Flavor at TAMBO: detecting high-energy $\bar{\nu}_e$ in a ν_τ detector

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Niels Bohr Institute, University of Copenhagen

TAMBO Collaboration Meeting
PUCP, August 18, 2026

UNIVERSITY OF COPENHAGEN

VILLUM FONDEN

Neutrinos are quintessential quantum particles

There are three types, or *flavors*, of neutrinos:

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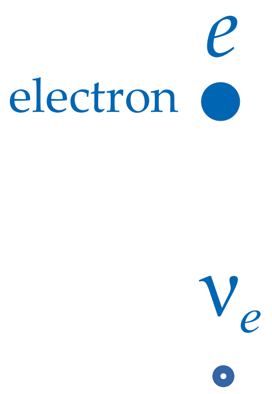

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e

electron

ν_e

electron
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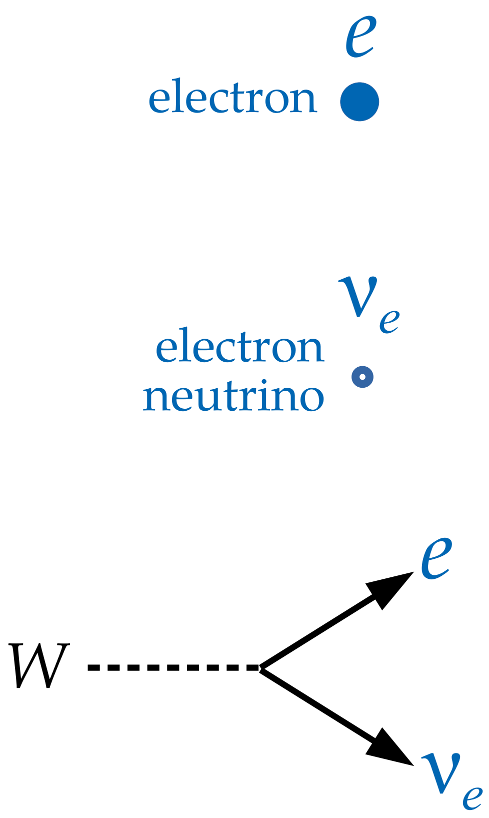

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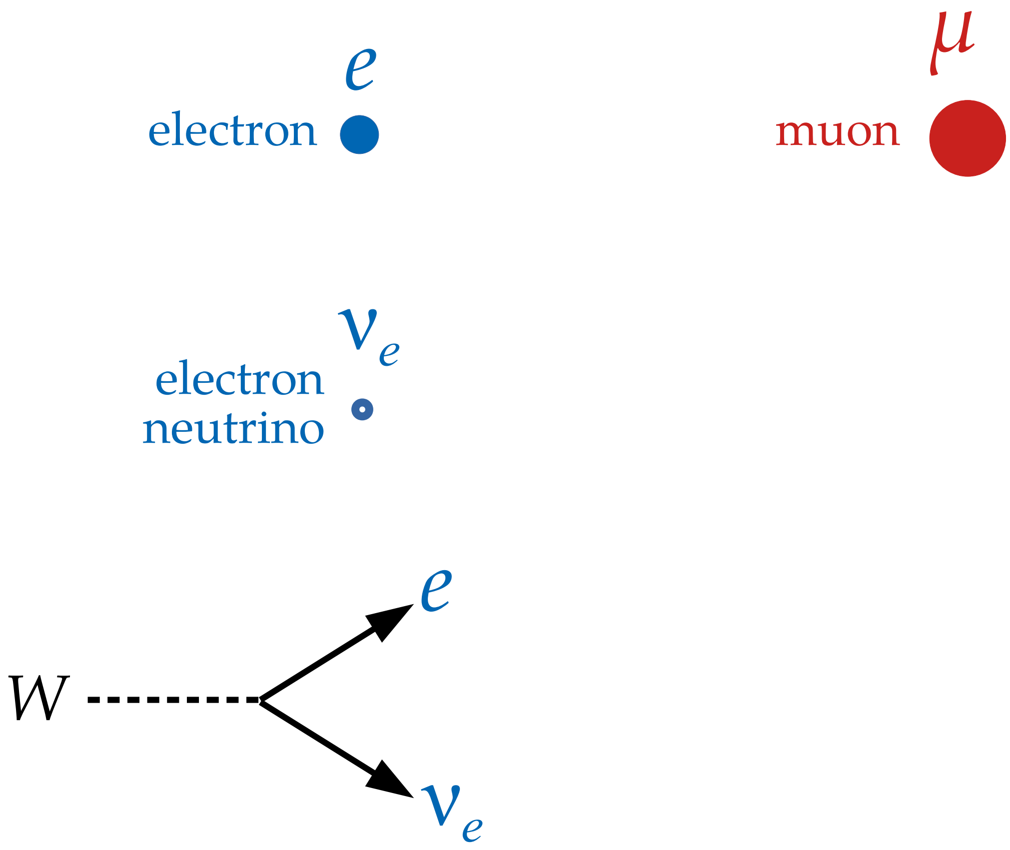

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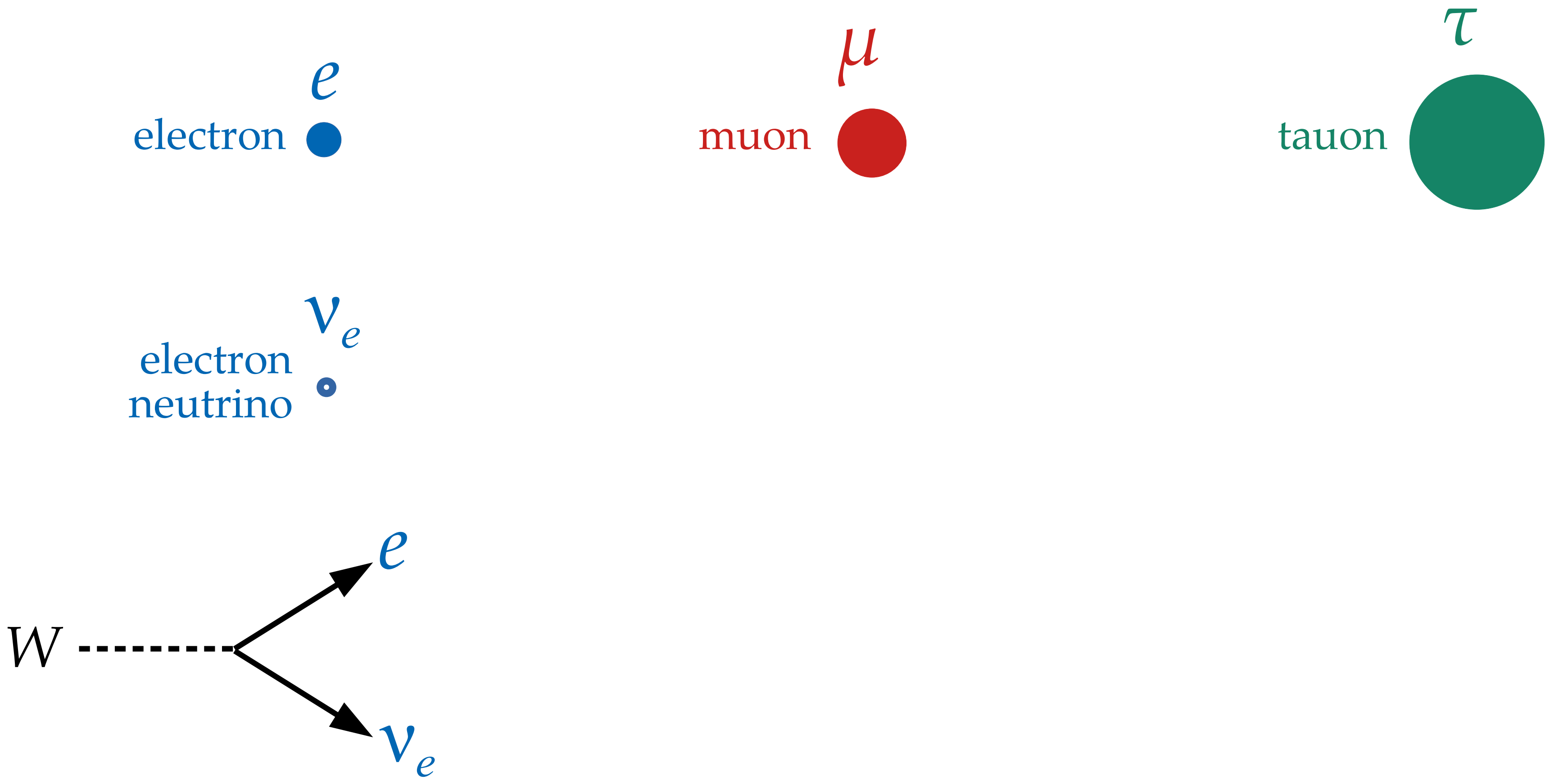

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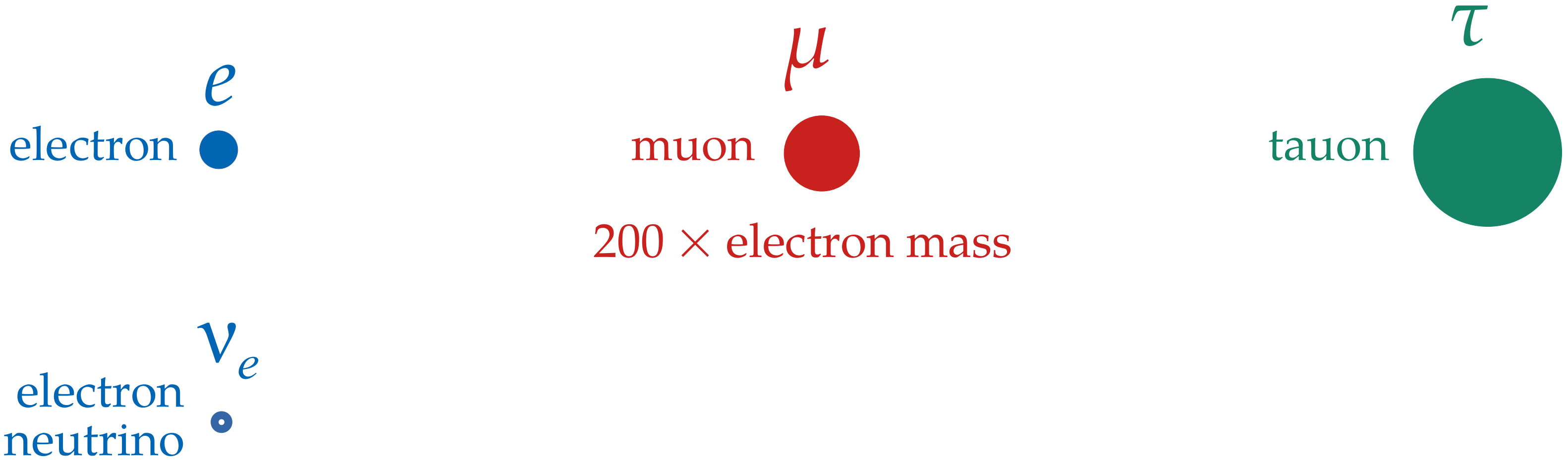

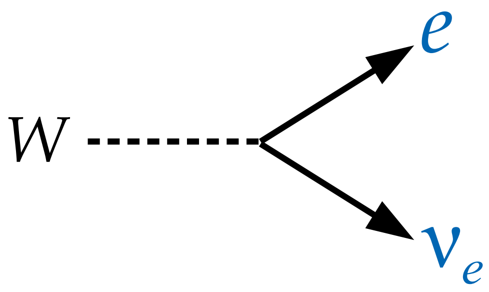

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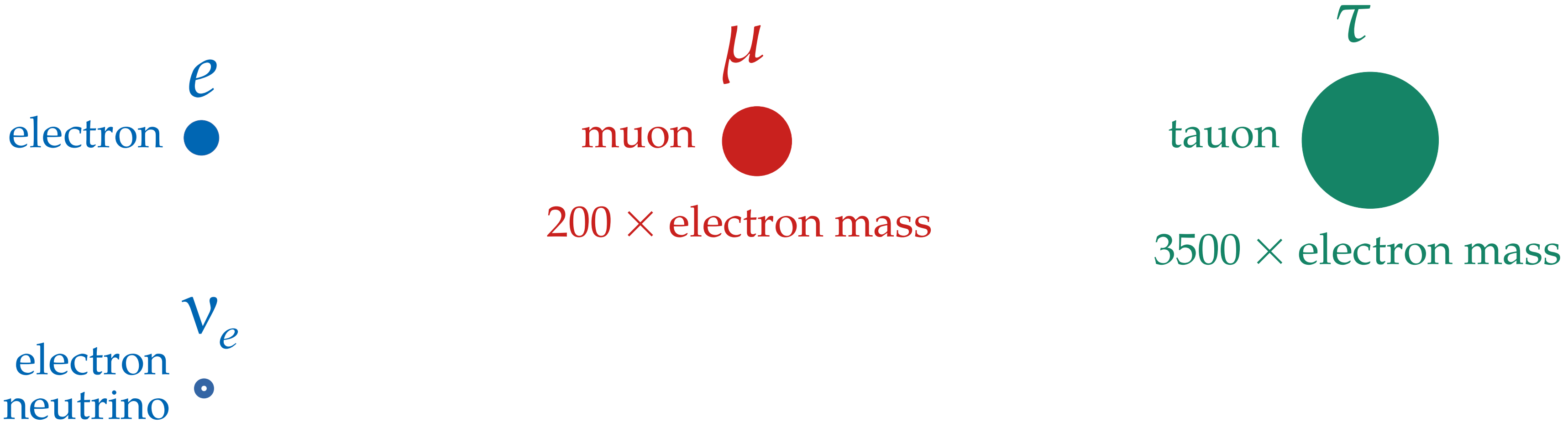

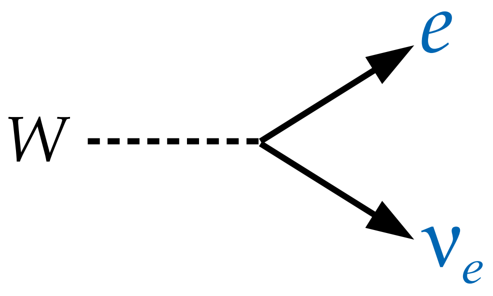

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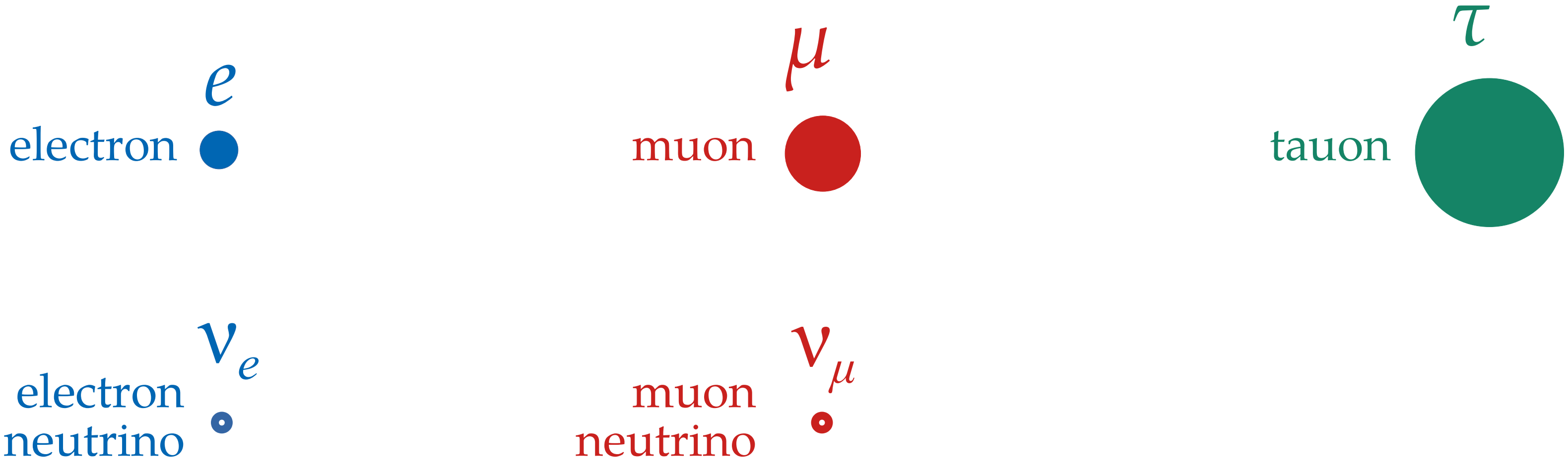

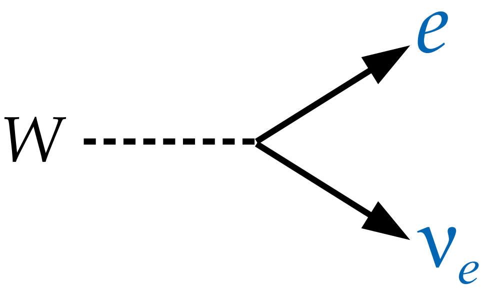

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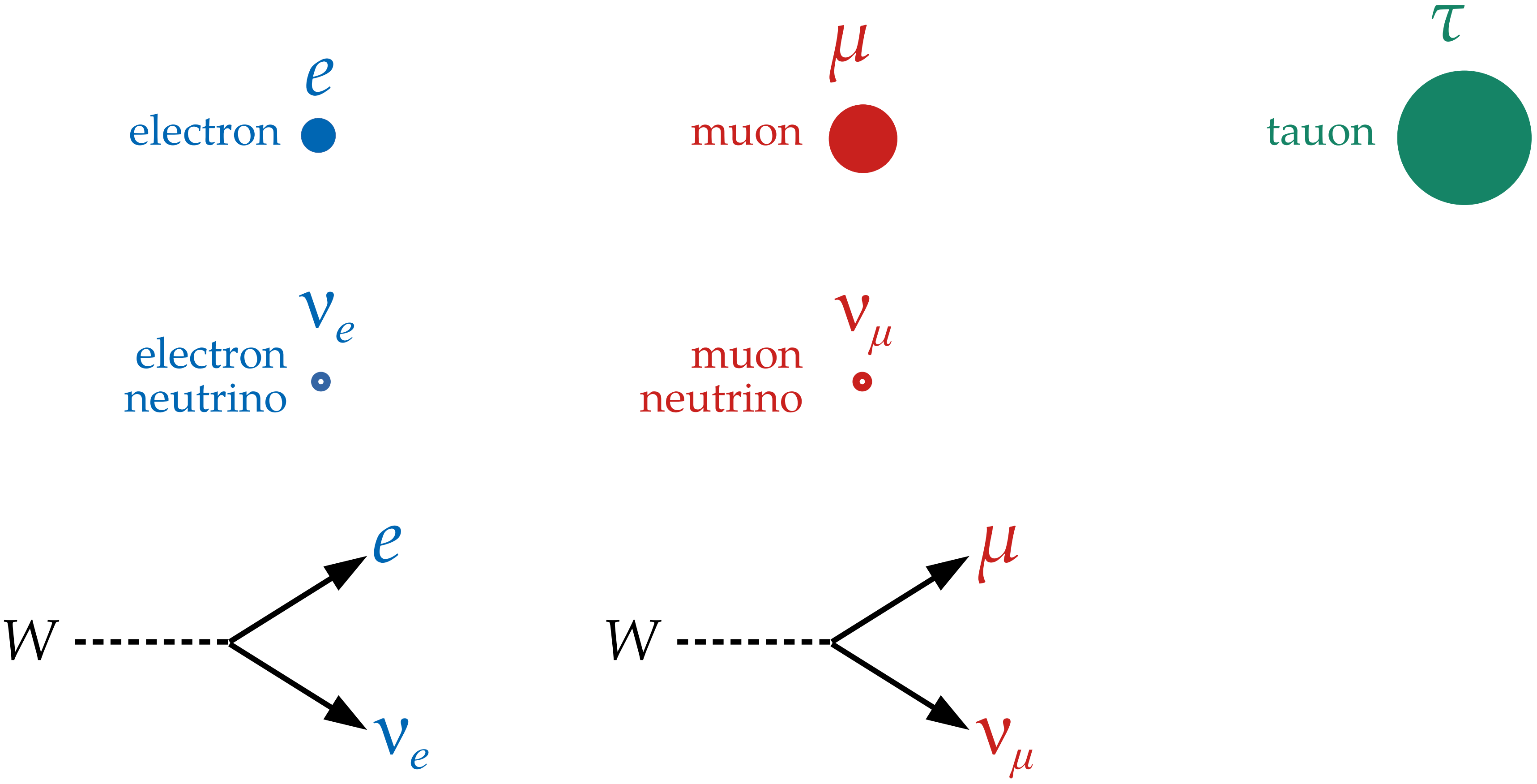

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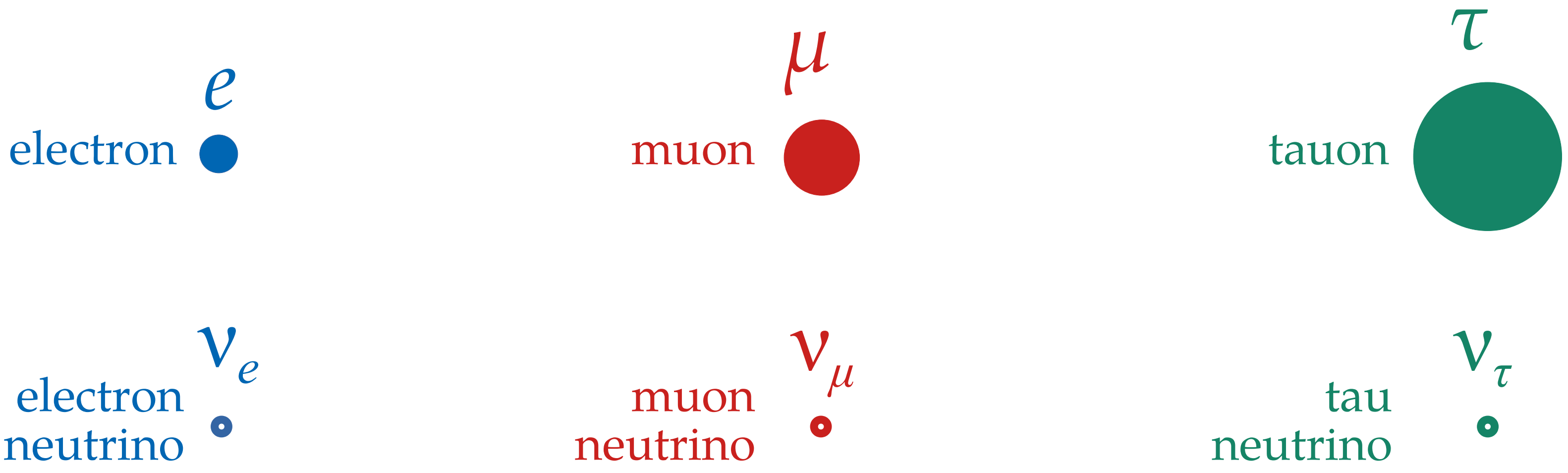

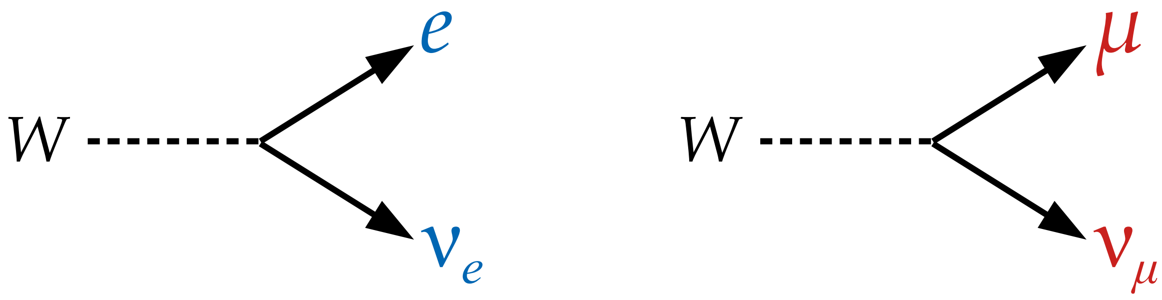

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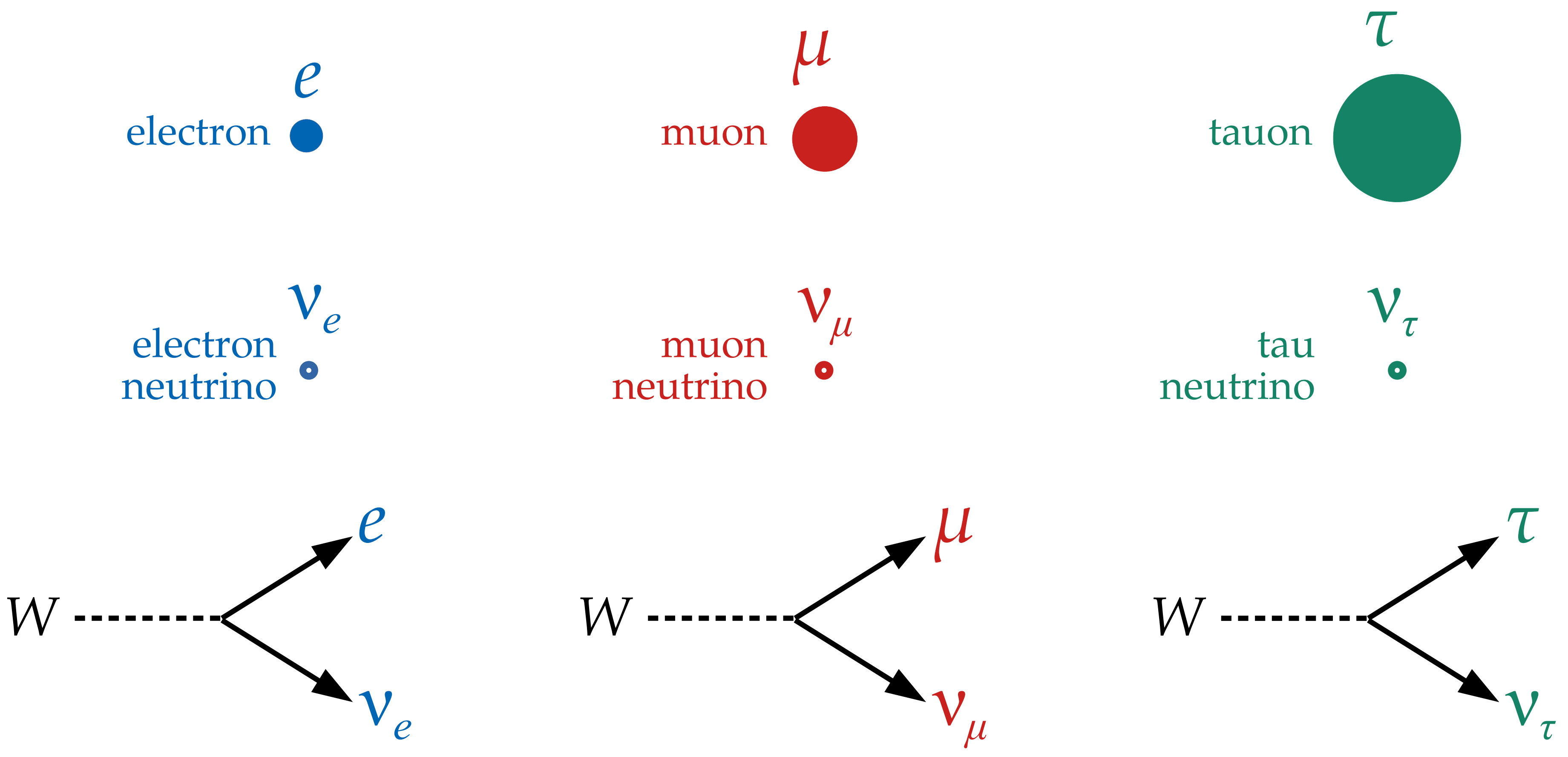

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with *one* definite flavor, *e.g.*,

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Neutrino source

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Neutrino detector

We use quantum mechanics to compute probabilities over *macroscopic* distances!

Why measure the high-energy ν flavor

The multi-messenger connection: a simple picture

(or $p + p$)

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

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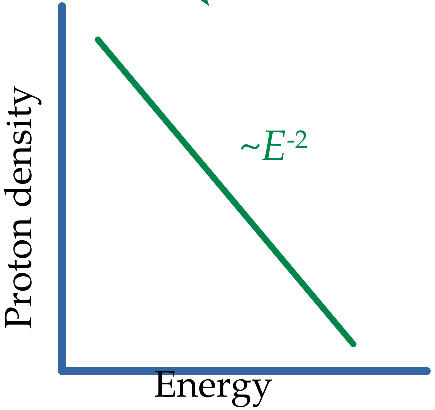

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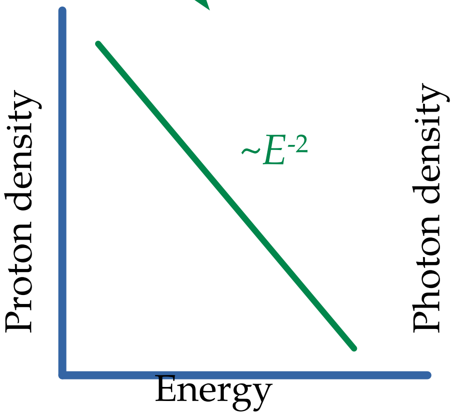

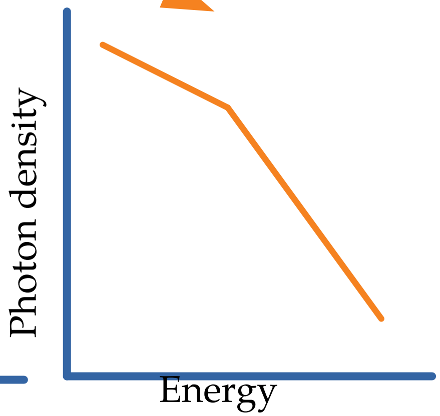

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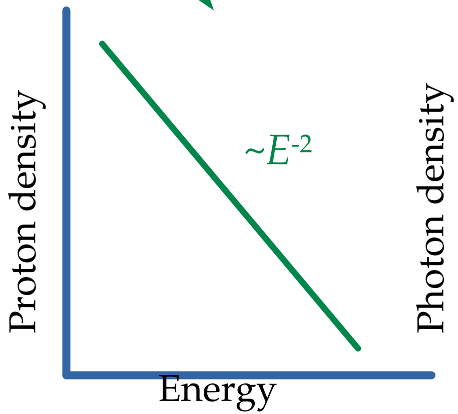
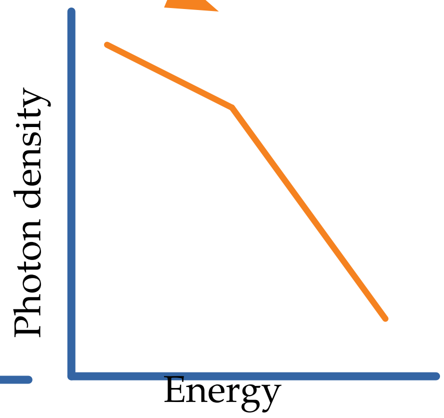
$$\pi^0 \longrightarrow \gamma + \gamma$$

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

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





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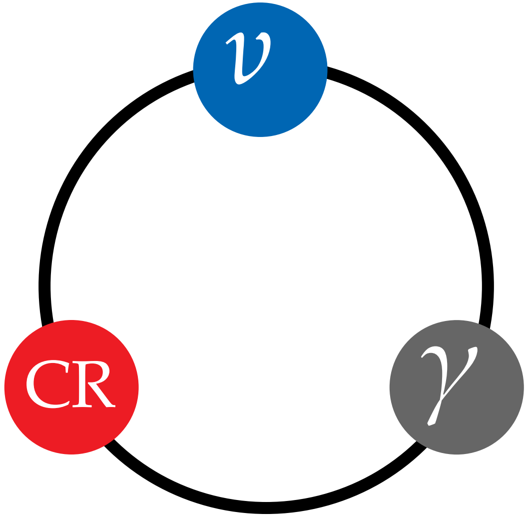

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Gamma-ray energy = Proton energy / 10

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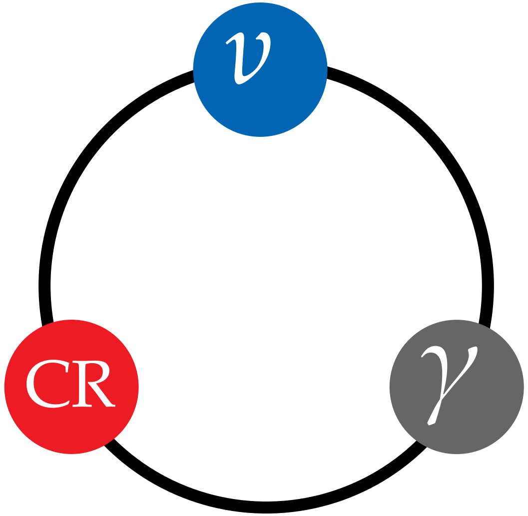

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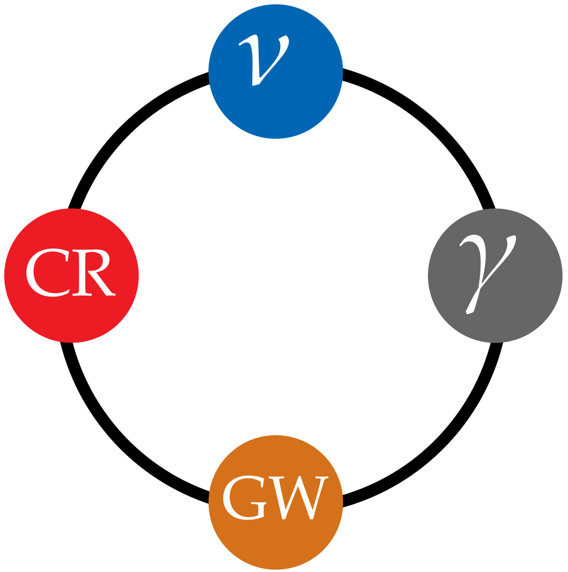

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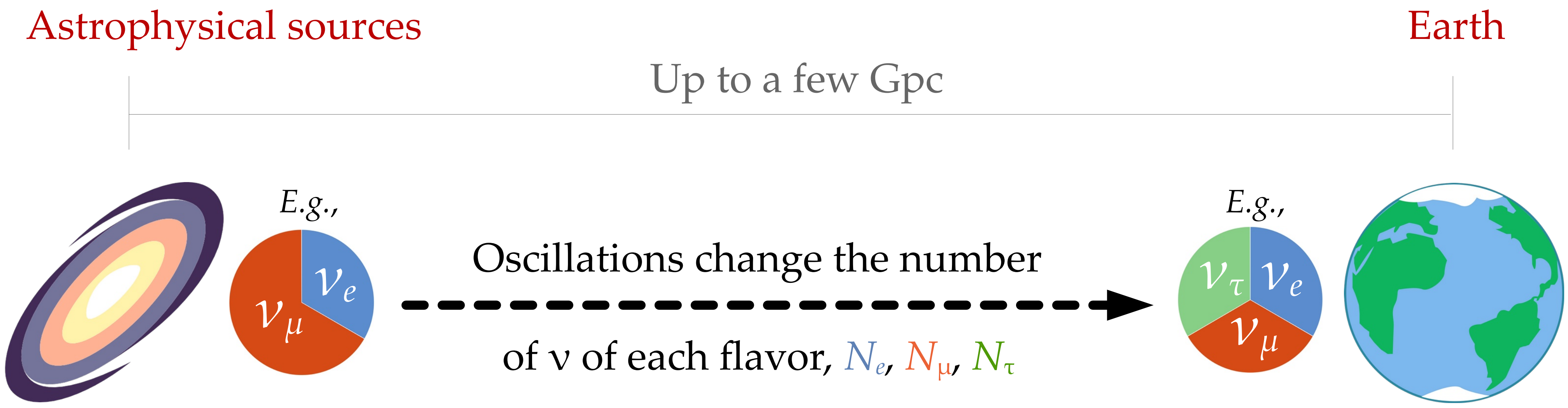
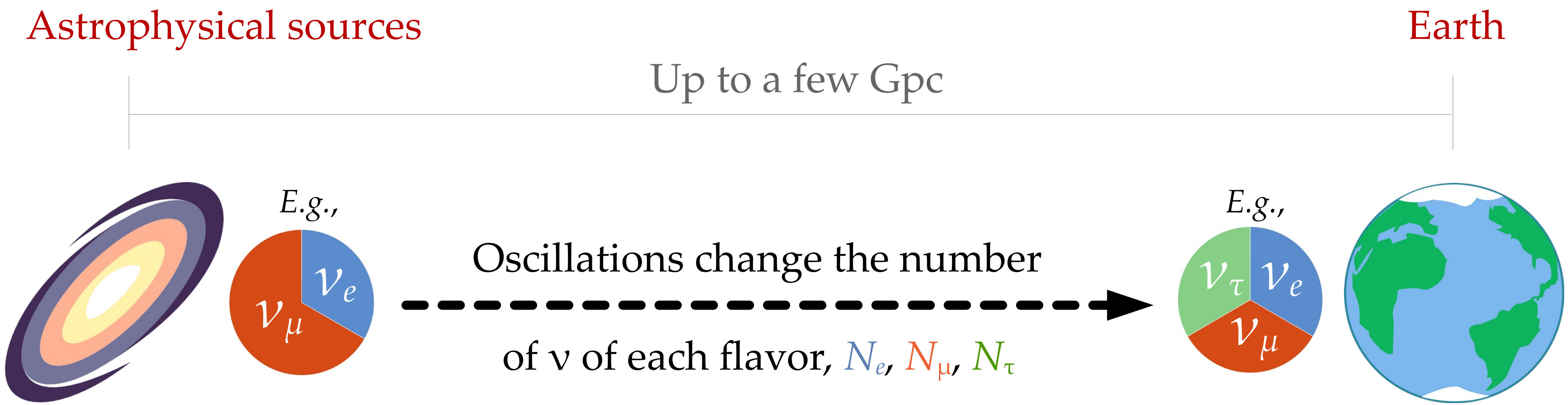


