The flavor composition of high-energy cosmic neutrinos

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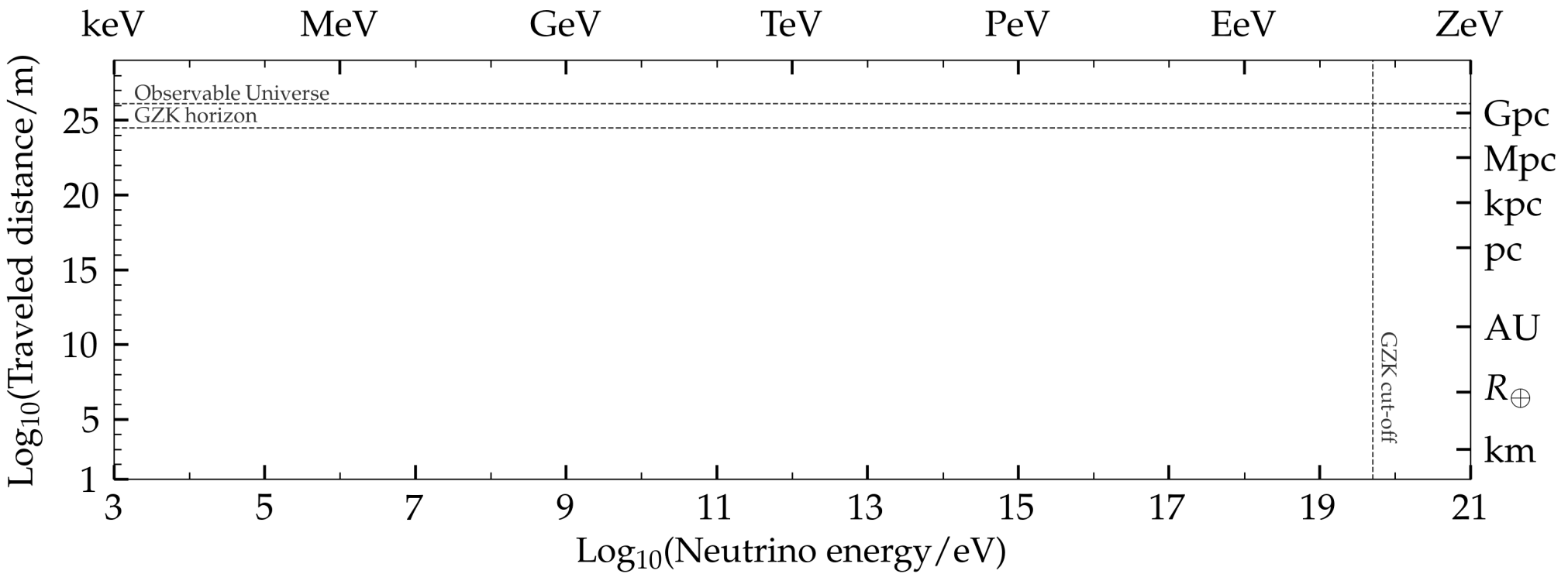
Niels Bohr Institute, University of Copenhagen

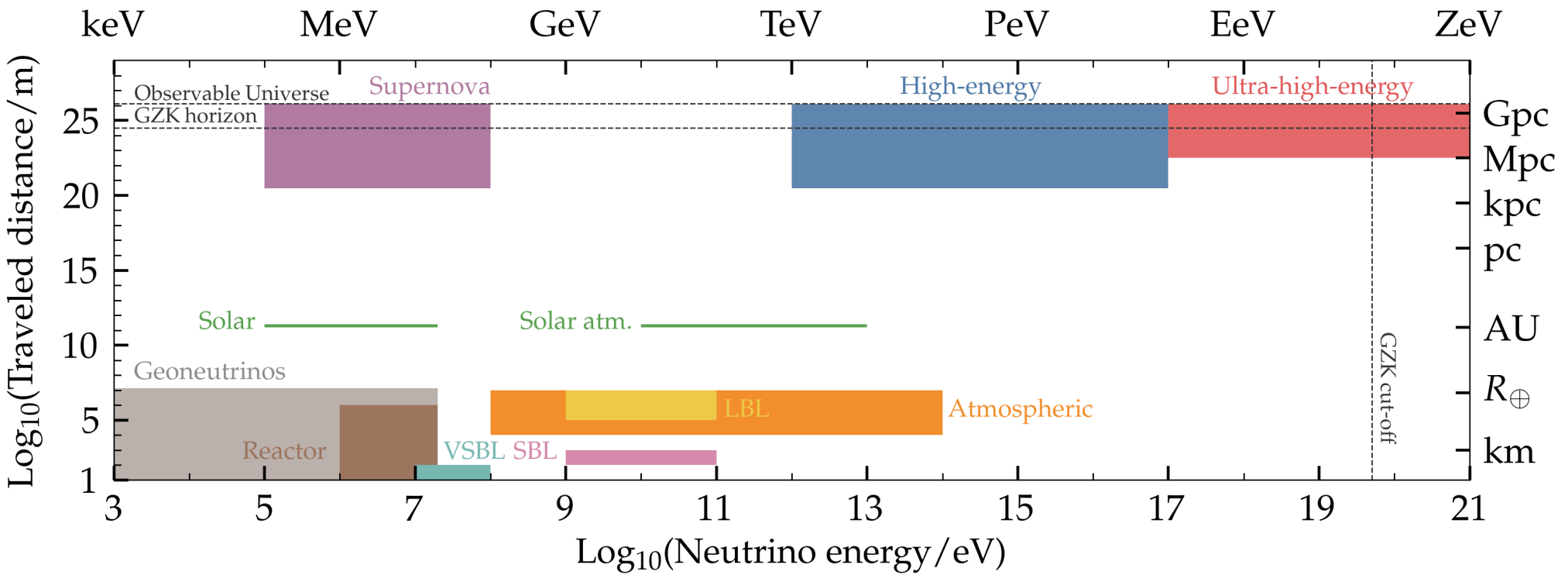
UNIVERSITY OF COPENHAGEN

VILLUM FONDEN

Neutrinos from Home
December 02–05 , 2025



Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333), adapted



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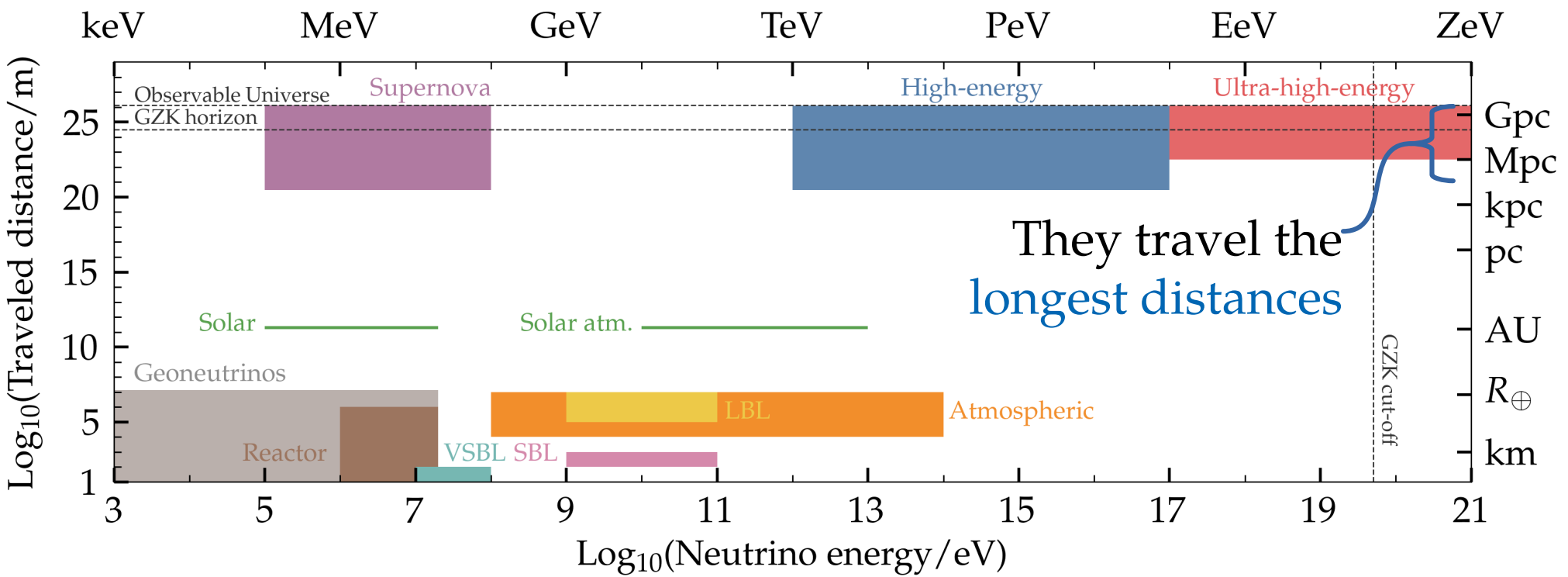
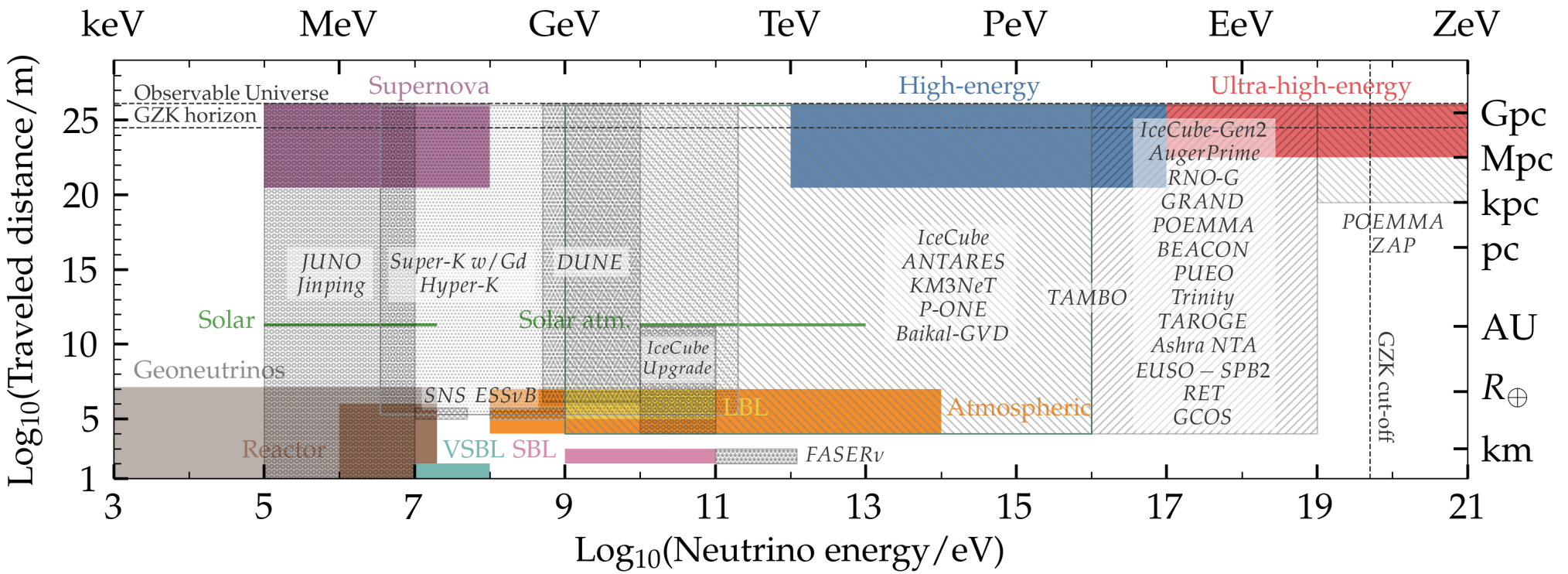
They have the highest energies



They travel the longest distances

Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333), adapted



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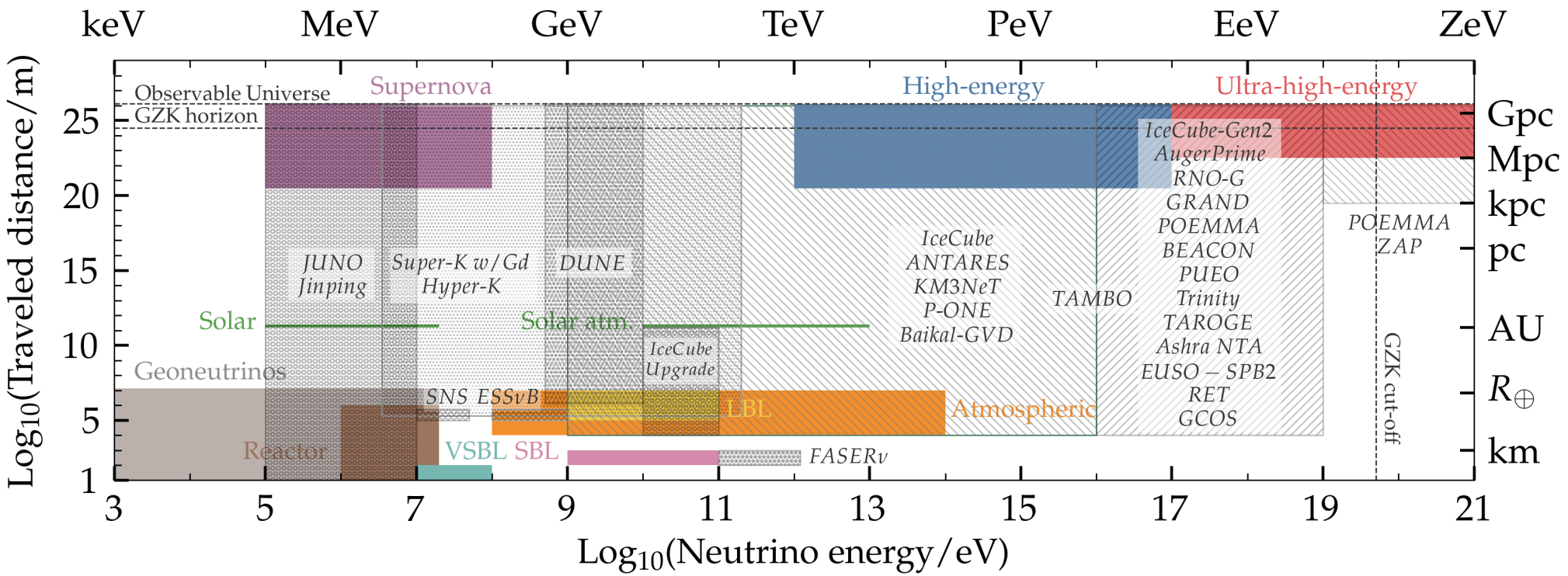
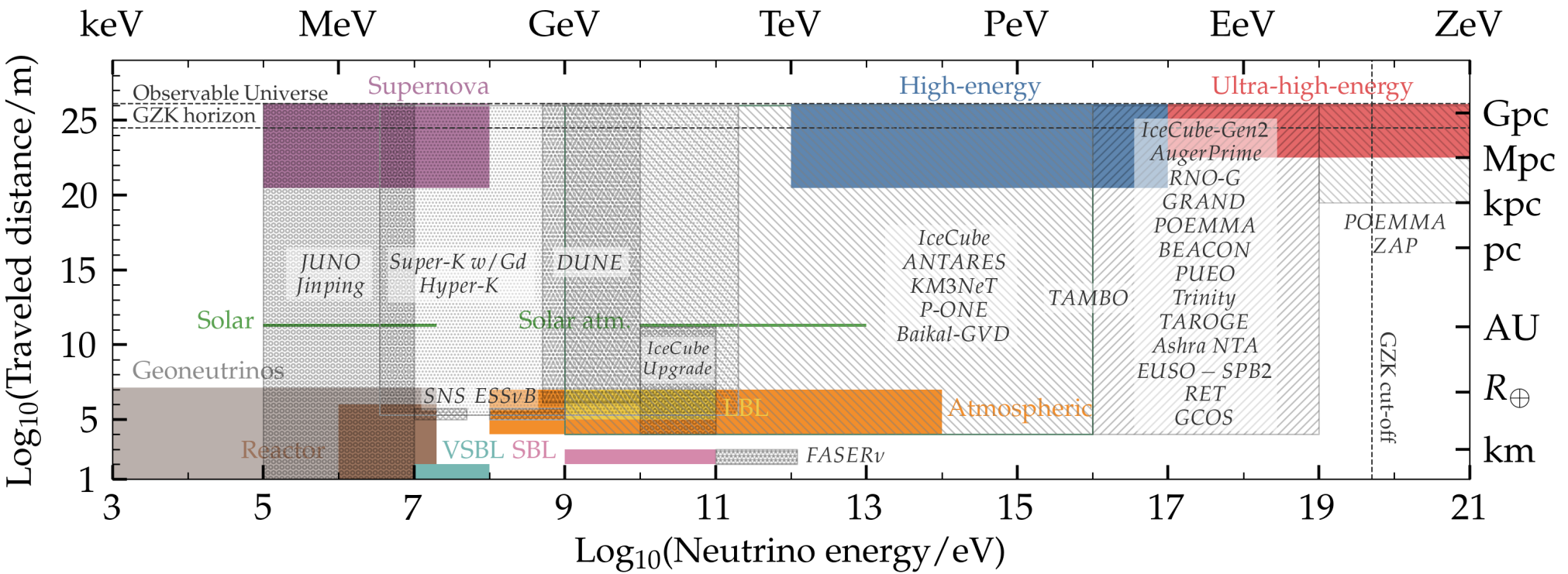


Synergies with lower energies

Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333), adapted

Discovered in 2013
by IceCube



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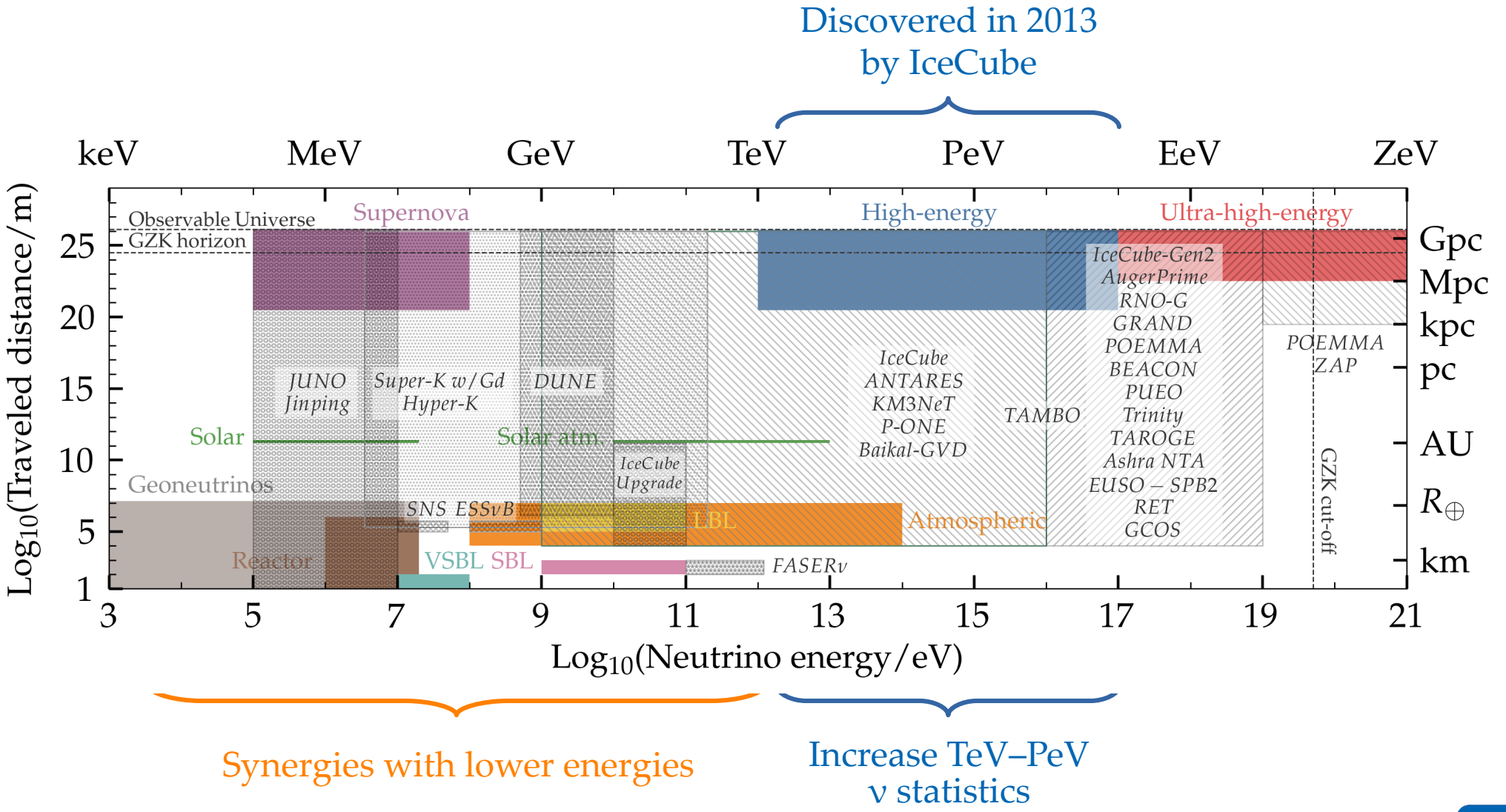

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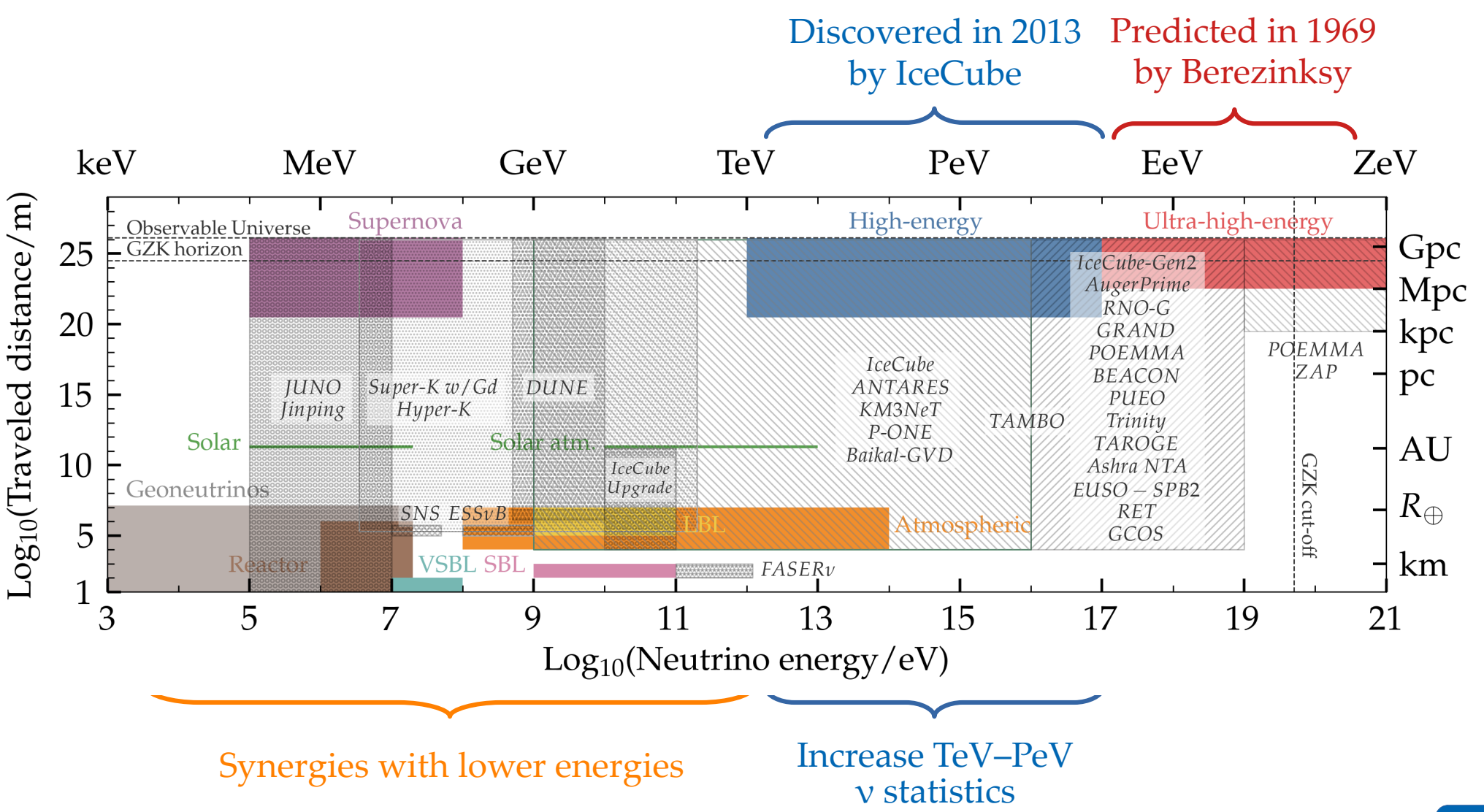

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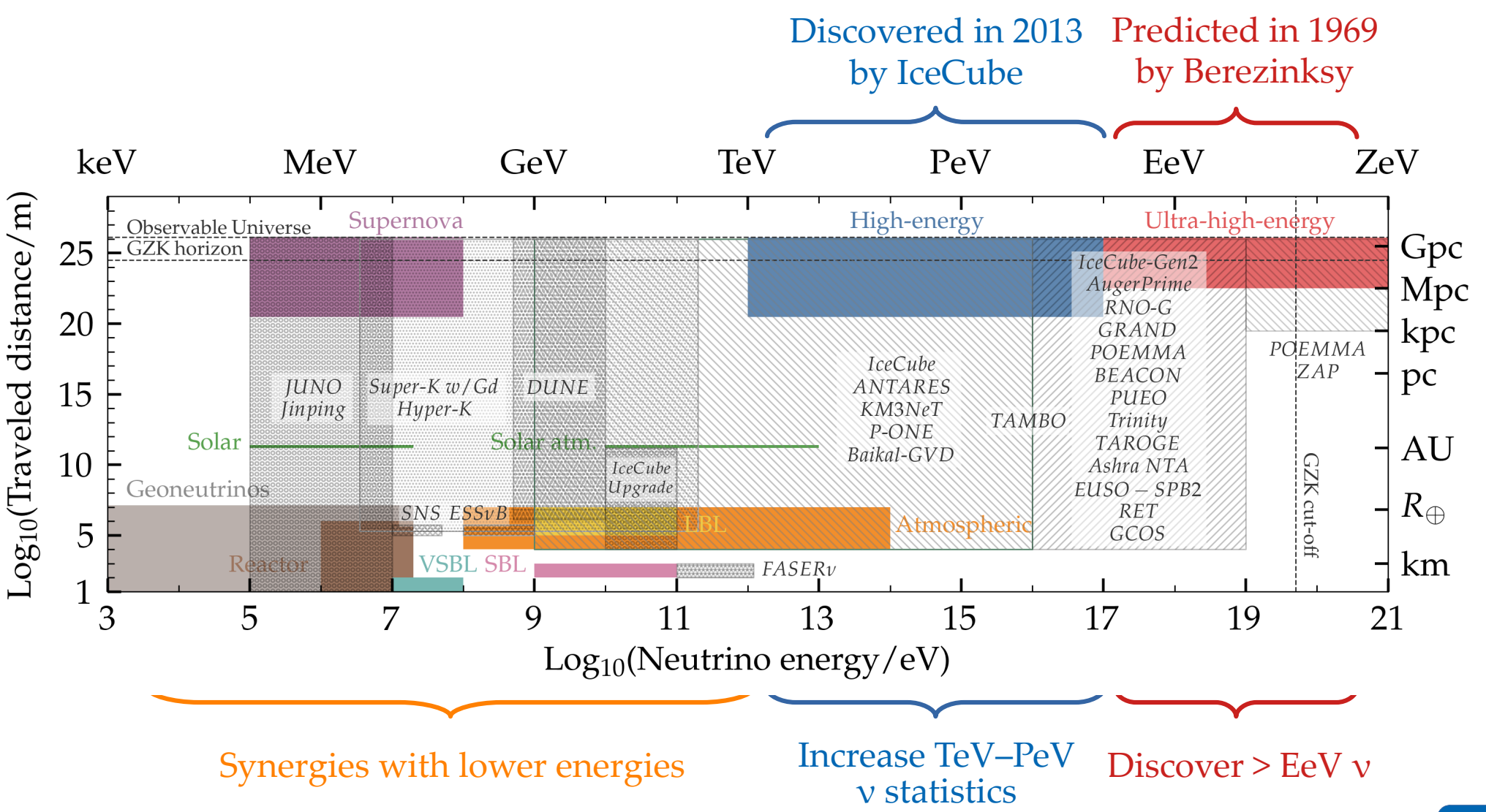
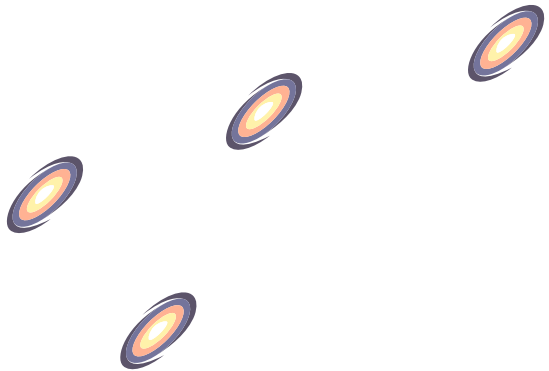
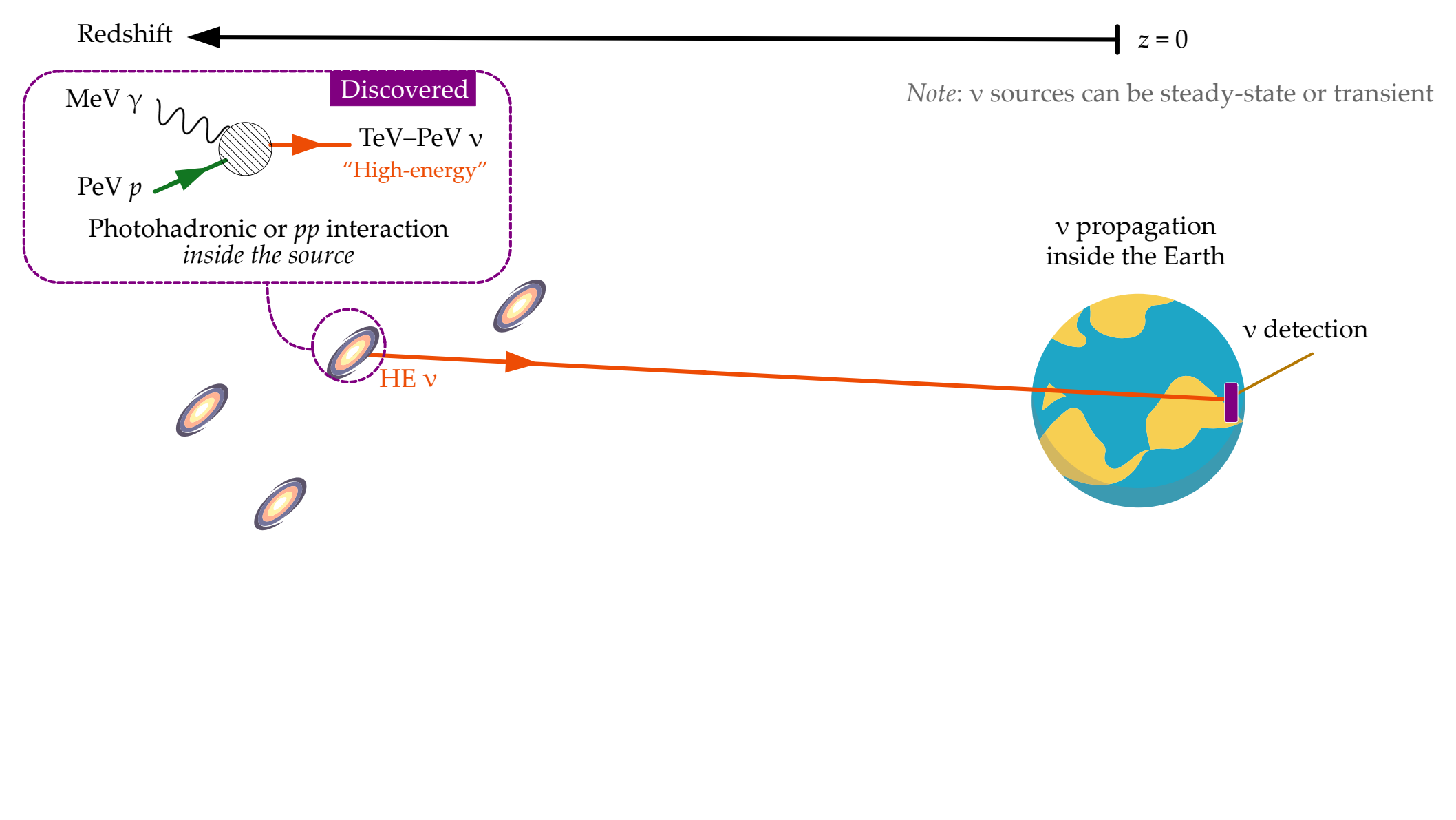


Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333), adapted

Redshift $z = 0$

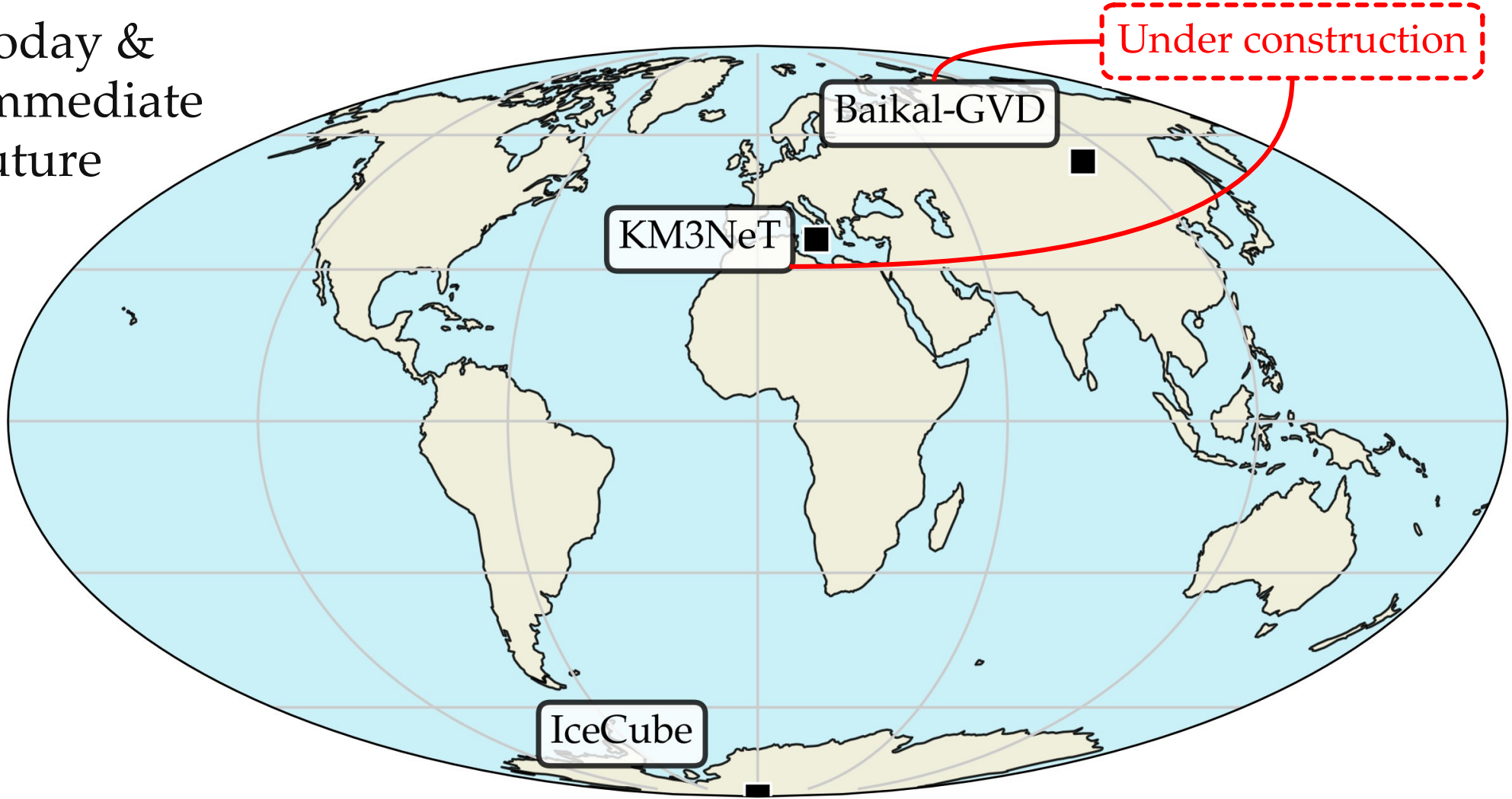
Note: ν sources can be steady-state or transient





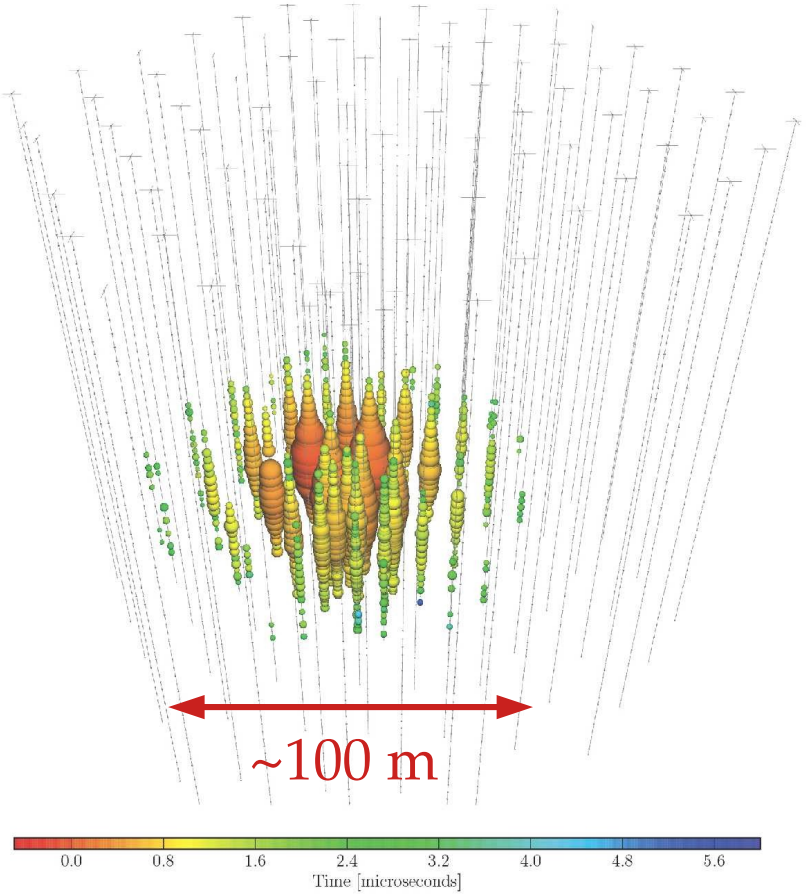
Note: ν sources can be steady-state or transient

Today & immediate future



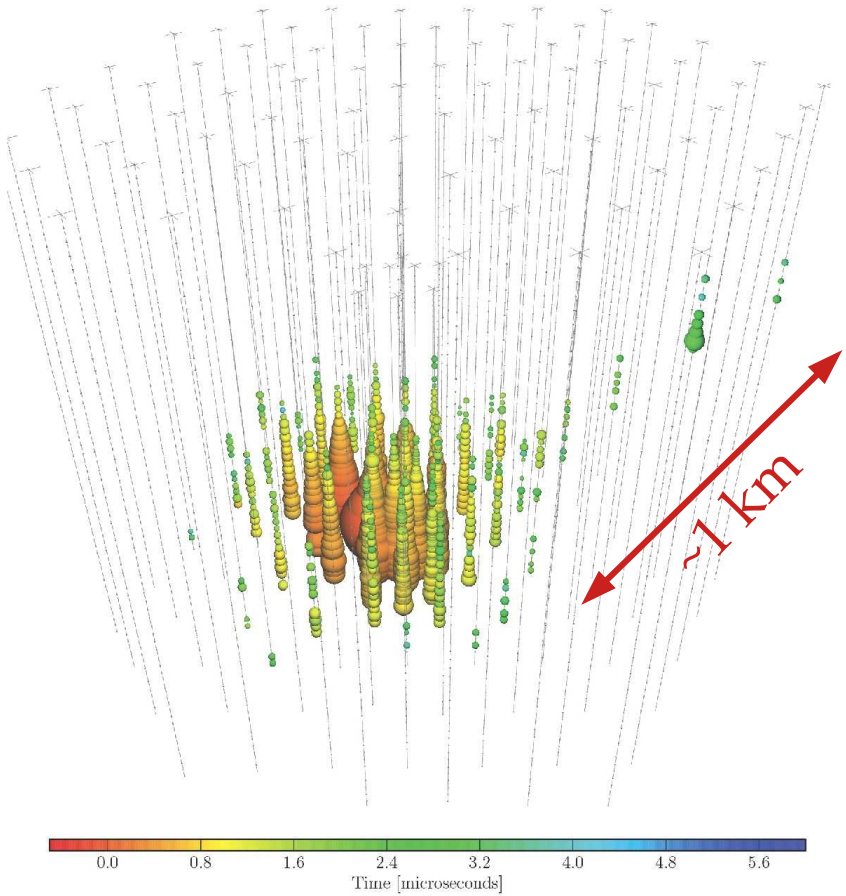
Schumacher, **MB**, Agostini, Oikonomou, Resconi, 2503.07549

Shower
(mainly from ν_e and ν_τ)

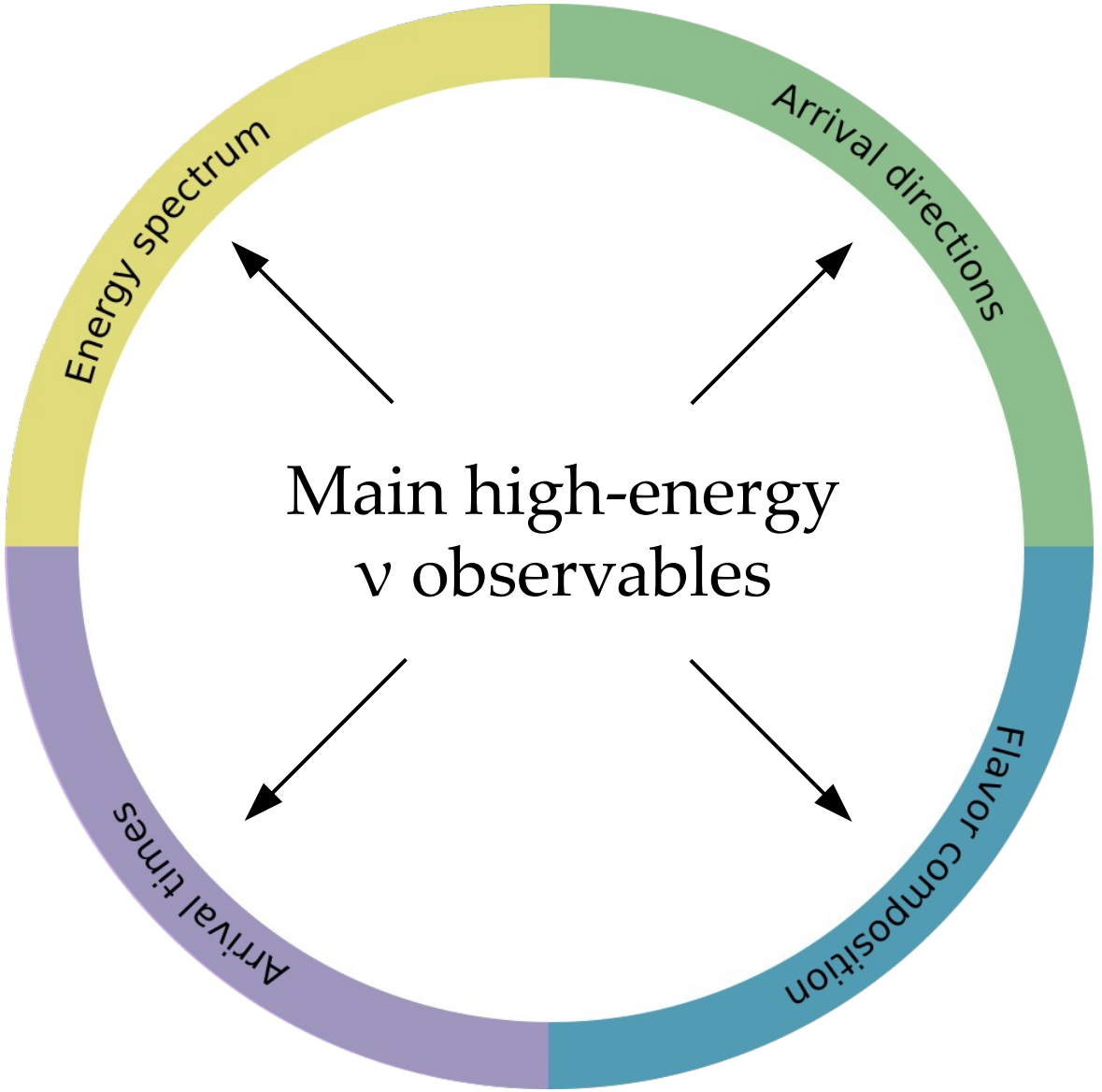


Poor angular resolution: < 5°

Track
(mainly from ν_μ)

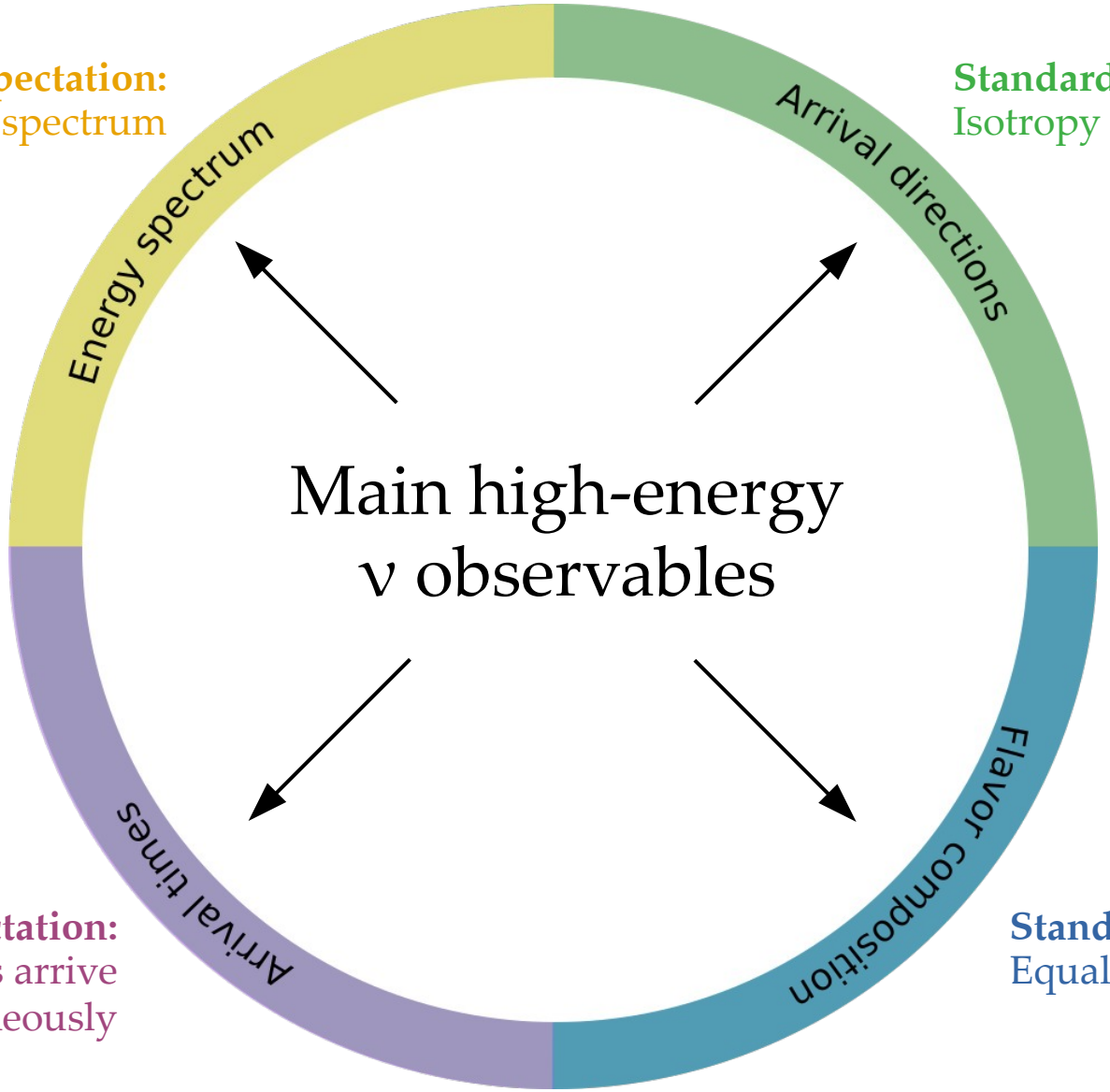


Angular resolution: < 1°


Energy spectrum
Arrival directions
Main high-energy
ν observables
Arrival times
Flavor composition

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



Standard expectation:
ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Standard expectation:
Power-law energy spectrum

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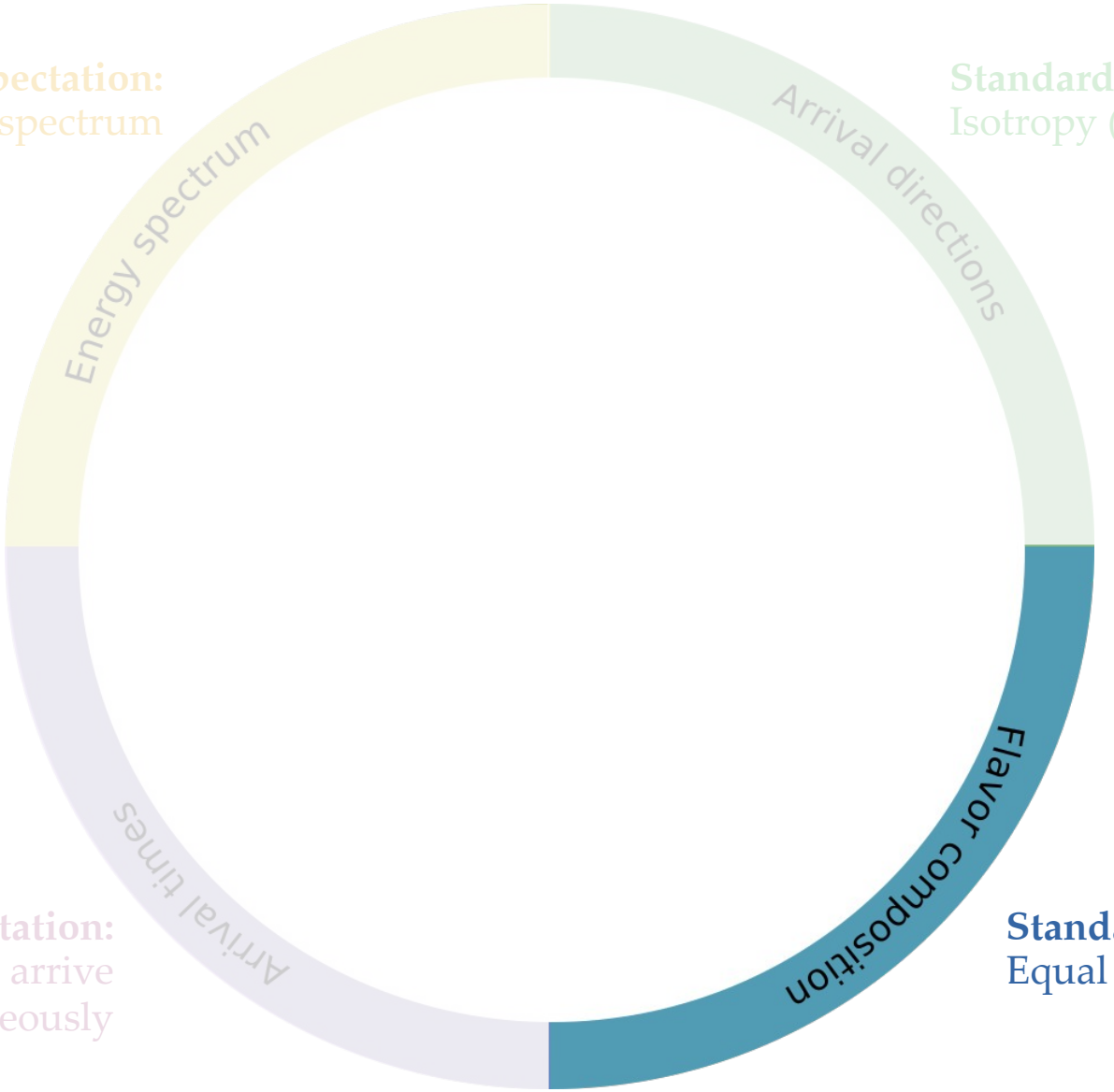


Standard expectation:
ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

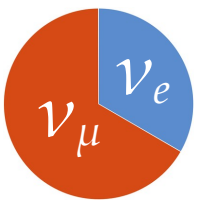
Predicting the flavor composition at Earth

Astrophysical sources

Earth

Up to a few Gpc

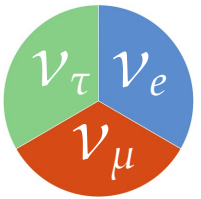
E.g.,



Oscillations change the number

of ν of each flavor, N_e, N_μ, N_τ

E.g.,



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

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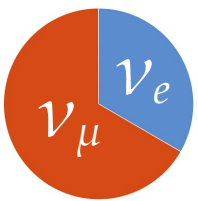

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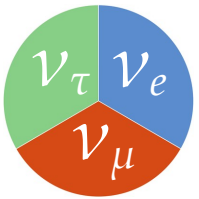

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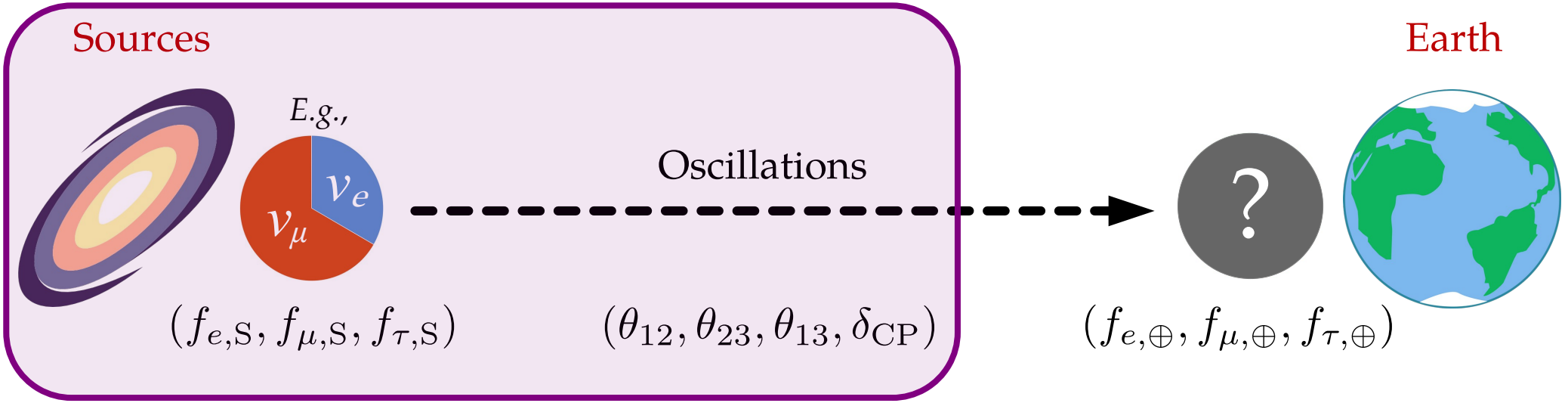
Standard oscillations *or* new physics

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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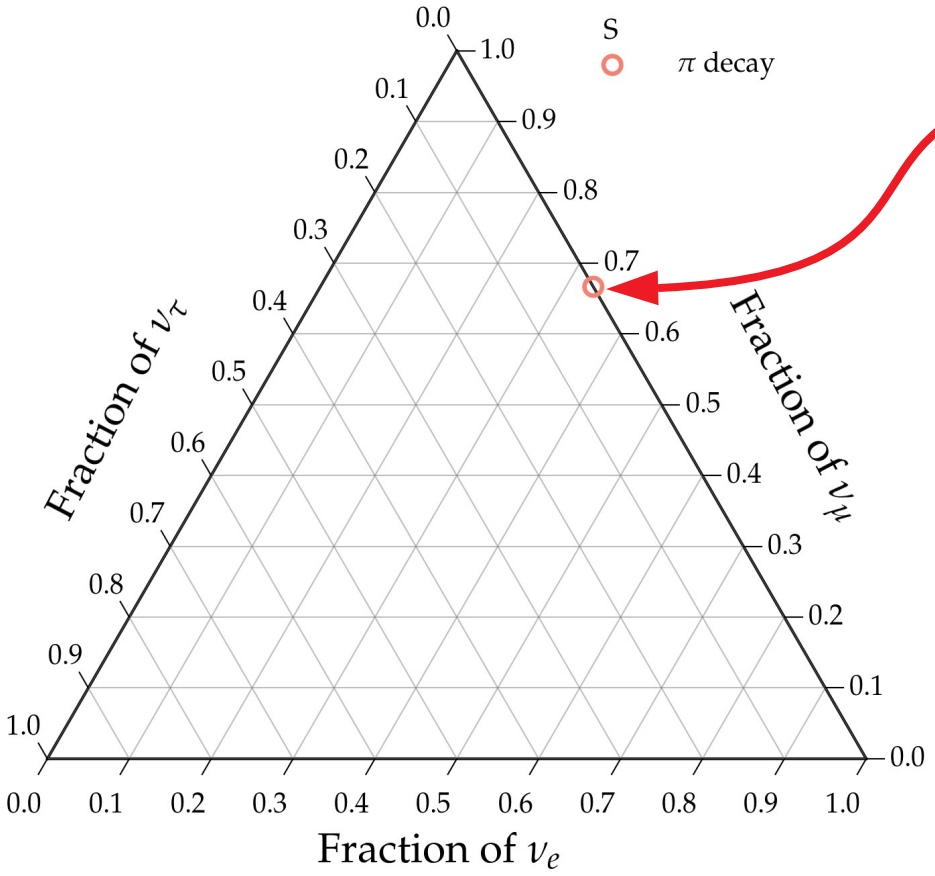

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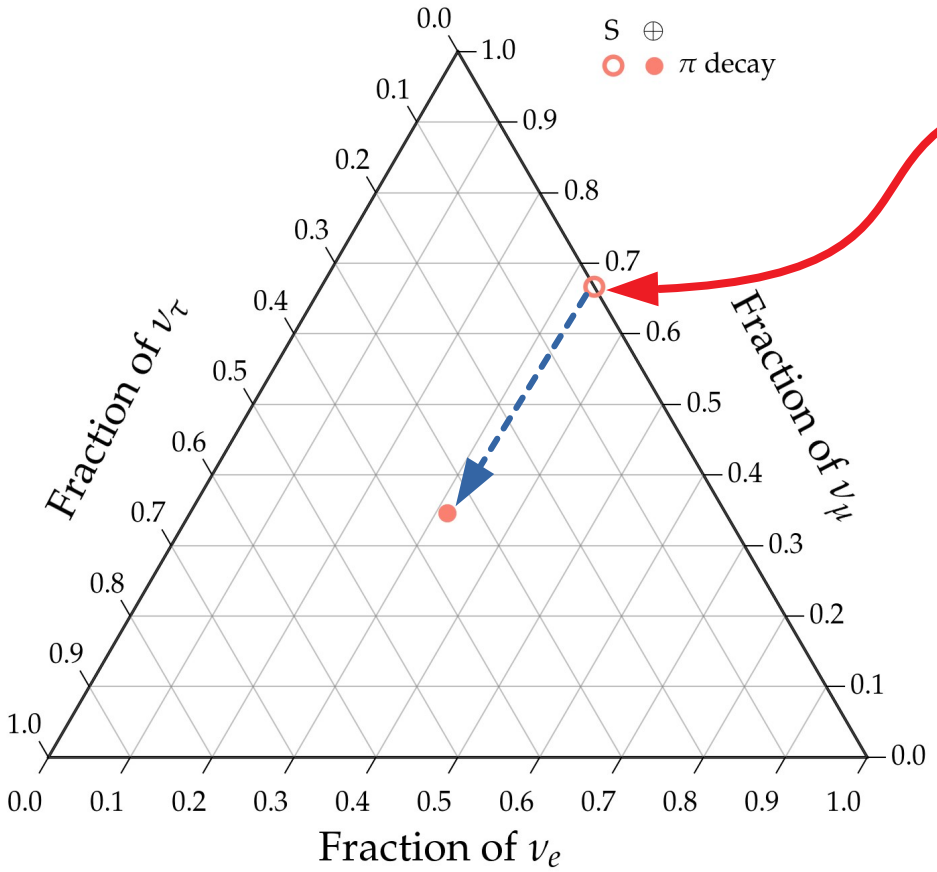

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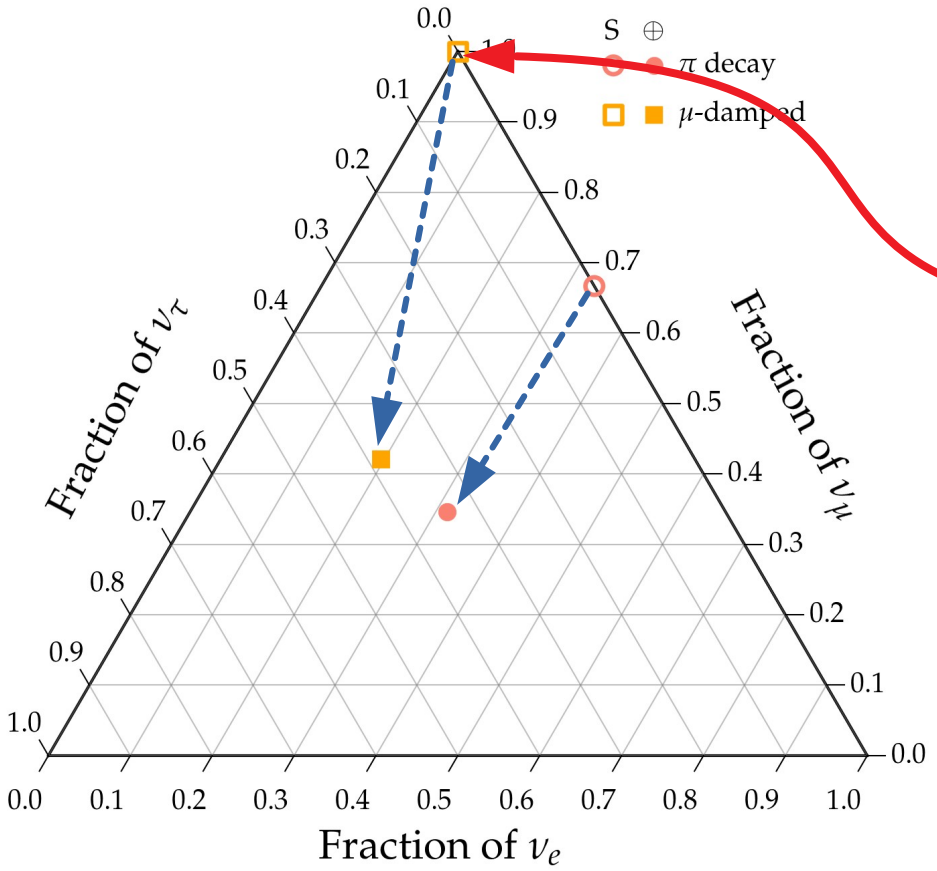

Full π decay chain

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

Muon damped

$(0:1:0)_S$

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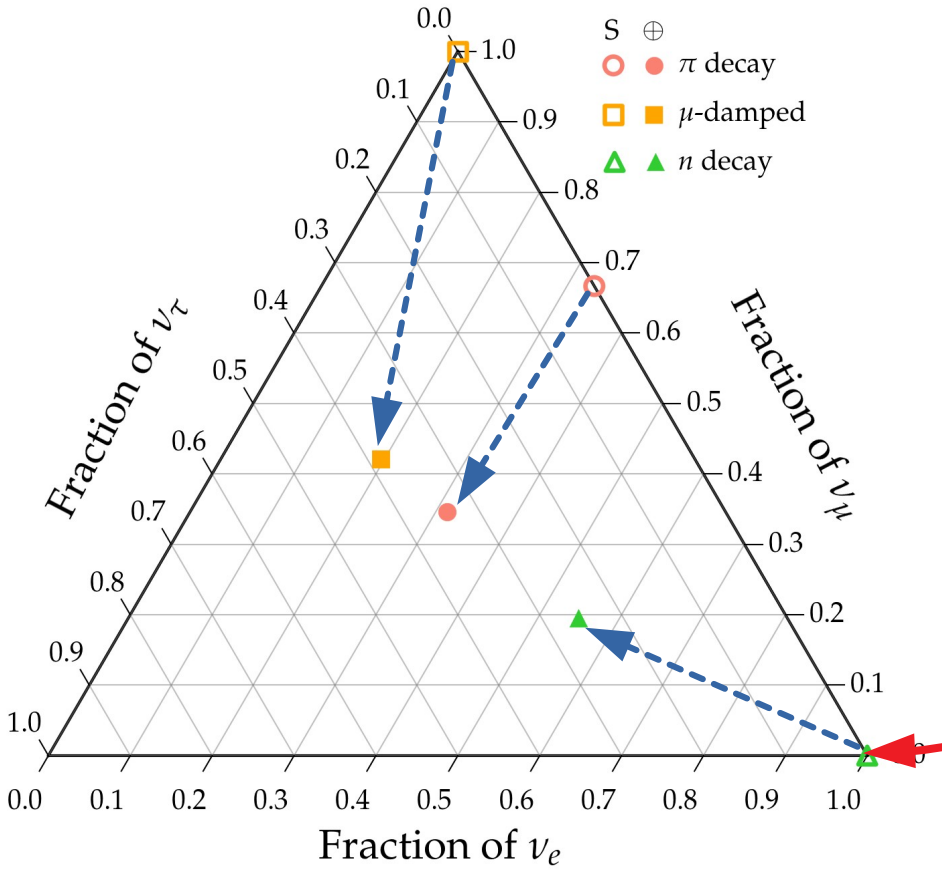

Full π decay chain

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Muon damped

$(0:1:0)_S$

Neutron decay

$(1:0:0)_S$

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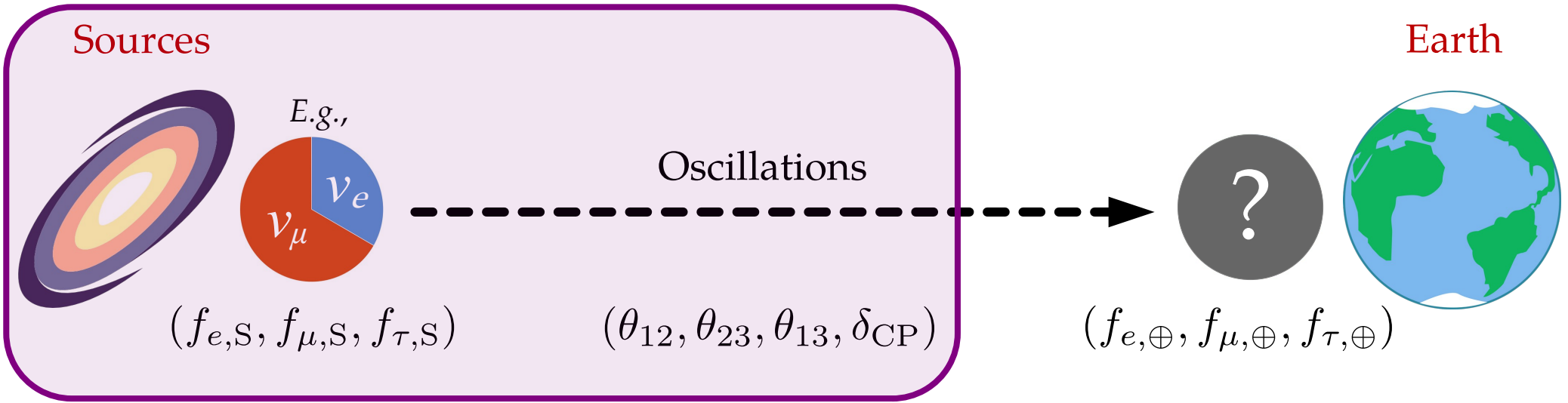
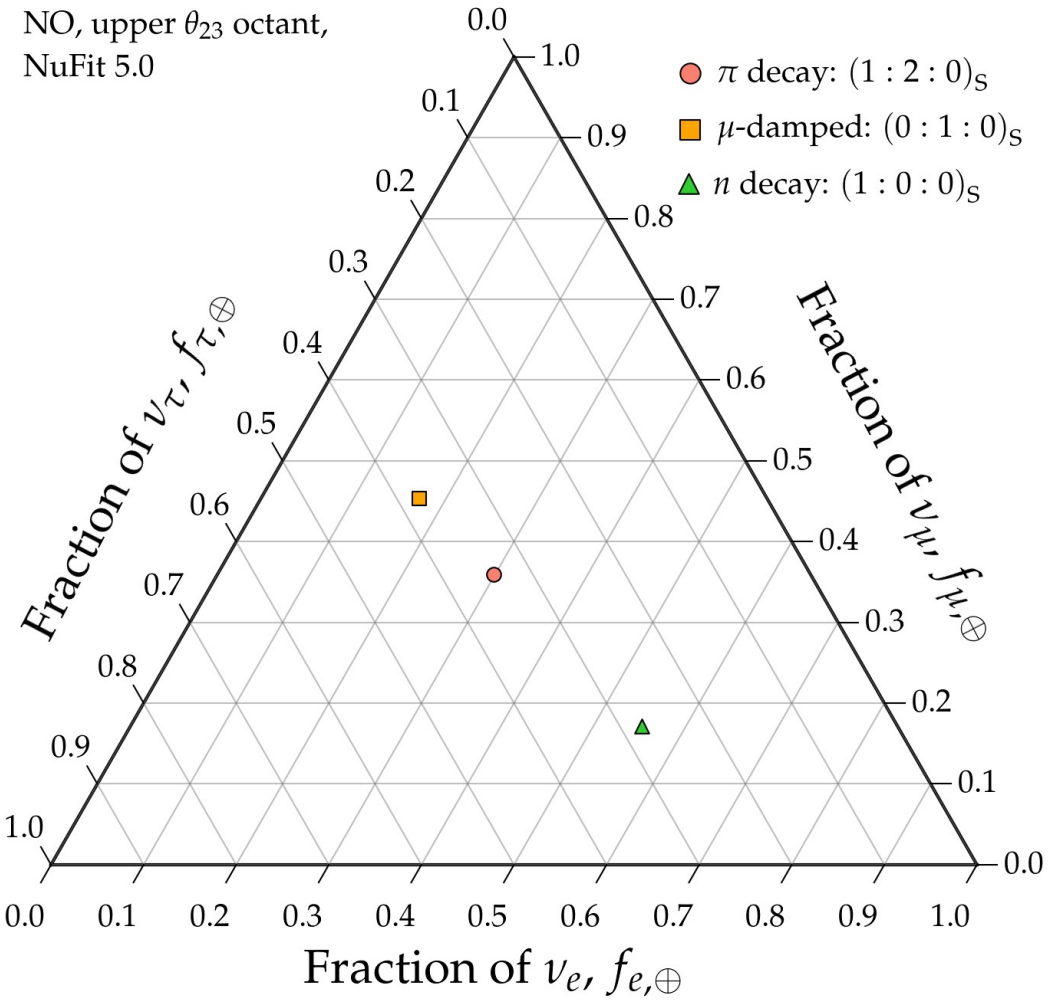


