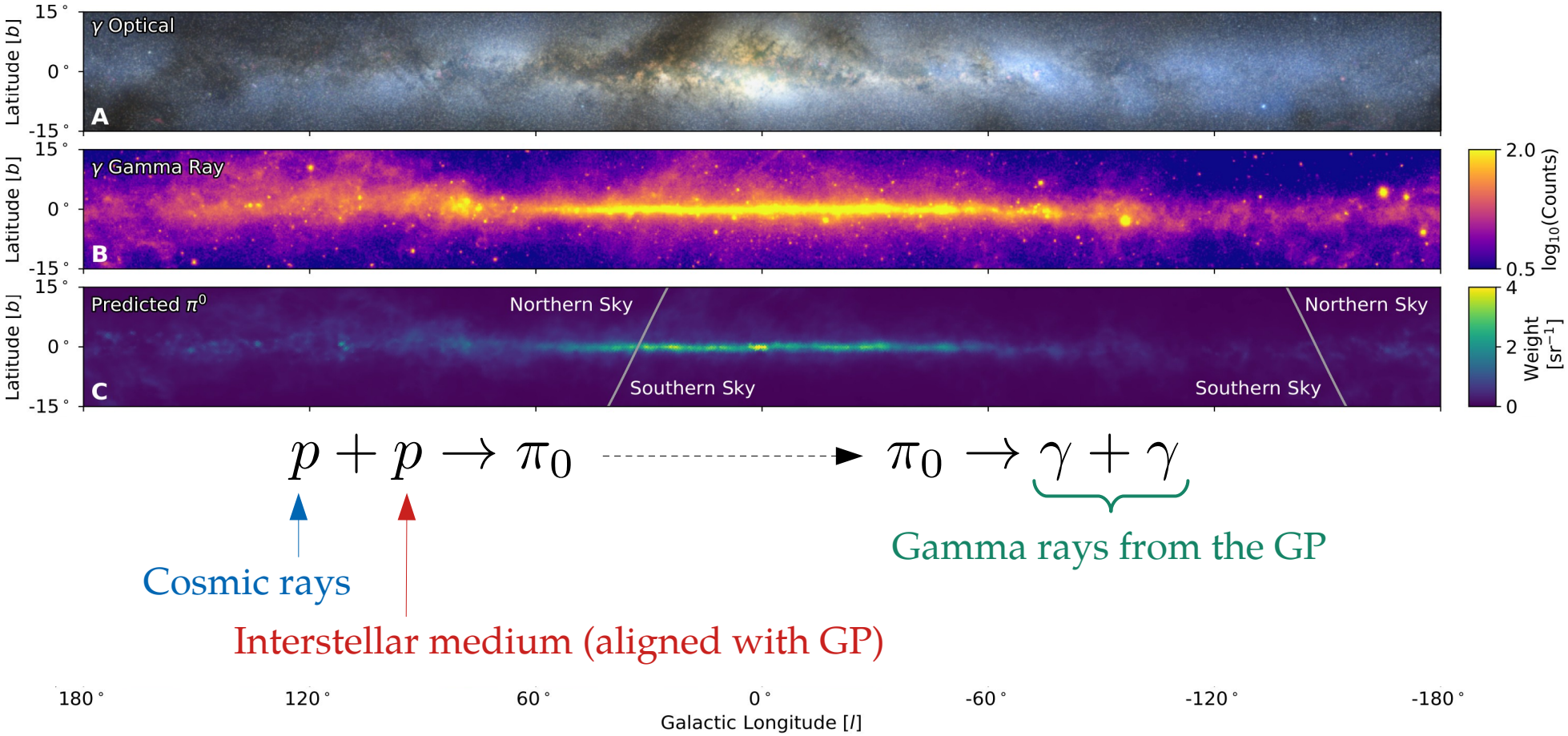
Neutrinos from the Milky Way

Neutrinos from the Galaxy



IceCube Collab., *Science* 2023

Neutrinos from the Galaxy



$$p + p \rightarrow \pi_0 \dashrightarrow \pi_0 \rightarrow \underbrace{\gamma + \gamma}$$

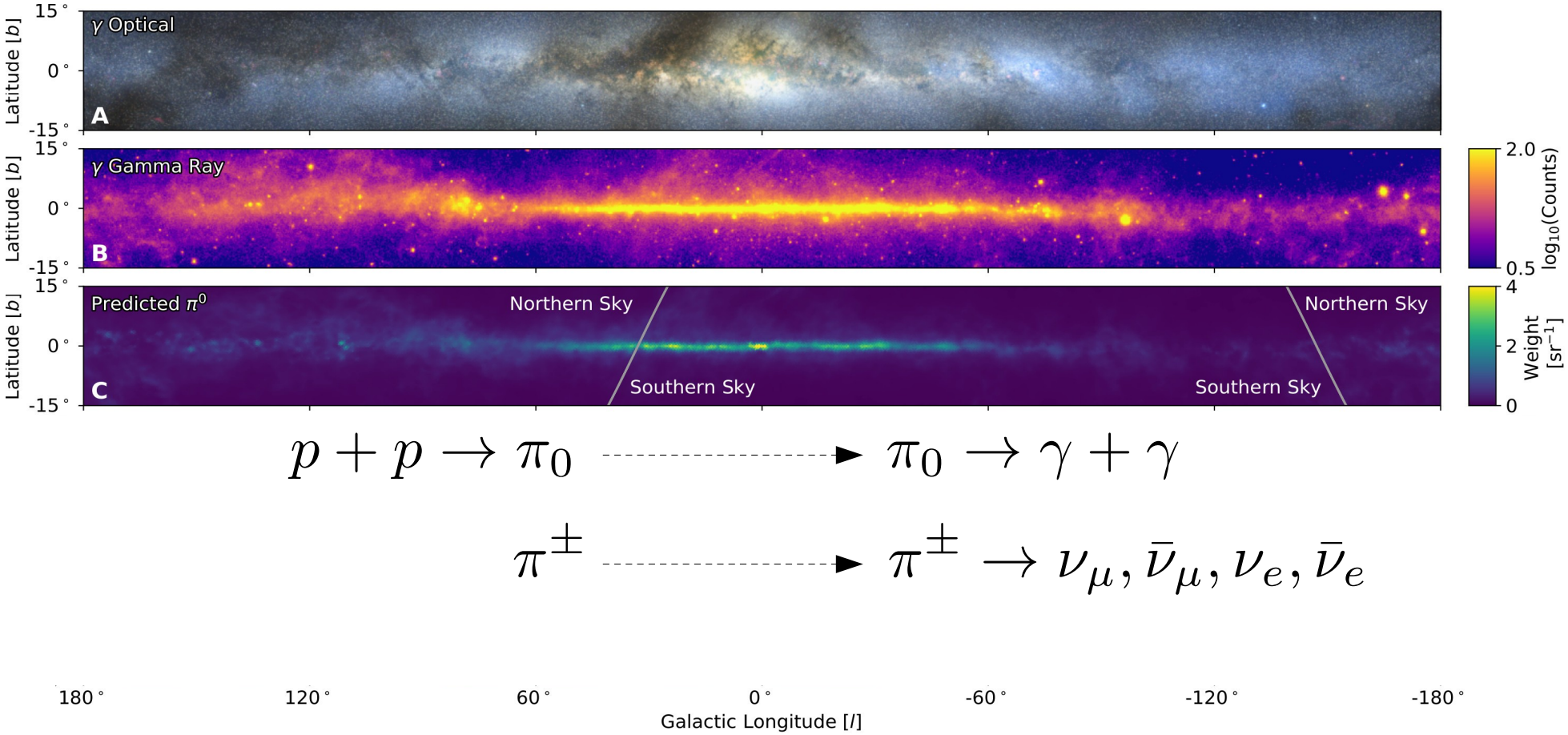
Cosmic rays

Interstellar medium (aligned with GP)

Gamma rays from the GP

IceCube Collab., *Science* 2023

Neutrinos from the Galaxy

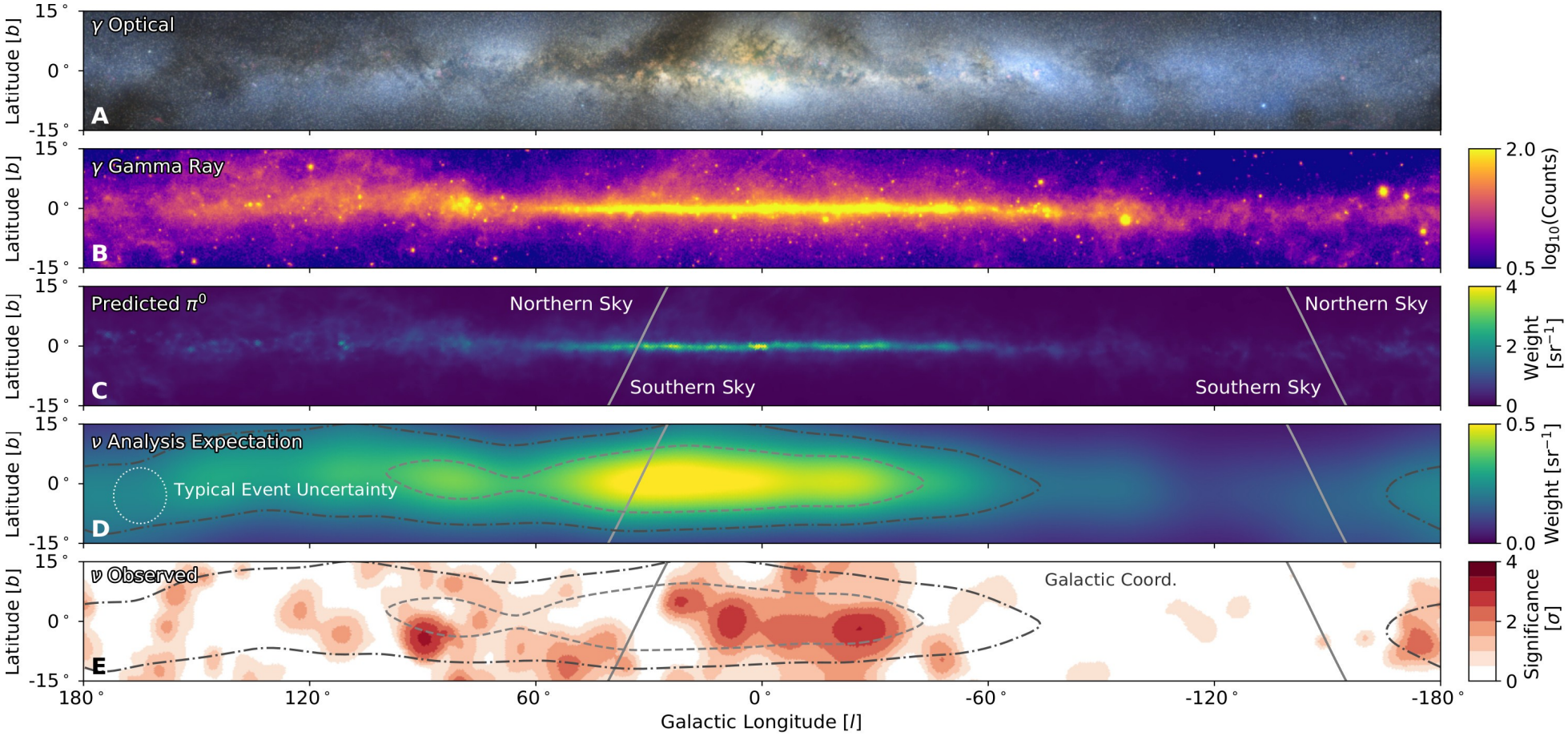


$$p + p \rightarrow \pi_0 \dashrightarrow \pi_0 \rightarrow \gamma + \gamma$$

$$\pi^{\pm} \dashrightarrow \pi^{\pm} \rightarrow \nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$$

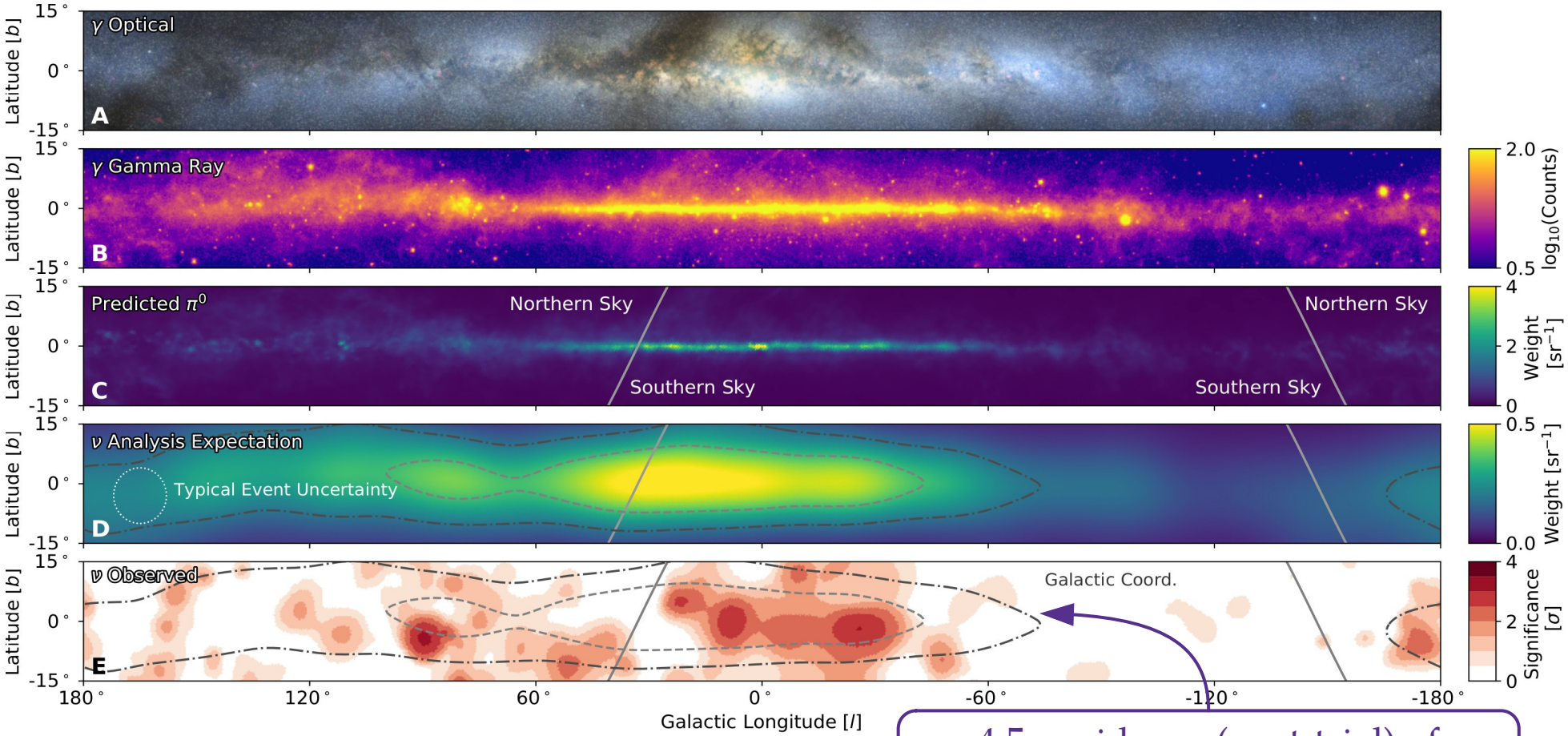
IceCube Collab., *Science* 2023

Neutrinos from the Galaxy



IceCube Collab., *Science* 2023

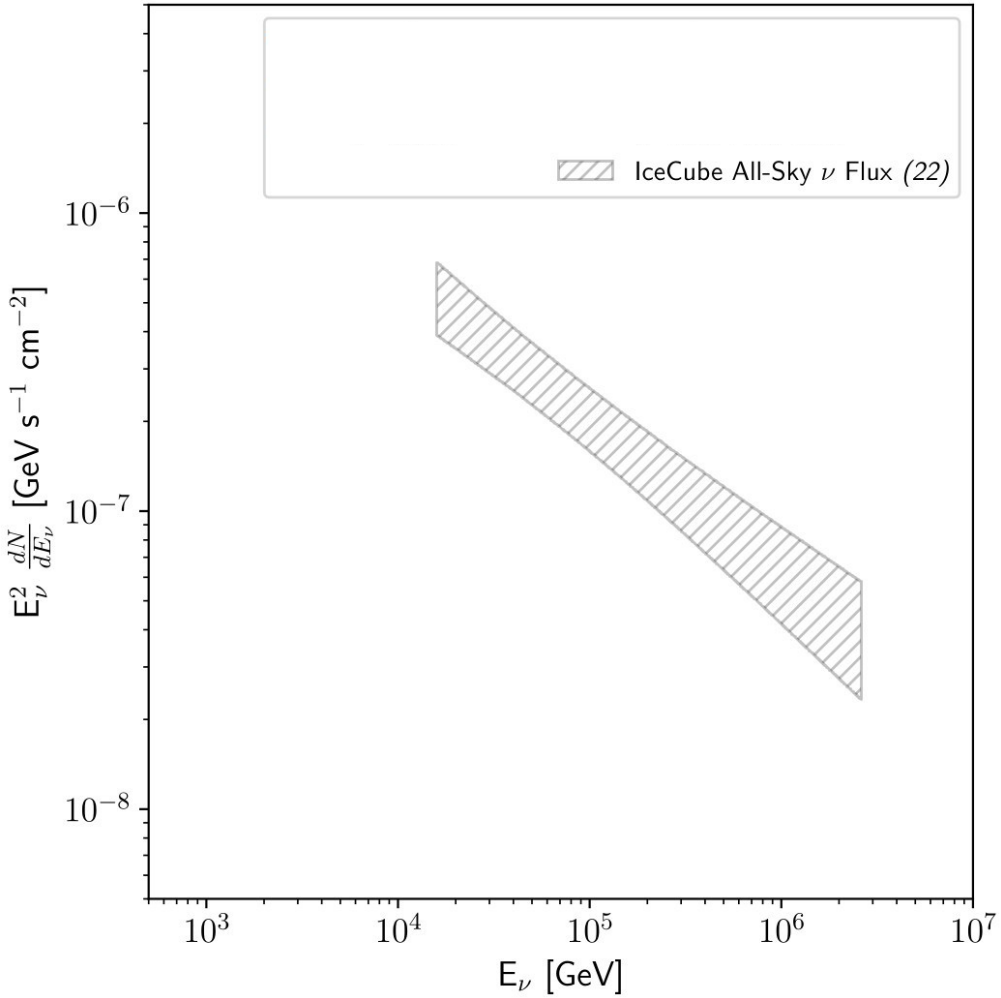
Neutrinos from the Galaxy



4.5σ evidence (post-trial) of diffuse flux of > TeV ν from the GP

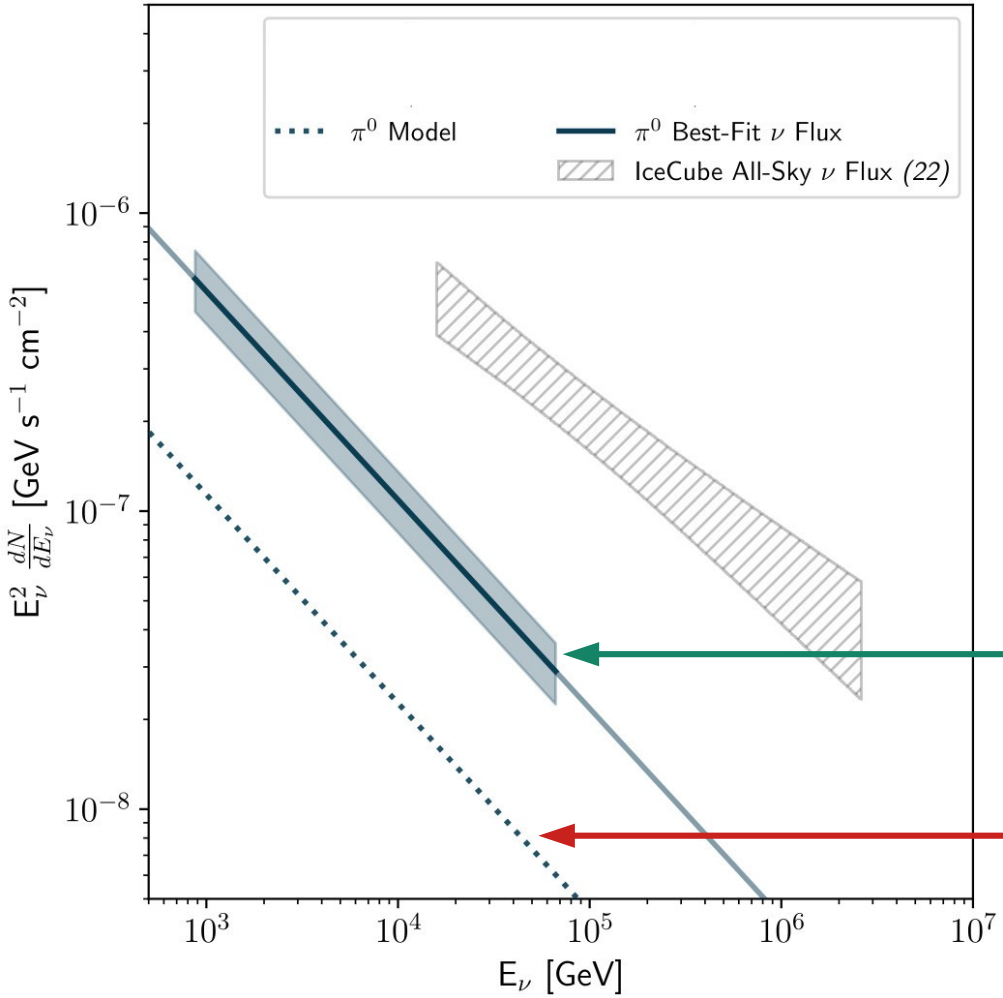
IceCube Collab., *Science* 2023

Neutrinos from the Galaxy: **IceCube**



IceCube Collab., *Science* 2023

Neutrinos from the Galaxy: **IceCube**



Three models of Galactic diffuse ν:

π^0: MeV–GeV π^0 template inferred from gamma rays extrapolated to TeV

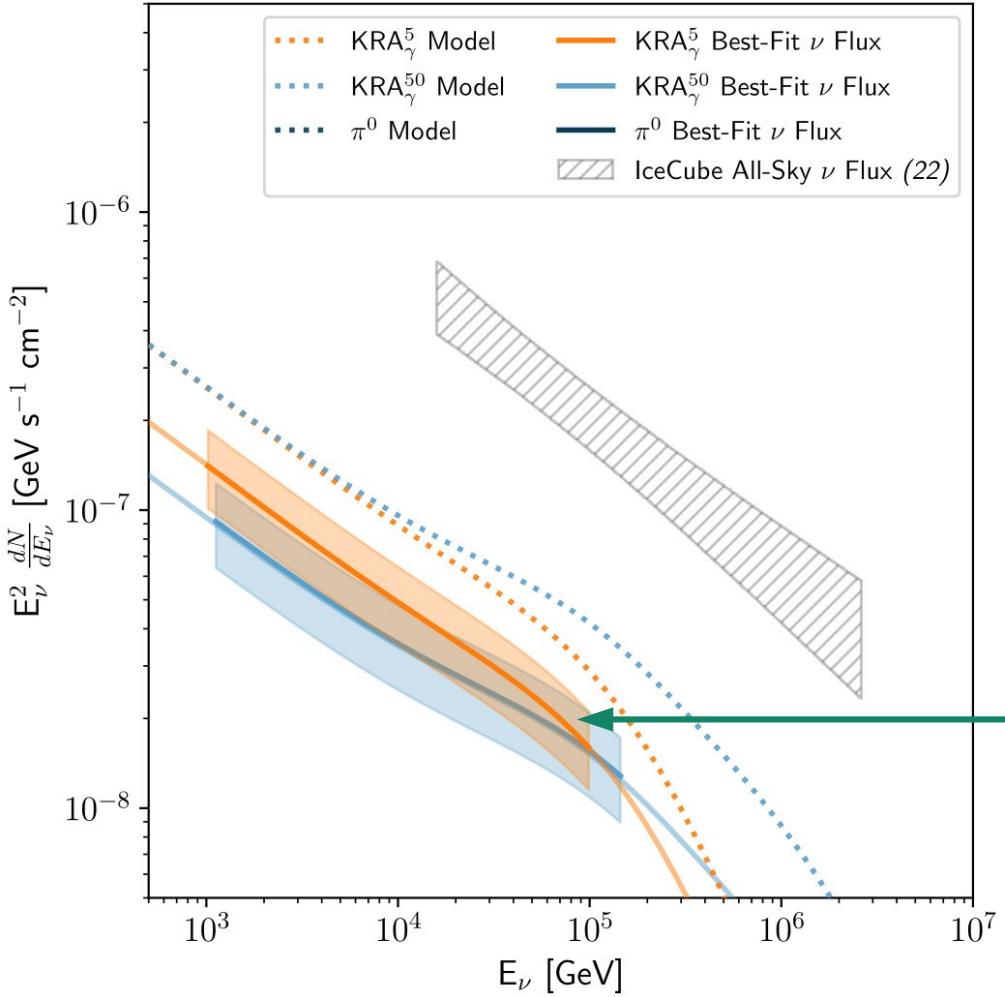
Observed (×5 model)

Consistent with 100-TeV observations by Tibet Air Shower Array

Model

IceCube Collab., *Science* 2023

Neutrinos from the Galaxy: **IceCube**



Three models of Galactic diffuse ν:

π^0: MeV–GeV π^0 template inferred from gamma rays extrapolated to TeV

KRA$^5_\gamma$: Spectrum varies spatially, harder ν spectrum, cut-off at 5 PeV in CR energy

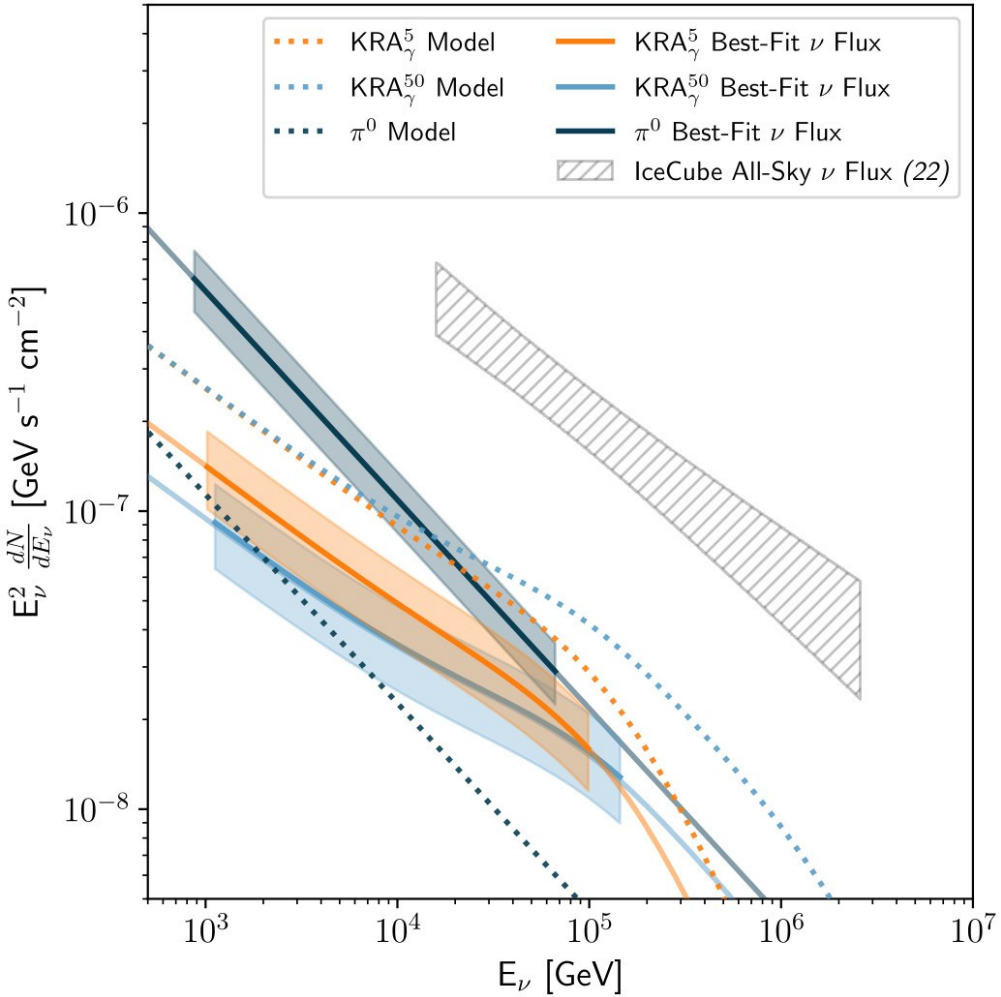
KRA$^{50}_\gamma$: Cut-off at 50 PeV in CR energy

Observed (×0.5 model)

Cut-off energy could be different from the 5 and 50 PeV tested

IceCube Collab., *Science* 2023

Neutrinos from the Galaxy: **IceCube**



IceCube Collab., *Science* 2023

Three models of Galactic diffuse ν:

π^0: MeV–GeV π^0 template inferred from gamma rays extrapolated to TeV

KRA^5_γ: Spectrum varies spatially, harder ν spectrum, cut-off at 5 PeV in CR energy

KRA^{50}_γ: Cut-off at 50 PeV in CR energy

None of the models matched data

(caveat: there are relatively simple models)

No Galactic ν source identified

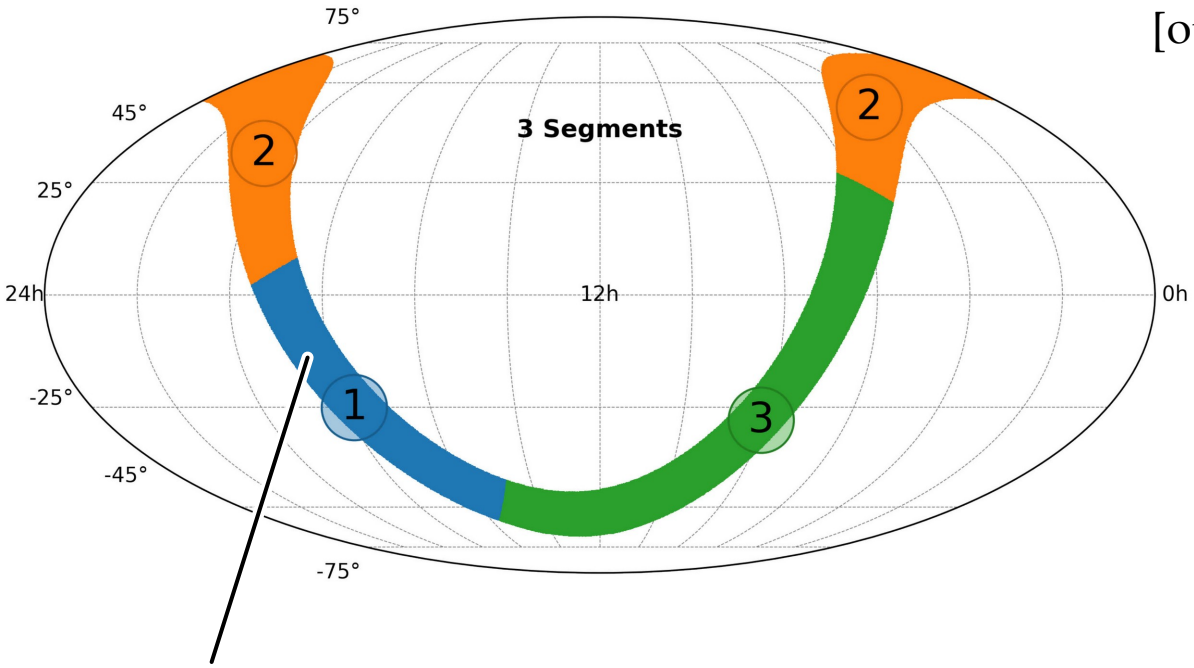
(likely diffuse + source: Fang & Murase, 2307.02905)

GP flux is 6–13% of all-sky at 30 TeV

Neutrinos from the Galaxy: **IceCube**

L. Neste, M. Hünnefeld, C. Finley
PoS(ICRC2025)1130 • Talk July 21

Improvements **without** template fitting



±8° width in Galactic latitude
-40° < Galactic longitude < 40°

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

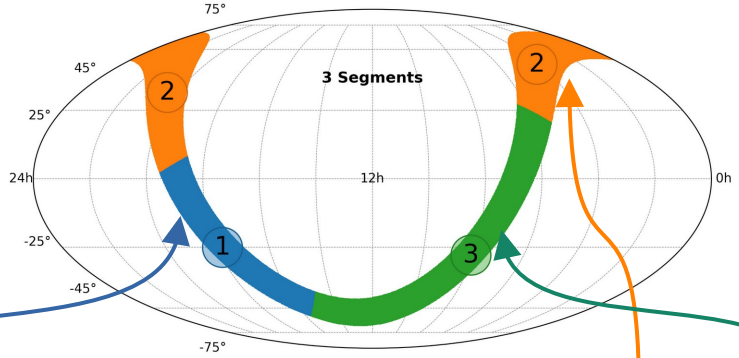
Fit flux normalization and spectral index

Note: No systematics yet

Neutrinos from the Galaxy: **IceCube**

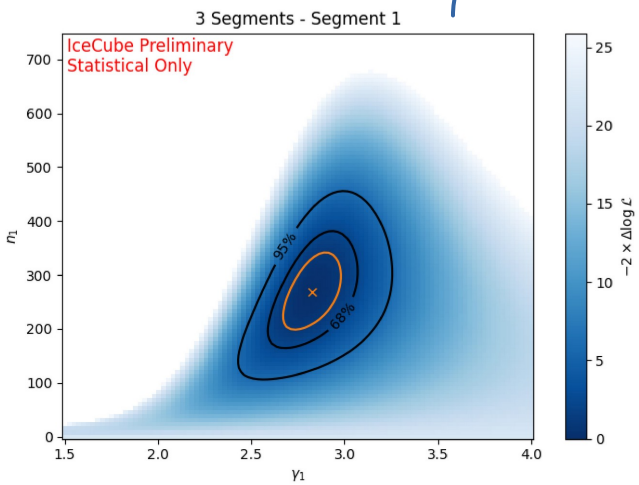
L. Neste, M. Hünnefeld, C. Finley
PoS(ICRC2025)1130 • Talk July 21

Improvements **without** template fitting

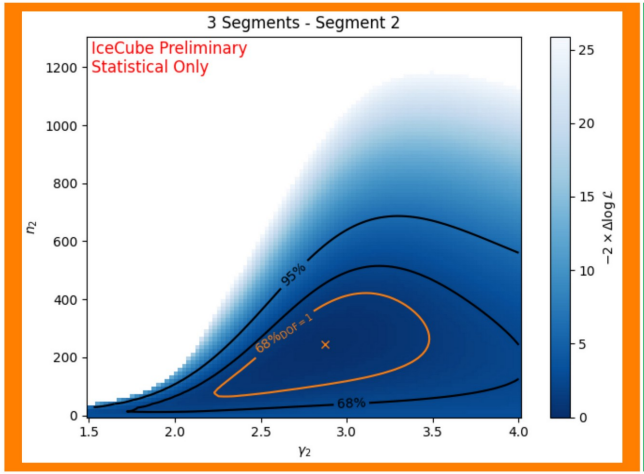


Inner galaxy

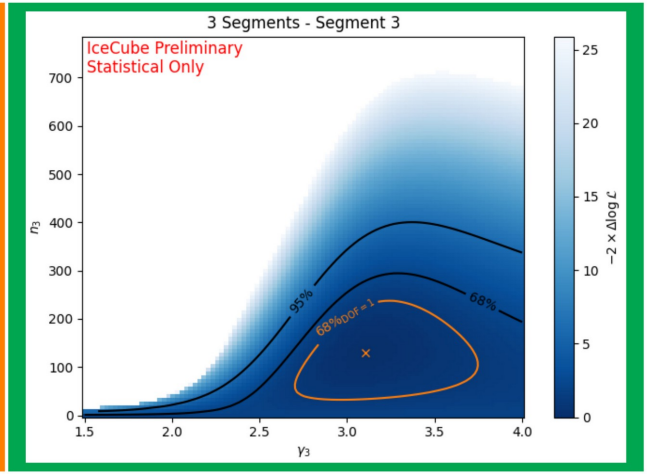
Outer galaxy



$-40^\circ < l < 40^\circ$



$40^\circ < l < 180^\circ$

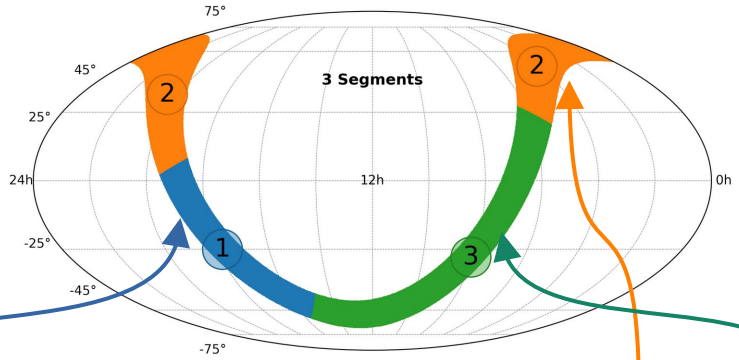


$-180^\circ < l < -40^\circ$

Neutrinos from the Galaxy: **IceCube**

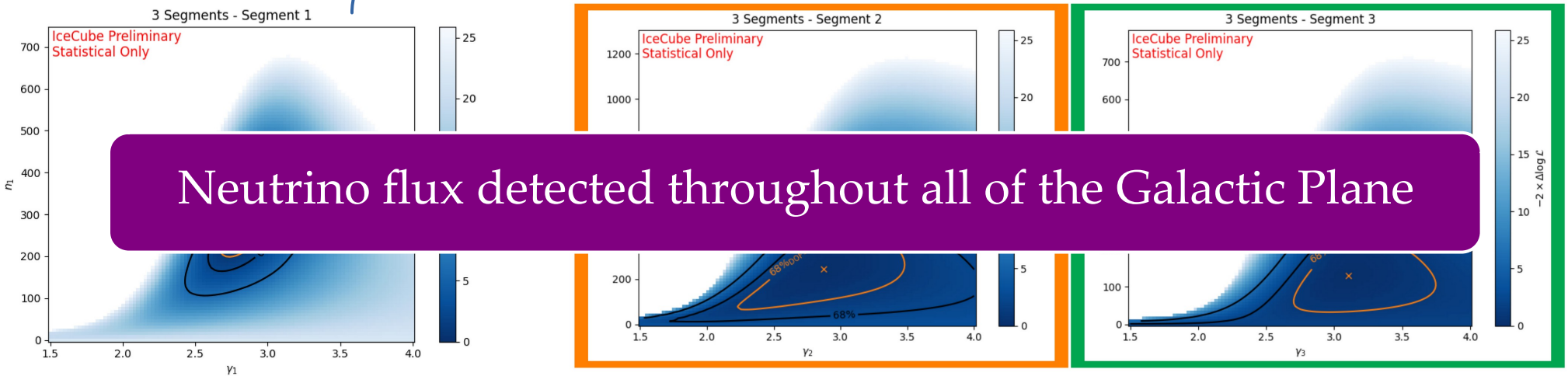
L. Neste, M. Hünnefeld, C. Finley
PoS(ICRC2025)1130 • Talk July 21

Improvements **without** template fitting



Inner galaxy

Outer galaxy



$-40^\circ < l < 40^\circ$

$40^\circ < l < 180^\circ$

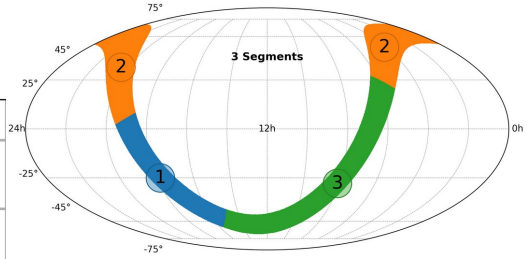
$-180^\circ < l < -40^\circ$

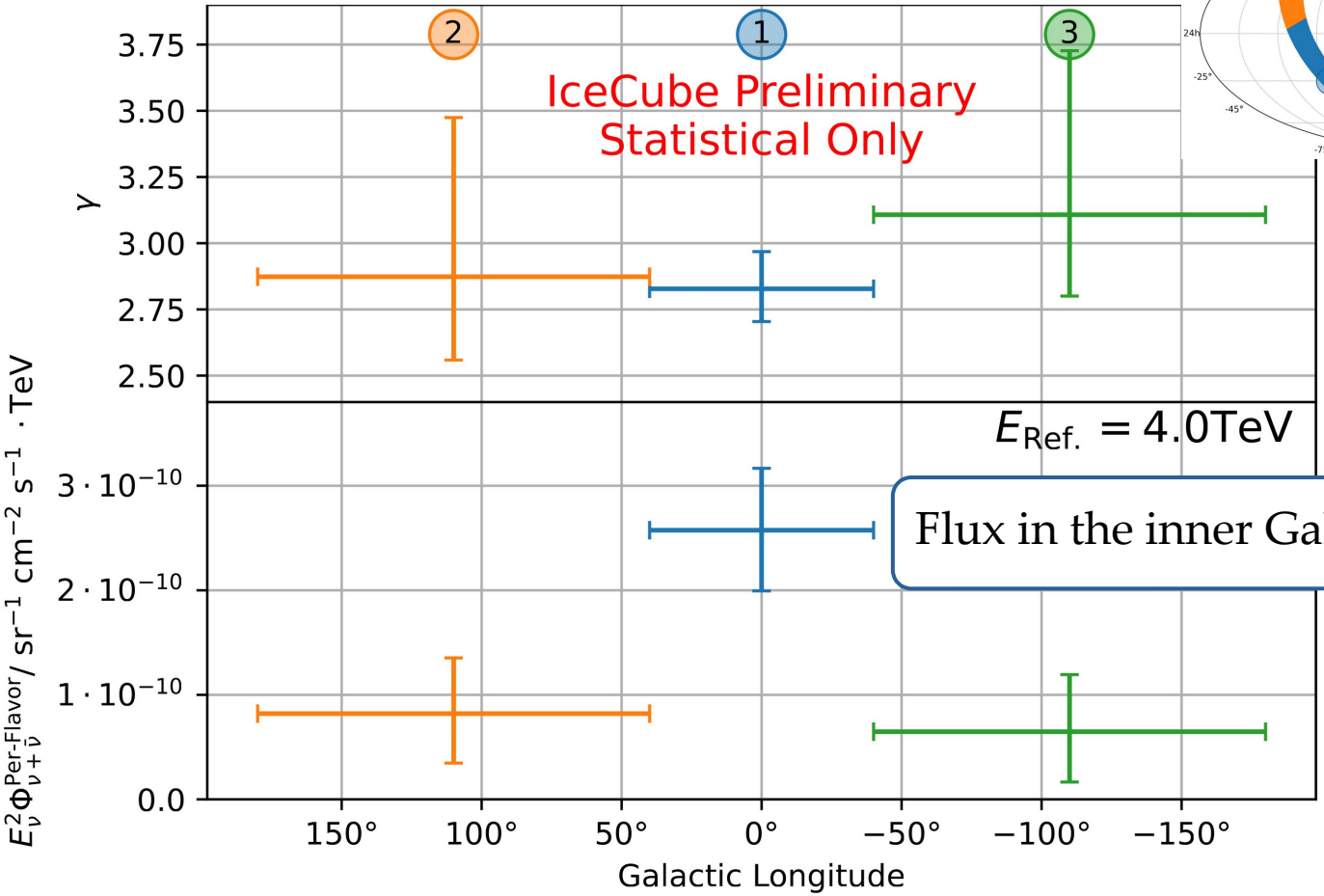
Neutrino flux detected throughout all of the Galactic Plane

Neutrinos from the Galaxy: **IceCube**

L. Neste, M. Hünnefeld, C. Finley
PoS(ICRC2025)1130 • Talk July 21

Improvements **without** template fitting



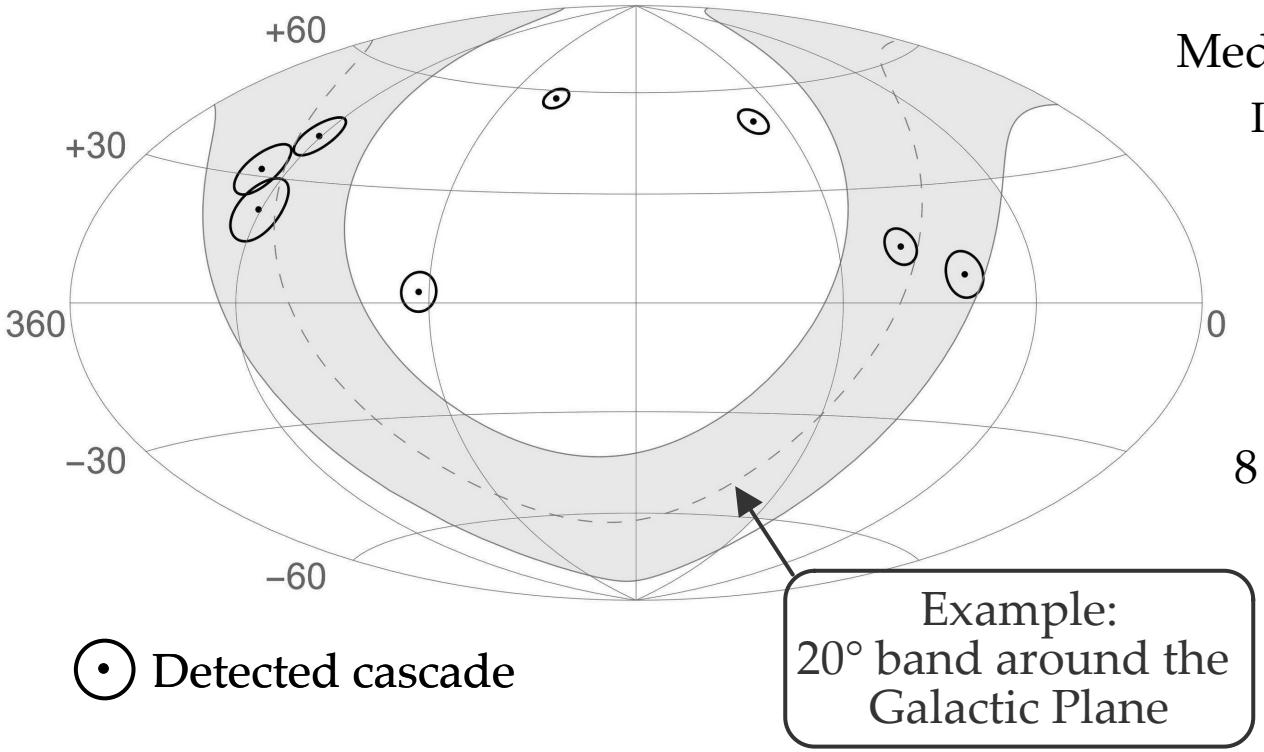


Flux in the inner Galaxy is 2× higher

Neutrinos from the Galaxy: **Baikal-GVD**

Y. Y. Kovalev, A. V. Plavin, D. V. Semikoz,
V. Troitsky, B. B. Ulzutuev
PoS(ICRC2025)1197 • Talk July 19

Using 6 yr of cascades, 2.5σ



Median Galactic latitude of events: $|b_{\mathrm{med}}|$

If events are concentrated along the Plane, $|b_{\mathrm{med}}|$ should be small

Method by Y. Kovalev et al. ApJ 2022 [2208.08423]
(formerly applied to IceCube tracks)

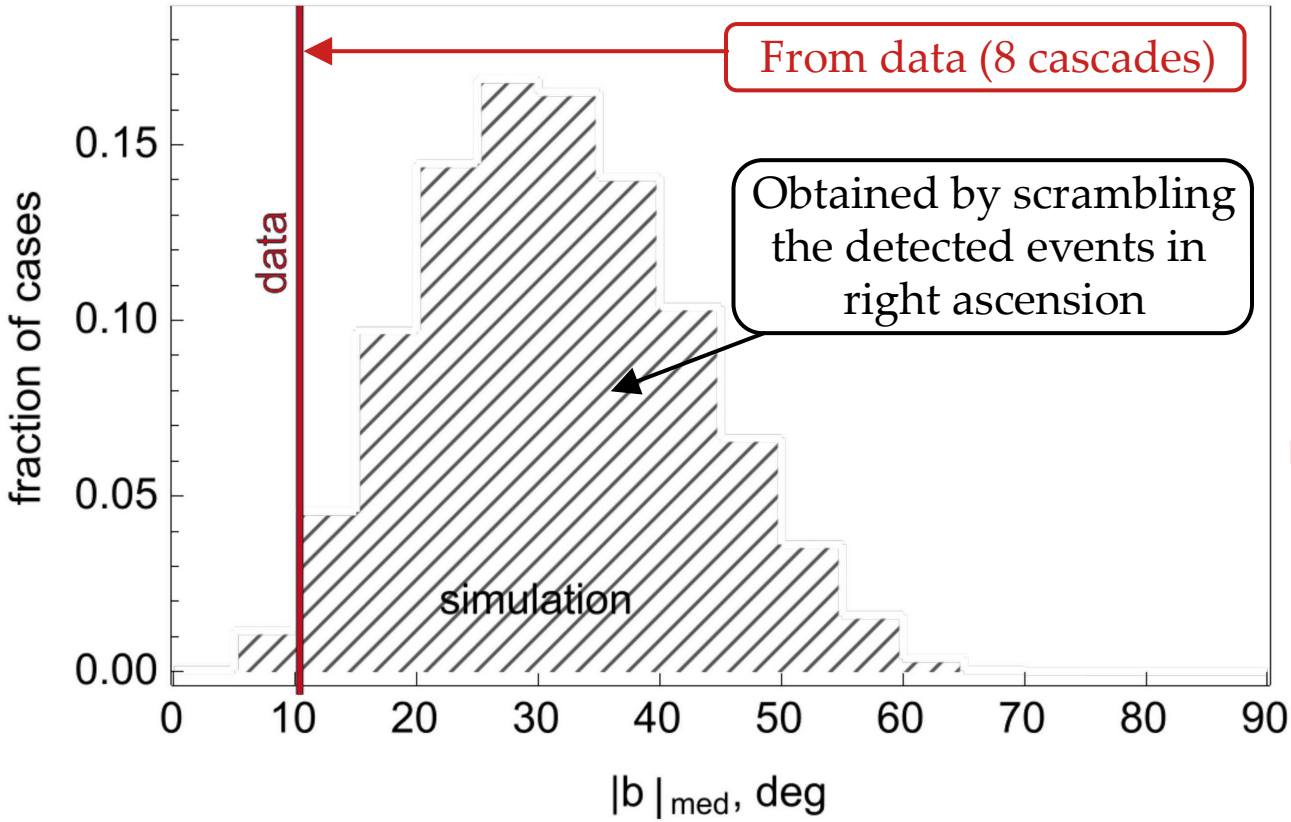
8 cascade events > 200 TeV, 2018–2024

~50% expected to be background

Neutrinos from the Galaxy: **Baikal-GVD**

Y. Y. Kovalev, A. V. Plavin, D. V. Semikoz,
V. Troitsky, B. B. Ulzutuev
PoS(ICRC2025)1197

Using 6 yr of cascades, 2.5σ



From data: $|b_{\rm med}| = 10.4°$

From simulations: $\langle |b_{\rm med}| \rangle \approx 31°$

p-value of observation: 0.014
(2.5σ significance, two-sided)

Rough flux estimate:

Num. events $|b_{\rm med}| < 10°$ (≈ 2.8)

All-sky astro flux (uses Baikal flux)

$$F_{\rm MW} \propto \frac{n_{\rm MW}}{n_{\rm all-sky}} \Phi_{\rm all-sky}$$

Num. astro events all-sky (5.1)

$$\approx 20.1^{+2.0}_{-0.9} \times 10^{-18} \left(\frac{E}{100\ \rm TeV}\right)^{-\gamma}$$

$$(\gamma = 2.58^{+0.27}_{-0.33})$$

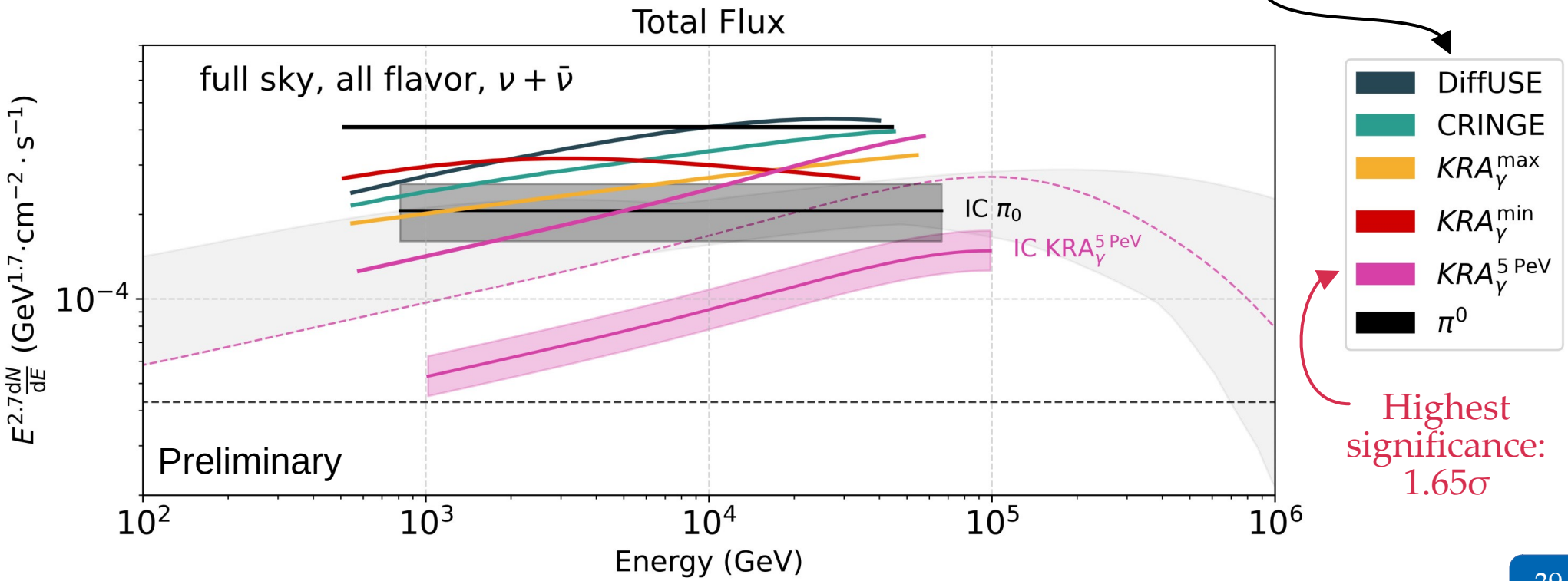
Neutrinos from the Galaxy: **ANTARES**

T. Cartraud
PoS(ICRC2025)1099 • Talk July 17

Template-based search

Full ANTARES data set, 2007–2022, all-flavor: 3392 tracks + 406 showers (> 300 GeV)

No evidence found — instead 90% C.L. upper limits placed on multiple template models



Highest significance: 1.65σ

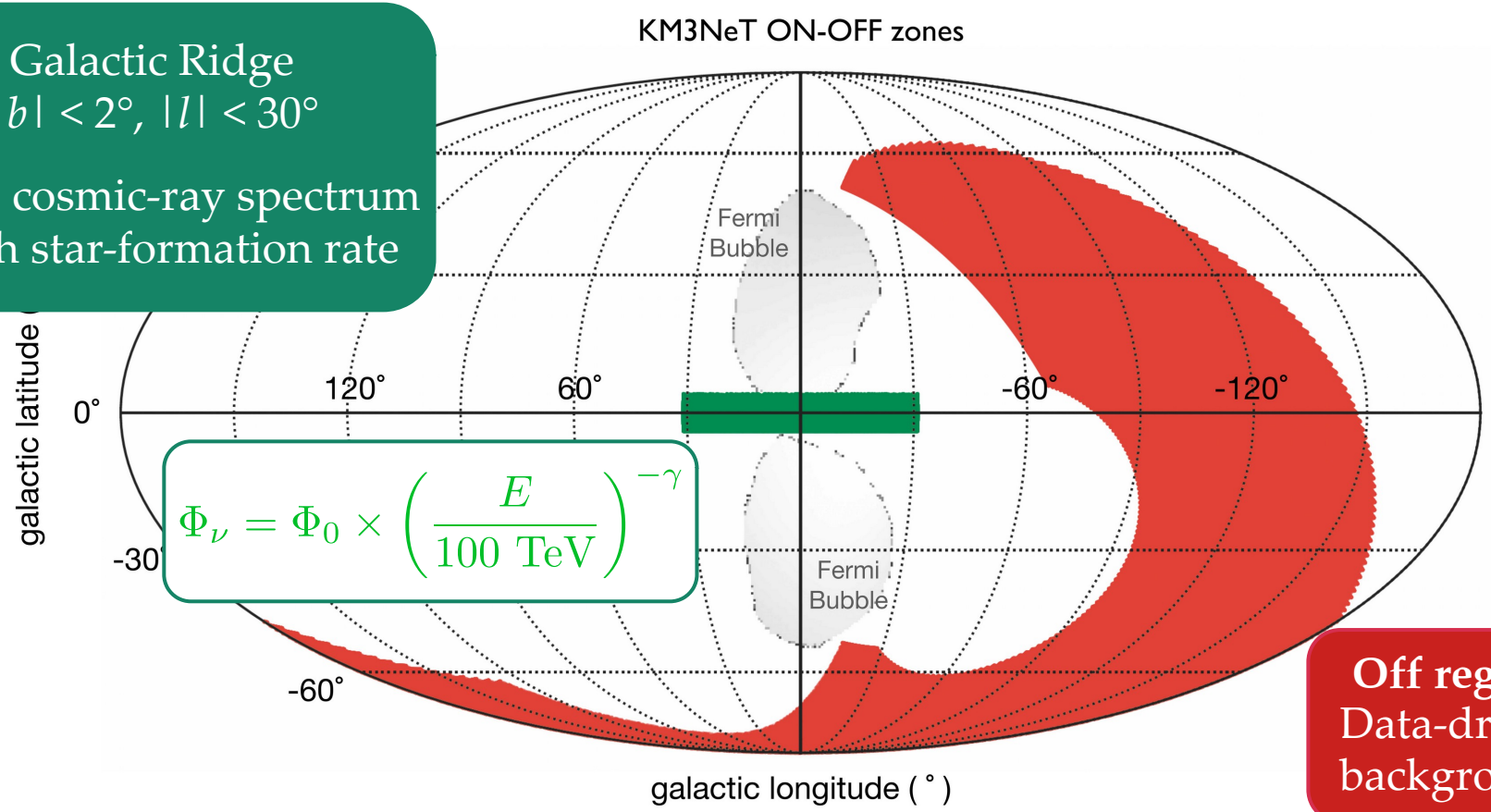
Neutrinos from the Galaxy: **KM3NeT**

F. Filippini
PoS(ICRC2025)1039 • Talk July 21

Look for neutrinos from the Galactic Ridge

Galactic Ridge
$|b| < 2°$, $|l| < 30°$

Hard cosmic-ray spectrum
High star-formation rate



$$\Phi_\nu = \Phi_0 \times \left(\frac{E}{100\ \mathrm{TeV}}\right)^{-\gamma}$$

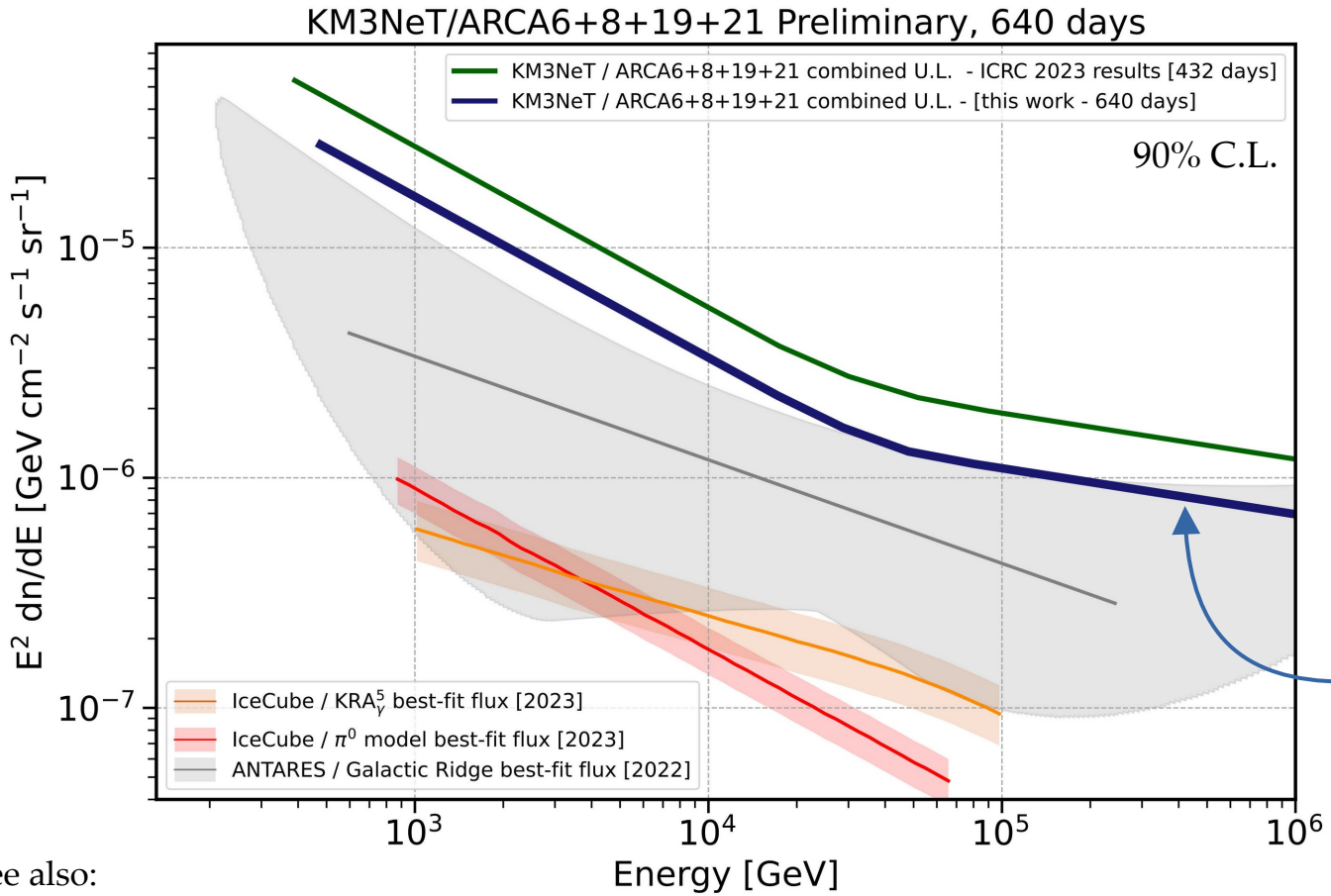
Off region
Data-driven background

See also:
ANTARES search, *PLB* 2023 [2212.11876]

