Systematics in Lorentz-invariance violation searches in high-energy astrophysical neutrinos

Mauricio Bustamante

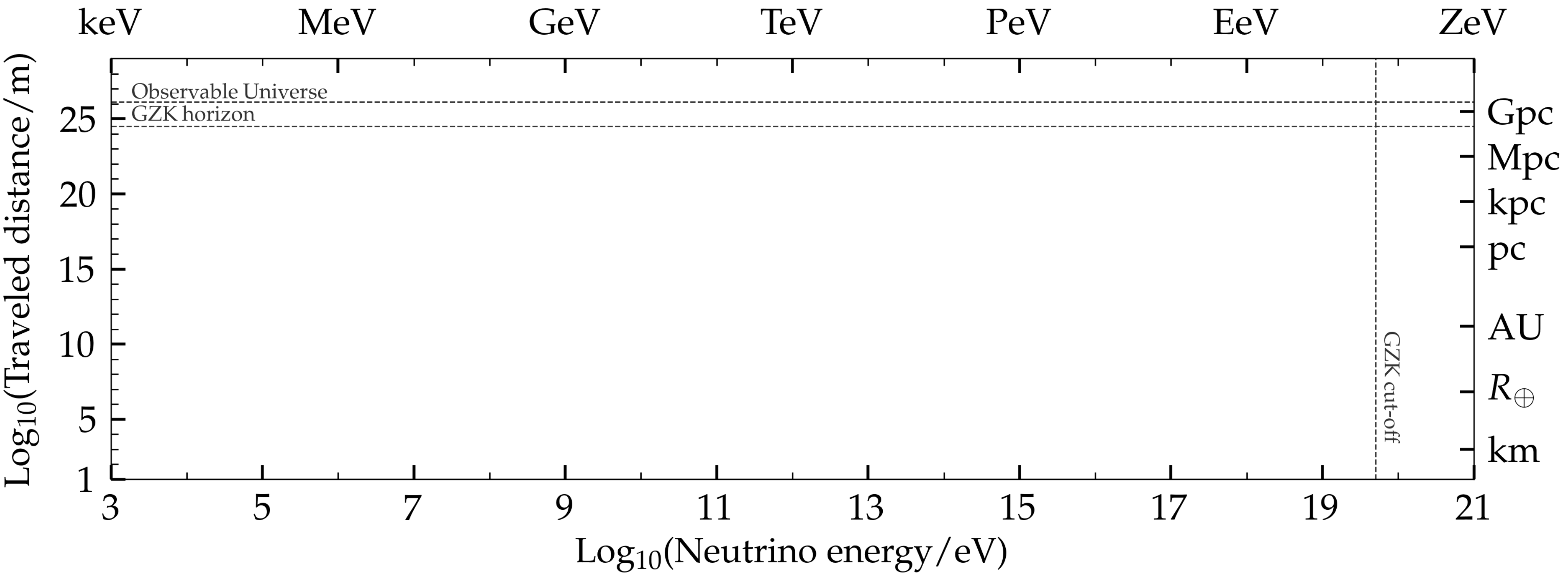
Niels Bohr Institute, University of Copenhagen

BridgeQG WG2 Meeting

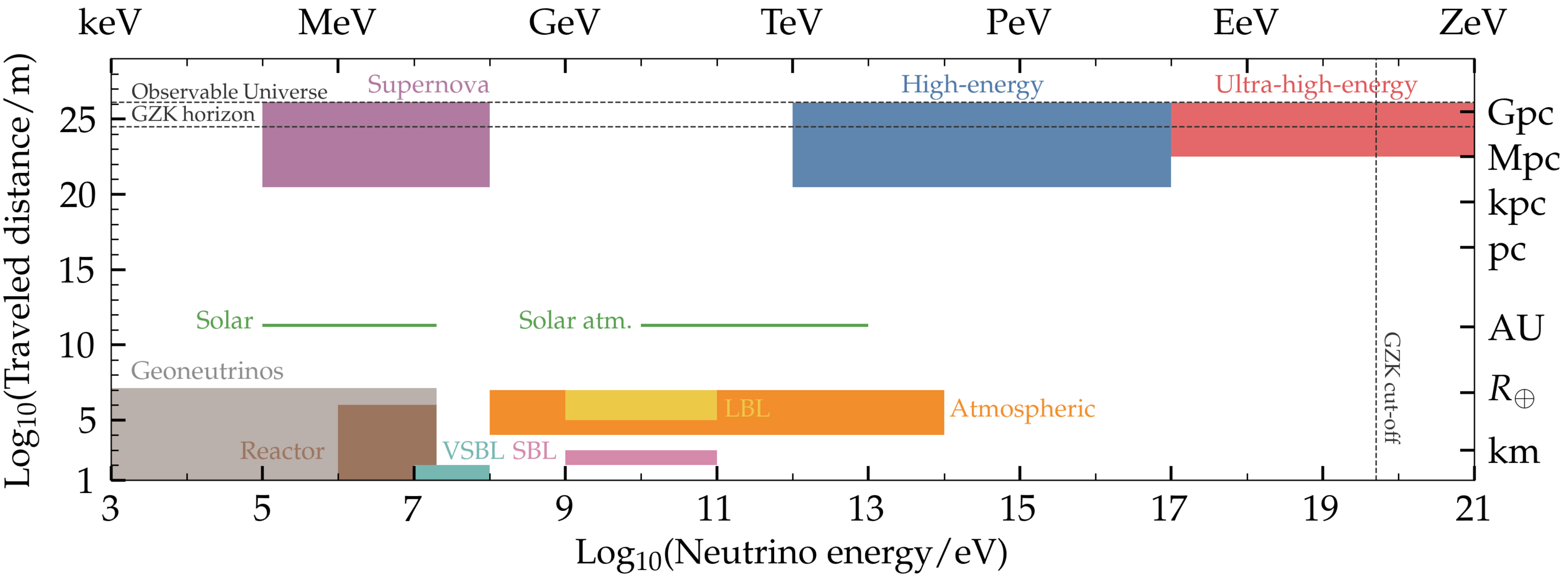
March 26, 2026

UNIVERSITY OF COPENHAGEN

VILLUM FONDEN



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



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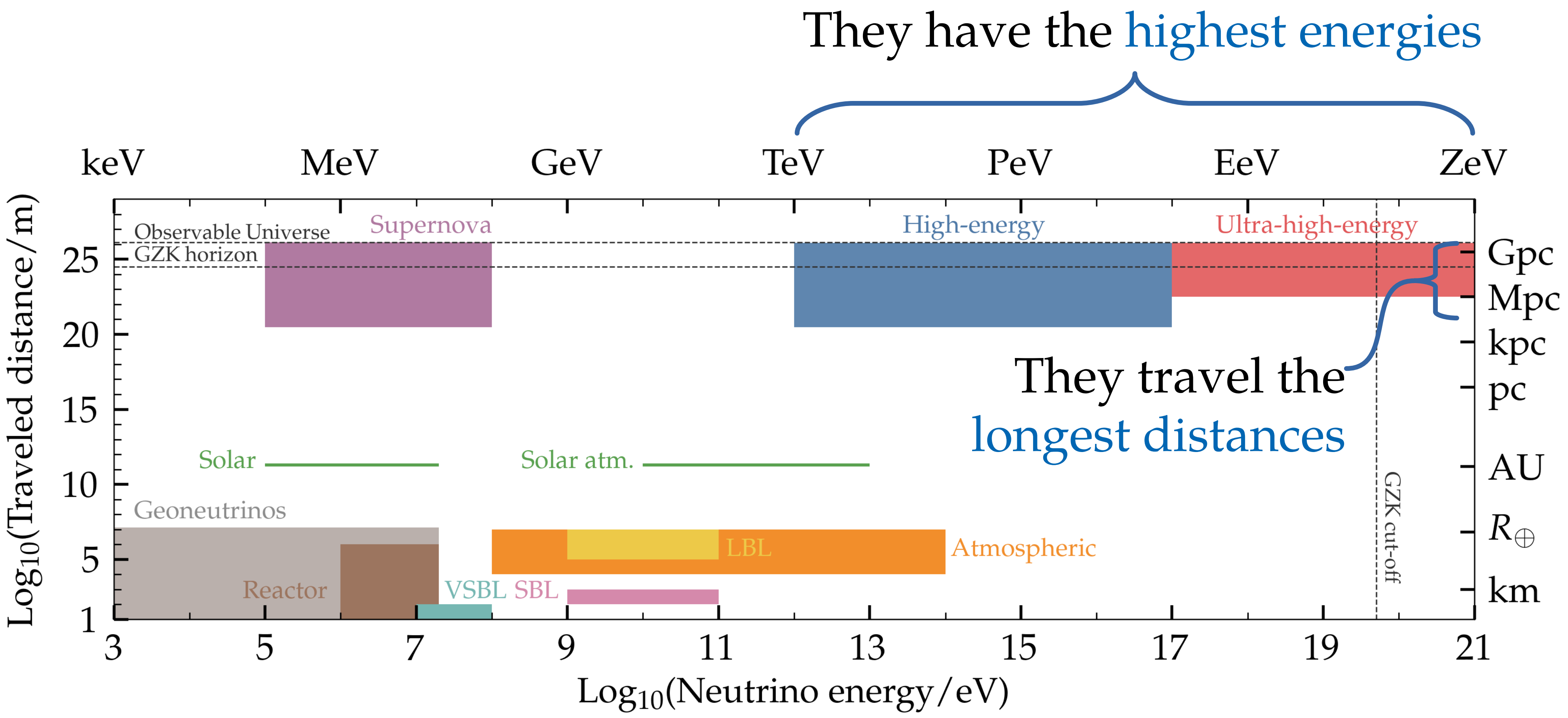

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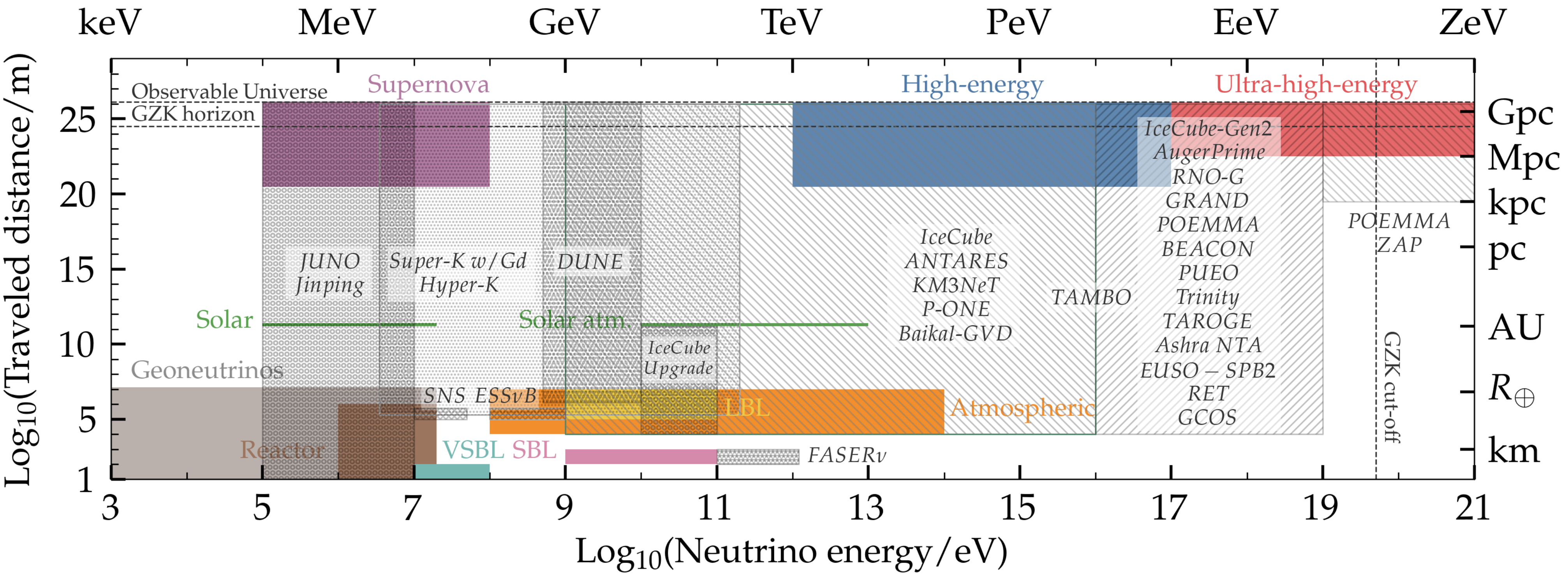

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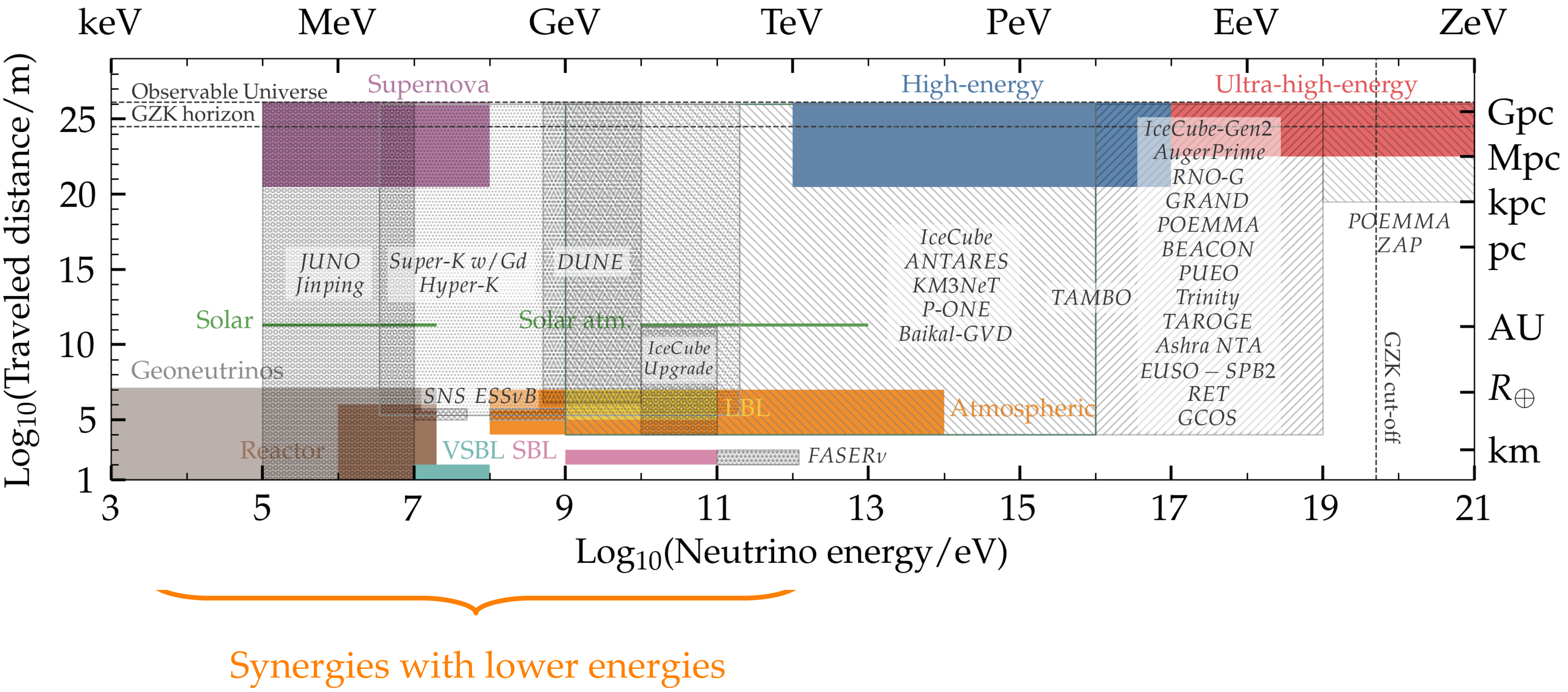

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Discovered in 2013
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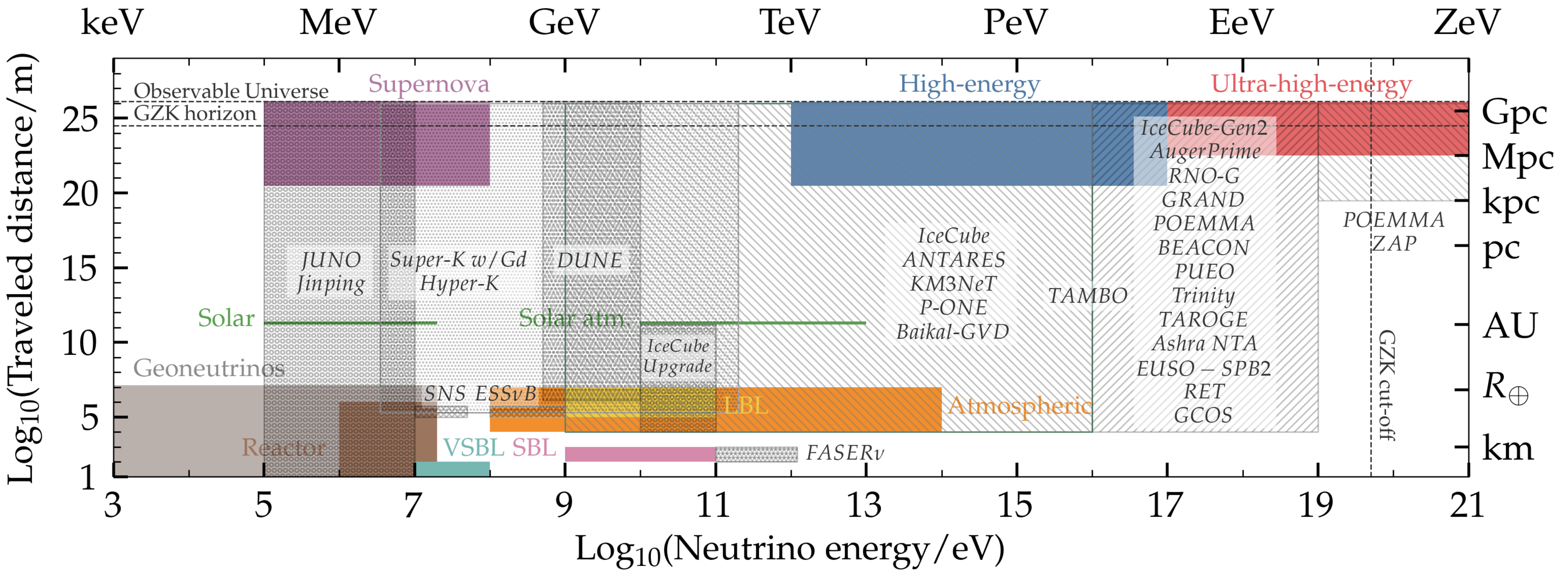

Synergies with lower energies

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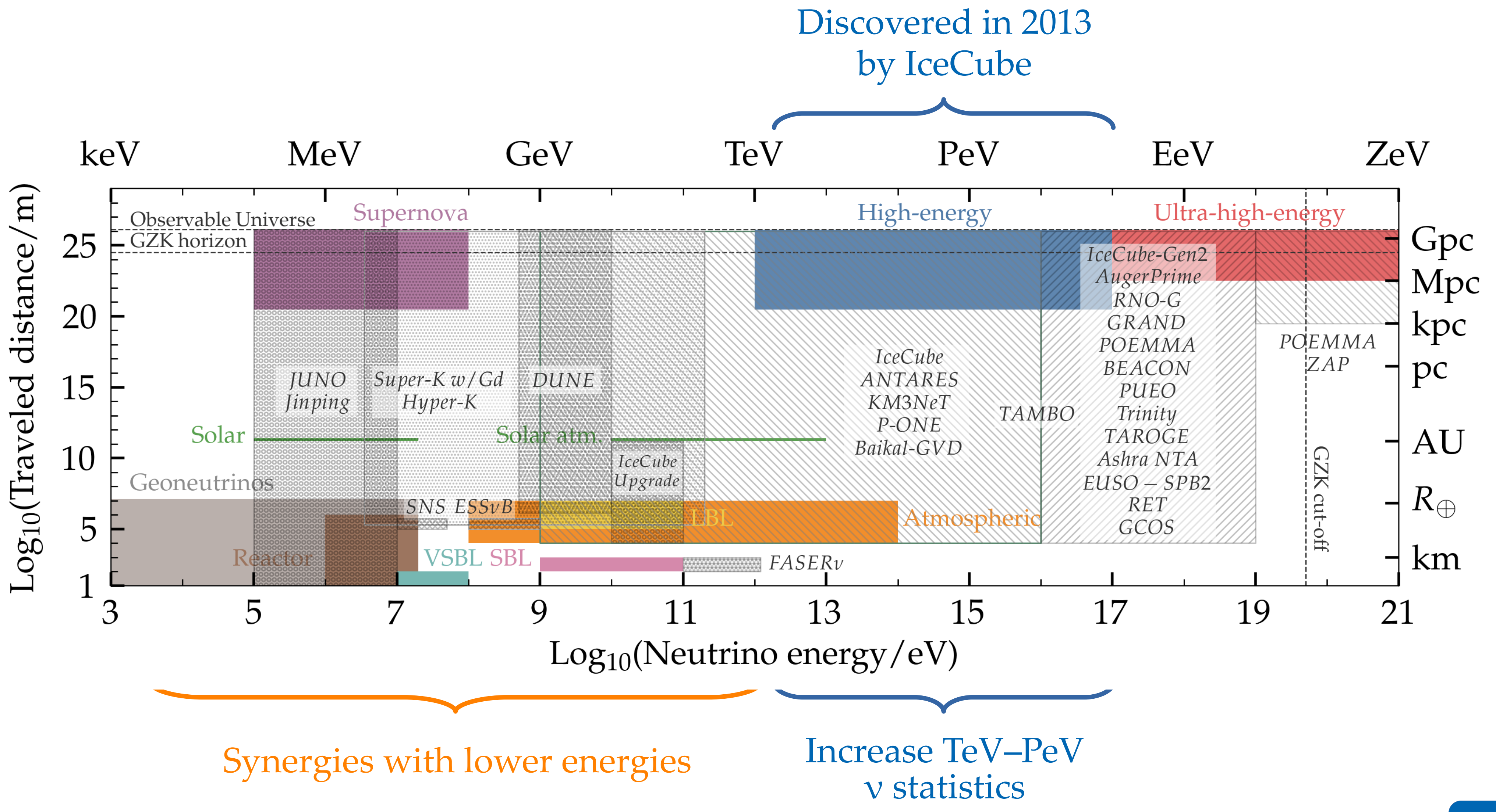
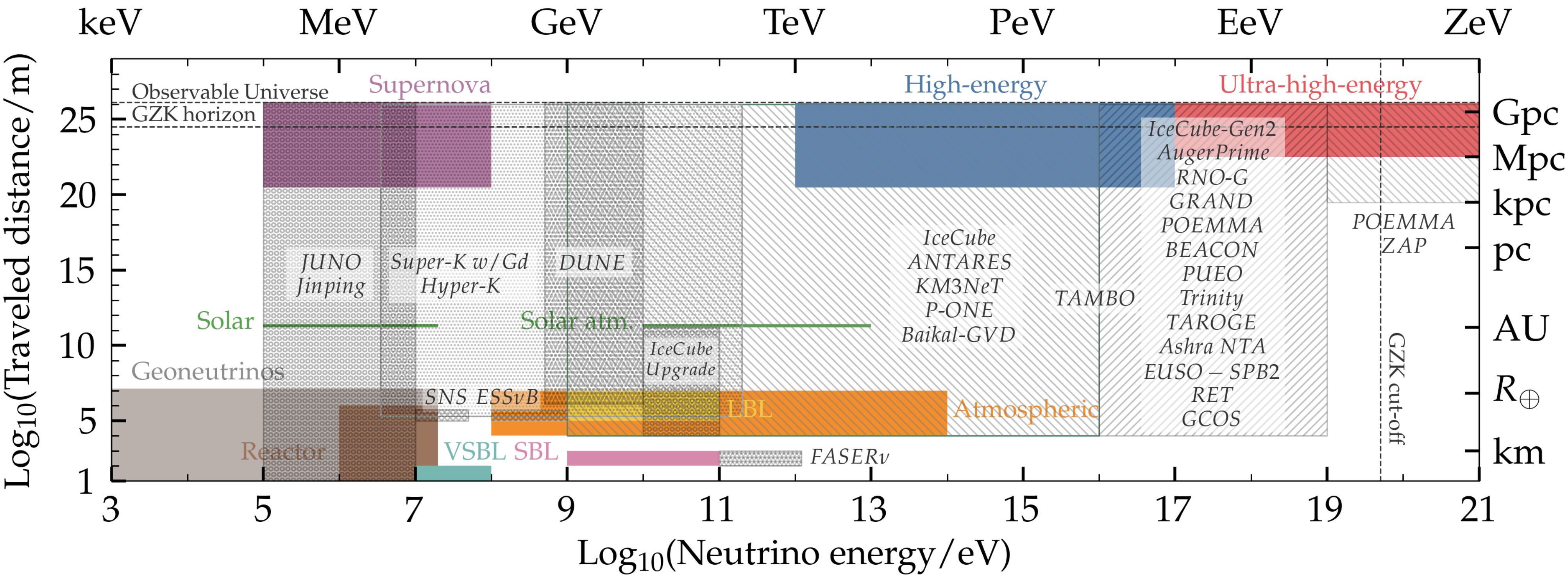


Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333), adapted

Discovered in 2013 by IceCube

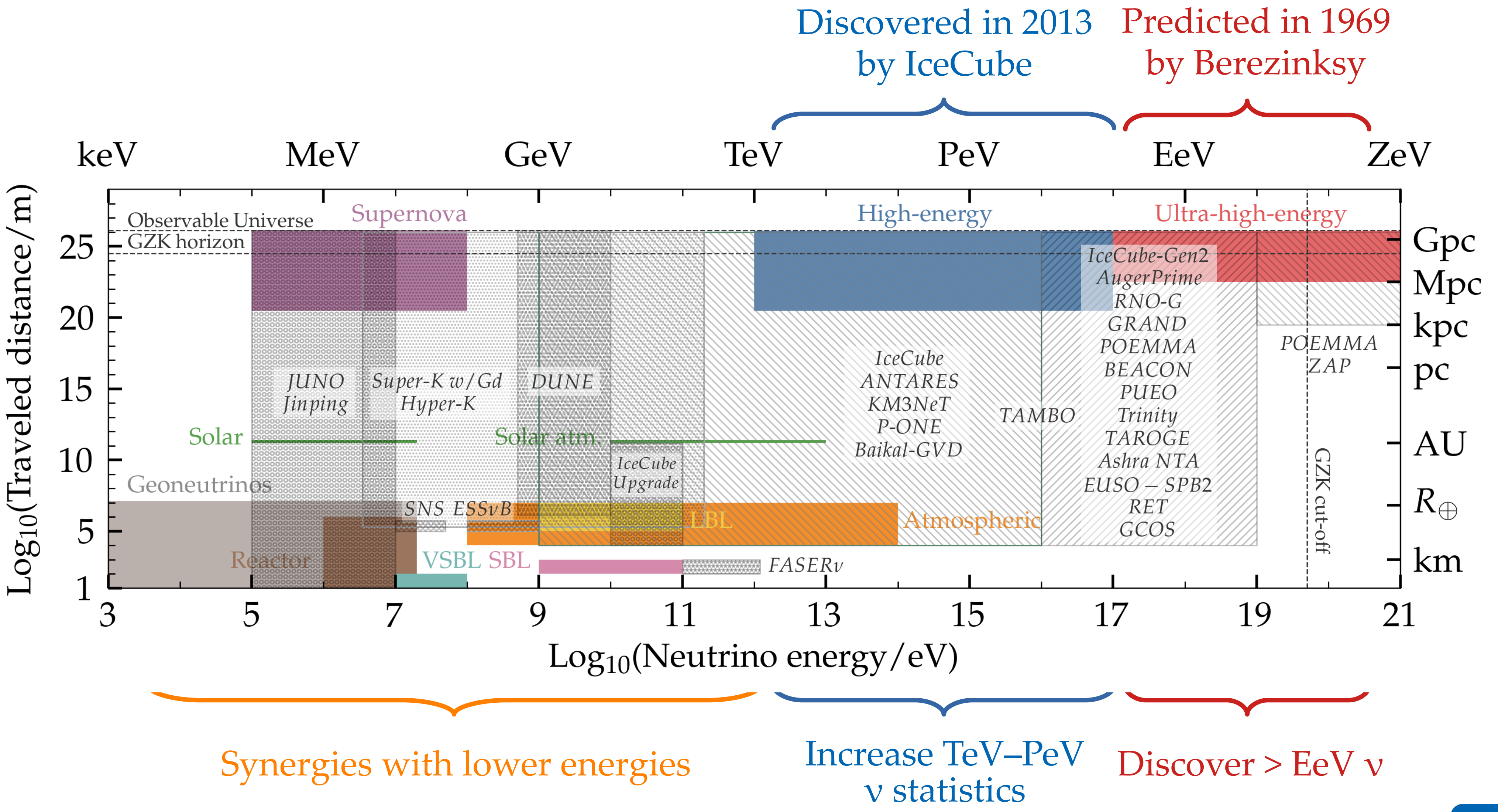
Predicted in 1969 by Berezinksy



Synergies with lower energies

Increase TeV–PeV ν statistics

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



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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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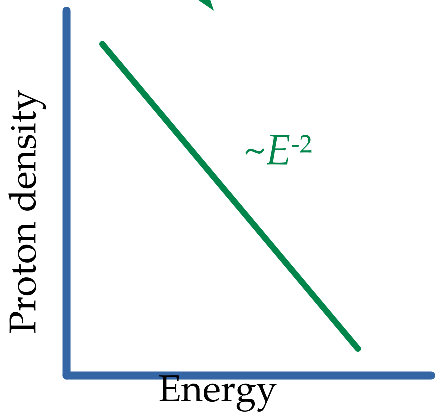

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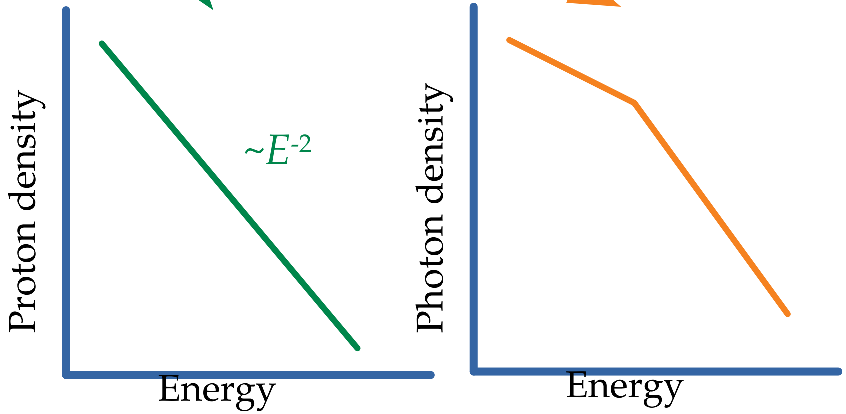

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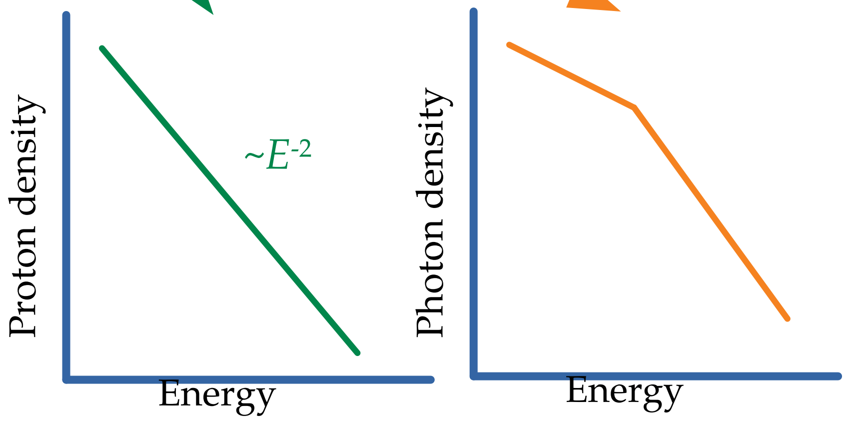
$$\pi^+ \longrightarrow \mu^+ + \nu_\mu \longrightarrow \bar{\nu}_\mu + e^+ + \nu_e + \nu_\mu$$

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



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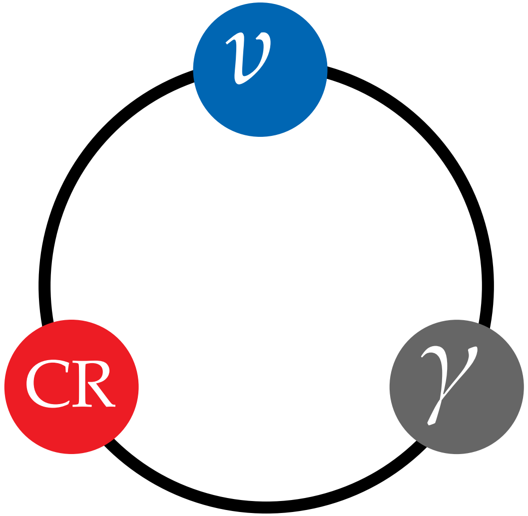

Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 10

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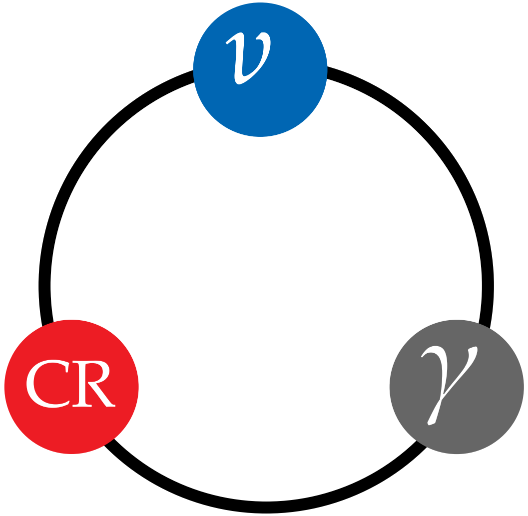

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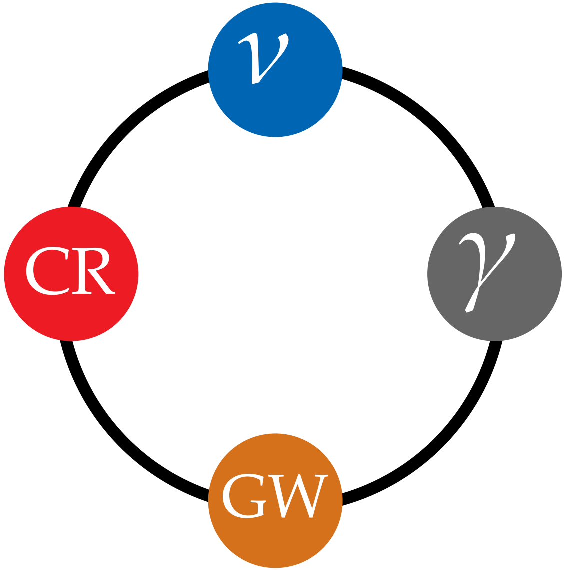

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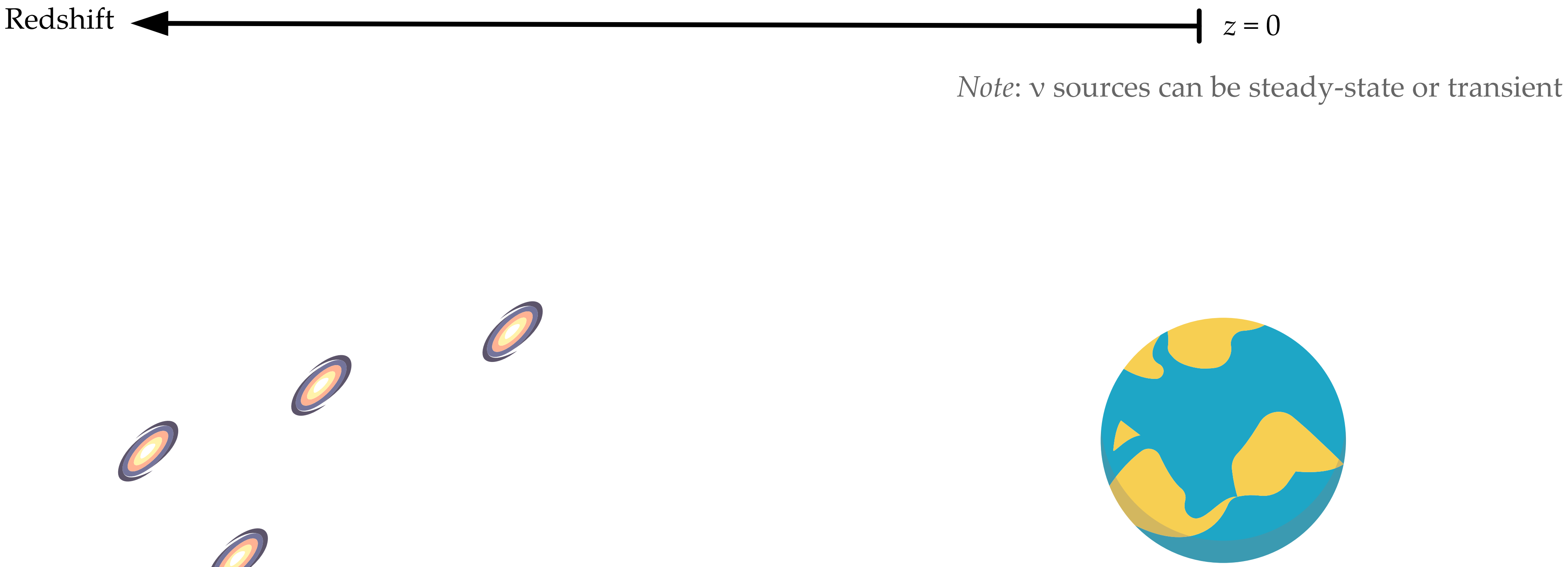
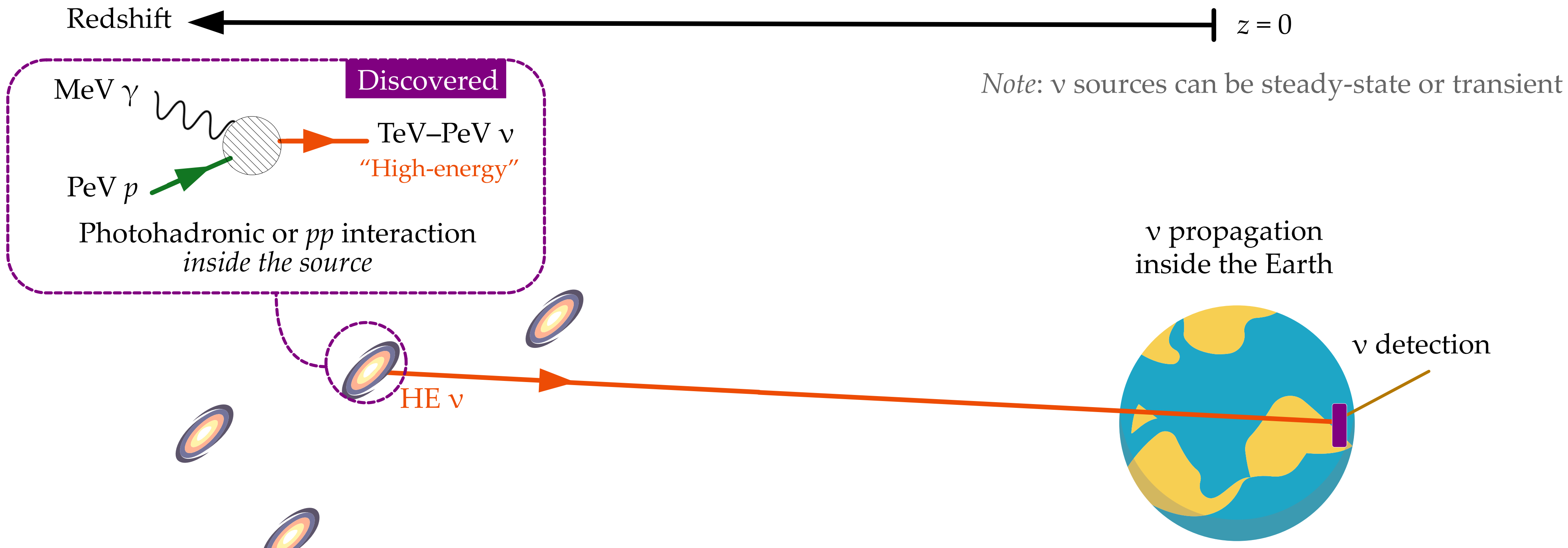
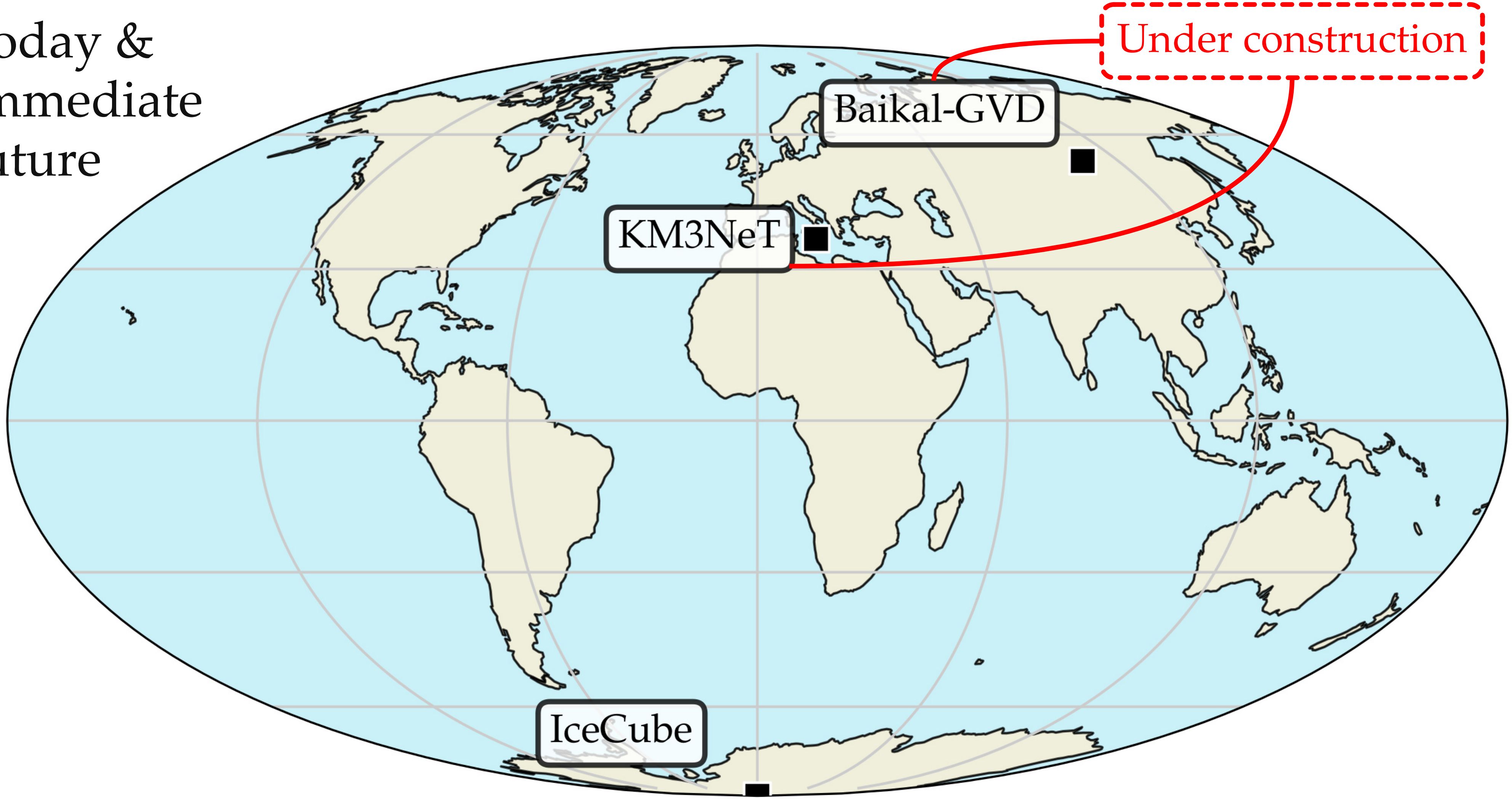

Redshift
$z = 0$
Note: ν sources can be steady-state or transient

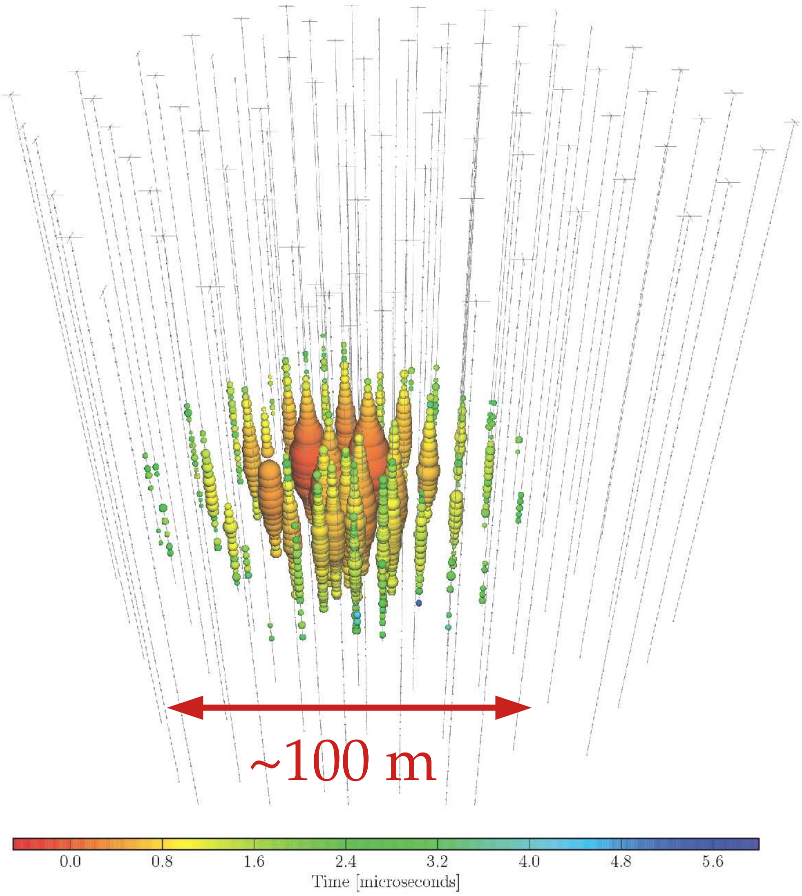

Redshift
$z = 0$
Discovered
MeV γ
TeV–PeV ν
"High-energy"
PeV p
Photohadronic or pp interaction
inside the source
Note: ν sources can be steady-state or transient
ν propagation
inside the Earth
ν detection
HE ν

Today &
immediate
future



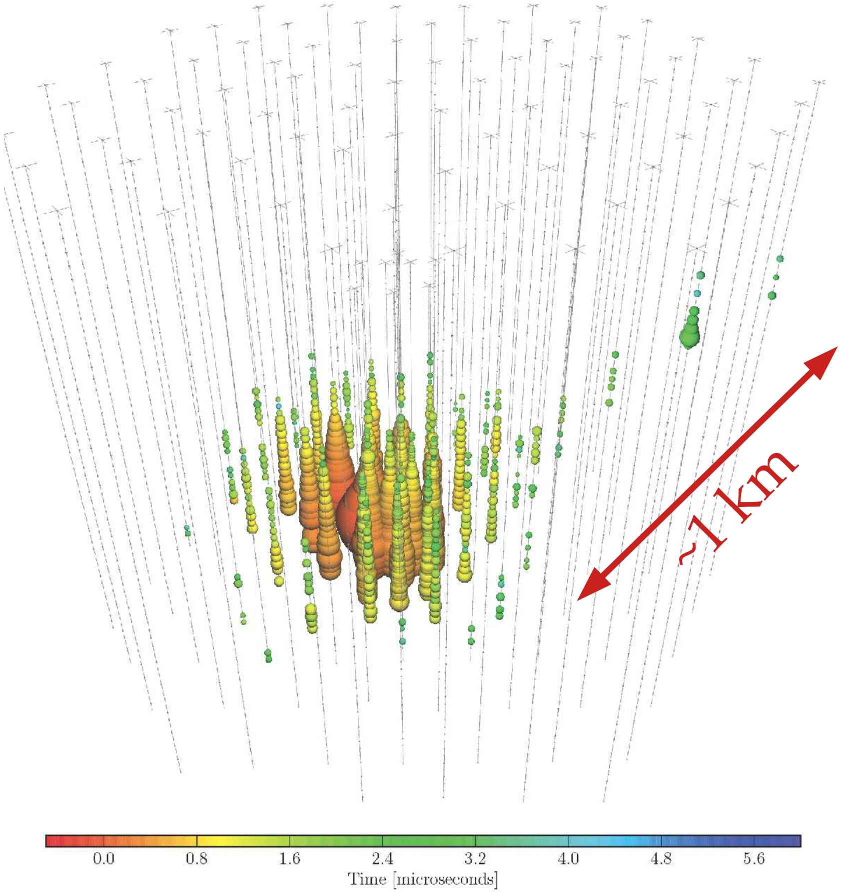
Schumacher, **MB**, Agostini, Oikonomou, Resconi, 2503.07549

Shower (mainly from ν_e and ν_τ)

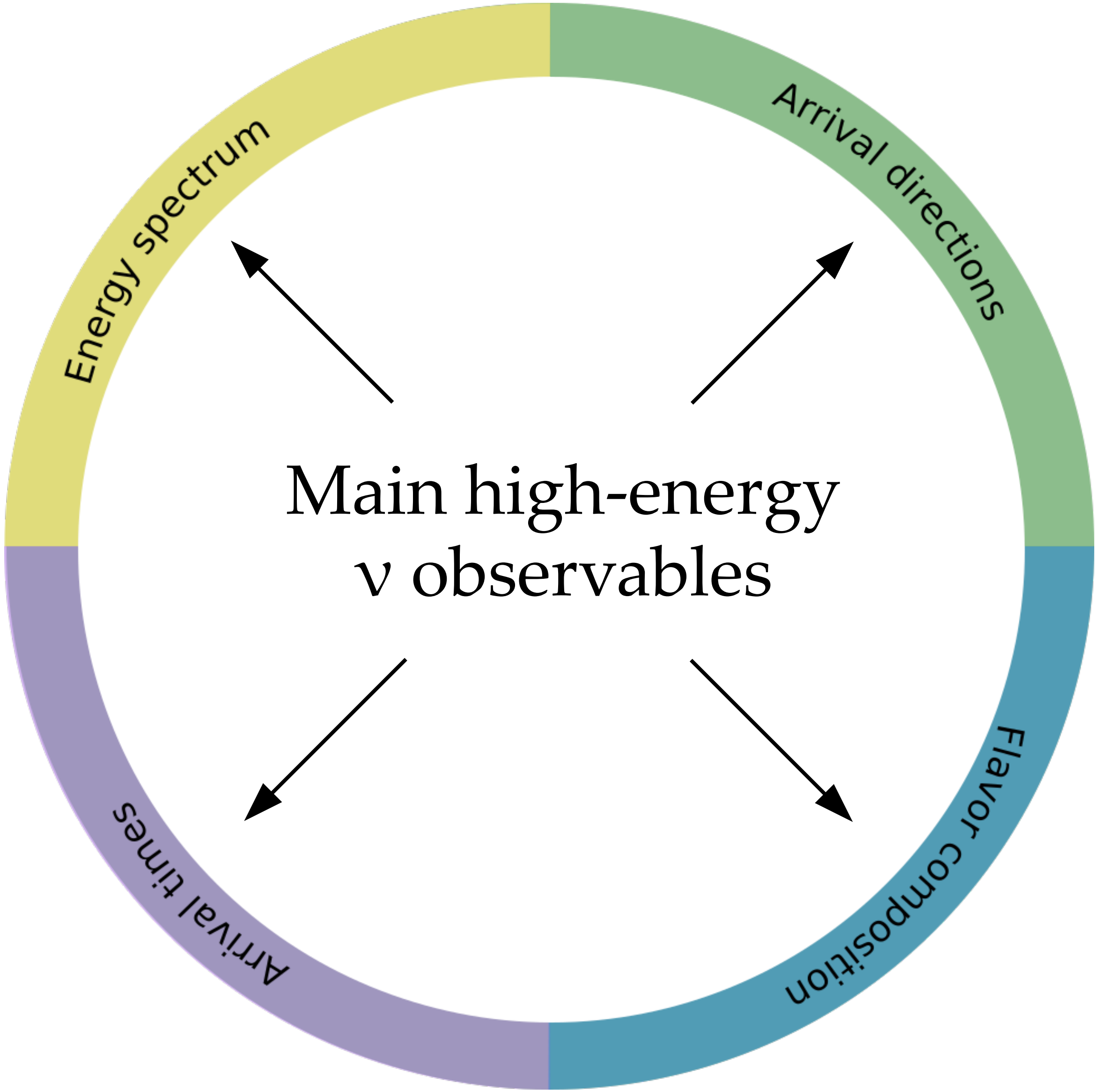


Poor angular resolution: < 5°

Track (mainly from ν_μ)

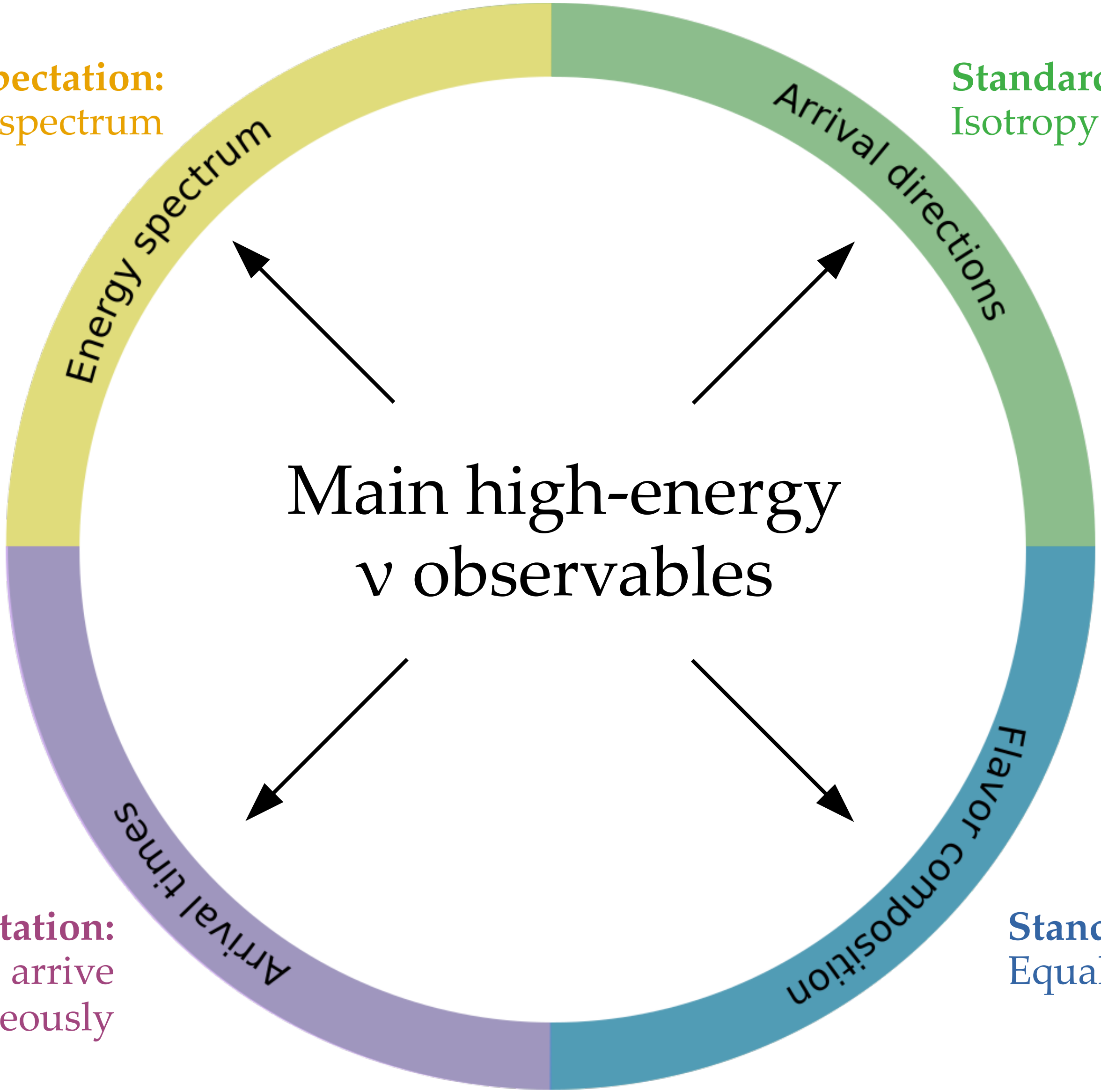


Angular resolution: < 1°


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

Note: Not an exhaustive list

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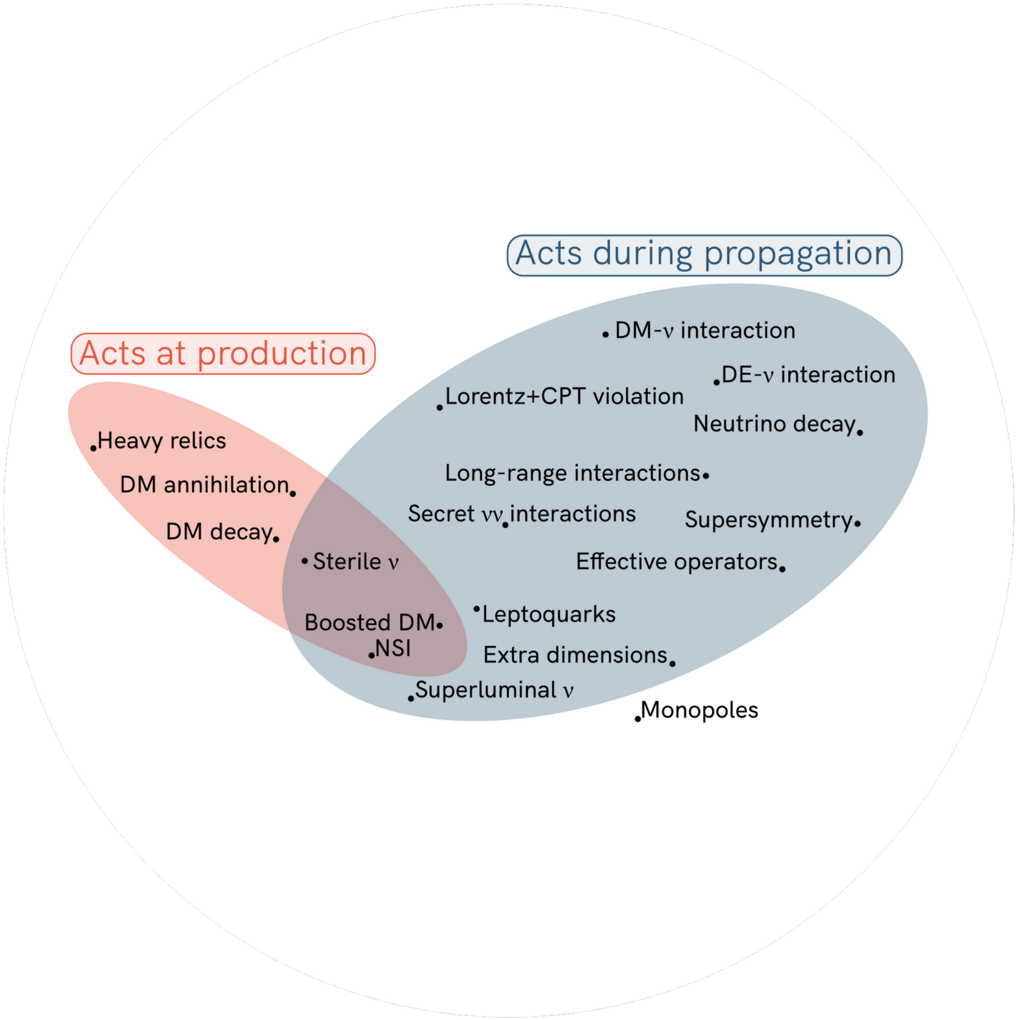

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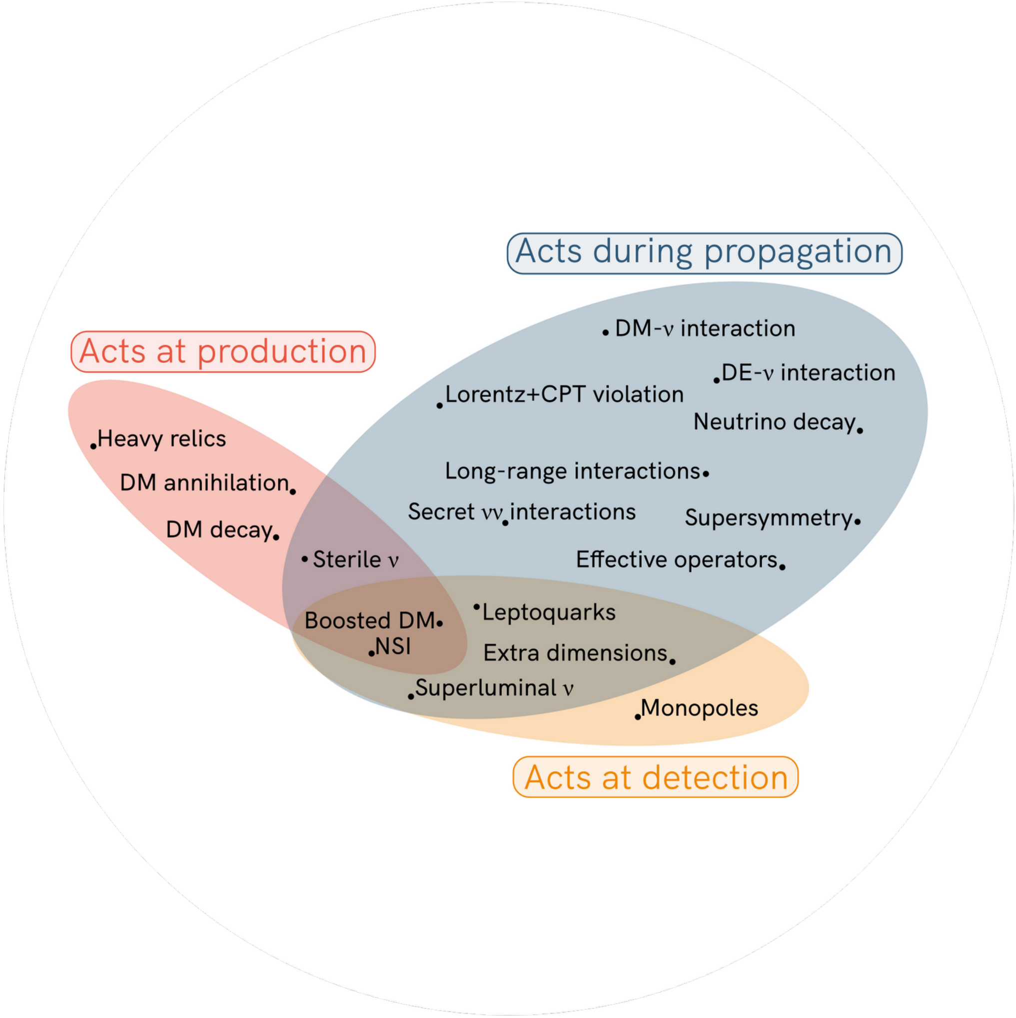

