Fundamental physics with high-energy and ultra-high-energy cosmic neutrinos

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BridgeQG Workshop

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UNIVERSITY OF COPENHAGEN

VILLUM FONDEN

"When you have eliminated all which is impossible, then whatever remains, however improbable, must be the truth."

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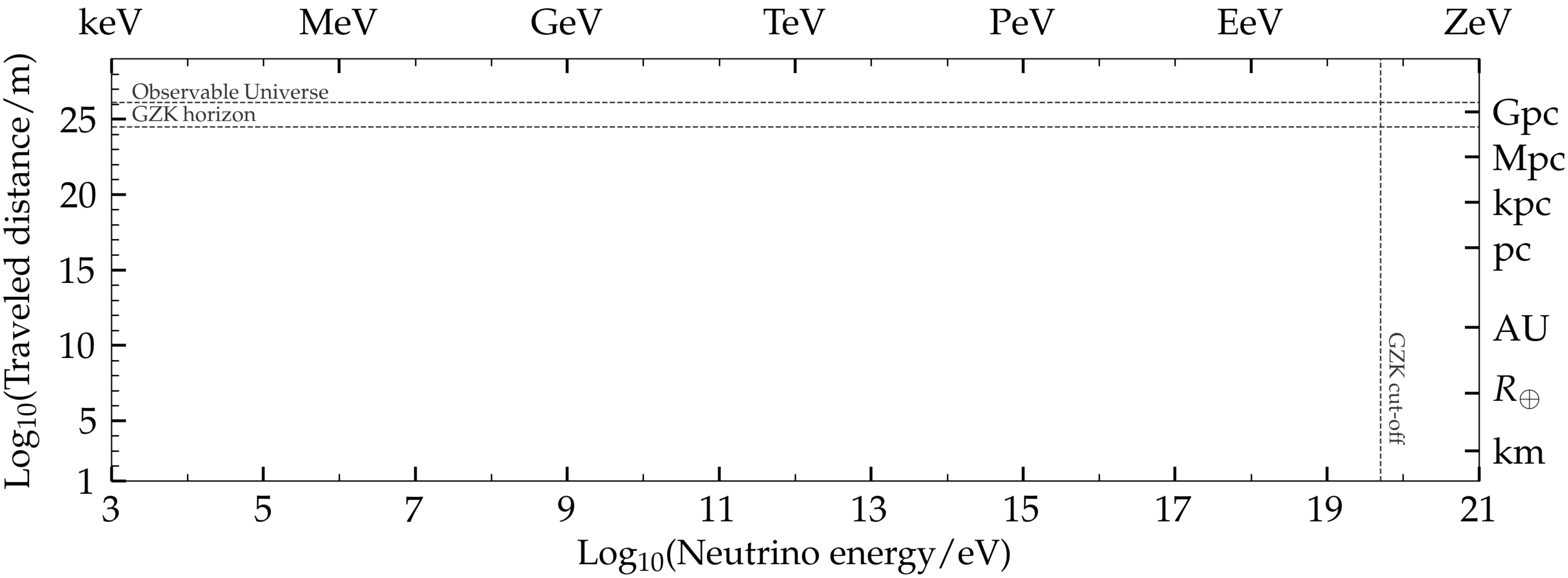
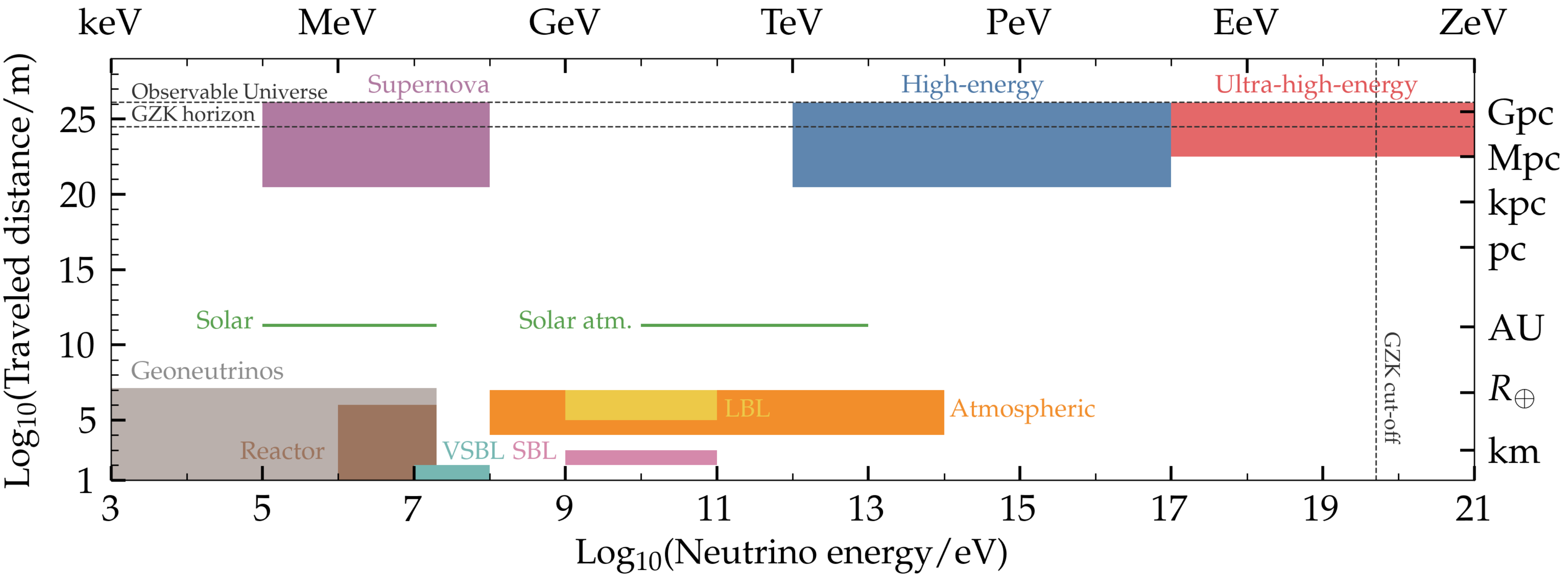
Arthur Conan-Doyle,
The Case-Book of Sherlock Holmes (1927)



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



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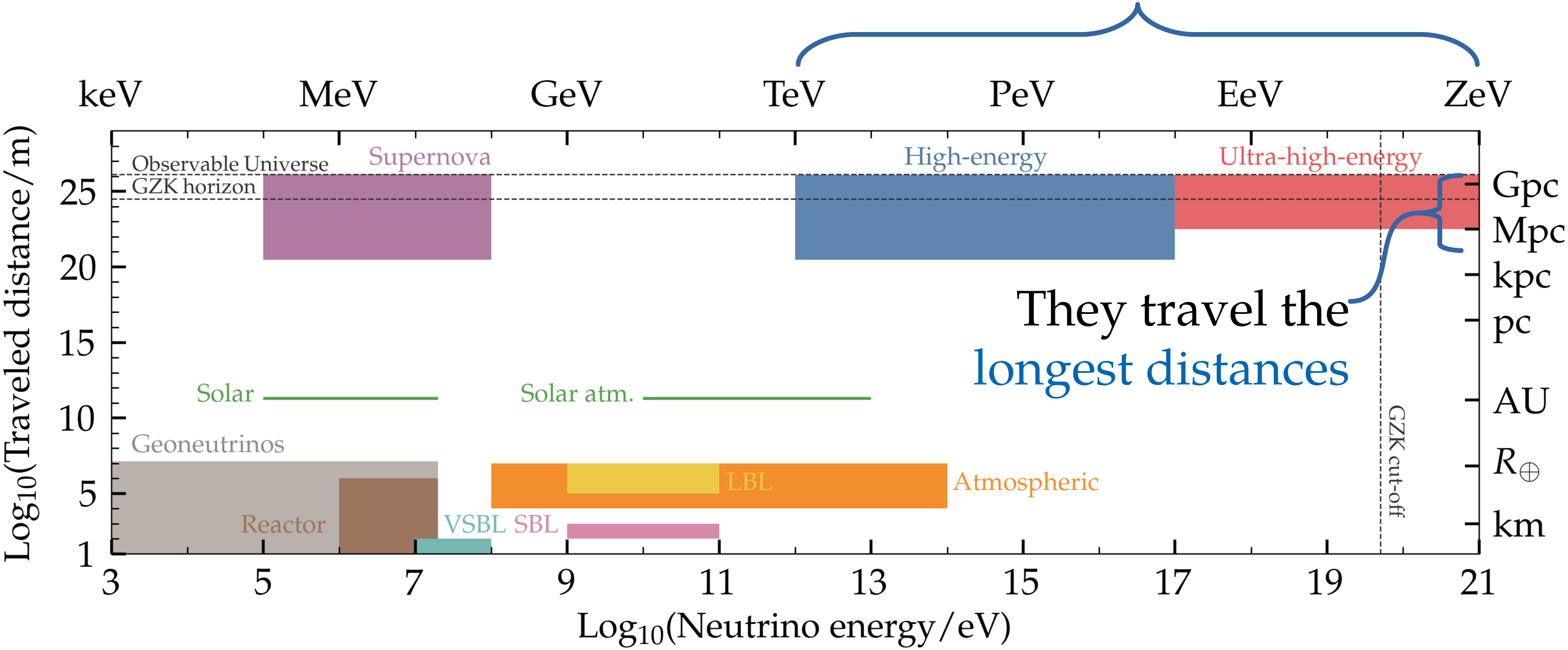
They have the highest energies



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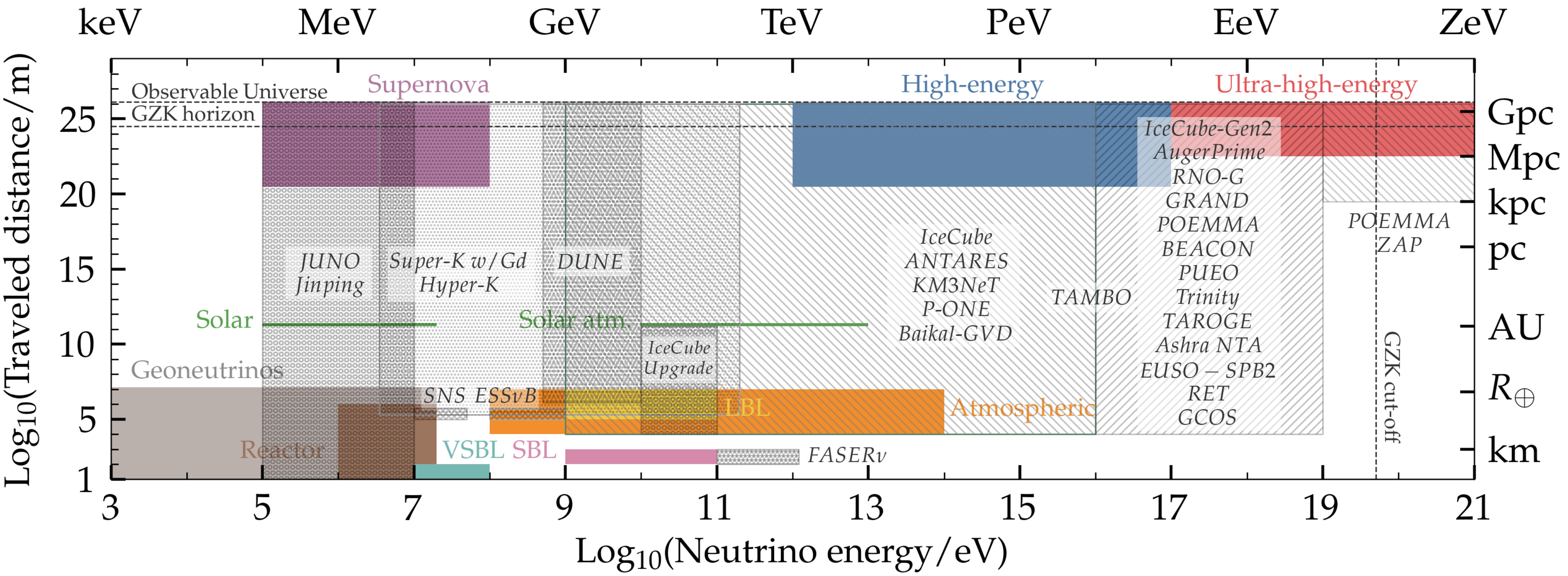

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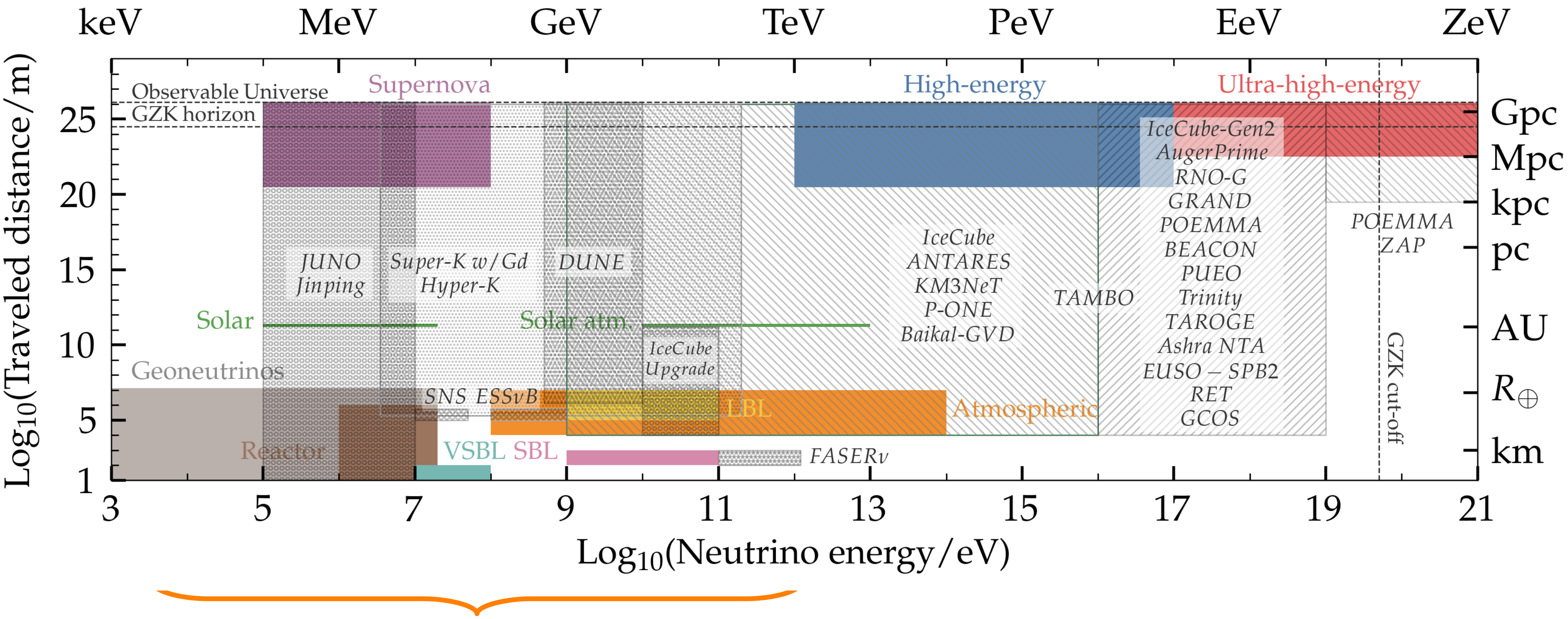

Synergies with lower energies

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Discovered in 2013
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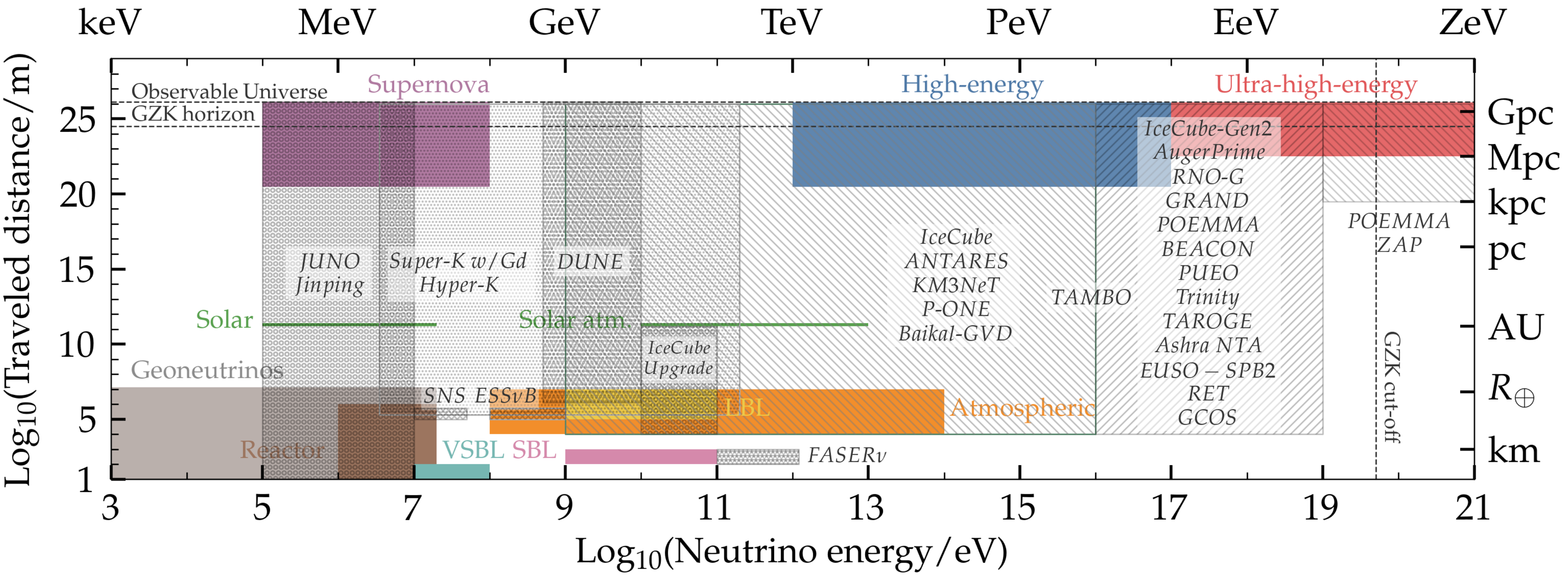

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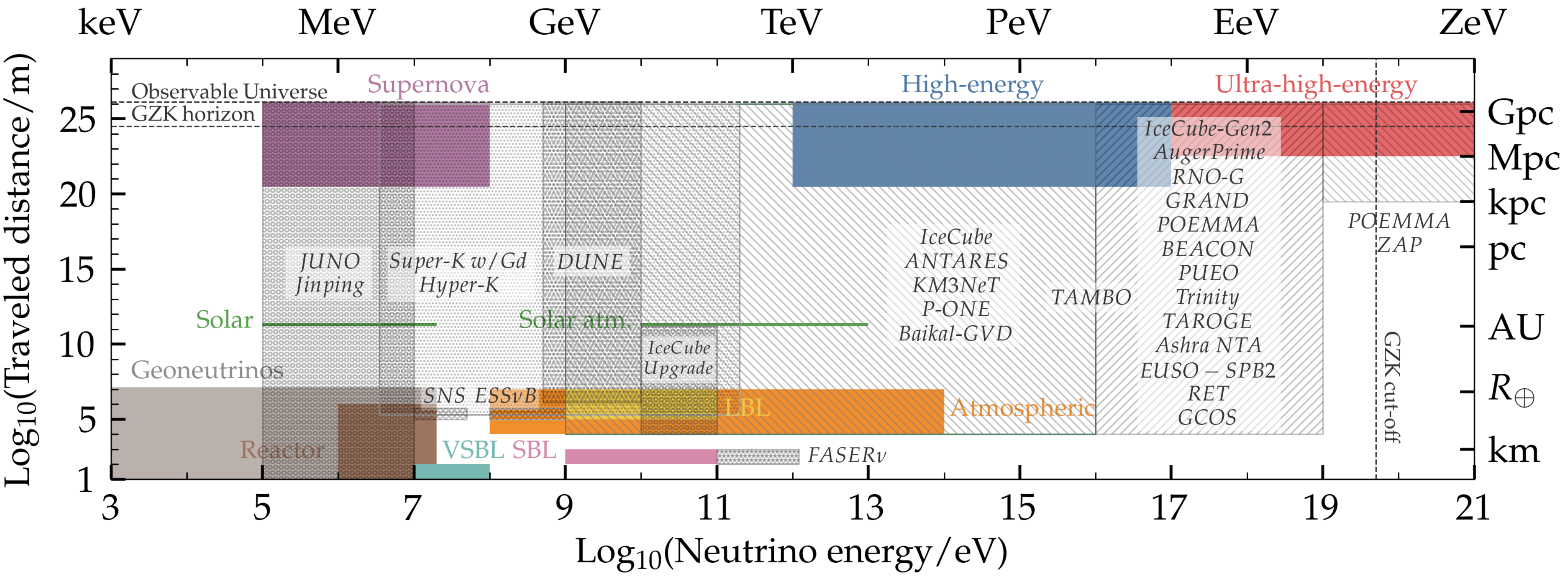

Synergies with lower energies

Increase TeV–PeV
ν statistics

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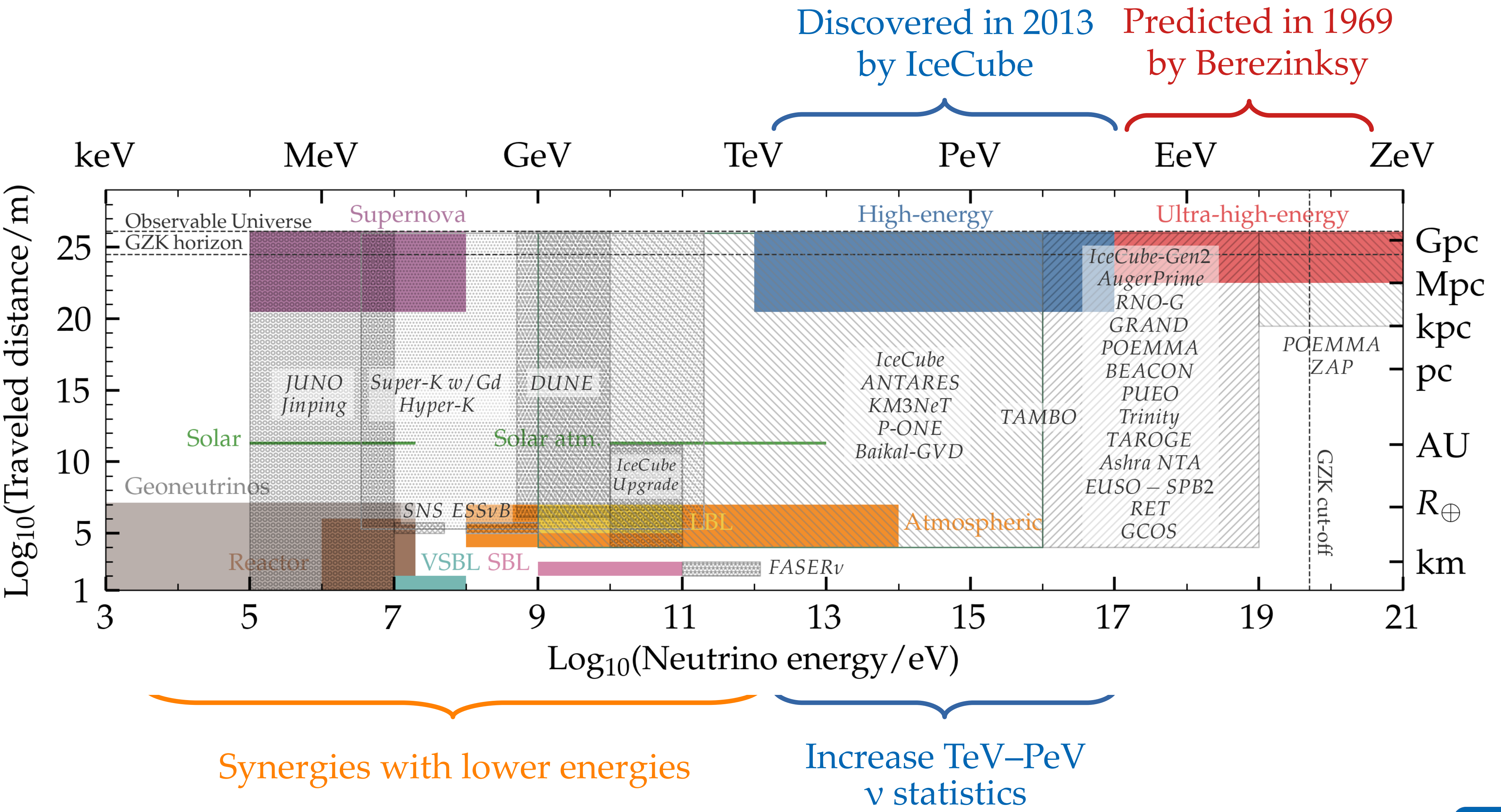

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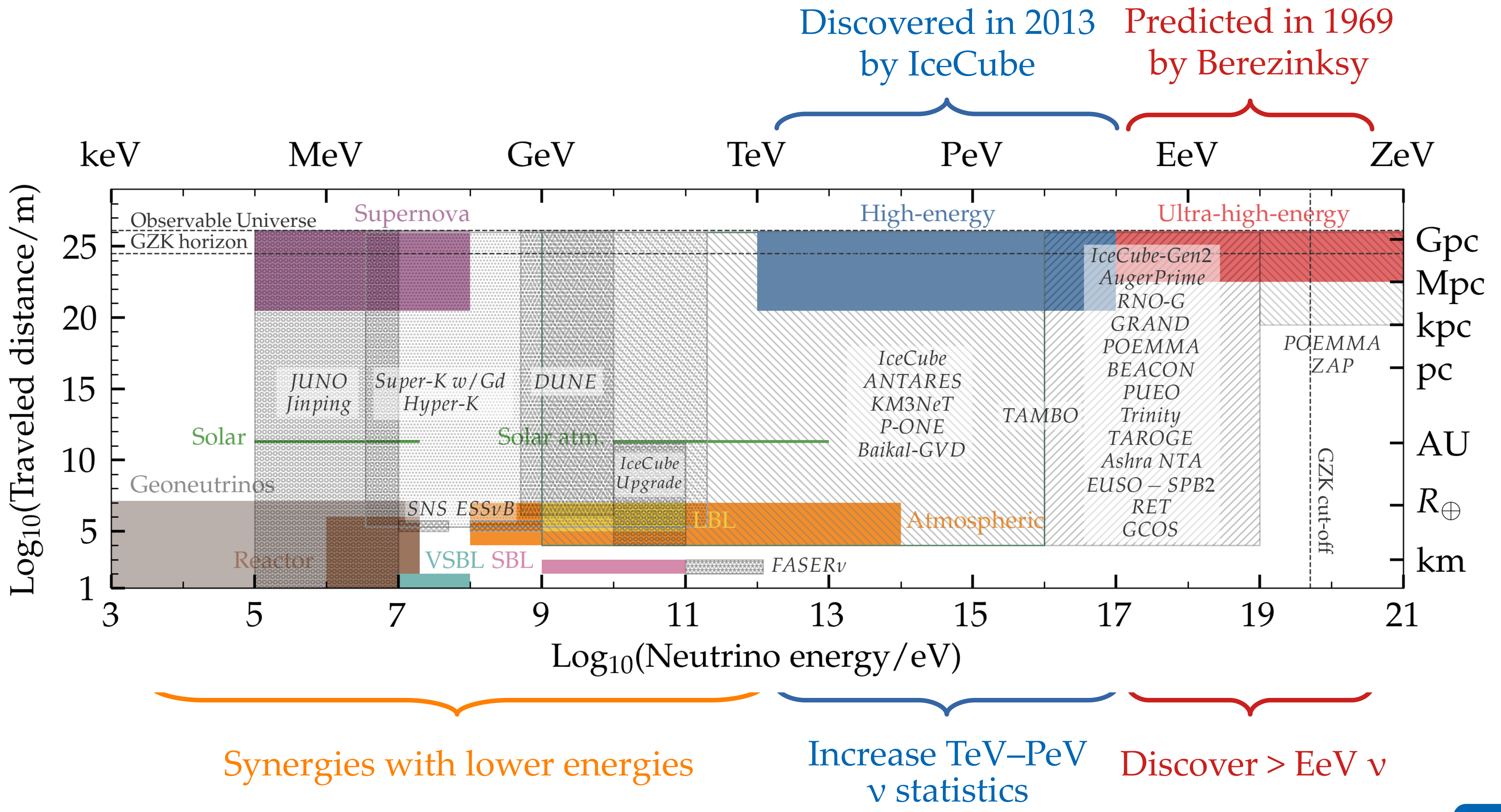

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Fundamental physics with high-energy cosmic neutrinos

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

If BSM effects are comparable in size to SM effects, then we can probe

$$\kappa_n \sim 10^{-47} \left(\frac{E}{\mathrm{PeV}}\right)^{-n} \left(\frac{L}{\mathrm{Gpc}}\right)^{-1} \mathrm{PeV}^{1-n}$$

With 1-PeV ν: $\kappa_2 \sim 10^{-47}\ \mathrm{PeV}^{-1}$

With 100-PeV ν: $\kappa_2 \sim 10^{-51}\ \mathrm{PeV}^{-1}$

Orders-of-magnitude improvement

Fundamental physics with high-energy cosmic neutrinos

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

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Orders-of-magnitude improvement

The multi-messenger connection: a simple picture

(or $p + p$)

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

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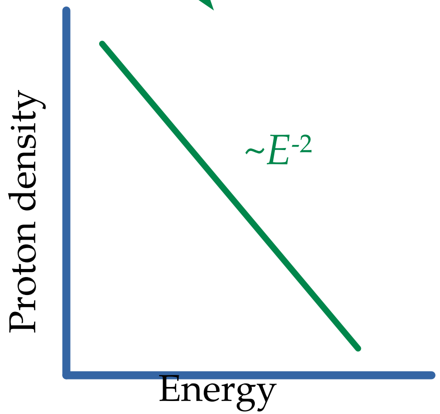

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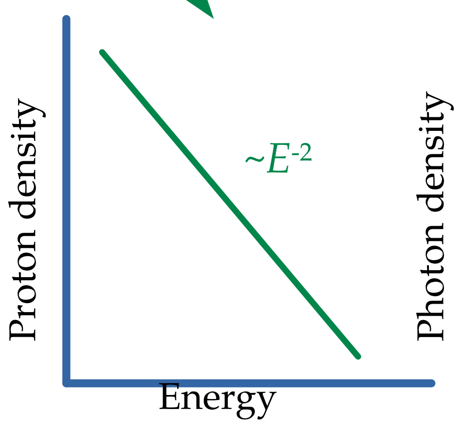

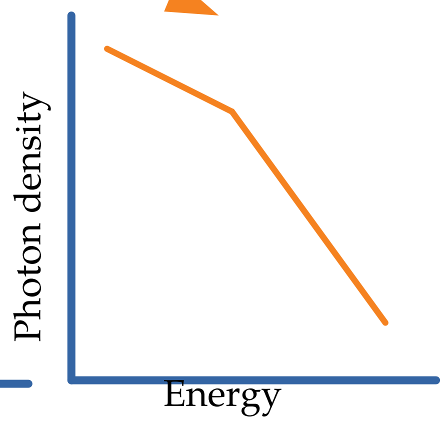

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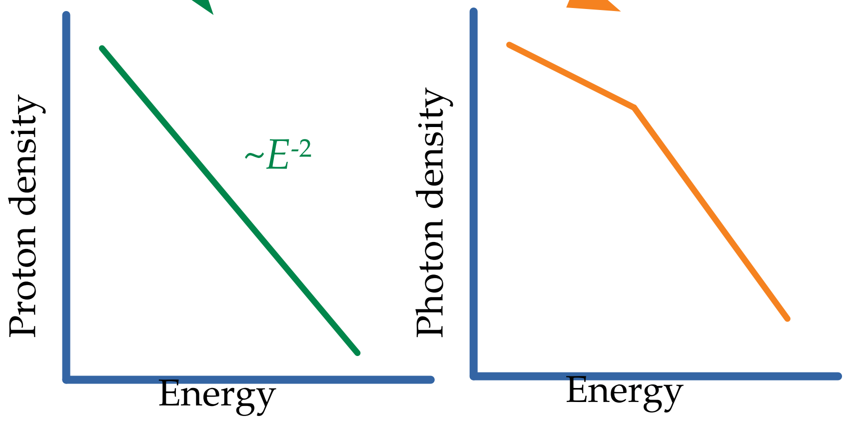
$$\pi^0 \to \gamma + \gamma$$

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

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



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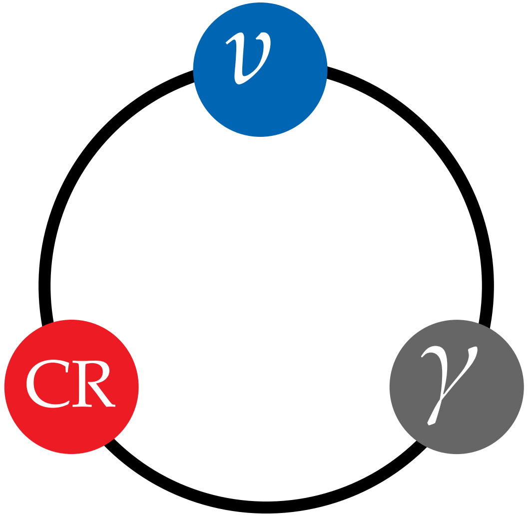

Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 10

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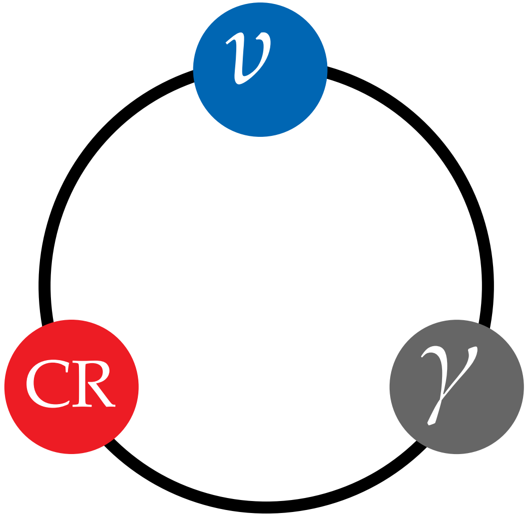

1 PeV — 20 PeV

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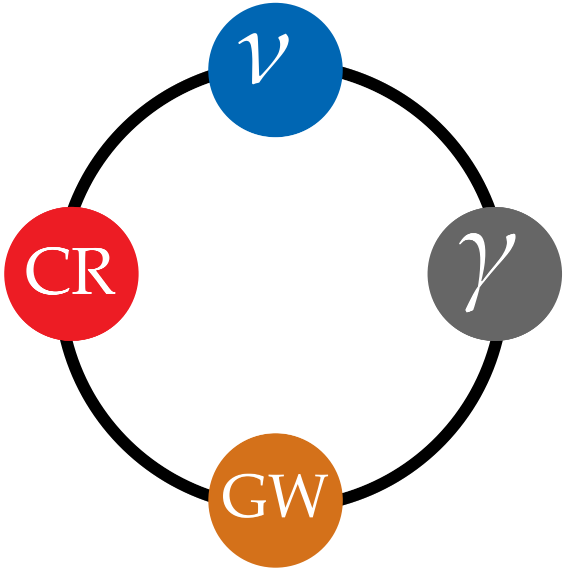

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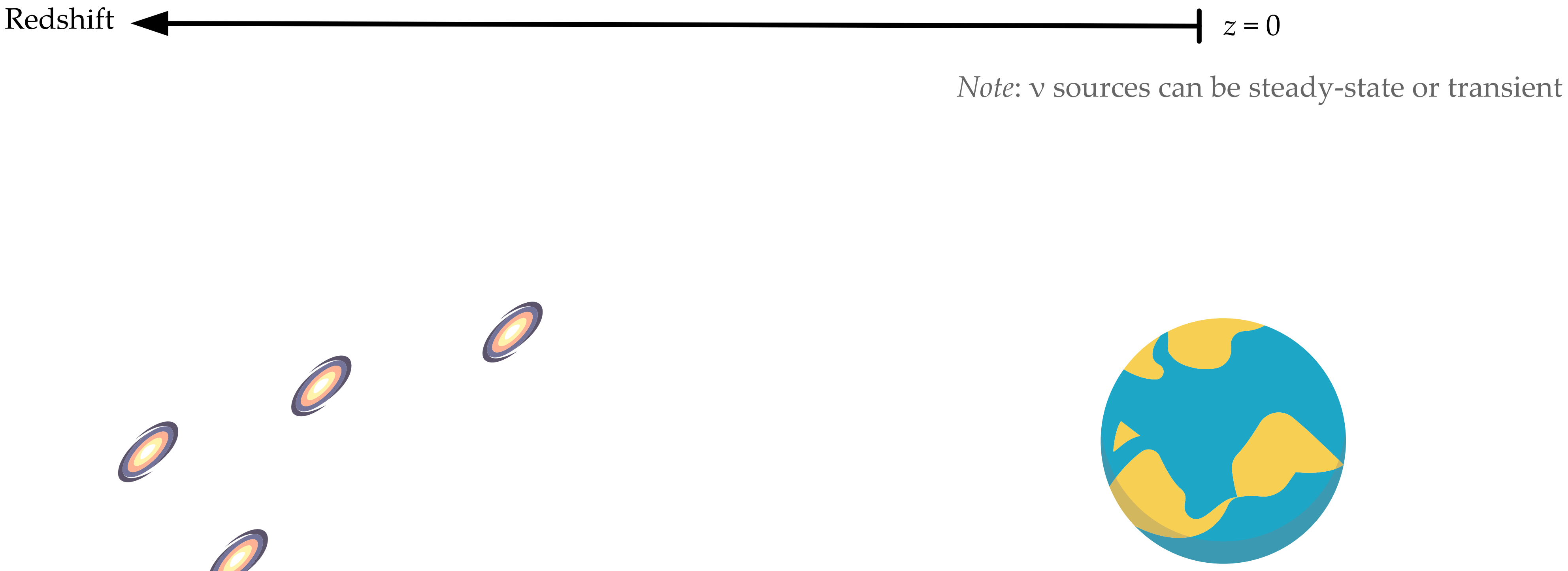
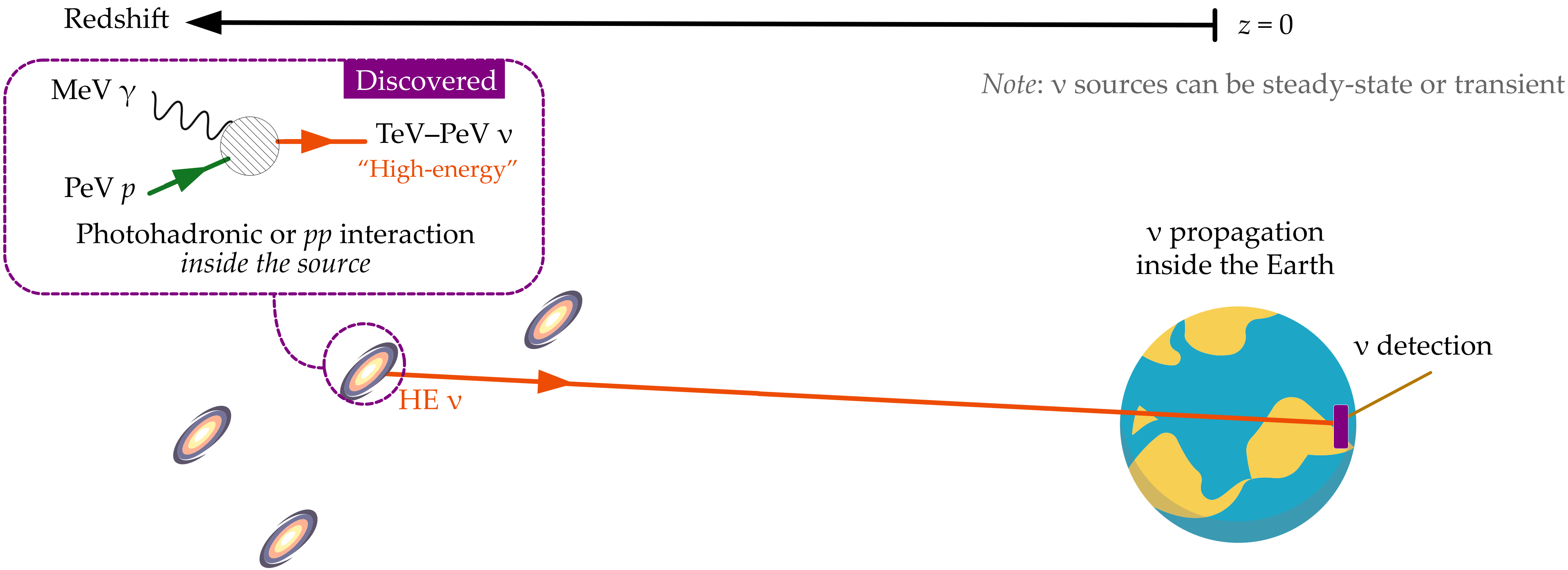
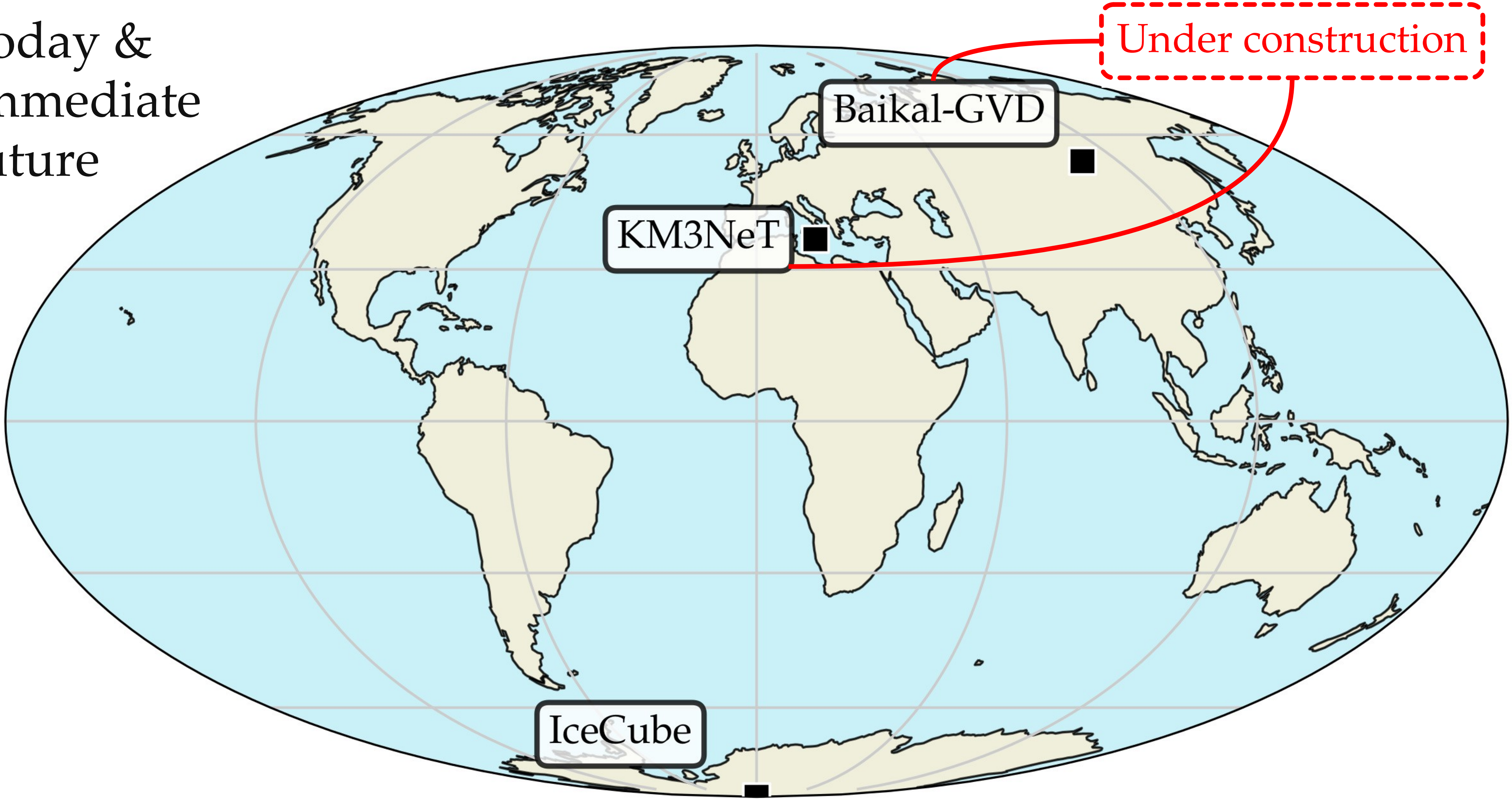


Redshift
$z = 0$
Note: ν sources can be steady-state or transient



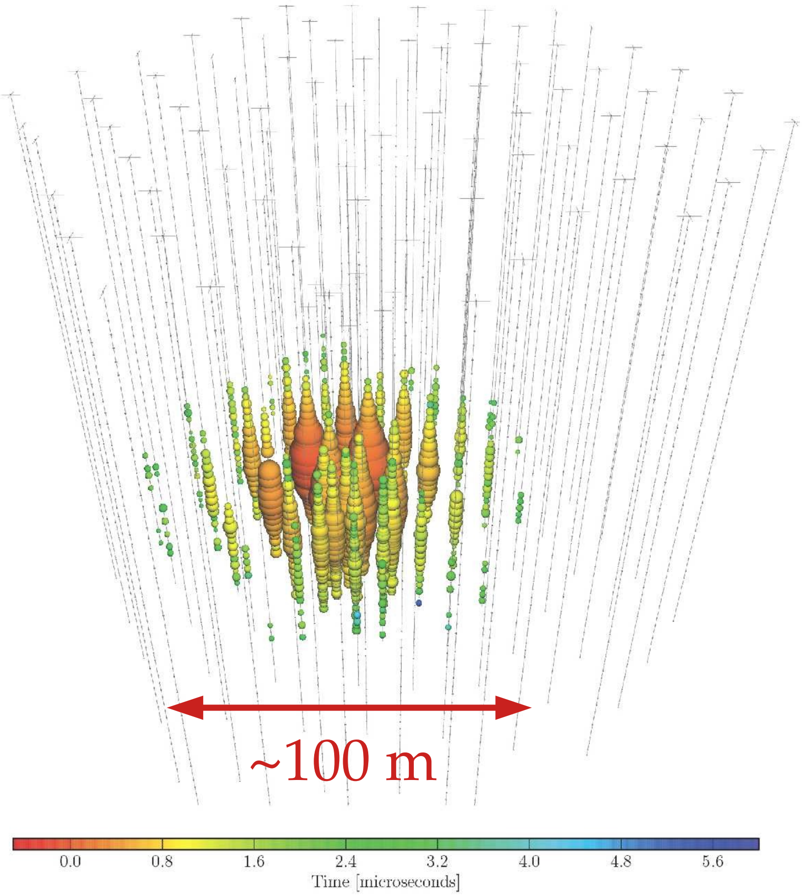
Redshift
$z = 0$
Discovered
MeV γ
TeV–PeV ν
"High-energy"
PeV p
Photohadronic or pp interaction
inside the source
Note: ν sources can be steady-state or transient
ν propagation
inside the Earth
ν detection
HE ν

Today & immediate future



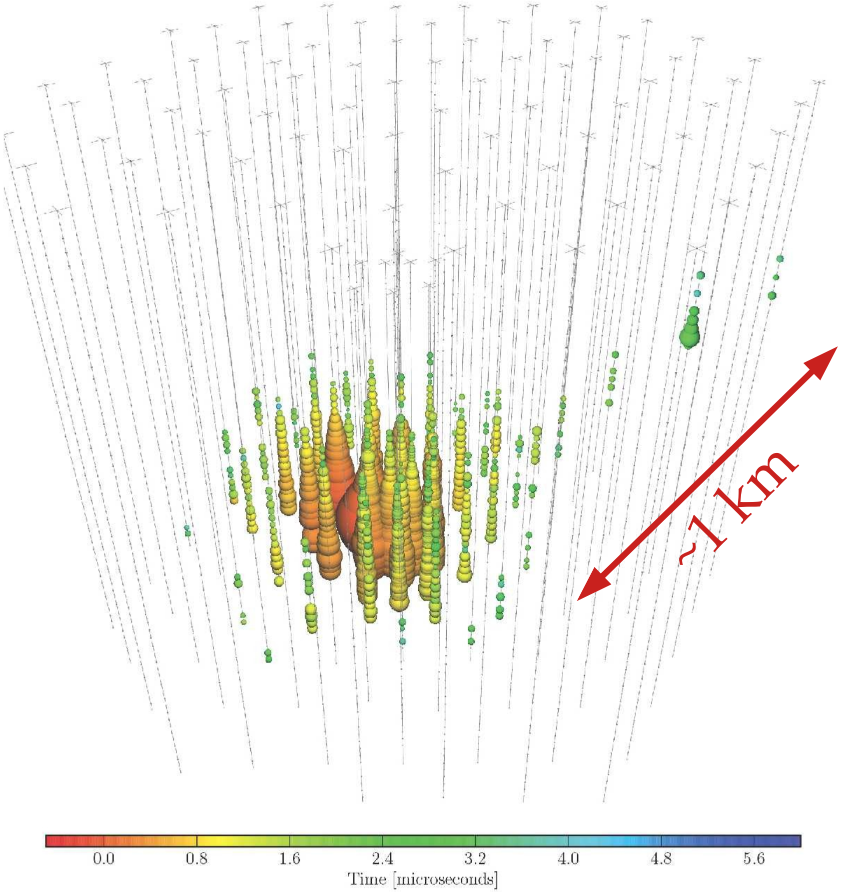
Schumacher, **MB**, Agostini, Oikonomou, Resconi, 2503.07549

Shower (mainly from ν_e and ν_τ)

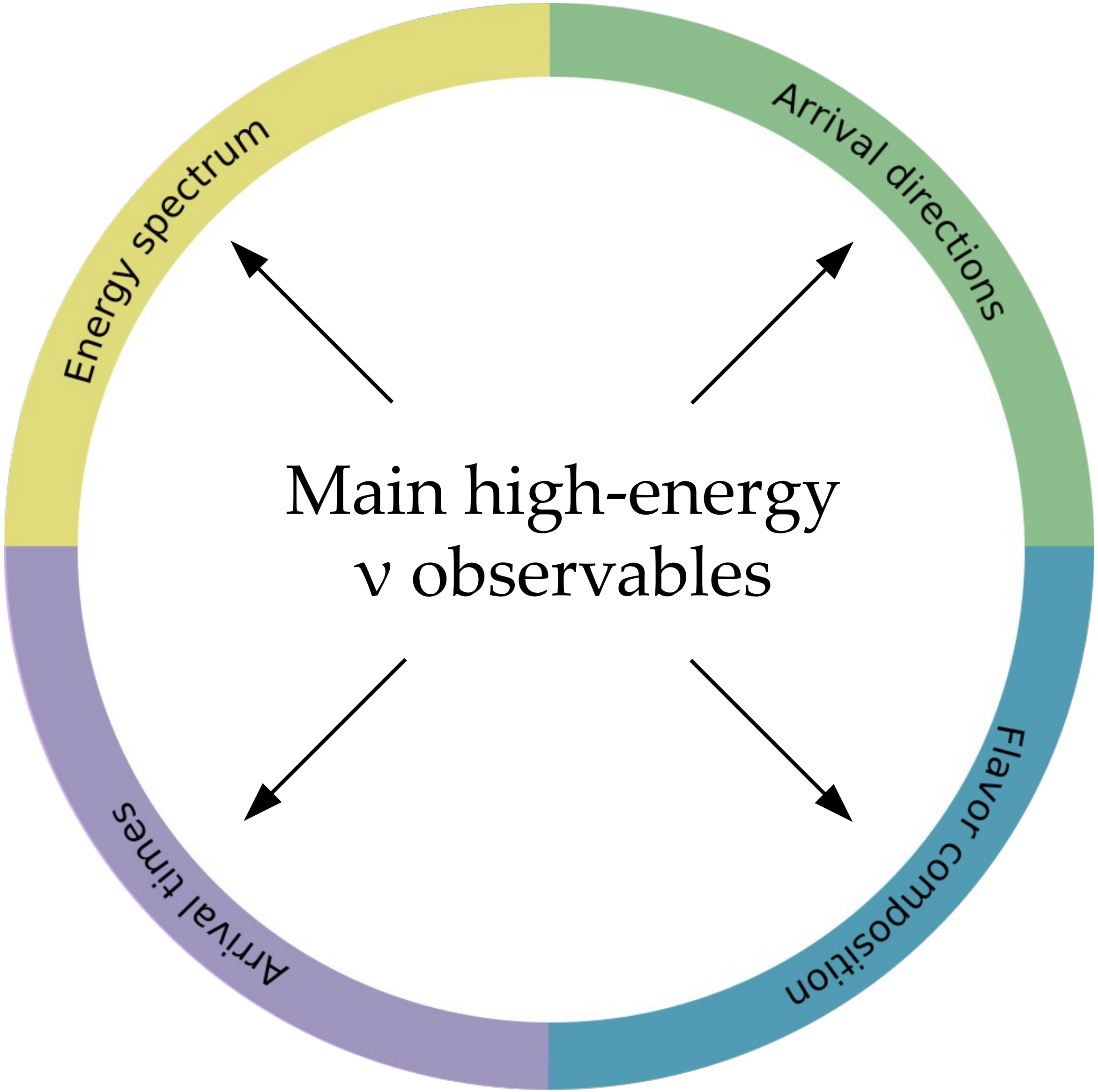


Poor angular resolution: < 5°

Track (mainly from ν_μ)