Neutrinos from the Galaxy: **KM3NeT**

F. Filippini
PoS(ICRC2025)1039 • Talk July 21

Look for neutrinos from the Galactic Ridge



KM3NeT/ARCA6+8+19+21
Same data as for diffuse flux

Upgoing + horizontal tracks
Resolution < 0.2° at PeV

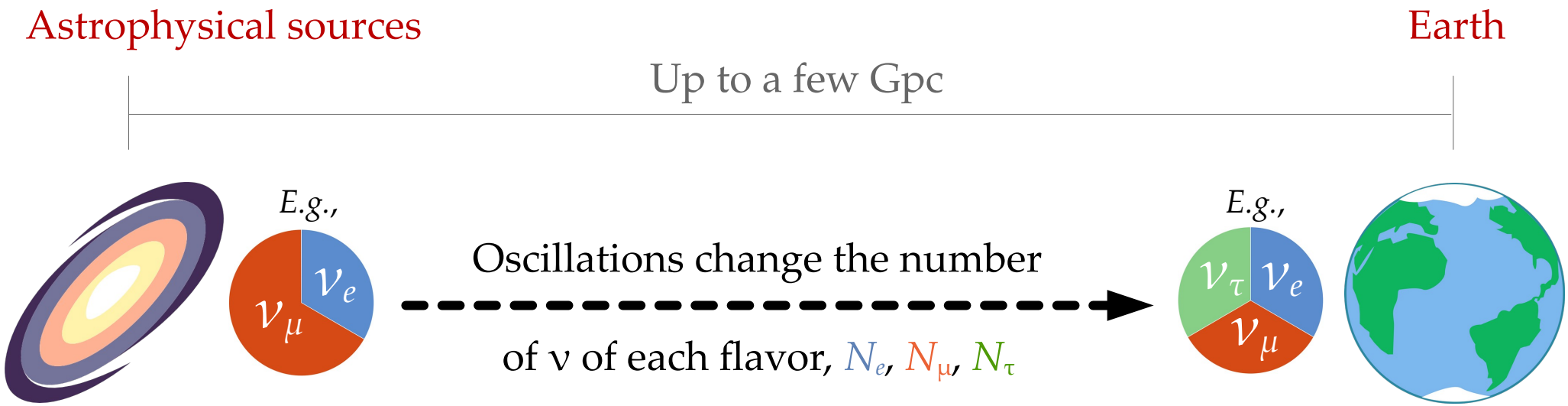
No evidence for Galactic Ridge found

New 90% C.L. upper limit

See also:
ANTARES search, *PLB* 2023 [2212.11876]

Three

Neutrino flavor composition



Different production mechanisms yield different flavor ratios:

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

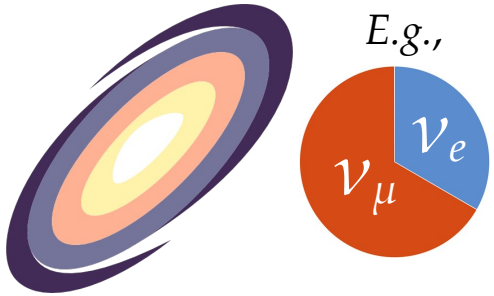
Flavor ratios at Earth ($\alpha = e, \mu, \tau$):

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

Astrophysical sources

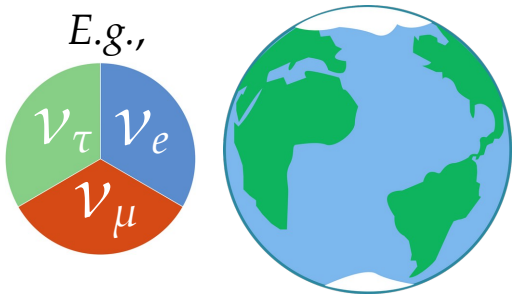
Earth

Up to a few Gpc



Oscillations change the number

of ν of each flavor, N_e, N_μ, N_τ



Different production mechanisms yield different flavor ratios:

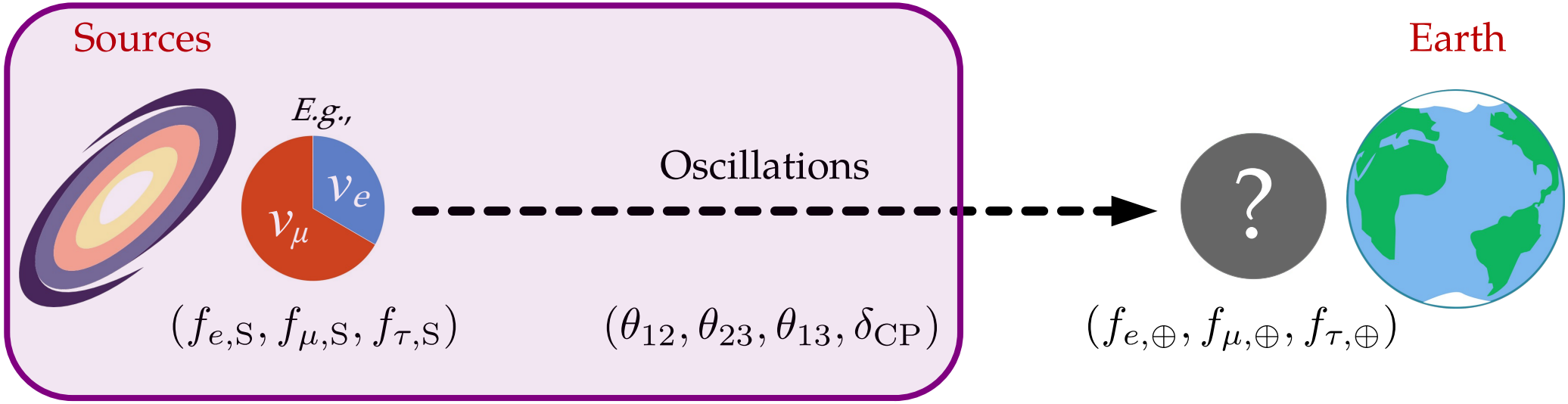
$$(f_{e,S}, f_{\mu,S}, f_{\tau,S}) \equiv (N_{e,S}, N_{\mu,S}, N_{\tau,S})/N_{tot}$$

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

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

Standard oscillations
or
new physics

From sources to Earth: we learn what to expect when measuring $f_{\alpha,\oplus}$



One likely TeV–PeV ν production scenario:

$p + \gamma \rightarrow \pi^+ \rightarrow \mu^+ + \nu_\mu$ followed by $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$

Full π decay chain

$(1/3{:}2/3{:}0)_S$

Note: ν and $\bar{\nu}$ are (so far) indistinguishable in neutrino telescopes

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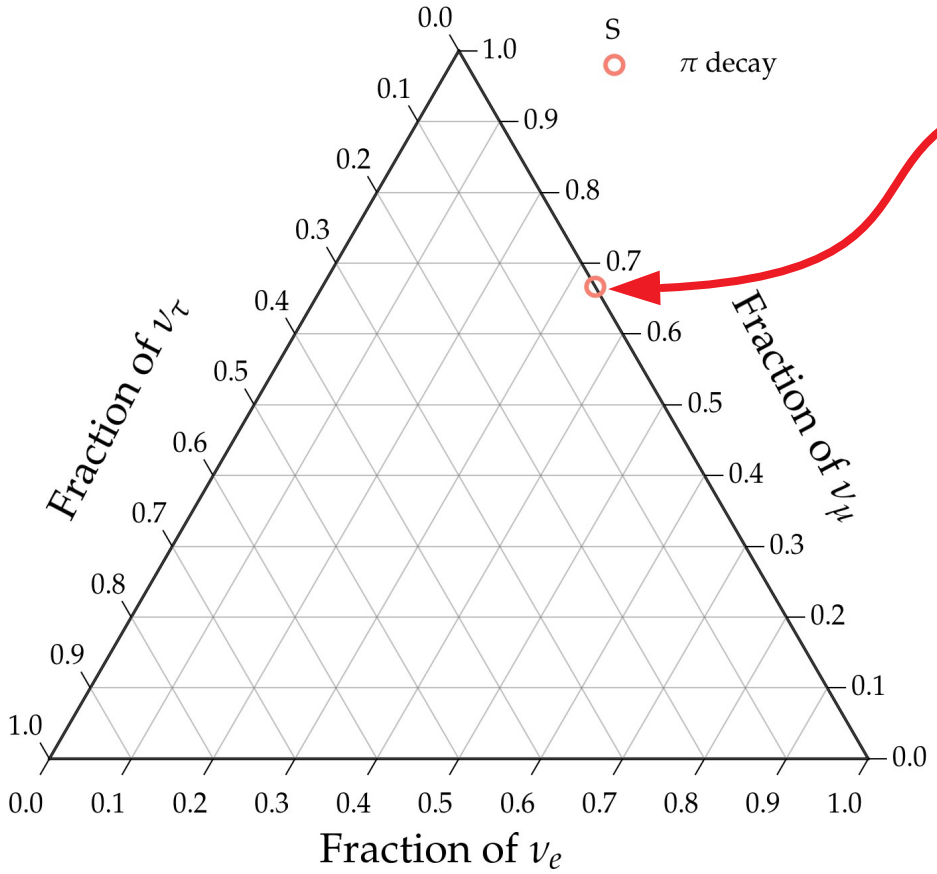

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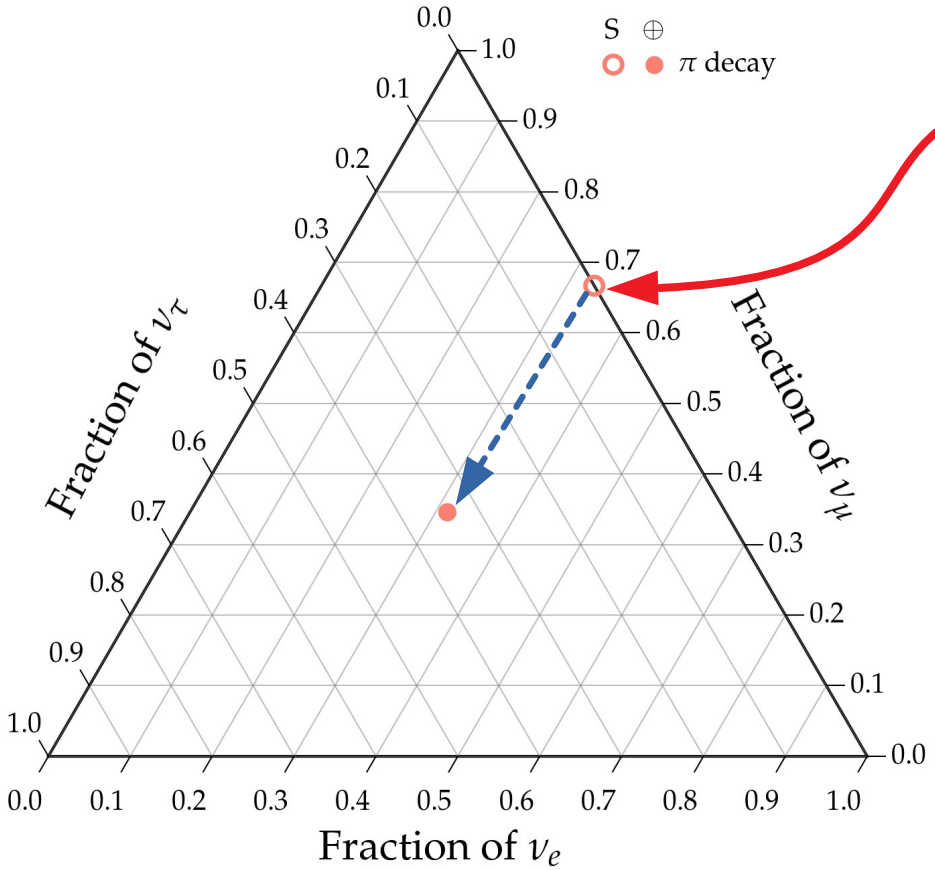

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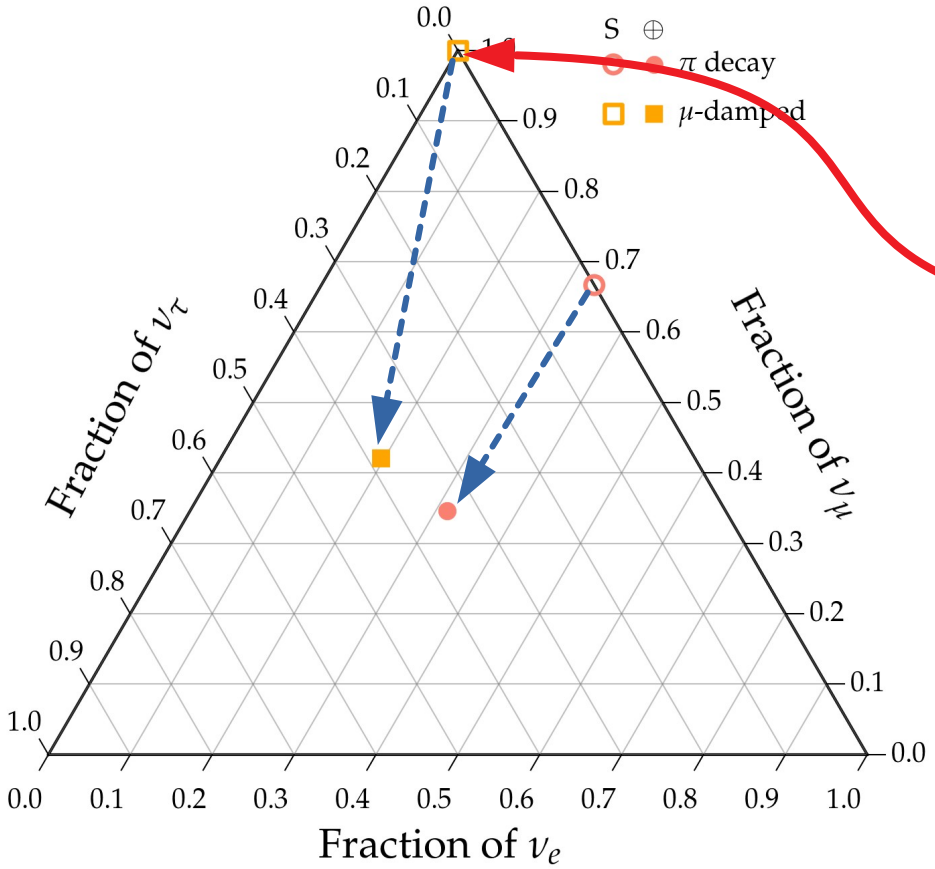

Full π decay chain

$(1/3:2/3:0)_S$

Muon damped

$(0:1:0)_S$

Note: ν and $\bar{\nu}$ are (so far) indistinguishable in neutrino telescopes

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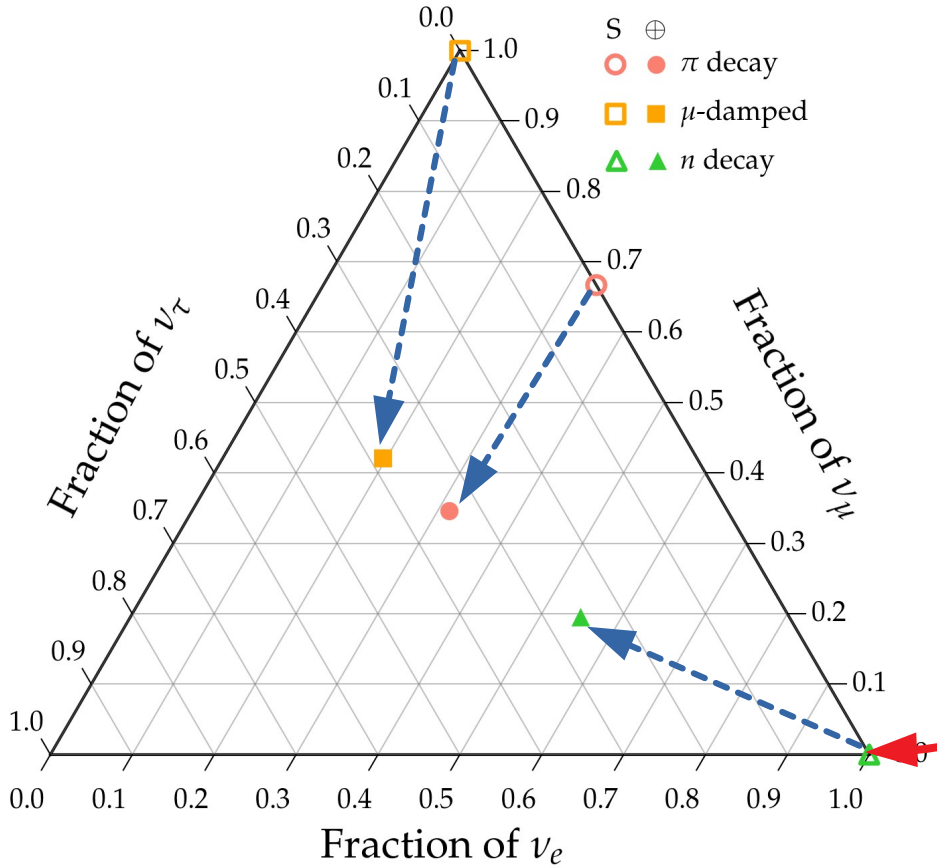


Full π decay chain

$(1/3{:}2/3{:}0)_S$

Muon damped

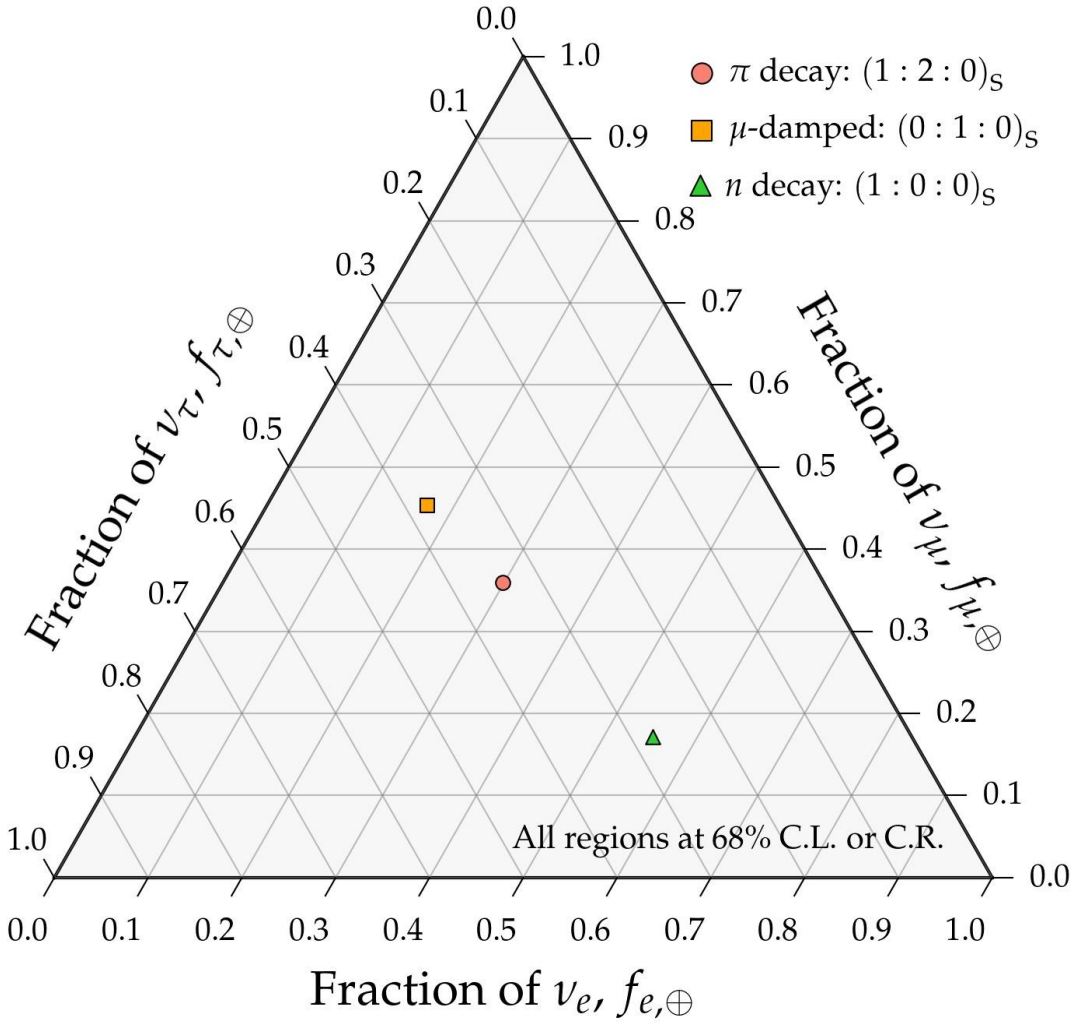
$(0{:}1{:}0)_S$

Neutron decay

$(1{:}0{:}0)_S$

Note: ν and $\bar{\nu}$ are (so far) indistinguishable in neutrino telescopes

Measuring flavor composition 2015–2025



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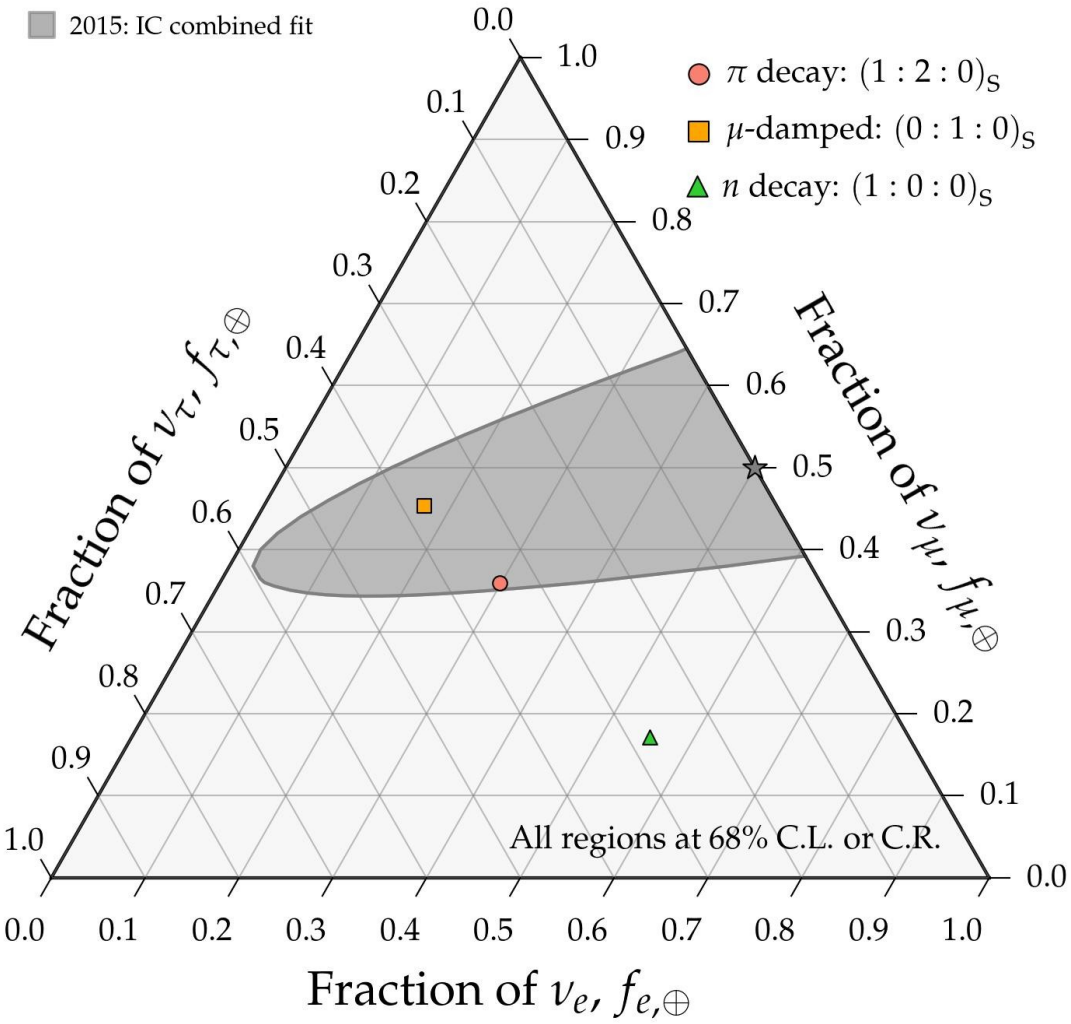

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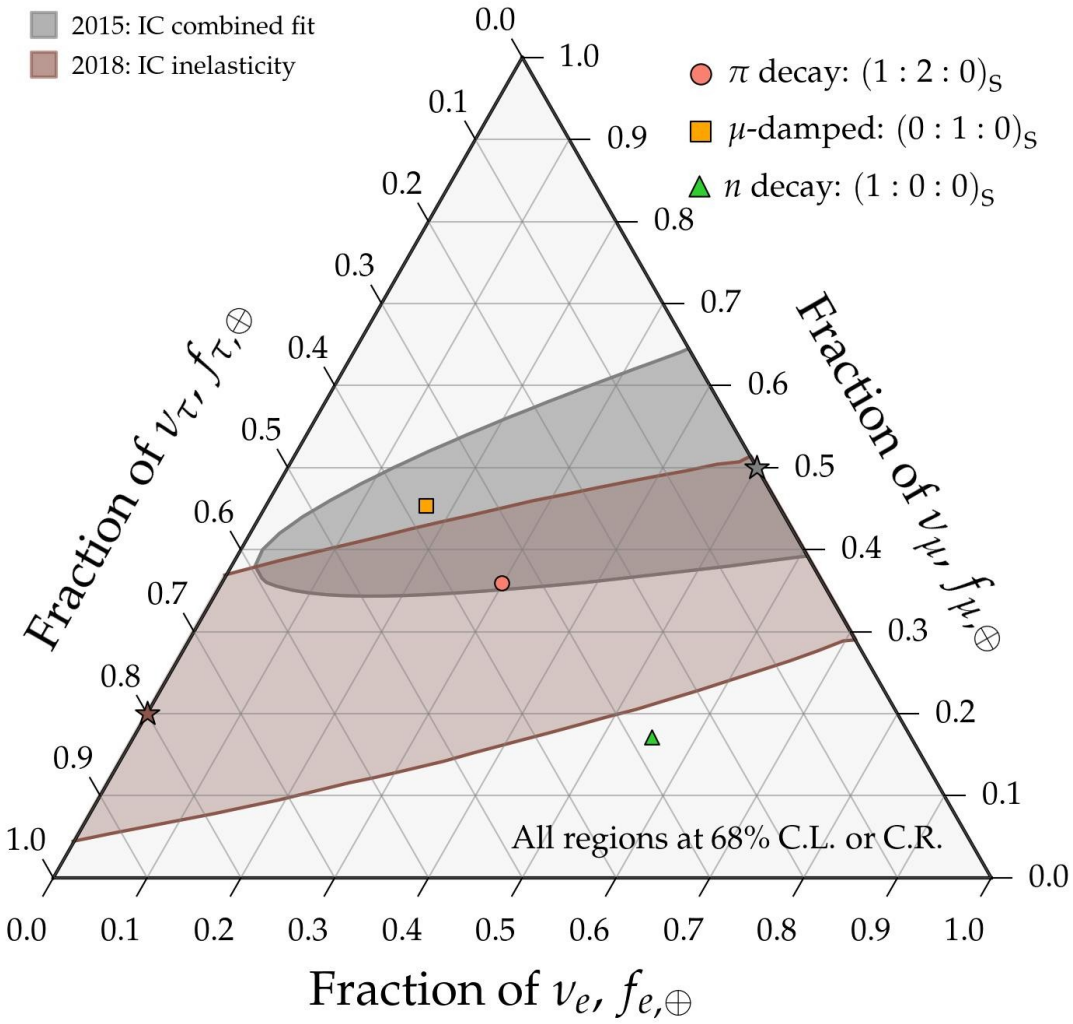
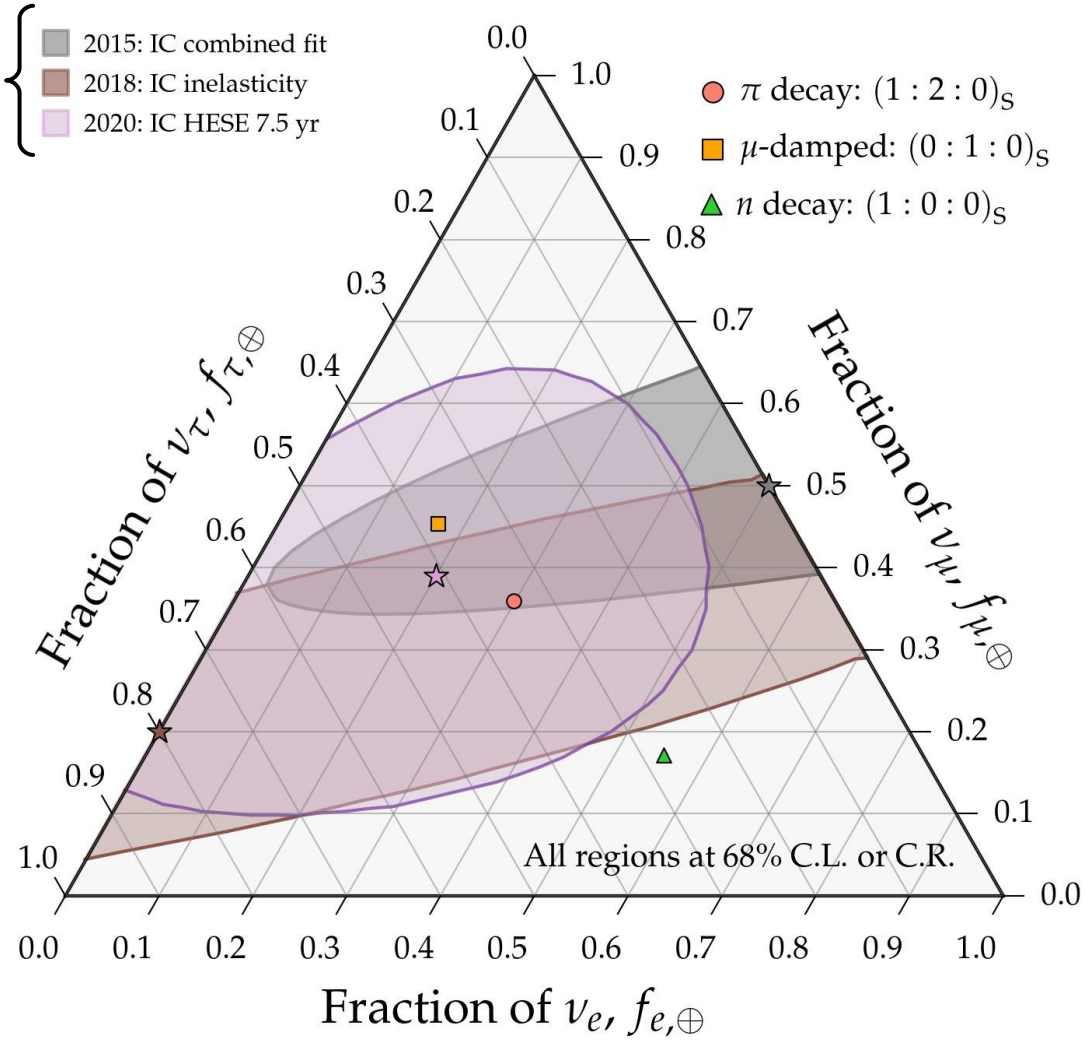


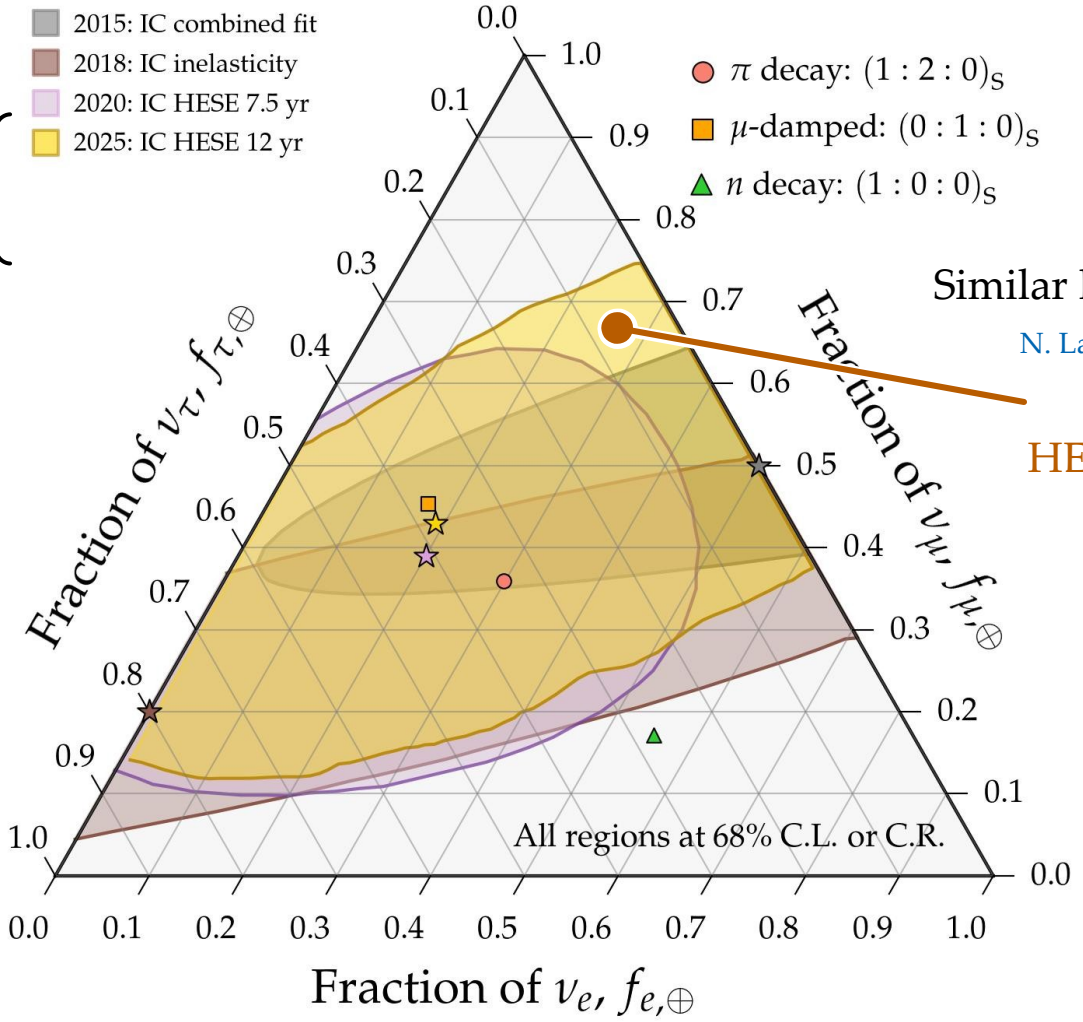
Measuring flavor composition 2015–2025

Before ICRC 2025



Measuring flavor composition 2015–2025

Presented at ICRC 2025



Similar likelihood as with 7.5 yr

N. Lad, T. J. van Eeden, M. Ackermann
PoS(ICRC2025)1198

HESE (> 60 TeV) are scarce
(~100 events in 12 yr)

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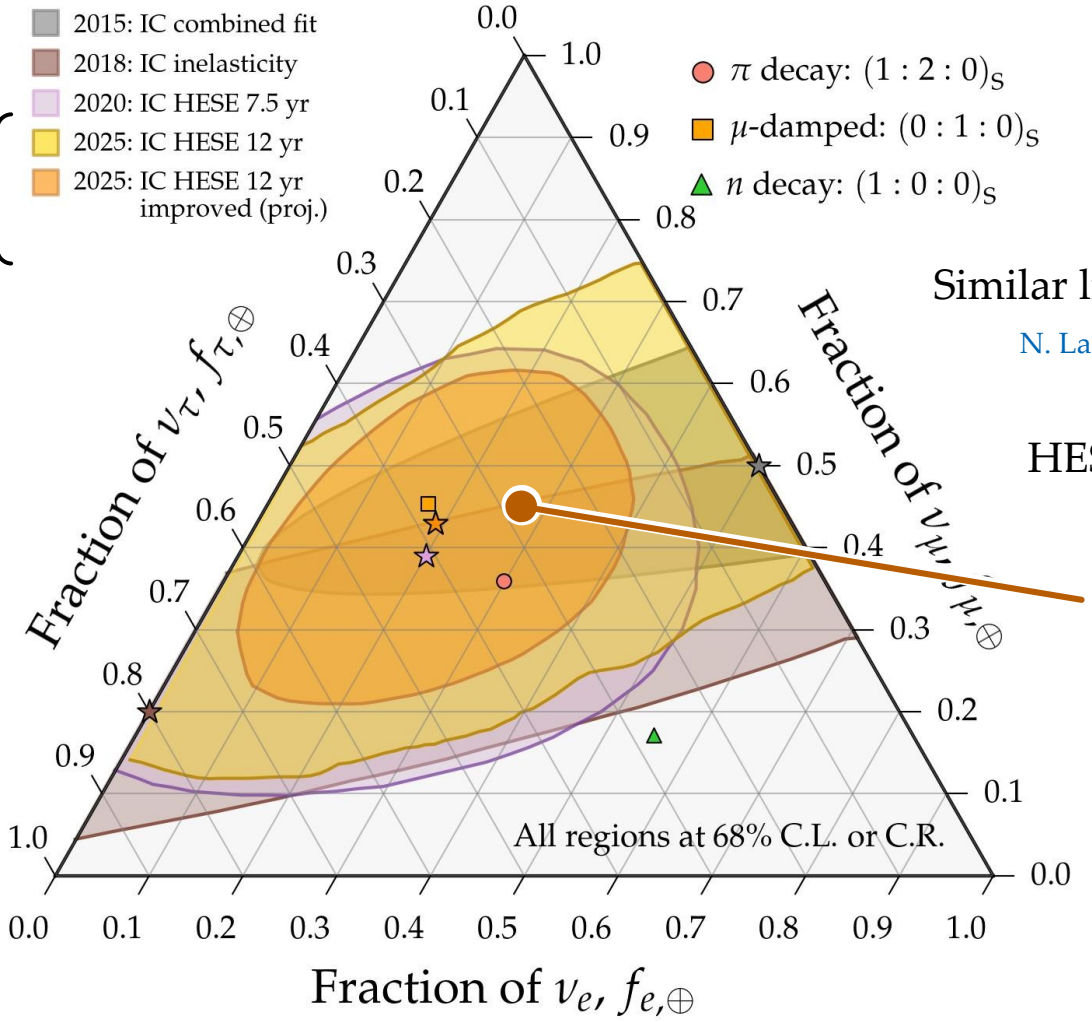
Presented at ICRC 2025



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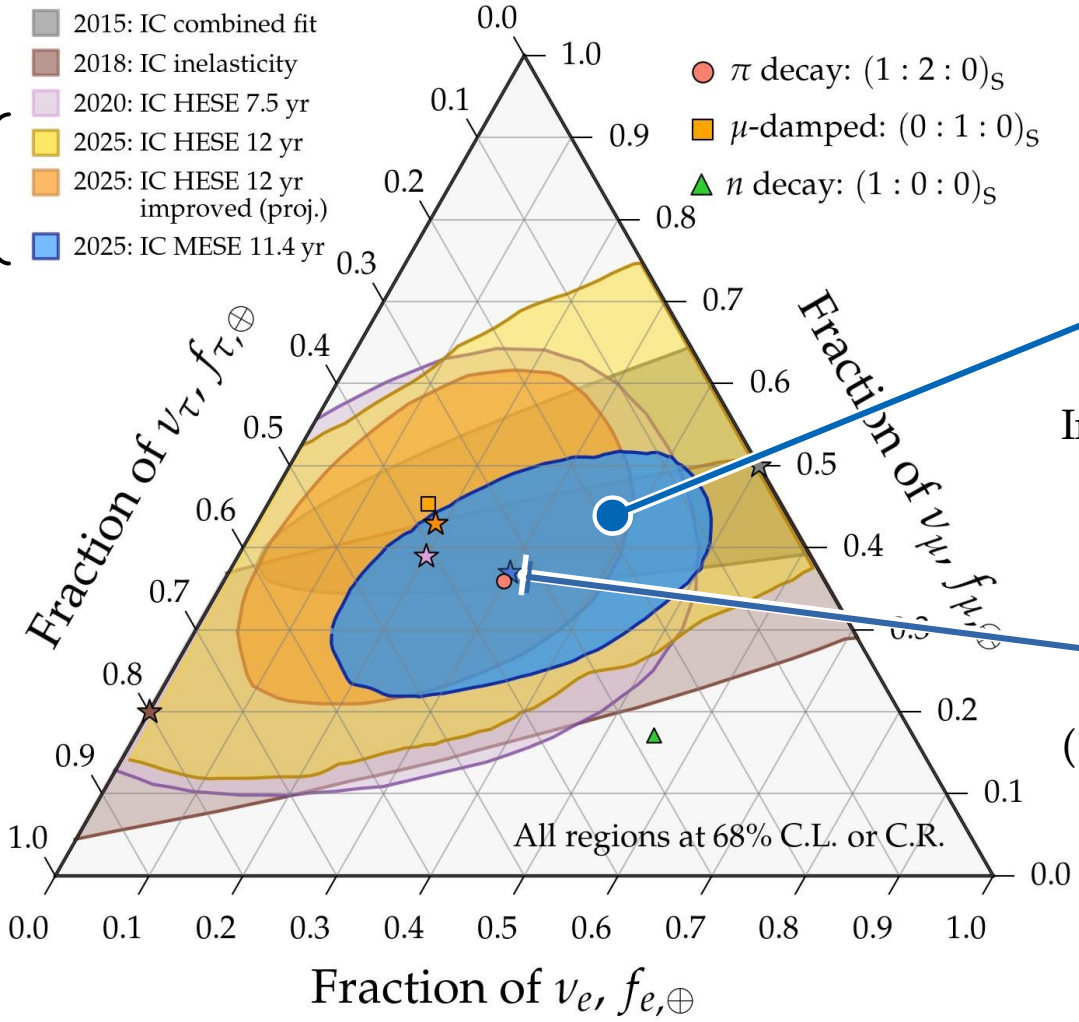
N. Lad, T. J. van Eeden, M. Ackermann
PoS(ICRC2025)1198

HESE (> 60 TeV) are scarce (~100 events in 12 yr)

Improve via a neural network that uses the energy asymmetry of the two bangs and the direction

Measuring flavor composition 2015–2025

Presented at ICRC 2025



MESE flavor:
A. Balagopal, July 22

MESE events (> 1 TeV) are more abundant

Includes classification of υ_τ

First time all flavors are nonzero at 68% C.L.

Best fit very close to nominal expectation of (1:1:1) from production via pion decay

Four

The First Neutrino of ultra-high energy

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

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But is it due to a neutrino?

Yes! Direction points underground, after traveling 150 km through Earth

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

(Assuming E^{-2} spectrum)

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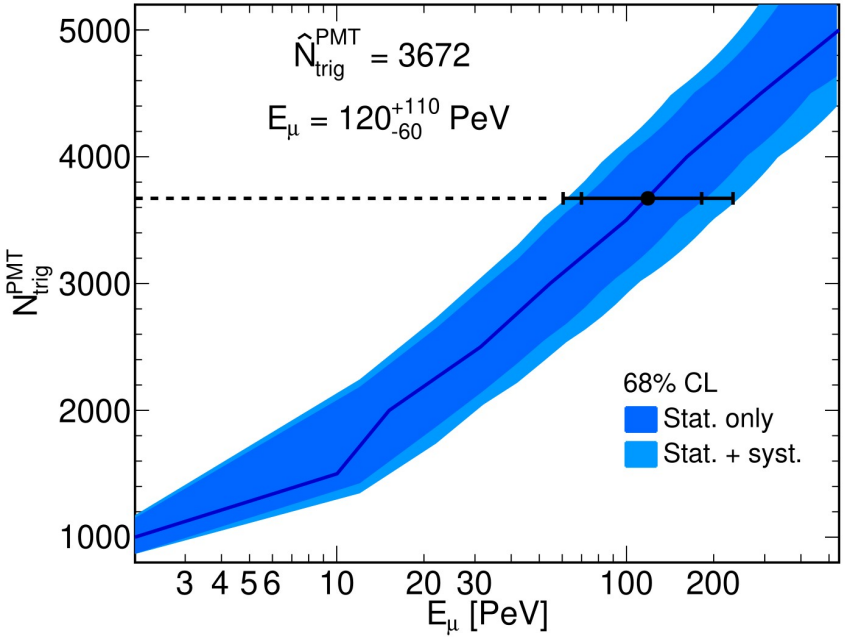
RECORD BREAKER

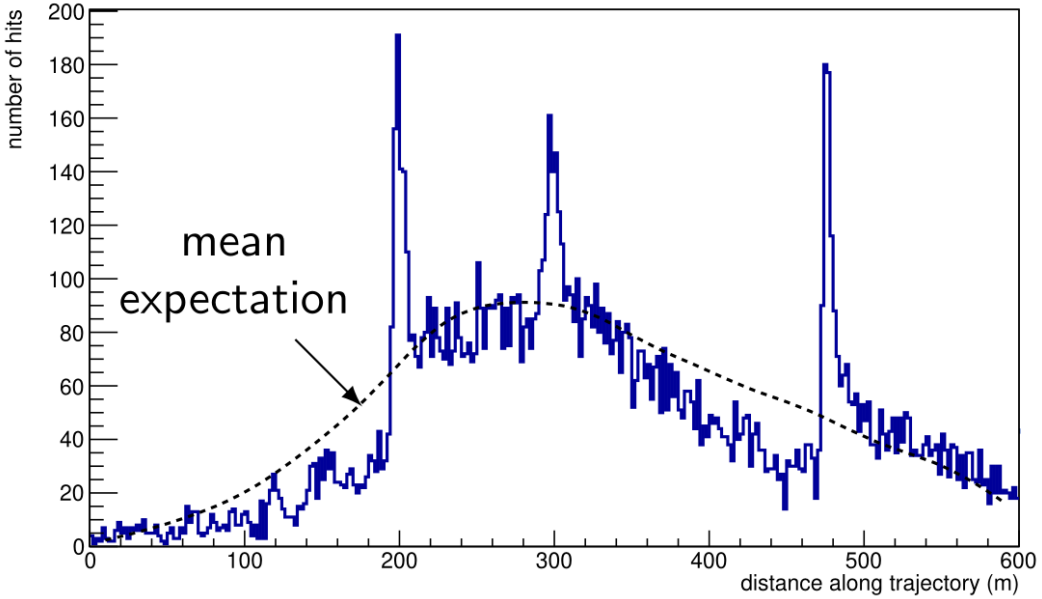
Energy estimation

Overview:
M. Lamoureux, July 17

Muon energy is estimated from the number of triggered PMTs



Stochastic losses consistent sith a single high-energy muon

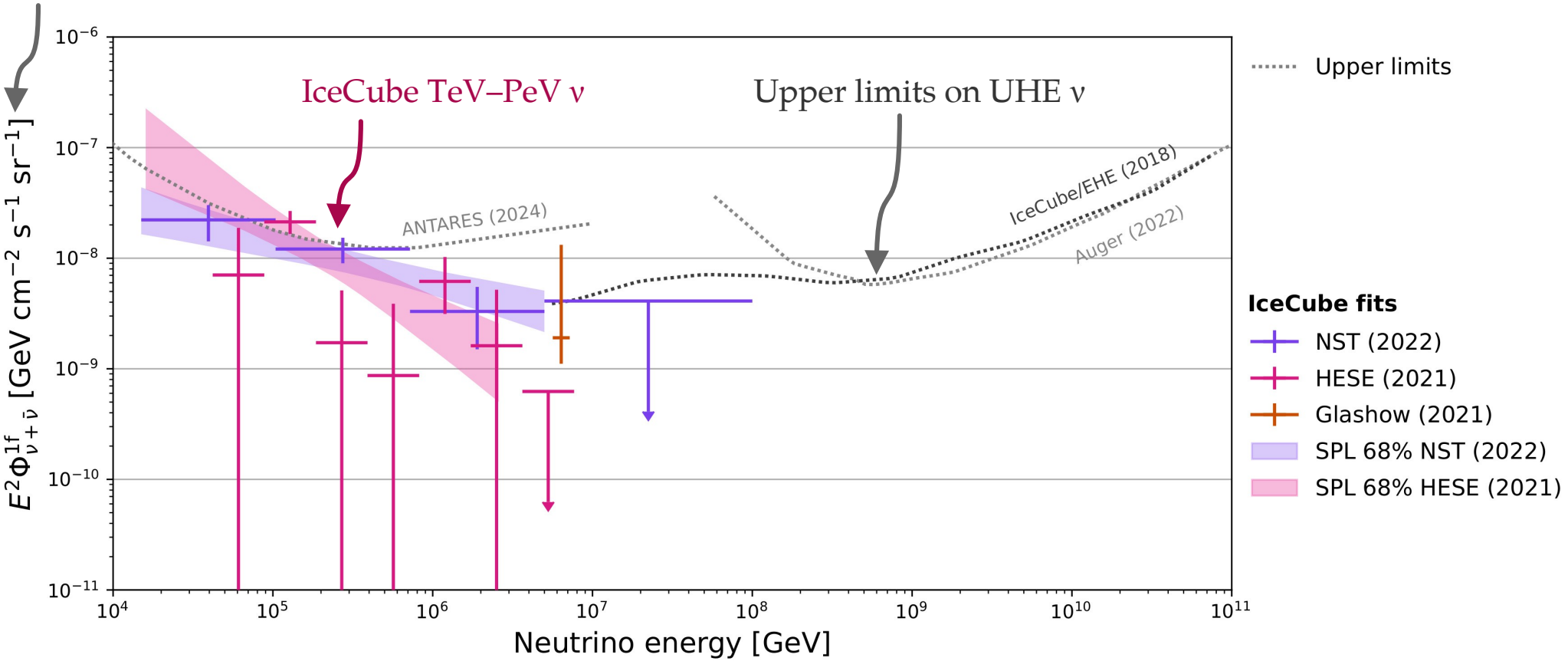


EeV-scale atmospheric muon? Unlikely: expectation is < 10^{-4} per year
Muon bundle? Unlikely: expectation is < 10^{-3} per year
Atmospheric neutrino? Unlikely: (1–5) × 10^{-5} per year

KM3NeT *vs.* IceCube & Auger

Joint fits:
J. Mauro, July 22

Diffuse flux of high-energy astrophysical ν



KM3NeT Collab., arXiv:2502.08173 (adapted)
KM3NeT Collab. *Nature* 638, 376 (2025)

KM3NeT *vs.* IceCube & Auger

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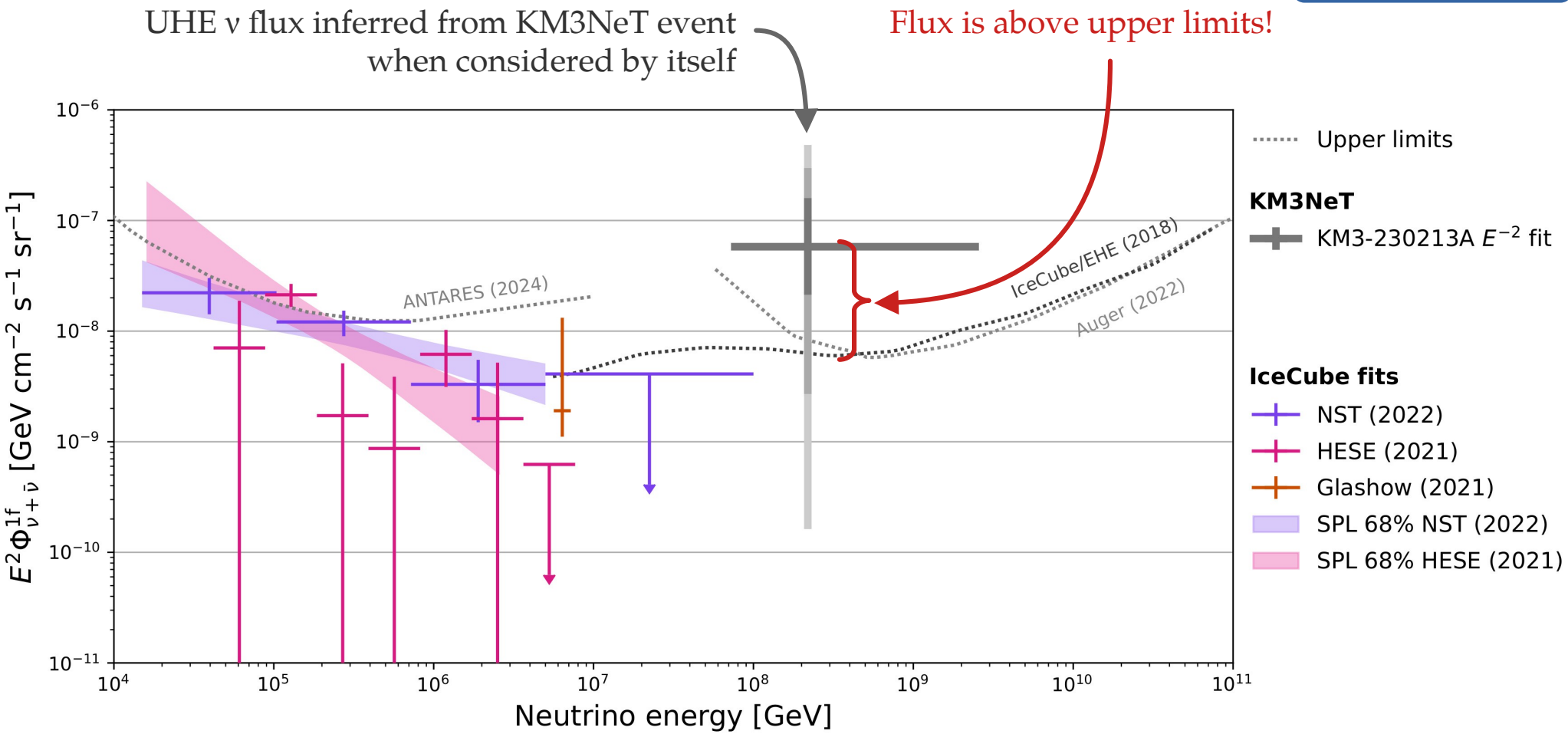