Different production mechanisms yield different flavor ratios:

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

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

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



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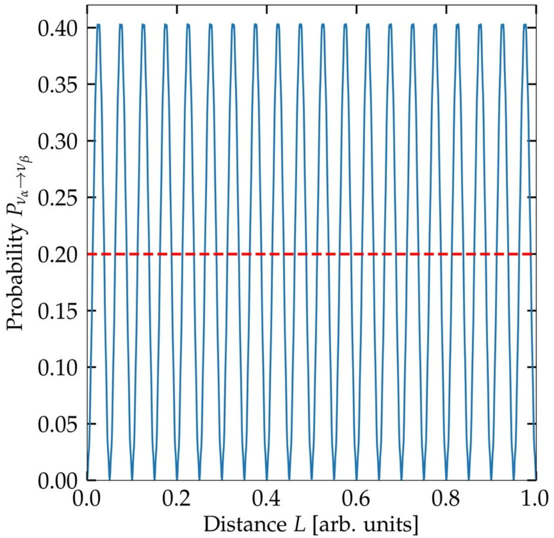
Standard oscillations
or
new physics

Full 3ν oscillation probability:

$$P_{\alpha\beta}(E,L) = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right) + 2\sum_{i>j} \mathrm{Im}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin\left(\frac{\Delta m^2_{ij}L}{2E}\right)$$



Oscillation length for 1-TeV ν: $2\pi \times 2E/\Delta m^2 \sim 0.1$ pc

~ 8% of the way to Proxima Centauri
≪ Distance to Galactic Center (8 kpc)
≪ Distance to Andromeda (1 Mpc)
≪ Cosmological distances (few Gpc)

We cannot resolve oscillations, so we use instead the average probability:

$$P_{\alpha\beta} = \sum_{i=1}^{3} |U_{\alpha i}|^2 \, |U_{\beta i}|^2$$

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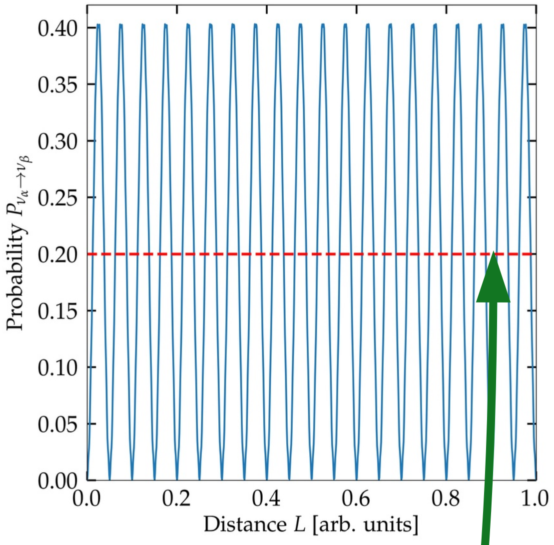

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Flavor composition at the Earth:

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Informed by astrophysics

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Assume no ν_τ production,
so we only need vary the ν_e fraction

Farzan, *JHEP* 2021

New physics in flavor composition

Use the flavor sensitivity to test new physics:

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Reviews:
Argüelles *et al.* (inc. ***MB***), *EPJC* 2023; Mehta & Winter, *JCAP* 2011; Rasmussen *et al.*, *PRD* 2017

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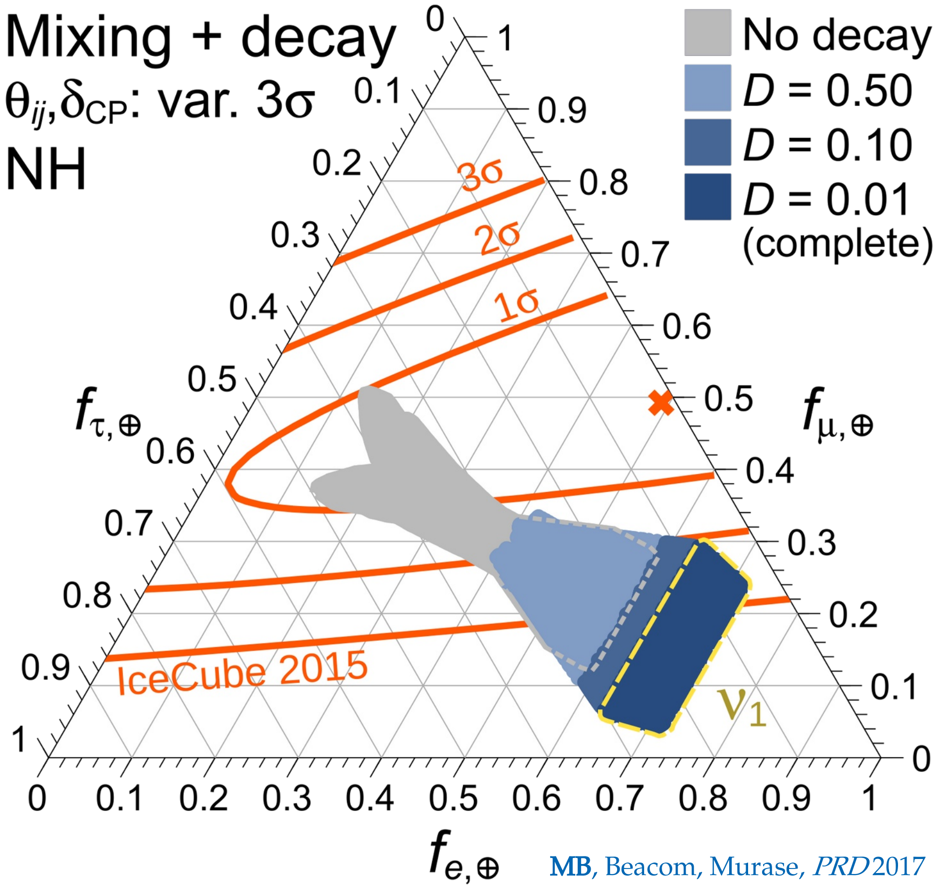
Use the flavor sensitivity to test new physics:

- Neutrino decay
  [Beacom *et al.*, *PRL* 2003; Baerwald, ***MB***, Winter, JCAP 2010; ***MB***, Beacom, Winter, *PRL* 2015; ***MB***, Beacom, Murase, *PRD* 2017]



MB, Beacom, Murase, *PRD* 2017

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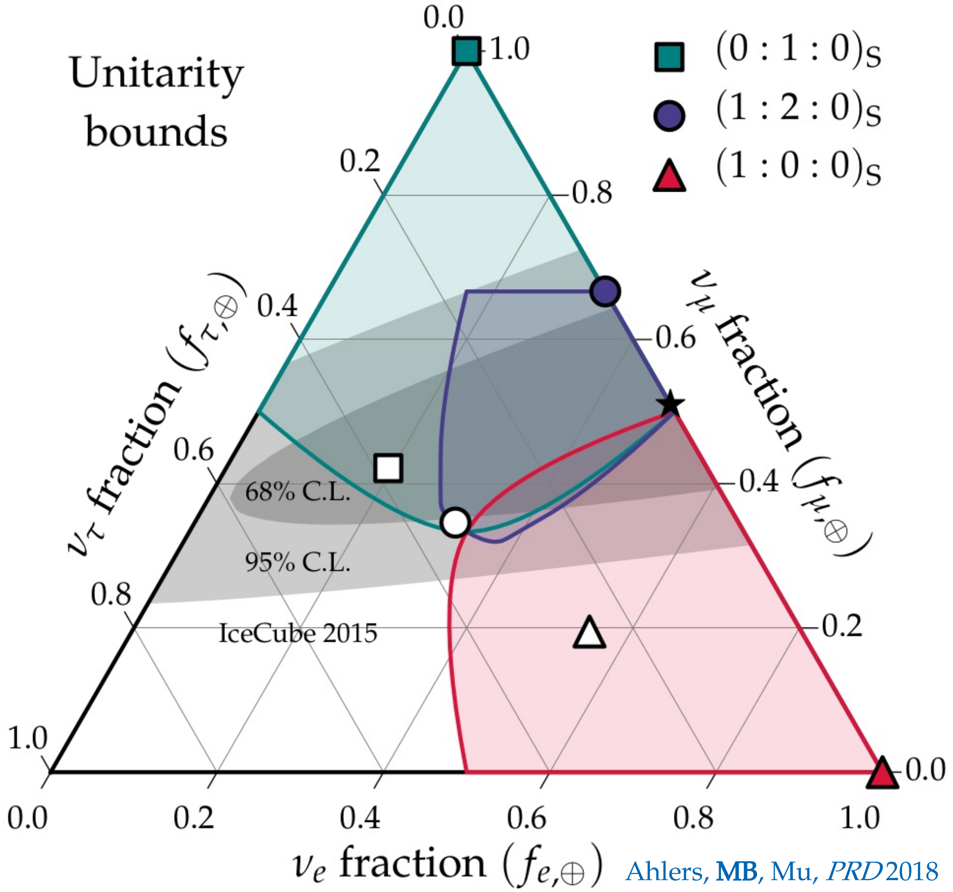

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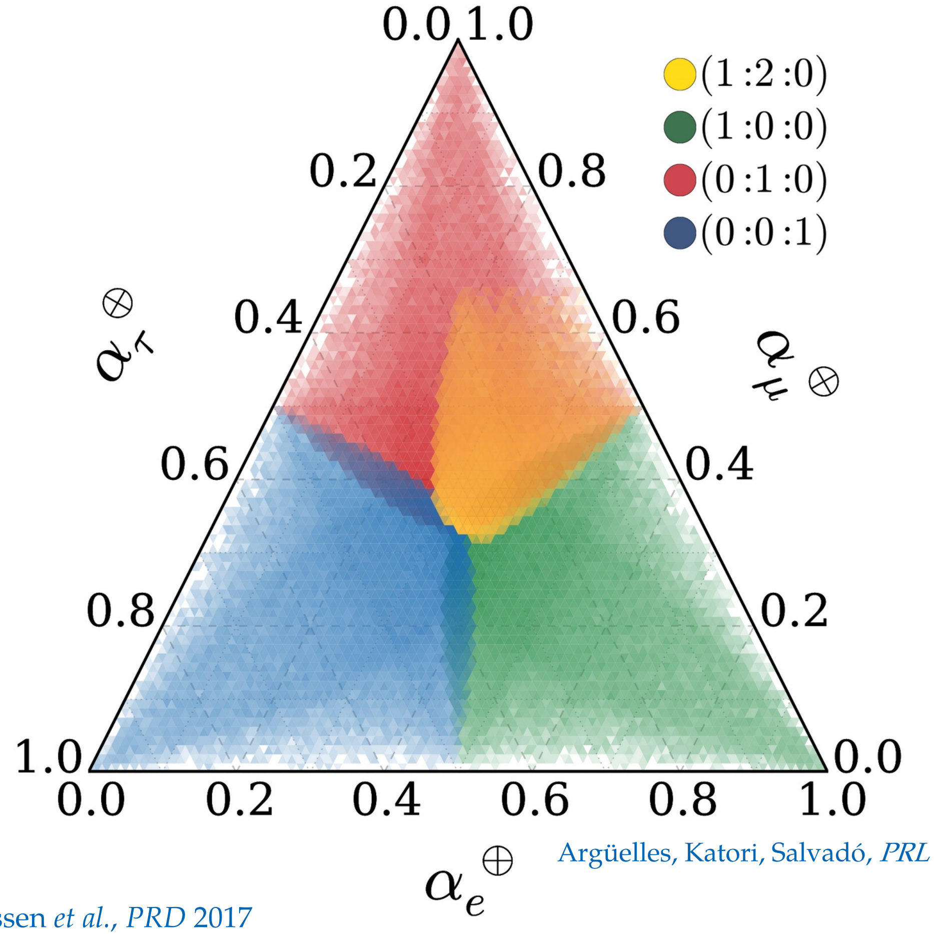

Argüelles, Katori, Salvadó, *PRL* 2015

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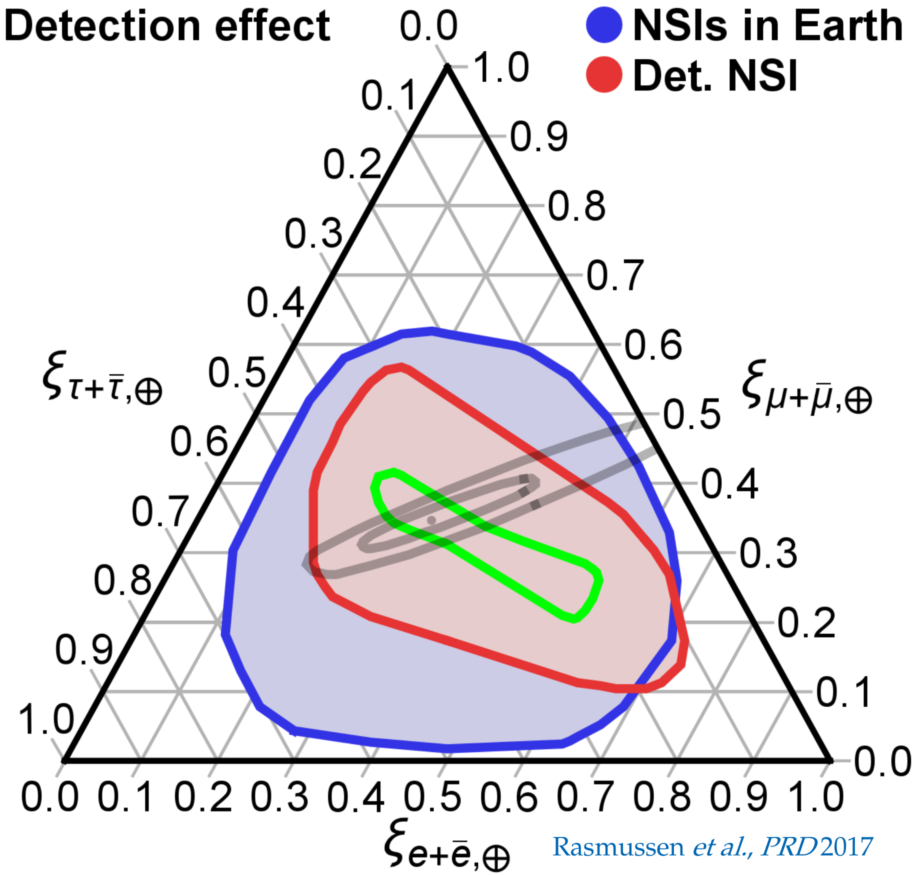

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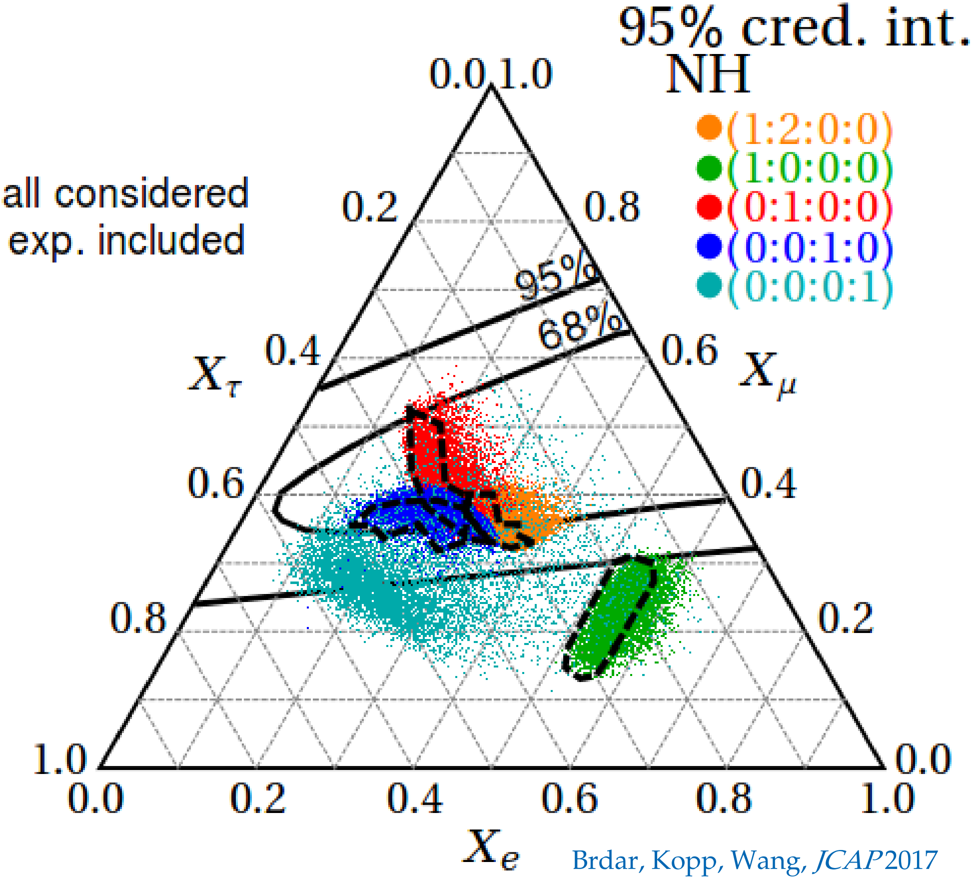
  [González-García *et al.*, *Astropart. Phys.* 2016; Rasmussen *et al.*, *PRD* 2017]
- Active-sterile ν mixing
  [Aeikens *et al.*, *JCAP* 2015; Brdar, Kopp, Wang, *JCAP* 2017; Argüelles *et al.*, *JCAP* 2020; Ahlers, ***MB***, *JCAP* 2021]



Brdar, Kopp, Wang, *JCAP* 2017

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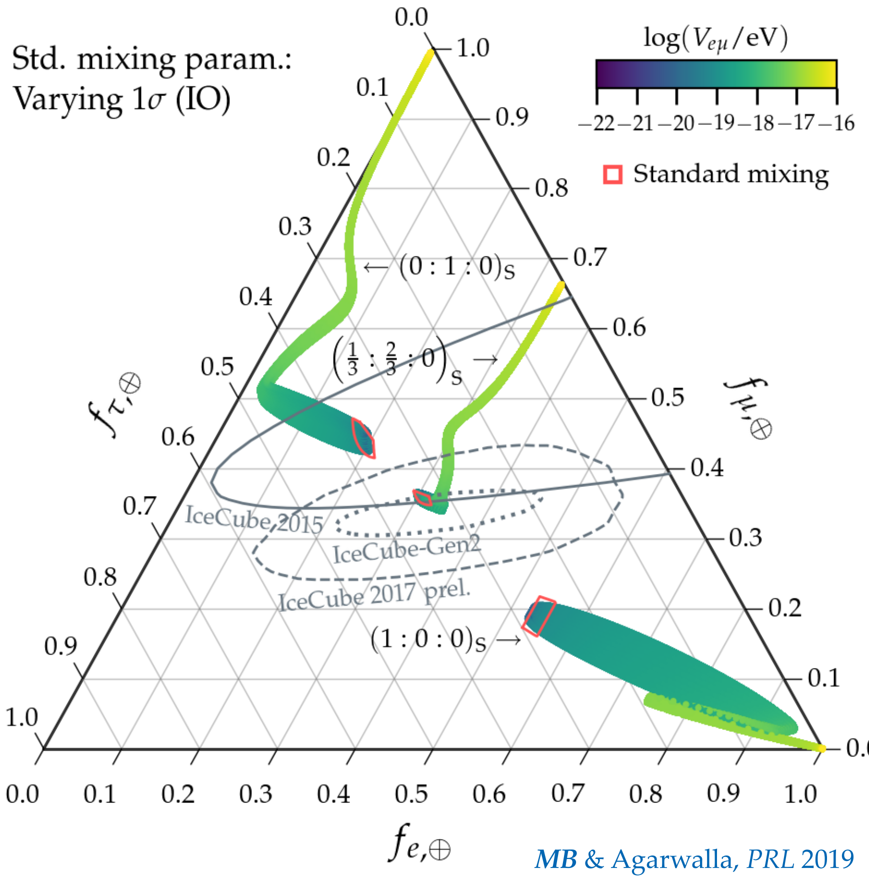
  [Barenboim & Quigg, *PRD* 2003; ***MB***, Gago, Peña-Garay, *JHEP* 2010; Kostelecky & Mewes 2004; Argüelles, Katori, Salvadó, *PRL* 2015]

- **Non-standard interactions**
  [González-García *et al.*, *Astropart. Phys.* 2016; Rasmussen *et al.*, *PRD* 2017]

- **Active-sterile ν mixing**
  [Aeikens *et al.*, *JCAP* 2015; Brdar, Kopp, Wang, *JCAP* 2017; Argüelles *et al.*, *JCAP* 2020; Ahlers, ***MB***, *JCAP* 2021]

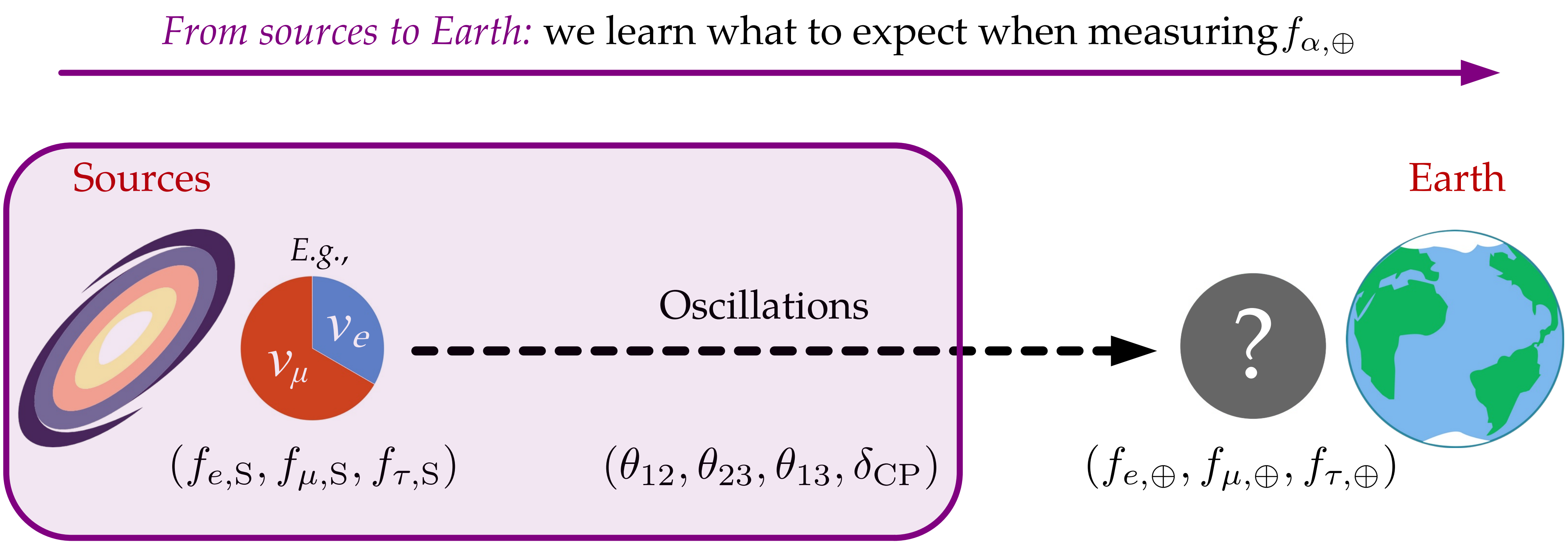
- **Long-range *eν* interactions**
  [***MB*** & Agarwalla, *PRL* 2019]



MB & Agarwalla, *PRL* 2019

Reviews:
Argüelles *et al.* (inc. ***MB***), *EPJC* 2023; Mehta & Winter, *JCAP* 2011; Rasmussen *et al.*, *PRD* 2017

How does IceCube measure flavor?



From sources to Earth: we learn what to expect when measuring $f_{\alpha,\oplus}$
Sources
Earth
E.g.,
ν_e
ν_μ
Oscillations
?
$(f_{e,\mathrm{S}}, f_{\mu,\mathrm{S}}, f_{\tau,\mathrm{S}})$
$(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\mathrm{CP}})$
$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$

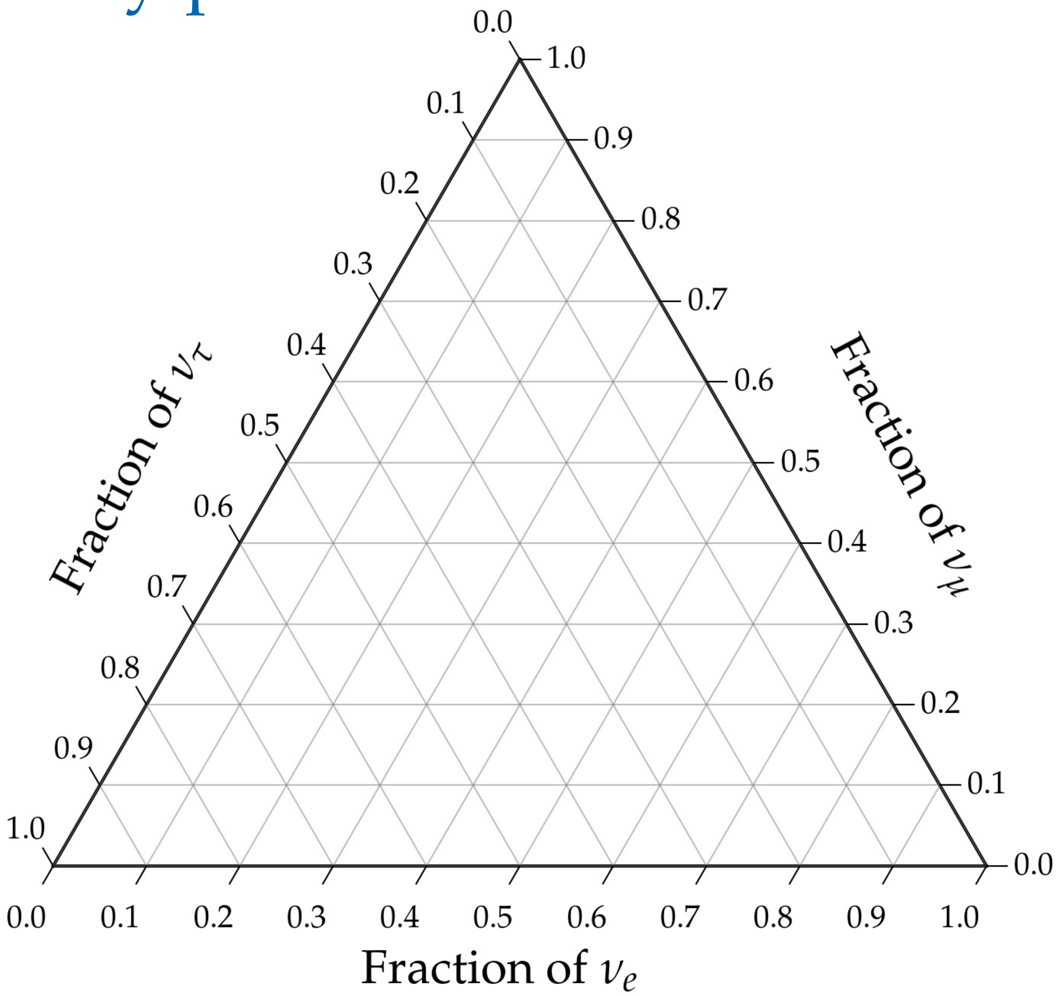
Quick aside: how to read a ternary plot

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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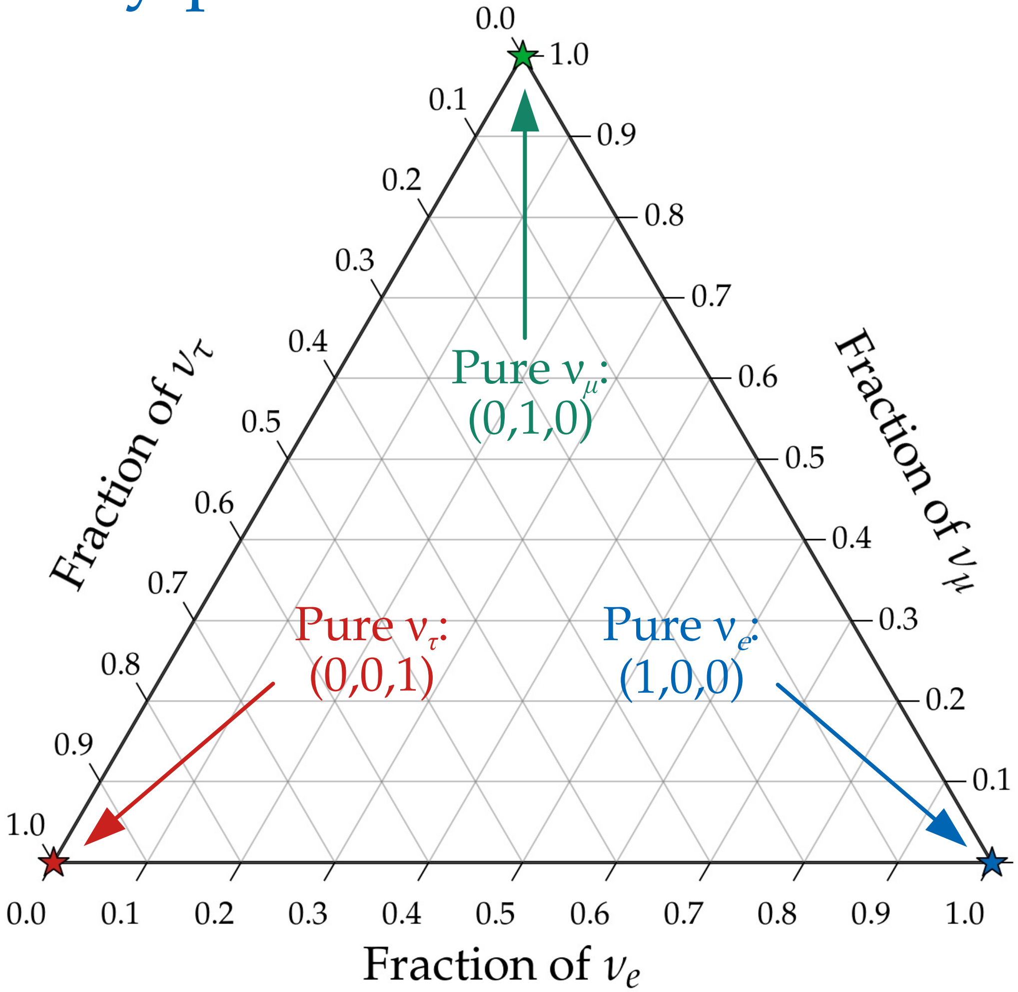

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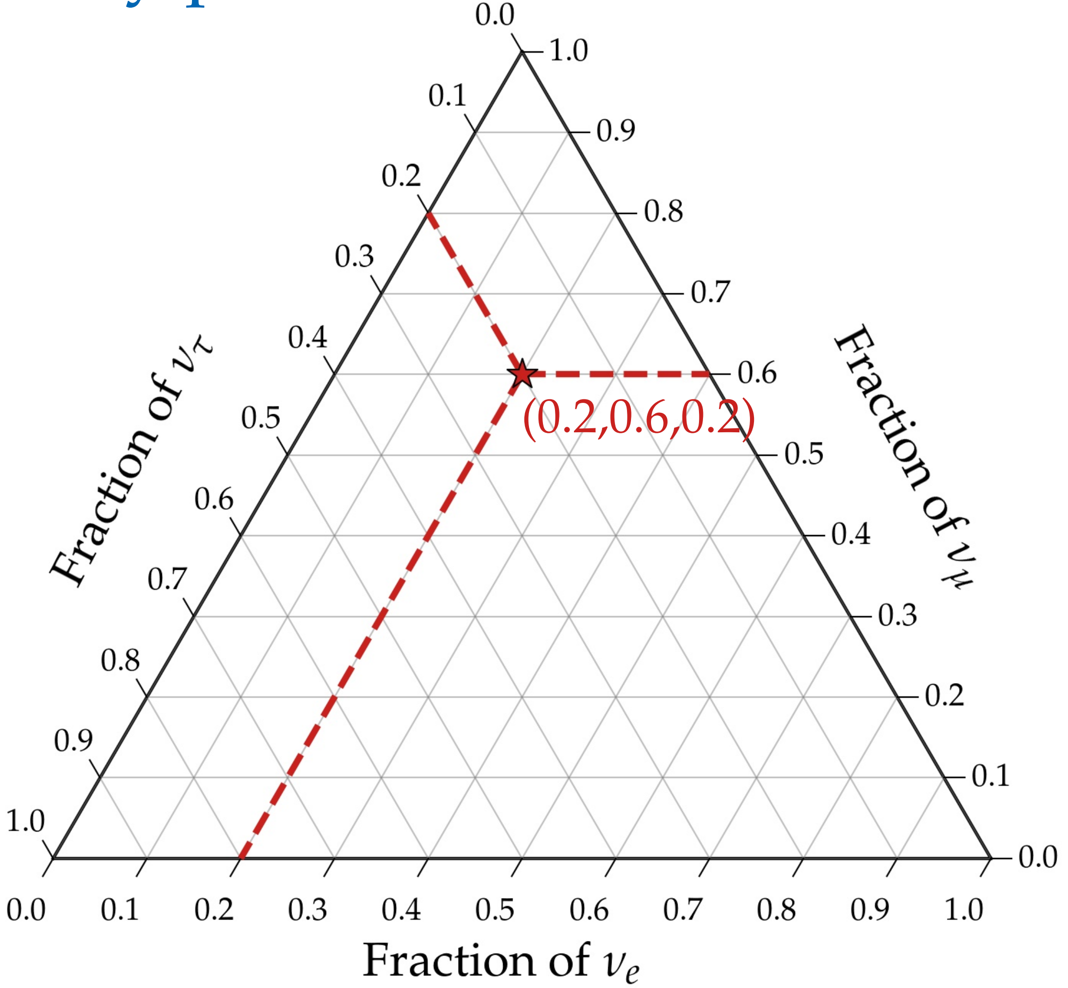

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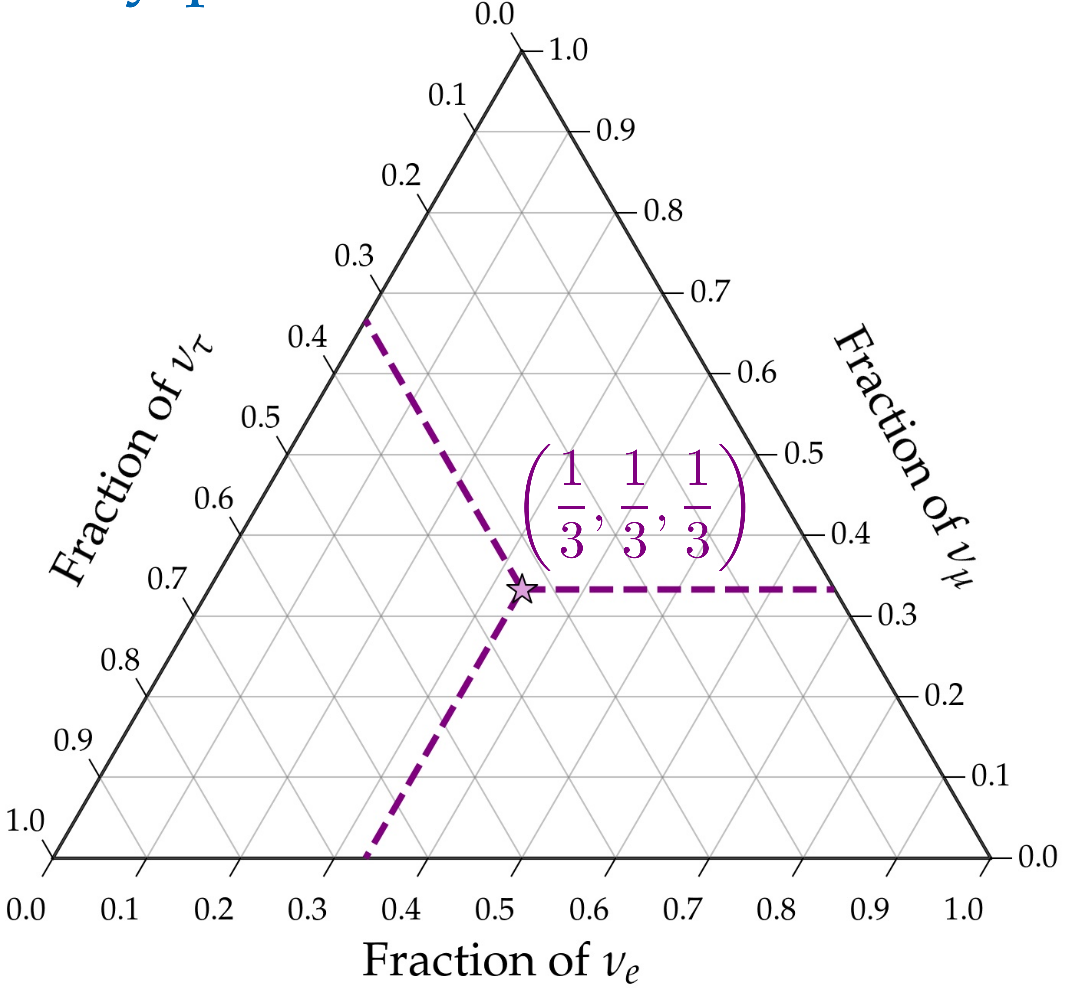