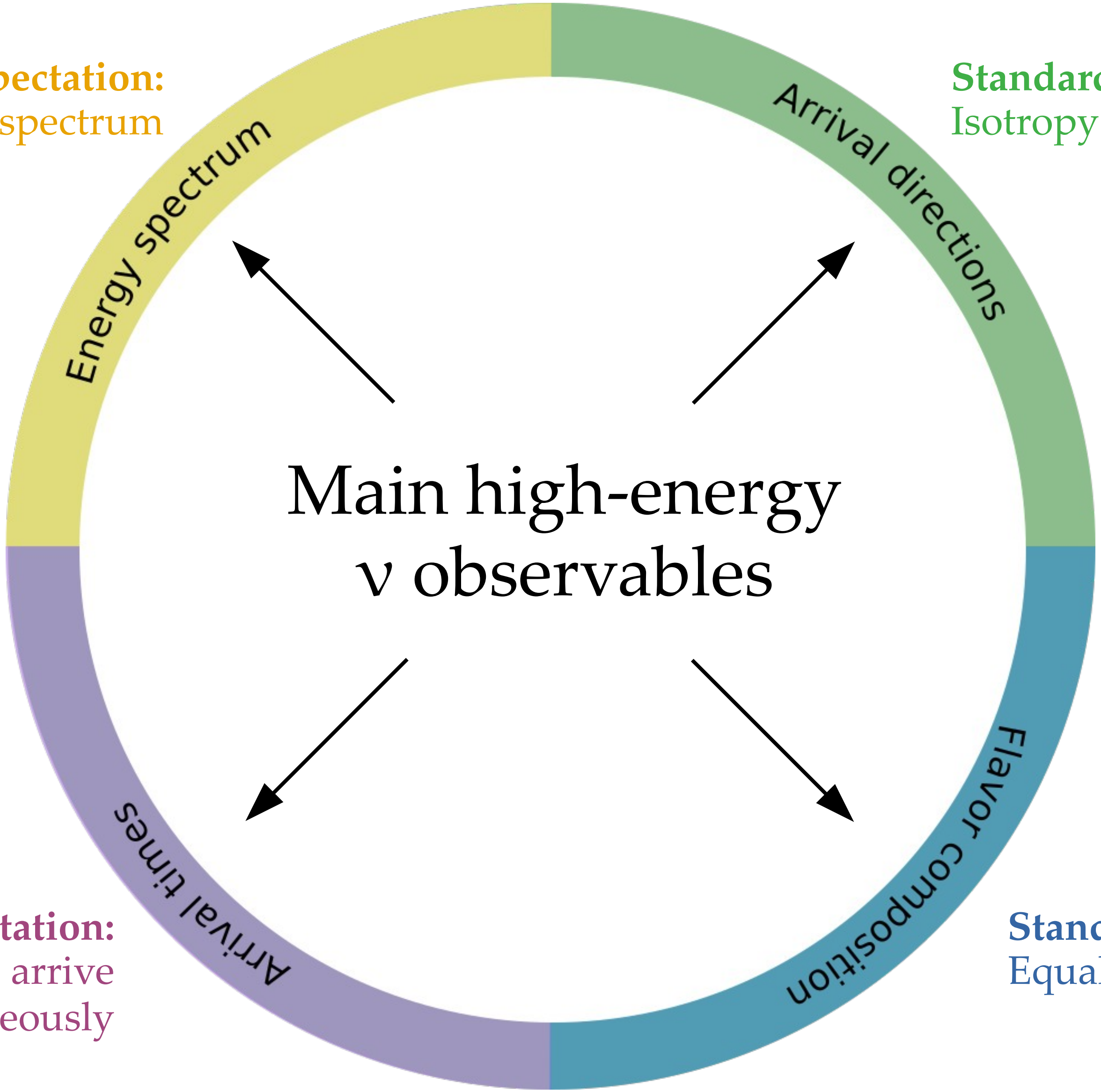


Angular resolution: < 1°


Main high-energy
ν observables
Energy spectrum
Arrival directions
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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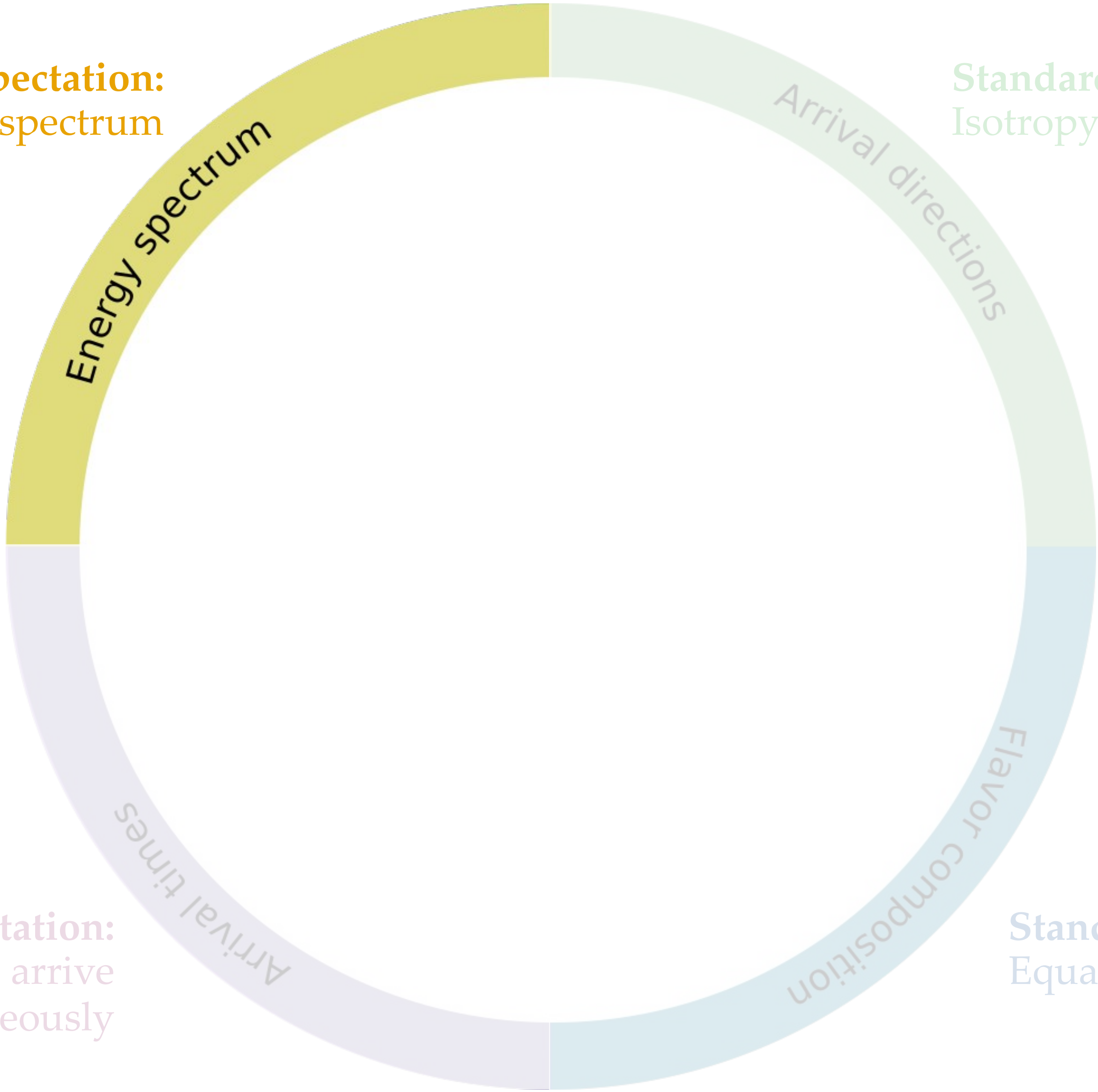

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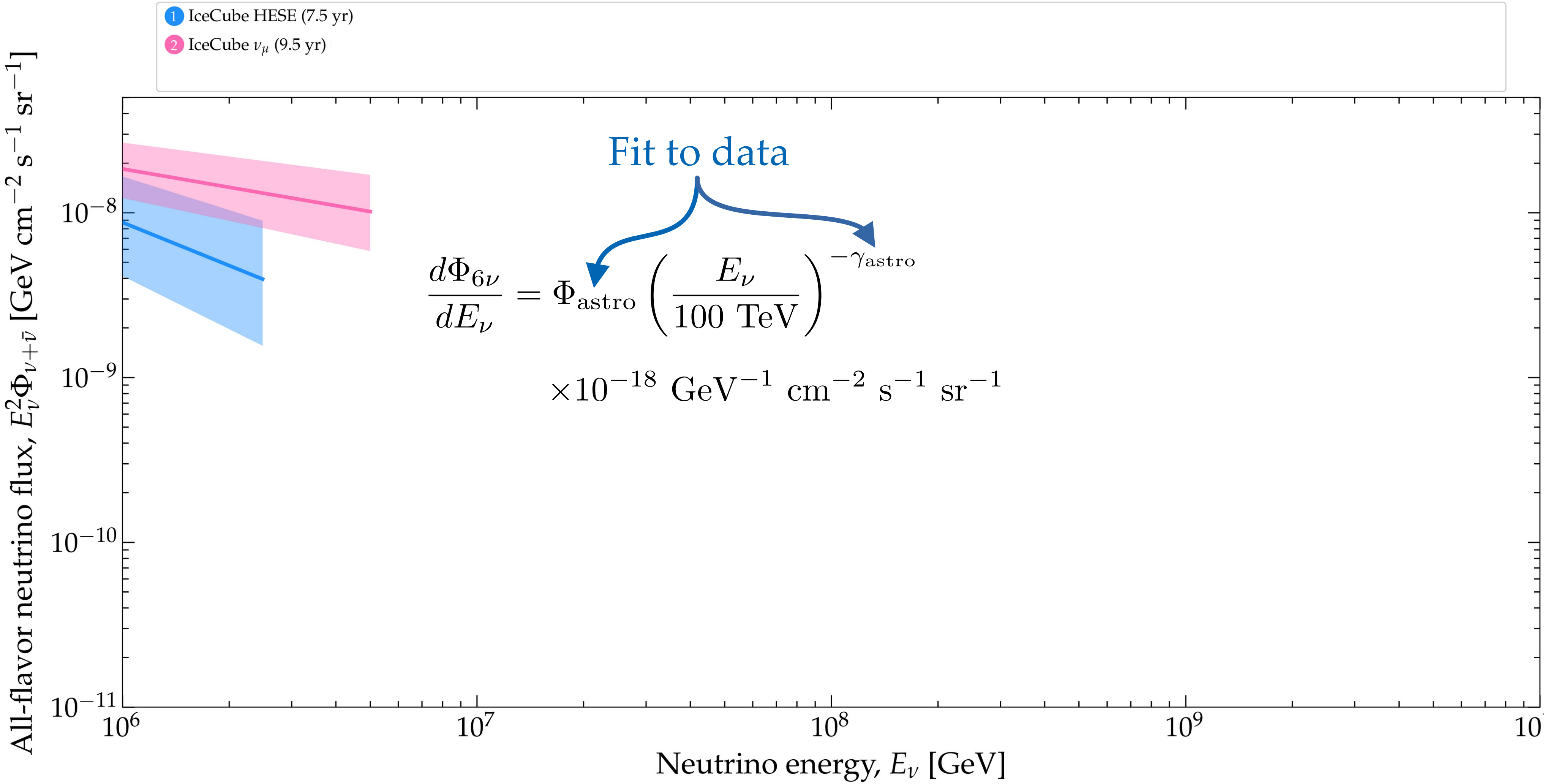
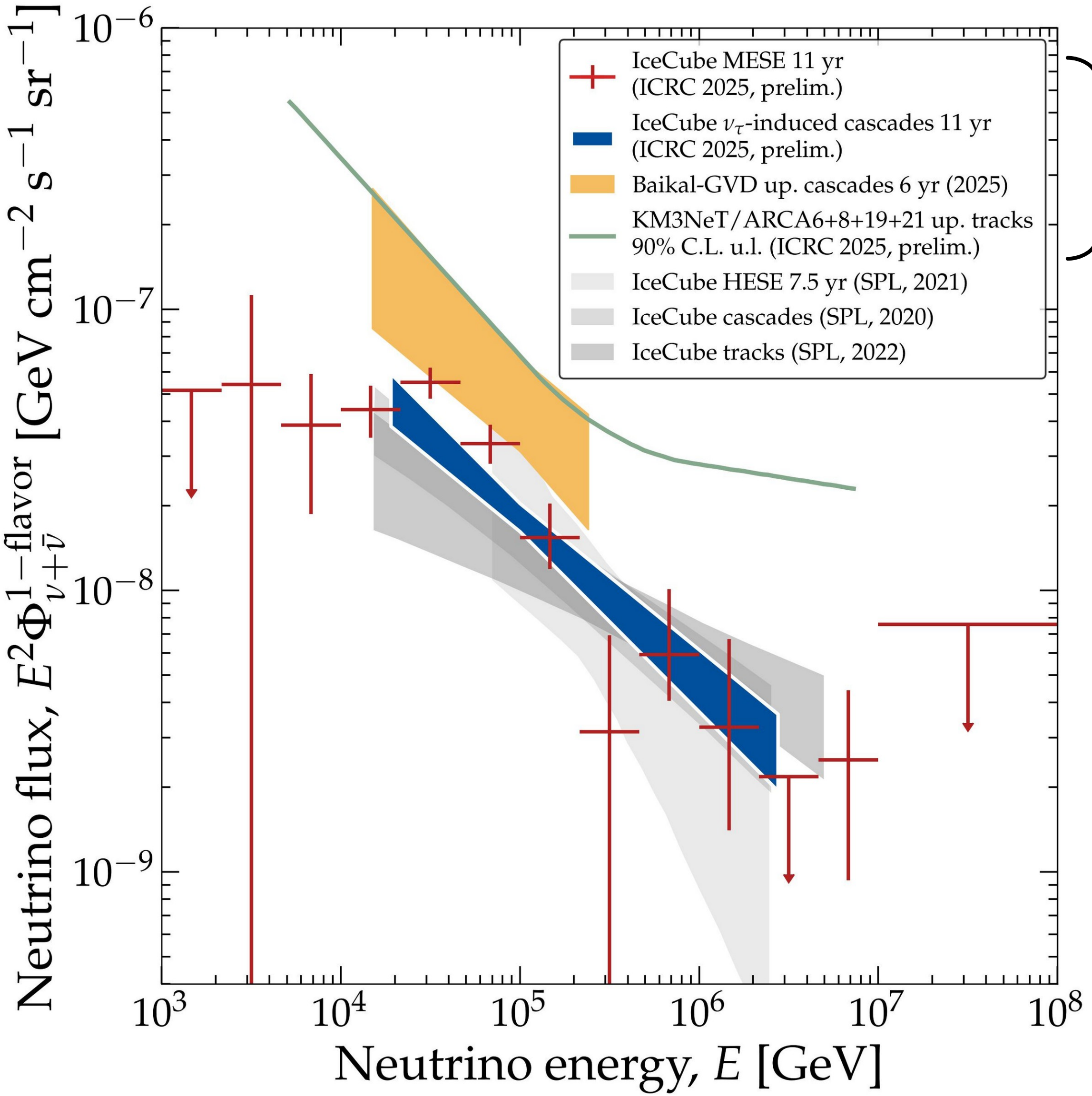


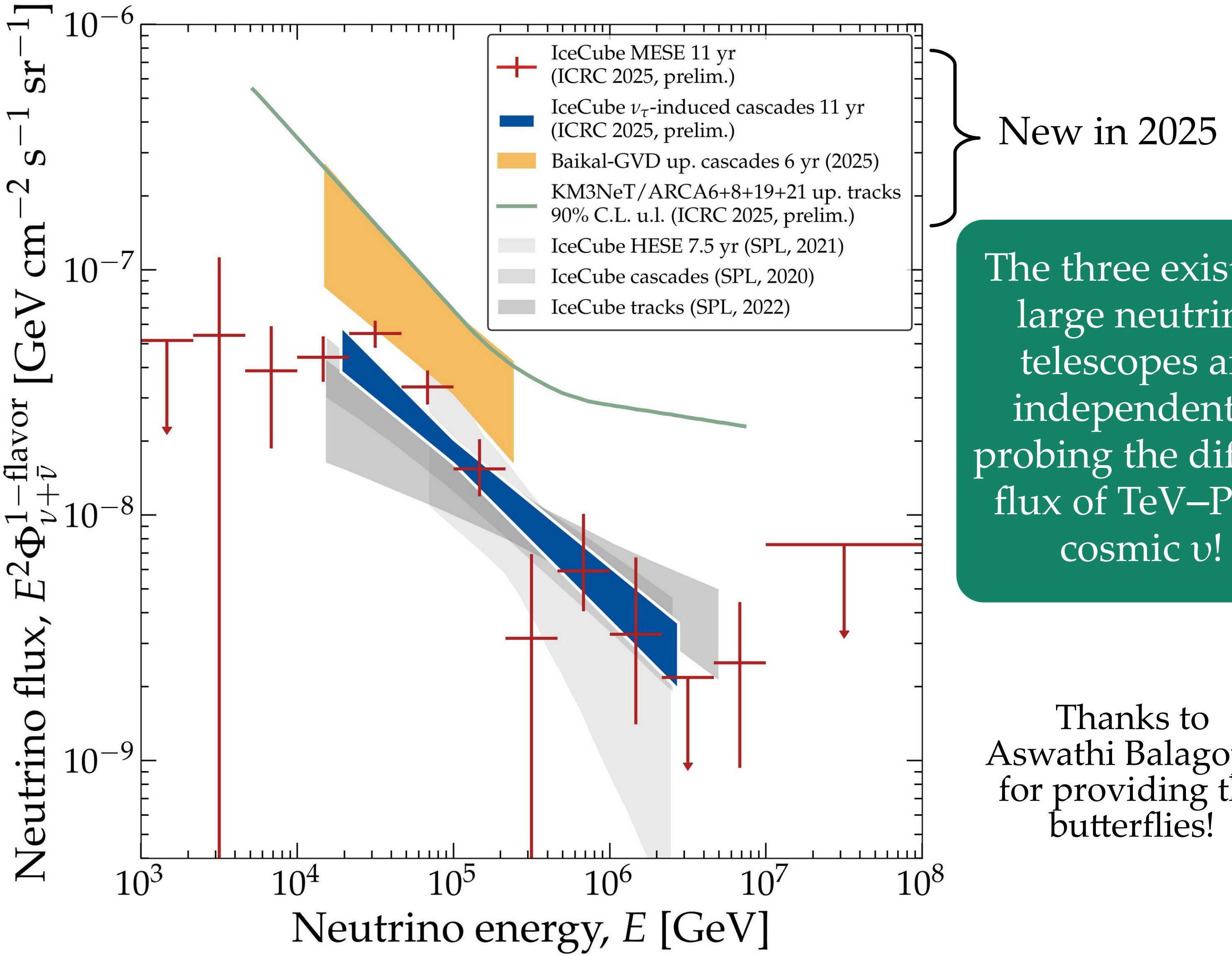
$$\frac{d\Phi_{6\nu}}{dE_\nu} = \Phi_{\rm astro} \left(\frac{E_\nu}{100~\rm TeV} \right)^{-\gamma_{\rm astro}}$$

$$\times 10^{-18}~\rm GeV^{-1}~cm^{-2}~s^{-1}~sr^{-1}$$



New in 2025

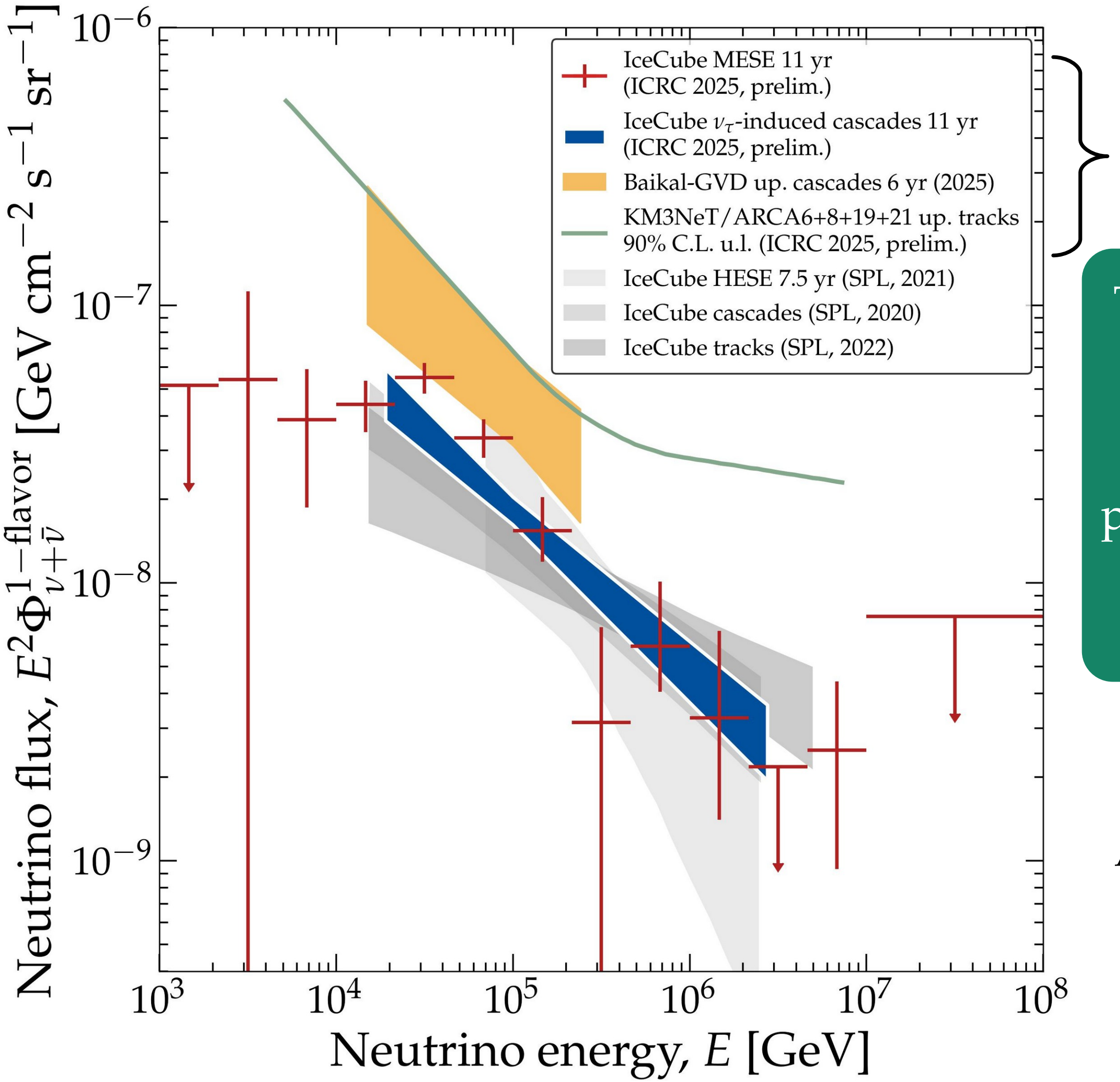
Thanks to Aswathi Balagopal for providing the butterflies!



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

Thanks to Aswathi Balagopal for providing the butterflies!

And IceCube is finding structure in the energy spectrum



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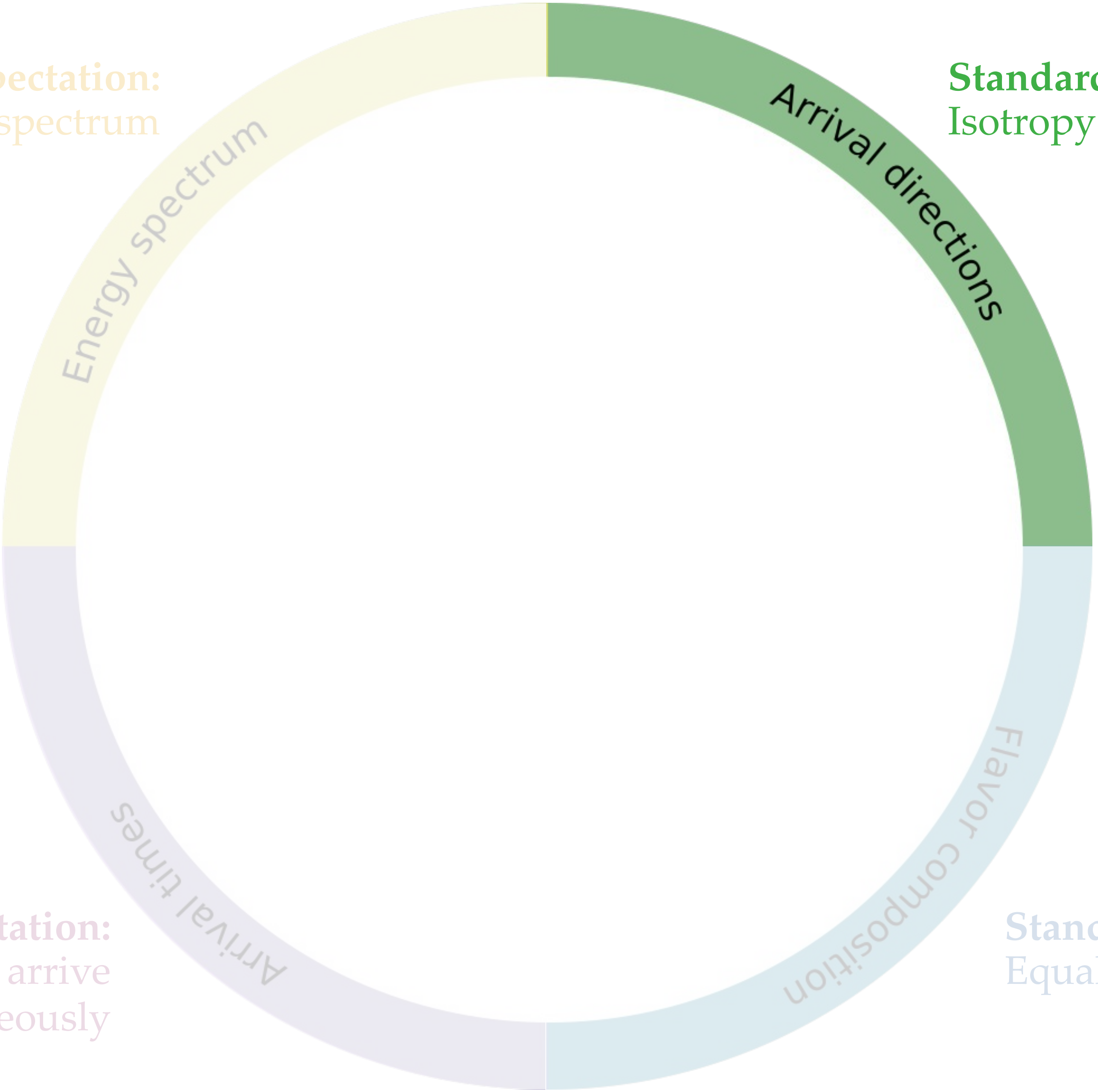

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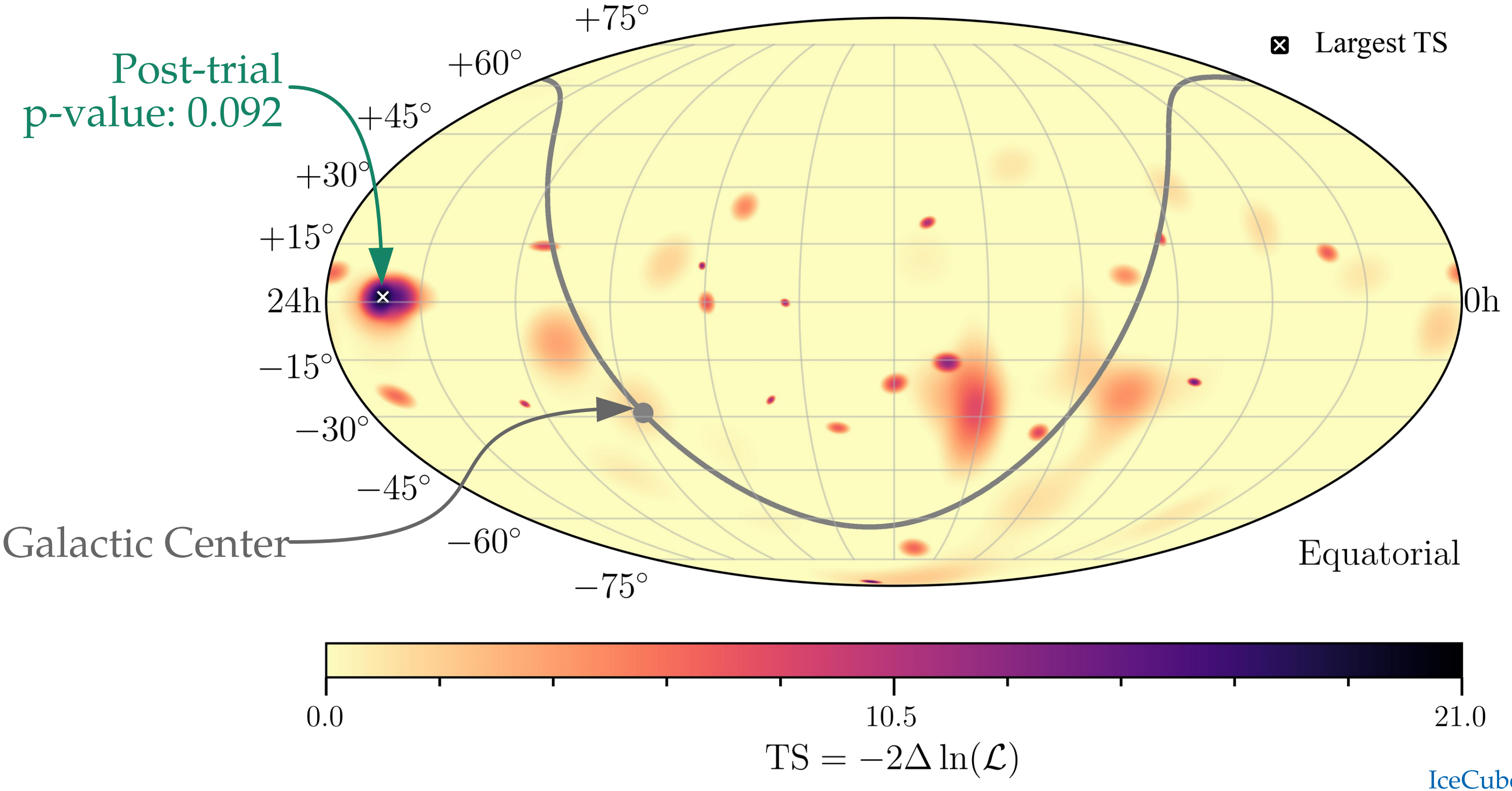
Arrival directions (7.5 yr)

No significant excess in the neutrino sky map:



IceCube, *PRD* 2021

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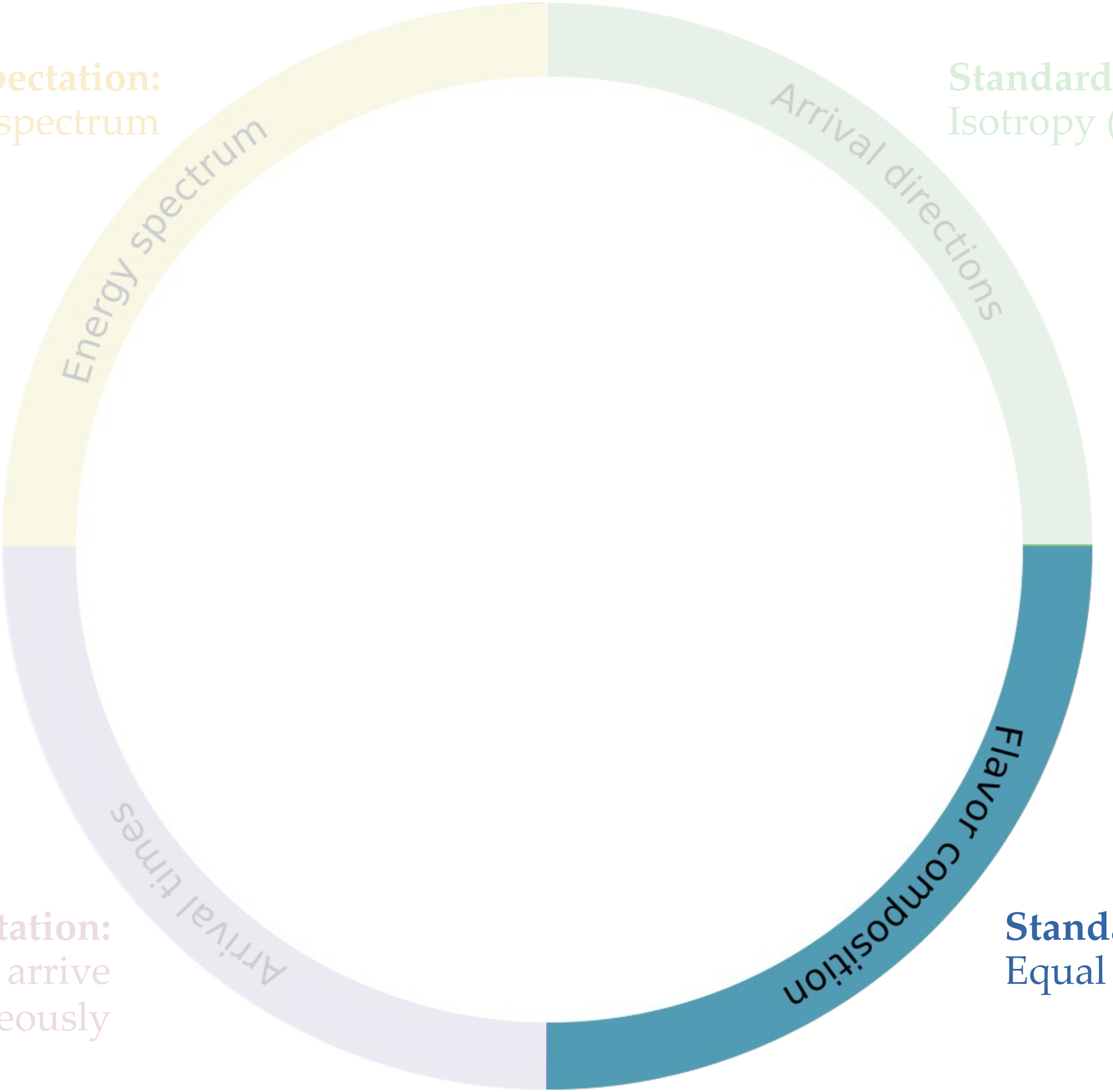

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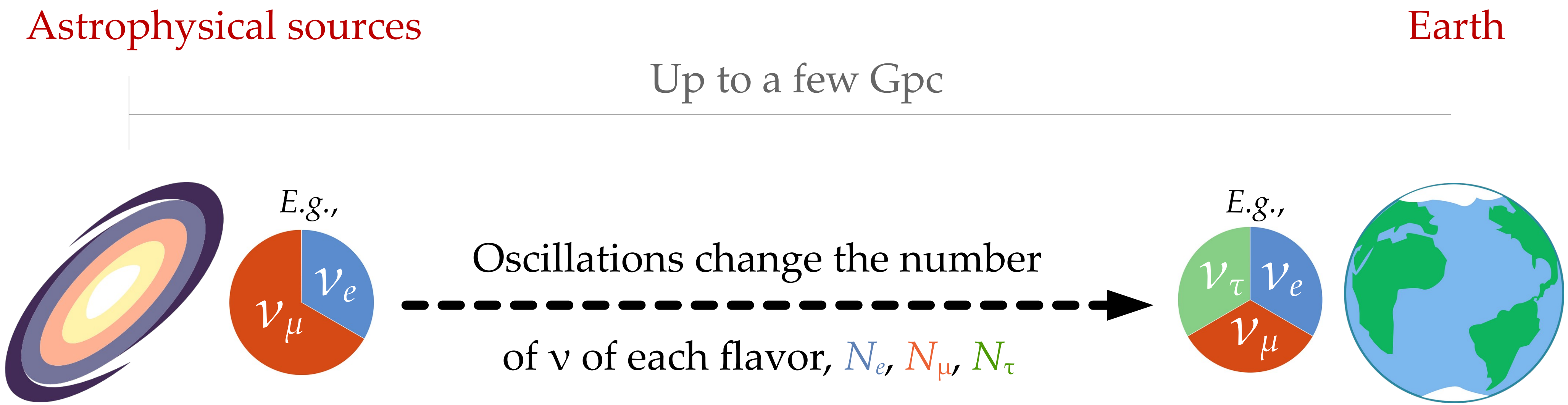
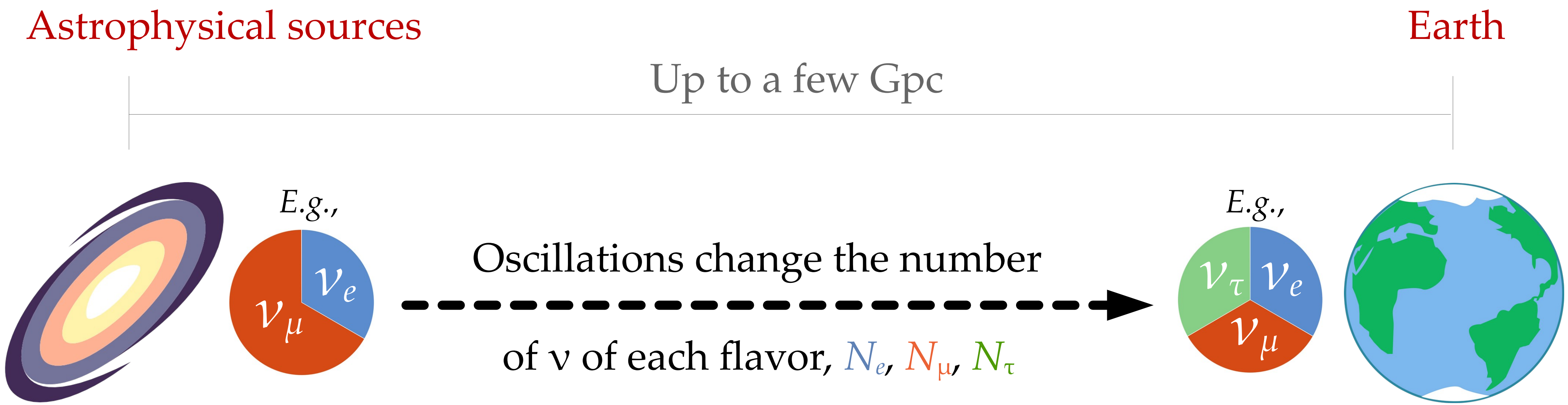


Different production mechanisms yield different flavor ratios:

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

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

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



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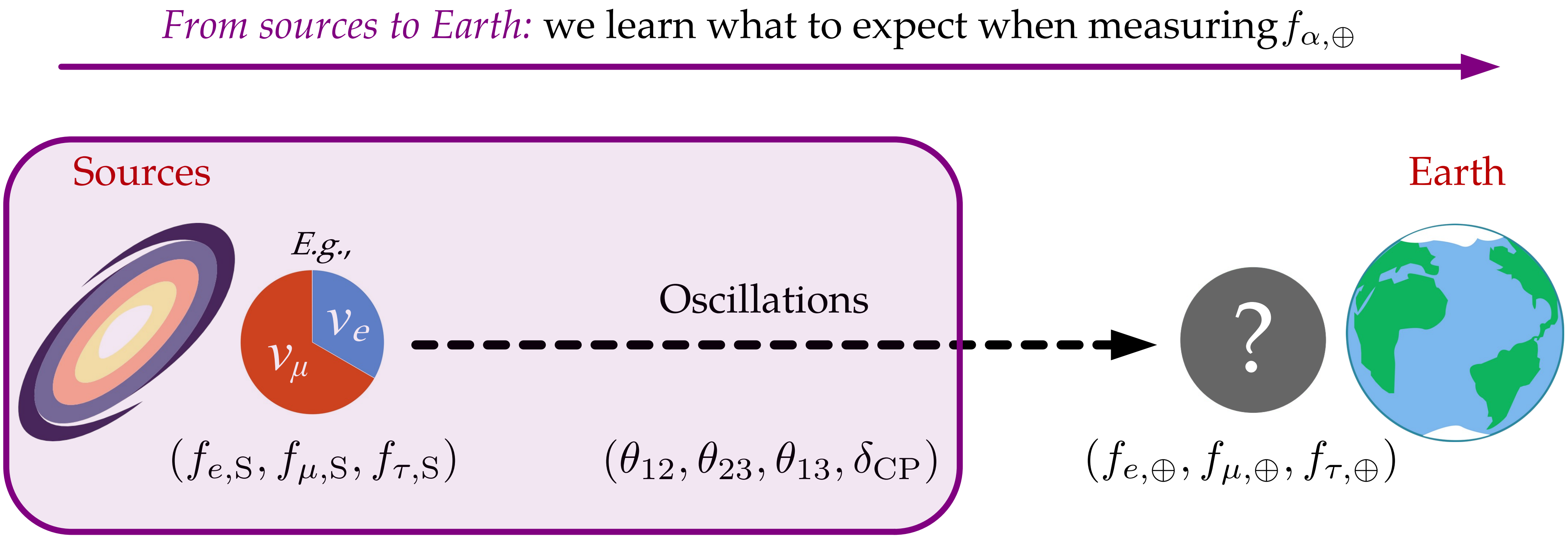
Standard oscillations
or
new physics



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

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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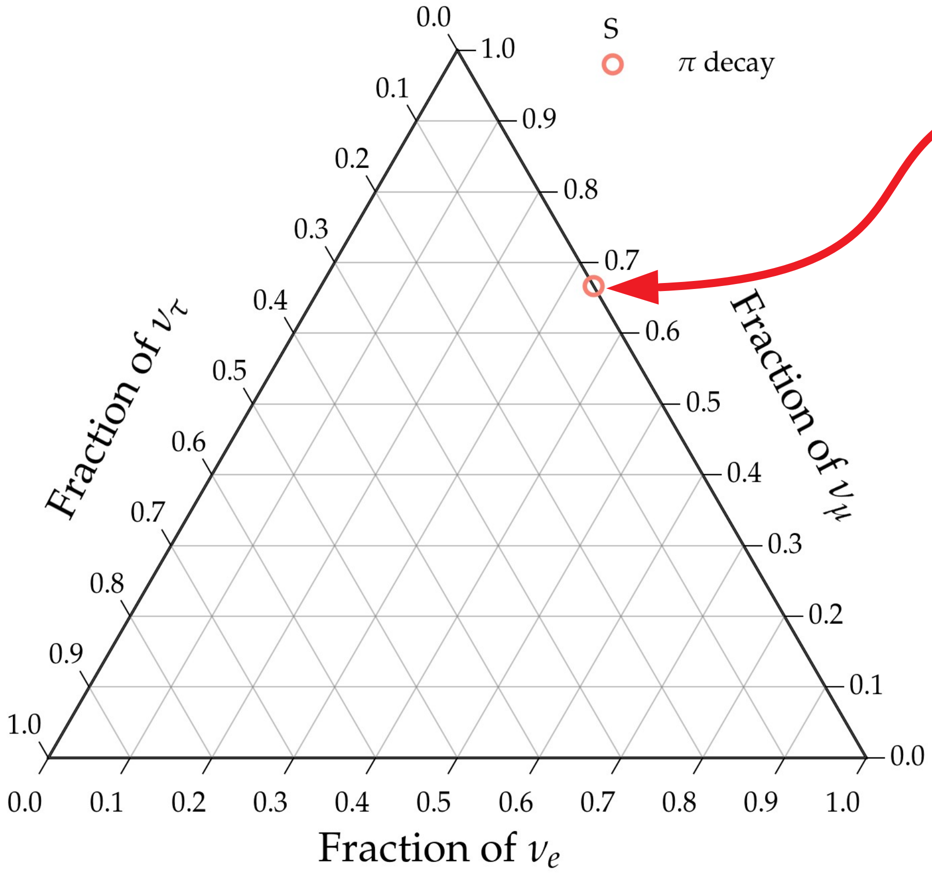

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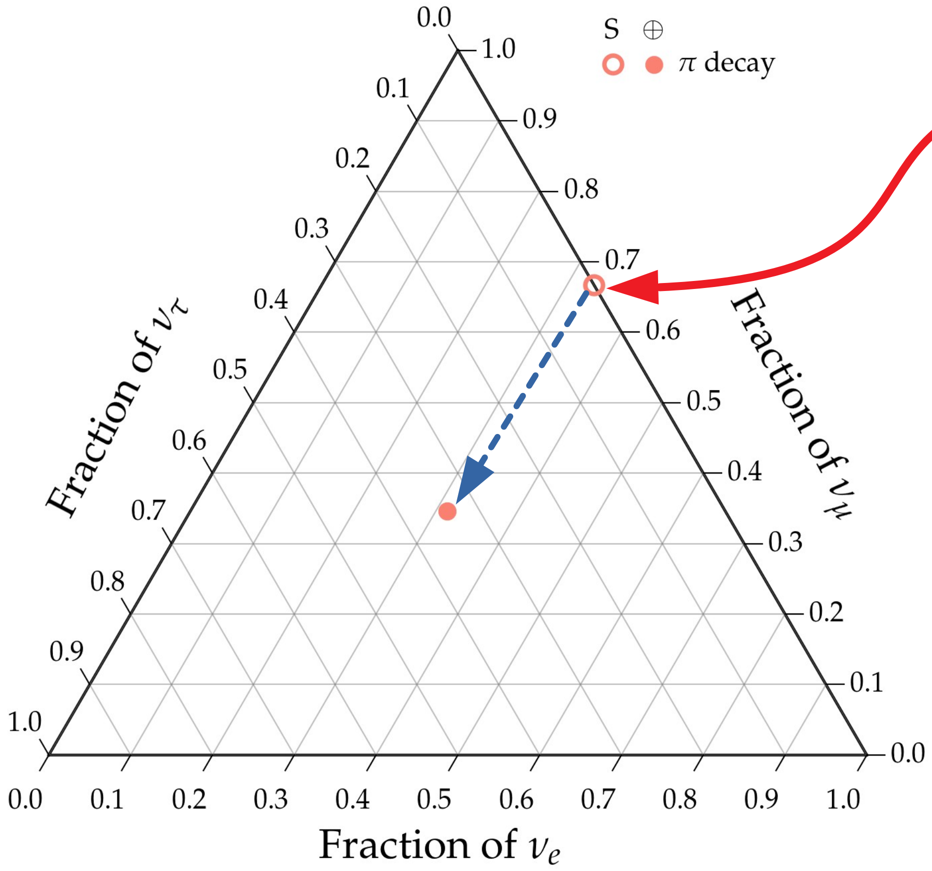

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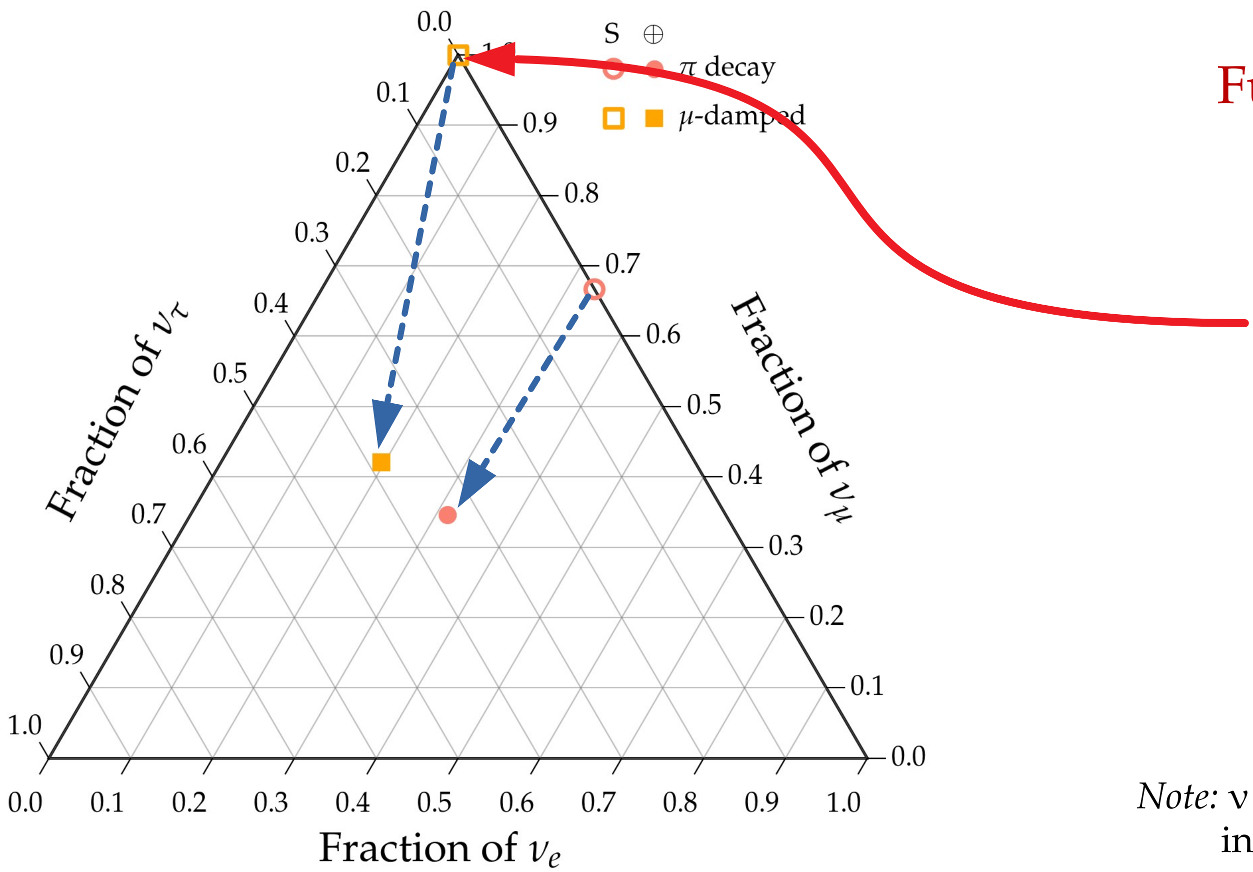