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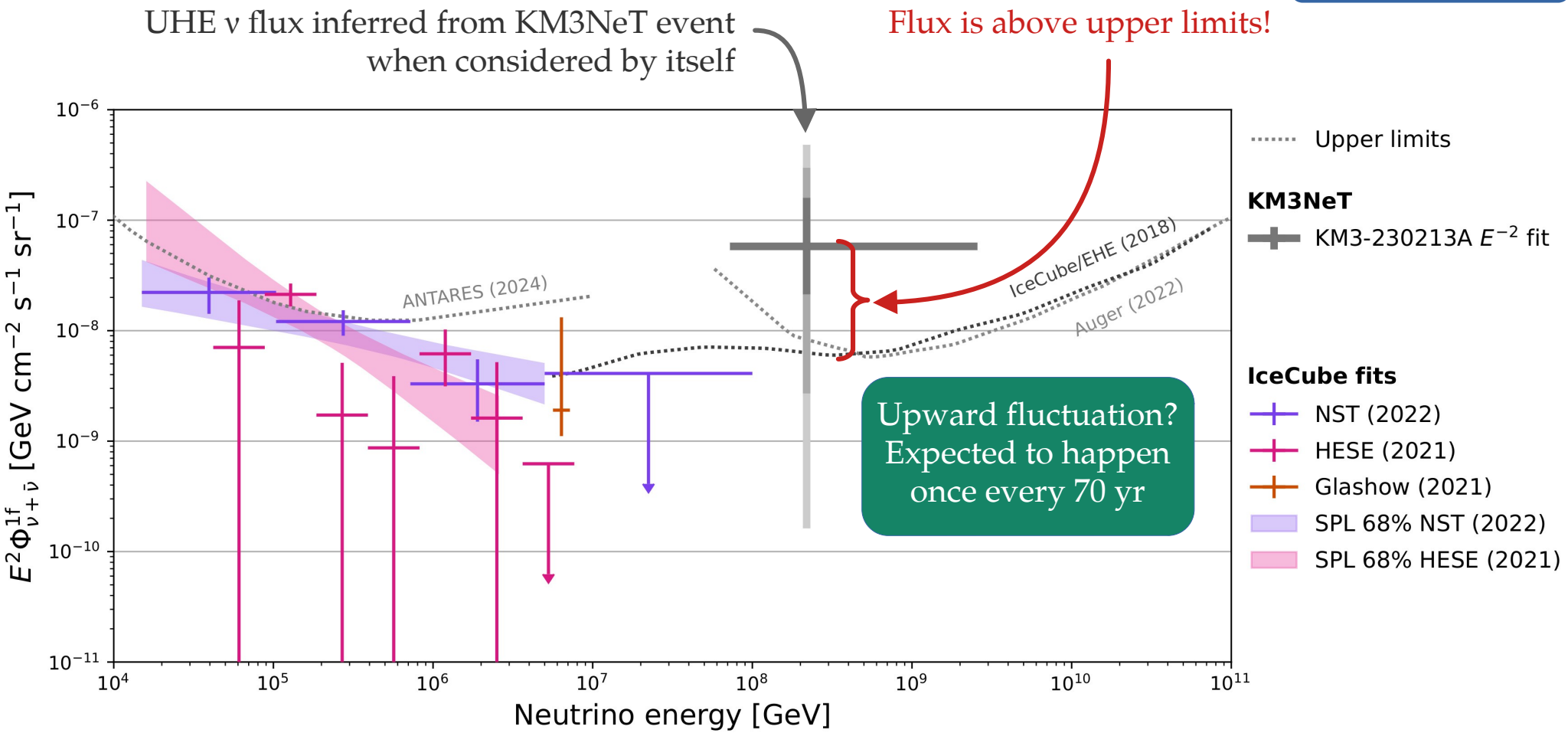
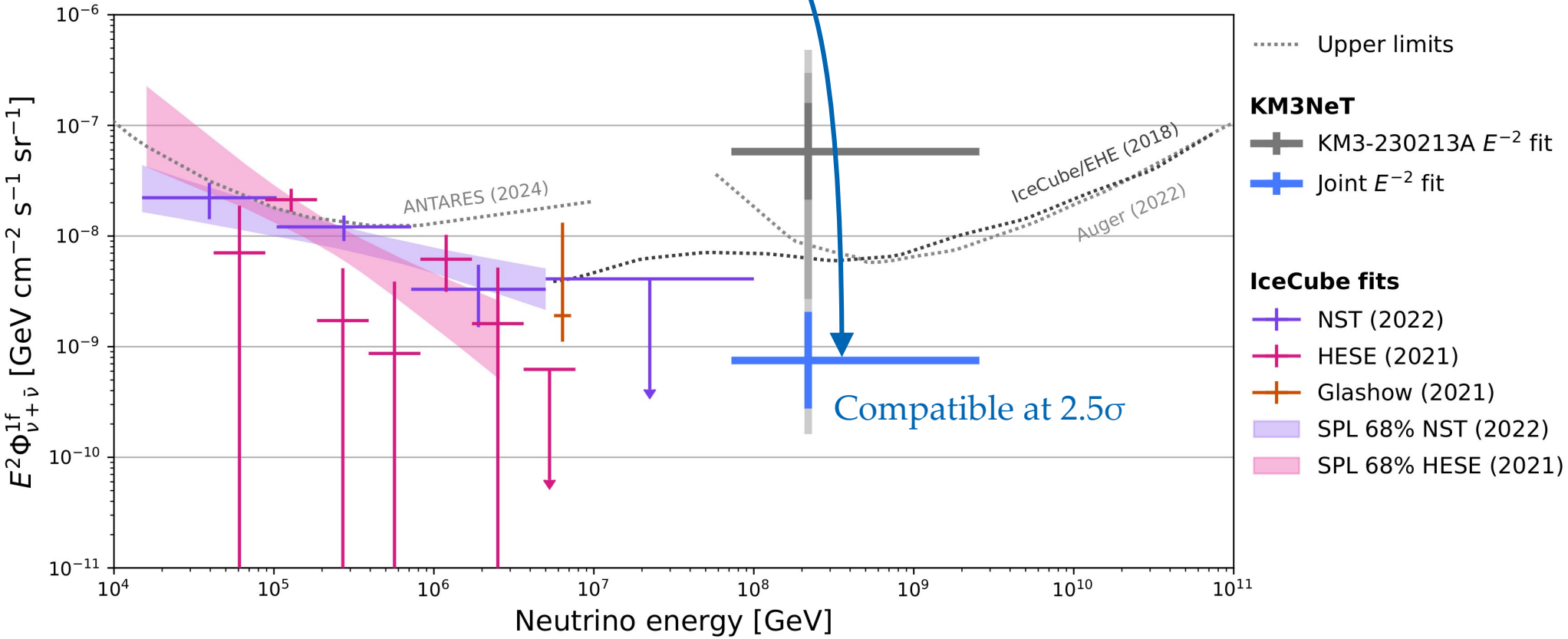


KM3NeT Collab., arXiv:2502.08173 (adapted)
KM3NeT Collab. *Nature* 638, 376 (2025)

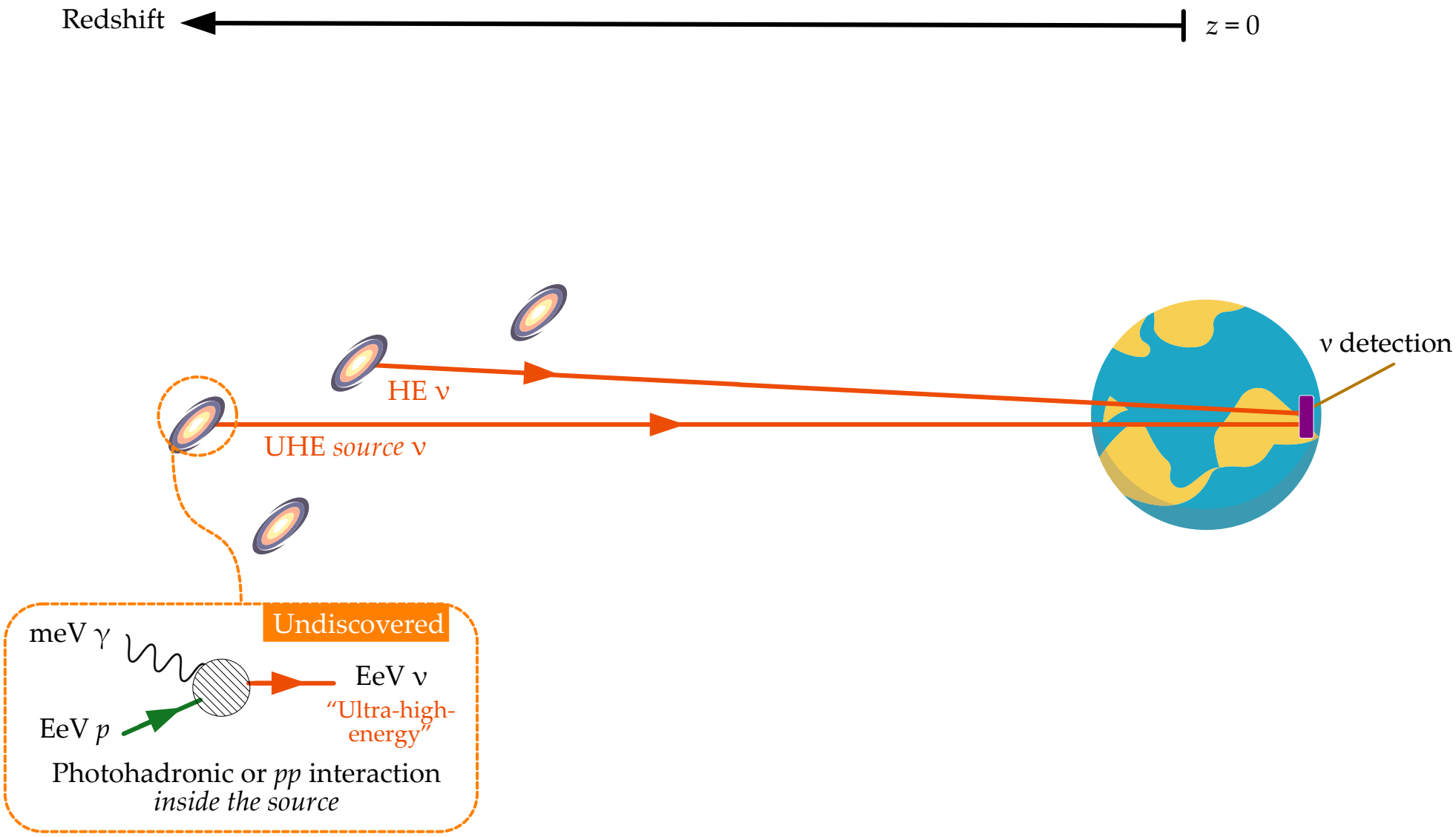
KM3NeT *vs.* IceCube & Auger

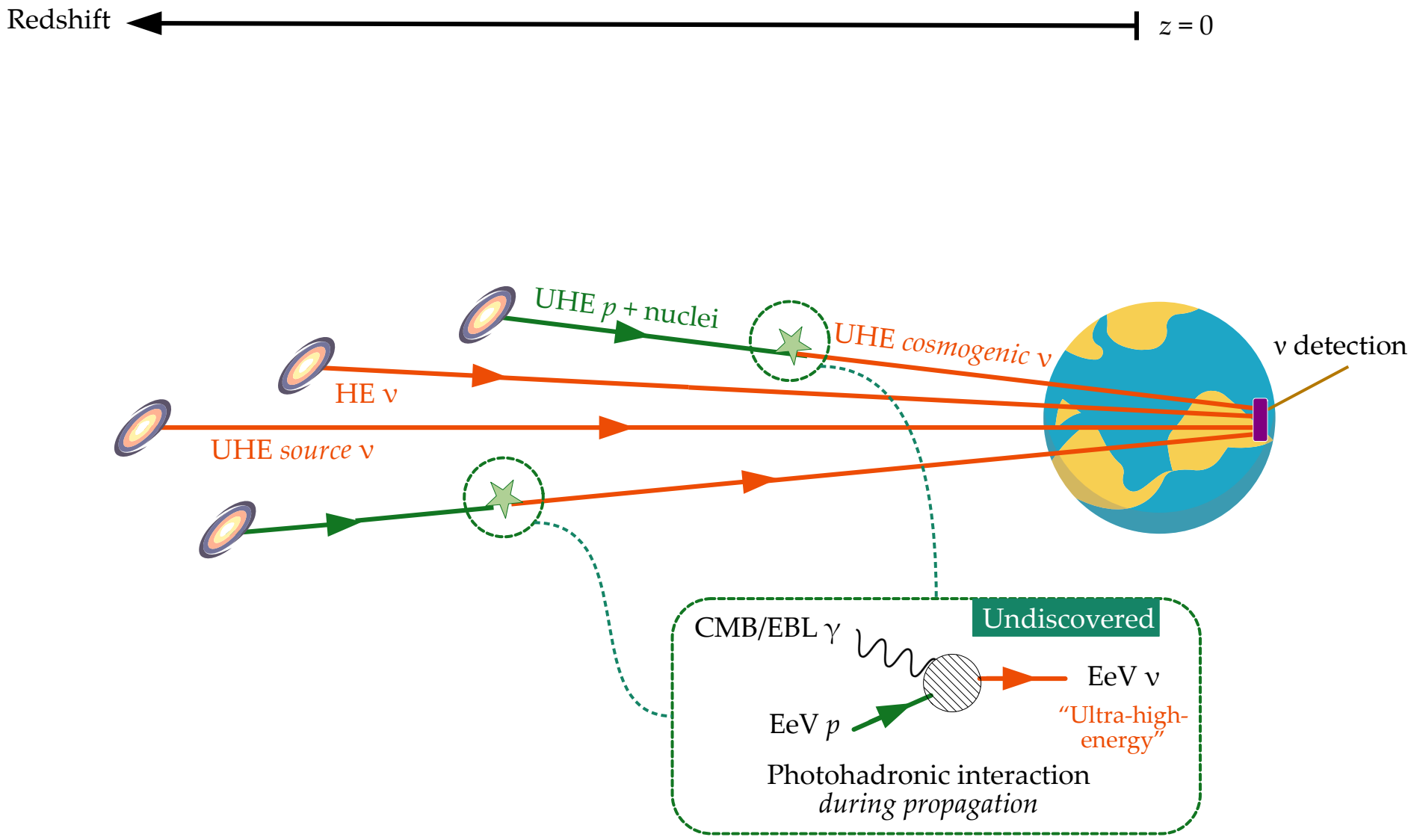
Joint fits:
J. Mauro, July 22

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



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


Redshift
z = 0
HE ν
UHE source ν
ν detection
Undiscovered
meV γ
EeV ν
"Ultra-high-energy"
EeV p
Photohadronic or pp interaction
inside the source


Redshift
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UHE source ν
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CMB/EBL γ
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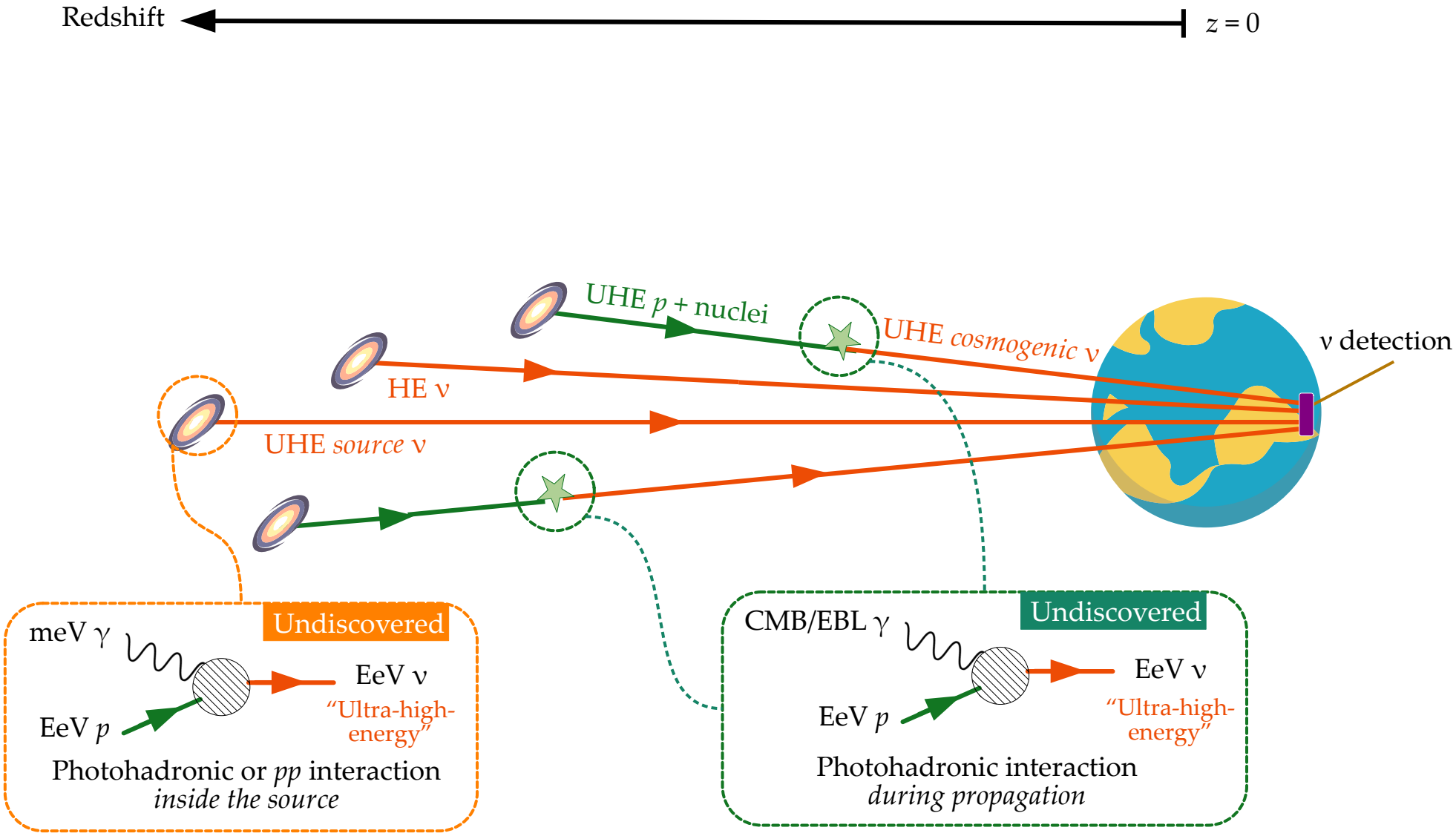
Photohadronic interaction
during propagation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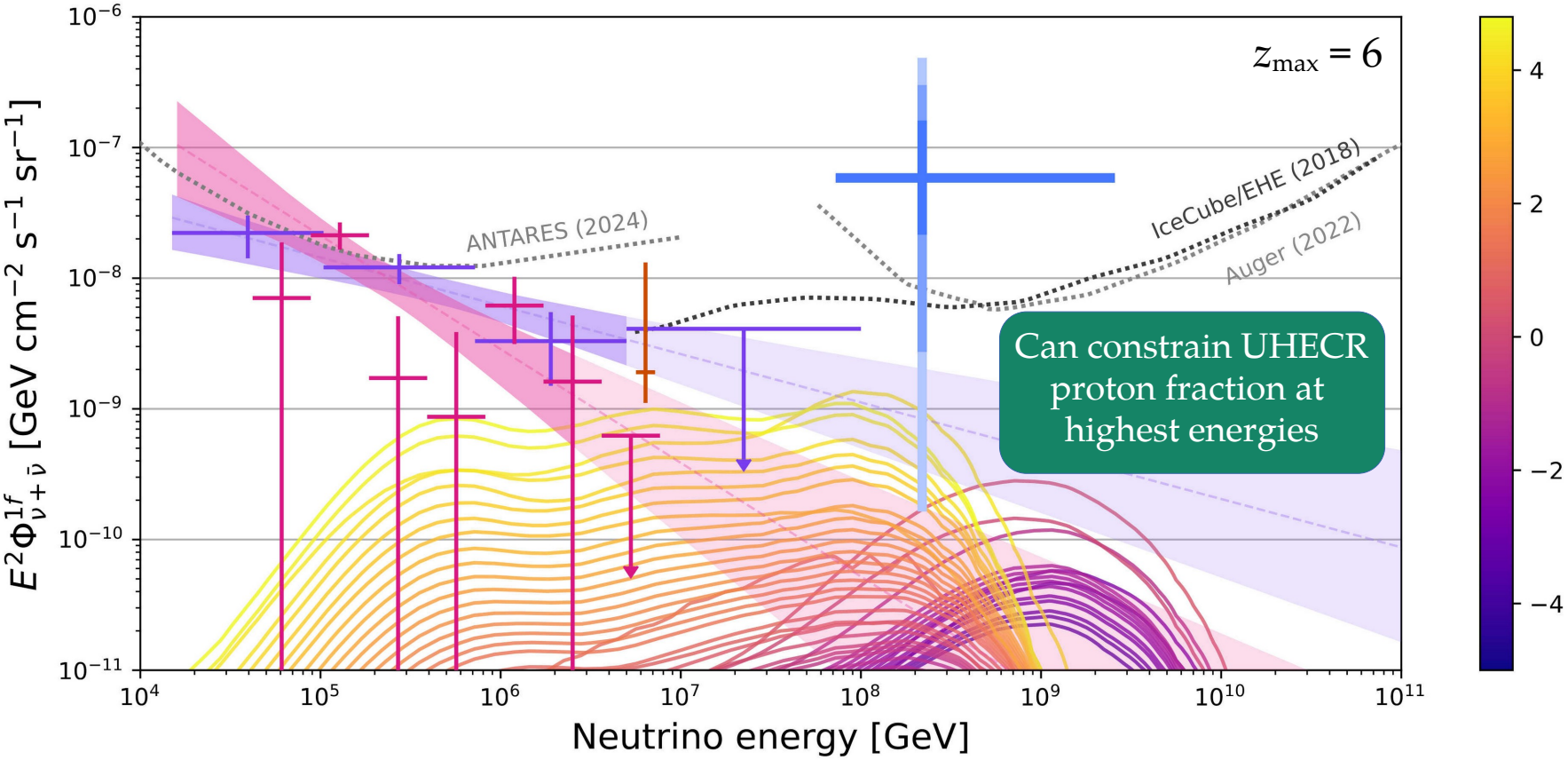
EeV p
Photohadronic interaction
during propagation

Was it a cosmogenic neutrino?

Cosmogenic origin:
A. Condorelli, July 22

Assume population of nondescript, identical UHECR sources
UHECR flux fit to Auger spectrum + mass composition, source abundance $(1+z)^m$



Positive evolution:
More sources faraway — more cosmogenic ν

Negative evolution:
More sources nearby — fewer cosmogenic ν

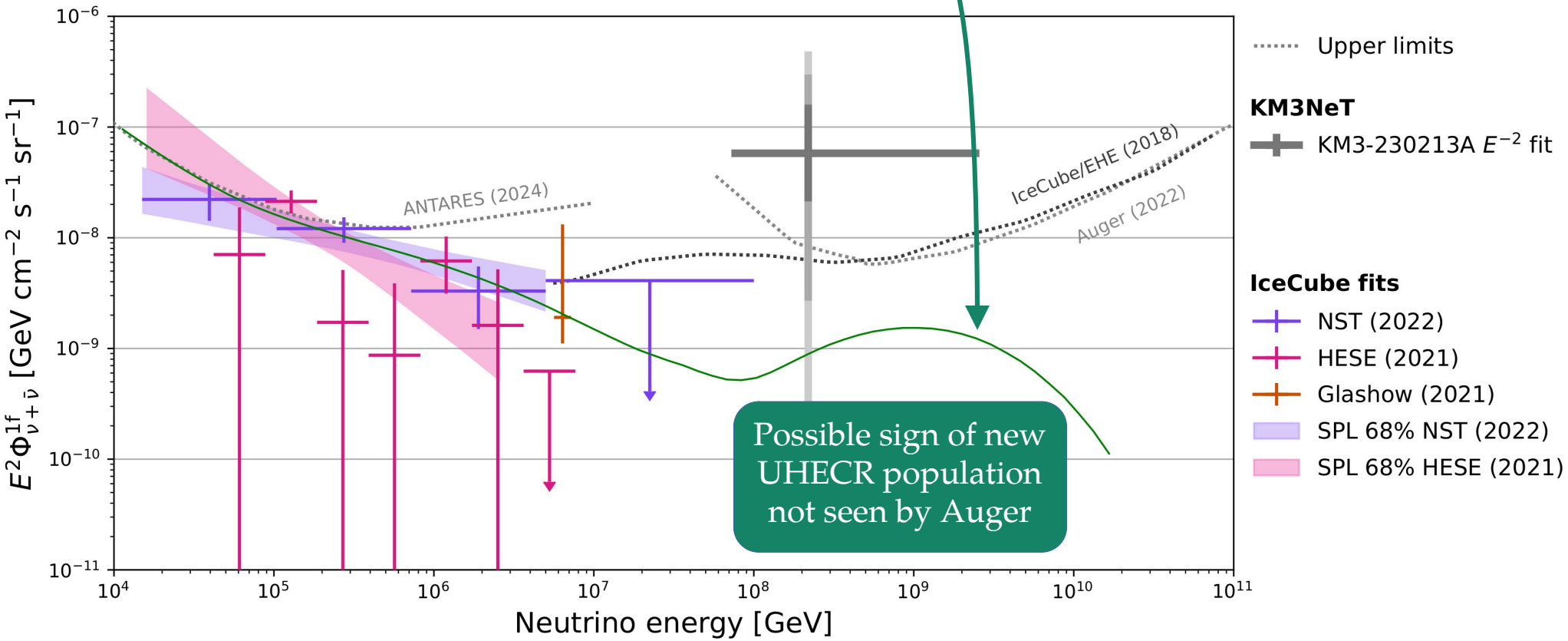
KM3NeT Collab. *ApJL* 2025

Joint neutrino + cosmic-ray interpretation

Muzio, Yuan, Lu, arXiv:2502.06944

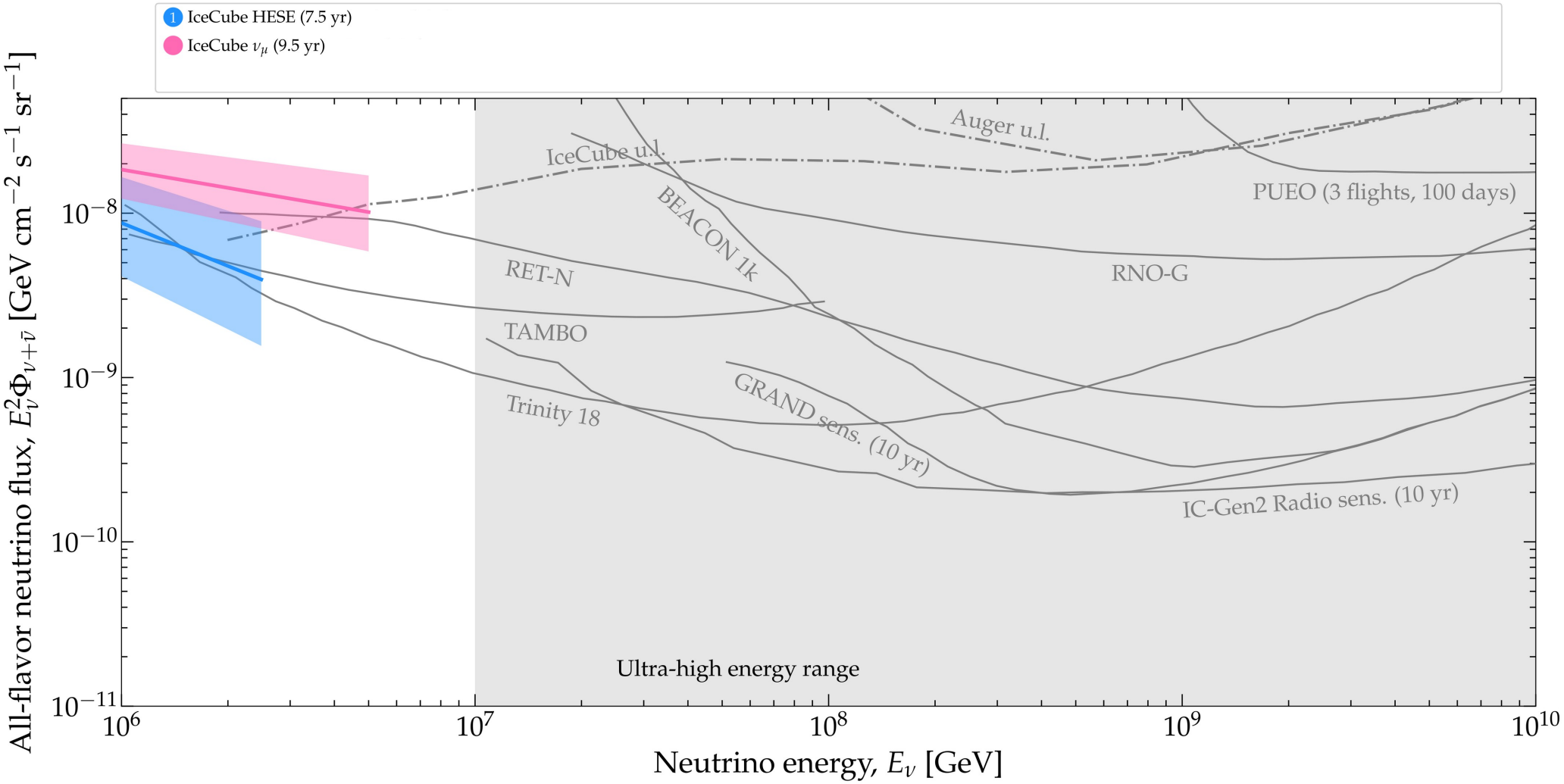
Joint fits ν + UHECRs:
T. Yuan, July 22

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

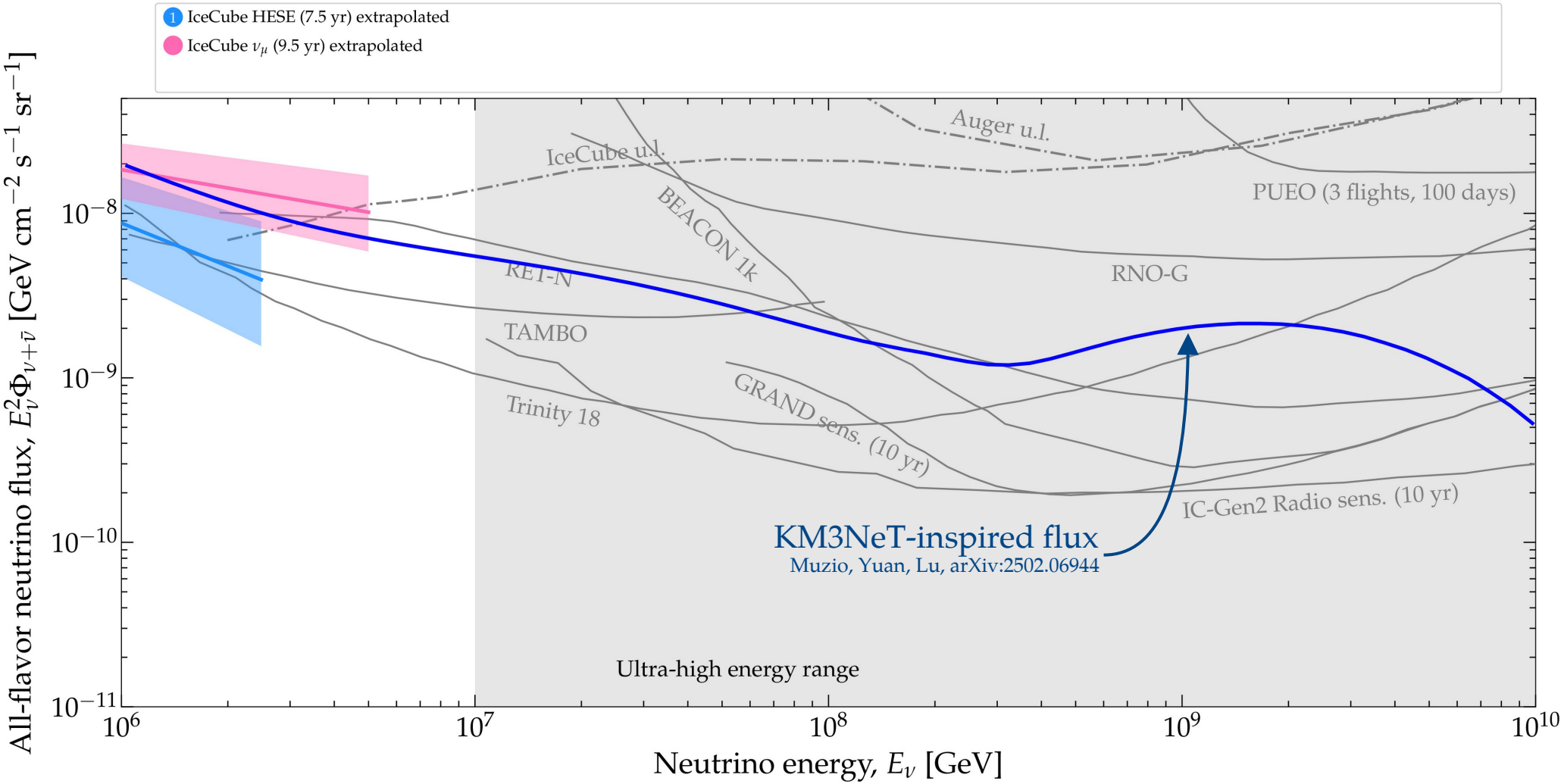


Possible sign of new UHECR population not seen by Auger

KM3NeT Collab., arXiv:2502.08173 (adapted)
KM3NeT Collab. *Nature* 638, 376 (2025)



V. Valera, **MB**, C. Glaser, *PRD* 2023 [2210.03756]



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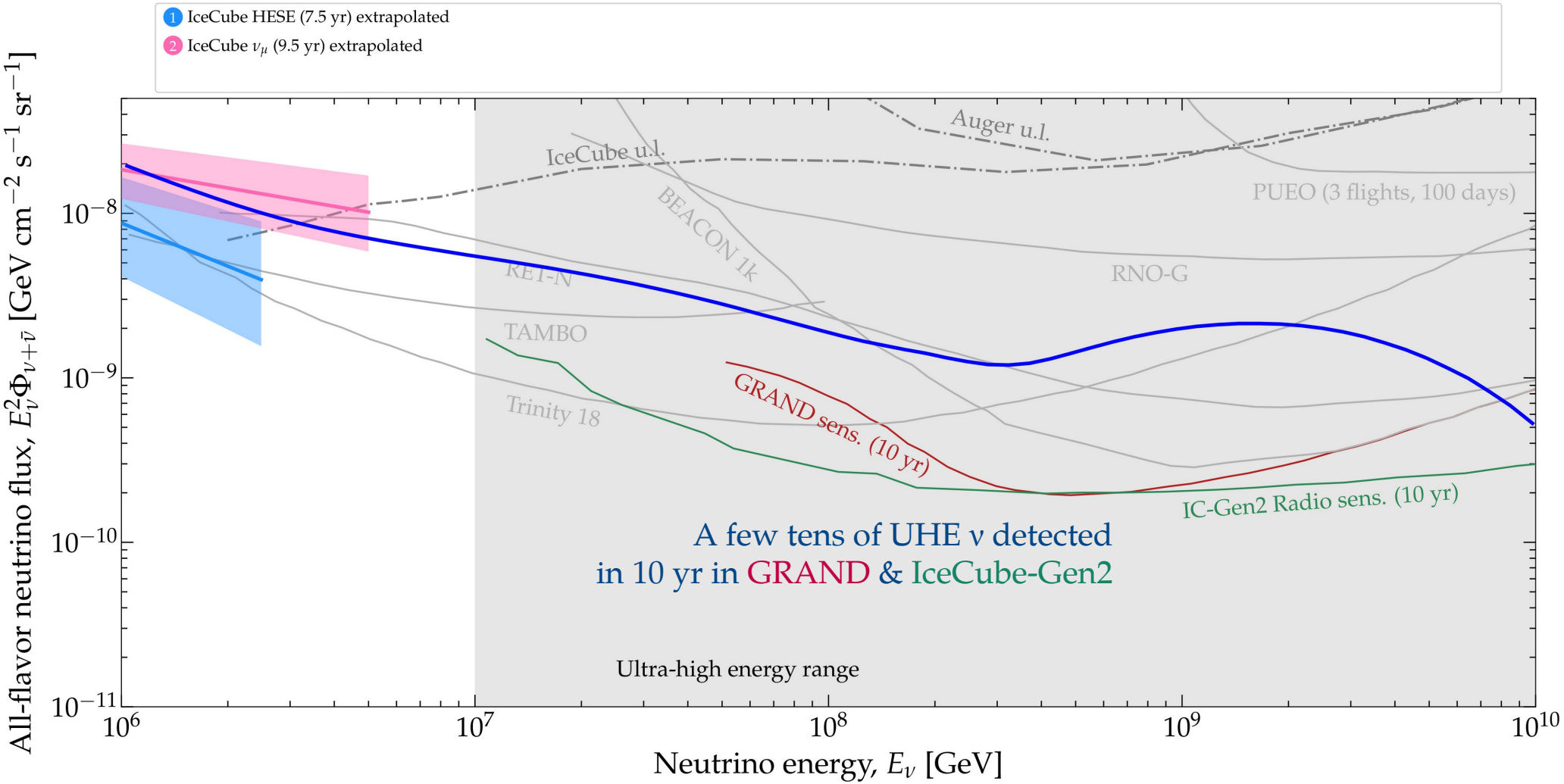

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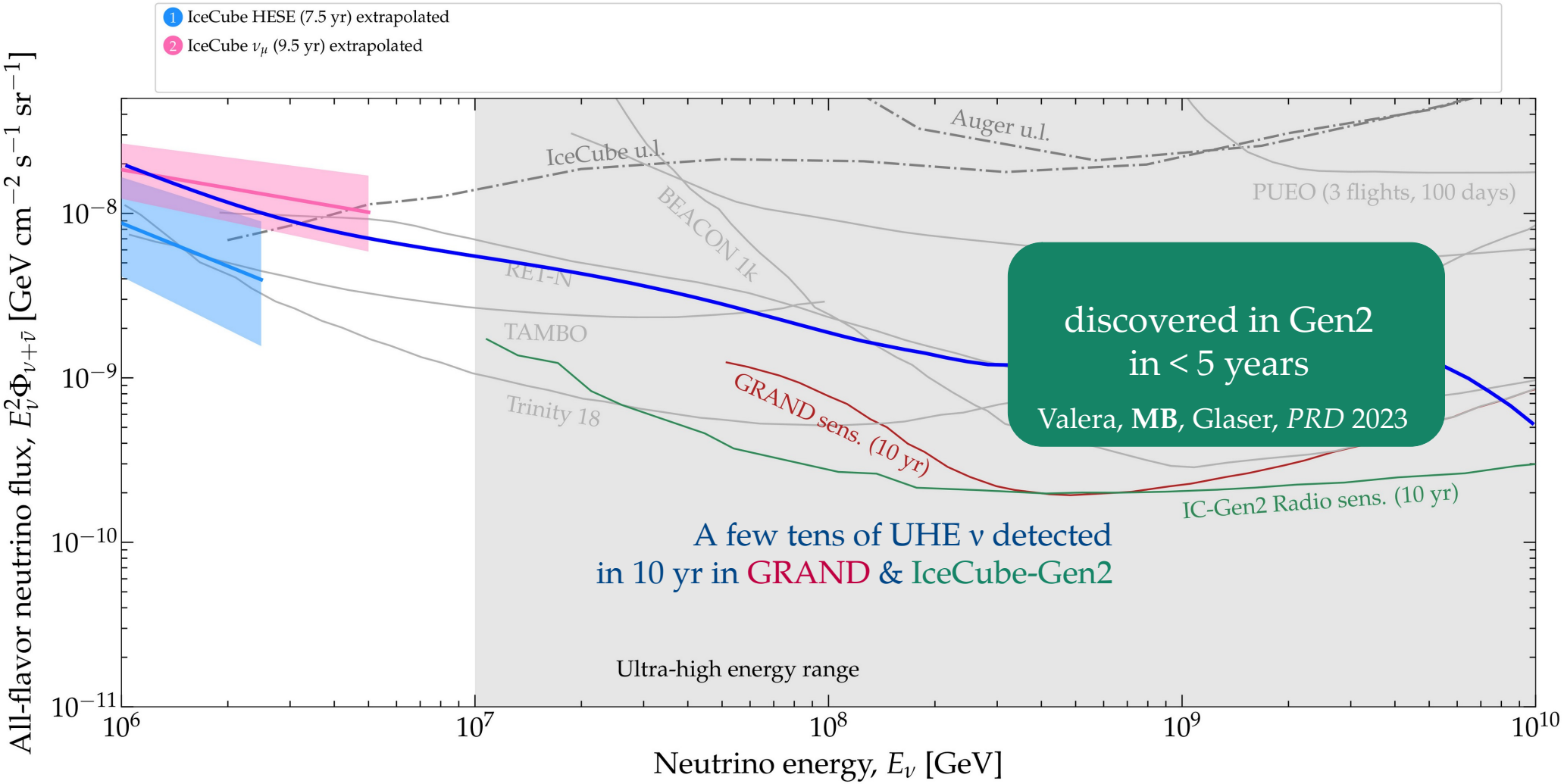

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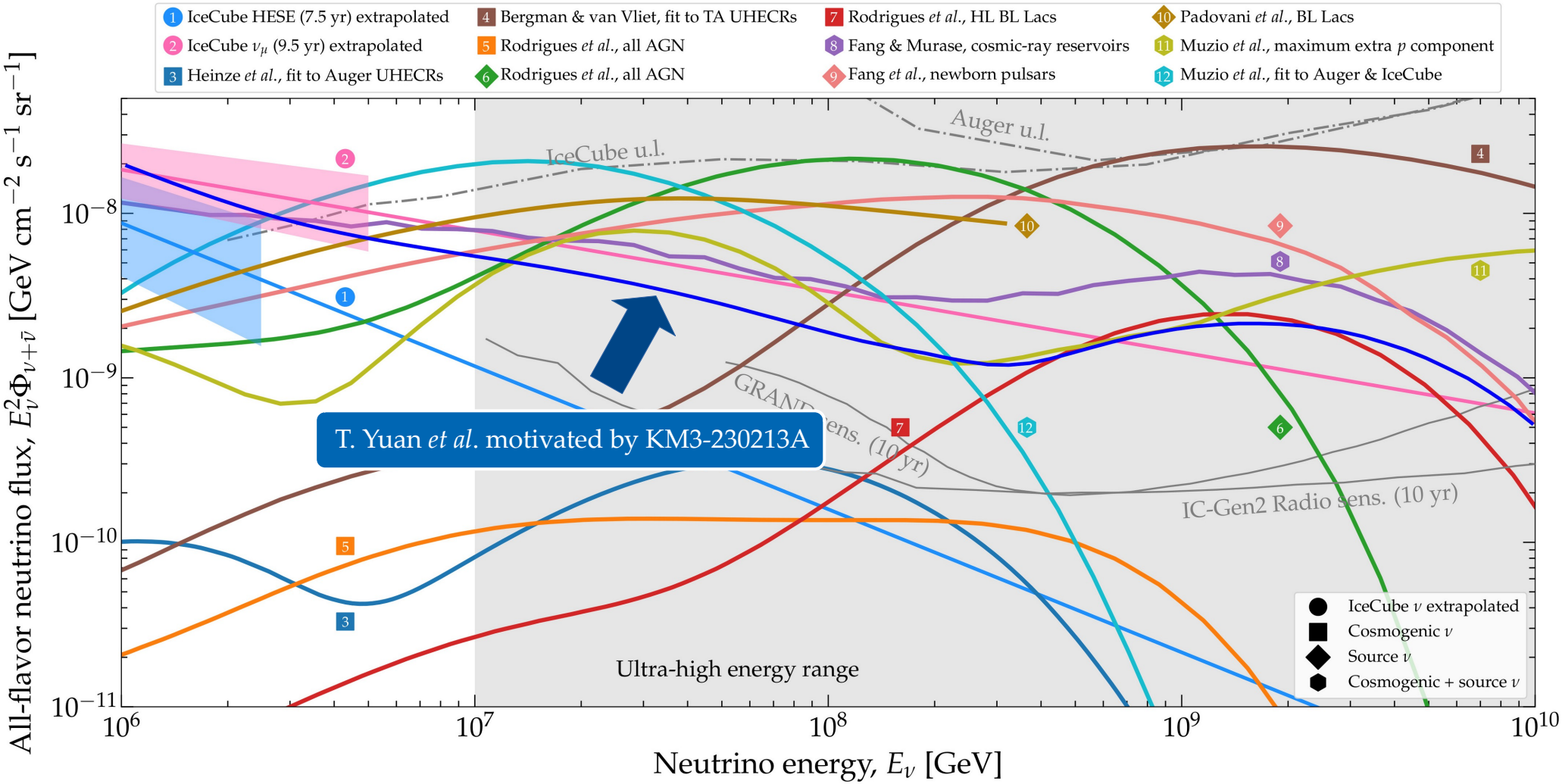

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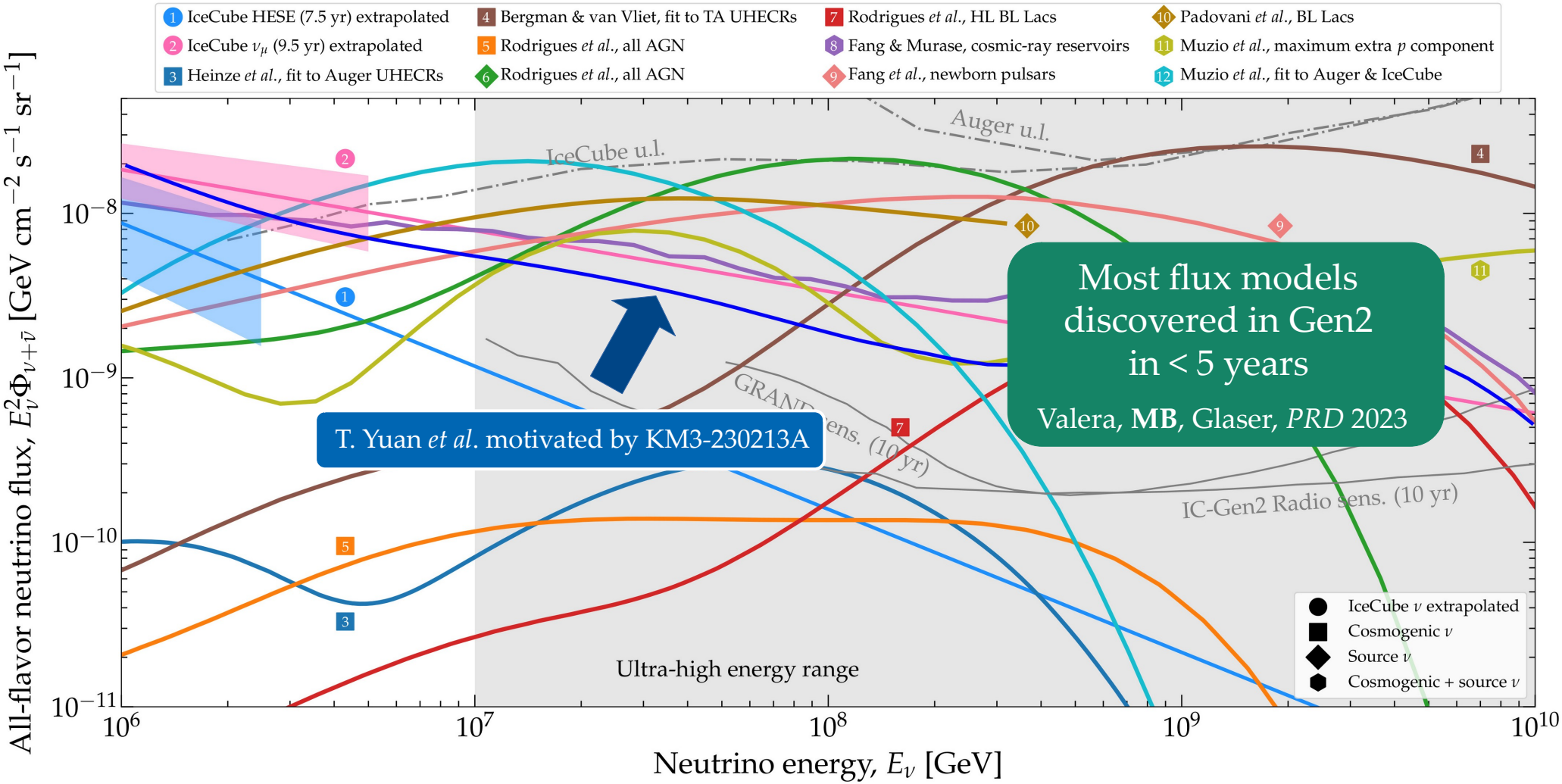


Most flux models discovered in Gen2 in < 5 years

Valera, **MB**, Glaser, *PRD* 2023

T. Yuan *et al.* motivated by KM3-230213A

V. Valera, **MB**, C. Glaser, *PRD* 2023 [2210.03756]

Where did it come from?

From the Southern Hemisphere
(RA = 94.3°, dec = -7.8°)

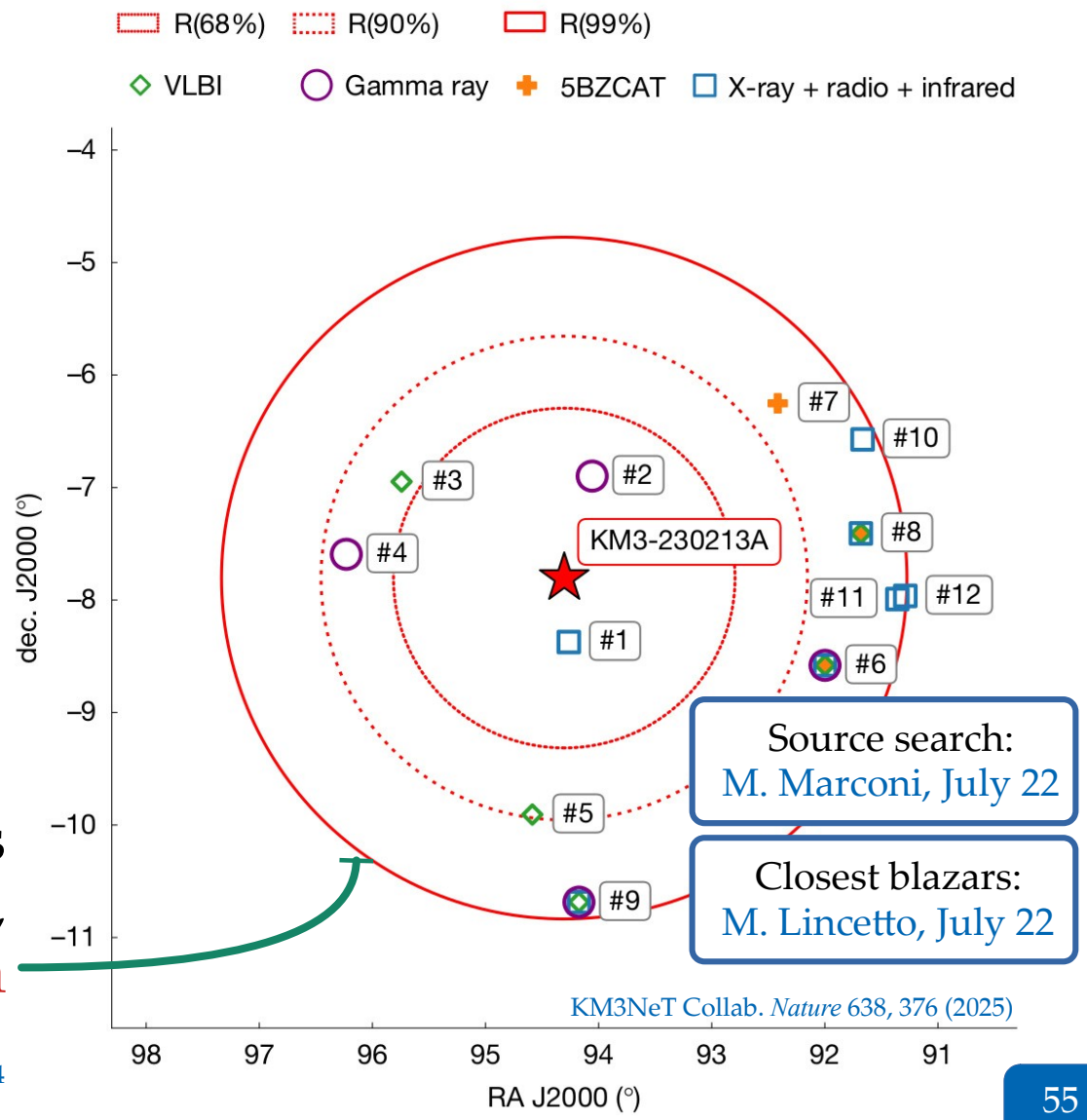
Not far from Milky Way plane
But likely not of Milky-Way origin

KM3NeT Collab. arXiv:2502.08387

Likely extragalactic origin

Few extragalactic sources (blazars) near event position, but no strong association

KM3NeT Collab. arXiv:2502.08484



Source search:
M. Marconi, July 22

Closest blazars:
M. Lincetto, July 22

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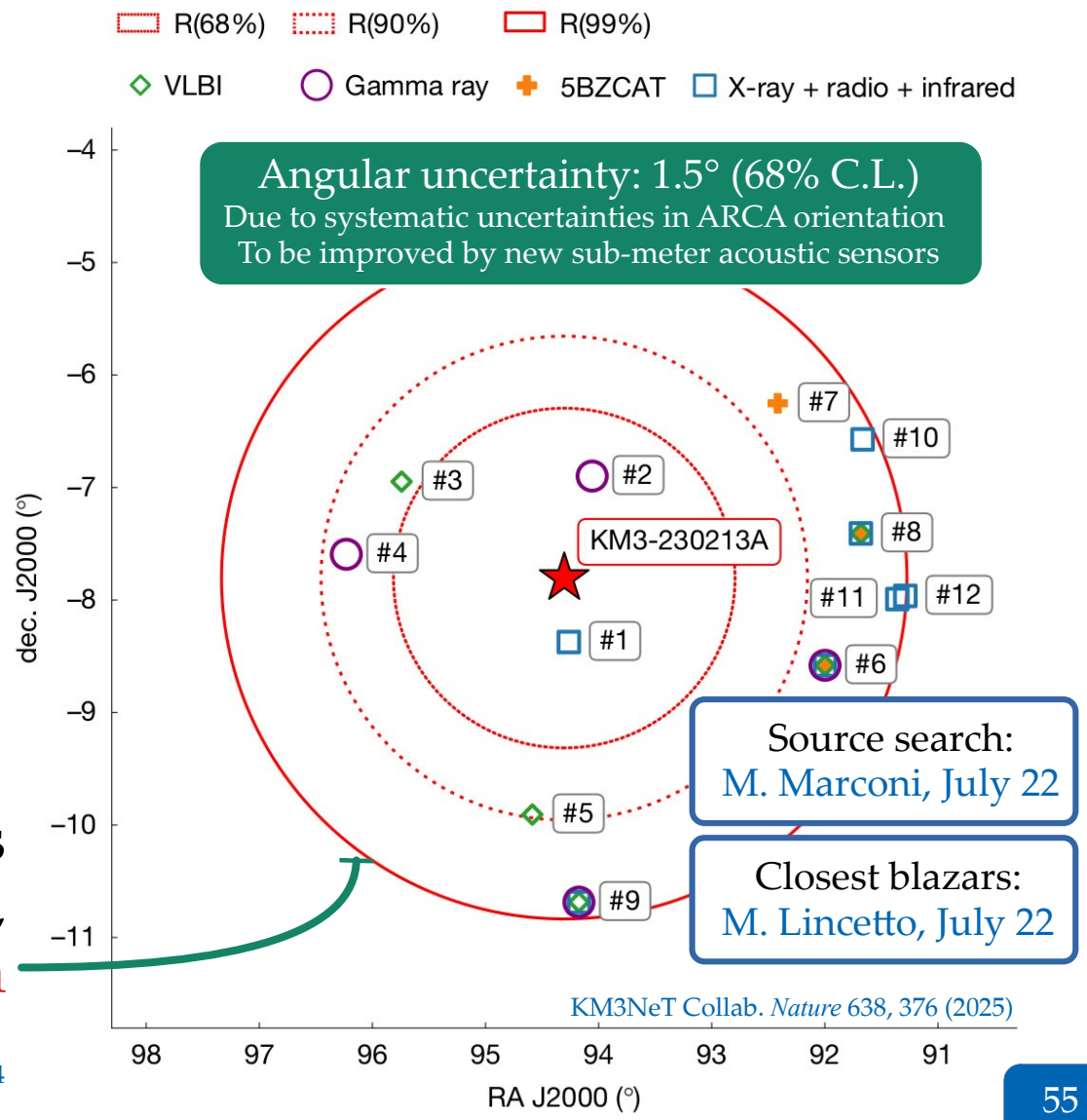
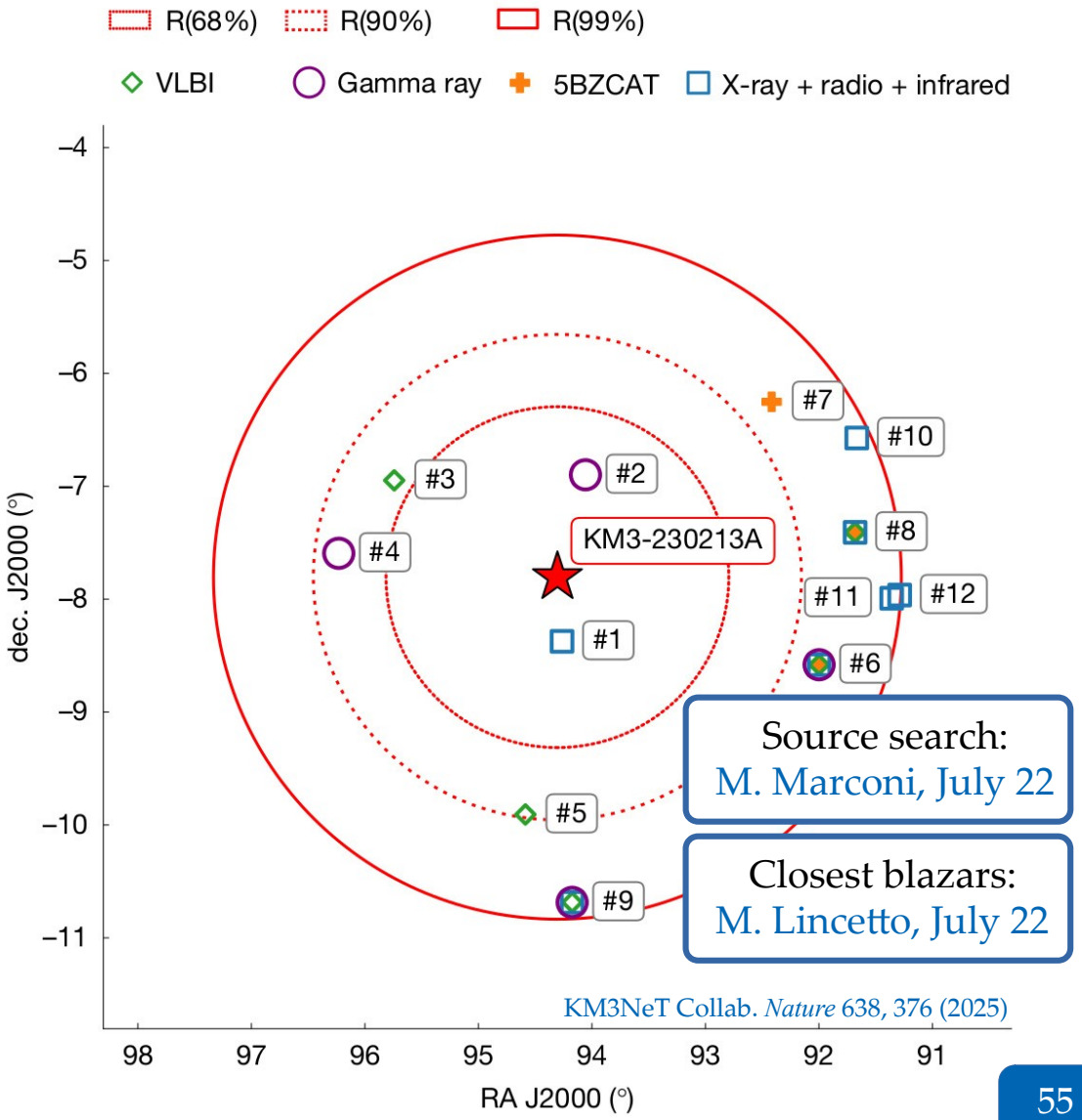


Where did it come from?

Compatible w/ diffuse blazar population
M. Bendahman, July 22

Used to constrain ν flux from GRBs
P. A. S. Myhr, July 21

Could be a year-long transient source
Li, Machado, Naredo-Tuero, Schwemberger, arXiv:2502.04508
Neronov, Oikonomou, Semikoz, arXiv:2502.12986



Source search:
M. Marconi, July 22

Closest blazars:
M. Lincetto, July 22

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

Beyond the Standard Model

New energies represent new opportunities to look for BSM physics, *e.g.*,

UHE ν from decay of super-heavy dark matter
UHE ν from primordial black holes
Sterile-active ν transitions
Lorentz-invariance violation

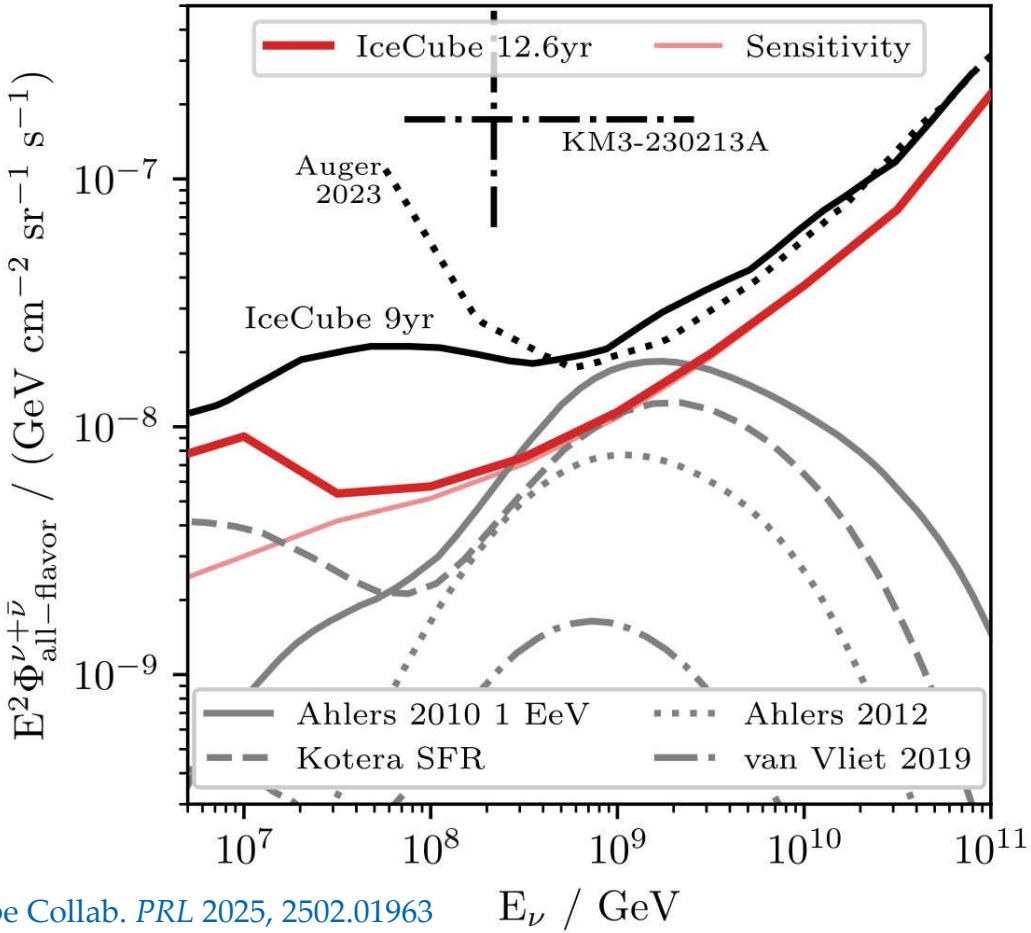
Caveat emptor!
Being able to explain KM3-230213A with BSM physics ***does not*** mean that a BSM explanation is preferred (always compute your Bayes factors!)