Known from oscillation experiments, to different levels of precision

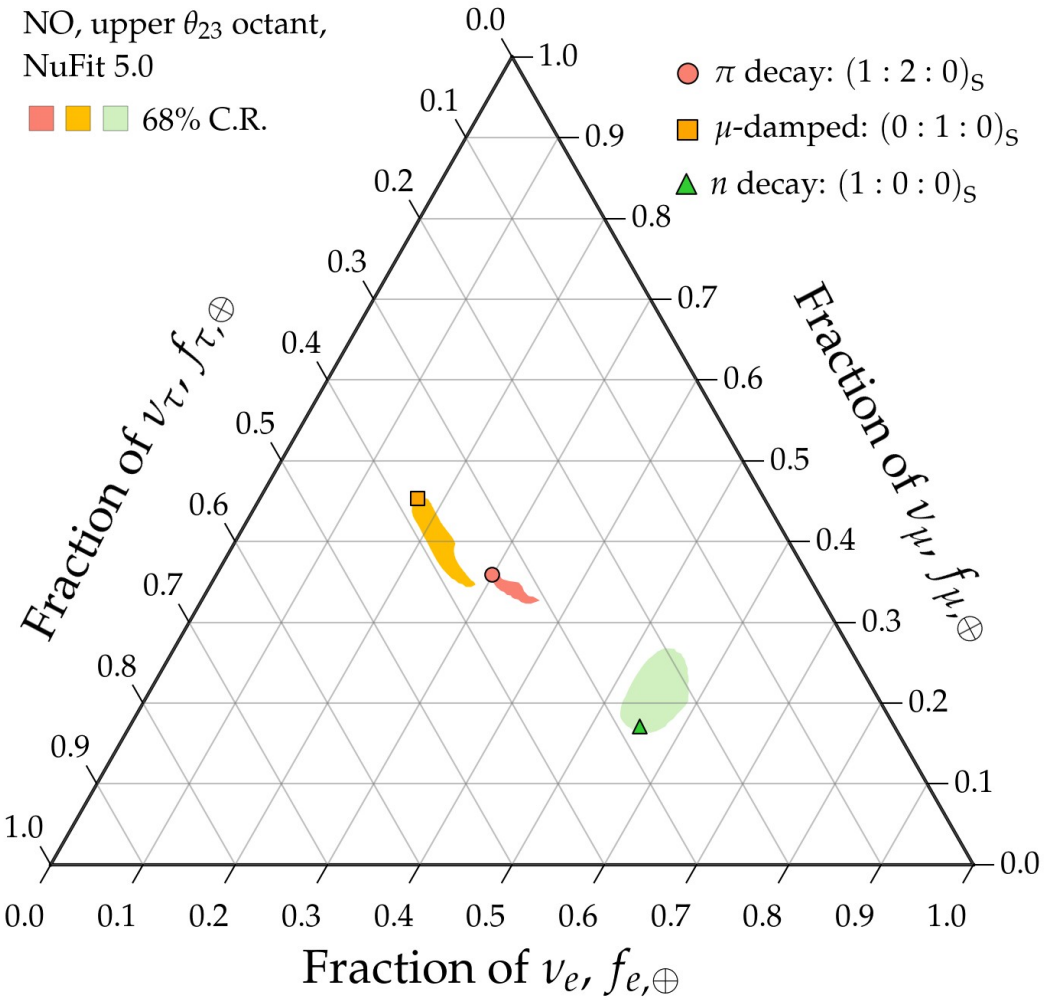
Theoretically palatable regions: today



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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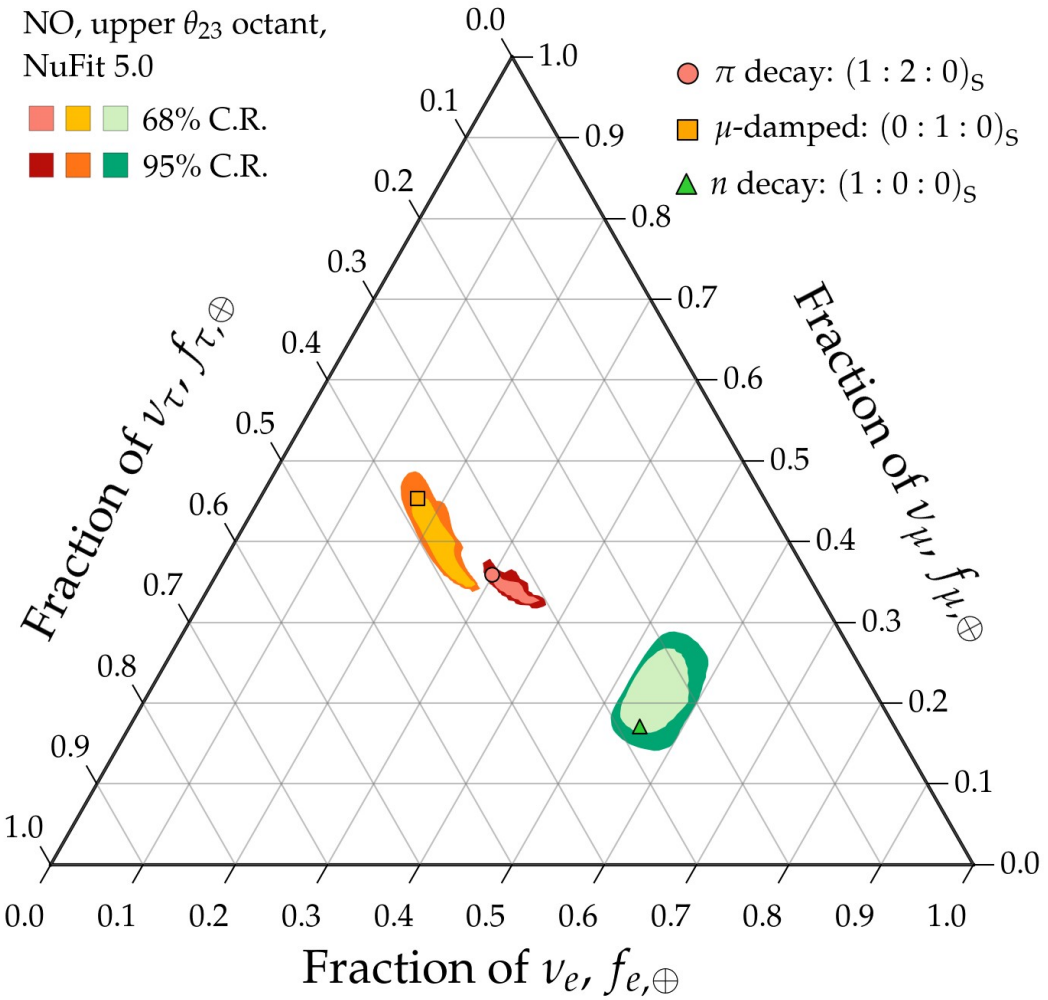

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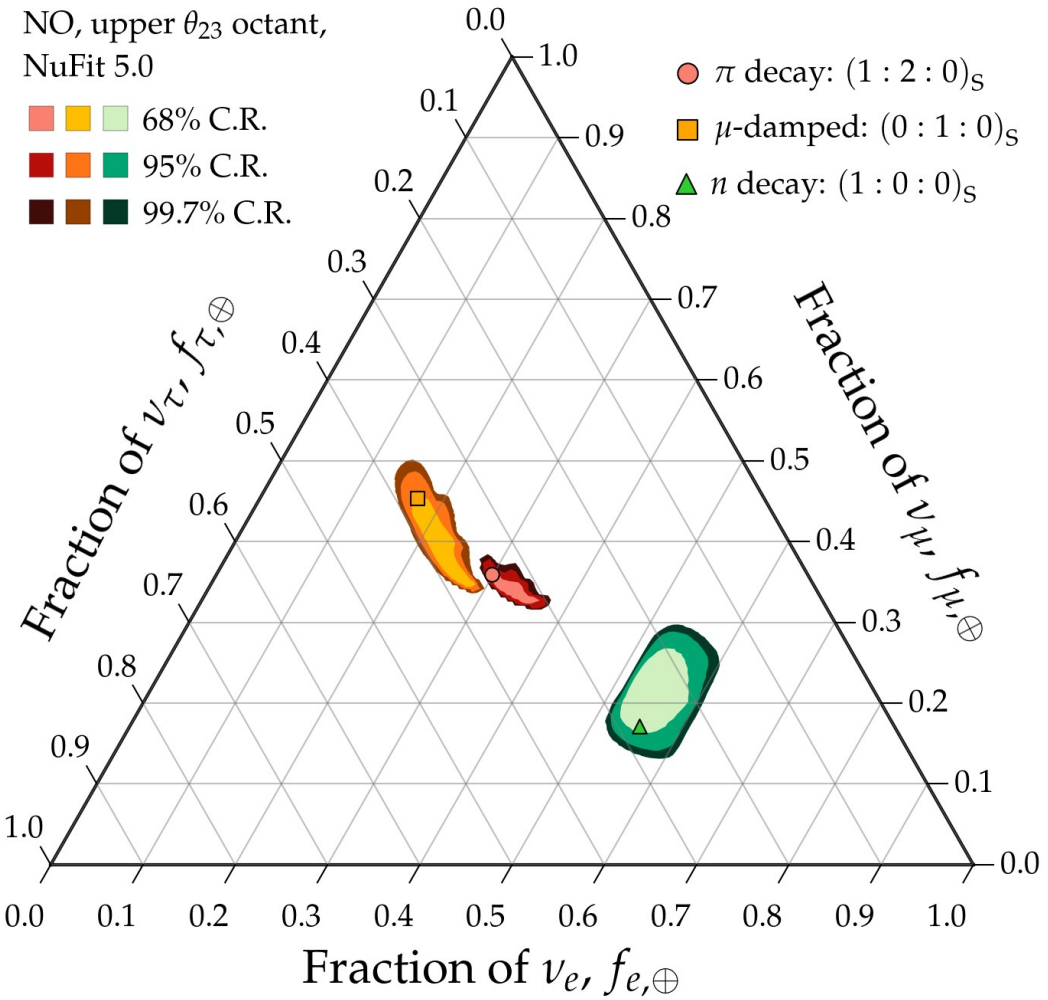

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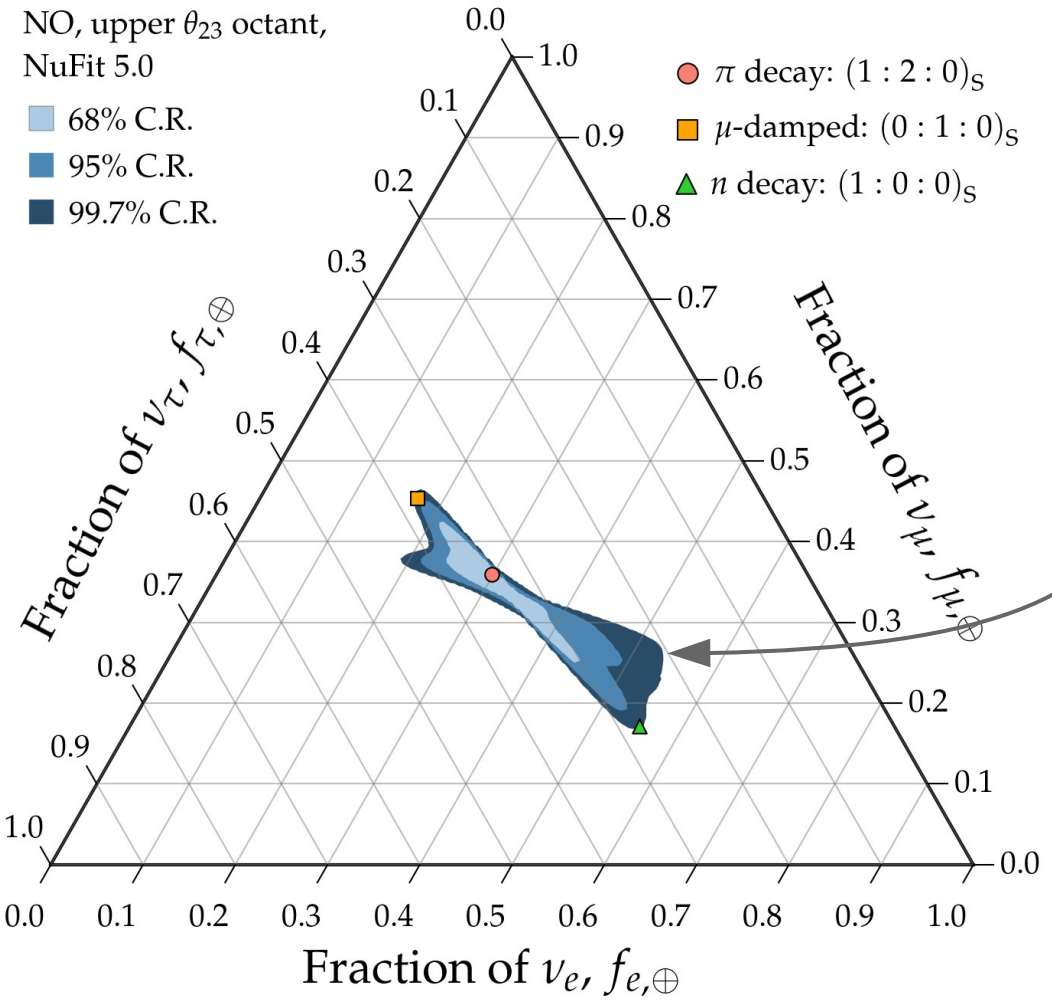

Varying over all possible flavor ratios at the source

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

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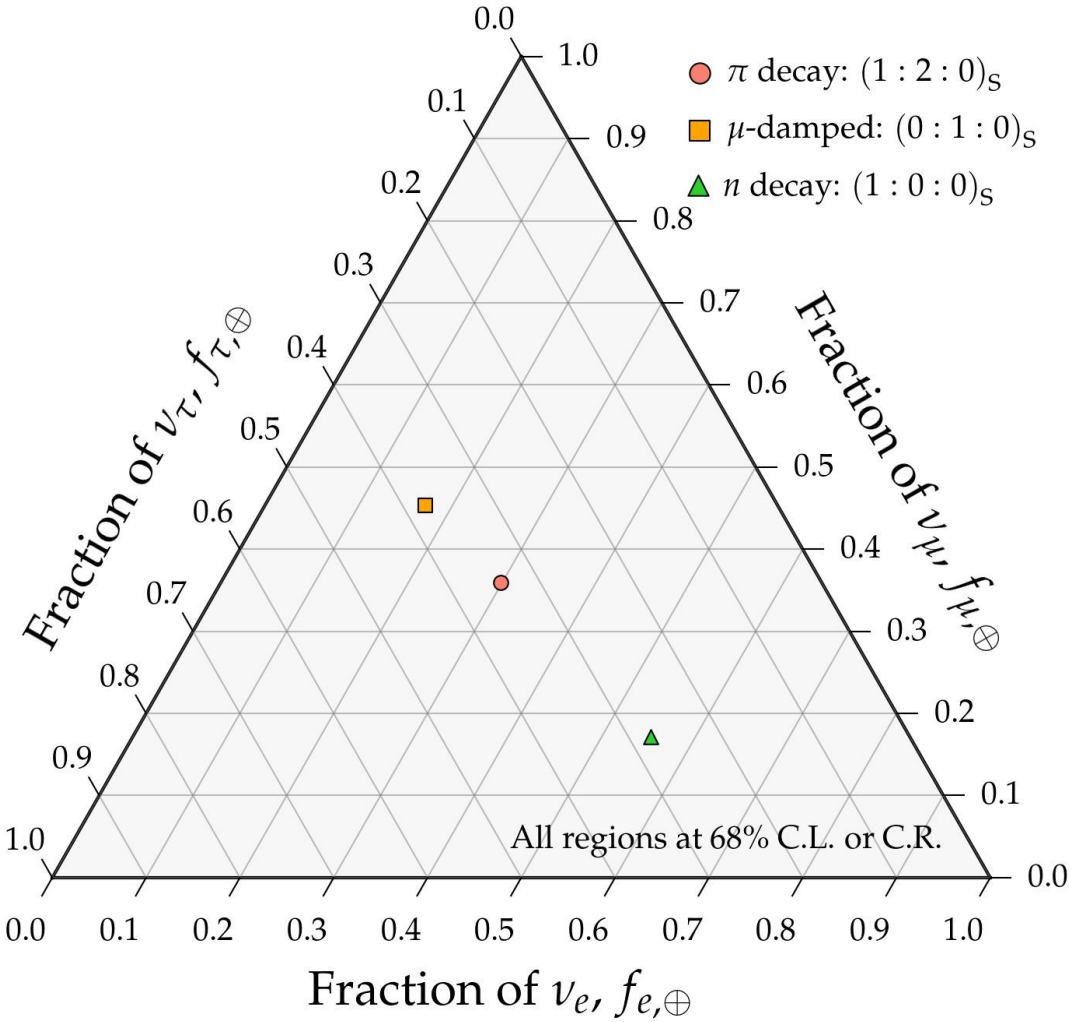
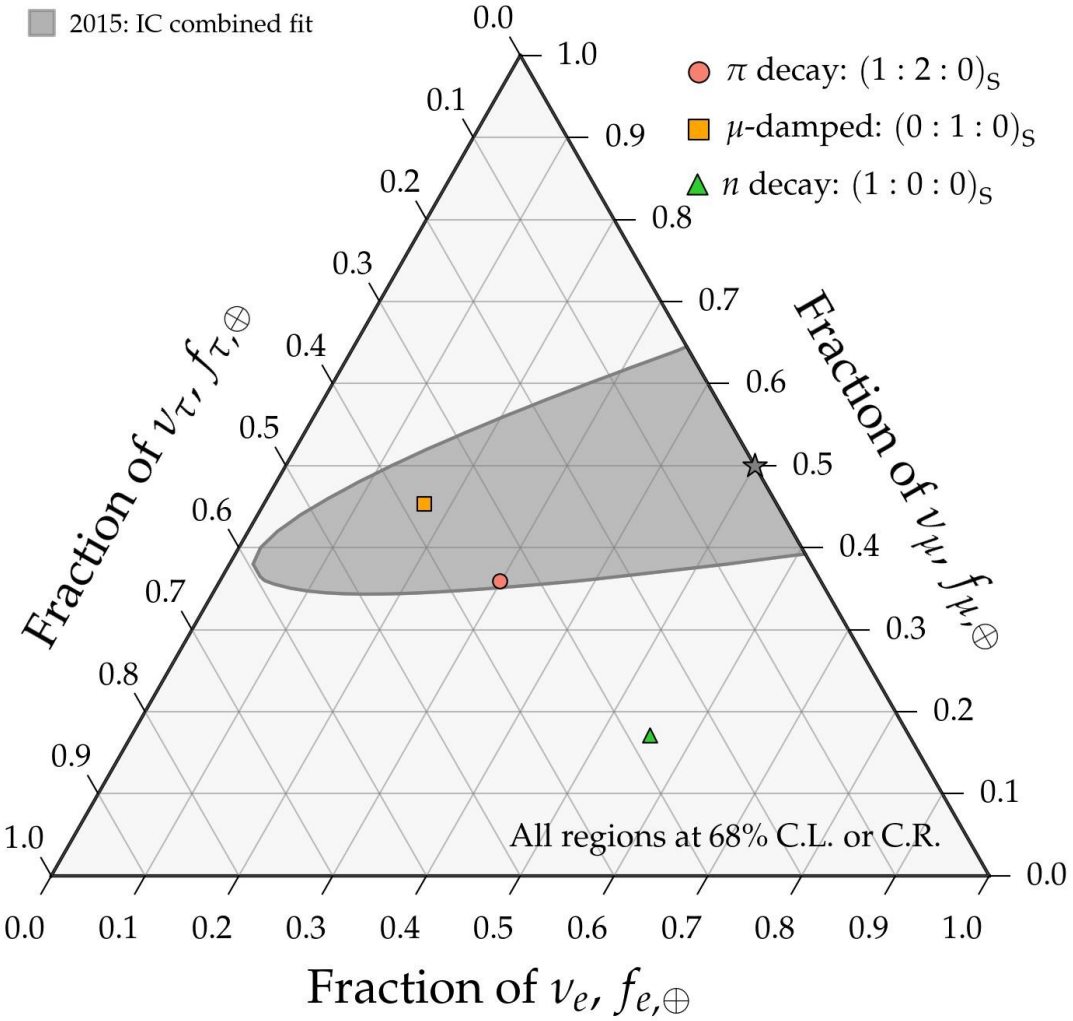
Measuring the flavor composition

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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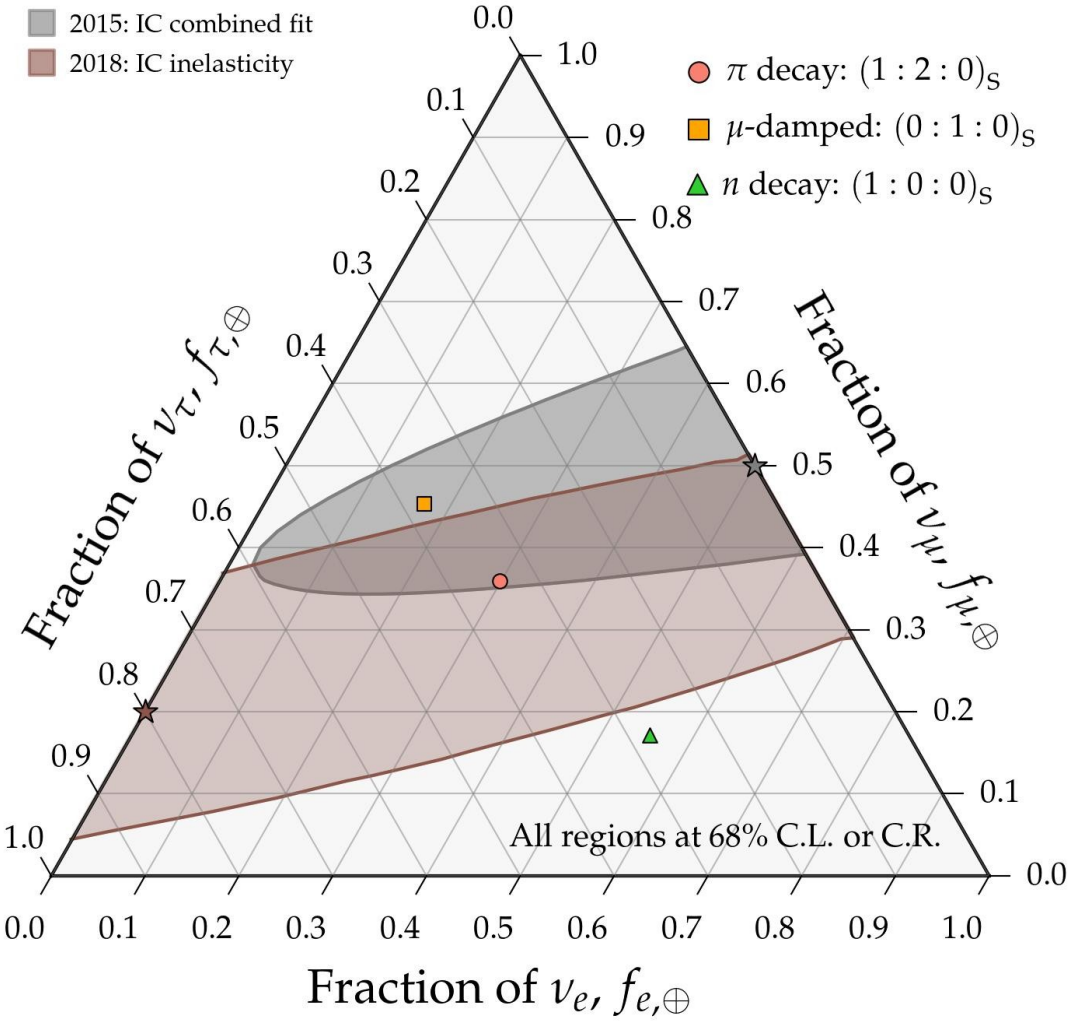

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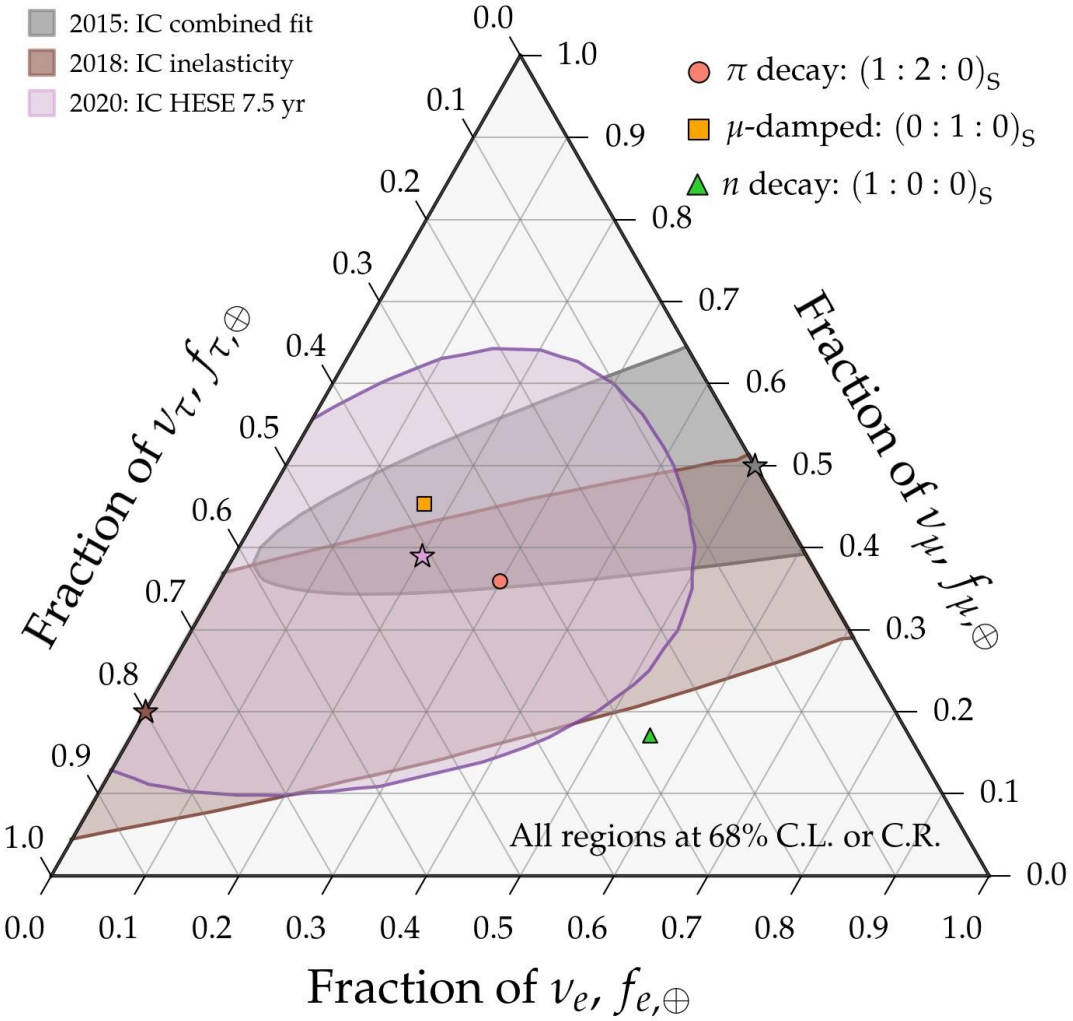

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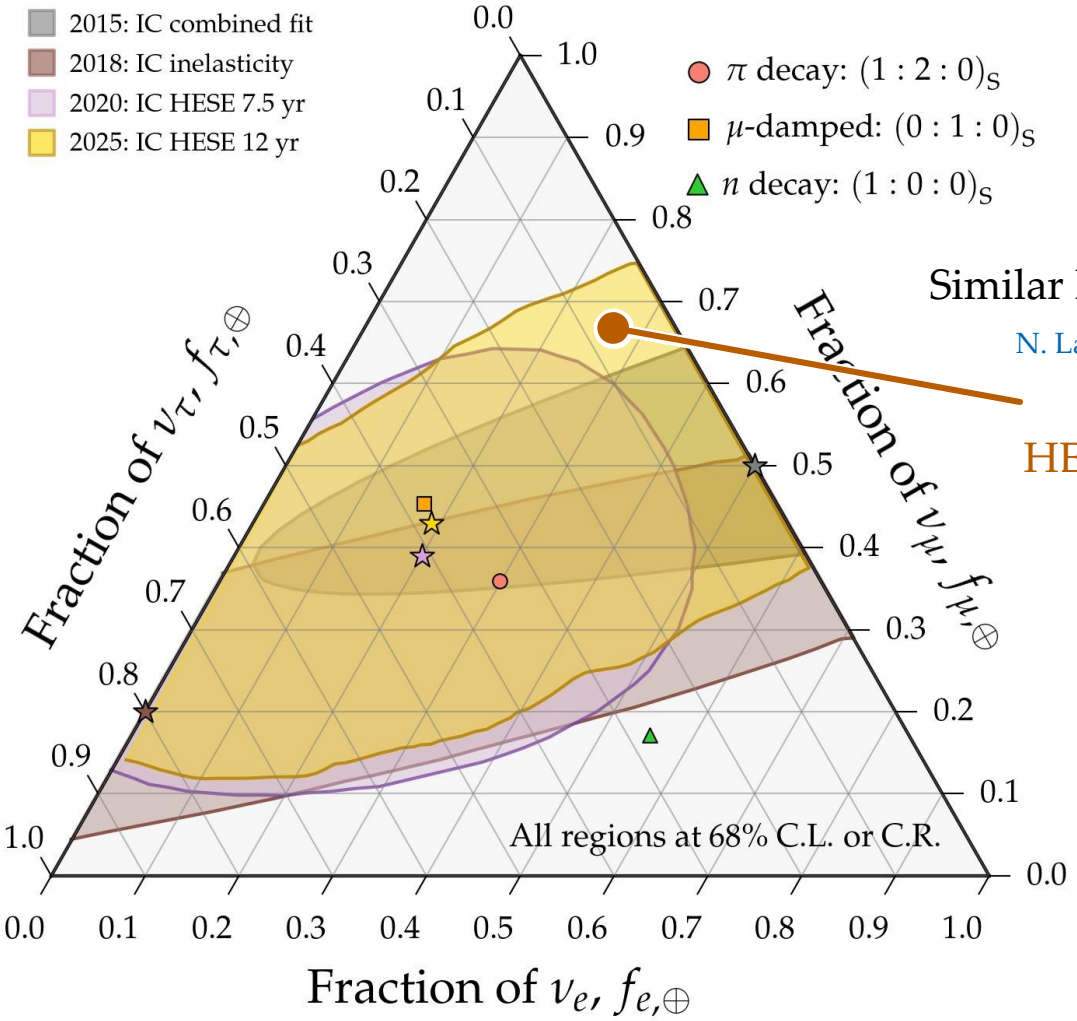


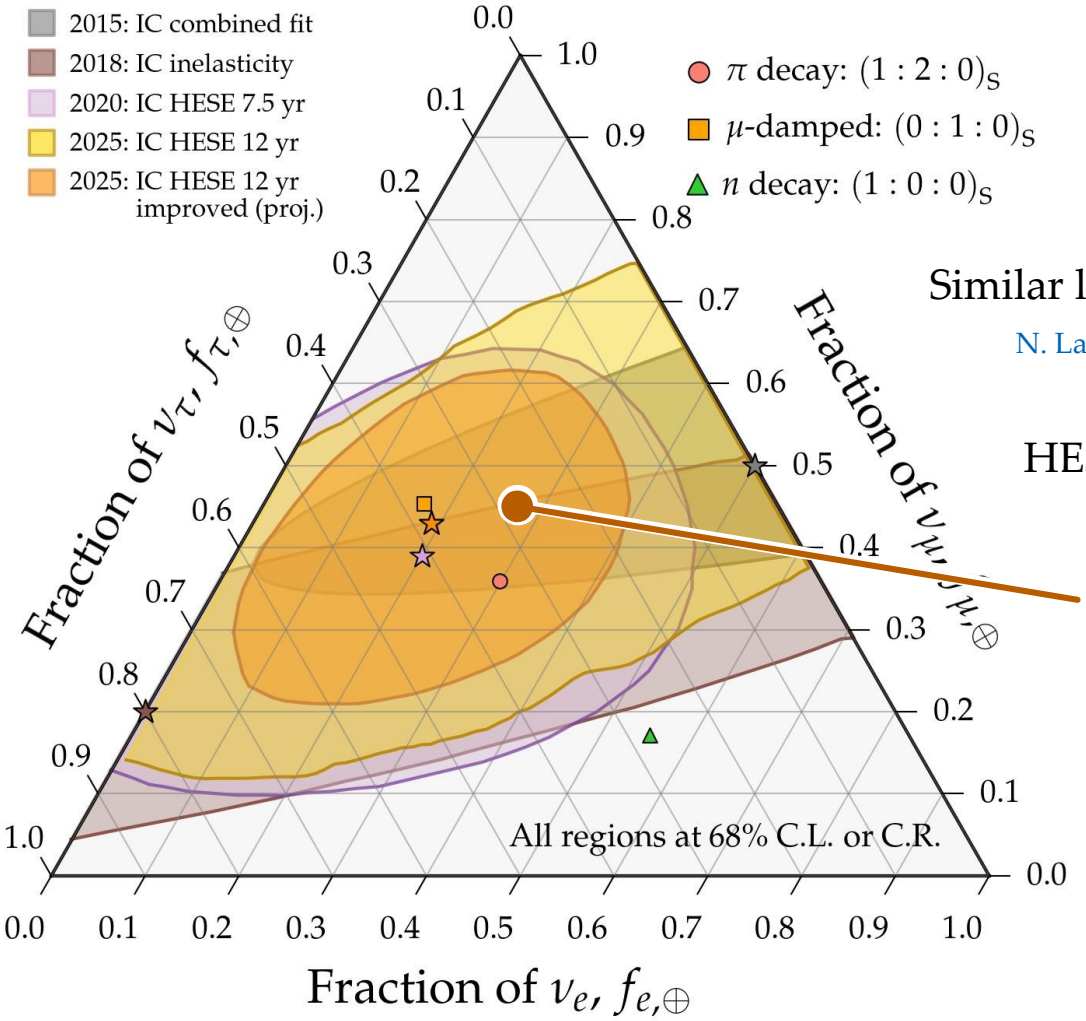
Similar likelihood as with 7.5 yr

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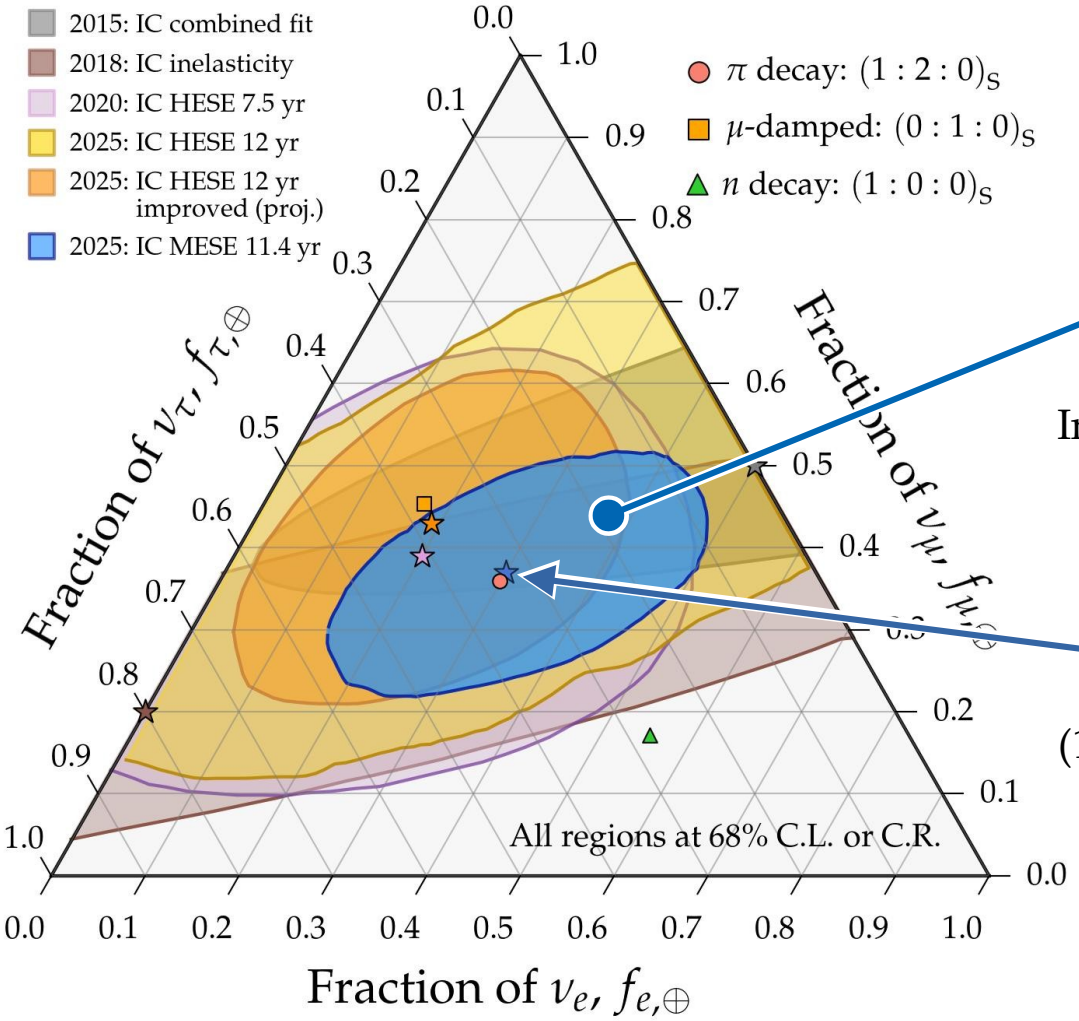
Improve via a neural network that uses the energy asymmetry of the two bangs and the direction

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.

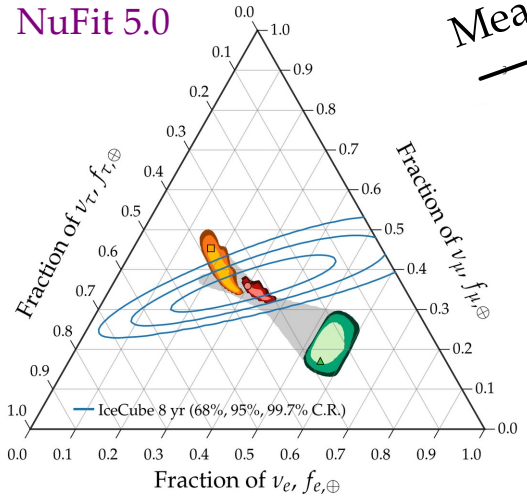
Best fit very close to nominal expectation of (1:1:1) from production via pion decay

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

How knowing the mixing parameters better helps

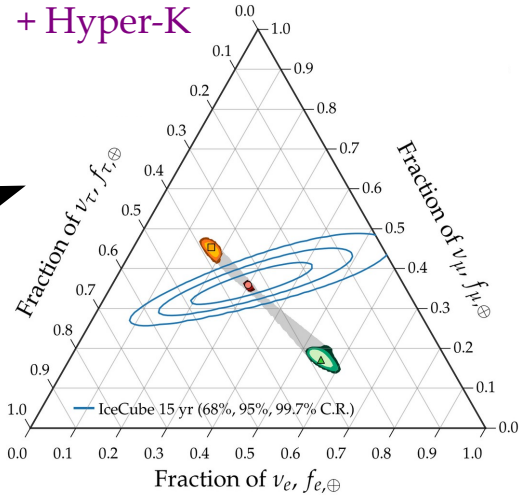
2020

NuFit 5.0

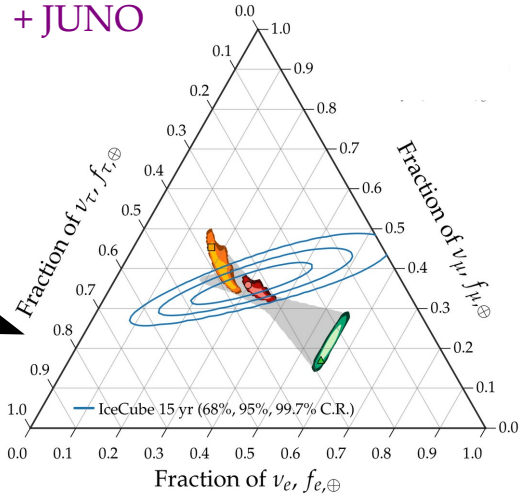


Measure θ_{23} better

+ Hyper-K



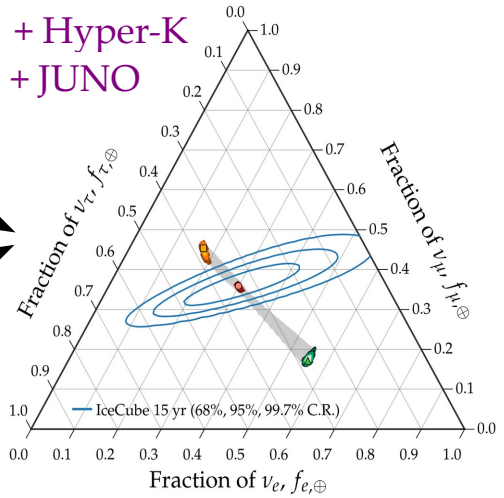
+ JUNO



Measure θ_{12} better

~2030

+ Hyper-K
+ JUNO



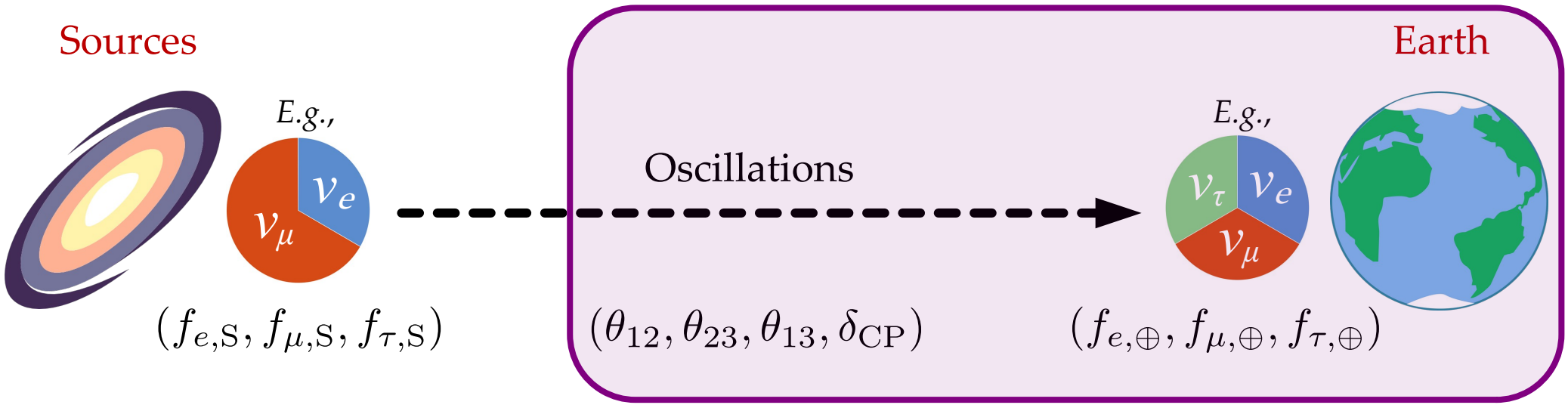
In our results:
JUNO + Hyper-K + DUNE

Marginal improvement til 2040

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

Back to the sources

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

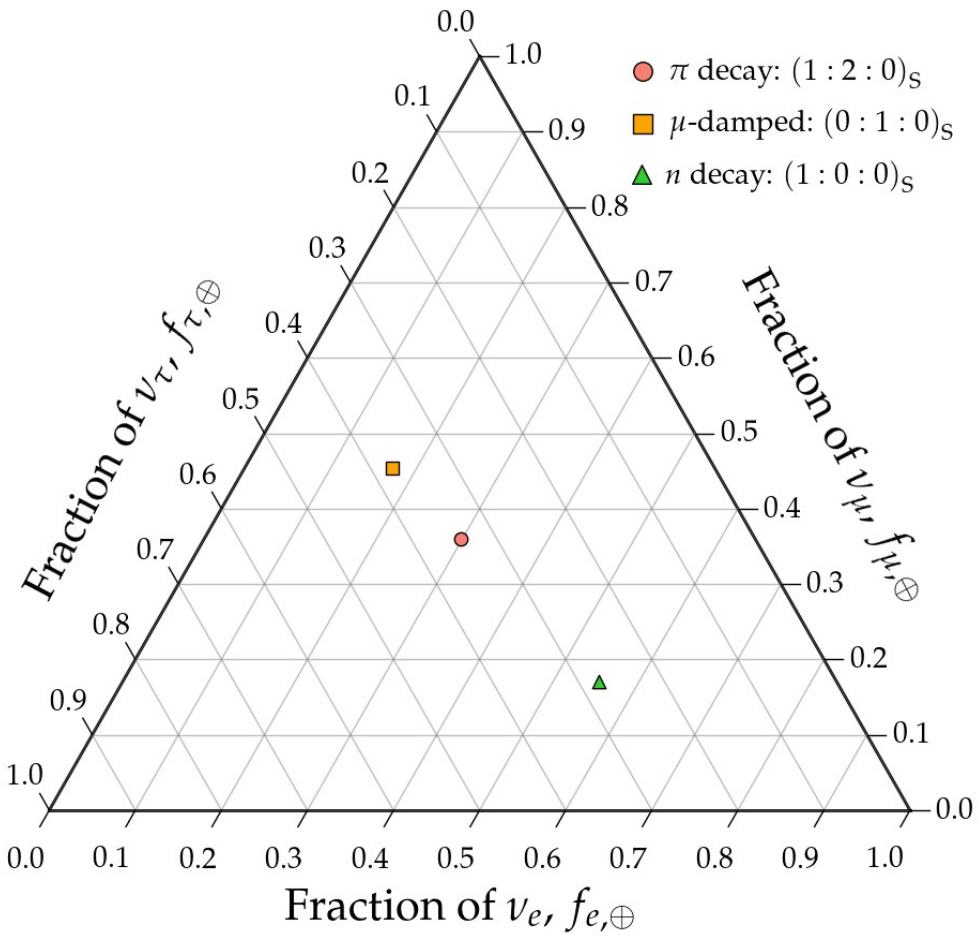


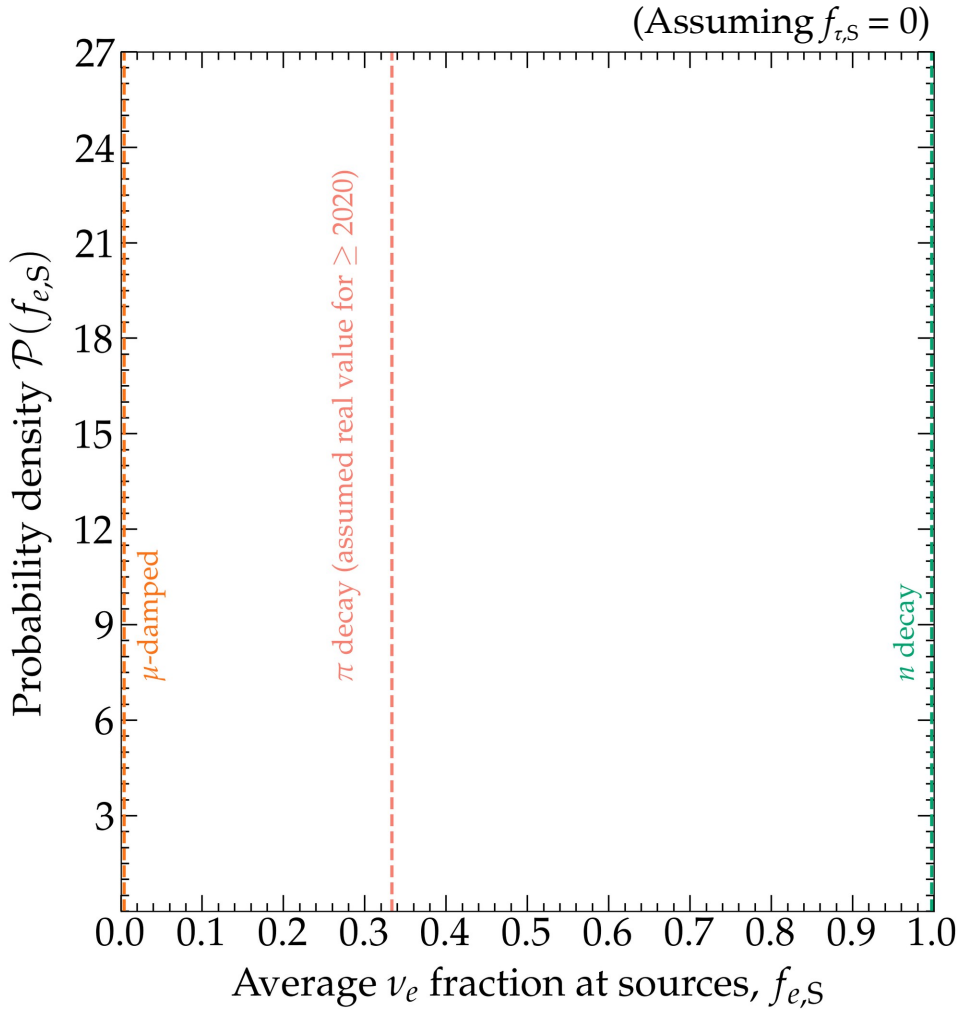
From Earth to sources: we let the data teach us about $f_{\alpha,\mathrm{S}}$

Inferring the flavor composition at the sources

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
MB & Ahlers, *PRL* 2019

Inferring the flavor composition at the sources





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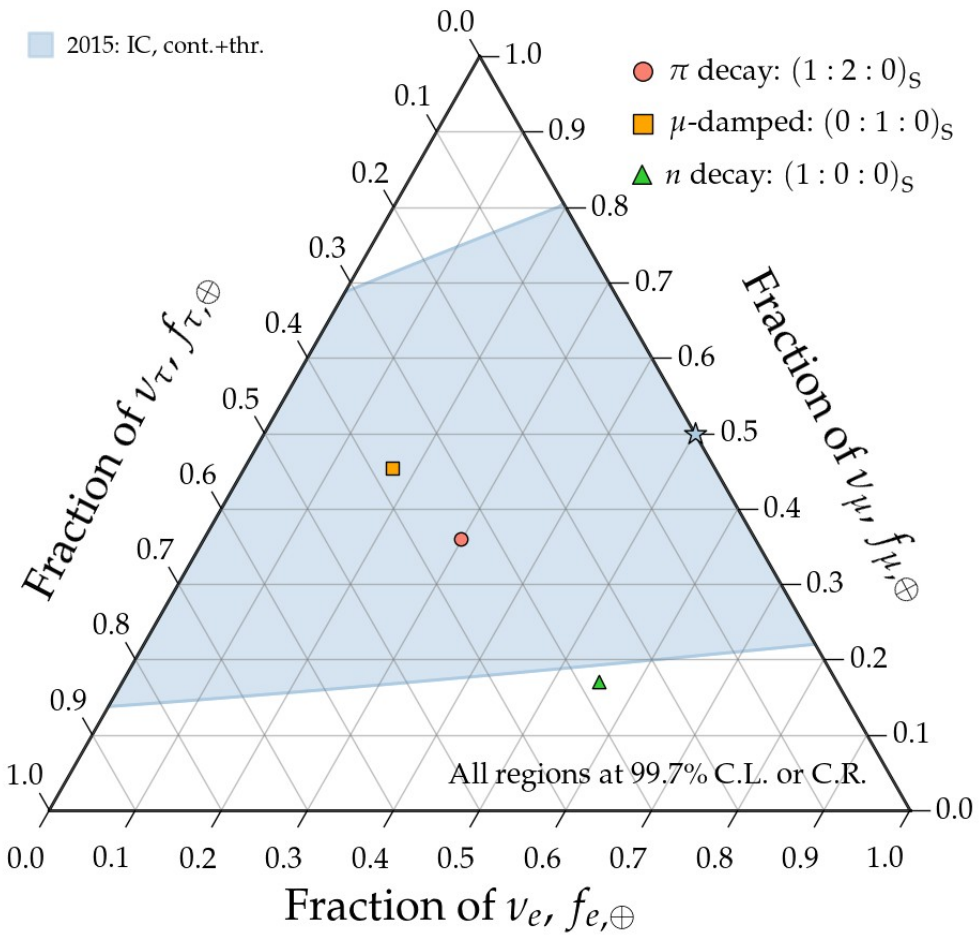

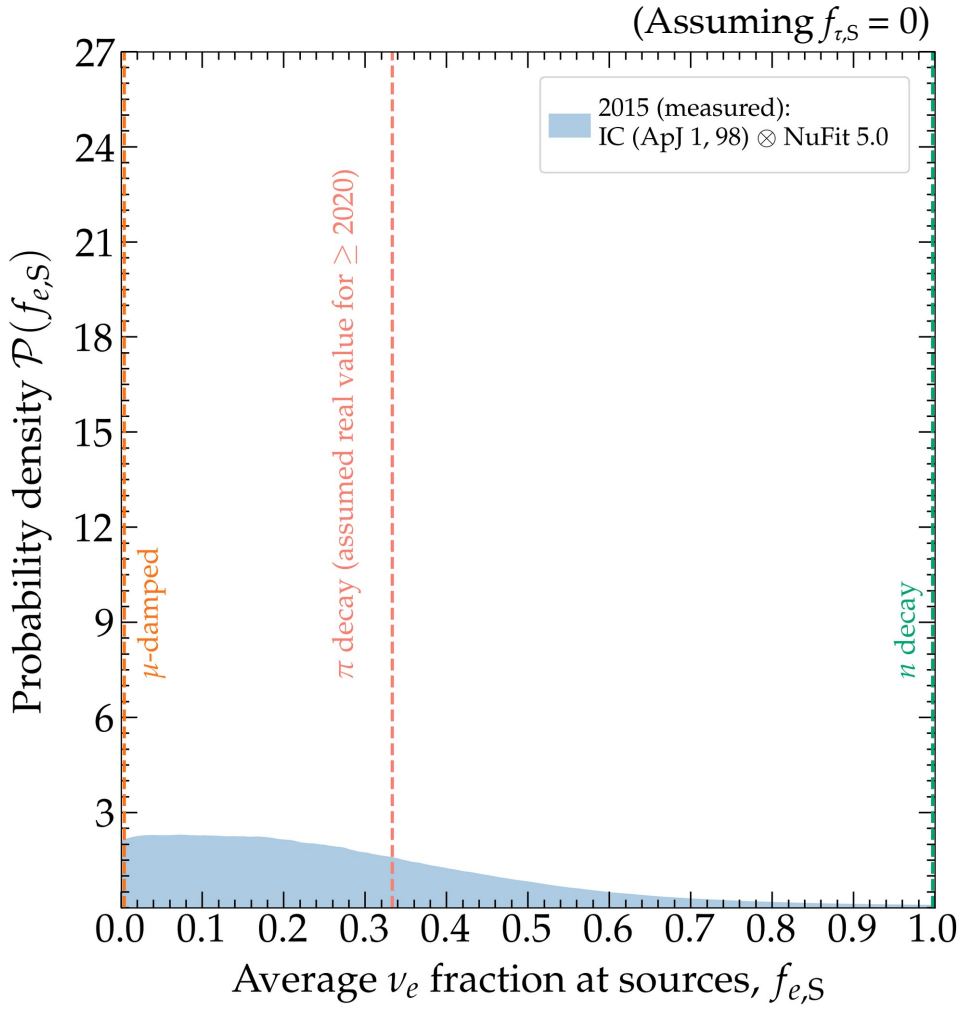

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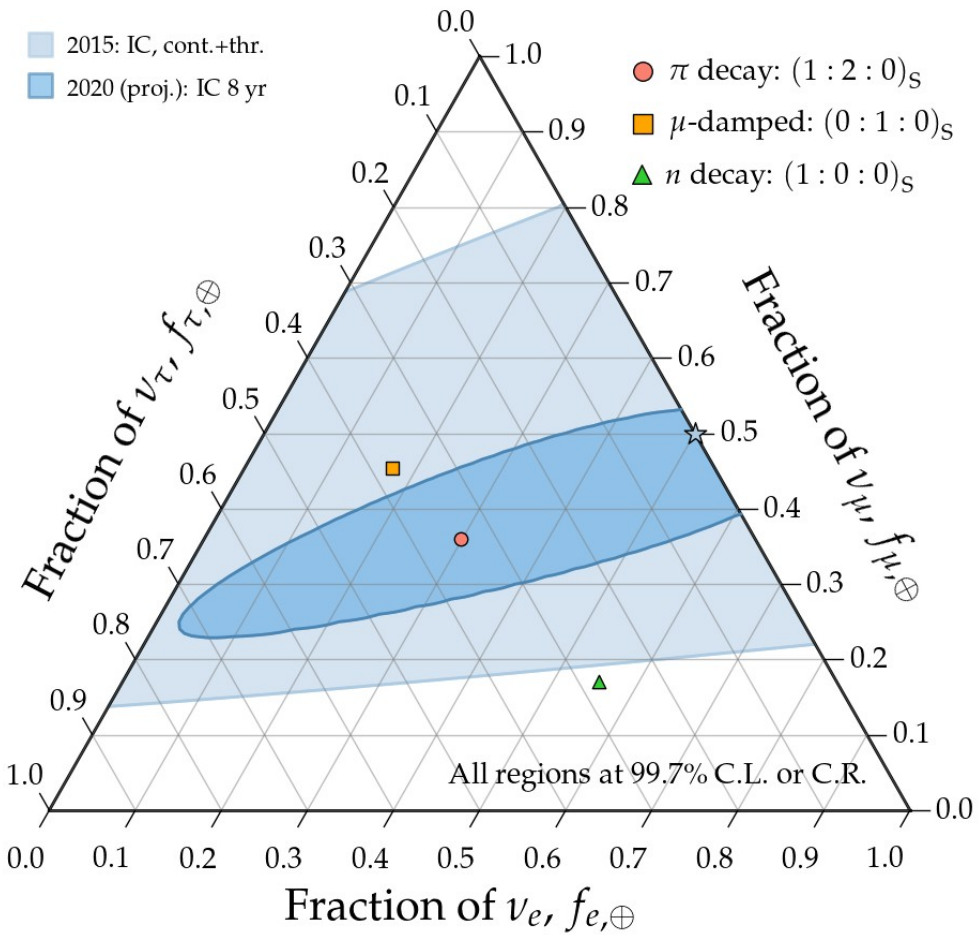

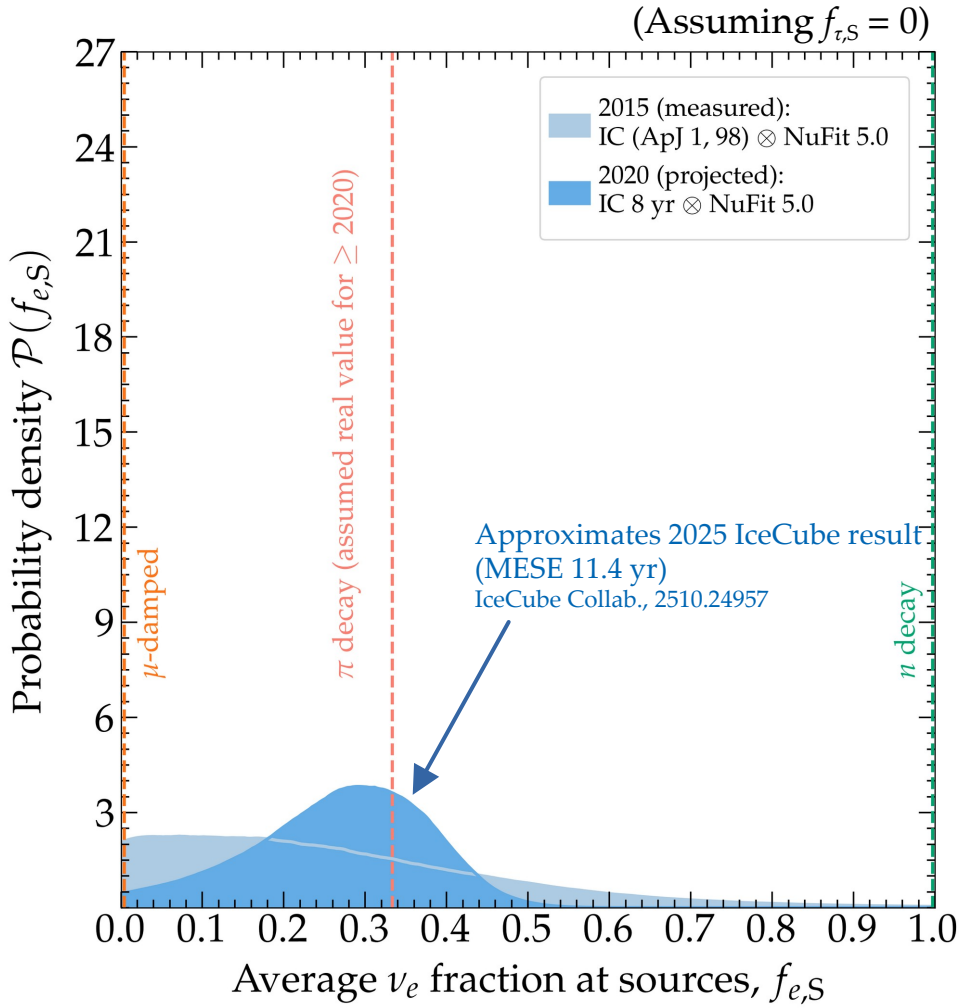

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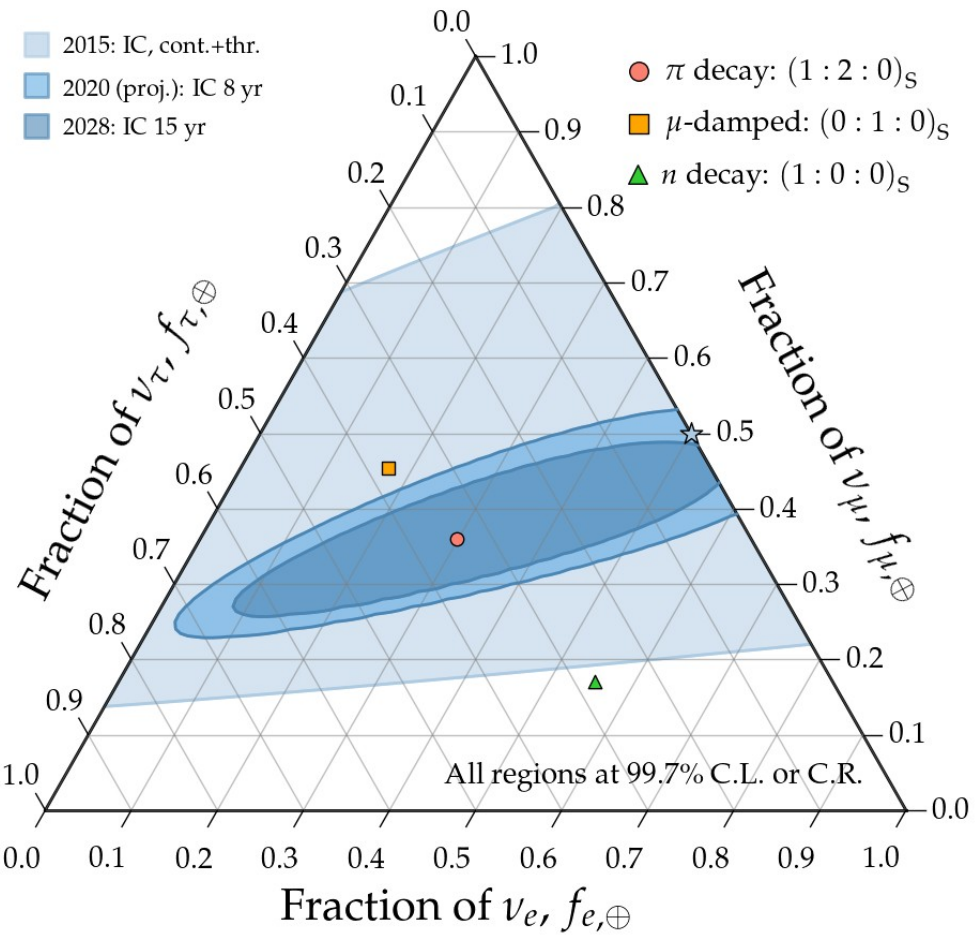

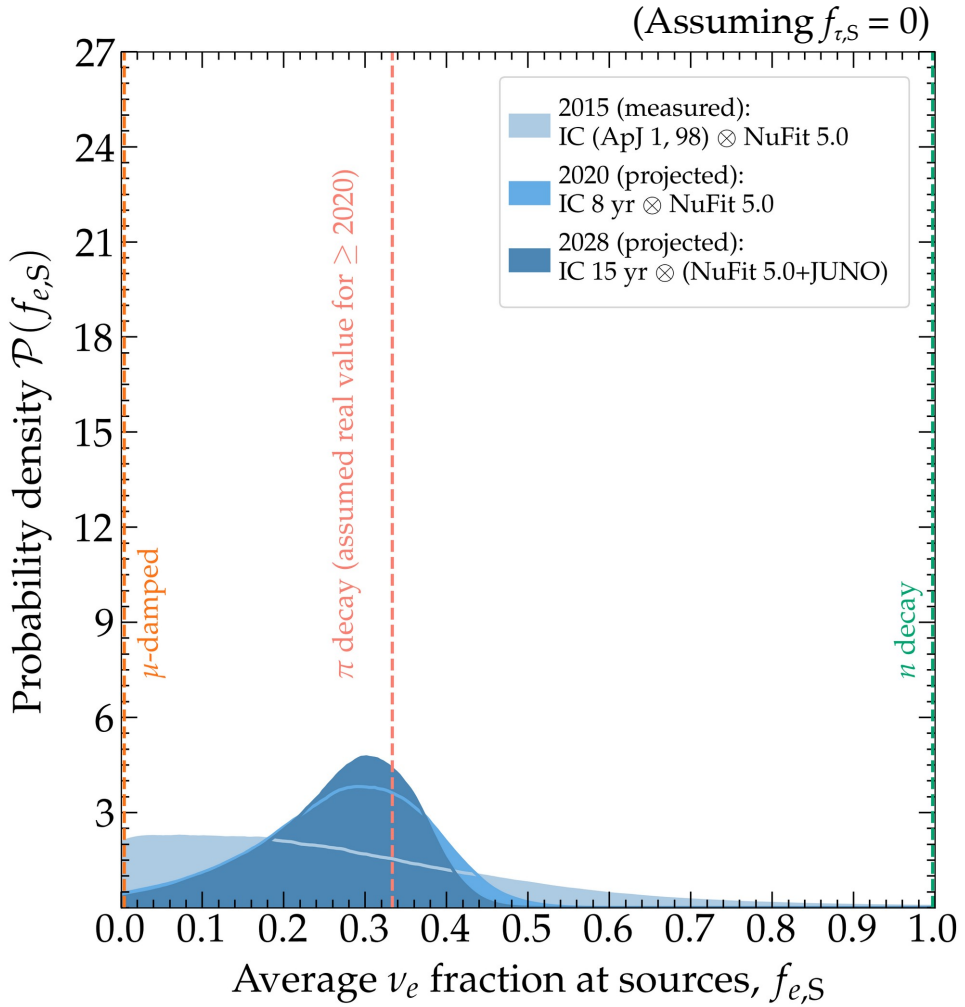

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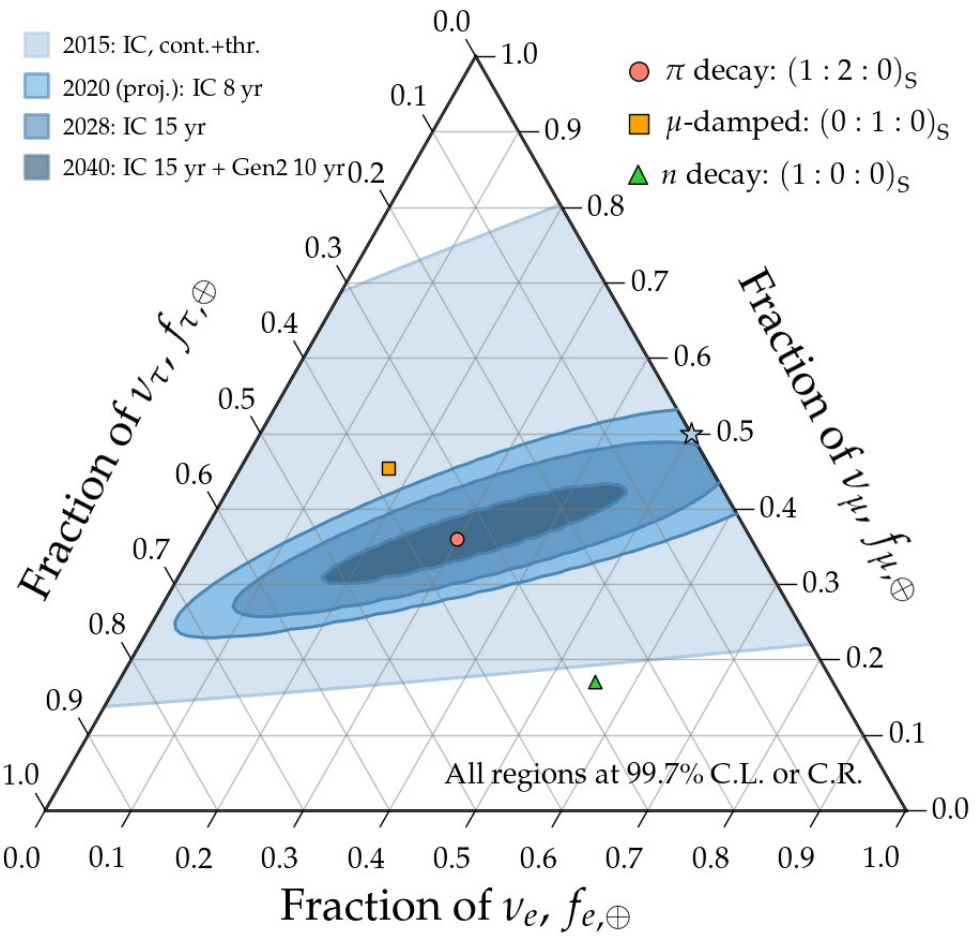

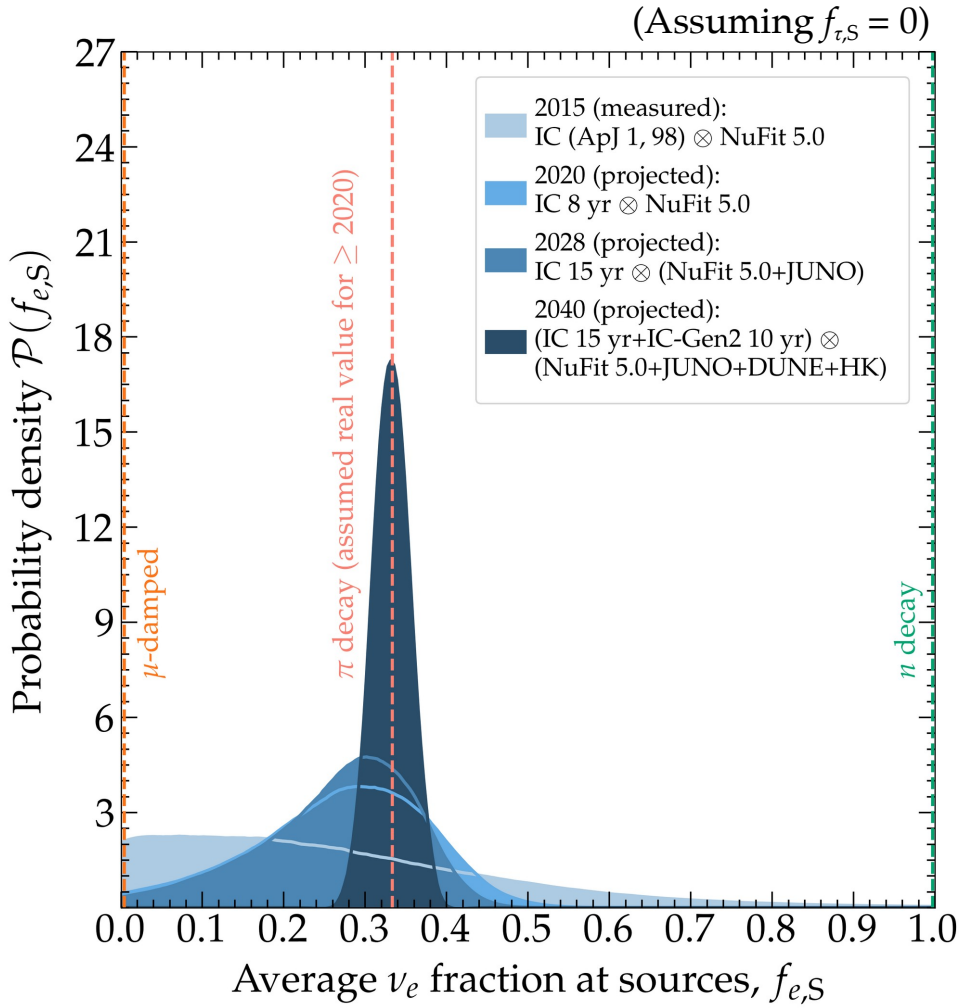

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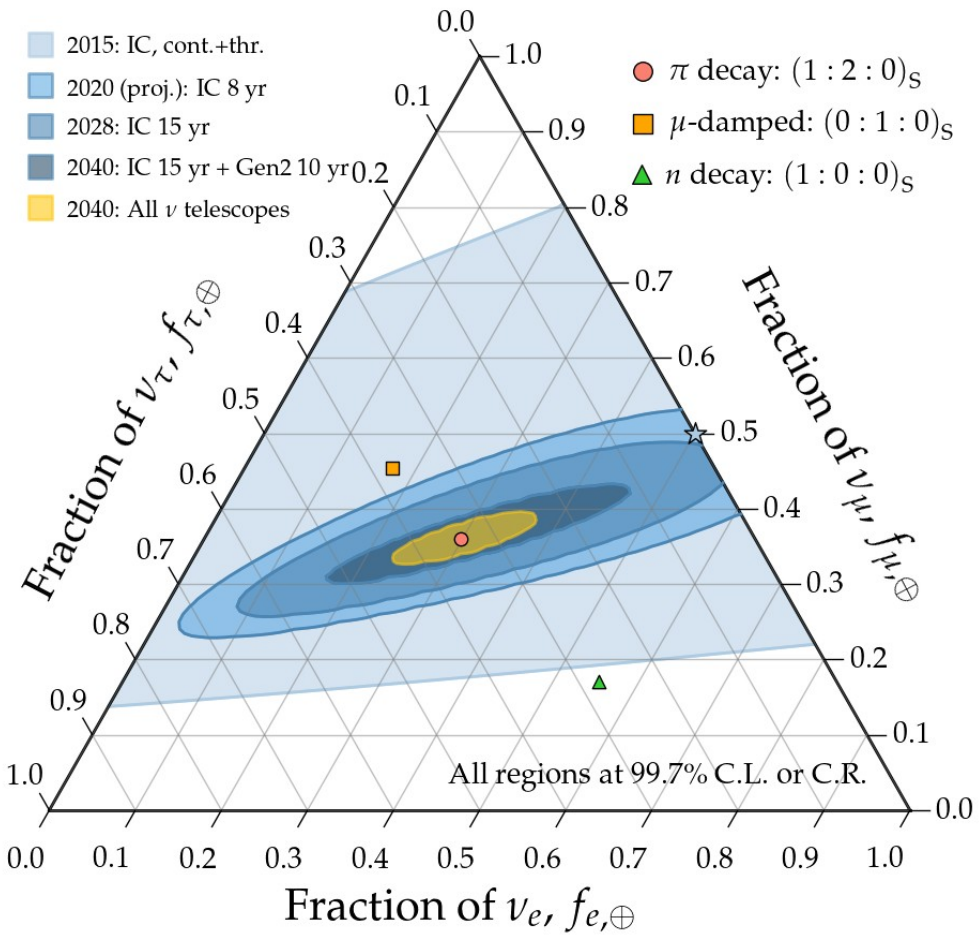

