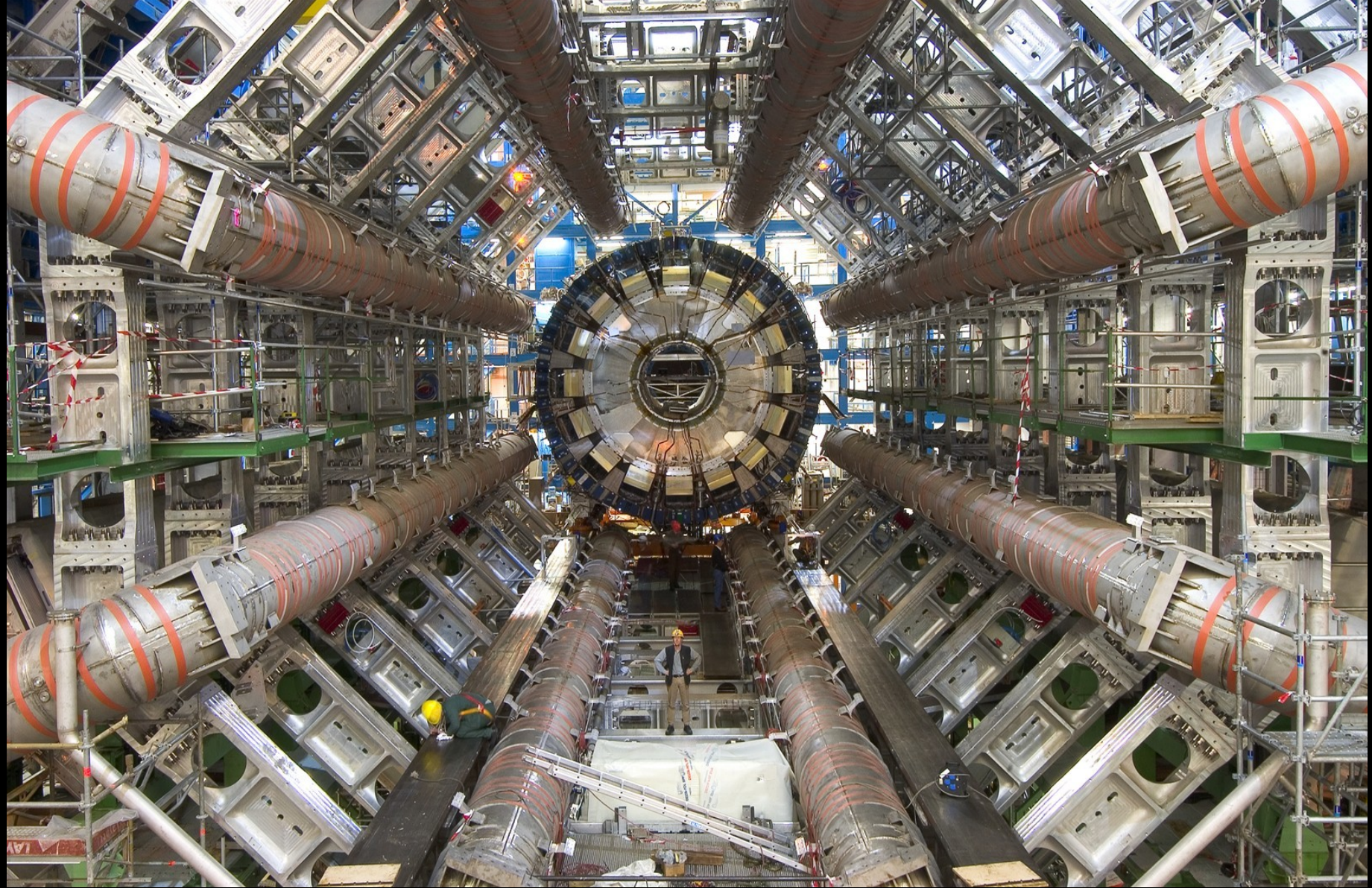
Beyond PMNS with high-energy astrophysical neutrinos

Mauricio Bustamante
Niels Bohr Institute, University of Copenhagen

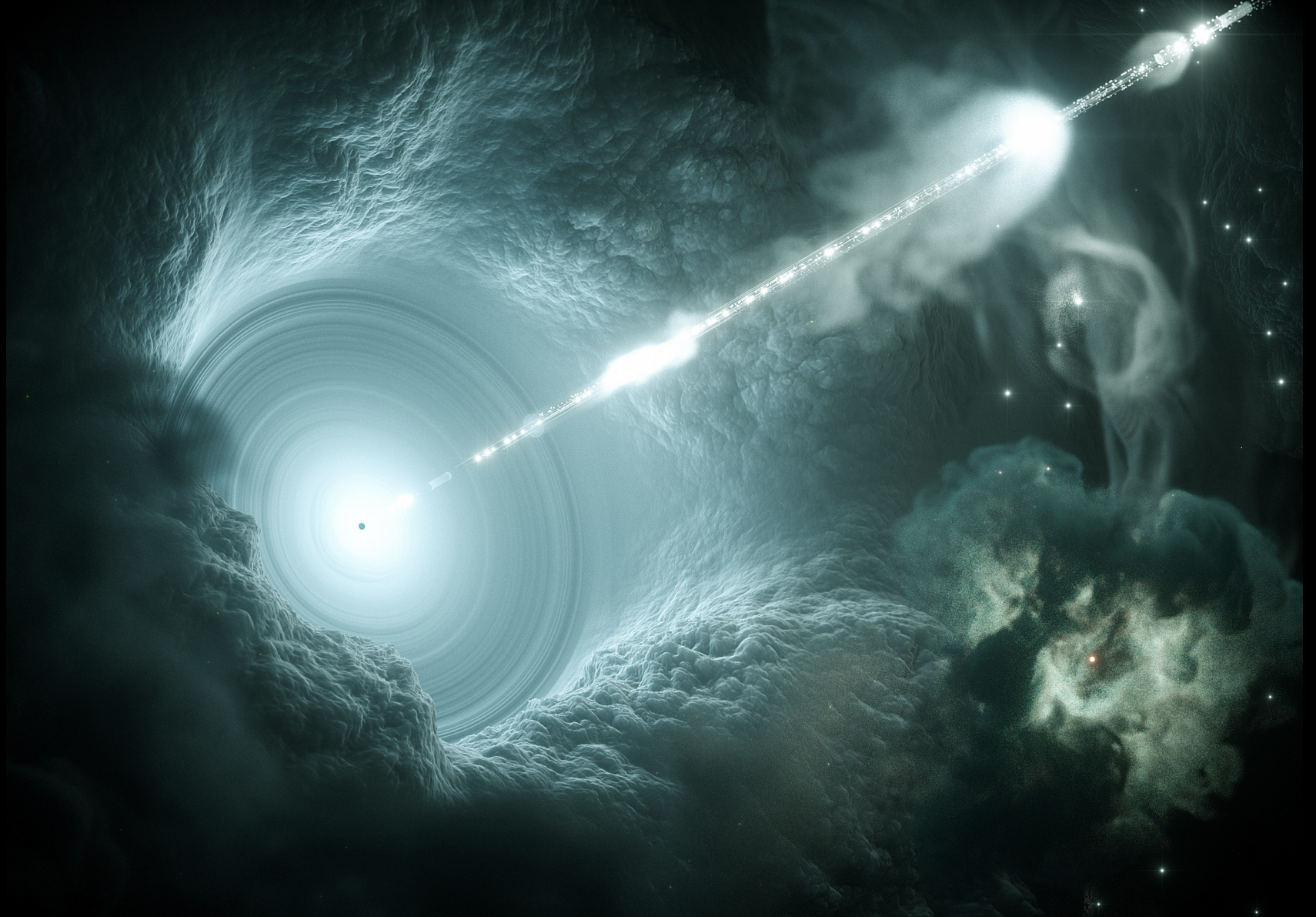
UNIVERSITY OF COPENHAGEN

VILLUM FONDEN

26th NuFact
Liverpool, September 04, 2025



ATLAS



DESY

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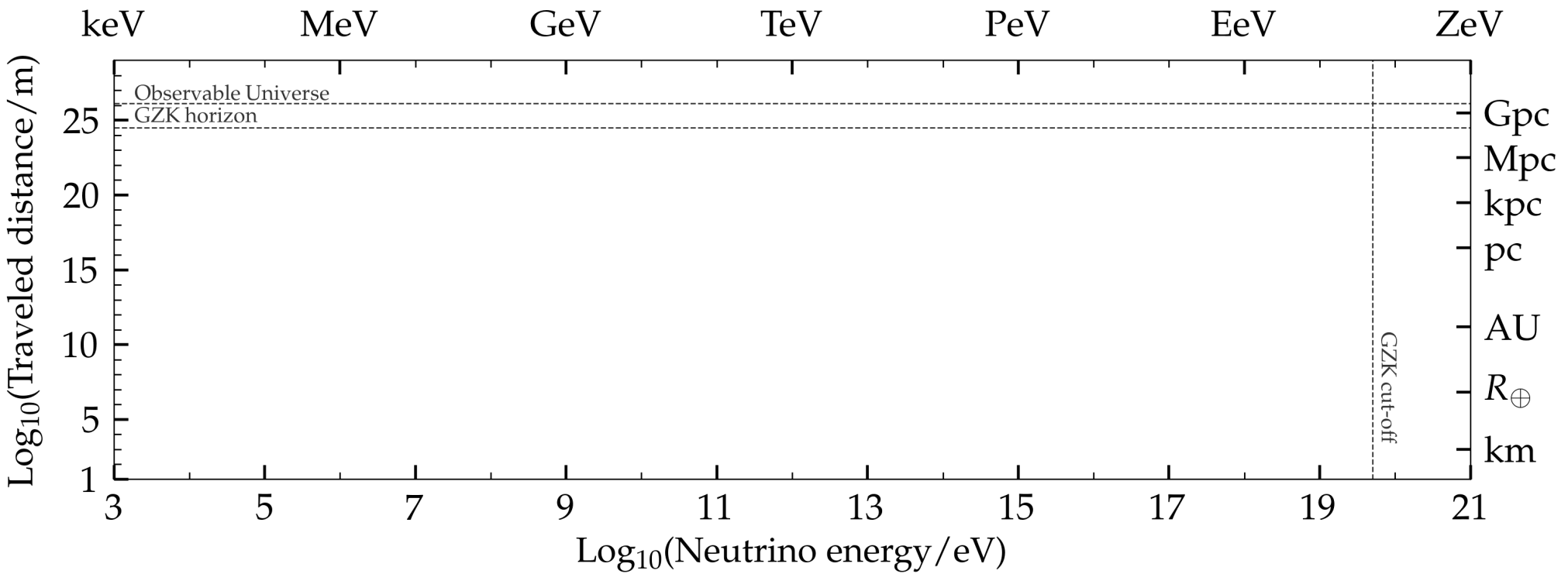
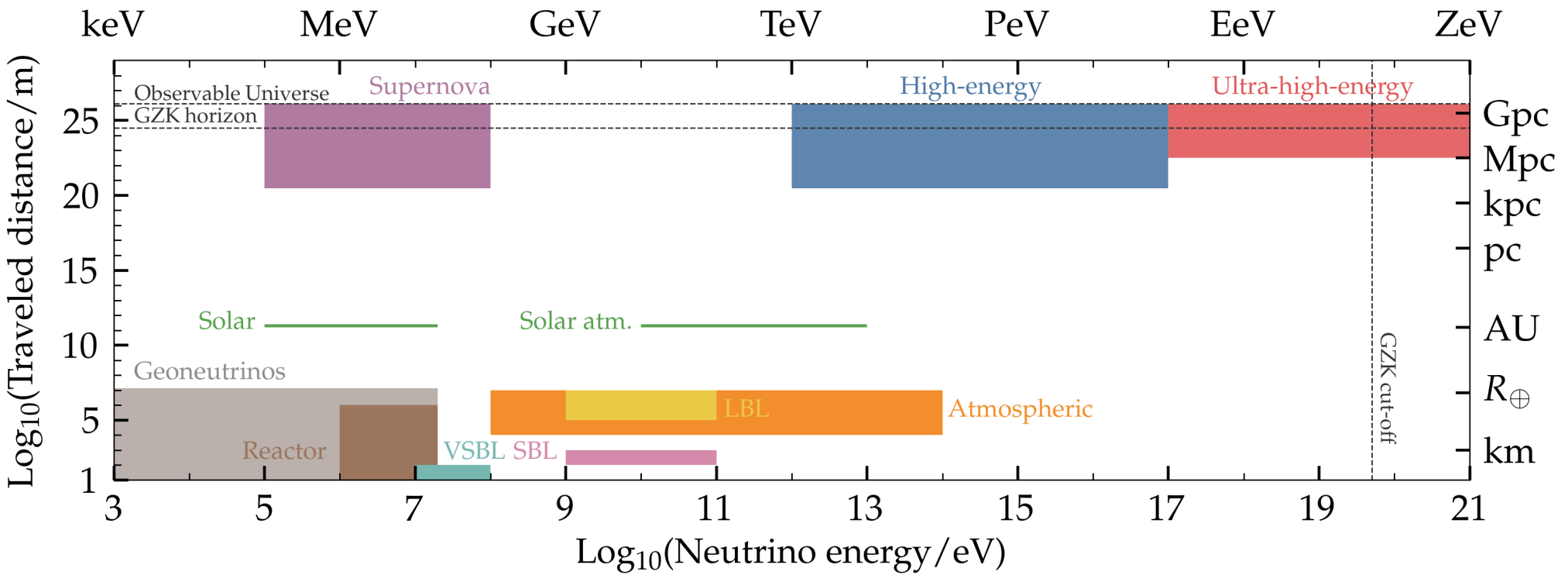


Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333), adapted



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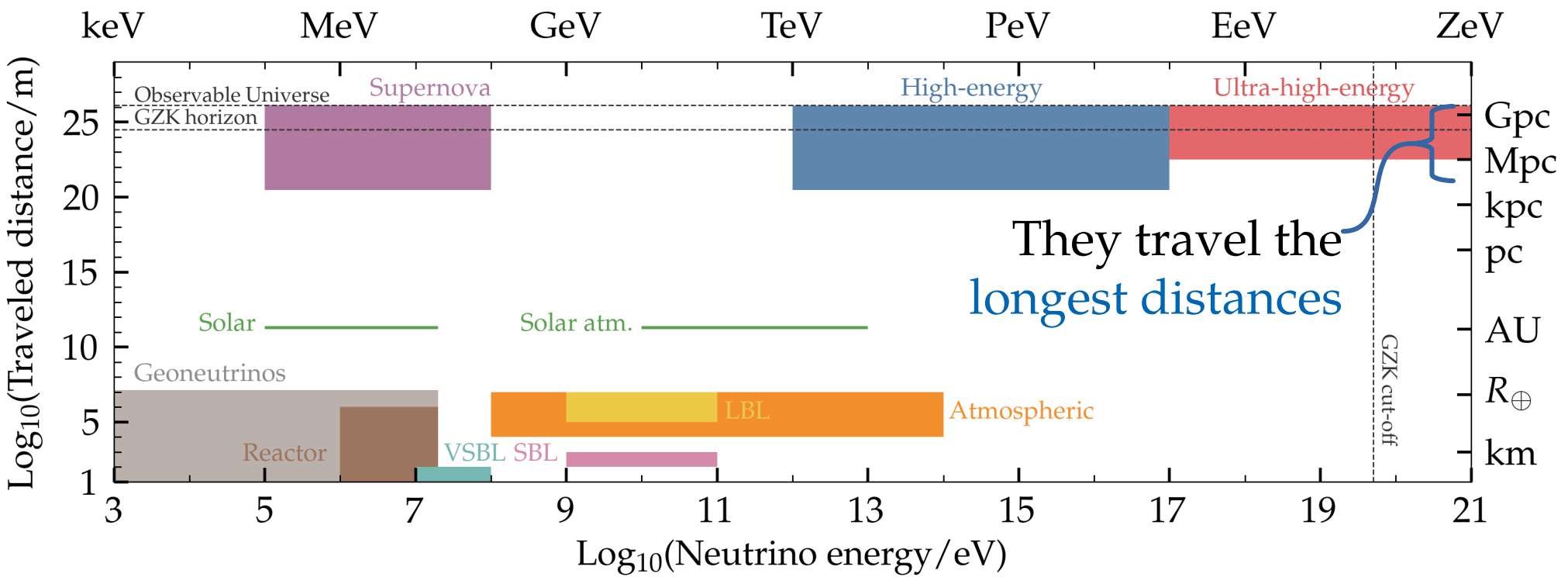
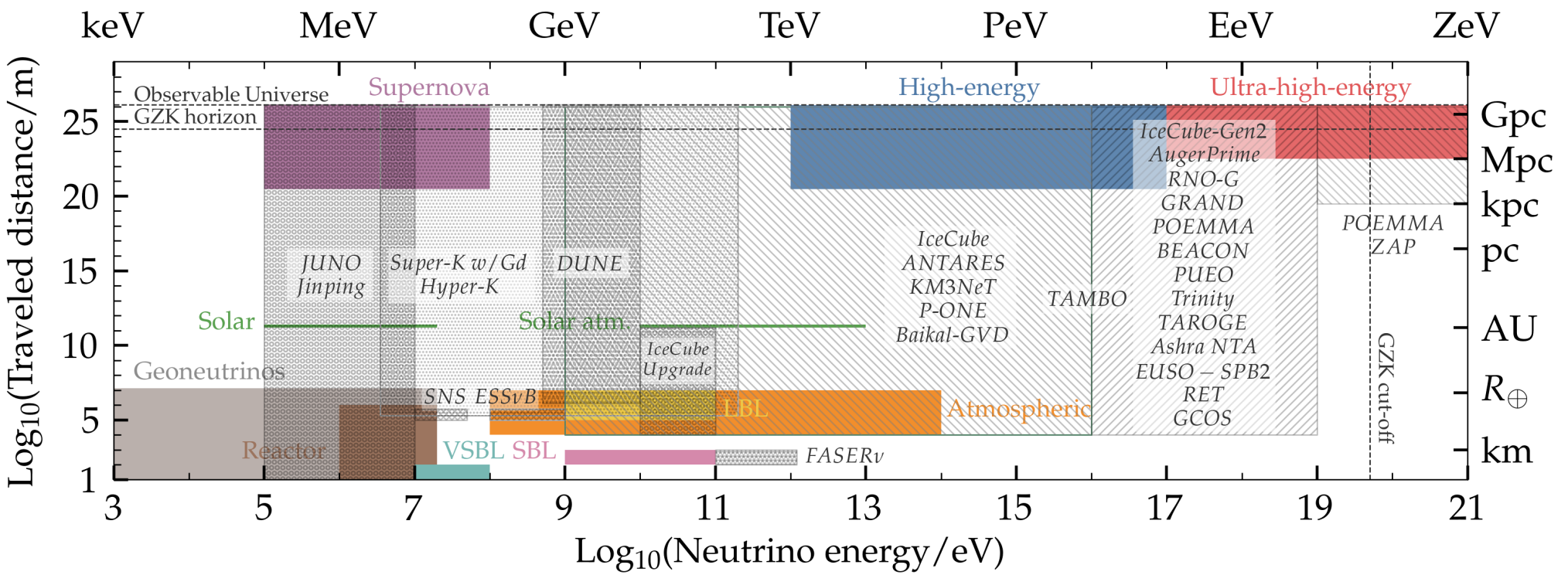
They have the highest energies



They travel the longest distances

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



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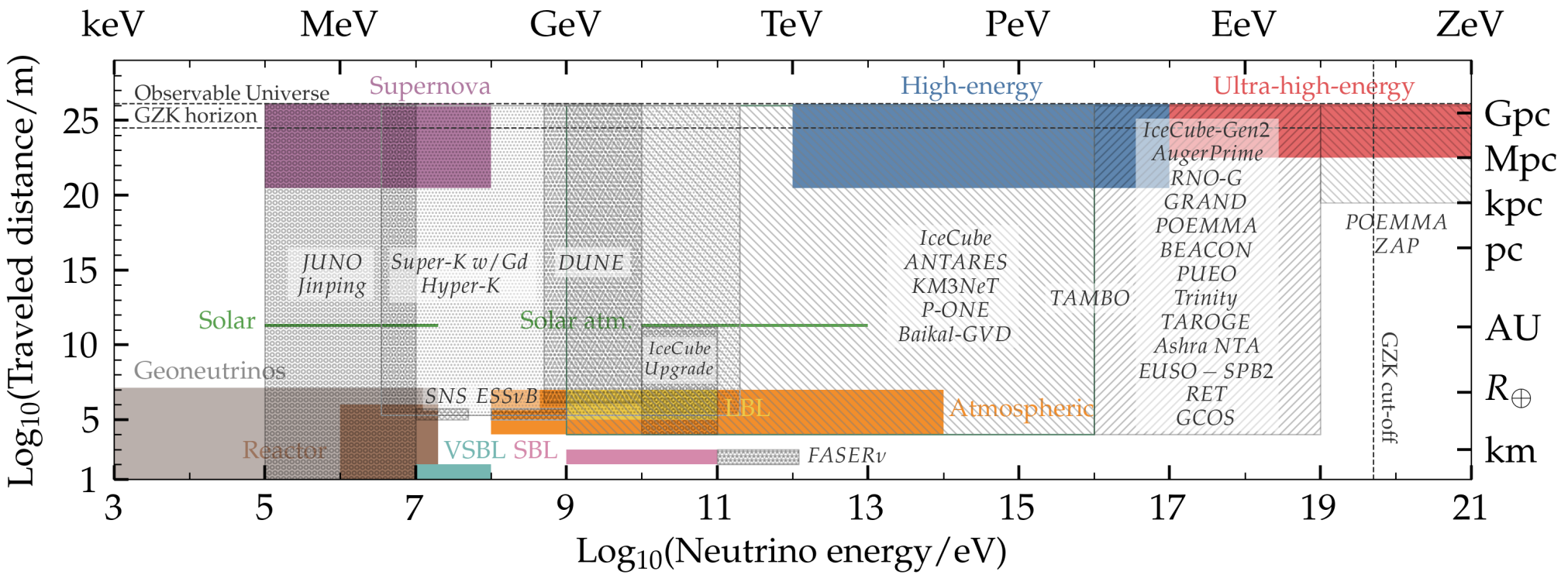
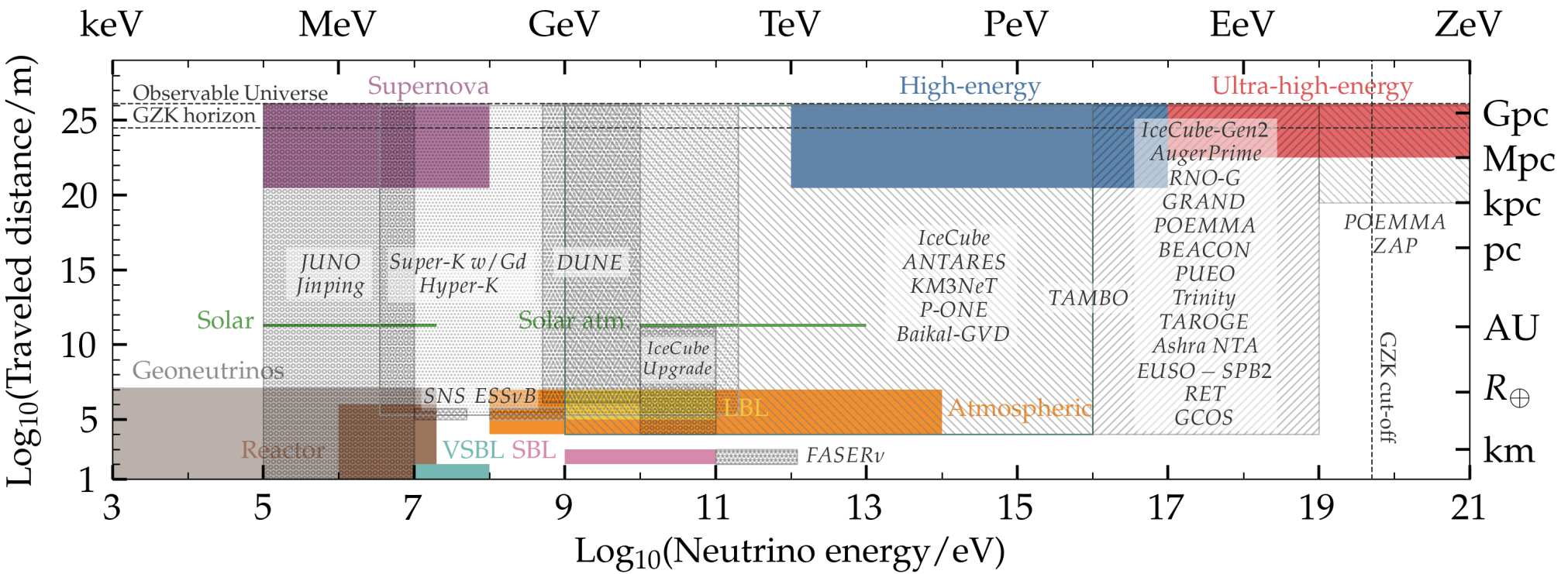


Synergies with lower energies

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

Discovered in 2013
by IceCube



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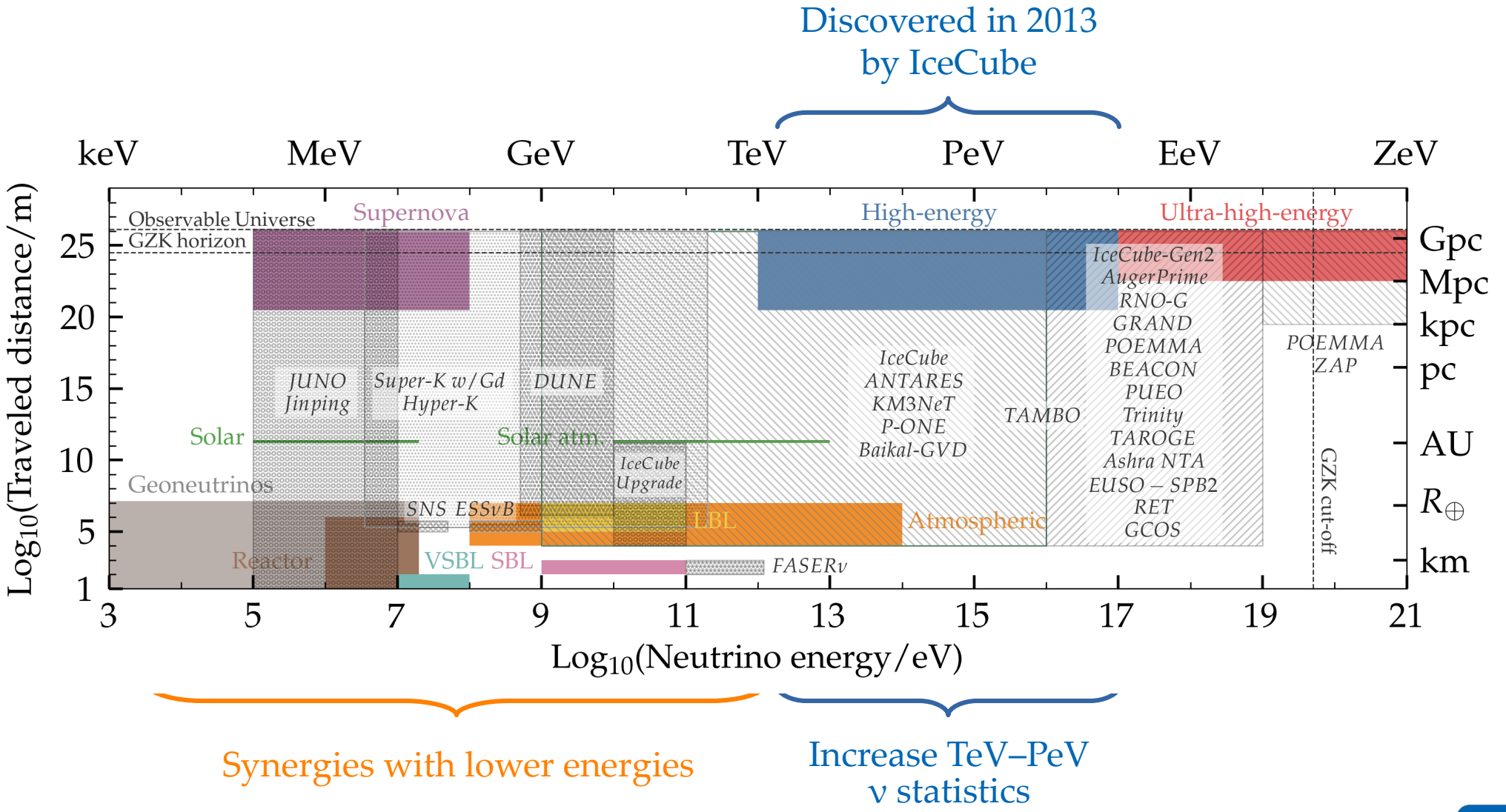

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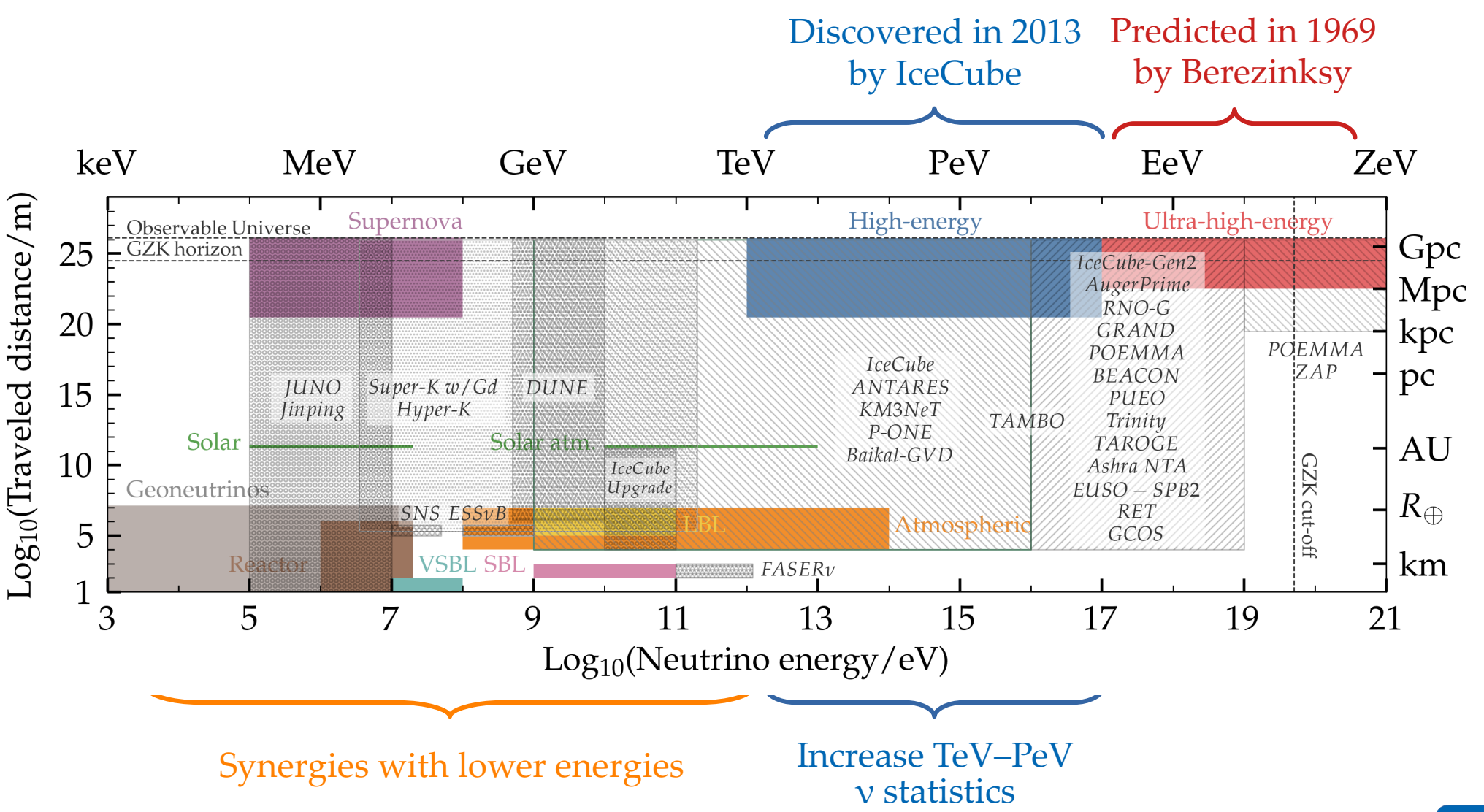

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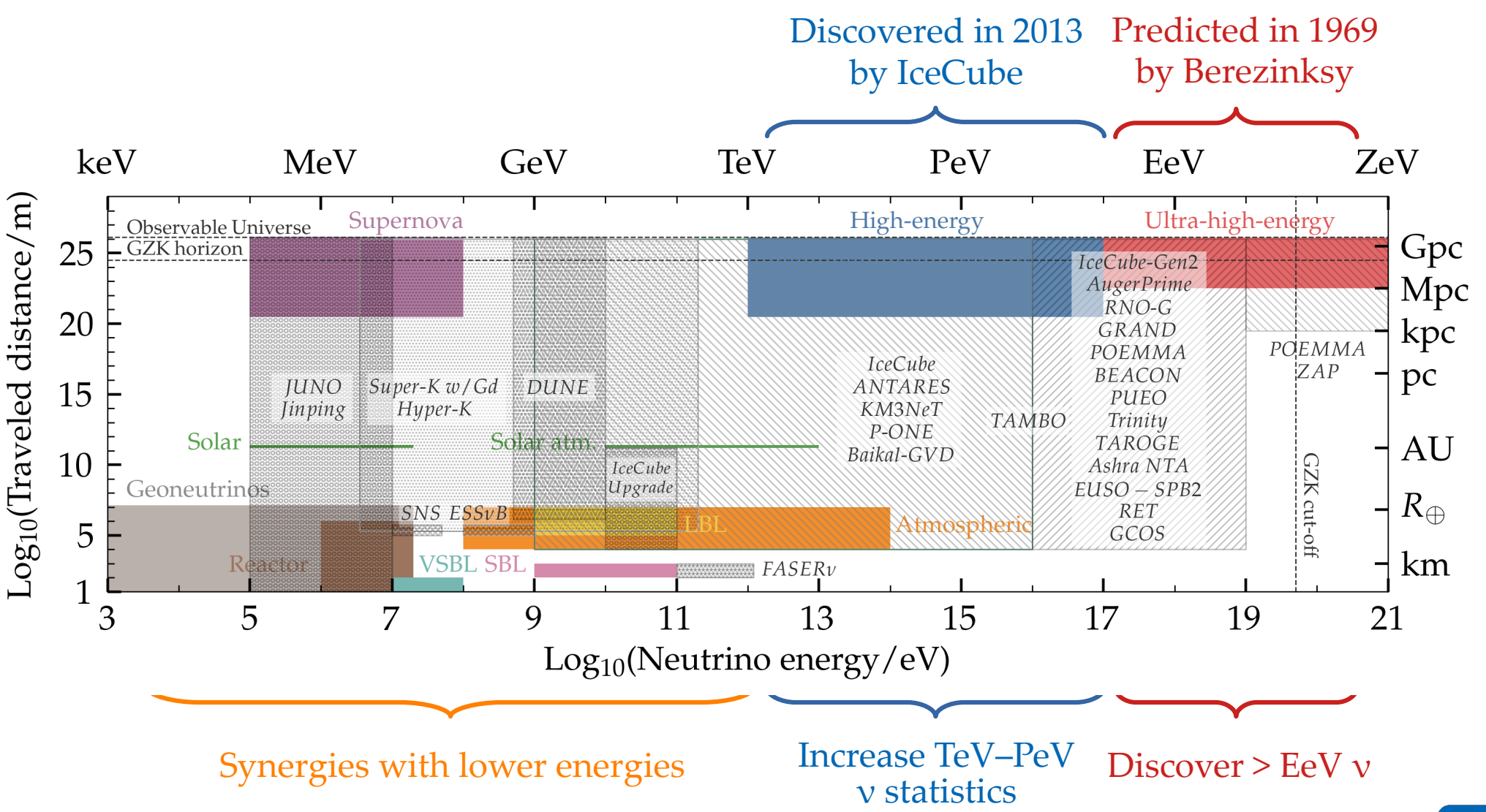

Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333), adapted

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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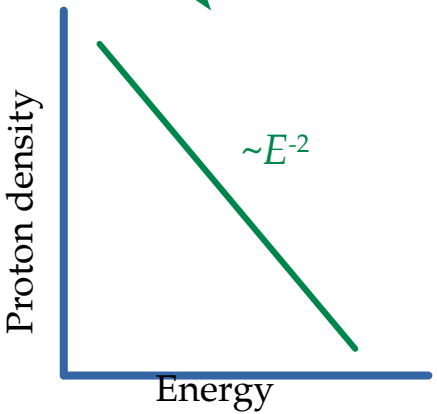

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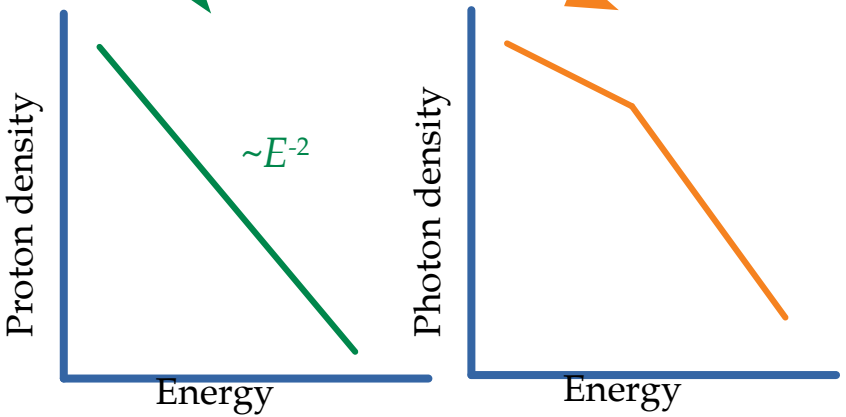

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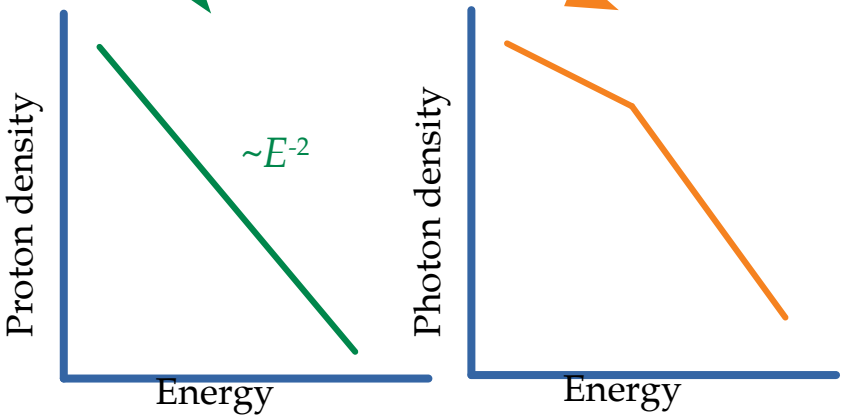
$$\pi^0 \rightarrow \gamma + \gamma$$

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

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



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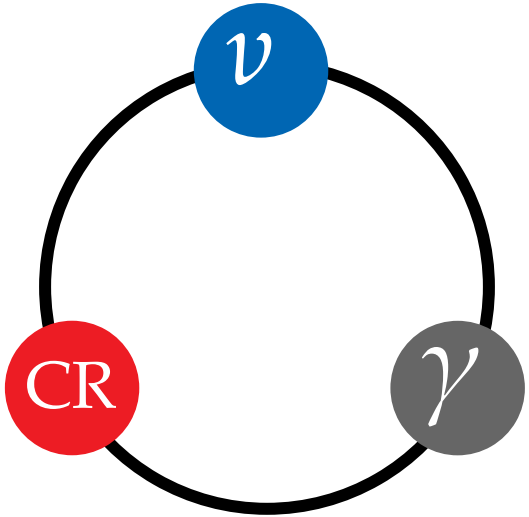

Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 10

The multi-messenger connection: a simple picture

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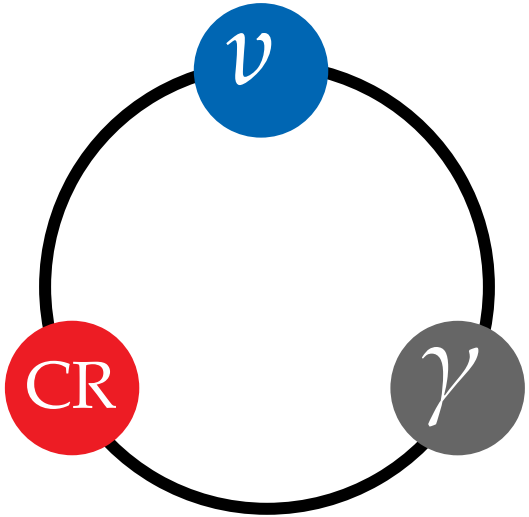

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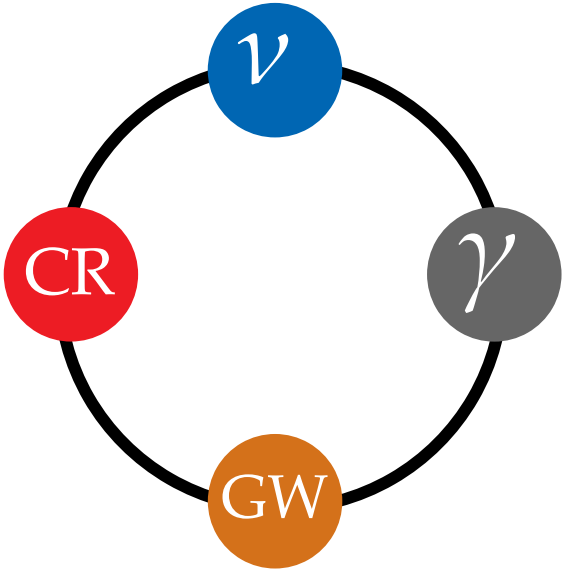

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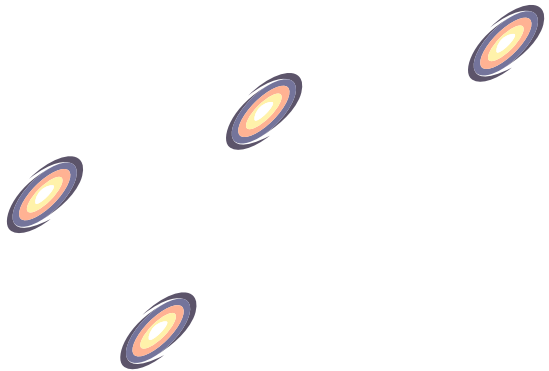
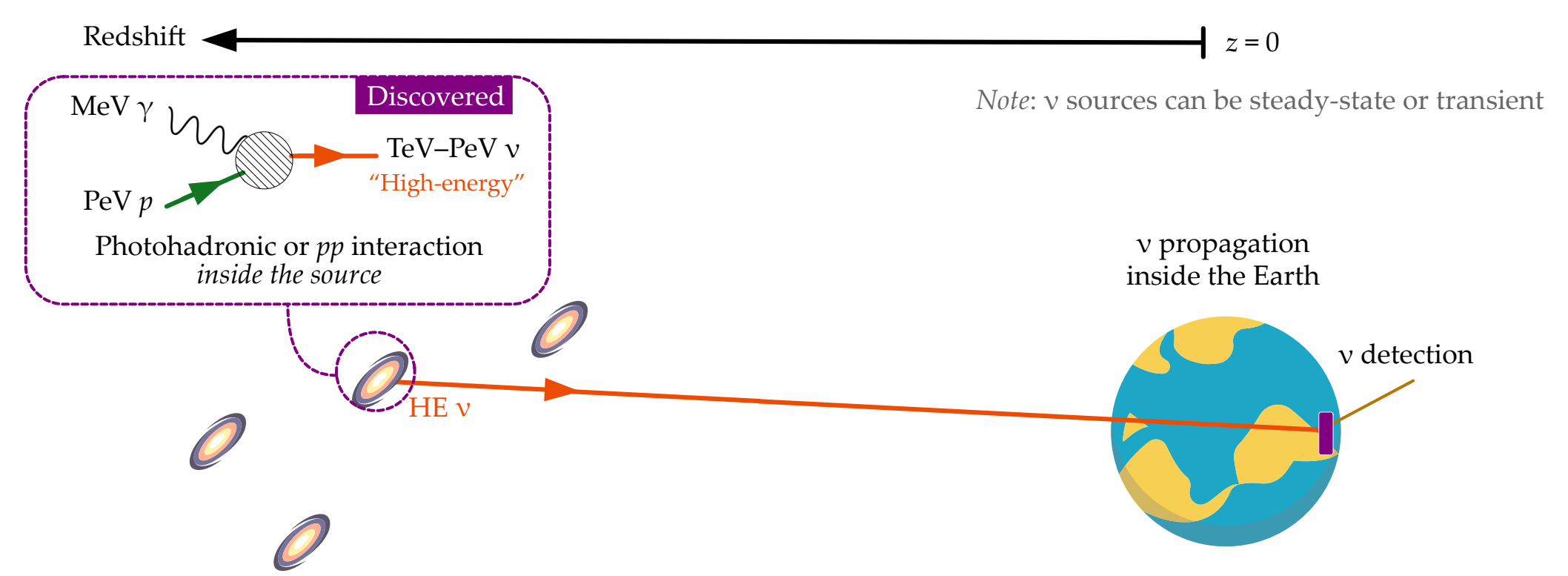
Redshift $z = 0$

Note: ν sources can be steady-state or transient





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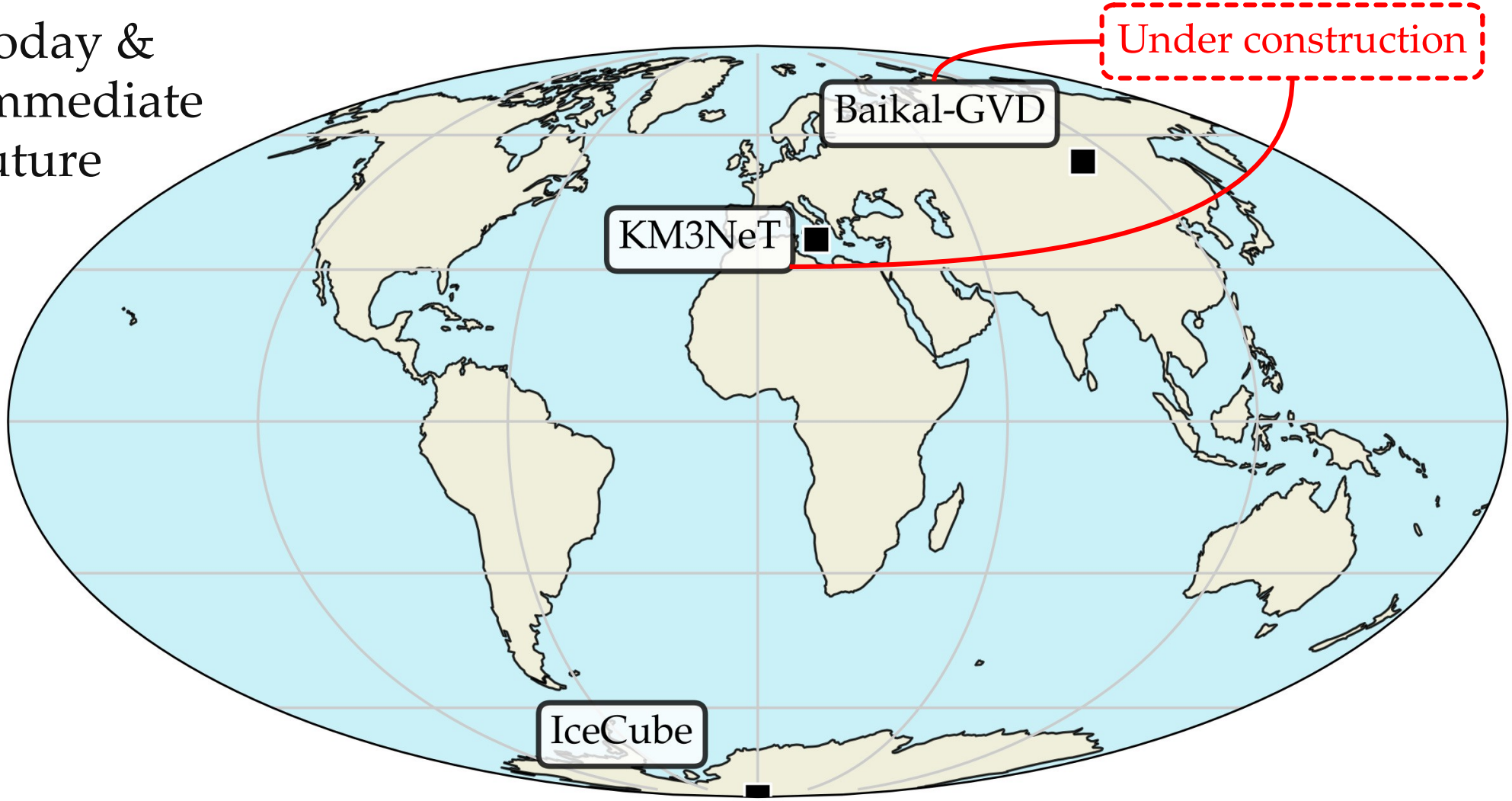
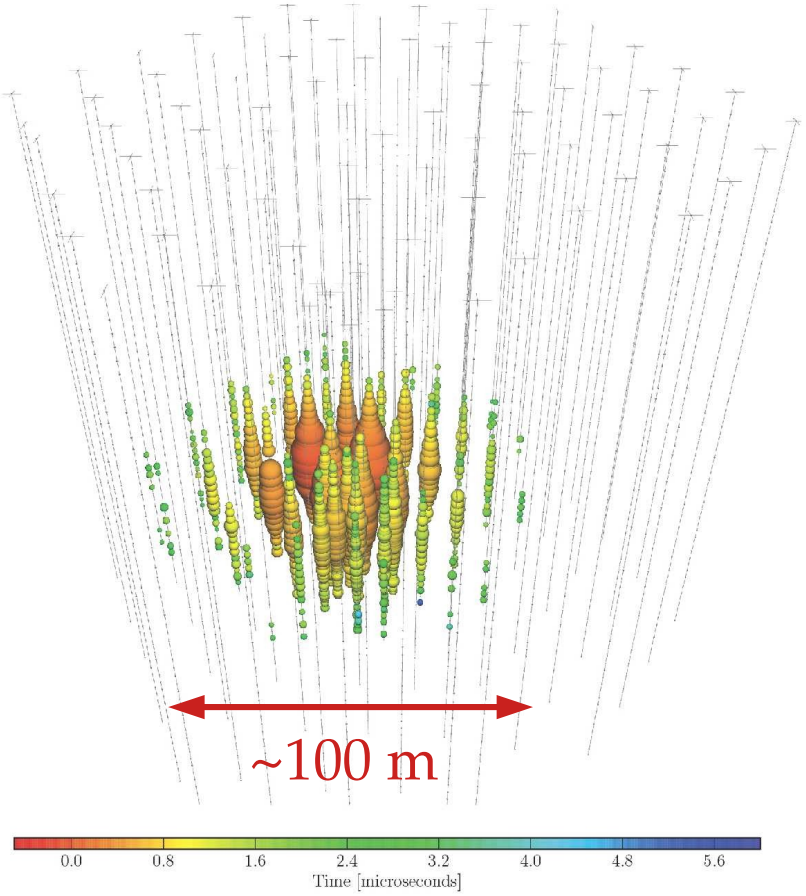
Today & immediate future



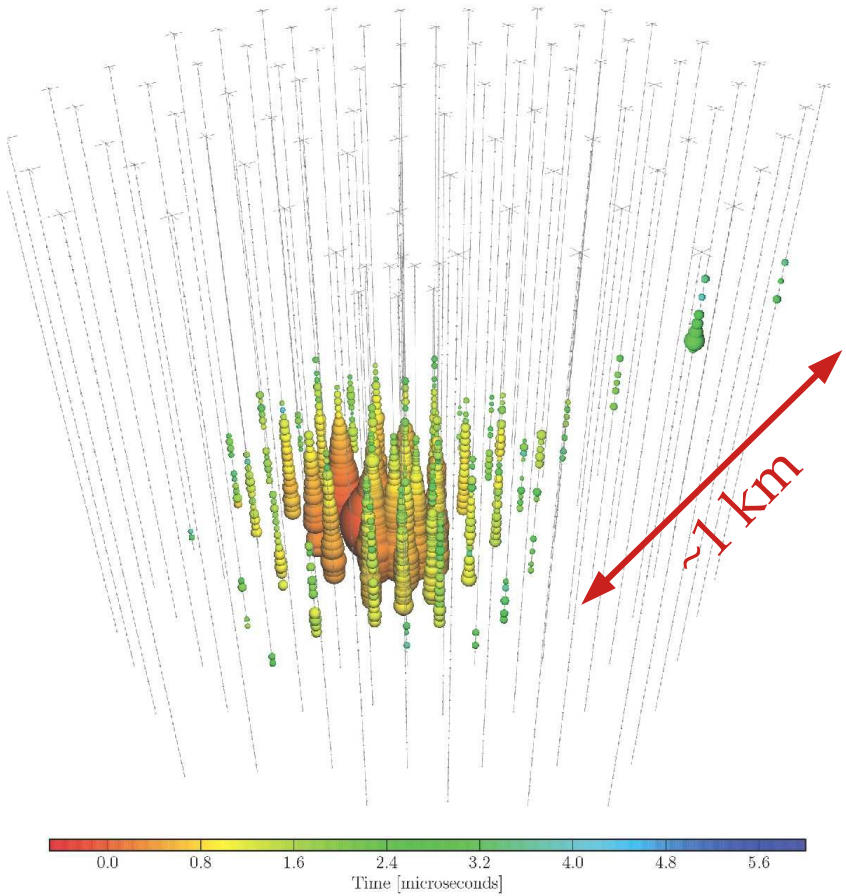
Schumacher, **MB**, Agostini, Oikonomou, Resconi, 2503.07549

Shower
(mainly from ν_e and ν_τ)

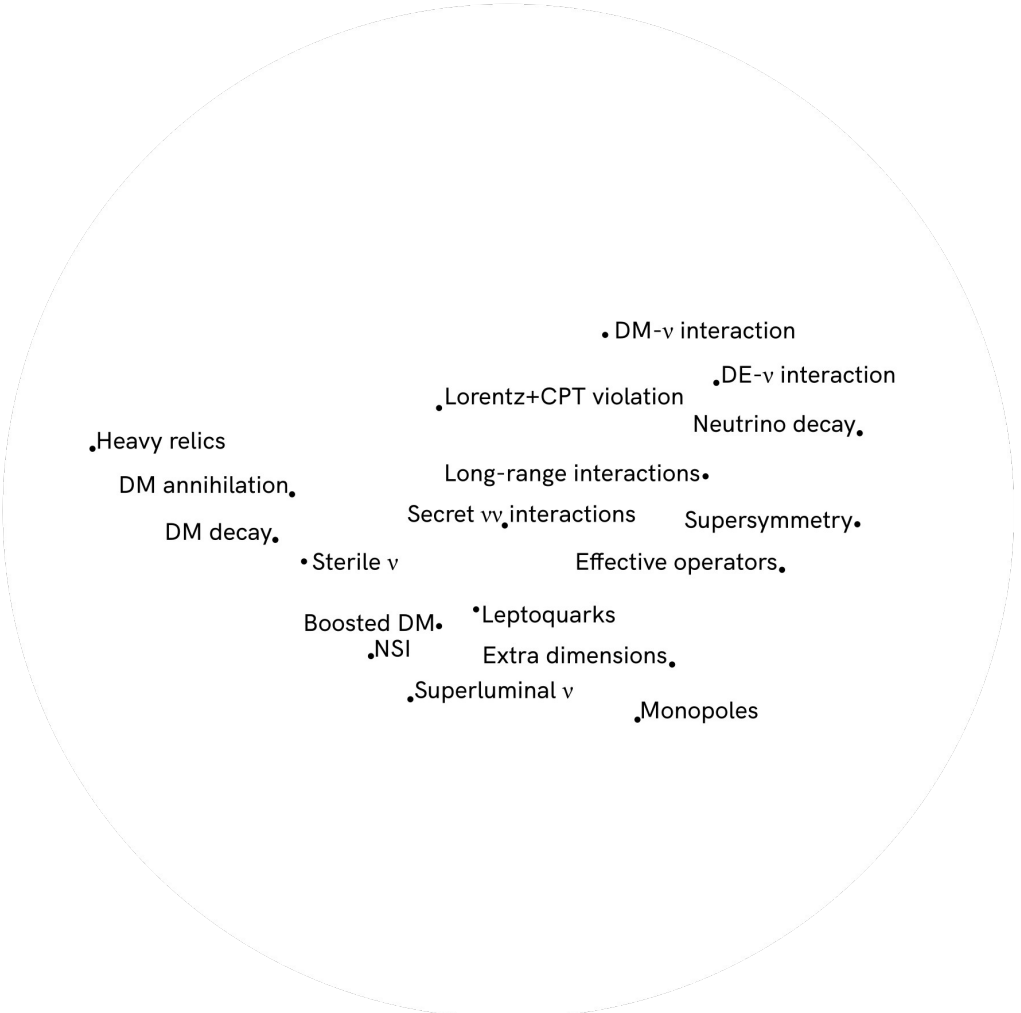


Poor angular resolution: < 5°

Track
(mainly from ν_μ)



Angular resolution: < 1°



Note: Not an exhaustive list

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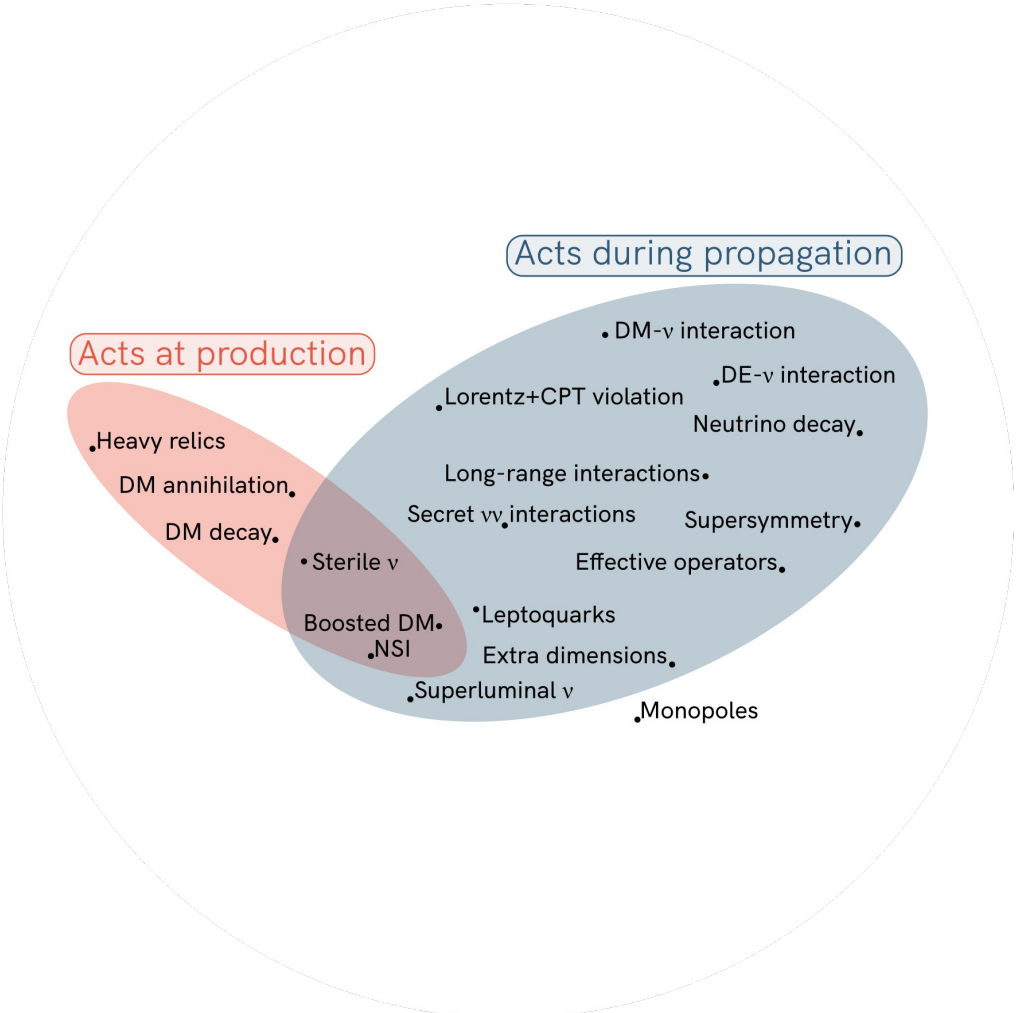

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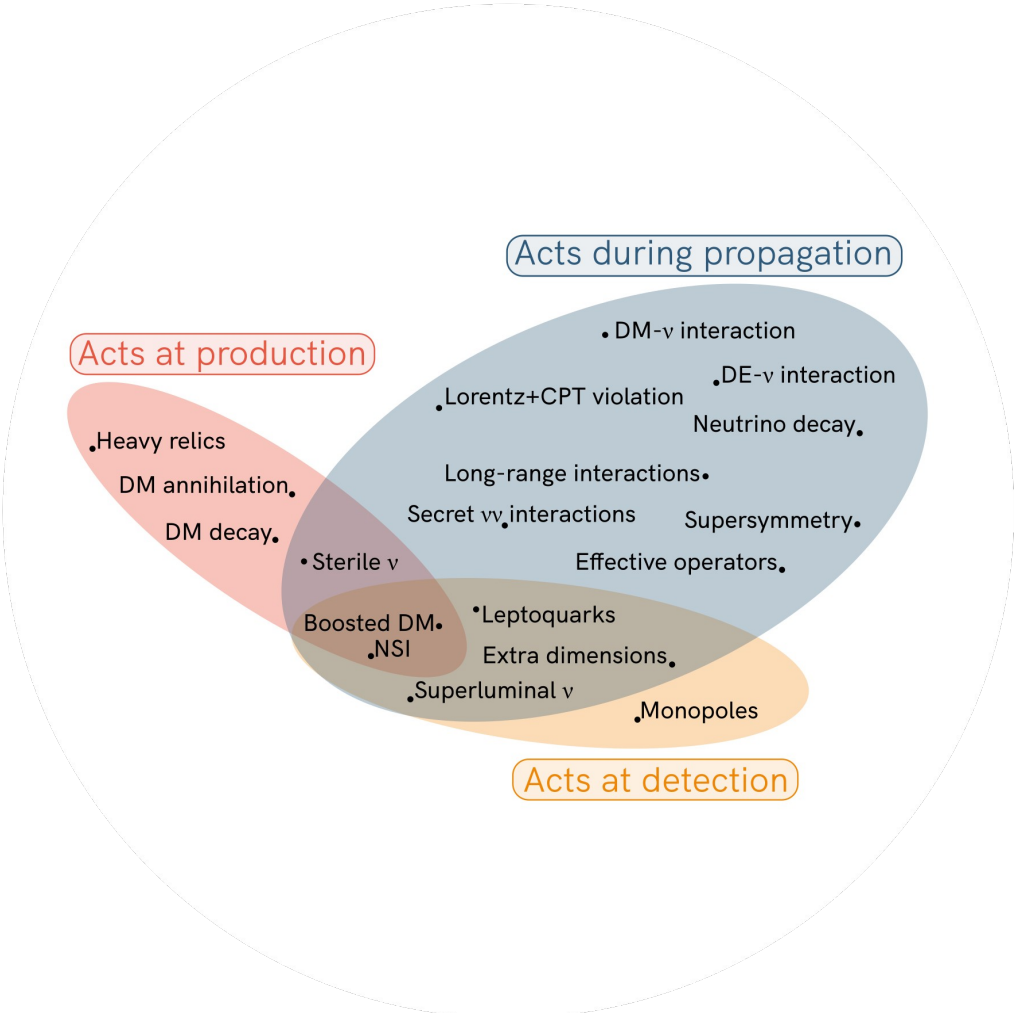
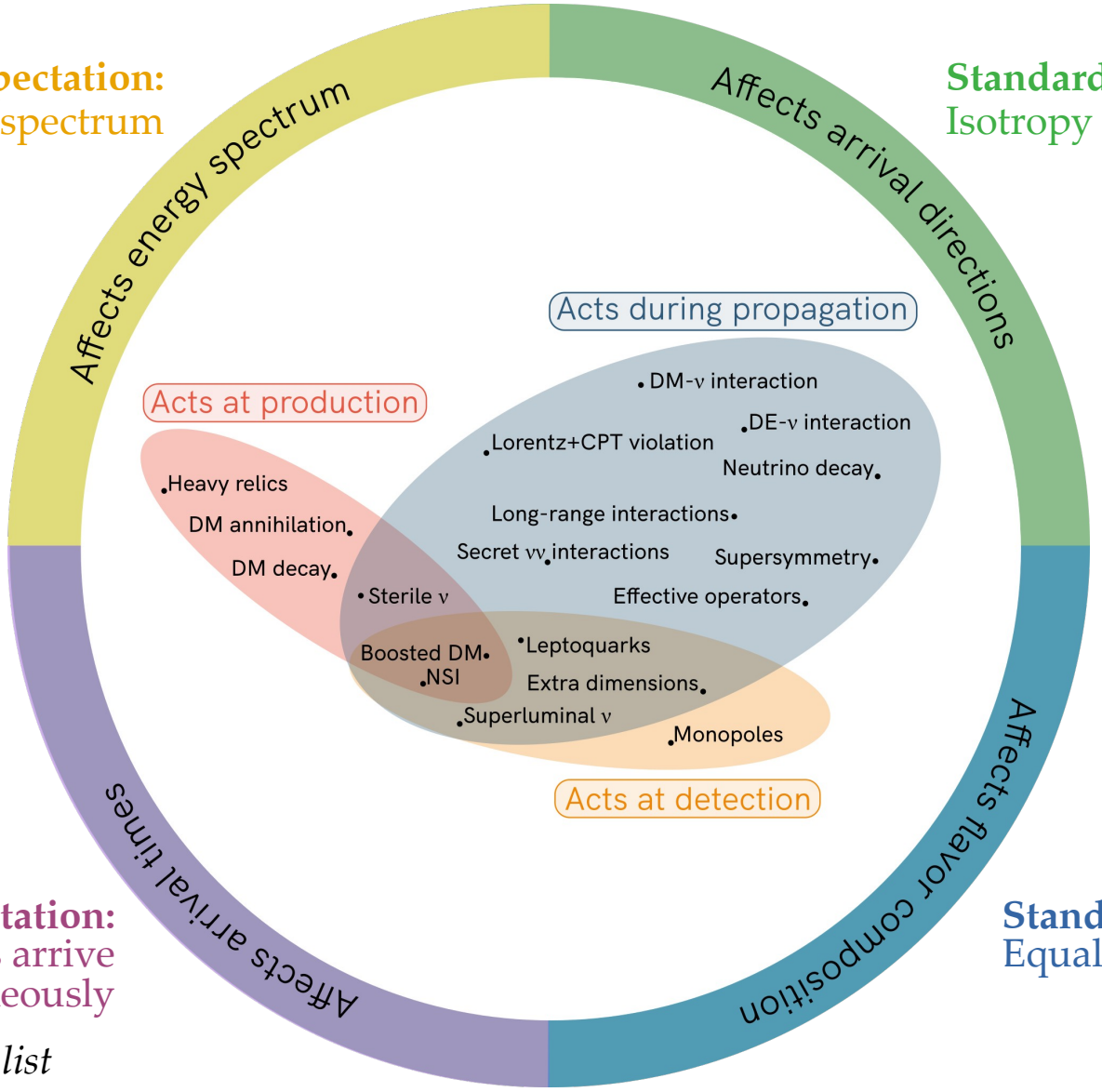


Note: Not an exhaustive list

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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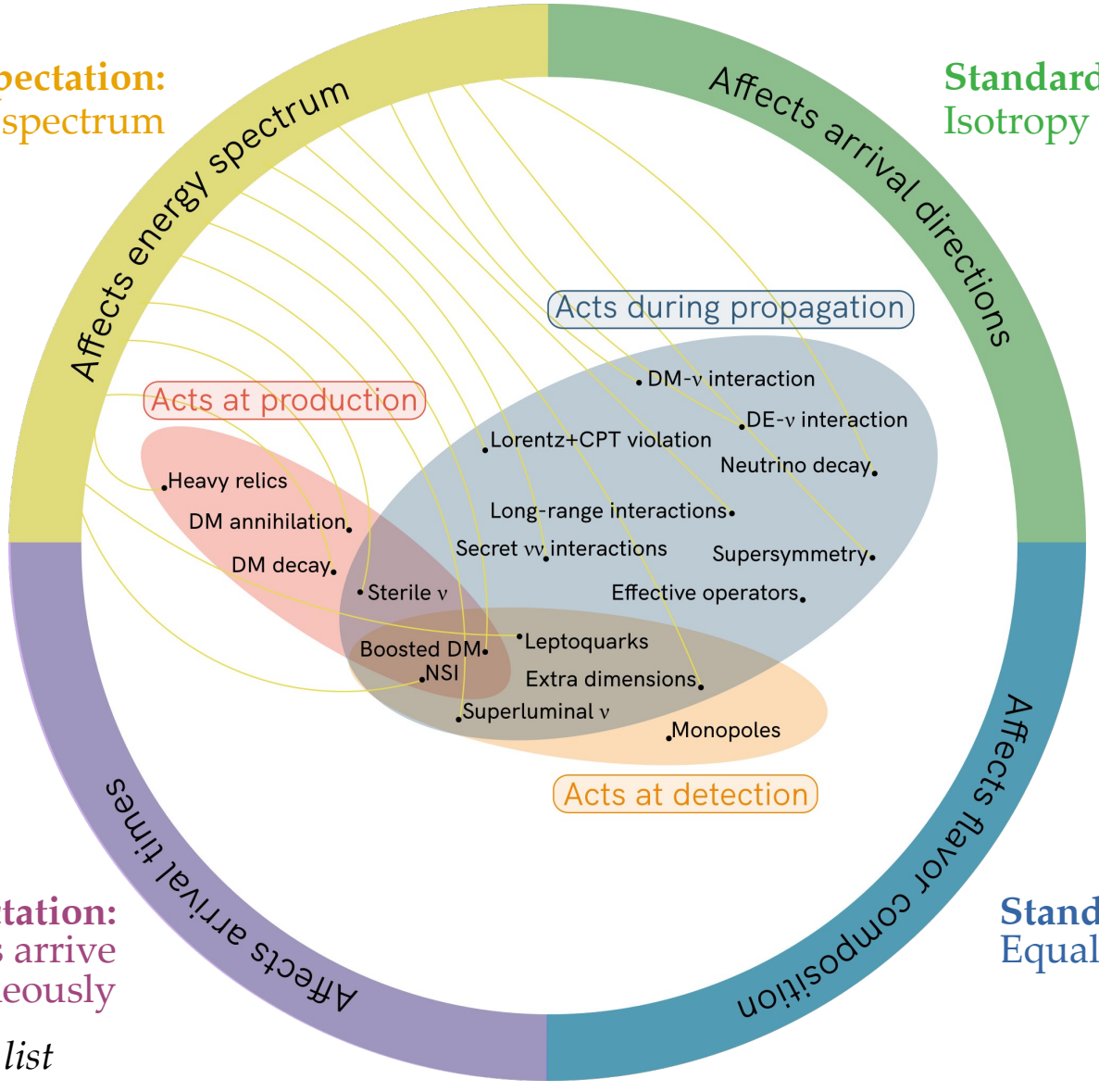