See backup slides for BSM proposals inspired by KM3-230213A

New upper limits on UHE neutrinos: **IceCube**

New limit:
M. Meier, July 17

Search for UHE ν updated from 9 to 12.6 yr



Strongest UHE limit today

Improvement due to 40% higher ν_μ A_{eff}:
- Improved angular resolution
- Looser muon bundle cuts

Repeating the joint fit of the UHE KM3-230213A with IceCube and Auger increases the tension from 2.5σ to 2.9σ

Also: new limits on UHECR proton fraction

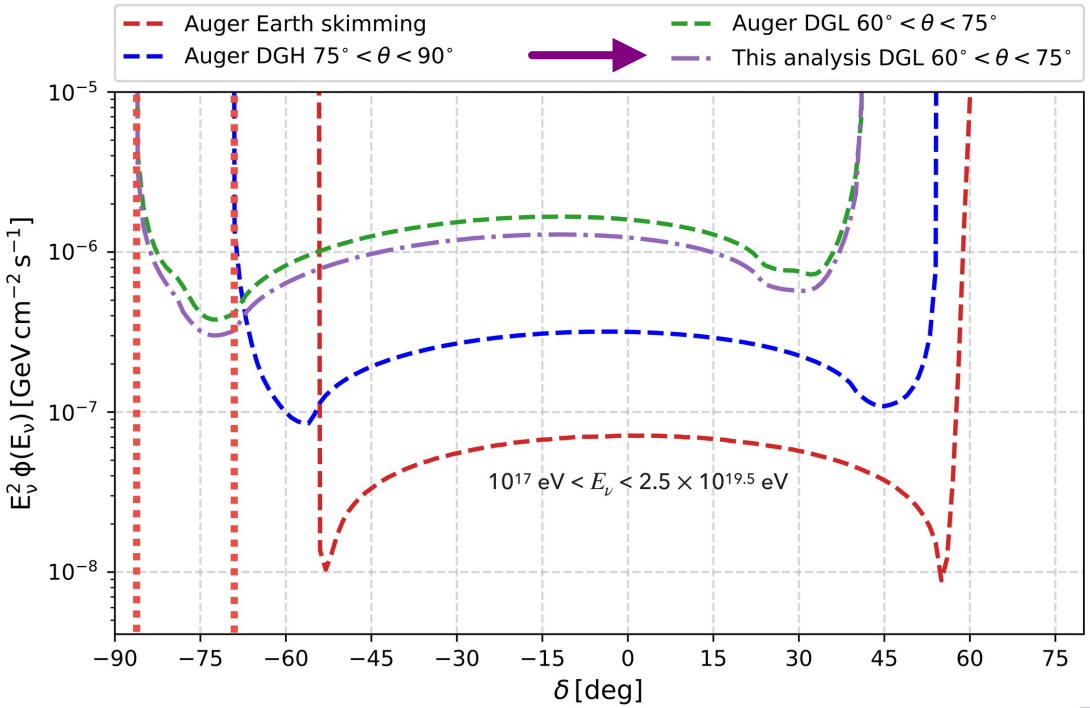
IceCube Collab. *PRL* 2025, 2502.01963

New upper limits on UHE neutrinos: **Auger** and **TA**

Auger surface detectors 7 yr

Search for downgoing low (DGL) showers: 60° < θ < 75°

Improvement in triggers

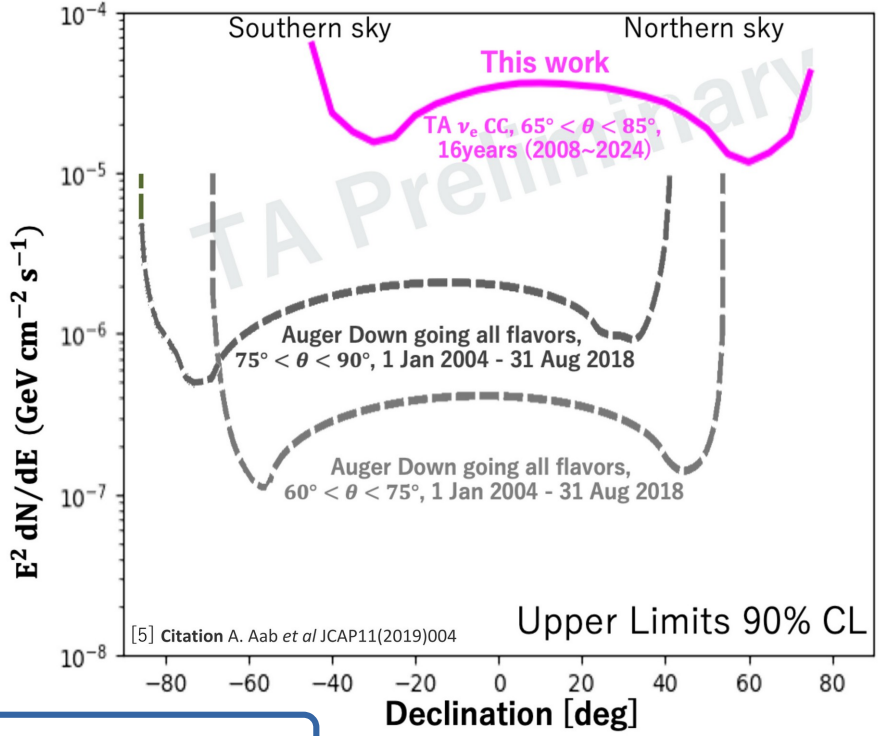


Auger limit:
S. Sehgal, July 17

TA surface detectors 16 yr

Search for showers with 65° < θ < 85°

Improvement in reconstruction method



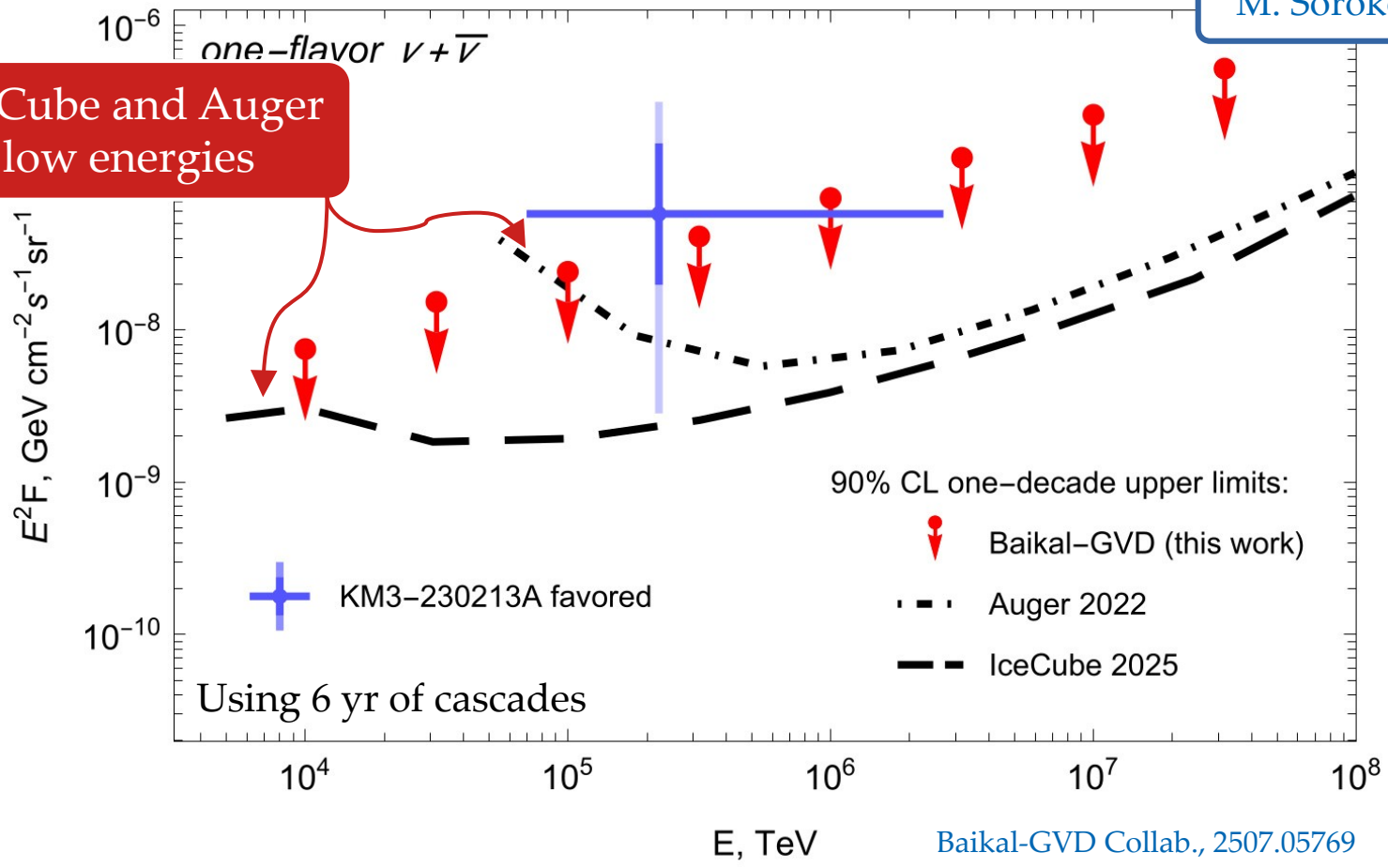
TA limit:
K. Takahashi July 21

New upper limits on UHE neutrinos: **Baikal-GVD**

First UHE ν flux limit placed by Baikal-GVD

New limit:
M. Sorokovikov, July 17

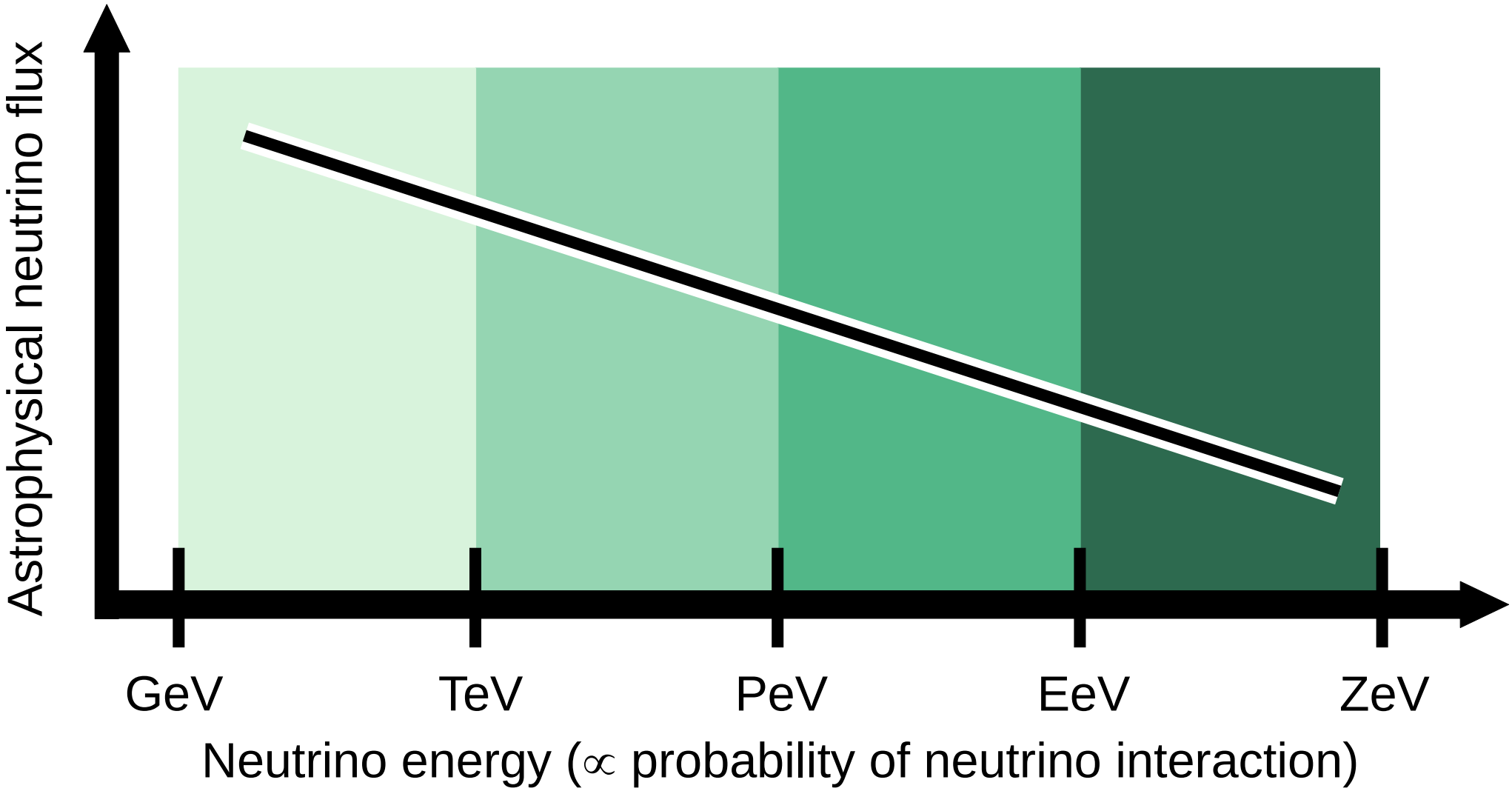
Matches IceCube and Auger limits at low energies

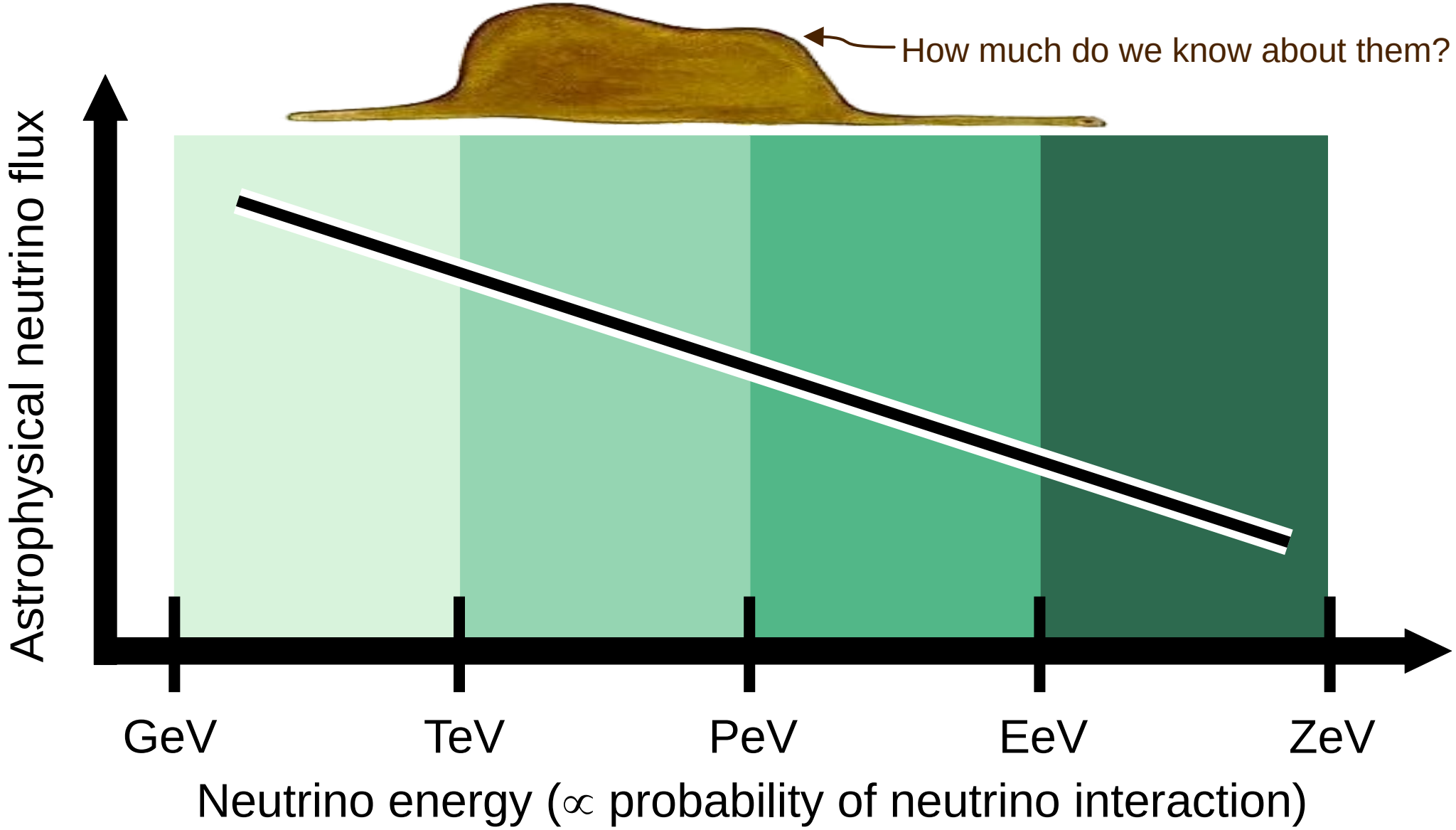


Baikal-GVD Collab., 2507.05769

Five

The shape of things to come


Astrophysical neutrino flux
GeV
TeV
PeV
EeV
ZeV
Neutrino energy (∝ probability of neutrino interaction)


How much do we know about them?
Astrophysical neutrino flux
GeV
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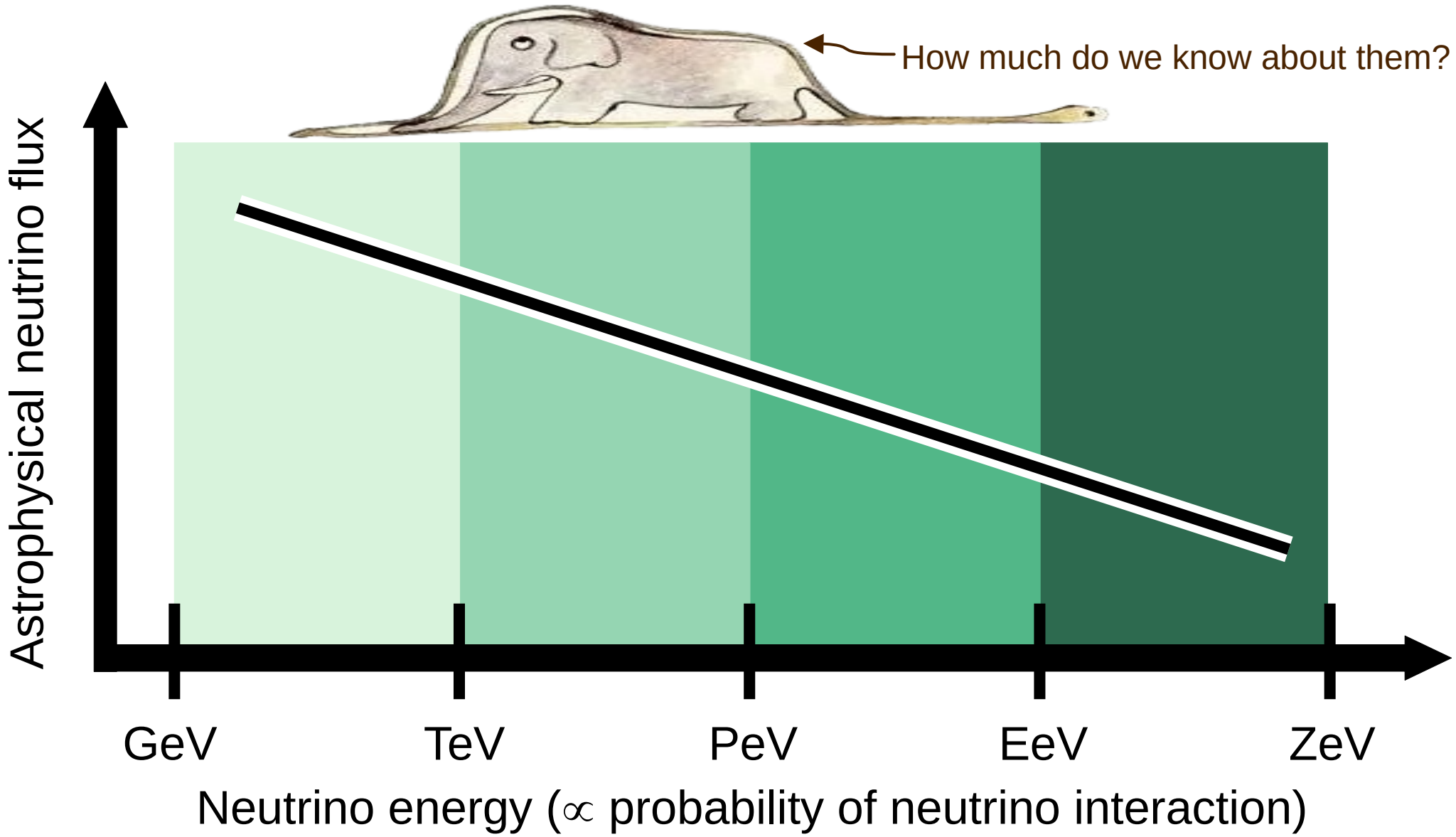
Neutrino energy (∝ probability of neutrino interaction)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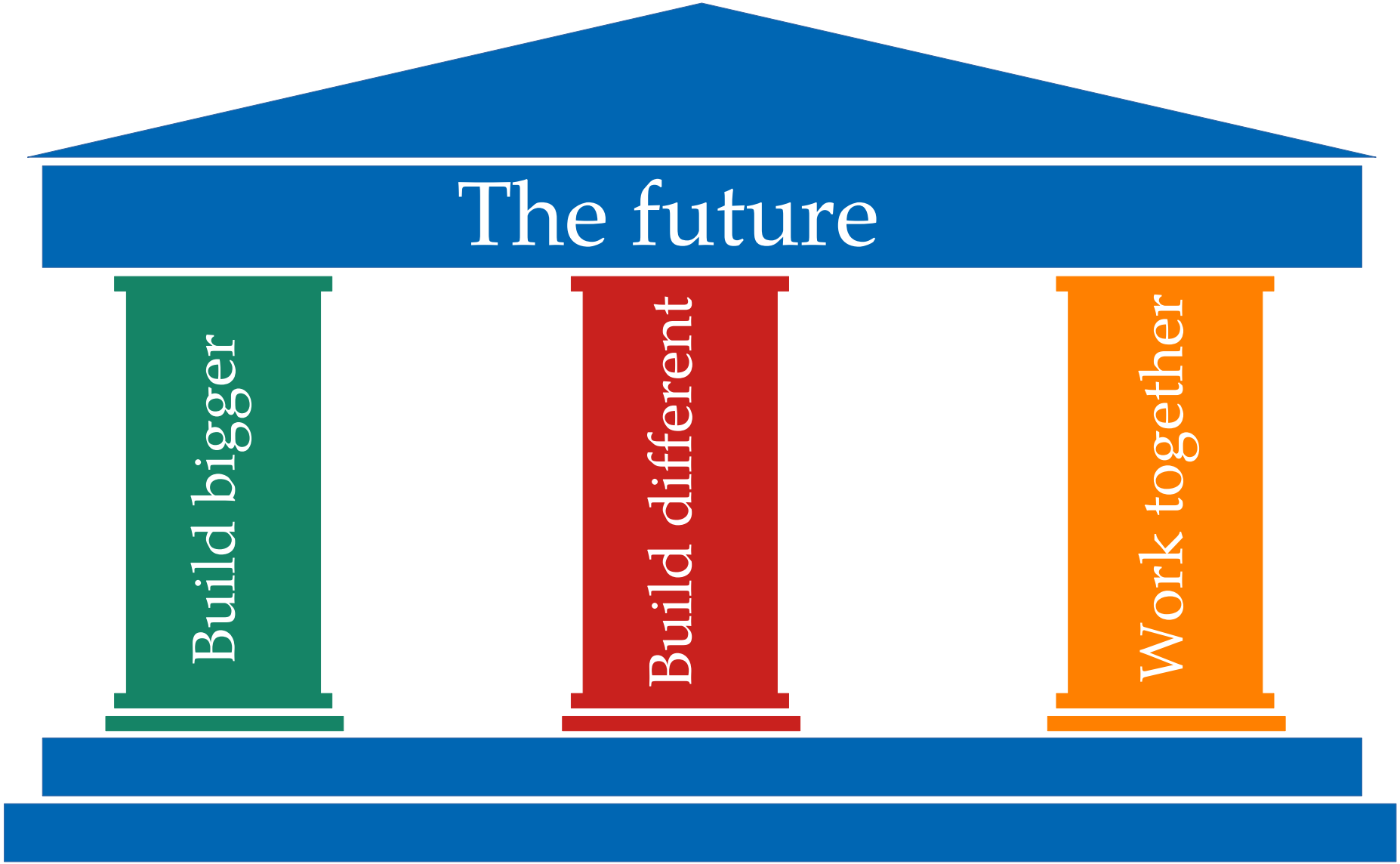
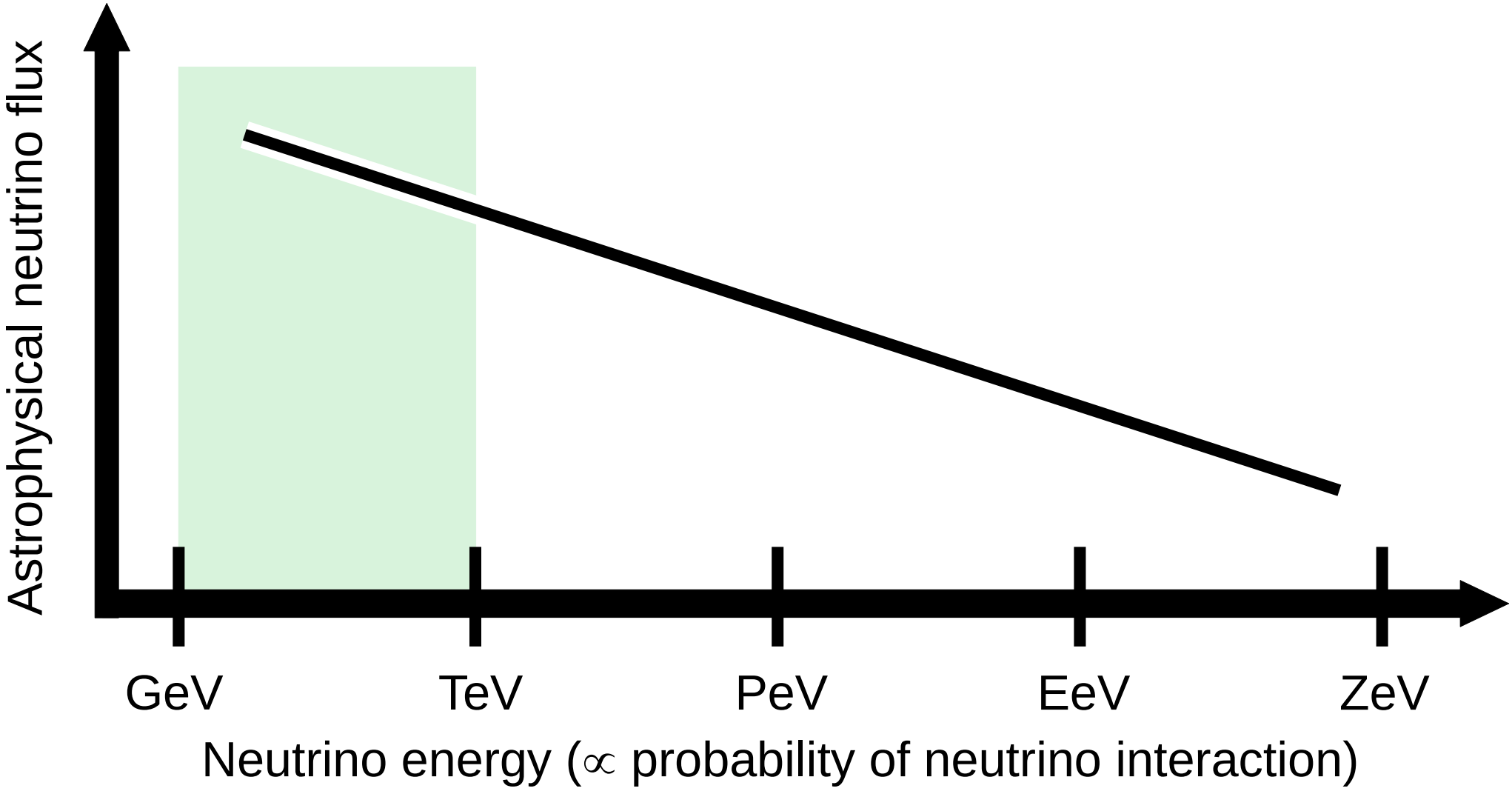

The future
Build bigger
Build different
Work together


Astrophysical neutrino flux
GeV
TeV
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Neutrino energy (∝ probability of neutrino interaction)

IceCube Upgrade

IceCube highlight:
A. Kappes, July 22

Seven new strings

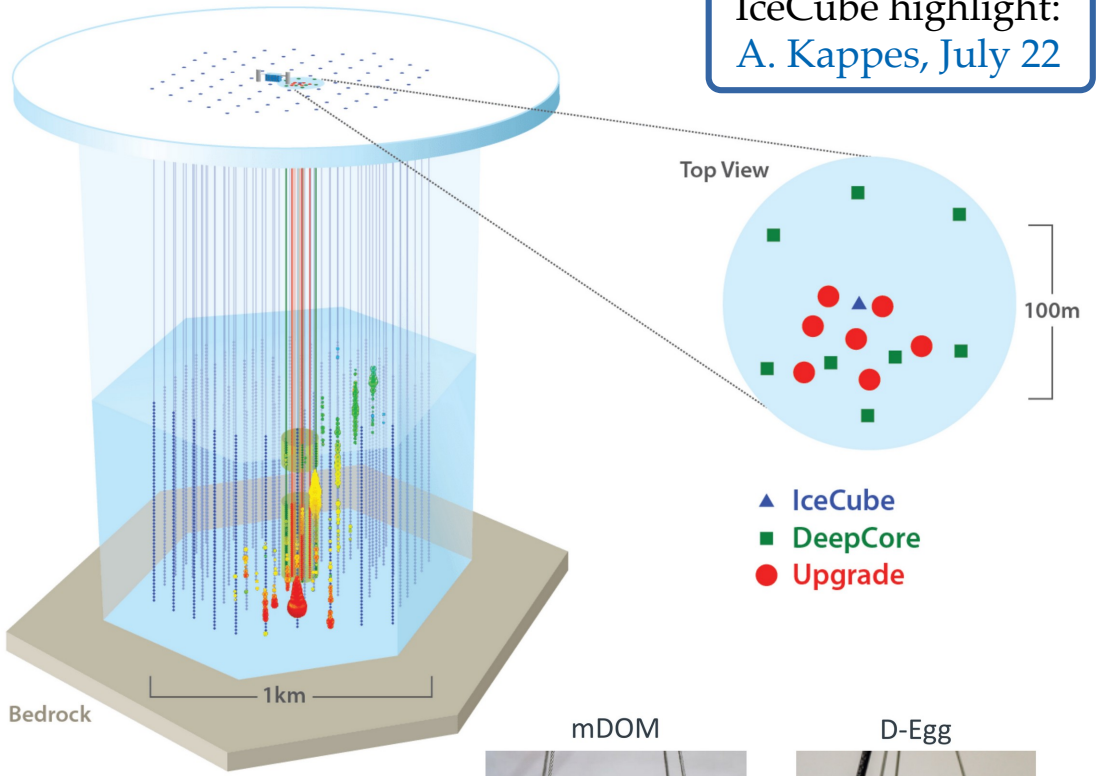
Enhance sensitivity to $O(10\ \mathrm{GeV})\ \upsilon$

Deployment in austral summer 2025/26

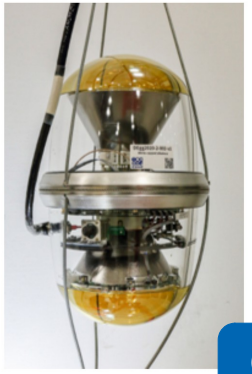
Major goal: improve calibration in the whole detector (ice properties)

Multiple calibration devices to be installed

But also science!



New, multi-PMT digital optical modules



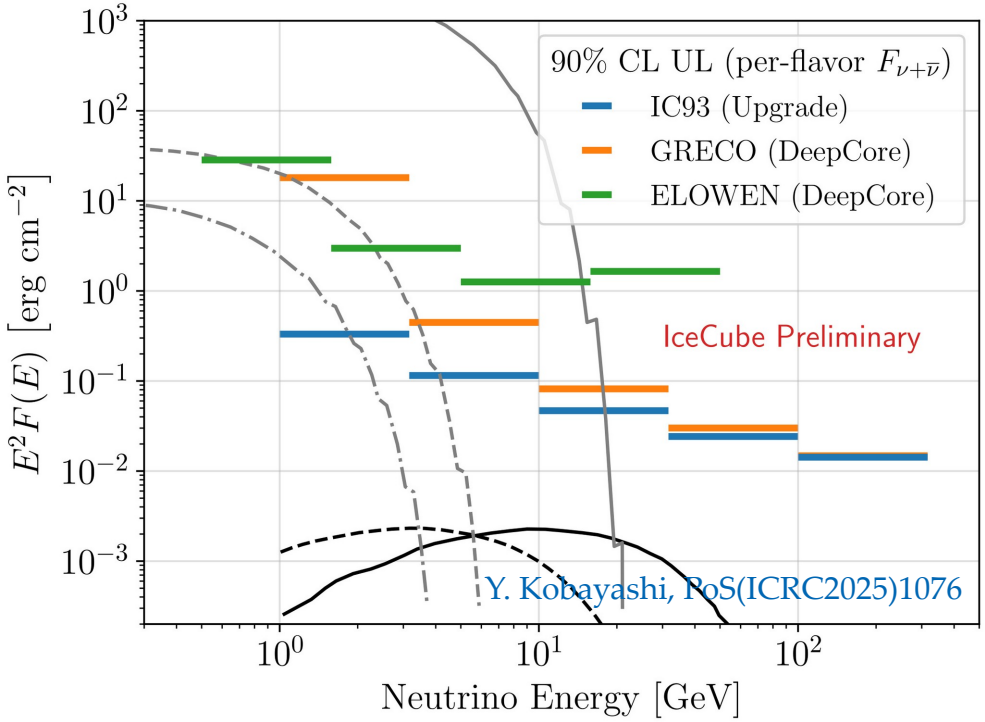
IceCube Collaboration

S. Partenheimer+ 78 | M. Vereecken+ 108 | J. Braun+ 448 | K. Dutta+ 1029 | A. Eimer+ 1034 | N. Chau+ 1037 | S. Fukami 1040 | S. Griffin+ 1044 | C. Rott+ 1069 | Y. Kobayashi 1076

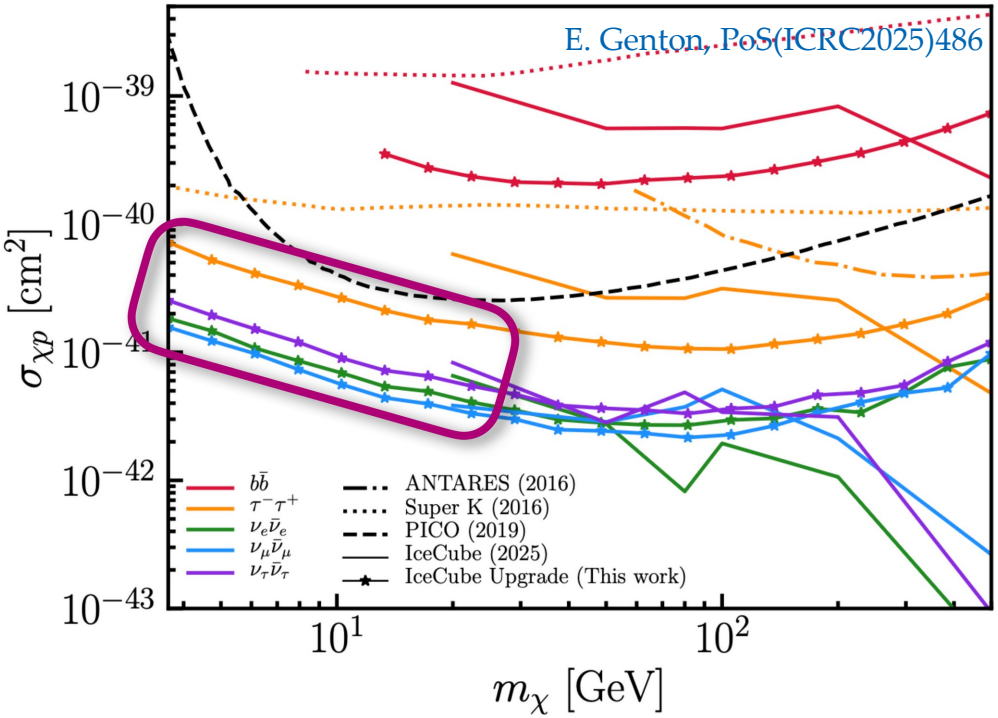
IceCube Upgrade

IceCube highlight:
A. Kappes, July 22

Sensitivity to GeV υ transients



WIMP DM annihilation in the Sun



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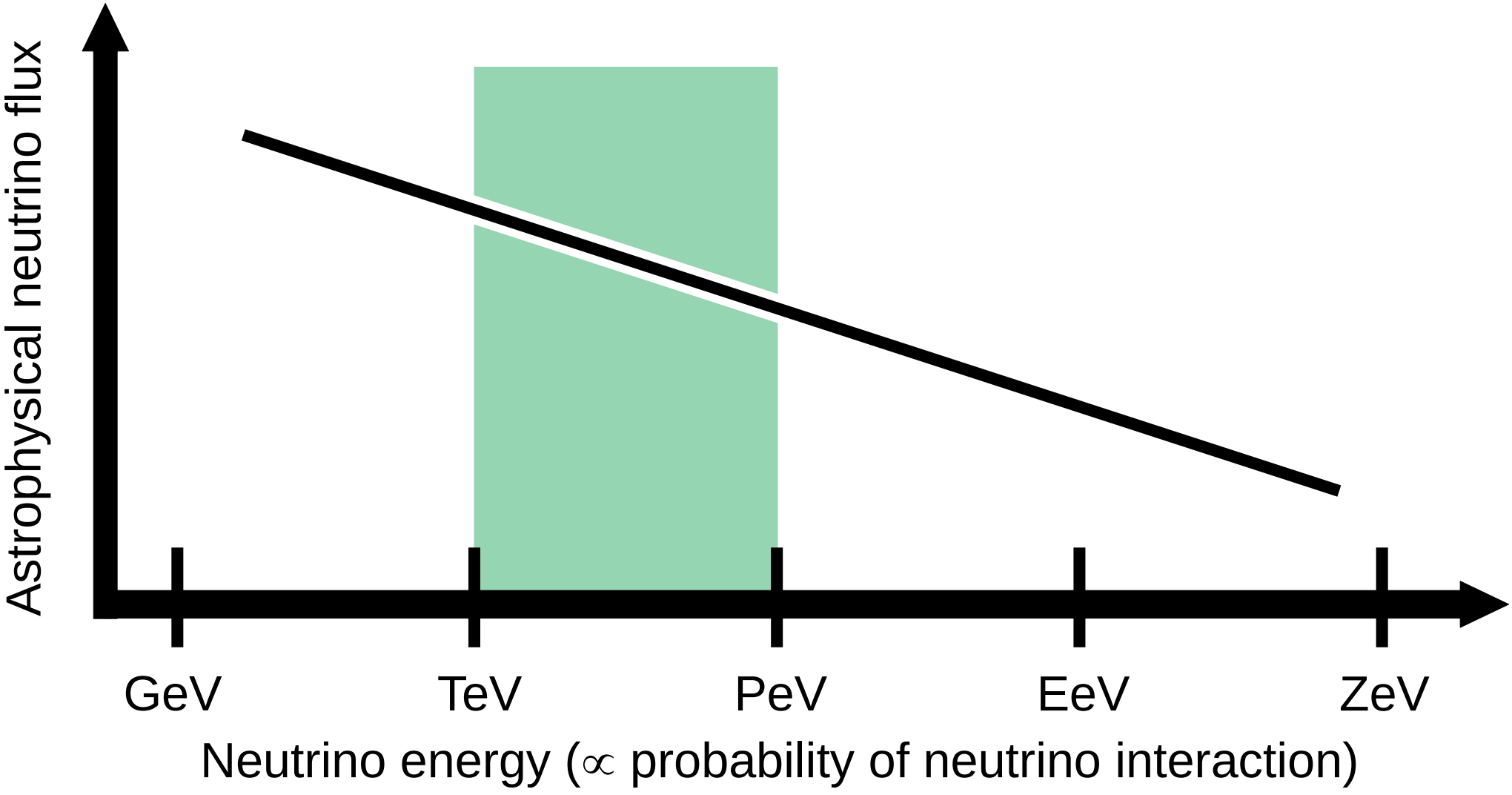
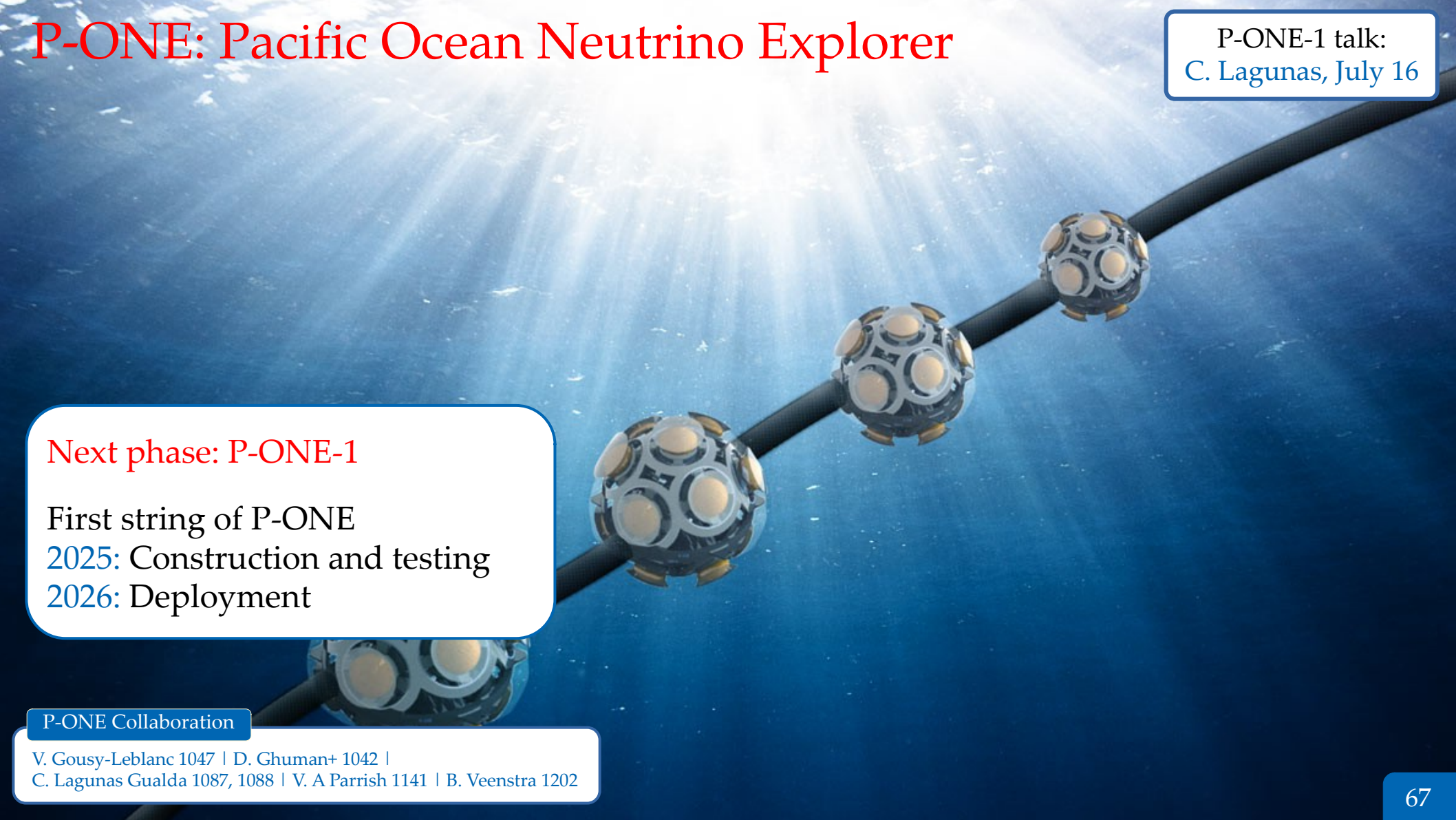

Astrophysical neutrino flux
GeV
TeV
PeV
EeV
ZeV
Neutrino energy (∝ probability of neutrino interaction)

P-ONE: Pacific Ocean Neutrino Explorer

P-ONE-1 talk:
C. Lagunas, July 16



Next phase: P-ONE-1

First string of P-ONE
2025: Construction and testing
2026: Deployment

P-ONE Collaboration

V. Gousy-Leblanc 1047 | D. Ghuman+ 1042 |
C. Lagunas Gualda 1087, 1088 | V. A Parrish 1141 | B. Veenstra 1202

P-ONE: Pacific Ocean Neutrino Explorer

P-ONE-1 talk:
C. Lagunas, July 16

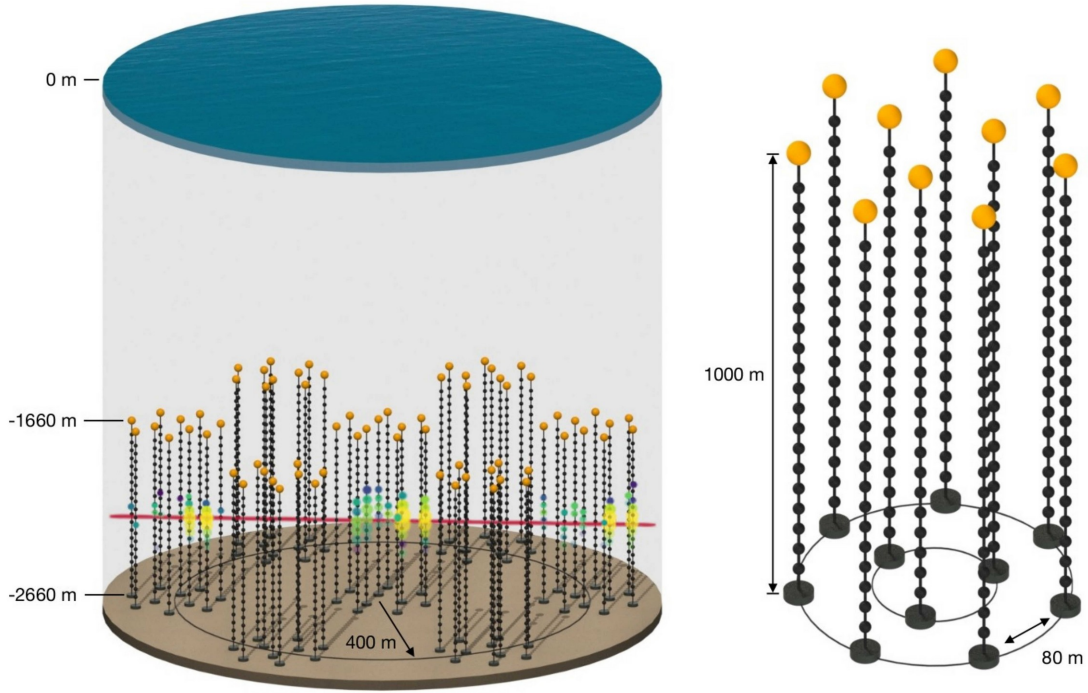
Cascadia Basin, Canada

Two pathfinder arrays
STRAW (2018) + STRAW-b (2020)
Measure water properties

Next phase: P-ONE-1

First string of P-ONE
2025: Construction and testing
2026: Deployment

Effective volume: > 1 km^3
70 strings, 1400 optical modules



P-ONE Collaboration

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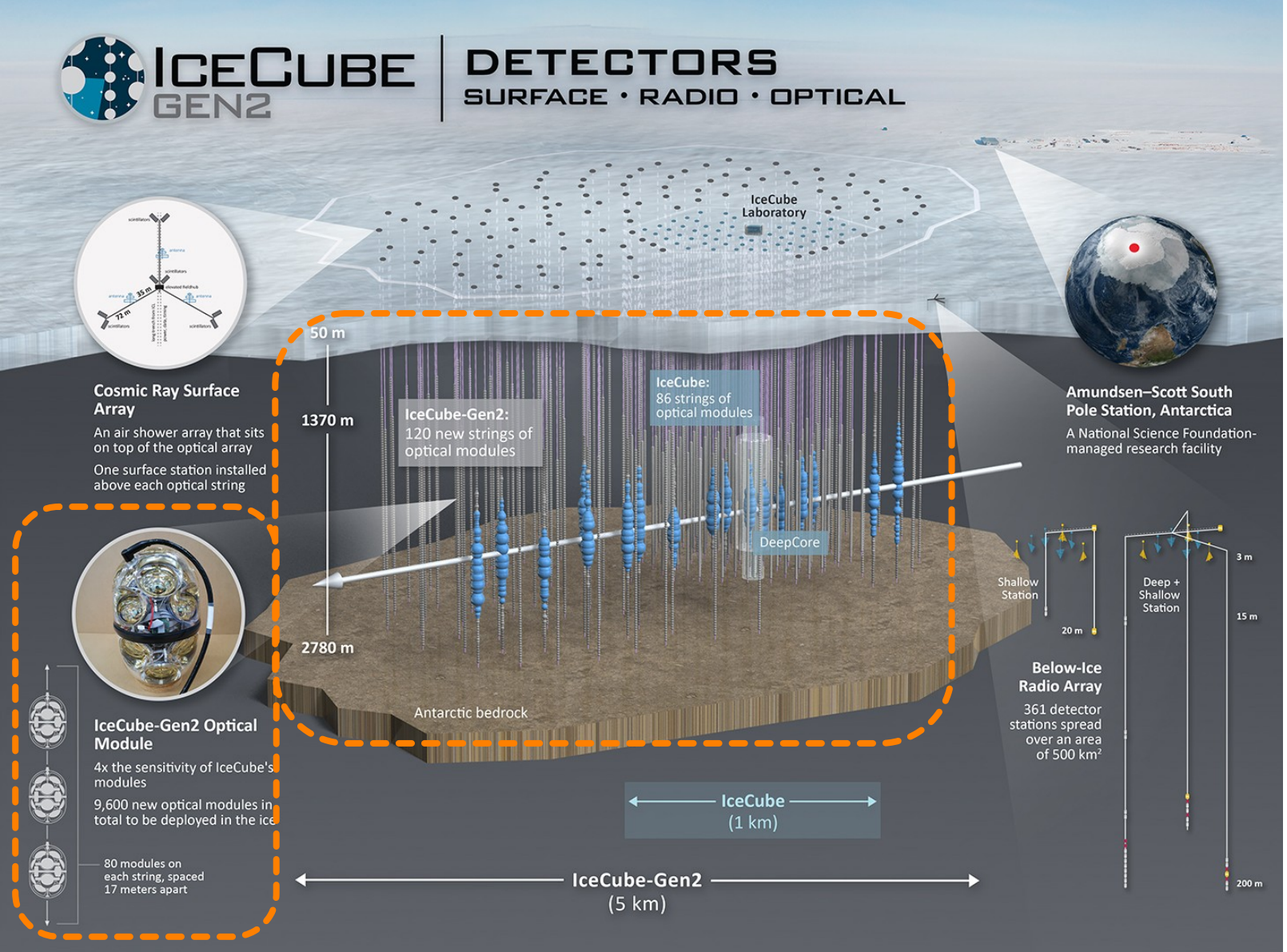


High-energy IceCube successor

Optical array:
TeV–PeV ν
~8 km³ (8× IceCube)
206 strings
9.6k new DOMs

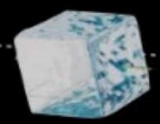
~10× rate of PeV ν *vs.* IceCube

IceCube-Gen2 overview:
M. Kowalski, July 21

IceCube-Gen2 Collaboration
List of contributions: 2507.08667

IceCube-Gen2

IceCube

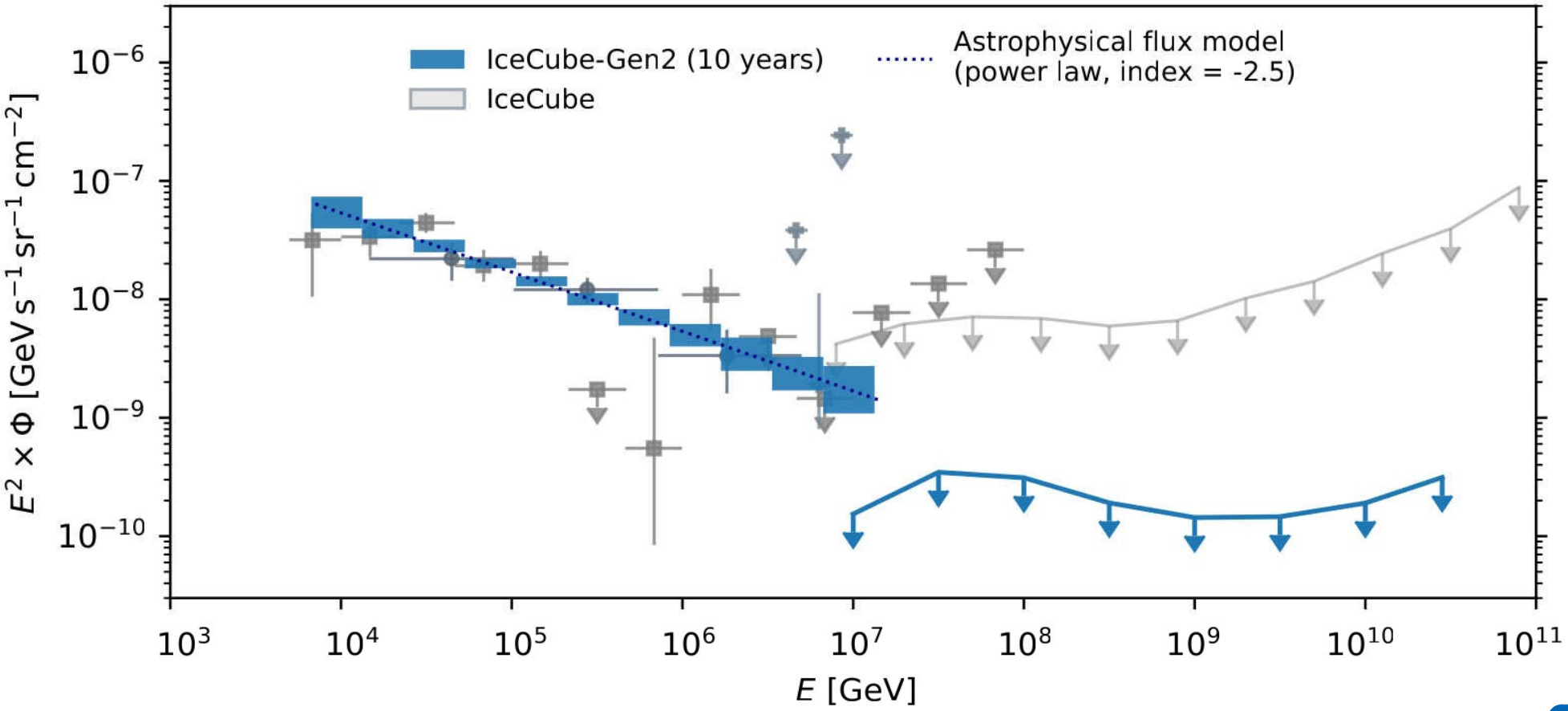


IceCube - 1 km^3
Energy > 10^{11} eV

Optical - 8 km^3
Energy > 10^{12} eV

IceCube-Gen2

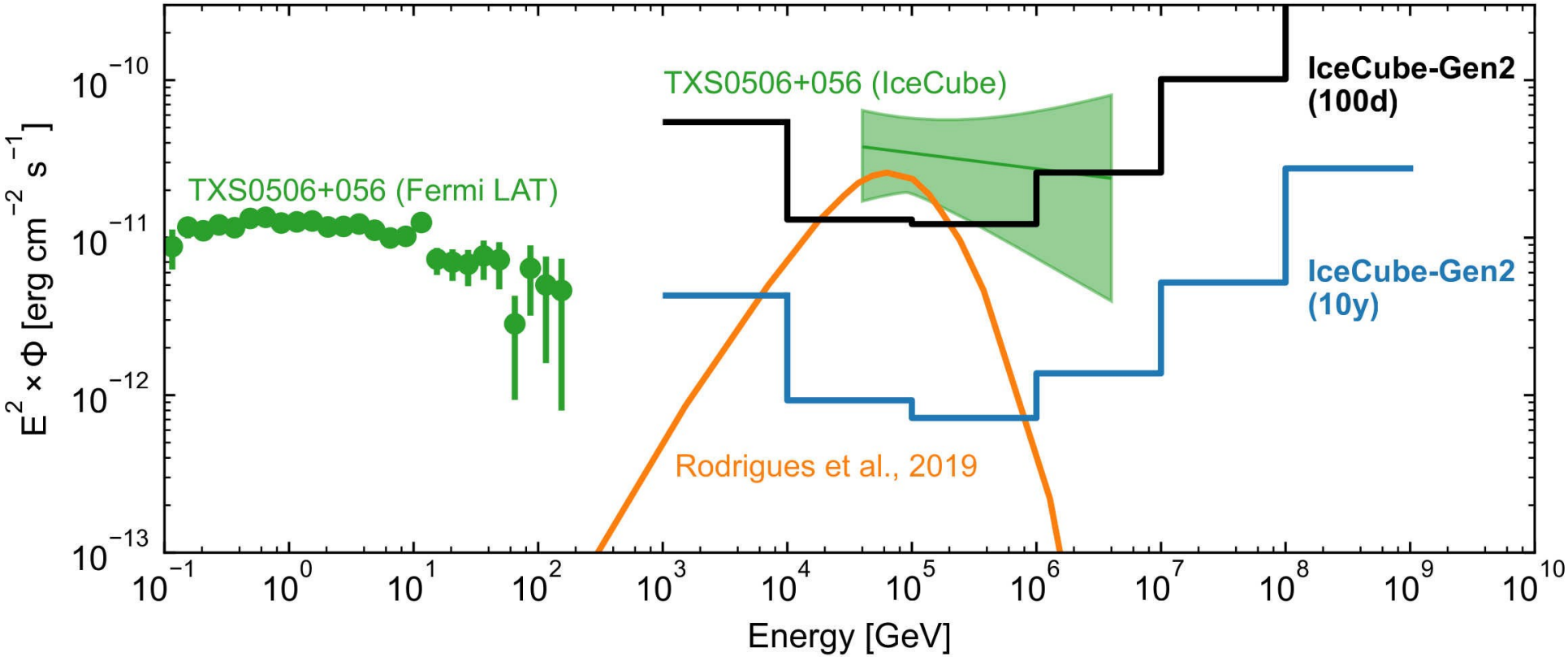
Precise measurement of the TeV–PeV diffuse ν flux



