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

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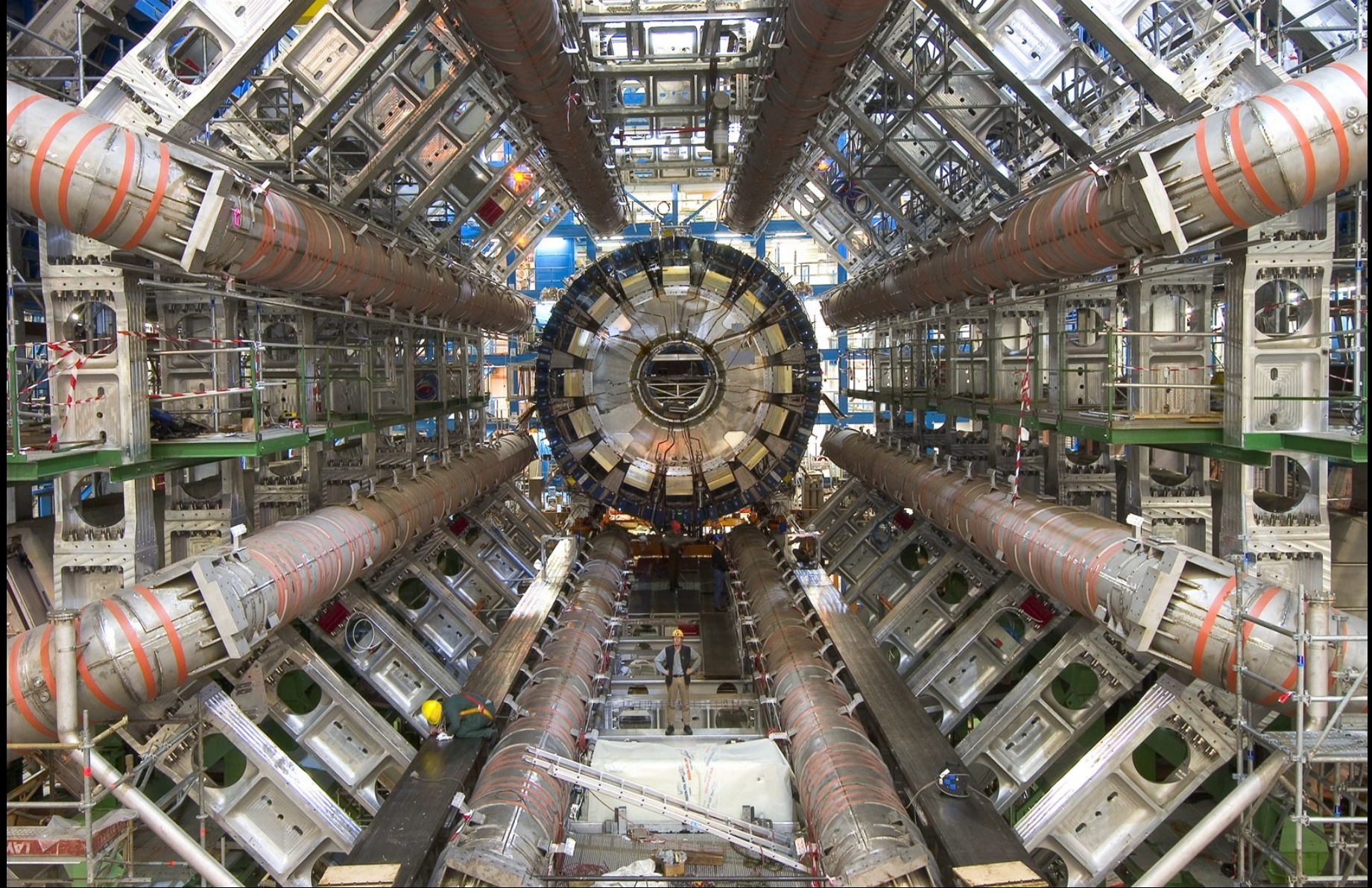
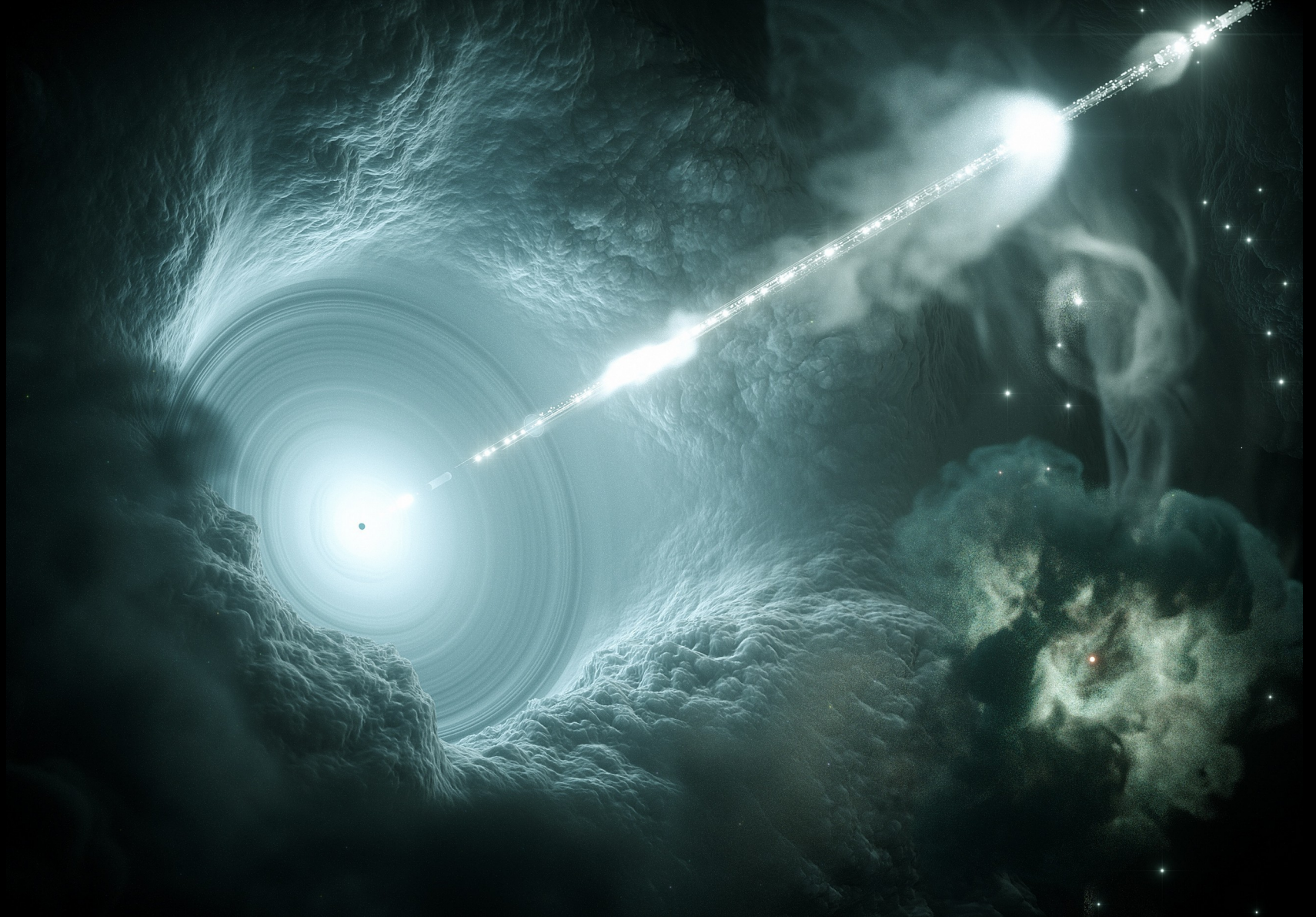
UNIVERSITY OF COPENHAGEN

VILLUM FONDEN

ECAP seminar
June 26, 2025



ATLAS



DESY

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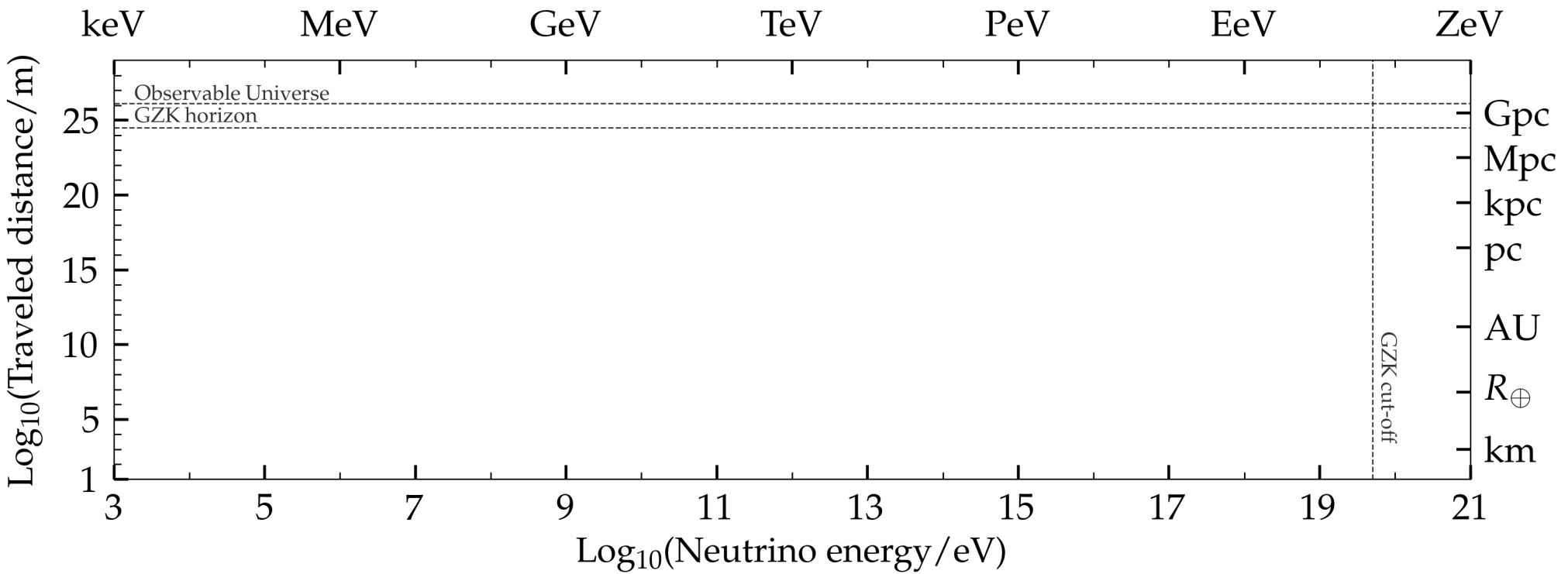
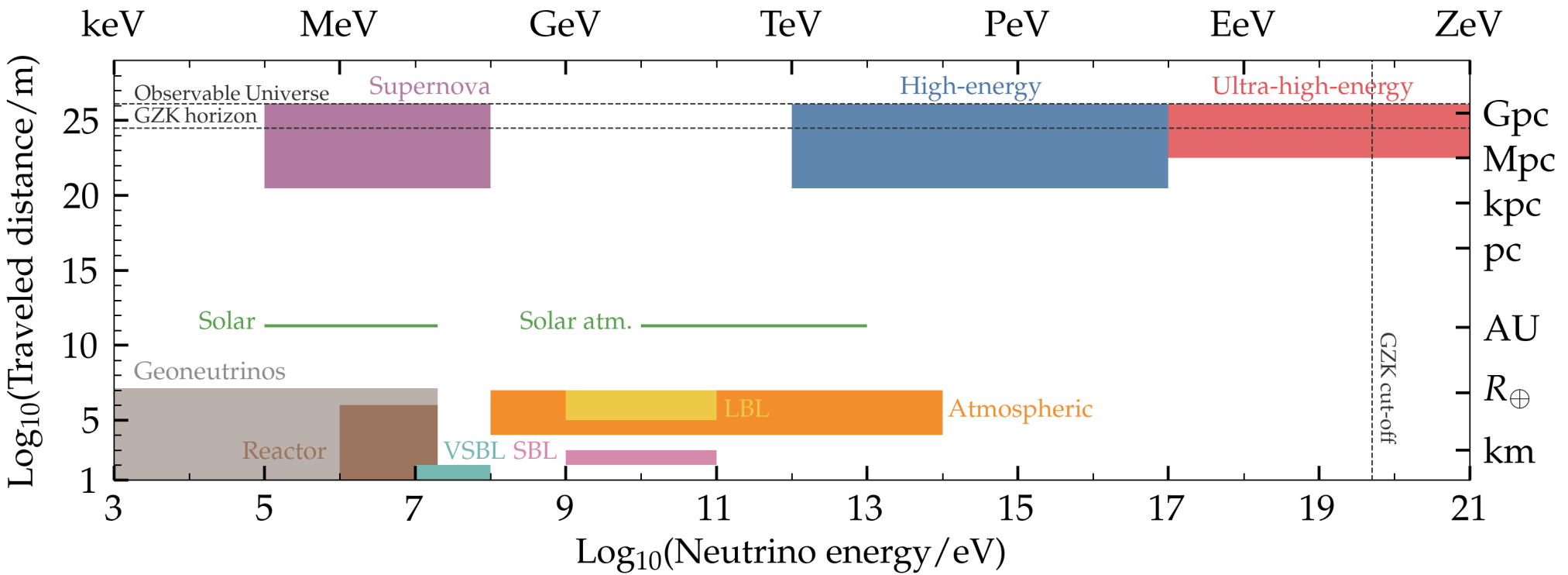


Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333), adapted



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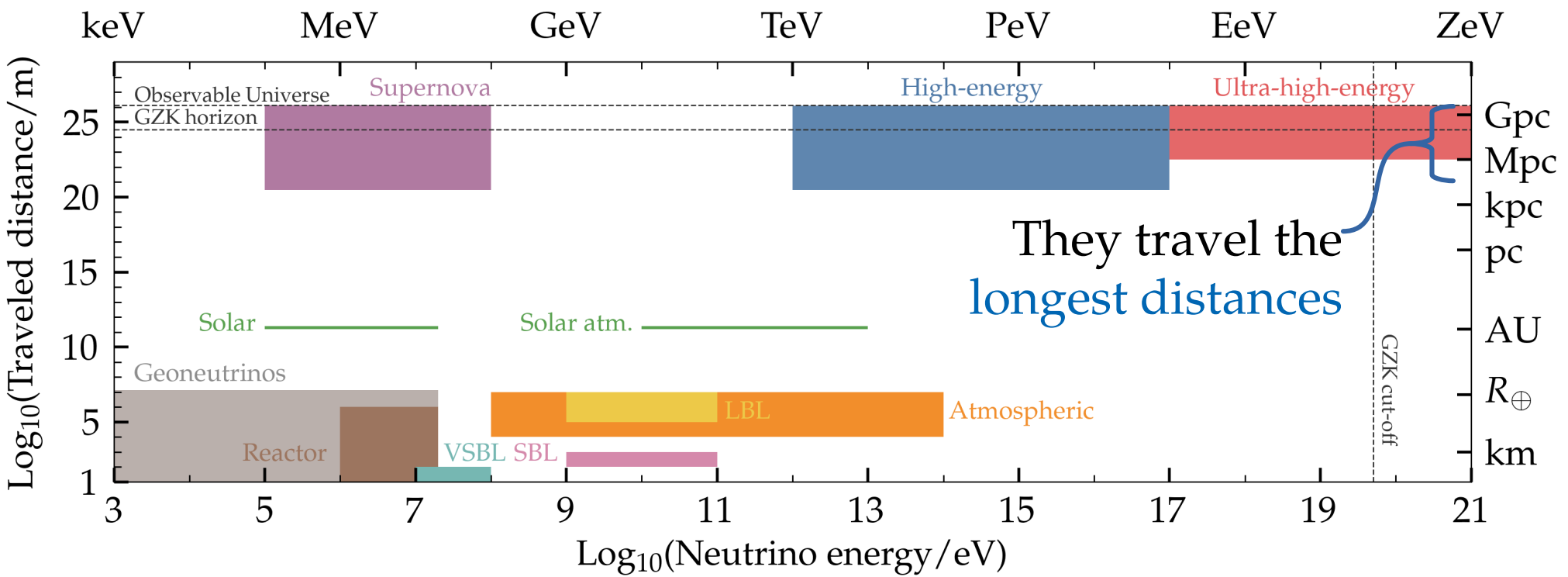
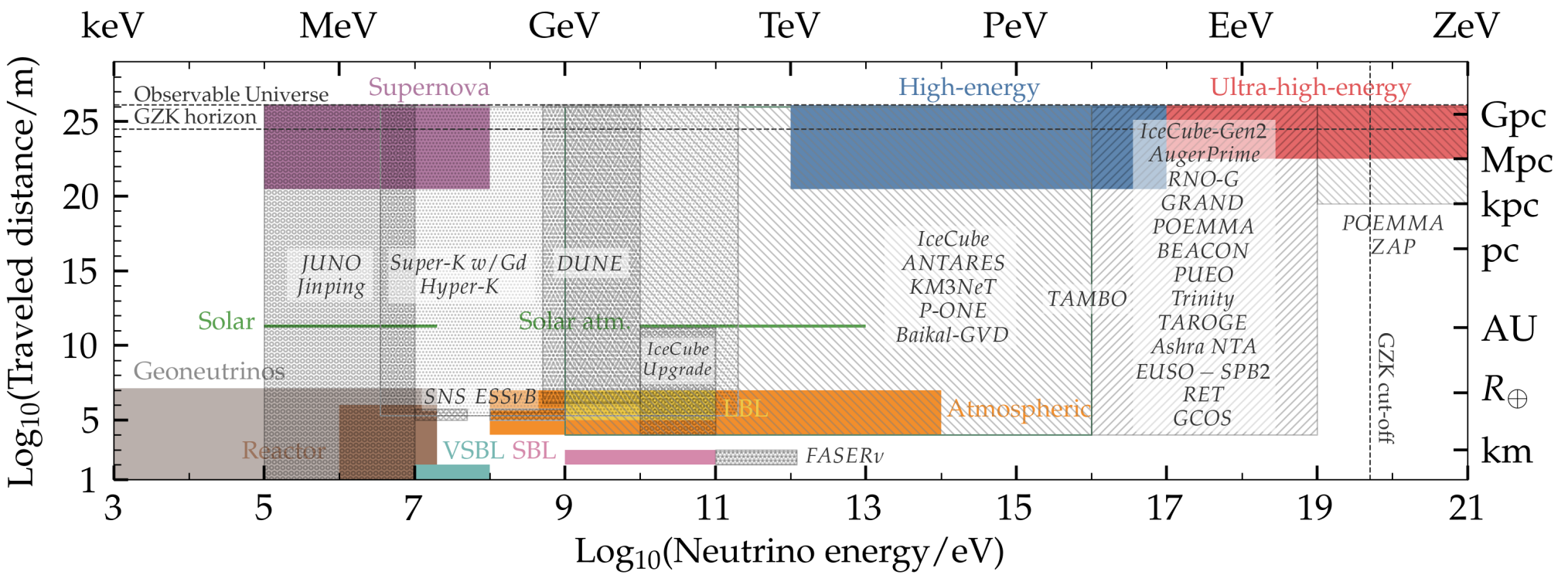
They have the highest energies



They travel the longest distances

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



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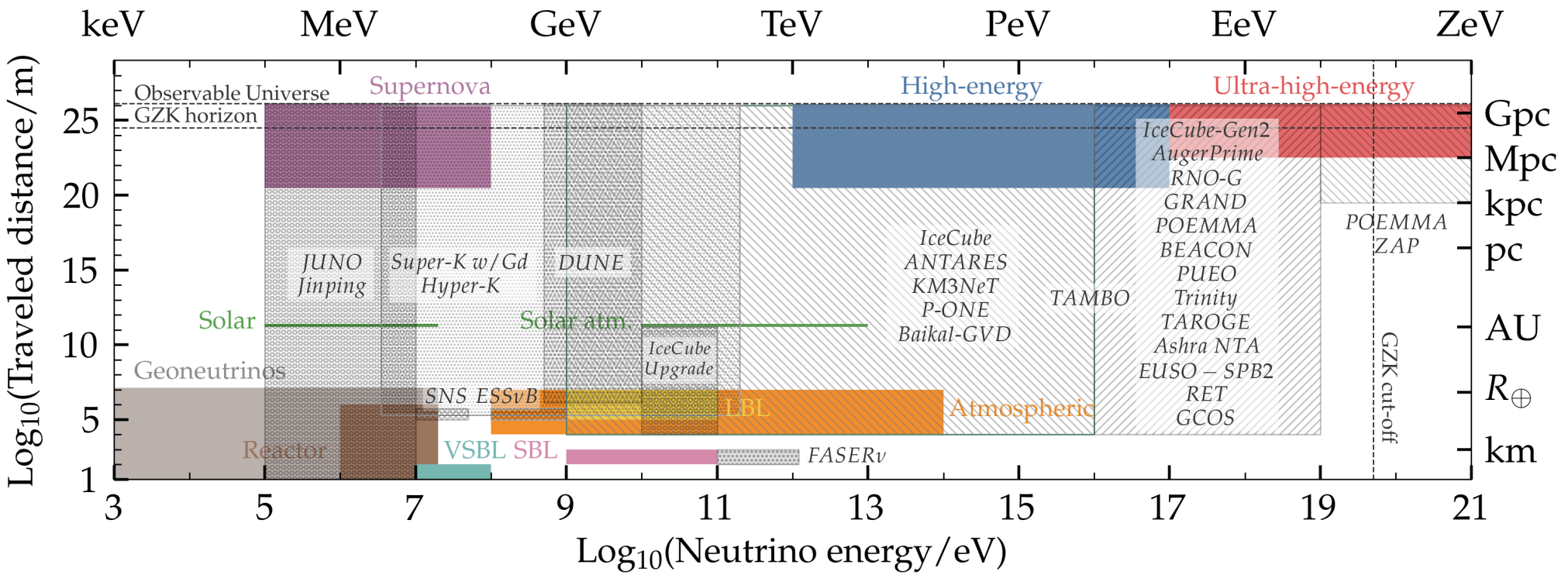
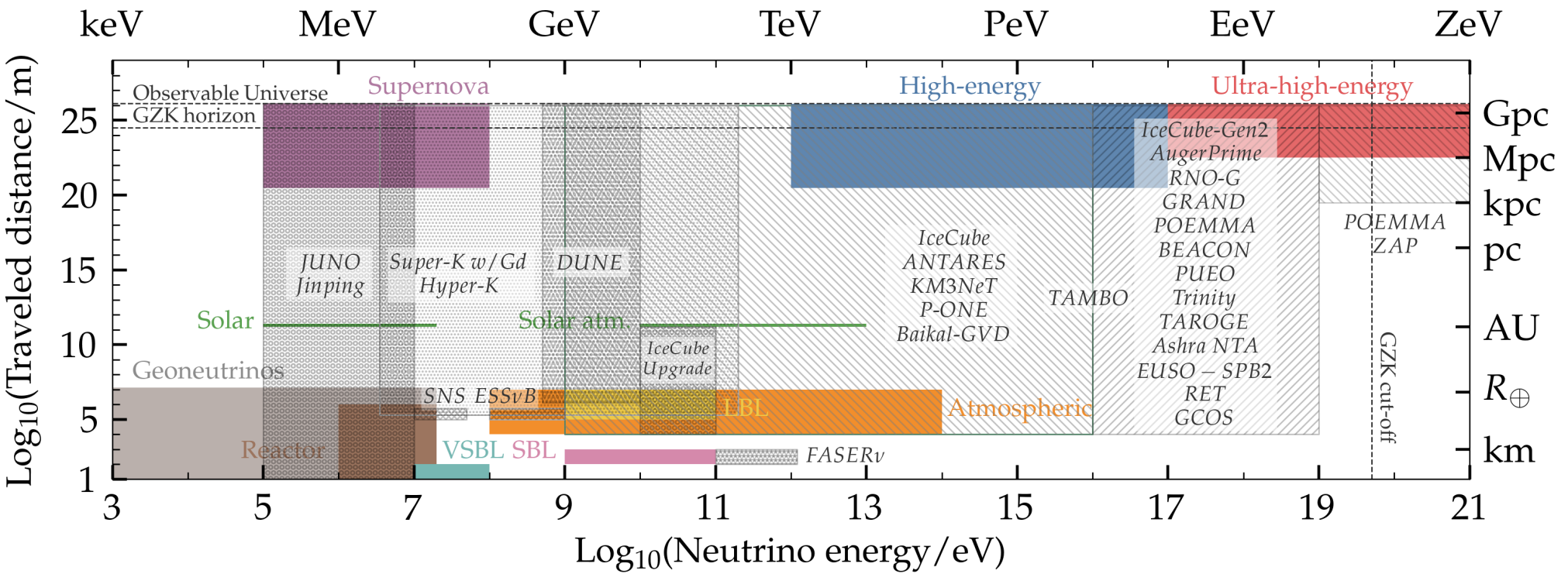


Synergies with lower energies

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

Discovered in 2013
by IceCube



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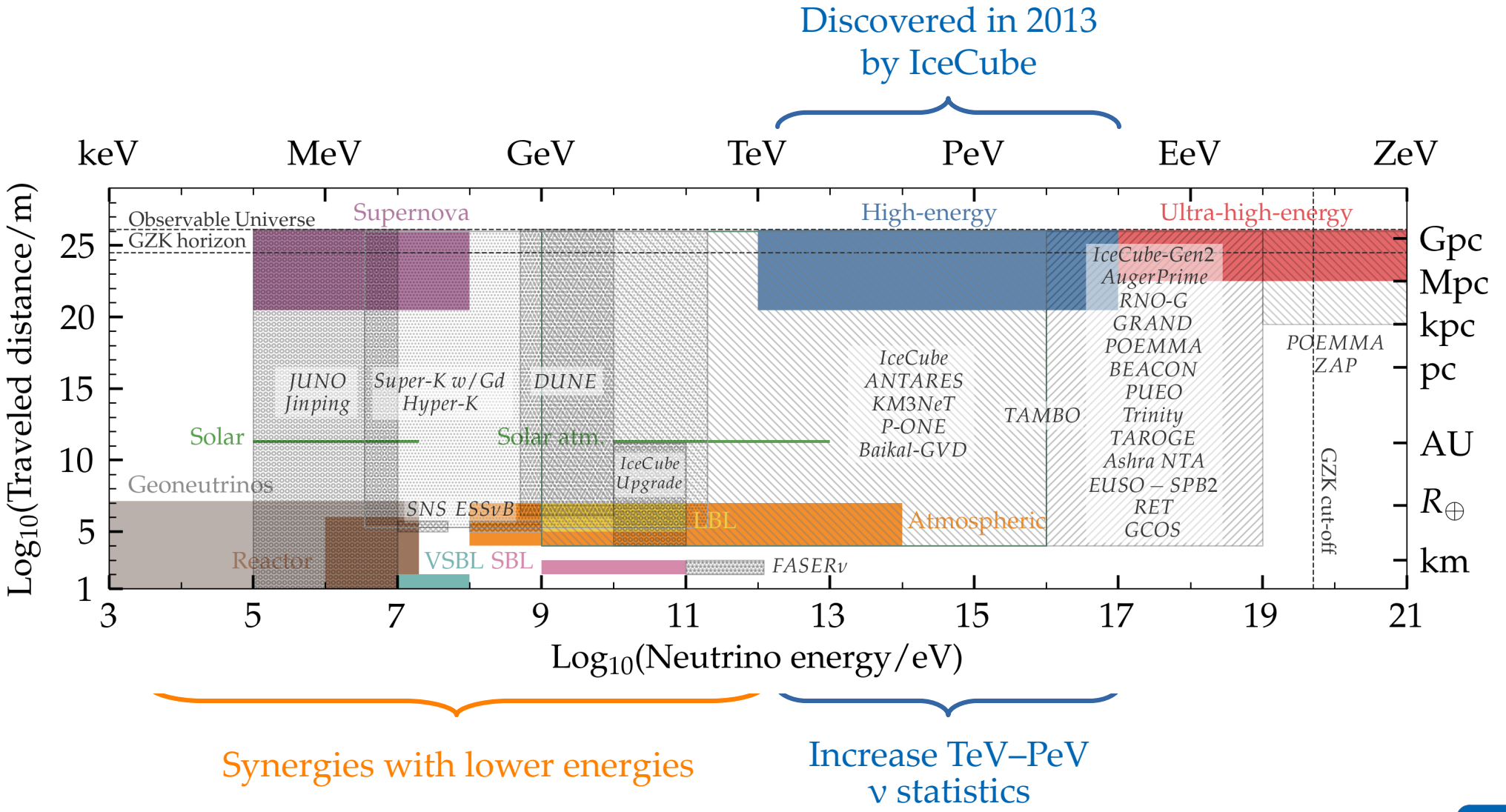

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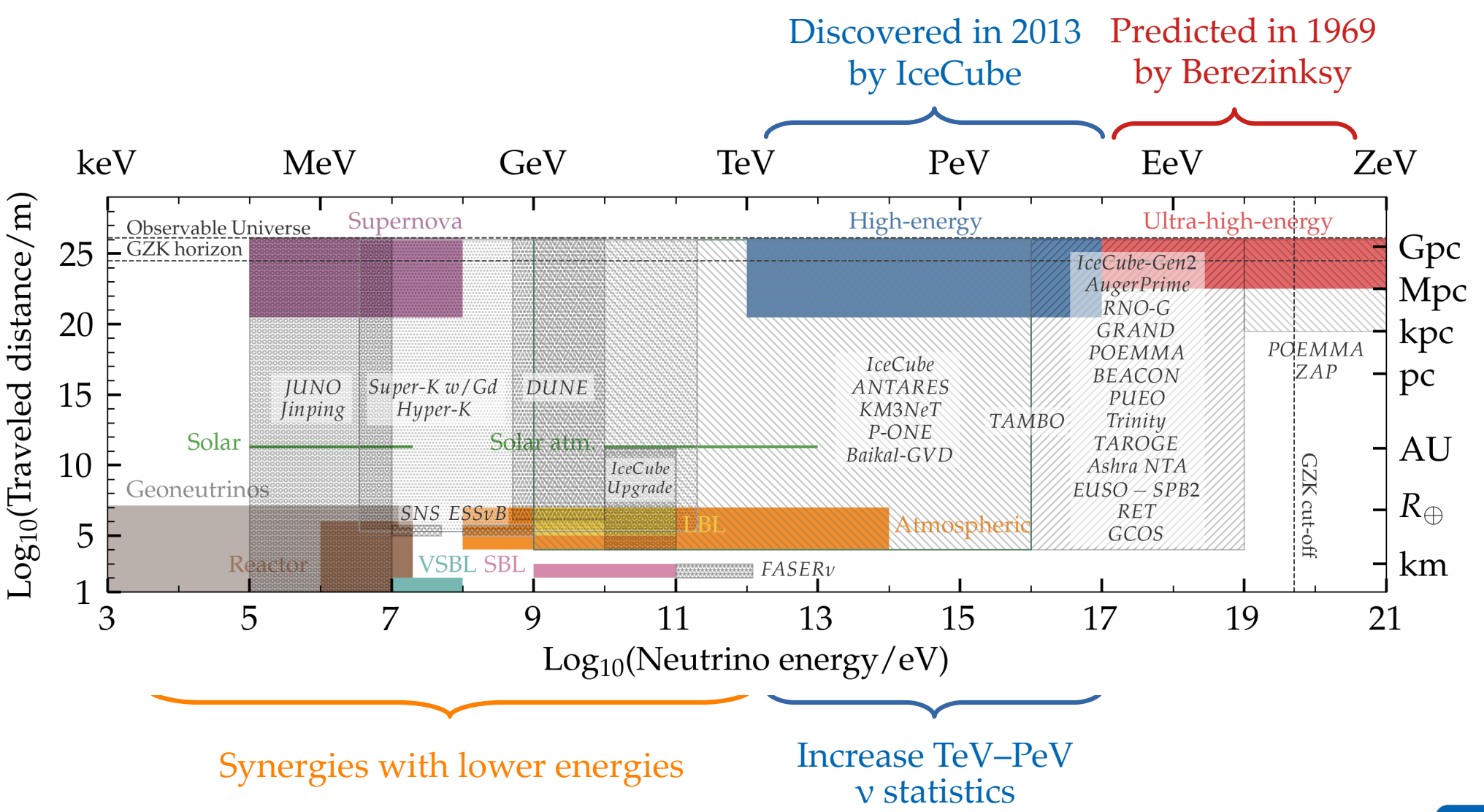

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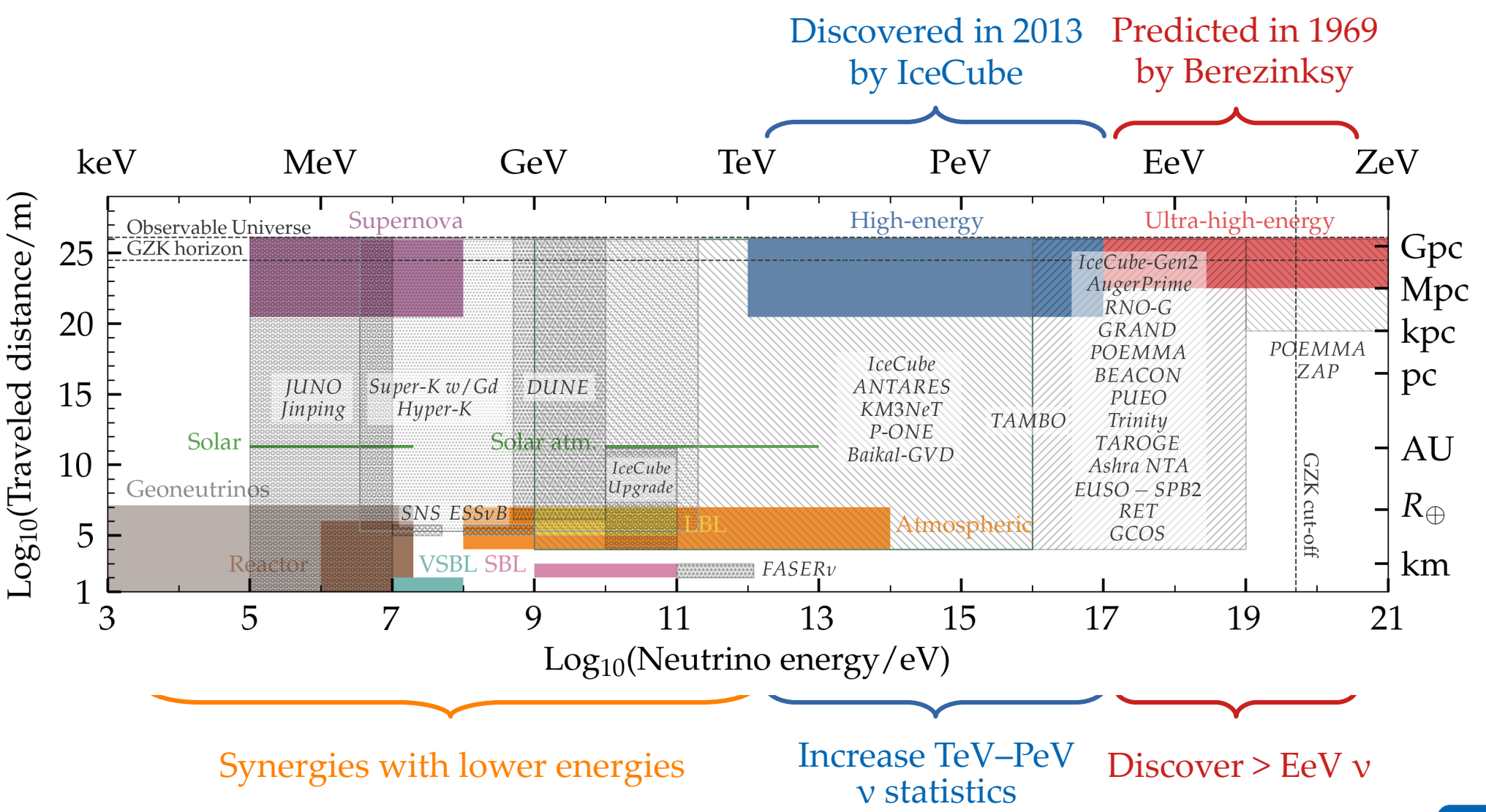

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The multi-messenger connection: a simple picture

(or $p + p$)

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

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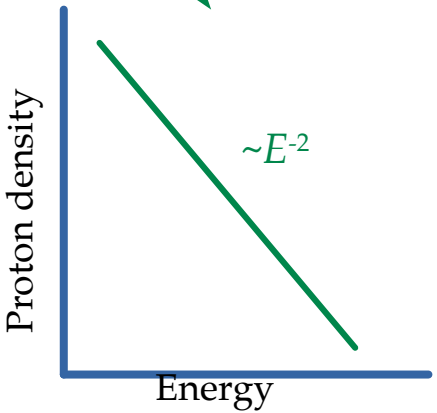

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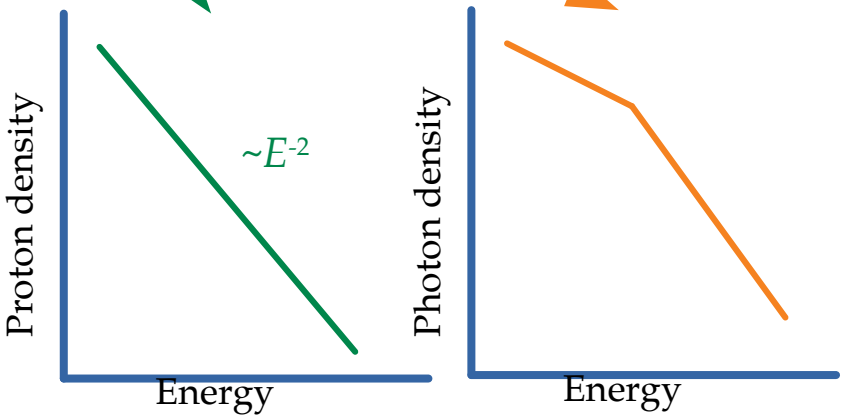

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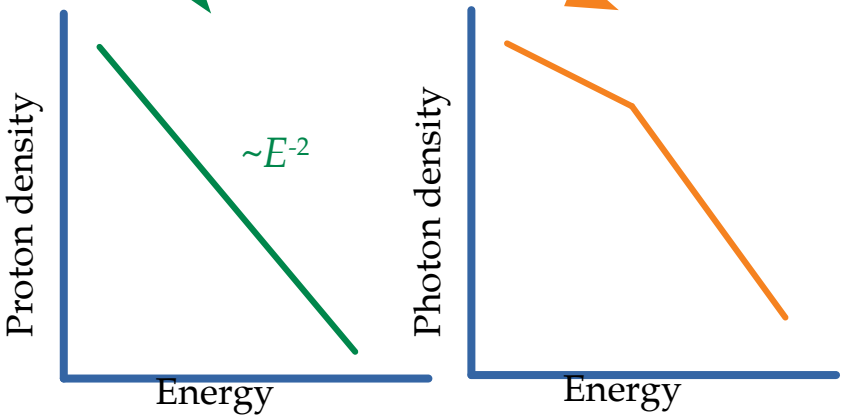
$$\pi^0 \rightarrow \gamma + \gamma$$

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

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



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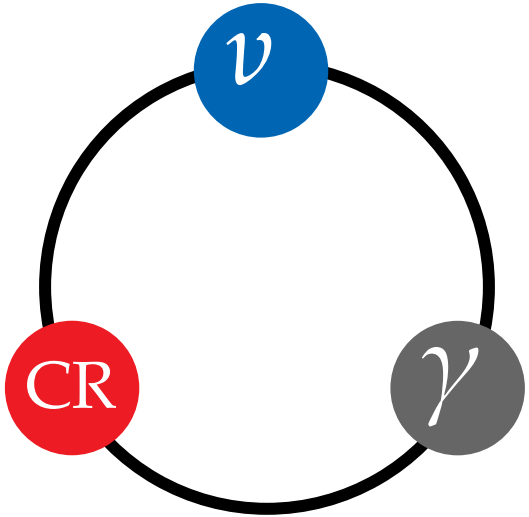

Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 10

The multi-messenger connection: a simple picture

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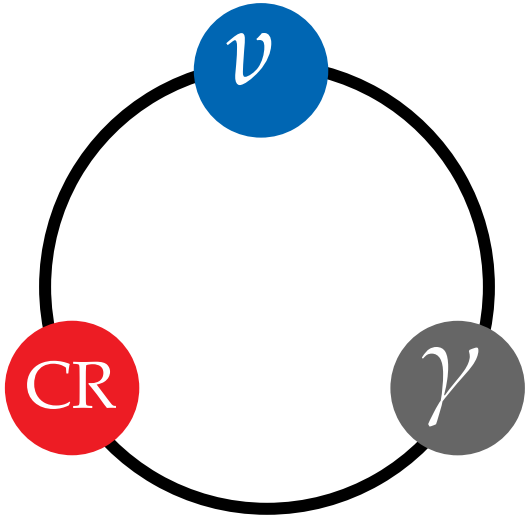

1 PeV 20 PeV

Neutrino energy = Proton energy / 20

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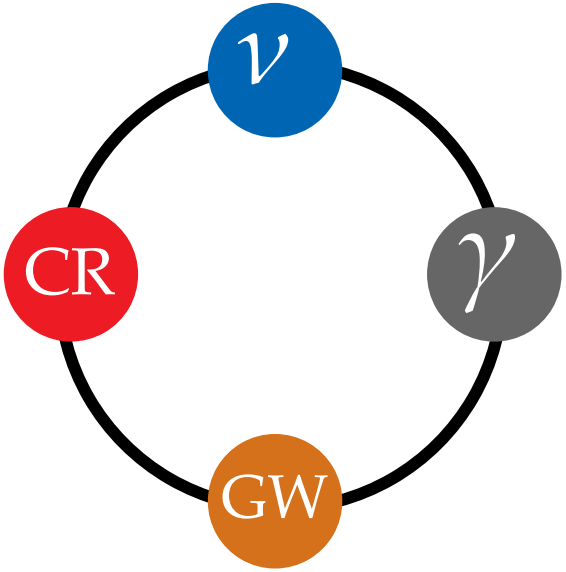


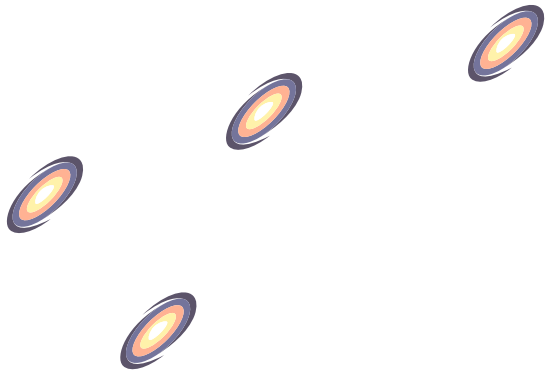
1 PeV 20 PeV

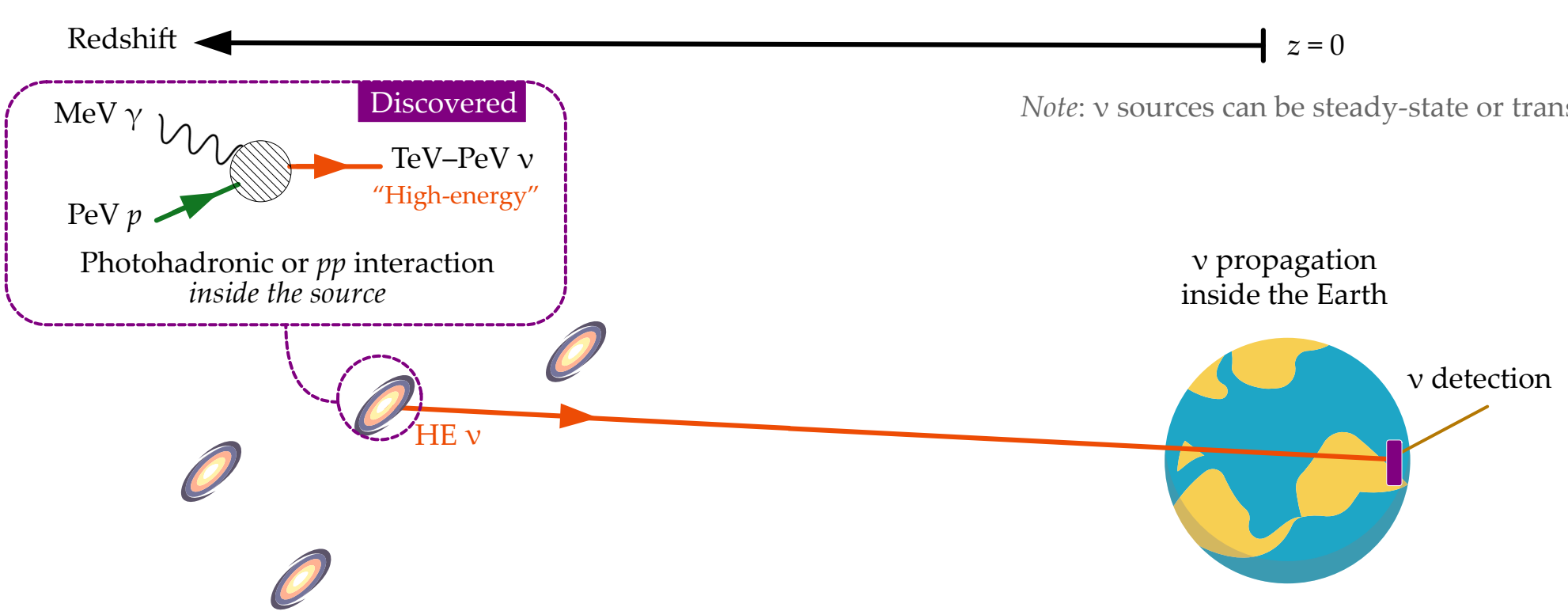
Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 10

Redshift $z = 0$

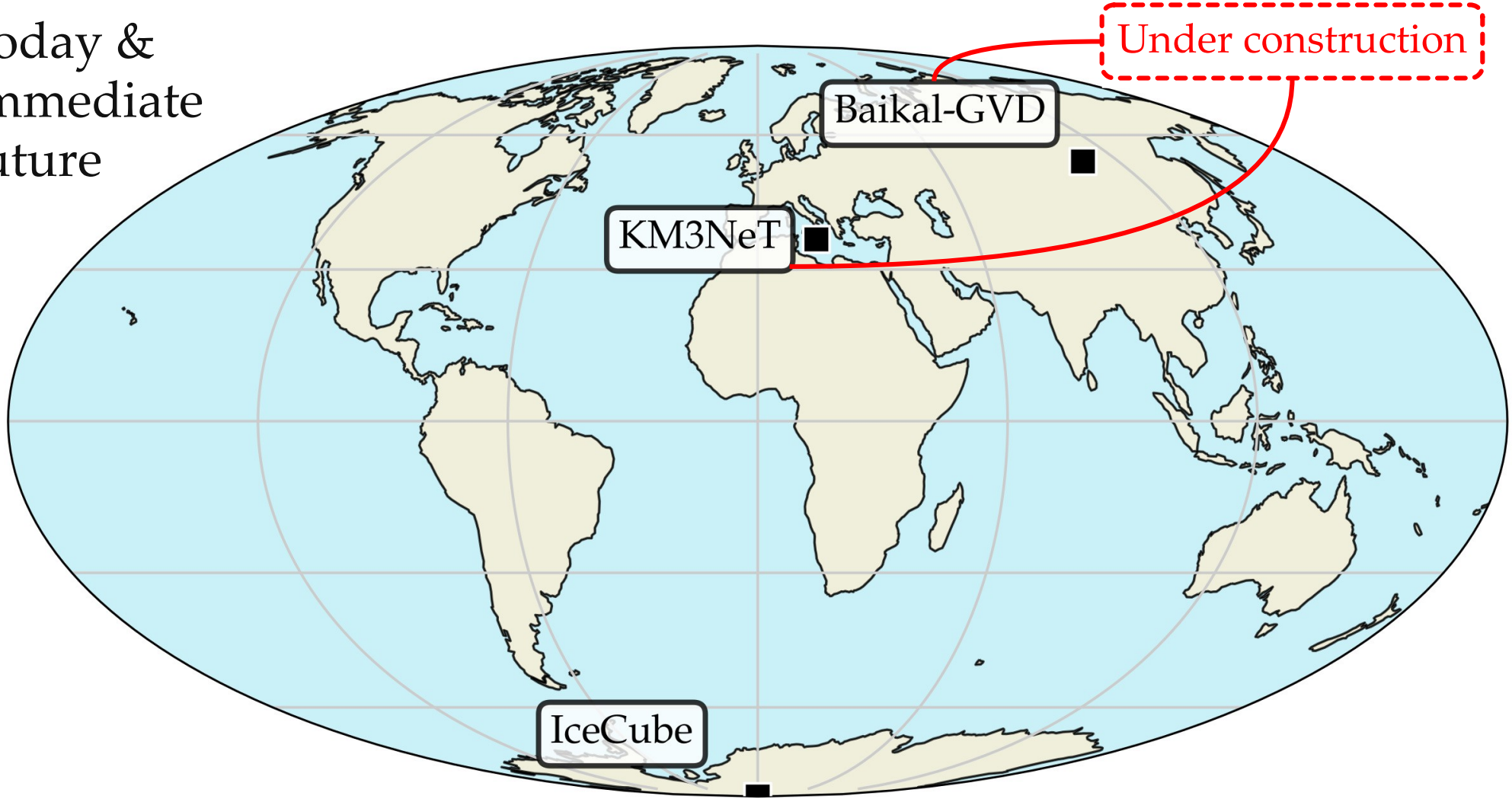
Note: ν sources can be steady-state or transient





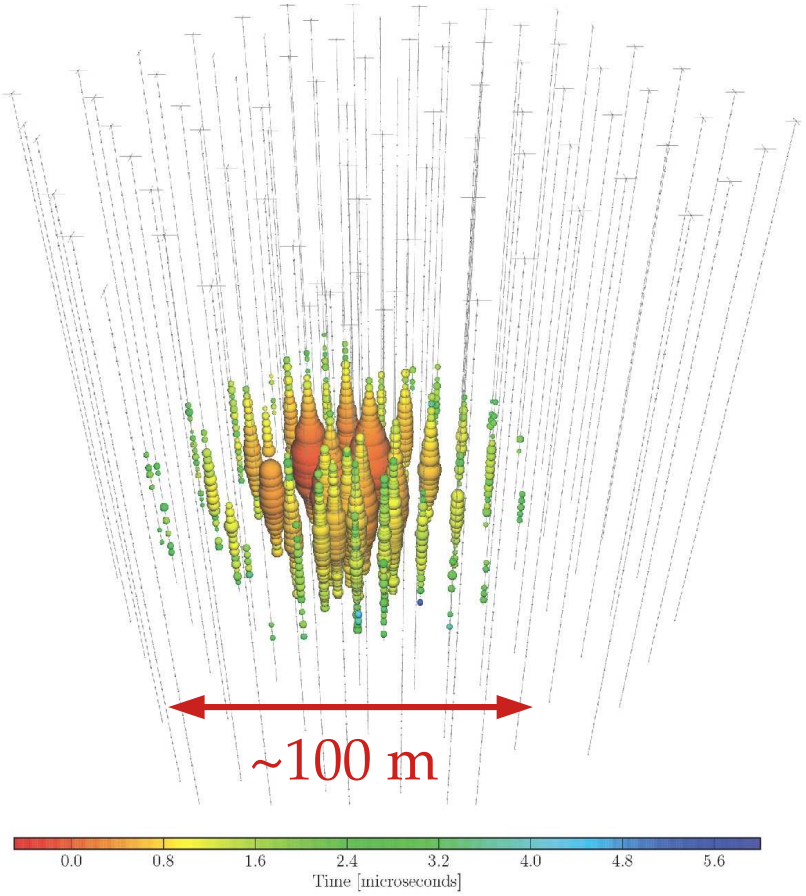
Note: ν sources can be steady-state or transient

Today & immediate future



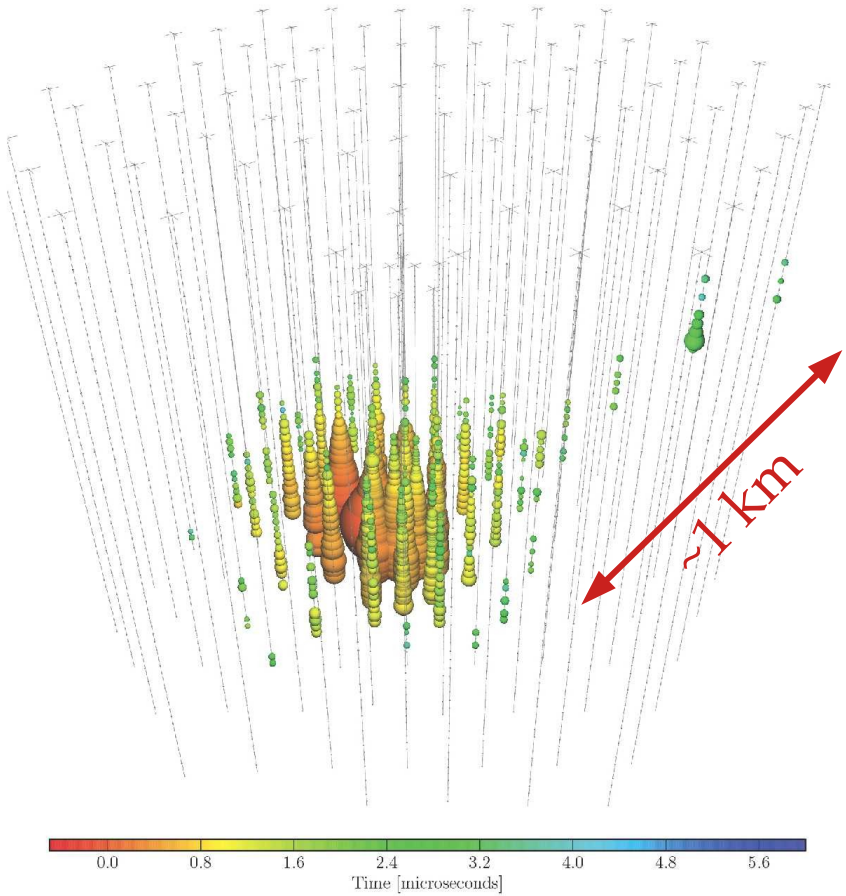
Schumacher, **MB**, Agostini, Oikonomou, Resconi, 2503.07549

Shower
(mainly from ν_e and ν_τ)

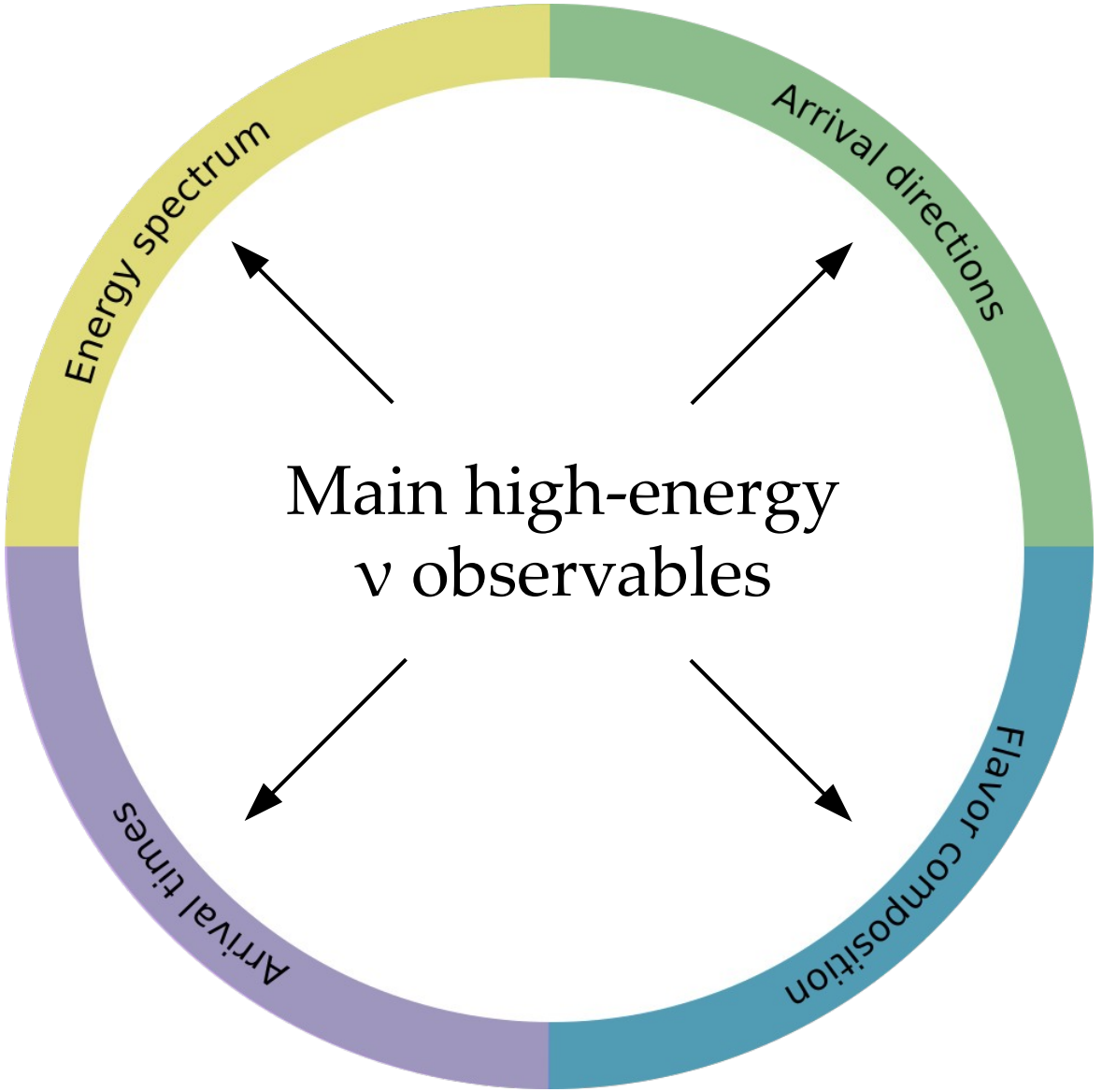


Poor angular resolution: < 5°

Track
(mainly from ν_μ)

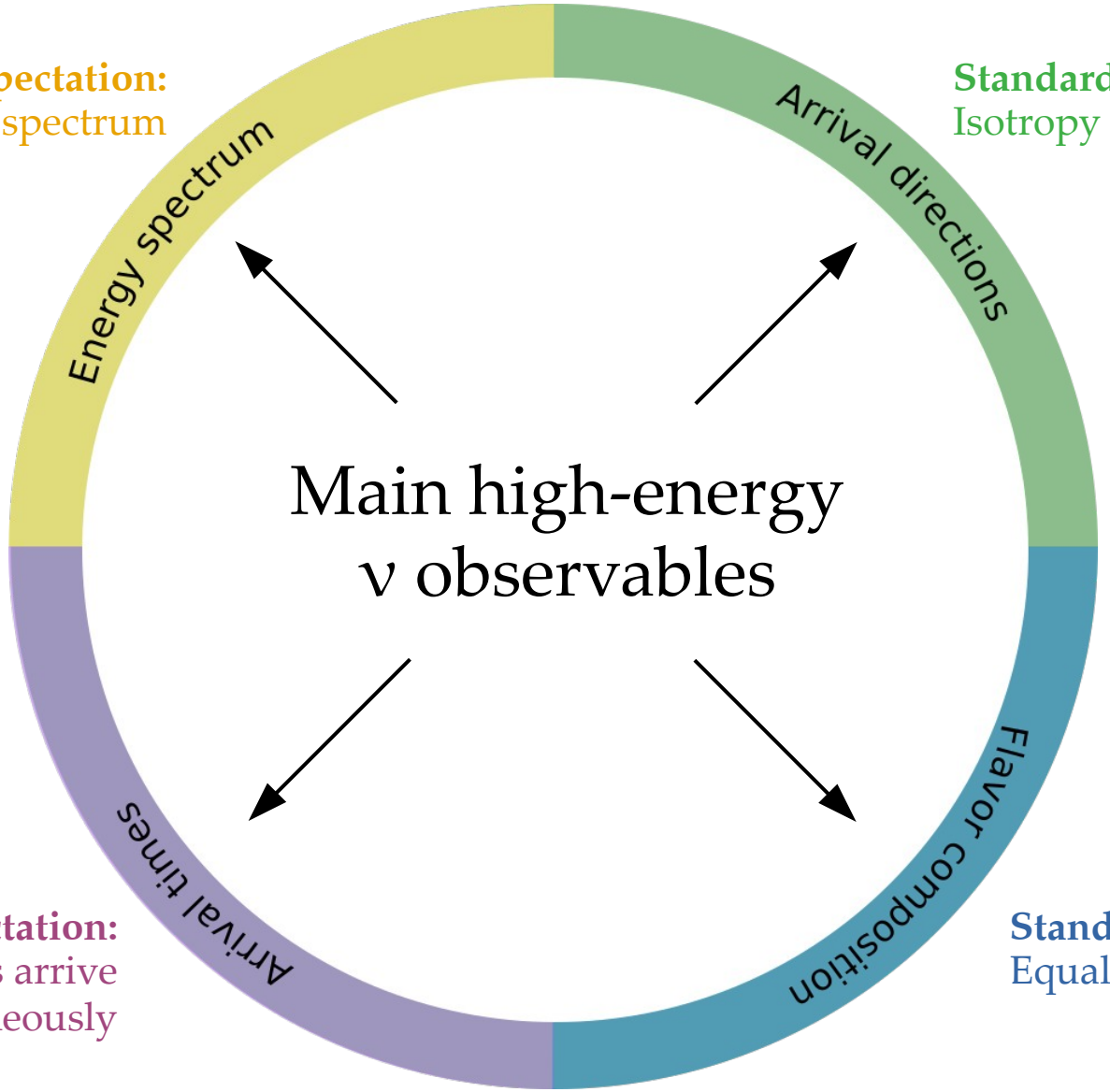


Angular resolution: < 1°


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

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



Standard expectation:
ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Standard expectation:
Power-law energy spectrum

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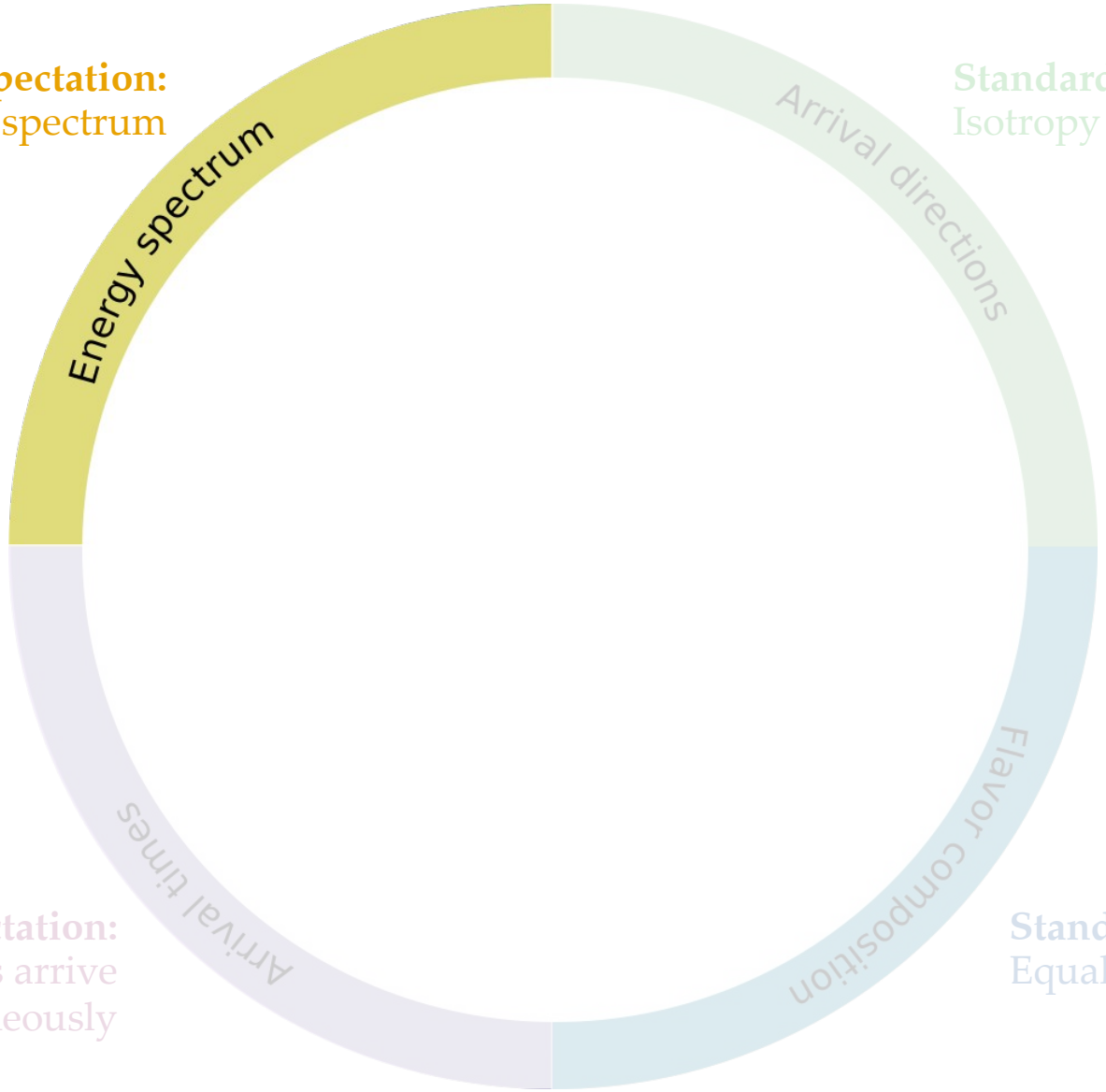
Isotropy (for diffuse flux)



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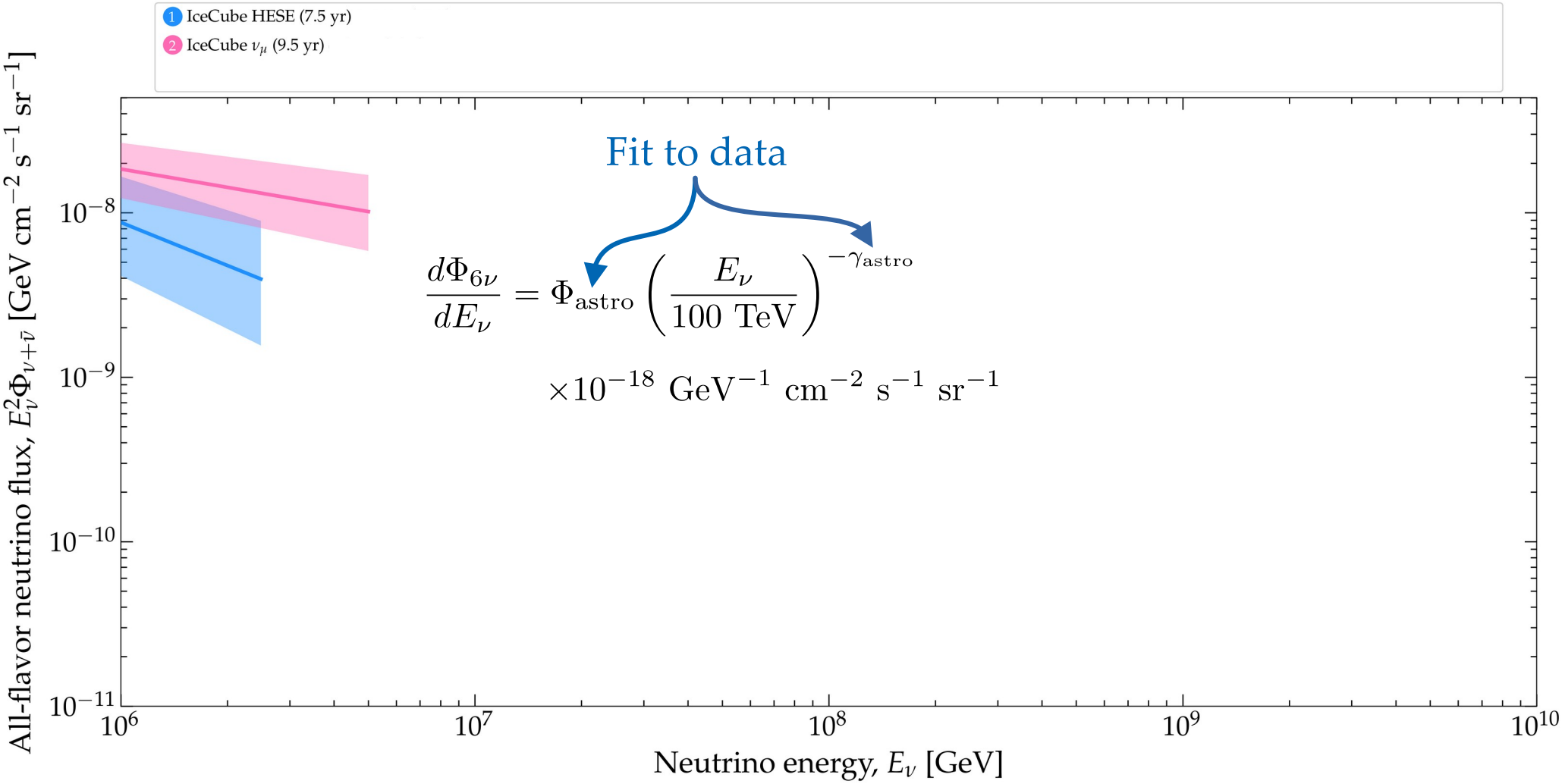
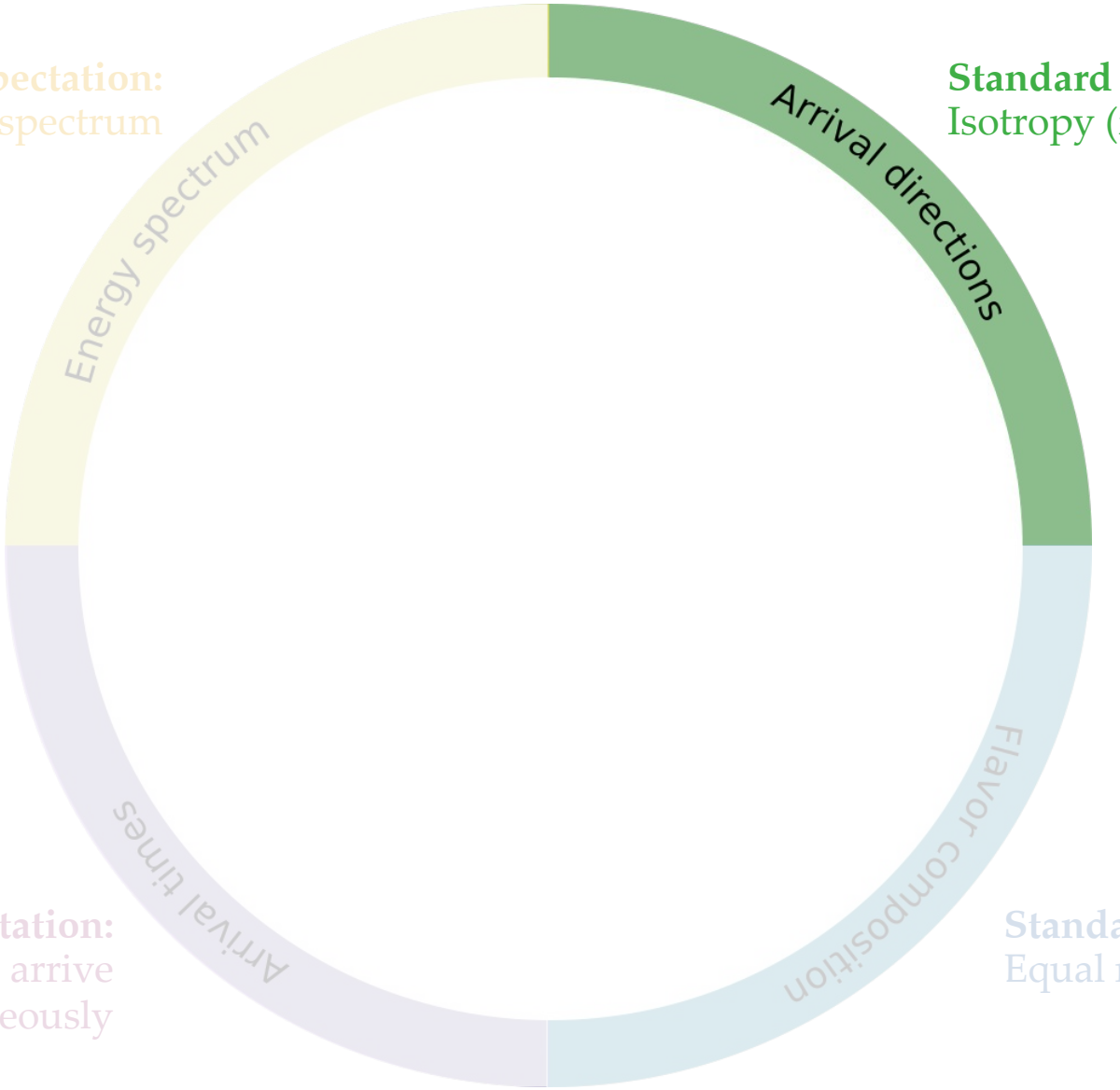

1 IceCube HESE (7.5 yr)
2 IceCube ν_μ (9.5 yr)
Fit to data
$\frac{d\Phi_{6\nu}}{dE_\nu} = \Phi_{\rm astro}\left(\frac{E_\nu}{100\ \rm TeV}\right)^{-\gamma_{\rm astro}}$
$\times 10^{-18}\ \rm GeV^{-1}\ cm^{-2}\ s^{-1}\ sr^{-1}$
All-flavor neutrino flux, $E_\nu^2\Phi_{\nu+\bar\nu}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



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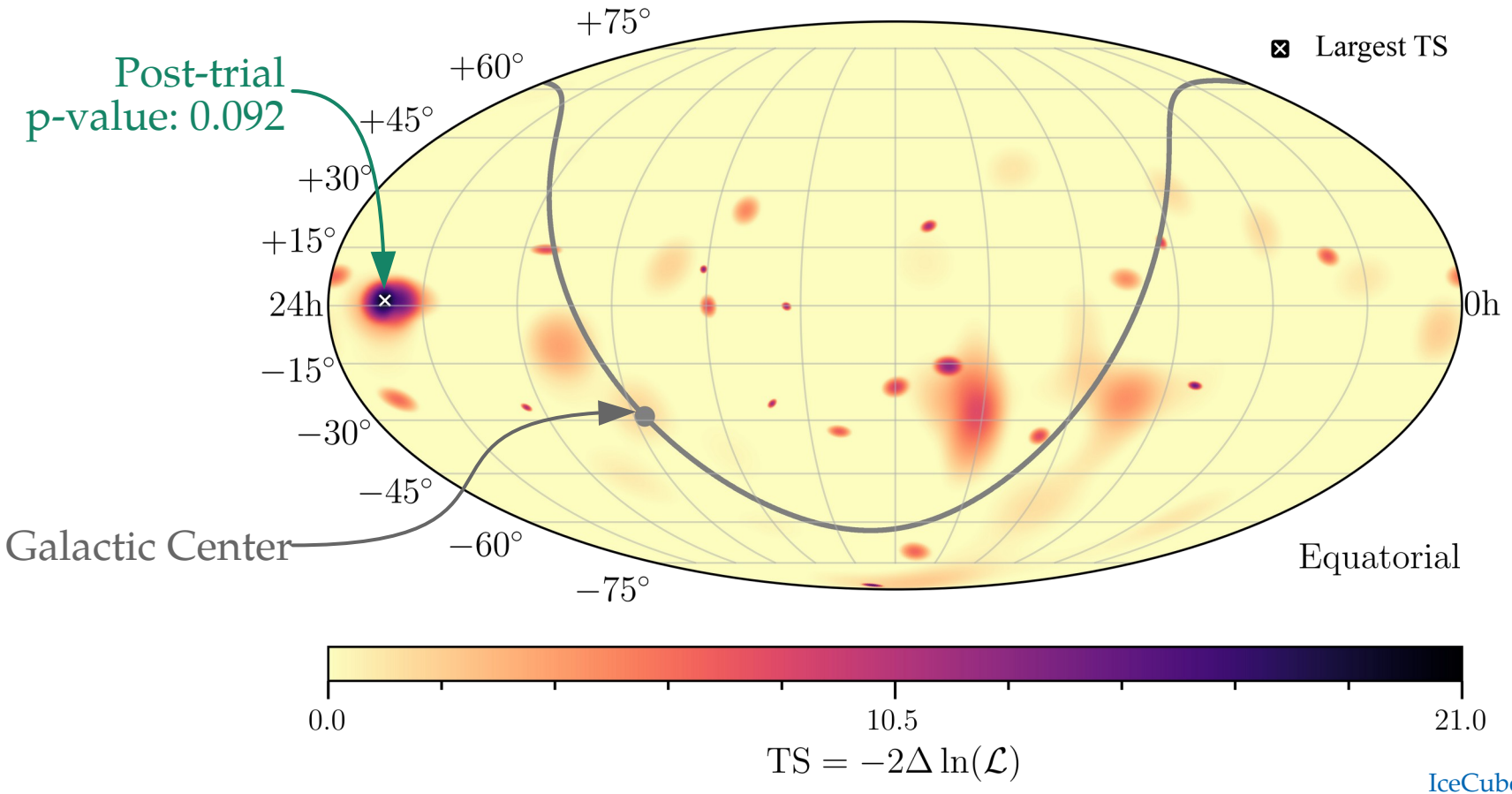
Arrival directions (7.5 yr)

No significant excess in the neutrino sky map:



IceCube, *PRD* 2021

Standard expectation:
Power-law energy spectrum

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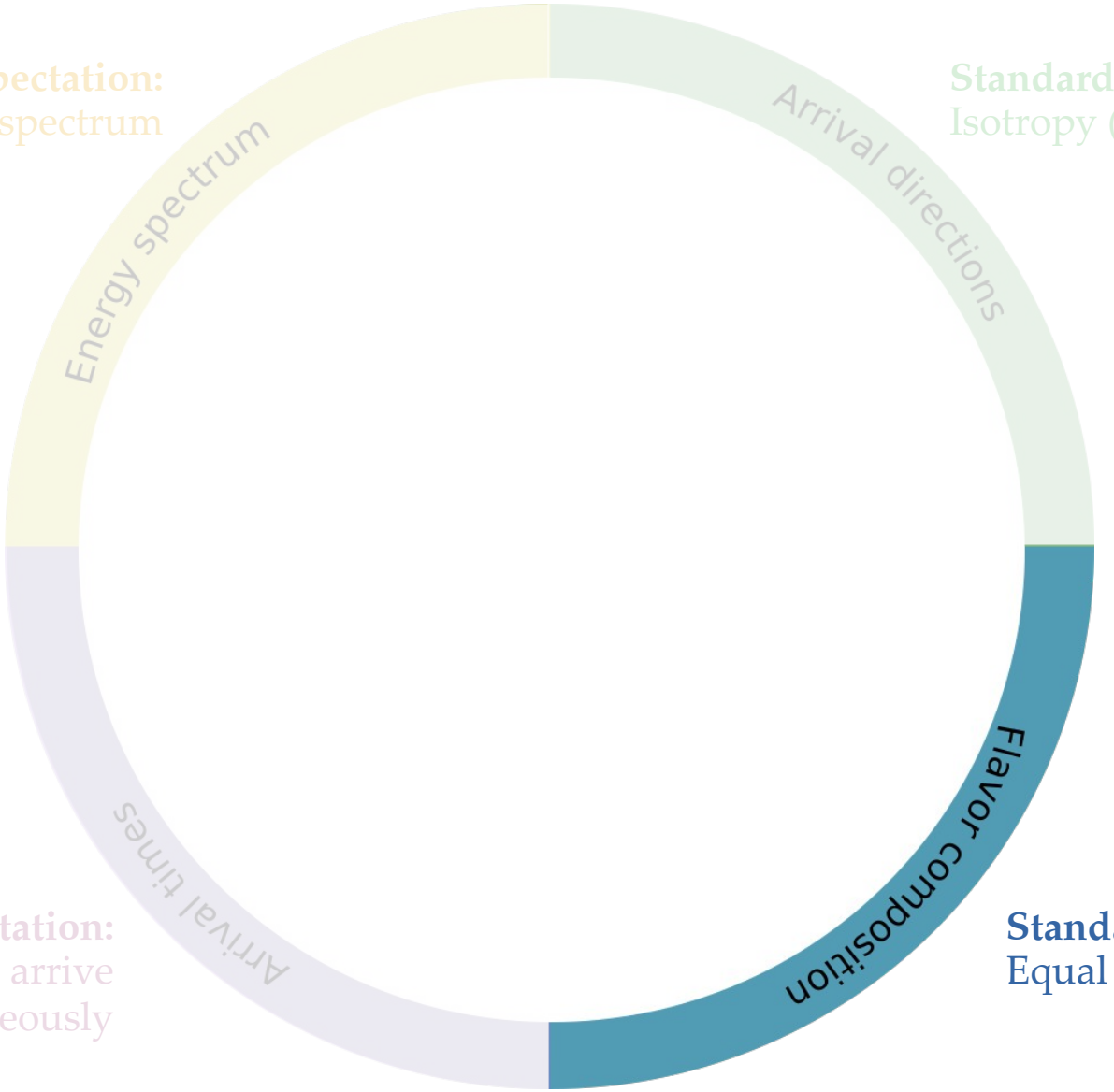