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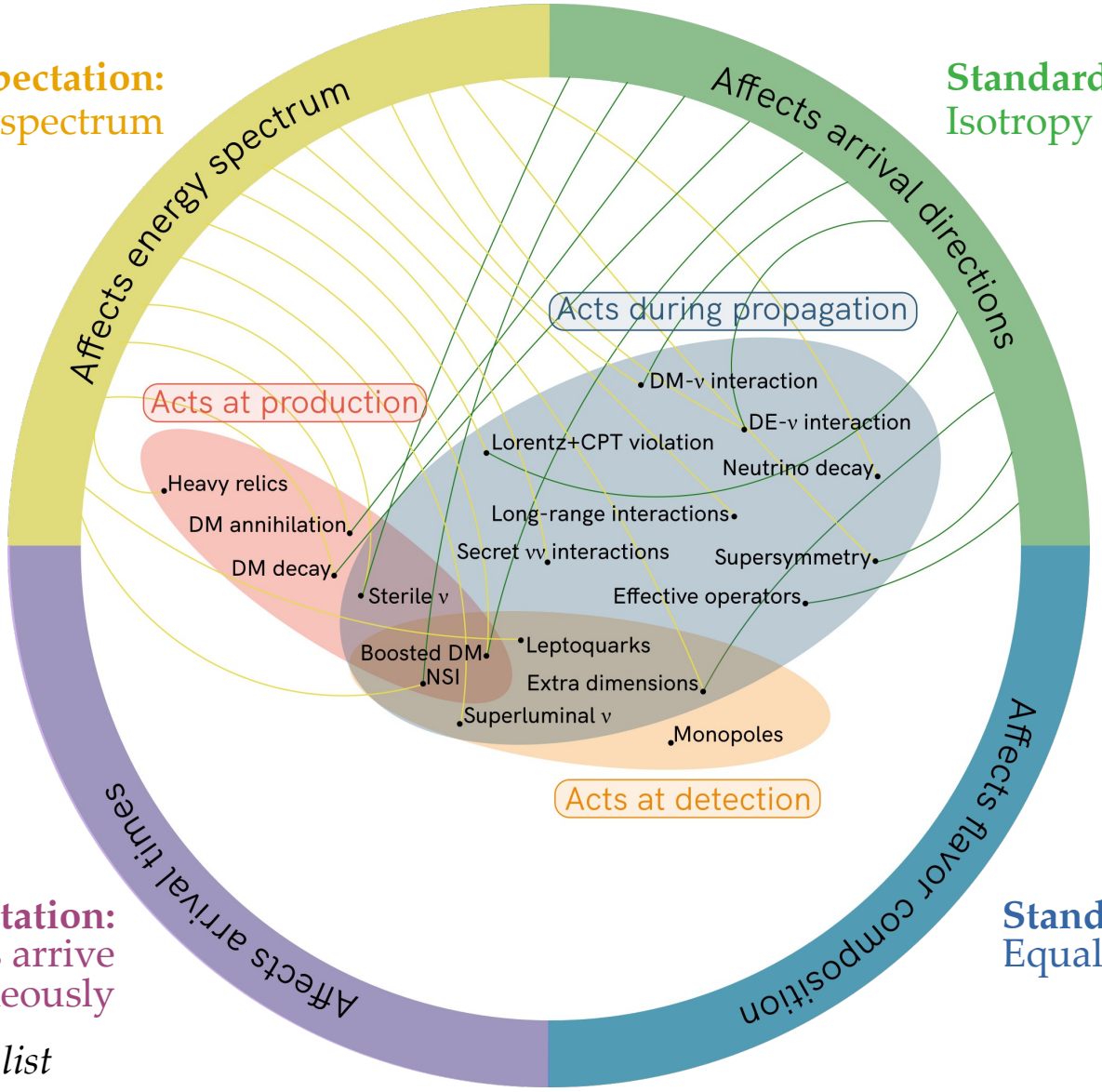

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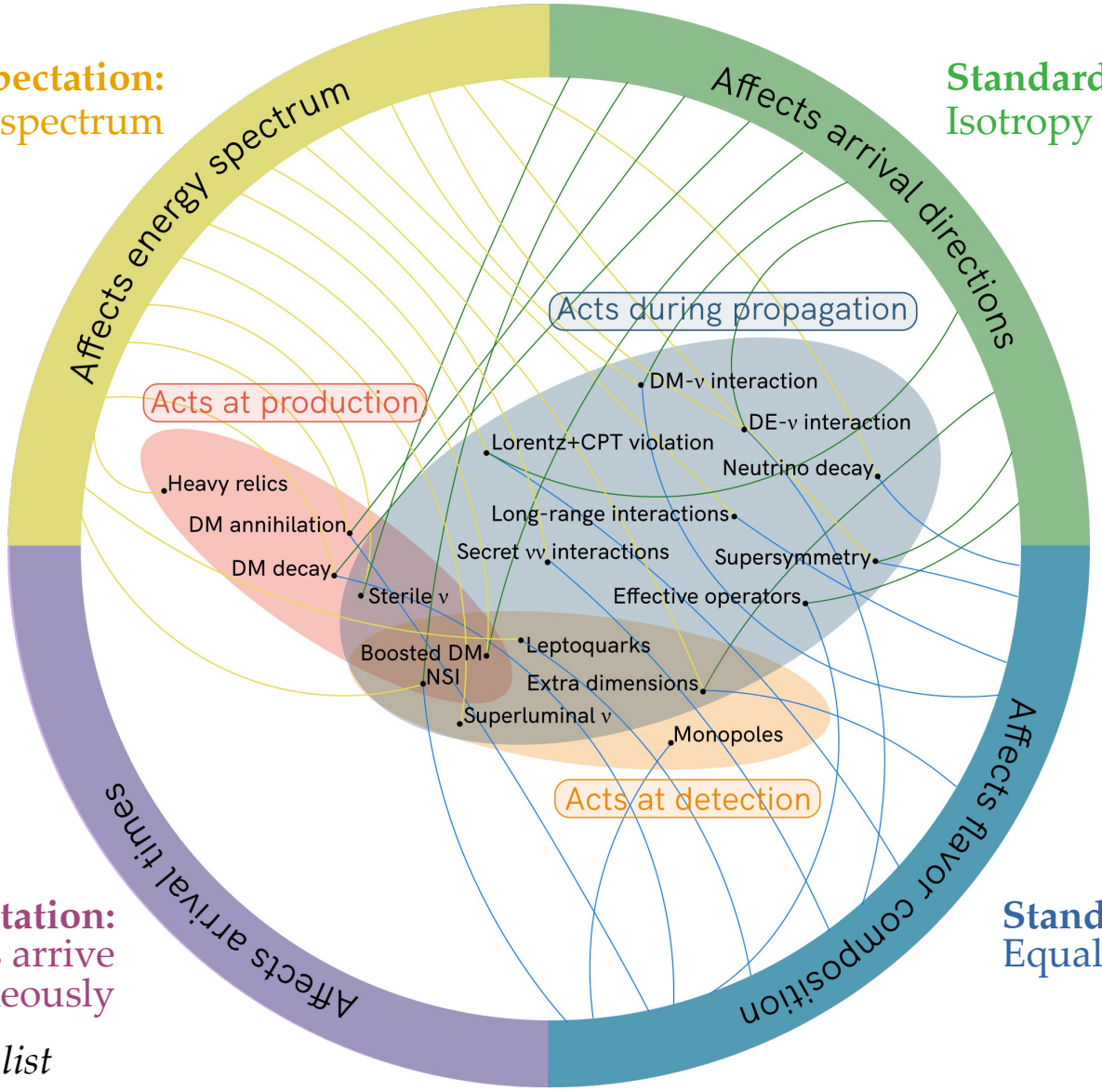

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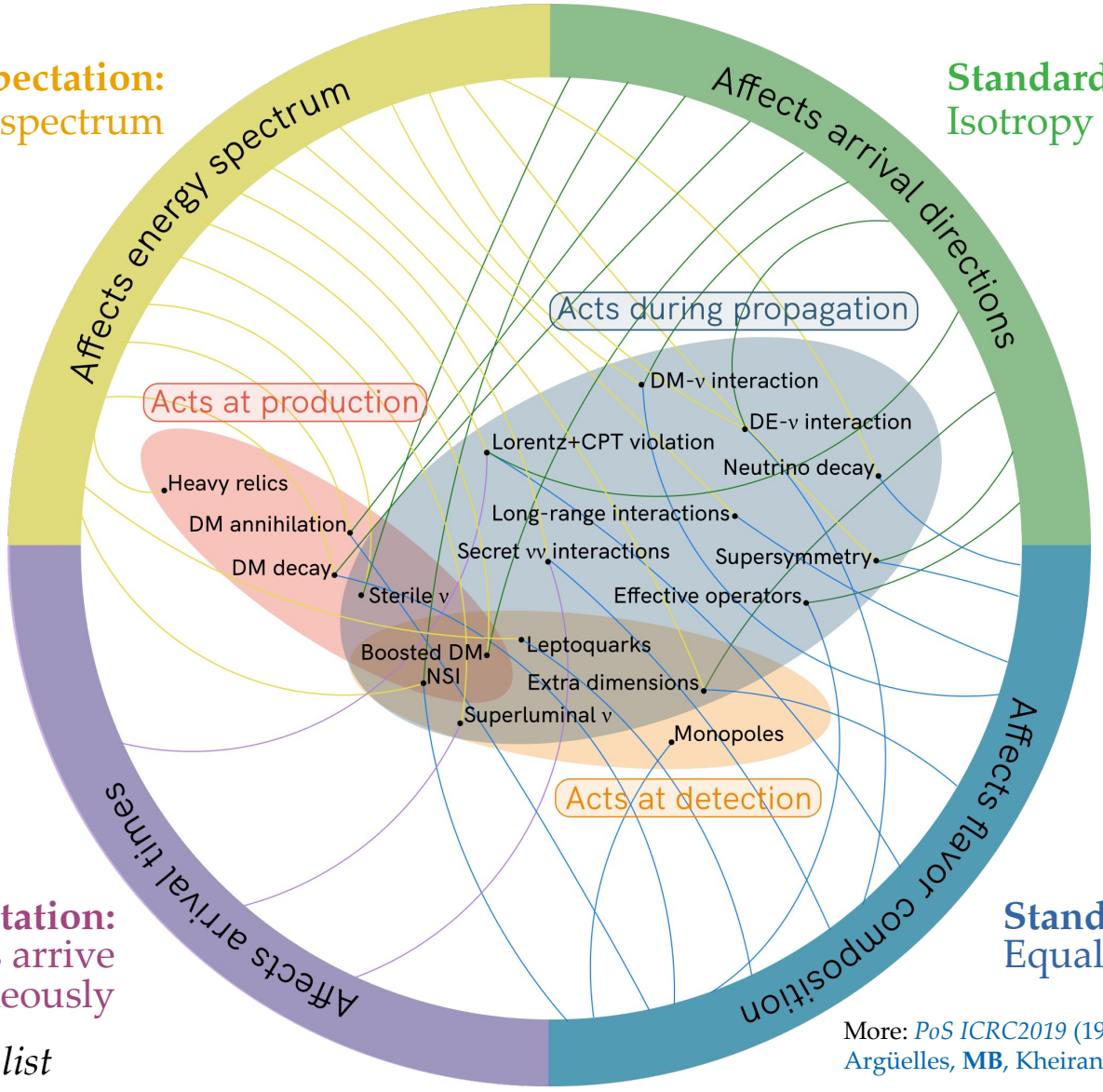

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More: *PoS ICRC2019* (1907.08690)
Argüelles, **MB**, Kheirandish, Palomares-Ruiz, Salvadó, Vincent

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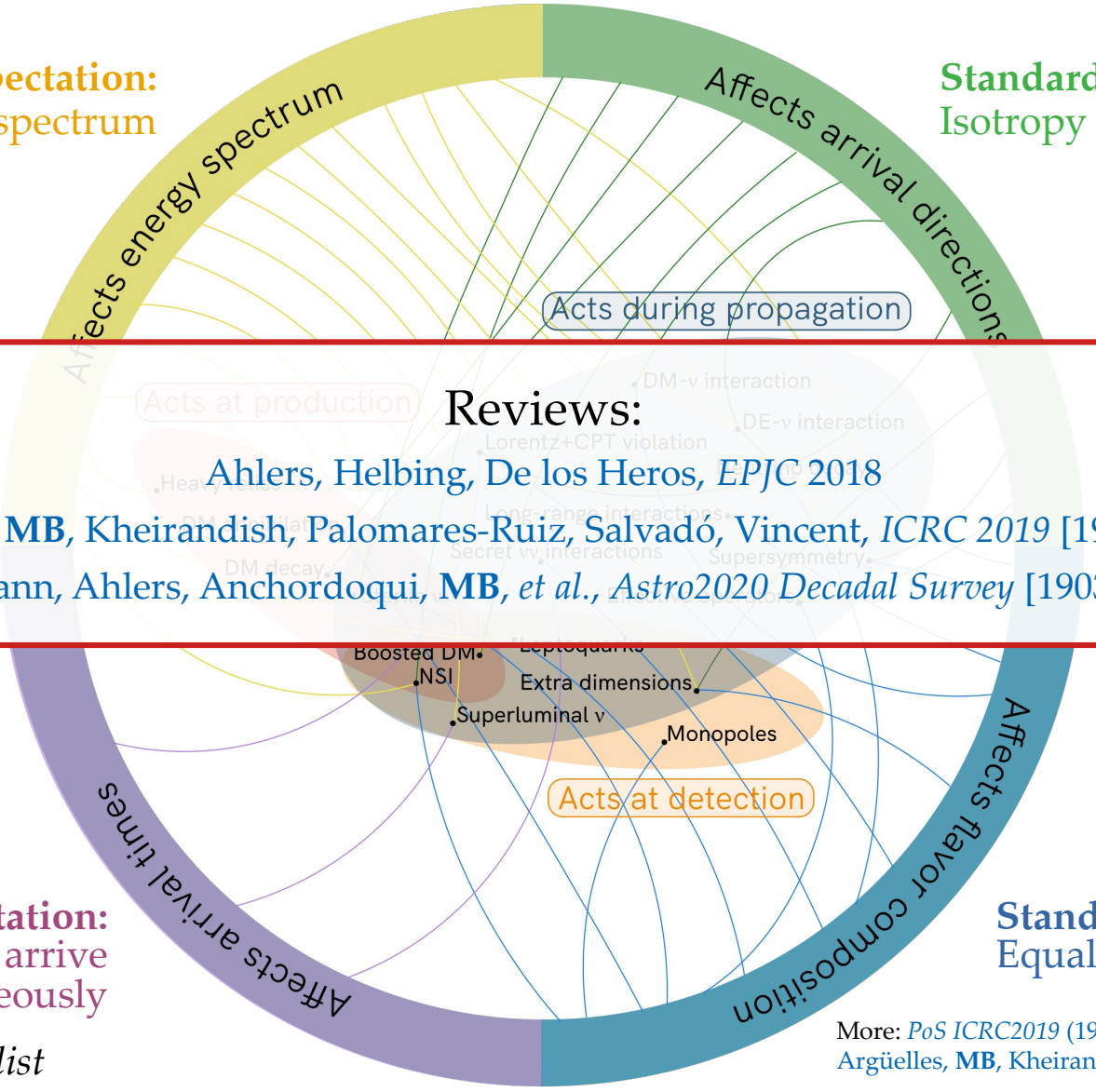

Reviews:

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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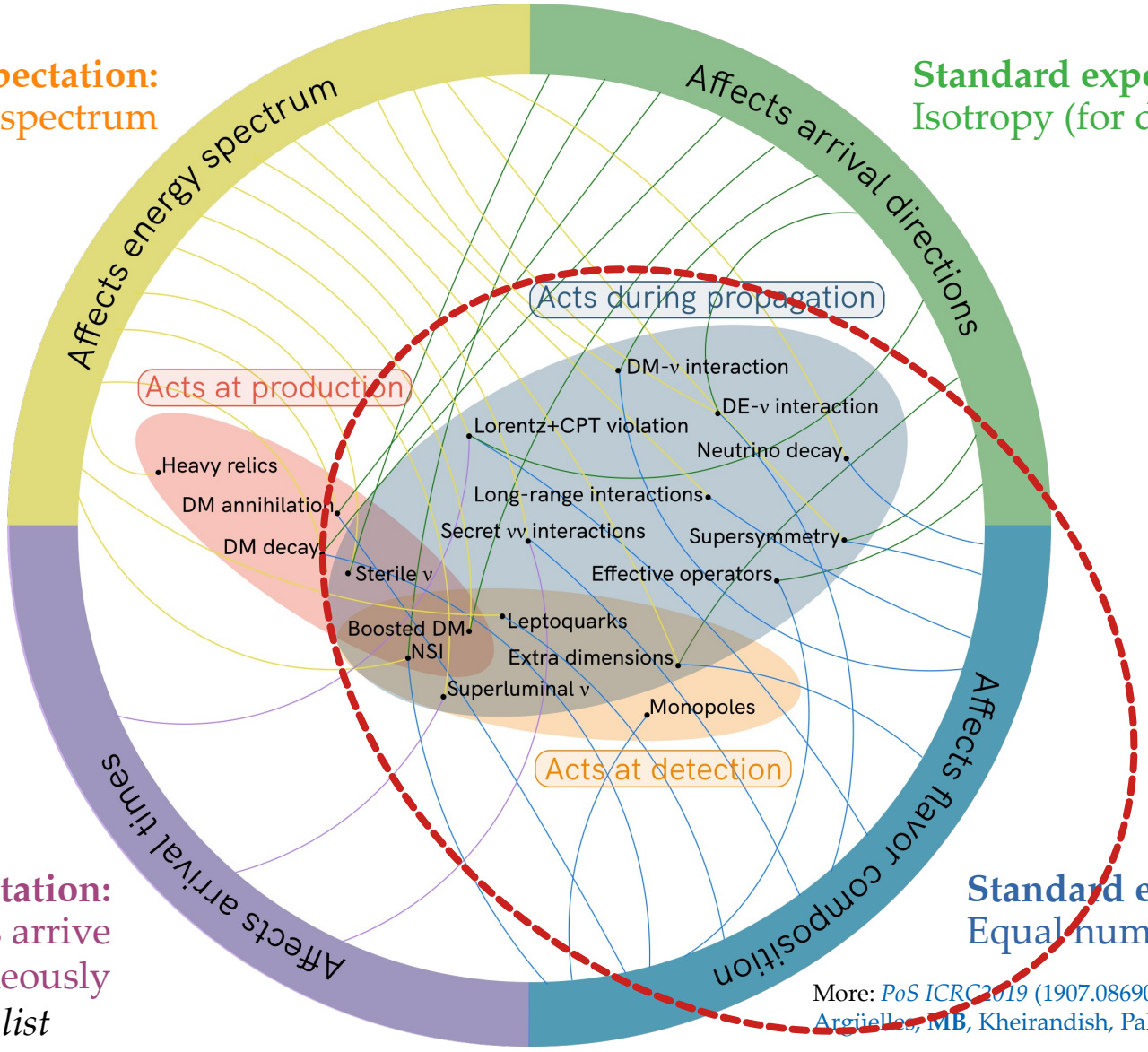

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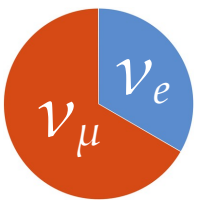
Predicting the flavor composition at Earth

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

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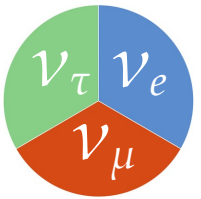

Different production mechanisms yield different flavor ratios:

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

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

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

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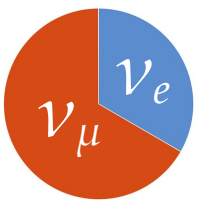

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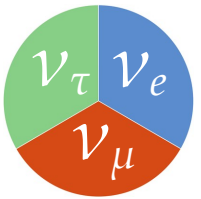

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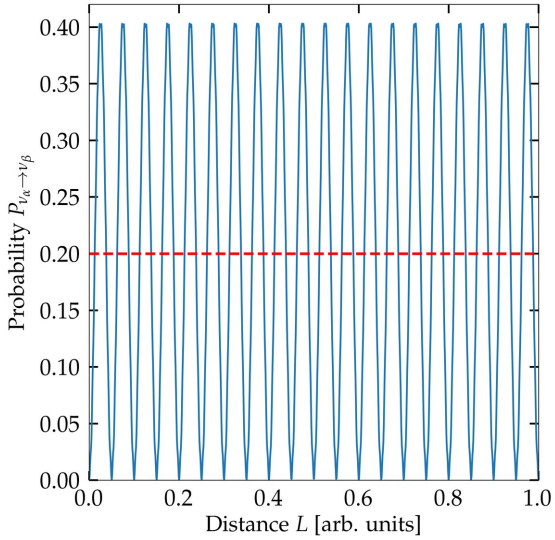
Standard oscillations *or* new physics

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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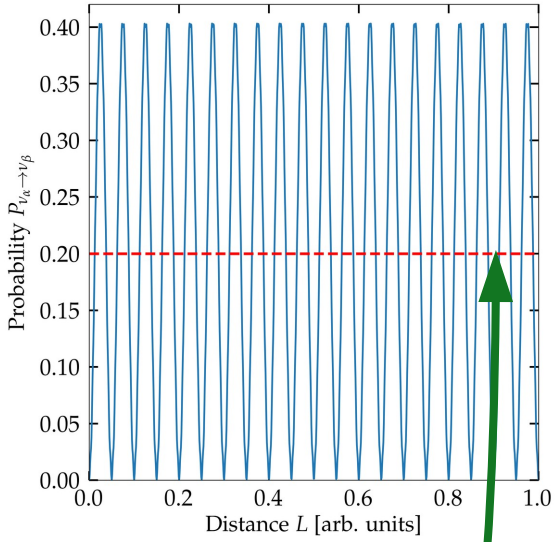

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Flavor composition at the Earth:

$$\begin{pmatrix} f_{e,\oplus} \\ f_{\mu,\oplus} \\ f_{\tau,\oplus} \end{pmatrix} = \begin{pmatrix} P_{ee} & P_{e\mu} & P_{e\tau} \\ P_{e\mu} & P_{\mu\mu} & P_{\mu\tau} \\ P_{e\tau} & P_{\mu\tau} & P_{\tau\tau} \end{pmatrix} \begin{pmatrix} f_{e,\mathrm{S}} \\ f_{\mu,\mathrm{S}} \\ f_{\tau,\mathrm{S}} \end{pmatrix}$$

Informed by particle physics

Informed by astrophysics

Flavor composition at the Earth:

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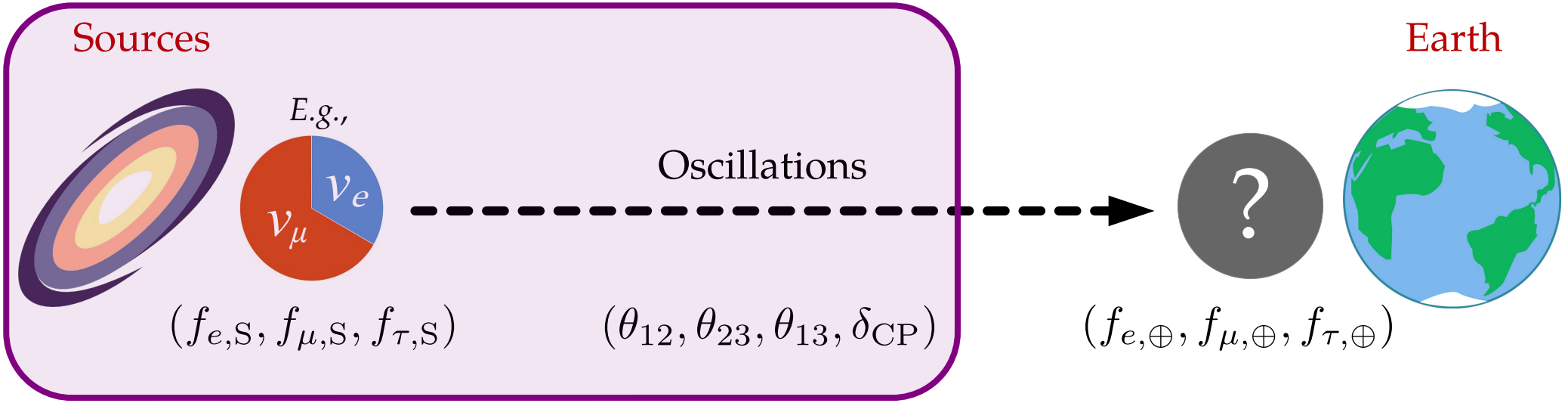
Assume no ν_τ production,
so we only need vary the ν_e fraction

Farzan, *JHEP* 2021

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



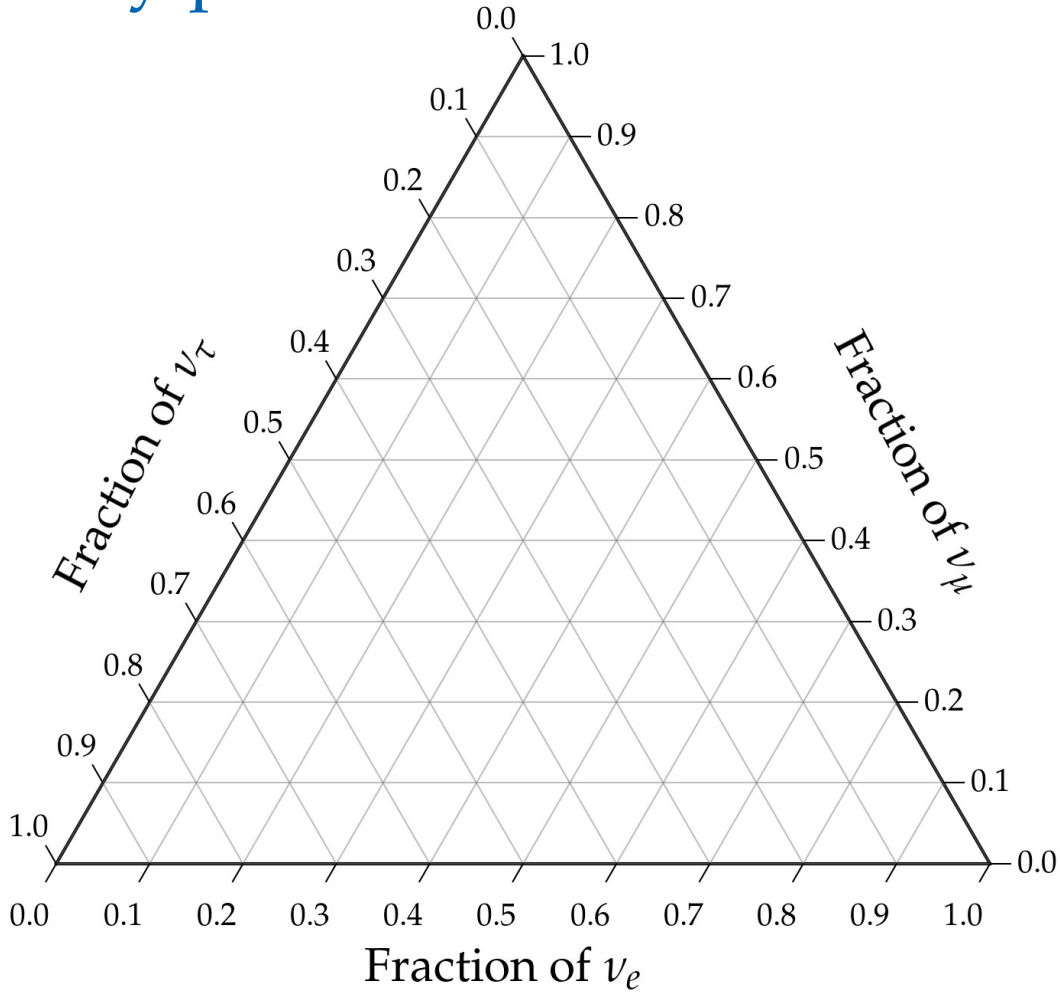
Quick aside: how to read a ternary plot

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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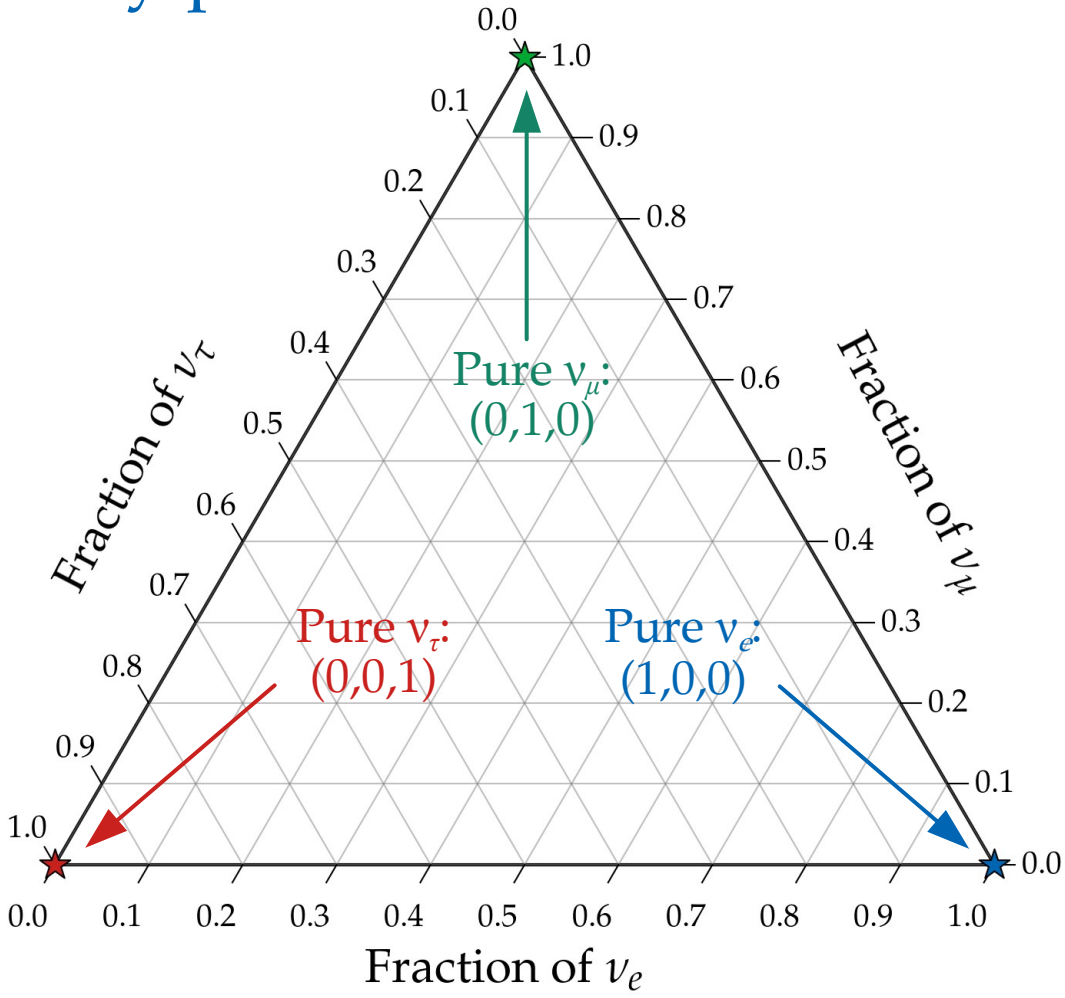

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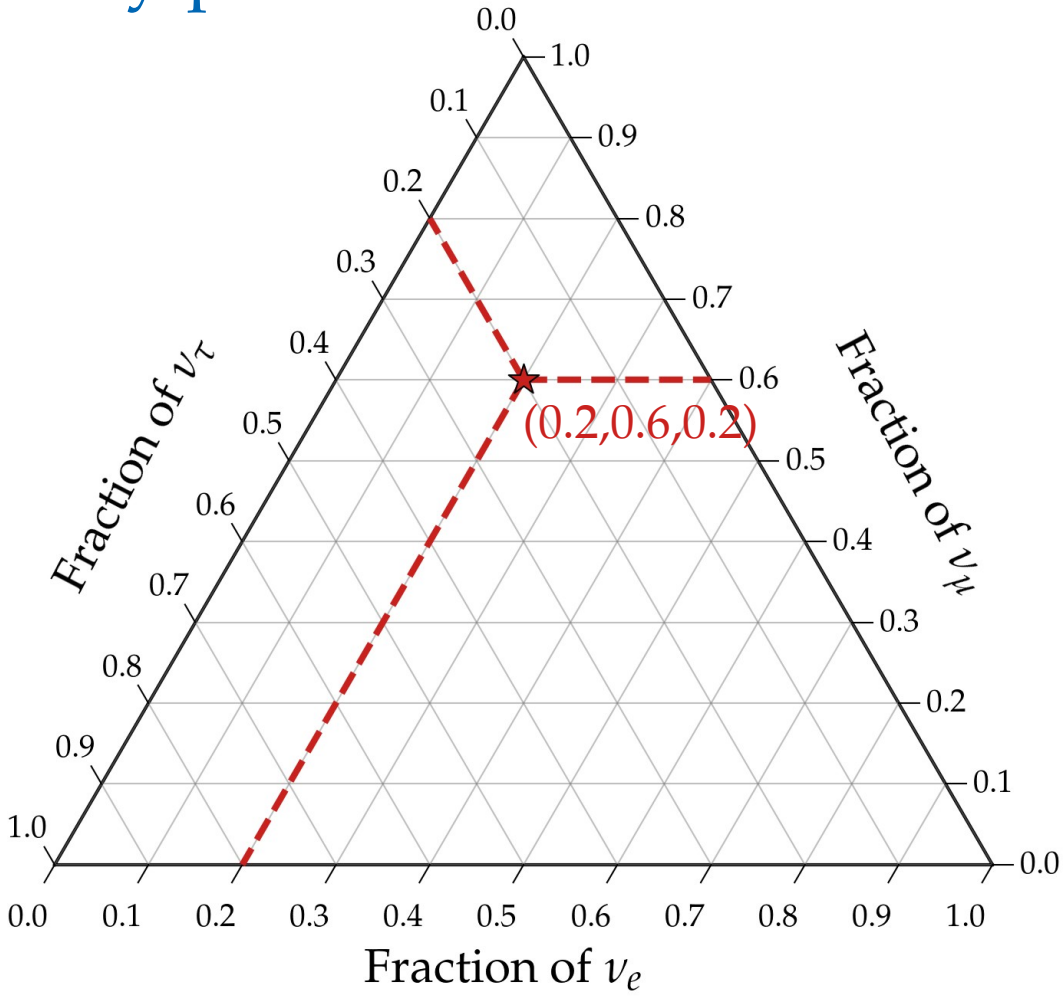

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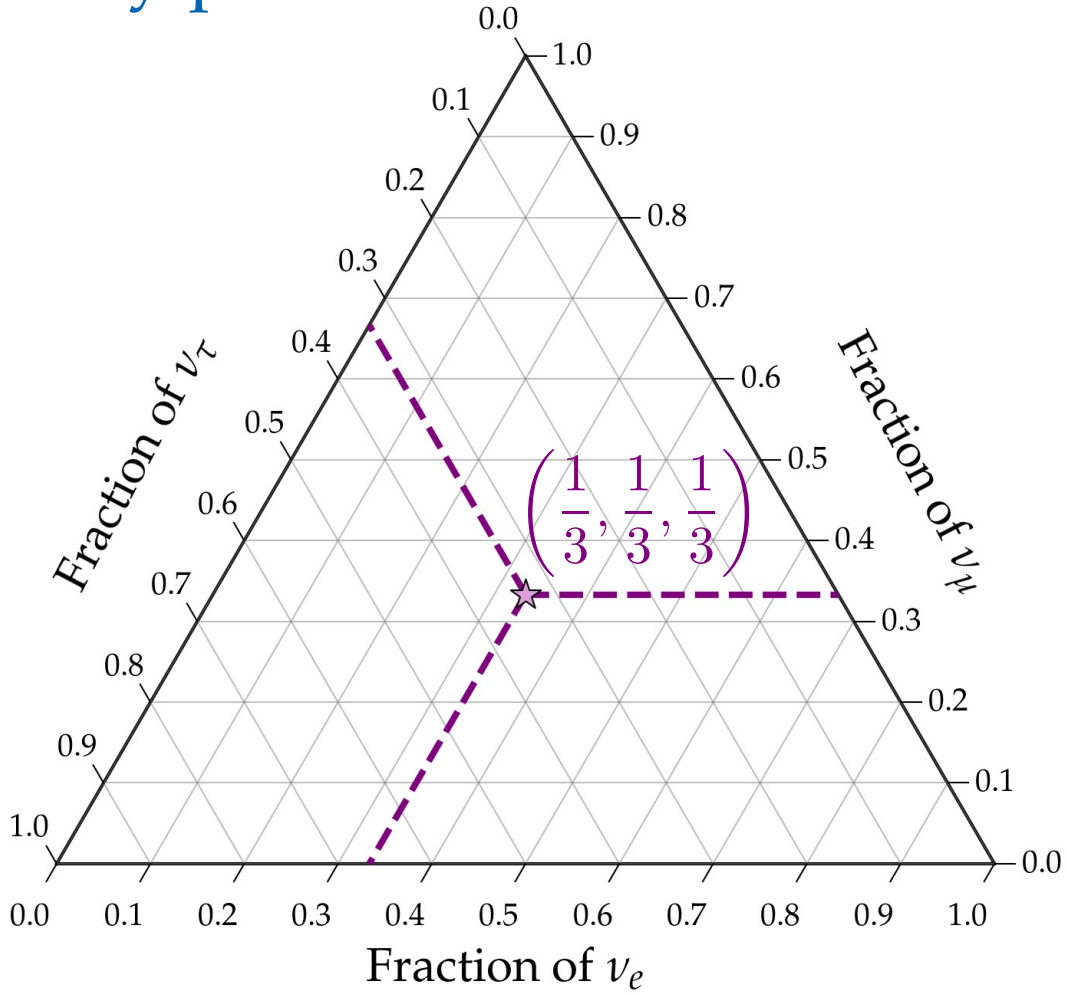

One likely TeV–PeV ν production scenario:

$p + \gamma \rightarrow \pi^+ \rightarrow \mu^+ + \nu_\mu$ 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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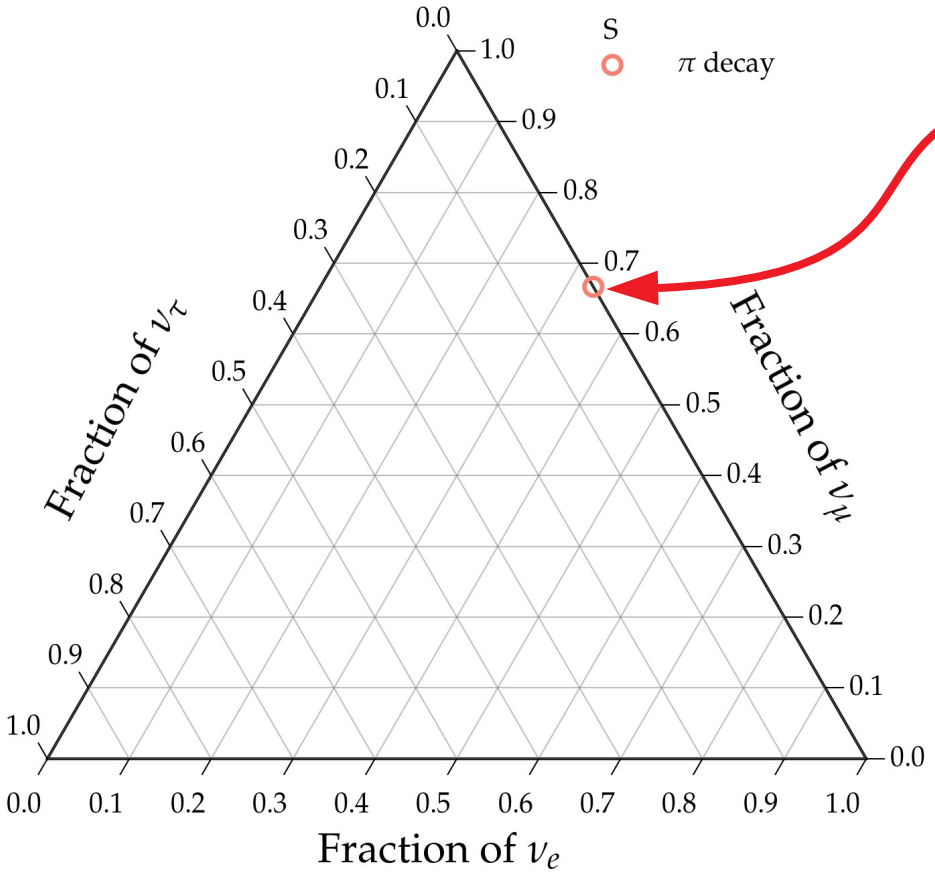

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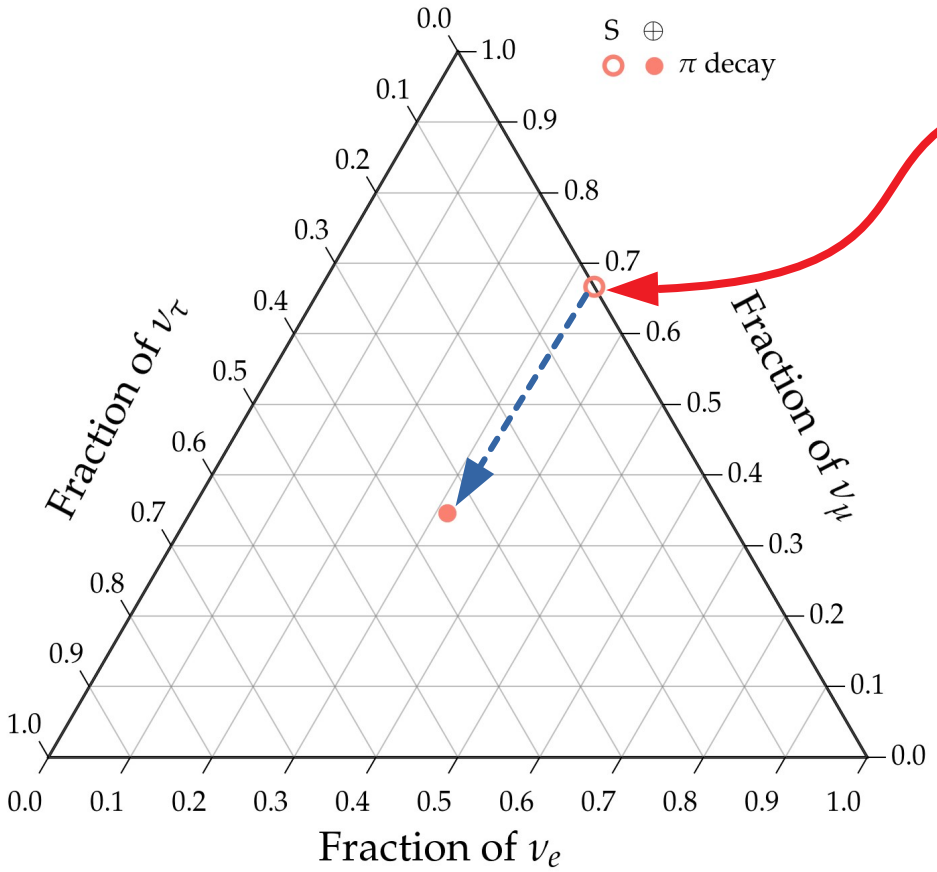

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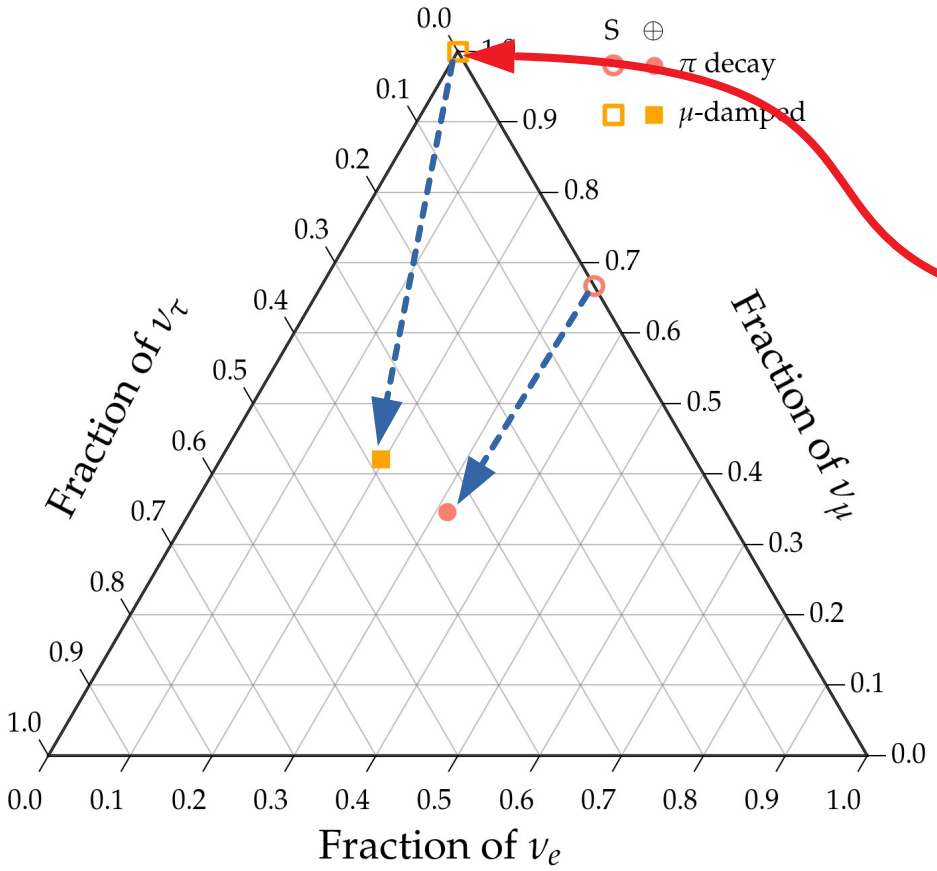

Full π decay chain

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Muon damped

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

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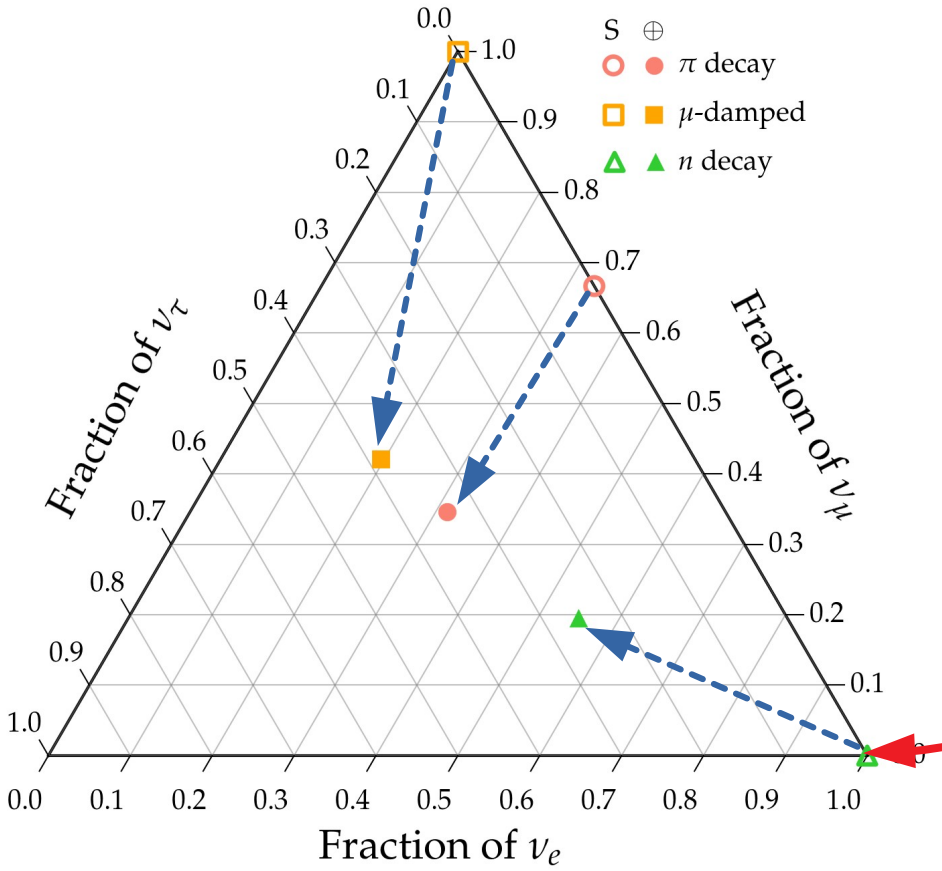


Full π decay chain

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

Muon damped

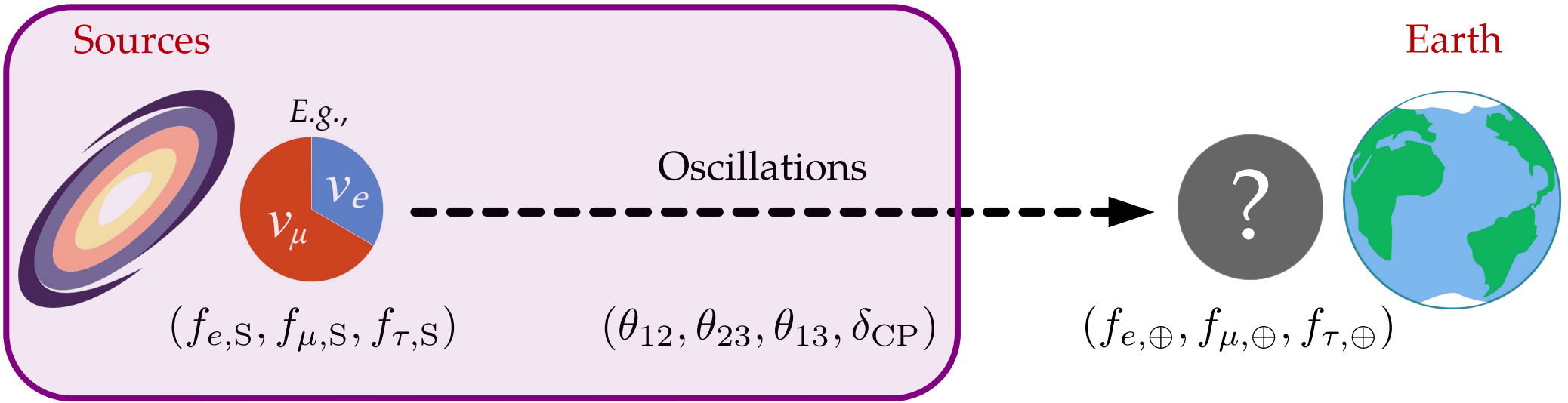
$(0{:}1{:}0)_S$

Neutron decay

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

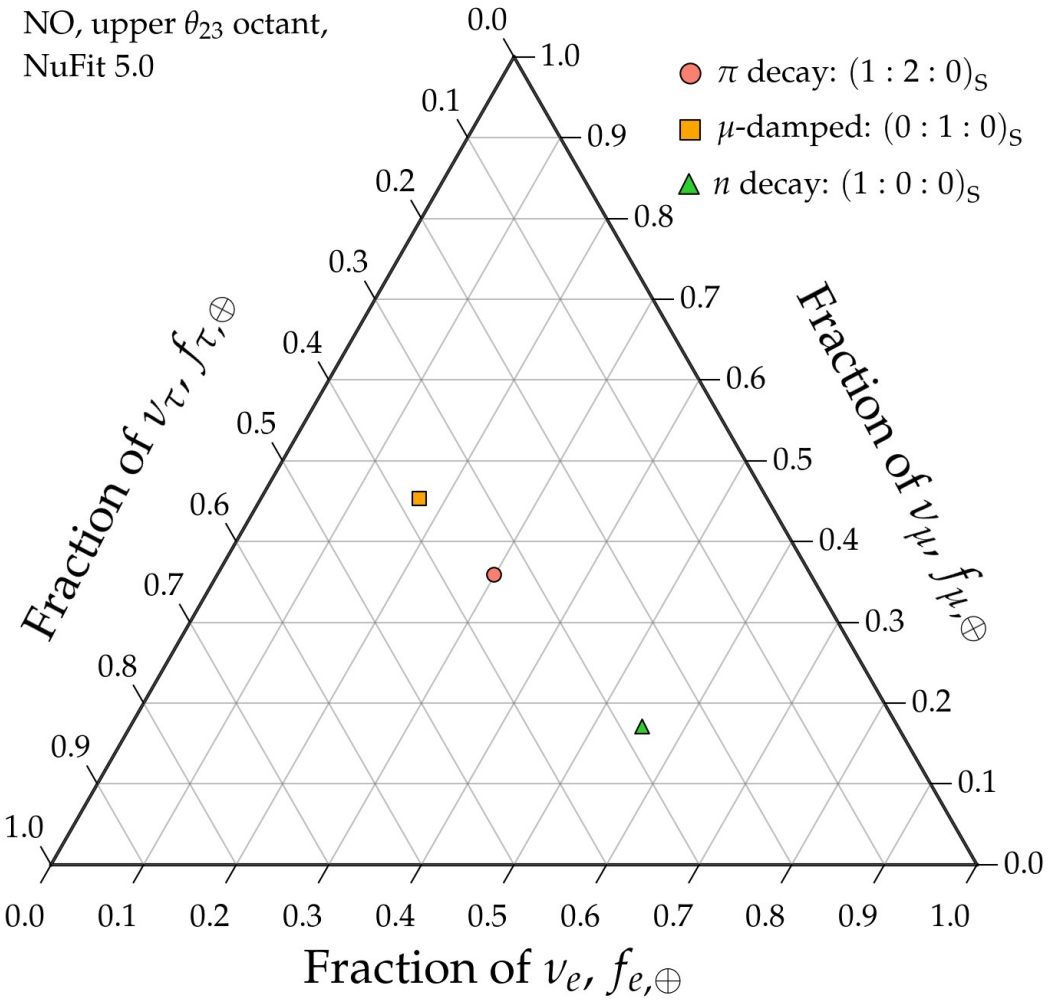
Note: ν and $\bar{\nu}$ are (so far) indistinguishable in neutrino telescopes

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



Known from oscillation experiments, to different levels of precision

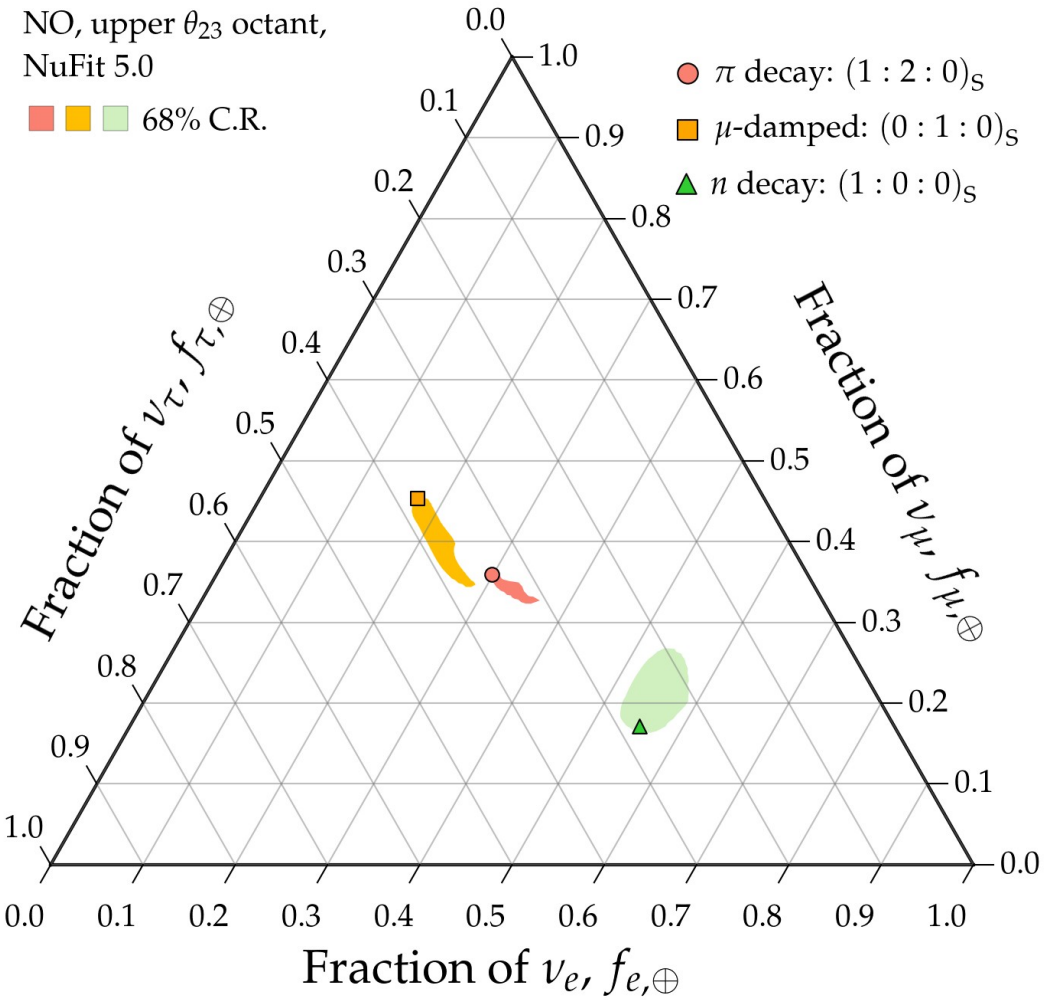
Theoretically palatable regions: today



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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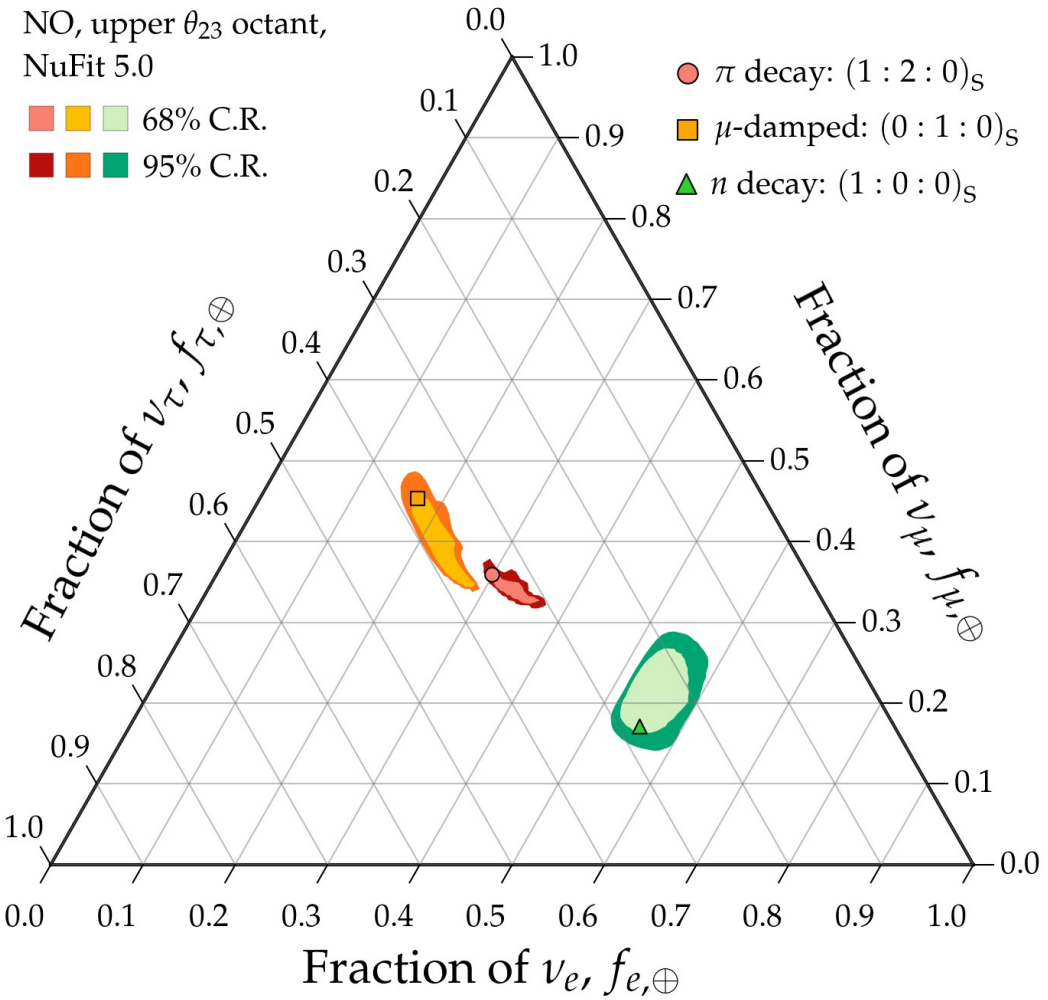

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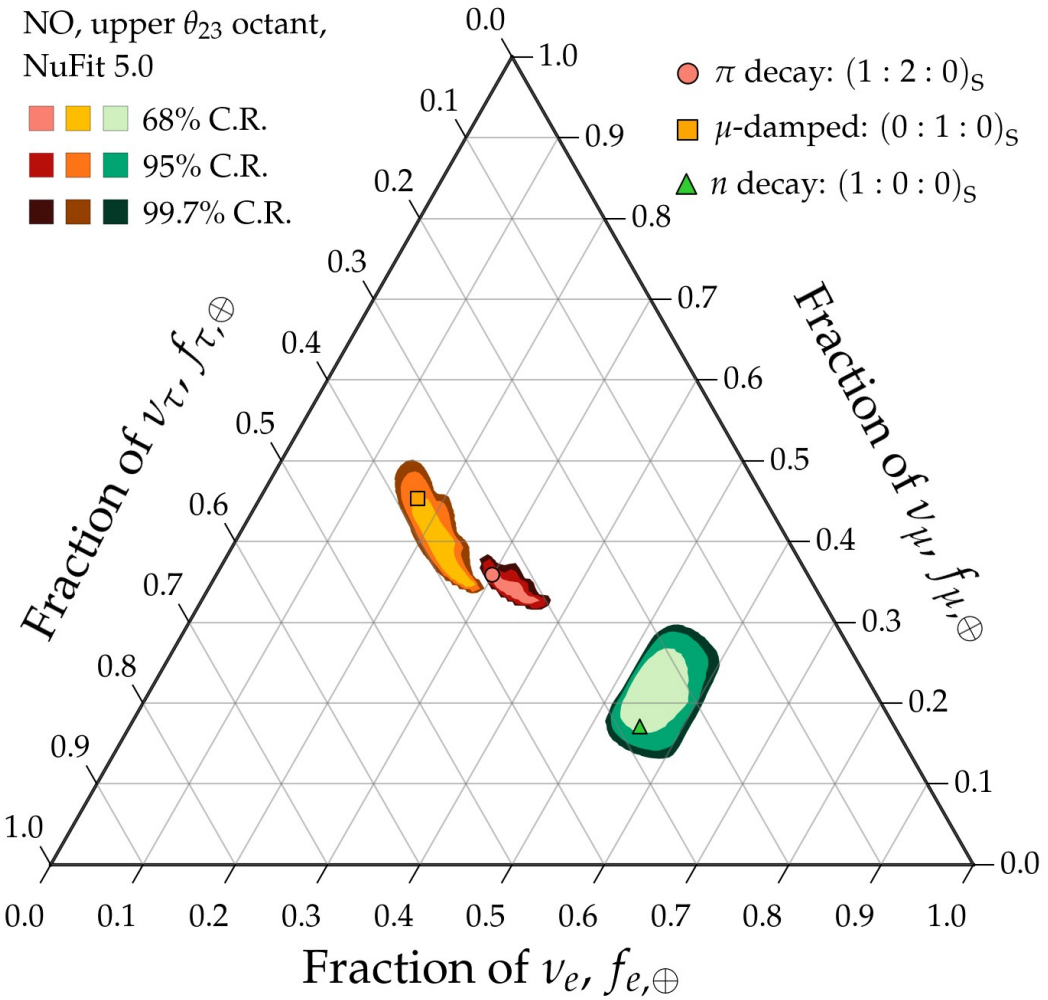

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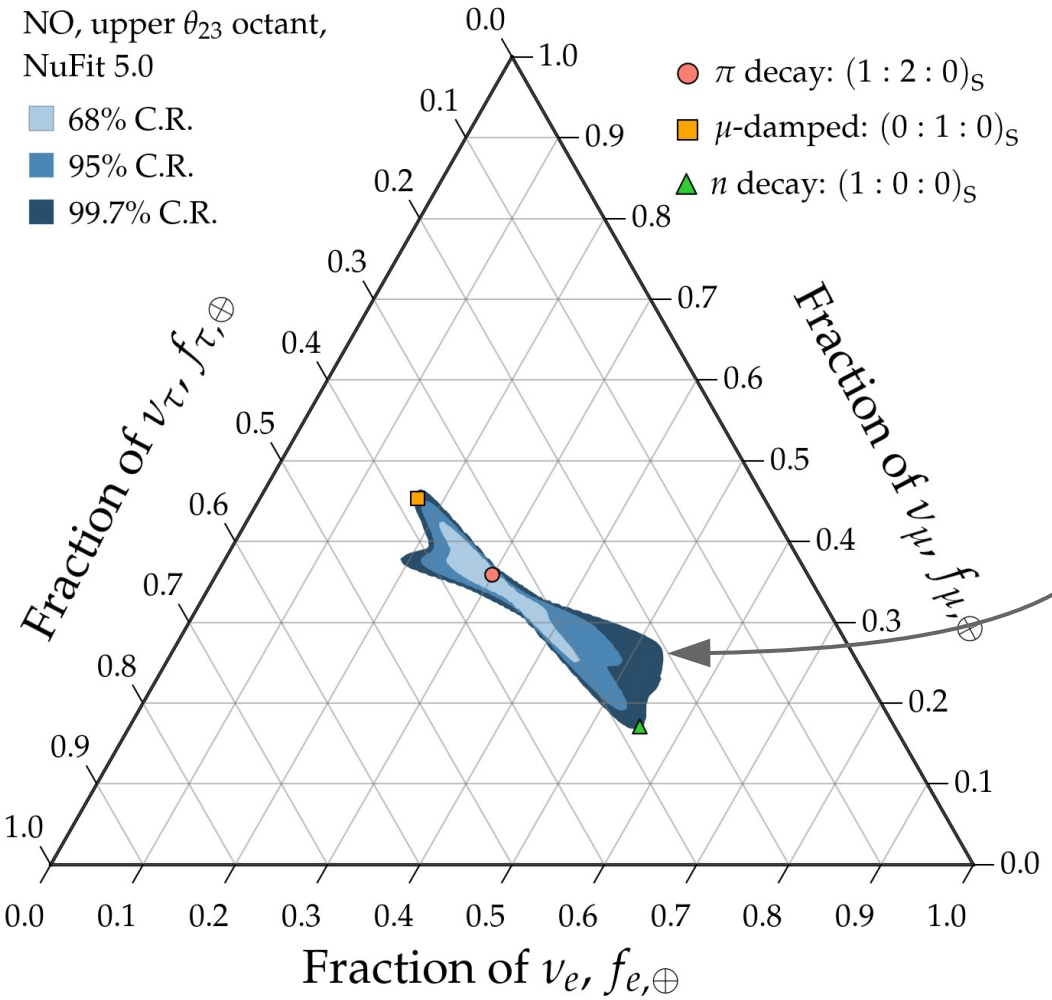


Varying over all possible flavor ratios at the source

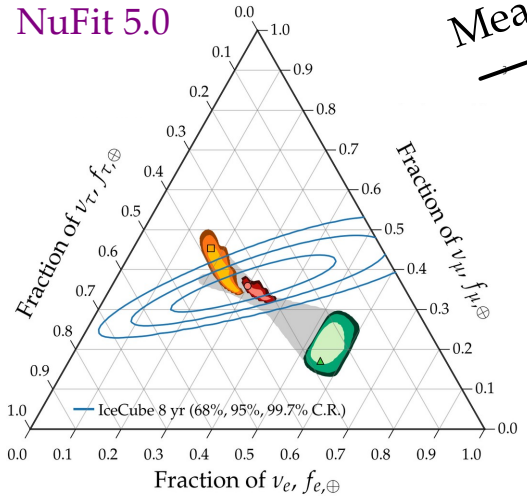
Note:
All plots shown are for normal neutrino mass ordering (NO); inverted ordering looks similar