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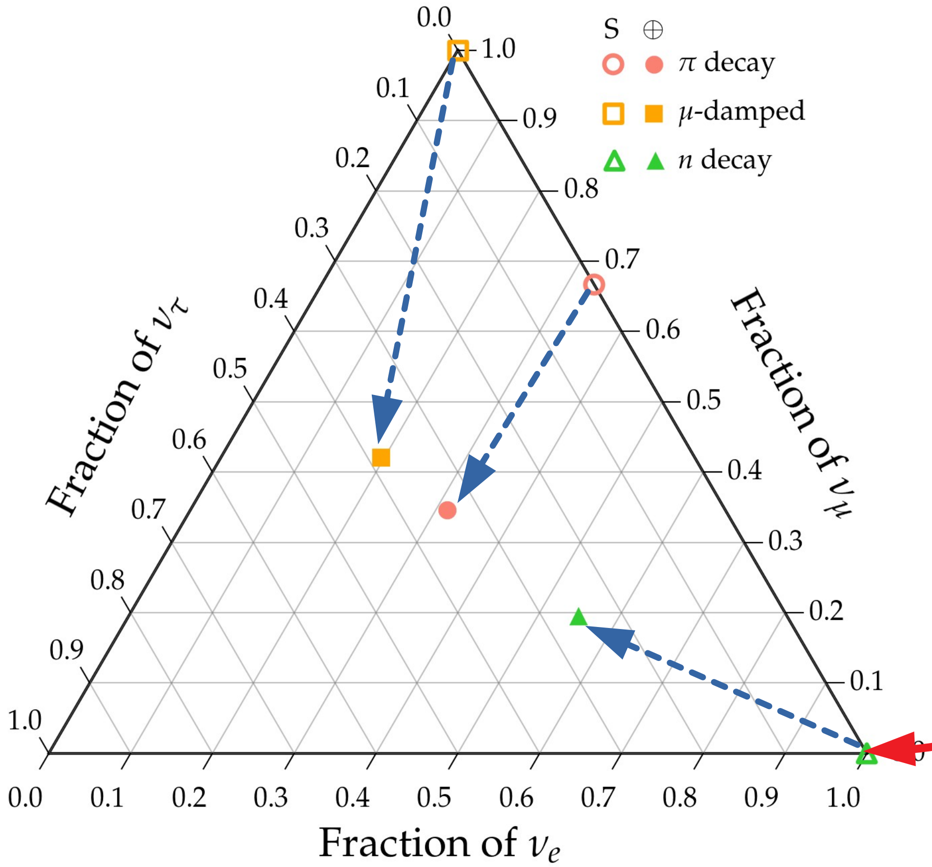

Full π decay chain

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

Muon damped

$(0:1:0)_S$

Neutron decay

$(1:0:0)_S$

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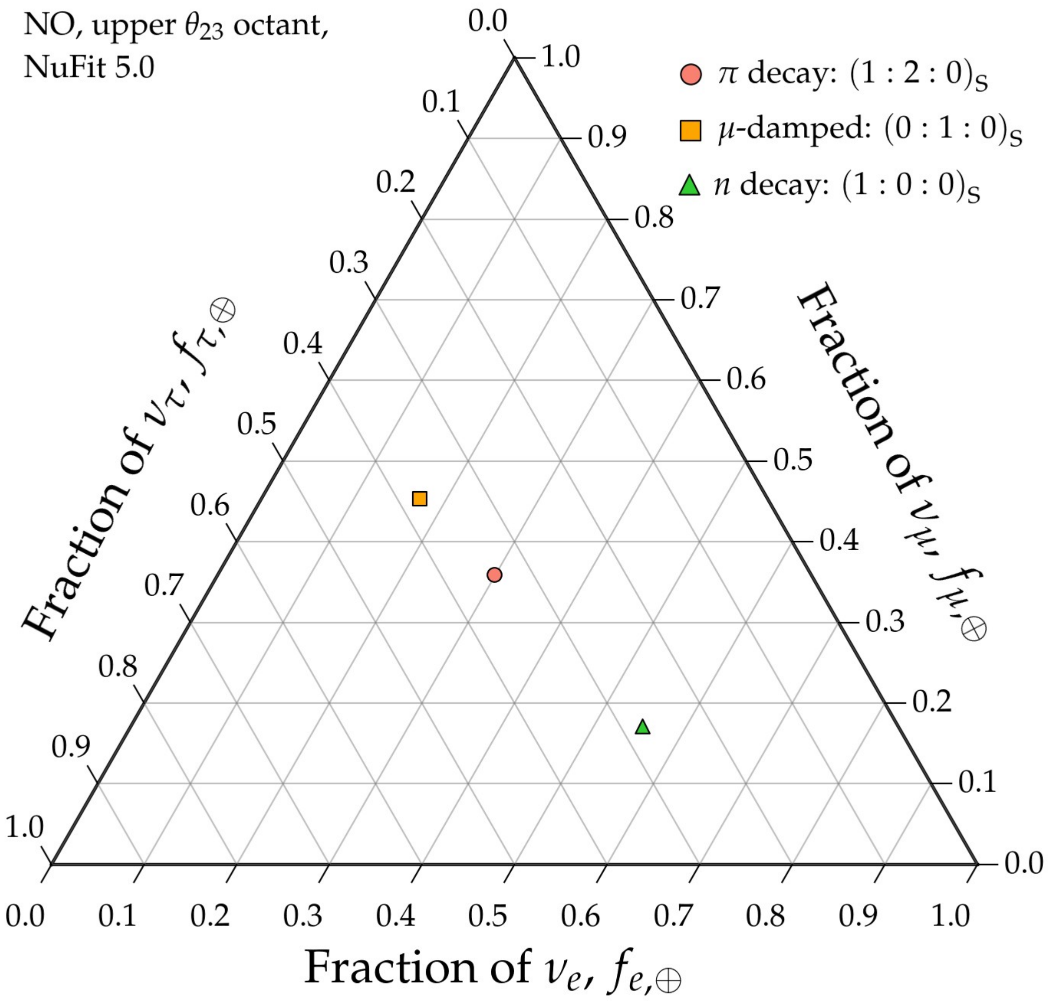
Theoretically palatable regions: today



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

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

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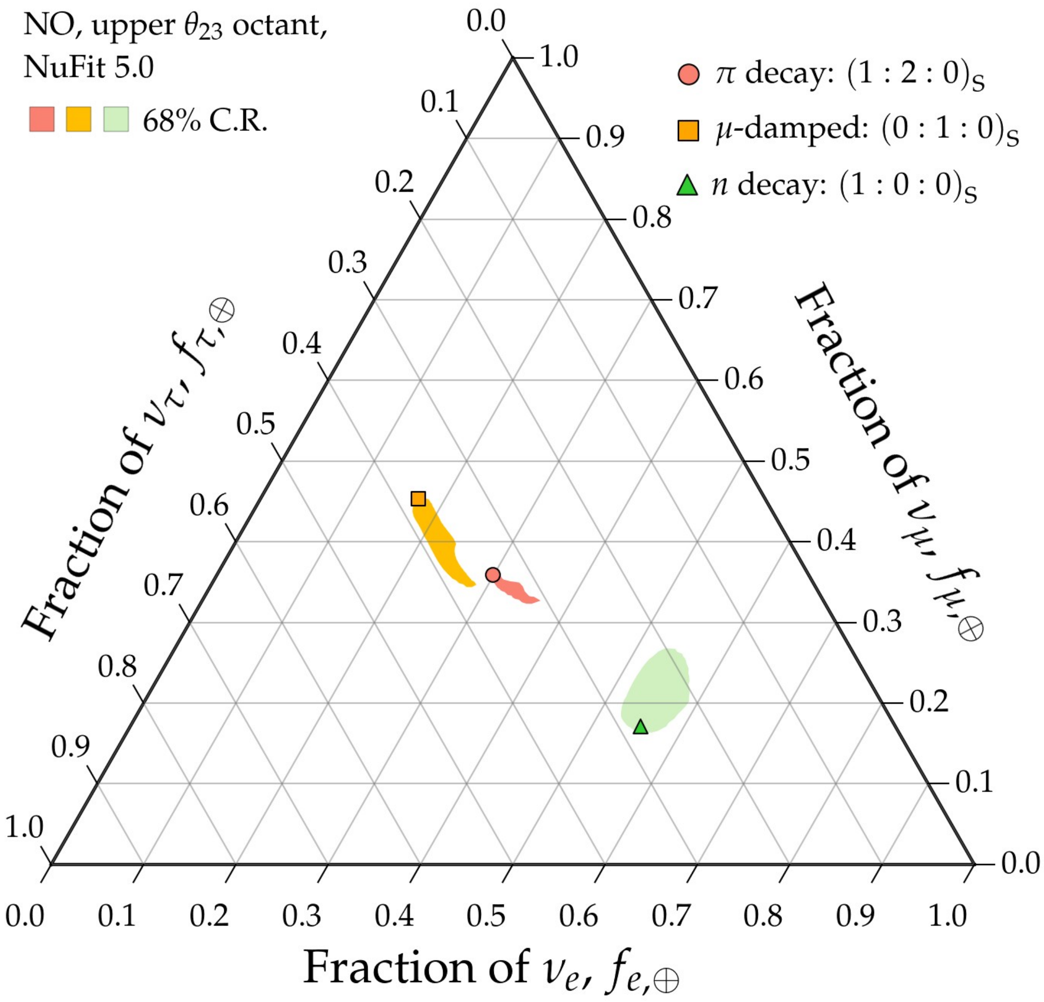

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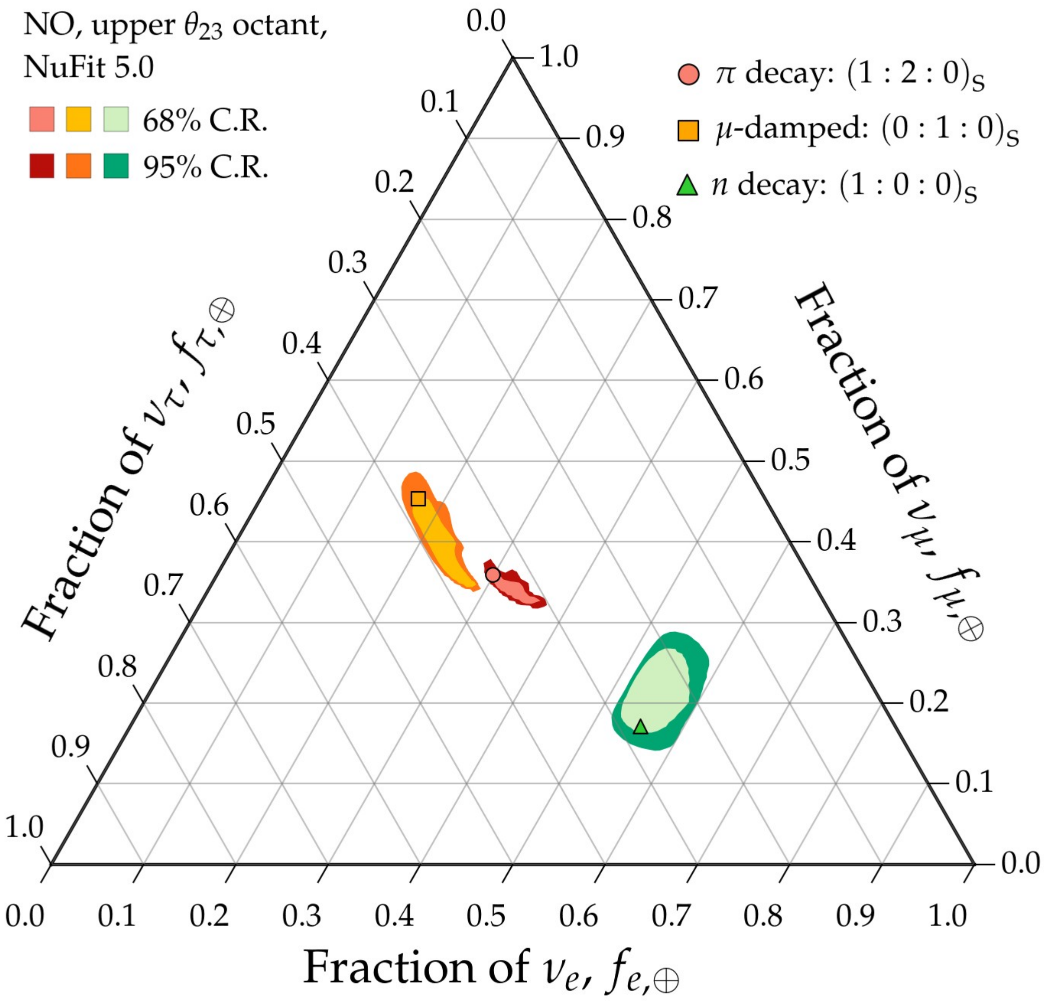

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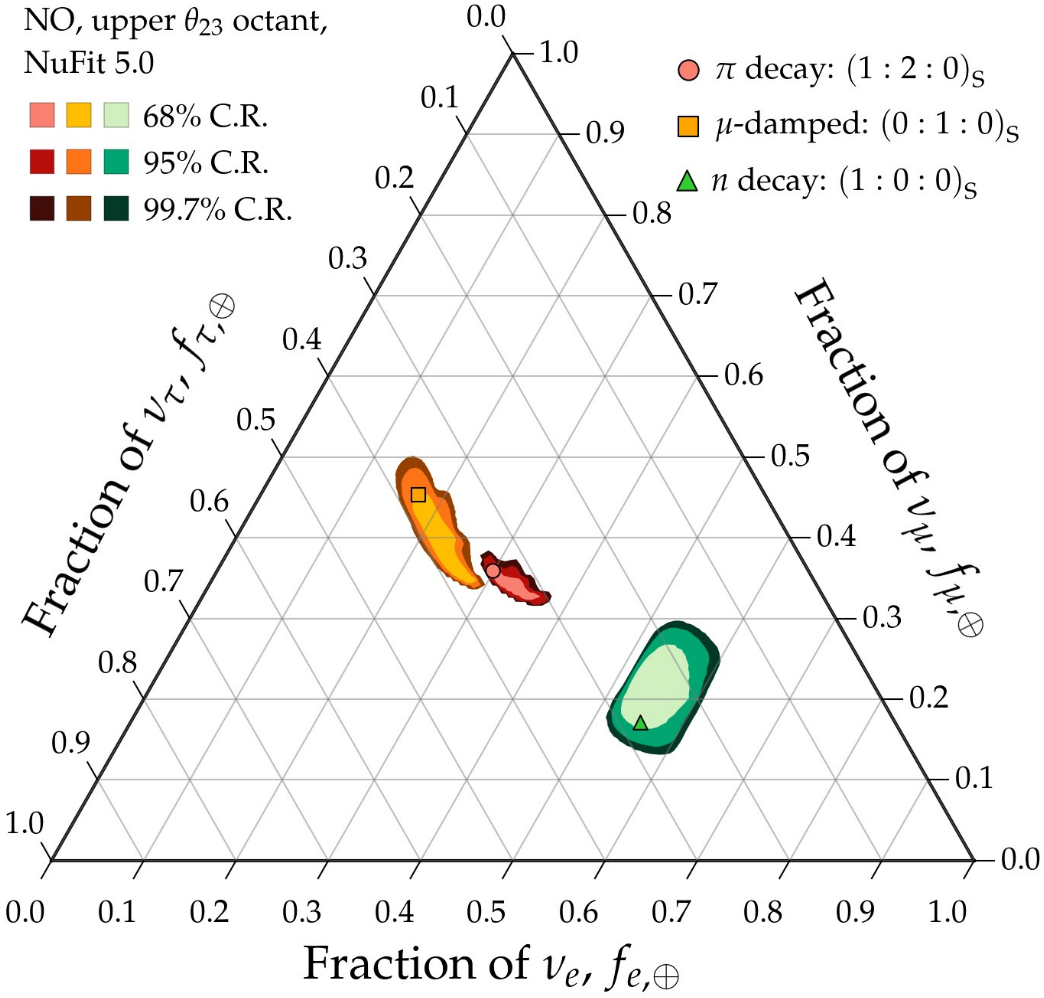

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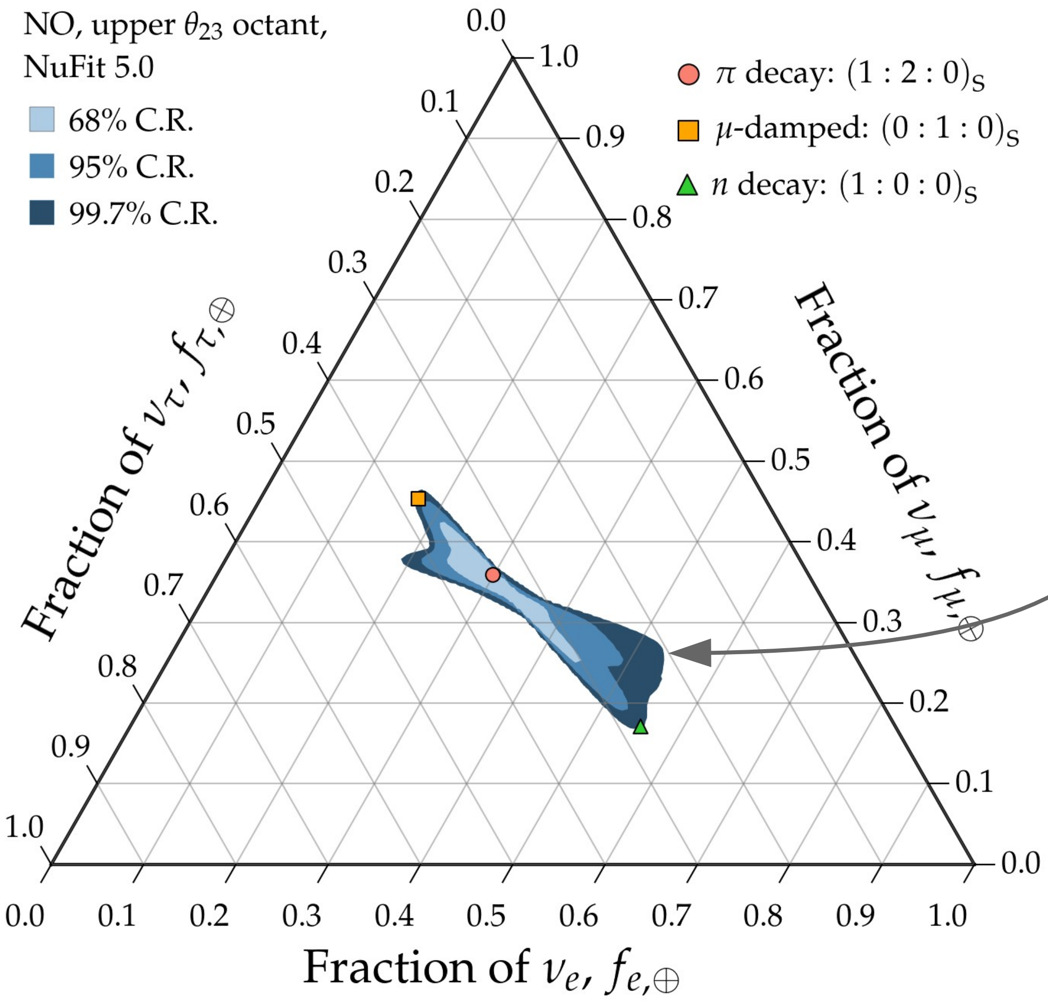
Theoretically palatable regions: today

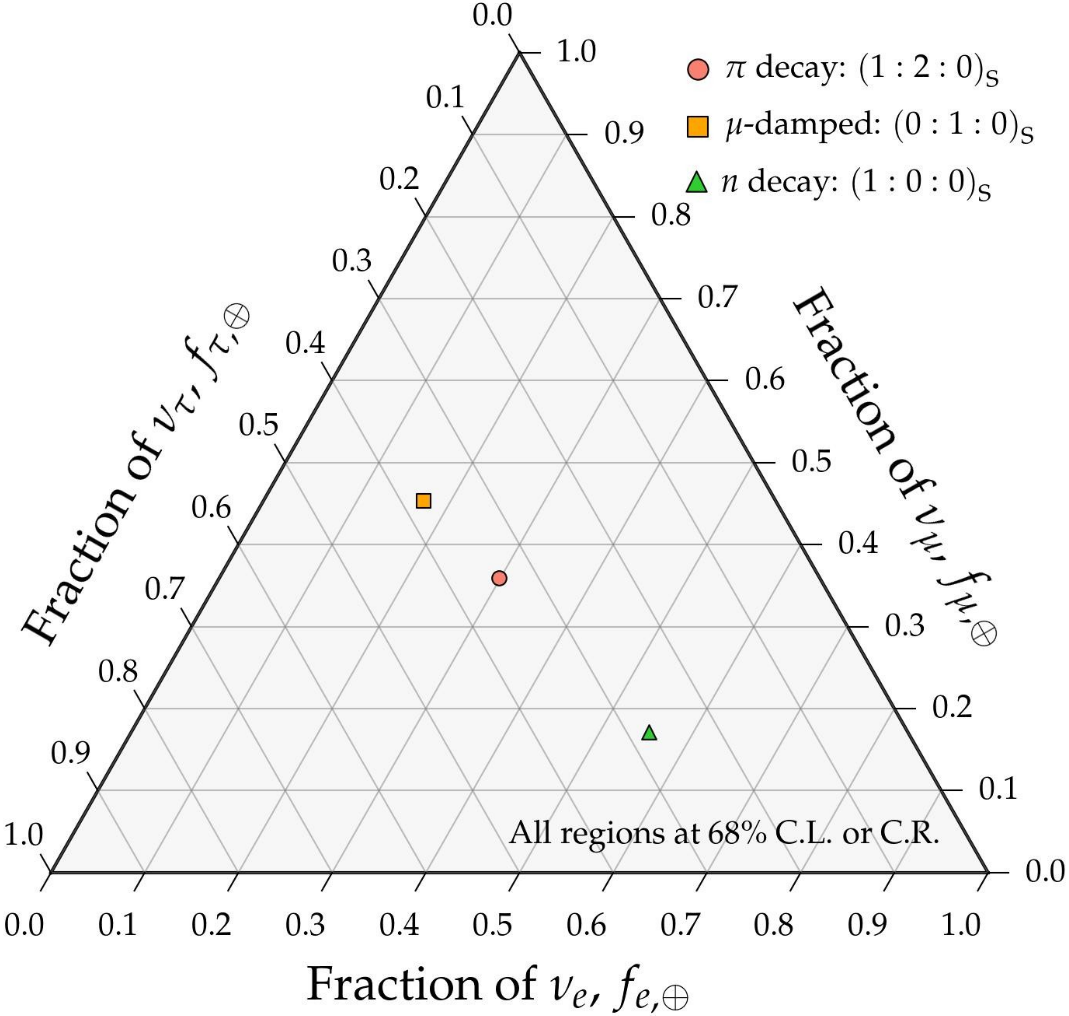


Varying over all possible flavor ratios at the source

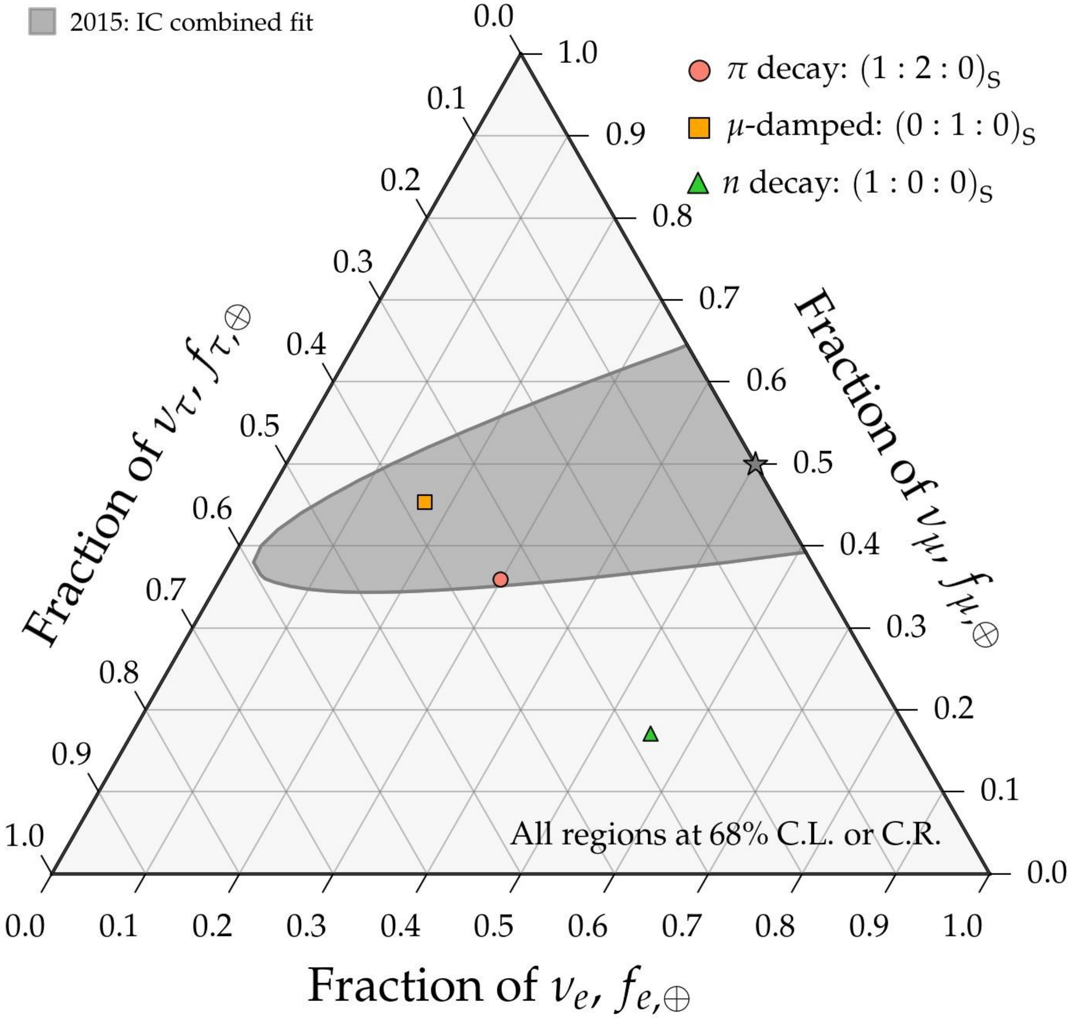
Note:
All plots shown are for normal neutrino mass ordering (NO); inverted ordering looks similar

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

Measuring flavor composition 2015–2025

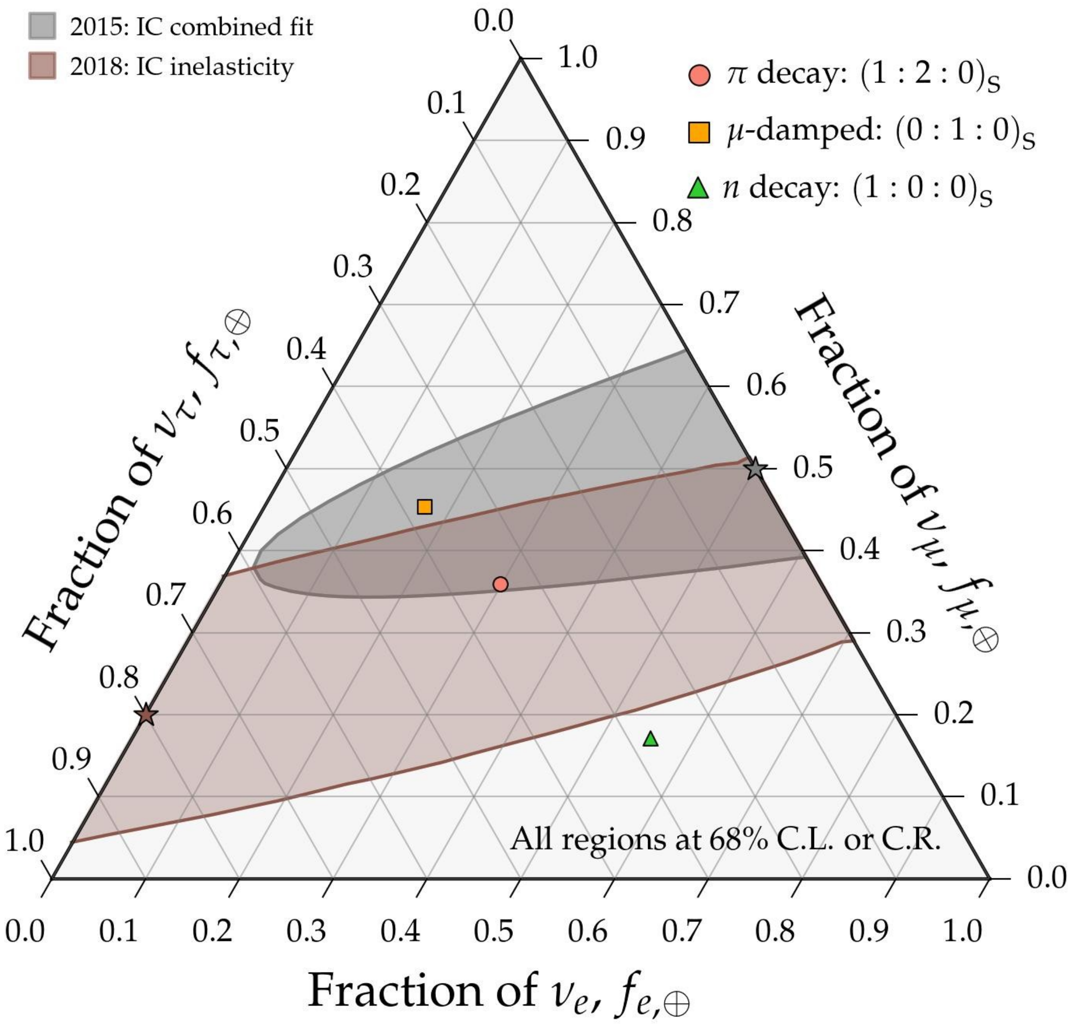


Measuring flavor composition 2015–2025



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

Measuring flavor composition 2015–2025



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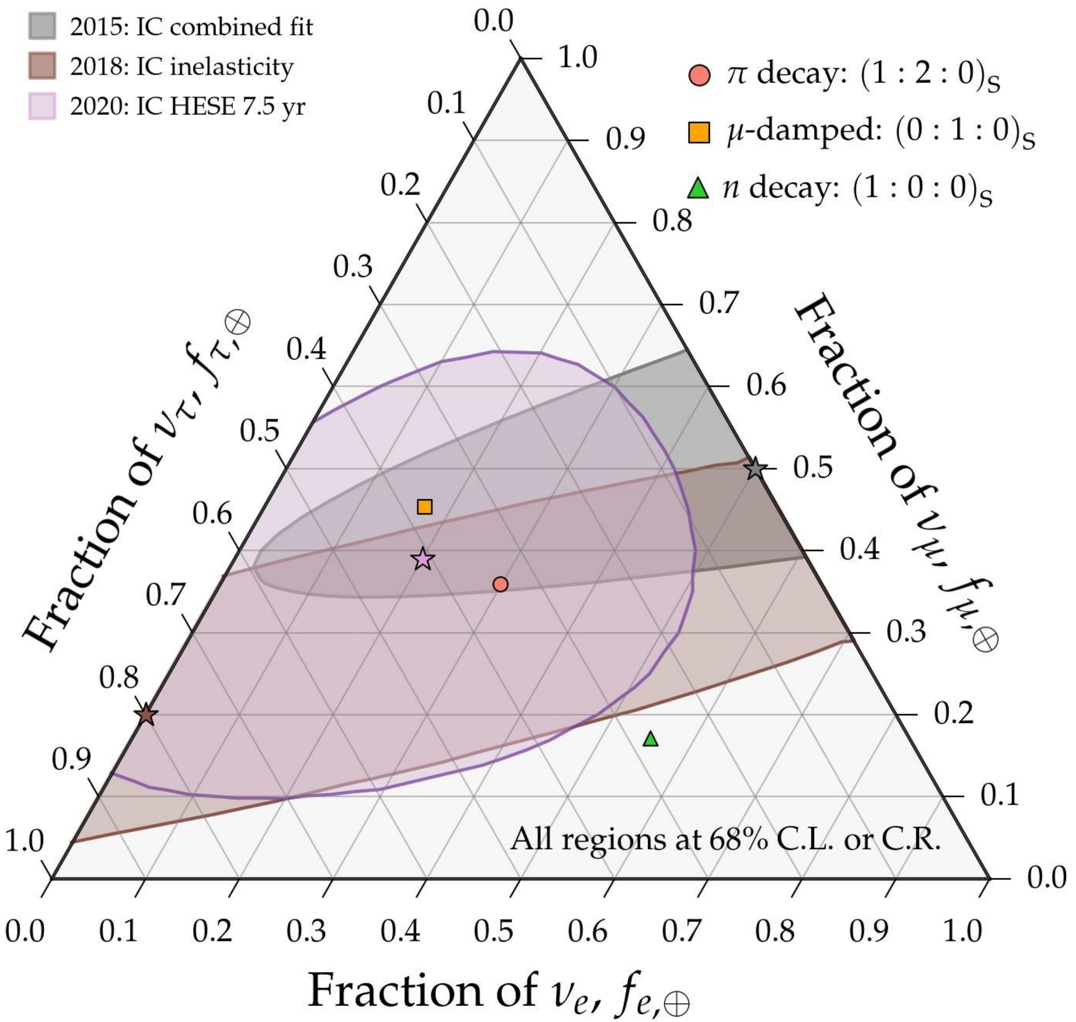

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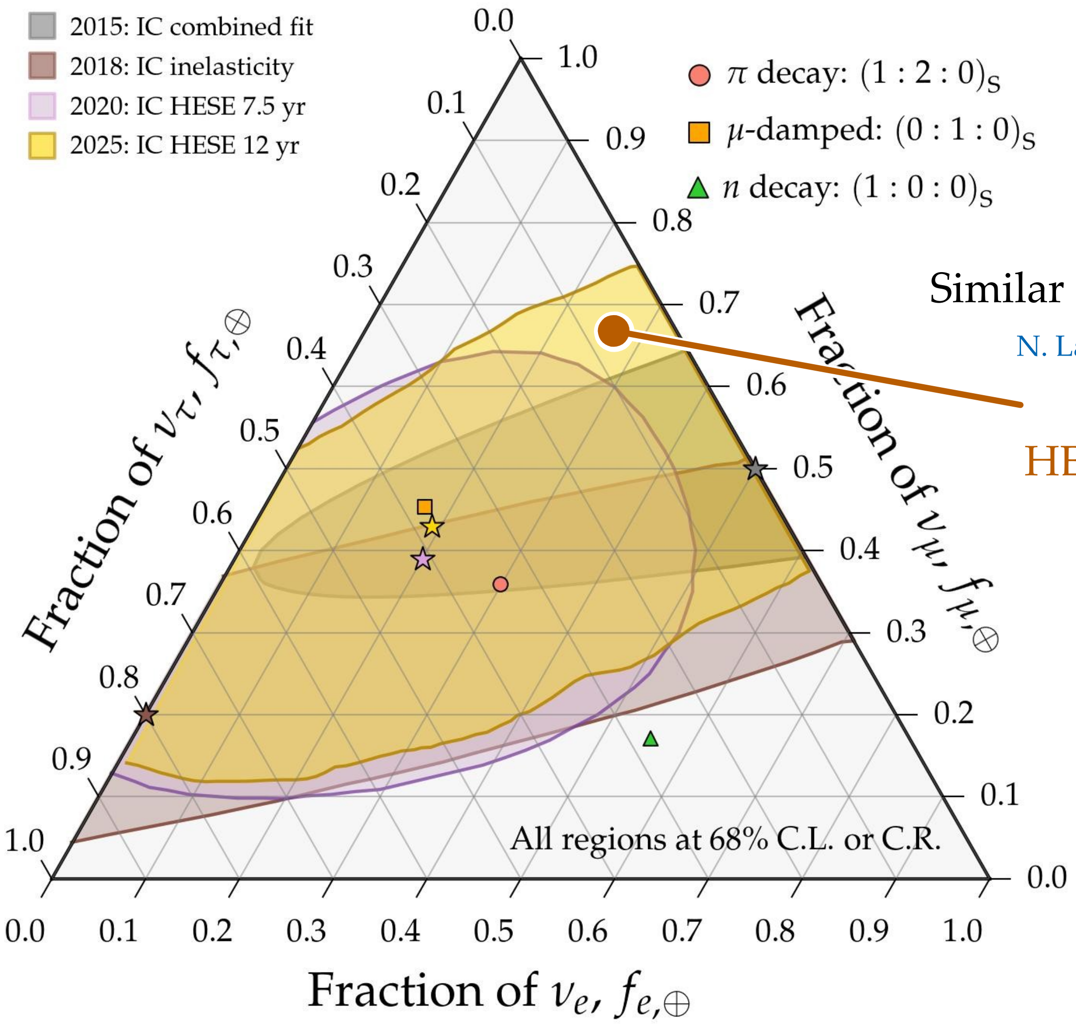

Similar likelihood as with 7.5 yr

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

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

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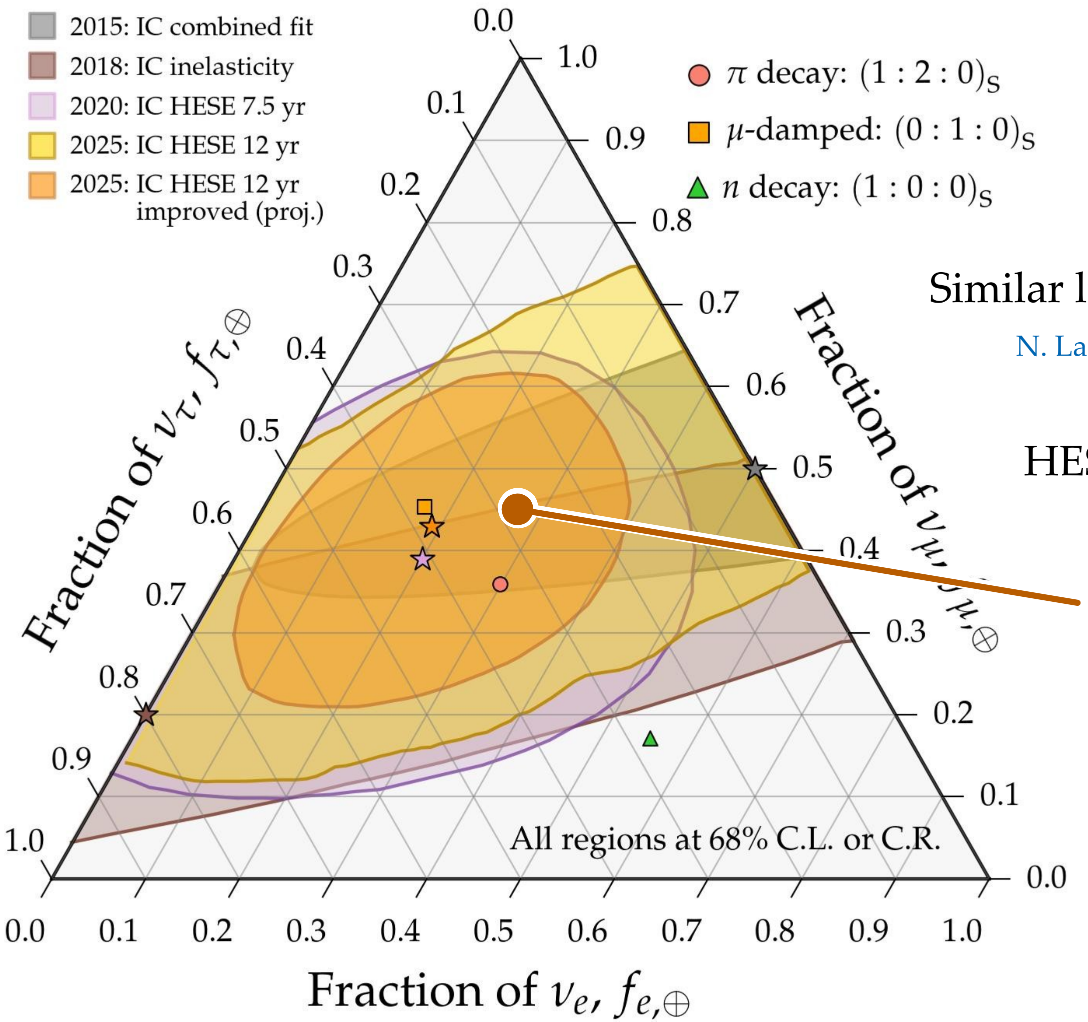


Similar likelihood as with 7.5 yr

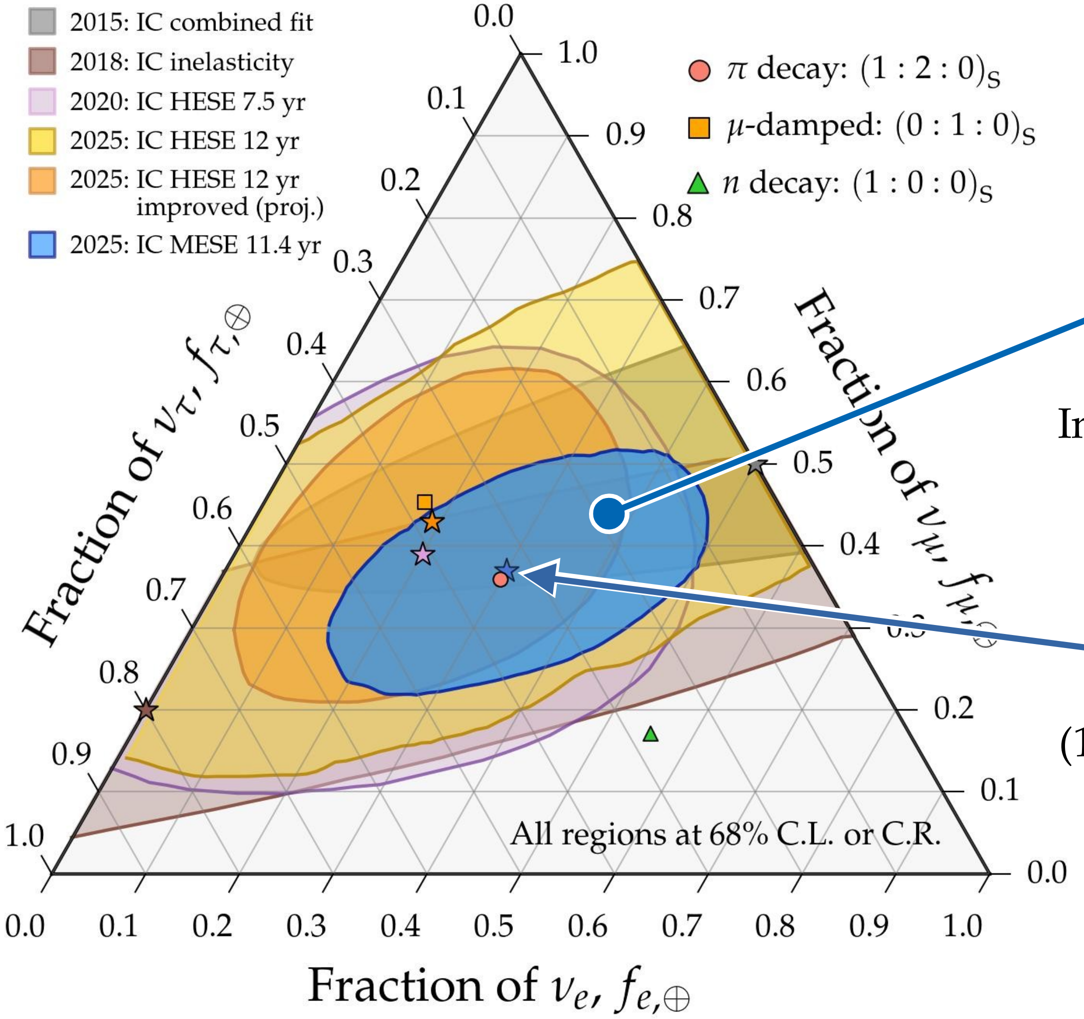
N. Lad, T. J. van Eeden, M. Ackermann
PoS(ICRC2025)1198

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

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

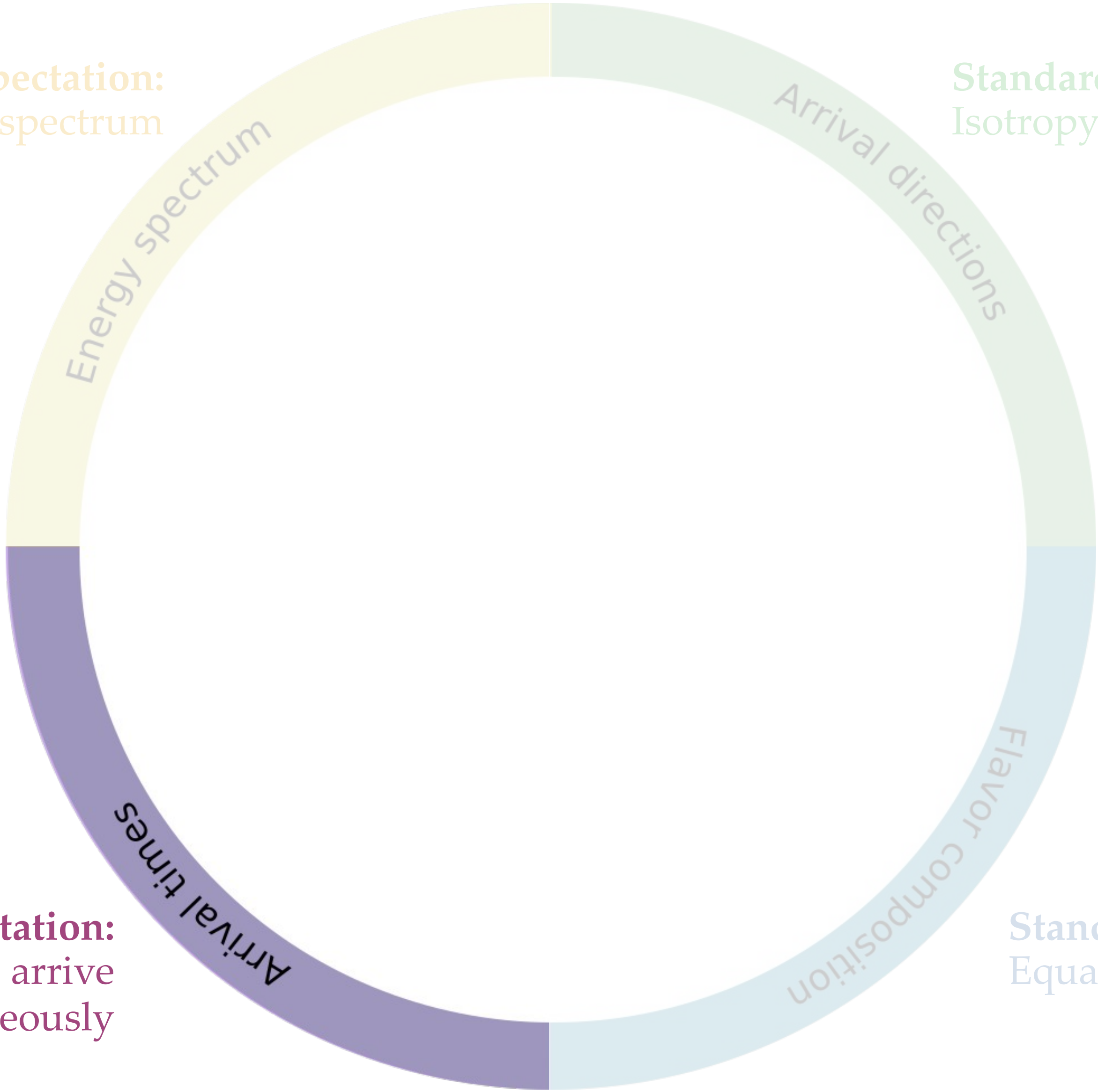
First time all flavors are nonzero at 68% C.L.