One likely TeV–PeV ν production scenario:

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

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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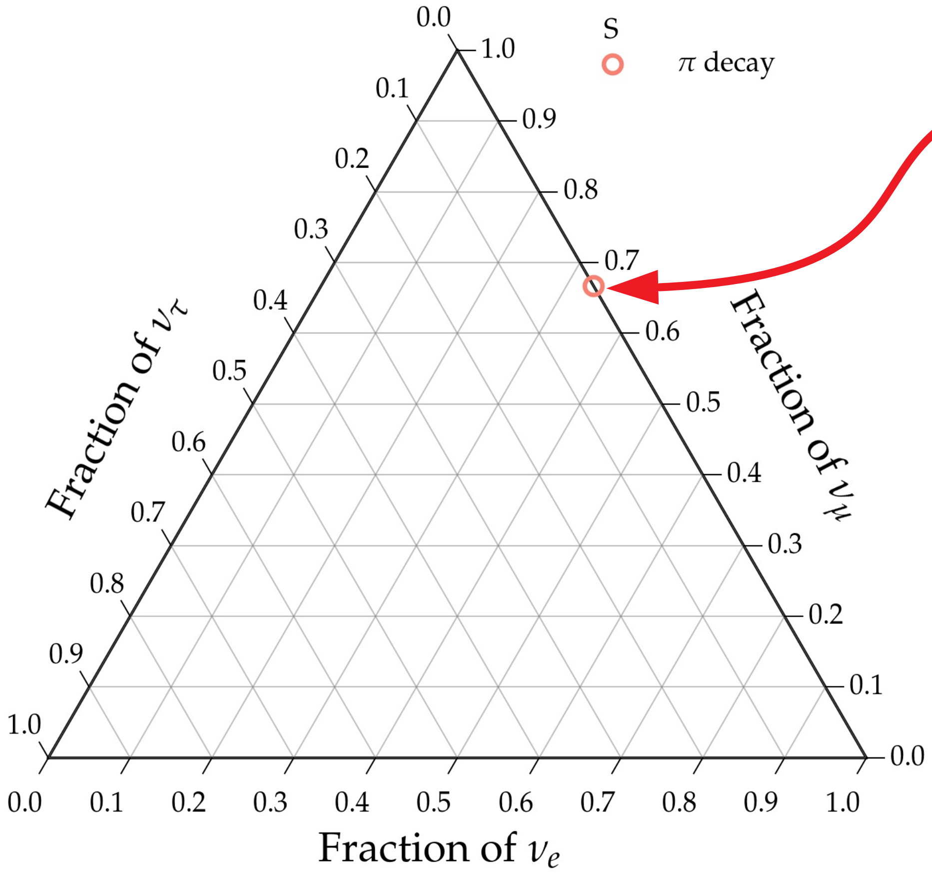

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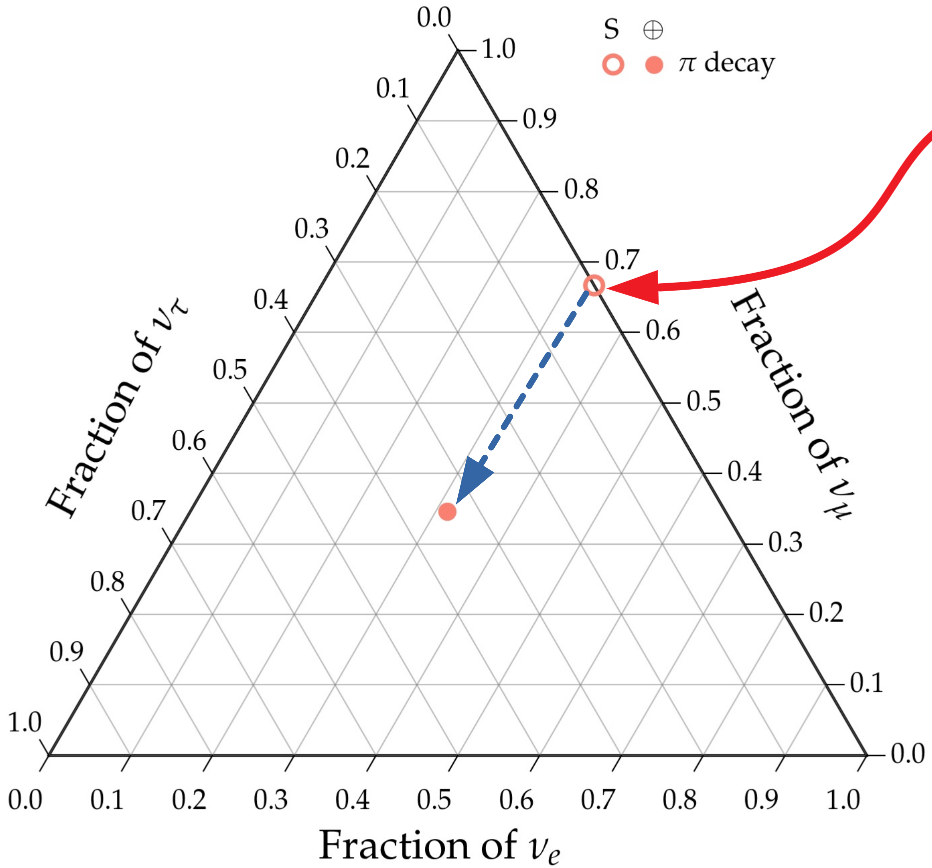

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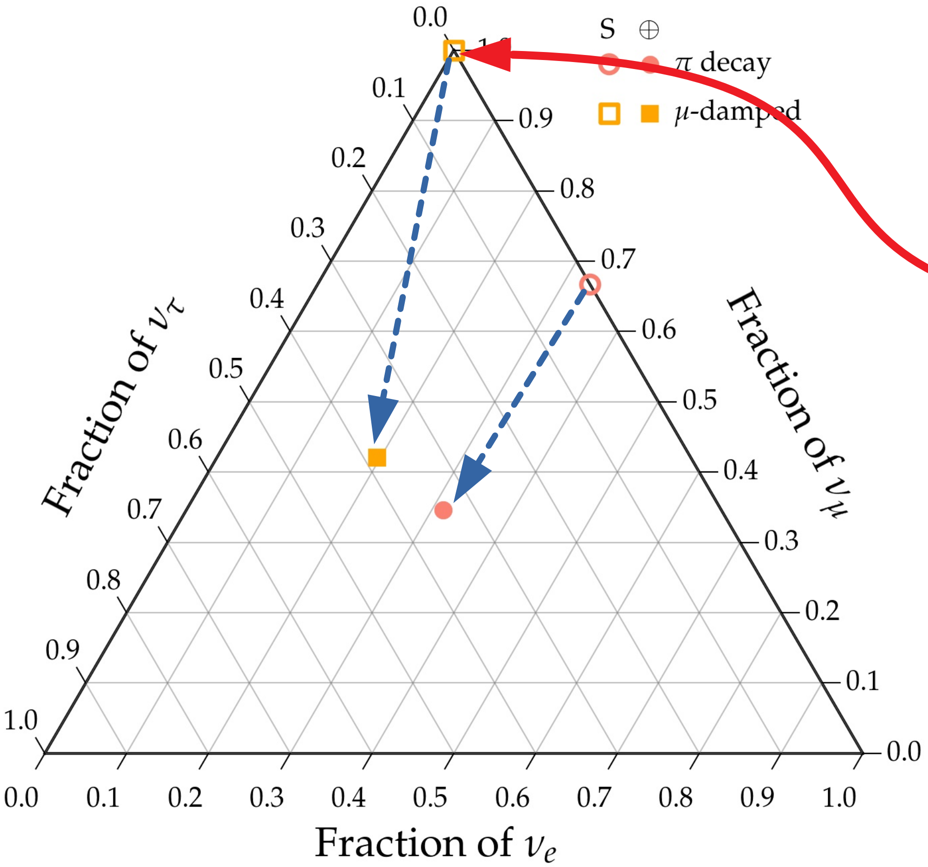

Full π decay chain

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

Muon damped

$(0:1:0)_S$

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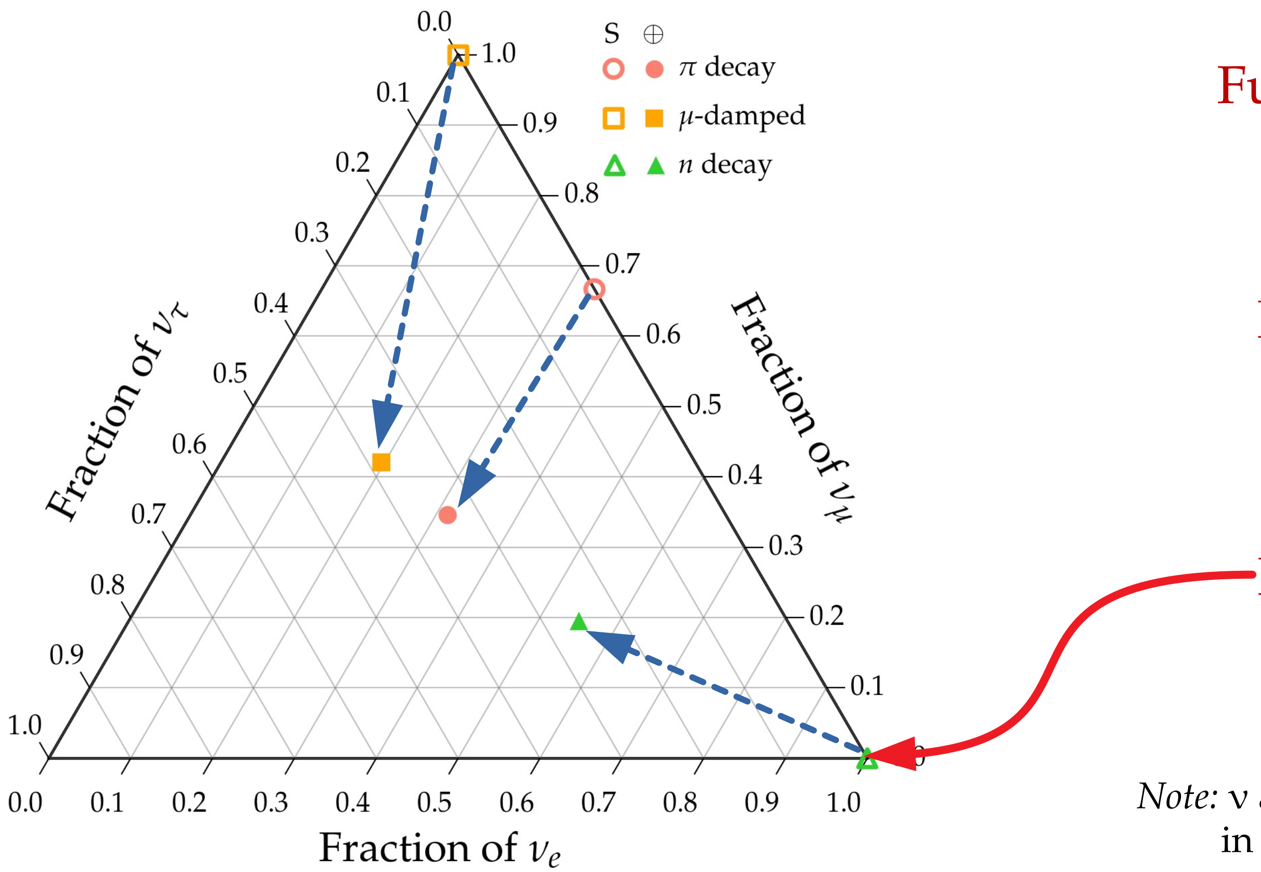


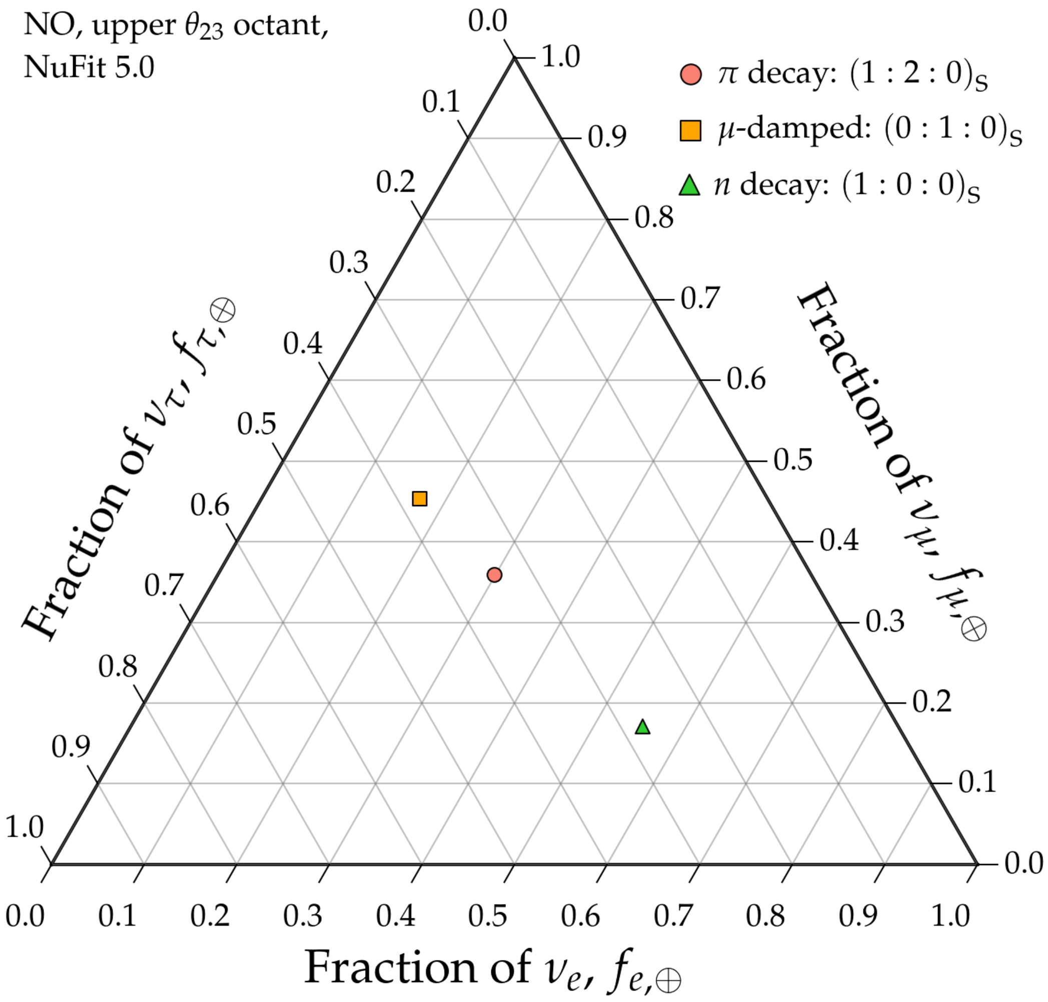
Full π decay chain
$(1/3:2/3:0)_S$

Muon damped
$(0:1:0)_S$

Neutron decay
$(1:0:0)_S$

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

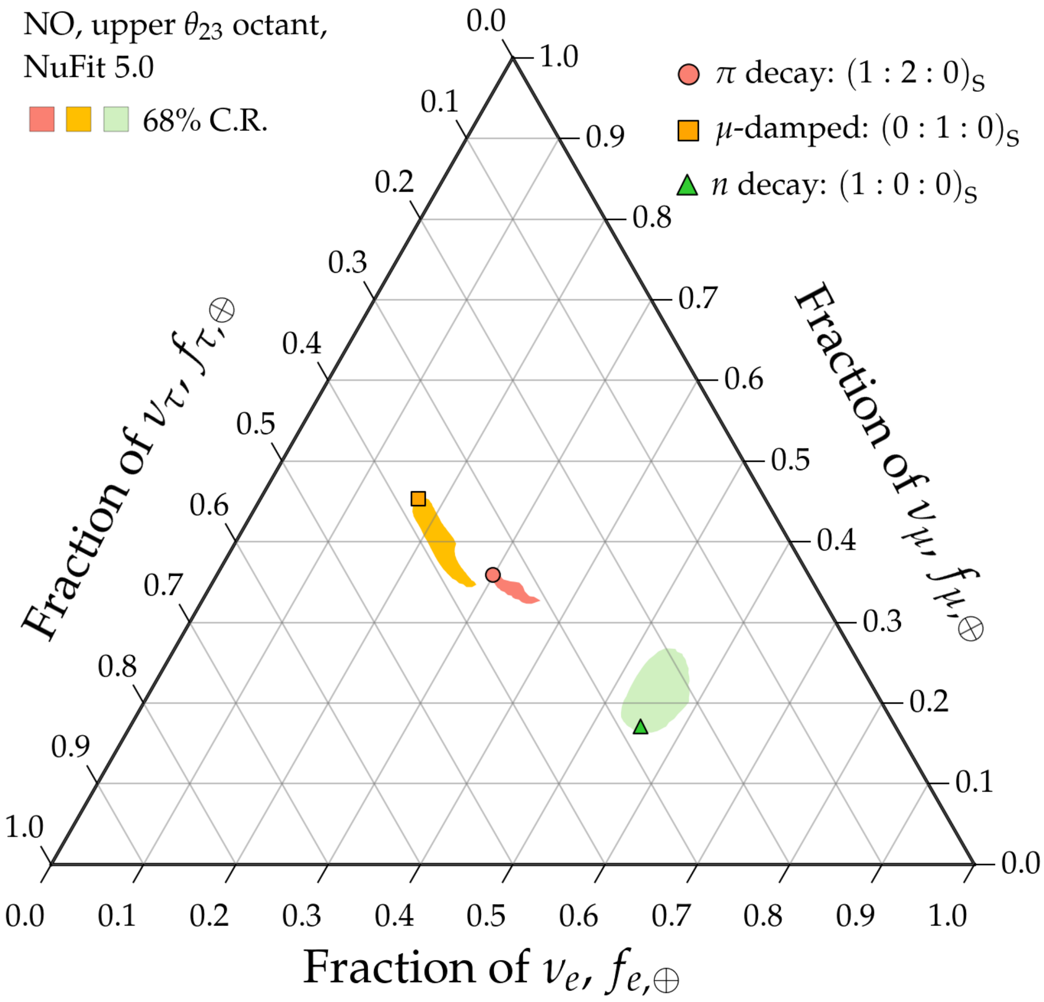
Theoretically palatable regions: today



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

Theoretically palatable regions: today



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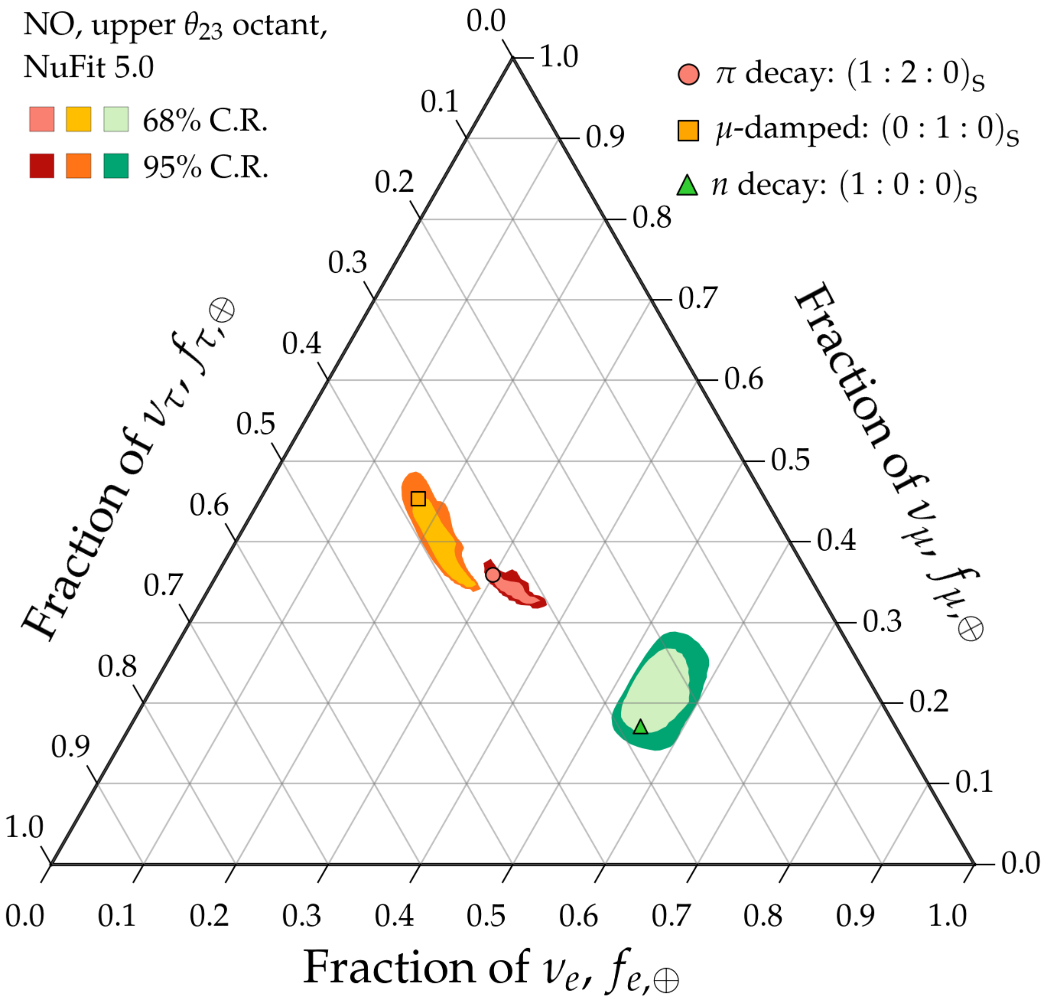

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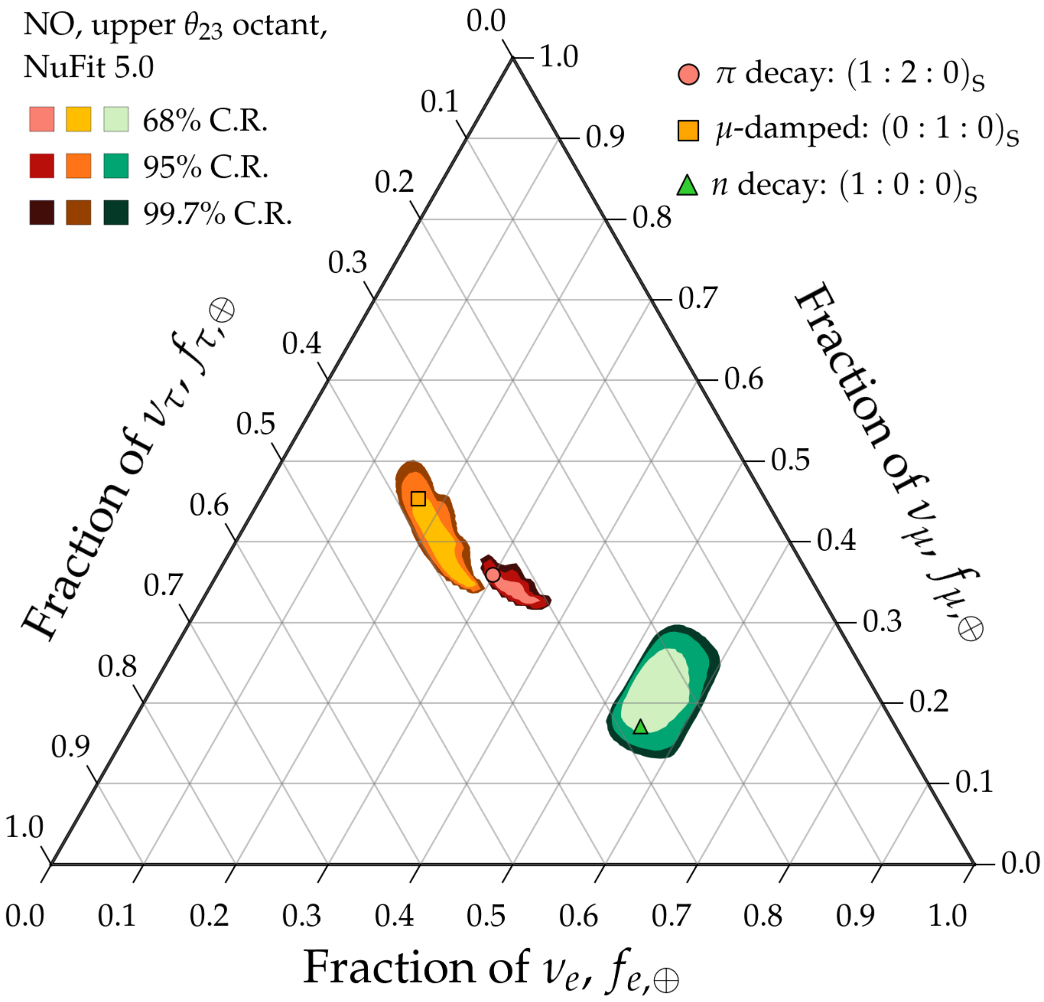

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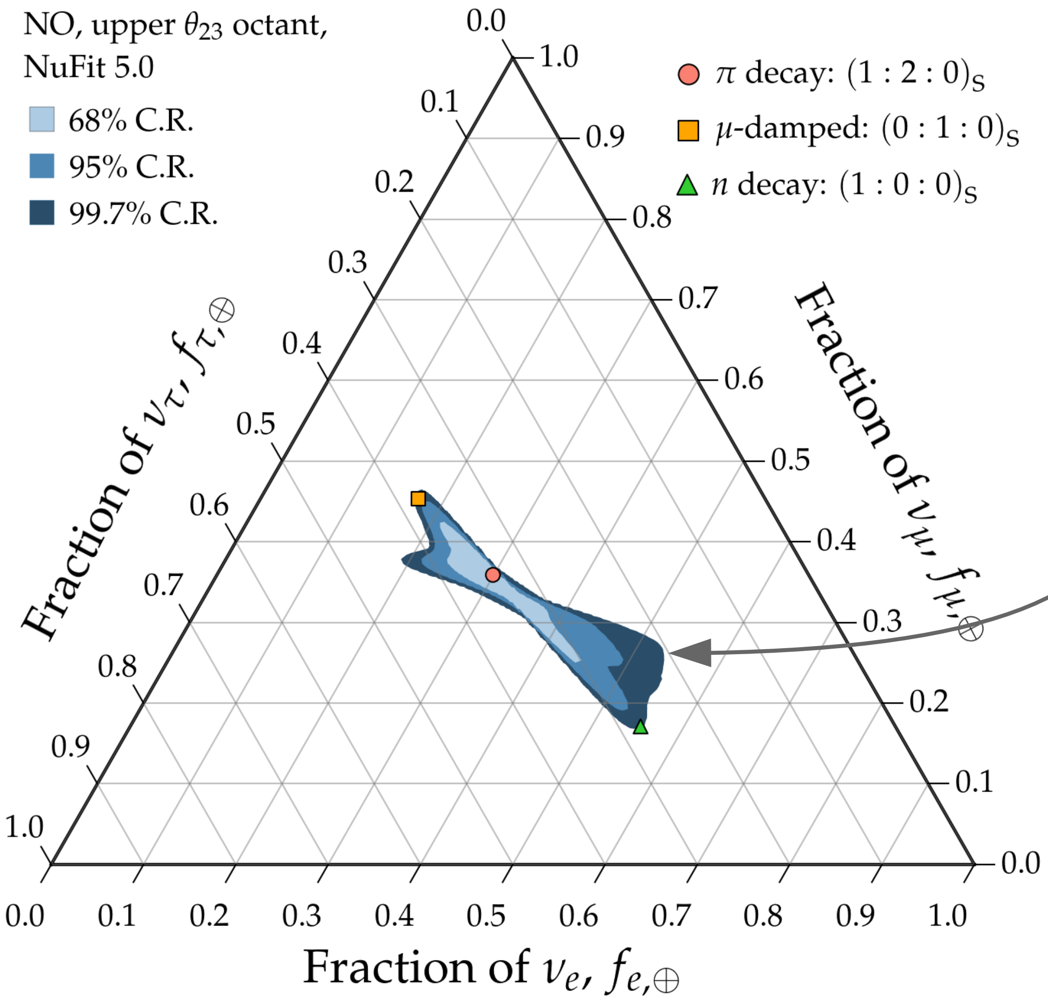
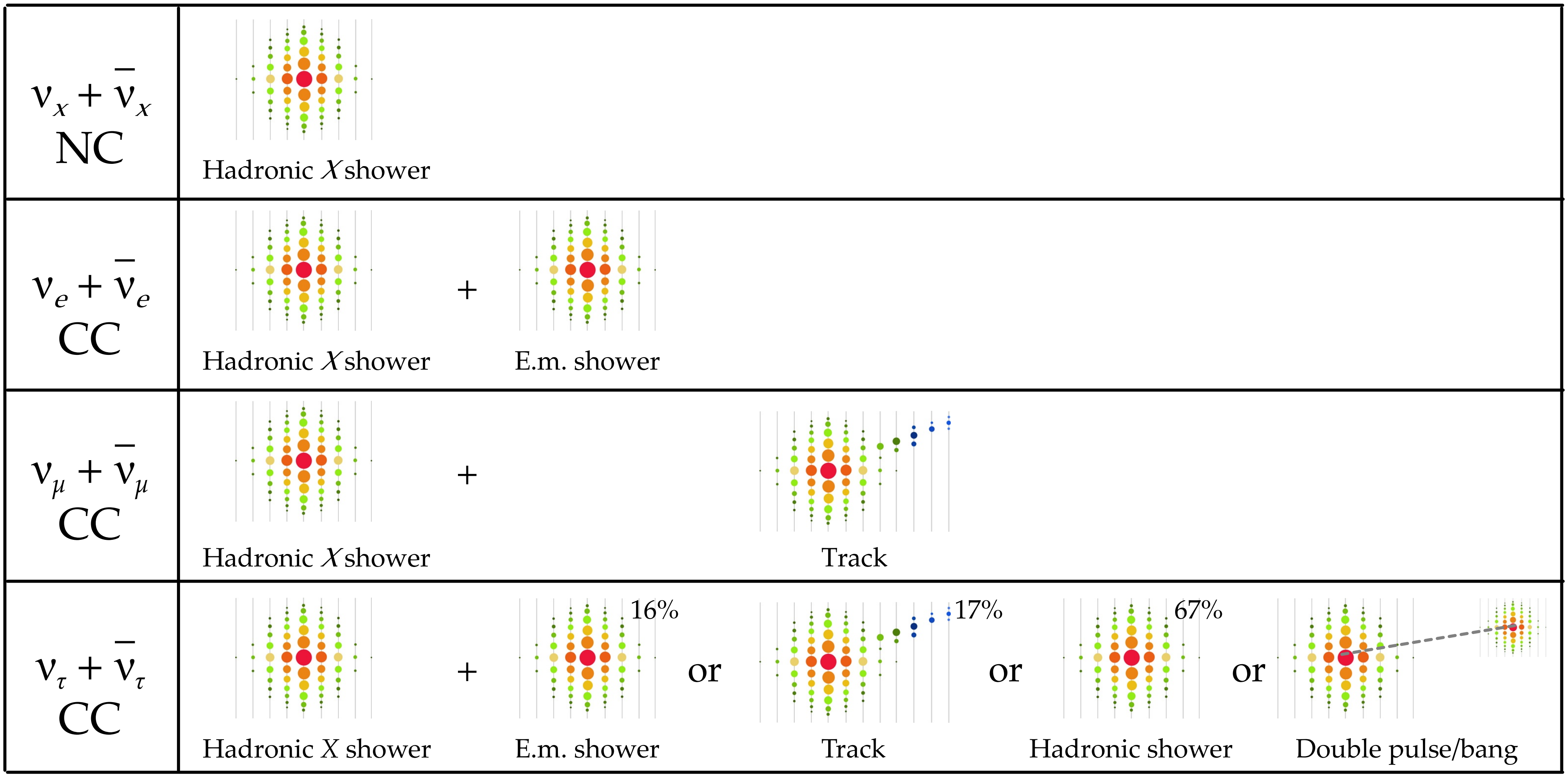


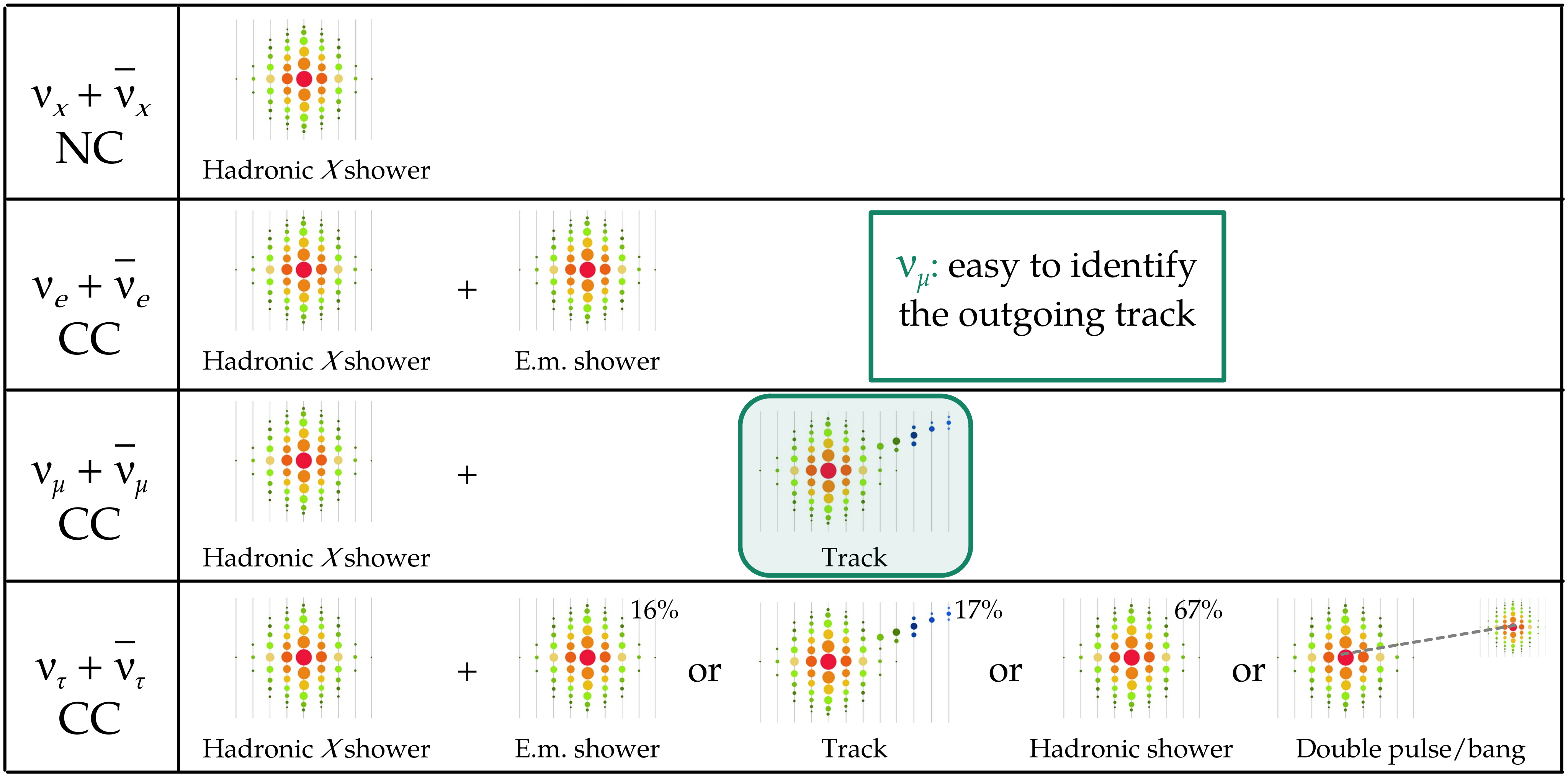
Varying over all possible flavor ratios at the source