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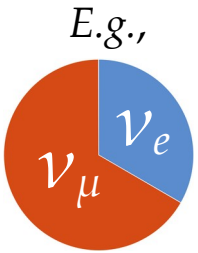
Astrophysical sources

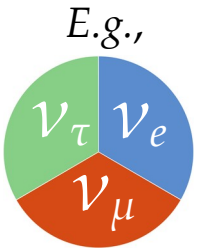
Earth

Up to a few Gpc



Oscillations change the number

of ν of each flavor, N_e, N_μ, N_τ



Different production mechanisms yield different flavor ratios:

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

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

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

Astrophysical sources

Earth

Up to a few Gpc

E.g., ν_e ν_μ

Oscillations change the number

of ν of each flavor, N_e, N_μ, N_τ

E.g., ν_τ ν_e ν_μ

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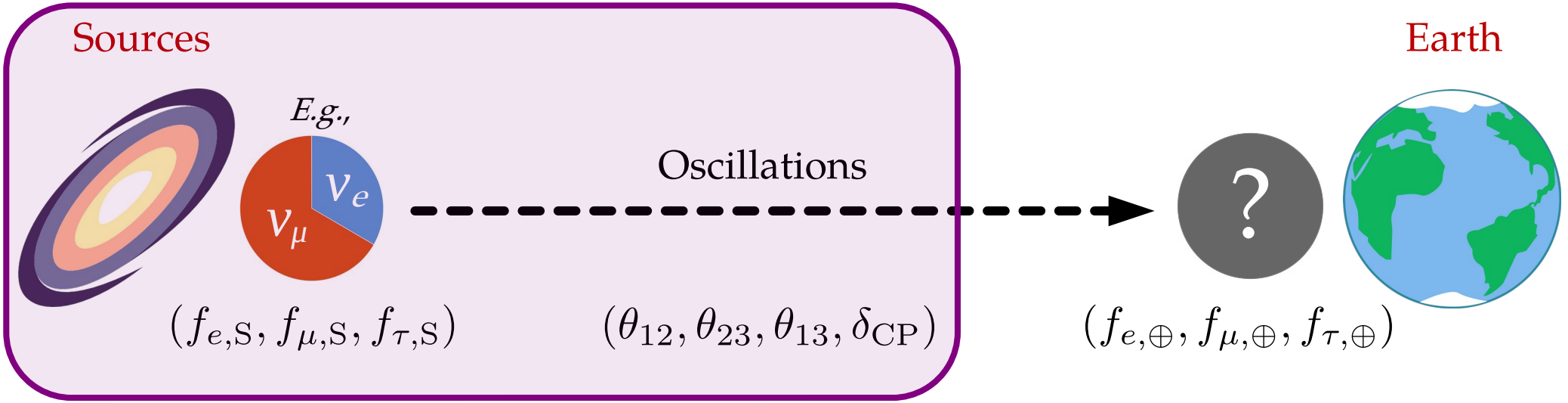
Standard oscillations *or* new physics

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



One likely TeV–PeV ν production scenario:

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

Full π decay chain

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

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

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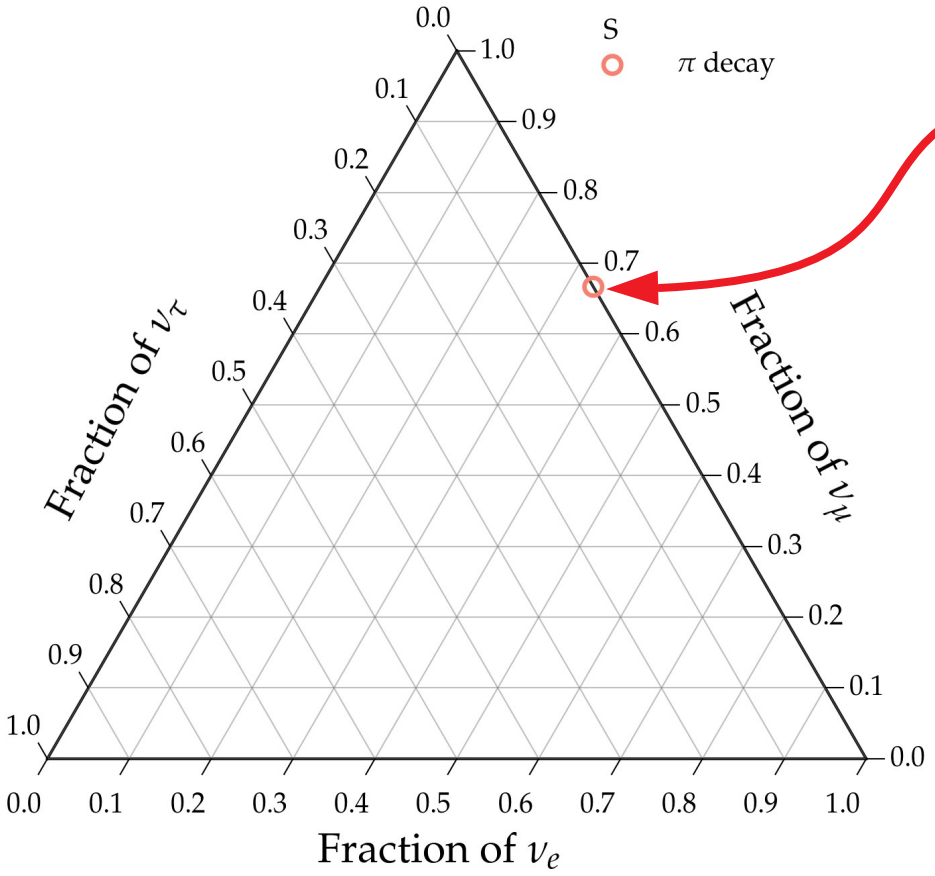

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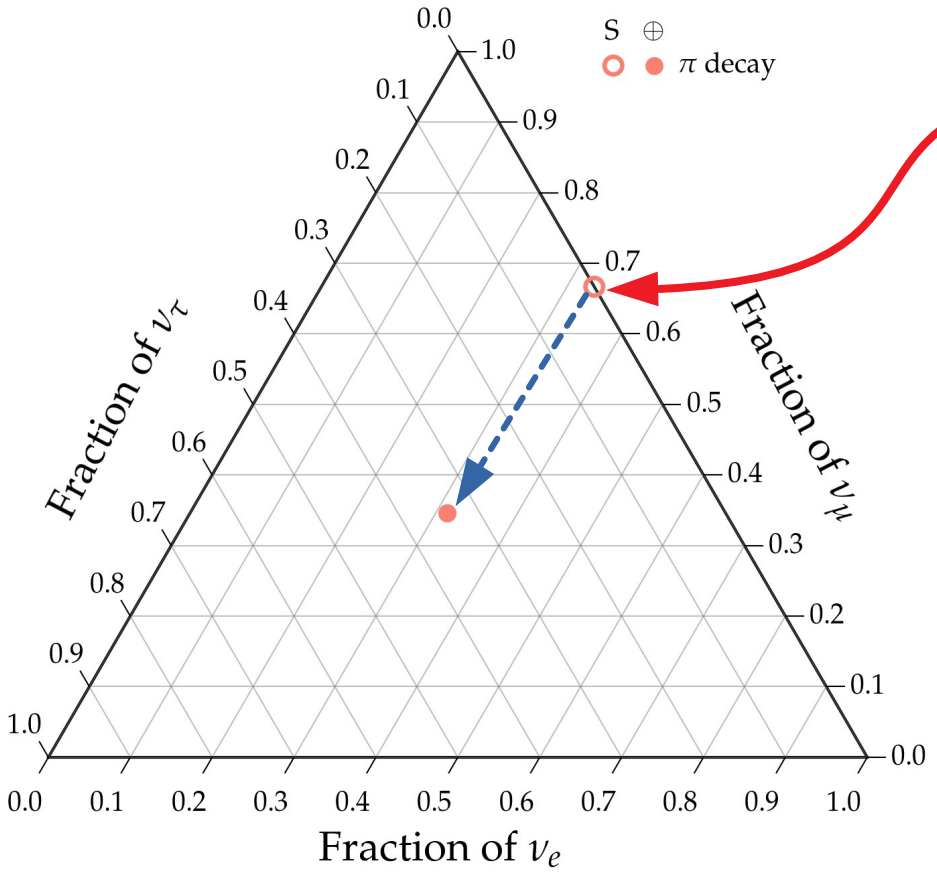

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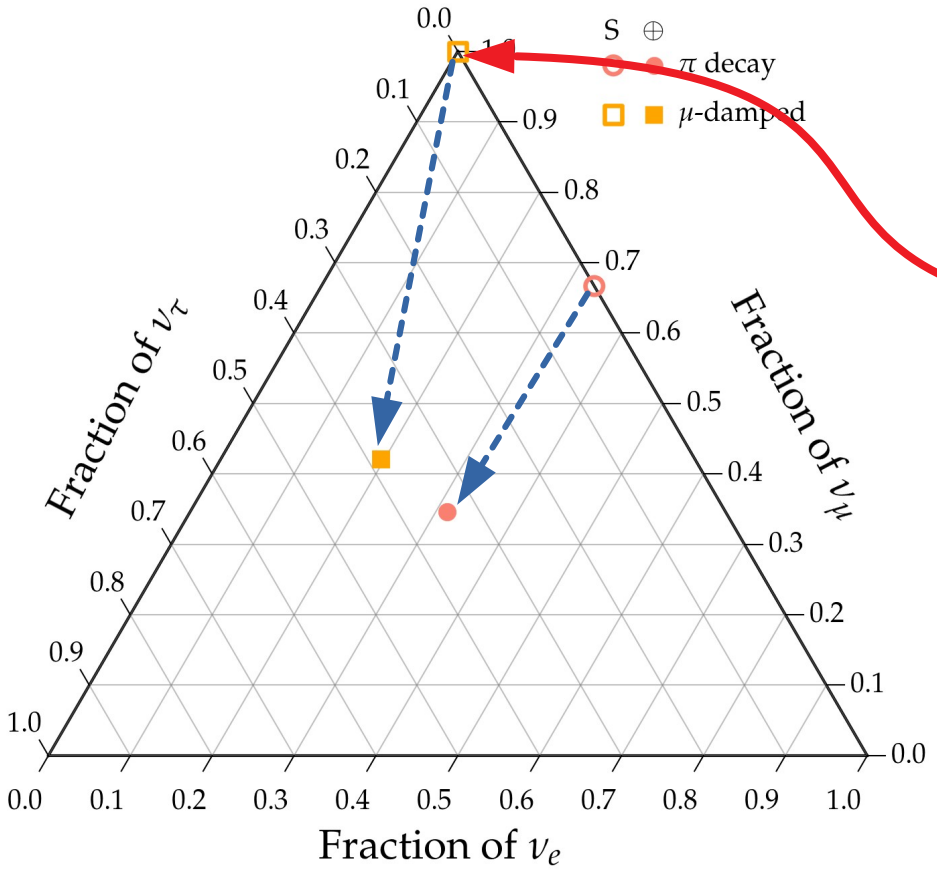

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Muon damped

$(0:1:0)_S$

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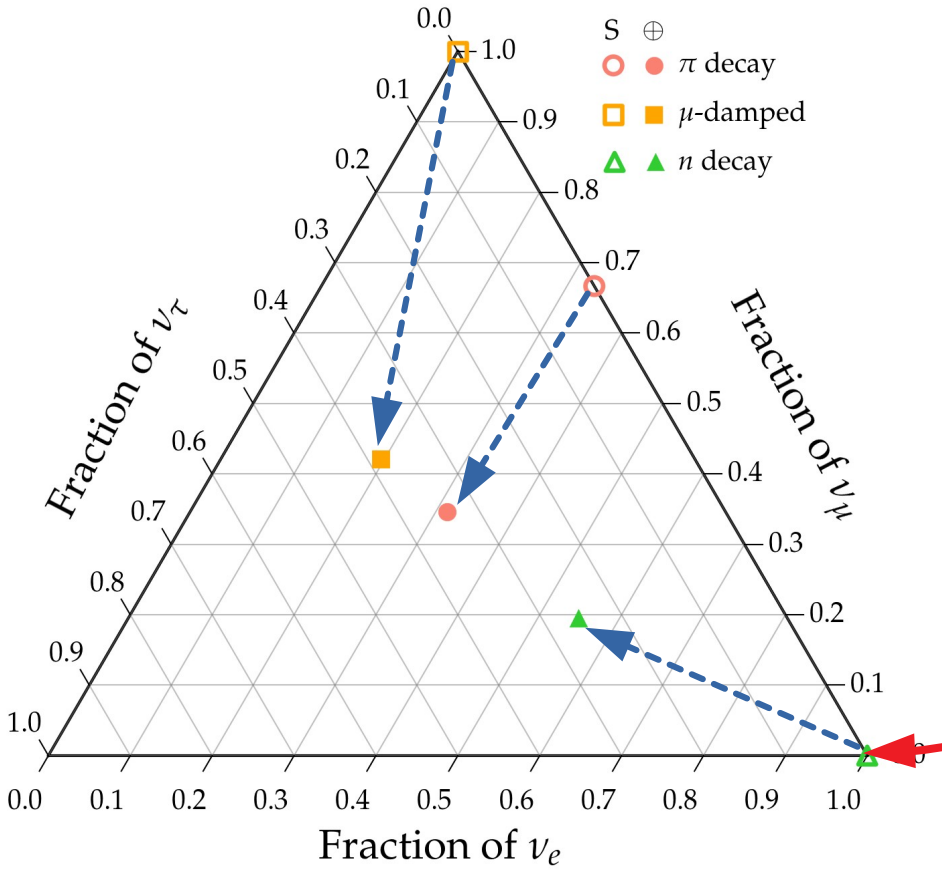

Full π decay chain

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

Muon damped

$(0:1:0)_S$

Neutron decay

$(1:0:0)_S$

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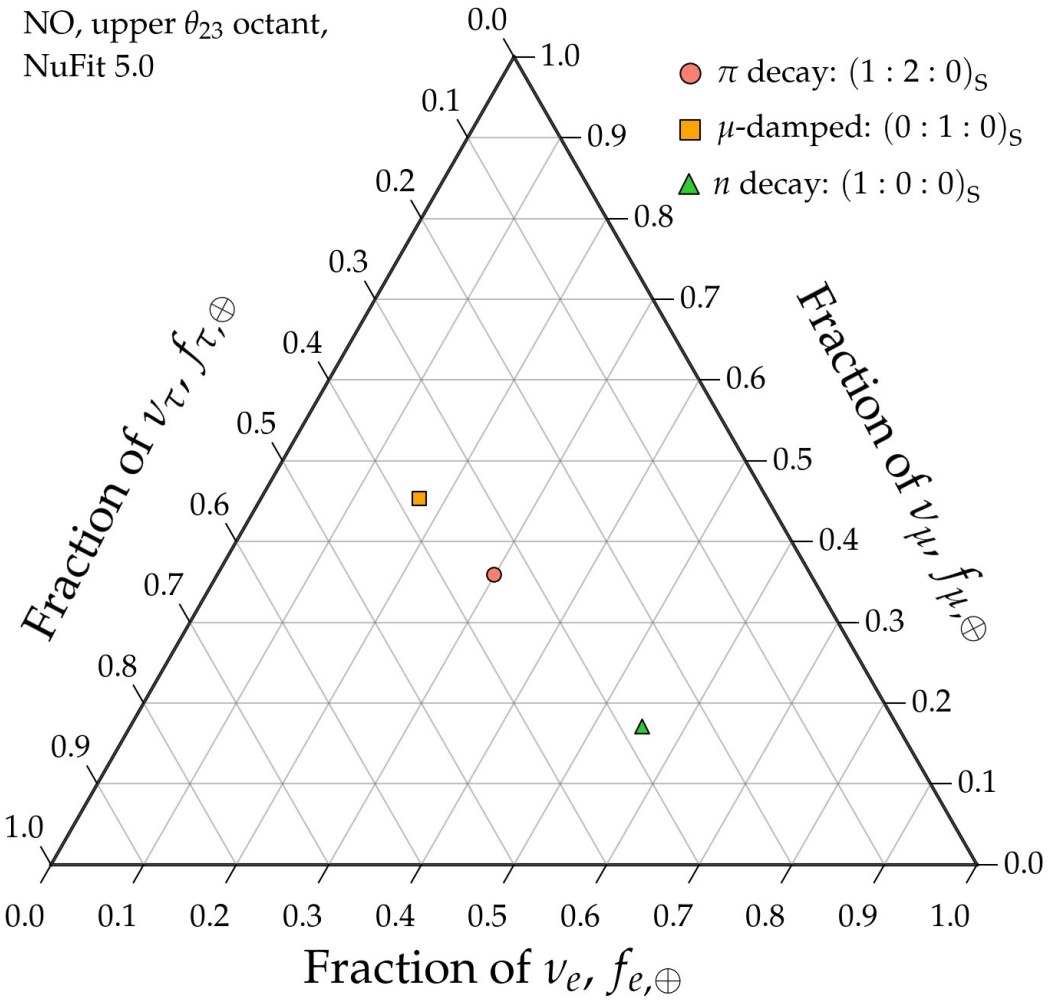
Theoretically palatable regions: today



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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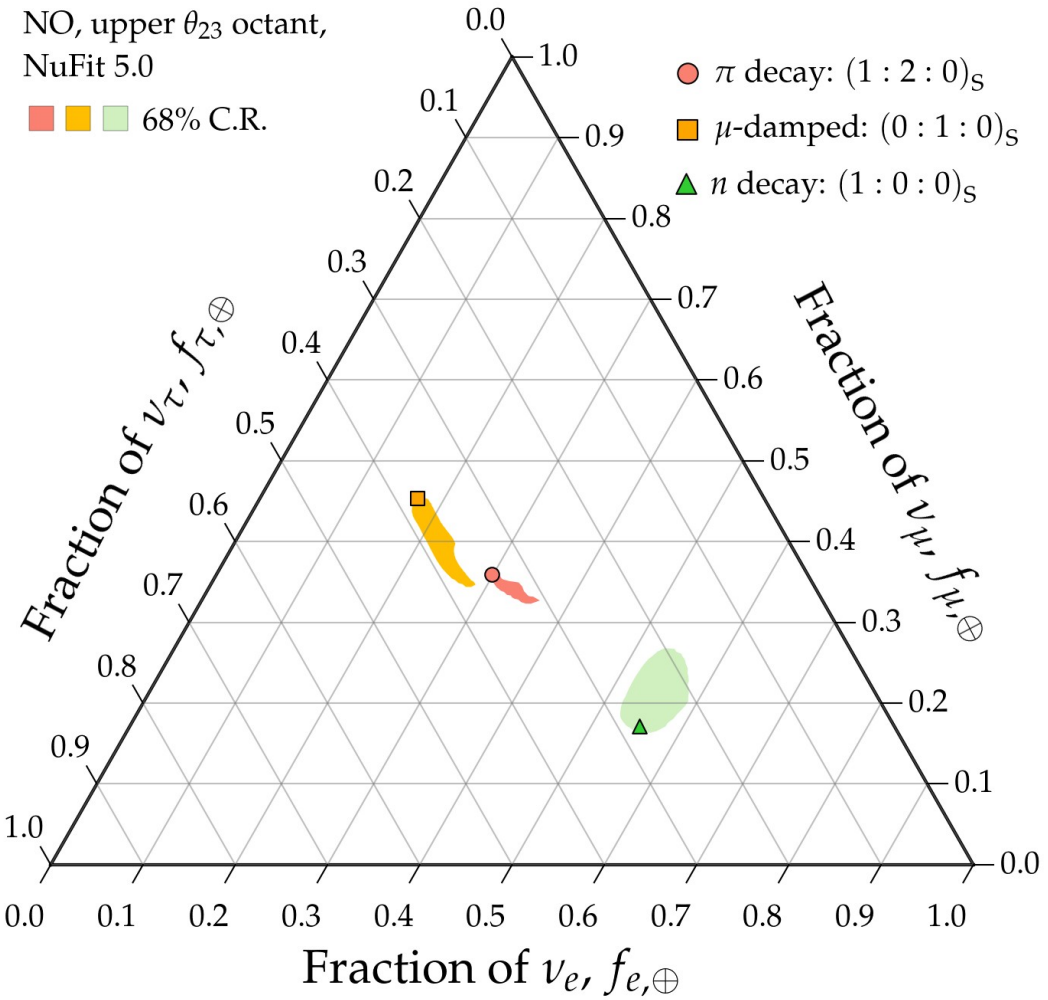

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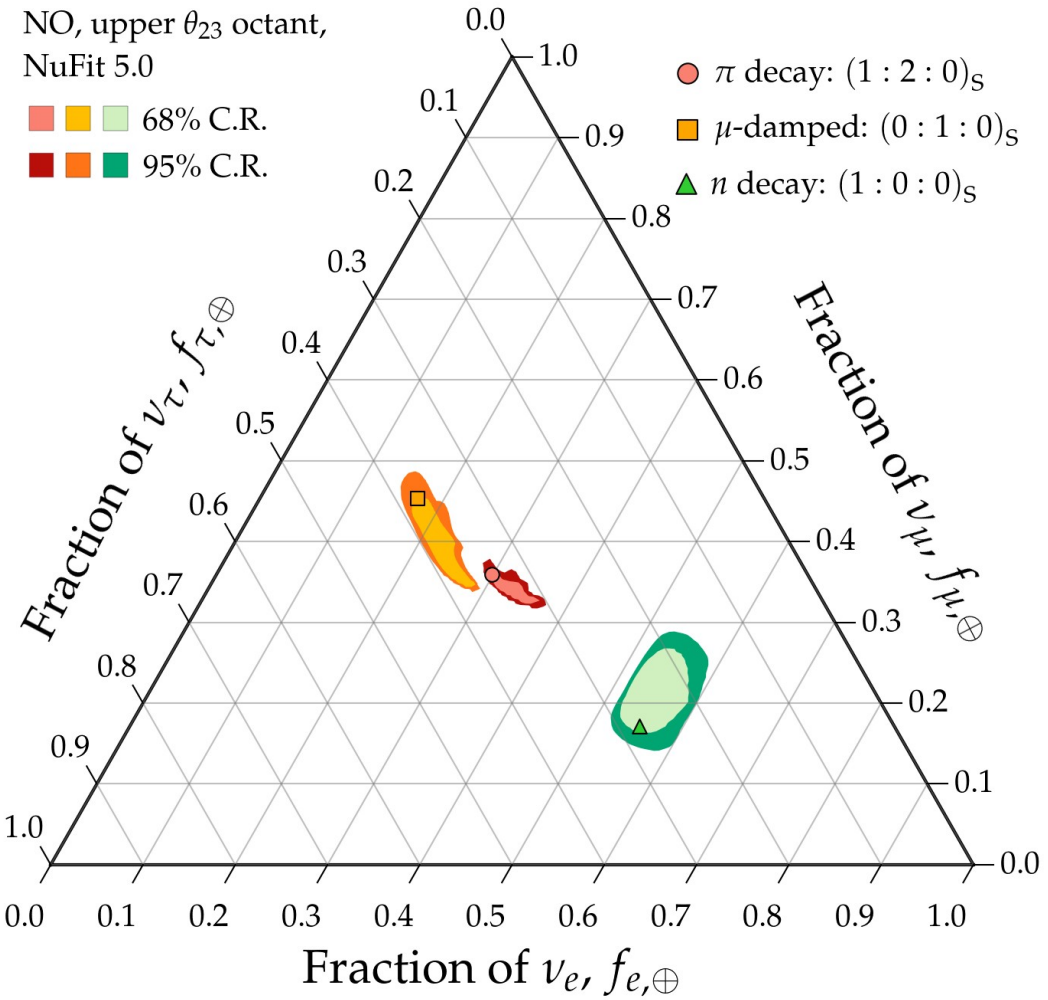

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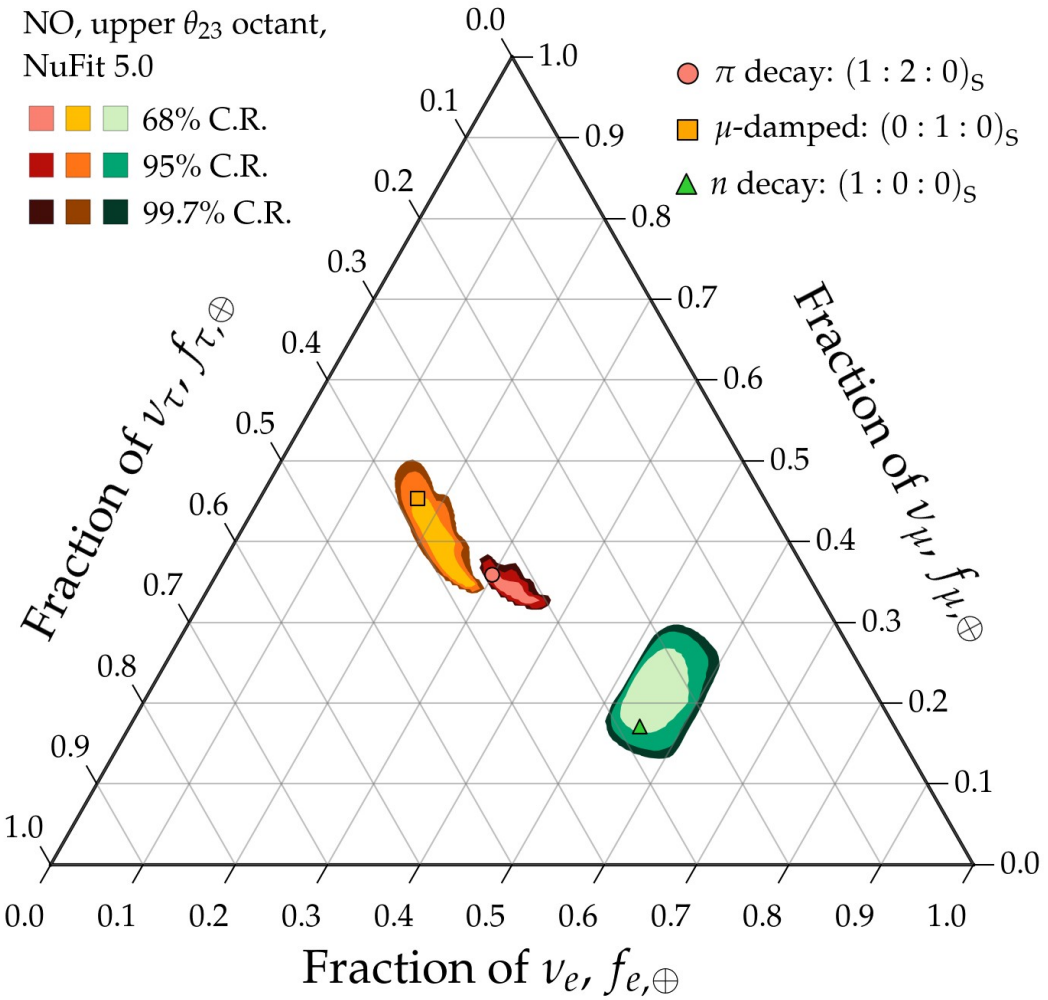
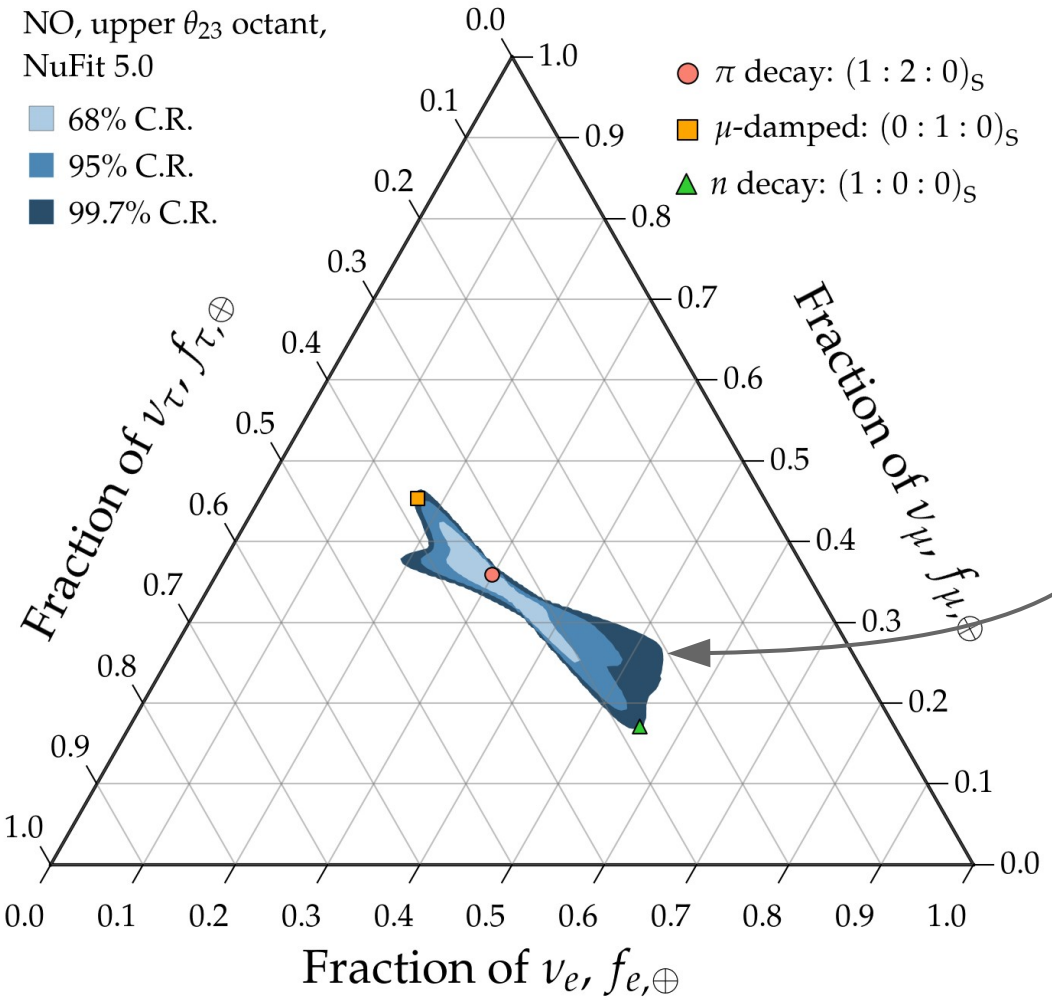


Note:
All plots shown are for normal neutrino mass ordering (NO); inverted ordering looks similar

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

Theoretically palatable regions: today



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

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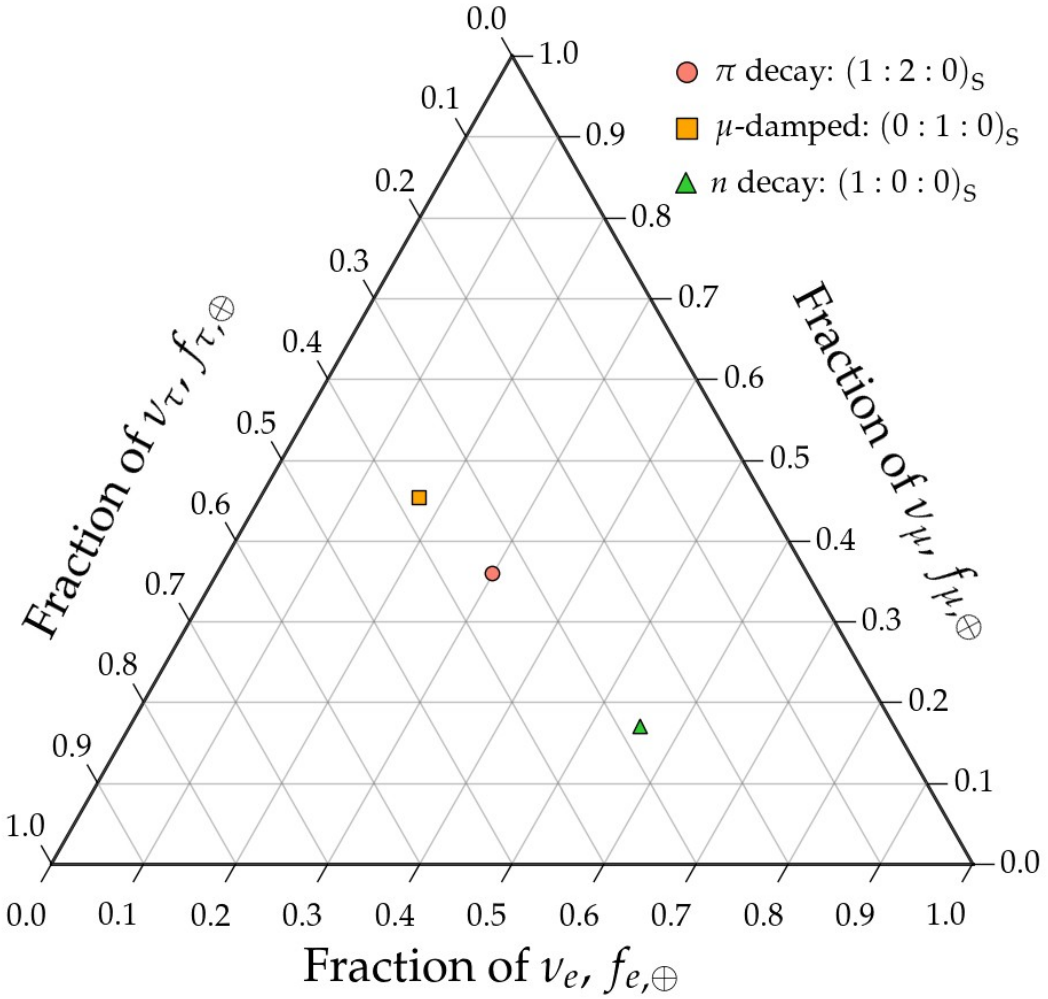

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

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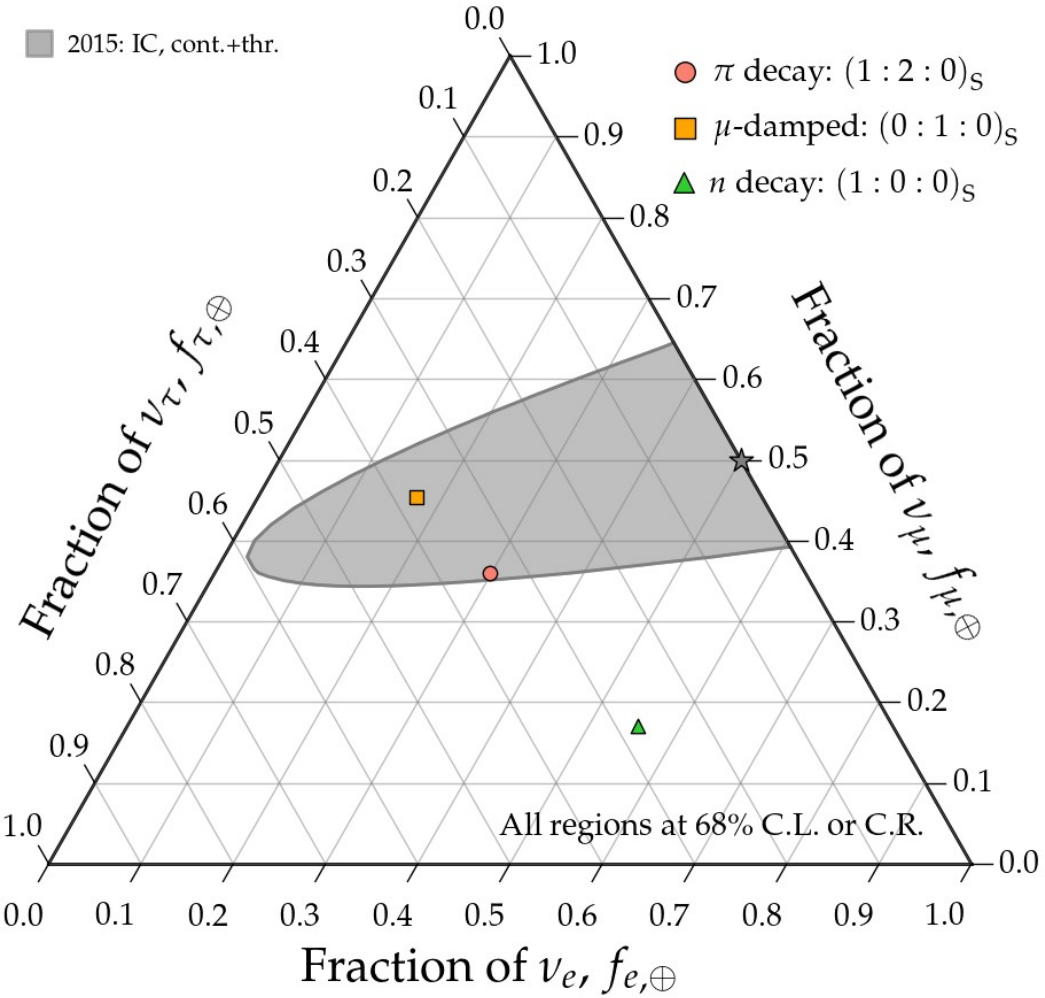

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

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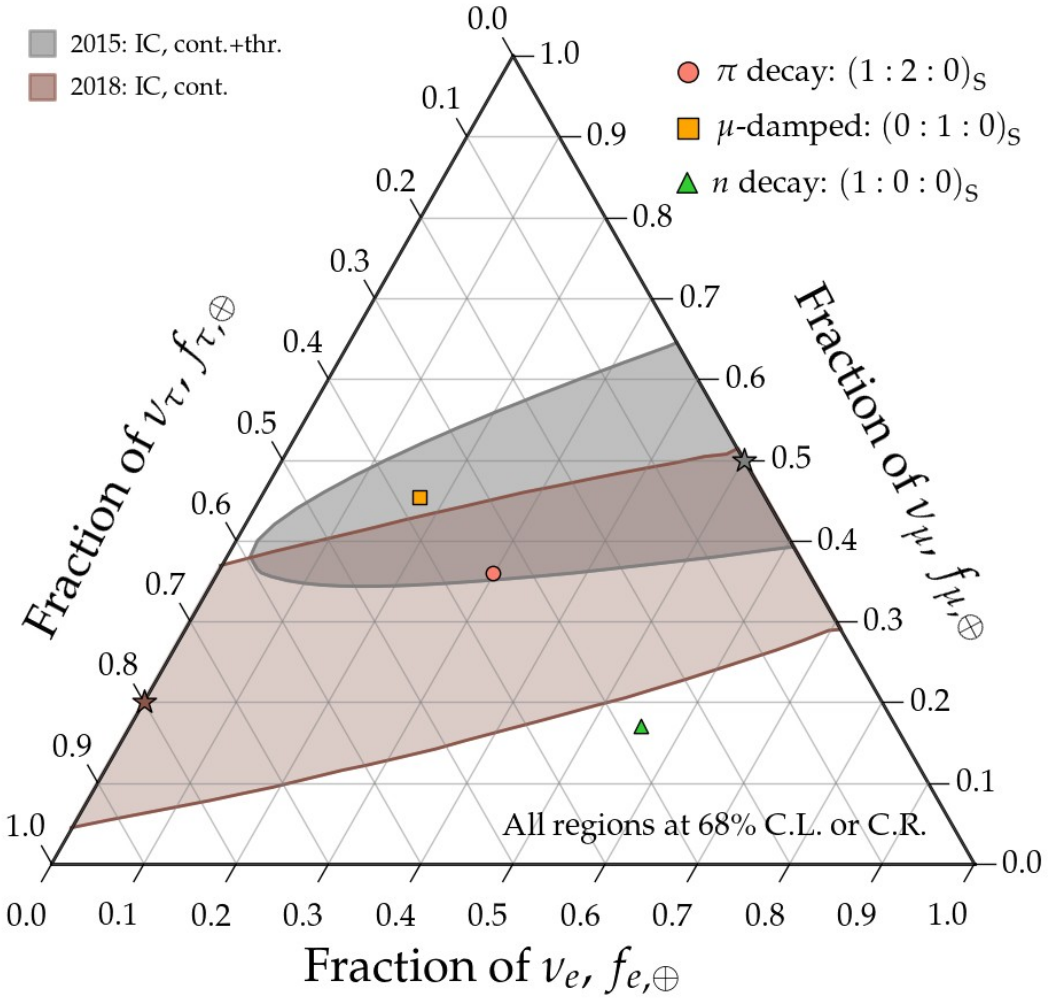

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

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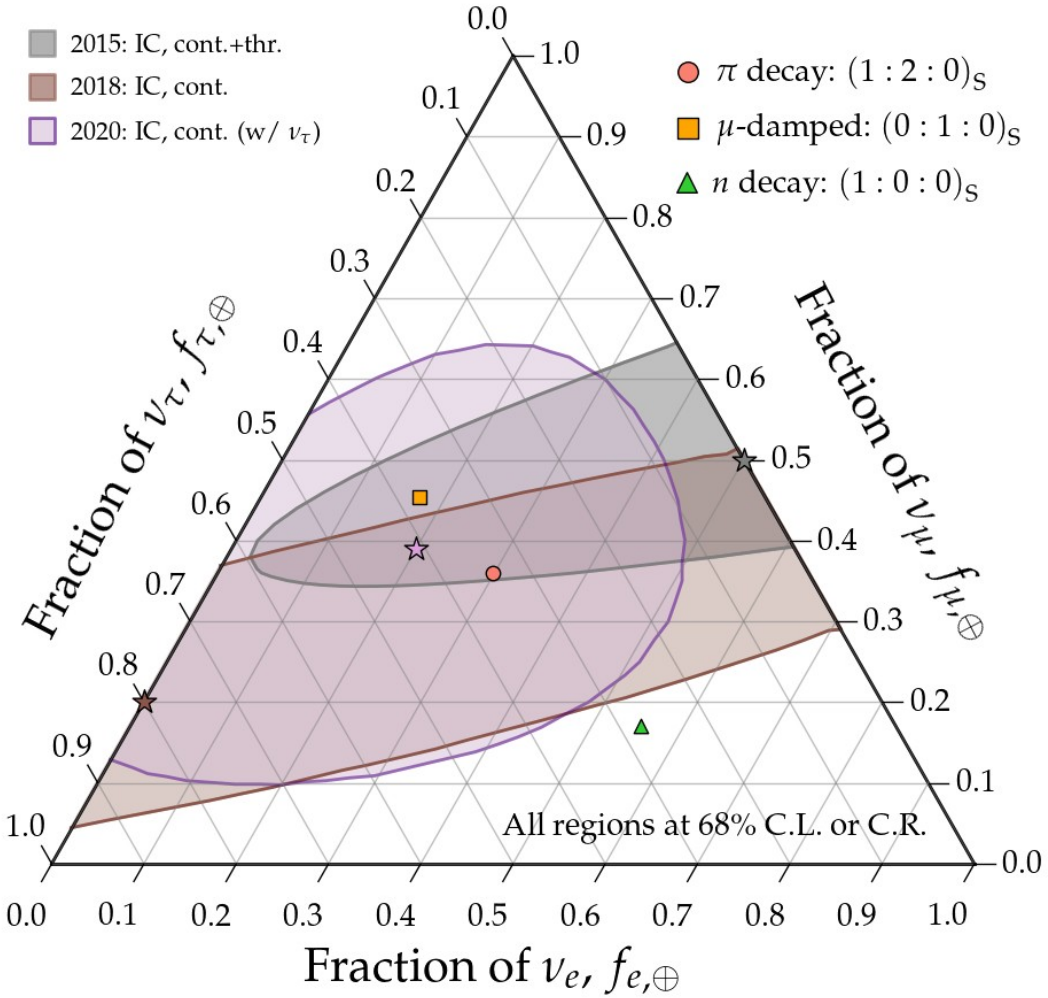

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Standard expectation:
Power-law energy spectrum

Standard expectation:
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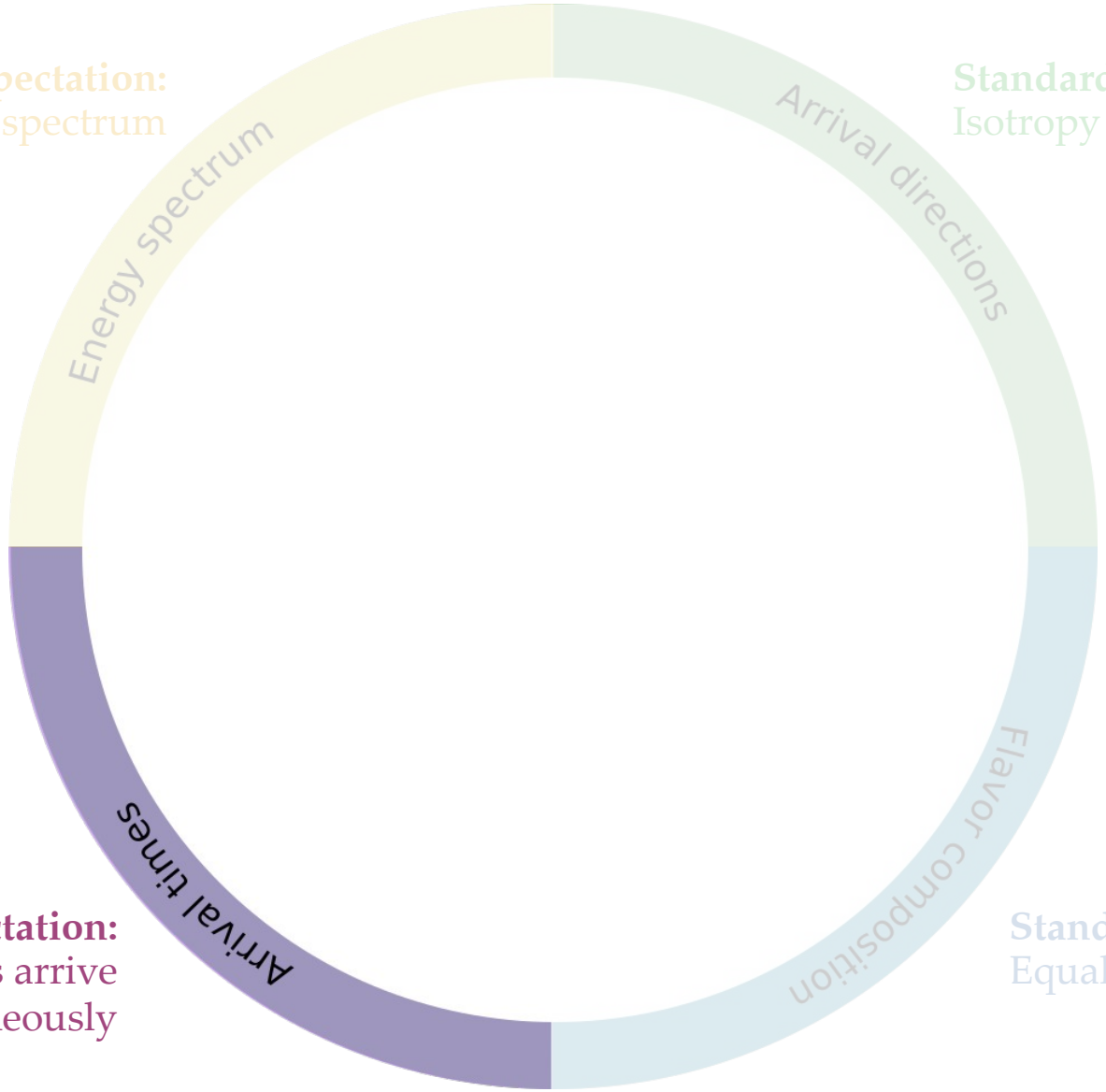

Standard expectation:
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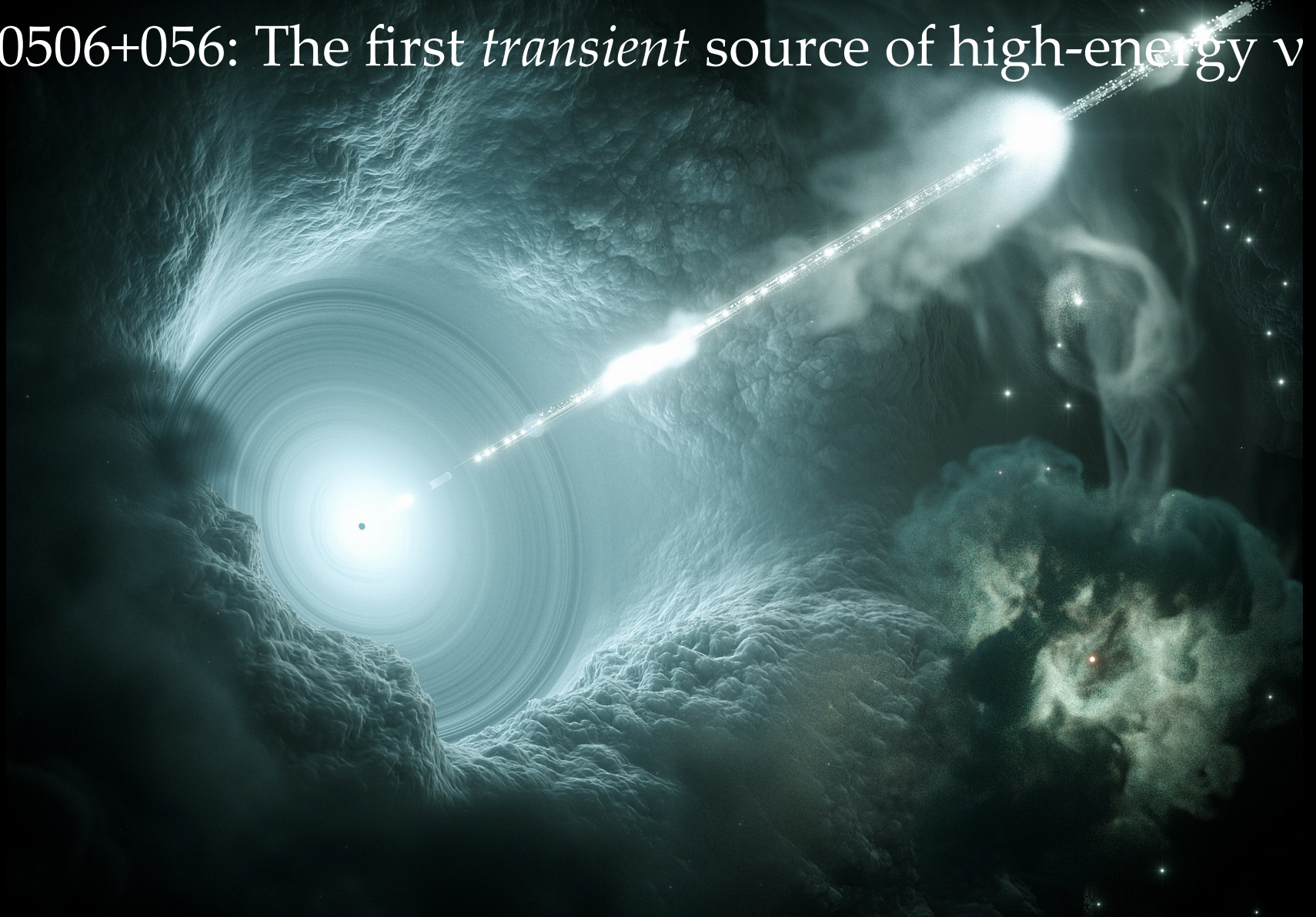
Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

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

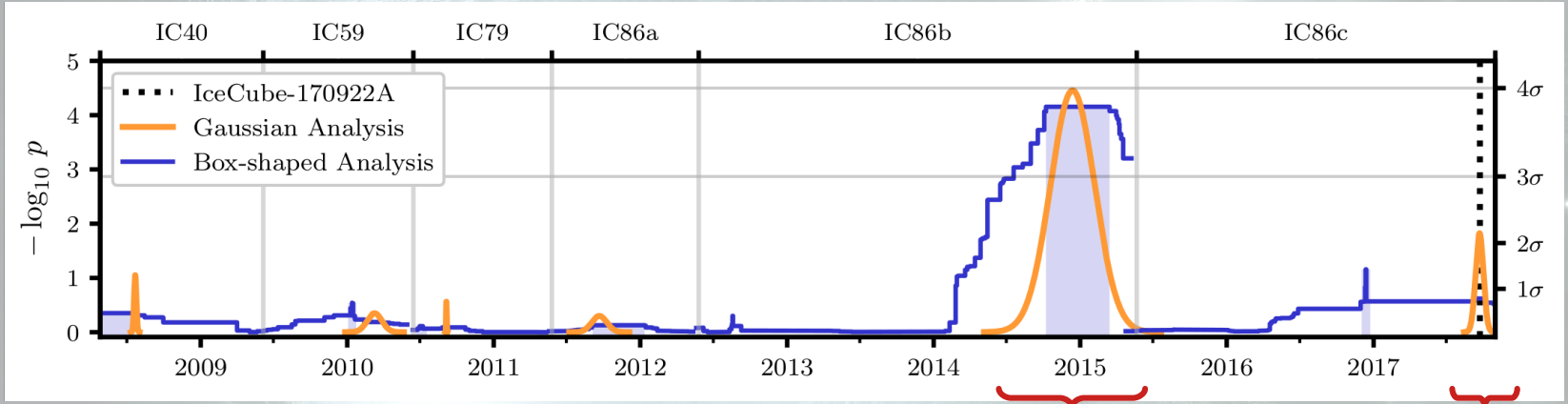


DESY

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=7×10^{-5} to p=8×10^{-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

Fundamental physics with high-energy cosmic neutrinos

- Numerous new ν physics effects grow as ~ $\kappa_n \cdot E^n \cdot L$
- So we can probe $\kappa_n \sim 4 \cdot 10^{-47}\ (E/\mathrm{PeV})^{-n}\ (L/\mathrm{Gpc})^{-1}\ \mathrm{PeV}^{1-n}$
- Improvement over limits using atmospheric ν: $\kappa_0 < 10^{-29}$ PeV, $\kappa_1 < 10^{-33}$

Fundamental physics with high-energy cosmic neutrinos

- Numerous new ν physics effects grow as ~ $\kappa_n \cdot E^n \cdot L$ } *E.g.*,
  n = -1: neutrino decay
  n = 0: CPT-odd Lorentz violation
  n = +1: CPT-even Lorentz violation

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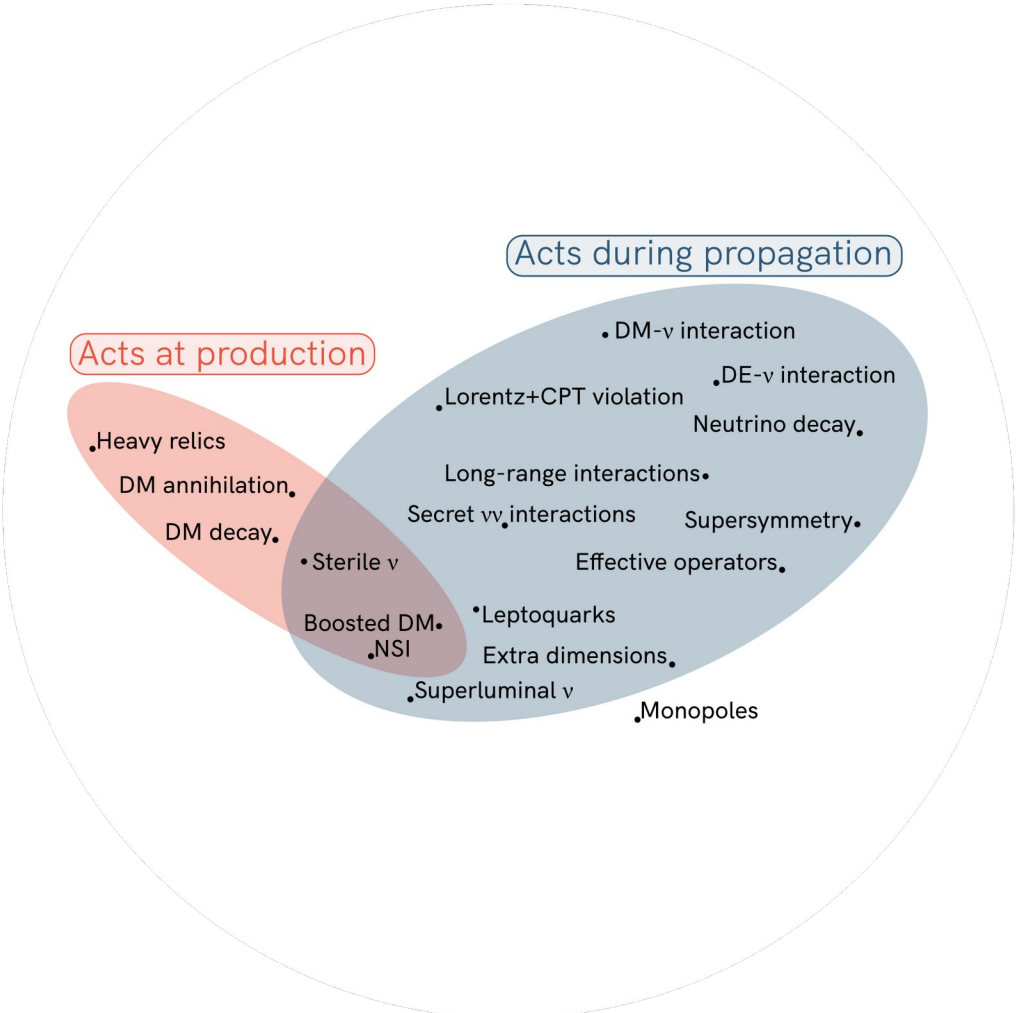

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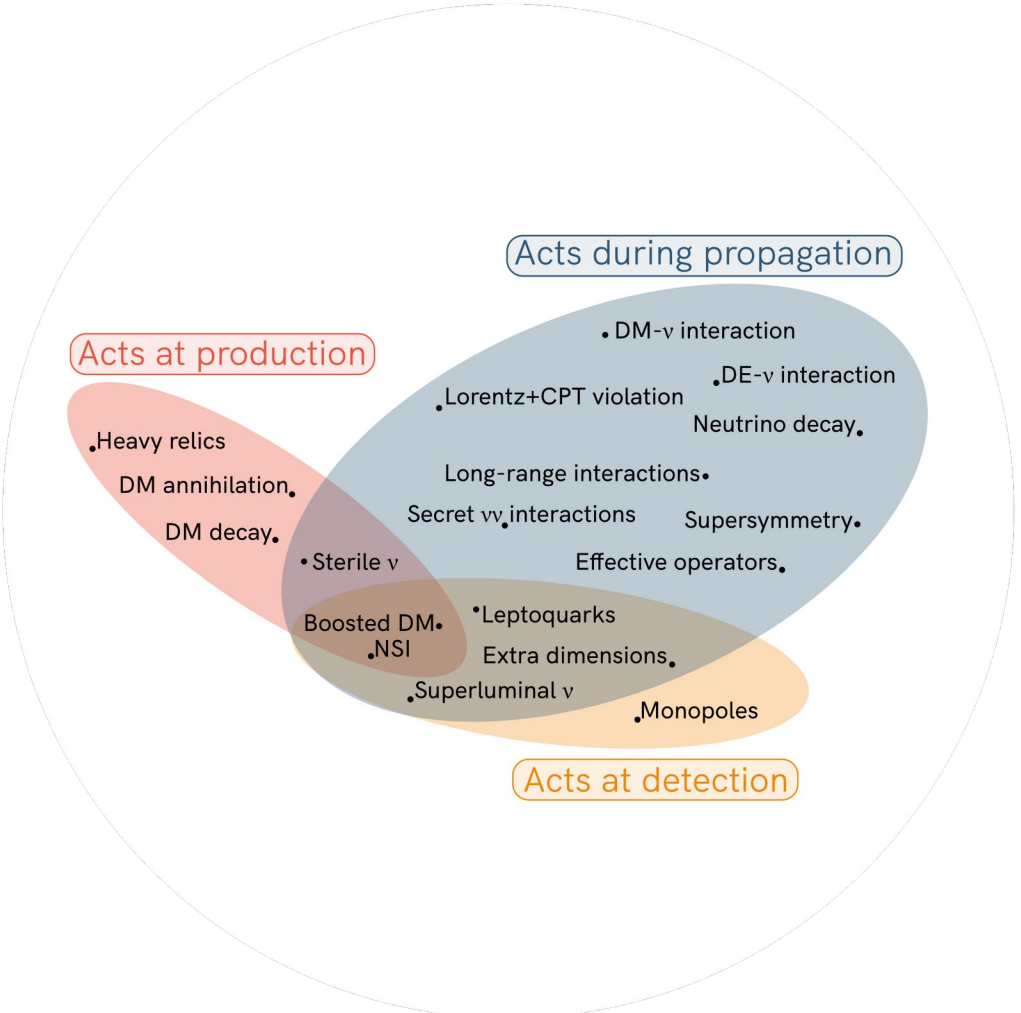

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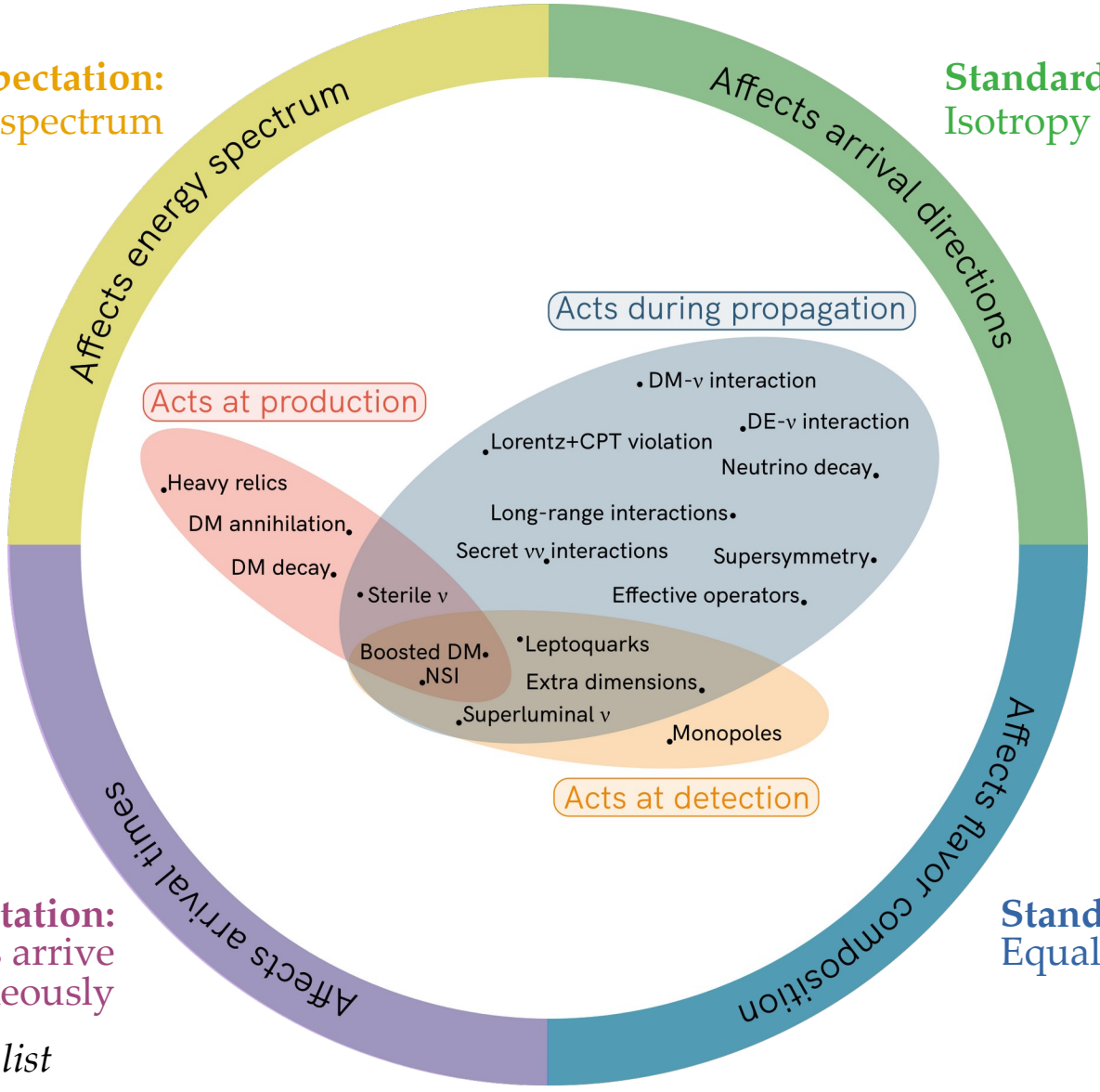

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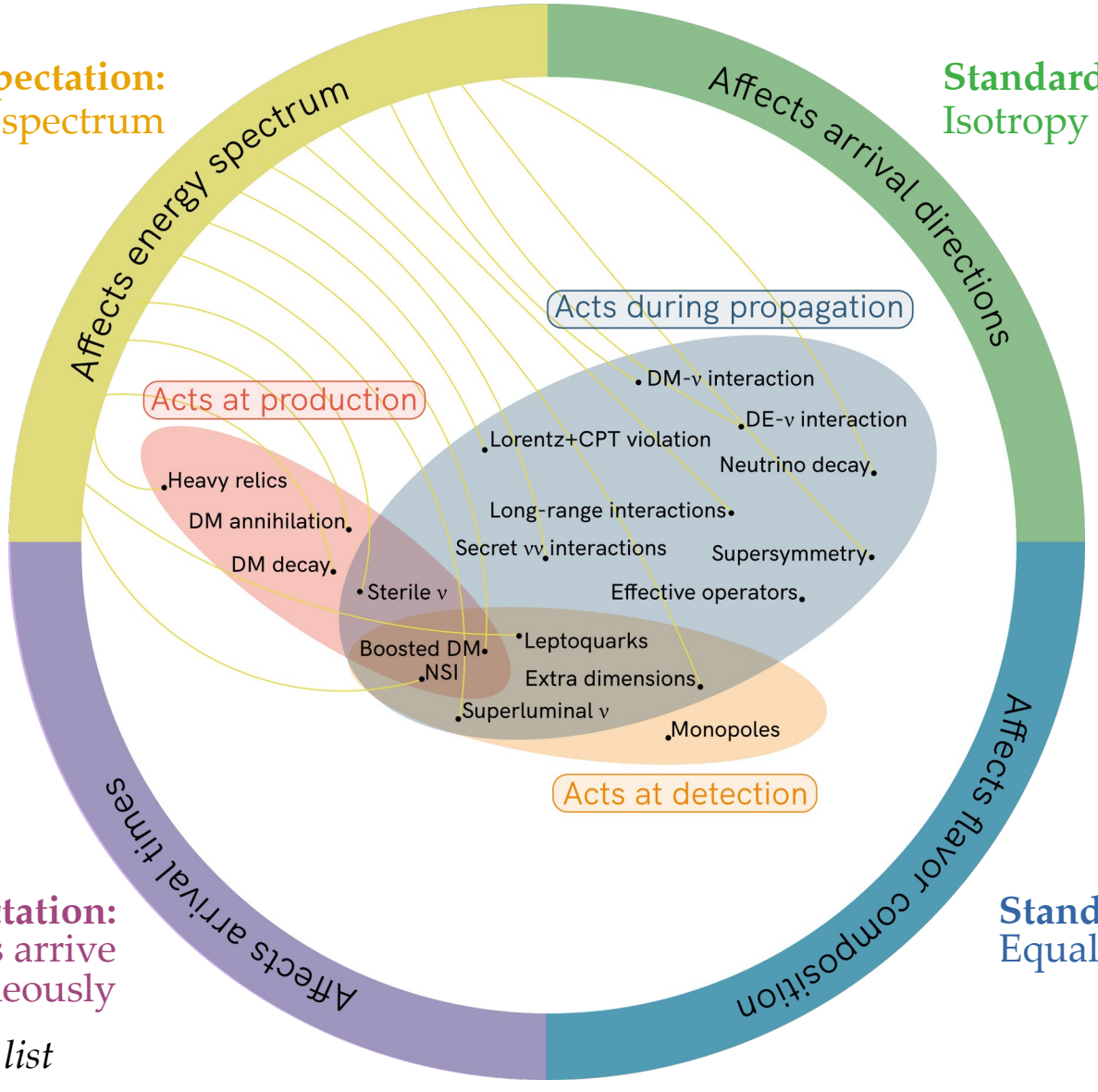

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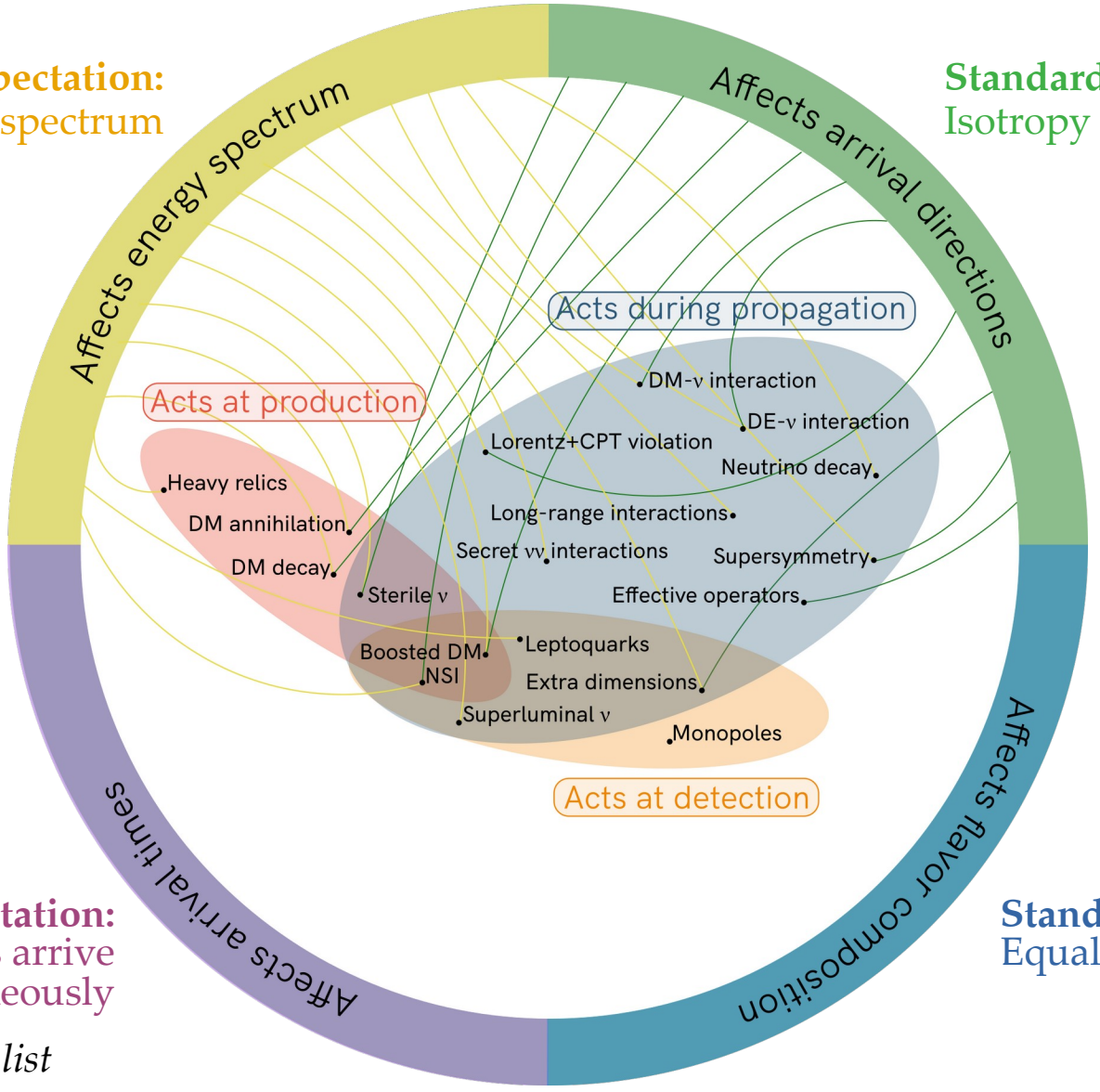

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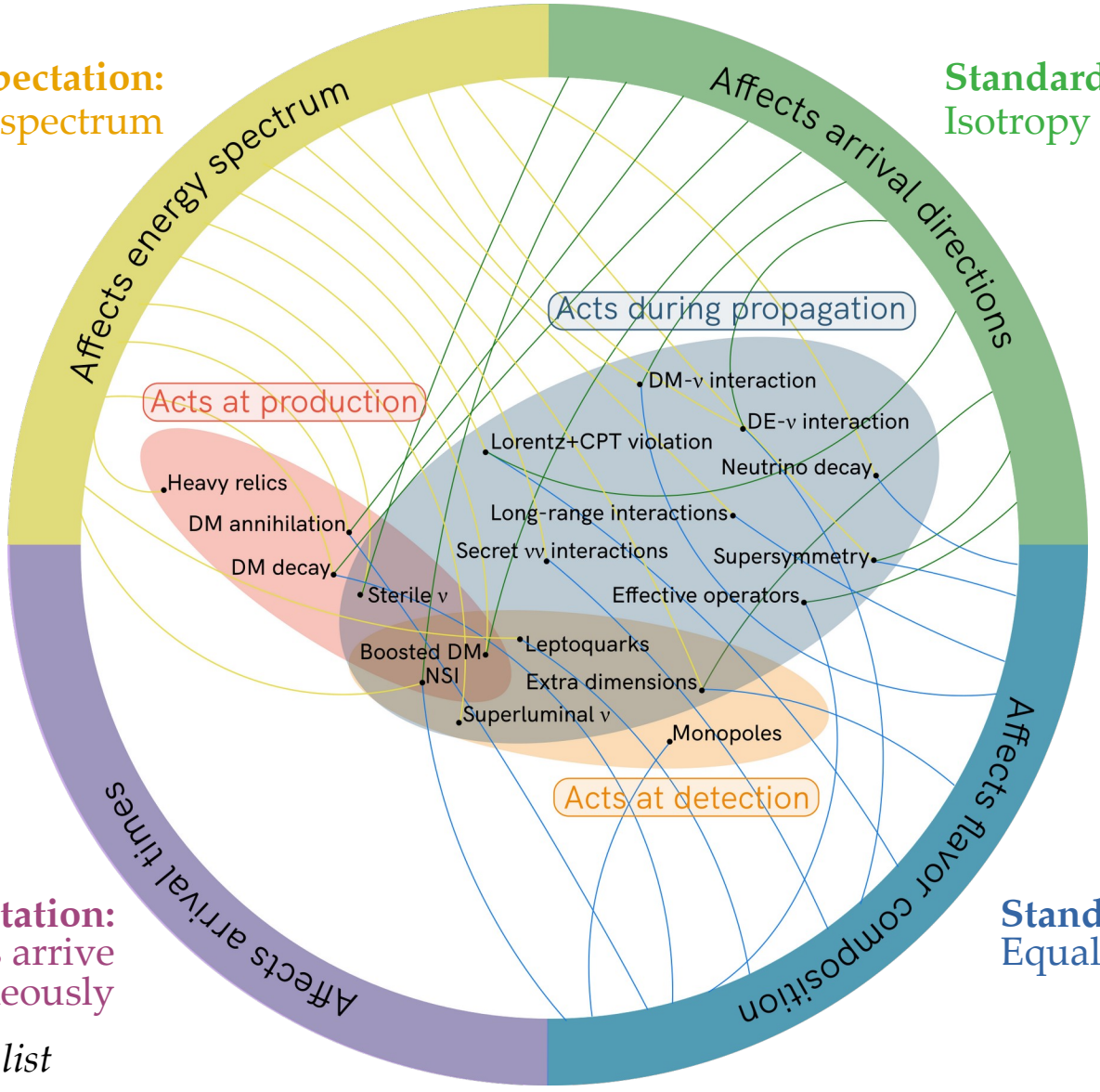

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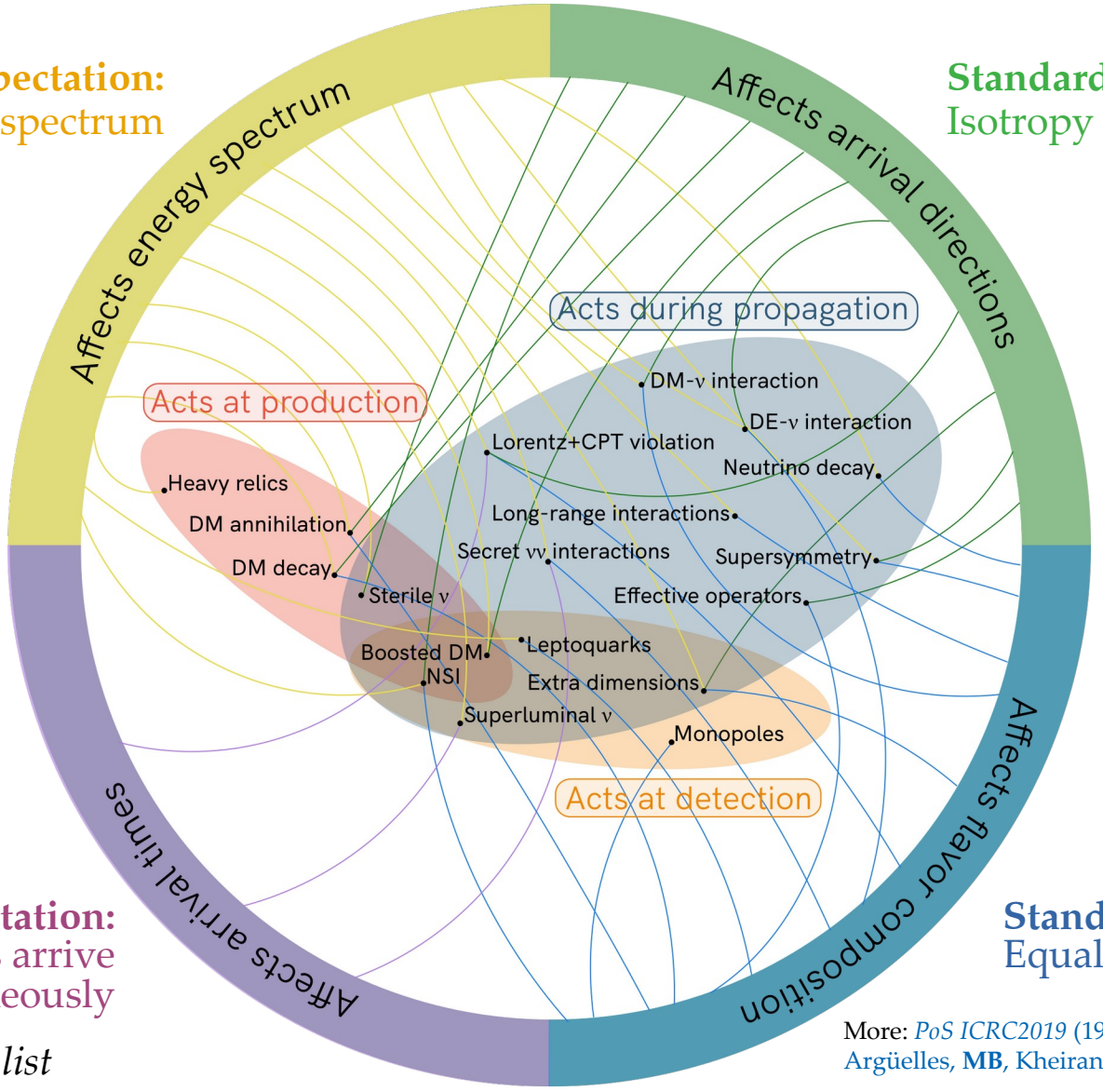