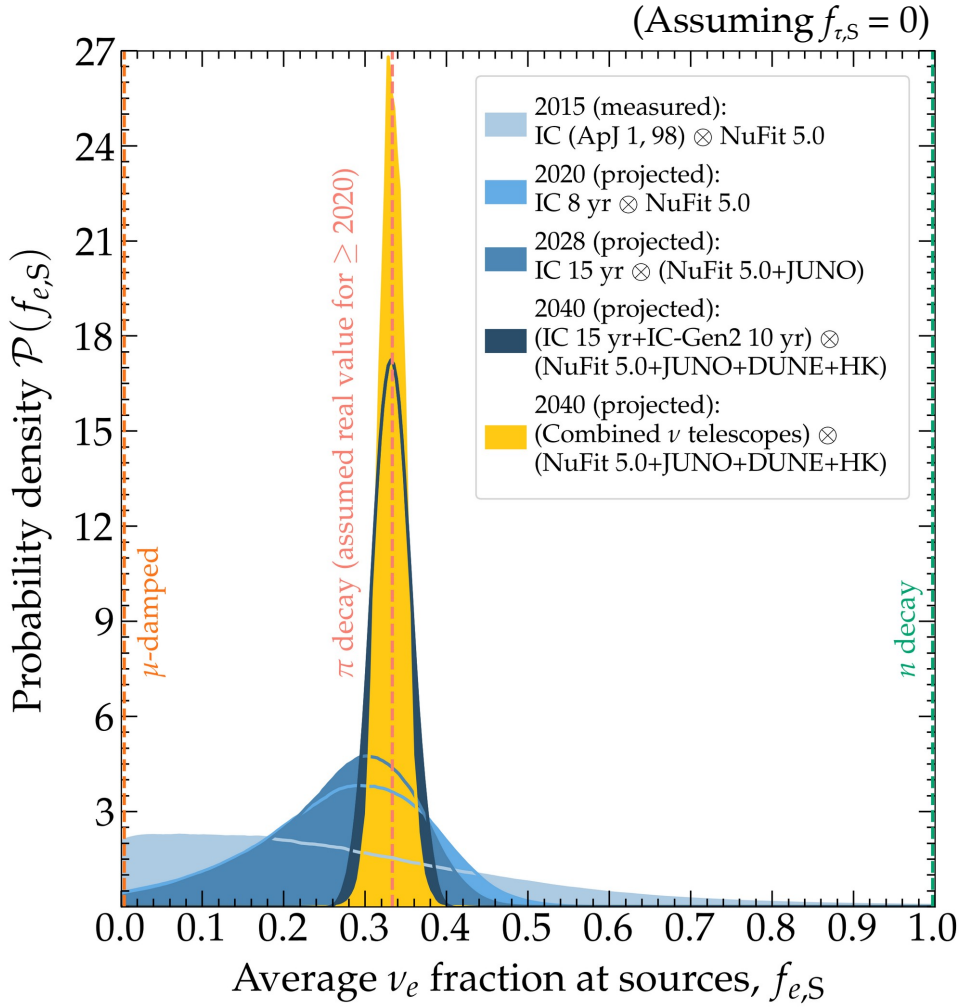

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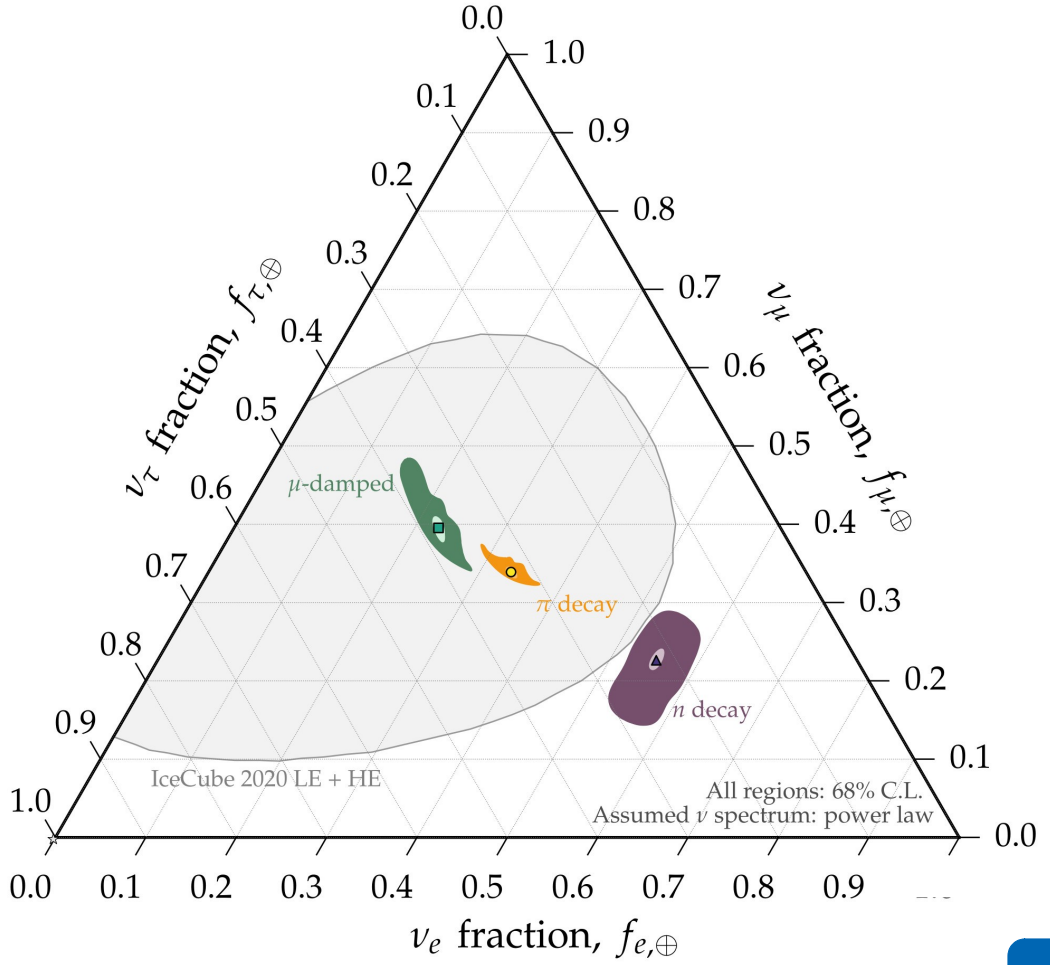
MB & Ahlers, *PRL* 2019

Energy-dependent flavor composition

Flavor composition: measuring the energy dependence



Liu, Fiorillo, Argüelles, **MB**, Song, Vincent, *PRD* 2025

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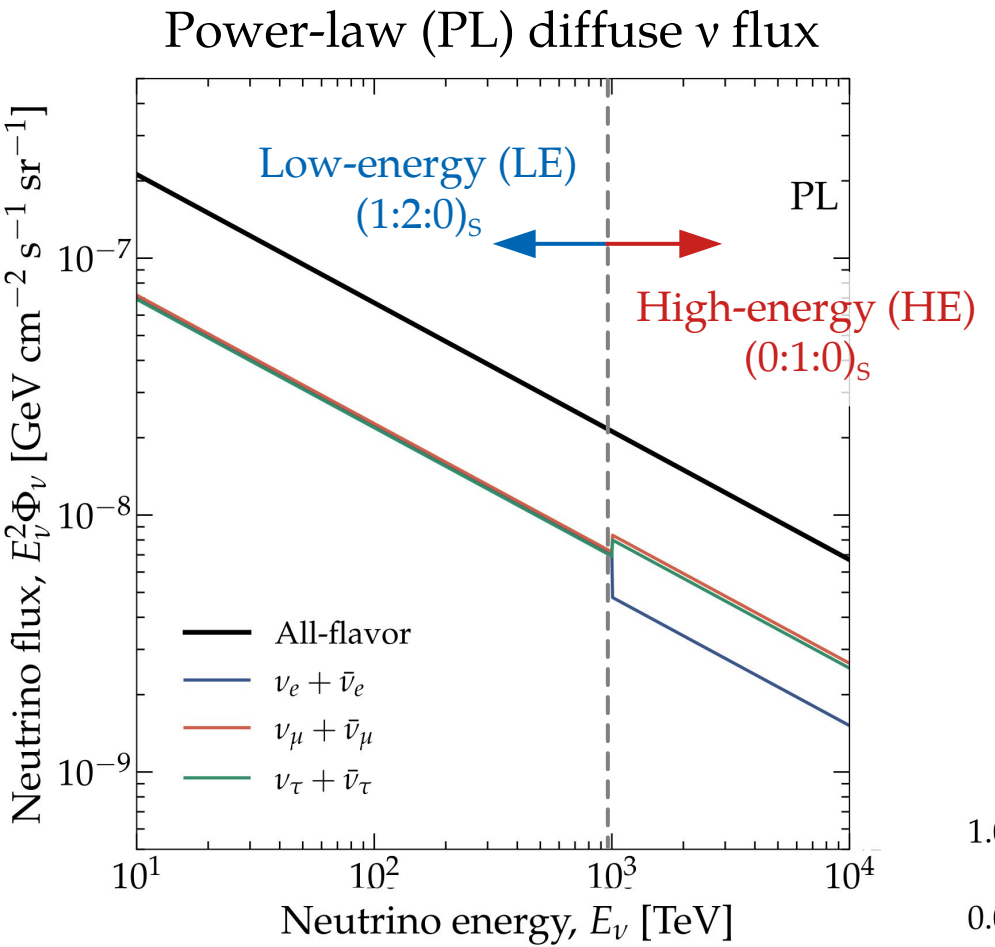

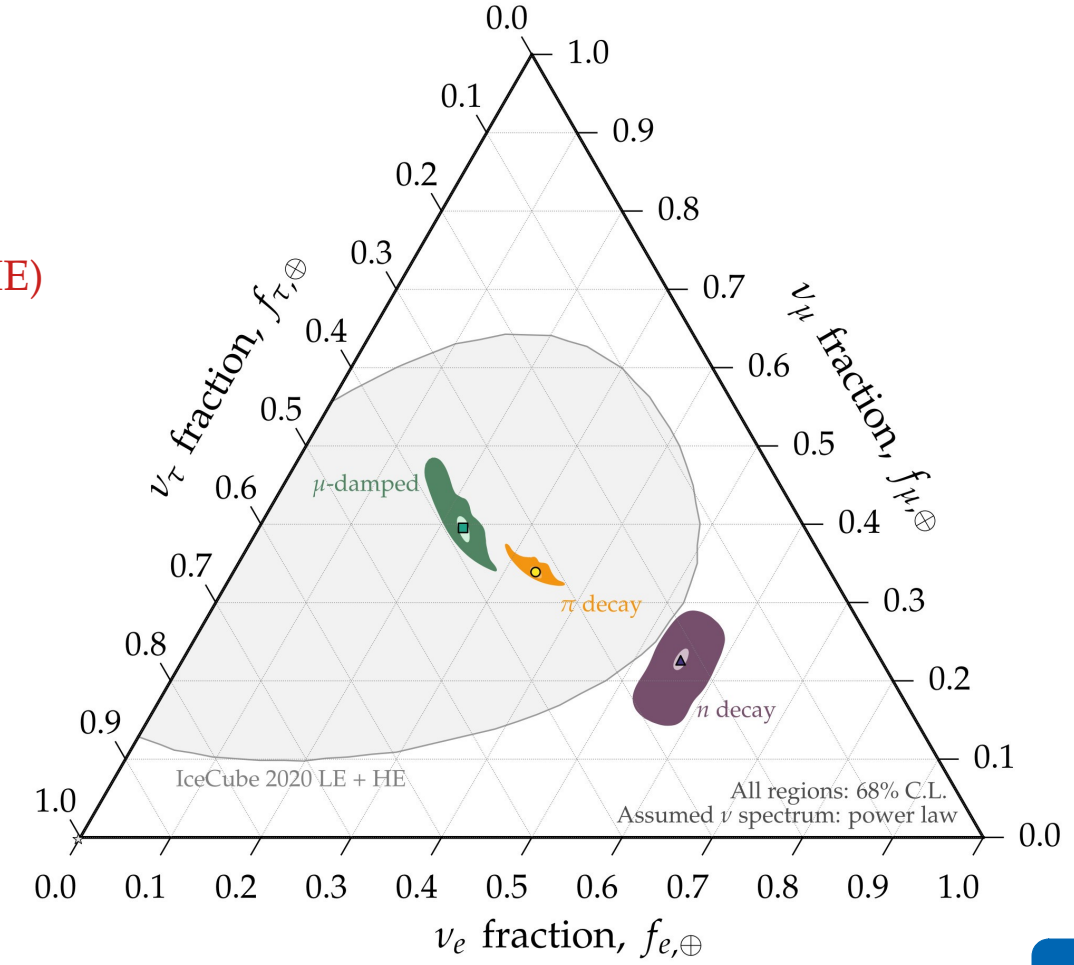

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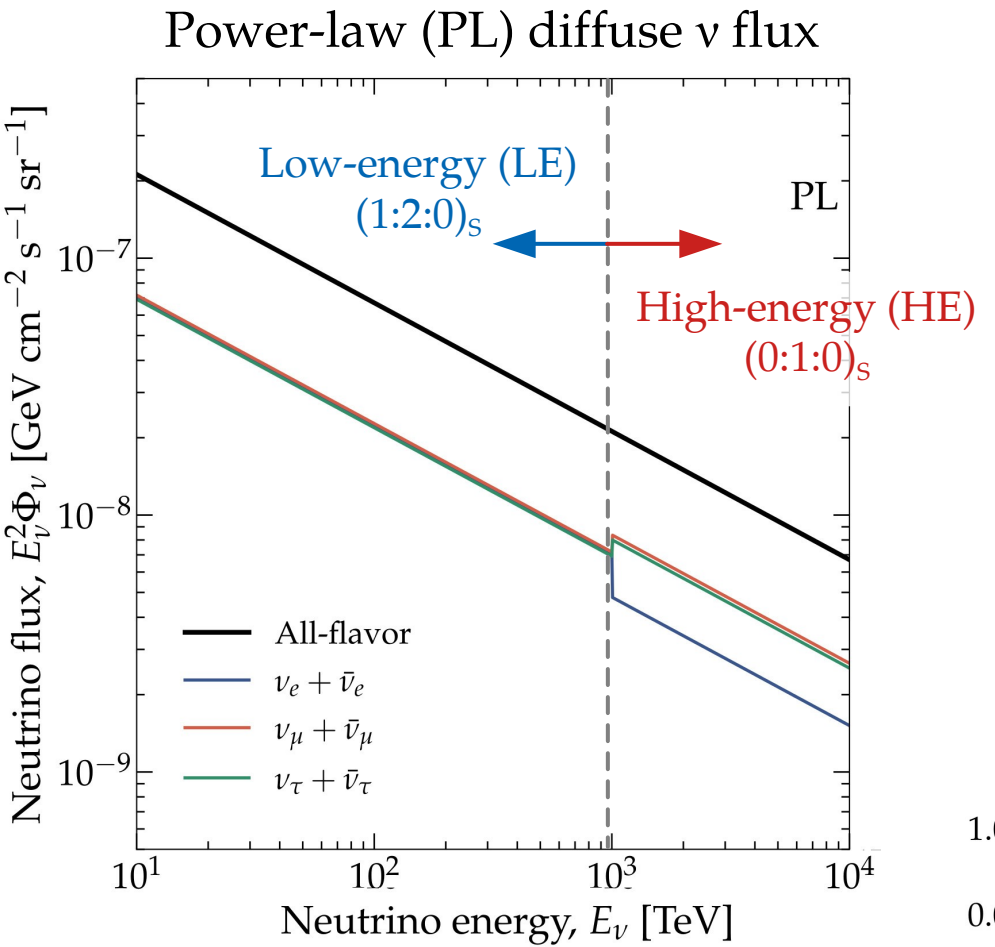
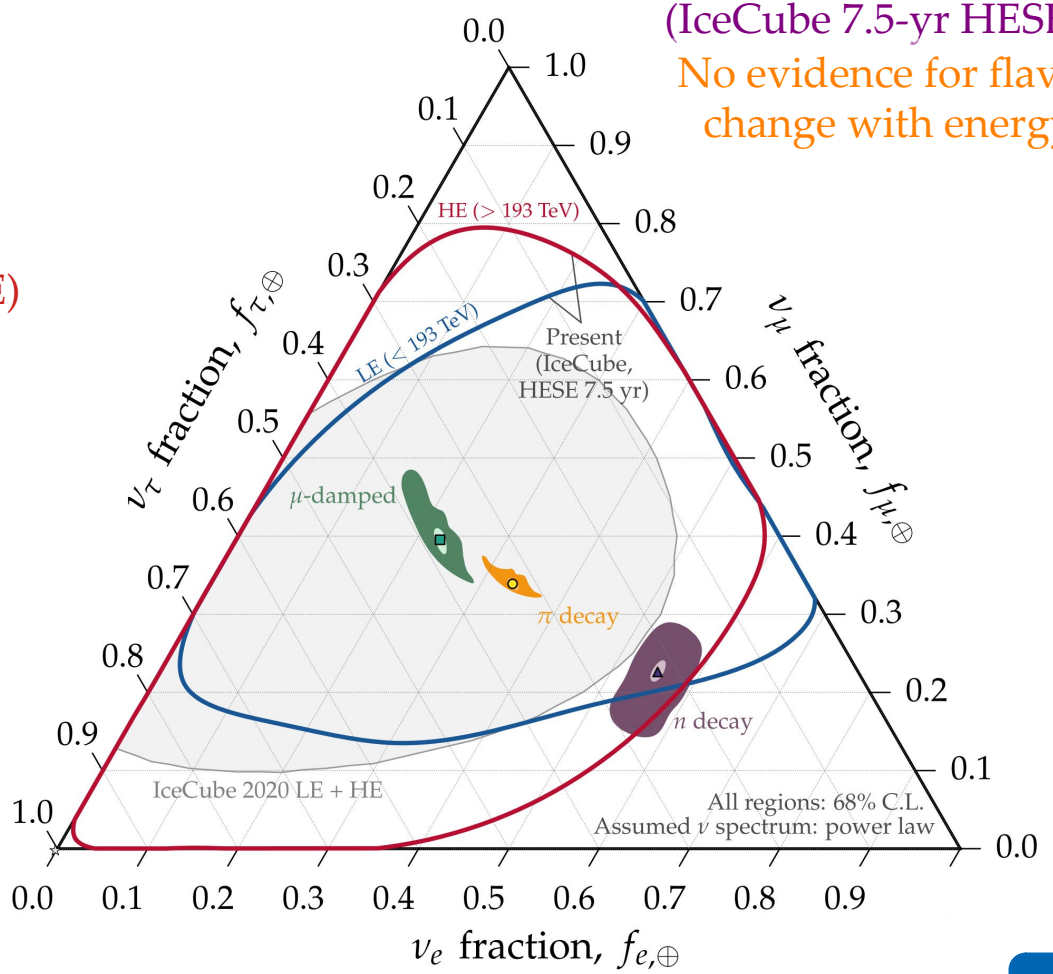


Today
(IceCube 7.5-yr HESE):
No evidence for flavor change with energy



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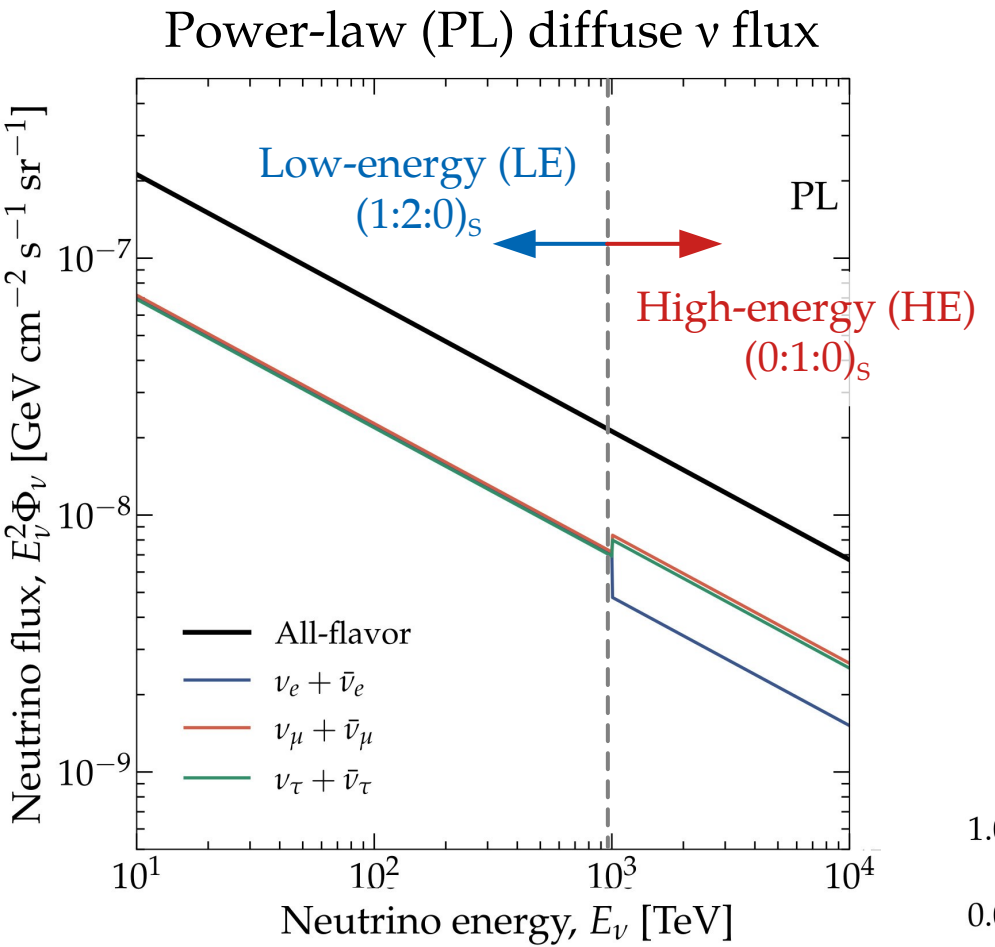
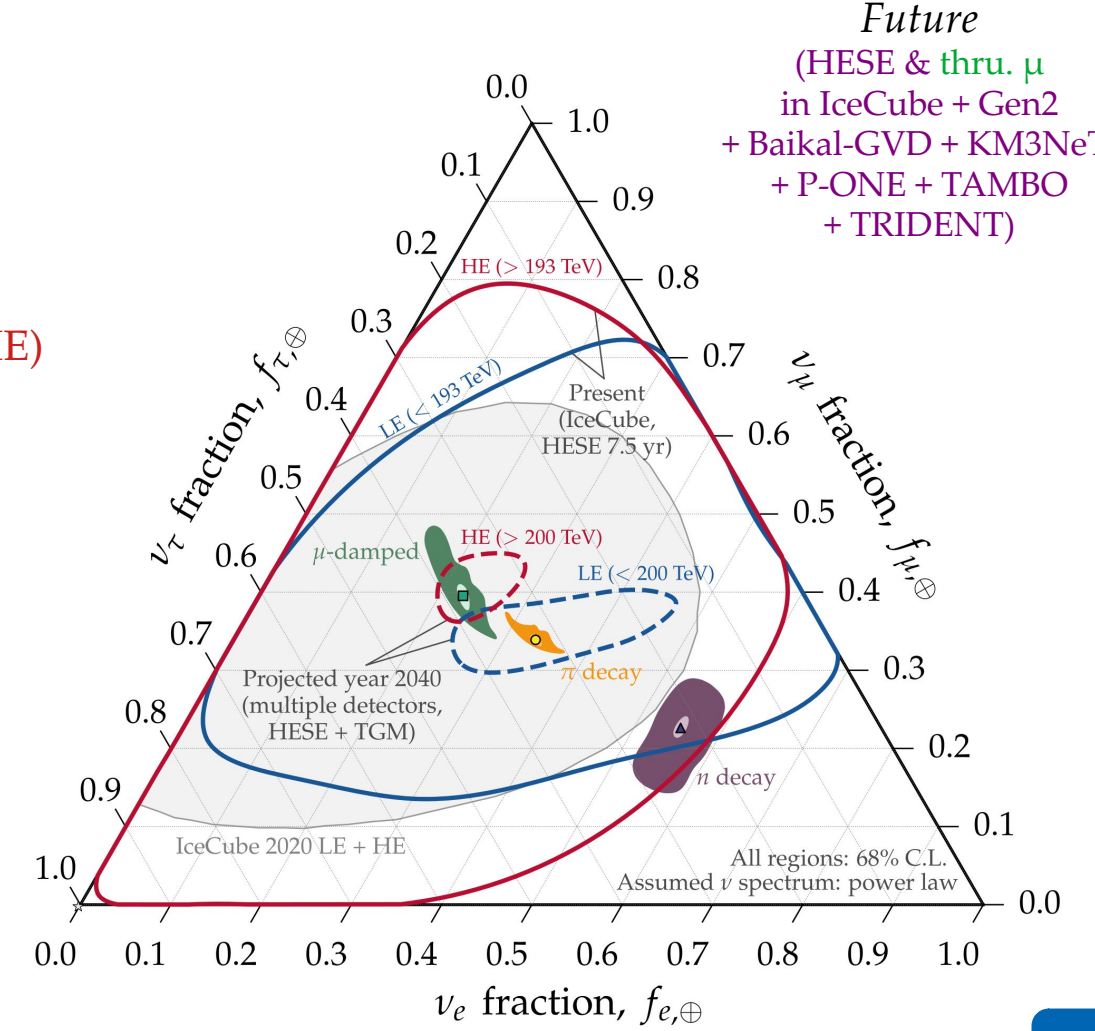
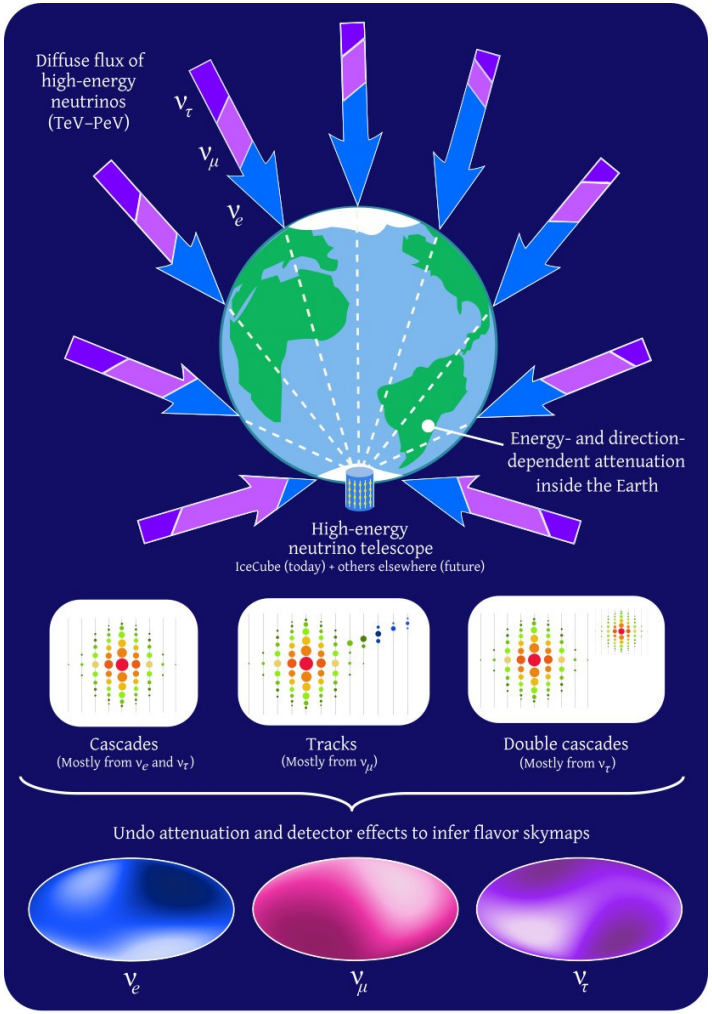




Liu, Fiorillo, Argüelles, **MB**, Song, Vincent, *PRD* 2025

Direction-dependent flavor composition

Flavor anisotropy in the high-energy neutrino sky



Does the high-energy sky shine equally brightly
In neutrinos of all flavors?

Telalovic, **MB**, *JCAP* 2025

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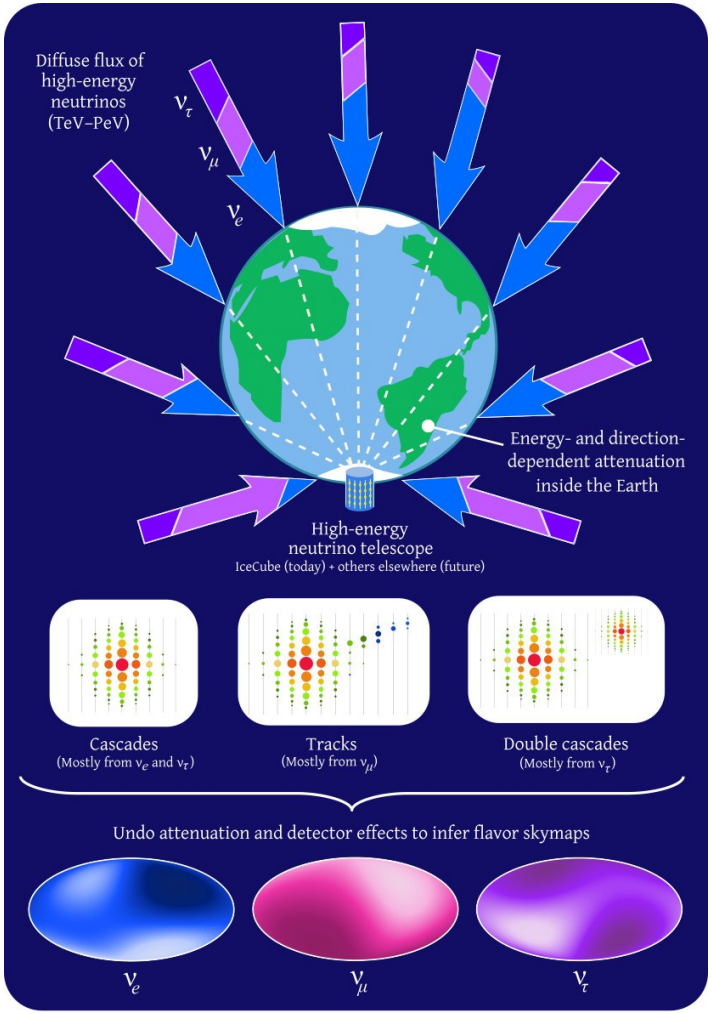

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From the angular distribution of detected events in neutrino telescopes
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Telalovic, **MB**, *JCAP* 2025

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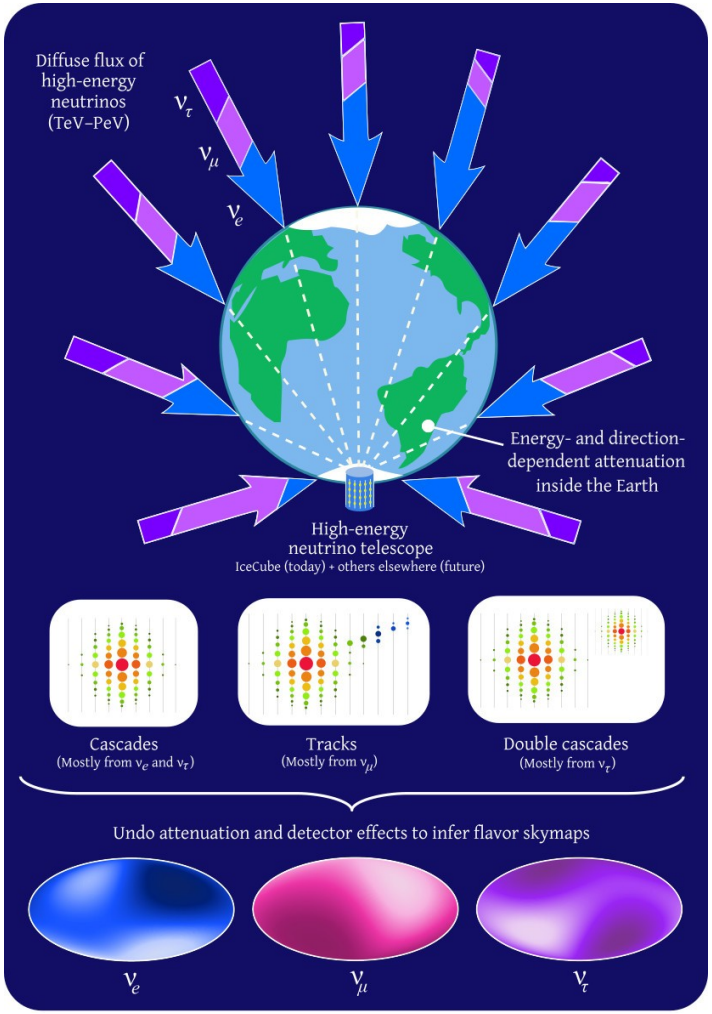

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… we infer the directional dependence of the diffuse fluxes of ν_e, ν_μ, ν_τ

Telalovic, **MB**, *JCAP* 2025

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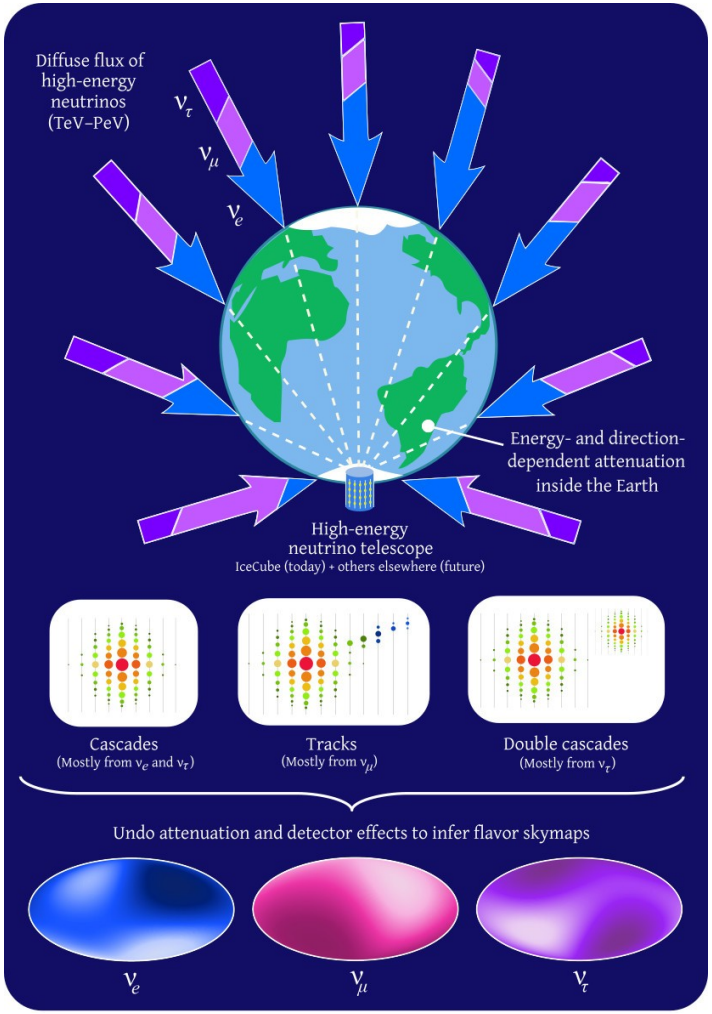

Does the high-energy sky shine equally brightly In neutrinos of all flavors?

From the angular distribution of detected events in neutrino telescopes (HESE cascades, tracks, double cascades) …

How? Undo detection effects (use public IceCube HESE Monte Carlo)

… we infer the directional dependence of the diffuse fluxes of ν_e, ν_μ, ν_τ

Telalovic, **MB**, *JCAP* 2025

Directional high-energy astrophysical neutrino flavor composition: IceCube HESE (7.5 yr)

Real, public data

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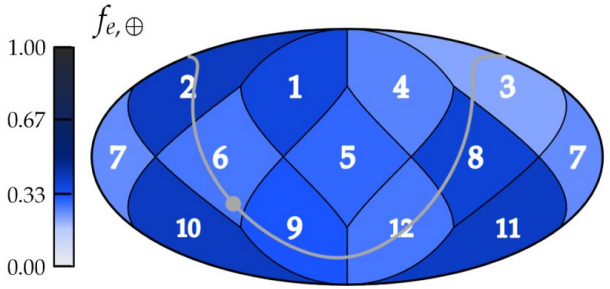

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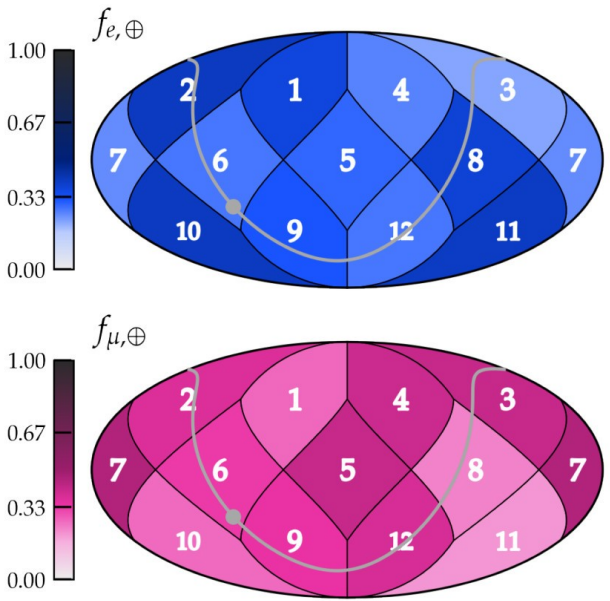

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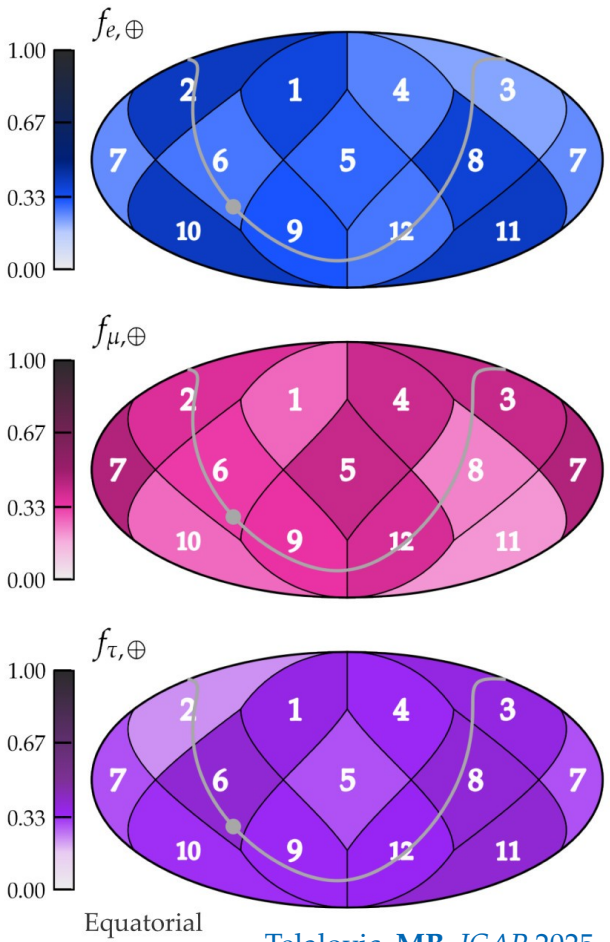

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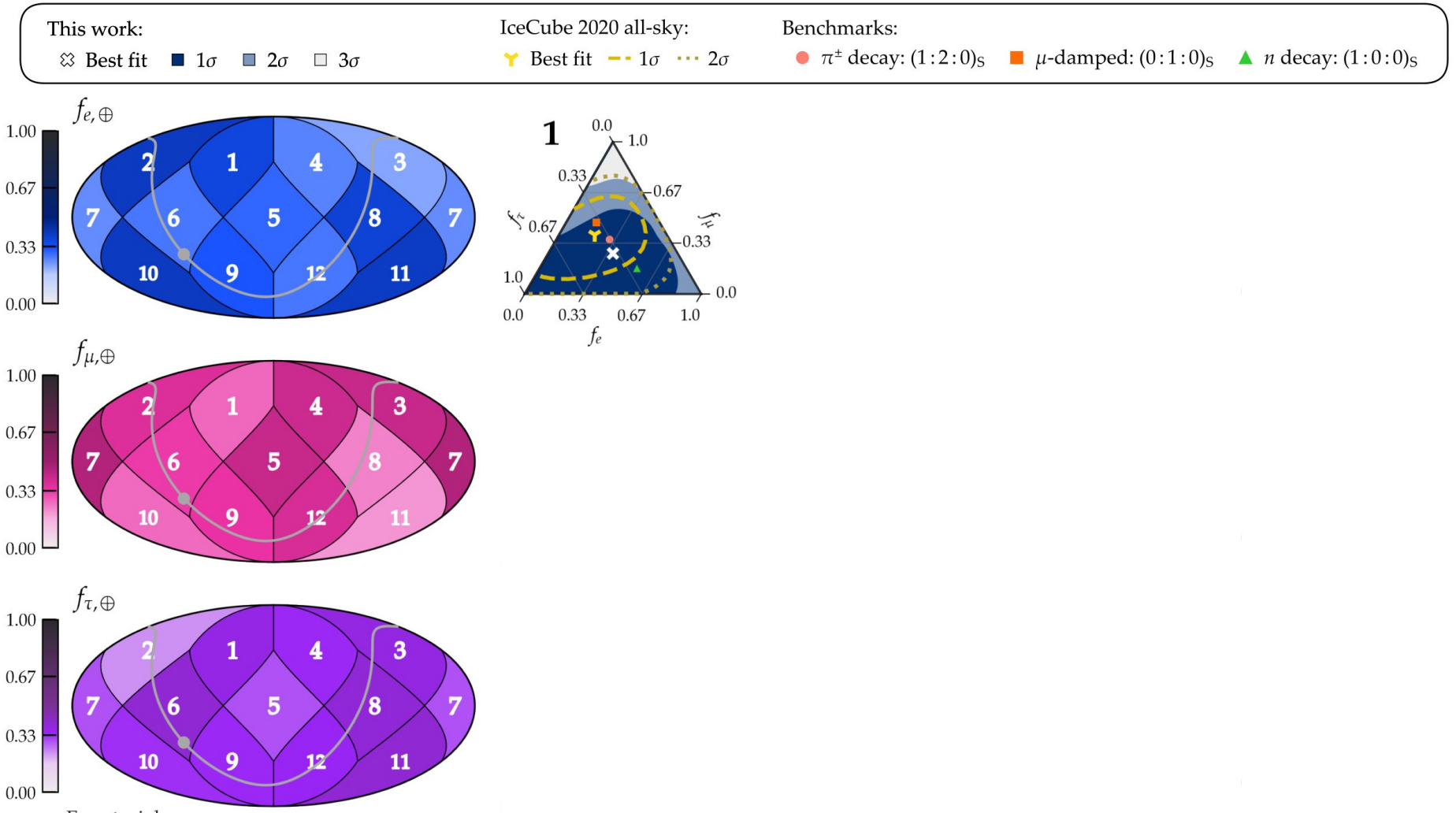

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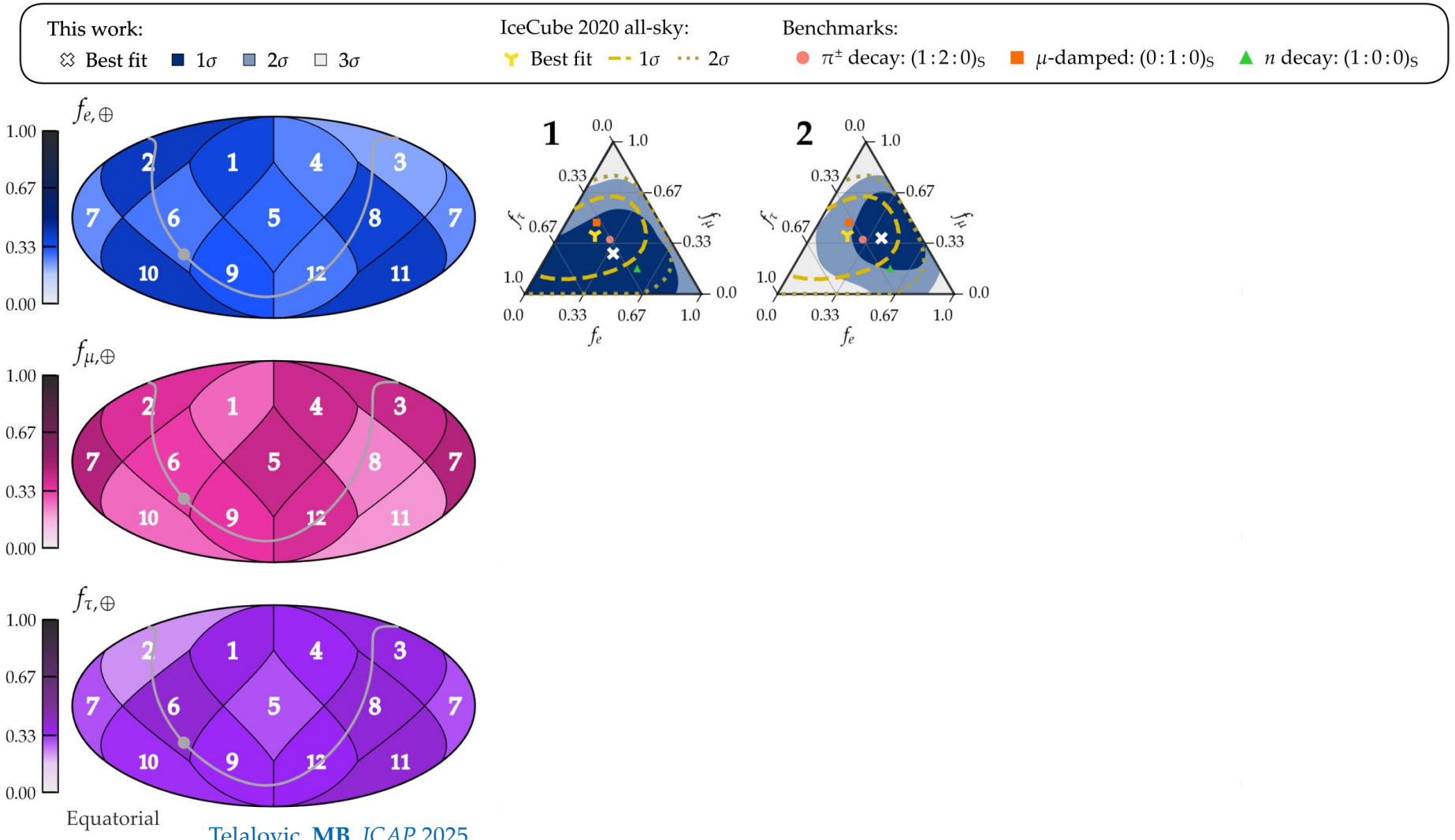

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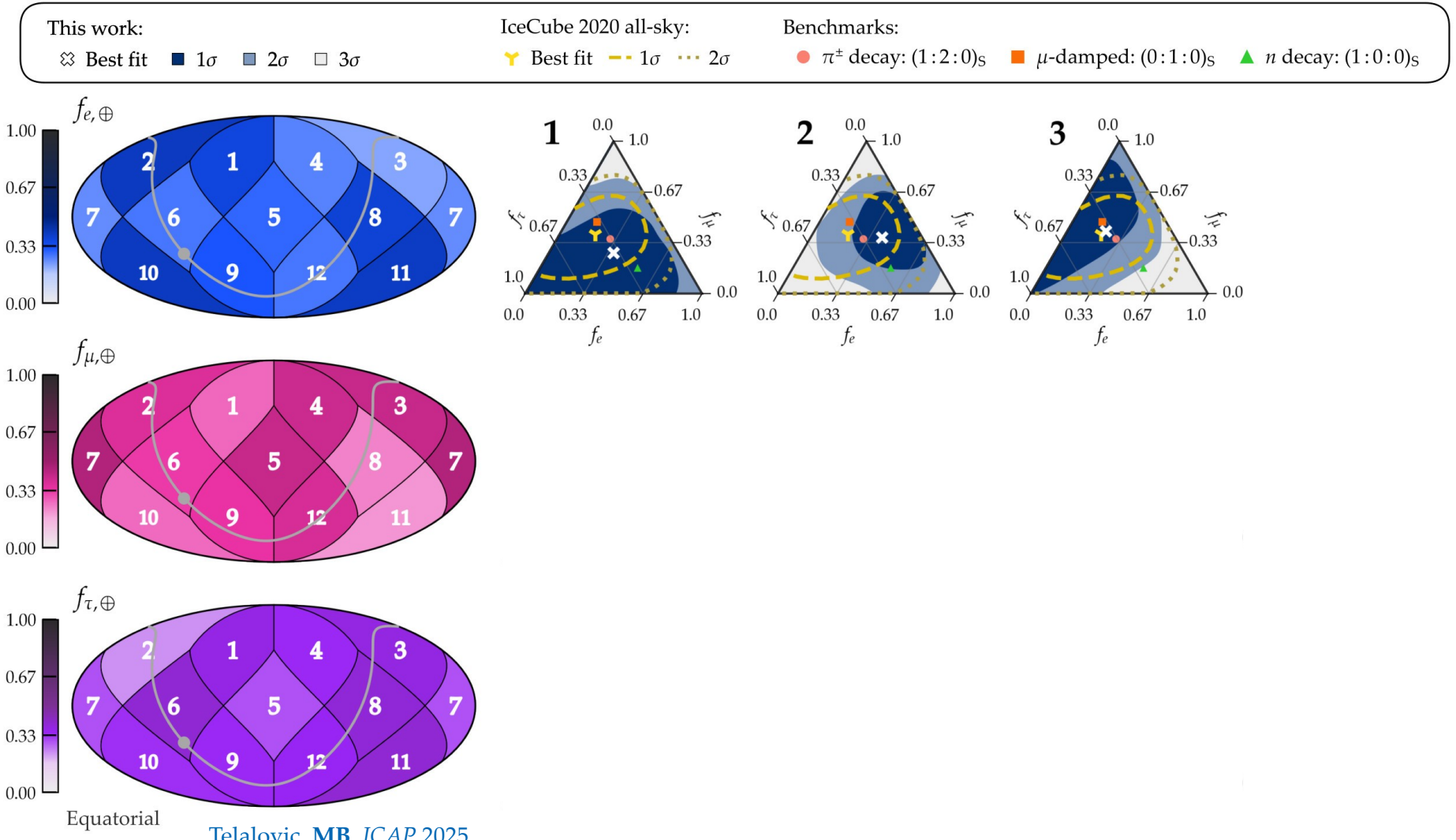

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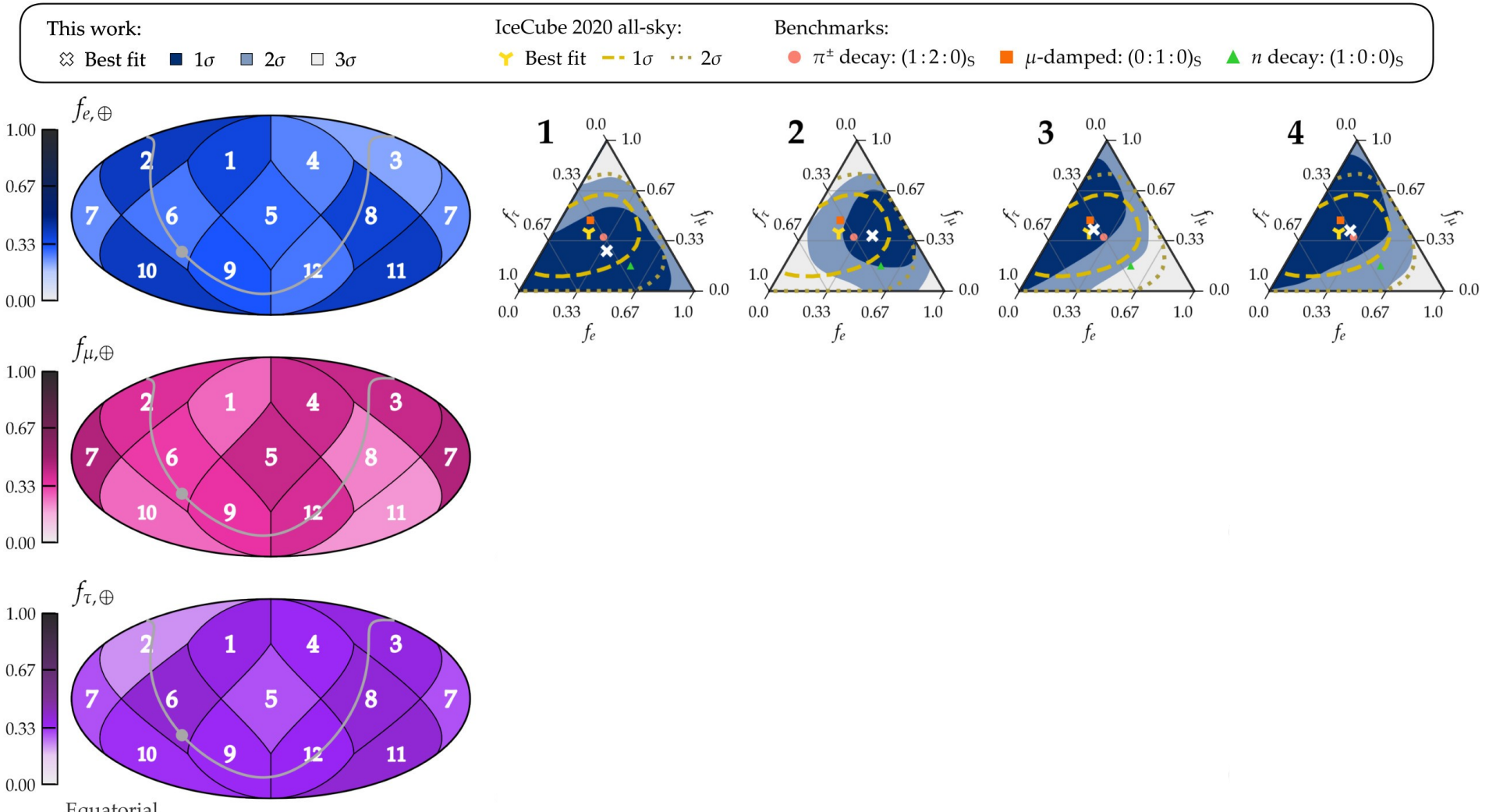

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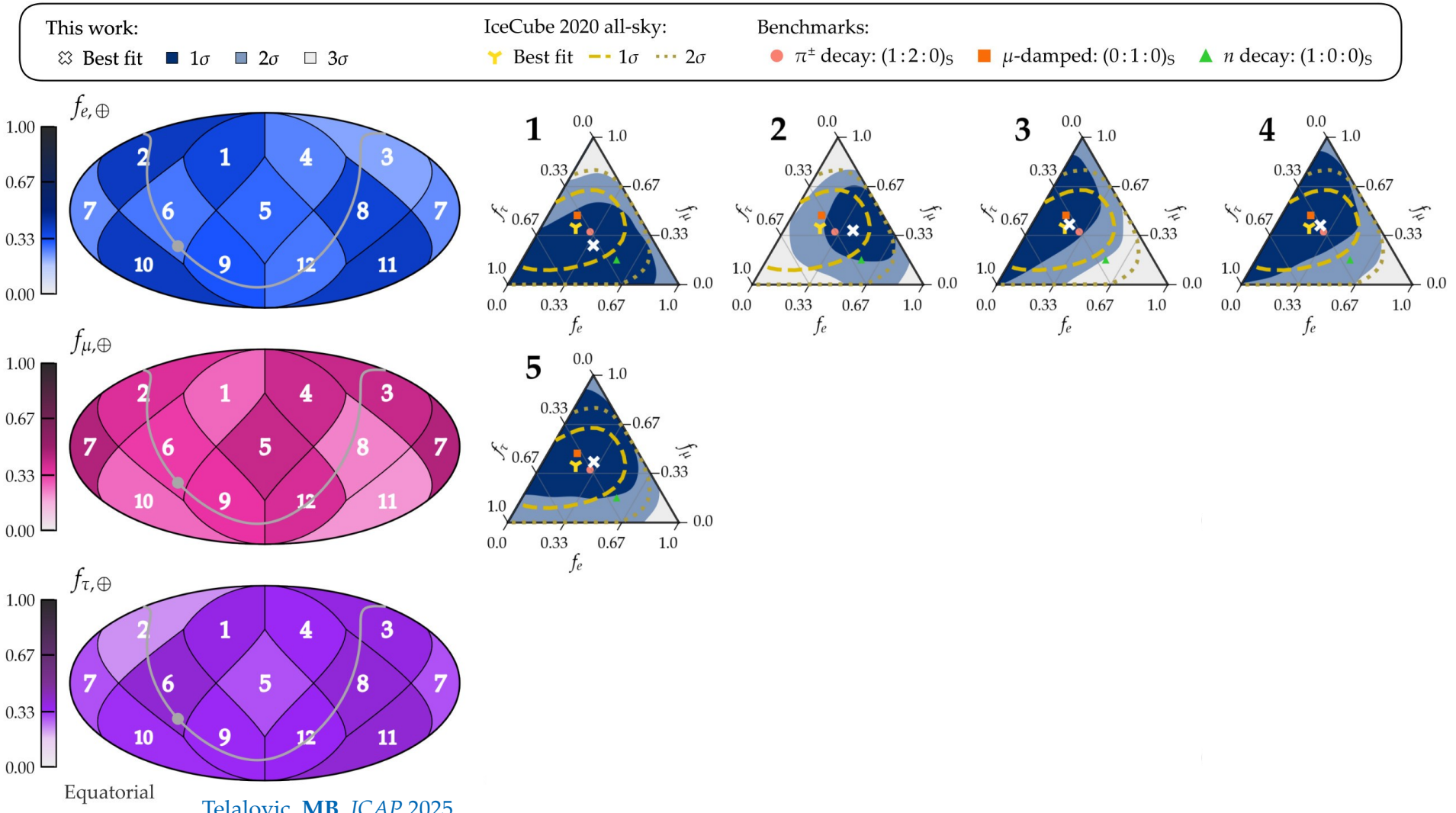

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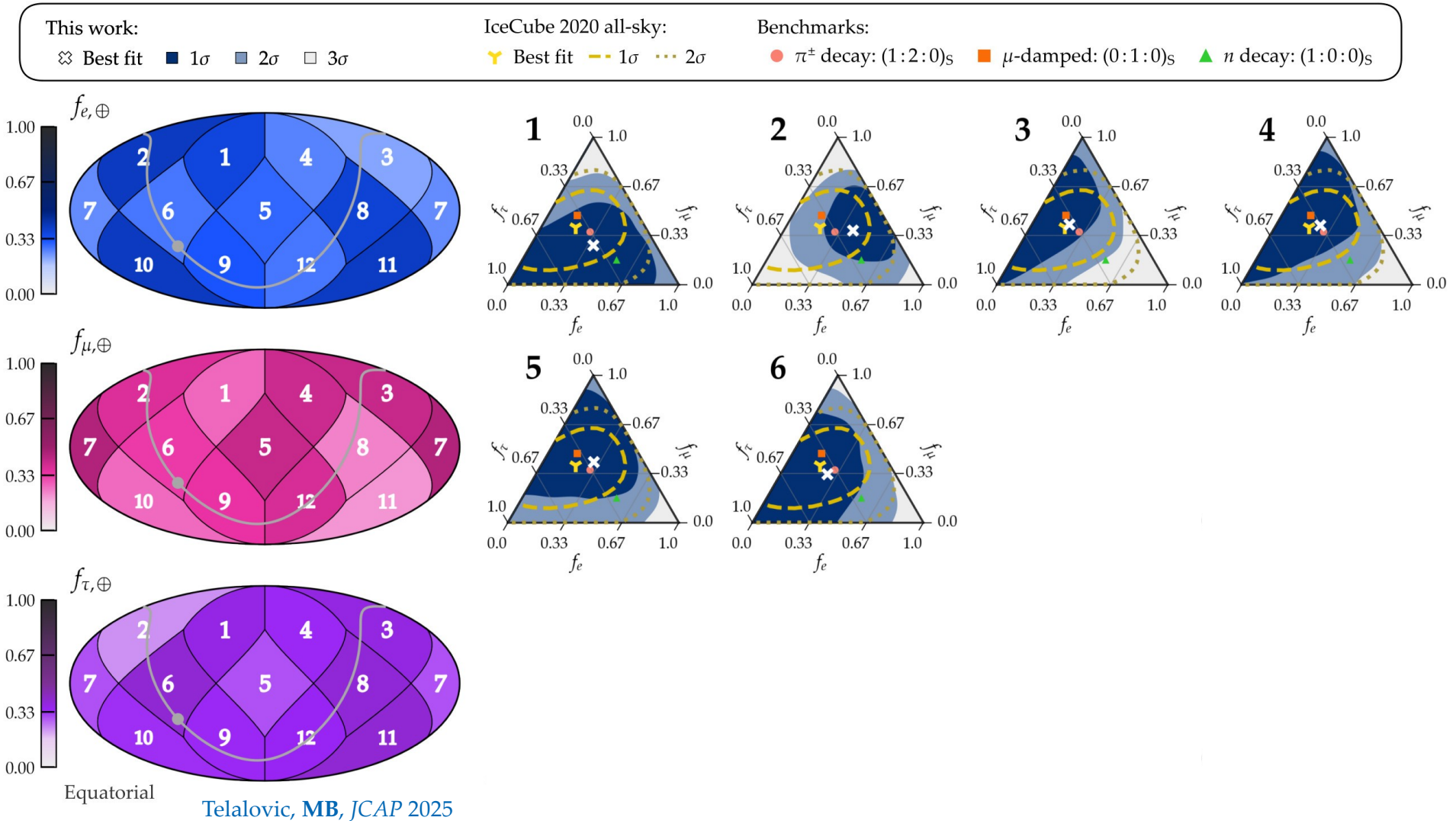

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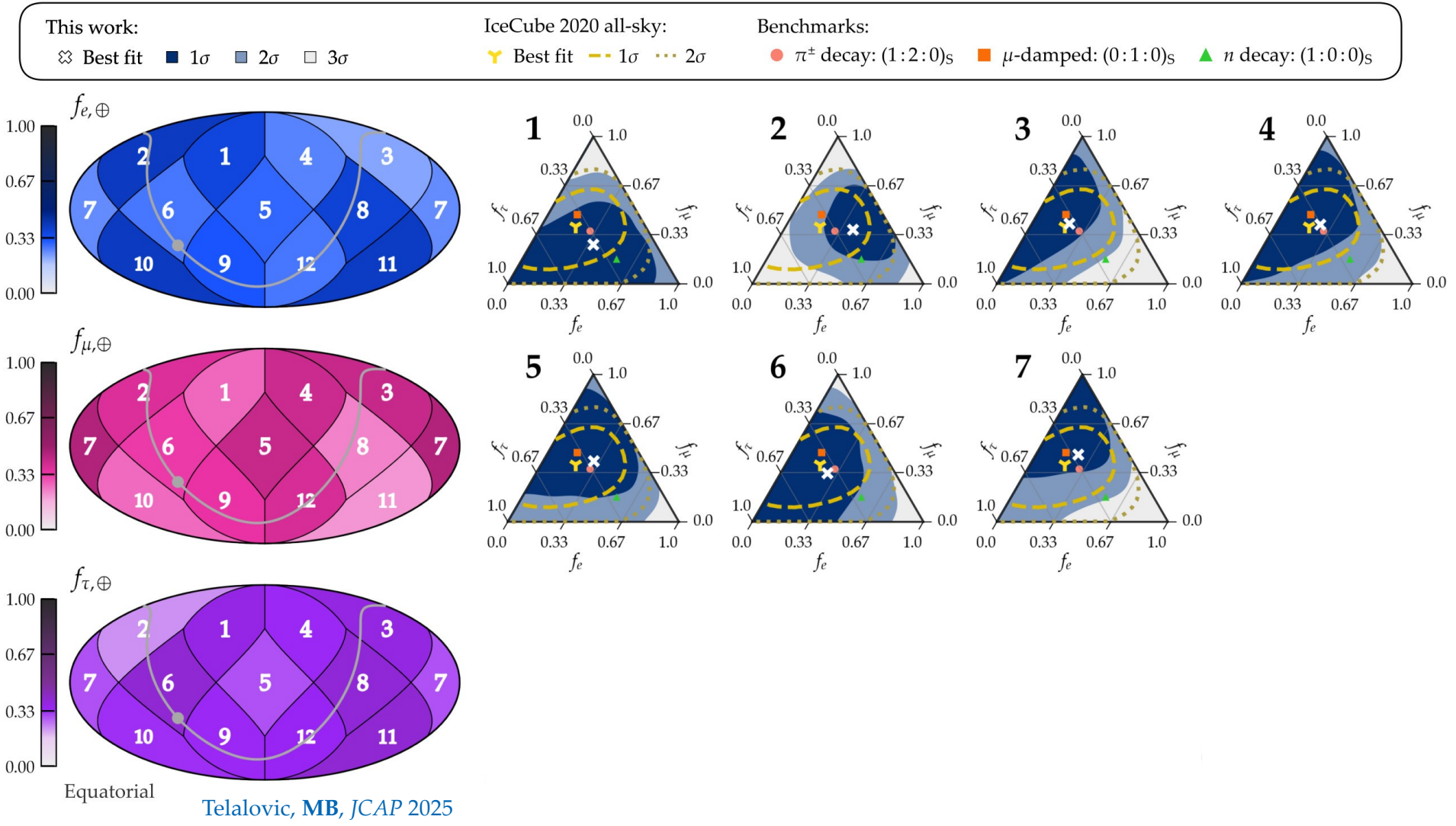

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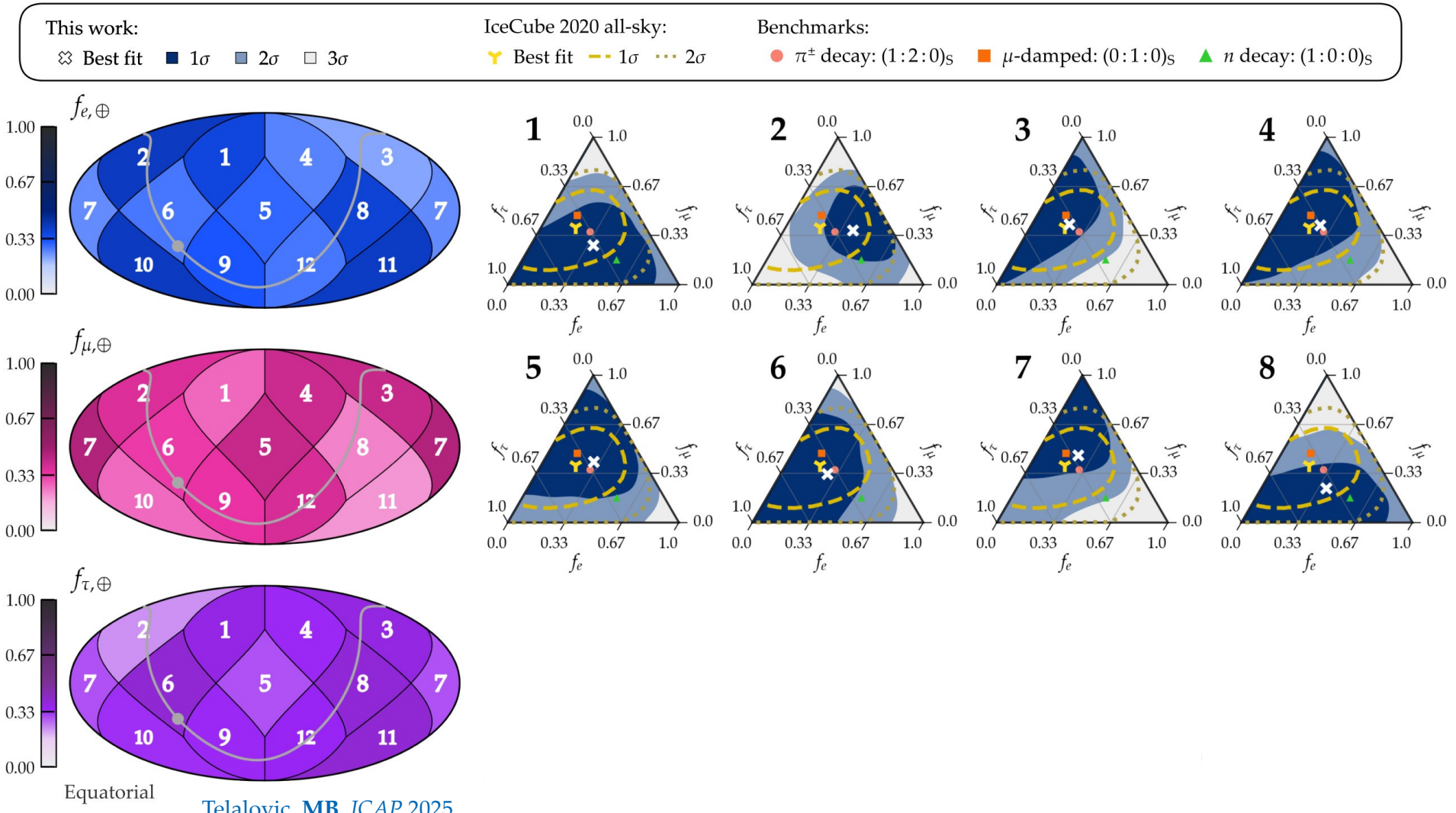