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

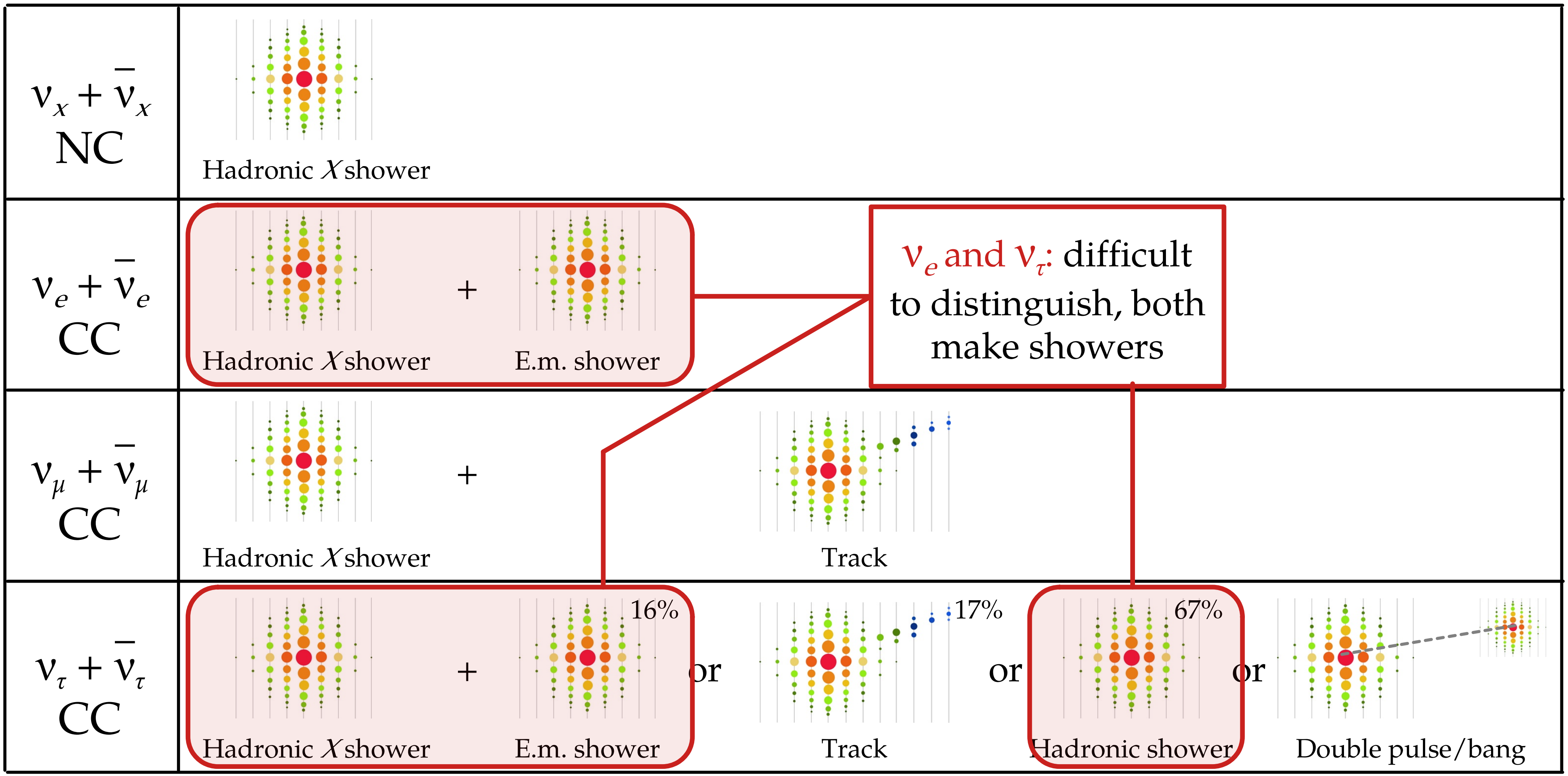
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
See also: **MB**, Beacom, Winter, *PRL* 2015



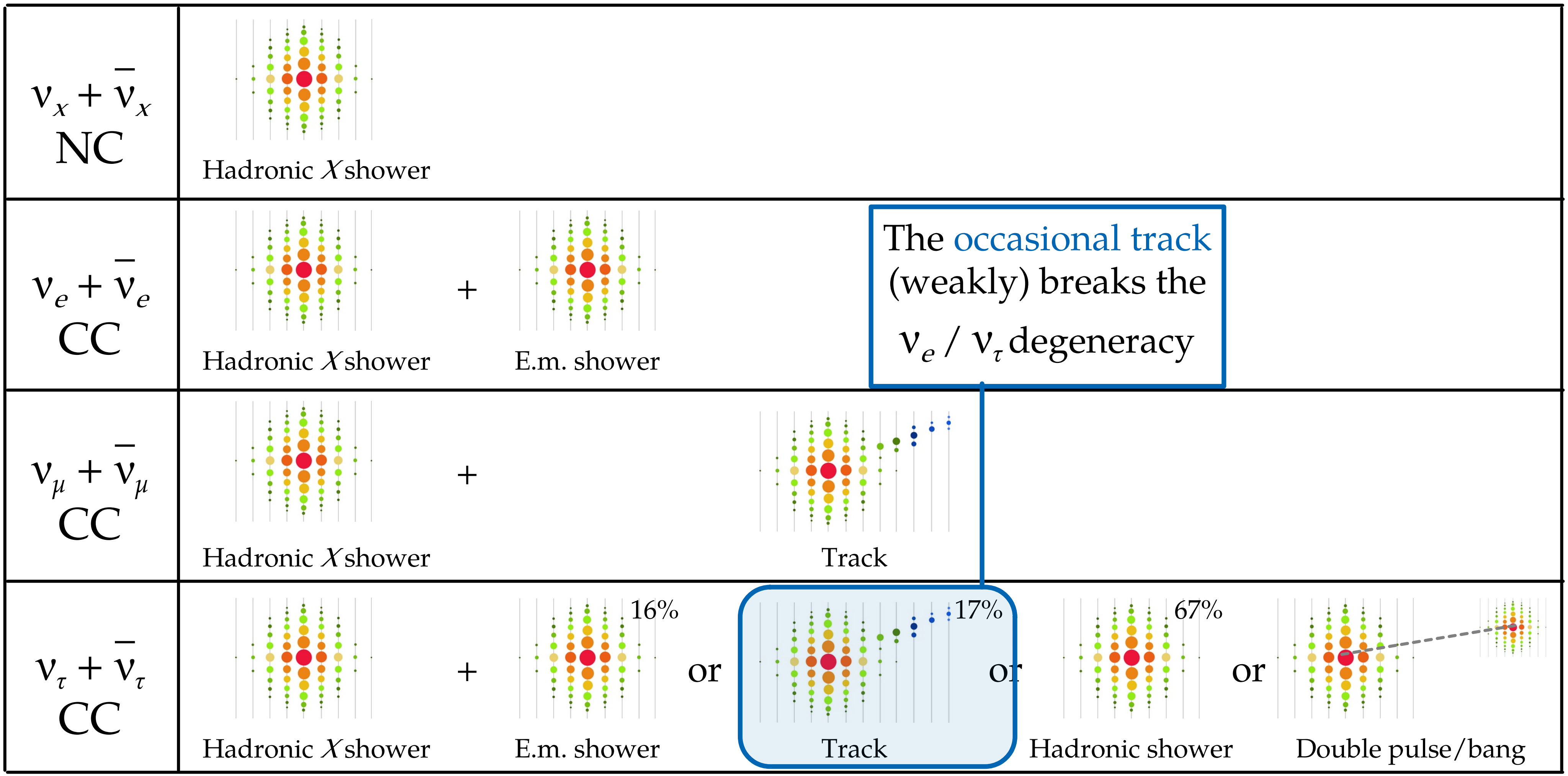
$\nu_x + \bar{\nu}_x$ NC
Hadronic X shower
$\nu_e + \bar{\nu}_e$ CC
Hadronic X shower
+
E.m. shower
$\nu_\mu + \bar{\nu}_\mu$ CC
Hadronic X shower
+
Track
$\nu_\tau + \bar{\nu}_\tau$ CC
Hadronic X shower
+
16%
E.m. shower
or
17%
Track
or
67%
Hadronic shower
or
Double pulse/bang



$\nu_x + \bar{\nu}_x$
NC
Hadronic X shower
$\nu_e + \bar{\nu}_e$
CC
Hadronic X shower
+
E.m. shower
ν_μ: easy to identify the outgoing track
$\nu_\mu + \bar{\nu}_\mu$
CC
Hadronic X shower
+
Track
$\nu_\tau + \bar{\nu}_\tau$
CC
Hadronic X shower
+
16%
E.m. shower
or
17%
Track
or
67%
Hadronic shower
or
Double pulse/bang

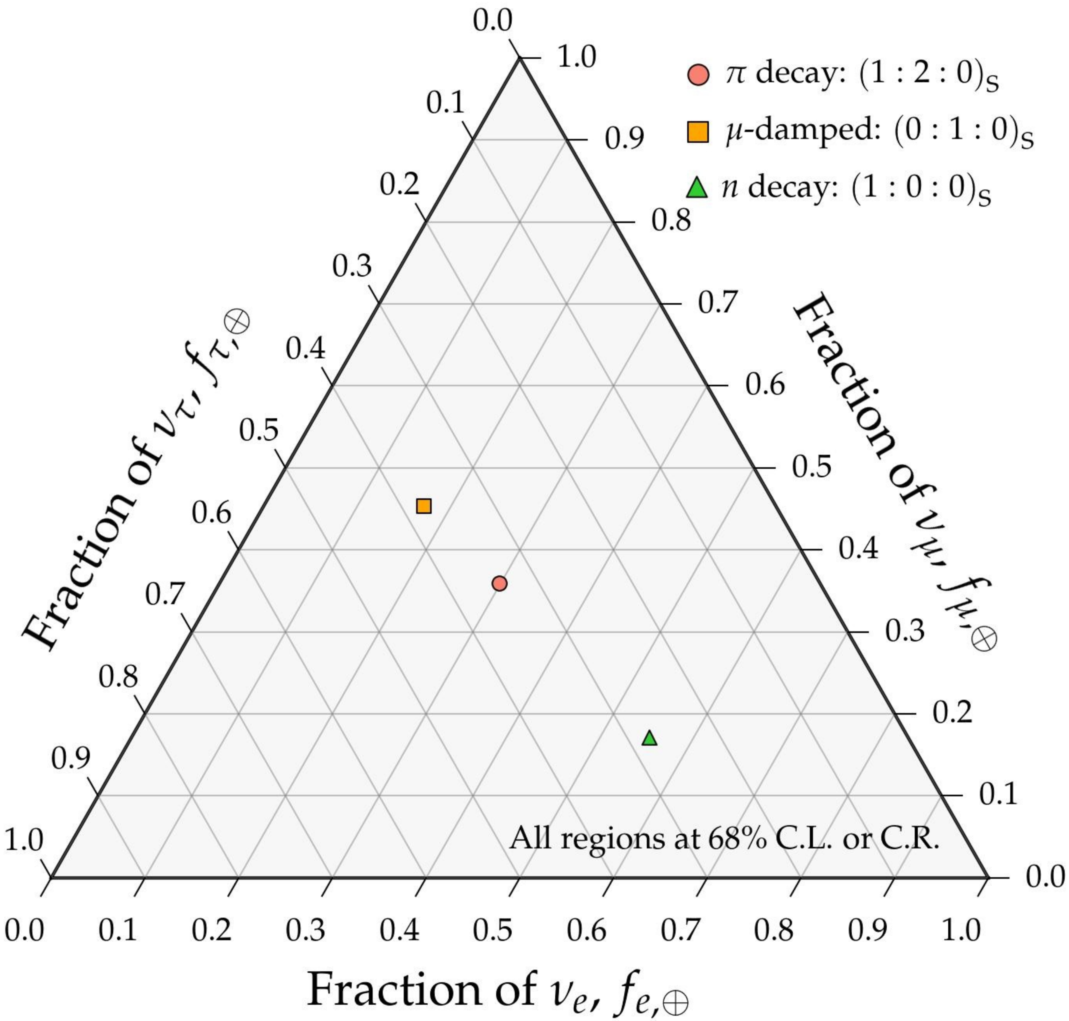


$\nu_x + \bar{\nu}_x$
NC
Hadronic X shower
$\nu_e + \bar{\nu}_e$
CC
Hadronic X shower
+
E.m. shower
ν_e and ν_τ: difficult to distinguish, both make showers
$\nu_\mu + \bar{\nu}_\mu$
CC
Hadronic X shower
+
Track
$\nu_\tau + \bar{\nu}_\tau$
CC
Hadronic X shower
+
E.m. shower
16%
or
Track
17%
or
Hadronic shower
67%
or
Double pulse/bang

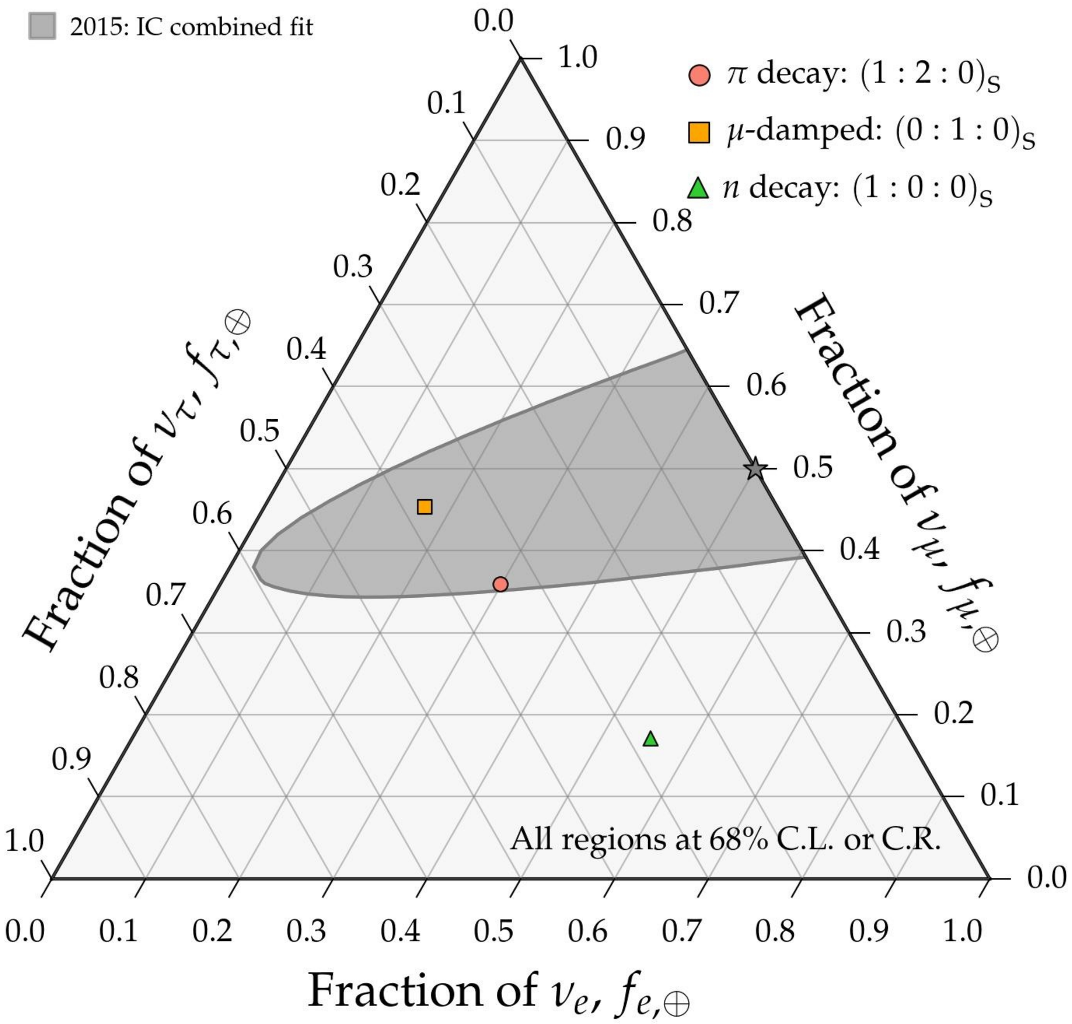


$\nu_x + \bar{\nu}_x$ NC
Hadronic X shower
$\nu_e + \bar{\nu}_e$ CC
Hadronic X shower
+
E.m. shower
The occasional track (weakly) breaks the ν_e / ν_τ degeneracy
$\nu_\mu + \bar{\nu}_\mu$ CC
Hadronic X shower
+
Track
$\nu_\tau + \bar{\nu}_\tau$ CC
Hadronic X shower
+
16%
E.m. shower
or
17%
Track
or
67%
Hadronic shower
or
Double pulse/bang

Measuring flavor composition 2015–2025



Measuring flavor composition 2015–2025



IceCube Collab., 2510.24957, 2507.06835, *EPJC* 2022, PRD 2019, *ApJ* 2015, *PRL* 2015

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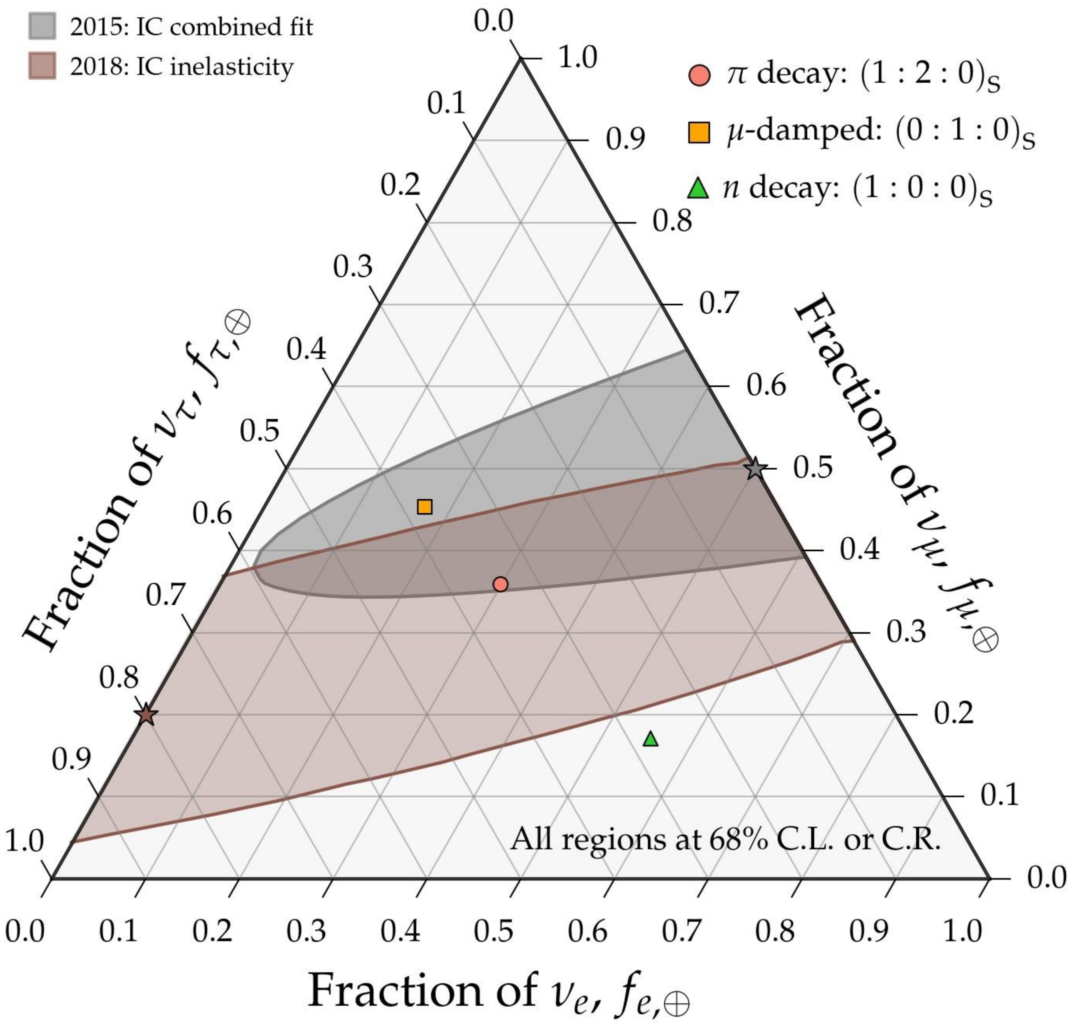

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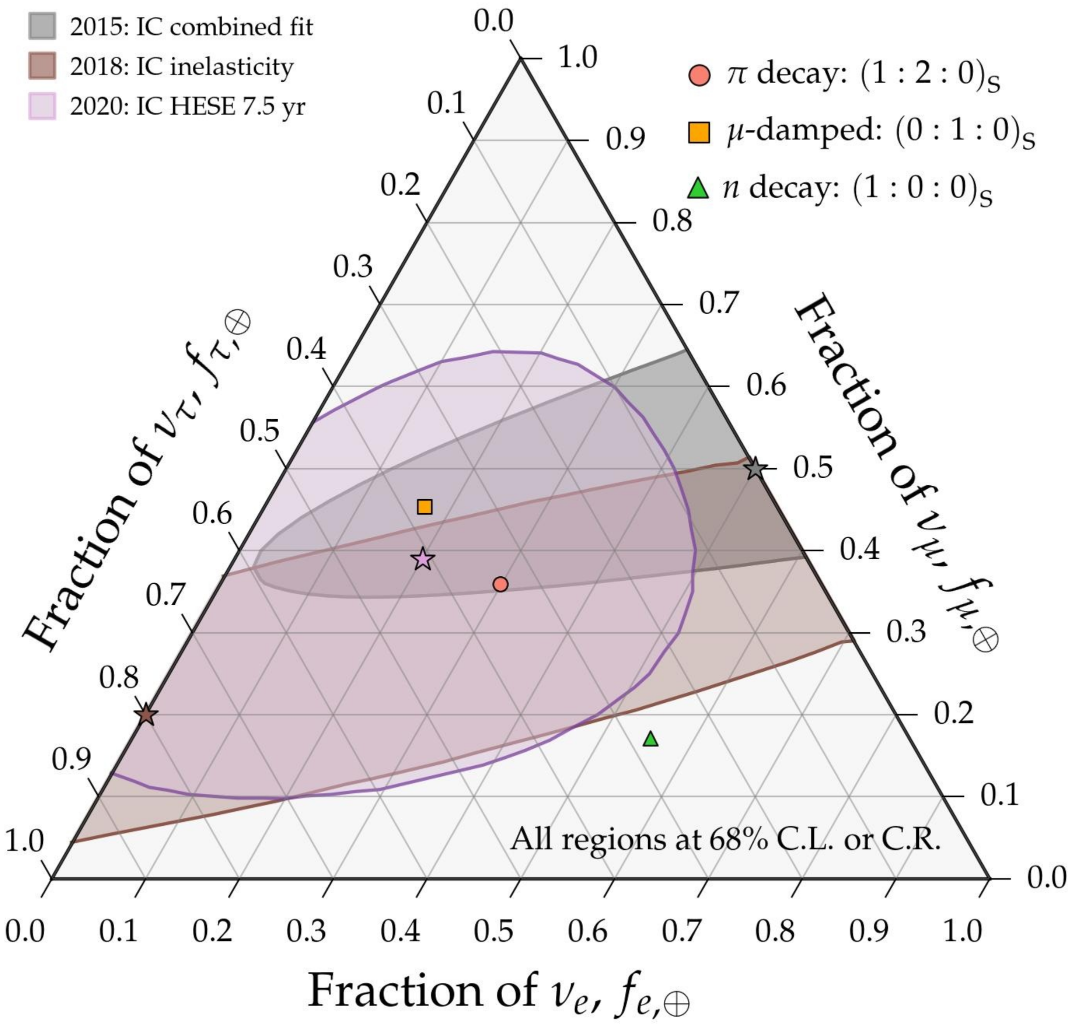

IceCube Collab., 2510.24957, 2507.06835, *EPJC* 2022, PRD 2019, *ApJ* 2015, *PRL* 2015

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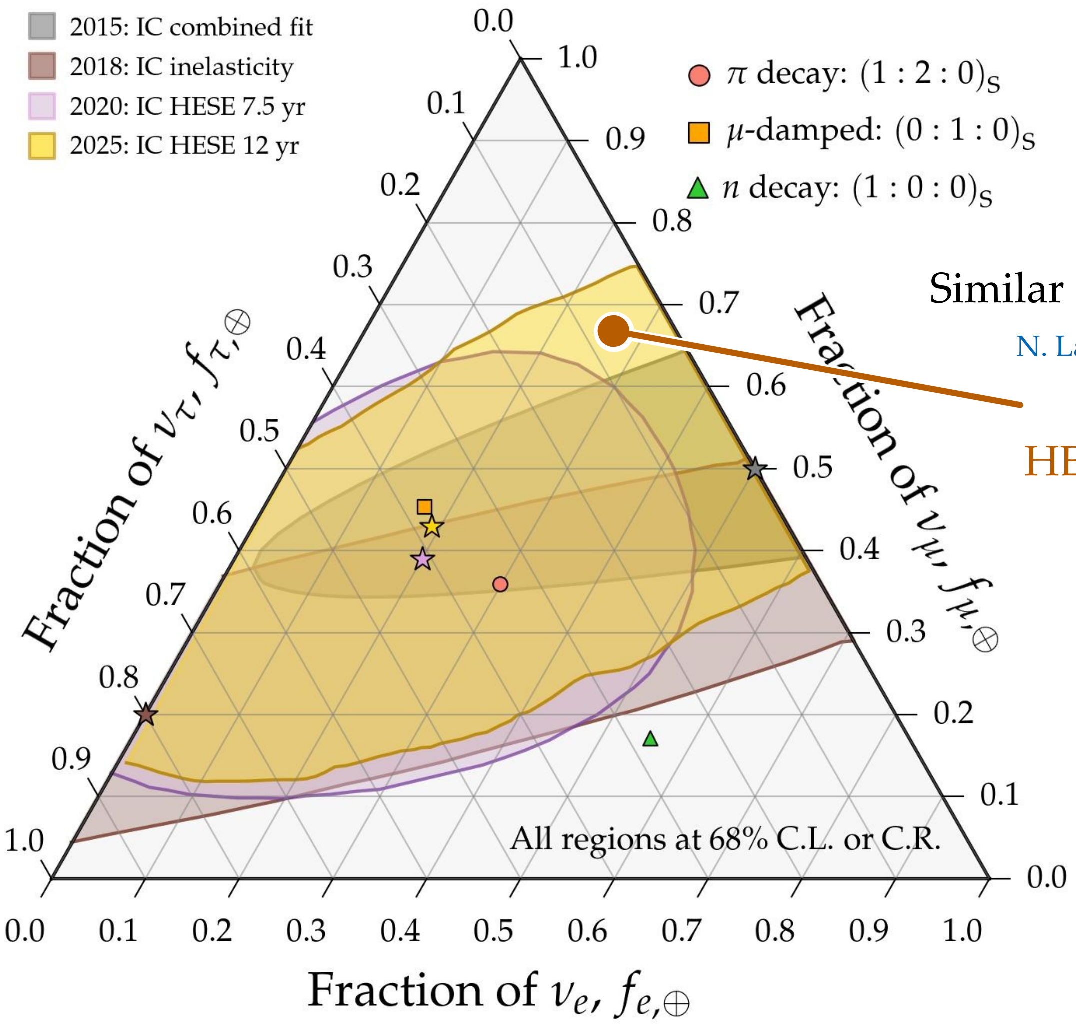


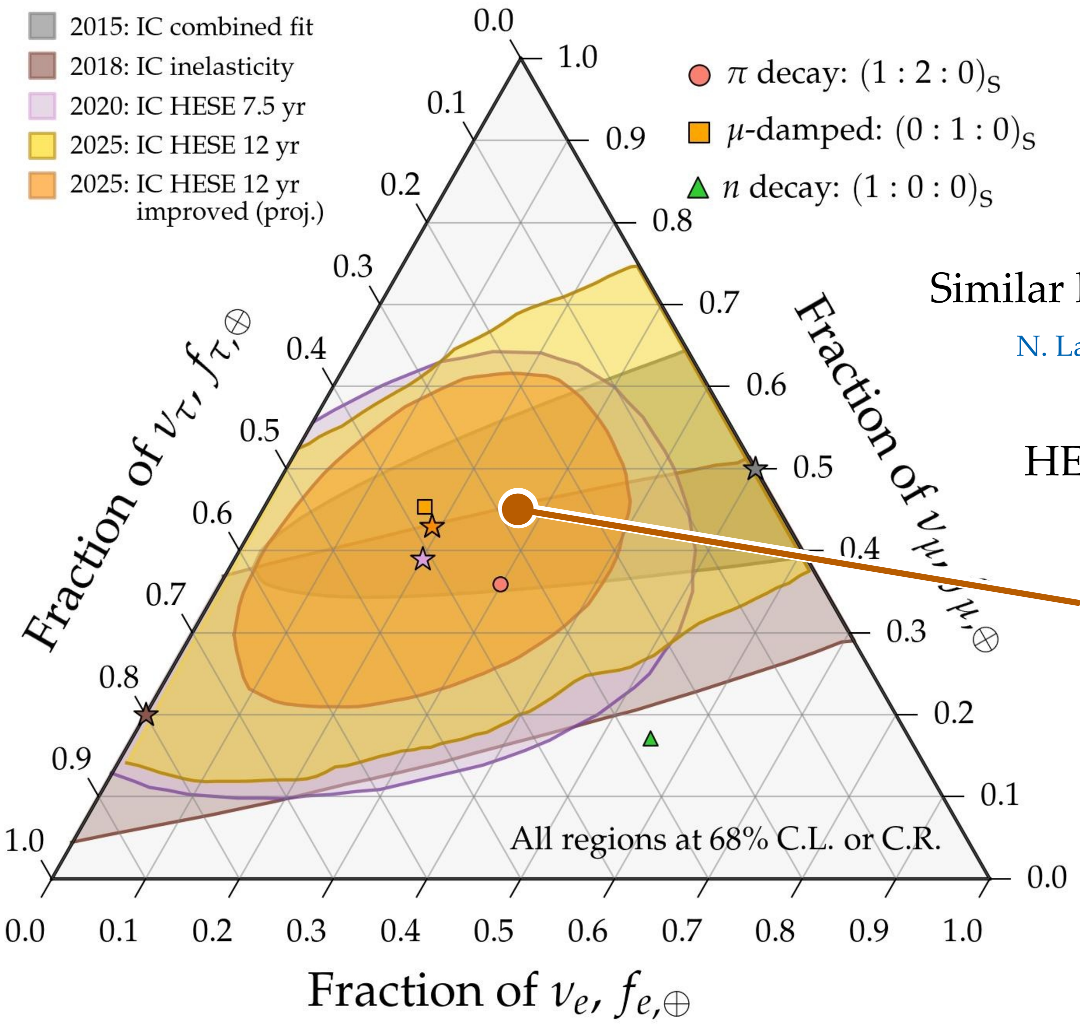
Similar likelihood as with 7.5 yr

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

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

IceCube Collab., 2510.24957, 2507.06835, *EPJC* 2022, PRD 2019, *ApJ* 2015, *PRL* 2015

Measuring flavor composition 2015–2025



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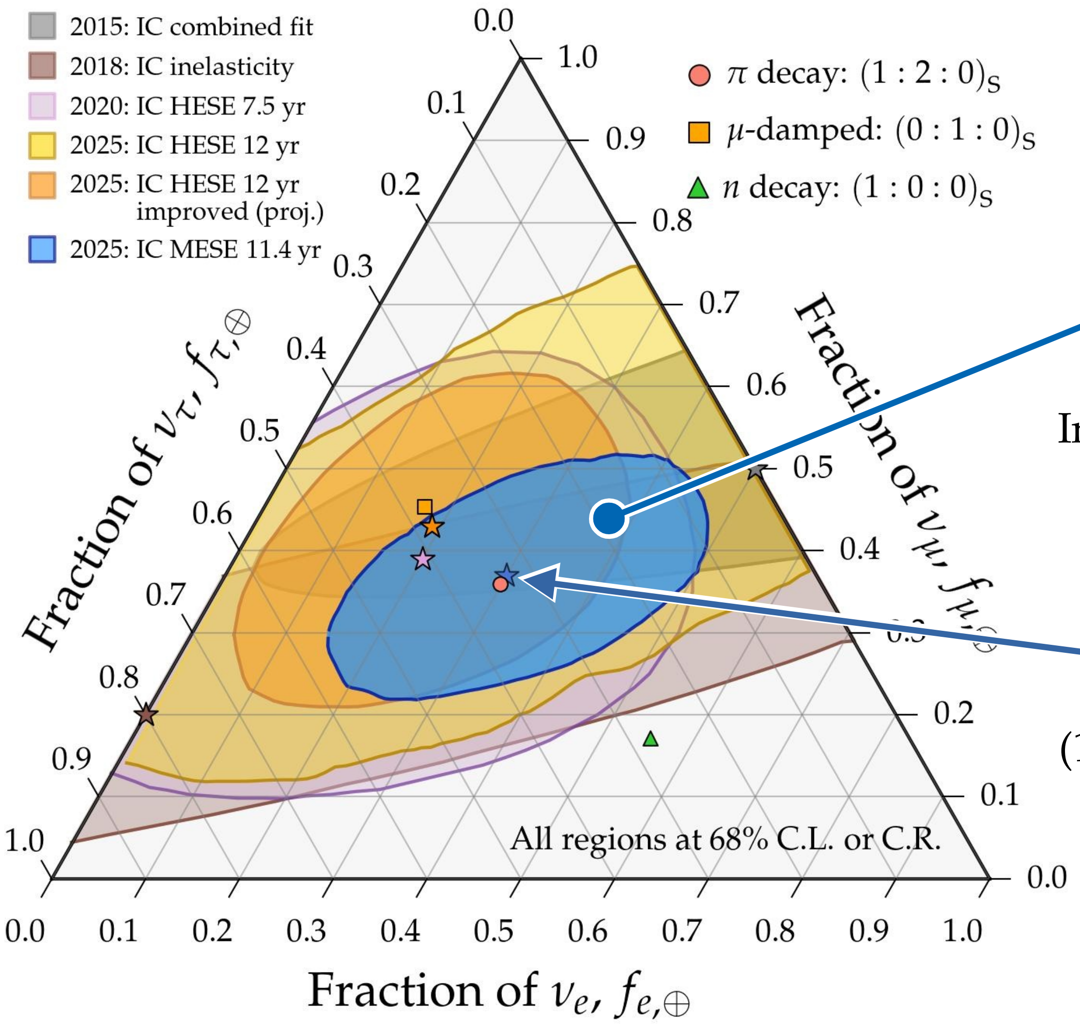
Improve via a neural network that uses the energy asymmetry of the two bangs and the direction

IceCube Collab., 2510.24957, 2507.06835, *EPJC* 2022, PRD 2019, *ApJ* 2015, *PRL* 2015

Measuring flavor composition 2015–2025



MESE events (> 1 TeV) are more abundant

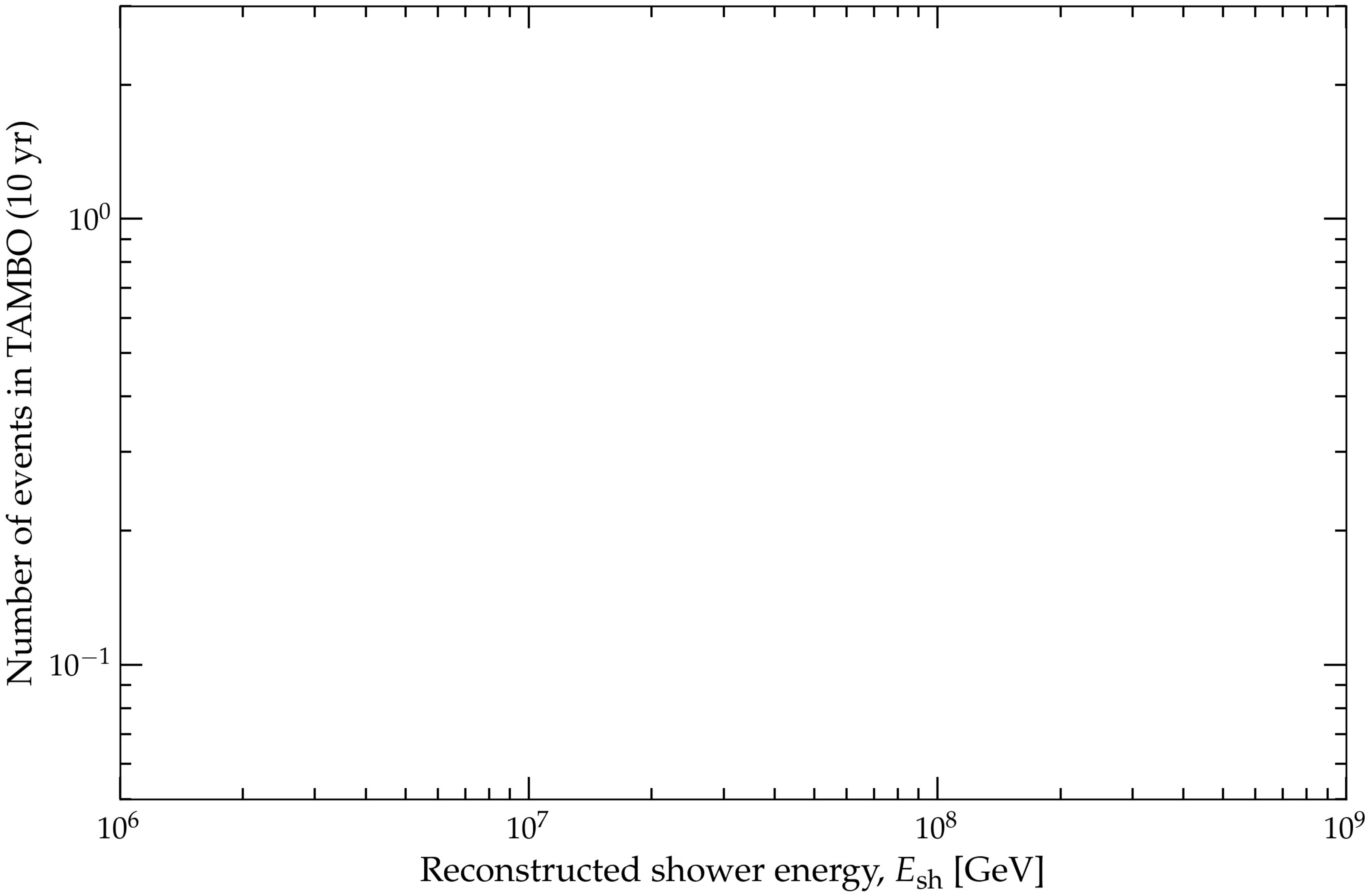
Includes classification of υ_τ

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

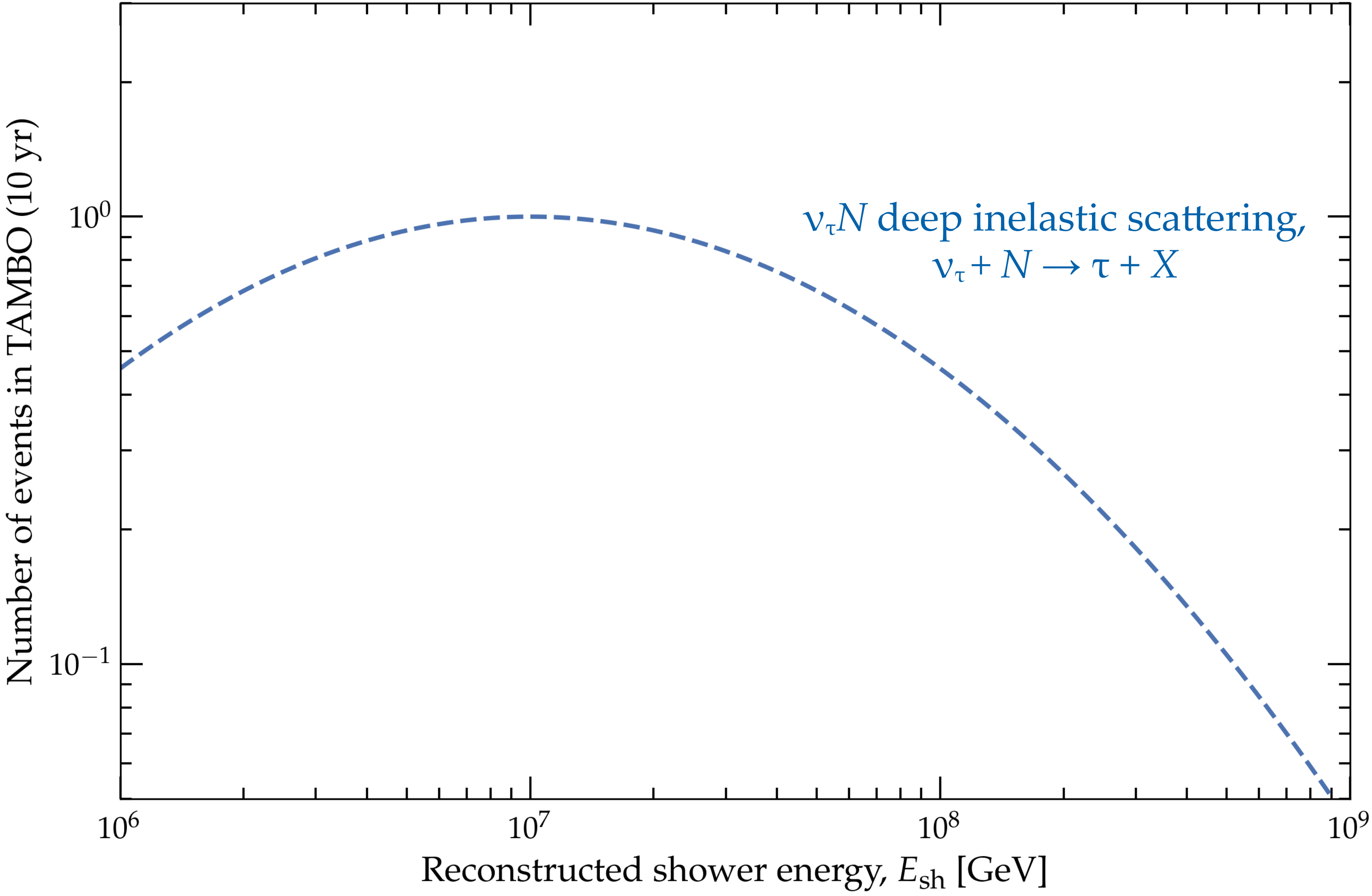
Best fit very close to nominal expectation of (1:1:1) from production via pion decay