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

How knowing the mixing parameters better helps

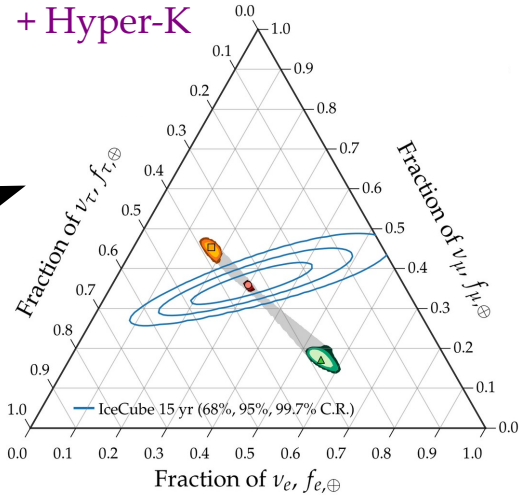
2020

NuFit 5.0

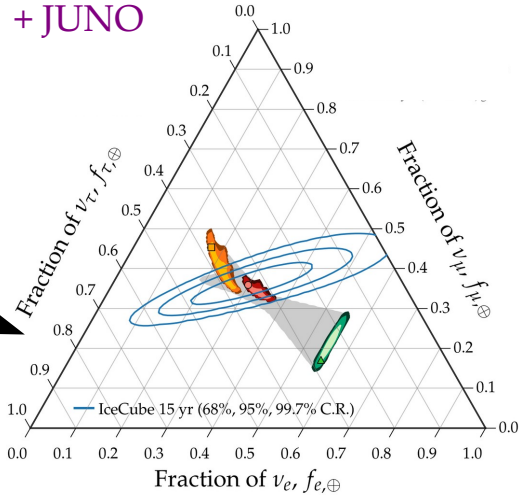


Measure θ_{23} better

+ Hyper-K



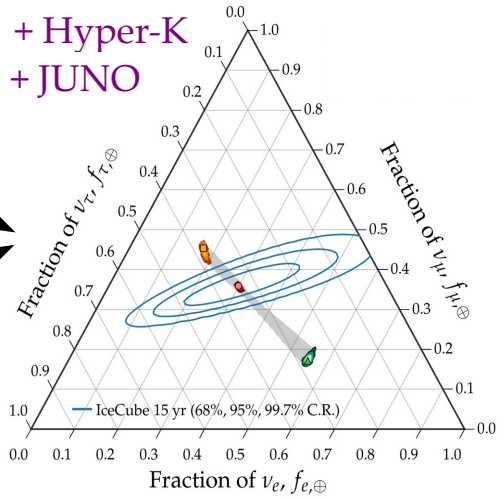
+ JUNO



Measure θ_{12} better

~2030

+ Hyper-K
+ JUNO



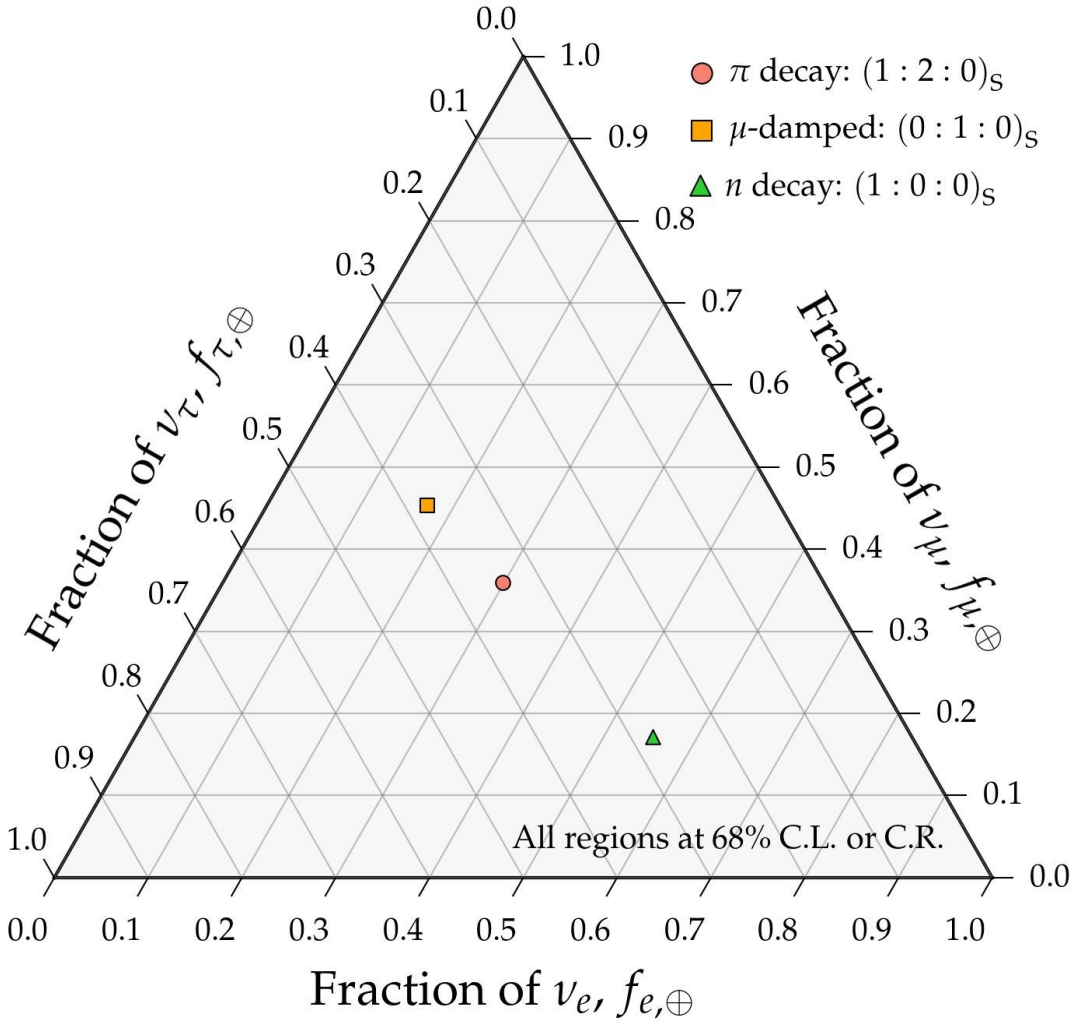
In our results:
JUNO + Hyper-K + DUNE

Marginal improvement til 2040

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

Measuring the flavor composition

Measuring flavor composition 2015–2025



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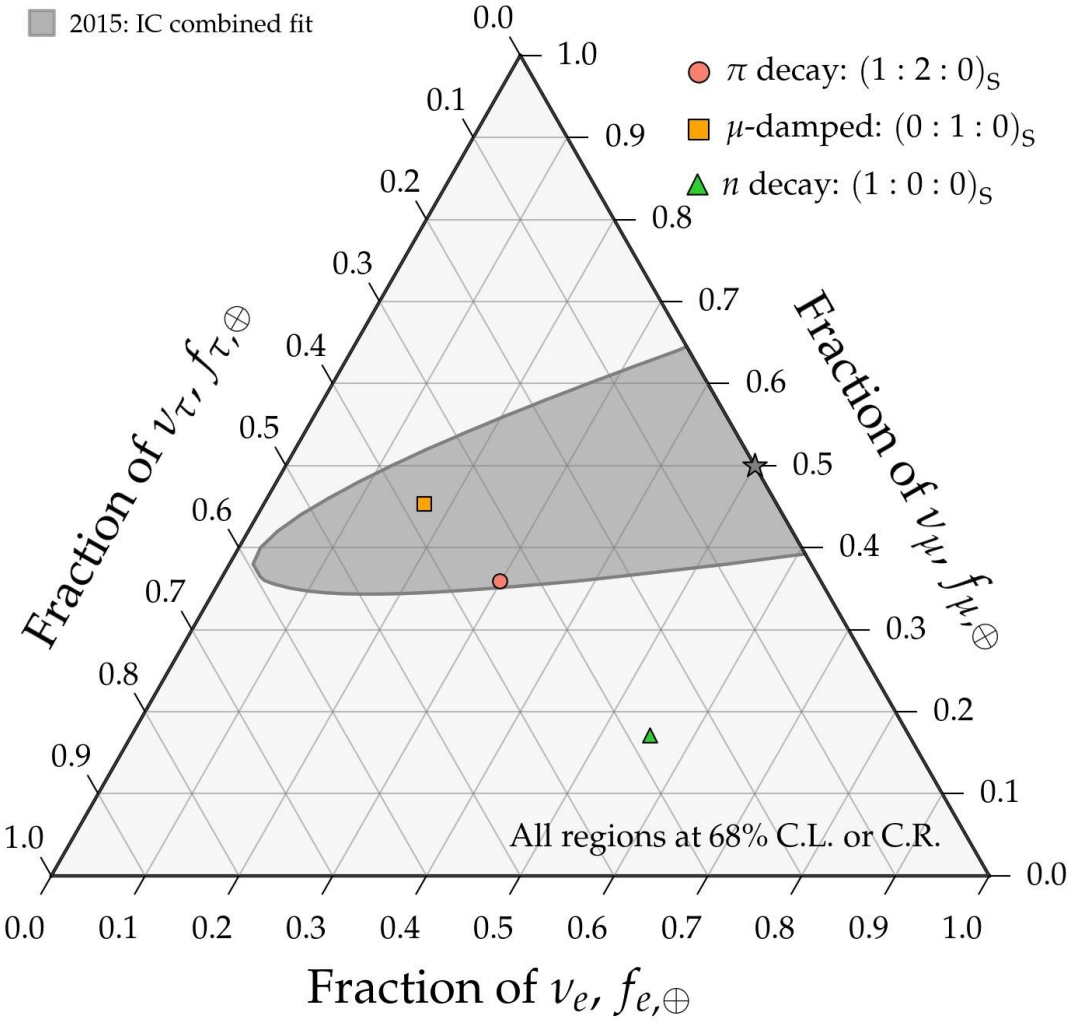

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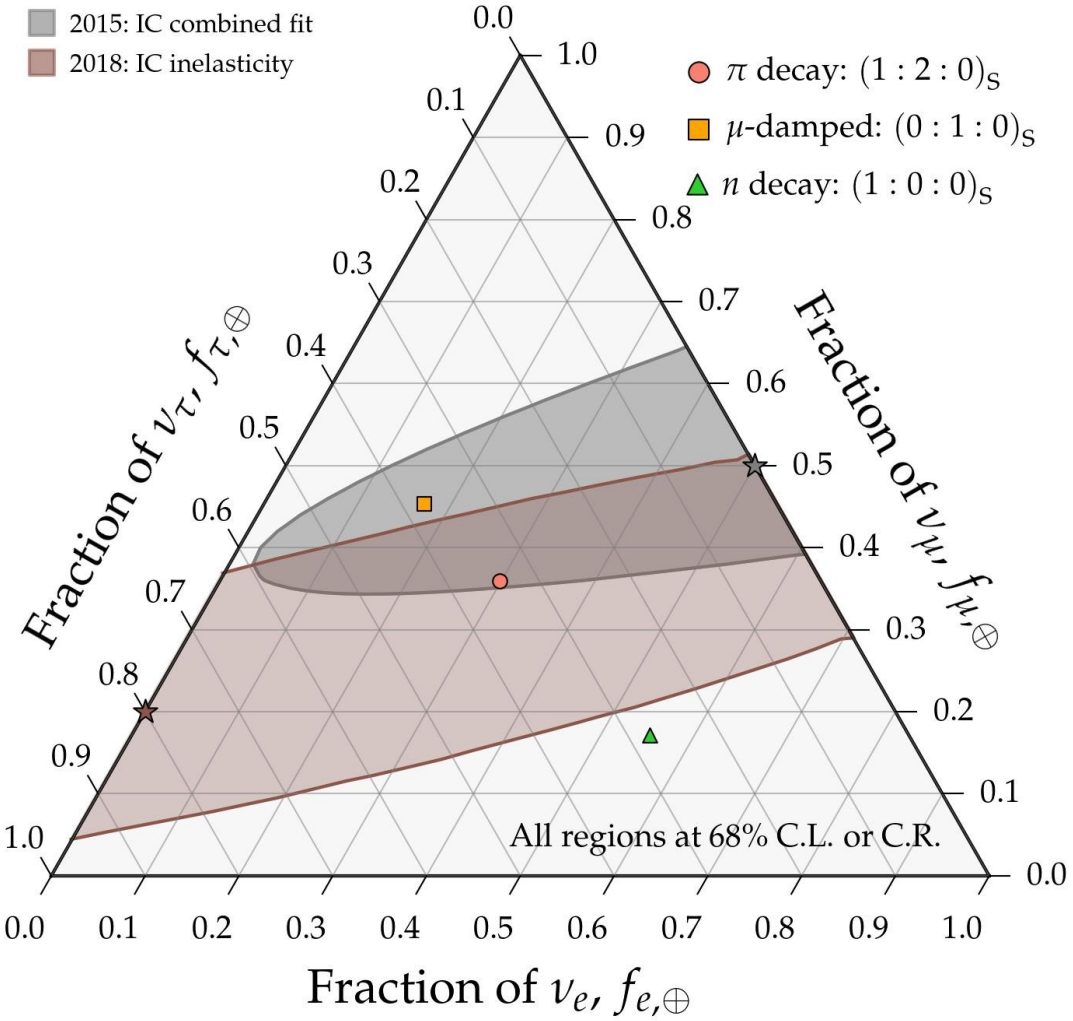

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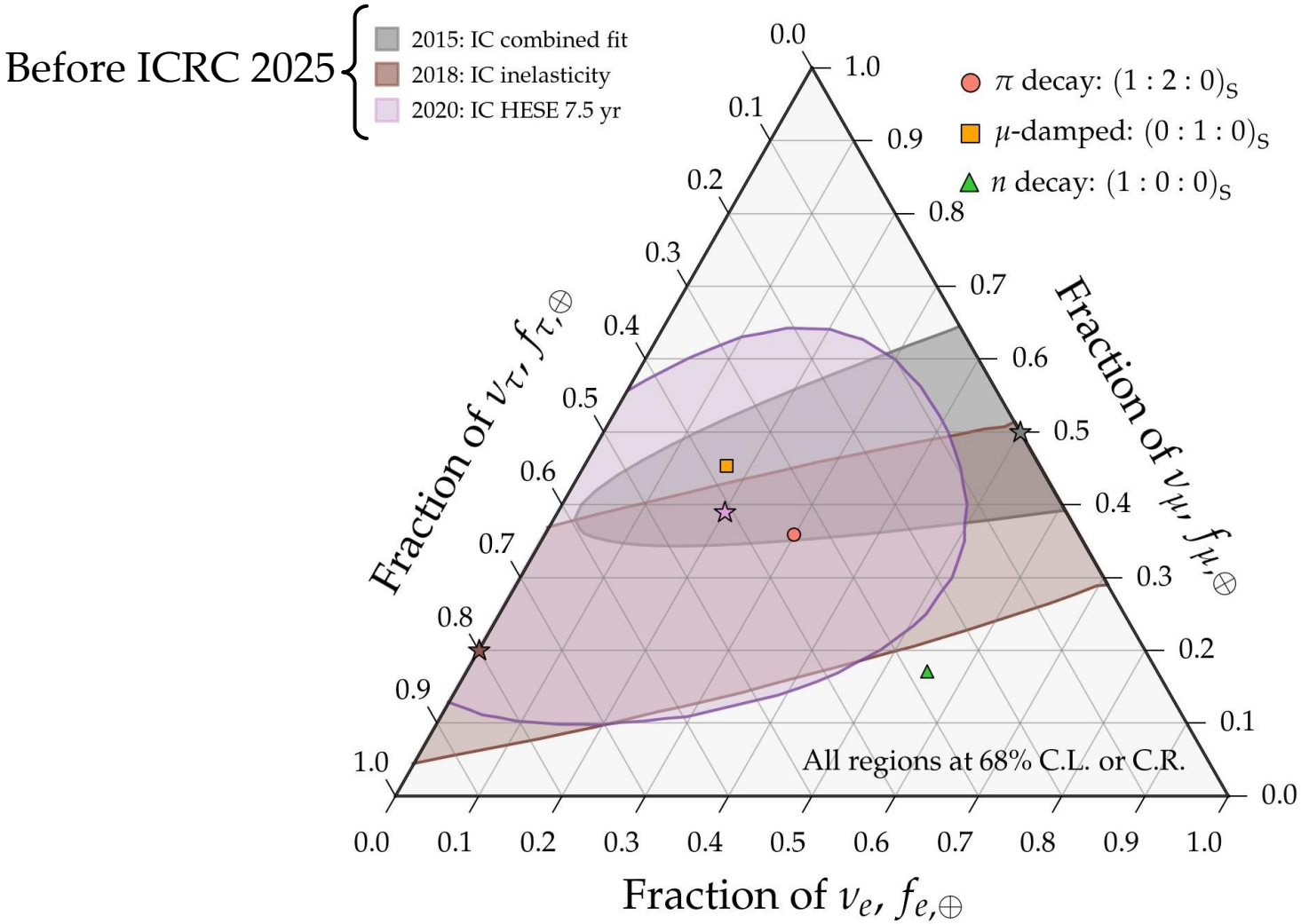
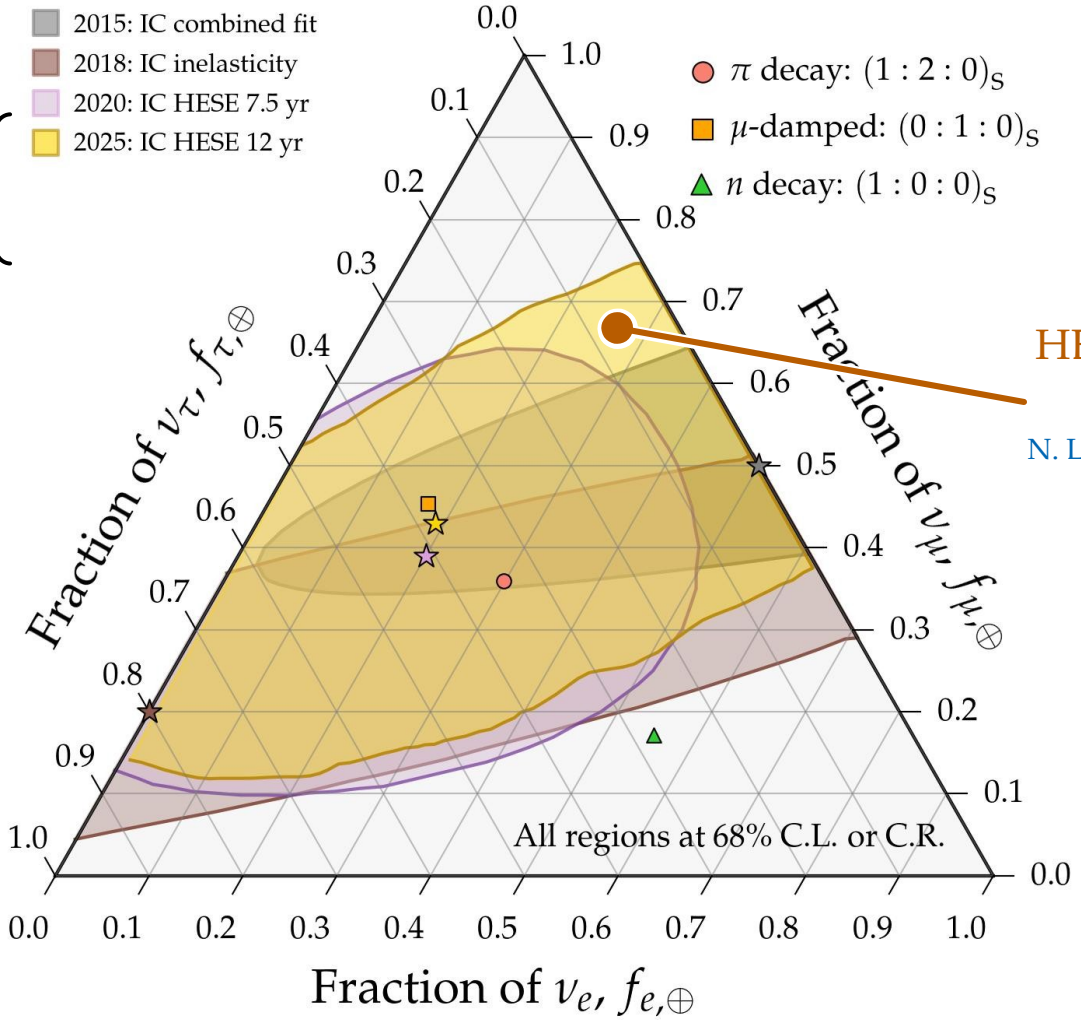


Measuring flavor composition 2015–2025

Presented at ICRC 2025

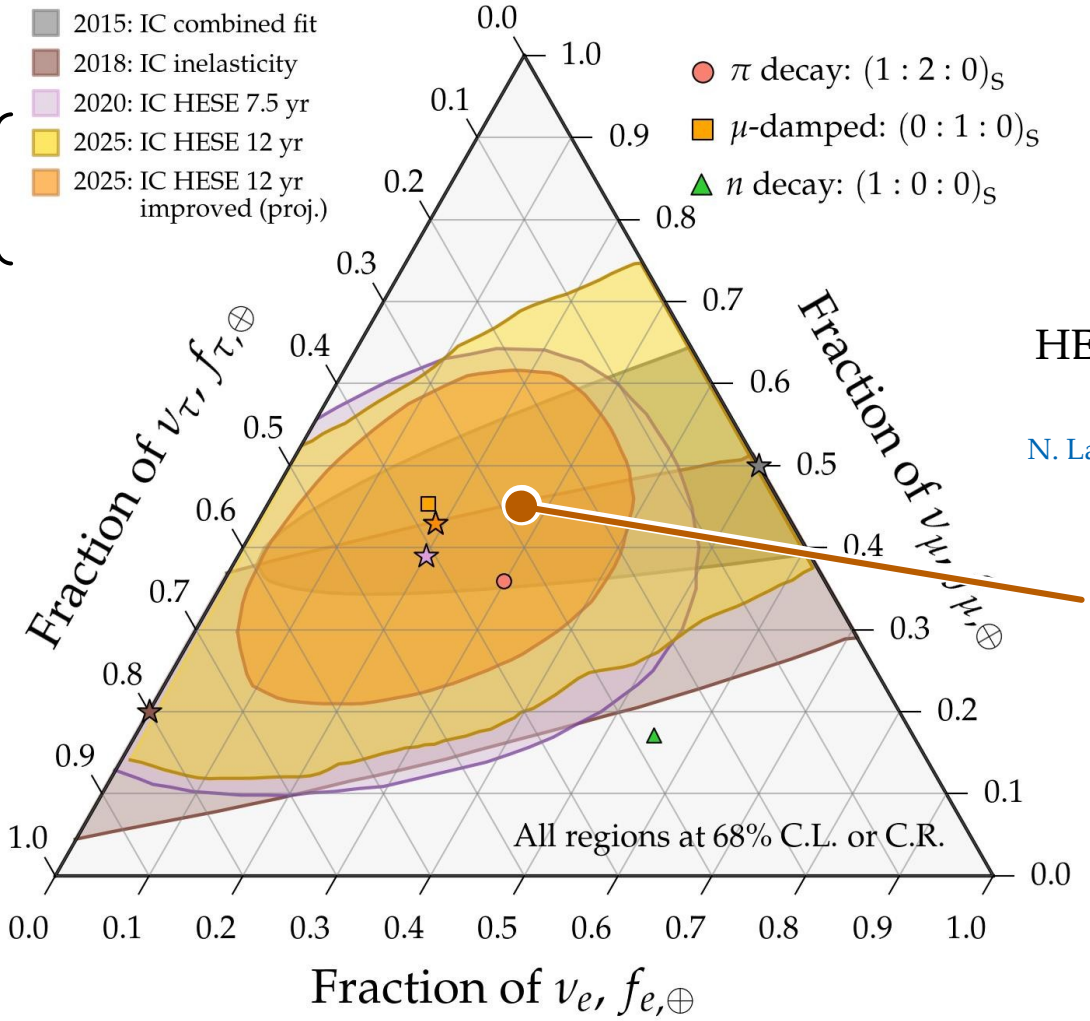


HESE (> 60 TeV) are scarce (~100 events in 12 yr)

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

Measuring flavor composition 2015–2025

Presented at ICRC 2025

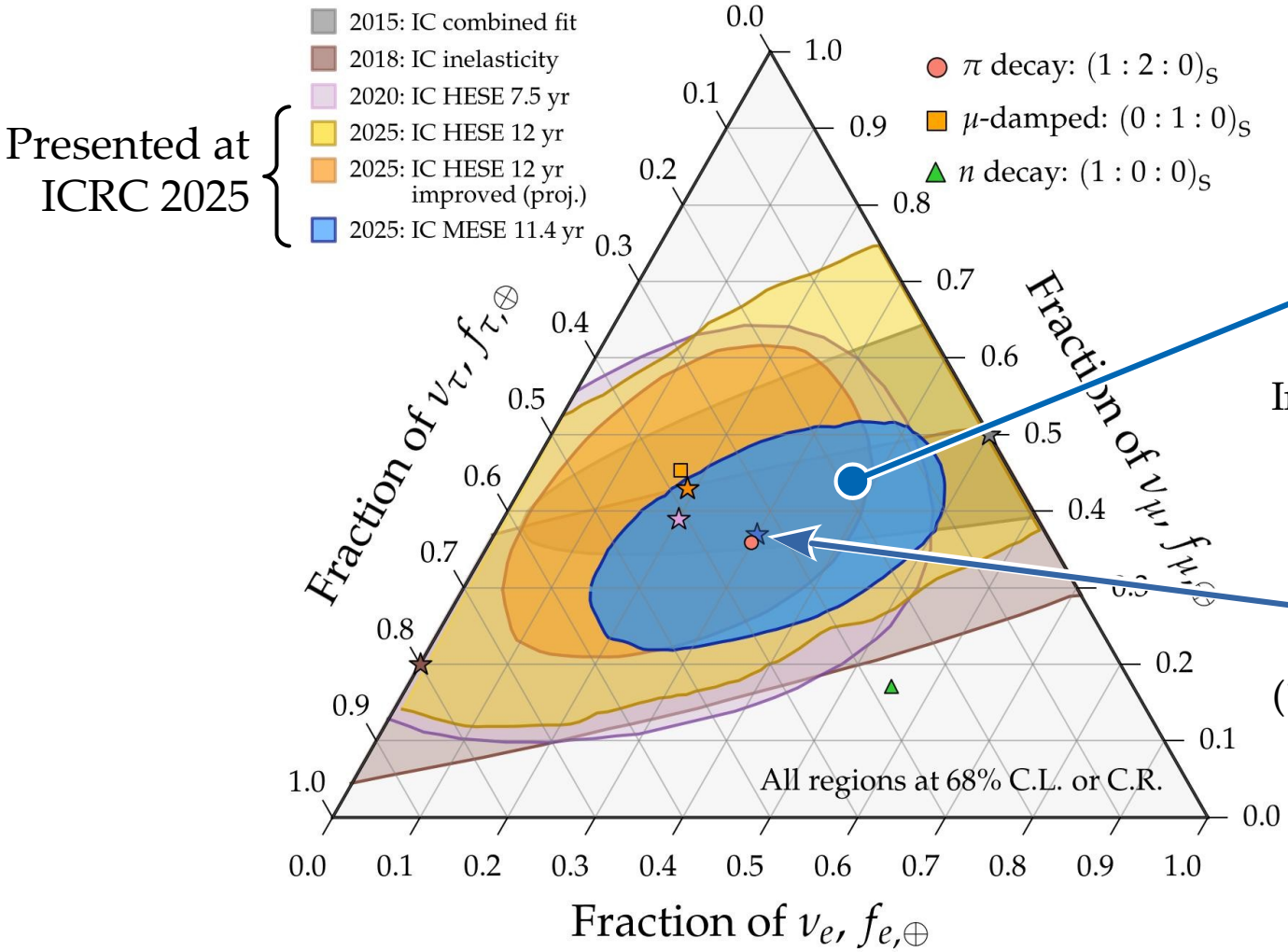


HESE (> 60 TeV) are scarce (~100 events in 12 yr)

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

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

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

A. Balagopal *et al.*
PoS(ICRC2025)983

Can we infer the mixing parameters?

We use Bayesian inference to infer the values of the mixing parameters:

$$\mathcal{P}(\boldsymbol{\theta}) = \int_0^1 \mathrm{d}f_{e,\mathrm{S}}\ \mathcal{L}(f_{\alpha,\oplus}(\boldsymbol{\theta}, f_{e,\mathrm{S}}))\ \pi(\boldsymbol{\theta})\ \pi(f_{e,\mathrm{S}})$$

Show 1D marginalized allowed intervals of each mixing parameters $\longrightarrow$

We use Bayesian inference to infer the values of the mixing parameters:

Joint posterior distribution of mixing parameters

$\boldsymbol{\theta} \equiv (\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\rm CP})$

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Likelihood function of flavor-composition measurements (from IceCube, *etc.*)

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Prior on $\boldsymbol{\theta}$ (flat or Haar measure on $U_{\rm PMNS}$)

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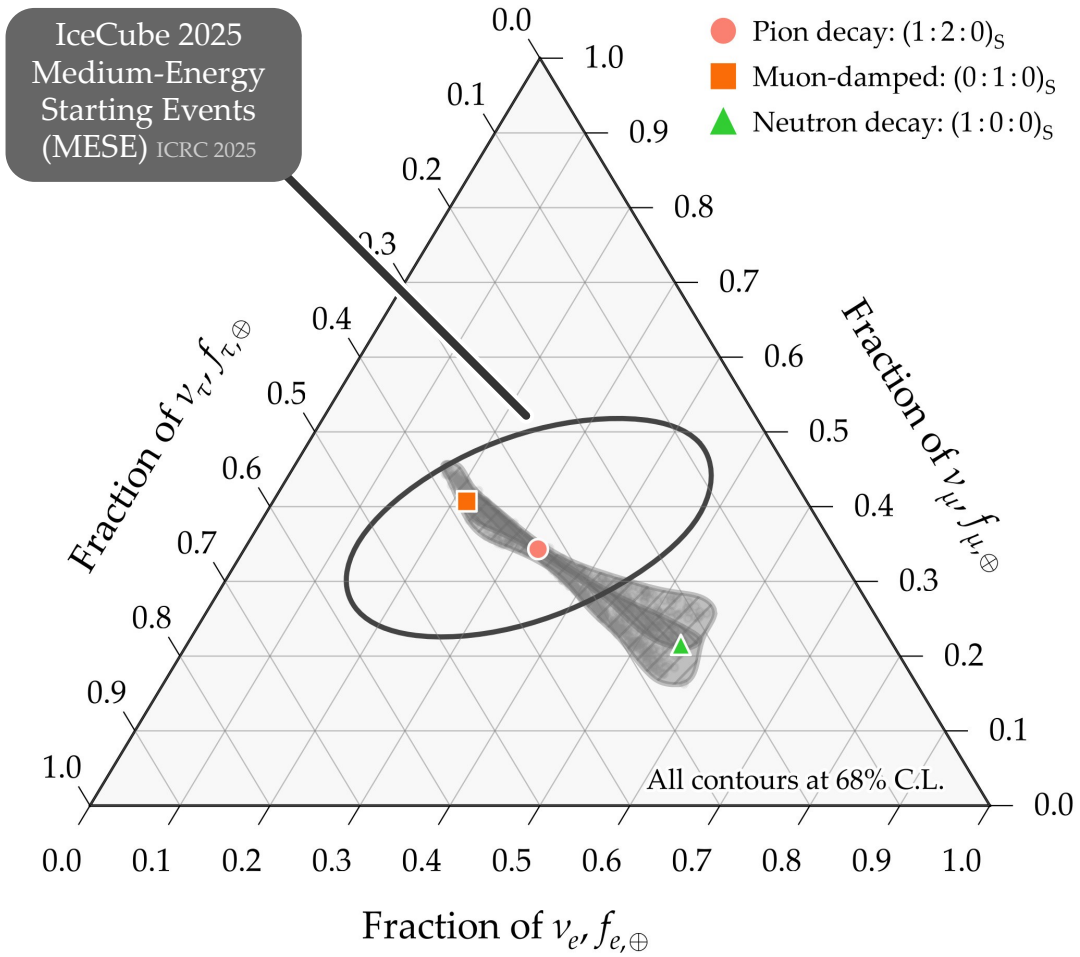
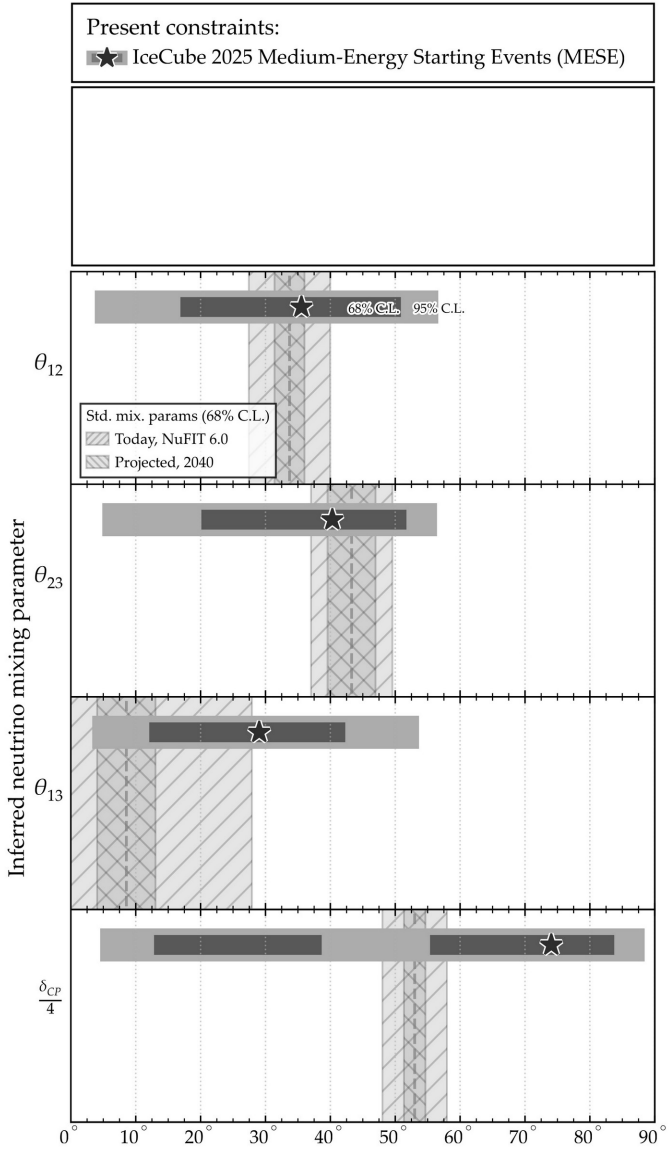
Likelihood function of flavor-composition measurements (from IceCube, *etc.*)

Prior on $f_{e,\rm S}$ (flat in [0,1])

Show 1D marginalized allowed intervals of each mixing parameters →

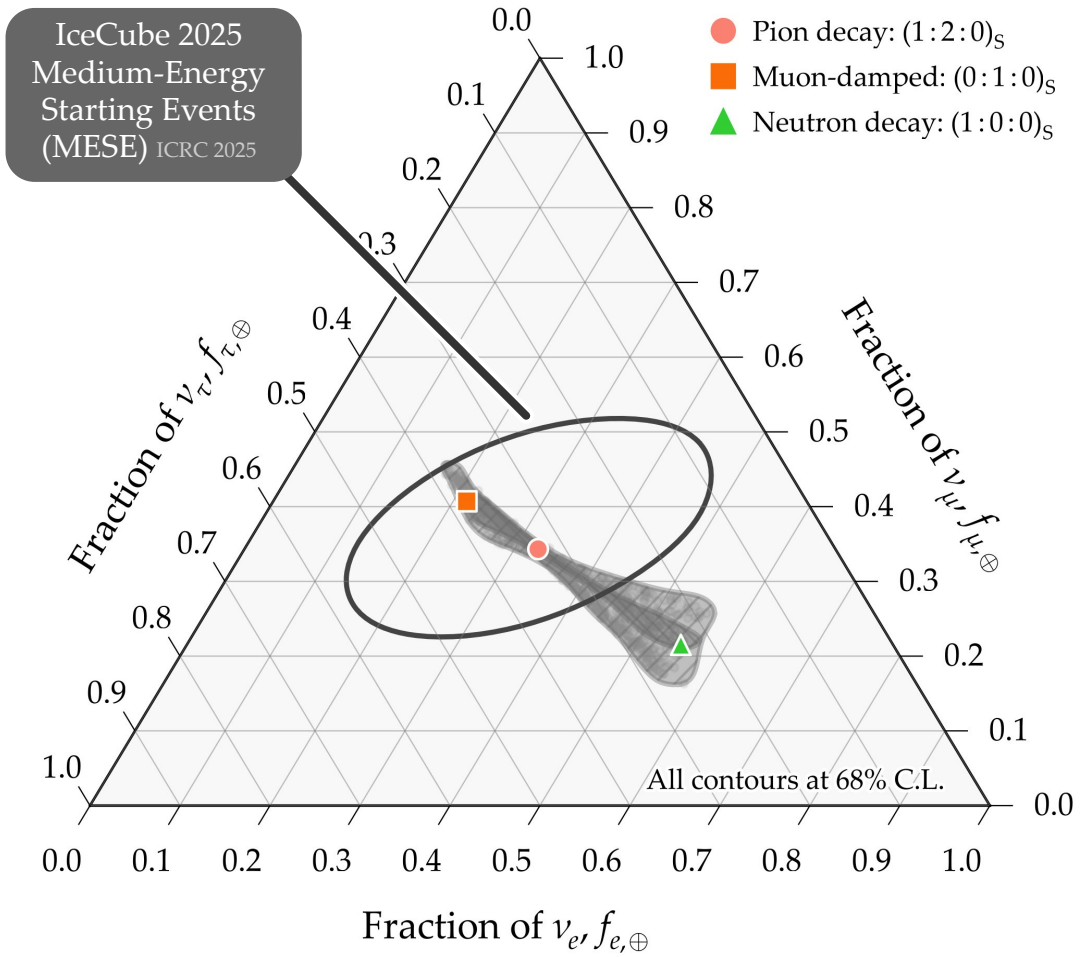
Measurement power *today* —





Telalovic, Liu, Barenboim, **MB**, *In prep.*

Measurement power *today* —



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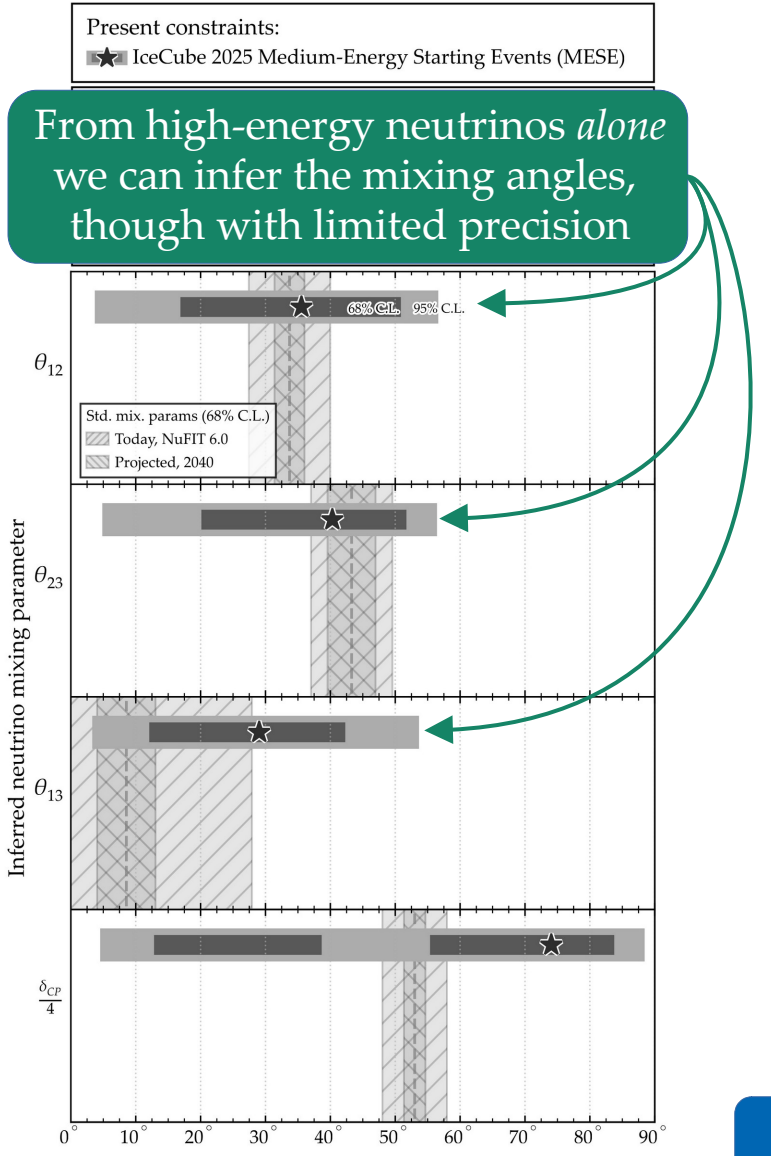
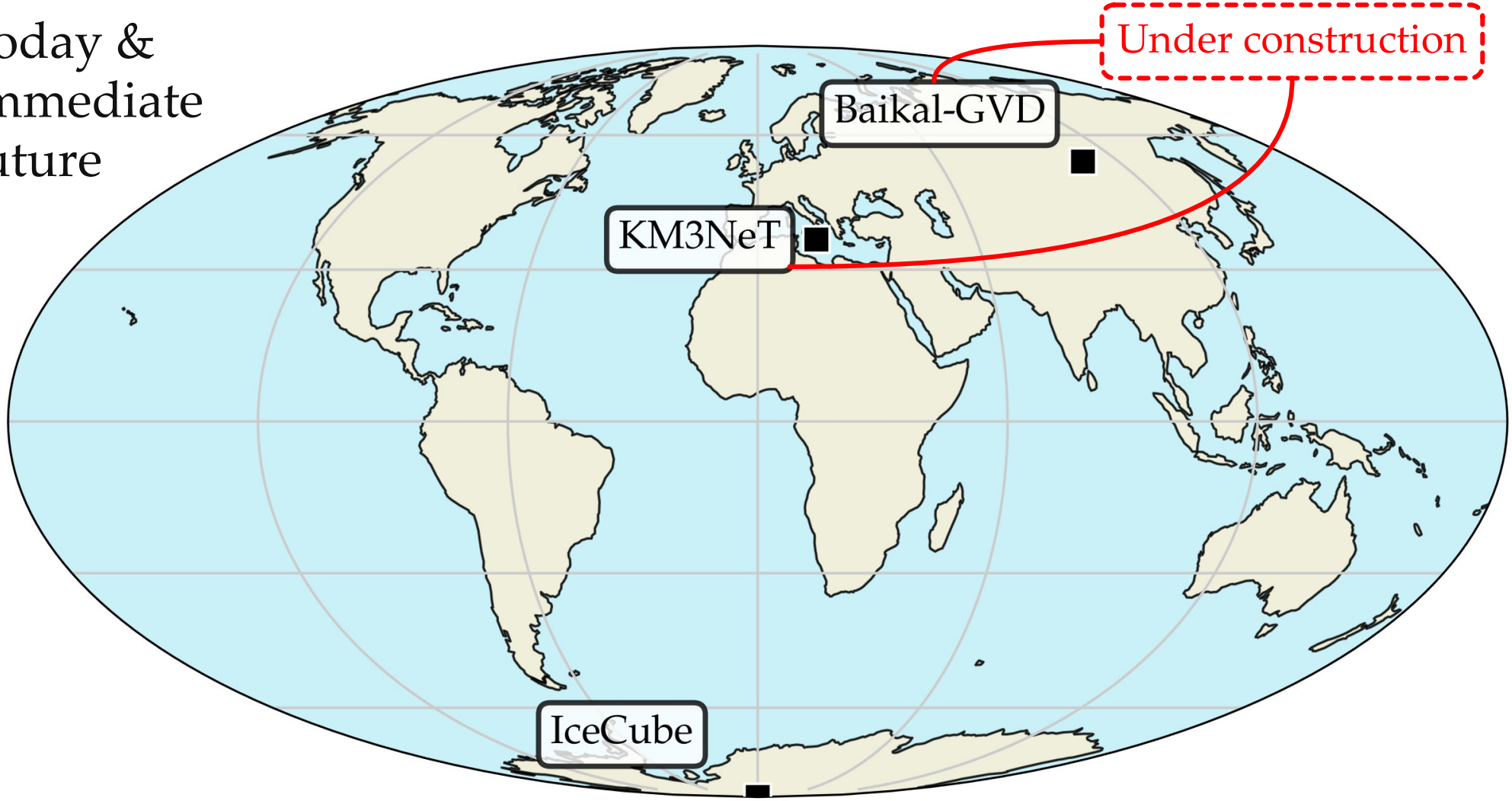
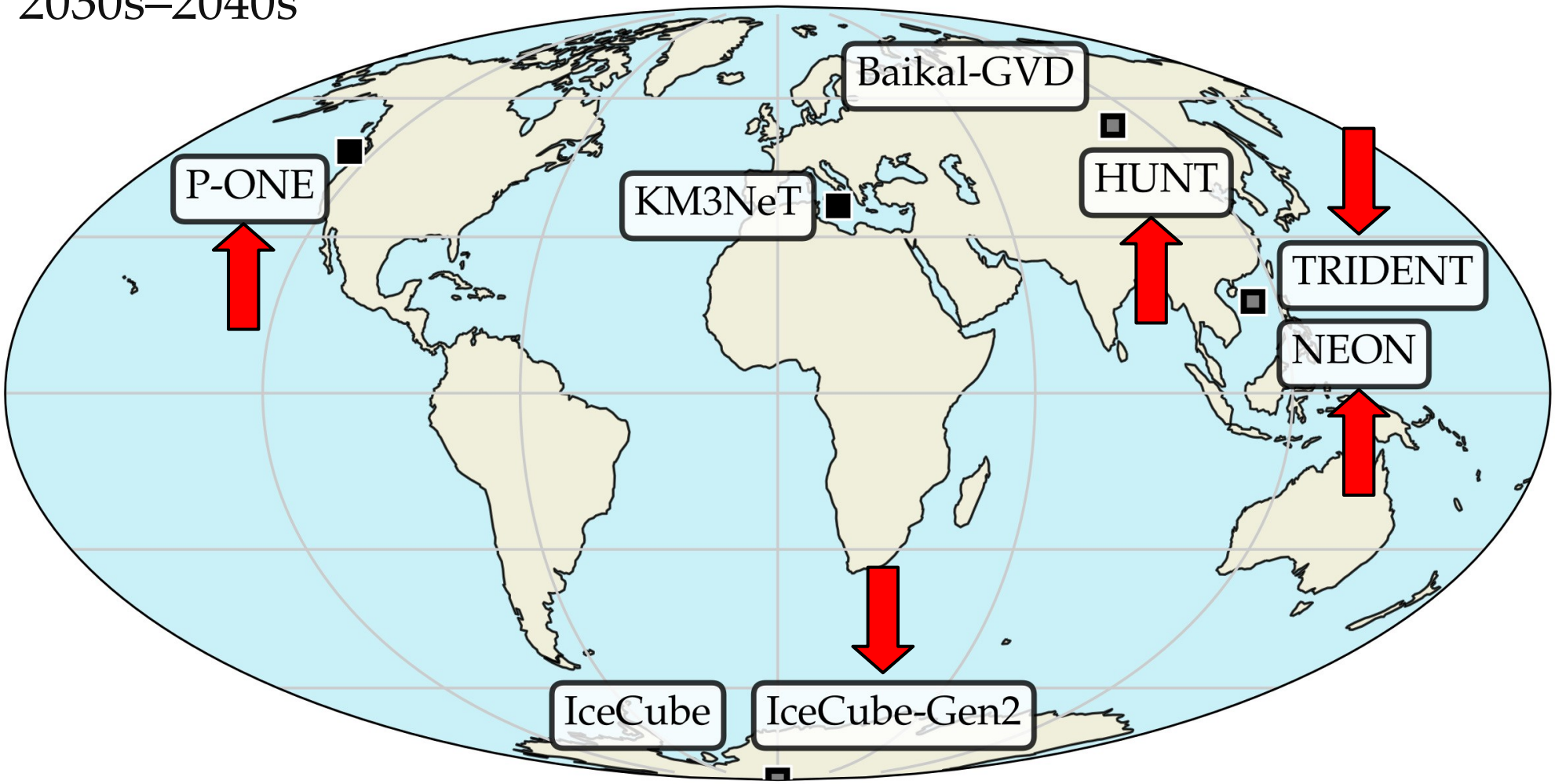


Today & immediate future



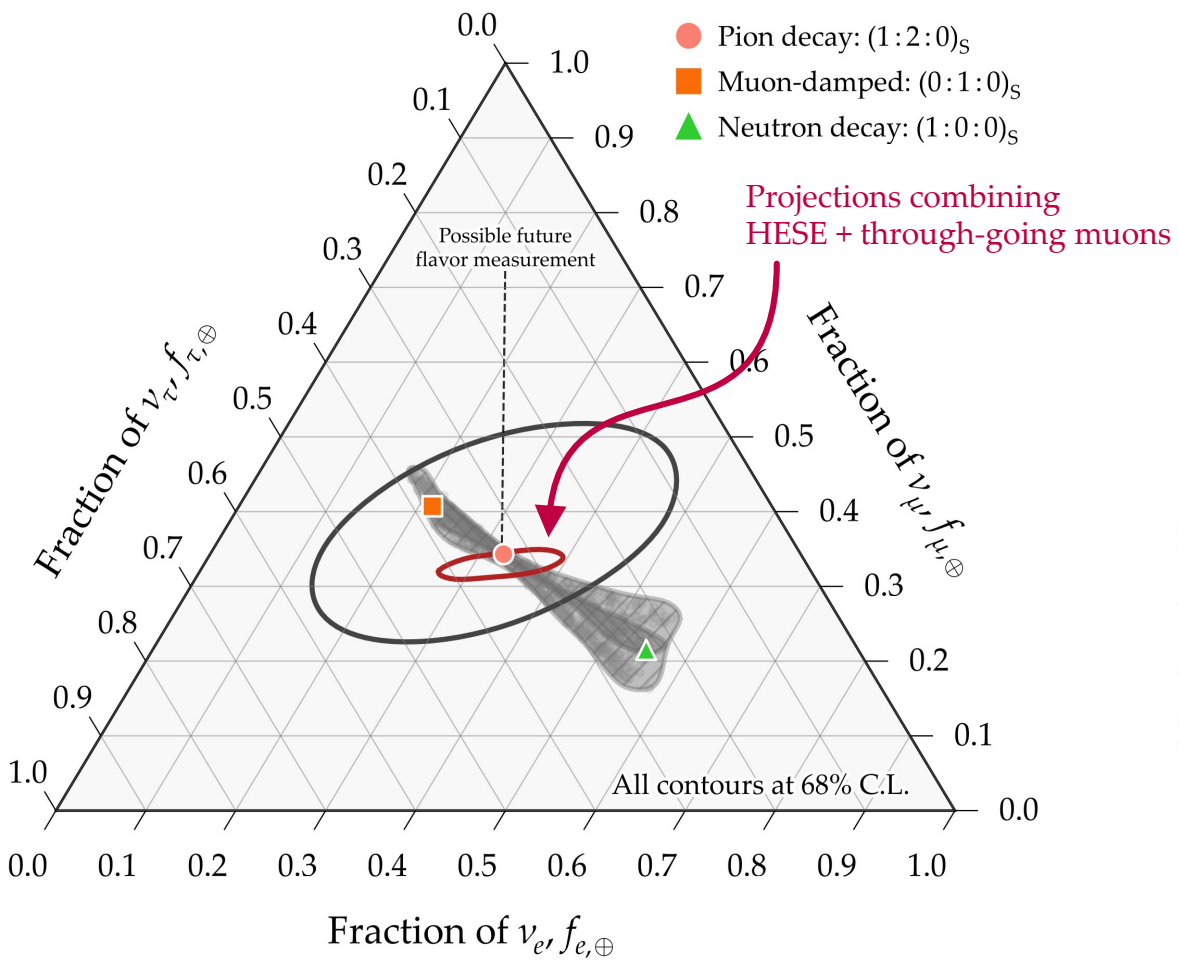
Schumacher, **MB**, Agostini, Oikonomou, Resconi, 2503.07549

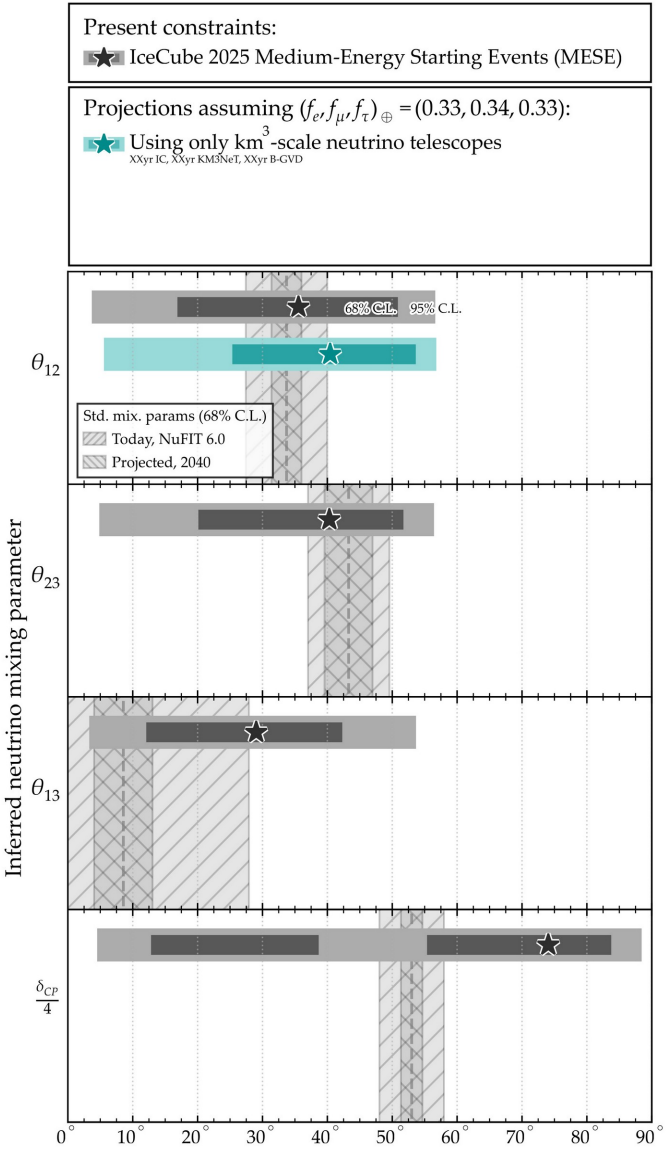
2030s–2040s



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

Measurement power *in the future* —





Telalovic, Liu, Barenboim, **MB**, *In prep.*

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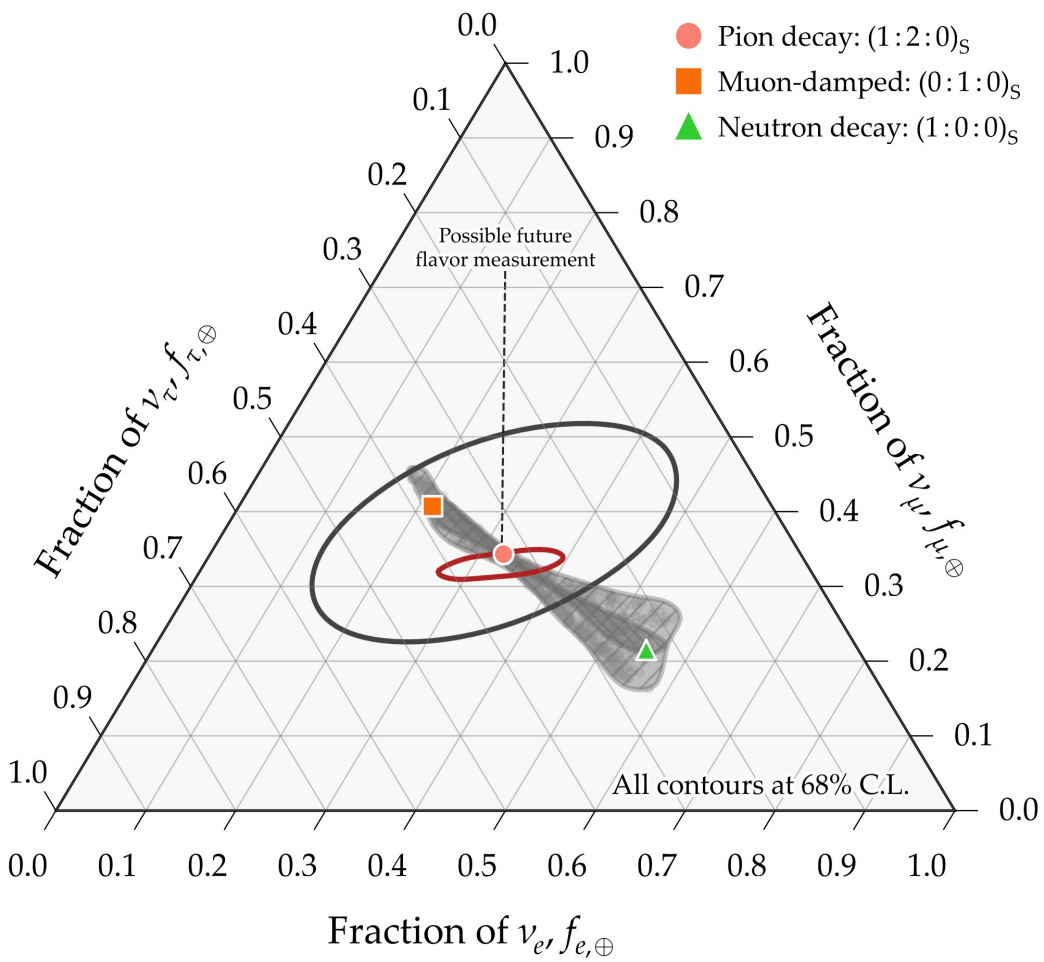
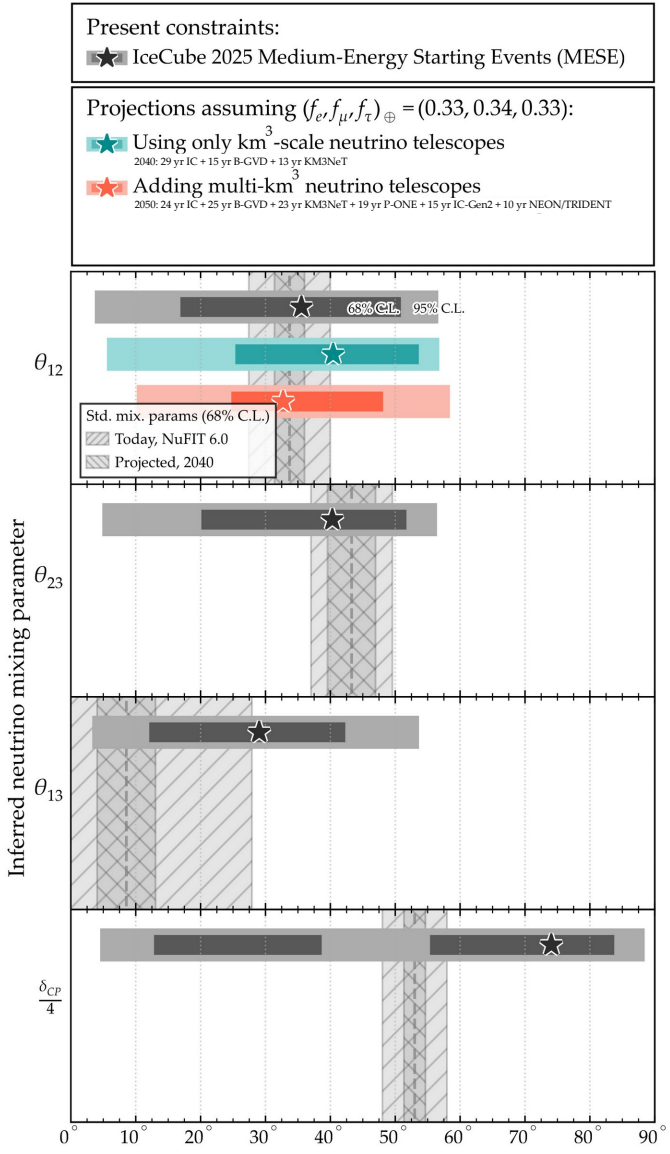
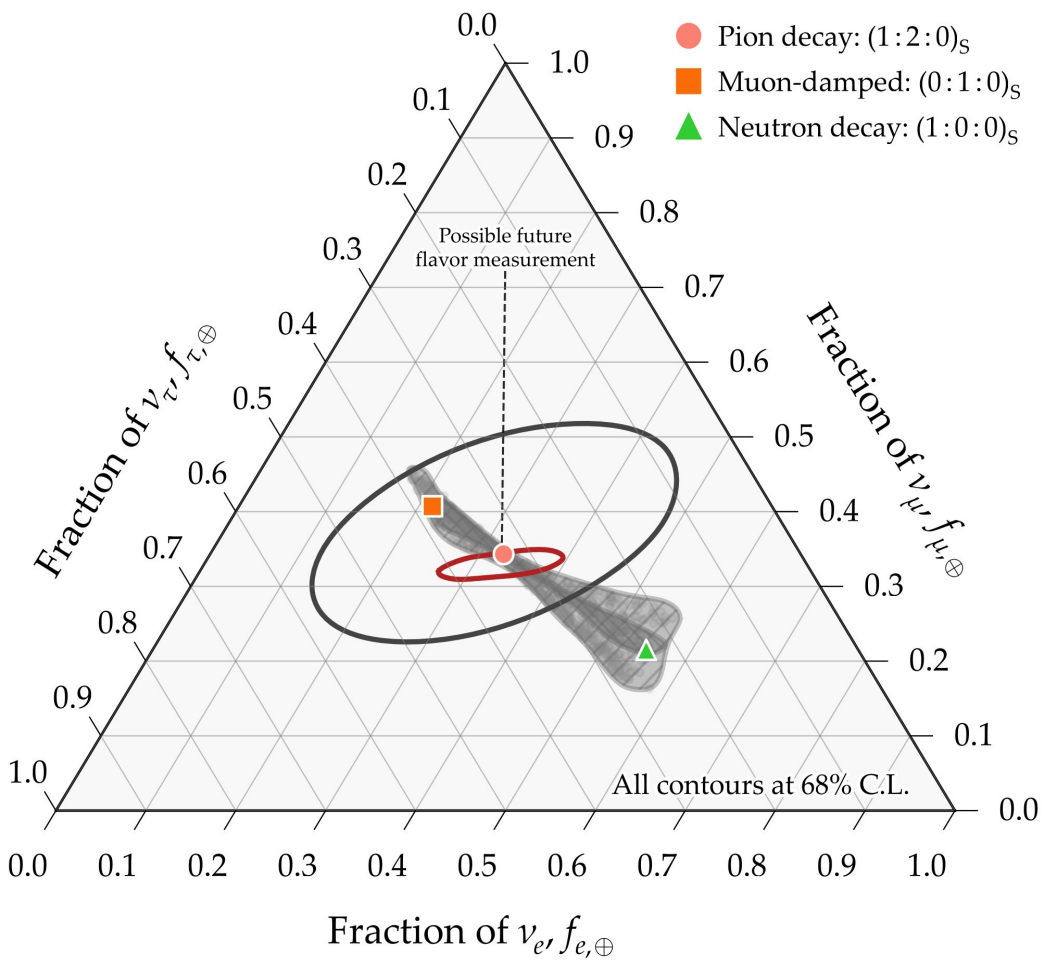
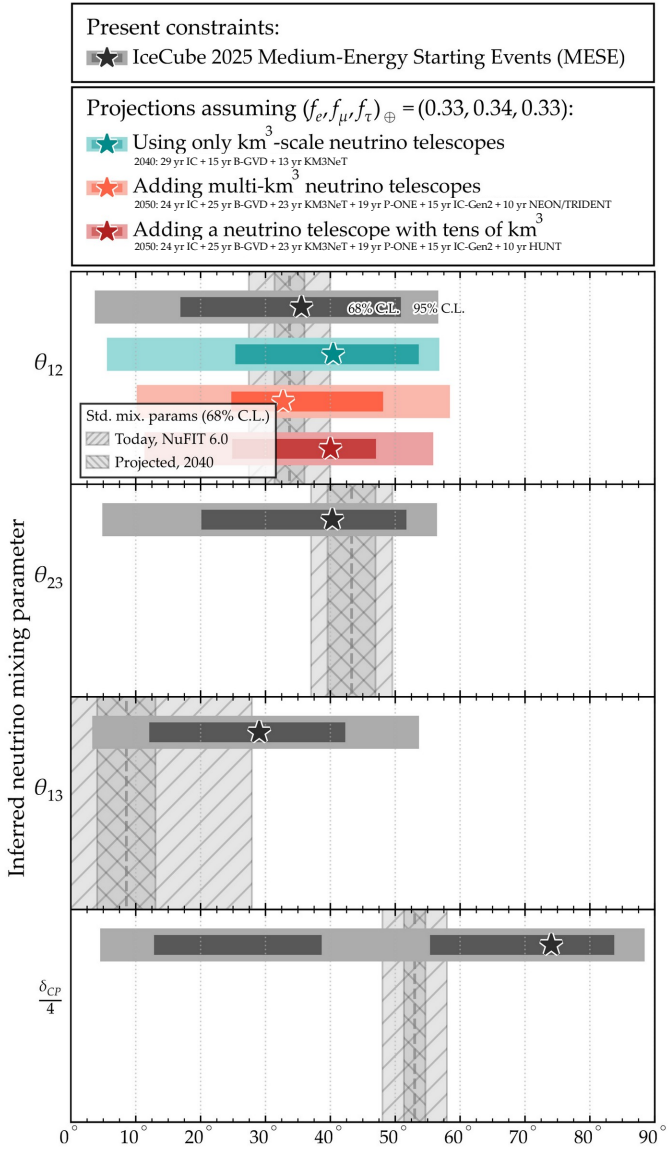




Telalovic, Liu, Barenboim, **MB**, *In prep.*

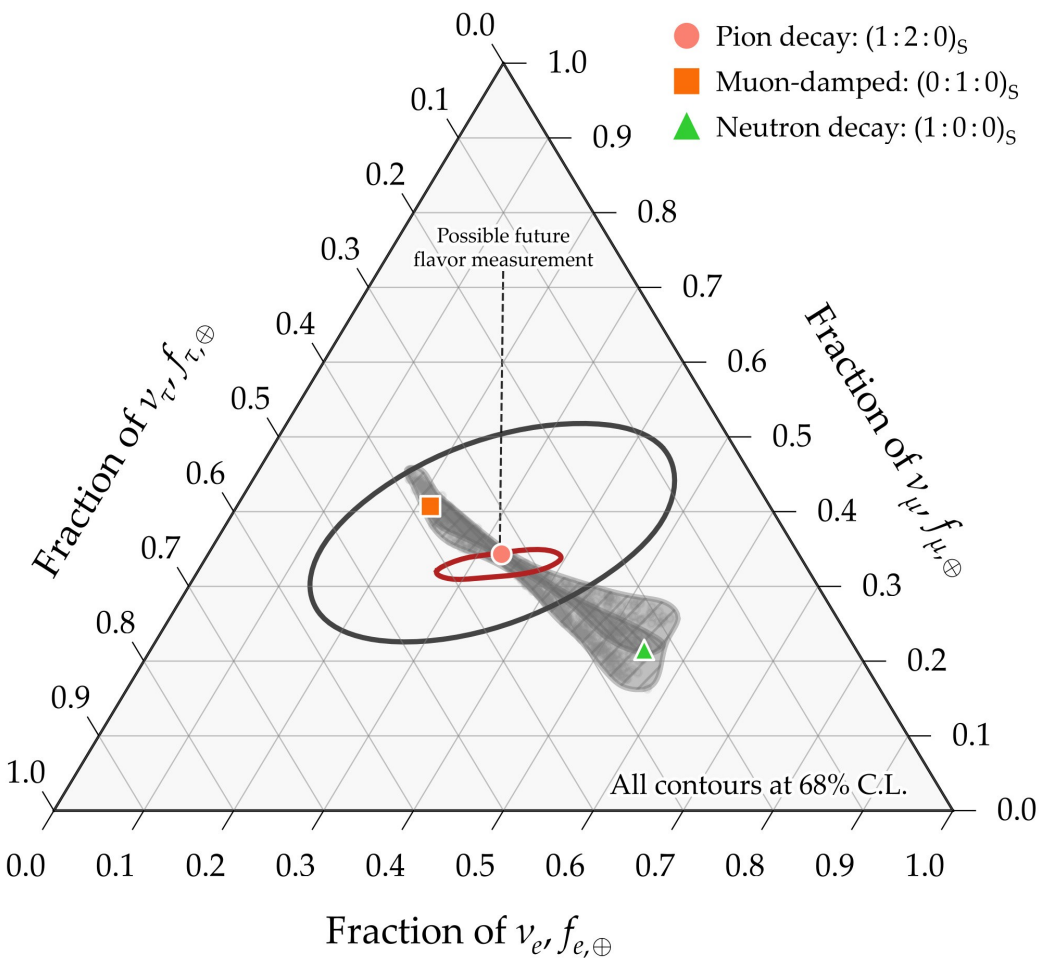
Measurement power *in the future* —

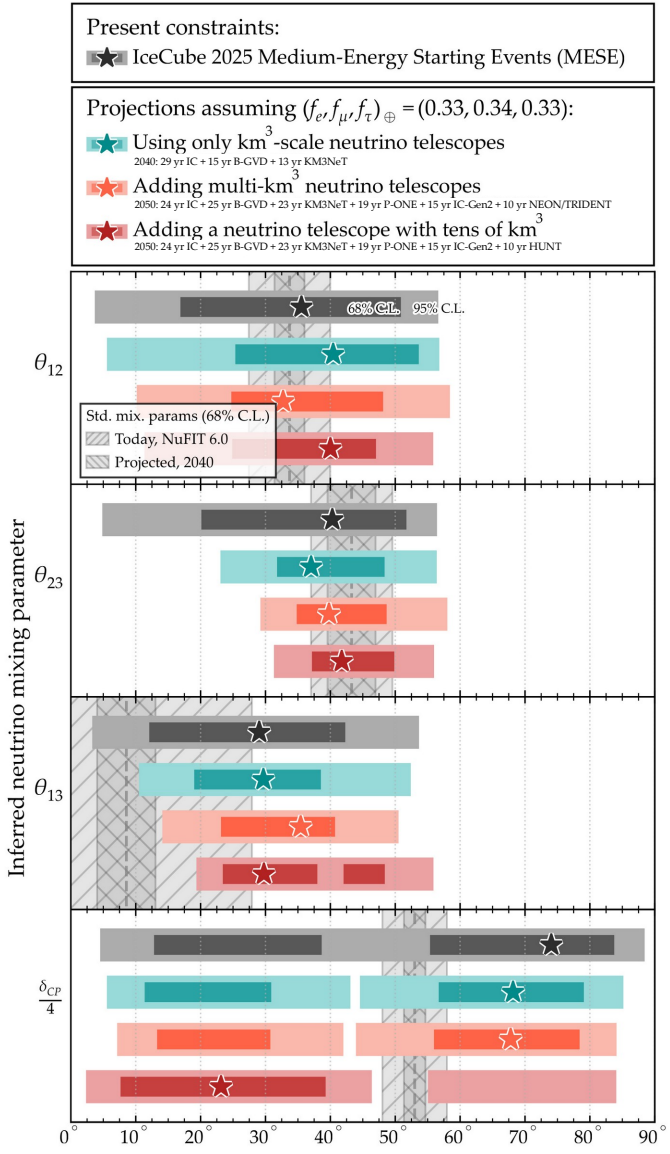




Telalovic, Liu, Barenboim, **MB**, *In prep.*

Measurement power *in the future* —





Telalovic, Liu, Barenboim, **MB**, *In prep.*

What can we expect from unitarity

Standard oscillations — driven by neutrino masses:

$$H_{\rm std} = \frac{1}{2E} U^{\dagger}_{\rm PMNS} {\rm diag}(0, \Delta m^2_{21}, \Delta m^2_{31}) U_{\rm PMNS}$$

Remember: $U_{\rm PMNS}$ is unitary

Average flavor-transition probability:

$$P_{\alpha\beta} = \sum_{i=1}^{3} |(U_{\rm PMNS})_{\alpha i}|^2 |(U_{\rm PMNS})_{\beta i}|^2 = \begin{pmatrix} P_{ee} & P_{e\mu} & P_{e\tau} \\ P_{\mu e} & P_{\mu\mu} & P_{\mu\tau} \\ P_{\tau e} & P_{\tau\mu} & P_{\tau\tau} \end{pmatrix}$$

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9 independent entries

↓

6 independent entries

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9 independent entries

6 independent entries

3 independent entries

Each column & row must sum to 1

Let's add a new interaction that conserves the number of ν:

$$H_{\rm new} = \left(\frac{E}{\Lambda}\right)^n U^\dagger_{\rm new} {\rm diag}(\mathcal{O}_1, \mathcal{O}_2, \mathcal{O}_3) U_{\rm new}$$

$U_{\rm new}$ is unitary
It rotates from the eigenbasis of $H_{\rm new}$ to the flavor basis

The total Hamiltonian,

$$H_{\rm tot} = H_{\rm std} + H_{\rm new} \ ,$$

is diagonalized by a new unitary rotation matrix $U_{\rm tot}$, that is a function of all the standard and new parameters (and the energy).