IceCube-Gen2 Collab., Technical Design Report Part I

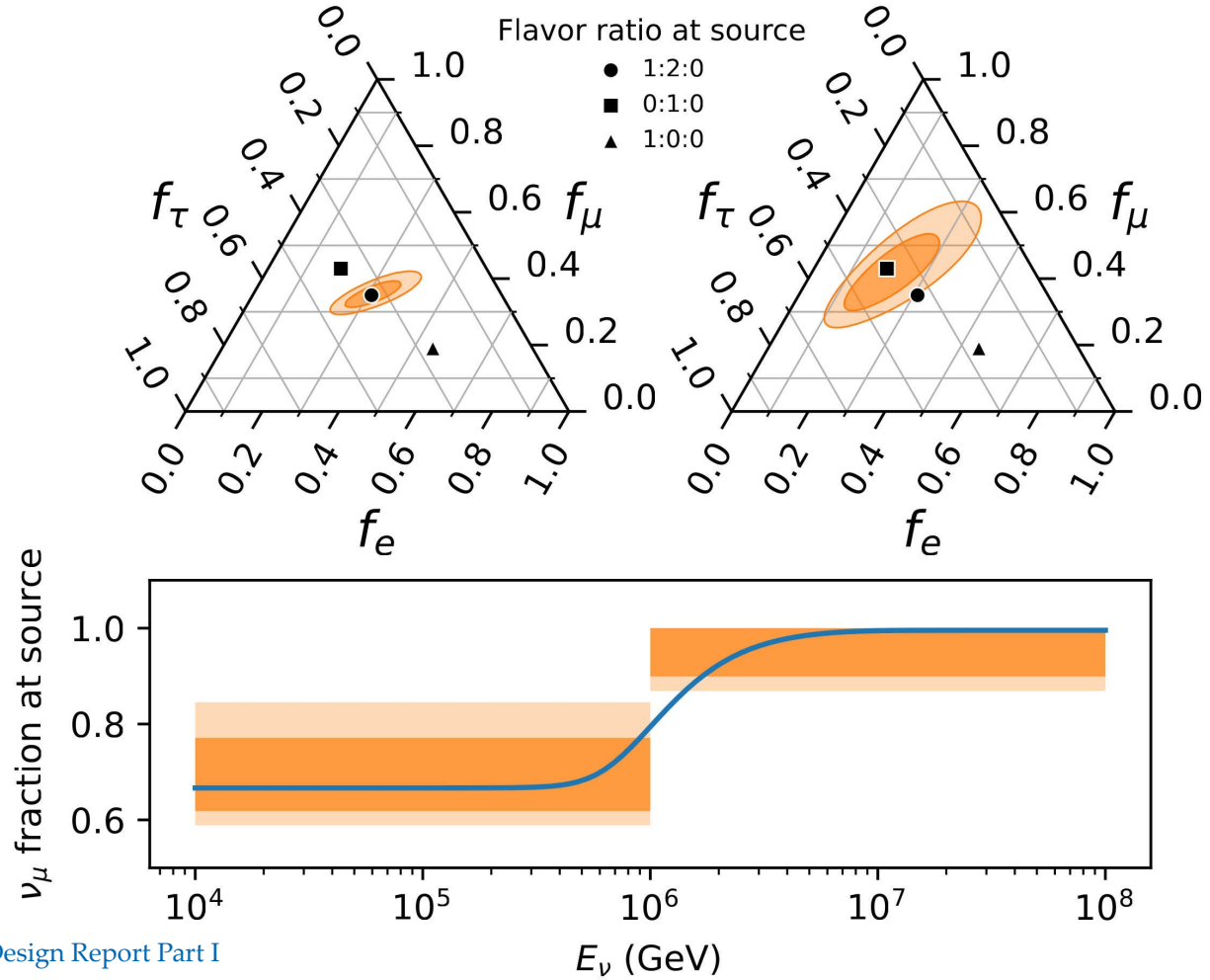
IceCube-Gen2

Discovery of TeV–PeV ν transients (*à la* TXS 0506+056)



IceCube-Gen2

Source and particle-physics tests via neutrino flavor



IceCube-Gen2 Collab., Technical Design Report Part I

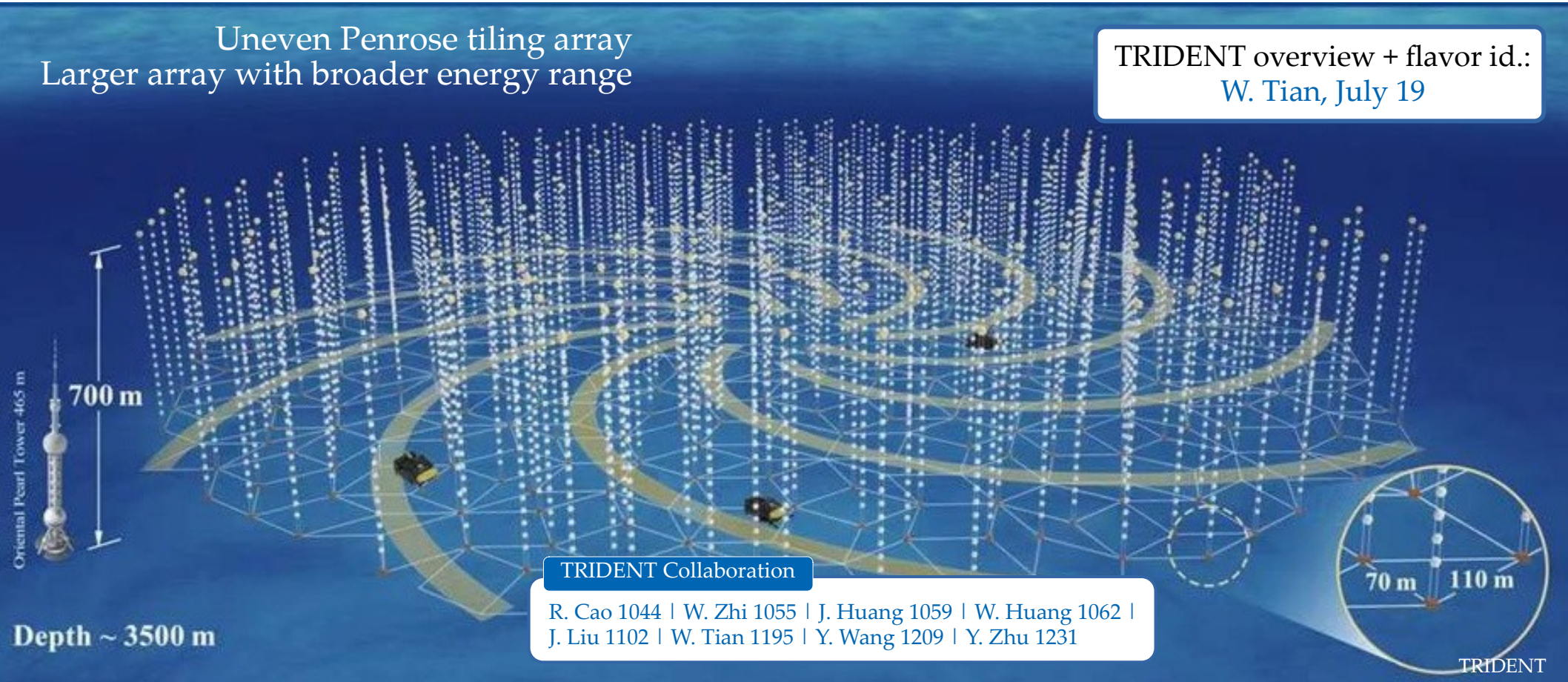
TRIDENT: The tRopIcal Deep sea Neutrino Telescope

South China Sea • Effective volume: 8 km^3 • 1000 strings, 20,000 optical modules

Sensitivity to TeV–EeV υ

Uneven Penrose tiling array
Larger array with broader energy range

TRIDENT overview + flavor id.:
W. Tian, July 19



TRIDENT Collaboration

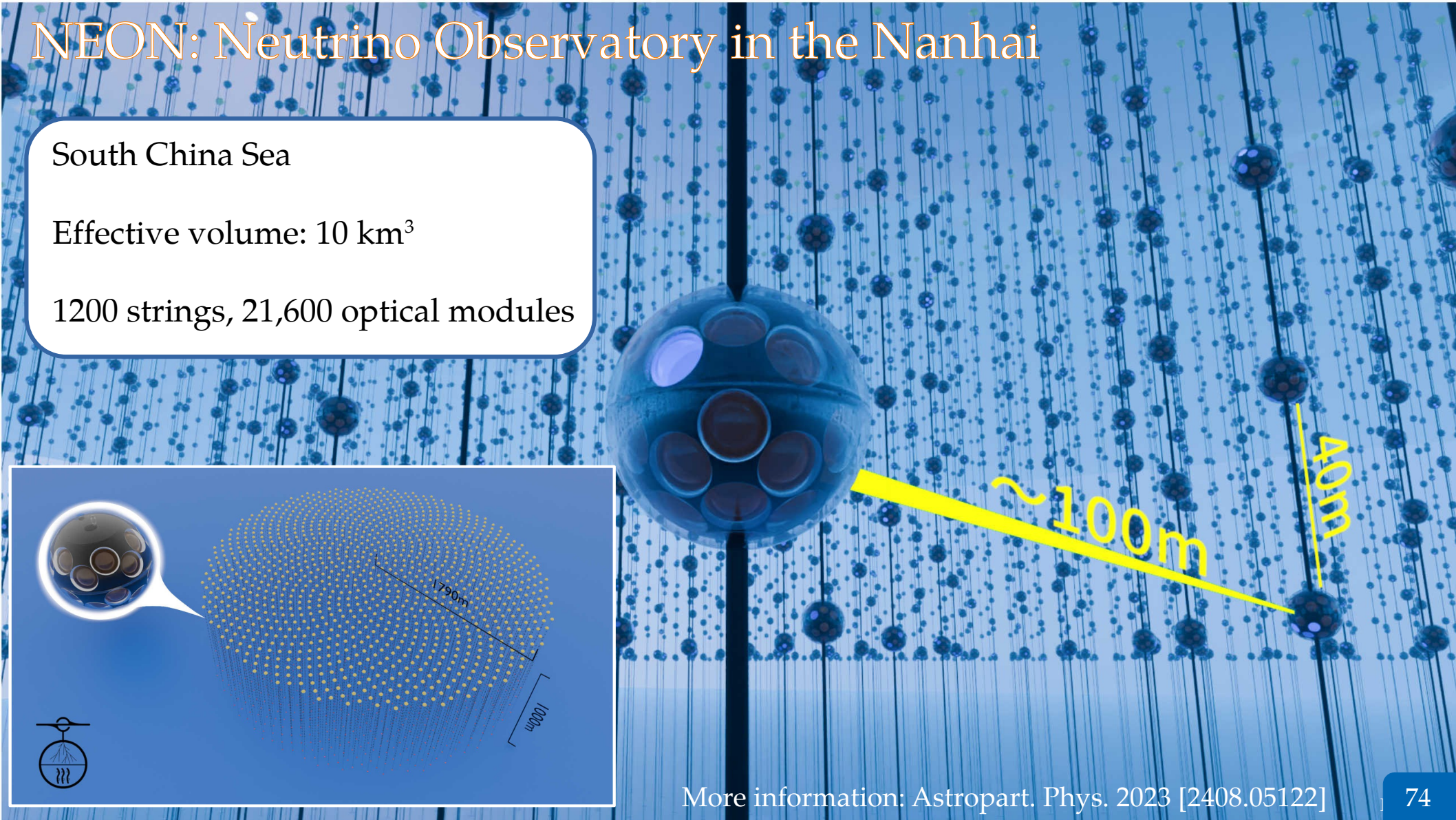
R. Cao 1044 | W. Zhi 1055 | J. Huang 1059 | W. Huang 1062 | J. Liu 1102 | W. Tian 1195 | Y. Wang 1209 | Y. Zhu 1231

NEON: Neutrino Observatory in the Nanhai

South China Sea

Effective volume: 10 km^3

1200 strings, 21,600 optical modules



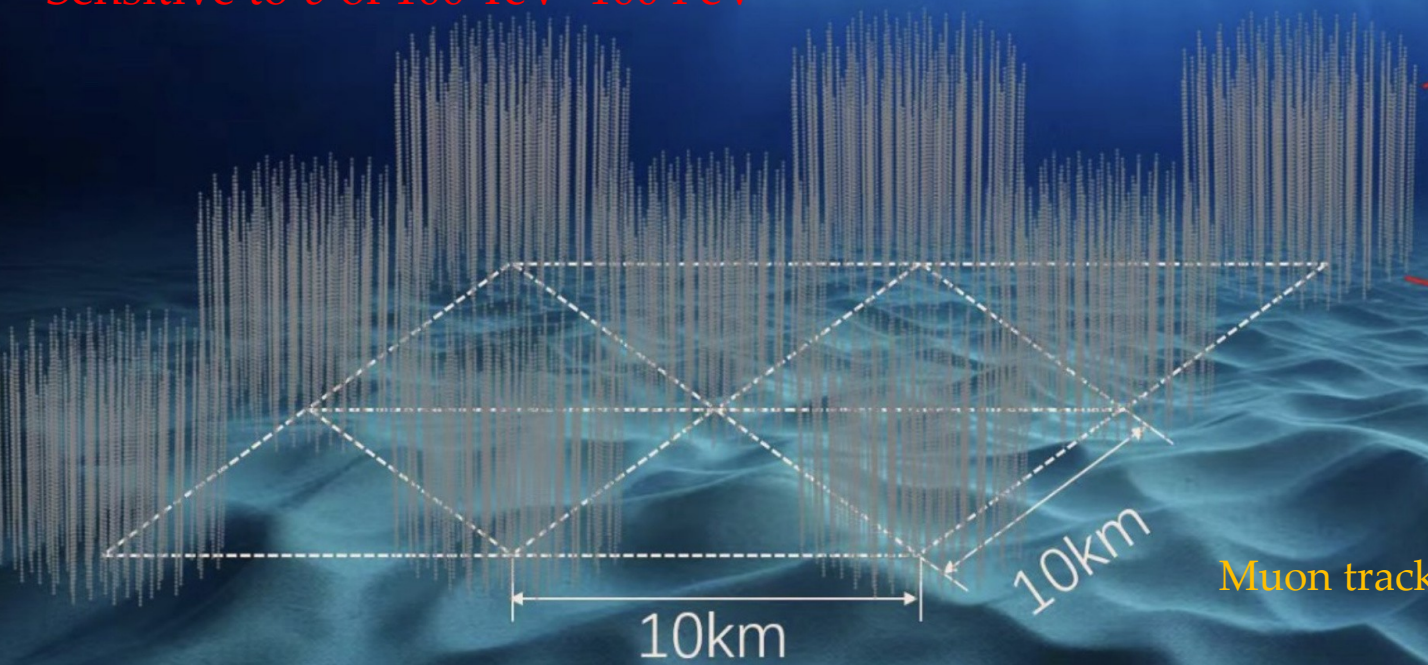
More information: Astropart. Phys. 2023 [2408.05122]

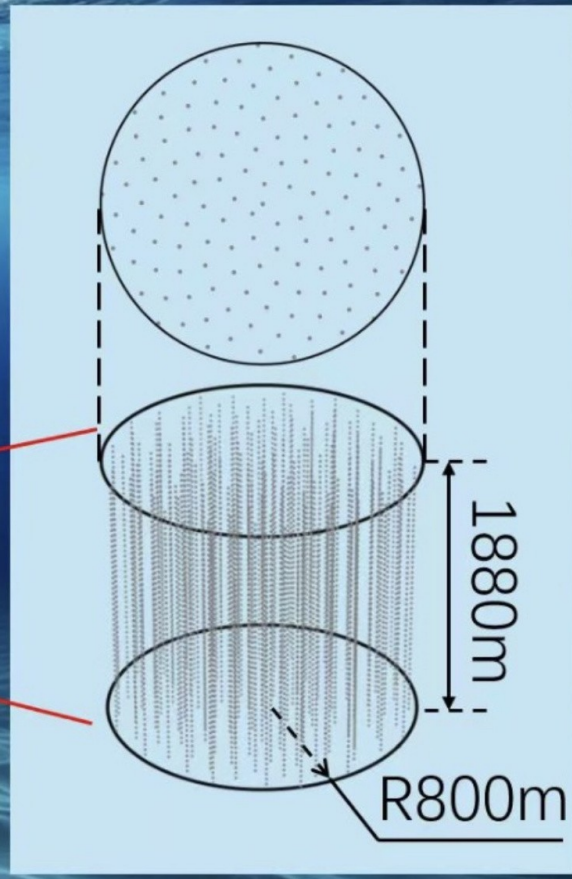
High-Energy Underwater Neutrino Telescope

HUNT Collaboration
T. Q. Huang 1061 | Z. K Zeng+ 1126 | C. Liu

South China Sea
Effective volume: 30 km^3
2304 strings, 55,296 optical modules
Sensitive to υ of 100 TeV–100 PeV

HUNT overview:
T. Q. Huang, July 21





9 clusters of 128 strings each

Muon track angular resolution as good as 0.05°
(for tracks of 6 km in length)

High-Energy Underwater Neutrino Telescope

HUNT Collaboration
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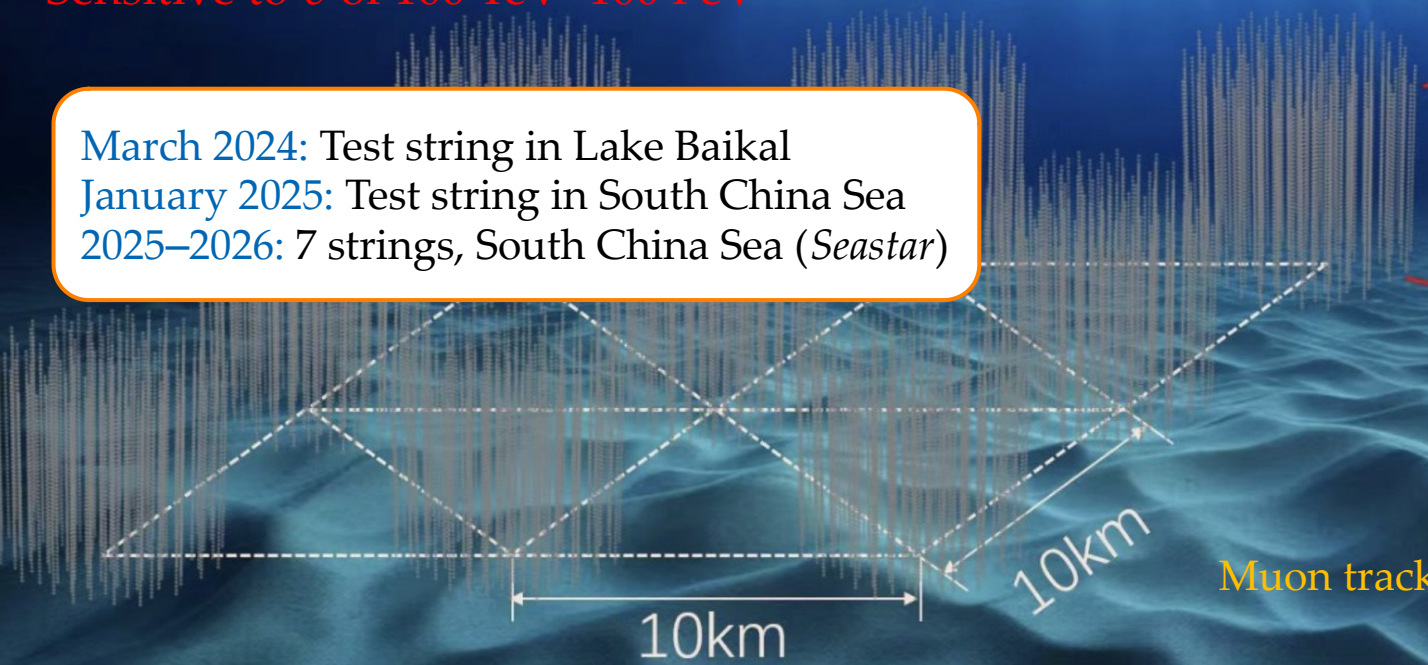
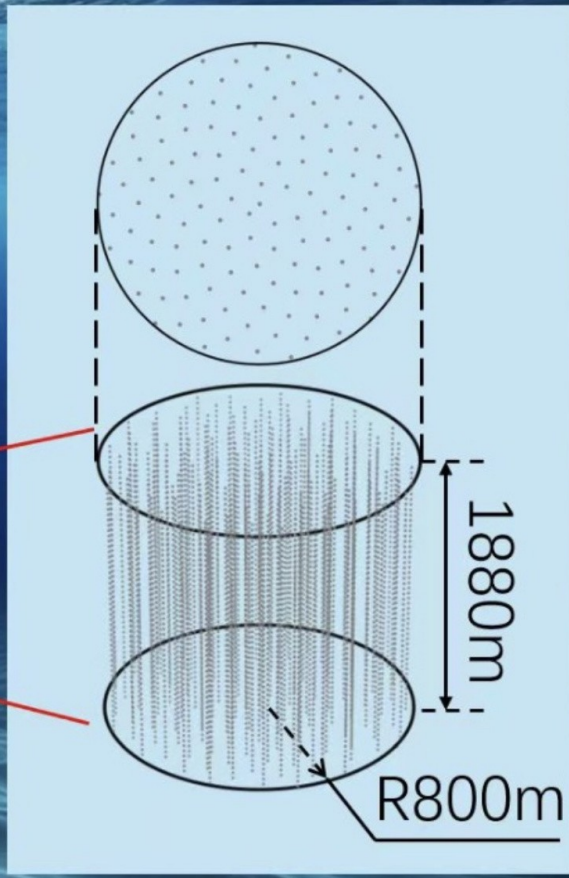
South China Sea
Effective volume: 30 km^3
2304 strings, 55,296 optical modules
Sensitive to υ of 100 TeV–100 PeV

HUNT overview:
T. Q. Huang, July 21

March 2024: Test string in Lake Baikal
January 2025: Test string in South China Sea
2025–2026: 7 strings, South China Sea (*Seastar*)





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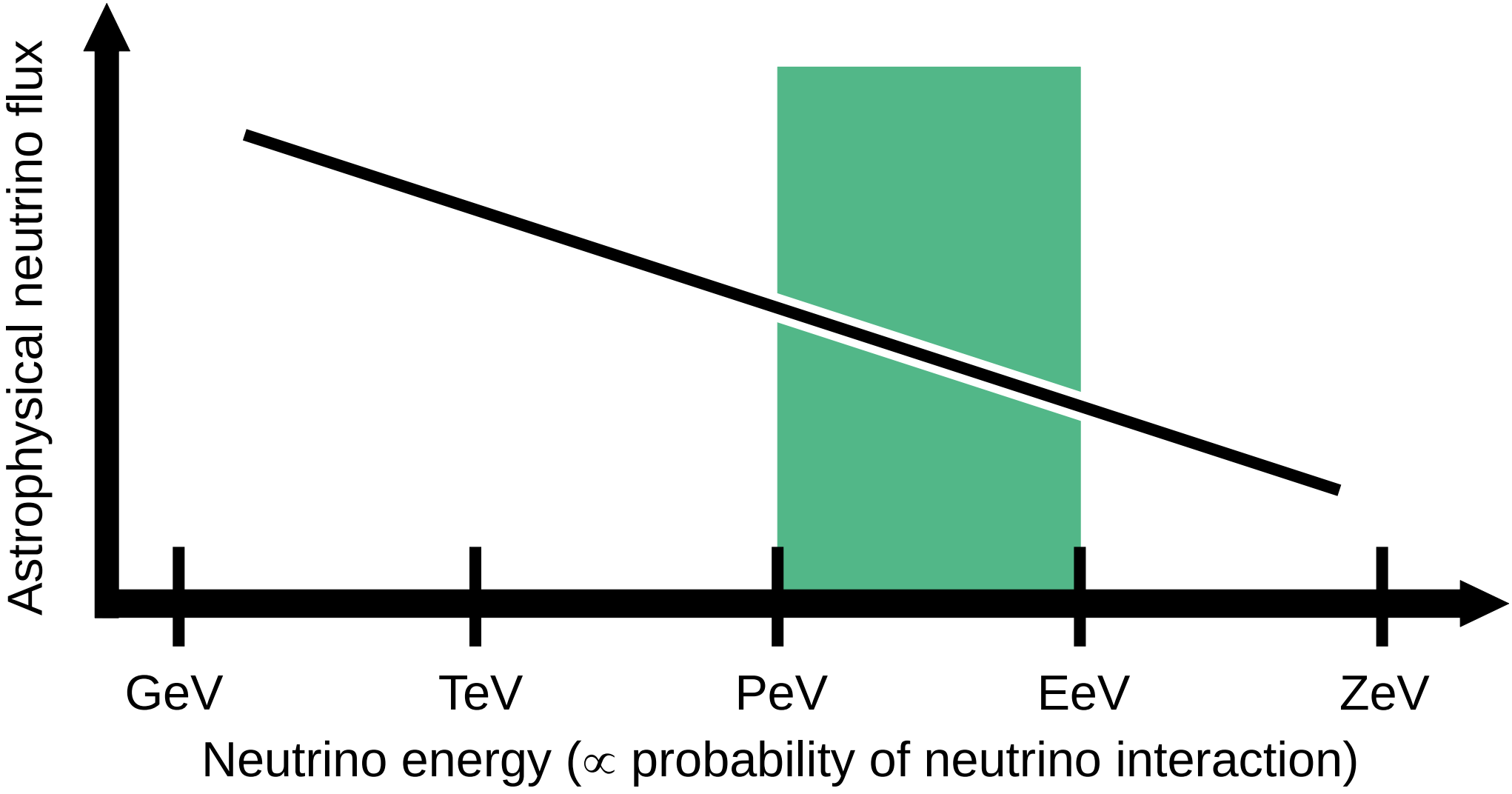
Astrophysical neutrino flux
GeV
TeV
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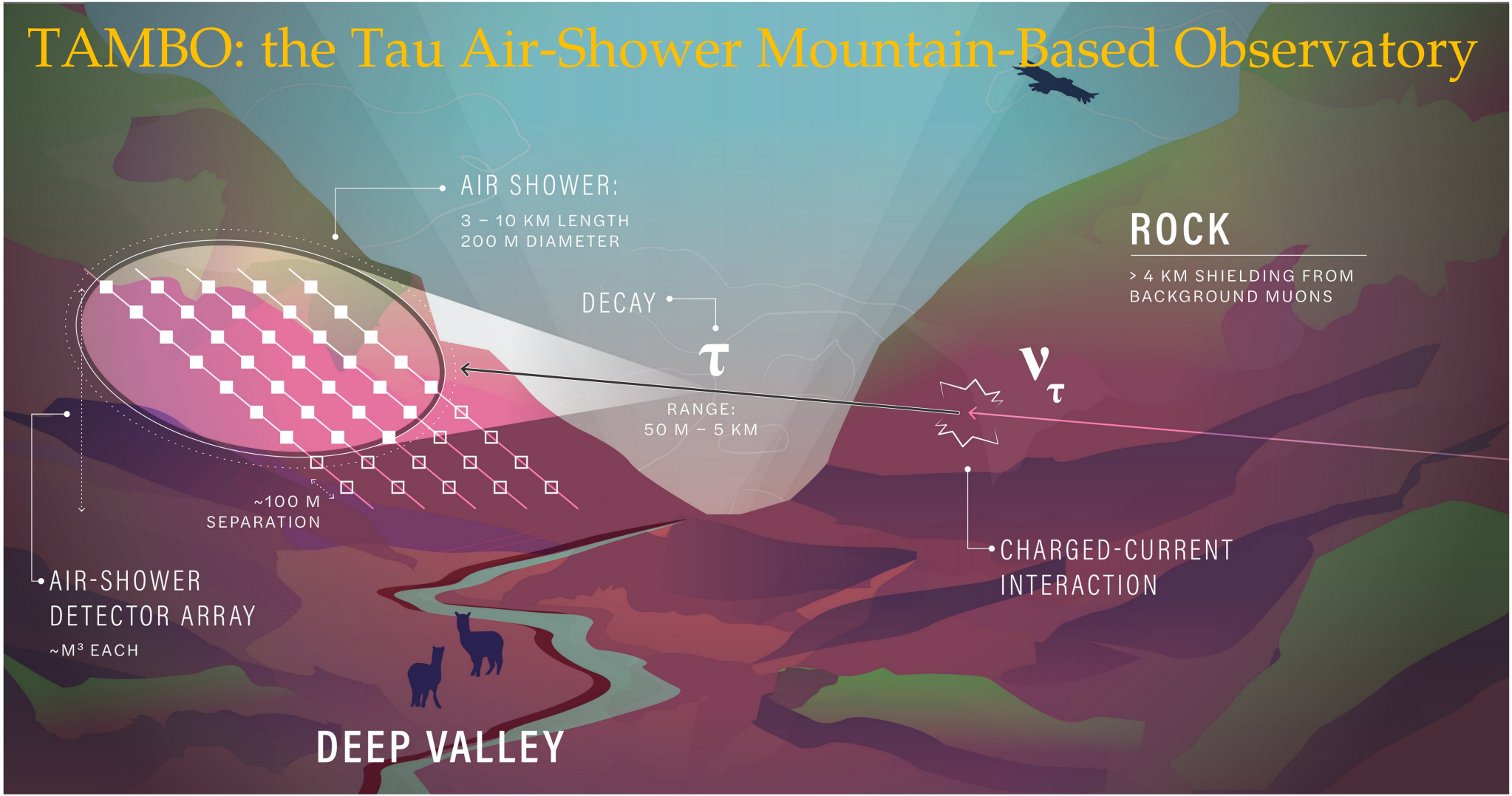
TAMBO: the Tau Air-Shower Mountain-Based Observatory

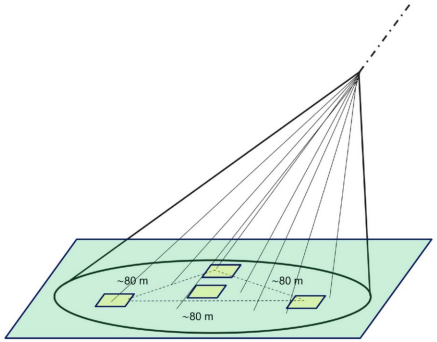


TAU AIR-SHOWER MOUNTAIN-BASED OBSERVATORY (TAMBO) · COLCA VALLEY, PERU

TAMBO: the Tau Air-Shower Mountain-Based Observatory

Today

TAMBO-4



Small test array

Electronics, detector prototypes

2025-2028

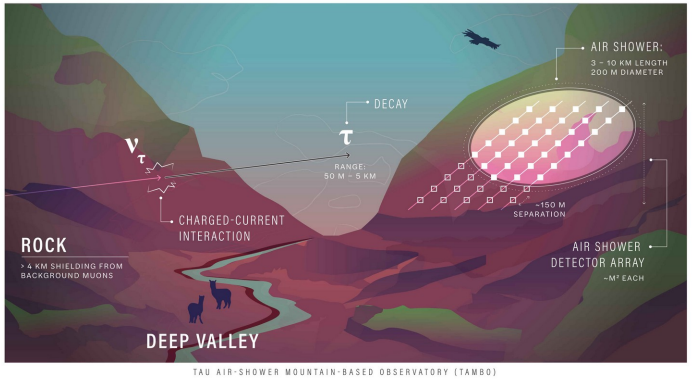
TAMBO-100
(aka TAMBITO)

Funded

Pilot array
Deployment techniques, background, and social science

2028 - ...

TAMBO-5k



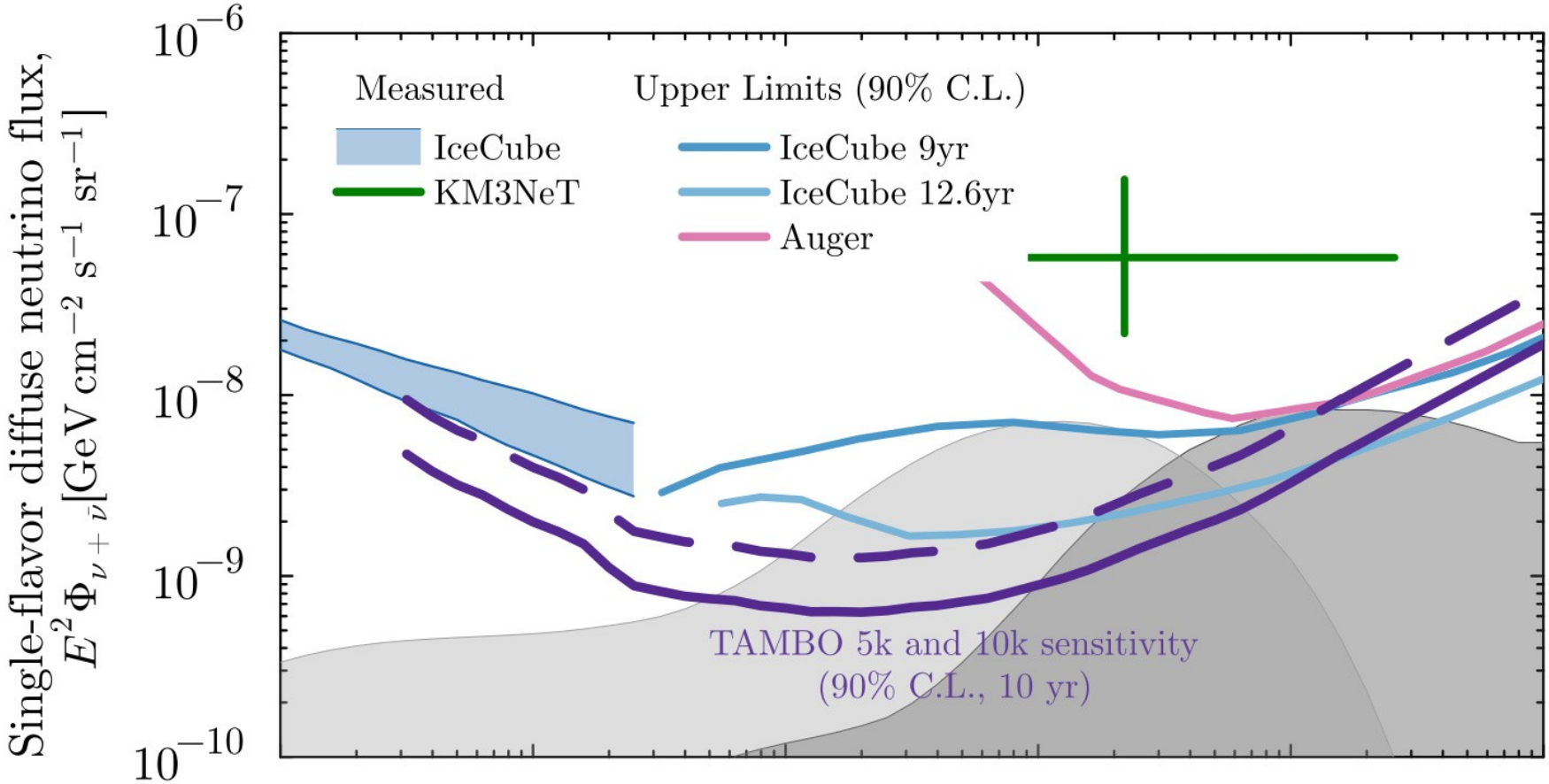
Array capable of detecting O(1) neutrinos per year in the PeV to 100 PeV energy range

TAMBO Collaboration

W. Thompson, 1194 | P. Zhelnin+ 981 | C. Argüelles+ 1091

TAMBO overview:
W. Thompson, July 16

TAMBO: the Tau Air-Shower Mountain-Based Observatory



TAMBO Collaboration

W. Thompson, 1194 | P. Zhelnin+ 981 | C. Argüelles+ 1091

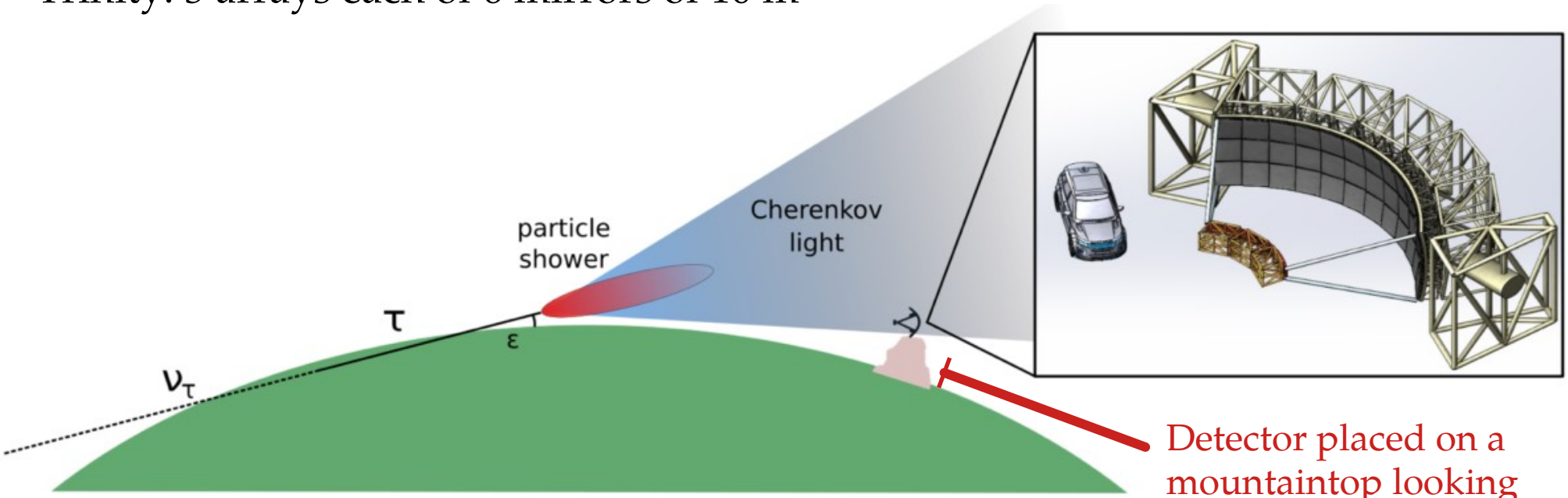
TAMBO overview:
W. Thompson, July 16

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



Detector placed on a mountaintop looking towards the horizon

Trinity Collaboration

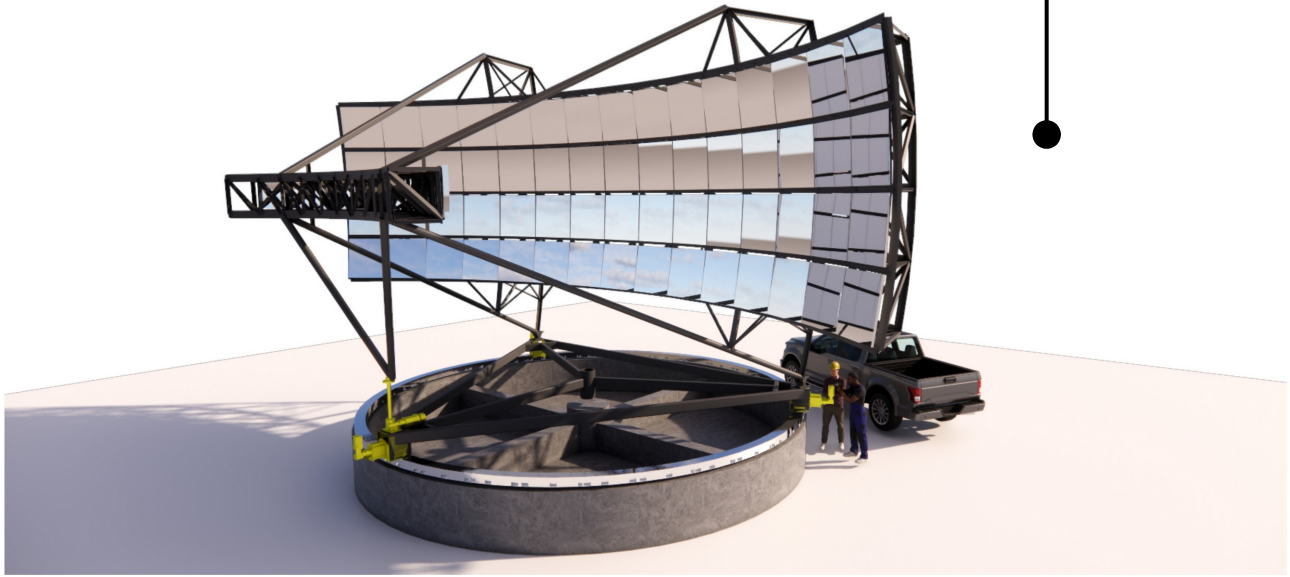
S. Stepanoff 1188 | D. A. Raudales+ 1136

Trinity

Trinity overview:
S. Stepanoff, July 17

Trinity Demonstrator: 1.36 m^2
Frisko Peak, Utah, deployed 2023

Trinity One: first telescope of the array
Sensitivity to neutrino fluxes

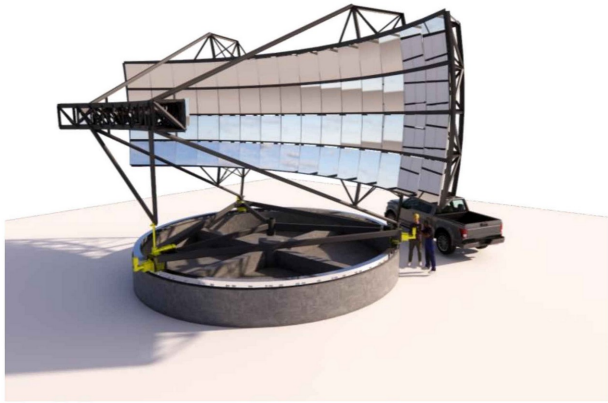


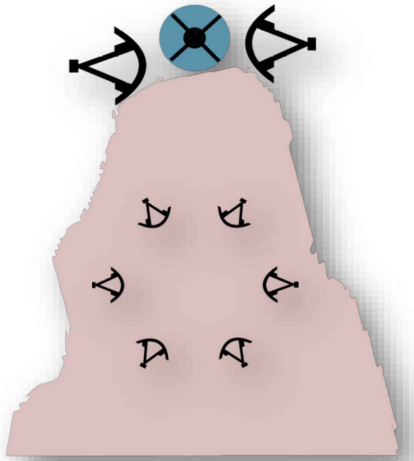
Trinity Collaboration

S. Stepanoff 1188 | D. A. Raudales+ 1136

Trinity

Trinity overview:
S. Stepanoff, July 17





Demonstrator Funding

Trinity One Funding

2021

2023

2026

2031

Demonstrator First Light

Trinity Observatory Funding

Trinity Collaboration

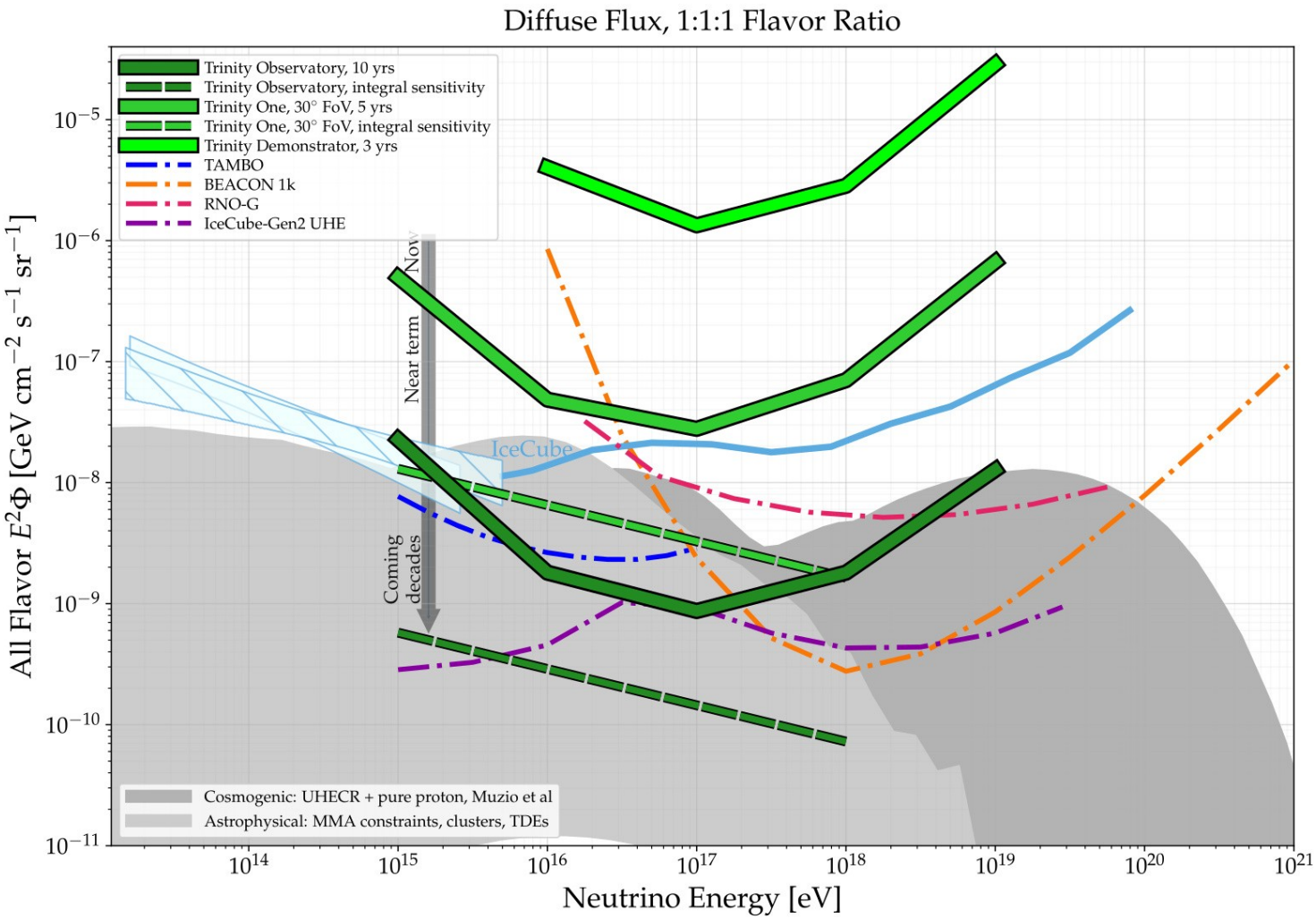
S. Stepanoff 1188 | D. A. Raudales+ 1136

Trinit

ity overview:
noff, July 17

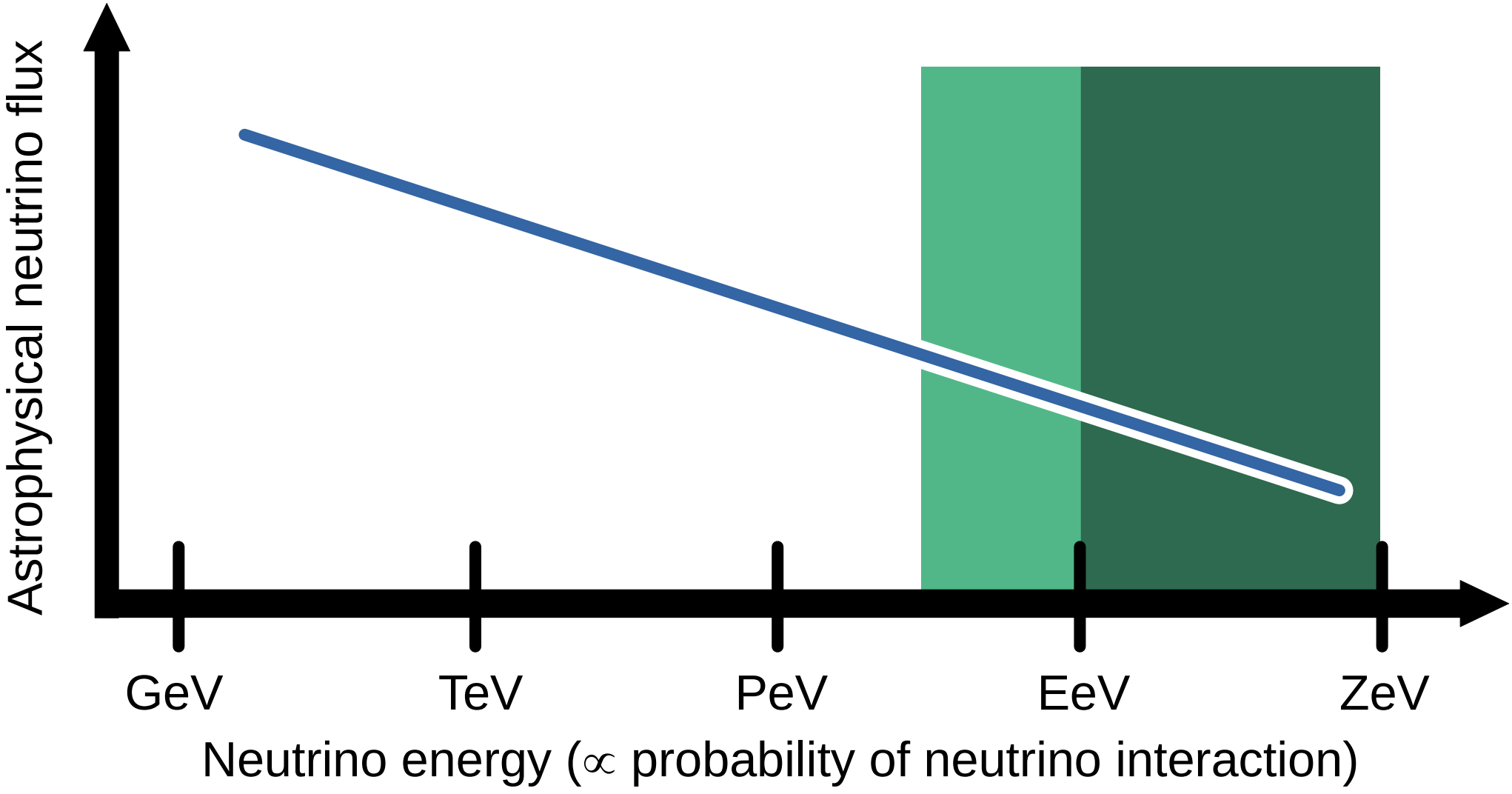
Demo

Funding



Trinity Coll

S. Stepanoff 1188


Astrophysical neutrino flux
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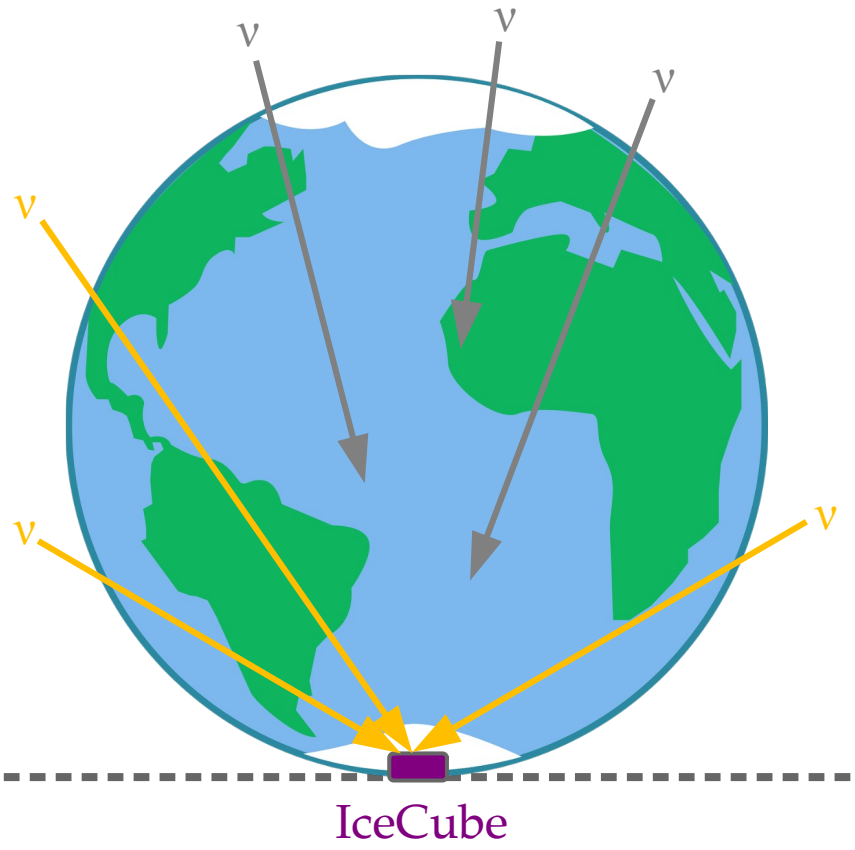
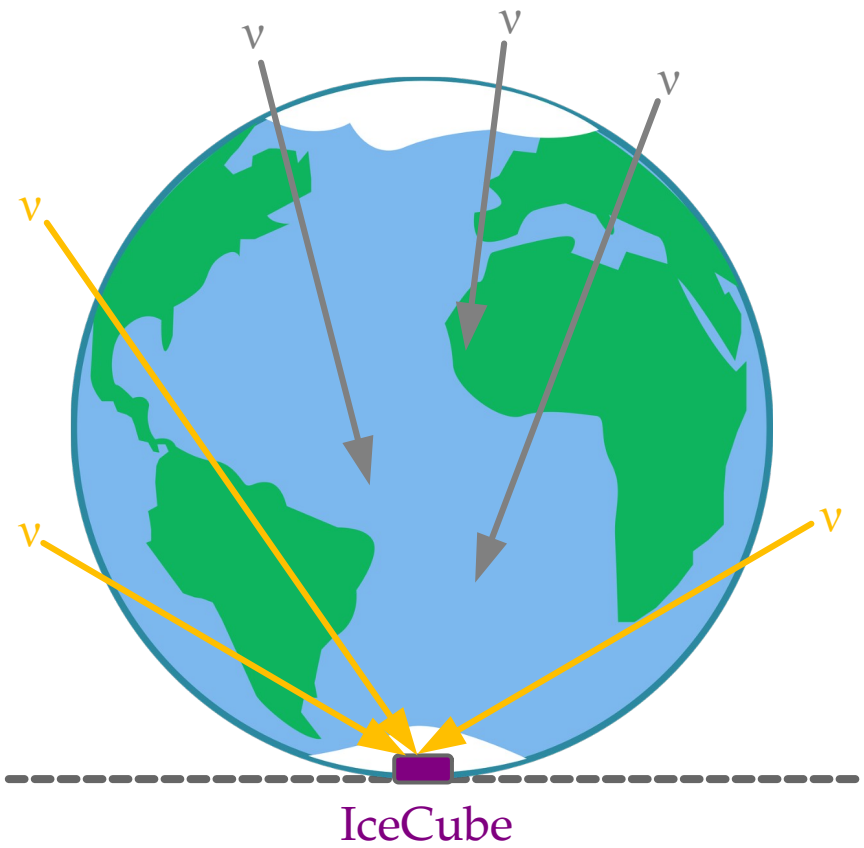
TeV–PeV:



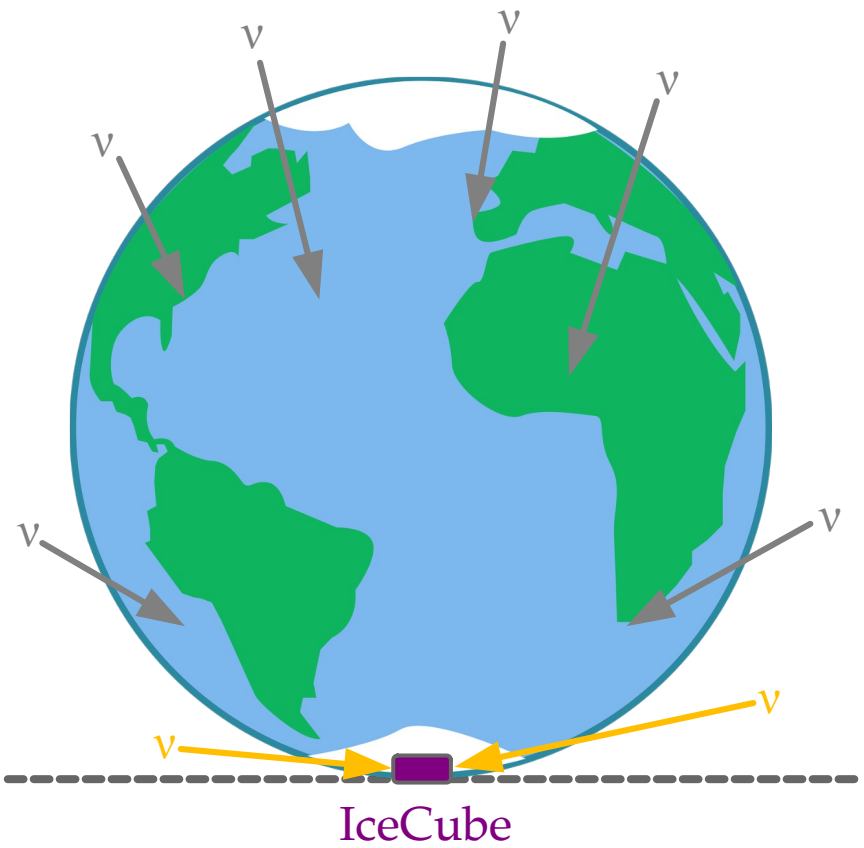
Earth is *almost fully* opaque,
some upgoing ν still make it through

TeV–PeV:



Earth is *almost fully* opaque,
some upgoing ν still make it through

> 100 PeV:



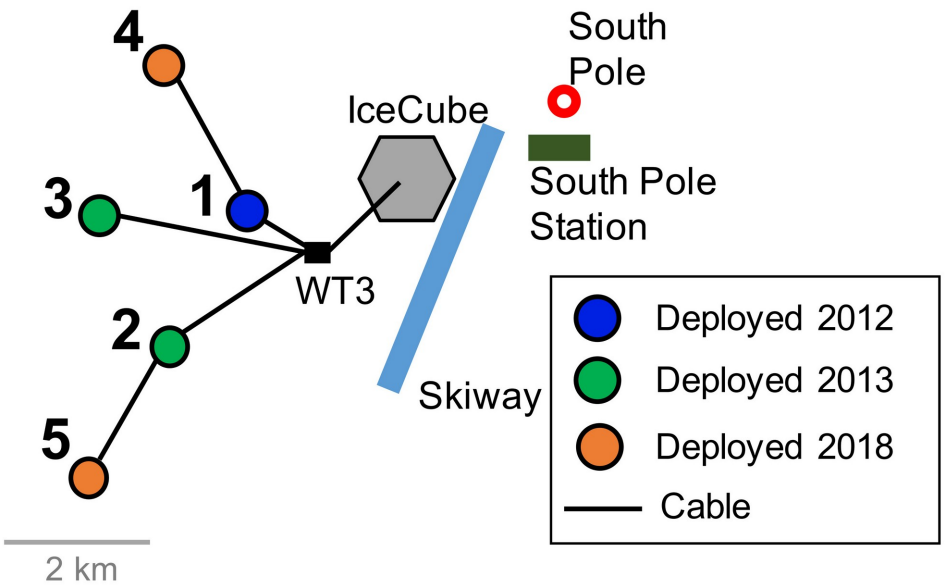
Earth is *completely* opaque,
but horizontal ν still make it through