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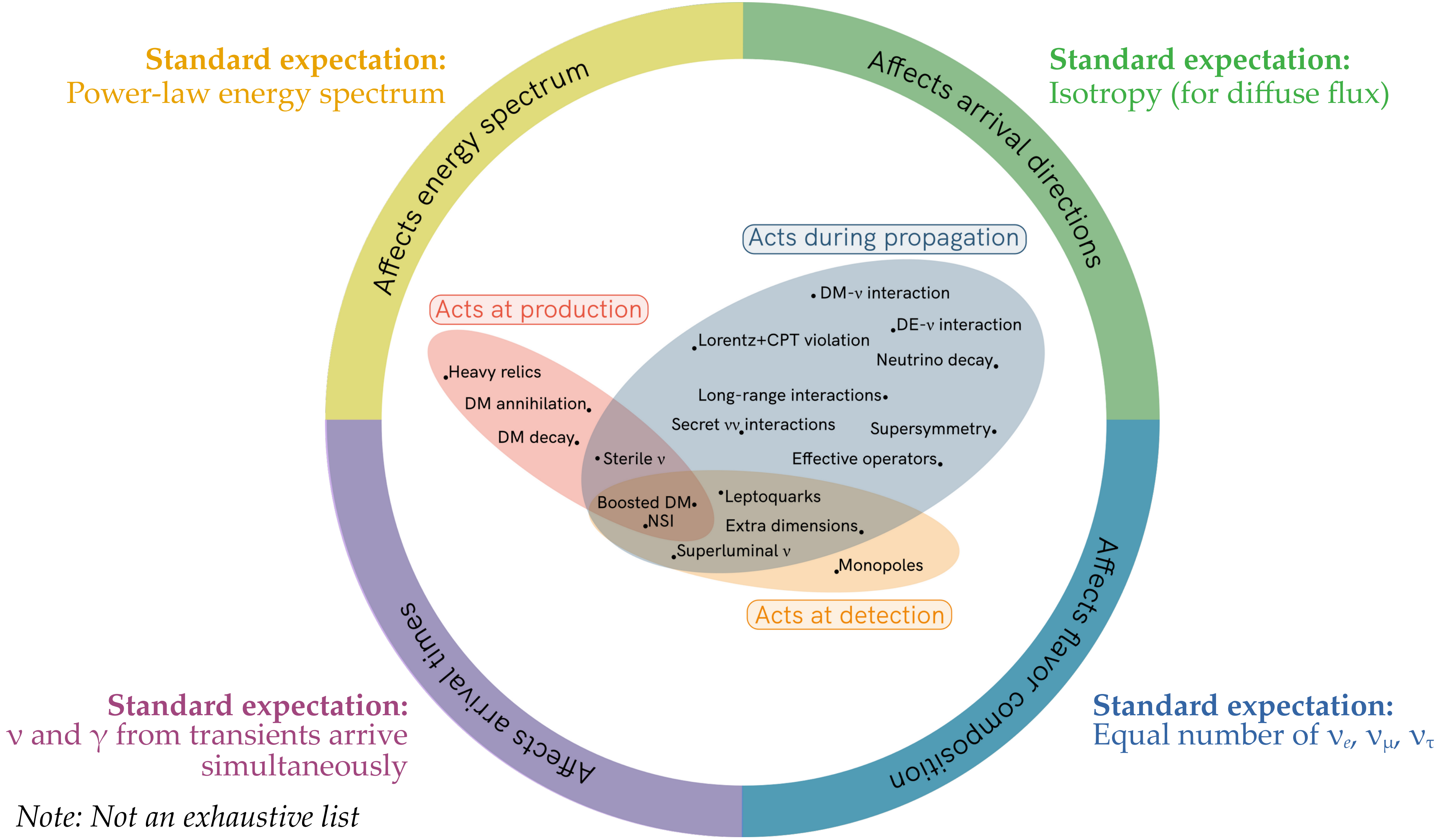

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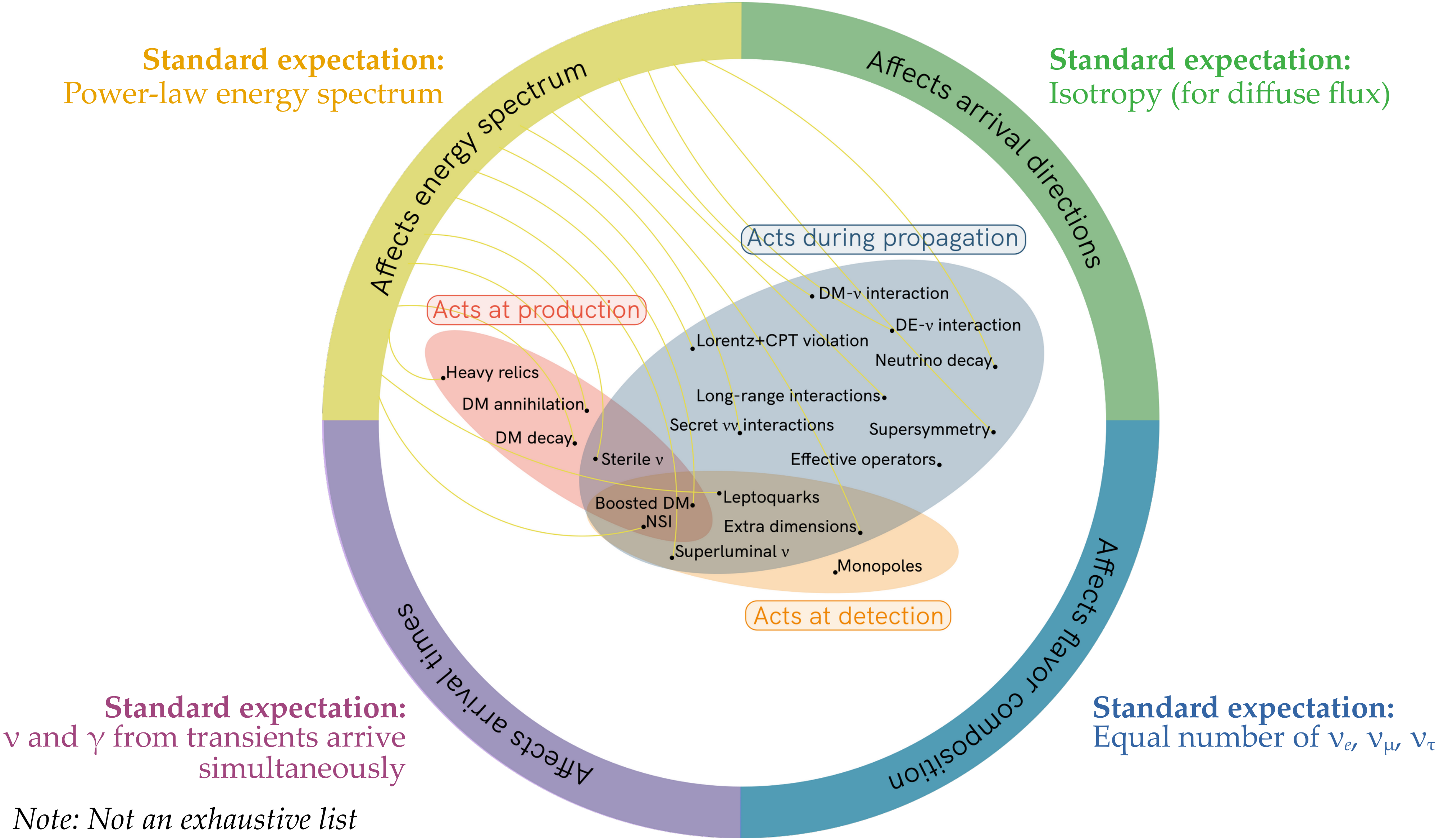

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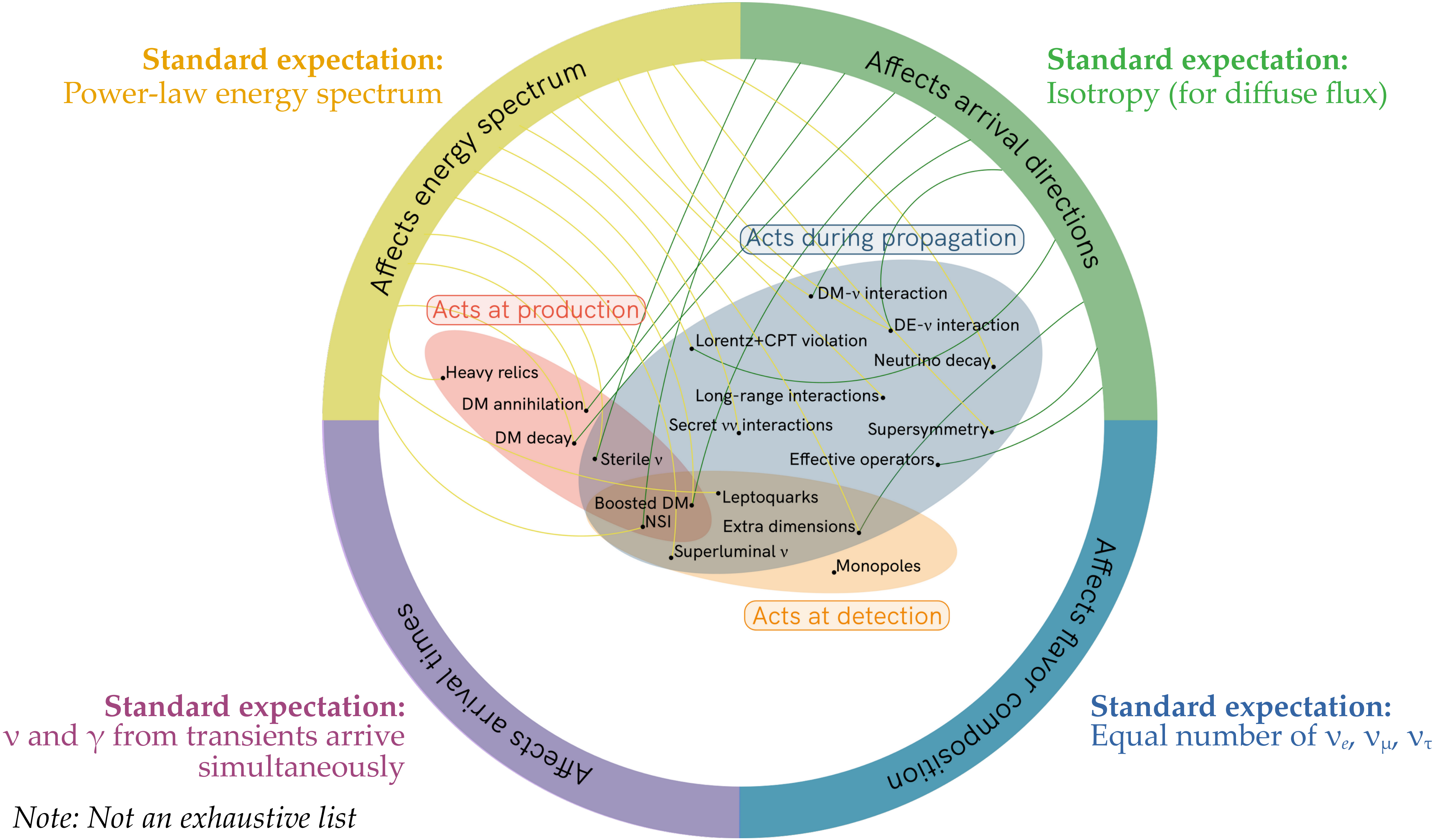

Standard expectation:
Power-law energy spectrum
Standard expectation:
Isotropy (for diffuse flux)
Affects energy spectrum
Affects arrival directions
Acts during propagation
Acts at production
DM-ν interaction
DE-ν interaction
Lorentz+CPT violation
Neutrino decay
Heavy relics
DM annihilation
Long-range interactions
Secret νν interactions
Supersymmetry
DM decay
Sterile ν
Effective operators
Leptoquarks
Boosted DM
NSI
Extra dimensions
Superluminal ν
Monopoles
Acts at detection
Affects flavor composition
Affects arrival times
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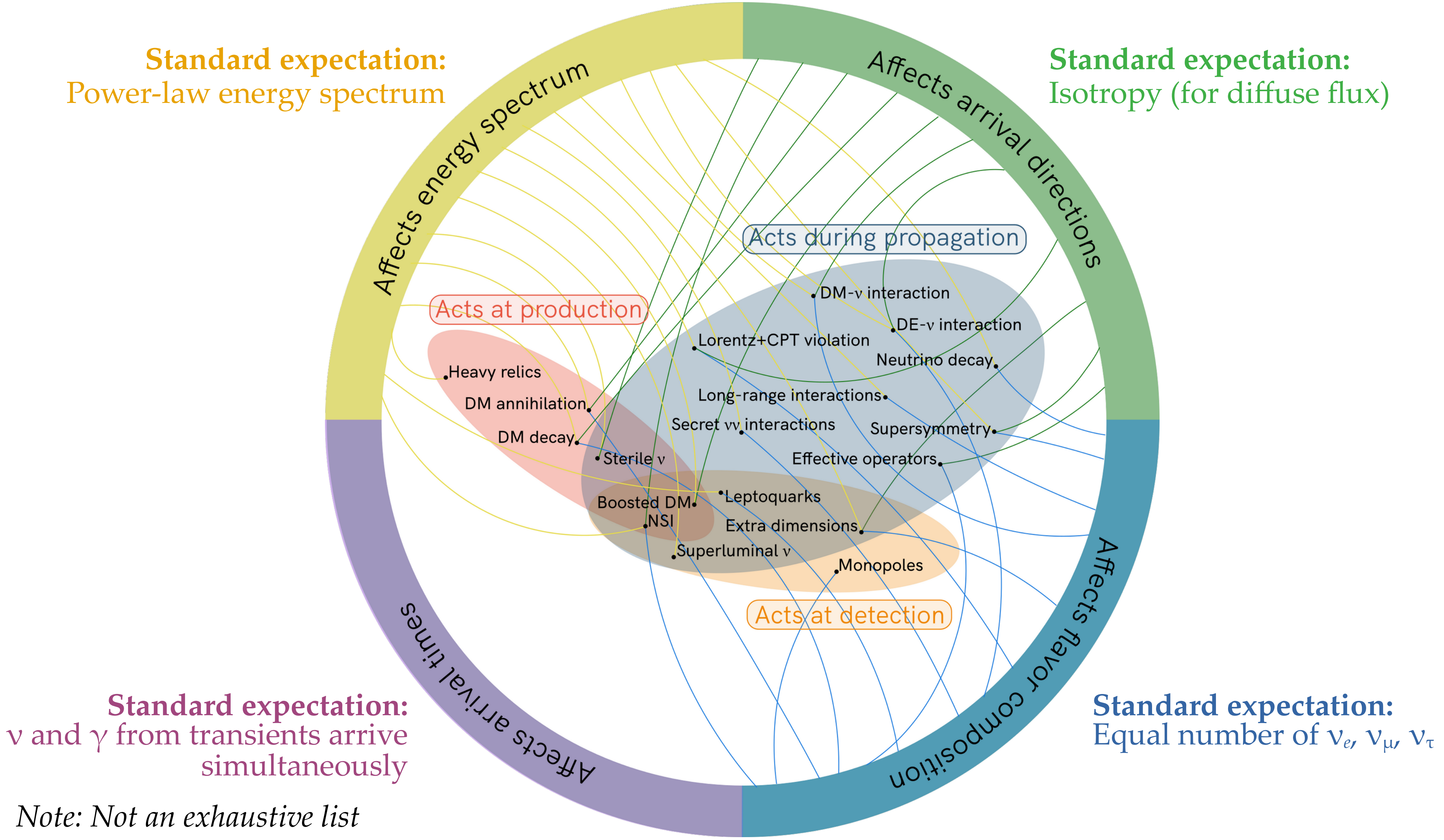

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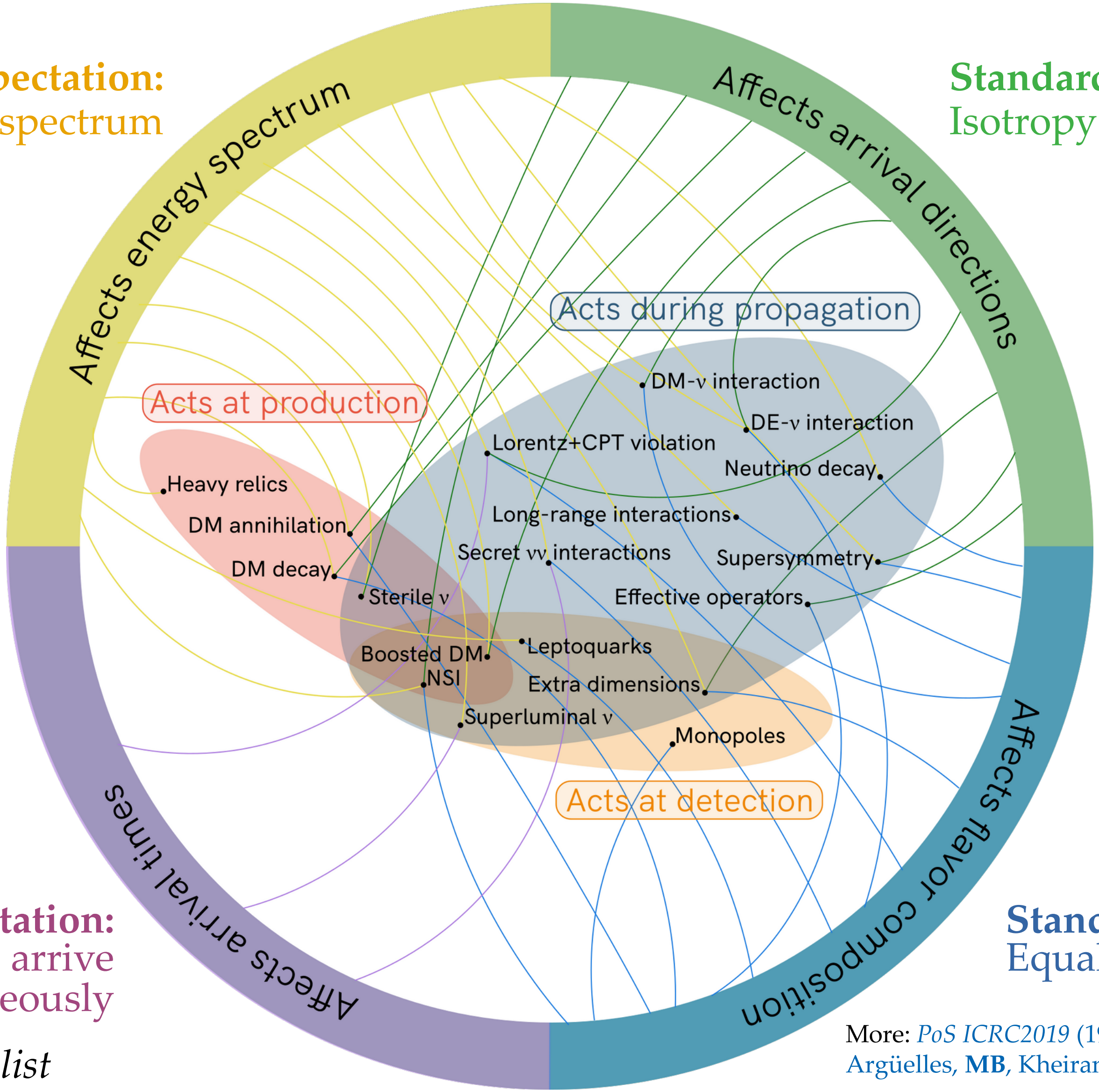

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Argüelles, **MB**, Kheirandish, Palomares-Ruiz, Salvadó, Vincent

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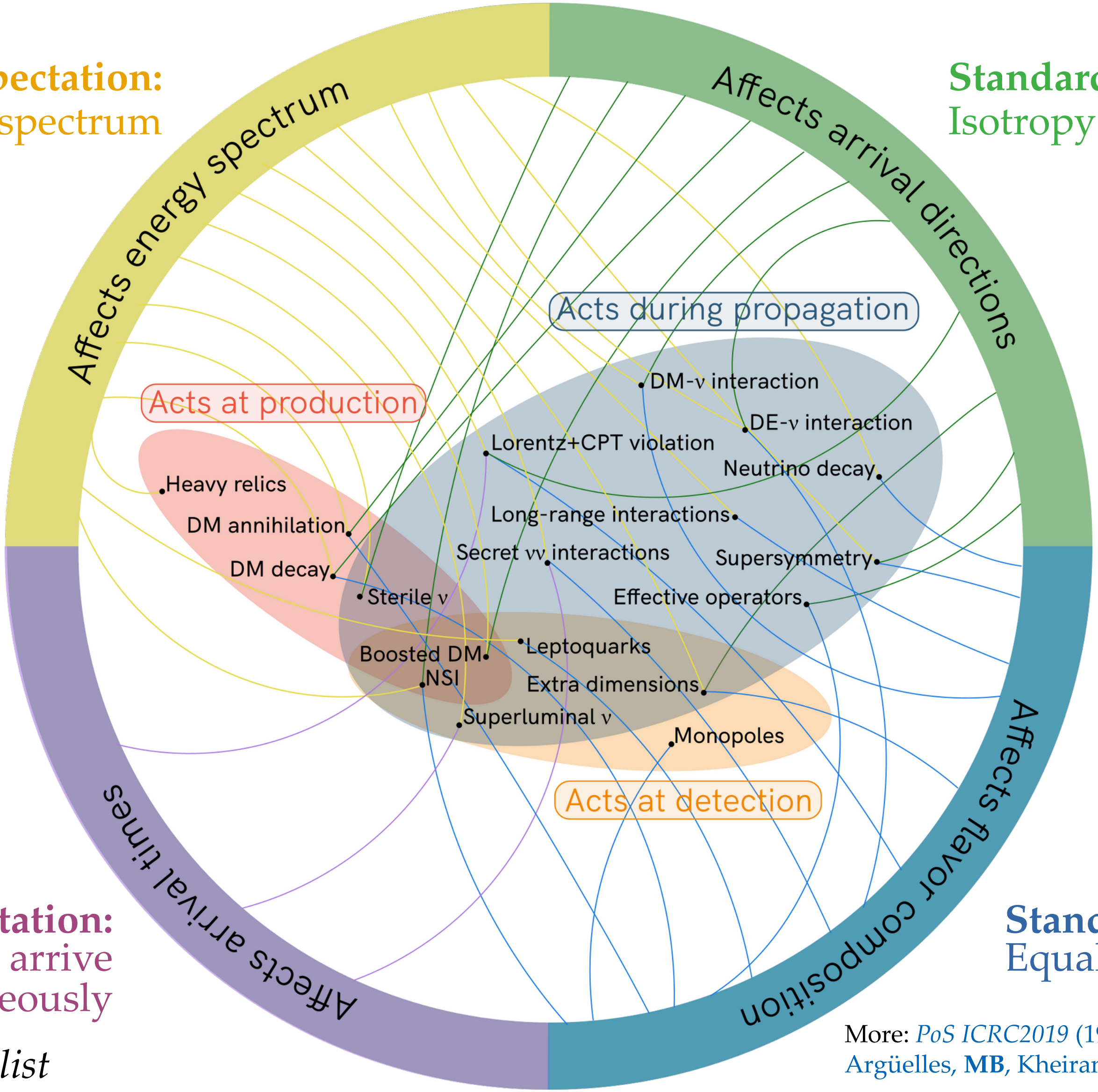

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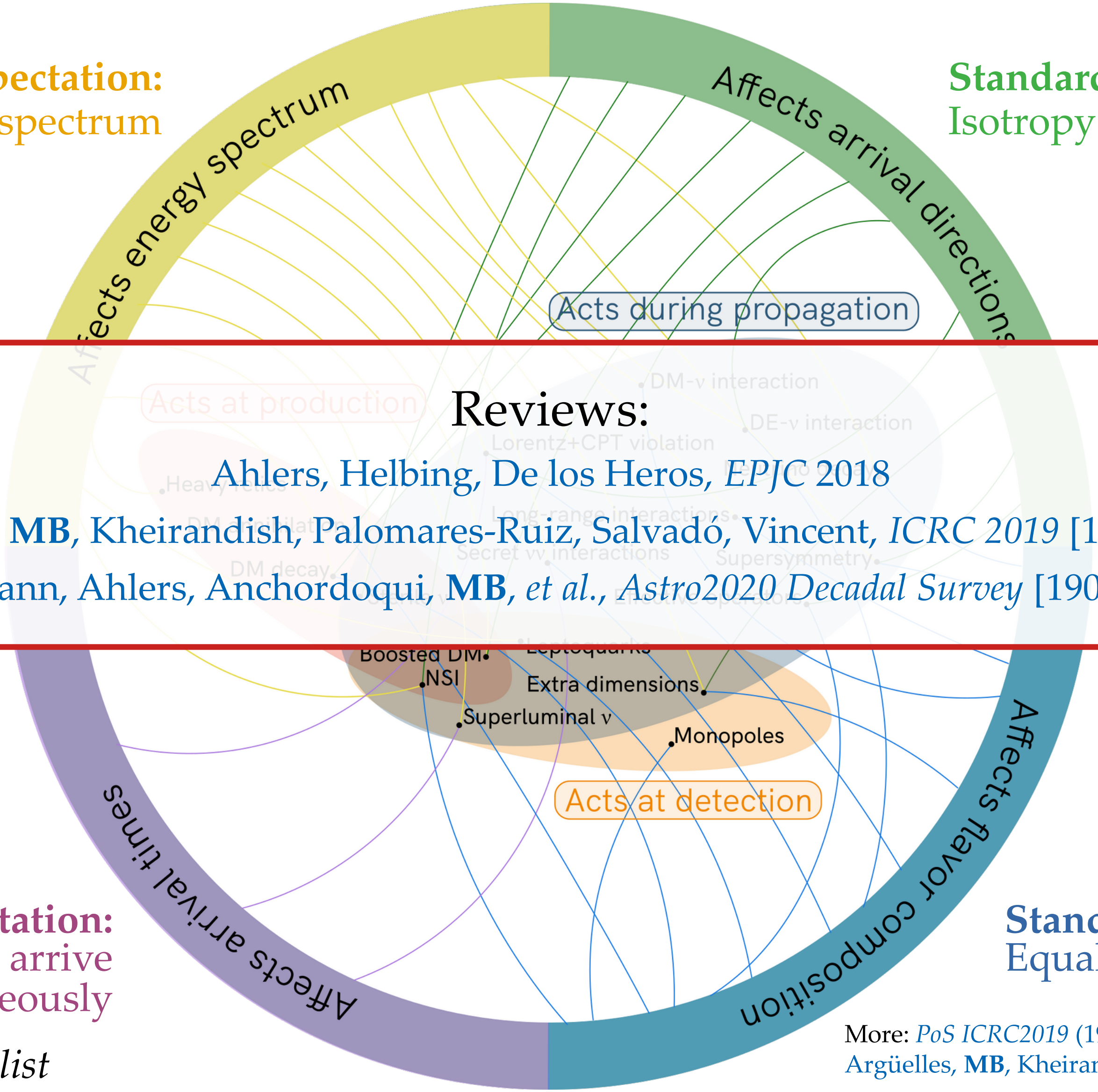

Reviews:

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

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Evidence for SM

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

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If $B \ll 1$: SM is favored

If $B \gg 1$: BSM is favored

If $B \sim 1$: No preference

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

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

Account for particle-physics + astrophysical + detector uncertainties

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"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)

Unavoidable systematics

Backgrounds

Atmospheric ν & muons, astrophysical non-BSM ν, cosmic rays

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Atmospheric ν & muons, astrophysical non-BSM ν, cosmic rays

Experimental limitations

Energy & angular resolution, detector efficiency, flavor identification

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Neutrino properties

Mixing parameters, cross sections, neutrino mass (sometimes)

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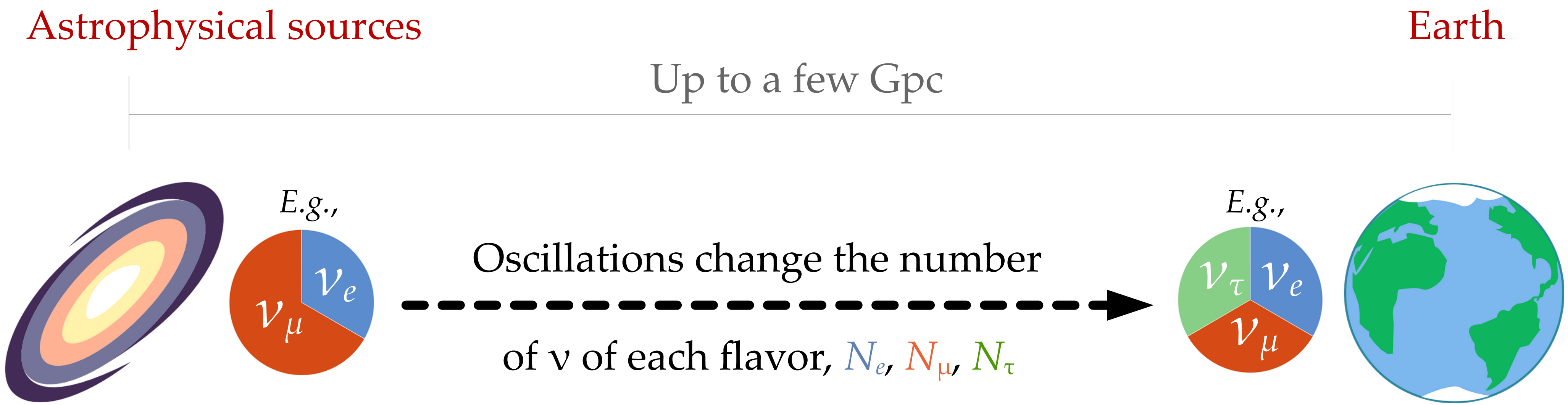
Theory bias

Look-elsewhere effect, astrophysical source models, oversimplified theory

Lorentz-invariance violation in flavor

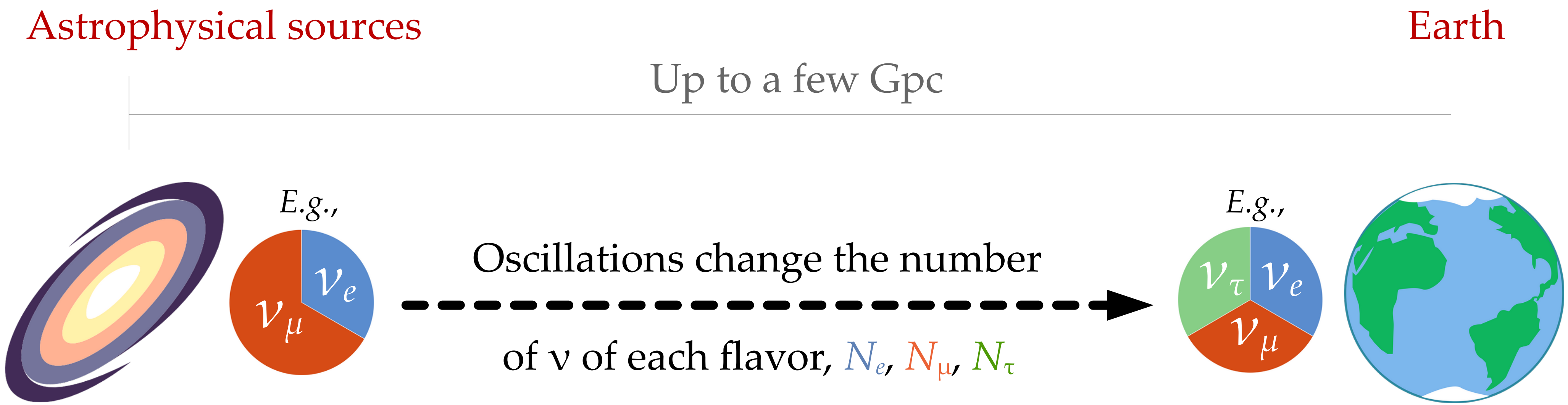


Different production mechanisms yield different flavor ratios:

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

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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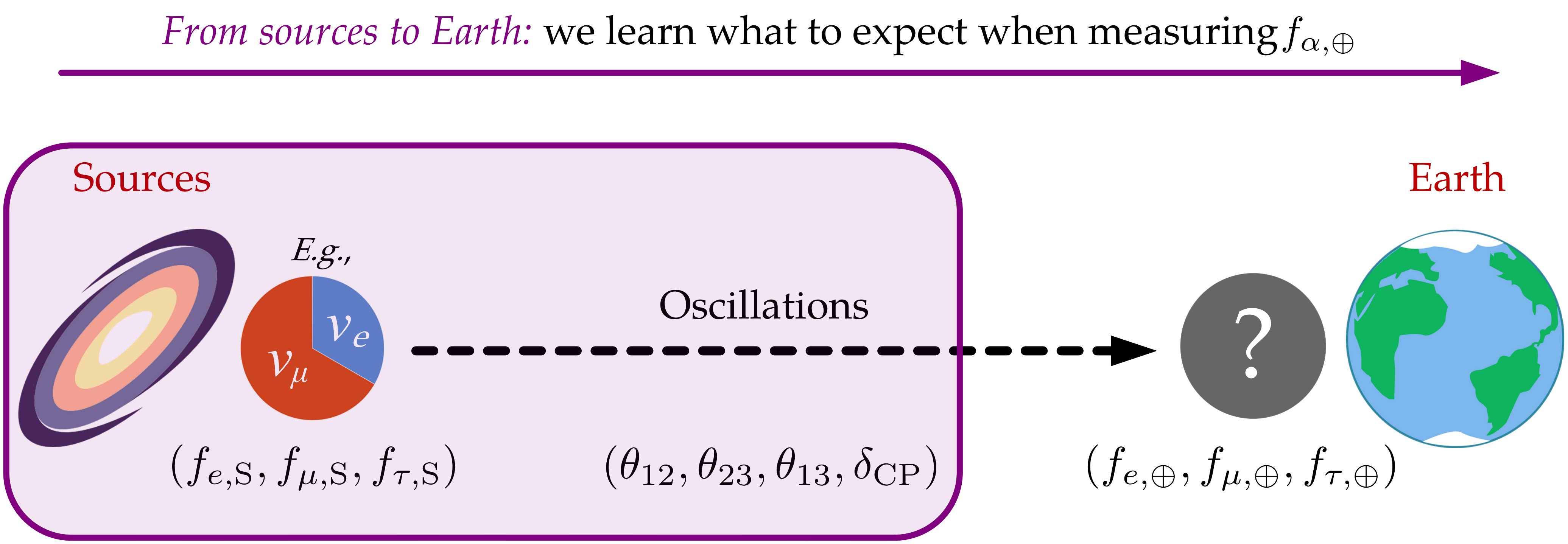
Standard oscillations
or
new physics


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

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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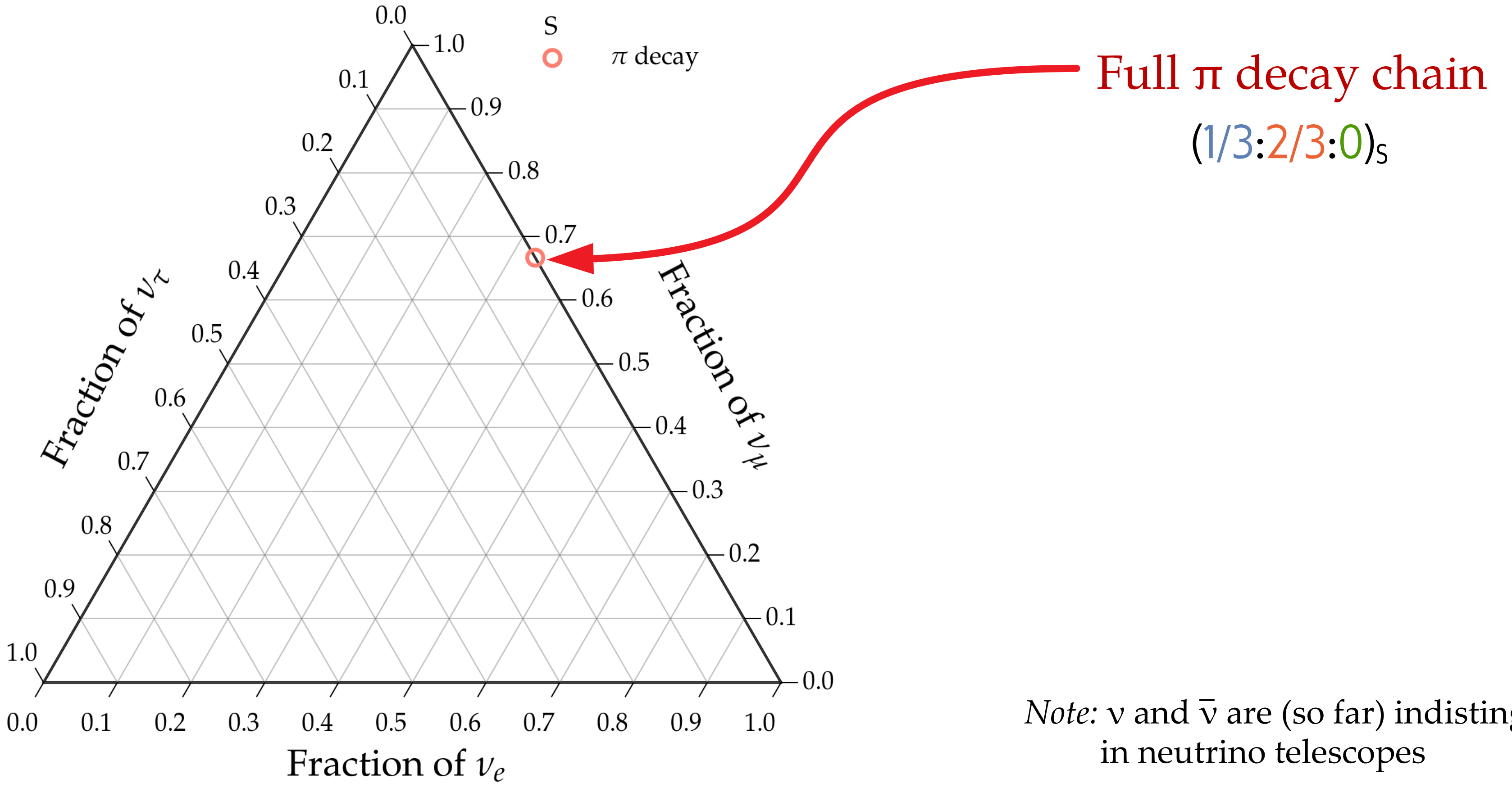

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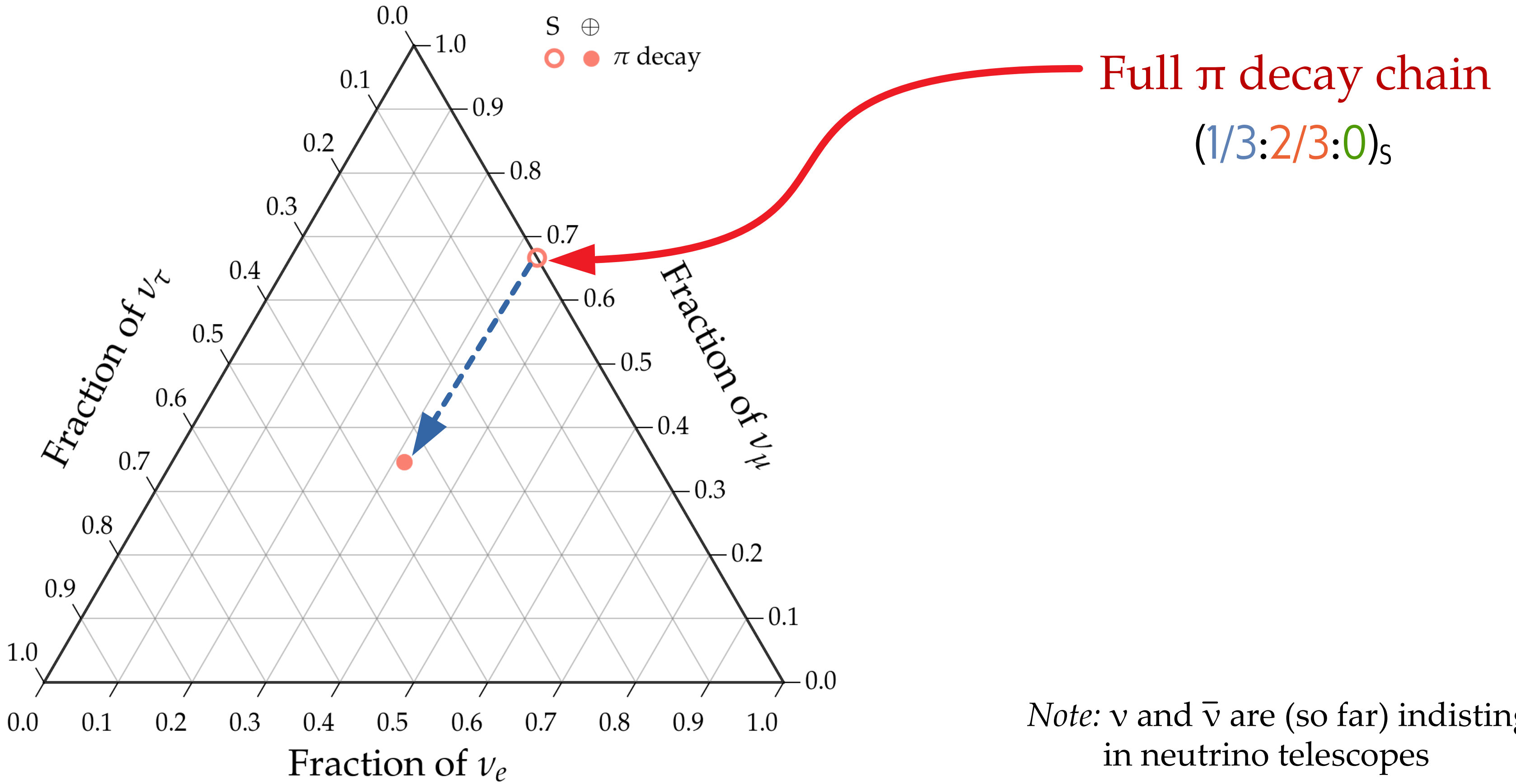

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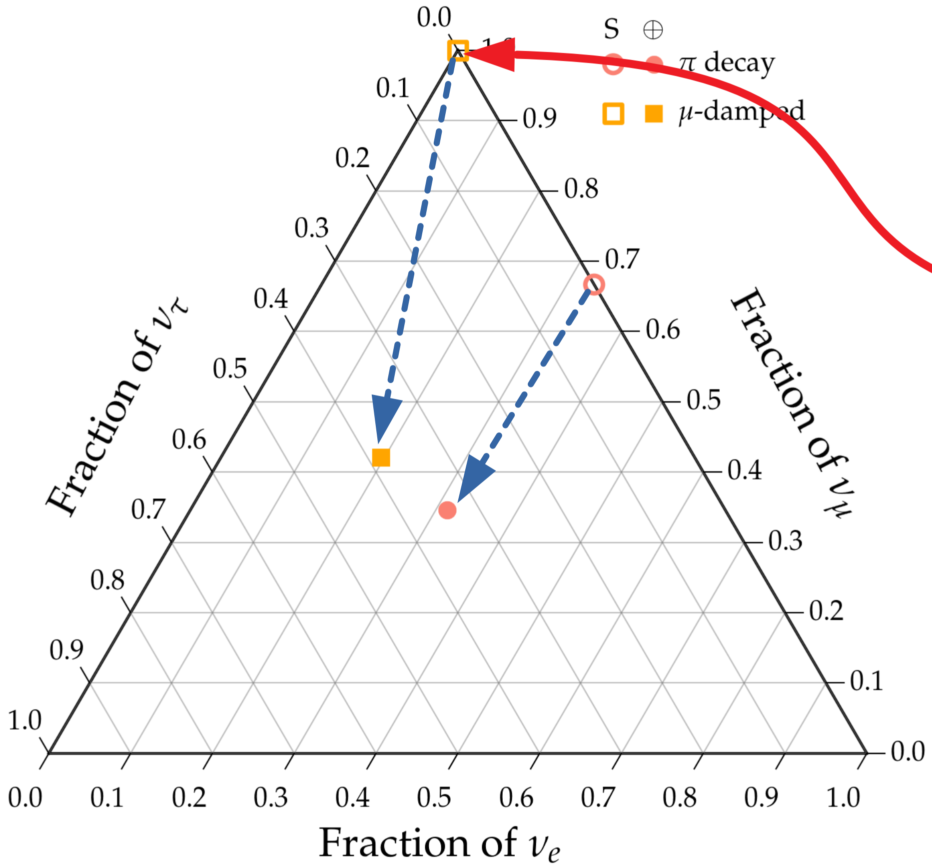


Full π decay chain

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

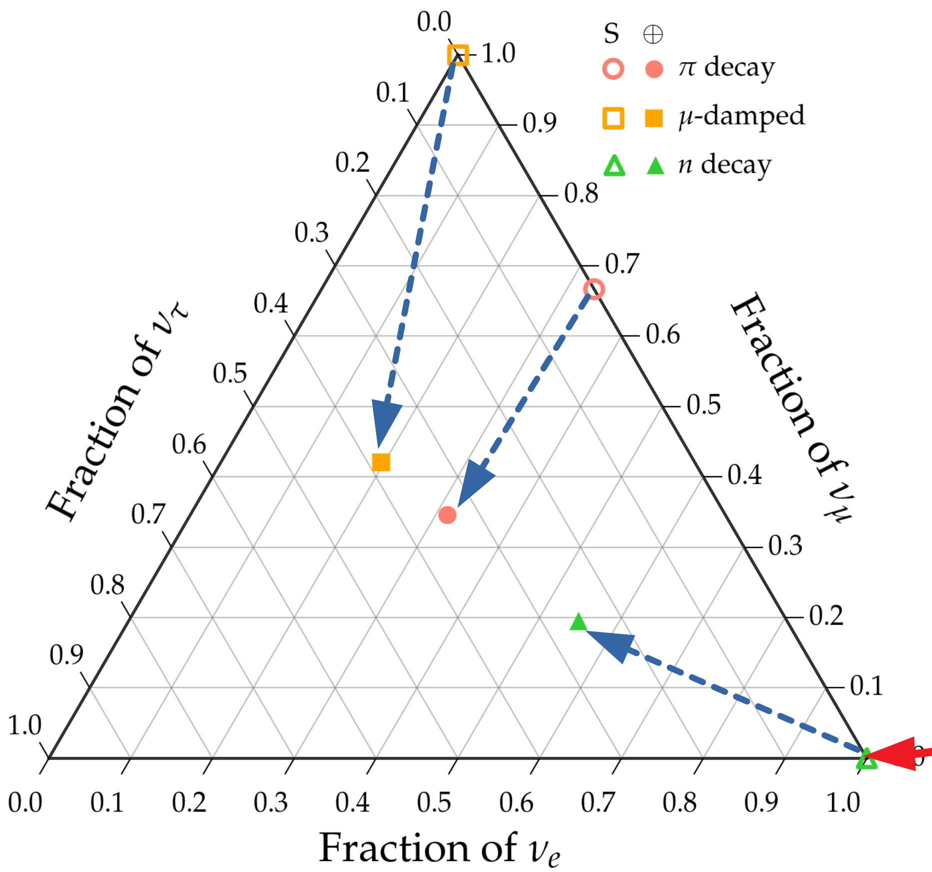
Muon damped

$(0:1:0)_S$

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

One likely TeV–PeV ν production scenario:

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



Full π decay chain

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

Muon damped

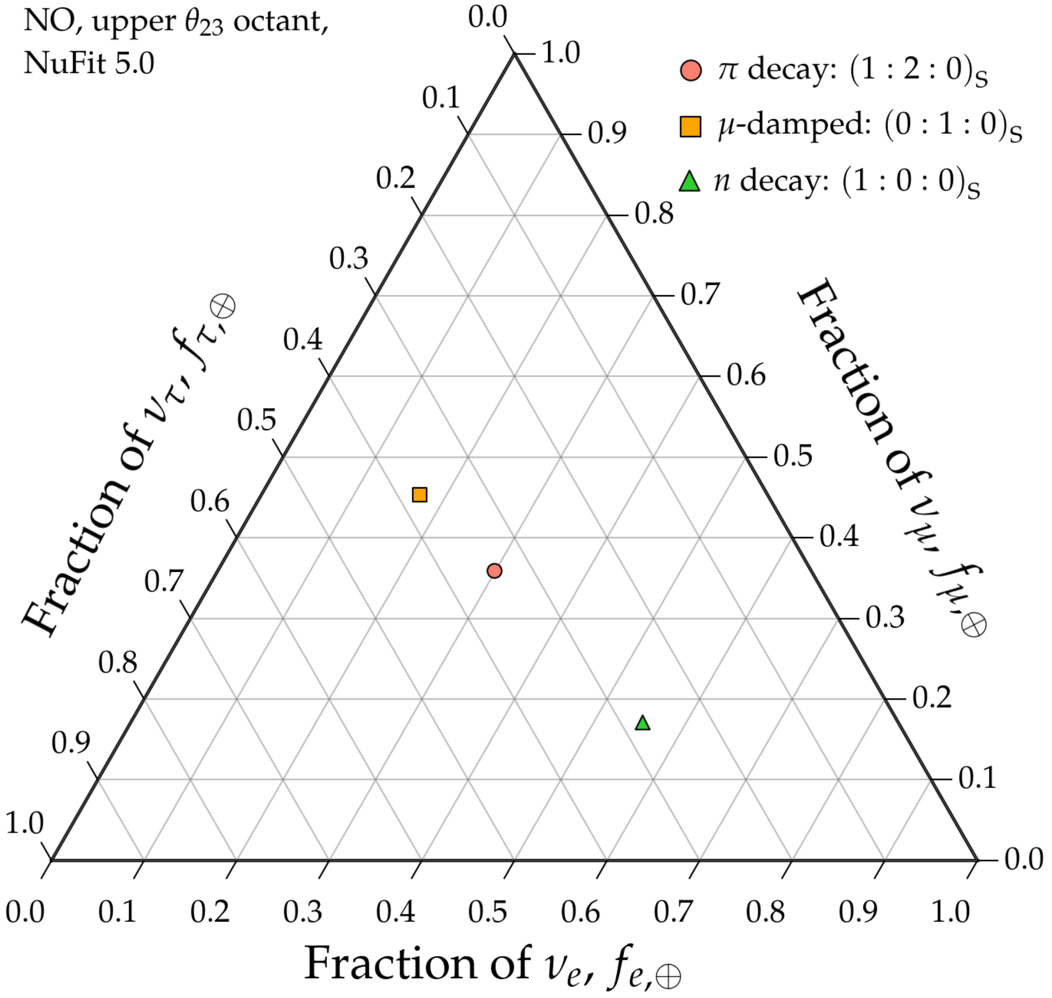
$(0:1:0)_S$

Neutron decay

$(1:0:0)_S$

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

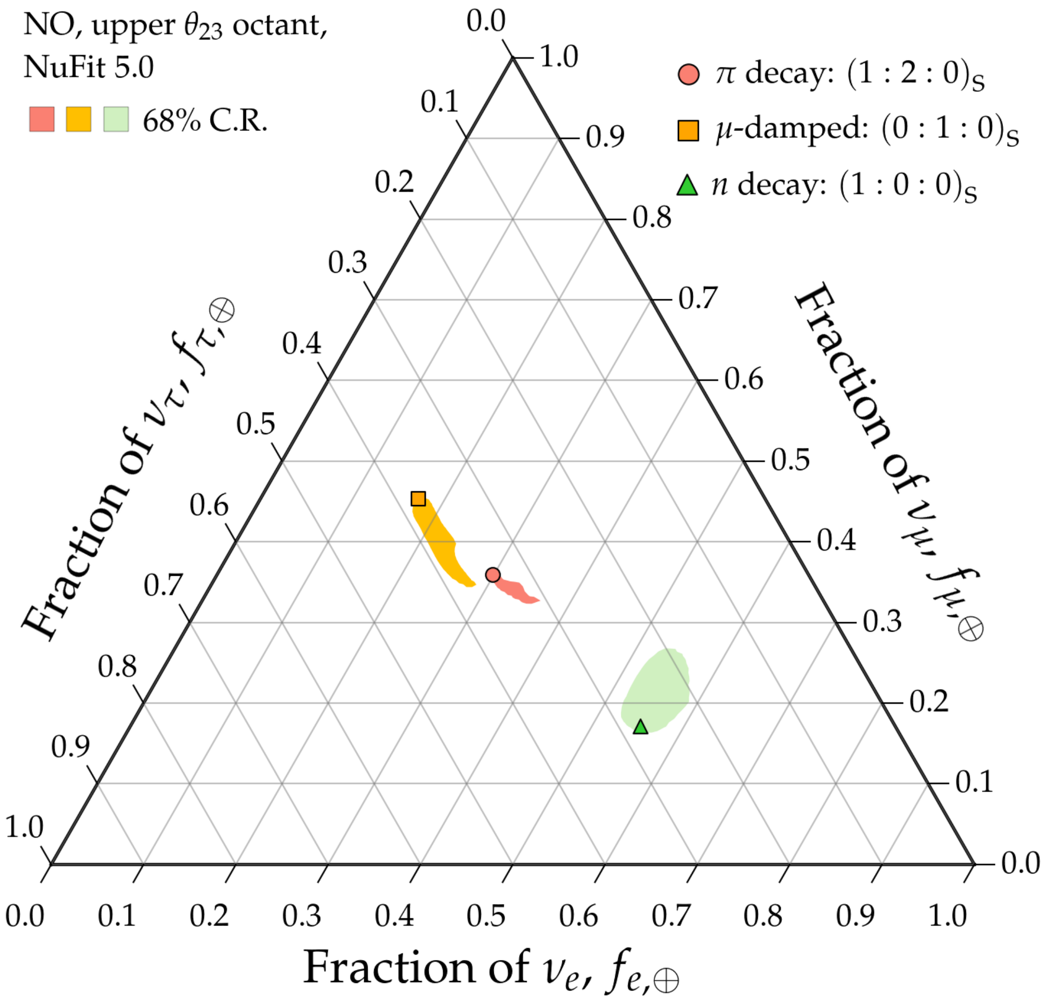
Theoretically palatable regions: today



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

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

Theoretically palatable regions: today



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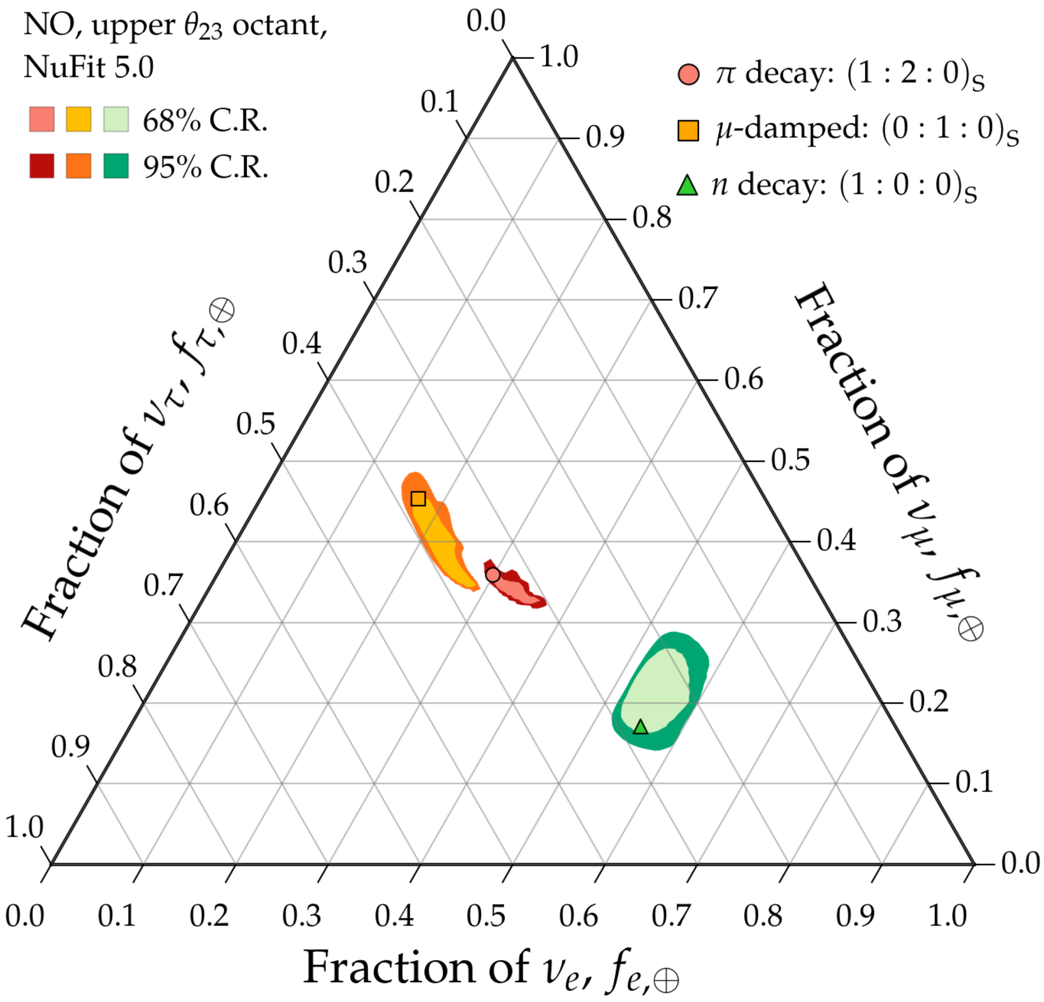

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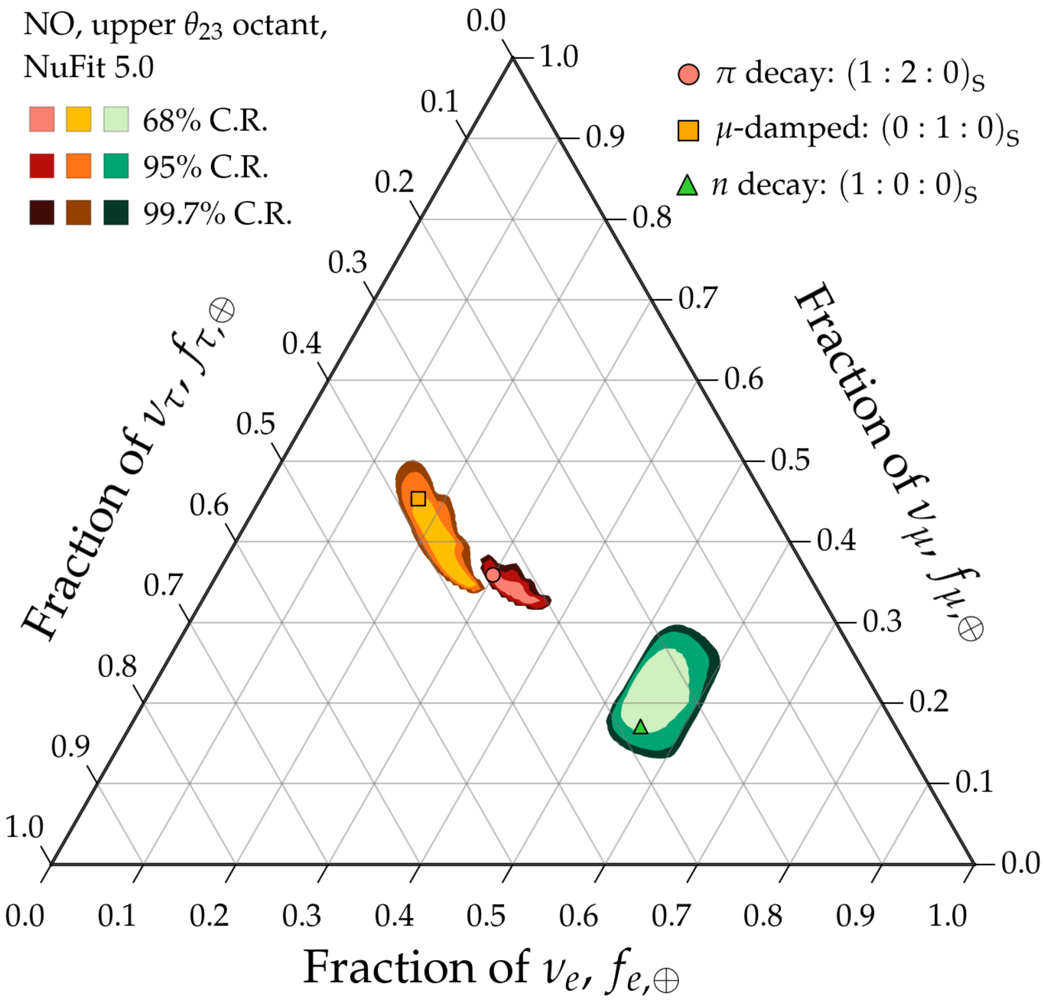

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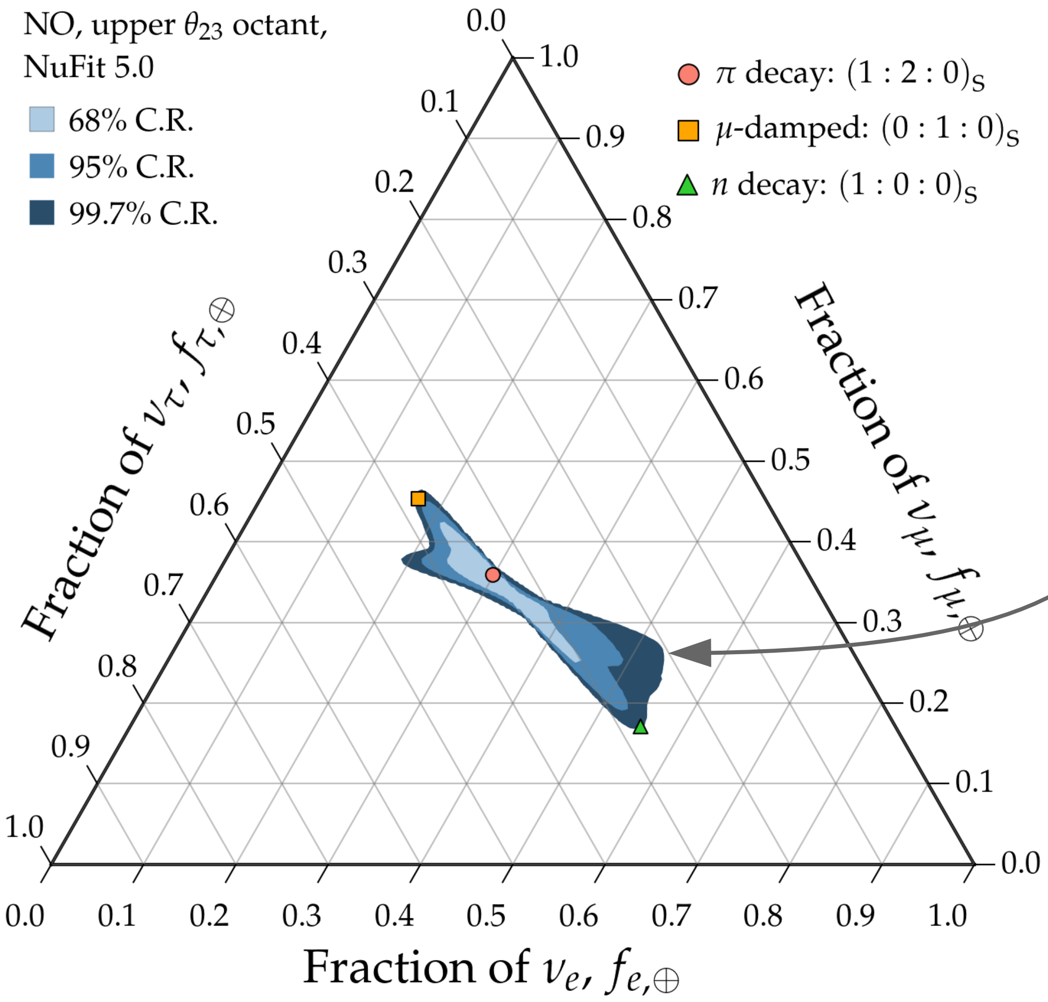