IceCube Collab., 2510.24957, 2507.06835, *EPJC* 2022, PRD 2019, *ApJ* 2015, *PRL* 2015

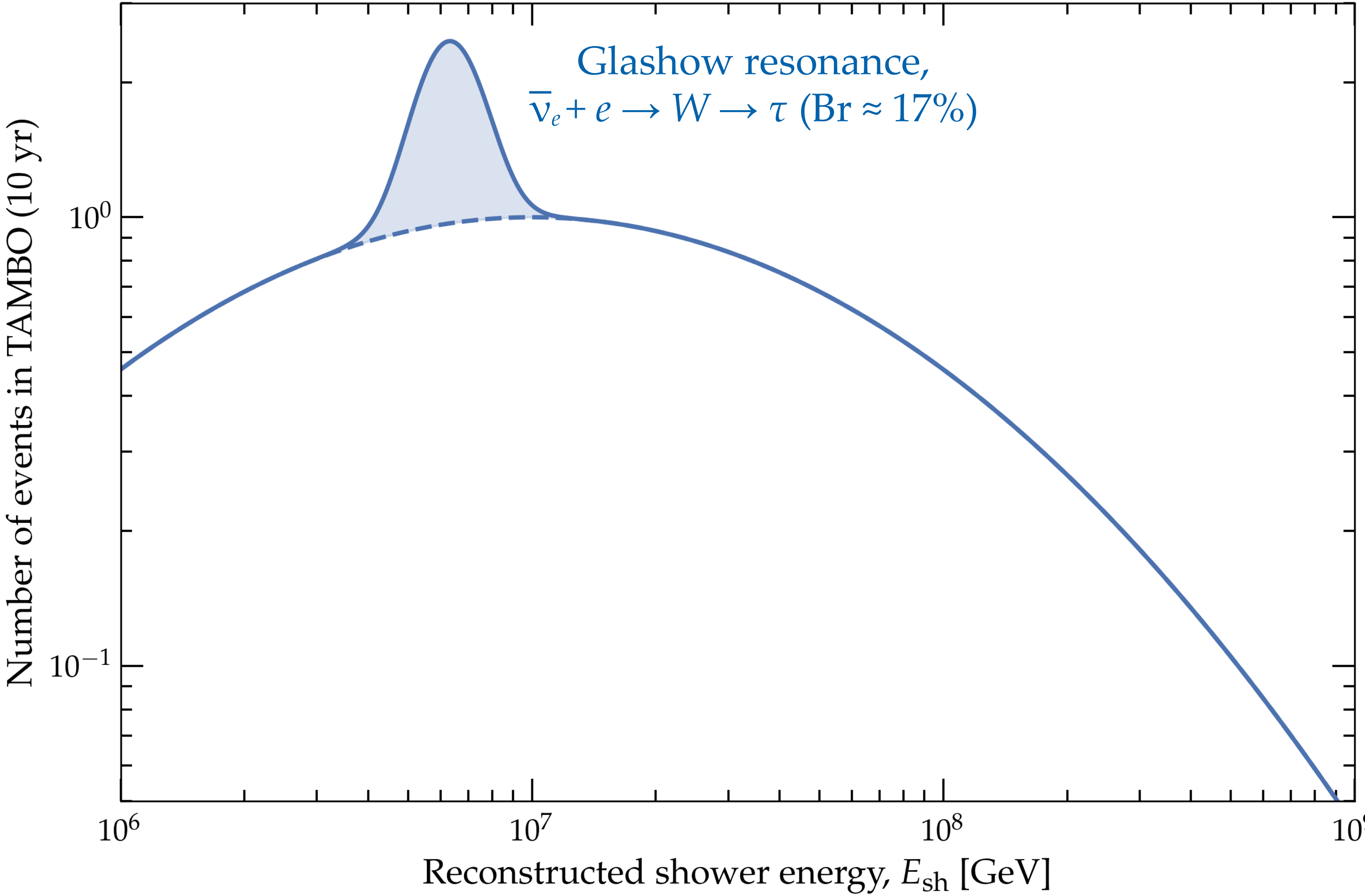
How to measure flavor in TAMBO

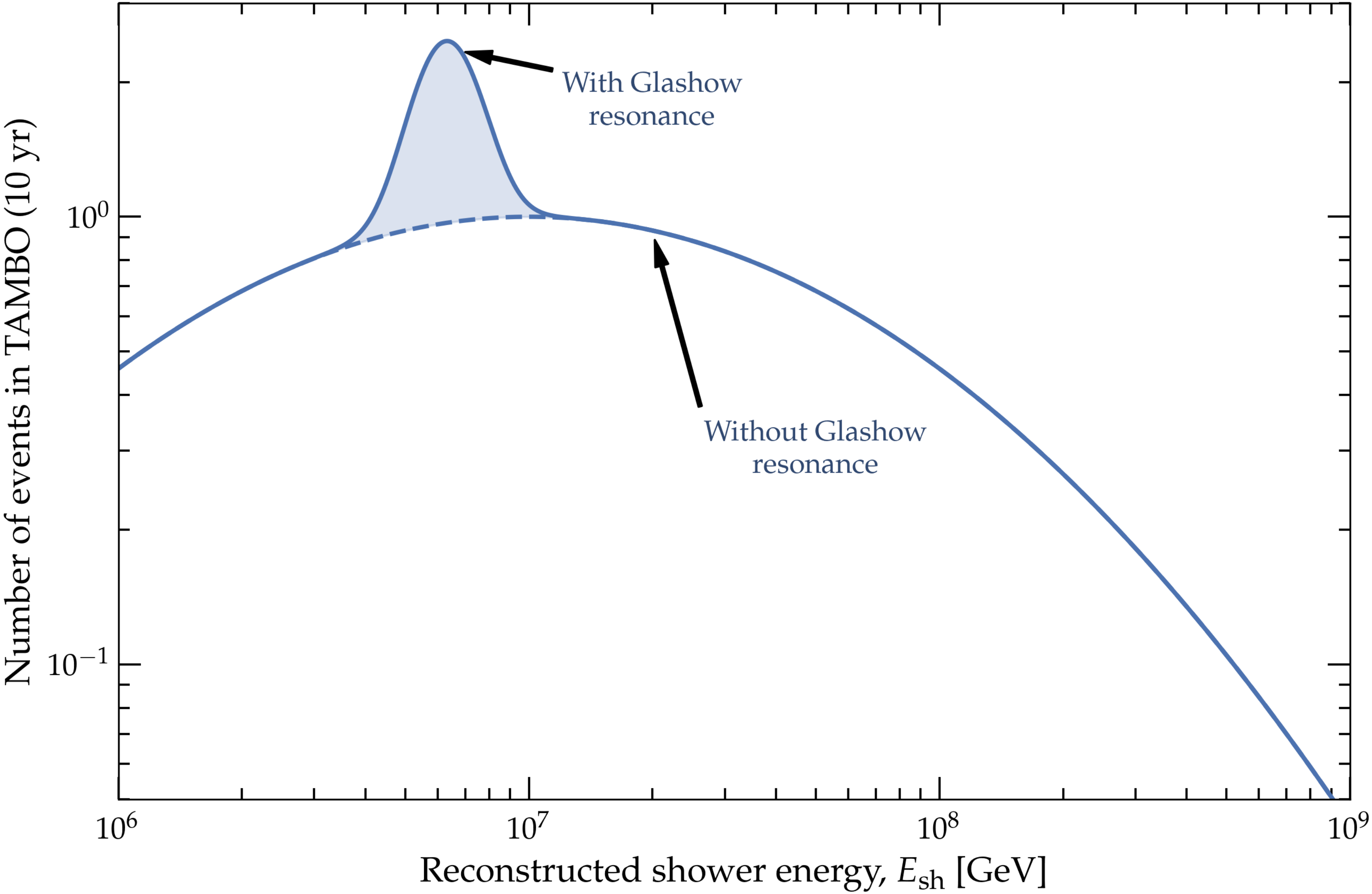


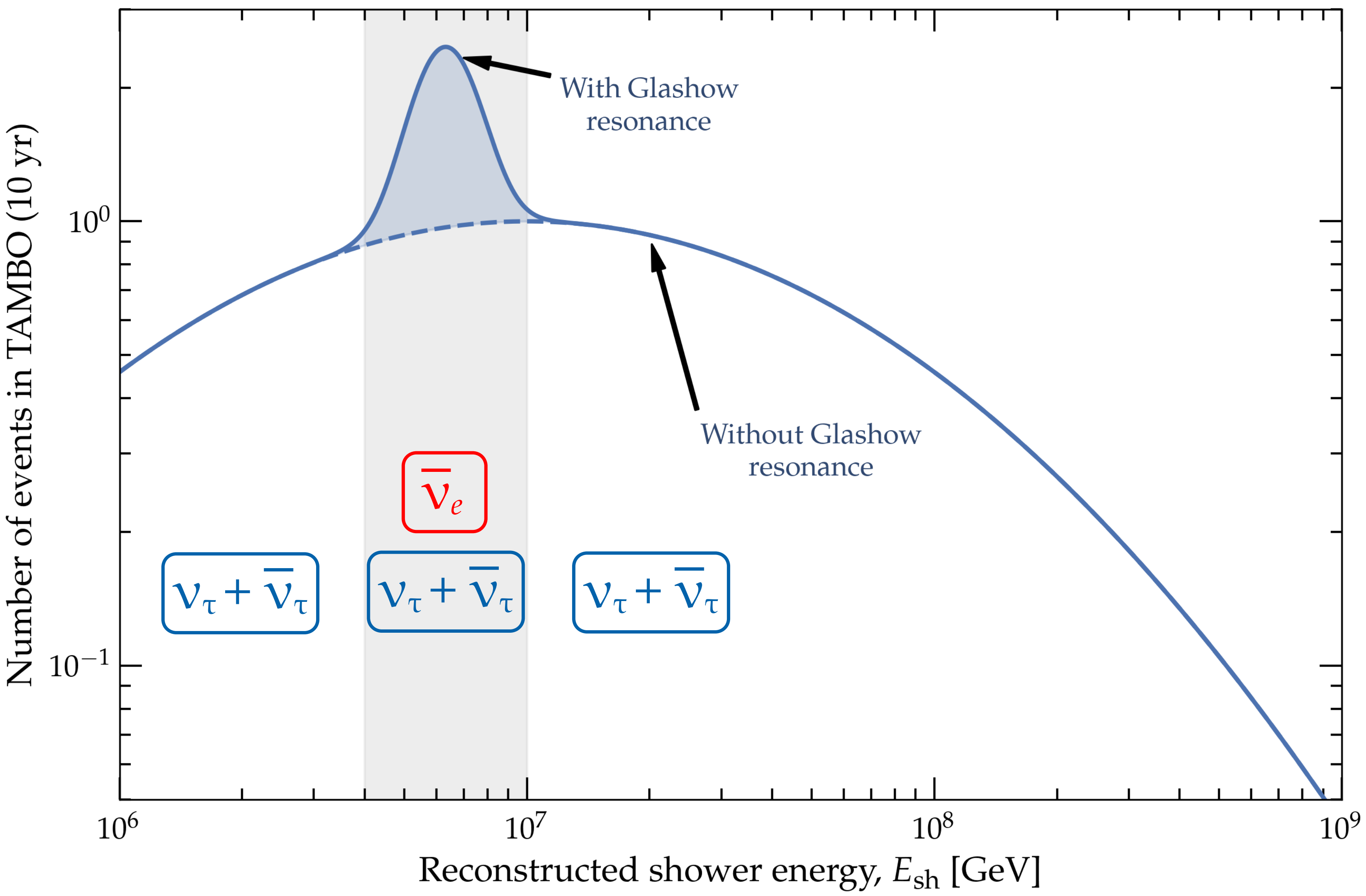
Number of events in TAMBO (10 yr)
10^{0}
10^{-1}
10^{6}
10^{7}
10^{8}
10^{9}
Reconstructed shower energy, E_{sh} [GeV]



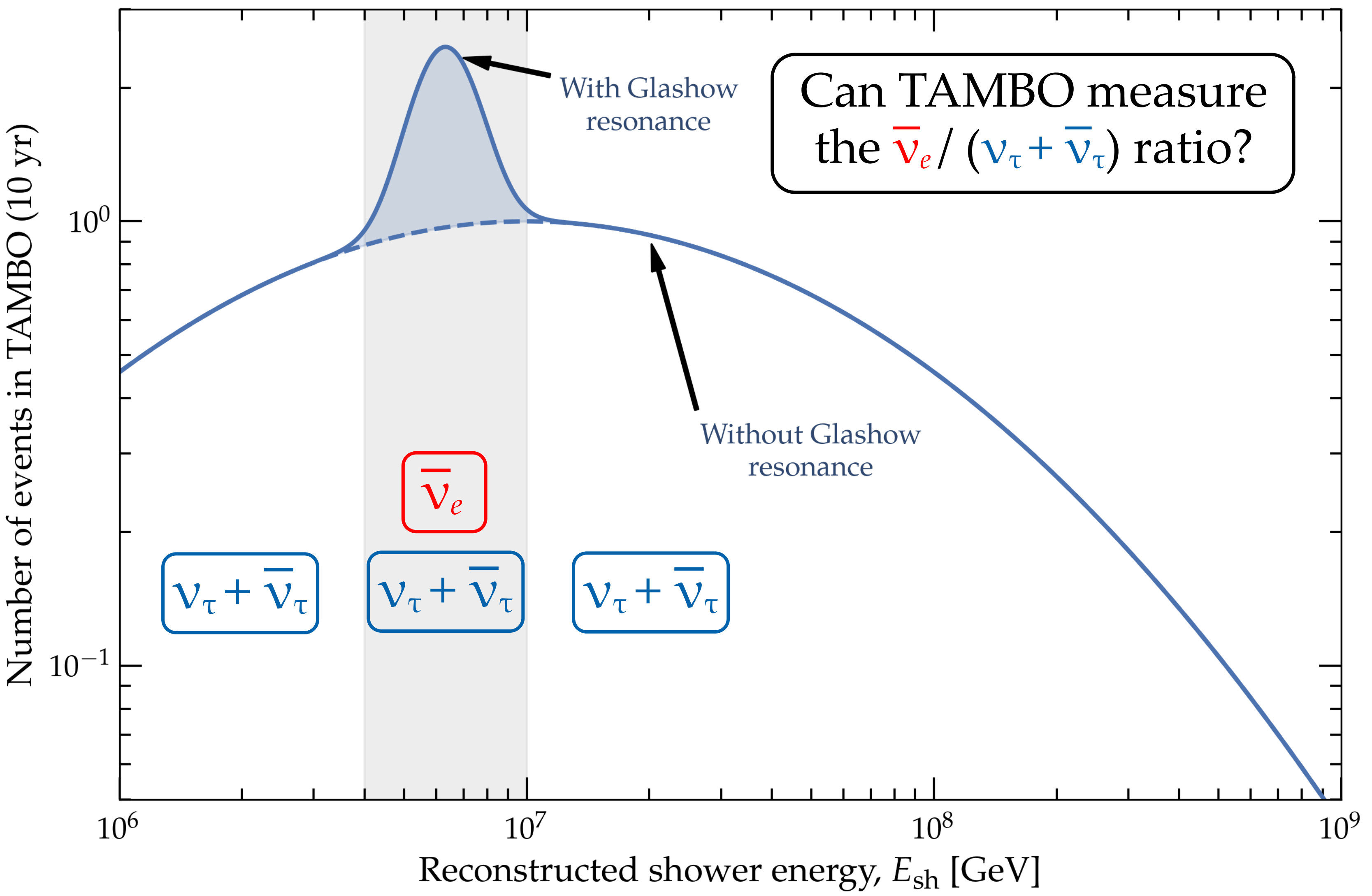
Number of events in TAMBO (10 yr)
10^0
10^{-1}
10^6
10^7
10^8
10^9
Reconstructed shower energy, E_{sh} [GeV]
$\nu_\tau N$ deep inelastic scattering,
$\nu_\tau + N \rightarrow \tau + X$


Glashow resonance,
$\bar{\nu}_e + e \rightarrow W \rightarrow \tau$ (Br ≈ 17%)
10^0
10^{-1}
Number of events in TAMBO (10 yr)
10^6
10^7
10^8
10^9
Reconstructed shower energy, E_{sh} [GeV]


With Glashow resonance
Without Glashow resonance
Number of events in TAMBO (10 yr)
10^0
10^{-1}
10^6
10^7
10^8
10^9
Reconstructed shower energy, E_{sh} [GeV]

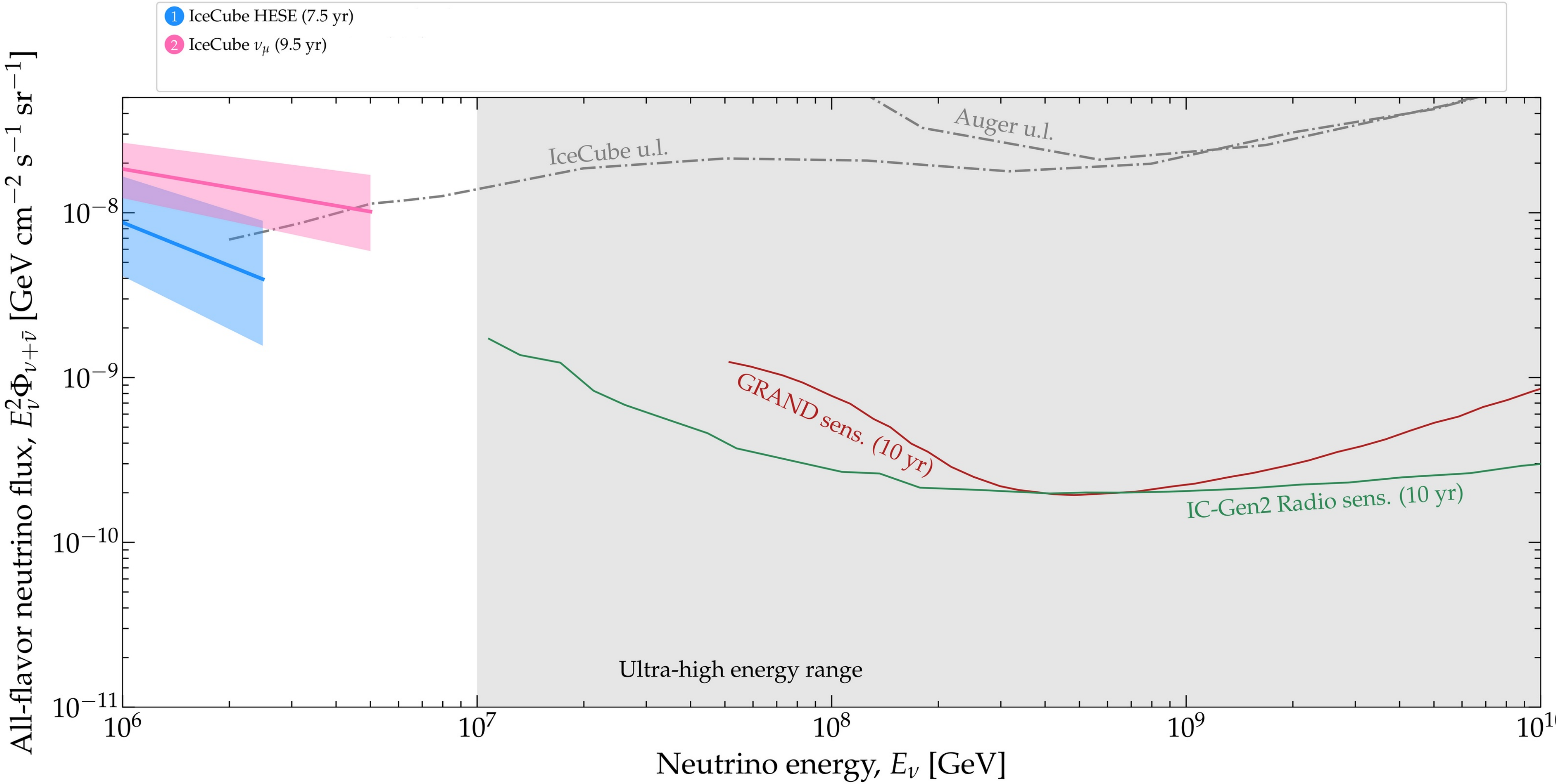


With Glashow resonance
Without Glashow resonance
$\bar{\nu}_e$
$\nu_\tau + \bar{\nu}_\tau$
$\nu_\tau + \bar{\nu}_\tau$
$\nu_\tau + \bar{\nu}_\tau$
Number of events in TAMBO (10 yr)
10^0
10^{-1}
10^6
10^7
10^8
10^9
Reconstructed shower energy, E_{sh} [GeV]

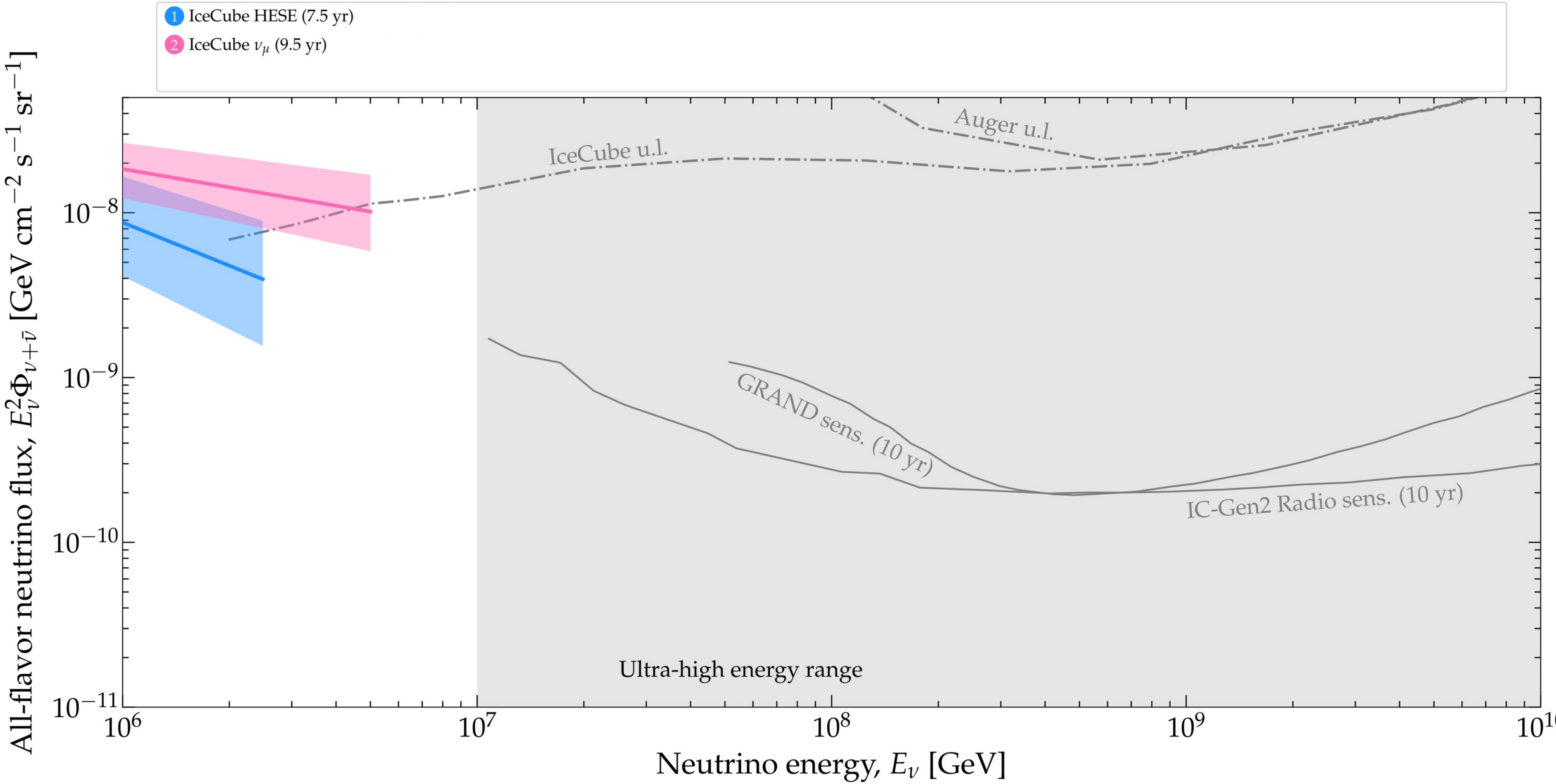


Can TAMBO measure the $\bar{\nu}_e / (\nu_\tau + \bar{\nu}_\tau)$ ratio?
With Glashow resonance
Without Glashow resonance
$\bar{\nu}_e$
$\nu_\tau + \bar{\nu}_\tau$
$\nu_\tau + \bar{\nu}_\tau$
$\nu_\tau + \bar{\nu}_\tau$
Number of events in TAMBO (10 yr)
10^0
10^{-1}
10^6
10^7
10^8
10^9
Reconstructed shower energy, E_{sh} [GeV]

Diffuse UHE ν flux predictions



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



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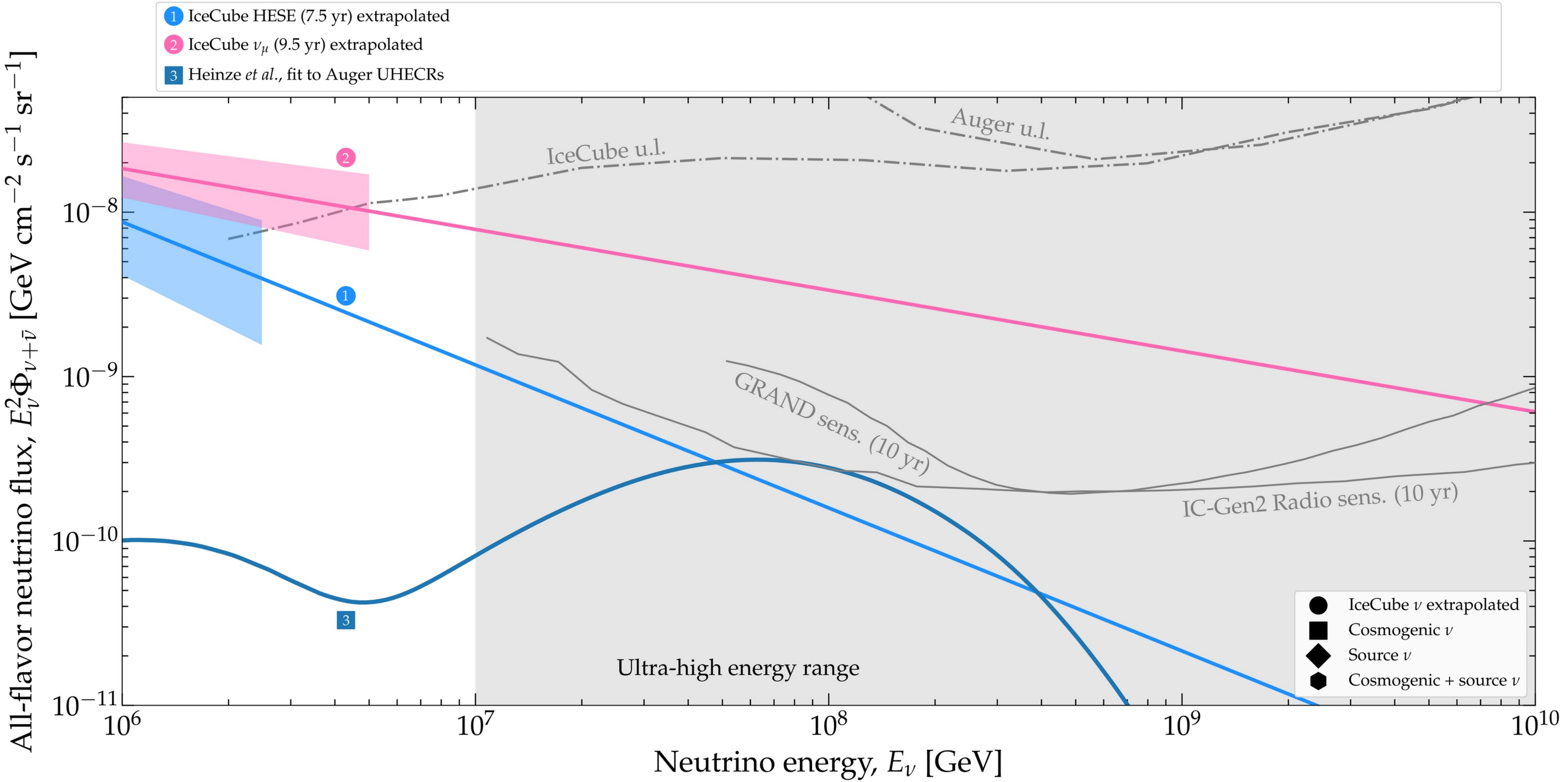

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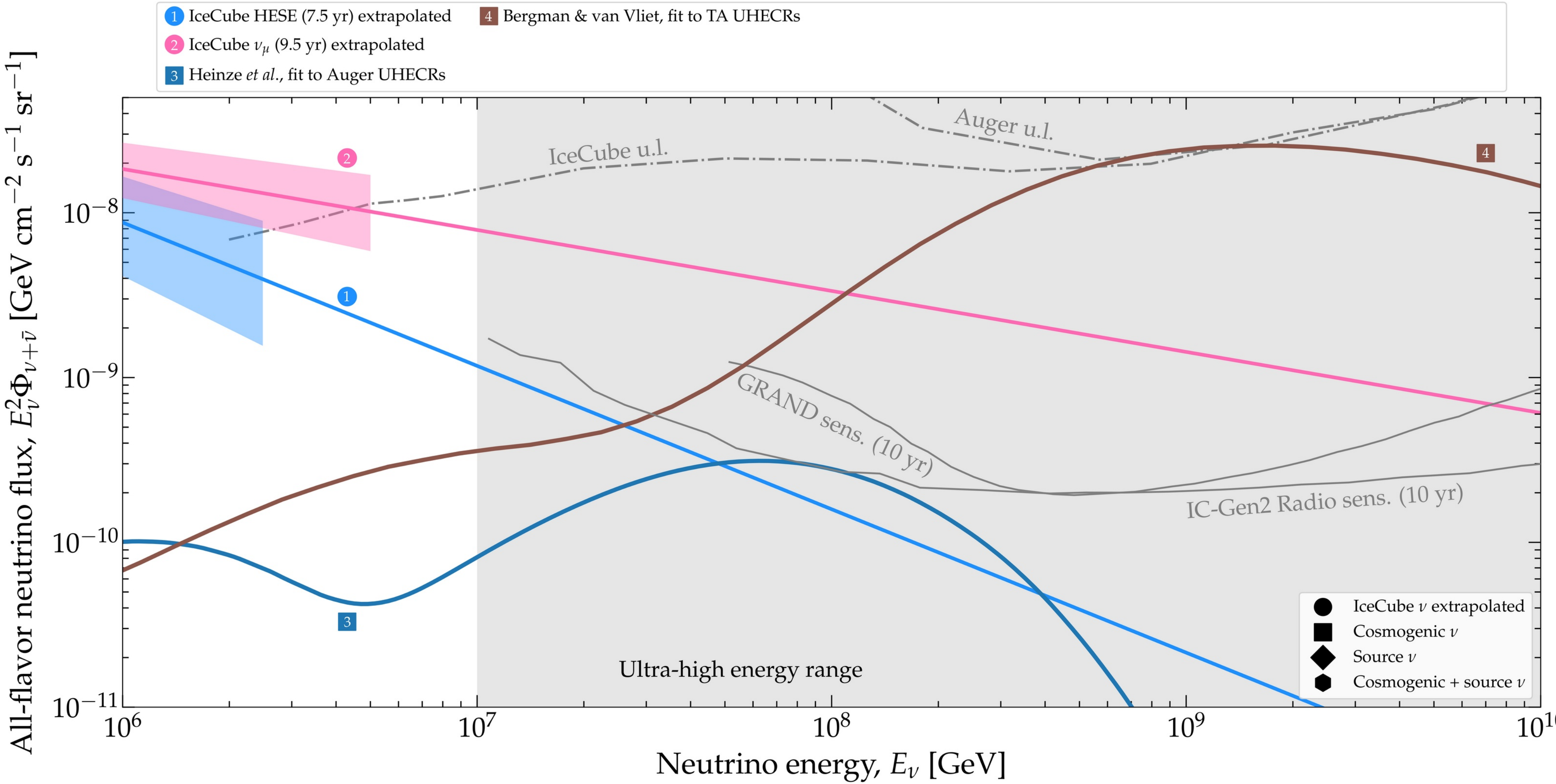