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More: *PoS ICRC2019* (1907.08690)
Argüelles, **MB**, Kheirandish, Palomares-Ruiz, Salvadó, Vincent

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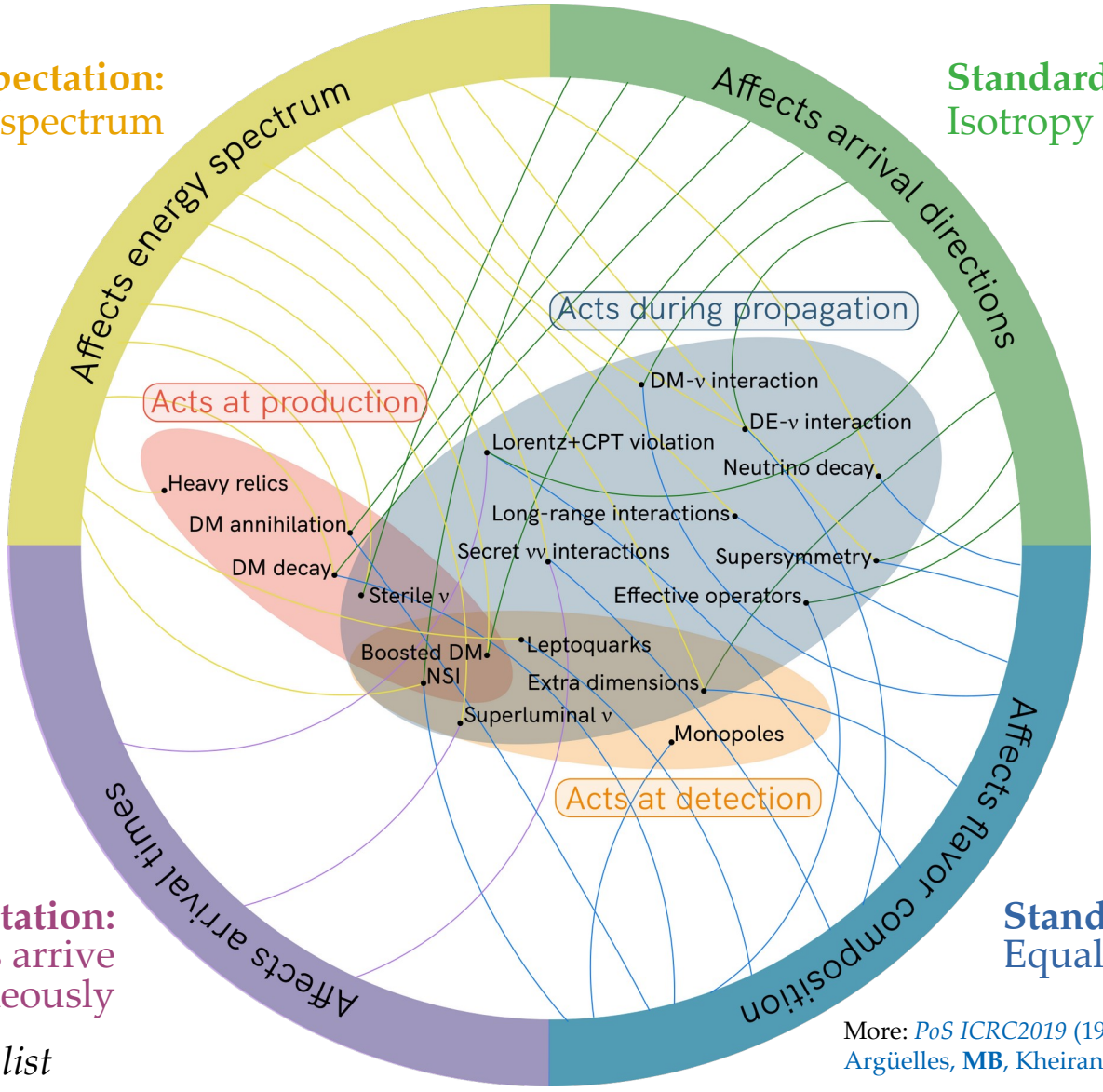

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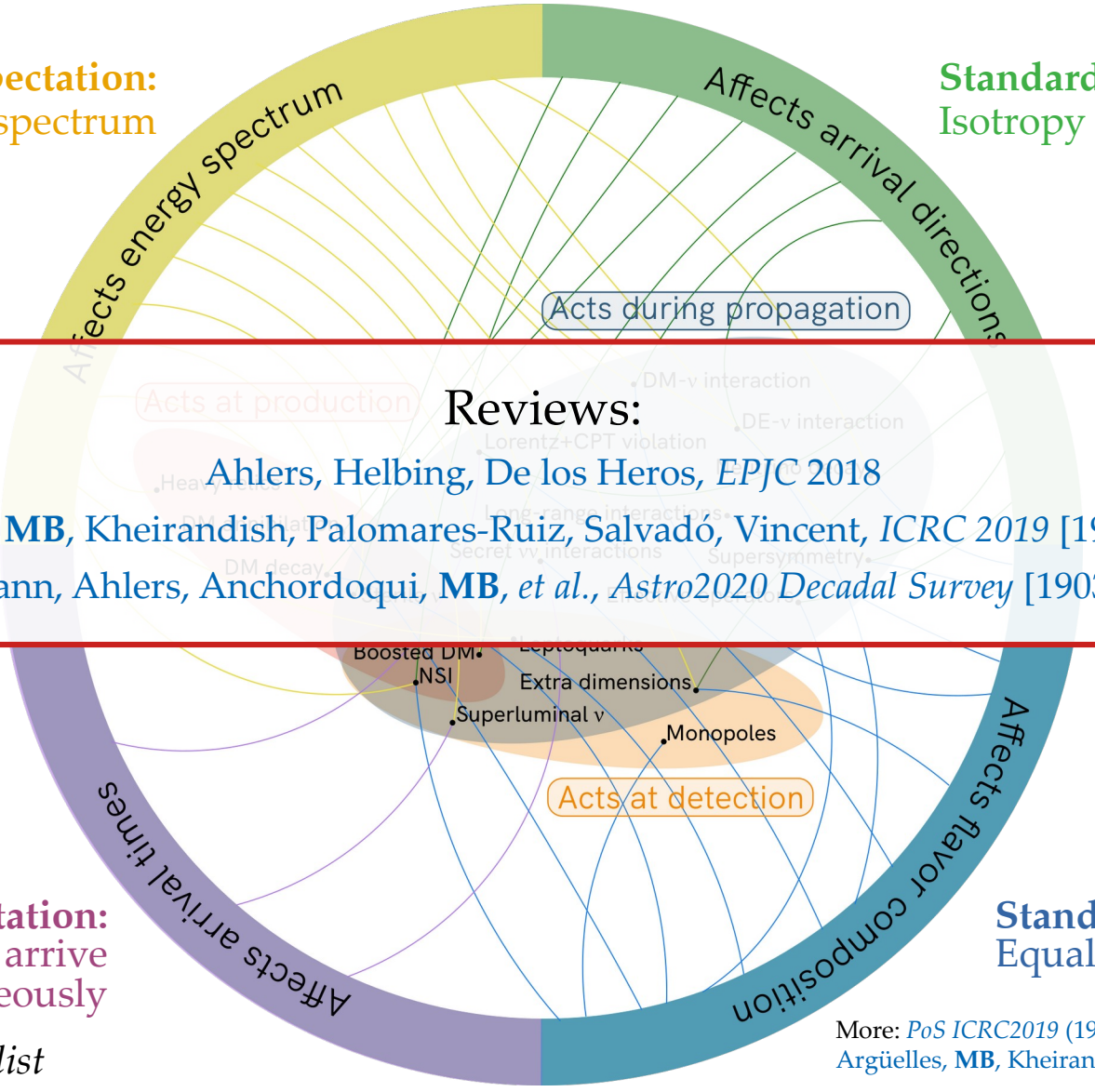

Reviews:

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

Account for particle-physics + astrophysical + detector uncertainties

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

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

Account for particle-physics + astrophysical + detector uncertainties

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

Evidence for BSM

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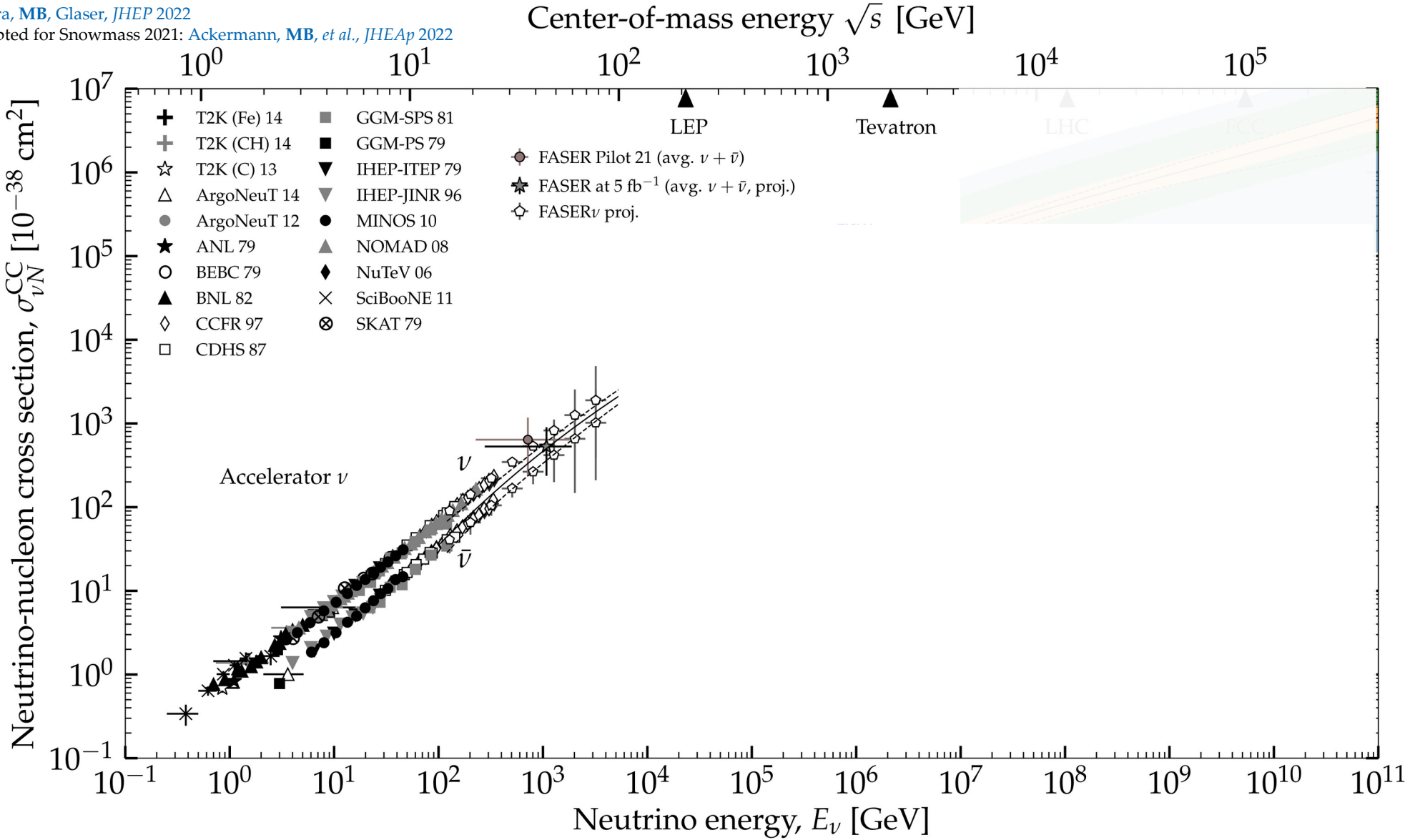
Account for particle-physics + astrophysical + detector uncertainties

1. Neutrino-matter cross section: *From TeV to PeV*

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



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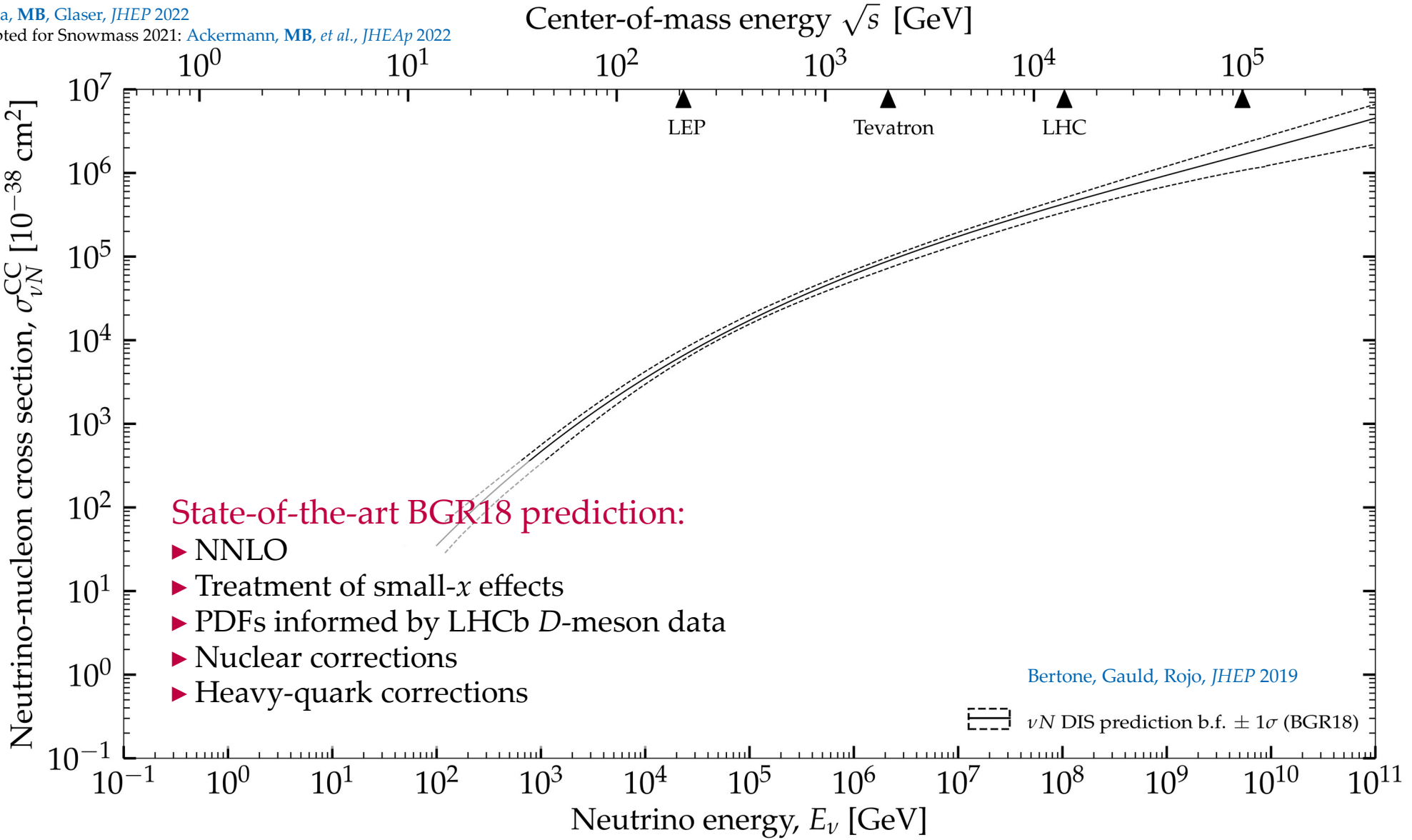

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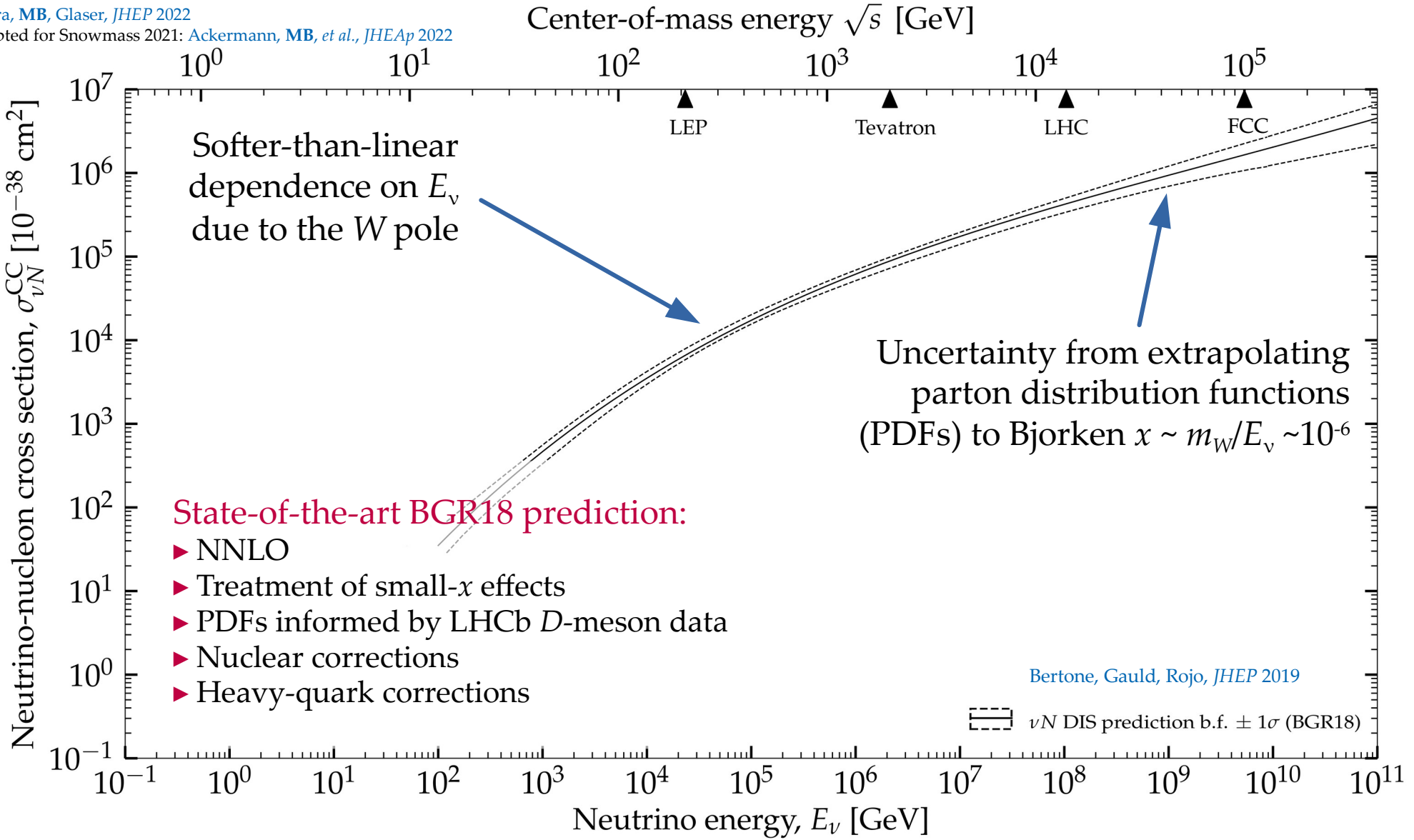

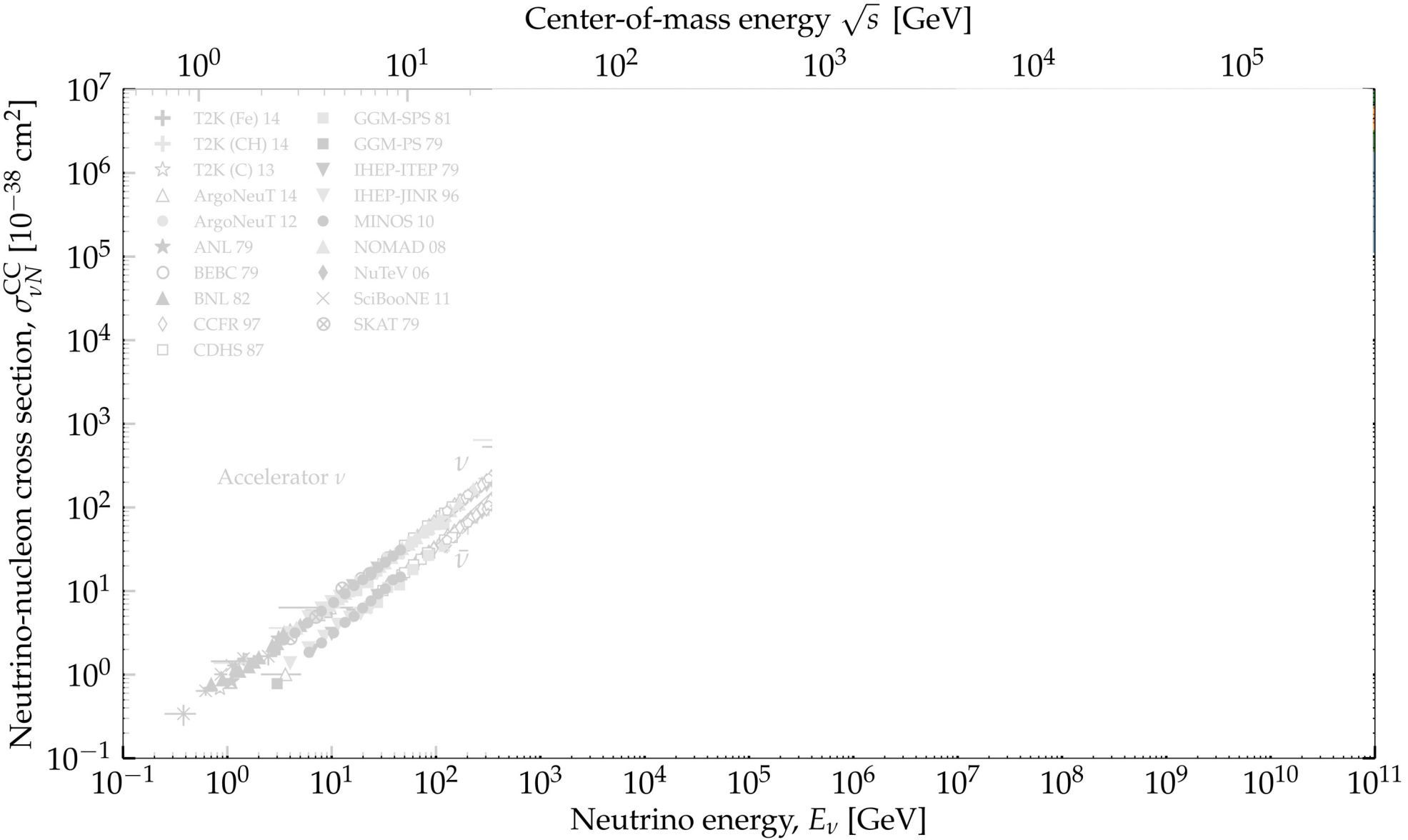
Center-of-mass energy $\sqrt{s}$ [GeV]
10^0
10^1
10^2
10^3
10^4
10^5
Neutrino-nucleon cross section, $\sigma_{\nu N}^{CC}$ [10^{-38} cm^2]
10^7
10^6
10^5
10^4
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10^0
10^{-1}
T2K (Fe) 14
T2K (CH) 14
T2K (C) 13
ArgoNeuT 14
ArgoNeuT 12
ANL 79
BEBC 79
BNL 82
CCFR 97
CDHS 87
GGM-SPS 81
GGM-PS 79
IHEP-ITEP 79
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MINOS 10
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NuTeV 06
SciBooNE 11
SKAT 79
Accelerator ν
ν
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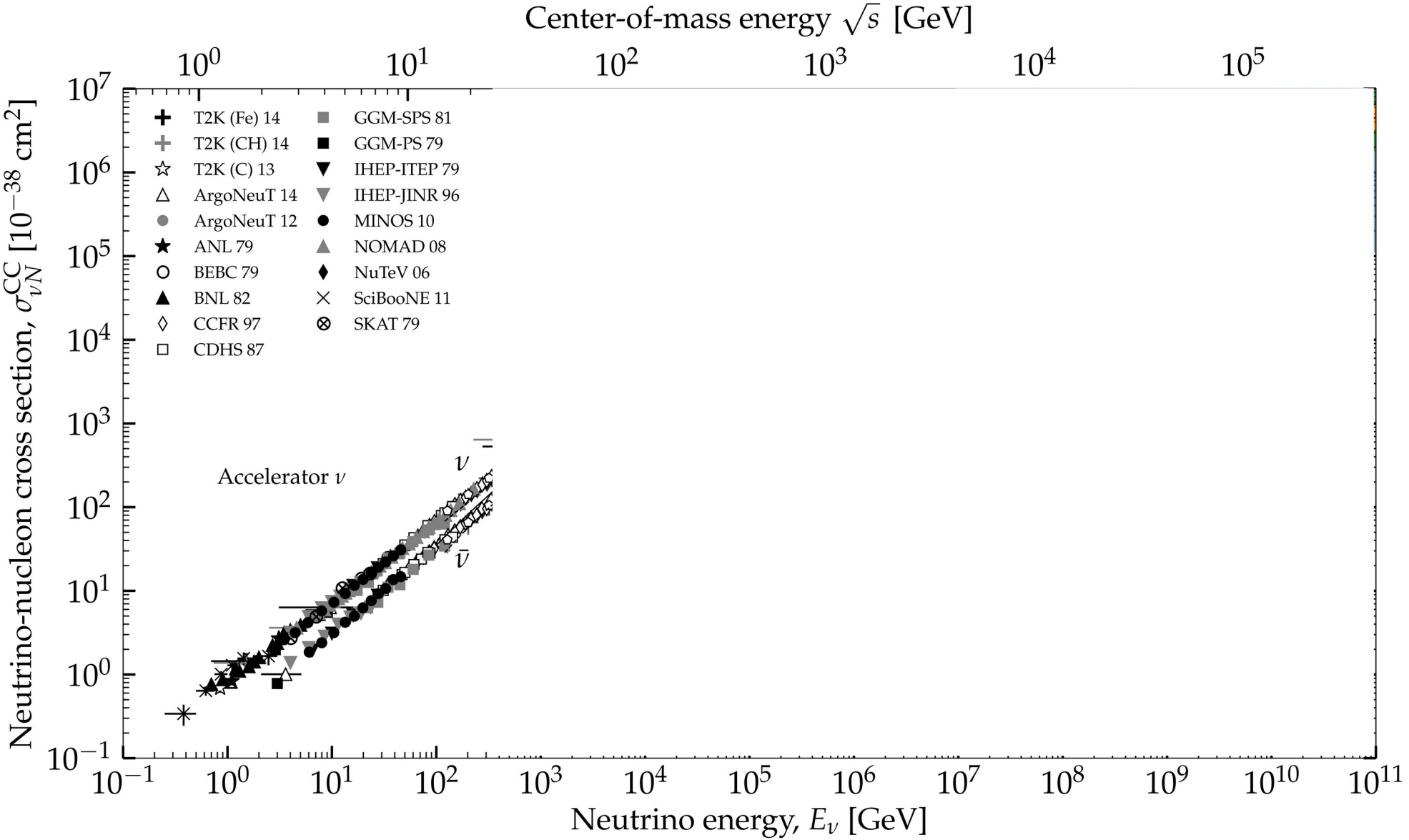
Neutrino energy, E_ν [GeV]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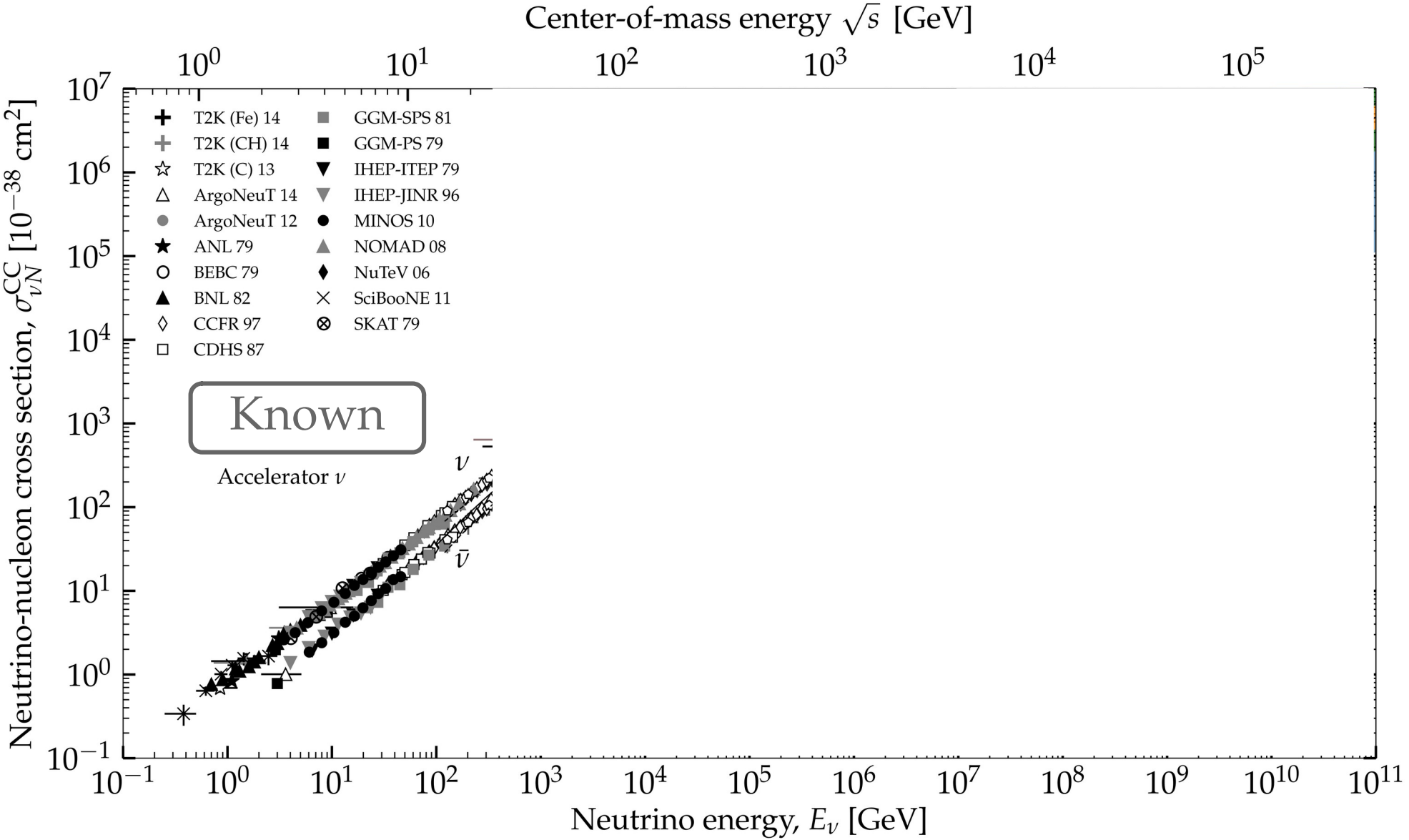
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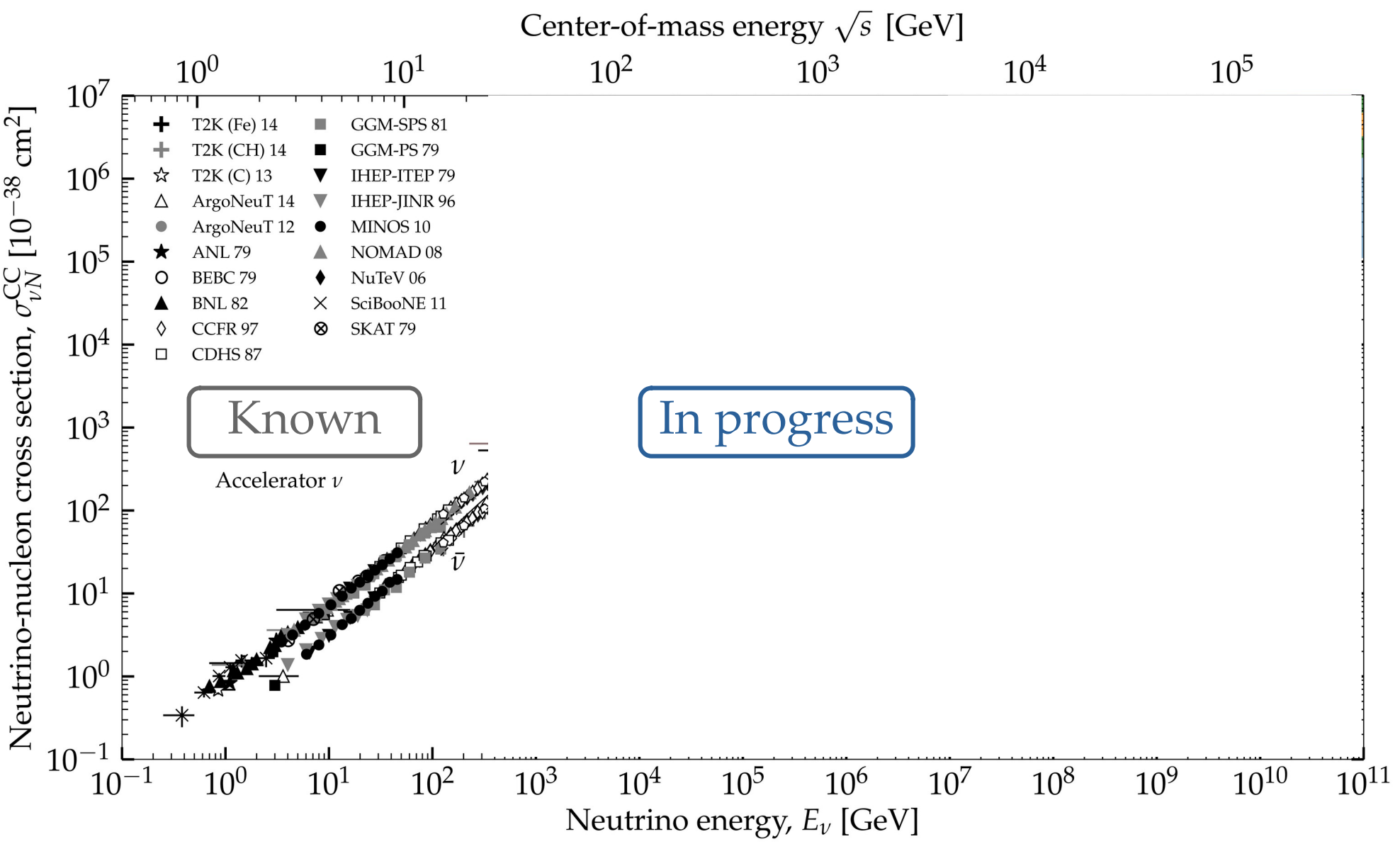
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In progress
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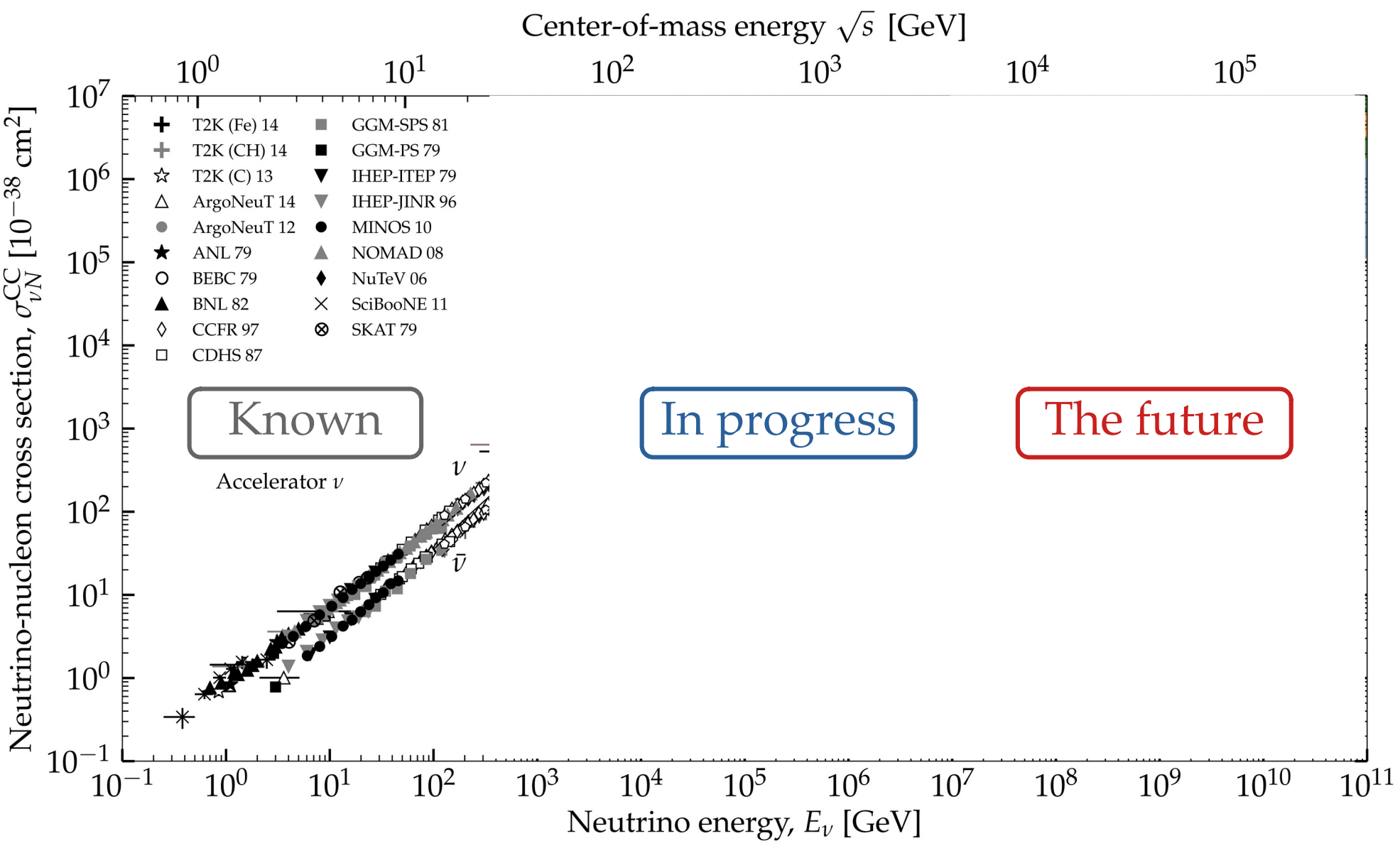
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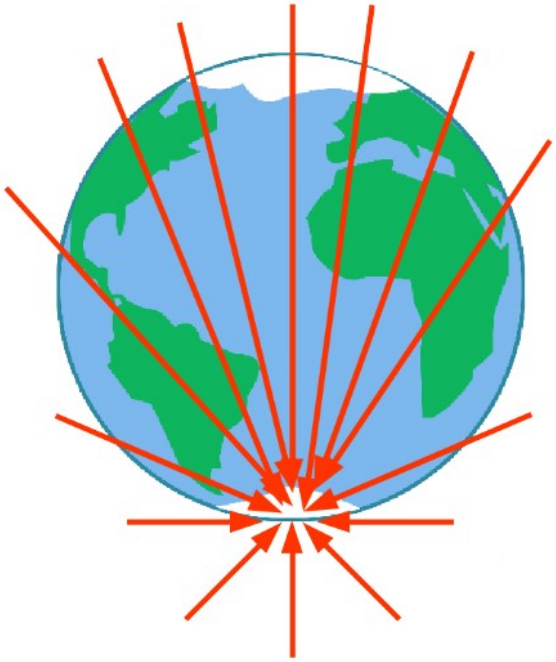
Measuring the high-energy νN cross section

Below ~ 10 TeV: Earth is transparent



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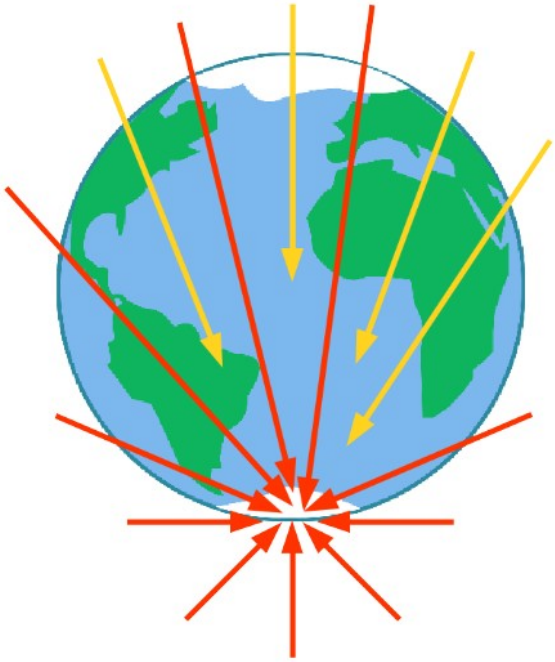
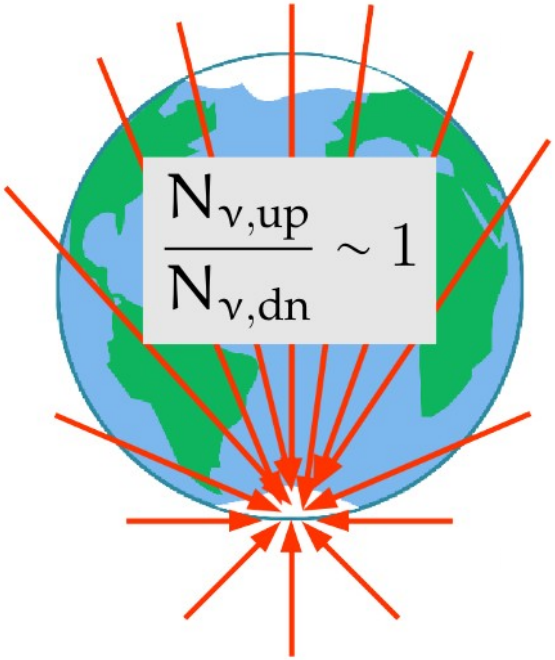


Hooper, *PRD* 2002; Hussain *et al.*, *PRL* 2006; Borriello *et al.*, *PRD* 2008
Hussain, Mafatia, McKay, *PRD* 2008; Connolly, Thorne, Waters, *PRD* 2011; Marfatia, McKay, Weiler, *PLB* 2015

Measuring the high-energy νN cross section

Below ~ 10 TeV: Earth is transparent



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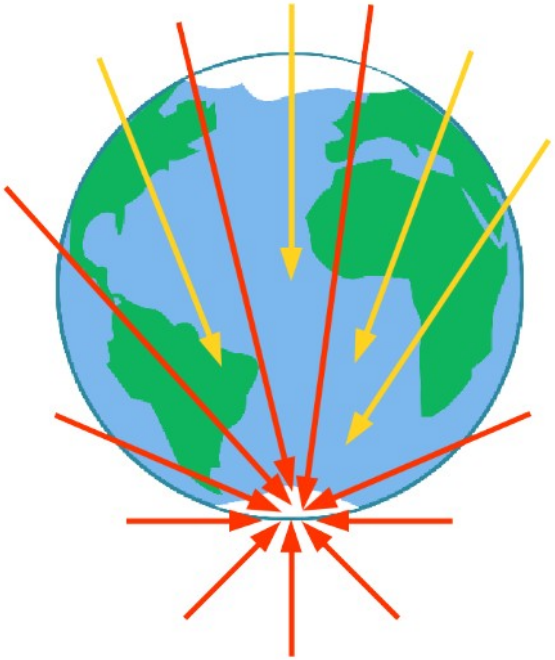

Hooper, *PRD* 2002; Hussain *et al.*, *PRL* 2006; Borriello *et al.*, *PRD* 2008
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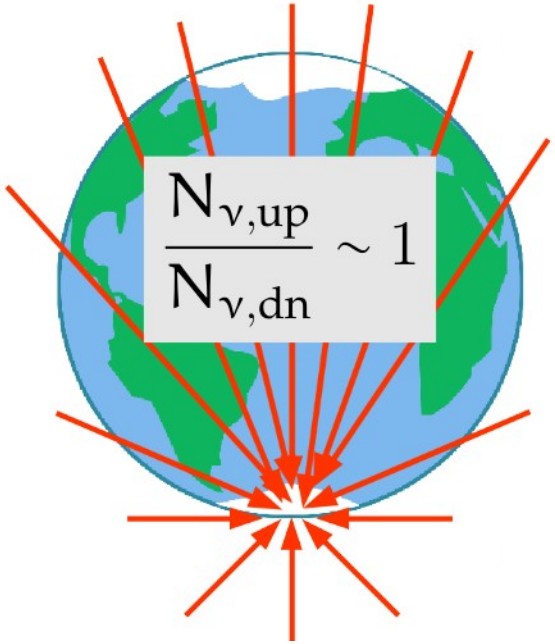

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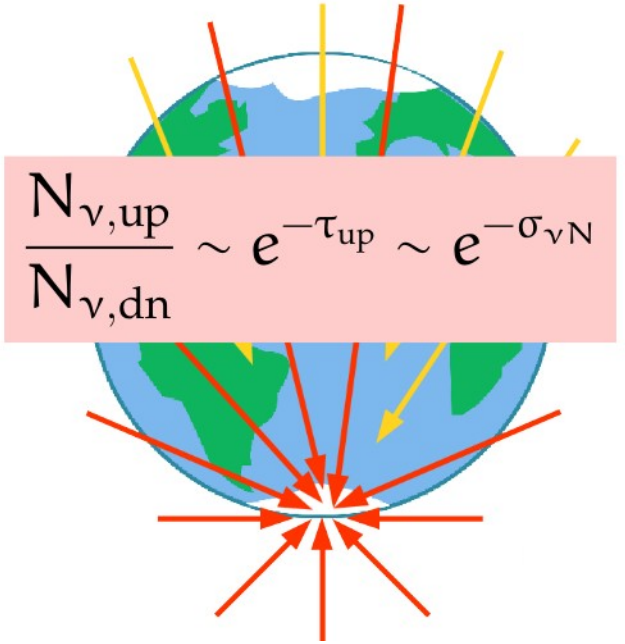

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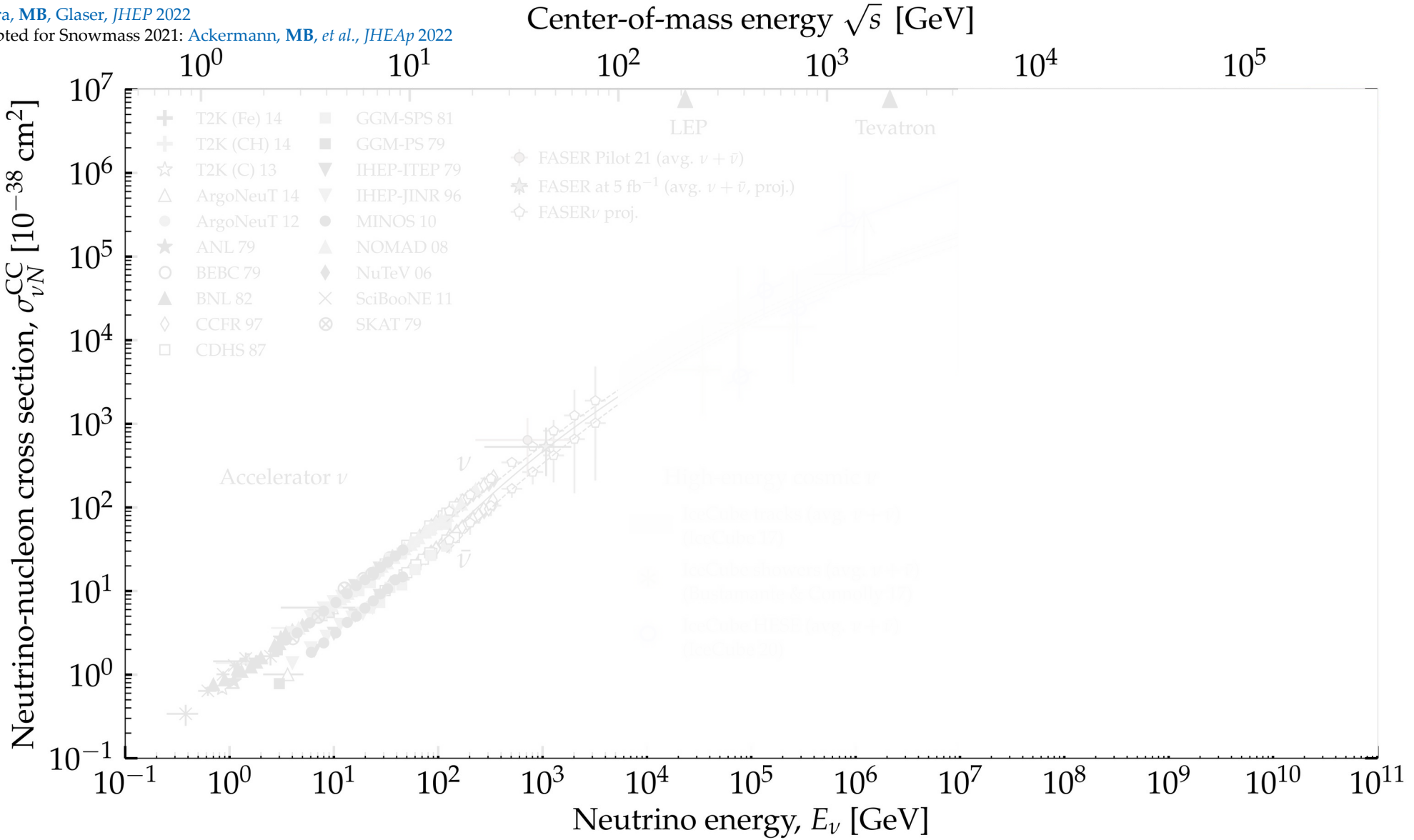
Valera, **MB**, Glaser, *JHEP* 2022
Adapted for Snowmass 2021: Ackermann, **MB**, *et al.*, *JHEAp* 2022



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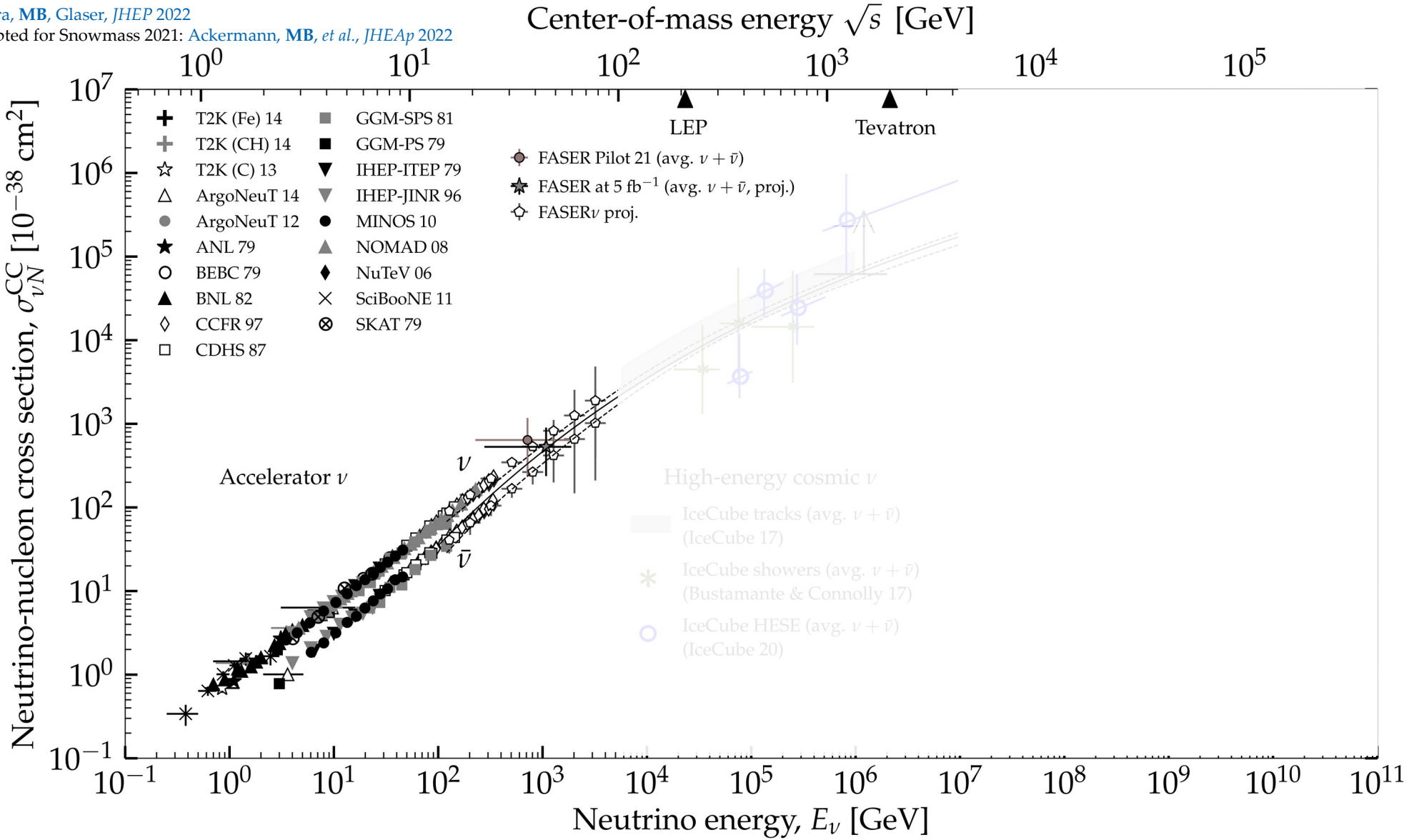

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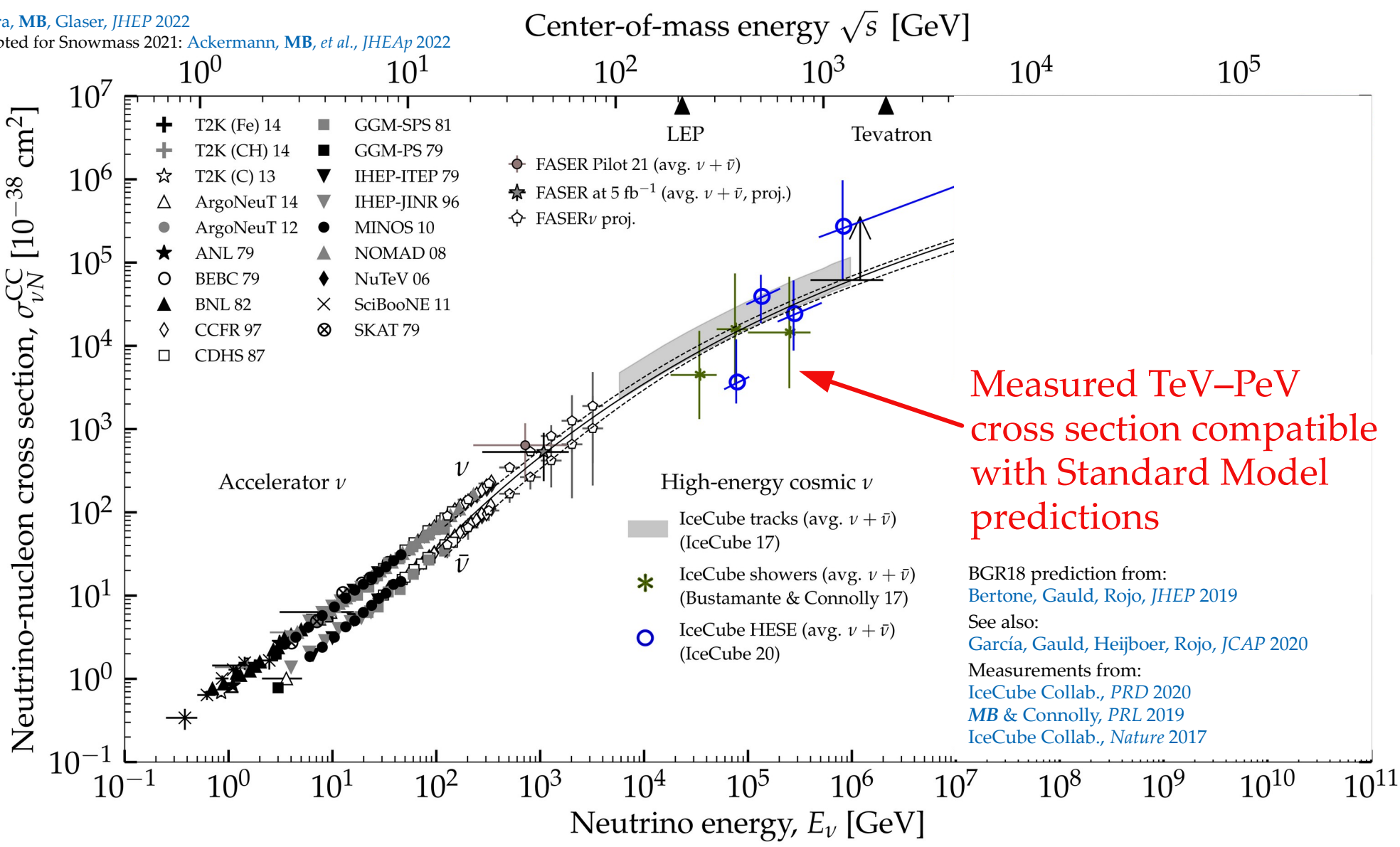

Measured TeV–PeV cross section compatible with Standard Model predictions

BGR18 prediction from:
Bertone, Gauld, Rojo, *JHEP* 2019
See also:
García, Gauld, Heijboer, Rojo, *JCAP* 2020
Measurements from:
IceCube Collab., *PRD* 2020
MB & Connolly, *PRL* 2019
IceCube Collab., *Nature* 2017

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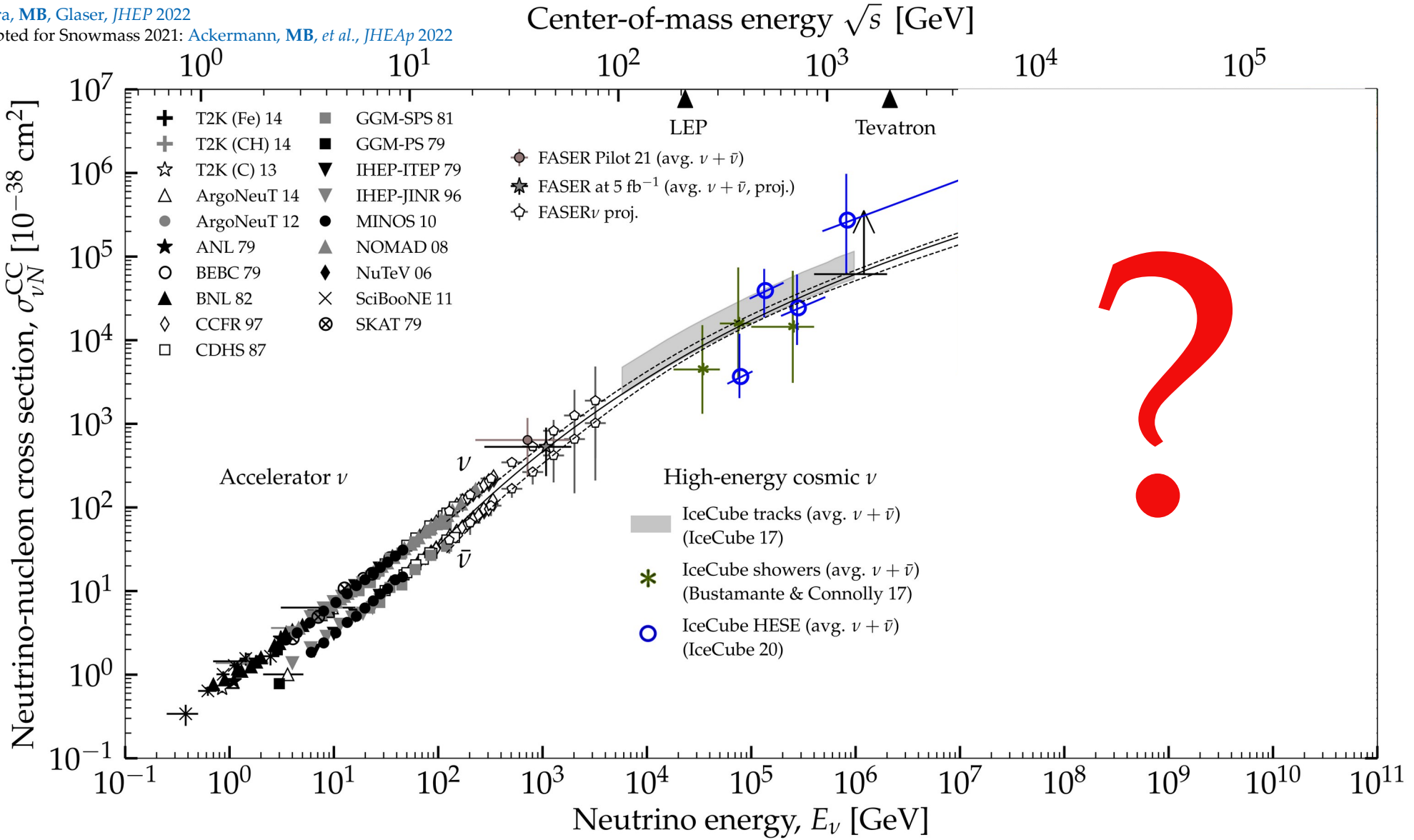

2. New neutrino interactions:
Are there secret νν interactions?

Astrophysical neutrino sources

Earth

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

Astrophysical neutrino sources

Earth

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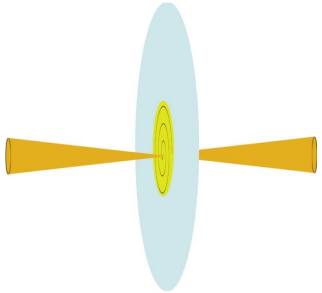

Standard case: ν free-stream

(And oscillate)

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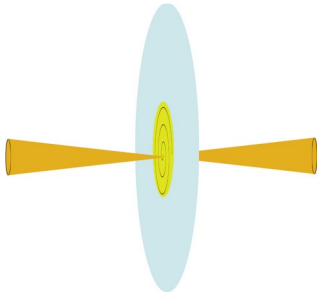

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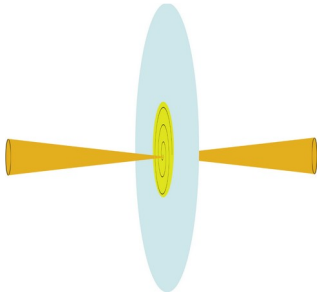

Non-standard case: high-energy ν scatter of CνB

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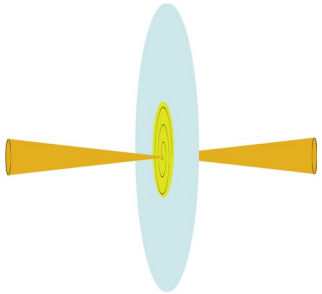

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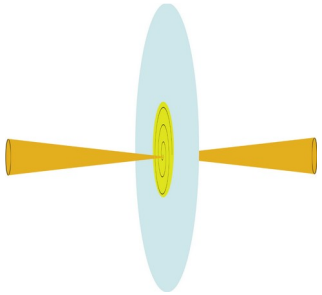

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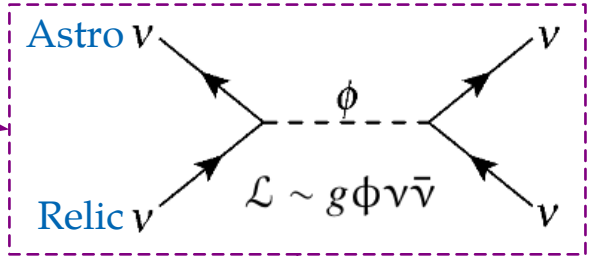
"Secret" ν interactions ≡ BSM ν self-interactions



Astrophysical neutrino sources

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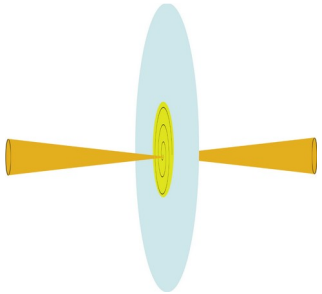

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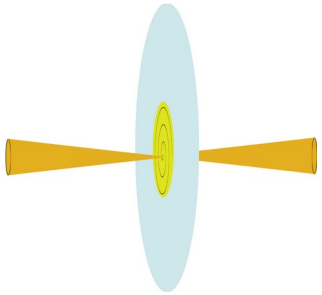

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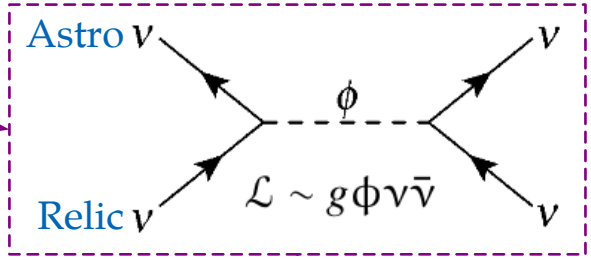

Can change:

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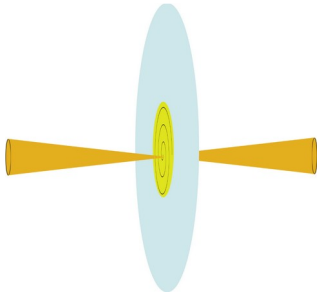

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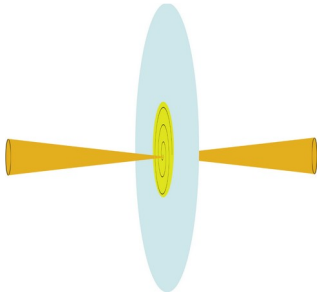

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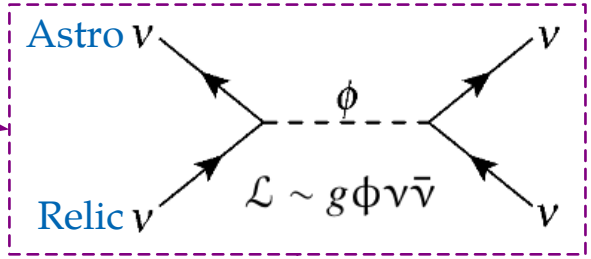

Can change:

- Energy spectrum

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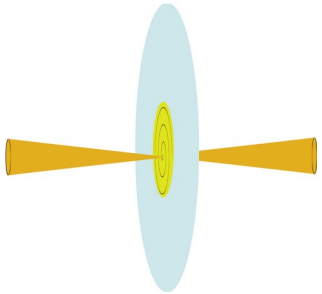

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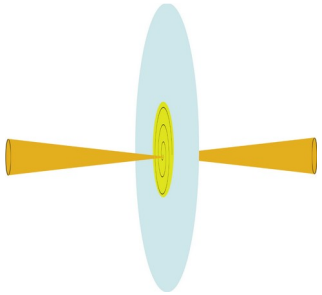

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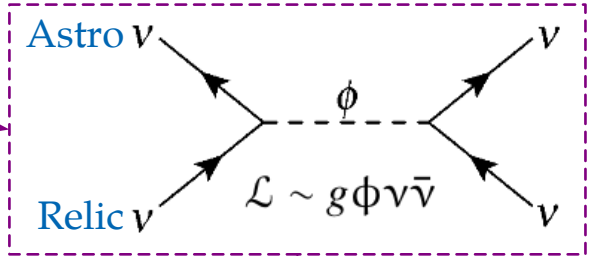

Can change:

- Energy spectrum
- Flavor composition

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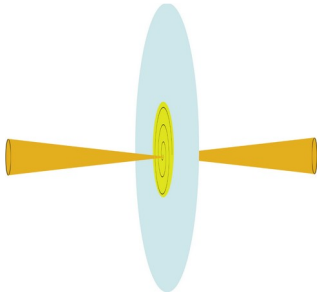

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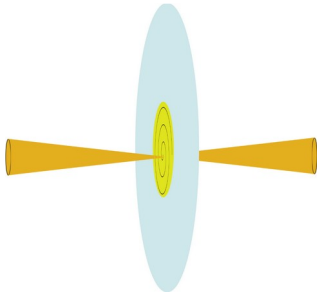

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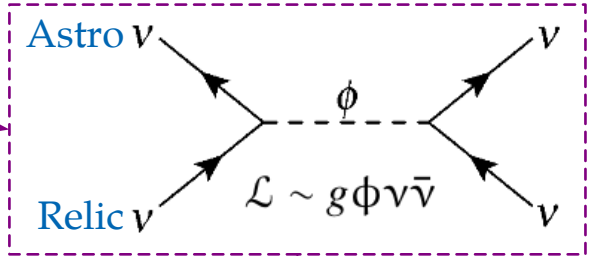

Can change:

- Energy spectrum
- Flavor composition
- Direction

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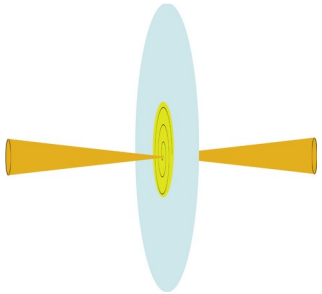

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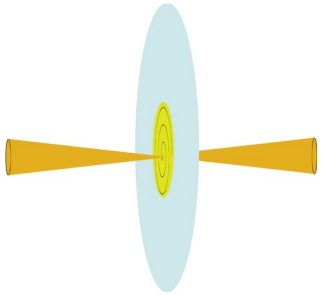

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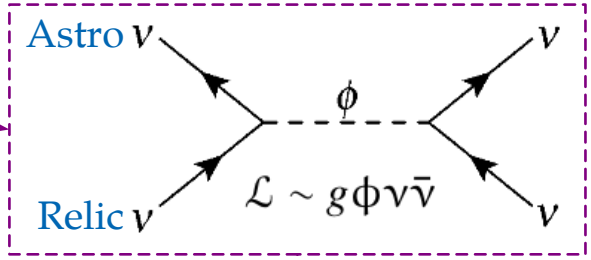
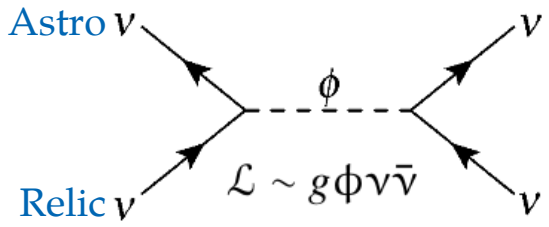


Can change:

- Energy spectrum
- 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
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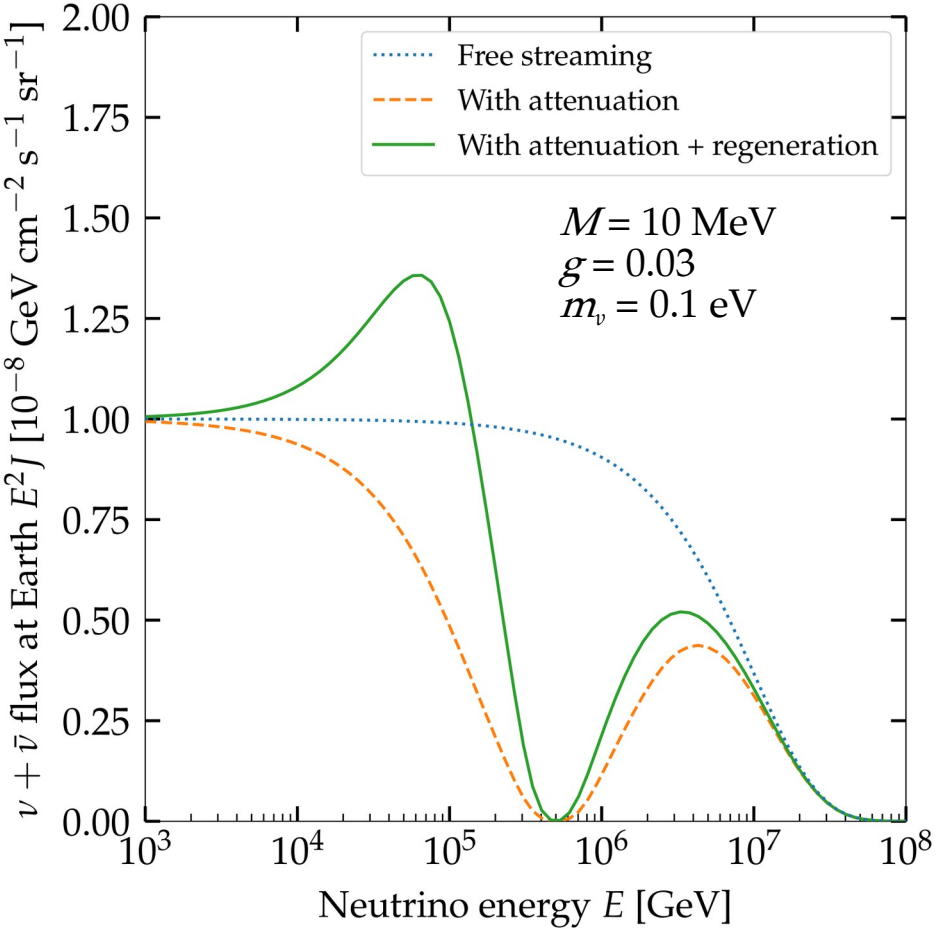

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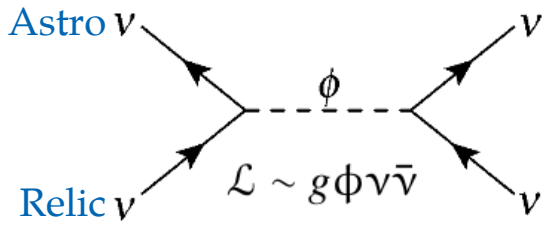

New coupling

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Mediator mass

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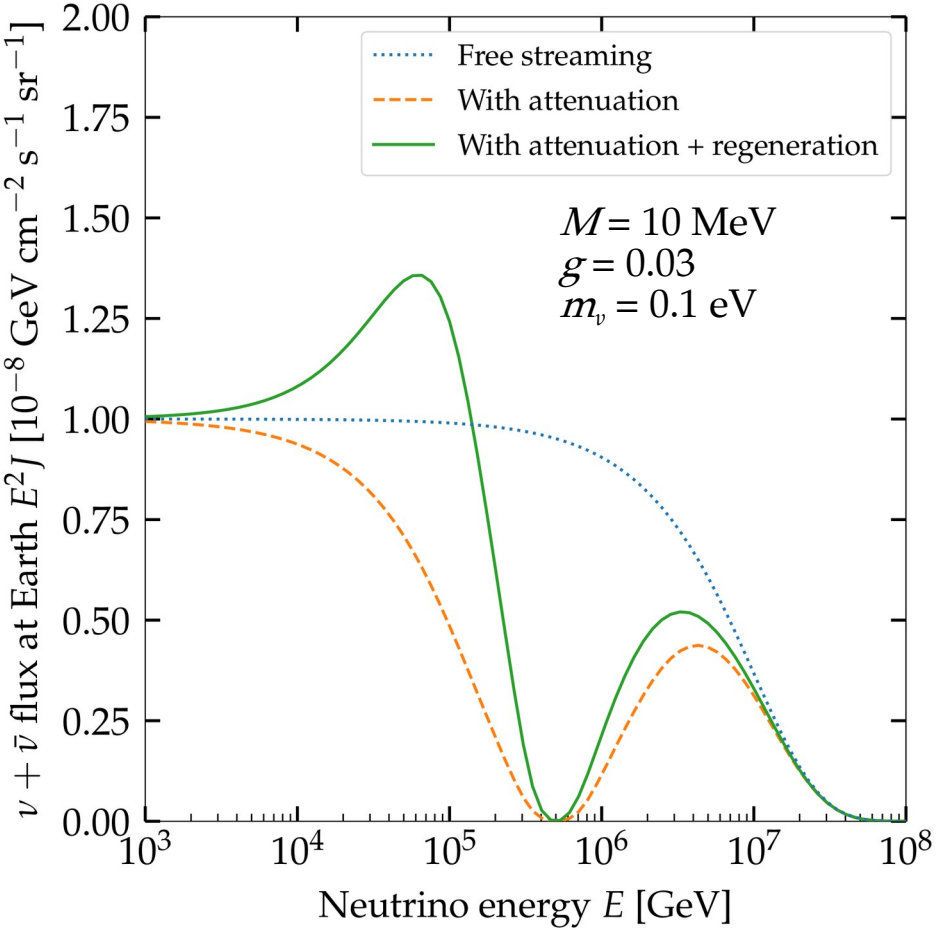

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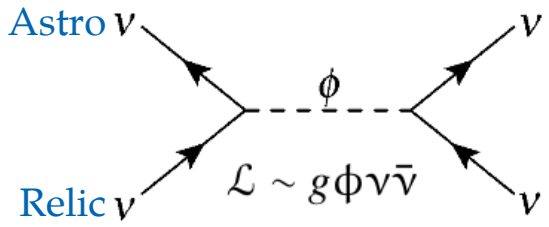

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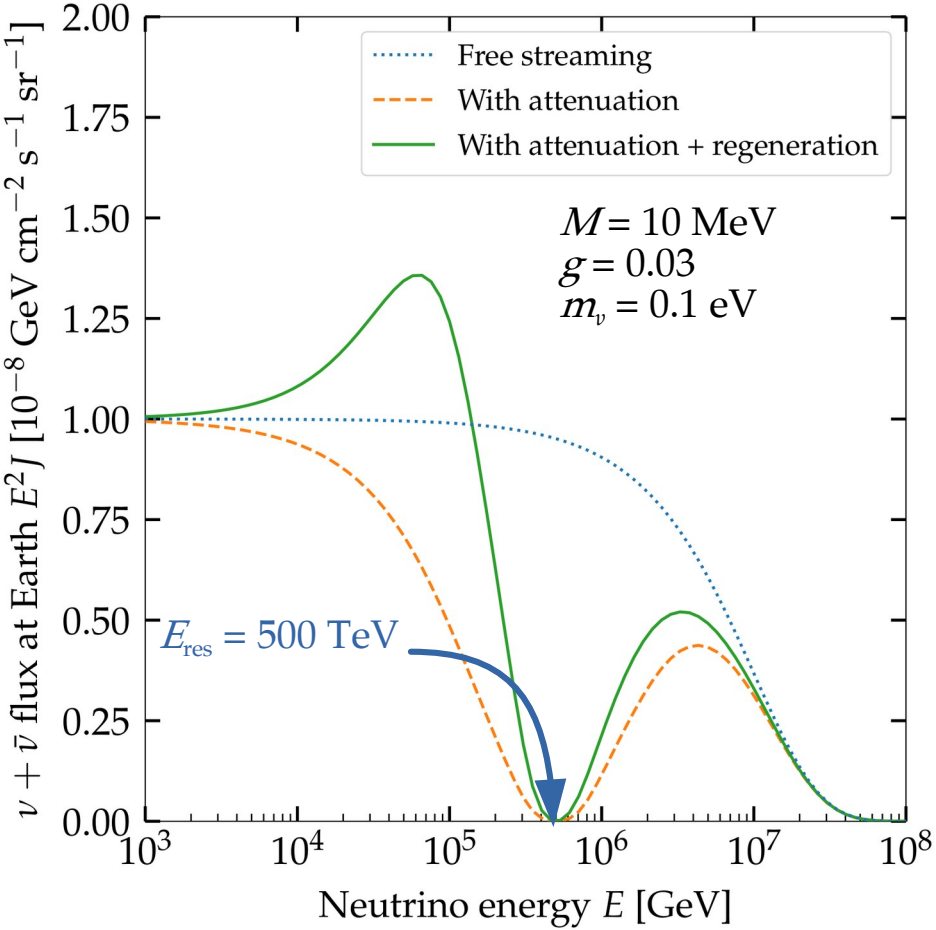

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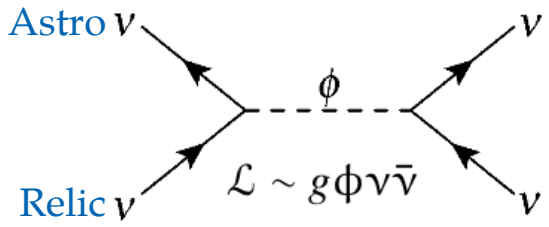