Varying over all possible flavor ratios at the source

Note:
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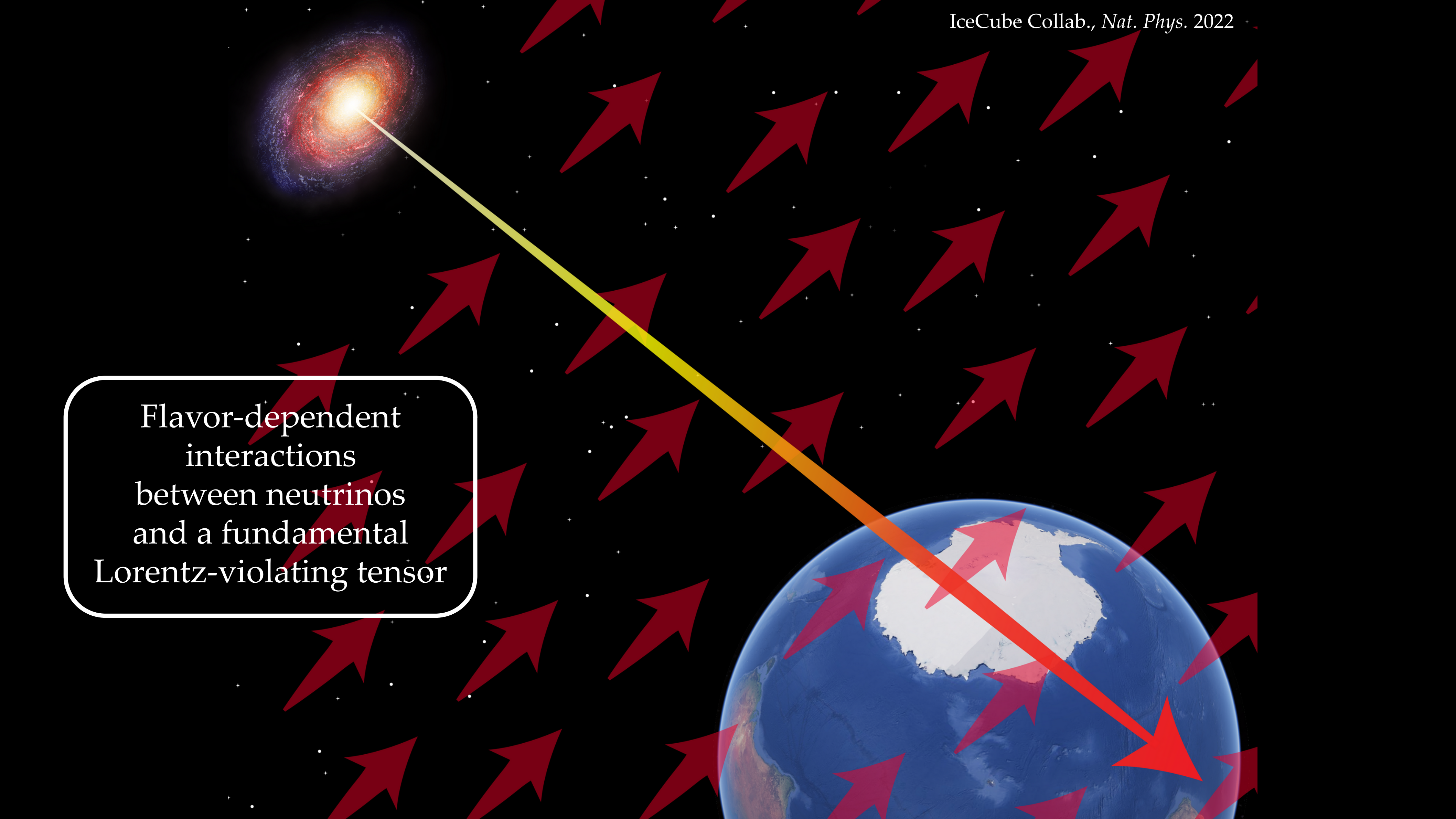
See also: **MB**, Beacom, Winter, *PRL* 2015


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

Standard oscillations:

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

Lorentz-violating interactions (Standard Model Extension):

Kostelecky, Mewes, *PRD* 2004

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

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

Total Hamiltonian:

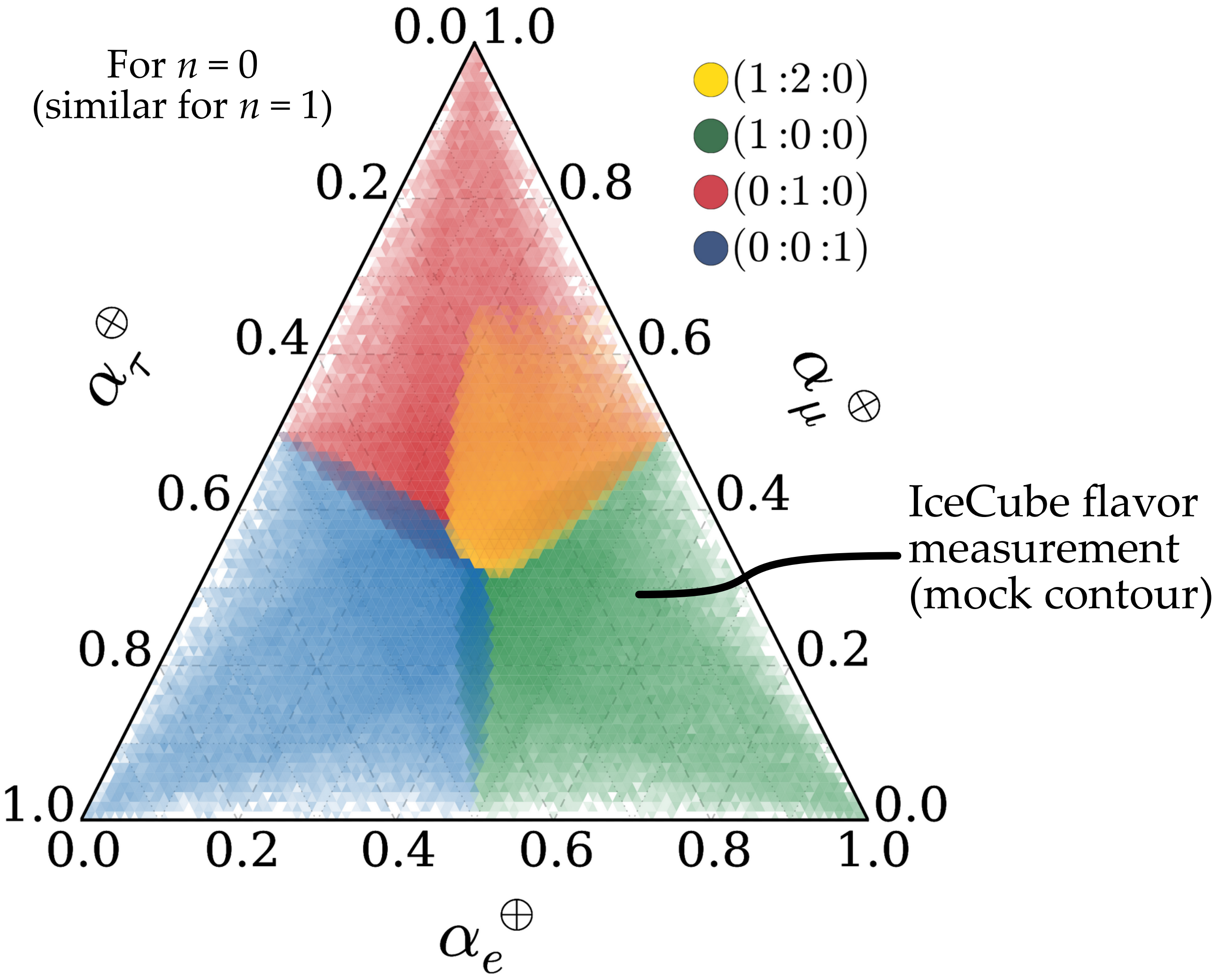
$$H_{\text{tot}} = H_{\text{std}} + H_{\text{new}}$$

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

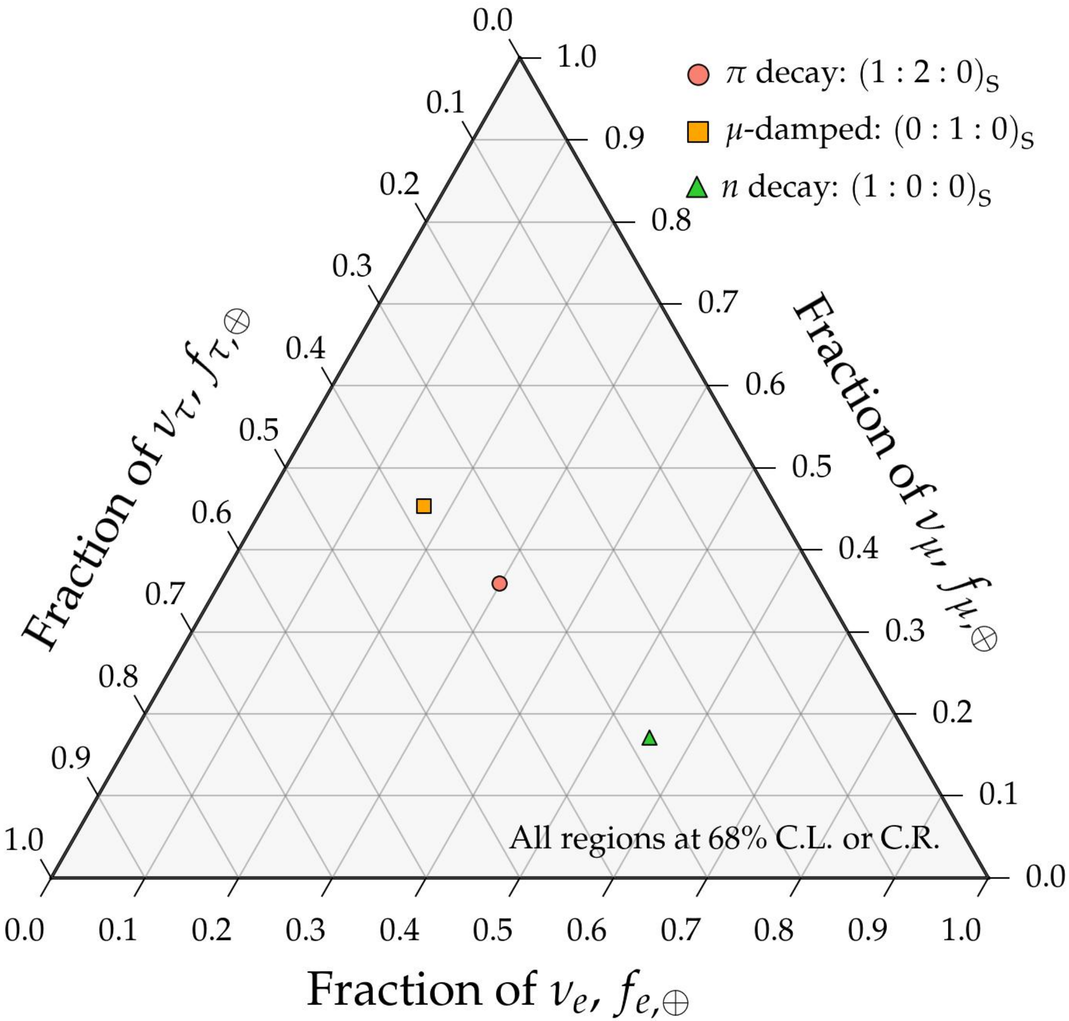
but now the lepton mixing matrix, U_{tot}, is the one that diagonalizes H_{tot}



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

Measuring flavor composition 2015–2025



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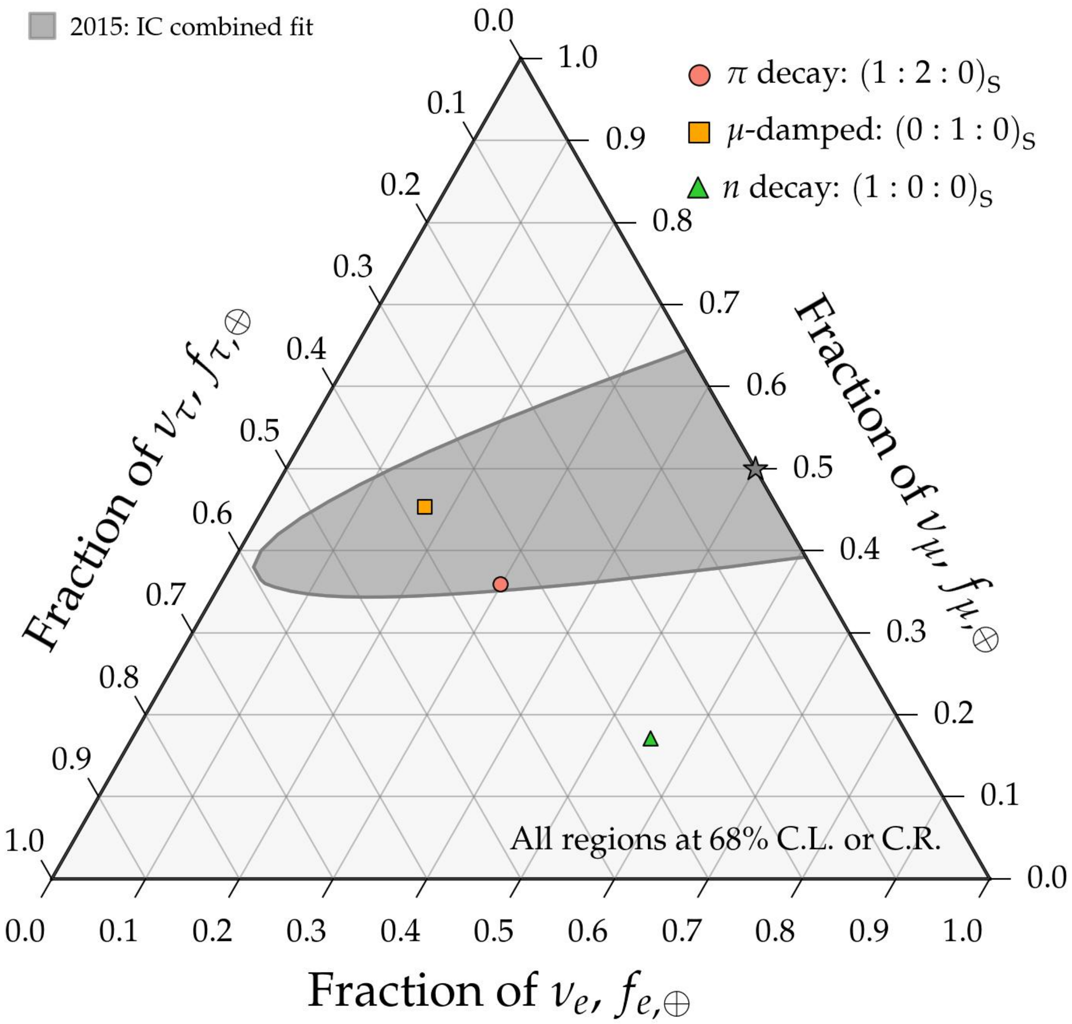

IceCube Collab., 2510.24957, 2507.06835, *EPJC* 2022, PRD 2019, *ApJ* 2015, *PRL* 2015

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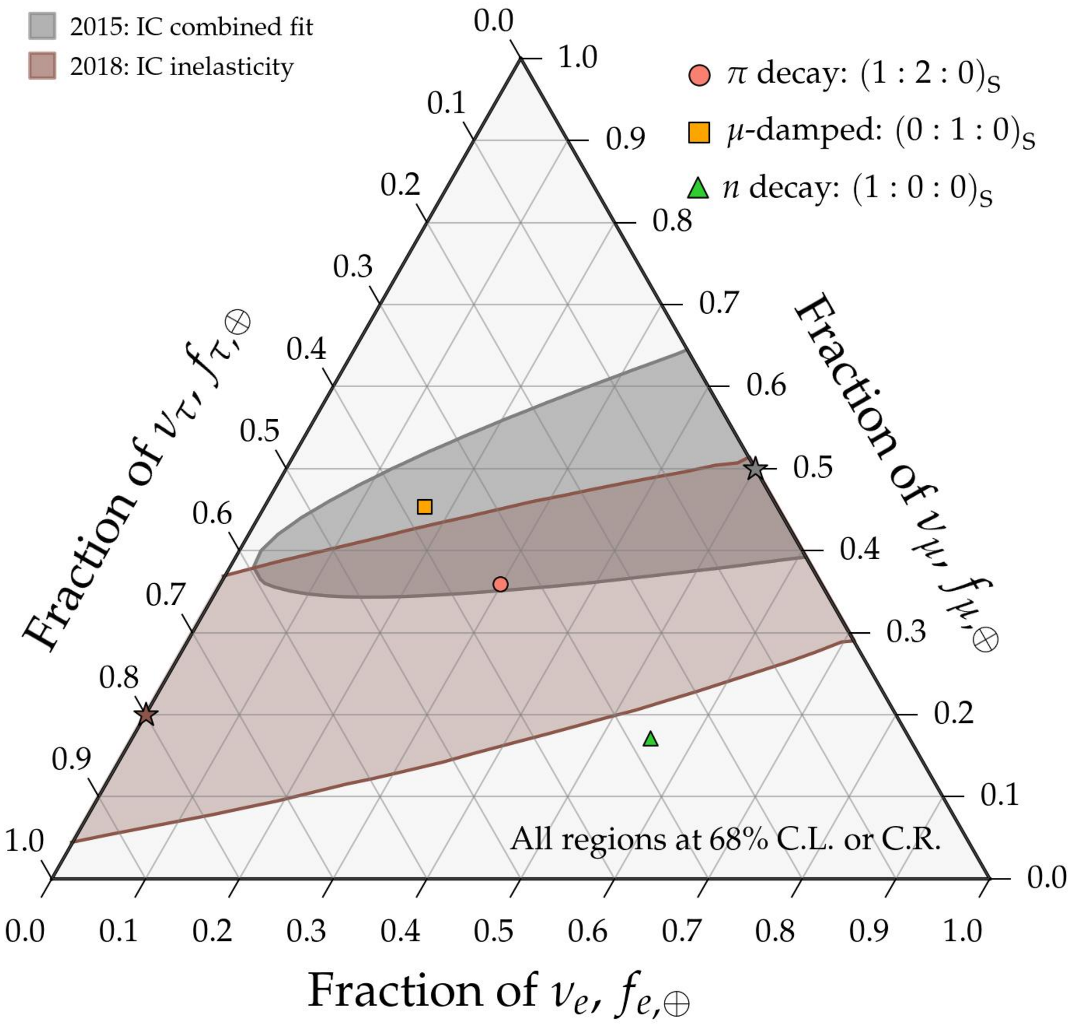

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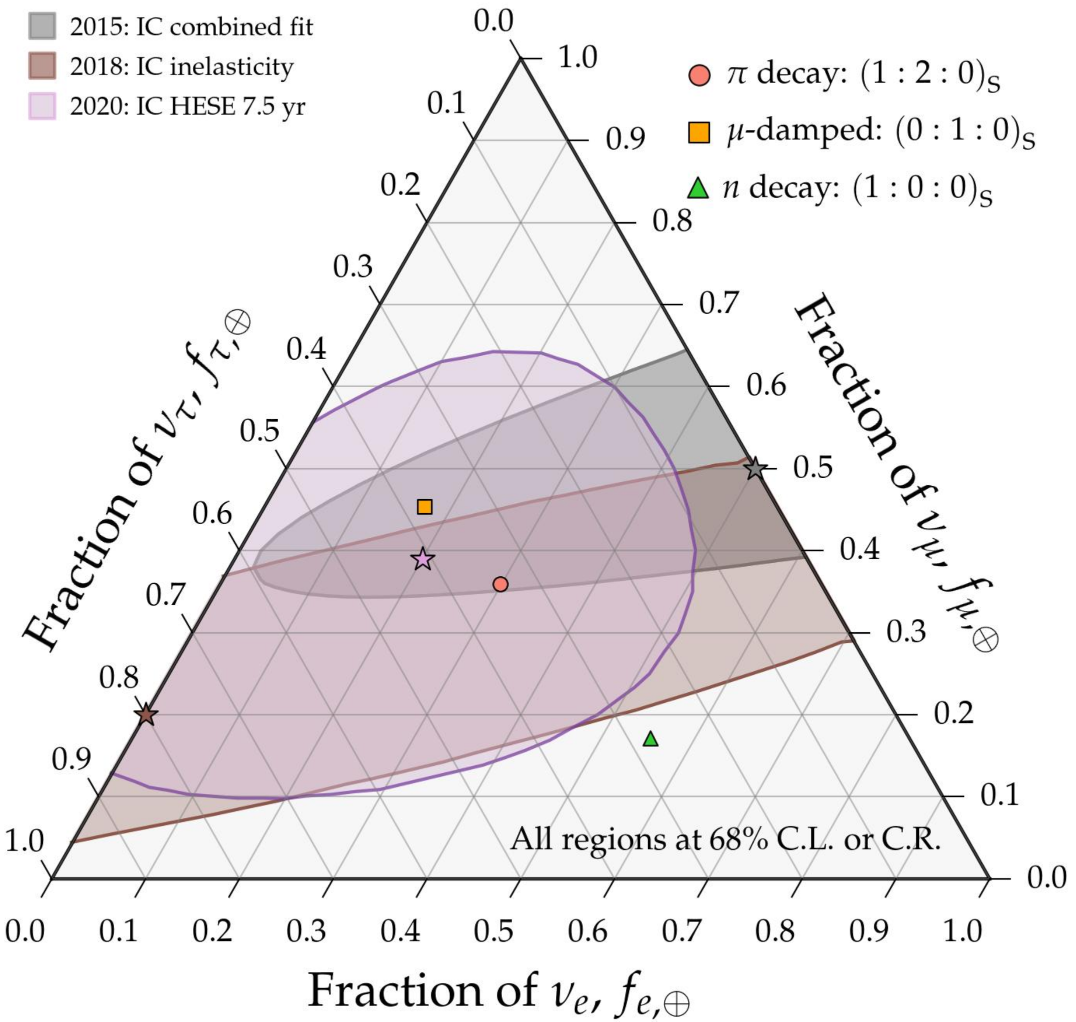

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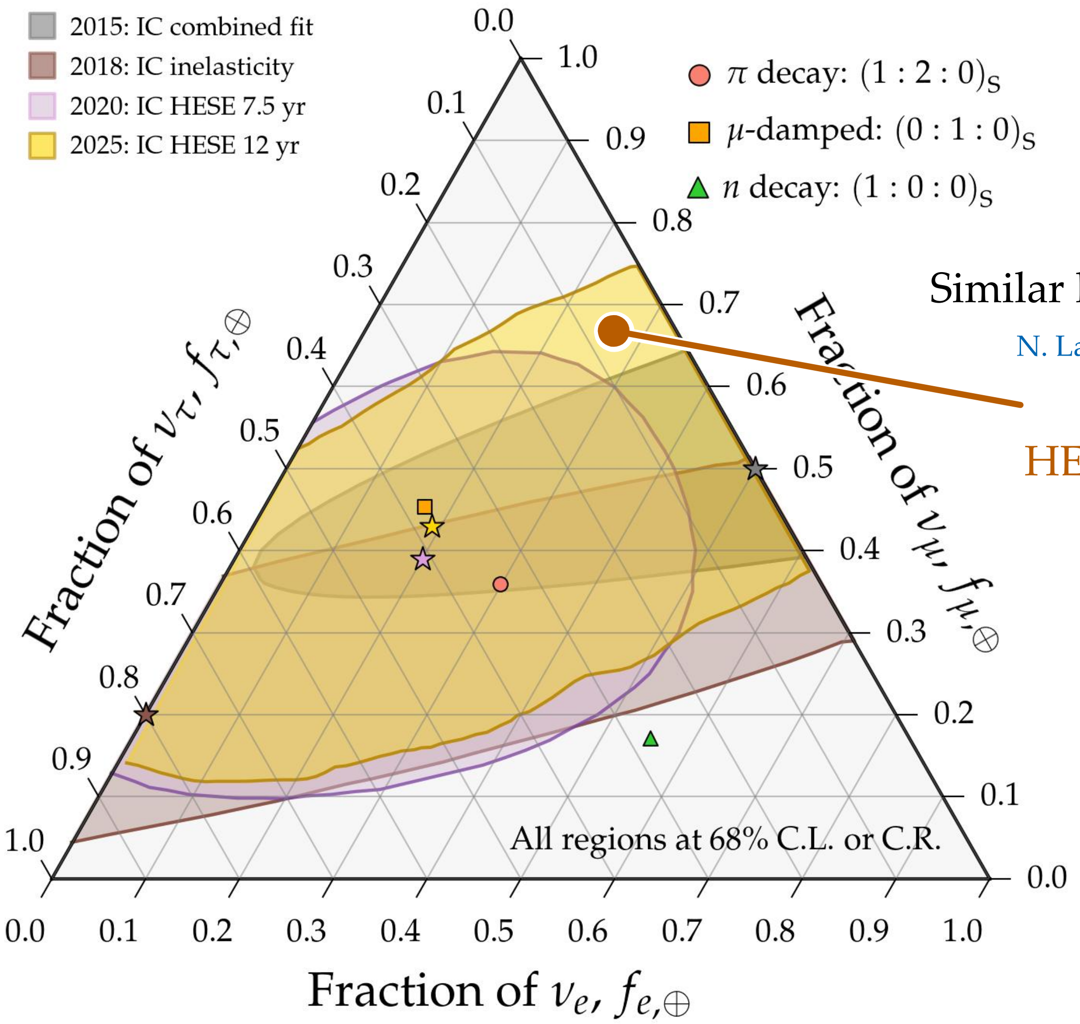

Similar likelihood as with 7.5 yr

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

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

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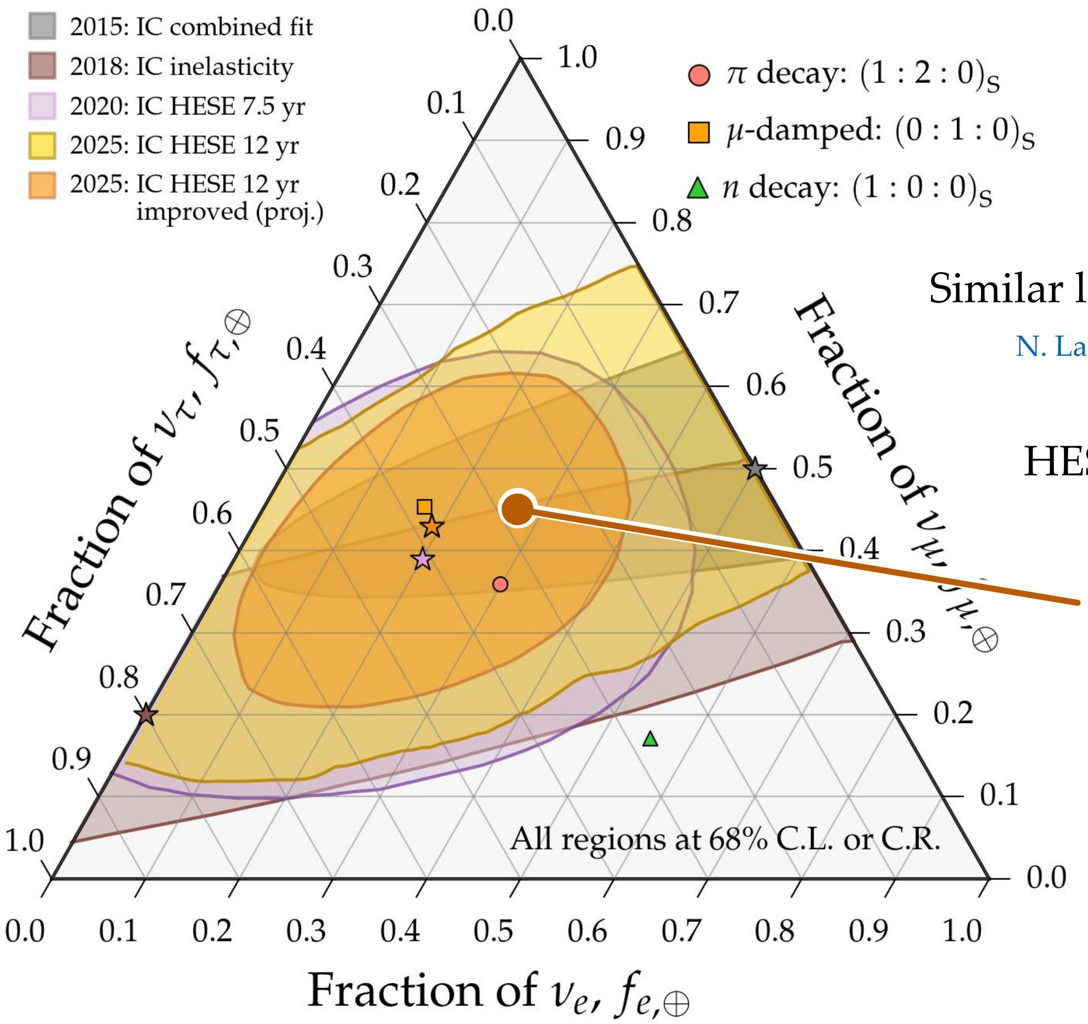

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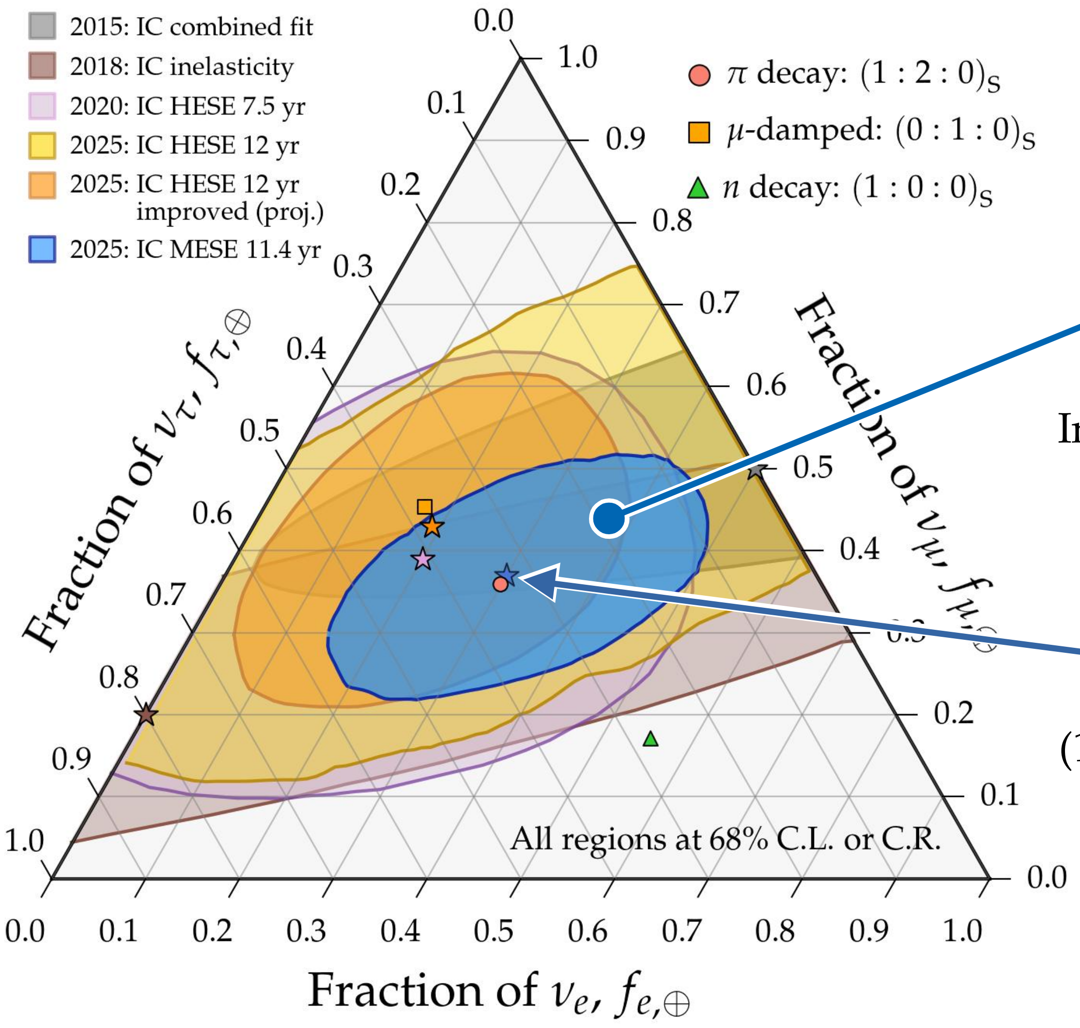
PoS(ICRC2025)1198

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



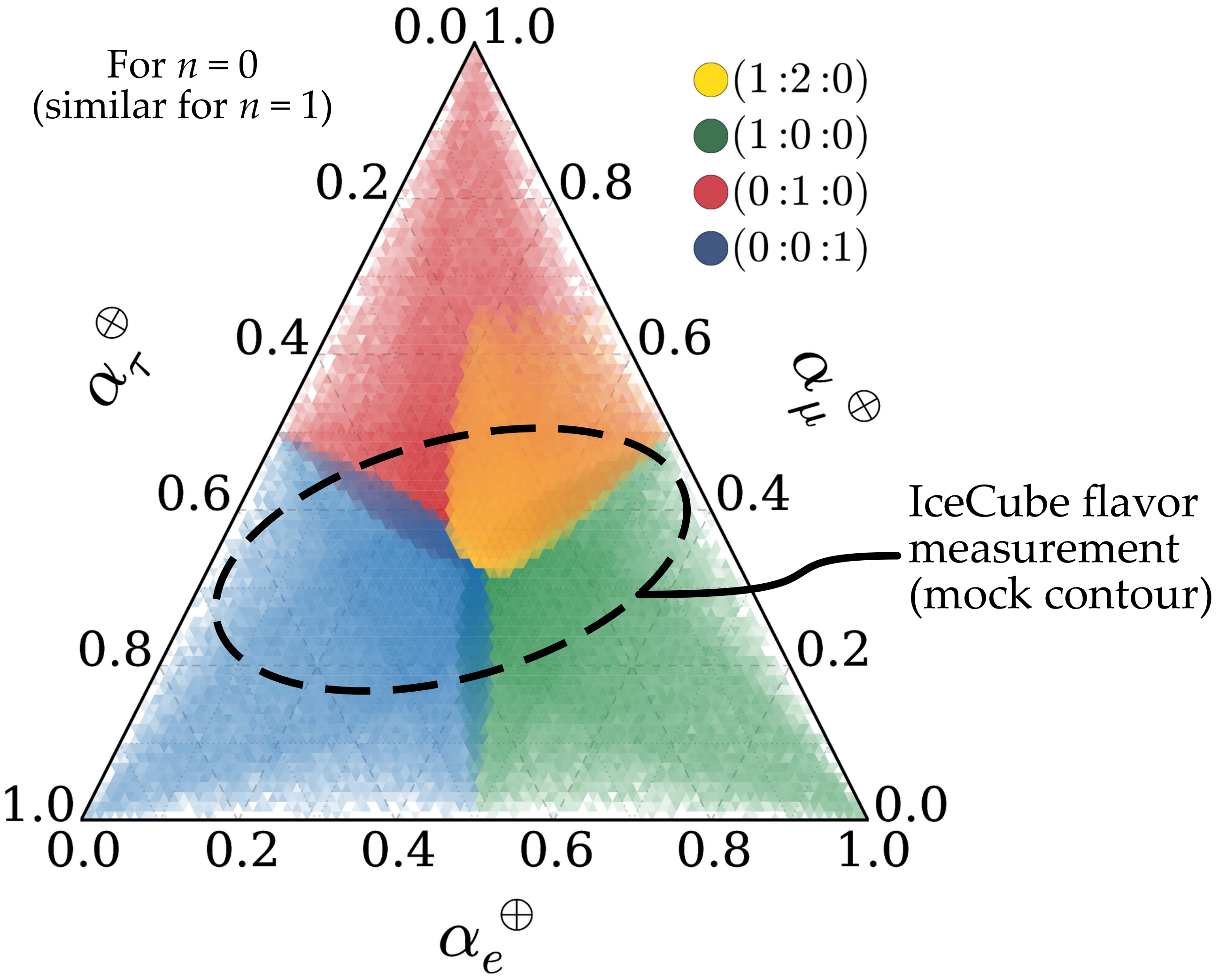
MESE events (> 1 TeV) are more abundant

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



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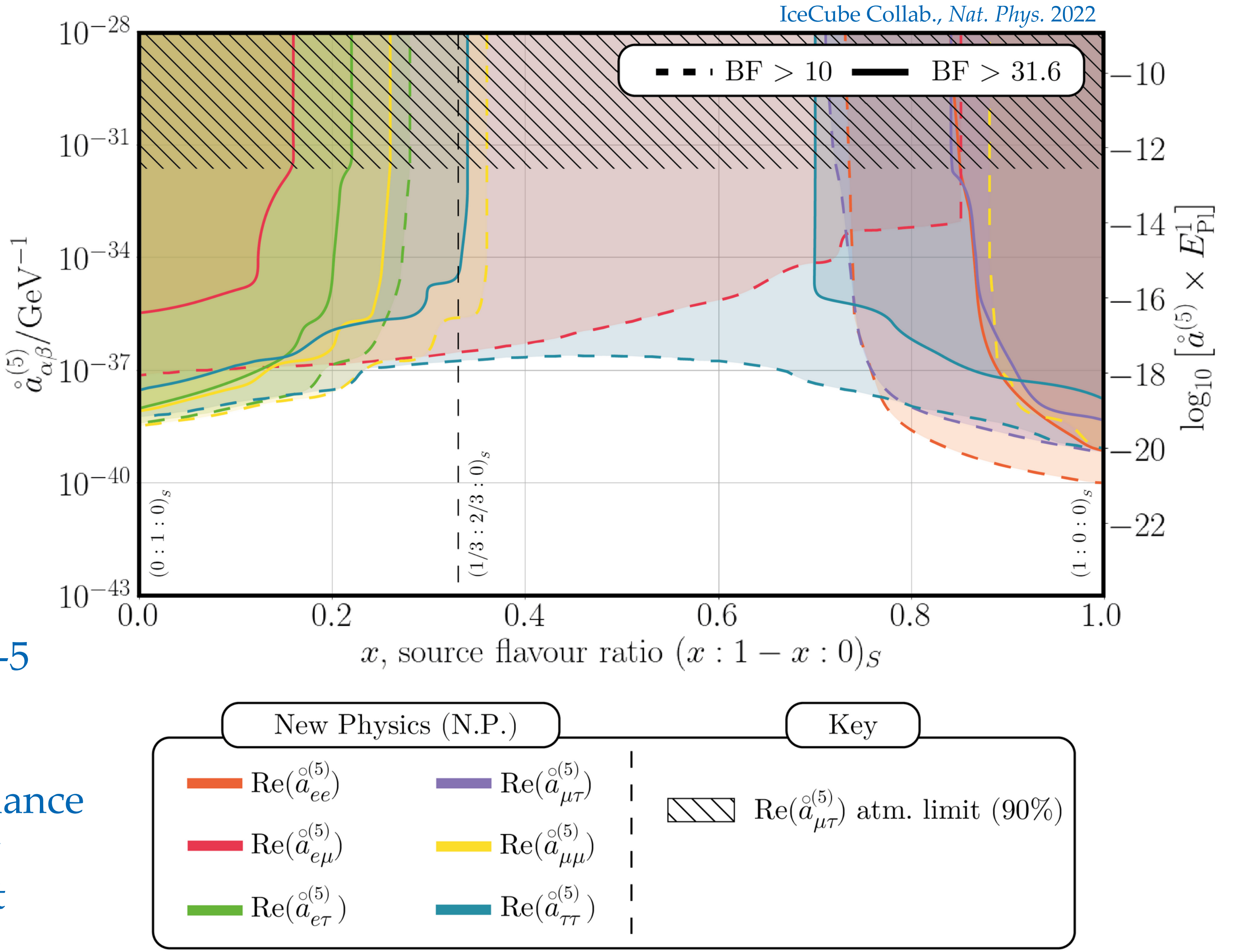


Dimension-5
CPT-odd
isotropic
Lorentz-invariance
-violating
coefficient

Backgrounds

Atmospheric ν & muons, astrophysical non-BSM ν, cosmic rays

Experimental limitations

Energy & angular resolution, detector efficiency, flavor identification

Neutrino properties

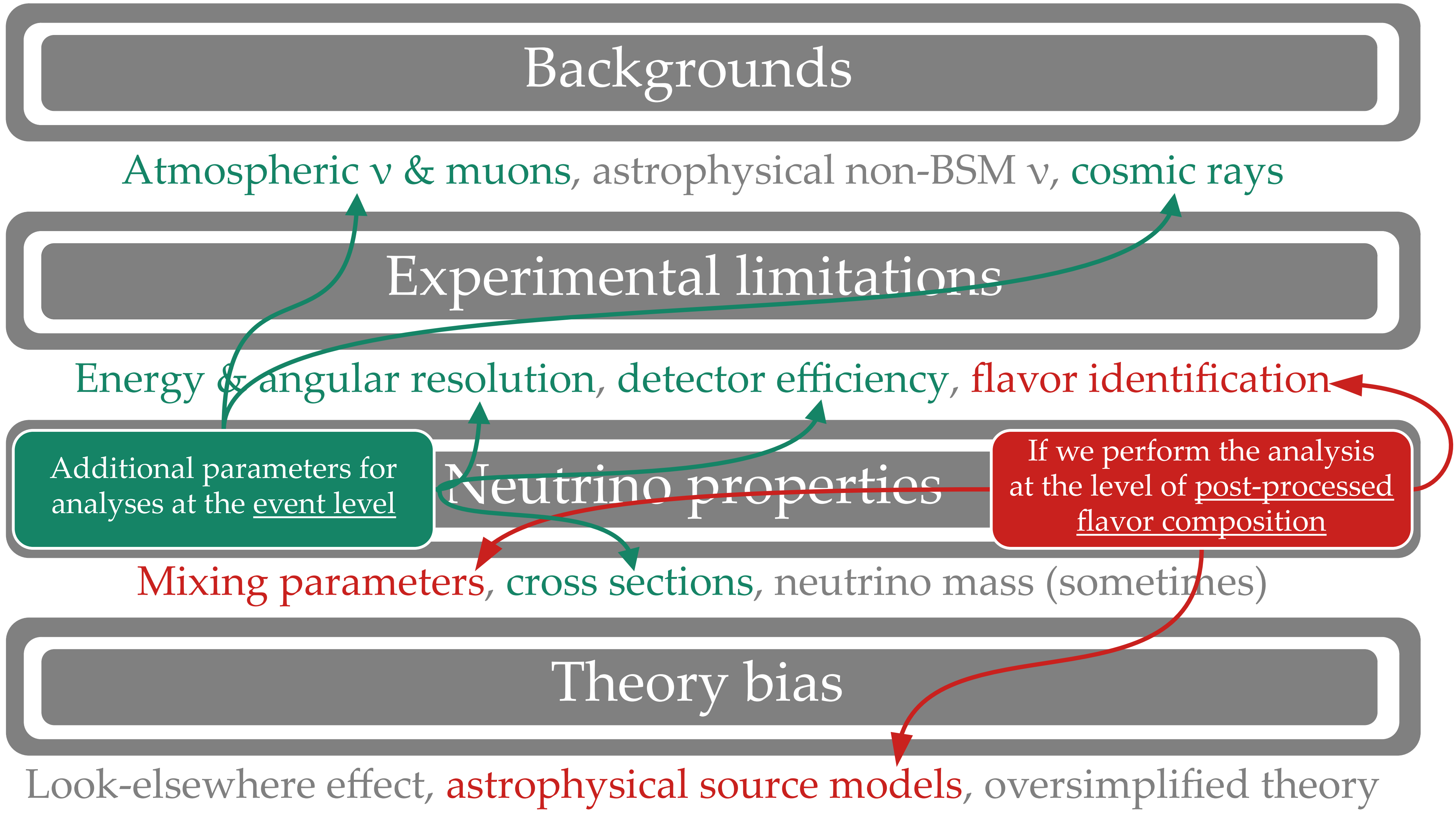
Mixing parameters, cross sections, neutrino mass (sometimes)

If we perform the analysis at the level of post-processed flavor composition

Theory bias

Look-elsewhere effect, astrophysical source models, oversimplified theory

Direction-dependent LIV in flavor



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Additional parameters for analyses at the event level
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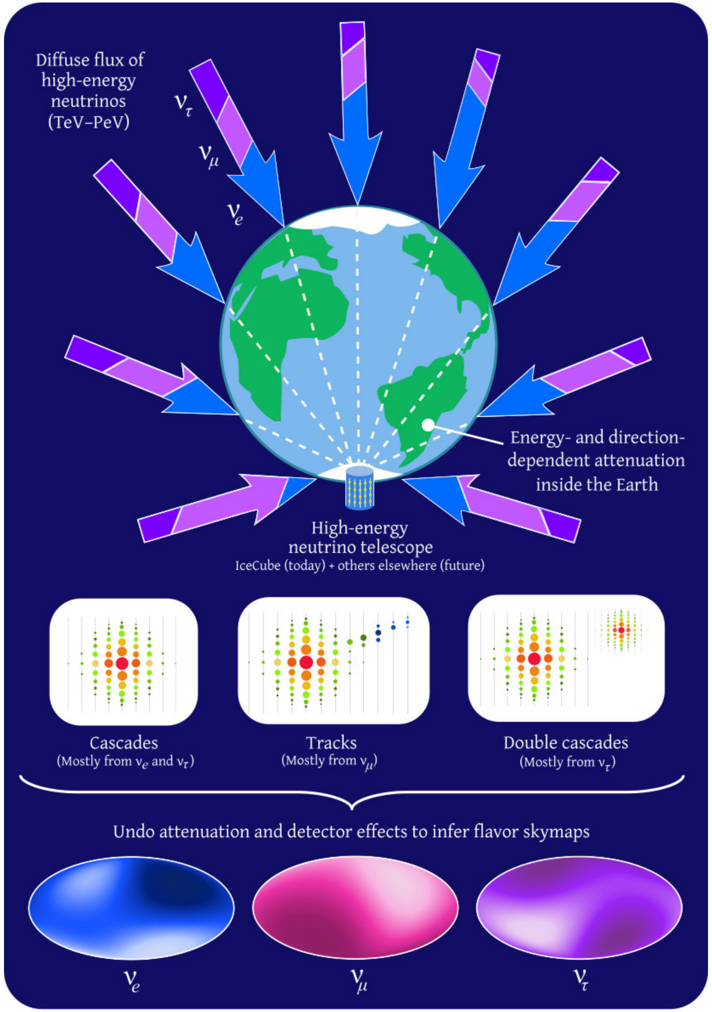
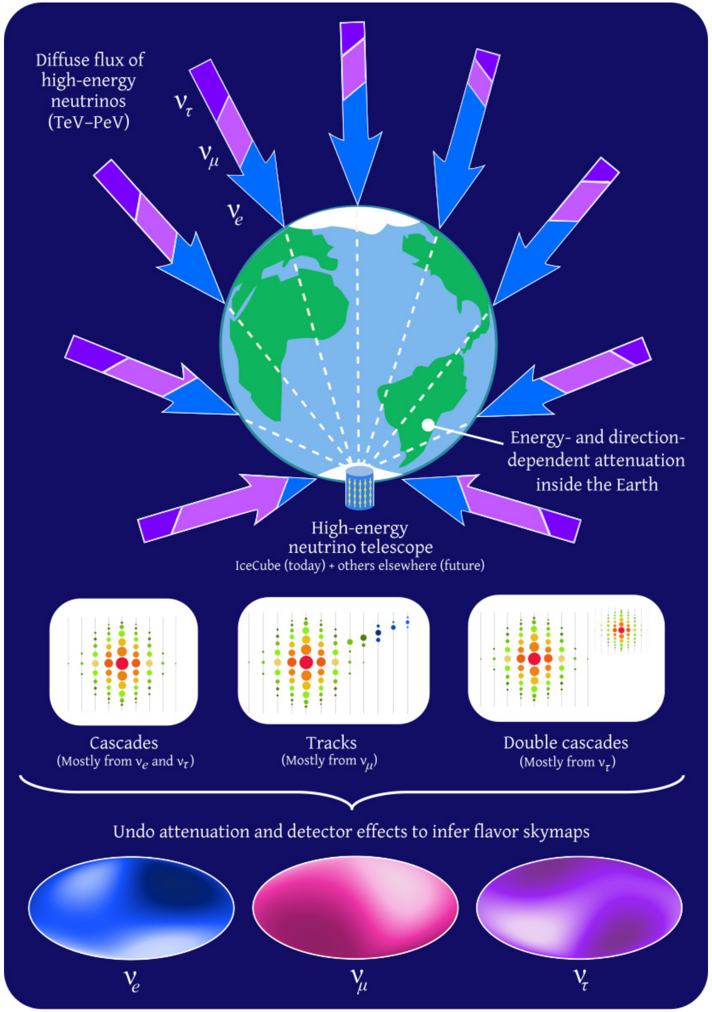
Flavor anisotropy in the high-energy neutrino sky



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



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

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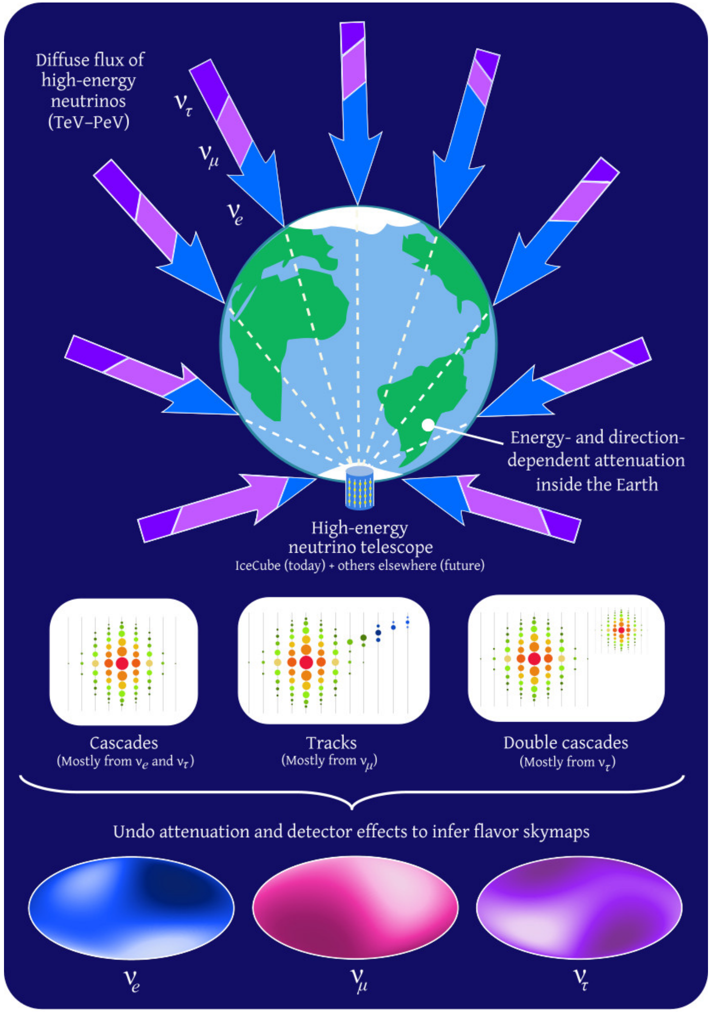

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Telalovic, **MB**, *JCAP* 2025

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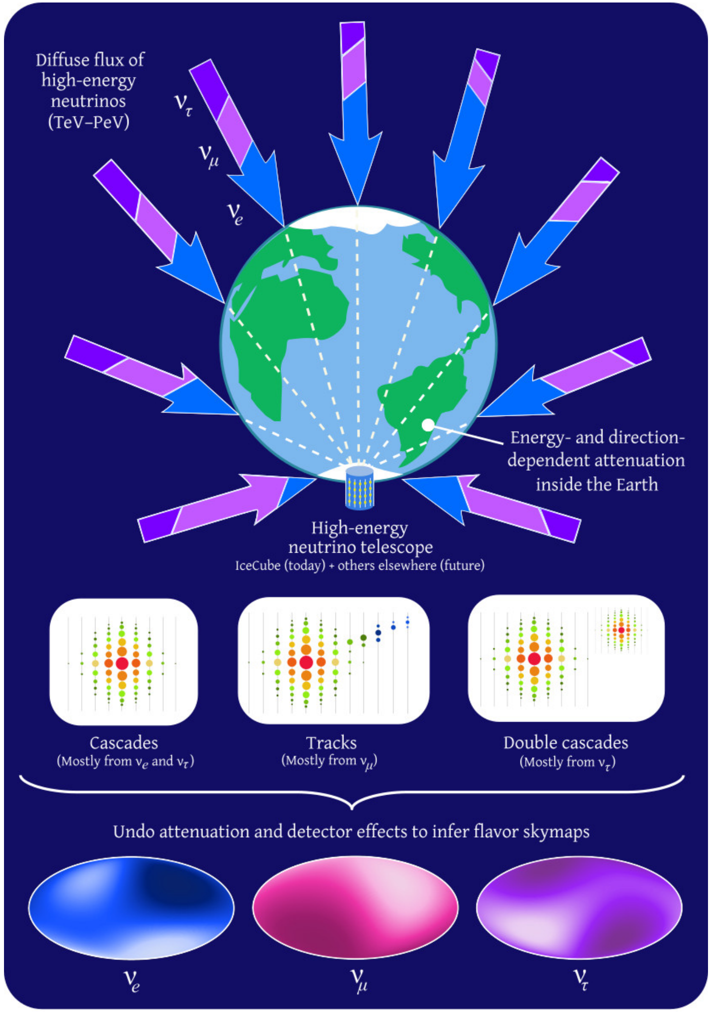

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From the angular distribution of detected events in neutrino telescopes (HESE cascades, tracks, double cascades) …

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

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

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

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

Real, public data

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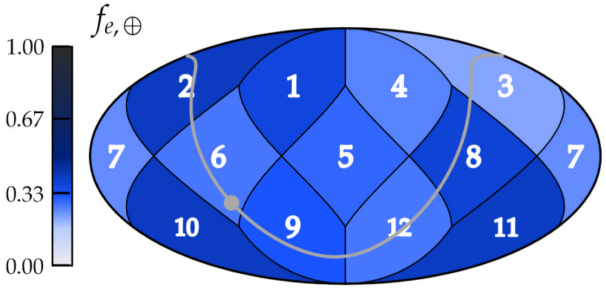

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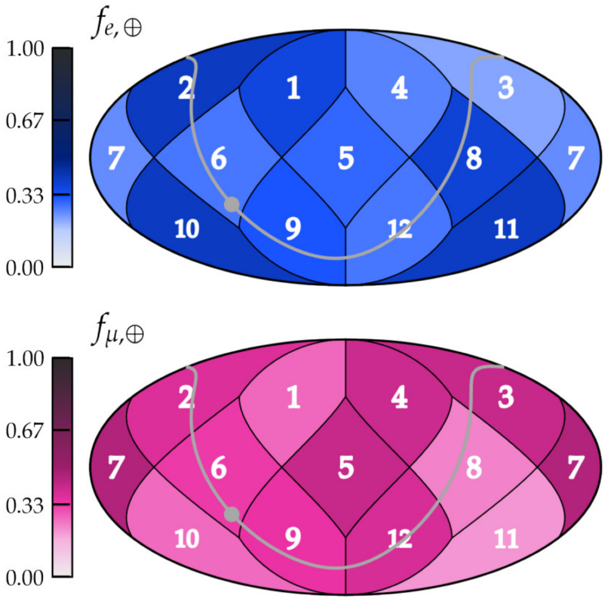

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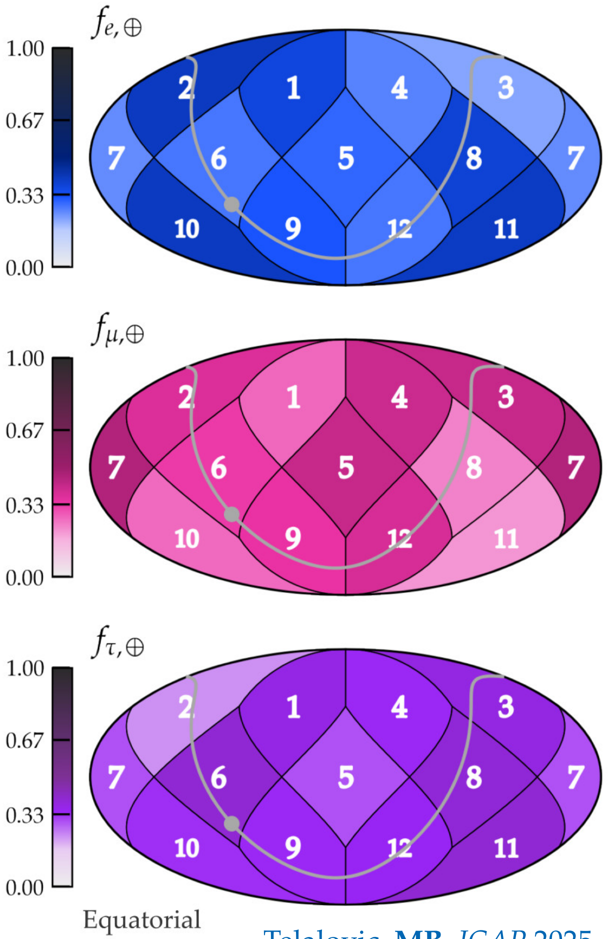

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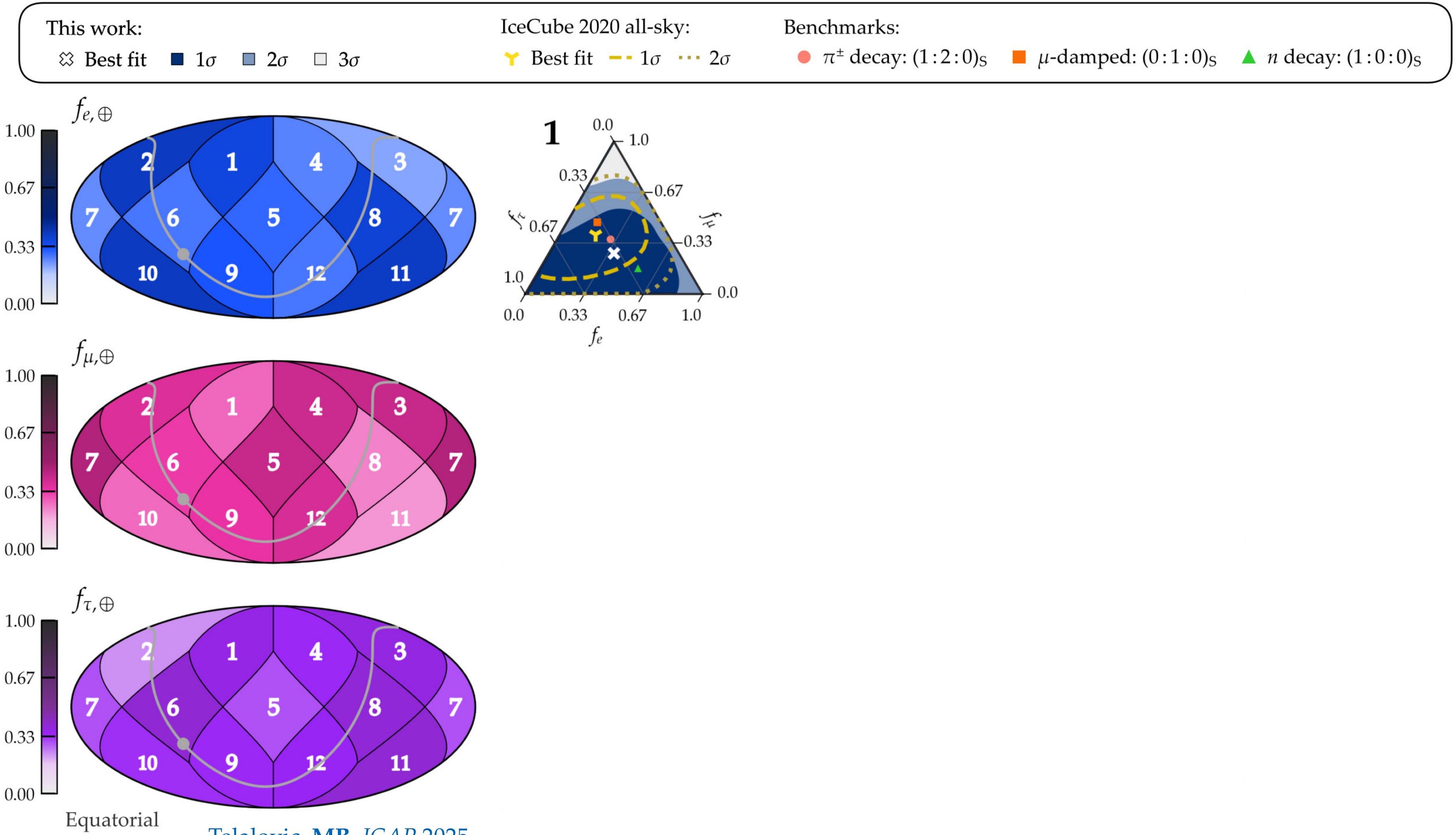

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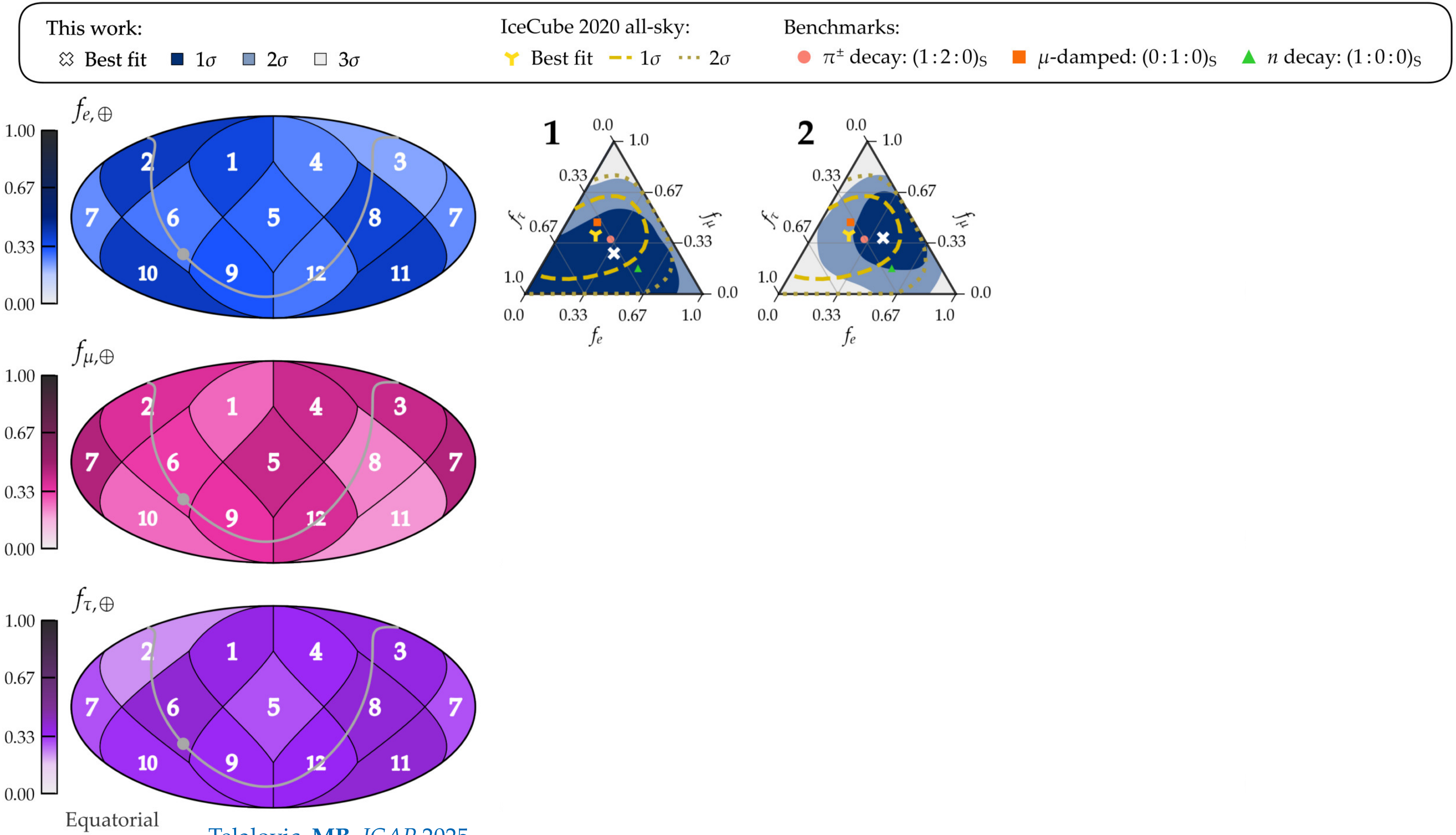