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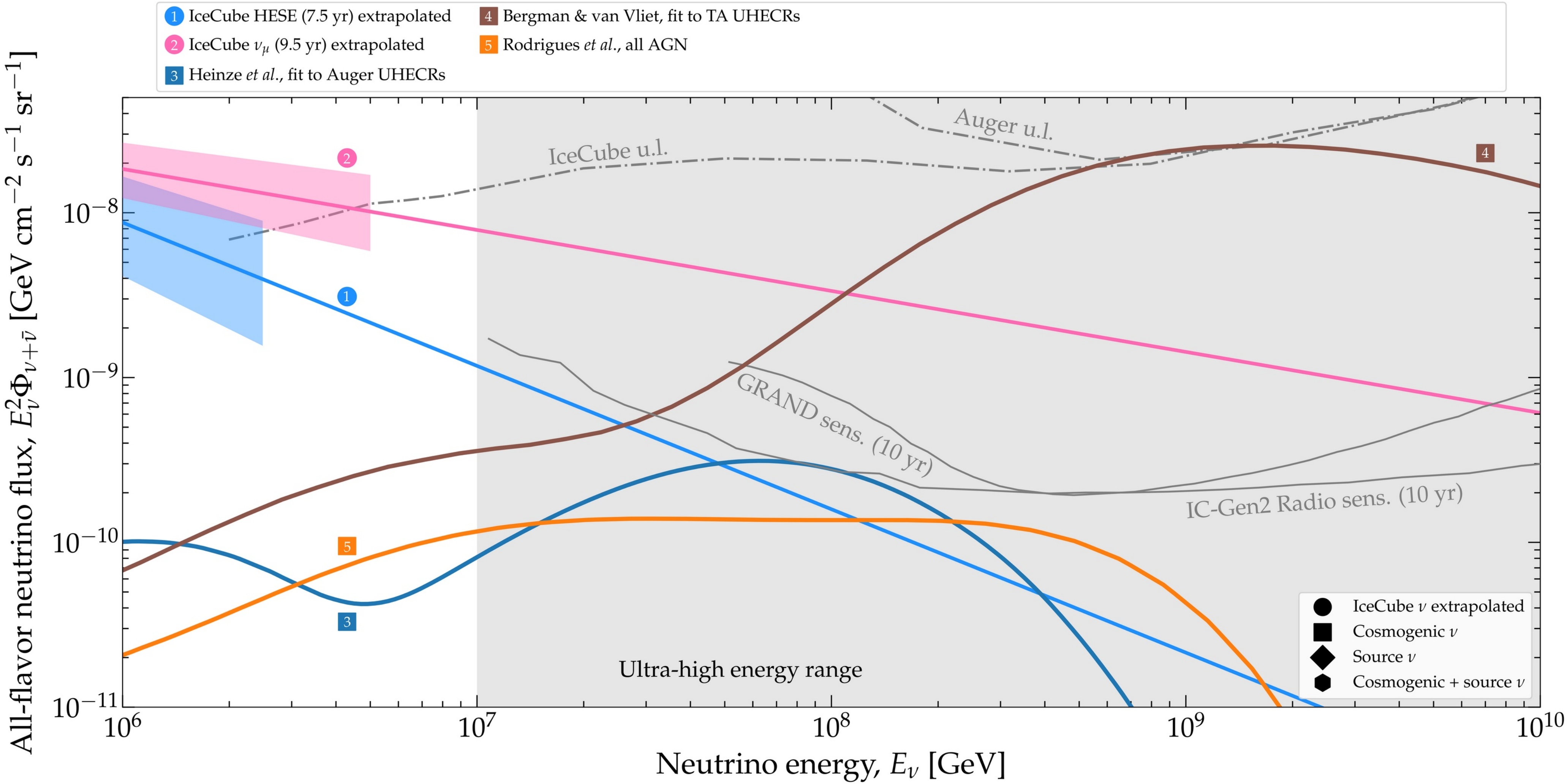
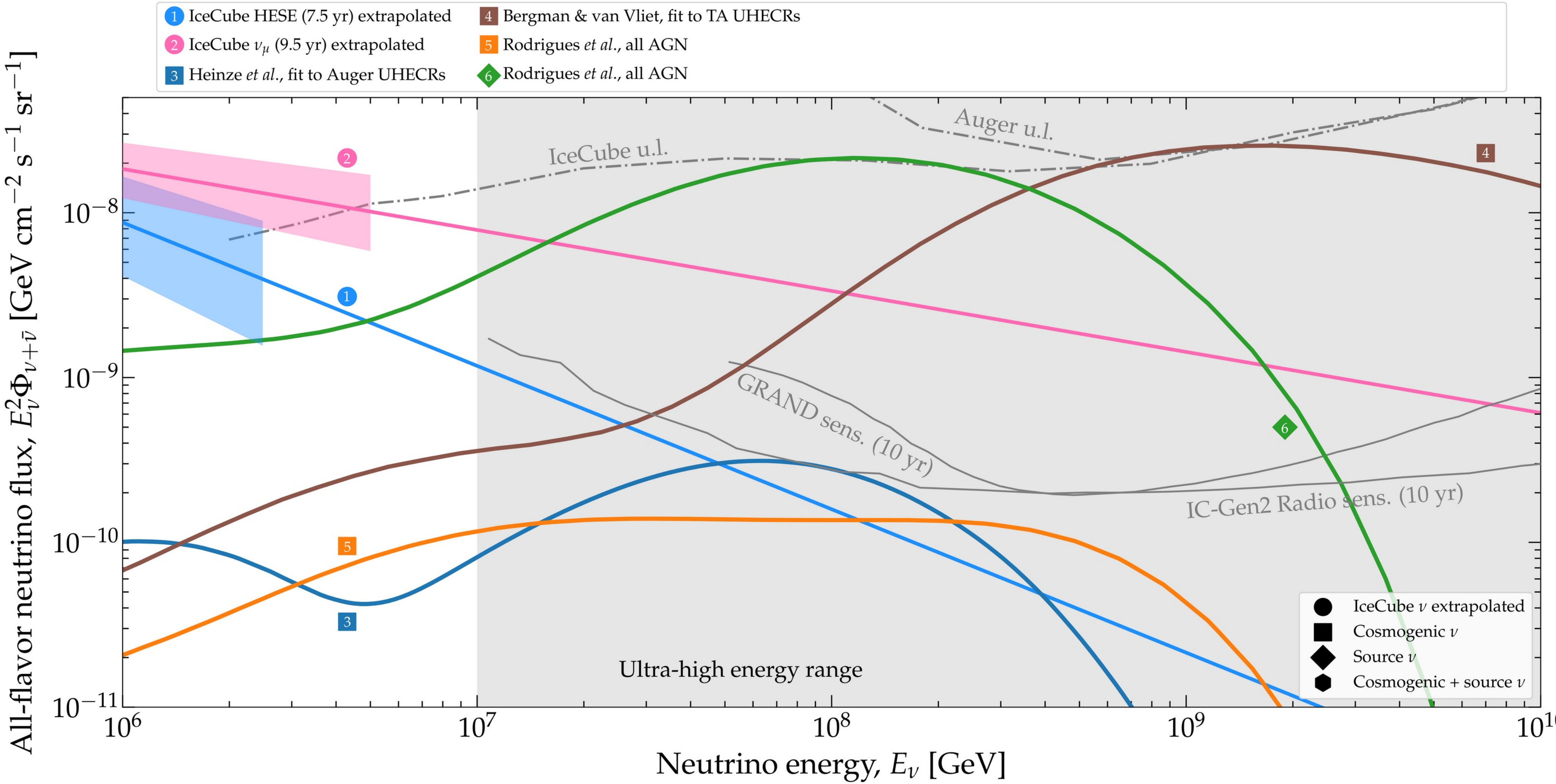


Valera, **MB**, Glaser, *PRD* 2023



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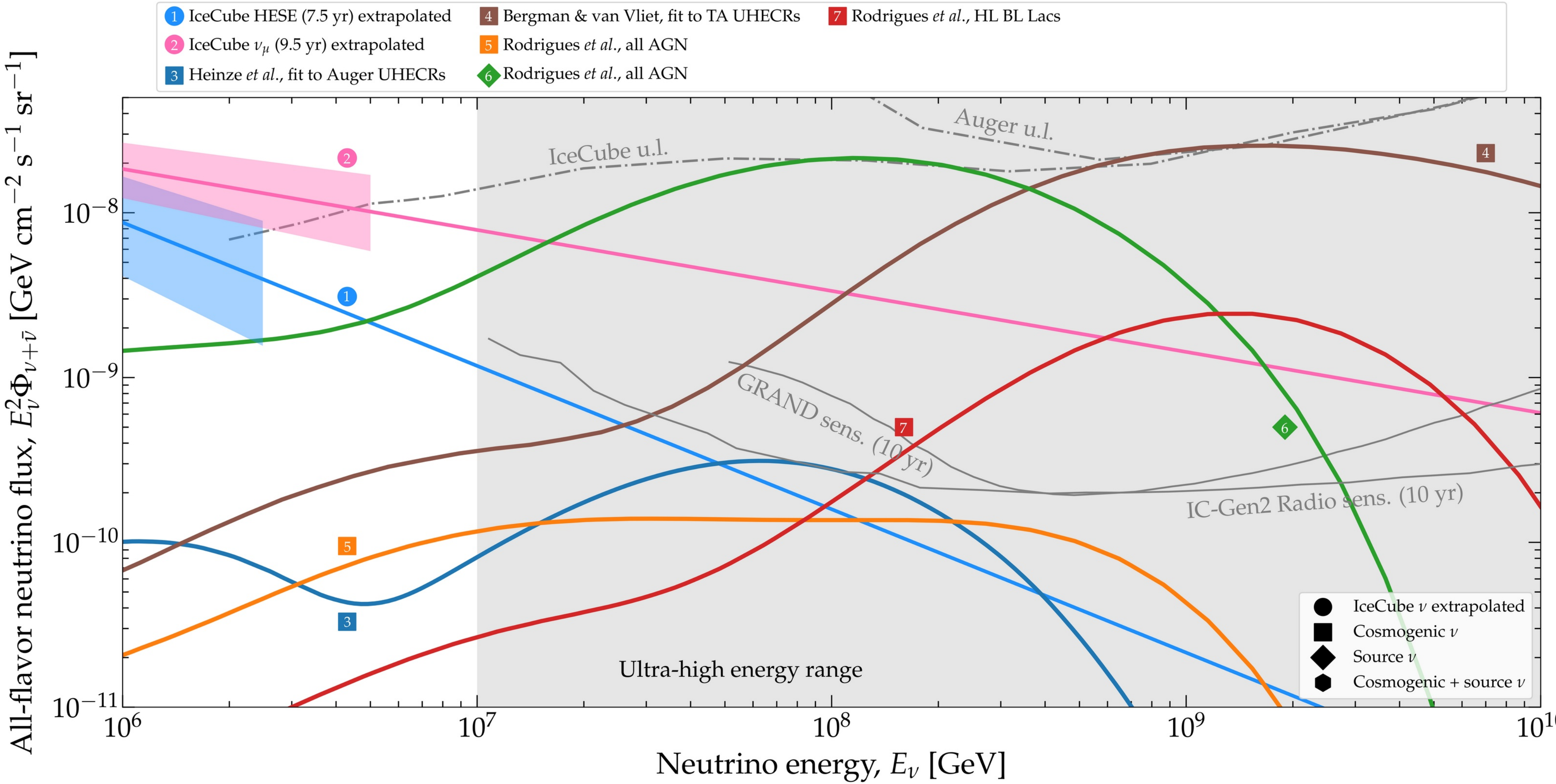

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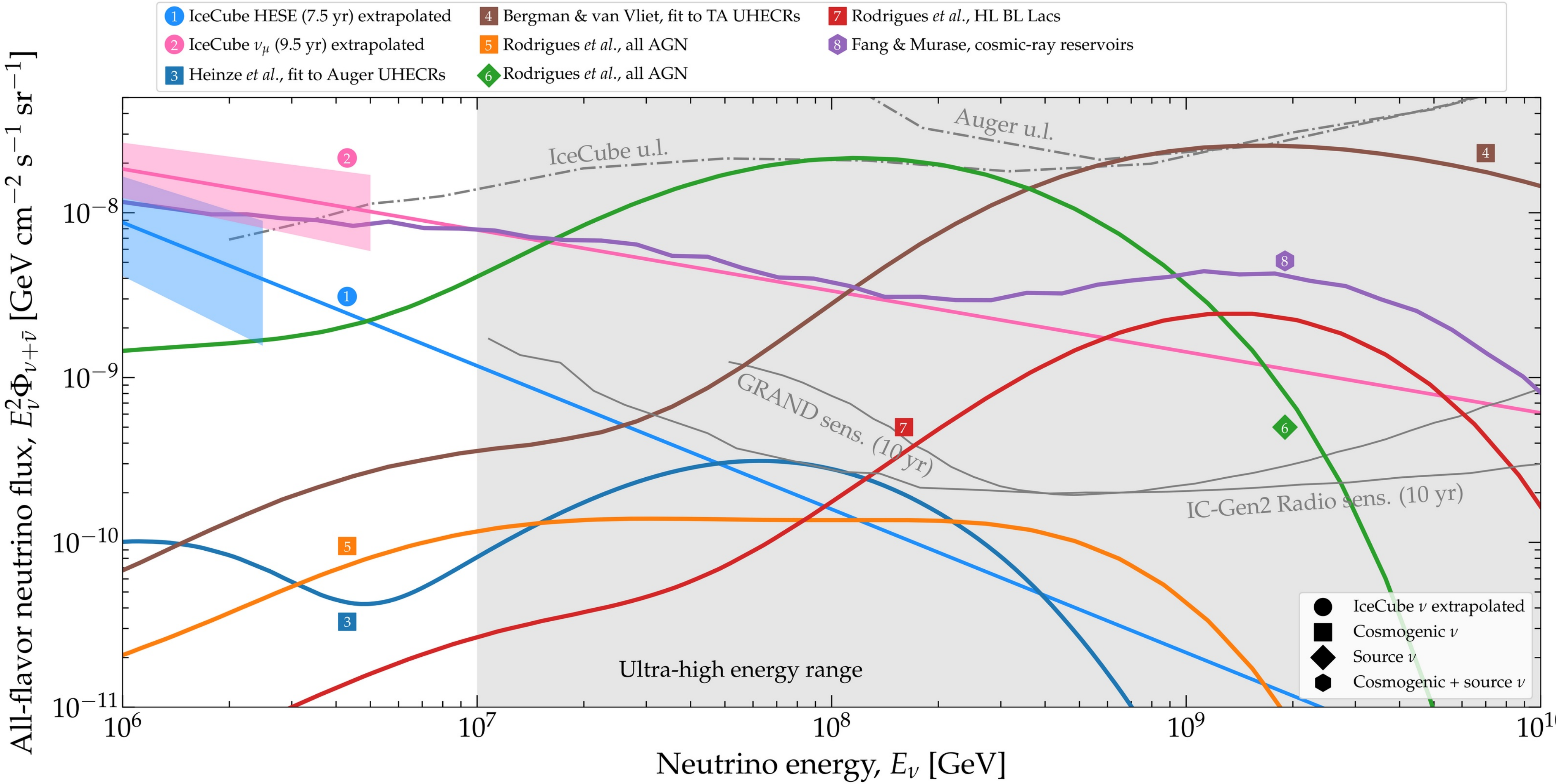

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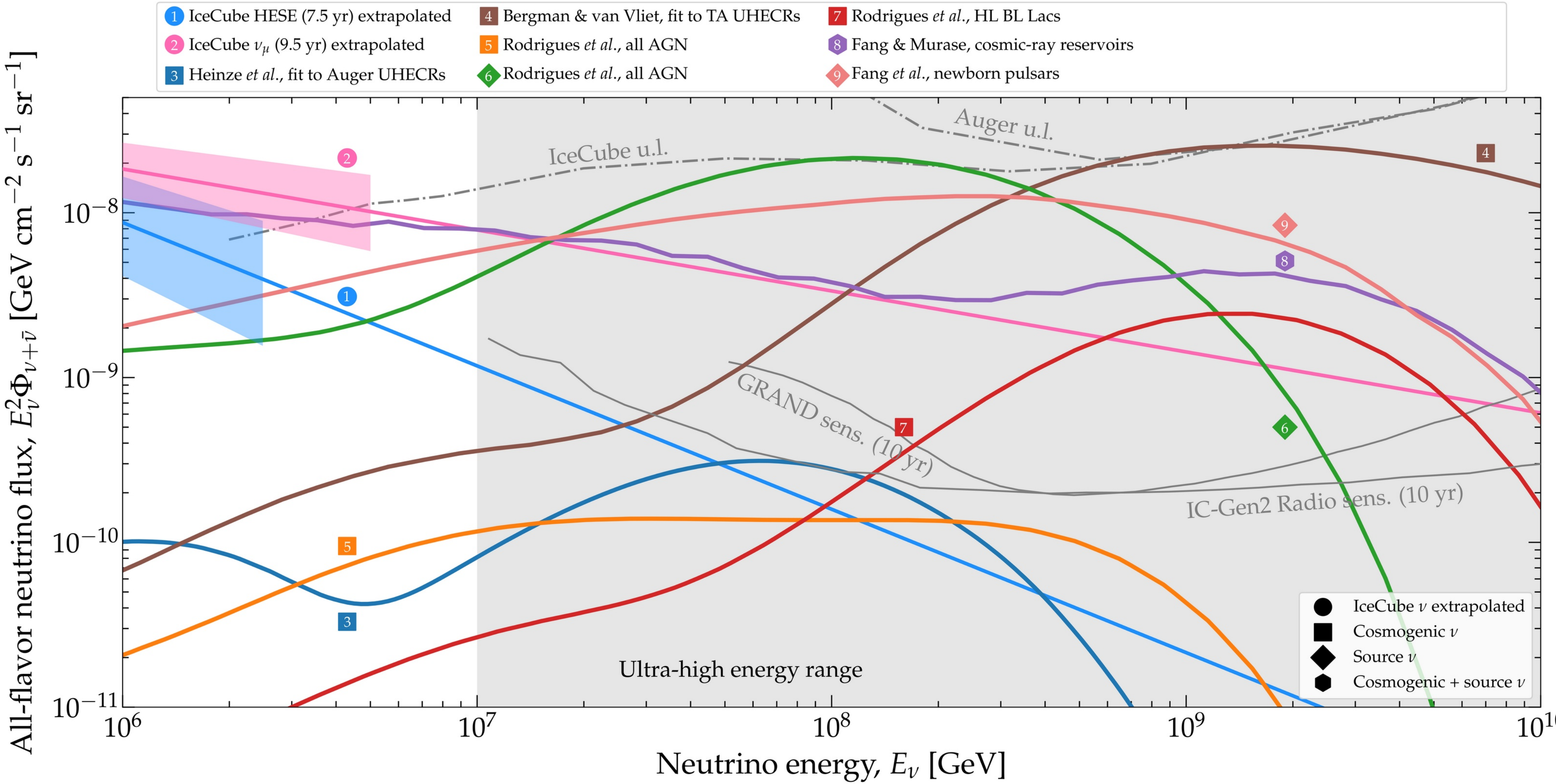
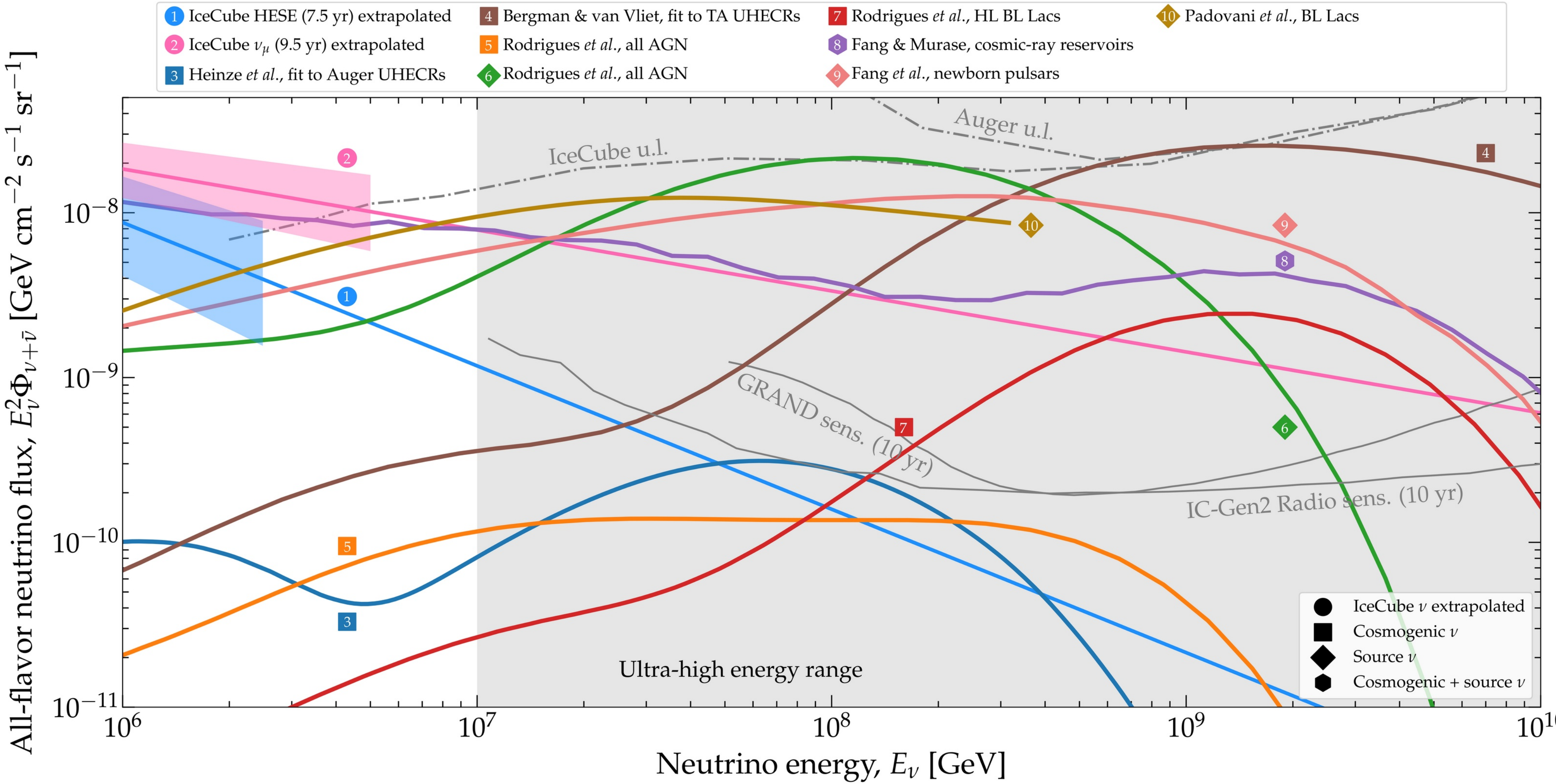
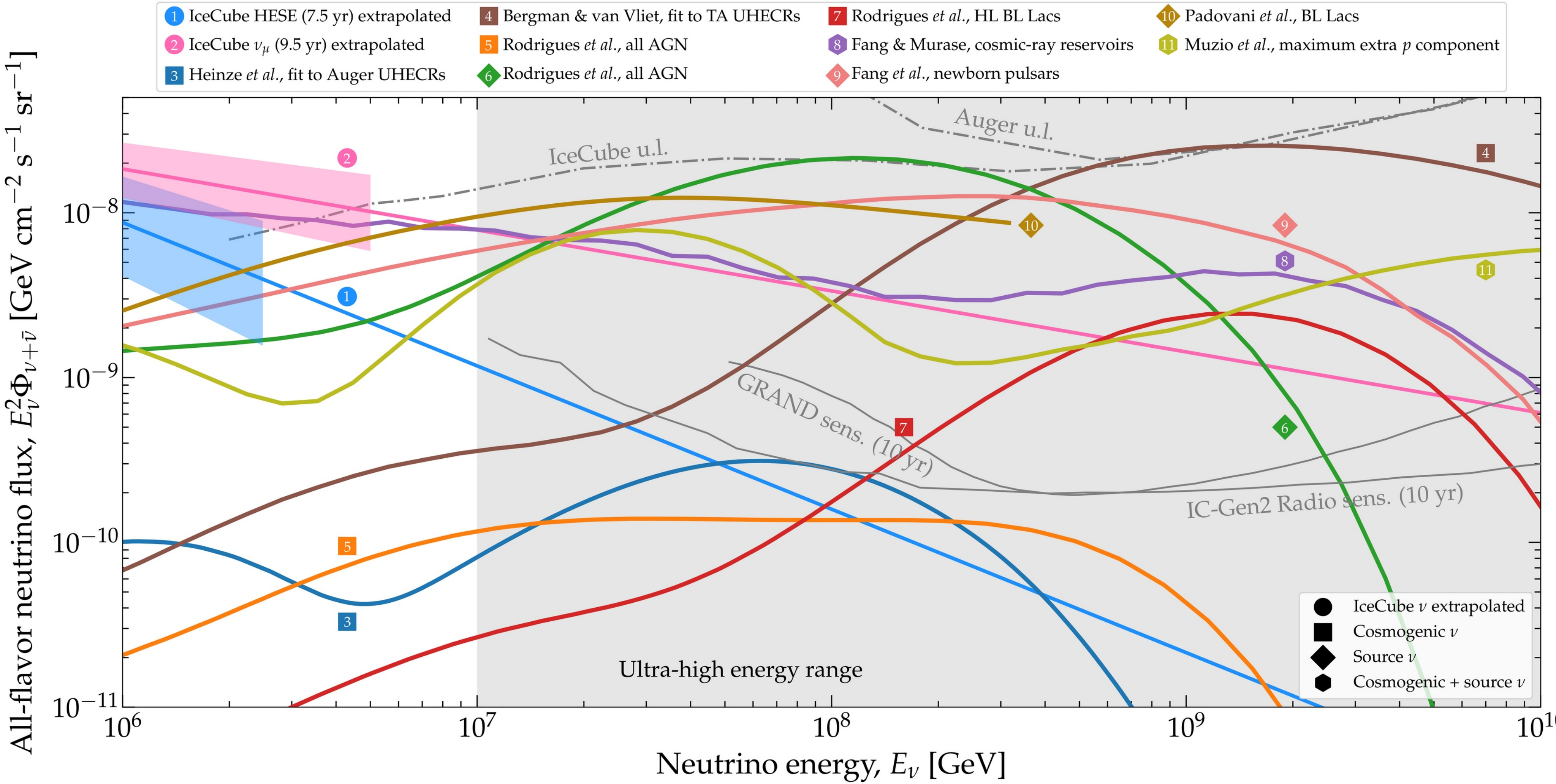


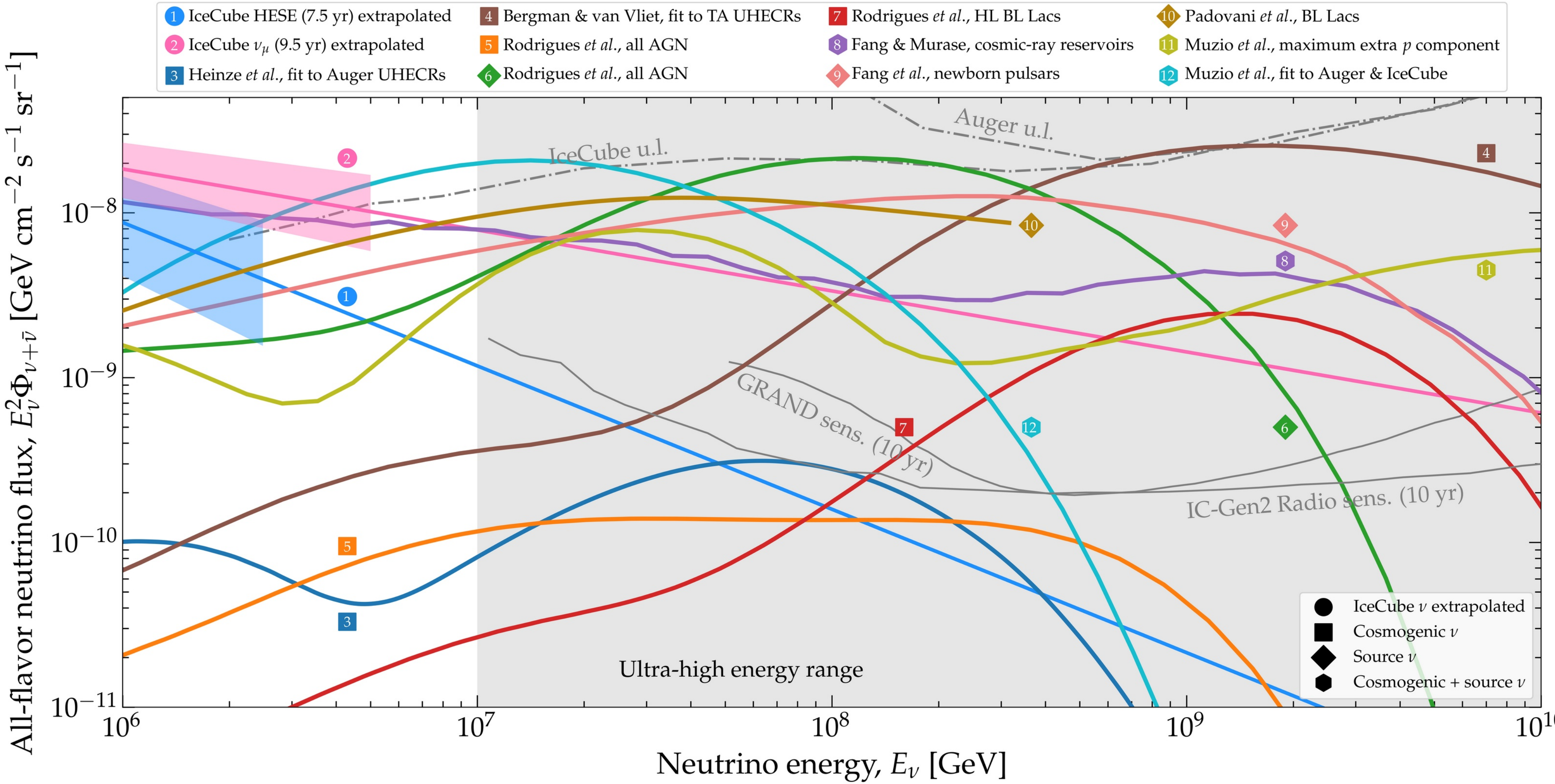
Valera, **MB**, Glaser, *PRD* 2023



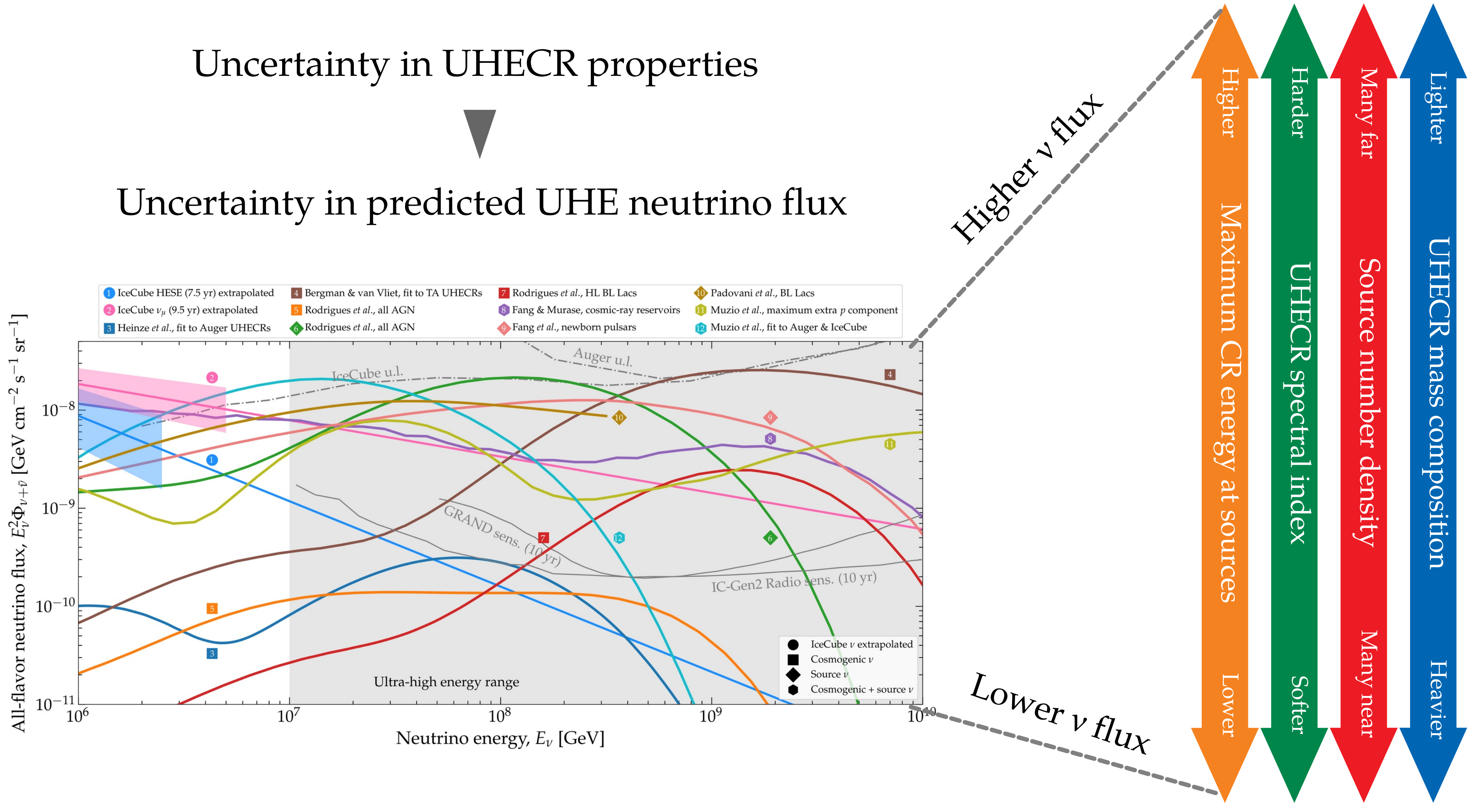
Valera, **MB**, Glaser, *PRD* 2023



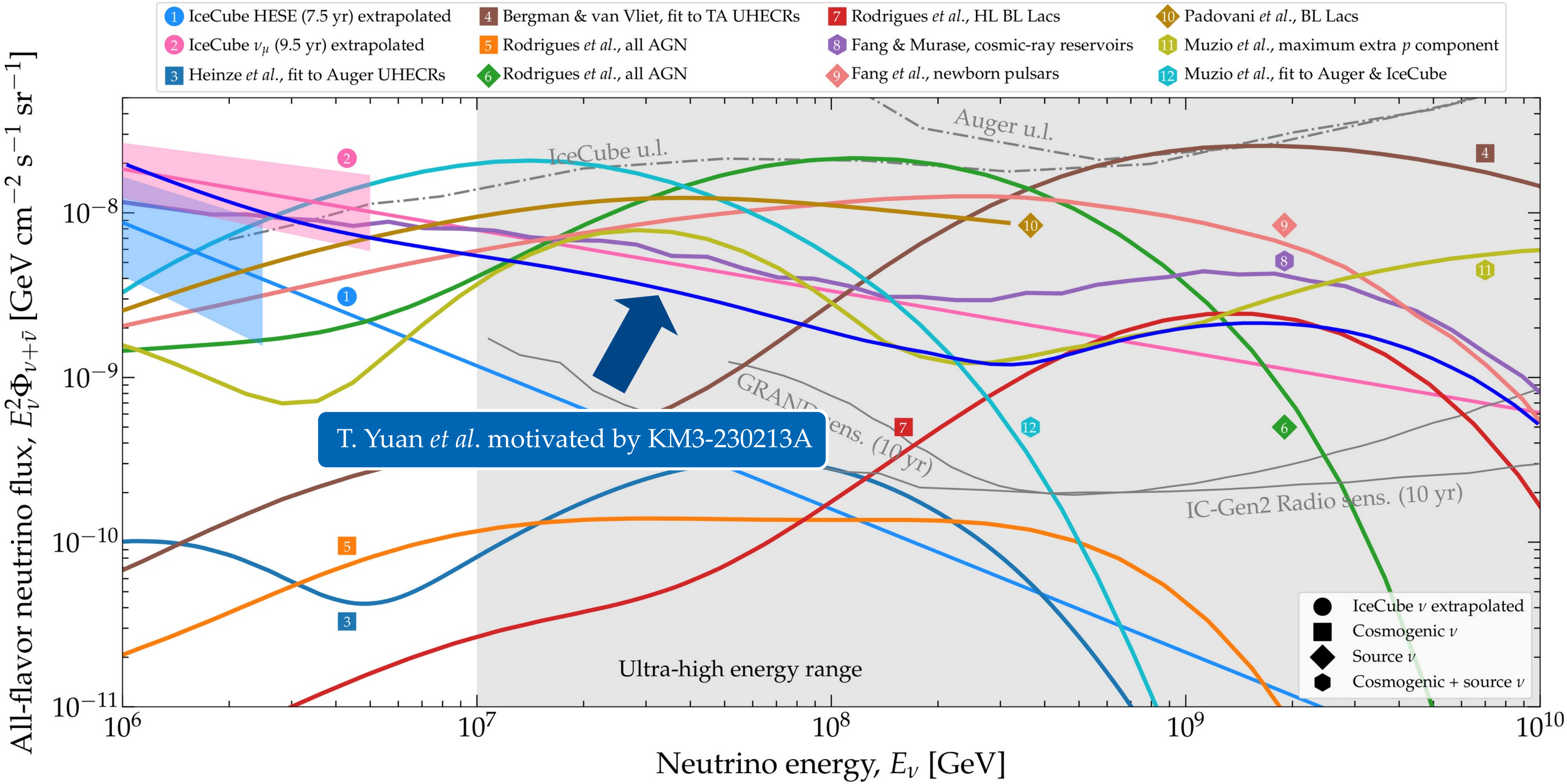
Valera, **MB**, Glaser, *PRD* 2023



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



Uncertainty in UHECR properties
Uncertainty in predicted UHE neutrino flux
1 IceCube HESE (7.5 yr) extrapolated
2 IceCube ν_μ (9.5 yr) extrapolated
3 Heinze et al., fit to Auger UHECRs
4 Bergman & van Vliet, fit to TA UHECRs
5 Rodrigues et al., all AGN
6 Rodrigues et al., all AGN
7 Rodrigues et al., HL BL Lacs
8 Fang & Murase, cosmic-ray reservoirs
9 Fang et al., newborn pulsars
10 Padovani et al., BL Lacs
11 Muzio et al., maximum extra p component
12 Muzio et al., fit to Auger & IceCube
IceCube u.l.
Auger u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
IceCube ν extrapolated
Cosmogenic ν
Source ν
Cosmogenic + source ν
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]
Higher ν flux
Lower ν flux
Higher
Maximum CR energy at sources
Lower
Harder
UHECR spectral index
Softer
Many far
Source number density
Many near
Lighter
UHECR mass composition
Heavier



V. Valera, **MB**, C. Glaser, *PRD* 2022

Event rates in TAMBO

Rate of neutrino interactions:

$$\frac{\mathrm{d}N_{\nu_\alpha}}{\mathrm{d}E_\nu} = T \cdot \Phi_{\nu_\alpha}(E_\nu) \cdot \Xi_\alpha(E_\nu)$$