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

Standard expectation:
Power-law energy spectrum

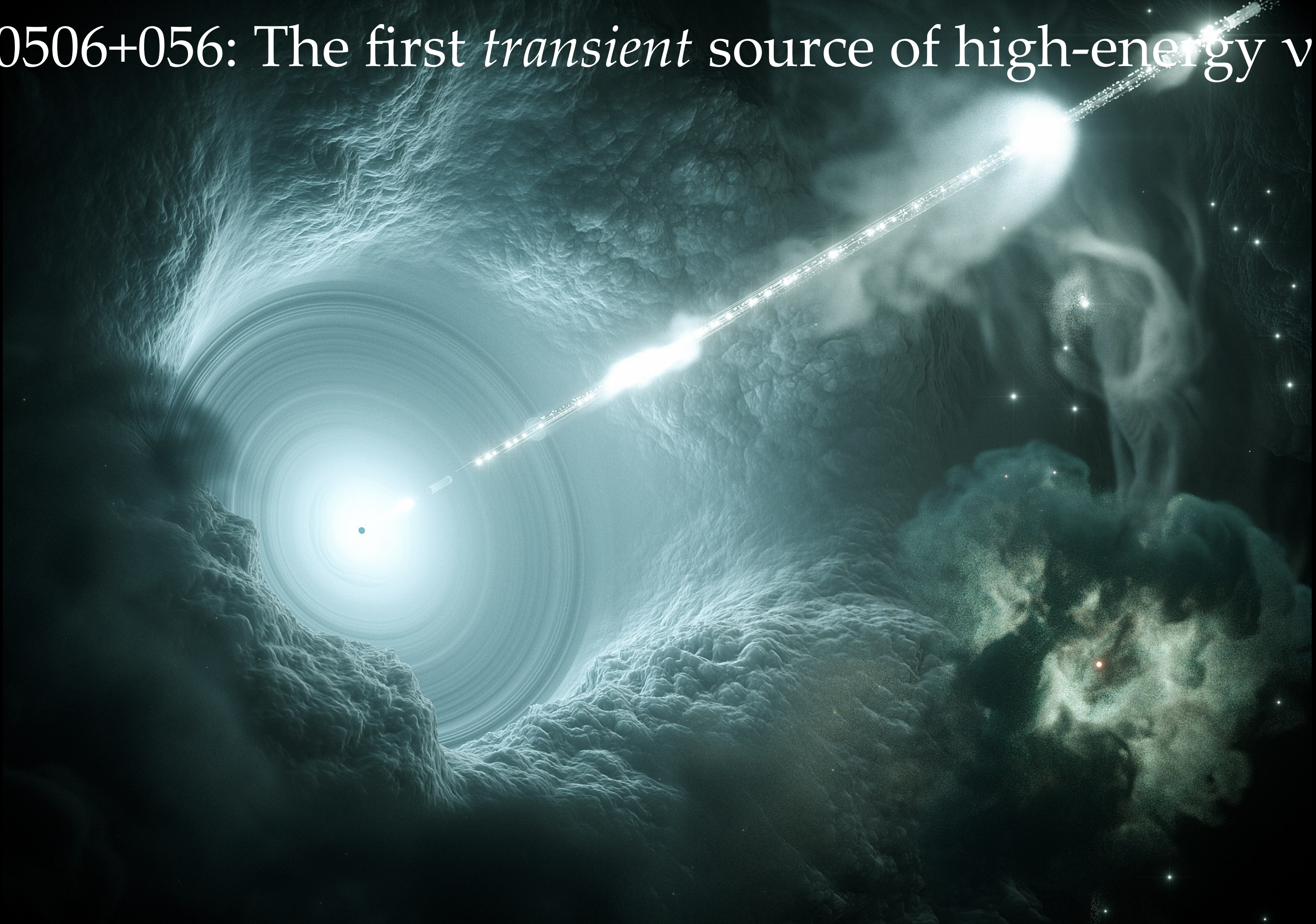
Standard expectation:
Isotropy (for diffuse flux)



Standard expectation:
ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

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

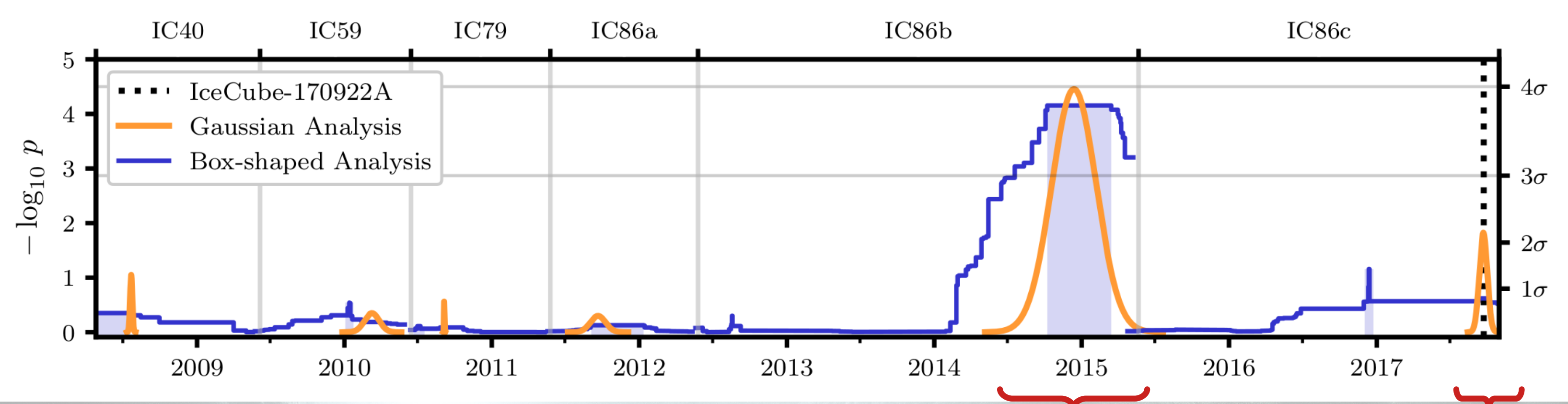


DESY

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

Note: Not an exhaustive list

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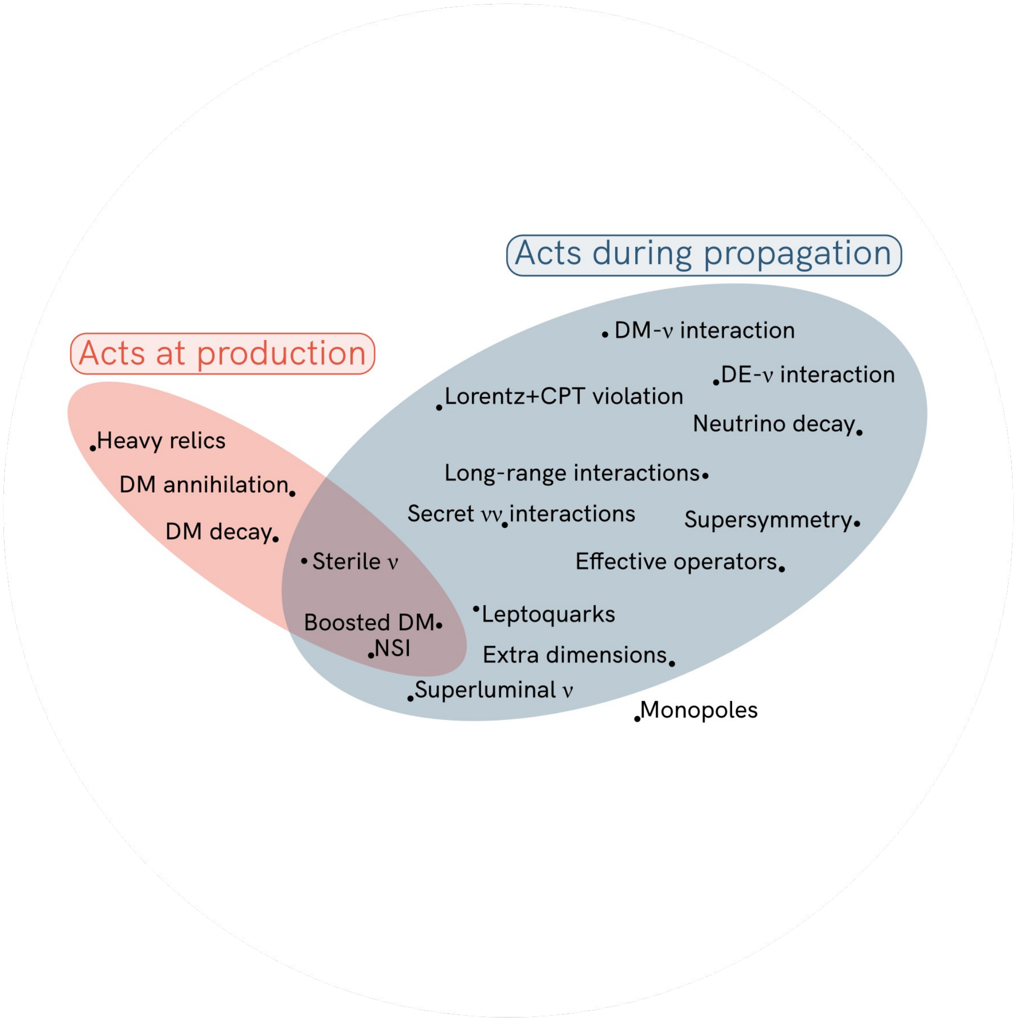

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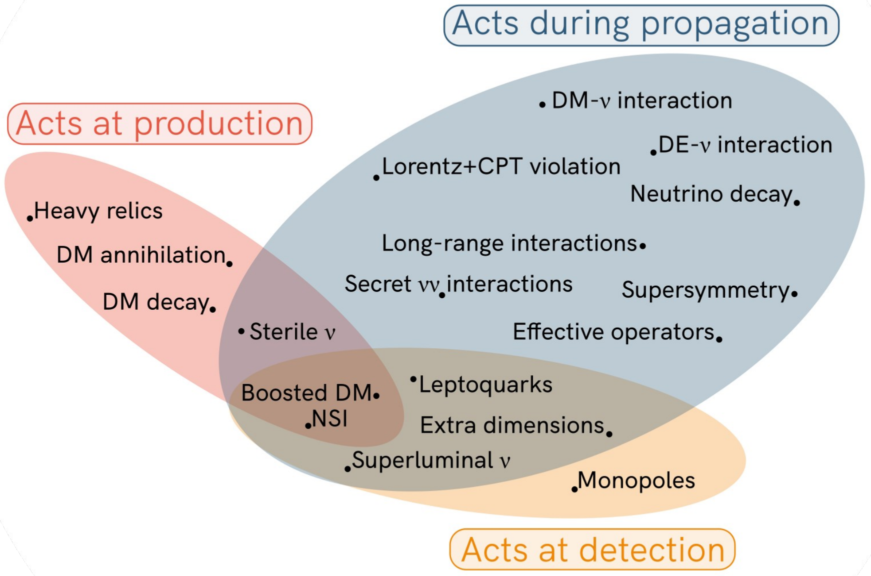

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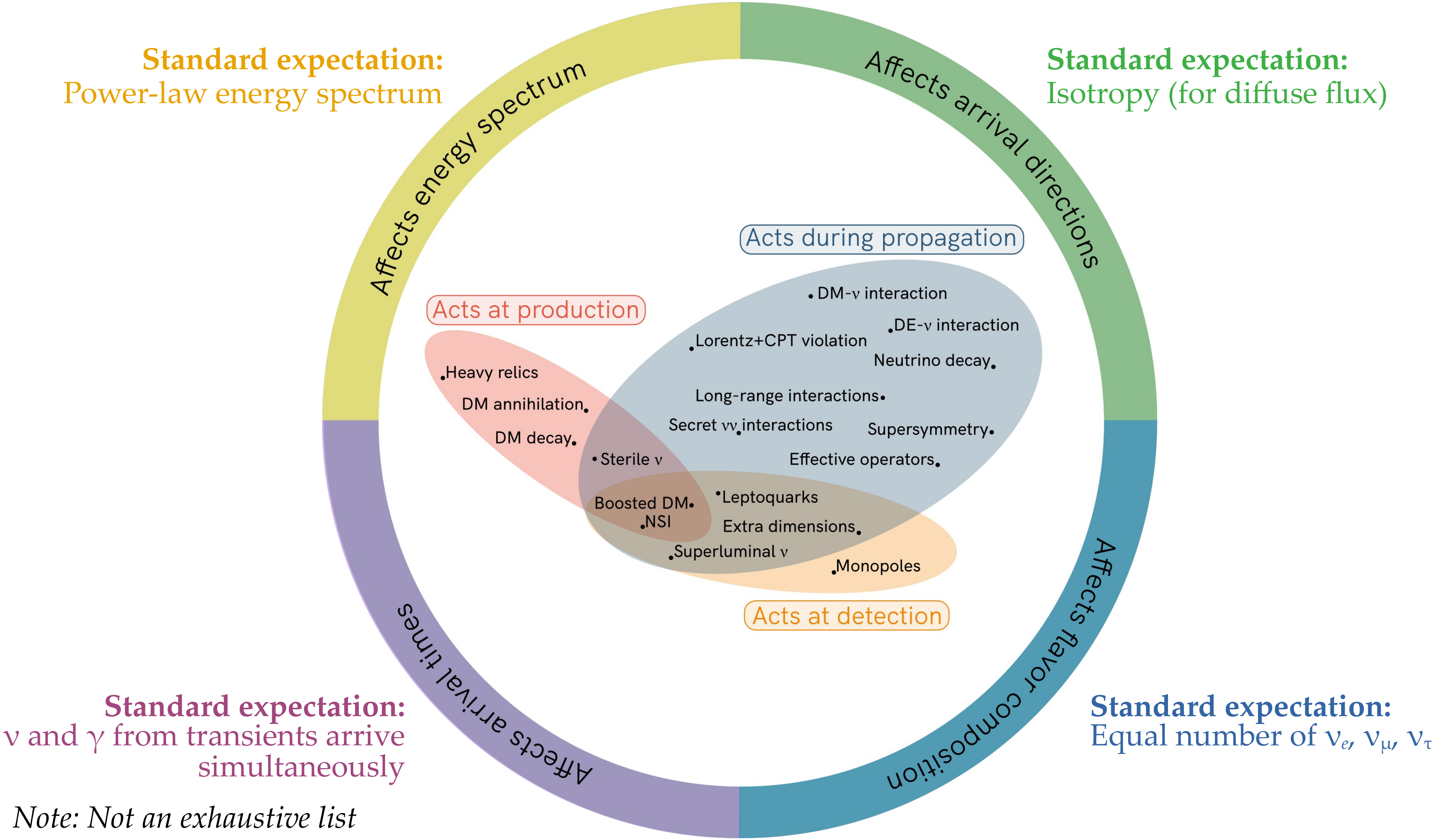
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Equal number of ν_e, ν_μ, ν_τ
Affects energy spectrum
Affects arrival directions
Affects flavor composition
Affects arrival times
Acts at production
Acts during propagation
Acts at detection
Heavy relics
DM annihilation
DM decay
Sterile ν
Boosted DM
NSI
DM-ν interaction
DE-ν interaction
Lorentz+CPT violation
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Secret νν interactions
Supersymmetry
Effective operators
Leptoquarks
Extra dimensions
Superluminal ν
Monopoles
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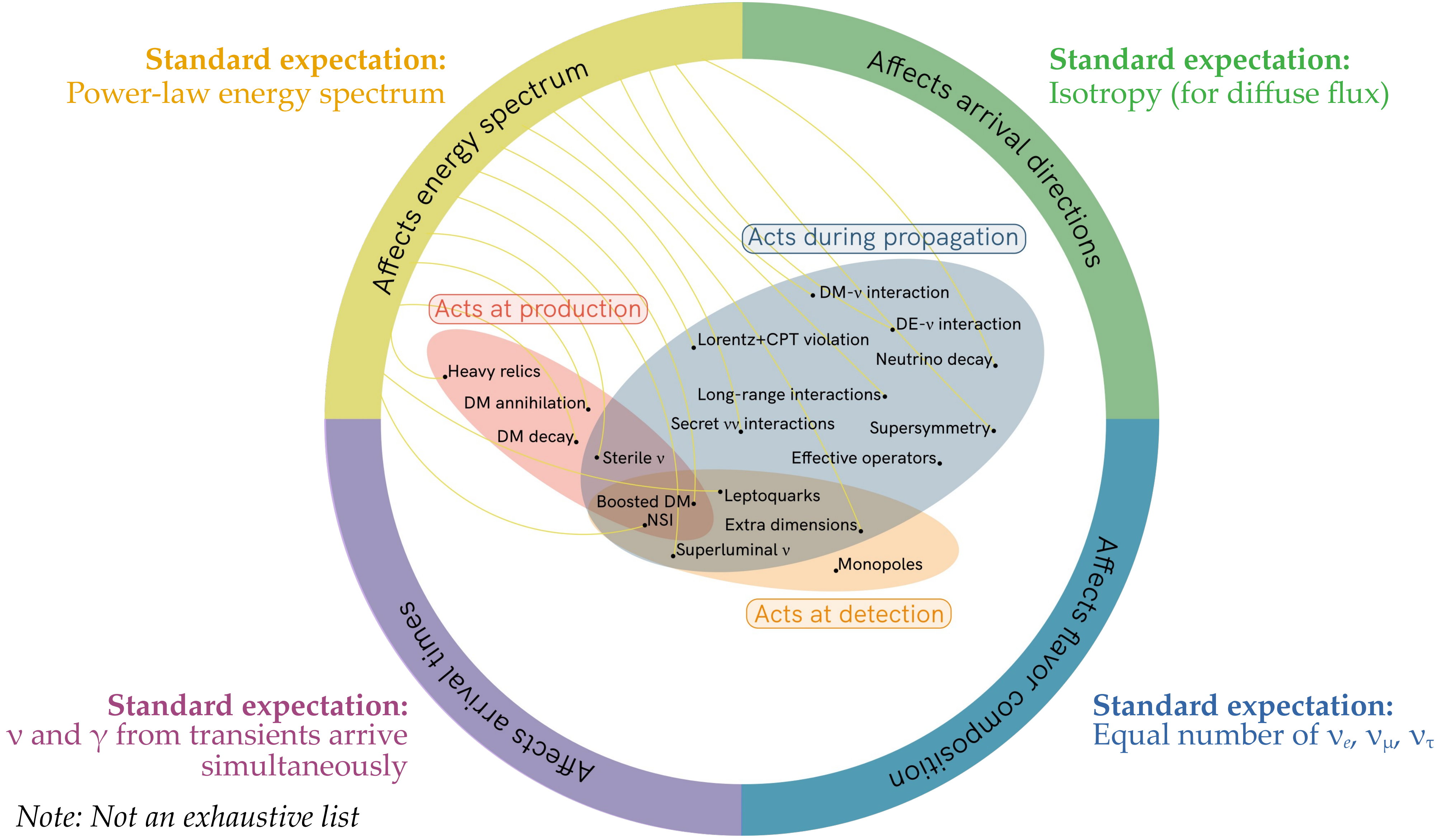

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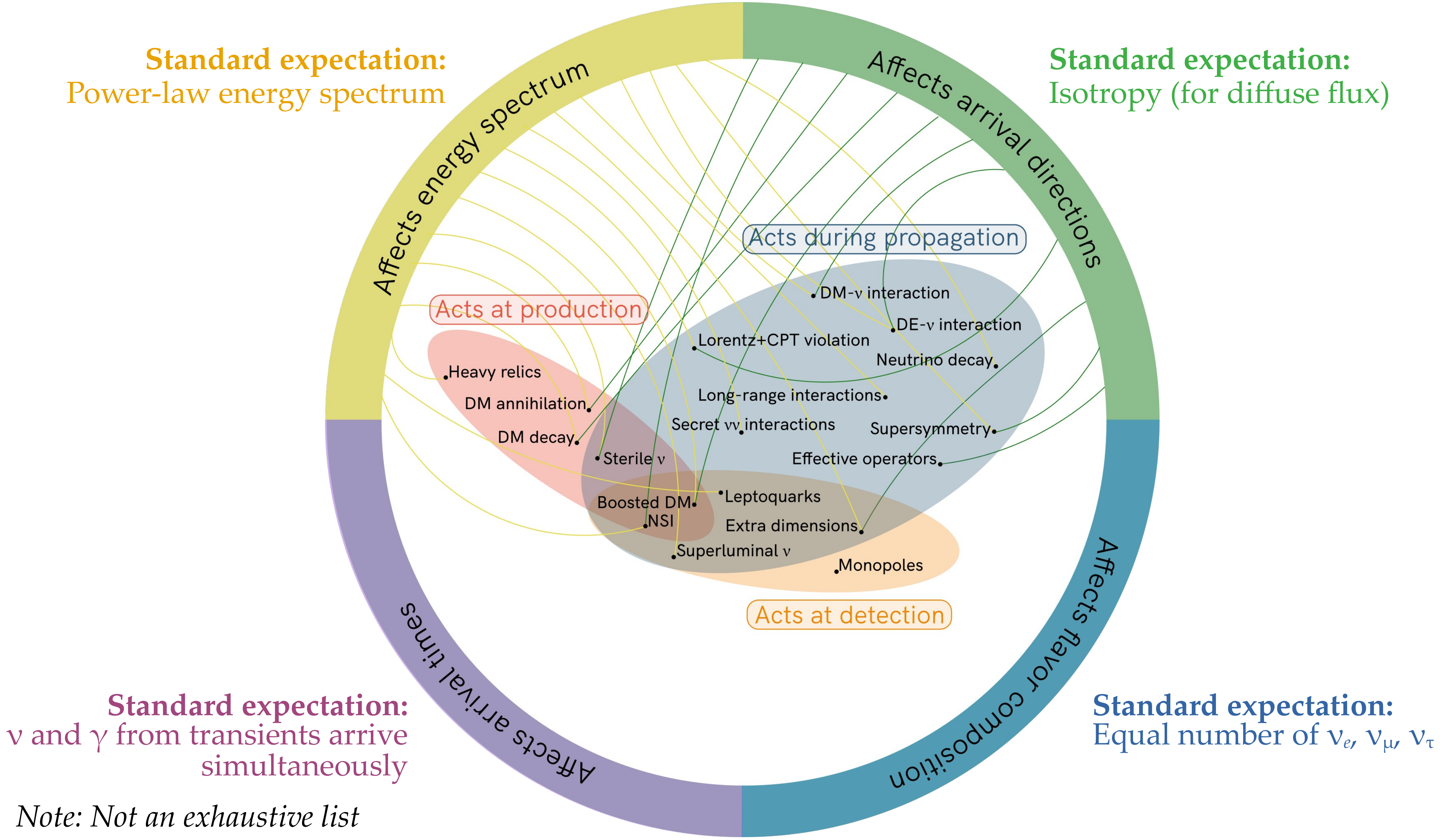
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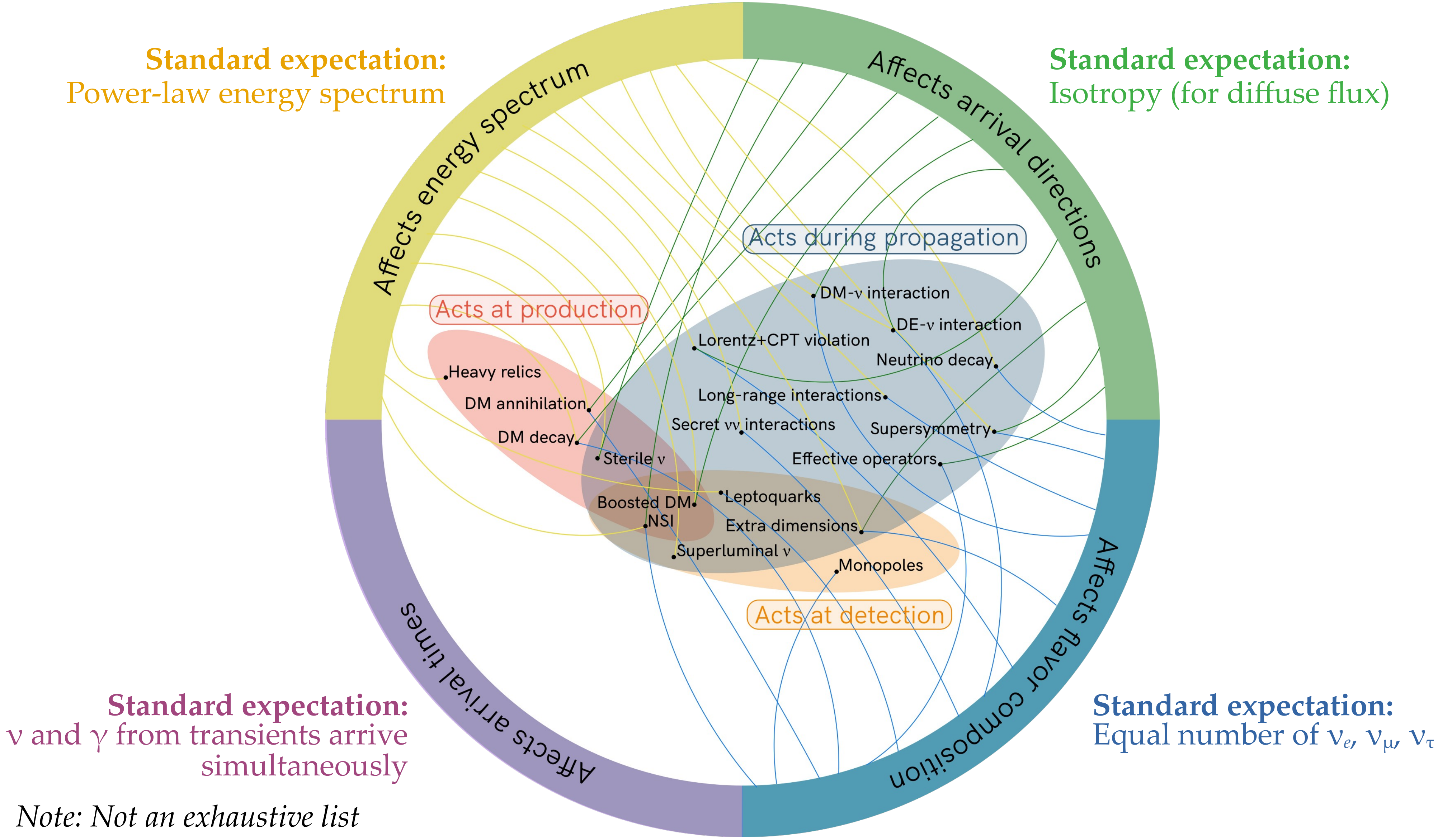

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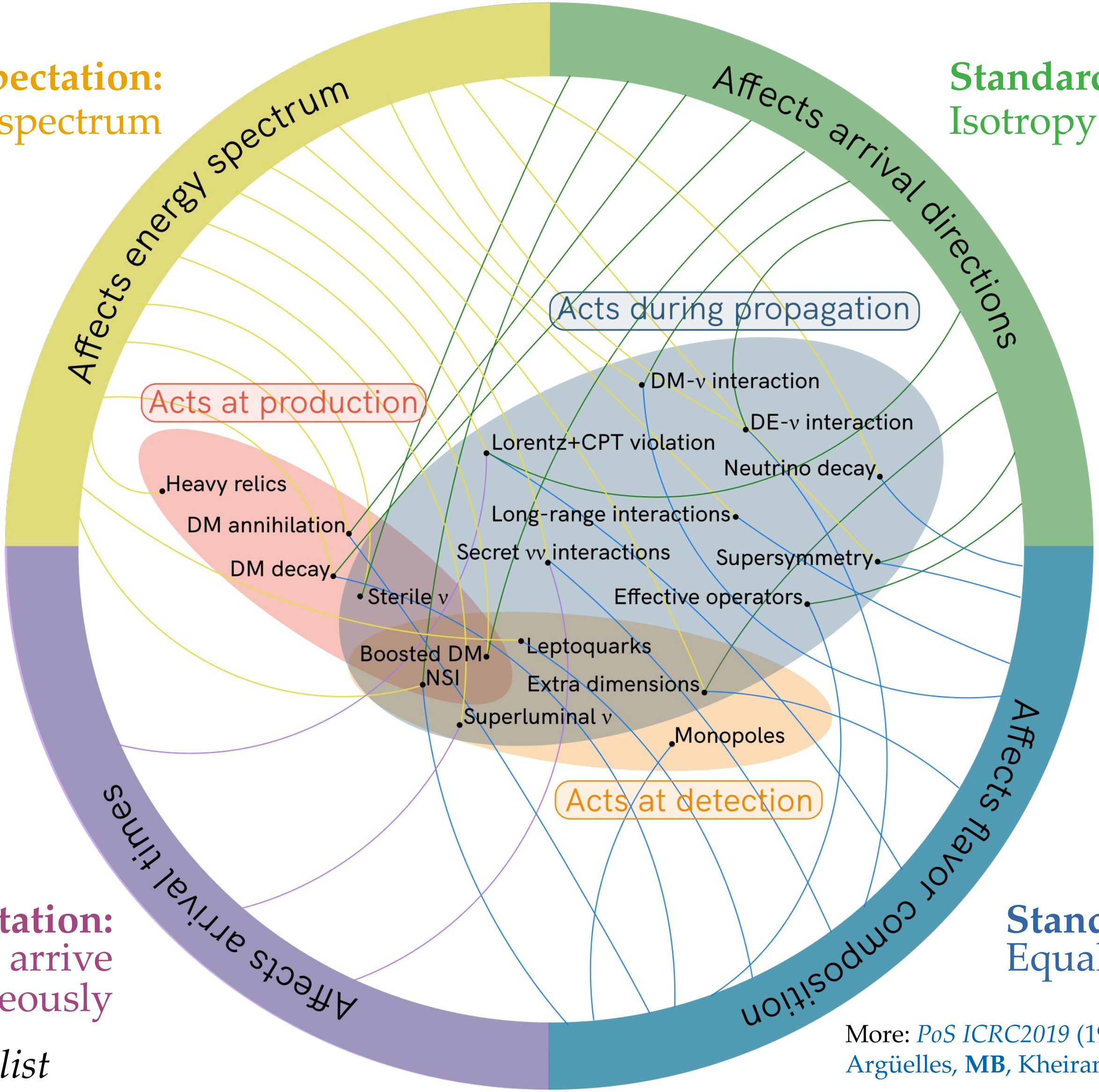

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More: *PoS ICRC2019* (1907.08690)
Argüelles, **MB**, Kheirandish, Palomares-Ruiz, Salvadó, Vincent

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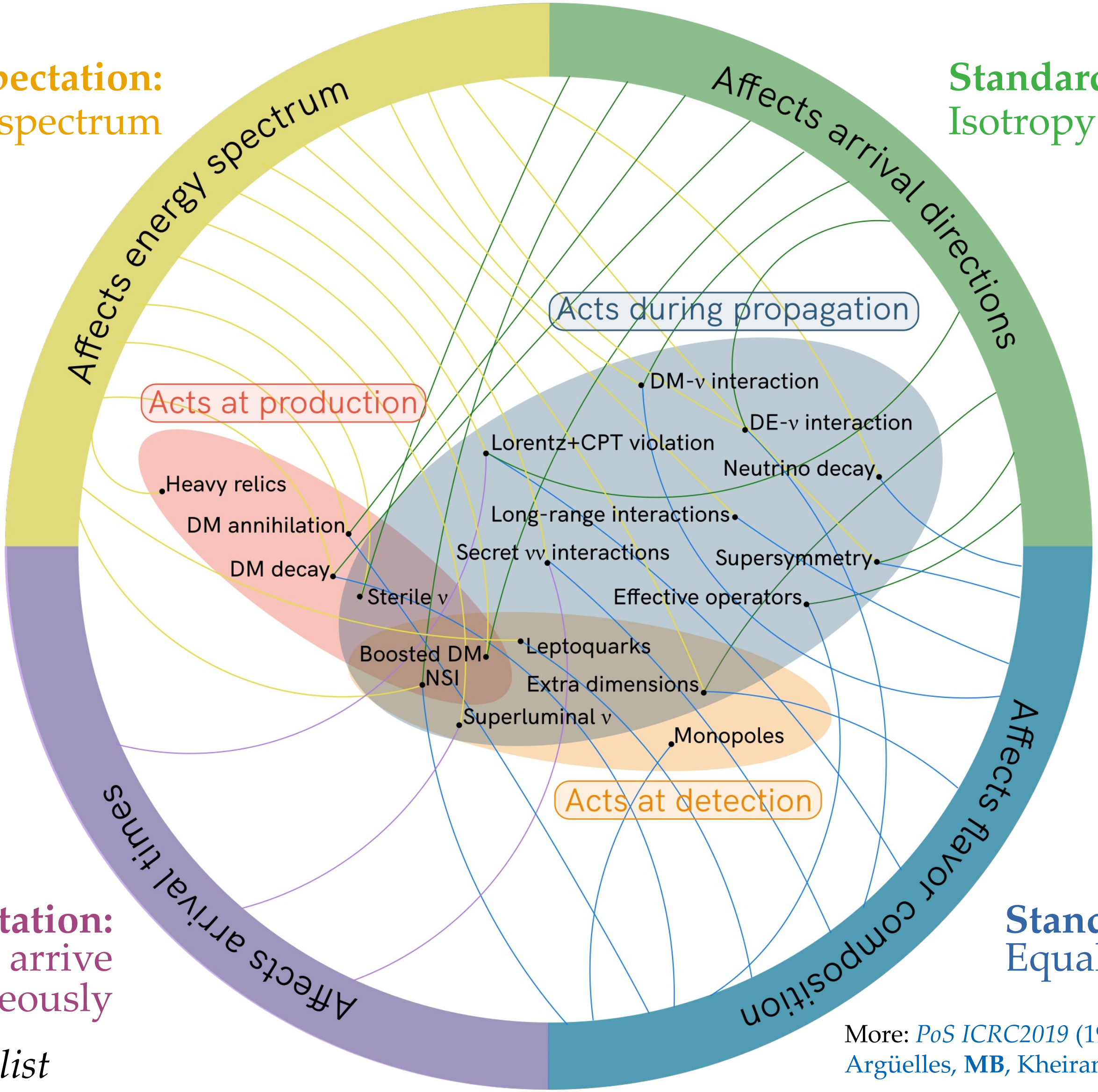

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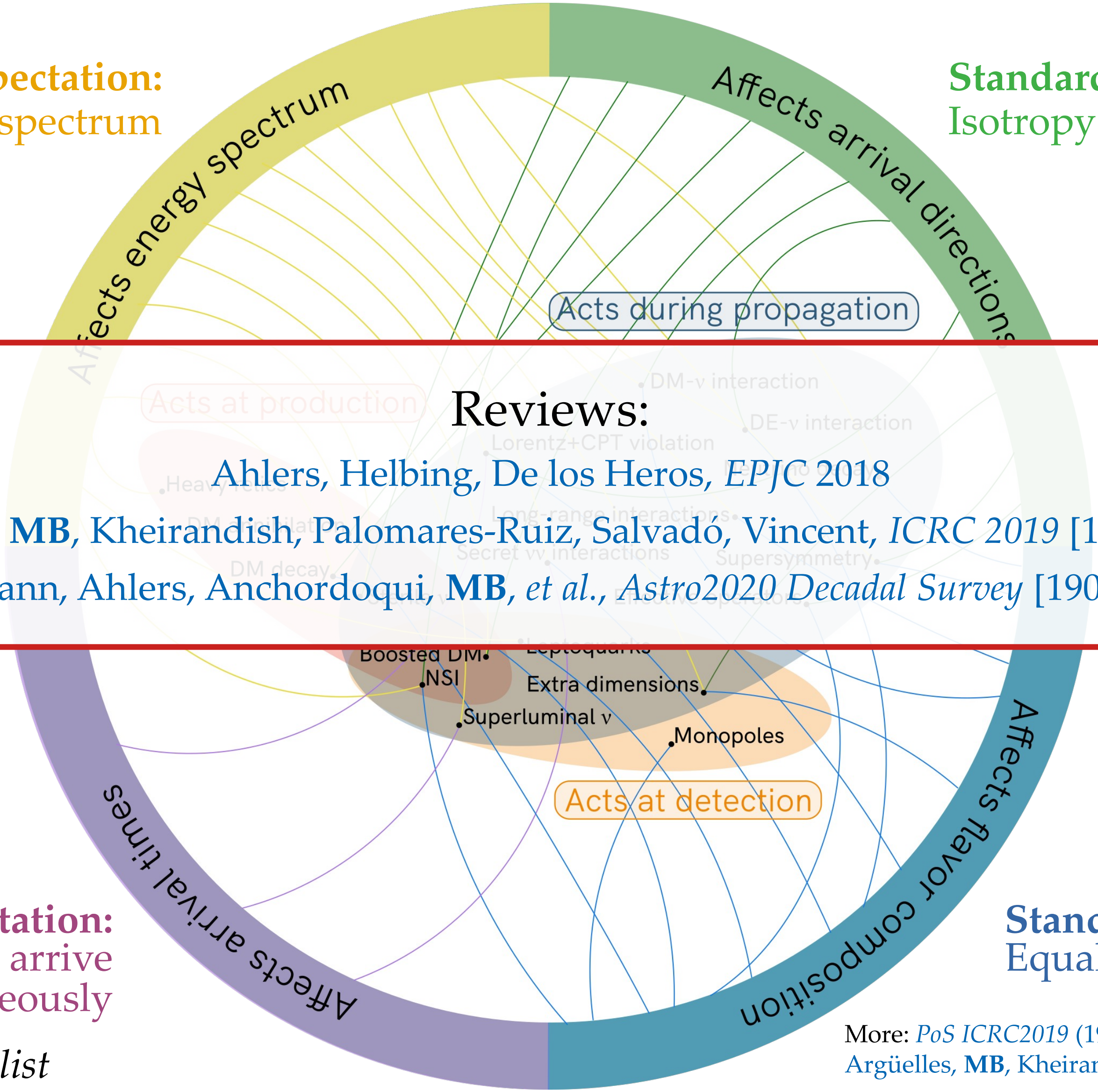

Reviews:

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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A warning

Evidence for BSM

Evidence for BSM

Evidence for SM

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

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

If $B \ll 1$: SM is favored

If $B \gg 1$: BSM is favored

If $B \sim 1$: No preference

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

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

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

Account for particle-physics + astrophysical + detector uncertainties

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

$$\mathcal{Z}_{\text{SM}} = \int \overbrace{\mathcal{L}(\theta_{\text{SM}}, \theta_{\text{astro}}, \theta_{\text{det}})}^{\text{Likelihood}} \overbrace{\pi(\theta_{\text{SM}}, \theta_{\text{astro}}, \theta_{\text{det}})}^{\text{Prior}} \mathrm{d}\theta_{\text{SM}} \mathrm{d}\theta_{\text{astro}} \mathrm{d}\theta_{\text{det}}$$

Account for particle-physics + astrophysical + detector uncertainties

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

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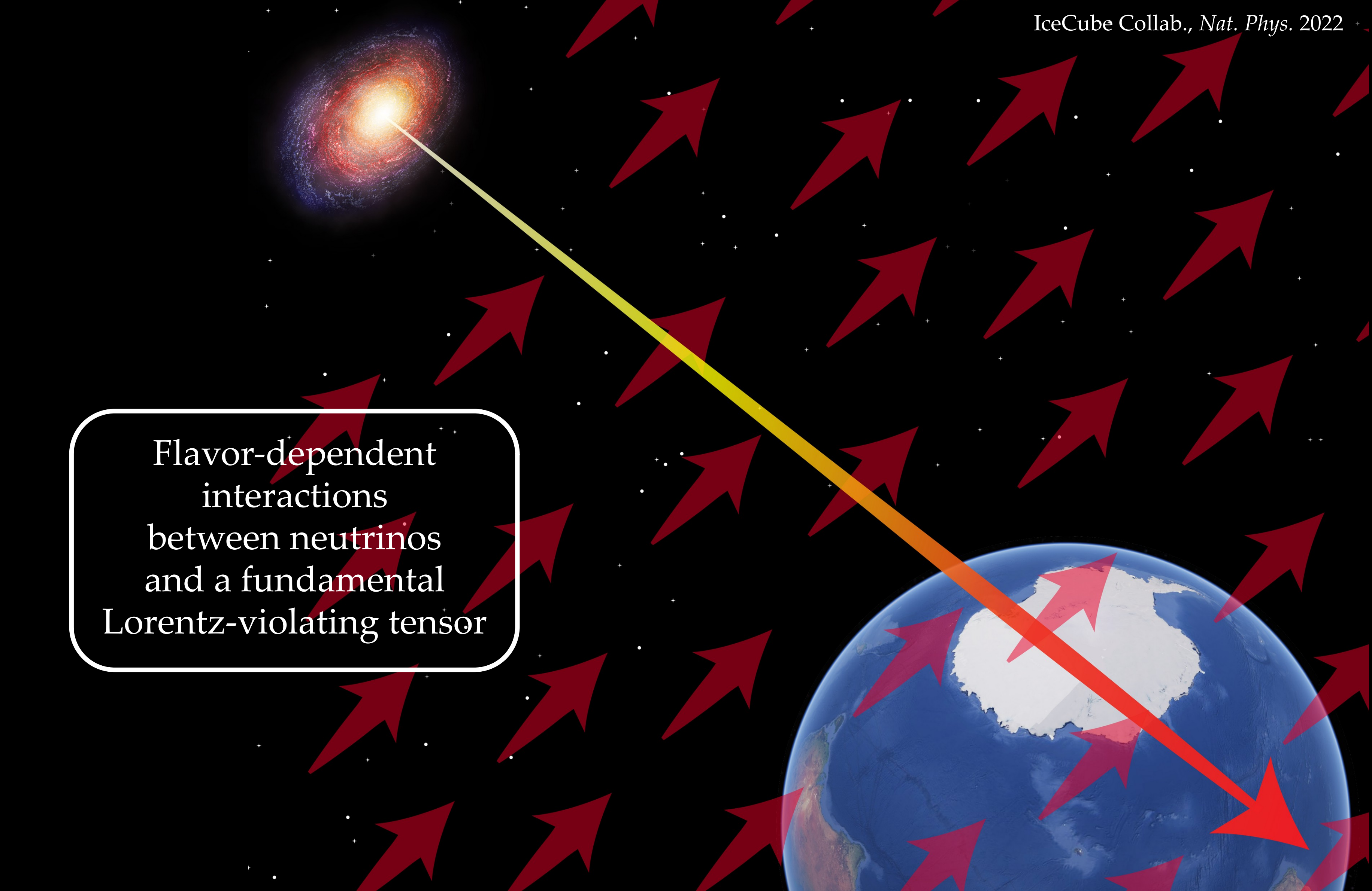
Account for particle-physics + astrophysical + detector uncertainties

Lorentz-invariance violation in flavor


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

Standard oscillations:

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

Lorentz-violating interactions (Standard Model Extension):

Kostelecky, Mewes, *PRD* 2004

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

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

Total Hamiltonian:

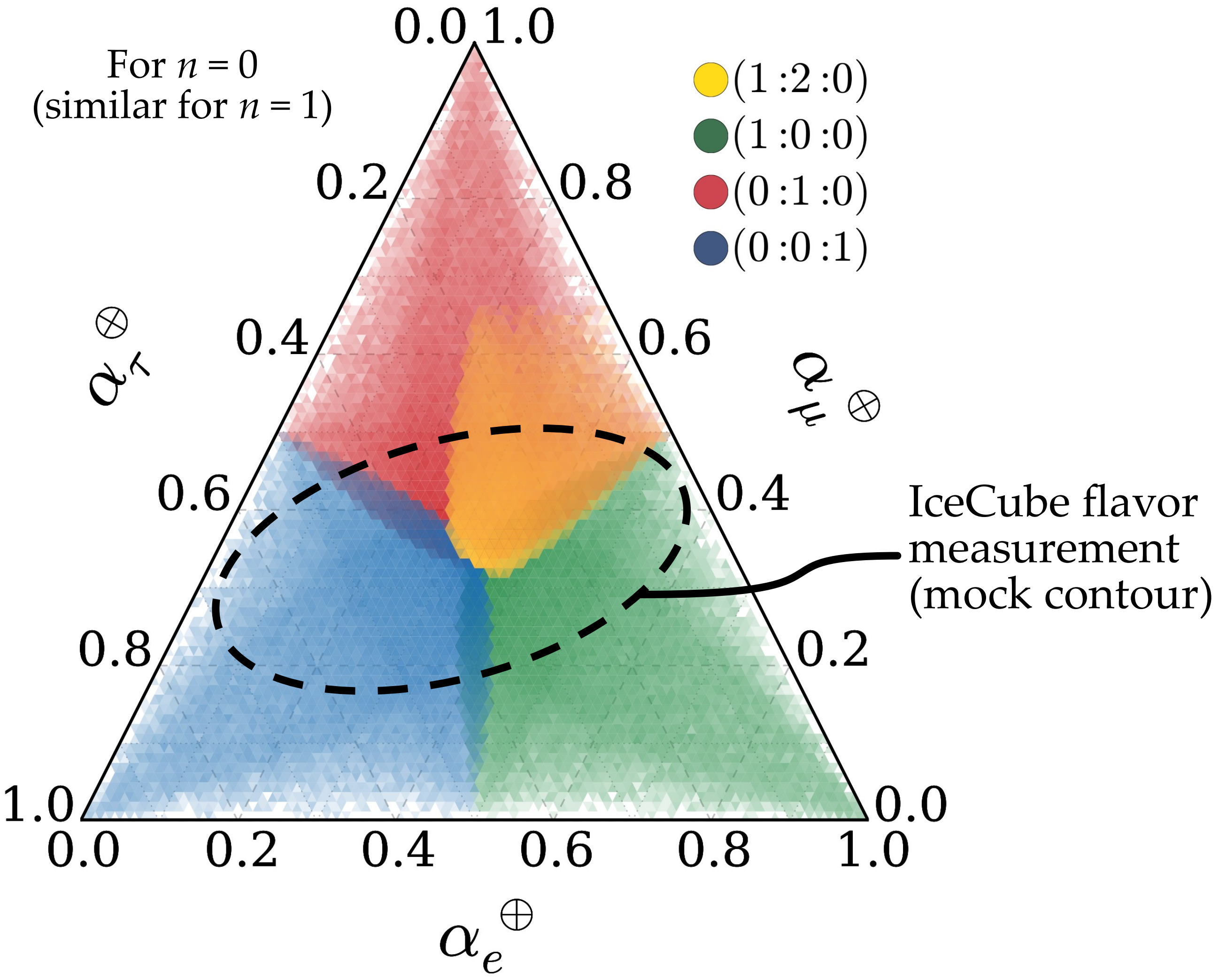
$$H_{\rm tot} = H_{\rm std} + H_{\rm new}$$

The flavor-transition probabilities are calculated as before,

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

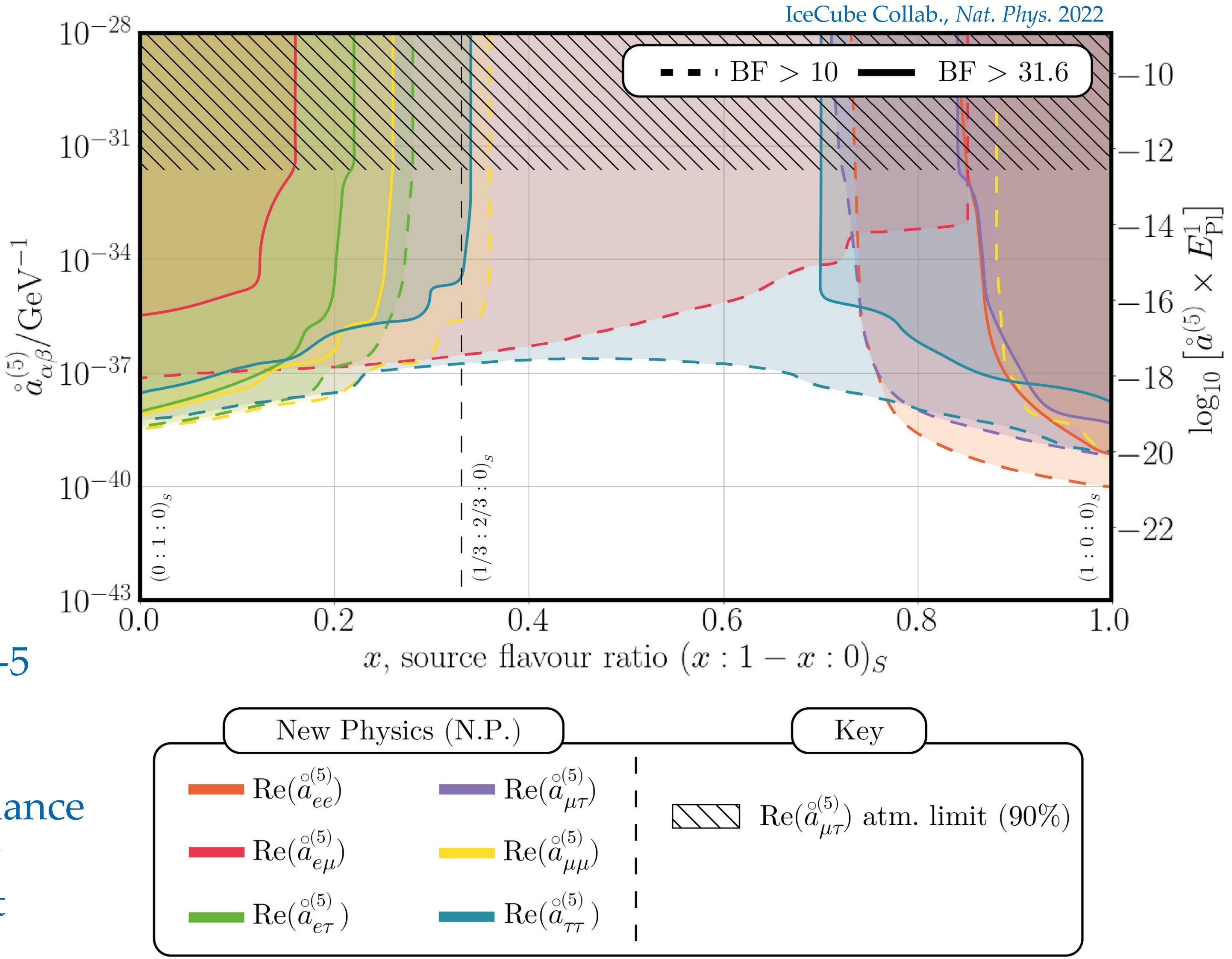
Depends on standard & new parameters

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



Argüelles, Katori, Salvadó, *PRL* 2015

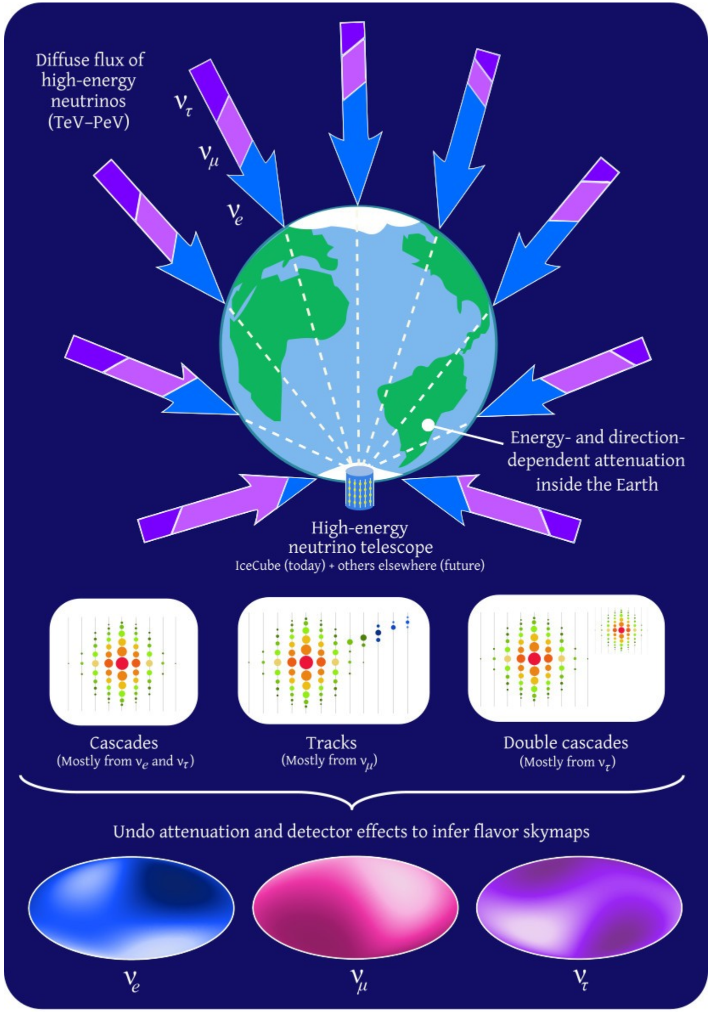
See also Ahlers, **MB**, Mu, *PRD* 2018; Rasmusen *et al.*, *PRD* 2017; **MB**, Beacom, Winter *PRL* 2015; **MB**, Gago, Peña-Garay *JCAP* 2010; Bazo, **MB**, Gago, Miranda *IJMPA* 2009; + many others



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

Direction-dependent LIV in flavor

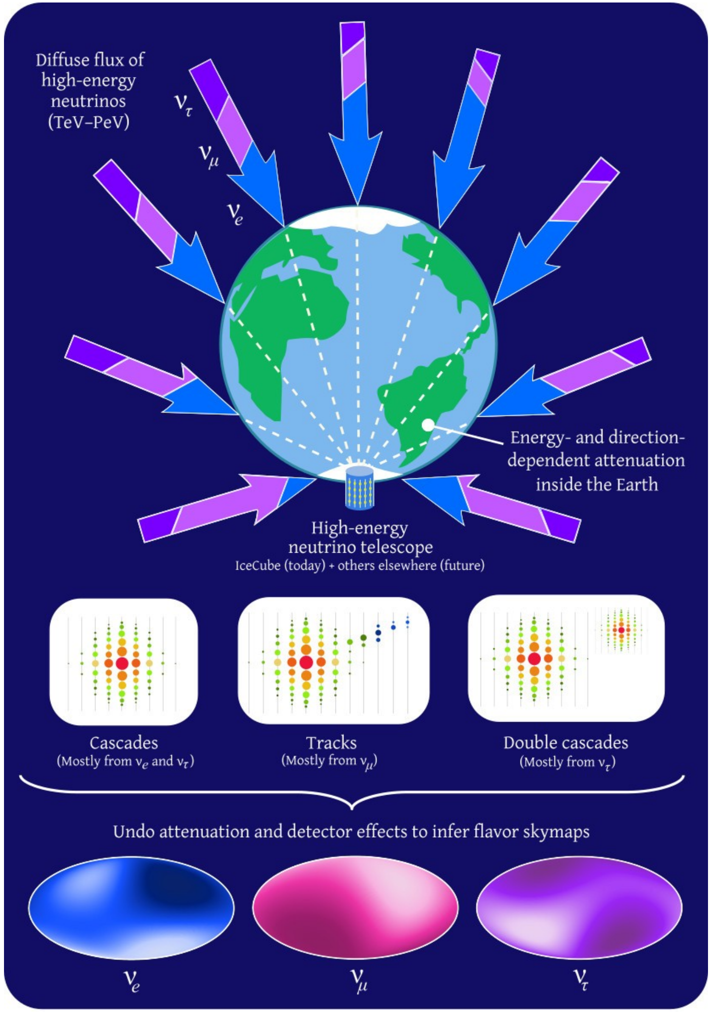
Flavor anisotropy in the high-energy neutrino sky



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

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

Flavor anisotropy in the high-energy neutrino sky

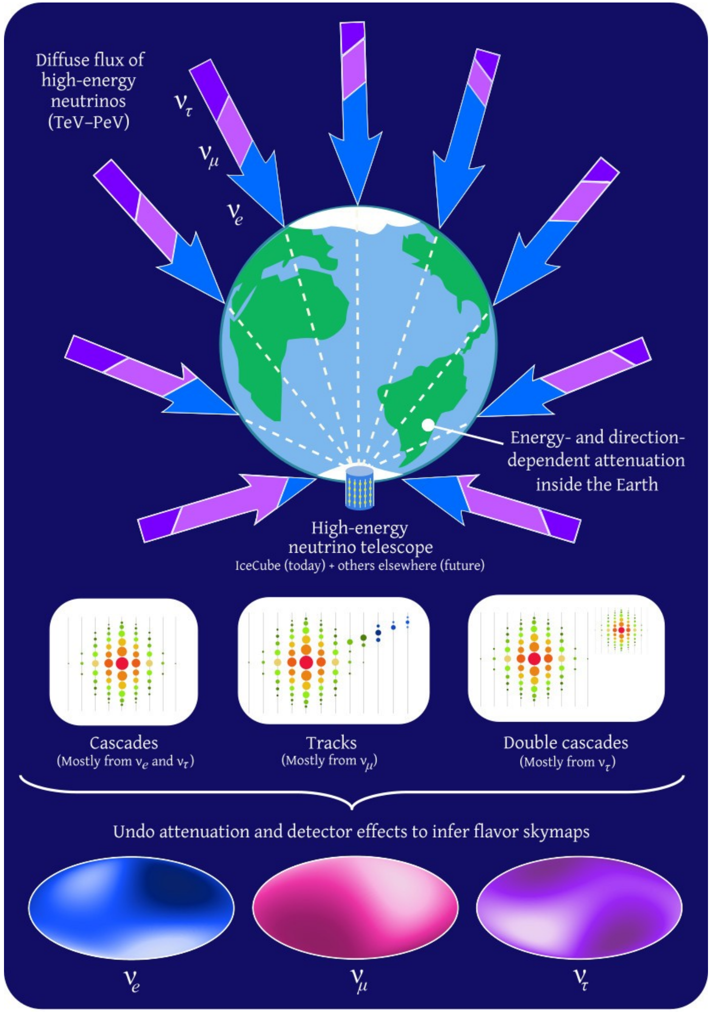


Does the high-energy sky shine equally brightly In neutrinos of all flavors?