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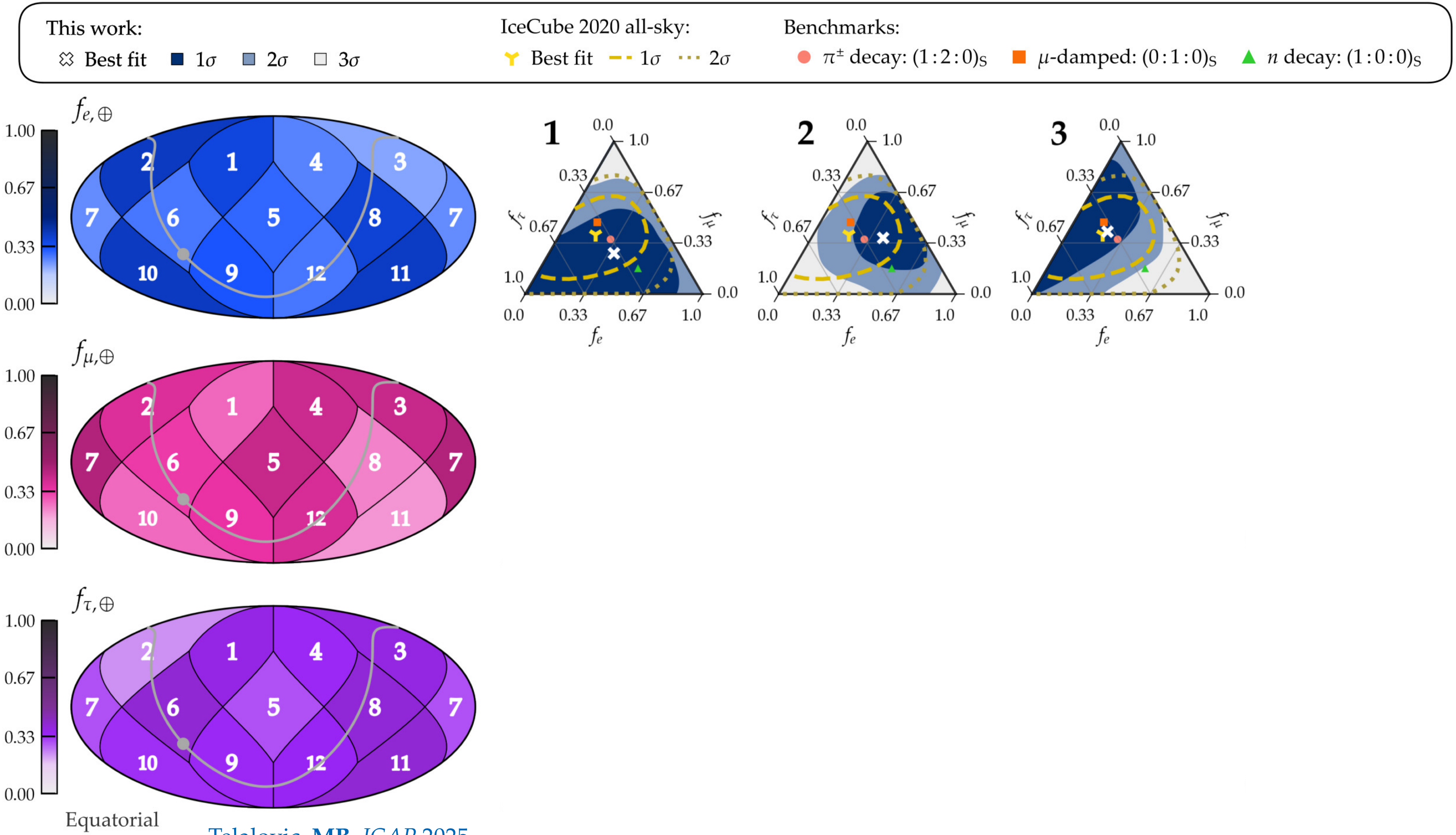

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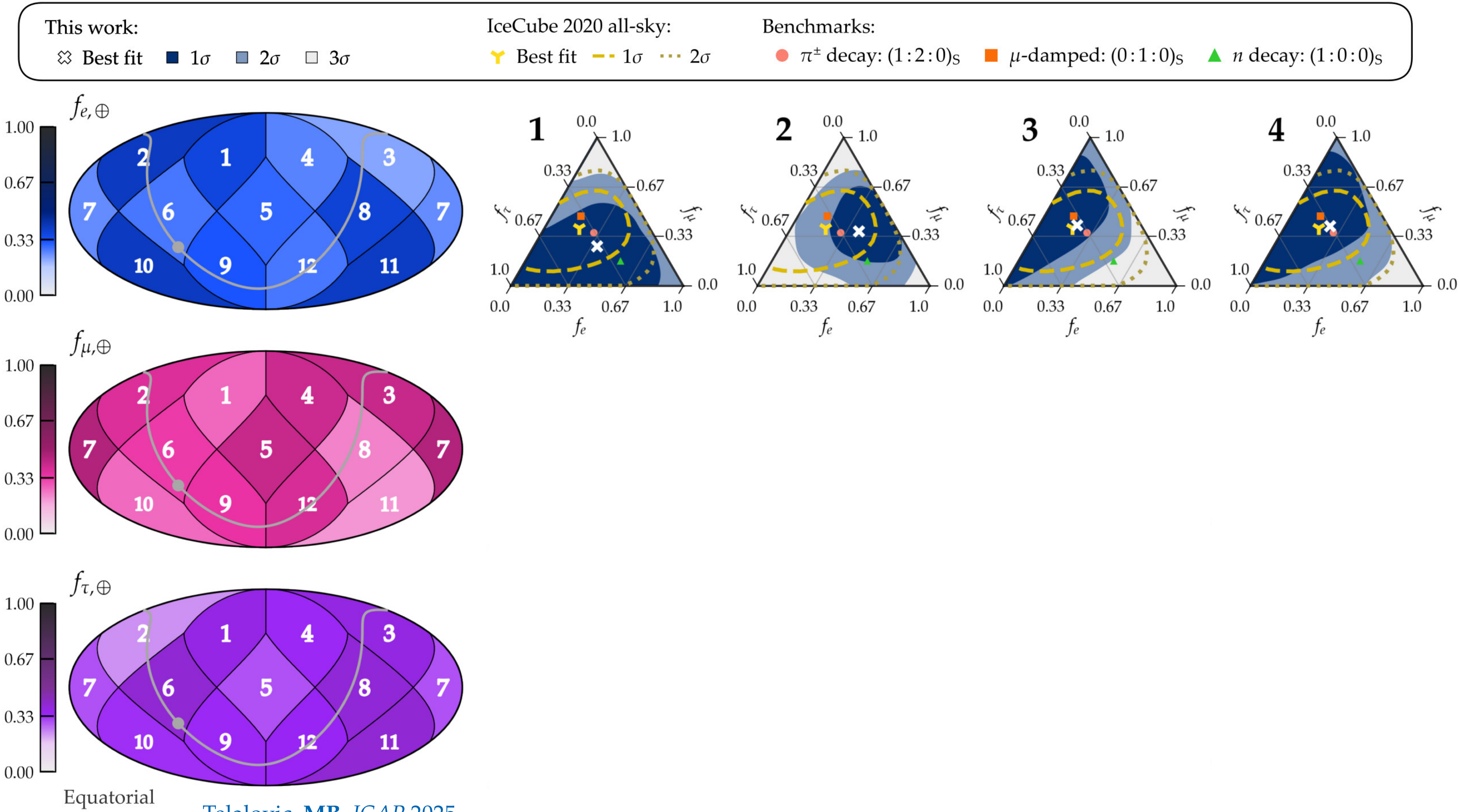

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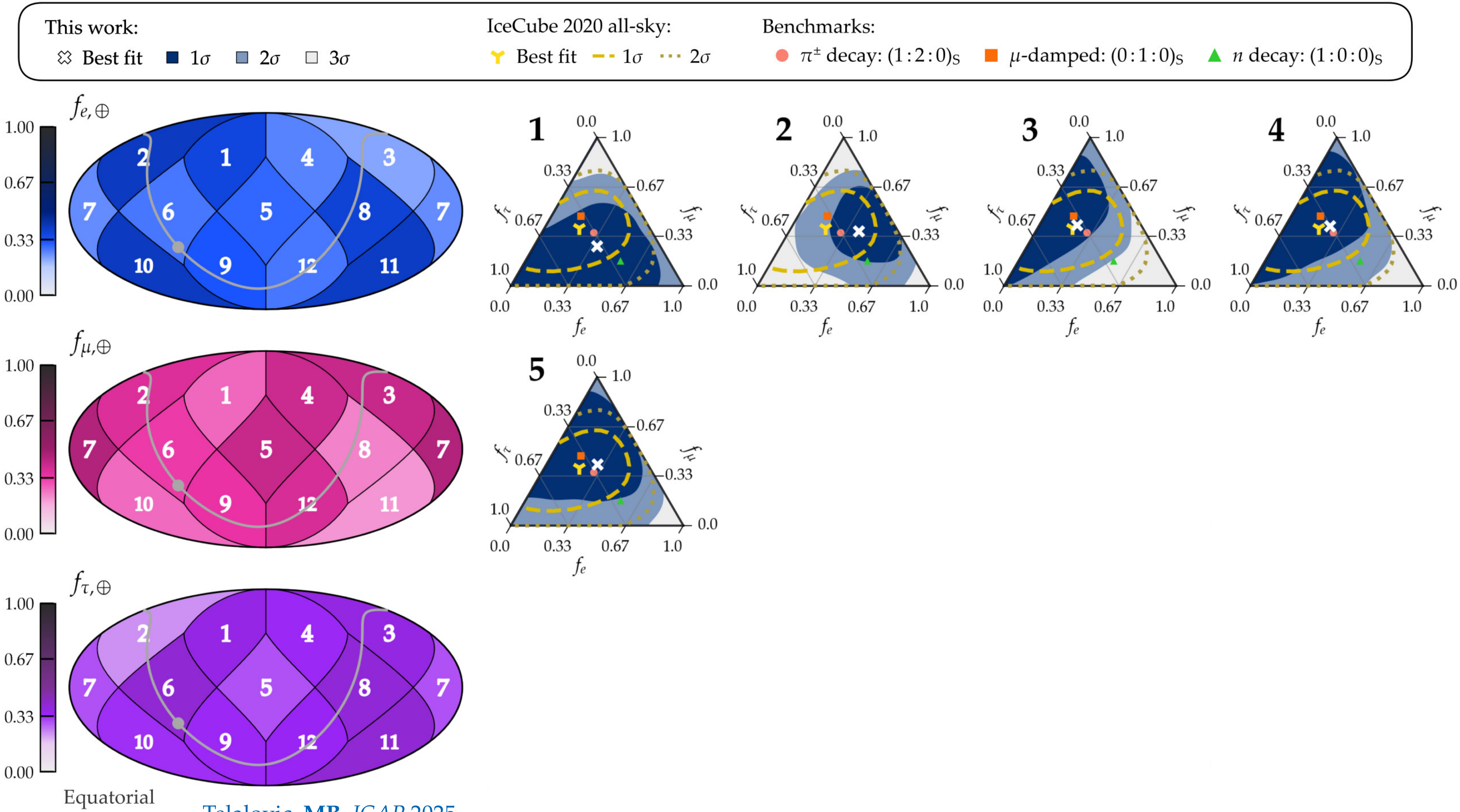

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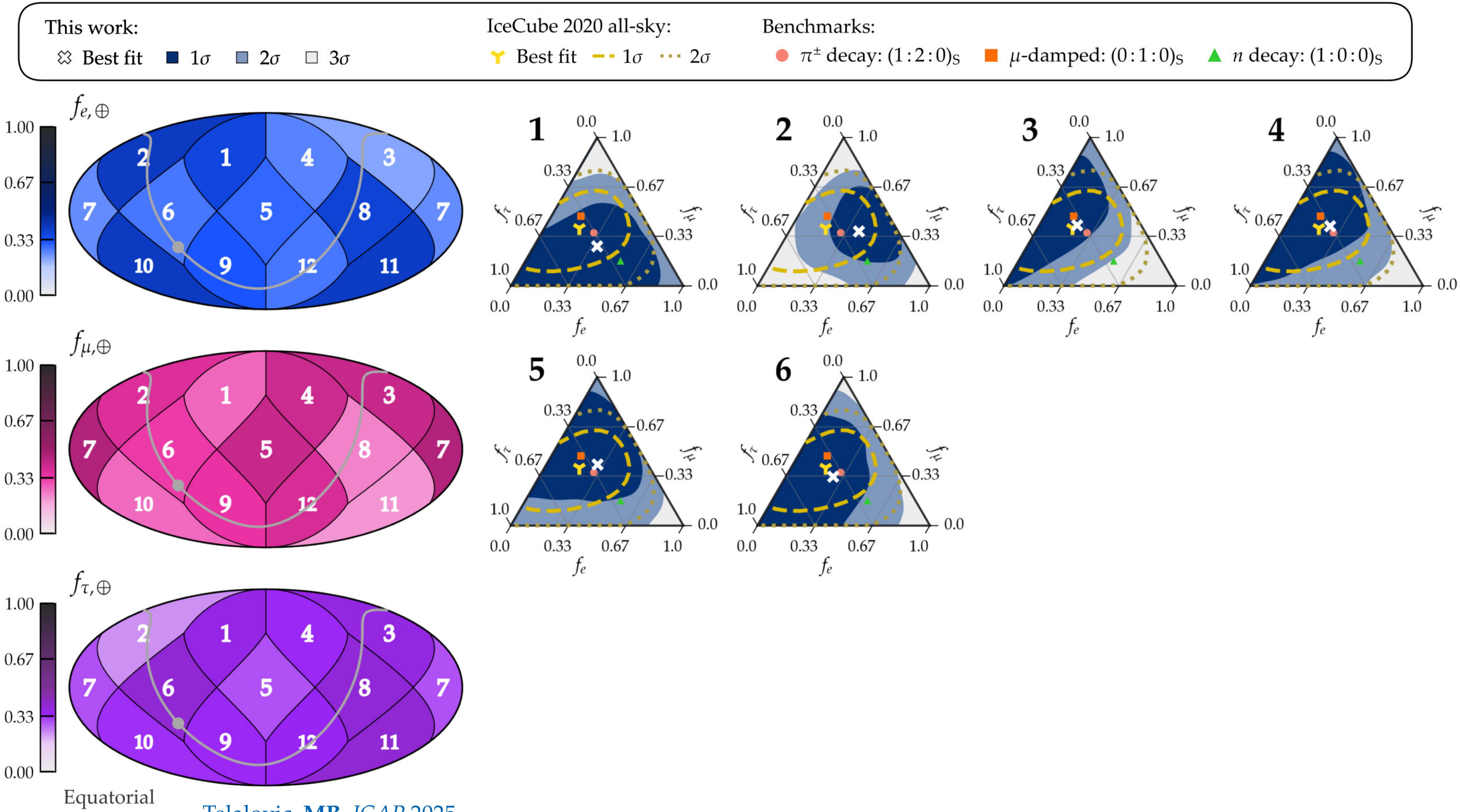

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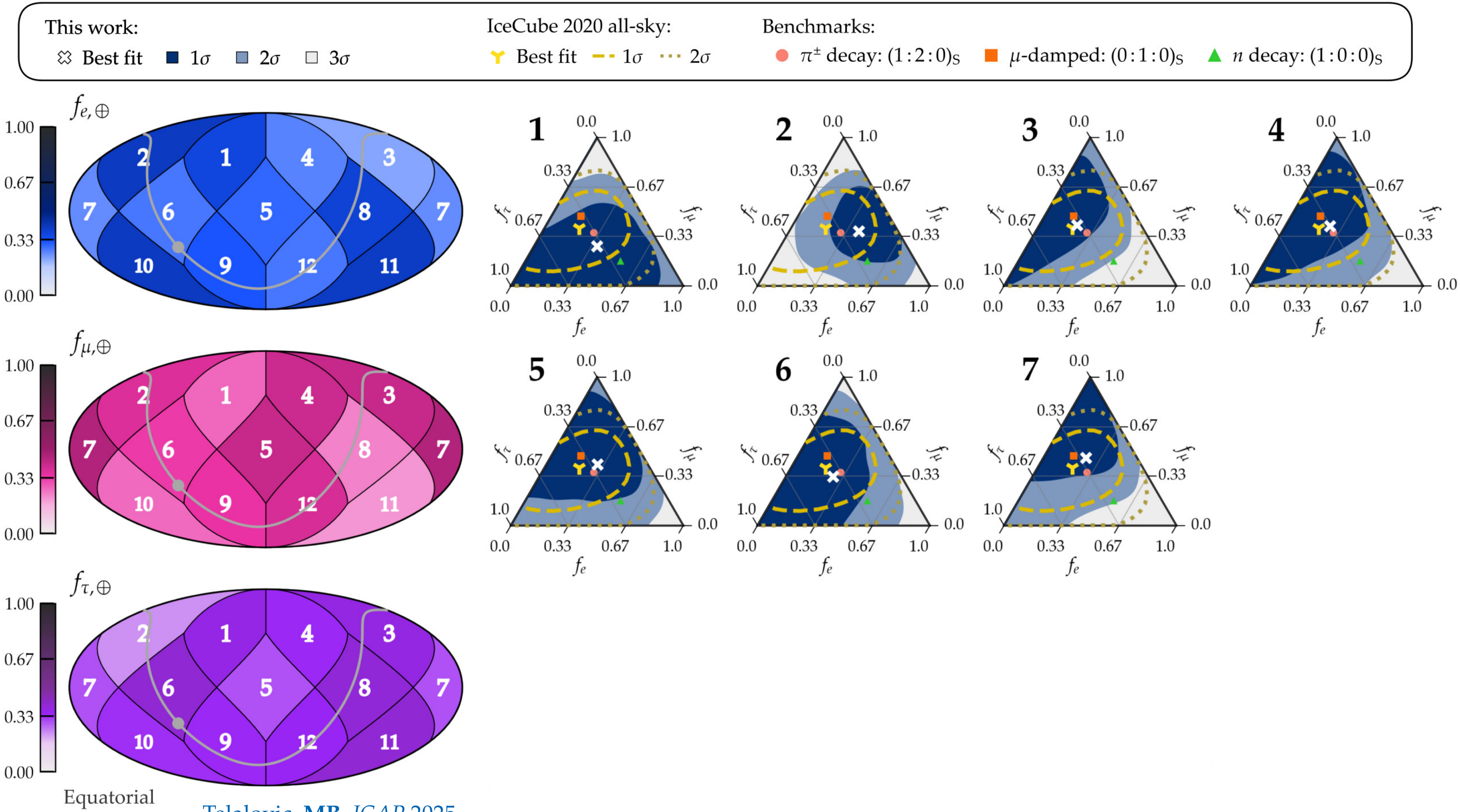


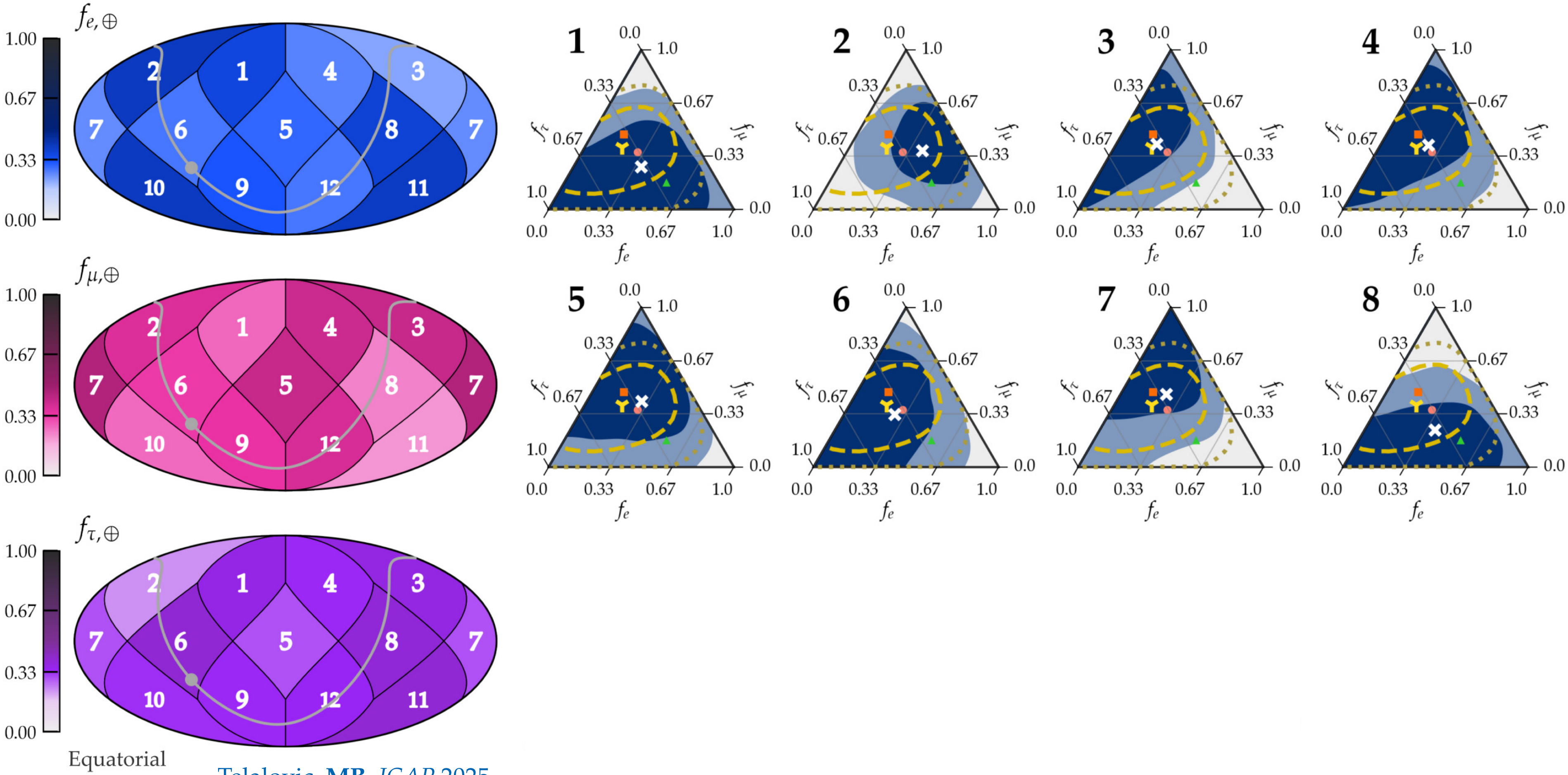
Telalovic, **MB**, *JCAP* 2025

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

This work: ✕ Best fit ■ 1σ ■ 2σ □ 3σ

IceCube 2020 all-sky: Y 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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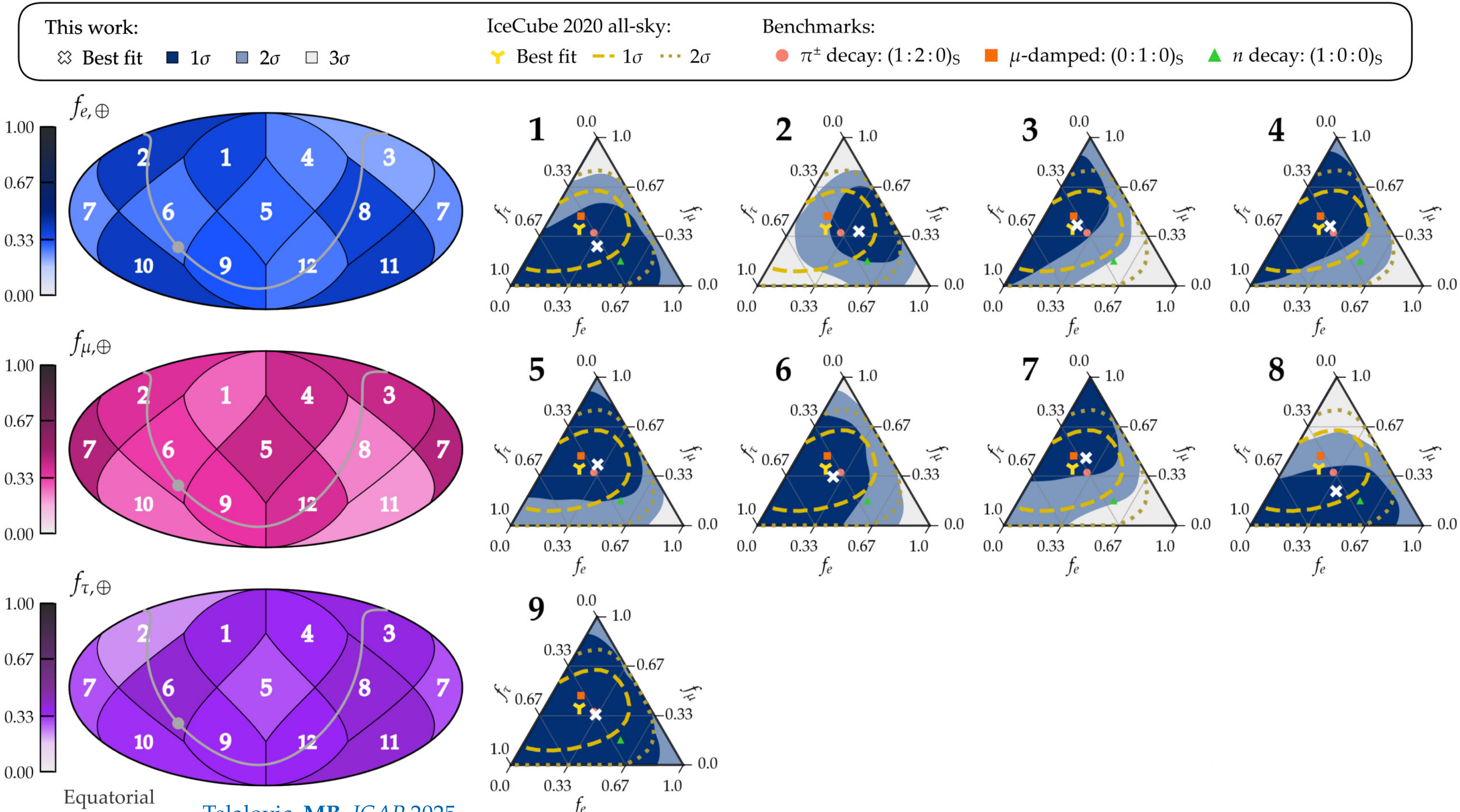

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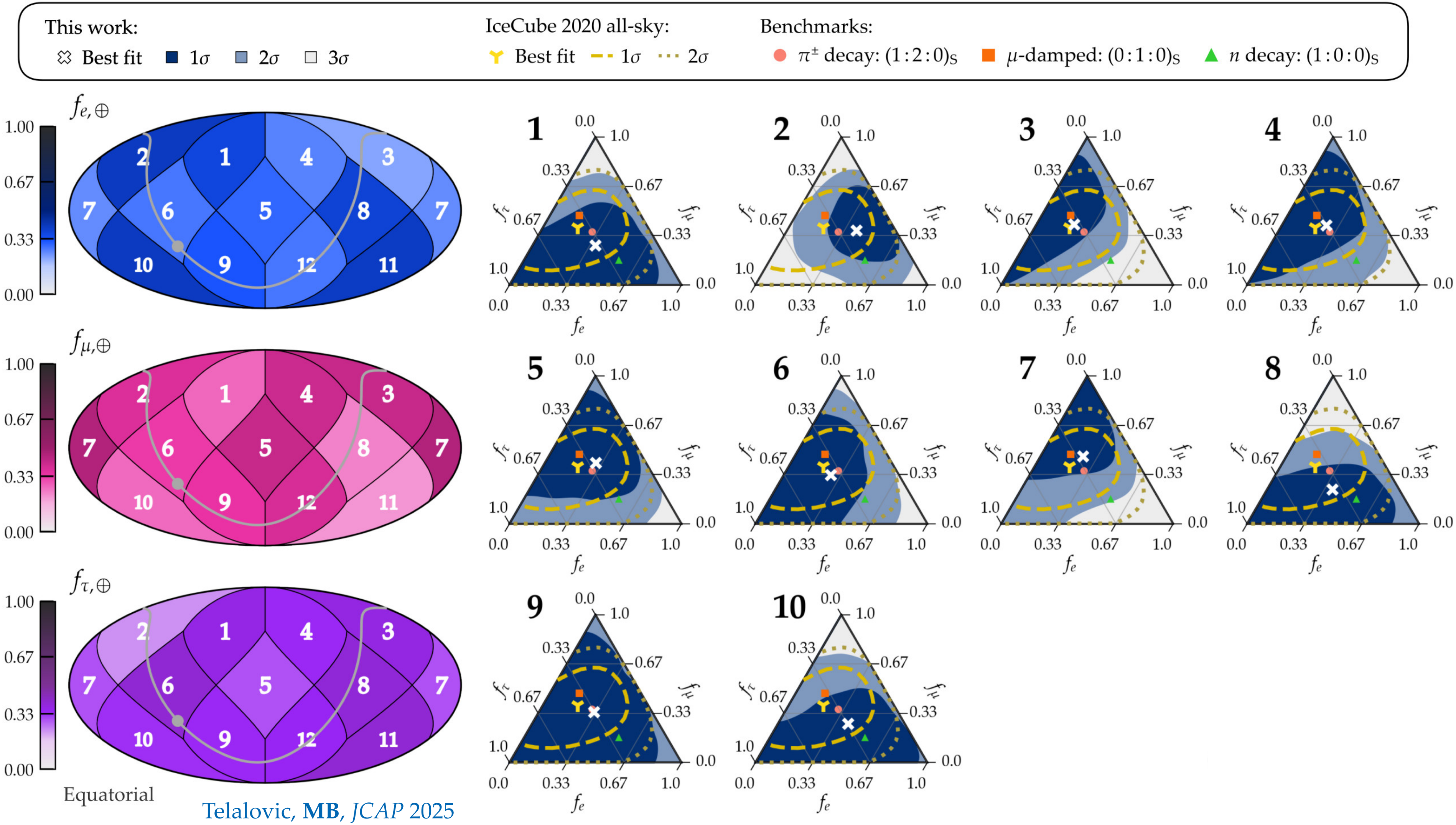

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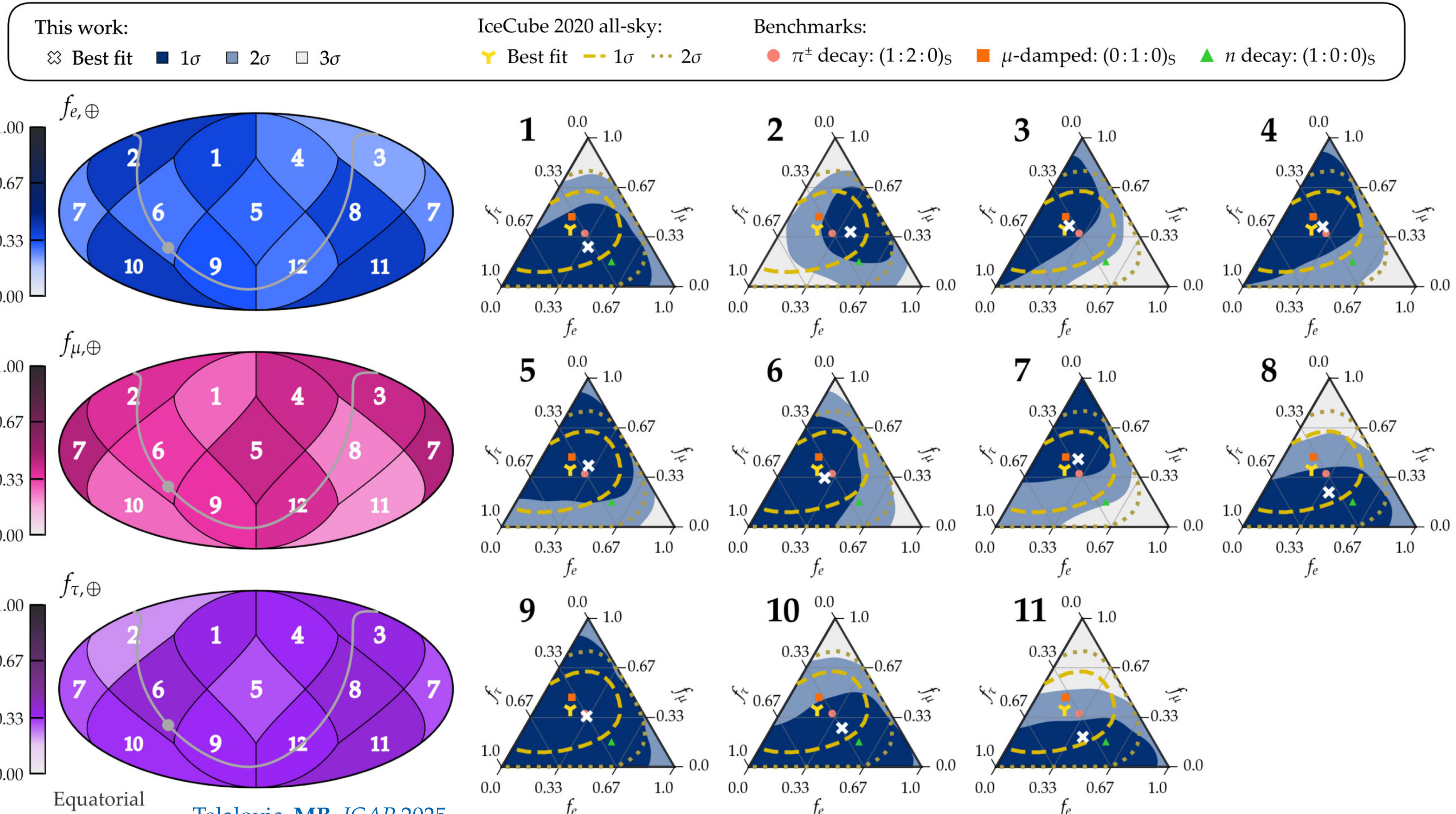

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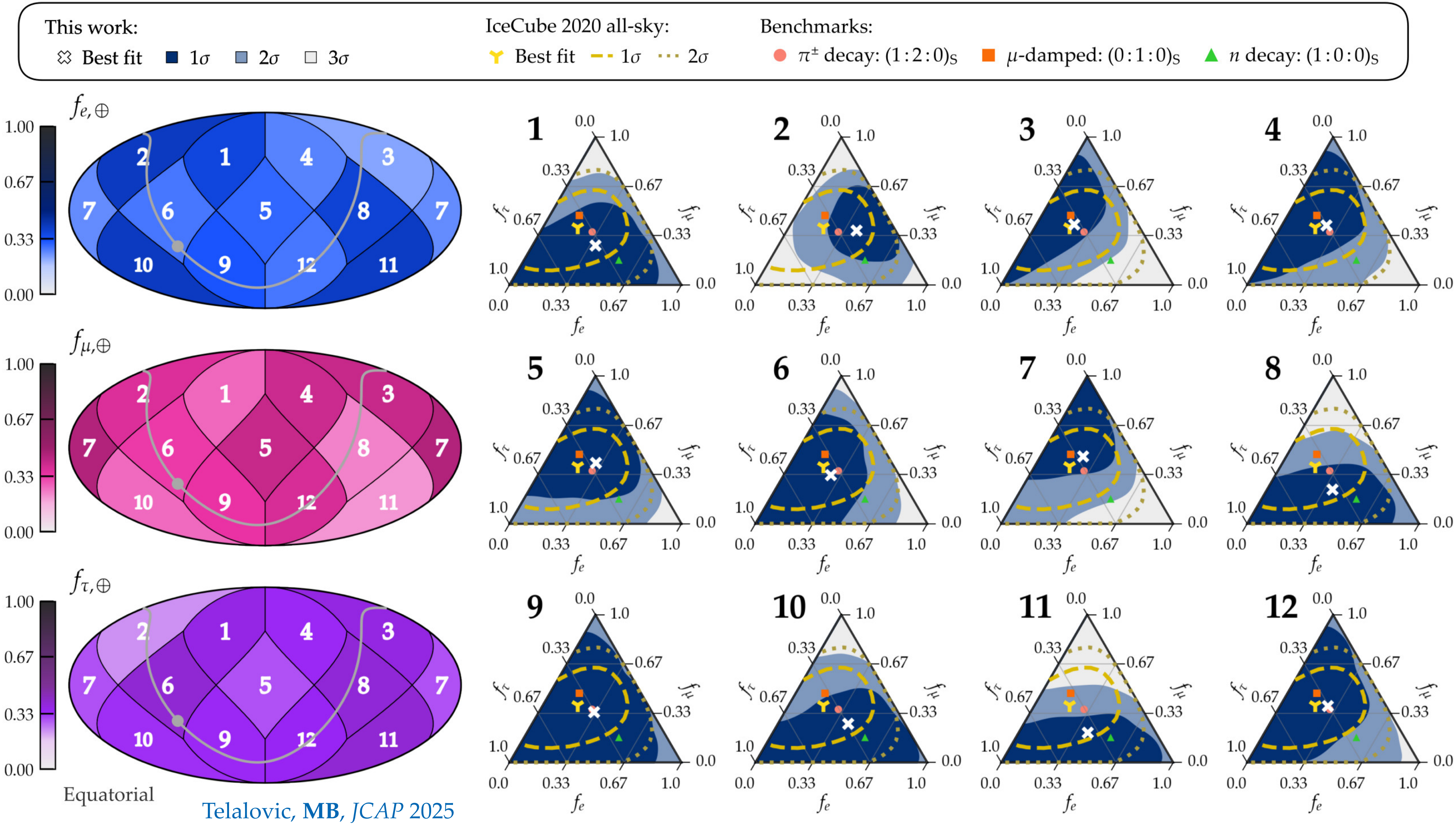

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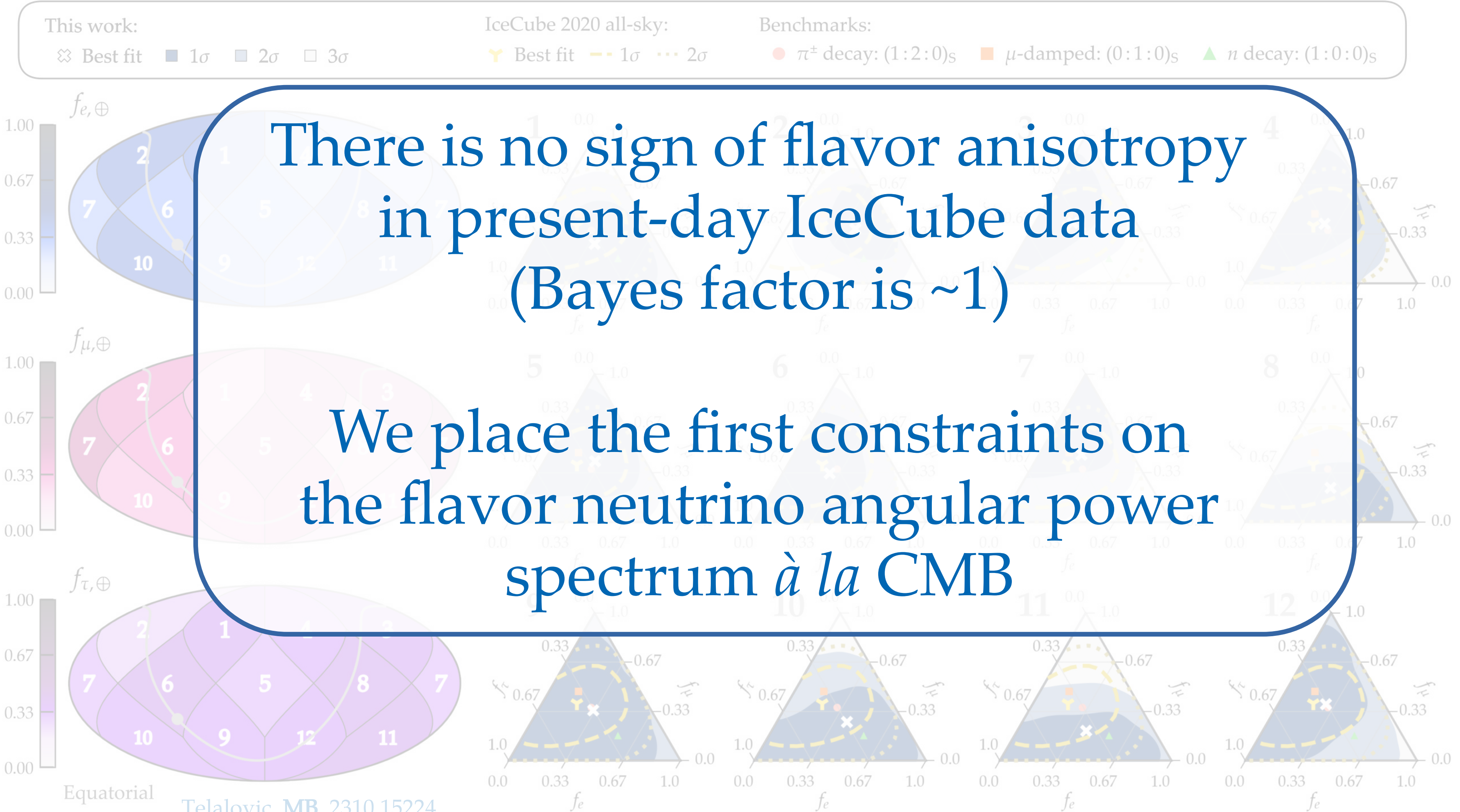
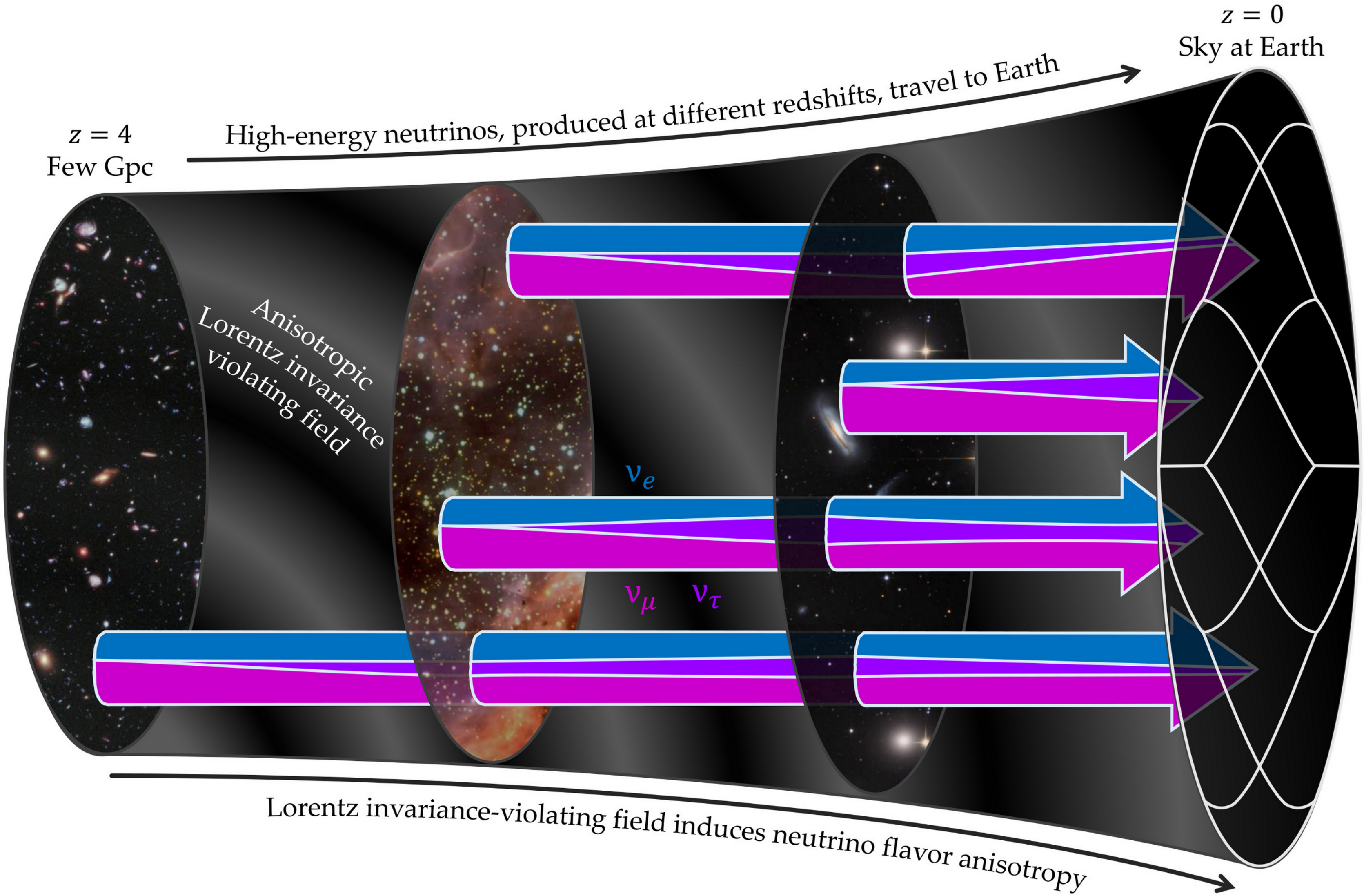


There is no sign of flavor anisotropy in present-day IceCube data (Bayes factor is ~1)

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

Telalovic, MB, 2310.15224



Telalovic, **MB**, *JHEP* 2026

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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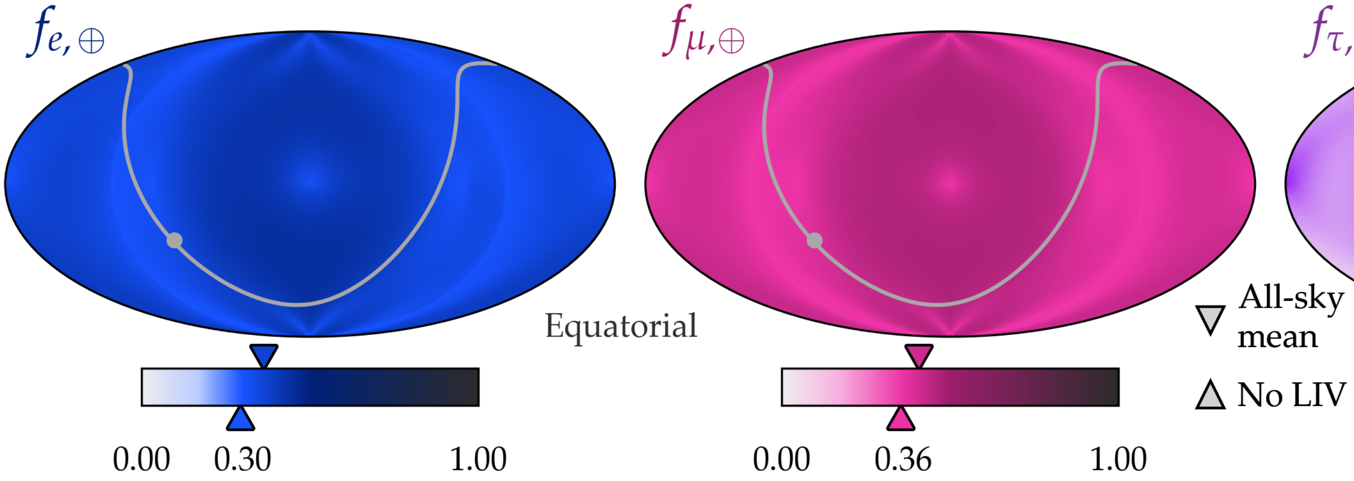

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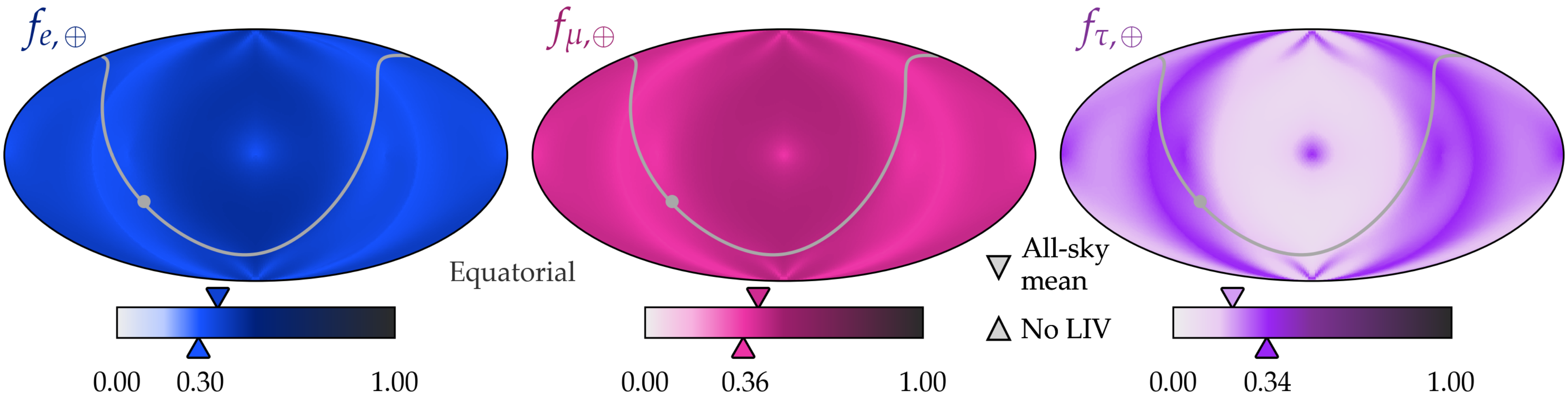

For dimension-5 CPT-odd LIV coefficient

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

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

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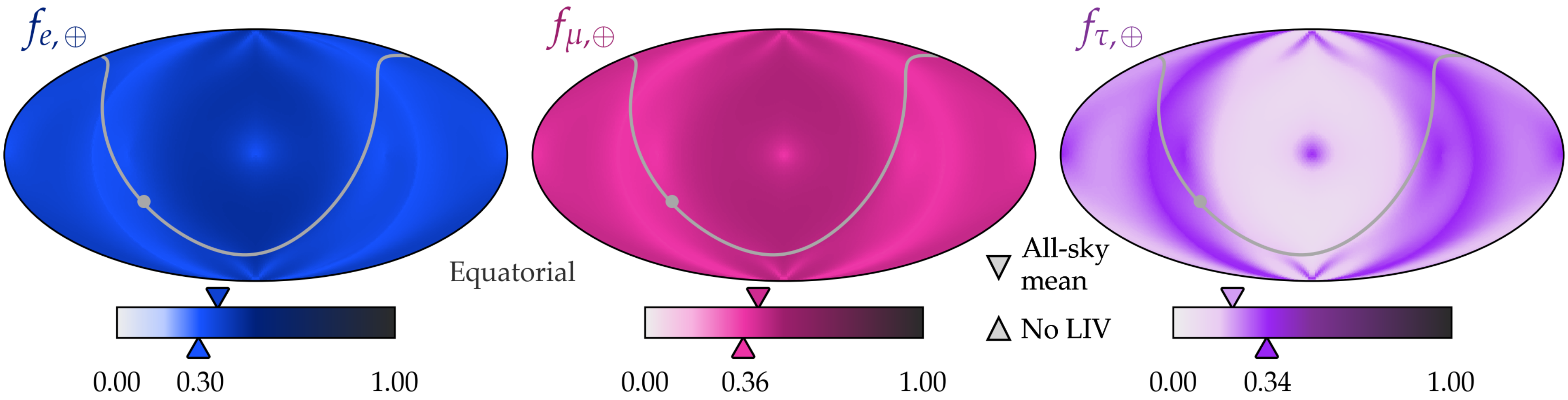