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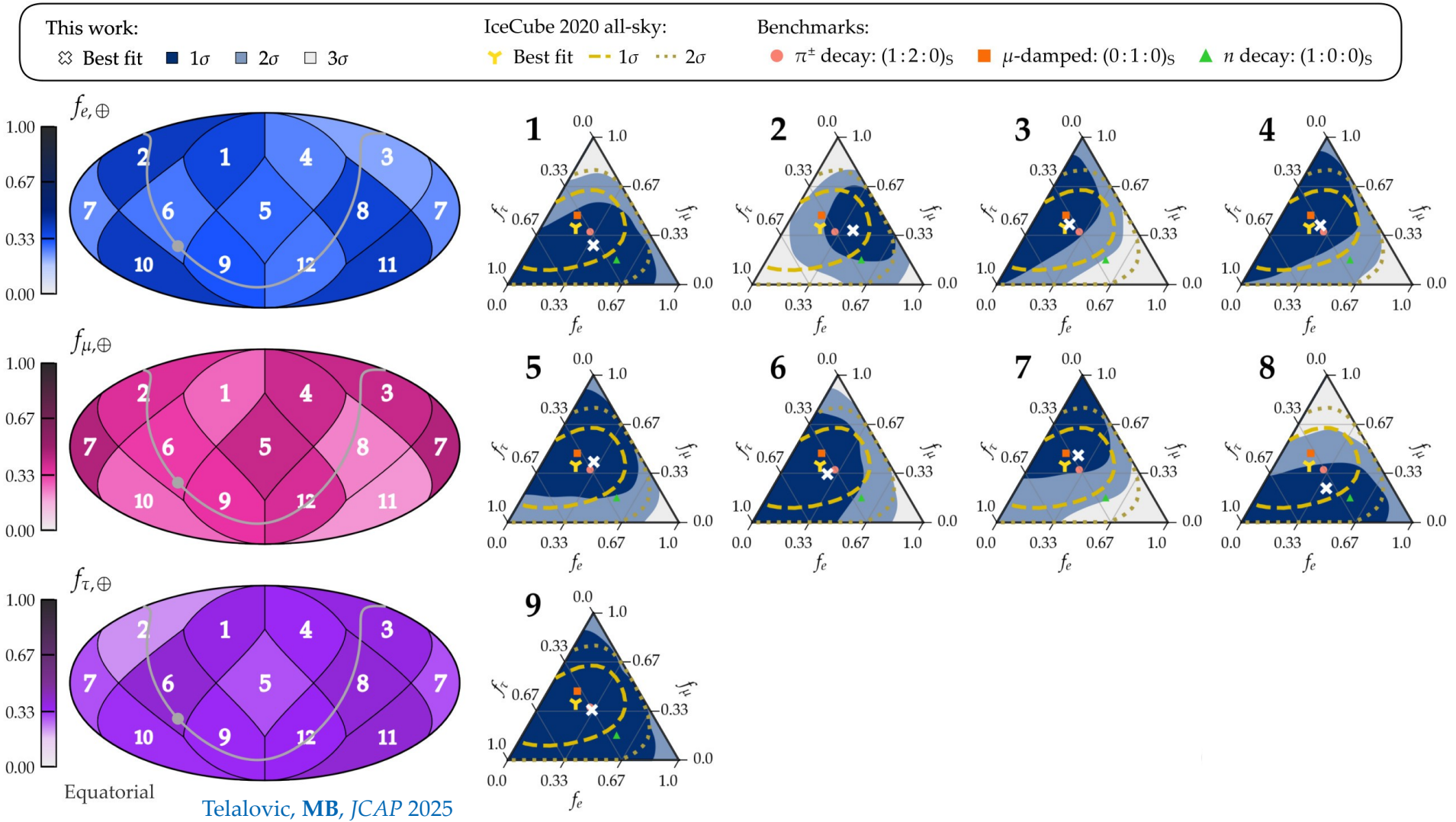

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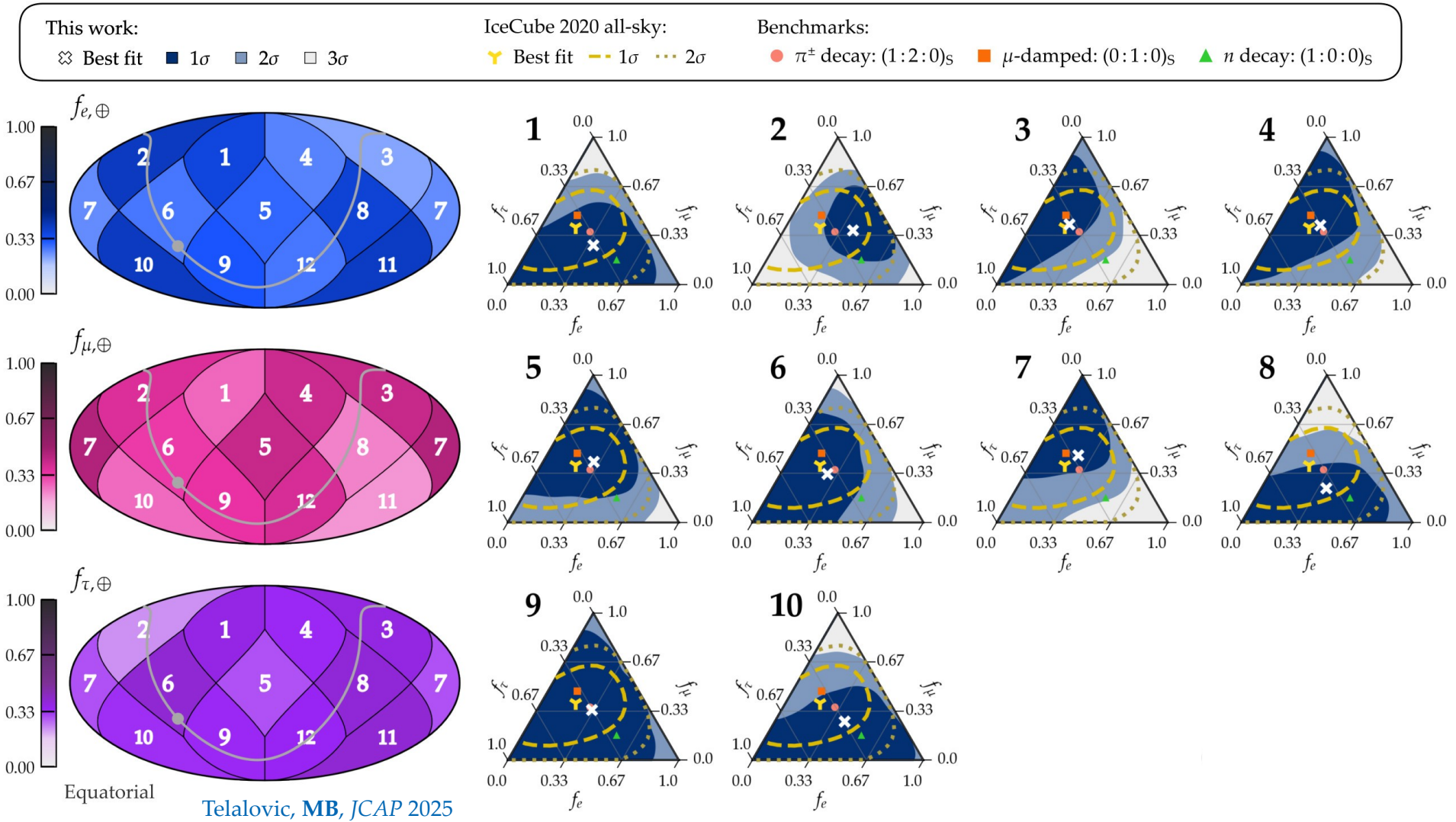

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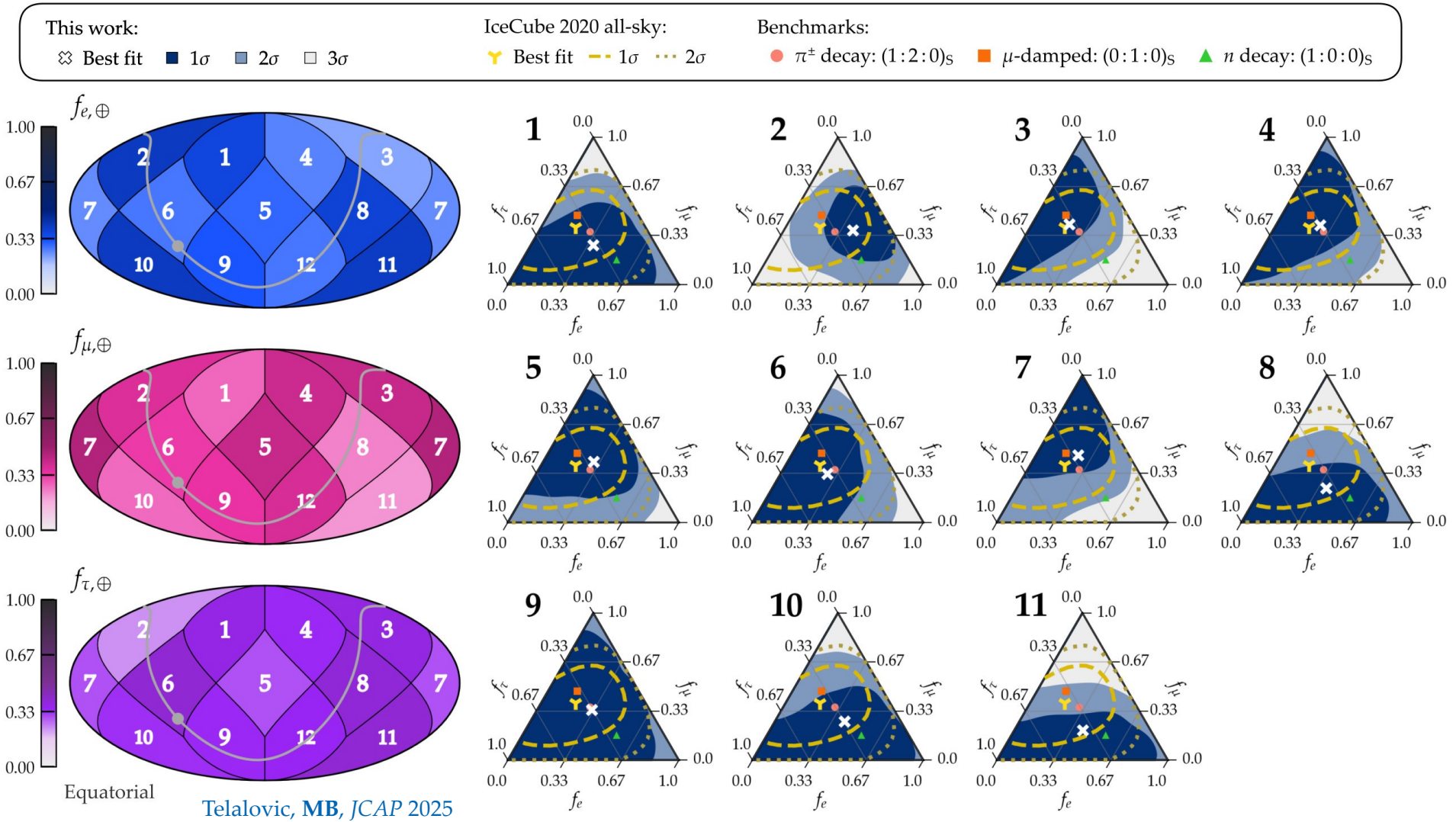

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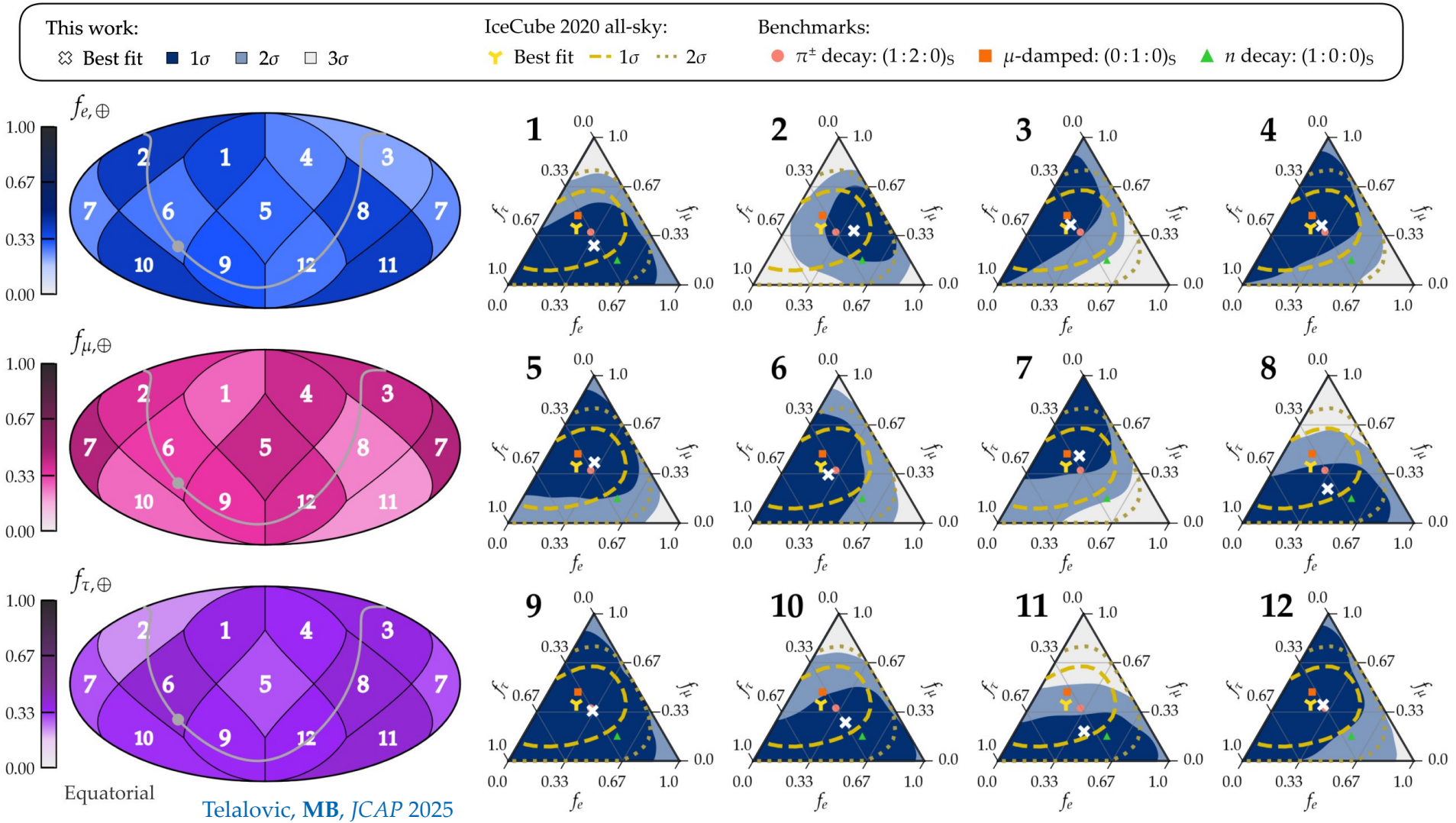


Telalovic, **MB**, *JCAP* 2025

Directional high-energy astrophysical neutrino flavor composition: IceCube HESE (7.5 yr)

This work: Best fit, 1σ, 2σ, 3σ | IceCube 2020 all-sky: Best fit, 1σ, 2σ | Benchmarks: $\pi^{\pm}$ decay: $(1:2:0)_S$, μ-damped: $(0:1:0)_S$, n decay: $(1:0:0)_S$

There is no sign of flavor anisotropy in present-day IceCube data (Bayes factor is ~1)

We place the first constraints on the flavor neutrino angular power spectrum *à la* CMB

Work led by Bernanda Telalovic

Equatorial

Telalovic, MB, 2310.15224

New physics in the flavor composition

Fundamental physics with high-energy cosmic neutrinos

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

So we can probe $\kappa_n \sim 4 \cdot 10^{-47}\ (E/\mathrm{PeV})^{-n}\ (L/\mathrm{Gpc})^{-1}\ \mathrm{PeV}^{1-n}$

Improvement over limits using atmospheric ν: $\kappa_0 < 10^{-29}$ PeV, $\kappa_1 < 10^{-33}$

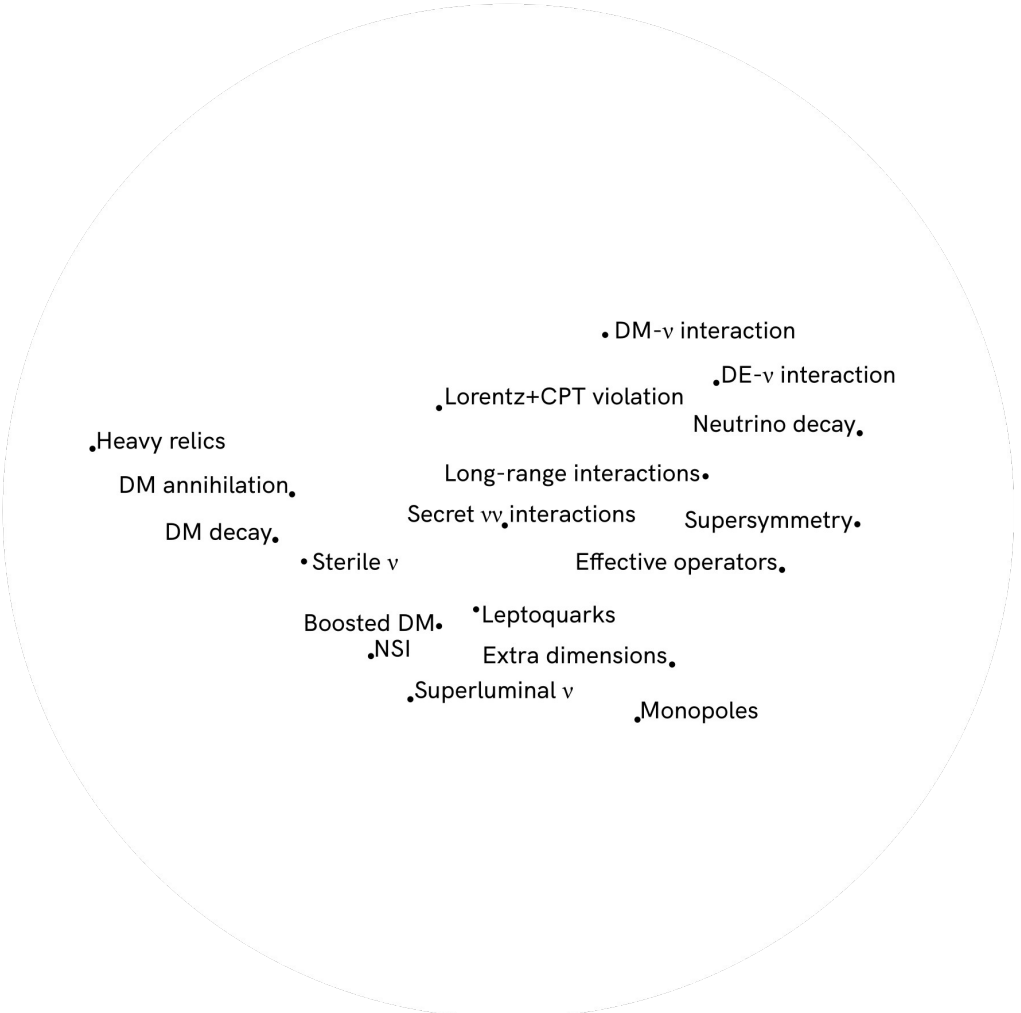
Fundamental physics with high-energy cosmic neutrinos

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

E.g.,
n = -1: neutrino decay
n = 0: CPT-odd Lorentz violation
n = +1: CPT-even Lorentz violation

So we can probe $\kappa_n \sim 4 \cdot 10^{-47}\ (E/\text{PeV})^{-n}\ (L/\text{Gpc})^{-1}\ \text{PeV}^{1-n}$

Improvement over limits using atmospheric ν: $\kappa_0 < 10^{-29}$ PeV, $\kappa_1 < 10^{-33}$



Note: Not an exhaustive list

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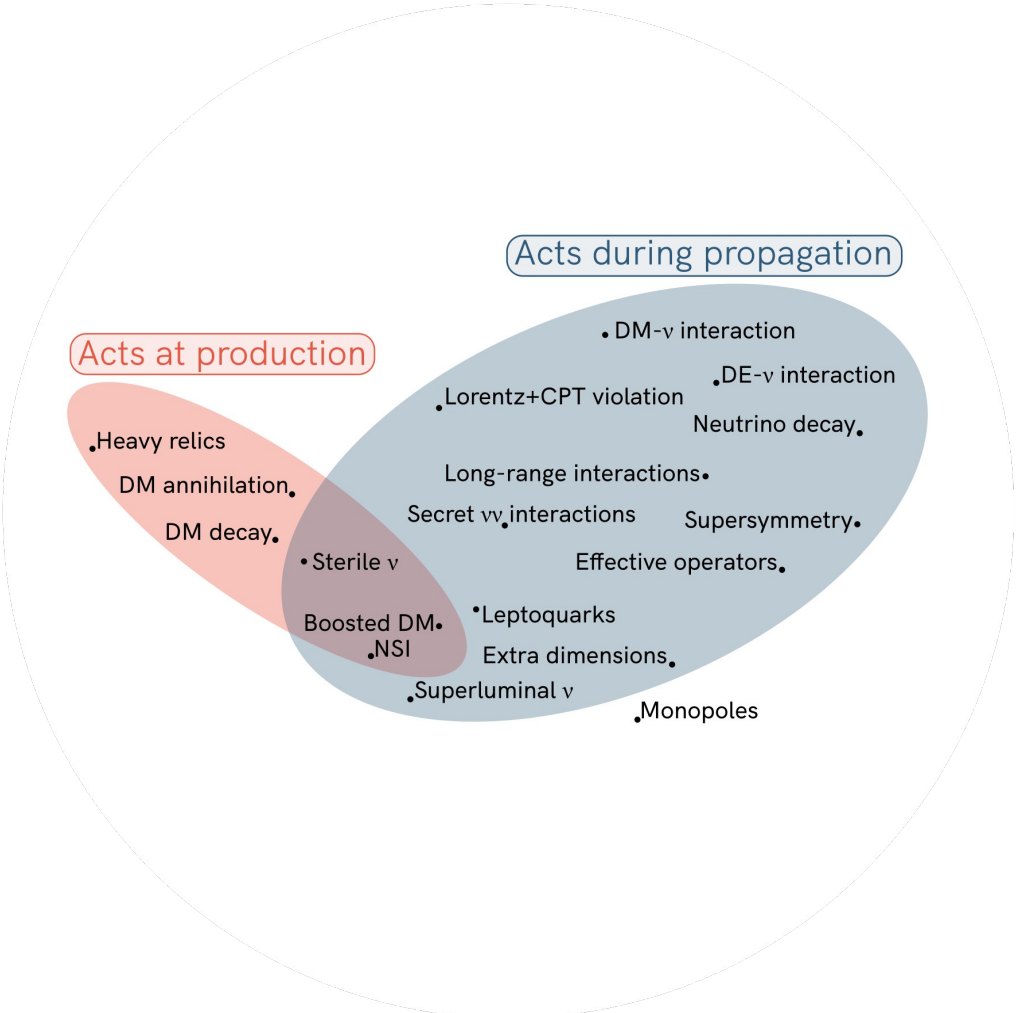

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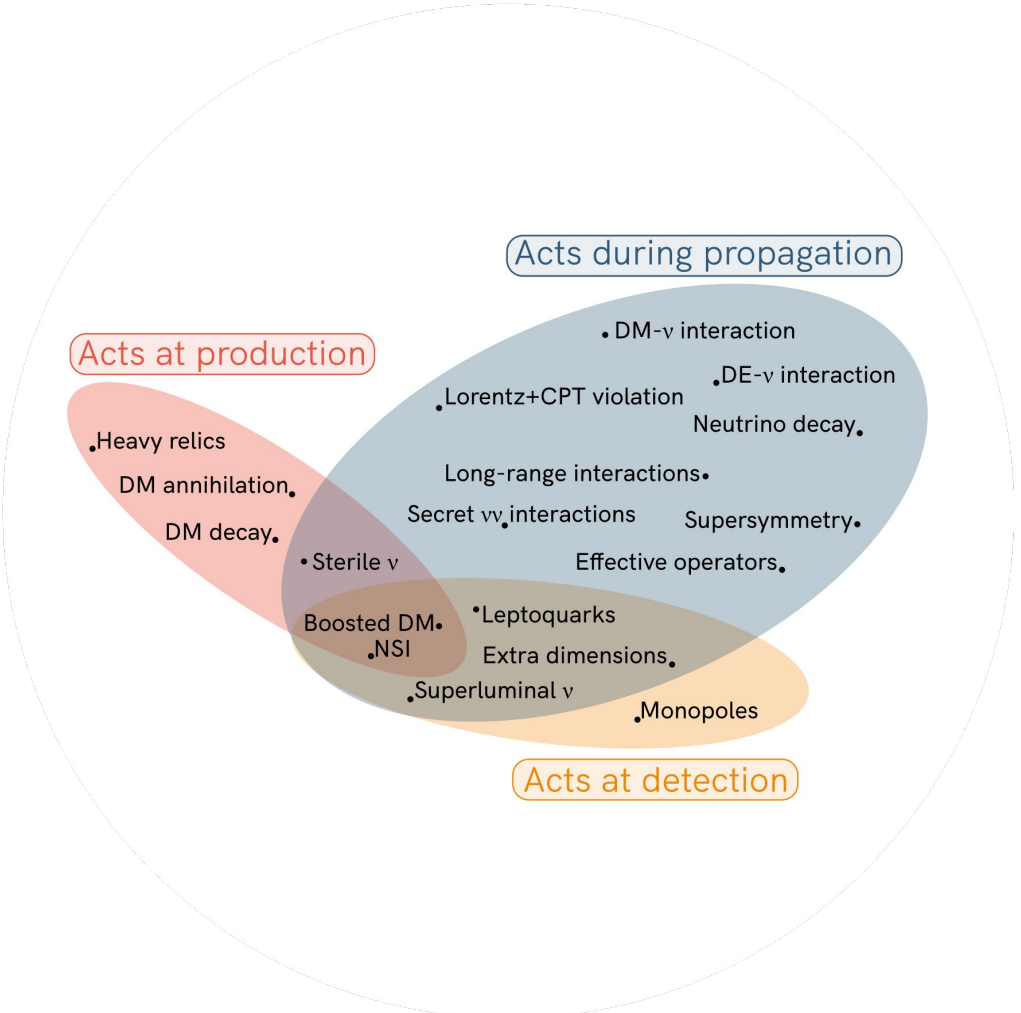

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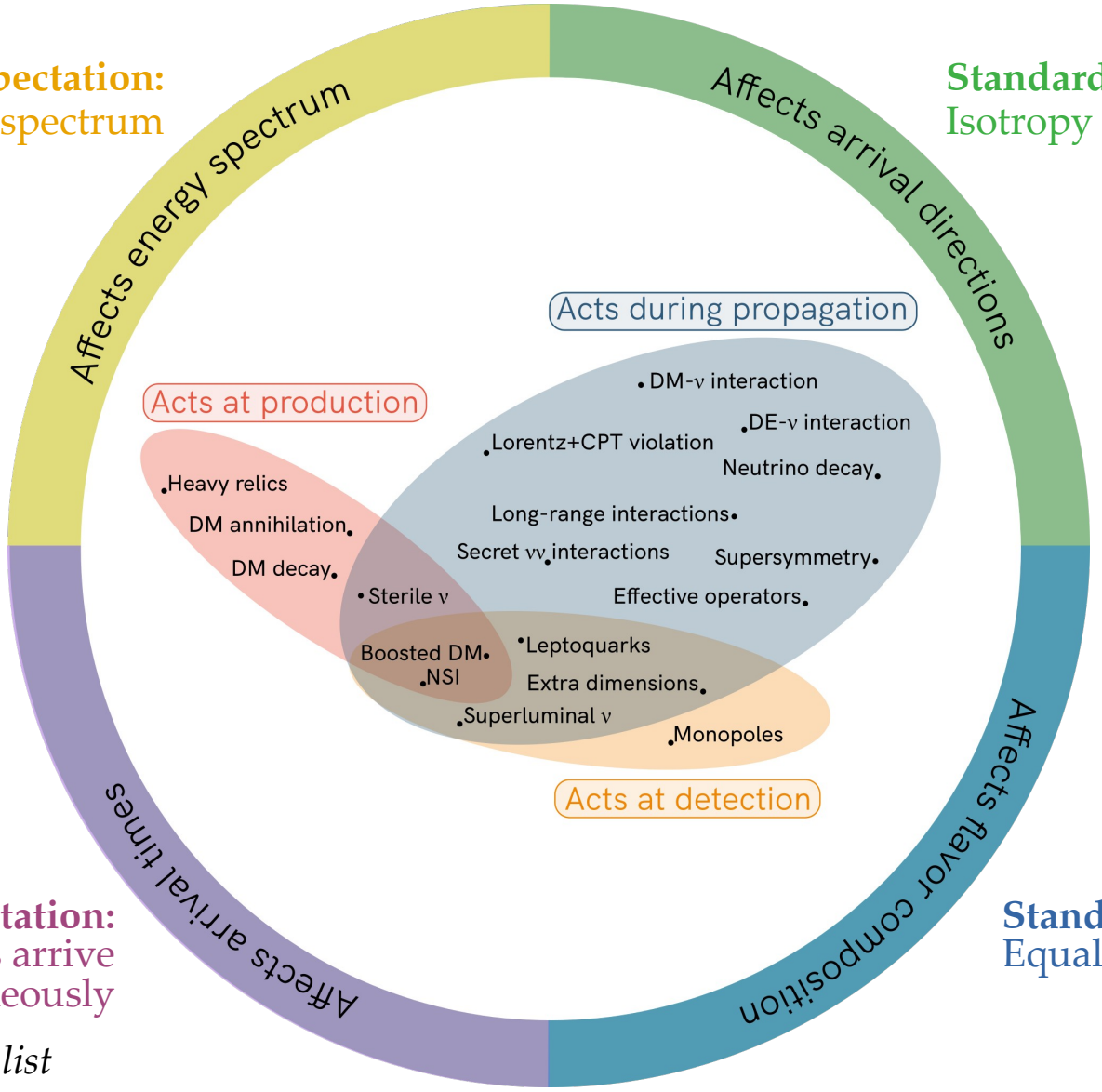
Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



Standard expectation:
ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

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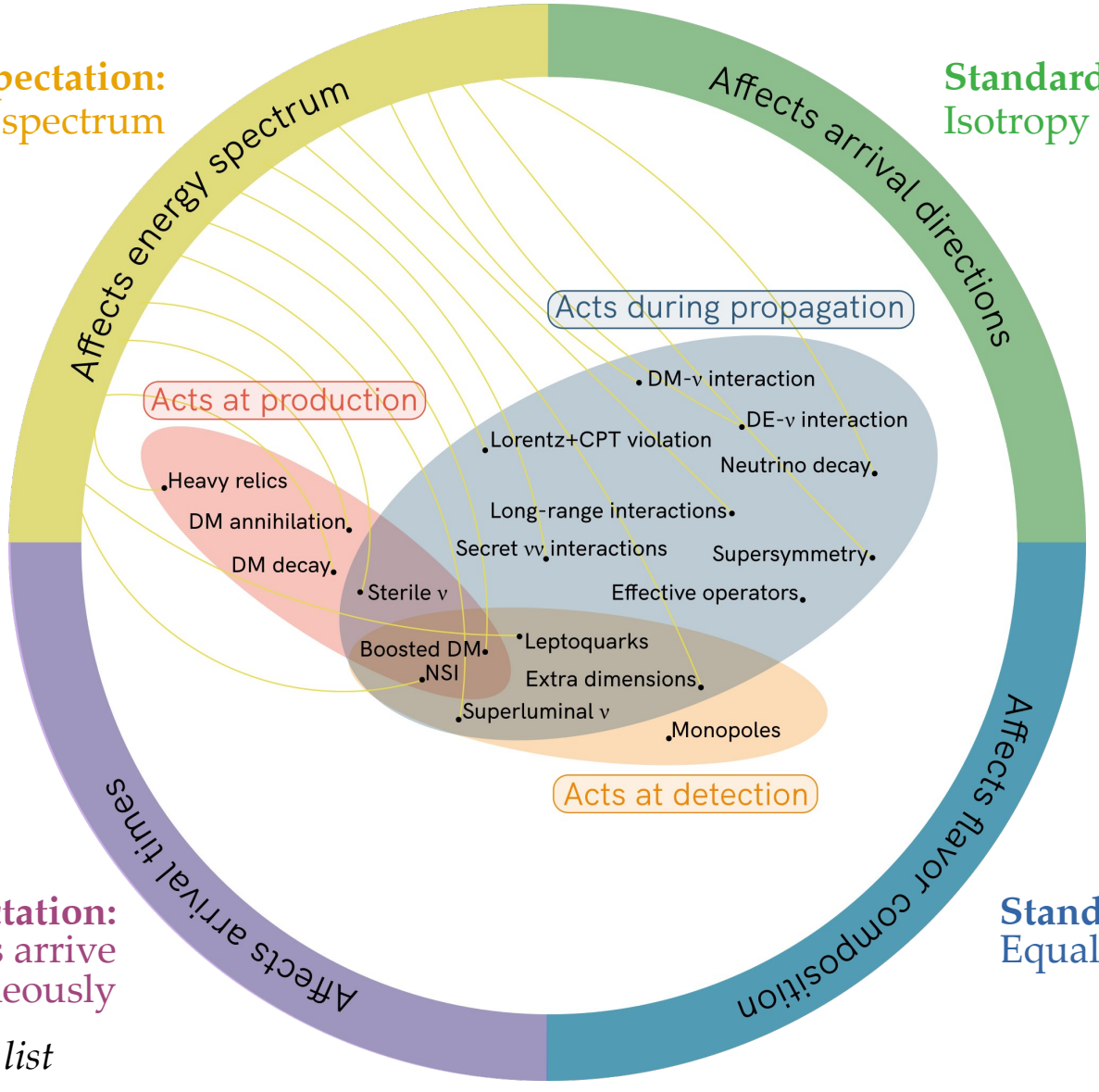

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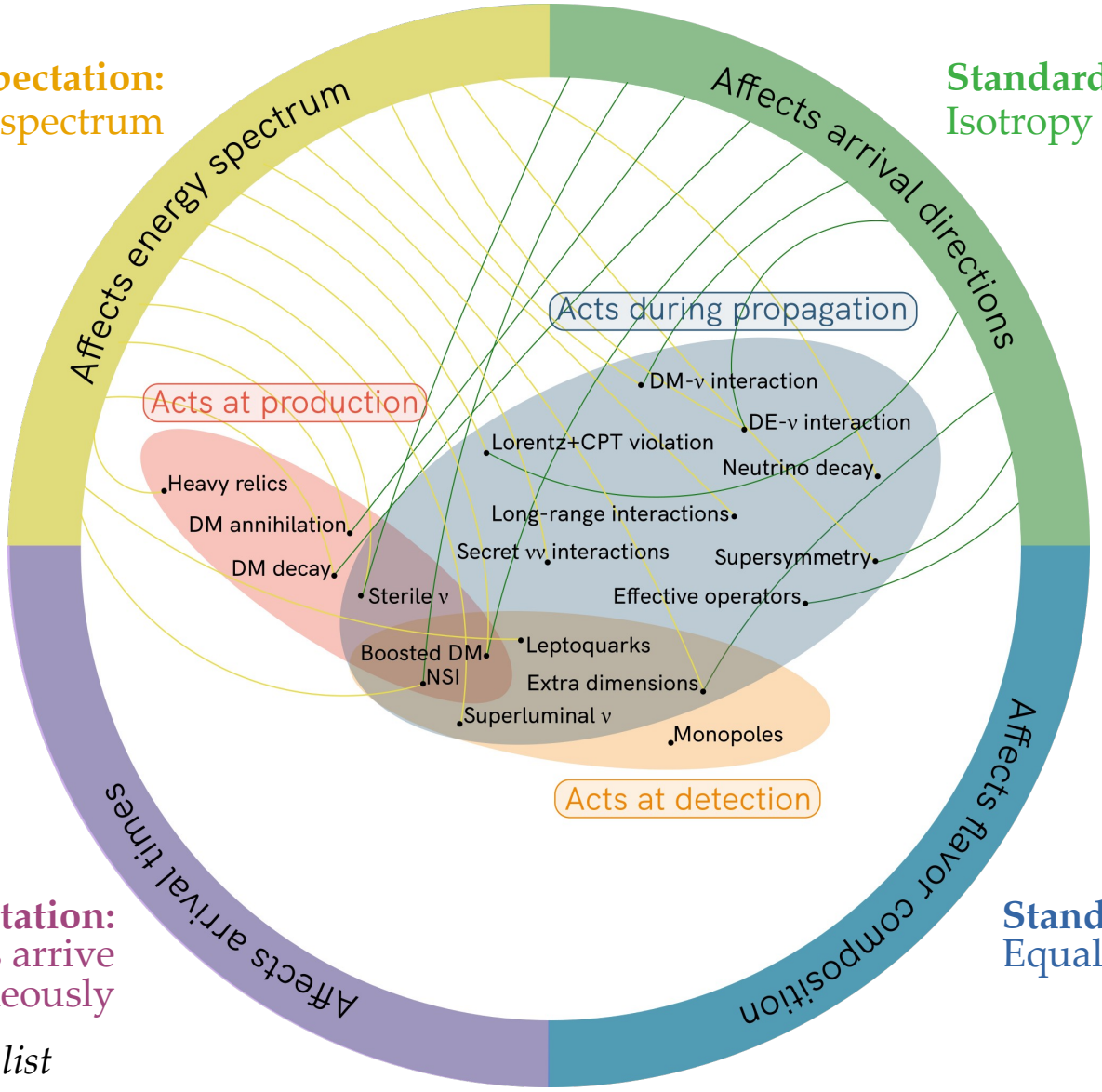

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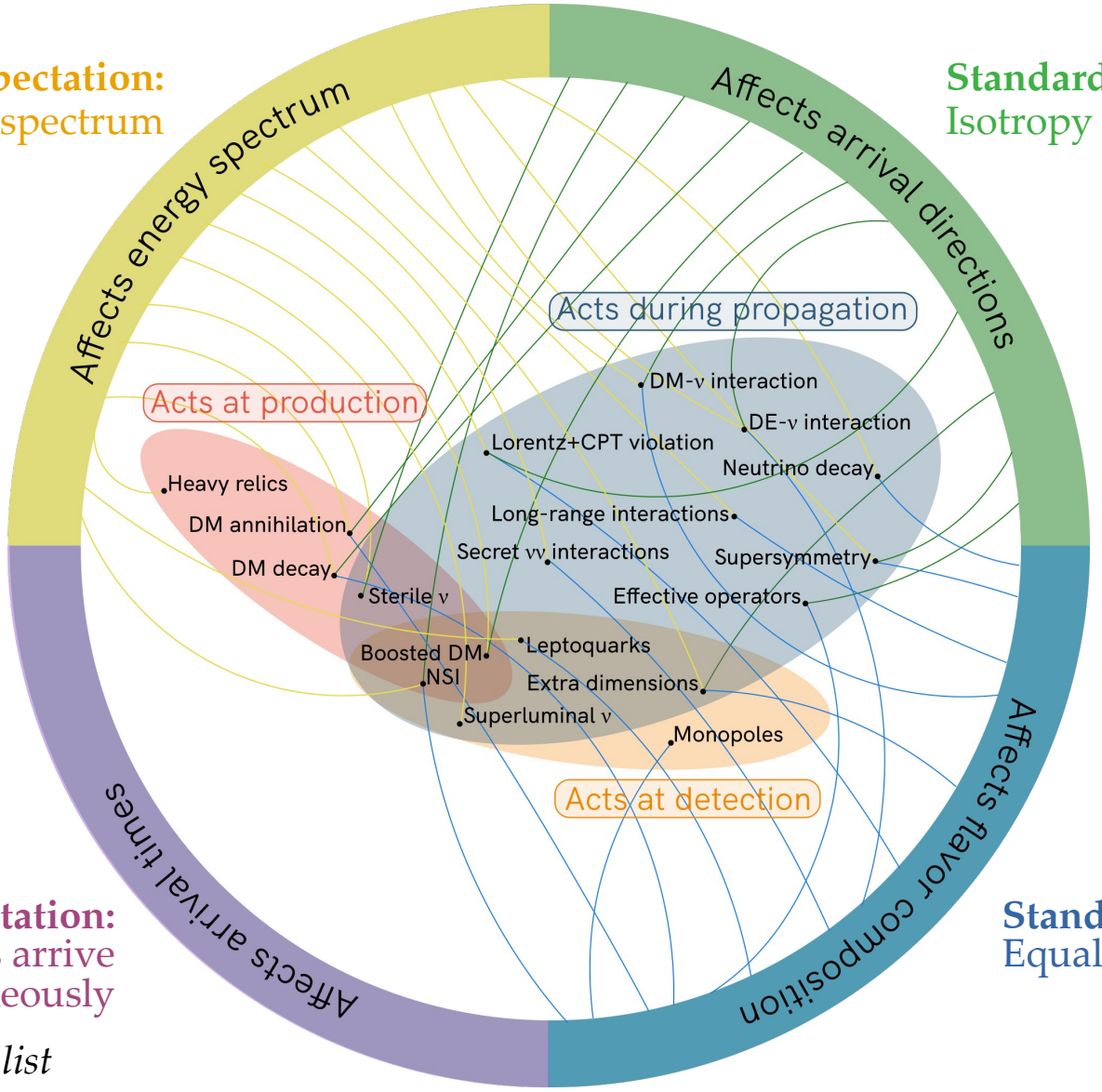

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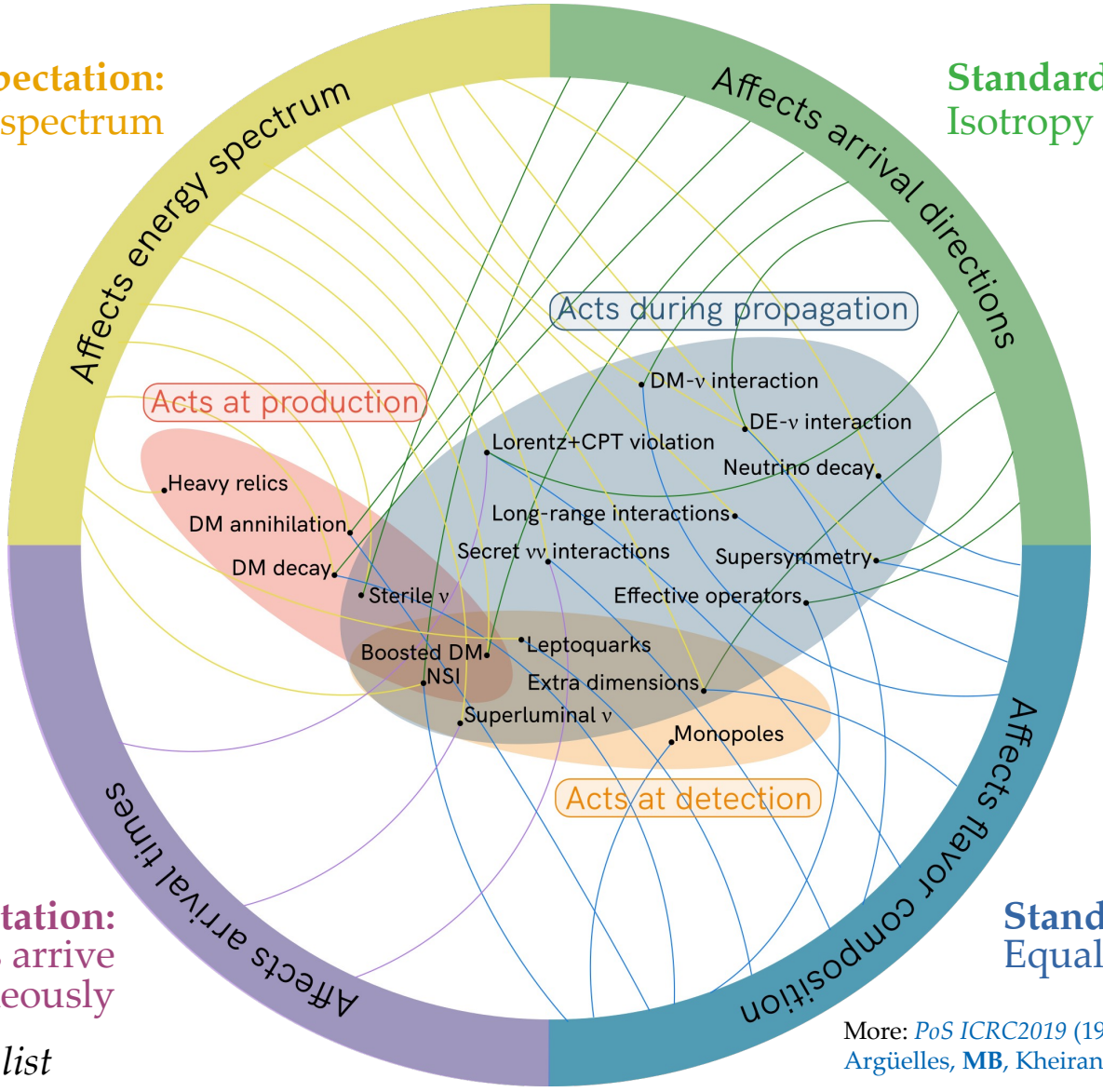

Standard expectation:
ν and γ from transients arrive simultaneously

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Equal number of ν_e, ν_μ, ν_τ

Note: Not an exhaustive list

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

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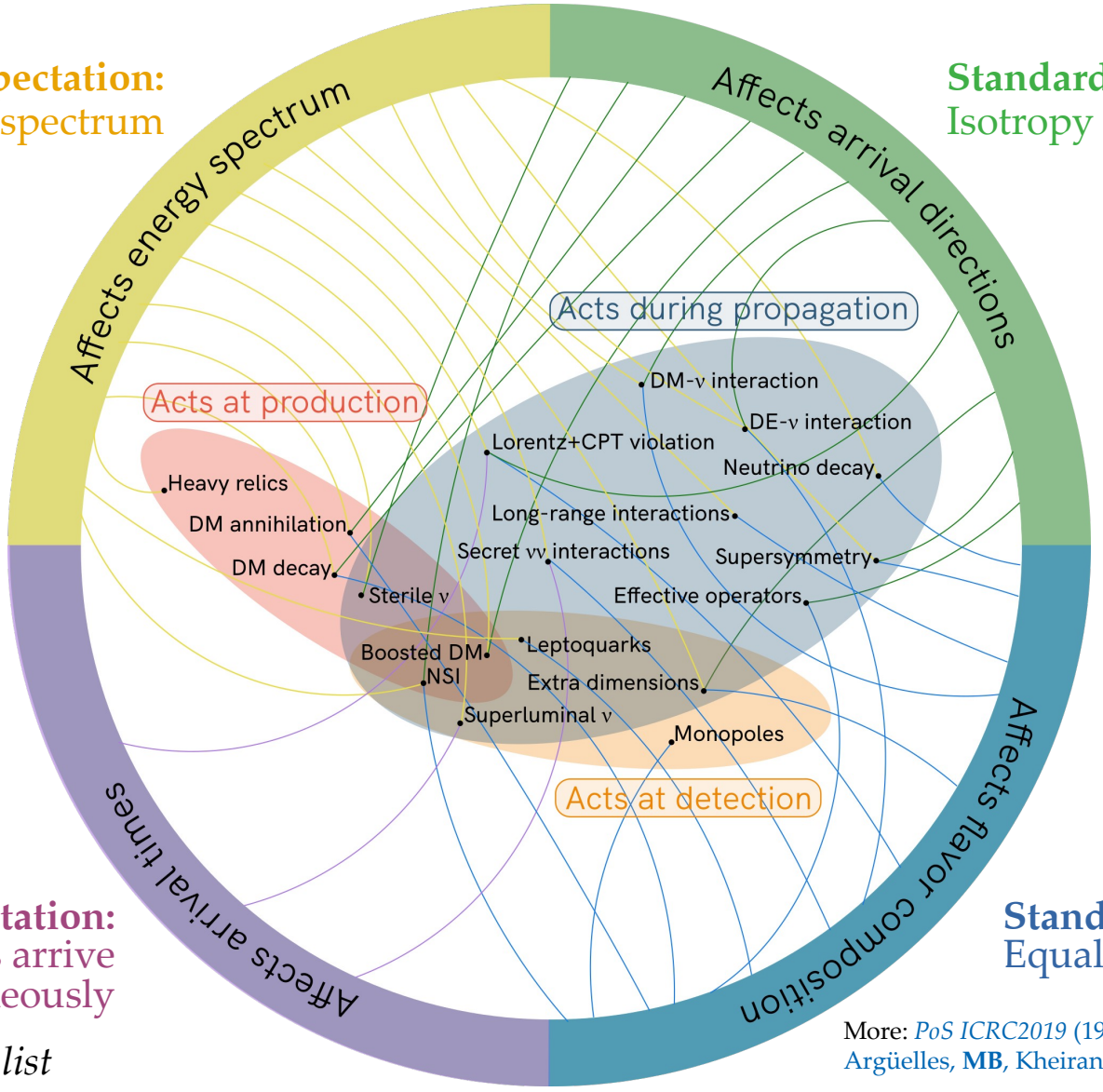

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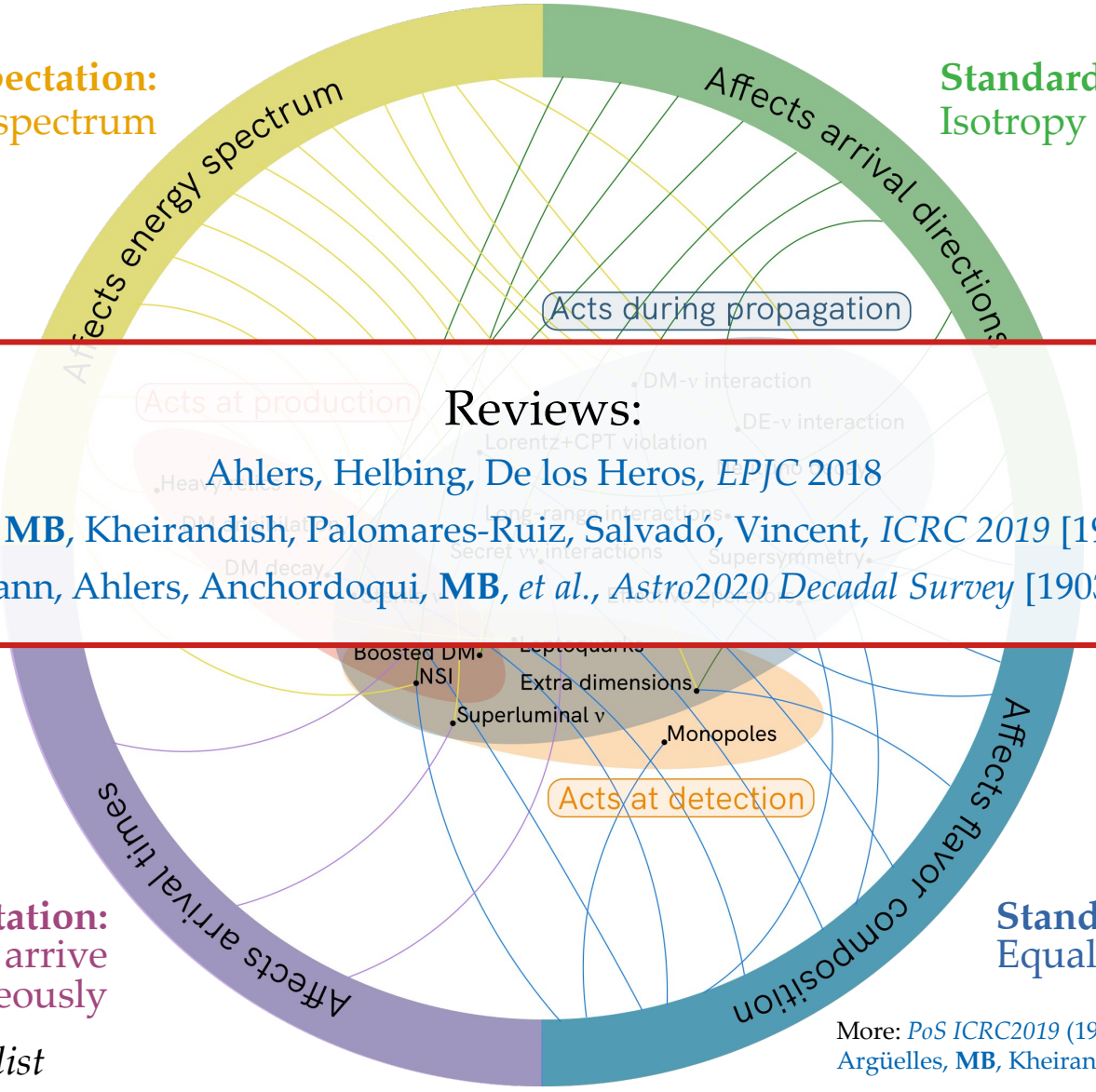

Reviews:

Ahlers, Helbing, De los Heros, *EPJC* 2018

Argüelles, **MB**, Kheirandish, Palomares-Ruiz, Salvadó, Vincent, *ICRC 2019* [1907.08690]

Ackermann, Ahlers, Anchordoqui, **MB**, *et al.*, *Astro2020 Decadal Survey* [1903.04333]

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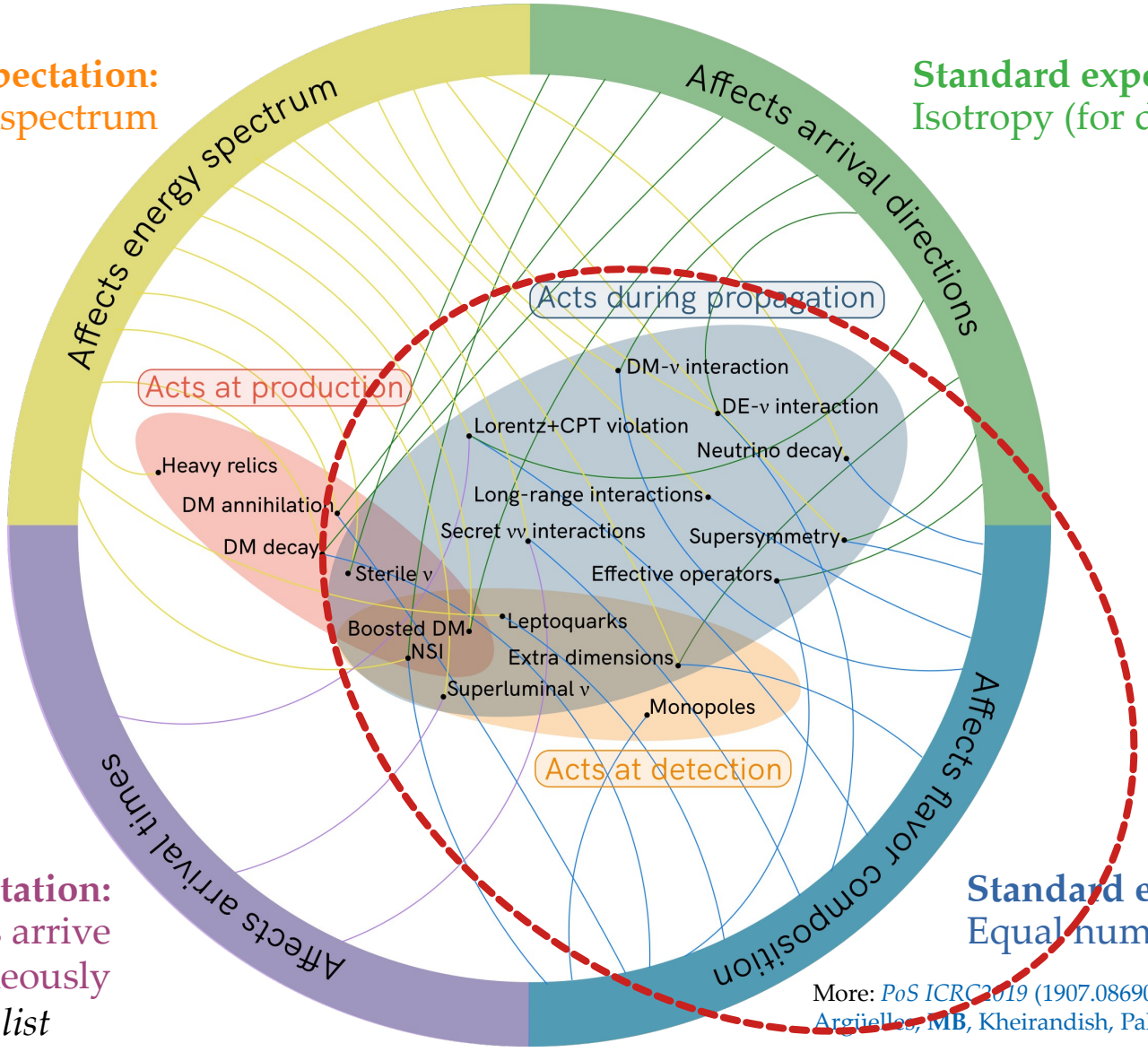

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New physics in flavor composition

Use the flavor sensitivity to test new physics:

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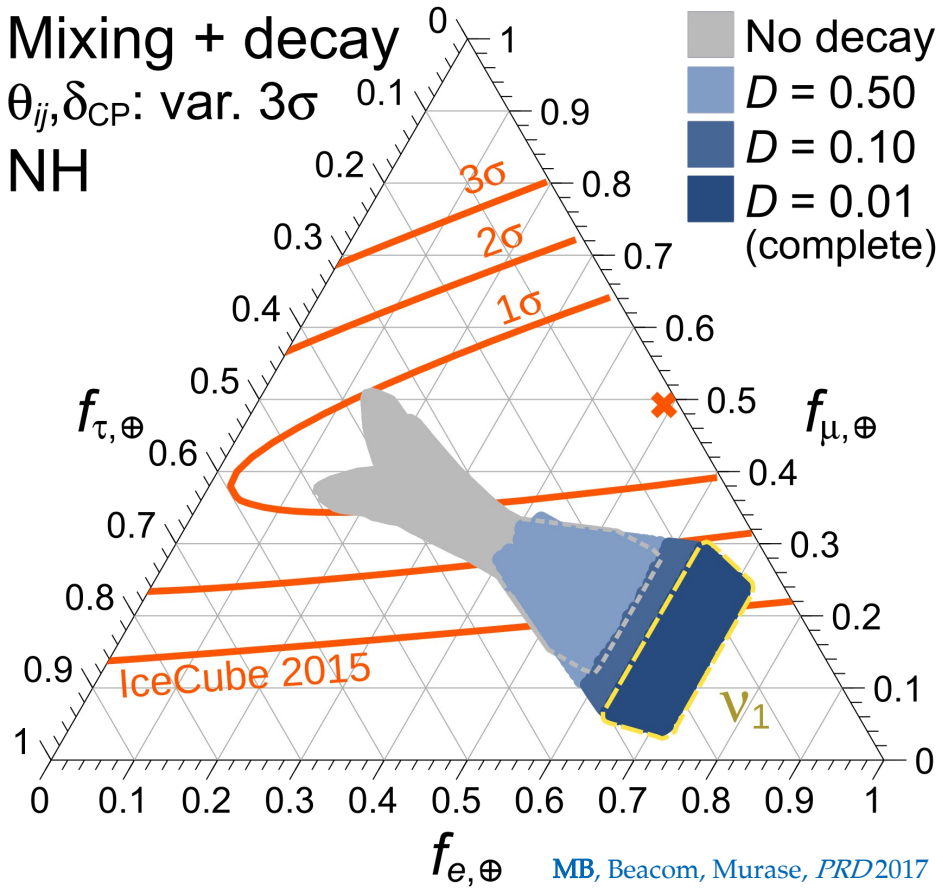

MB, Beacom, Murase, *PRD* 2017

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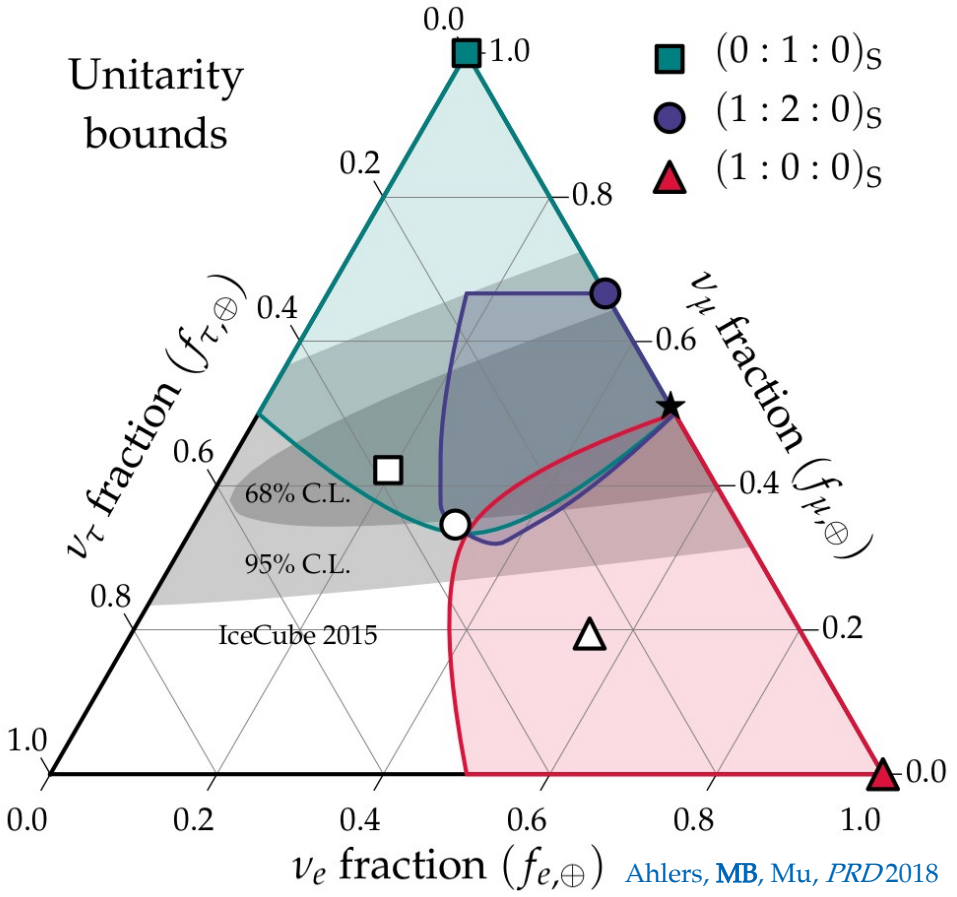

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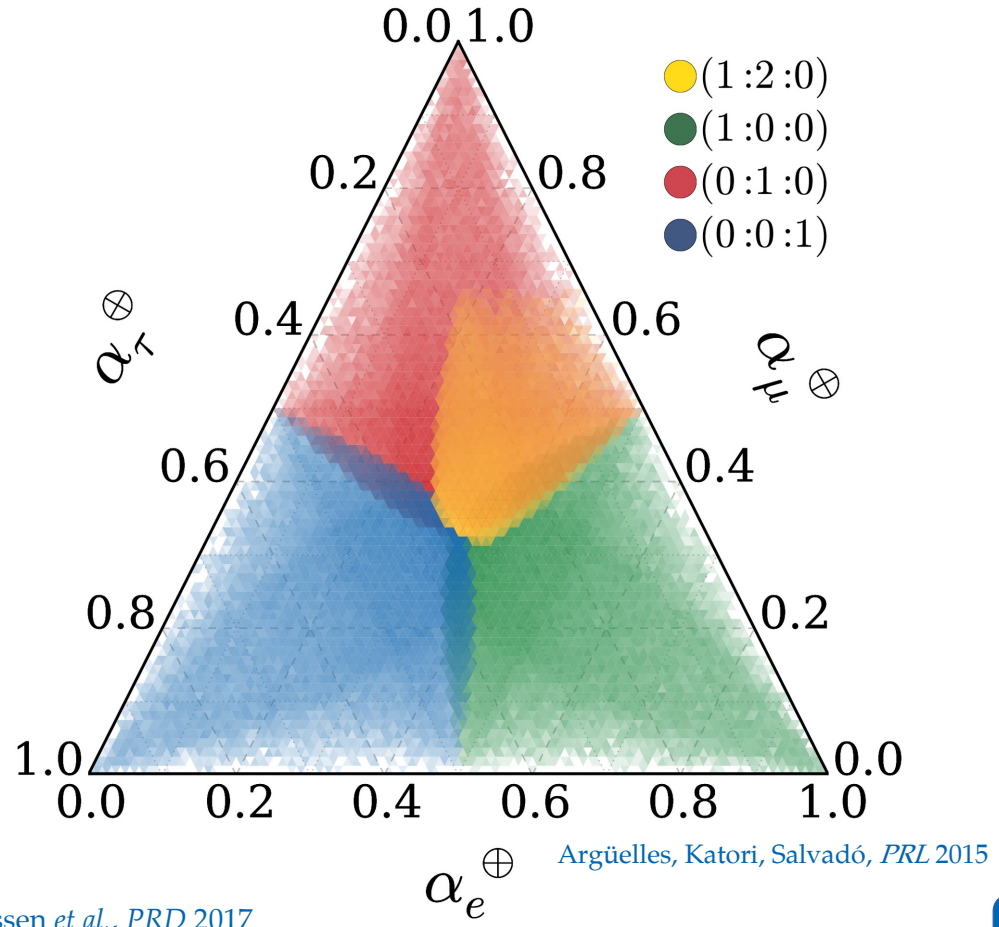

Argüelles, Katori, Salvadó, *PRL* 2015

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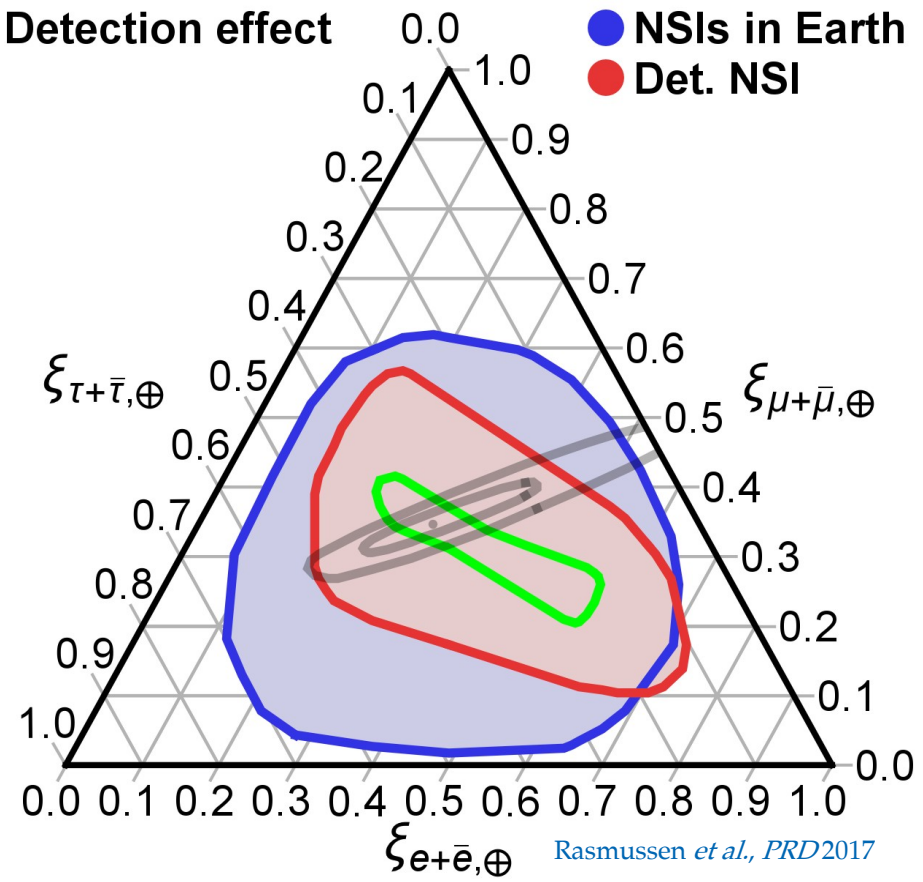

Rasmussen *et al.*, *PRD* 2017

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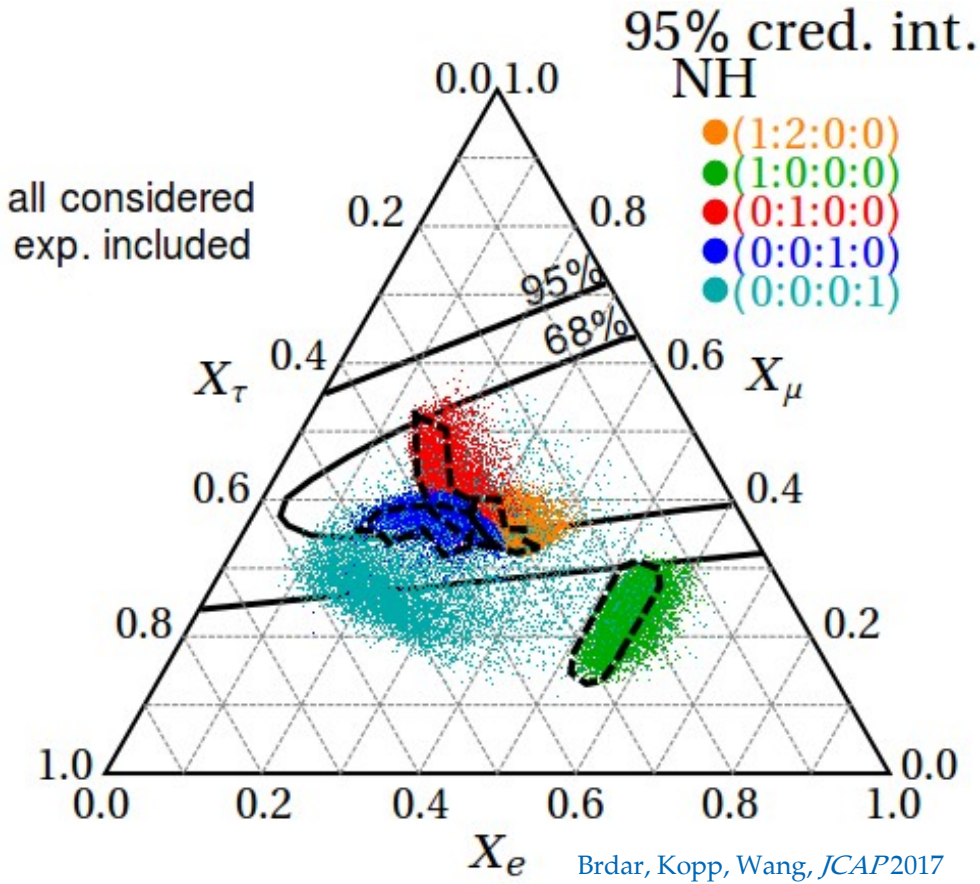

Brdar, Kopp, Wang, *JCAP* 2017

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

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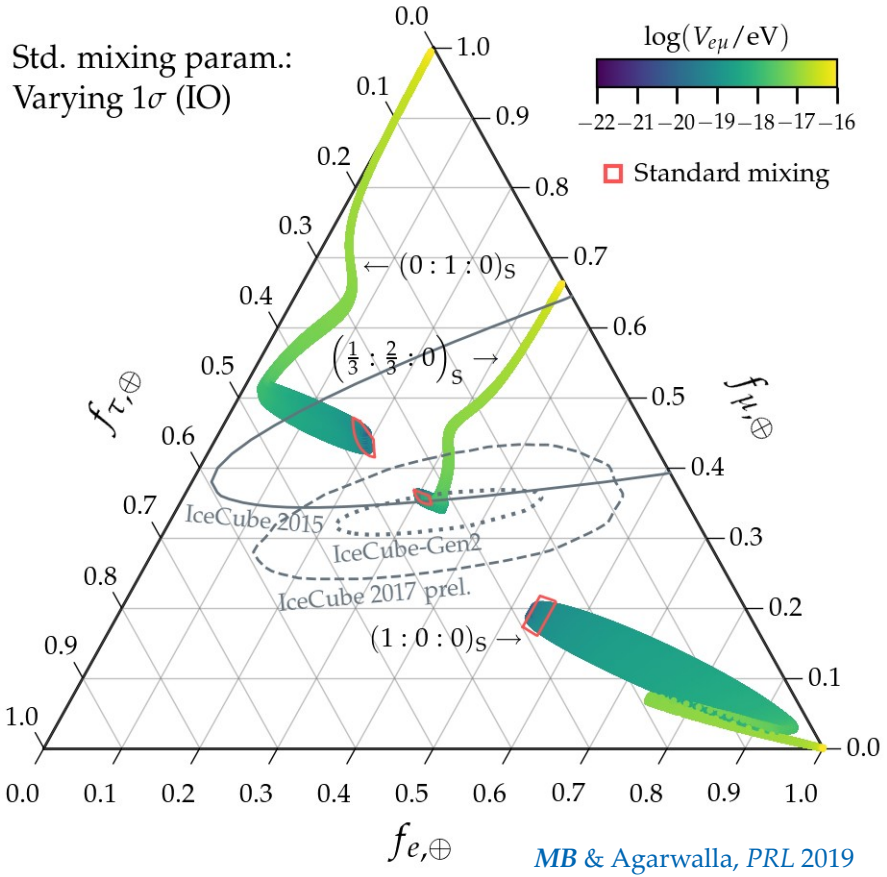
- Long-range *e*ν interactions
  [***MB*** & Agarwalla, *PRL* 2019]