Since $U_{\rm tot}$ is unitary, the probability matrix has the same shape as before:

$$P_{\alpha\beta} = \sum_{i=1}^{3} |(U_{\rm tot})_{\alpha i}|^2 |(U_{\rm tot})_{\beta i}|^2 = \begin{pmatrix} P_{ee} & P_{e\mu} & P_{e\tau} \\ P_{\mu e} & P_{\mu\mu} & P_{\mu\tau} \\ P_{\tau e} & P_{\tau\mu} & P_{\tau\tau} \end{pmatrix}$$

The unitarity of $U_{\rm tot}$ bounds the space of linear combinations

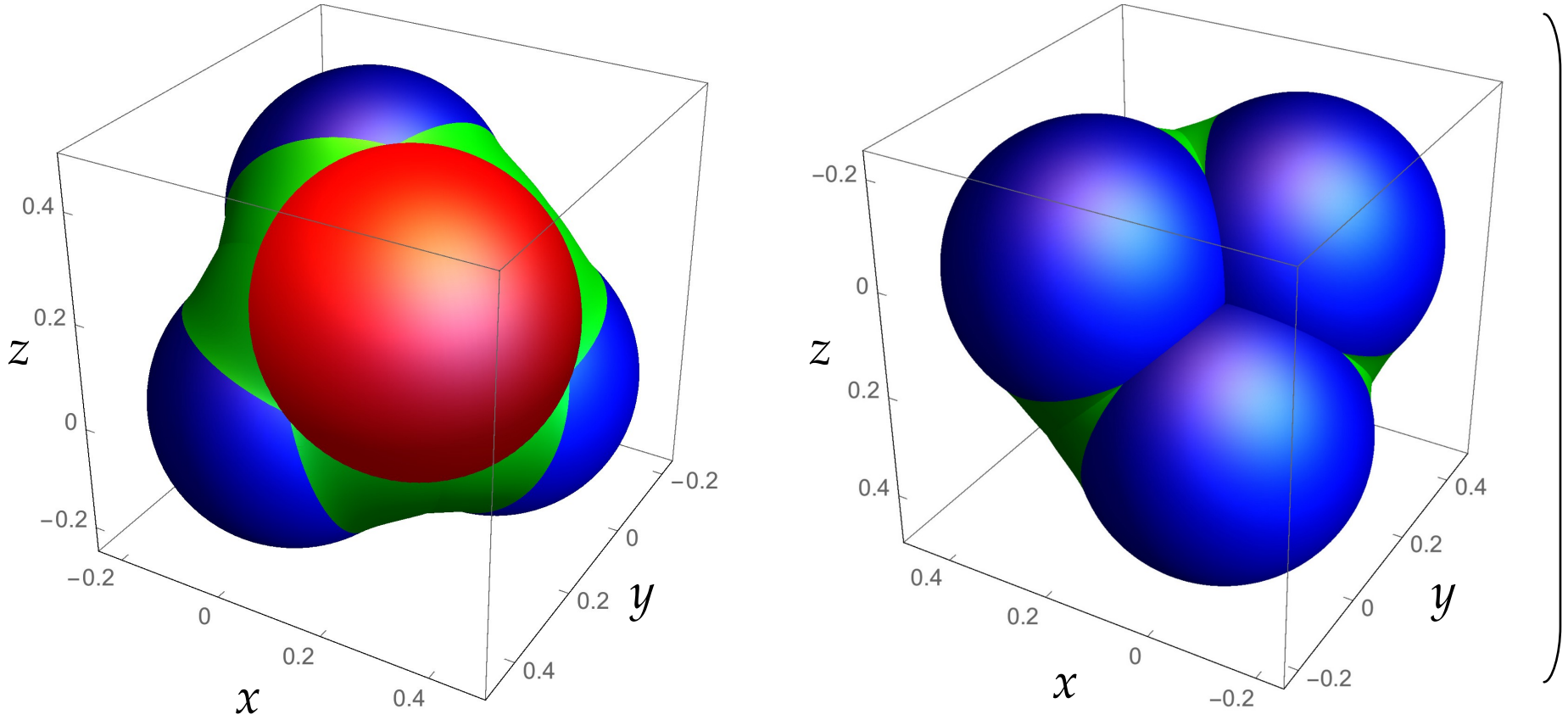
$$xP_{\mu\tau} + yP_{e\tau} + zP_{e\mu} \leq B(x, y, z)$$

Arbitrary coefficients

Complex function that traces over all possible values of the components of $U_{\rm tot}$

Ahlers, **MB**, Mu, *PRD* 2018
See also Xu, He, Rodejohann, *JCAP* 2014

(If you were curious, this is how the boundary function B looks:



Ahlers, **MB**, Mu, *PRD* 2018

Flavor composition at the Earth:

$$\begin{pmatrix} f_{e,\oplus} \\ f_{\mu,\oplus} \\ f_{\tau,\oplus} \end{pmatrix} = \underbrace{\begin{pmatrix} P_{ee} & P_{e\mu} & P_{e\tau} \\ P_{e\mu} & P_{\mu\mu} & P_{\mu\tau} \\ P_{e\tau} & P_{\mu\tau} & P_{\tau\tau} \end{pmatrix}} \begin{pmatrix} f_{e,\mathrm{S}} \\ 1 - f_{e,\mathrm{S}} \\ 0 \end{pmatrix}$$

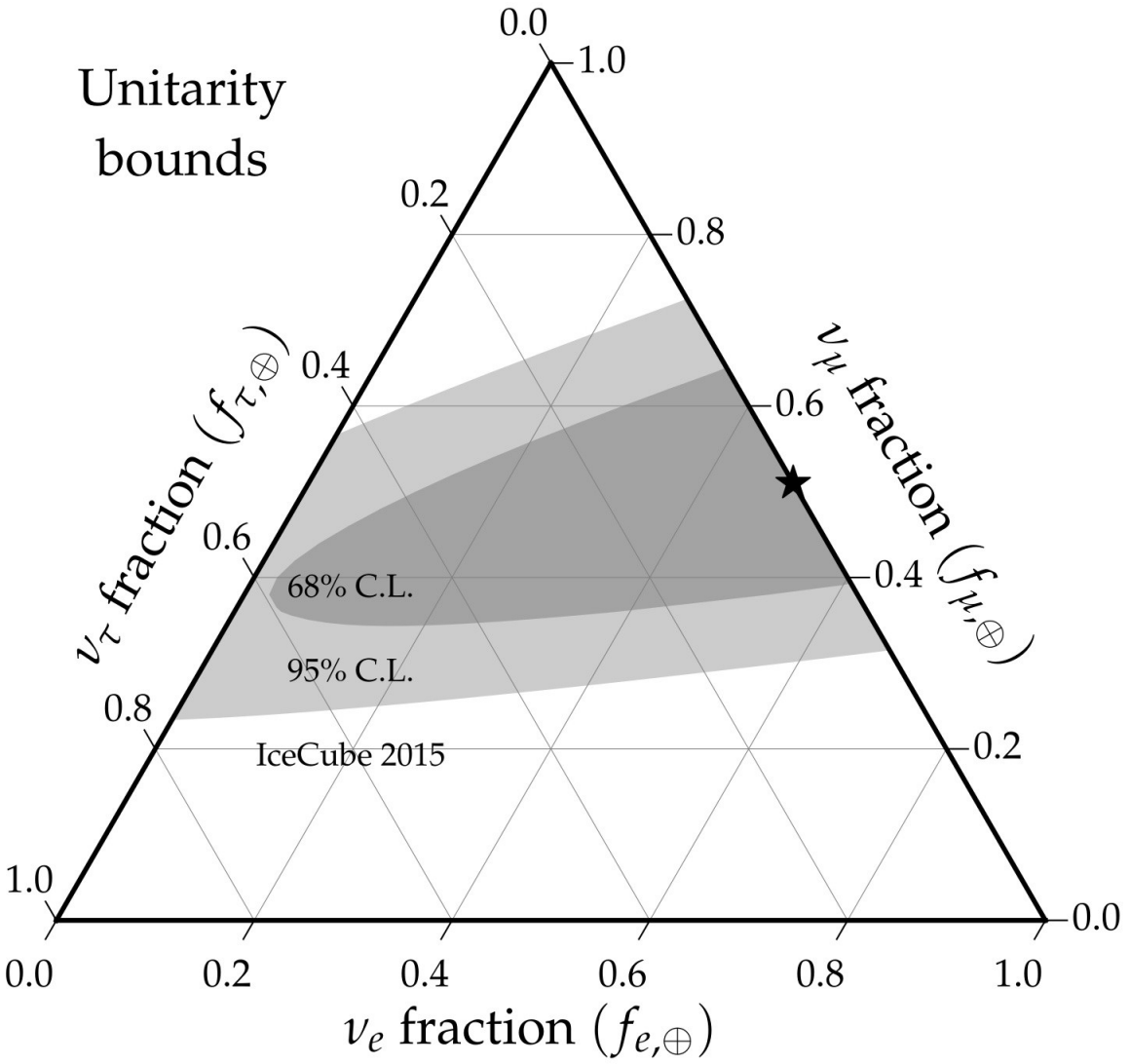
Because the probabilities are bound by unitarity…

Ahlers, **MB**, Mu, *PRD* 2018
See also Xu, He, Rodejohann, *JCAP* 2014

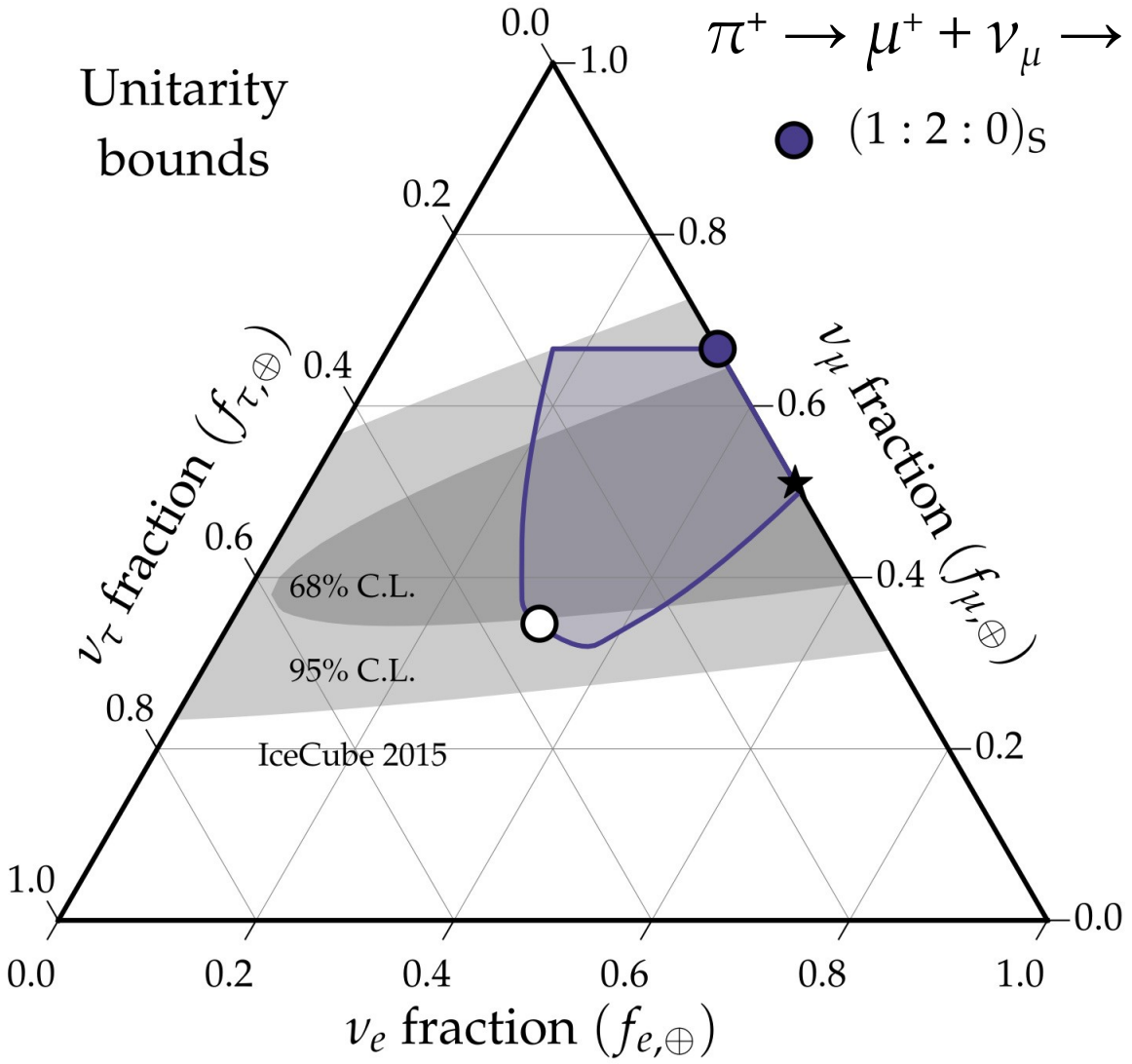
Flavor composition at the Earth:

$$\underbrace{\begin{pmatrix} f_{e,\oplus} \\ f_{\mu,\oplus} \\ f_{\tau,\oplus} \end{pmatrix}}_{\text{… so is the predicted flavor composition at the Earth}} = \underbrace{\begin{pmatrix} P_{ee} & P_{e\mu} & P_{e\tau} \\ P_{e\mu} & P_{\mu\mu} & P_{\mu\tau} \\ P_{e\tau} & P_{\mu\tau} & P_{\tau\tau} \end{pmatrix}}_{\text{Because the probabilities are bound by unitarity…}} \begin{pmatrix} f_{e,\mathrm{S}} \\ 1 - f_{e,\mathrm{S}} \\ 0 \end{pmatrix}$$

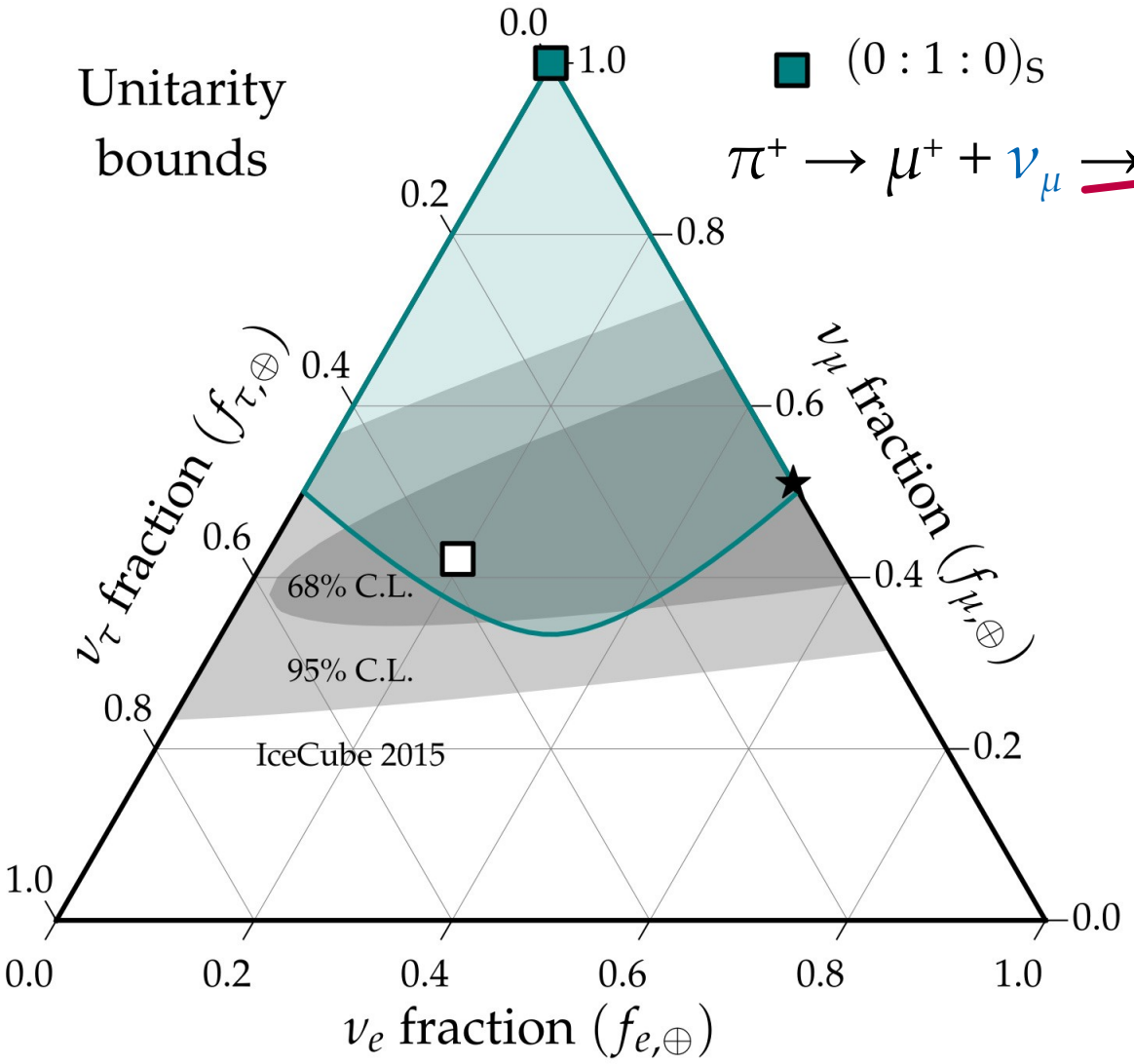
Ahlers, **MB**, Mu, *PRD* 2018
See also Xu, He, Rodejohann, *JCAP* 2014



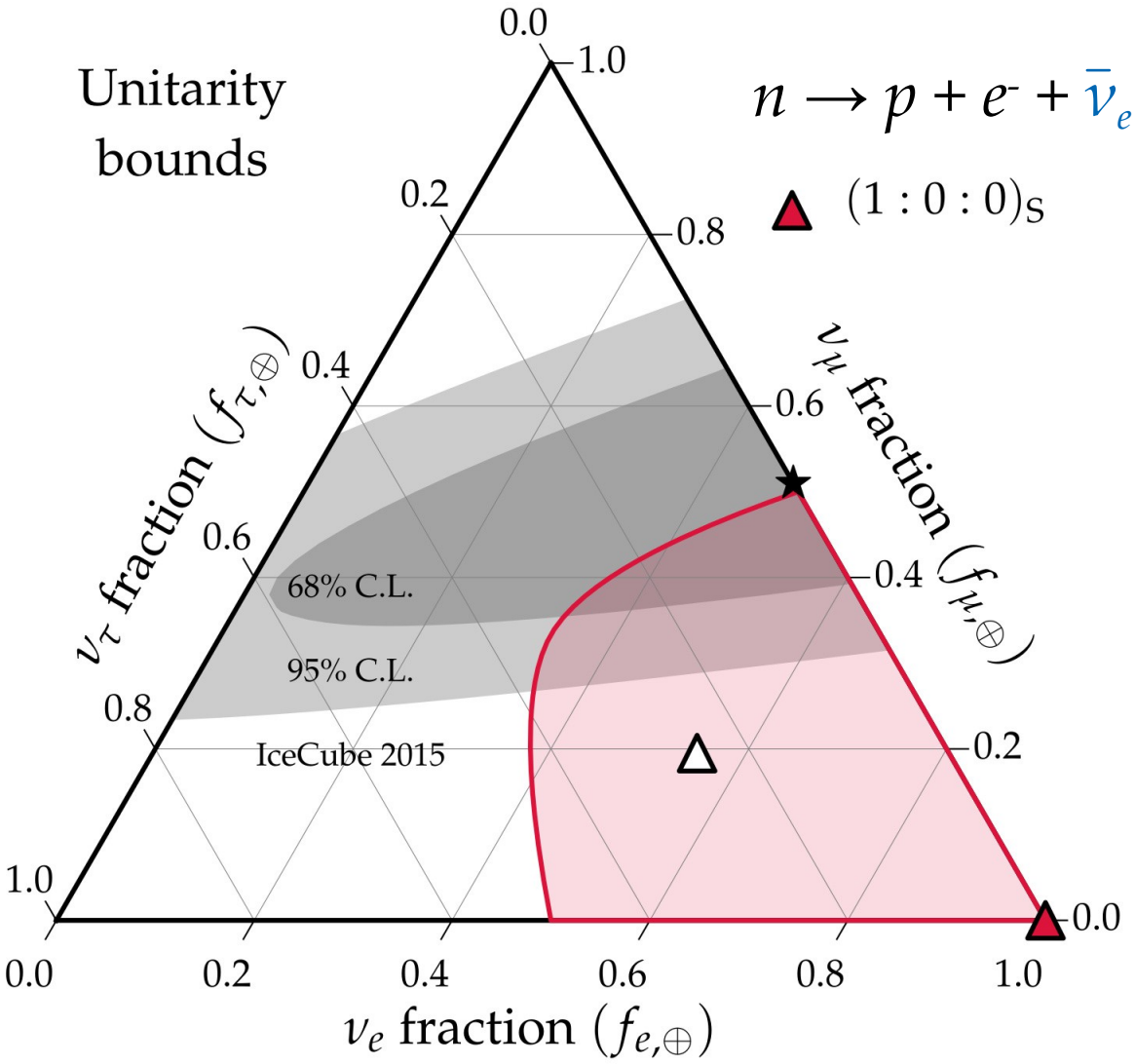
Ahlers, **MB**, Mu, *PRD* 2018



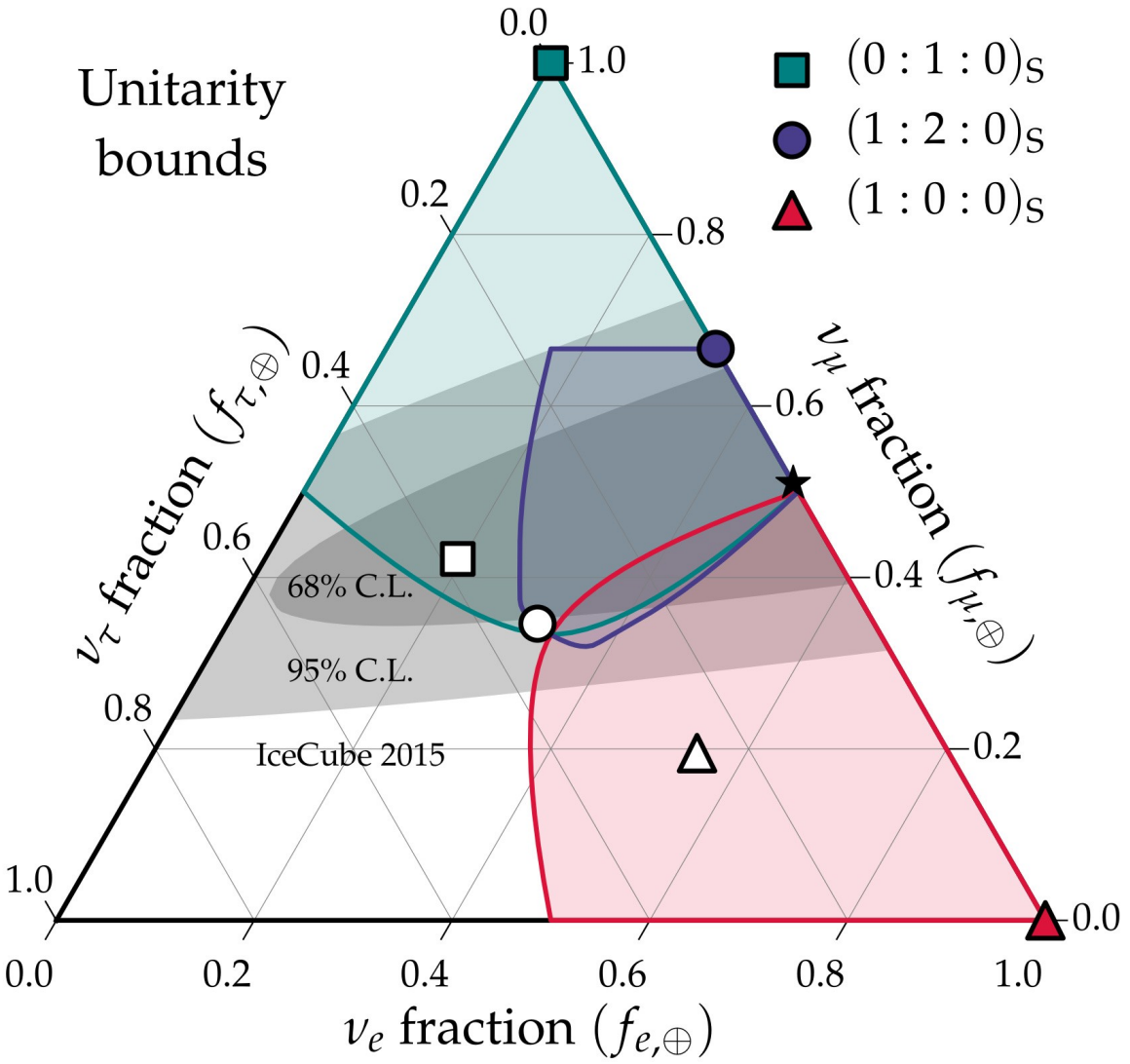
Ahlers, **MB**, Mu, *PRD* 2018



Ahlers, **MB**, Mu, *PRD* 2018

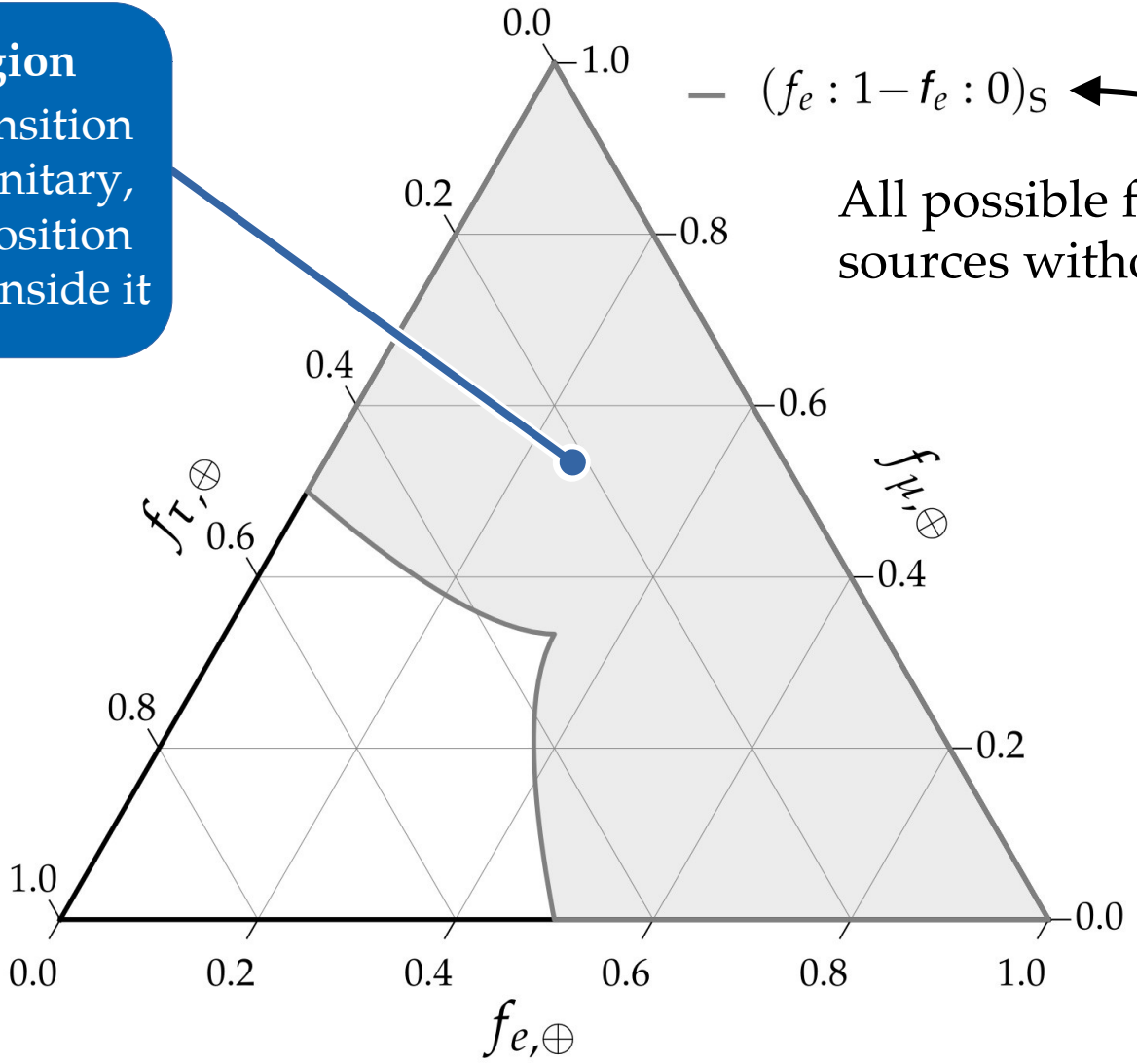


Ahlers, **MB**, Mu, *PRD* 2018

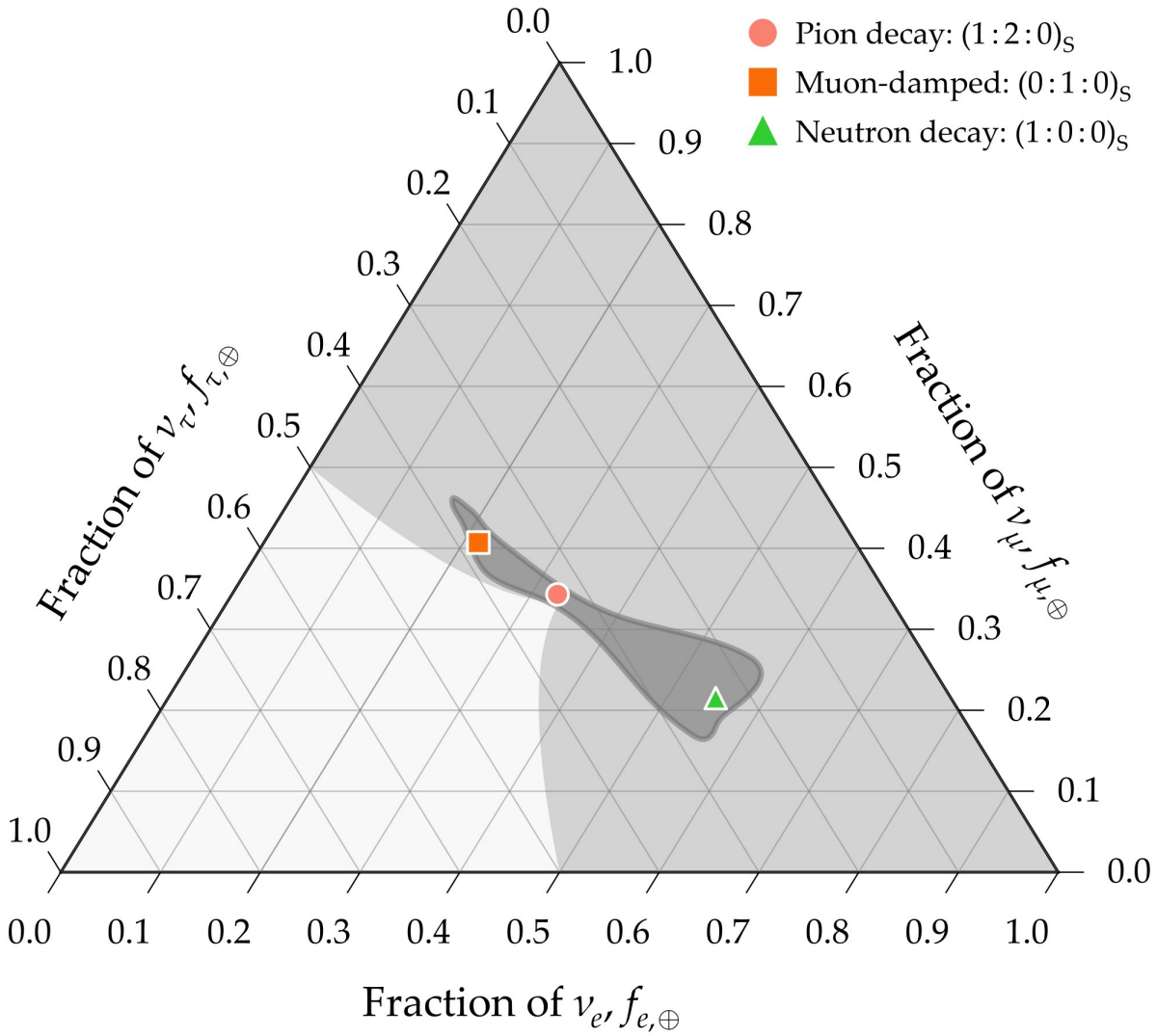


Ahlers, **MB**, Mu, *PRD* 2018

Unitarity region
If the flavor-transition mechanism is unitary, the flavor composition at Earth will be inside it

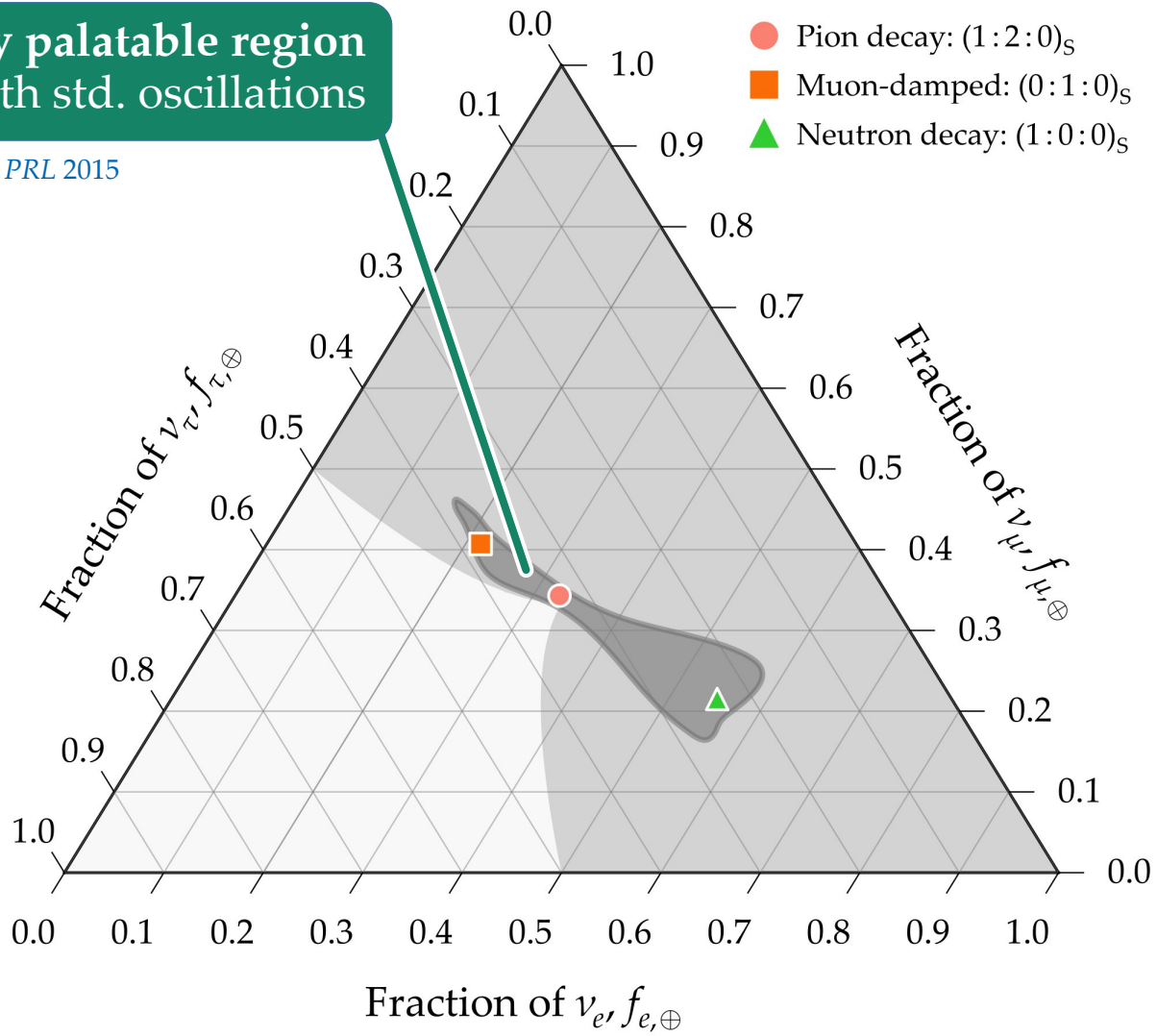


Ahlers, **MB**, Mu, *PRD* 2018


Pion decay: $(1:2:0)_S$
Muon-damped: $(0:1:0)_S$
Neutron decay: $(1:0:0)_S$
Fraction of ν_e, $f_{e,\oplus}$
Fraction of ν_μ, $f_{\mu,\oplus}$
Fraction of ν_τ, $f_{\tau,\oplus}$
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

Theoretically palatable region
Accessible with std. oscillations

MB, Beacom, Winter, *PRL* 2015



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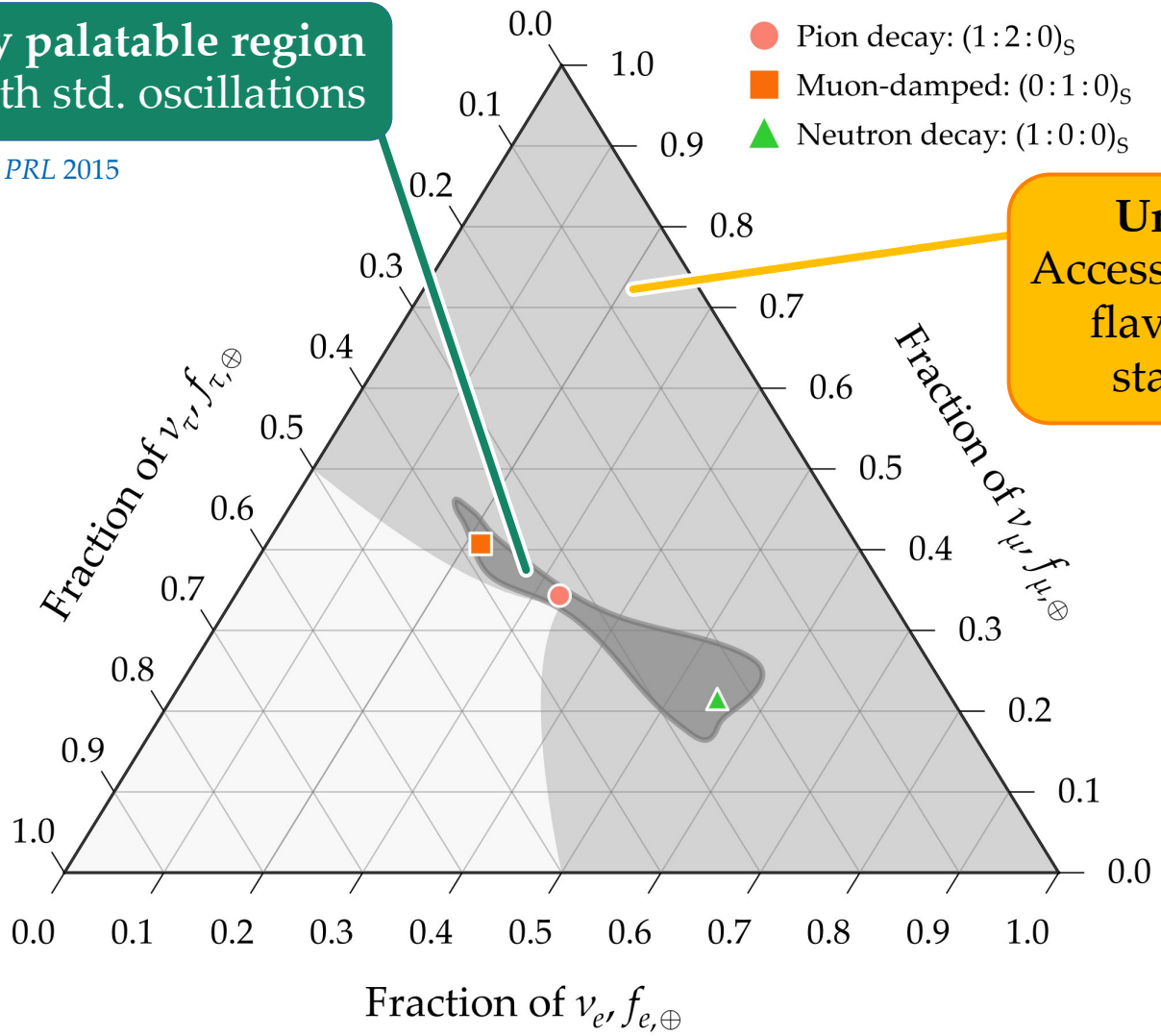


Unitary region
Accessible with unitary flavor transitions, standard or not

Ahlers, **MB**, Mu, *PRD* 2018

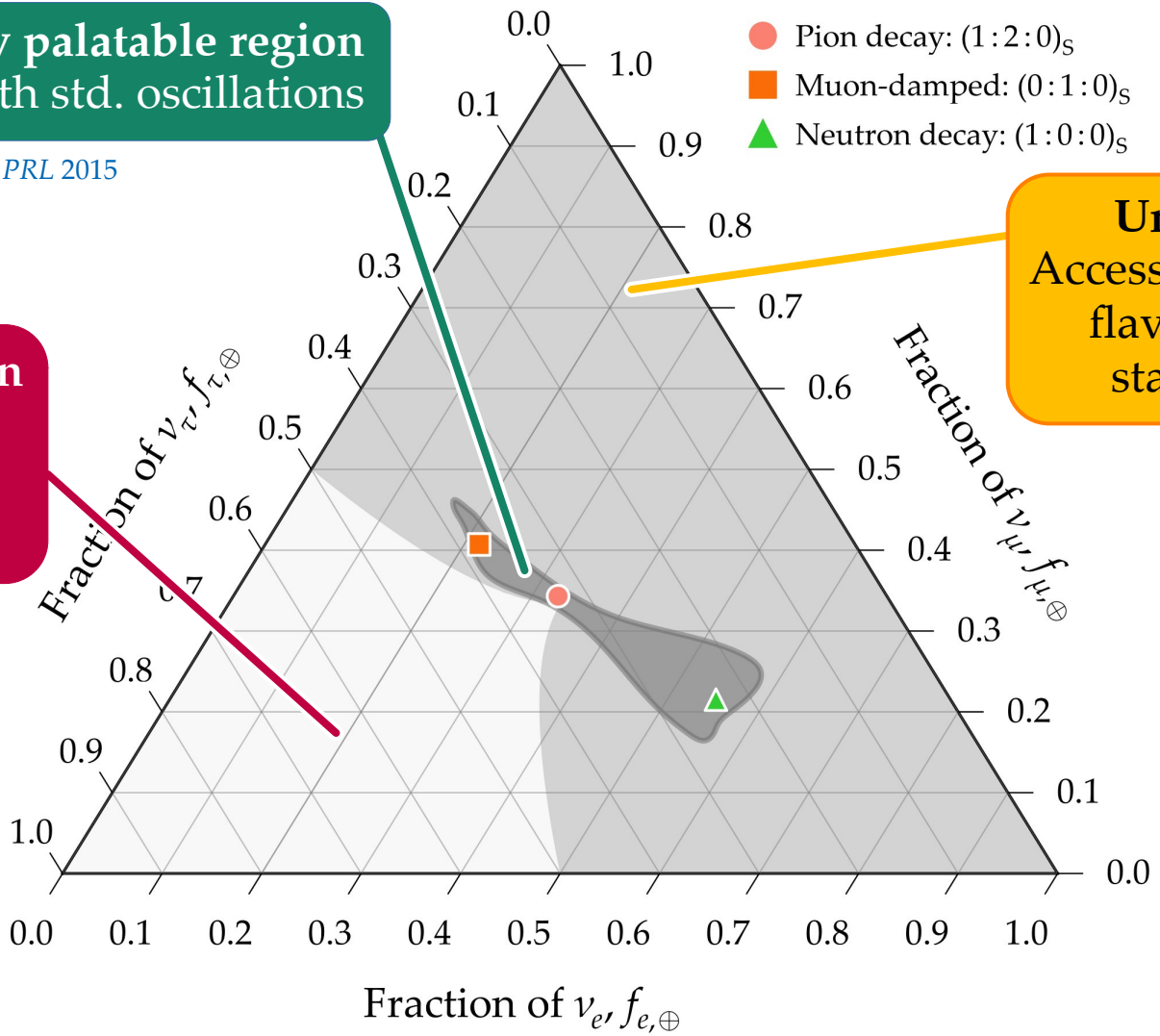
Theoretically palatable region
Accessible with std. oscillations

MB, Beacom, Winter, *PRL* 2015

Non-unitary region
Accessible only with non-unitary flavor transitions

Unitary region
Accessible with unitary flavor transitions, standard or not

Ahlers, **MB**, Mu, *PRD* 2018



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MB, Beacom, Winter, *PRL* 2015

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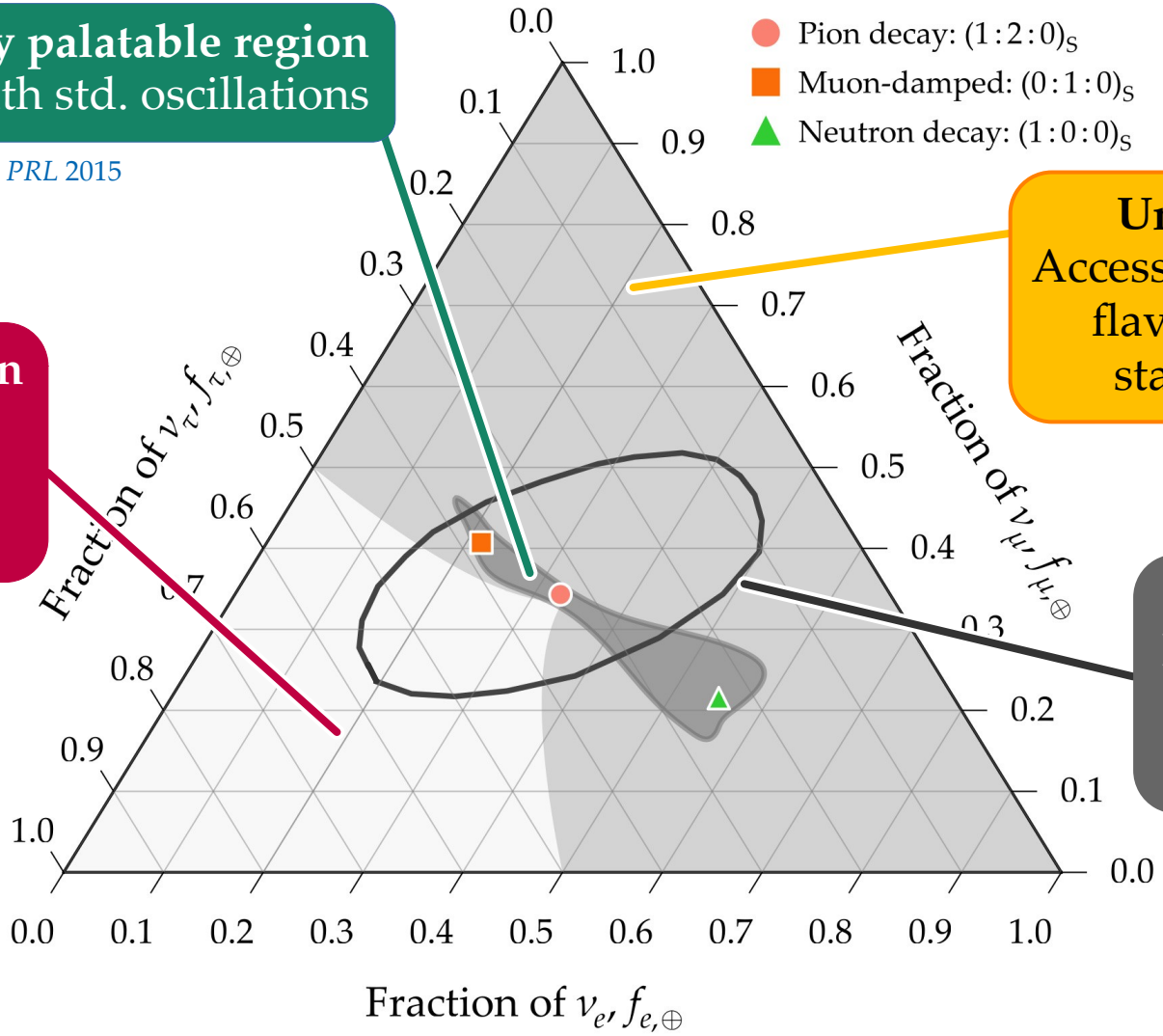
Unitary region
Accessible with unitary flavor transitions, standard or not

Ahlers, **MB**, Mu, *PRD* 2018

IceCube 2025 Medium-Energy Starting Events (MESE) ICRC 2025



Theoretically palatable region
Accessible with std. oscillations

MB, Beacom, Winter, *PRL* 2015

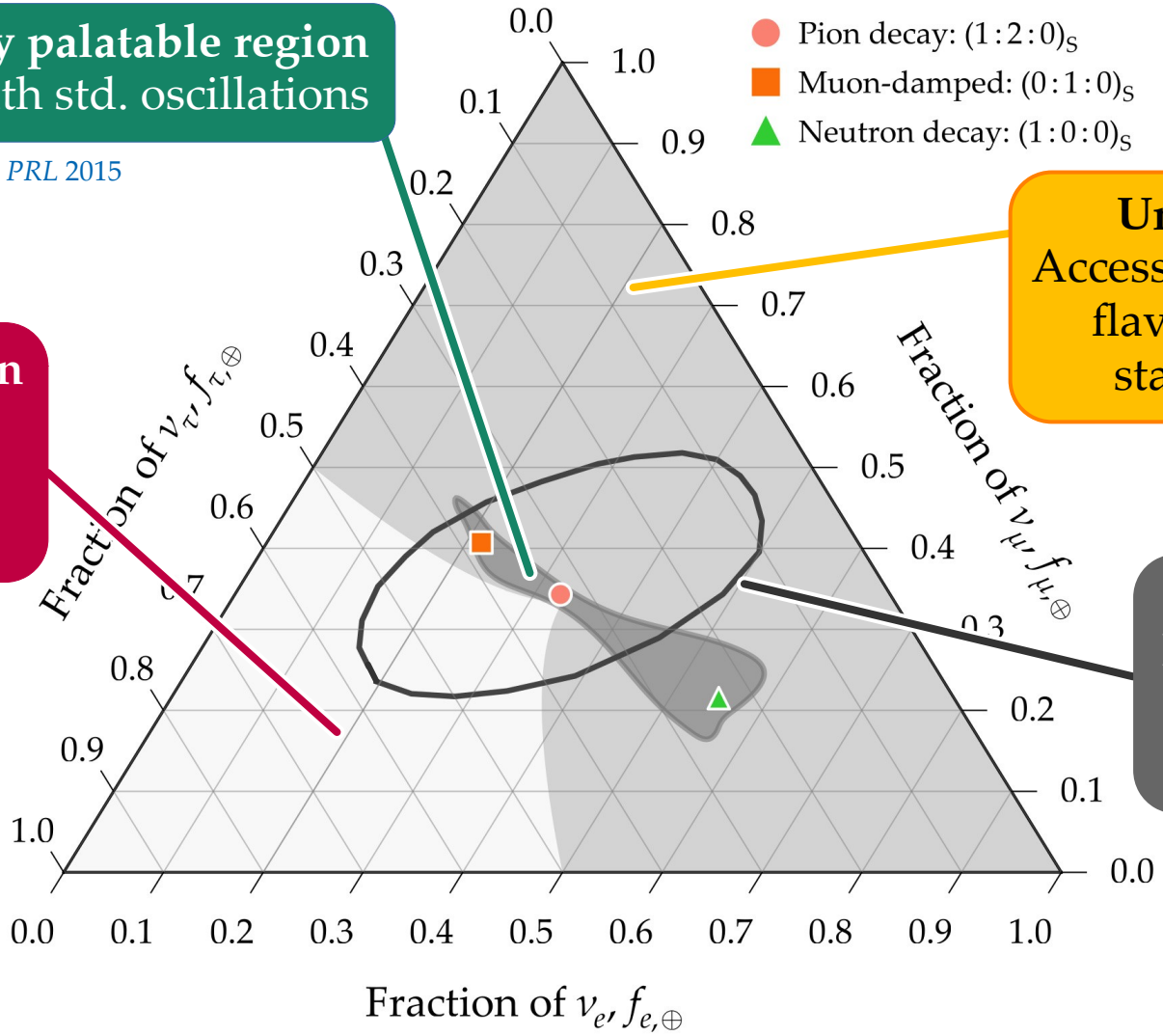
Non-unitary region
Accessible only with non-unitary flavor transitions

What lives here?
Let's see...

Unitary region
Accessible with unitary flavor transitions, standard or not

Ahlers, **MB**, Mu, *PRD* 2018

IceCube 2025 Medium-Energy Starting Events (MESE) ICRC 2025



Beyond 3×3 unitarity

Consider 3+1 neutrino flavors (s: sterile neutrino)

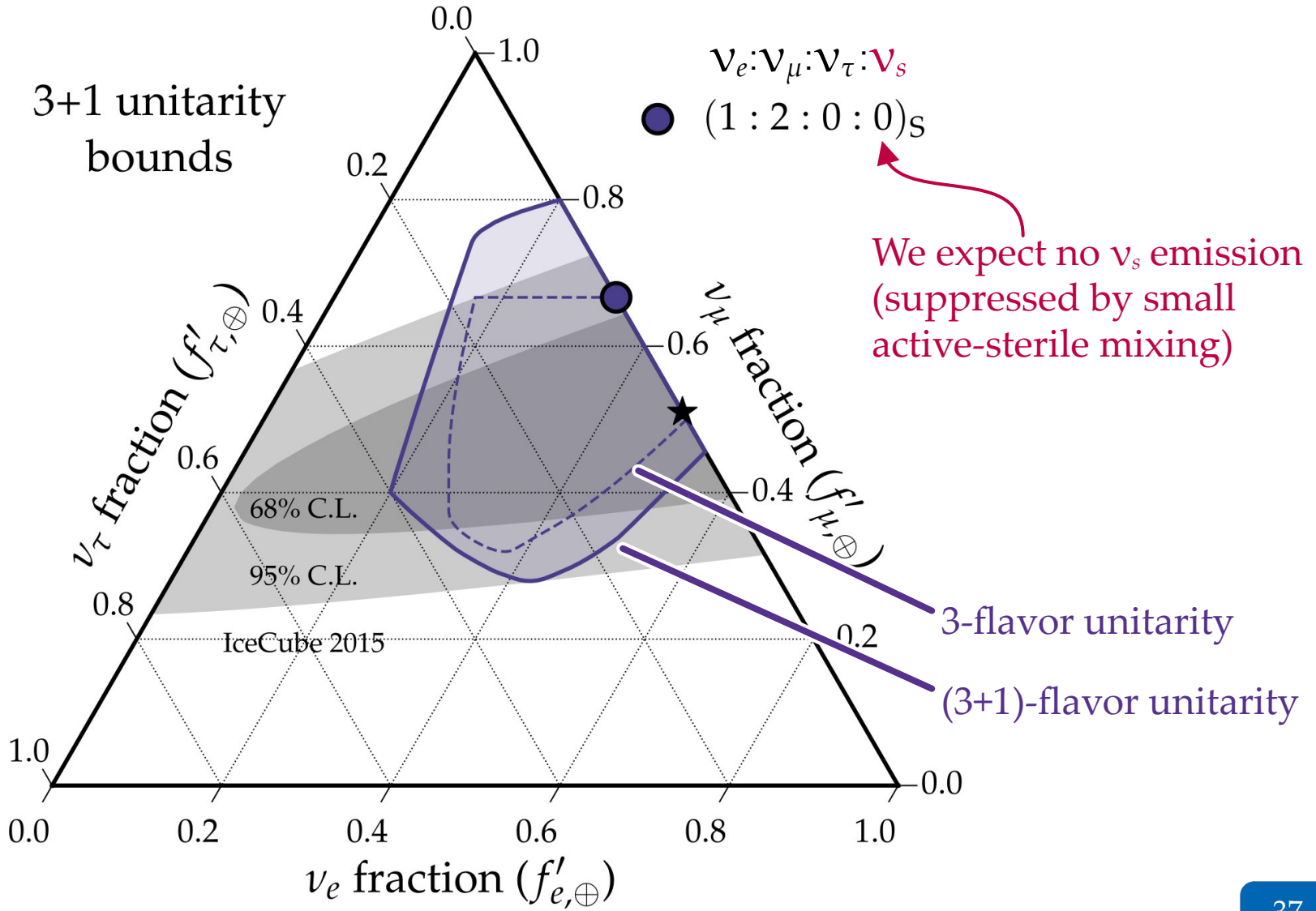
Probabilities for *any kind* of unitary flavor transitions among them:

$$P_{\alpha\beta} = \sum_{i=1}^{4} |(U_{\rm tot})_{\alpha i}|^2 |(U_{\rm tot})_{\beta i}|^2 = \begin{pmatrix} P_{ee} & P_{e\mu} & P_{e\tau} & P_{es} \\ P_{e\mu} & P_{\mu\mu} & P_{\mu\tau} & P_{\mu s} \\ P_{e\tau} & P_{\mu\tau} & P_{\tau\tau} & P_{\tau s} \\ P_{es} & P_{\mu s} & P_{\tau s} & P_{ss} \end{pmatrix}$$

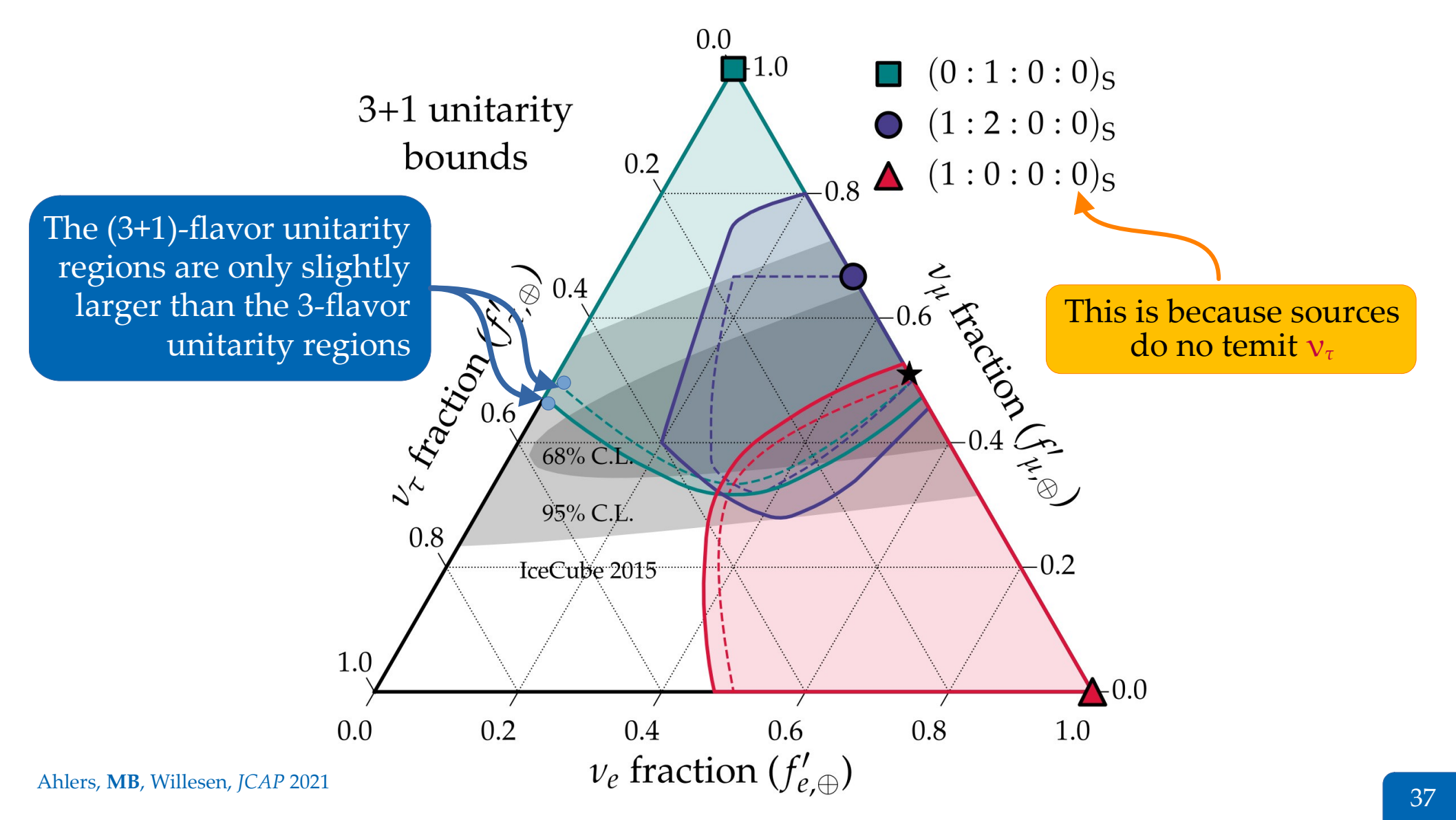
6 independent entries

Like before, we find the boundary of the independent entries for any possible value of the components of $U_{\rm tot}$

Ahlers, **MB**, Willesen, *JCAP* 2021



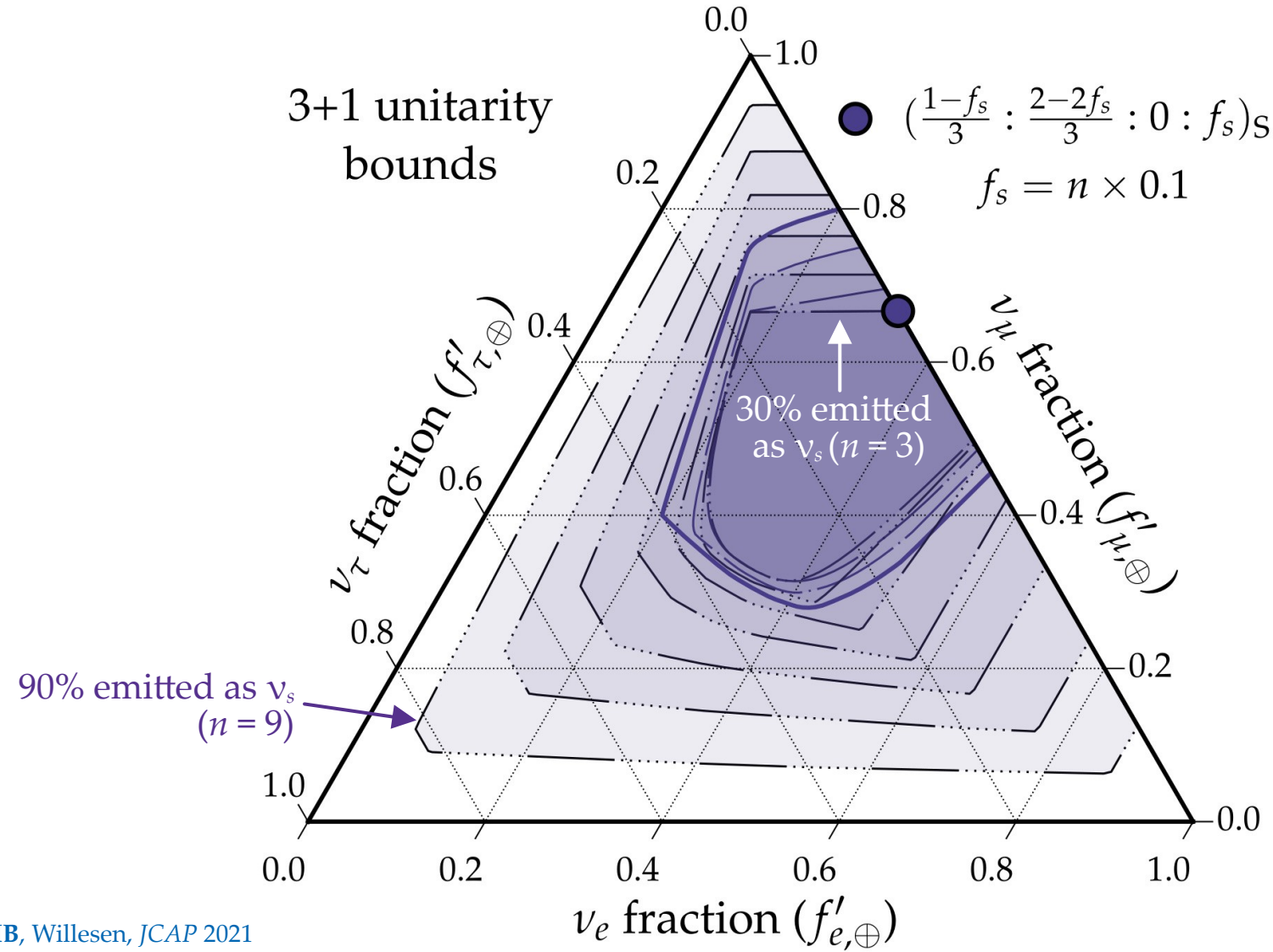
Ahlers, **MB**, Willesen, *JCAP* 2021



The (3+1)-flavor unitarity regions are only slightly larger than the 3-flavor unitarity regions

This is because sources do no temit ν_τ

Ahlers, **MB**, Willesen, *JCAP* 2021



Ahlers, **MB**, Willesen, *JCAP* 2021

Measuring high-energy non-unitarity

Generic parametrization of a non-unitary 3×3 leptonic mixing matrix:

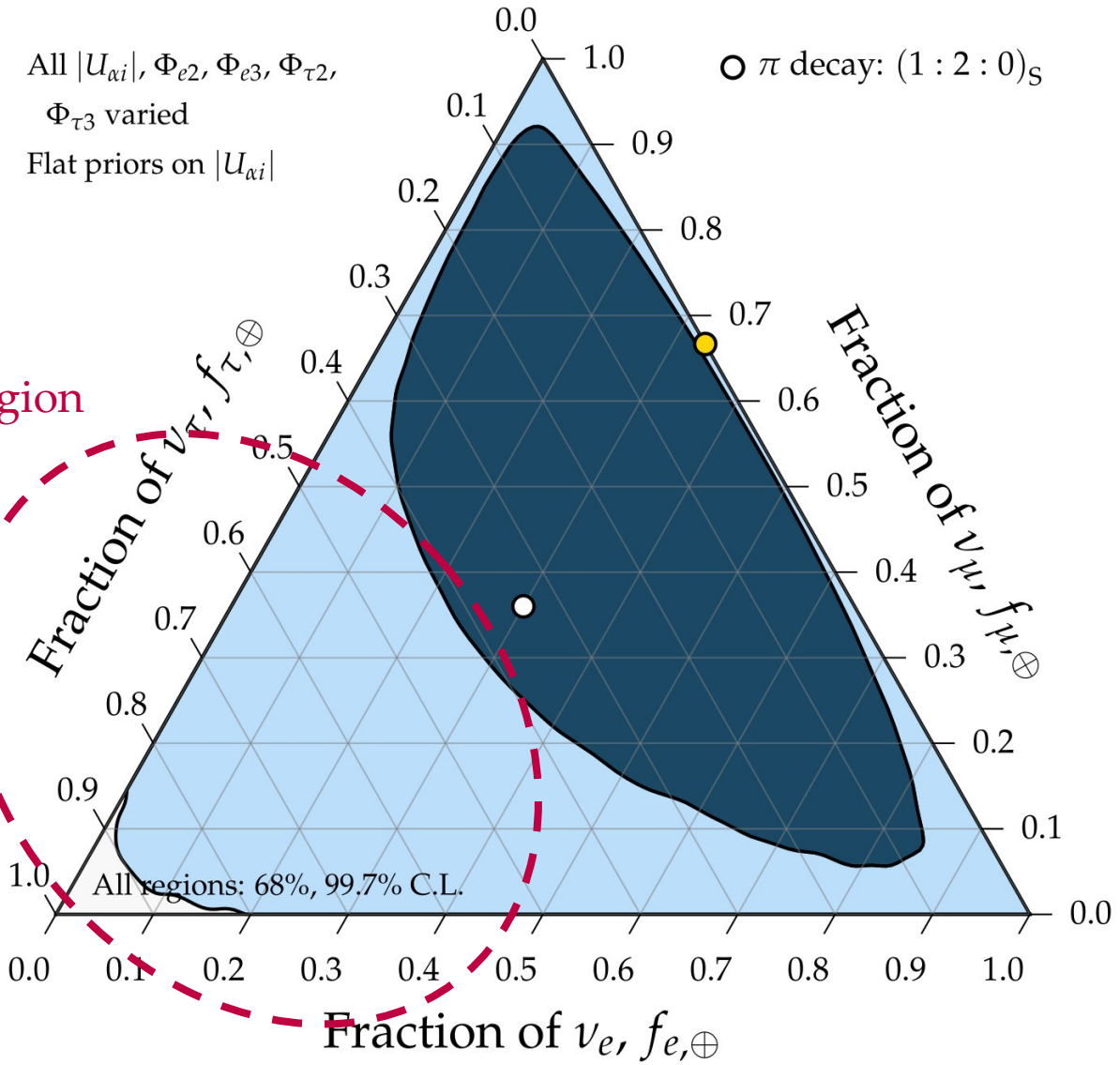
$$U = \begin{pmatrix} |U_{e1}| & |U_{e2}|e^{i\phi_{e2}} & |U_{e3}|e^{i\phi_{e3}} \\ |U_{\mu 1}| & |U_{\mu 2}| & |U_{\mu 3}| \\ |U_{\tau 1}| & |U_{\tau 2}|e^{i\phi_{\tau 2}} & |U_{\tau 3}|e^{i\phi_{\tau 3}} \end{pmatrix}$$