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

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

Flavor anisotropy in the high-energy neutrino sky



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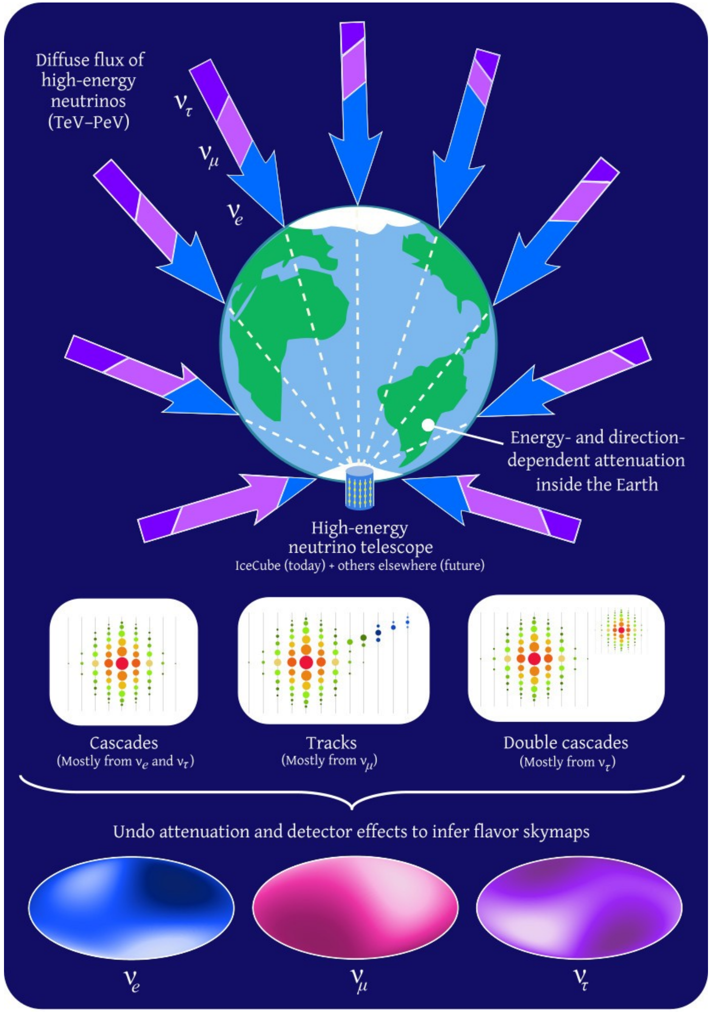
… we infer the directional dependence of the diffuse fluxes of ν_e, ν_μ, ν_τ

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

Flavor anisotropy in the high-energy neutrino sky



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

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

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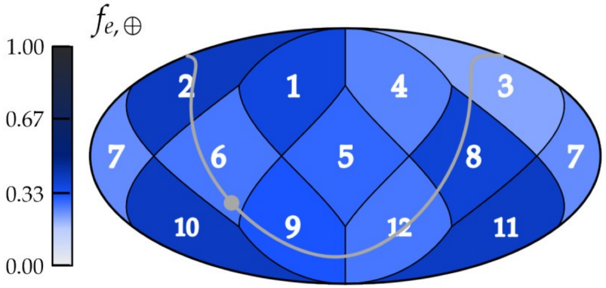

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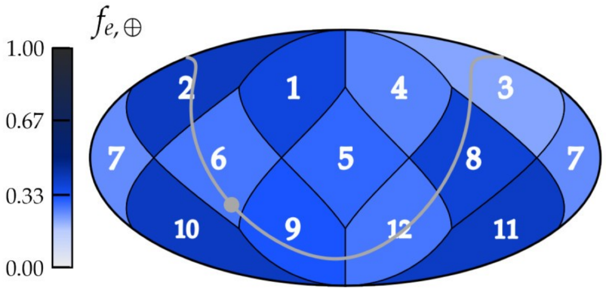

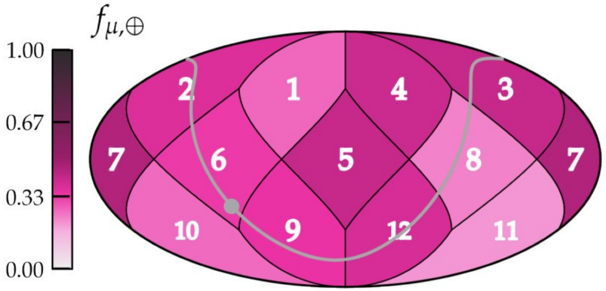

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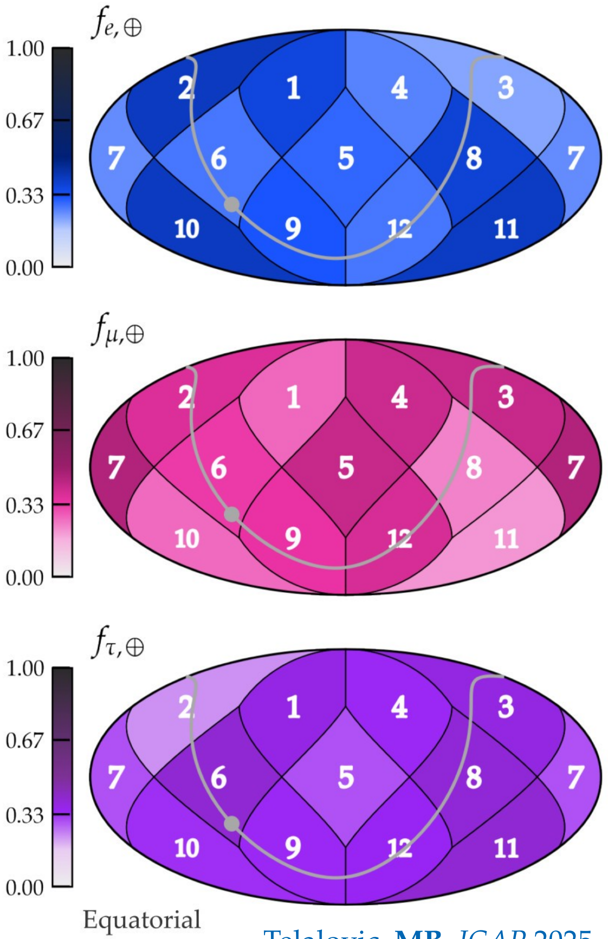
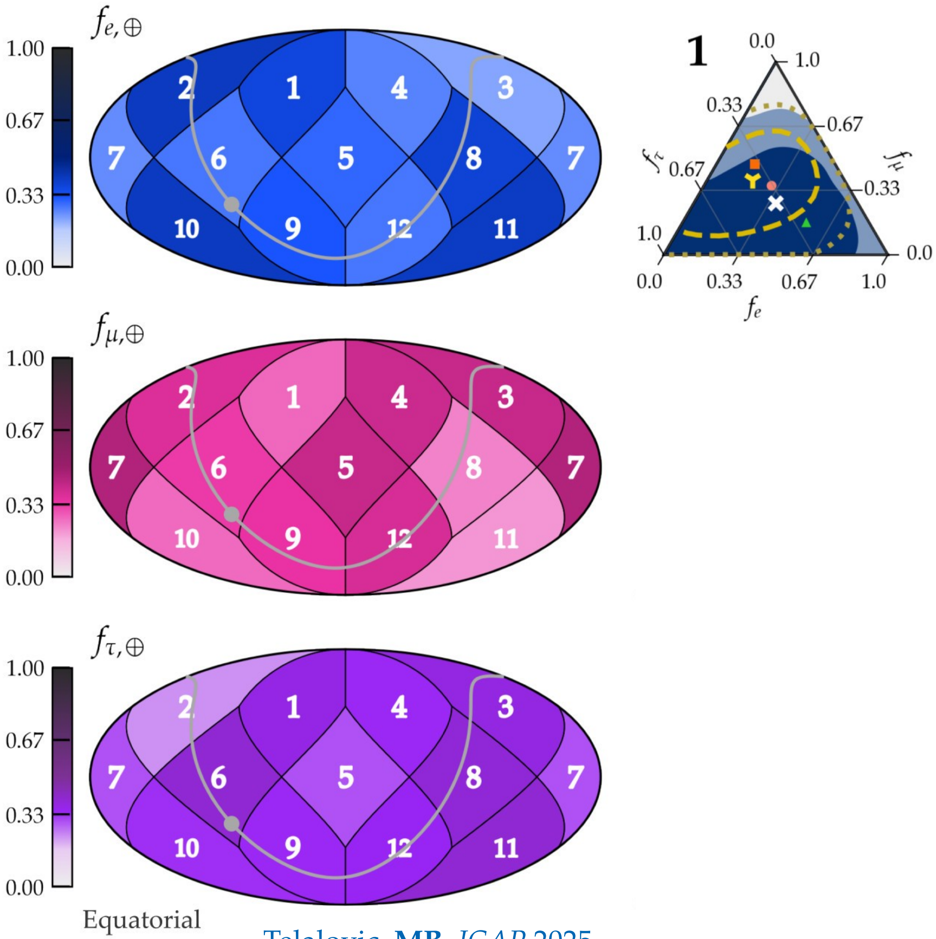


Telalovic, **MB**, *JCAP* 2025

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: $(1:0:0)_S$



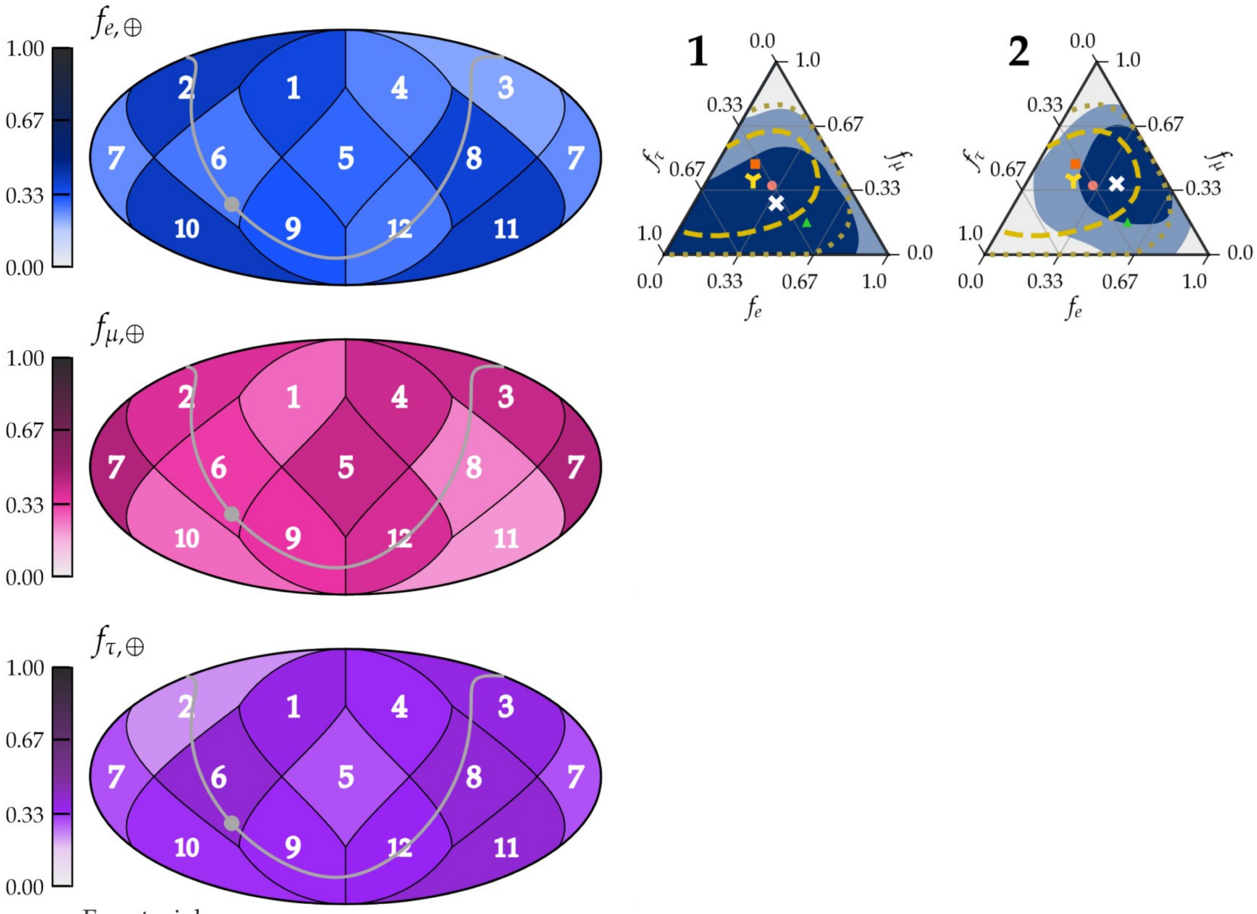
Telalovic, **MB**, *JCAP* 2025

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

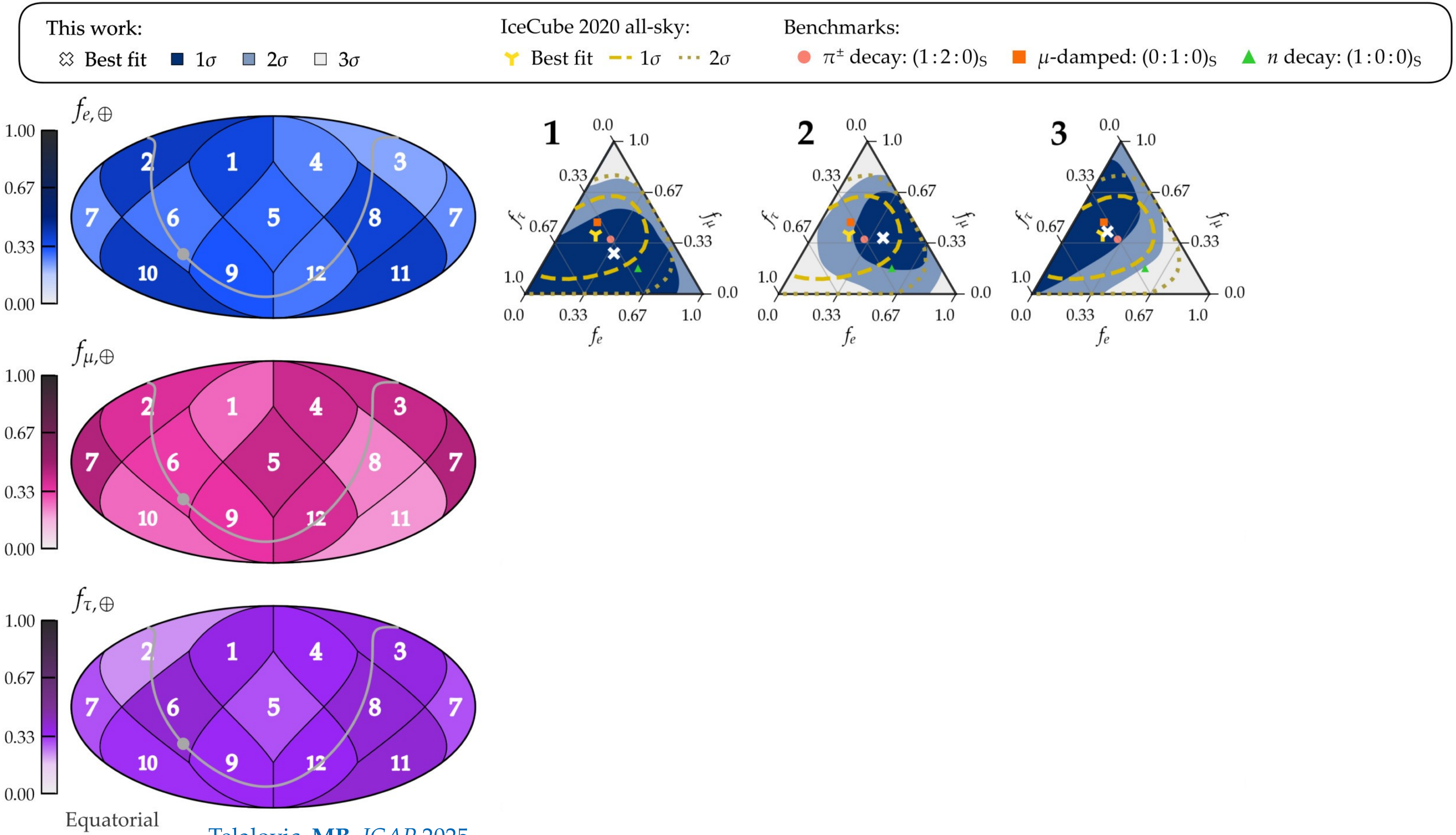
Benchmarks: $\pi^{\pm}$ decay: $(1:2:0)_S$; μ-damped: $(0:1:0)_S$; n decay: $(1:0:0)_S$



Equatorial

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

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



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

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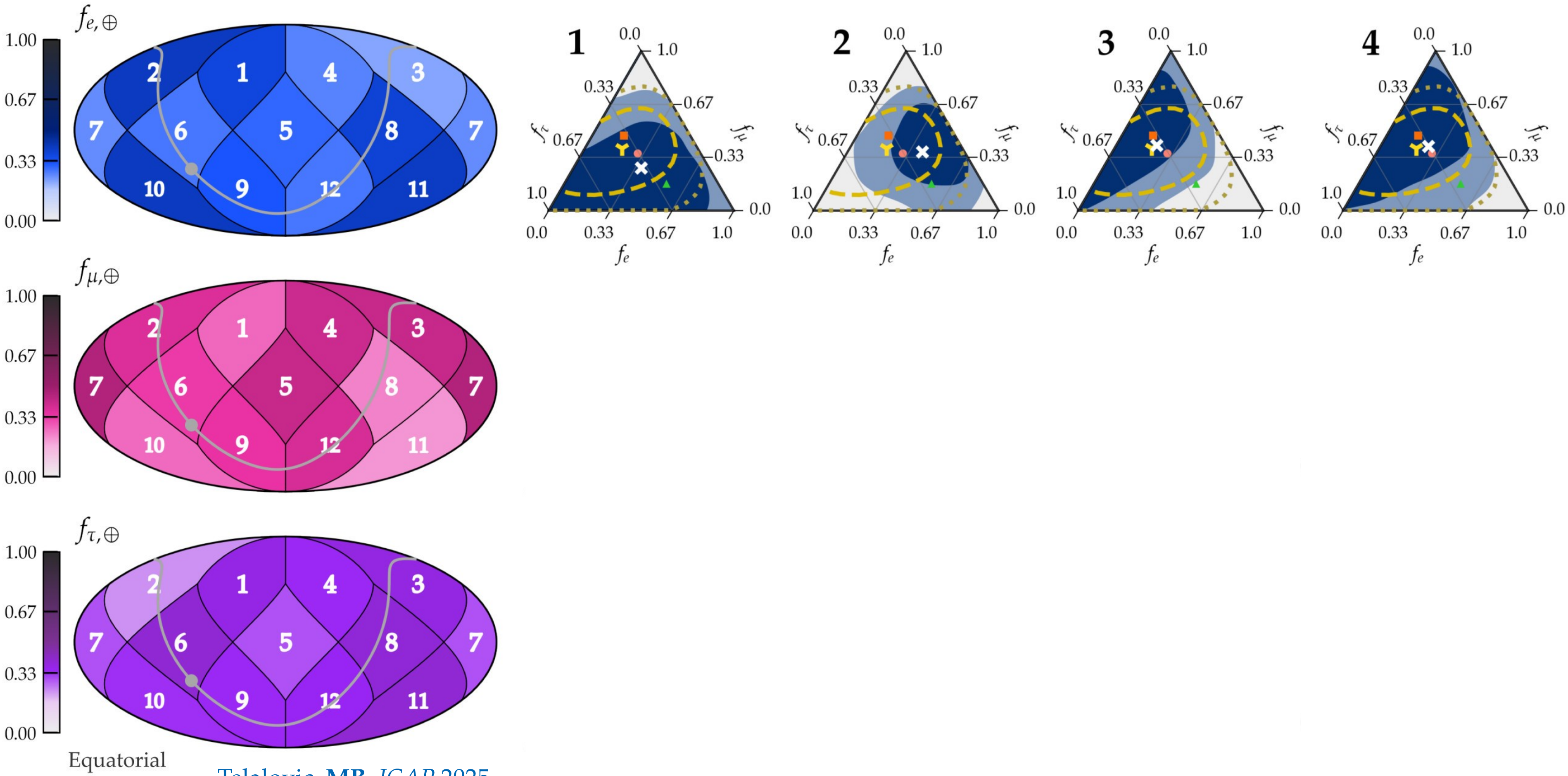

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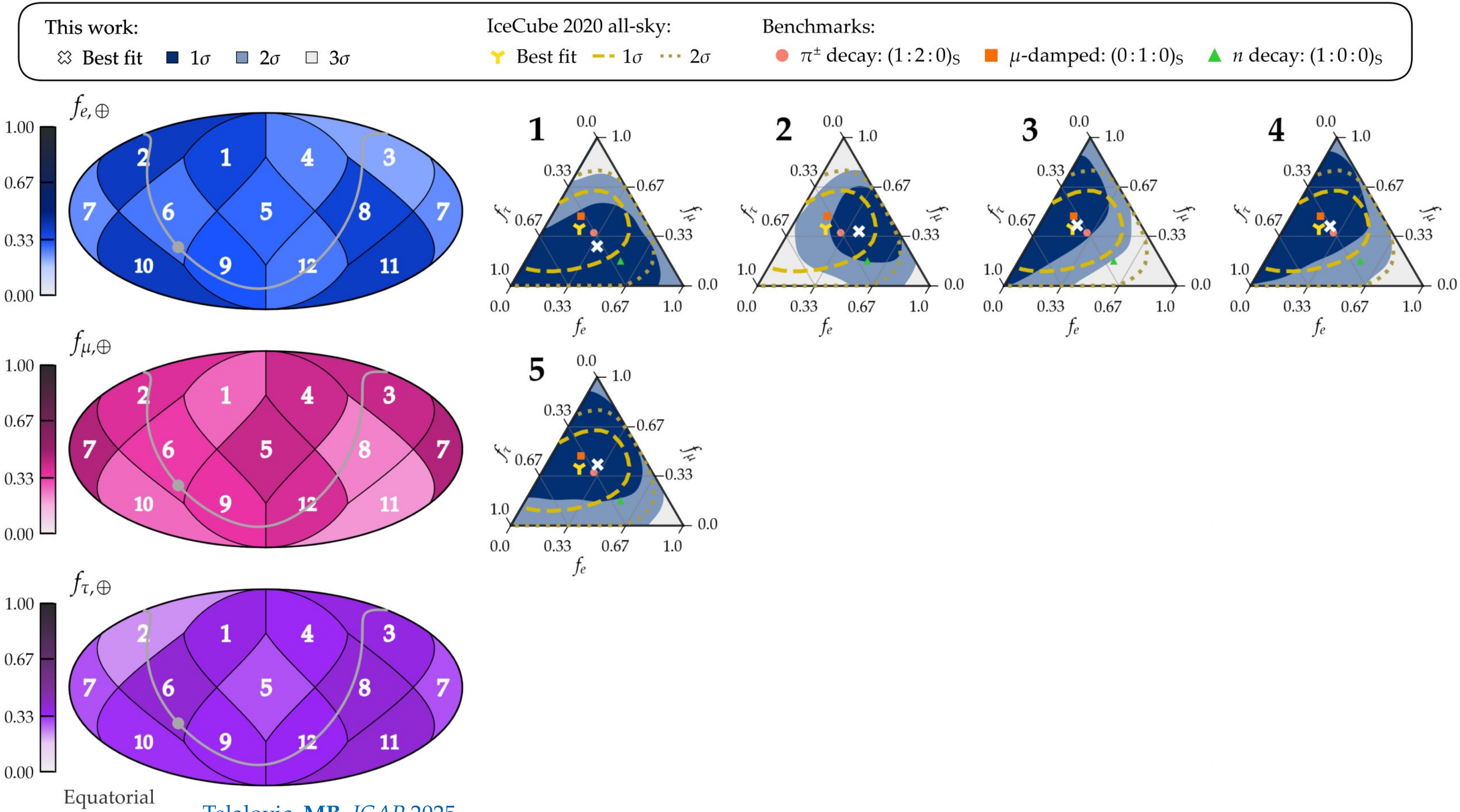
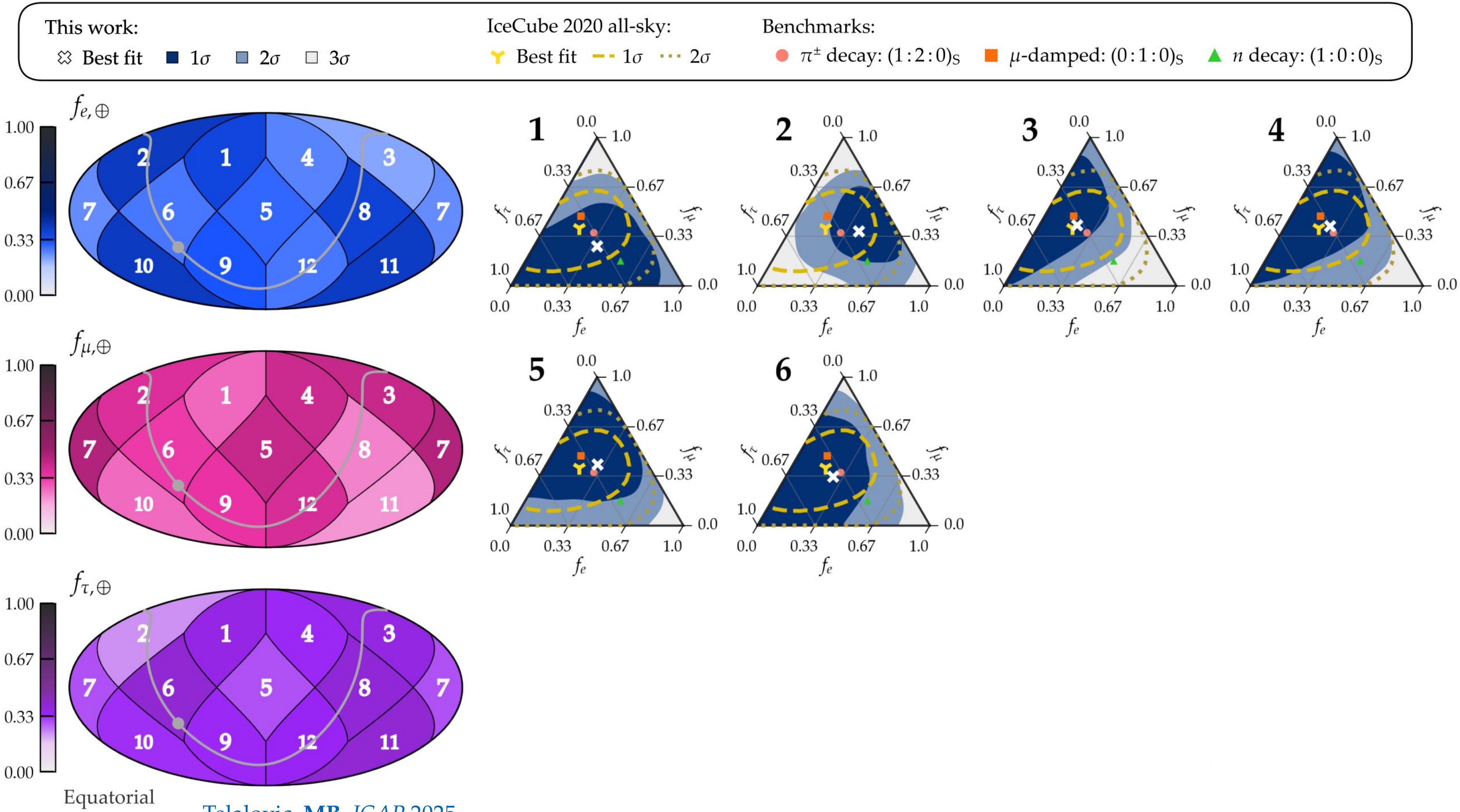


Telalovic, **MB**, *JCAP* 2025

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



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

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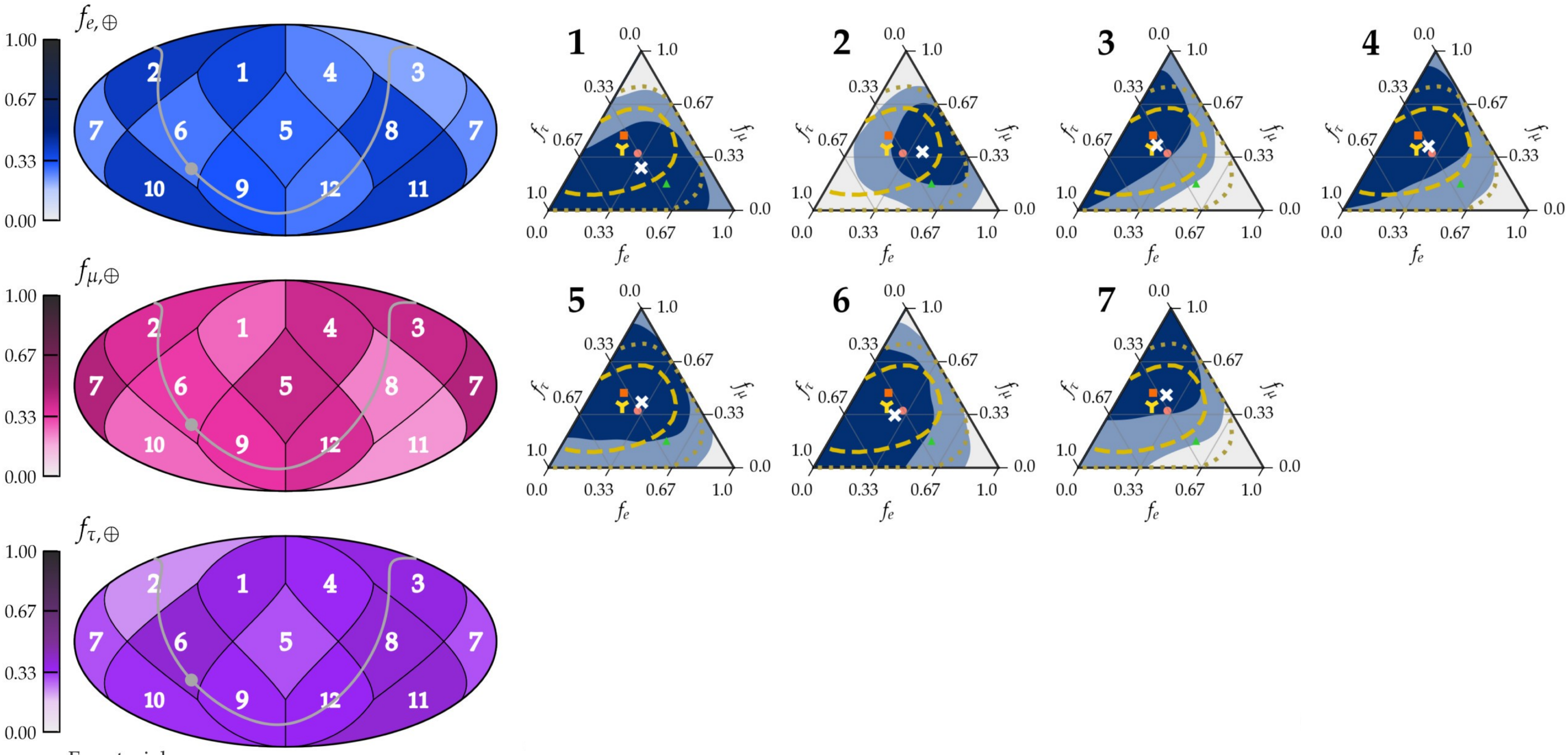
This work: Best fit, 1σ, 2σ, 3σ | IceCube 2020 all-sky: Best fit, 1σ, 2σ | Benchmarks: $\pi^{\pm}$ decay: $(1:2:0)_S$, μ-damped: $(0:1:0)_S$, n decay: $(1:0:0)_S$



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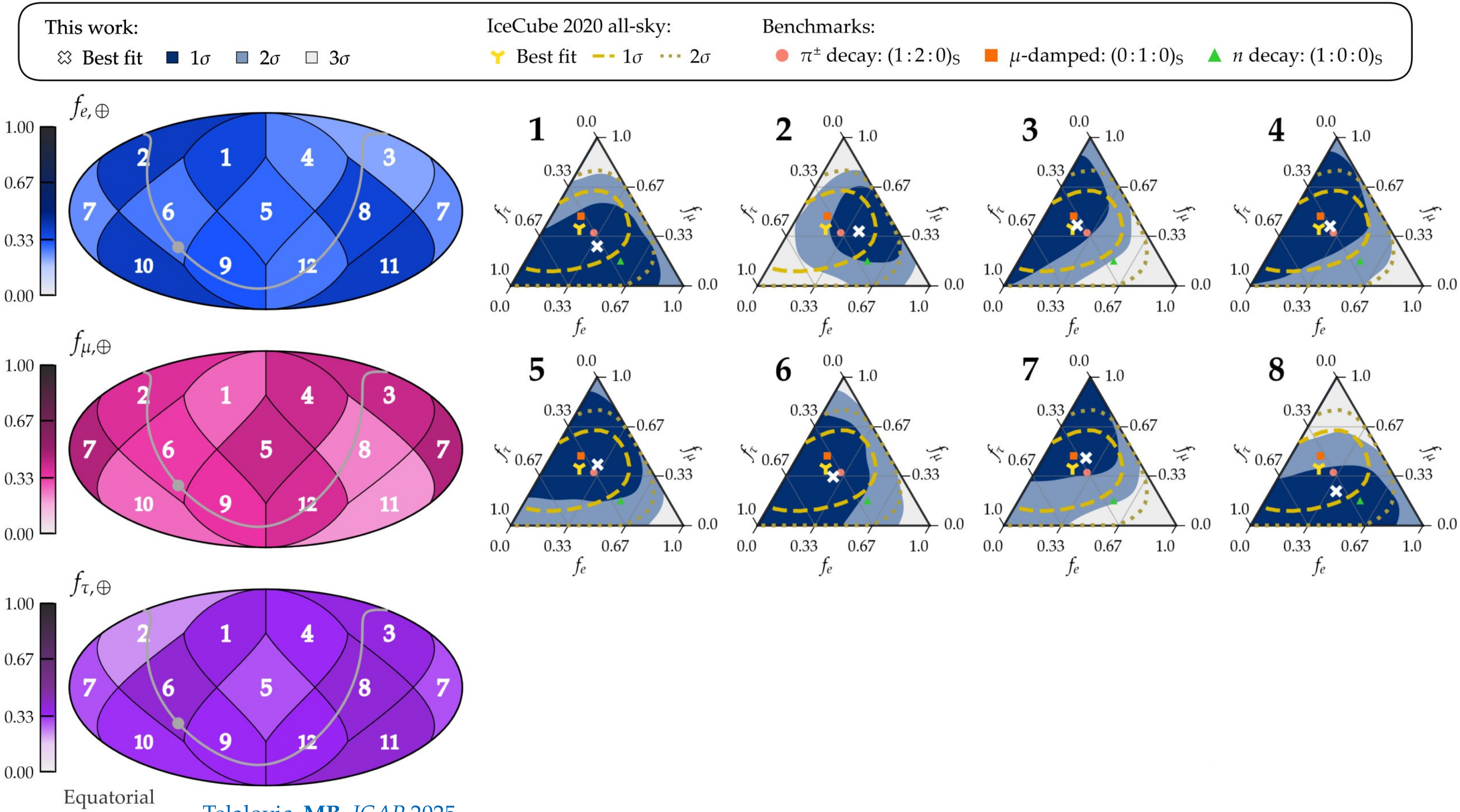

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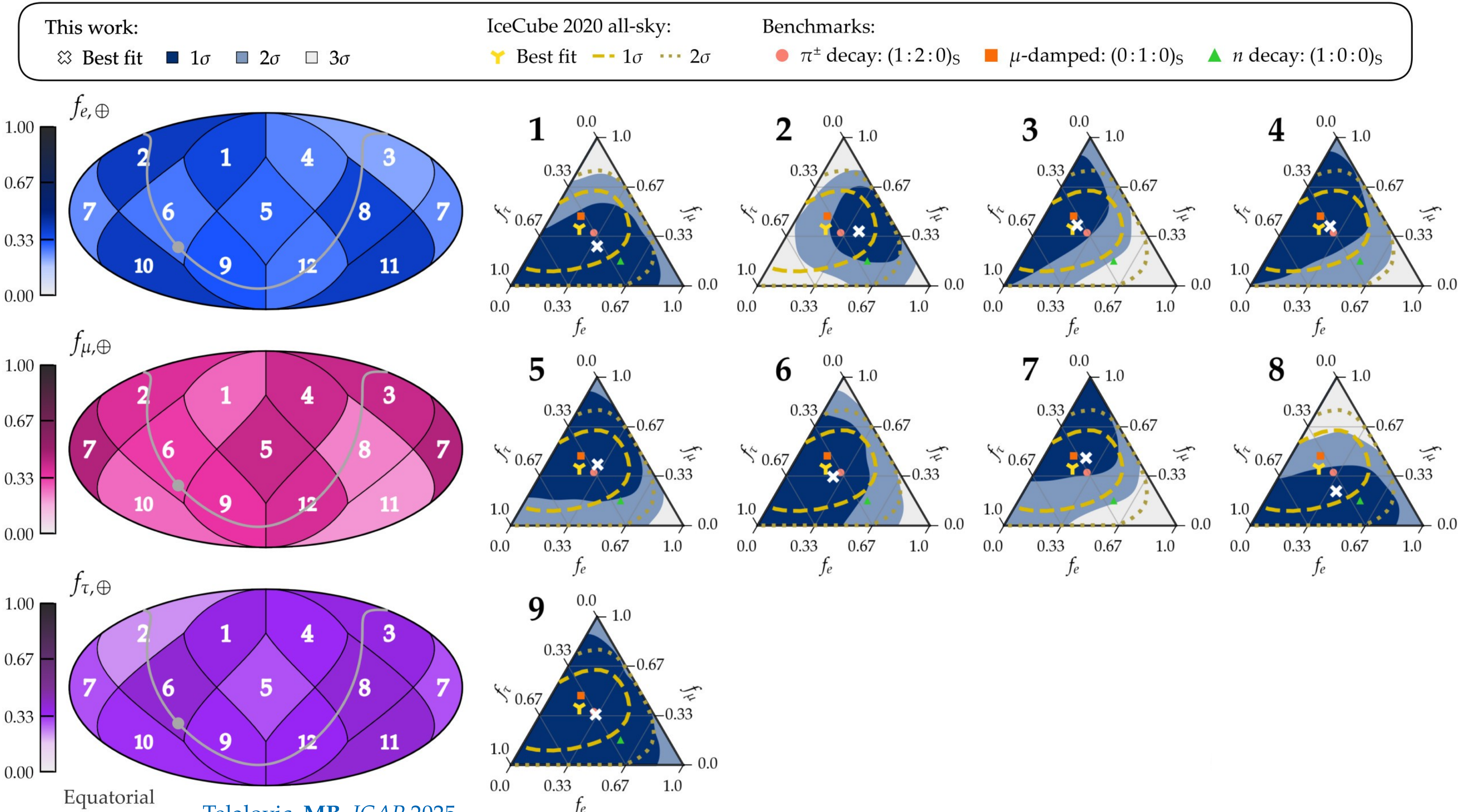

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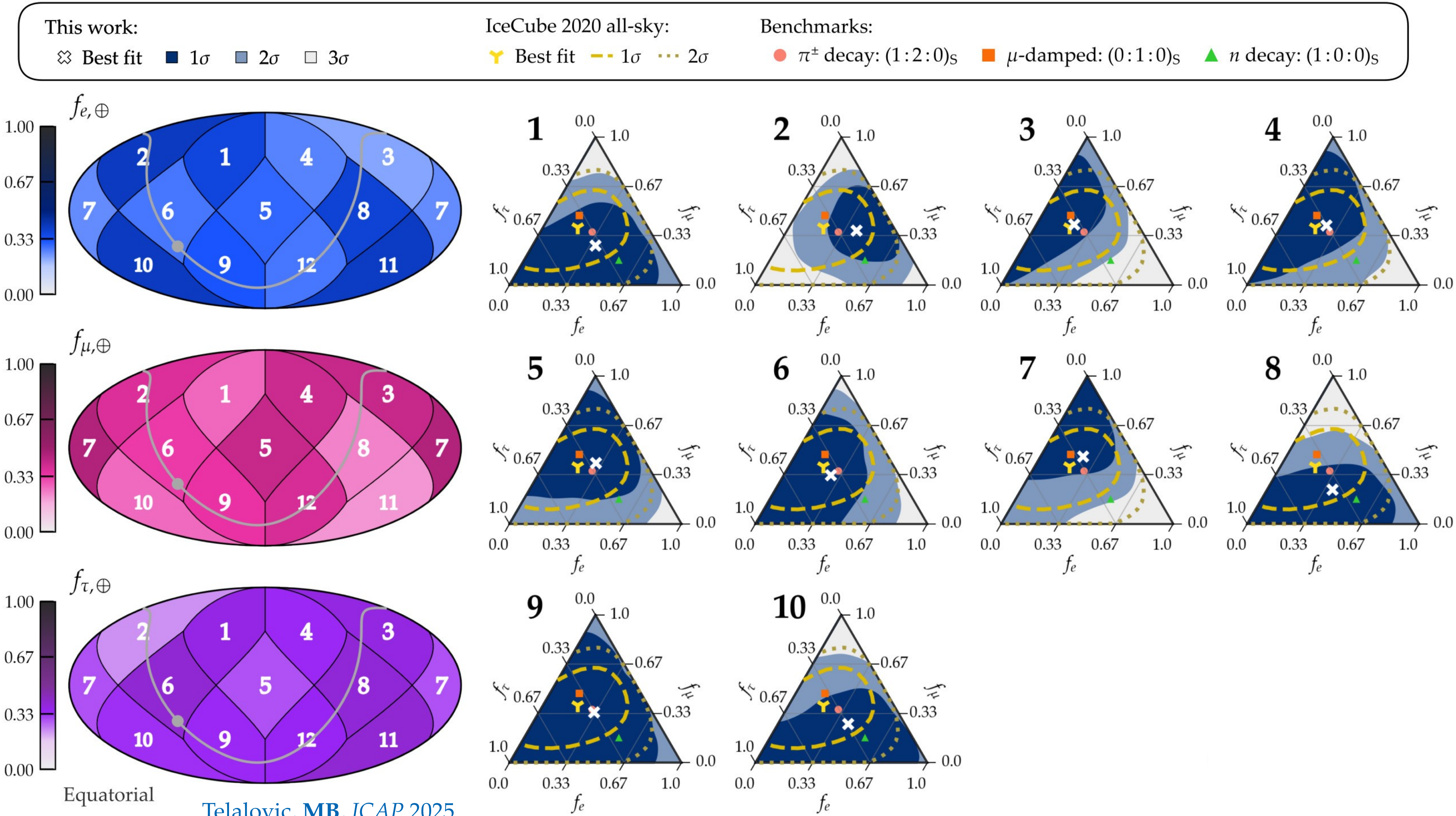

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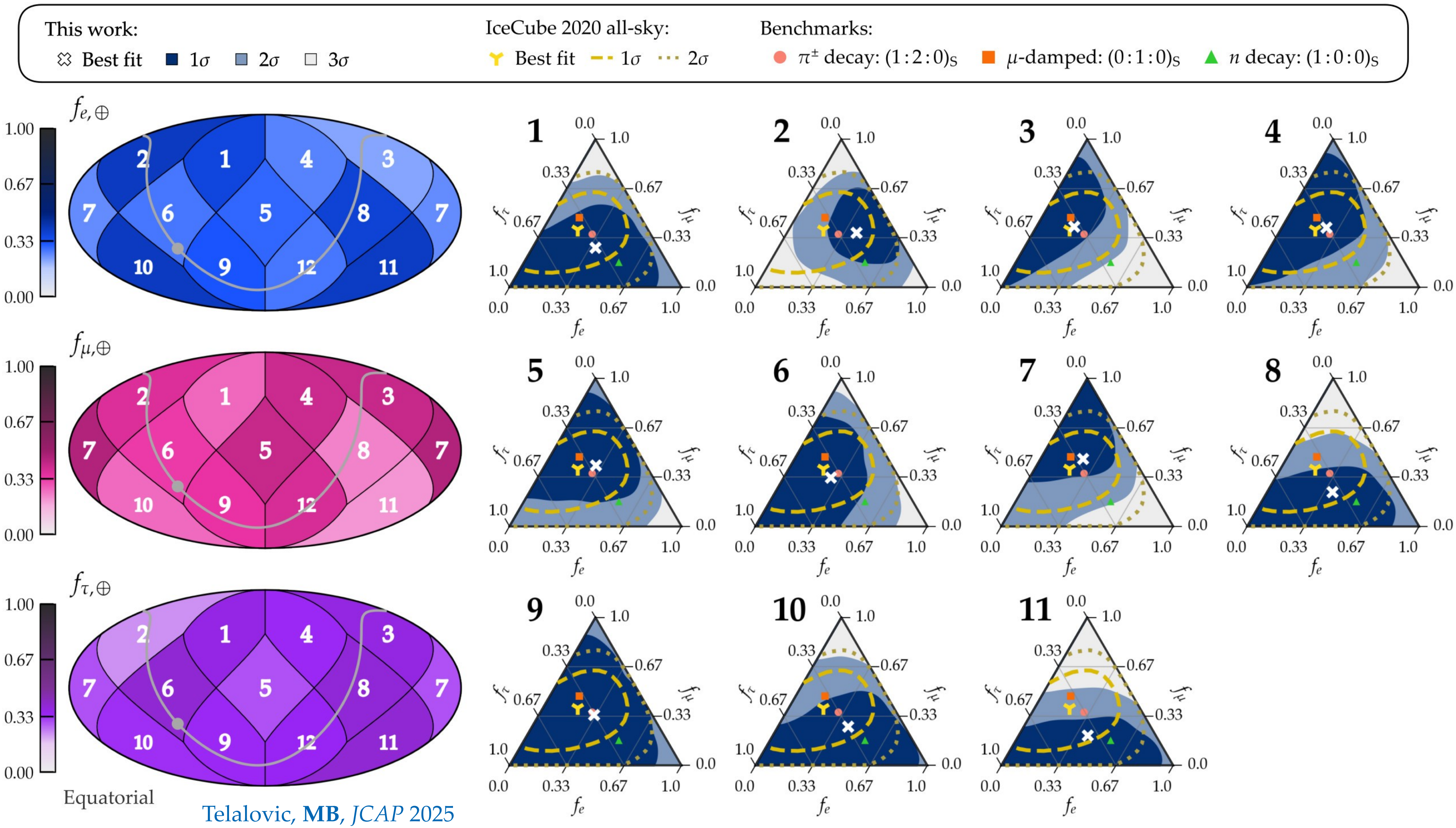

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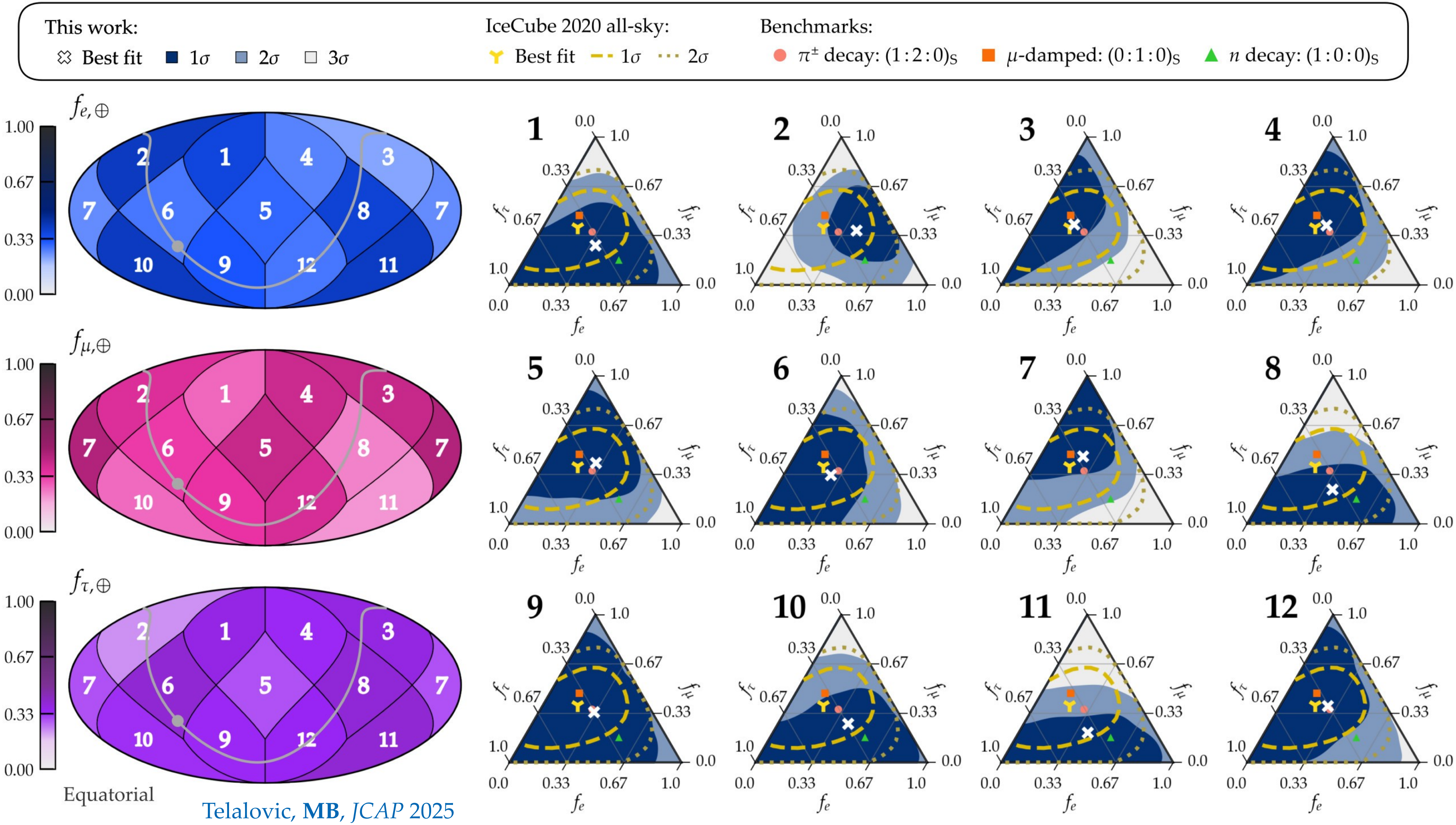