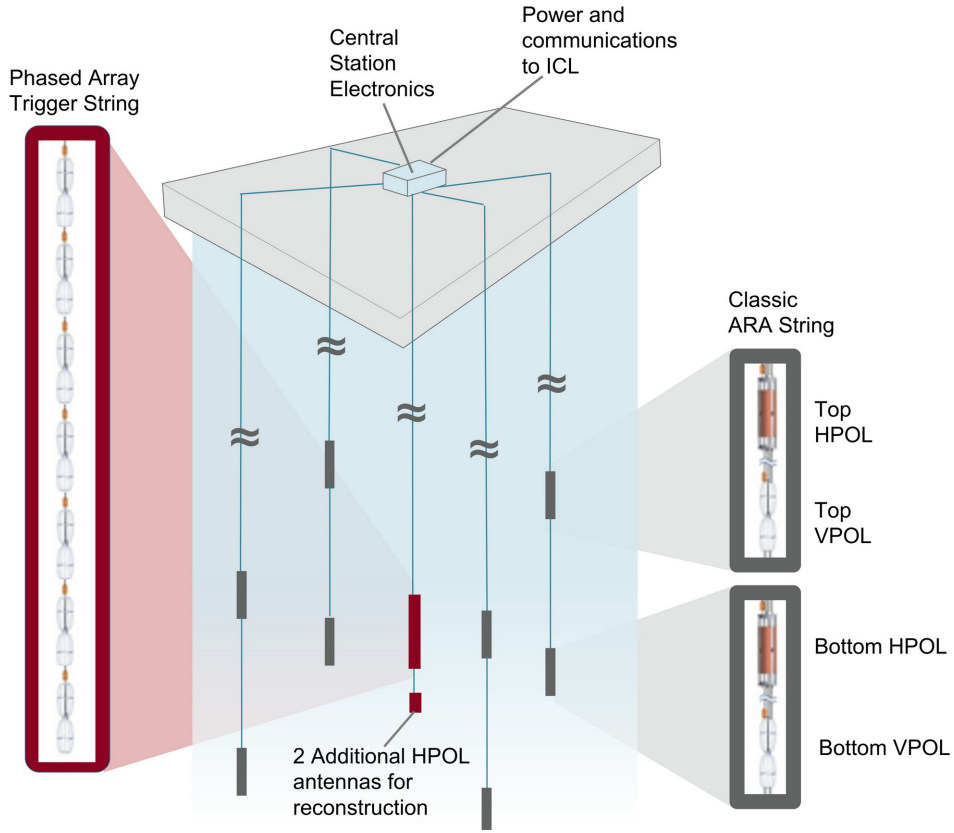
ARA: Askaryan Radio Array

Five radio stations at > 200 m underground

Running since 2011

Proof of concept for larger arrays
(RNO-G, IceCube-Gen2)





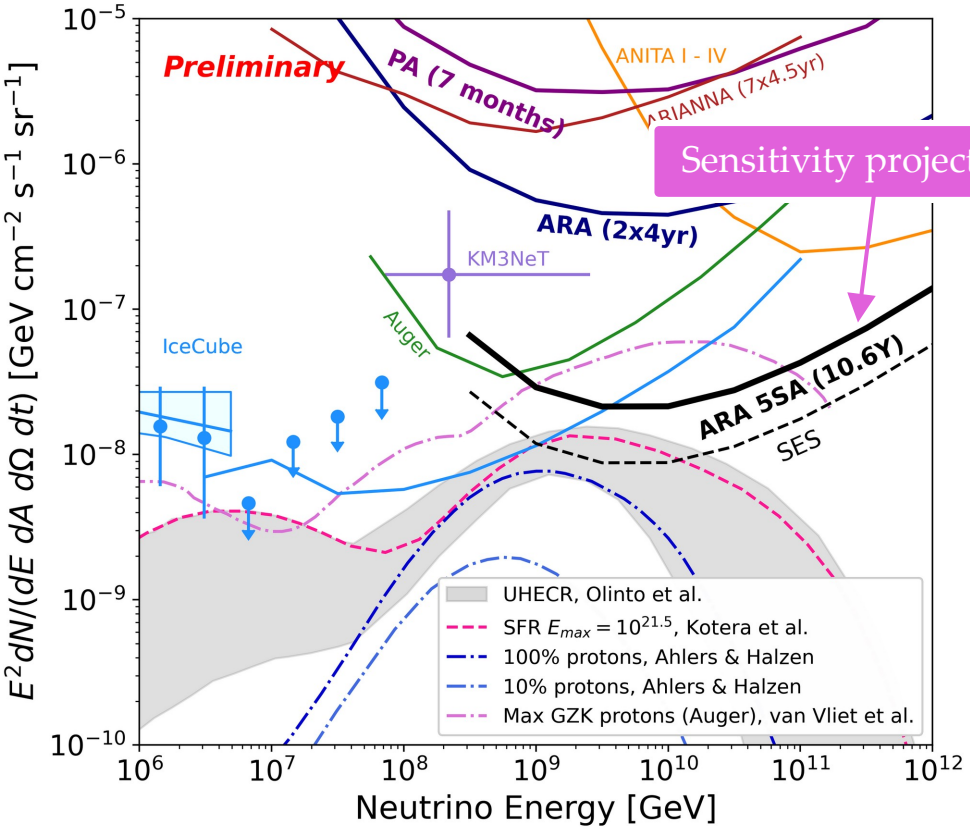
ARA Collaboration

S. Ali+ 977 | A. Bishop+ 991 | P. Dasgupta+ 1022 | P. Giri+ | M. Muzio+ 1126 | M. F. H. Seikh+ 1171 | P. Windischhofer+ 1213 | A. Machtay | I. Kravchenko+

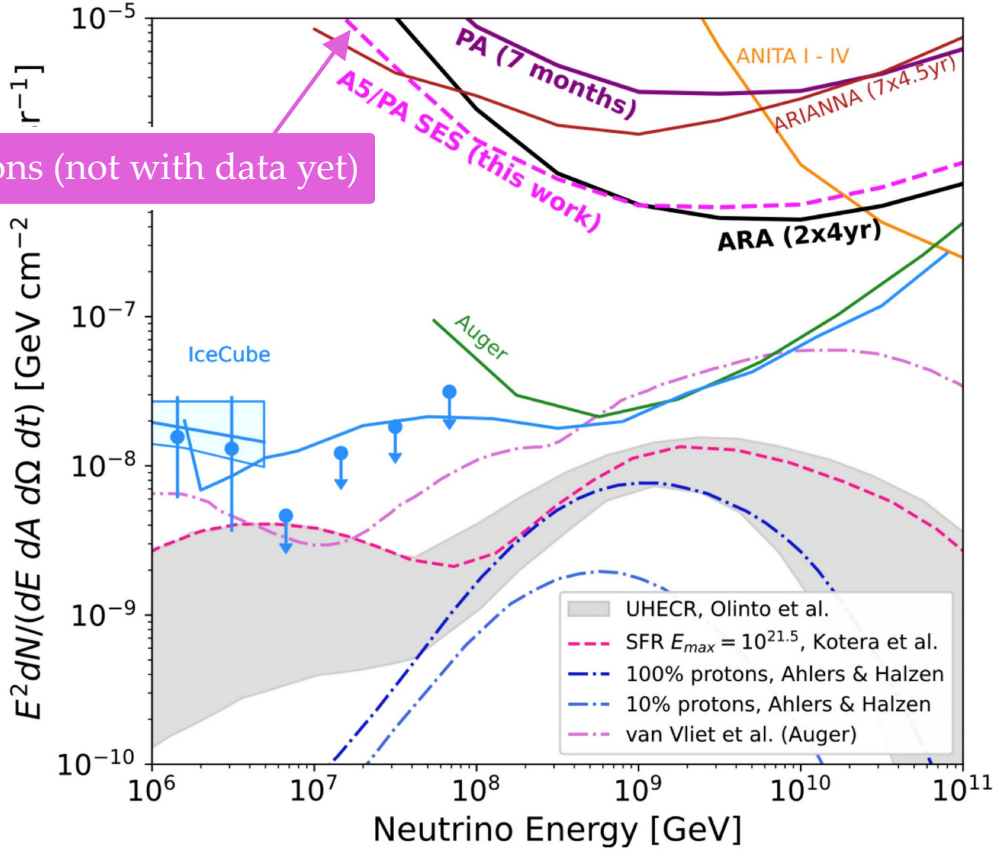
ARA: Askaryan Radio Array

First station-wide search for UHE υ

First UHE υ search phased + traditional stations



Sensitivity projections (not with data yet)



M. Muzio, July 17, PoS(ICRC2025)1126

P. Dasgupta, July 15, PoS(ICRC2025)1022

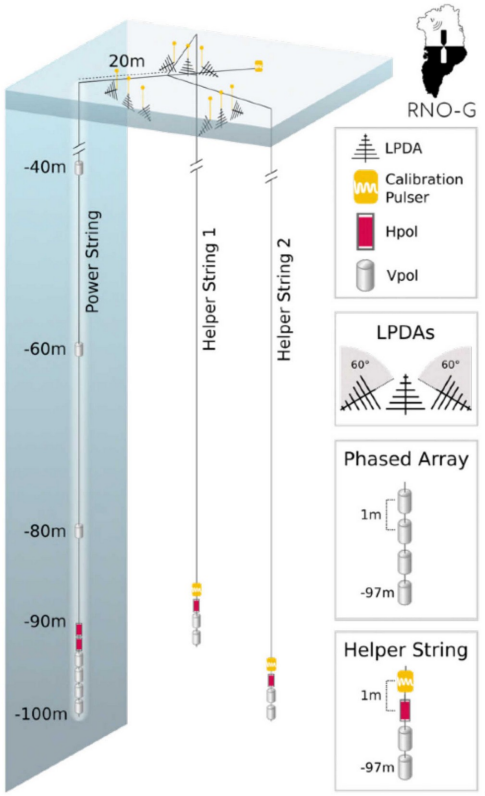
RNO-G: Radio Neutrino Observatory - Greenland

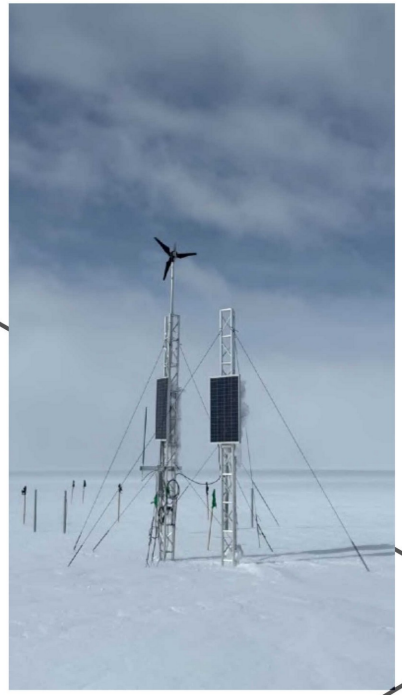
In construction

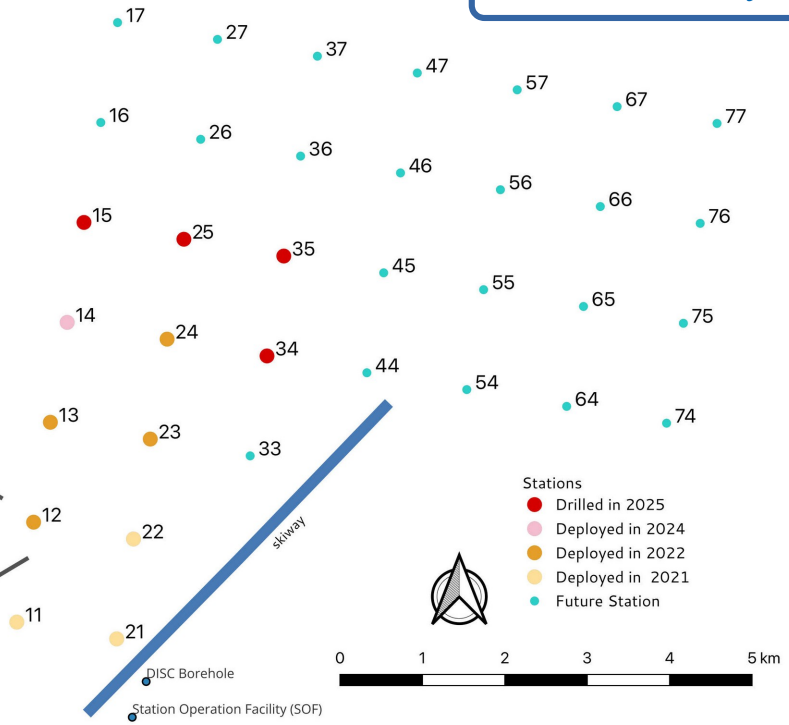
35 in-ice radio stations planned

ARA + ARIANNA experience

RNO-G overview:
A. Nelles, July 16



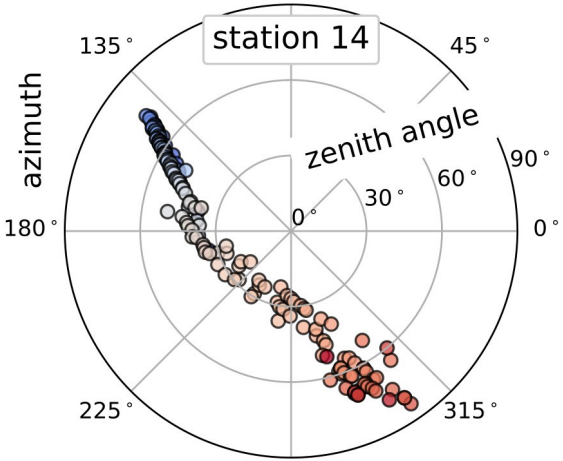


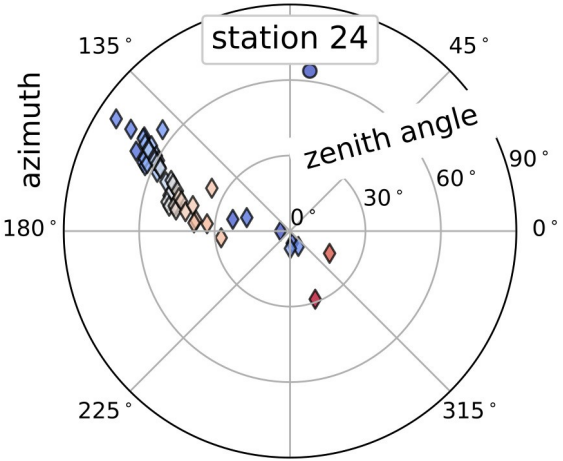


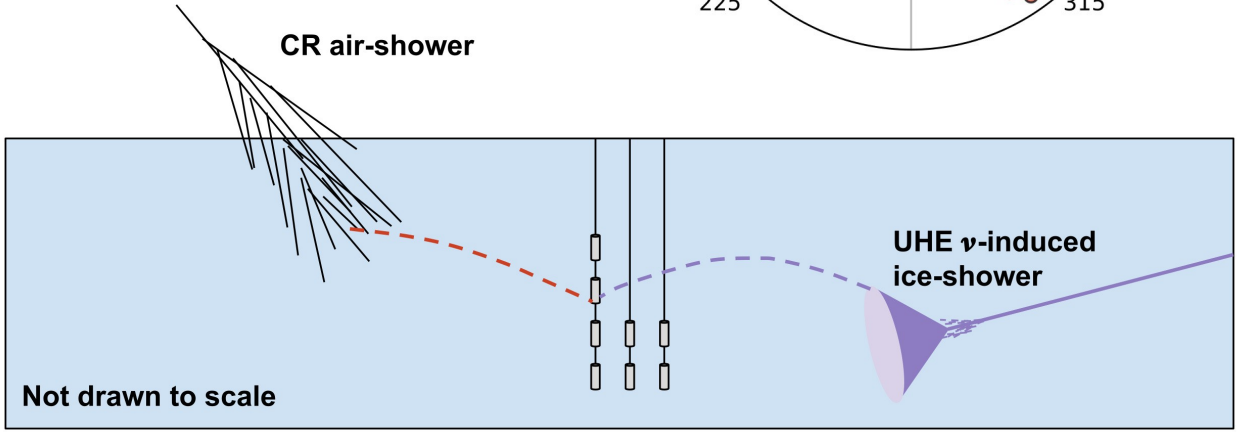
- 8 stations operational (Apr - Oct), Wind-power tested
- 4 additional stations drilled (as of today)

RNO-G: Radio Neutrino Observatory - Greenland

Flights over Antarctica [2506.17522] and solar flares [2404.14995] detected (good for calibration)







Cosmic-ray searches will be proof-of-concept for neutrino searches

A. Vijai, PoS(ICRC2025)1204 July 23

B. Hendricks, PoS(ICRC2025)1057

RNO-G Collaboration

A. Nelles+ | F. Schülter+ 1168 | J. Henrichs+ 288 | B. Clark+ 1204 | B. Hendricks+ 1057 | M. Liu+ 319 | M. Punsuebsay 366 | C. McLennan+ 288 | R. Camphyn 288 | J. Stoffels 1189 | M. Hossain Seikh 1356 | S. Bouma 135

RNO-G: Radio Neutrino Observatory - Greenland

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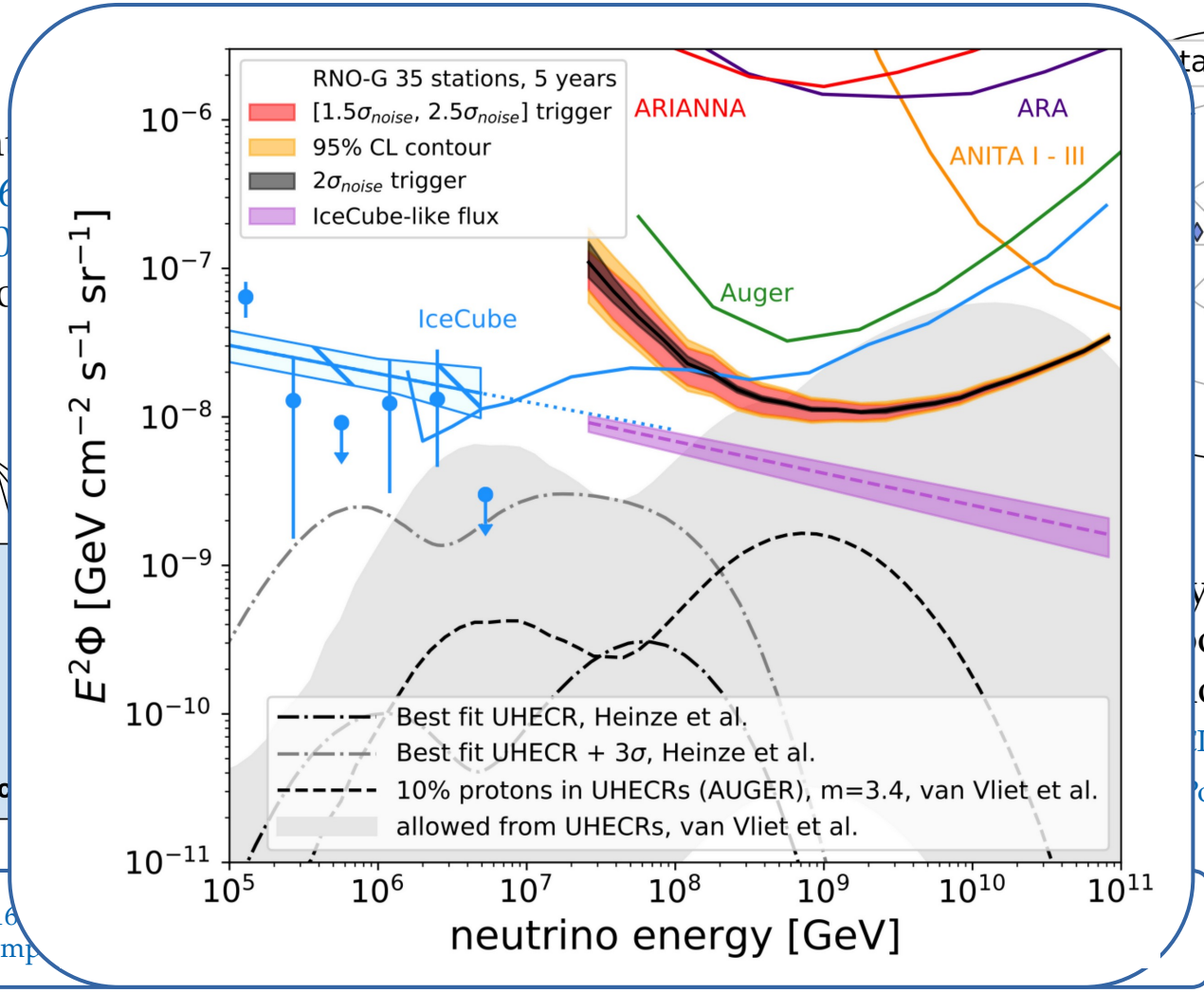
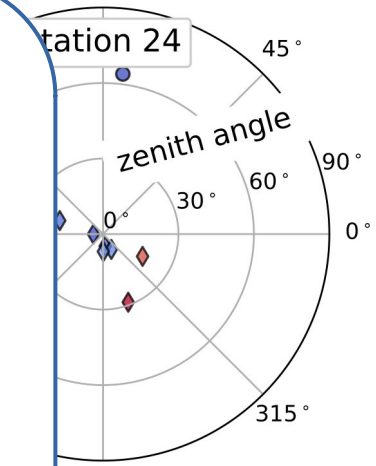
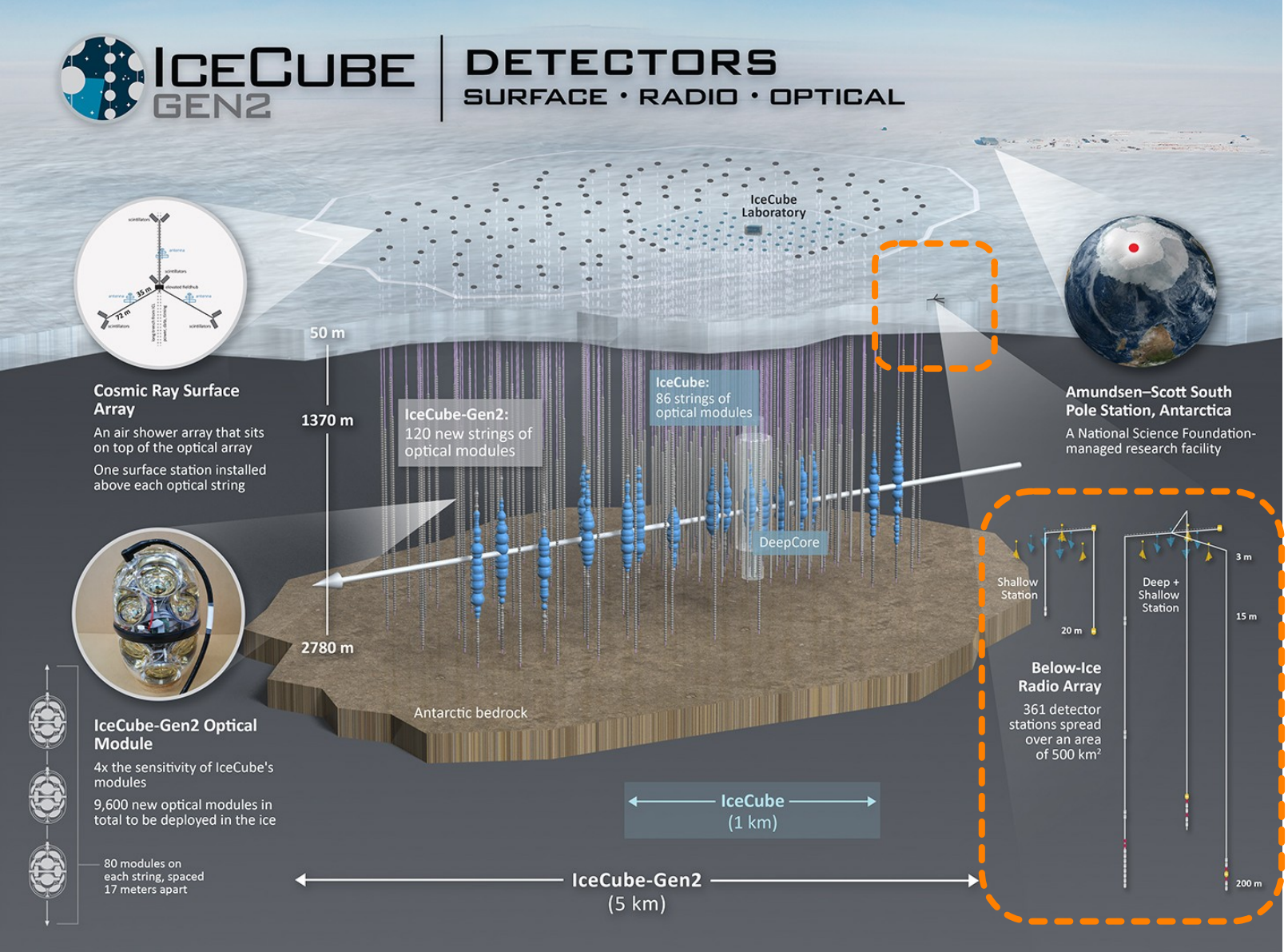




y searches
of-of-concept
o searches
RC2025)1204 July 23
oS(ICRC2025)1057

RNO-G Collaboration

A. Nelles+ | F. Schülter+ 116
C. McLennan+ 288 | R. Camp



High-energy IceCube successor

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

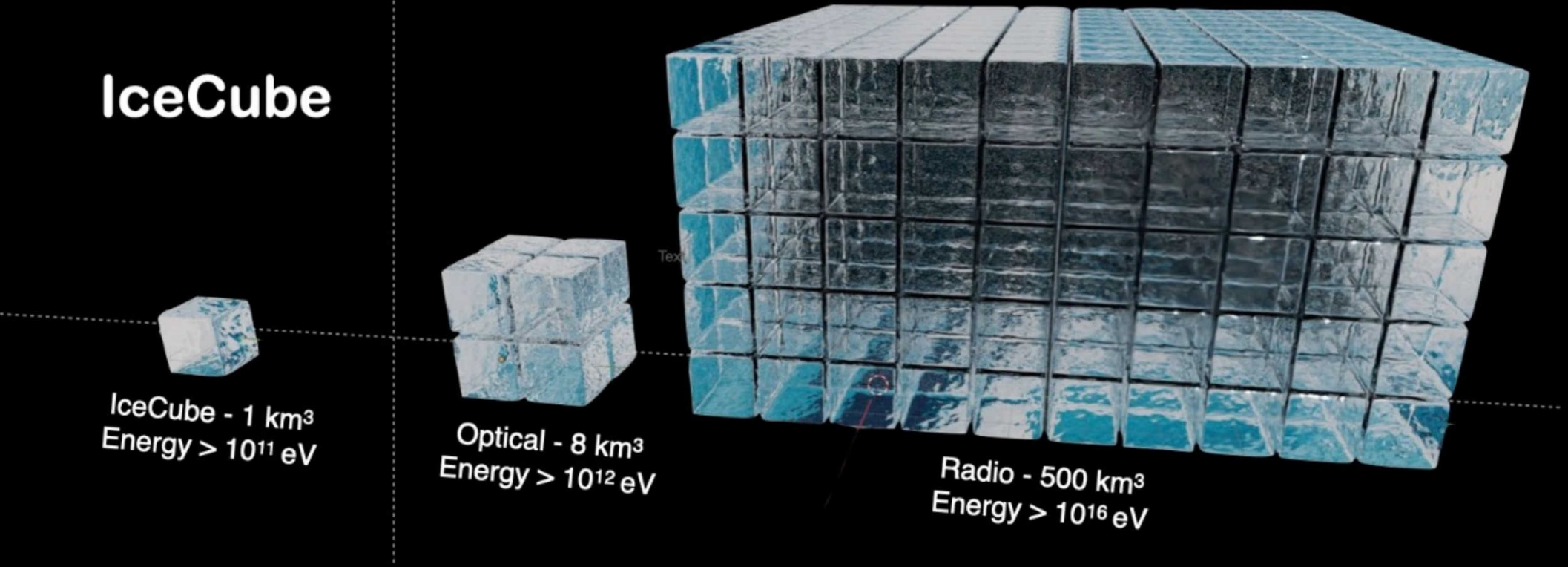
~100× rate of EeV ν *vs.* IceCube

IceCube-Gen2 radio:
C. Glaser, July 21

IceCube-Gen2 Collaboration
List of contributions: 2507.08667

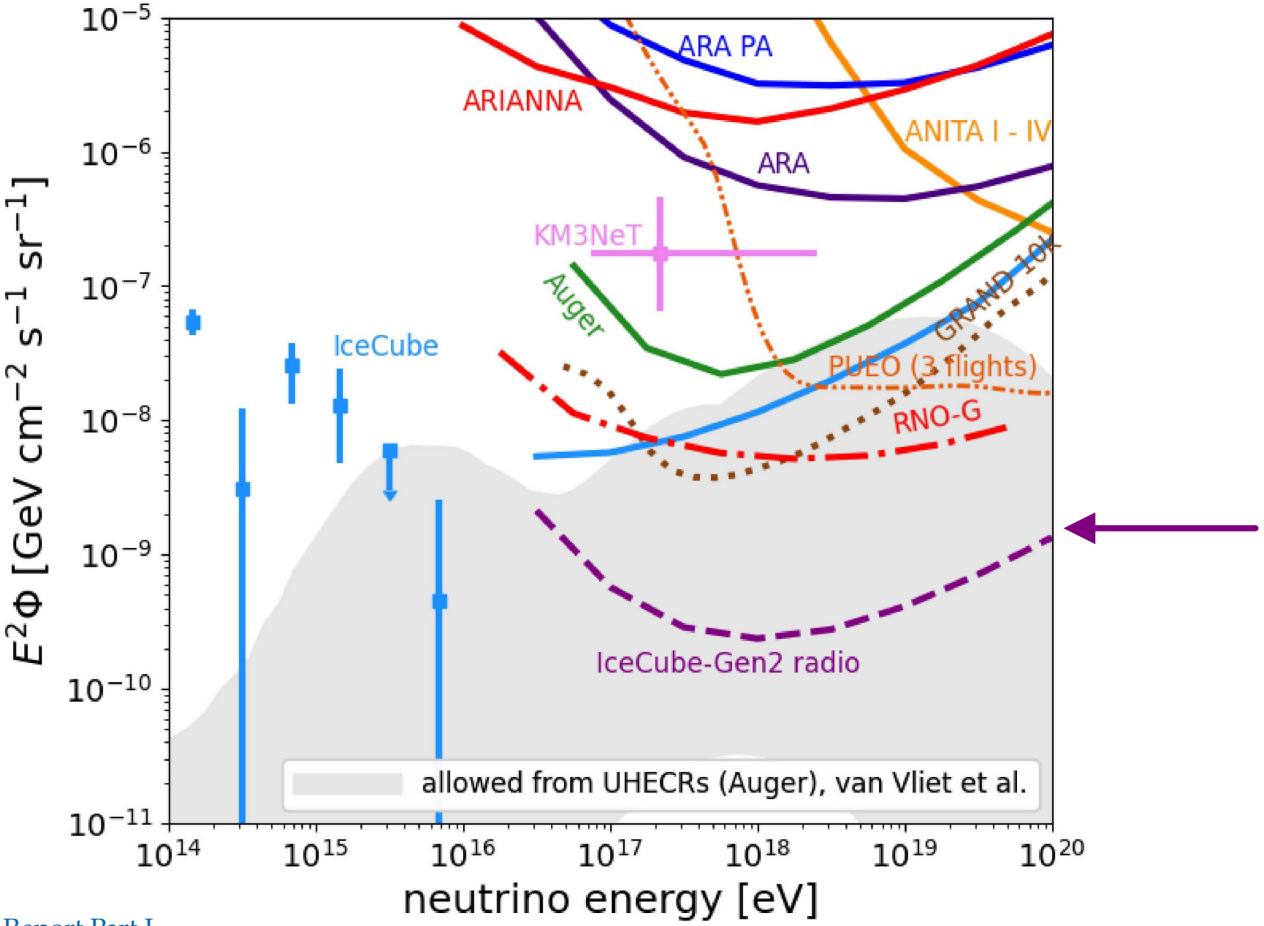
IceCube-Gen2

IceCube



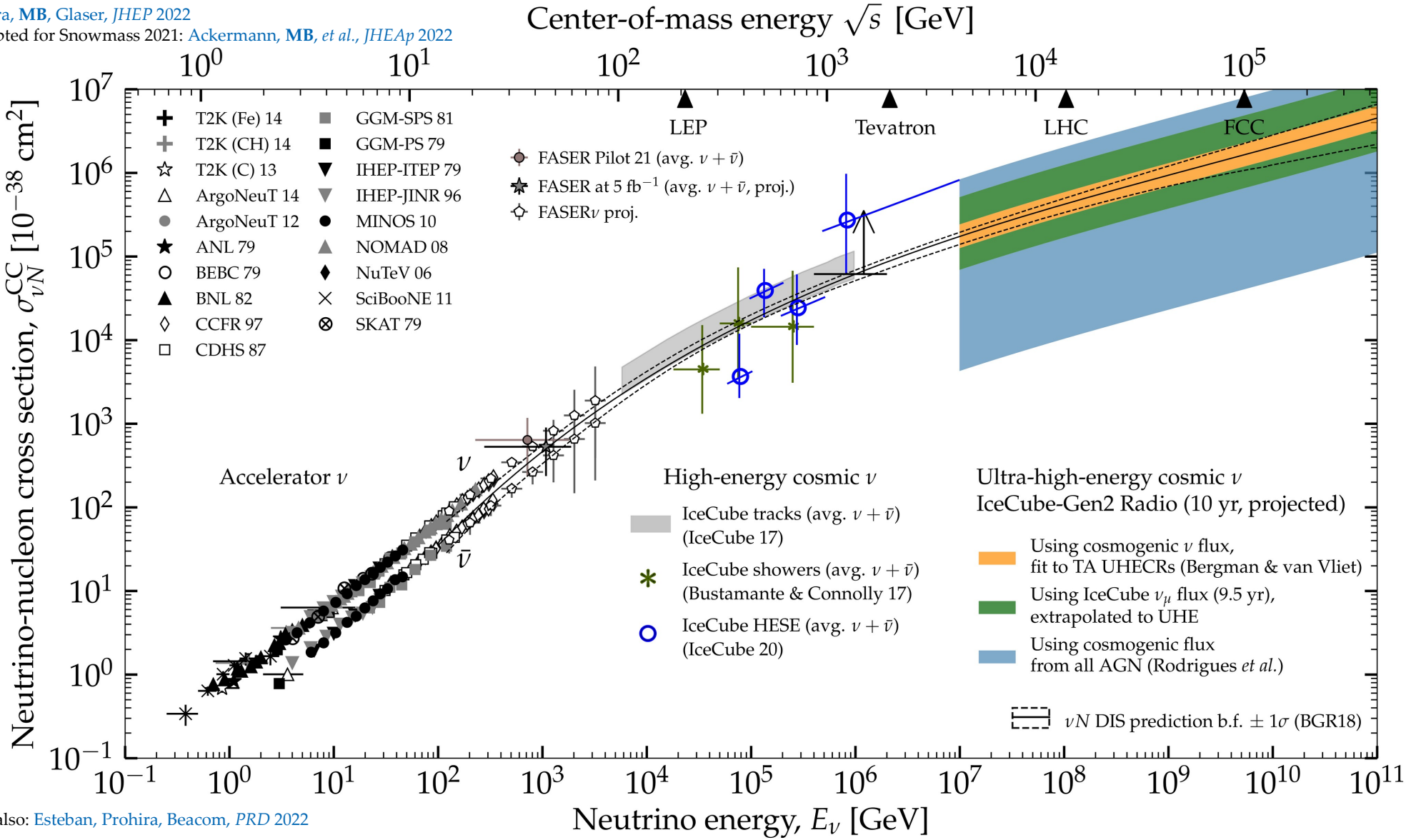
IceCube-Gen2 in-ice radio array

Detect the diffuse UHE ν flux even if it is small



IceCube-Gen2 Collab., Technical Design Report Part I

Valera, **MB**, Glaser, *JHEP* 2022
Adapted for Snowmass 2021: Ackermann, **MB**, *et al.*, *JHEAp* 2022



See also: Esteban, Prohira, Beacom, *PRD* 2022

Valera, **MB**, Glaser, *JHEP* 2022
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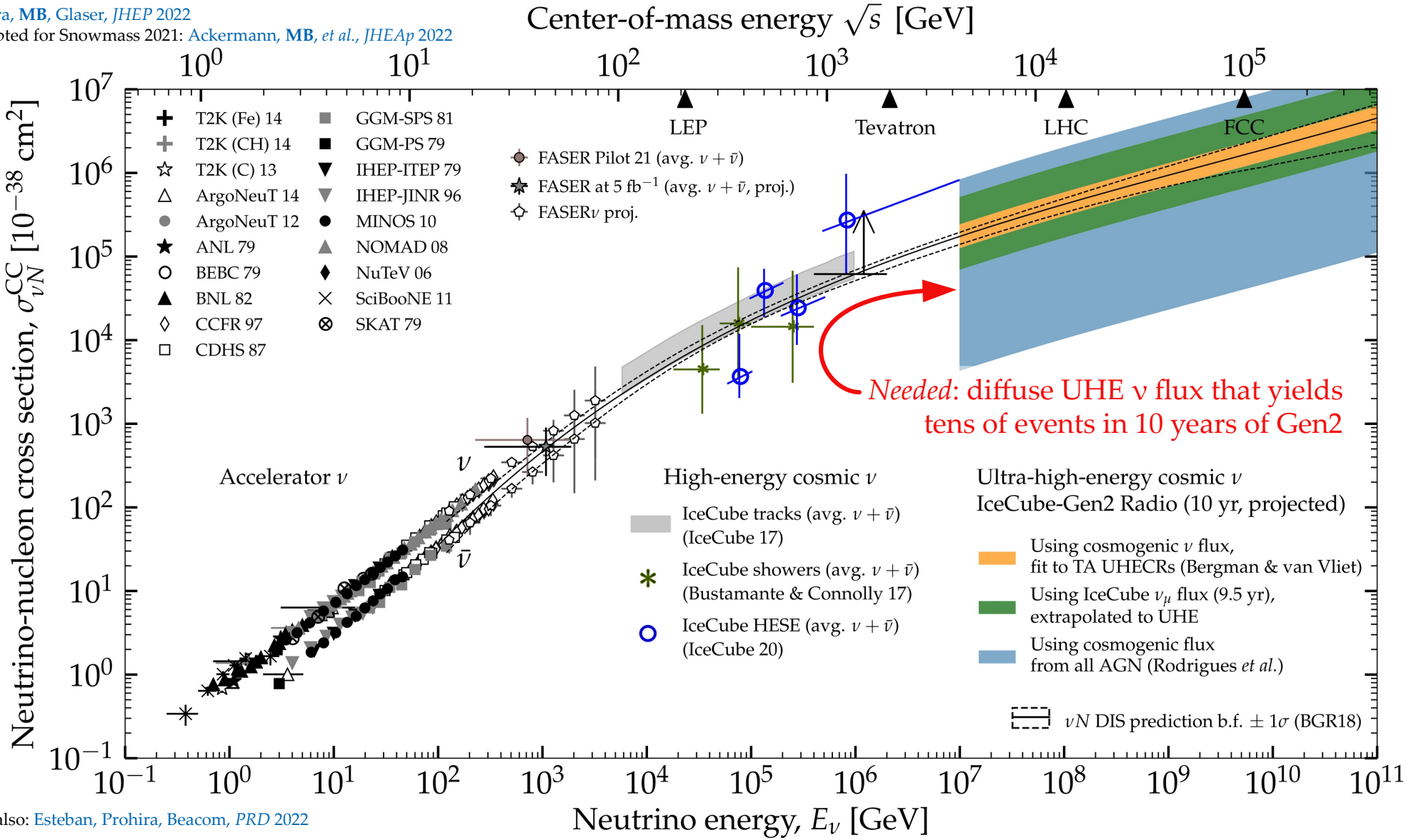

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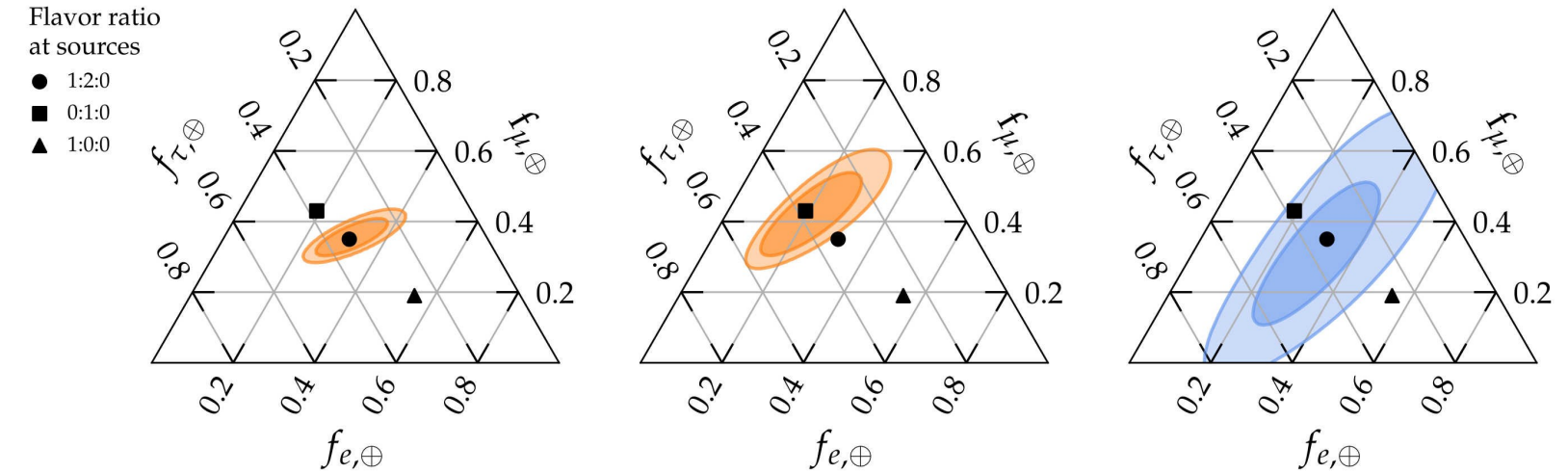
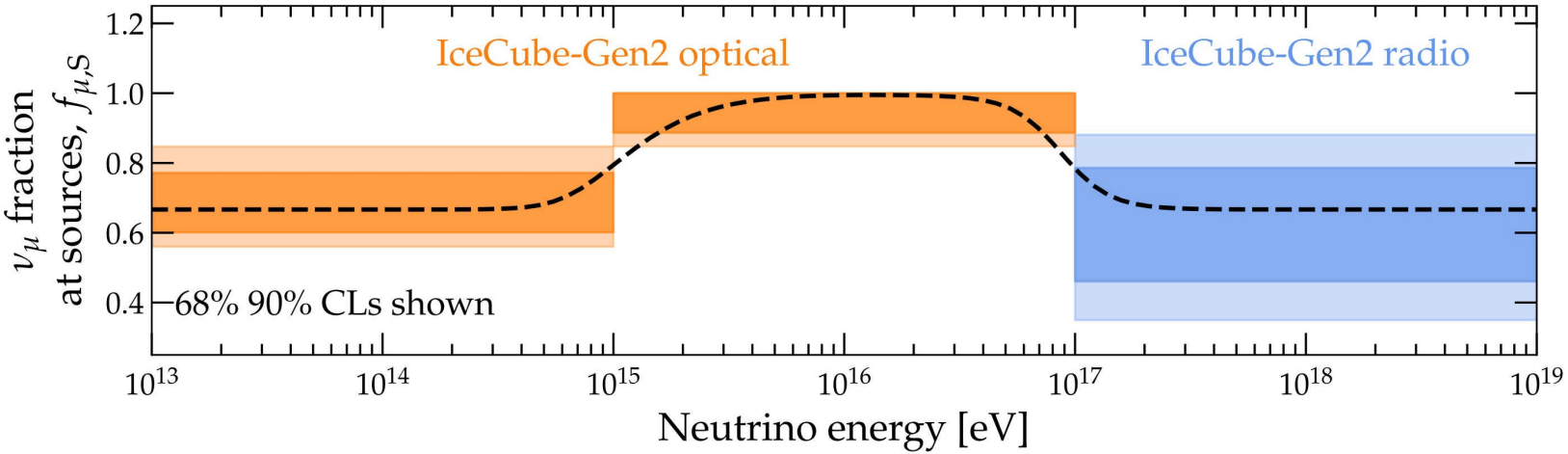
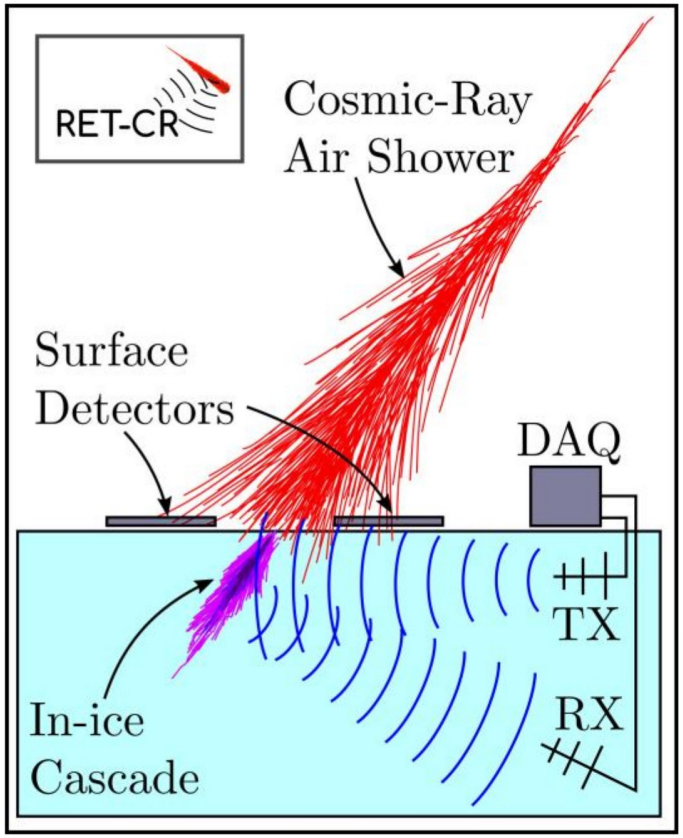
IceCube-Gen2 in-ice radio array





A. Coleman, O. Ericsson, C. Glaser, **MB**, *PRD* 2024 [2402.02432]

RET: Radar Echo Telescope

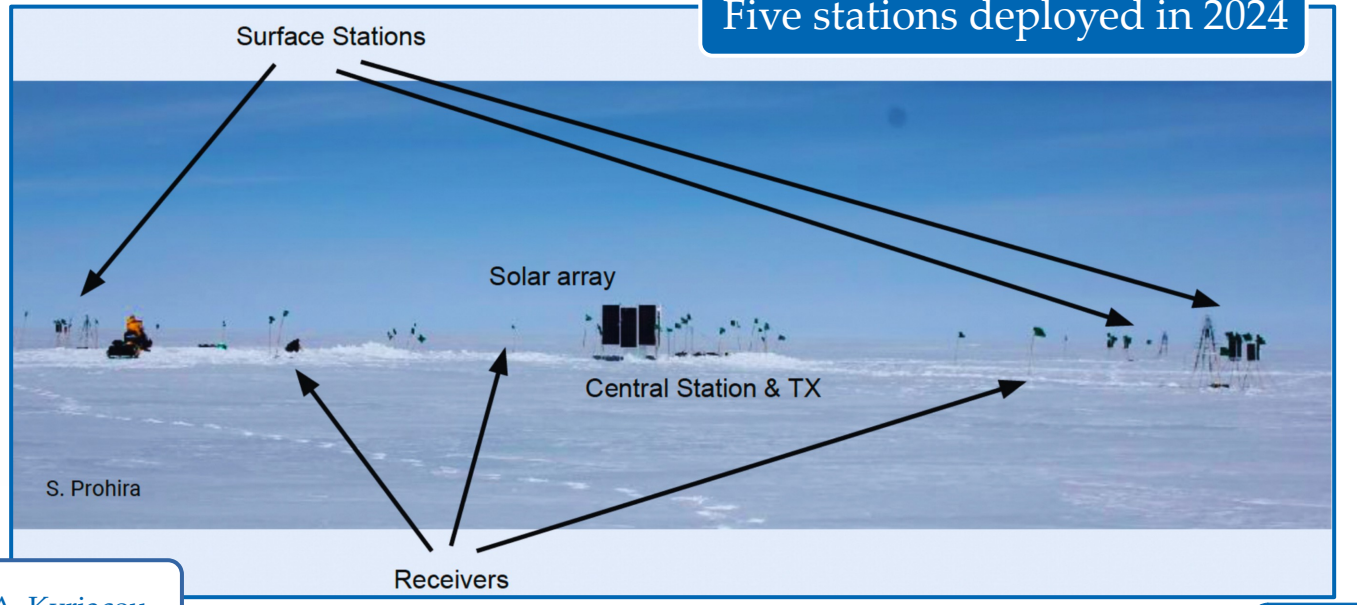


Detect the ionization trail made by in-ice high-energy particle showers via active radar sounding

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

Future: RET-N to detect neutrinos

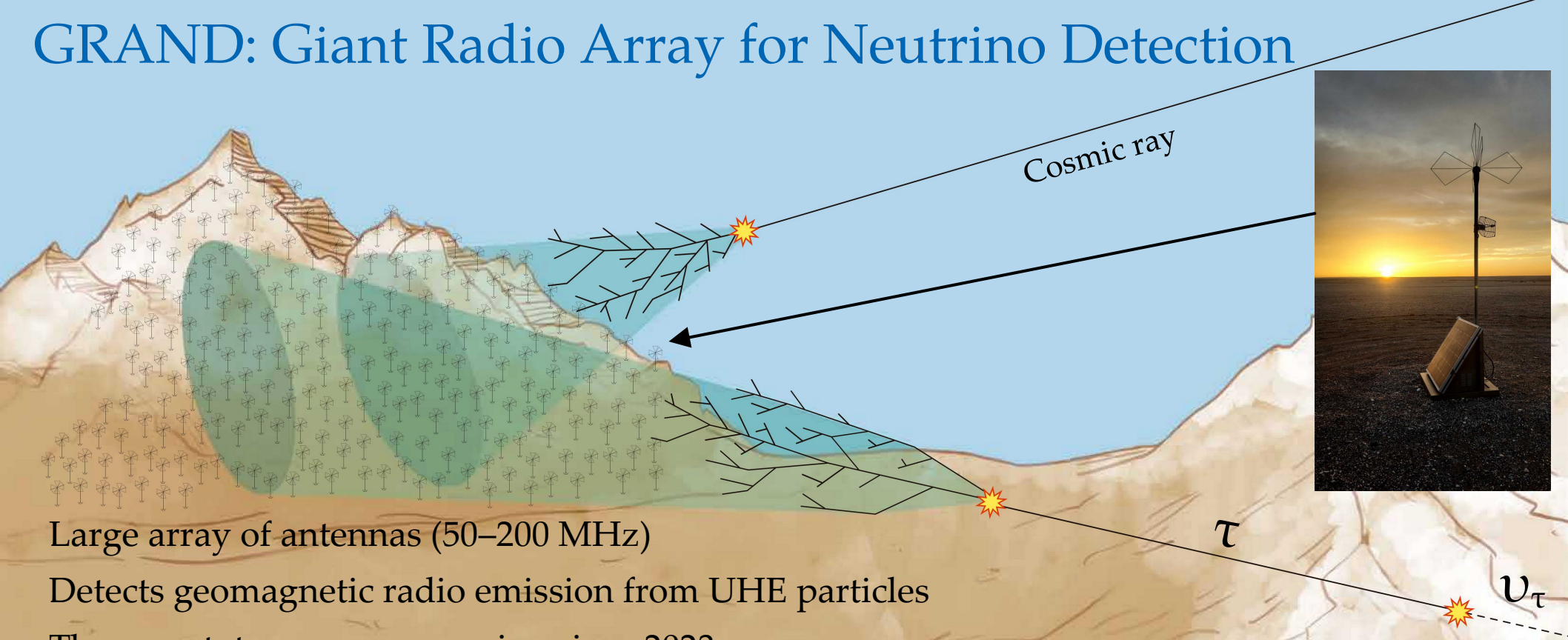
Five stations deployed in 2024



RET Collaboration

J. Loonen | D. Frikken | I. Loudon | K. N. Gopinath | A. Kyriacou

GRAND: Giant Radio Array for Neutrino Detection



Large array of antennas (50–200 MHz)

Detects geomagnetic radio emission from UHE particles

Three prototype arrays running since 2023:

GRANDProto300 • GRAND@Auger • GRAND@Nançay

65 antennas, China | 10 antennas, Argentina | 5 antennas, France

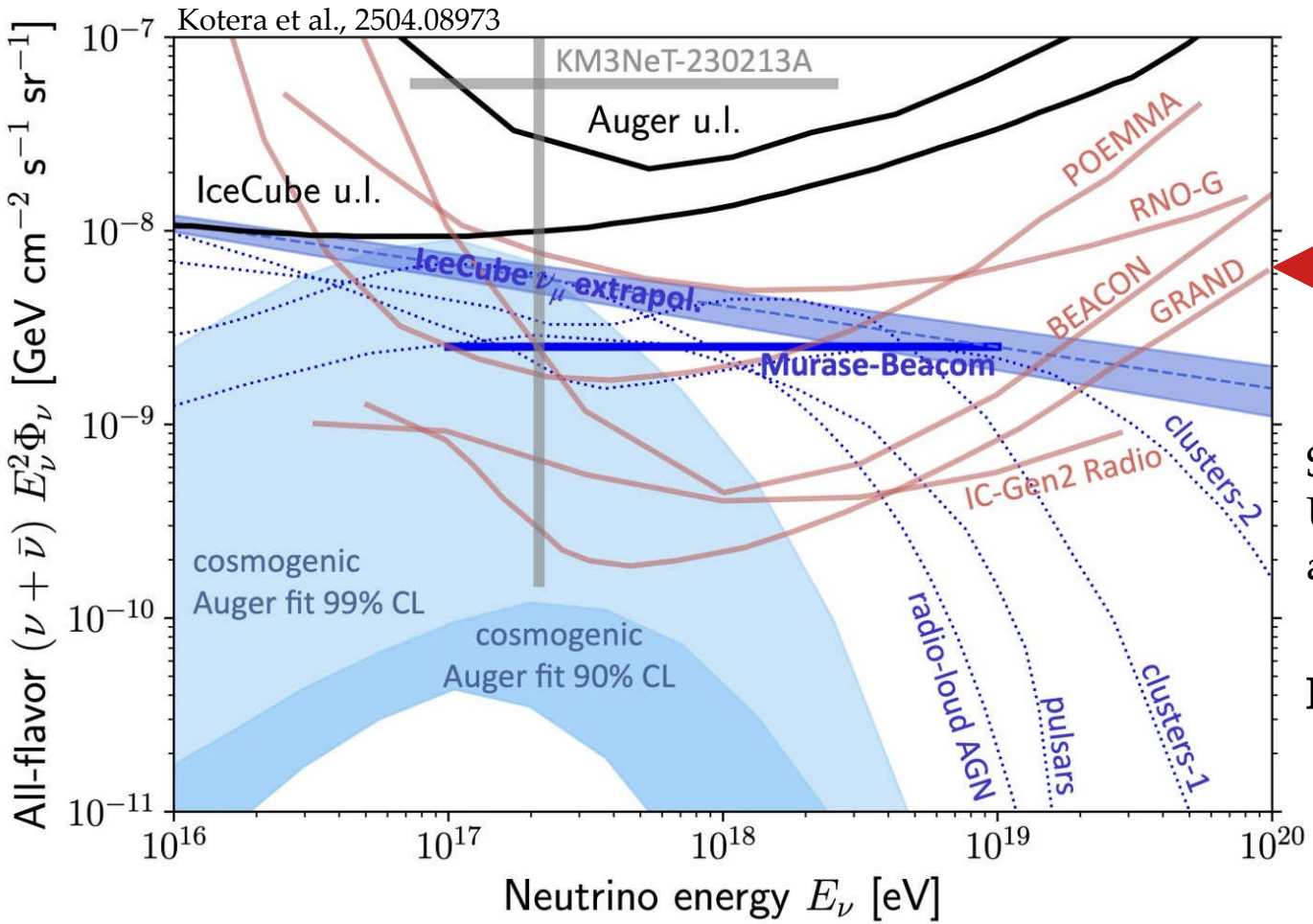
GRAND overview:
O. Martineau, July 16

First cosmic-ray candidates shown at ICRC 2025

GRAND Collaboration

J. R. T. de Mello Neto 1024 | O. Martineau 1114 | P. Ma 453 | L. Piotrowksi

GRAND: Giant Radio Array for Neutrino Detection



UHE υ sensitivity reachable with full detector (~200k antennas, distributed)

Sufficient to test UHE diffuse flux models and transients (not shown)

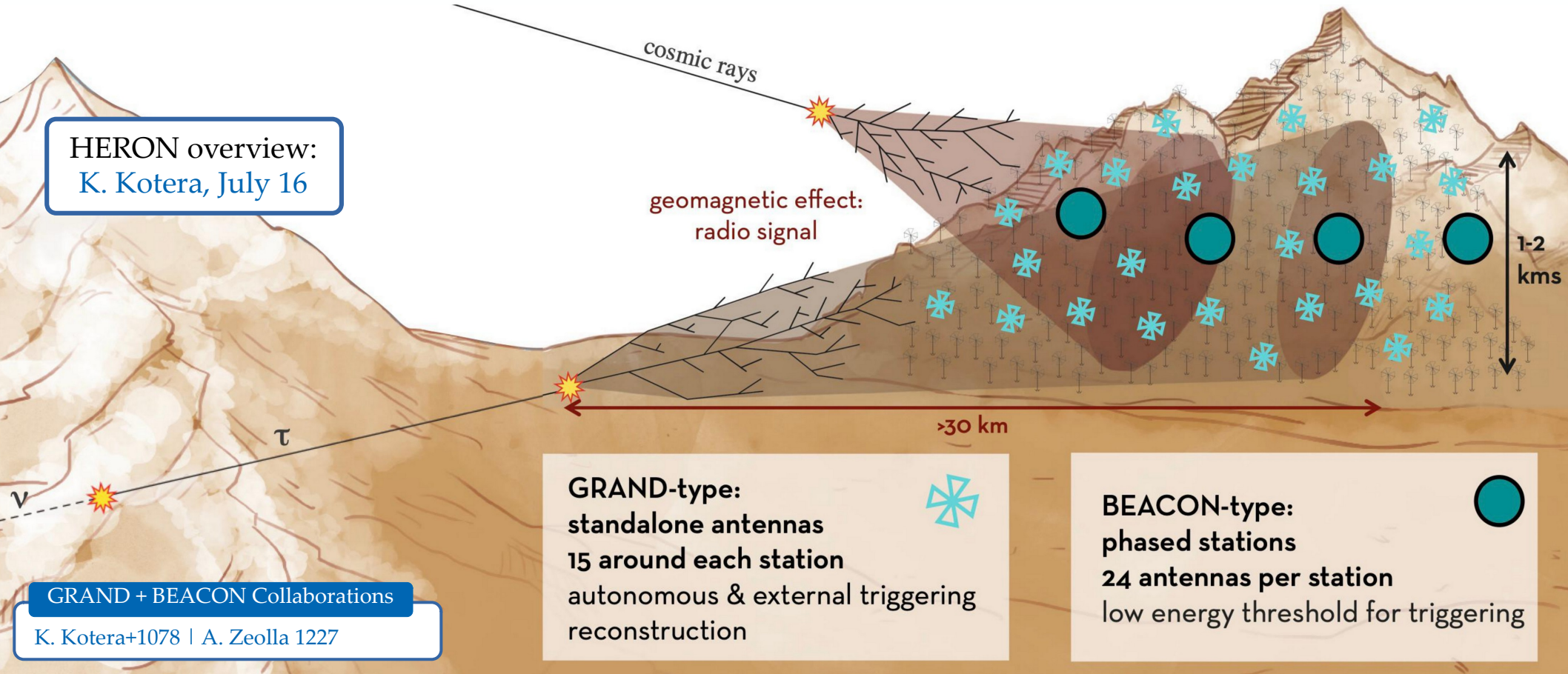
Next phase: GRAND10k

First

otrowksi

HERON: Hybrid Elevated Radio Observatory for Neutrinos

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



HERON overview:
K. Kotera, July 16

GRAND + BEACON Collaborations

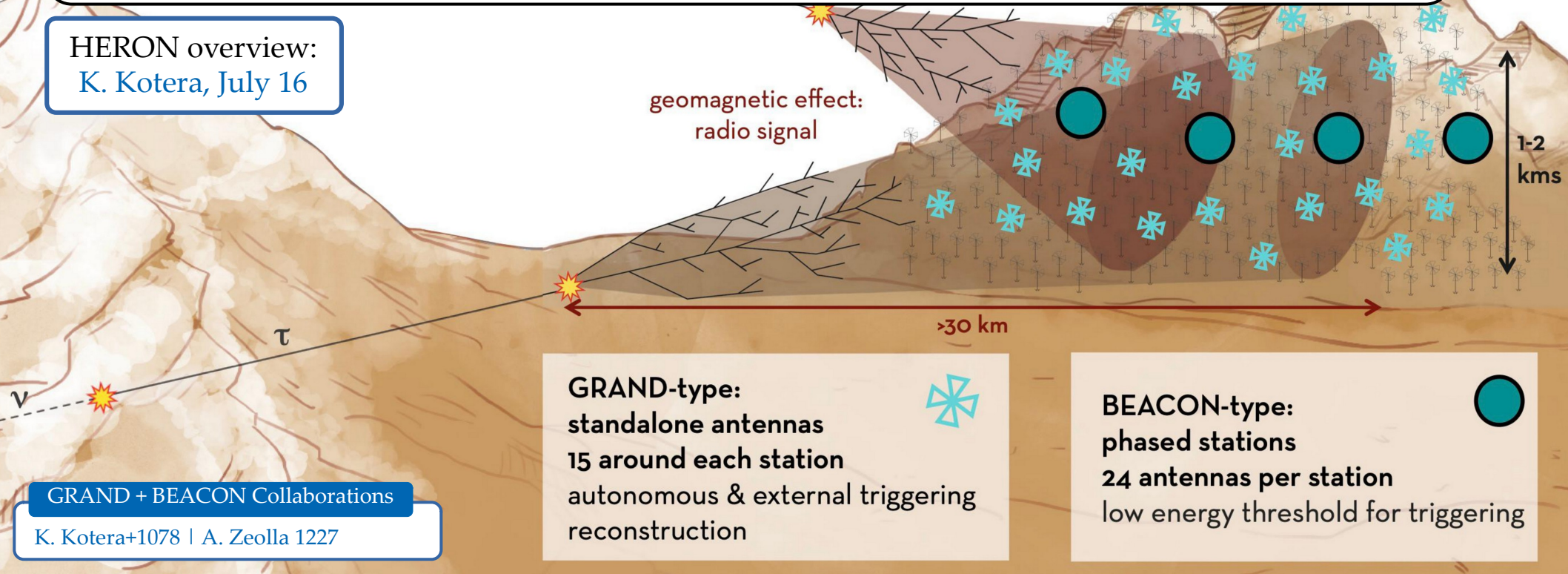
K. Kotera+1078 | A. Zeolla 1227

HERON: Hybrid Elevated Radio Observatory for Neutrinos

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

Narrow field of view, high sensitivity:
Phase 1: 24 BEACON stations + 360 GRAND antennas [≈ GRAND10k sens. for point sources]
Phase 2: 200 BEACON stations + 3k GRAND antennas [≈ GRAND, IC-Gen2 sens. for diffuse flux]