13 parameters = 9 magnitudes + 4 CP-violating phases

To predict the flavor composition at Earth, we also need $f_{e,S}$

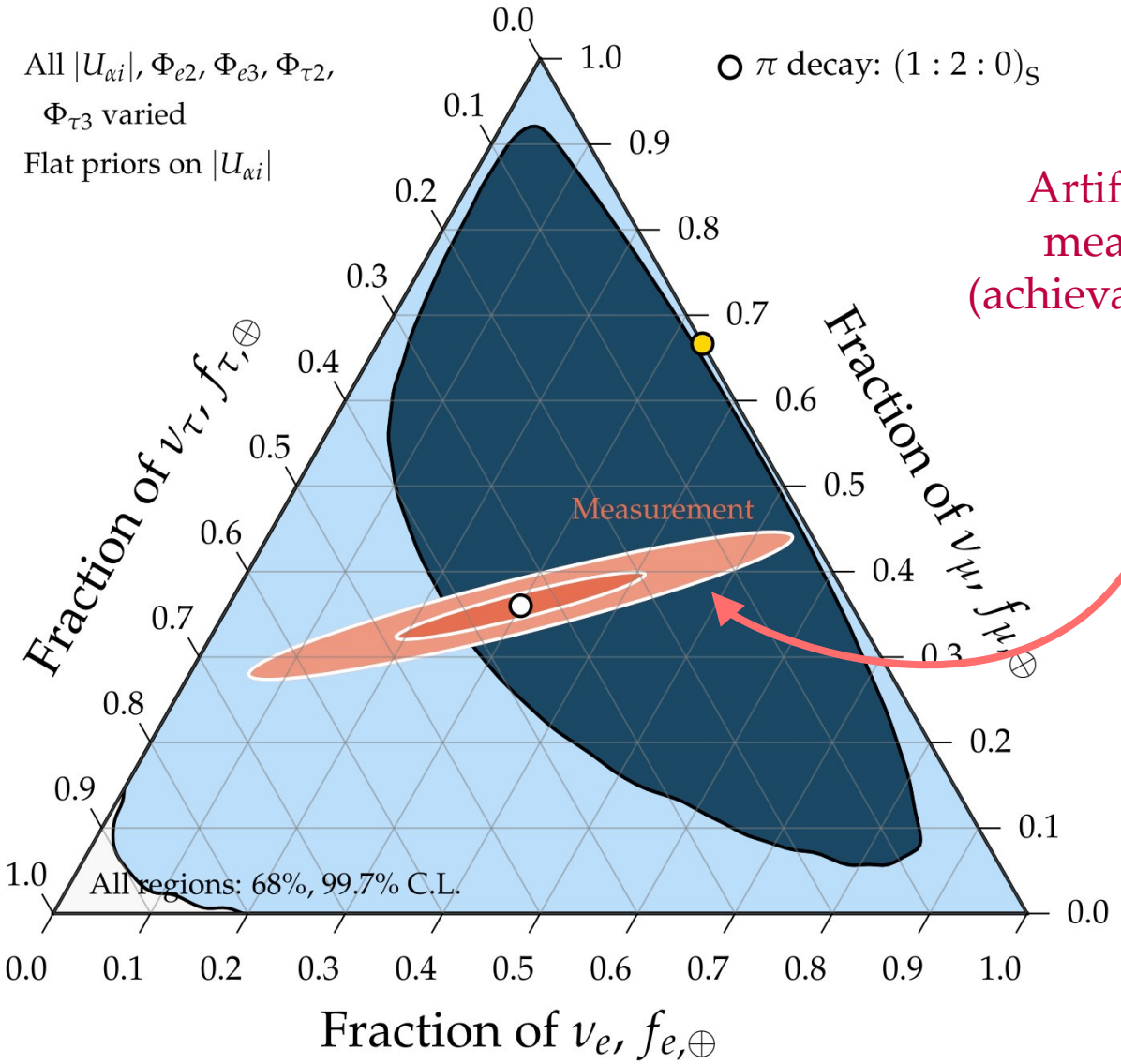
[Start by fixing it to 1/3 (from pion decay); later, we marginalize over it]

Ellis, Kelly, Li, *JCAP* 2020



Extends into the region accessible only with non-unitary mixing

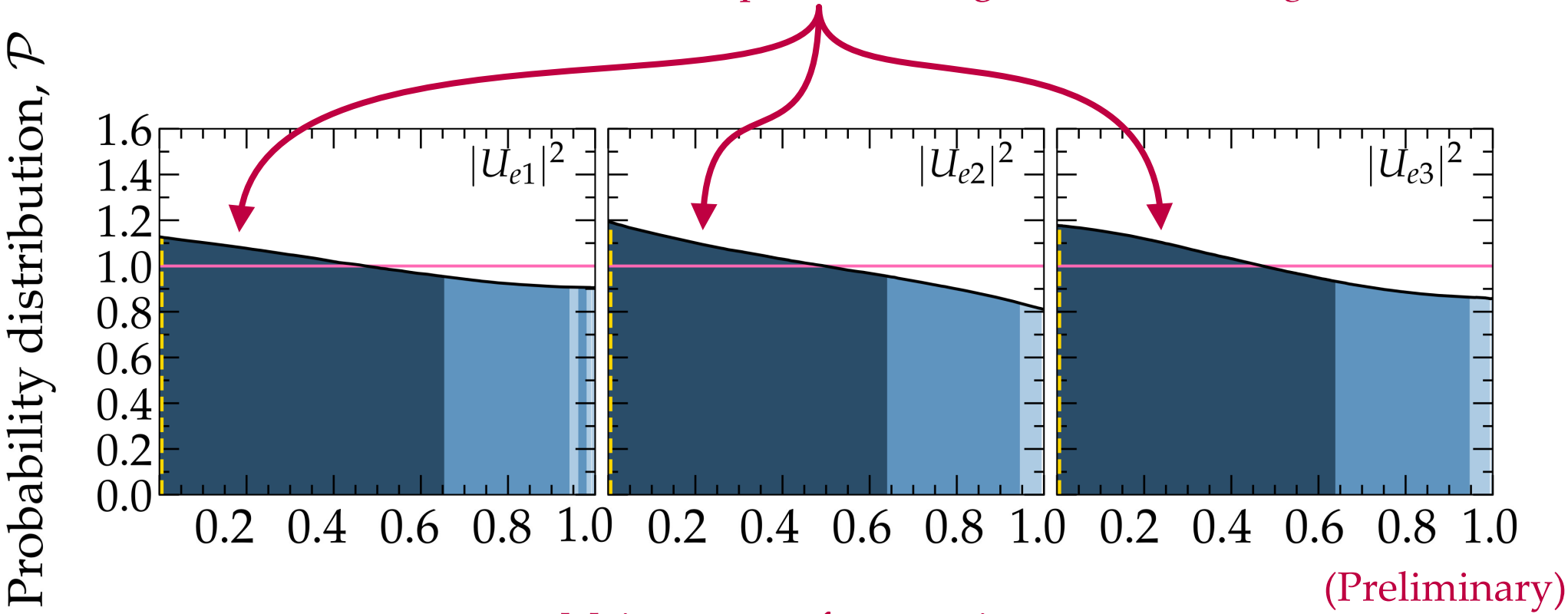
MB, *In prep.*



Artificial flavor measurement (achievable in ~10 yr)

MB, *In prep.*

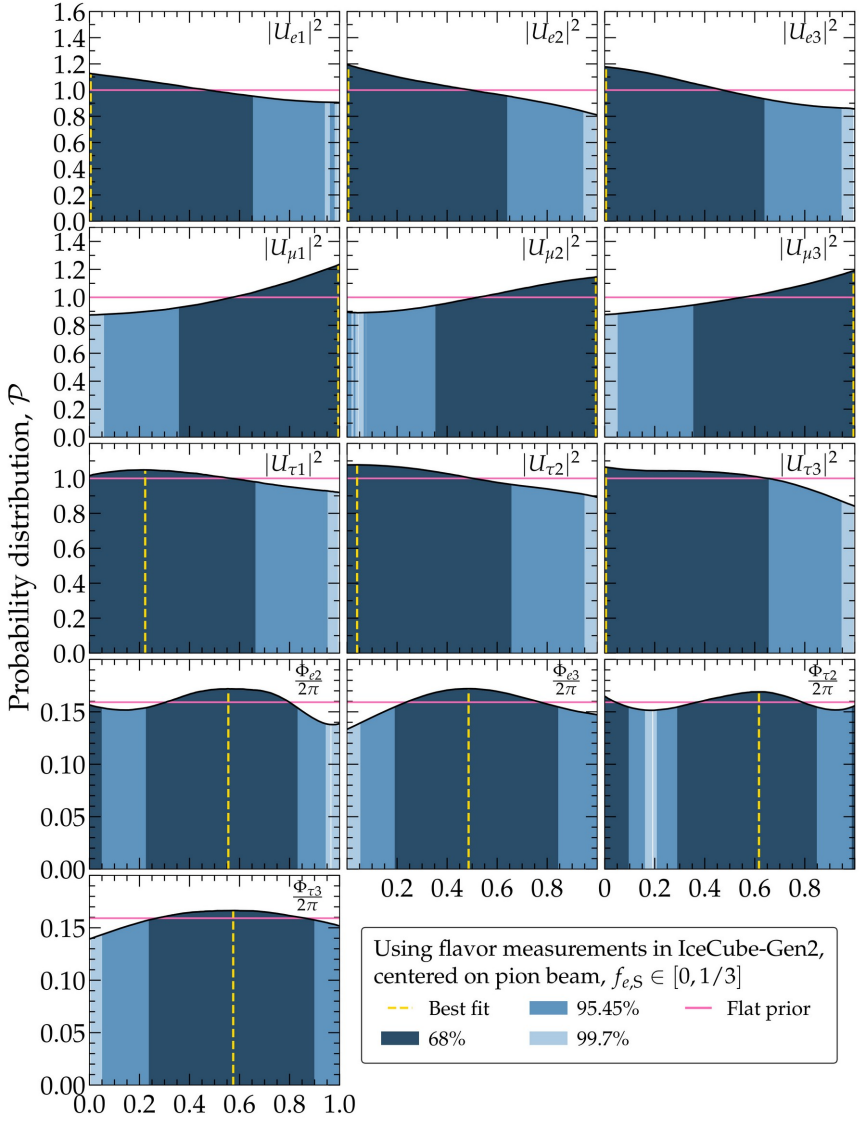
The 68% C.L. allowed parameter regions are wide, *e.g.*,



(Preliminary)

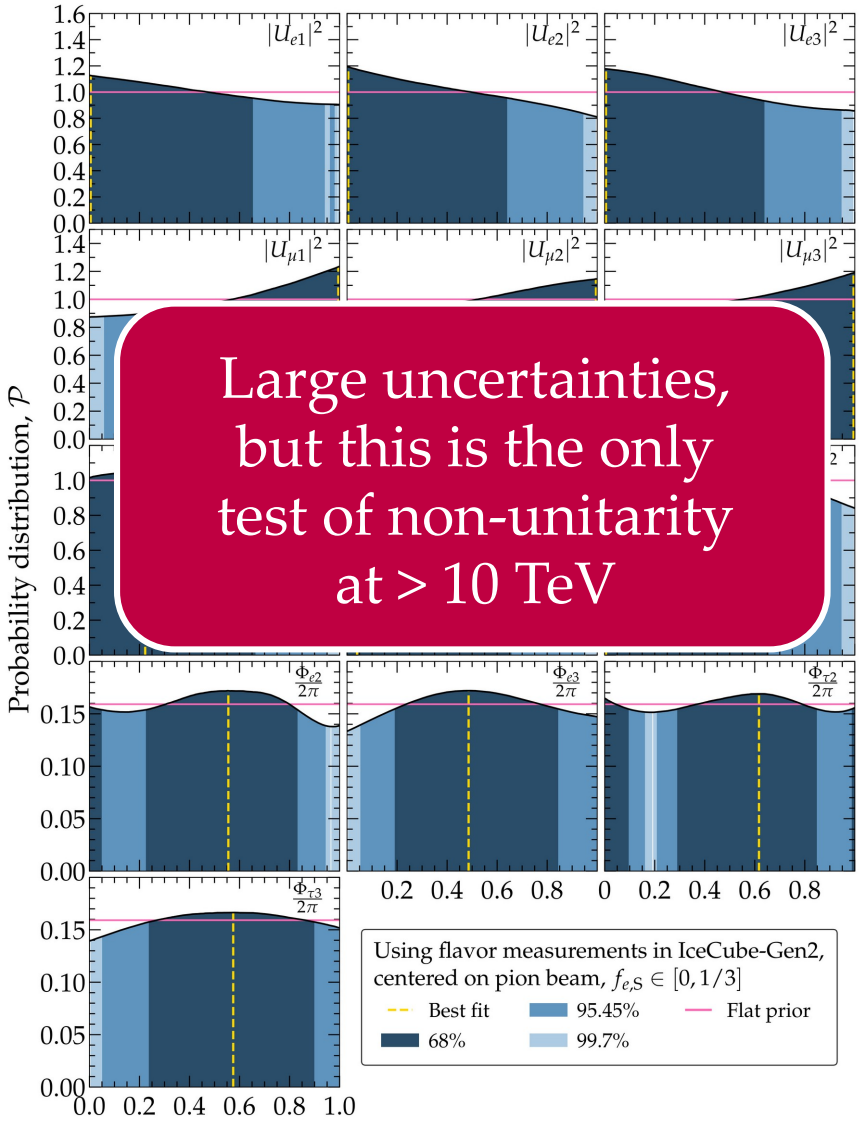
Main source of uncertainty:
ignorance of the flavor composition at the sources, $f_{e,S}$

MB, *In prep.*



(Preliminary)

MB, *In prep.*



(Preliminary)

MB, *In prep.*

Is ν mixing different at high energies?

Renormalization group running — the values of the neutrino masses and mixing parameters change with the energy scale, μ

E.g., for the masses, the renormalization-group-running equation (RGE) is

$$16\pi^2 \frac{dm_i}{d\ln\mu} = \left[(\alpha_\kappa + 2\alpha_H) + 2C_\kappa \sum_{a=e,\mu,\tau} |U_{ai}|^2 {y_a}^2 \right] m_i$$

These depend on the effective field theory adopted (SM or beyond)

Yukawa coefficient of charged lepton of flavor α

Note: the running is negligible in the SM

Babu, Leung, Pantaleone, *PLB* 1993; Casas, Espinosa, Ibarra, Navarro, *Nucl. Phys. B* 2000; Antusch, Kersten, Lindner, Ratz, *Nucl. Phys. B* 2003

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and this determines the RGE running of the mixing angles, *i.e.*,

$$\frac{d\theta_{ij}}{d\ln\mu} = F(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\rm CP}, m_1, m_2, m_3)$$

Babu, Leung, Pantaleone, *PLB* 1993; Casas, Espinosa, Ibarra, Navarro, *Nucl. Phys. B* 2000; Antusch, Kersten, Lindner, Ratz, *Nucl. Phys. B* 2003

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$$\frac{d\theta_{ij}}{d\ln\mu} = F(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\rm CP}, m_1, m_2, m_3)$$

We set μ to the transferred momentum, $\mu = Q \equiv \sqrt{-q^2}$.

Babu, Leung, Pantaleone, *PLB* 1993; Casas, Espinosa, Ibarra, Navarro, *Nucl. Phys. B* 2000; Antusch, Kersten, Lindner, Ratz, *Nucl. Phys. B* 2003

Two energy scales:

Low-energy scale at neutrino production:
in astrophysical sources, ν are made in π decays

$Q = m_\pi \approx 140$ MeV

Mixing parameters have PMNS values

Two energy scales:

Low-energy scale at neutrino production:
in astrophysical sources, ν are made in π decays

$$Q = m_\pi \approx 140 \text{ MeV}$$

Mixing parameters have PMNS values

High-energy scale at neutrino detection:
at Earth, ν are detected in νN deep-inelastic scattering

$$Q = \sqrt{2 m_N E_\nu x y} \lesssim \sqrt{m_N E_\nu} \lesssim 10^3 \text{ GeV}$$

(x: Bjorken-x; y: inelasticity)

Mixing parameters have potentially non-PMNS values

Two energy scales:

Low-energy scale at neutrino production:
in astrophysical sources, ν are made in π decays

$$Q = m_\pi \approx 140 \text{ MeV}$$

Mixing parameters have PMNS values

RGE running

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(x: Bjorken-x, y: inelasticity)

Mixing parameters have potentially non-PMNS values

In lieu of explicit RGE running we use two lepton mixing matrices:

$U_{\rm PMNS}$

Low-energy scale at neutrino production:
in astrophysical sources, ν are made in π decays

$$Q = m_\pi \approx 140 \text{ MeV}$$

Mixing parameters have PMNS values

U'

High-energy scale at neutrino detection:
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(x: Bjorken-x; y: inelasticity)

Mixing parameters have potentially non-PMNS values

Average flavor-transition probability:

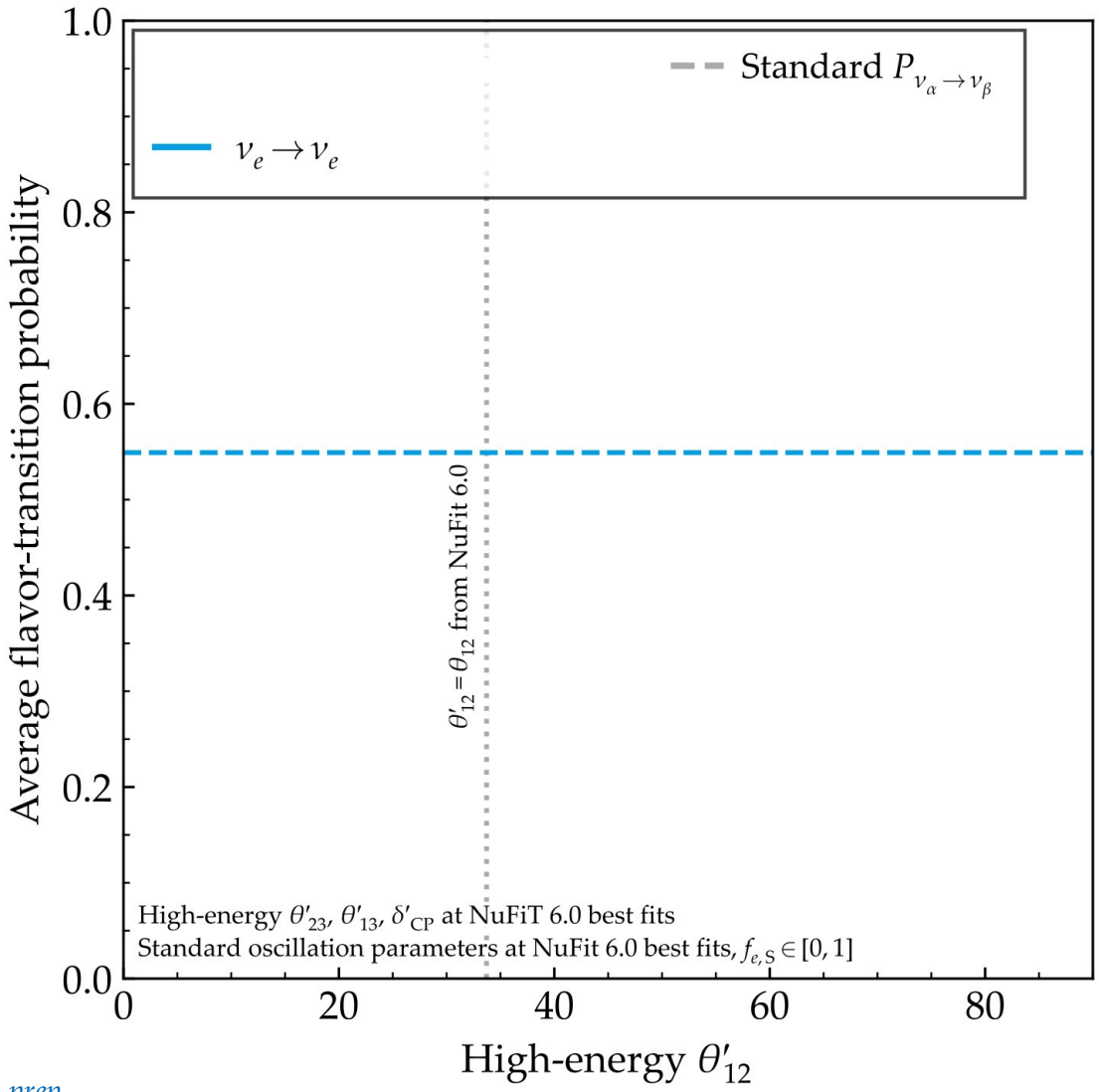
They now depend on **low-energy** & **high-energy** mixing parameters

$$P_{\alpha\beta} = \sum_{i=1}^{3} |(U_{\rm PMNS})_{\alpha i}|^2 |U'_{\beta i}(\theta'_{12}, \theta'_{23}, \theta'_{13}, \delta'_{\rm CP})|^2$$

At neutrino production

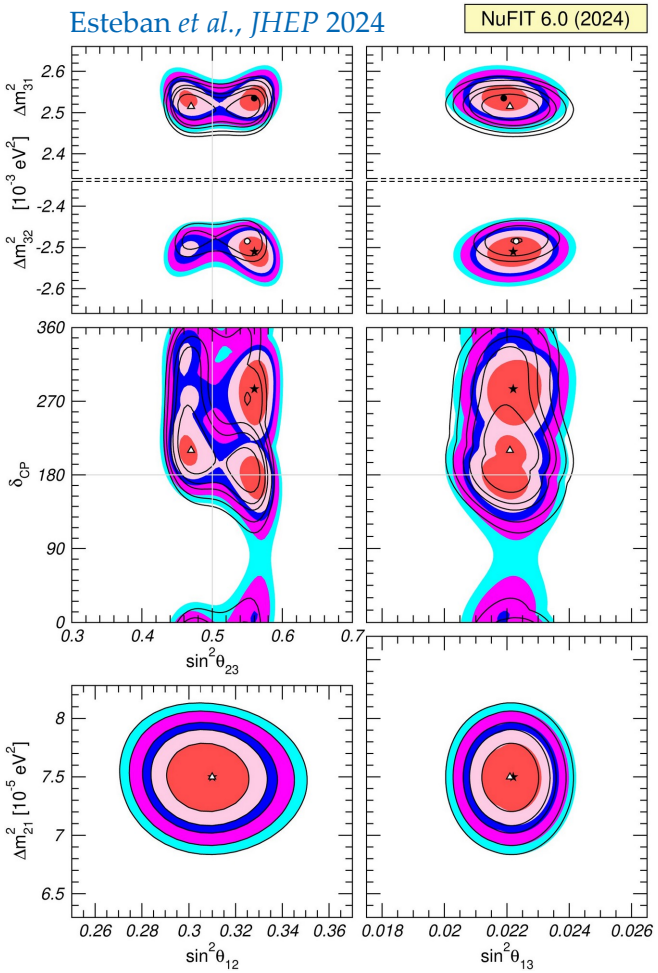
At neutrino detection

MB, Gago, Jones-Pérez, *JHEP* 2011
See also Antusch *et al.*, *JHEP* 2005; Babu, Brdar, de Gouvêa, Machado, *PRD* 2023



Telalovic, Liu, Barenboim, **MB**, *In prep.*

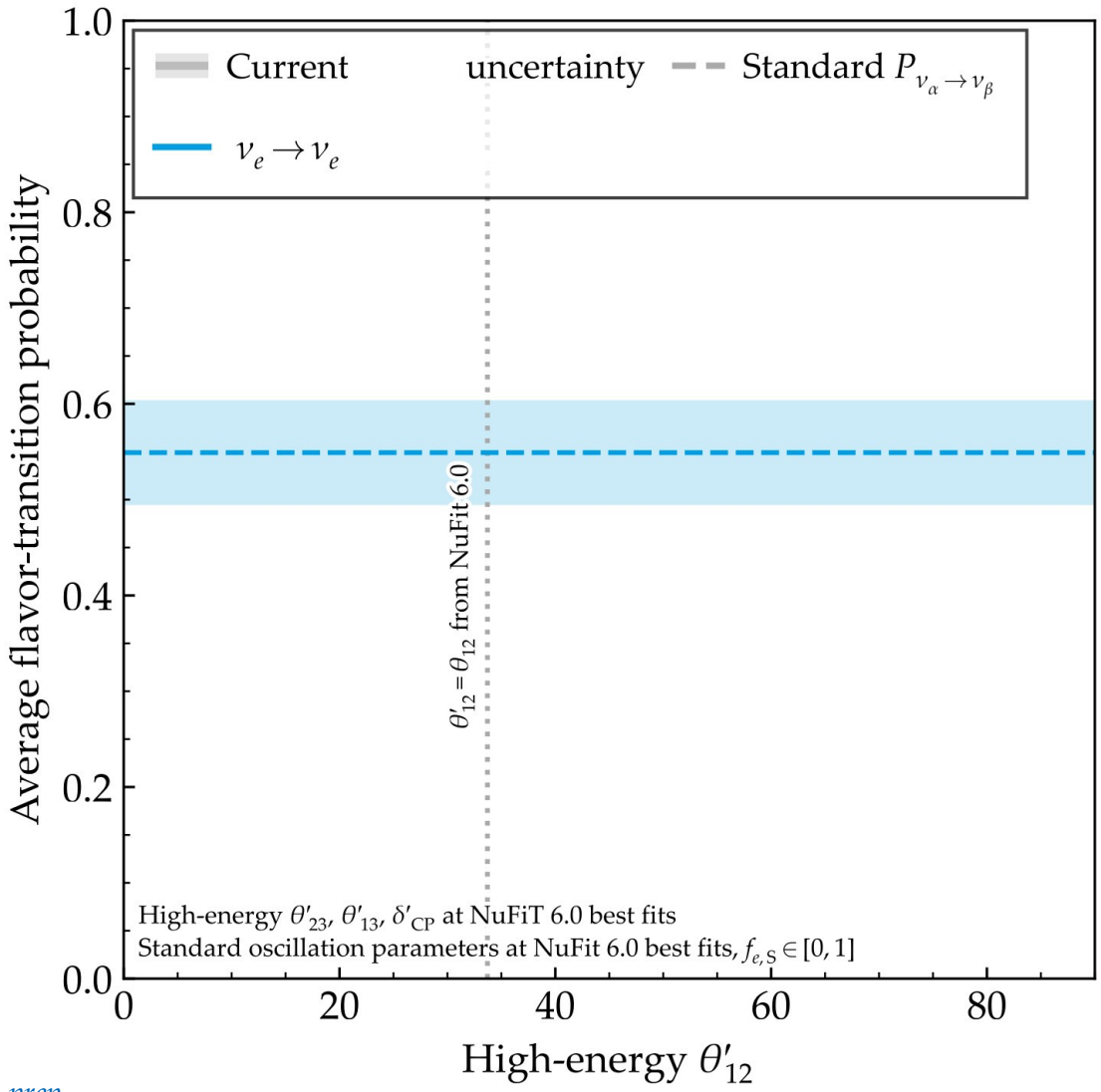
Best-fit & current uncertainties on mixing angles and CP-violation phase



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

PMNS

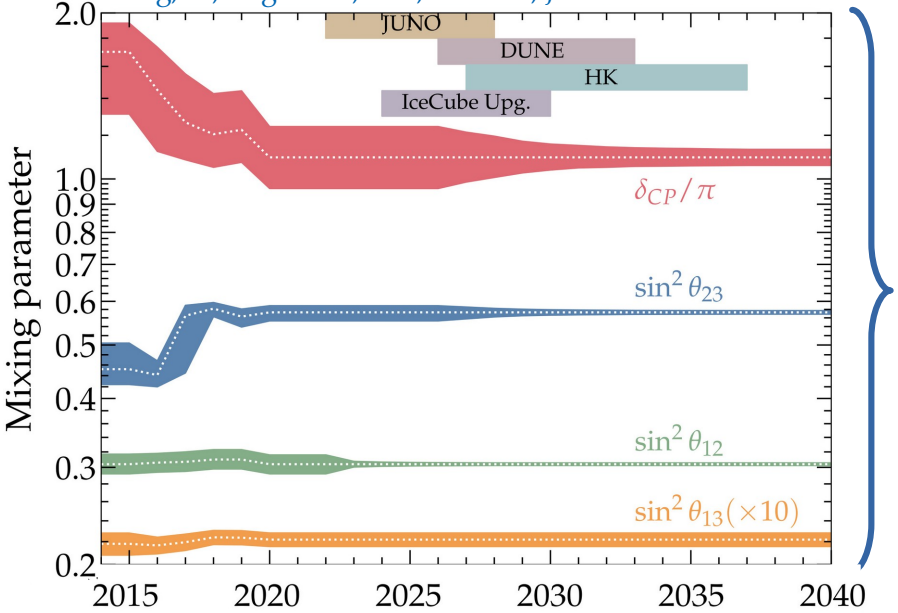
→ Best-fit & current uncertainties on the standard probabilities



Telalovic, Liu, Barenboim, **MB**, *In prep.*

Future uncertainties on mixing angles and CP-violation phase

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

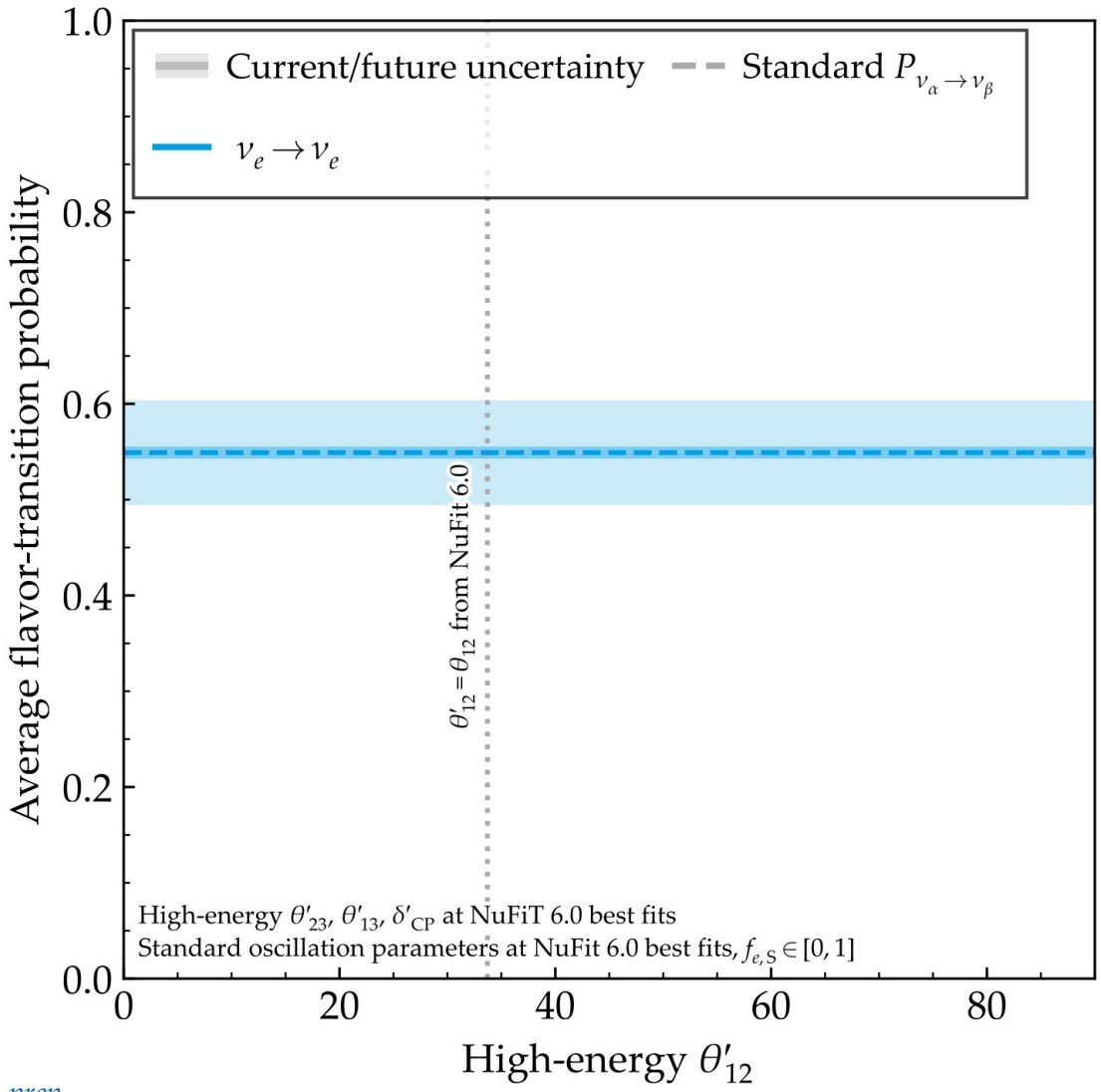


$$P_{\alpha\beta} = \sum_{i=1}^{3} |U_{\alpha i}|^2 |U_{\beta i}|^2$$

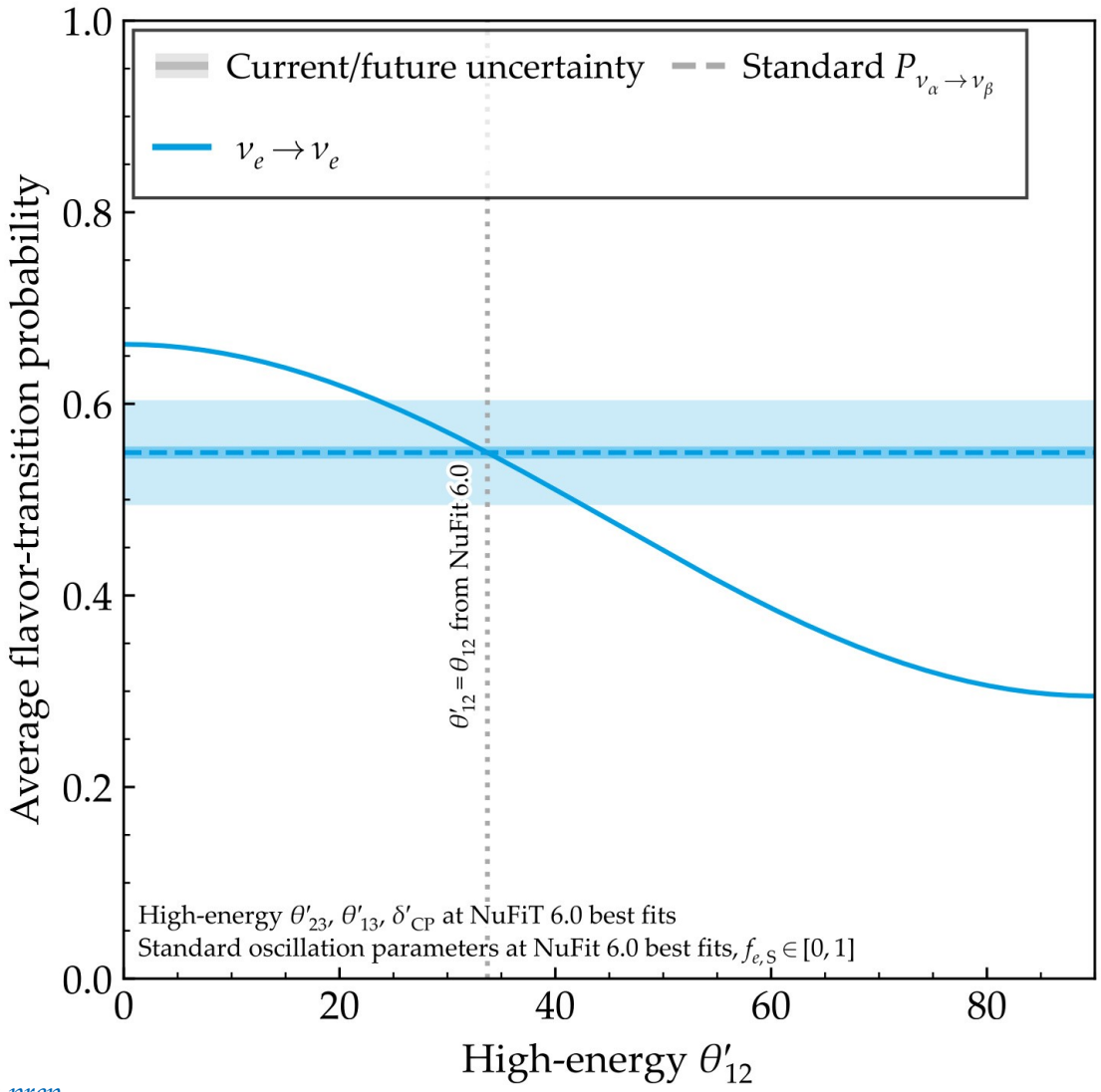
PMNS

→ Future uncertainties on the standard probabilities

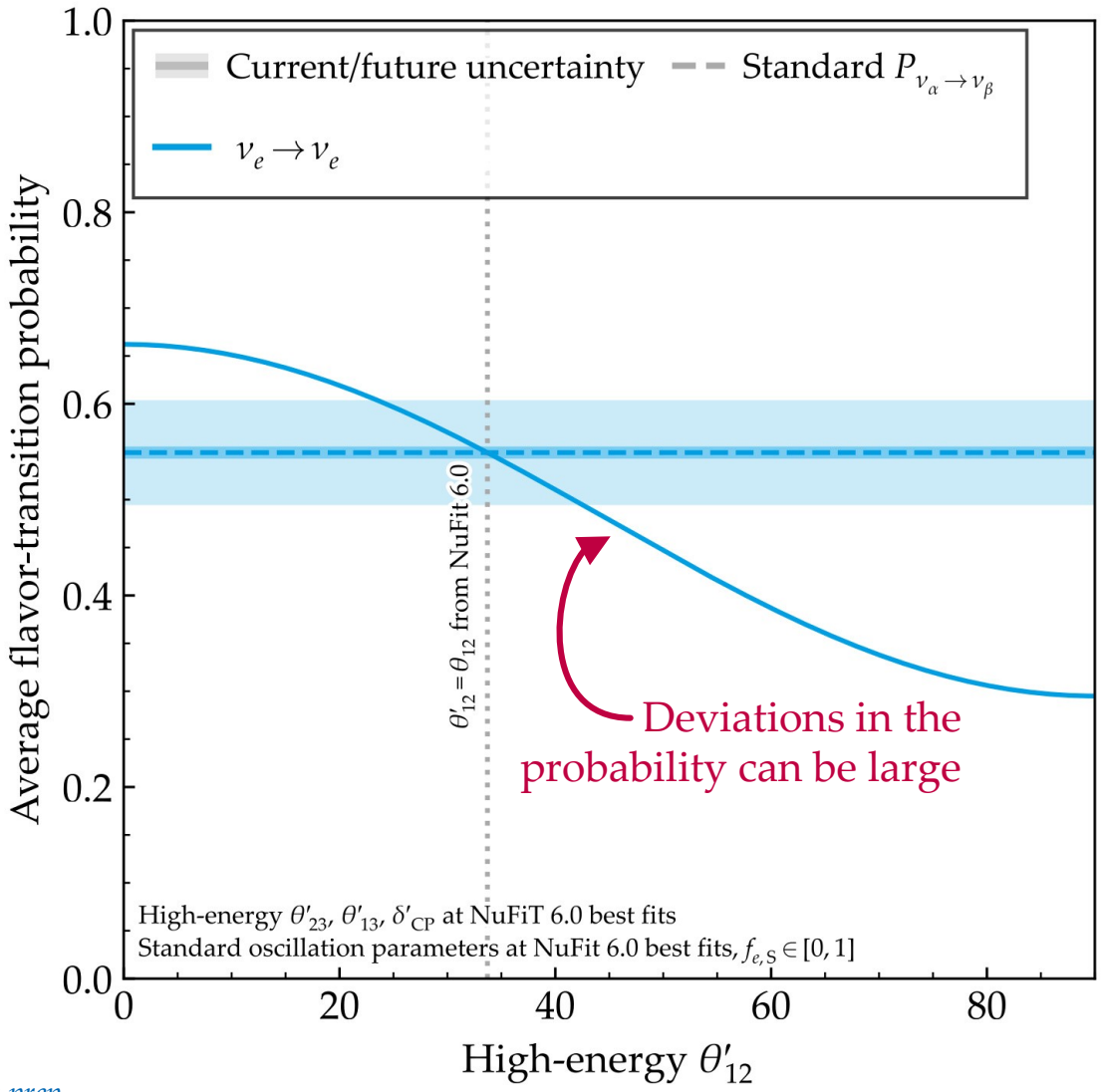
(Central values fixed at current NuFIT best fits)



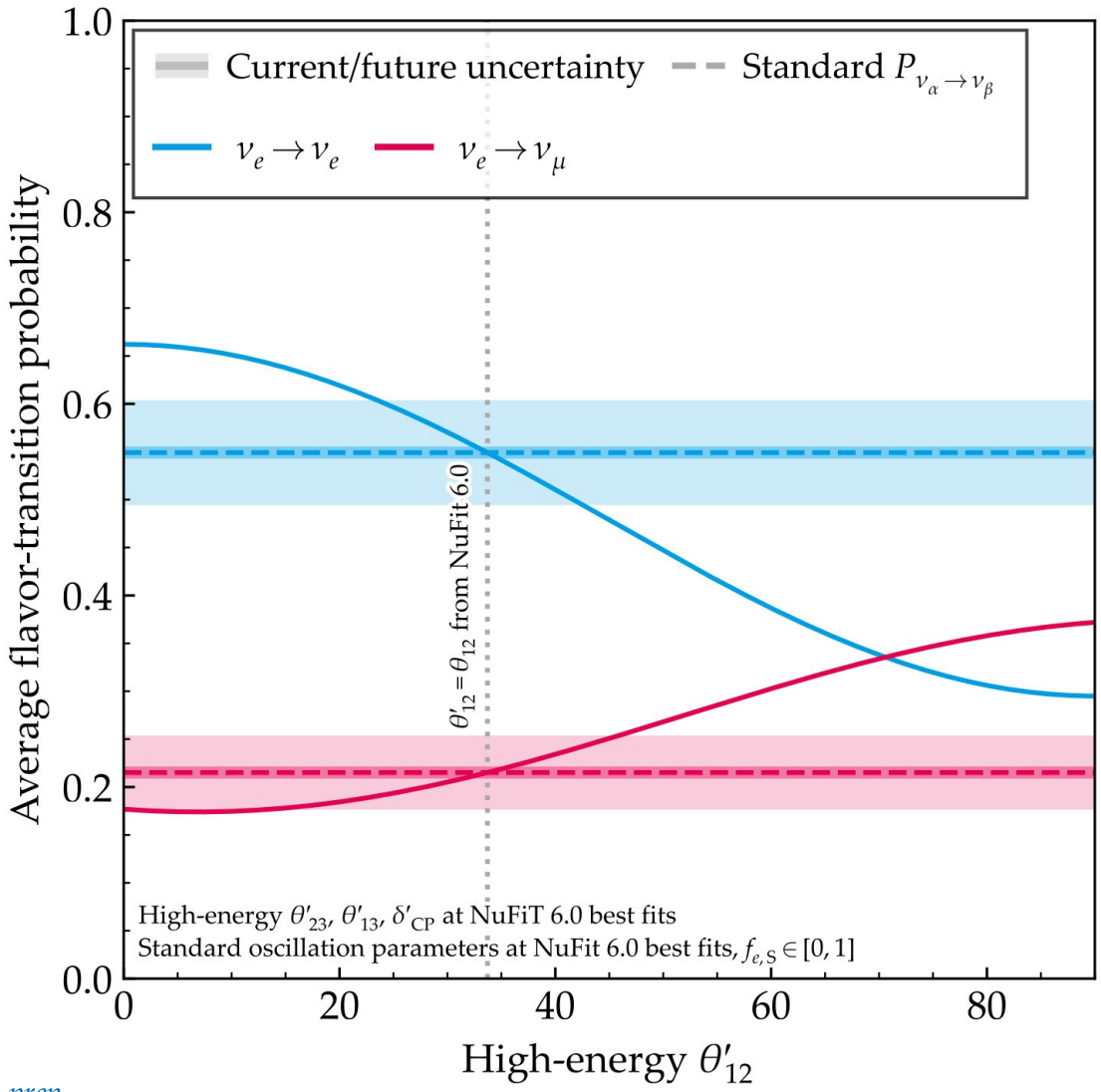
Telalovic, Liu, Barenboim, **MB**, *In prep.*



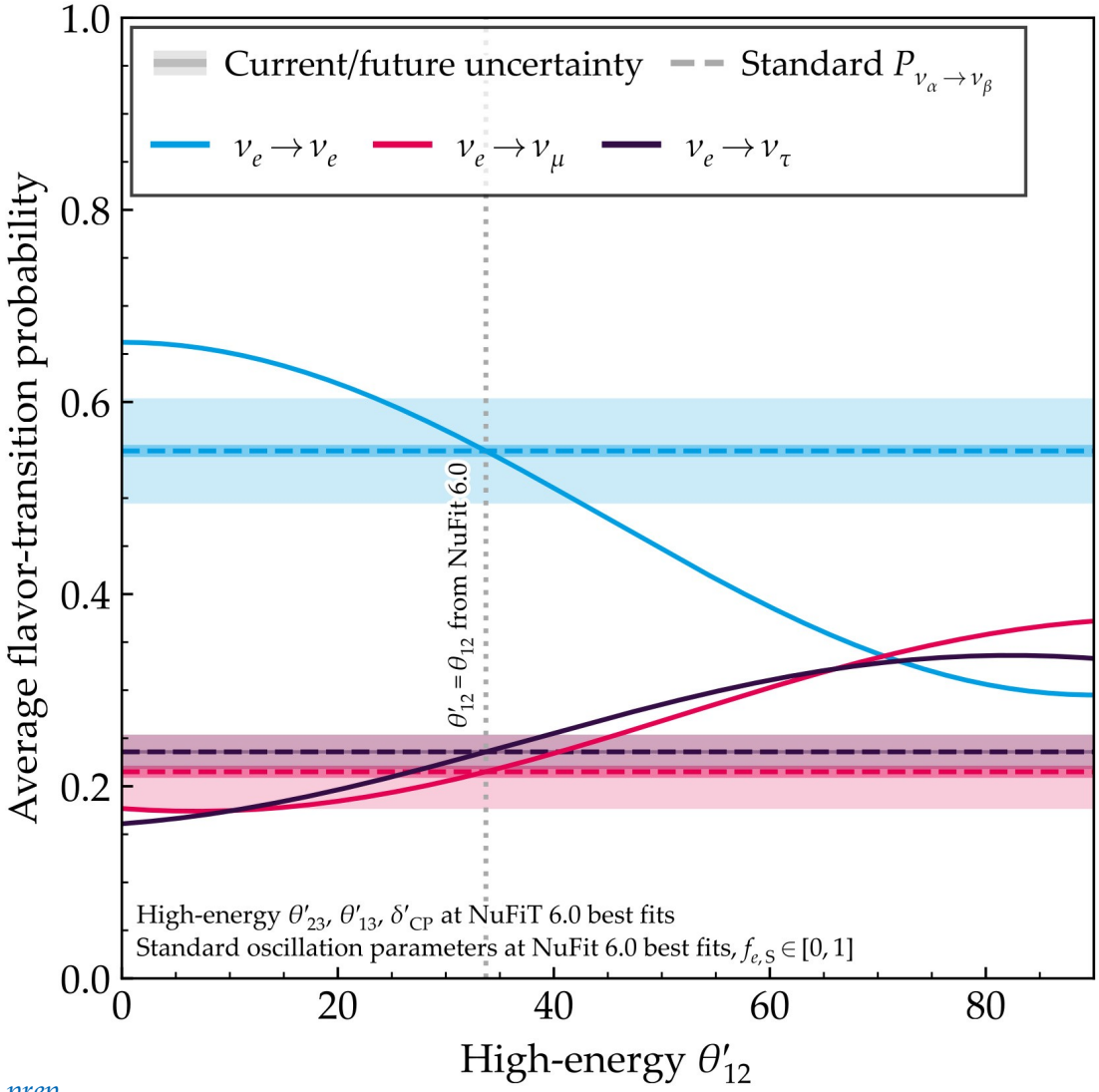
Telalovic, Liu, Barenboim, **MB**, *In prep.*



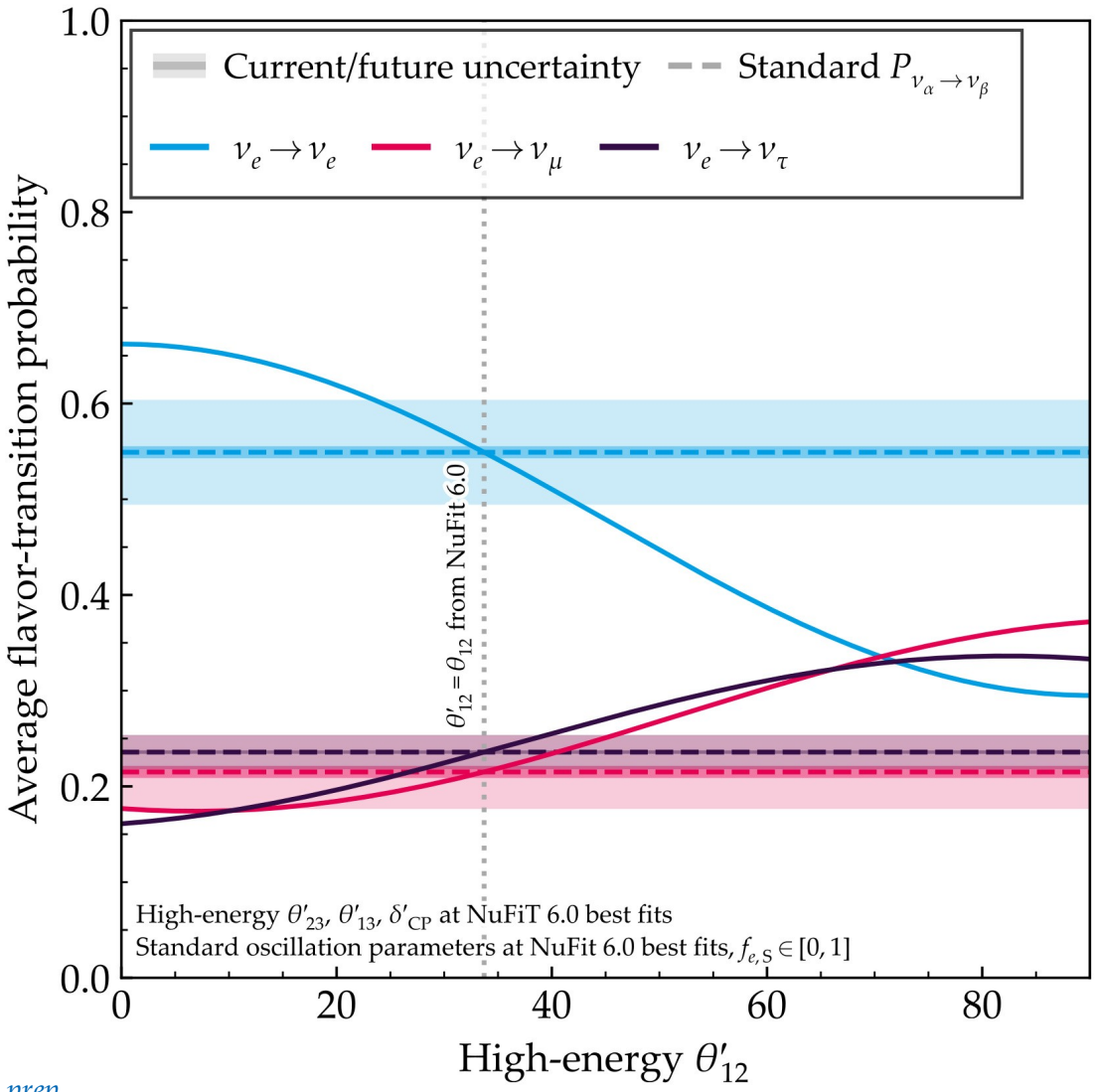
Telalovic, Liu, Barenboim, **MB**, *In prep.*



Telalovic, Liu, Barenboim, **MB**, *In prep.*



Telalovic, Liu, Barenboim, **MB**, *In prep.*



Results for the other high-energy mixing parameters are similar (not shown here)

Telalovic, Liu, Barenboim, **MB**, *In prep.*

Flavor composition at the Earth:

$$\begin{pmatrix} f_{e,\oplus} \\ f_{\mu,\oplus} \\ f_{\tau,\oplus} \end{pmatrix} = \underbrace{\begin{pmatrix} P_{ee} & P_{e\mu} & P_{e\tau} \\ P_{e\mu} & P_{\mu\mu} & P_{\mu\tau} \\ P_{e\tau} & P_{\mu\tau} & P_{\tau\tau} \end{pmatrix}} \begin{pmatrix} f_{e,\mathrm{S}} \\ 1 - f_{e,\mathrm{S}} \\ 0 \end{pmatrix}$$

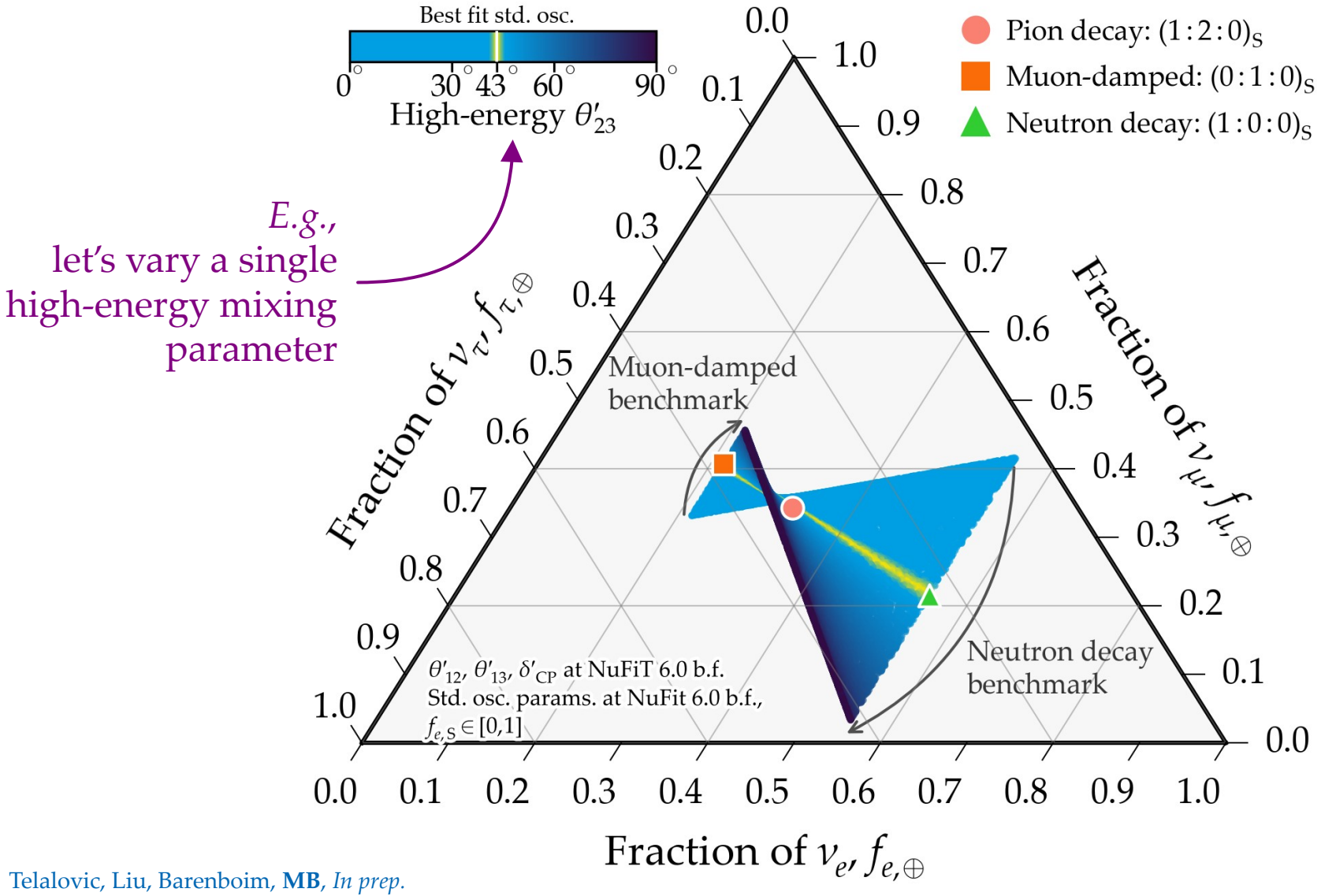
Probabilities now depend on **low-energy** & **high-energy** mixing parameters

$$P_{\alpha\beta} = \sum_{i=1}^{3} |(U_{\mathrm{PMNS}})_{\alpha i}|^2 |U'_{\beta i}(\theta'_{12}, \theta'_{23}, \theta'_{13}, \delta'_{\mathrm{CP}})|^2$$

Varied within current or future uncertainties

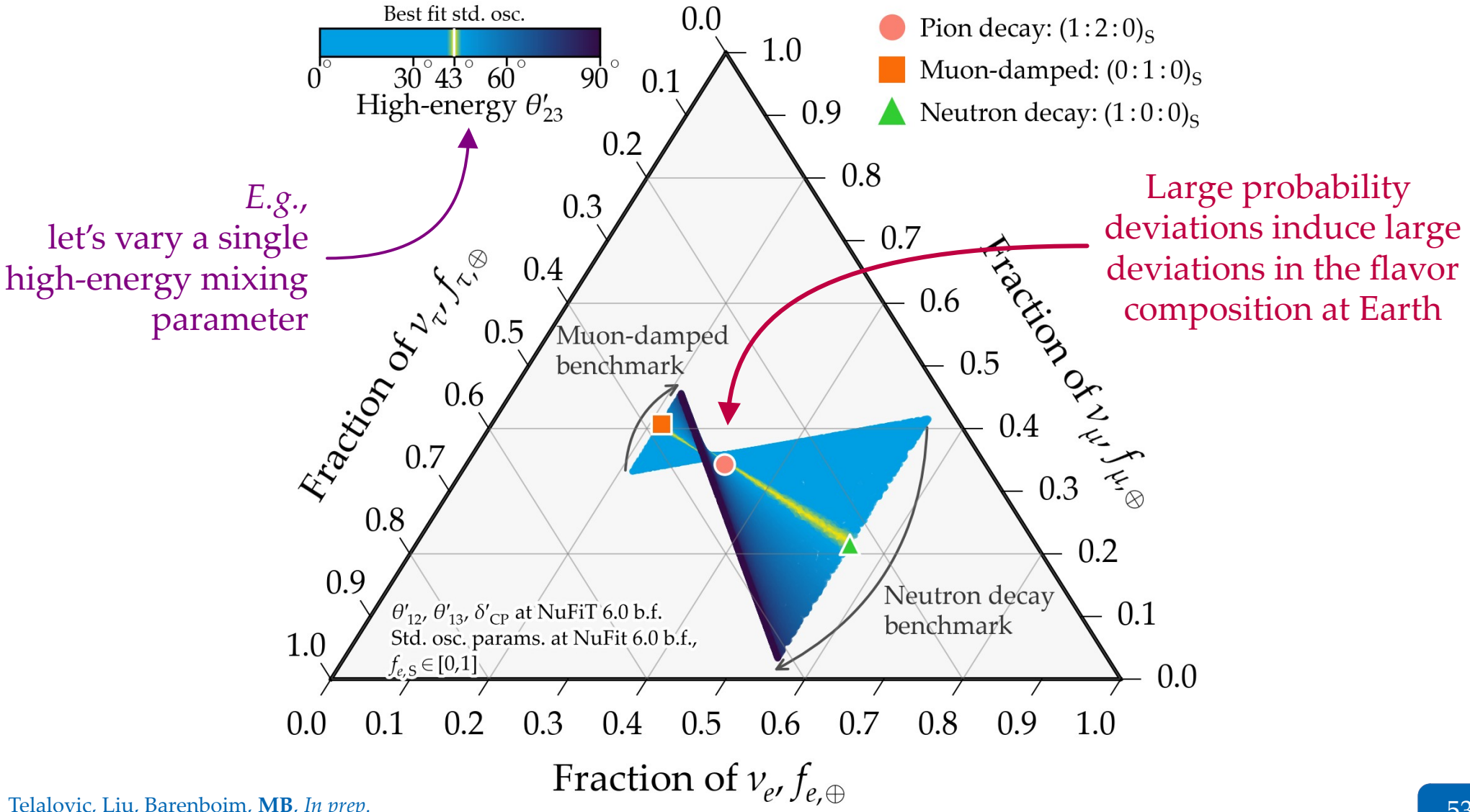
Varied with uninformed priors (flat or Haar measure on *U'*)

MB, Gago, Jones-Pérez, *JHEP* 2011
See also Antusch *et al.*, *JHEP* 2005; Babu, Brdar, de Gouvêa, Machado, *PRD* 2023

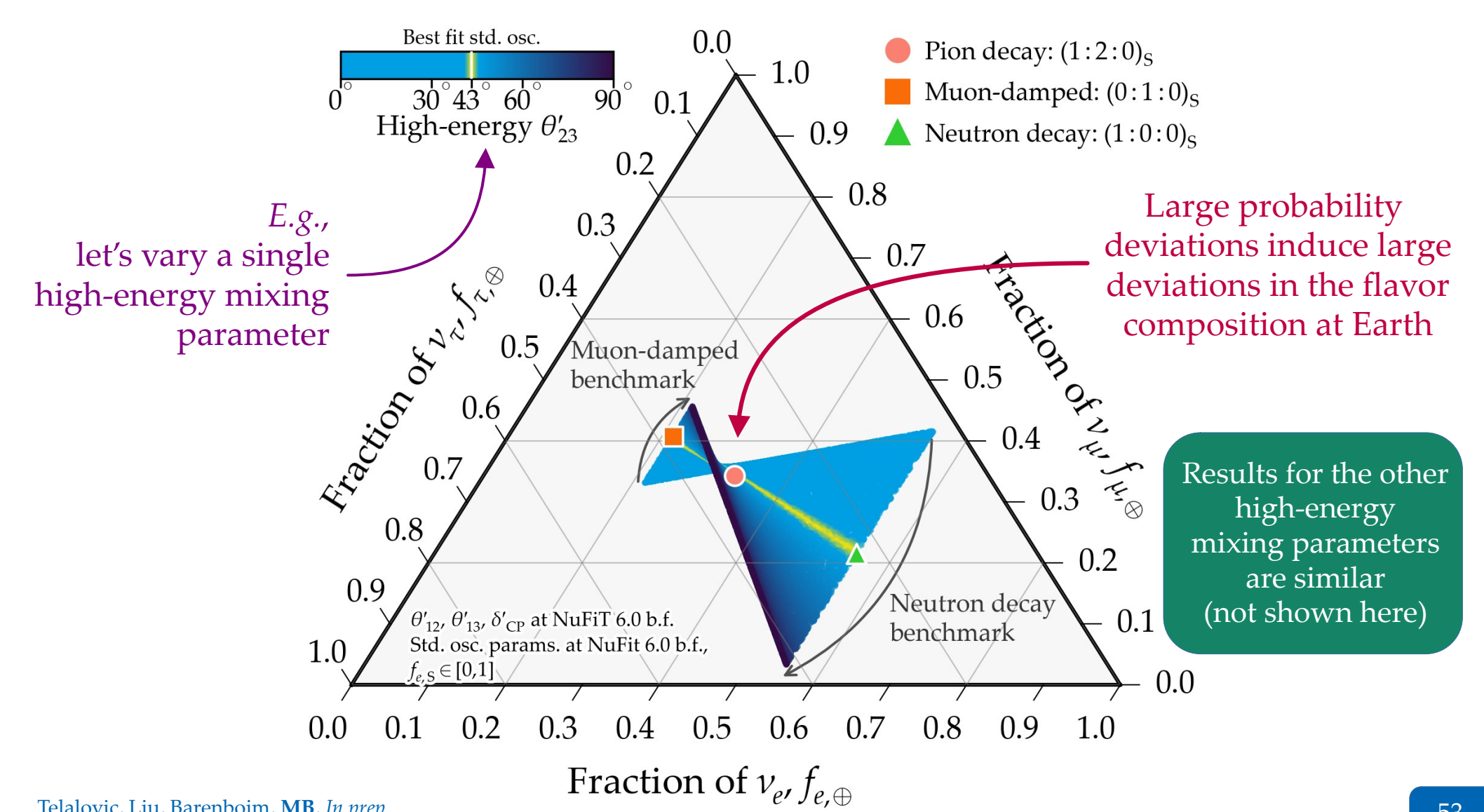


E.g.,
let's vary a single high-energy mixing parameter

Telalovic, Liu, Barenboim, **MB**, *In prep.*



Telalovic, Liu, Barenboim, **MB**, *In prep.*



Telalovic, Liu, Barenboim, **MB**, *In prep.*

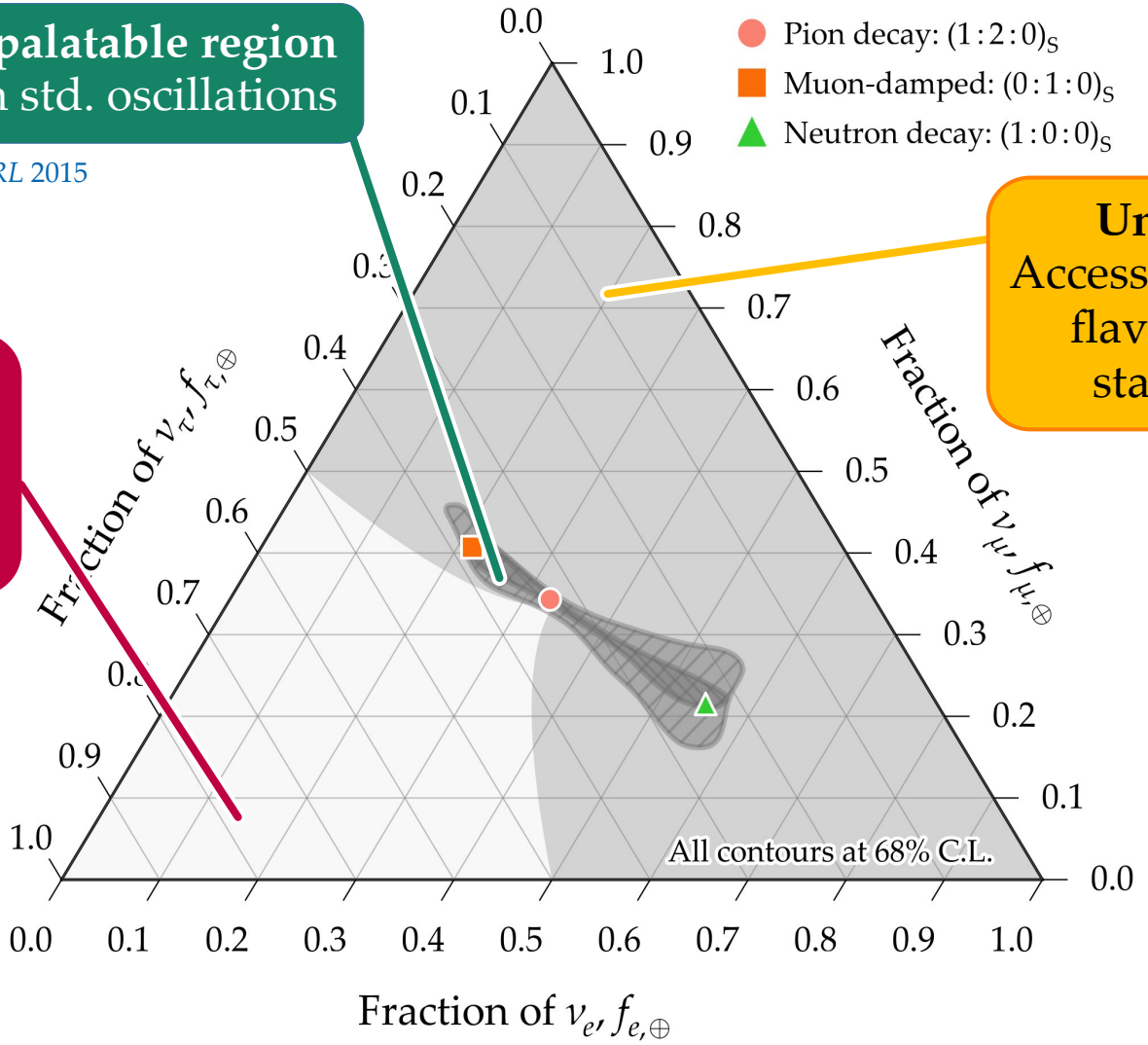
Theoretically palatable region
Accessible with std. oscillations

MB, Beacom, Winter, *PRL* 2015

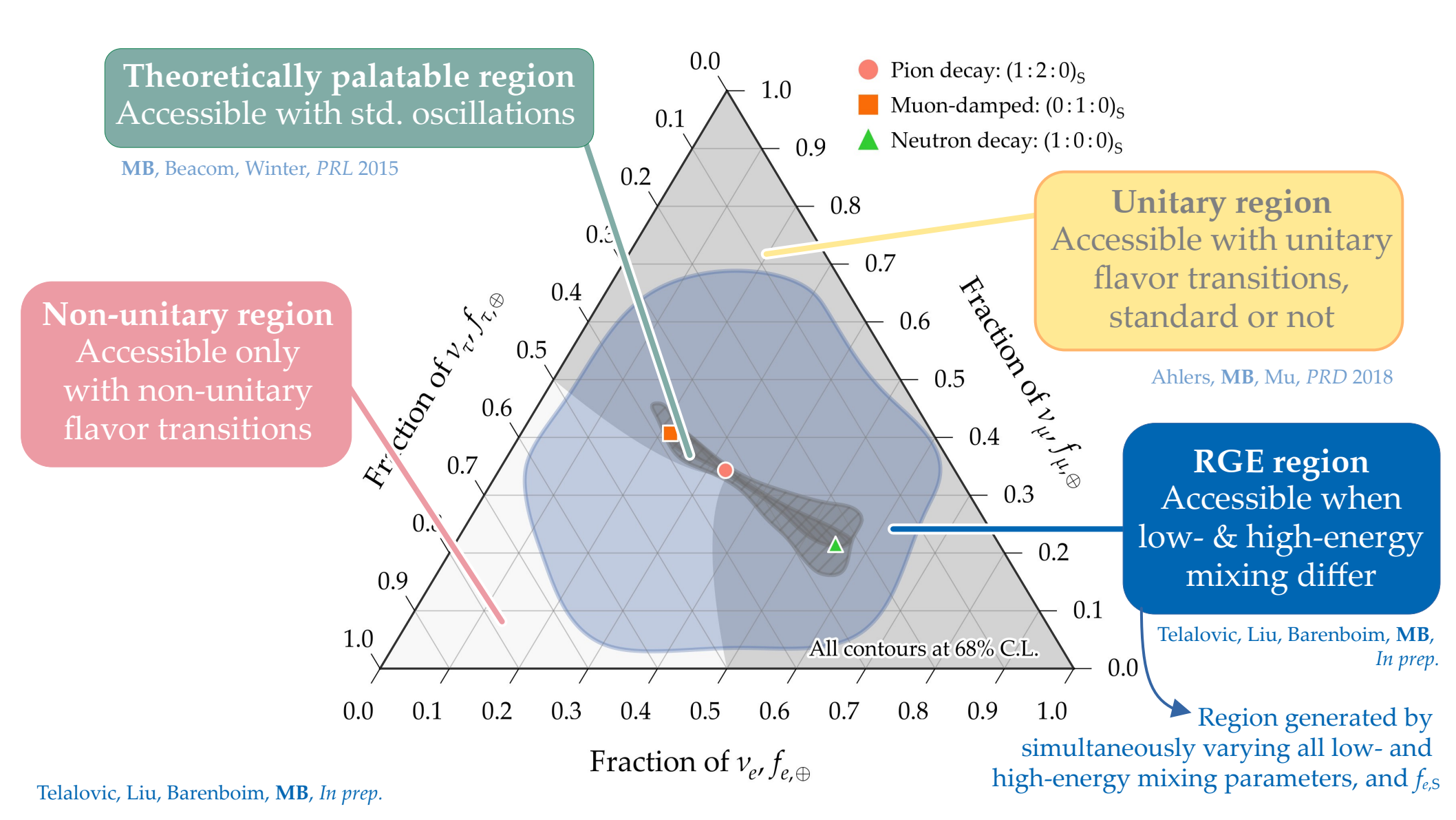
Non-unitary region
Accessible only with non-unitary flavor transitions

Unitary region
Accessible with unitary flavor transitions, standard or not

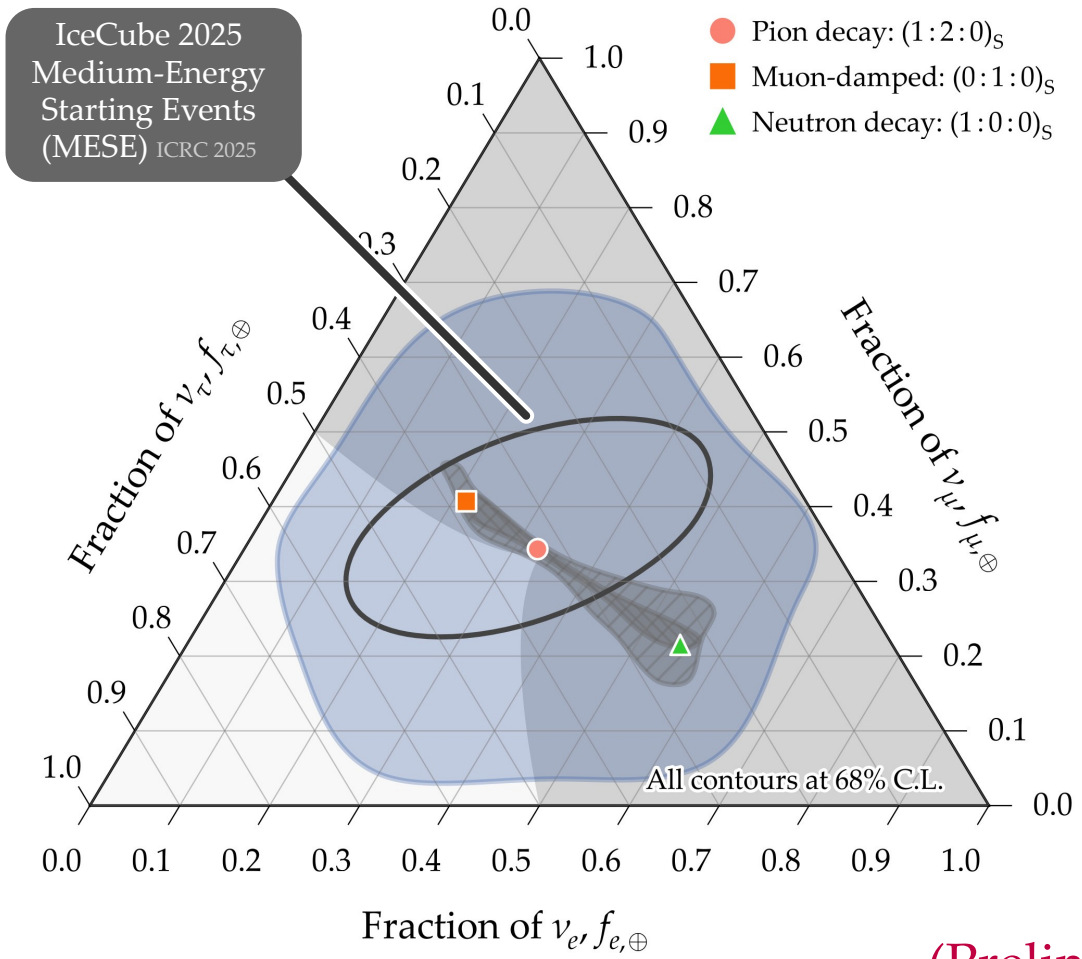
Ahlers, **MB**, Mu, *PRD* 2018



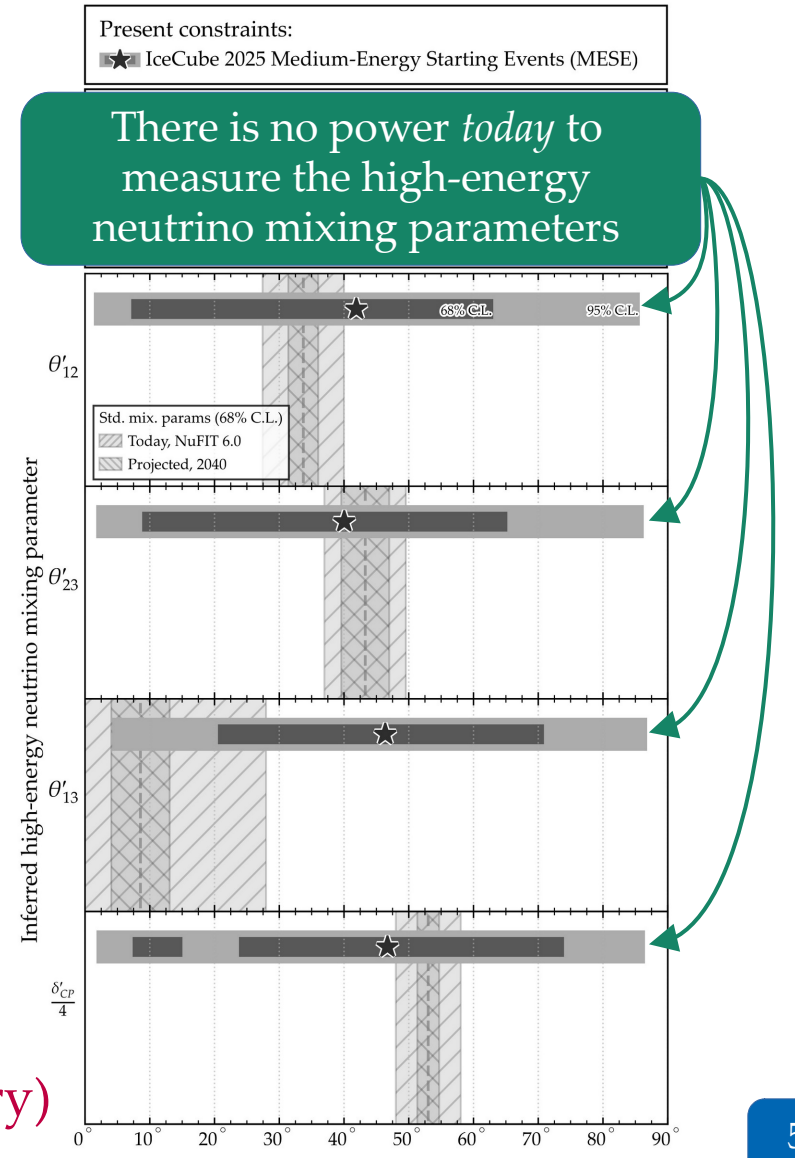
Telalovic, Liu, Barenboim, **MB**, *In prep.*


Theoretically palatable region
Accessible with std. oscillations
MB, Beacom, Winter, PRL 2015
Non-unitary region
Accessible only with non-unitary flavor transitions
Unitary region
Accessible with unitary flavor transitions, standard or not
Ahlers, MB, Mu, PRD 2018
RGE region
Accessible when low- & high-energy mixing differ
Telalovic, Liu, Barenboim, MB, In prep.
Region generated by simultaneously varying all low- and high-energy mixing parameters, and $f_{e,S}$
Pion decay: $(1:2:0)_S$
Muon-damped: $(0:1:0)_S$
Neutron decay: $(1:0:0)_S$
All contours at 68% C.L.
Fraction of ν_e, $f_{e,\oplus}$
Fraction of ν_μ, $f_{\mu,\oplus}$
Fraction of ν_τ, $f_{\tau,\oplus}$
Telalovic, Liu, Barenboim, MB, In prep.