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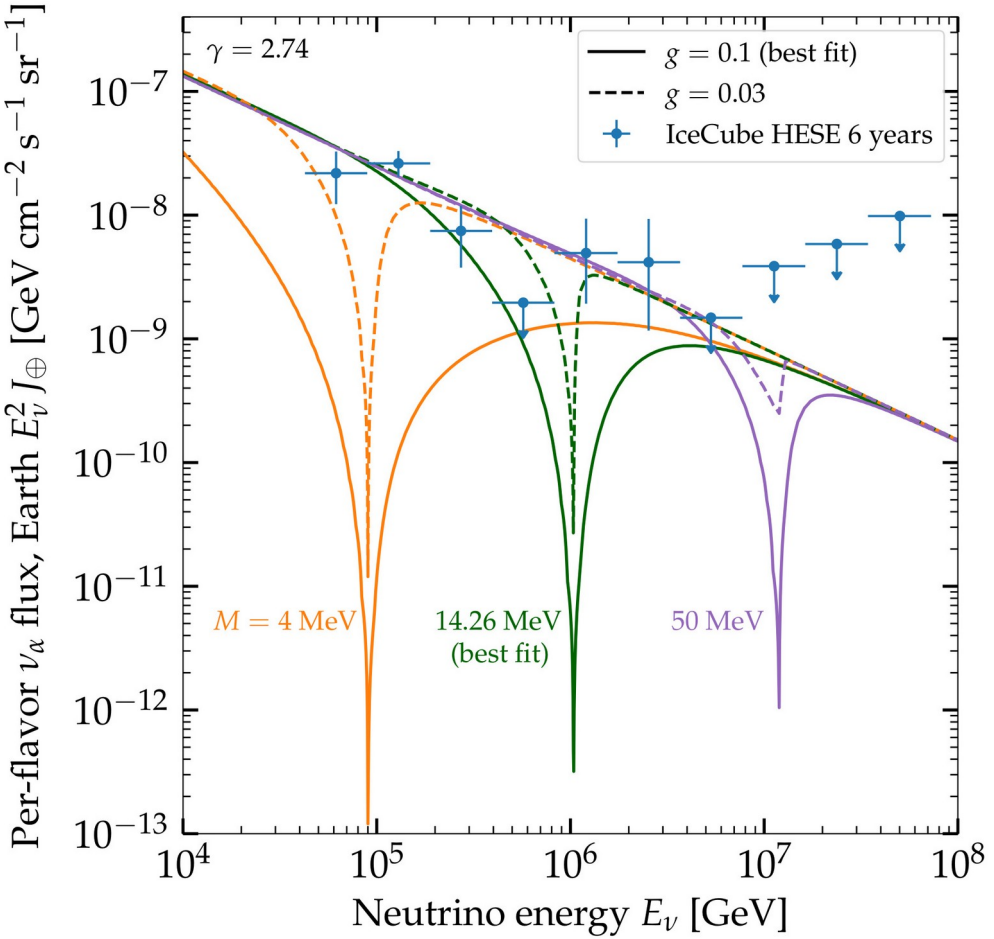

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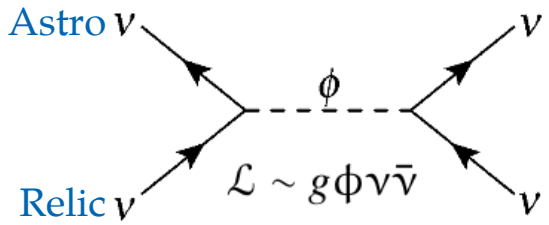

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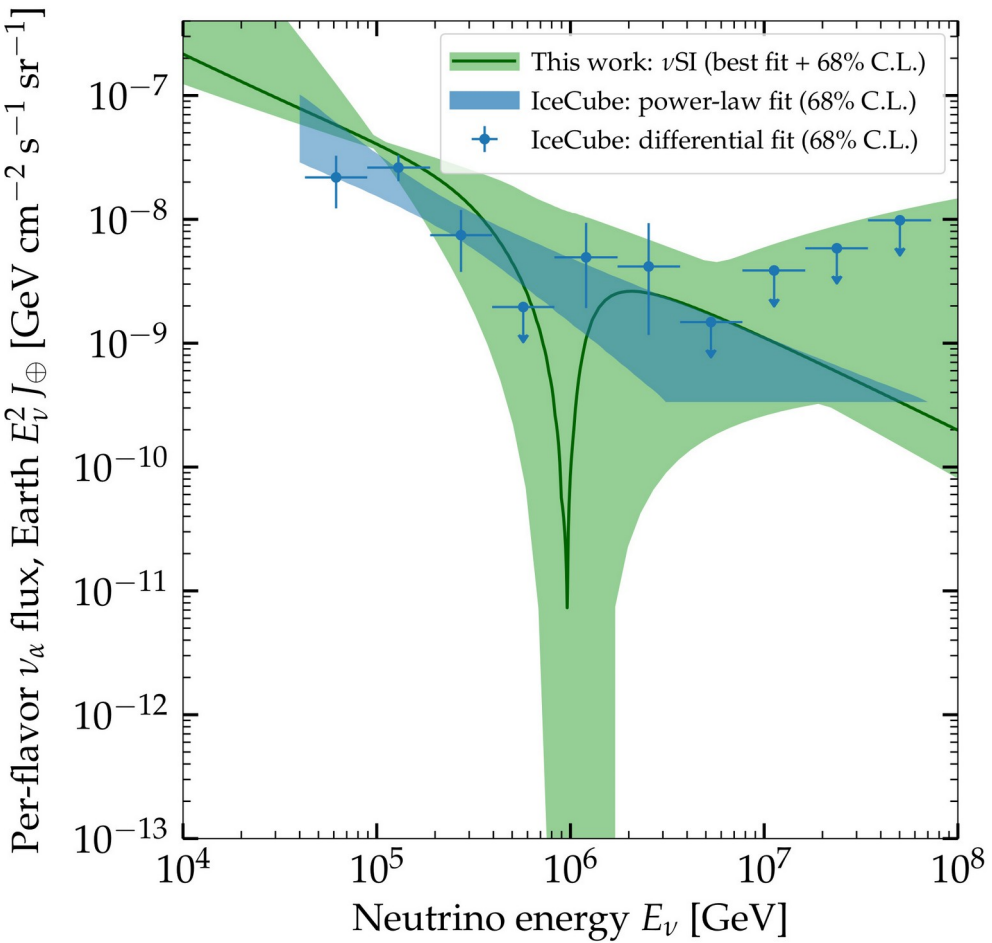
Looking for evidence of νSI

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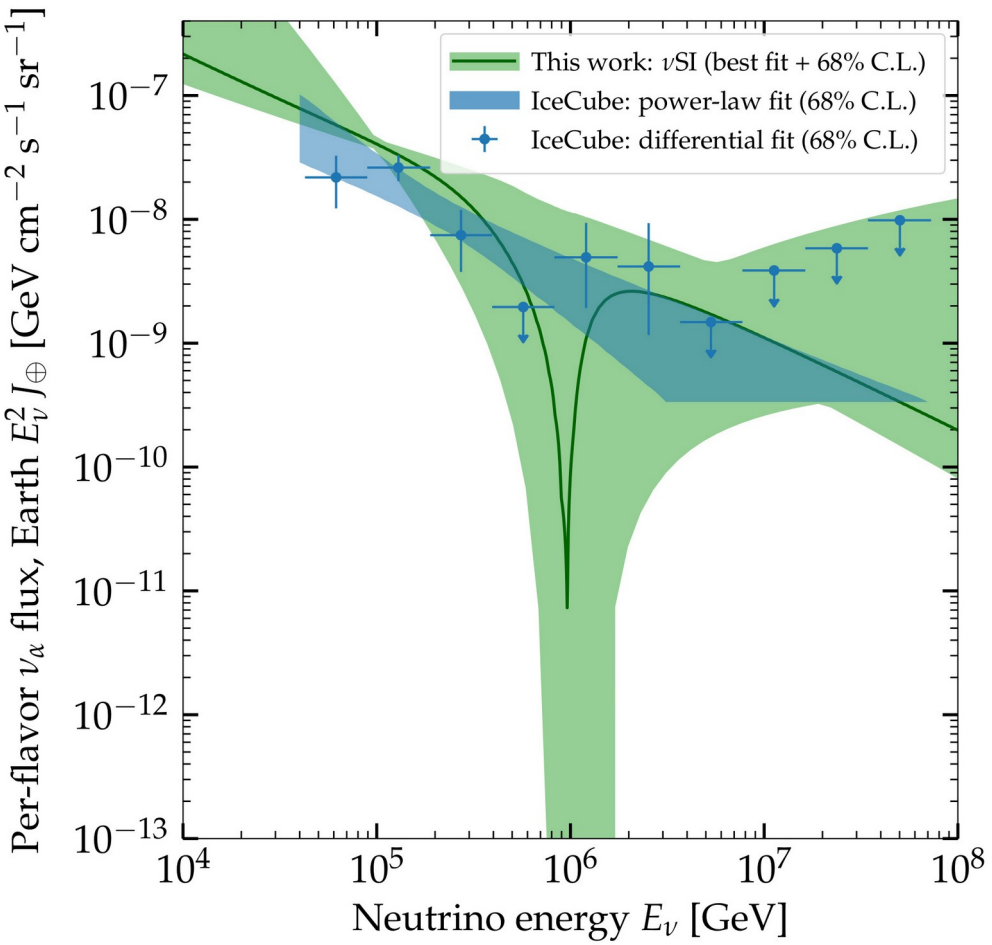
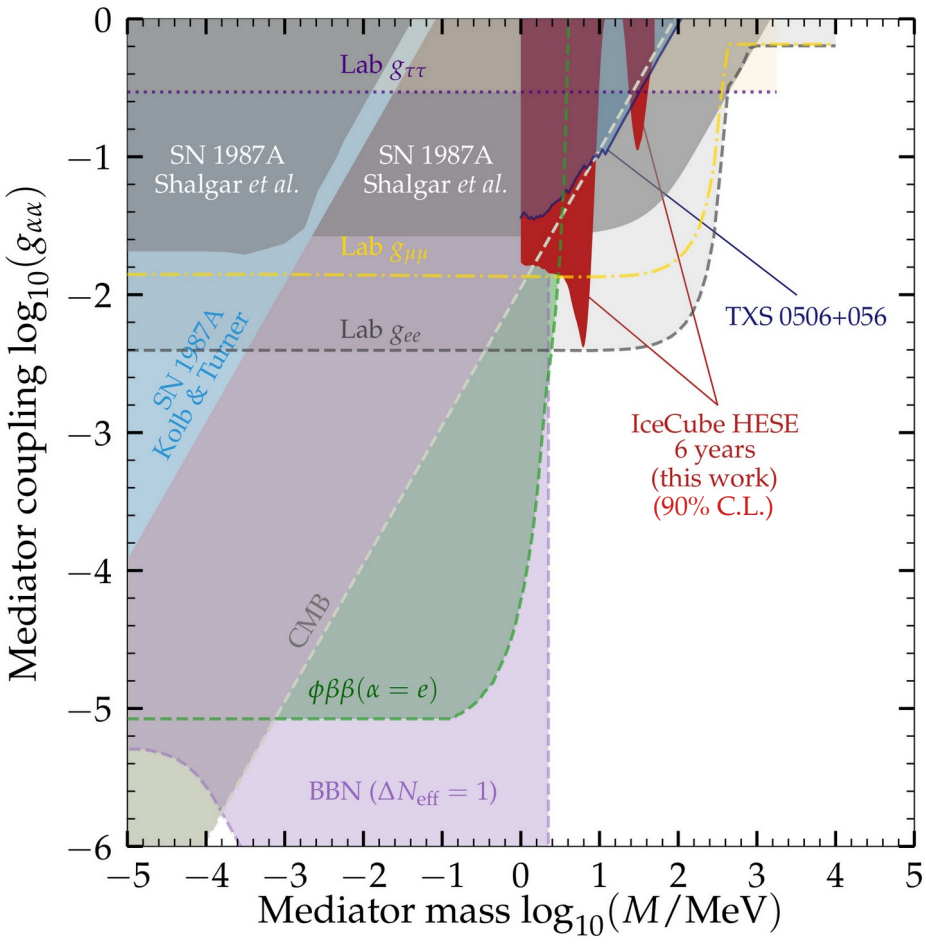
No significant (> 3σ) evidence for a spectral dip …

… so we set upper limits on the coupling g





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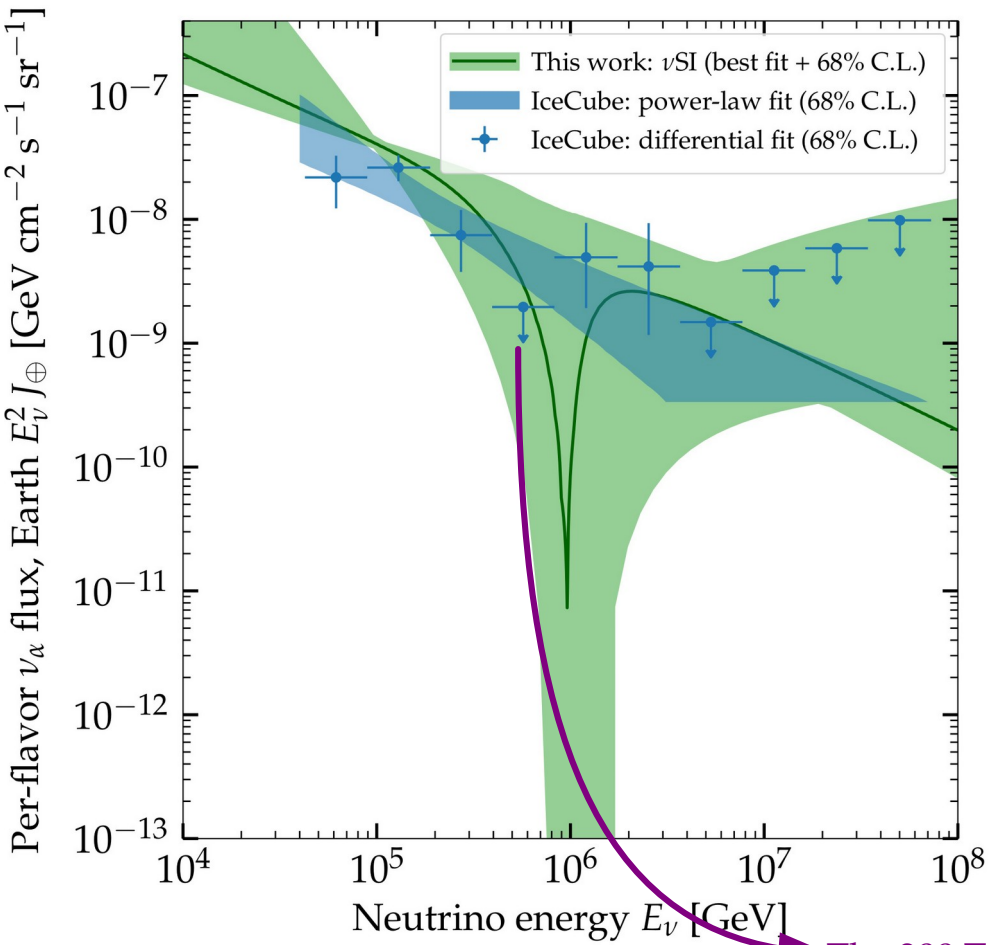
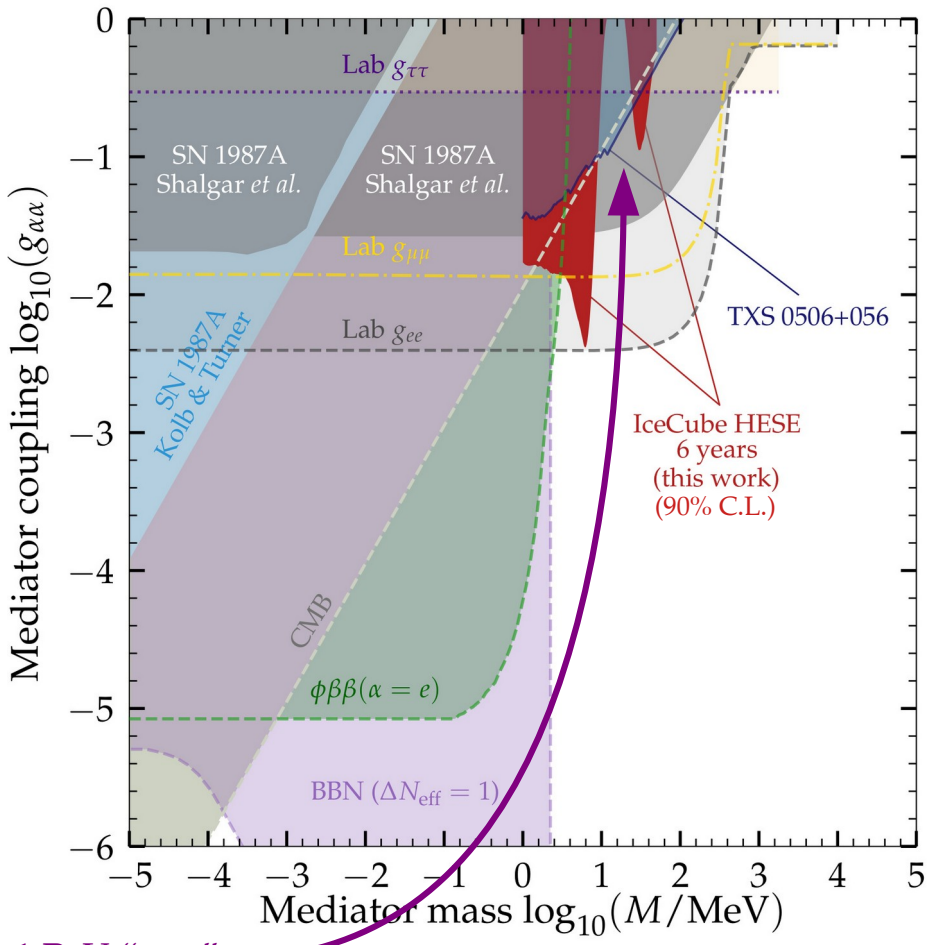
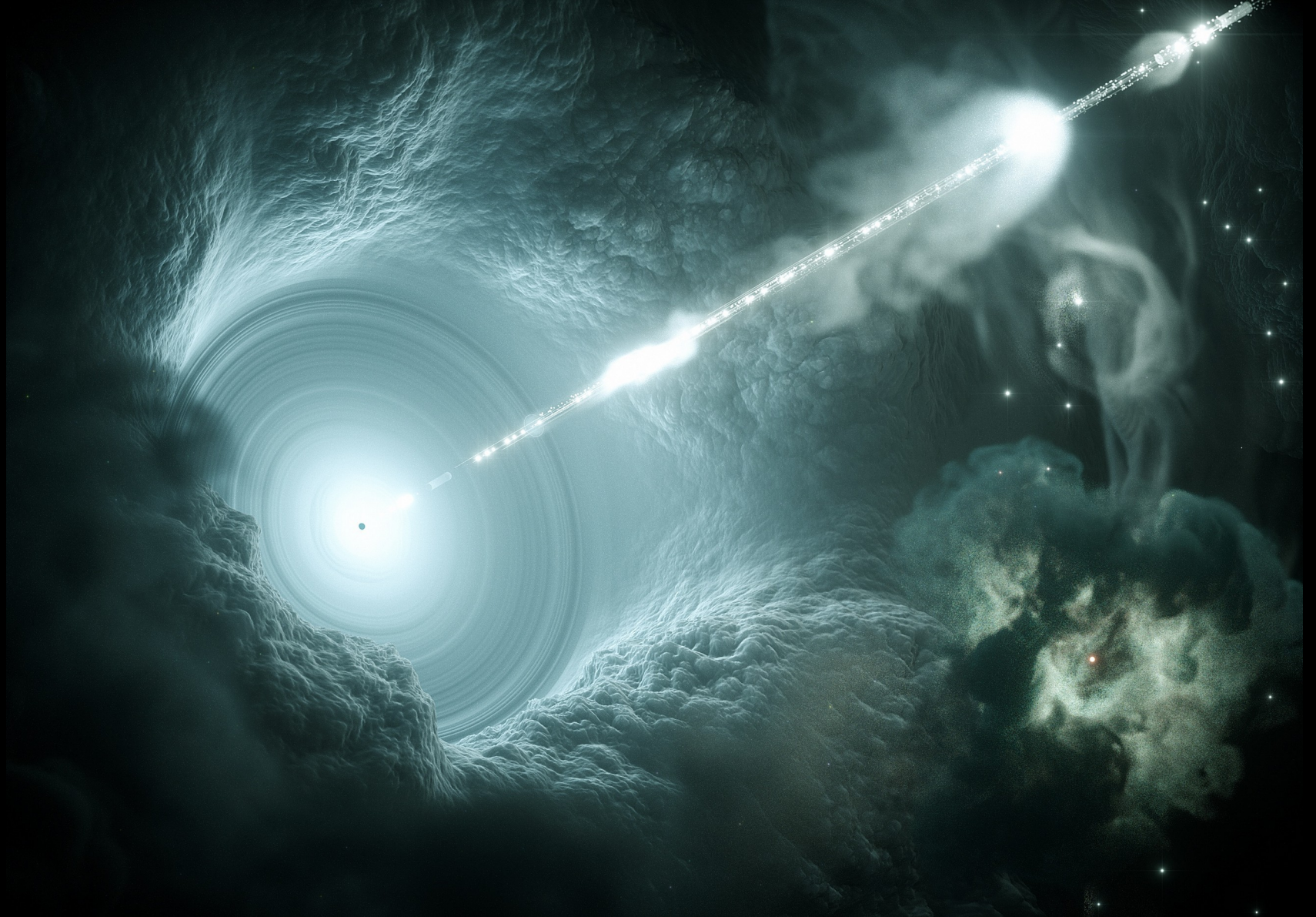




The 300 TeV–1 PeV "gap" degrades the limit at ~10 MeV

MB, Rosenstroem, Shalgar, Tamborra, *PRD* 2020
See also: Shalgar, **MB**, Tamborra, *PRD* 2020
Esteban, Pandey, Brdar, Beacom, *PRD* 2021

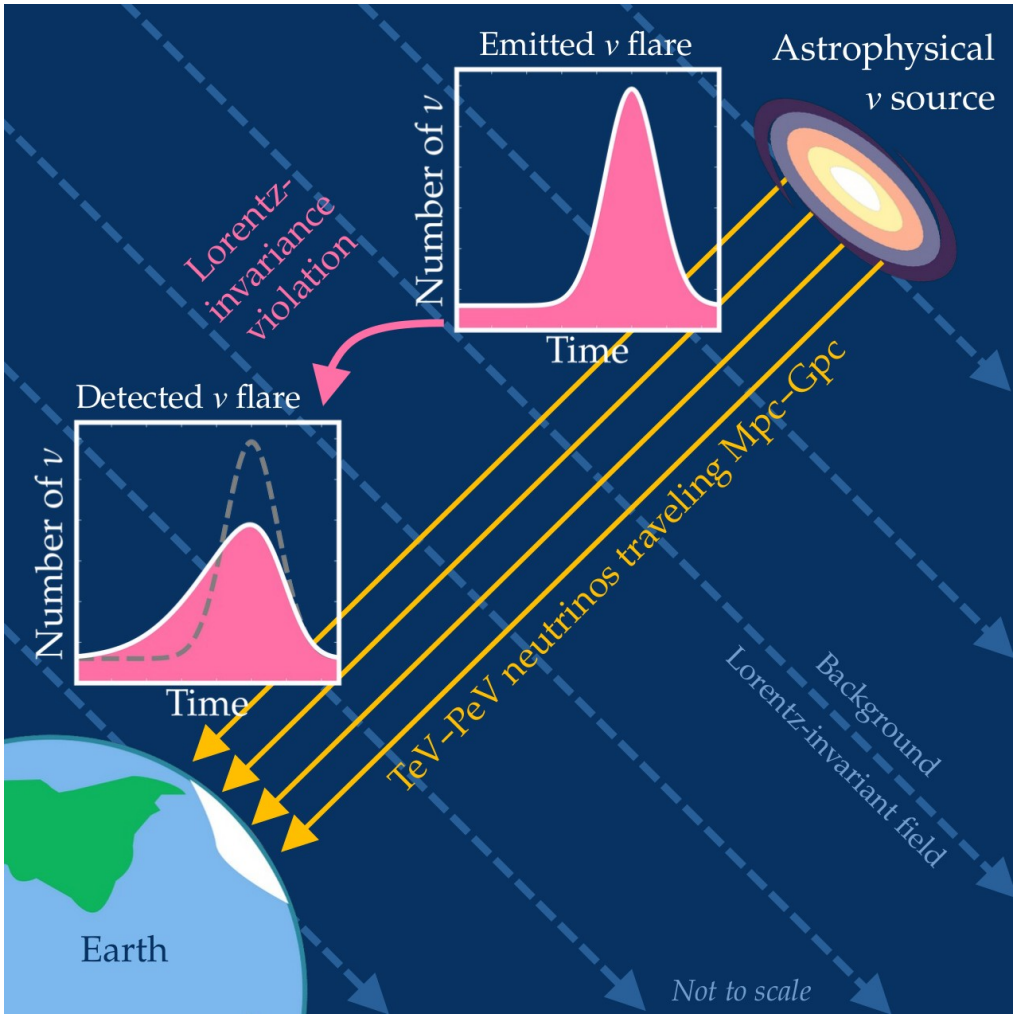
3. New physics from a neutrino flare:
From the time-distribution



DESY

DESY

New physics from high-energy neutrino flares



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

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

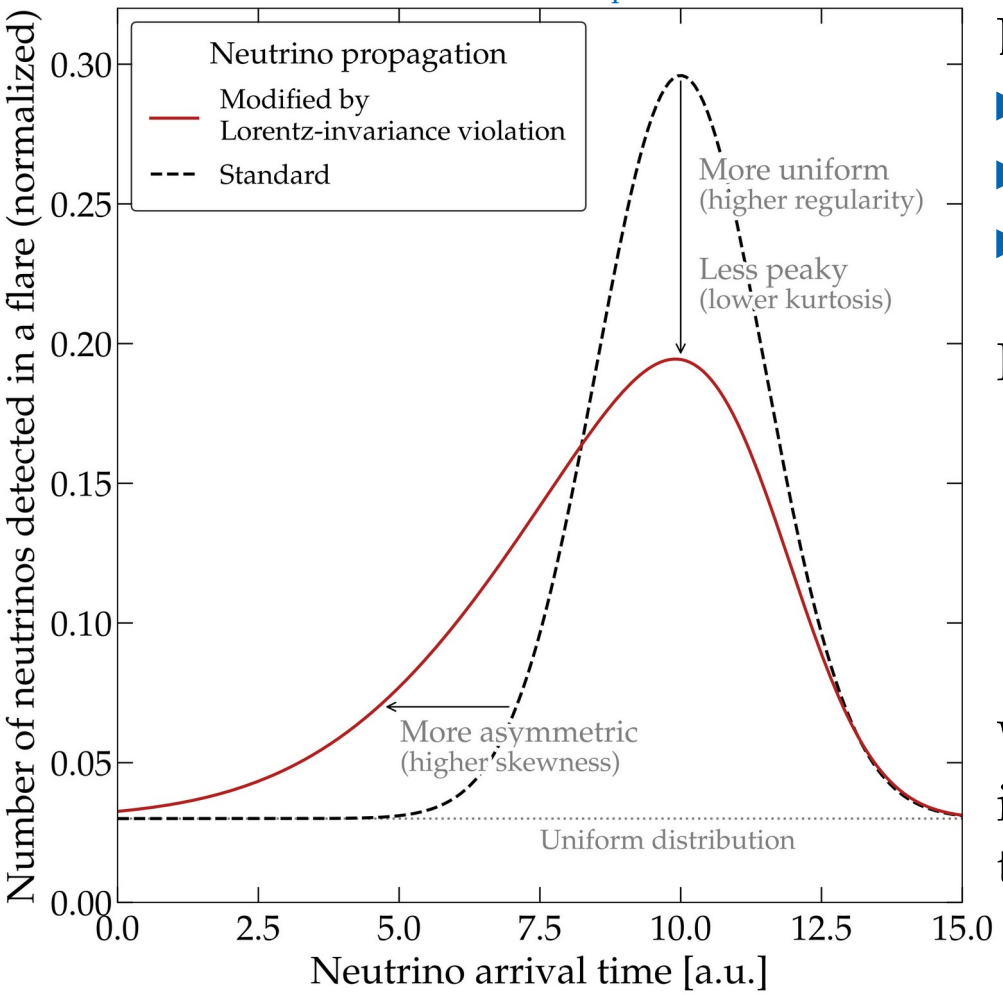
M_n: LIV energy scale (unknown)

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:

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

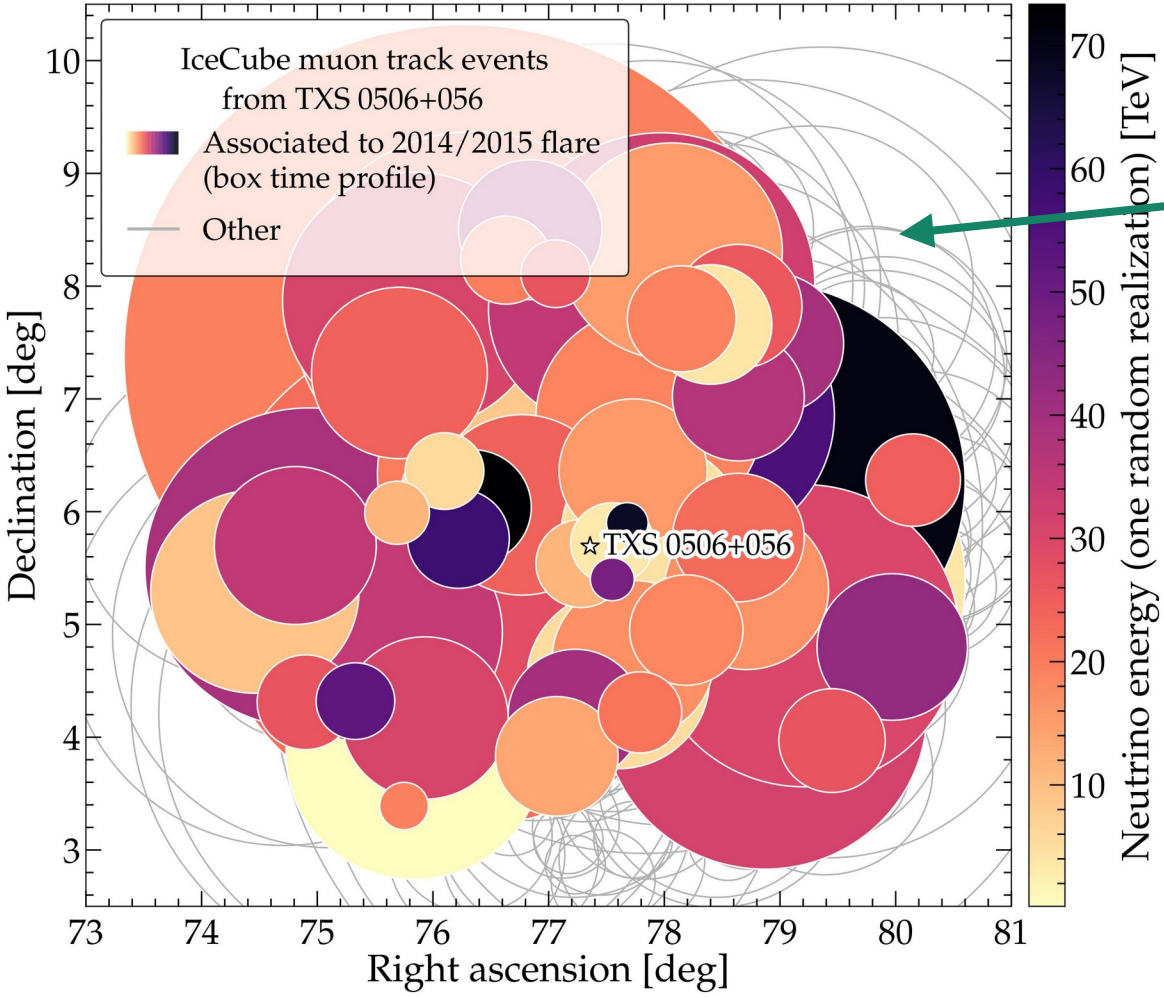
Detection time of a at Earth

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

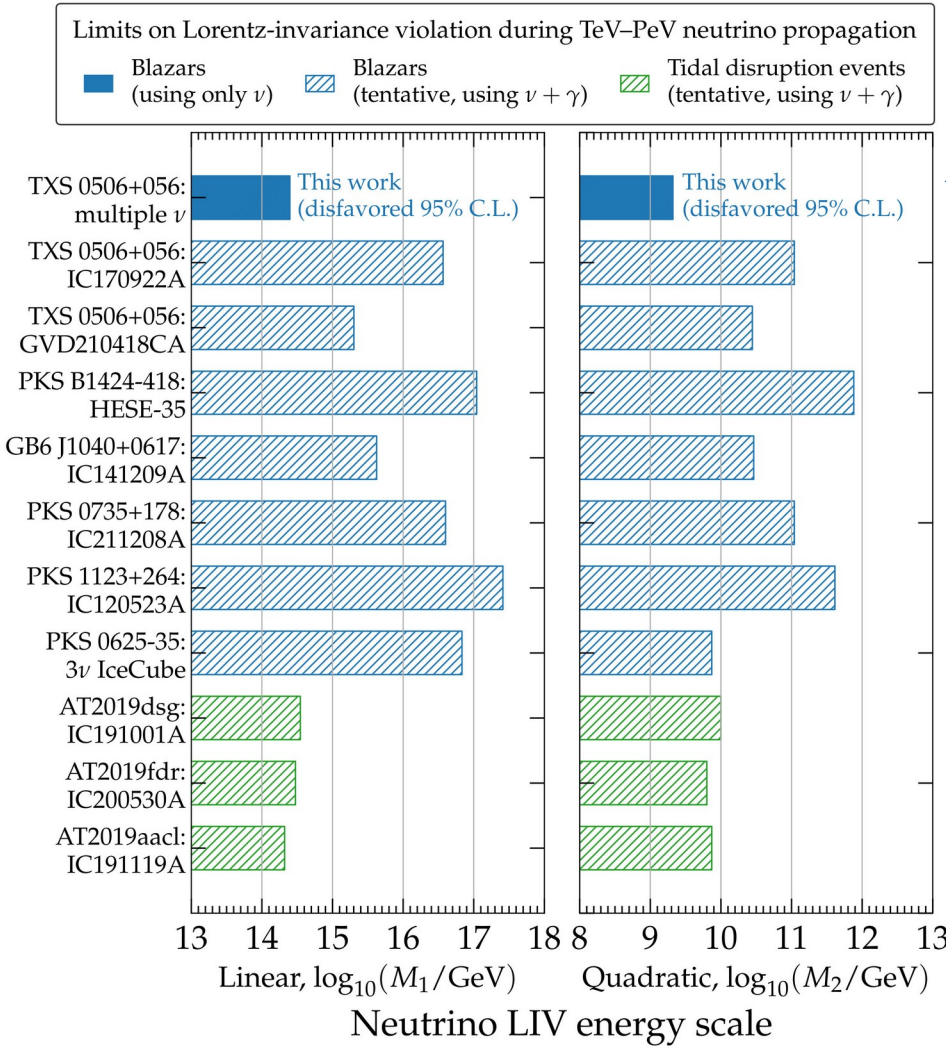


Use IceCube through-going muons associated to the 2015/2015 flare of TXS 0506+056

- 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

New physics from high-energy neutrino flares



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

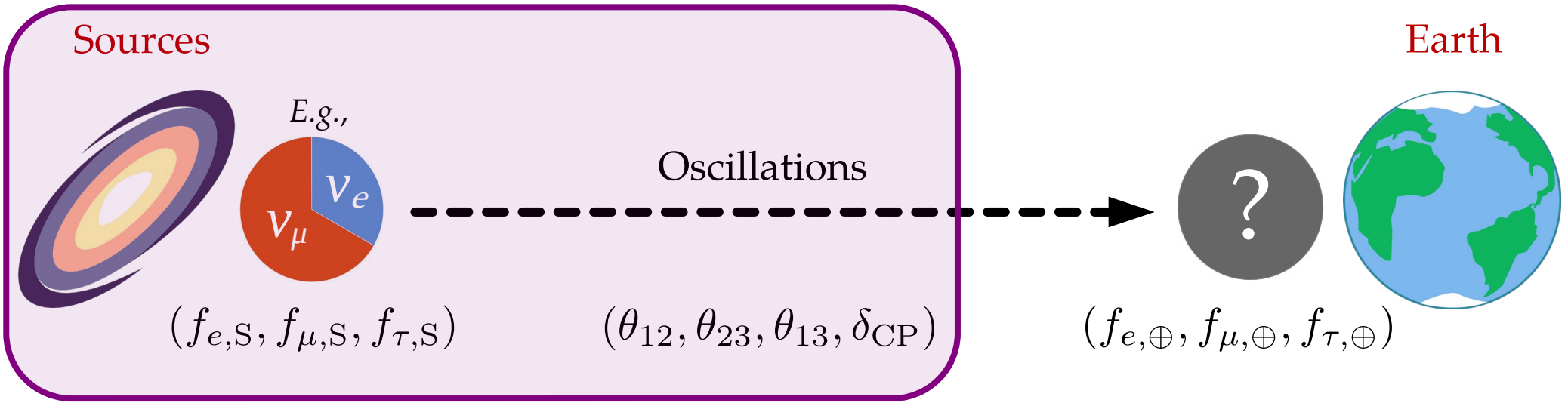
Limits from the coincident emission of neutrinos and electromagnetic emission (generally low or unspecified credibility)

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

4. New physics via flavor

Hard to do, but worth it

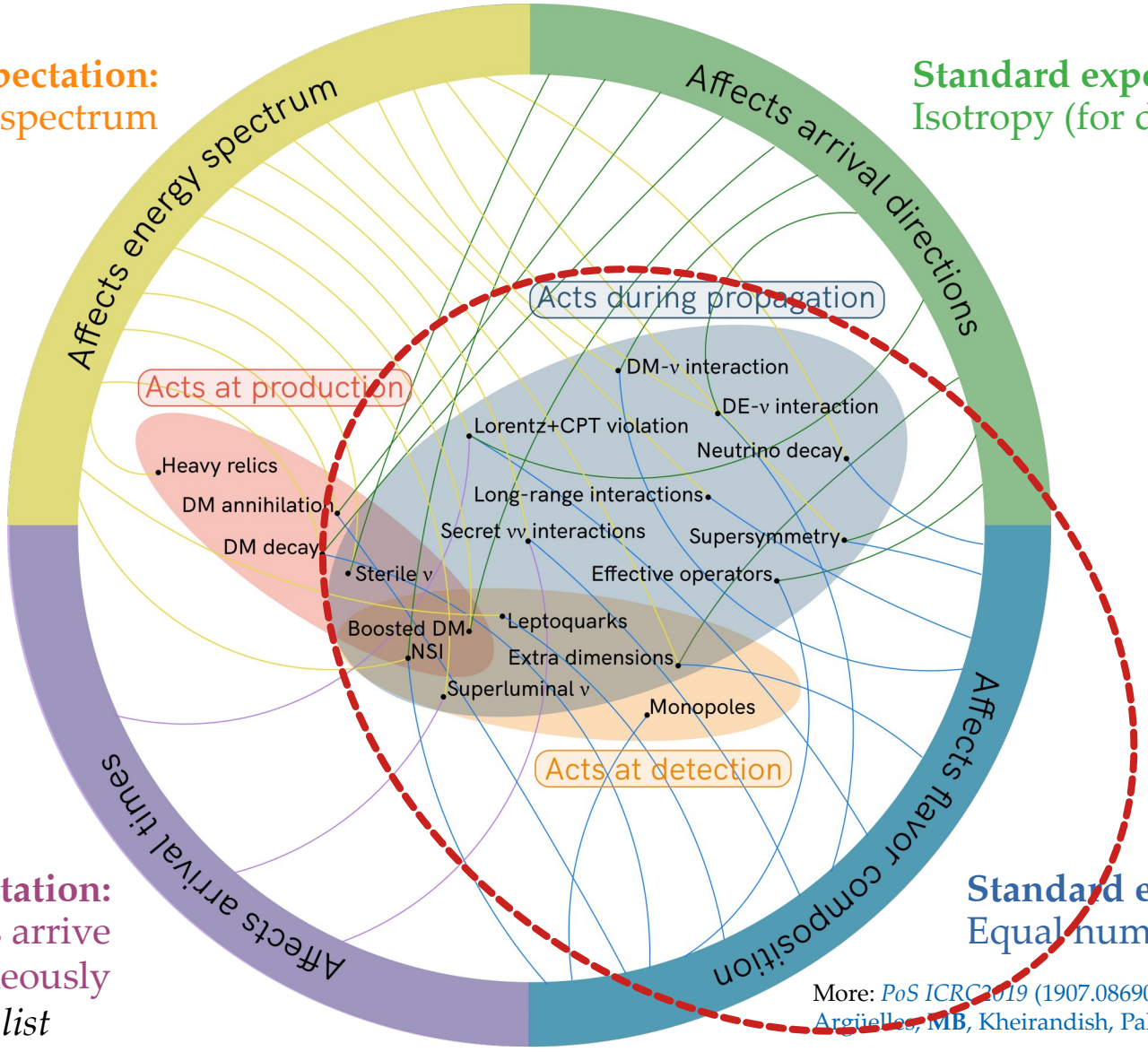
From sources to Earth: we learn what to expect when measuring $f_{\alpha,\oplus}$



Known from oscillation experiments, to different levels of precision

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



Standard expectation:
ν and γ from transients arrive simultaneously

Note: Not an exhaustive list

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

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

New physics in flavor composition

Use the flavor sensitivity to test new physics:

New physics in flavor composition

Use the flavor sensitivity to test new physics:

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

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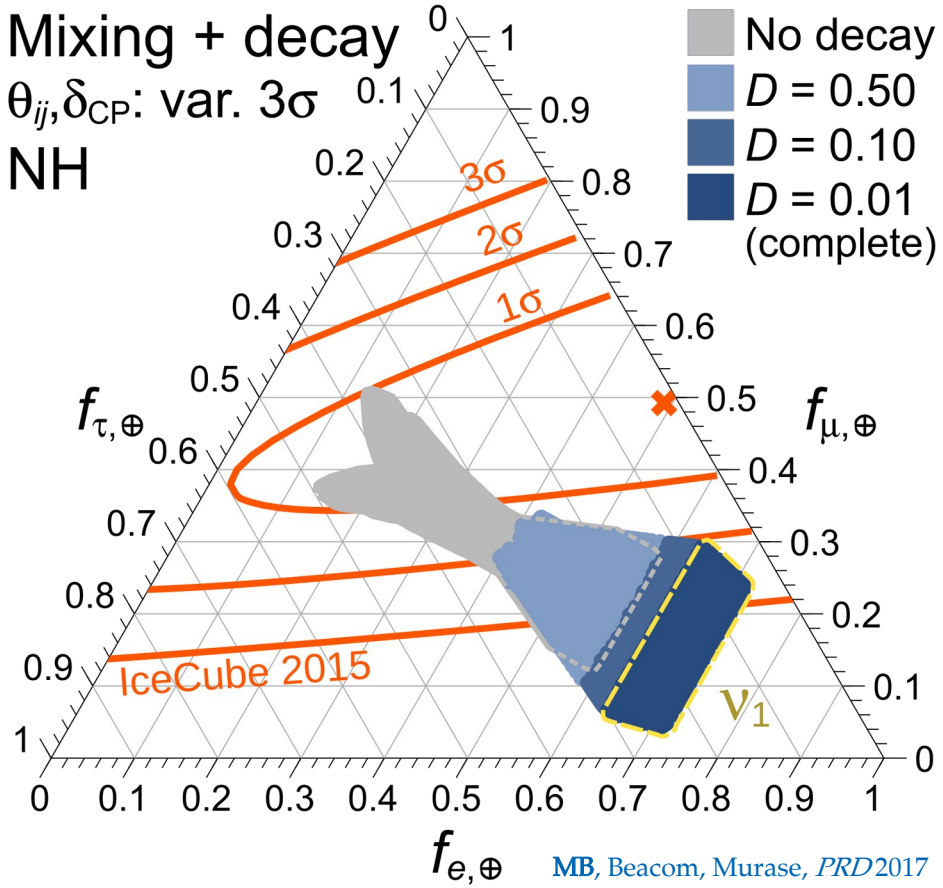

MB, Beacom, Murase, *PRD* 2017

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

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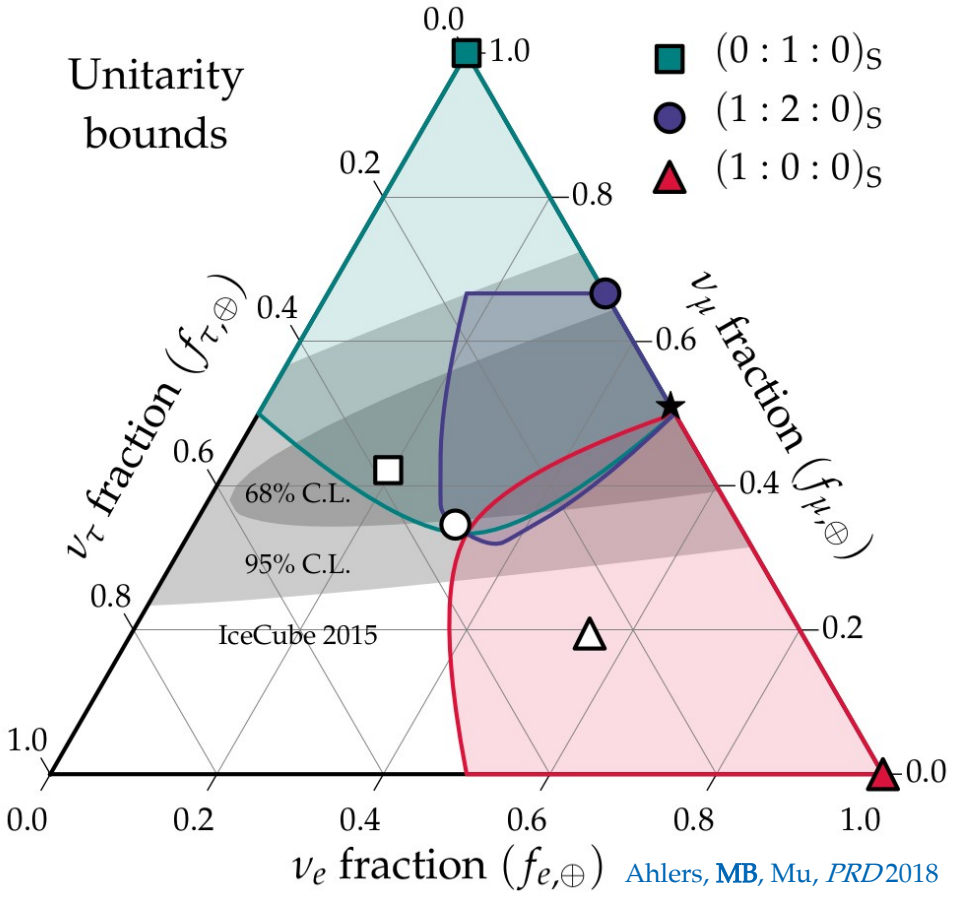

Ahlers, **MB**, Mu, *PRD* 2018

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

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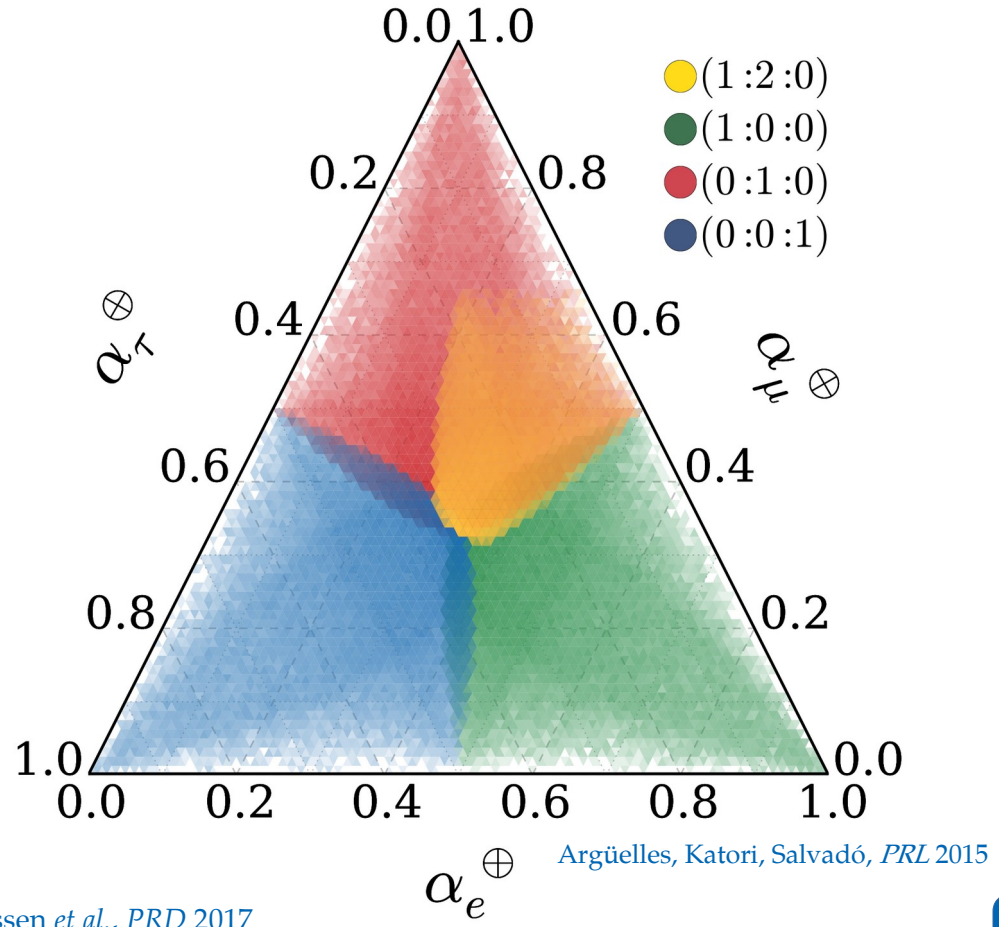

Argüelles, Katori, Salvadó, *PRL* 2015

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

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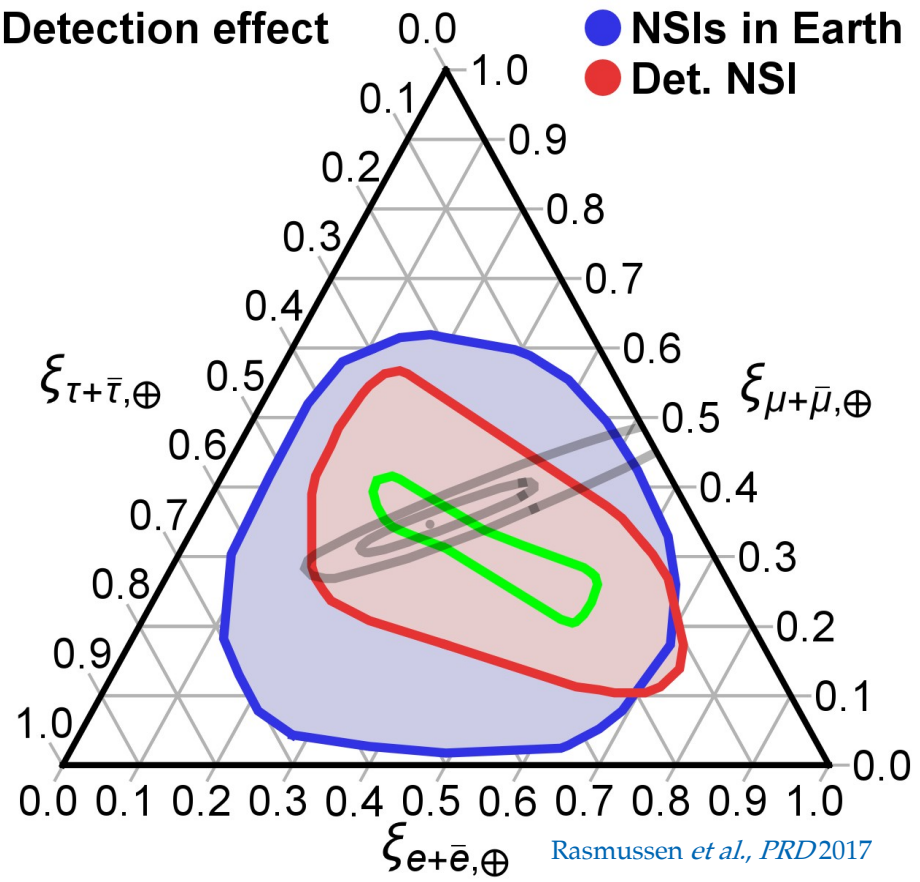

Rasmussen *et al.*, *PRD* 2017

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

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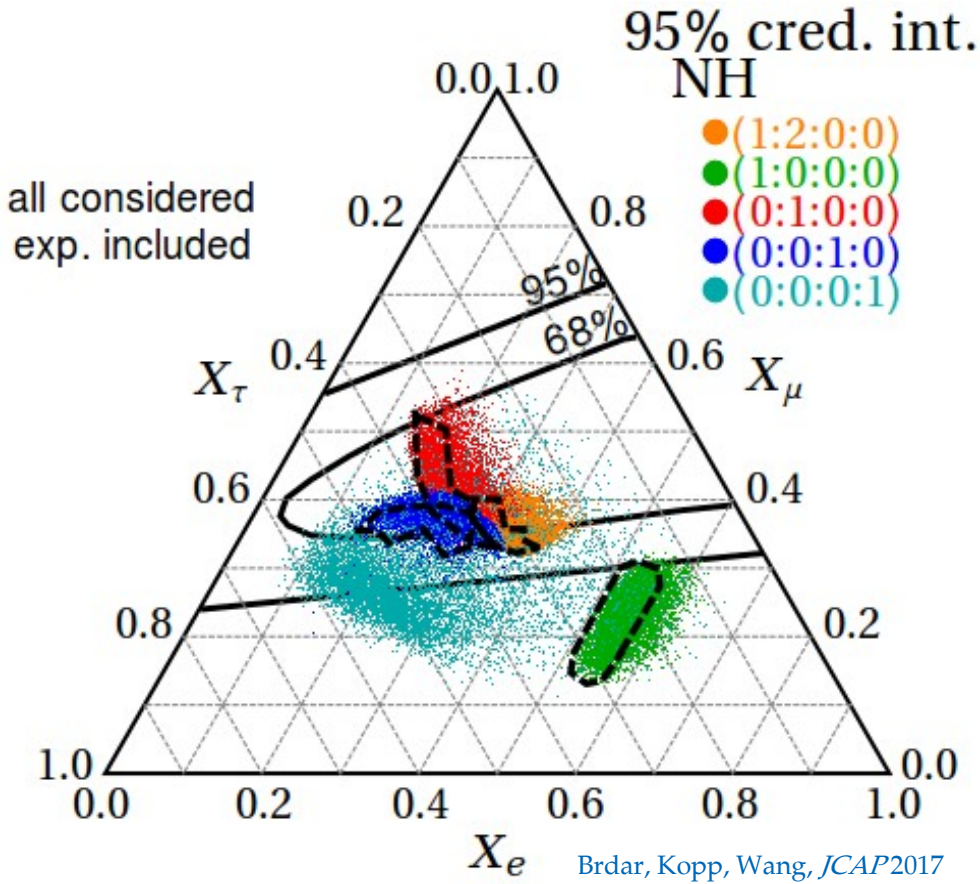

Brdar, Kopp, Wang, *JCAP* 2017

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

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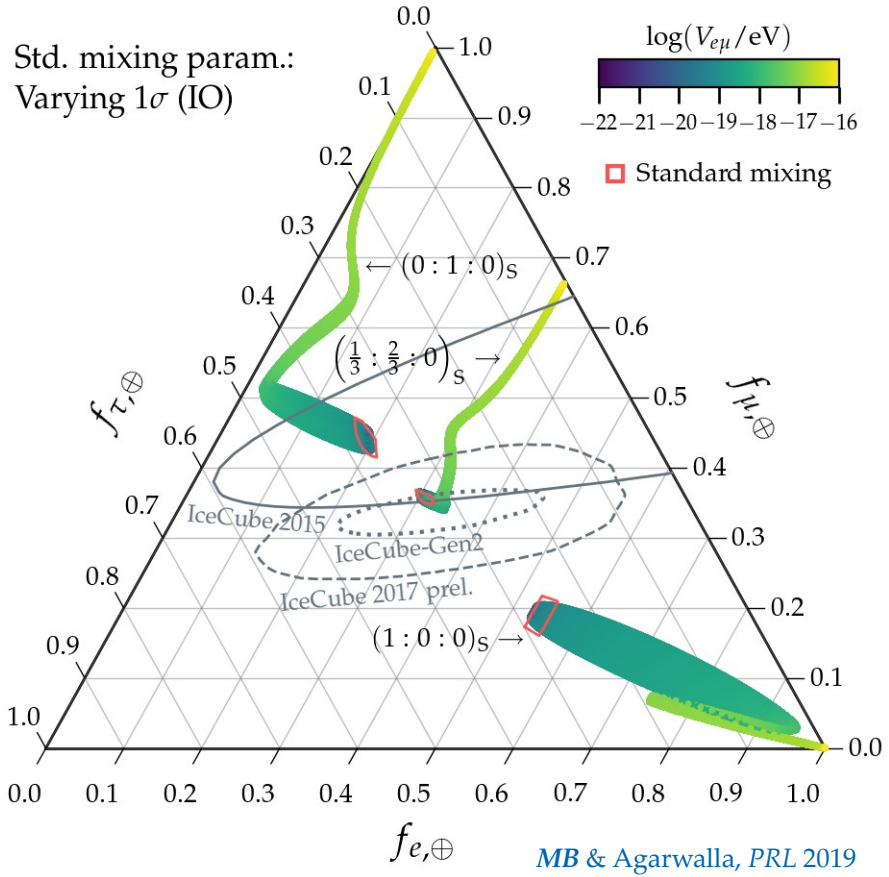
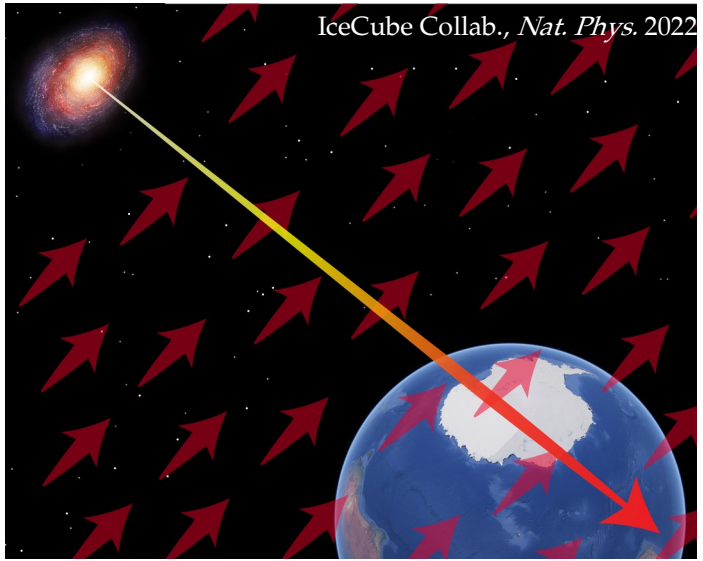
- Long-range *e*ν interactions
  [***MB*** & Agarwalla, *PRL* 2019]



MB & Agarwalla, *PRL* 2019

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

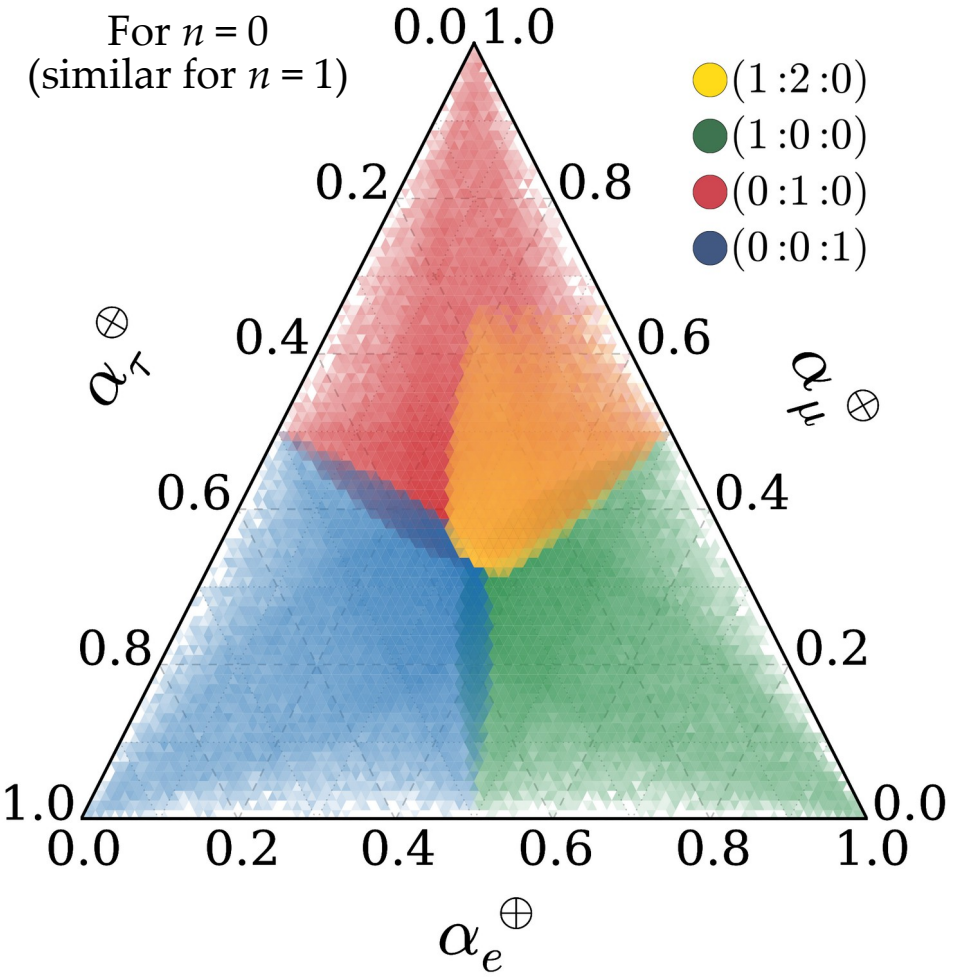
Lorentz-invariance violation can fill up the flavor triangle



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

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

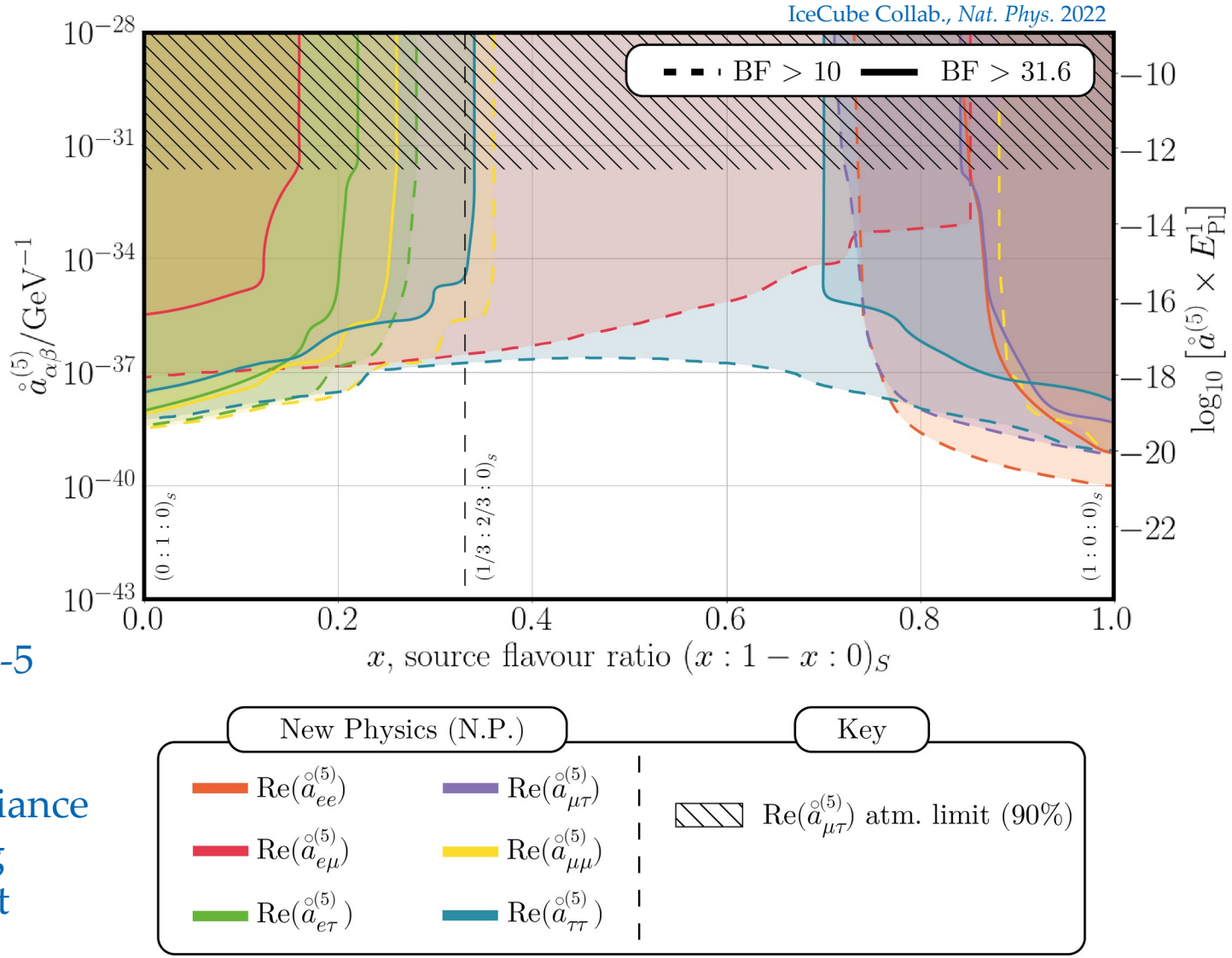
$$H_{\text{NP}} = \sum_n \left(\frac{E}{\Lambda_n}\right)^n U_n^{\dagger}\, \text{diag}\left(O_{n,1}, O_{n,2}, O_{n,3}\right) U_n$$



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

Argüelles, Katori, Salvadó, *PRL* 2015

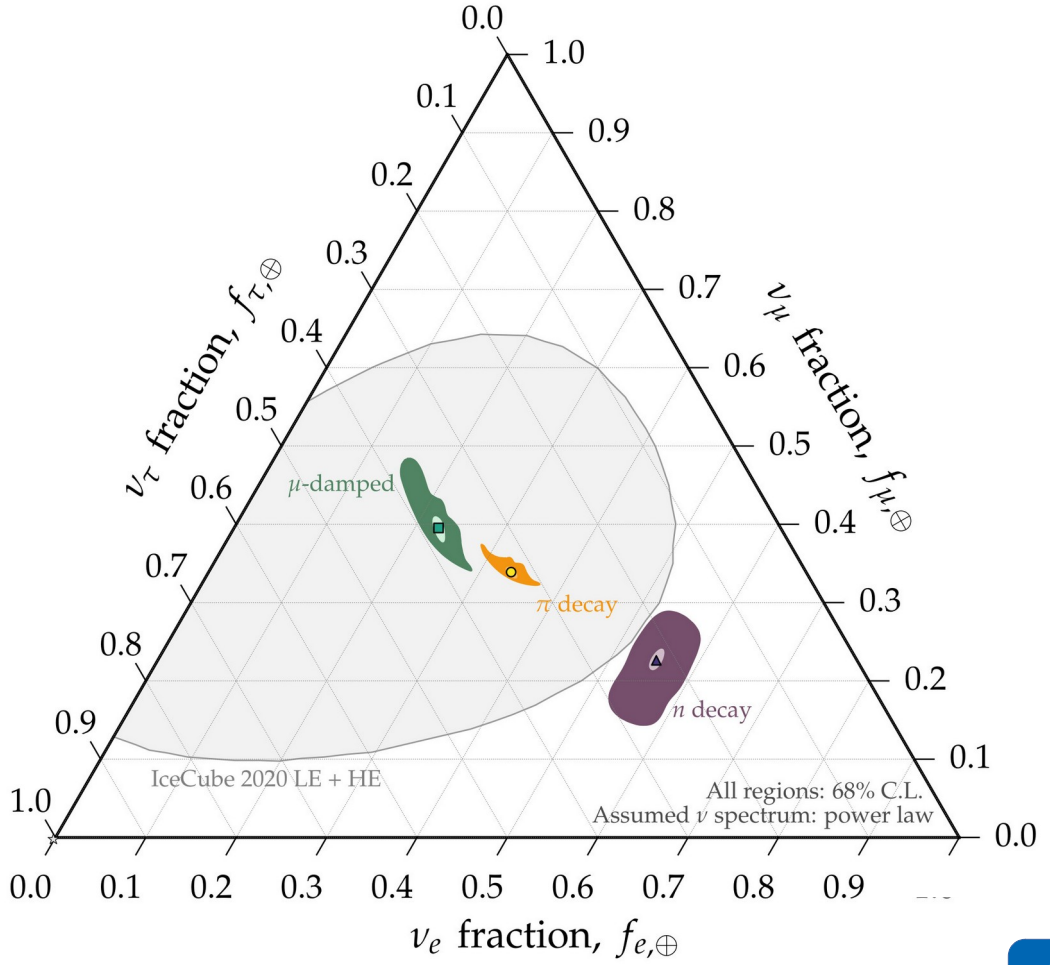
IceCube Collab., *Nat. Phys.* 2022



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

Measuring energy-dependent flavor composition

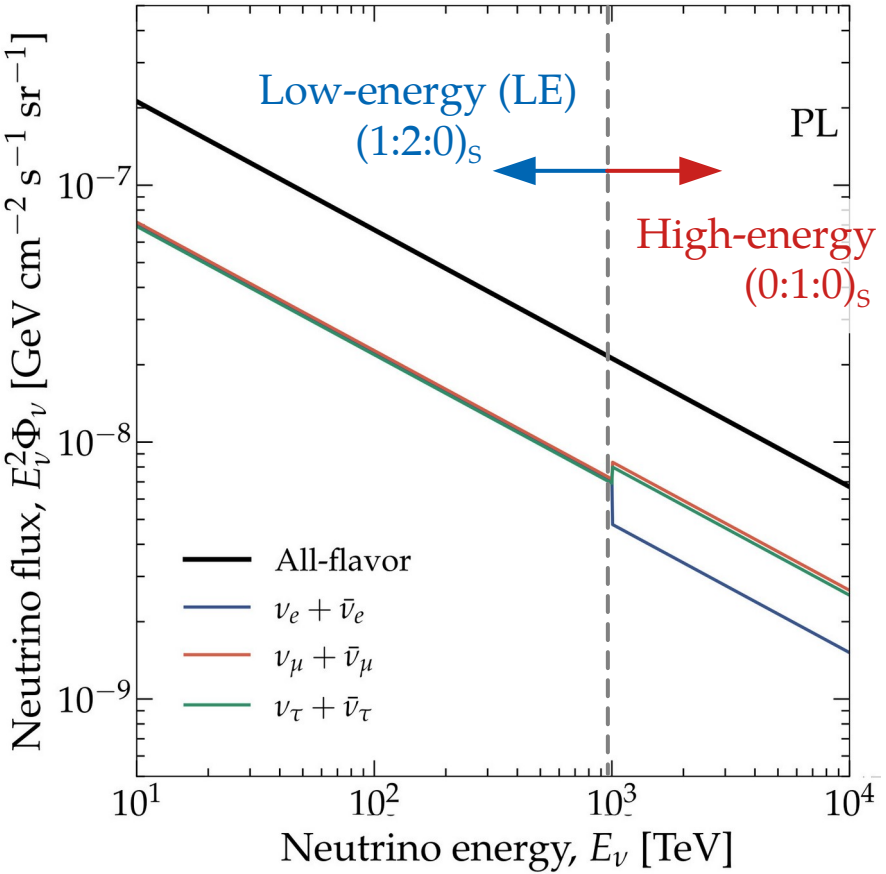
Flavor composition: measuring the energy dependence



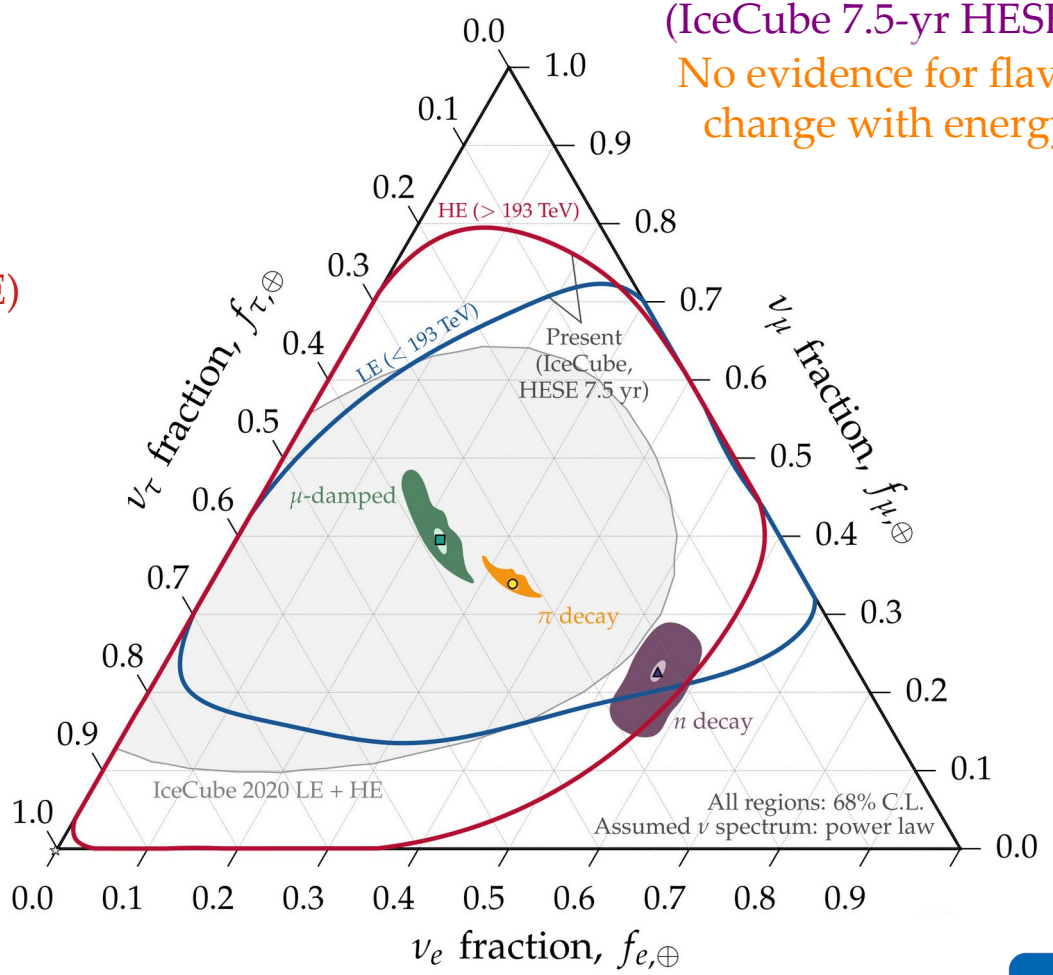
Liu, Fiorillo, Argüelles, **MB**, Song, Vincent, 2312.07649

Flavor composition: measuring the energy dependence

Power-law (PL) diffuse ν flux



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



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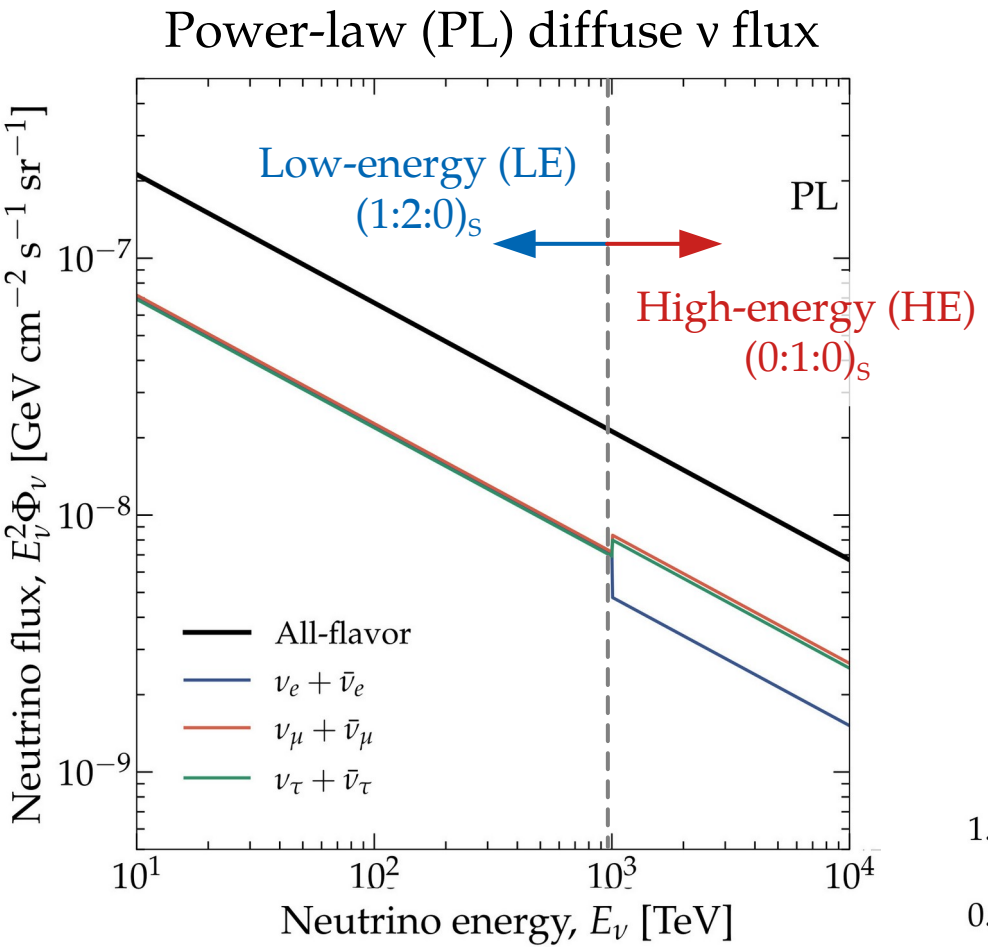
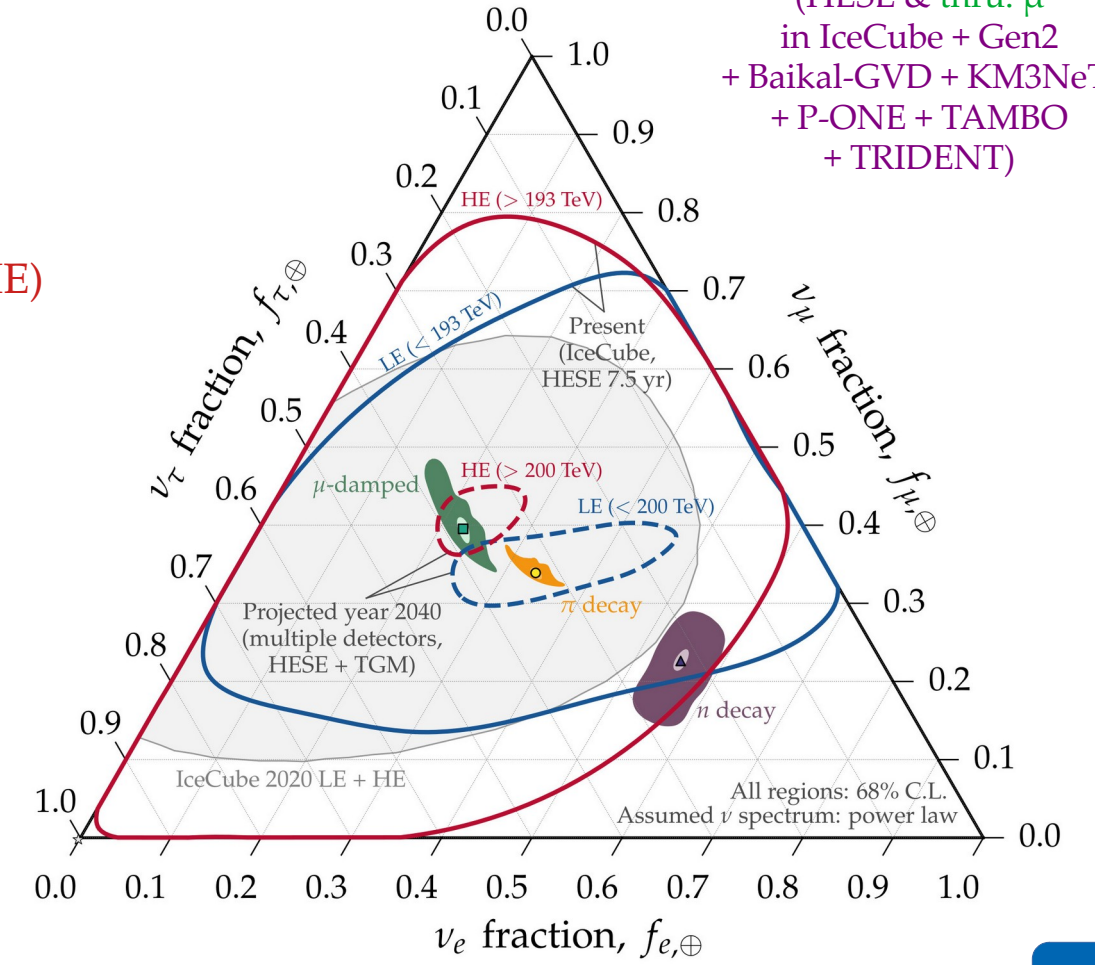
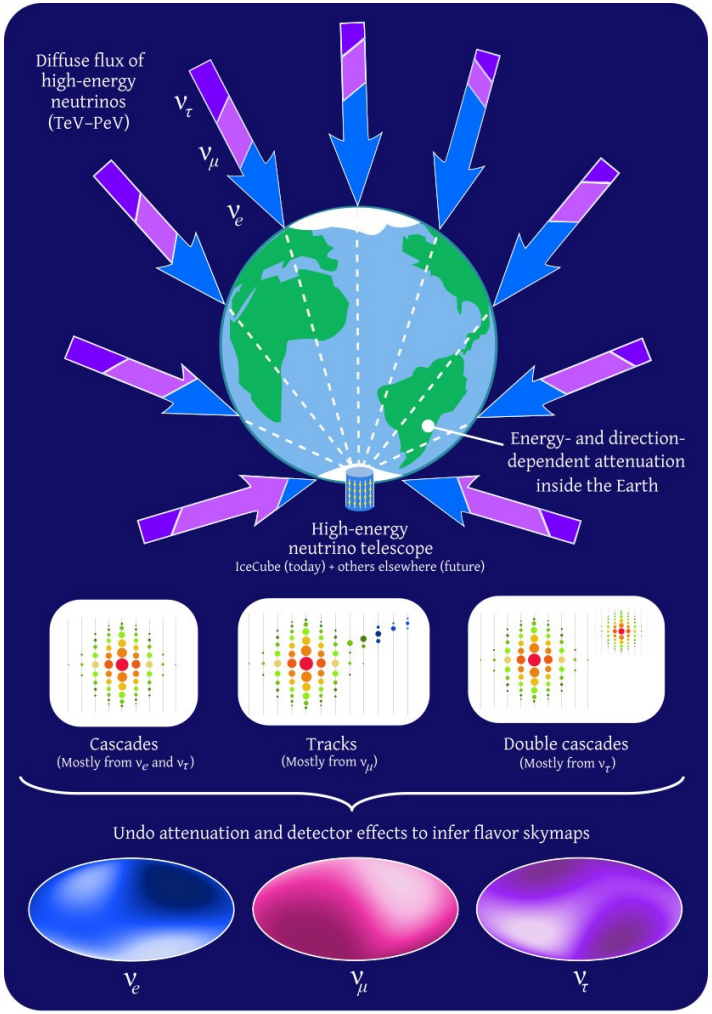




Liu, Fiorillo, Argüelles, **MB**, Song, Vincent, 2312.07649

Measuring flavor anisotropy

Flavor anisotropy in the high-energy neutrino sky



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

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

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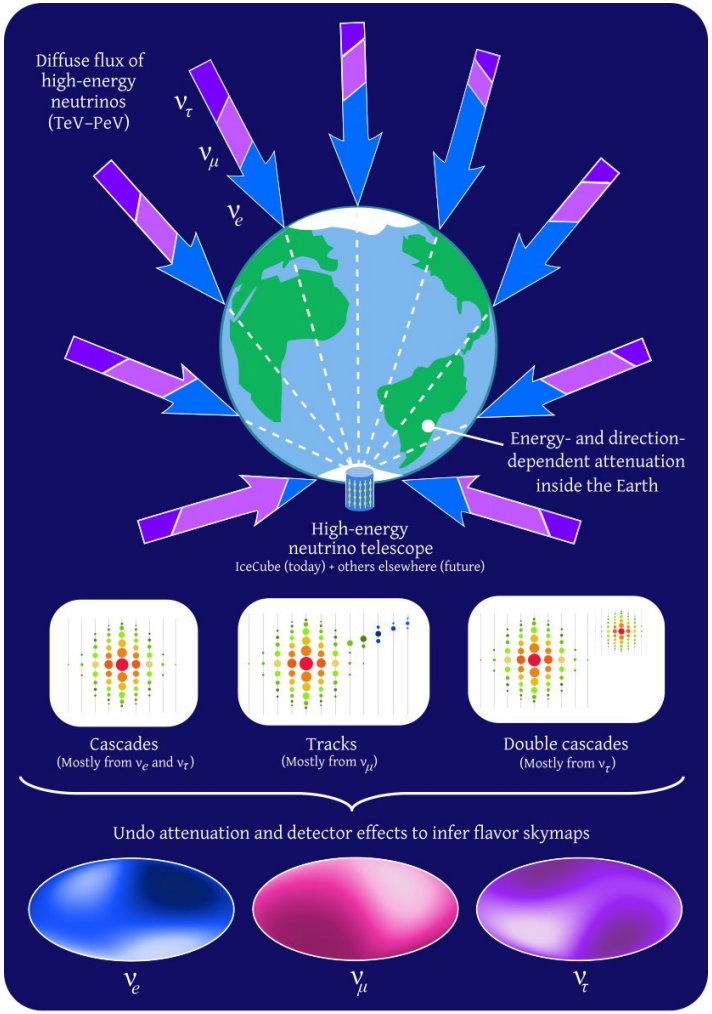

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From the angular distribution of detected events in neutrino telescopes (HESE cascades, tracks, double cascades) …

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

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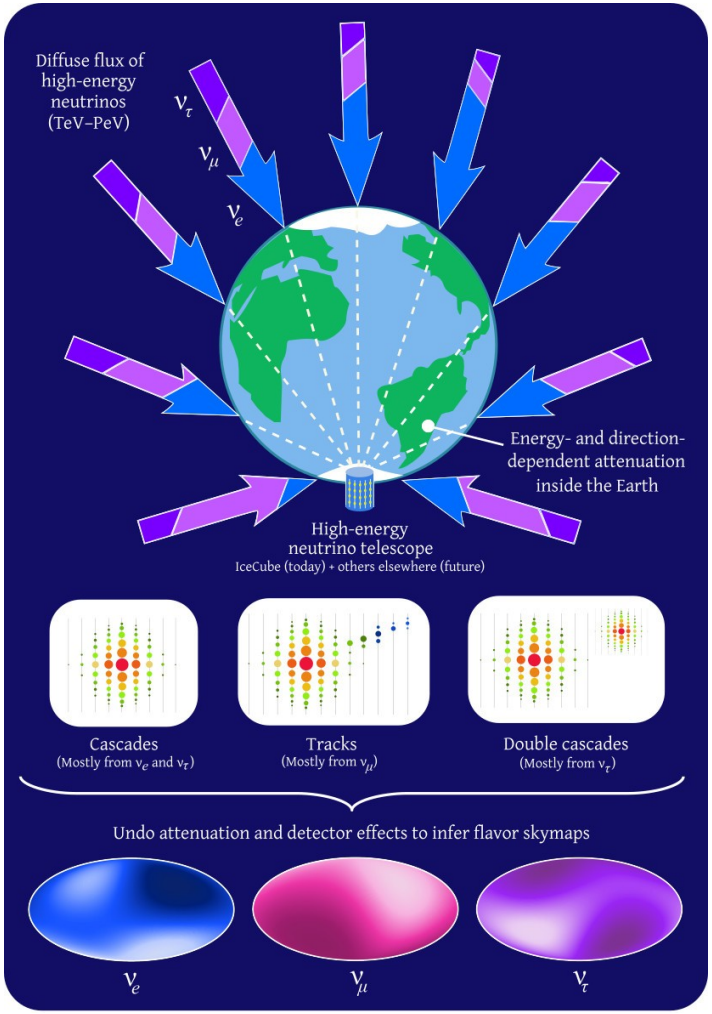

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… we infer the directional dependence of the diffuse fluxes of ν_e, ν_μ, ν_τ

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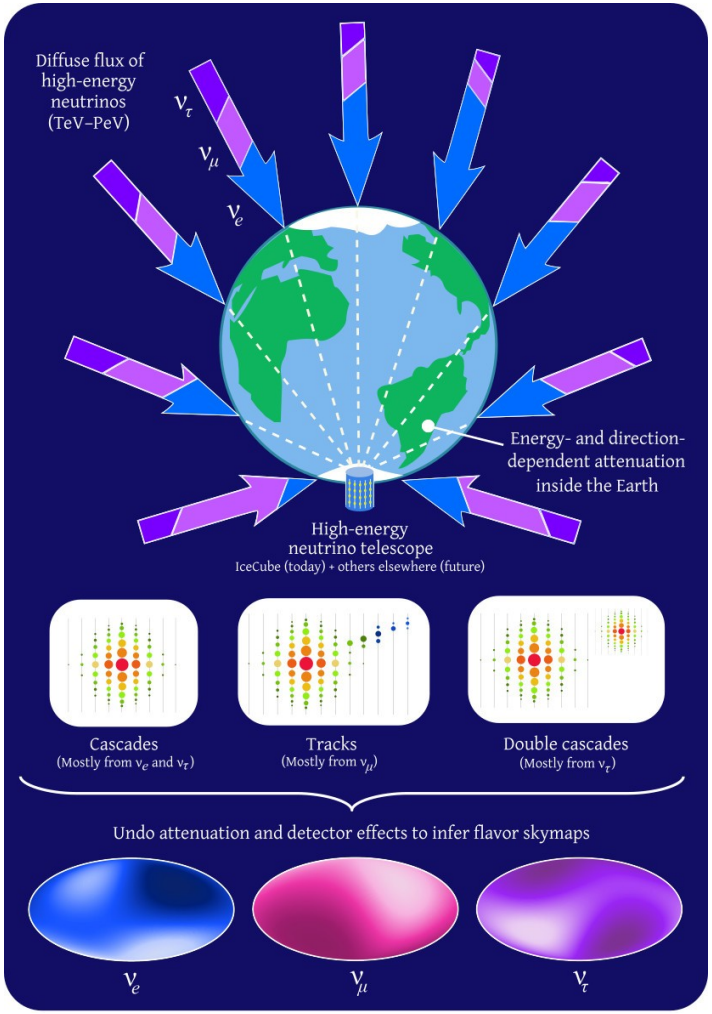

Does the high-energy sky shine equally brightly In neutrinos of all flavors?