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Rate of detected showers:

$$\frac{\mathrm{d}N_{\nu_\alpha}}{\mathrm{d}E_{\mathrm{sh}}} = \int_{E_{\mathrm{sh}}}^{\infty} \mathrm{d}E_\nu \, \frac{\mathrm{d}N_{\nu_\alpha}}{\mathrm{d}E_\nu} R_{E_{\mathrm{sh}}}(E_{\mathrm{sh}}, E_\nu)$$

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Rate in terms of *reconstructed* shower energy:

$$\frac{\mathrm{d}N_{\nu_\alpha}}{\mathrm{d}E_{\mathrm{sh}}^{\mathrm{rec}}} = \int_{0}^{\infty} \mathrm{d}E_{\mathrm{sh}} \; \frac{\mathrm{d}N_{\nu_\alpha}}{\mathrm{d}E_{\mathrm{sh}}} R_{E_{\mathrm{sh}}^{\mathrm{rec}}}(E_{\mathrm{sh}}^{\mathrm{rec}}, E_{\mathrm{sh}})$$

Rate of neutrino interactions:

$$\frac{\mathrm{d}N_{\nu_\alpha}}{\mathrm{d}E_\nu} = T \cdot \Phi_{\nu_\alpha}(E_\nu) \cdot \Xi_\alpha(E_\nu)$$

Rate of detected showers:

Gaussian with width
$\sigma_{E_{\mathrm{sh}}} = 0.62\ E_\nu$

$$\frac{\mathrm{d}N_{\nu_\alpha}}{\mathrm{d}E_{\mathrm{sh}}} = \int_{E_{\mathrm{sh}}}^{\infty} \mathrm{d}E_\nu \ \frac{\mathrm{d}N_{\nu_\alpha}}{\mathrm{d}E_\nu} R_{E_{\mathrm{sh}}}(E_{\mathrm{sh}}, E_\nu)$$

Rate in terms of *reconstructed* shower energy:

Gaussian with width
$\sigma_{E_{\mathrm{sh}}^{\mathrm{rec}}} = 0.80\ E_{\mathrm{sh}}$

$$\frac{\mathrm{d}N_{\nu_\alpha}}{\mathrm{d}E_{\mathrm{sh}}^{\mathrm{rec}}} = \int_0^{\infty} \mathrm{d}E_{\mathrm{sh}} \ \frac{\mathrm{d}N_{\nu_\alpha}}{\mathrm{d}E_{\mathrm{sh}}} R_{E_{\mathrm{sh}}^{\mathrm{rec}}}(E_{\mathrm{sh}}^{\mathrm{rec}}, E_{\mathrm{sh}})$$

Rate of neutrino interactions:

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Rate in terms of *reconstructed* shower energy:

Gaussian with width
$\sigma_{E_{\mathrm{sh}}^{\mathrm{rec}}} = 0.80\ E_{\mathrm{sh}}$

Flavor measurements are based on this $\rightarrow$

$$\frac{\mathrm{d}N_{\nu_\alpha}}{\mathrm{d}E_{\mathrm{sh}}^{\mathrm{rec}}} = \int_0^{\infty} \mathrm{d}E_{\mathrm{sh}}\ \frac{\mathrm{d}N_{\nu_\alpha}}{\mathrm{d}E_{\mathrm{sh}}} R_{E_{\mathrm{sh}}^{\mathrm{rec}}}(E_{\mathrm{sh}}^{\mathrm{rec}}, E_{\mathrm{sh}})$$

Total event rate in TAMBO:

$$\frac{\mathrm{d}N_{\nu}}{\mathrm{d}E_{\mathrm{sh}}^{\mathrm{rec}}} = \frac{\mathrm{d}N_{\nu_\tau}}{\mathrm{d}E_{\mathrm{sh}}^{\mathrm{rec}}} + \frac{\mathrm{d}N_{\bar{\nu}_\tau}}{\mathrm{d}E_{\mathrm{sh}}^{\mathrm{rec}}} + \frac{\mathrm{d}N_{\bar{\nu}_e}}{\mathrm{d}E_{\mathrm{sh}}^{\mathrm{rec}}}$$

$$\frac{\mathrm{d}N_{\nu}}{\mathrm{d}E_{\mathrm{sh}}^{\mathrm{rec}}} = T \int_0^{\infty} \mathrm{d}E_{\mathrm{sh}} \int_{E_{\mathrm{sh}}}^{\infty} \mathrm{d}E_{\nu} \left[\Xi_\tau(E_\nu) f_{\tau,\oplus} + \Xi_e(E_\nu) f_{e,\oplus} f_{\bar{\nu}/\nu} \right]$$

$$\times \Phi_{\mathrm{all}}(E_\nu) \times R_{E_{\mathrm{sh}}^{\mathrm{rec}}}(E_{\mathrm{sh}}^{\mathrm{rec}}, E_{\mathrm{sh}}) R_{E_{\mathrm{sh}}}(E_{\mathrm{sh}}, E_\nu)$$

Events on and off the Glashow resonance:

$$N_{\mathrm{GR}}(\tilde{f}_{e,\oplus}, f_{\tau,\oplus}, \boldsymbol{\theta}) = \int_{E_{\mathrm{sh}}^{\mathrm{rec}} \approx E_{\nu}^{\mathrm{GR}}} \mathrm{d}E_{\mathrm{sh}}^{\mathrm{rec}} \, \frac{\mathrm{d}N_{\nu}}{\mathrm{d}E_{\mathrm{sh}}^{\mathrm{rec}}}(\tilde{f}_{e,\oplus}, f_{\tau,\oplus}, \boldsymbol{\theta})$$

$$N_{\cancel{\mathrm{GR}}}(f_{\tau,\oplus}, \boldsymbol{\theta}) = \int_{E_{\mathrm{sh}}^{\mathrm{rec}} \neq E_{\nu}^{\mathrm{GR}}} \mathrm{d}E_{\mathrm{sh}}^{\mathrm{rec}} \, \frac{\mathrm{d}N_{\nu}}{\mathrm{d}E_{\mathrm{sh}}^{\mathrm{rec}}}(f_{\tau,\oplus}, \boldsymbol{\theta})$$

Statistics:

$$\mathcal{L}_{\mathrm{GR}}(\tilde{f}_{e,\oplus}, f_{\tau,\oplus}, \boldsymbol{\theta}) = \frac{{N_{\mathrm{GR}}}^{N_{\mathrm{GR}}^{\mathrm{obs}}} e^{-N_{\mathrm{GR}}}}{N_{\mathrm{GR}}^{\mathrm{obs}}!}$$

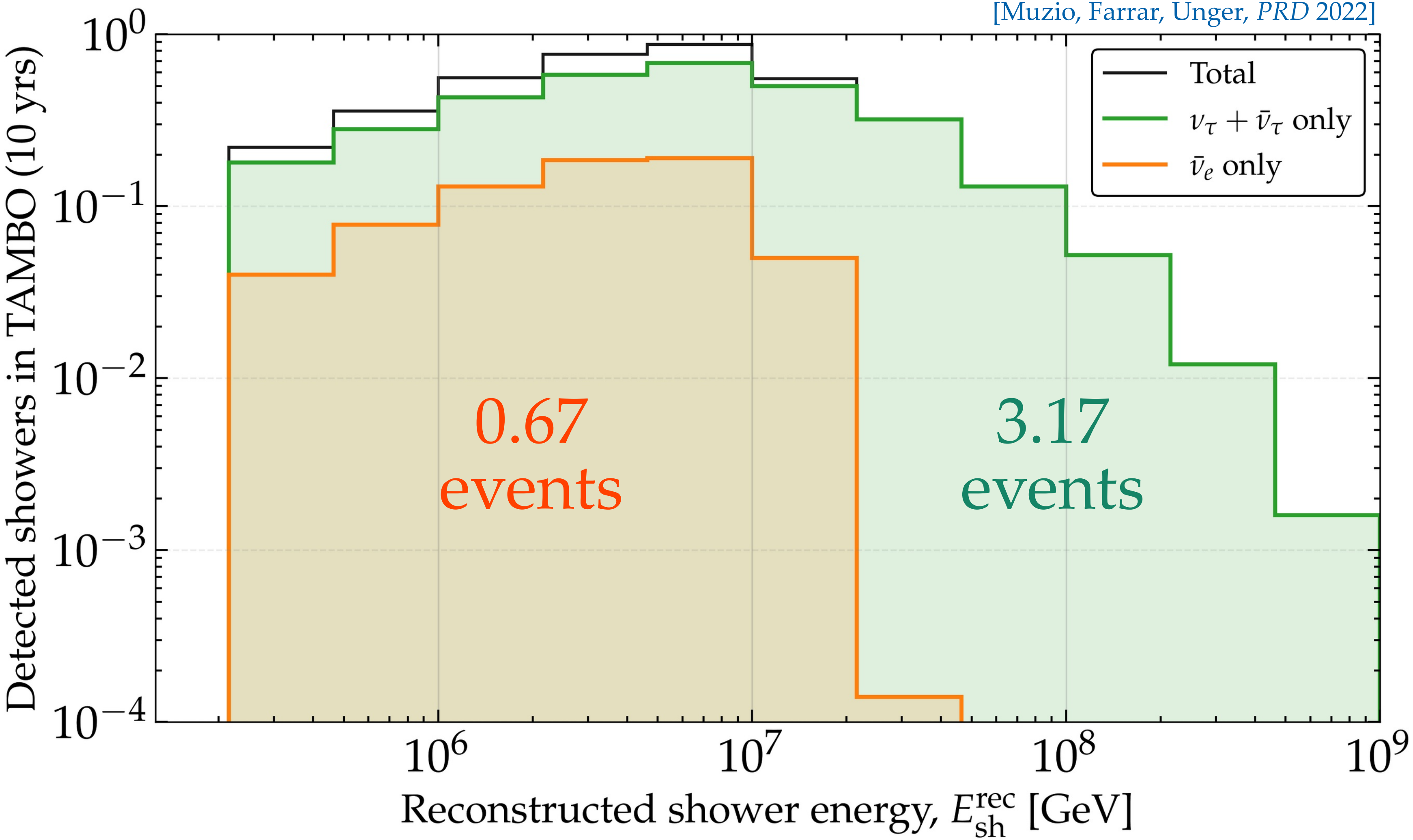
$$\mathcal{L}_{\cancel{\mathrm{GR}}}(f_{\tau,\oplus}, \boldsymbol{\theta}) = \frac{{N_{\cancel{\mathrm{GR}}}}^{N_{\cancel{\mathrm{GR}}}^{\mathrm{obs}}} e^{-N_{\cancel{\mathrm{GR}}}}}{N_{\cancel{\mathrm{GR}}}^{\mathrm{obs}}!}$$

Total likelihood:

$$\mathcal{L}(\tilde{f}_{e,\oplus}, f_{\tau,\oplus}, \boldsymbol{\theta})$$
$$= \mathcal{L}_{\mathrm{GR}}(\tilde{f}_{e,\oplus}, f_{\tau,\oplus}, \boldsymbol{\theta}) \cdot \mathcal{L}_{\cancel{\mathrm{GR}}}(f_{\tau,\oplus}, \boldsymbol{\theta})$$

Diffuse-flux event rates

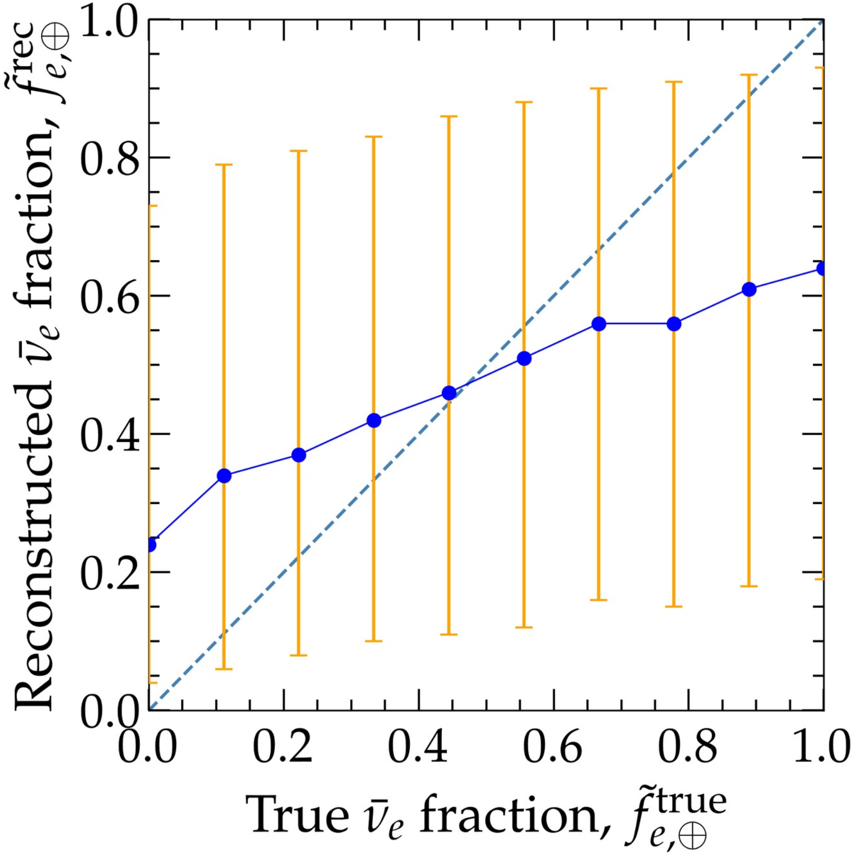
Flux: Joint fit to Auger + IceCube (pre-KM3-230213A)
[Muzio, Farrar, Unger, *PRD* 2022]



Measuring $\tilde{f}_{e,\oplus}$ only

KM3-230213A UHE ν-inspired flux

[Muzio, Yuan, Luan, 2502.06944]



Measuring $\tilde{f}_{e,\oplus}$ only

KM3-230213A UHE ν-inspired flux
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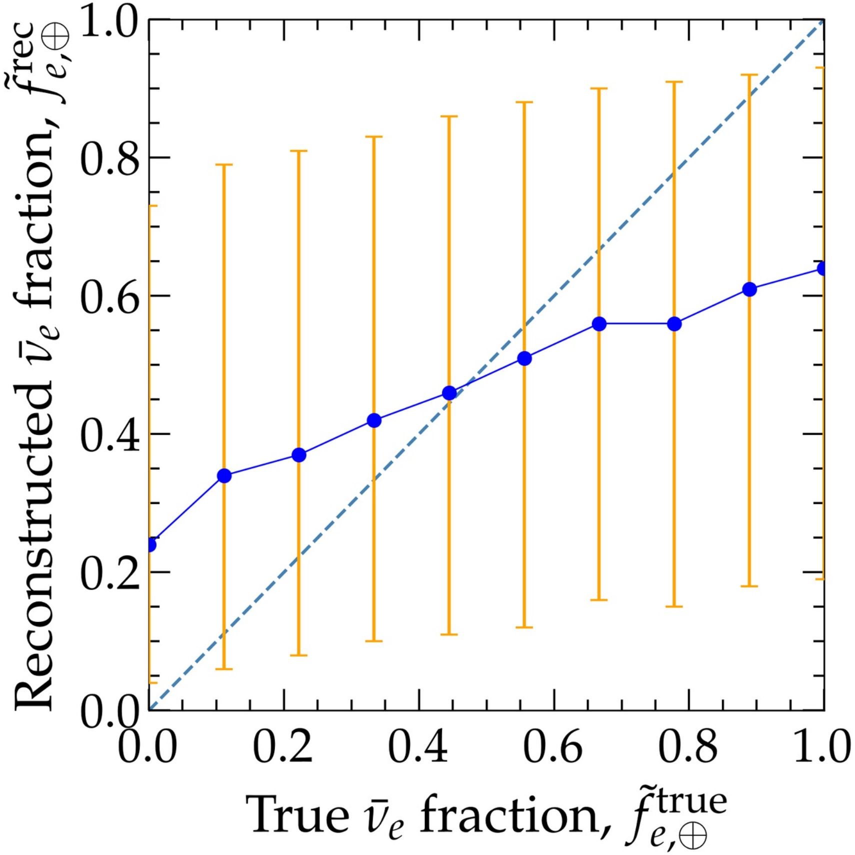
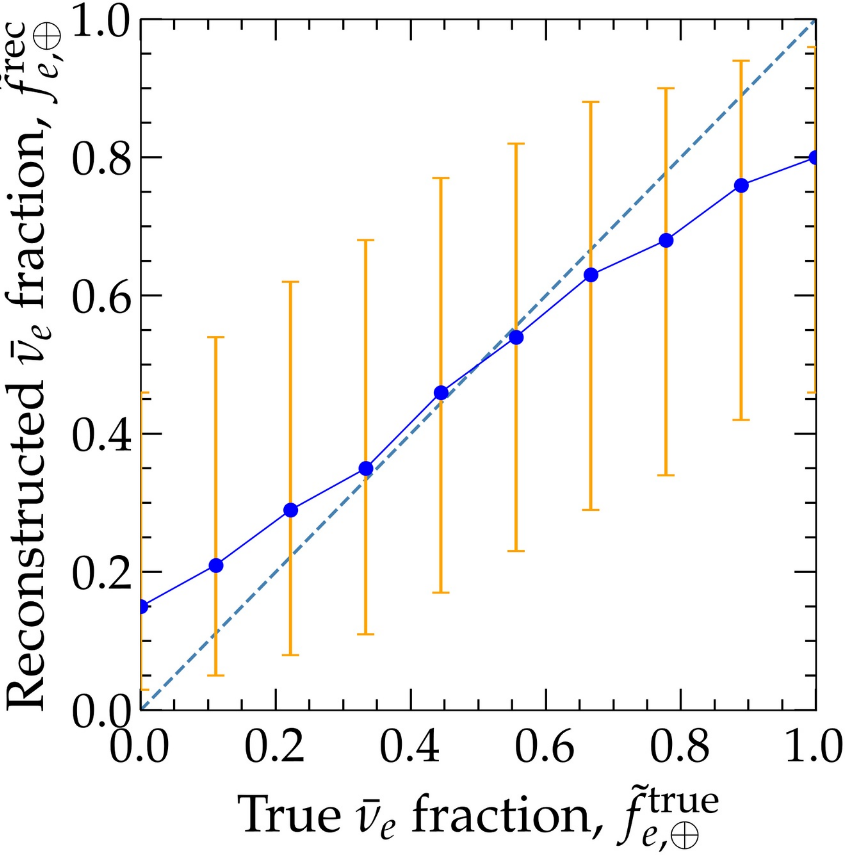


Joint fit to Auger + IceCube (pre-KM3-230213A)
[Muzio, Farrar, Unger, *PRD* 2022]



Diffuse-flux event rates

Flux: Joint fit to Auger + IceCube (pre-KM3-230213A)
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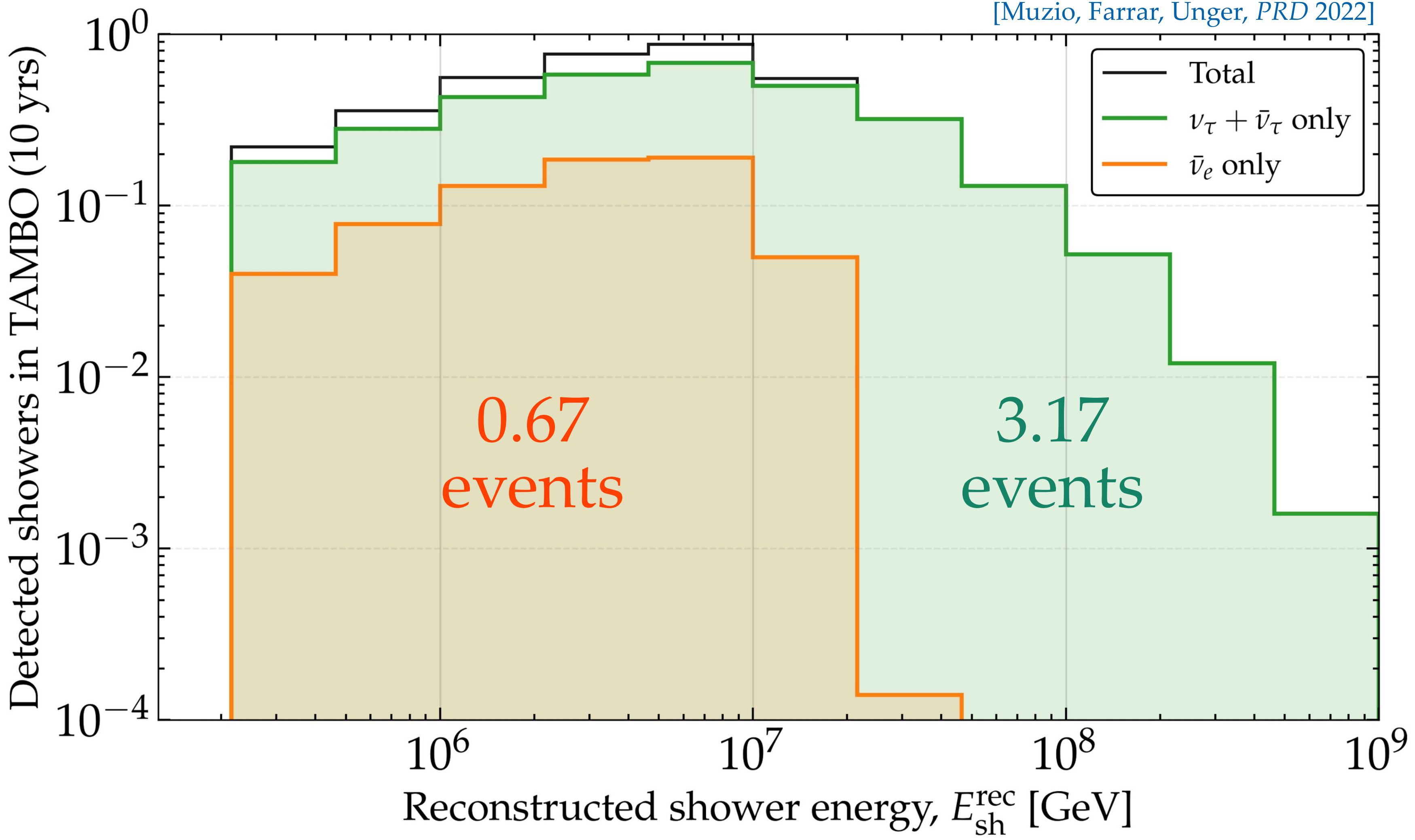

Diffuse-flux event rates

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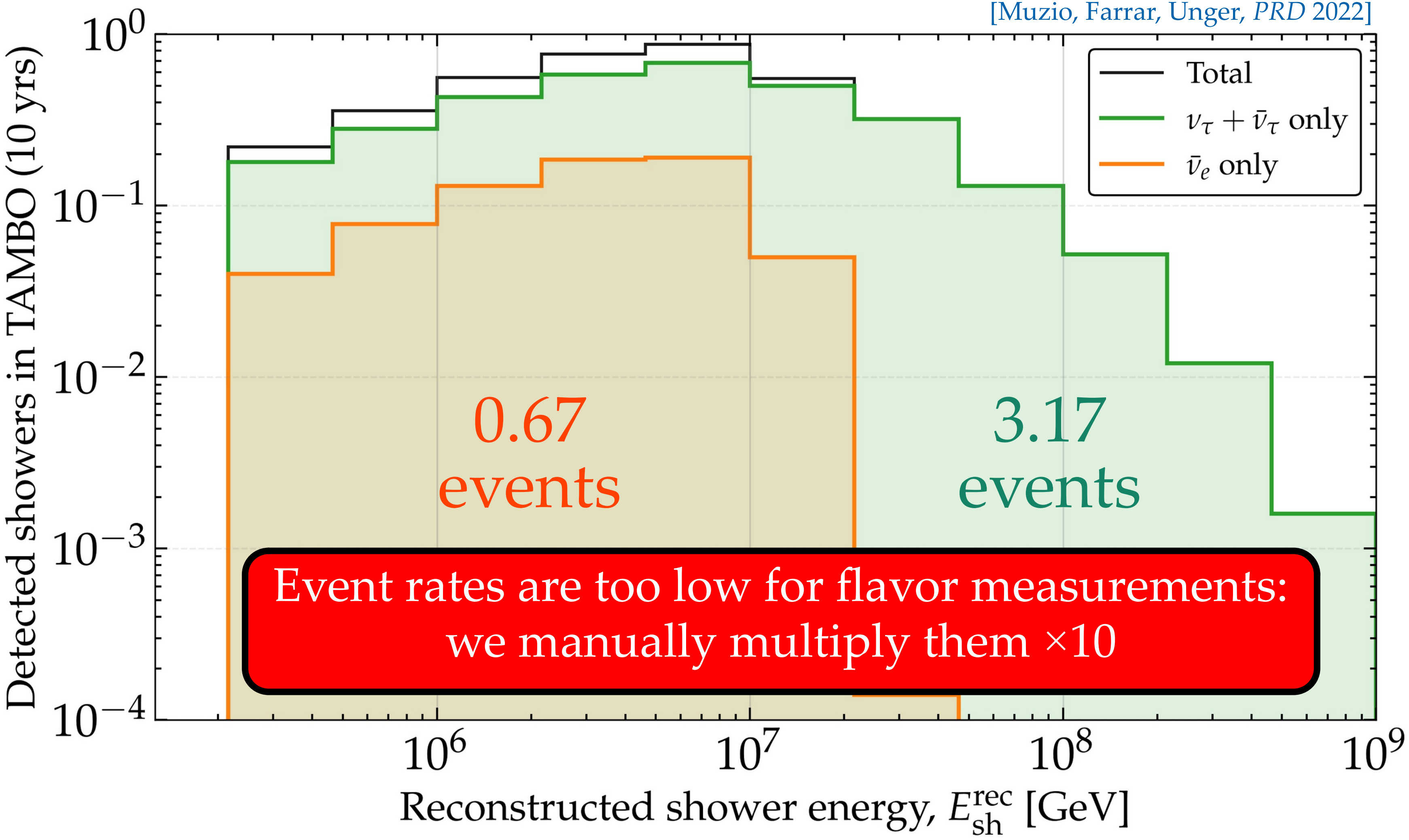
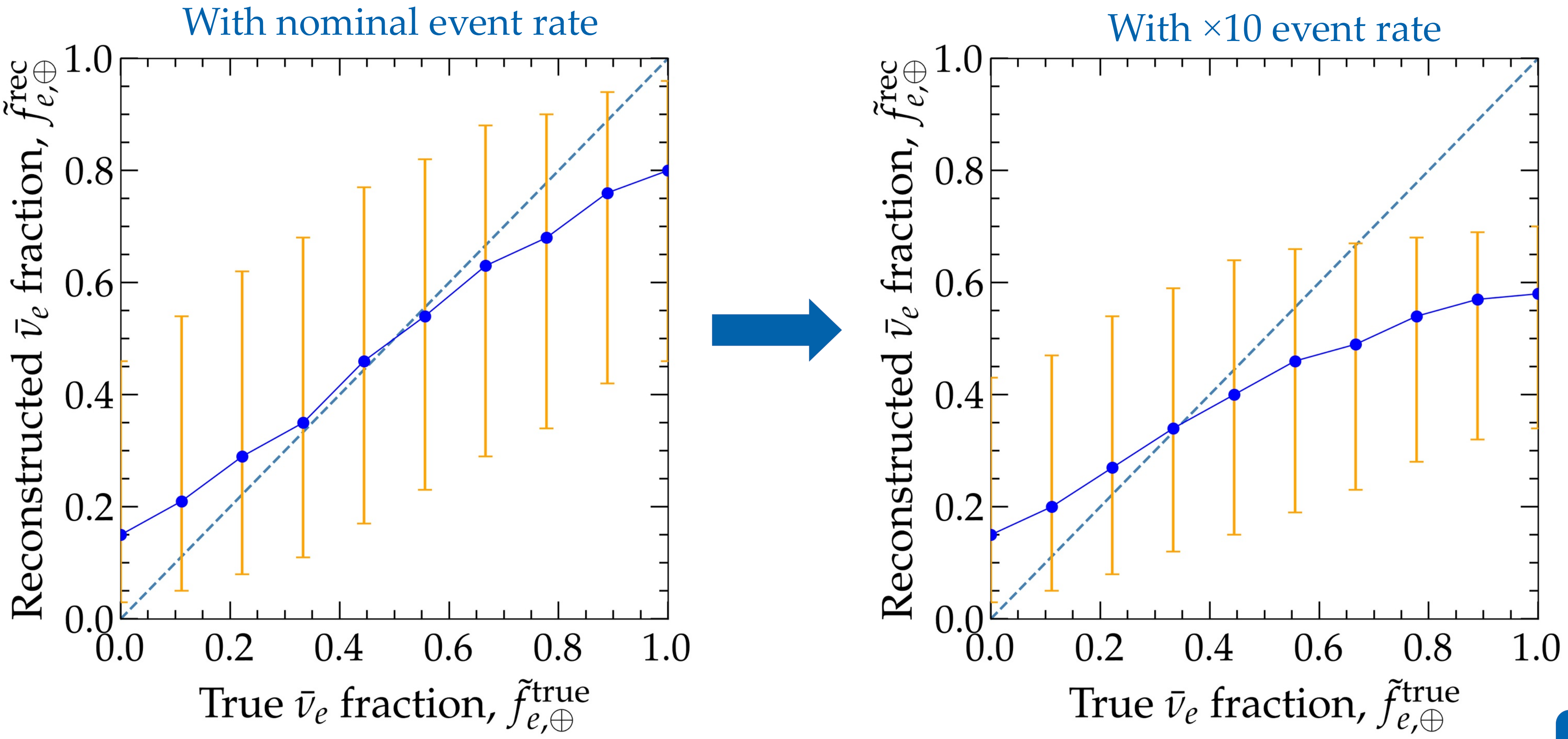


Event rates are too low for flavor measurements: we manually multiply them ×10

Measuring only the electron fraction

Measuring $\tilde{f}_{e,\oplus}$ only — with ×10 event rates

Flux: Joint fit to Auger + IceCube (pre-KM3-230213A) [Muzio, Farrar, Unger, *PRD* 2022]

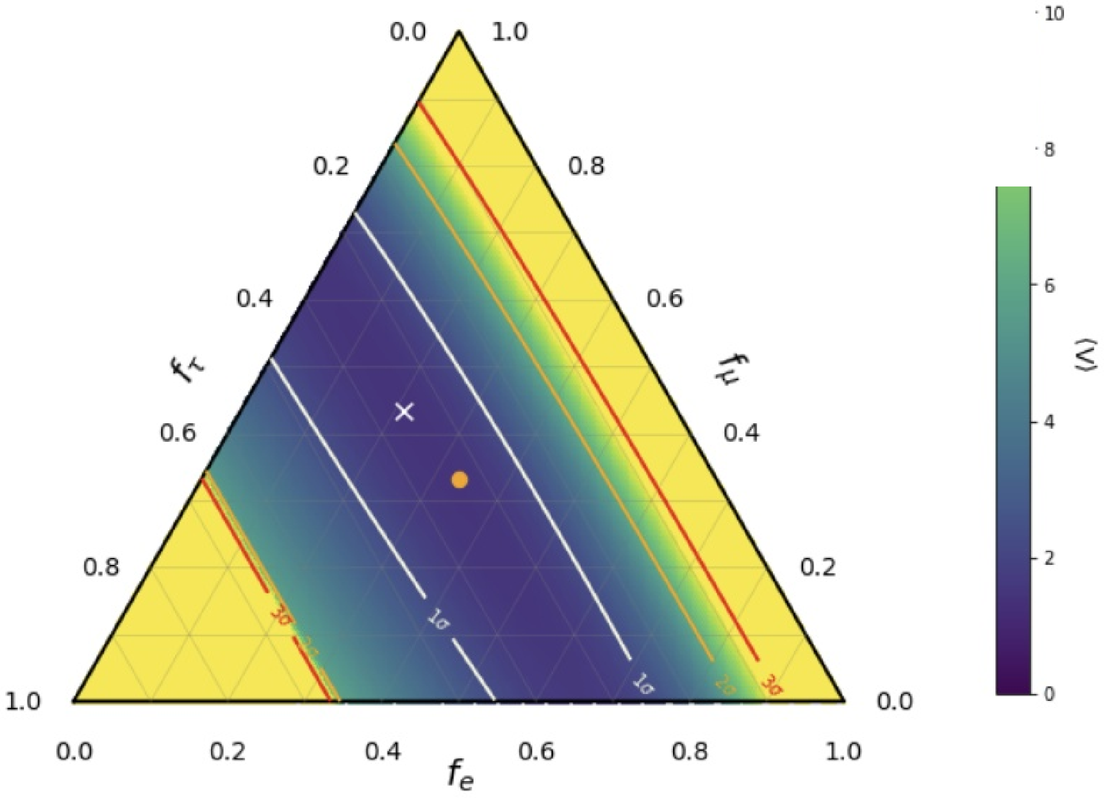


Measuring the e & τ content

Flavor composition at TAMBO

KM3-230213A UHE ν-inspired flux

[Muzio, Yuan, Luan, 2502.06944]



Flavor composition at TAMBO

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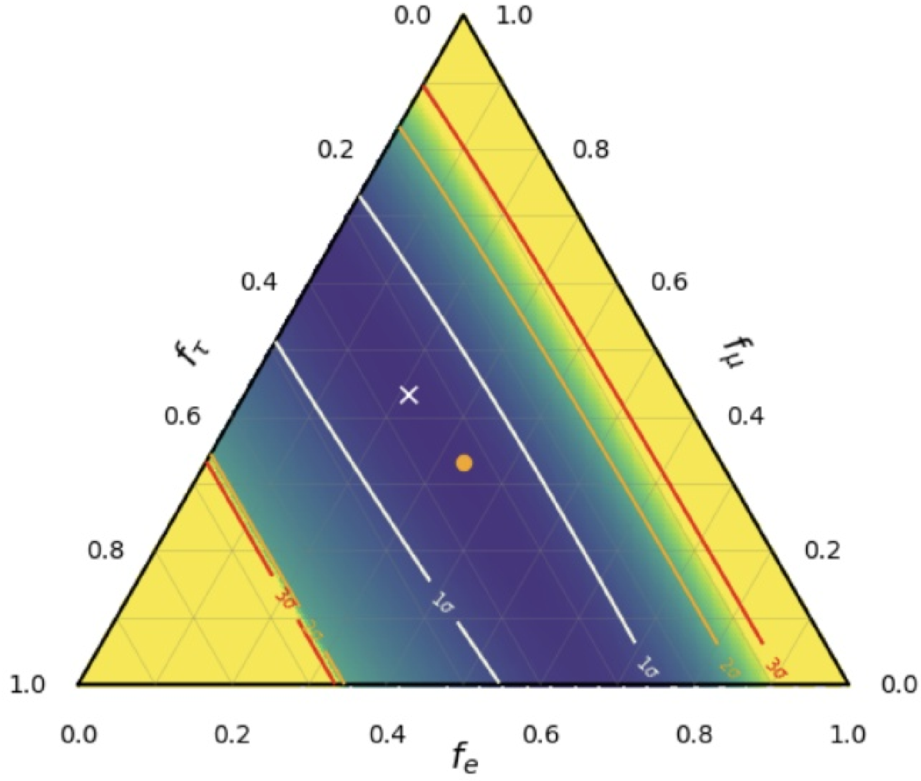
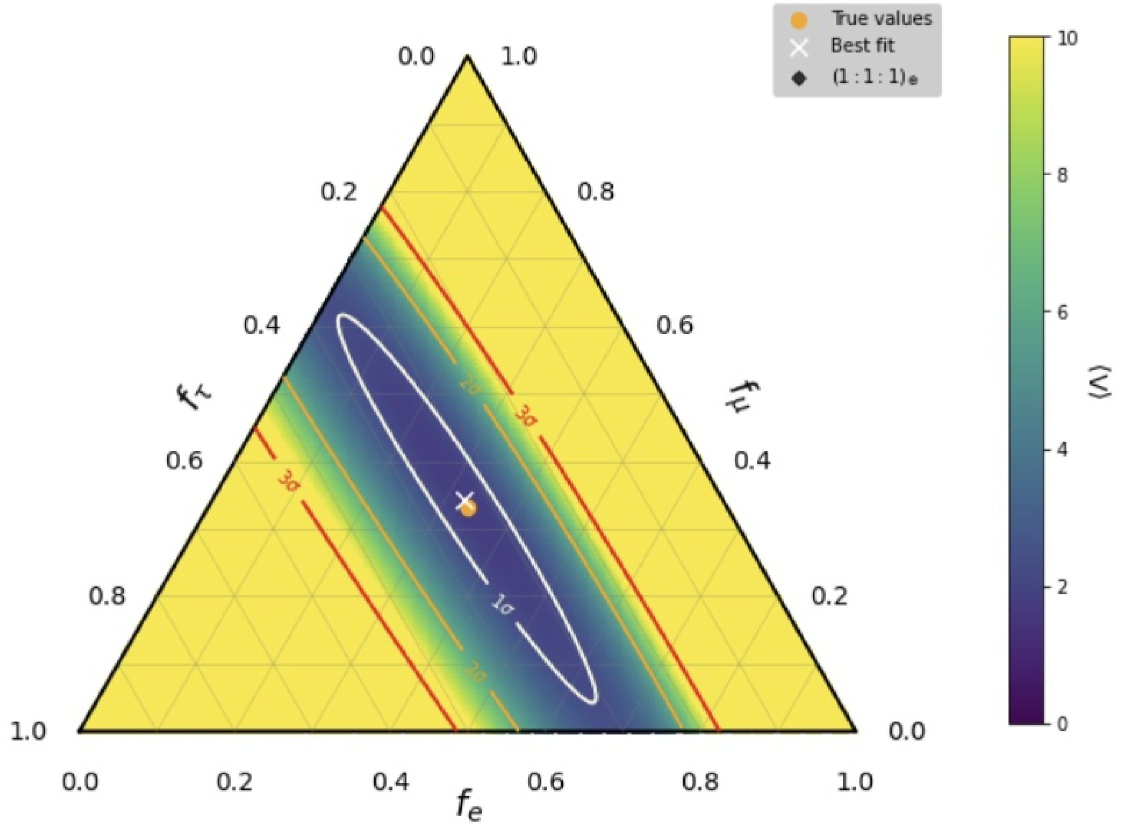
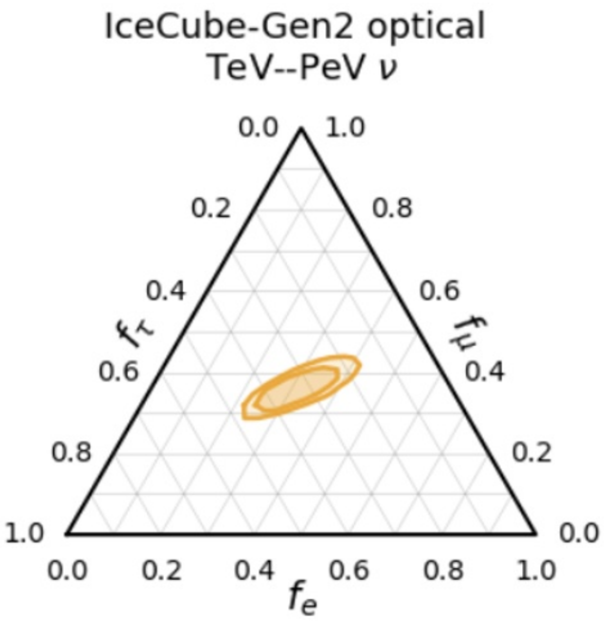
[Muzio, Yuan, Luan, 2502.06944]