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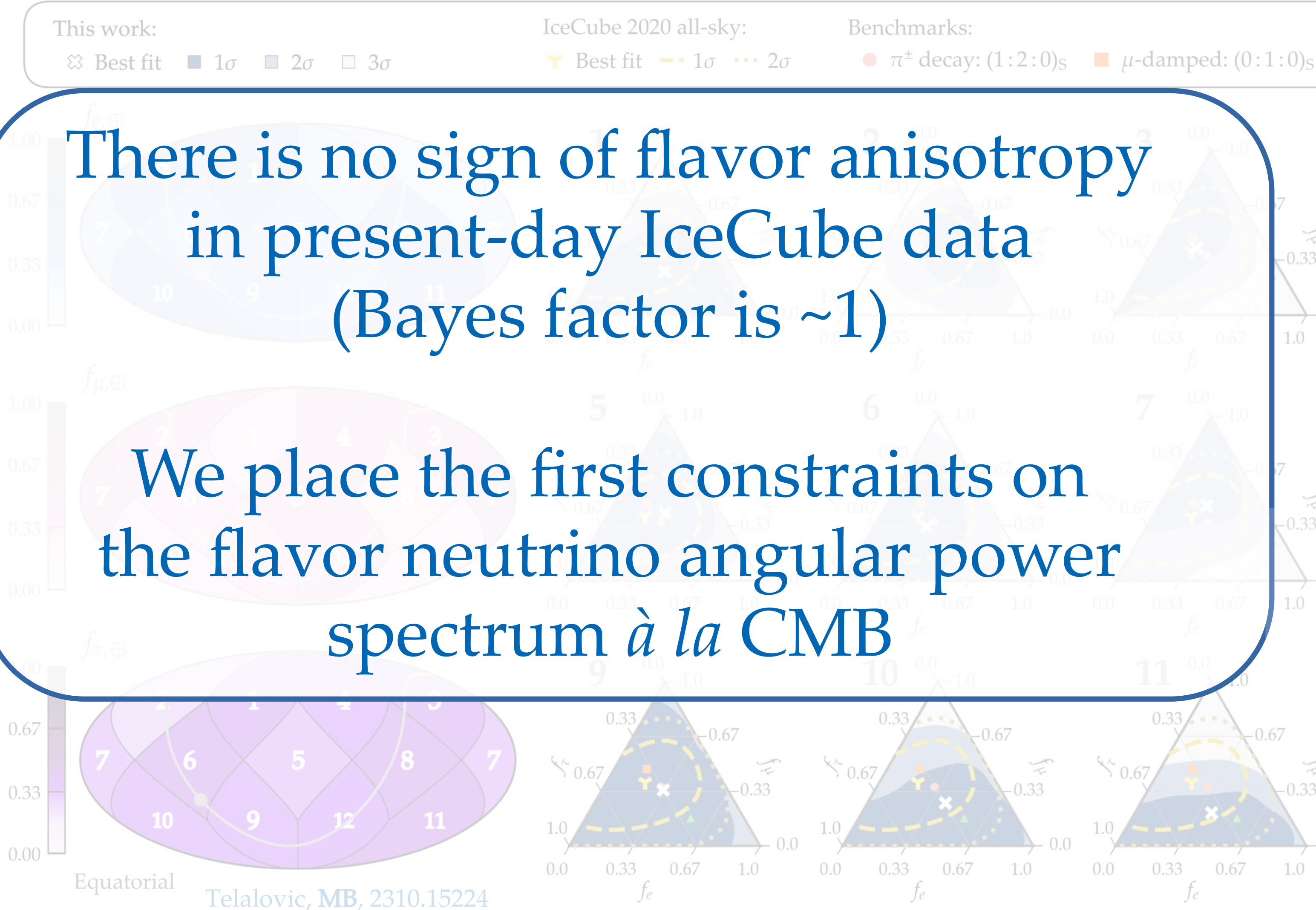
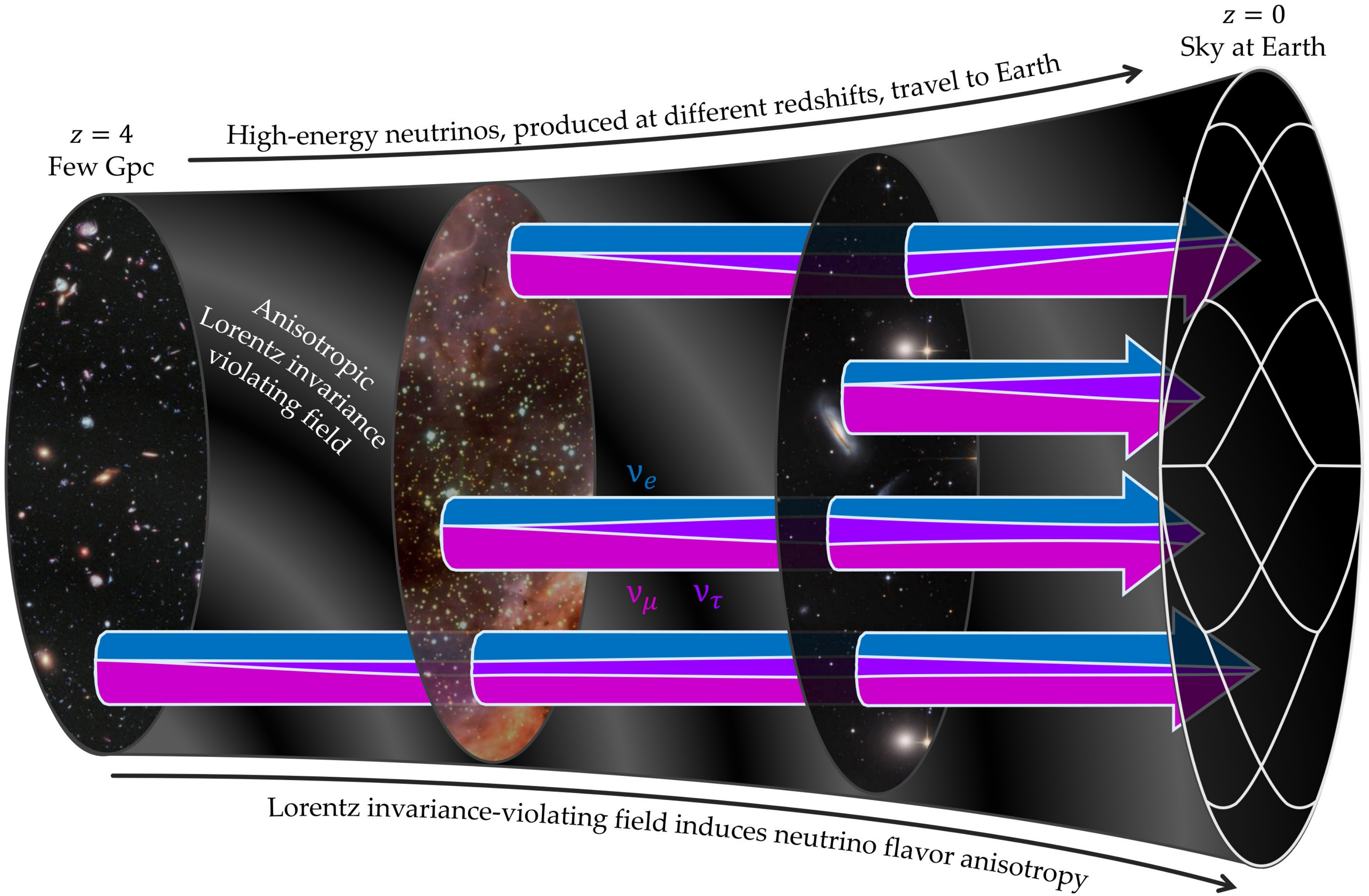


There is no sign of flavor anisotropy in present-day IceCube data (Bayes factor is ~1)

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

Work led by Bernanda Telalovic

Telalovic, MB, 2310.15224



Telalovic, **MB**, 2503.15468 (*JHEP*, to appear)

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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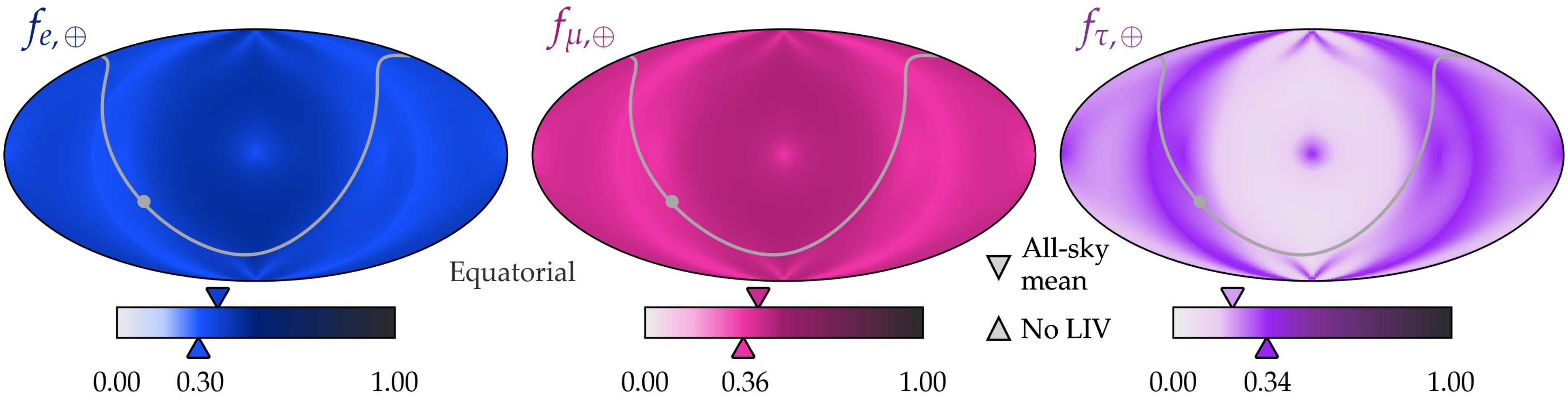

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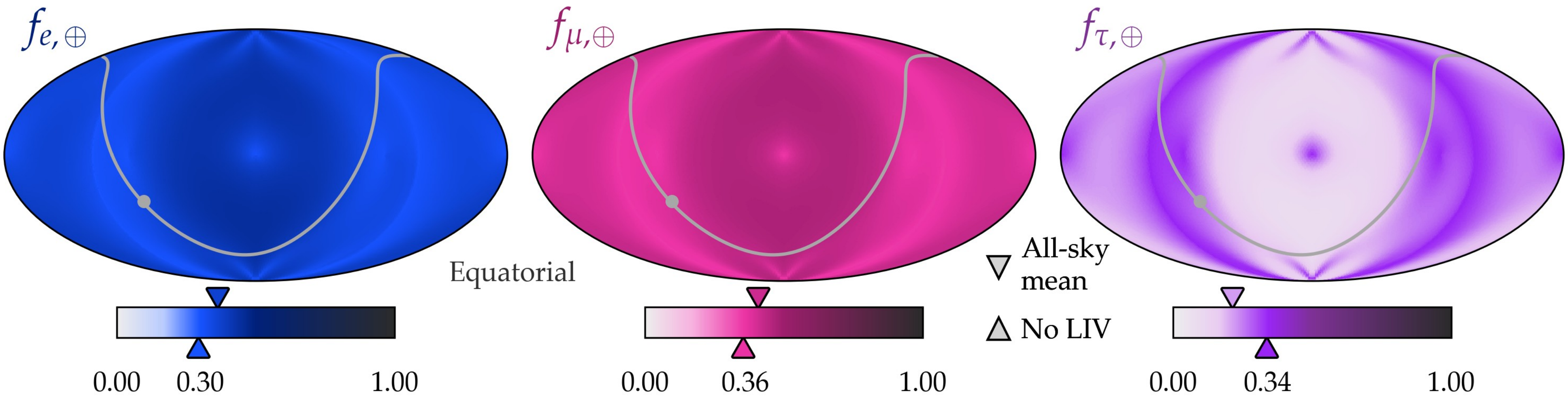

For dimension-5 CPT-odd LIV coefficient

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

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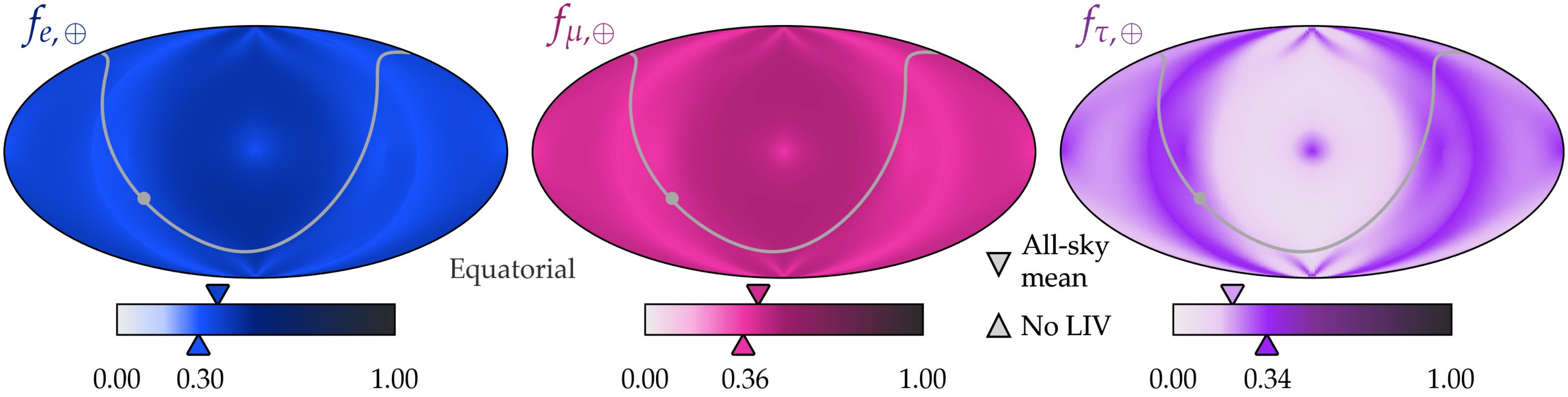

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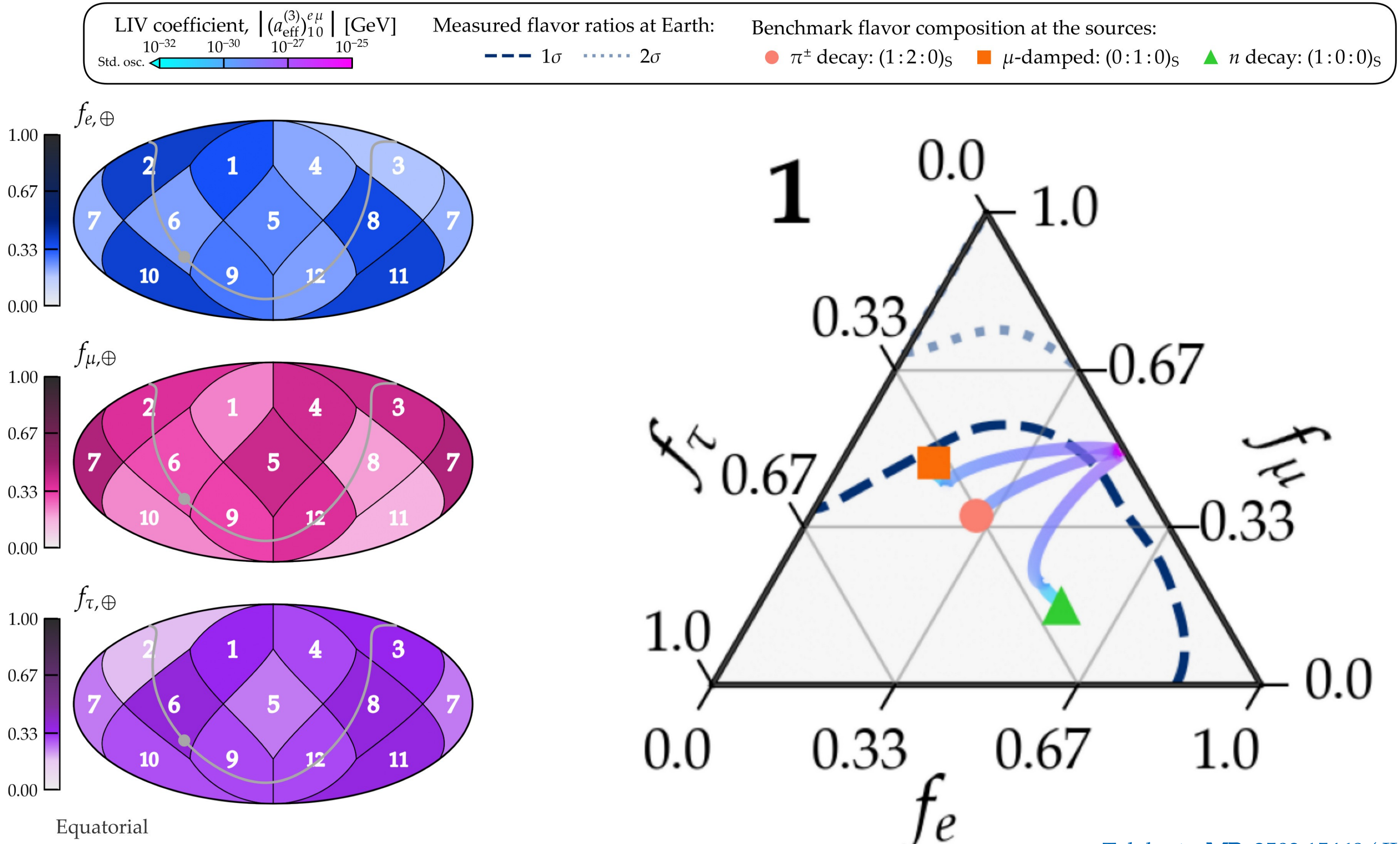
Telalovic, **MB**, *JCAP* 2025

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



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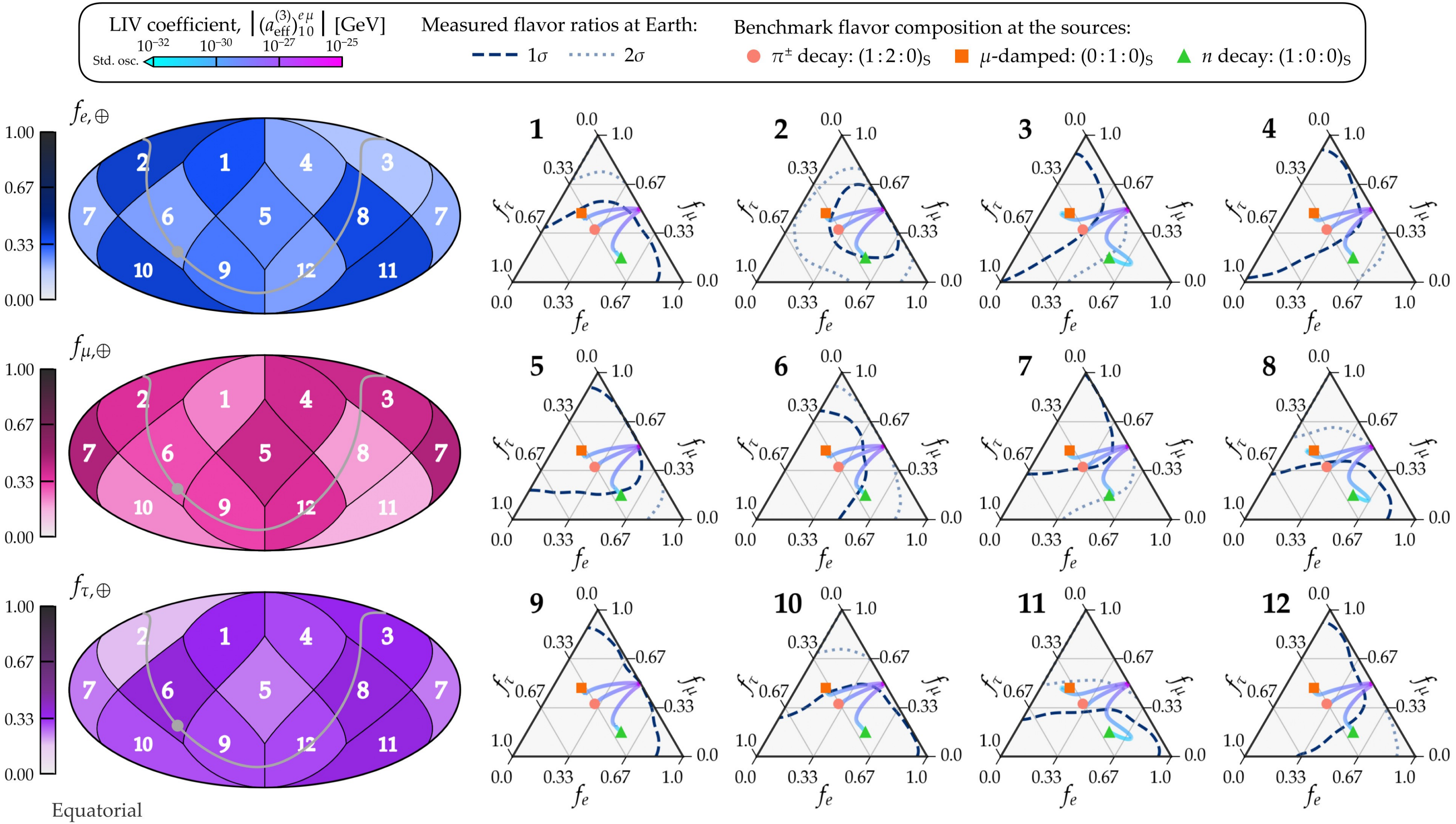

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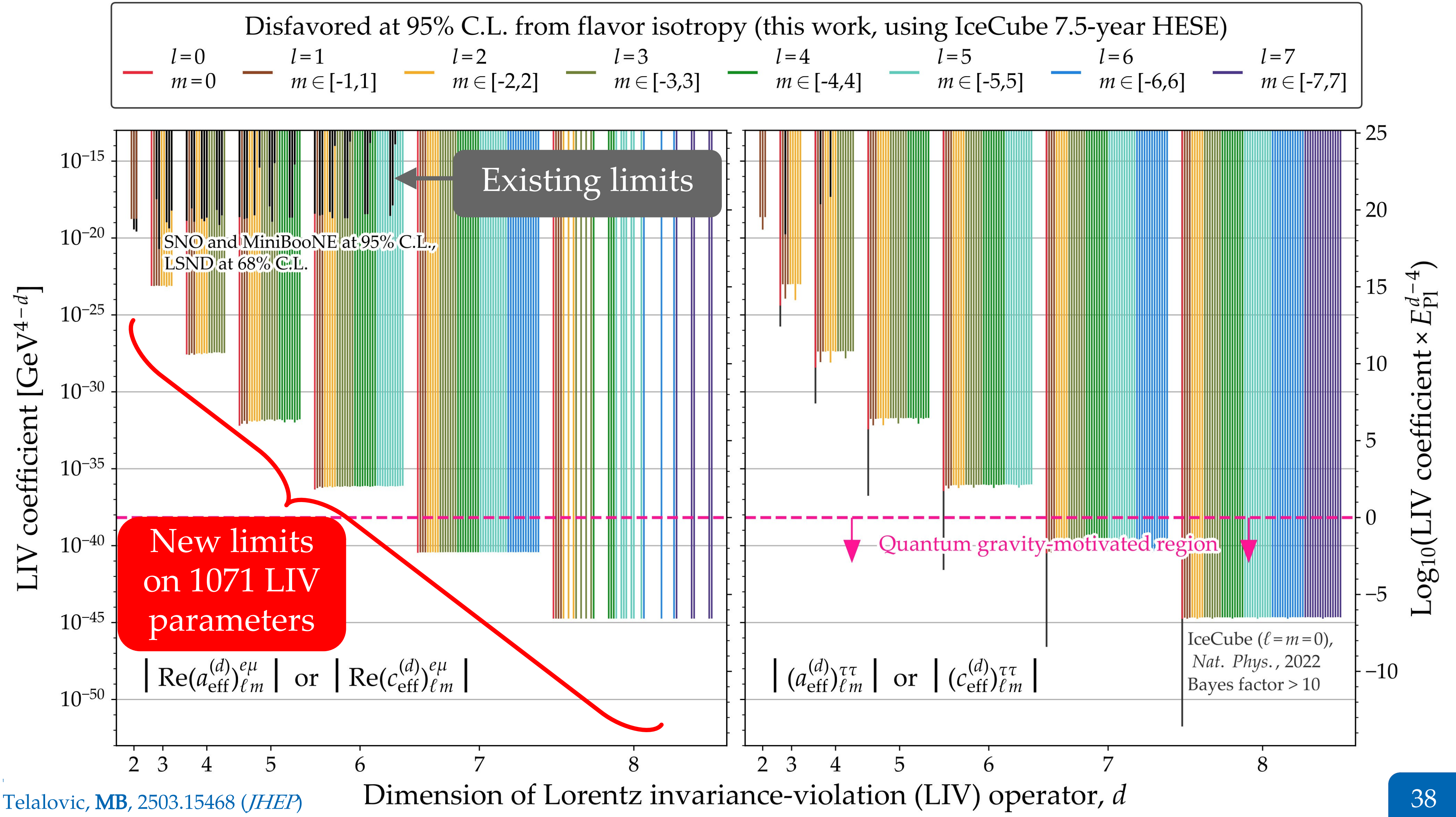
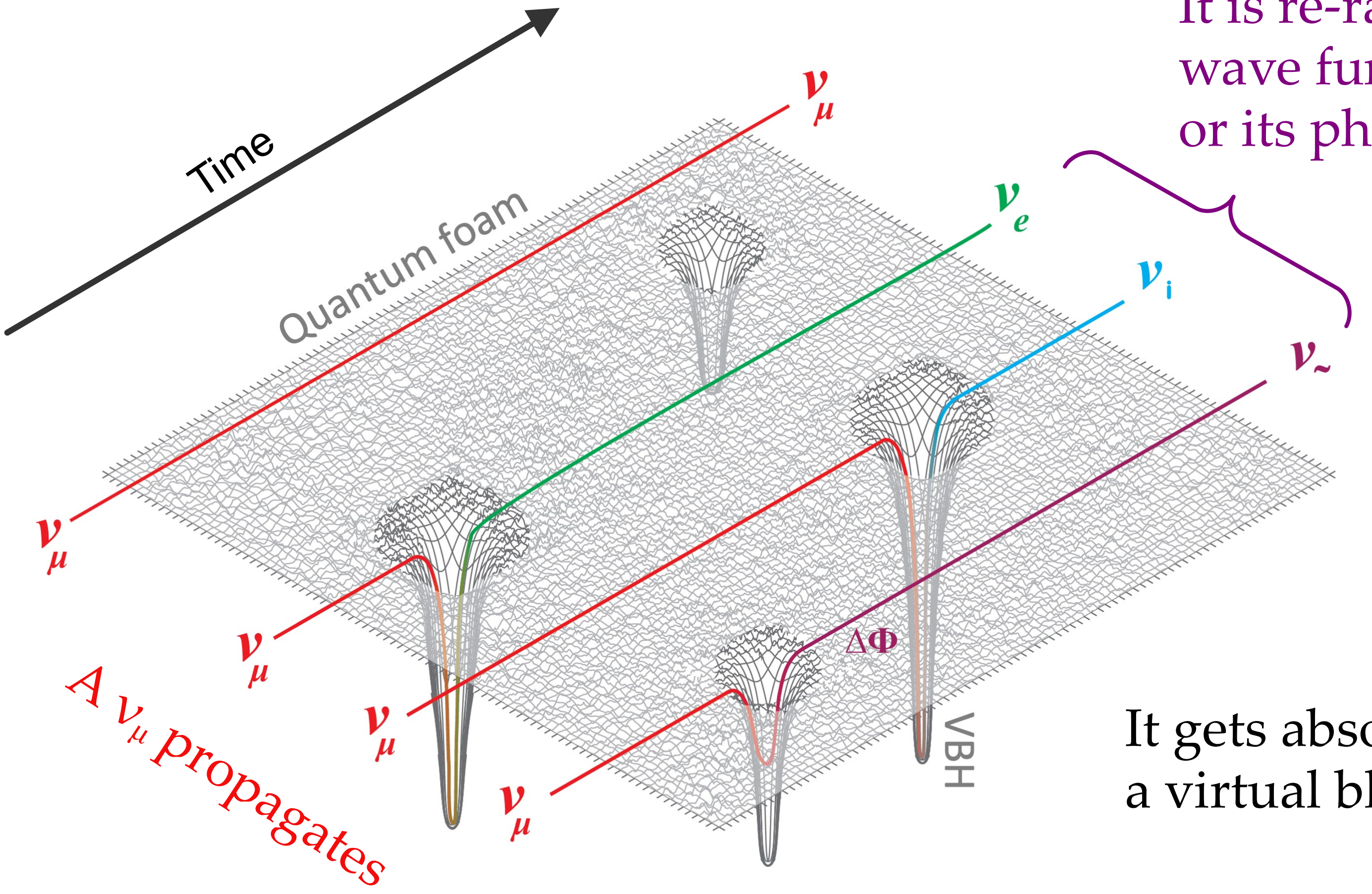


Telalovic, **MB**, 2503.15468 (*JHEP*)

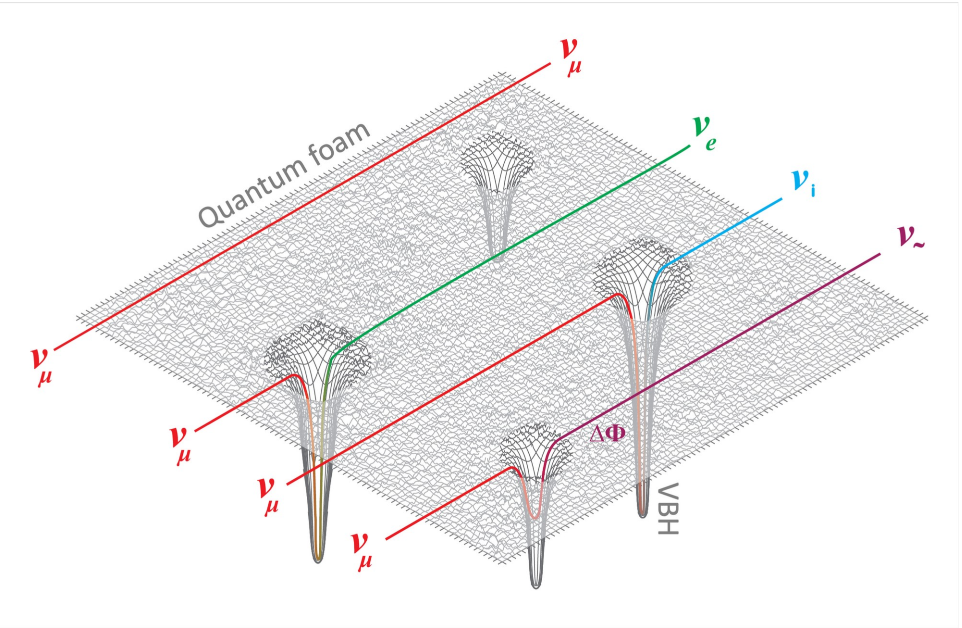
Quantum-gravity decoherence

It is re-radiated with its wave function collapse or its phase perturbed

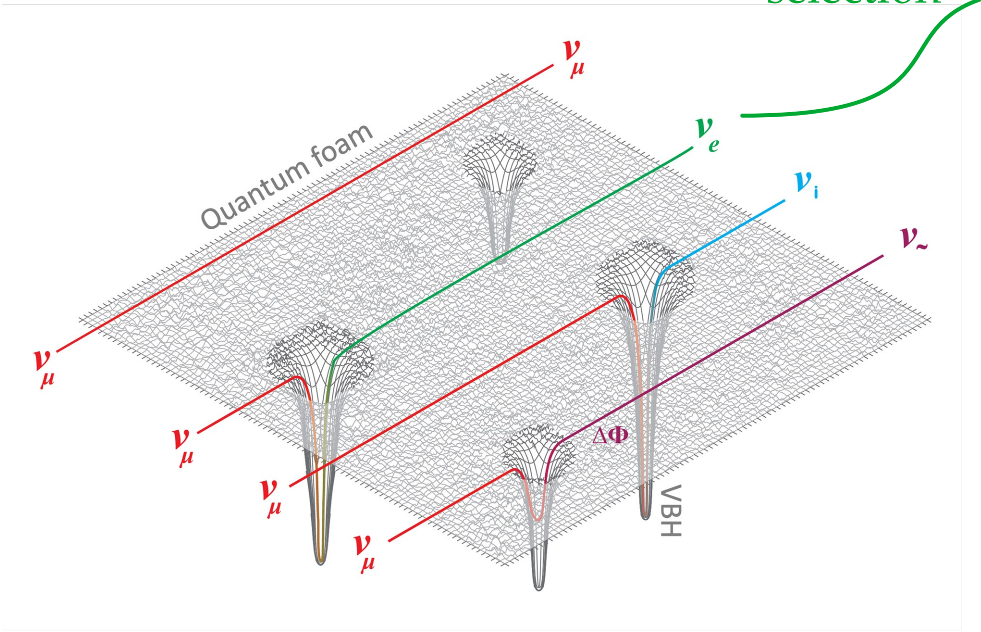


It gets absorbed by a virtual black hole

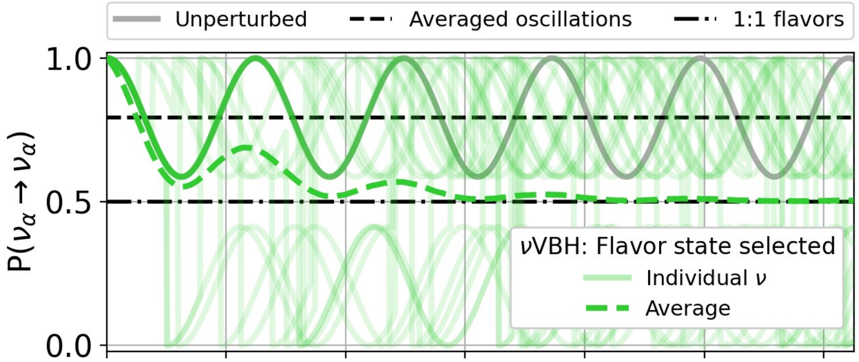
IceCube Collab., *Nature Phys.* 2024



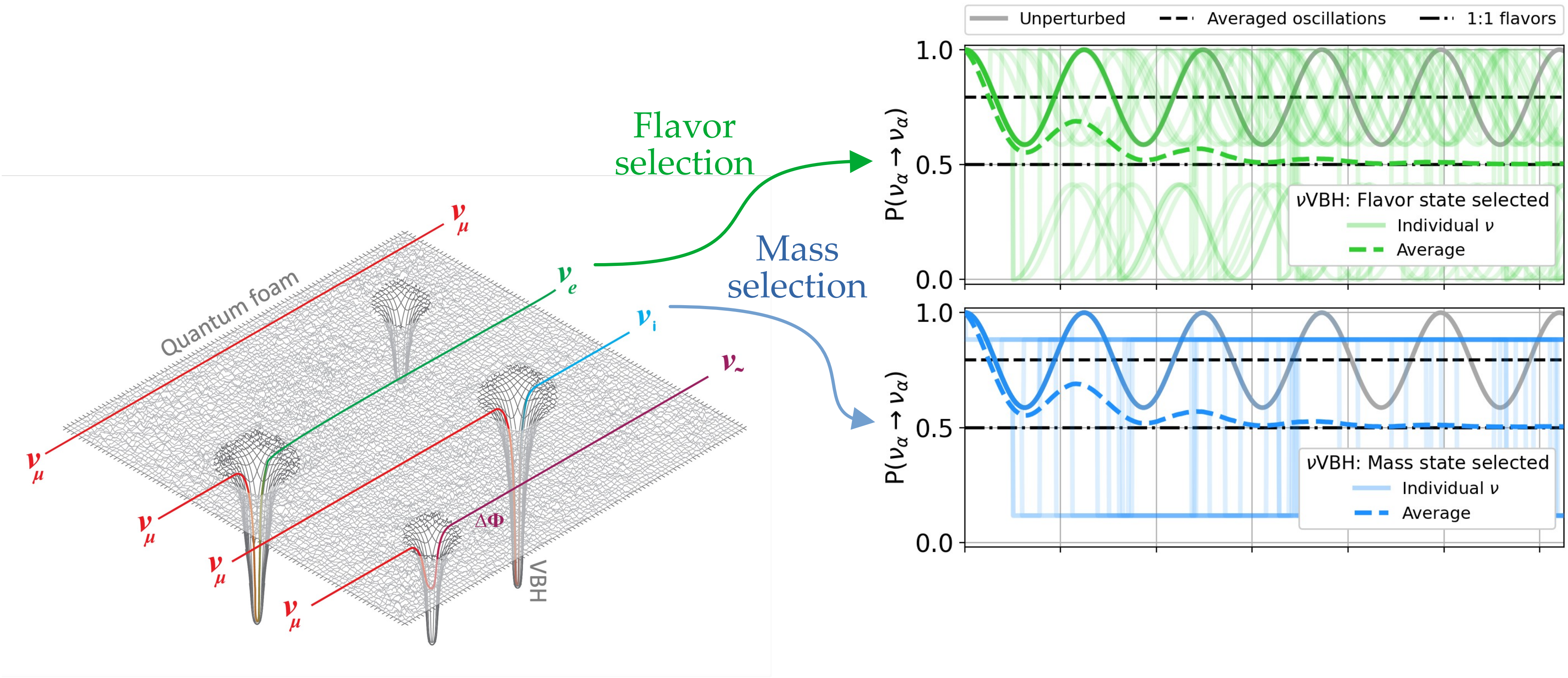
IceCube Collab., *Nature Phys.* 2024



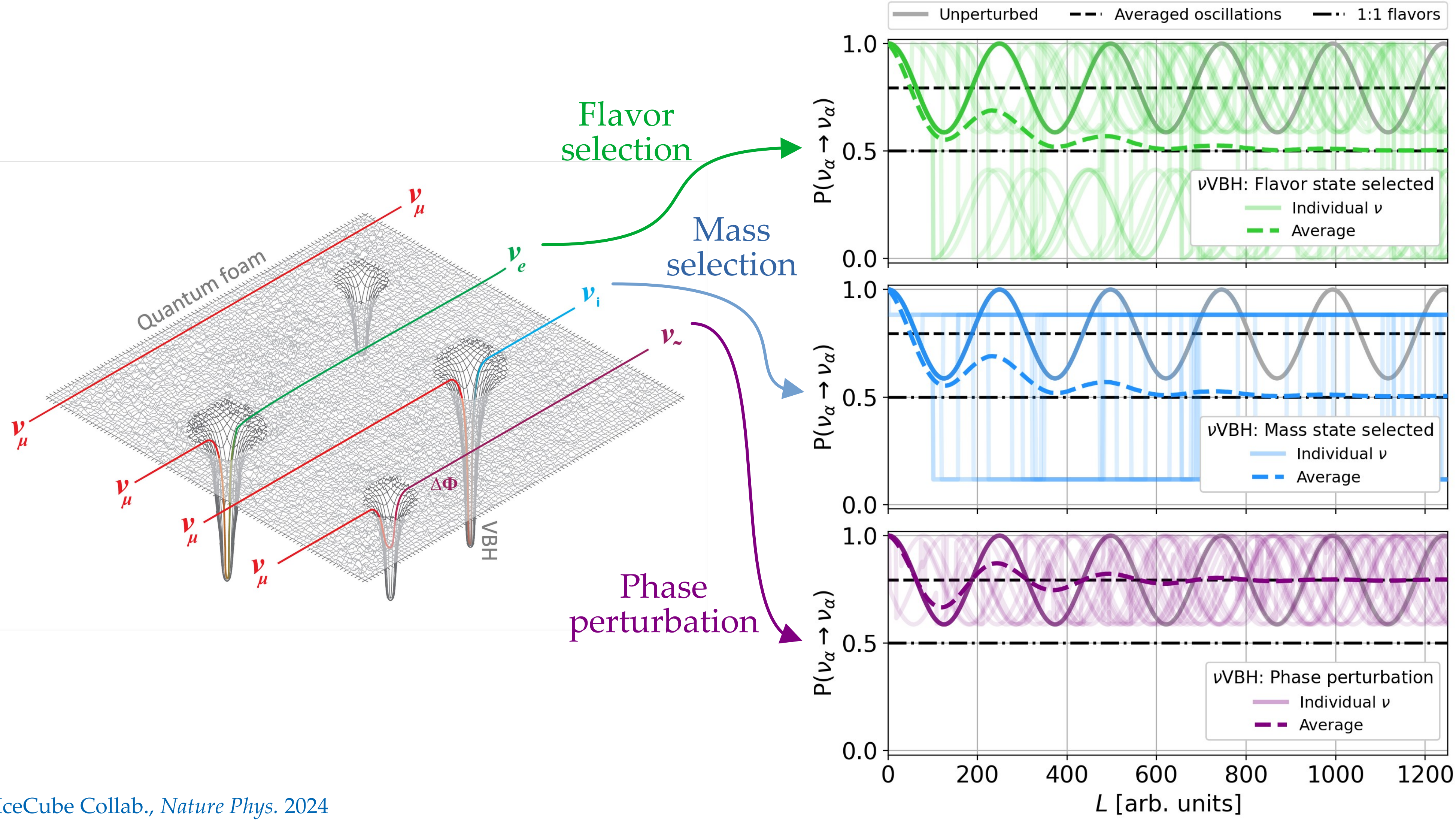
Flavor selection



IceCube Collab., *Nature Phys.* 2024



IceCube Collab., *Nature Phys.* 2024



IceCube Collab., *Nature Phys.* 2024

The density matrix ρ of the neutrino system evolves as

Standard unitary time evolution

Non-unitary unitary time evolution

$$\mathcal{D}[\rho] = (D_{\mu\nu}\rho^{\nu})\, b^{\mu}$$

$$\dot{\rho} = -i[H, \rho] - \mathcal{D}[\rho]$$

Gell-Mann matrices

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9×9 matrix

Gell-Mann matrices

Phase perturbation:

$$\mathcal{D}_{\text{phase}} = \text{diag}(0, \Gamma, \Gamma, 0, \Gamma, \Gamma, \Gamma, \Gamma, 0)$$

($L \gg 1/\Gamma$: incoherent sum of mass eigenstates)

State selection:

$$\mathcal{D}_{\text{state}} = \text{diag}(0, \Gamma, \Gamma, \Gamma, \Gamma, \Gamma, \Gamma, \Gamma, \Gamma)$$

($L \gg 1/\Gamma$: democratization of mass eigenstates or flavors)

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Use ~300k IceCube atmospheric ν_μ with 0.5–10 TeV

Strongest constraints to date

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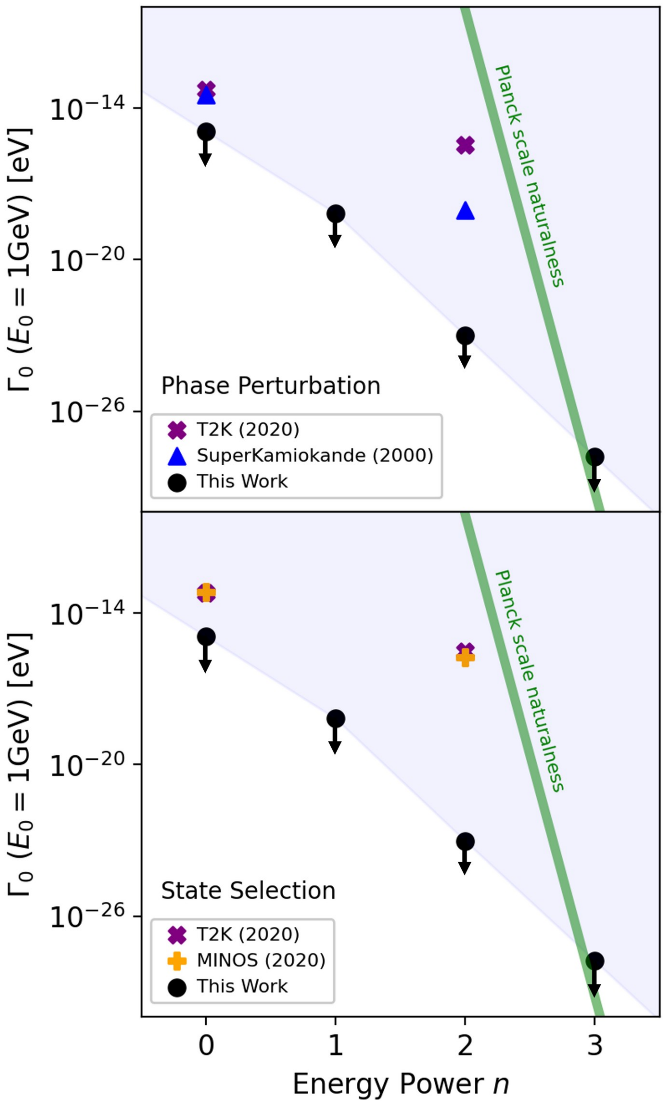

IceCube Collab., *Nature Phys.* 2024

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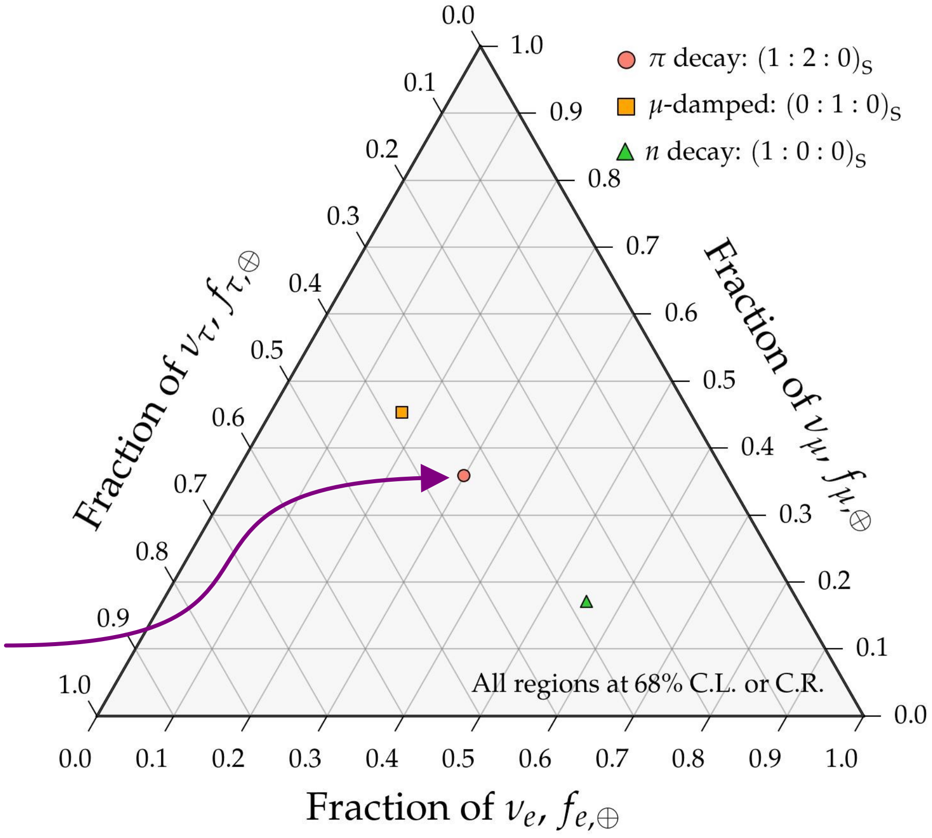
Strongest constraints to date

$$\Gamma(E_\nu) = \Gamma_0 \left(\frac{E_\nu}{E_0} \right)$$

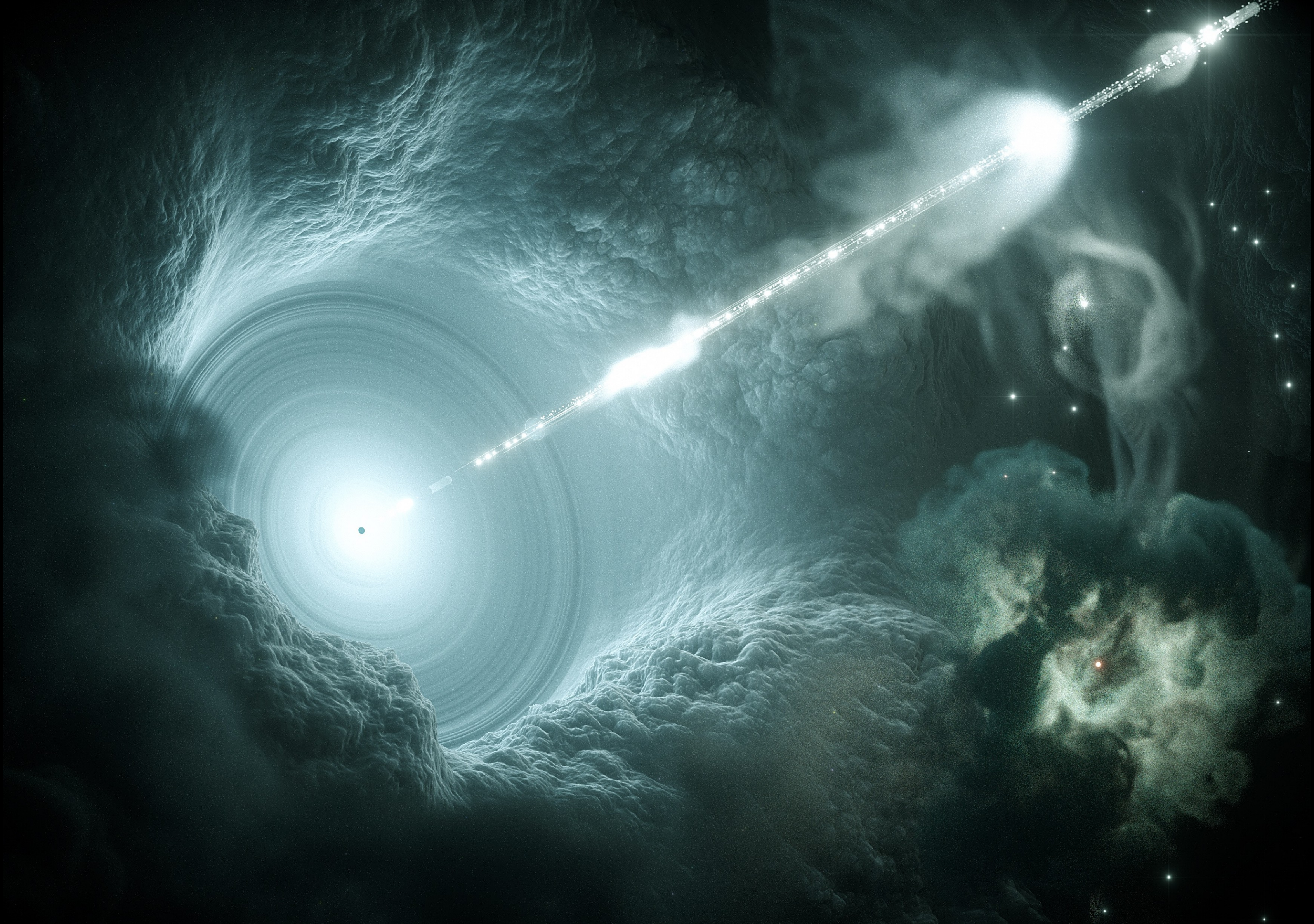
How about using astrophysical TeV—PeV ν?