HERON overview:
K. Kotera, July 16



GRAND + BEACON Collaborations

K. Kotera+1078 | A. Zeolla 1227

HERON: Hybrid Elevated Radio Observatory for Neutrinos

BEACON phased-

Narrow field of

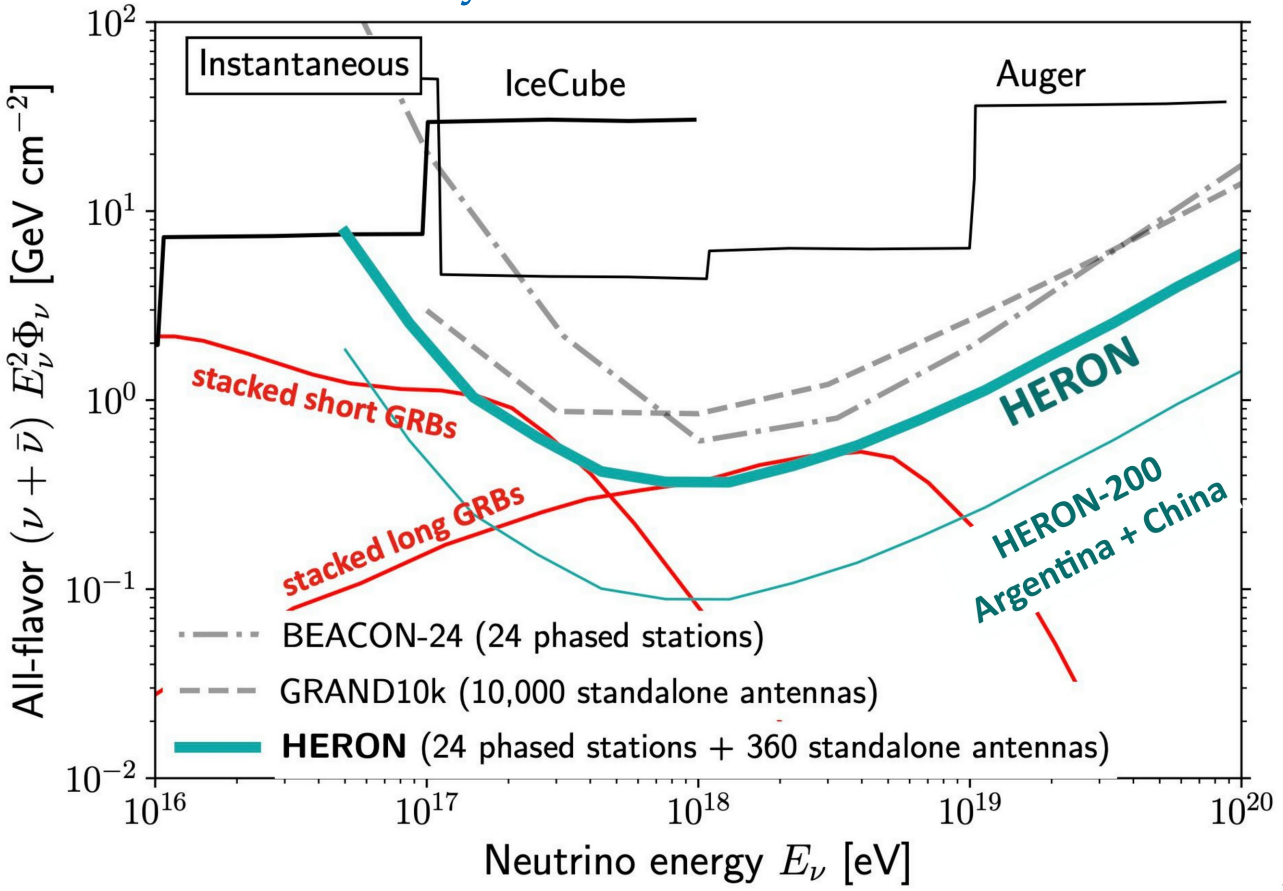
Phase 1: 24 BEA

Phase 2: 200 BEA

HERON overview

K. Kotera, July 1

Sensitivity to short UHE υ transients



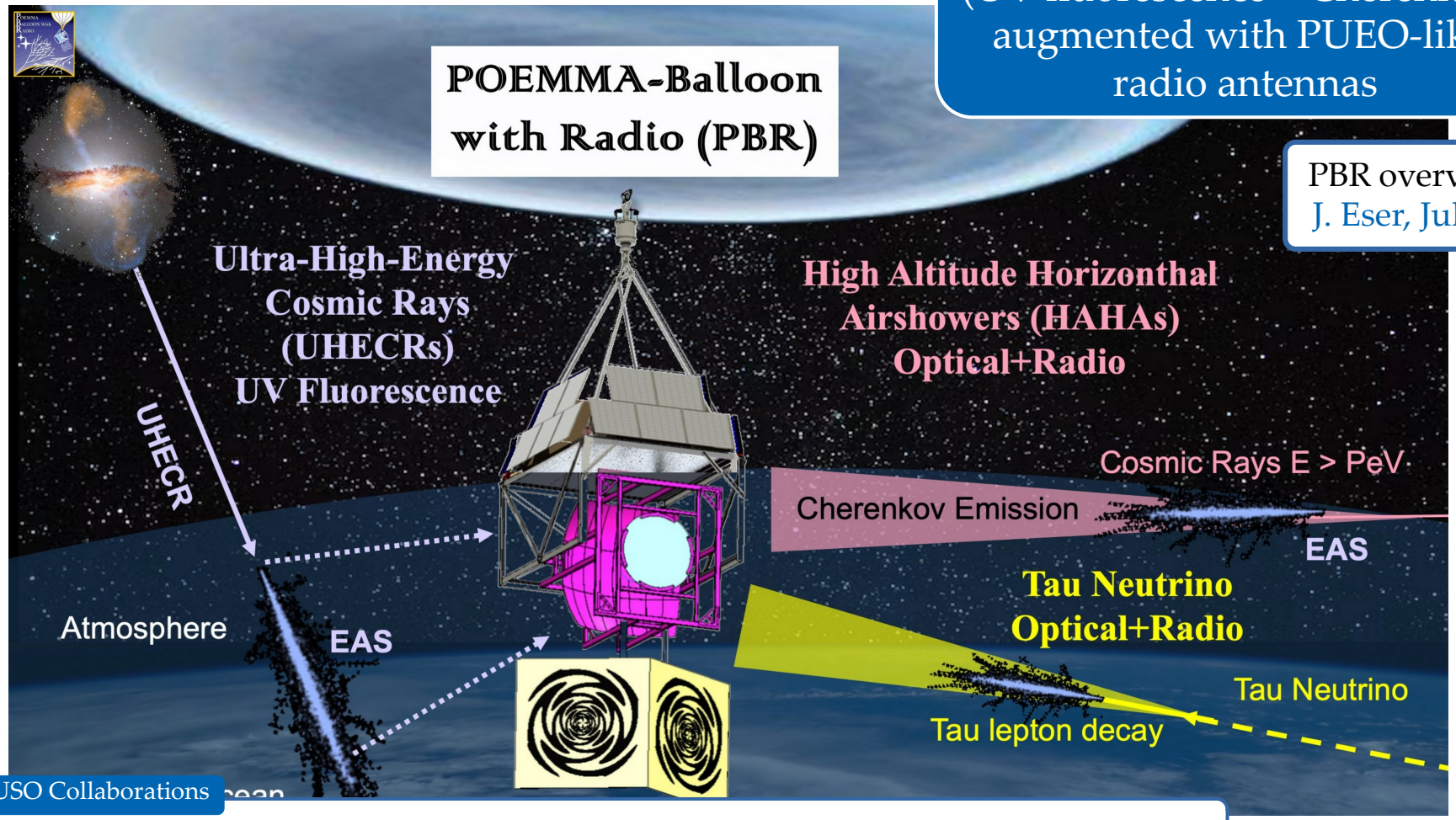
GRAND + BEACON Collabor

K. Kotera+1078 | A. Zeolla 1227

PBR: POEMMA-Balloon with Radio

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

PBR overview: J. Eser, July 22



PBR/JEM-EUSO Collaborations
J. Eser | F. Cafagna | V. Scotti | A. V. Olinto | Z. PLebaniak | M. Bertaina | M. Battisti | L. Wiencke | E. Mayotte | R. Caruso

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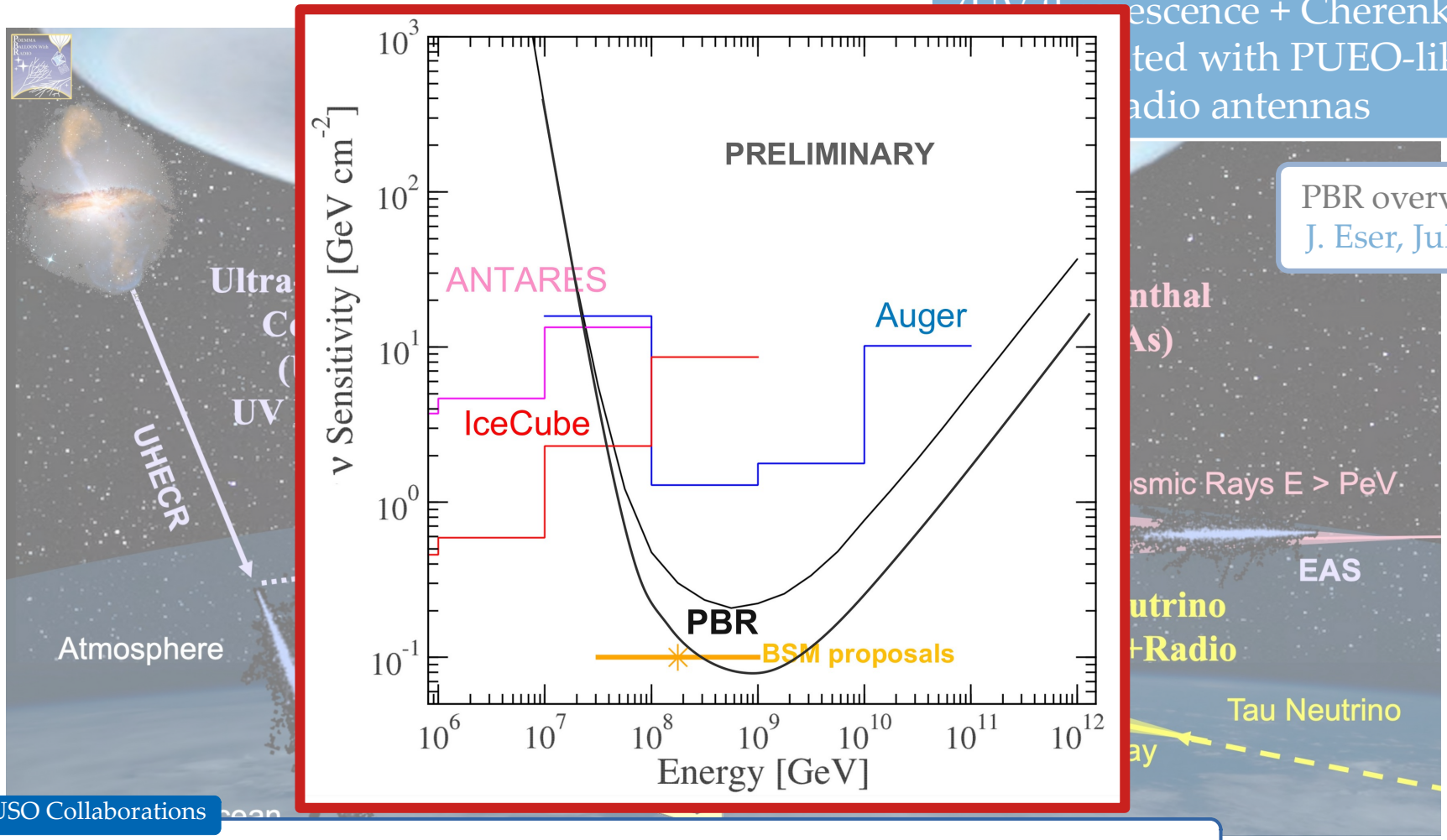

PBR/JEM-EUSO Collaborations

J. Eser | F. Cafagna | V. Scotti | A. V. Olinto | Z. PLebaniak | M. Bertaina | M. Battisti | L. Wiencke | E. Mayotte | R. Caruso

What did I think 10 years ago?

From a 2015 talk (about neutrino flavor) at U. Cincinnati:

What we know / don't know

What we know

- compatible with isotropy
- power-law $\propto E^{-2.5}$
- not coincident with transient sources (*e.g.*, GRBs)
- not correlated with known sources
- **flavor composition: compatible with equal proportion of ν_e, ν_μ, ν_τ**
- also: no prompt atmospheric neutrinos

What we don't know

- what are the sources?
- what is the production mechanism?
- is there a cut-off at 2 PeV?
- what is the Galactic contribution, if any?
- what is the precise relation to UHE cosmic rays?
- is there new physics?
- **what is the precise flavor composition of the flux?**

. . . but we have good ideas on all

From a 2015 talk (about neutrino flavor) at U. Cincinnati:

What we know / don't know

What we know

- compatible with isotropy — Still true (2310.15224)
- power-law $\propto E^{-2.5}$ — Still true
- not coincident with transient sources (*e.g.*, GRBs) — TXS 0506+056 (+ TDEs?)
- not correlated with known sources — NGC 1068
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What we don't know

- what are the sources? — Unknown, but closer
- what is the production mechanism? — Still unknown
- is there a cut-off at 2 PeV? — Still unknown
- what is the Galactic contribution, if any? — About 10% at ~ TeV
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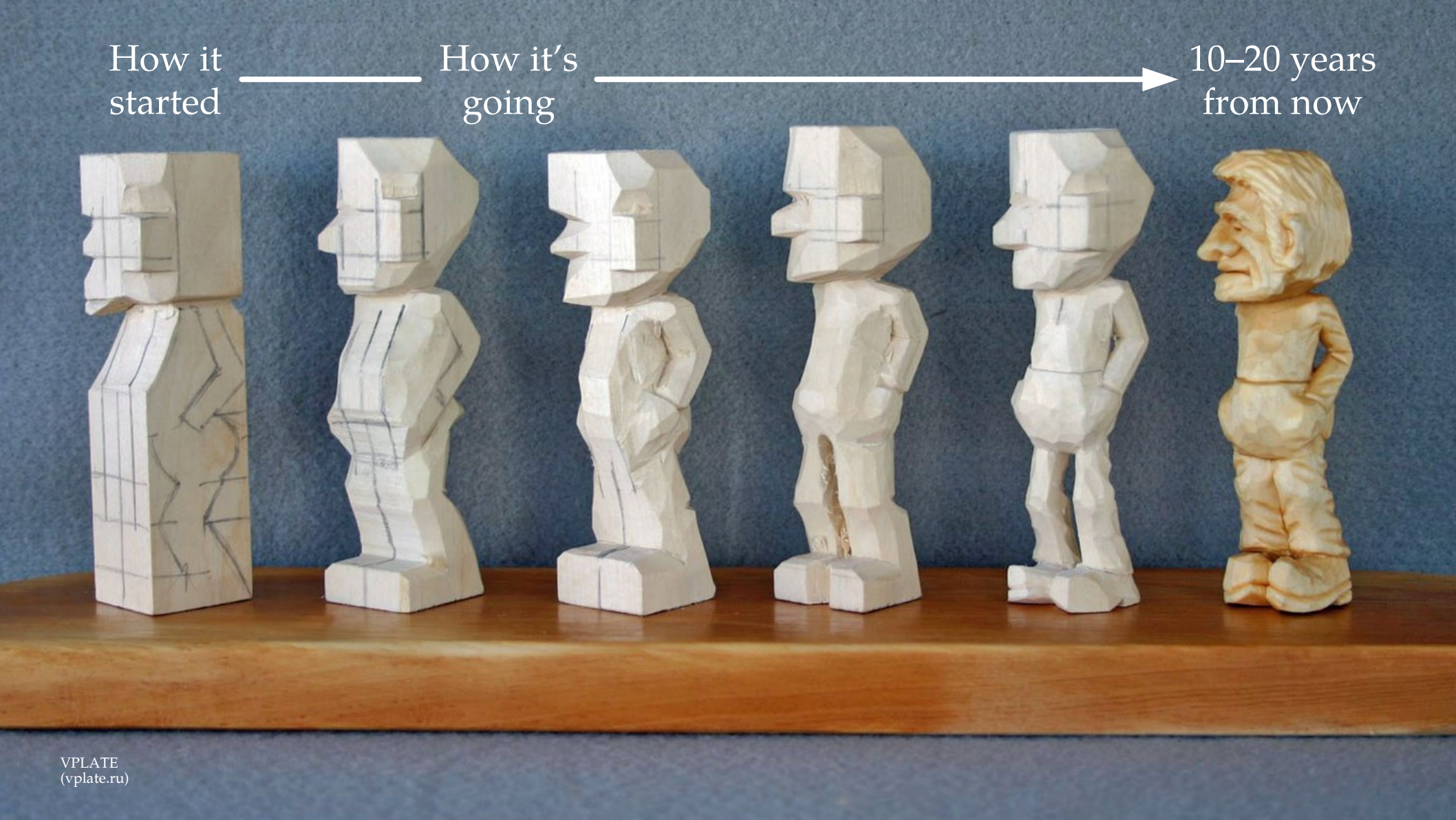
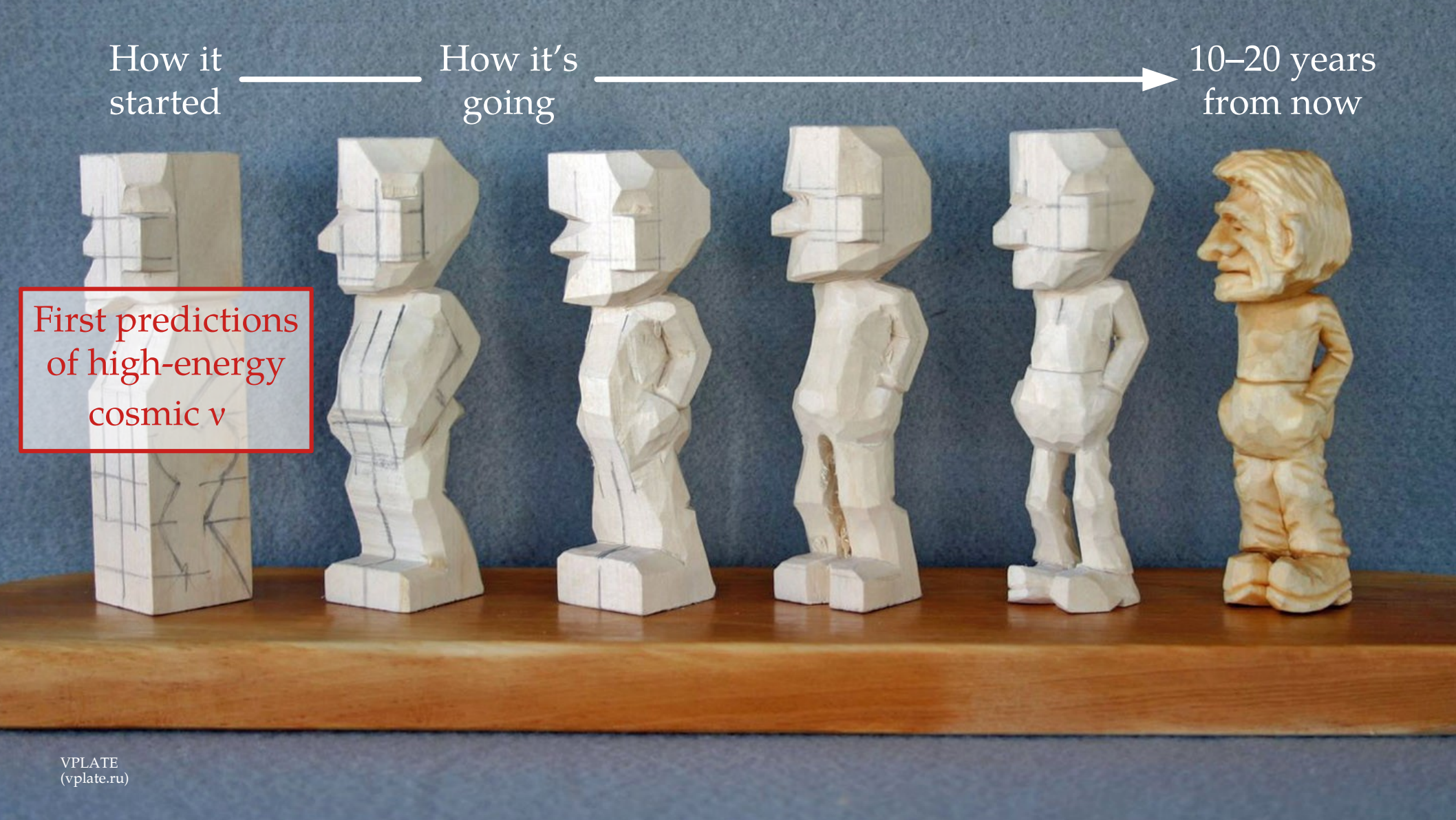
~~. . . but we have good ideas on all~~

… but we have made solid progress on all


How it started
How it's going
10–20 years from now
VPLATE
(vplate.ru)


How it started
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First predictions of high-energy cosmic ν
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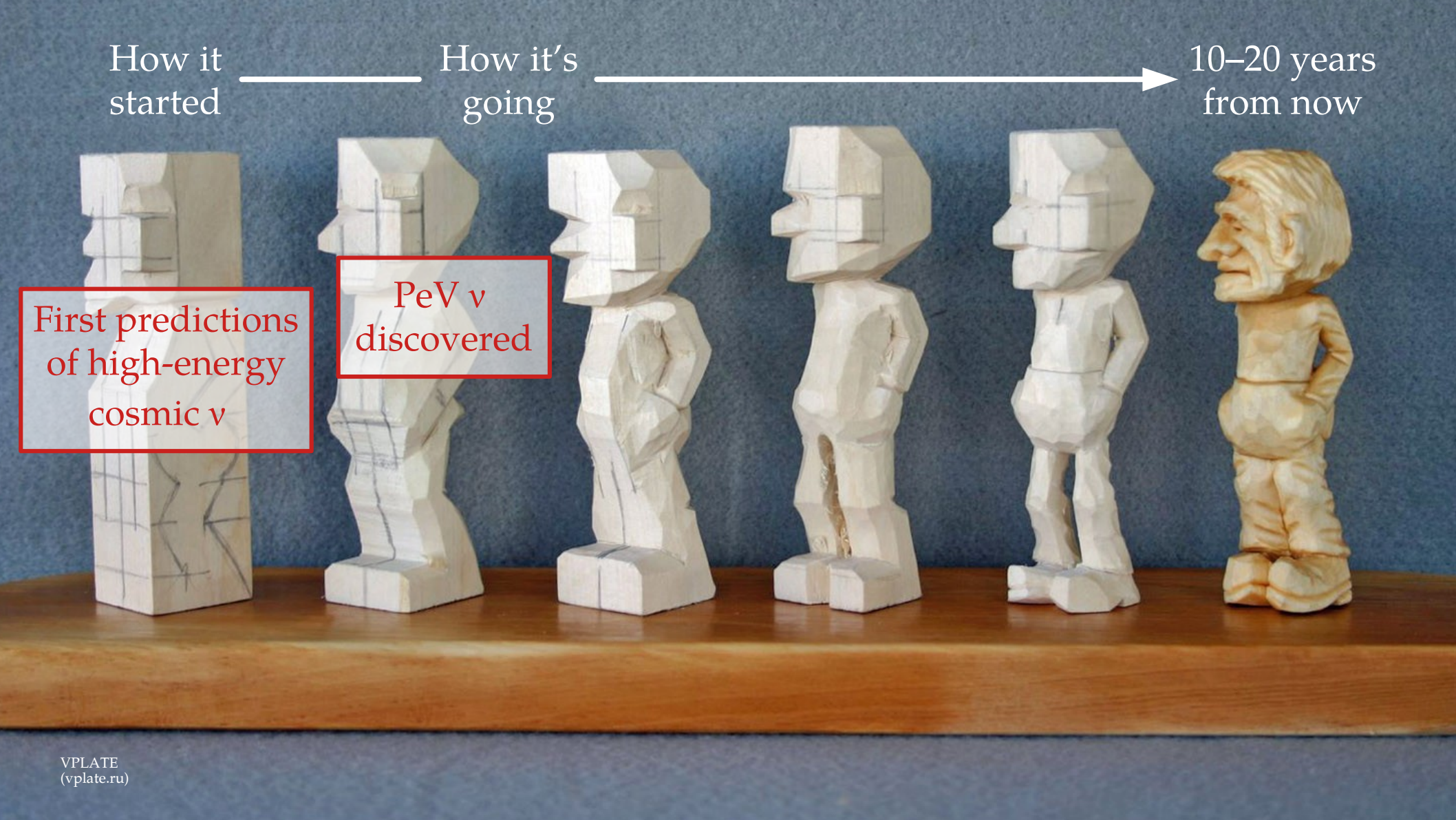
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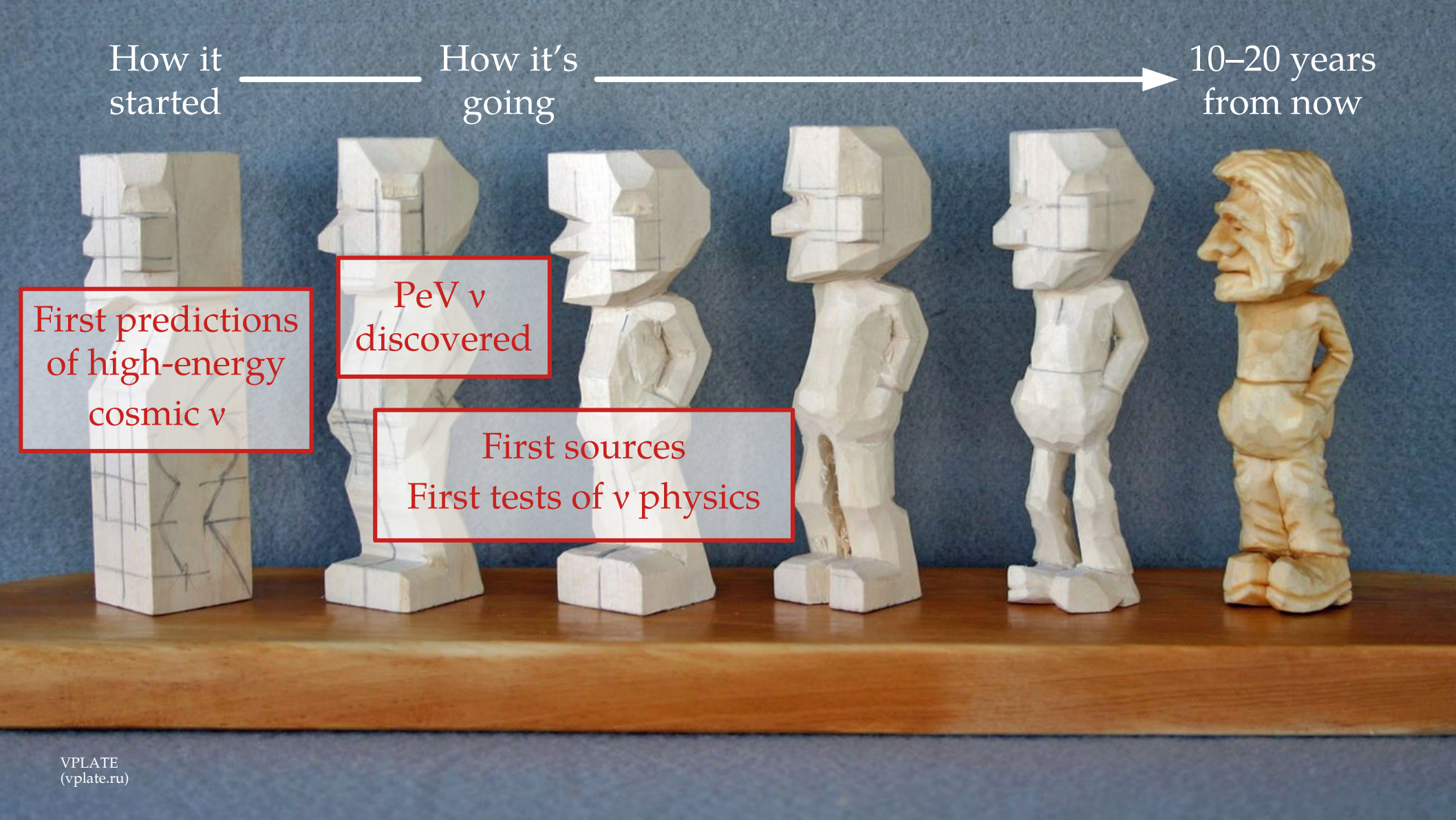
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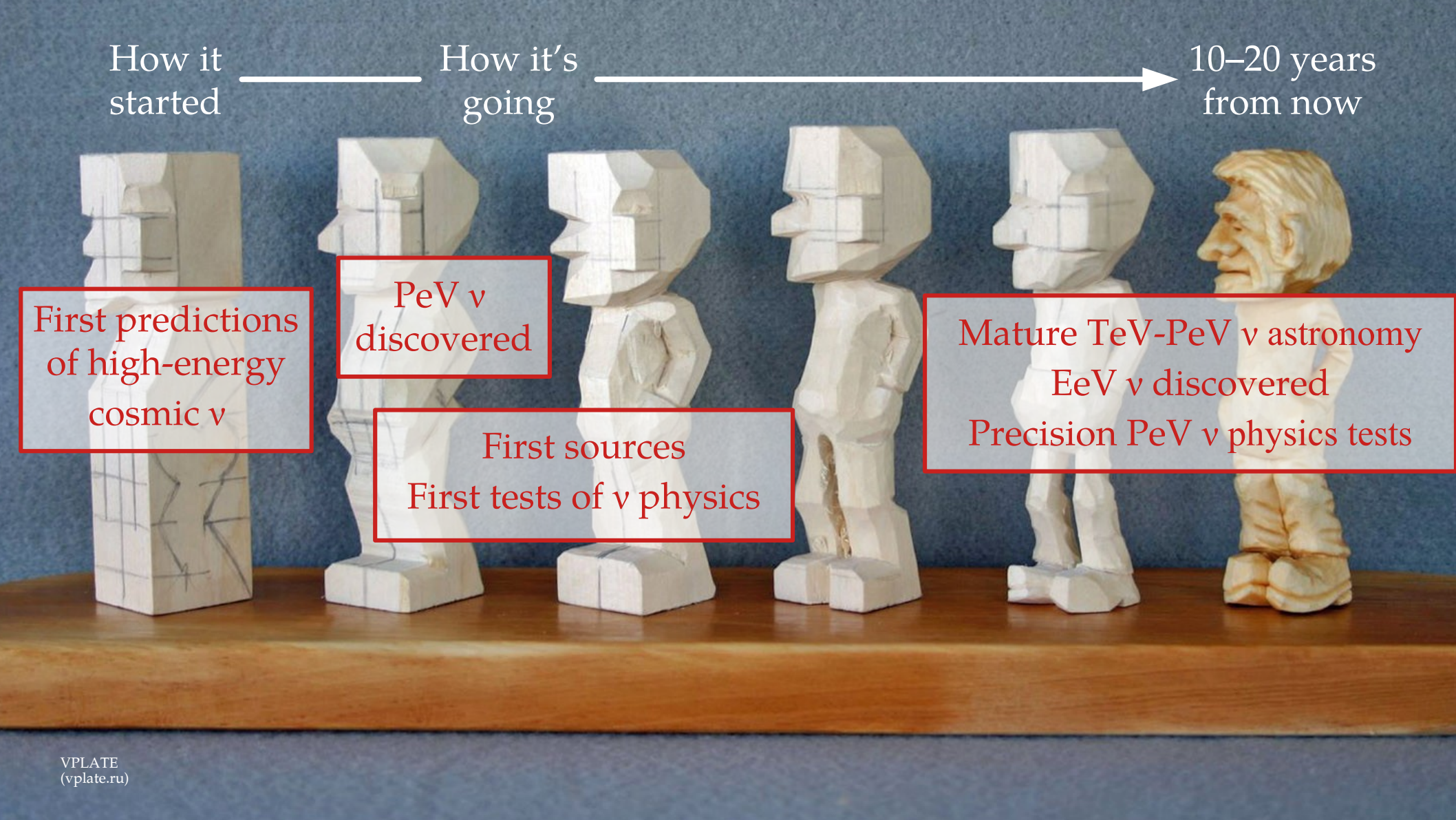
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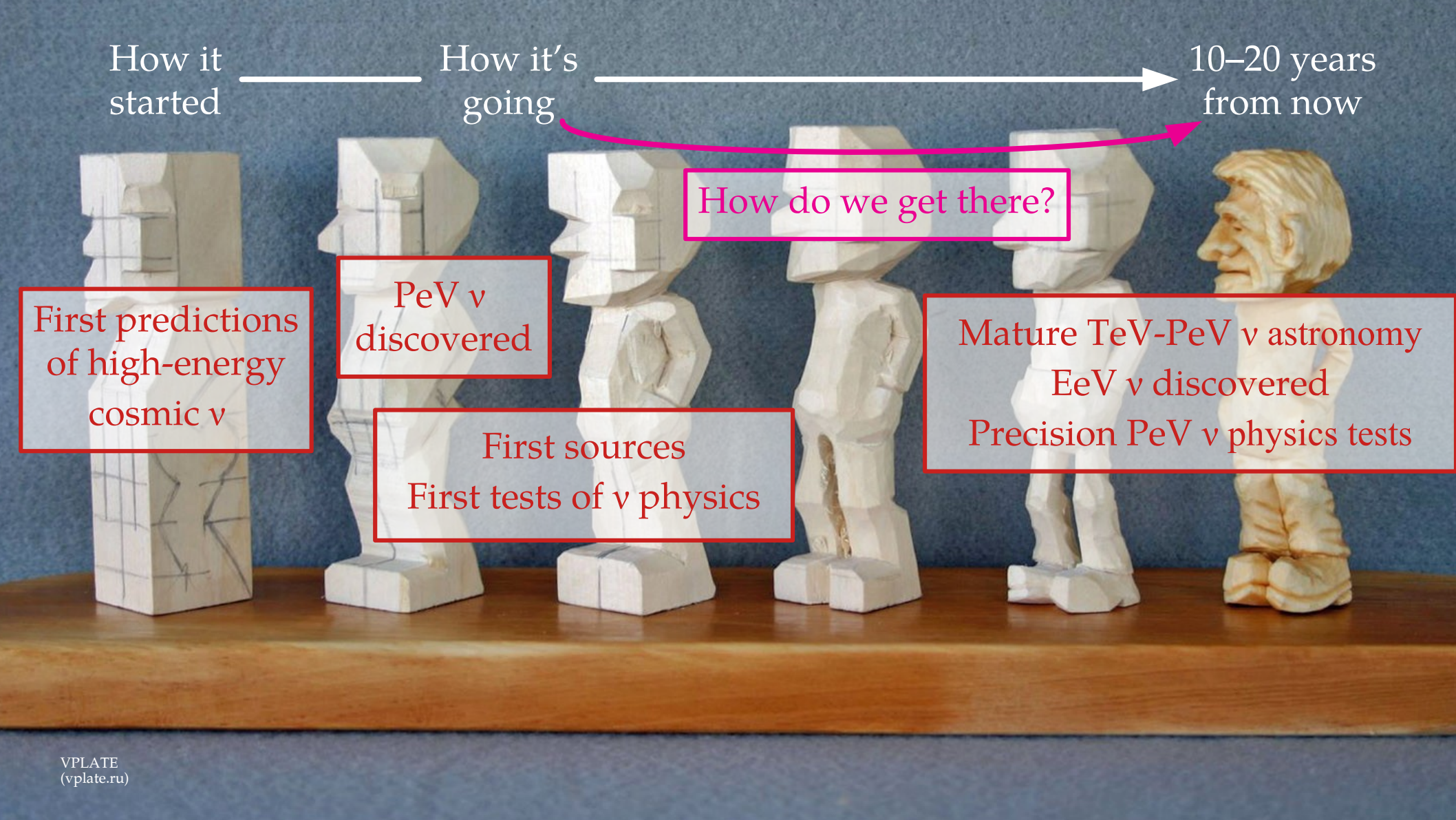
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How do we get there?
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VPLATE
(vplate.ru)

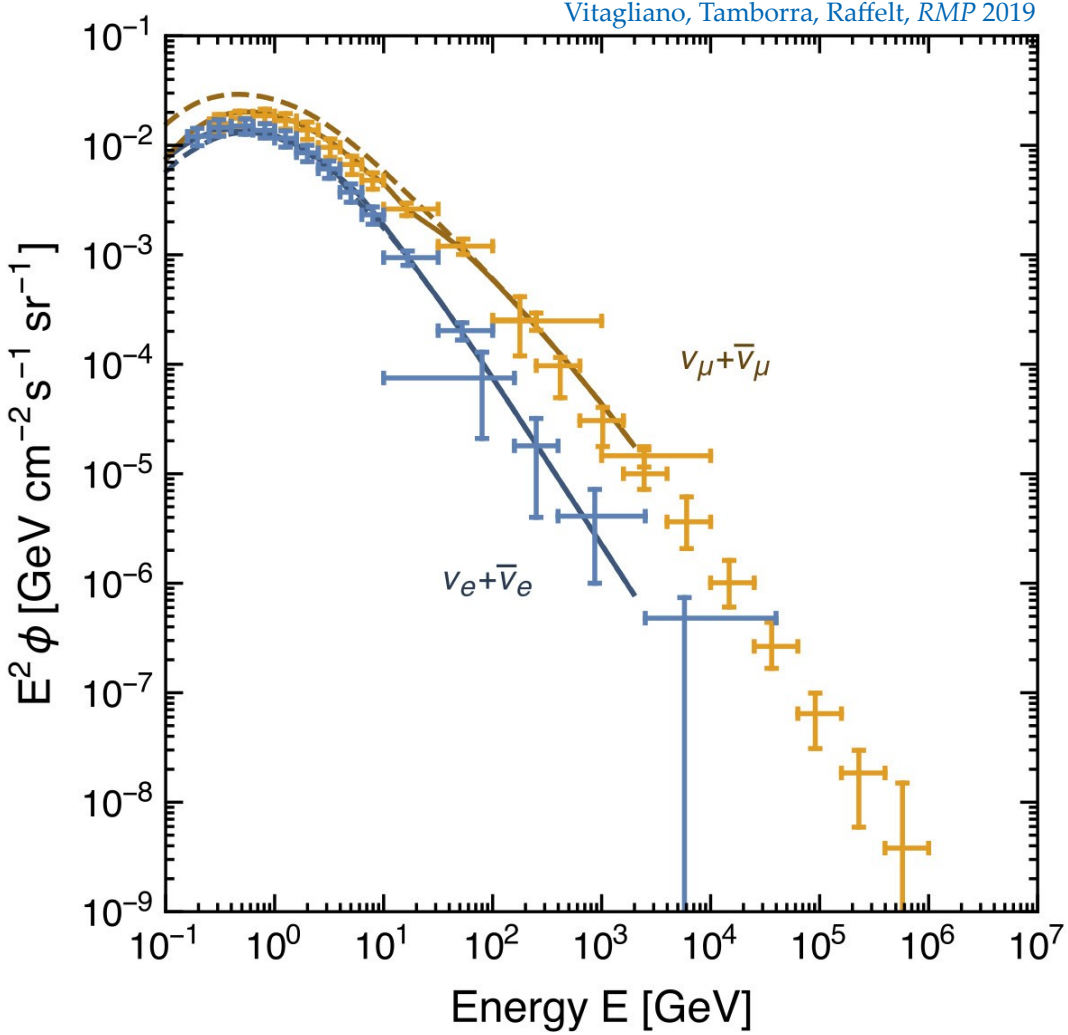
Thank you

(And heartfelt apologies for skipping some contributions)

Backup slides

Neutrinos from the Galaxy

Vitagliano, Tamborra, Raffelt, *RMP* 2019



See also: Beacom & Candia, *JCAP* 2004

Neutrinos from the Galaxy

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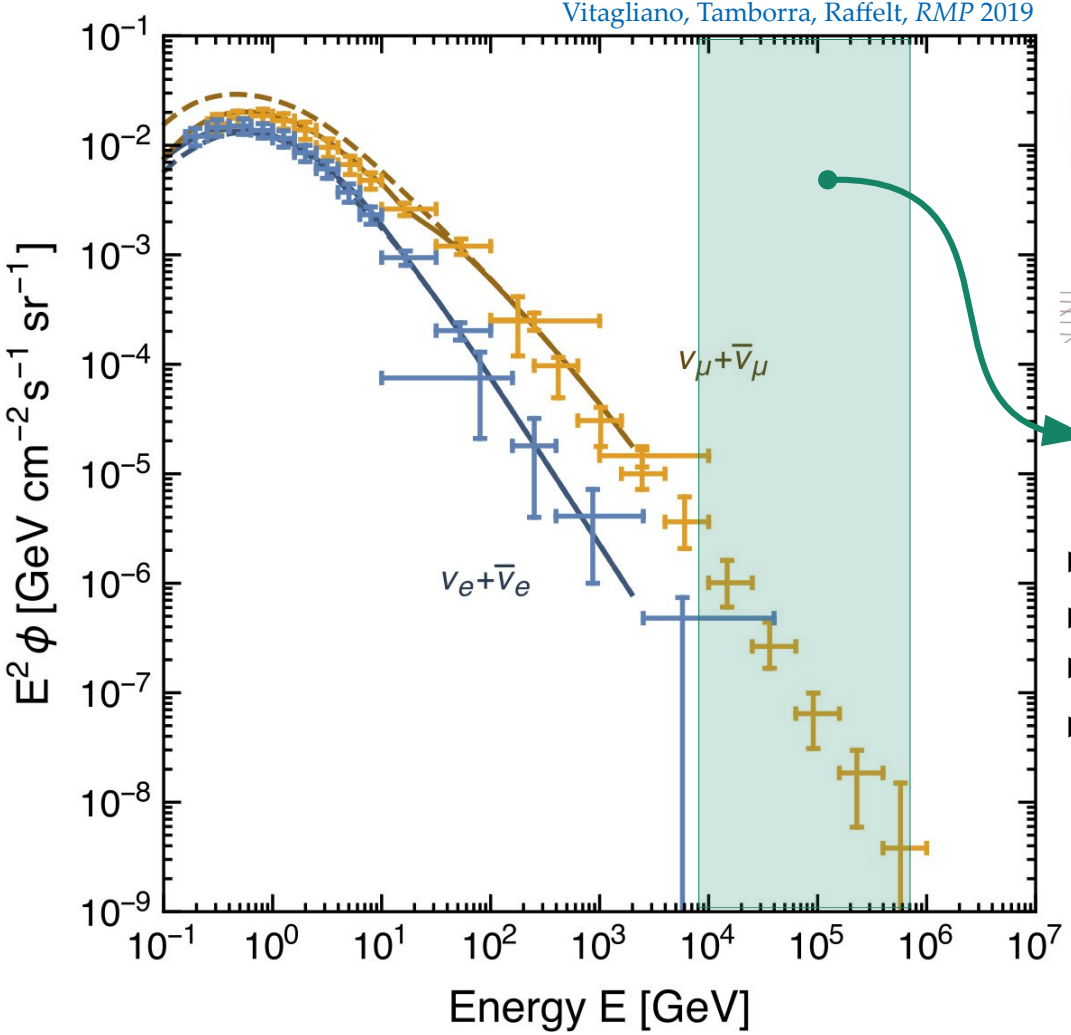
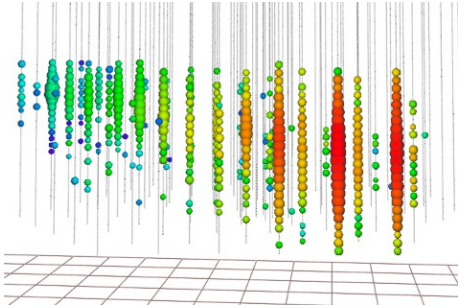


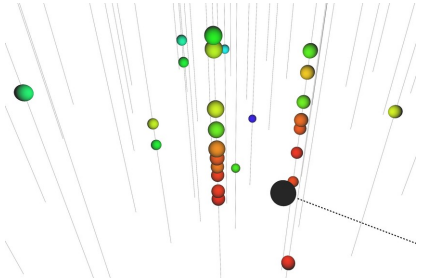


Search for **>10-TeV** astrophysical ν

- Use ***muon tracks***
- Pointing accuracy: ~1°
- Atm. bg. is mostly ν_μ
- Self-veto screens for atm. muons to cut ν bg.

See also: Beacom & Candia, *JCAP* 2004

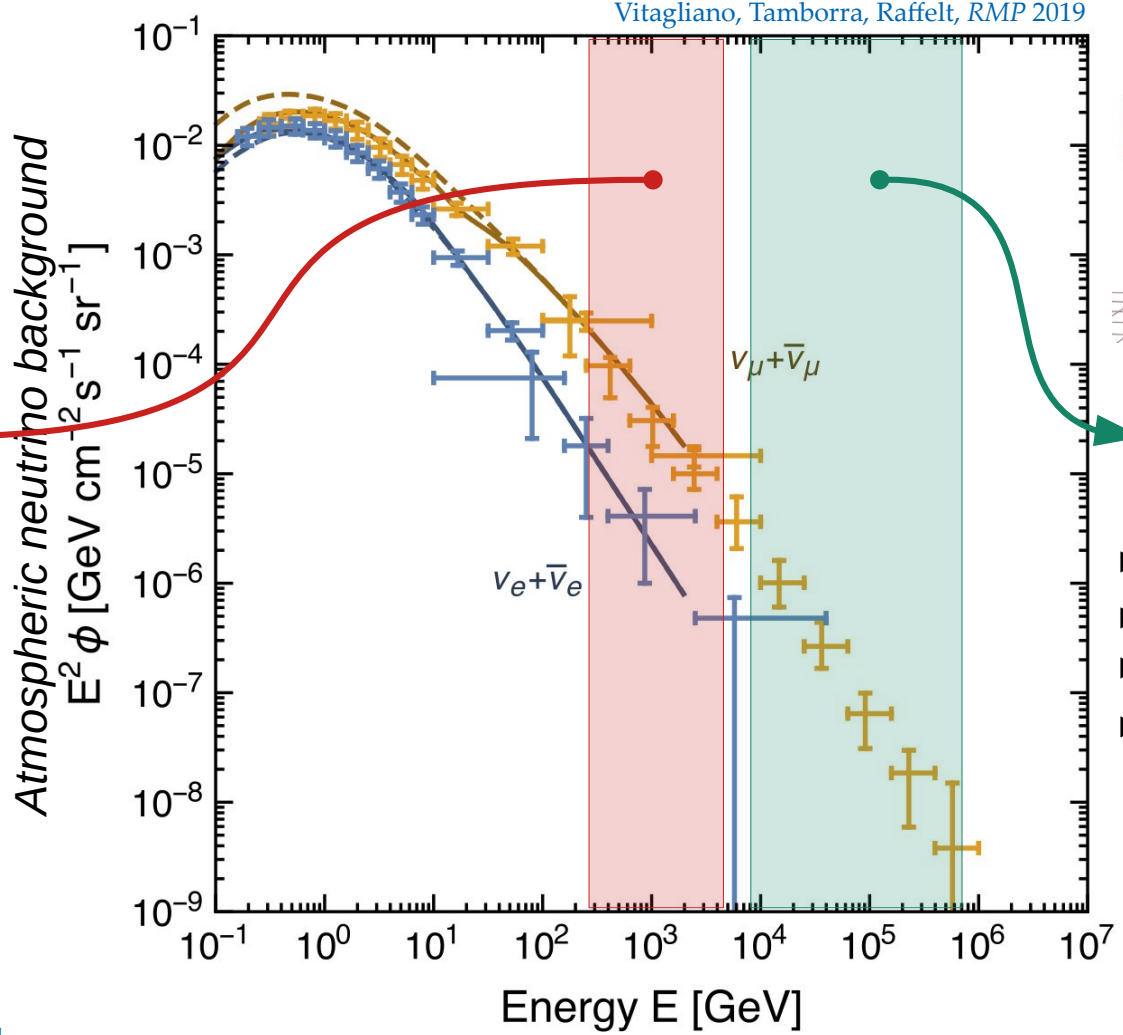
Neutrinos from the Galaxy

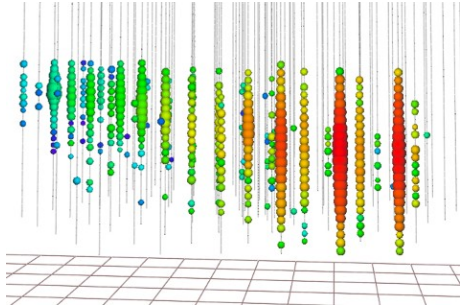


Search for **TeV** astrophysical ν

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

Vitagliano, Tamborra, Raffelt, *RMP* 2019





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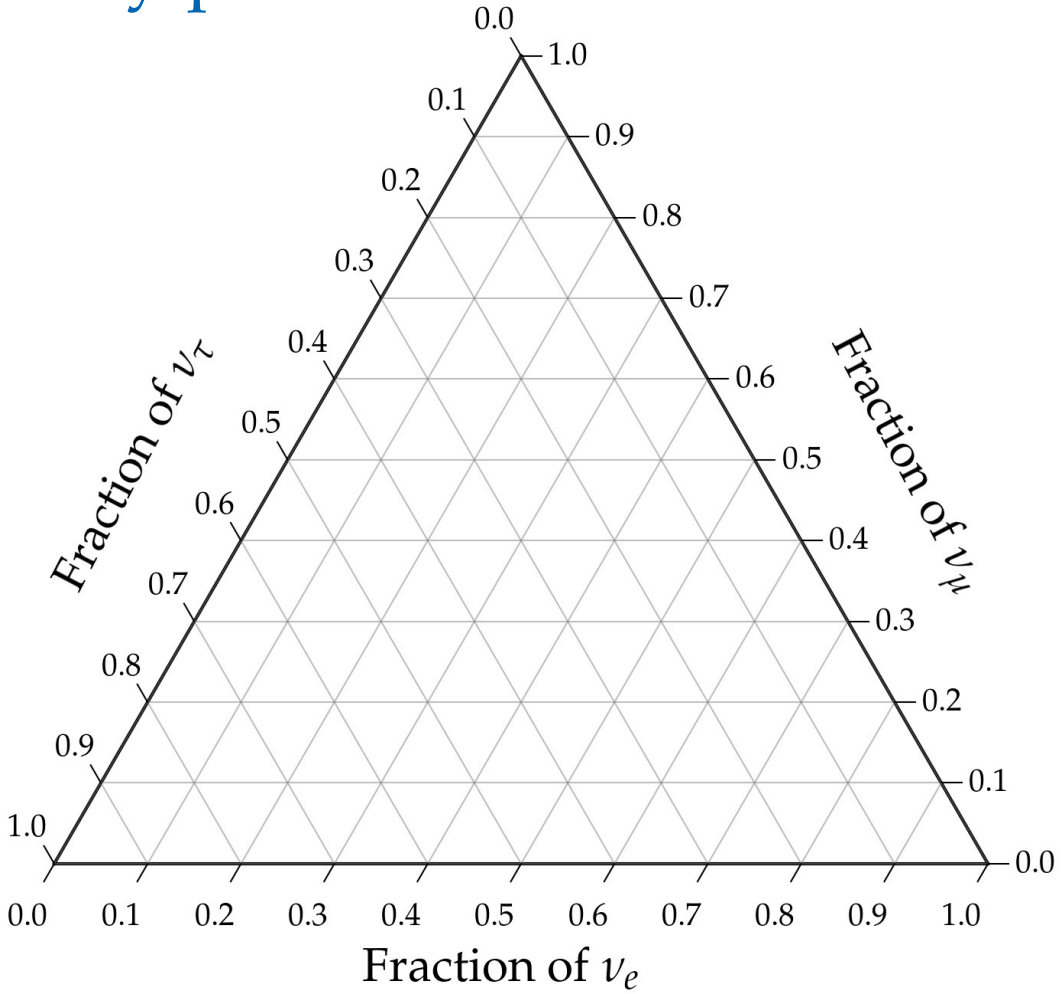
Quick aside: how to read a ternary plot

Assumes underlying unitarity –
sum of projections on each axis is 1

How to read it:

Follow the tilt of the tick marks

Always in this order: (f_e, f_μ, f_τ)



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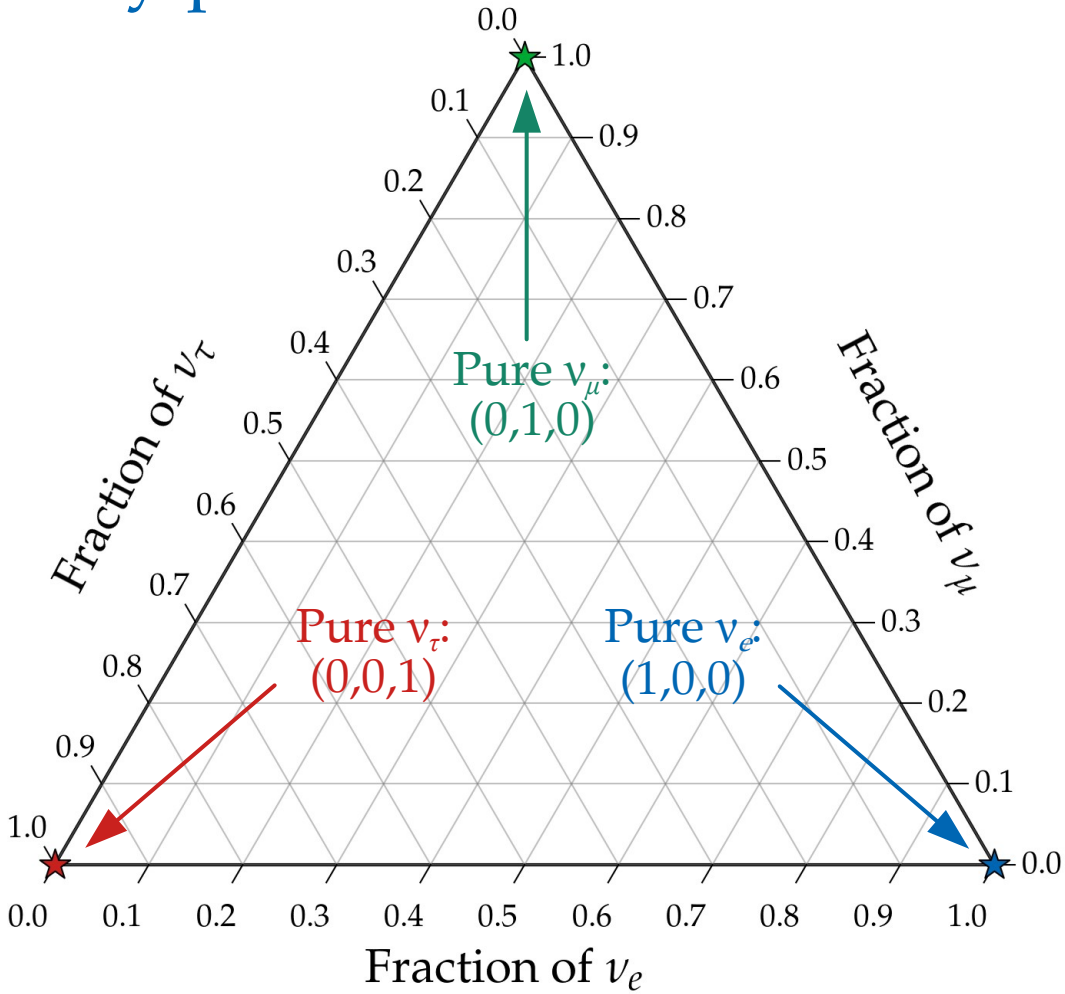
sum of projections on each axis is 1

How to read it:

Follow the tilt of the tick marks

Always in this order: (f_e, f_μ, f_τ)