MB & Agarwalla, *PRL* 2019

Reviews:
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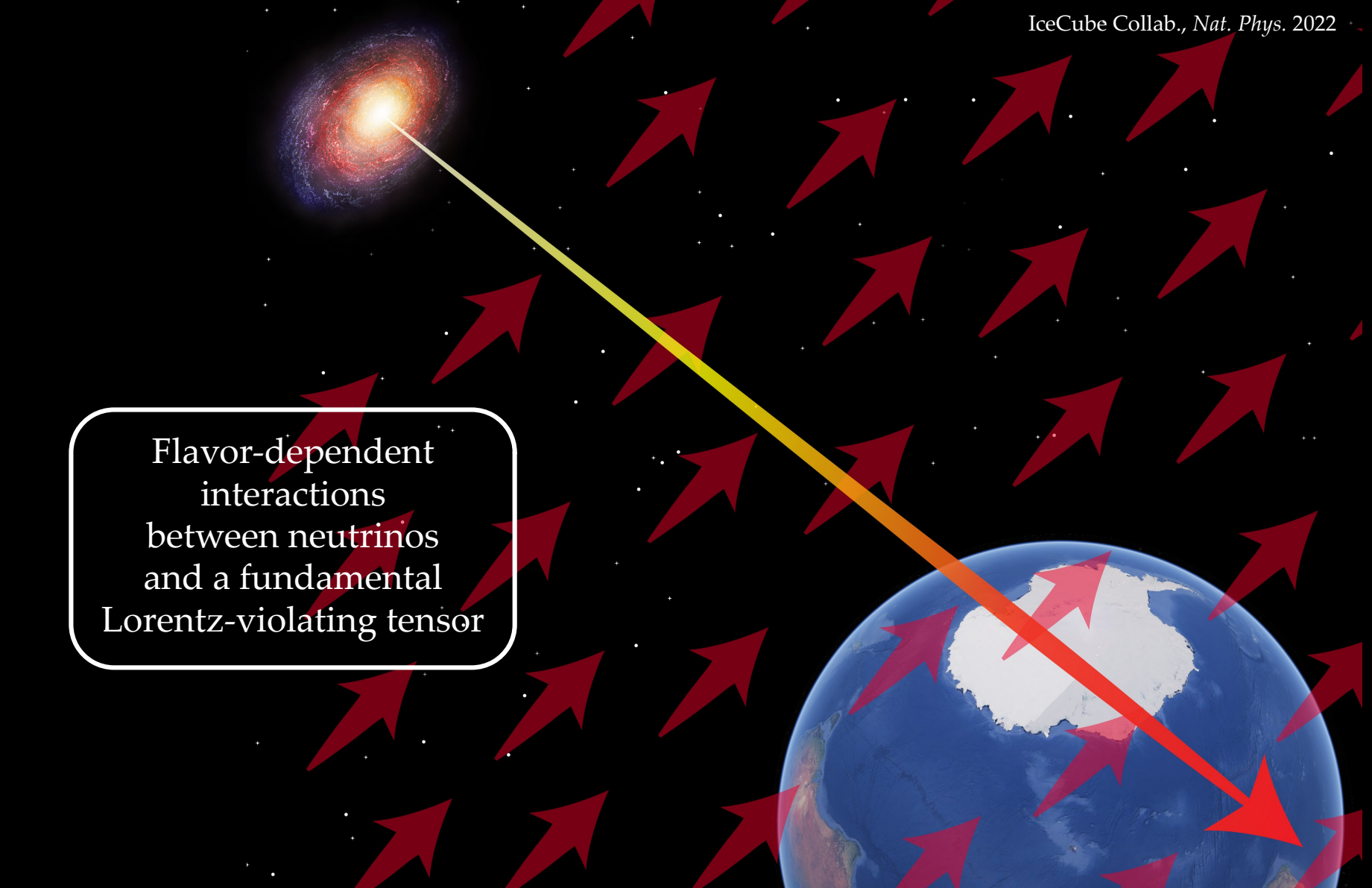
An example:
Lorentz violation


IceCube Collab., *Nat. Phys.* 2022
Flavor-dependent interactions between neutrinos and a fundamental Lorentz-violating tensor

Standard oscillations:

$$H_{\text{std}} = \frac{1}{2E} U_{\text{PMNS}}^{\dagger} \text{diag}(0, \Delta m_{21}^2, \Delta m_{31}^2) U_{\text{PMNS}}$$

Lorentz-violating interactions (Standard Model Extension):

Kostelecky, Mewes, *PRD* 2004

$$H_{\text{new}} = \sum_{n \geq 0} \left(\frac{E}{\Lambda_n} \right)^n U_n^{\dagger} (\mathcal{O}_{n,1}, \mathcal{O}_{n,2}, \mathcal{O}_{n,3}) U_n$$

U_n has the same shape as U_{PMNS},
but its entries are a priori undetermined

Total Hamiltonian:

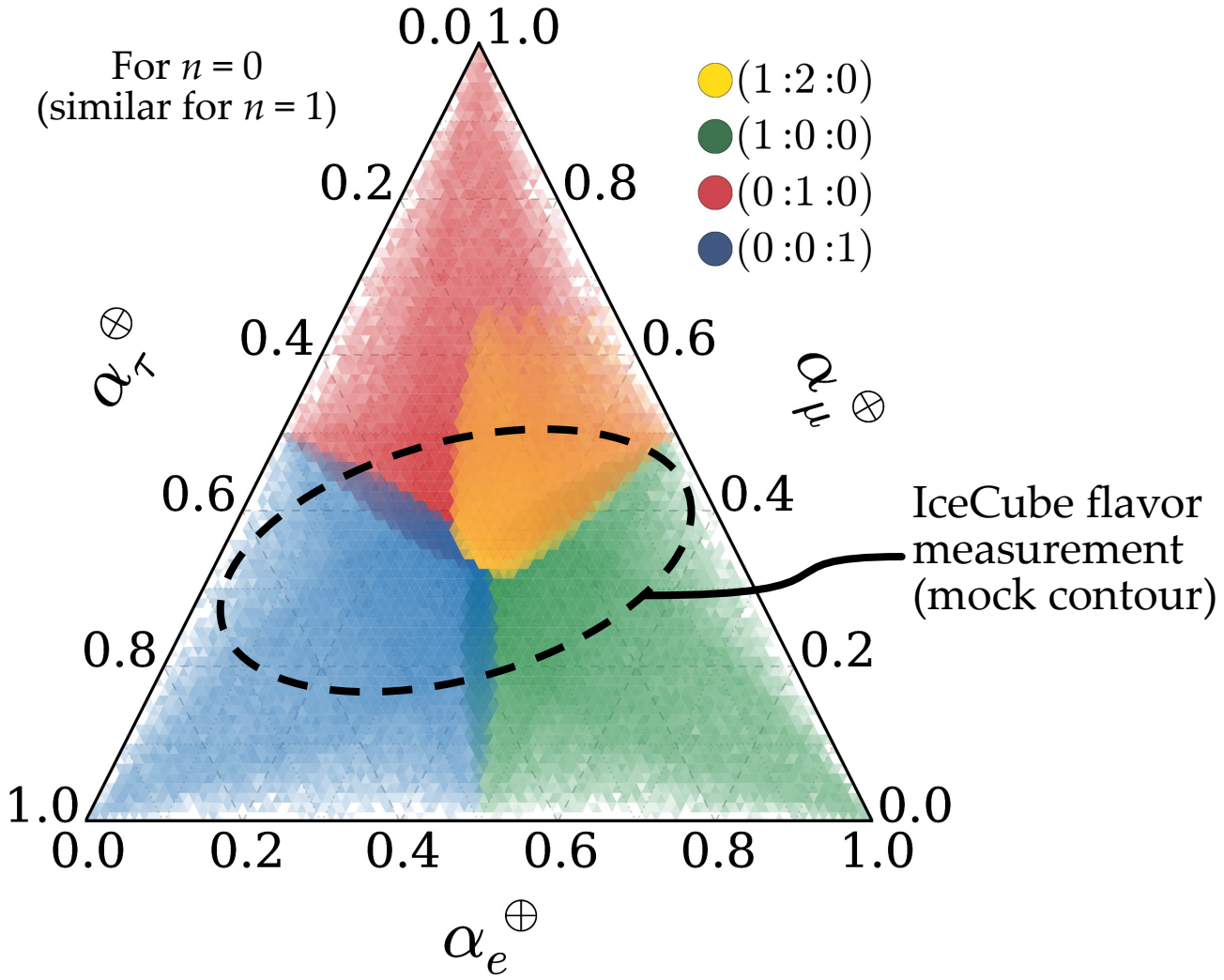
$$H_{\text{tot}} = H_{\text{std}} + H_{\text{new}}$$

The flavor-transition probabilities are calculated as before

$$P_{\alpha\beta} = \sum_{i=1}^{3} |(U_{\text{tot}})_{\alpha i}|^2 |(U_{\text{tot}})_{\beta i}|^2 \ ,$$

Depends on standard & new parameters

but now the lepton mixing matrix, U_{tot}, is the one that diagonalizes H_{tot}



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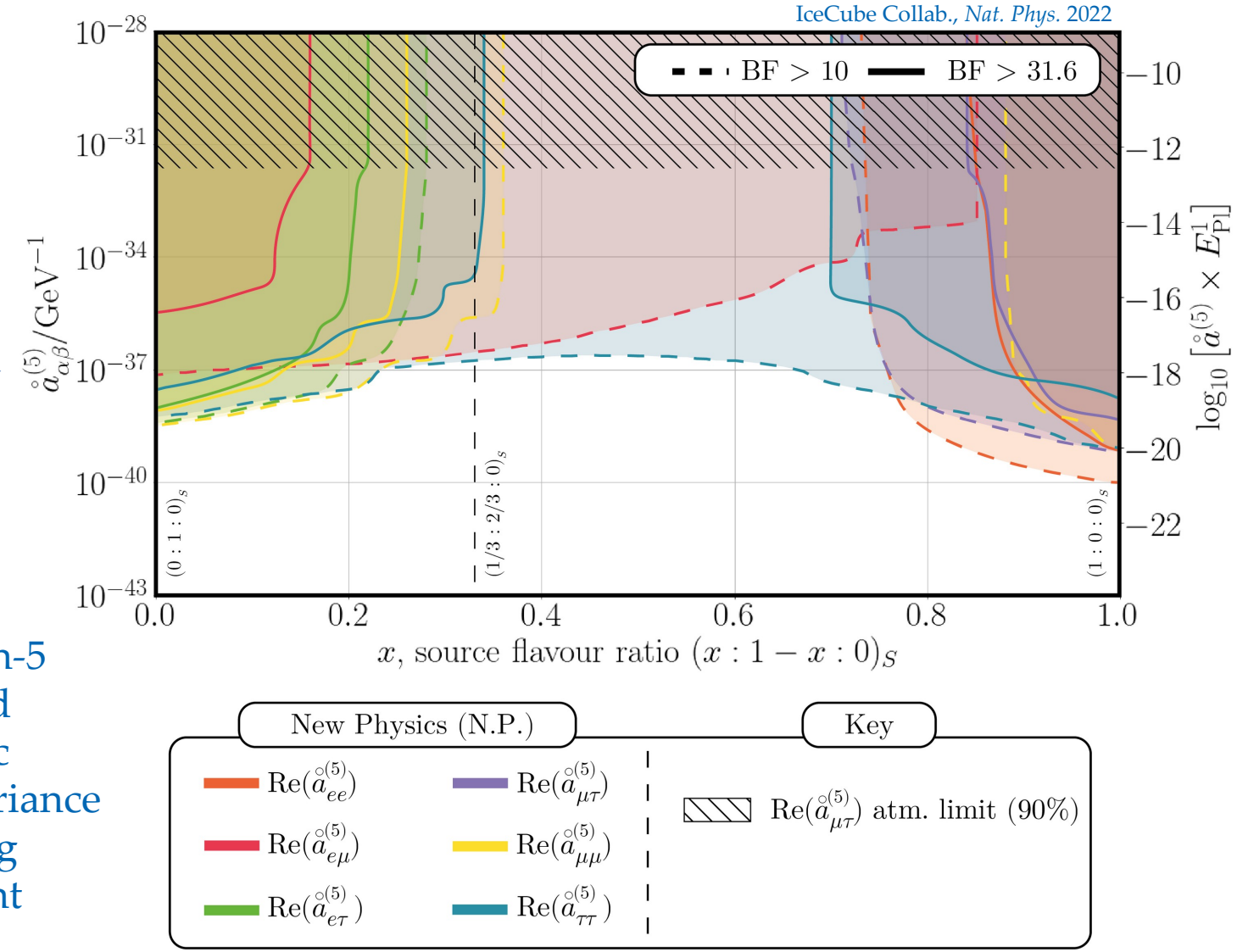
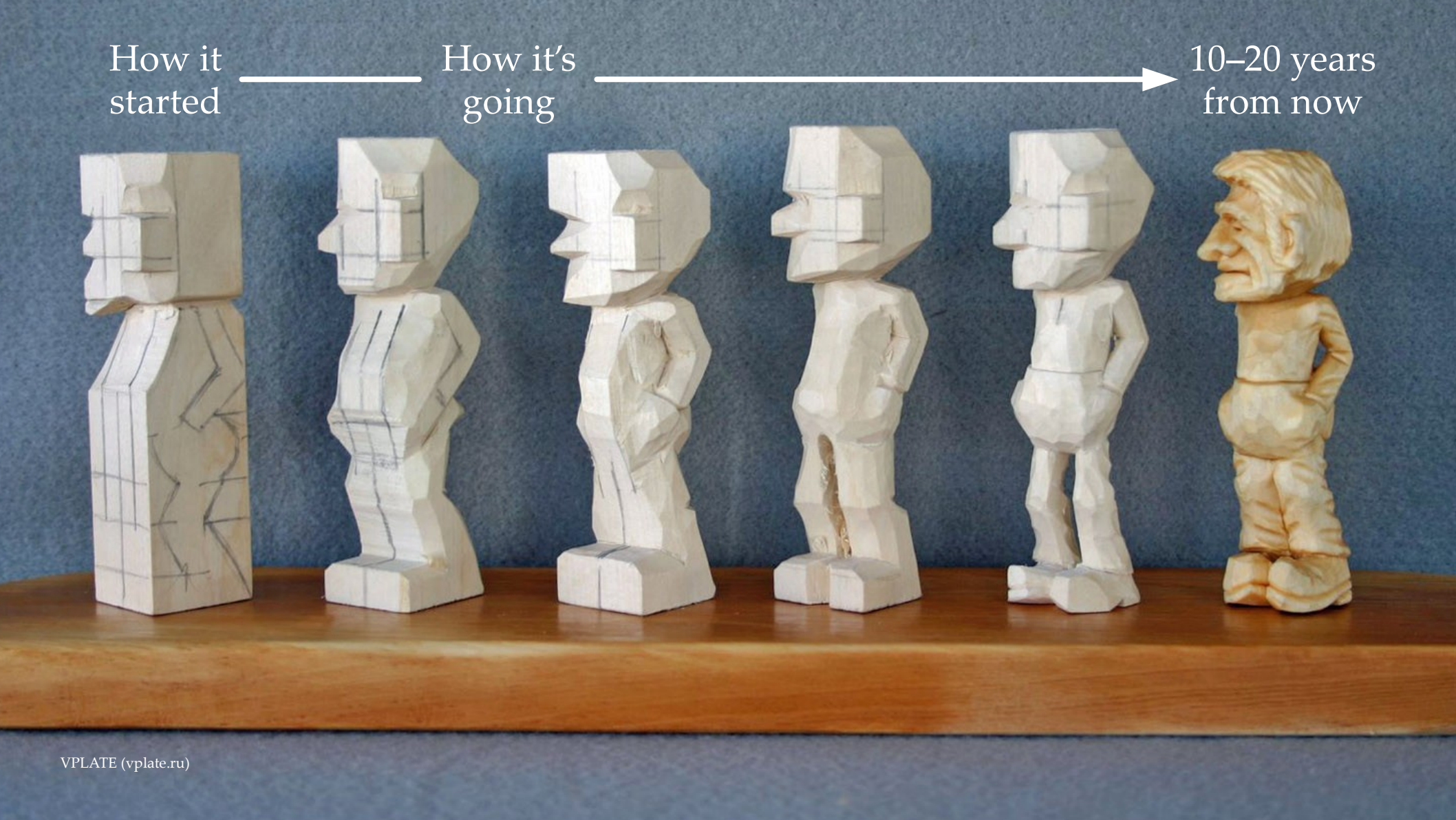
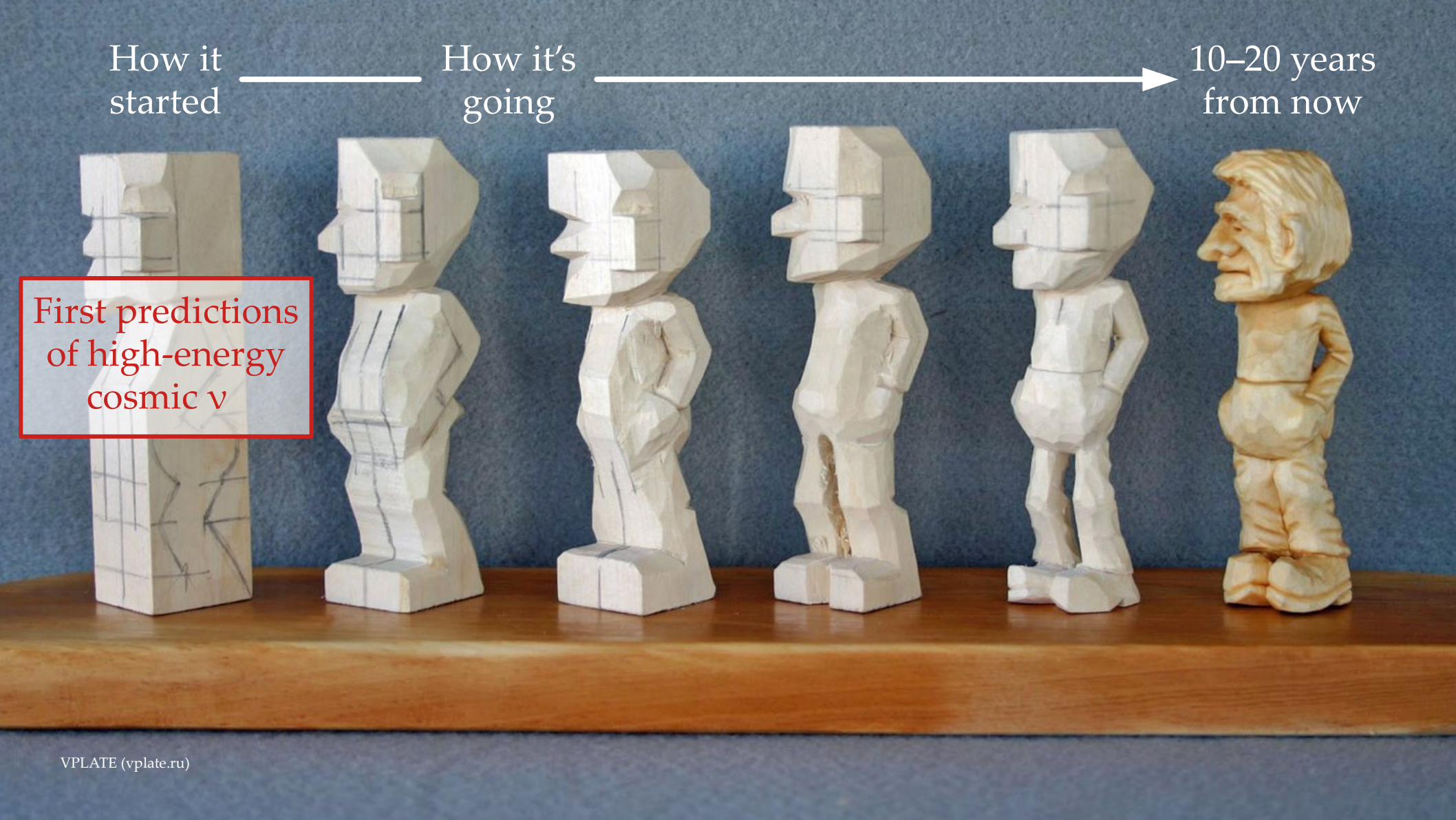
See also Ahlers, **MB**, Mu, *PRD* 2018; Rasmusen *et al.*, *PRD* 2017; **MB**, Beacom, Winter *PRL* 2015; **MB**, Gago, Peña-Garay *JCAP* 2010; Bazo, **MB**, Gago, Miranda *IJMPA* 2009; + many others

IceCube Collab., *Nat. Phys.* 2022



Dimension-5 CPT-odd isotropic Lorentz-invariance -violating coefficient


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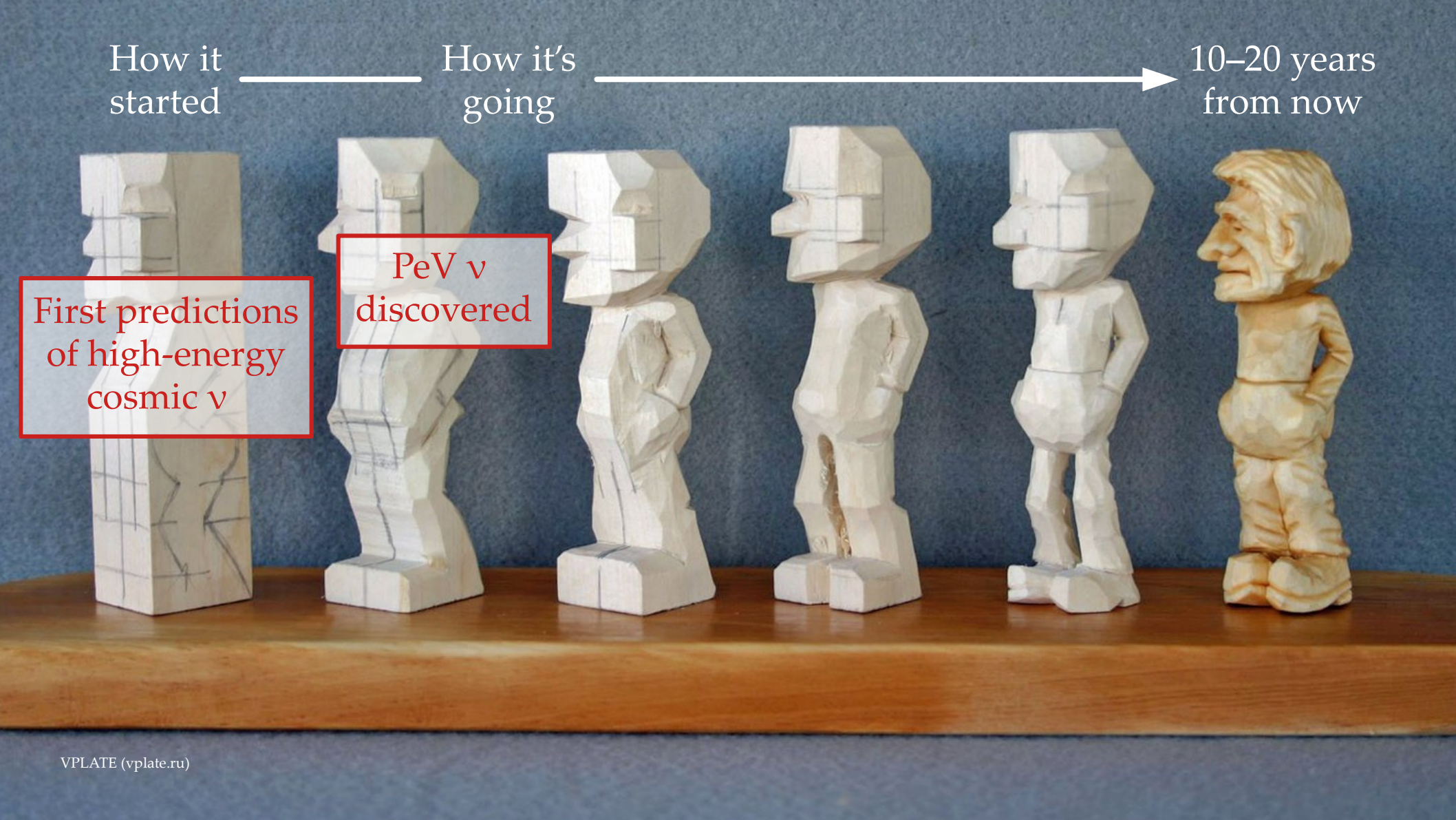
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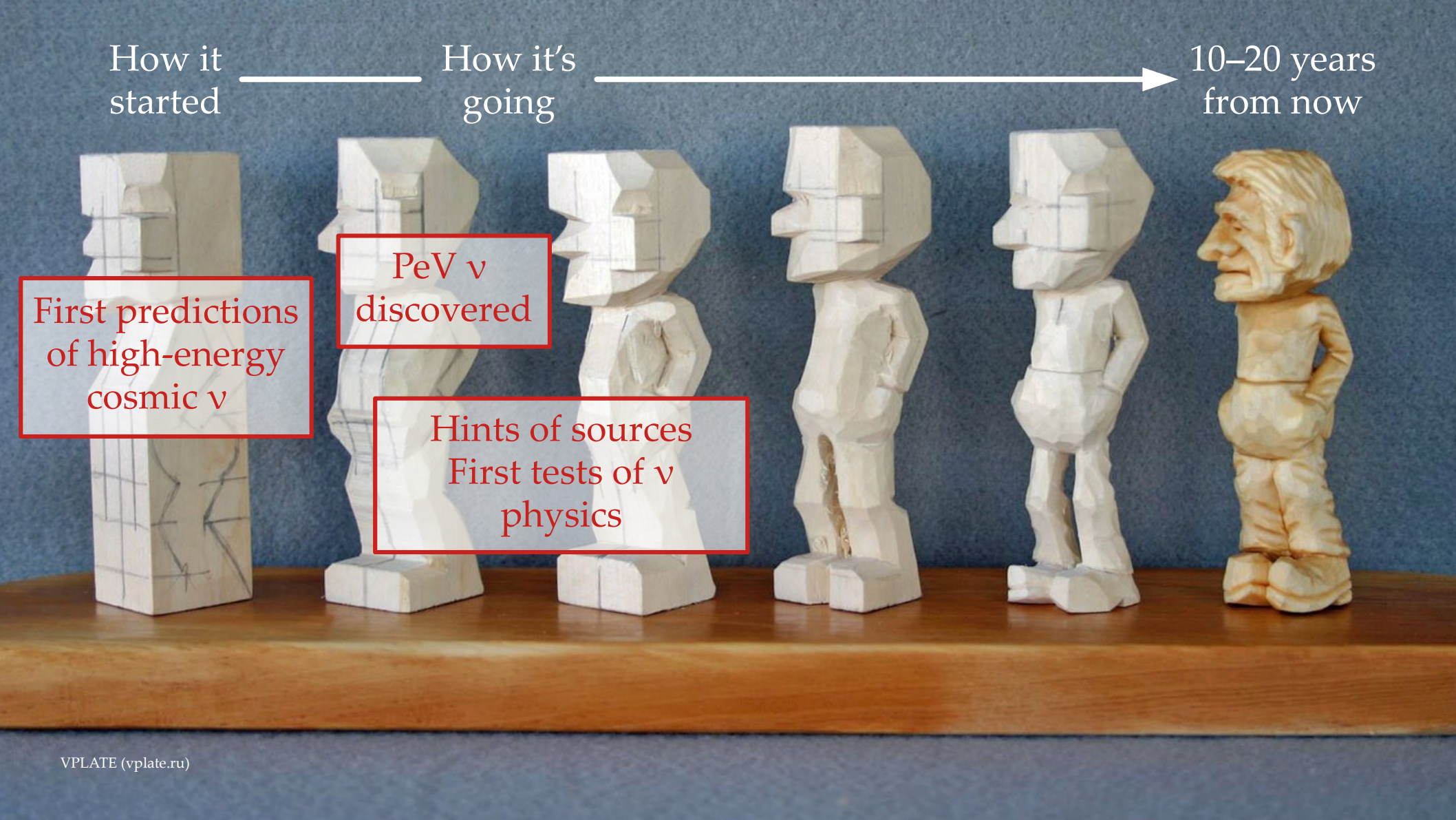
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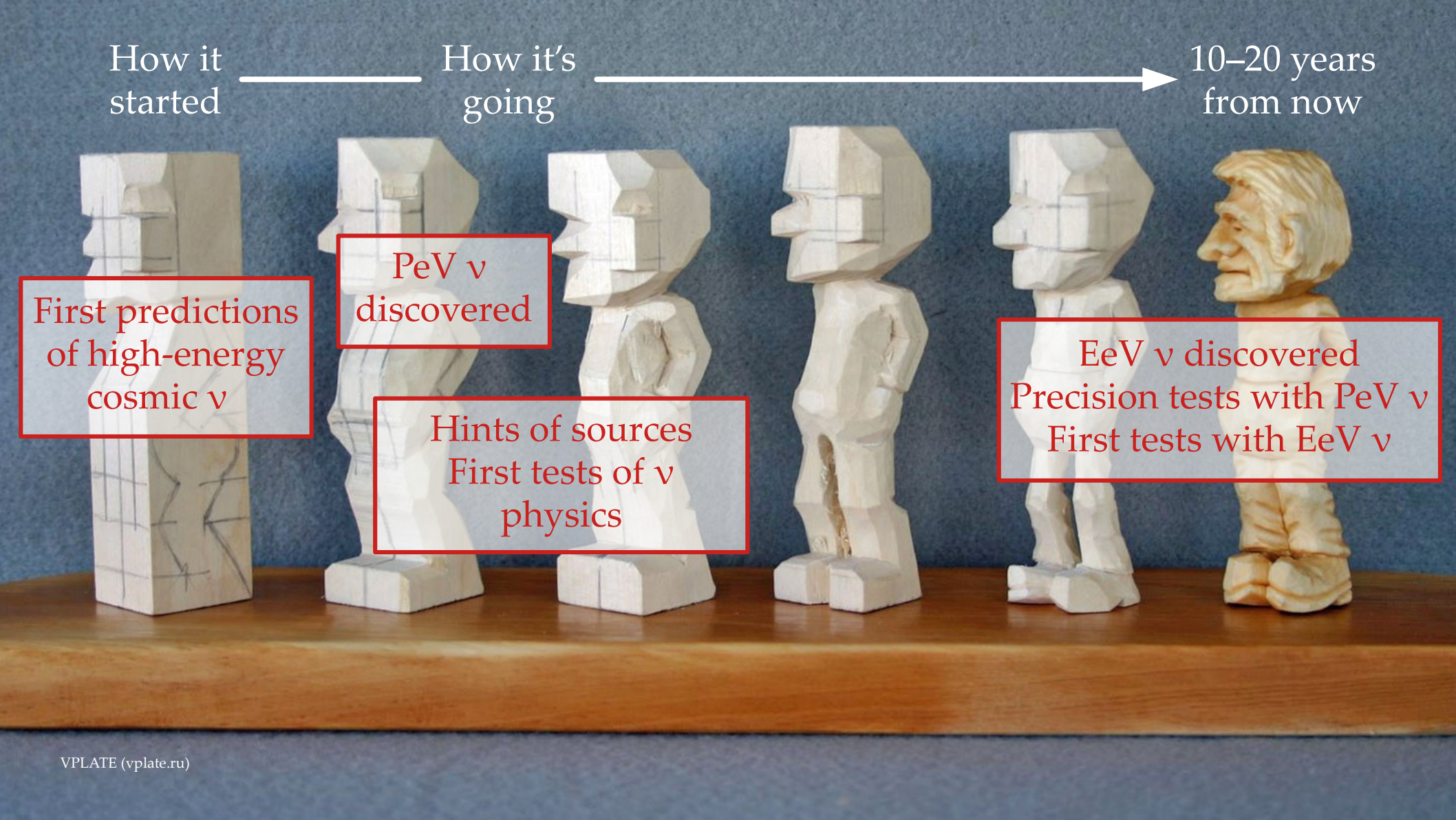
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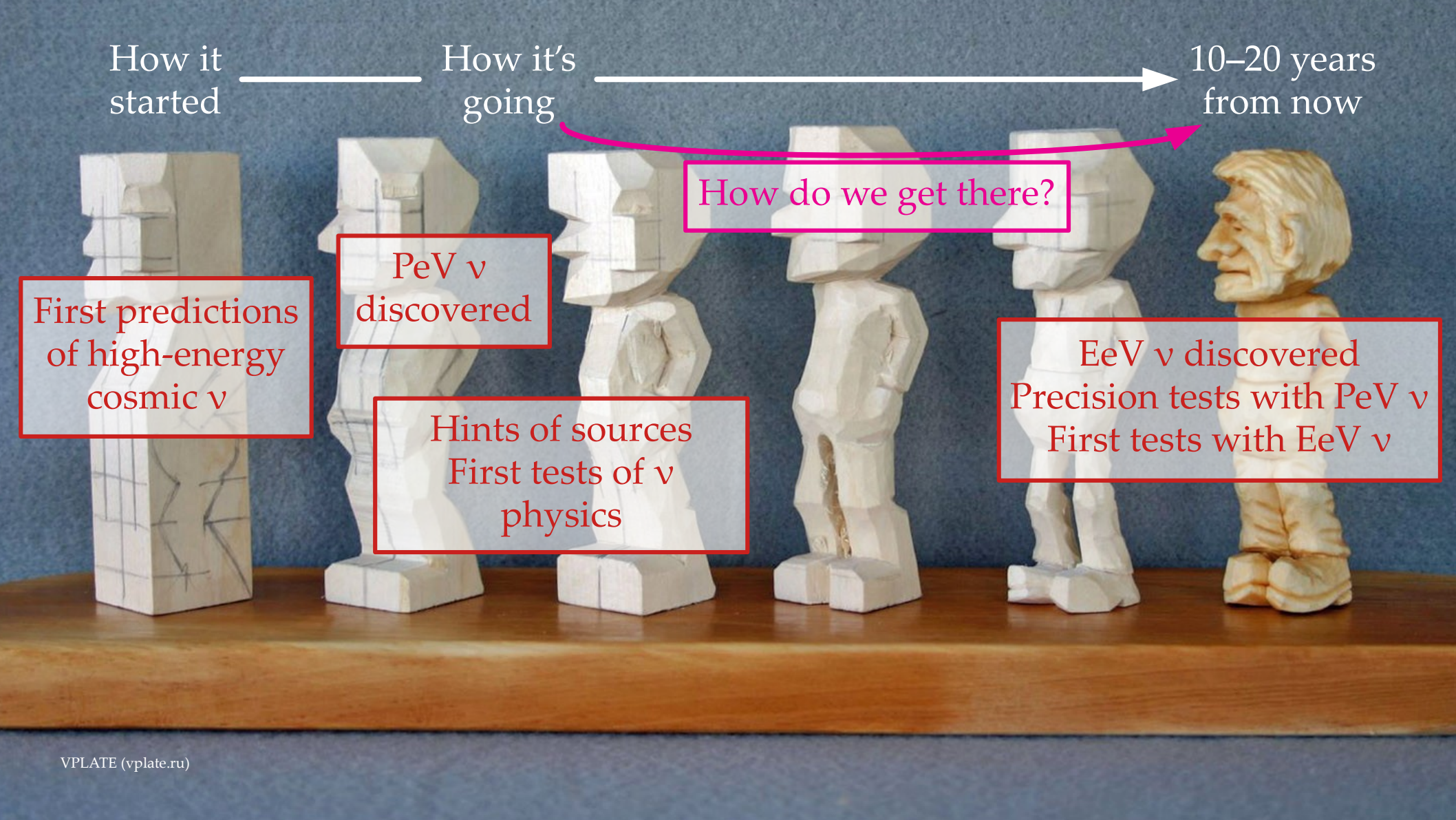
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Thanks!

Backup slides

The multi-messenger connection: a simple picture

(or $p + p$)

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

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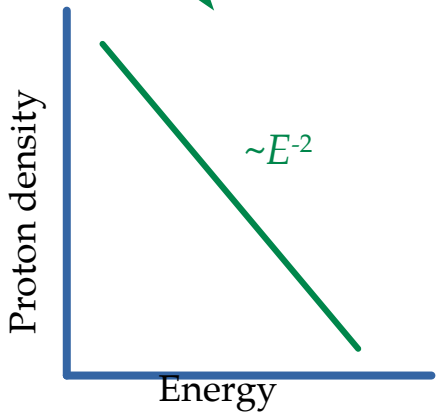

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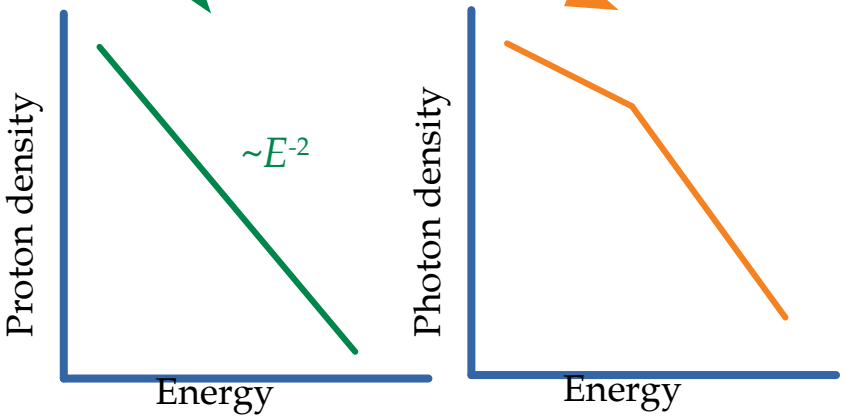

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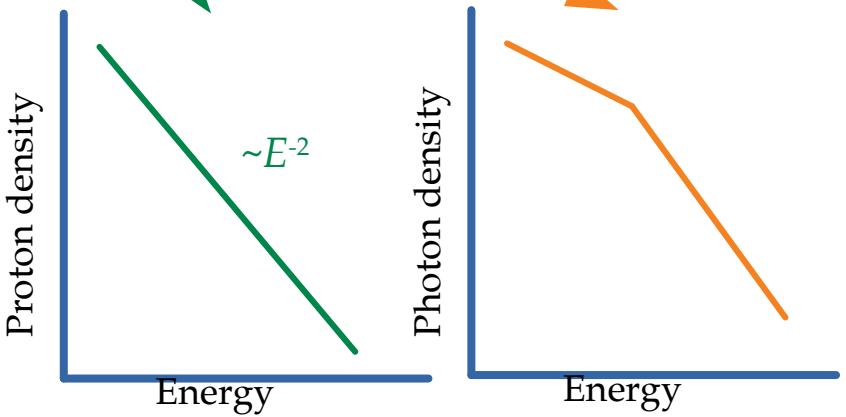
$$\pi^0 \rightarrow \gamma + \gamma$$

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

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



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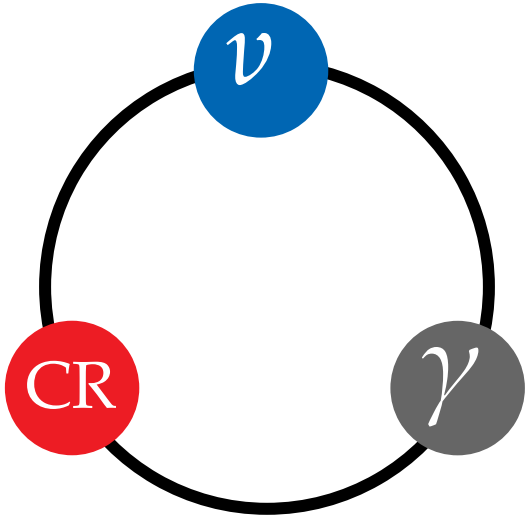

Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 10

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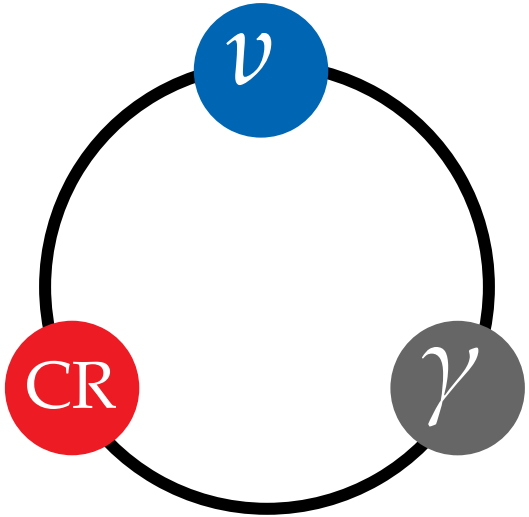

1 PeV 20 PeV

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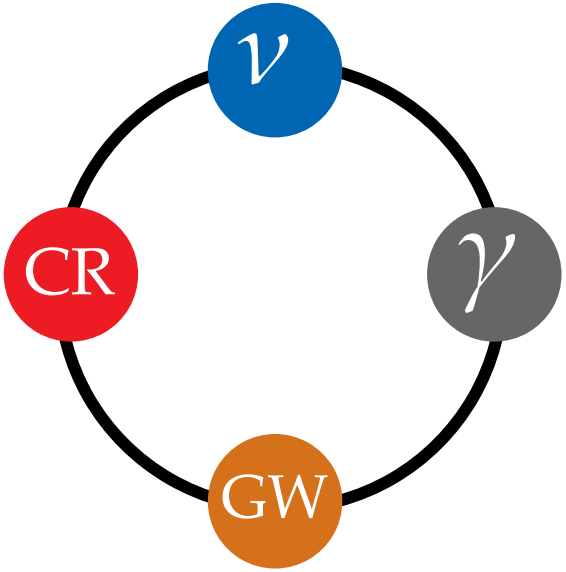

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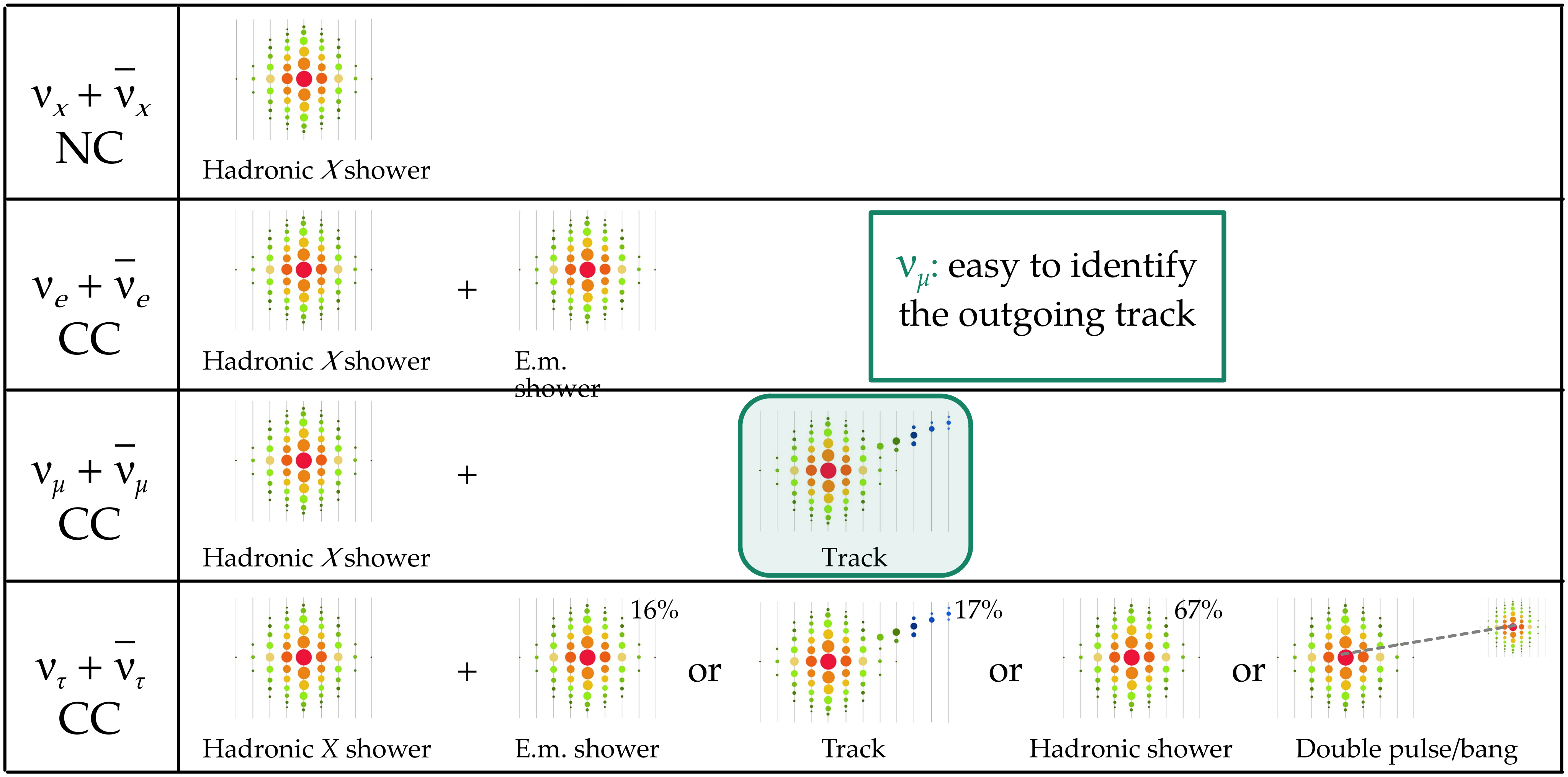
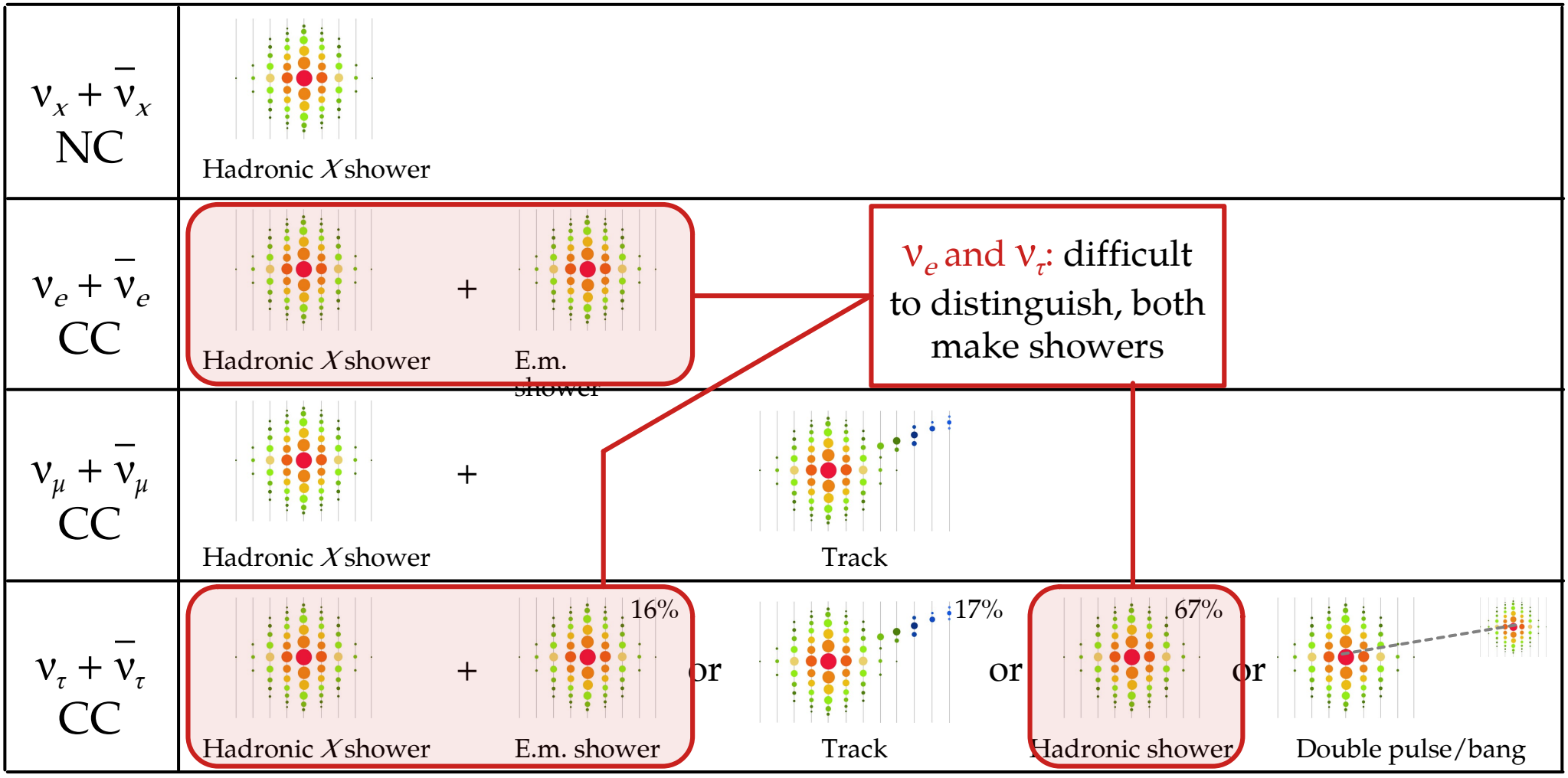
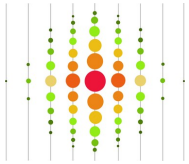
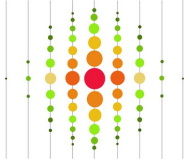
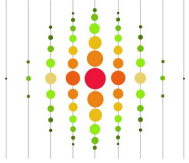
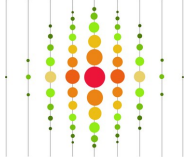
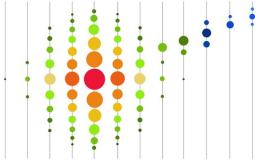
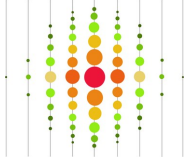
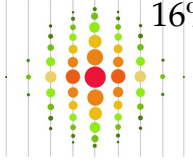
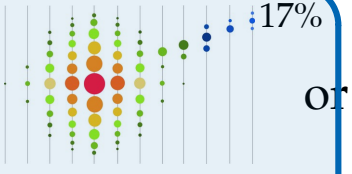
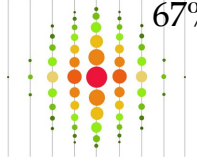
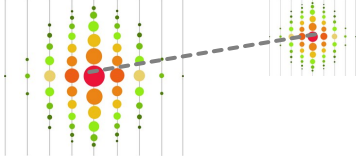


$\nu_x + \bar{\nu}_x$ NC
Hadronic X shower
$\nu_e + \bar{\nu}_e$ CC
Hadronic X shower
+
E.m. shower
ν_μ: easy to identify the outgoing track
$\nu_\mu + \bar{\nu}_\mu$ CC
Hadronic X shower
+
Track
$\nu_\tau + \bar{\nu}_\tau$ CC
Hadronic X shower
+
16%
E.m. shower
or
17%
Track
or
67%
Hadronic shower
or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

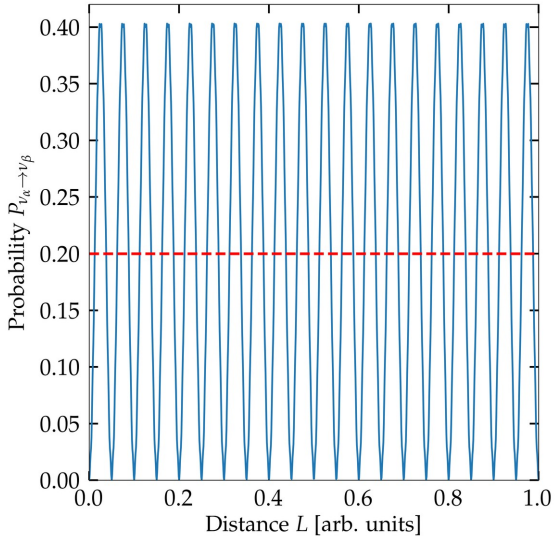
$\nu_x + \bar{\nu}_x$ NC	 Hadronic X shower							
$\nu_e + \bar{\nu}_e$ CC	 Hadronic X shower	+	 E.m. shower					
$\nu_\mu + \bar{\nu}_\mu$ CC	 Hadronic X shower	+			 Track			
$\nu_\tau + \bar{\nu}_\tau$ CC	 Hadronic X shower	+	 E.m. shower	16%	or	 Track	17%	or

The occasional track (weakly) breaks the ν_e / ν_τ degeneracy

 Hadronic shower	67%	or	 Double pulse/bang

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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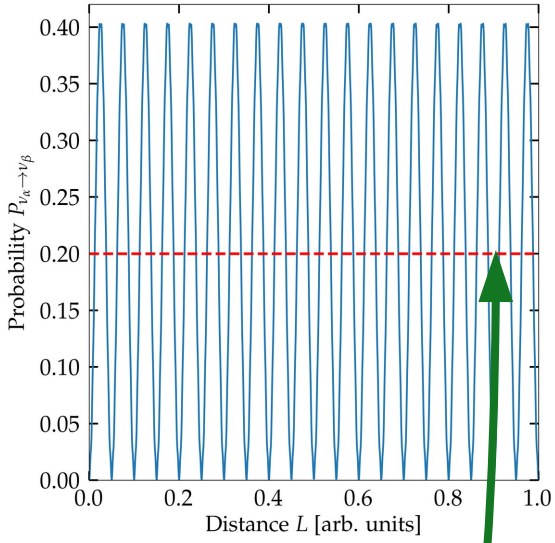

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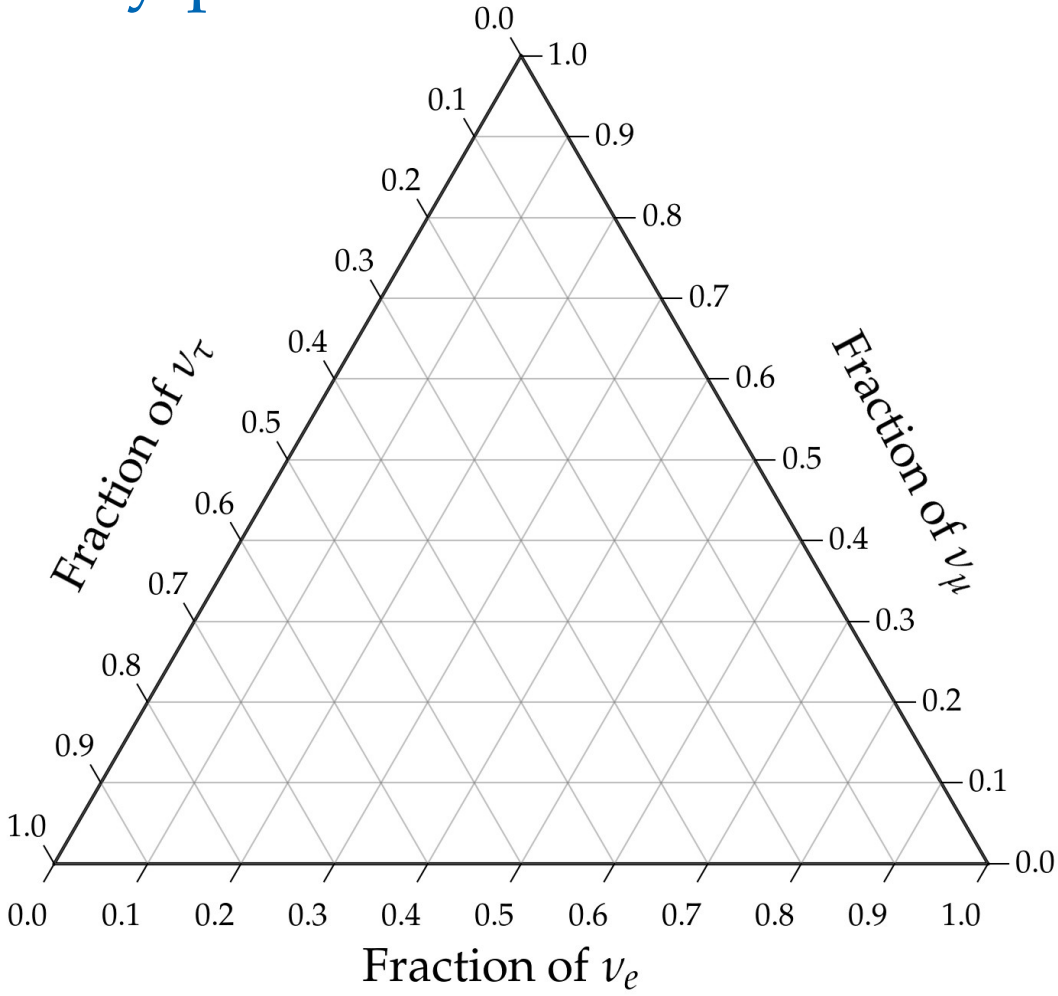
Quick aside: how to read a ternary plot

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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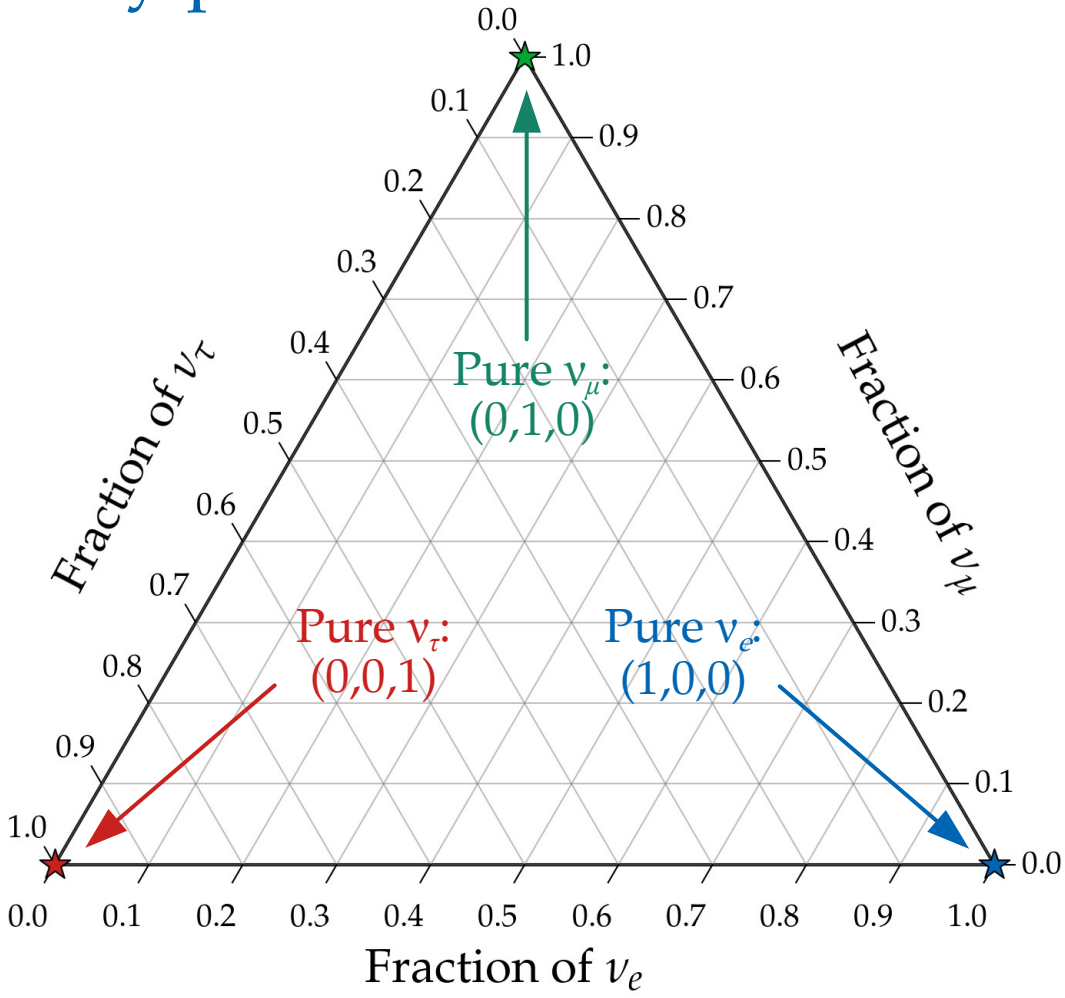

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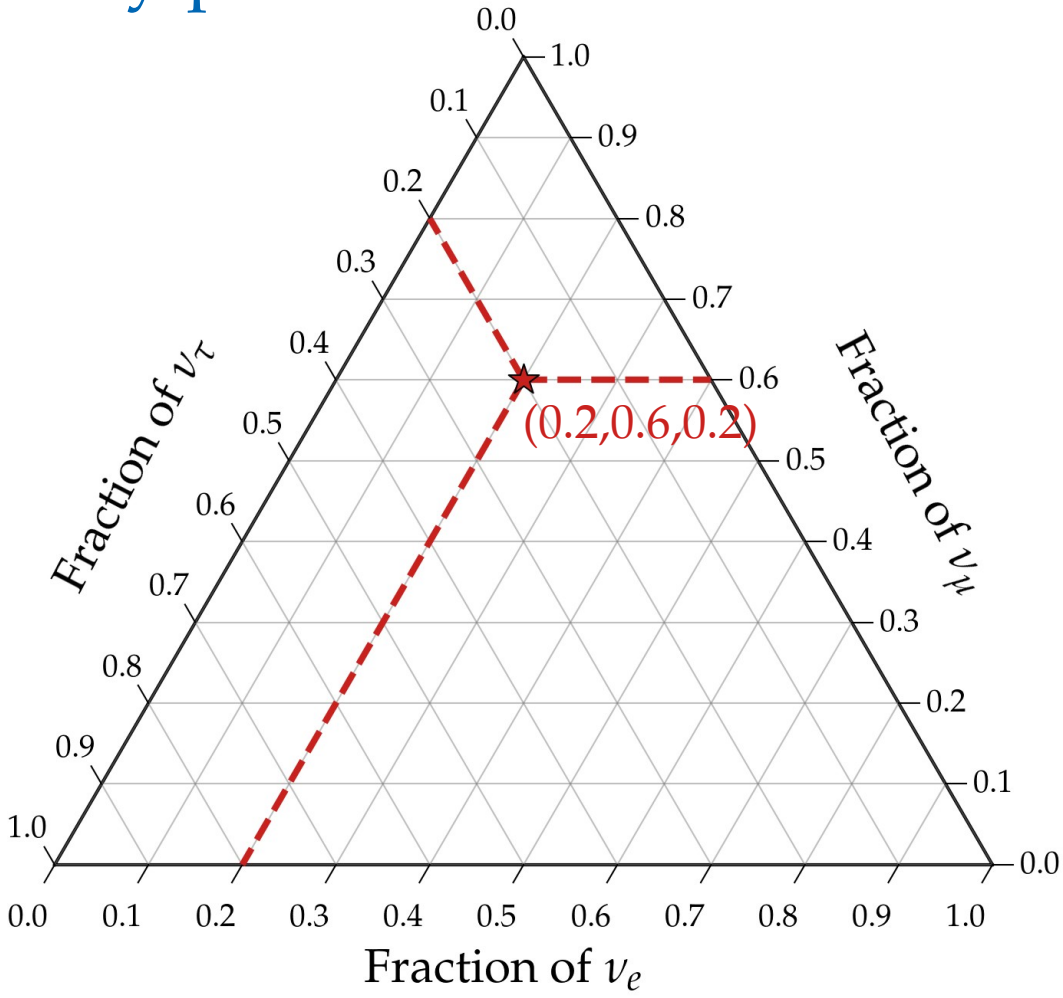

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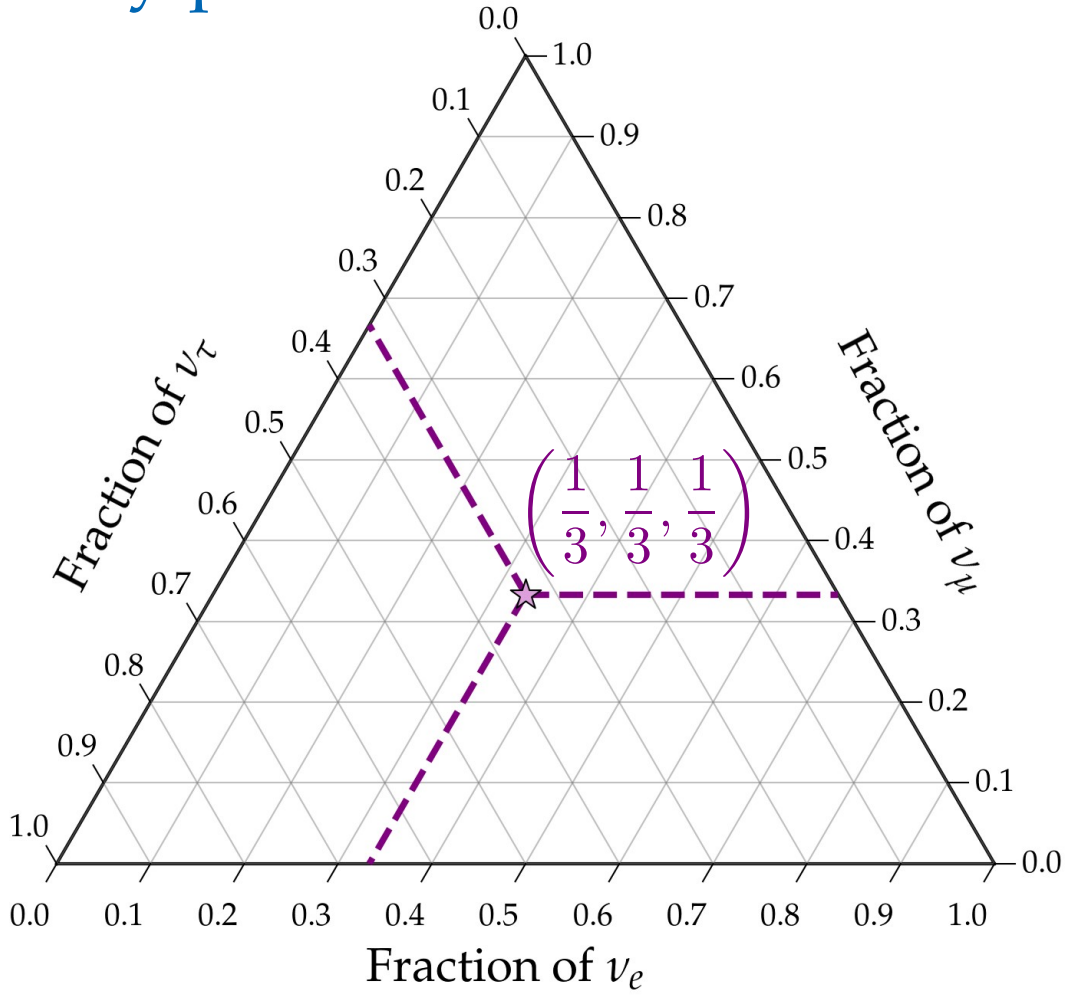
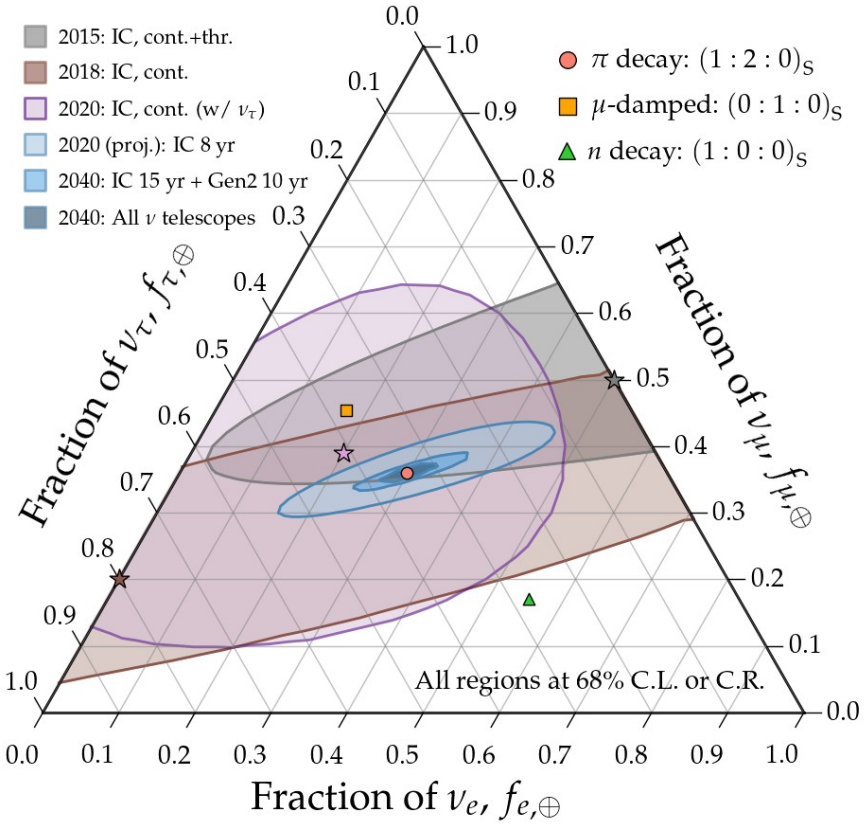


Inferring the flavor composition at the sources

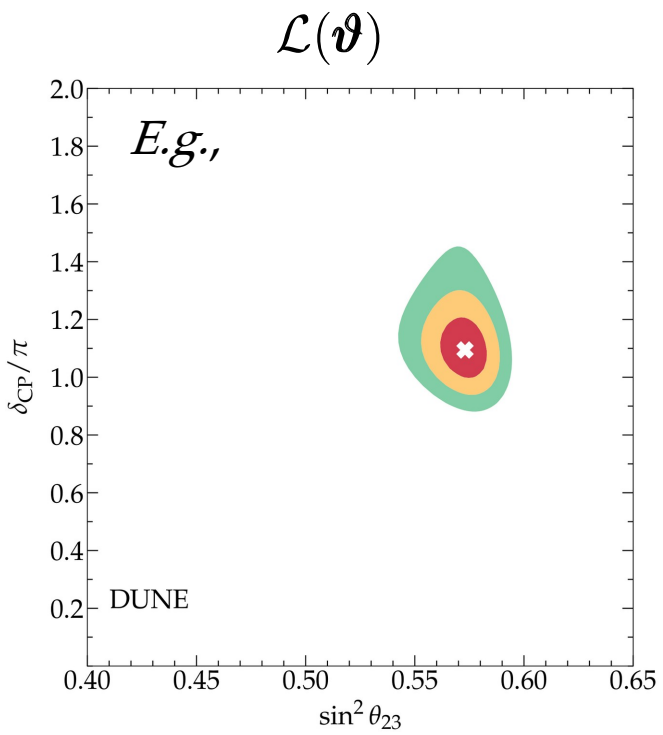
Ingredient #1:

Flavor ratios measured at Earth, $(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$



Ingredient #2:

Probability density of mixing parameters $(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{CP})$



Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
MB & Ahlers, *PRL* 2019

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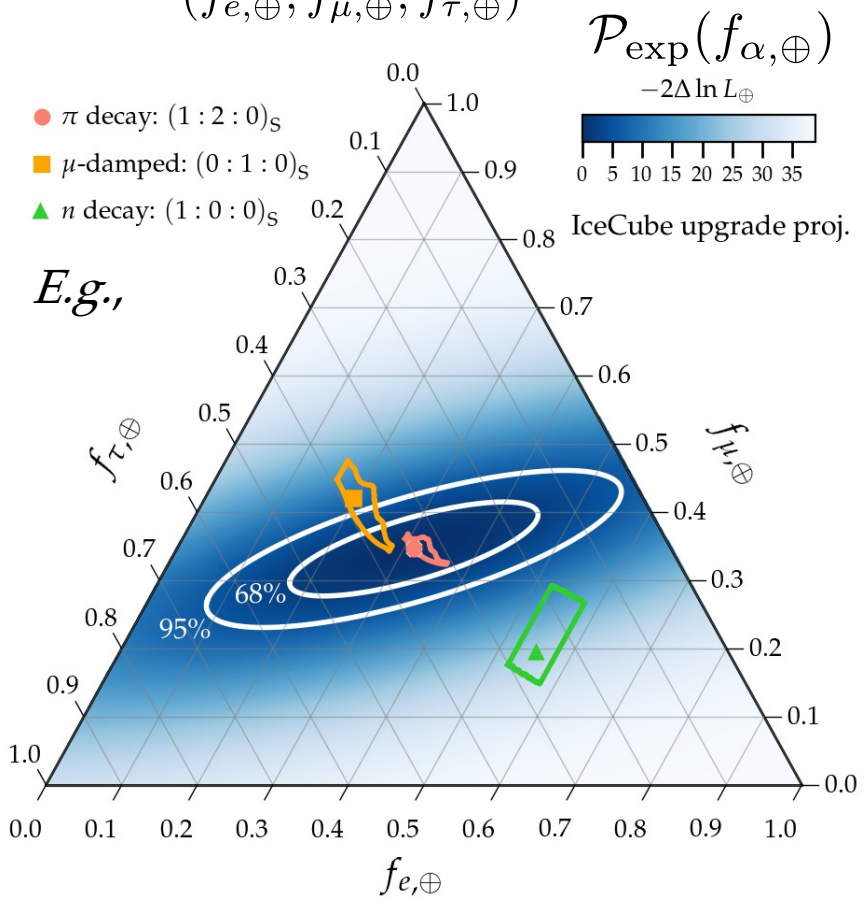