Measurement power *today* —



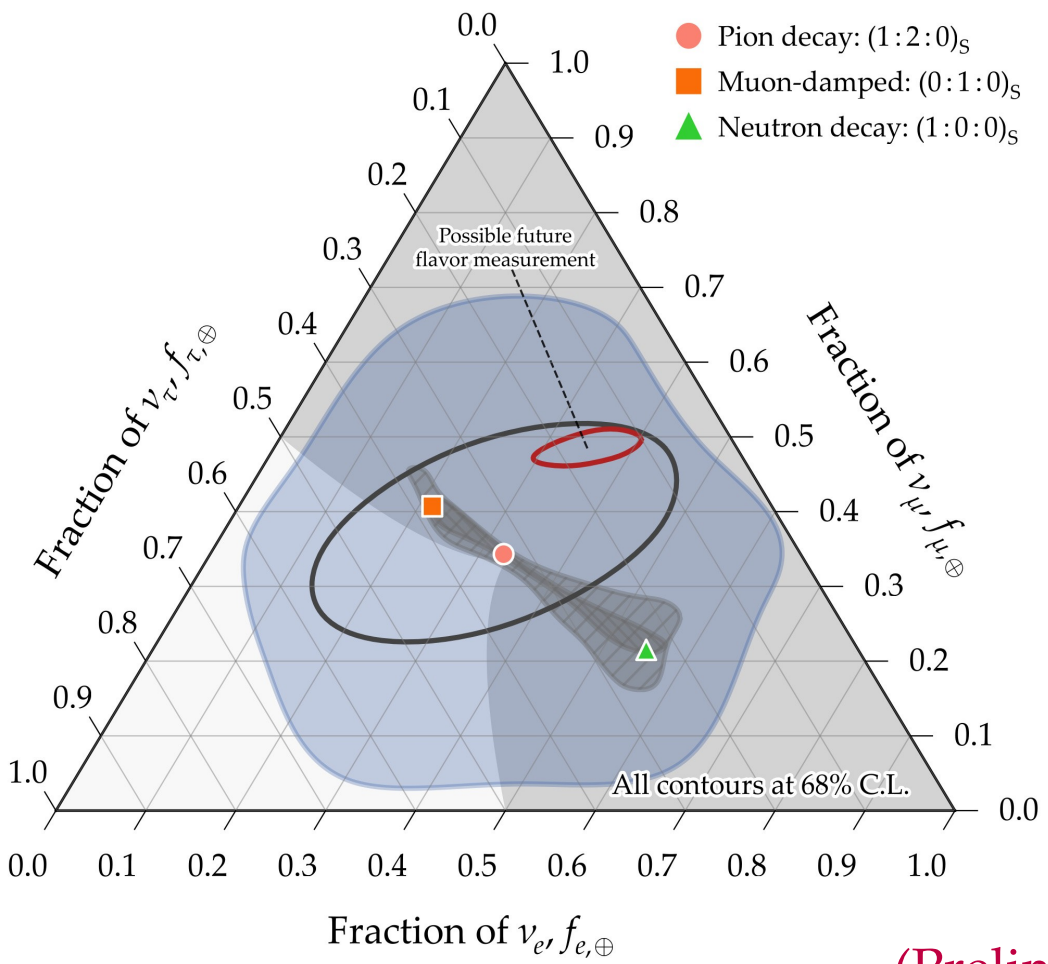
There is no power *today* to measure the high-energy neutrino mixing parameters

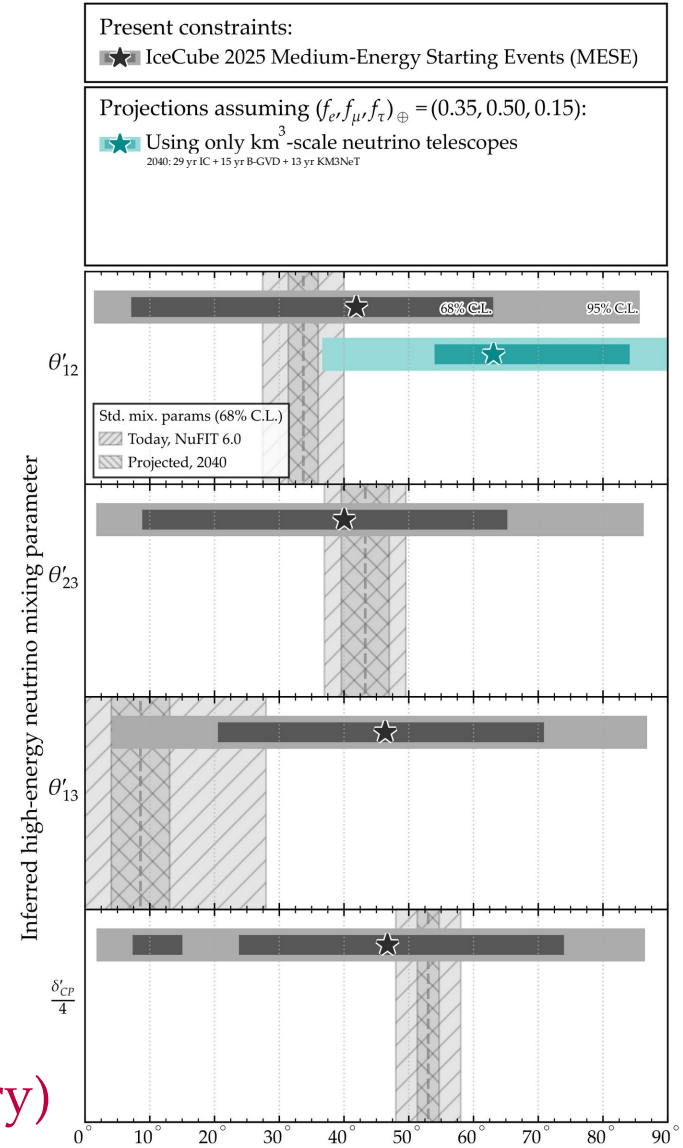


(Preliminary)

Telalovic, Liu, Barenboim, **MB**, *In prep.*

Measurement power *in the future* —

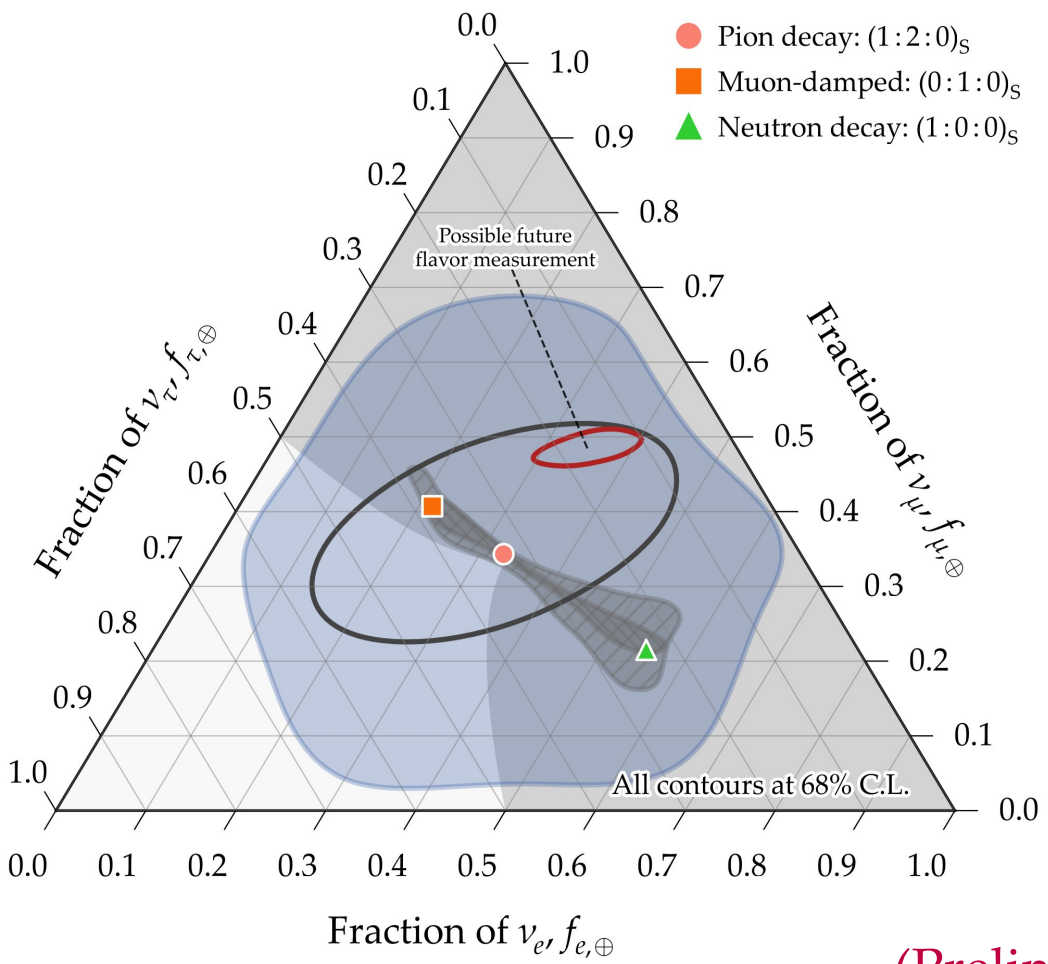


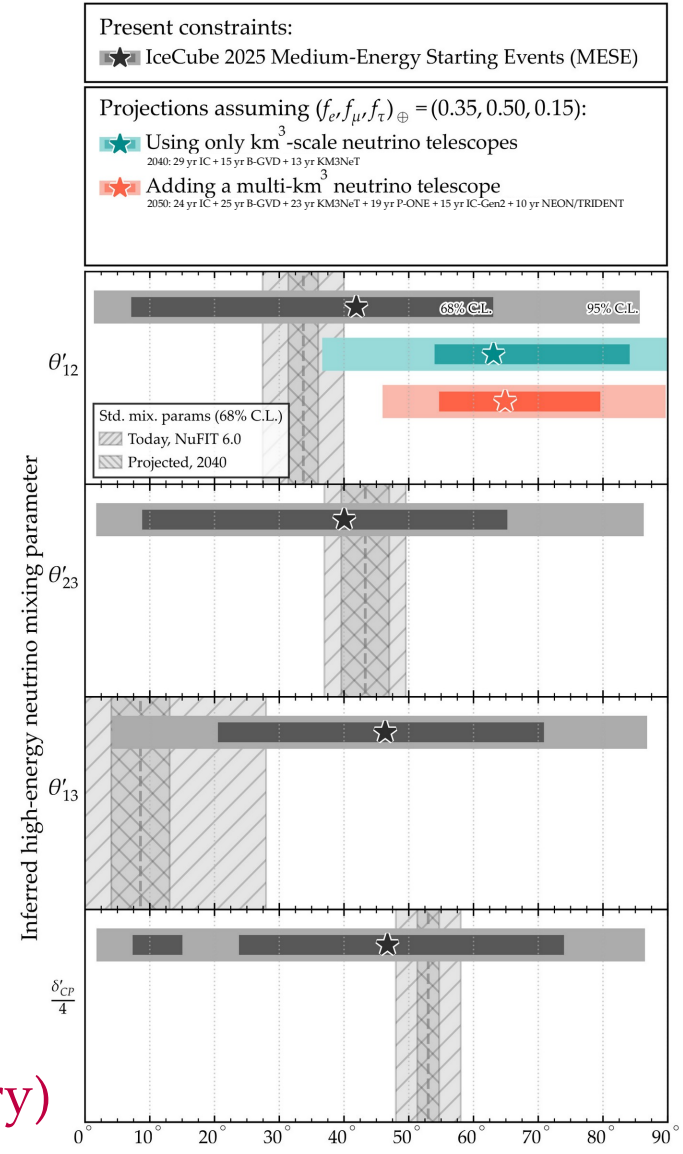


(Preliminary)

Telalovic, Liu, Barenboim, **MB**, *In prep.*

Measurement power *in the future* —

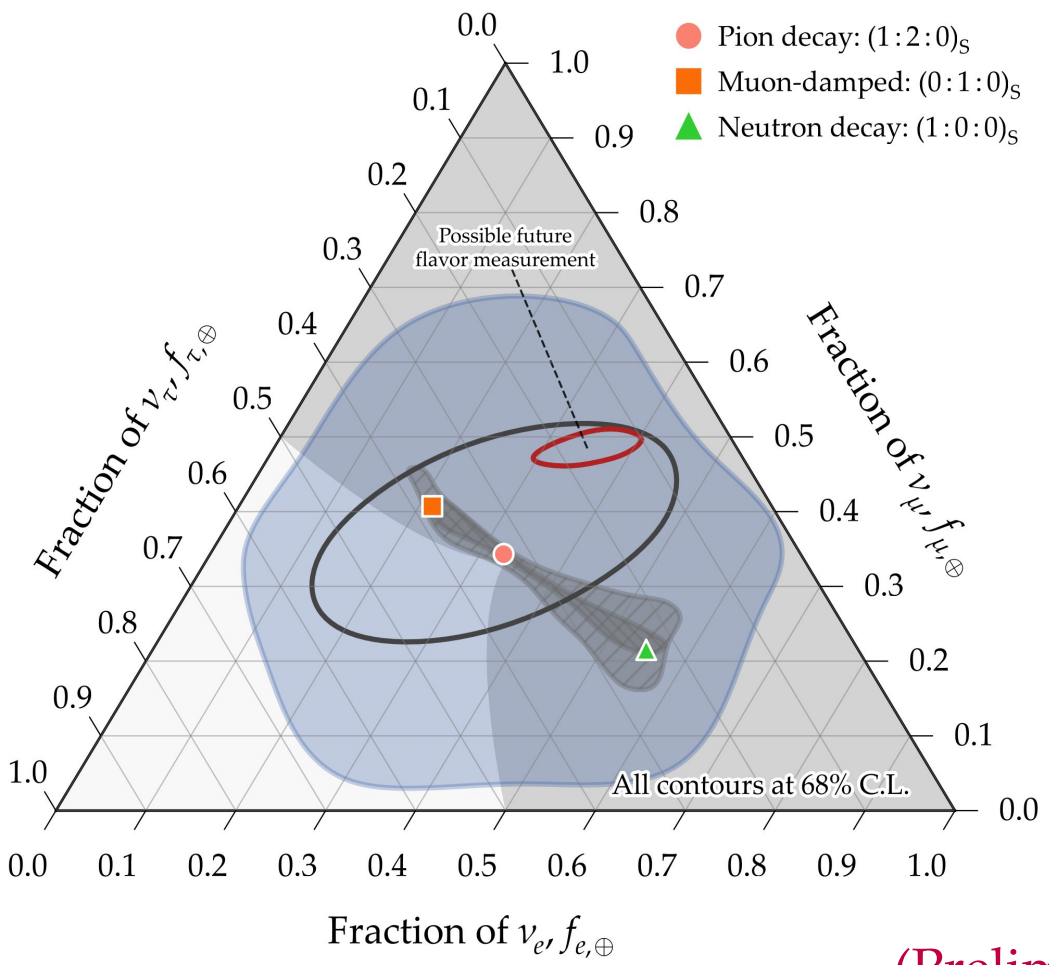


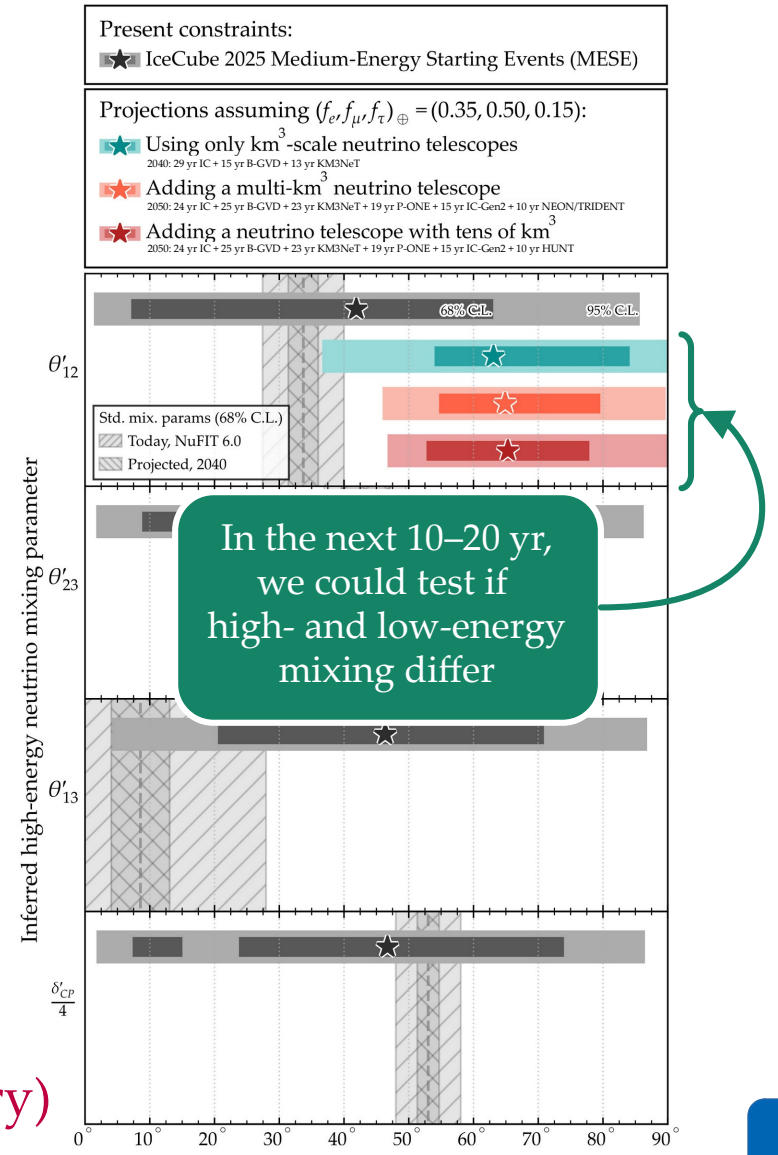


(Preliminary)

Telalovic, Liu, Barenboim, **MB**, *In prep.*

Measurement power *in the future* —

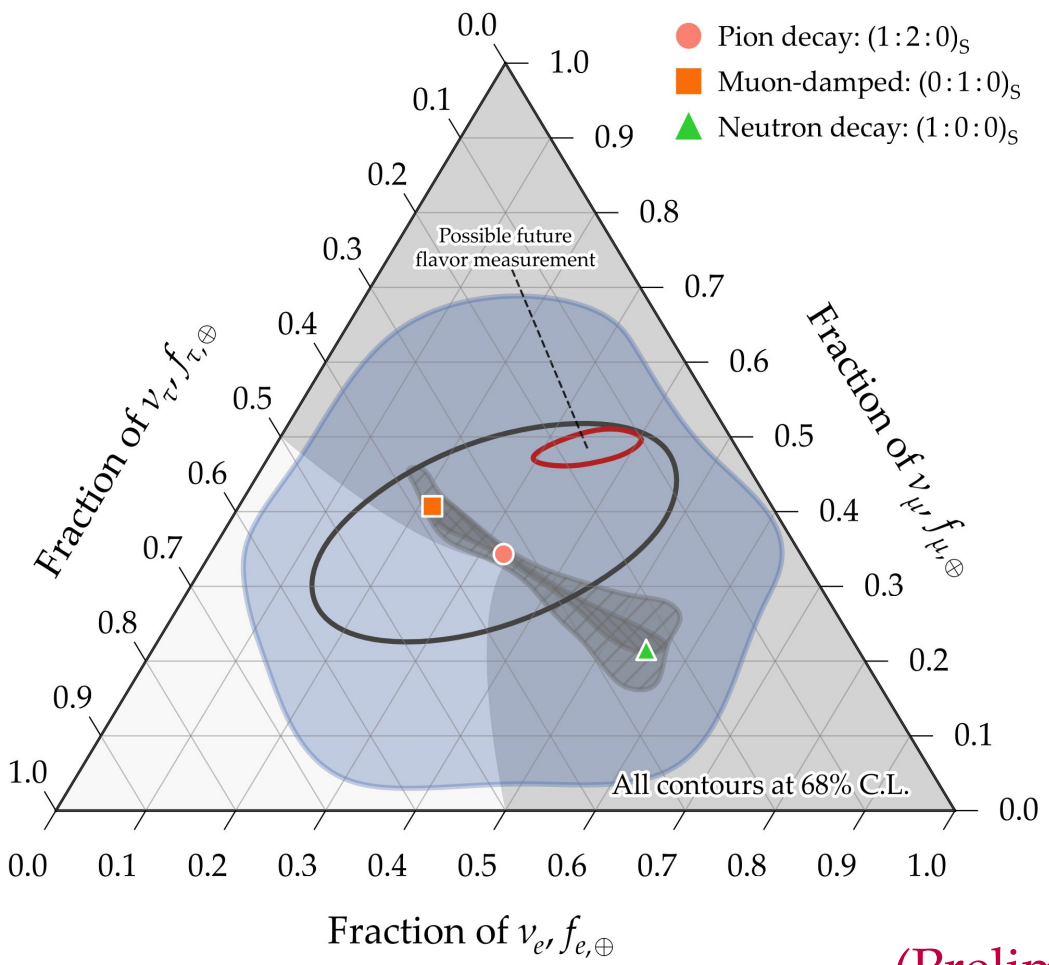


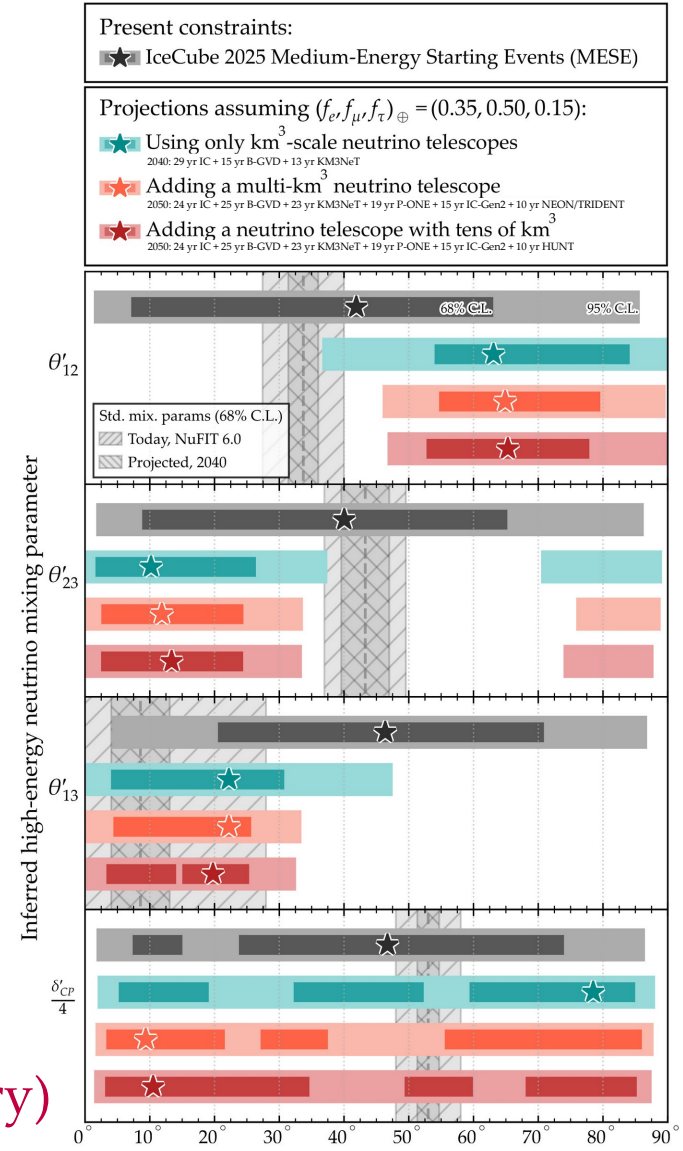


(Preliminary)

Telalovic, Liu, Barenboim, **MB**, *In prep.*

Measurement power *in the future* —

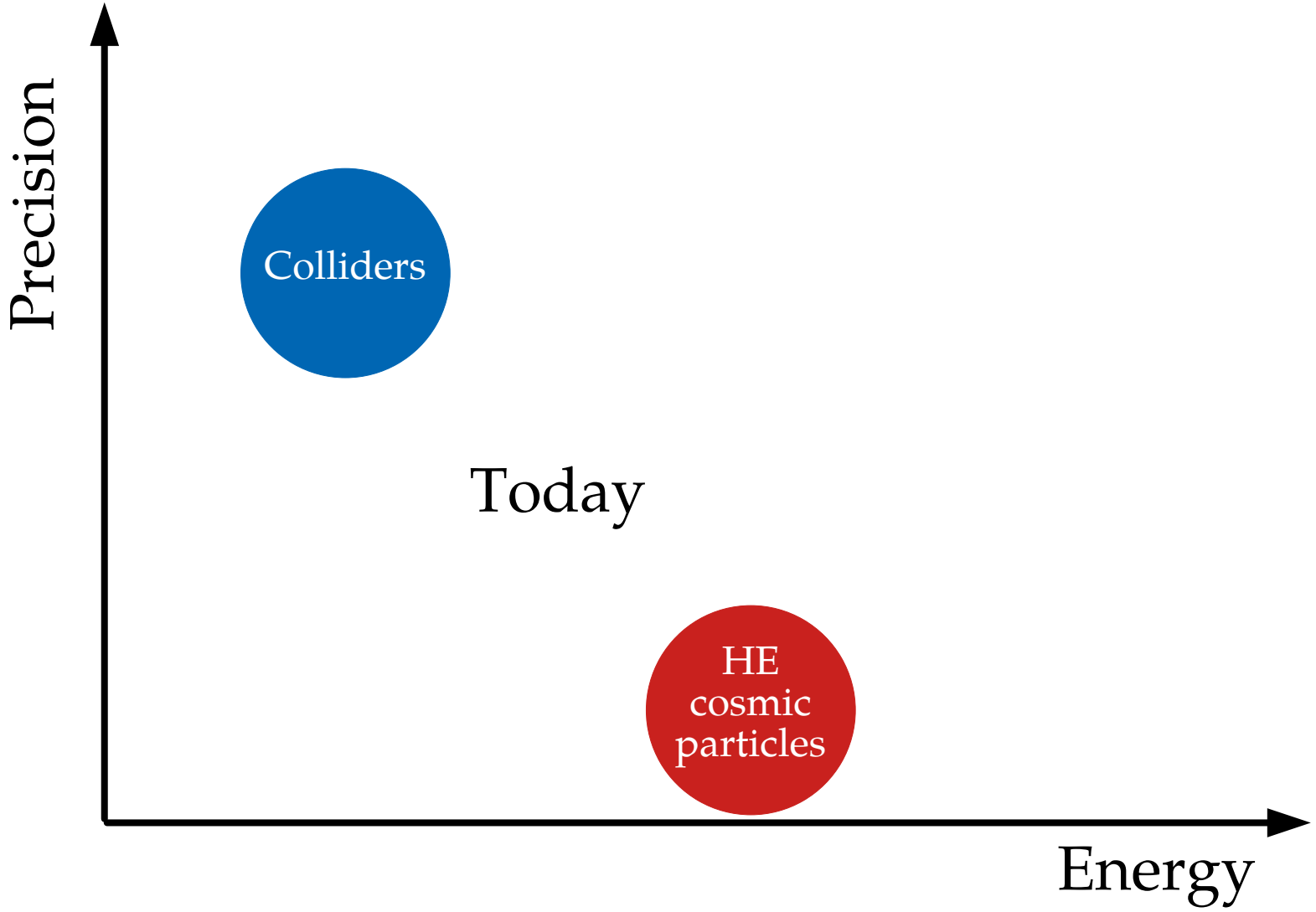


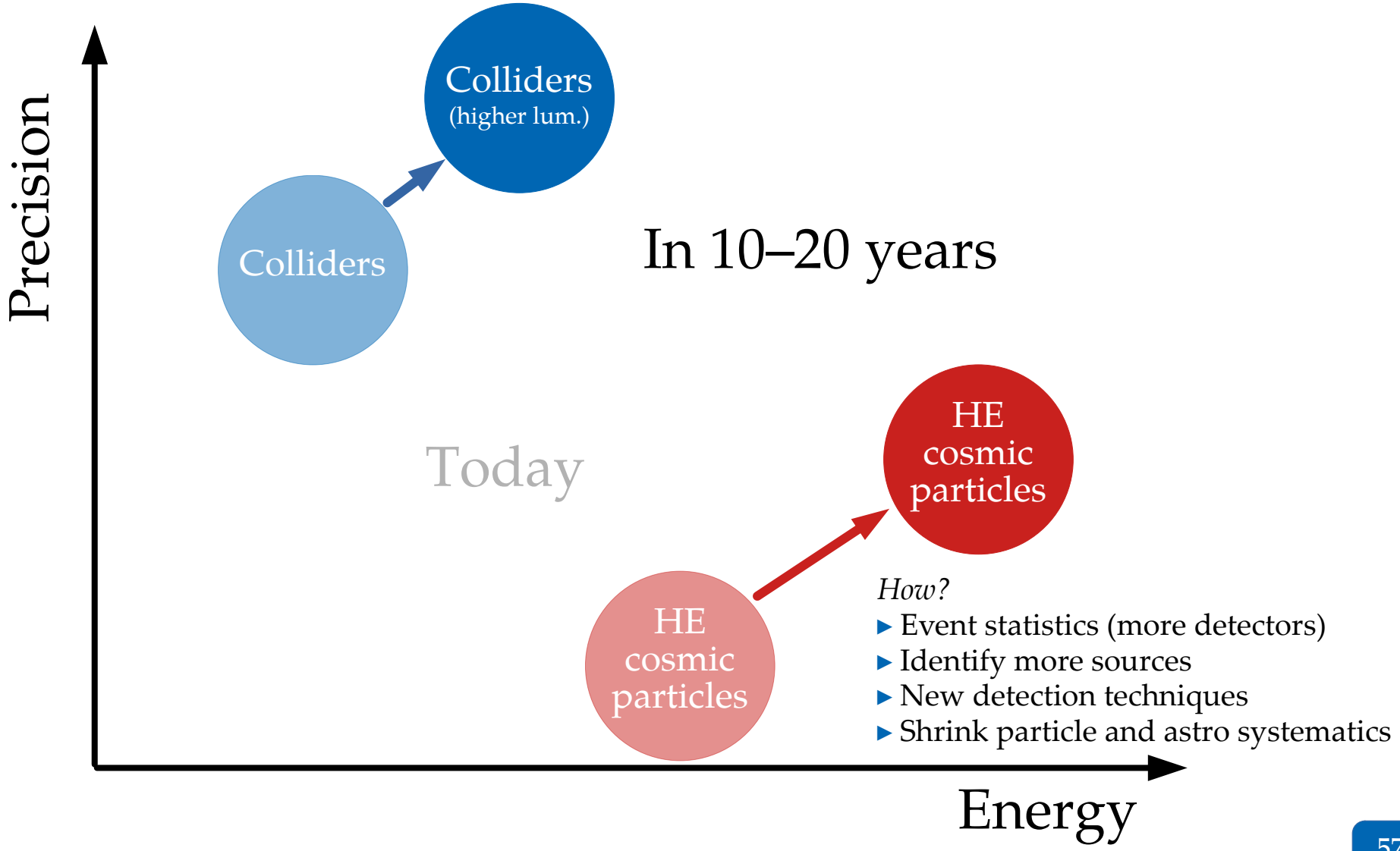


(Preliminary)

Telalovic, Liu, Barenboim, **MB**, *In prep.*

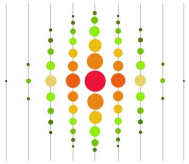
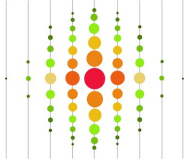
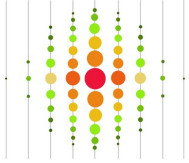
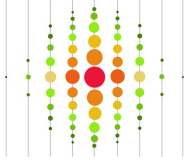
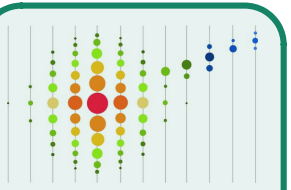
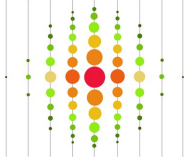
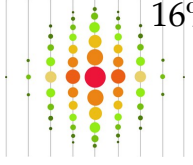
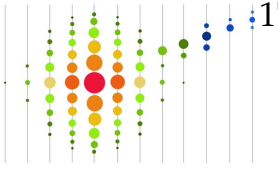
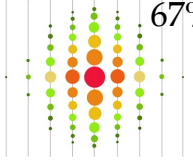
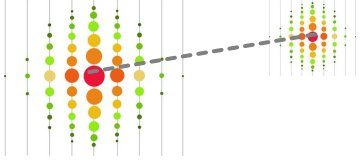
So…


Precision
Colliders
Today
HE
cosmic
particles
Energy

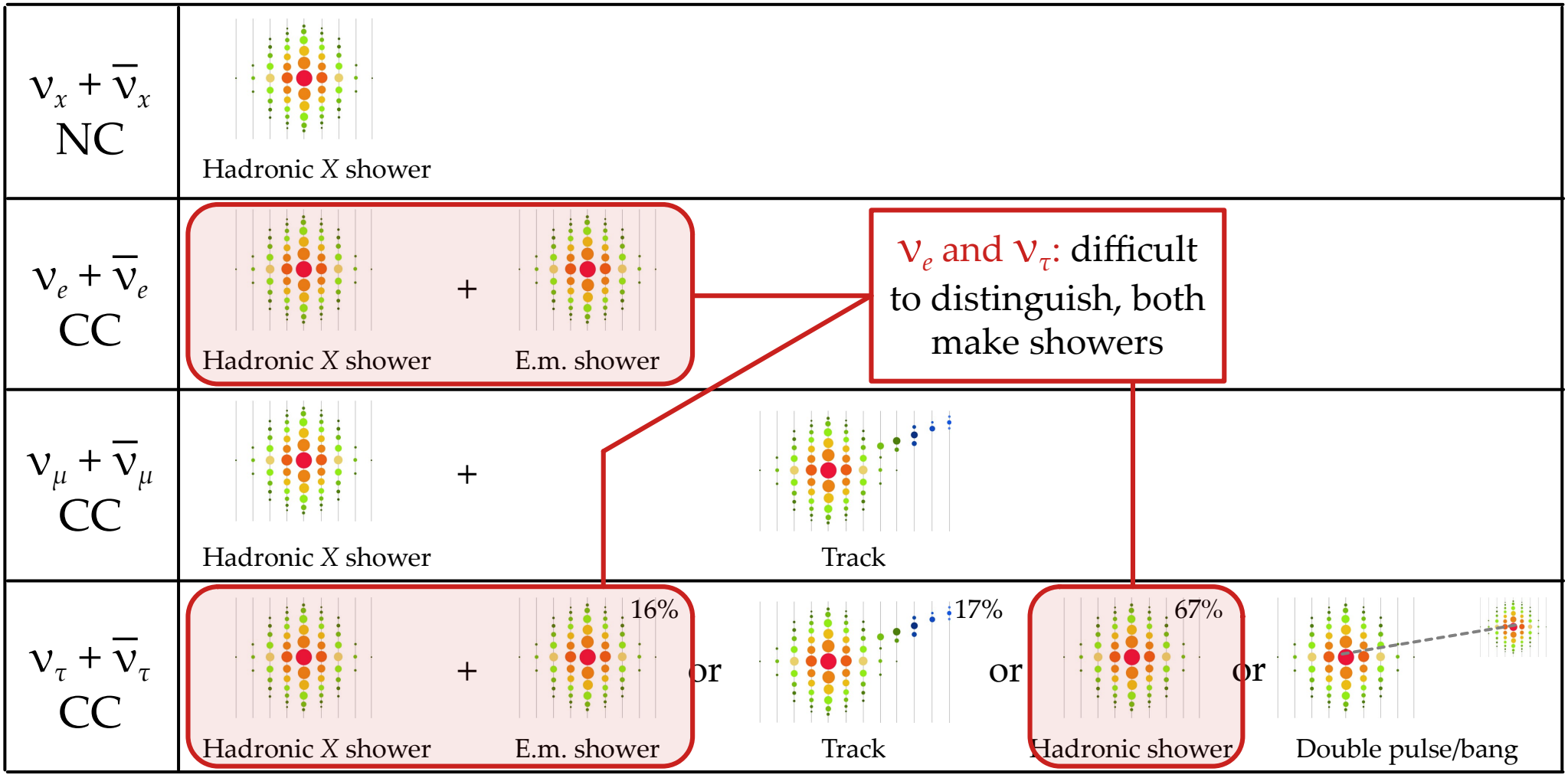

Precision
Colliders
(higher lum.)
Colliders
In 10–20 years
Today
HE
cosmic
particles
HE
cosmic
particles
How?
Event statistics (more detectors)
Identify more sources
New detection techniques
Shrink particle and astro systematics
Energy

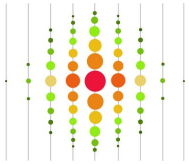
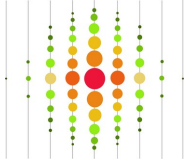
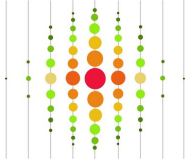
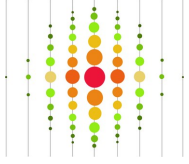
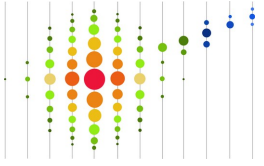
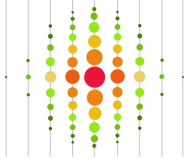
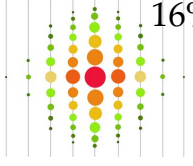
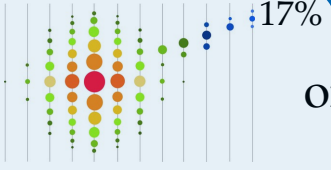
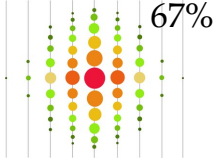
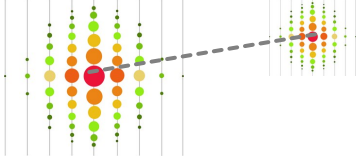
Thank you!

Backup slides

$\nu_x + \bar{\nu}_x$ 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  Hadronic shower 67% or  Double pulse/bang

ν_μ: easy to identify the outgoing track


$\nu_x + \bar{\nu}_x$ 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	+	 E.m. shower	16%	or	 Track	17%	or
								 Hadronic shower
								67%
								or
								 Double pulse/bang

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

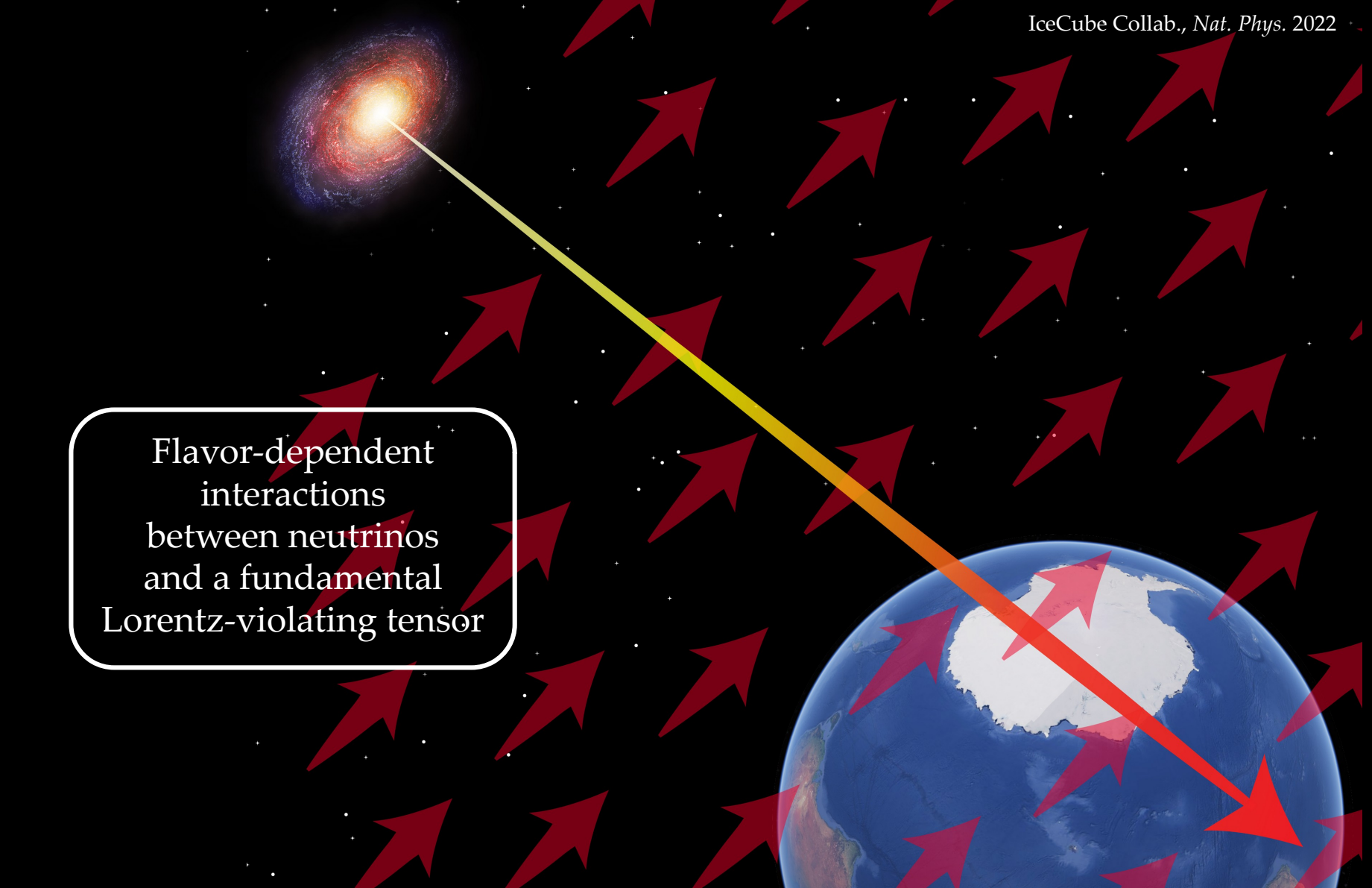
Numerous new ν physics effects grow as ~ $\kappa_n \cdot E^n \cdot L$

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

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

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

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:

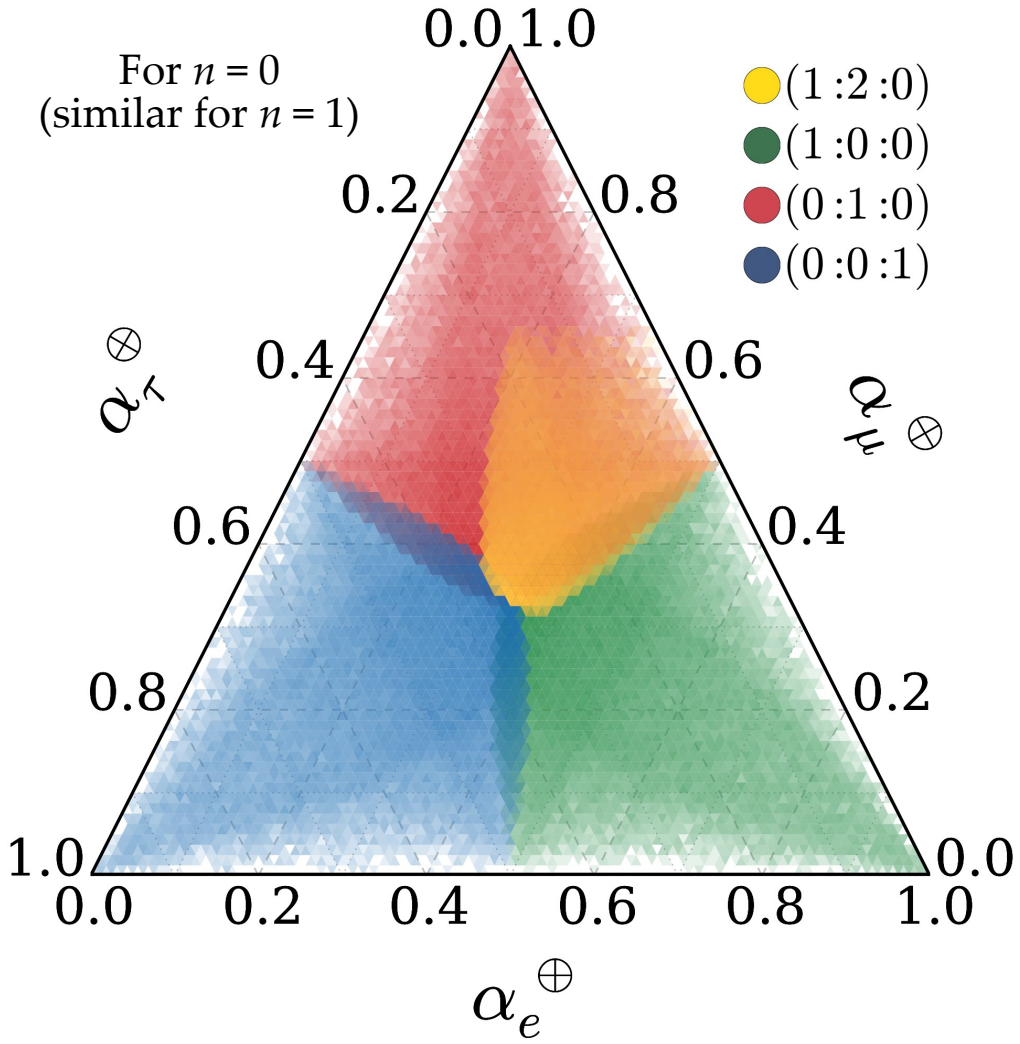
$$H_{\text{tot}} = H_{\text{std}} + H_{\text{new}}$$

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

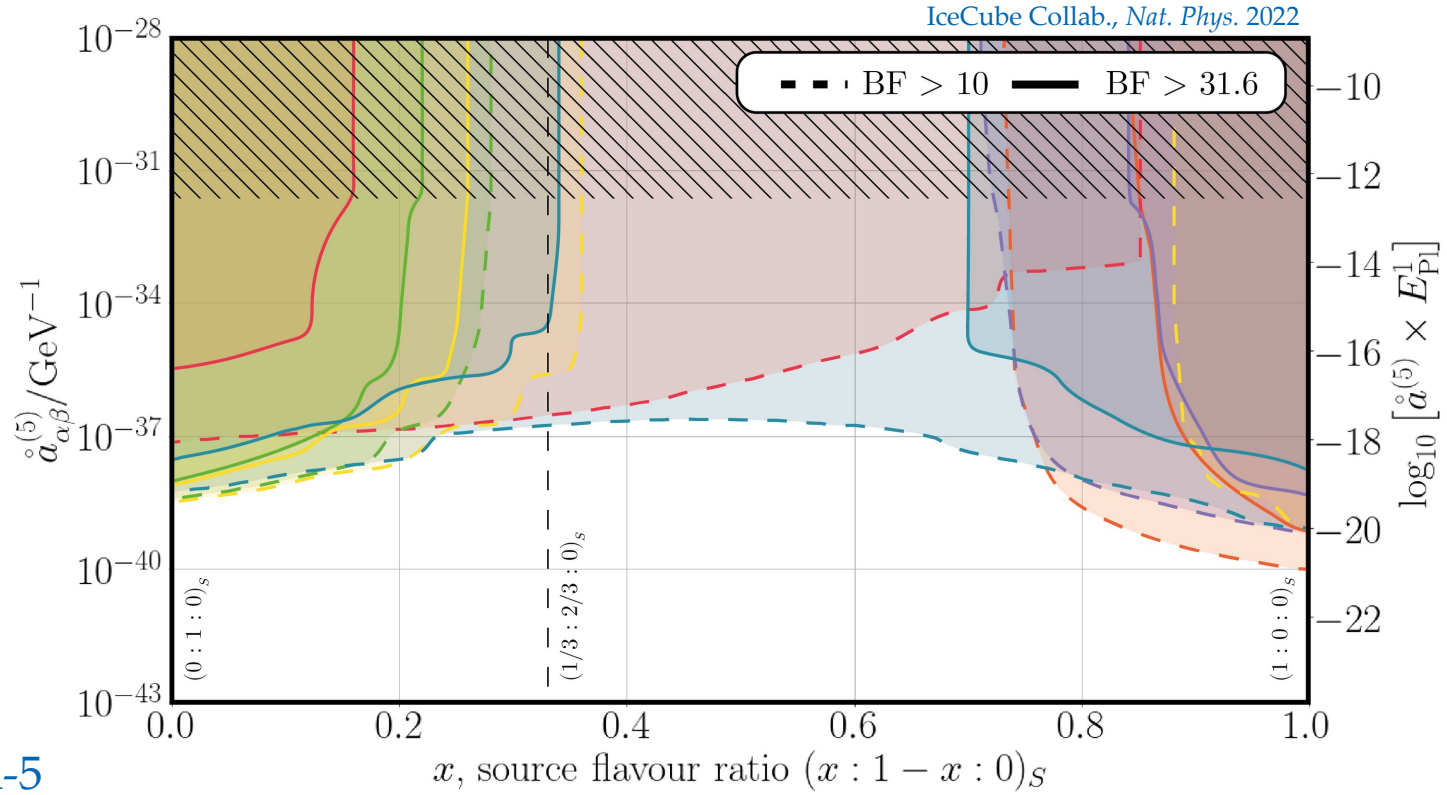
but now the lepton mixing matrix, U_{tot}, is the one that diagonalizes H_{tot}



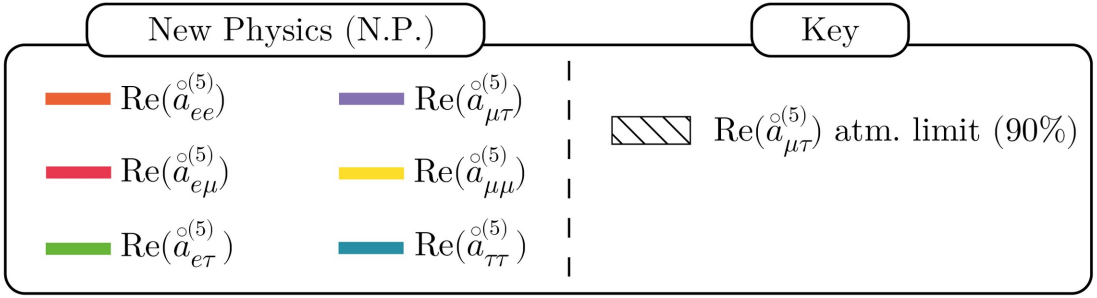
Argüelles, Katori, Salvadó, *PRL* 2015

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

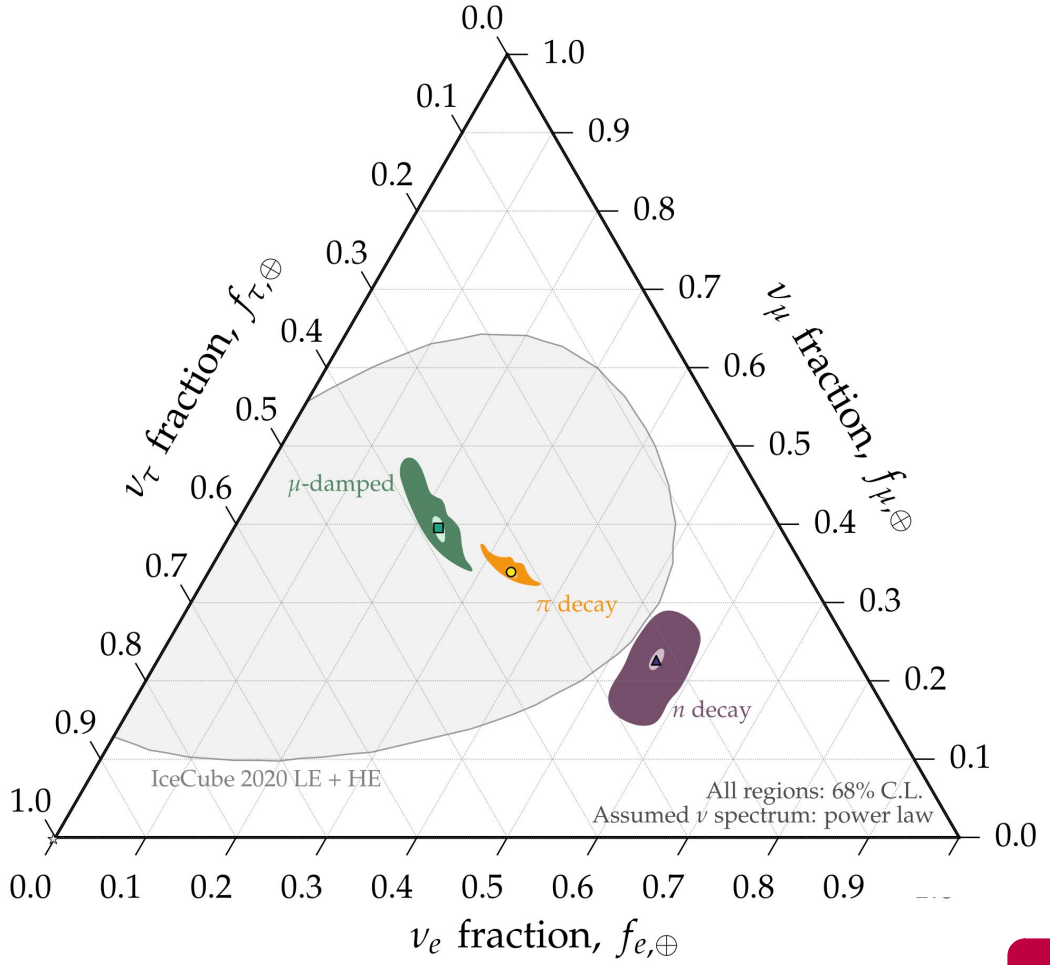


Dimension-5 CPT-odd isotropic Lorentz-invariance -violating coefficient



Energy-dependent flavor composition

Flavor composition: measuring the energy dependence



Liu, Fiorillo, Argüelles, **MB**, Song, Vincent, 2312.07649

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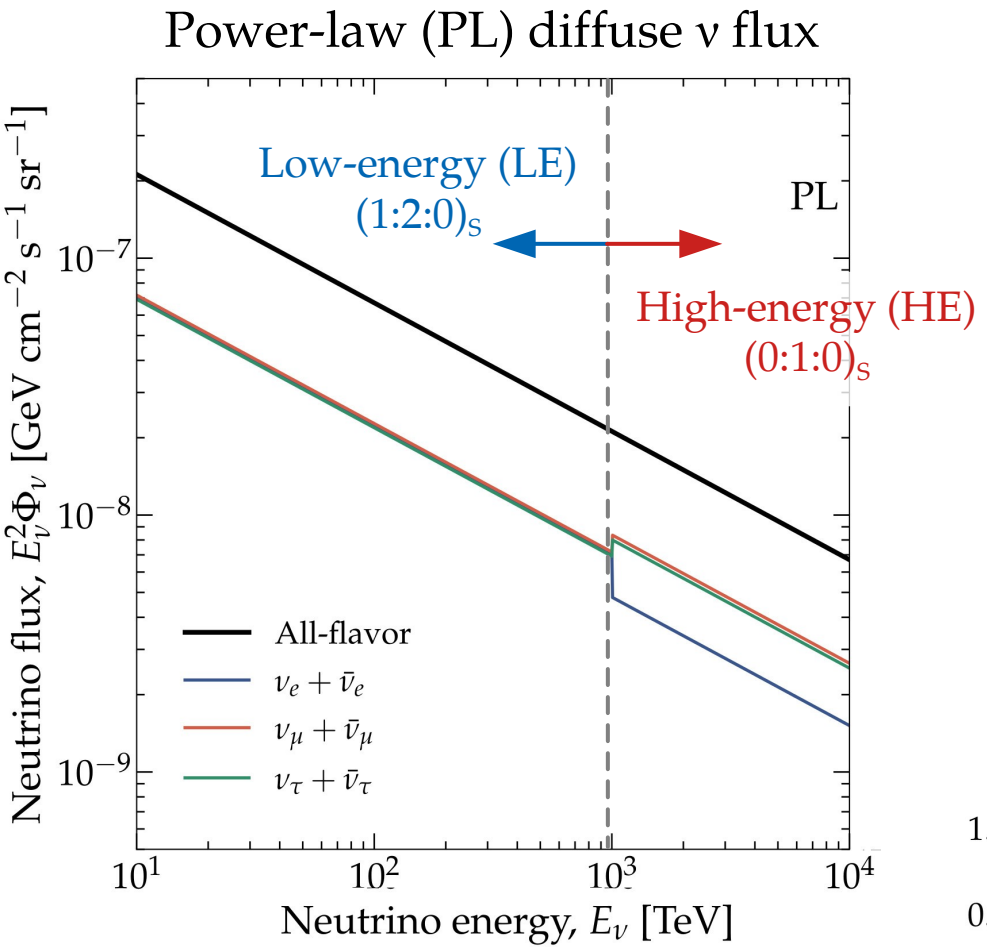
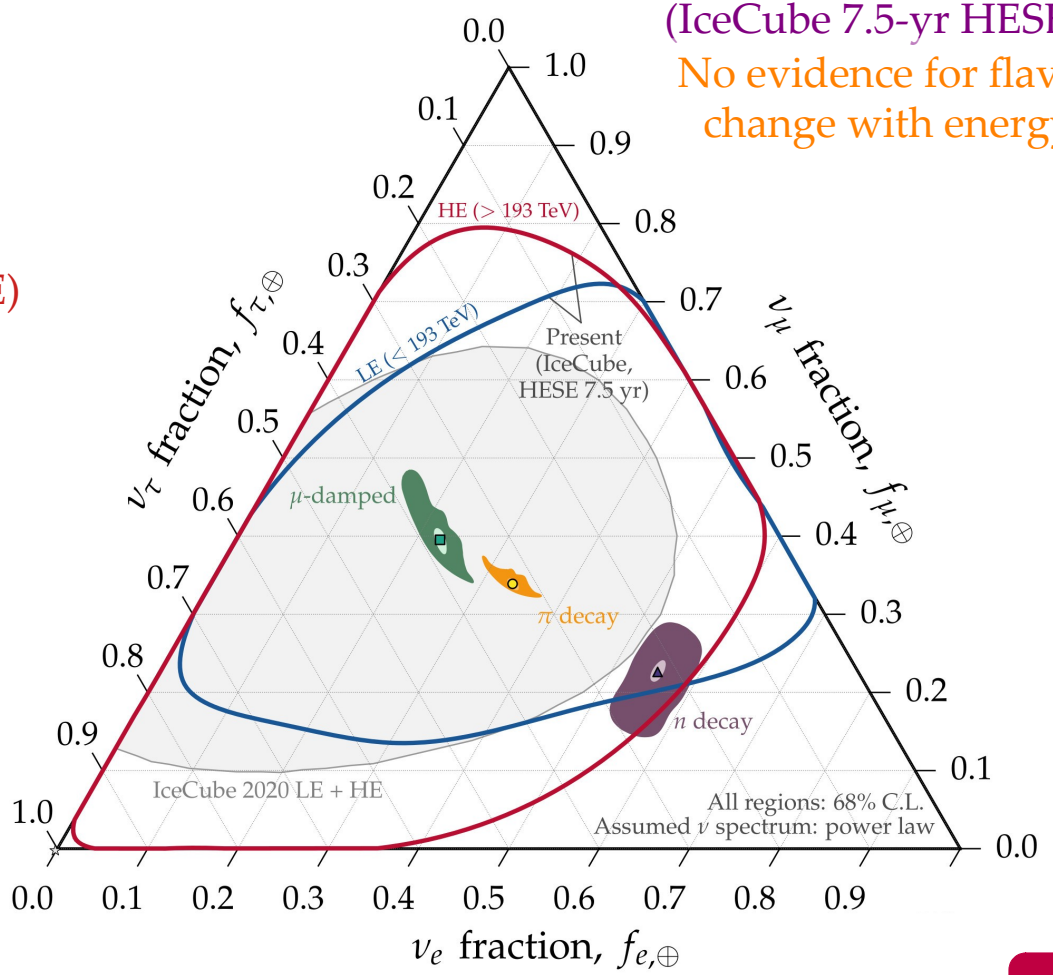


Today
(IceCube 7.5-yr HESE):
No evidence for flavor change with energy



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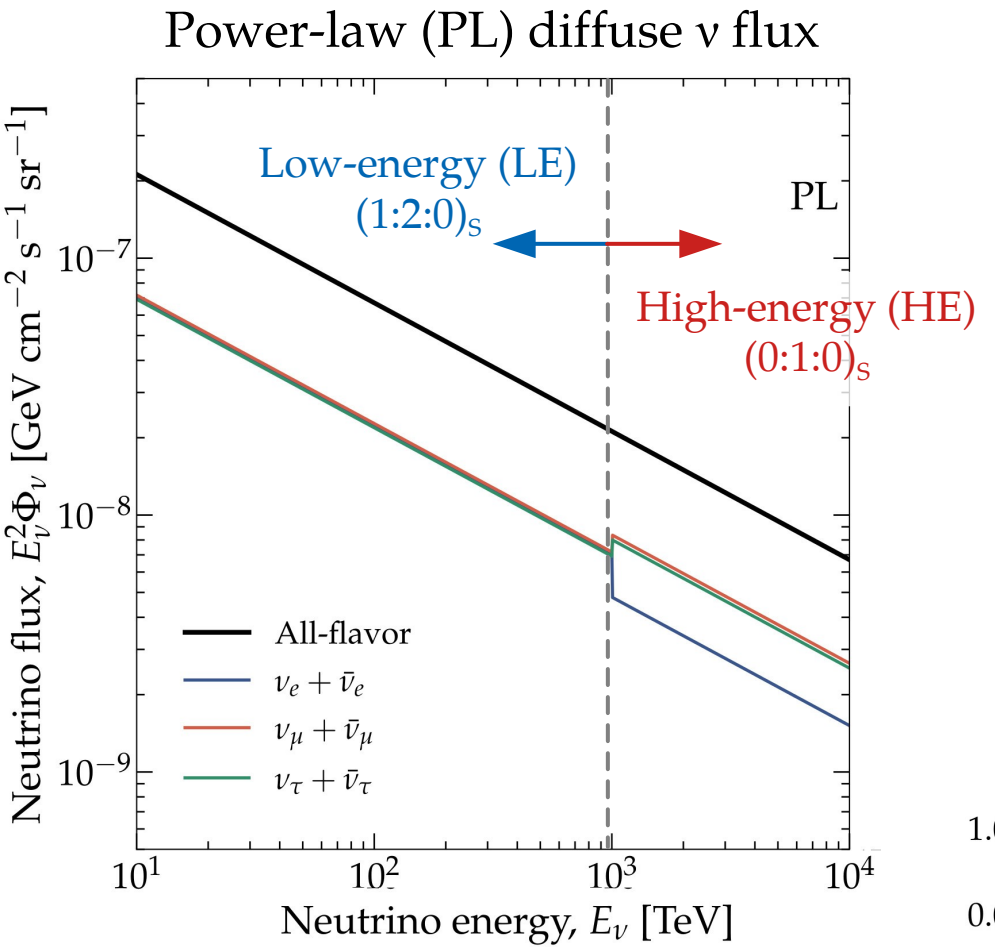
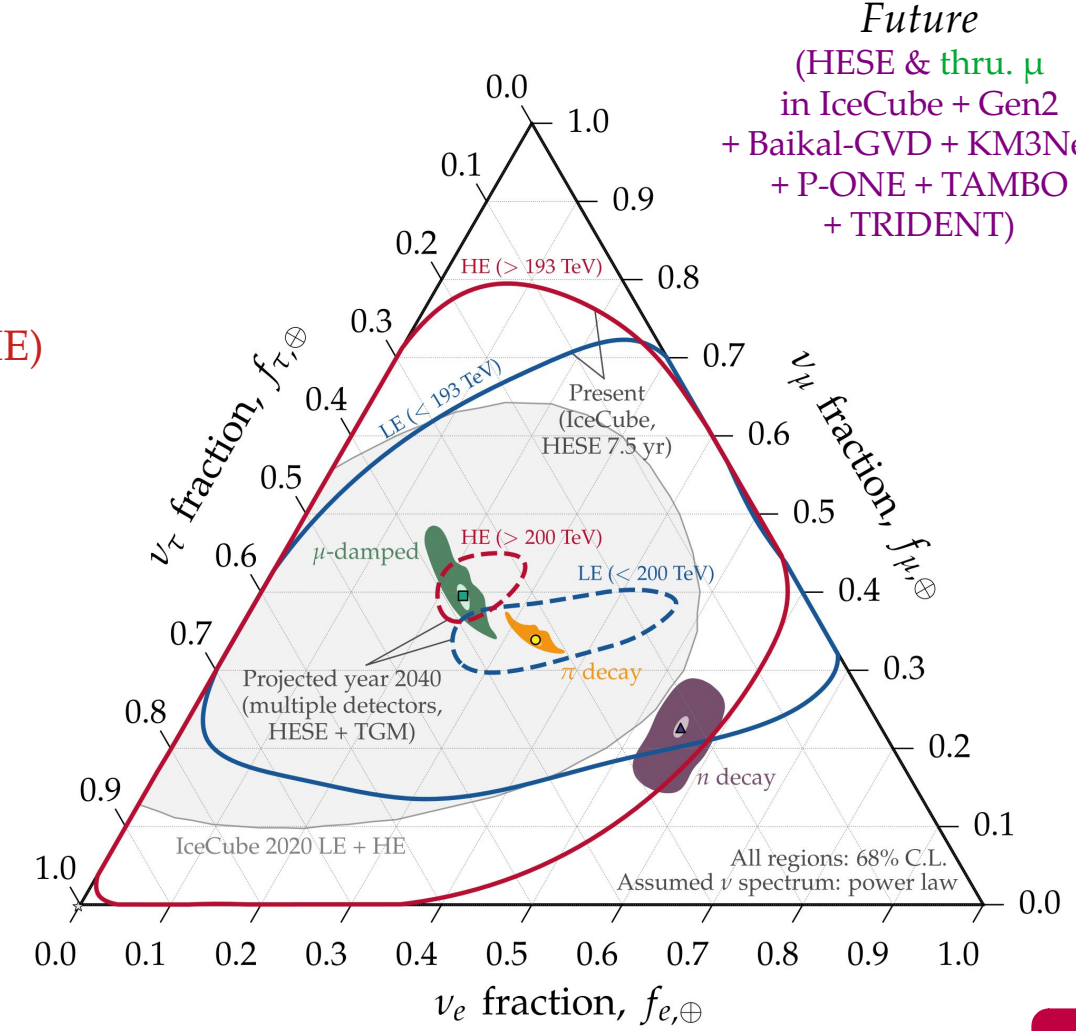




Liu, Fiorillo, Argüelles, **MB**, Song, Vincent, 2312.07649

Flavor composition: measuring the energy dependence

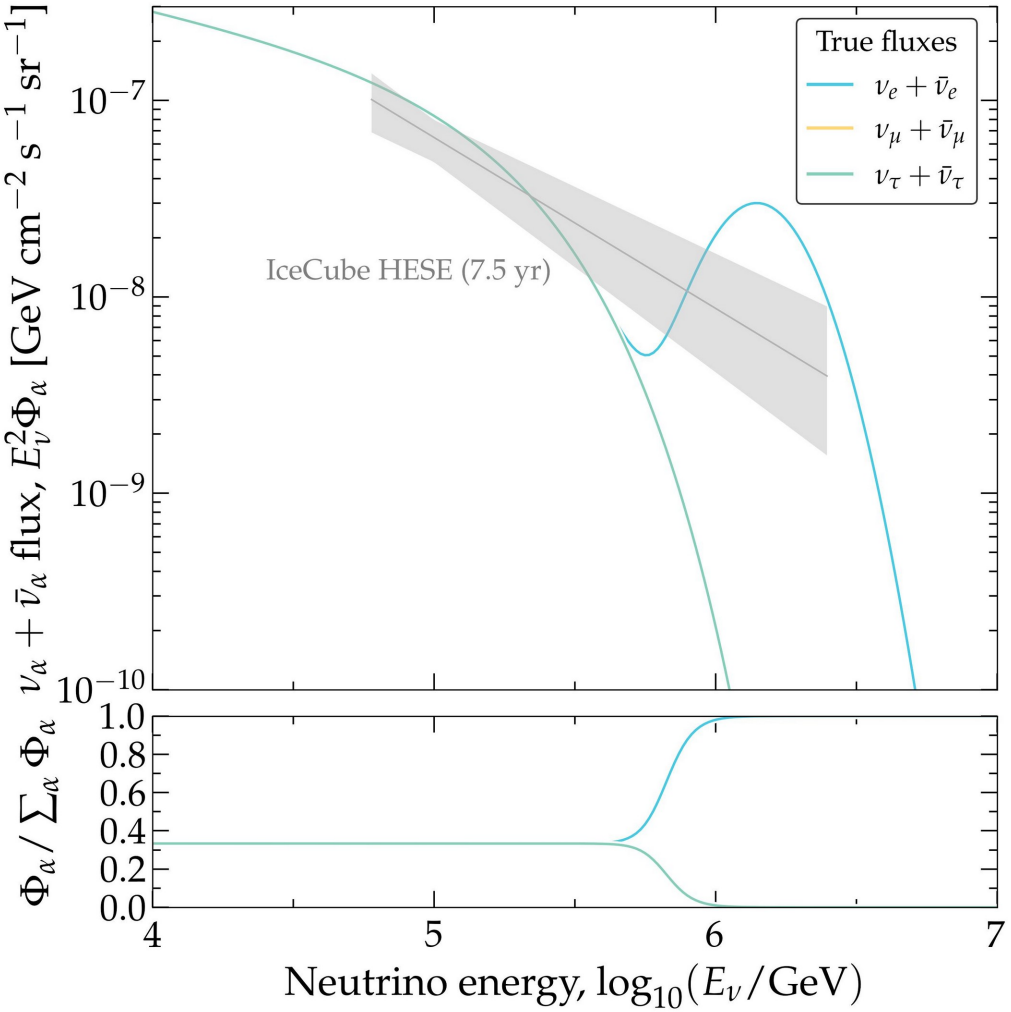
Can we do better?