Quick aside: how to read a ternary plot

Assumes underlying unitarity –
sum of projections on each axis is 1

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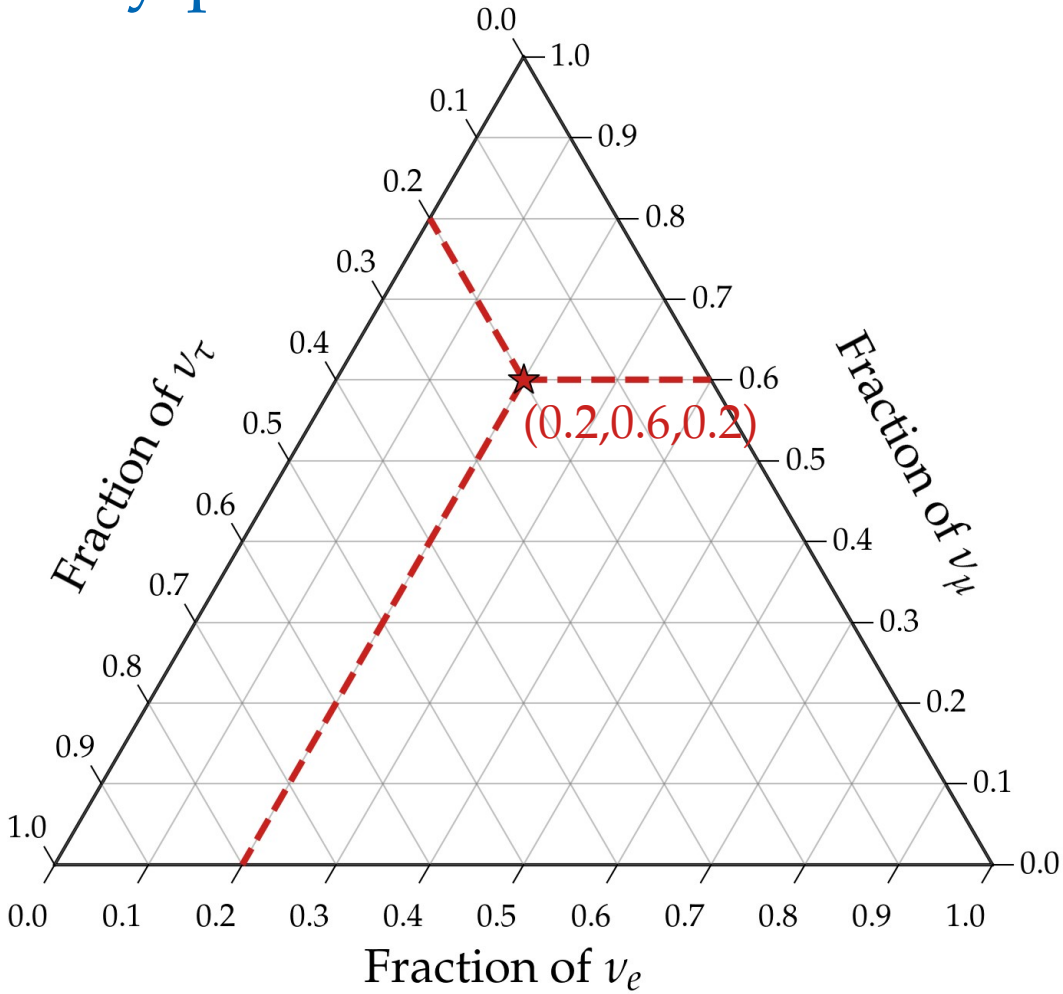

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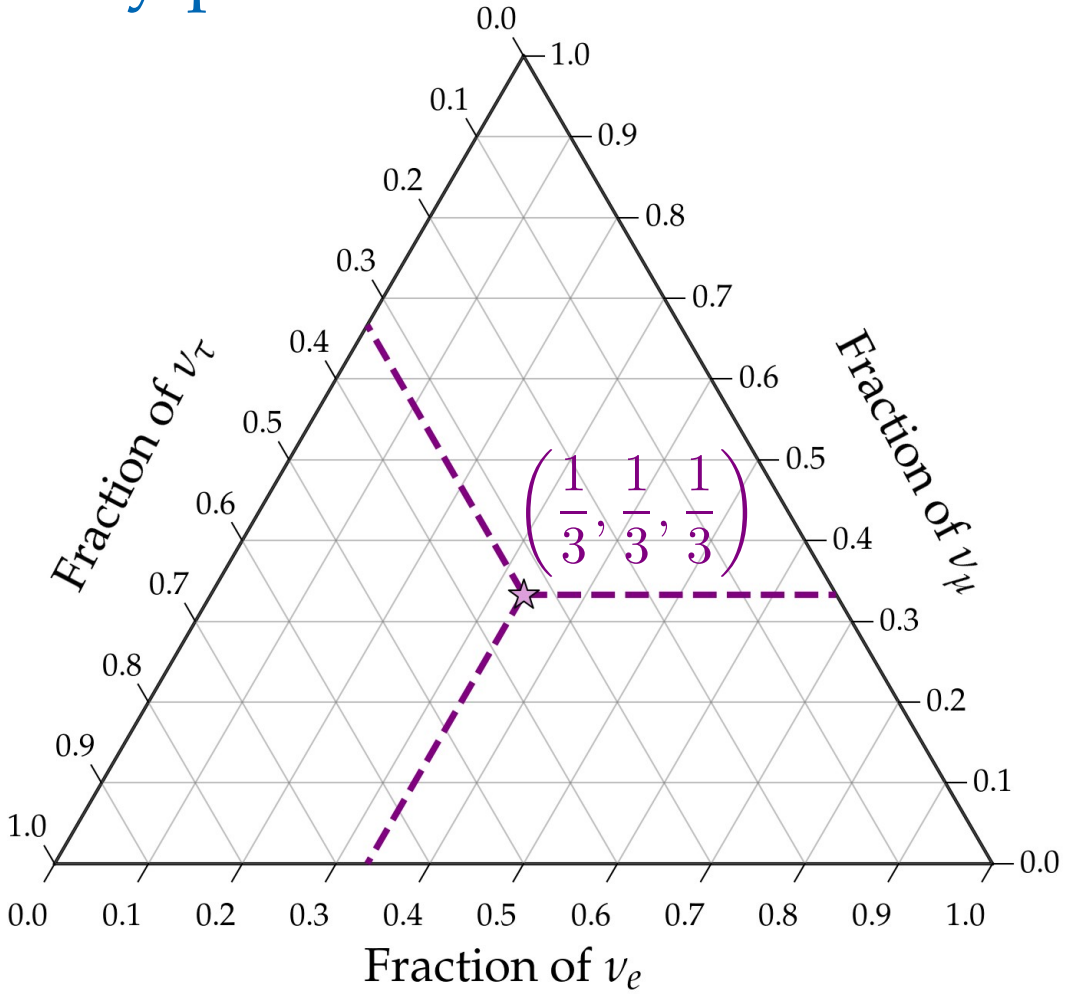
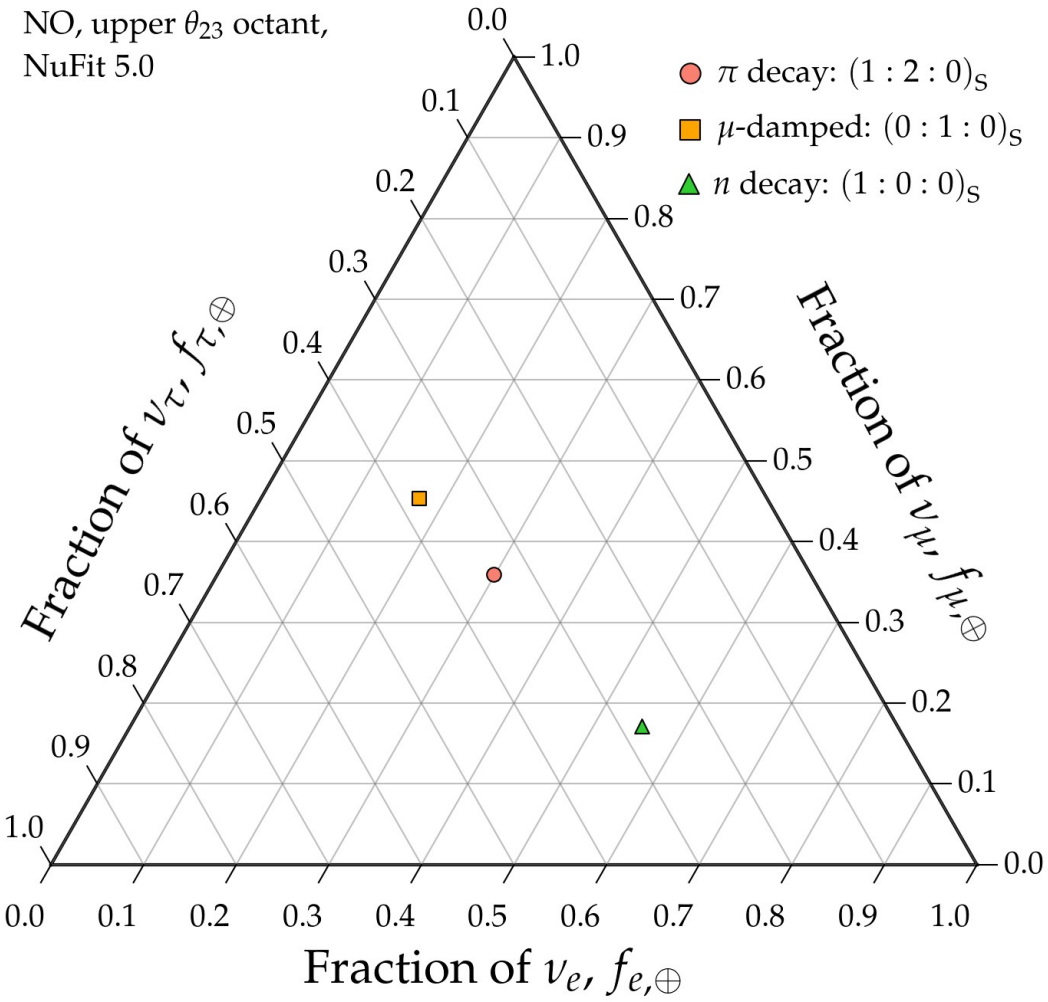


Theoretically palatable regions: today



Note:
All plots shown are for normal neutrino mass ordering (NO); inverted ordering looks similar

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
See also: **MB**, Beacom, Winter, *PRL* 2015

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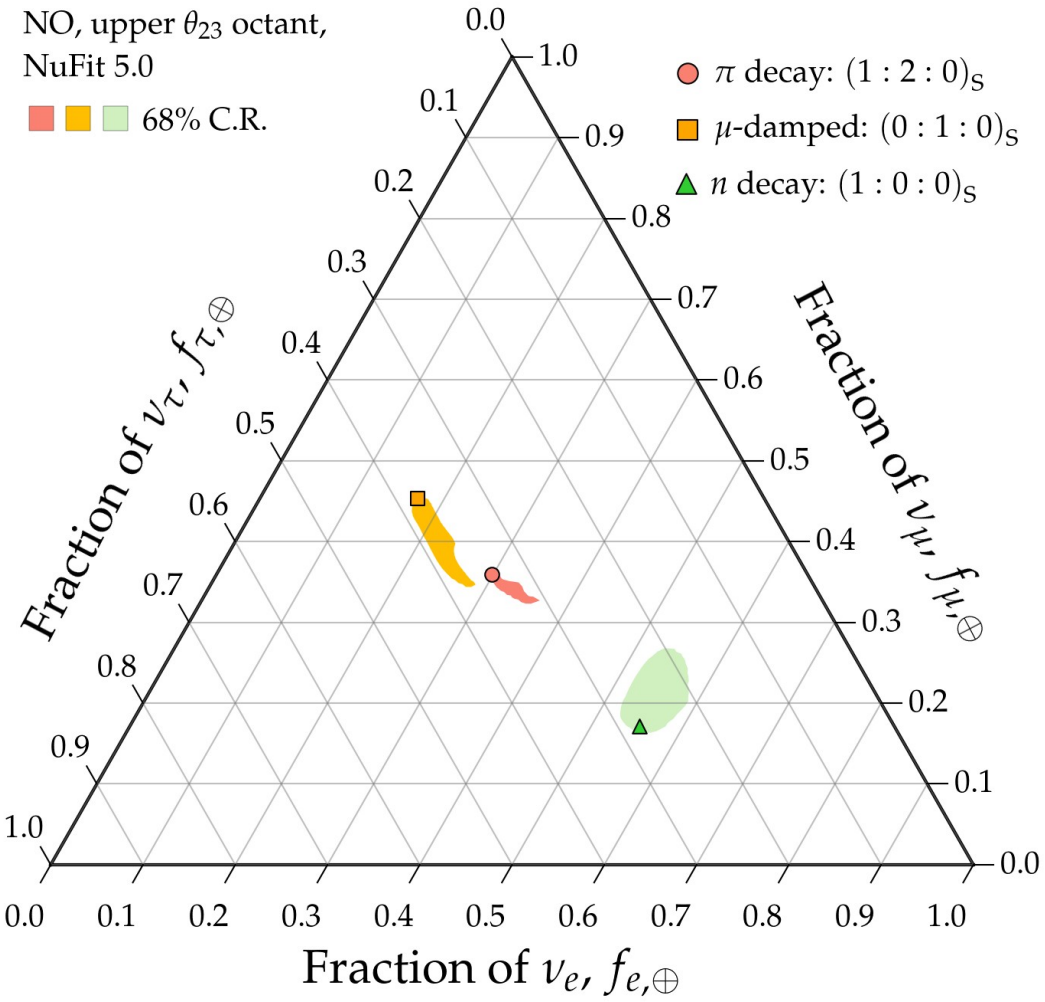

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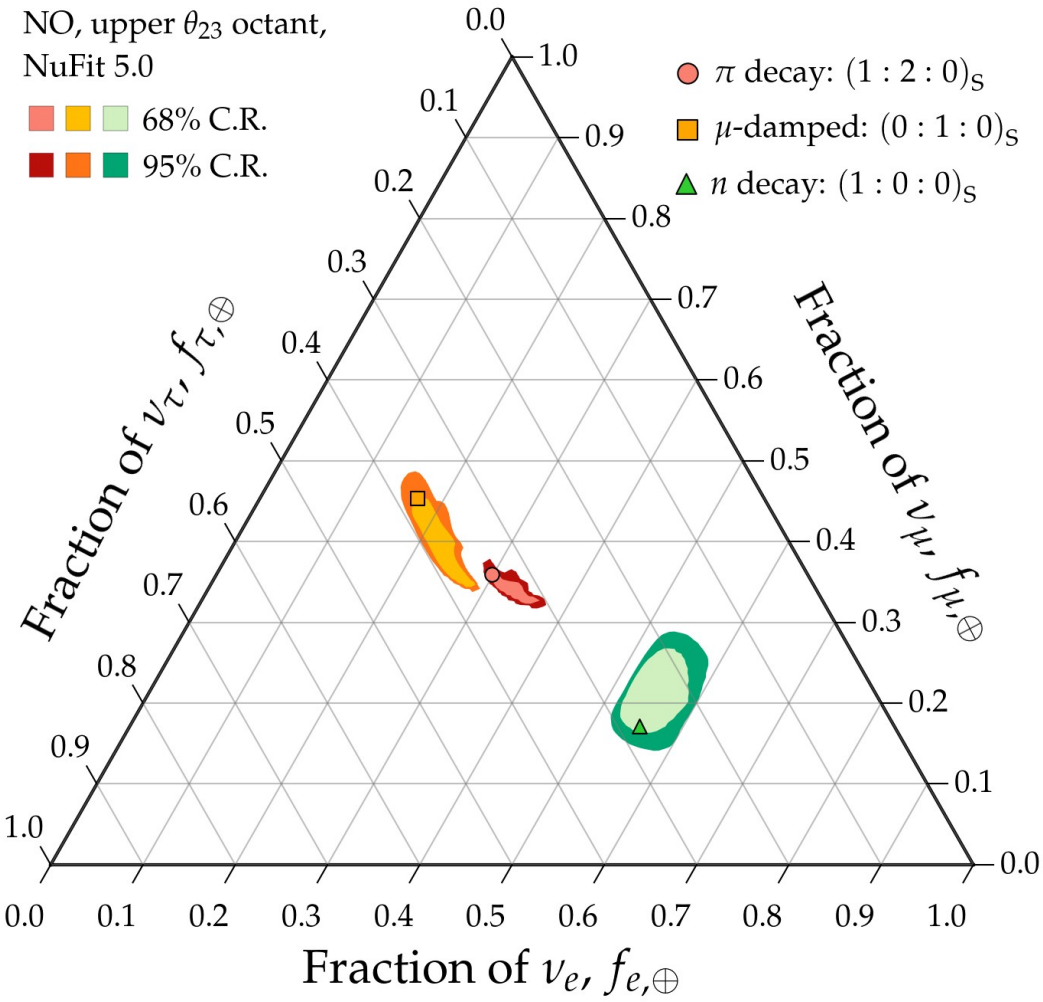

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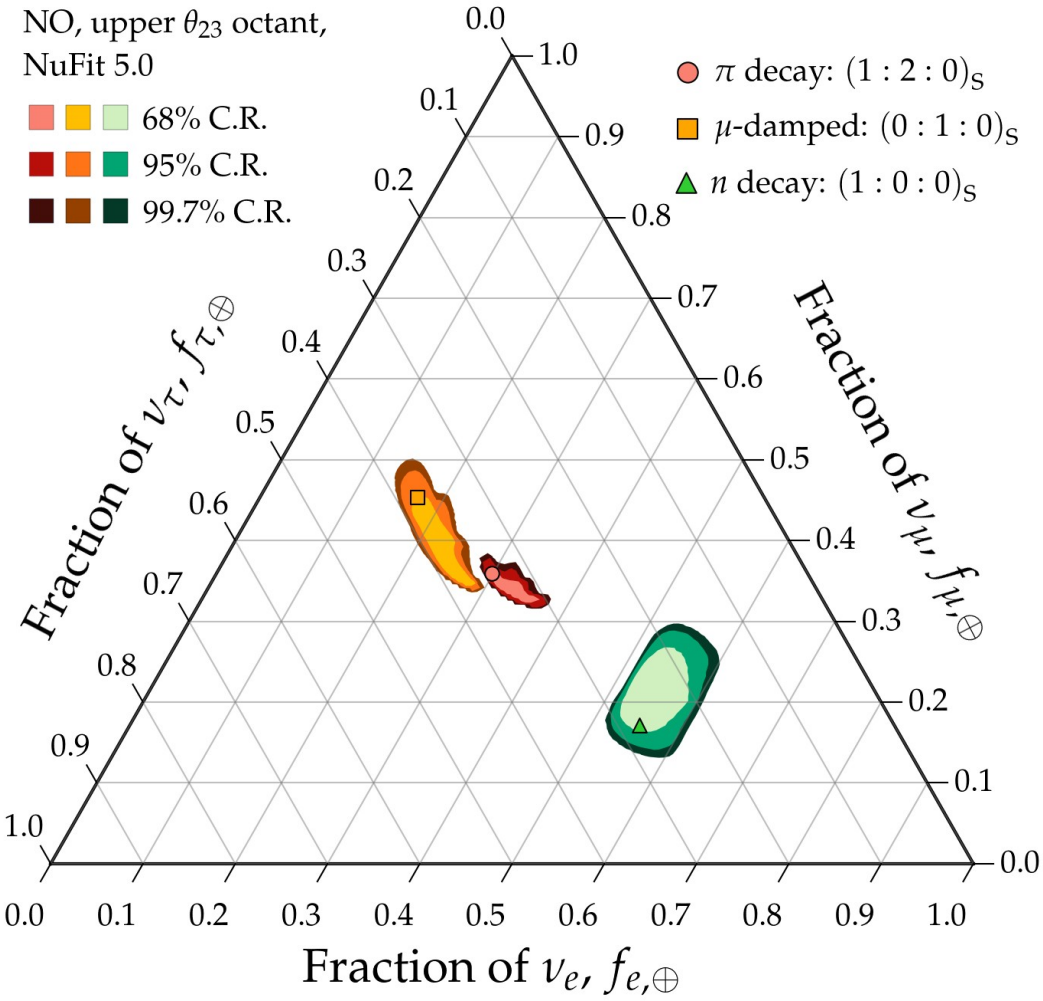

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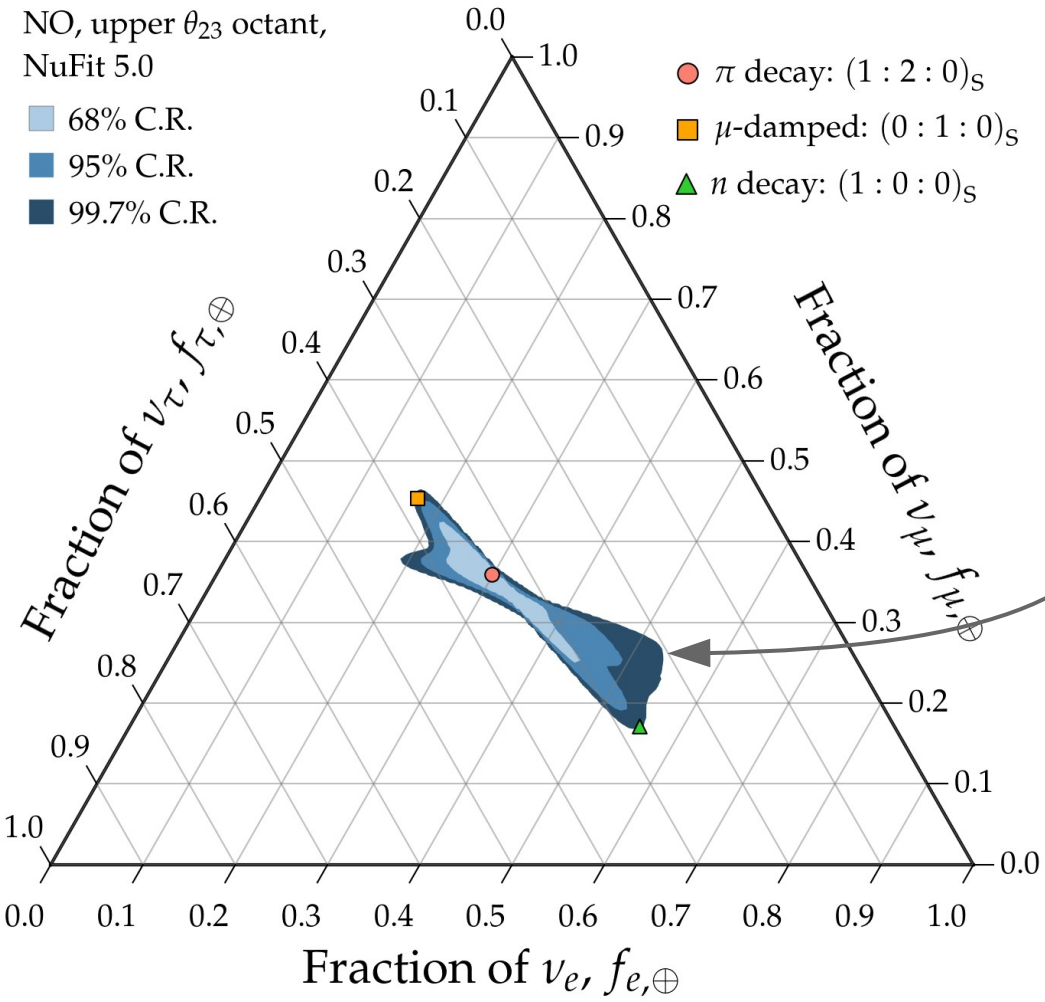

Varying over all possible flavor ratios at the source

Note:
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Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
See also: **MB**, Beacom, Winter, *PRL* 2015

BSM models in connection to KM3-230213A

Lorentz-invariance violation

Superluminal neutrinos (2502.09548, 2502.12070, 2502.18256)
Time delay (14 years!) *vs.* gamma rays from a GRB (2502.13093, 2503.14471)
From the muon surviving enhanced $\mu \to e + \gamma$ while traveling underground (2502.13201)

Decay of heavy dark matter

Decay of 400-PeV DM (2503.00097, 2503.04464, 2503.14332, 2503.18737, 2504.01447)
Heavy scalar decays into sterile ν that decays into active ν (2503.07776)

Sterile-active neutrino transition

Motivated by observation in KM3NeT, but not IceCube (2502.21299)

Primordial black hole evaporation

Possibly with "memory burden" to lengthen PBH life (2502.19245, 2503.19227, 2503.21740)

Mirror neutrons

UHE $n' \to n \to \nu$ reconciles heavy UHECR masses with high cosmogenic ν flux (2503.14419)

Do we live in a simulation? (2504.08461)

Lorentz-invariance violation — from superluminal speeds

A superluminal ν loses energy via pair production, *i.e.*,

$$\nu \rightarrow \nu + e^{+} + e^{-}$$

Cohen & Glashow, *PRL* 2011

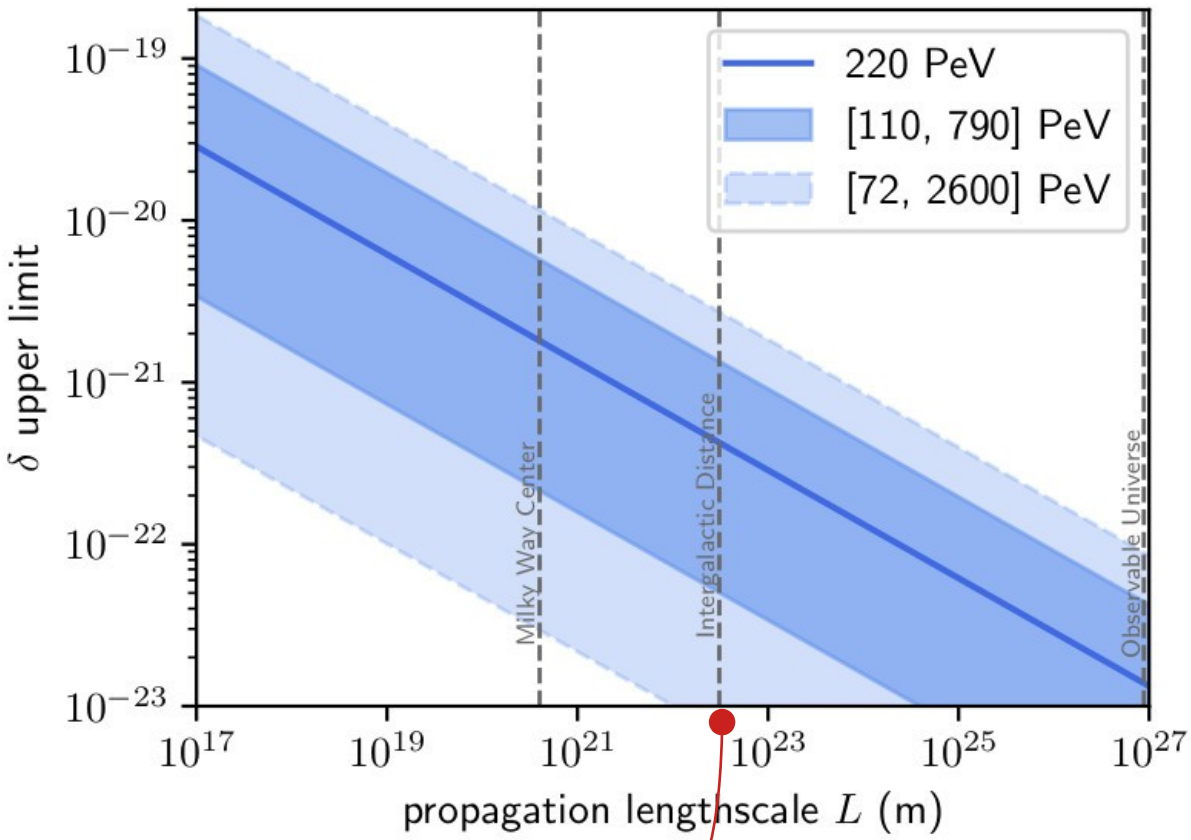
Excess over light speed: $\delta = c_\nu - 1$

Decay length: $L_{dec} = c_\nu / \Gamma \propto E^{-5} \delta^{-3}$

Decay width

Demanding that the travel distance $L < 10\, L_{dec}$ sets upper limits on δ

KM3NeT Collab., 2502.12070



New limit is ~1000 times stronger than previous one from TXS 0506+056

Lorentz-invariance violation — from a GRB association

GRB emitted neutrinos & photons simultaneously

Time delay induced by dispersion of neutrinos on spacetime foam:

Neutrino energy

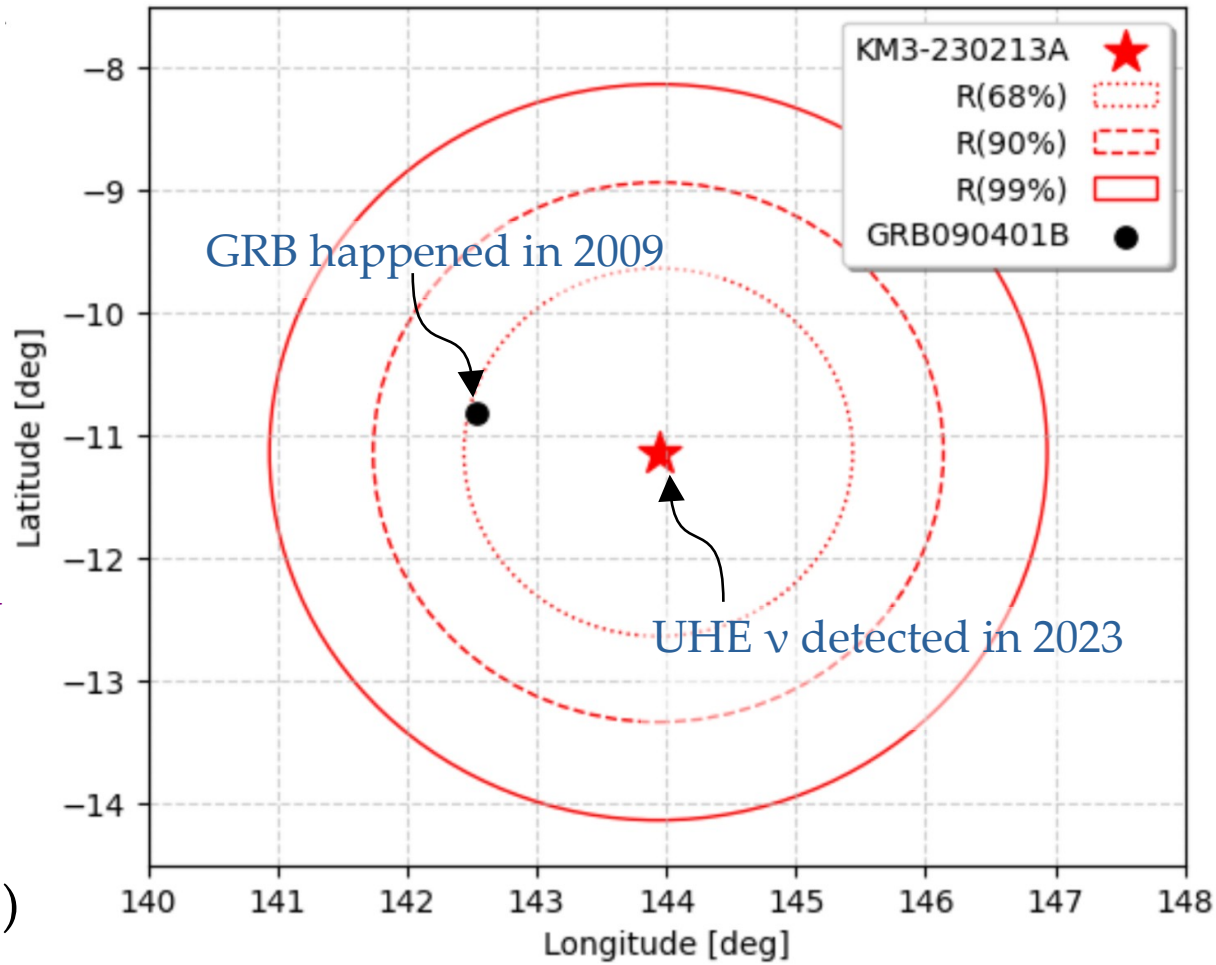
$$\Delta t = D(z)\frac{E}{\Lambda} \approx 14 \text{ years}$$

Cosmological expansion

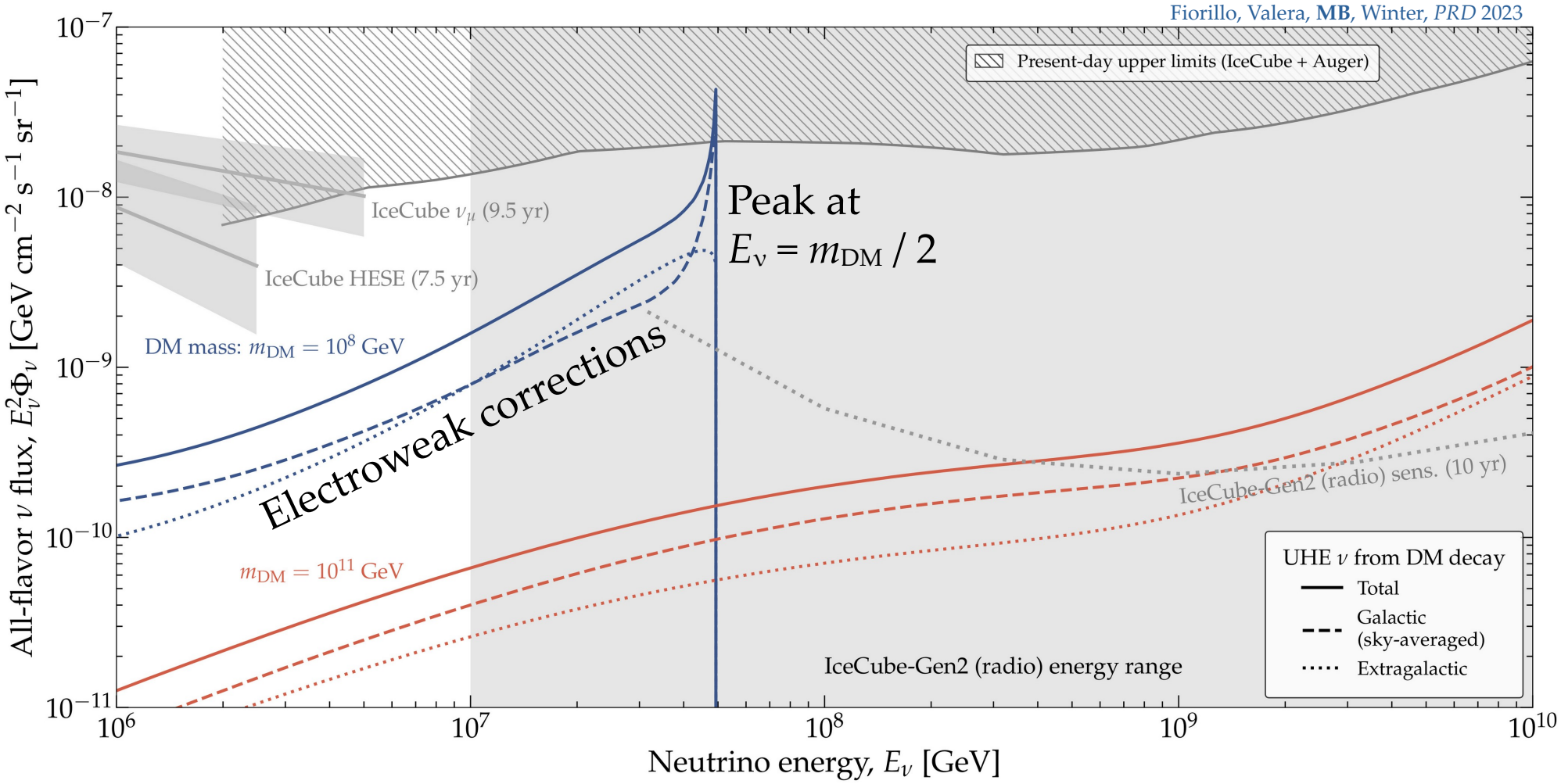
Energy scale of LIV (10^{14}–10^{15} GeV)

GRB-ν association: 2.4σ
(p-value of 0.015)

Amelino-Camelia *et al.*, 2502.13093



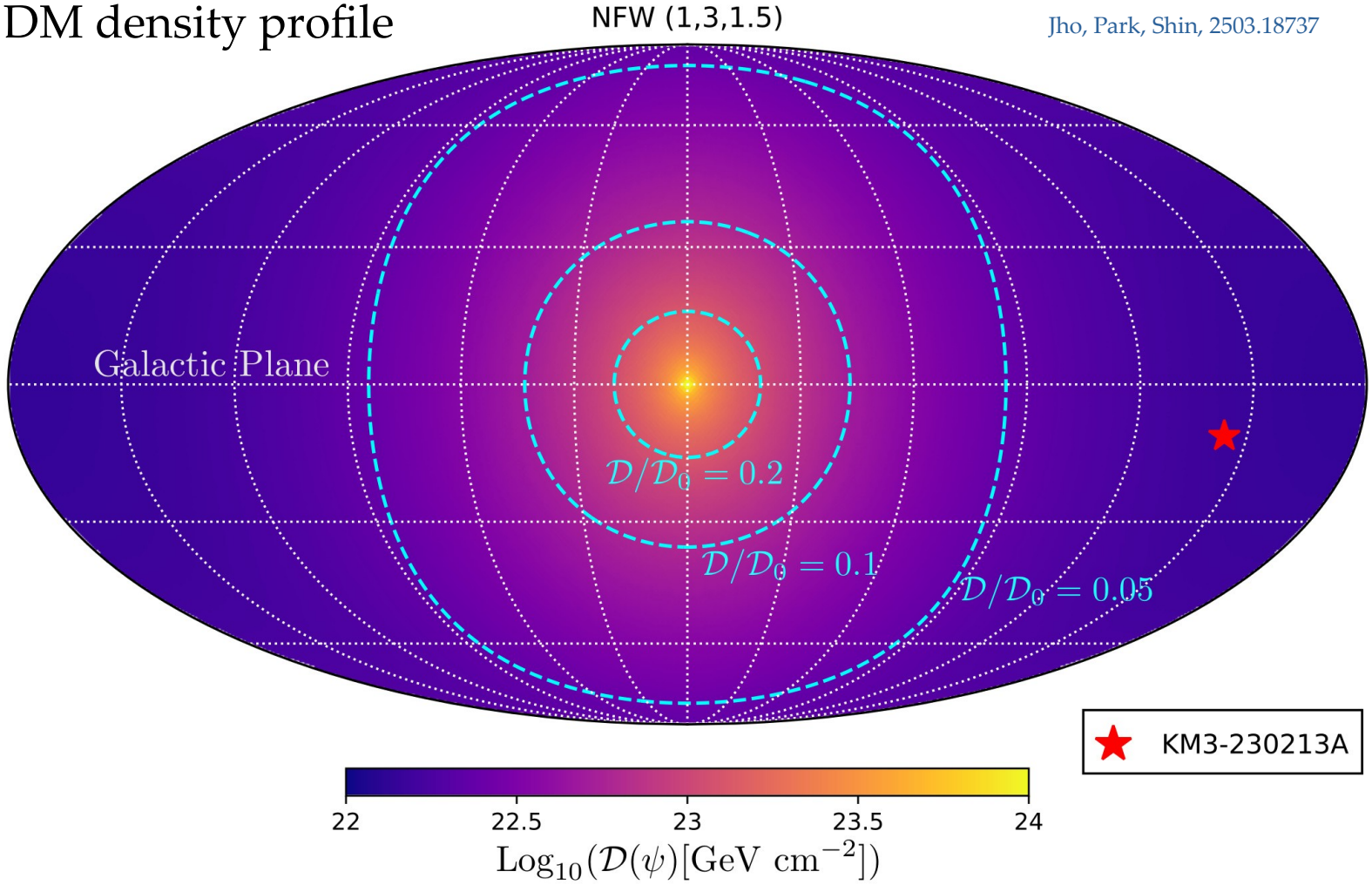
Decay of heavy dark matter (DM → ν + ν)



Decay of heavy dark matter (DM → ν + ν)

Galactic DM density profile

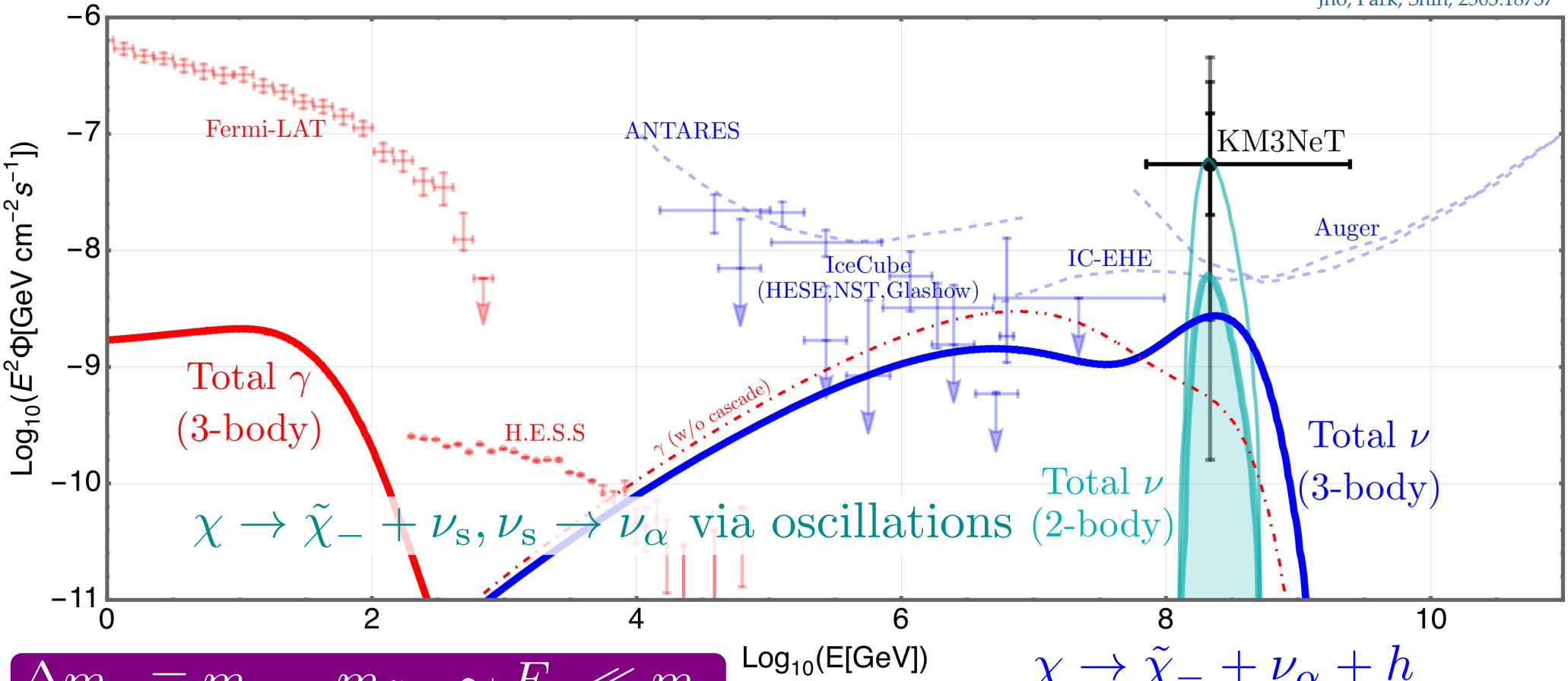
Jho, Park, Shin, 2503.18737



Decay of heavy dark matter — supersymmetric

Multi-component DM: heavy (χ, unstable) & lighter ($\tilde{\chi}_-$, stable)

Jho, Park, Shin, 2503.18737



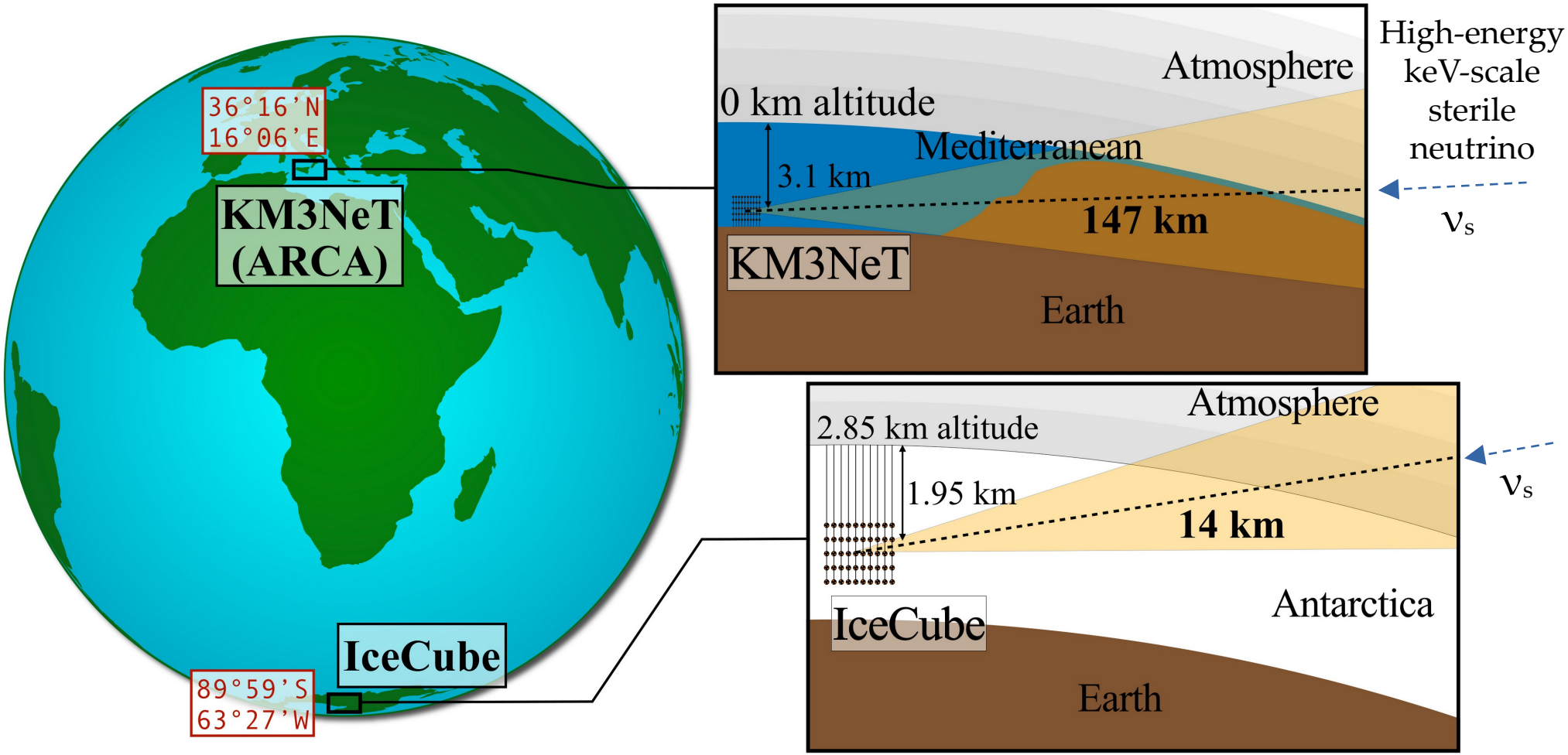
$$\Delta m_\chi \equiv m_\chi - m_{\tilde{\chi}_-} \sim E_\nu \ll m_\chi$$

$$\chi \to \tilde{\chi}_- + \nu_\alpha + h$$

(Higgs decays into γ)

Sterile-active ν transitions

Brdar & Chattopadhyay, 2502.21299

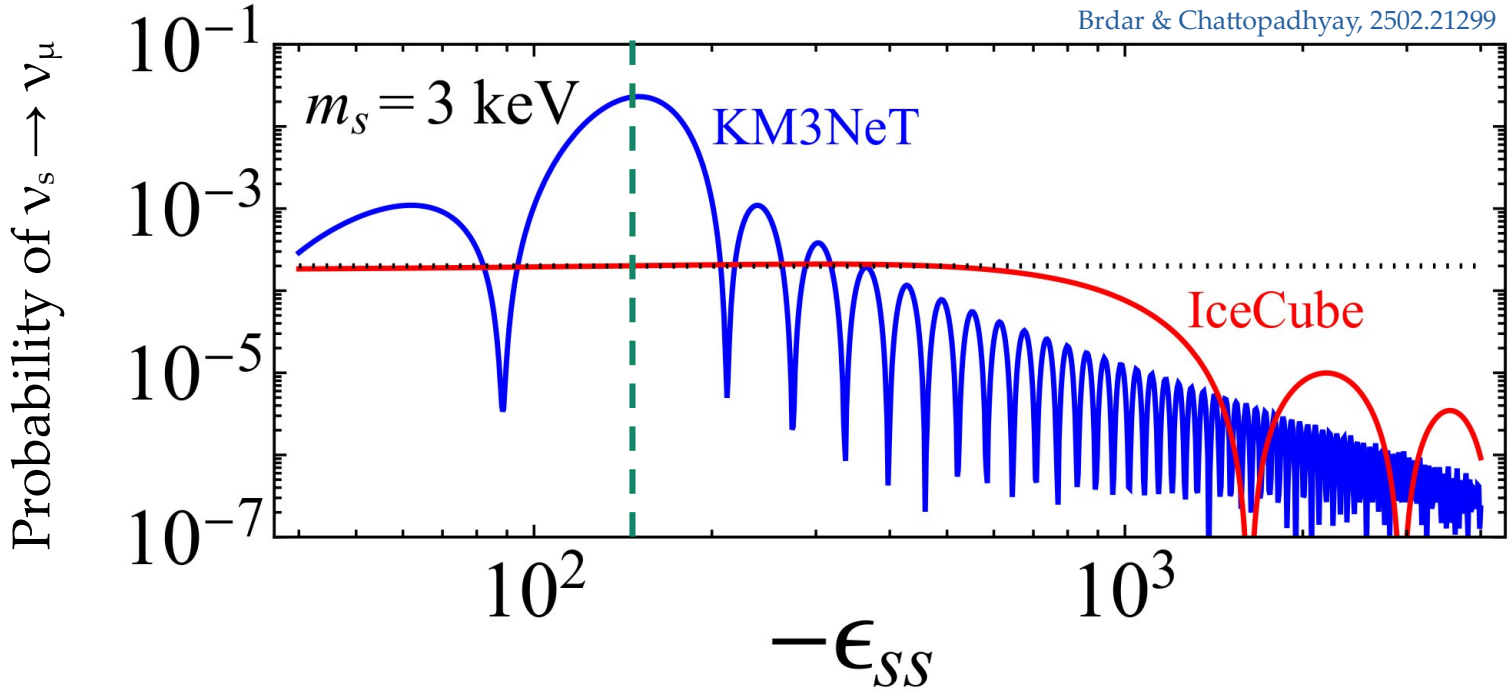


Sterile-active ν transitions

New neutrino-baryon interactions inside Earth (by gauging $U(1)_B$ symmetry)

Relative strength *vs.* standard weak interaction: $\epsilon_{ss} = G_B/(\sqrt{2}G_F)$

For $-\epsilon_{ss} = 150$, transitions are resonant in KM3NeT, but not in IceCube



Primordial black hole evaporation

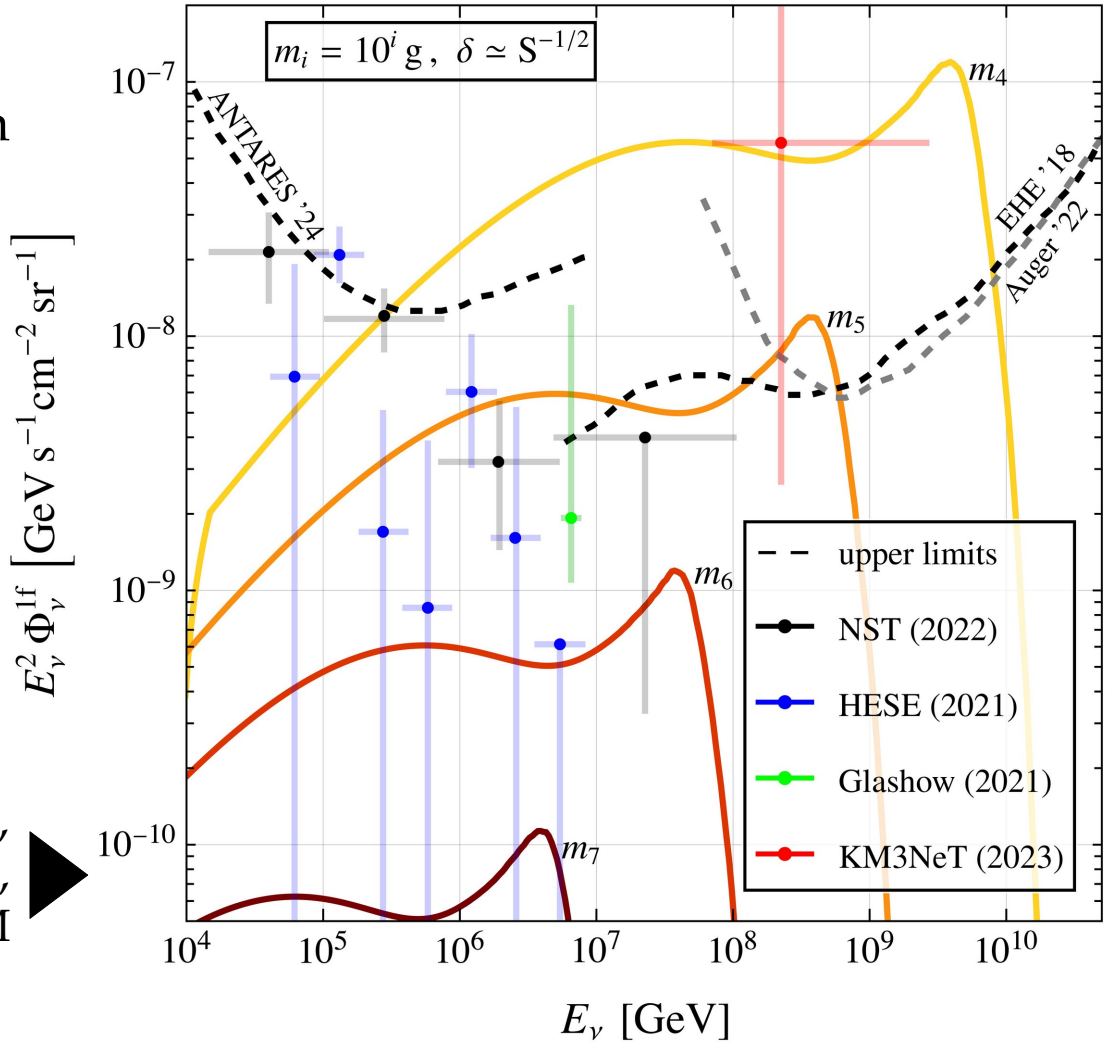
Dvali, Zantedeschi, Zell, 2503.21740

Primordial black holes (PBHs) evaporate through Hawking radiation

"Memory burden" effect: quantum back-reaction lengthens the life of the black hole

Most of the contribution is from intermediate-mass PBHs, transitioning to memory burden

Galactic + extragalactic contributions, monochromatic mass spectrum, PBHs make up all of DM

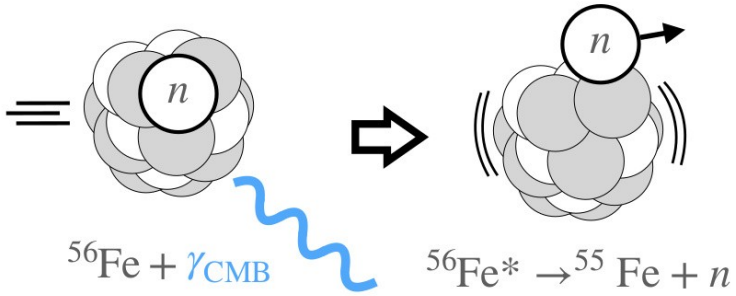


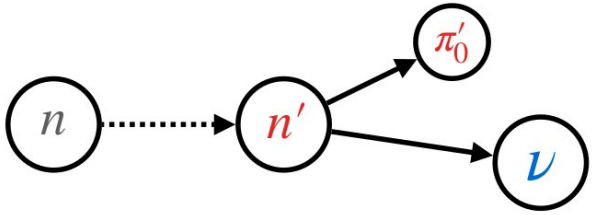
Mirror neutrons

Can reconcile large cosmogenic ν flux inspired by KM3-230213A and heavy UHECR mass composition

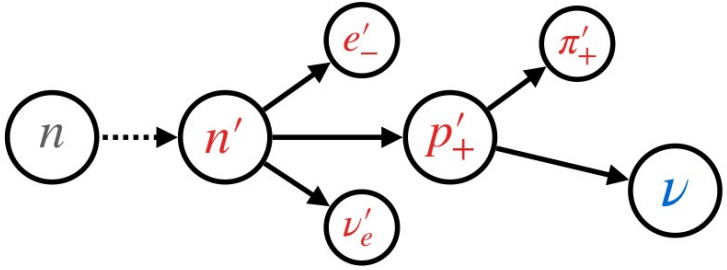
But cannot explain lack of IceCube events

Joint fits to Auger UHECR data + neutrino data from IceCube and KM3NeT





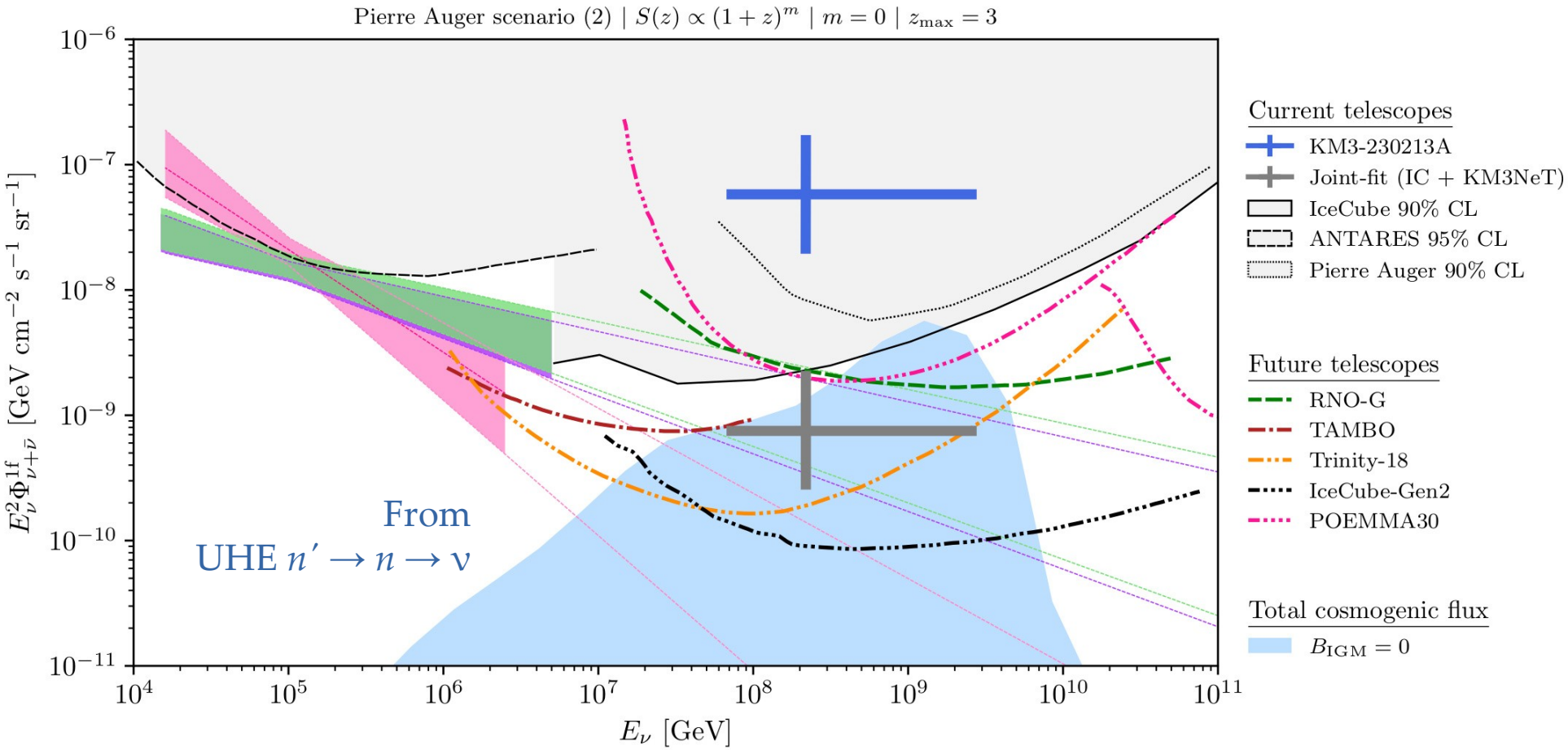
$n \to n' \qquad n' \to \pi'_0\, \nu$



$n \to n' \quad n' \to \bar{\nu}'_e + e'_- + (p'_+ \to \pi'_+ \nu\ )$

Alves, Hostert, Pospelov, 2503.14419

Mirror neutrons



Alves, Hostert, Pospelov, 2503.14419