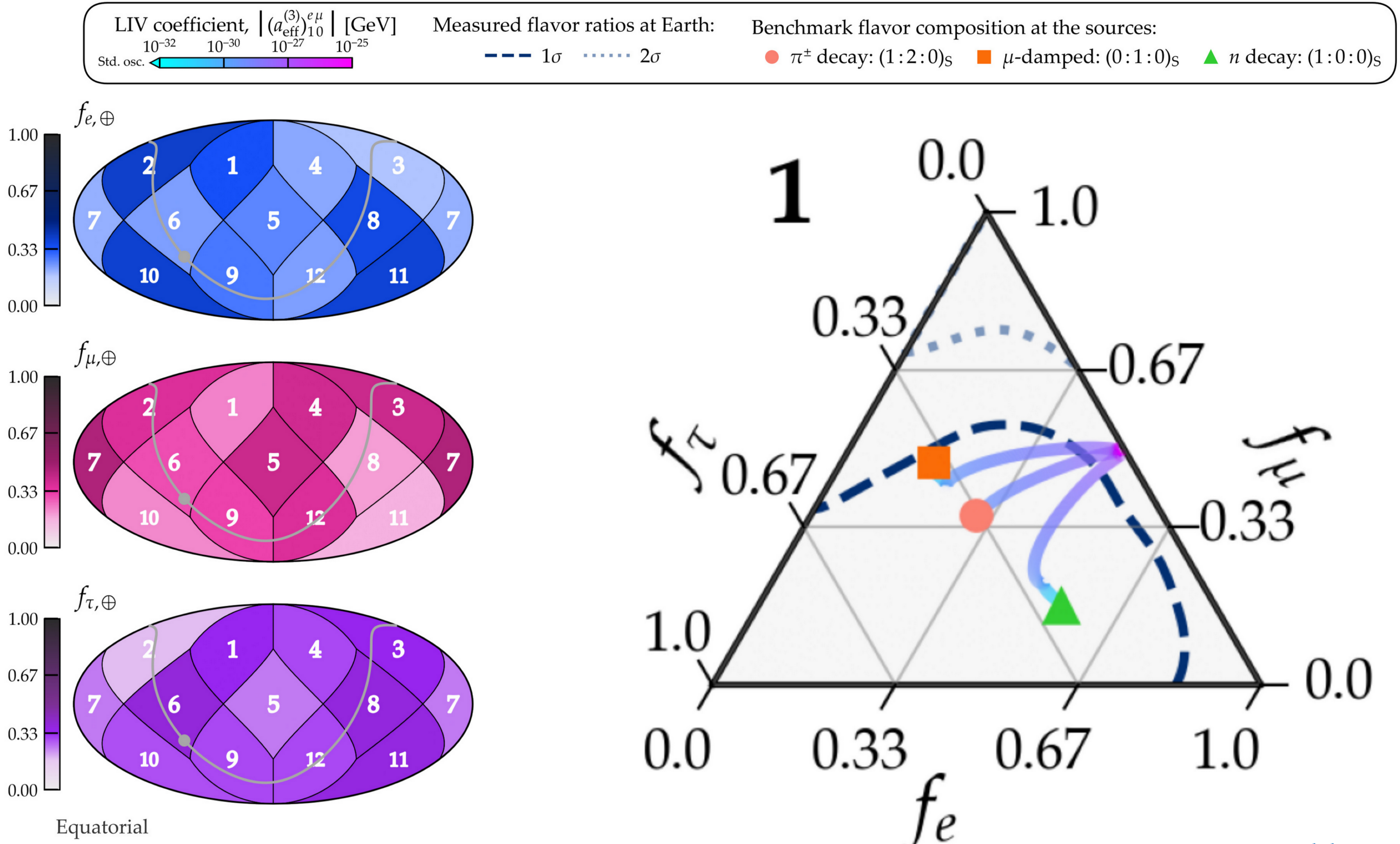
For dimension-5 CPT-odd LIV coefficient

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

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

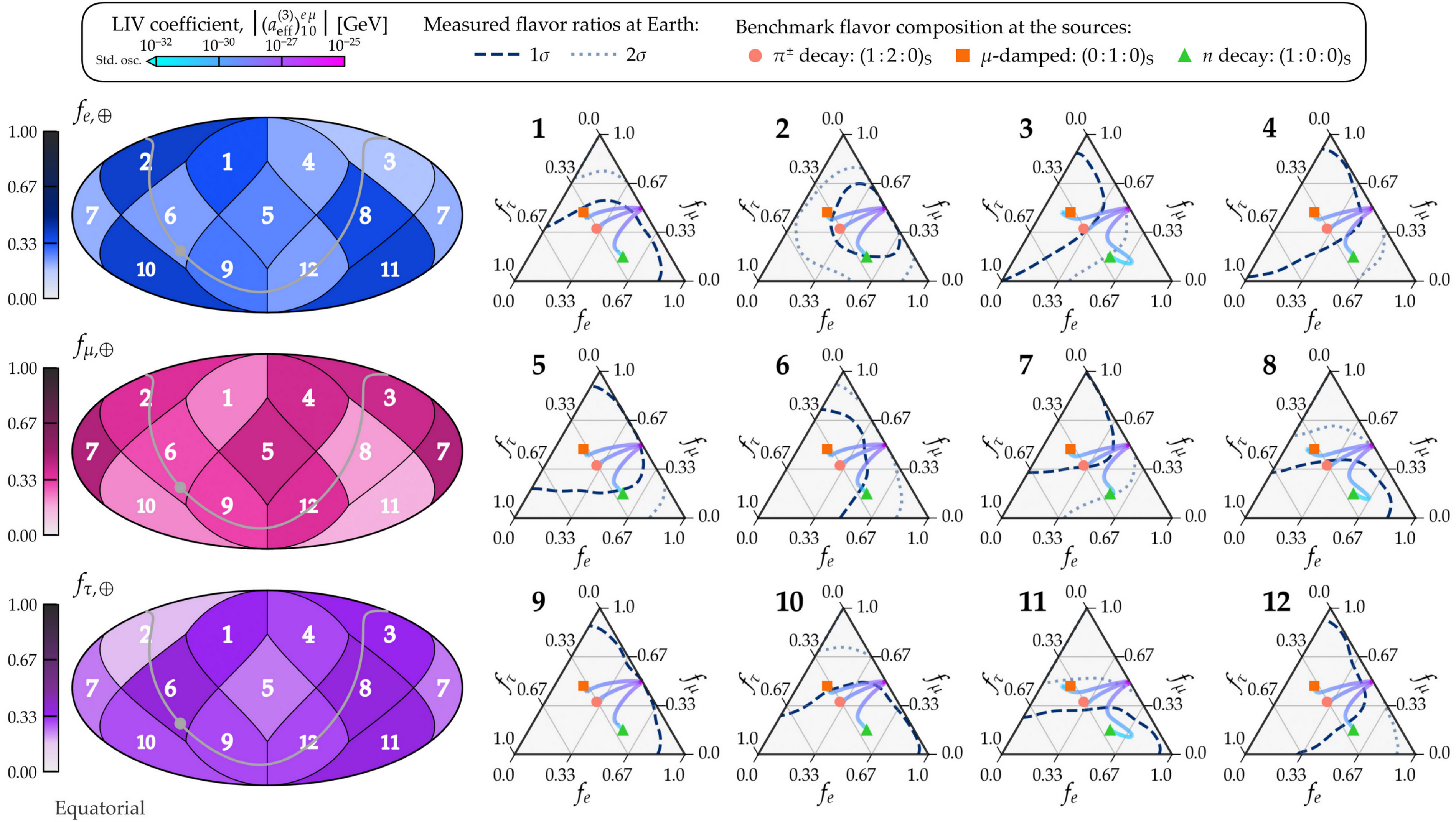
Telalovic, **MB**, *JCAP* 2025

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

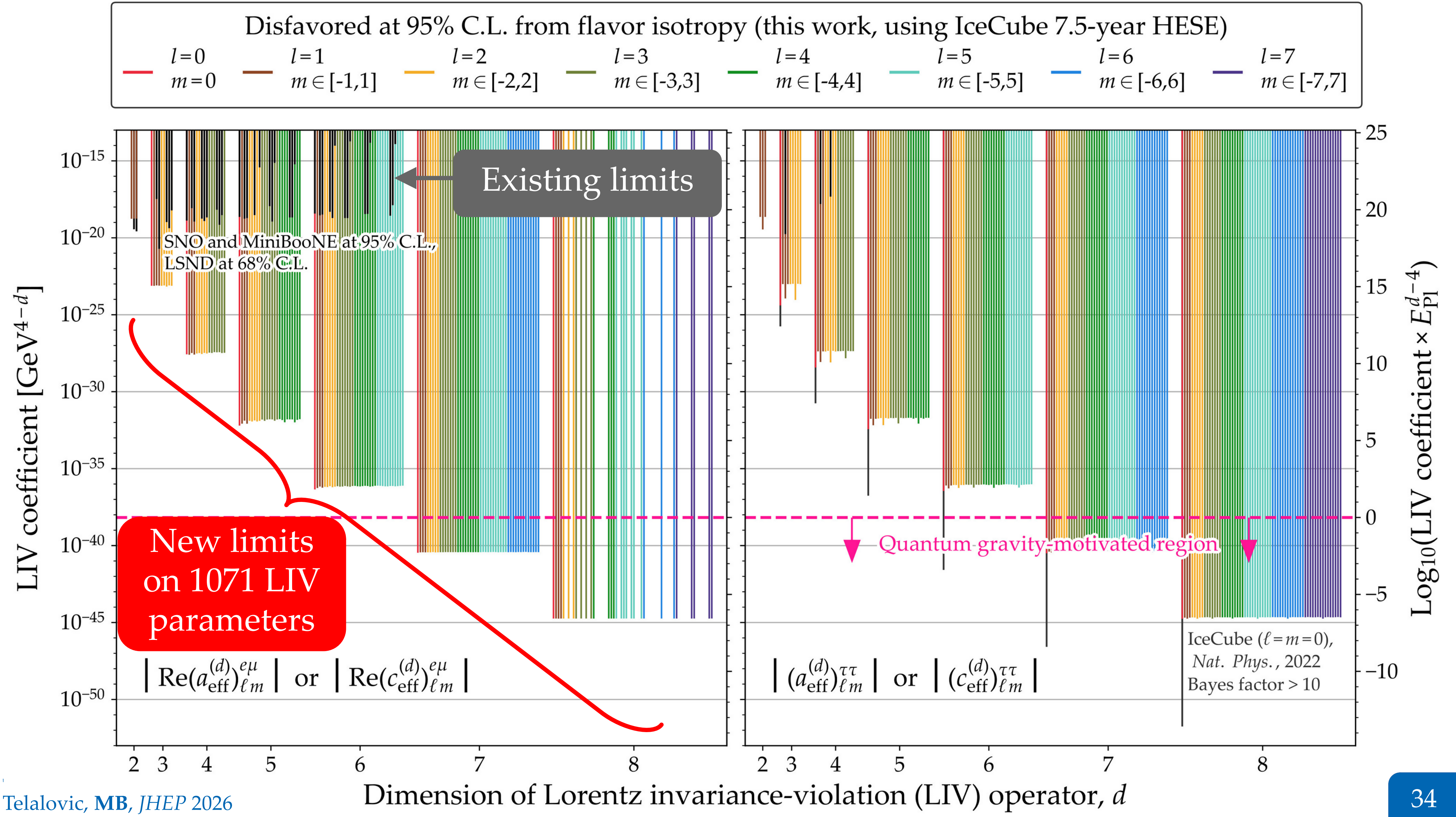


Telalovic, **MB**, *JHEP* 2026

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

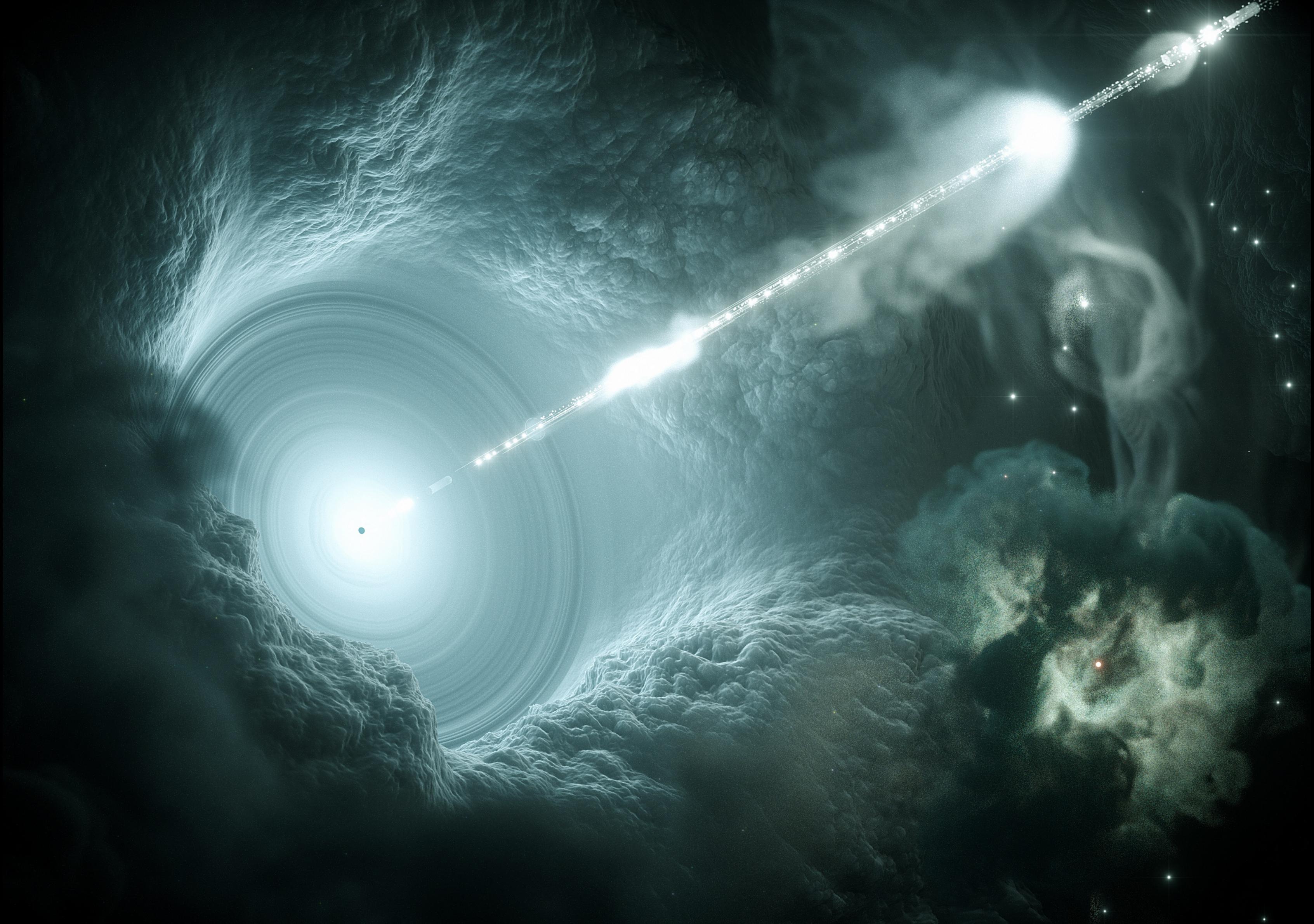


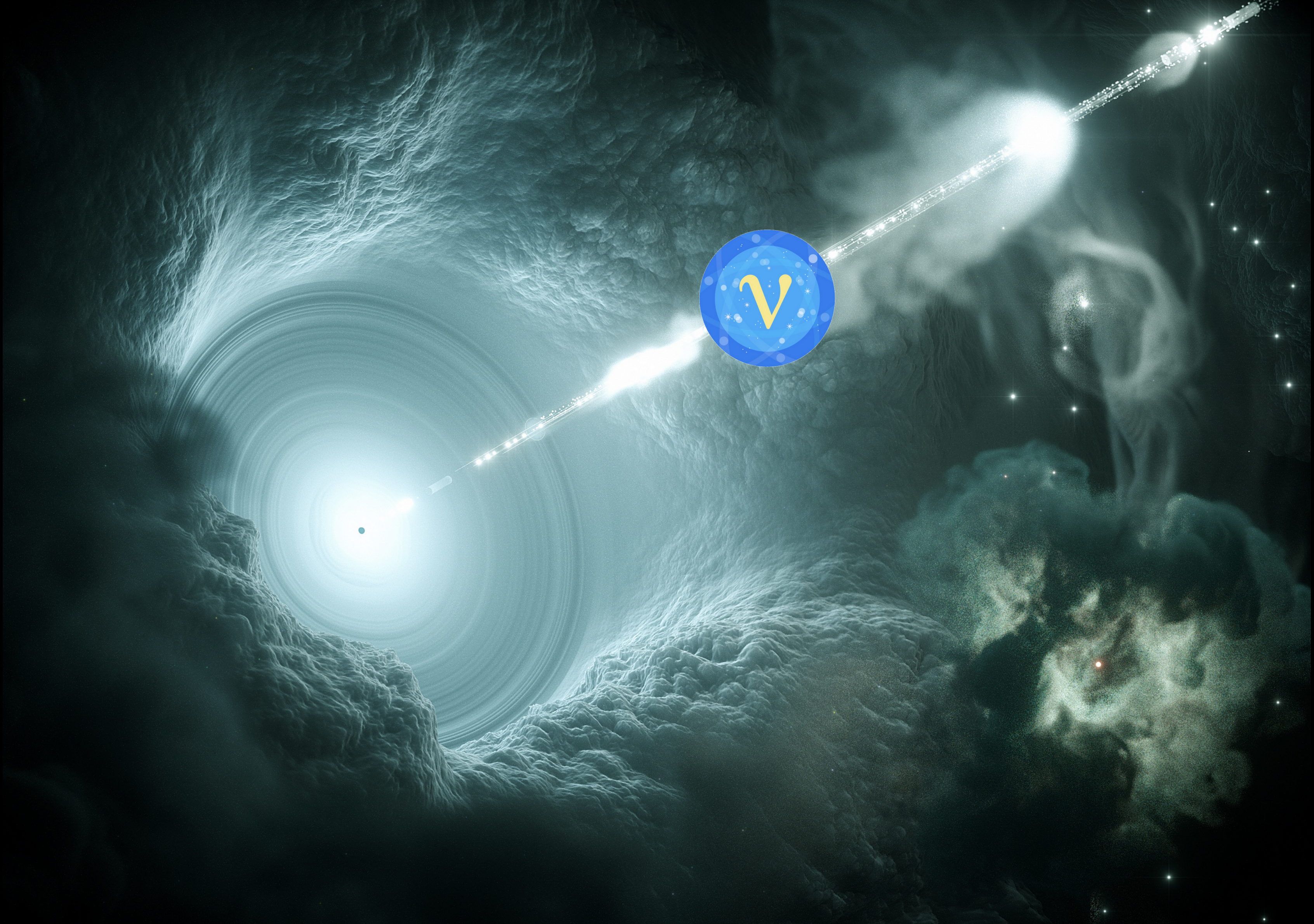
Telalovic, **MB**, *JHEP* 2026



Telalovic, **MB**, *JHEP* 2026

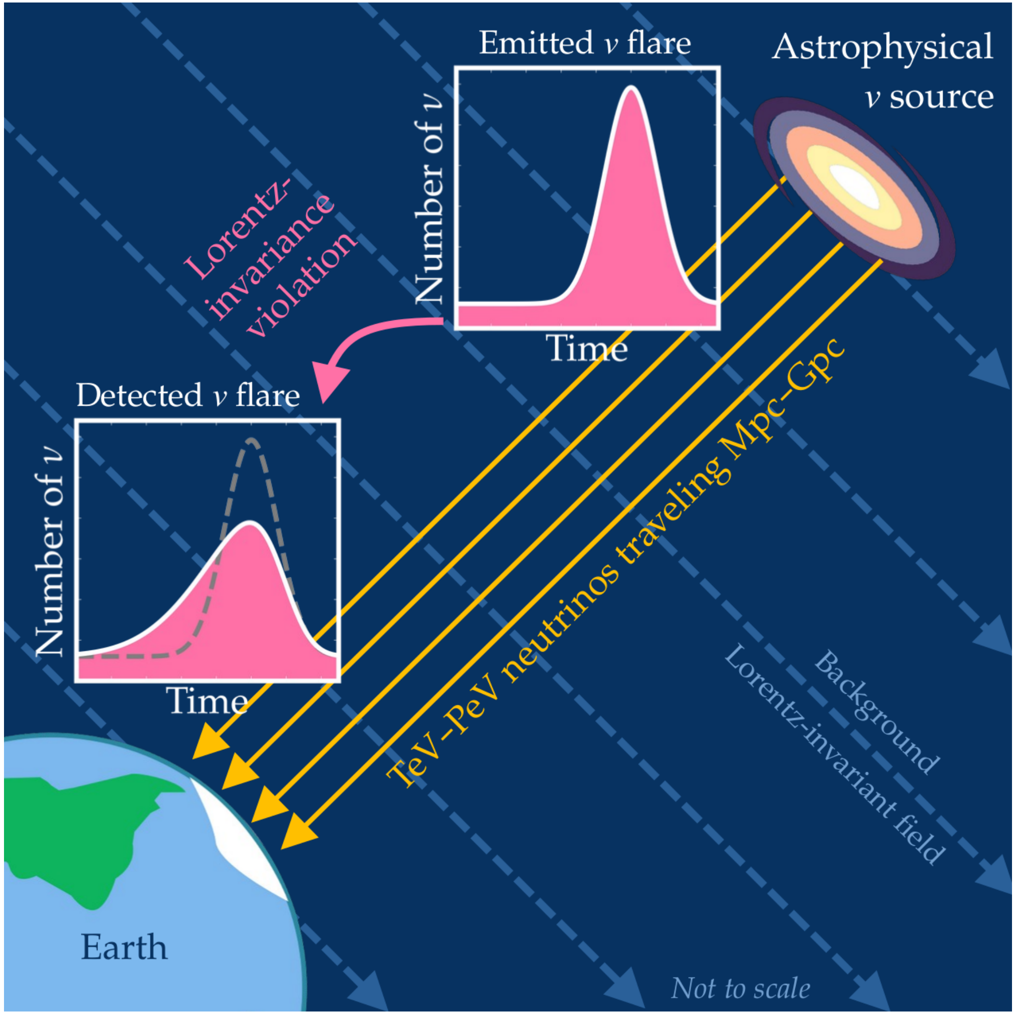
LIV from a high-energy ν flare


DESY



DESY

New physics from high-energy neutrino flares



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

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

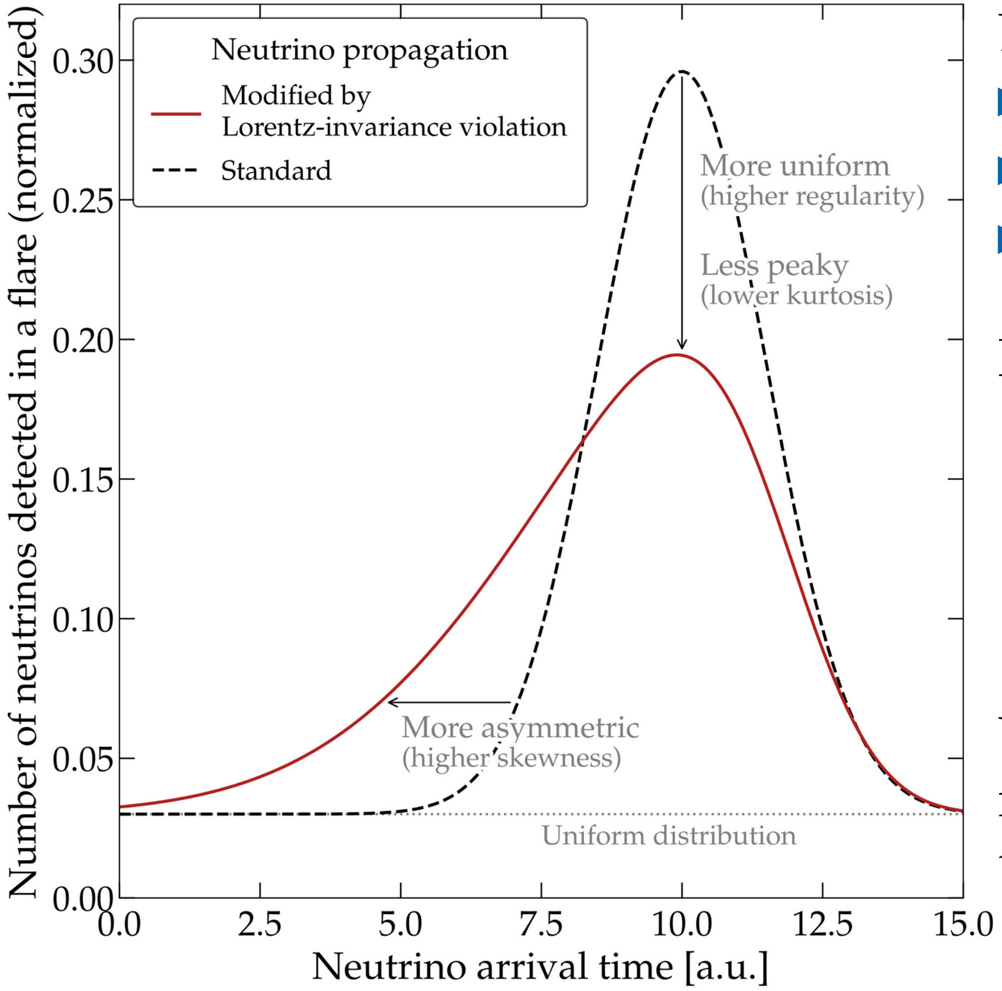
M_n: LIV energy scale (unknown)

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 υ flare time-distribution...

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

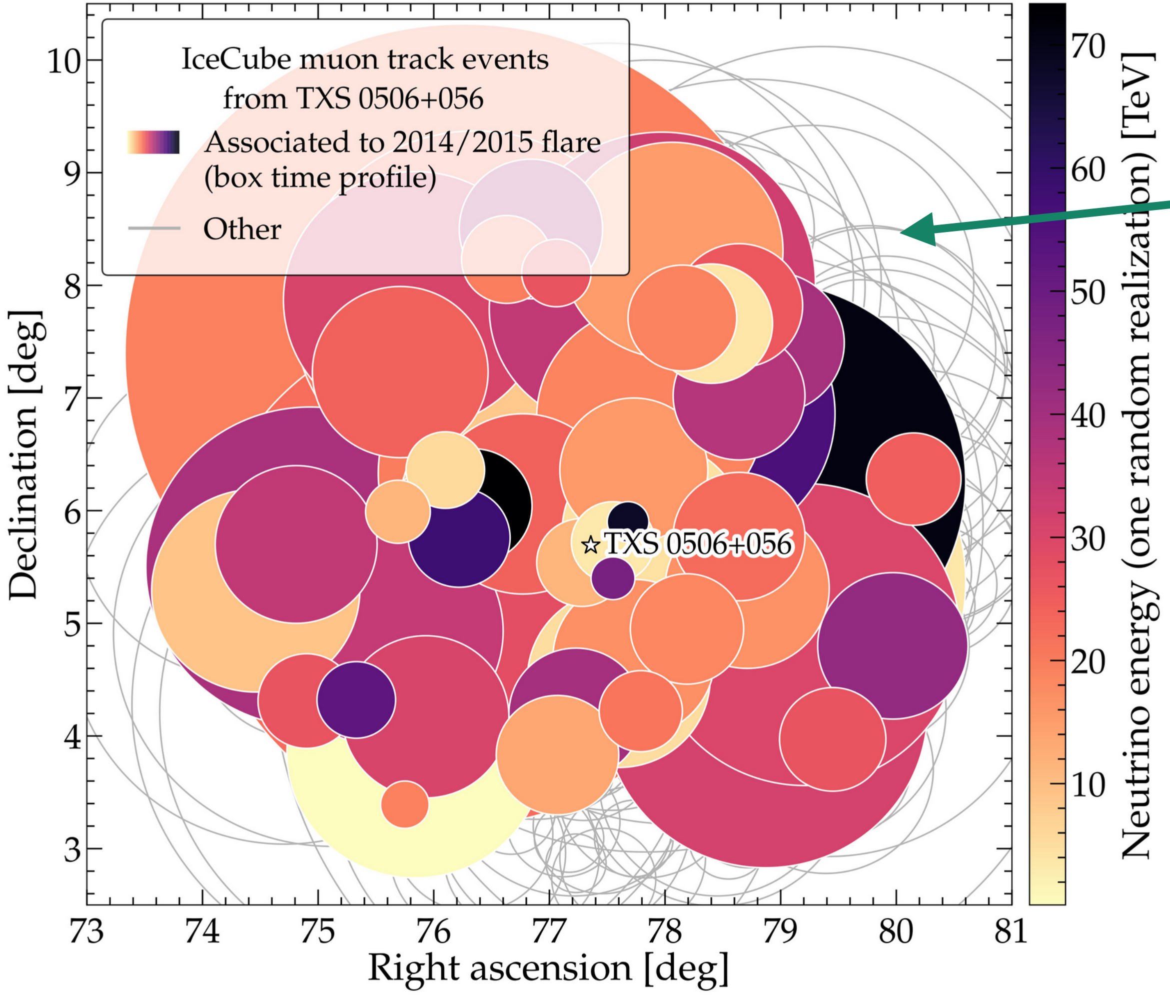
For a detected neutrino with E_υ in a flare:

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

Detection time of a at Earth | Intrinsic lag in the source | 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

Backgrounds

Atmospheric ν & muons, astrophysical non-BSM ν, cosmic rays

Experimental limitations

Energy & angular resolution, detector efficiency, flavor identification

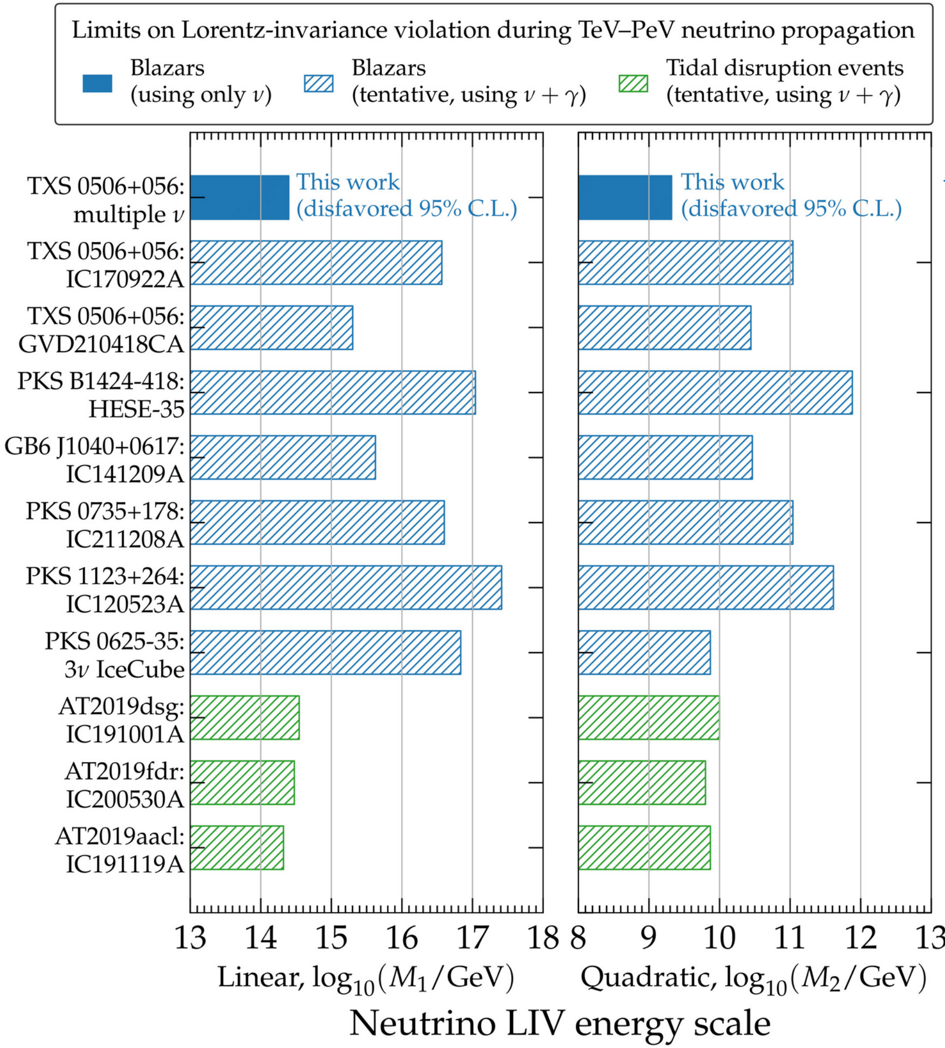
Neutrino properties

Mixing parameters, cross sections, neutrino mass (sometimes)

Theory bias

Look-elsewhere effect, astrophysical source models, oversimplified theory

New physics from high-energy neutrino flares

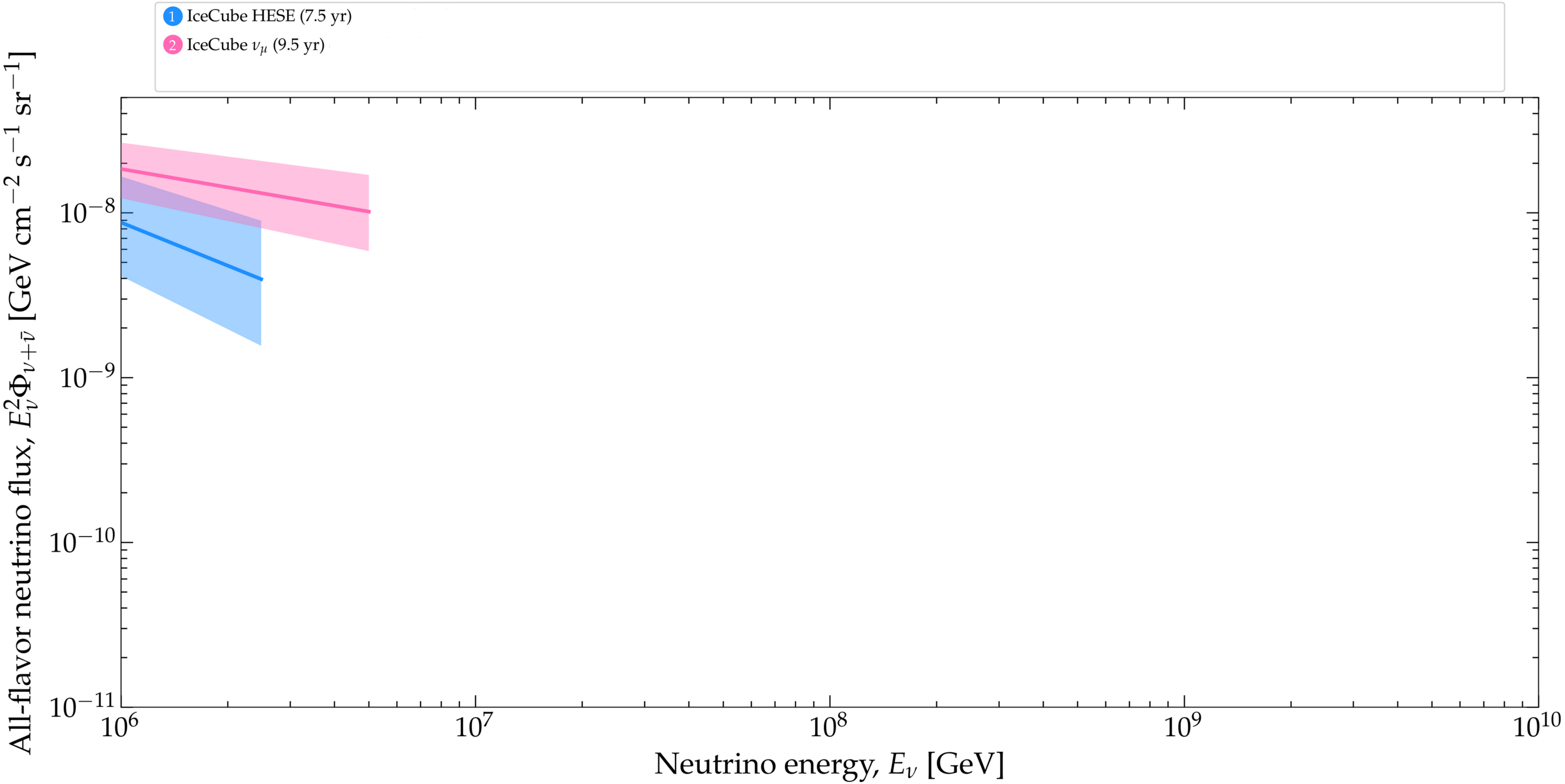


New limits from the TXS 0506+056 2014/2015 flare *using only neutrinos*

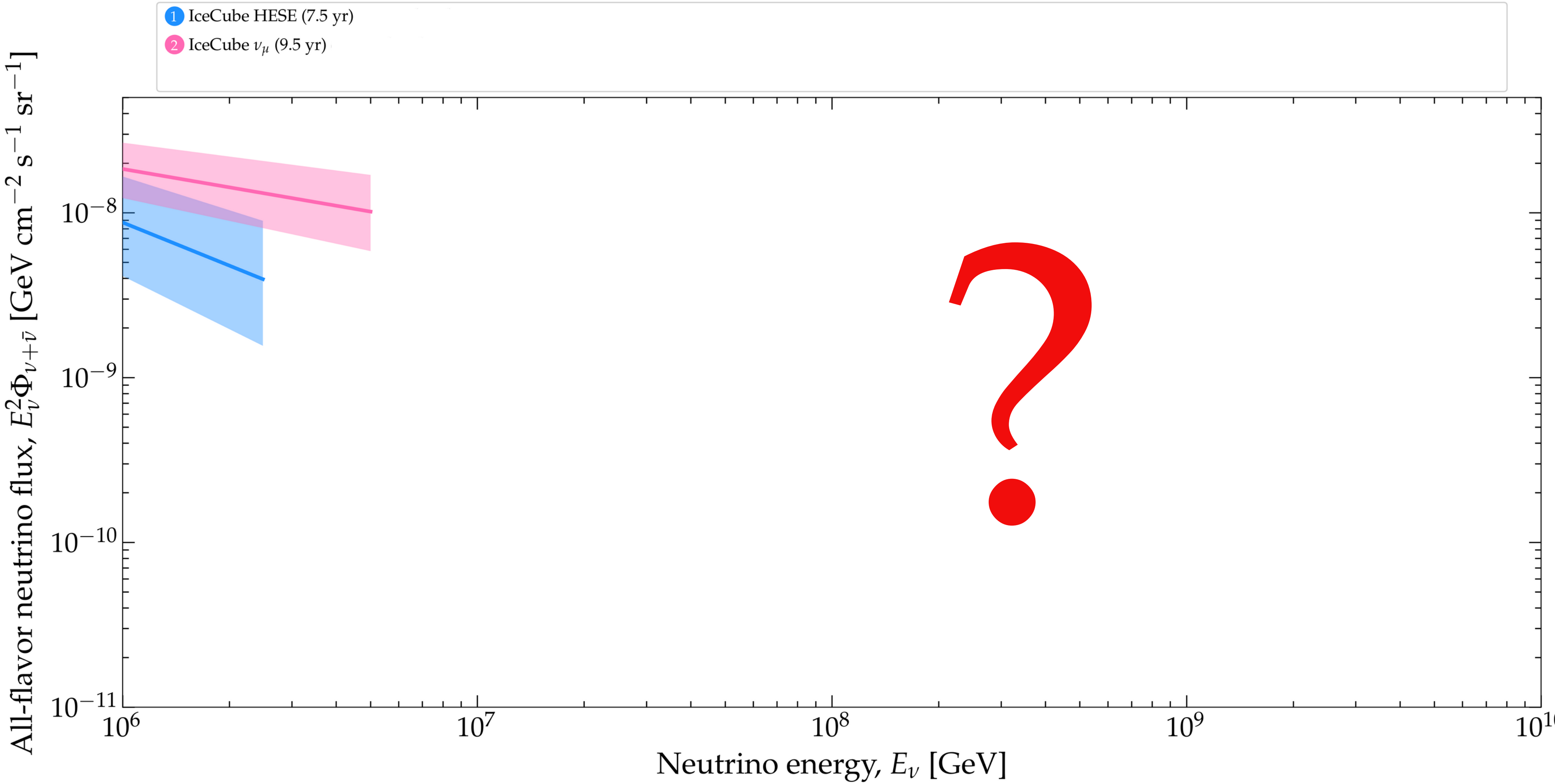
Limits from the coincident emission of neutrinos and electromagnetic emission (generally low or unspecified credibility)

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



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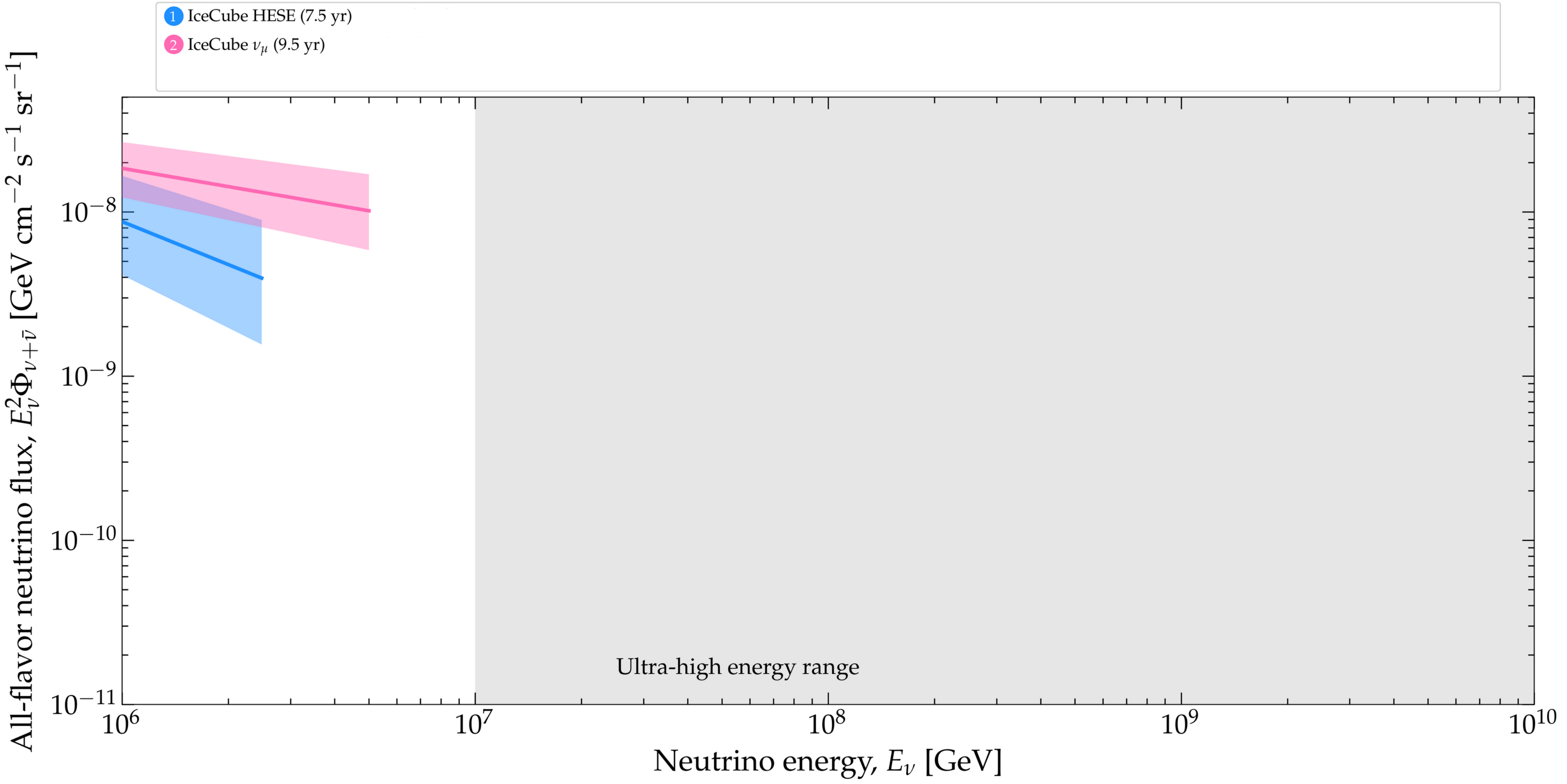
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]
?



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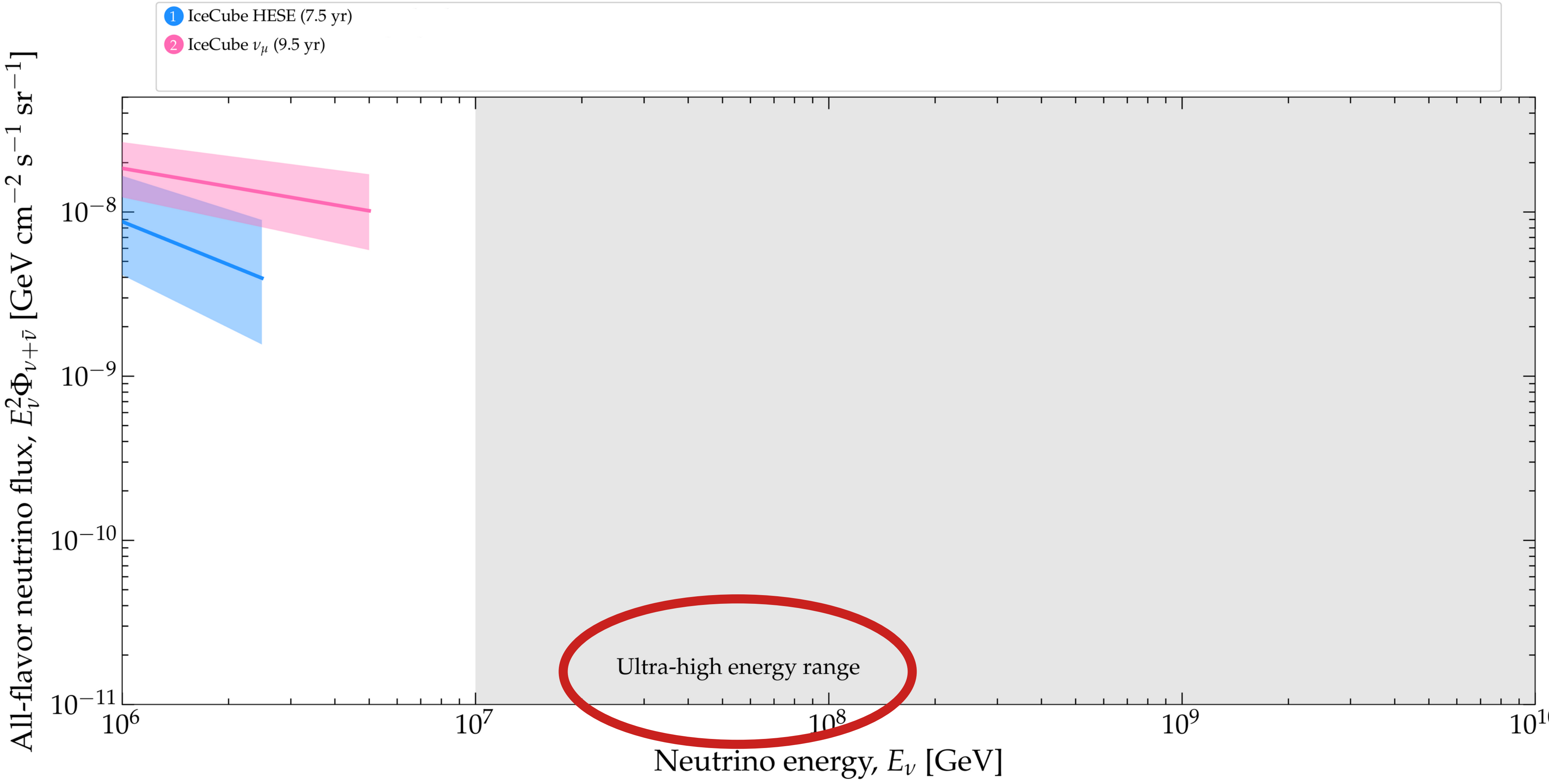
Ultra-high energy range



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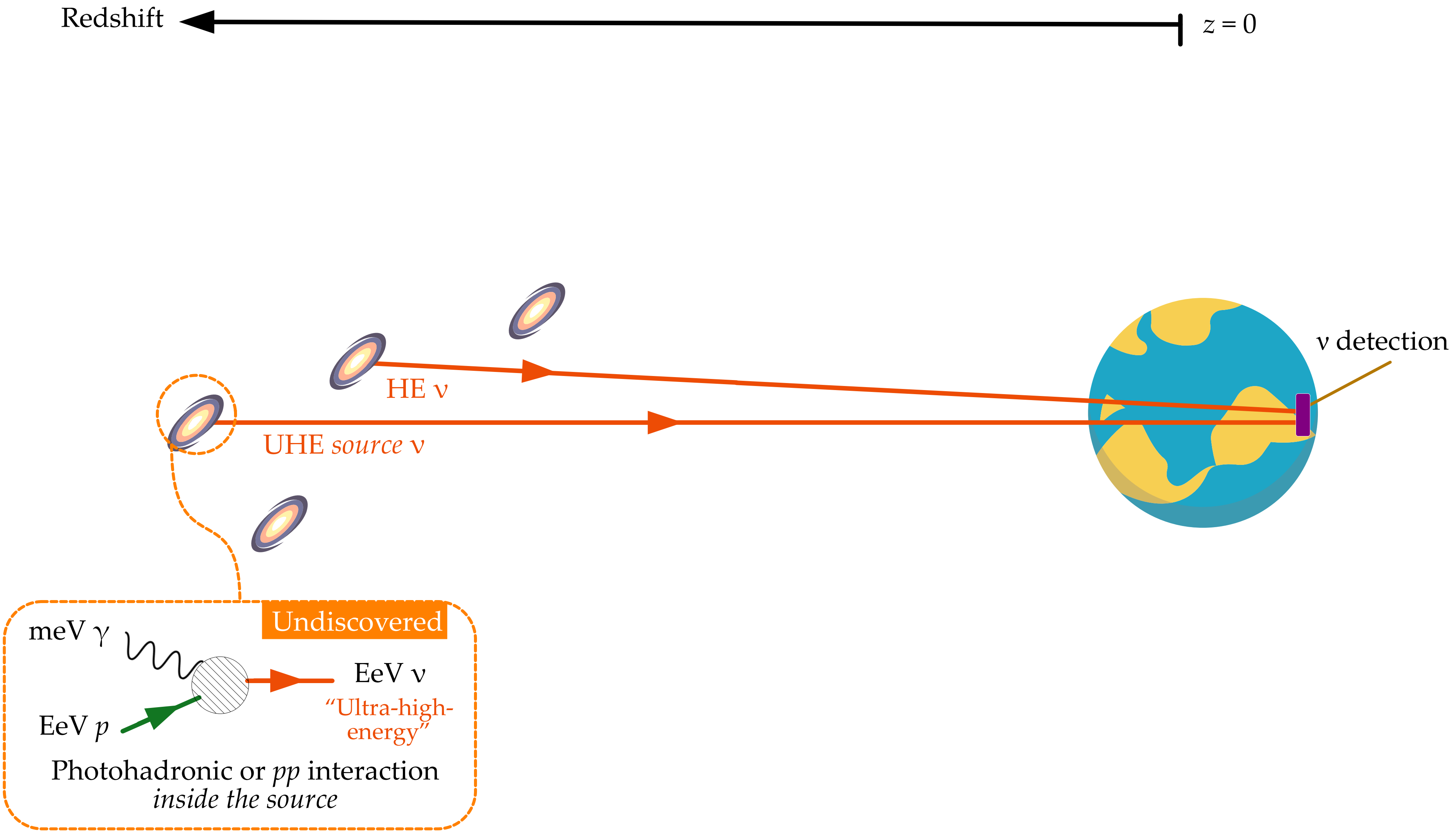
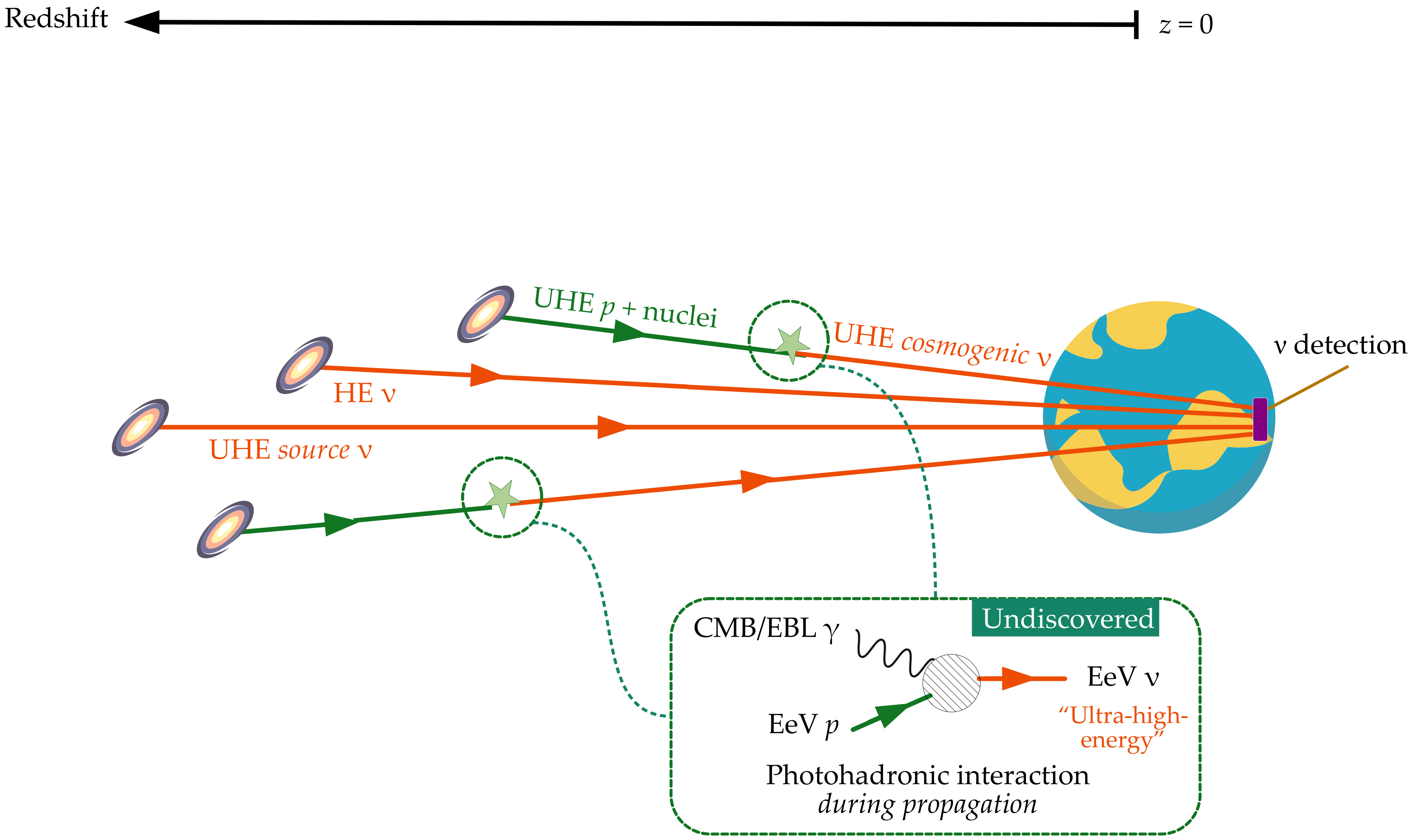
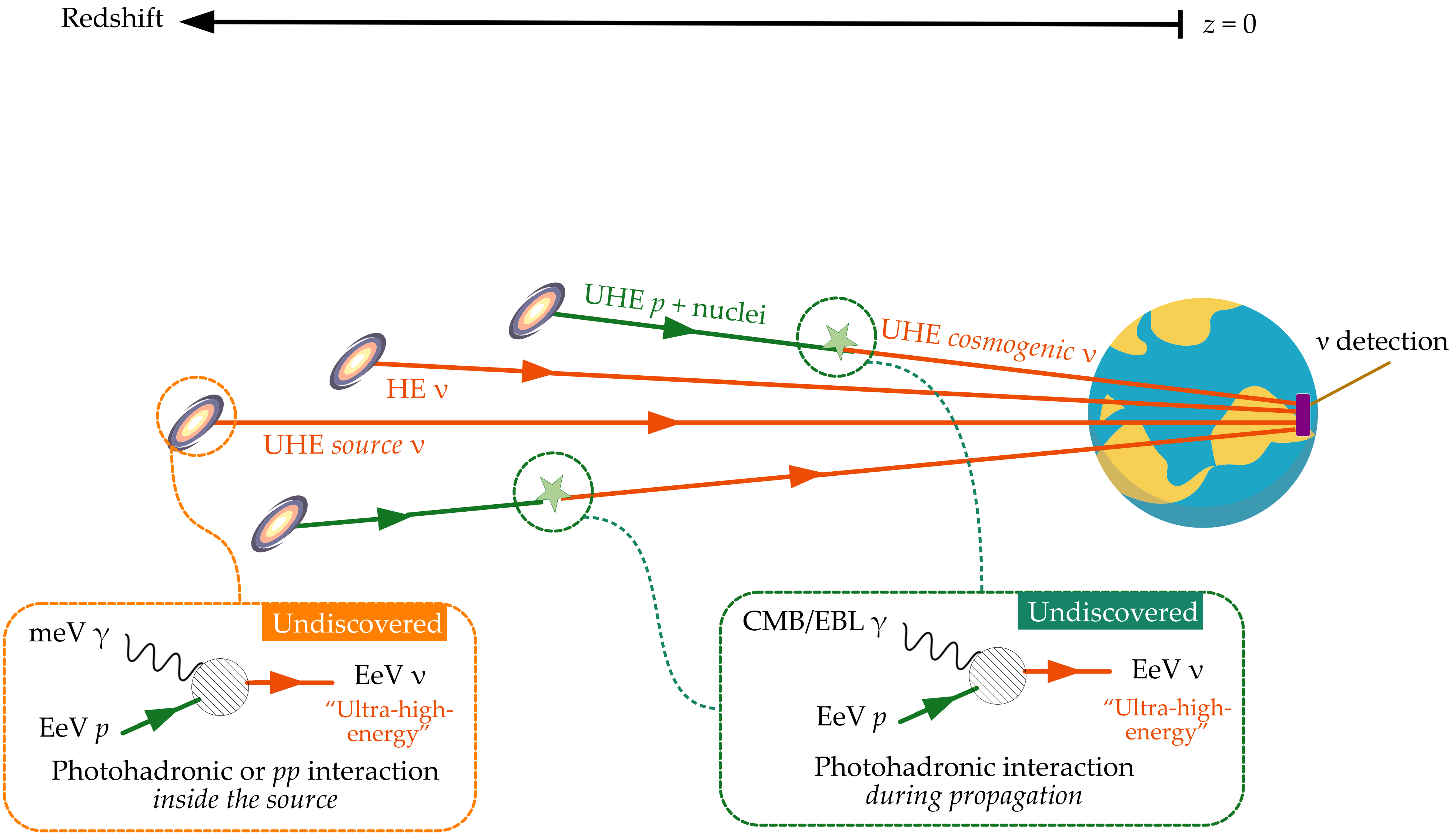

Redshift
$z = 0$
HE ν
UHE *source* ν
ν detection
Undiscovered
meV γ
EeV ν
"Ultra-high-energy"
EeV *p*
Photohadronic or *pp* interaction
inside the source



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



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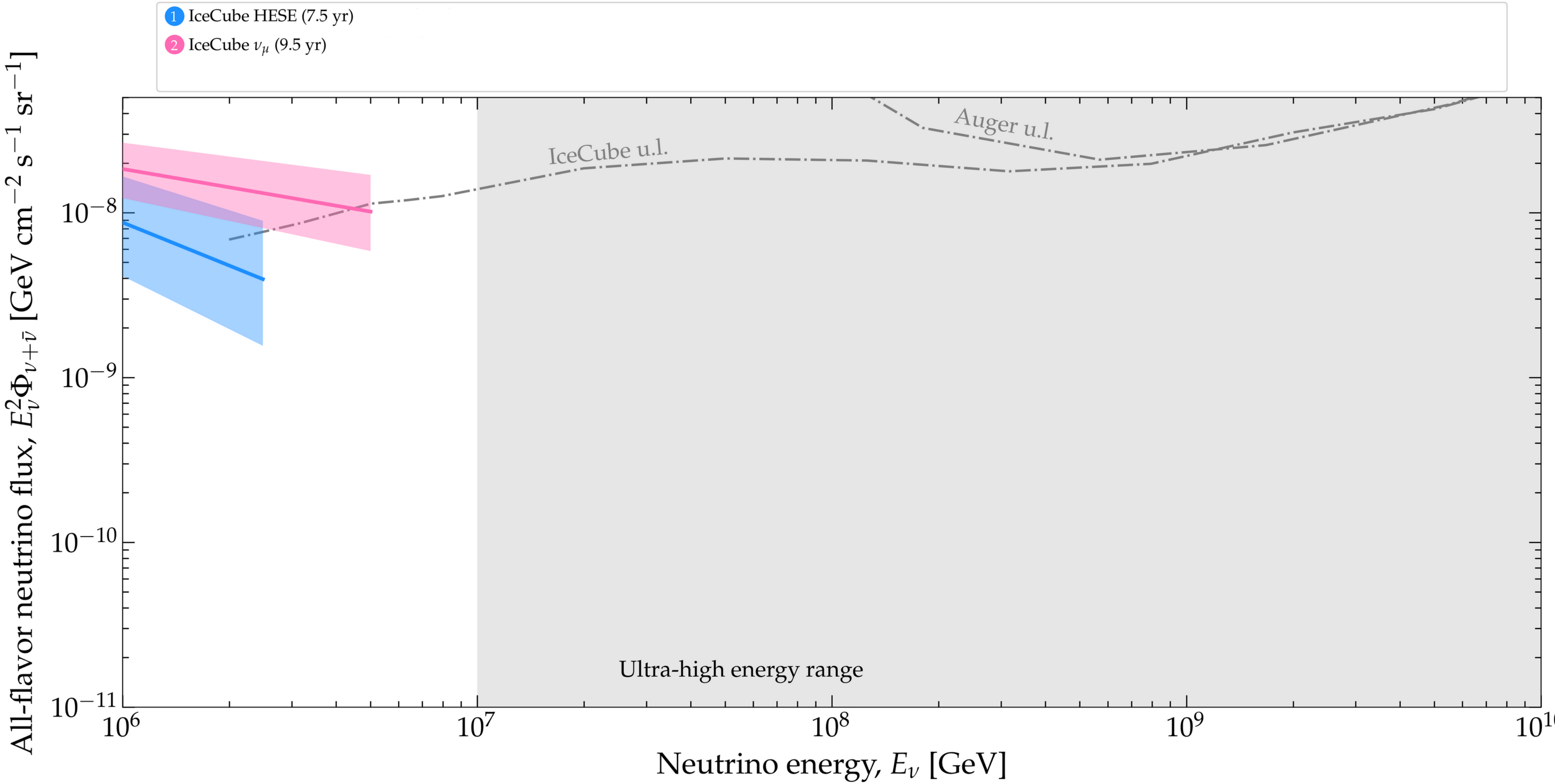
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Auger u.l.
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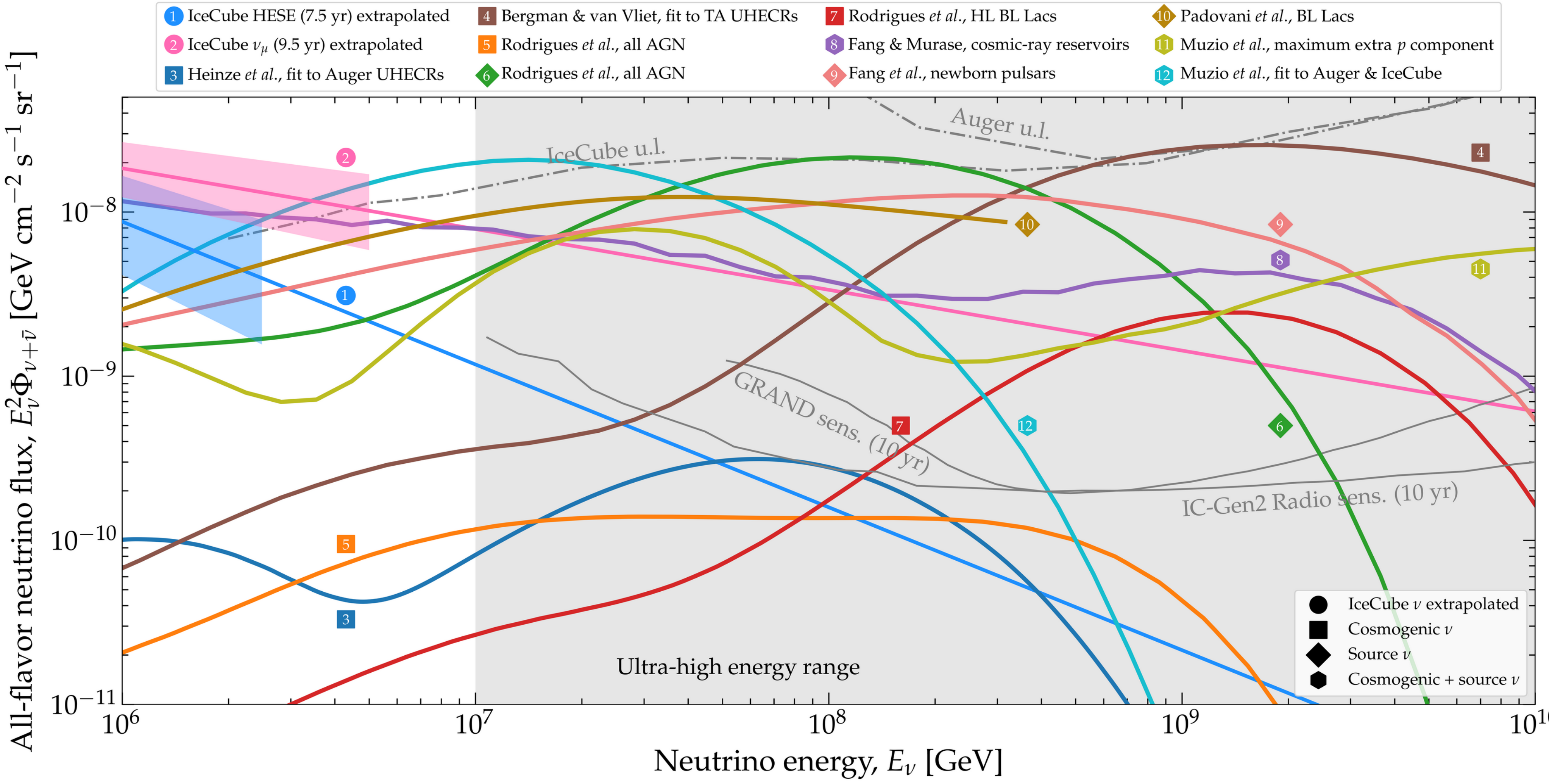
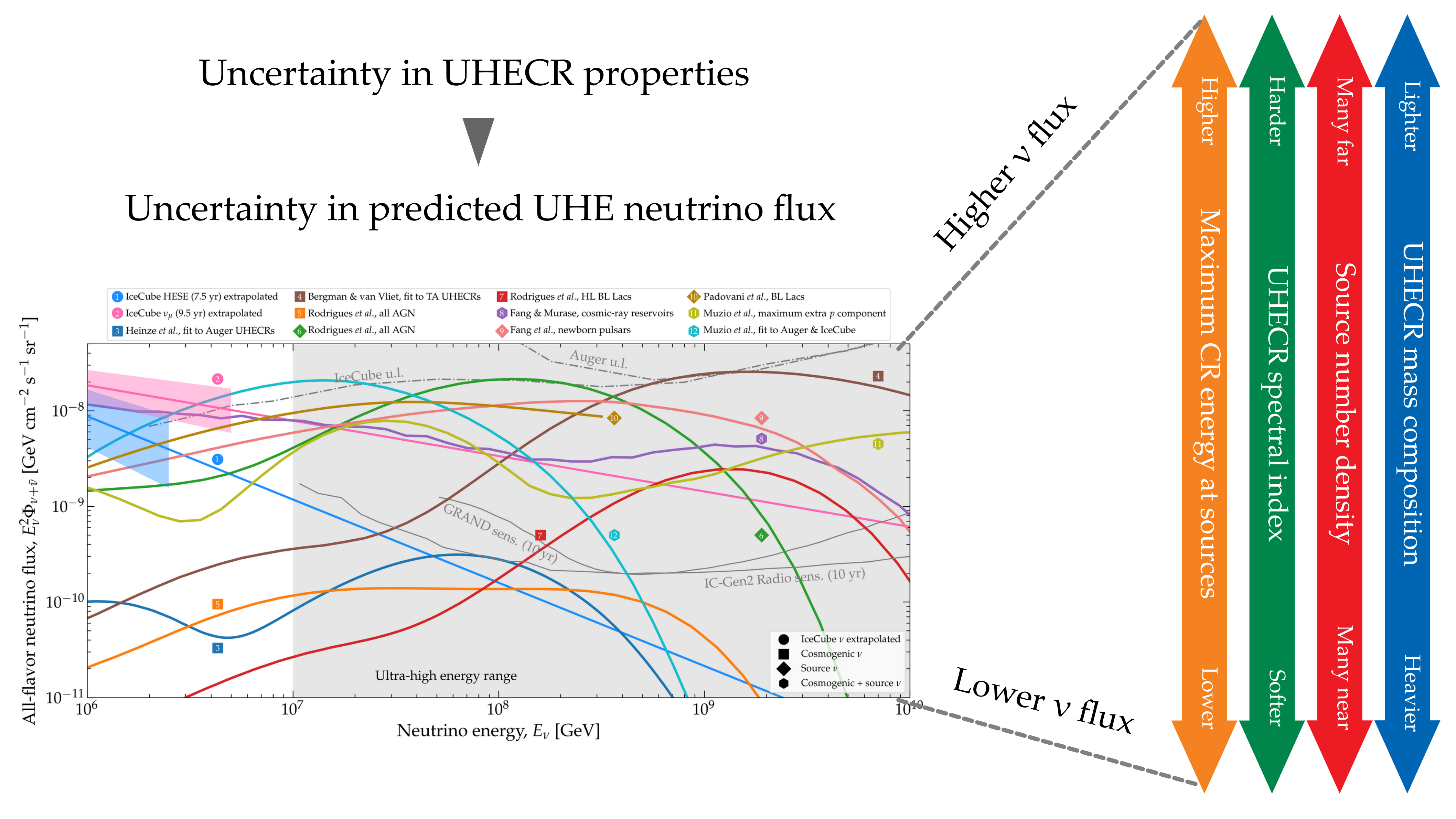


Valera, **MB**, Glaser, *PRD* 2023


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

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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But is it due to a neutrino?