Maybe

— If we do not try to pinpoint the energy of flavor transition

How?

— Infer the spectrum of ν_e, ν_μ, ν_τ separately



Liu, ***MB***, *In prep.*

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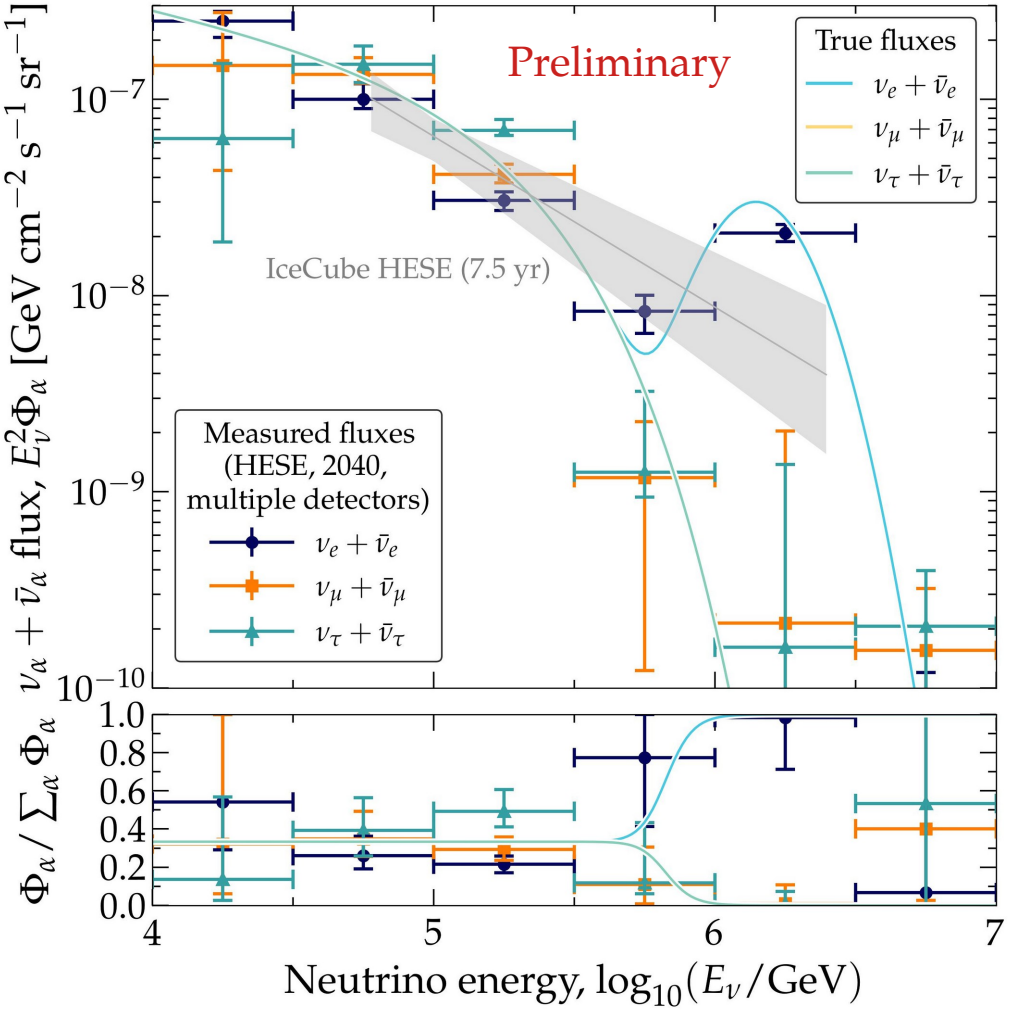
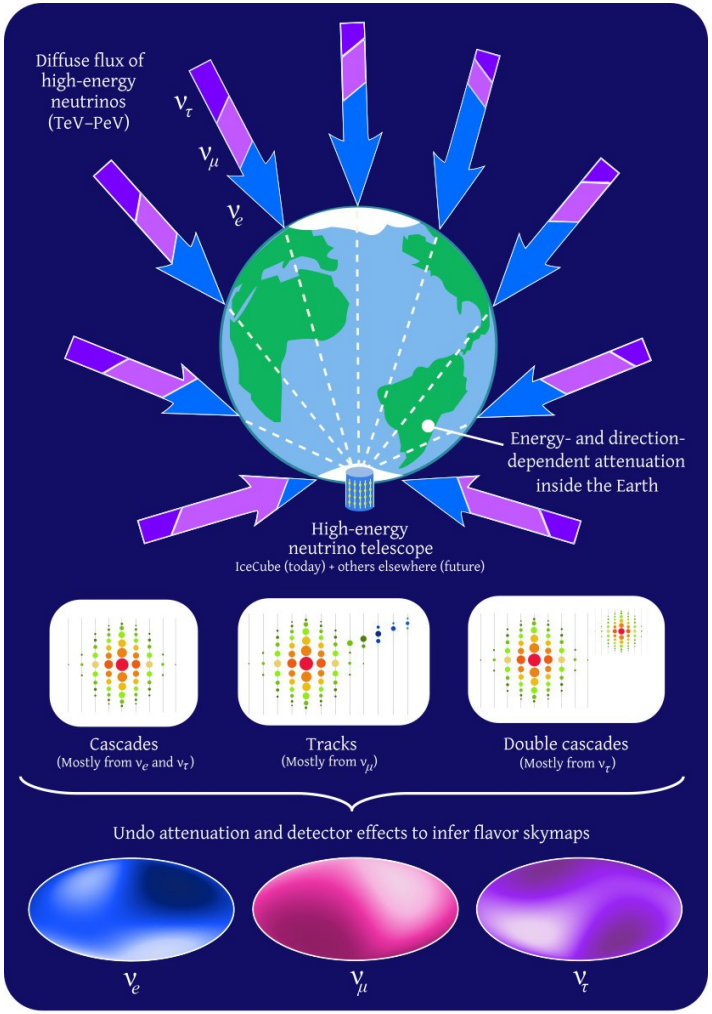


Liu, **MB**, *In prep.*

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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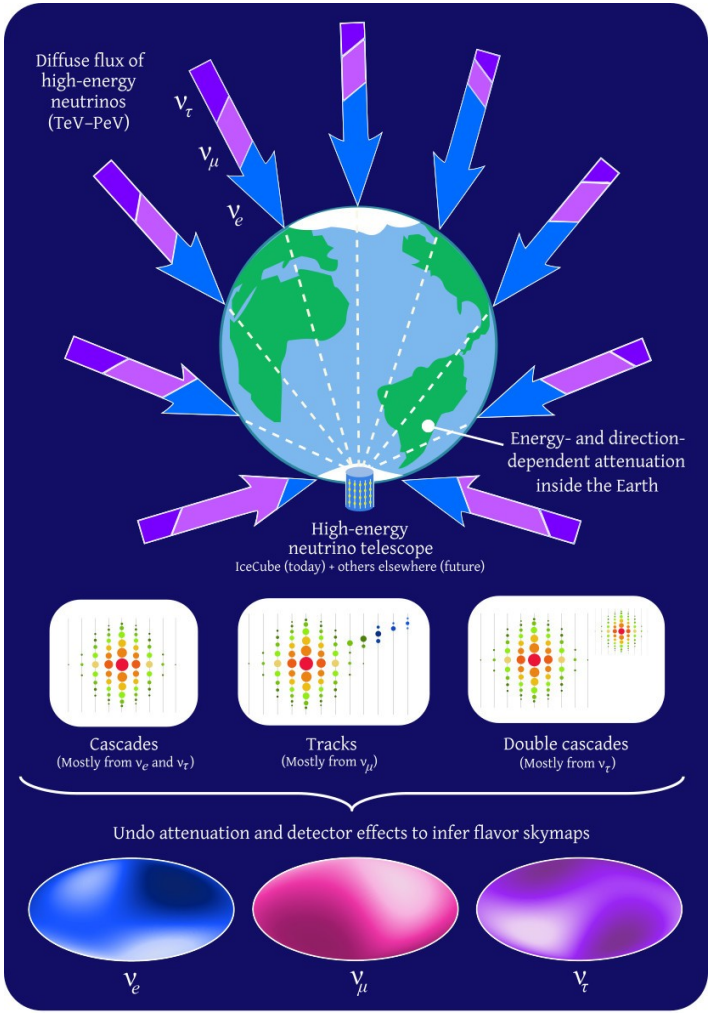

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Telalovic, **MB**, *JCAP* 2025

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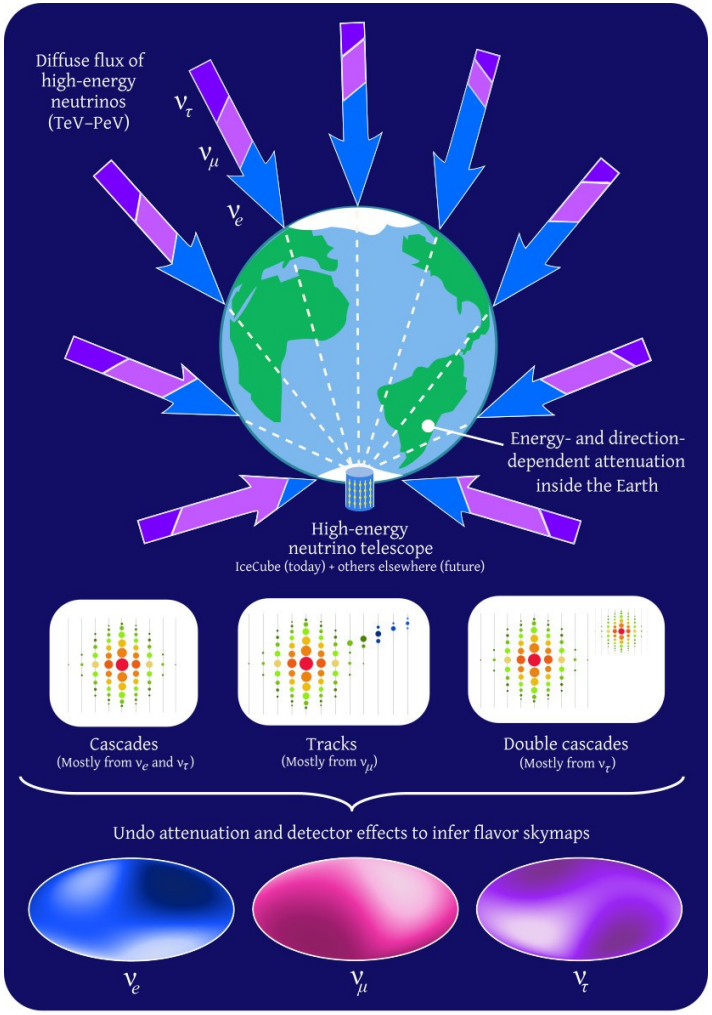

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Telalovic, **MB**, *JCAP* 2025

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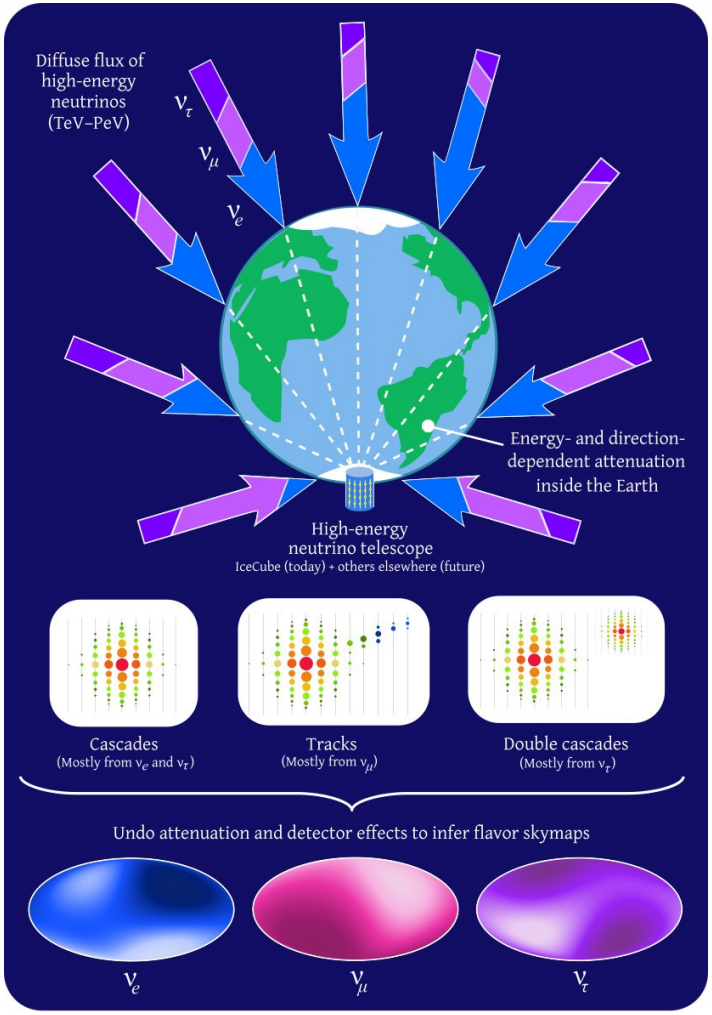

Does the high-energy sky shine equally brightly In neutrinos of all flavors?

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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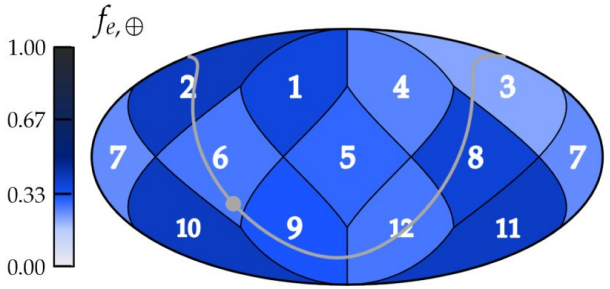

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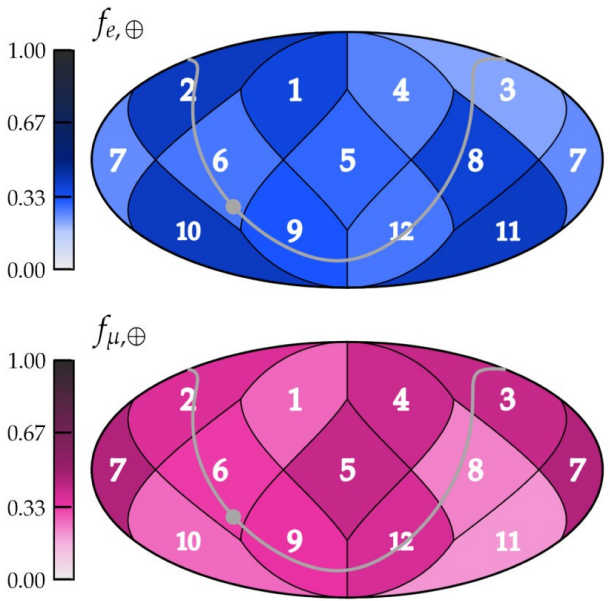

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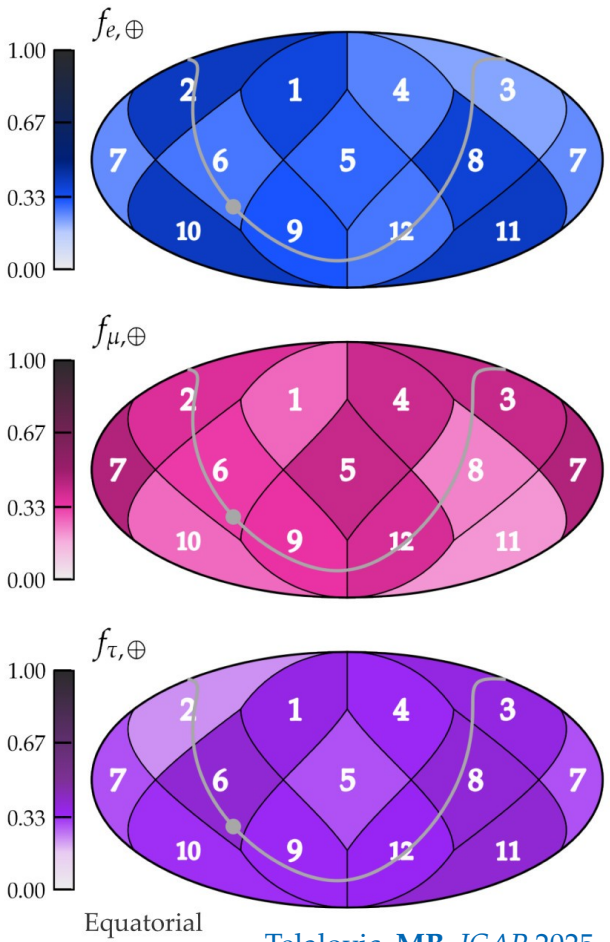

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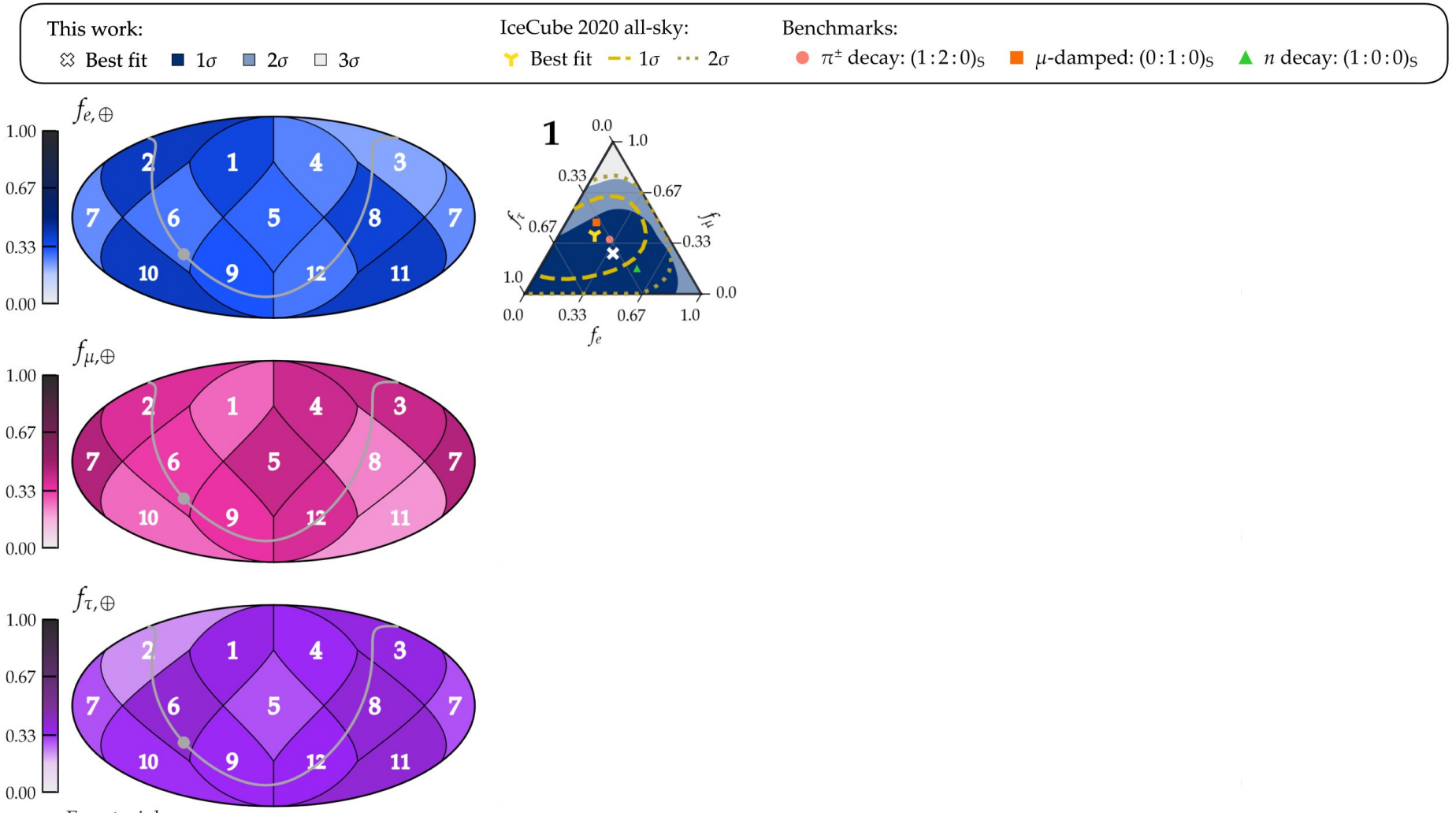

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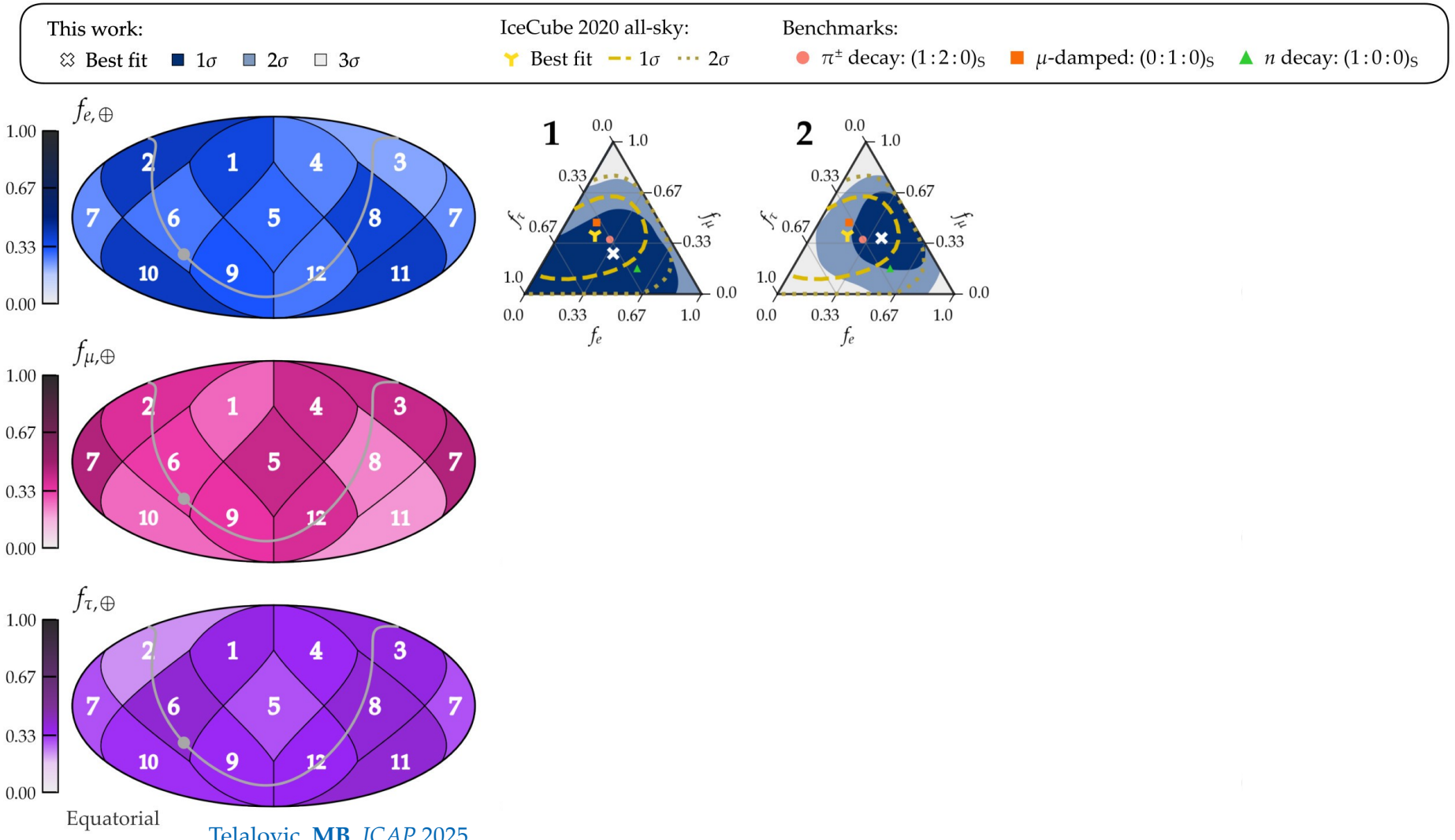

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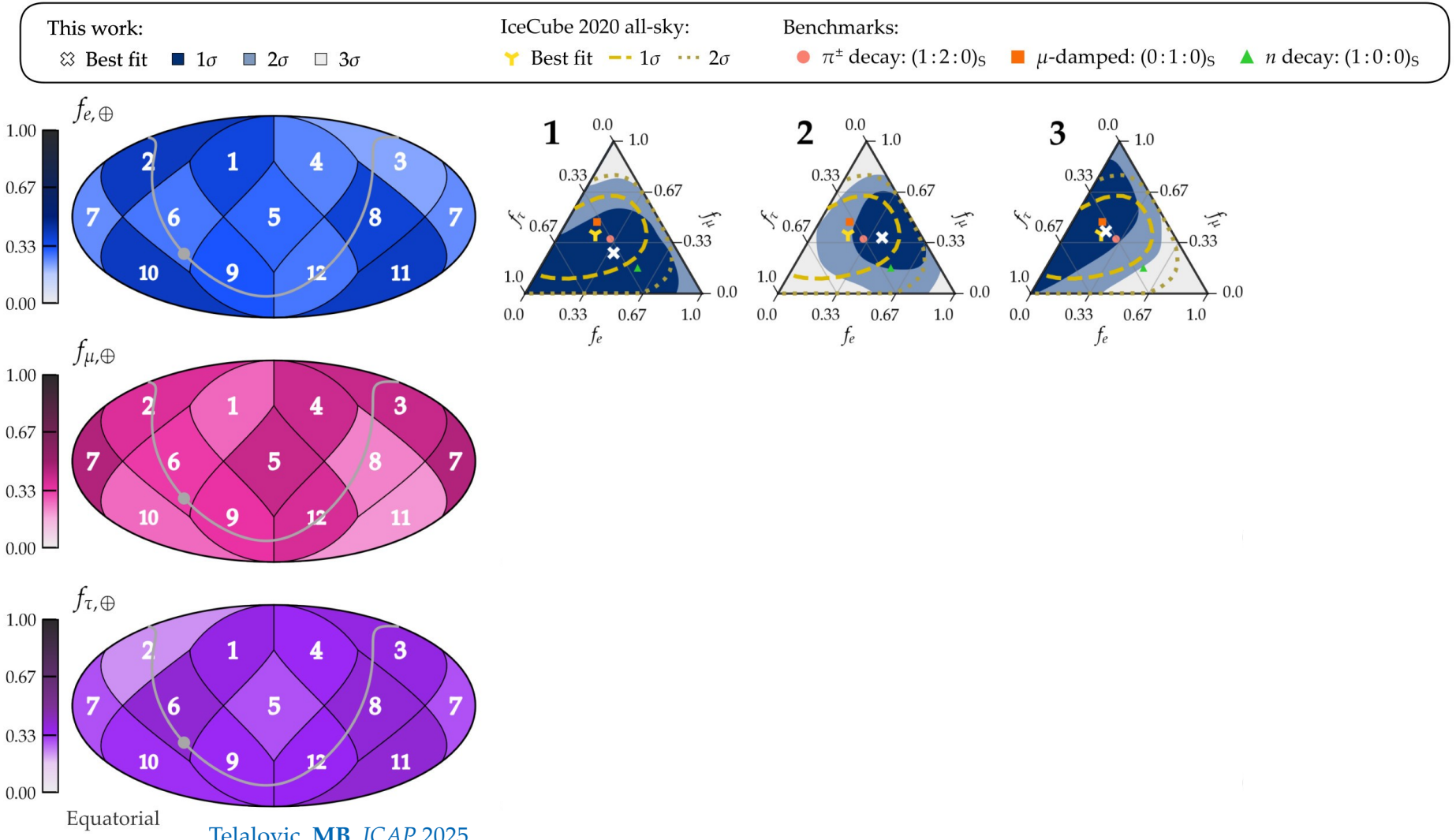

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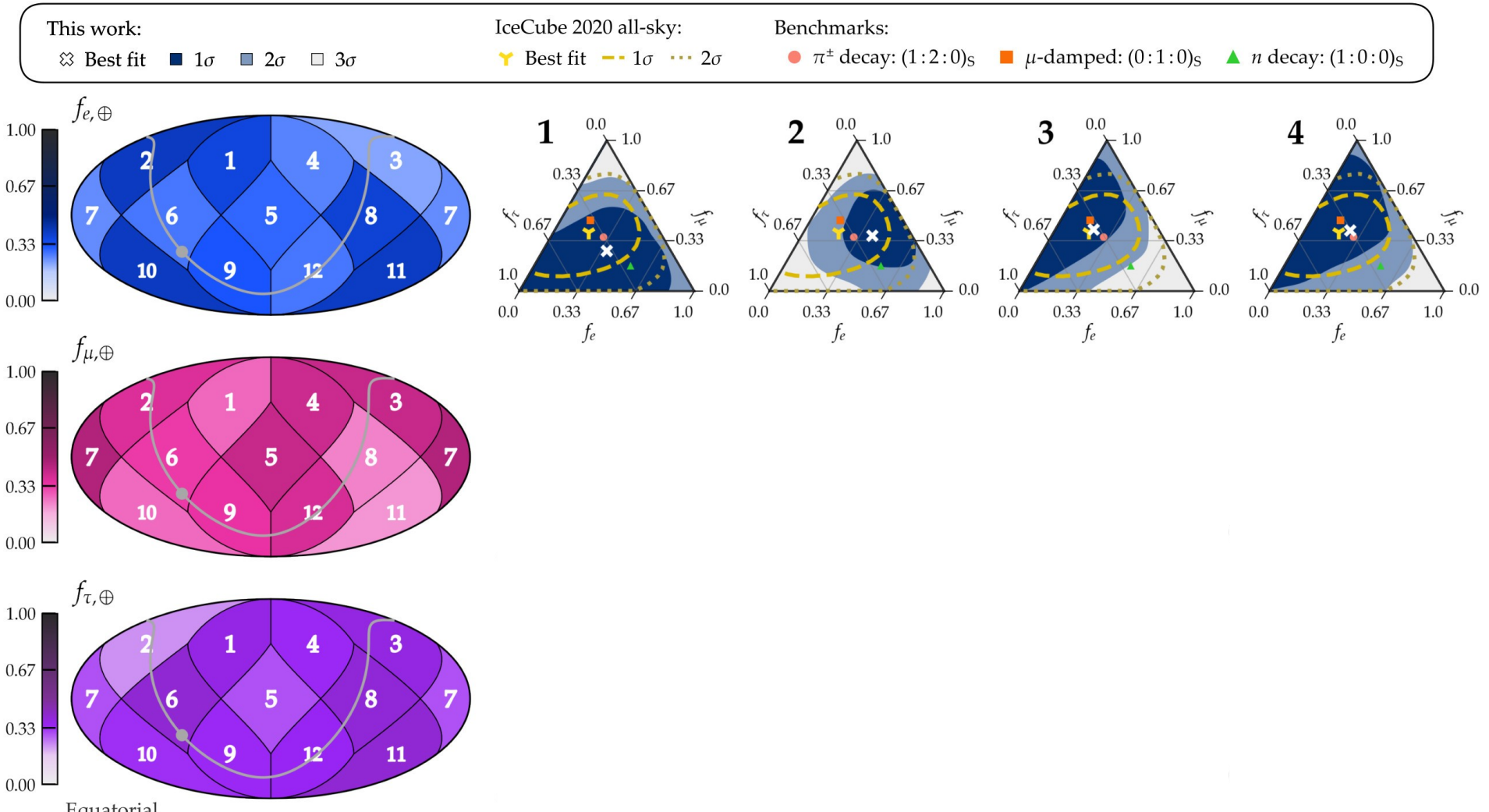

Telalovic, **MB**, *JCAP* 2025

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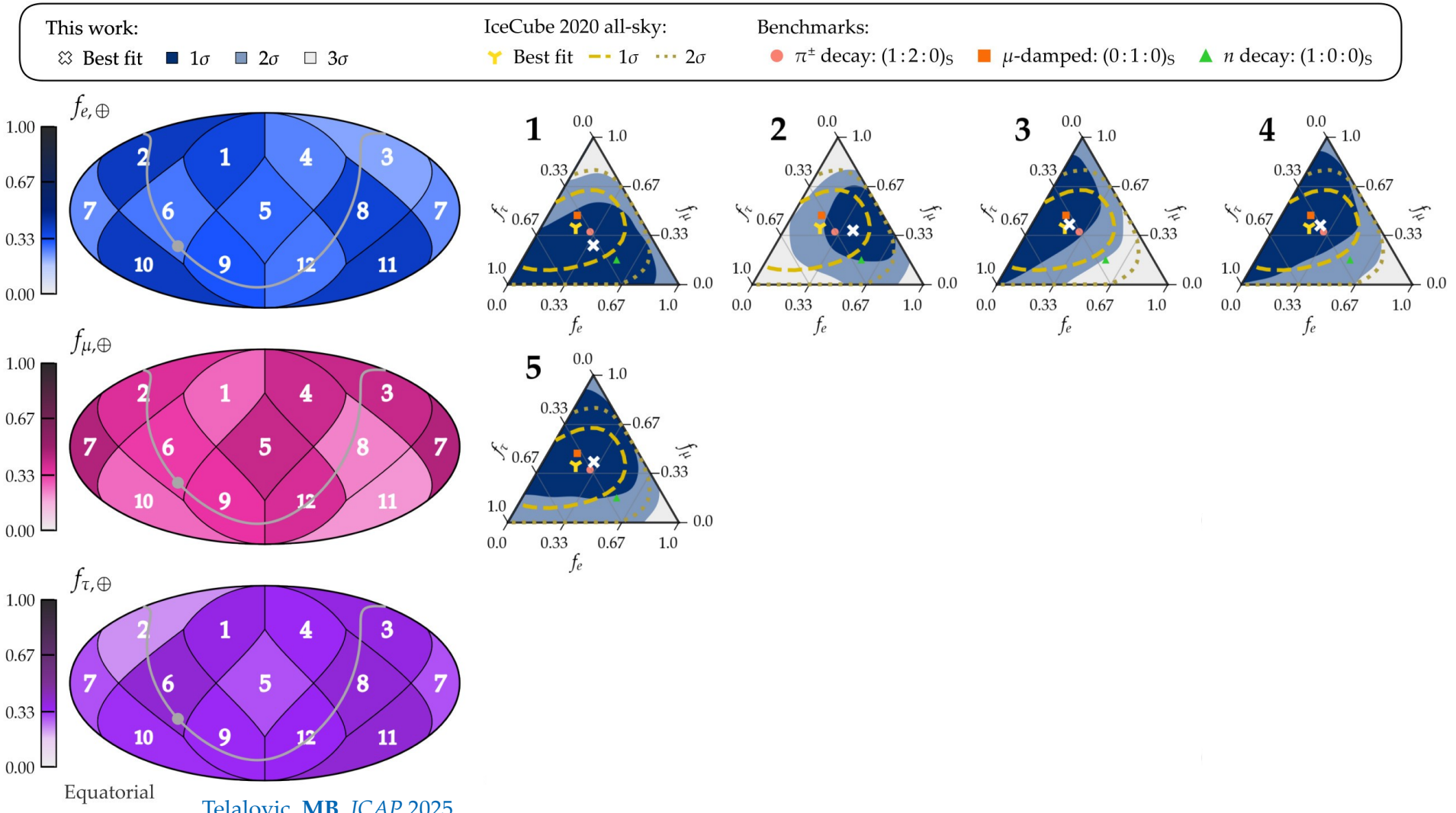

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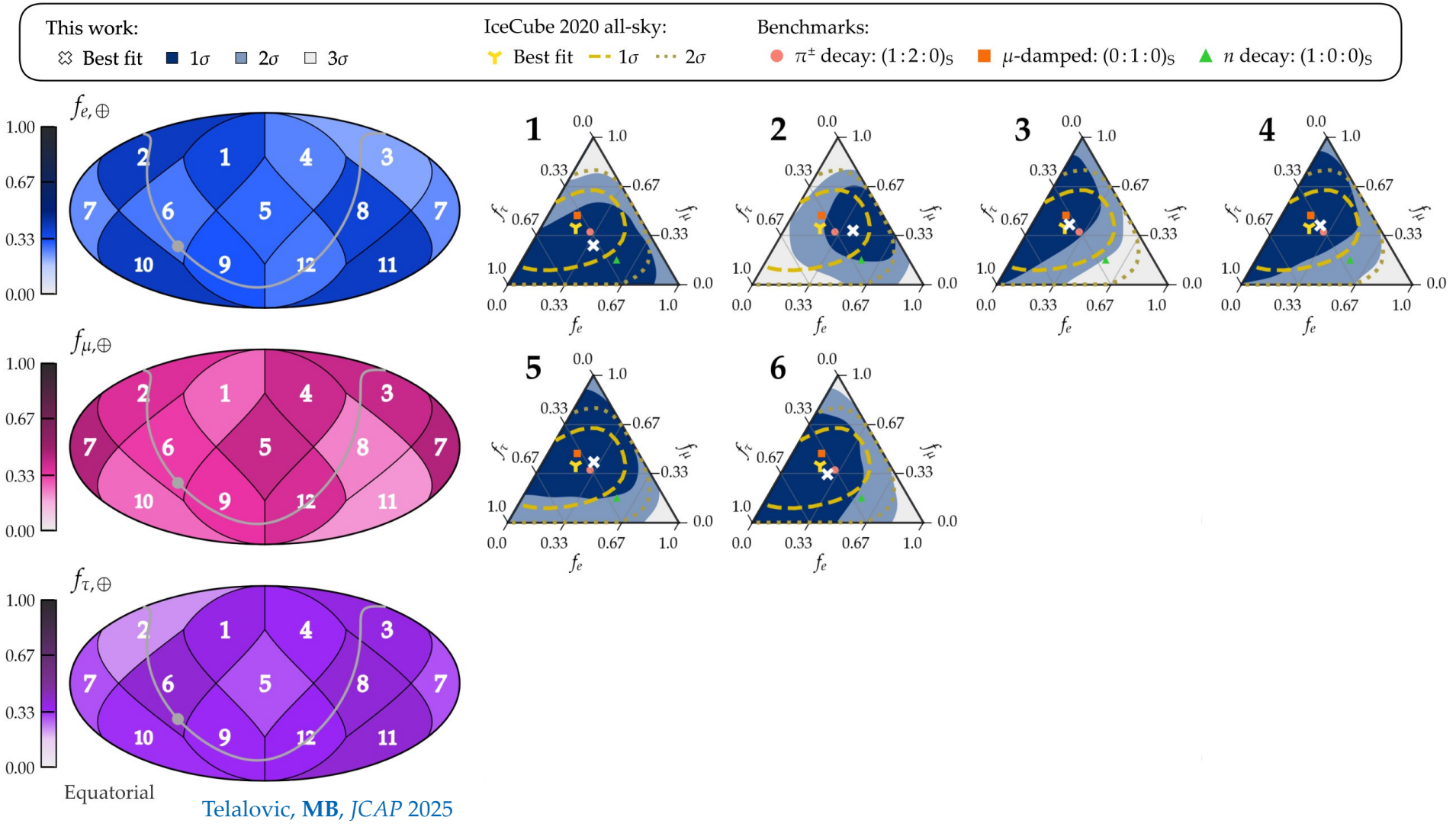

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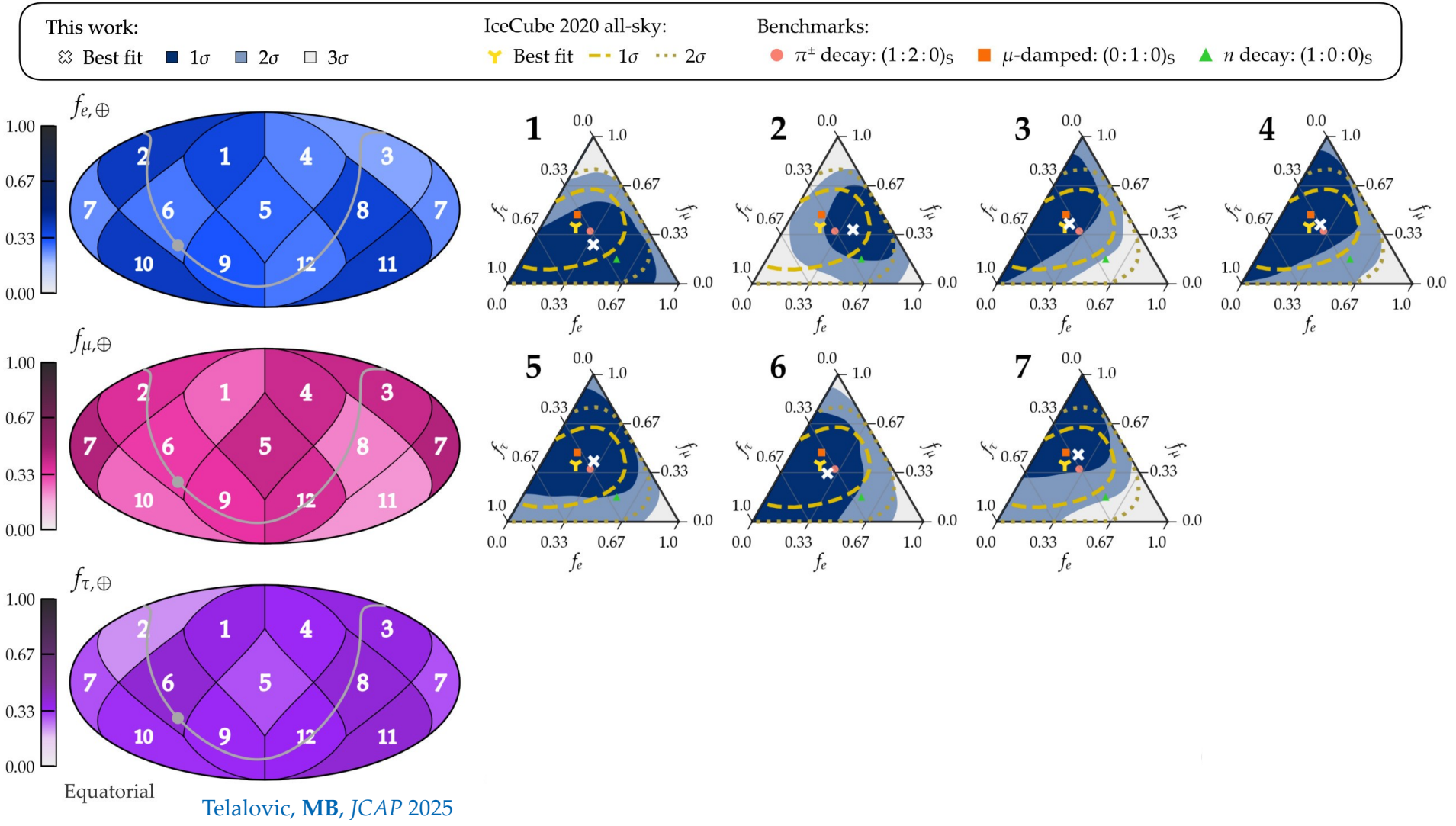

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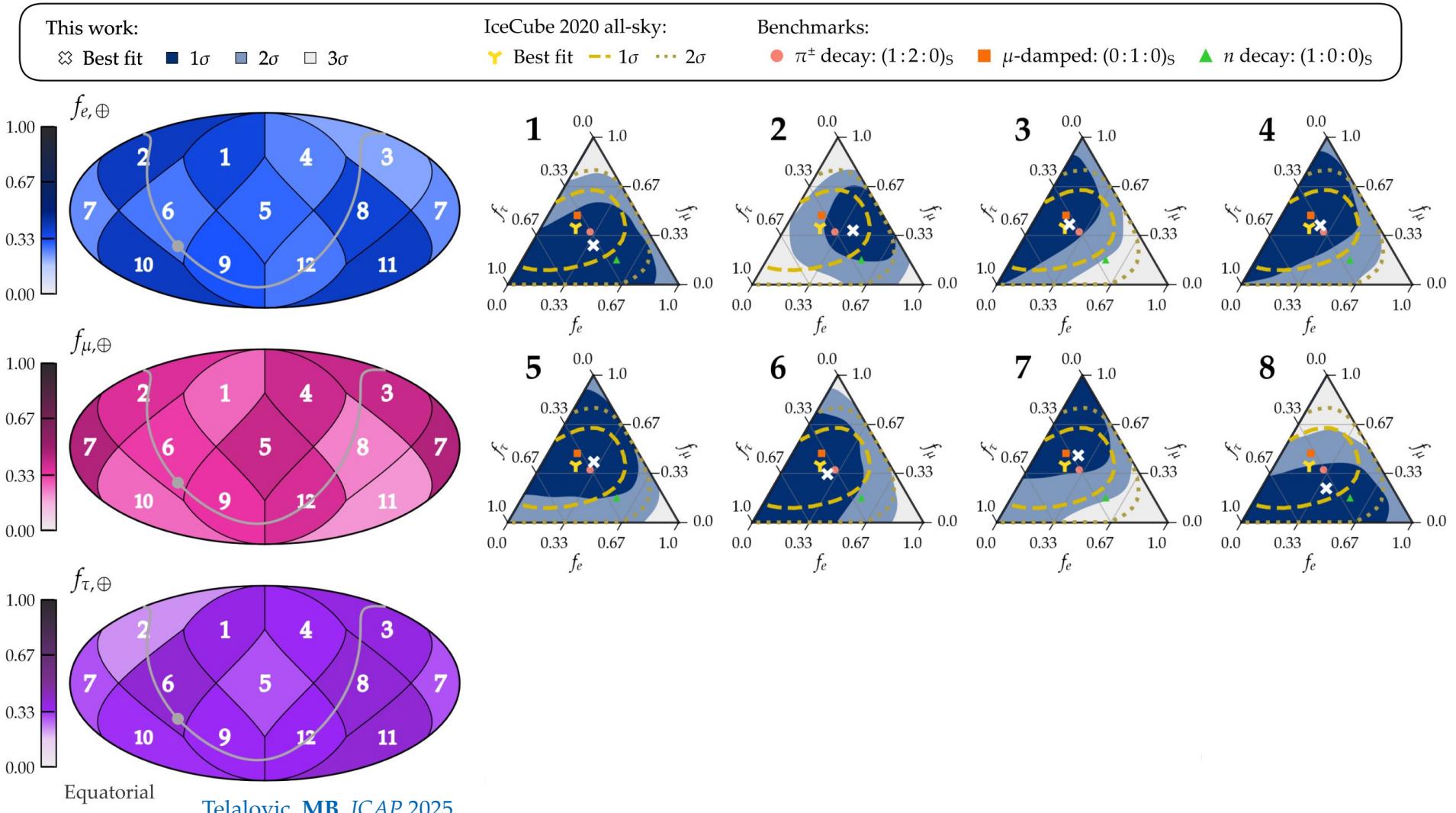

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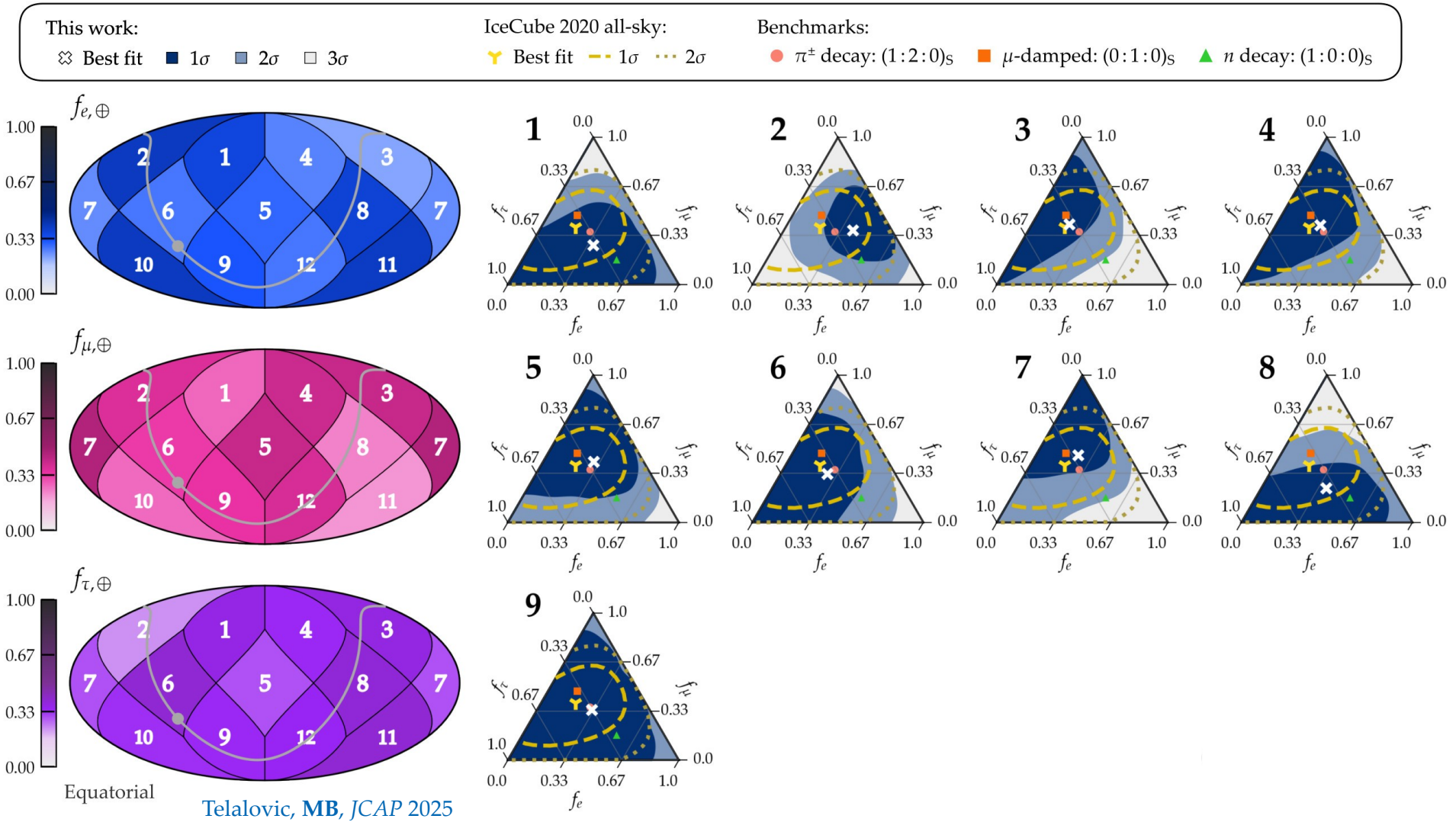

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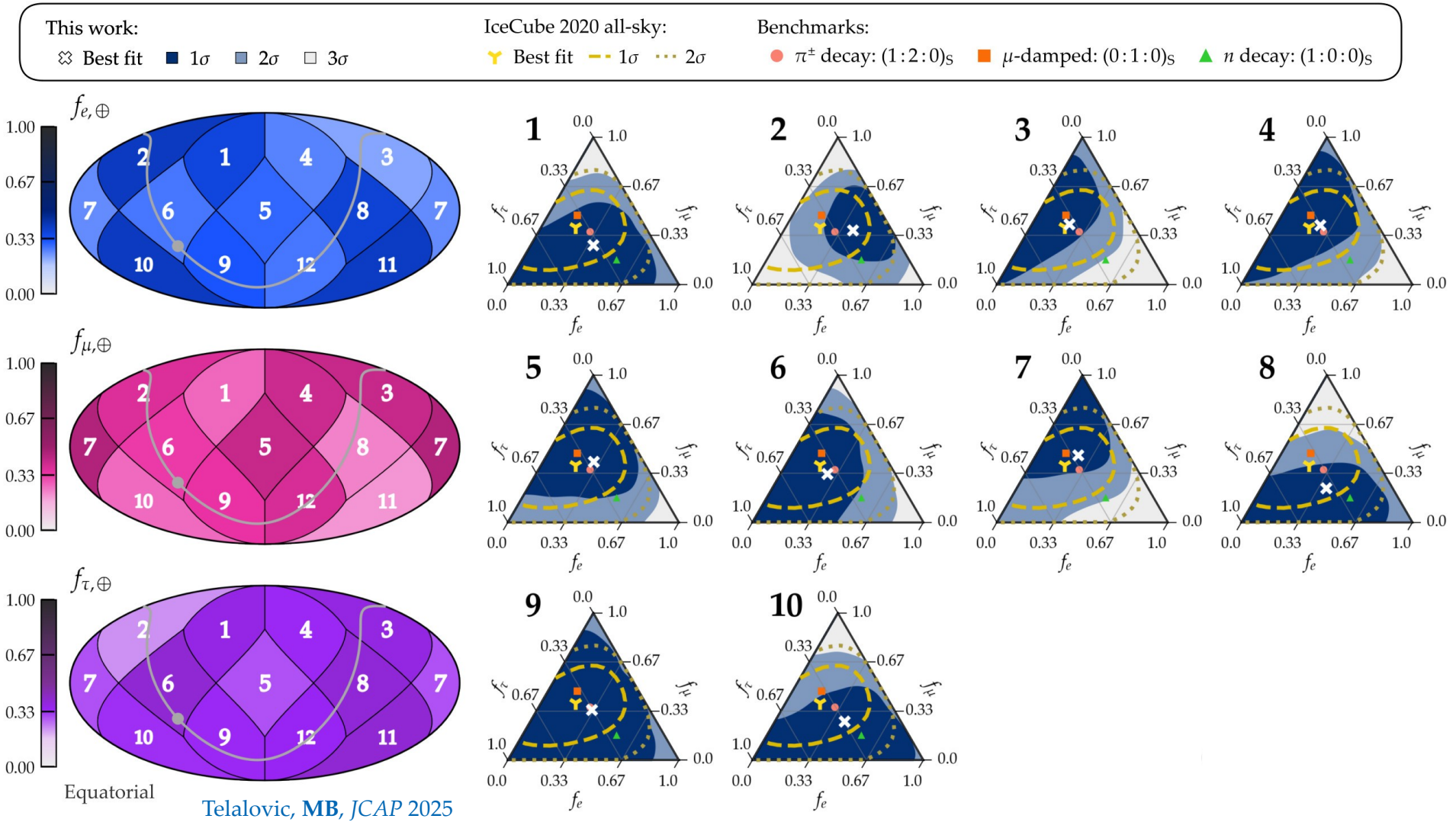

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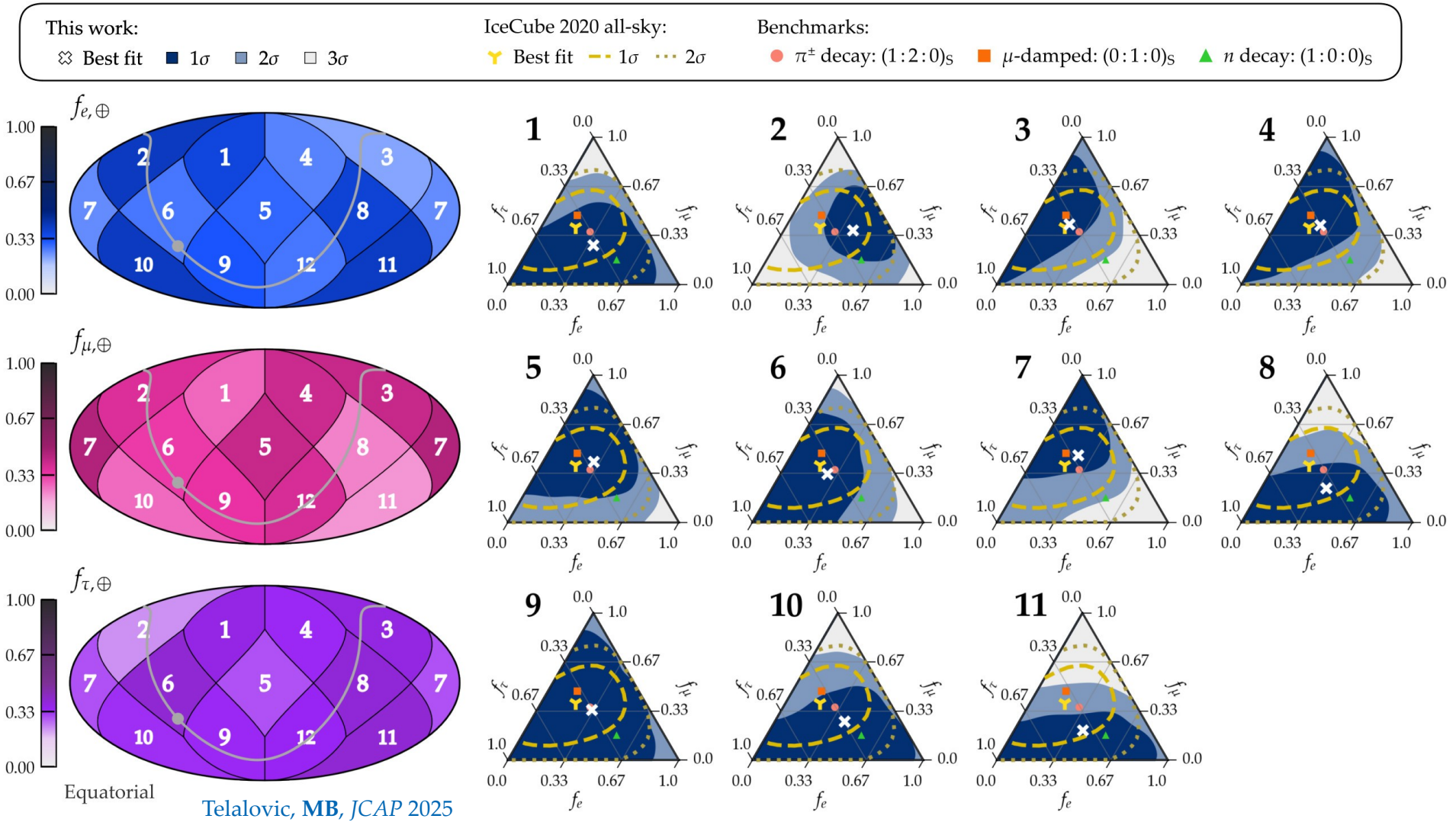

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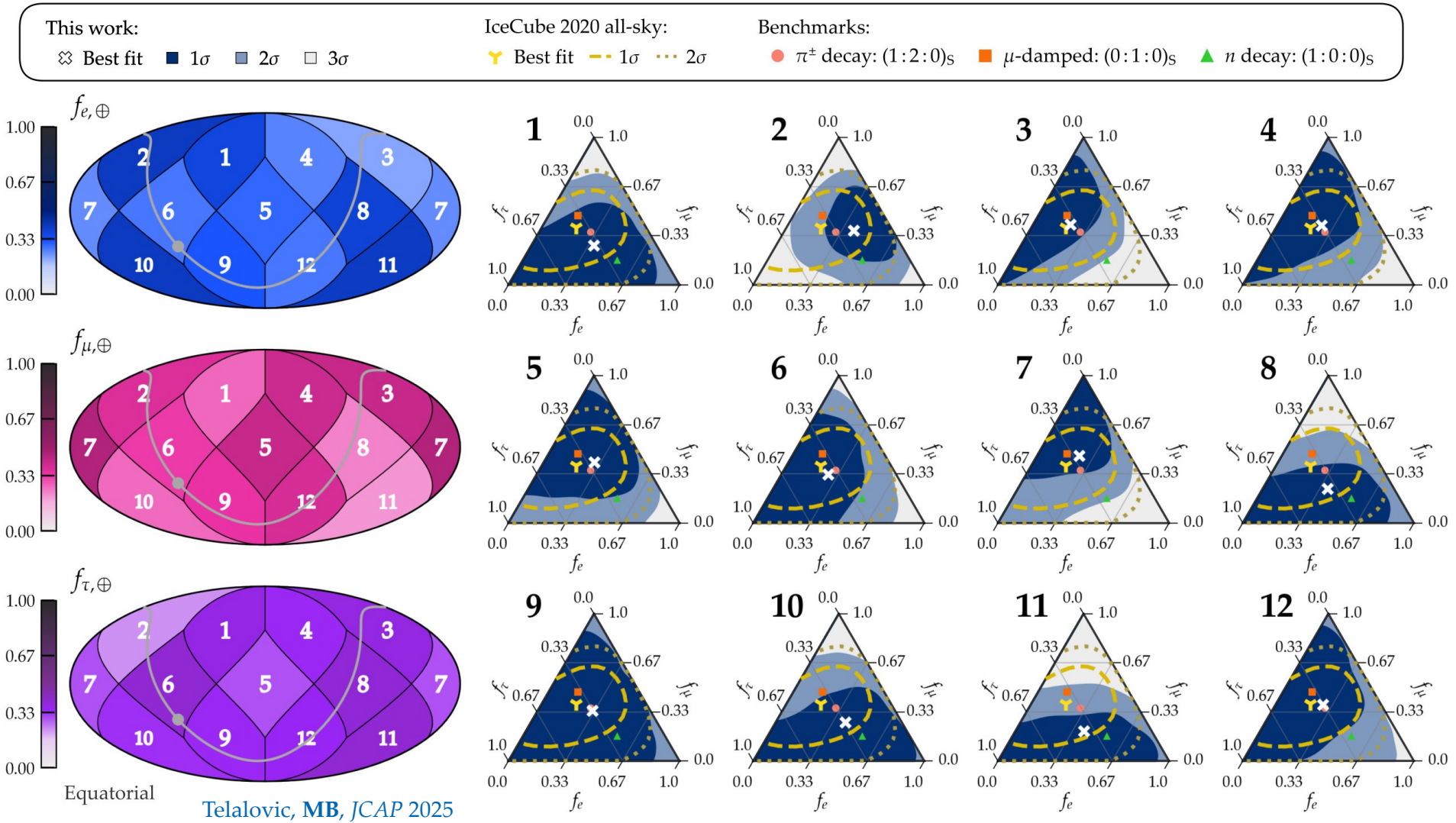