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

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

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

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

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

Real, public data

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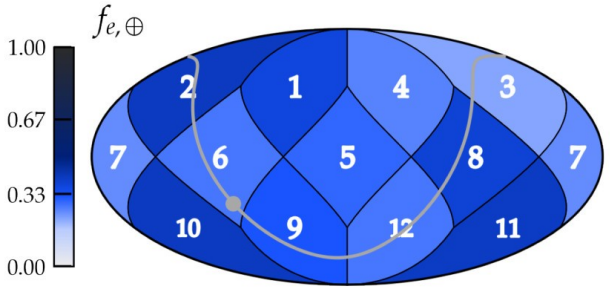

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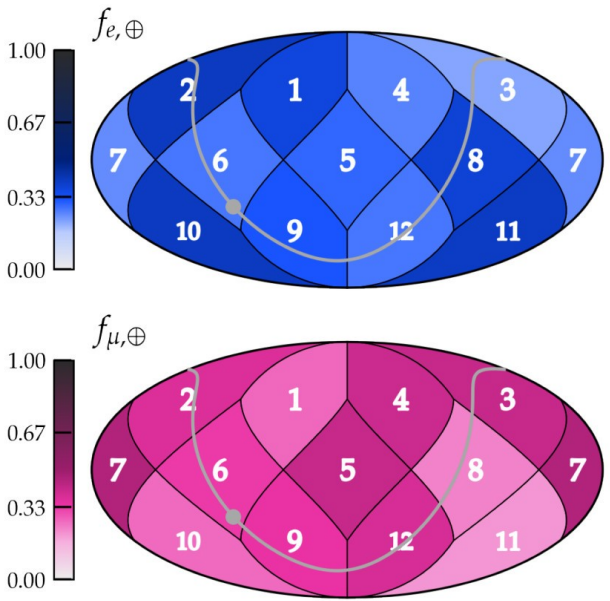

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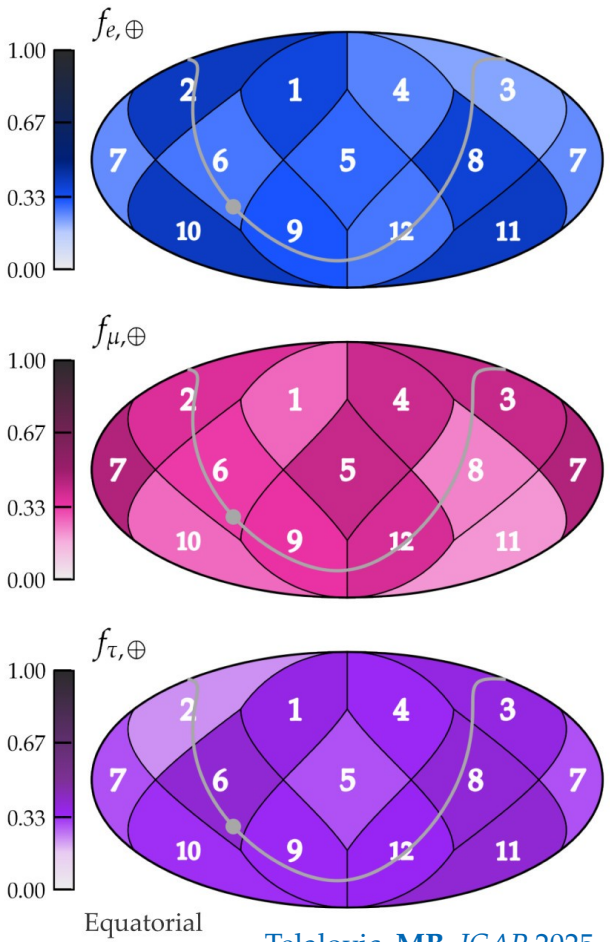

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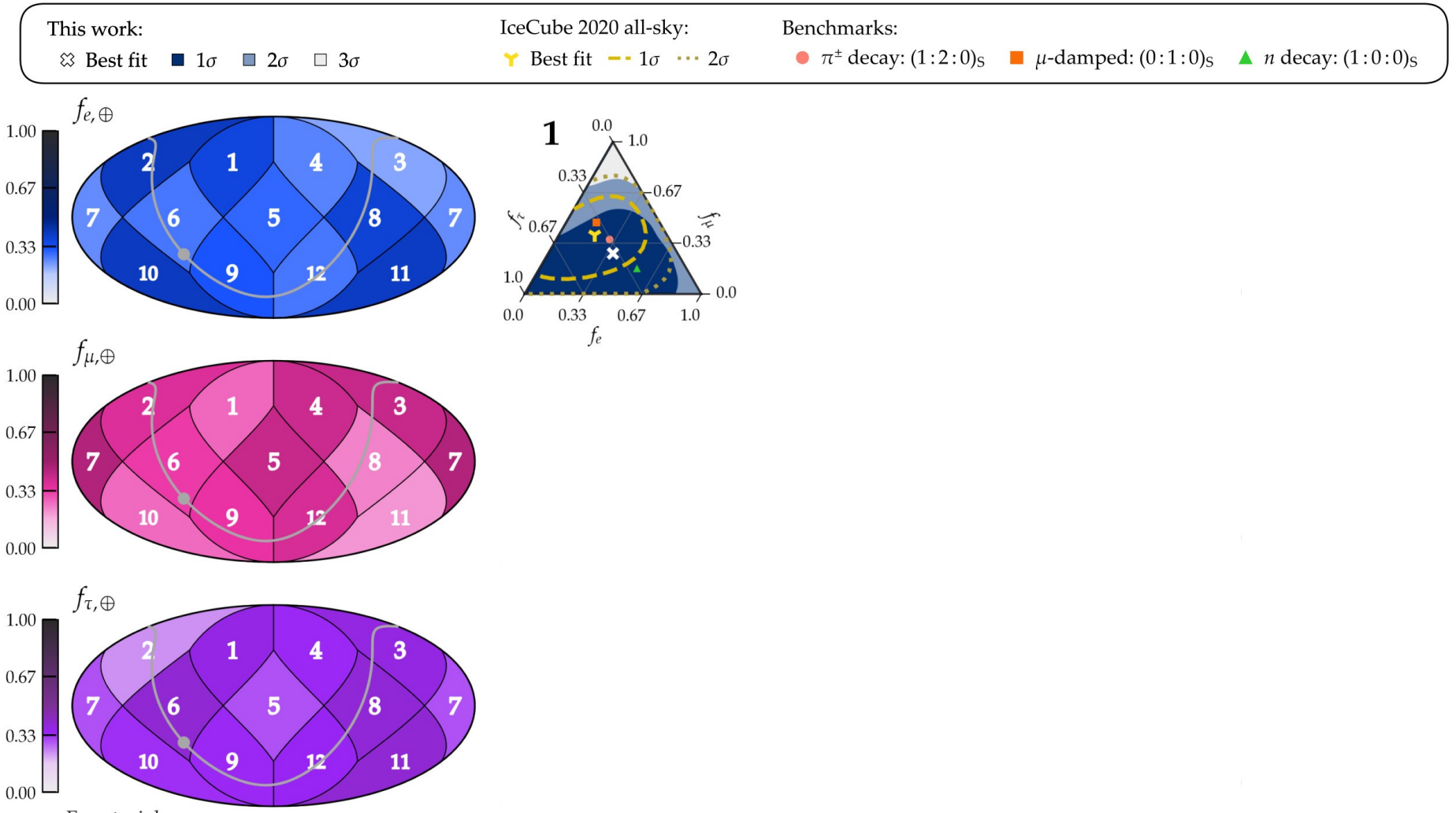

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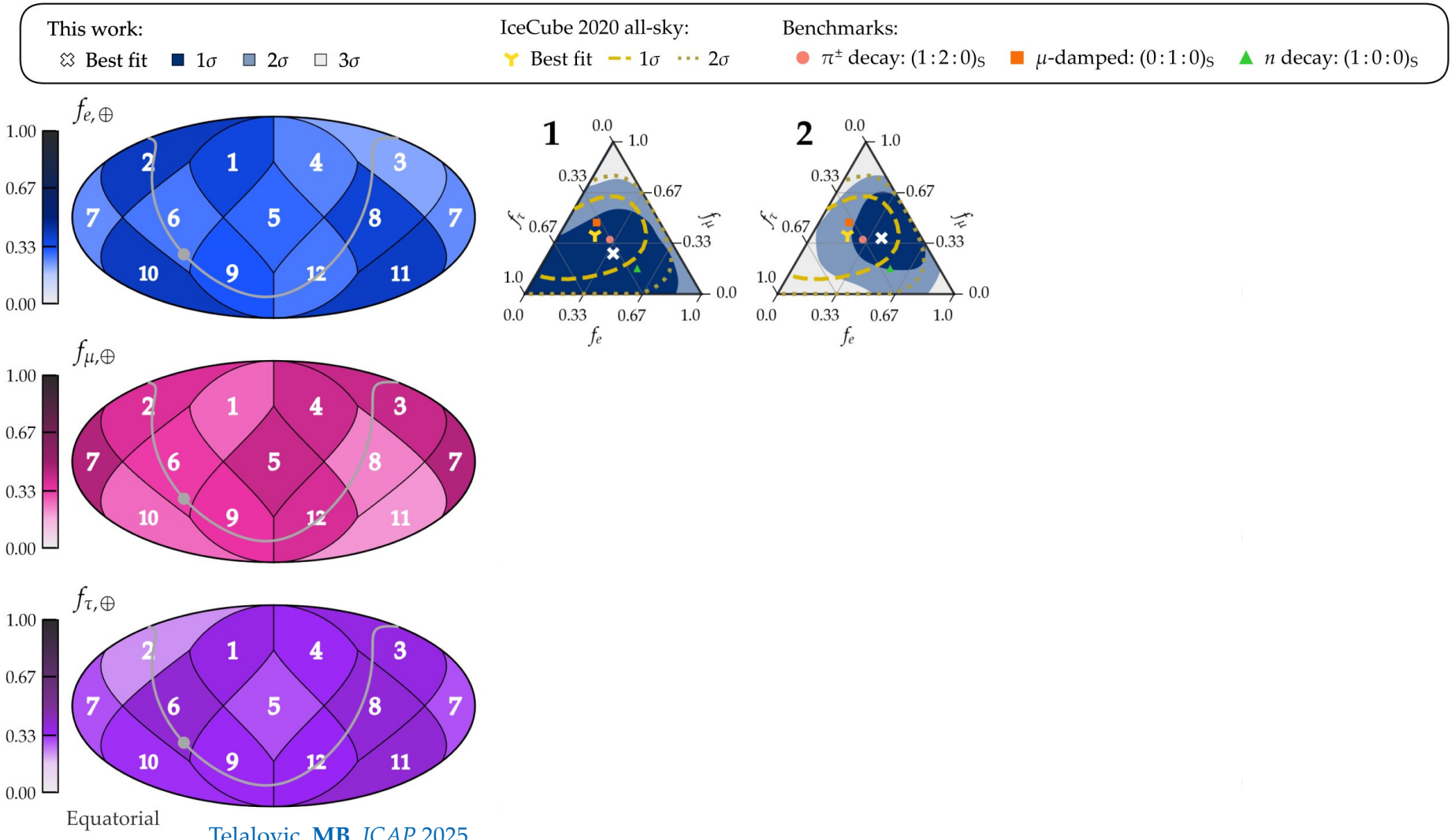

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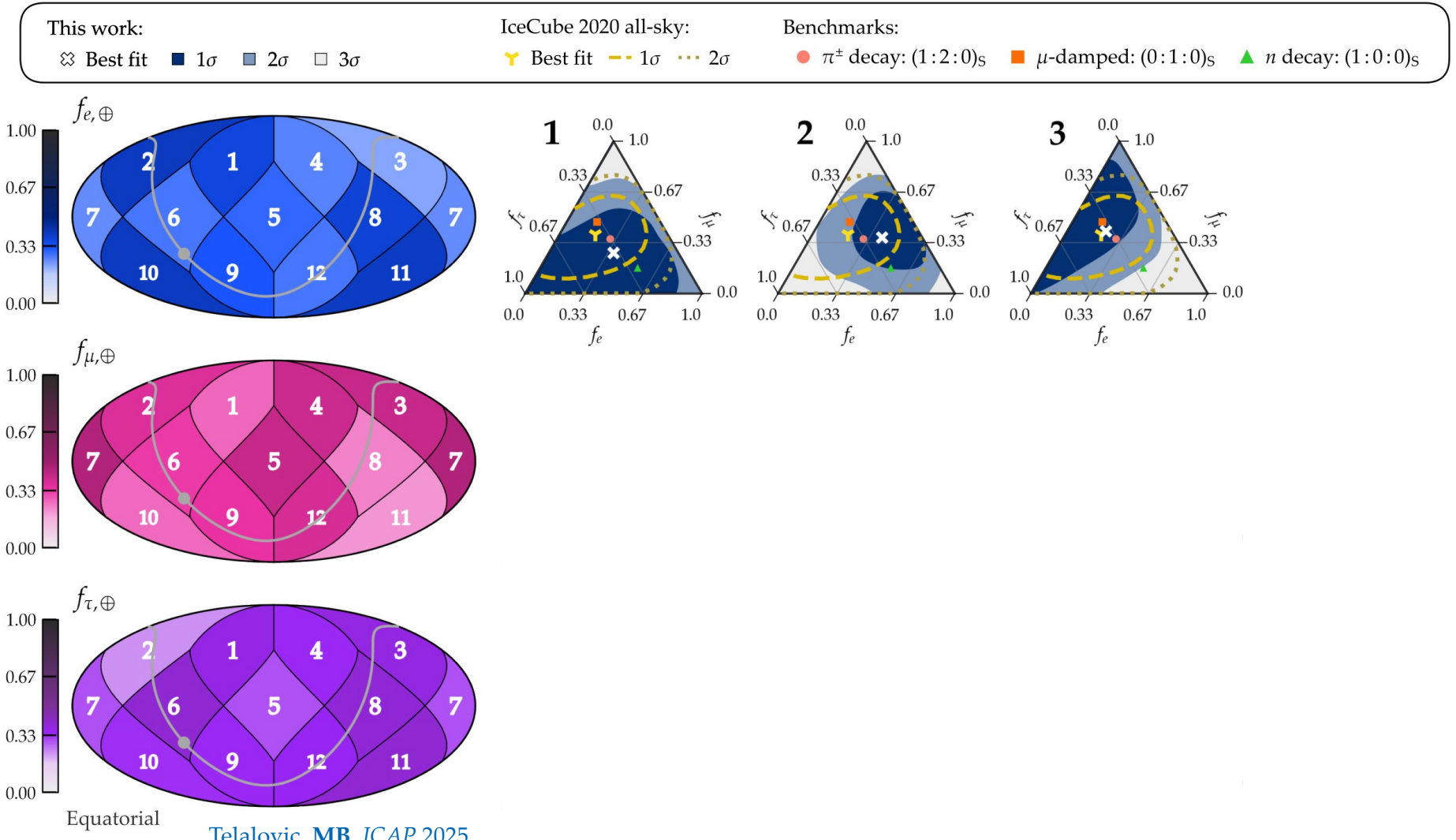

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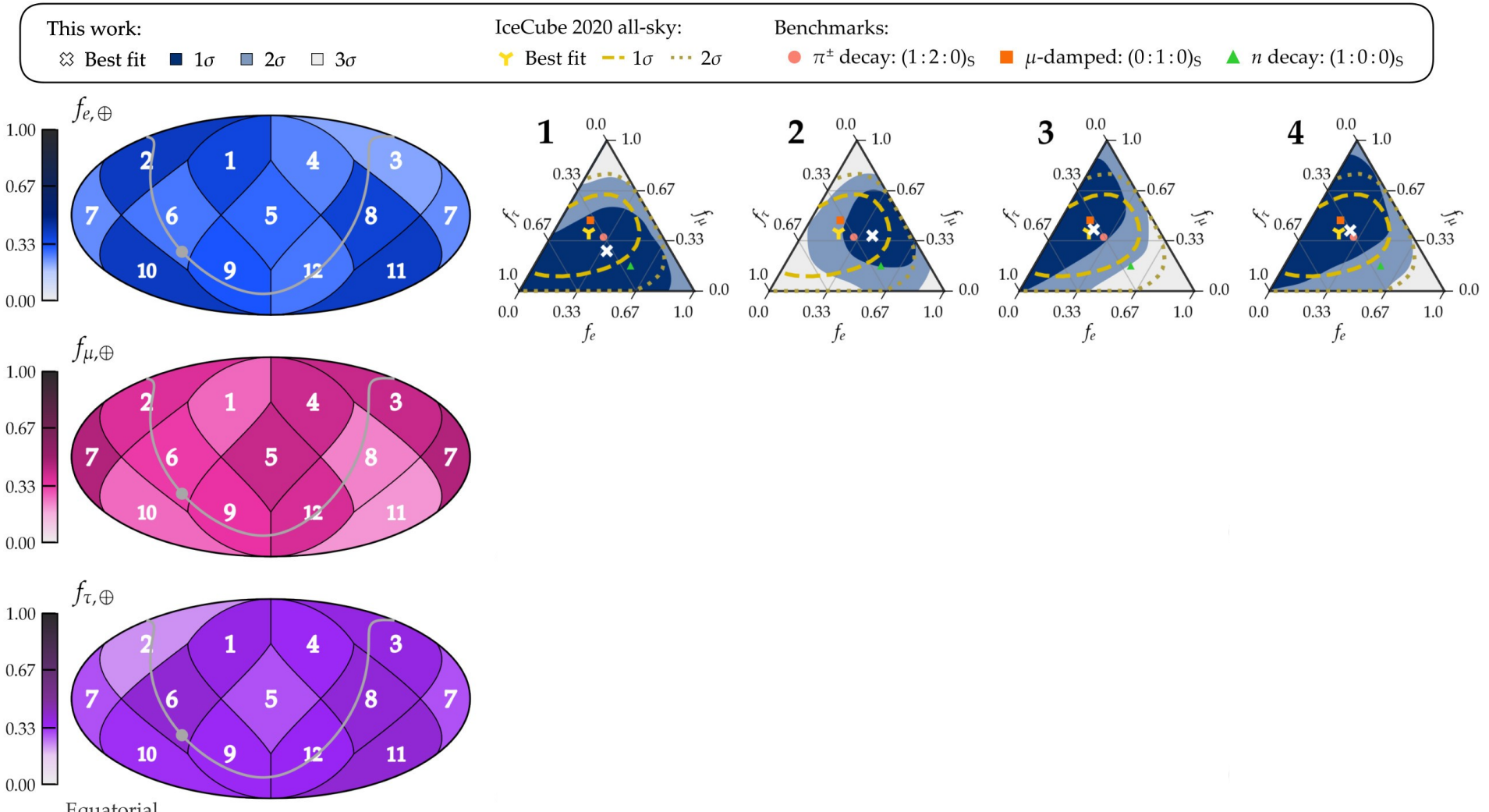

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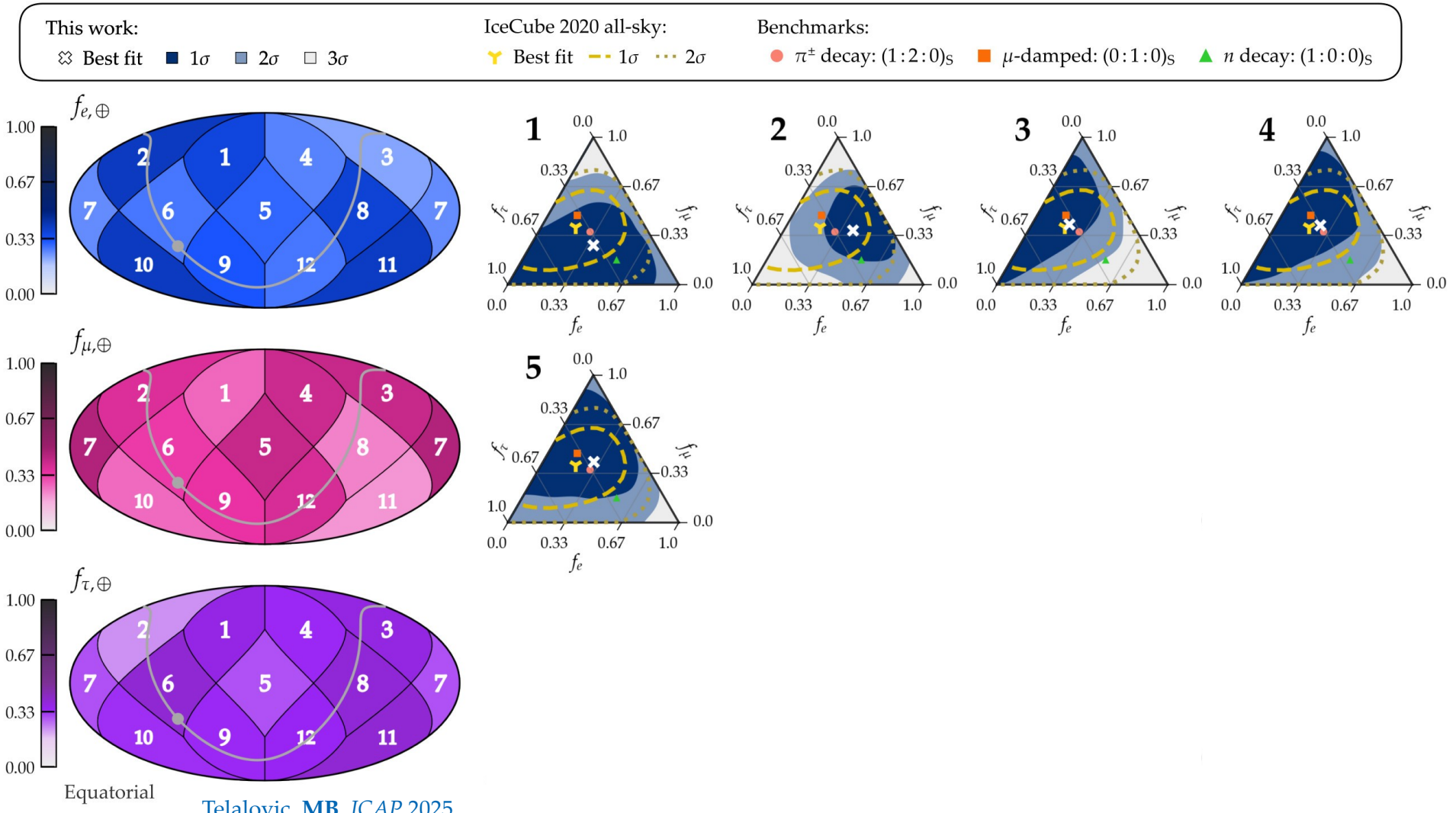
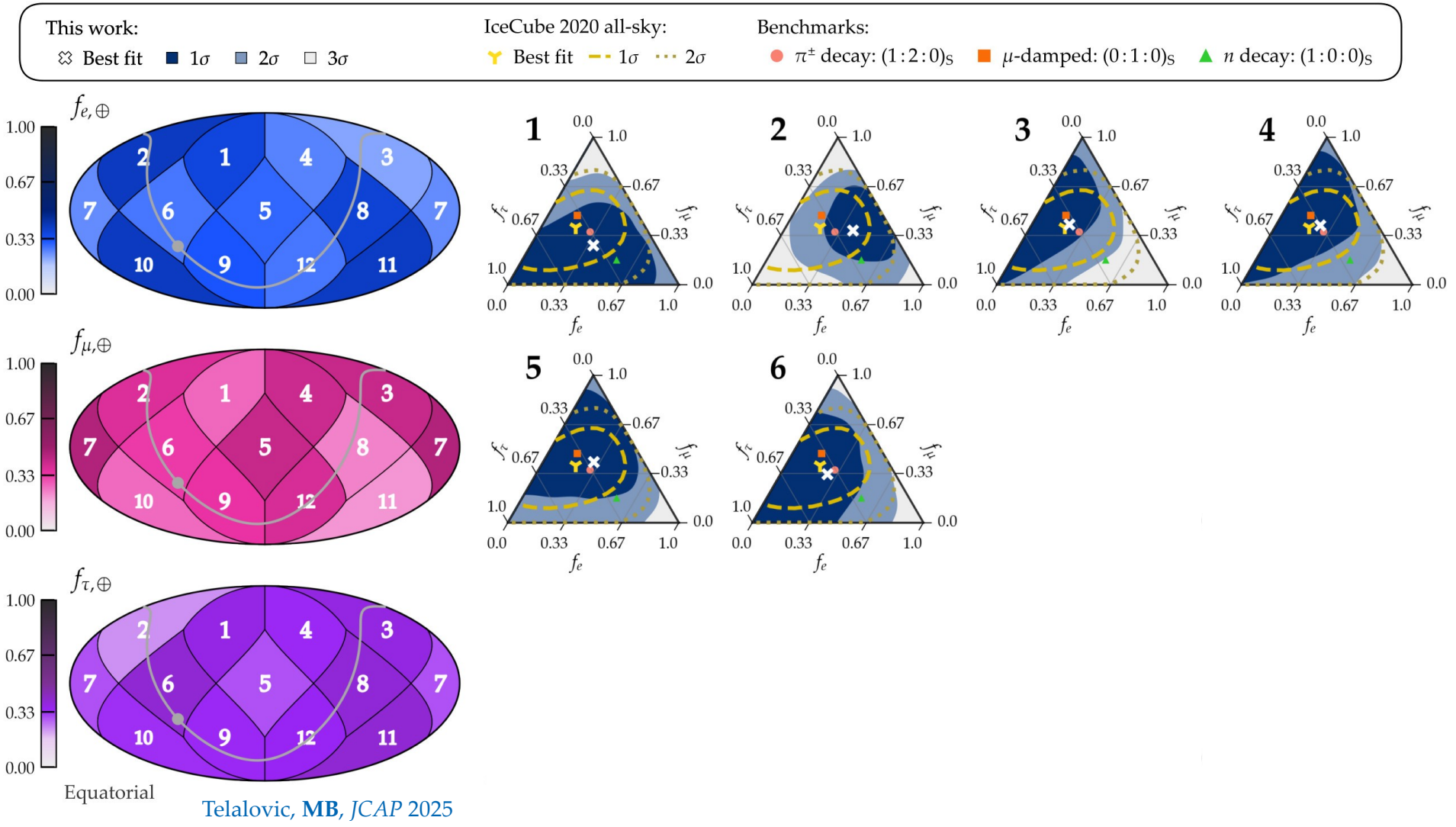


Telalovic, **MB**, *JCAP* 2025

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



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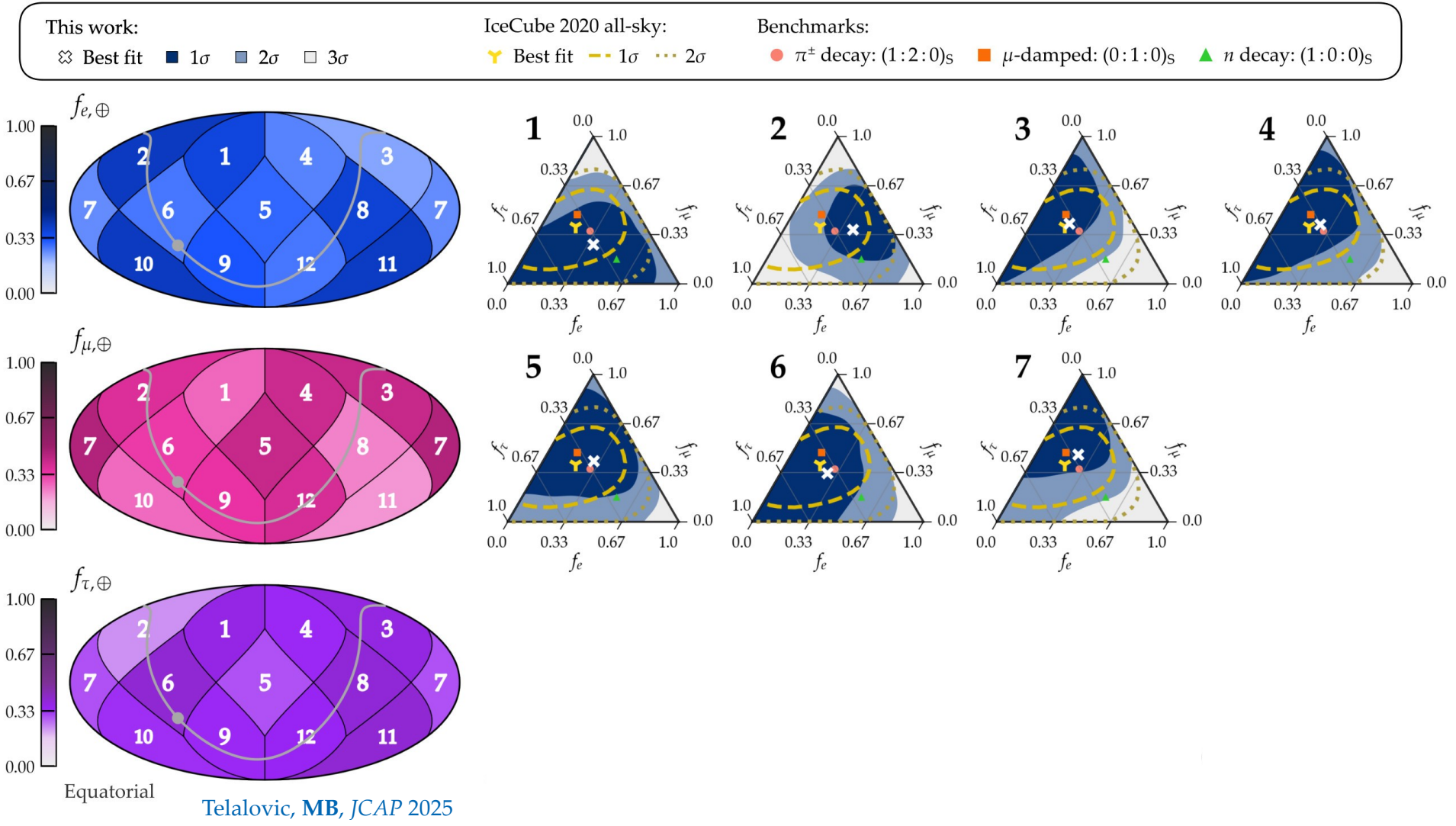

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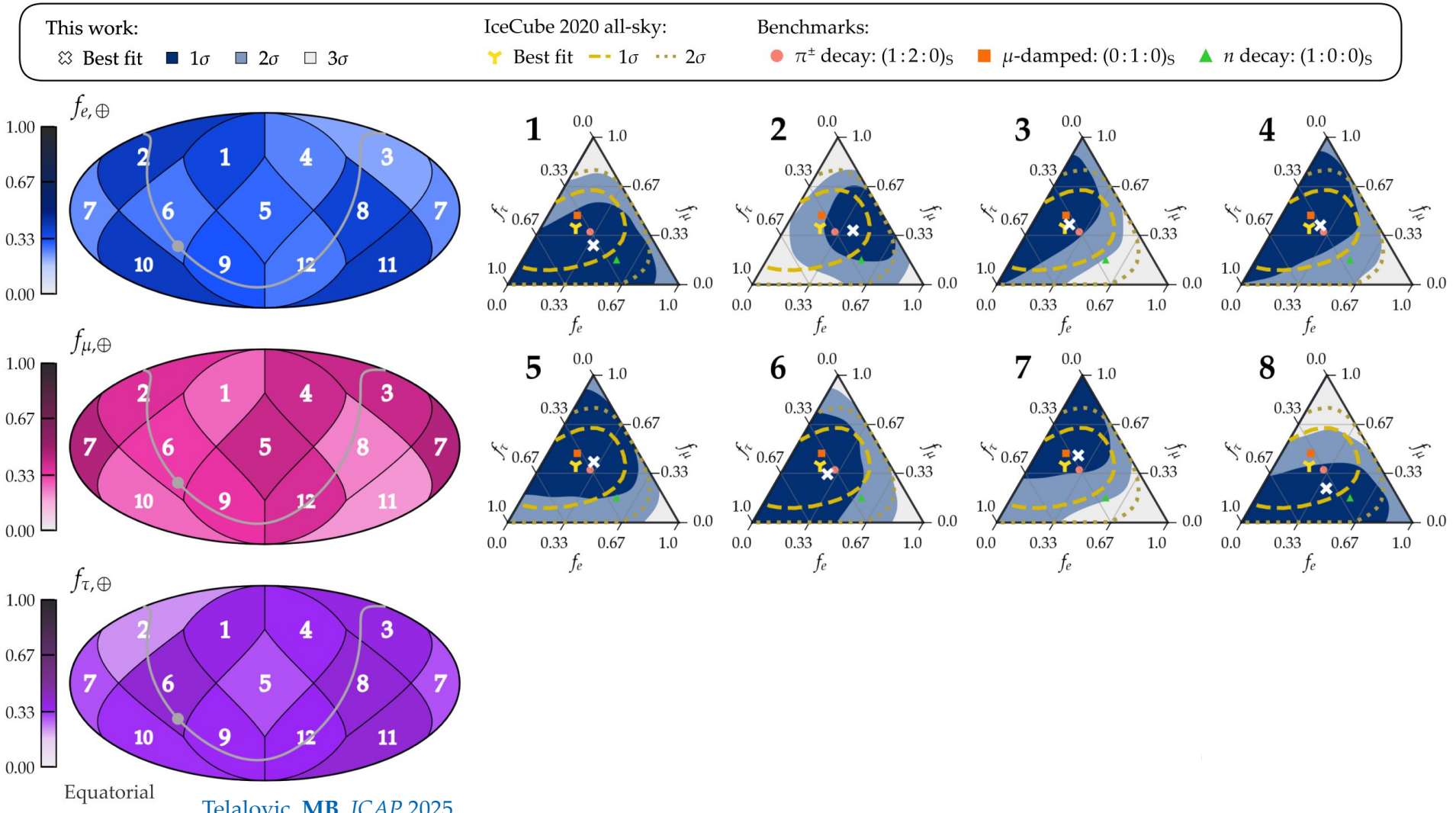

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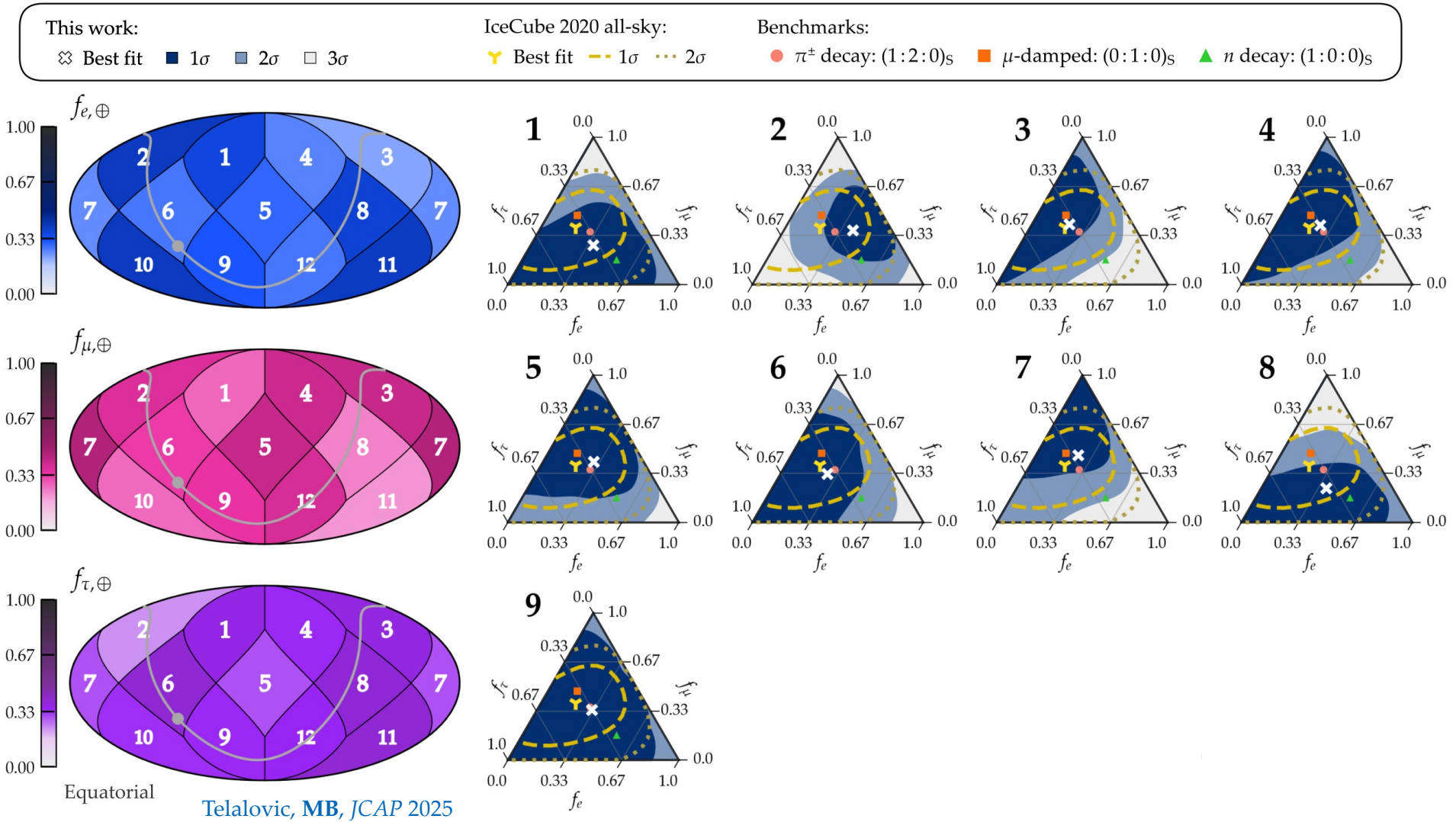

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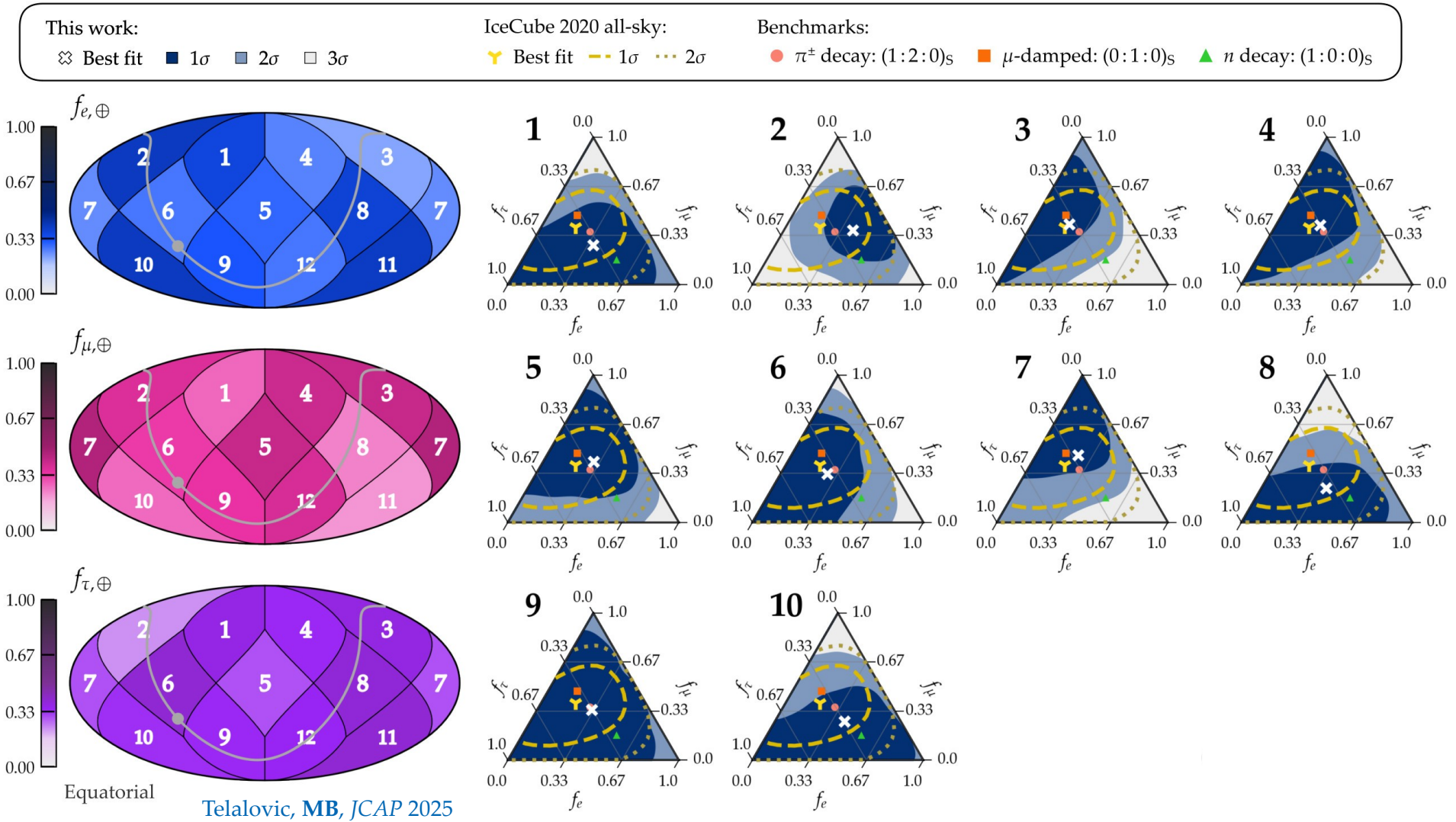

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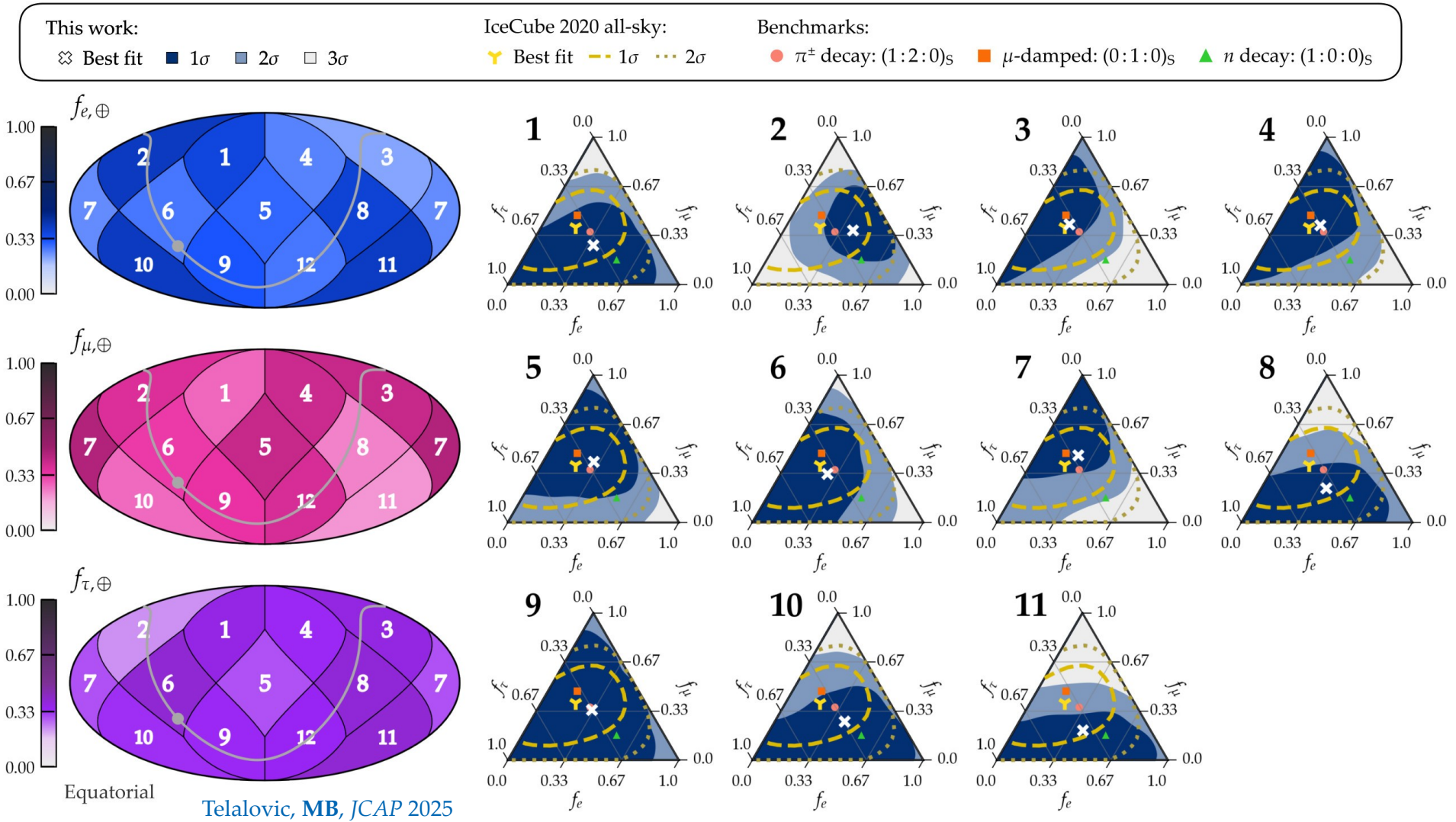

Telalovic, **MB**, *JCAP* 2025

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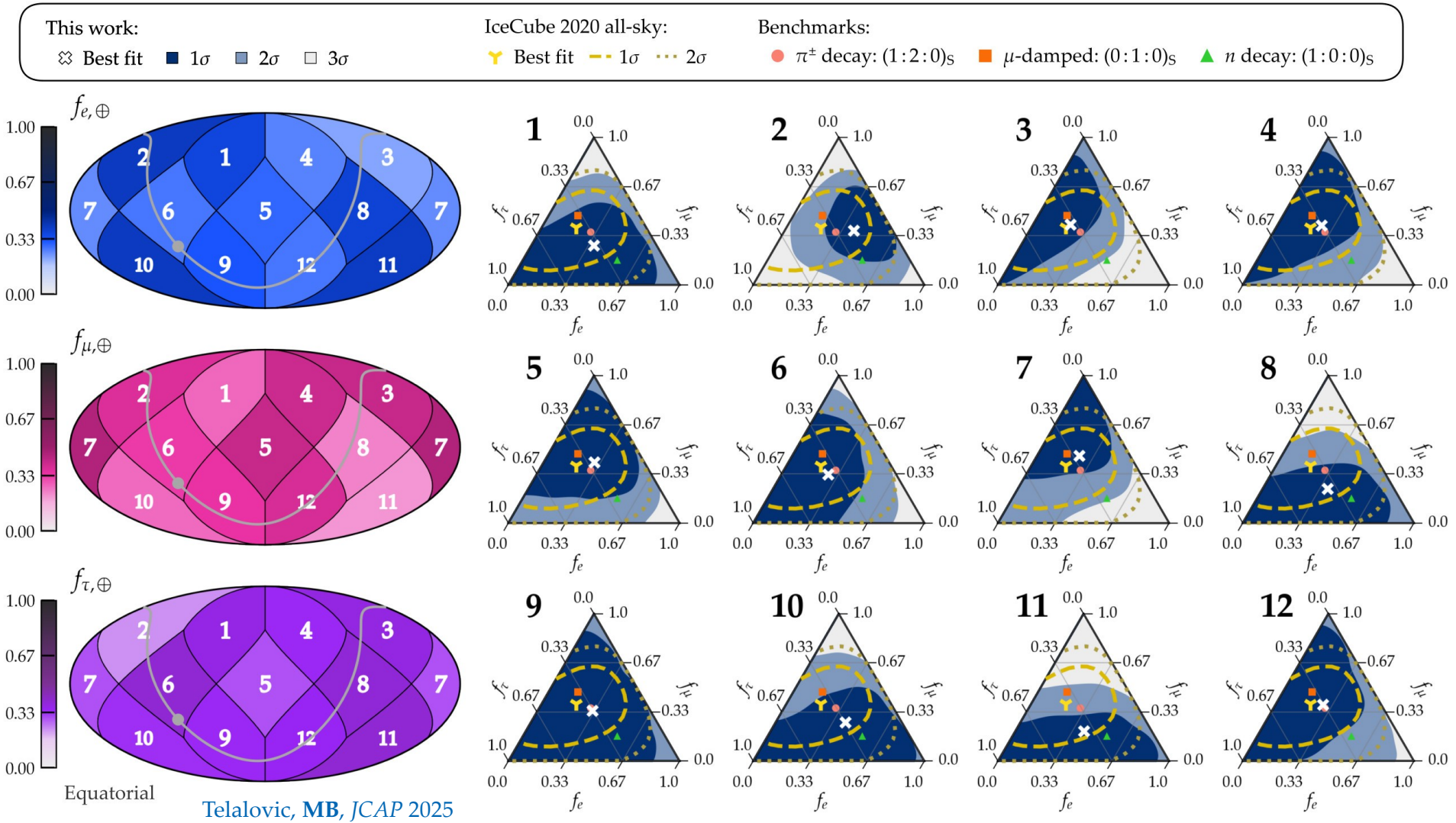


Telalovic, **MB**, *JCAP* 2025

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

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

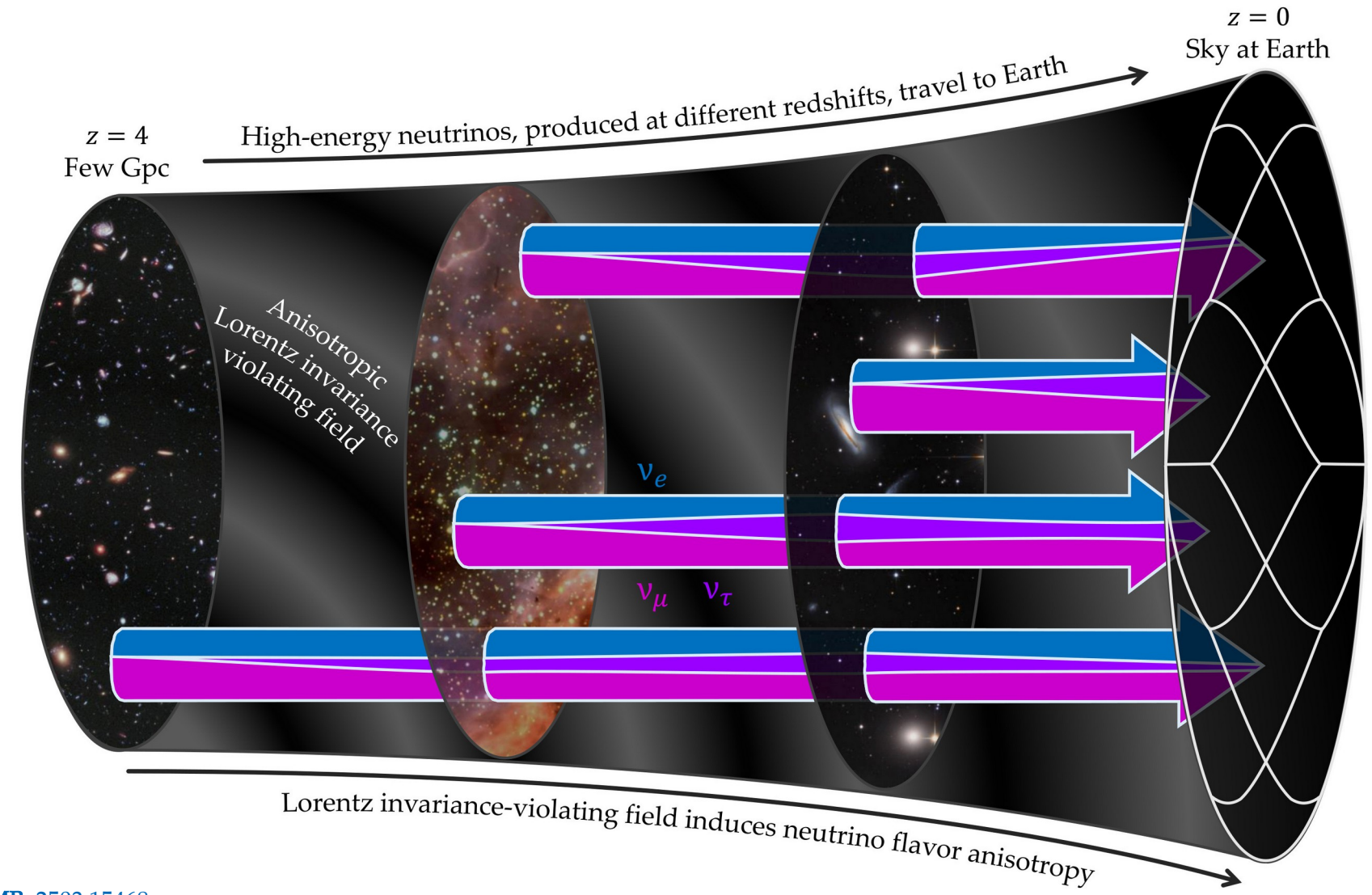
There is no sign of flavor anisotropy in present-day IceCube data (Bayes factor is ~1)

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

Work led by Bernanda Telalovic

Equatorial

Telalovic, MB, 2310.15224



Telalovic, **MB**, 2503.15468

Anisotropic Lorentz-invariance violation makes the flavor sky anisotropic:

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

Neutrino oscillation probability becomes direction-dependent

Telalovic, **MB**, 2310.15224

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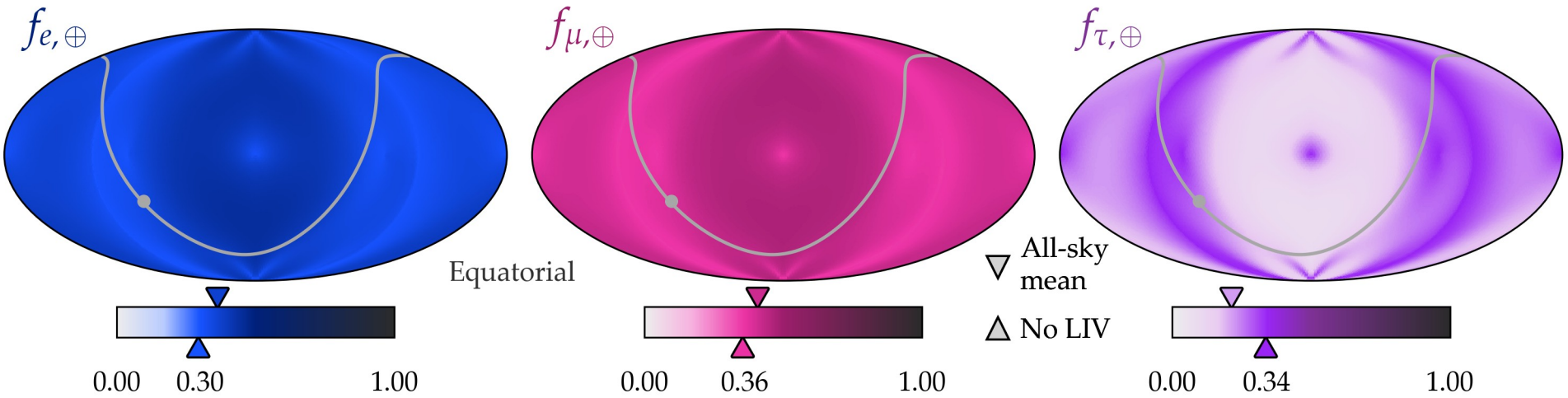

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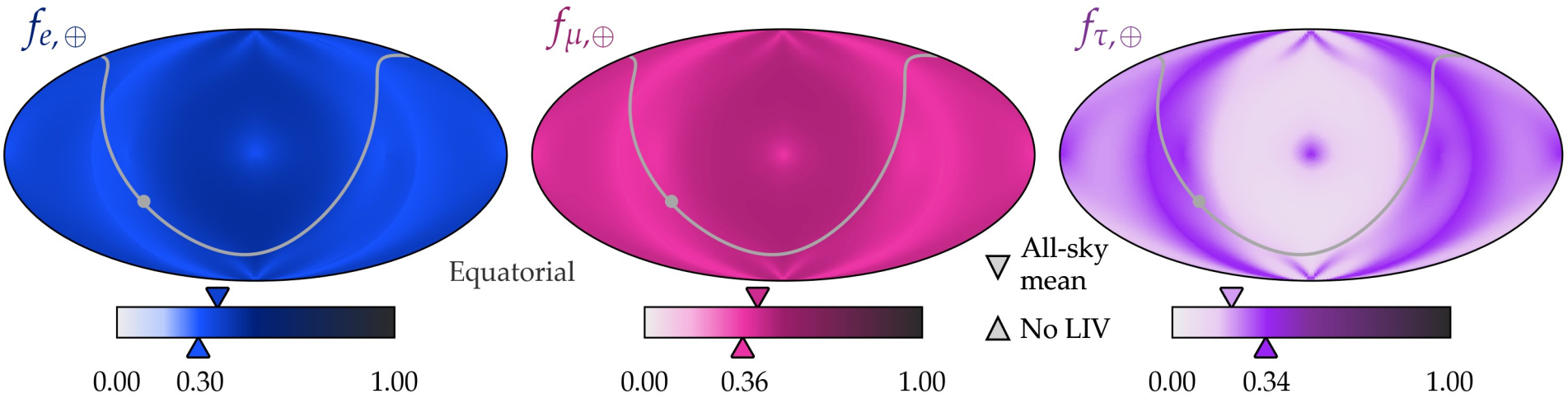

For dimension-5 CPT-odd LIV coefficient

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

Telalovic, **MB**, 2310.15224

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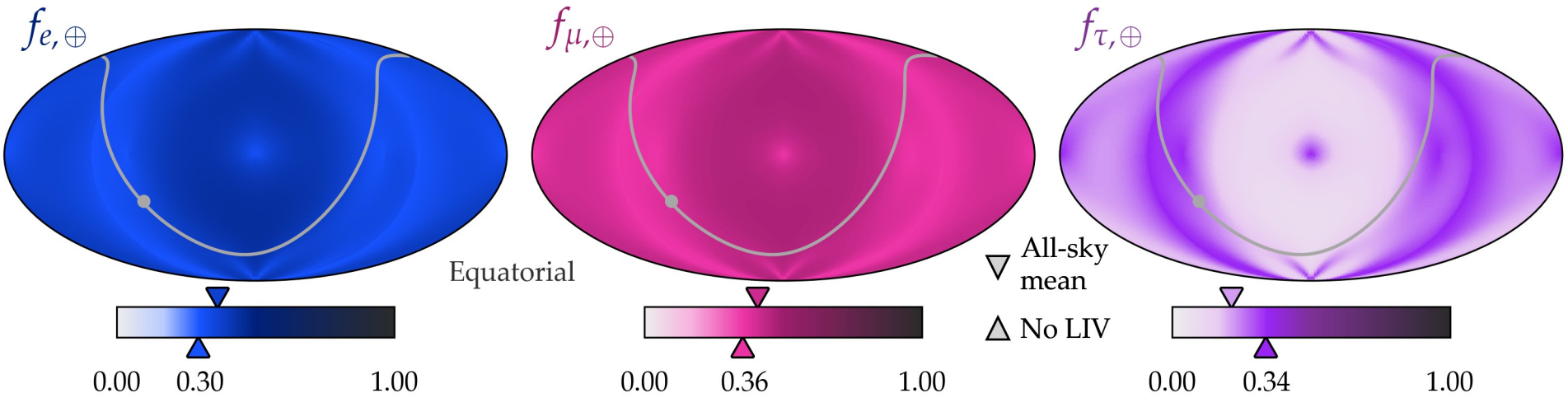
Neutrino oscillation probability becomes direction-dependent



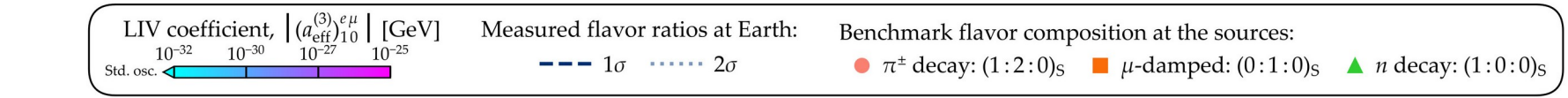
For dimension-5 CPT-odd LIV coefficient

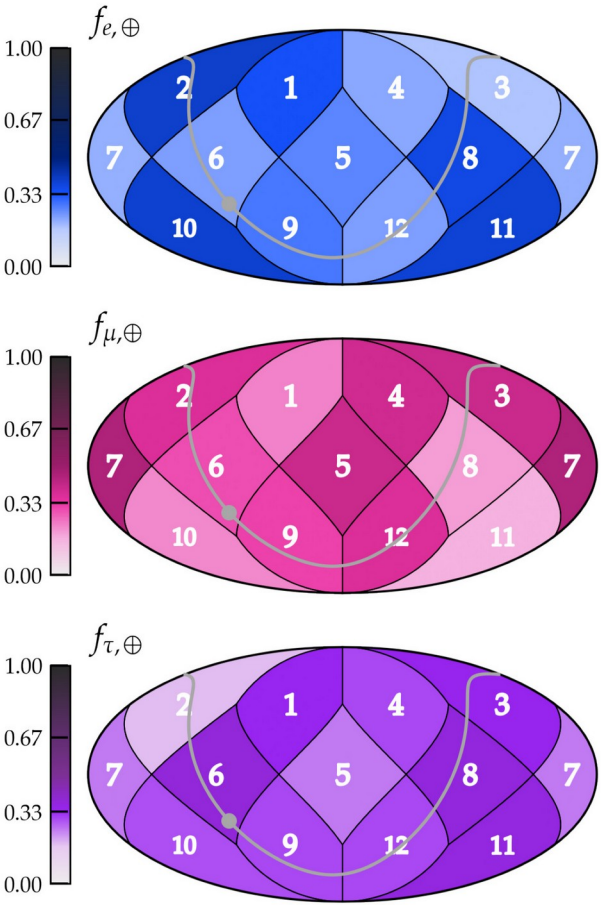
Upper limits from accelerator ν (MINOS): $< 10^{-20}$–10^{-15} GeV^{-1}

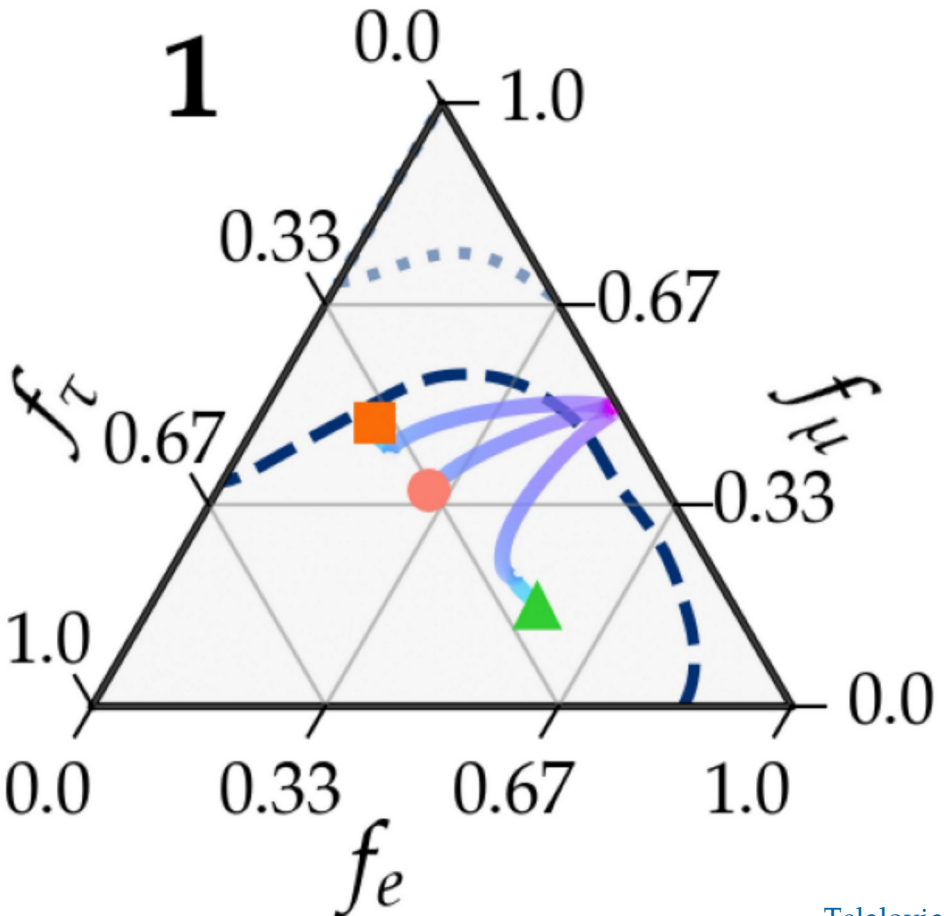
Upper limits from 7.5-year HESE: $< 10^{-34}$ GeV^{-1}