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

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

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RECORD BREAKER

Lorentz-invariance violation — from superluminal speeds

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

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

Cohen & Glashow, *PRL* 2011

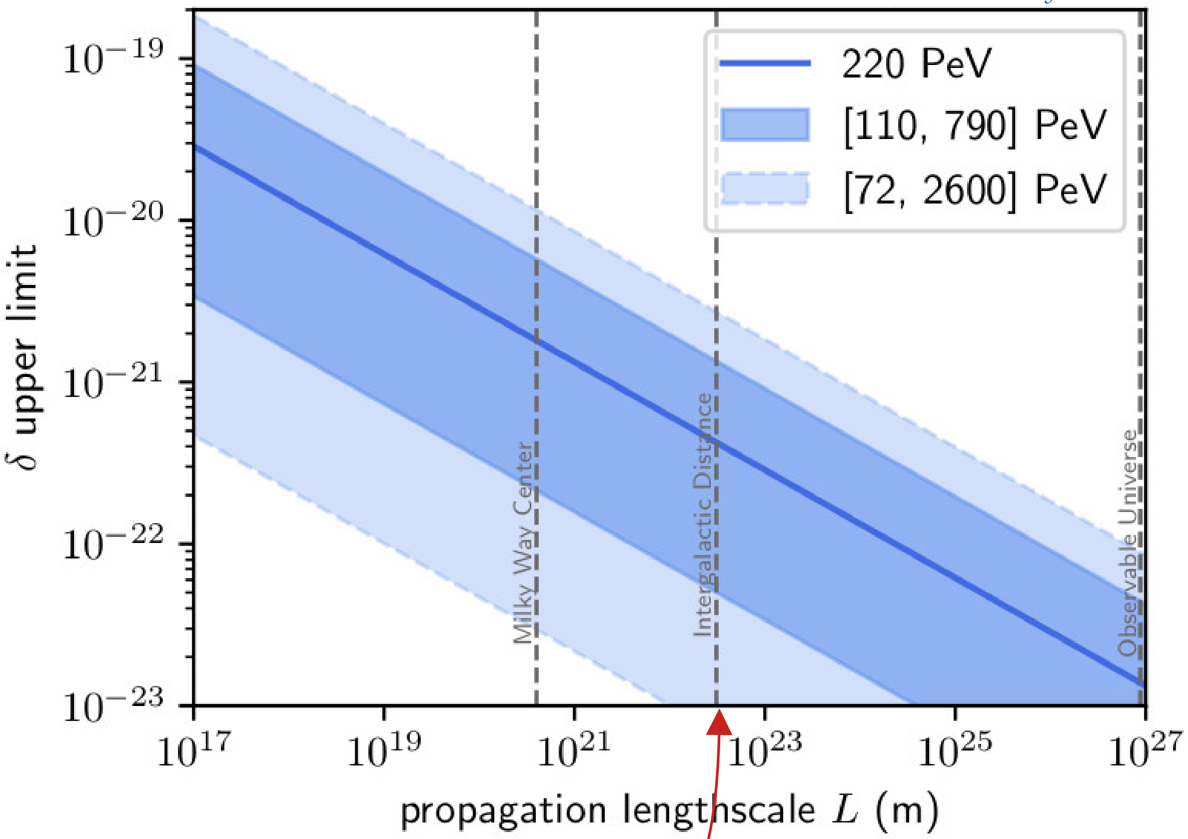
Excess over light speed: $\delta = c_\nu - 1$

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

Decay width

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

KM3NeT Collab., *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

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

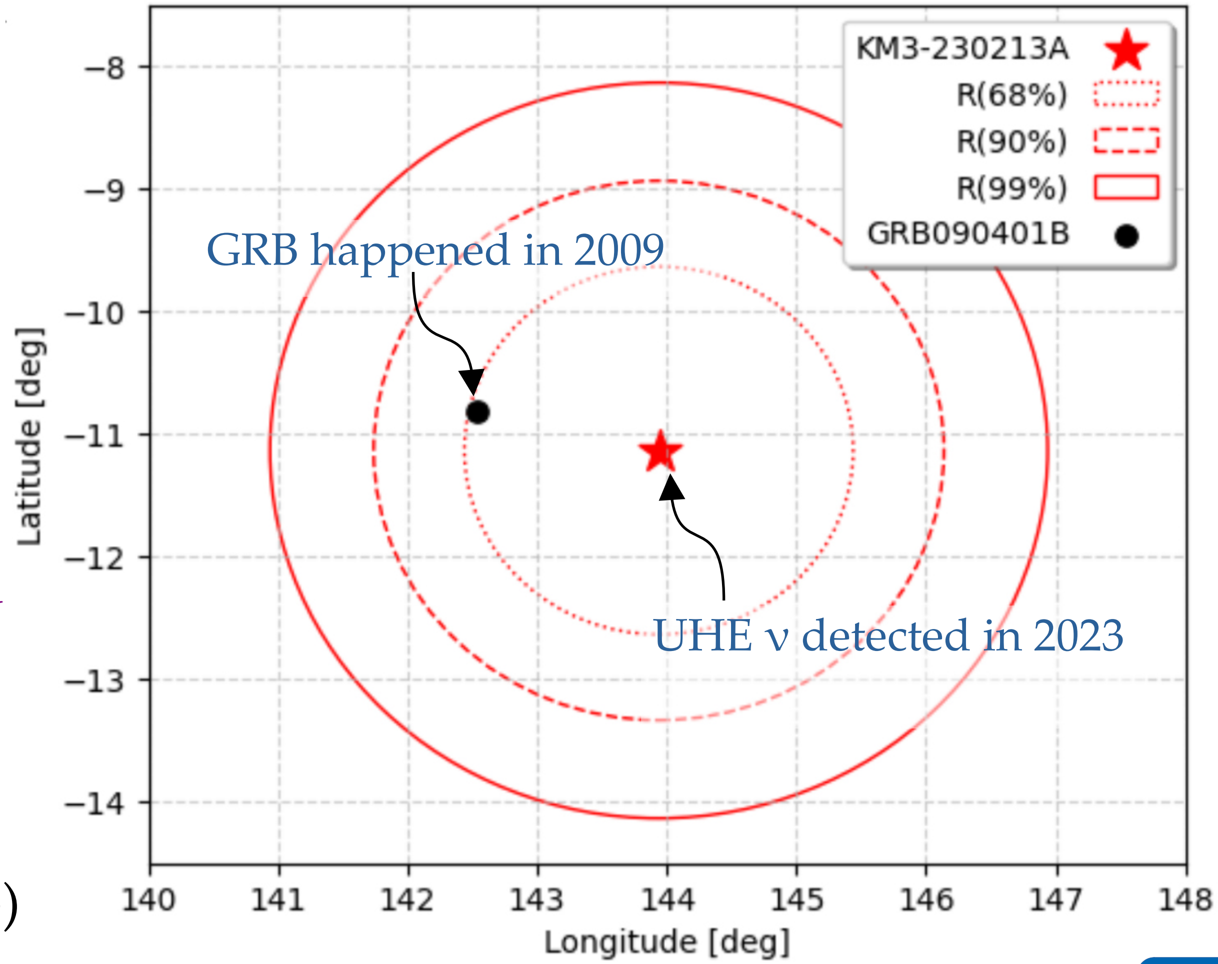
Cosmological expansion

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



Assorted examples

(not necessarily LIV)

Backgrounds

Atmospheric ν & muons, astrophysical non-BSM ν, cosmic rays

Experimental limitations

Energy & angular resolution, detector efficiency, flavor identification

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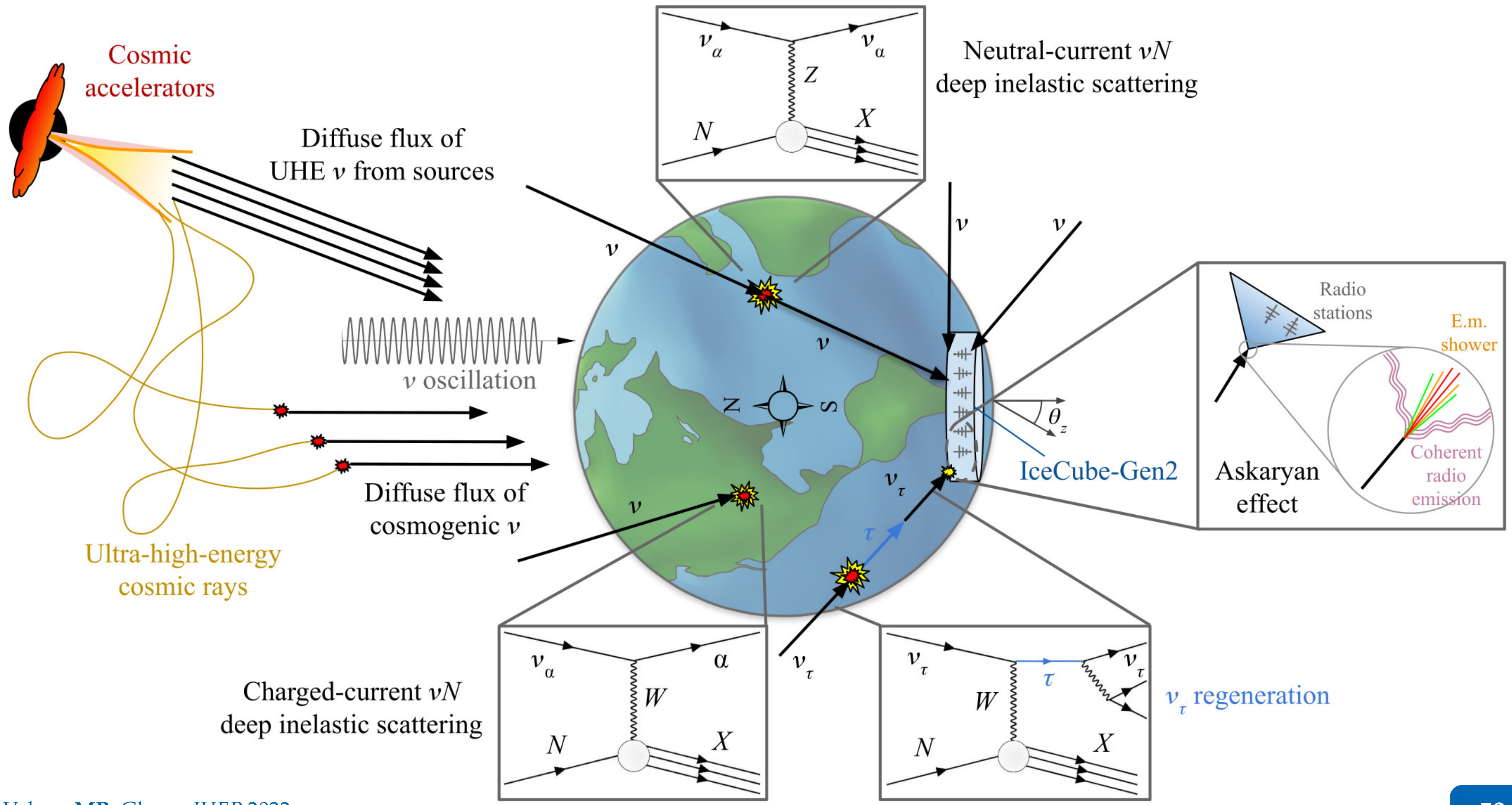
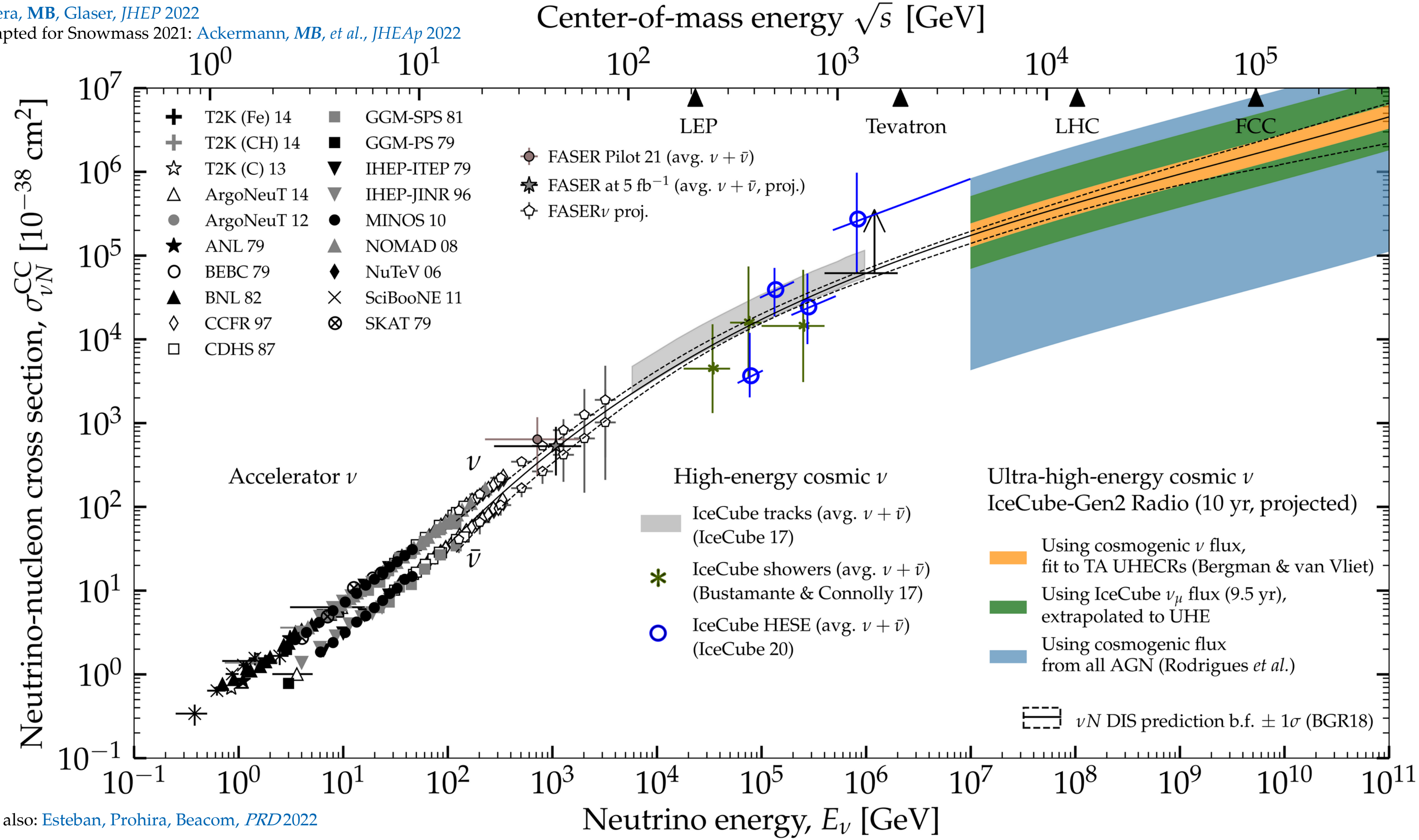
Mixing parameters, cross sections, neutrino mass (sometimes)

Theory bias

Look-elsewhere effect, astrophysical source models, oversimplified theory


Cosmic accelerators
Diffuse flux of UHE ν from sources
ν oscillation
Diffuse flux of cosmogenic ν
Ultra-high-energy cosmic rays
Neutral-current νN deep inelastic scattering
ν_α
ν_α
Z
N
X
ν
N
S
IceCube-Gen2
θ_z
ν_τ
τ
Radio stations
E.m. shower
Askaryan effect
Coherent radio emission
Charged-current νN deep inelastic scattering
α
W
ν_τ regeneration

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



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

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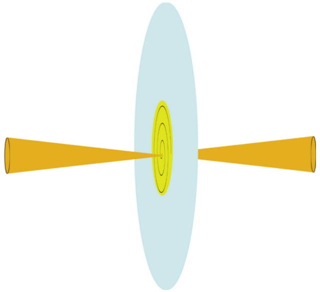
Astrophysical neutrino sources Earth

Galactic (kpc) or extragalactic (Mpc – Gpc) distance

Astrophysical neutrino sources

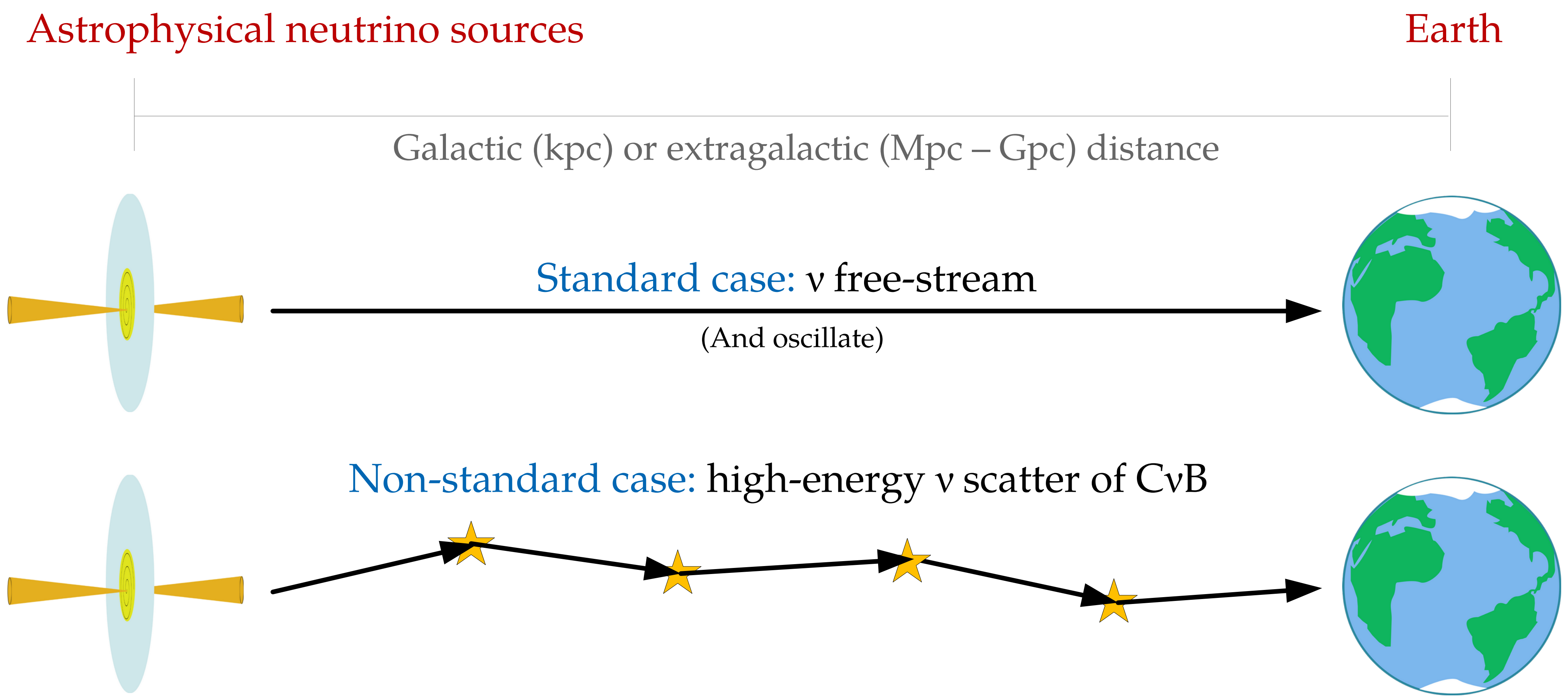
Earth

Galactic (kpc) or extragalactic (Mpc – Gpc) distance



Standard case: ν free-stream

(And oscillate)



Astrophysical neutrino sources
Earth
Galactic (kpc) or extragalactic (Mpc – Gpc) distance
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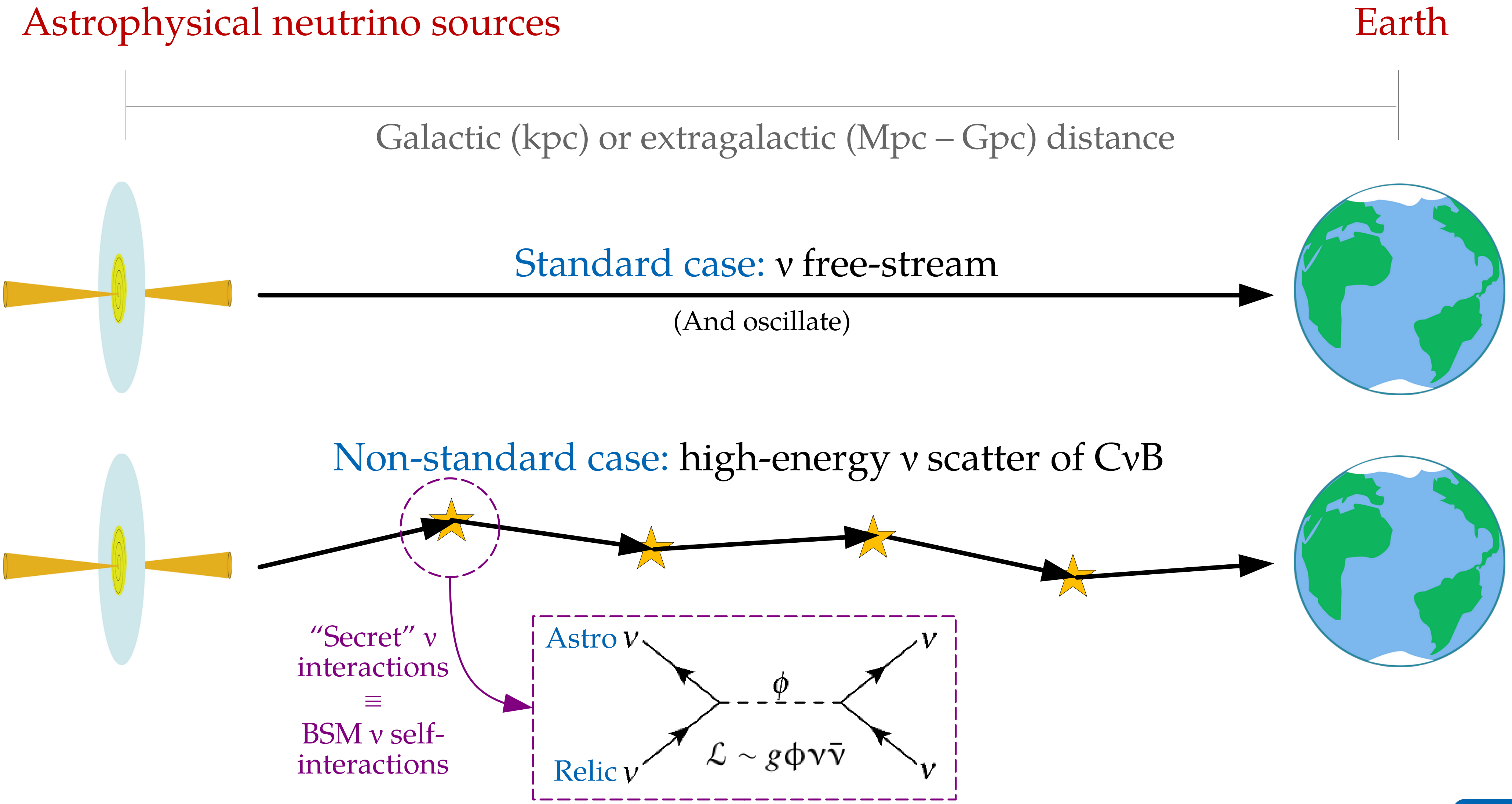
Non-standard case: high-energy ν scatter of CνB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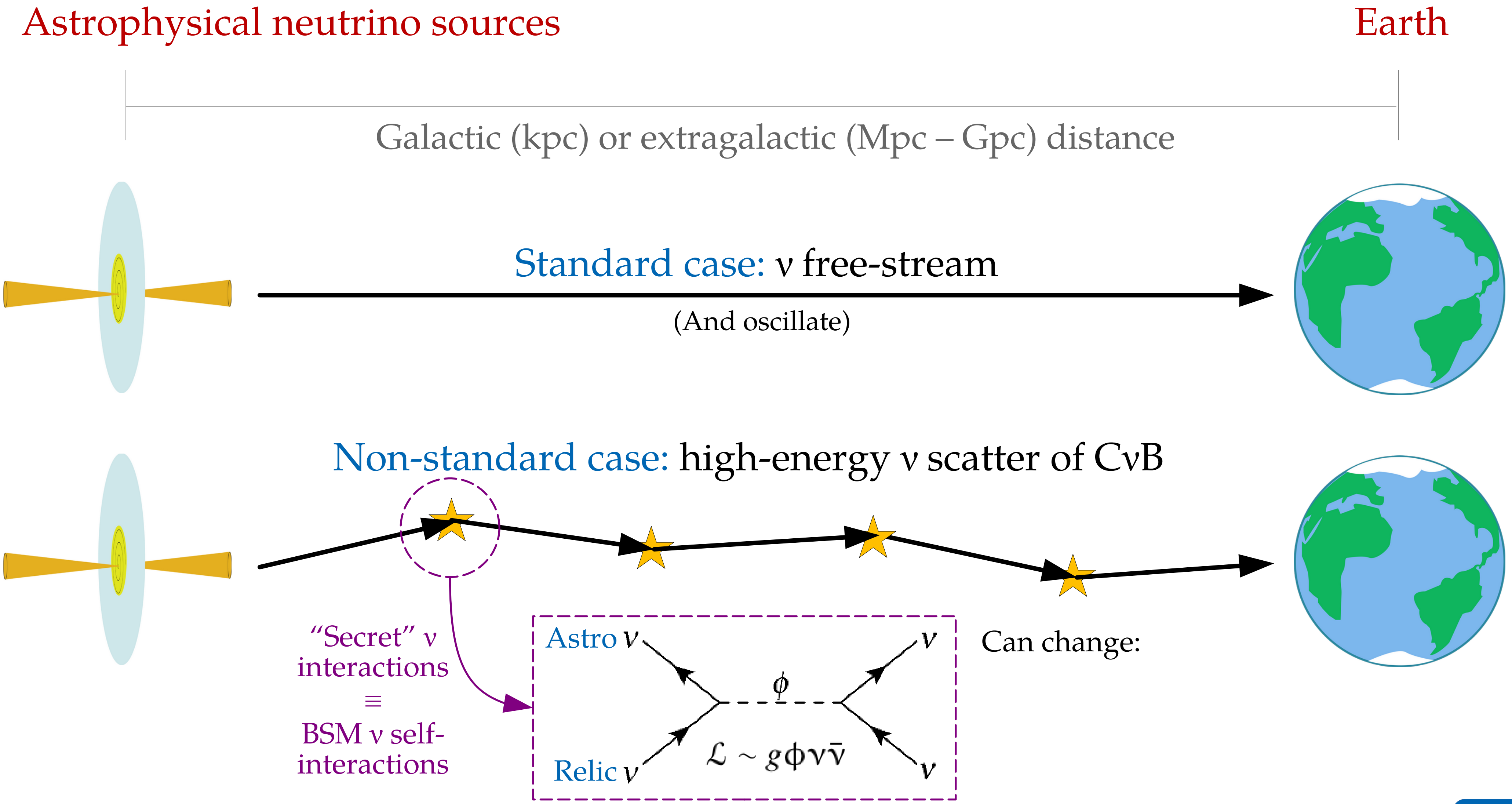
"Secret" ν interactions ≡ BSM ν self-interactions
Astro ν
Relic ν
ν
ν
ϕ
$\mathcal{L} \sim g\phi\nu\bar{\nu}$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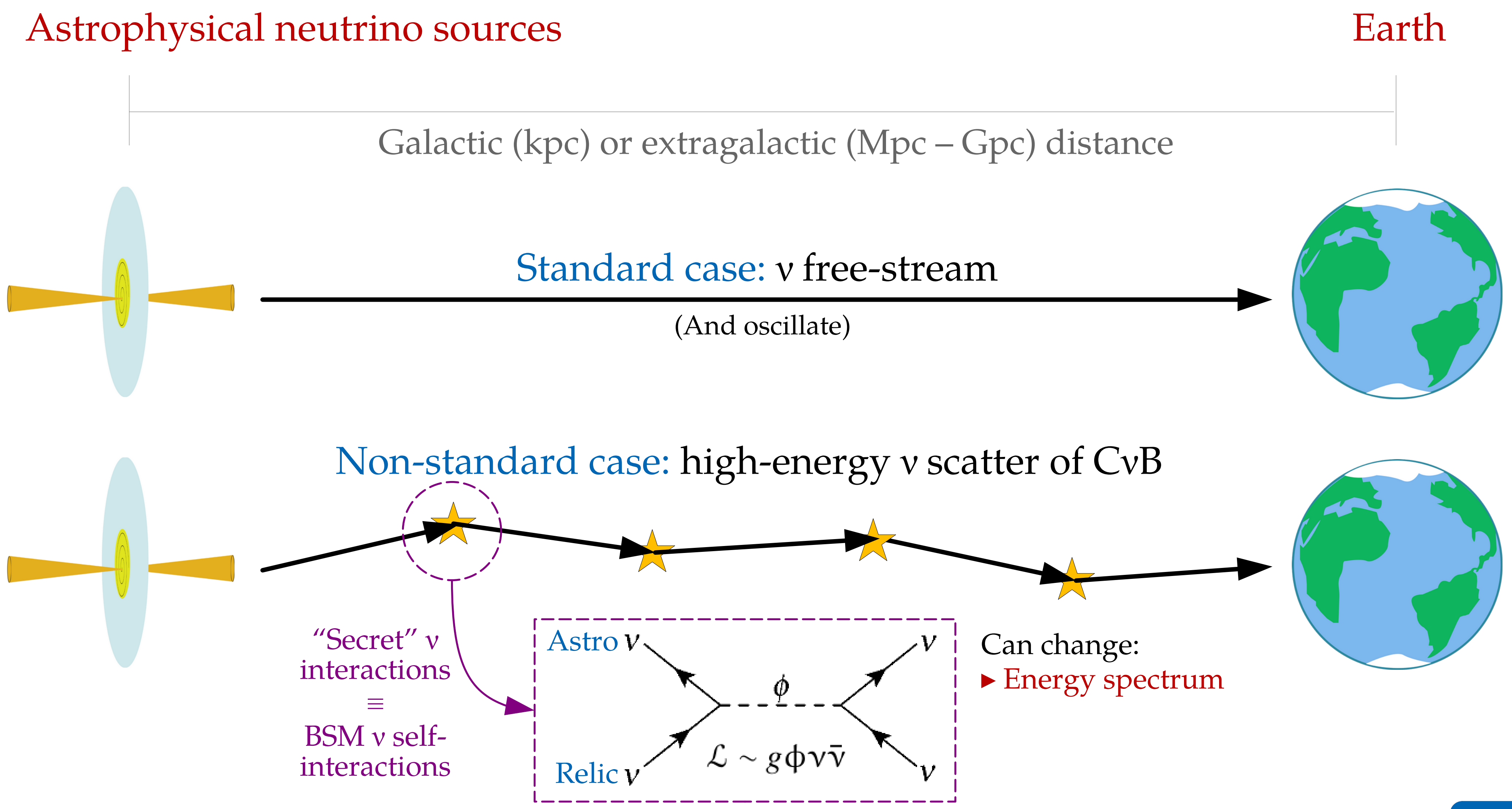
Can change: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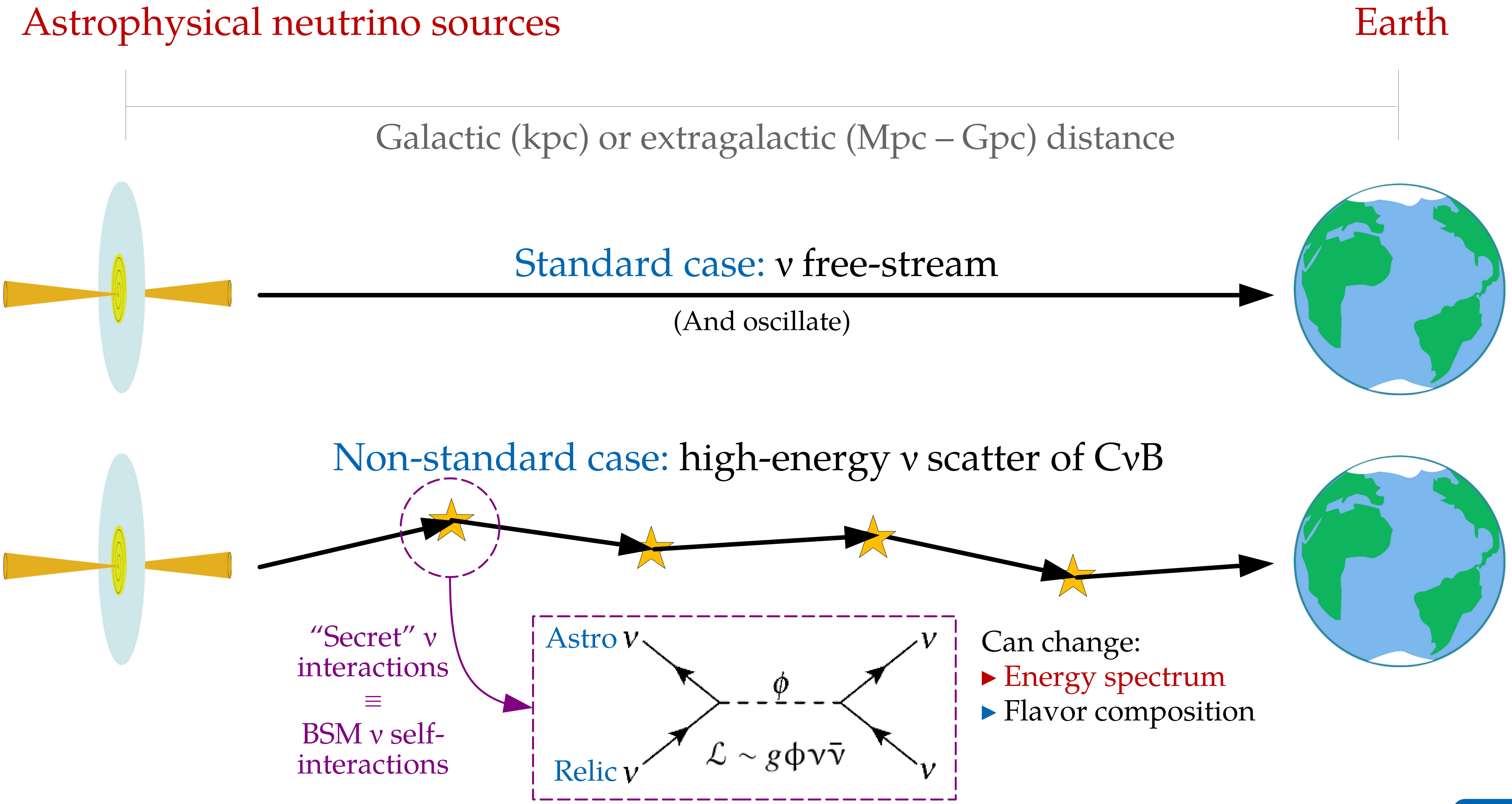
Can change:
▸ Energy spectrum



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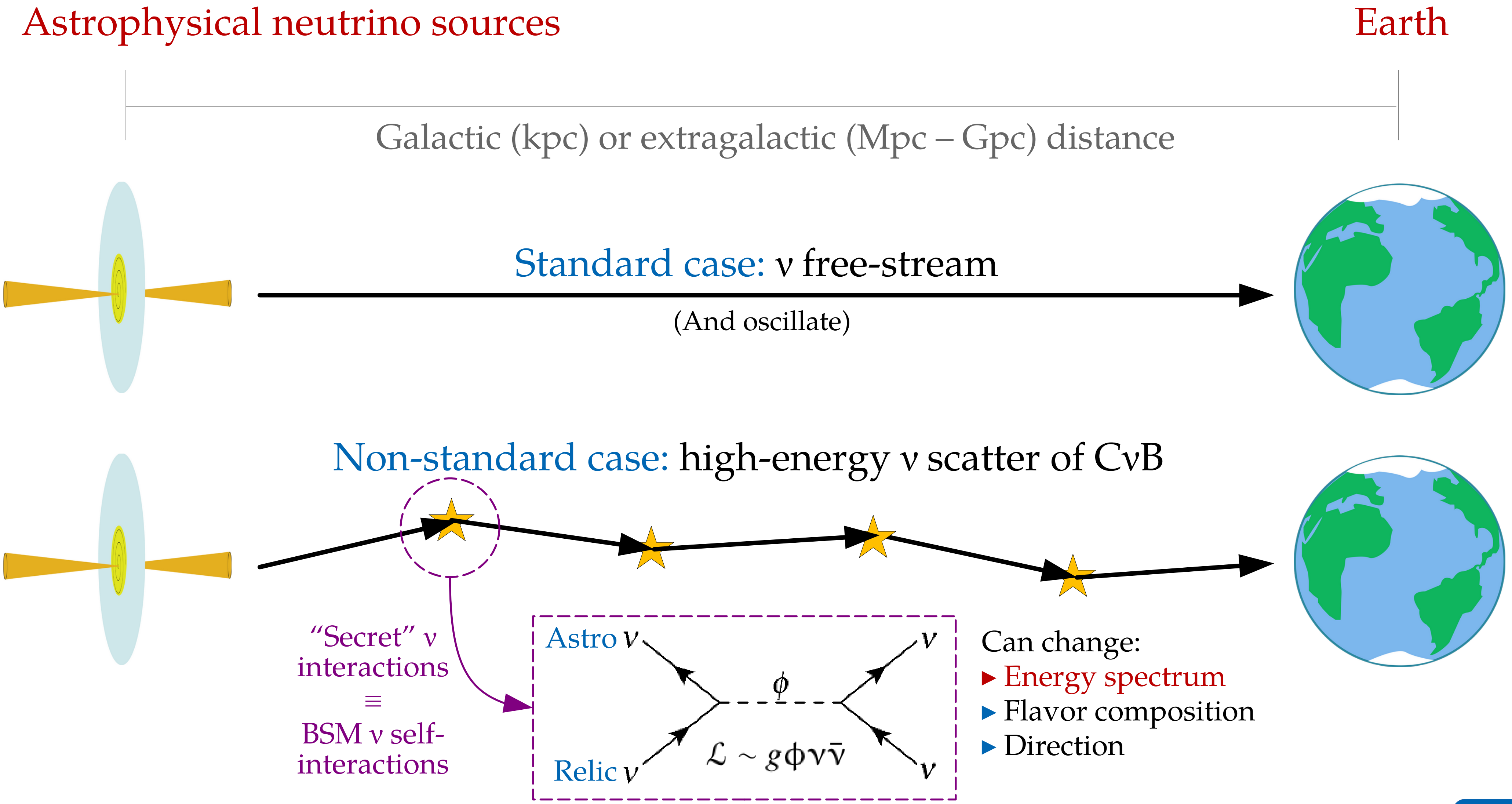
Can change:
▸ Energy spectrum
▸ Flavor composition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Can change:
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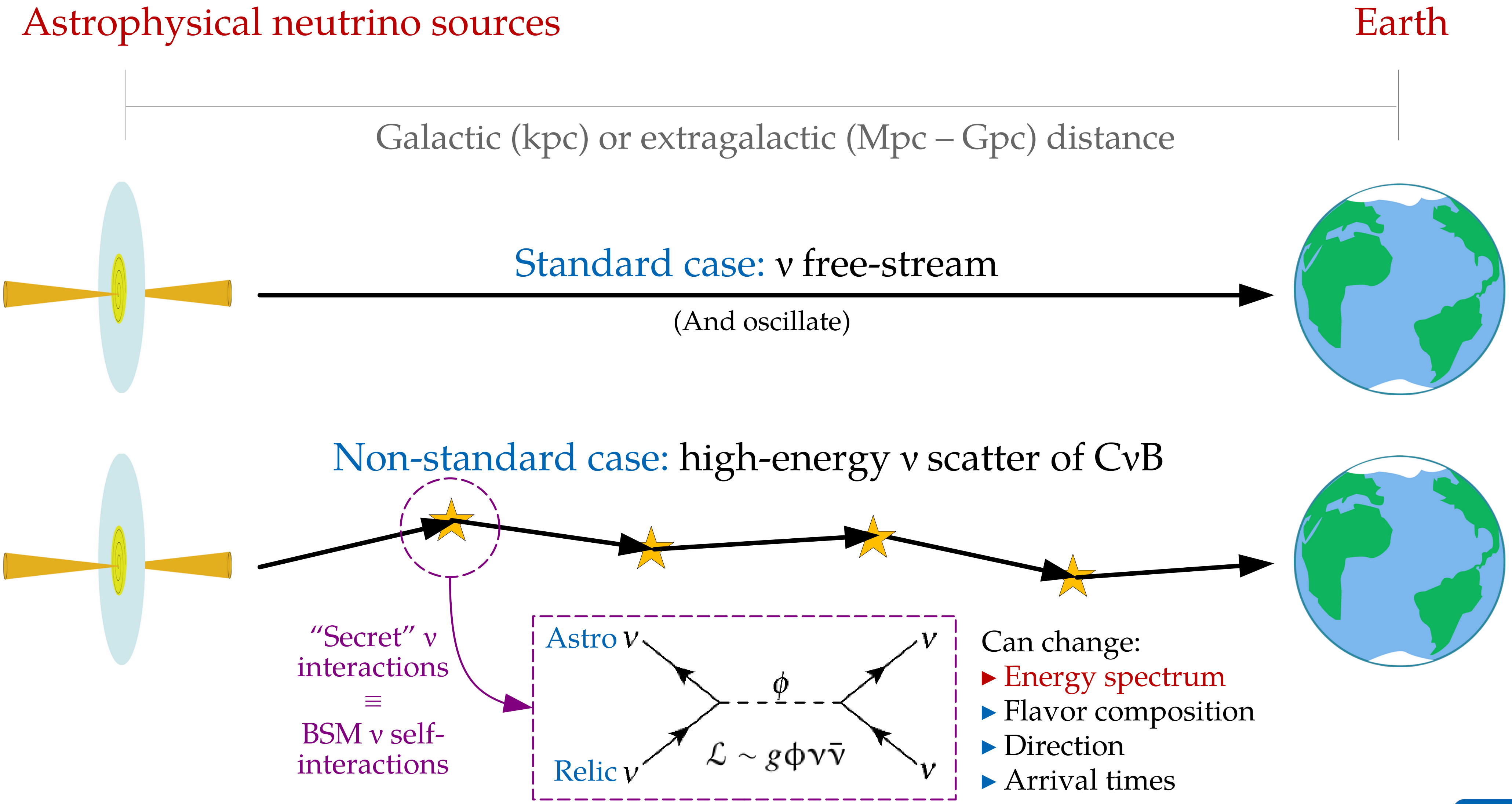
▸ Direction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Can change:
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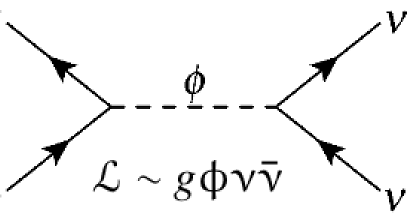
▸ Flavor composition
▸ Direction
▸ Arrival times

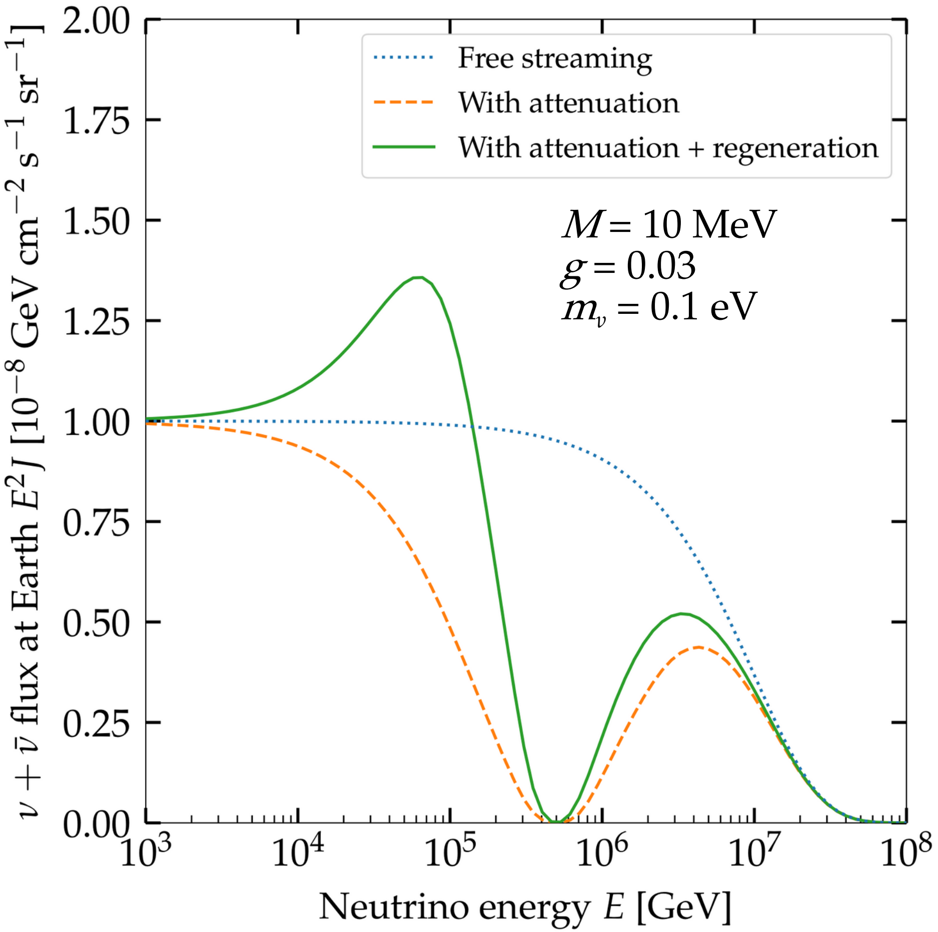
Secret interactions of high-energy astrophysical neutrinos

"Secret" neutrino interactions between astrophysical ν (PeV) and relic ν (0.1 meV):



Cross section: $\sigma = \frac{g^4}{4\pi} \frac{s}{(s - M^2)^2 + M^2\Gamma^2}$

Resonance energy: $E_{\rm res} = \frac{M^2}{2m_\nu}$



MB, Rosenstroem, Shalgar, Tamborra, *PRD* 2020
See also: Esteban, Pandey, Brdar, Beacom, *PRD* 2021
Creque-Sarbinowski, Hyde, Kamionkowski, *PRD* 2021
Ng & Beacom, *PRD* 2014
Cherry, Friedland, Shoemaker, 1411.1071
Blum, Hook, Murase, 1408.3799

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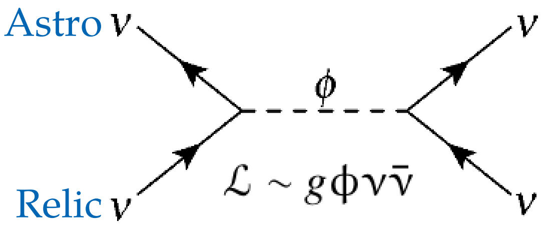
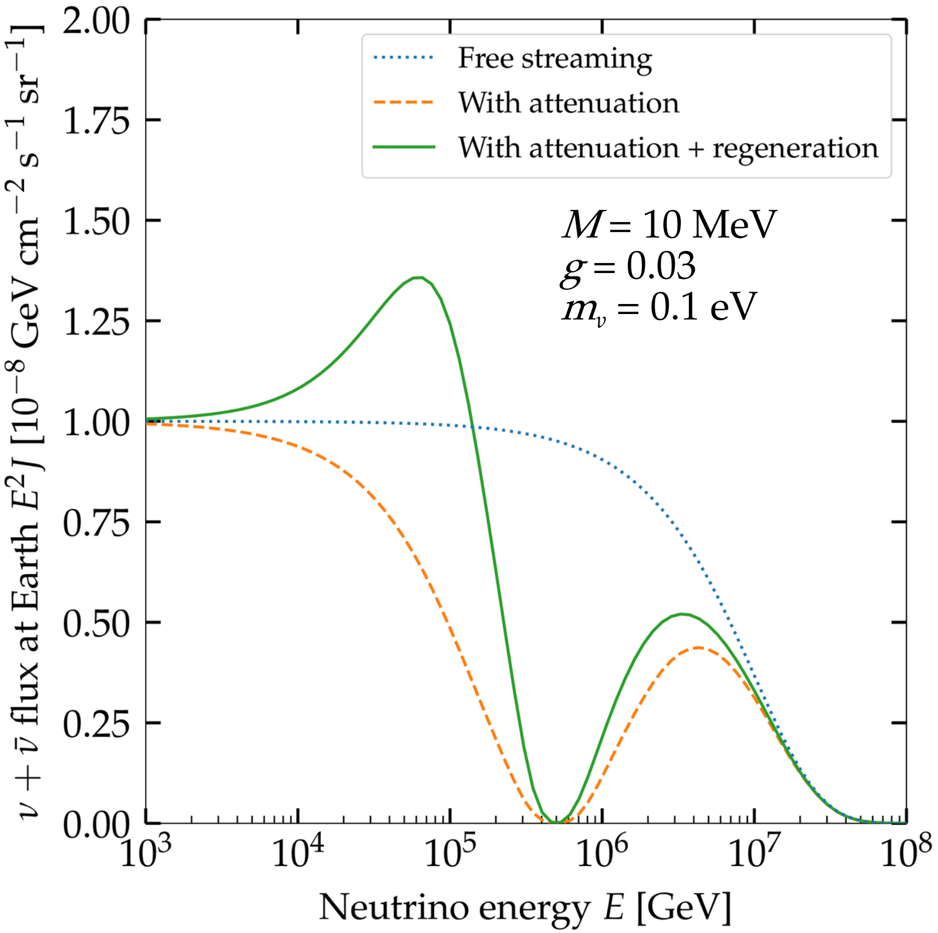


New coupling

Cross section: $$\sigma = \frac{g^4}{4\pi} \frac{s}{(s - M^2)^2 + M^2\Gamma^2}$$

Mediator mass

Resonance energy: $$E_{\rm res} = \frac{M^2}{2m_\nu}$$



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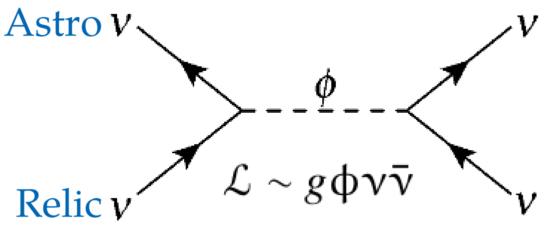

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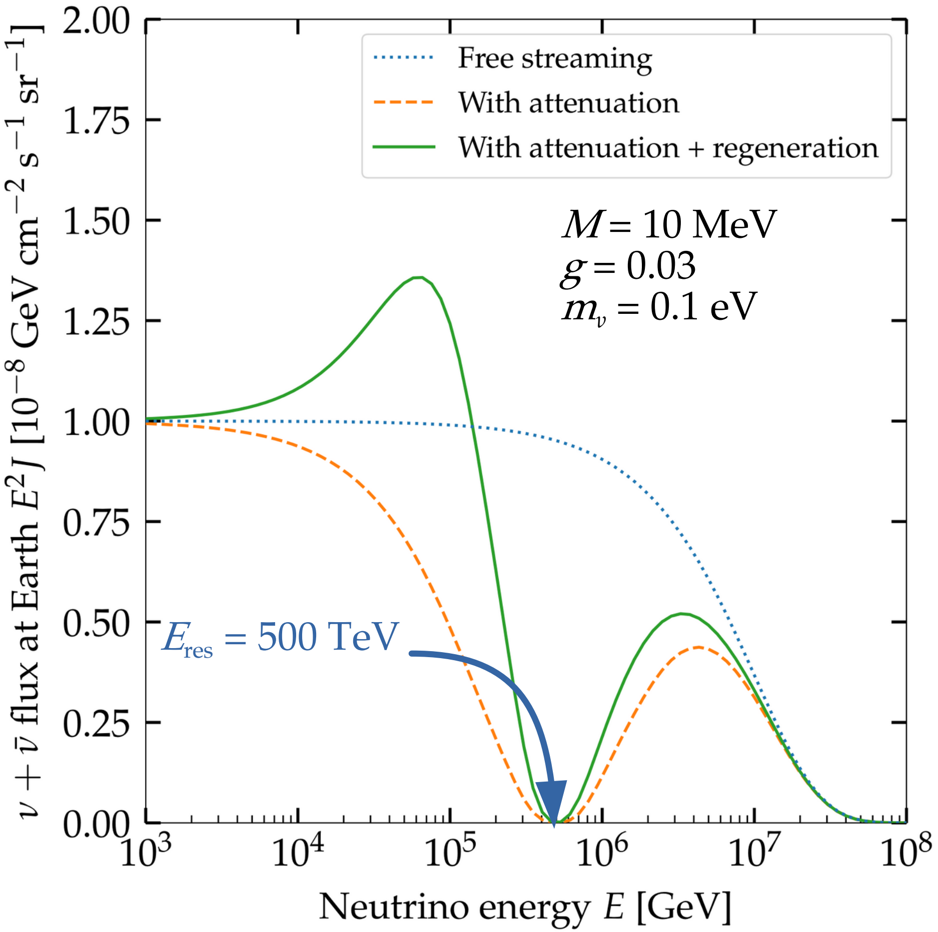
Mediator mass

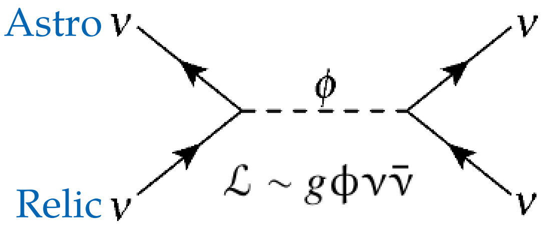
Resonance energy: $$E_{\rm res} = \frac{M^2}{2m_\nu}$$



MB, Rosenstroem, Shalgar, Tamborra, *PRD* 2020
See also: Esteban, Pandey, Brdar, Beacom, *PRD* 2021
Creque-Sarbinowski, Hyde, Kamionkowski, *PRD* 2021
Ng & Beacom, *PRD* 2014
Cherry, Friedland, Shoemaker, 1411.1071
Blum, Hook, Murase, 1408.3799

Secret interactions of high-energy astrophysical neutrinos

"Secret" neutrino interactions between astrophysical ν (PeV) and relic ν (0.1 meV):



New coupling

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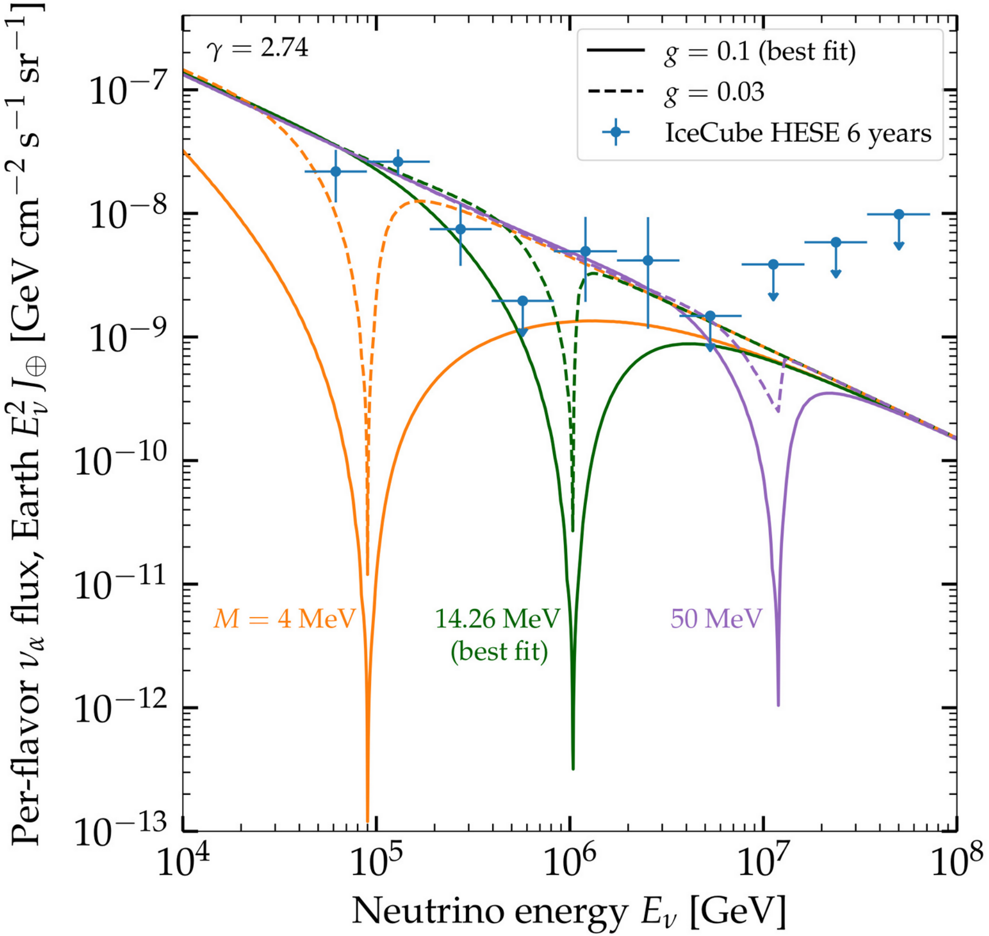

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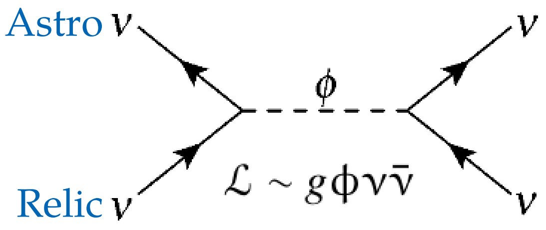

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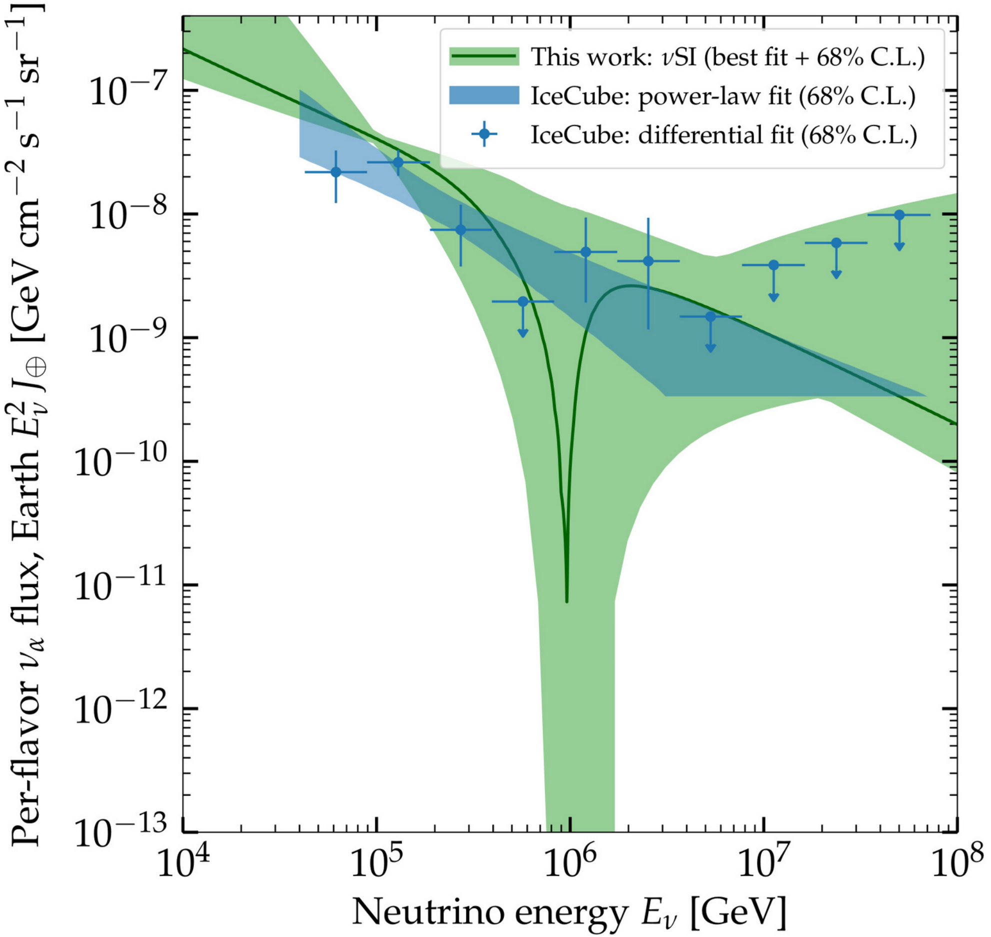
Looking for evidence of νSI

- Look for dips in 6 years of public IceCube data (HESE)
- 80 events, 18 TeV–2 PeV
- Assume flavor-diagonal and universal: $g_{\alpha\alpha} = g\,\delta_{\alpha\alpha}$
- Bayesian analysis varying M, g, shape of emitted flux (γ)
- Account for atmospheric ν, in-Earth propagation, detector uncertainties

No significant (> 3σ) evidence for a spectral dip …



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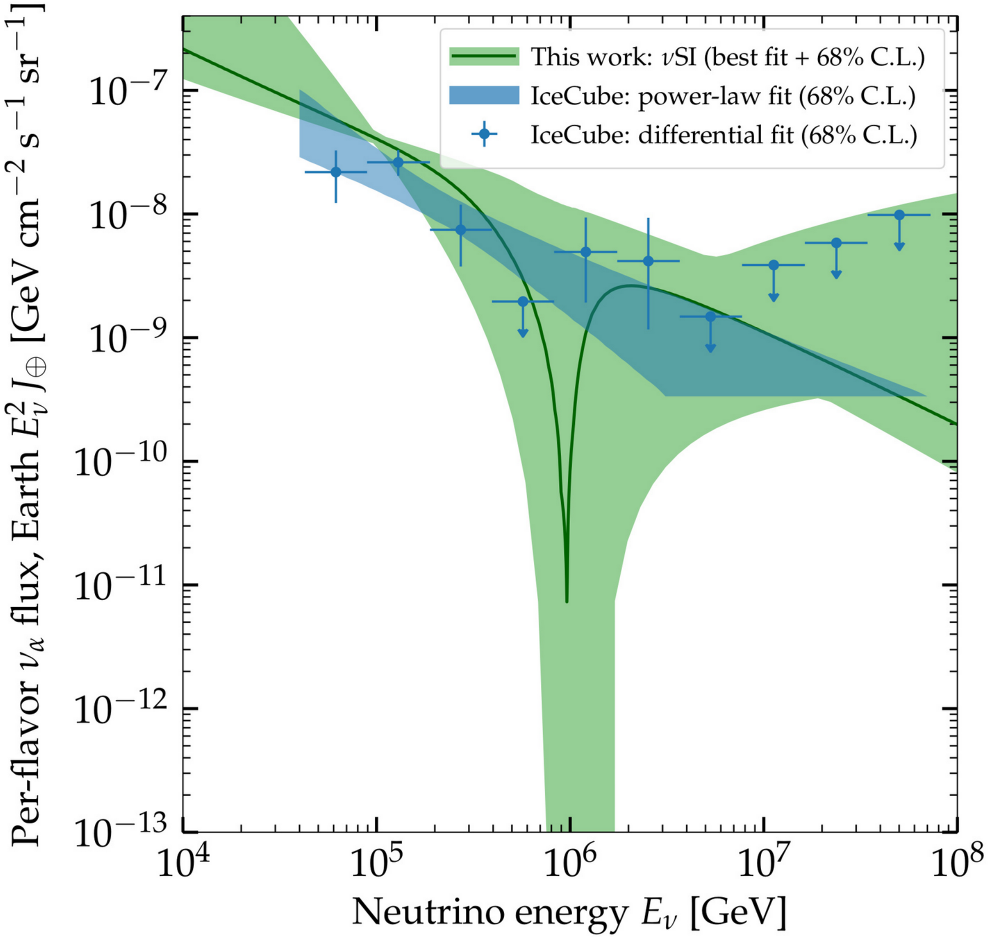
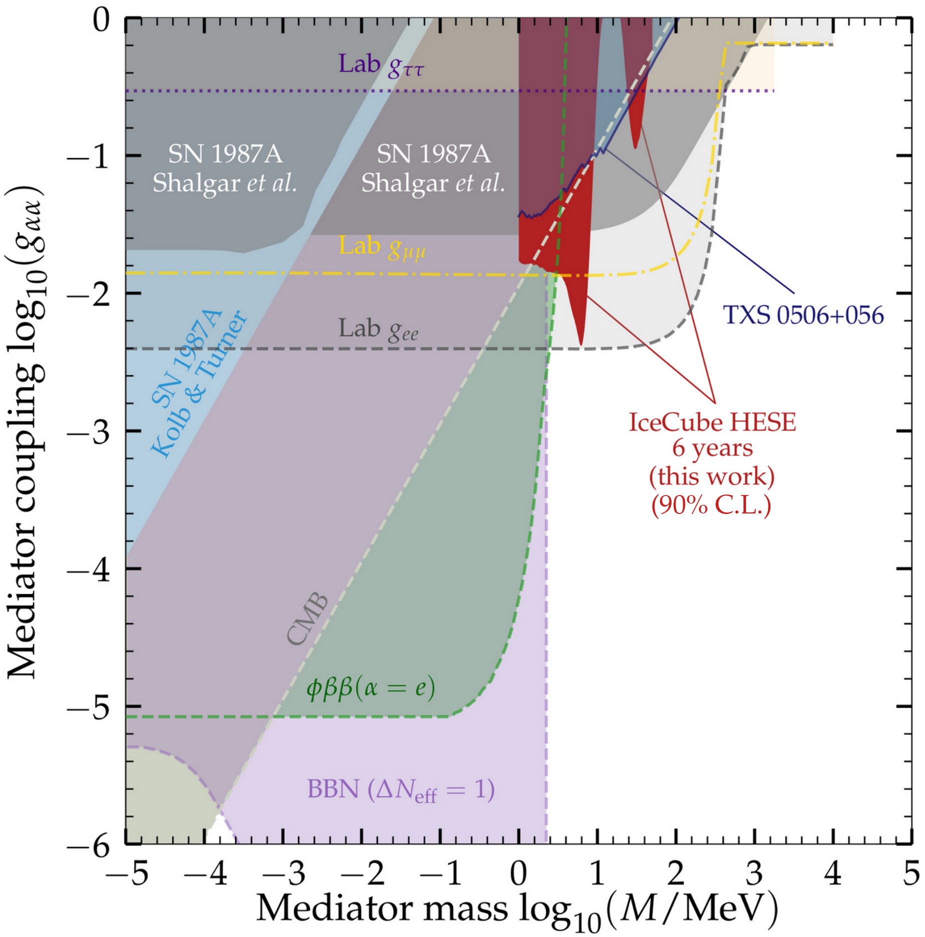
No significant (> 3σ) evidence for a spectral dip … … so we set upper limits on the coupling g





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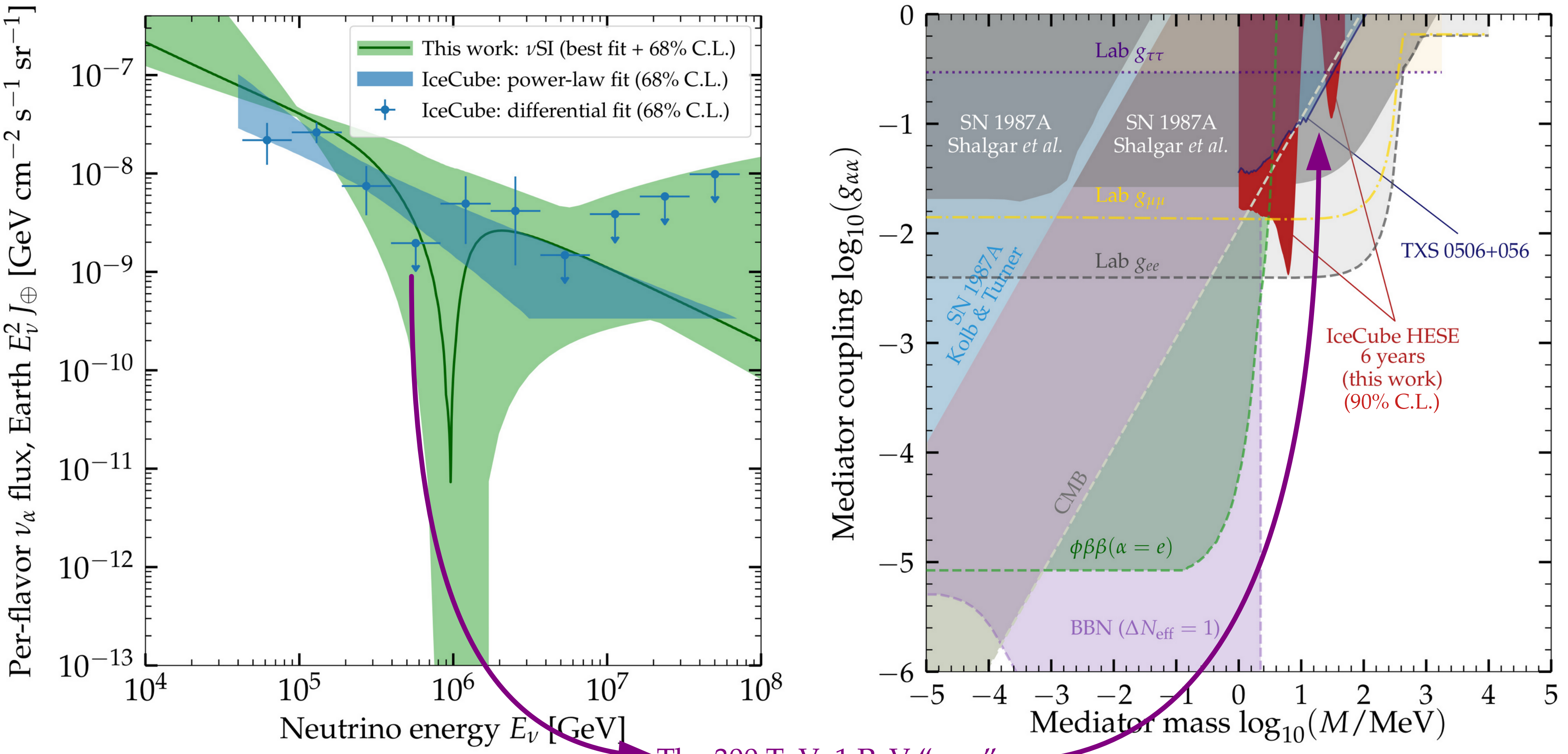


The 300 TeV–1 PeV "gap" degrades the limit at ~10 MeV

MB, Rosenstroem, Shalgar, Tamborra, *PRD* 2020
See also: Shalgar, **MB**, Tamborra, *PRD* 2020

Backgrounds

Atmospheric ν & muons, astrophysical non-BSM ν, cosmic rays

Experimental limitations

Energy & angular resolution, detector efficiency, flavor identification

Neutrino properties

Mixing parameters, cross sections, neutrino mass (sometimes)

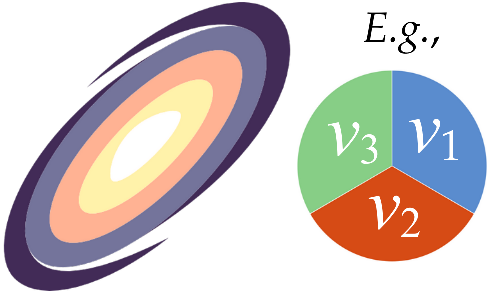
Theory bias

Look-elsewhere effect, astrophysical source models, oversimplified theory

Astrophysical sources — Earth

L ~ up to a few Gpc

E.g.,



Decay changes the number of each ν mass eigenstate, N_1, N_2, N_3 ?