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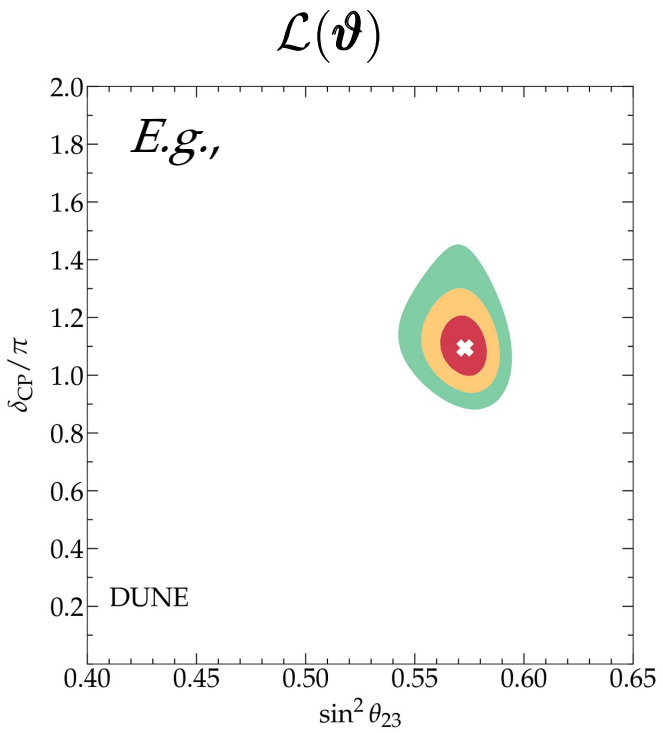

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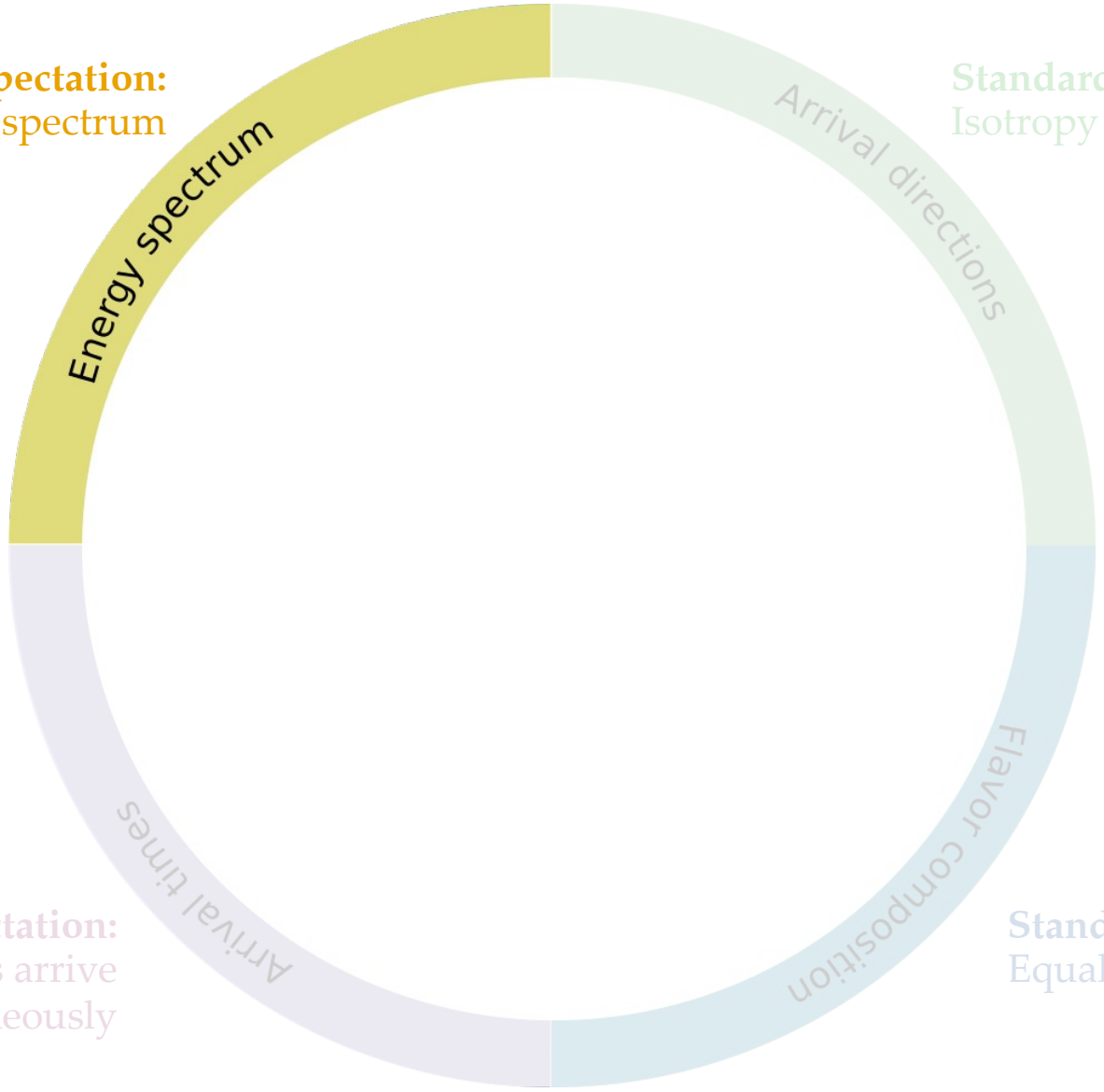
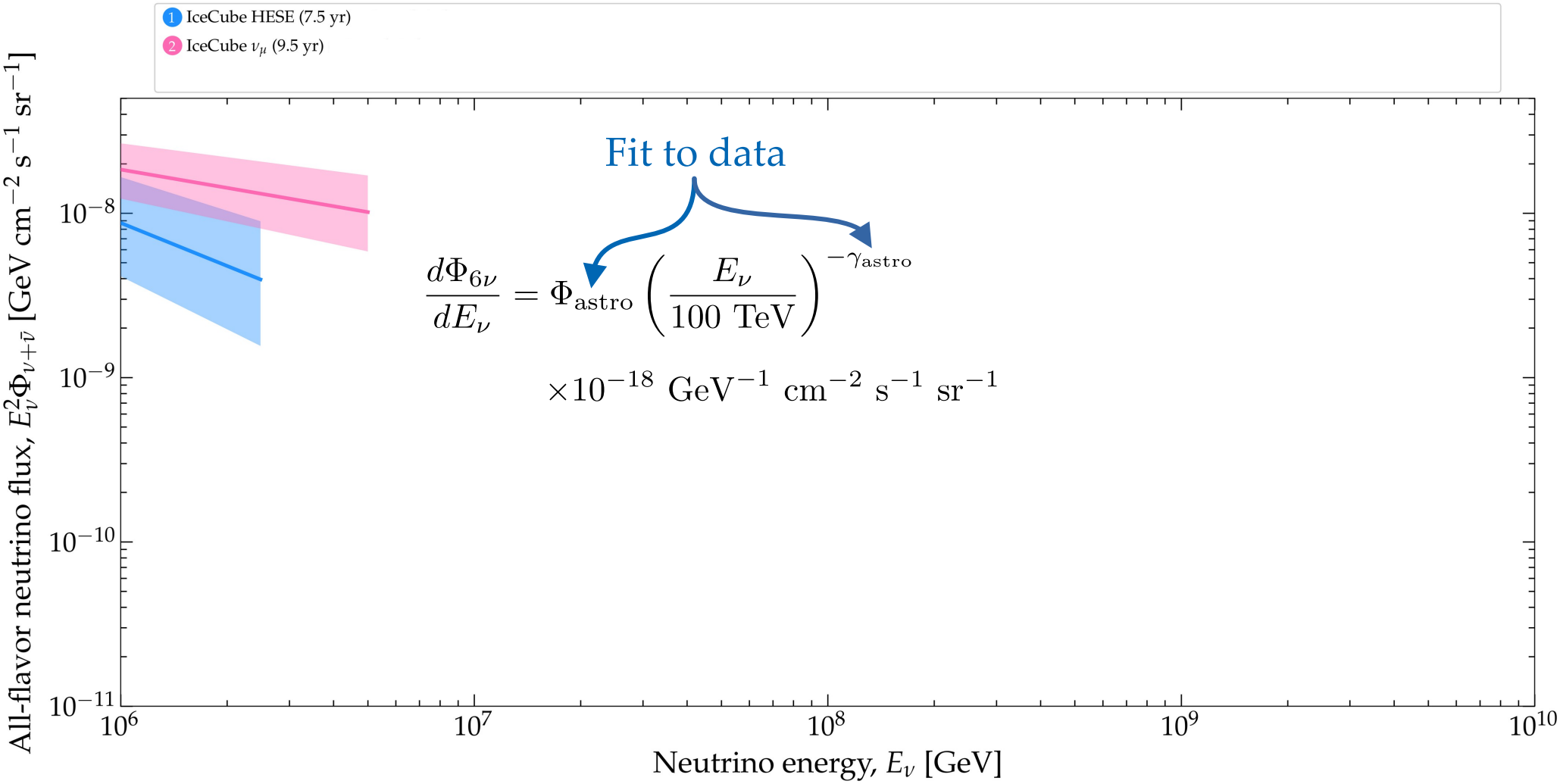


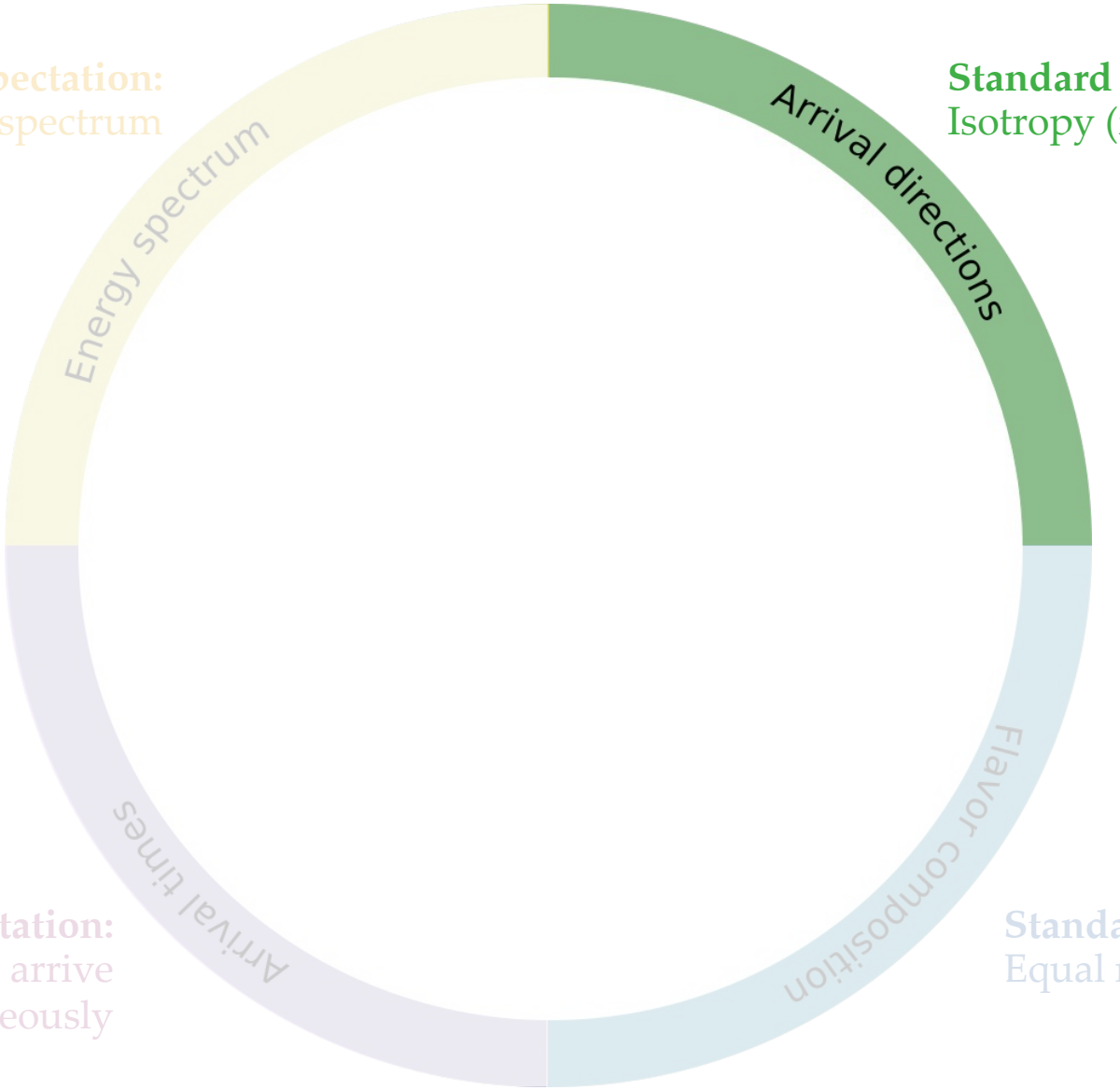
Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Standard expectation:
ν and γ from transients arrive simultaneously


1 IceCube HESE (7.5 yr)
2 IceCube ν_μ (9.5 yr)
Fit to data
$\frac{d\Phi_{6\nu}}{dE_\nu} = \Phi_{\rm astro}\left(\frac{E_\nu}{100\ \rm TeV}\right)^{-\gamma_{\rm astro}}$
$\times 10^{-18}\ \rm GeV^{-1}\ cm^{-2}\ s^{-1}\ sr^{-1}$
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]



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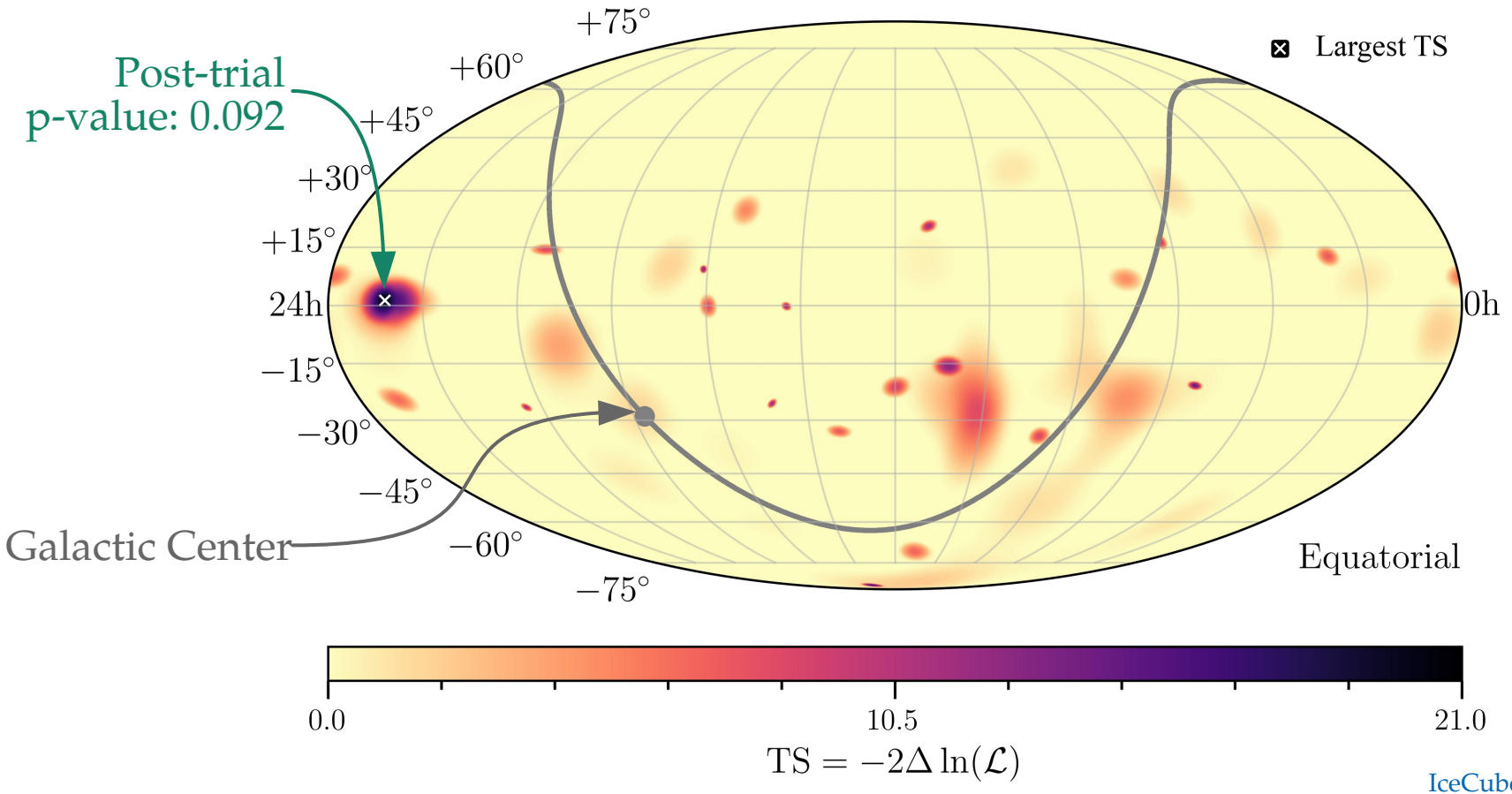
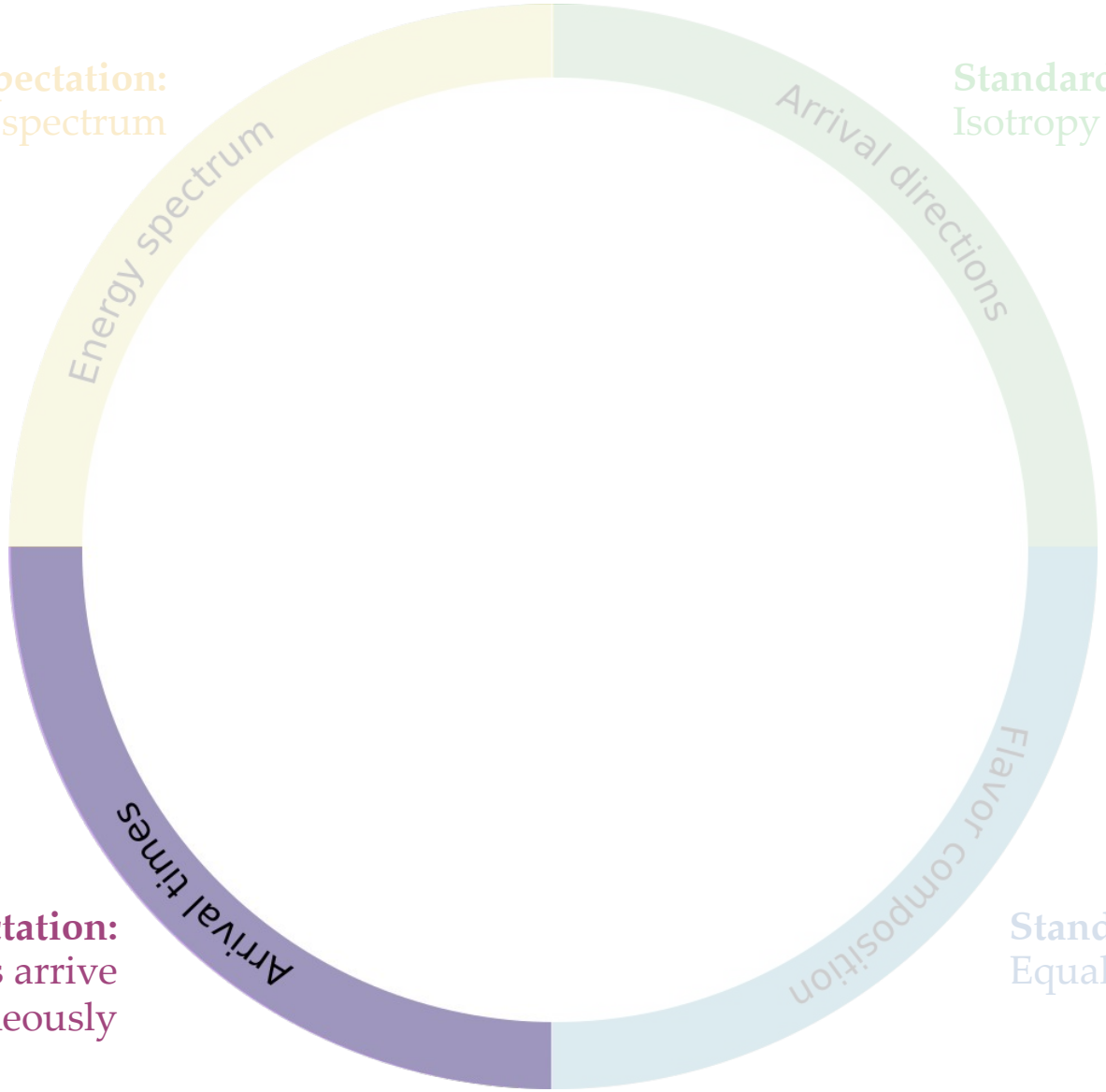
Arrival directions (7.5 yr)

No significant excess in the neutrino sky map:



IceCube, *PRD* 2021



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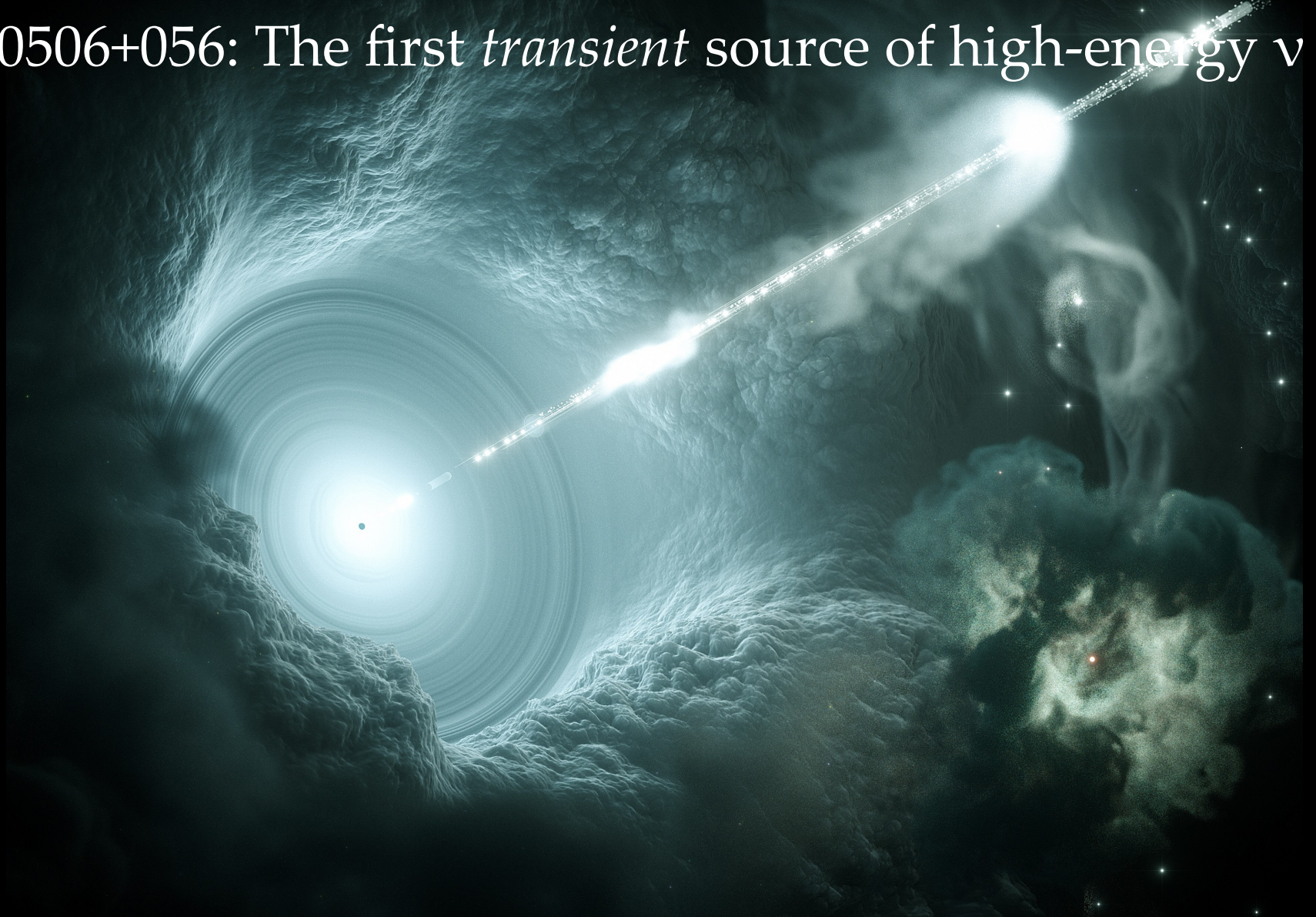
TXS 0506+056: The first *transient* source of high-energy ν

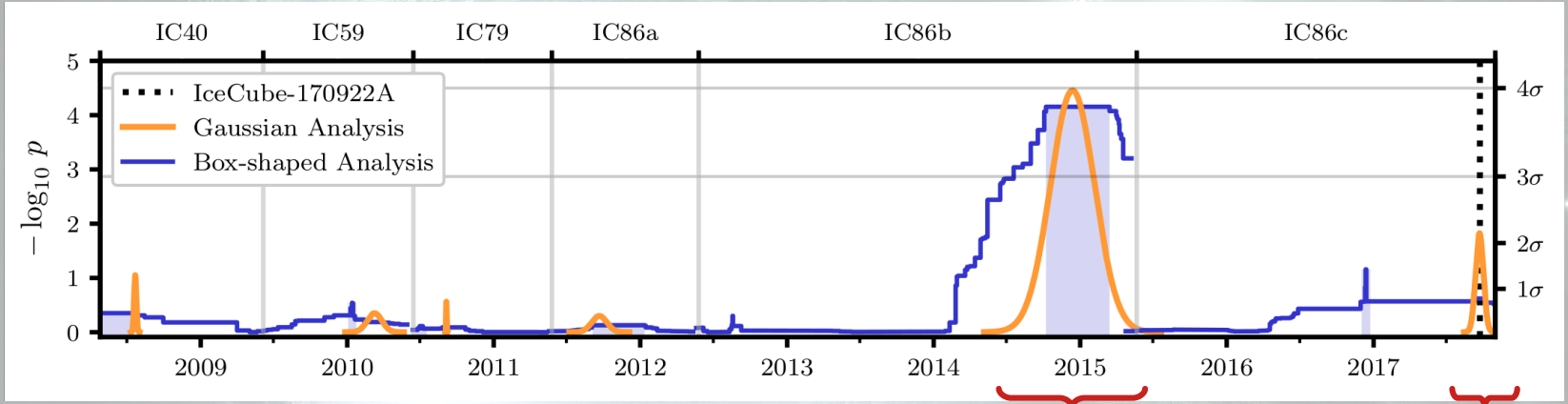


DESY

TXS 0506+056: The first *transient* source of high-energy ν

Blazar TXS 0506+056:

IceCube, *Science* 2018



After re-analysis (2101.09836), significance dropped from $p=7\times10^{-5}$ to $p=8\times10^{-3}$

2014–2015: 13±5 ν flare, no X-ray flare
3.5σ significance of correlation (post-trial)

2017: one 290-TeV ν + X-ray flare
1.4σ significance of correlation

Combined (pre-trial): 4.1σ

Evidence for BSM

Evidence for BSM

Evidence for SM

$$\text{Bayes factor} = \frac{\text{Evidence for BSM}}{\text{Evidence for SM}}$$

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If $B \ll 1$: SM is favored

If $B \gg 1$: BSM is favored

If $B \sim 1$: No preference

$$\text{Bayes factor} = \frac{\text{Evidence for BSM}}{\text{Evidence for SM}}$$

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$$\mathcal{Z}_{\rm SM} = \int \mathcal{L}(\theta_{\rm SM}, \theta_{\rm astro}, \theta_{\rm det}) \pi(\theta_{\rm SM}, \theta_{\rm astro}, \theta_{\rm det}) \mathrm{d}\theta_{\rm SM} \mathrm{d}\theta_{\rm astro} \mathrm{d}\theta_{\rm det}$$

Account for particle-physics + astrophysical + detector uncertainties

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Account for particle-physics + astrophysical + detector uncertainties

Neutrino decay

Are neutrinos forever?

- In the Standard Model (νSM), neutrinos are essentially stable ($\tau > 10^{36}$ yr):
  - One-photon decay ($\nu_i \to \nu_j + \gamma$): $\tau > 10^{36}\ (m_i/\mathrm{eV})^{-5}$ yr
  - Two-photon decay ($\nu_i \to \nu_j + \gamma + \gamma$): $\tau > 10^{57}\ (m_i/\mathrm{eV})^{-9}$ yr
  - Three-neutrino decay ($\nu_i \to \nu_j + \nu_k + \bar{\nu}_k$): $\tau > 10^{55}\ (m_i/\mathrm{eV})^{-5}$ yr

  } » Age of Universe (~ 14.5 Gyr)

- BSM decays may have significantly higher rates: $\nu_i \to \nu_j + \varphi$

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  the nature of φ is unimportant if it is invisible to neutrino detectors

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Astrophysical sources

Earth

L ~ up to a few Gpc

E.g.,

Decay changes the number

of each ν mass eigenstate, N_1, N_2, N_3

?

The flux of ν_i is attenuated by $\exp[-(L/E) \cdot (m_i/\tau_i)]$

Mass of ν_i Lifetime of ν_i

Astrophysical sources

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E.g.,

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Only sensitive to their ratio

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Mass of ν_i Lifetime of ν_i

Astrophysical sources

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L ~ up to a few Gpc

E.g.,

Decay changes the number

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?

Lower-E ν are longer-lived…

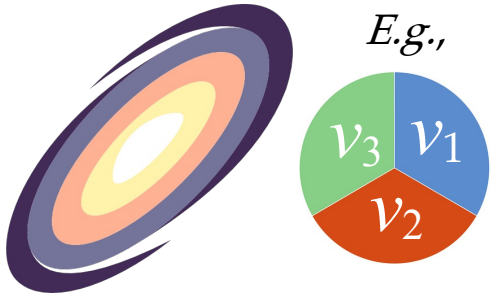
The flux of ν_i is attenuated by $\exp[-(L/E)\cdot(m_i/\tau_i)]$

… but ν that travel longer L are more attenuated!

Astrophysical sources

Earth

L ~ up to a few Gpc



E.g.,

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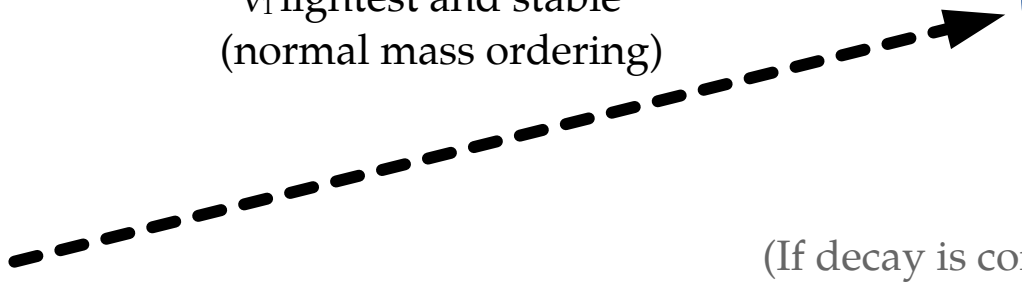
$L \sim$ up to a few Gpc

$\nu_2, \nu_3 \rightarrow \nu_1$

ν_1 lightest and stable
(normal mass ordering)

E.g.,



(If decay is complete)

Astrophysical sources

Earth

$L \sim$ up to a few Gpc

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ν_1 lightest and stable
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E.g.,

ν_1

(If decay is complete)

$\nu_1, \nu_2 \rightarrow \nu_3$

ν_3

ν_3 lightest and stable
(inverted mass
ordering)

Astrophysical sources

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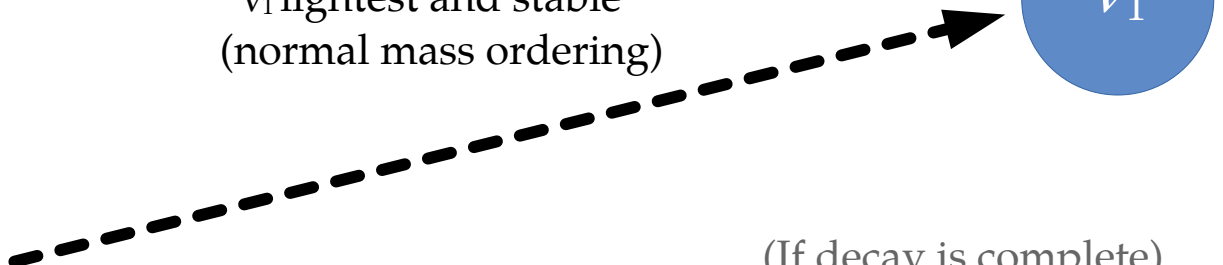

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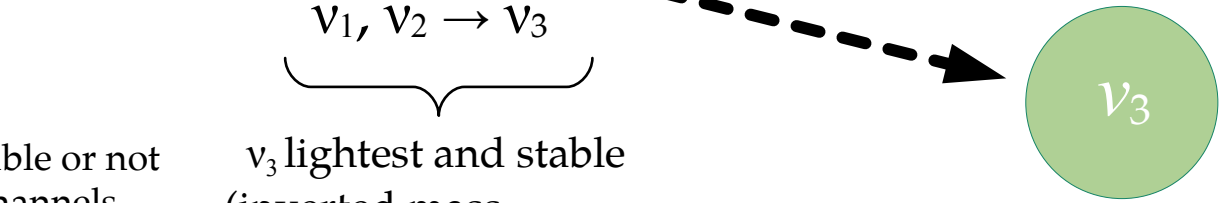

$\nu_1, \nu_2 \rightarrow \nu_3$

ν_3 lightest and stable
(inverted mass
ordering)

Fine print:

- Decay can be incomplete
- Final-state ν might be detectable or not
- Many more possible decay channels
  (see Winter & Mehta, *JCAP* 2011)

Astrophysical sources

Earth

$L \sim$ up to a few Gpc

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ν_1 lightest and stable
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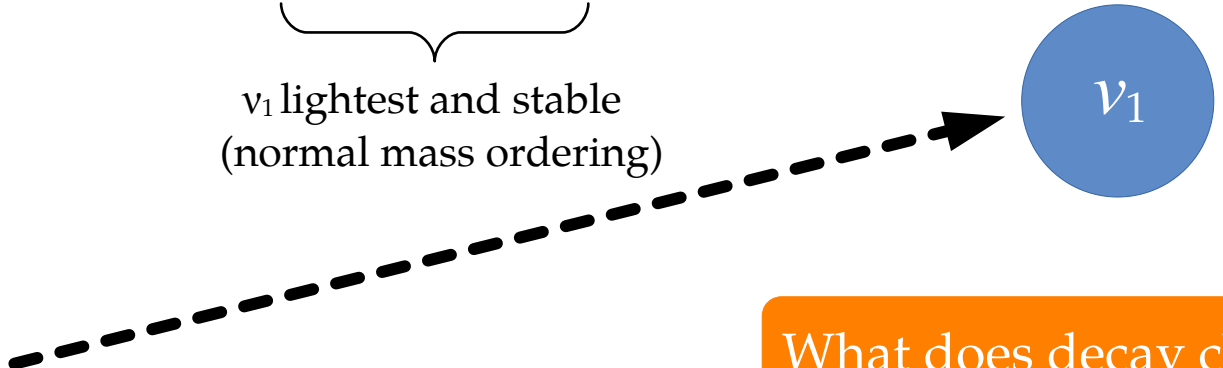
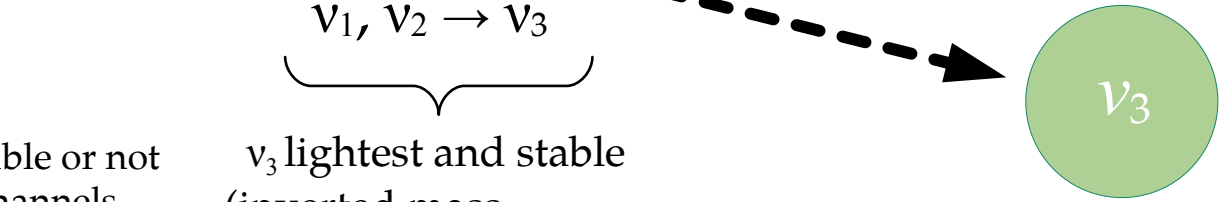
E.g.,





What does decay change?

$\nu_1, \nu_2 \rightarrow \nu_3$

ν_3 lightest and stable
(inverted mass
ordering)

Fine print:

- Decay can be incomplete
- Final-state ν might be detectable or not
- Many more possible decay channels
  (see Winter & Mehta, *JCAP* 2011)

What does neutrino decay change?

Flavor composition ⟺ Spectrum shape ⟺ Event rate

What does neutrino decay change?

Flavor composition ⟺ Spectrum shape ⟺ Event rate

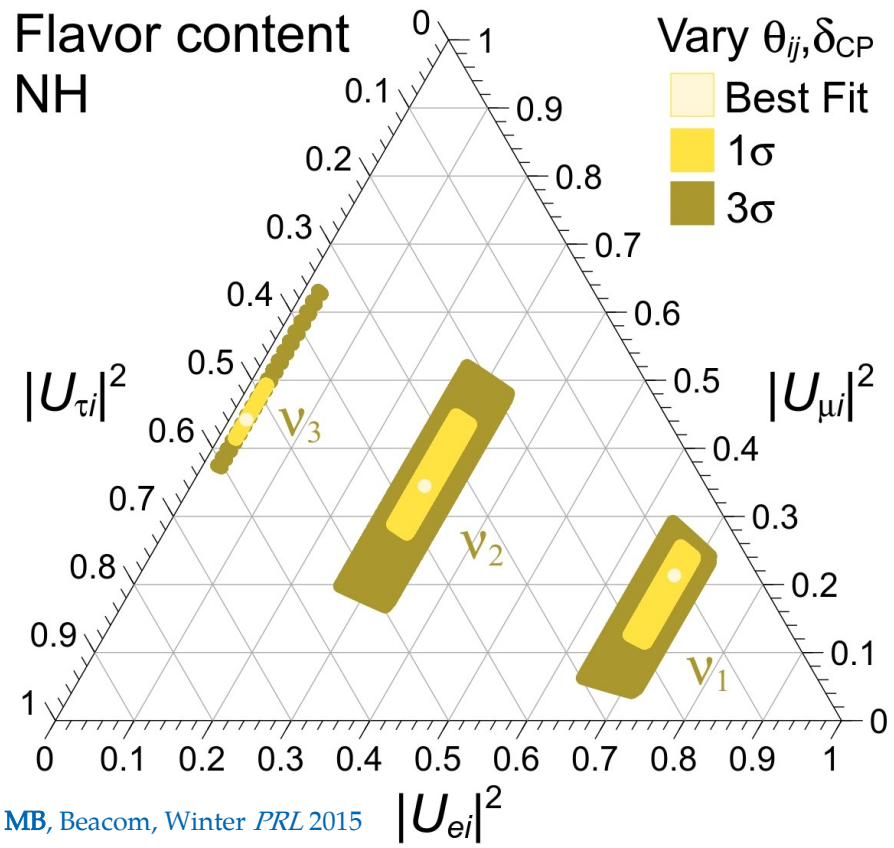
Flavor content of mass eigenstates:

Known to within 2%

$$|U_{\alpha i}|^2 = |U_{\alpha i}(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{CP})|^2$$

Known to within 8%

Known to within 20% (or worse)



MB, Beacom, Winter *PRL* 2015

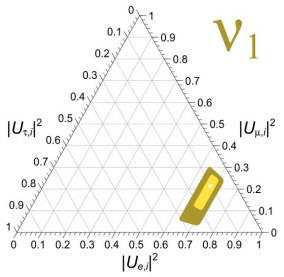
What does neutrino decay change?

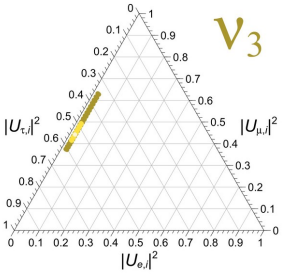
Flavor composition ⟺ Spectrum shape ⟺ Event rate

$\nu_2, \nu_3 \to \nu_1$

ν_1 lightest and stable (normal mass ordering)

E.g.,





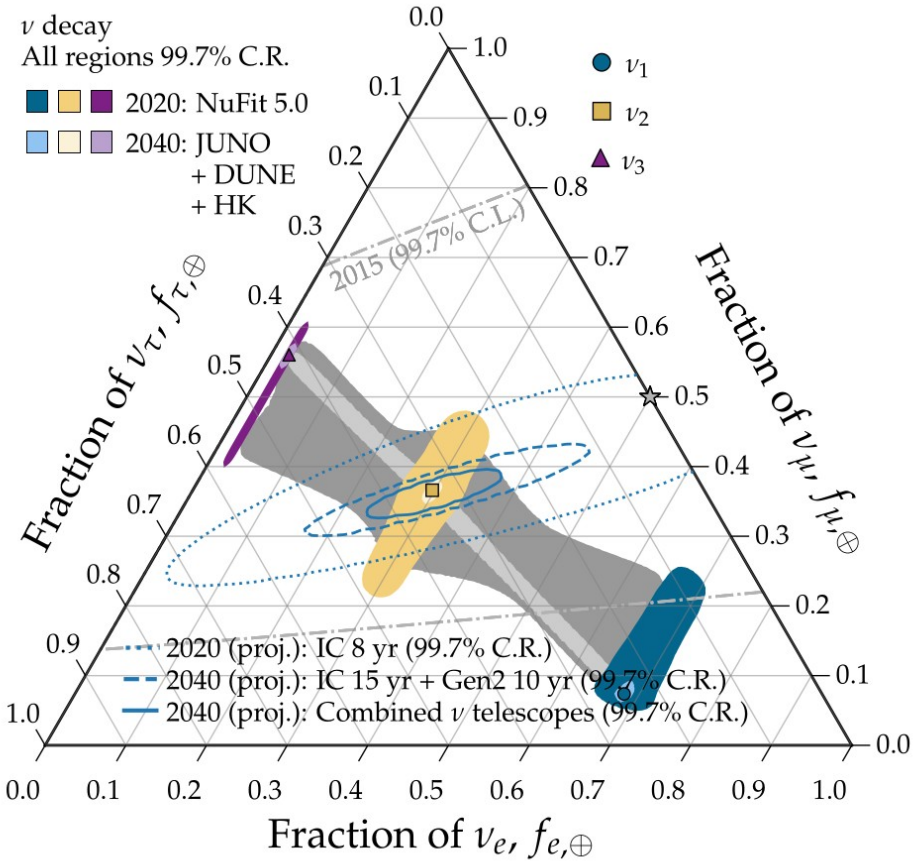
$\nu_1, \nu_2 \to \nu_3$

ν_3 lightest and stable (inverted mass ordering)

What does neutrino decay change?

See also: Beacom *et al.*, *PRL* 2002 / Baerwald, **MB**, Winter, *JCAP* 2012 / **MB**, Beacom, Murase, *PRD* 2017 / Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / **MB**, 2004.06844

Flavor composition ⟺ Spectrum shape ⟺ Event rate



What does neutrino decay change?

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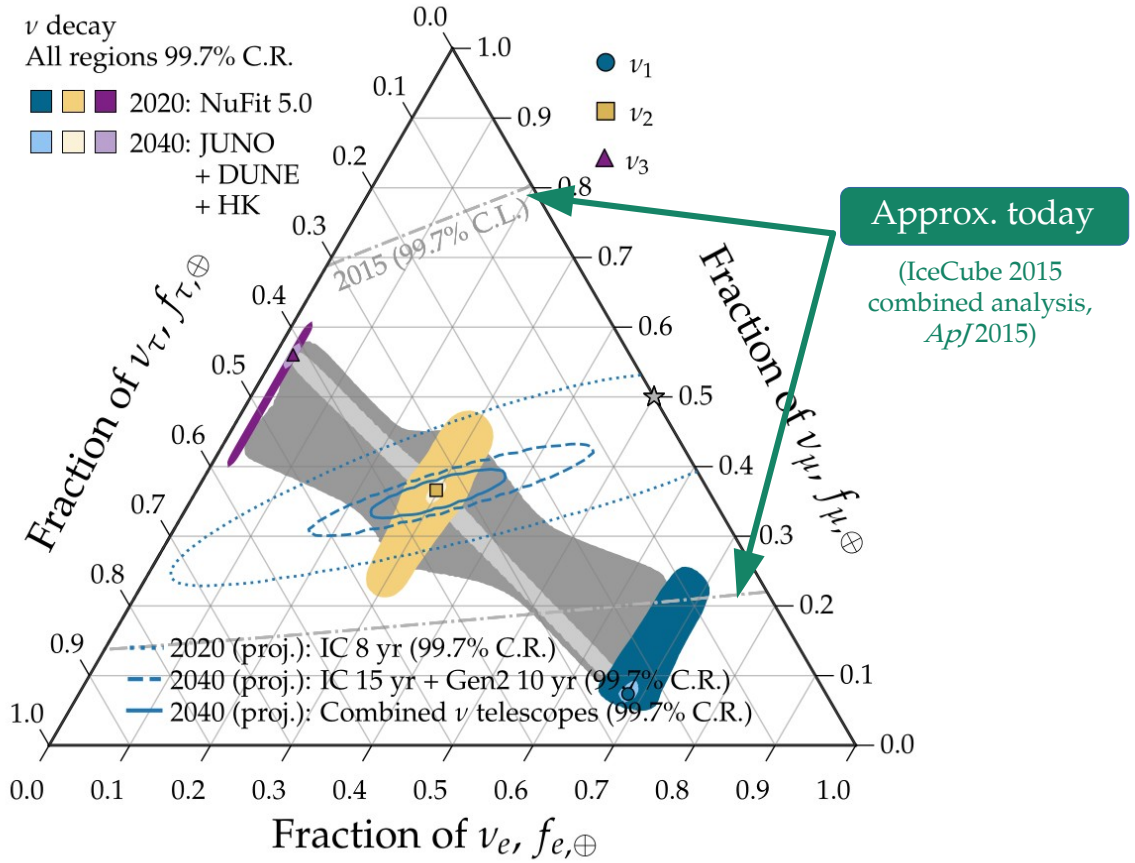
Flavor composition ⟺ Spectrum shape ⟺ Event rate



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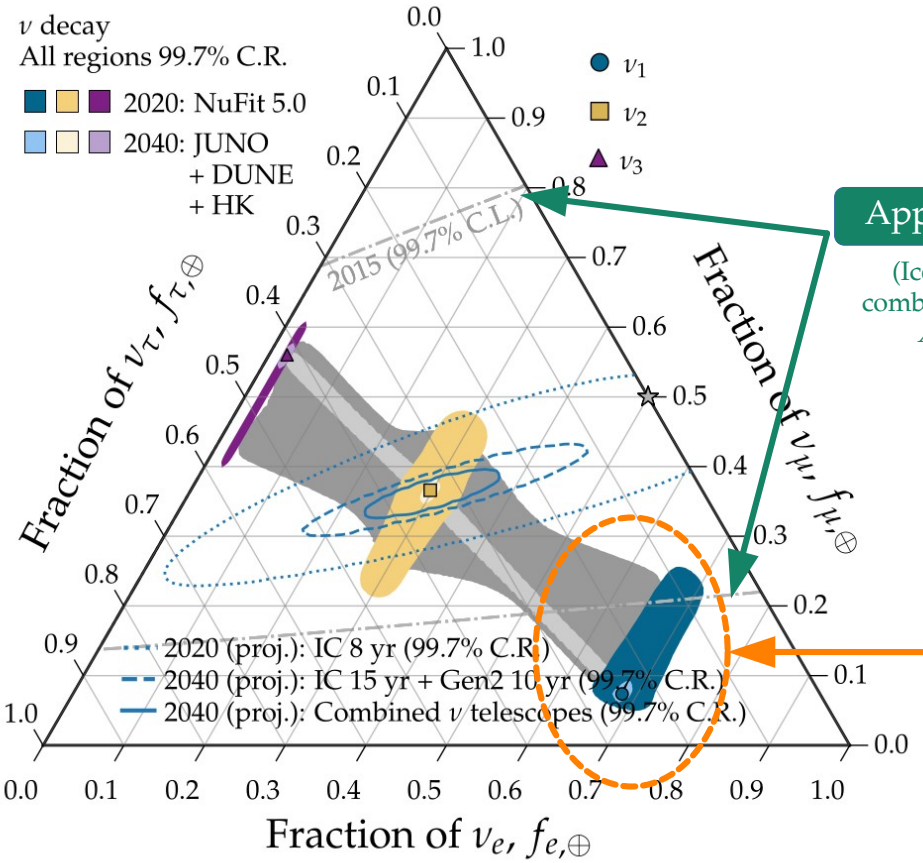
Flavor composition ⟺ Spectrum shape ⟺ Event rate



Approx. today

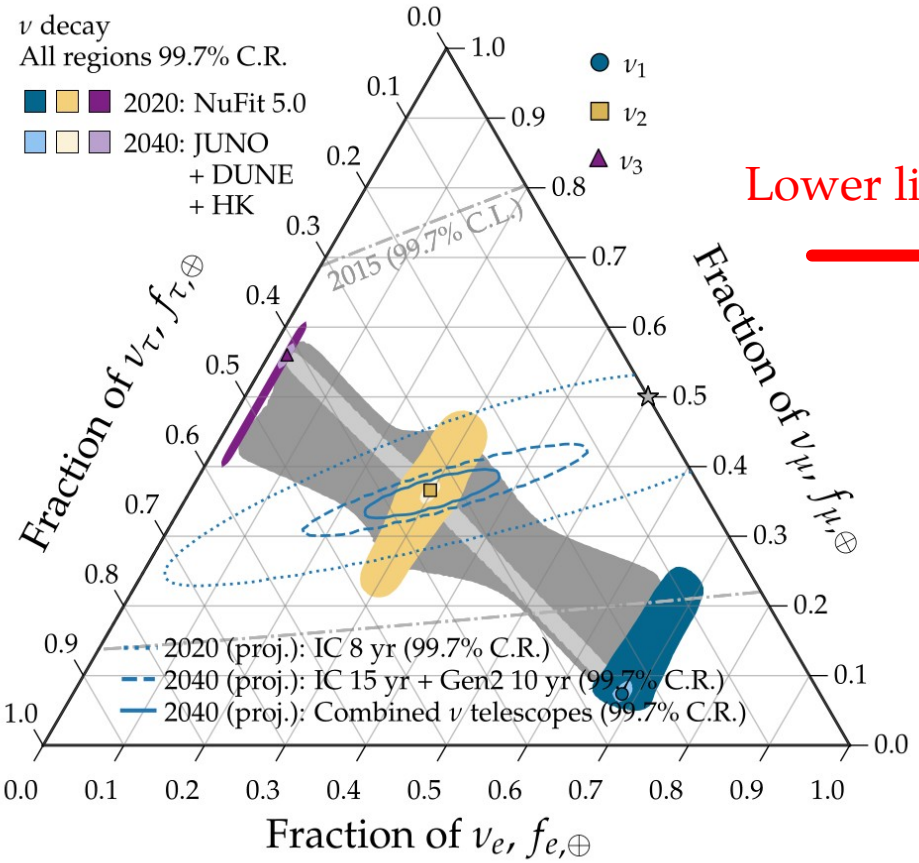
(IceCube 2015 combined analysis, *ApJ* 2015)

Complete decay into ν_1 disfavored by 2015 IceCube flavor measurement

What does neutrino decay change?

See also: Beacom *et al.*, *PRL* 2002 / Baerwald, **MB**, Winter, *JCAP* 2012 / **MB**, Beacom, Murase, *PRD* 2017 / Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / **MB**, 2004.06844

Flavor composition ⟺ Spectrum shape ⟺ Event rate

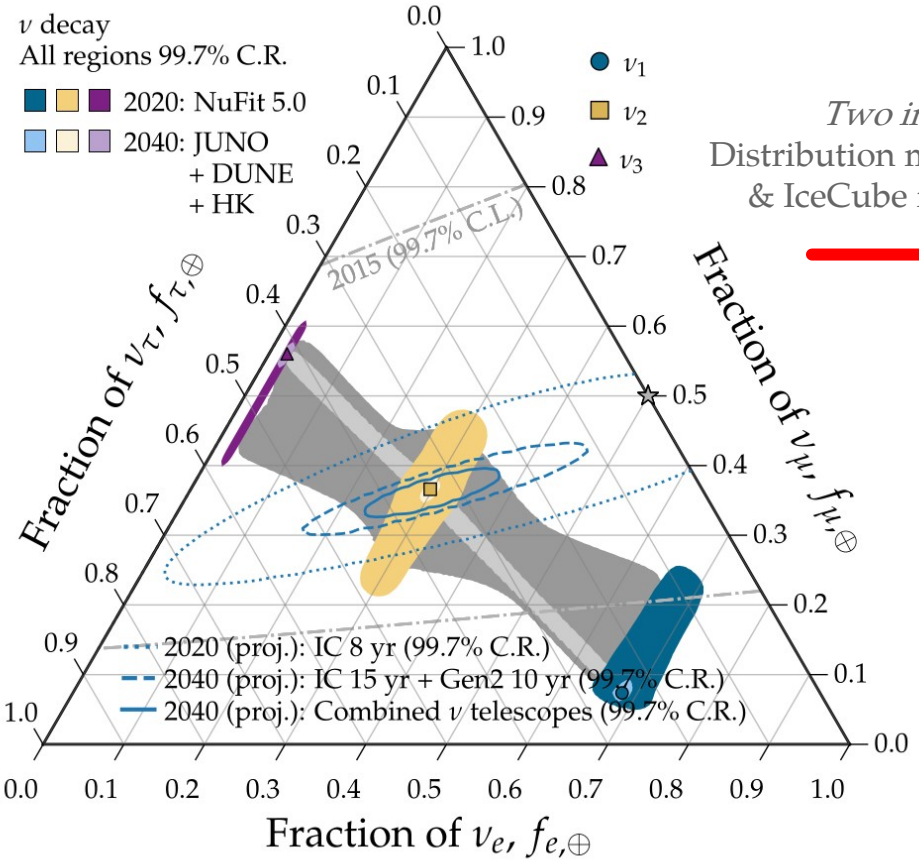


Lower limit on τ/m →

What does neutrino decay change?

See also: Beacom *et al.*, *PRL* 2002 / Baerwald, **MB**, Winter, *JCAP* 2012 / **MB**, Beacom, Murase, *PRD* 2017 / Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / **MB**, 2004.06844

Flavor composition ⟺ Spectrum shape ⟺ Event rate

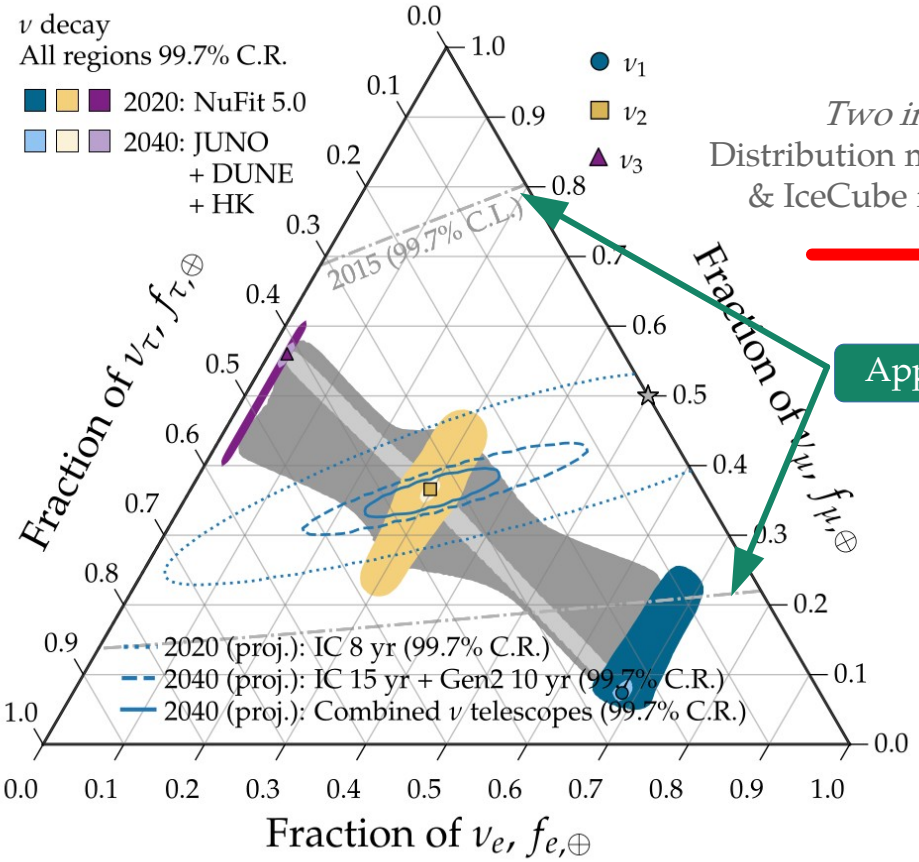


Two ingredients:
Distribution mixing parameters
& IceCube flavor posterior

What does neutrino decay change?

See also: Beacom *et al.*, *PRL* 2002 / Baerwald, **MB**, Winter, *JCAP* 2012 / **MB**, Beacom, Murase, *PRD* 2017 / Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / **MB**, 2004.06844

Flavor composition ⟺ Spectrum shape ⟺ Event rate



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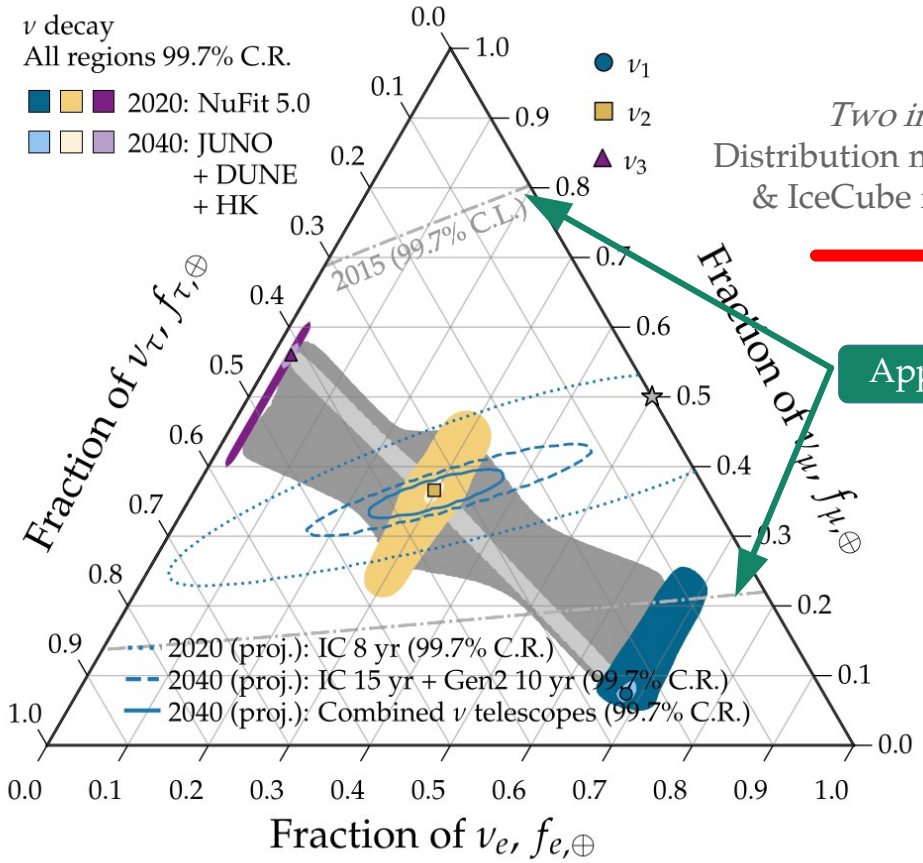
Approx. today

What does neutrino decay change?

See also: Beacom *et al.*, *PRL* 2002 / Baerwald, **MB**, Winter, *JCAP* 2012 / **MB**, Beacom, Murase, *PRD* 2017 / Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / **MB**, 2004.06844

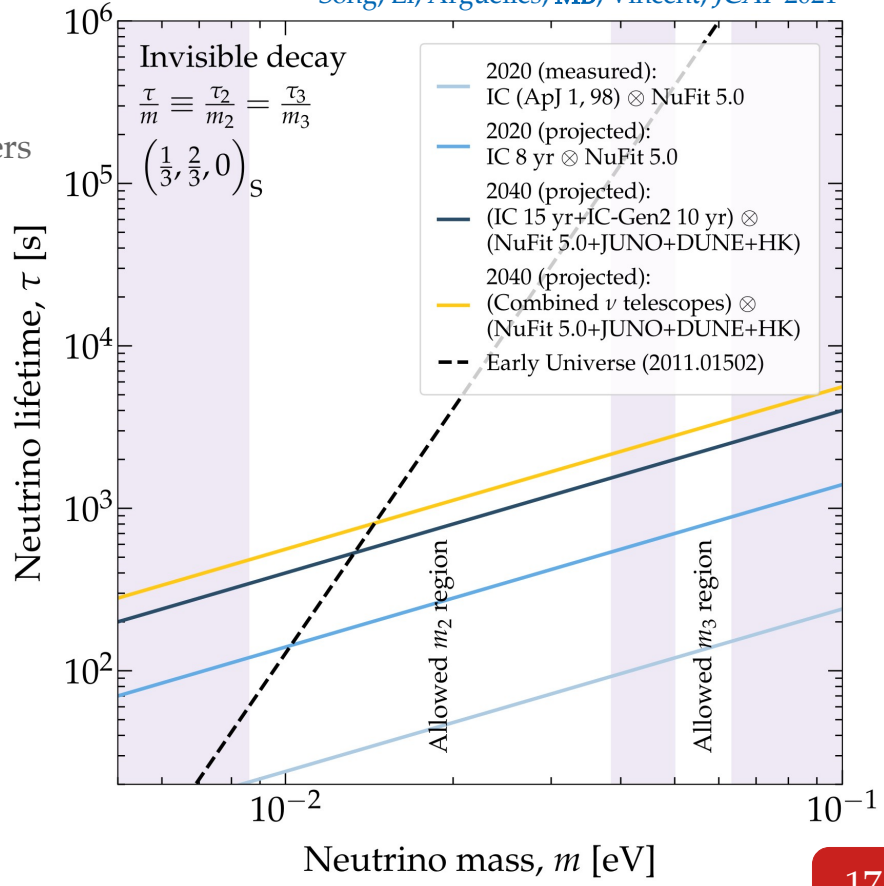
Flavor composition ⟺ Spectrum shape ⟺ Event rate



Two ingredients:
Distribution mixing parameters
& IceCube flavor posterior

Approx. today

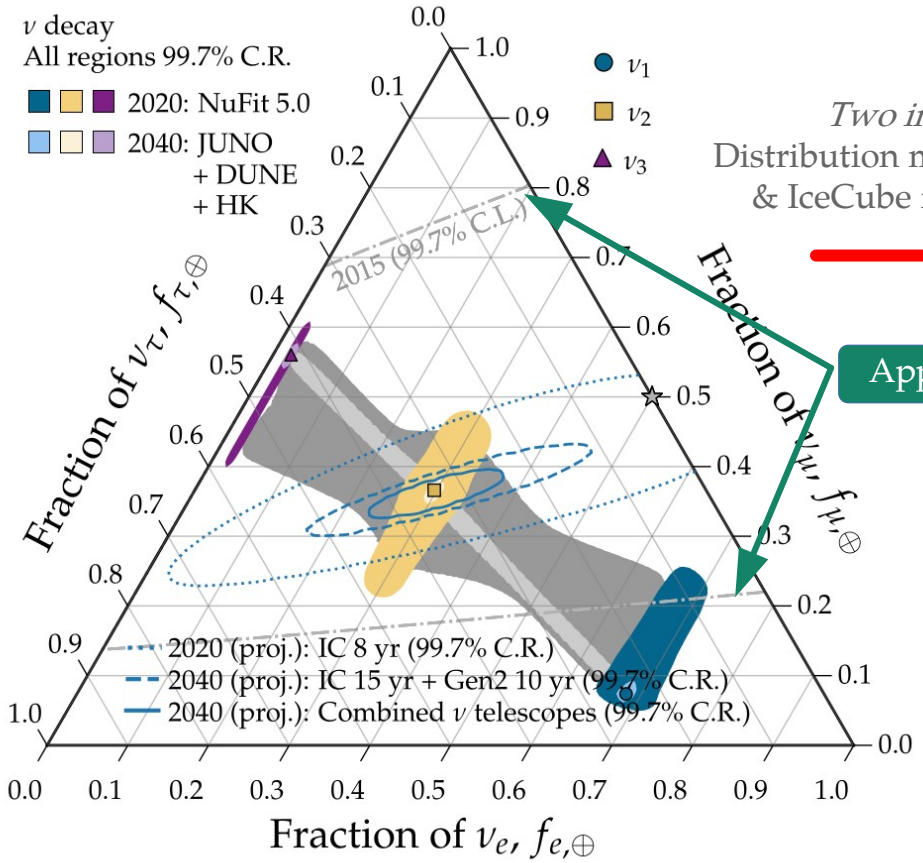
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



What does neutrino decay change?

See also: Beacom *et al.*, *PRL* 2002 / Baerwald, **MB**, Winter, *JCAP* 2012 / **MB**, Beacom, Murase, *PRD* 2017 / Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / **MB**, 2004.06844

Flavor composition ⟺ Spectrum shape ⟺ Event rate



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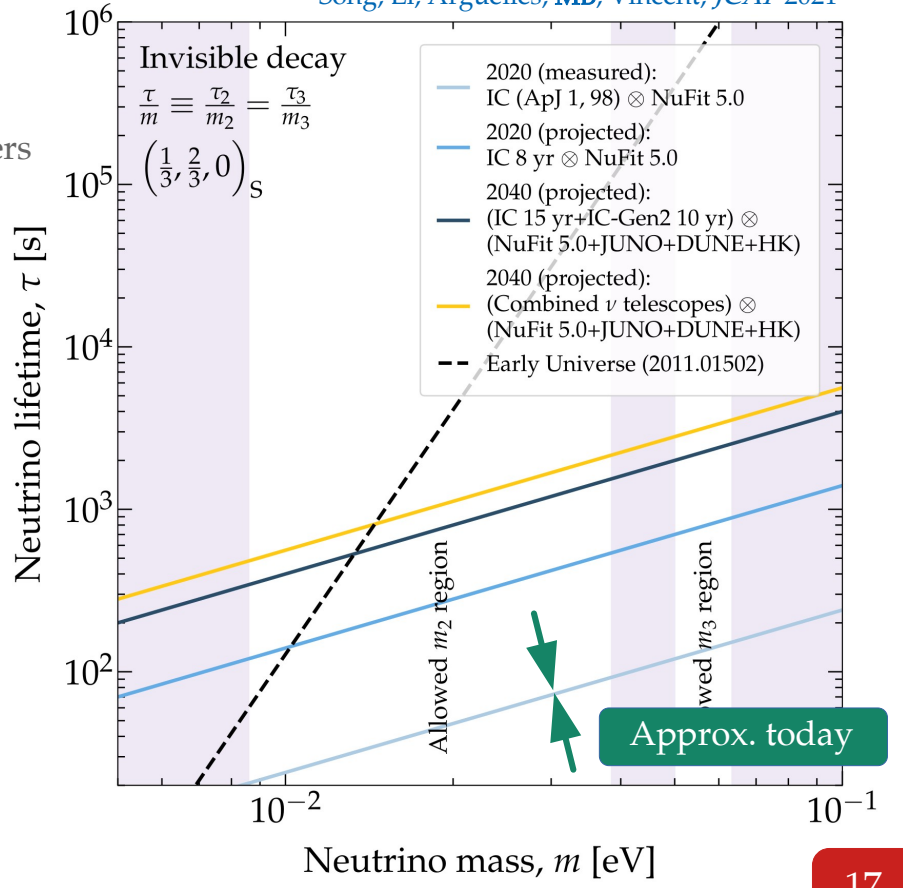
& IceCube flavor posterior

Approx. today

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

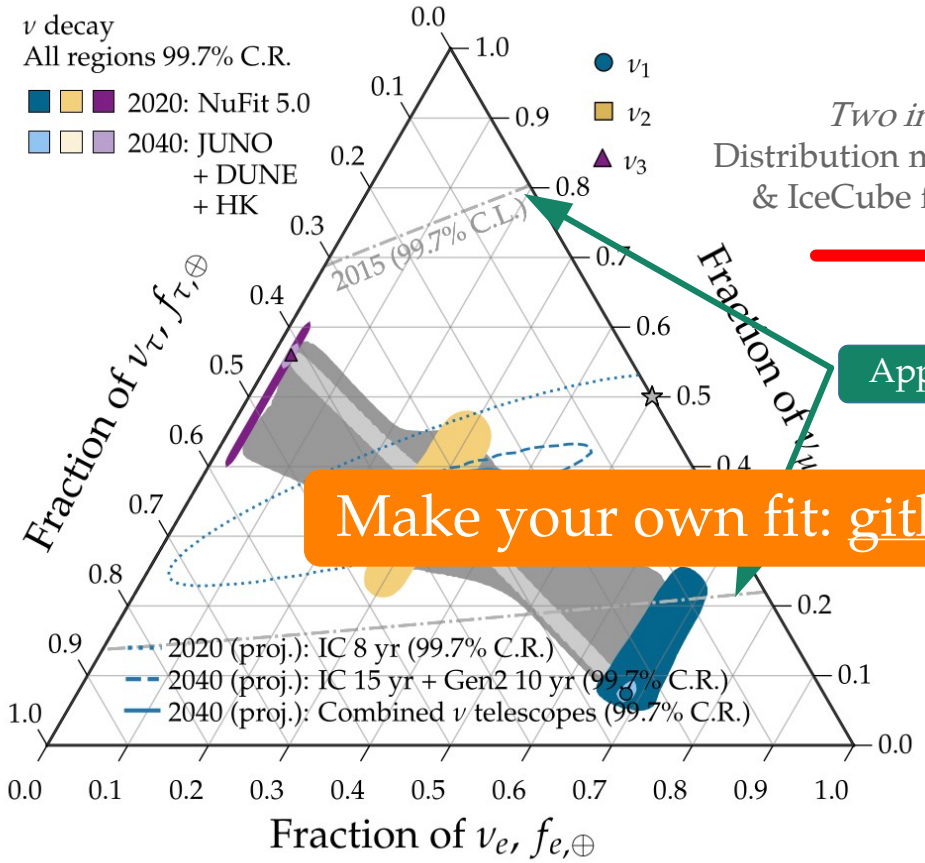


Approx. today

What does neutrino decay change?