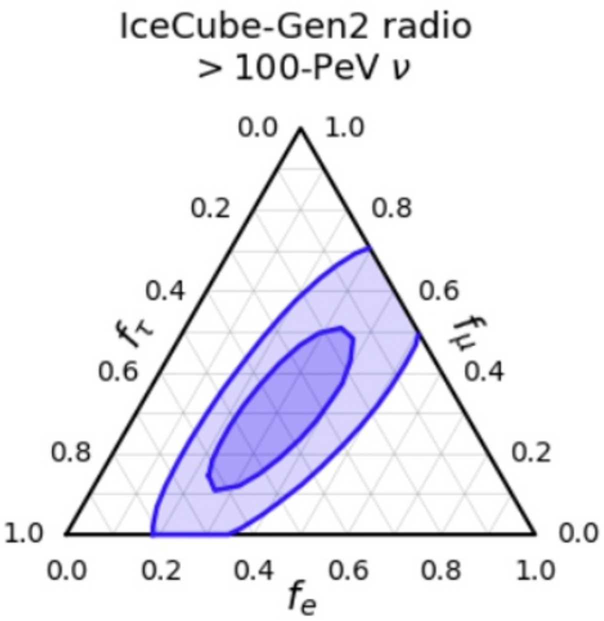
Joint fit to Auger + IceCube (pre-KM3-230213A)
[Muzio, Farrar, Unger, *PRD* 2022]



Flavor composition at TAMBO

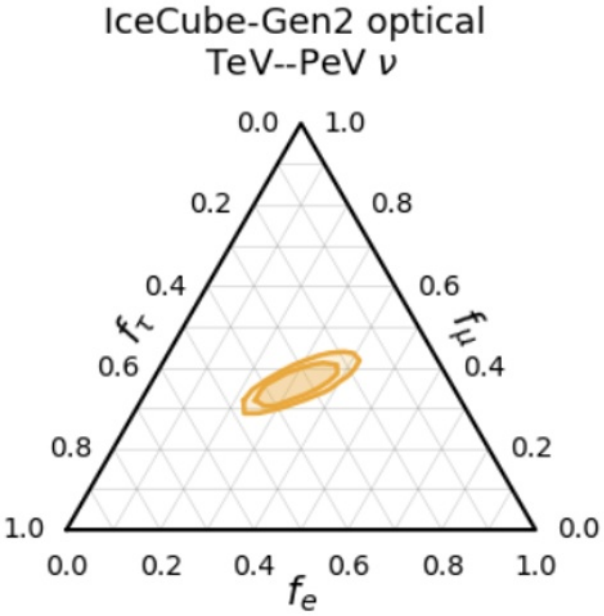


[IceCube-Gen2 TDR]

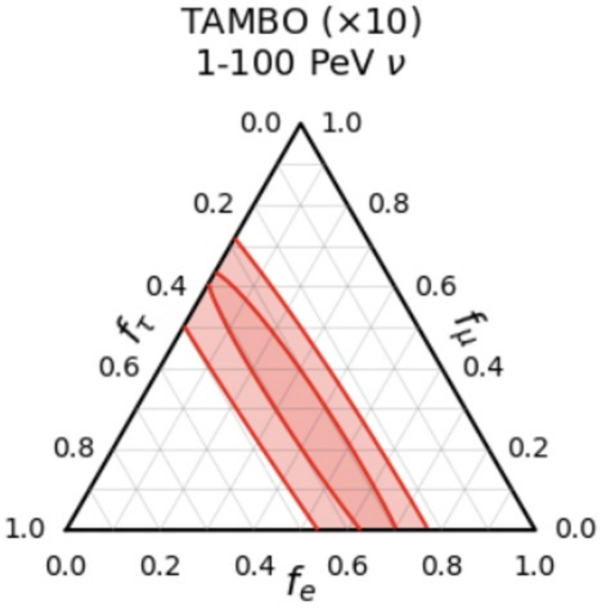


[Coleman, Ericsson, Glaser, **MB**, *PRD* 2024]

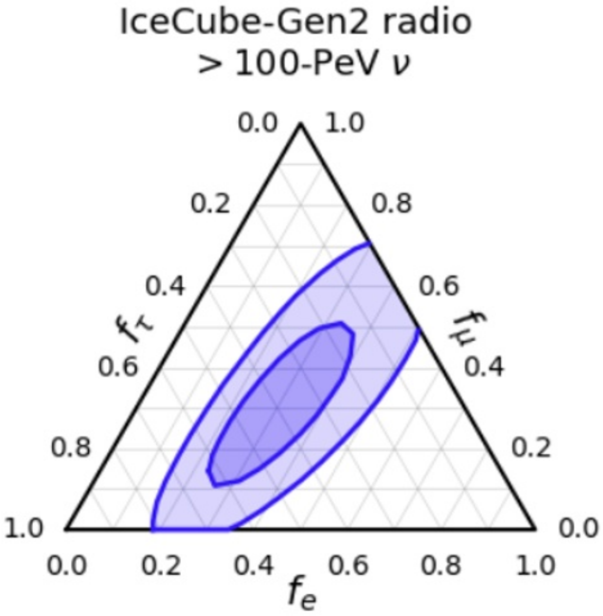
Flavor composition at TAMBO



[IceCube-Gen2 TDR]



Aske's work



[Coleman, Ericsson, Glaser, **MB**, *PRD* 2024]

Recent work:

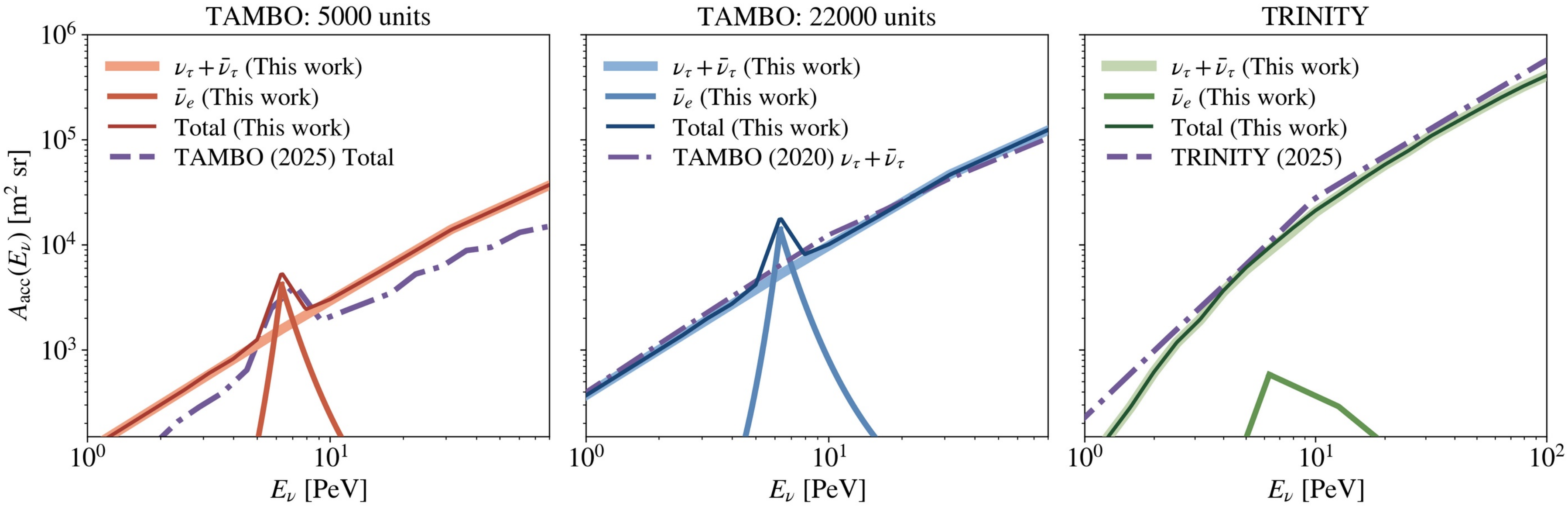
Tianyi Ding & Qinrui Liu,
arXiv:2607.26128

Same question, asked independently

Answered with dedicated end-to-end Monte Carlo simulations:

- ☑ TauRunner propagates ν through Earth
- ☑ Pythia 8.3 simulates *W*-boson decays
- ☑ Topography of Colca Valley

Ding & Liu, 2607.26128

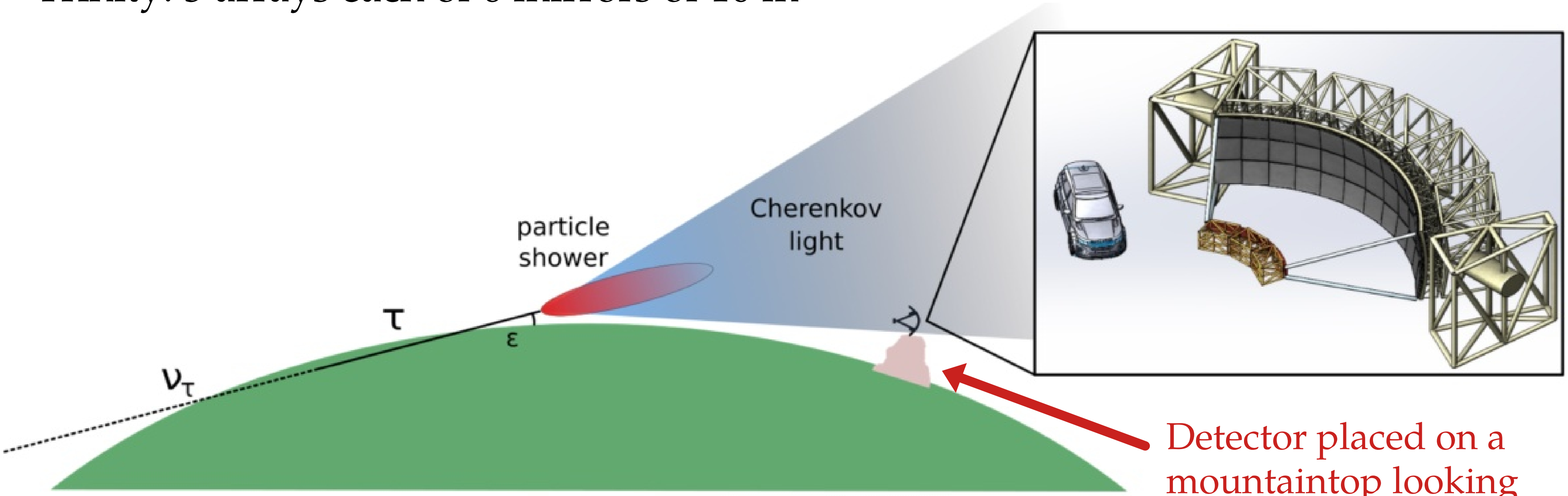


Trinity

Atmospheric Cherenkov imaging applied to PeV tau neutrinos

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

Trinity: 3 arrays each of 6 mirrors of 10 m^2



Detector placed on a mountaintop looking towards the horizon

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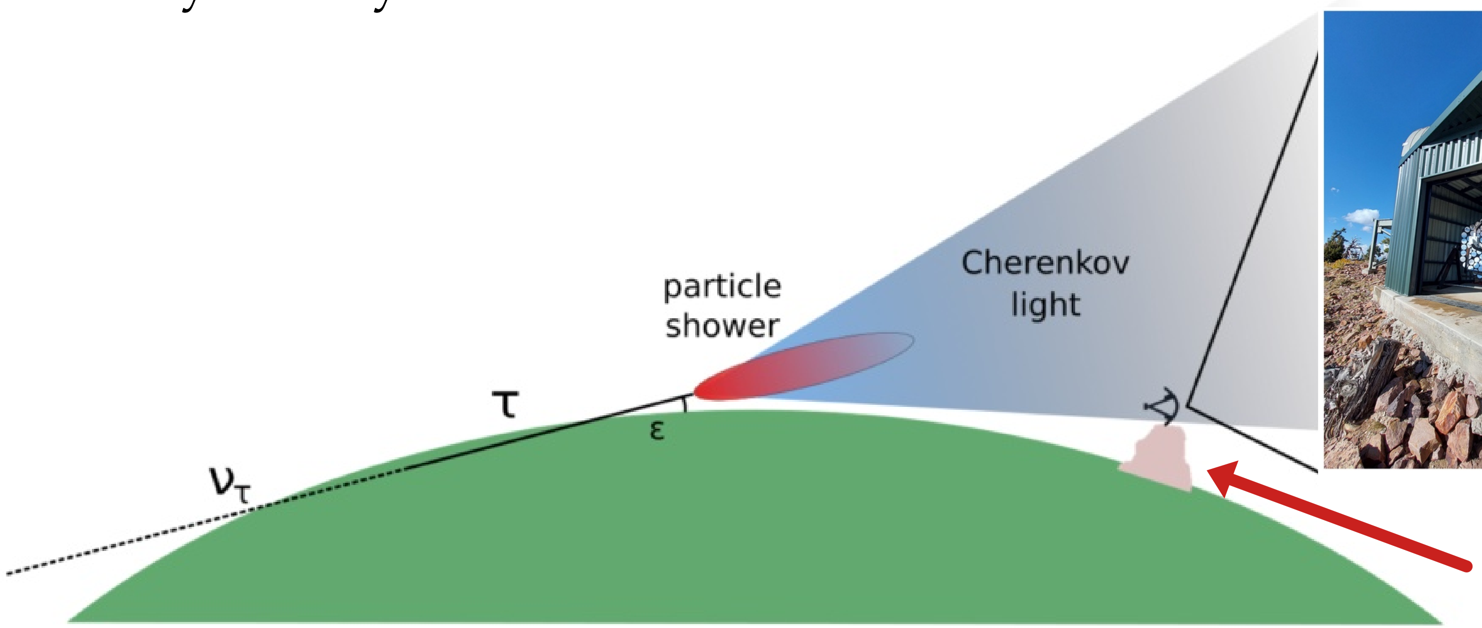
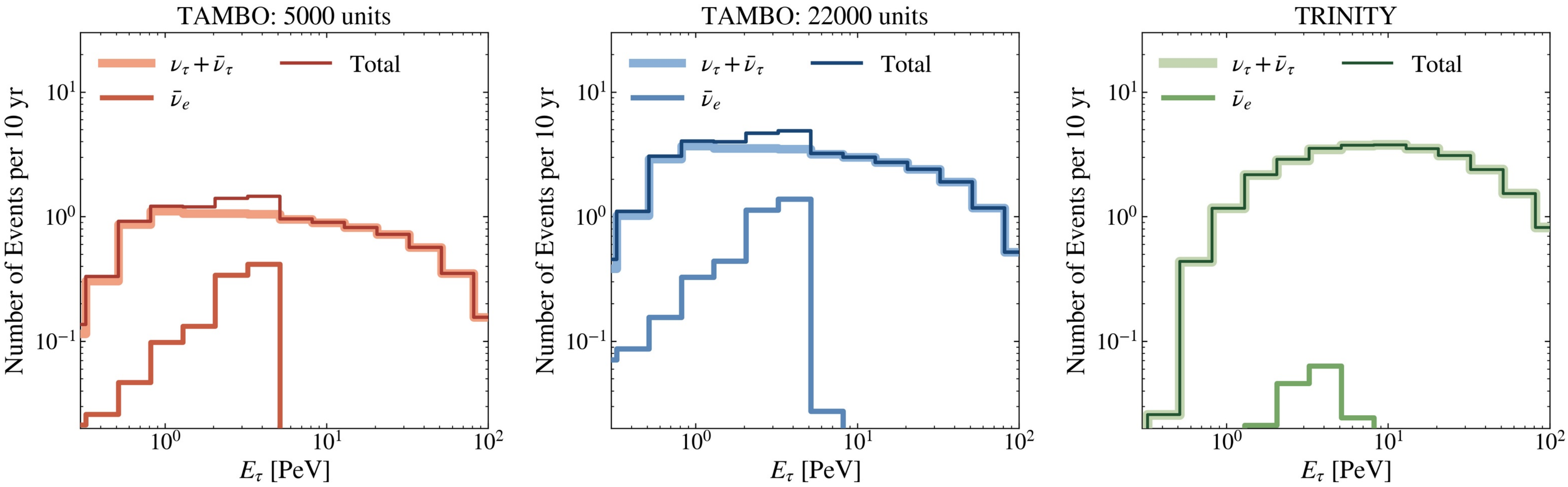


Trinity Demonstrator:
1.36 m²
Frisko Peak, Utah,
deployed 2023

Detector placed on a mountaintop looking towards the horizon

Assumed ν flux: IceCube $E_\nu^{-2.5}$ extrapolated to ultra-high energies

(This is a somewhat optimistic choice)



Ding & Liu, 2607.26128

Measuring the flavor ratio

Compress flavor information into $R = \dfrac{\Phi_{\bar{\nu}_e}}{\Phi_{\nu_\tau + \bar{\nu}_\tau}}$

(Same information as $\tilde{f}_{e,\oplus} = R/(1+R)$ from Bustamante & Matthiesen)

Different ν production mechanisms predict different R:

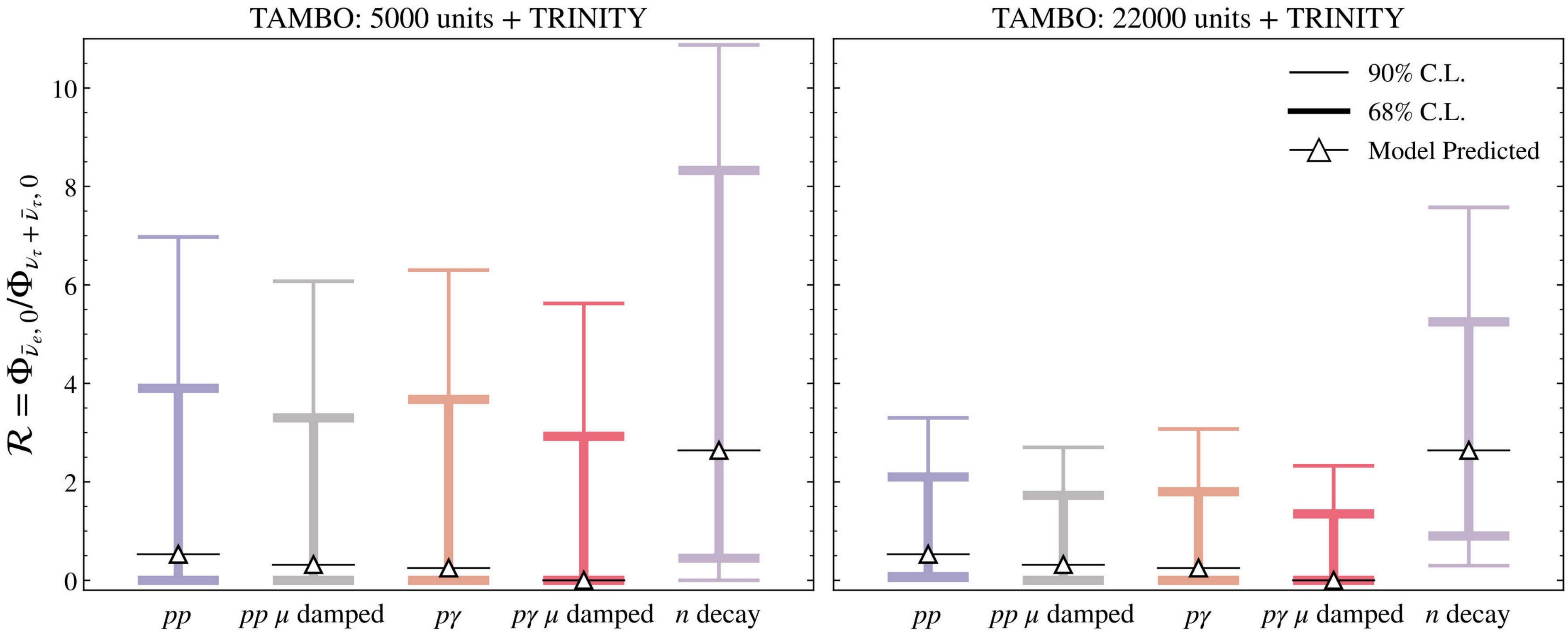
Proton-proton (pp): 0.53 (pure), 0.32 (muon-damped)

Proton-photon ($p\gamma$): 0.25 (pure), 0 (muon-damped)

Neutron decay: 2.64

Forecasts: upper limits using 10 yr of TAMBO + TRINITY

Measuring the flavor ratio



Ding & Liu, 2607.26128

pp and *pγ* channels are indistinguishable

Neutron-rich channels (and possible BSM) might be

Where to?

Main challenge:
Measuring flavor in TAMBO requires higher event rates than nominal

Dealing with this:
Possible to improve the effective area? Identify GR events better?

(Other improvements in the calculation possible)

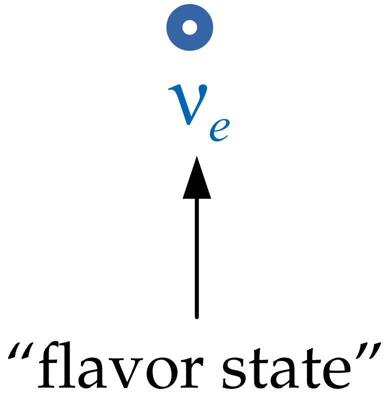
Backup slides

Neutrinos are quintessential quantum particles

A neutrino of a given flavor is a quantum superposition:

Neutrinos are quintessential quantum particles

A neutrino of a given flavor is a quantum superposition:



Neutrinos are quintessential quantum particles

A neutrino of a given flavor is a quantum superposition:

$$\nu_e = (\nu_1 + \nu_2 + \nu_3)$$

"flavor state"

Neutrinos are quintessential quantum particles

A neutrino of a given flavor is a quantum superposition:

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“flavor state”

“mass state”

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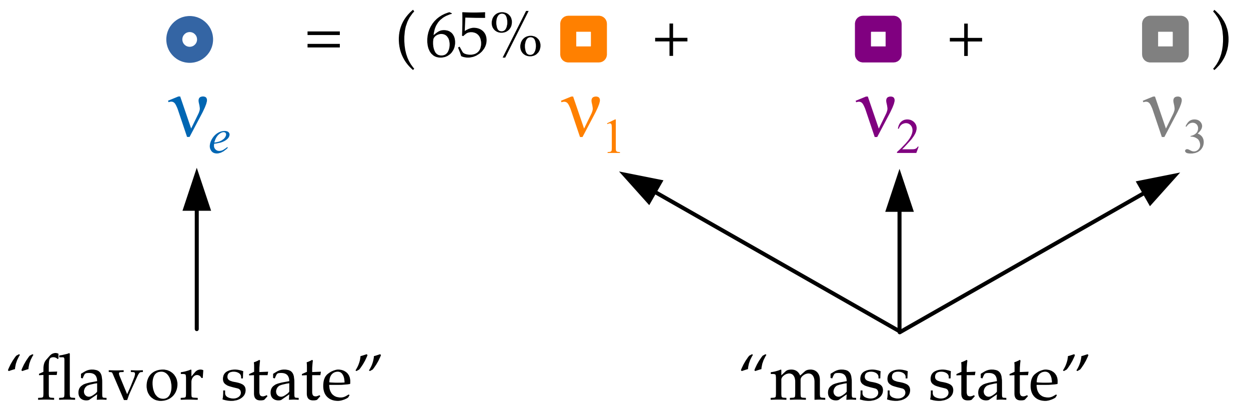

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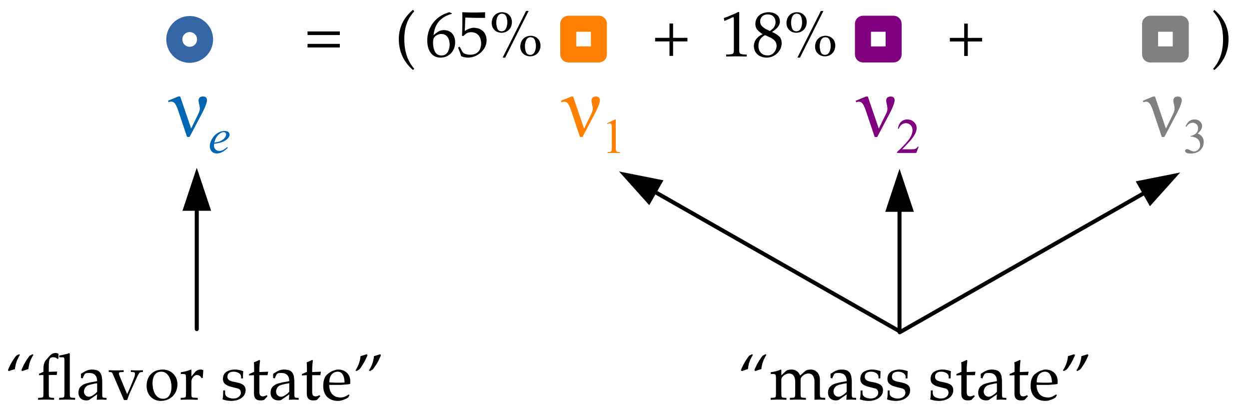


Neutrinos are quintessential quantum particles

A neutrino of a given flavor is a quantum superposition:

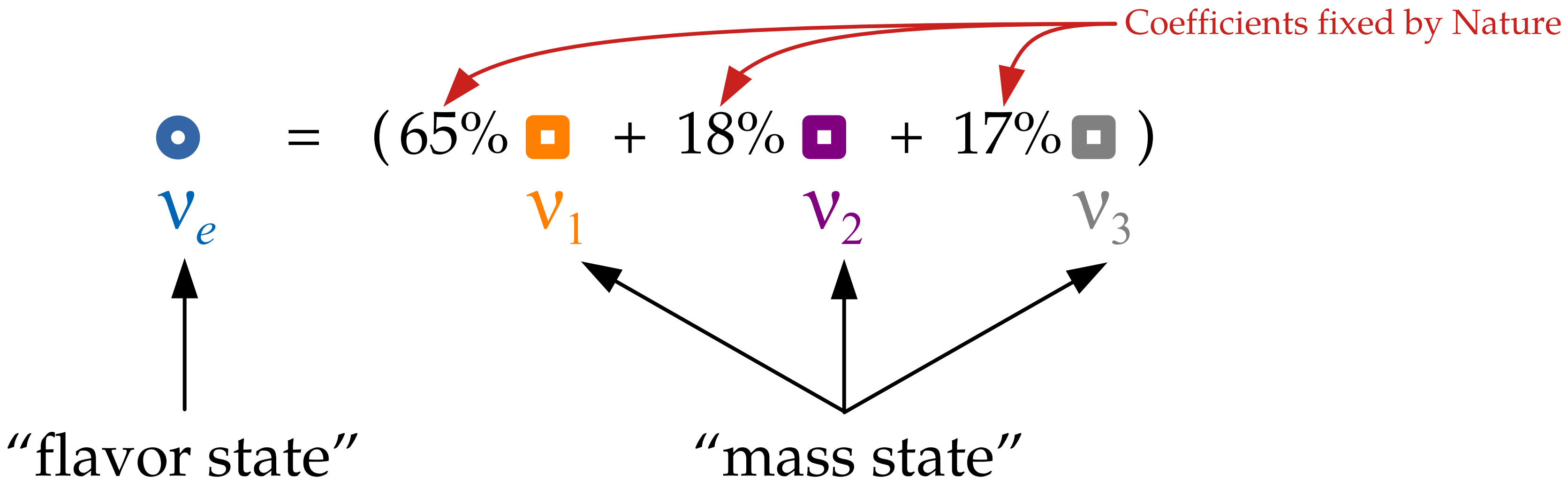
$$\nu_e = (65\%\,\nu_1 + 18\%\,\nu_2 + 17\%\,\nu_3)$$

"flavor state"

"mass state"

Neutrinos are quintessential quantum particles

A neutrino of a given flavor is a quantum superposition:



Neutrinos are quintessential quantum particles

A neutrino of a given flavor is a quantum superposition:

Coefficients fixed by Nature

$$\nu_e = (65\%\,\nu_1 + 18\%\,\nu_2 + 17\%\,\nu_3)$$

"flavor state"

"mass state"

Defined flavor (e)

Neutrinos are quintessential quantum particles

A neutrino of a given flavor is a quantum superposition:

Coefficients fixed by Nature

$$\nu_e = (65\%\ \nu_1 + 18\%\ \nu_2 + 17\%\ \nu_3)$$

“flavor state”

“mass state”

Defined flavor (e)
Undefined mass

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"flavor state"

"mass state"

Defined flavor (e)
Undefined mass

Defined mass (m_1, m_2, m_3)

Neutrinos are quintessential quantum particles

A neutrino of a given flavor is a quantum superposition:

Coefficients fixed by Nature

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"flavor state"

Defined flavor (e)
Undefined mass

"mass state"

Defined mass (m_1, m_2, m_3)
Undefined flavor

Neutrinos are quintessential quantum particles

A neutrino of a given flavor is a quantum superposition:

$$\begin{array}{cccccc} & & \nu_1 & \nu_2 & \nu_3 & \\ \nu_e & = & (65\% & +\ 18\% & +\ 17\% &) \end{array}$$

Neutrinos are quintessential quantum particles

A neutrino of a given flavor is a quantum superposition:

$$\nu_e \odot = \left(U_{e1} \overset{\nu_1}{\boxdot} + U_{e2} \overset{\nu_2}{\boxdot} + U_{e3} \overset{\nu_3}{\boxdot} \right)$$

Neutrinos are quintessential quantum particles

A neutrino of a given flavor is a quantum superposition:

$$\begin{array}{cccccccccc} & & & & \nu_1 & & \nu_2 & & \nu_3 & \\ \nu_e & = & (& U_{e1} & \square & + \; U_{e2} & \square & + \; U_{e3} & \square &) \\ \nu_\mu & = & (& U_{\mu 1} & \square & + \; U_{\mu 2} & \square & + \; U_{\mu 3} & \square &) \end{array}$$

Neutrinos are quintessential quantum particles

A neutrino of a given flavor is a quantum superposition:

$$
\begin{array}{cccccccc}
 & & & \nu_1 & & \nu_2 & & \nu_3 \\
\nu_e & = & (& U_{e1} & + & U_{e2} & + & U_{e3} &) \\
\nu_\mu & = & (& U_{\mu 1} & + & U_{\mu 2} & + & U_{\mu 3} &) \\
\nu_\tau & = & (& U_{\tau 1} & + & U_{\tau 2} & + & U_{\tau 3} &)
\end{array}
$$

Neutrinos are quintessential quantum particles

A neutrino of a given flavor is a quantum superposition:

$$\begin{array}{lcccccc} & & \nu_1 & & \nu_2 & & \nu_3 \\ \nu_e & = & (U_{e1} & + & U_{e2} & + & U_{e3}) \\ \nu_\mu & = & (U_{\mu 1} & + & U_{\mu 2} & + & U_{\mu 3}) \\ \nu_\tau & = & (U_{\tau 1} & + & U_{\tau 2} & + & U_{\tau 3}) \end{array}$$

[Or, you can write: $\nu_\alpha = \sum_{j=1}^{3} U^*_{\alpha i} \nu_j$ for $\alpha = e, \mu, \tau$]

Neutrinos are quintessential quantum particles

A neutrino of a given flavor is a quantum superposition:

$$
\begin{array}{cclcll}
 & & \nu_1 & & \nu_2 & \nu_3 \\
\nu_e \odot & = & (U_{e1} \boxdot & + & U_{e2} \boxdot & + \; U_{e3} \boxdot) \\
\nu_\mu \odot & = & (U_{\mu 1} \boxdot & + & U_{\mu 2} \boxdot & + \; U_{\mu 3} \boxdot) \\
\nu_\tau \odot & = & (U_{\tau 1} \boxdot & + & U_{\tau 2} \boxdot & + \; U_{\tau 3} \boxdot)
\end{array}
$$

ν_1, ν_2, ν_3 have different masses, so they travel at different speeds

So the coefficients of the superposition change with time!

Neutrinos are quintessential quantum particles

A neutrino of a given flavor is a quantum superposition:

Neutrinos are quintessential quantum particles

A neutrino of a given flavor is a quantum superposition:

$$\text{Produced as:} \quad \nu_e \odot \quad = \quad \left(U_{e1} \overset{\nu_1}{\square} + U_{e2} \overset{\nu_2}{\square} + U_{e3} \overset{\nu_3}{\square} \right)$$

Neutrinos are quintessential quantum particles

A neutrino of a given flavor is a quantum superposition:

$$\text{Produced as: } \nu_e \odot = \left(U_{e1} \underset{\nu_1}{\boxdot} + U_{e2} \underset{\nu_2}{\boxdot} + U_{e3} \underset{\nu_3}{\boxdot} \right)$$

Travel a distance
L to the detector

Neutrinos are quintessential quantum particles

A neutrino of a given flavor is a quantum superposition:

$$\begin{array}{ccccccc} & & \nu_1 & & \nu_2 & & \nu_3 \\ \text{Produced as: } \nu_e & = (& U_{e1} & + & U_{e2} & + & U_{e3} \;) \end{array}$$

Travel a distance
L to the detector

Detected as:

Neutrinos are quintessential quantum particles

A neutrino of a given flavor is a quantum superposition:

$$\nu_1 \qquad \nu_2 \qquad \nu_3$$

Produced as: $\nu_e = (U_{e1} + U_{e2} + U_{e3})$

Travel a distance L to the detector

Detected as: $U_{e1}\, \overbrace{e^{-i m_1 L/E}}$

Neutrinos are quintessential quantum particles

A neutrino of a given flavor is a quantum superposition:

$$\nu_1 \qquad \nu_2 \qquad \nu_3$$

Produced as: $\nu_e \odot \; = \; \left(U_{e1} \boxdot + U_{e2} \boxdot + U_{e3} \boxdot \right)$

Travel a distance L to the detector

Detected as: $U_{e1}\, e^{-i m_1 L/E} \boxdot + U_{e2}\, e^{-i m_2 L/E} \boxdot$

Neutrinos are quintessential quantum particles

A neutrino of a given flavor is a quantum superposition:

$$\qquad\qquad\qquad\qquad\quad \nu_1 \qquad\qquad \nu_2 \qquad\qquad \nu_3$$

Produced as: $\nu_e \odot \;=\; \left(U_{e1} \boxdot + U_{e2} \boxdot + U_{e3} \boxdot \right)$

Travel a distance
L to the detector

Detected as: $U_{e1}\, e^{-i m_1 L/E} \boxdot + U_{e2}\, e^{-i m_2 L/E} \boxdot + U_{e3}\, e^{-i m_3 L/E} \boxdot$

Neutrinos are quintessential quantum particles

A neutrino of a given flavor is a quantum superposition:

$$\nu_1 \qquad \nu_2 \qquad \nu_3$$

Produced as: $$\nu_e \odot = \left(U_{e1} \,\blacksquare + U_{e2} \,\blacksquare + U_{e3} \,\blacksquare \right)$$

Travel a distance L to the detector

The mass states evolve with time

Detected as: $$U_{e1}\, \overbrace{e^{-im_1 L/E} \,\blacksquare} + U_{e2}\, \overbrace{e^{-im_2 L/E} \,\blacksquare} + U_{e3}\, \overbrace{e^{-im_3 L/E} \,\blacksquare}$$

Neutrinos are quintessential quantum particles

A neutrino of a given flavor is a quantum superposition:

$$\nu_1 \qquad \nu_2 \qquad \nu_3$$

Produced as: $\nu_e \odot \;=\; \left(U_{e1} \boxdot + U_{e2} \boxdot + U_{e3} \boxdot \right)$

Travel a distance L to the detector

The mass states evolve with time

Detected as: $\underbrace{U_{e1}\, \overbrace{e^{-im_1 L/E} \boxdot} + U_{e2}\, \overbrace{e^{-im_2 L/E} \boxdot} + U_{e3}\, \overbrace{e^{-im_3 L/E} \boxdot}}_{\text{This is no longer a } \nu_e}$