Telalovic, **MB**, 2310.15224

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

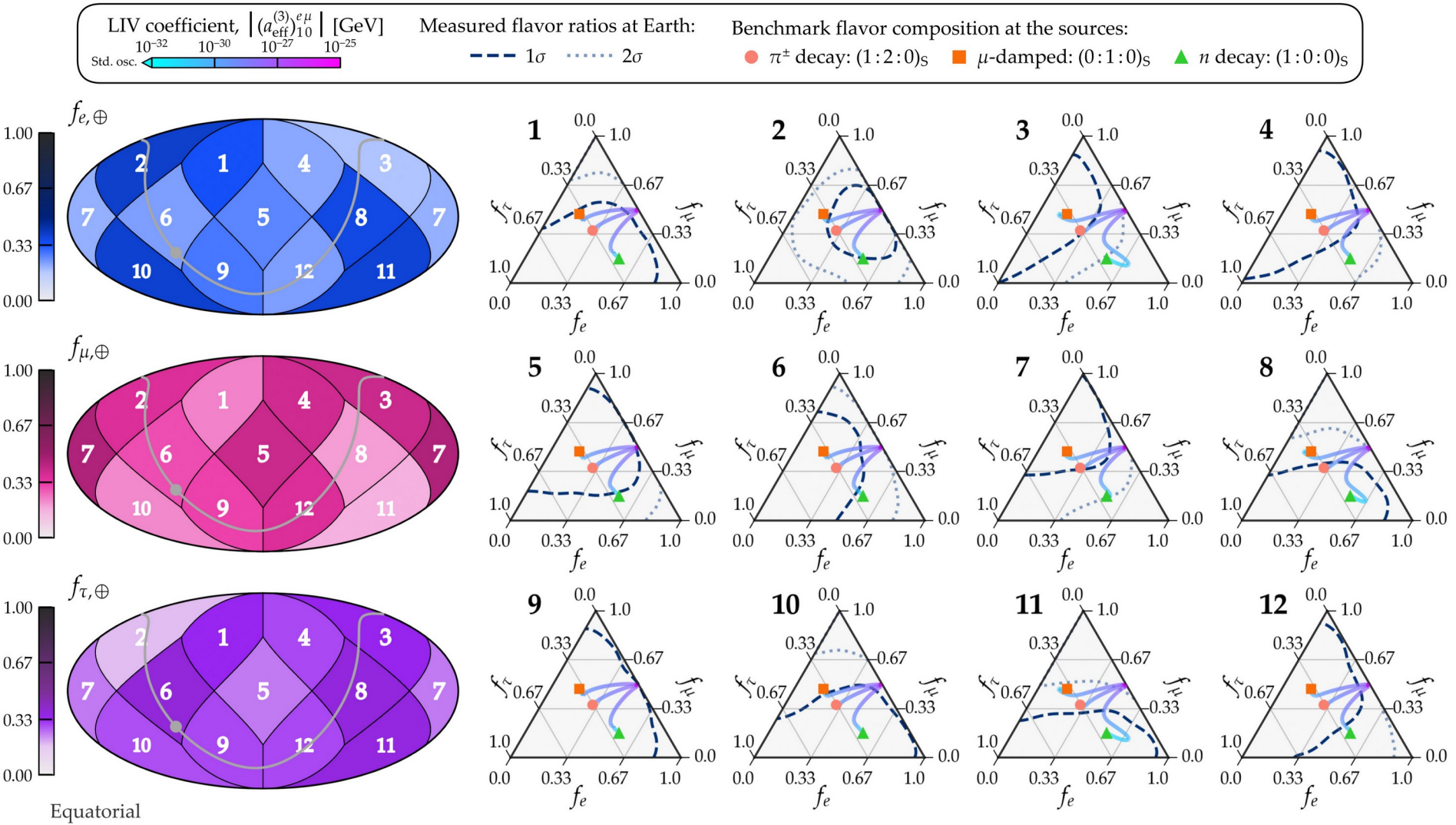




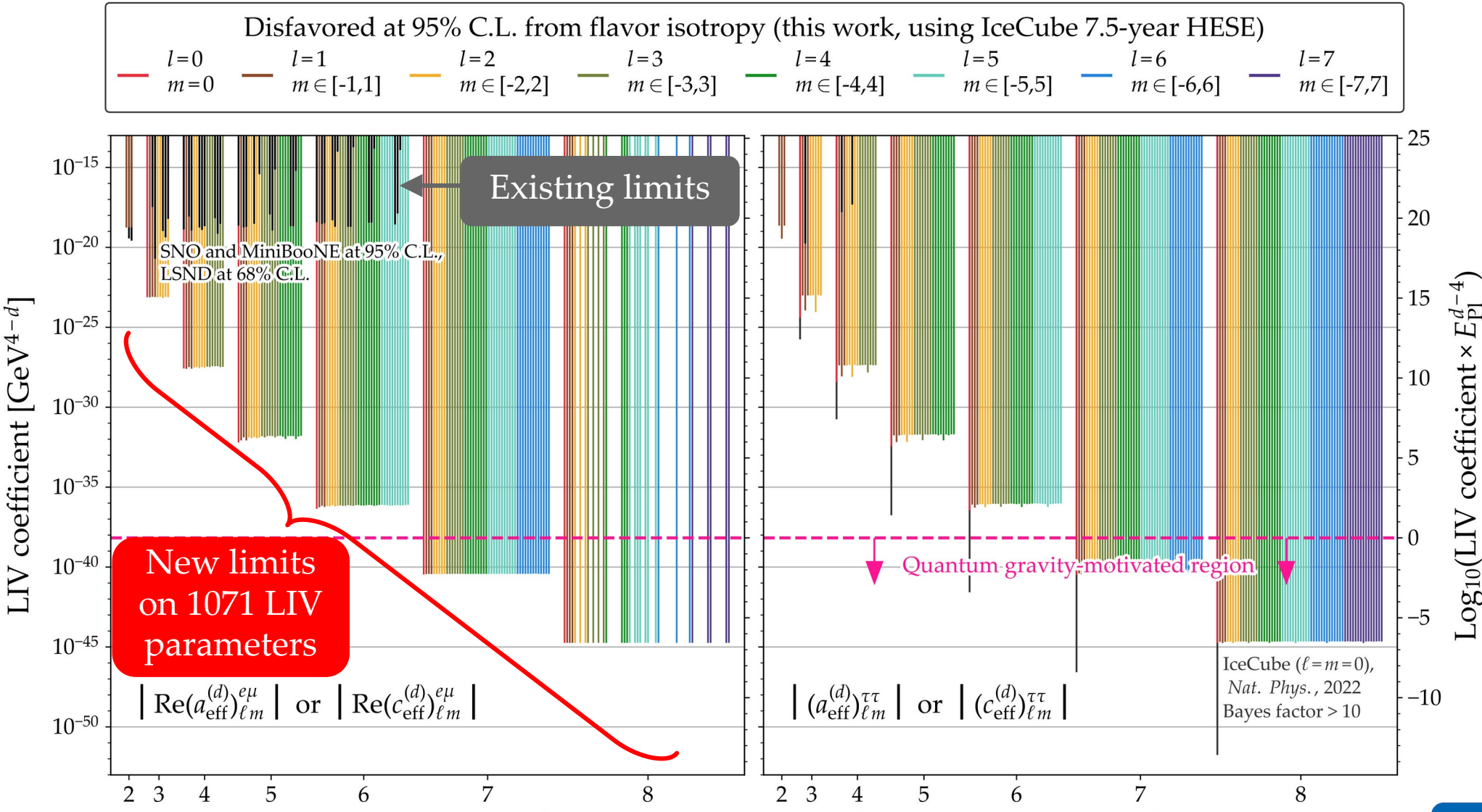


Telalovic, MB, 2503.15468

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

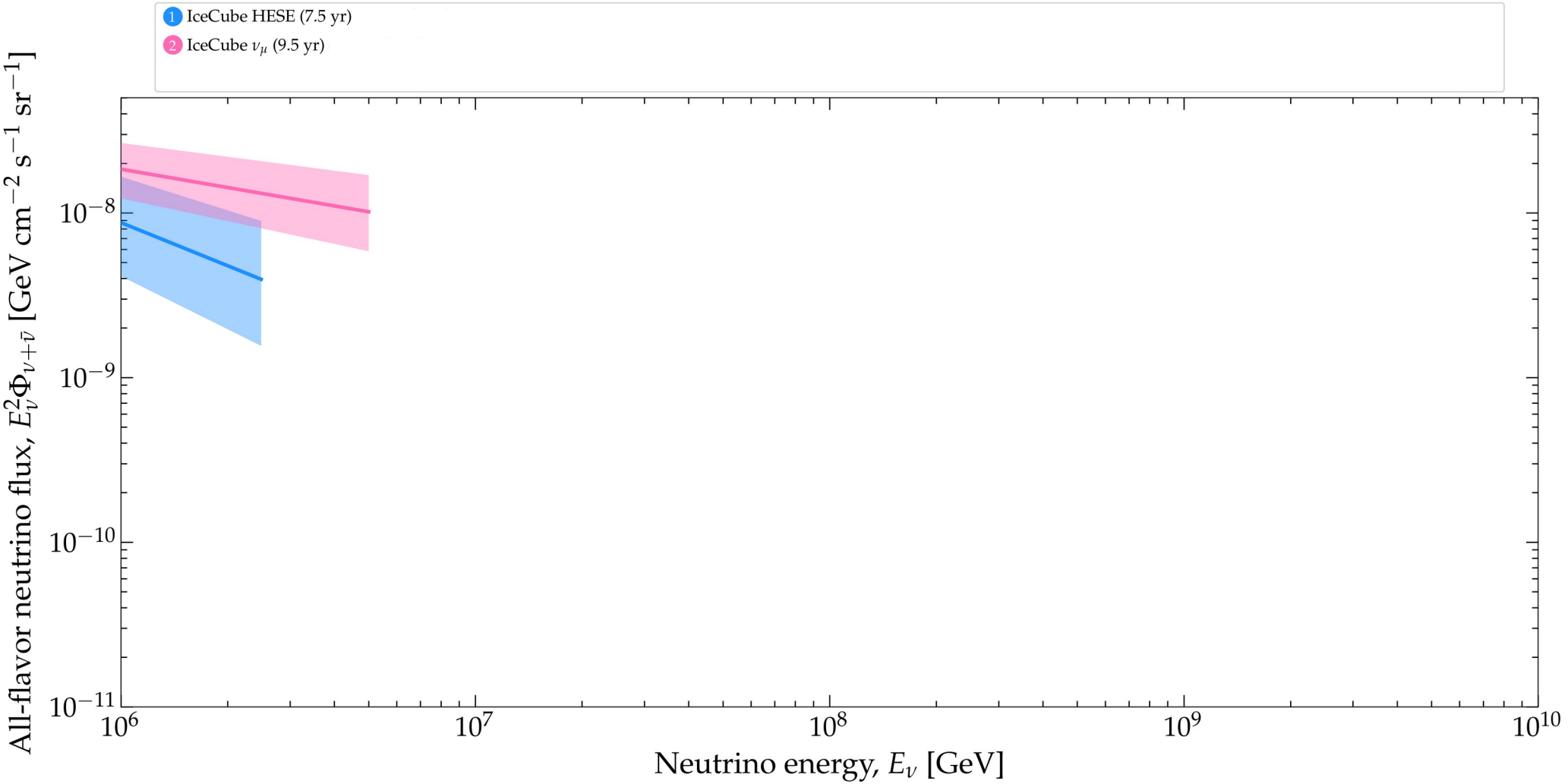


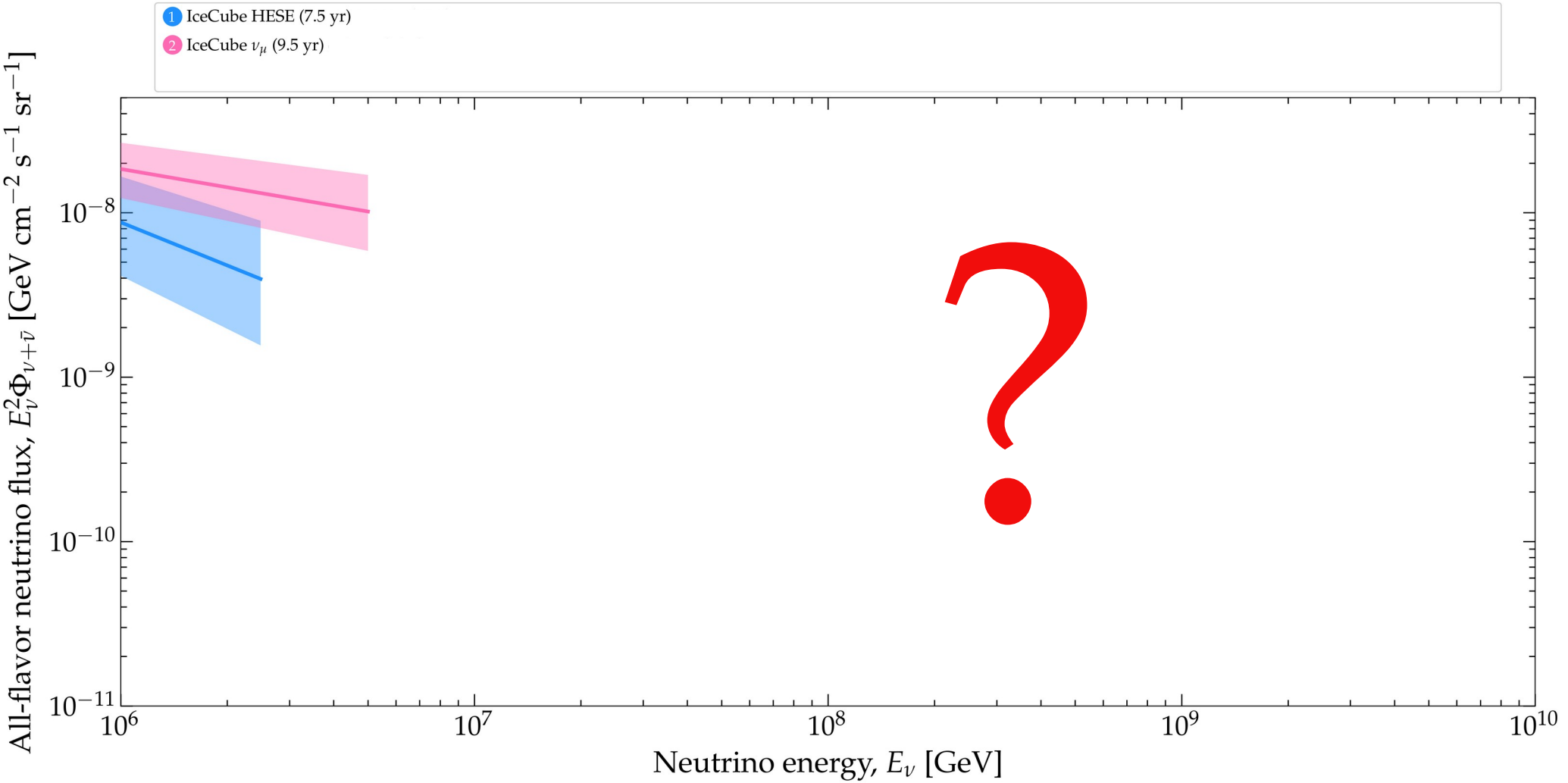
Telalovic, MB, 2503.15468



Telalovic, MB, 2503.15468

Prospects at ultra-high energies


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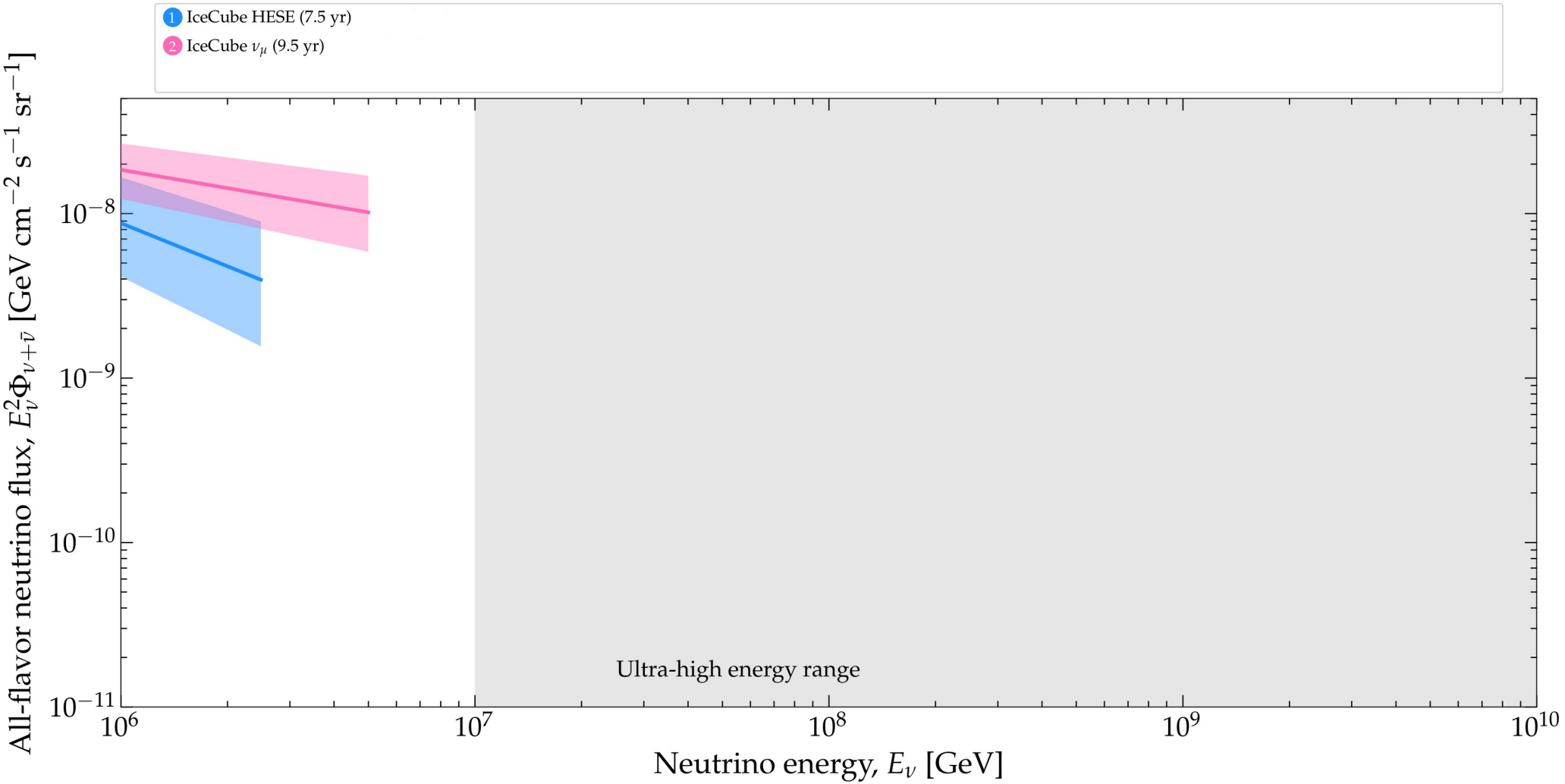
10^{-11}
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]
?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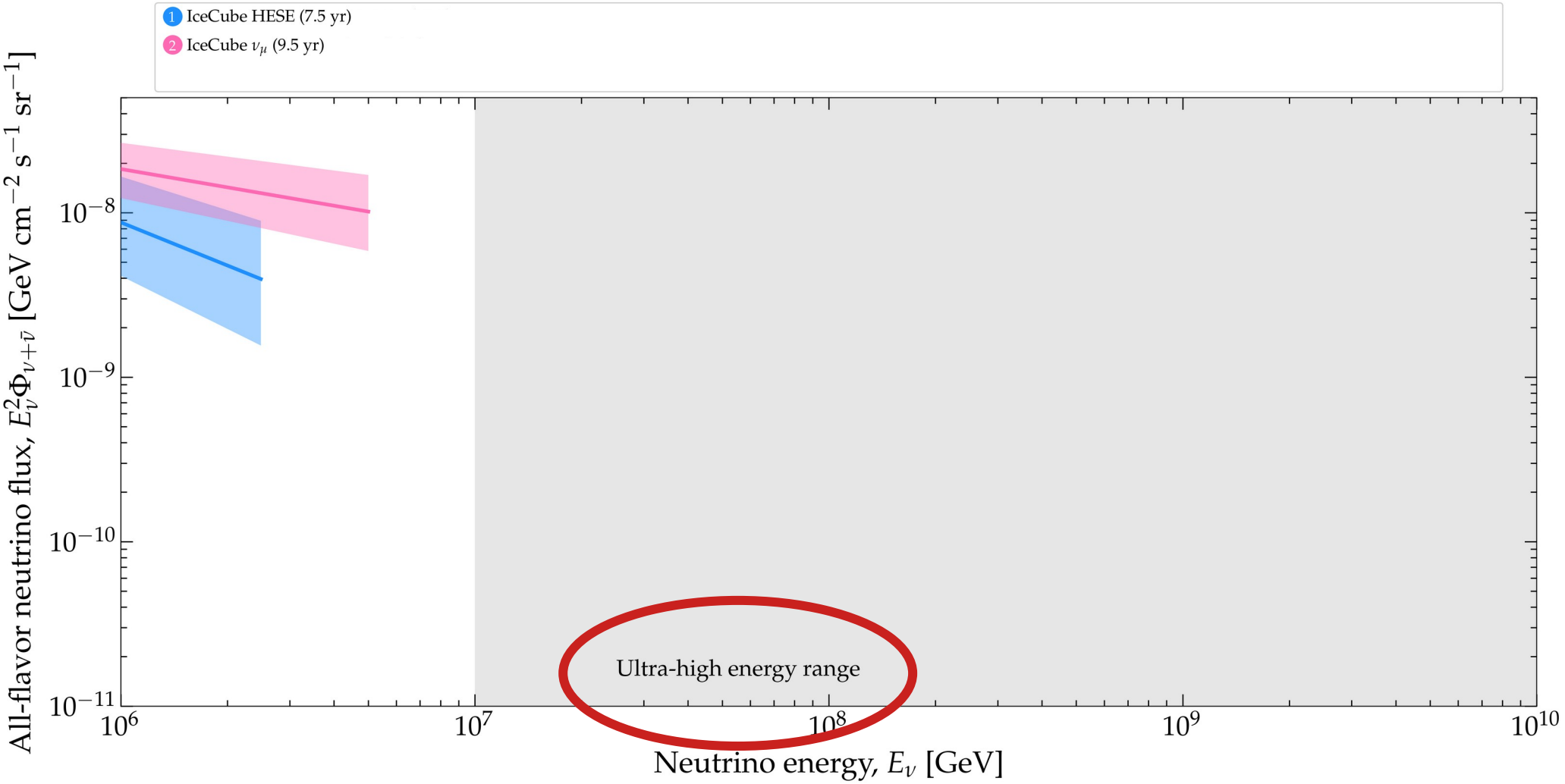
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
Ultra-high energy range
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]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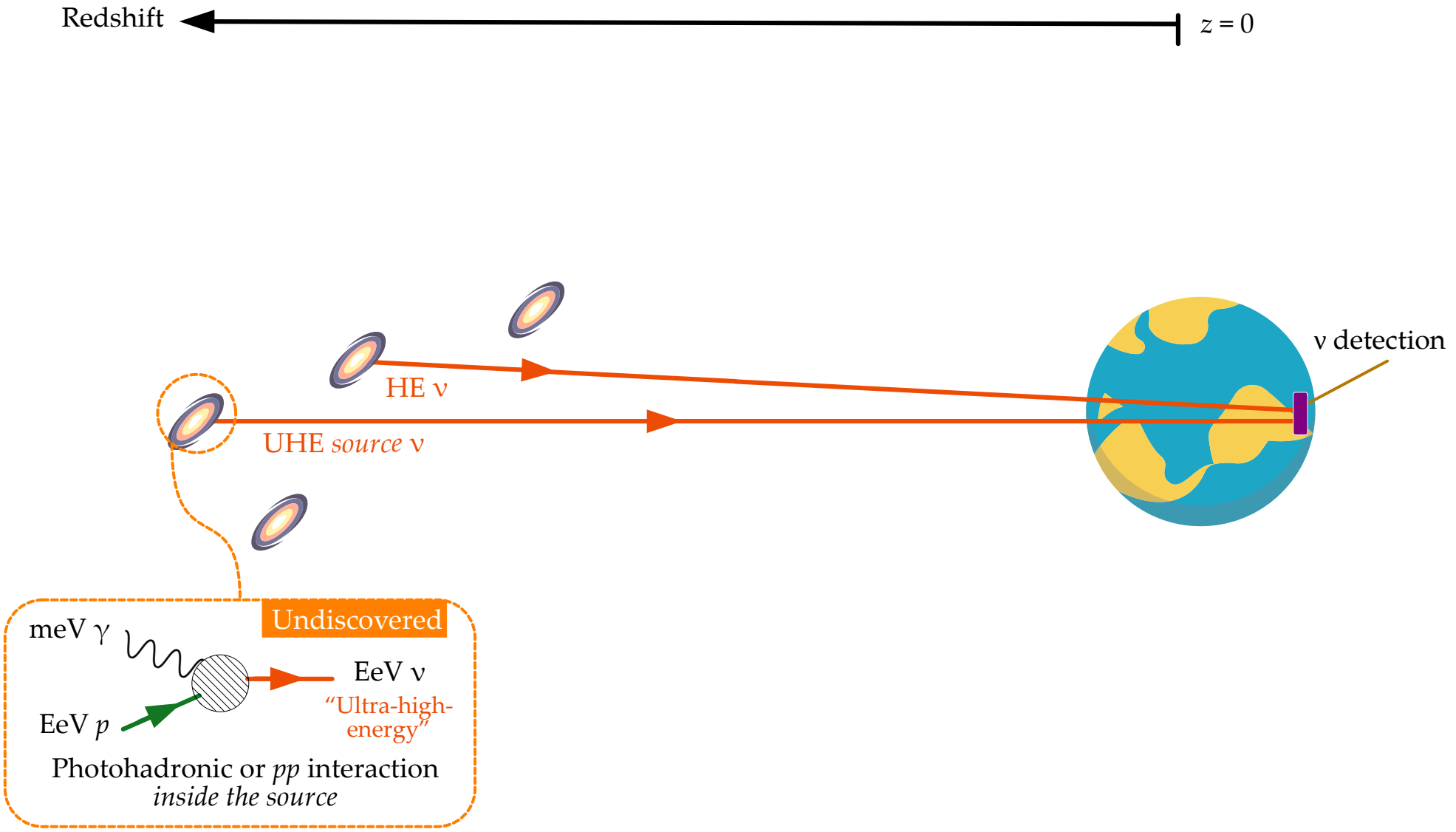
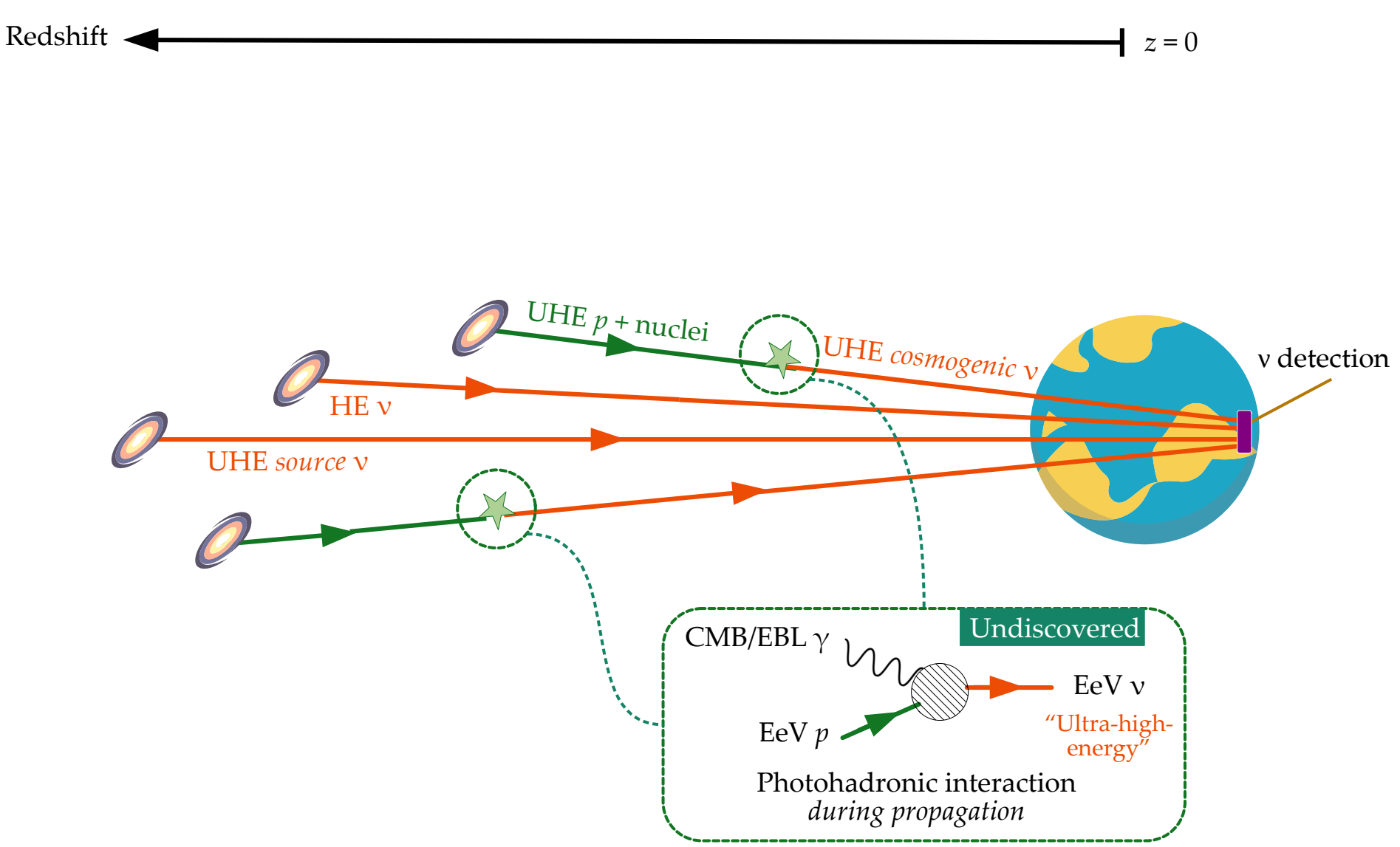
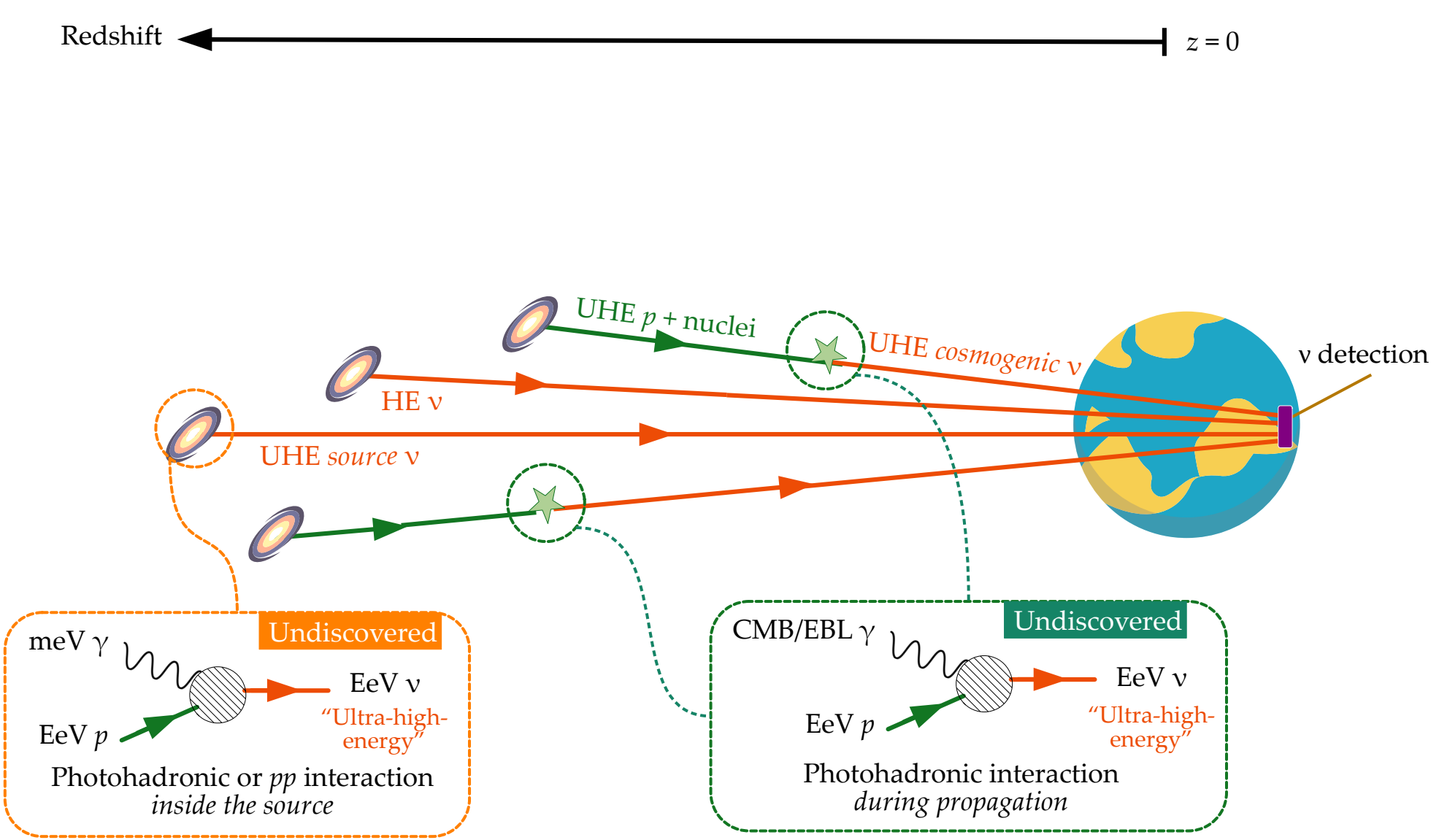

Redshift
$z = 0$
HE ν
UHE *source* ν
ν detection
Undiscovered
meV γ
EeV ν
"Ultra-high-energy"
EeV *p*
Photohadronic or *pp* interaction
inside the source


Redshift
z = 0
UHE p + nuclei
UHE cosmogenic ν
ν detection
HE ν
UHE source ν
Undiscovered
CMB/EBL γ
EeV ν
EeV p
"Ultra-high-energy"
Photohadronic interaction
during propagation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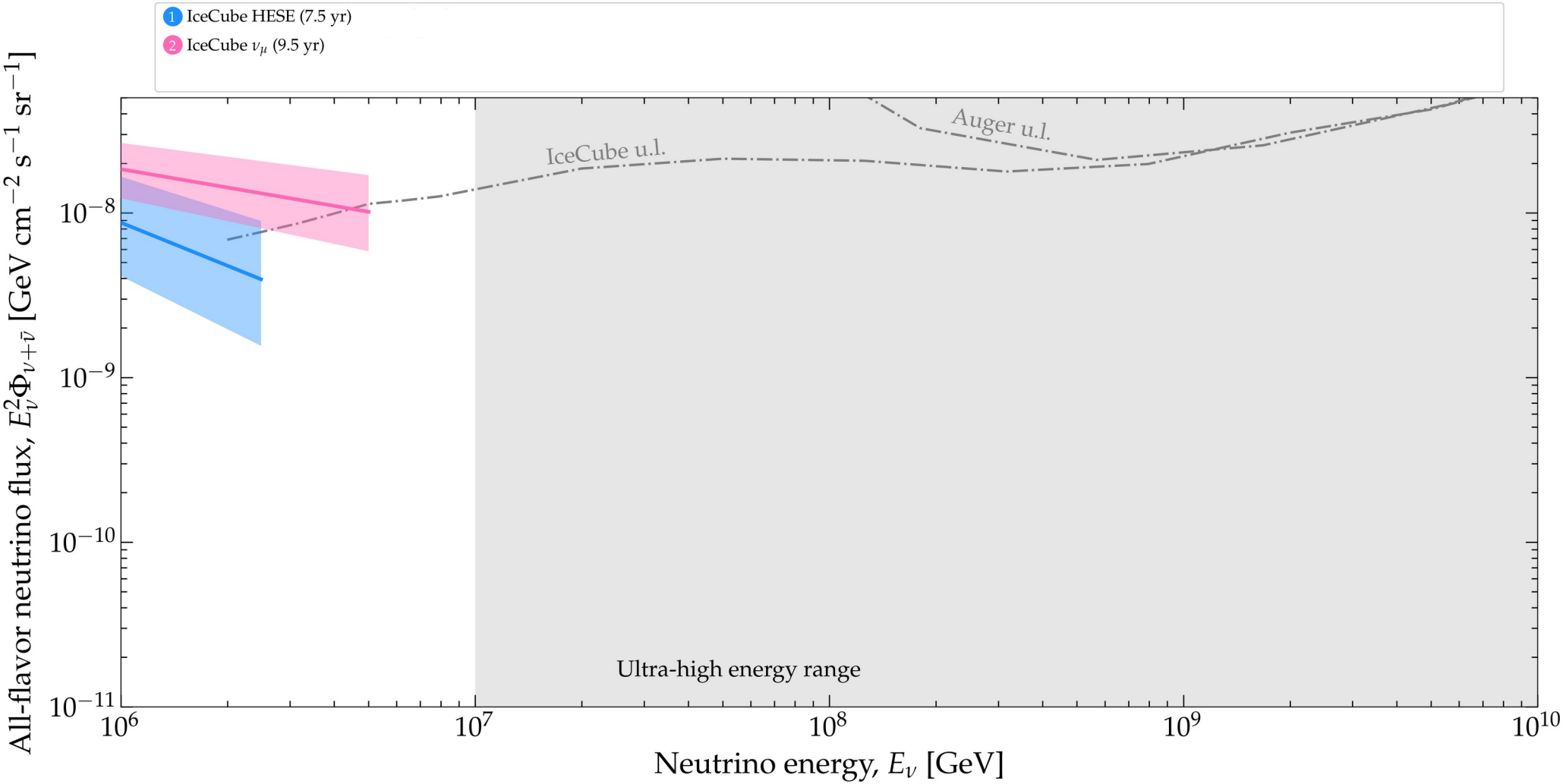
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New physics from the first UHE neutrino

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

Article

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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

BSM models in connection to KM3-230213A

Lorentz-invariance violation

Superluminal neutrinos (2502.09548, 2502.12070, 2502.18256)
Time delay (14 years!) *vs.* gamma rays from a GRB (2502.13093, 2503.14471)
From the muon surviving enhanced $\mu \to e + \gamma$ while traveling underground (2502.13201)

Decay of heavy dark matter

Decay of 400-PeV DM (2503.00097, 2503.04464, 2503.14332, 2503.18737, 2504.01447)
Heavy scalar decays into sterile ν that decays into active ν (2503.07776)

Sterile-active neutrino transition

Motivated by observation in KM3NeT, but not IceCube (2502.21299)

Primordial black hole evaporation

Possibly with "memory burden" to lengthen PBH life (2502.19245, 2503.19227, 2503.21740)

Mirror neutrons

UHE $n' \to n \to \nu$ reconciles heavy UHECR masses with high cosmogenic ν flux (2503.14419)

Do we live in a simulation? (2504.08461)

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

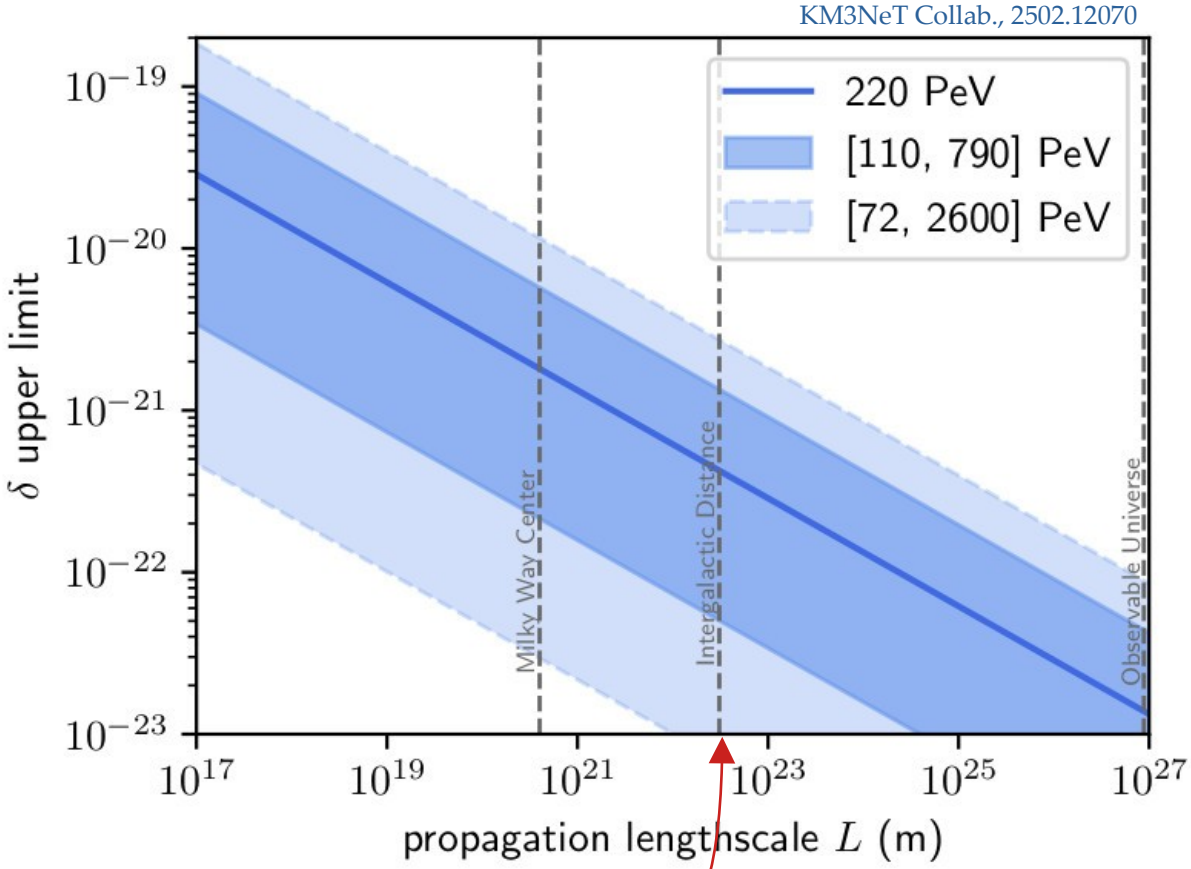
Excess over light speed: $\delta = c_\nu - 1$

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., 2502.12070



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

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

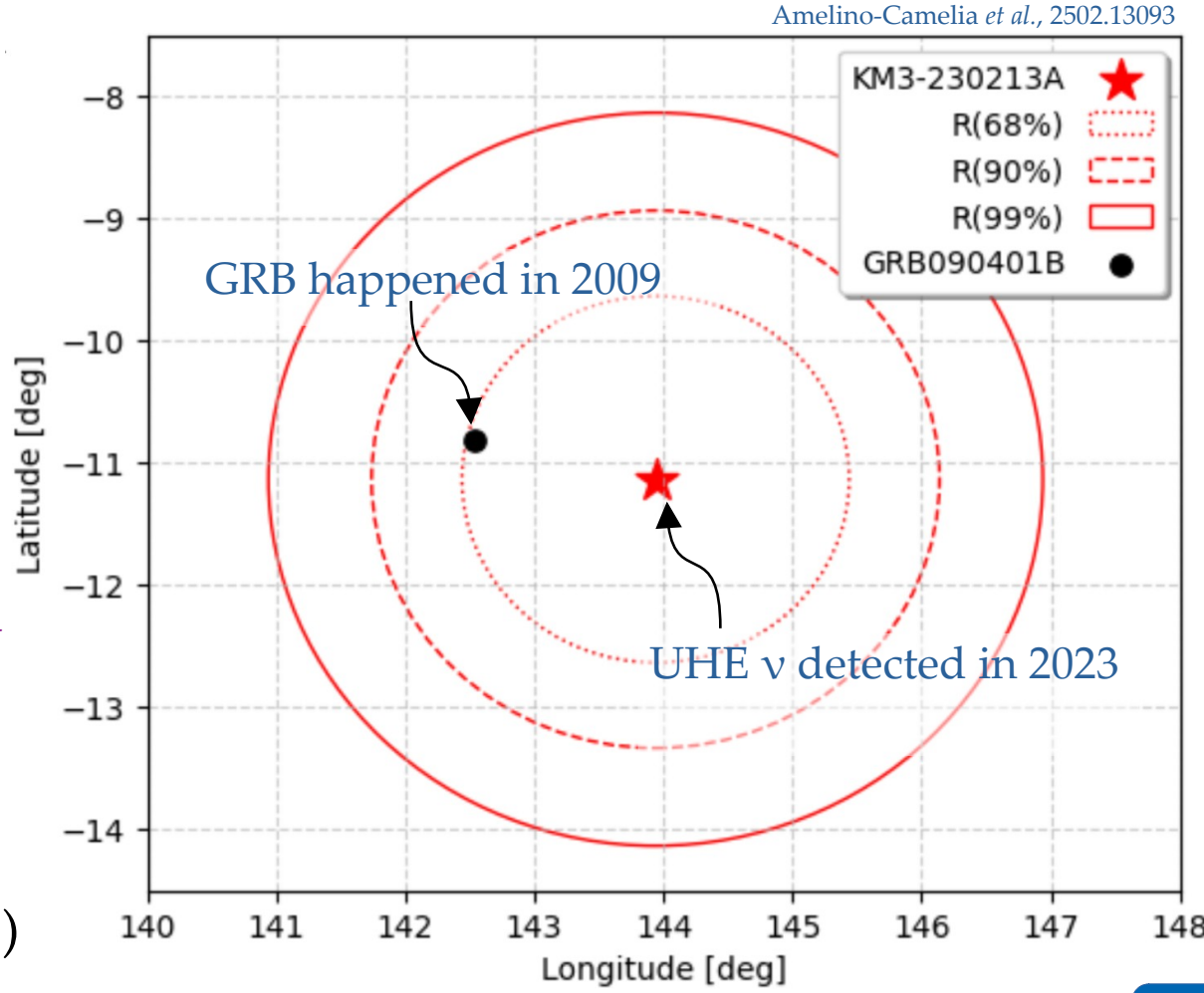
Cosmological expansion

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

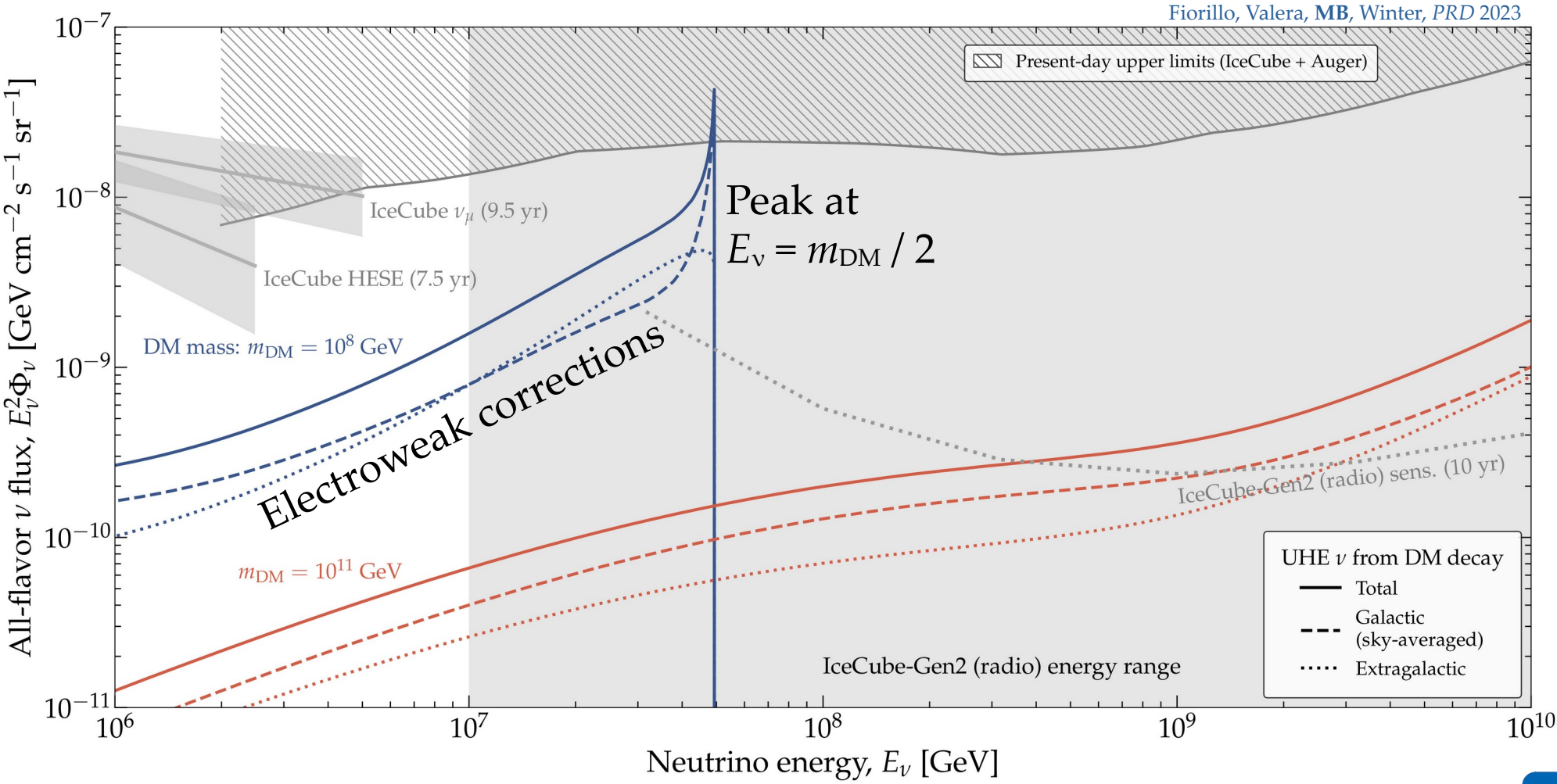
GRB-ν association: 2.4σ

(p-value of 0.015)

Amelino-Camelia *et al.*, 2502.13093



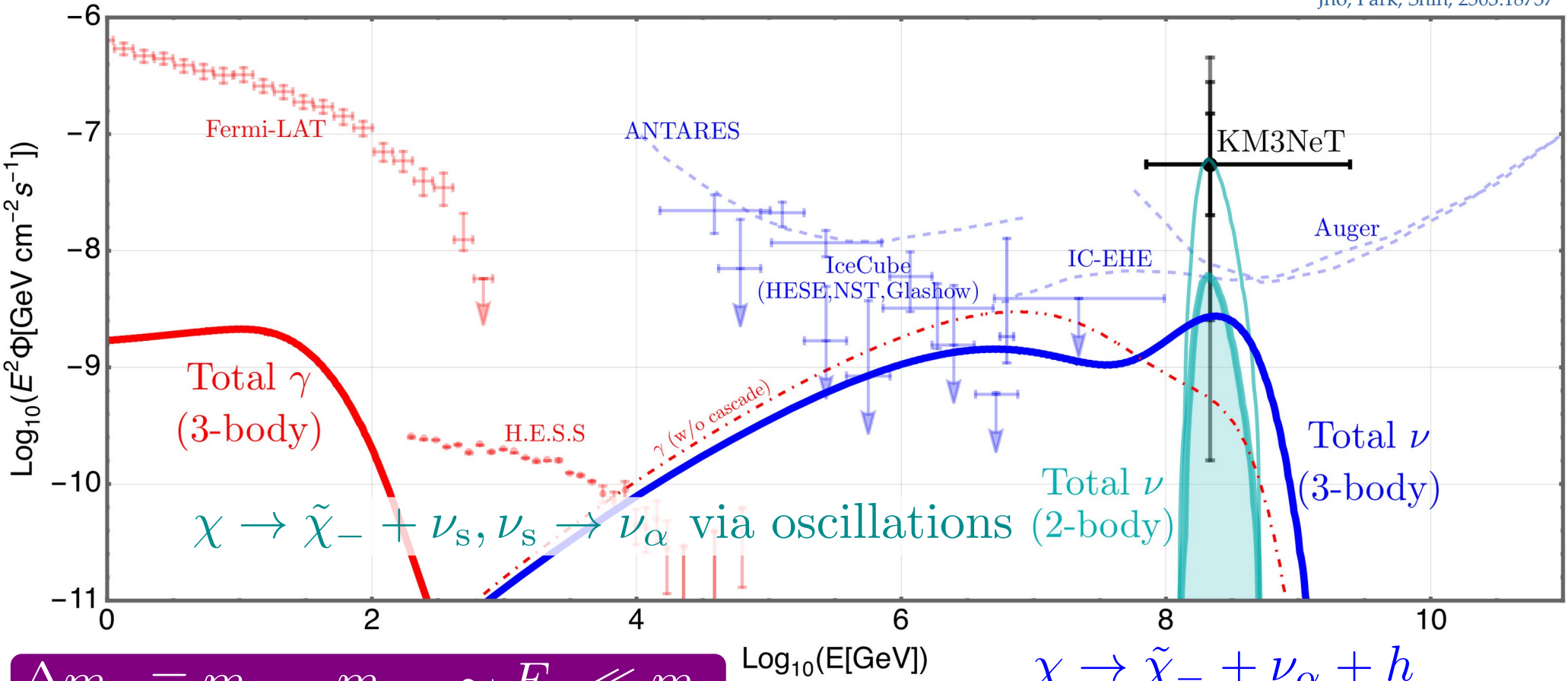
Decay of heavy dark matter (DM → ν + ν)



Decay of heavy dark matter — supersymmetric

Multi-component DM: heavy (χ, unstable) & lighter ($\tilde{\chi}_-$, stable)

Jho, Park, Shin, 2503.18737

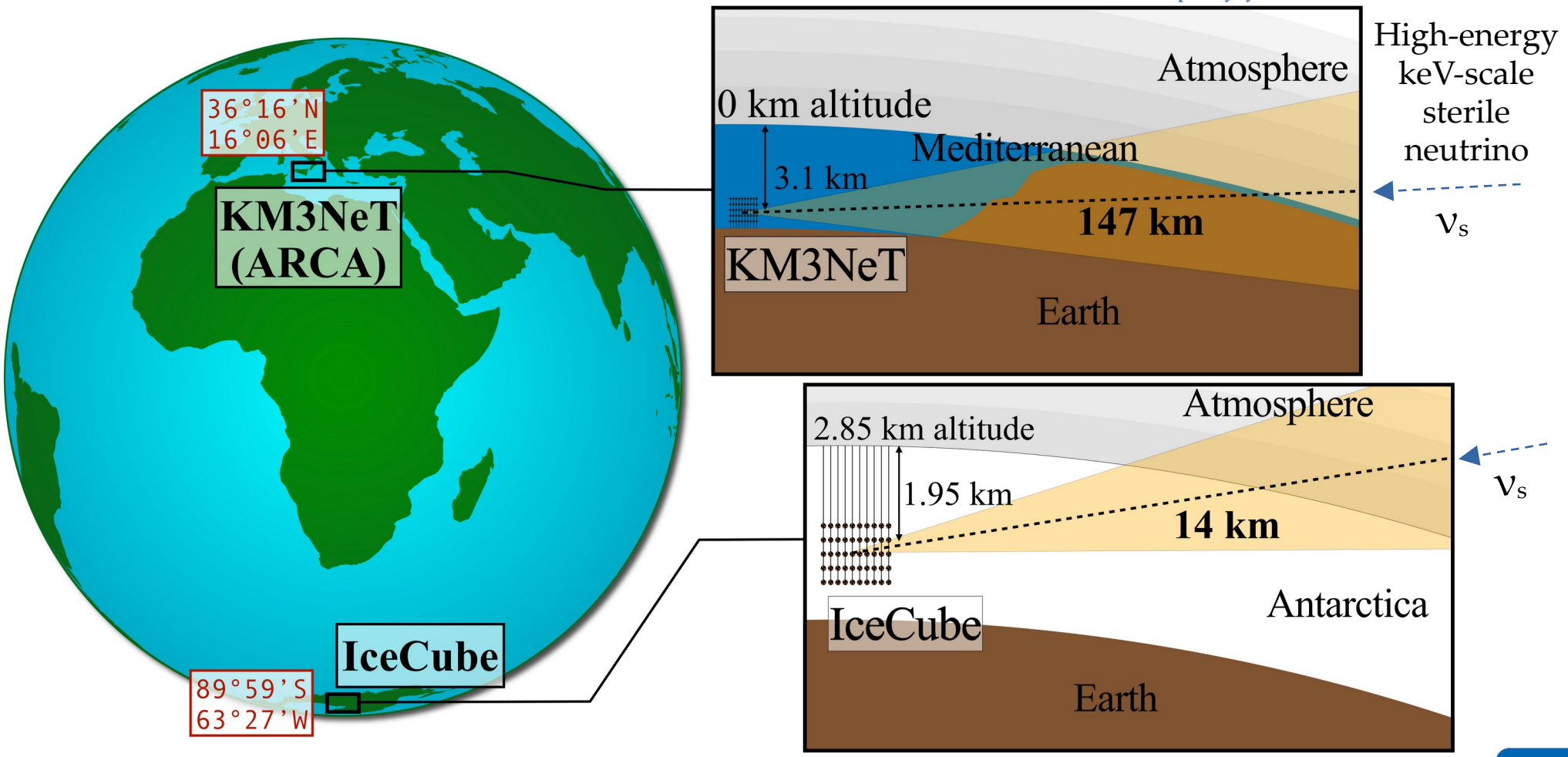


$$\Delta m_\chi \equiv m_\chi - m_{\tilde{\chi}_-} \sim E_\nu \ll m_\chi$$

$\chi \to \tilde{\chi}_- + \nu_\alpha + h$
(Higgs decays into γ)

Sterile-active ν transitions

Brdar & Chattopadhyay, 2502.21299



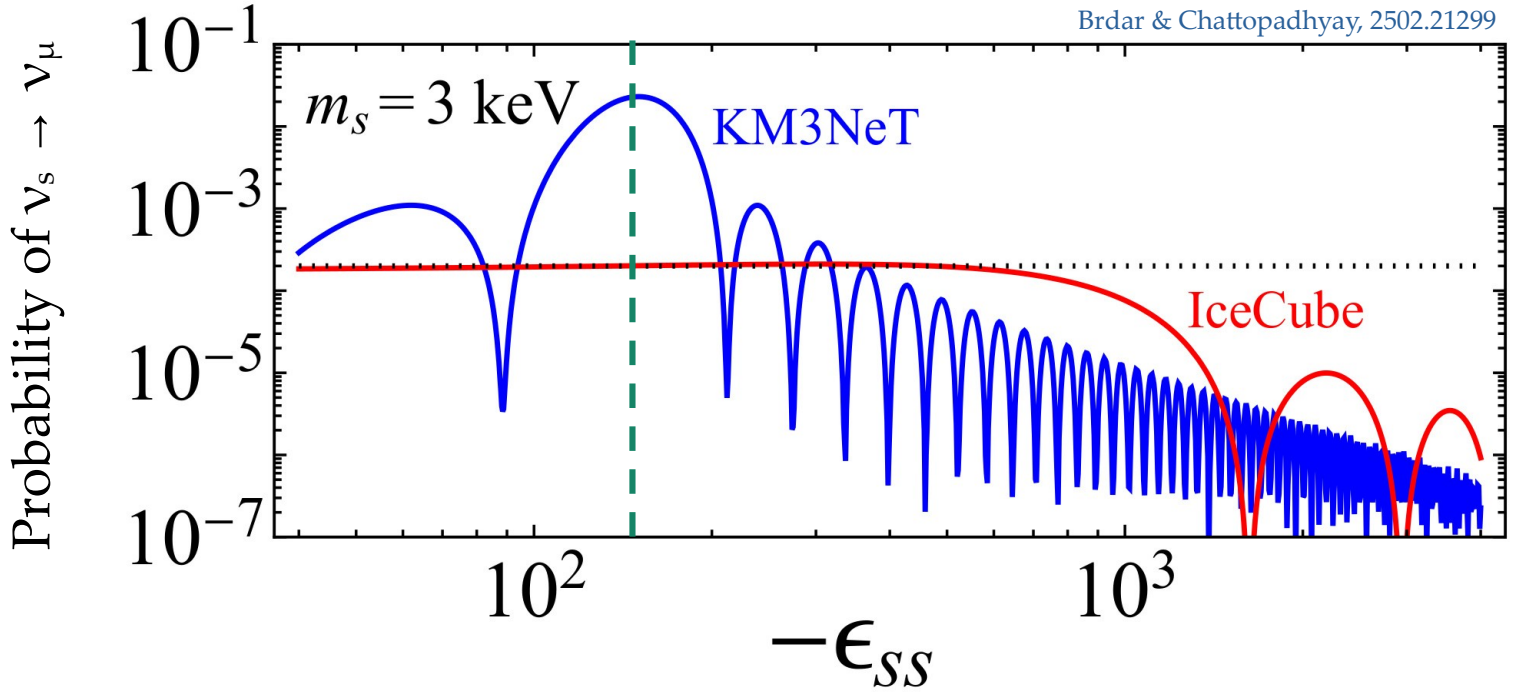
Sterile-active ν transitions

New neutrino-baryon interactions inside Earth (by gauging $U(1)_B$ symmetry)

Relative strength *vs.* standard weak interaction: $\epsilon_{ss} = G_B/(\sqrt{2}G_F)$

For -ϵ_{ss} = 150, transitions are resonant in KM3NeT, but not in IceCube

Brdar & Chattopadhyay, 2502.21299



Primordial black hole evaporation

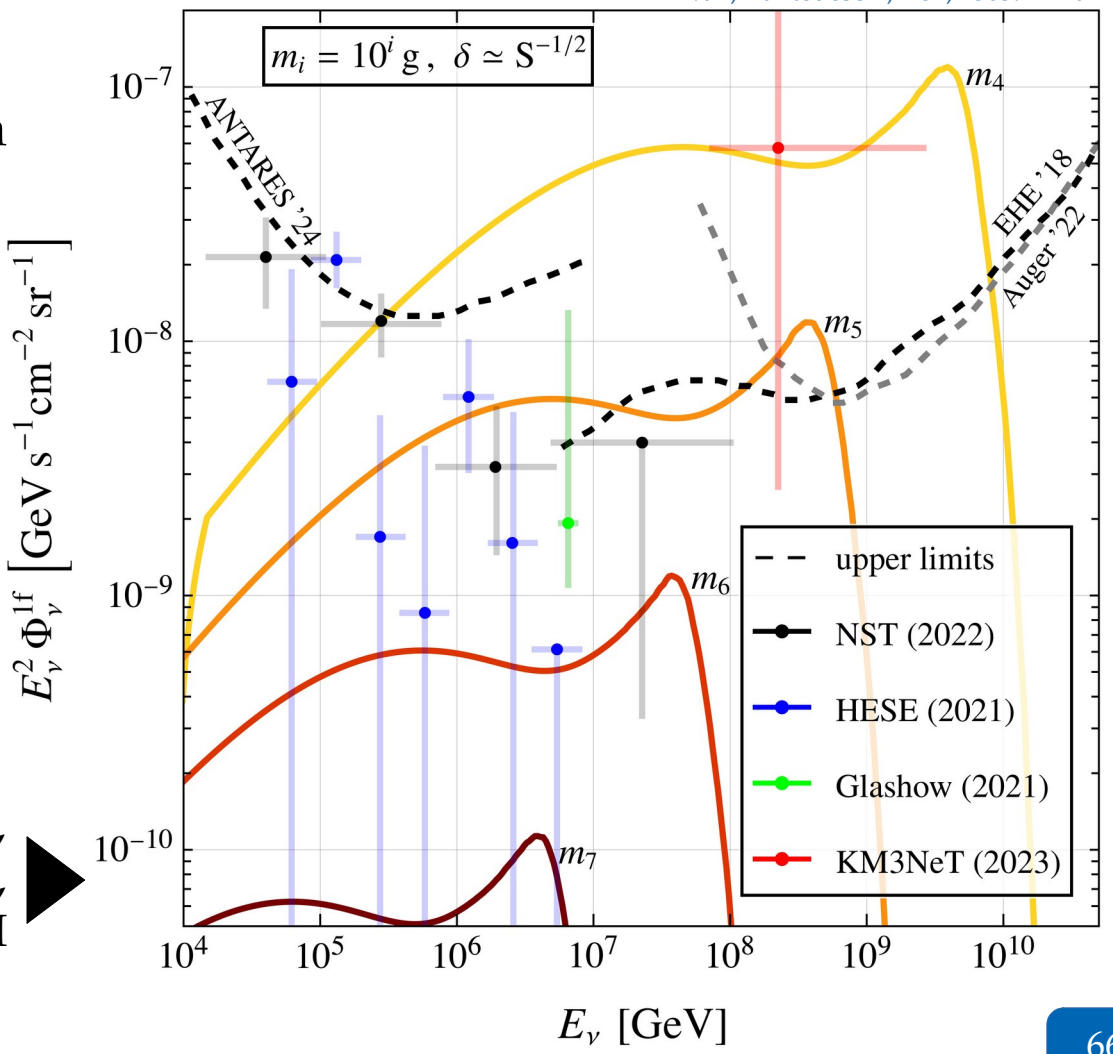
Primordial black holes (PBHs) evaporate through Hawking radiation

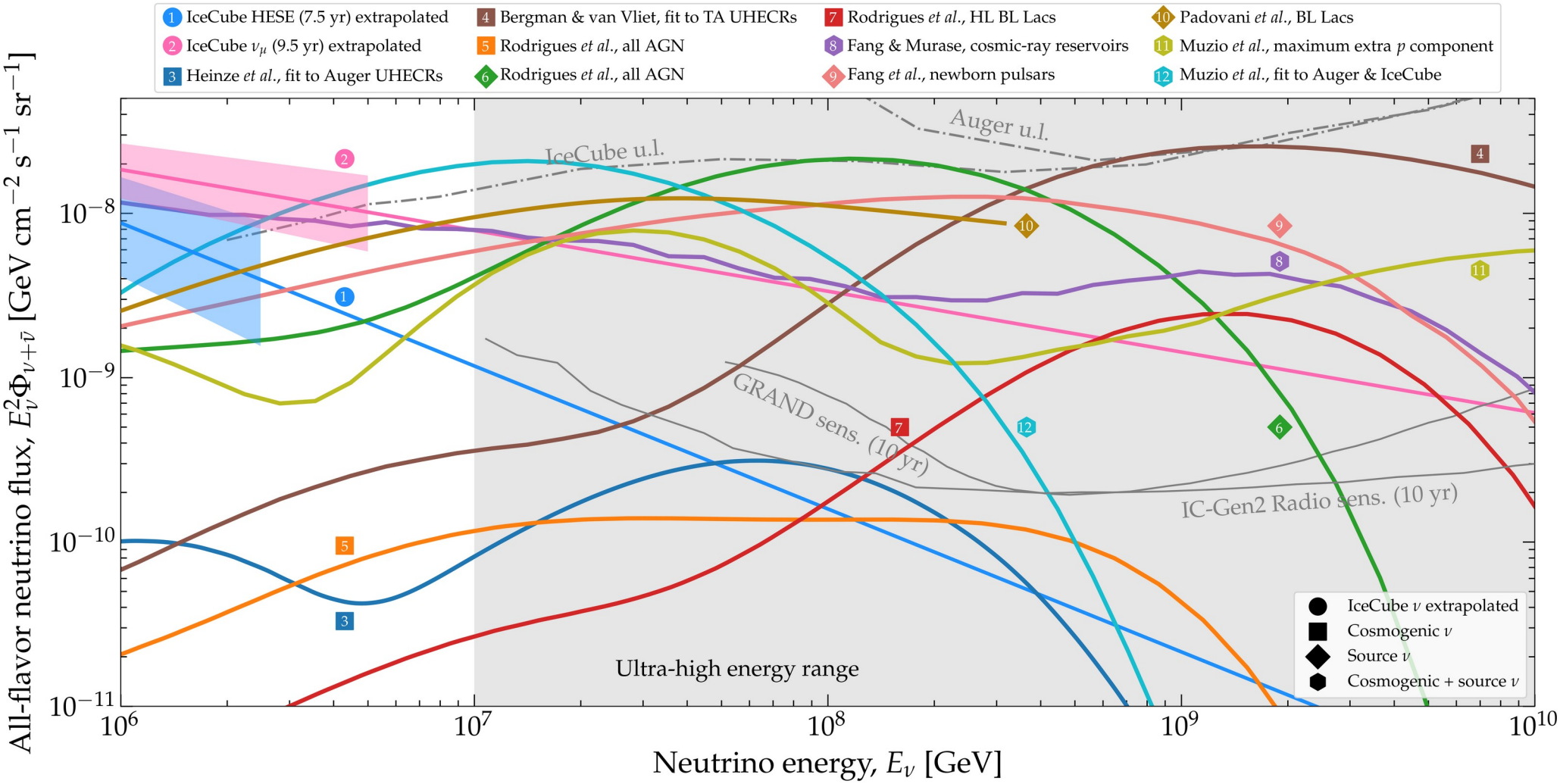
"Memory burden" effect: quantum back-reaction lengthens the life of the black hole

Most of the contribution is from intermediate-mass PBHs, transitioning to memory burden

Galactic + extragalactic contributions, monochromatic mass spectrum, PBHs make up all of DM

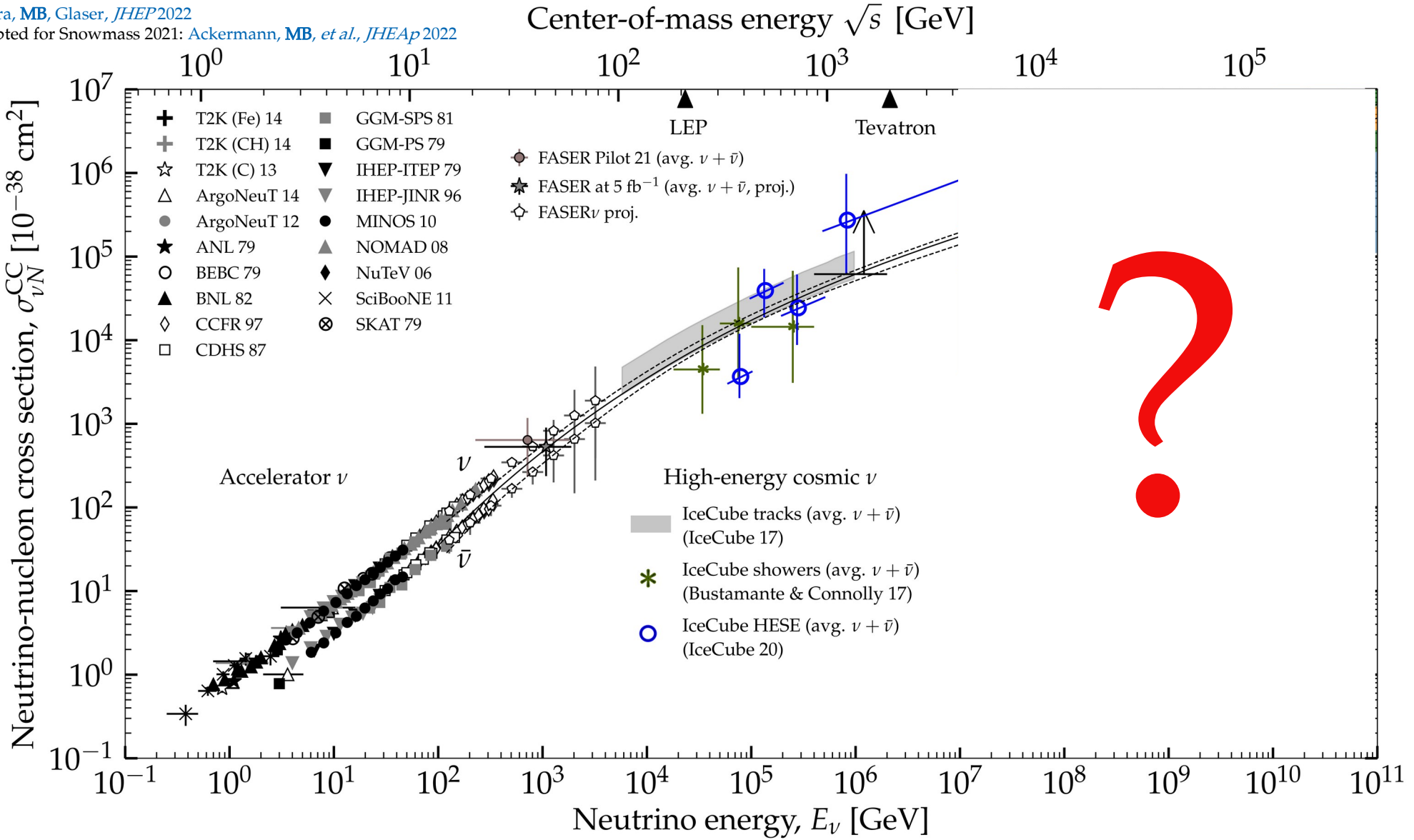
Dvali, Zantedeschi, Zell, 2503.21740



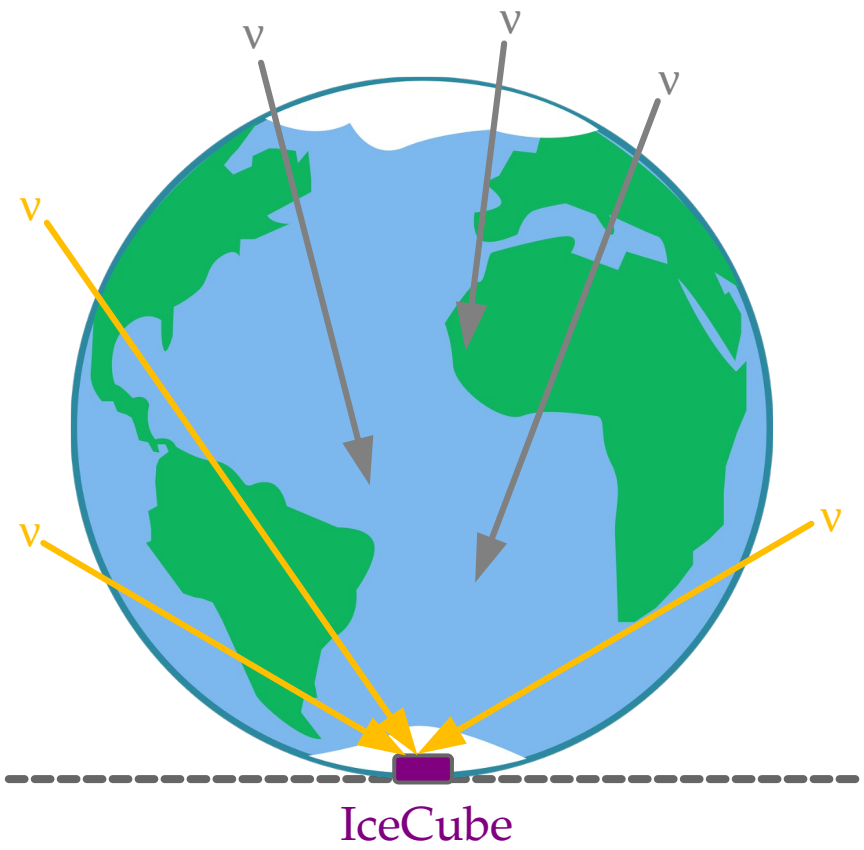

1 IceCube HESE (7.5 yr) extrapolated
2 IceCube ν_μ (9.5 yr) extrapolated
3 Heinze et al., fit to Auger UHECRs
4 Bergman & van Vliet, fit to TA UHECRs
5 Rodrigues et al., all AGN
6 Rodrigues et al., all AGN
7 Rodrigues et al., HL BL Lacs
8 Fang & Murase, cosmic-ray reservoirs
9 Fang et al., newborn pulsars
10 Padovani et al., BL Lacs
11 Muzio et al., maximum extra p component
12 Muzio et al., fit to Auger & IceCube
IceCube u.l.
Auger u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
IceCube ν extrapolated
Cosmogenic ν
Source ν
Cosmogenic + source ν
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]

Neutrino cross section at ultra-high energies

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



TeV–PeV:



Earth is *almost fully* opaque,
some upgoing ν still make it through

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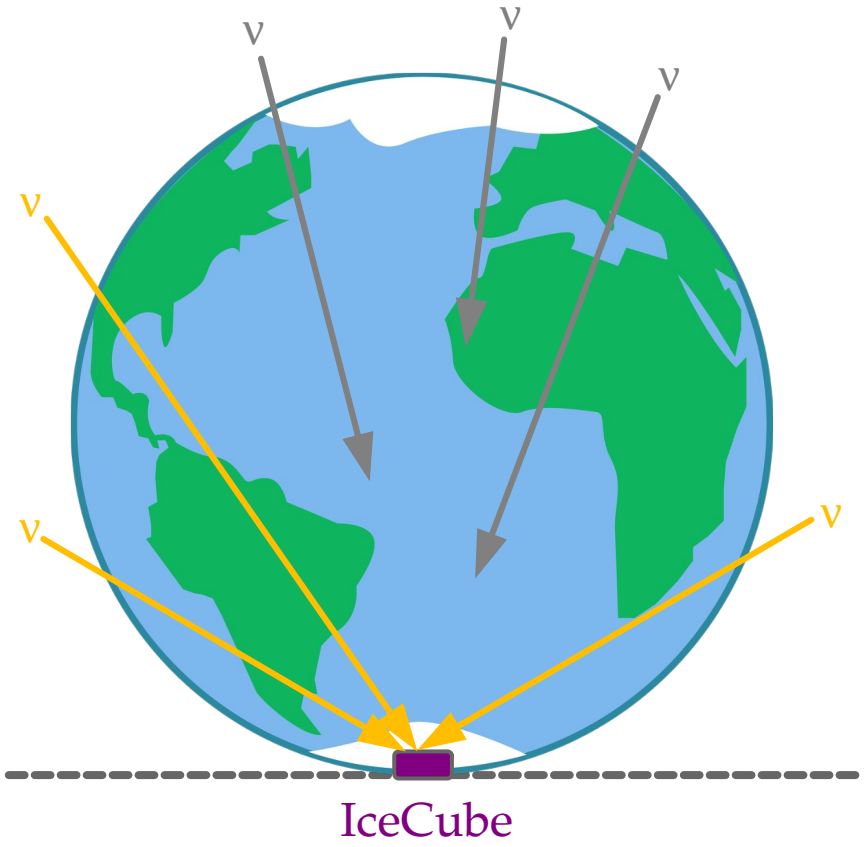

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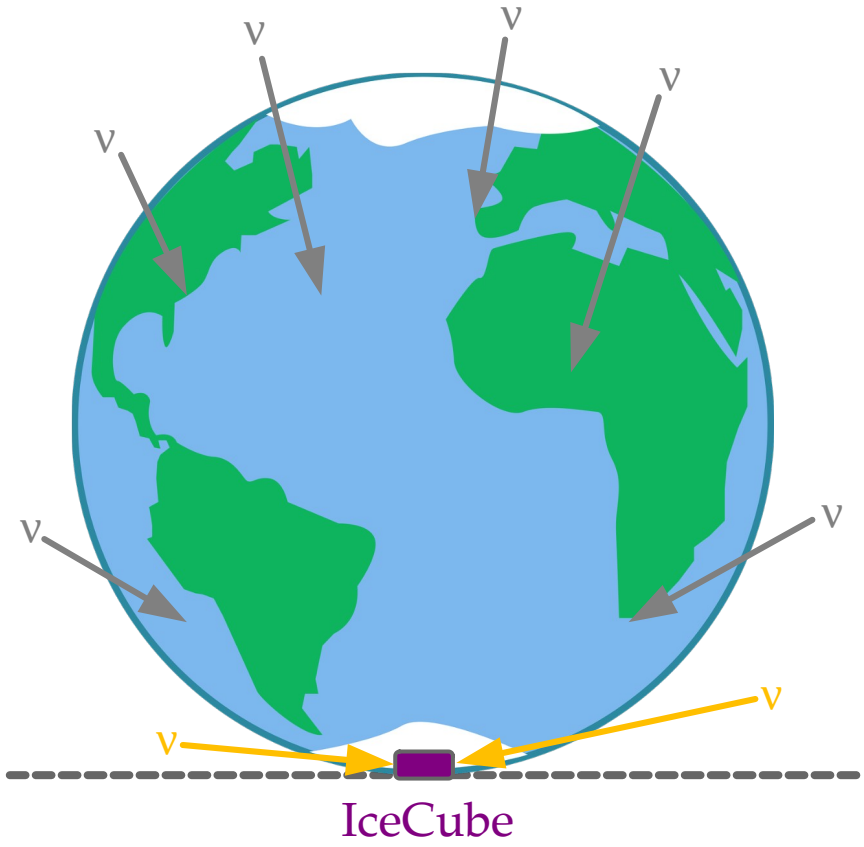
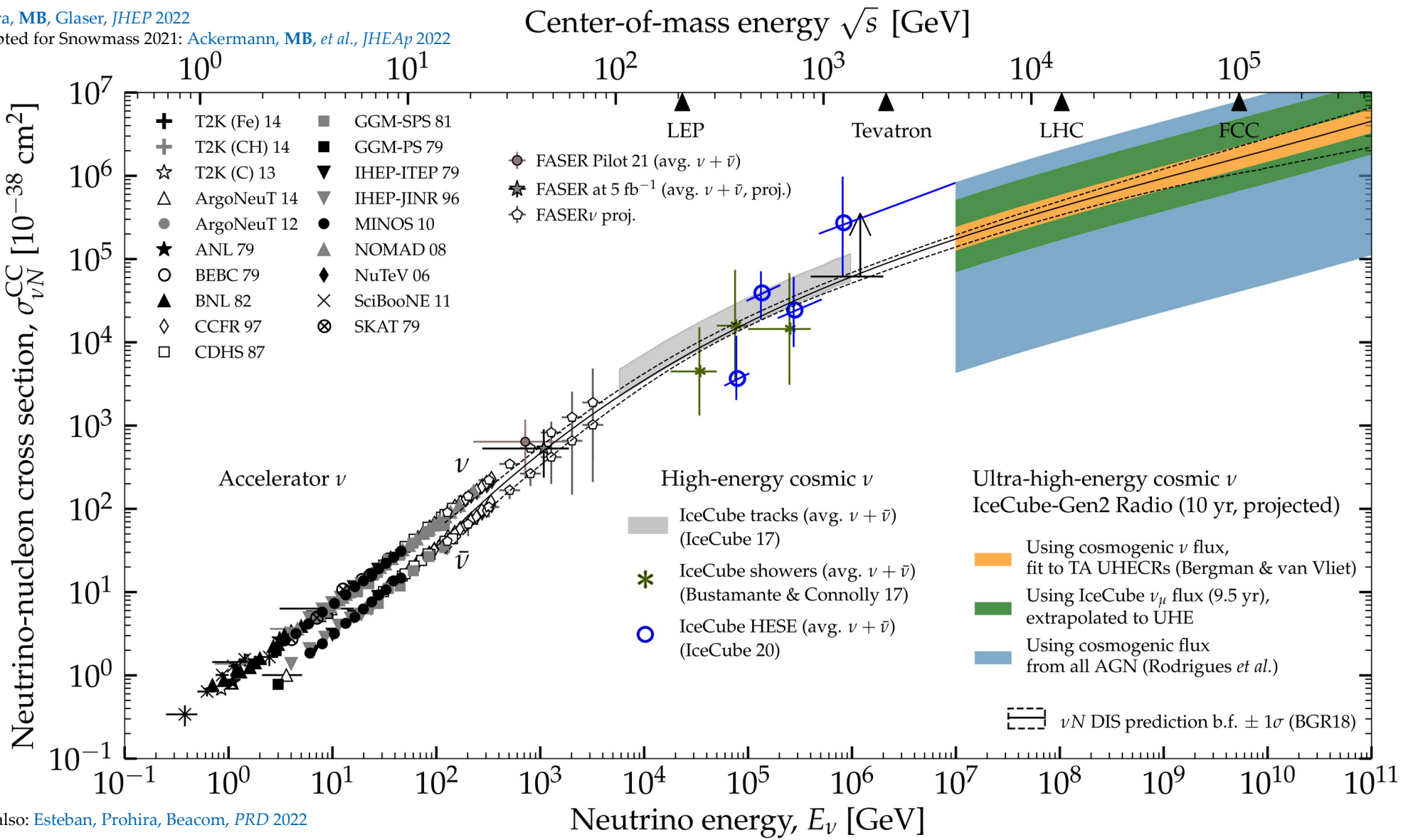
> 100 PeV:



Earth is *completely* opaque,
but horizontal ν still make it through

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



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

Valera, **MB**, Glaser, *JHEP* 2022
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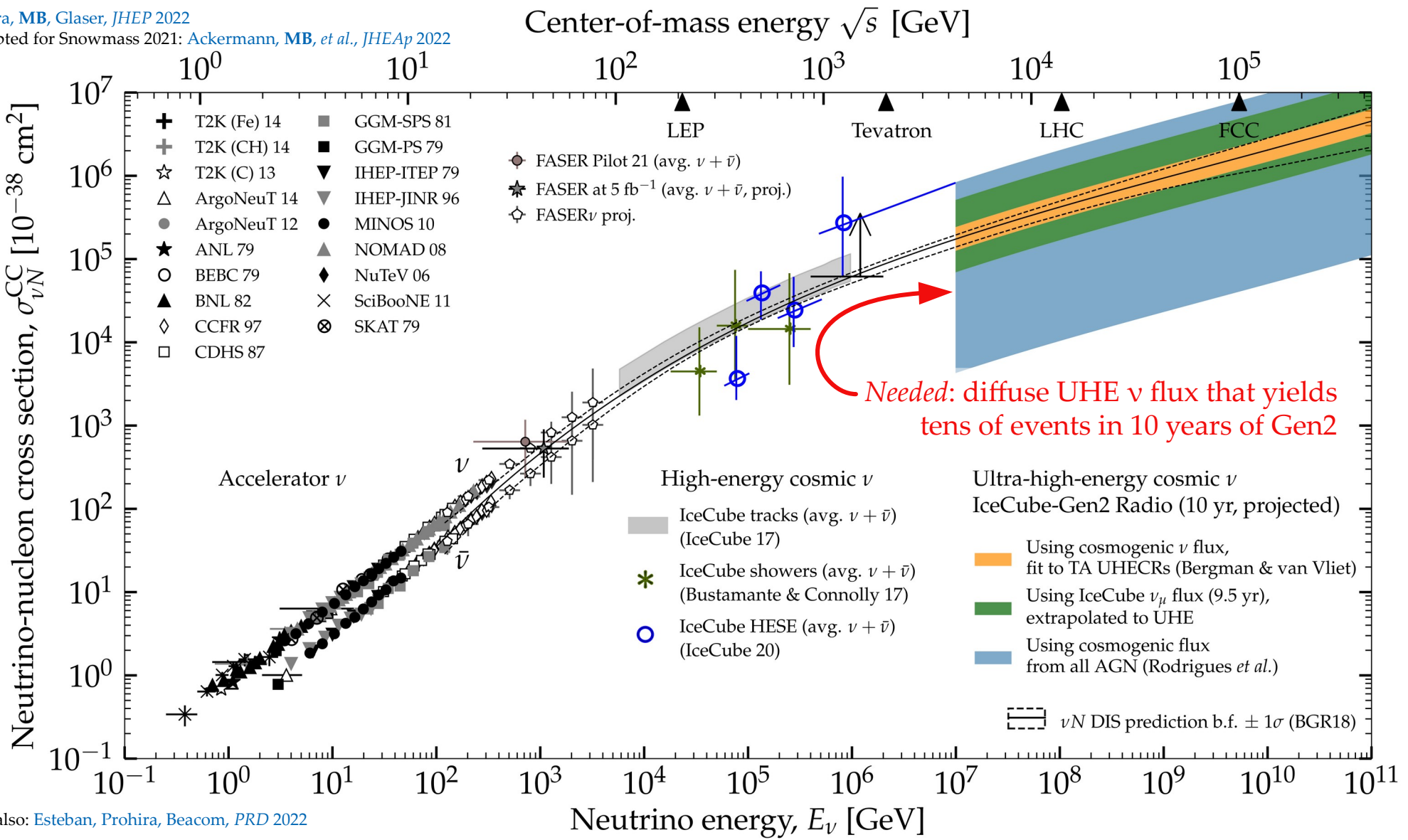


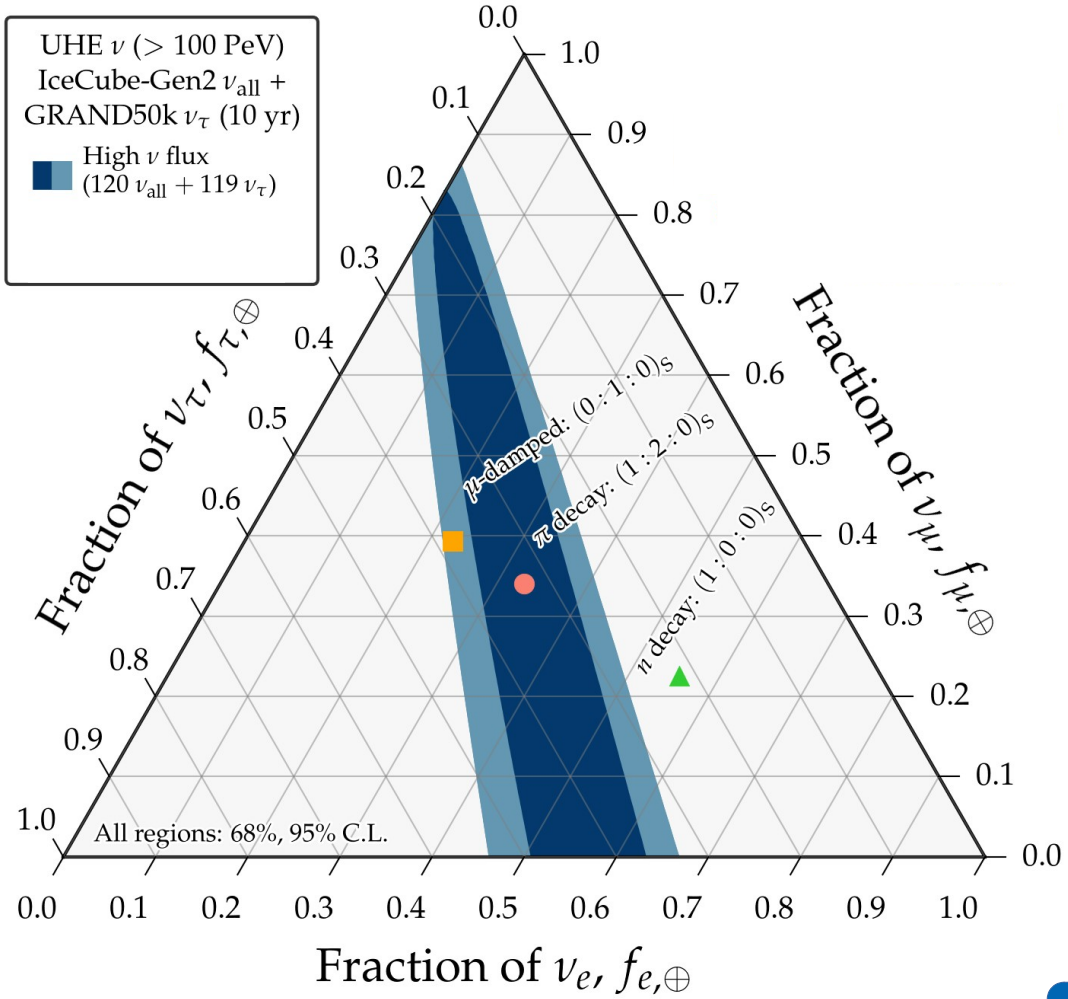
See also: Esteban, Prohira, Beacom, *PRD* 2022

Flavor at ultra-high energies

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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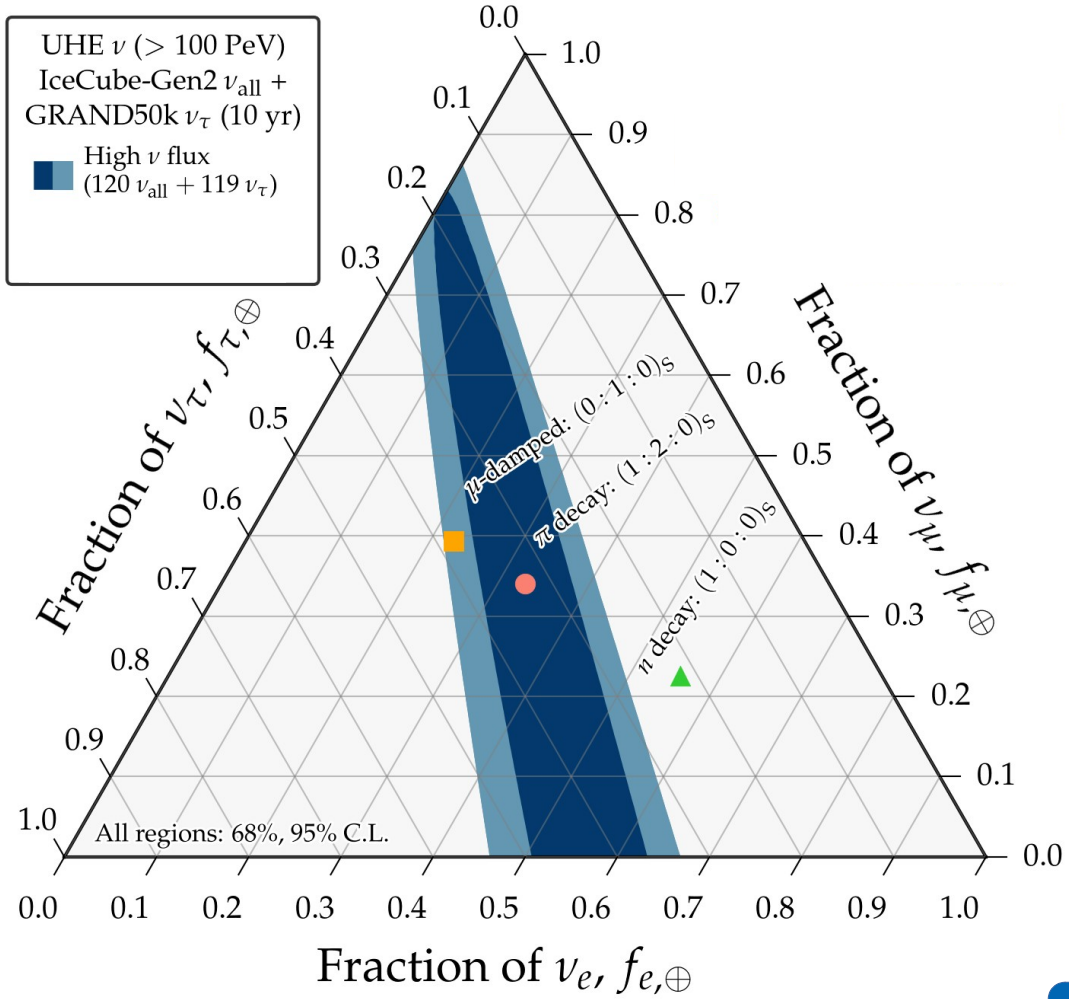

Testagrossa, Fiorillo, **MB**, *PRD* 2024

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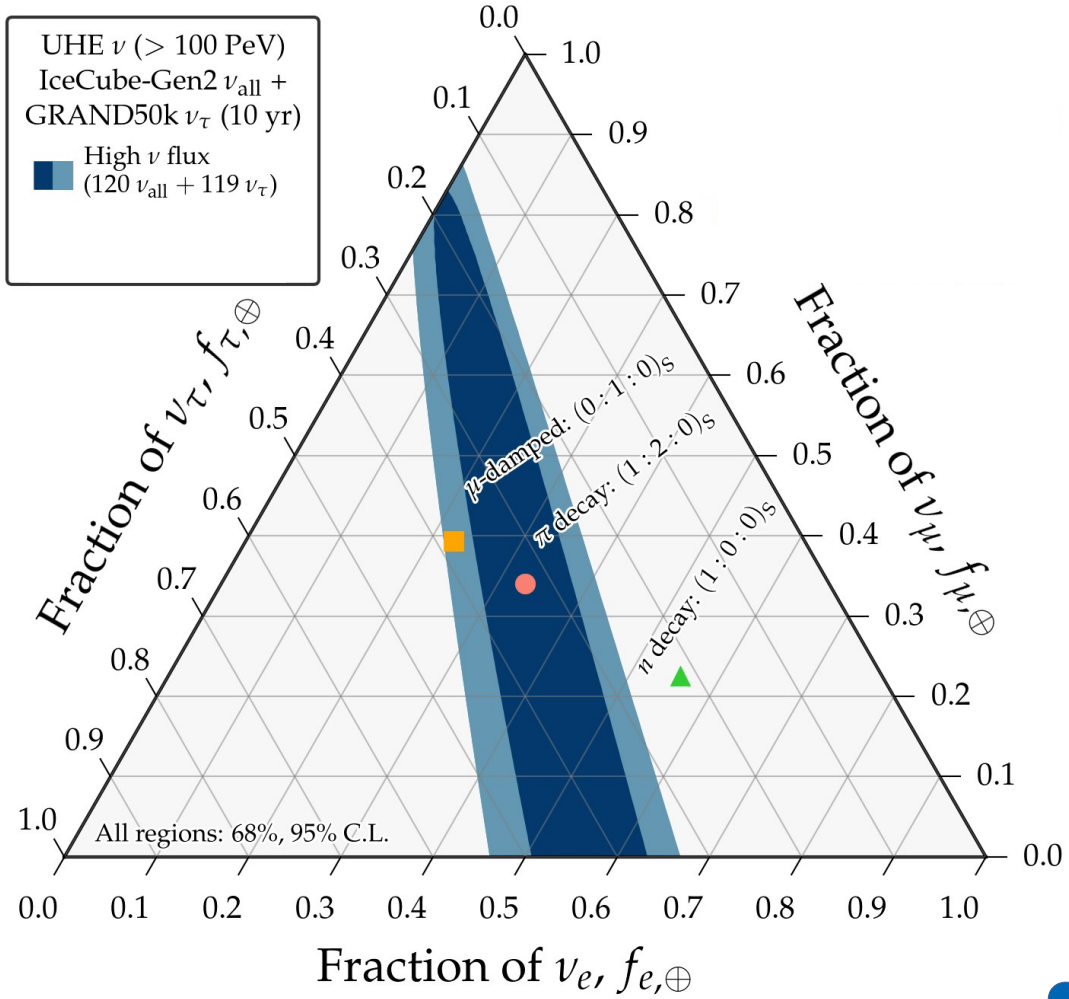
predominant detection of ν_τ
by GRAND



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

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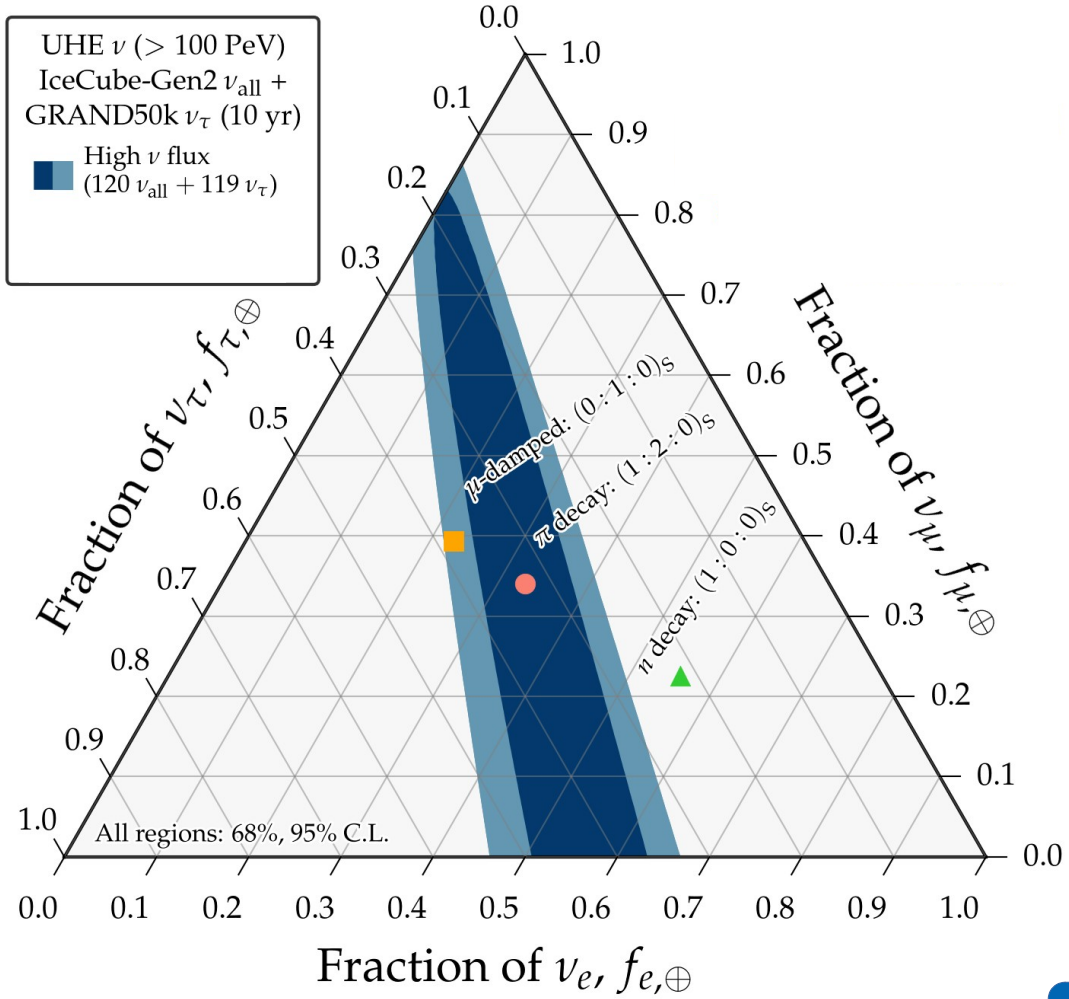

Testagrossa, Fiorillo, **MB**, *PRD* 2024

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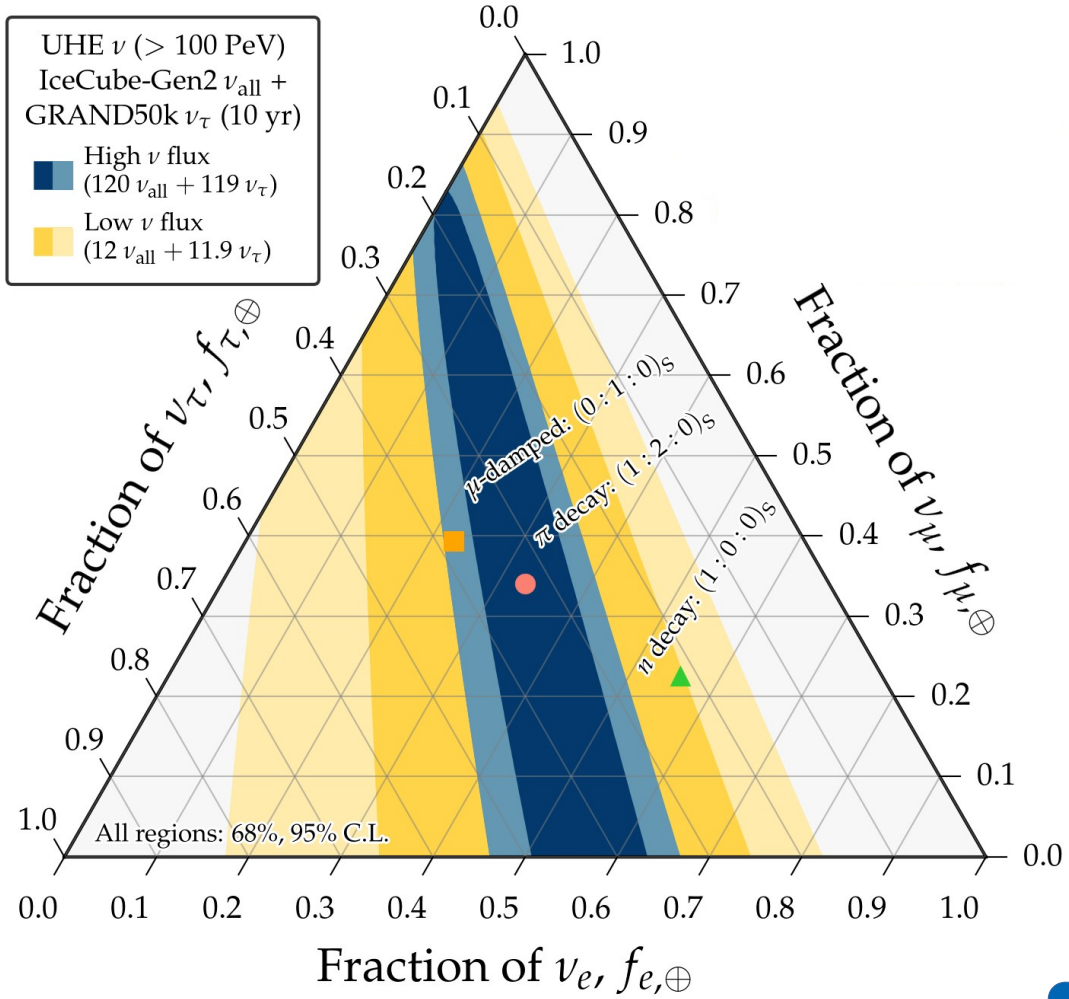

Testagrossa, Fiorillo, **MB**, *PRD* 2024

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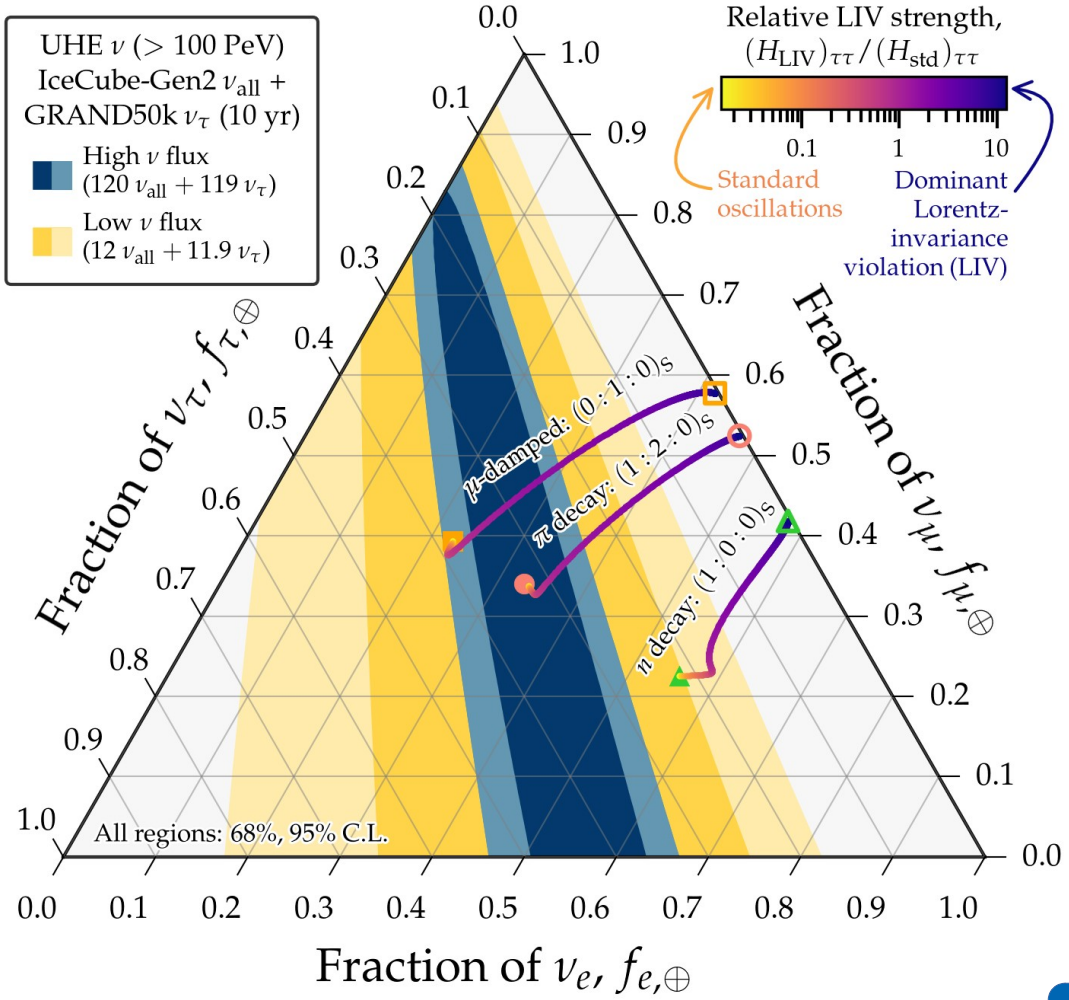
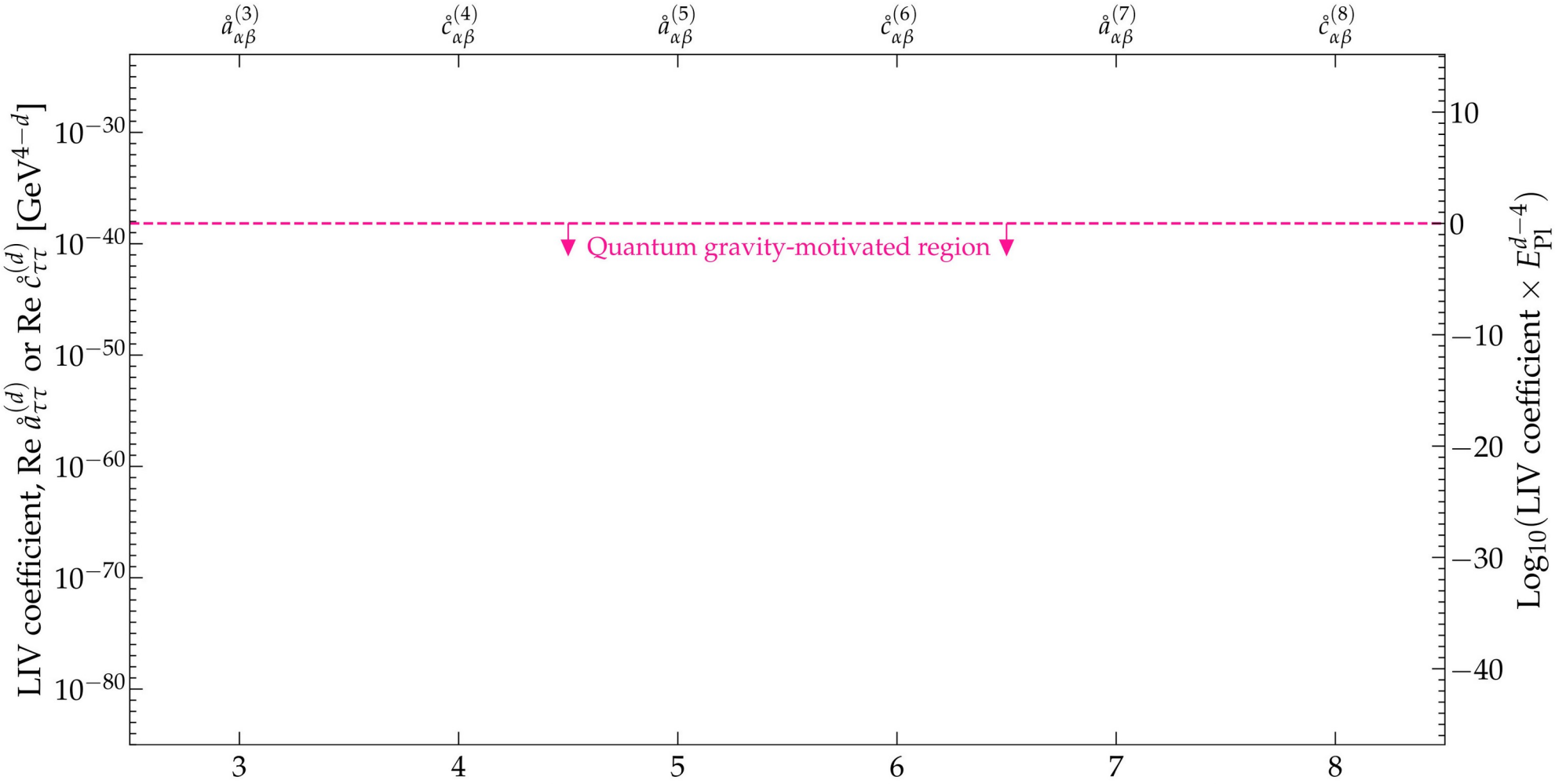


Testagrossa, Fiorillo, **MB**, *PRD* 2024

Lorentz-invariance violation at ultra-high energies



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

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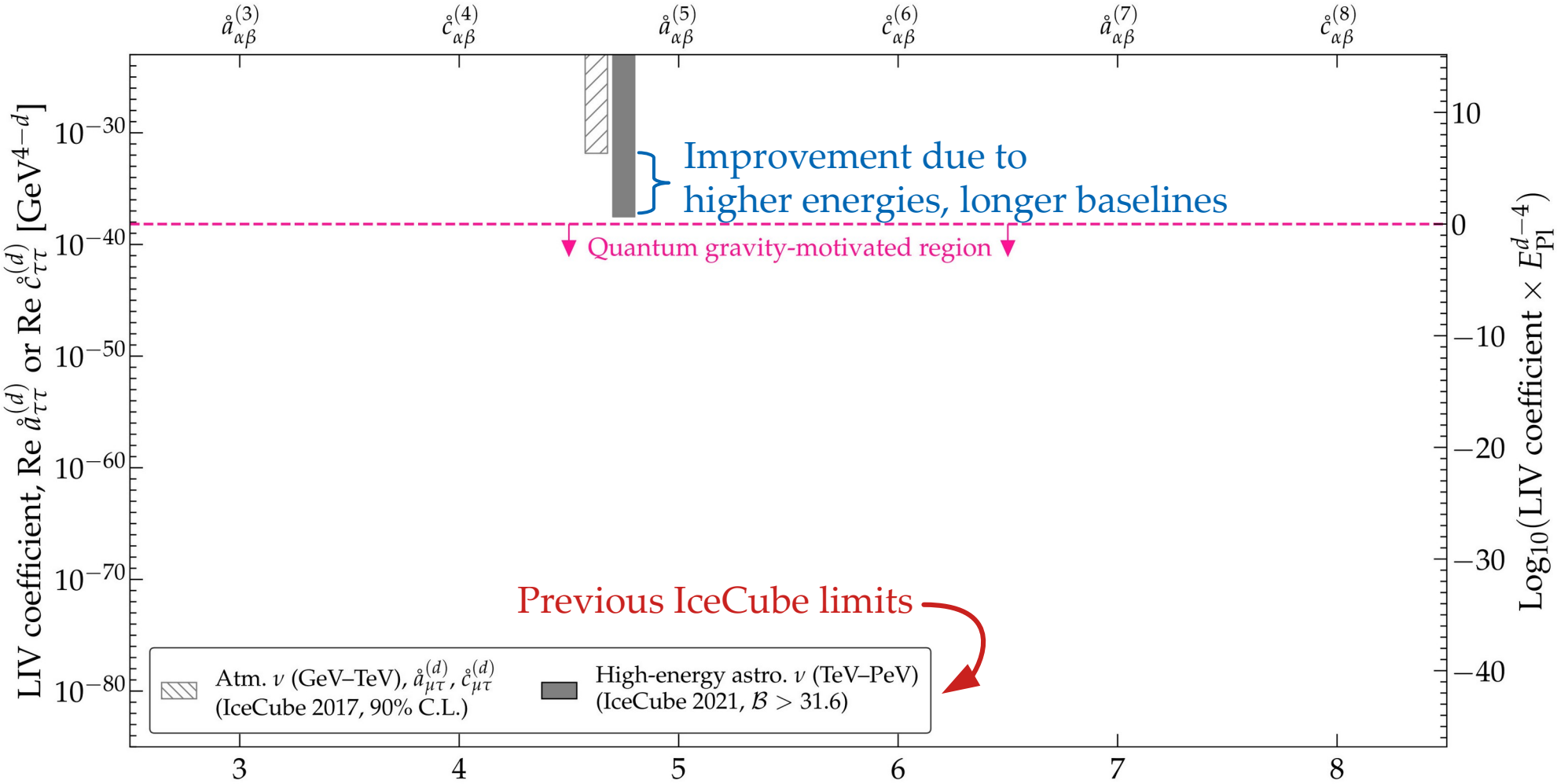

Testagrossa, Fiorillo, **MB**, *PRD* 2024

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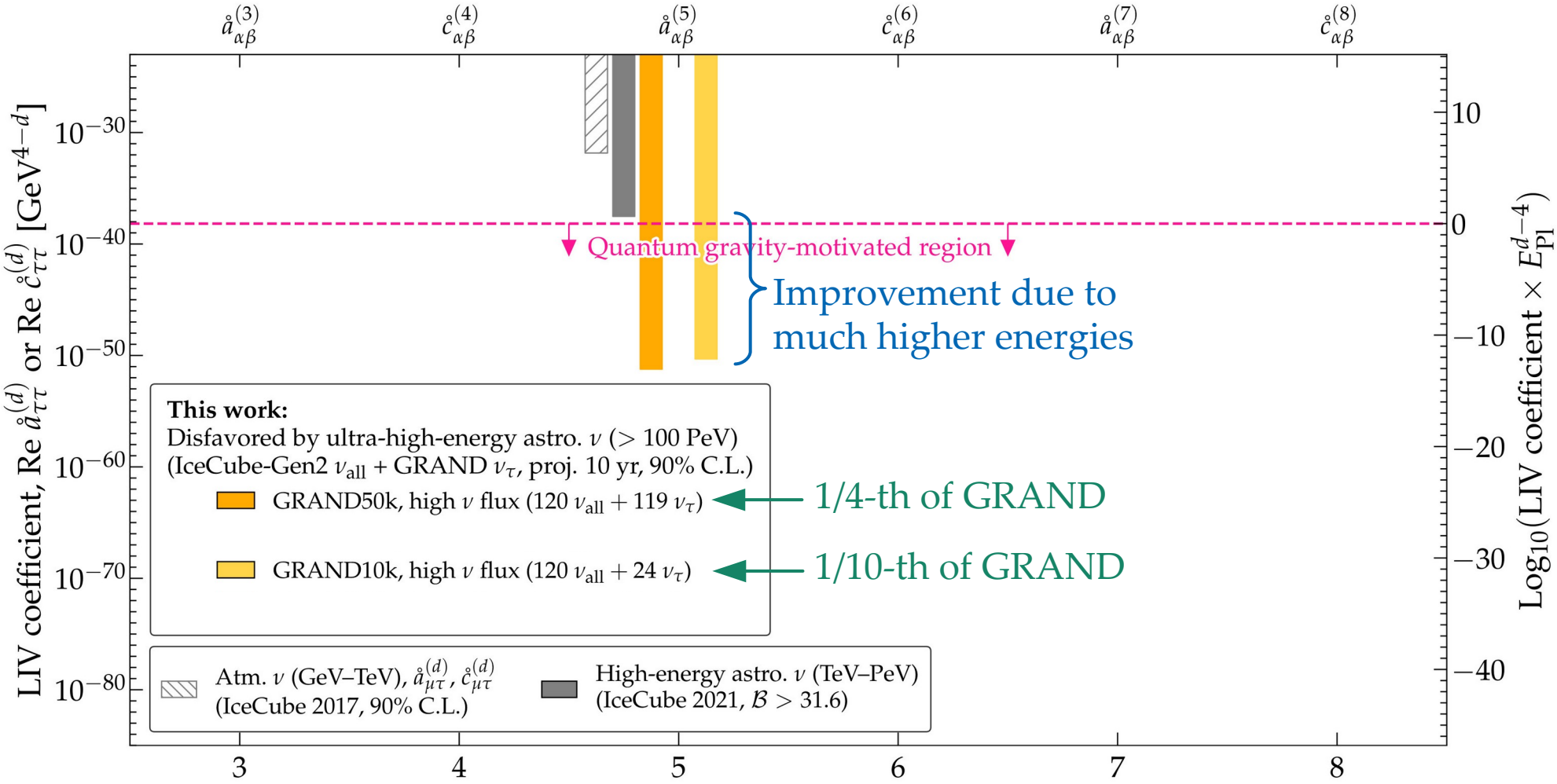

Testagrossa, Fiorillo, **MB**, *PRD* 2024

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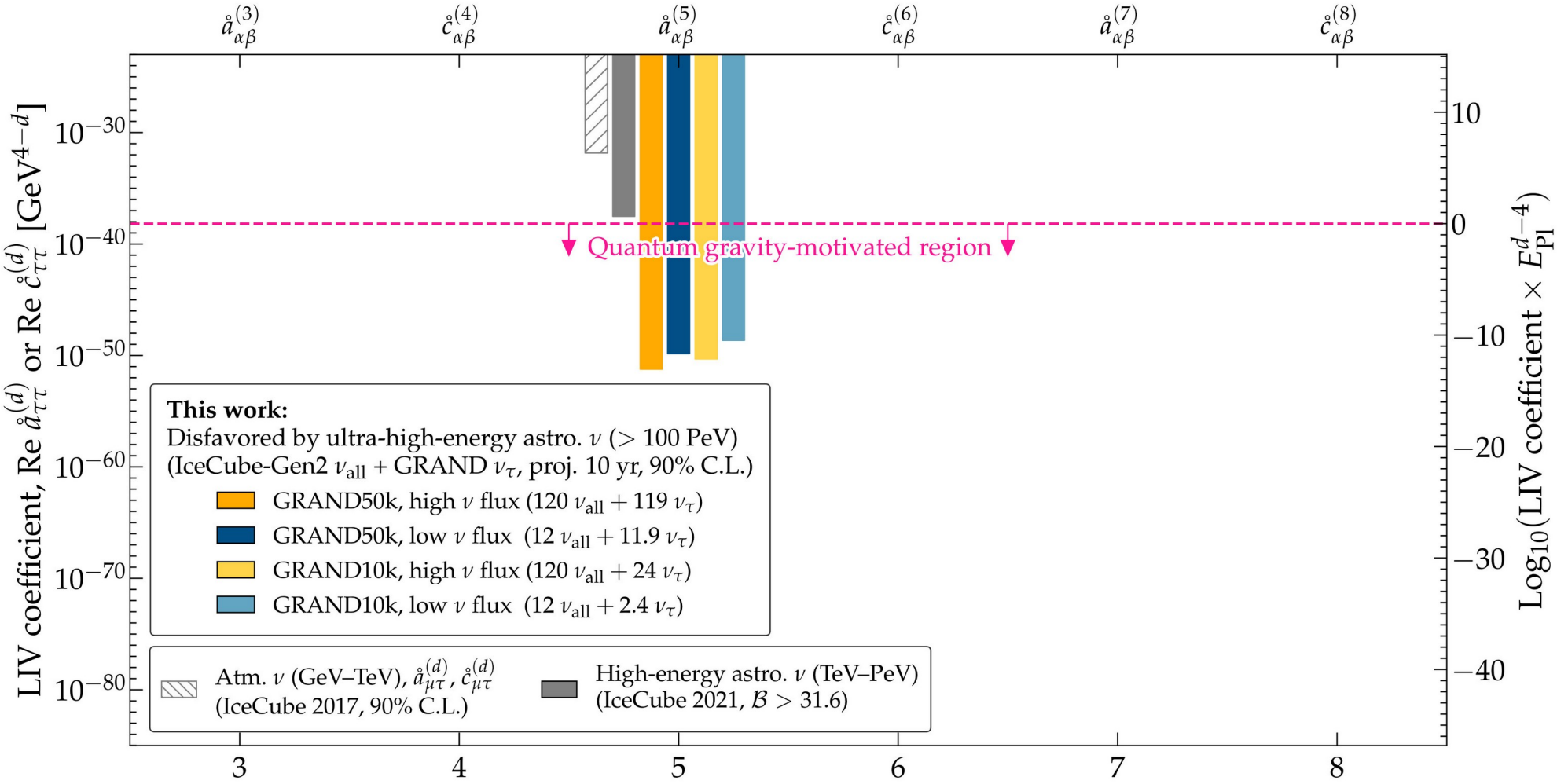

Testagrossa, Fiorillo, **MB**, *PRD* 2024

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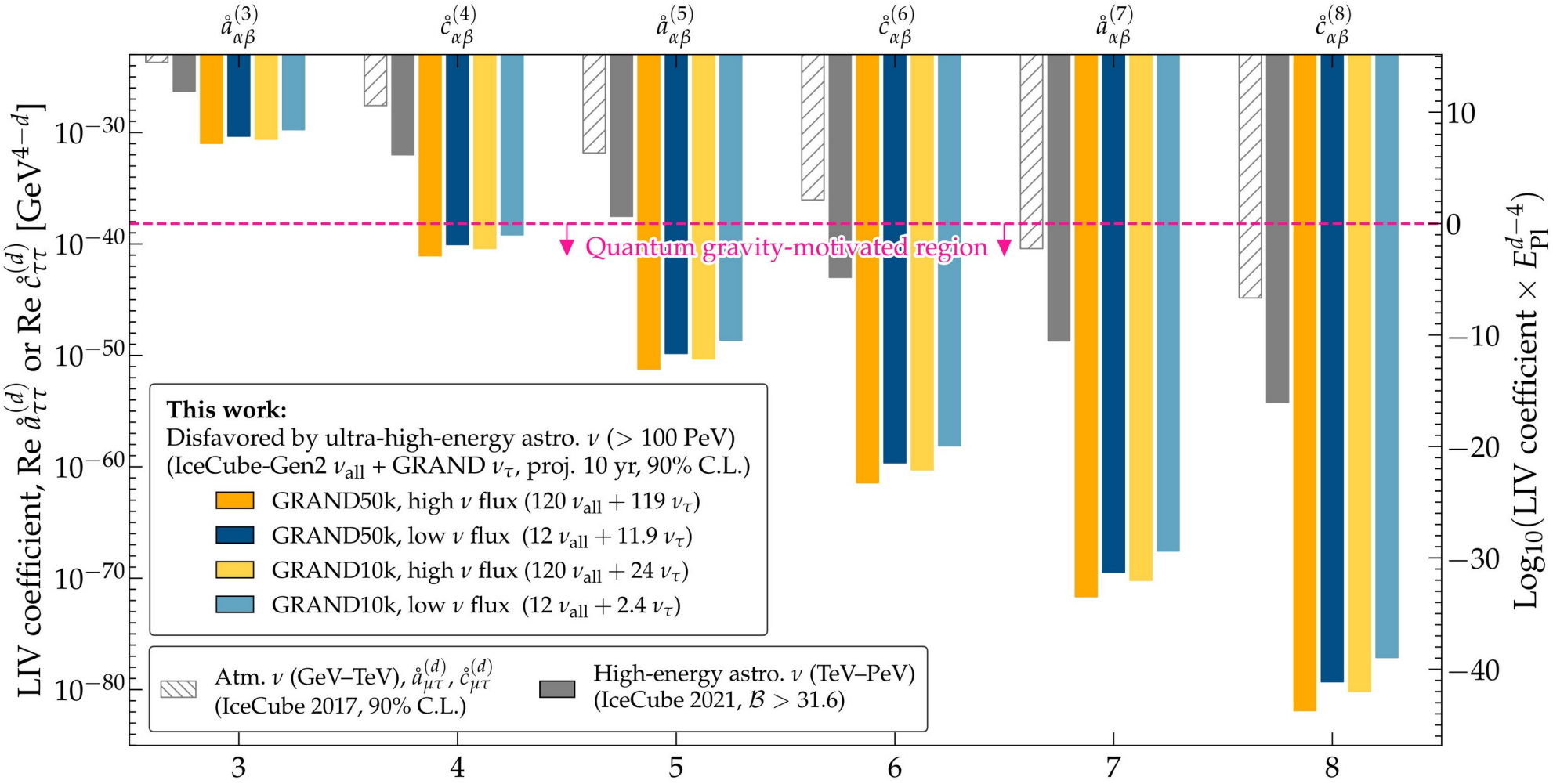
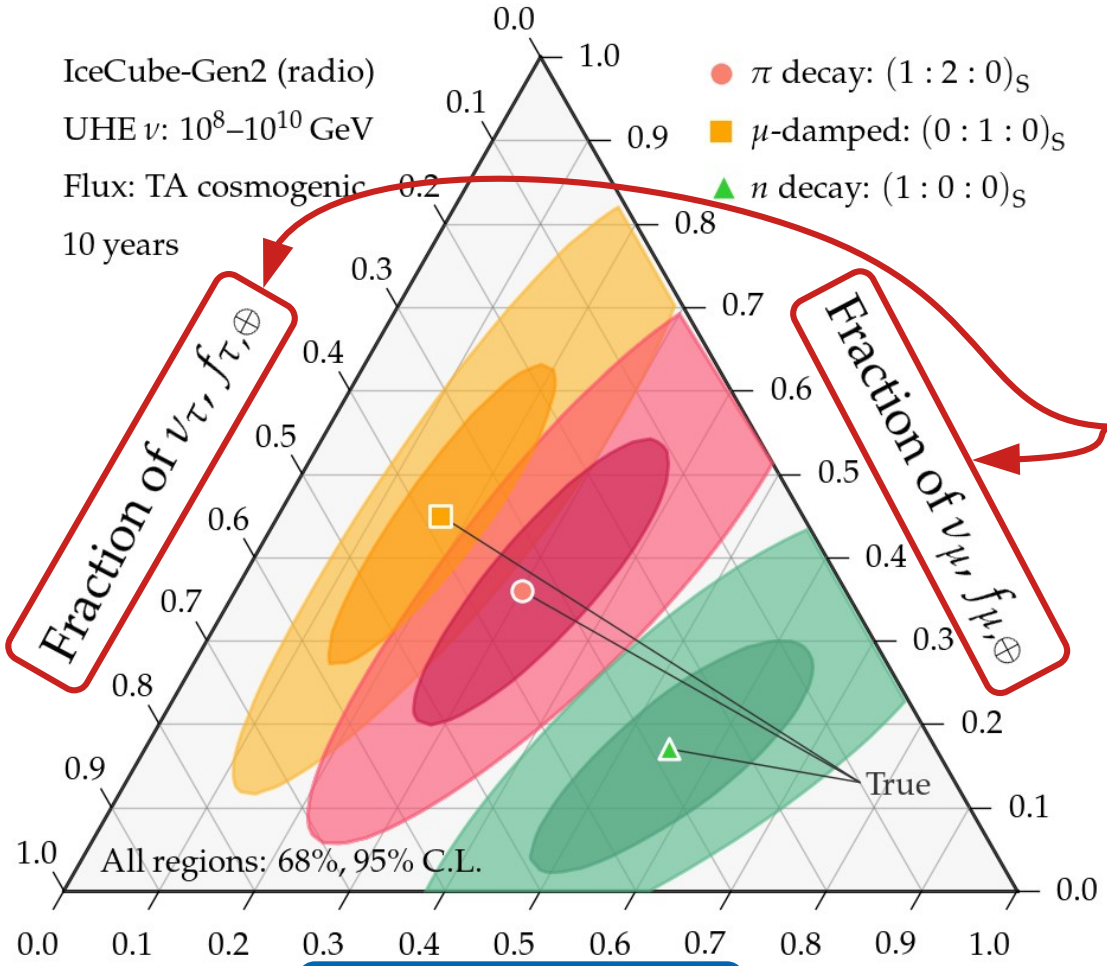


Testagrossa, Fiorillo, **MB**, *PRD* 2024

IceCube-Gen2 (radio) alone might measure flavor



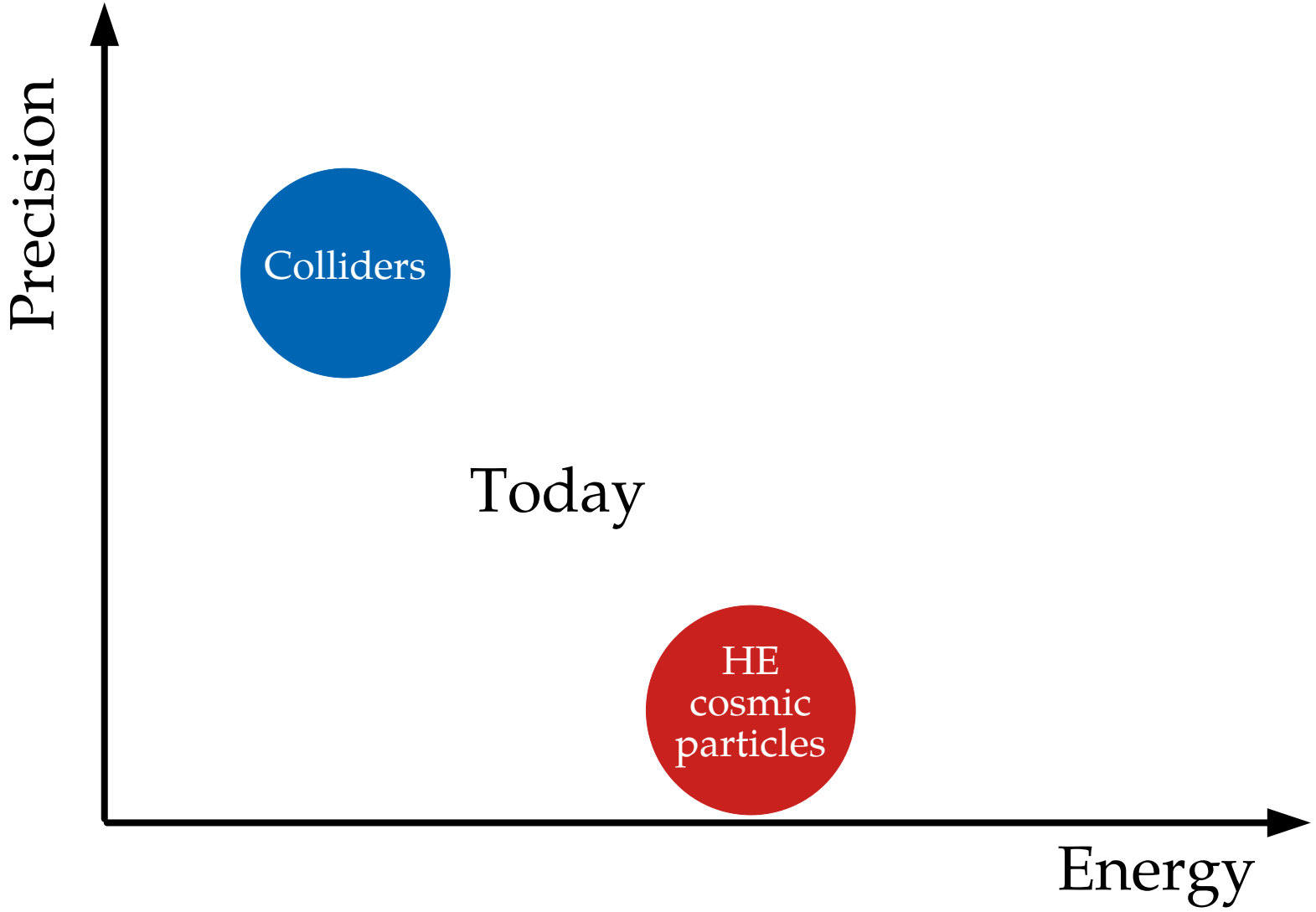
Fraction of ν_e

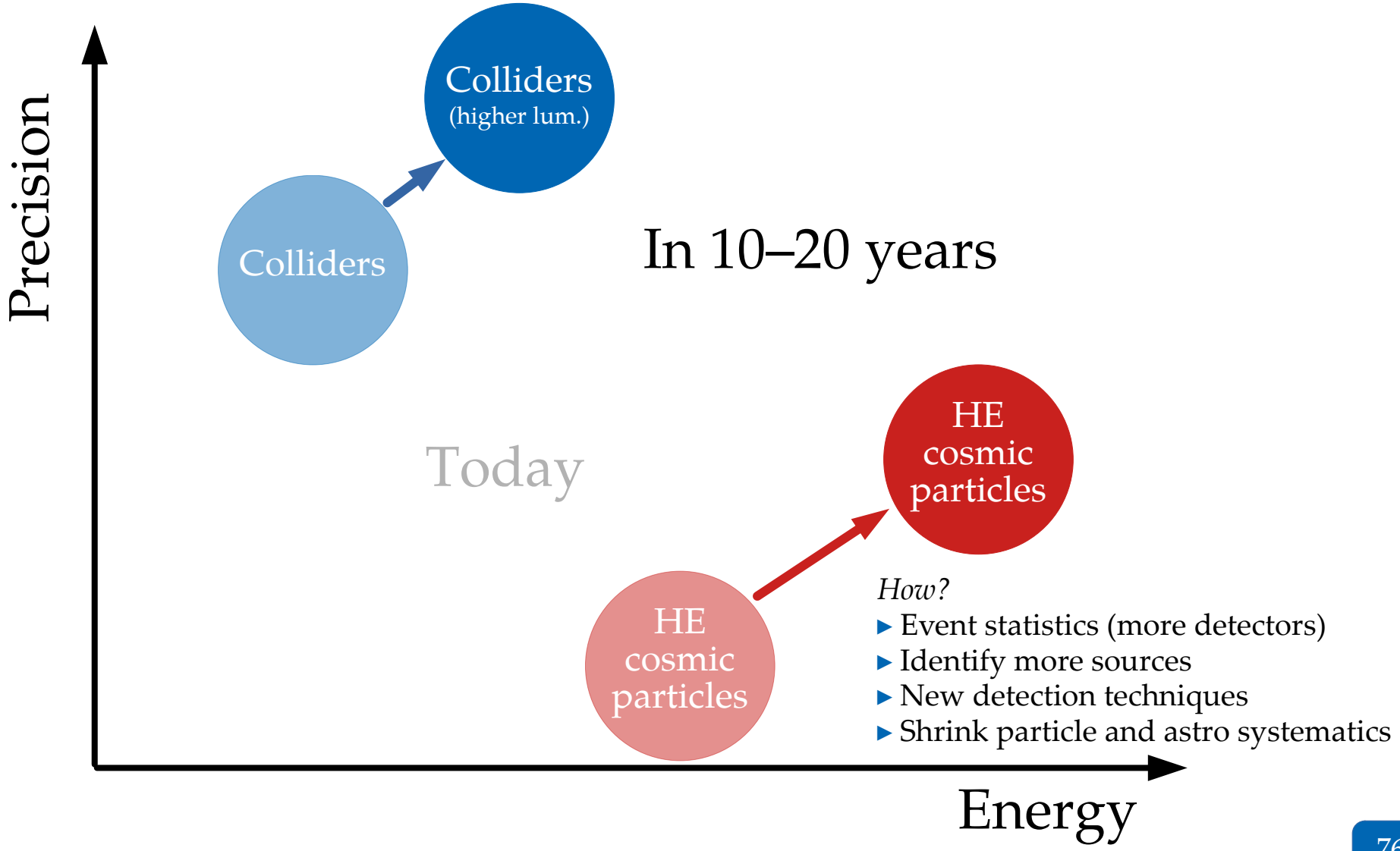
Showers are elongated due to the LPM effect

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

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

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


Precision
Colliders
Today
HE
cosmic
particles
Energy

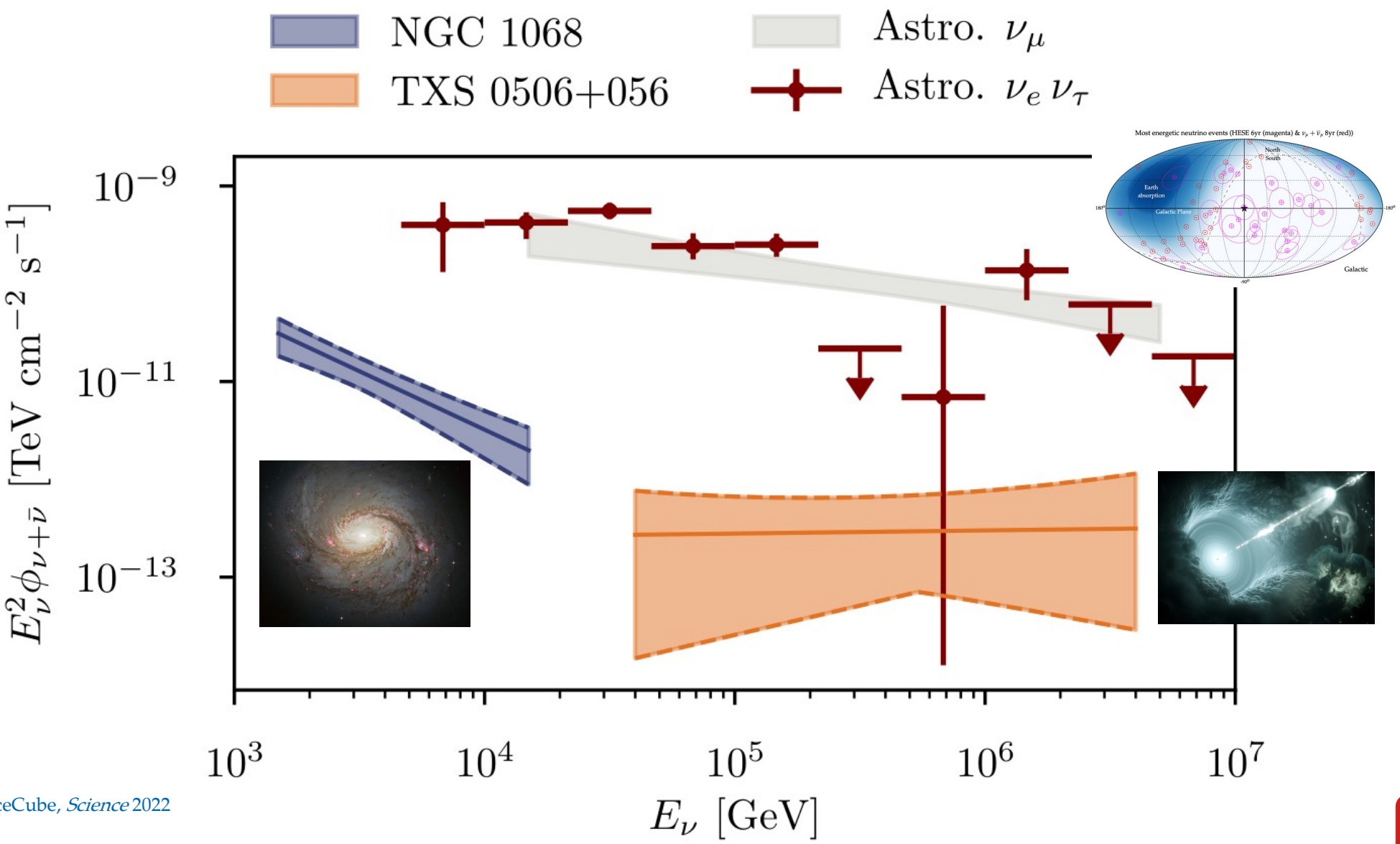

Precision
Colliders
(higher lum.)
Colliders
In 10–20 years
Today
HE
cosmic
particles
HE
cosmic
particles
How?
Event statistics (more detectors)
Identify more sources
New detection techniques
Shrink particle and astro systematics
Energy

Thanks!

- Three tracks:
  - Neutrino phenomenology:
    Mariam Tórtola (Valencia)
  - Neutrino astrophysics:
    Maria Petropoulou (Athens)
  - Neutrino cosmology:
    Vivian Poulin (Montpellier)
- Plus topical seminars & student talks
- Registration remains open for remote participation (no charge!)

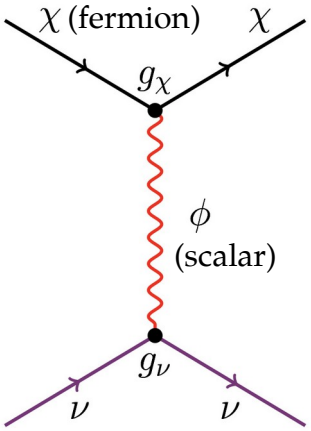
nbia.dk/neutrino2025

Backup slides



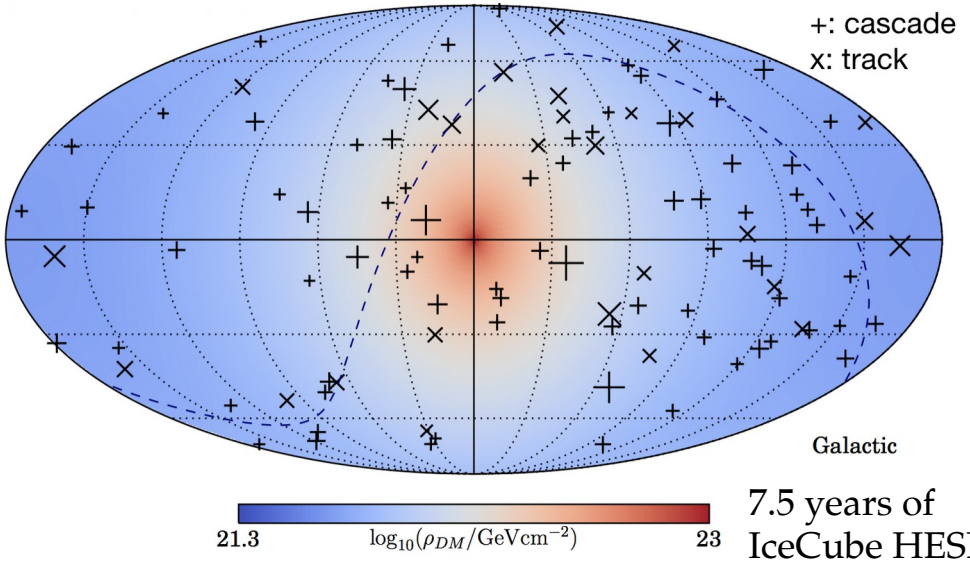
IceCube, *Science* 2022

Neutrino-dark matter scattering



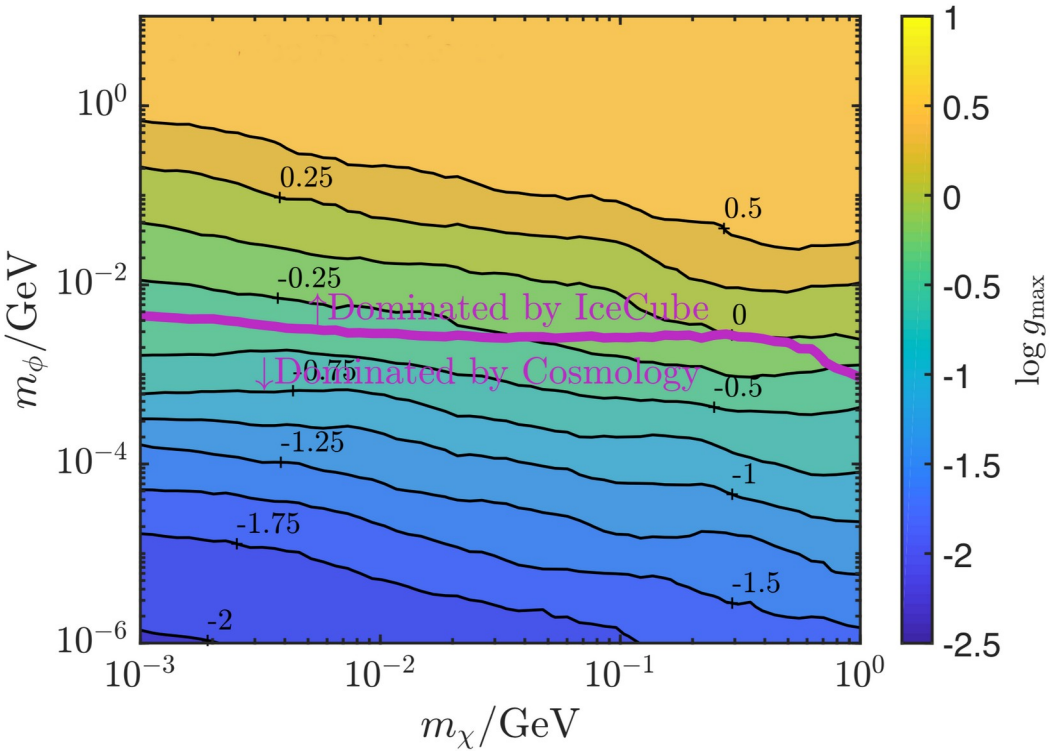
Signature:

Deficit of high-energy ν
from the Galactic Center



7.5 years of
IceCube HESE data

Upper limits (90% C.L.)
on $g_{\max} = \sqrt{g_\chi g_\nu}$



IceCube, *JCAP* 2023
Argüelles, Kheirandish, Vincent, *PRL* 2017

Measuring the high-energy νN cross section

Number of detected neutrinos (simplified for presentation):

$$N \propto \underbrace{\Phi_\nu}_{\text{Neutrino flux}} \underbrace{\sigma_{\nu N}}_{\text{Cross section}} e^{-\tau_{\nu N}} = \Phi_\nu \sigma_{\nu N} e^{-L \sigma_{\nu N} n_N}$$

Hooper, *PRD* 2002; Hussain *et al.*, *PRL* 2006; Borriello *et al.*, *PRD* 2008
Hussain, Mafatia, McKay, *PRD* 2008 Connolly, Thorne, Waters, *PRD* 2011; Marfatia, McKay, Weiler, *PLB* 2015

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Downgoing neutrinos
(L short $\rightarrow$ no matter)

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Upgoing neutrinos
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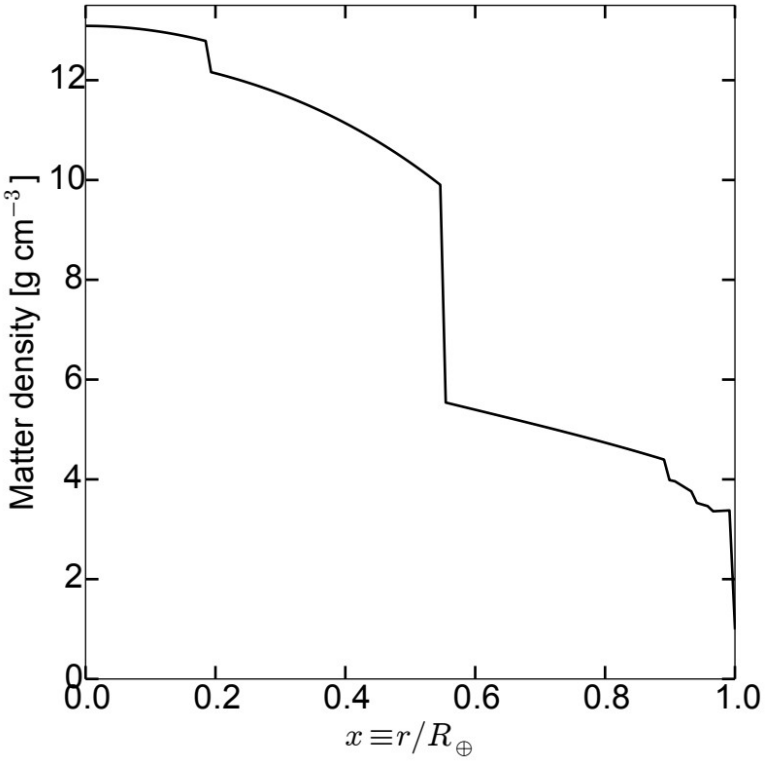
$$N \propto \Phi_\nu \sigma_{\nu N} \underbrace{e^{-L \sigma_{\nu N} n_N}}_{\text{Breaks the degeneracy}}$$

Hooper, *PRD* 2002; Hussain *et al.*, *PRL* 2006; Borriello *et al.*, *PRD* 2008
Hussain, Mafatia, McKay, *PRD* 2008 Connolly, Thorne, Waters, *PRD* 2011; Marfatia, McKay, Weiler, *PLB* 2015

A feel for the in-Earth attenuation

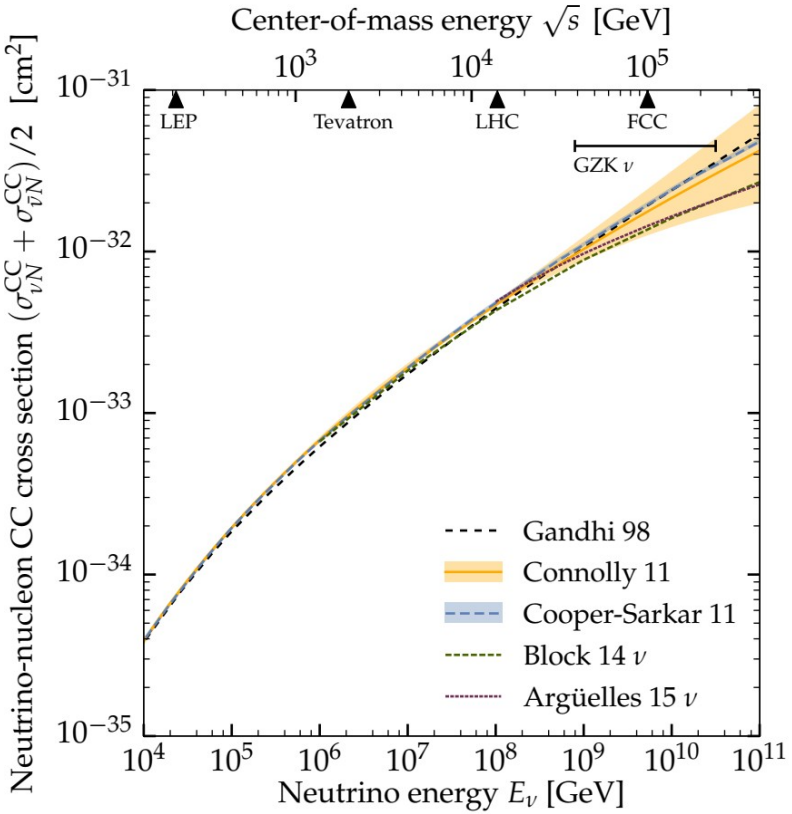
Earth matter density

(Preliminary Reference Earth Model)