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

Mass of ν_i — Lifetime of ν_i

Astrophysical sources Earth

L ~ up to a few Gpc

E.g.,

Decay changes the number

of each ν mass eigenstate, N_1, N_2, N_3

?

Only sensitive to their ratio

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

Mass of ν_i Lifetime of ν_i

Astrophysical sources — Earth

L ~ up to a few Gpc

E.g.,

Decay changes the number

of each ν mass eigenstate, N_1, N_2, N_3

?

Lower-E ν are longer-lived…

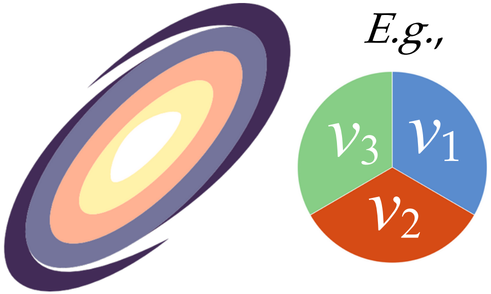
The flux of ν_i is attenuated by $\exp[-\,(L/E)\cdot(m_i/\tau_i)]$

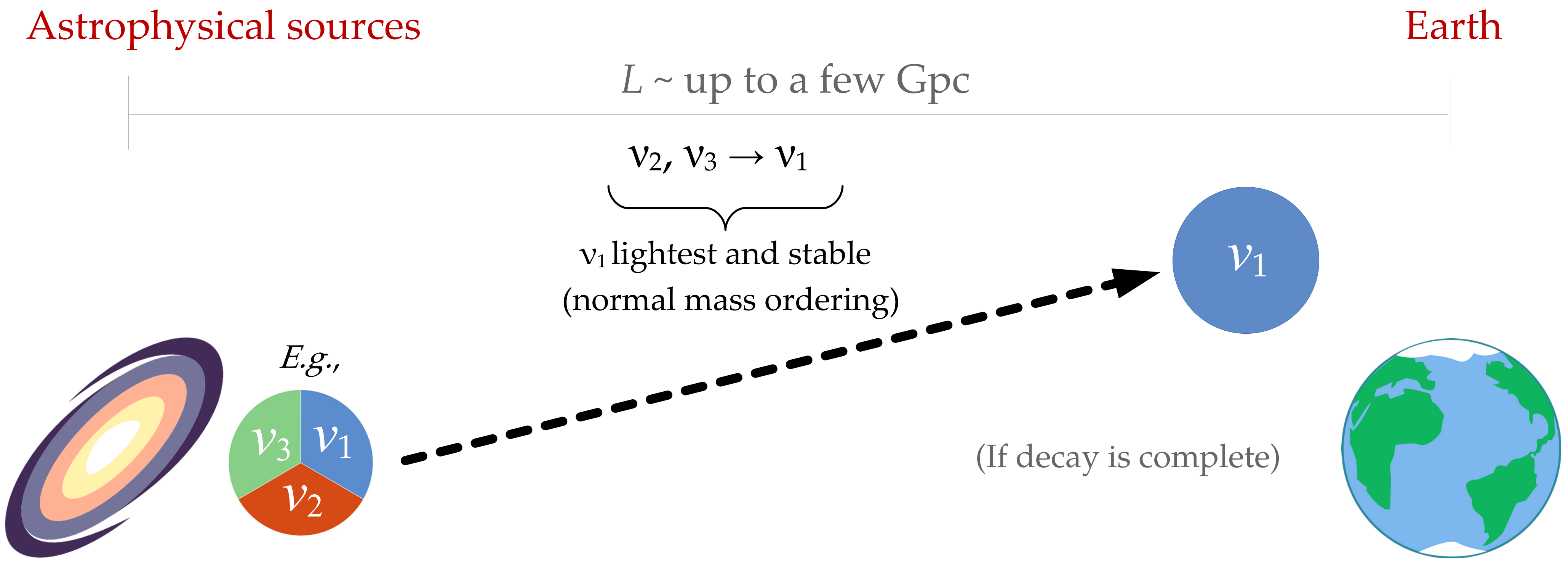
… but ν that travel longer L are more attenuated!

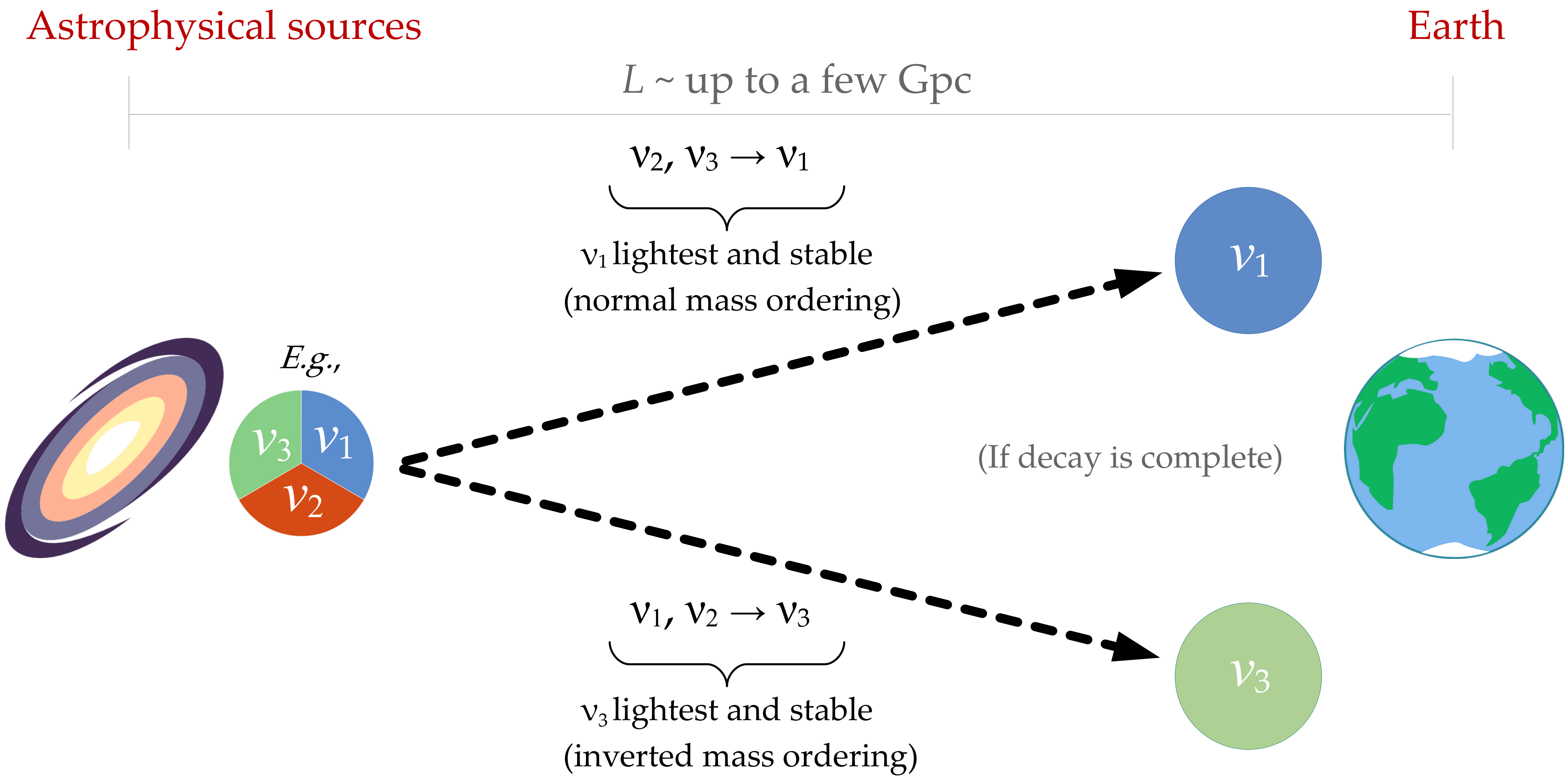
Astrophysical sources

Earth

L ~ up to a few Gpc




Astrophysical sources
Earth
L ~ up to a few Gpc
ν2, ν3 → ν1
ν1 lightest and stable
(normal mass ordering)
E.g.,
ν3
ν1
ν2
ν1
(If decay is complete)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ν1, ν2 → ν3
ν3 lightest and stable
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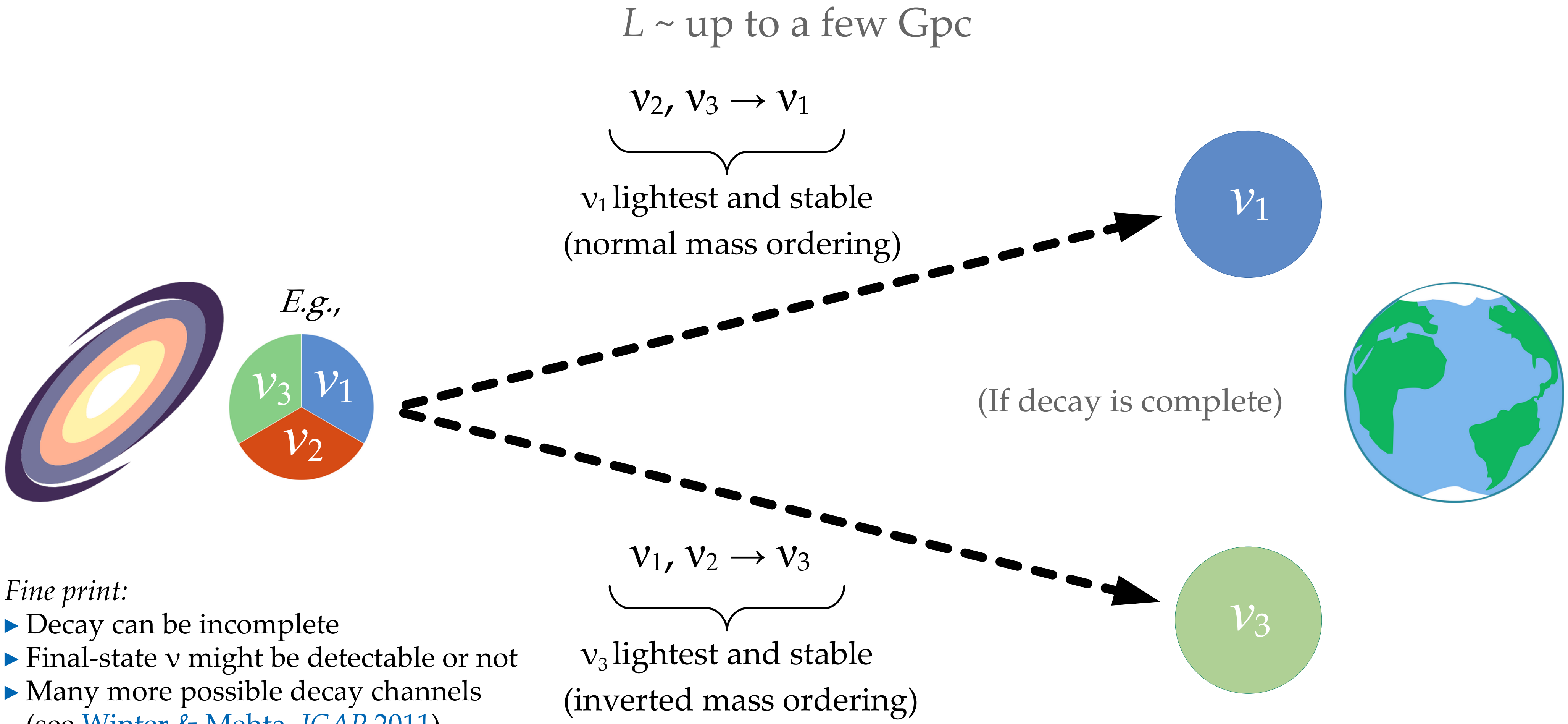
ν3

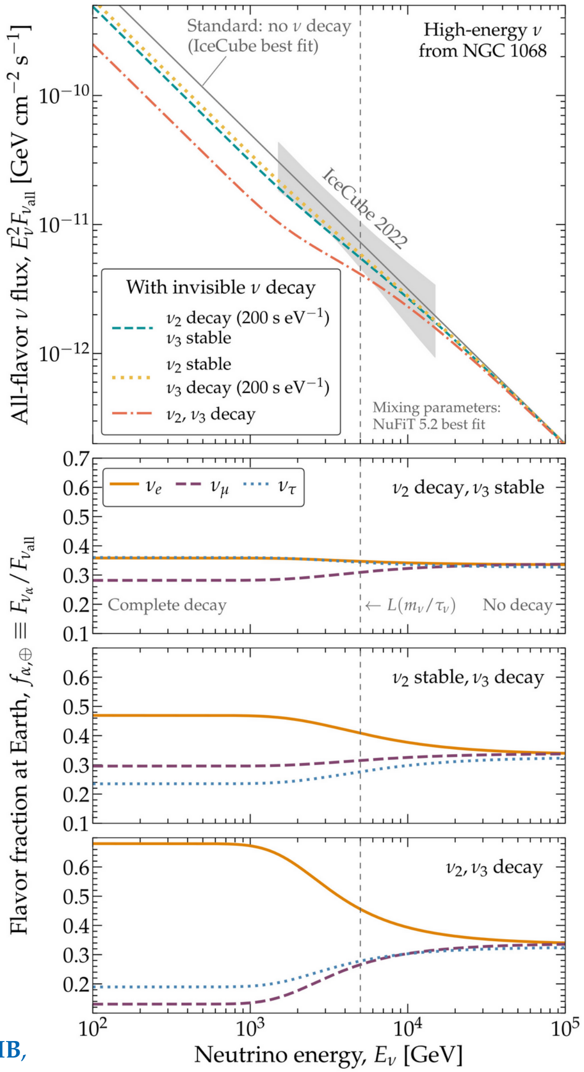
Astrophysical sources — Earth



Fine print:

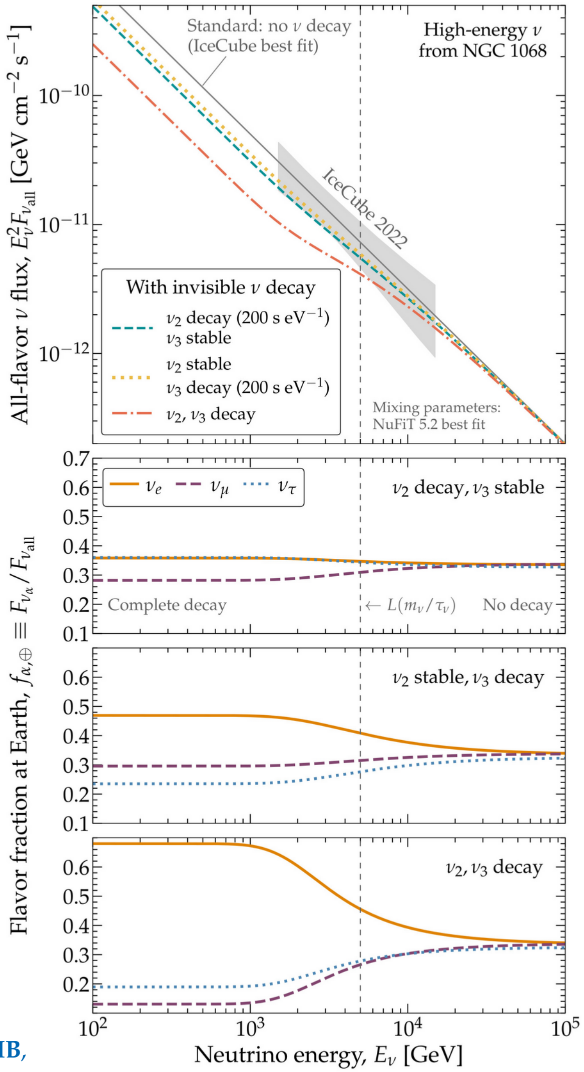
- Decay can be incomplete
- Final-state ν might be detectable or not
- Many more possible decay channels (see Winter & Mehta, *JCAP* 2011)

Neutrino flux

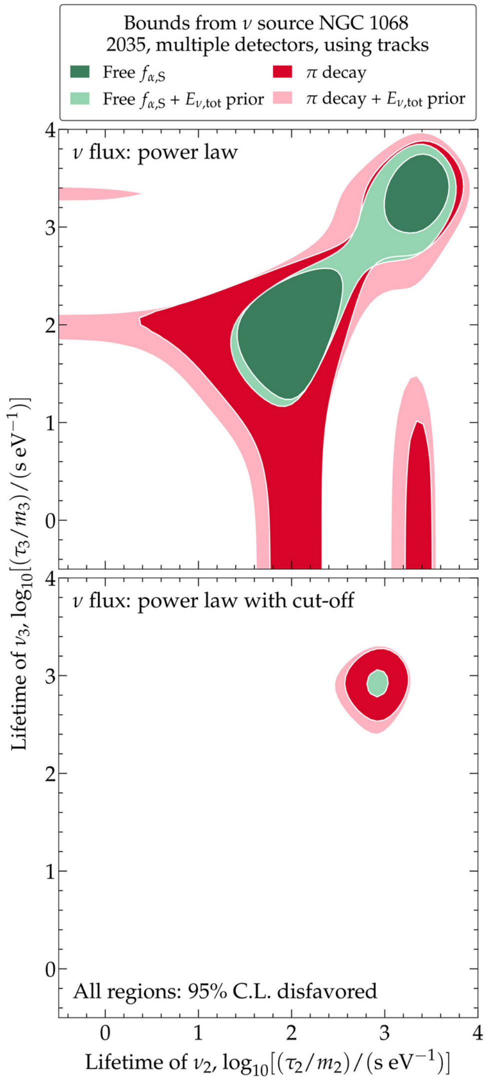


Valera, Fiorillo, Esteban **MB**,
PRD 2024

Neutrino flux

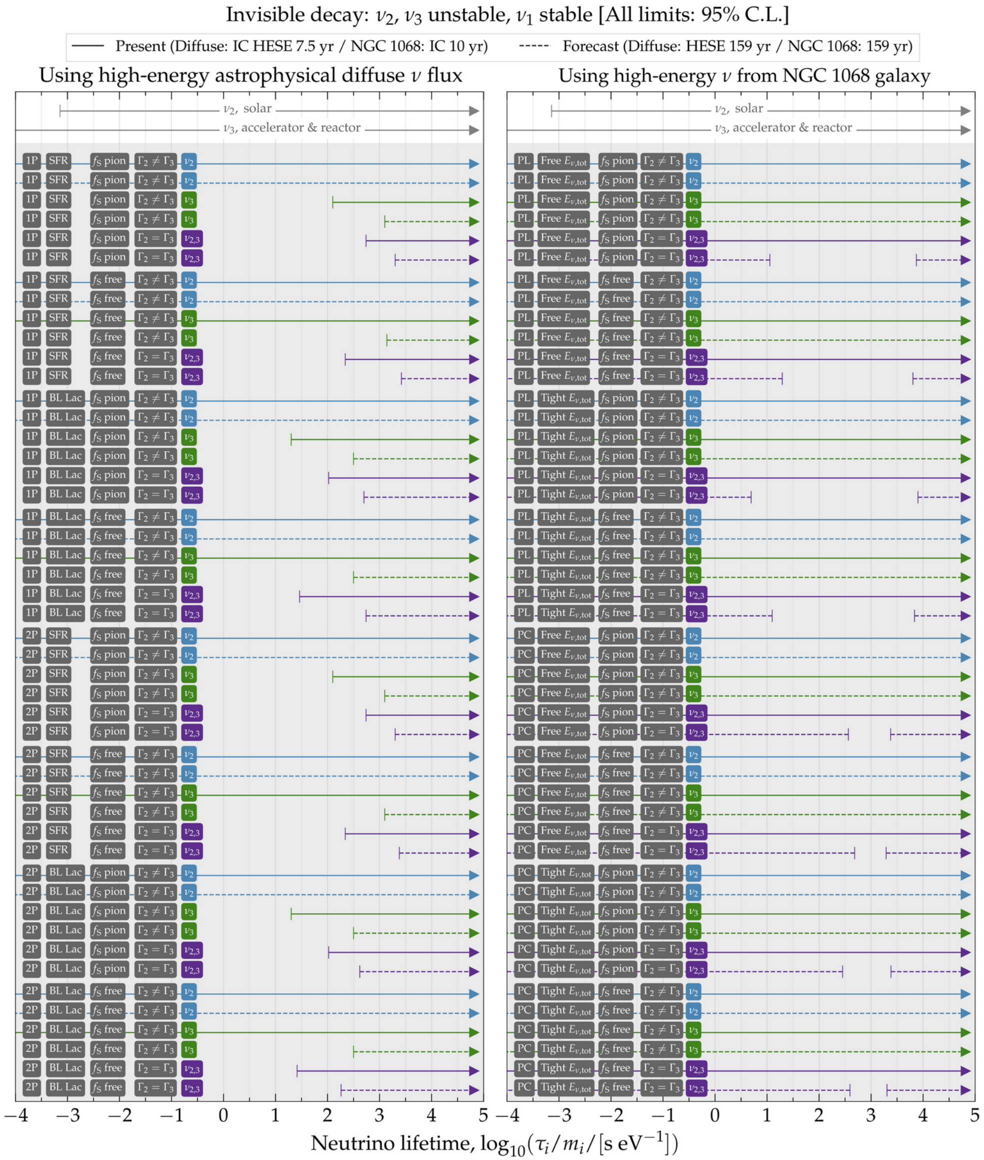


Lifetime bounds



Valera, Fiorillo, Esteban **MB**,
PRD 2024

The limits on neutrino lifetime depend strongly on whether we assume one vs. two source populations, the redshift distribution of sources, and which parameters of the decay model are allowed to float



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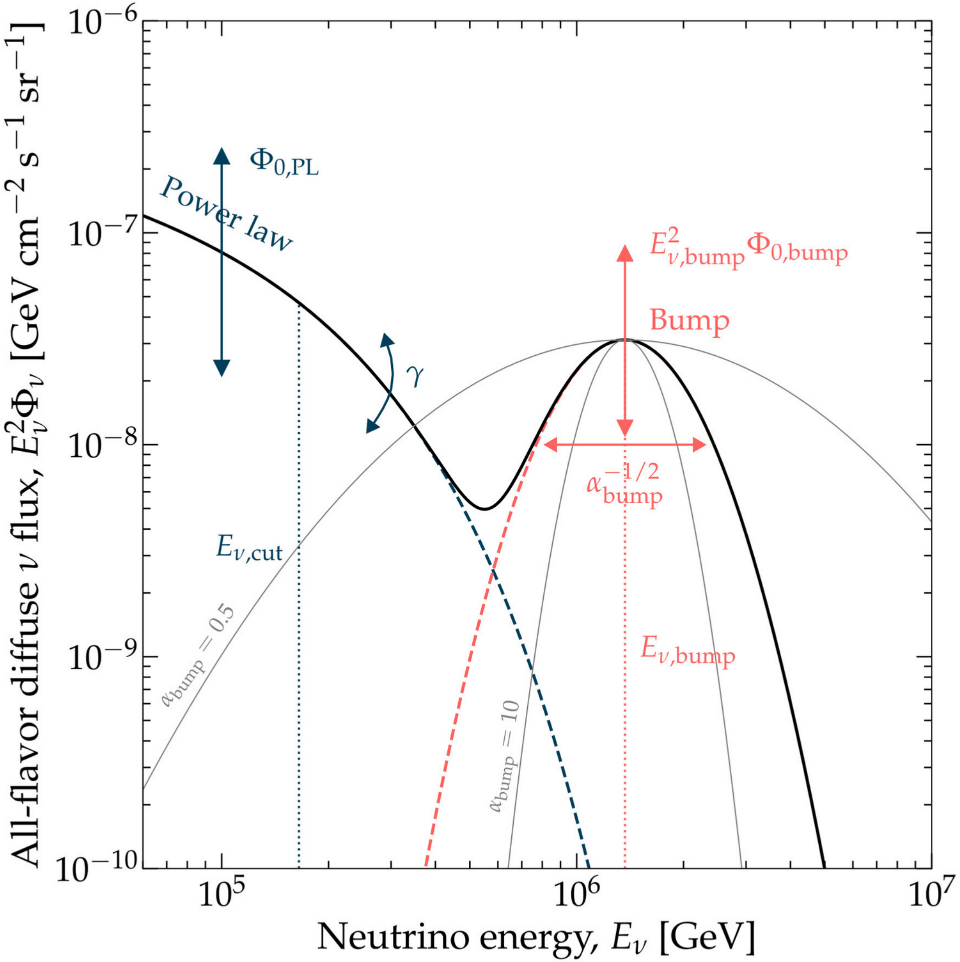
Bump-hunting in the diffuse flux of high-energy neutrinos

Bump-like spectra can reveal the presence of ν production via $p\gamma$ or new physics:



D. F. G. Fiorillo, **MB**, *PRD* 2023

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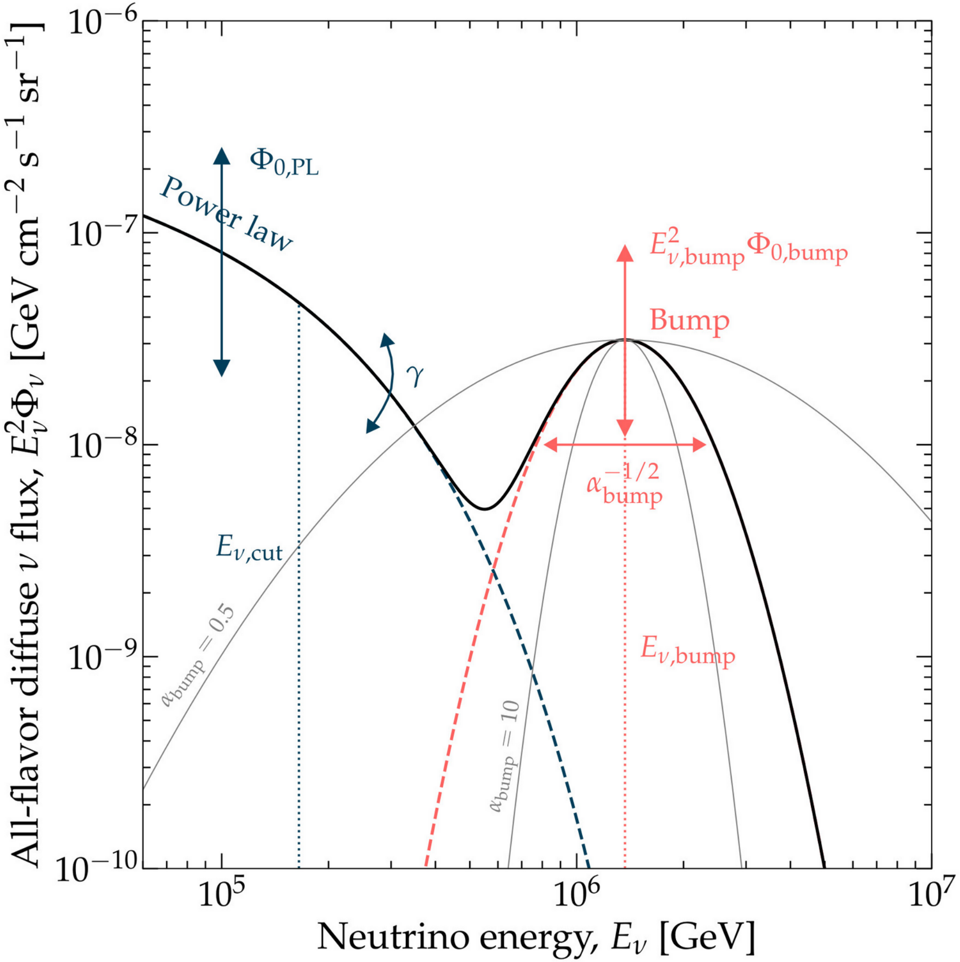

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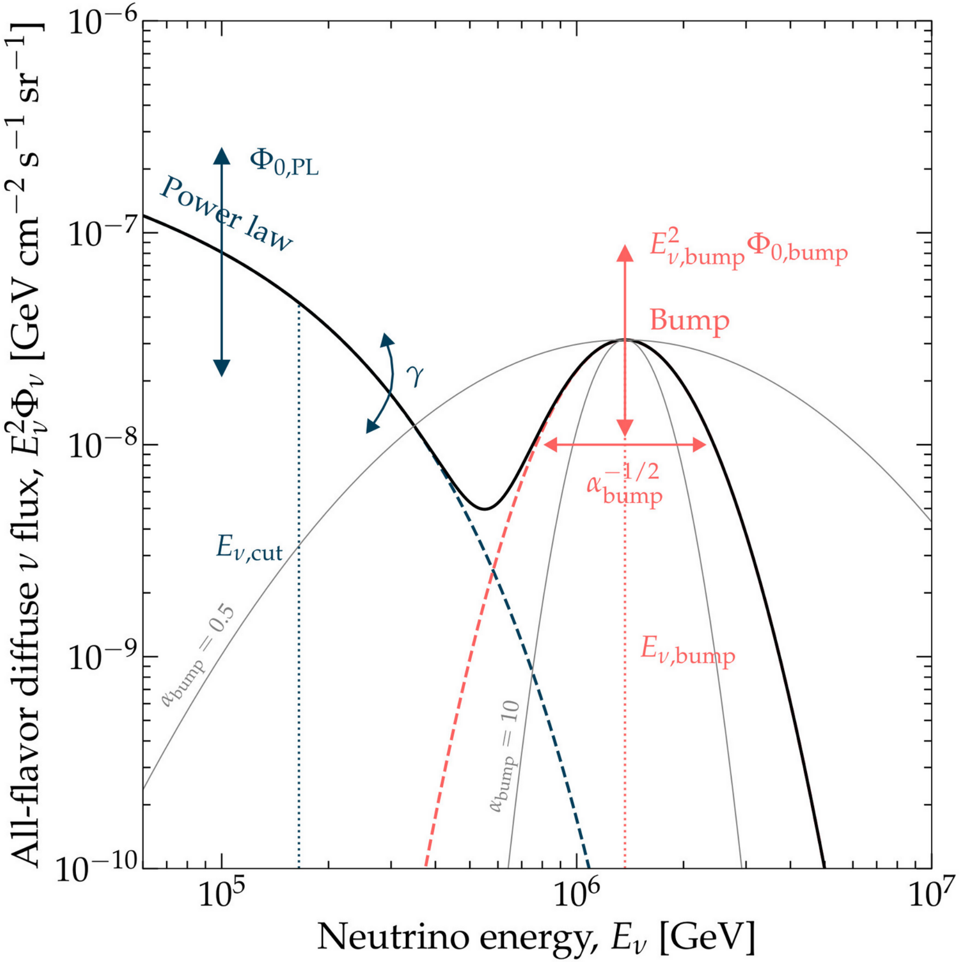

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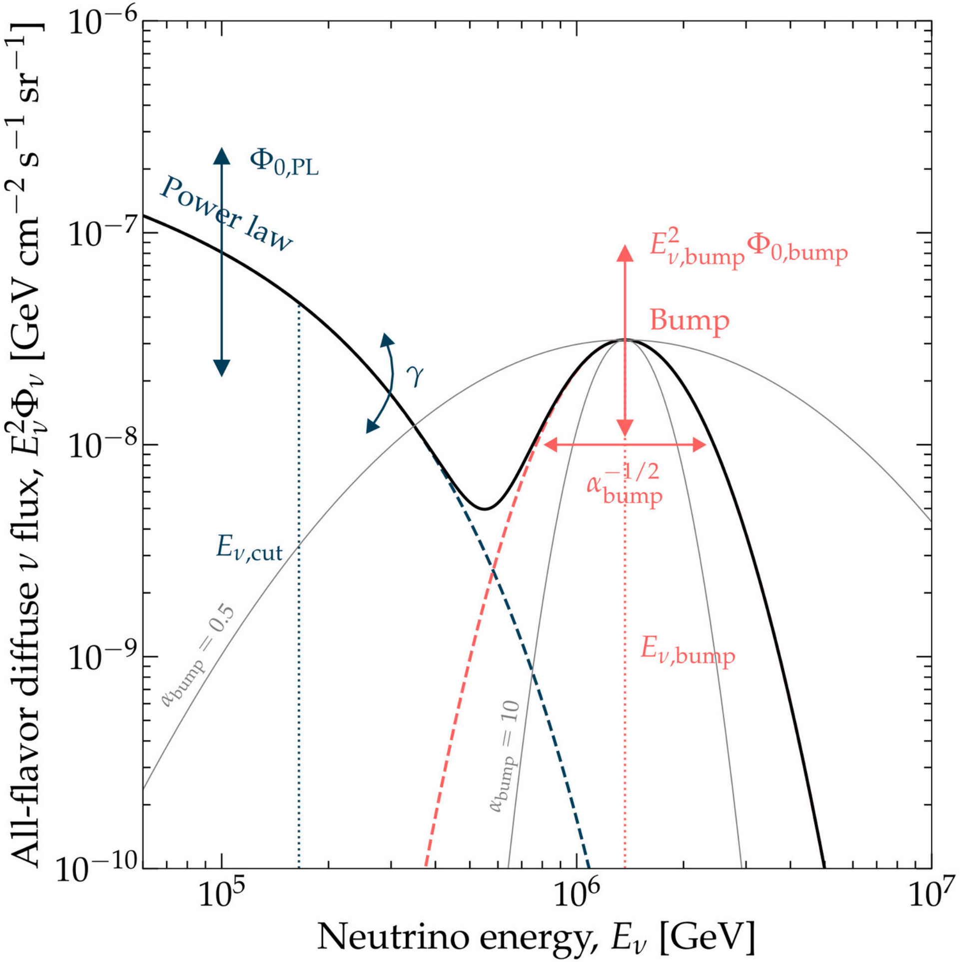

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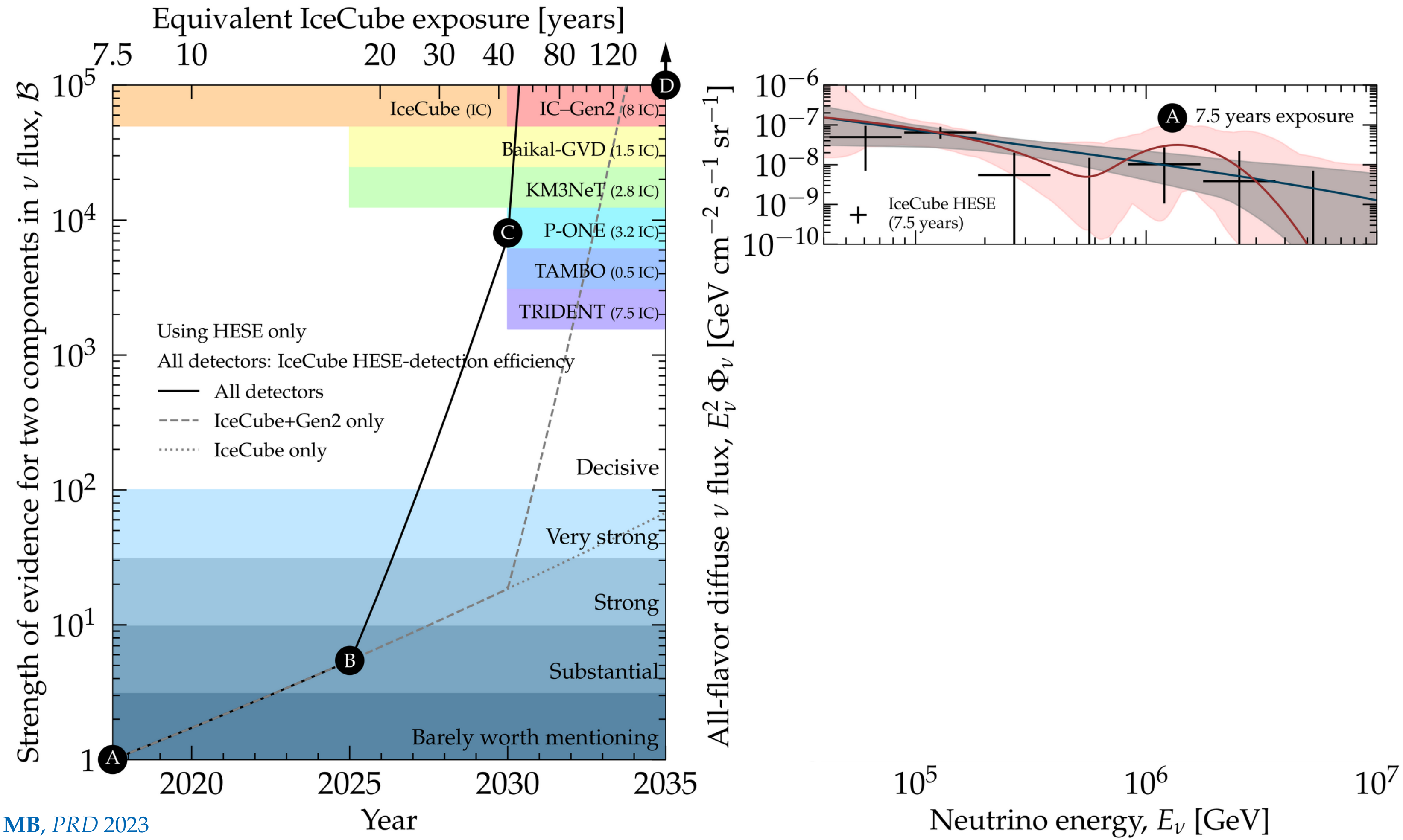

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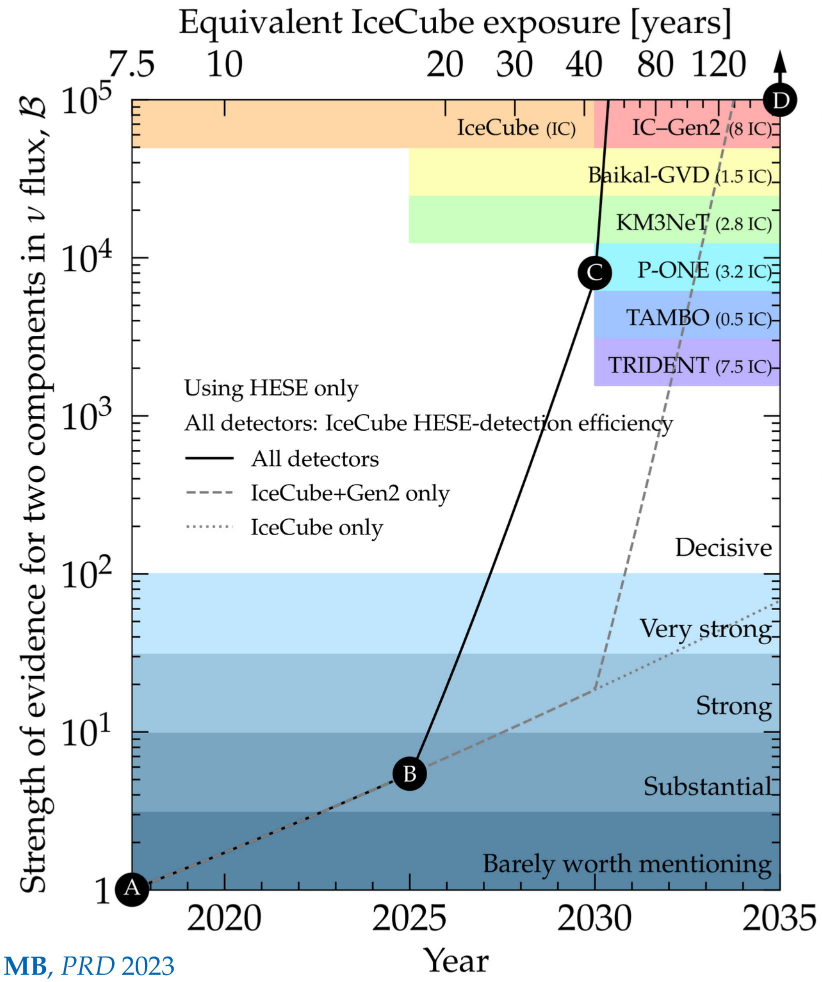

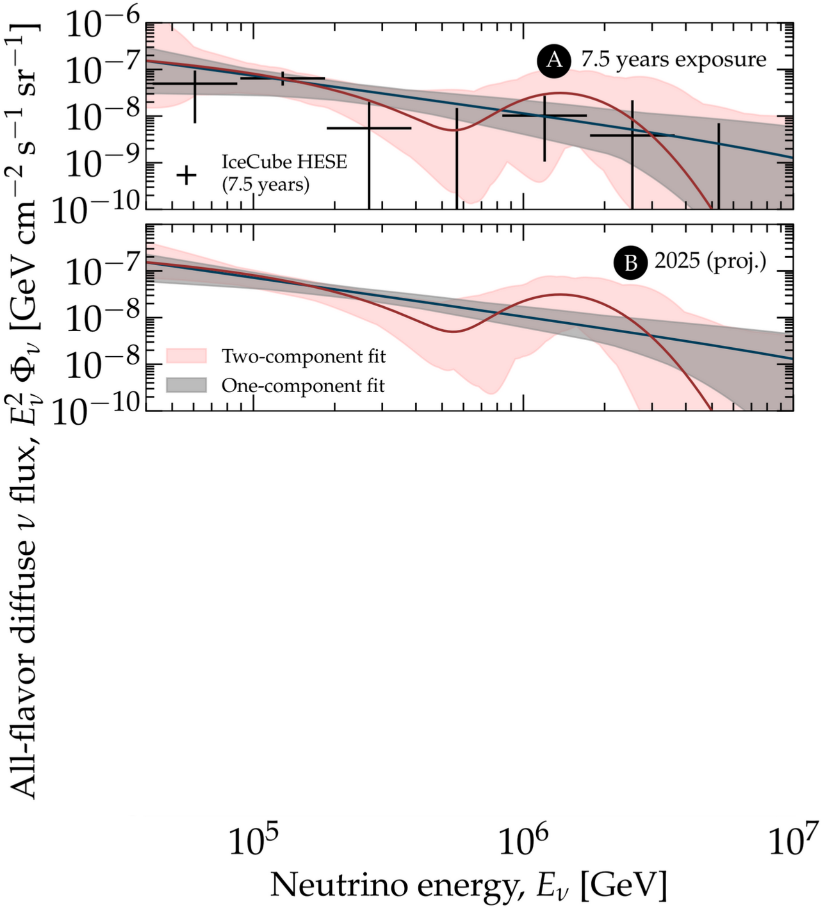

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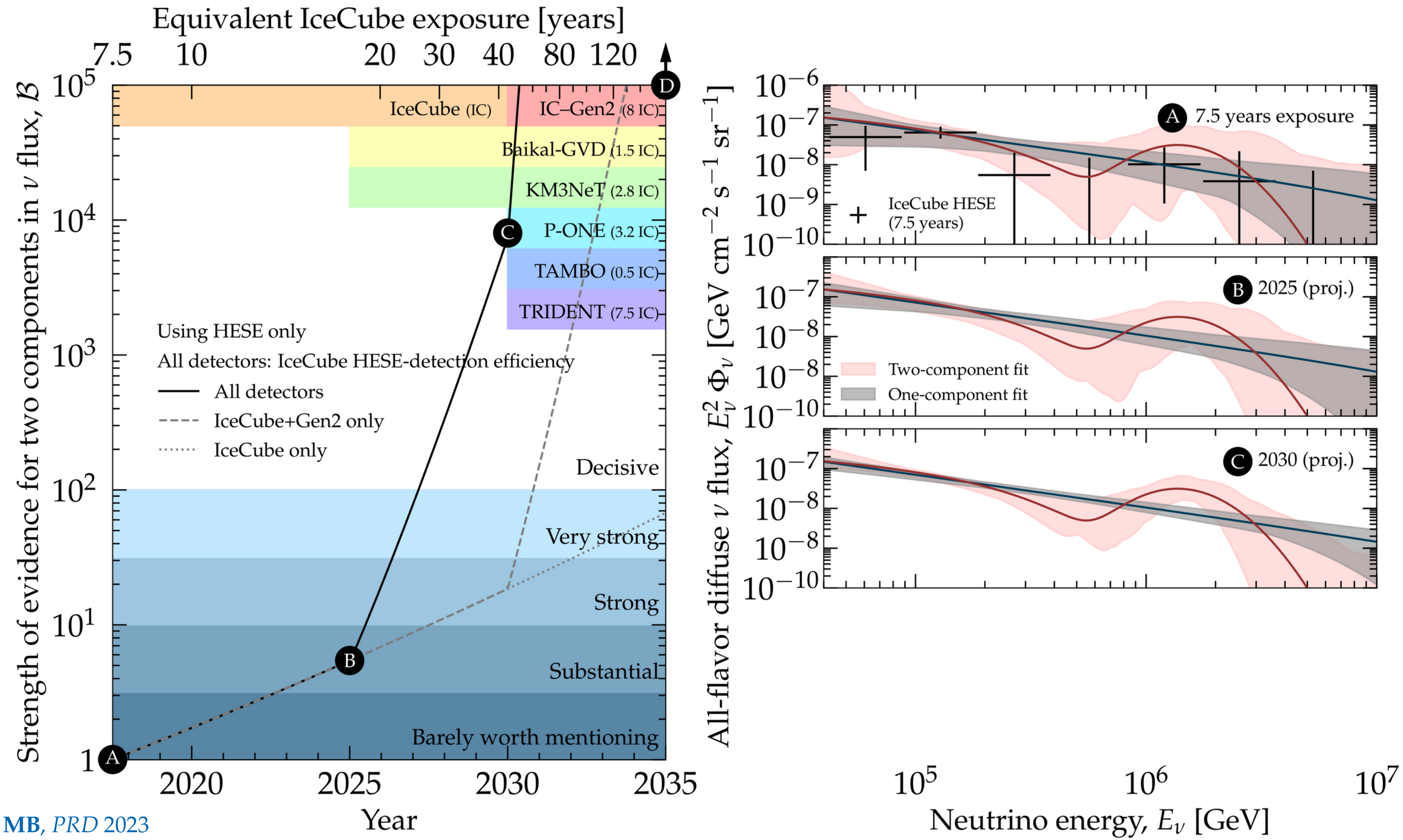

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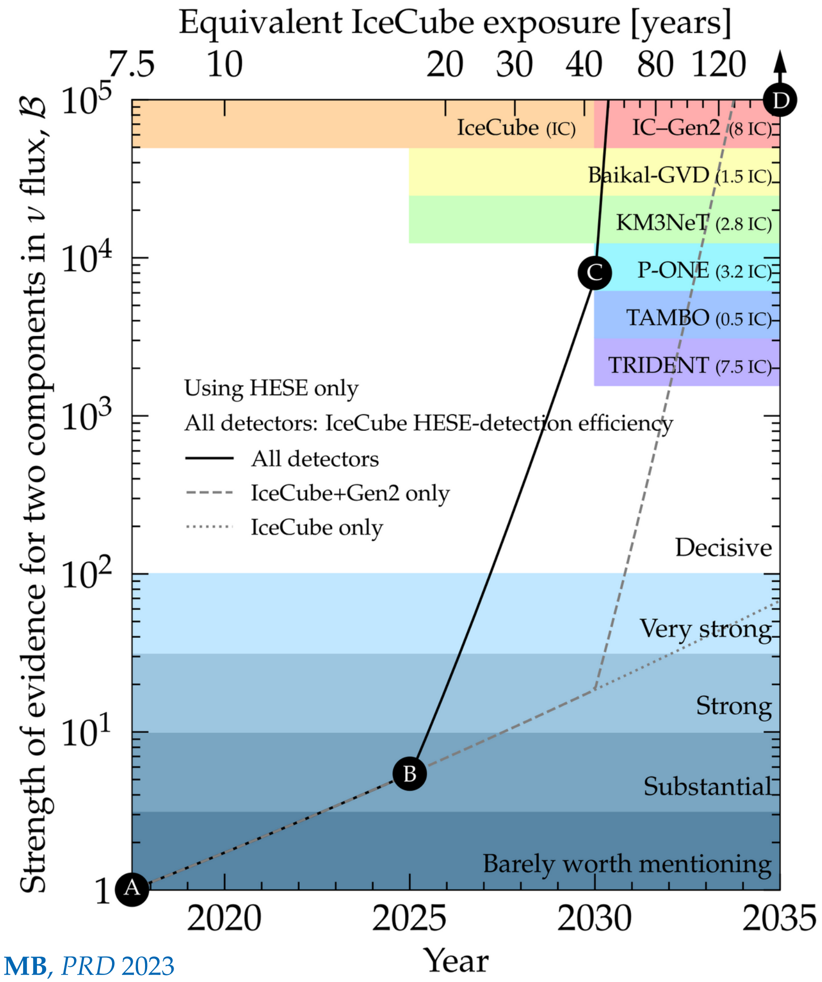
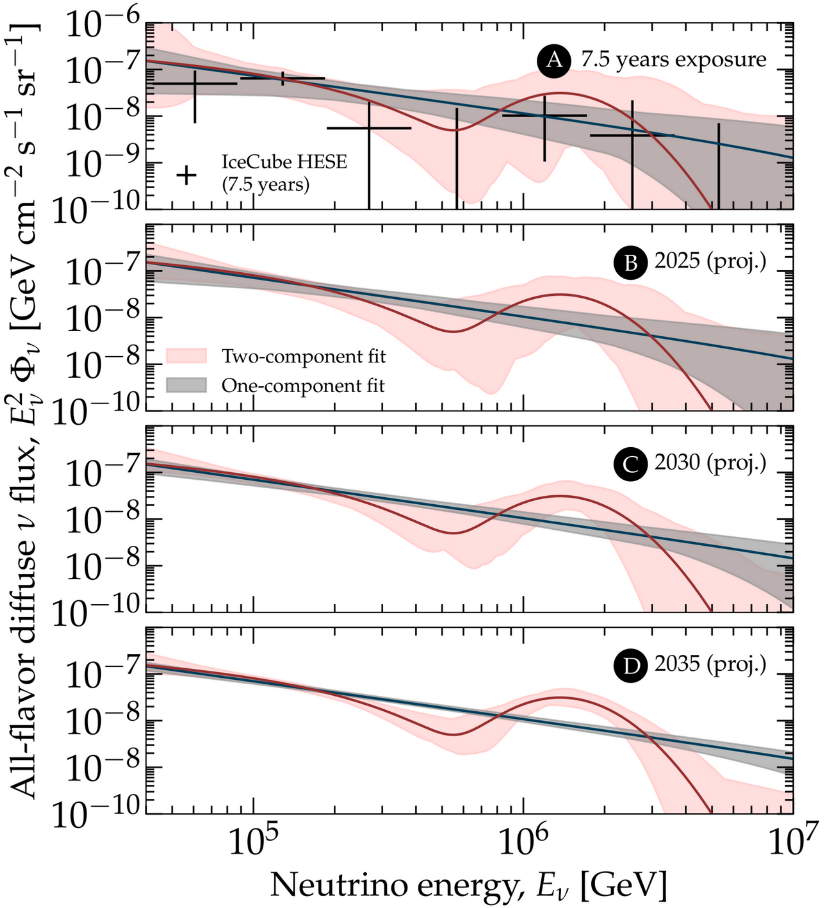
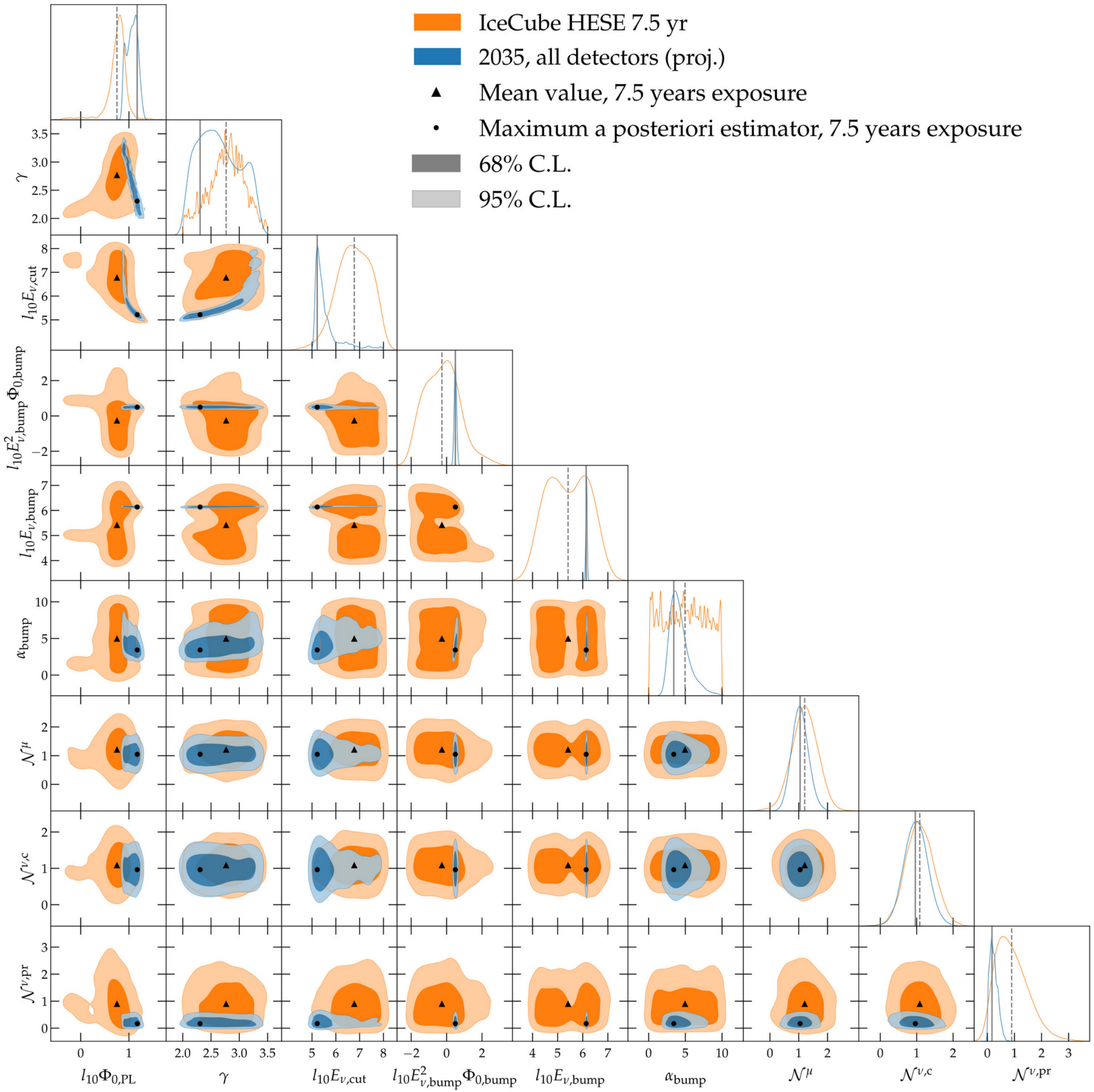




D. F. G. Fiorillo, **MB**, *PRD* 2023



D. F. G. Fiorillo, **MB**, *PRD* 2023

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

Thanks!

Backup slides

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

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

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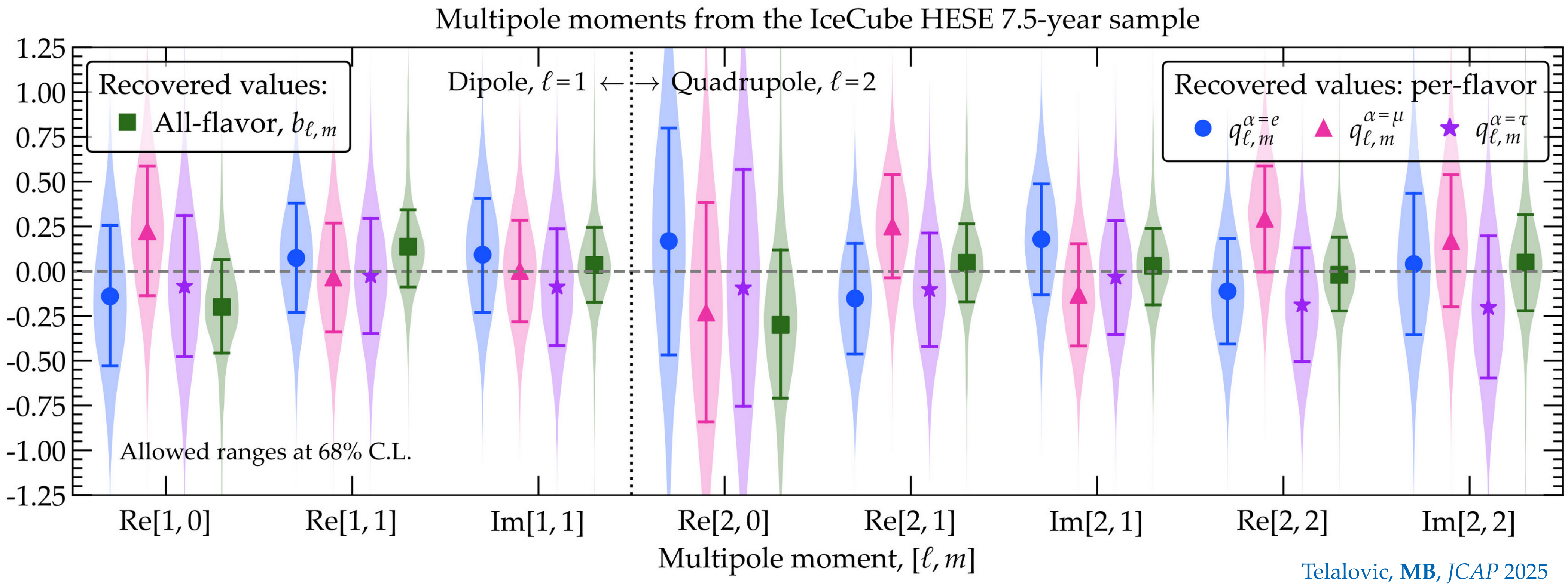
Orders-of-magnitude improvement

Flavor dipoles and quadrupoles in the sky?