See also: Beacom *et al.*, *PRL* 2002 / Baerwald, **MB**, Winter, *JCAP* 2012 / **MB**, Beacom, Murase, *PRD* 2017 / Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / **MB**, 2004.06844

Flavor composition ⟺ Spectrum shape ⟺ Event rate

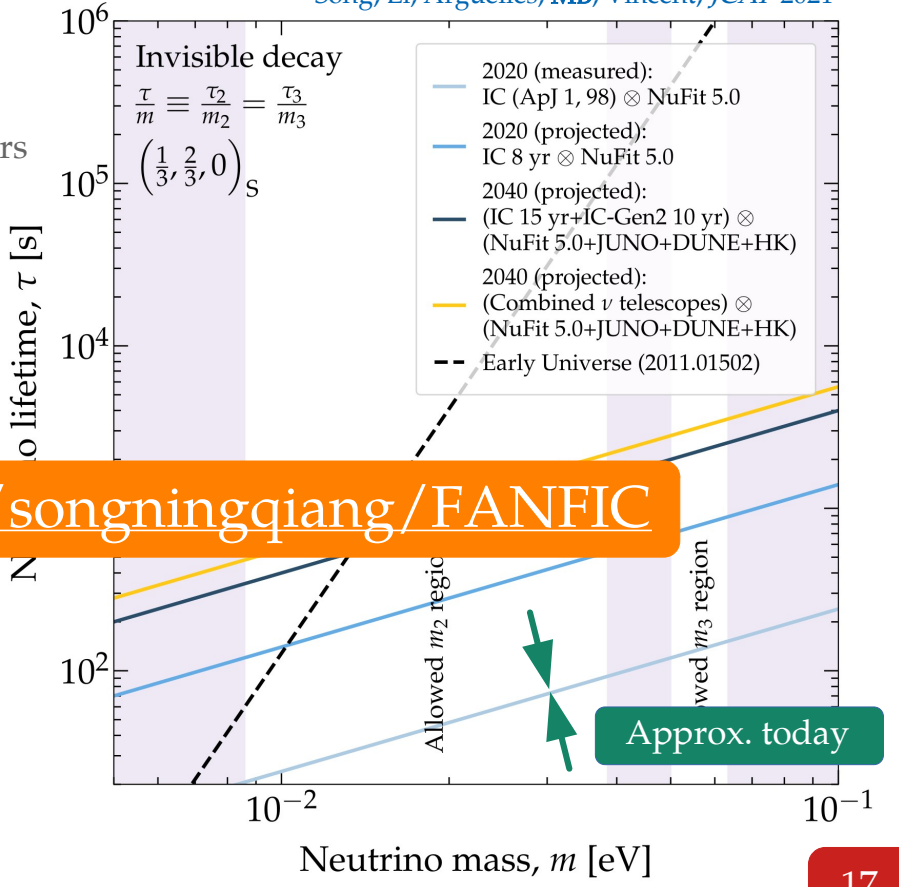


Two ingredients:
Distribution mixing parameters
& IceCube flavor posterior

Approx. today

Make your own fit: github.com/songningqiang/FANFIC

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

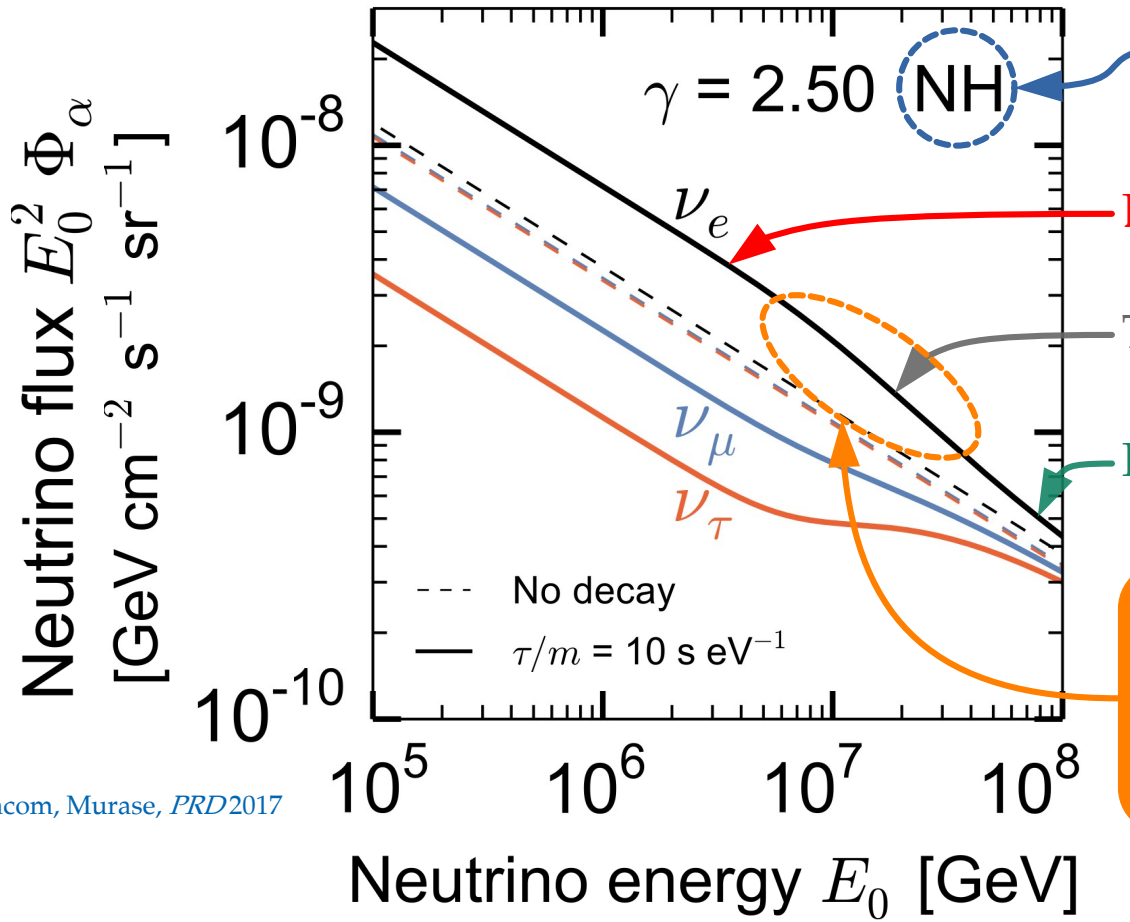


Approx. today

What does neutrino decay change?

See also: Beacom *et al.*, *PRL* 2002 / Baerwald, **MB**, Winter, *JCAP* 2012 / Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / **MB**, 2004.06844 / Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2020

Flavor composition ⟺ Spectrum shape ⟺ Event rate



$\nu_2, \nu_3 \to \nu_1$

Low energy: decay evident

Transition region

High energy: no decay

Look for sigmoid-like transition in spectrum: *challenging, but possible with more statistics*!

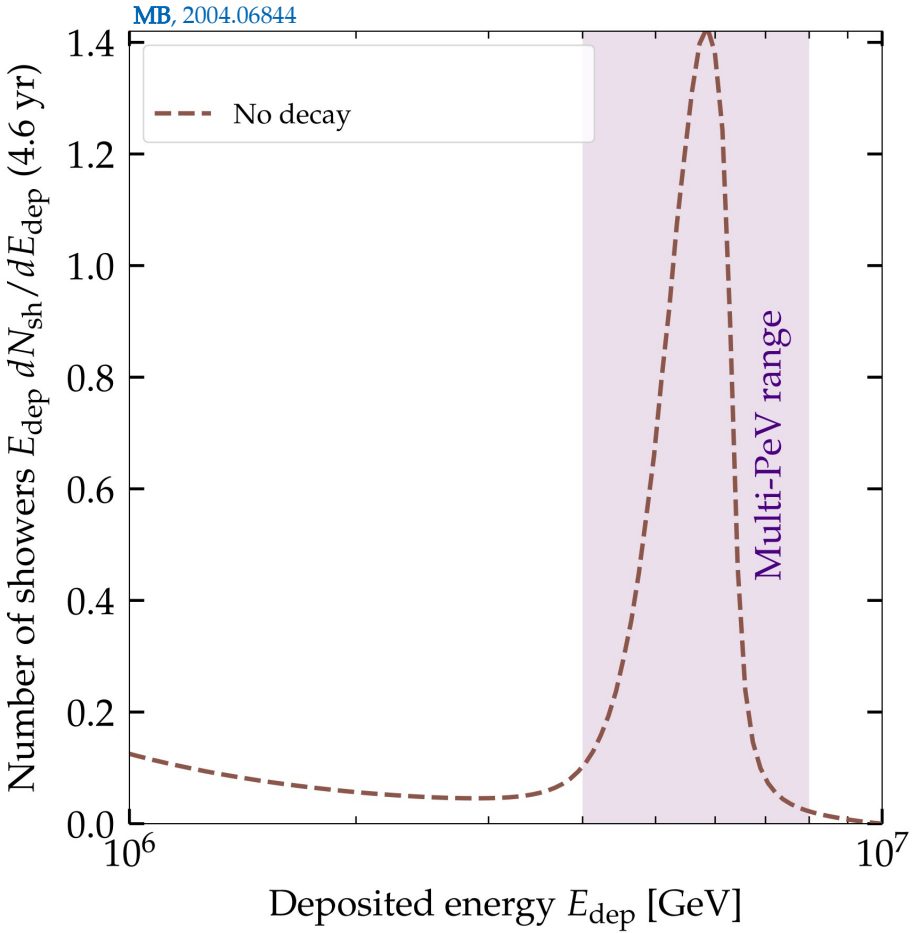
MB, Beacom, Murase, *PRD* 2017

What does neutrino decay change?

See also: Beacom *et al.*, *PRL* 2002 / Baerwald, **MB**, Winter, *JCAP* 2012 / **MB**, Beacom, Murase, *PRD* 2017 / Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2020

Flavor composition ⟺ Spectrum shape ⟺ Event rate

MB, 2004.06844



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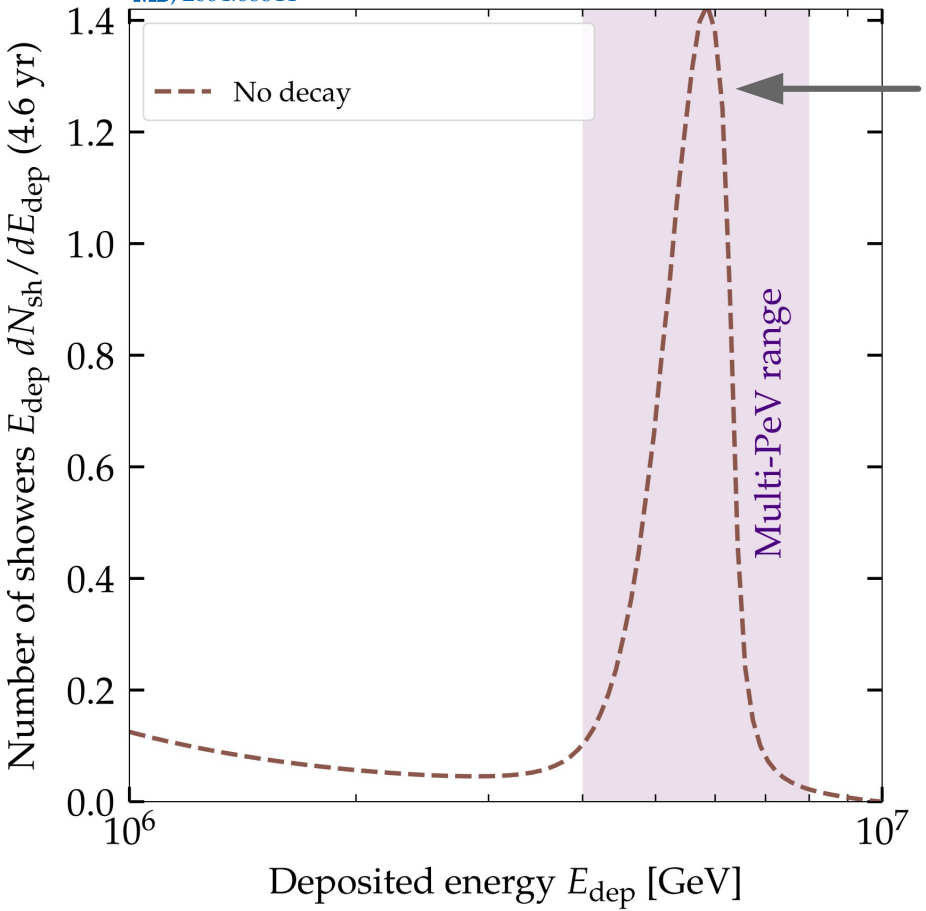
Flavor composition ⟺ Spectrum shape ⟺ Event rate

MB, 2004.06844



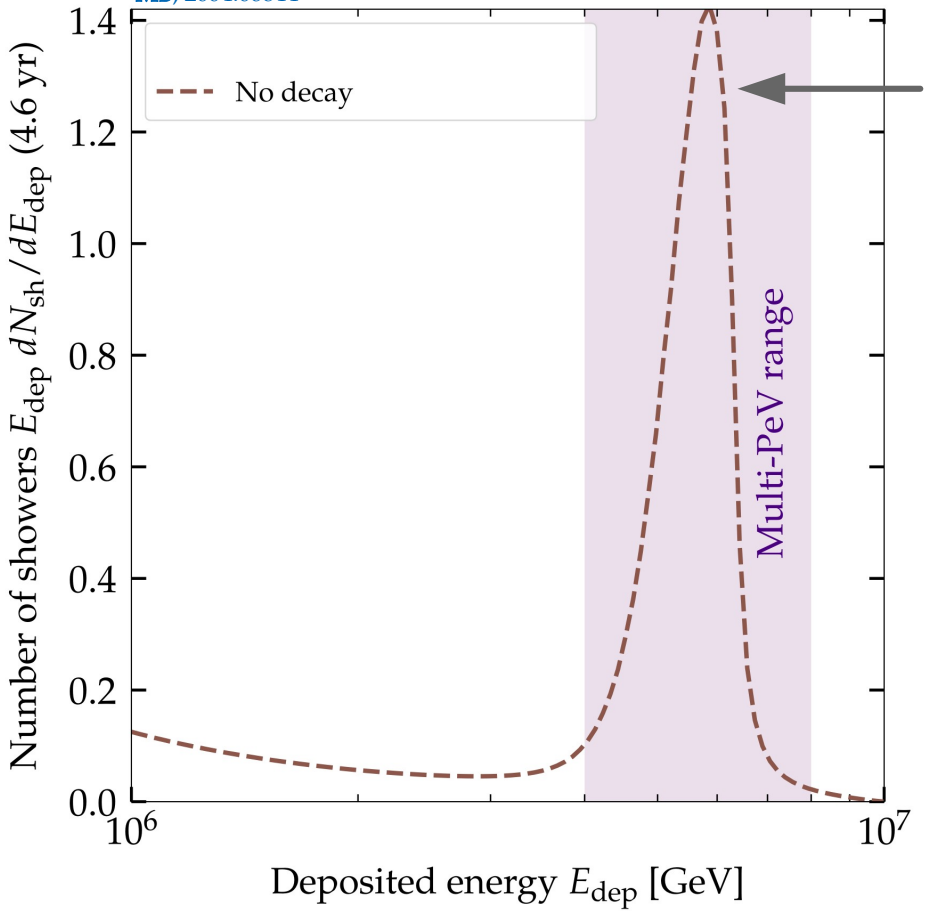
Glashow resonance (GR):
$\bar{\nu}_e + e \to W \to$ hadrons $\to$ shower

What does neutrino decay change?

See also: Beacom *et al.*, *PRL* 2002 / Baerwald, **MB**, Winter, *JCAP* 2012 / **MB**, Beacom, Murase, *PRD* 2017 / Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2020

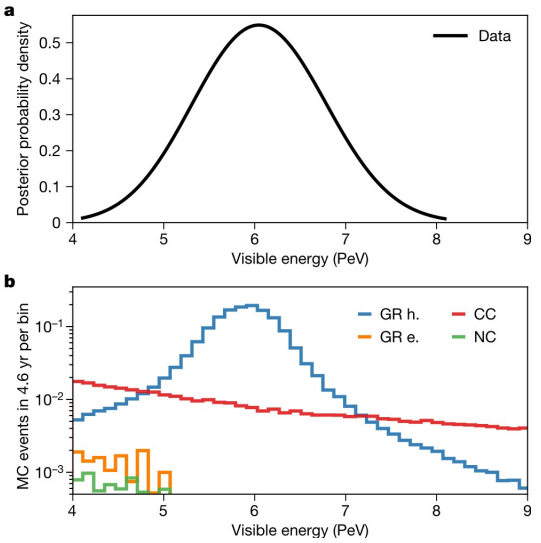
Flavor composition ⟺ Spectrum shape ⟺ Event rate

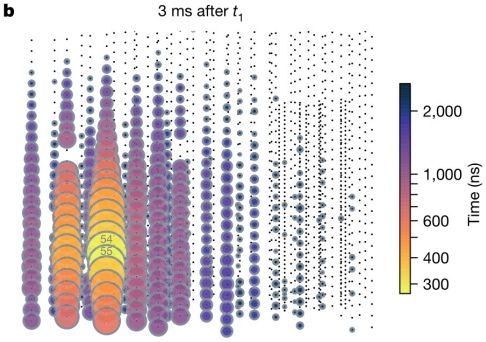
MB, 2004.06844



Glashow resonance (GR):
$\bar{\nu}_e + e \to W \to$ hadrons $\to$ shower

IceCube has seen one GR candidate in 4.6 years:





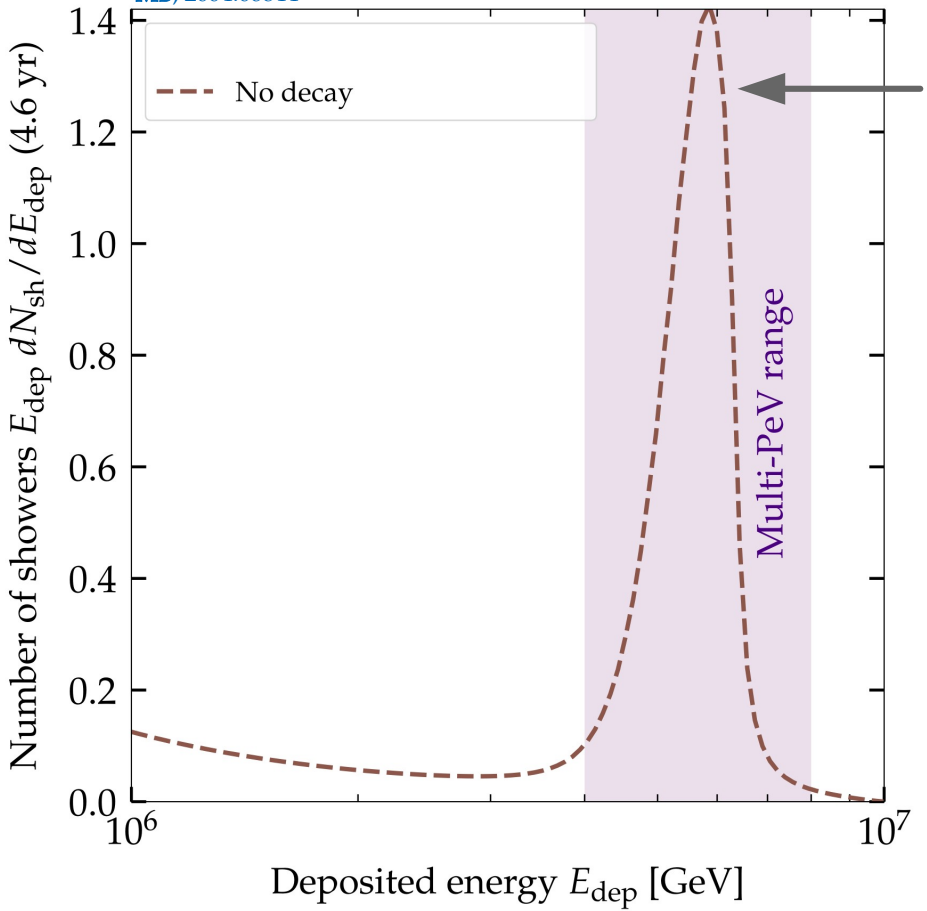
IceCube Collab., *Nature* 2021

What does neutrino decay change?

See also: Beacom *et al.*, *PRL* 2002 / Baerwald, **MB**, Winter, *JCAP* 2012 / **MB**, Beacom, Murase, *PRD* 2017 / Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2020

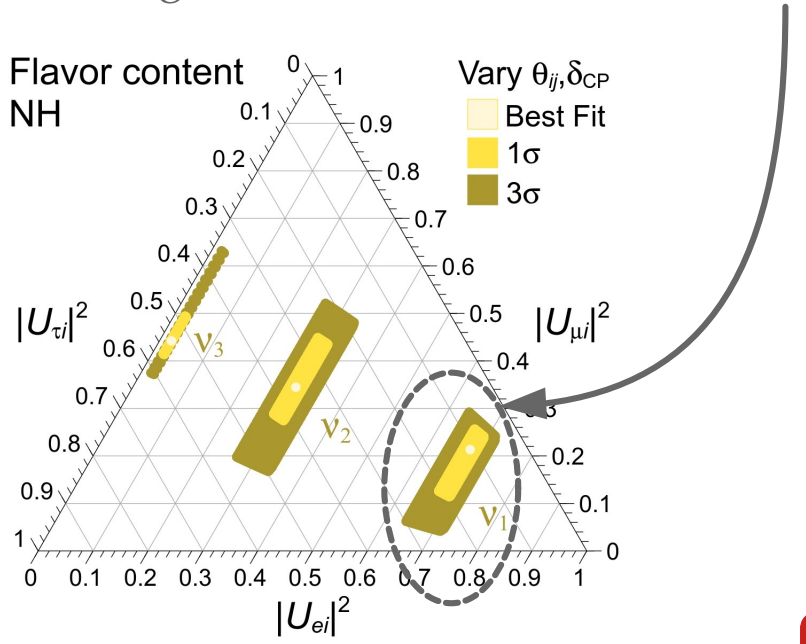
Flavor composition ⟺ Spectrum shape ⟺ Event rate

MB, 2004.06844



Glashow resonance (GR):
$\bar{\nu}_e + e \rightarrow W \rightarrow$ hadrons $\rightarrow$ shower

ν_1 is the mass eigenstate with the most e flavor



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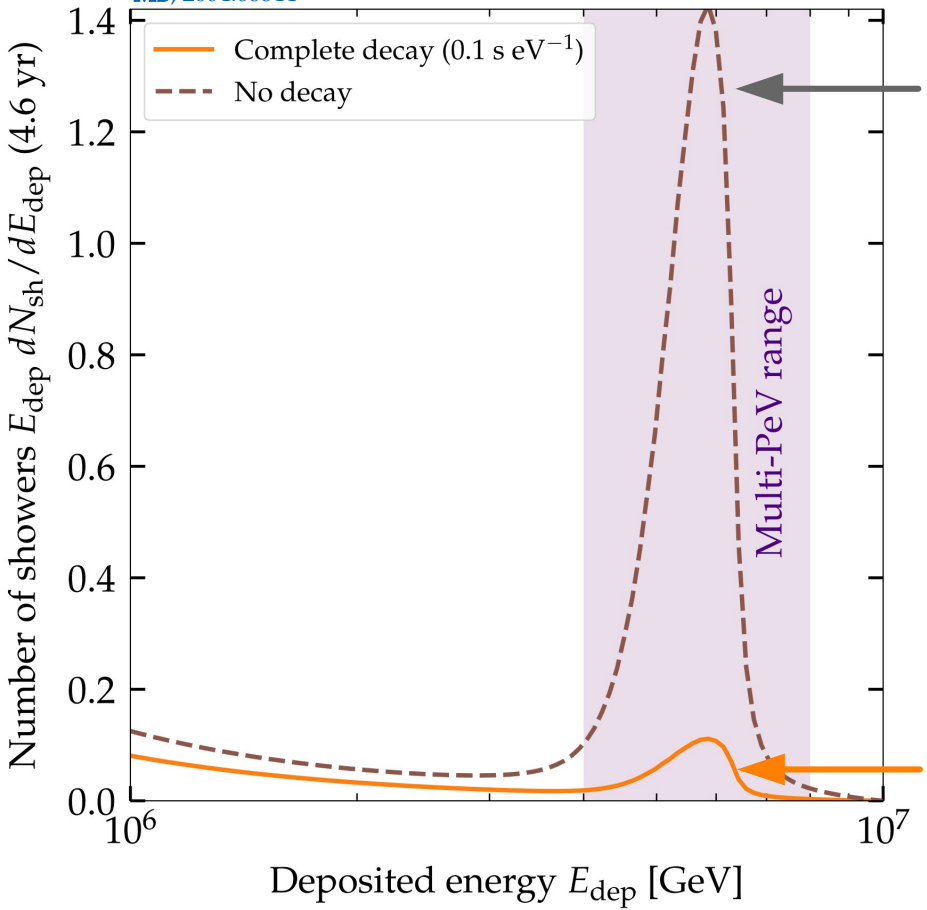
Flavor composition ⟺ Spectrum shape ⟺ Event rate

MB, 2004.06844



Glashow resonance (GR):
$\bar{\nu}_e + e \rightarrow W \rightarrow$ hadrons $\rightarrow$ shower

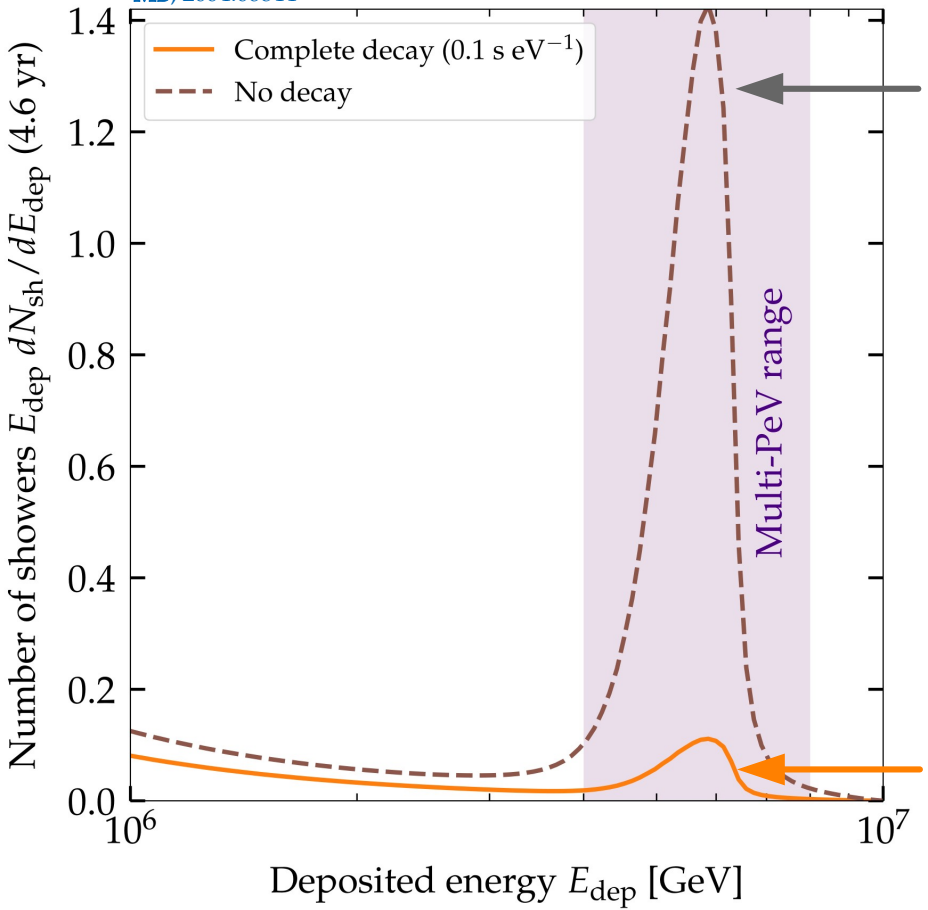
If $\bar{\nu}_1$ had decayed en route to Earth,
there would not have been $\bar{\nu}_e$ left to trigger a GR

What does neutrino decay change?

See also: Beacom *et al.*, *PRL* 2002 / Baerwald, **MB**, Winter, *JCAP* 2012 / **MB**, Beacom, Murase, *PRD* 2017 / Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2020

Flavor composition ⟺ Spectrum shape ⟺ Event rate

MB, 2004.06844



Glashow resonance (GR):
$\bar{\nu}_e + e \rightarrow W \rightarrow$ hadrons $\rightarrow$ shower

So by having observed 1 GR event we can place a *lower* limit on the lifetime of $\bar{\nu}_1$ (= ν_1)

If $\bar{\nu}_1$ had decayed en route to Earth, there would not have been $\bar{\nu}_e$ left to trigger a GR

What does neutrino decay change?

See also: Beacom *et al.*, *PRL* 2002 / Baerwald, **MB**, Winter, *JCAP* 2012 / **MB**, Beacom, Murase, *PRD* 2017 / Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2020

Flavor composition ⟺ Spectrum shape ⟺ Event rate

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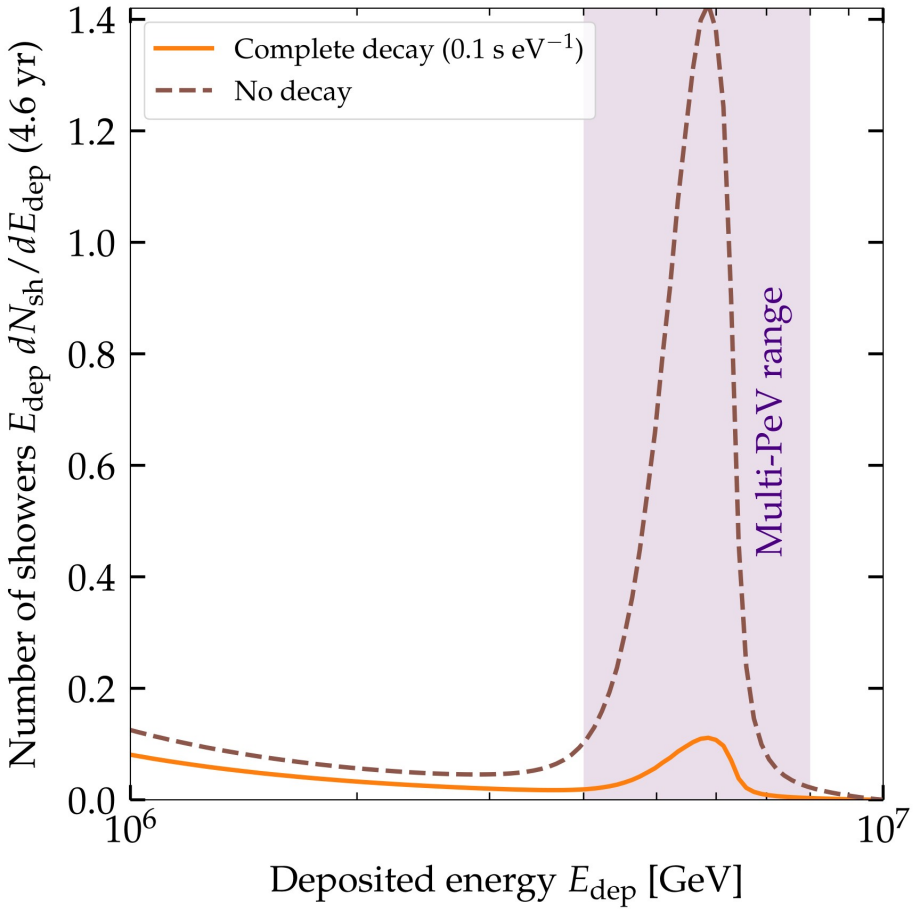

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Flavor composition ⟺ Spectrum shape ⟺ Event rate

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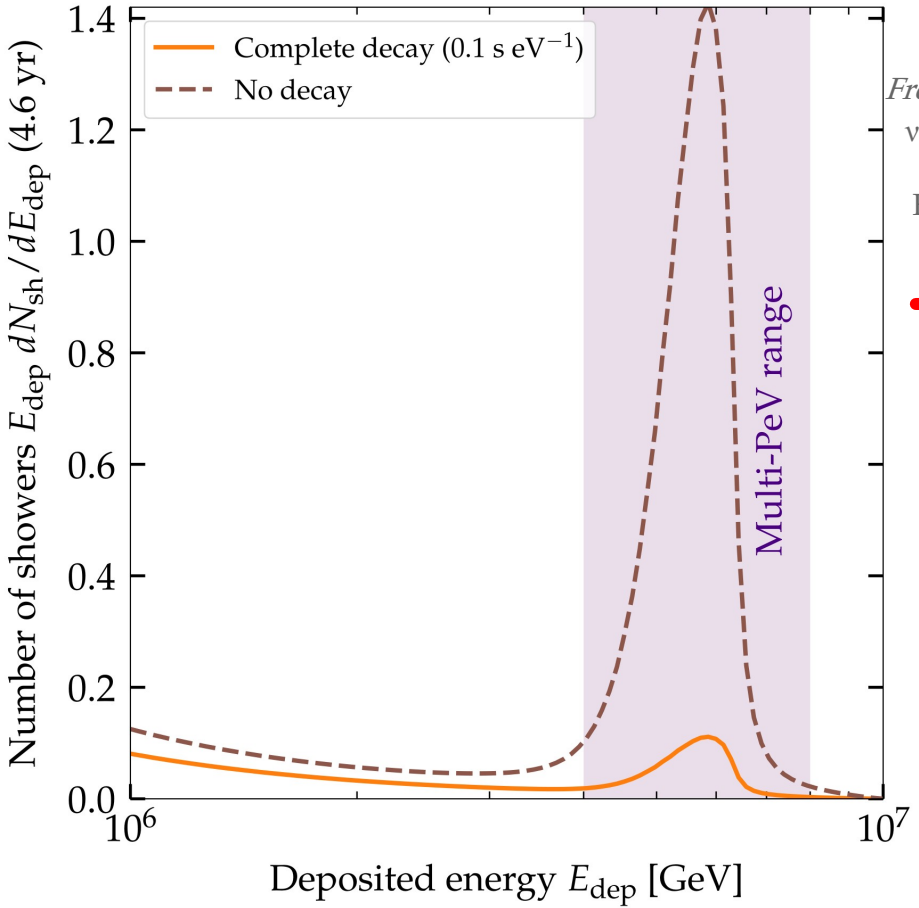
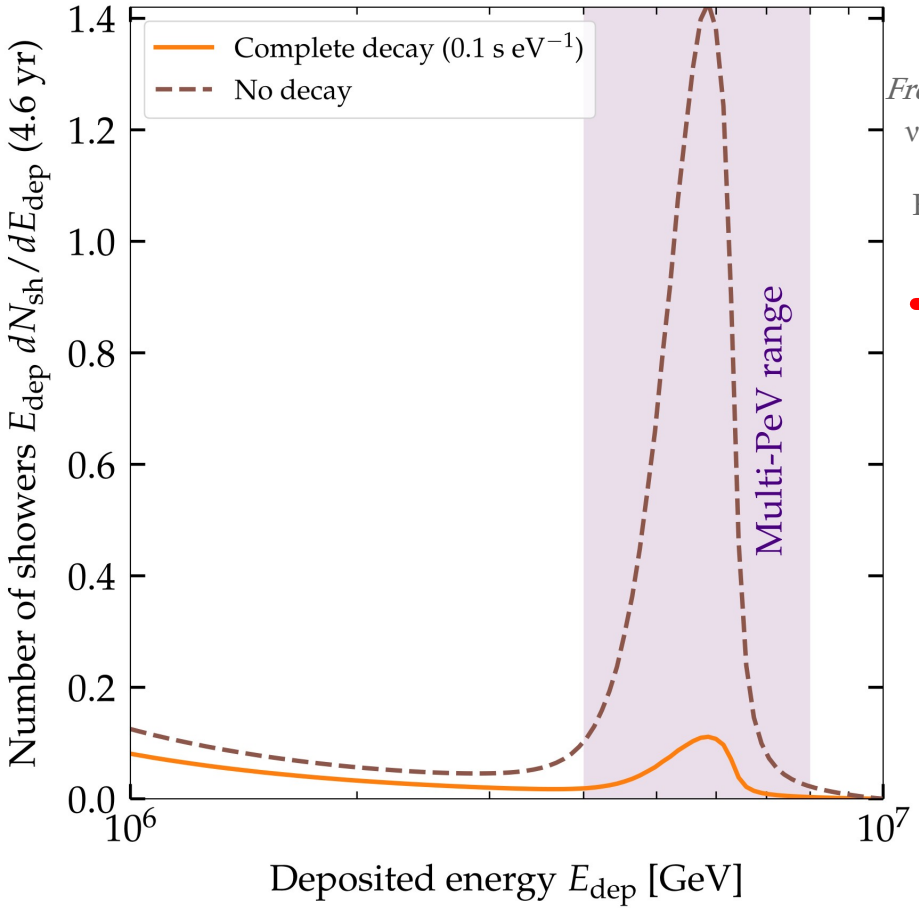


Free parameters:
ν_1, ν_2 lifetimes
Mix. par.
Flavor ratios
$\bar{\nu}/\nu$ ratio

What does neutrino decay change?

See also: Beacom *et al.*, *PRL* 2002 / Baerwald, **MB**, Winter, *JCAP* 2012 / **MB**, Beacom, Murase, *PRD* 2017 / Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2020

Flavor composition ⟺ Spectrum shape ⟺ Event rate



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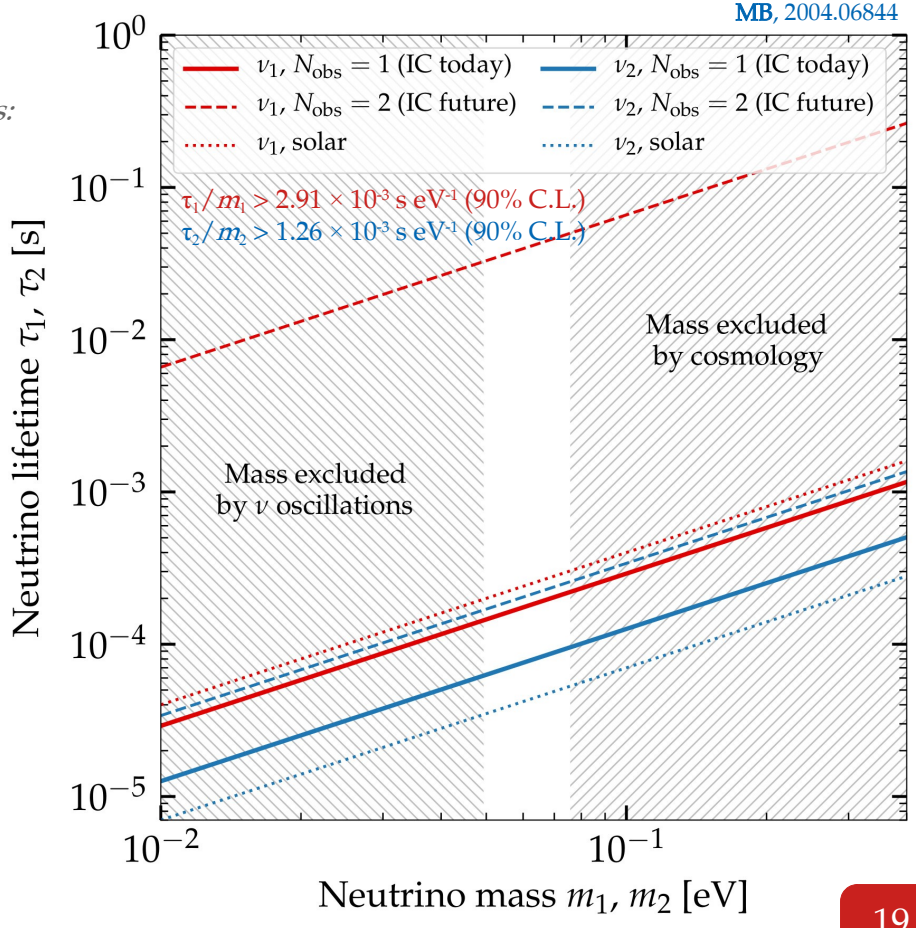
MB, 2004.06844



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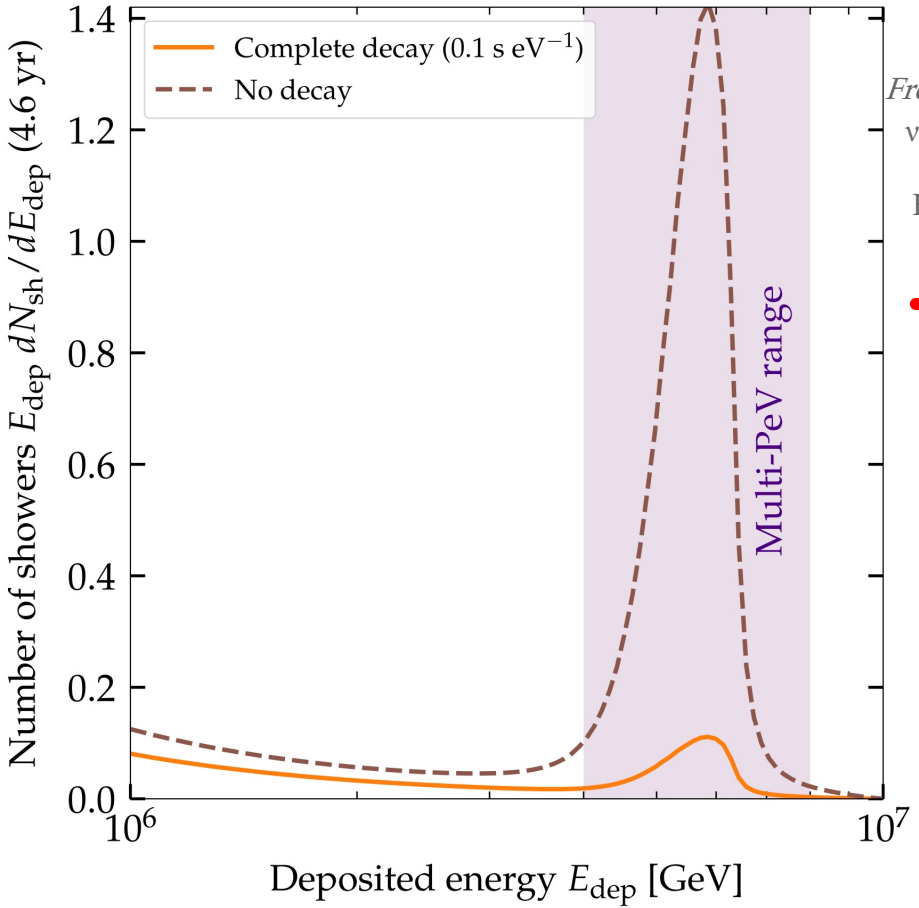
Flavor composition ⟺ Spectrum shape ⟺ Event rate



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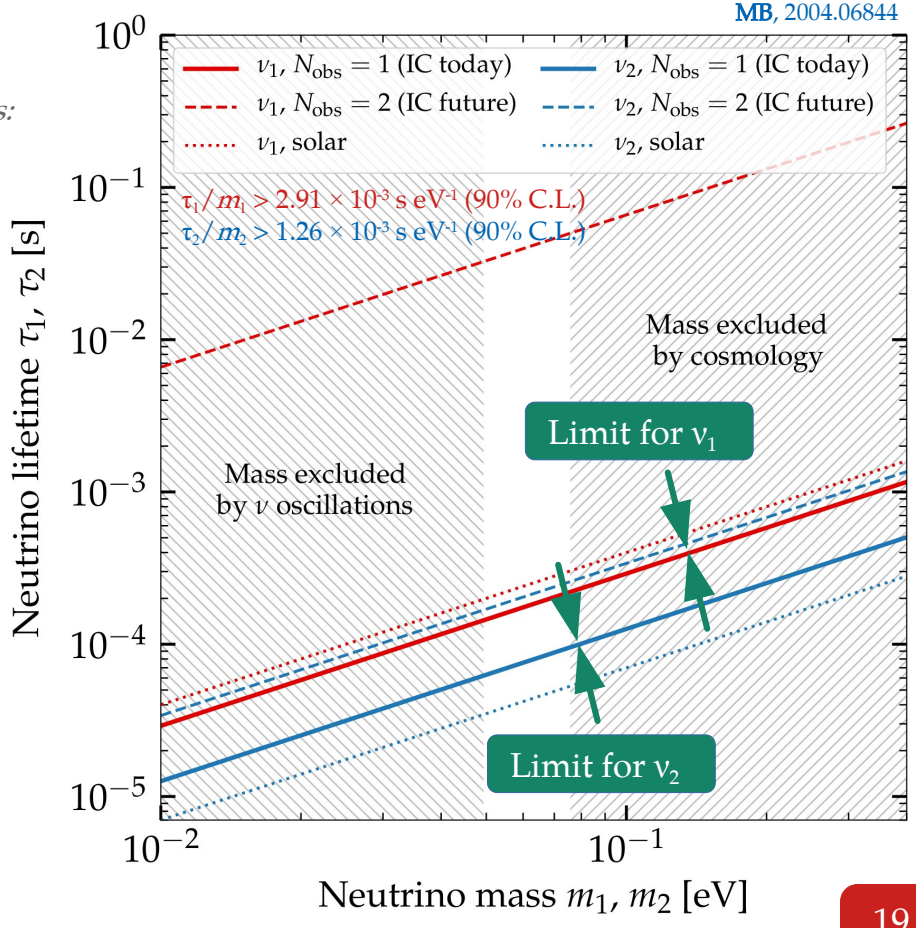
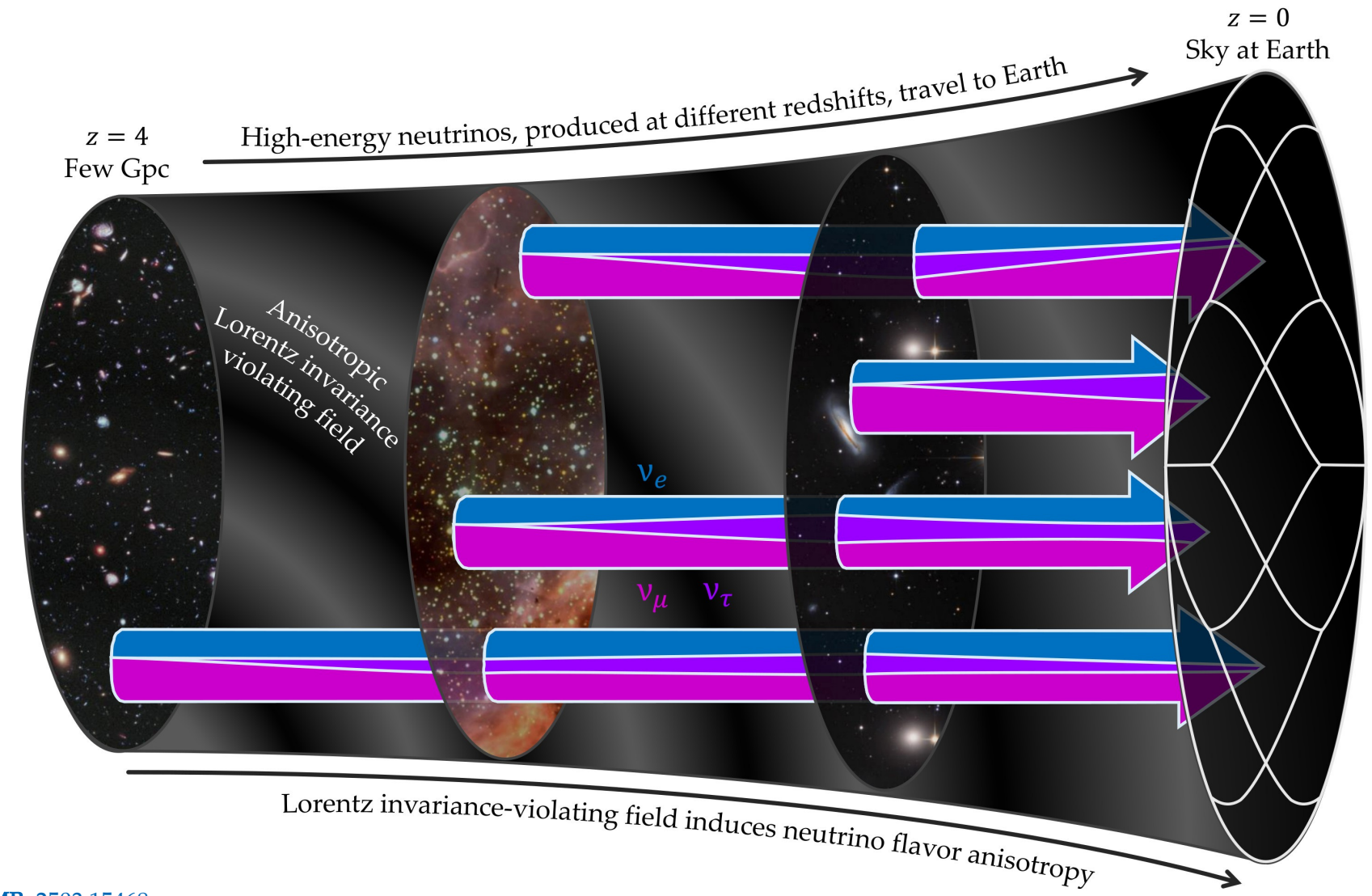


Direction-dependent flavor composition



Telalovic, **MB**, 2503.15468

Anisotropic Lorentz-invariance violation makes the flavor sky anisotropic:

$$H_{\rm tot} = H_{\rm vac} + \sum_{d=2}^{\infty} H_{\rm LIV}^{(d)} = H_{\rm vac} + E^{d-3} \sum_{\ell=0}^{d-1} \sum_{m=-\ell}^{\ell} Y_\ell^m(\hat{\boldsymbol{p}}) (a_{\rm eff}^{(d)})_{\ell m}^{\alpha\beta}$$

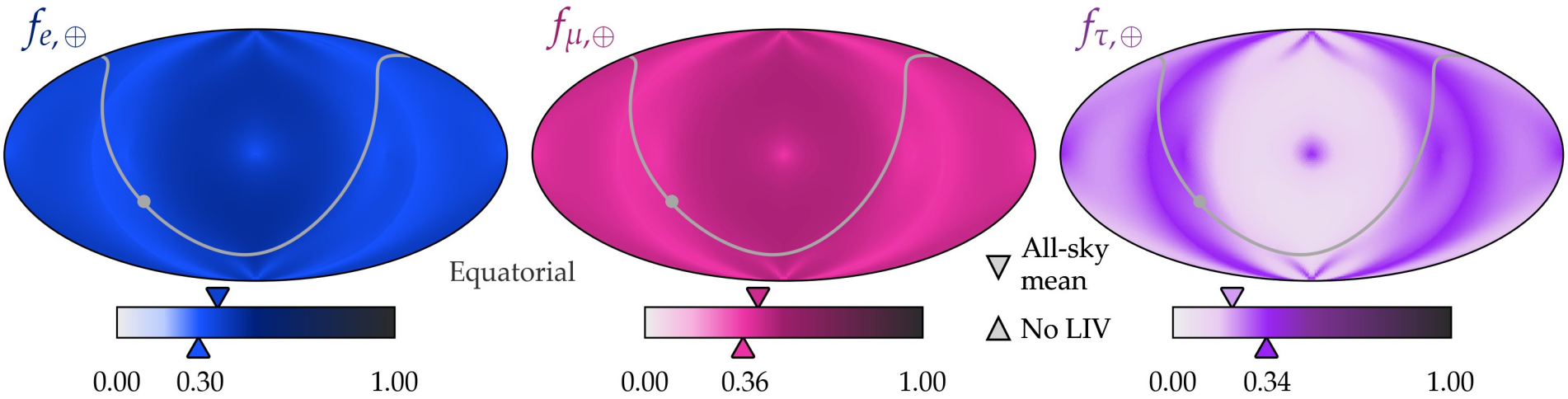
Neutrino oscillation probability becomes direction-dependent

Telalovic, **MB**, *JCAP* 2025

Anisotropic Lorentz-invariance violation makes the flavor sky anisotropic:

$$H_{\rm tot} = H_{\rm vac} + \sum_{d=2}^{\infty} H_{\rm LIV}^{(d)} = H_{\rm vac} + E^{d-3} \sum_{\ell=0}^{d-1} \sum_{m=-\ell}^{\ell} Y_\ell^m(\hat{\boldsymbol{p}}) (a_{\rm eff}^{(d)})_{\ell m}^{\alpha\beta}$$

Neutrino oscillation probability becomes direction-dependent



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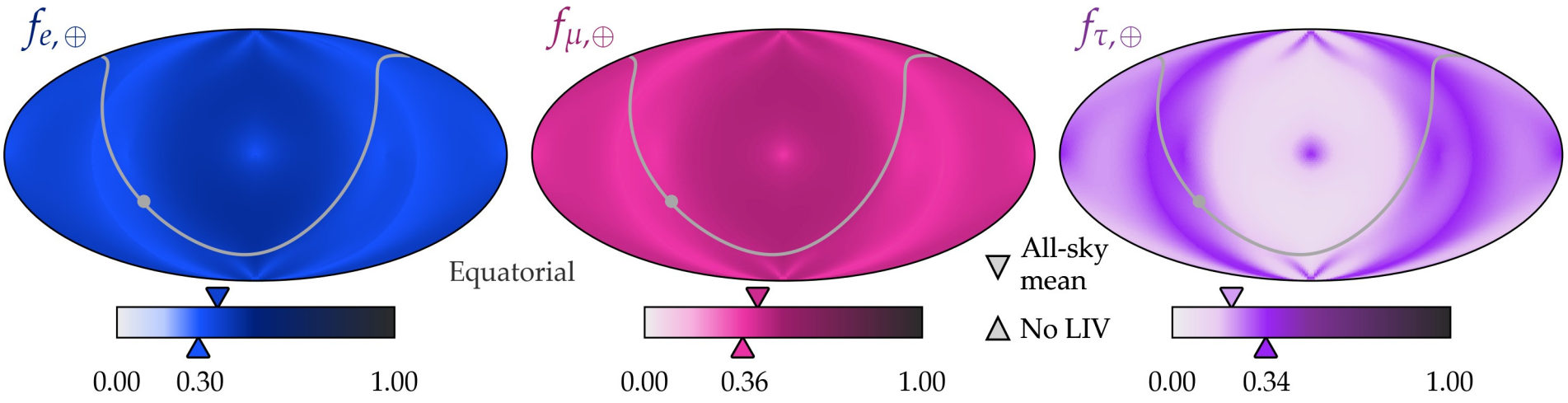

For dimension-5 CPT-odd LIV coefficient

Upper limits from accelerator ν (MINOS): $< 10^{-20}$–10^{-15} GeV^{-1}

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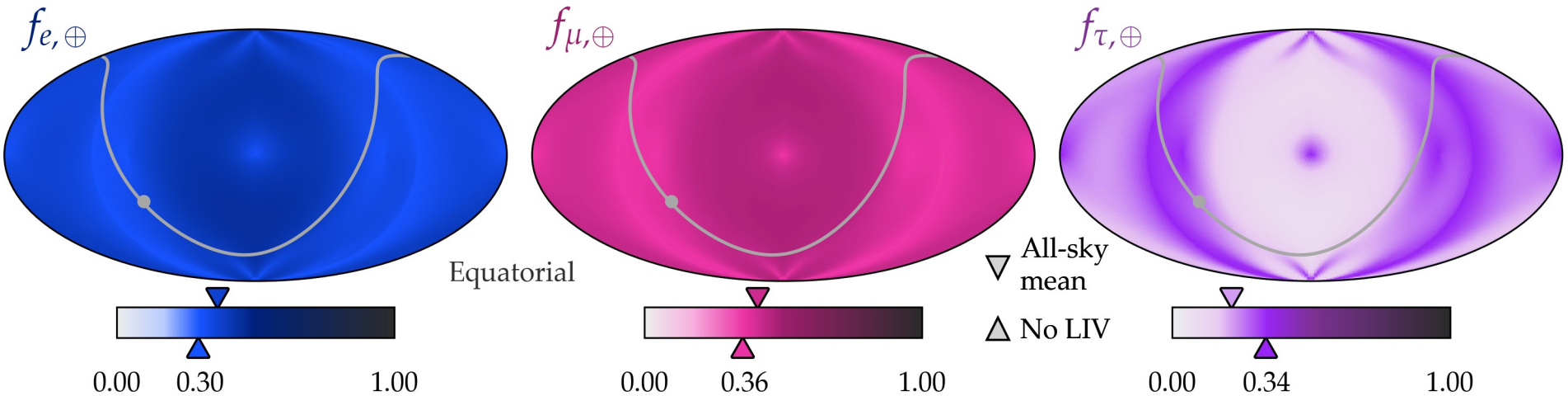

For dimension-5 CPT-odd LIV coefficient

Upper limits from accelerator ν (MINOS): $< 10^{-20}$–10^{-15} GeV^{-1}

Upper limits from 7.5-year HESE: $< 10^{-34}$ GeV^{-1}

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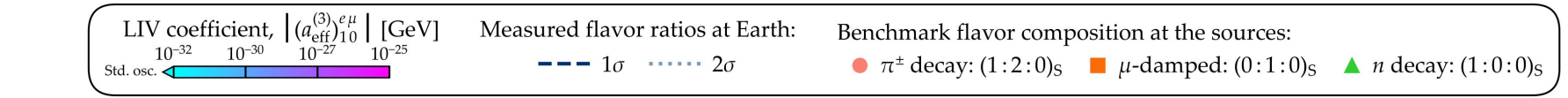
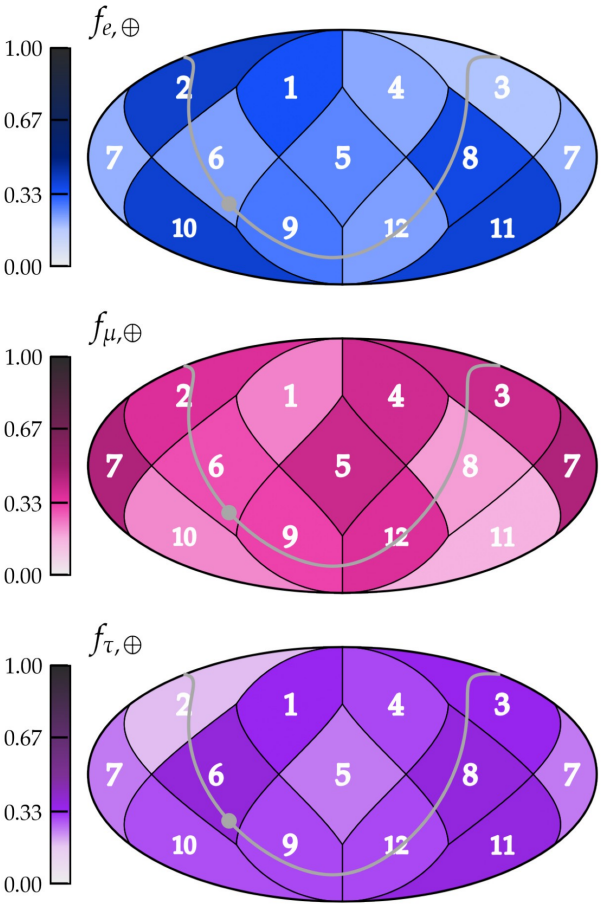
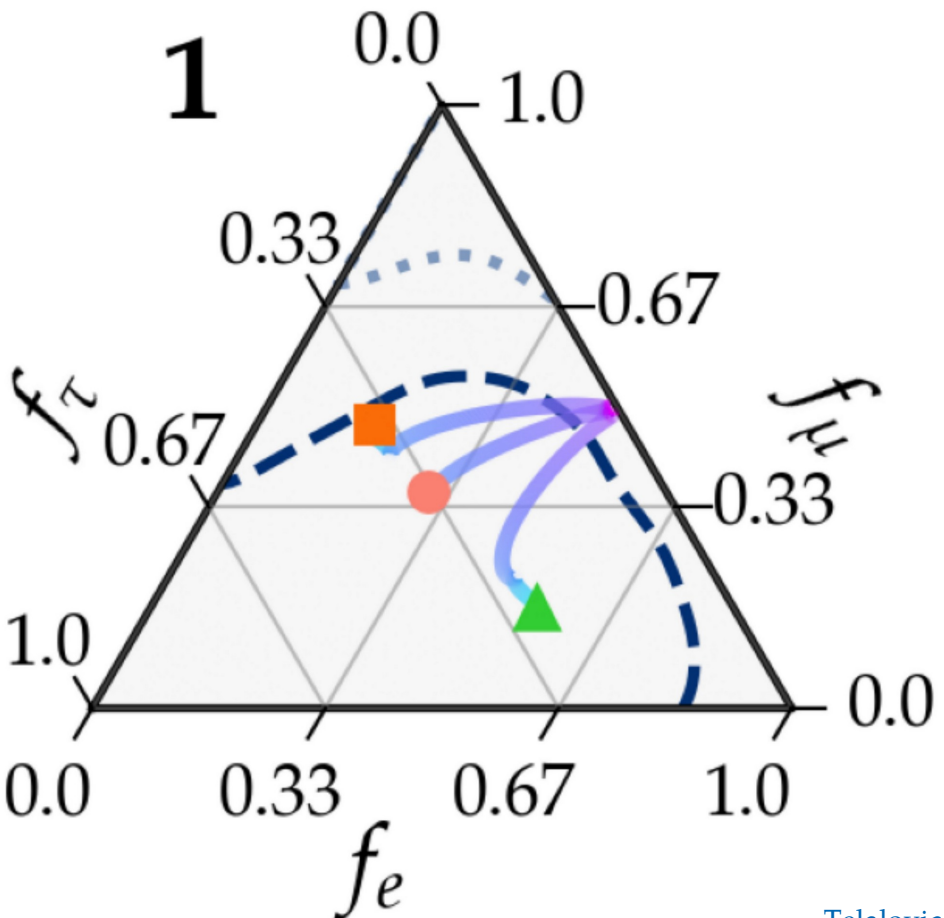
Lorentz-violating high-energy neutrino flavor anisotropy (IceCube HESE 7.5 years)

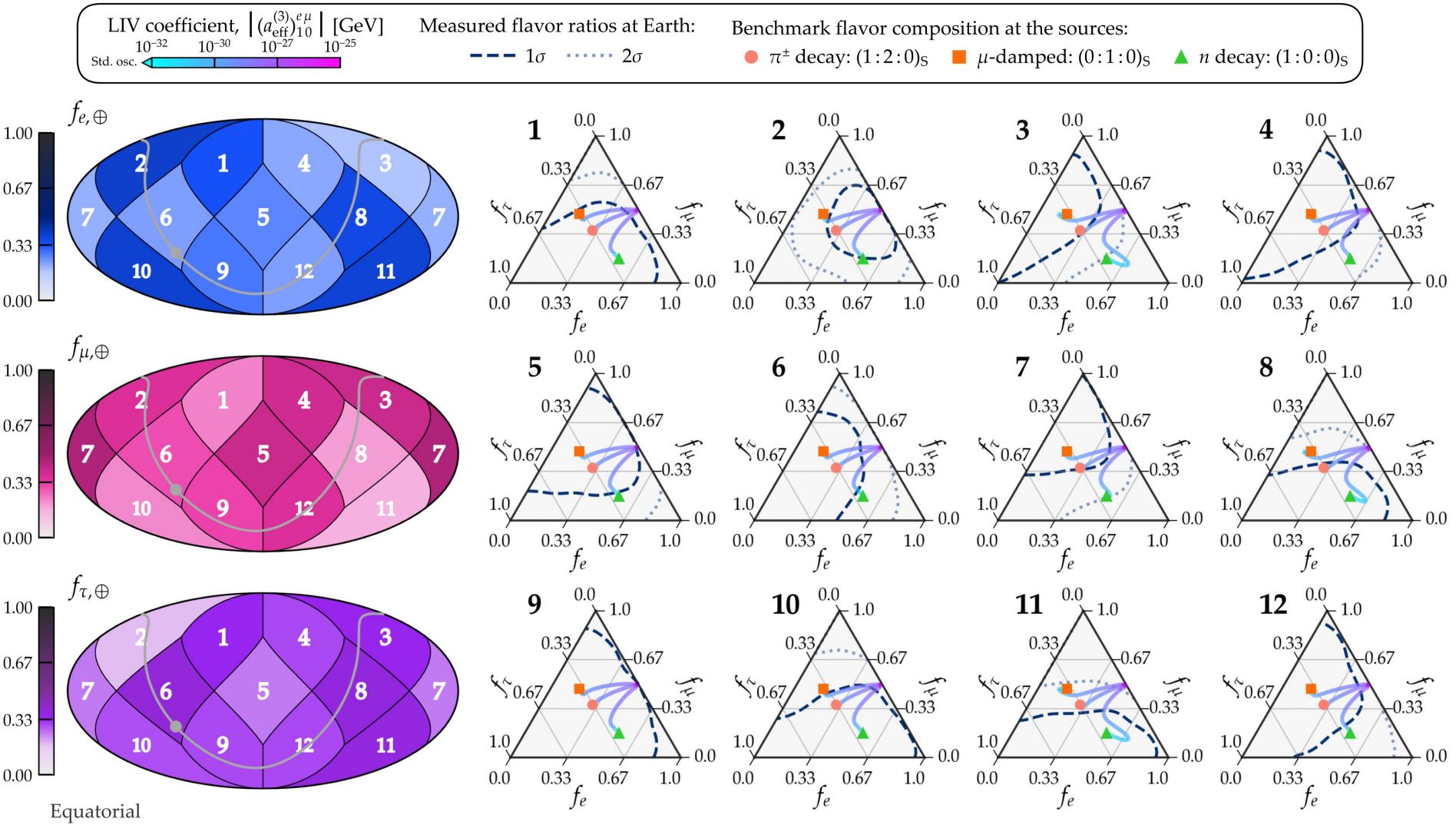




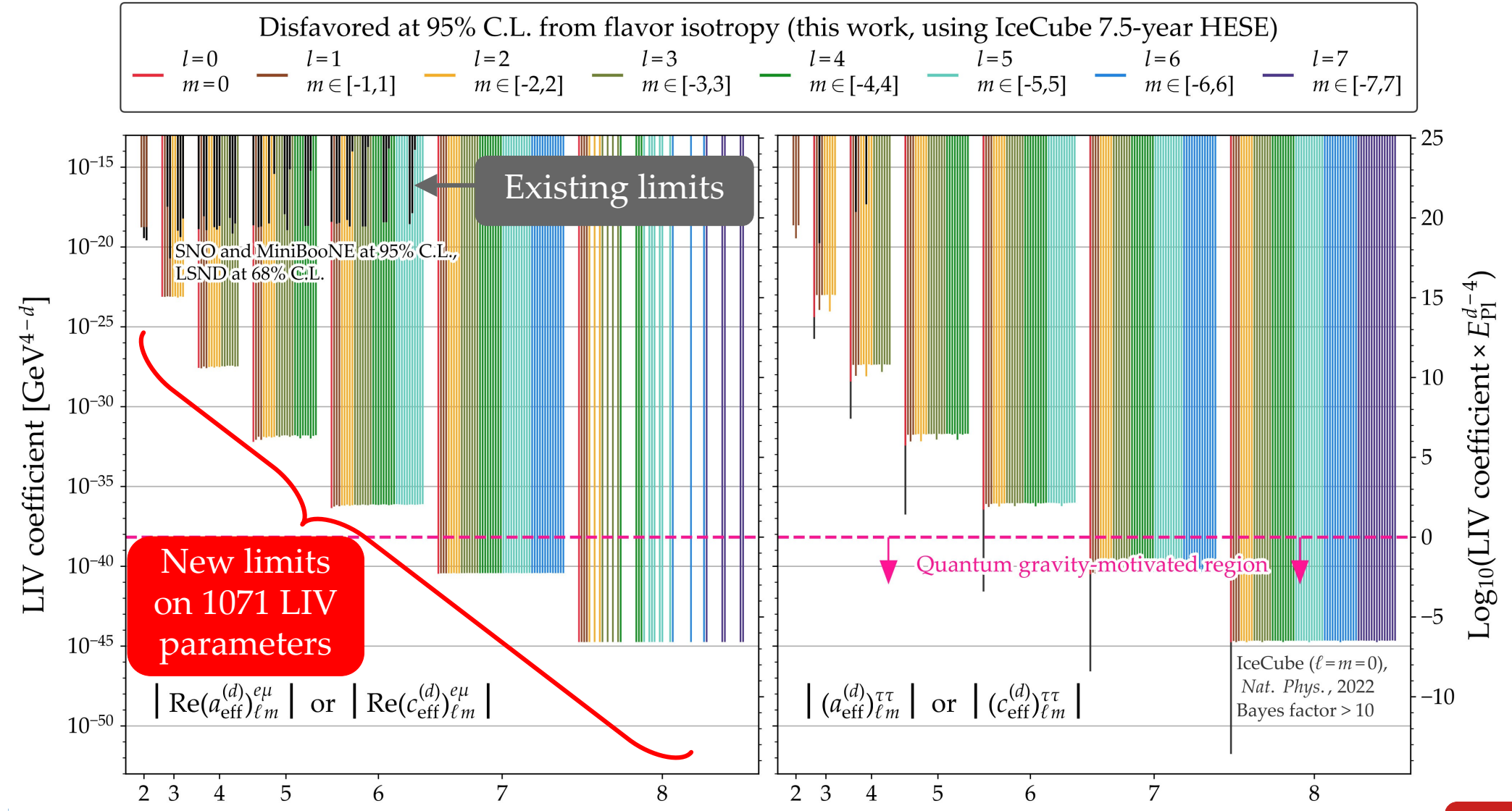


Telalovic, MB, 2503.15468

Lorentz-violating high-energy neutrino flavor anisotropy (IceCube HESE 7.5 years)



Telalovic, **MB**, 2503.15468



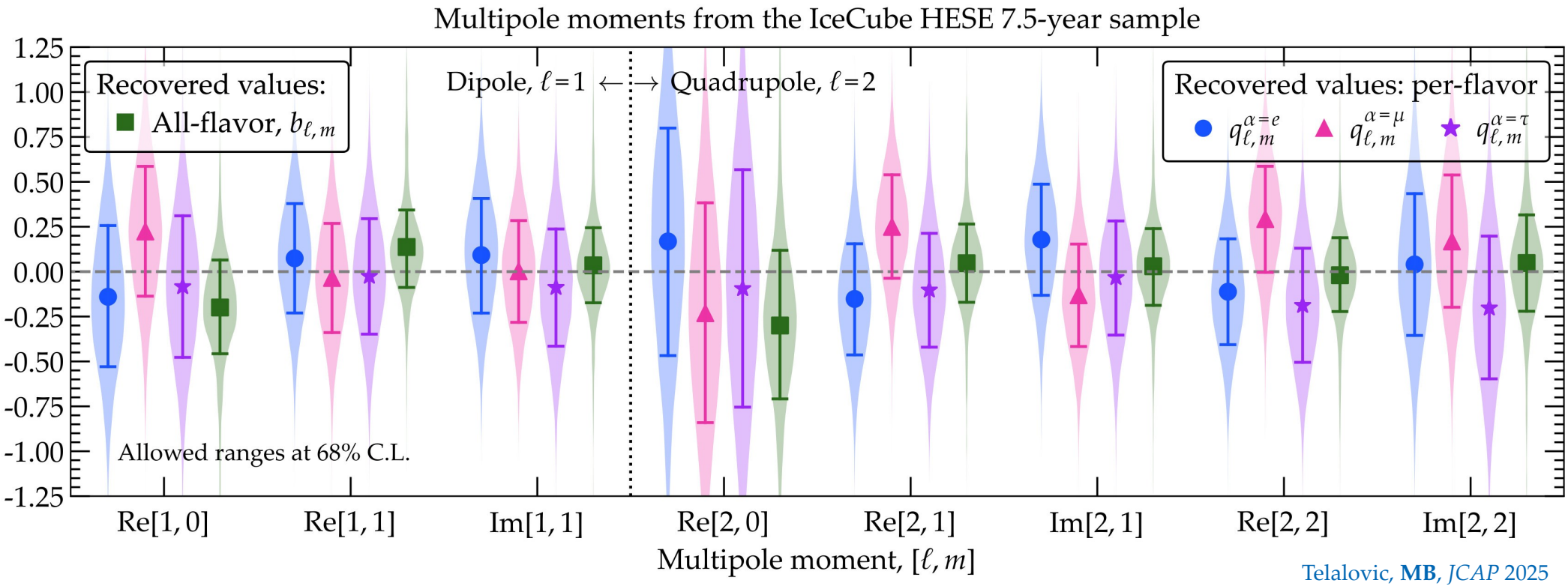
Telalovic, MB, 2503.15468

Flavor dipoles and quadrupoles in the sky?