Telalovic, **MB**, *JCAP* 2025

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

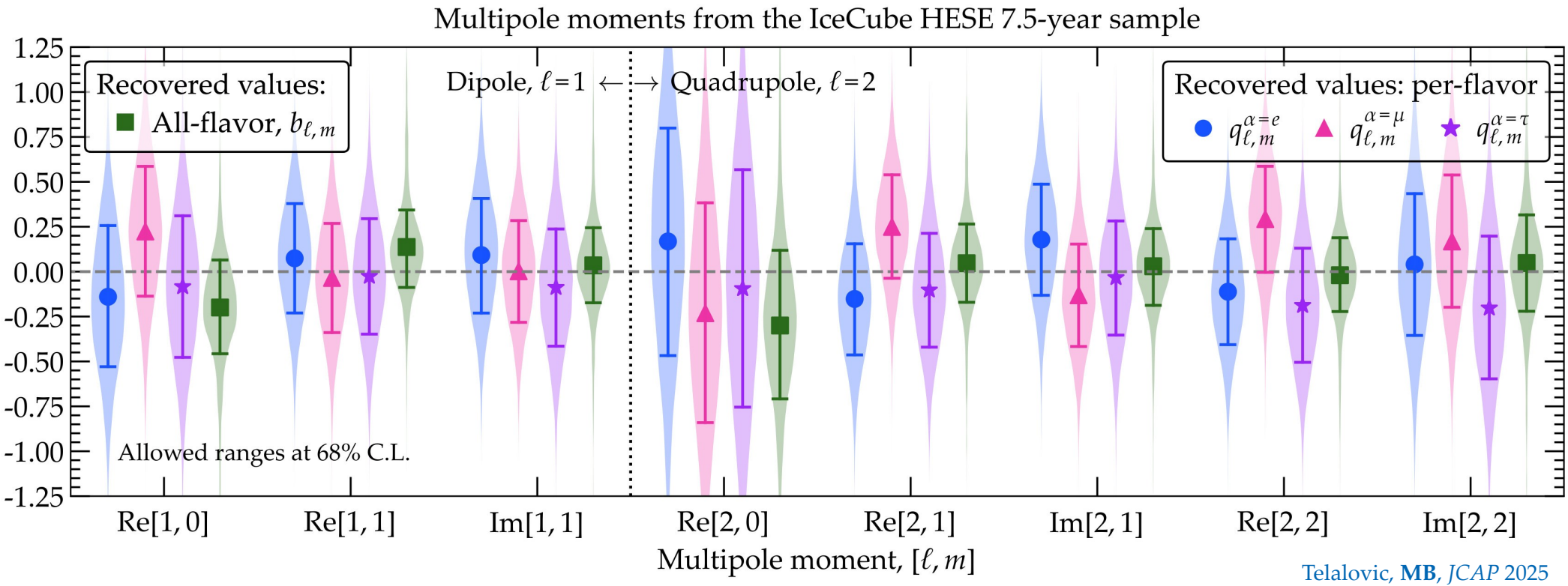
Telalovic, MB, 2310.15224

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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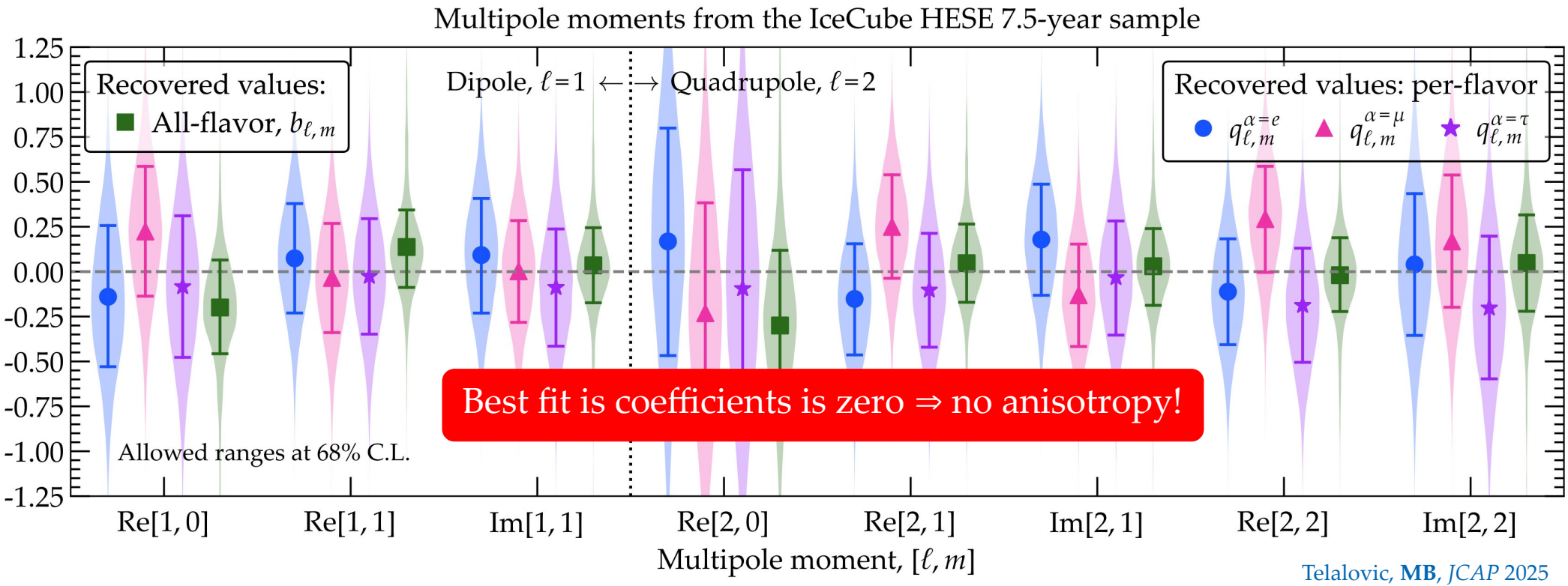

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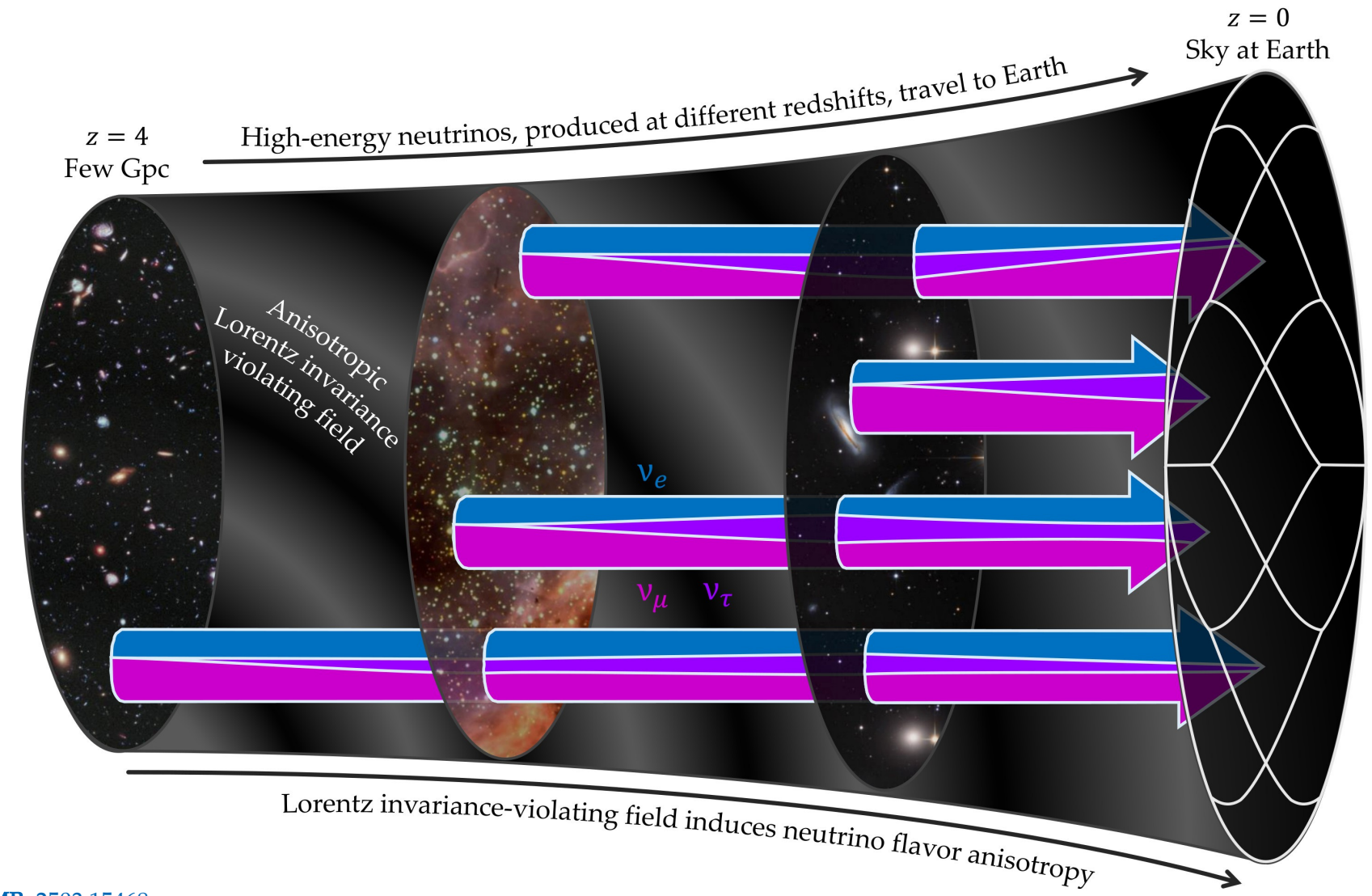

Telalovic, **MB**, 2503.15468

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

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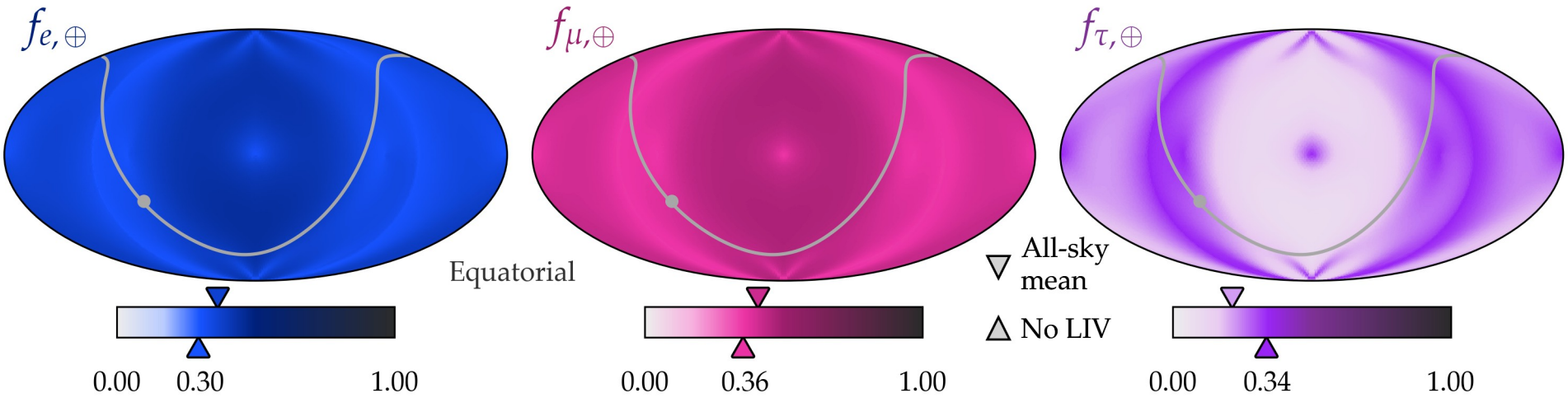

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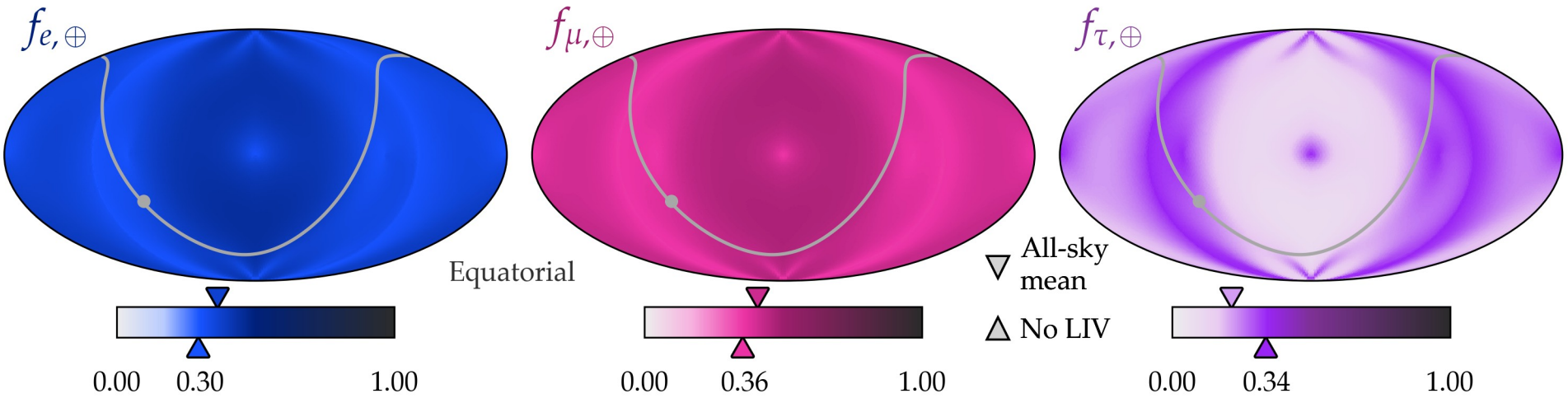

For dimension-5 CPT-odd LIV coefficient

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

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

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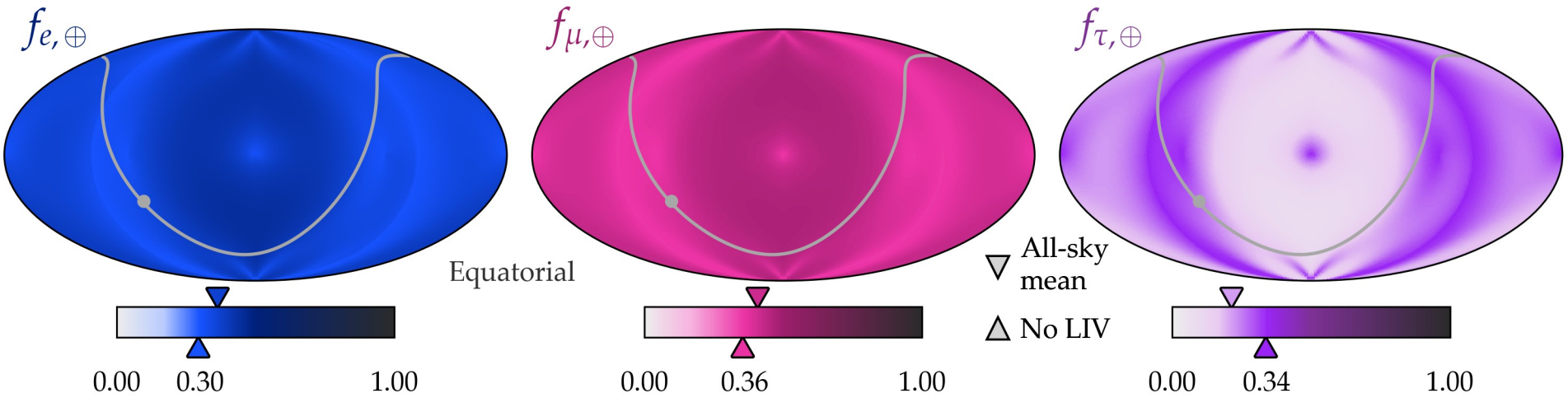

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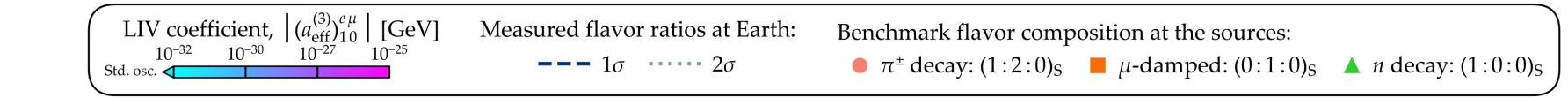
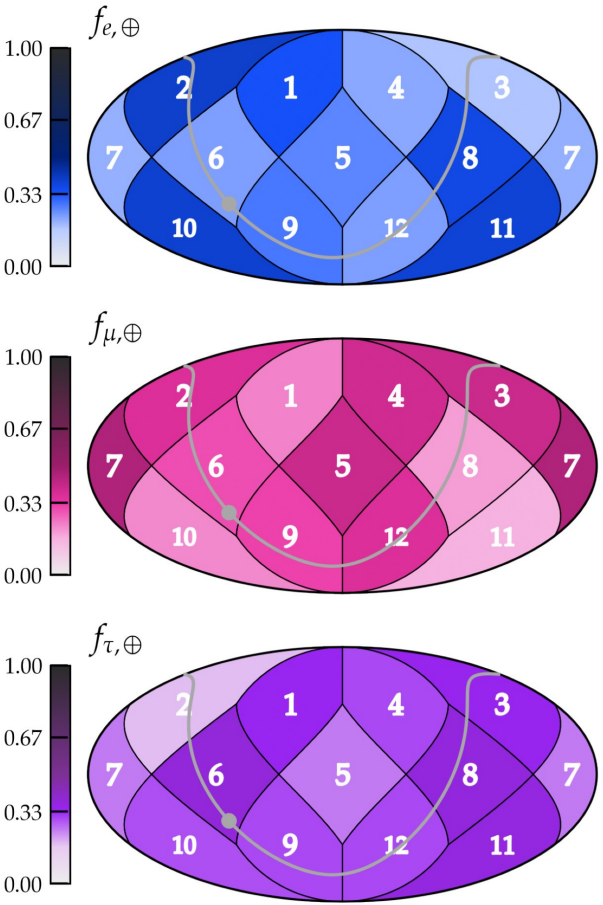
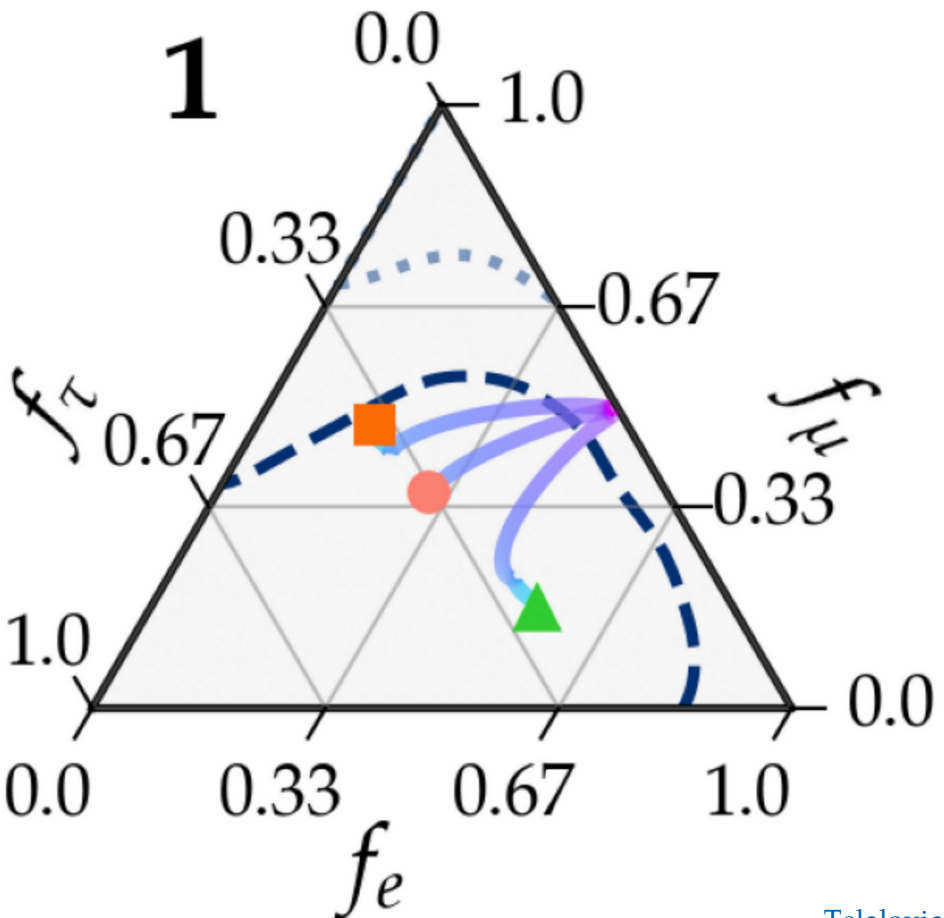
Upper limits from 7.5-year HESE: $< 10^{-34}$ GeV^{-1}

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

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







Telalovic, MB, 2503.15468

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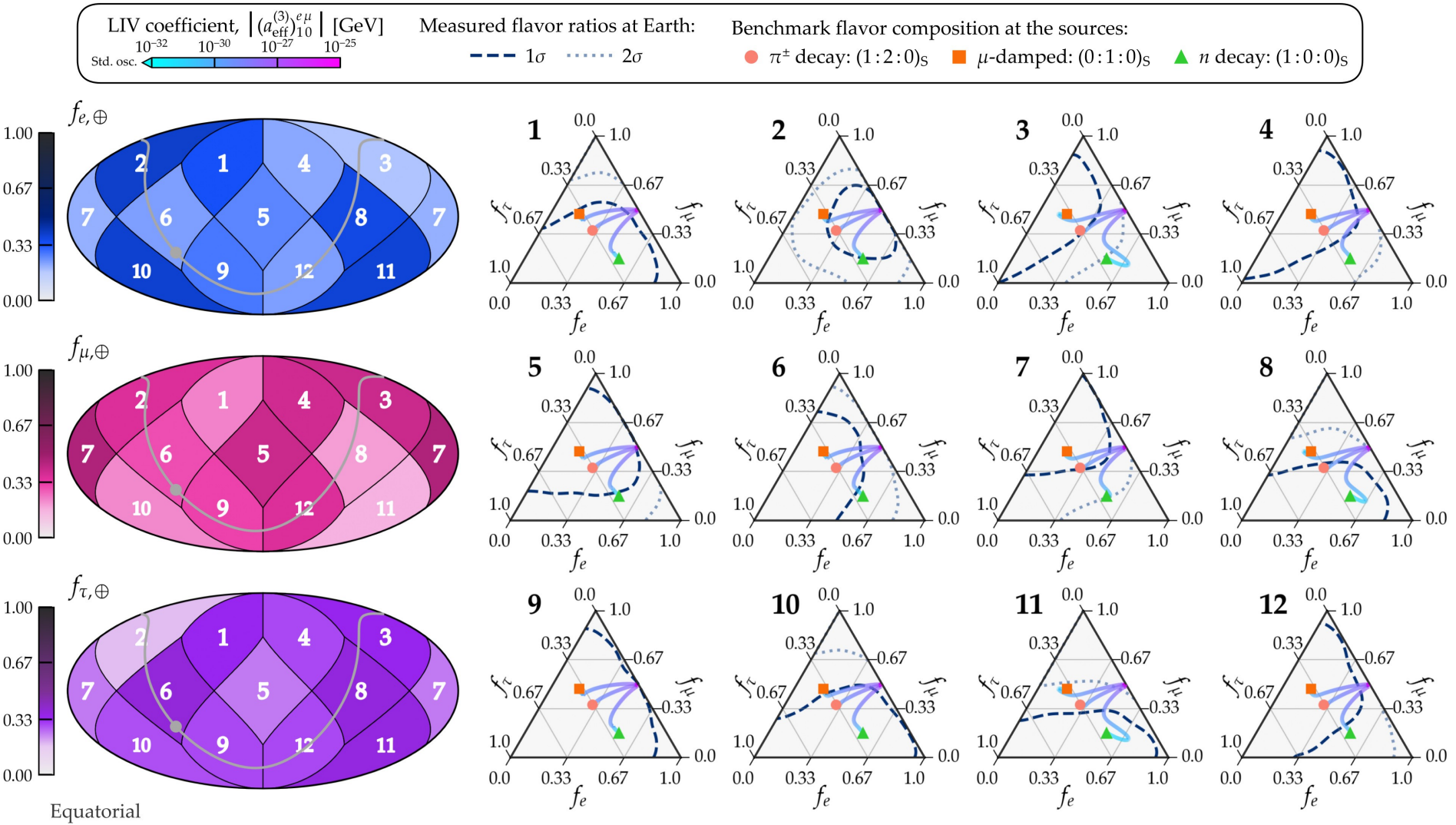

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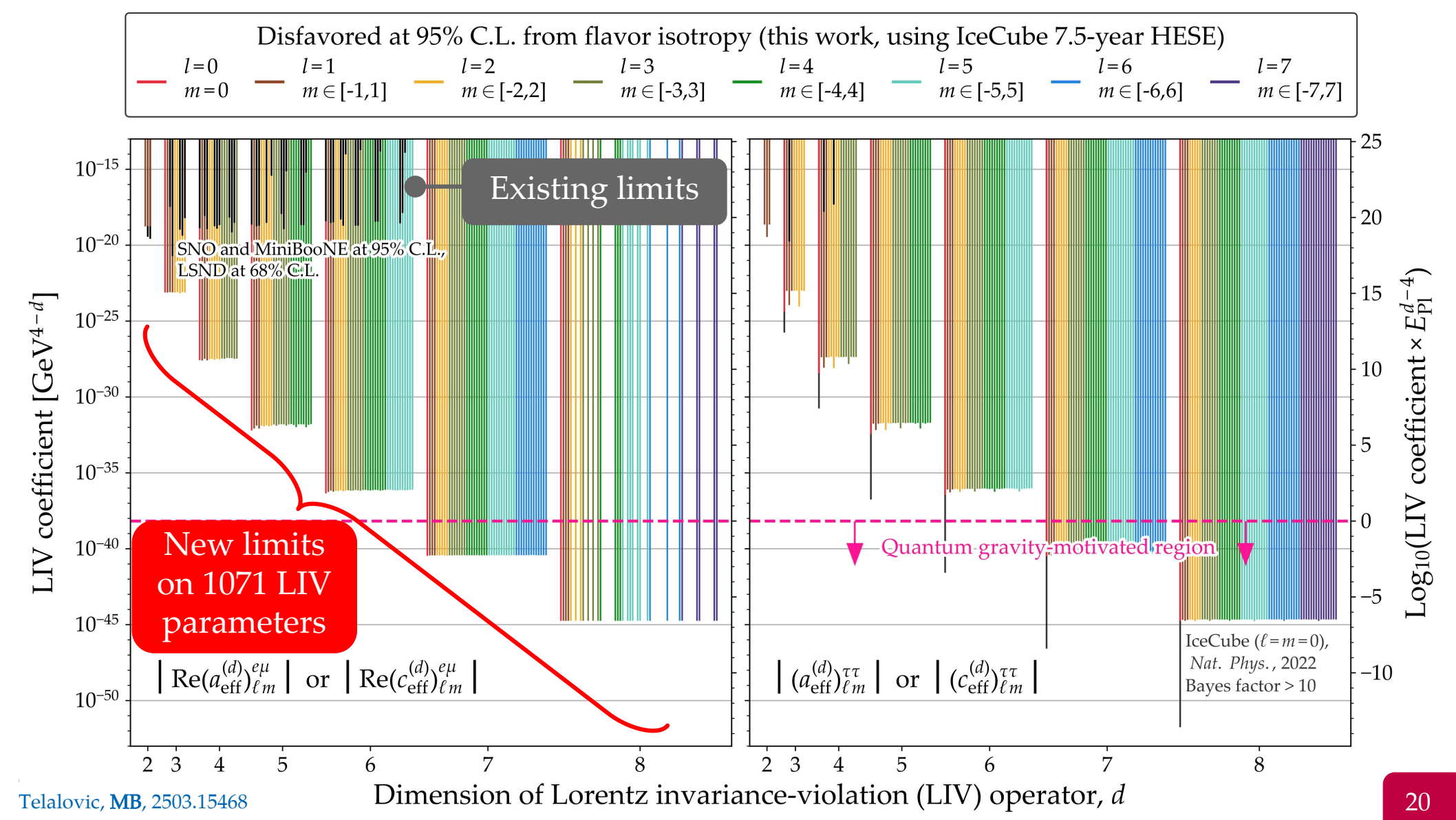


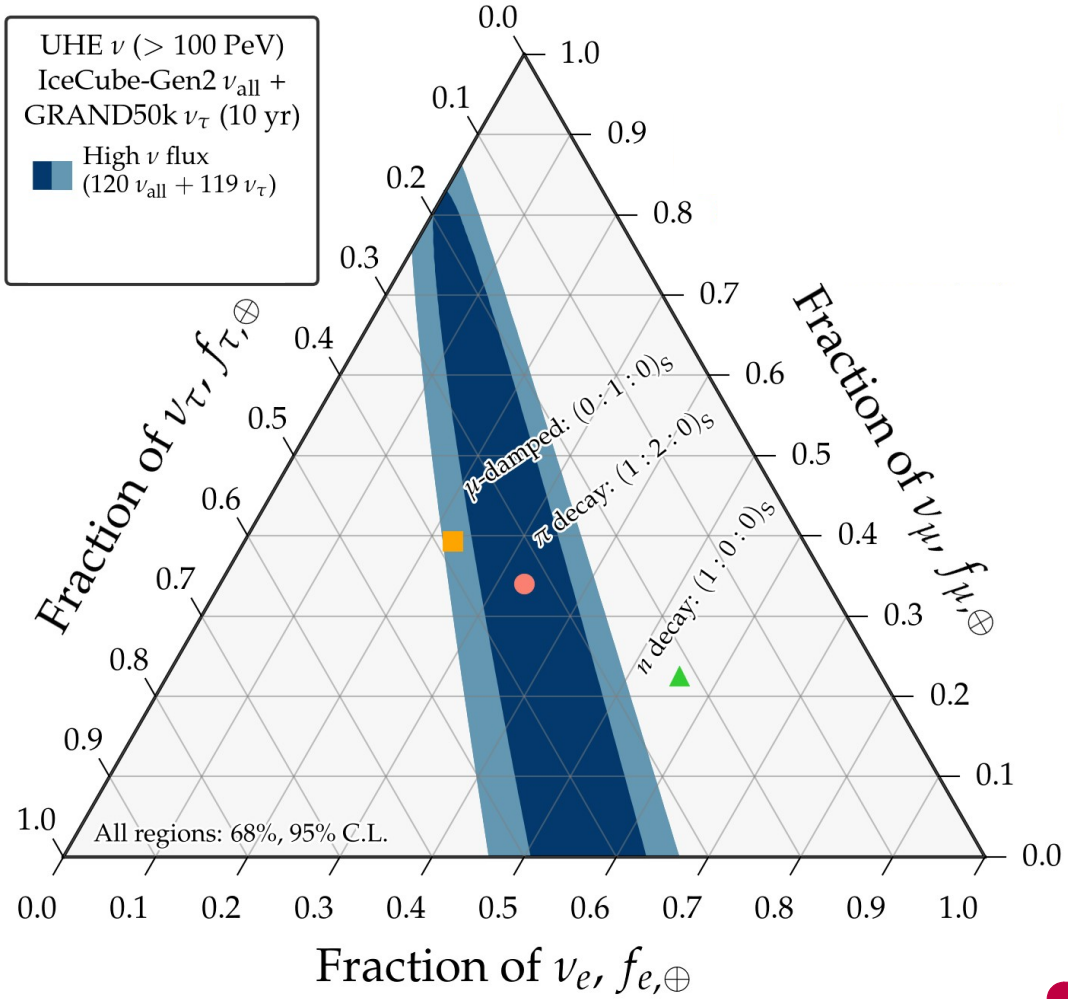
Telalovic, MB, 2503.15468

Flavor at ultra-high energies (> 100 PeV)

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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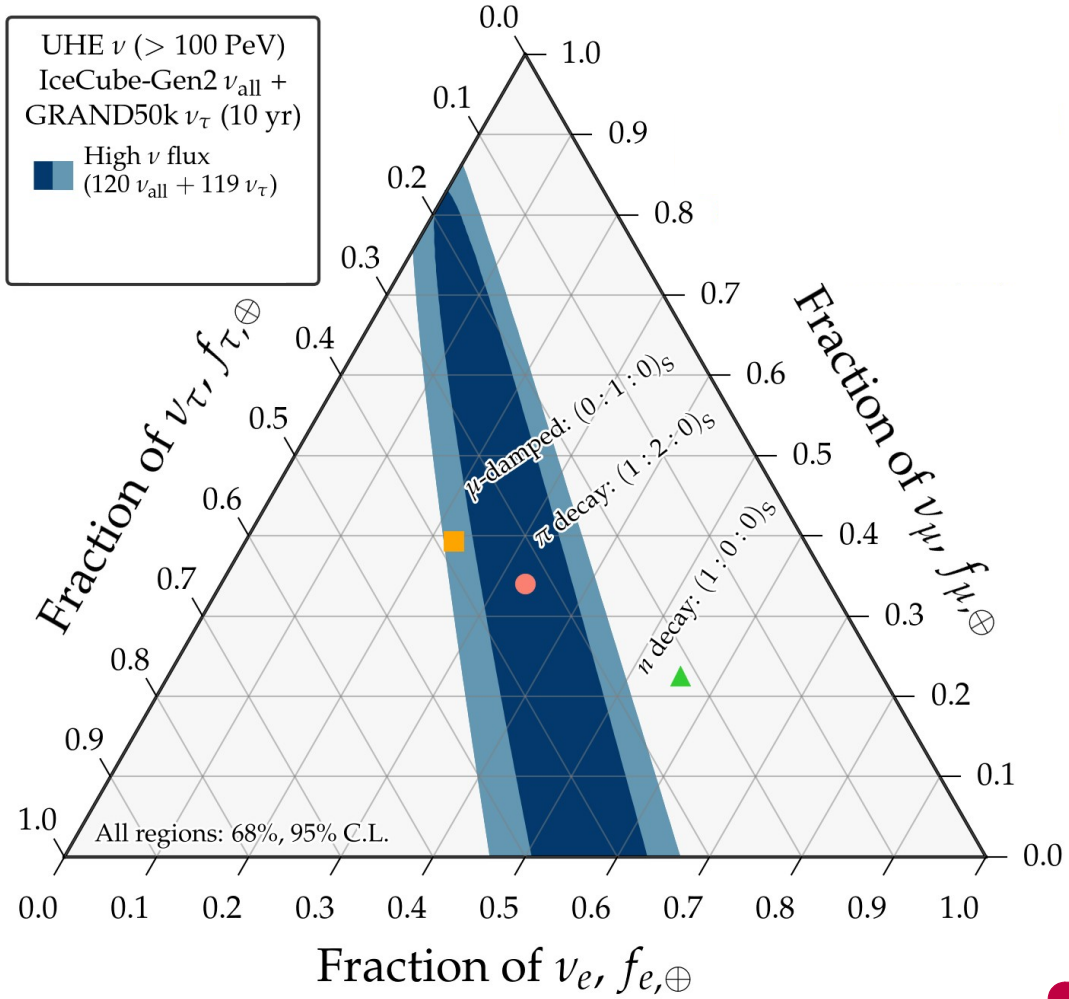
indistinct detection of all flavors by IceCube-Gen2 (radio)



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

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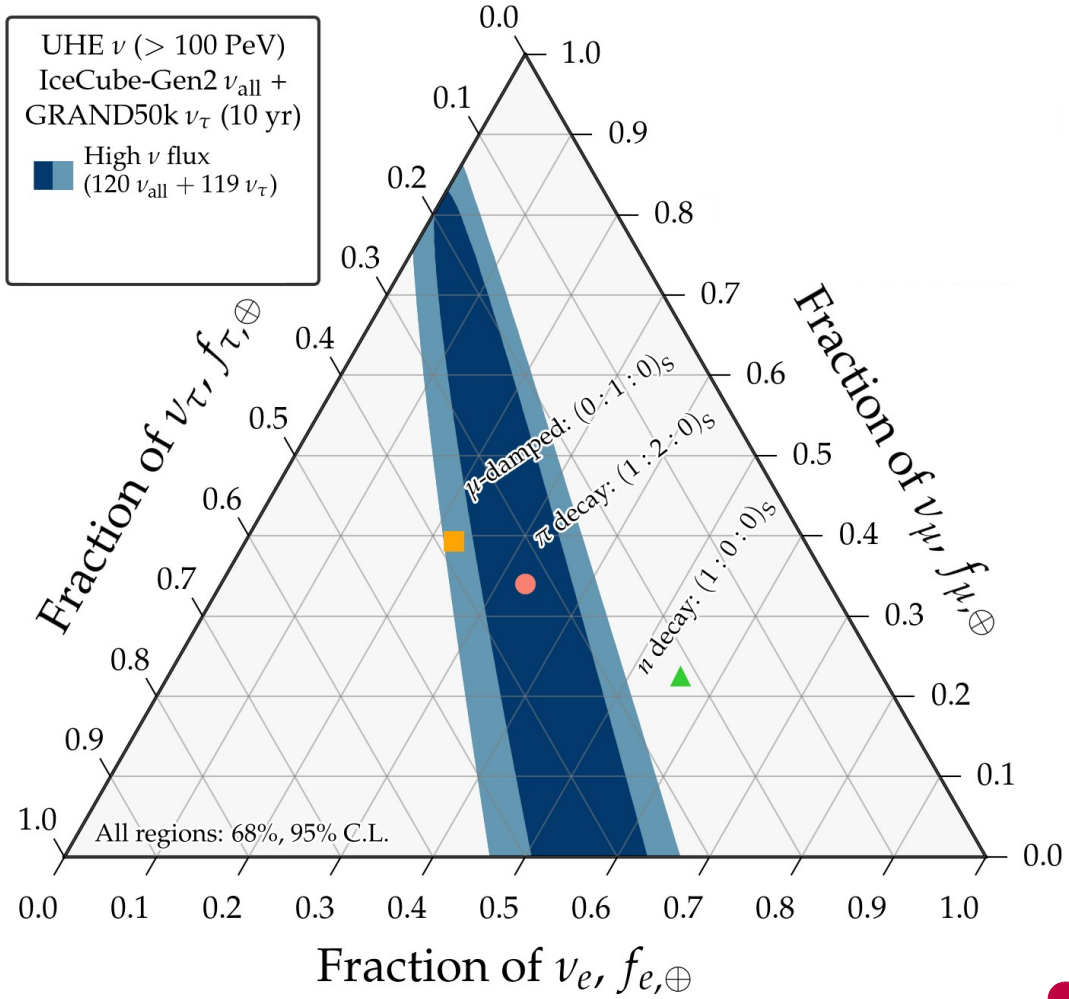
indistinct detection of all flavors by IceCube-Gen2 (radio)

+

predominant detection of ν_τ by GRAND



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

Manufacturing UHE flavor sensitivity with two detectors

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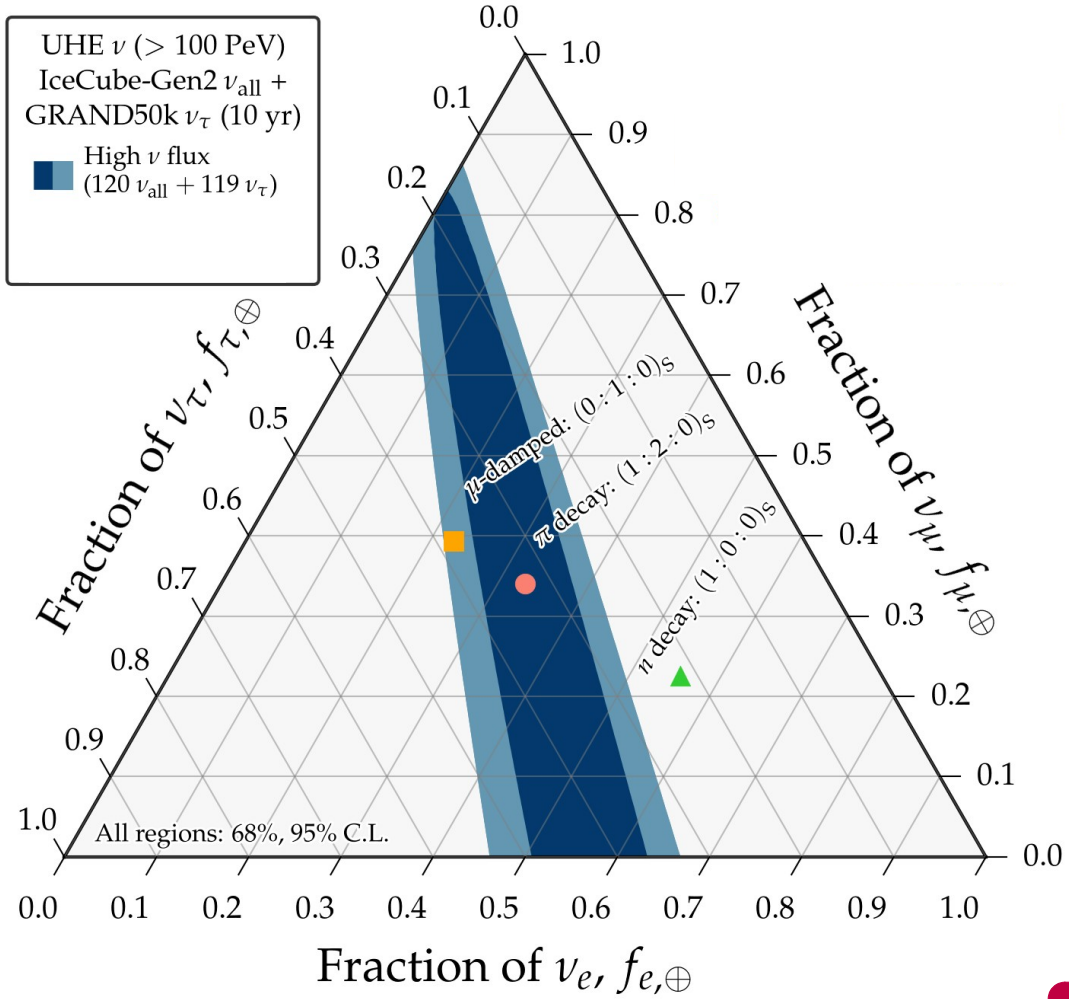

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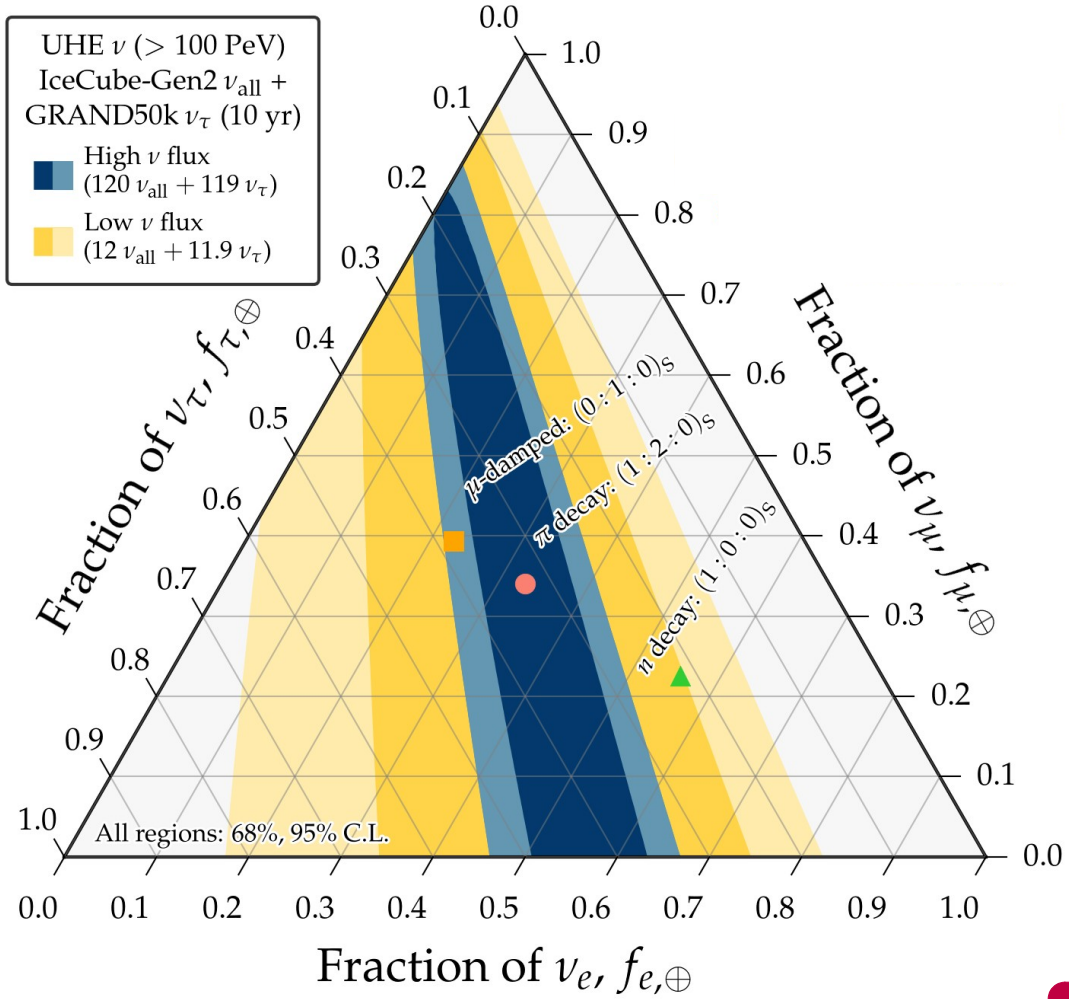

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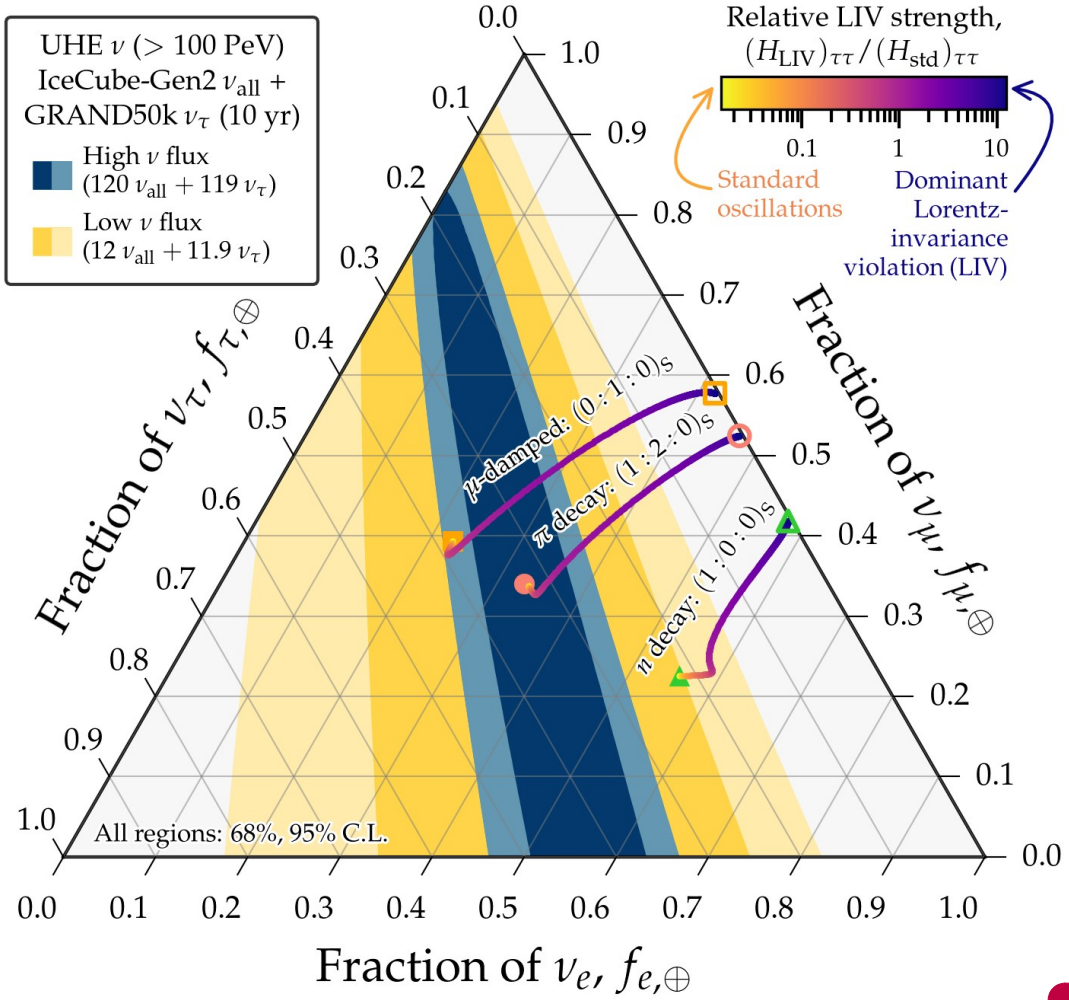

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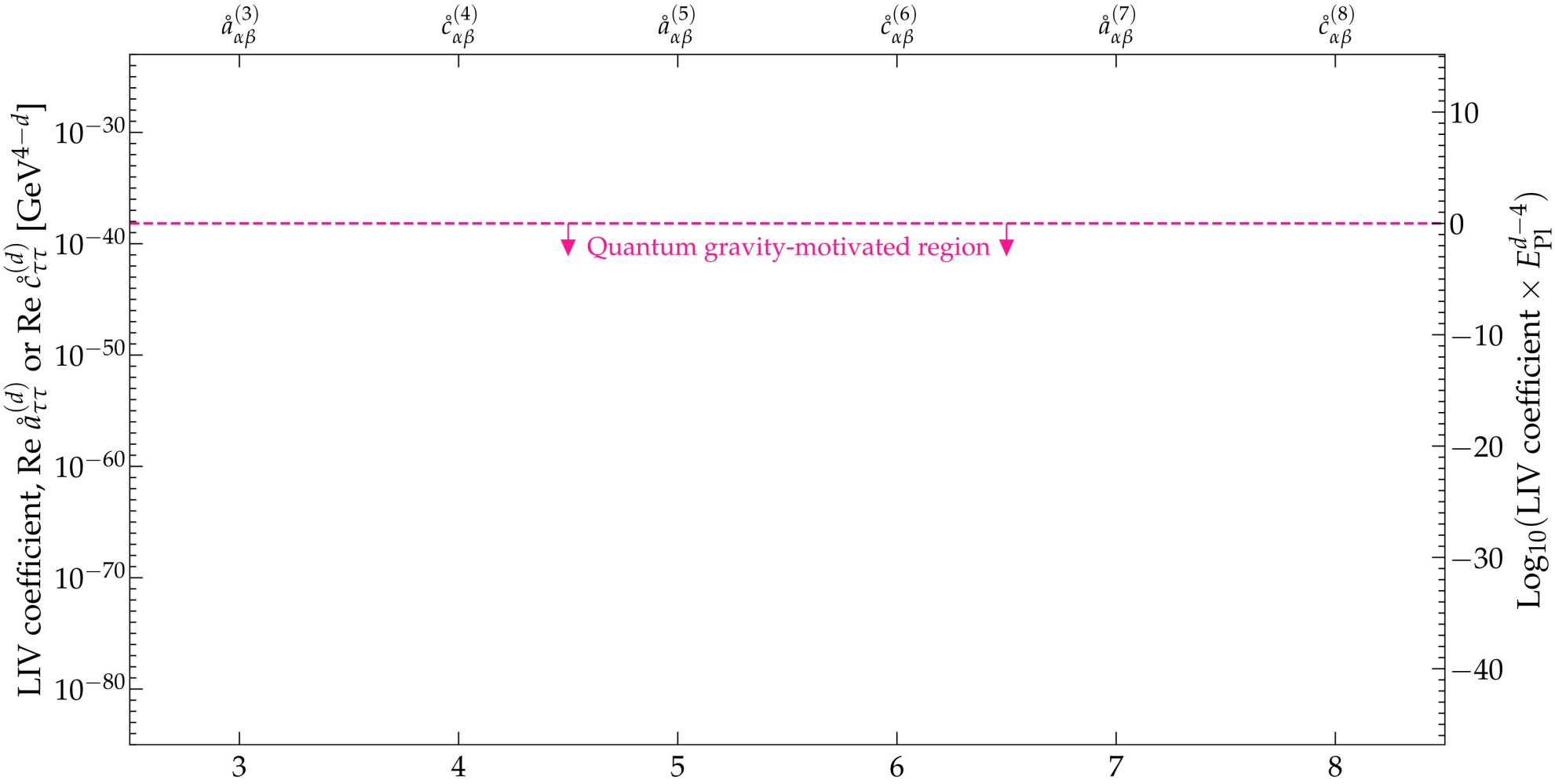
Lorentz-invariance violation at ultra-high energies



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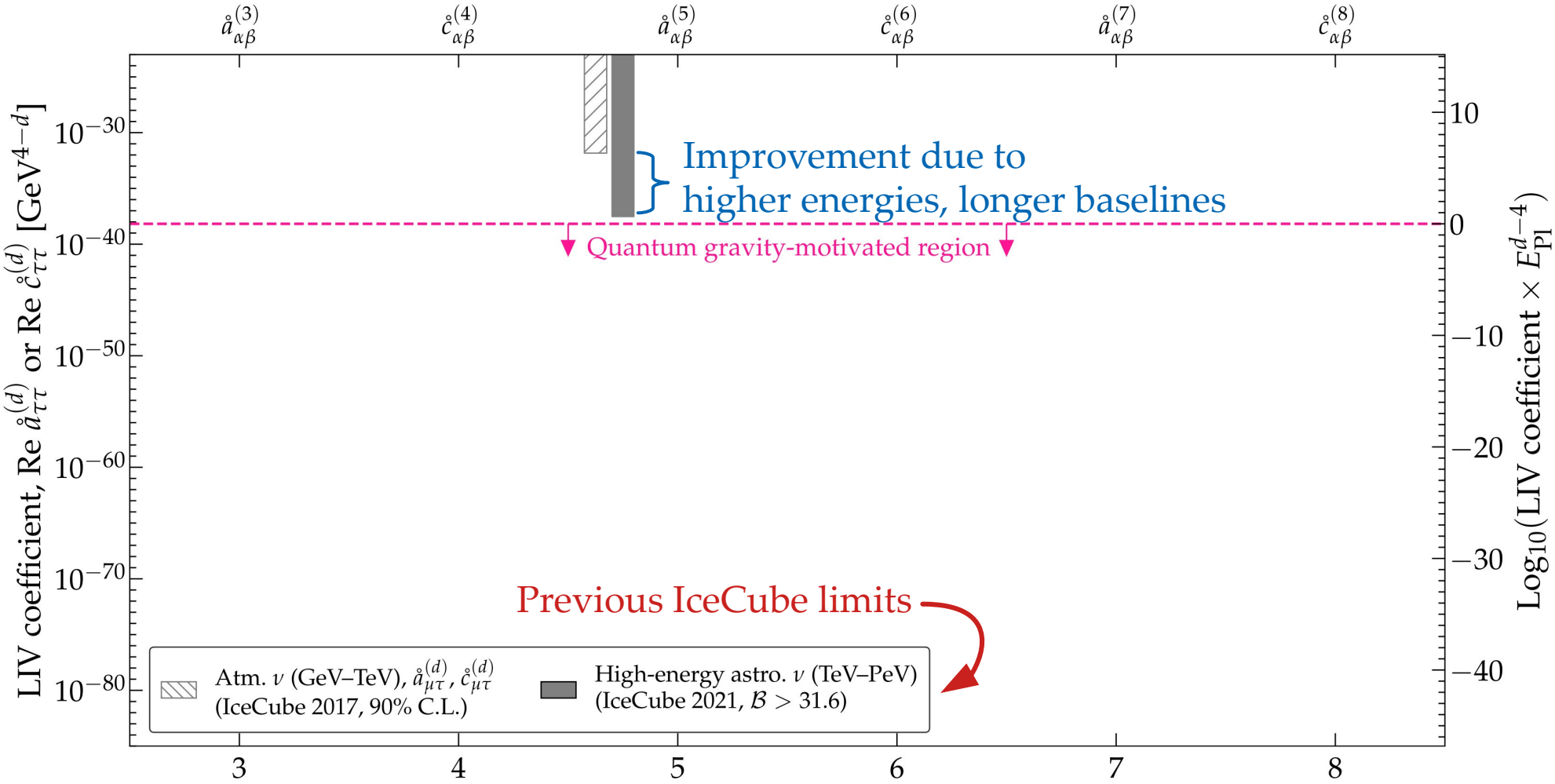

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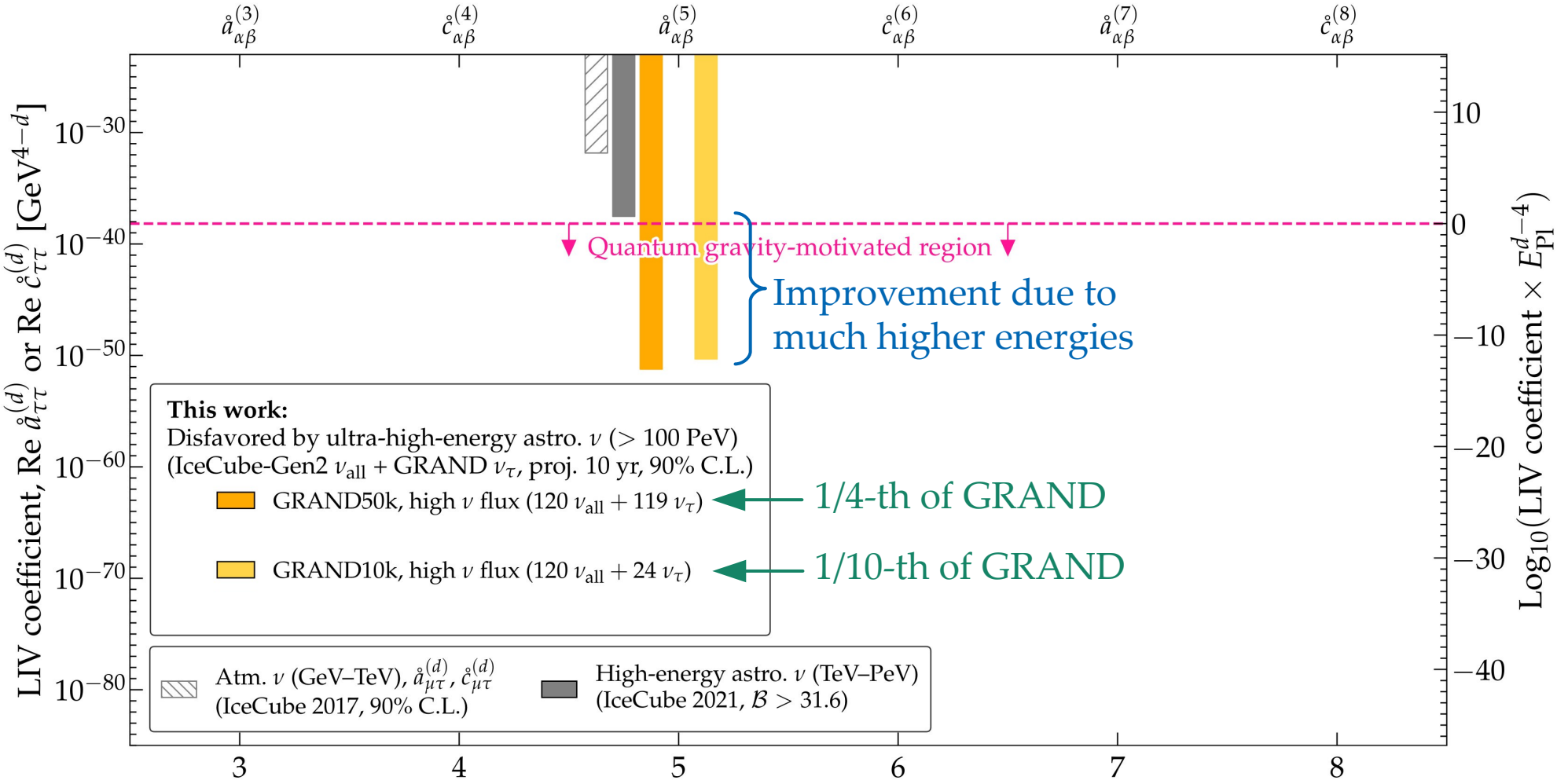

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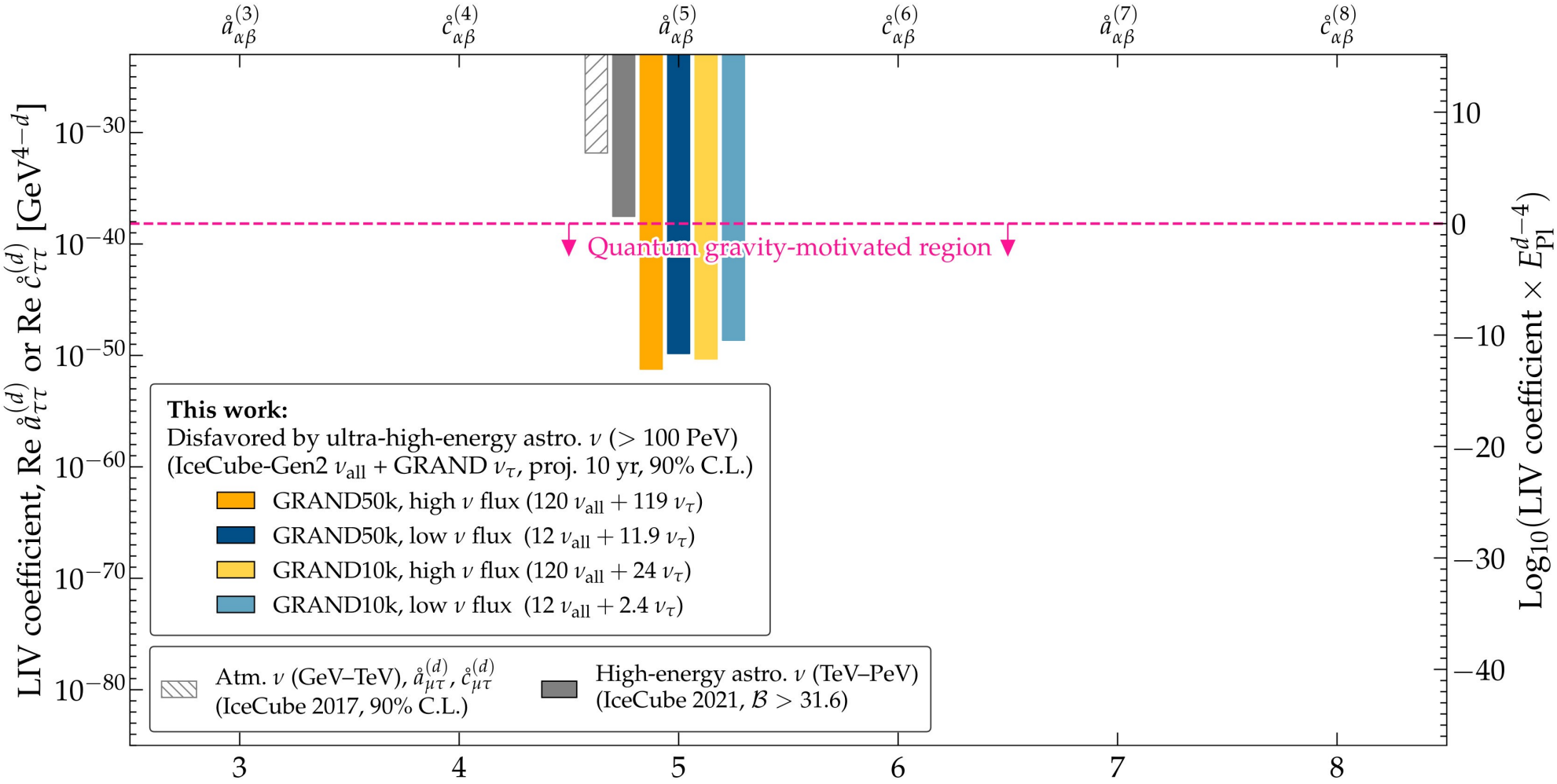

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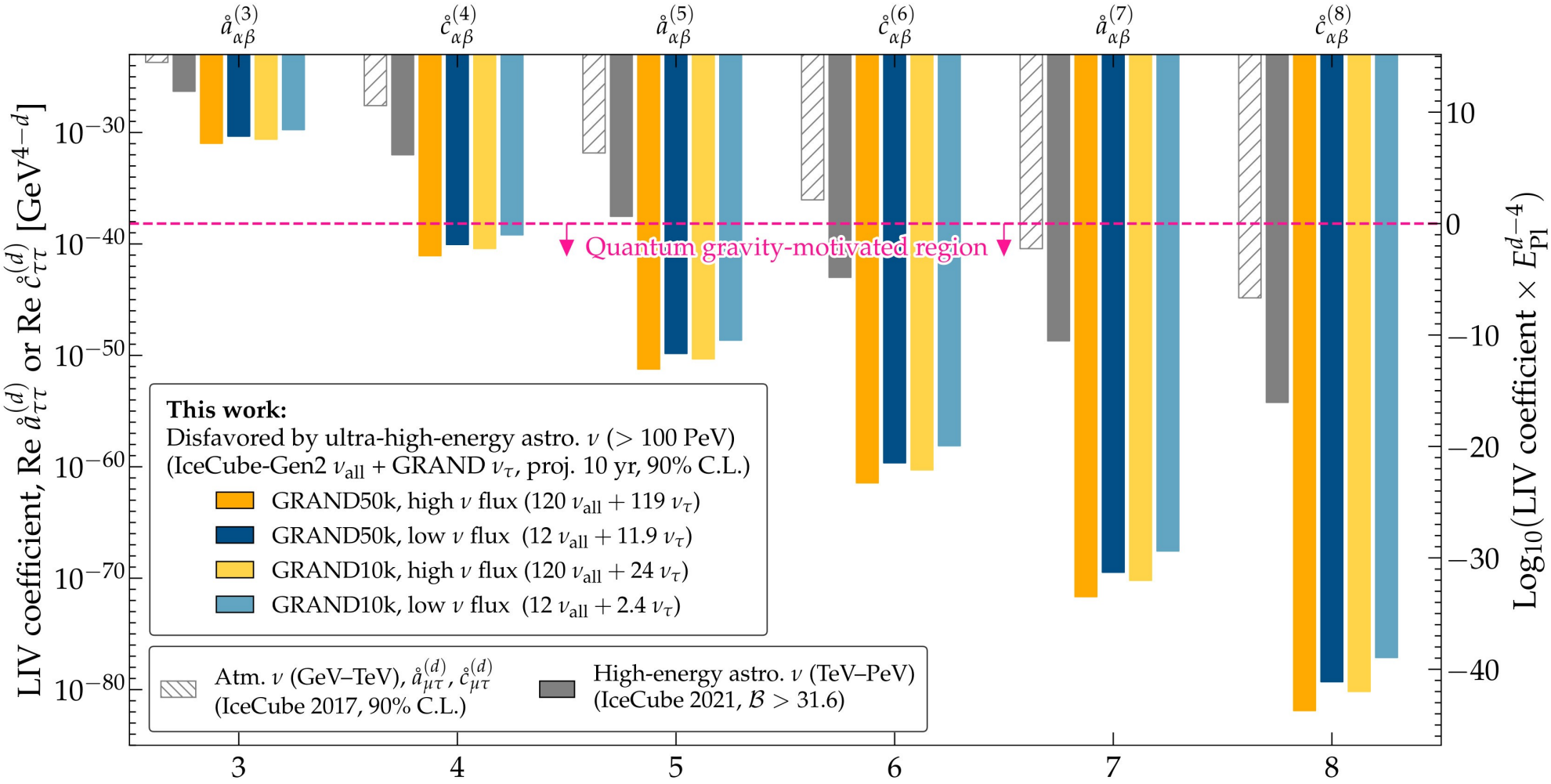

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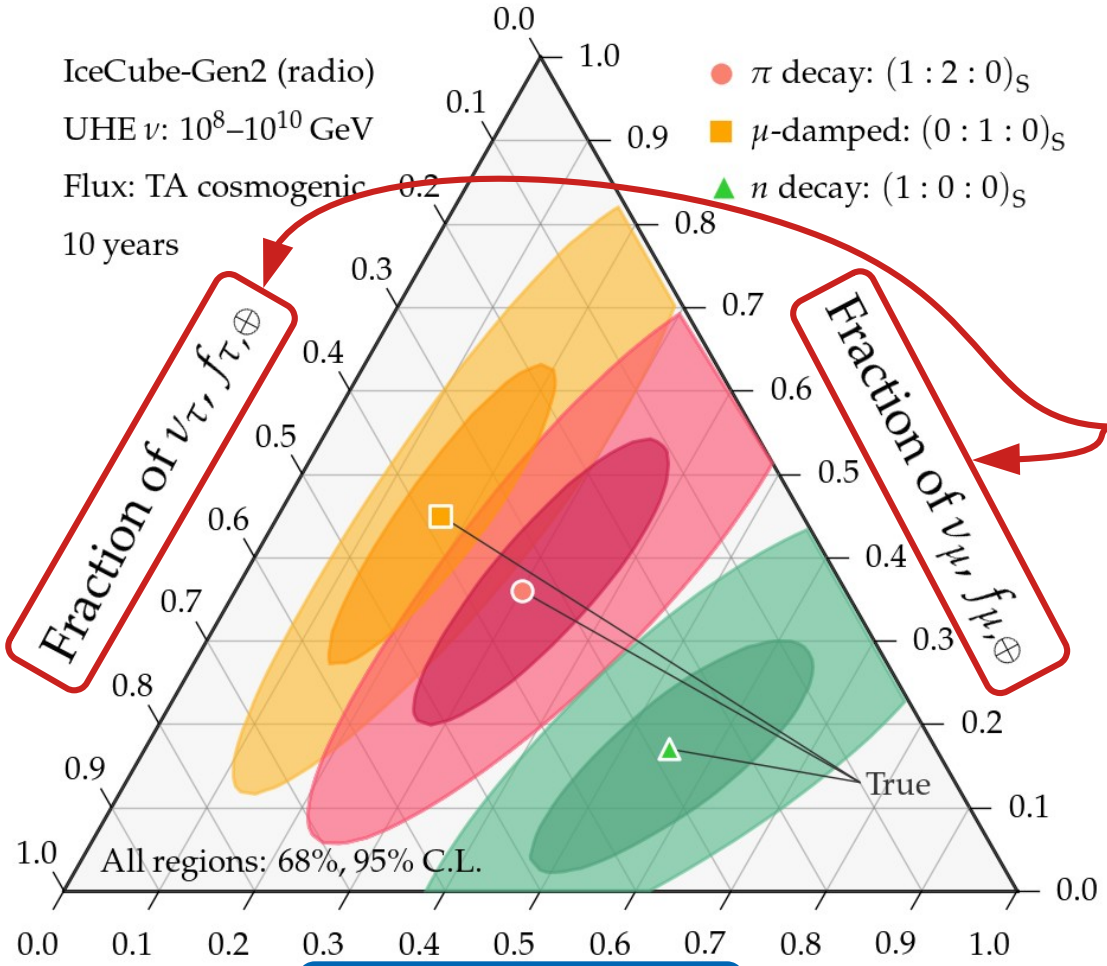
IceCube-Gen2 (radio) alone might measure flavor



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*