Isotropic flux

Flavor-dependent multipole expansion

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



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

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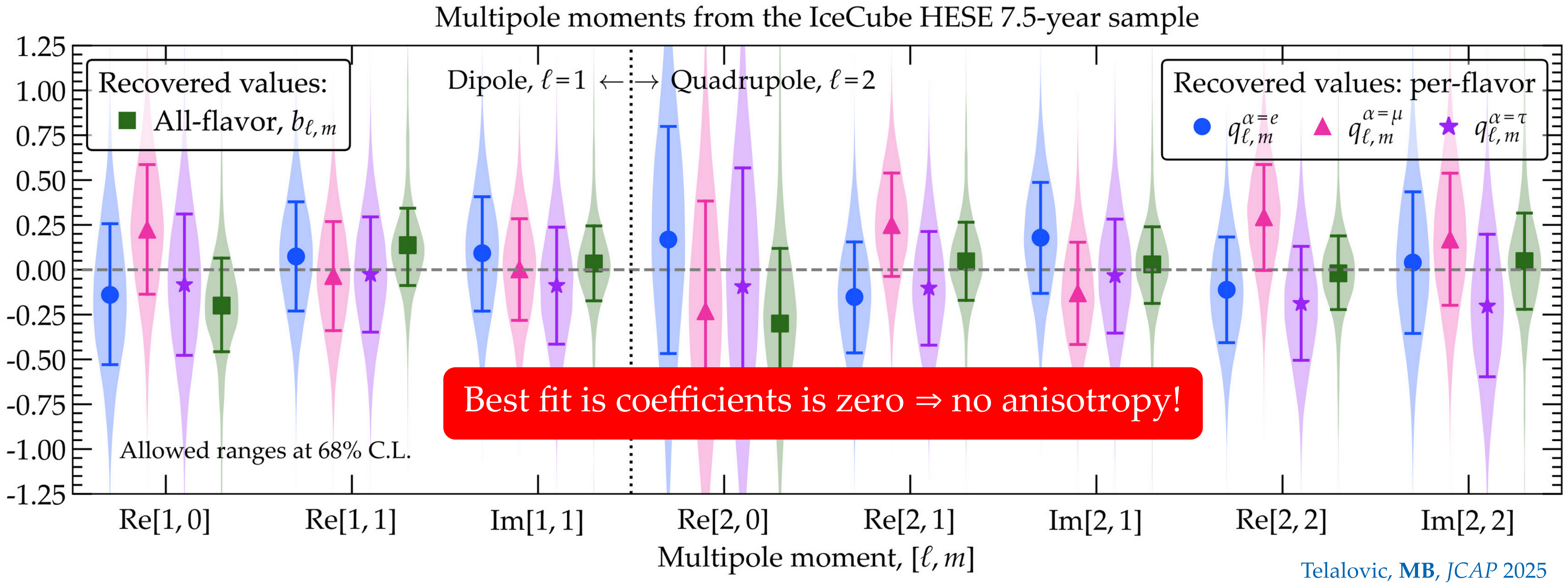
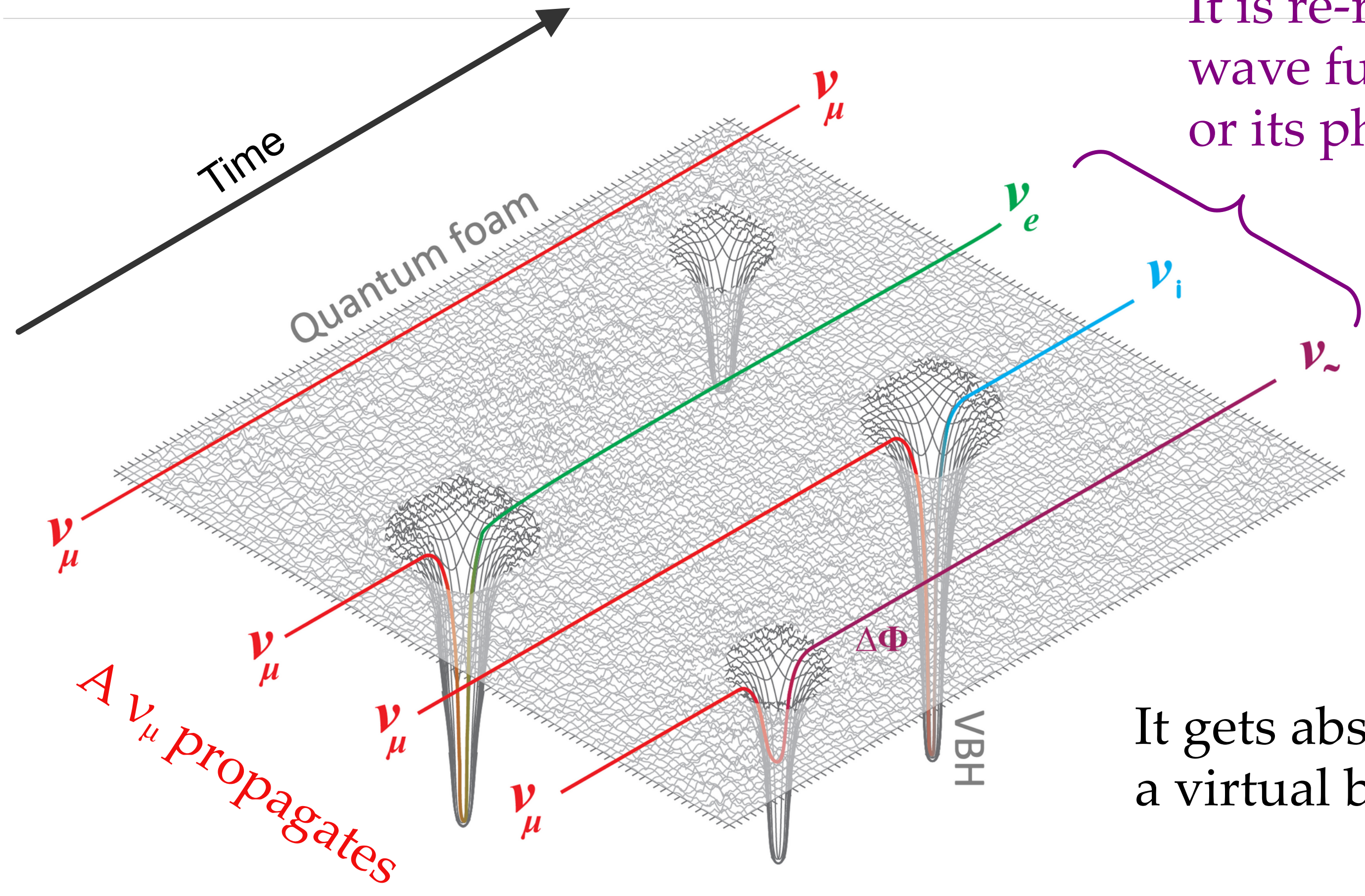


Telalovic, **MB**, *JCAP* 2025

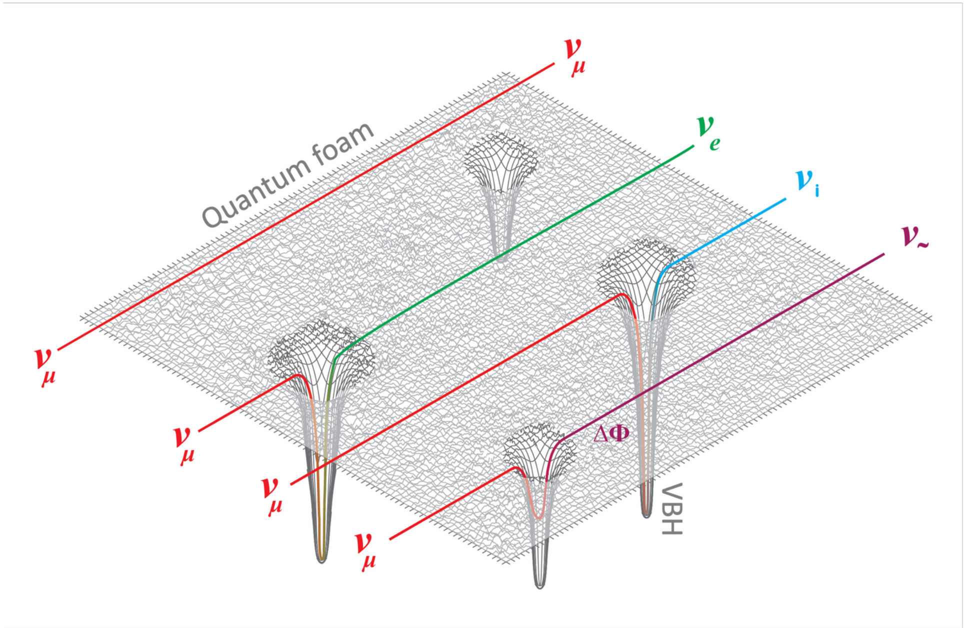
Quantum-gravity decoherence

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



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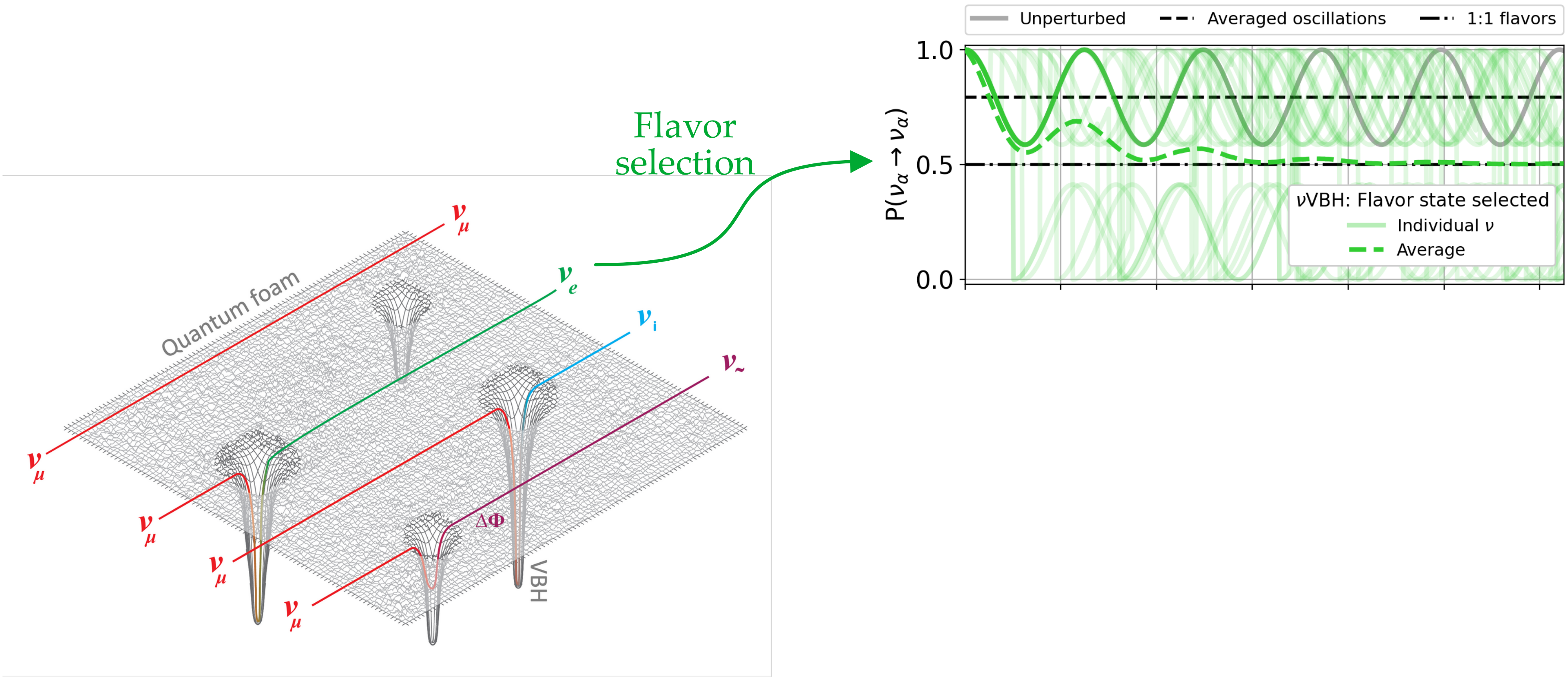

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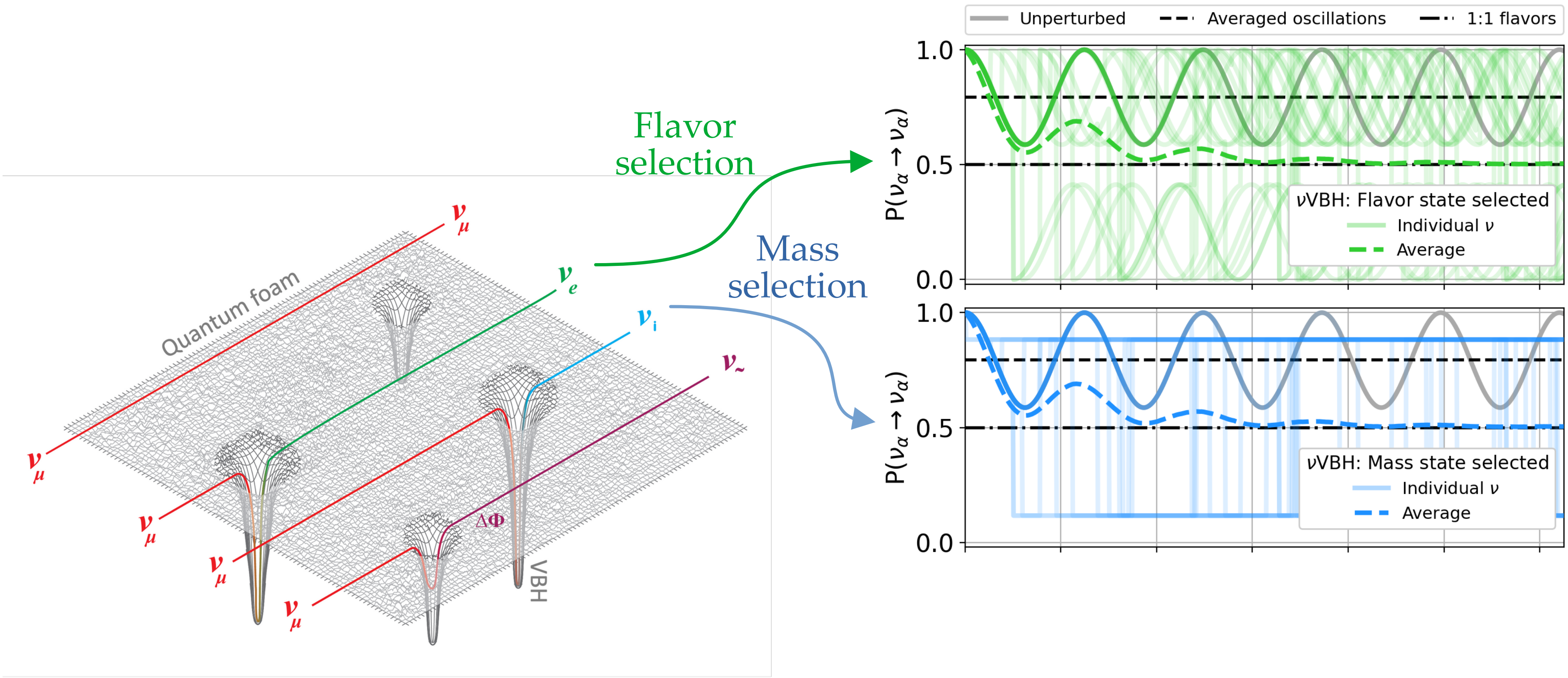

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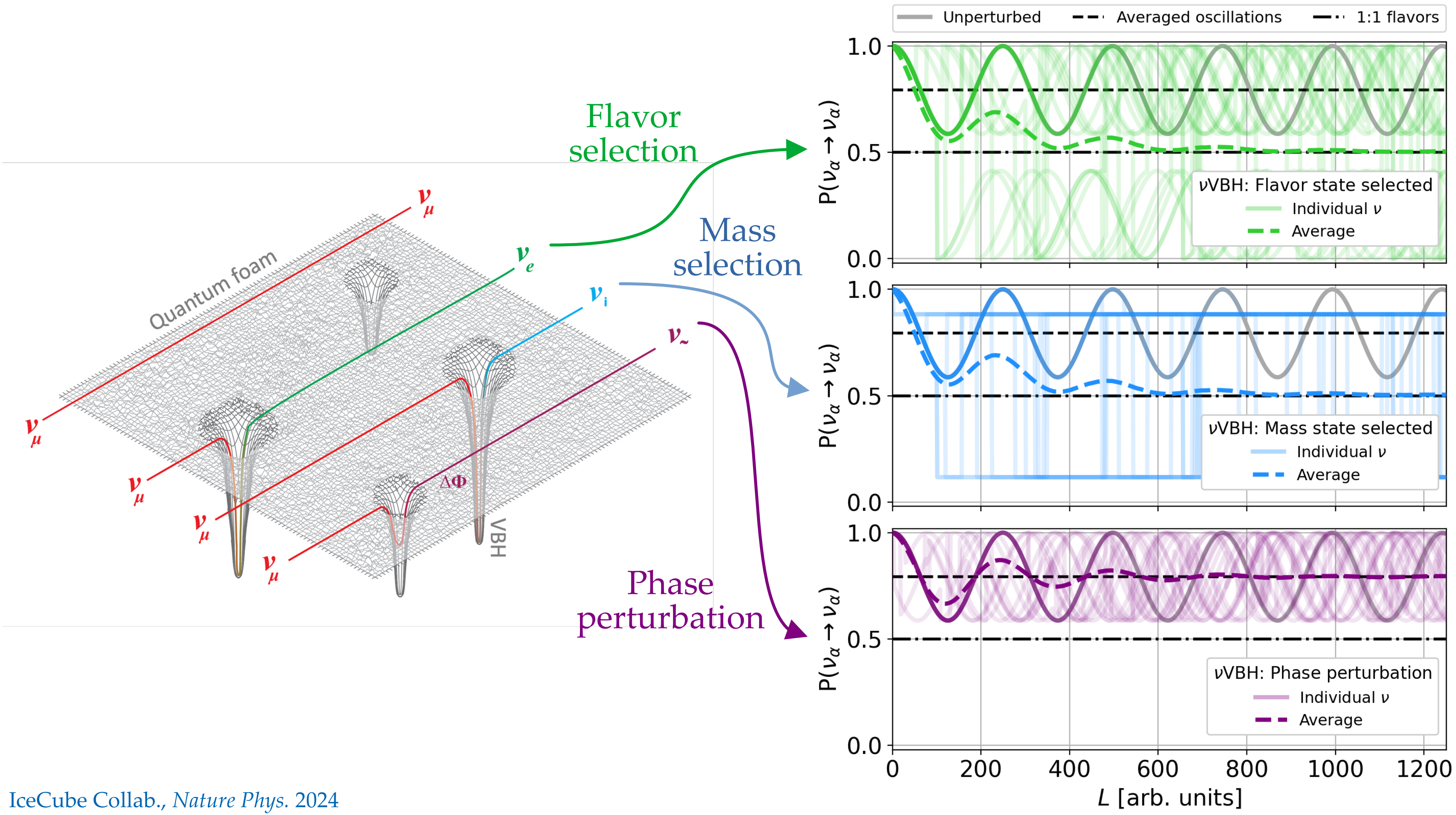

IceCube Collab., *Nature Phys.* 2024

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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Gell-Mann matrices

9×9 matrix

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

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

Strongest constraints to date

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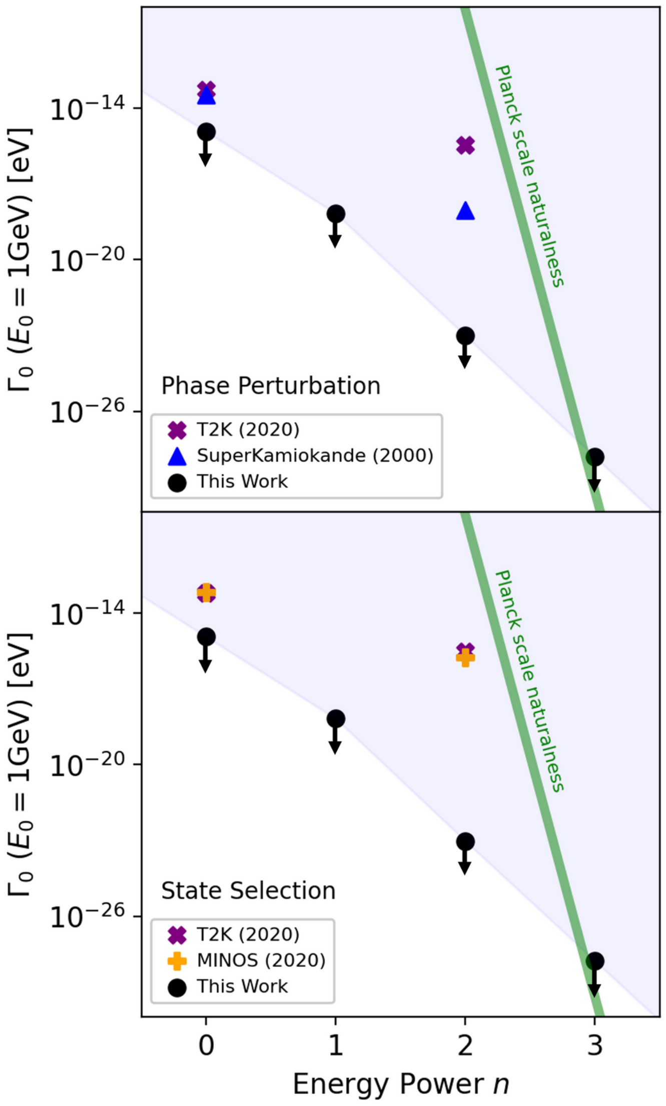

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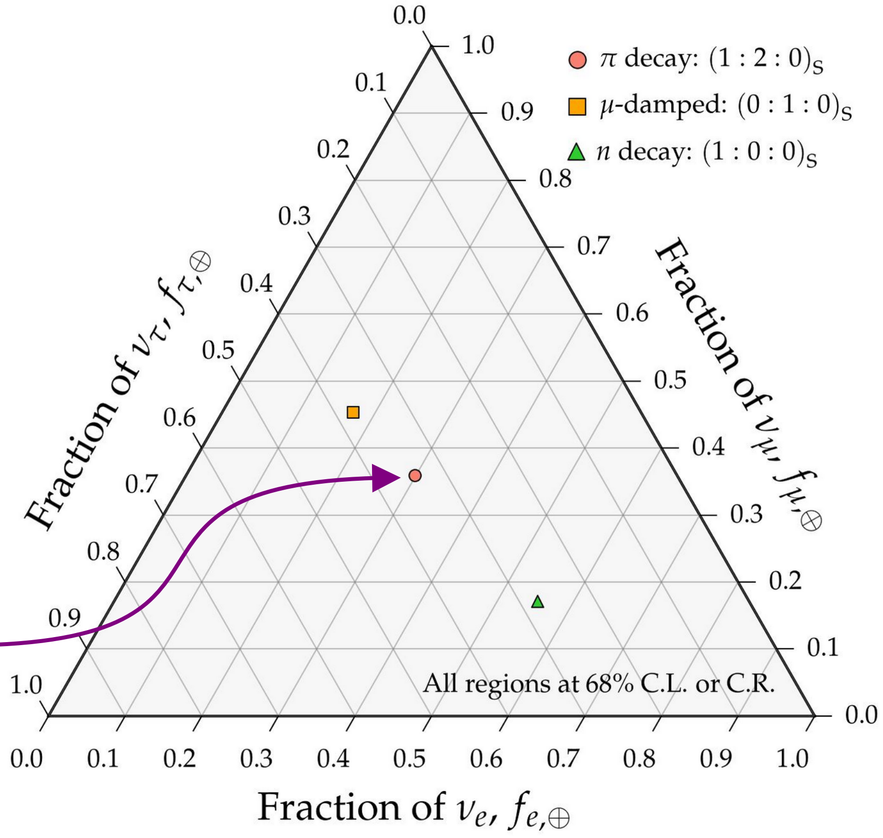
How about using astrophysical TeV—PeV ν?

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

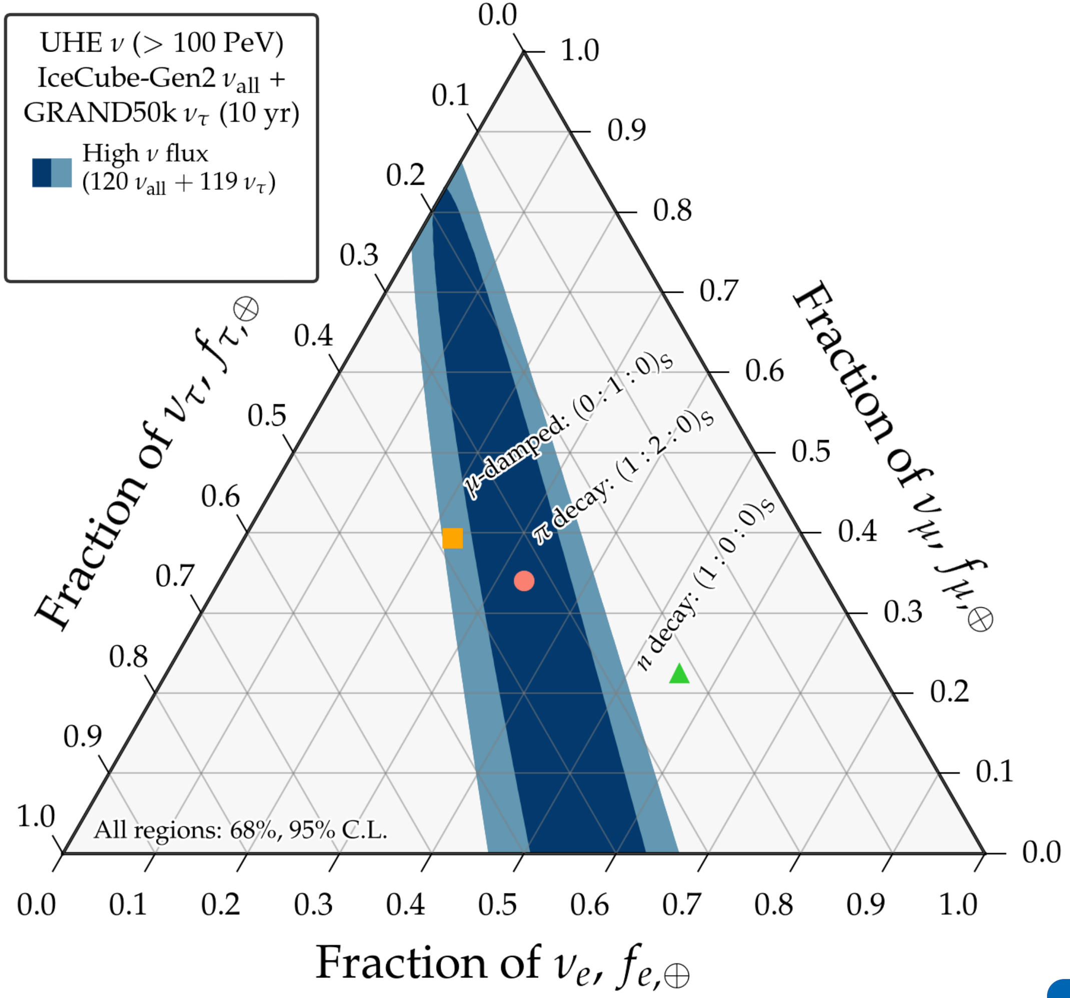


Flavor at ultra-high energies (> 100 PeV)

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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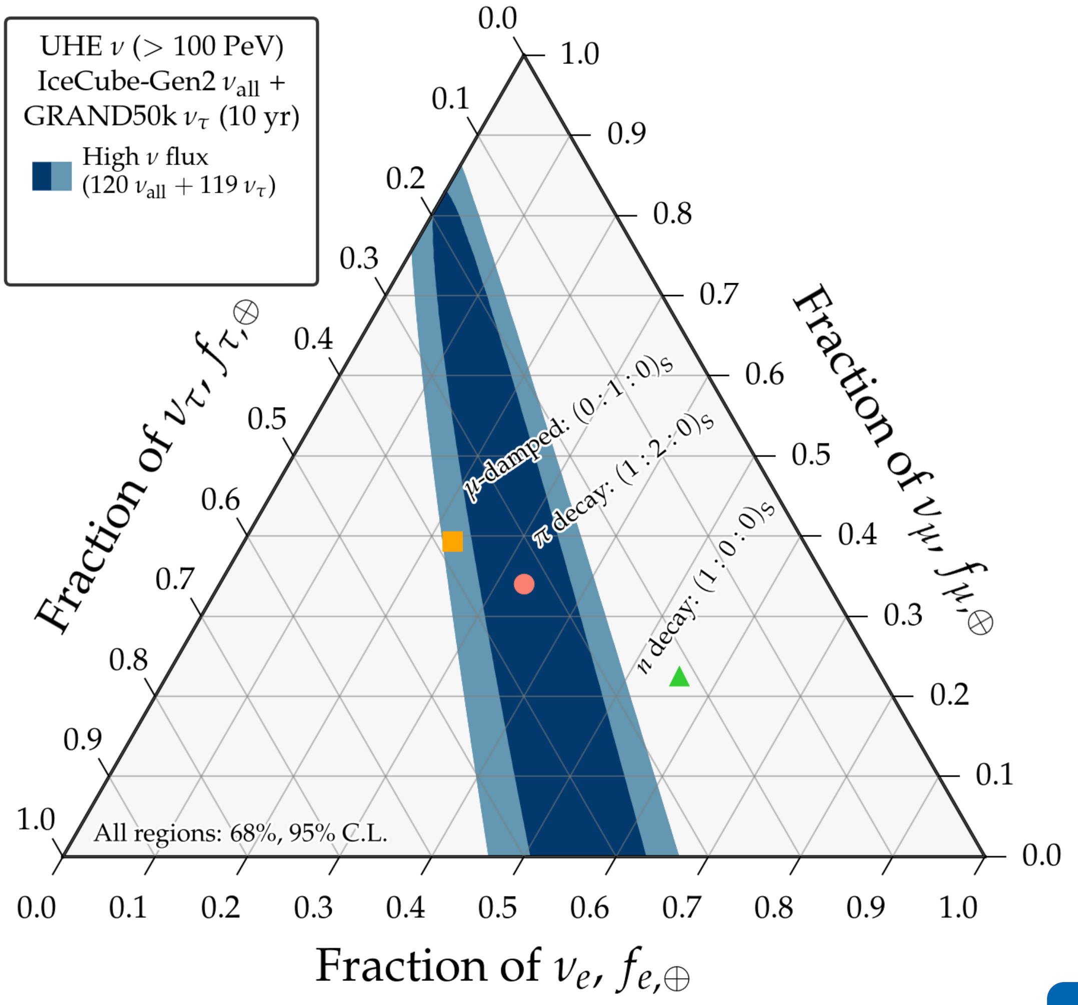

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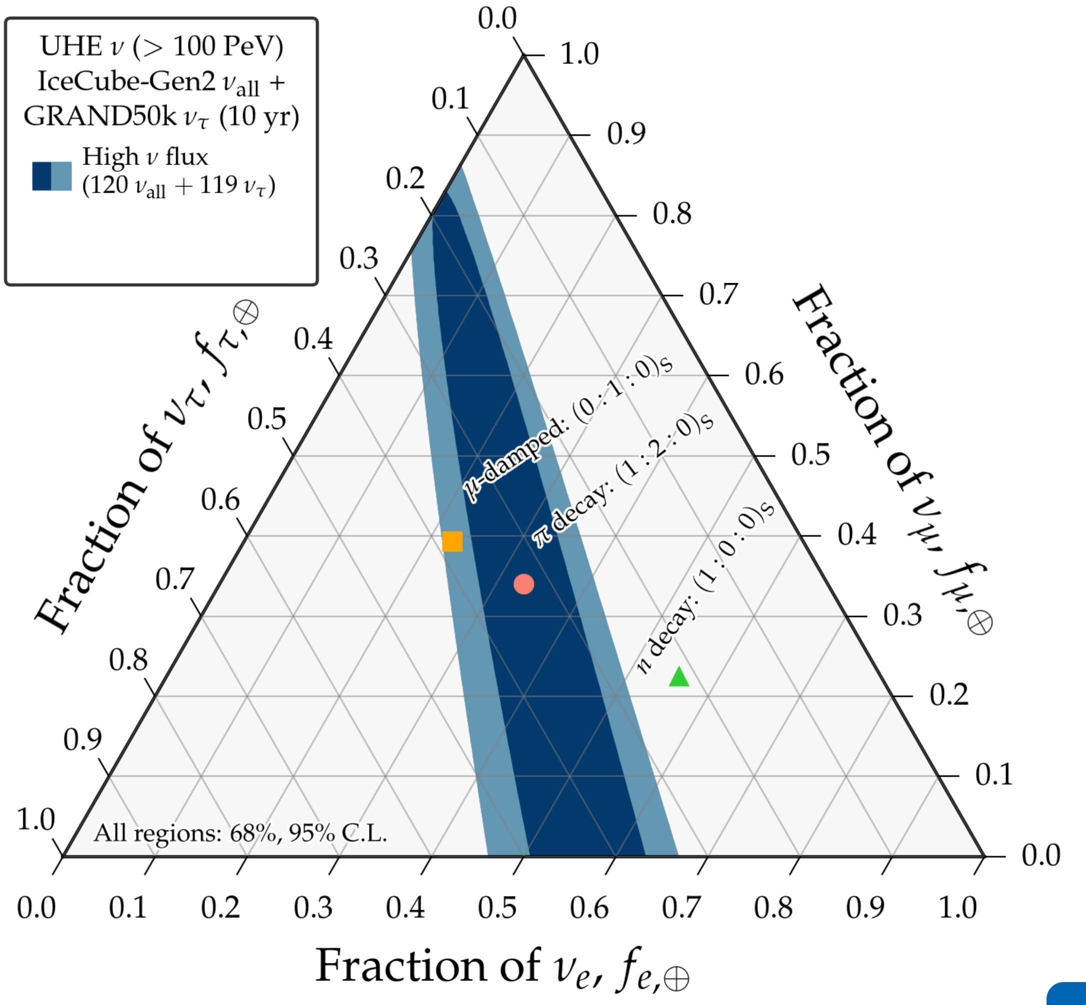
+

predominant detection of ν_τ by GRAND



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

Manufacturing UHE flavor sensitivity with two detectors

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

Then we combine two of detectors:

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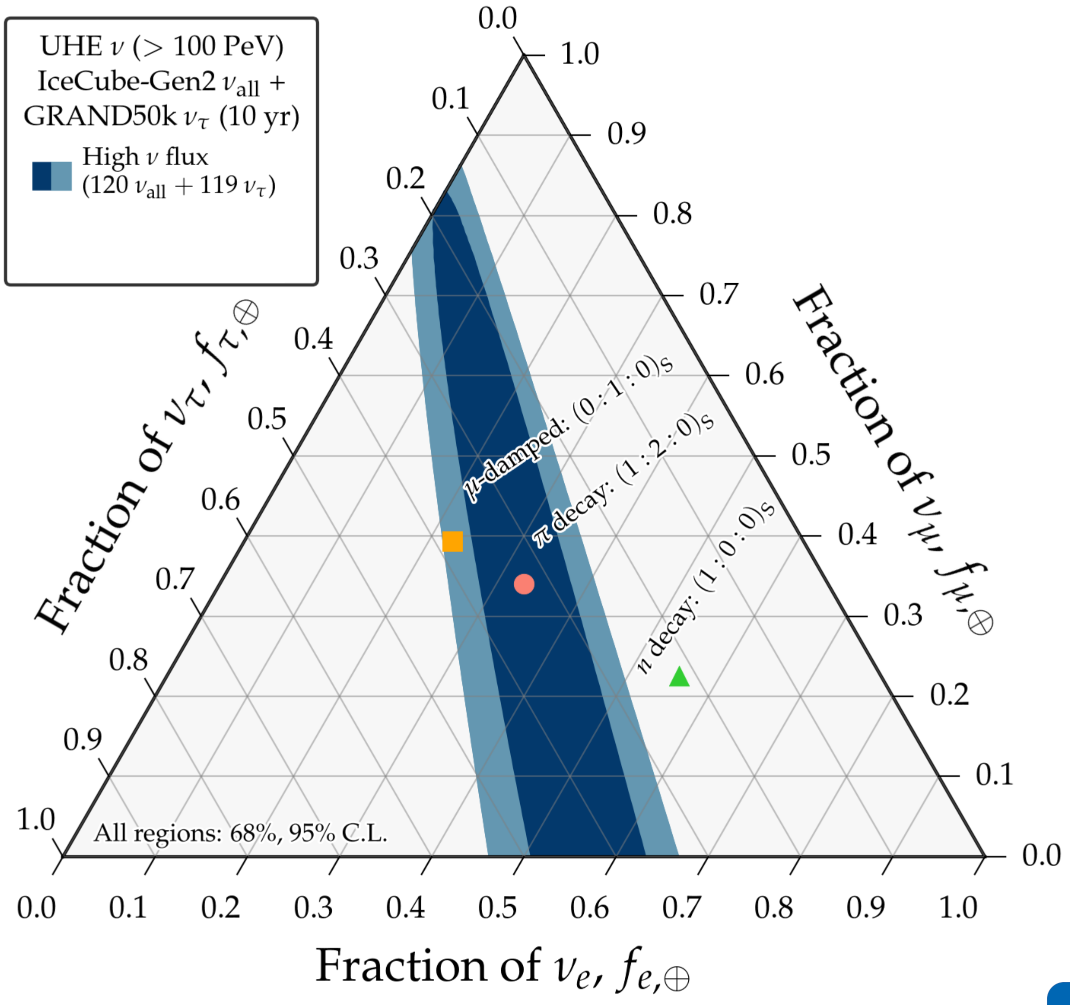
sensitivity to the fraction of UHE ν_τ



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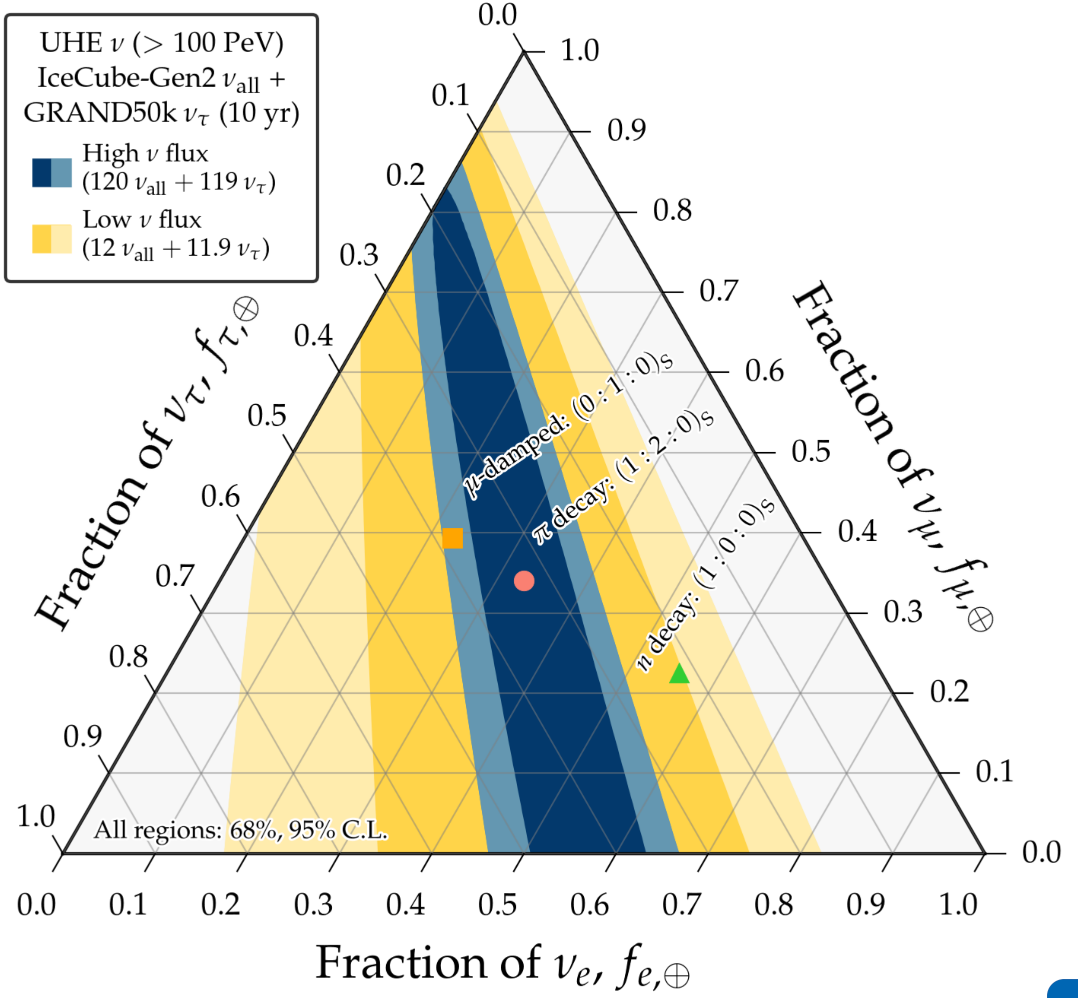

Testagrossa, Fiorillo, **MB**, *PRD* 2024

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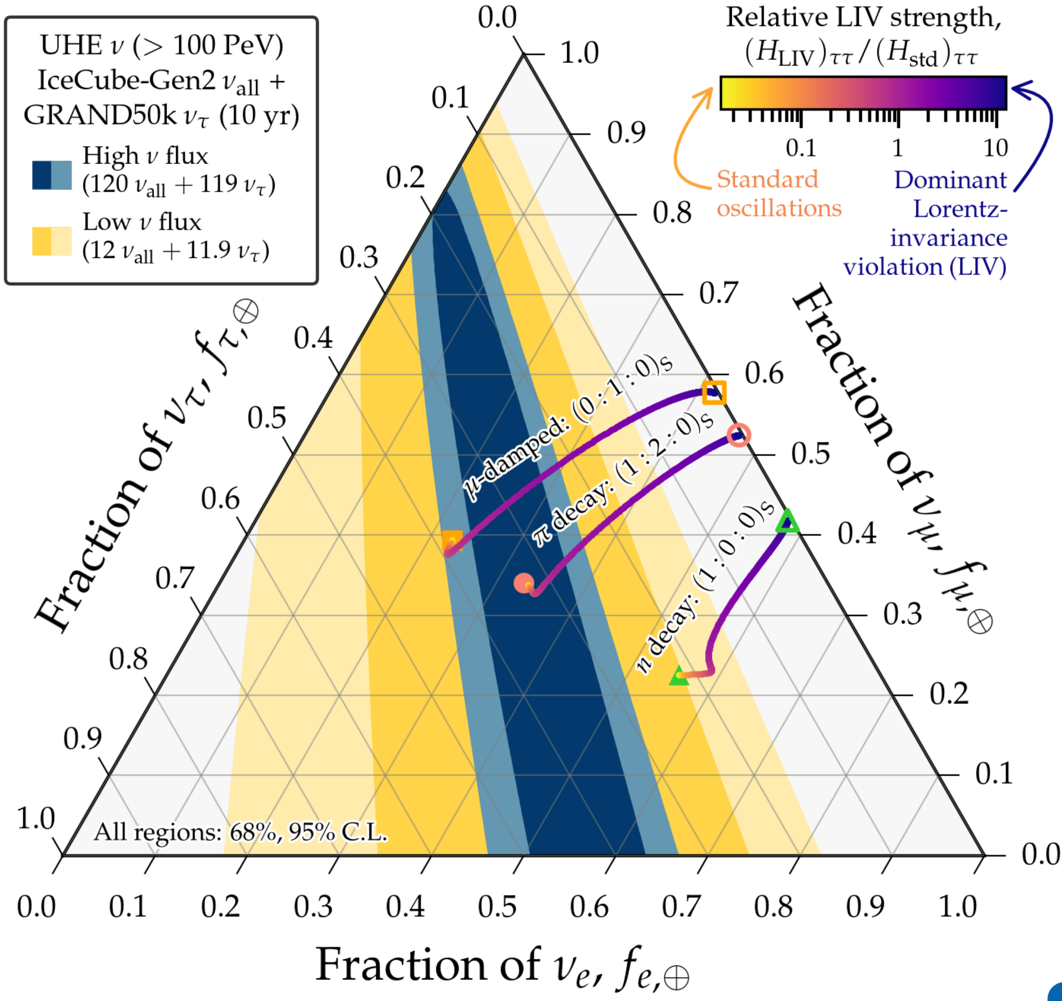
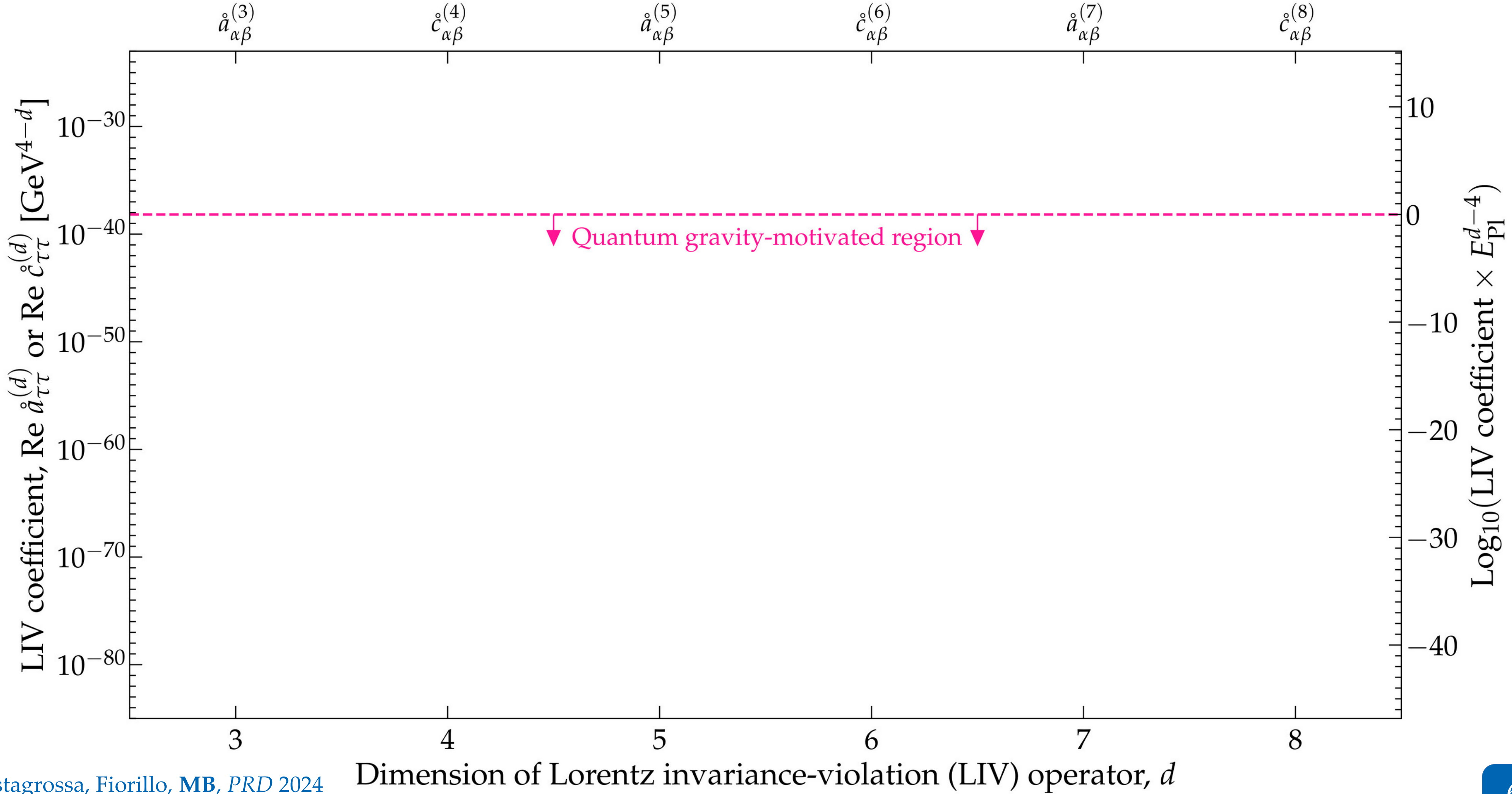


Testagrossa, Fiorillo, **MB**, *PRD* 2024

Lorentz-invariance violation at ultra-high energies



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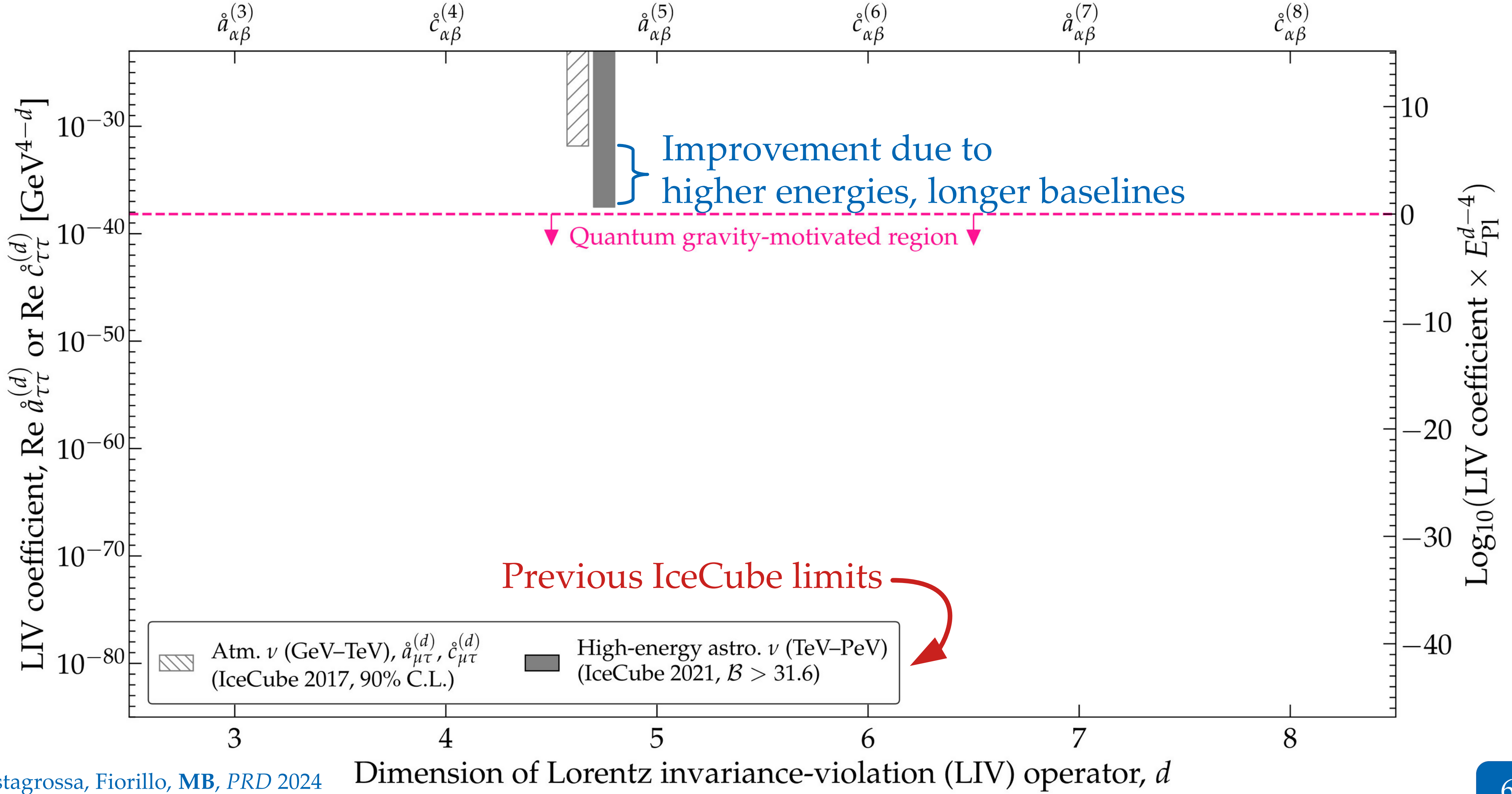
Lorentz-invariance violation at ultra-high energies



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

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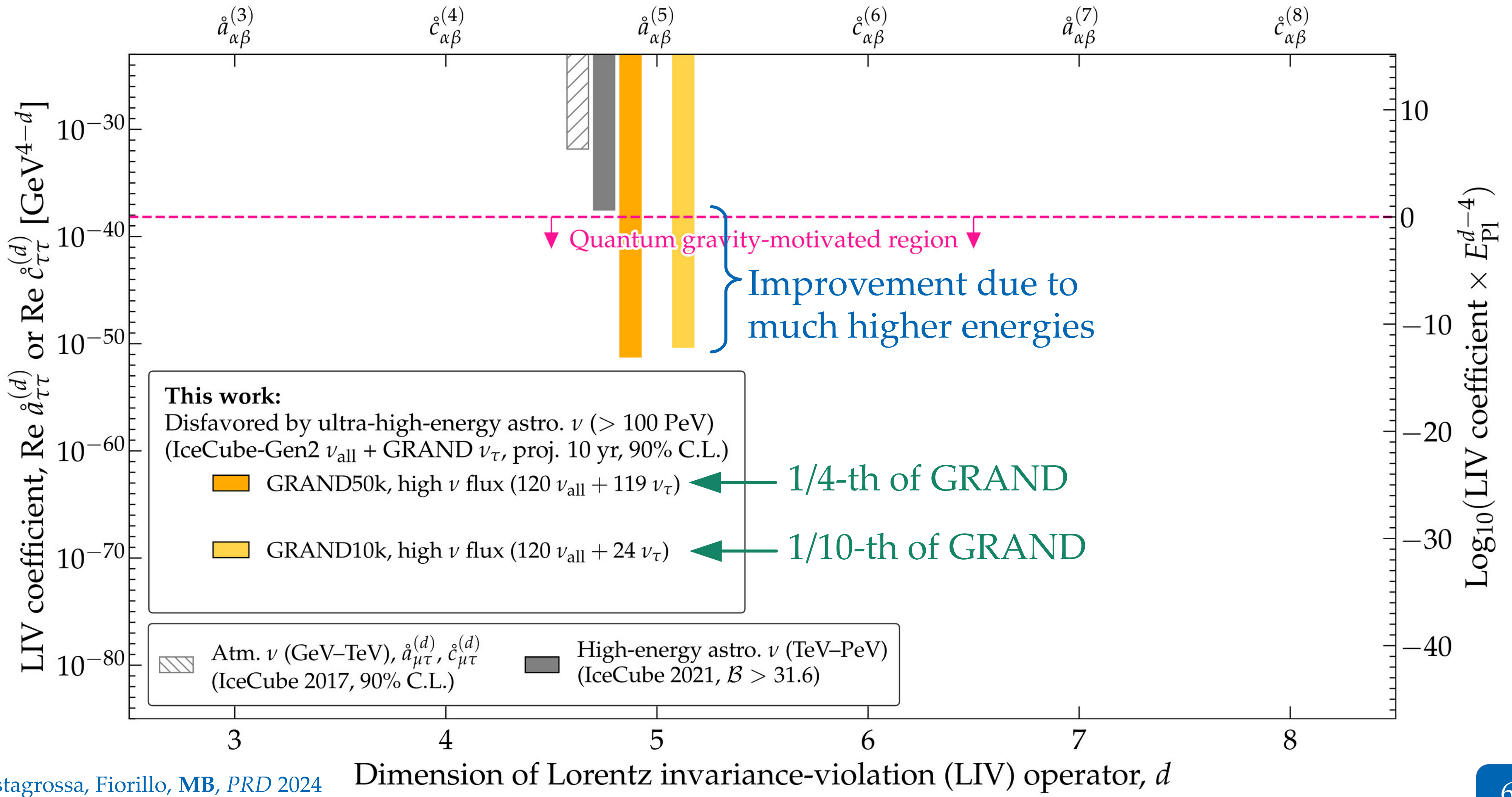

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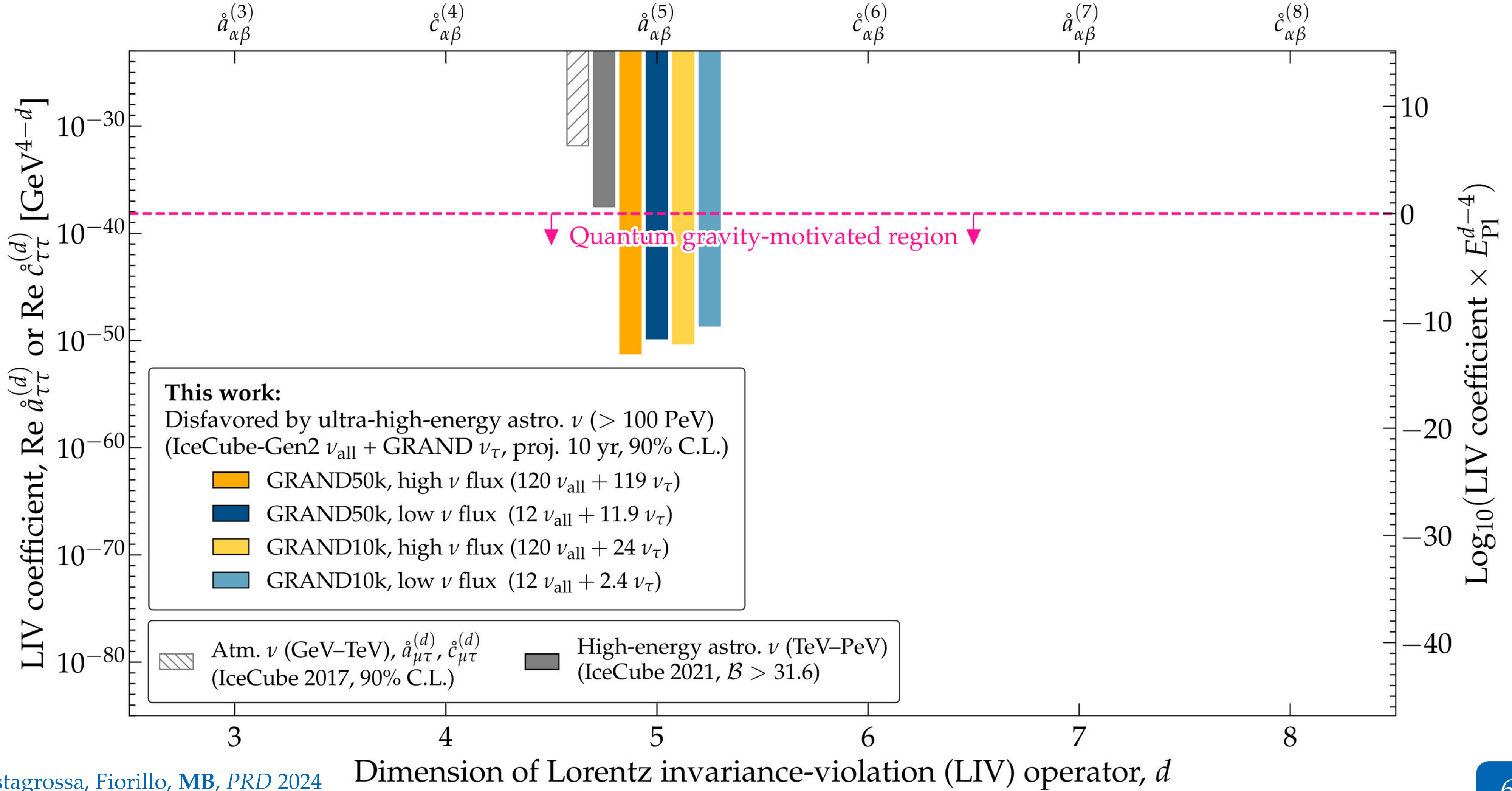

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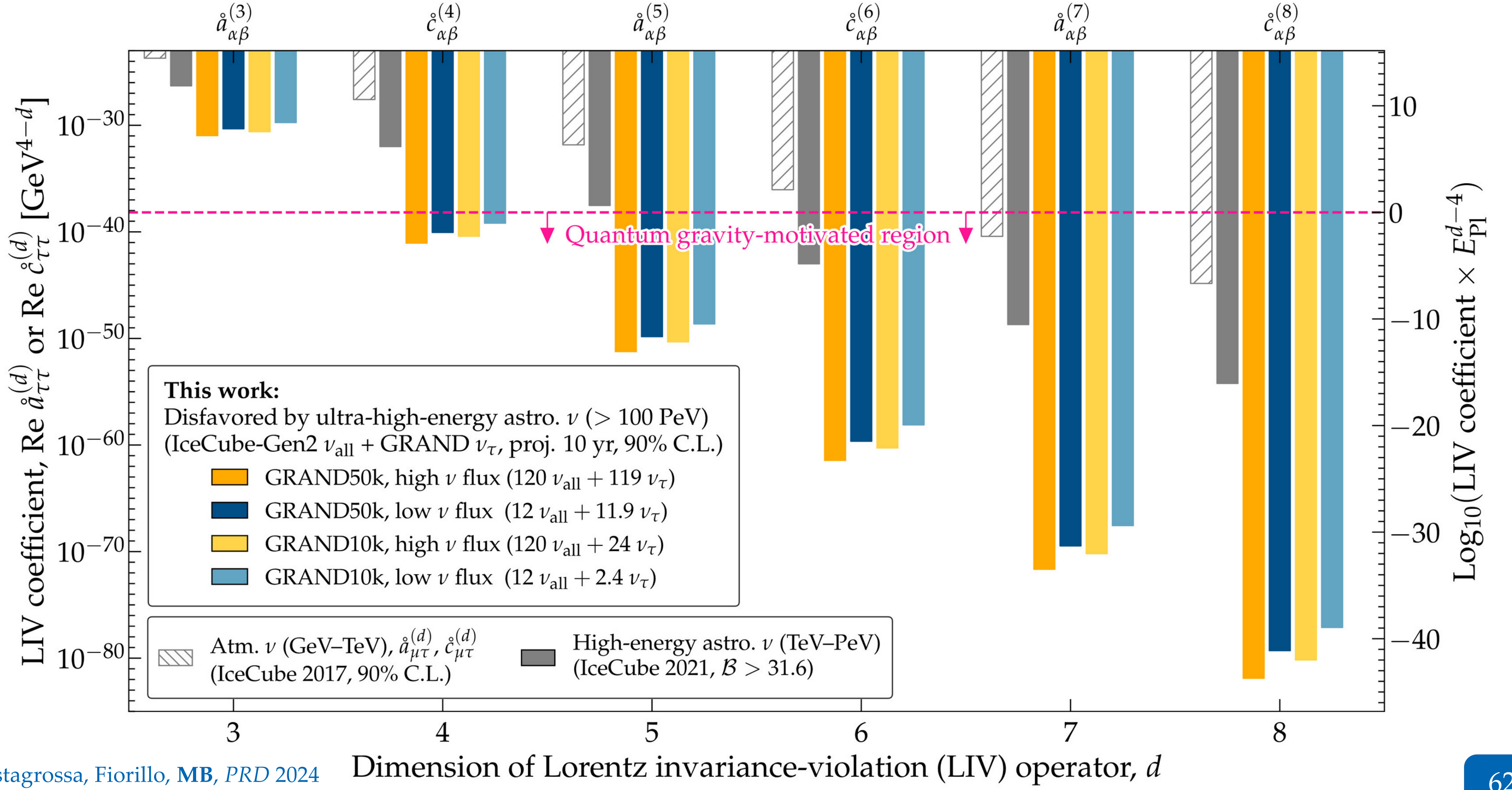

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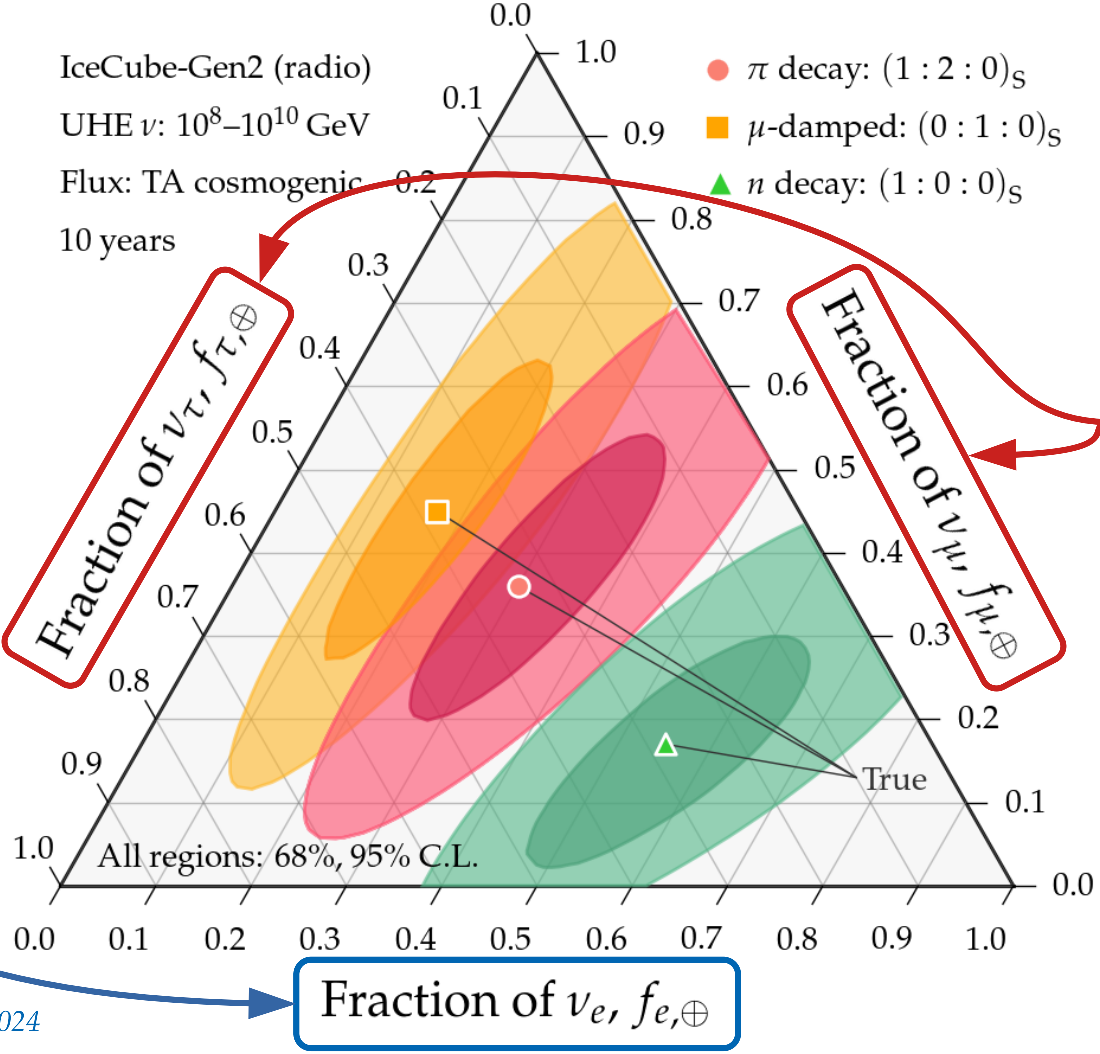
IceCube-Gen2 (radio) alone might measure flavor



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

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

Fraction of ν_e

Showers are elongated due to the LPM effect

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