Flavor-dependent multipole expansion

Isotropic flux

$$\Phi_{\nu_\alpha}(E_\nu, \theta_z, \phi) = \Phi_0 \left(\frac{E_\nu}{100\ \text{TeV}}\right)^{-\gamma} \times \frac{1}{6}\left[1 + \sum_{\ell=1}^{\infty}\sum_{m=-\ell}^{\ell} q^{\alpha}_{\ell,m} Y^m_\ell(\theta_z, \phi)\right]$$



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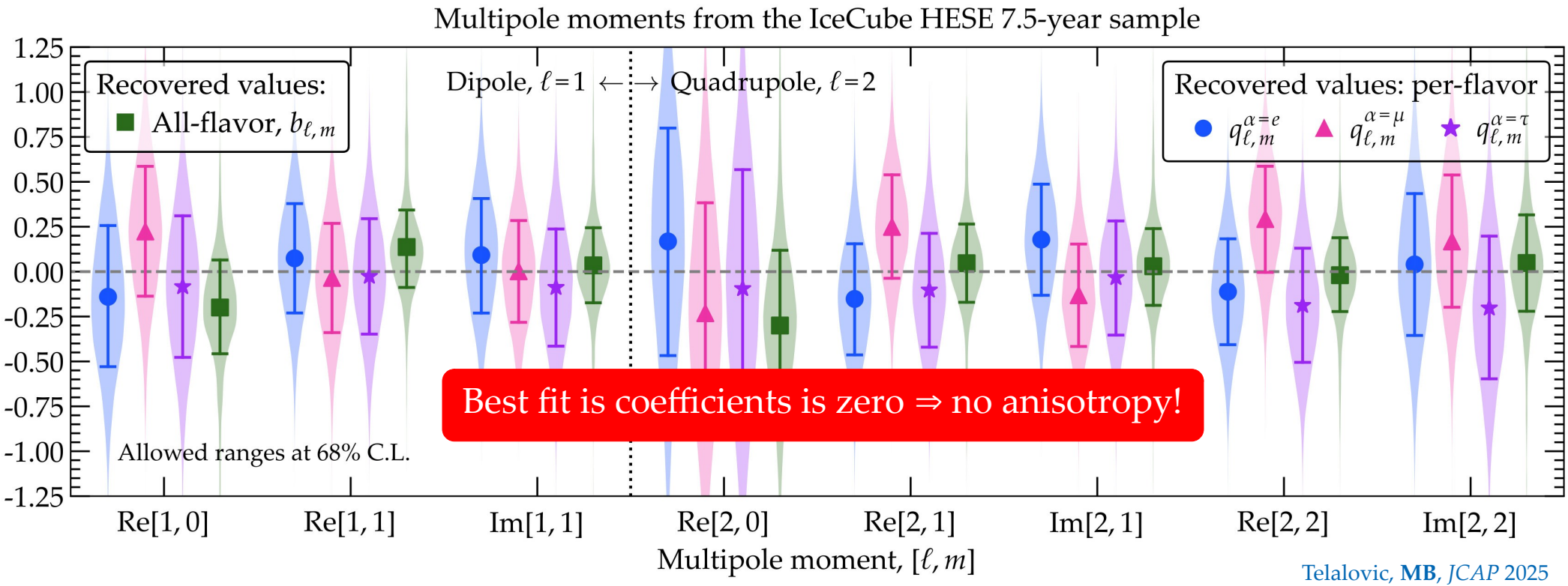

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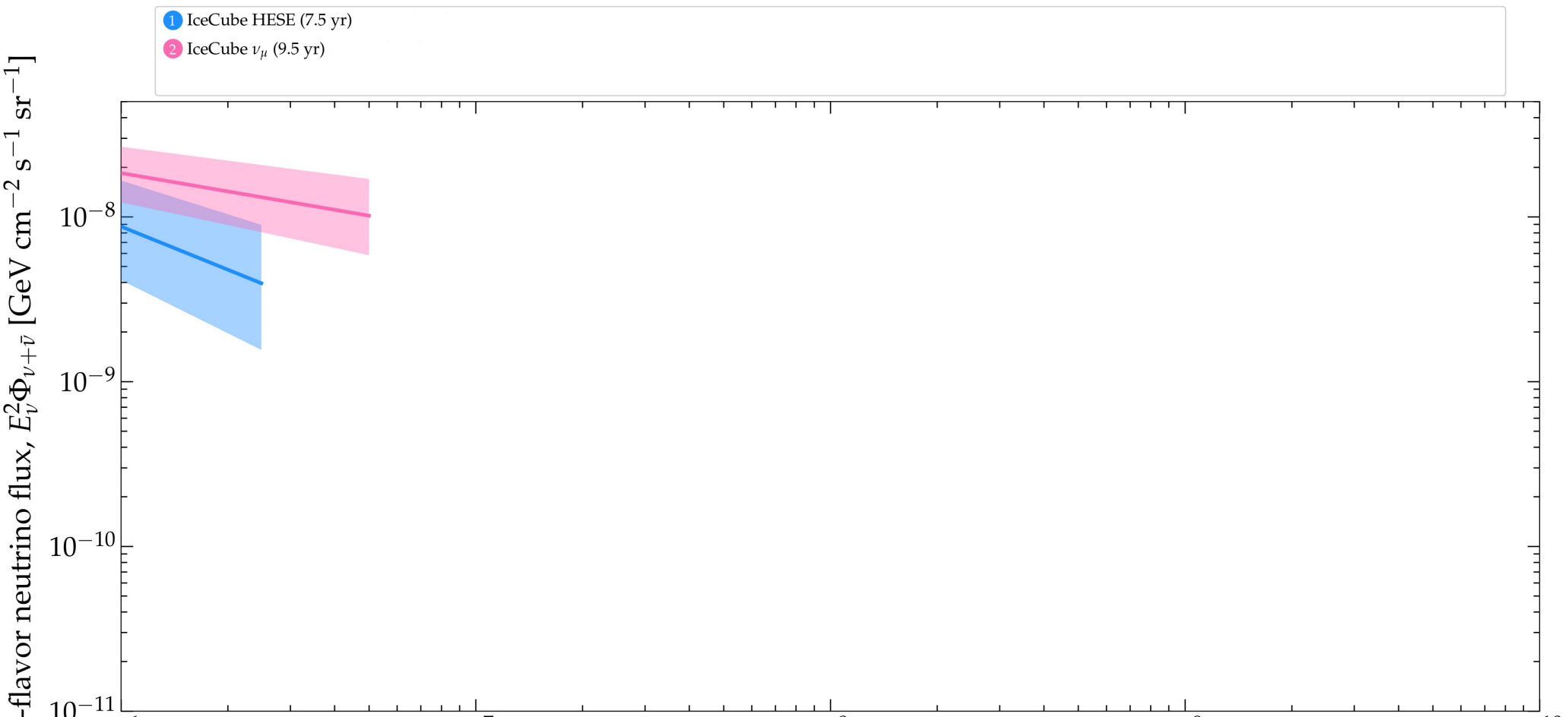
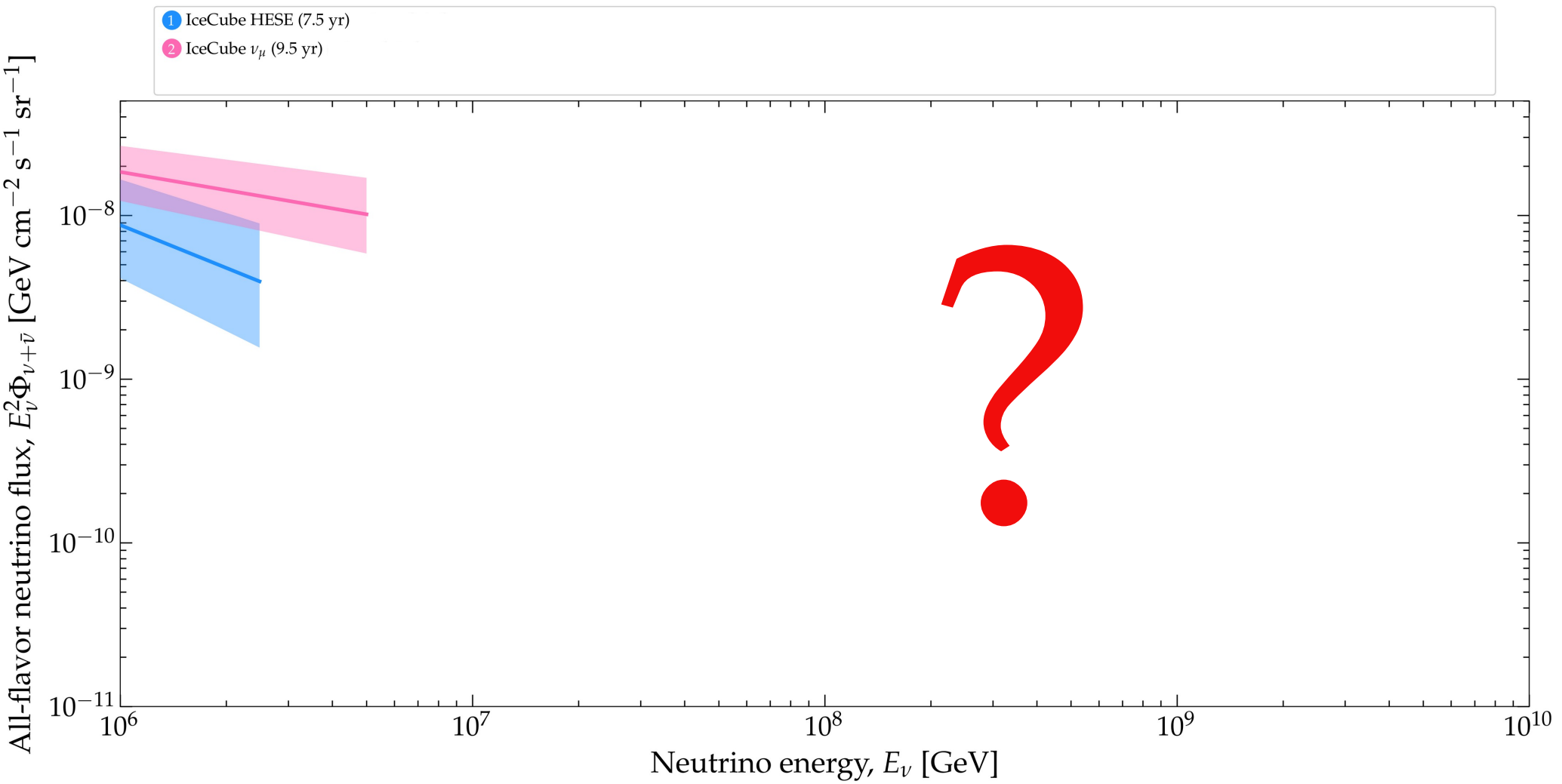
Flavor at ultra-high energies (> 100 PeV)


1 IceCube HESE (7.5 yr)
2 IceCube ν_μ (9.5 yr)
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]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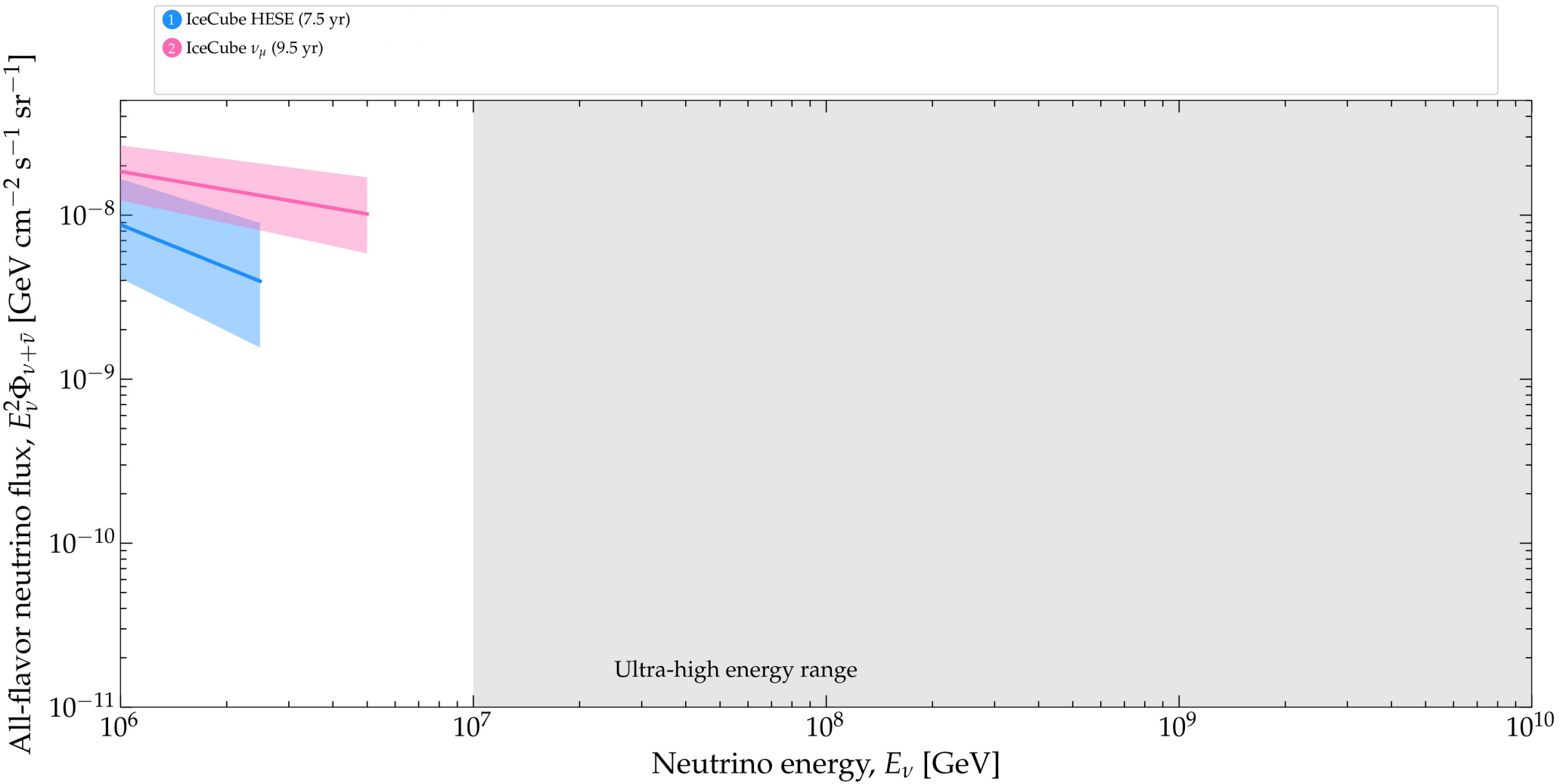
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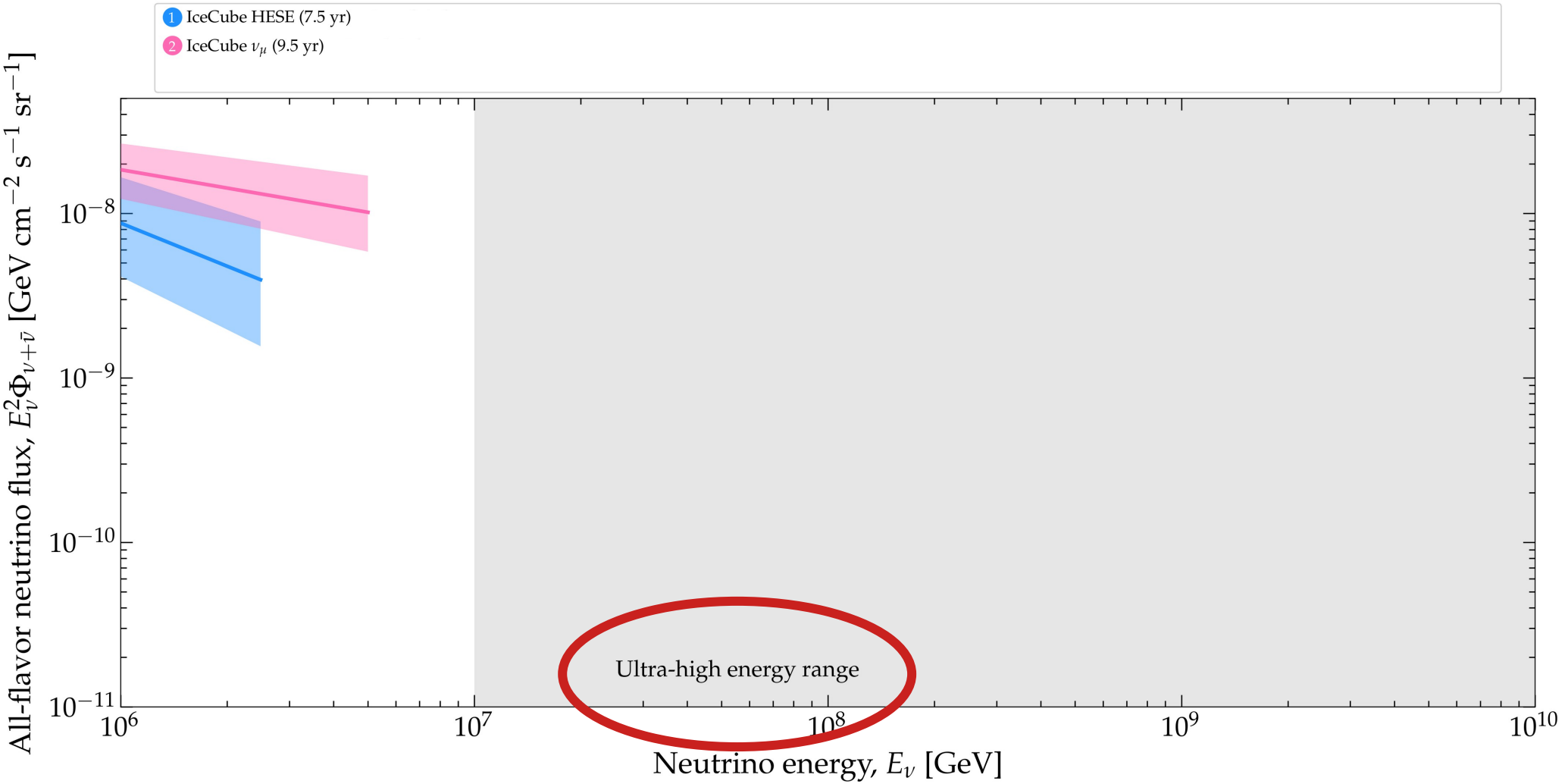
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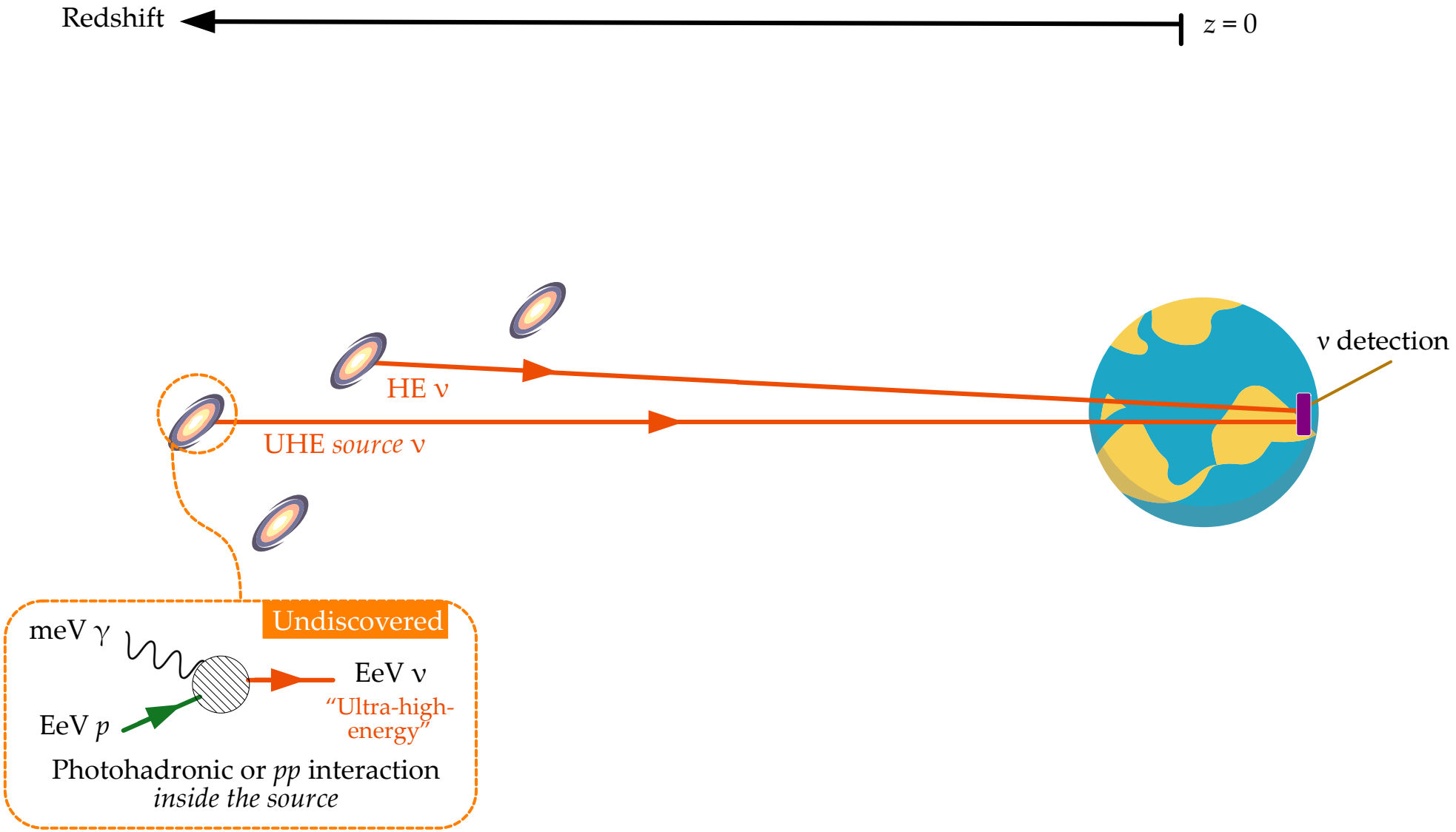
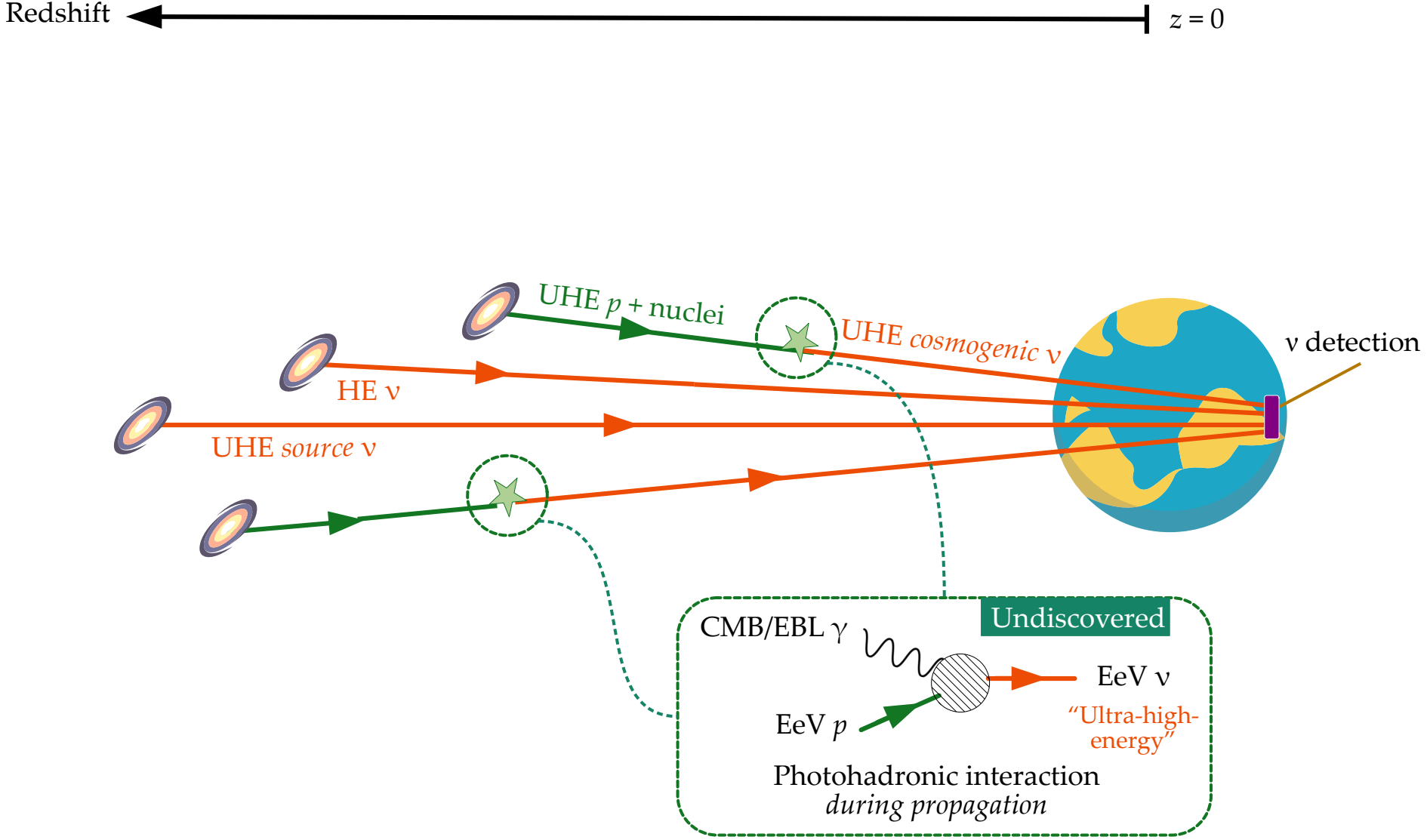

Redshift
z = 0
HE ν
UHE source ν
ν detection
Undiscovered
meV γ
EeV ν
"Ultra-high-energy"
EeV p
Photohadronic or pp interaction
inside the source


Redshift
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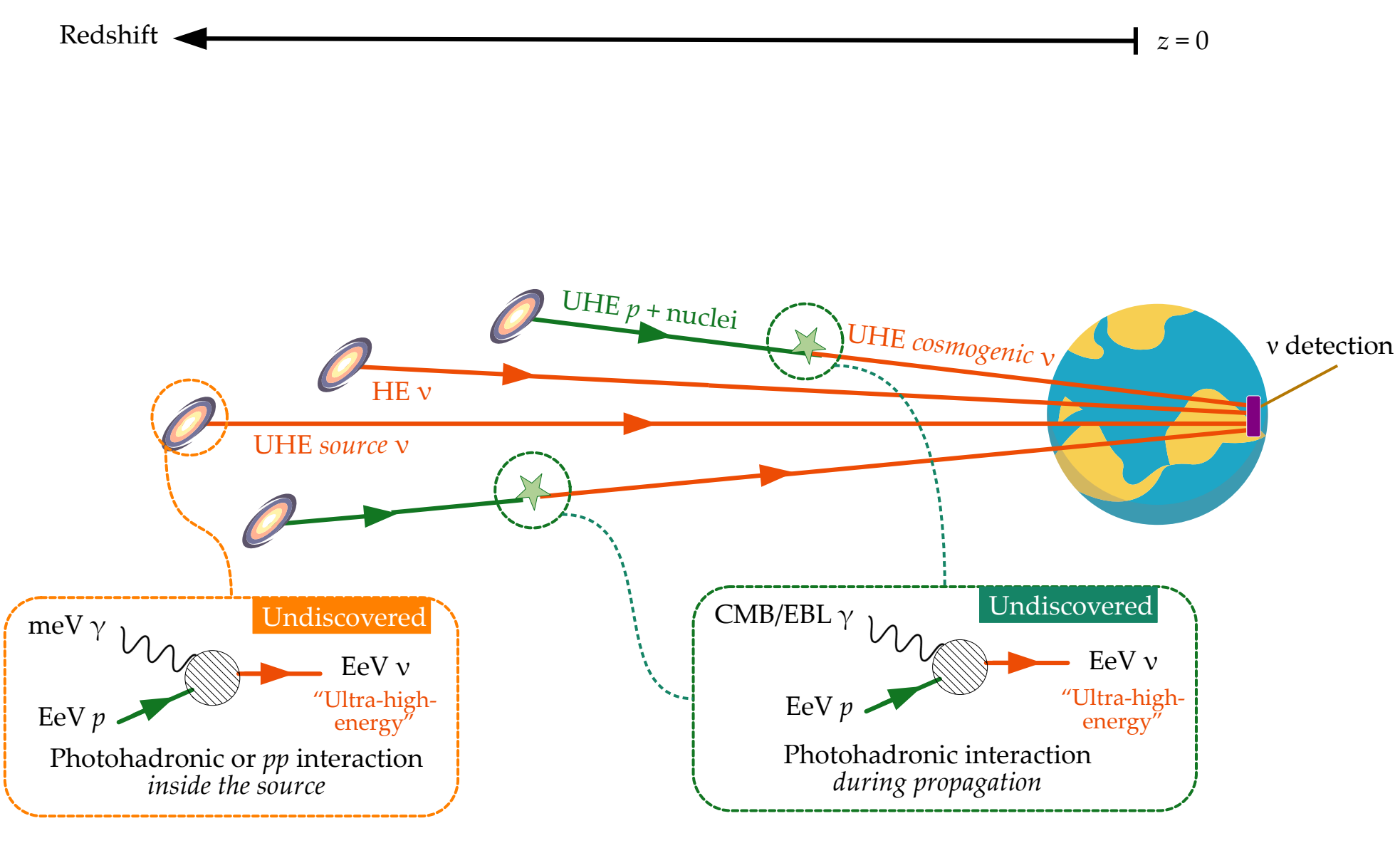
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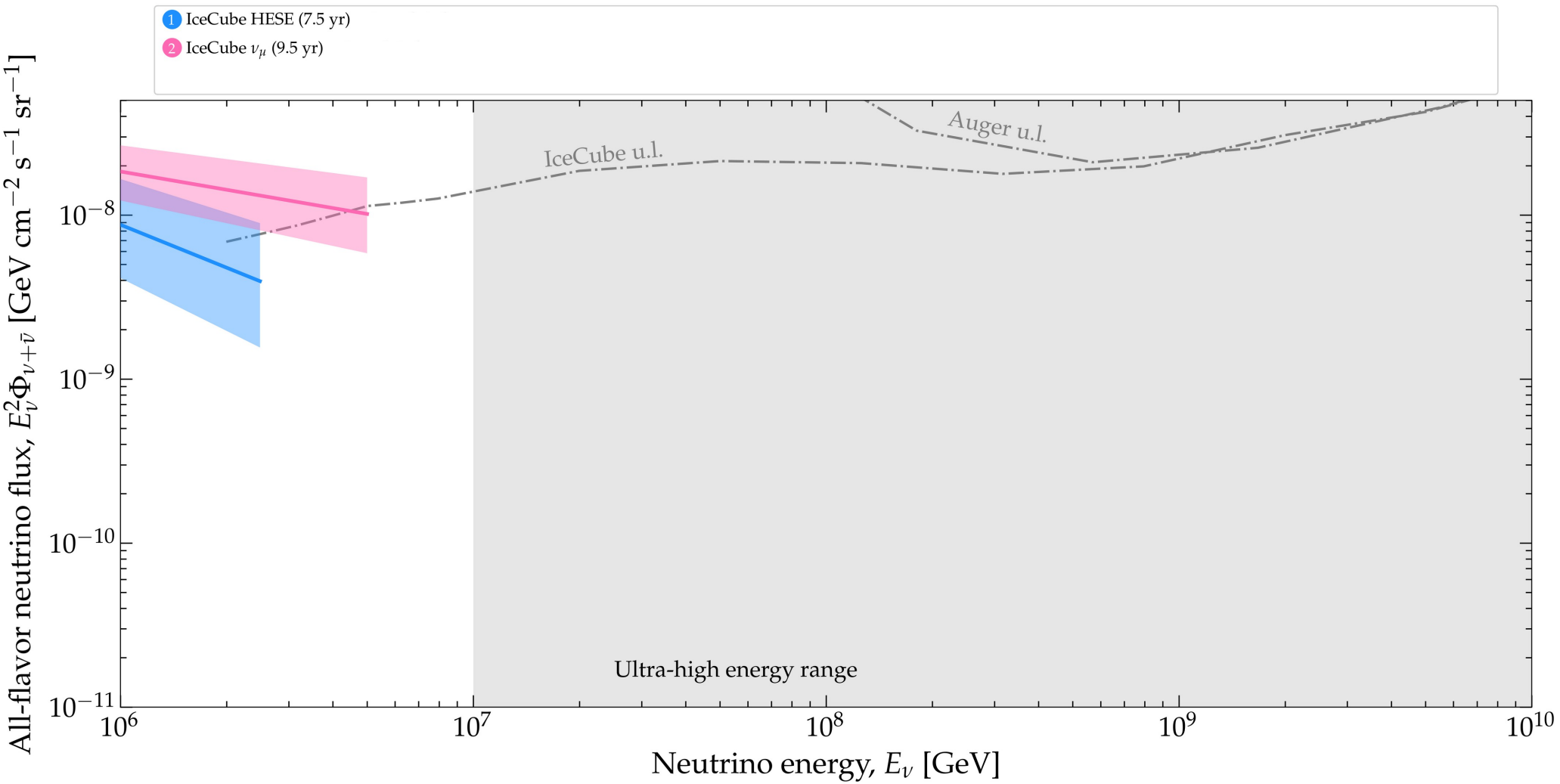
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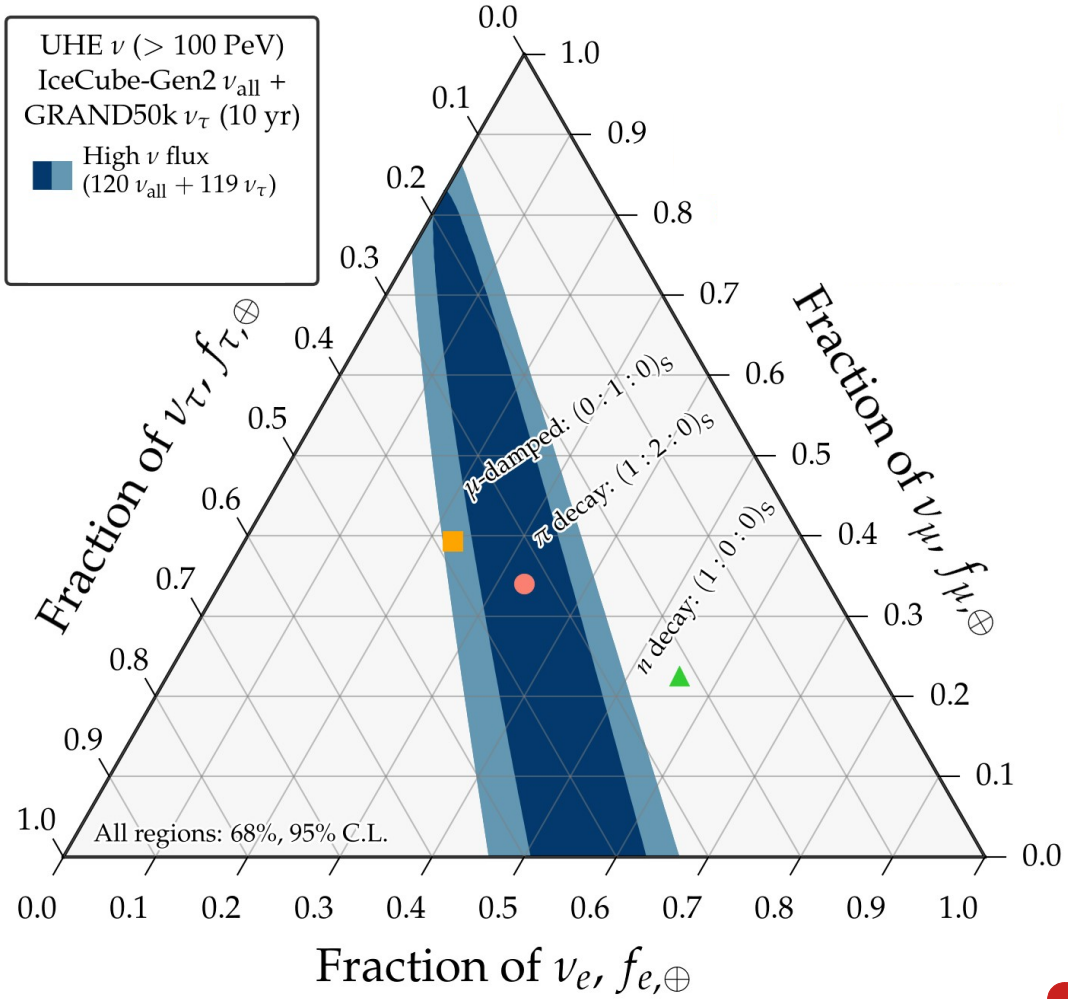
Manufacturing UHE flavor sensitivity with two detectors

What if future UHE radio-detection neutrino telescopes cannot see flavor?

Then we combine two of detectors:



Testagrossa, Fiorillo, **MB**, *PRD* 2024

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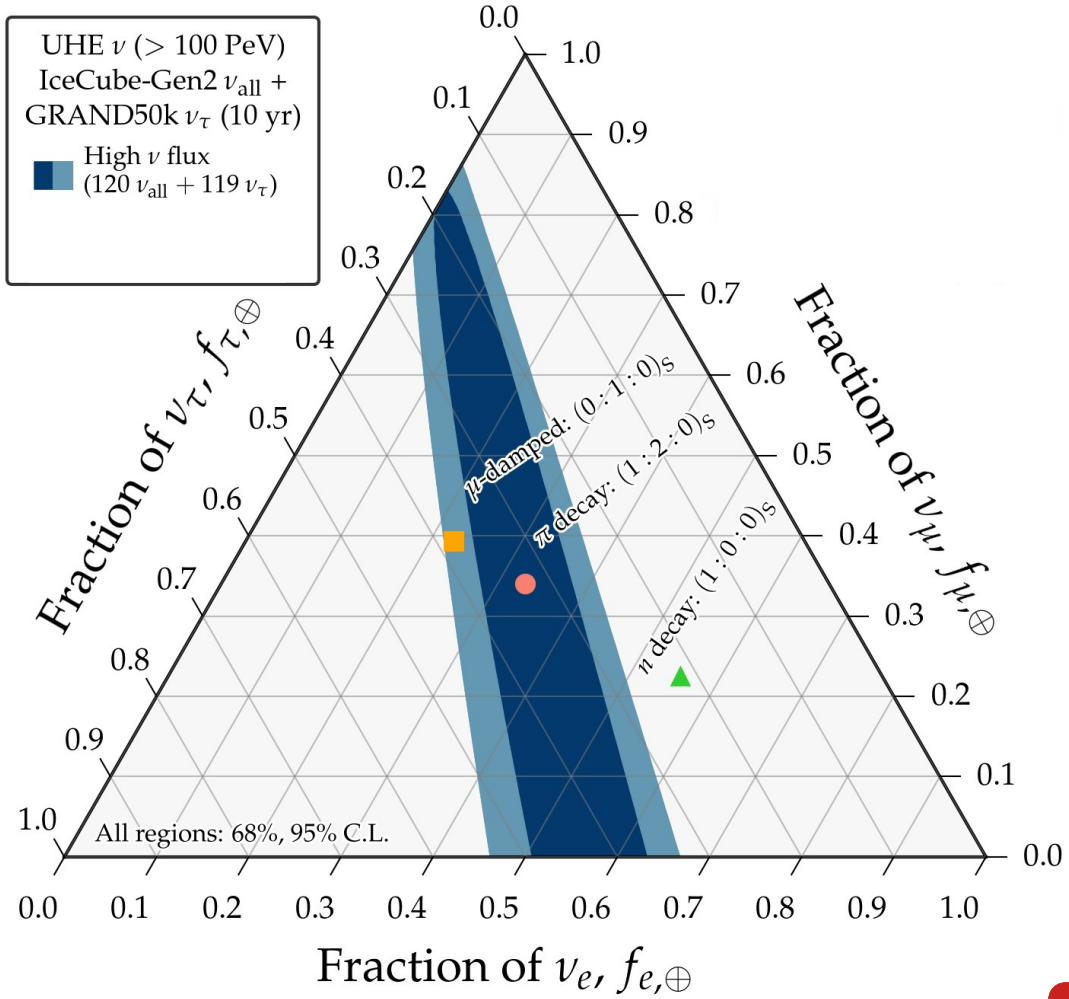

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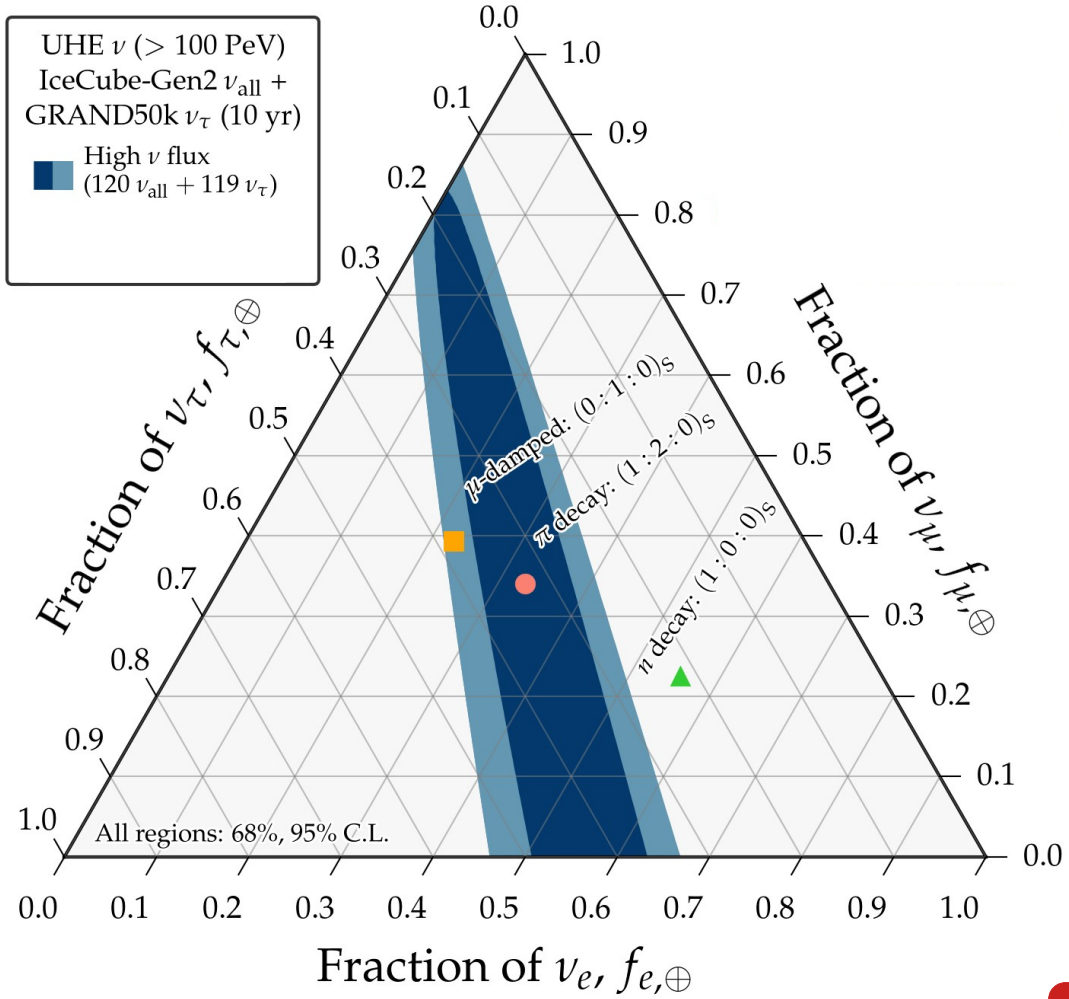

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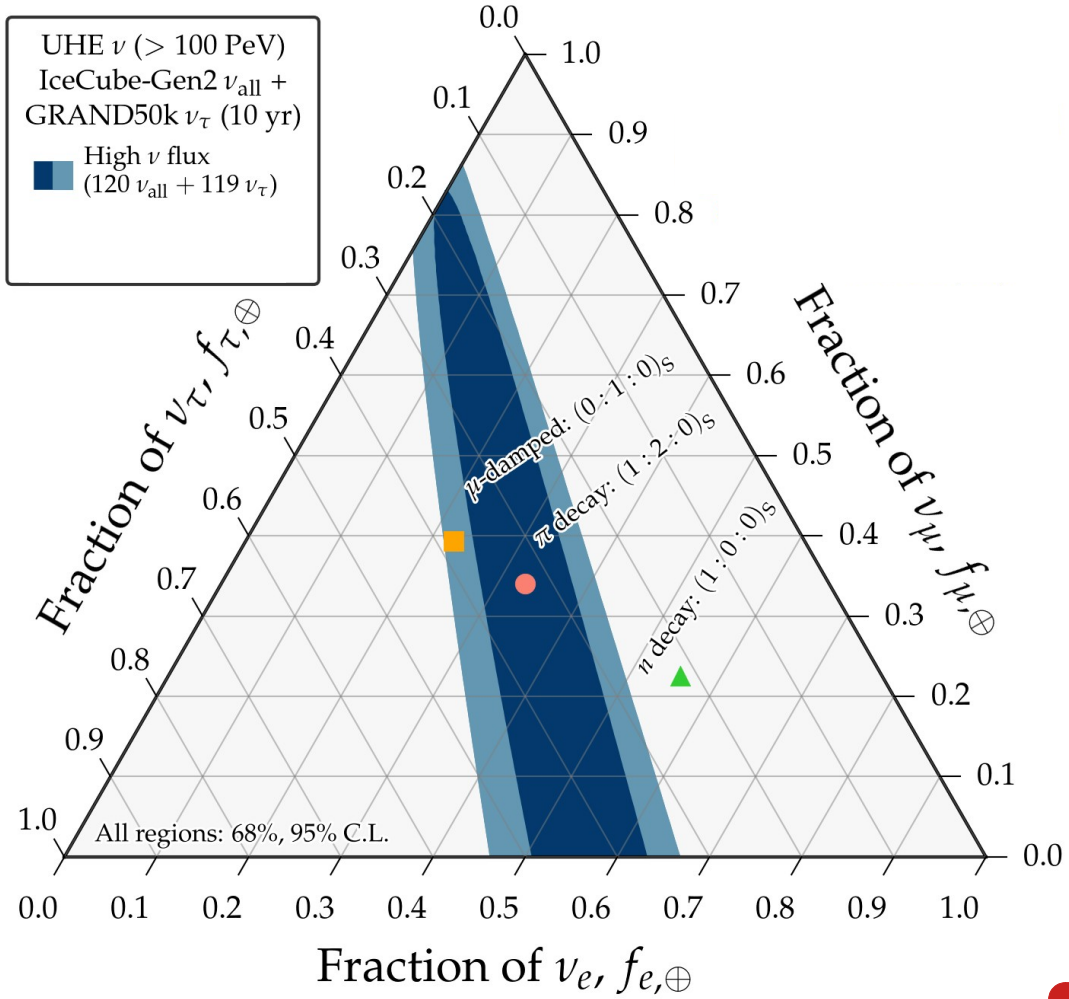

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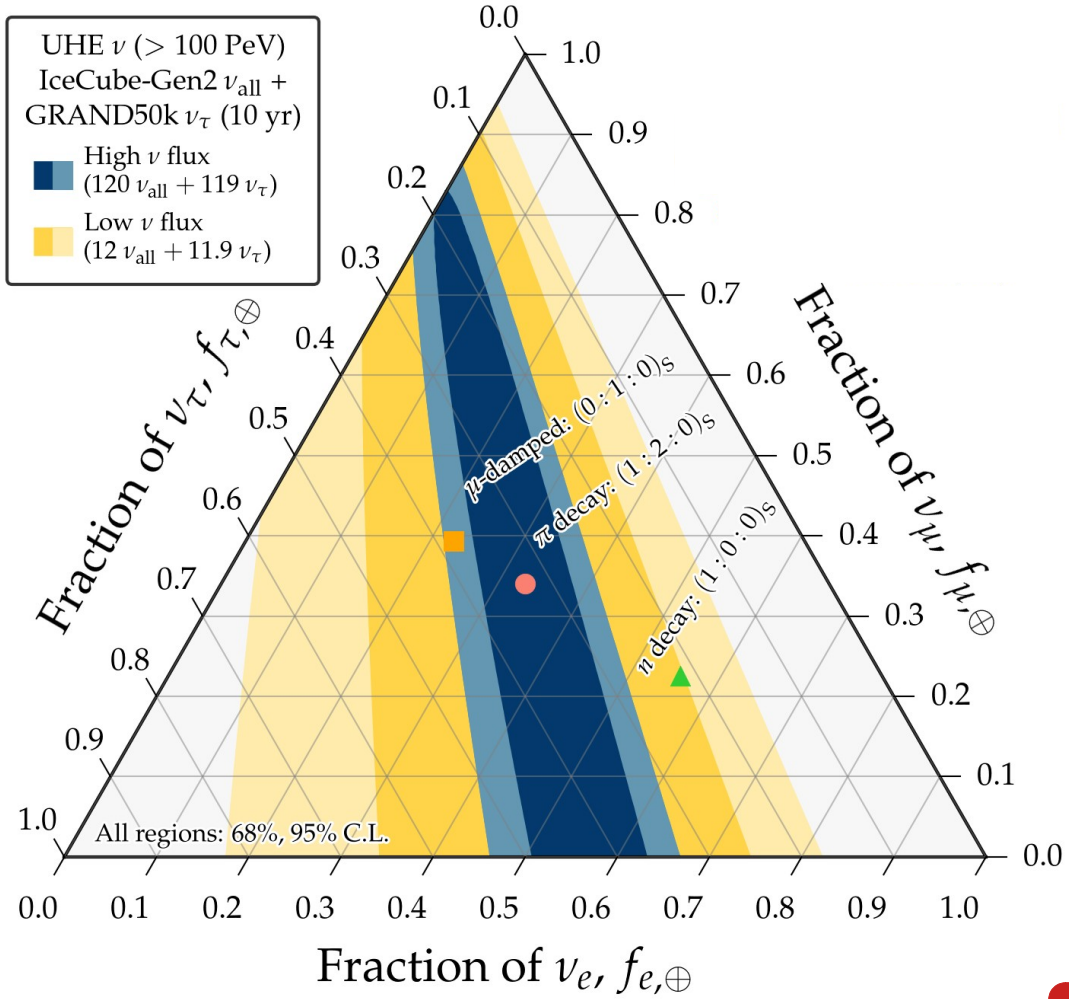

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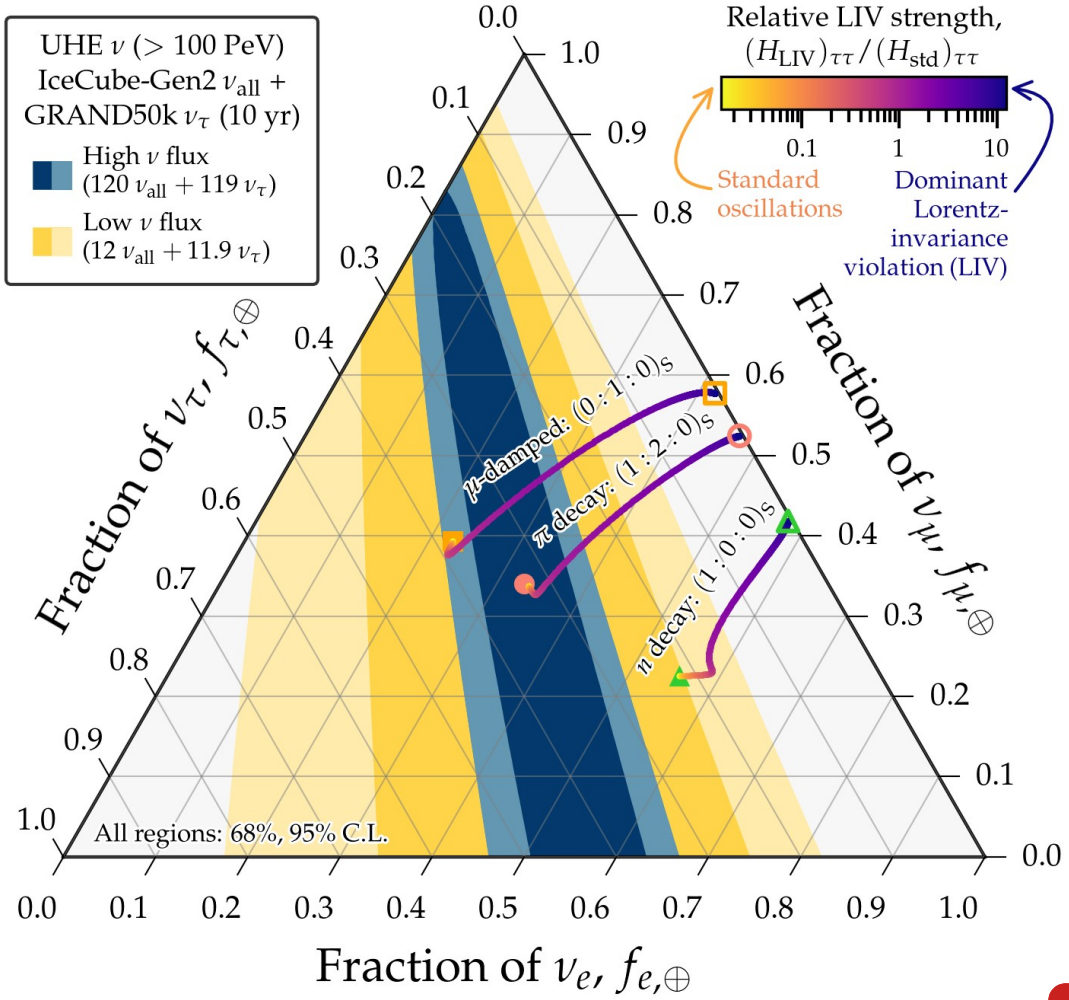

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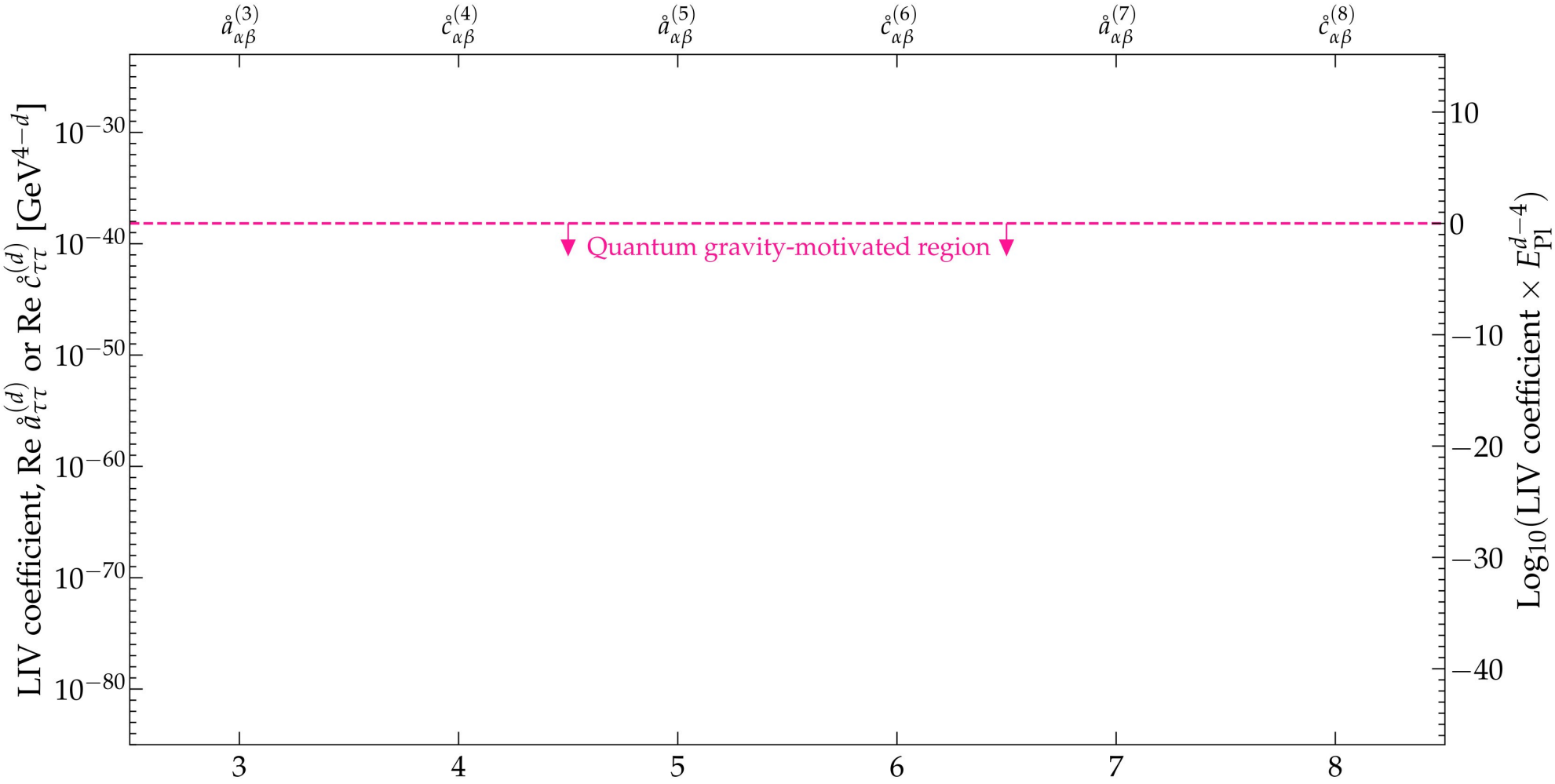
Lorentz-invariance violation at ultra-high energies



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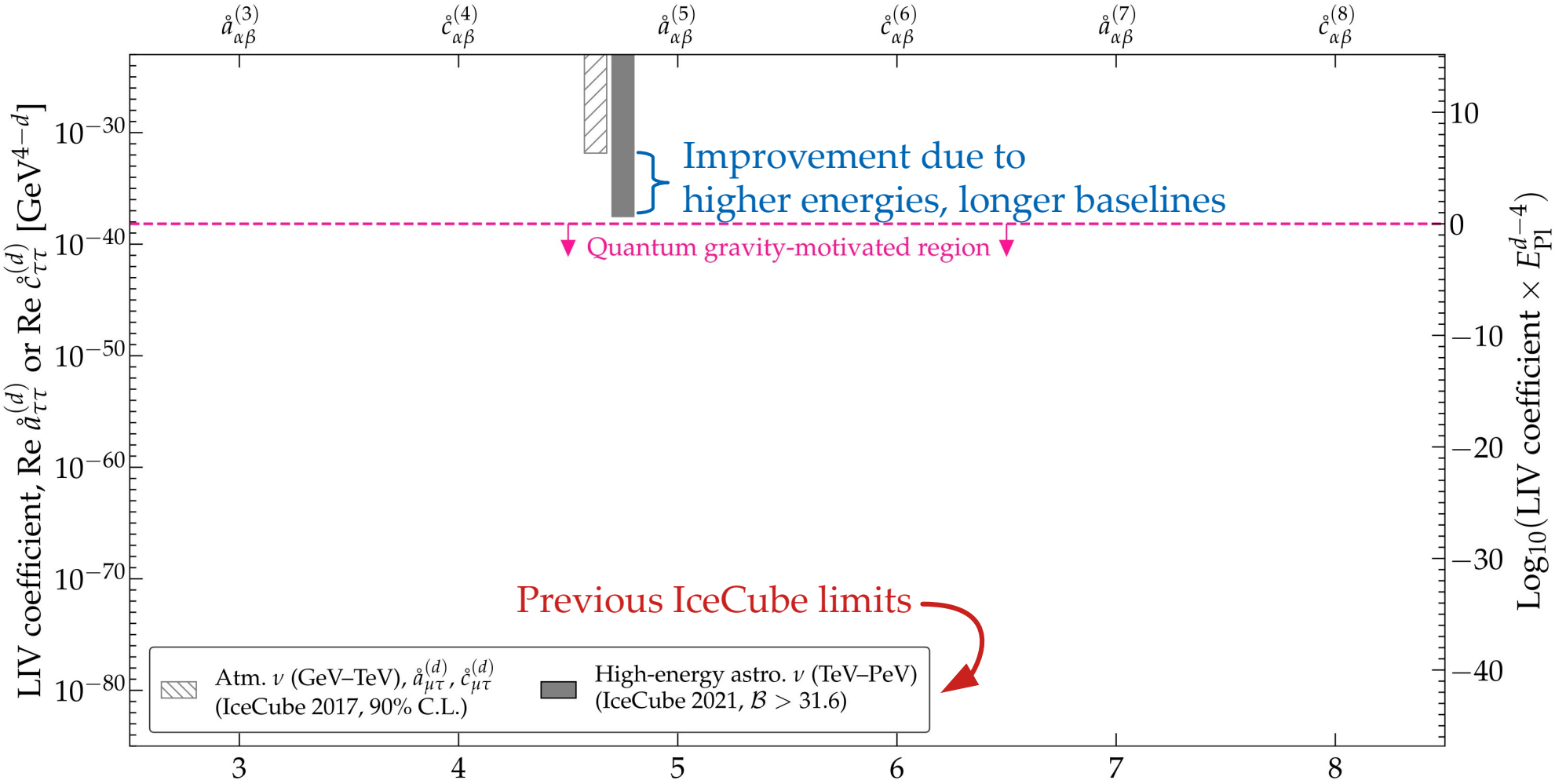

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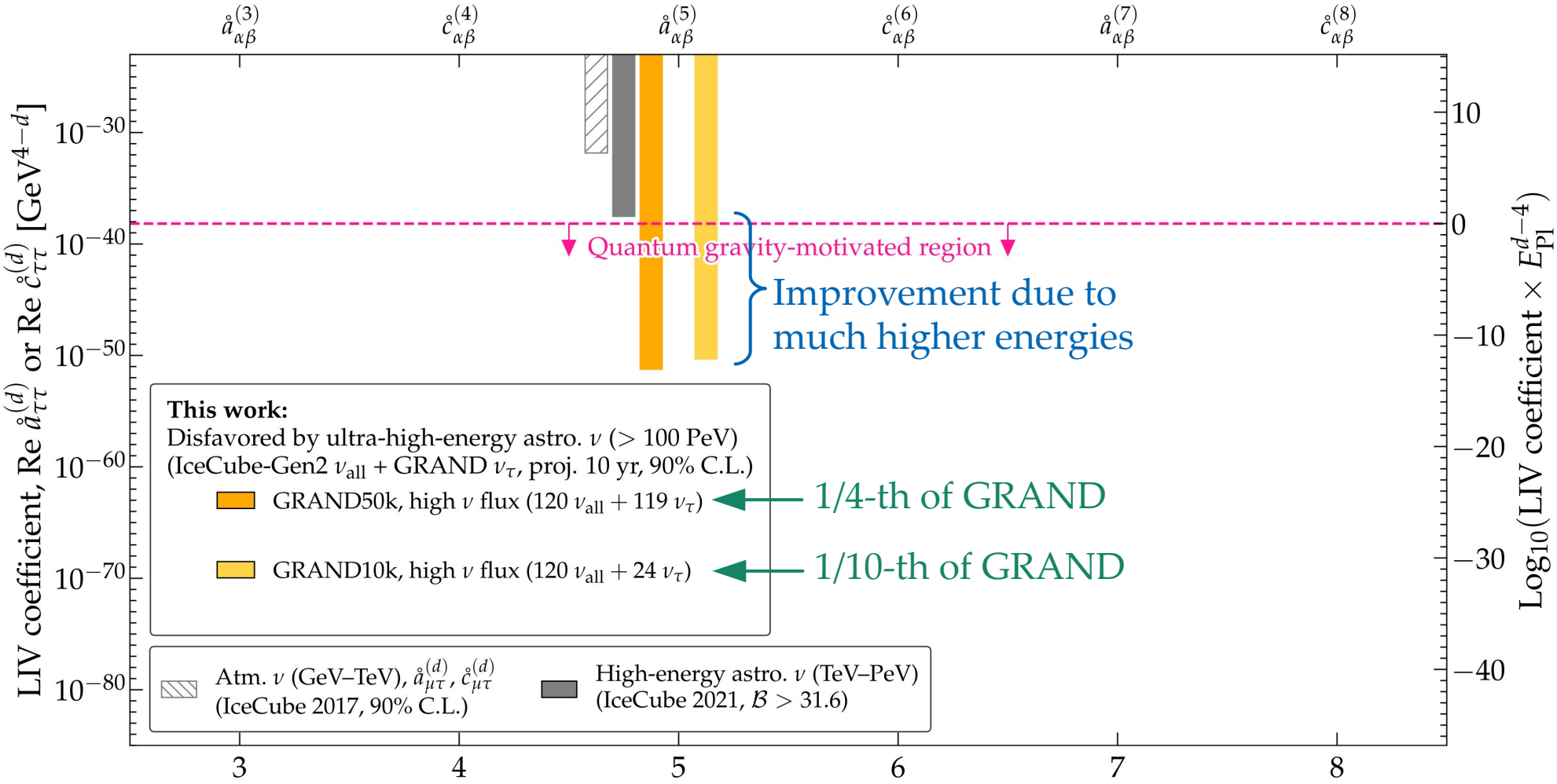

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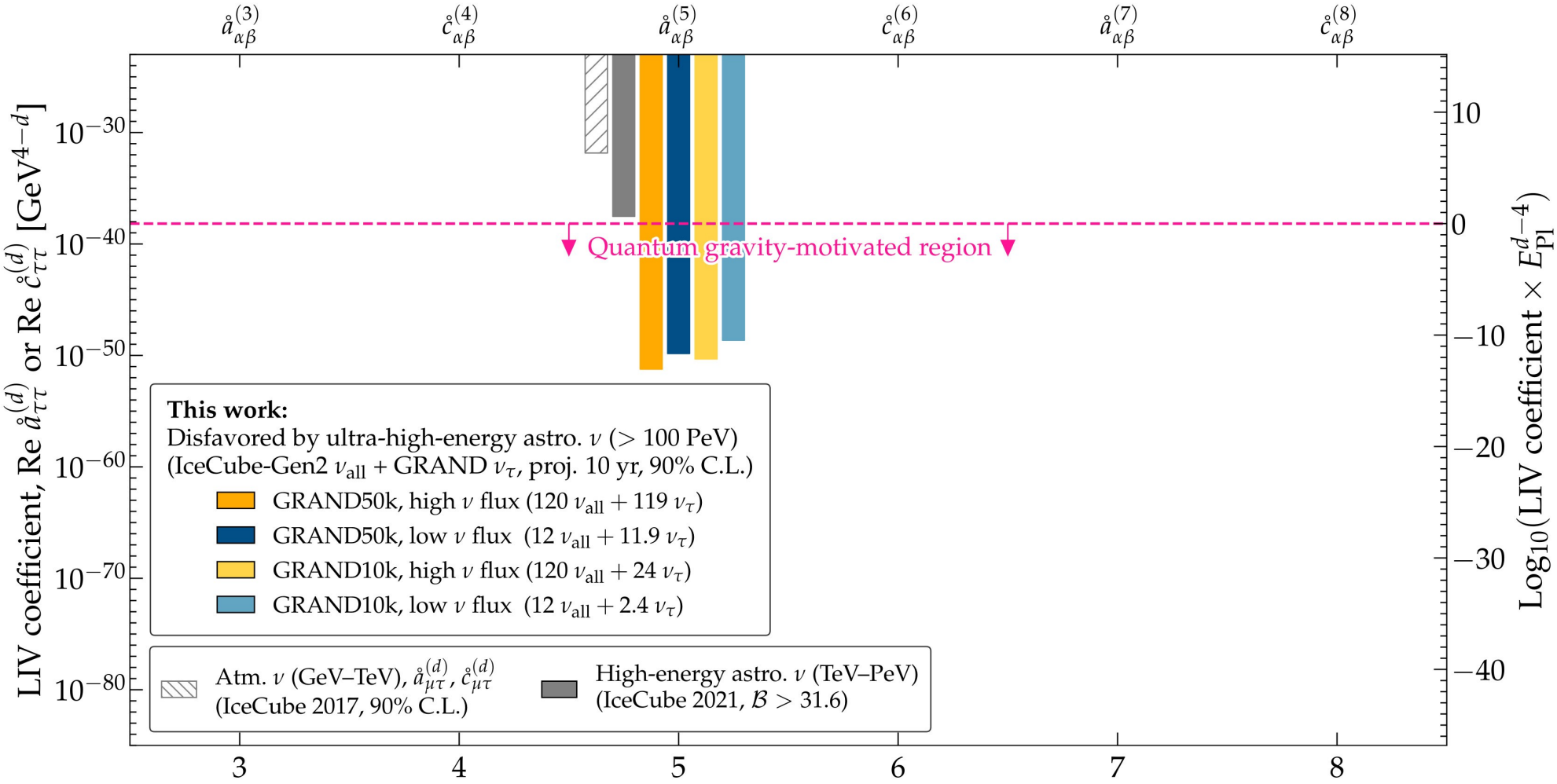

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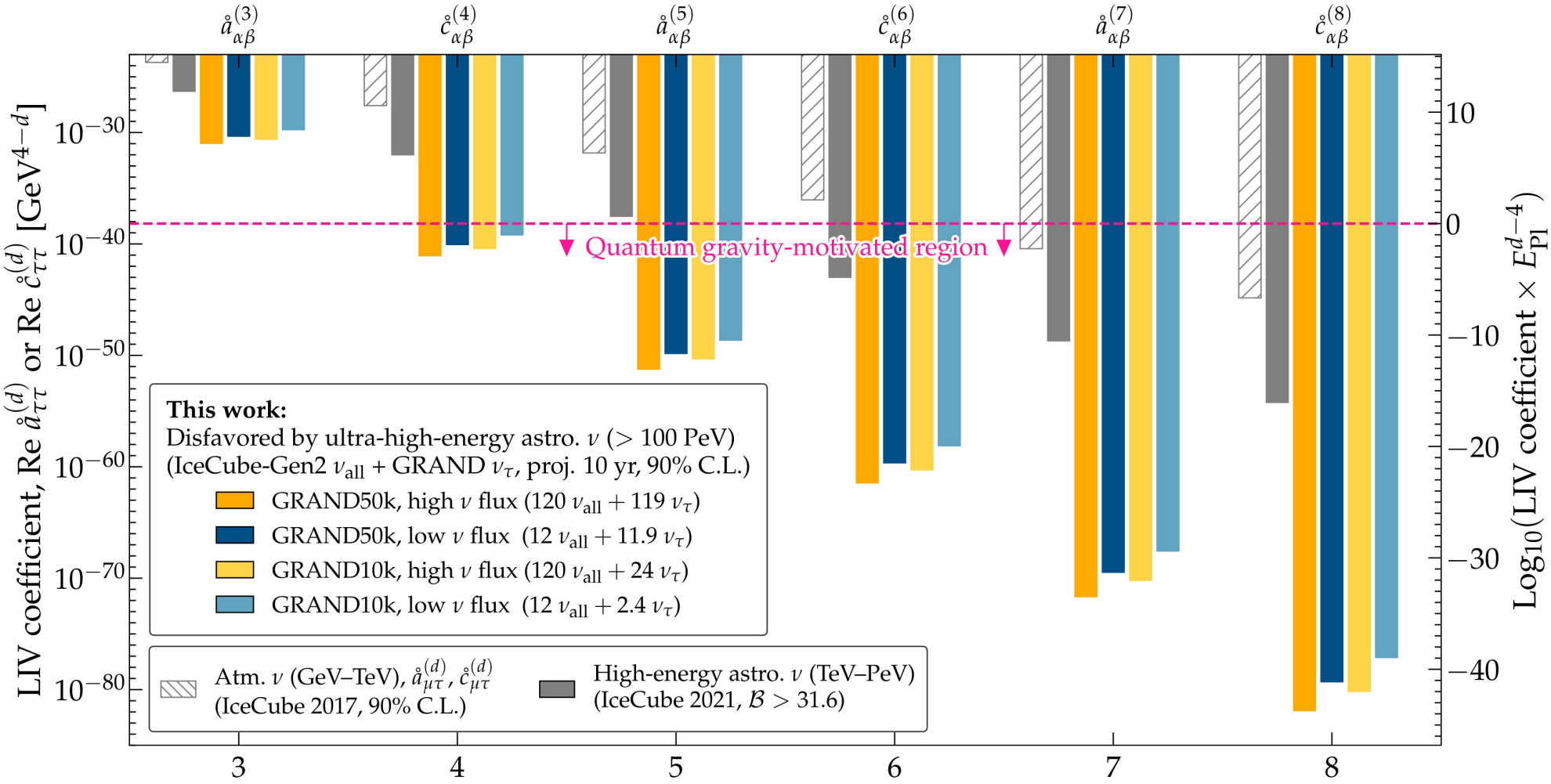

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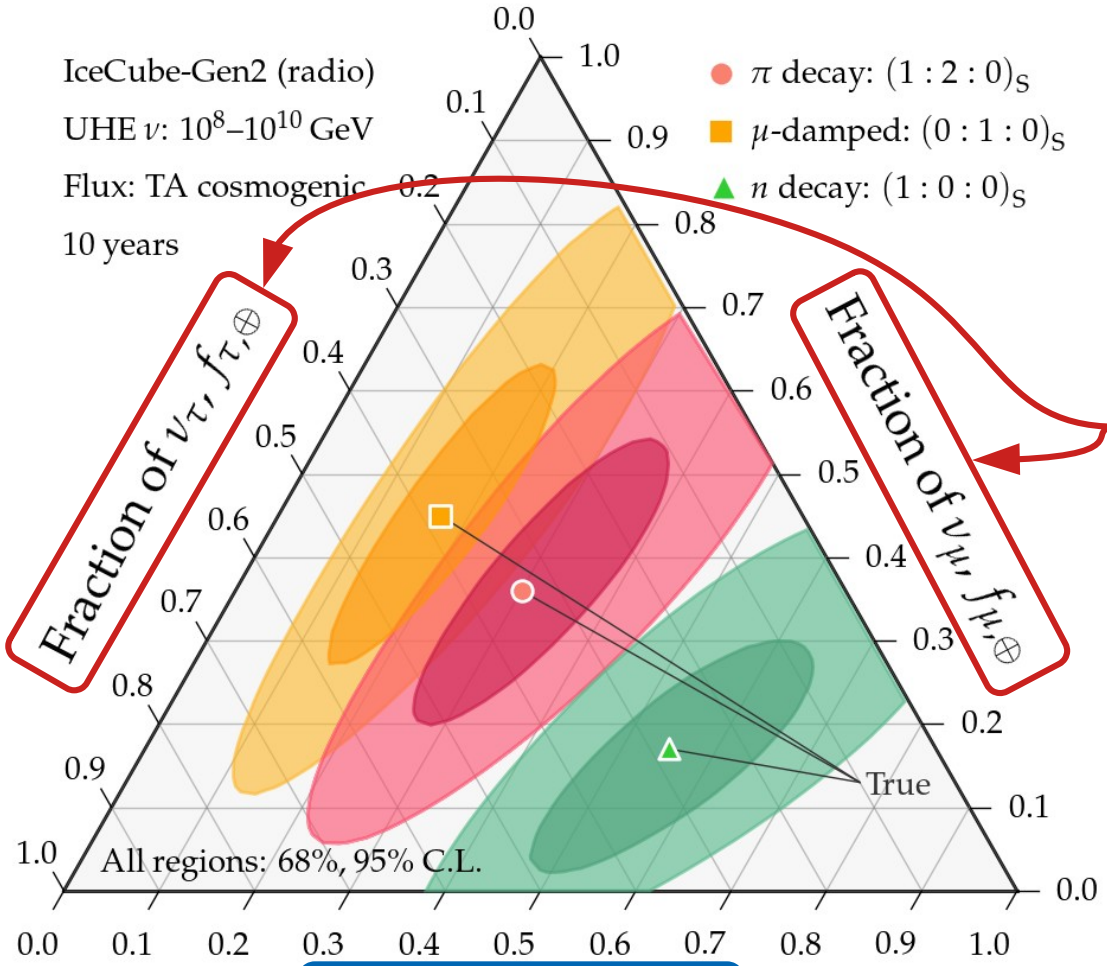
IceCube-Gen2 (radio) alone might measure flavor



Fraction of ν_e

Showers are elongated due to the LPM effect

Fraction of $\nu_\mu + \nu_\tau$

Secondary muons and tauons create showers that hit >1 radio station

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