State selection yields ν_e:ν_μ:ν_τ ≈ 1:1:1
Problem: this matches the standard expectation

Phase perturbation yields something different
Could be worth exploring



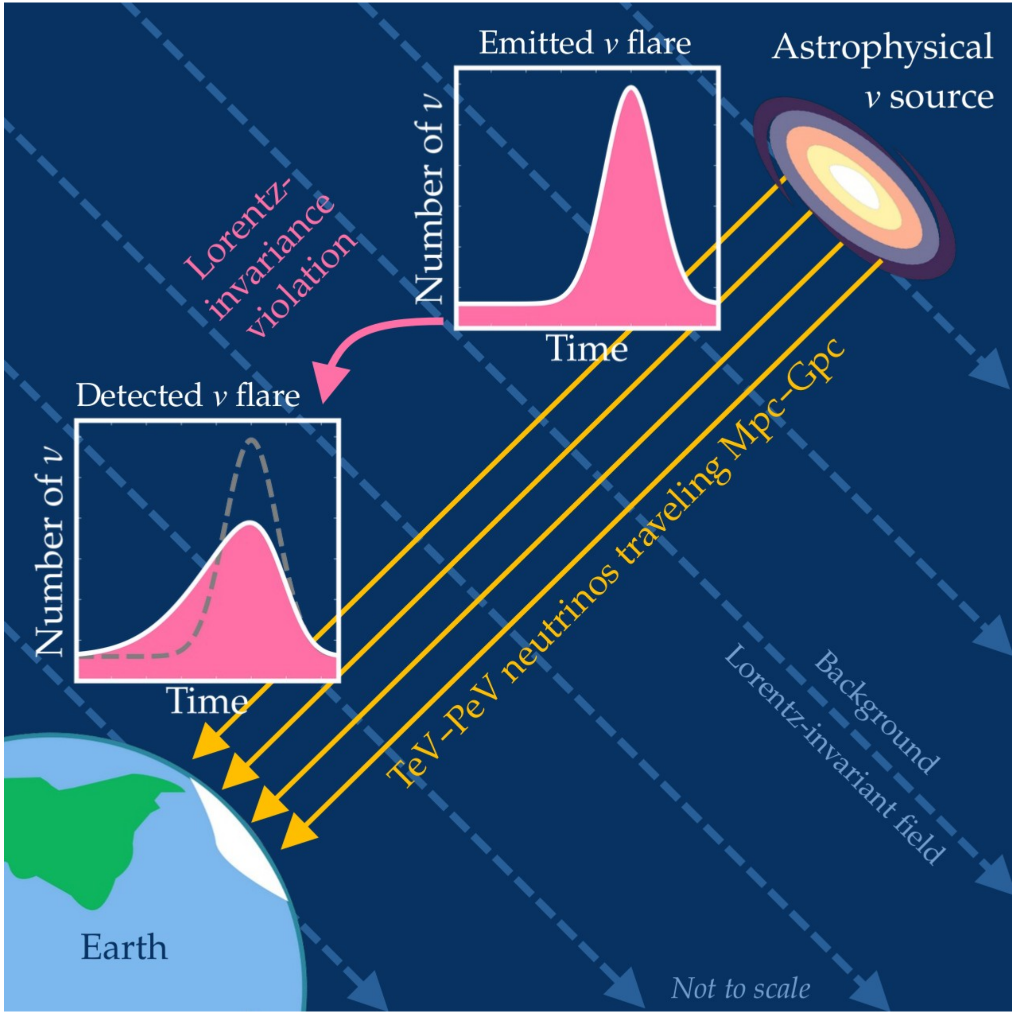
LIV from a high-energy ν flare



DESY

DESY

New physics from high-energy neutrino flares



Lorentz-invariance violation may change the neutrino speed relative to light speed:

$$v(E_\nu) = \left[1 - \frac{n+1}{2}\left(\frac{E_\nu}{M_n}\right)^n\right] \equiv 1 - \Delta v(E_\nu)$$

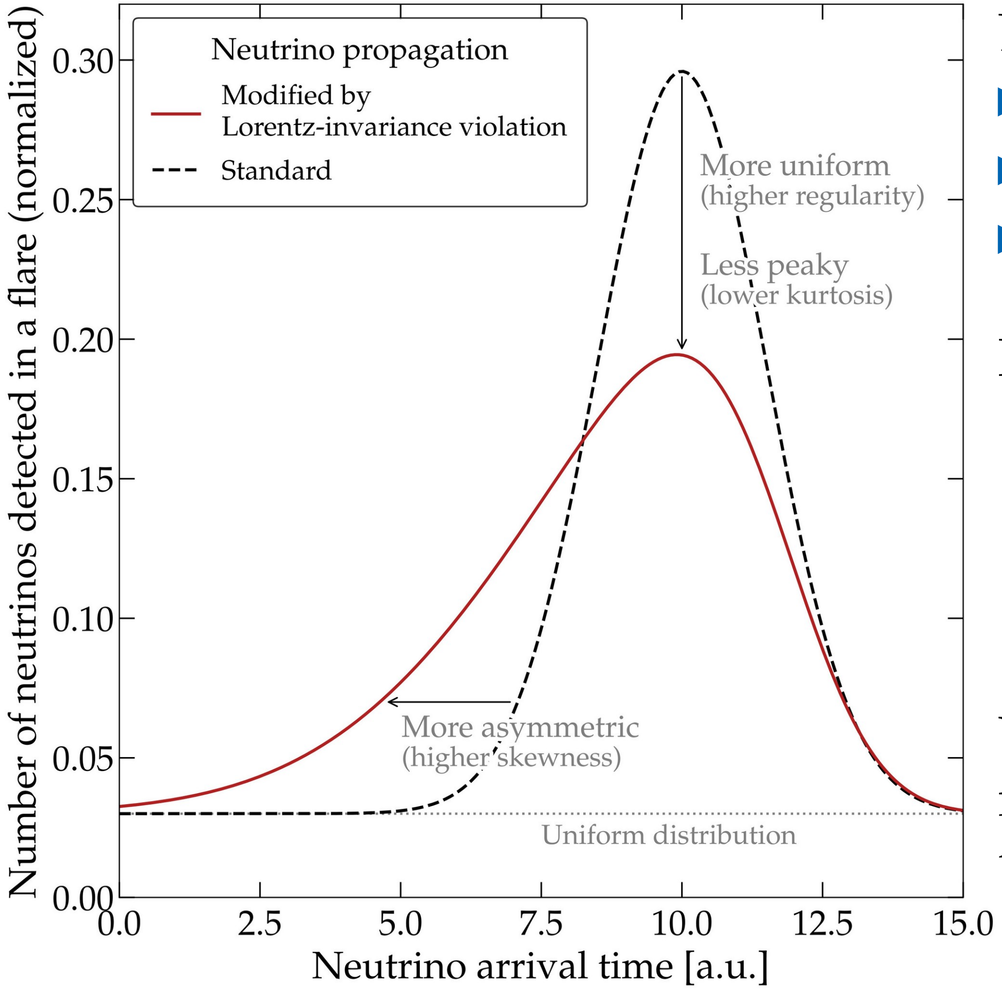
M_n: LIV energy scale (unknown)

From the time profile of a neutrino flare we can bound the value of M_n *without an electromagnetic counterpart* and *without knowing the original time profile*

MB, Ellis, Konoplich, Sakharov, *PRD* 2025

New physics from high-energy neutrino flares

MB, Ellis, Konoplich, Sakharov, *PRD* 2025



LIV makes the ν flare time-distribution...

- More uniform
- Less peaky (lower kurtosis)
- More asymmetric (negative skewness)

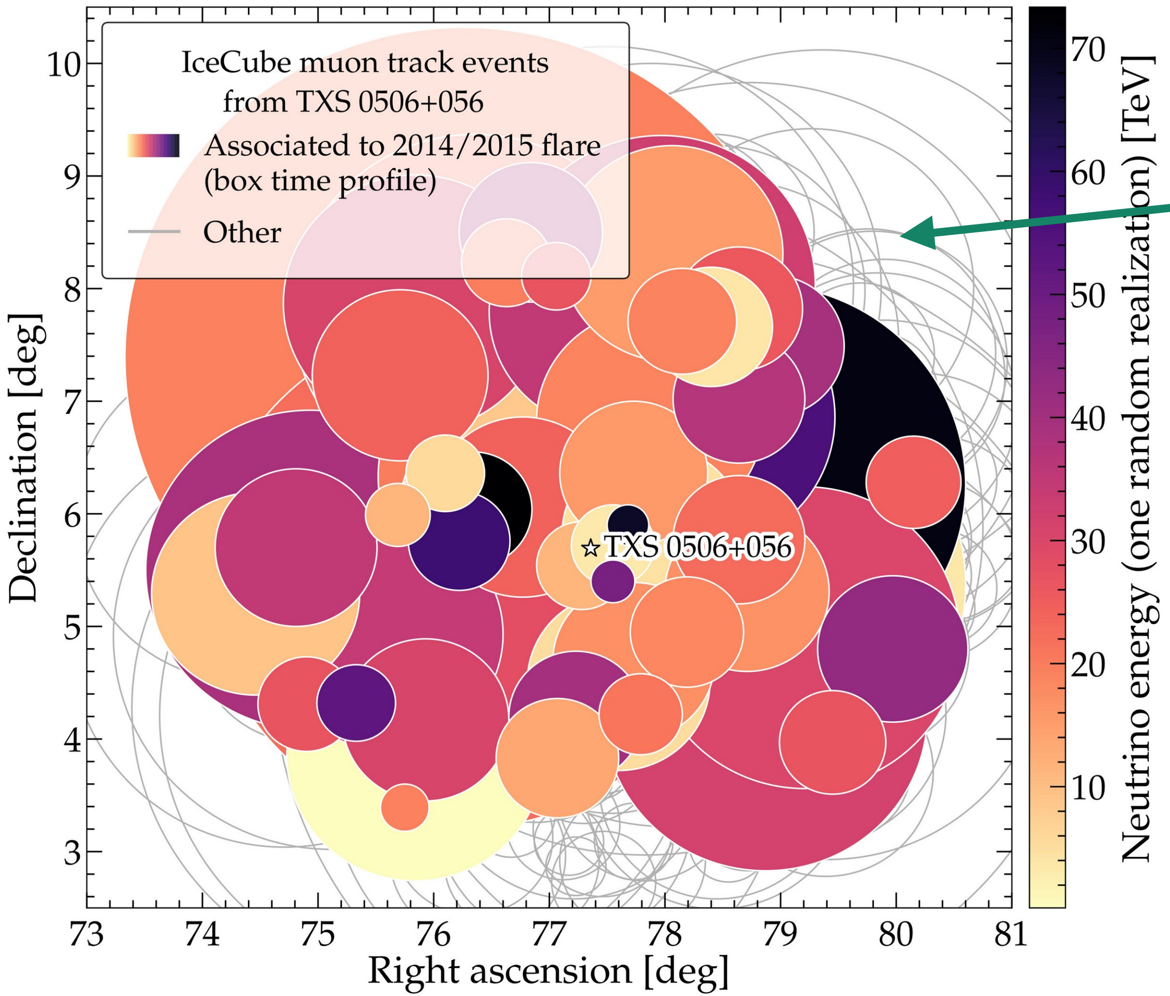
For a detected neutrino with E_ν in a flare:

$$t_{\rm obs}(E_\nu) = b_{\rm s}(E_\nu)(1+z_{\rm src}) + \tau_n(z_{\rm src})E_\nu^n$$

- $t_{\rm obs}(E_\nu)$: Detection time of a at Earth
- $(1+z_{\rm src})$: Intrinsic lag in the source
- $\tau_n(z_{\rm src})$: Effect of LIV

We find the value of τ_n that restores irregularity, peakiness, and asymmetry to time-distribution of the flare

New physics from high-energy neutrino flares

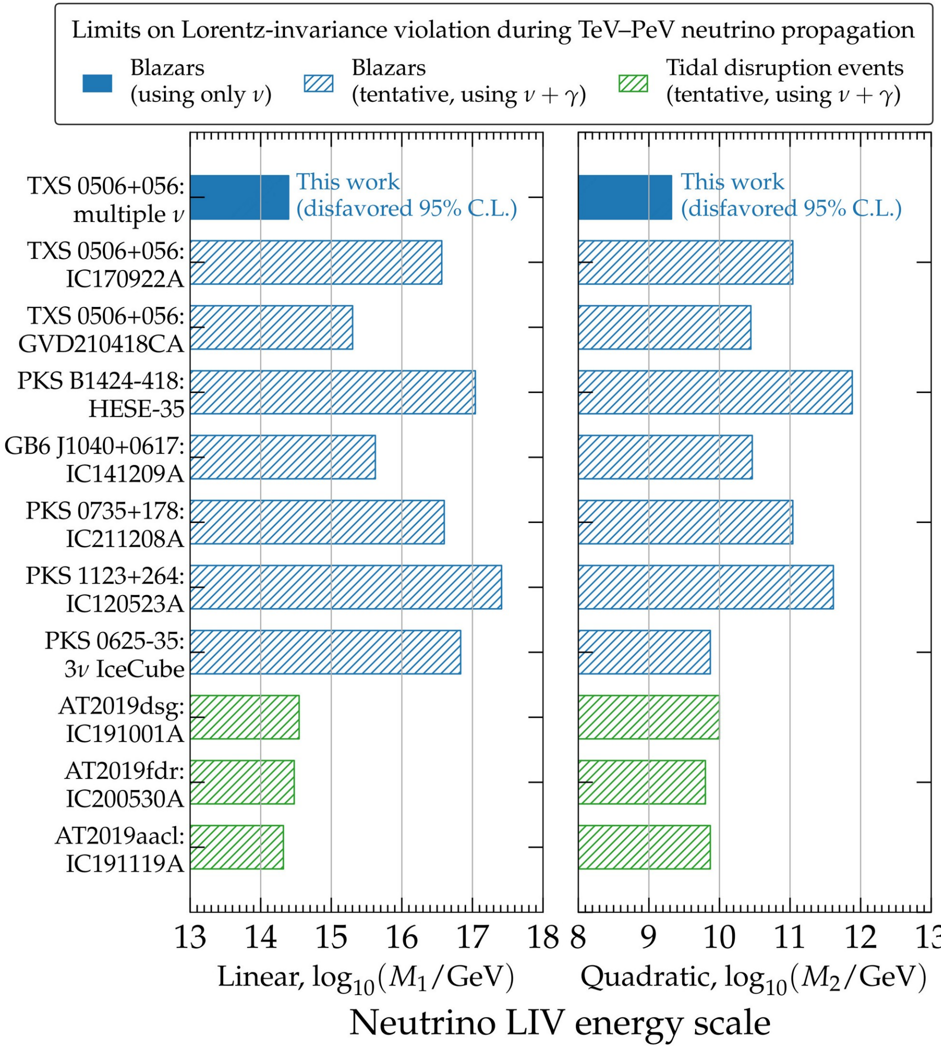


Use IceCube through-going muons associated to the 2015/2015 flare of TXS 0506+056

- Higher weight if closer to the source
- Account for uncertainty in linking muon energy (measured) to neutrino energy (inferred)

MB, Ellis, Konoplich, Sakharov, *PRD* 2025

New physics from high-energy neutrino flares

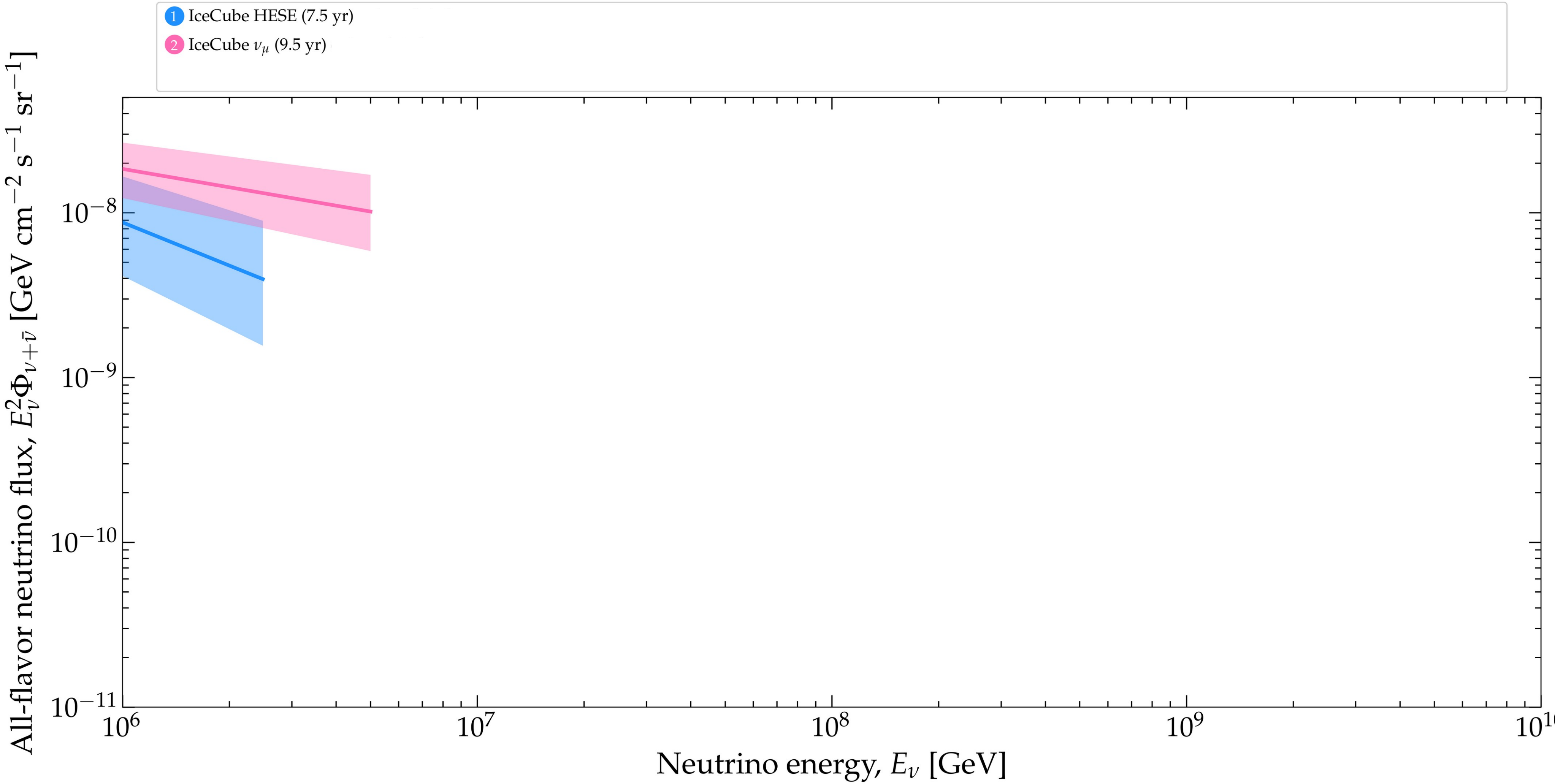


New limits from the TXS 0506+056 2014/2015 flare *using only neutrinos*

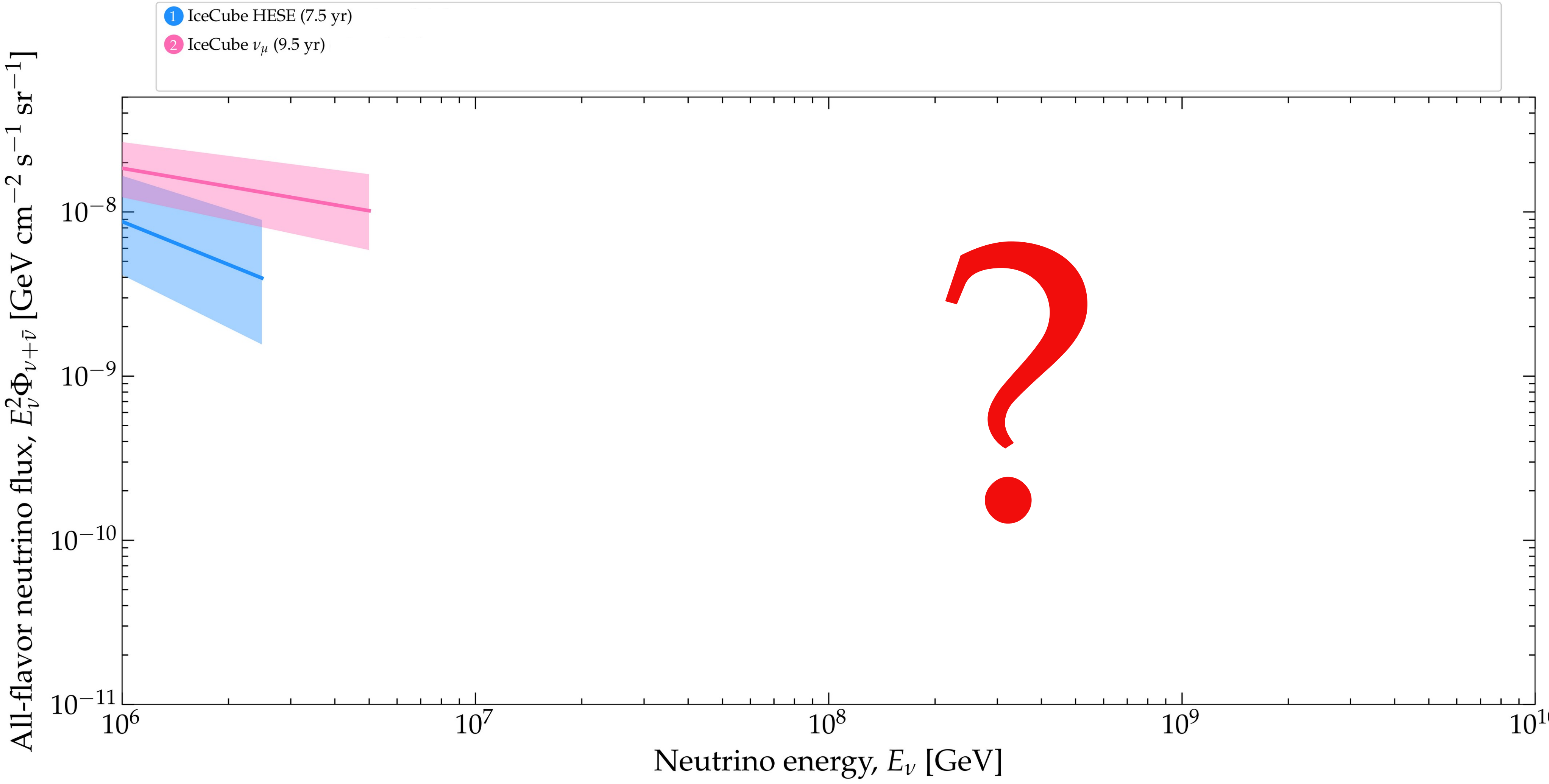
Limits from the coincident emission of neutrinos and electromagnetic emission (generally low or unspecified credibility)

MB, Ellis, Konoplich, Sakharov, *PRD* 2025

Tests at ultra-high energies (> 100 PeV)



1 IceCube HESE (7.5 yr)
2 IceCube ν_μ (9.5 yr)
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}
All-flavor neutrino flux, $E_\nu^2\Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy, E_ν [GeV]



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10^8
10^9
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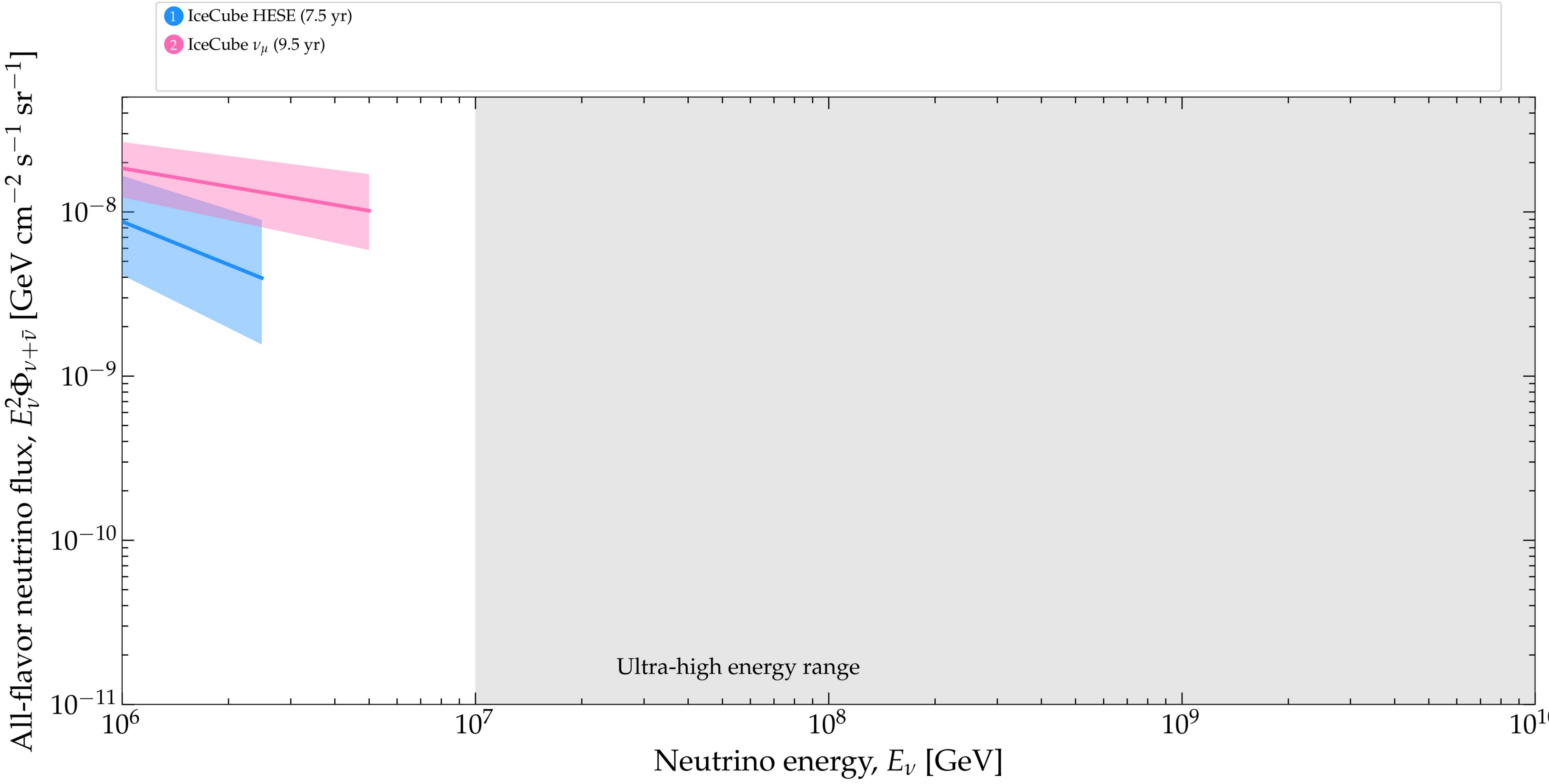
Neutrino energy, E_ν [GeV]
?



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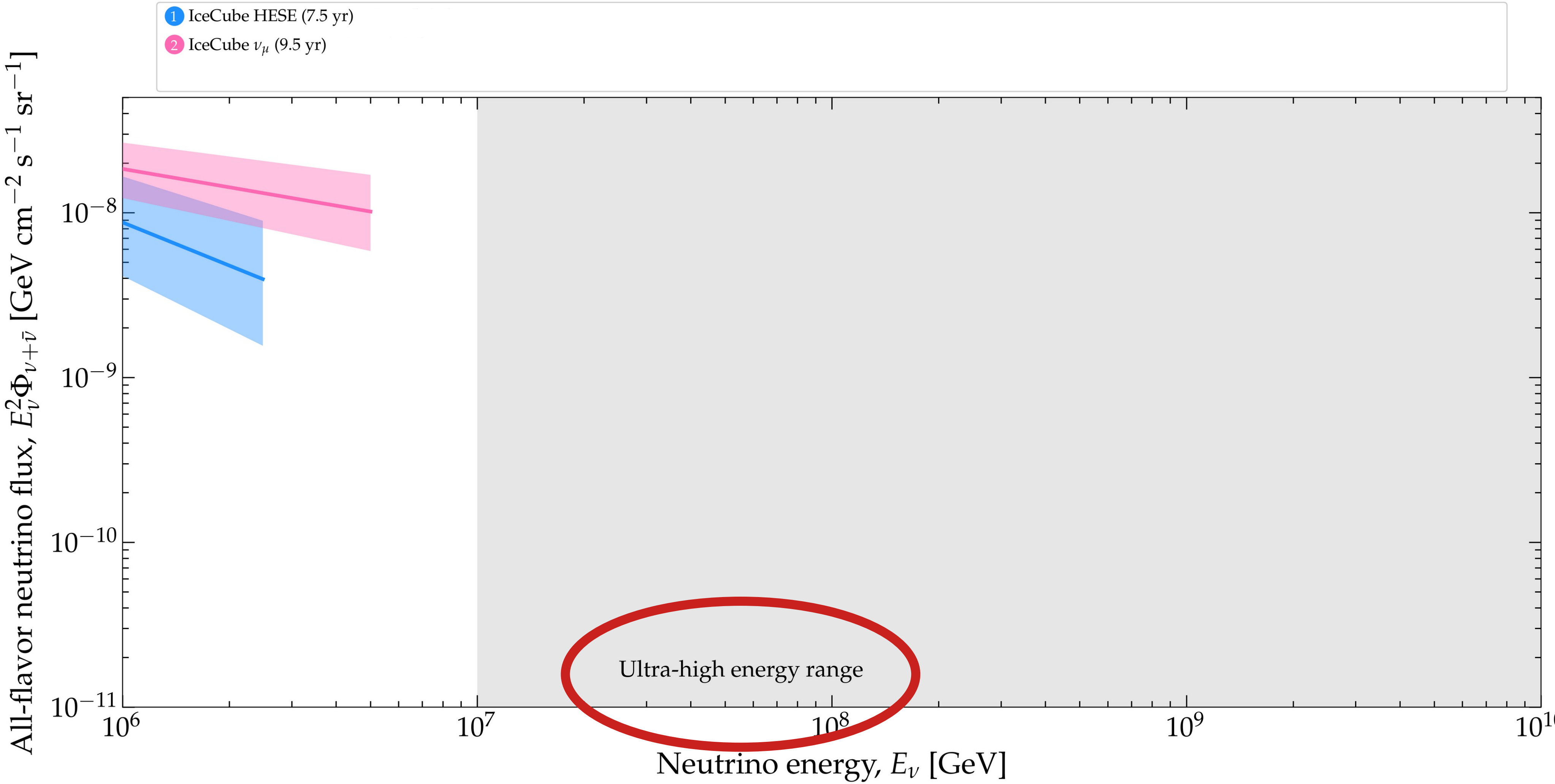

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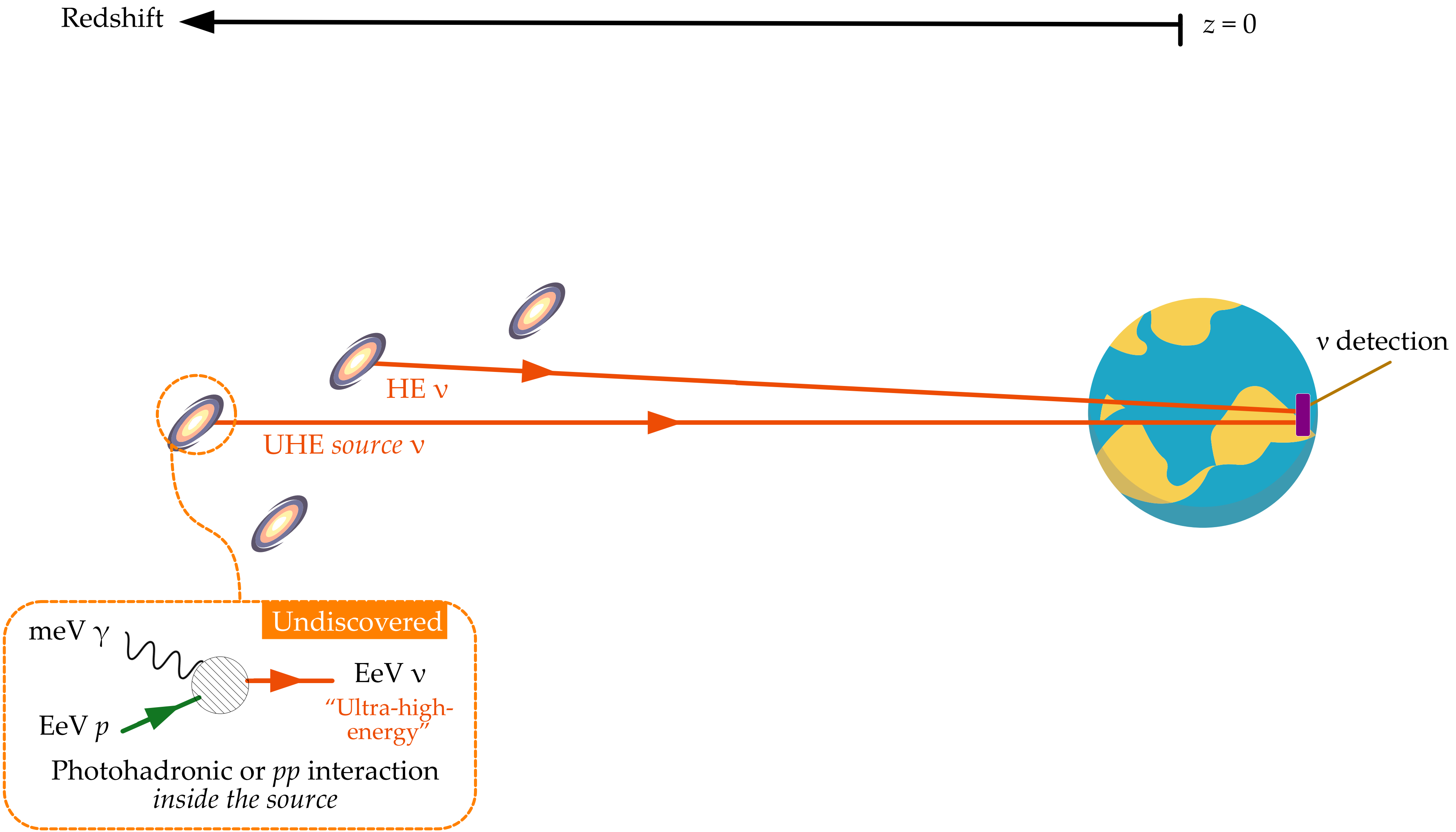
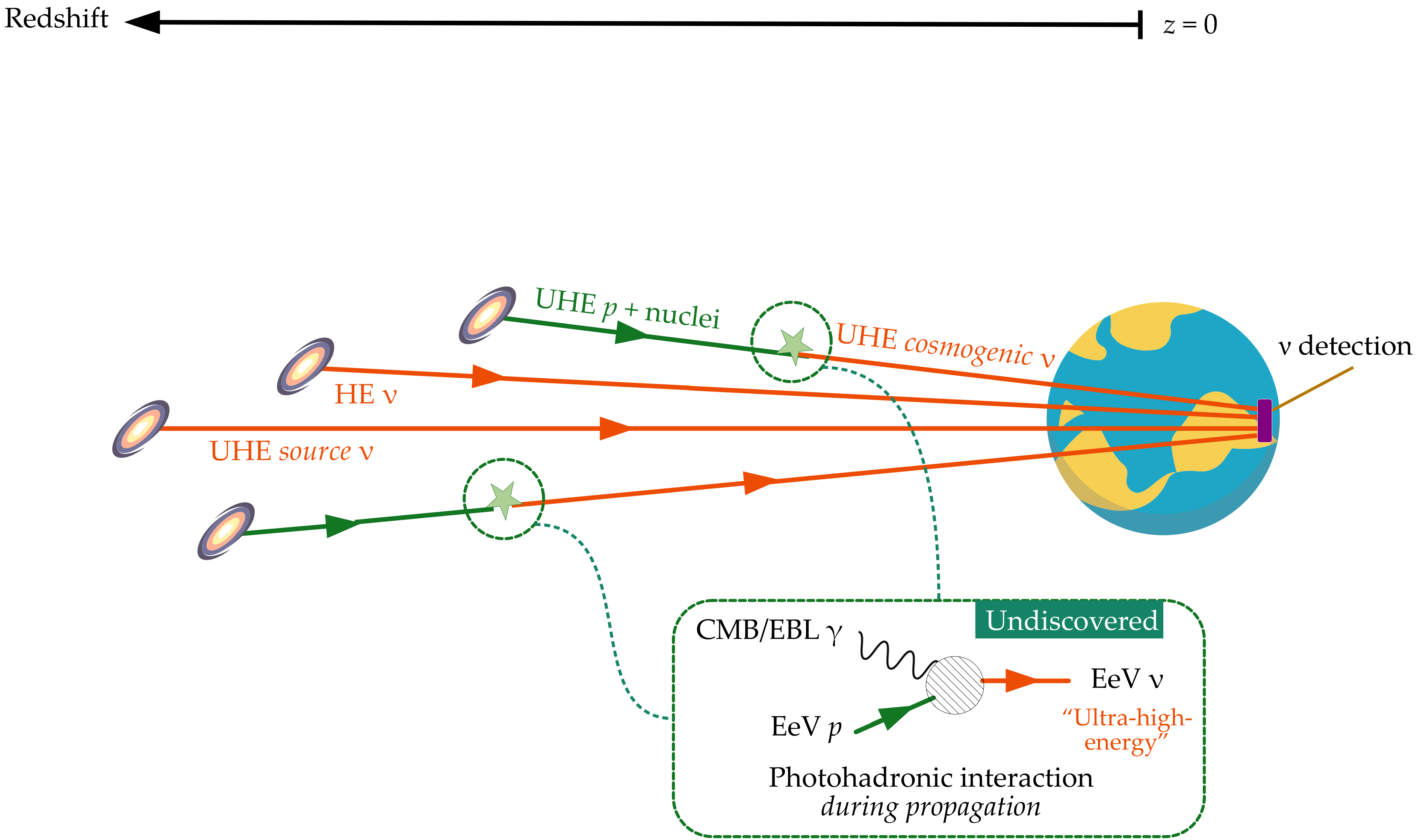
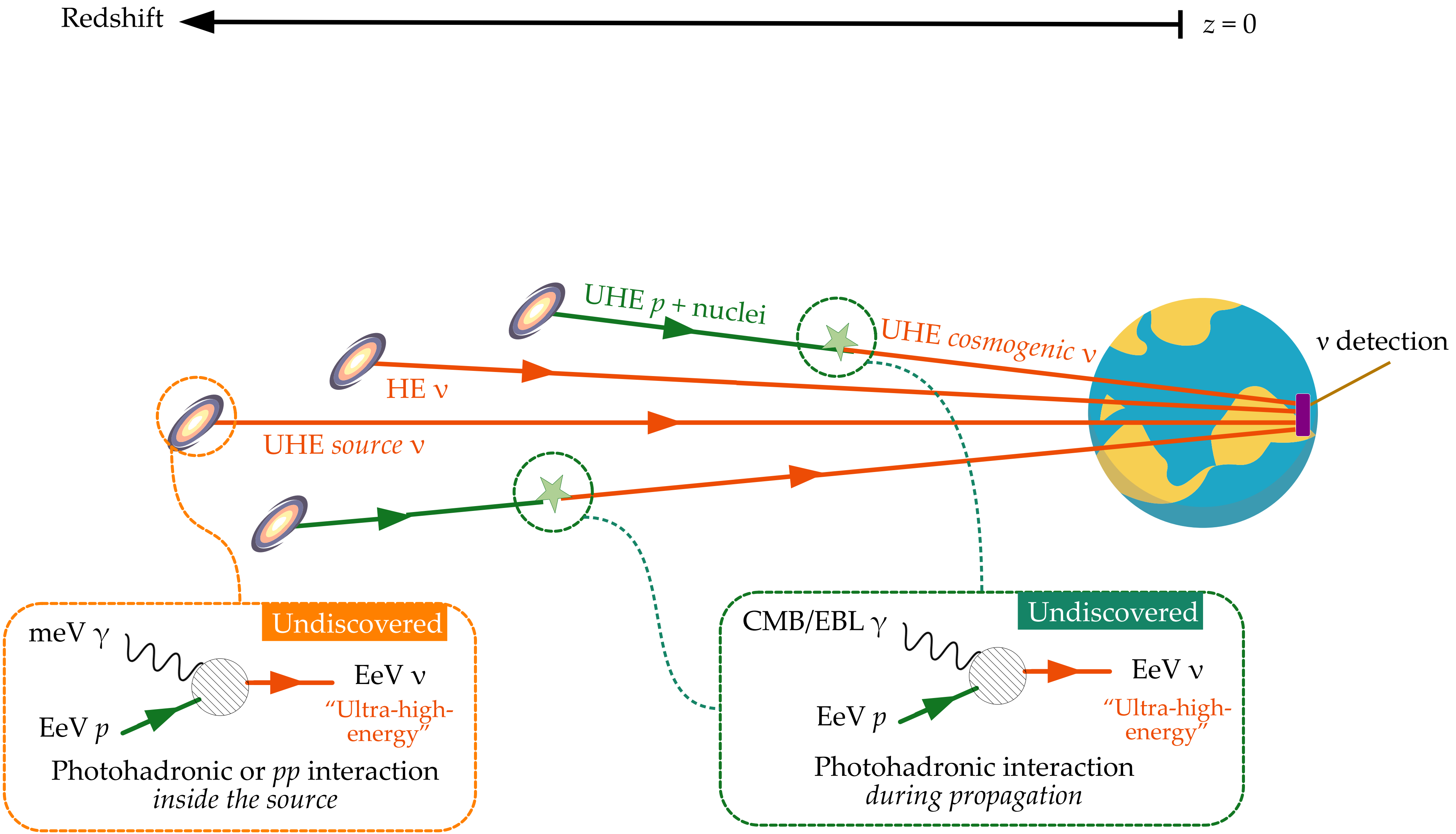


Redshift
z = 0
HE ν
UHE source ν
ν detection
Undiscovered
meV γ
EeV ν
"Ultra-high-energy"
EeV p
Photohadronic or pp interaction
inside the source



Redshift
$z = 0$
UHE p + nuclei
UHE *cosmogenic* ν
HE ν
ν detection
UHE *source* ν
Undiscovered
CMB/EBL γ
EeV ν
EeV p
"Ultra-high-energy"
Photohadronic interaction
during propagation



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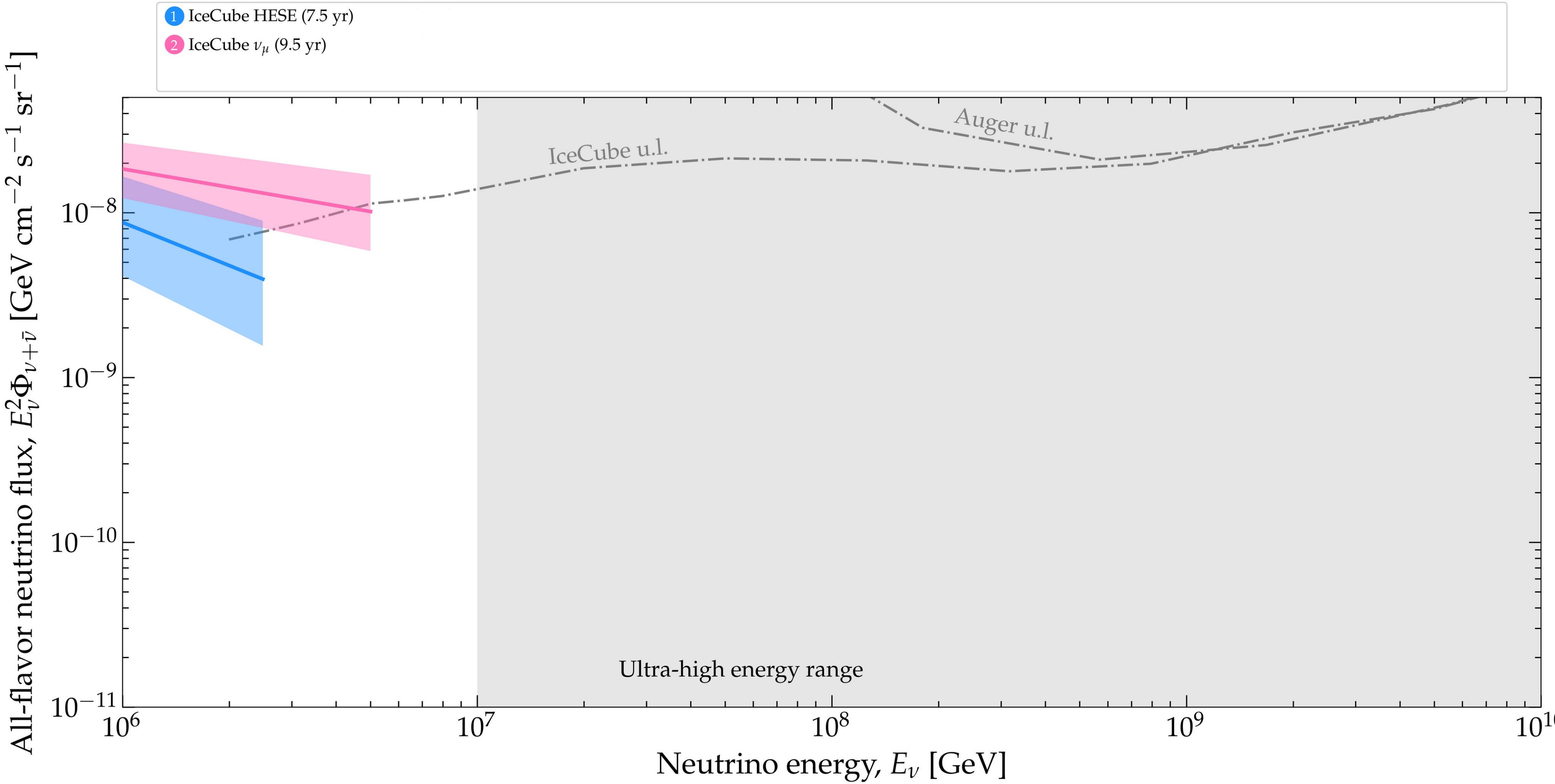

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IceCube u.l.
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Neutrino energy, E_ν [GeV]

Lorentz-invariance violation at UHE

Article

Observation of an ultra-high-energy cosmic neutrino with KM3NeT

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

One muon detected with 120^{+110}_{-60} PeV

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

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

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RECORD BREAKER

Fundamental physics with high-energy cosmic neutrinos

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

If BSM effects are comparable in size to SM effects, then we can probe

$$\kappa_n \sim 10^{-47} \left(\frac{E}{\mathrm{PeV}}\right)^{-n} \left(\frac{L}{\mathrm{Gpc}}\right)^{-1} \mathrm{PeV}^{1-n}$$

With 1-PeV ν: $\kappa_2 \sim 10^{-47}$ PeV^{-1}

With 100-PeV ν: $\kappa_2 \sim 10^{-51}$ PeV^{-1}

Orders-of-magnitude improvement

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

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Orders-of-magnitude improvement

Lorentz-invariance violation — from superluminal speeds

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

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

Cohen & Glashow, *PRL* 2011

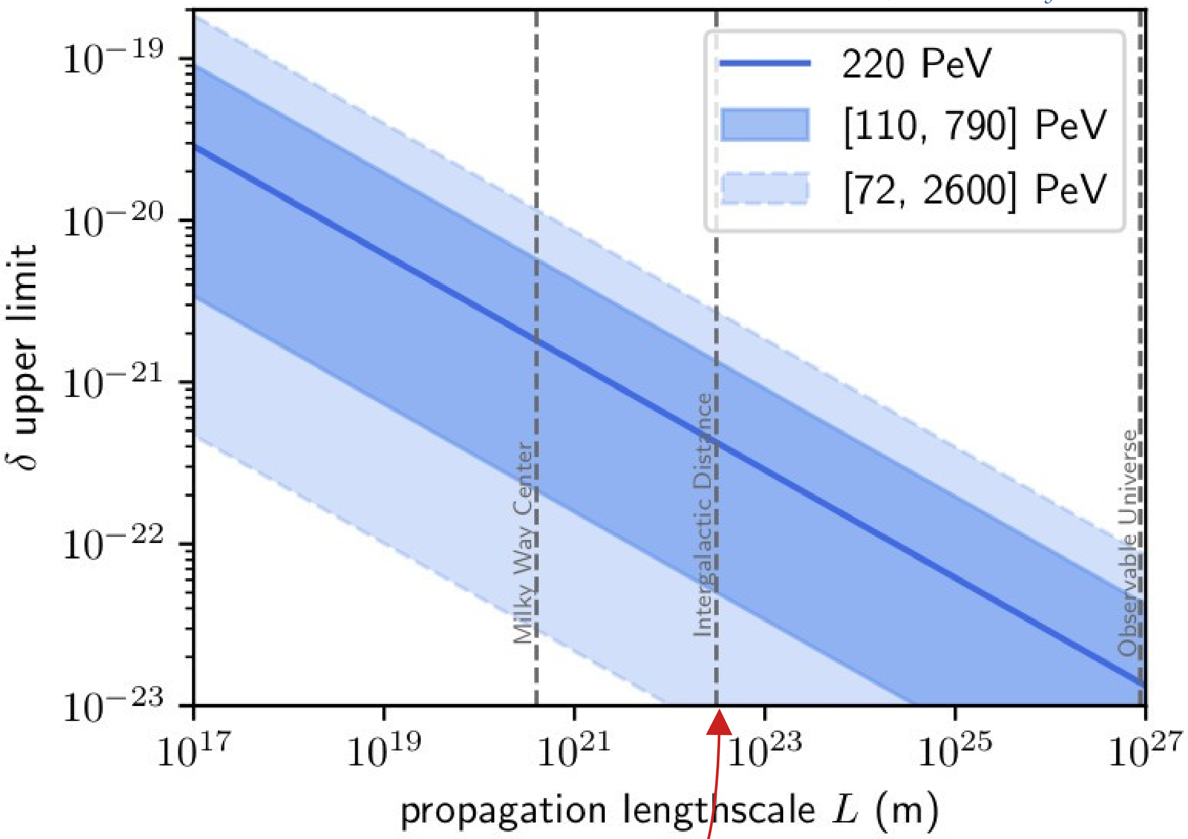
Excess over light speed: $\delta = c_\nu - 1$

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

Decay width (Γ)

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

KM3NeT Collab., *Commun. Phys.* 2025



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

Lorentz-invariance violation — from a GRB association

GRB emitted neutrinos & photons simultaneously

Time delay induced by dispersion of neutrinos on spacetime foam:

Neutrino energy

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

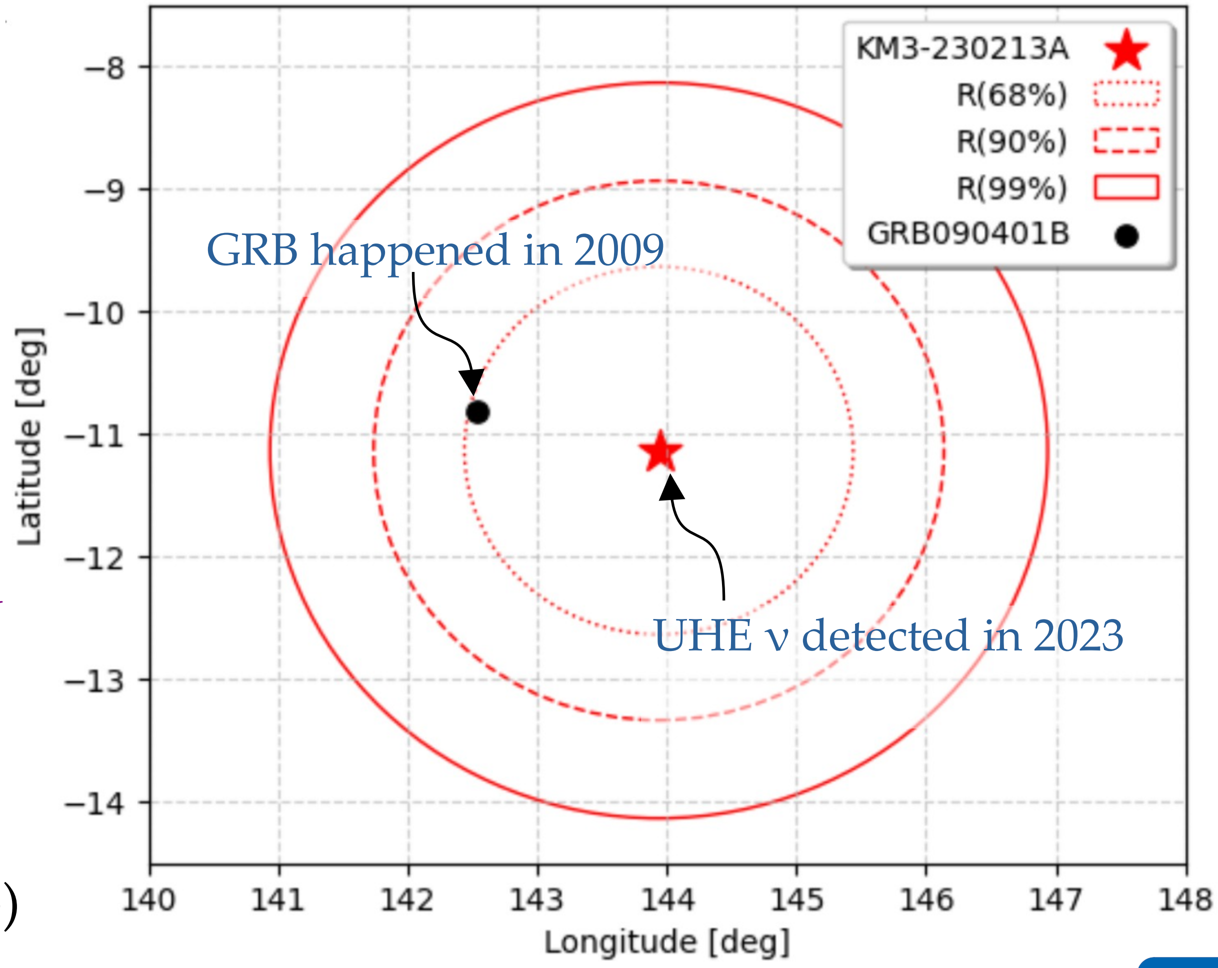
Cosmological expansion

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

GRB-ν association: 2.4σ

(*p*-value of 0.015)

Amelino-Camelia *et al.*, *PLB* 2025

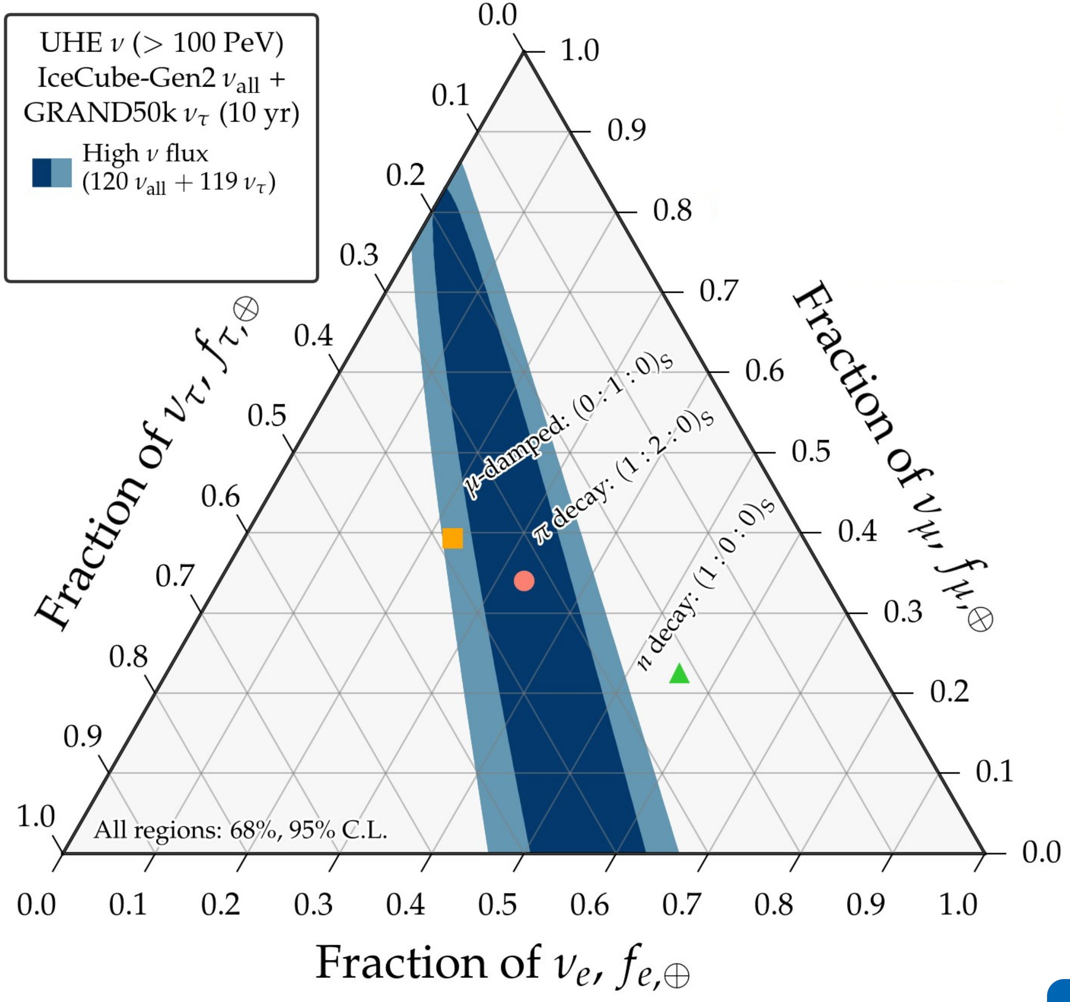


Flavor at ultra-high energies (> 100 PeV)

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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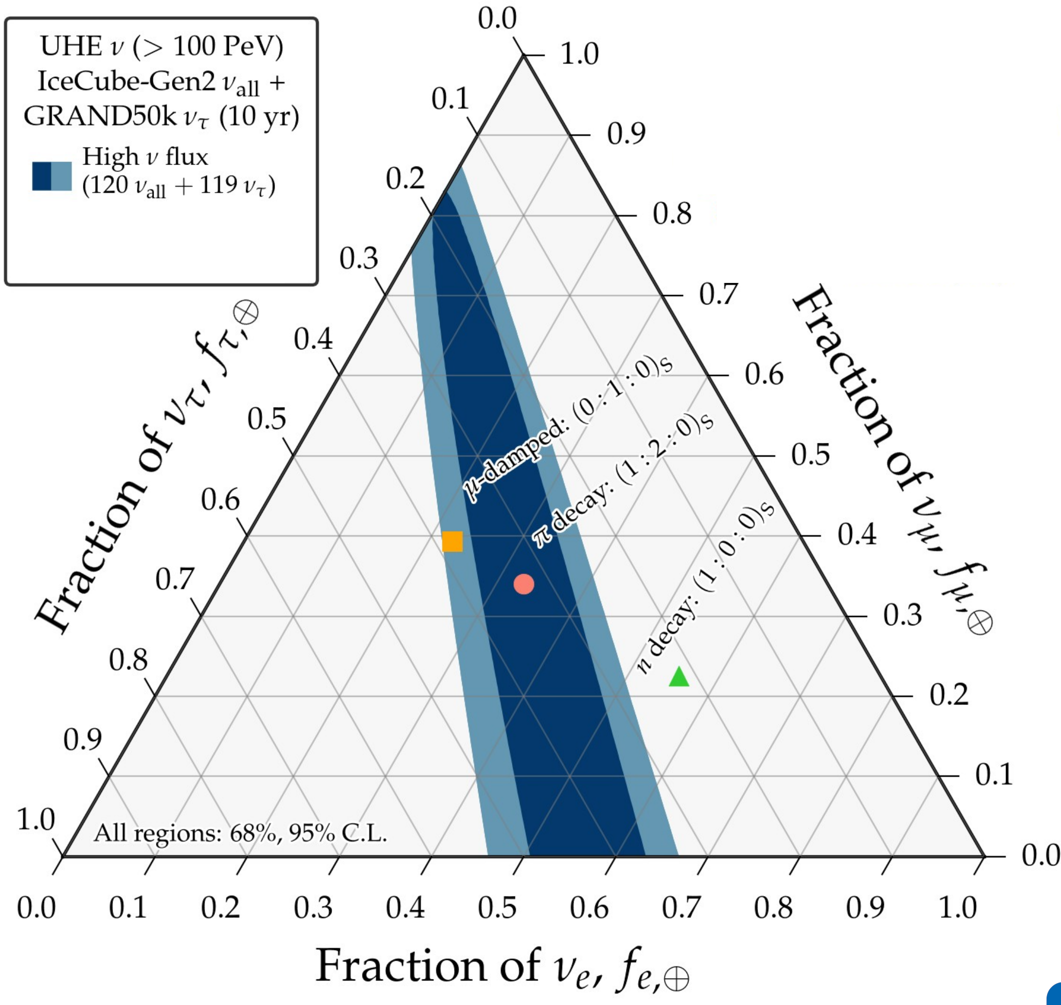

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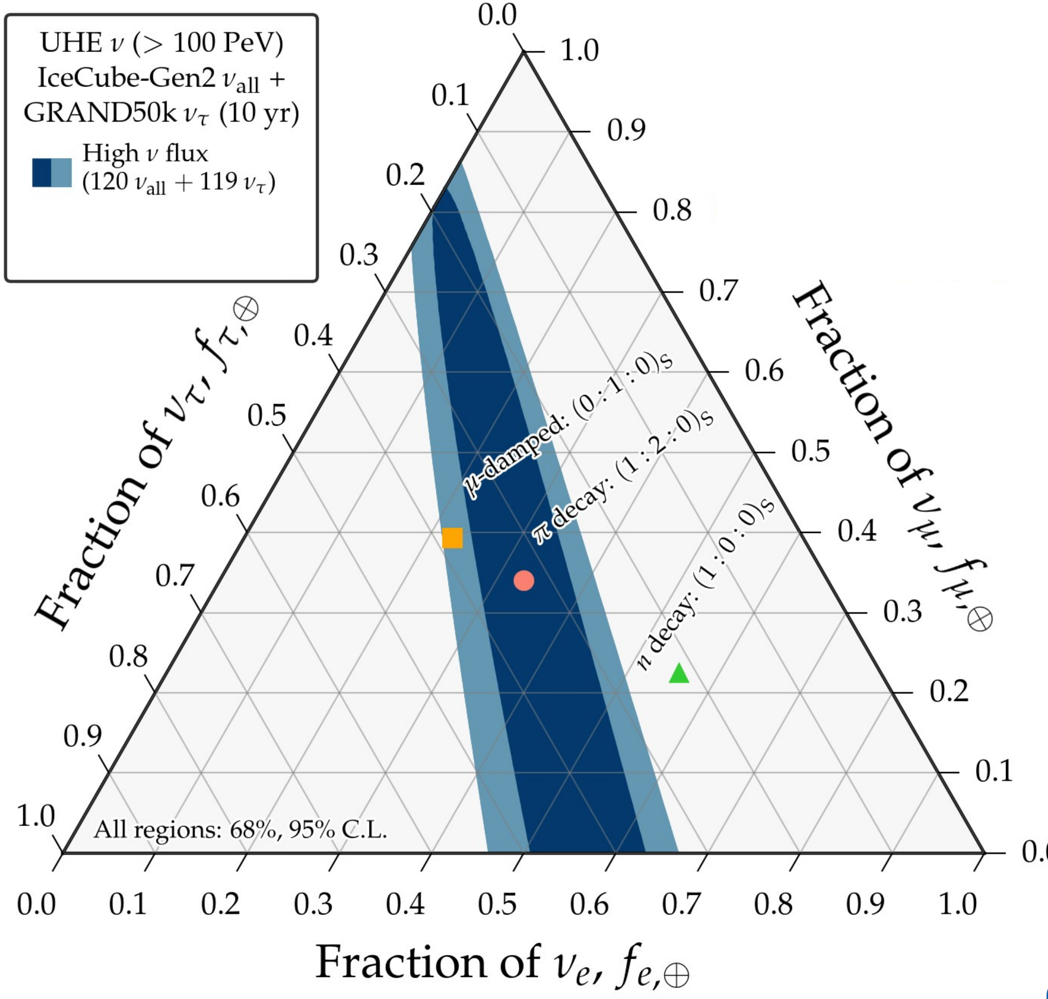
predominant detection of ν_τ by GRAND



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

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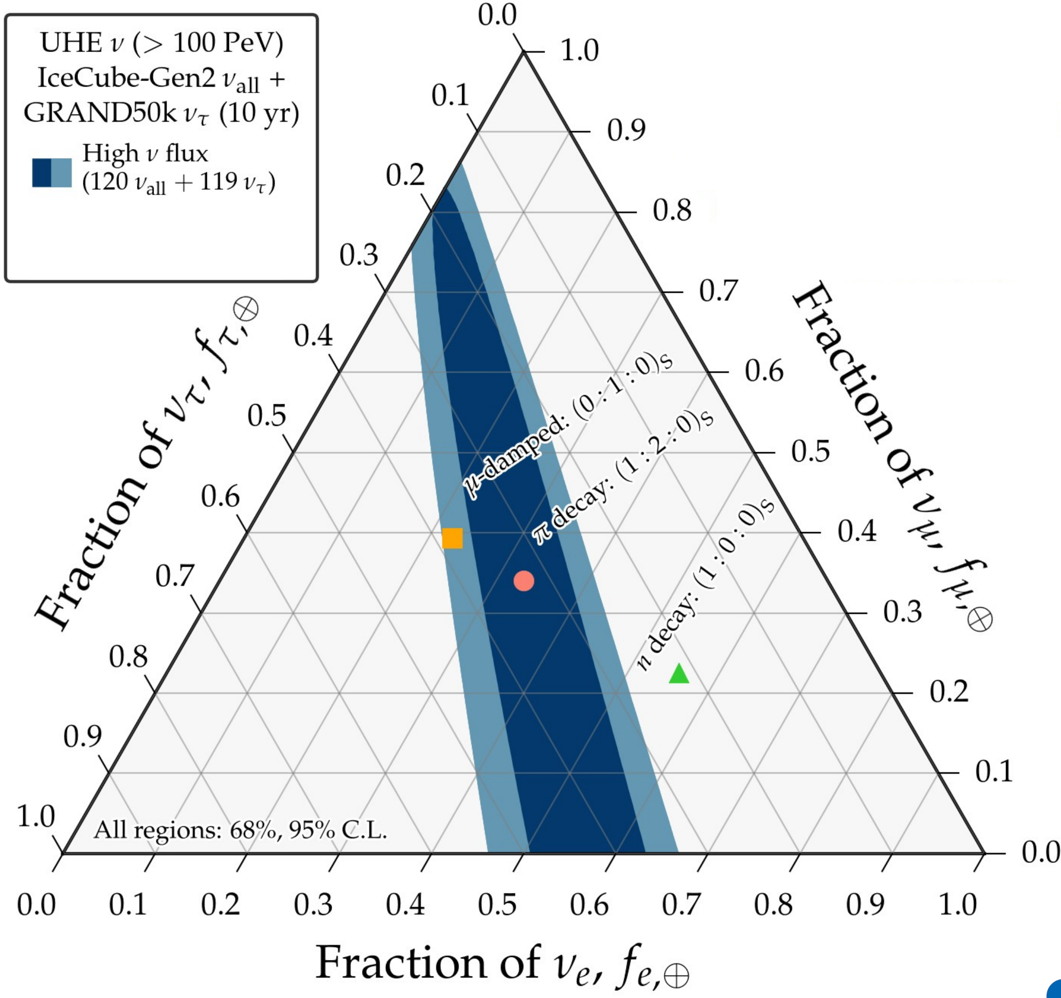

Testagrossa, Fiorillo, **MB**, *PRD* 2024

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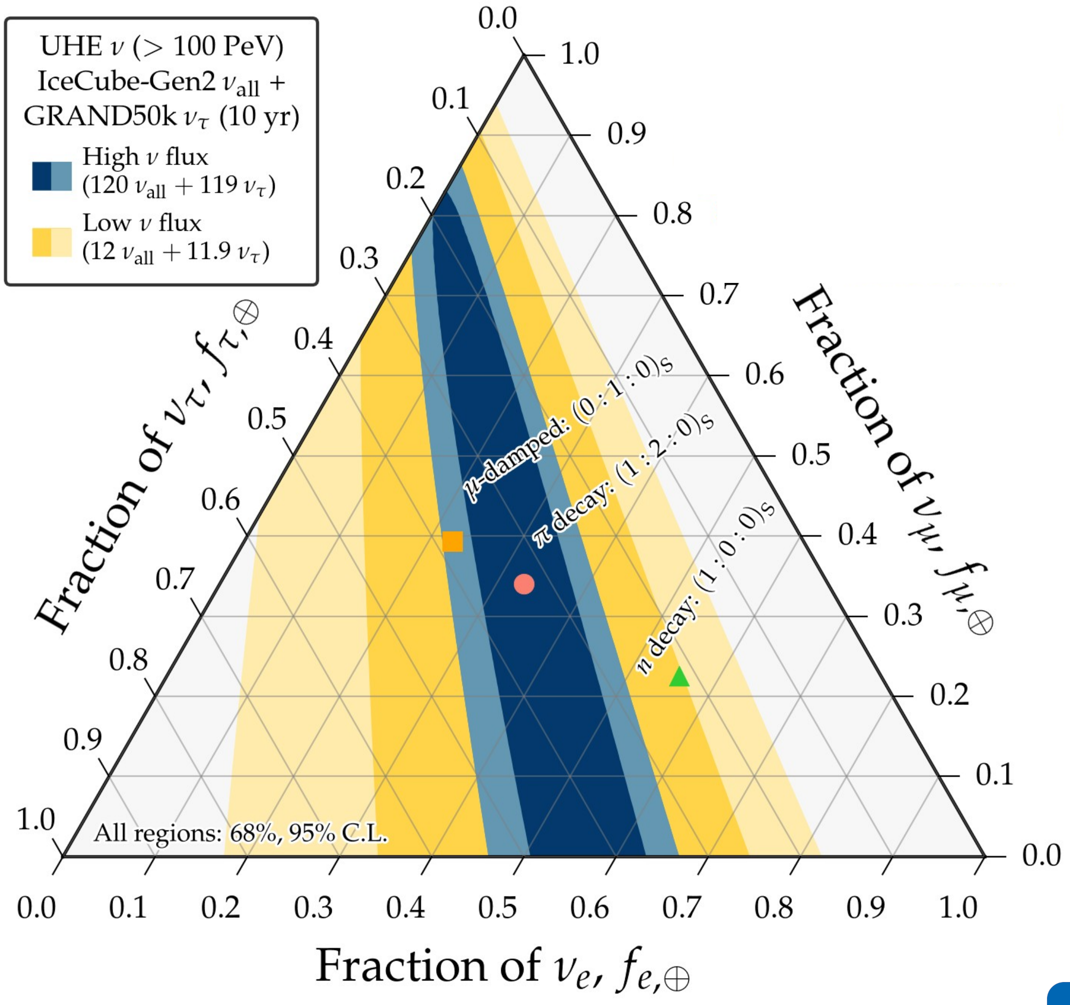

Testagrossa, Fiorillo, **MB**, *PRD* 2024

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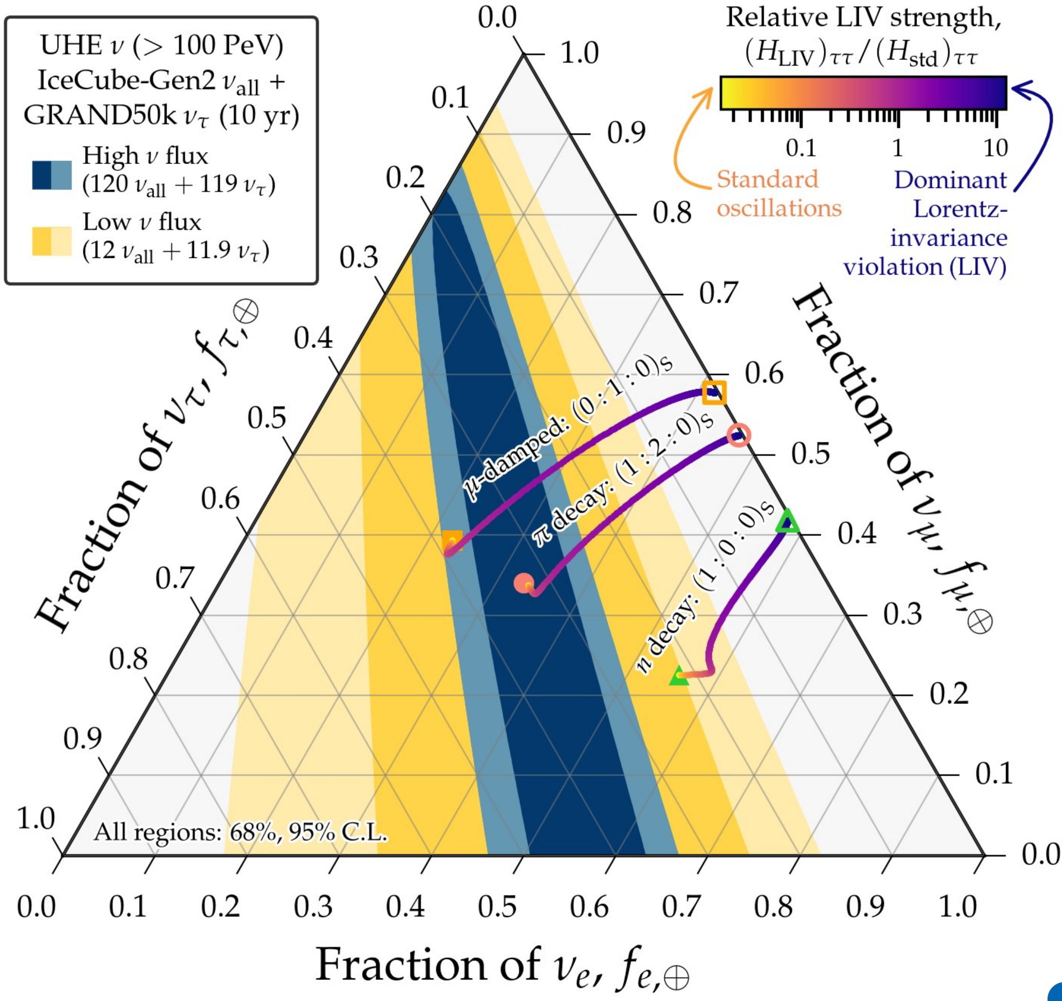
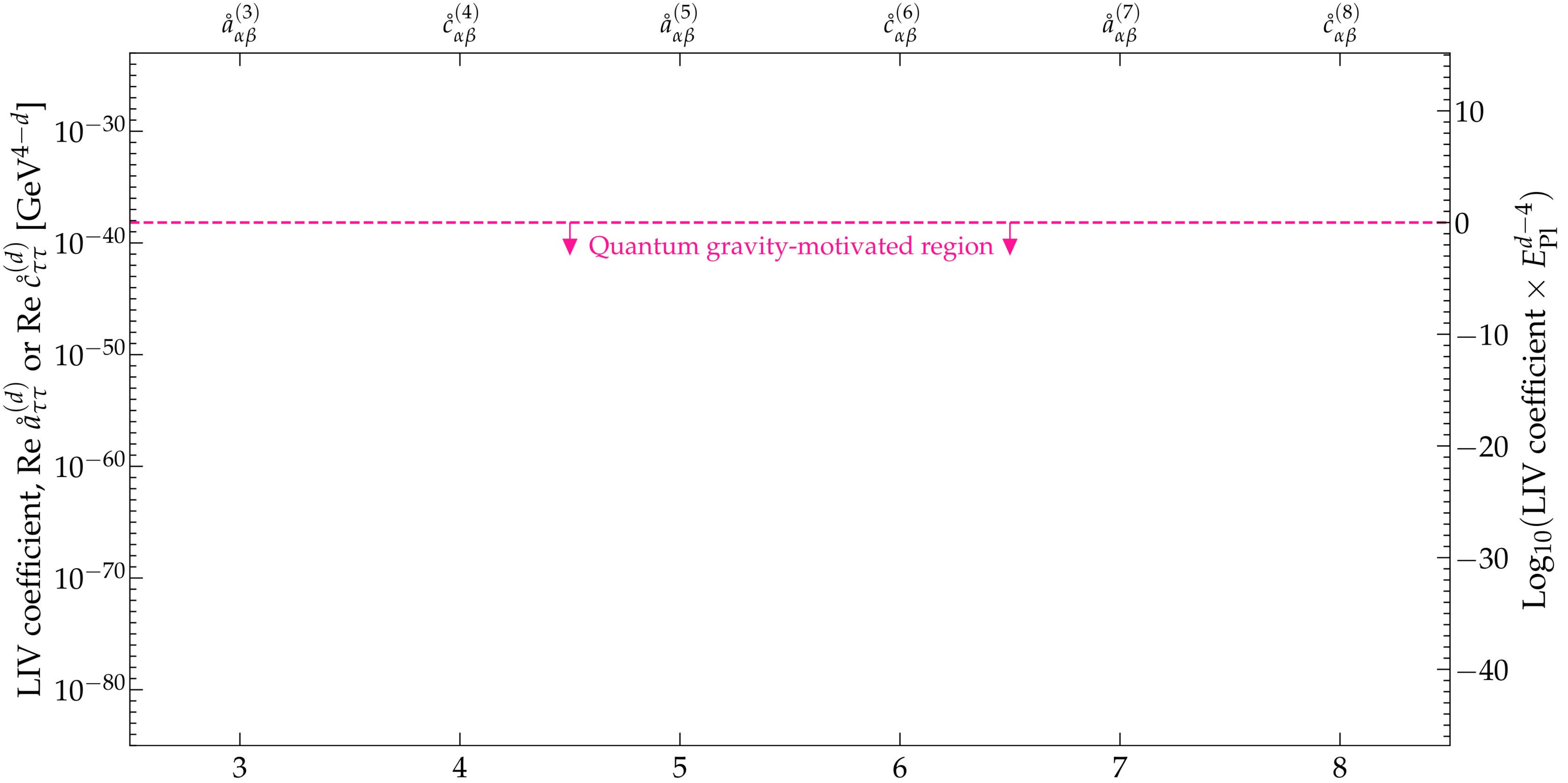


Testagrossa, Fiorillo, **MB**, *PRD* 2024

Lorentz-invariance violation at ultra-high energies



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

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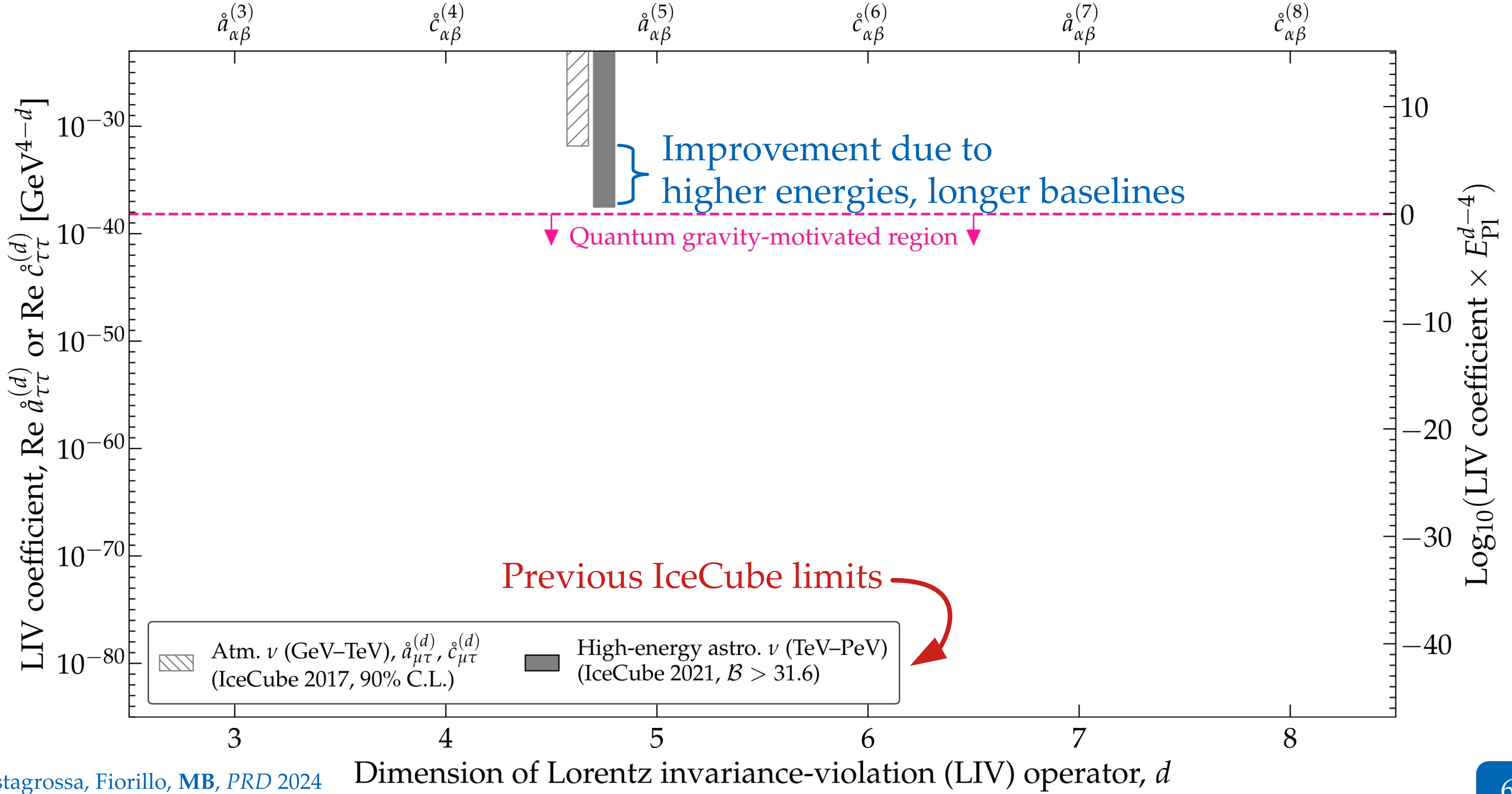

Testagrossa, Fiorillo, **MB**, *PRD* 2024

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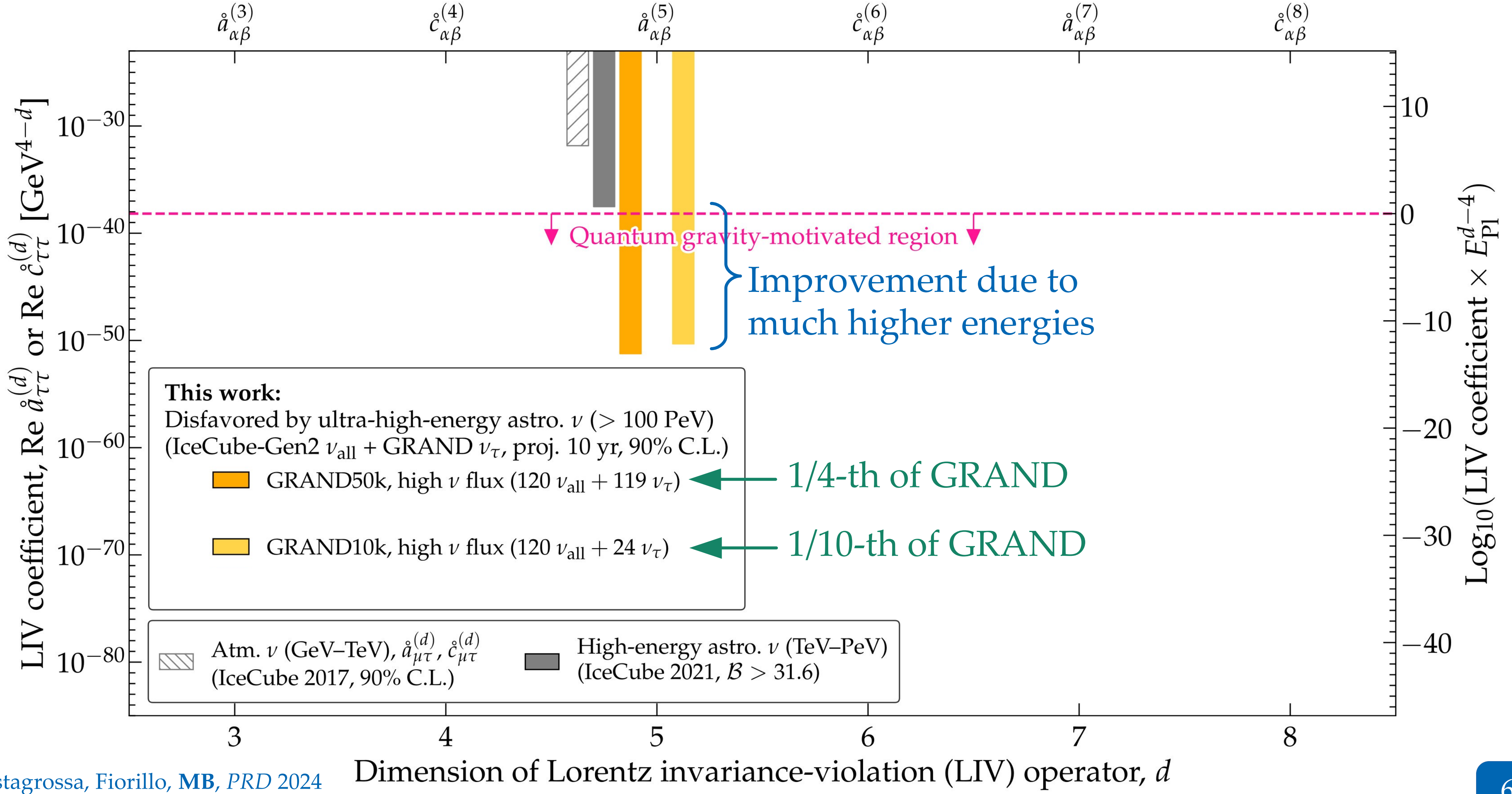

Testagrossa, Fiorillo, **MB**, *PRD* 2024

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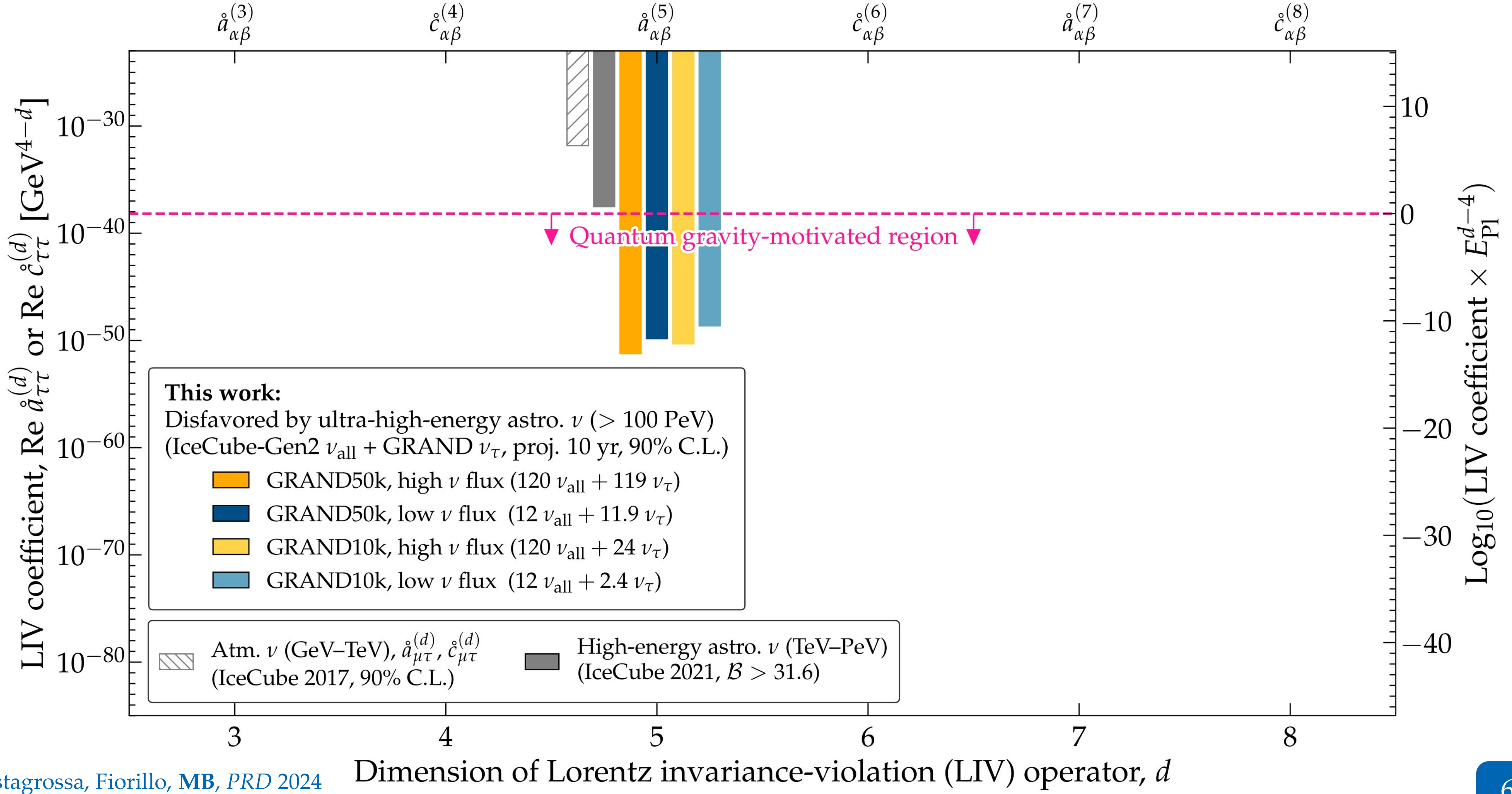

Testagrossa, Fiorillo, **MB**, *PRD* 2024

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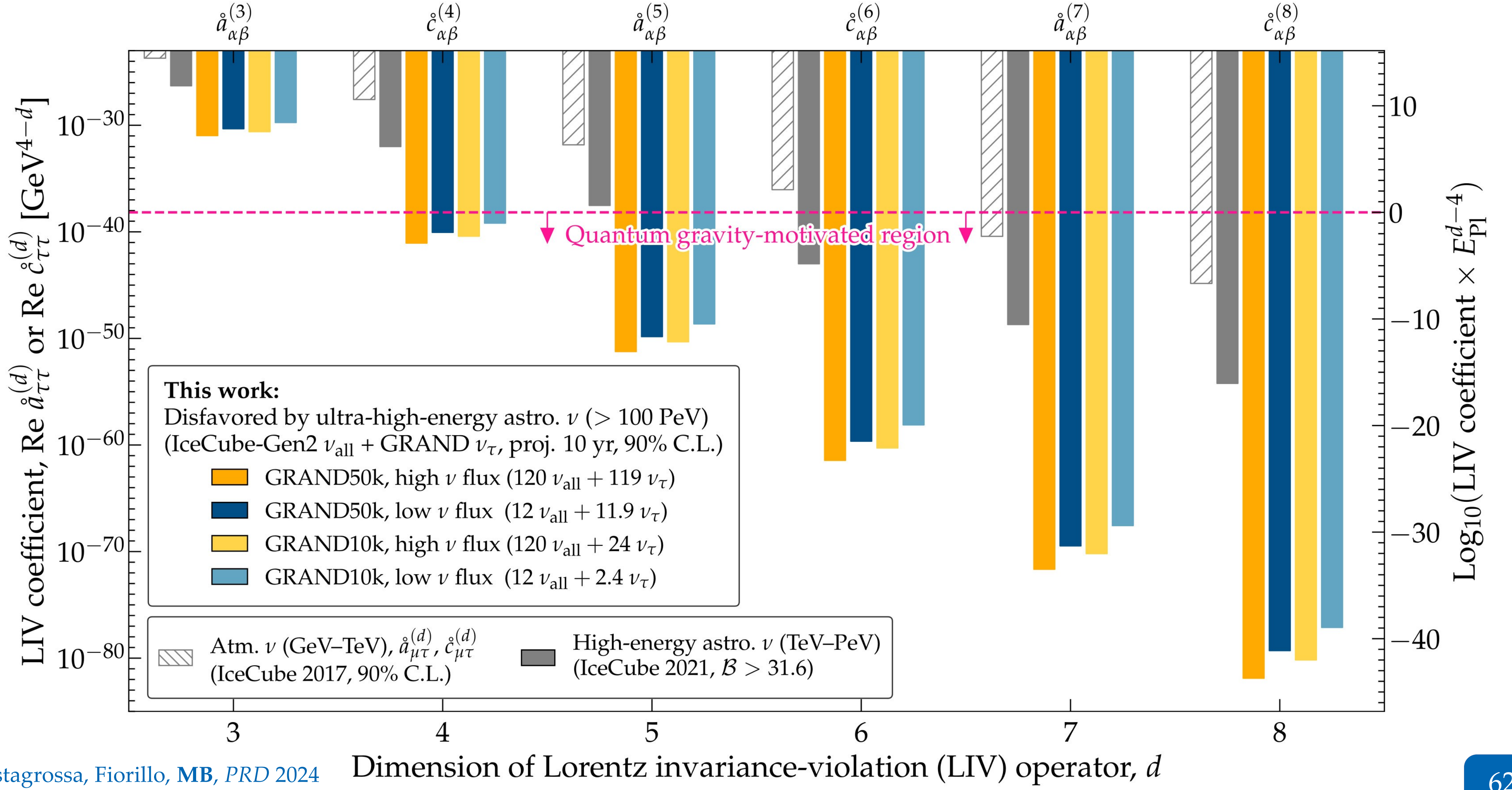
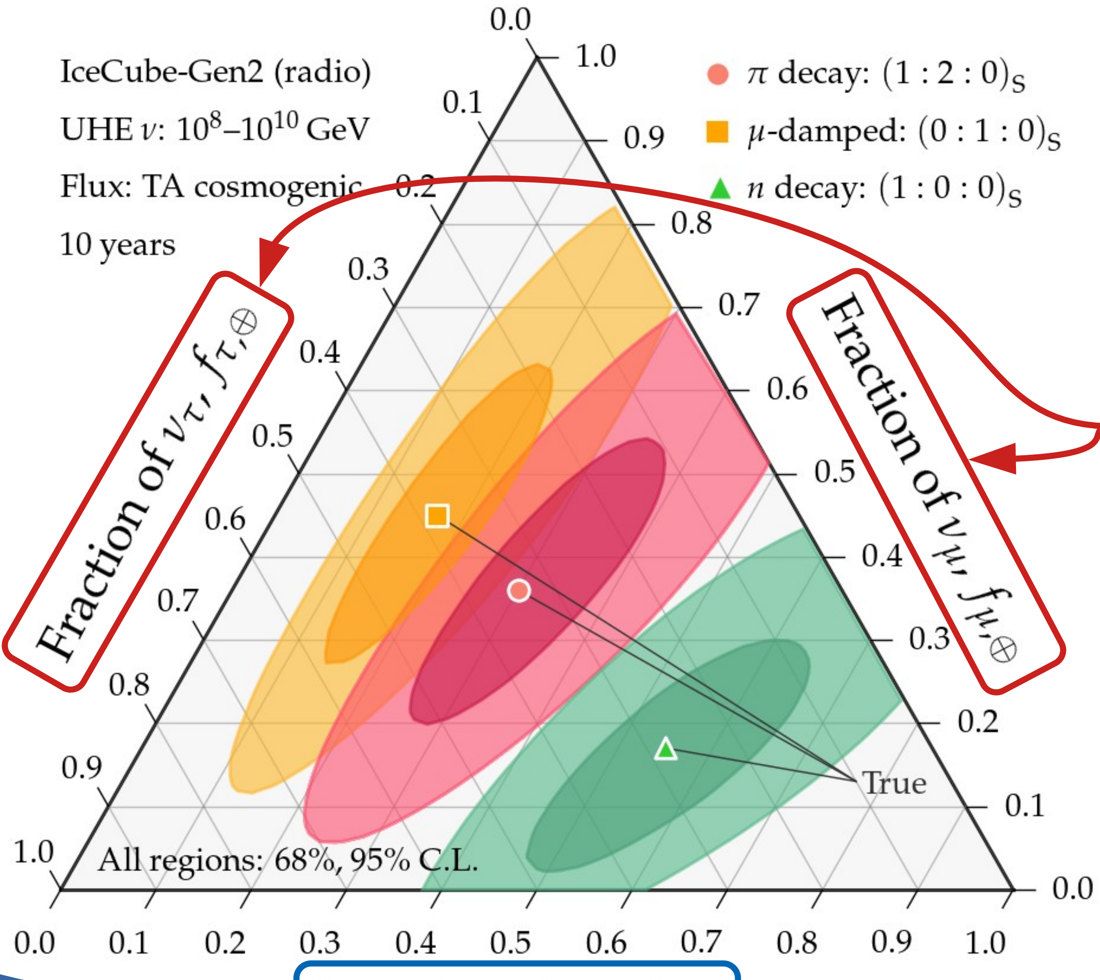


Testagrossa, Fiorillo, **MB**, *PRD* 2024

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*

Perspectives

1. Look for large effects first
   There is no sensitivity to small effects *yet*

2. Weigh any new-physics claims by astrophysics + particle uncertainties
   I.e., marginalize or profile over all relevant known unknowns

3. Always perform hypothesis testing
   E.g., compute Bayes factors,

4. Be mindful of experimental limitations when making claims
   Account for the detector response, energy resolution, *etc.*

5. Do not use overly simplified theory models
   Otherwise, we might end up claiming unrealistically good sensitivity

Questions

What signals are *unique* to quantum-gravity effects?

Might need to look at multiple observables to pinpoint the origin

Extract new physics with individual ν sources?

E.g., neutrino lifetime limits from NGC 1068 [Valera, Fiorillo, Esteban, MB, *PRD* 2024]
LIV bounds from TXS 0506+056 [MB, Ellis, Konoplich, Sakharov, *PRD* 2025]

Can we be systematic in our searches?

E.g., in an EFT theory, write down all possible couplings, work out predictions for the energy spectrum, directions, flavor timing, and compare to data

Thanks!

Backup slides

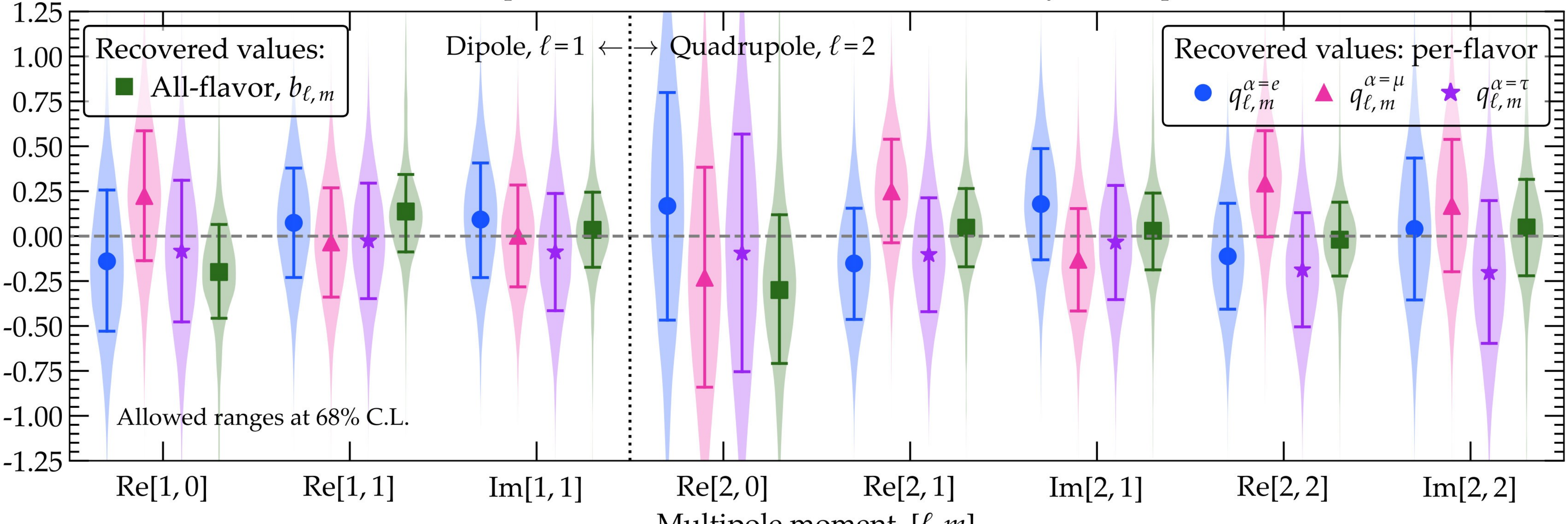
Flavor dipoles and quadrupoles in the sky?

Isotropic flux

Flavor-dependent multipole expansion

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

Multipole moments from the IceCube HESE 7.5-year sample



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

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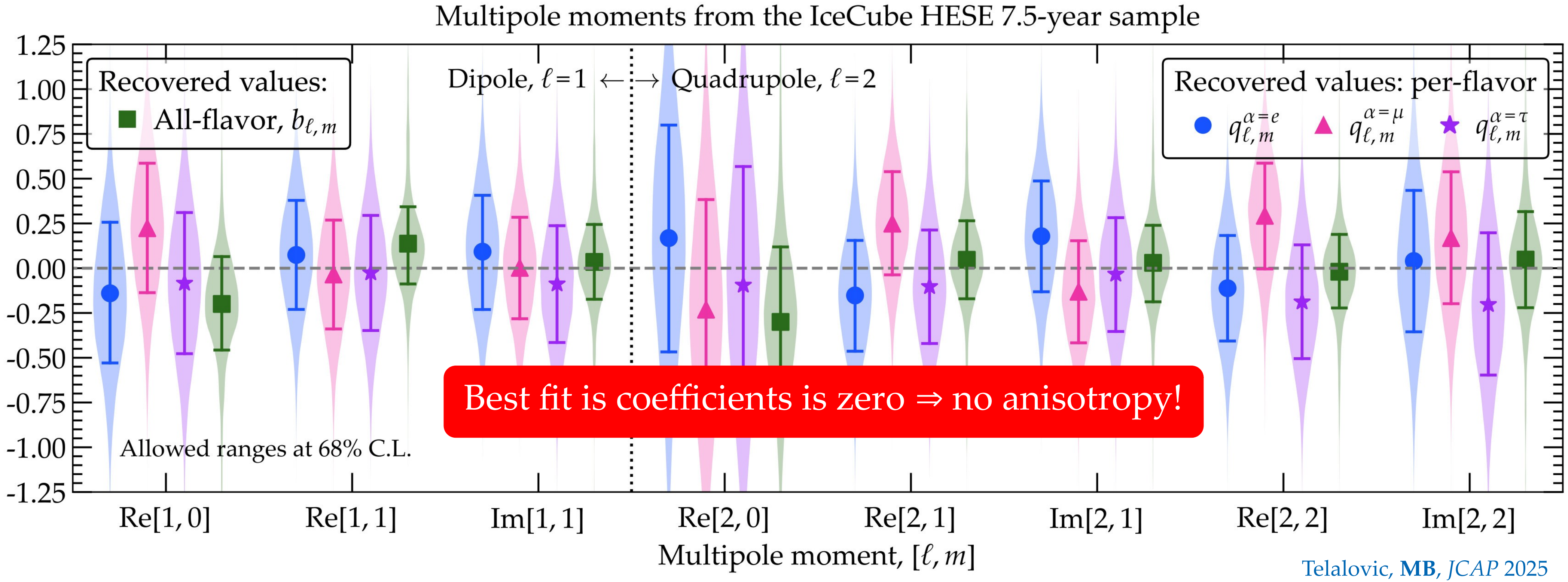

Telalovic, **MB**, *JCAP* 2025