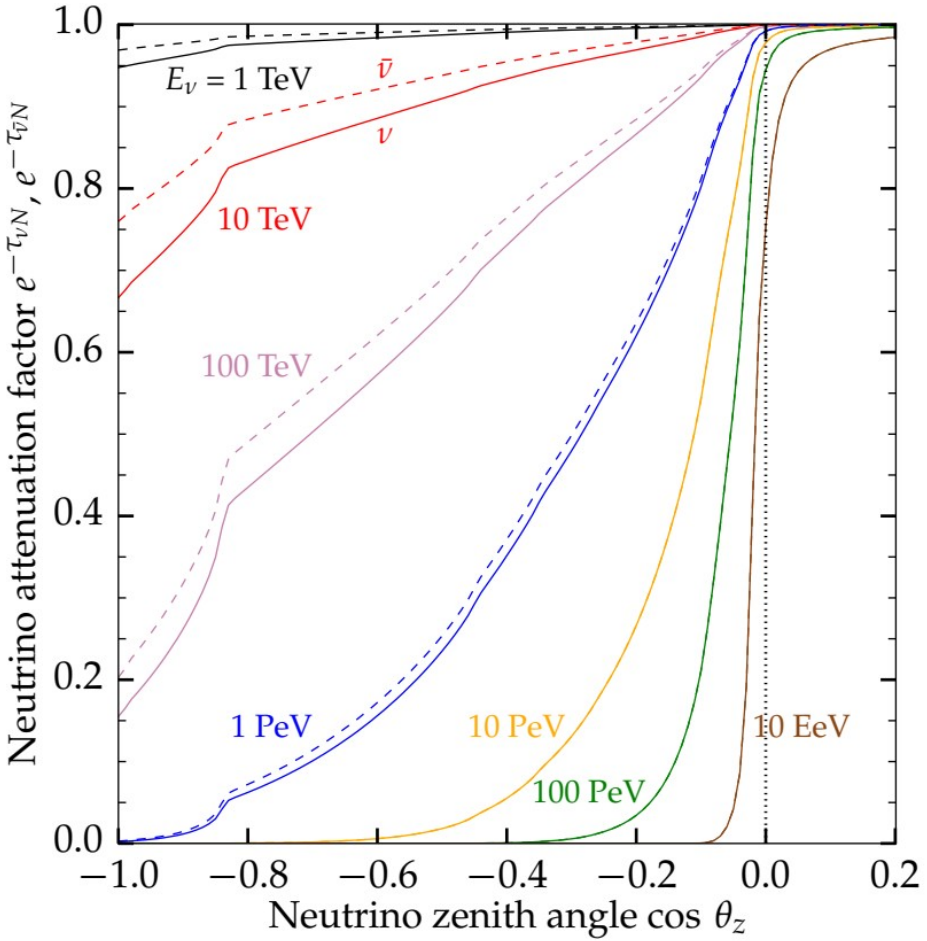
+

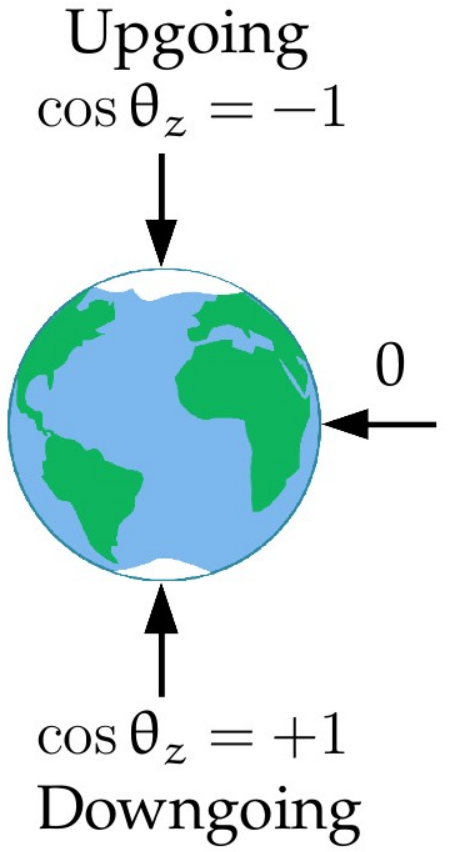
Neutrino-nucleon cross section



A feel for the in-Earth attenuation

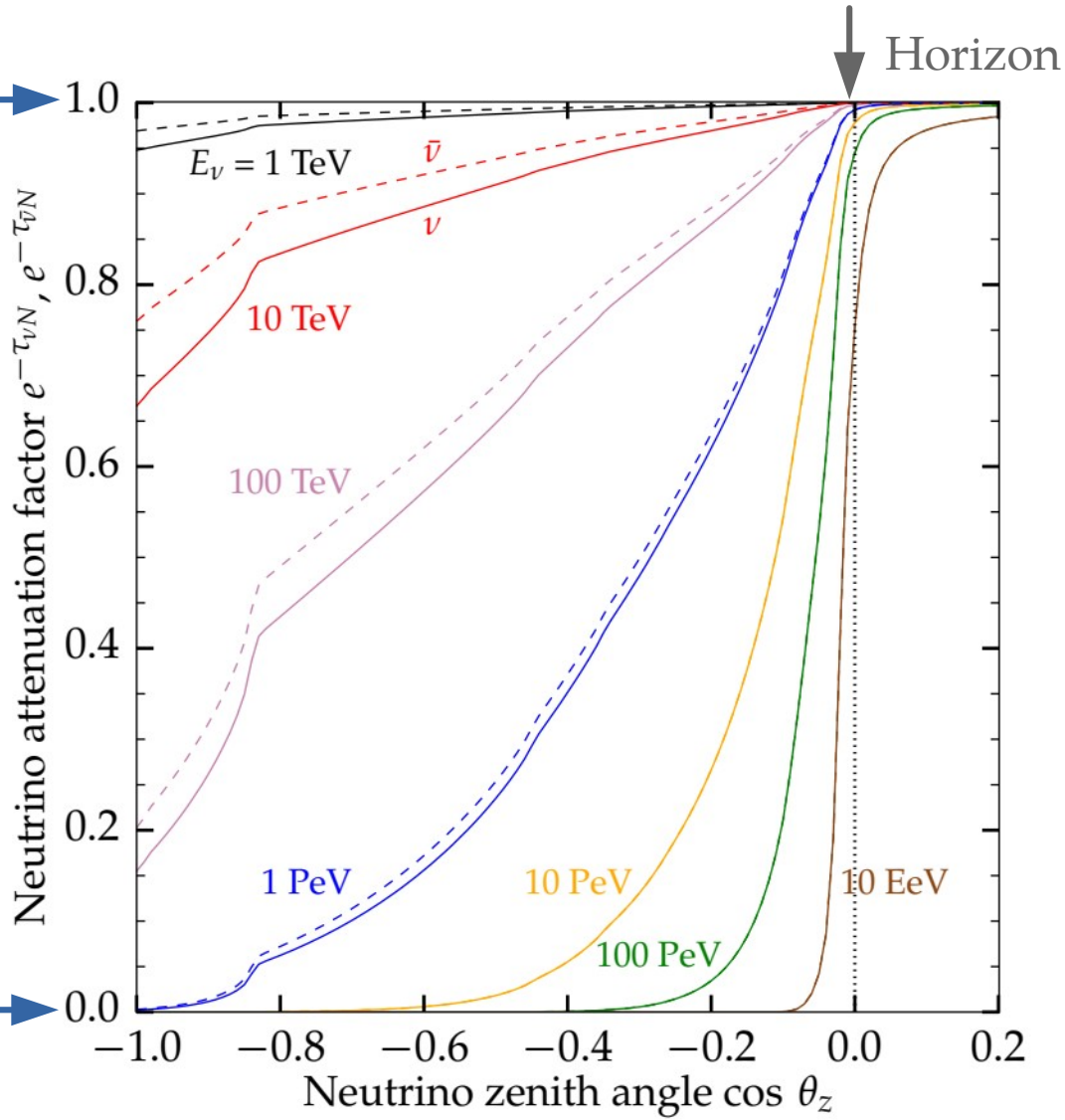
=

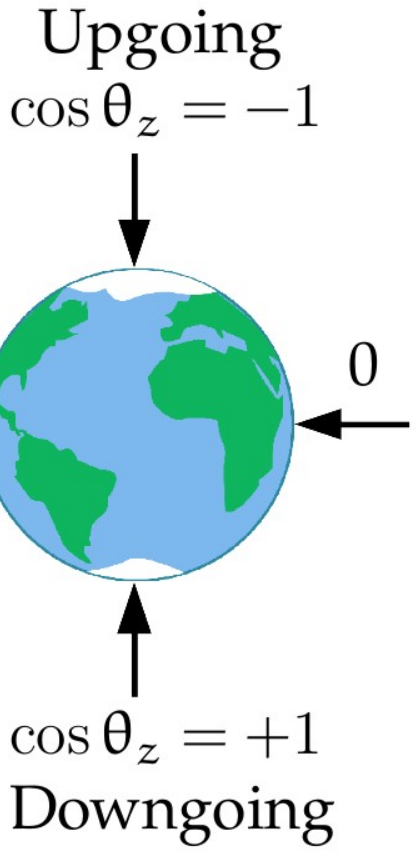




No attenuation

Full attenuation





MB & Connolly, *PRL* 2019

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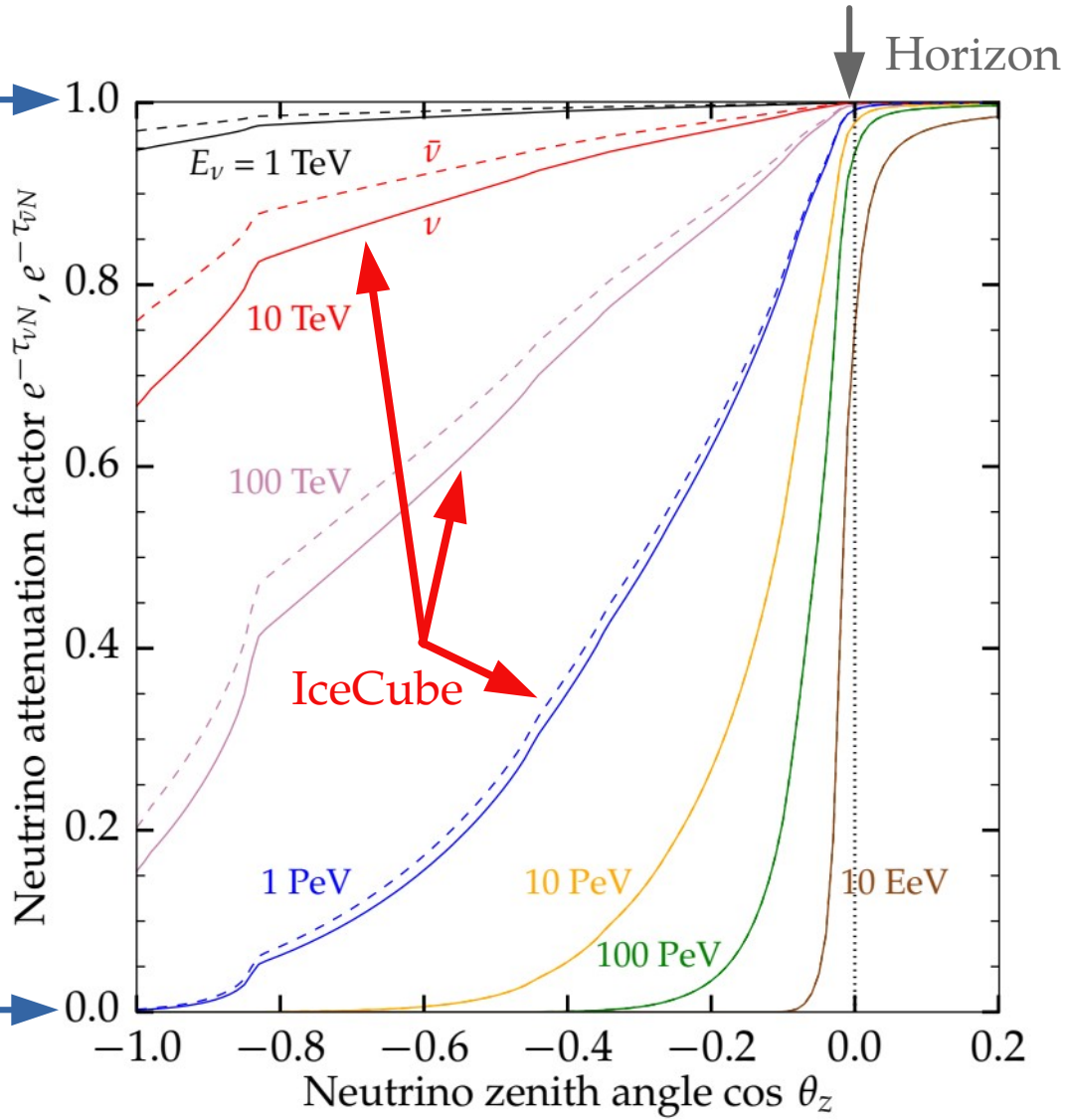
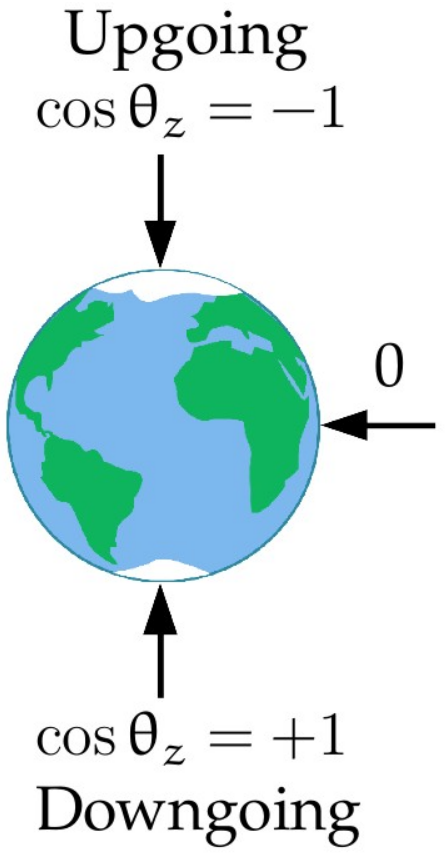
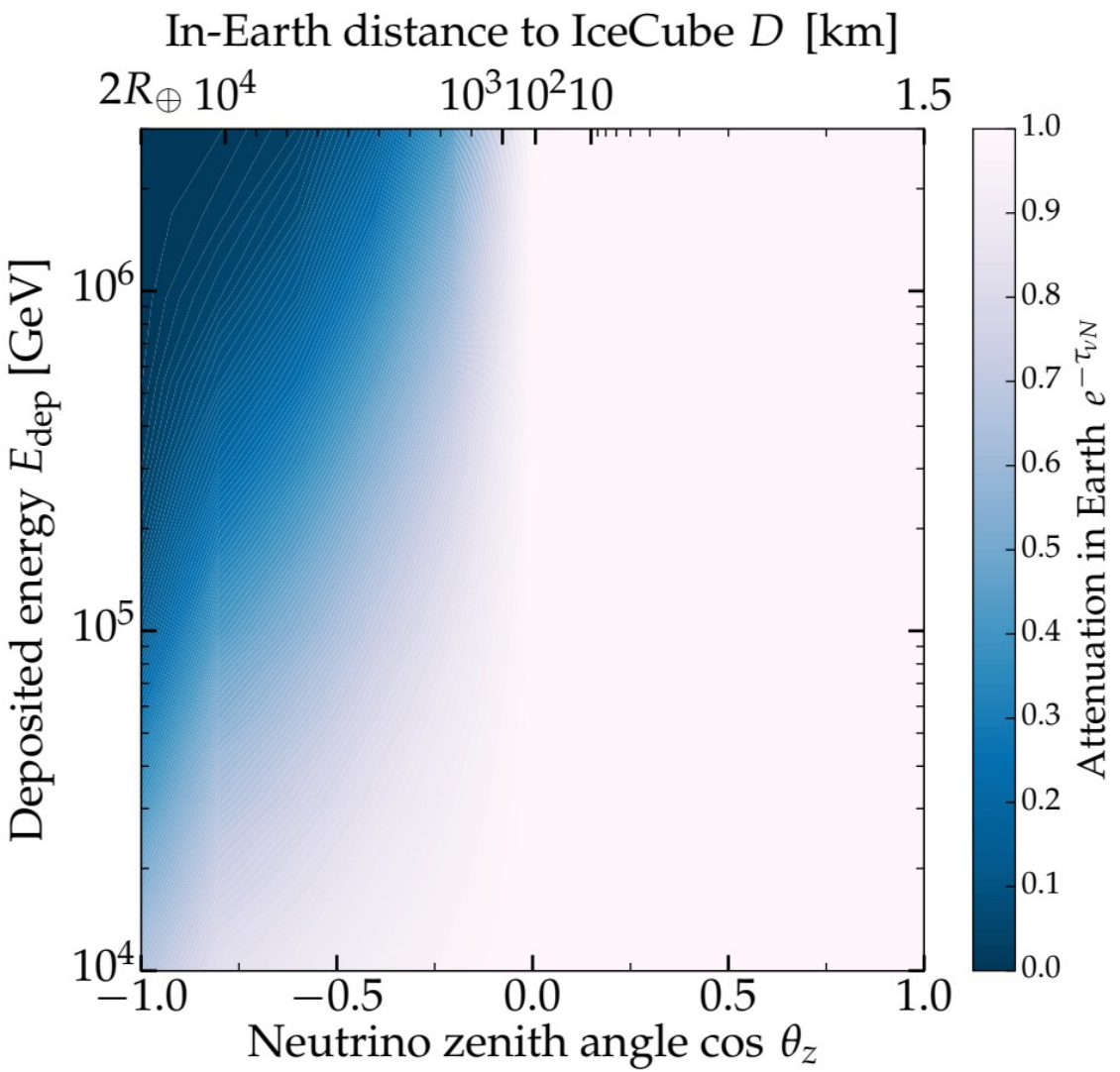
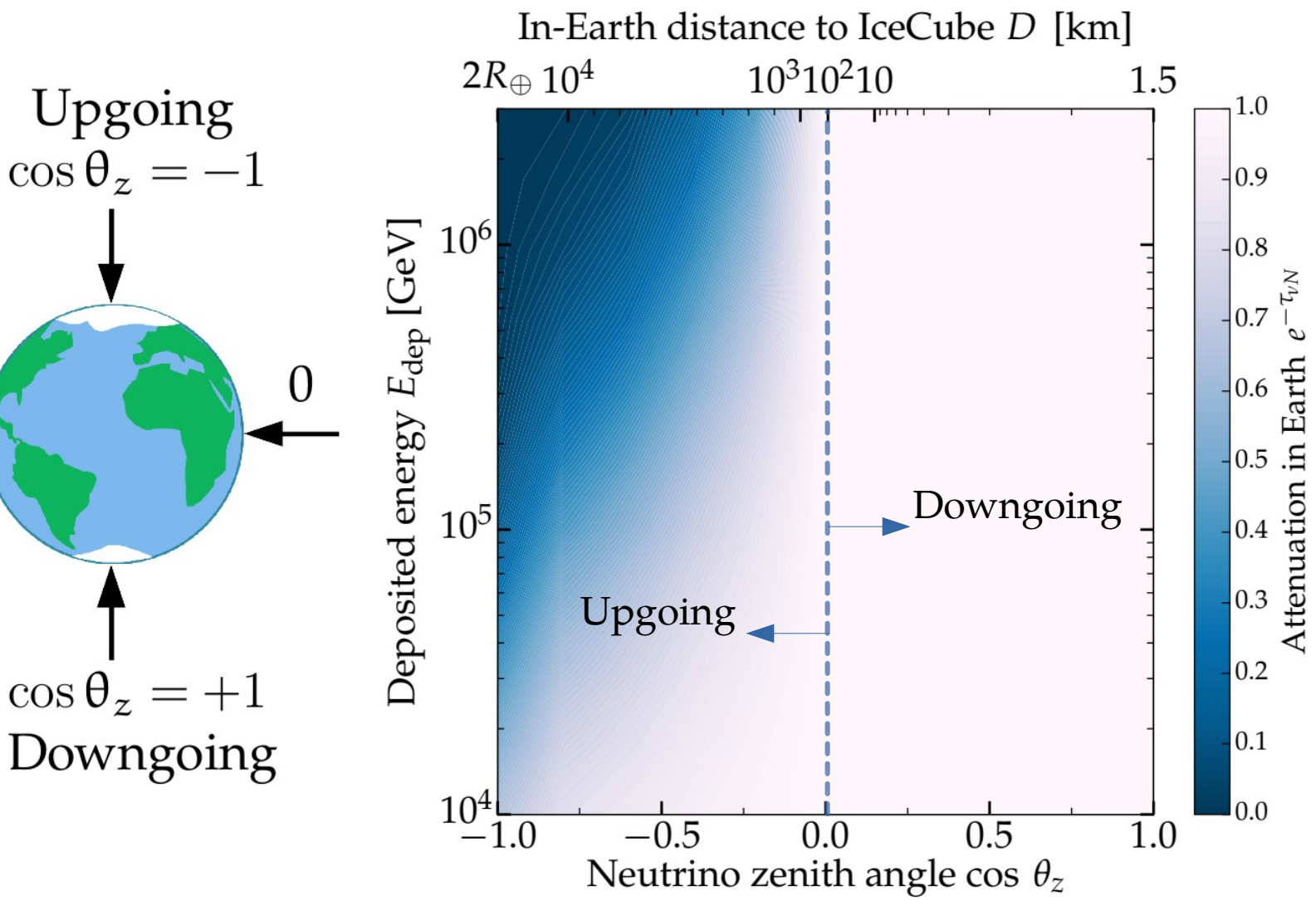
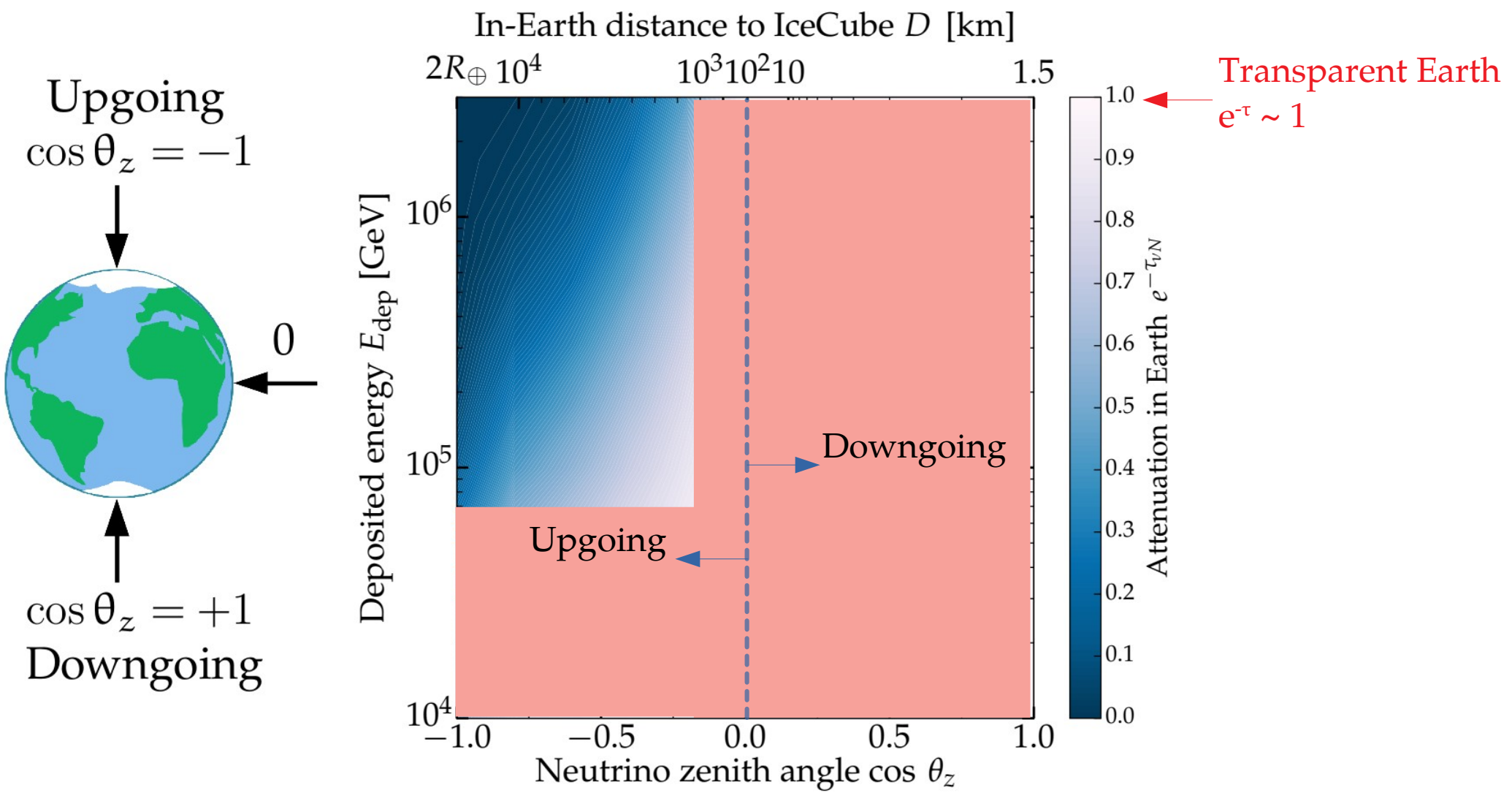




MB & Connolly, *PRL* 2019


In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4
10^3 10^2 10
1.5
Deposited energy $E_{\rm dep}$ [GeV]
10^6
10^5
10^4
−1.0
−0.5
0.0
0.5
1.0
Neutrino zenith angle cos θ_z
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Attenuation in Earth $e^{-\tau_{\nu N}}$


Upgoing
$\cos\theta_z = -1$
0
$\cos\theta_z = +1$
Downgoing
In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4
10^3 10^2 10
1.5
Deposited energy $E_{\rm dep}$ [GeV]
10^6
10^5
10^4
Downgoing
Upgoing
−1.0
−0.5
0.0
0.5
1.0
Neutrino zenith angle cos θ_z
Attenuation in Earth $e^{-\tau_{\nu N}}$
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0


Upgoing
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0
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$2R_\oplus$ 10^4
10^3 10^2 10
1.5
Deposited energy $E_{\rm dep}$ [GeV]
10^6
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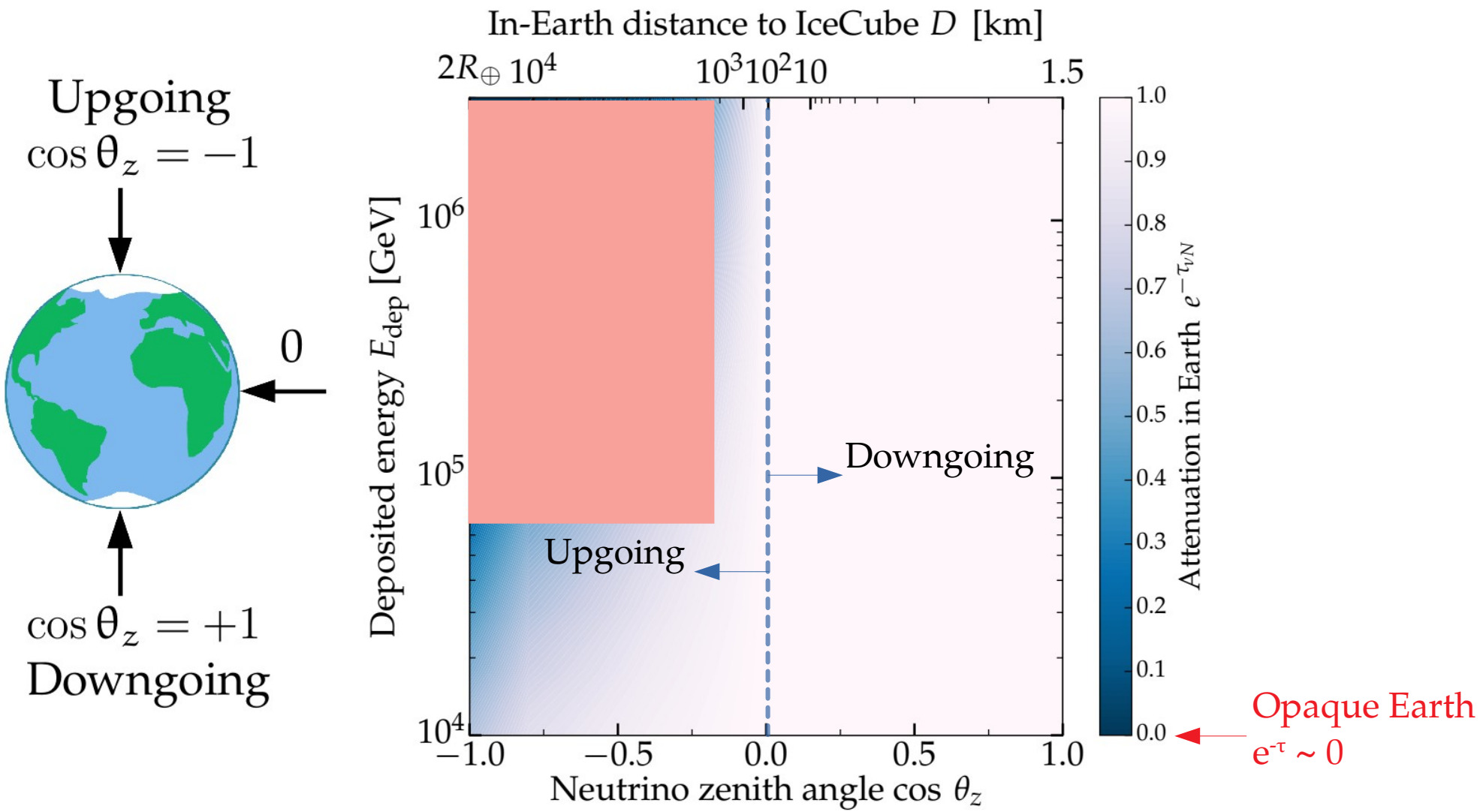
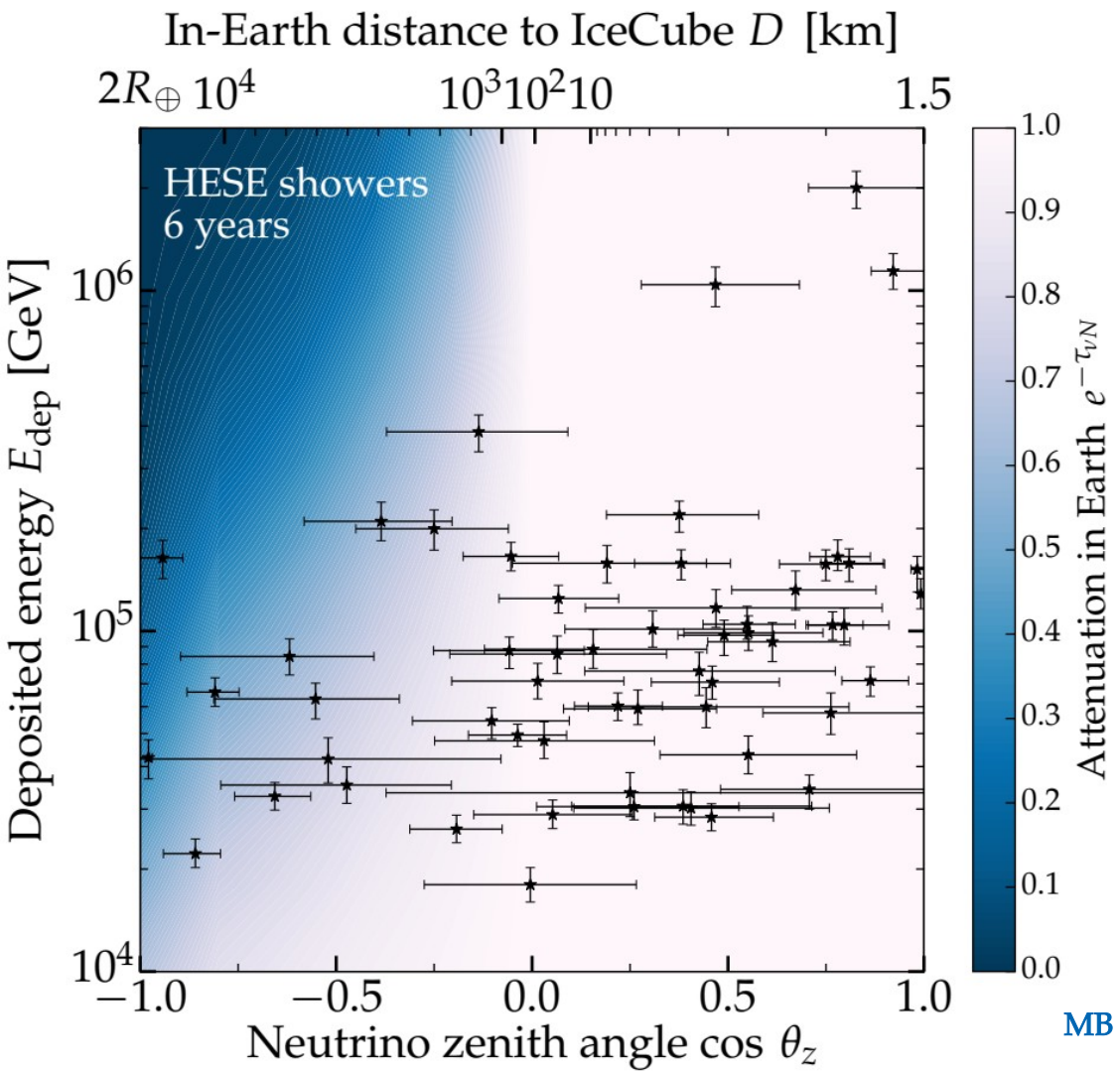
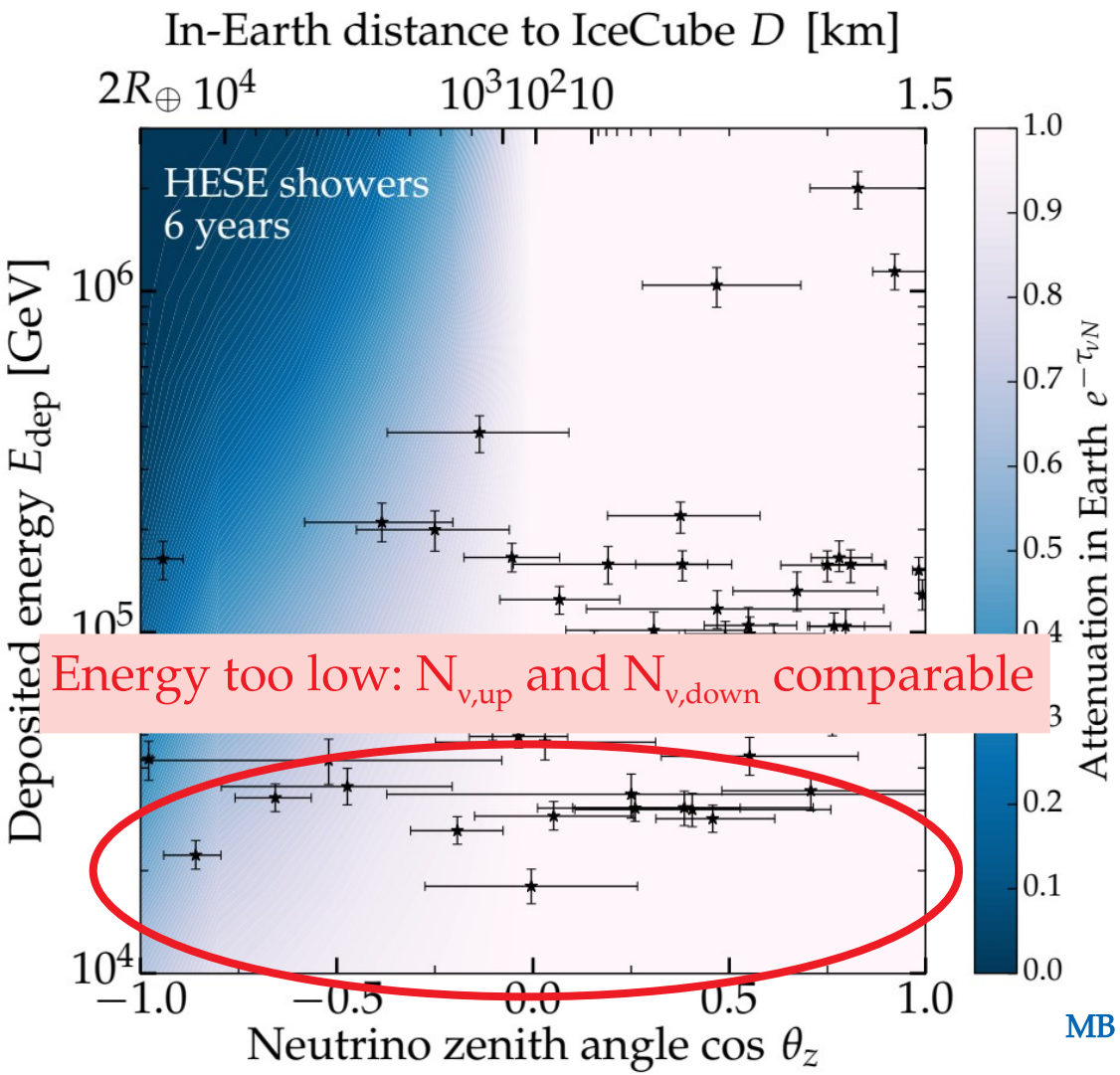
10^4
Downgoing
Upgoing
−1.0
−0.5
0.0
0.5
1.0
Neutrino zenith angle cos θ_z
Attenuation in Earth $e^{-\tau_{\nu N}}$
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Transparent Earth
$e^{-\tau} \sim 1$

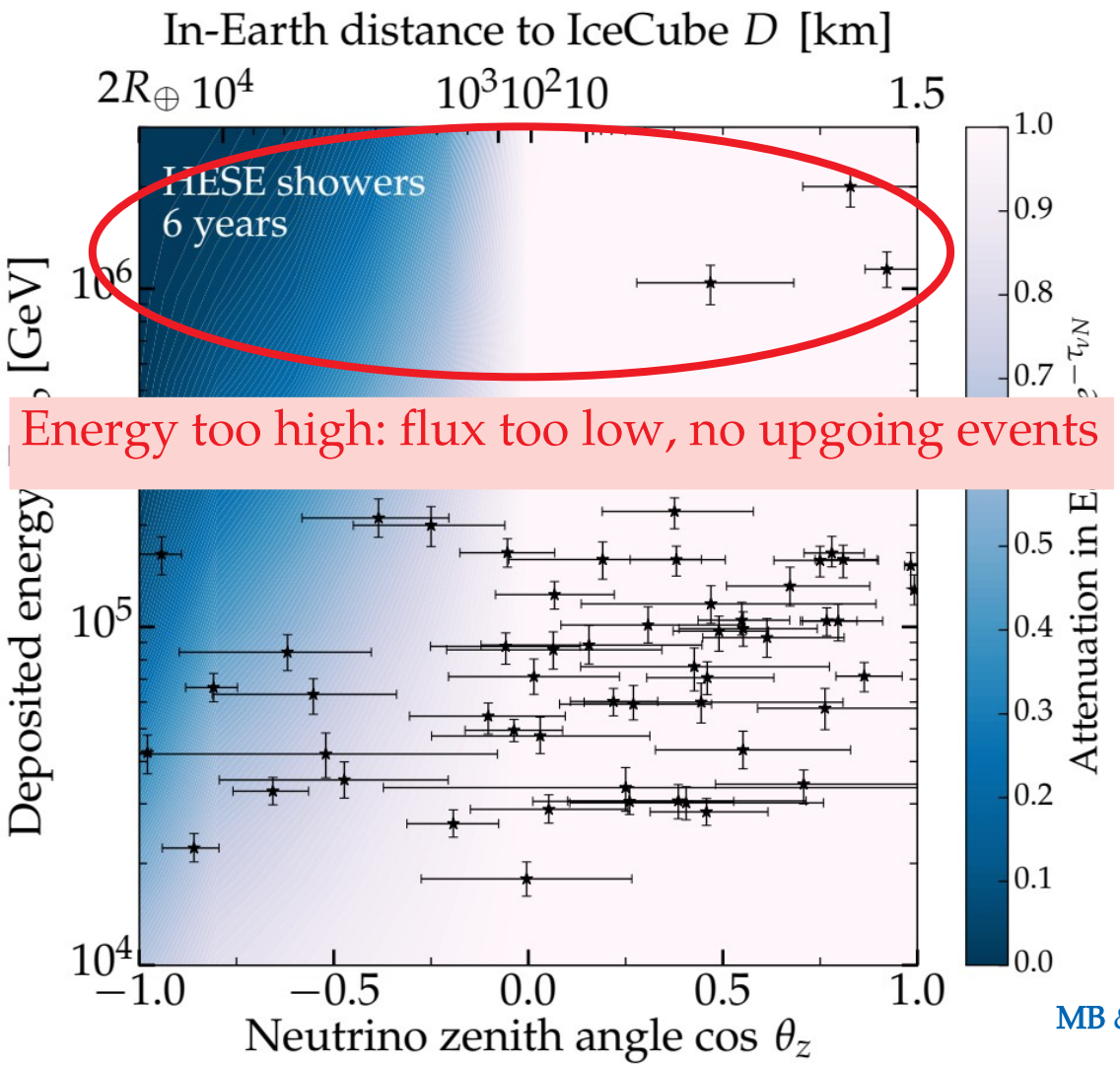

Upgoing
$\cos\theta_z = -1$
0
$\cos\theta_z = +1$
Downgoing
In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4
10^3 10^2 10
1.5
Deposited energy $E_{\rm dep}$ [GeV]
10^6
10^5
10^4
Upgoing
Downgoing
−1.0
−0.5
0.0
0.5
1.0
Neutrino zenith angle cos θ_z
Attenuation in Earth $e^{-\tau_{\nu N}}$
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Opaque Earth
$e^{-\tau} \sim 0$



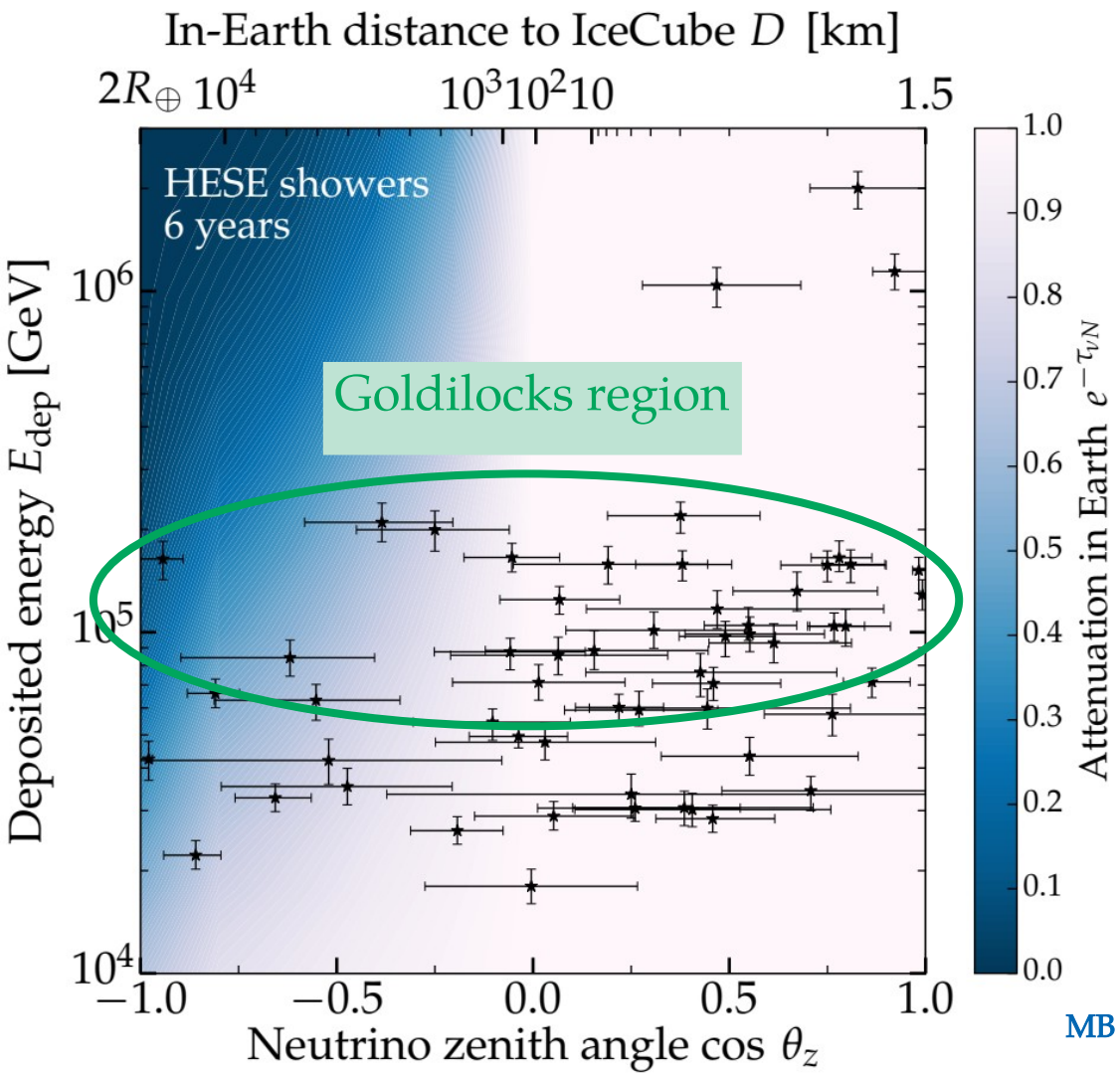
MB & Connolly, *PRL* 2019



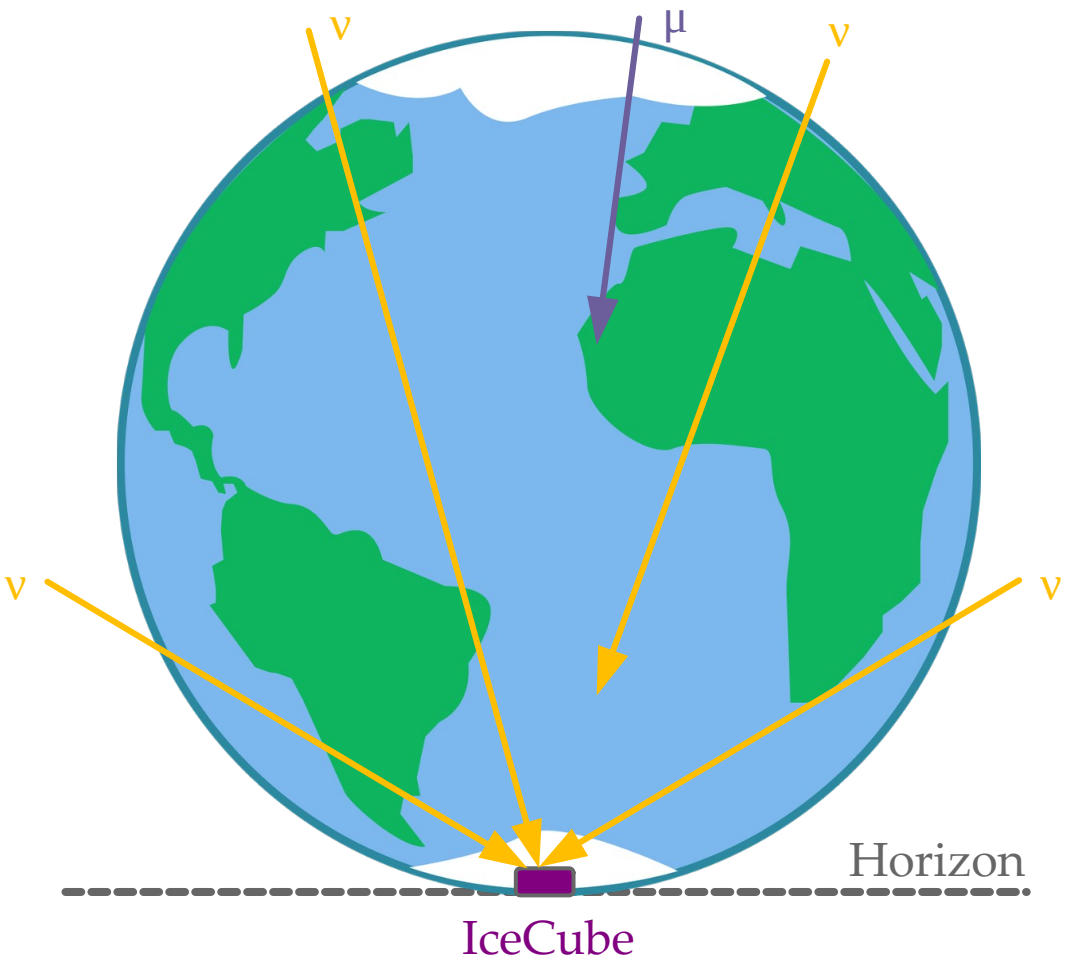
MB & Connolly, *PRL* 2019

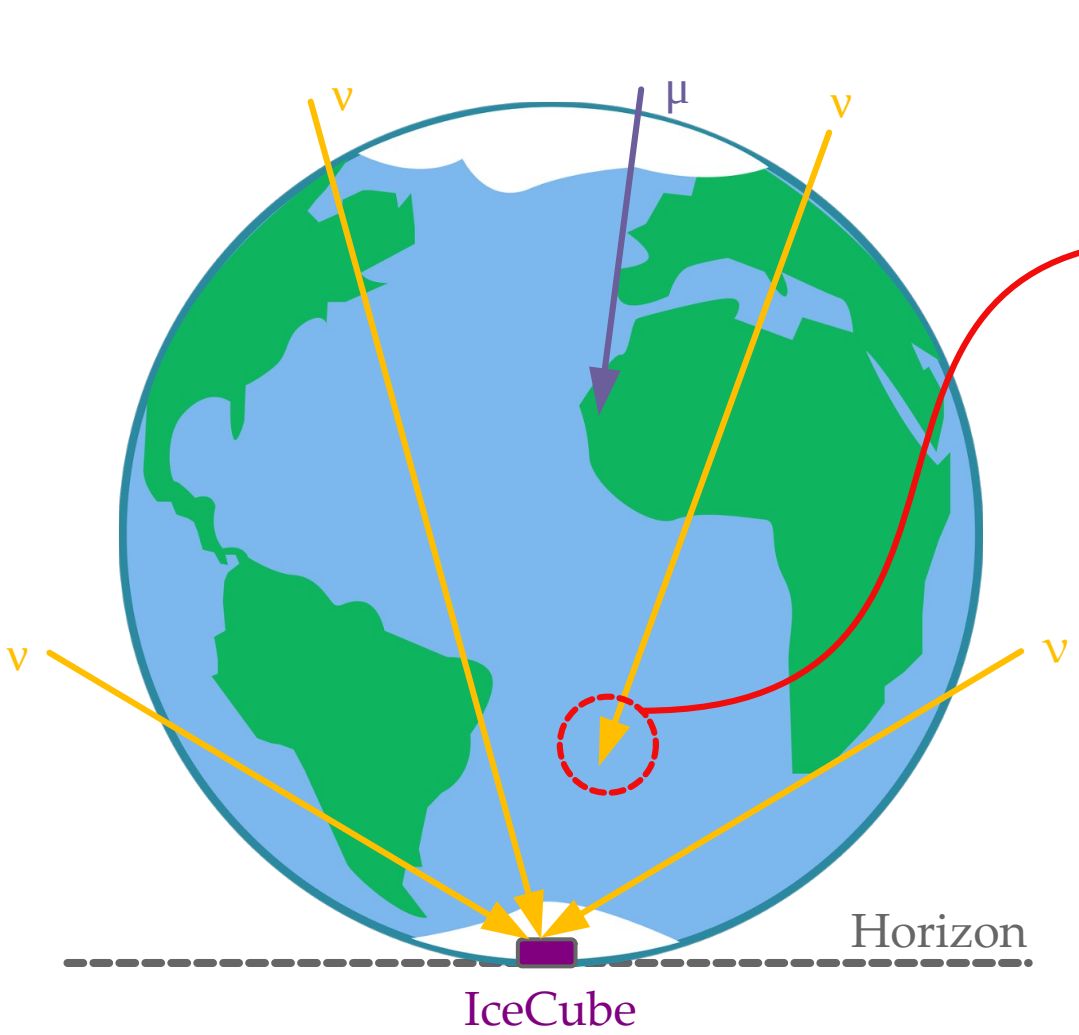


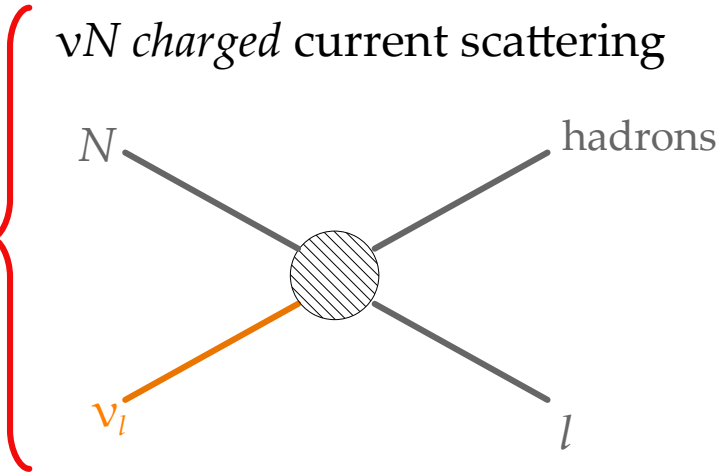
MB & Connolly, *PRL* 2019

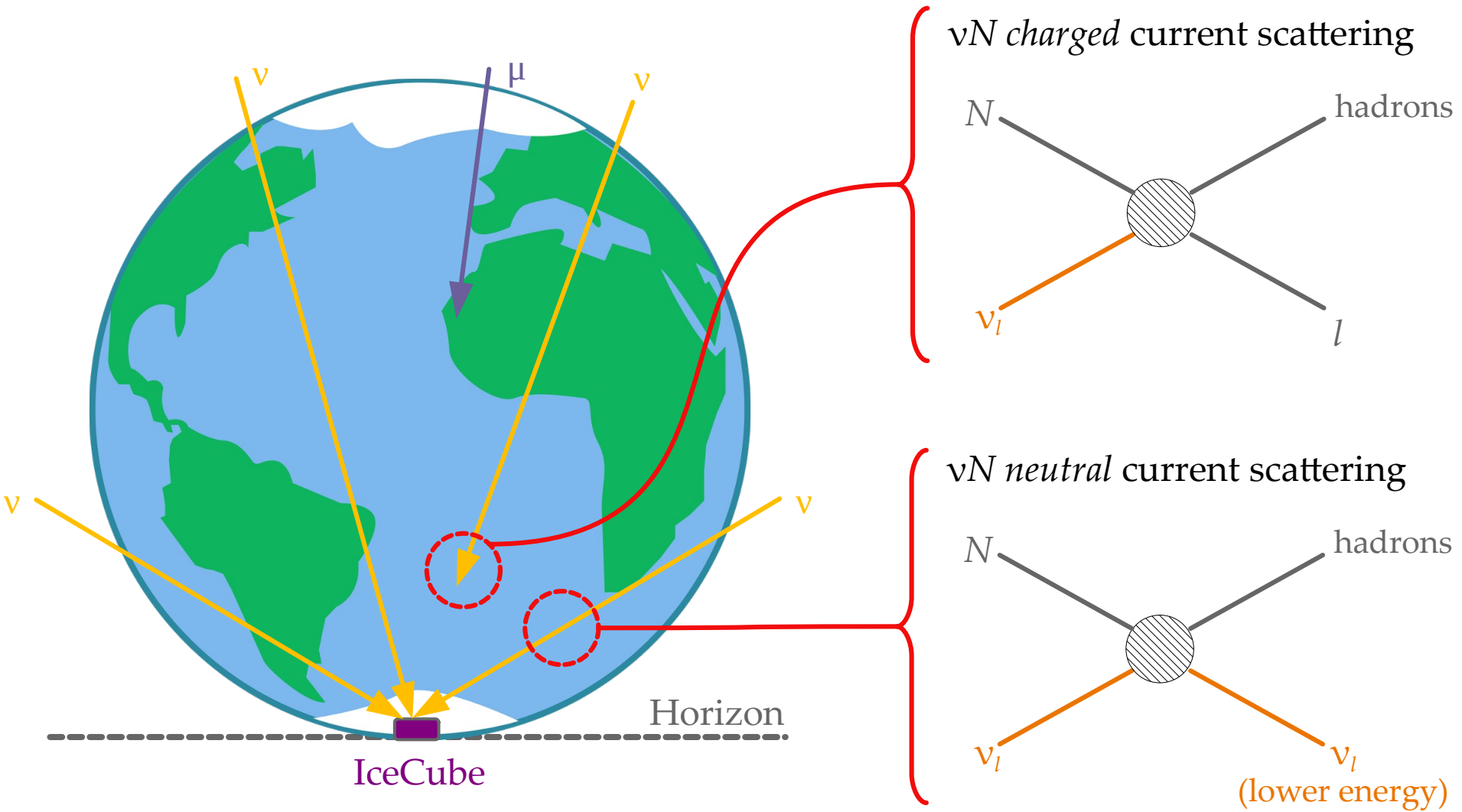


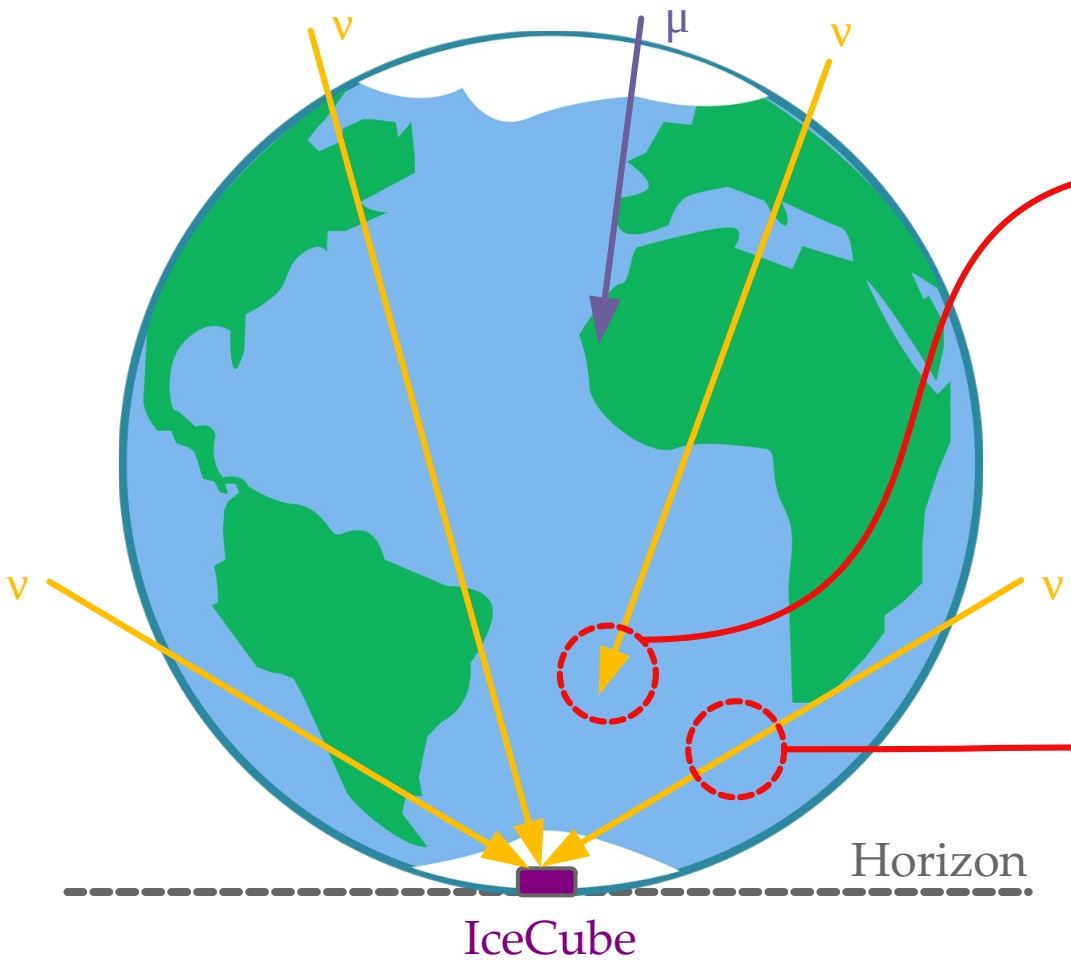
MB & Connolly, *PRL* 2019


ν
μ
ν
ν
ν
Horizon
IceCube

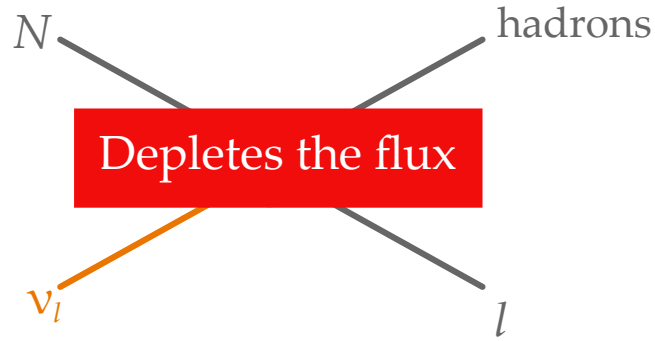

ν
μ
ν
ν
ν
Horizon
IceCube


νN charged current scattering
N
hadrons
ν_l
l

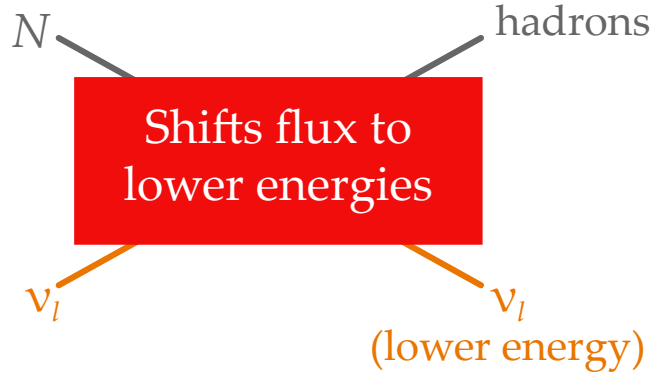

ν
μ
ν
ν
ν
Horizon
IceCube
νN charged current scattering
N
hadrons
ν_l
l
νN neutral current scattering
N
hadrons
ν_l
ν_l
(lower energy)



νN *charged* current scattering

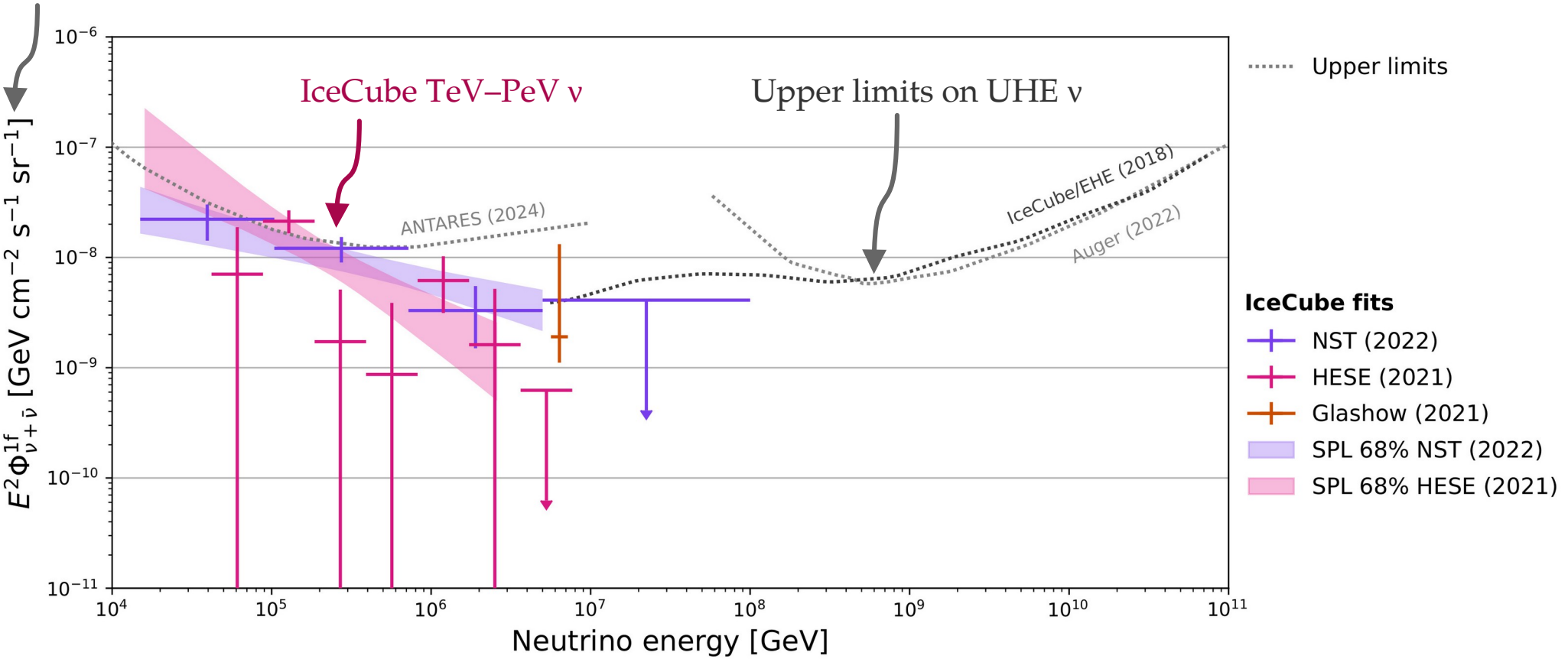


νN *neutral* current scattering



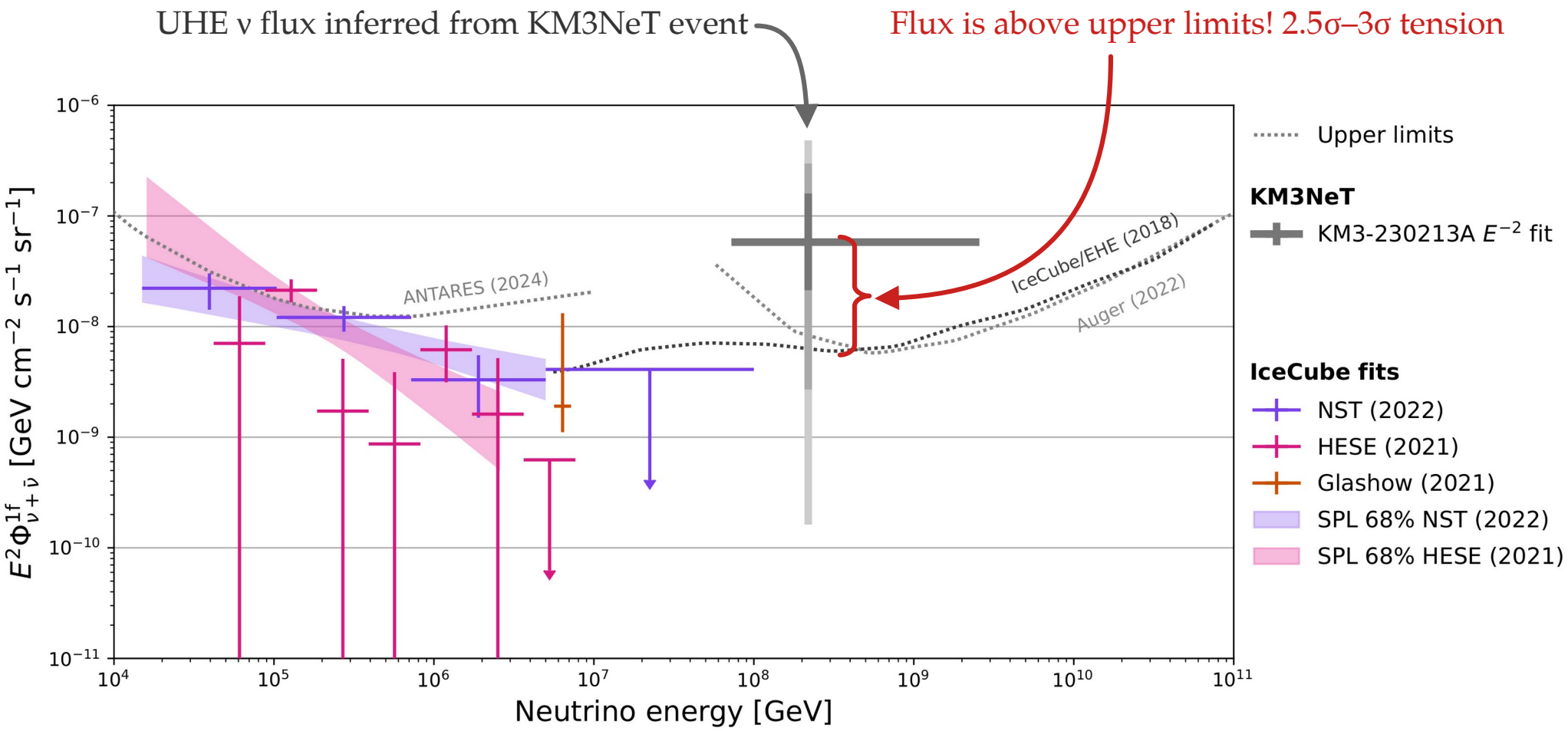
Was it a *cosmogenic* neutrino? KM3NeT *vs.* IceCube

Diffuse flux of high-energy astrophysical ν



KM3NeT Collab., arXiv:2502.08173 (adapted)
KM3NeT Collab. *Nature* 638, 376 (2025)

Was it a *cosmogenic* neutrino? KM3NeT *vs.* IceCube



KM3NeT Collab., arXiv:2502.08173 (adapted)
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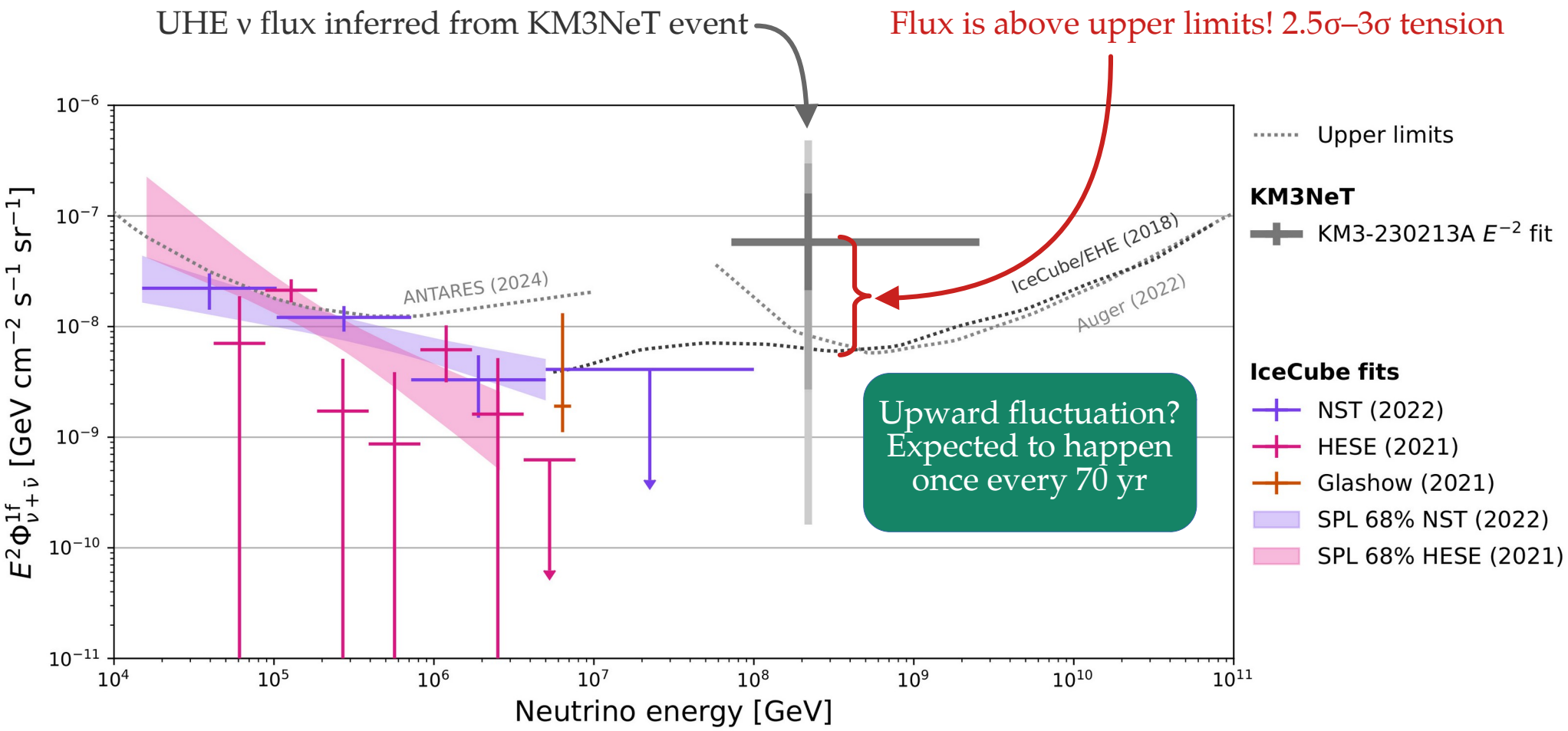

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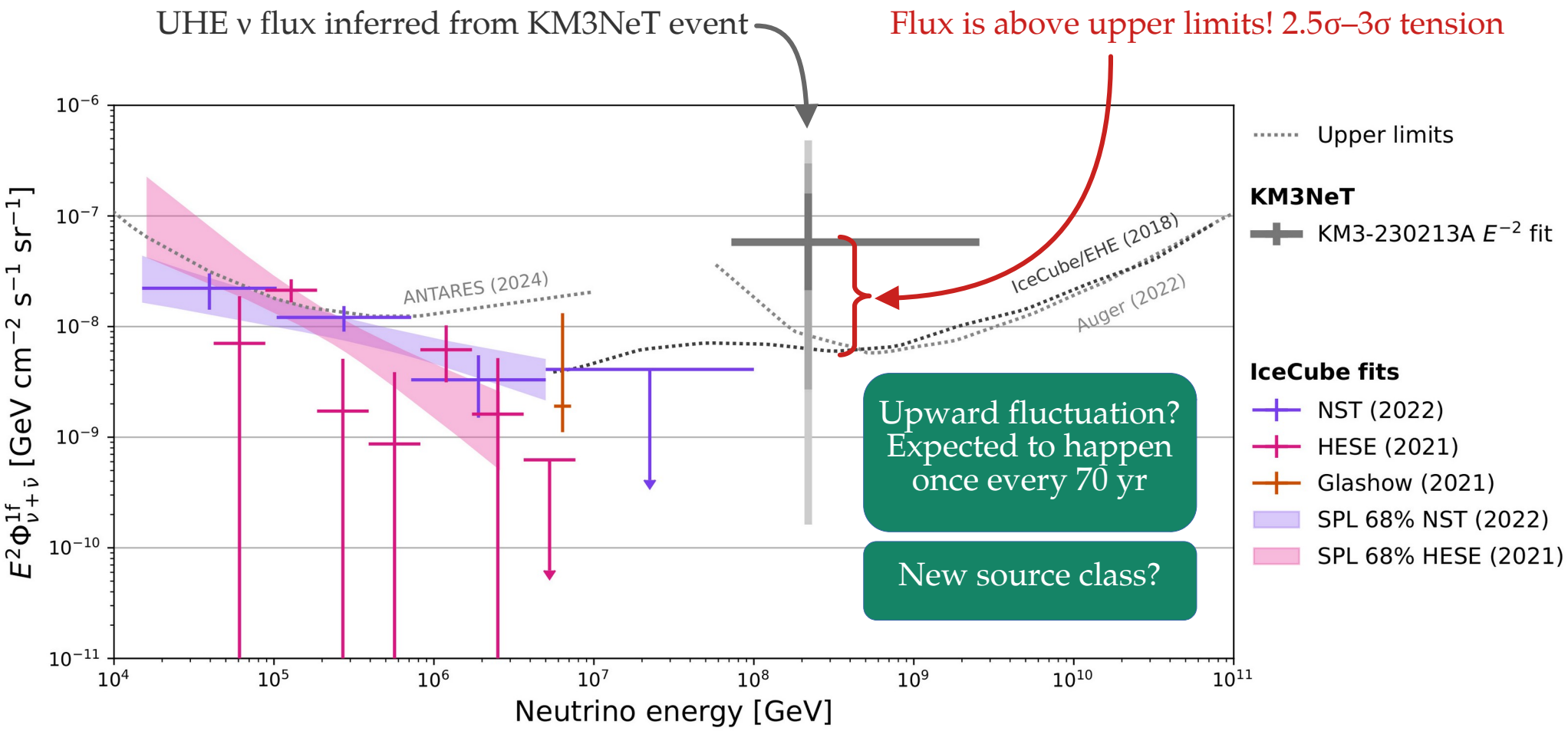
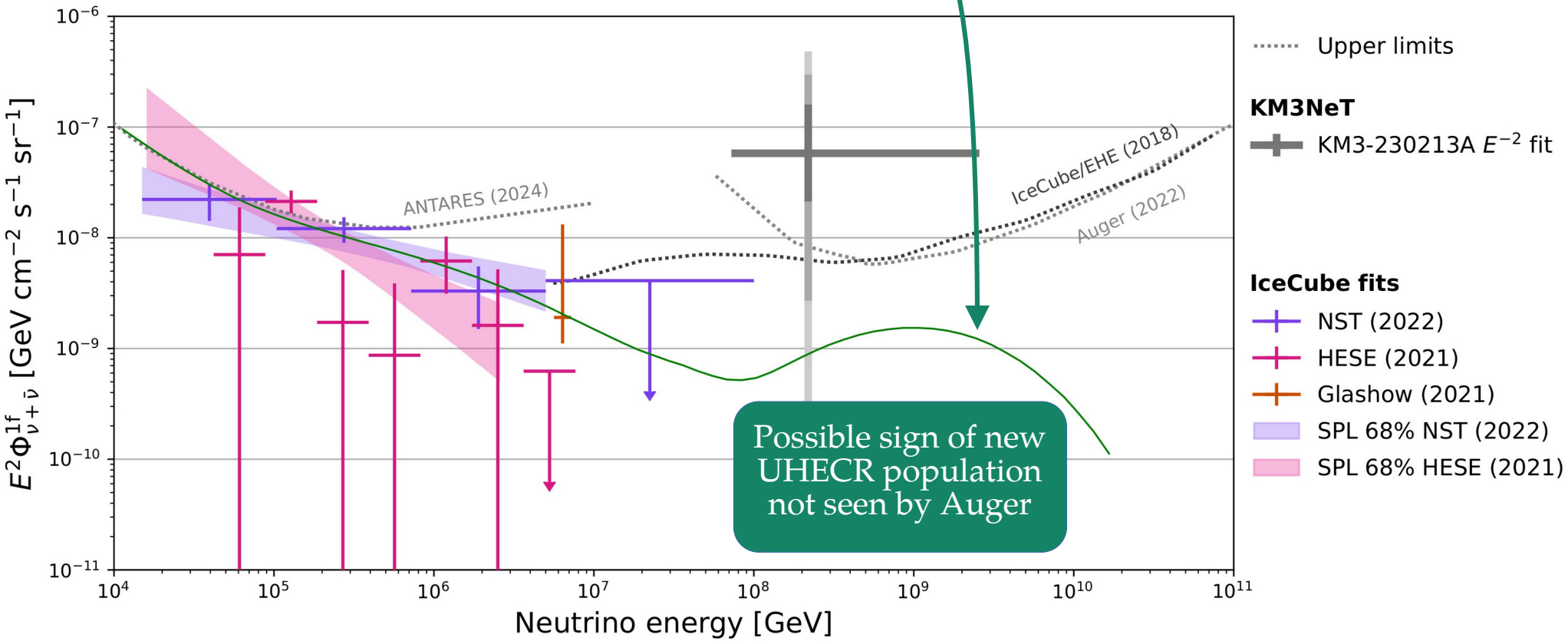


KM3NeT Collab., arXiv:2502.08173 (adapted)
KM3NeT Collab. *Nature* 638, 376 (2025)

Was it a *cosmogenic* neutrino? KM3NeT *vs.* IceCube

Joint fit to IceCube and KM3NeT ν data + Auger UHECR data

Muzio, Yuan, Lu, arXiv:2502.06944



KM3NeT Collab., arXiv:2502.08173 (adapted)
KM3NeT Collab. *Nature* 638, 376 (2025)

5. Dark matter:
Annihilation and decay into ν

High-energy neutrinos from dark matter

Dark matter co-annihilation:

$$\chi + \chi \to \nu + \bar{\nu}$$

$$\chi + \chi \to \ldots \to \nu + \bar{\nu} + \ldots$$

$$E_{\max} = m_\chi$$

Dark matter decay:

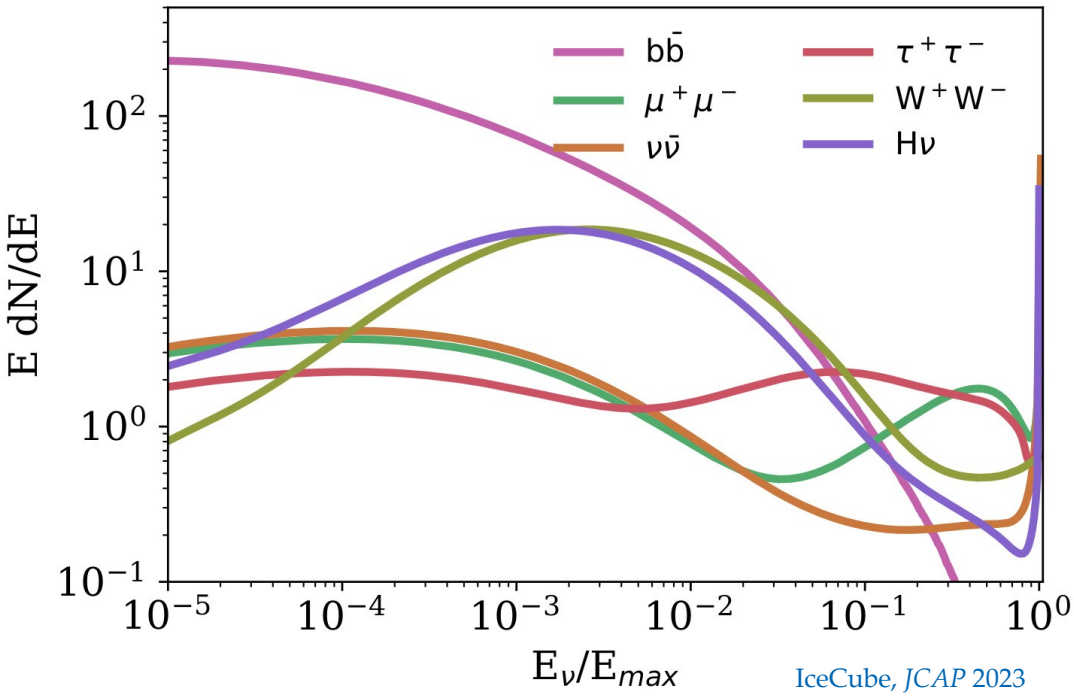
$$\chi \to \nu + \bar{\nu}$$

$$\chi \to \ldots \to \nu + \bar{\nu} + \ldots$$

$$E_{\max} = m_\chi/2$$

Electroweak corrections (off-shell W and Z emission) broaden the ν spectrum

ν + ν yield from DM (at source)

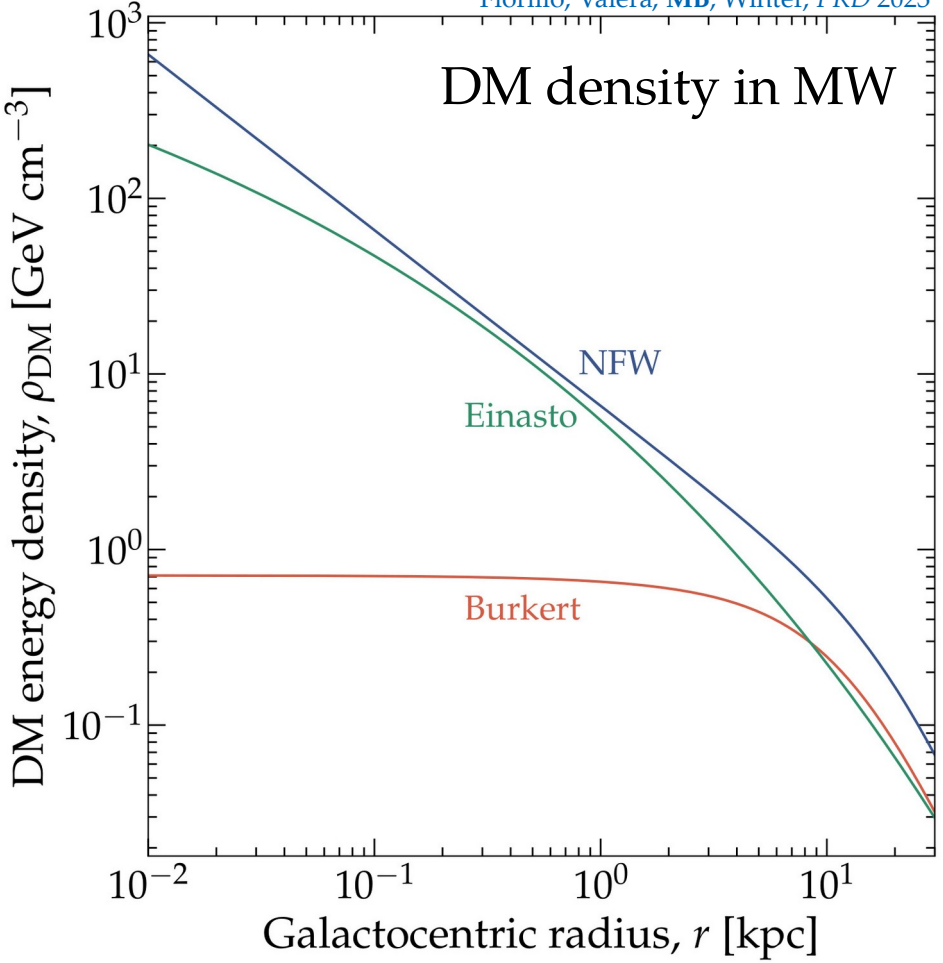


IceCube, *JCAP* 2023

Approximate independence on m_χ valid for $m_\chi \approx 100$ TeV–10 PeV

Dark matter in the Milky Way

Fiorillo, Valera, **MB**, Winter, *PRD* 2023



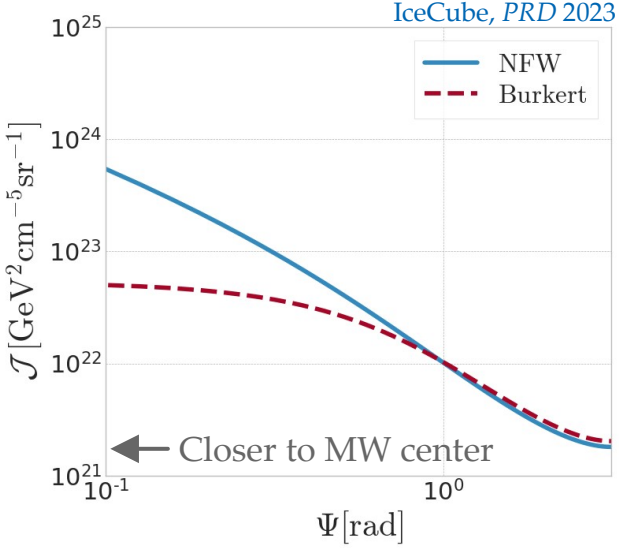
DM annihilation

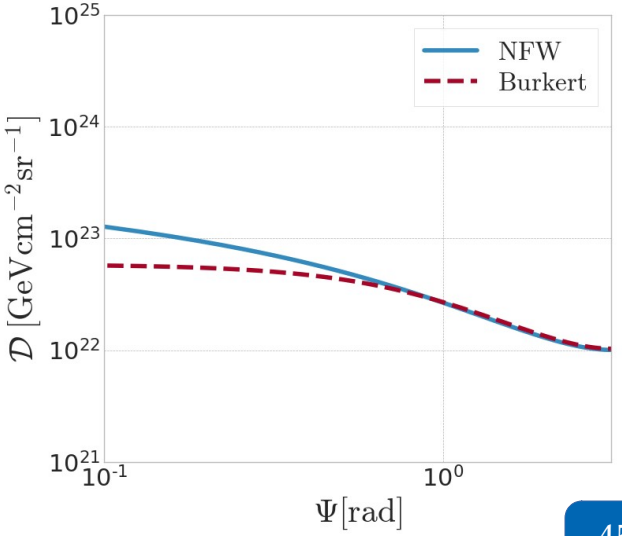
$\Phi_\nu \propto \mathcal{I} \propto \rho^2_{\rm DM}$

DM decay

$\Phi_\nu \propto \mathcal{D} \propto \rho_{\rm DM}$

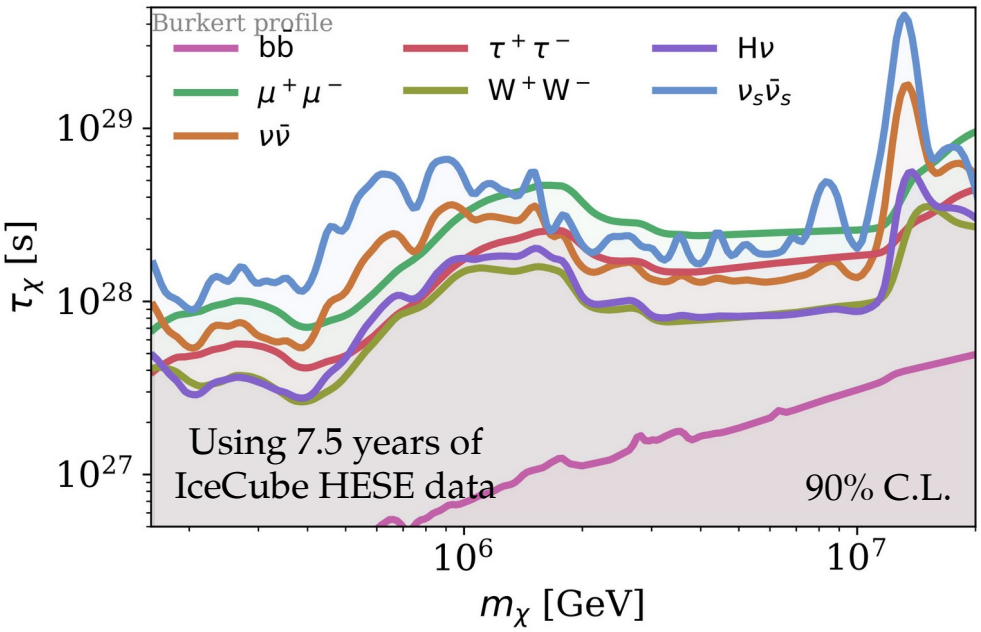
IceCube, *PRD* 2023



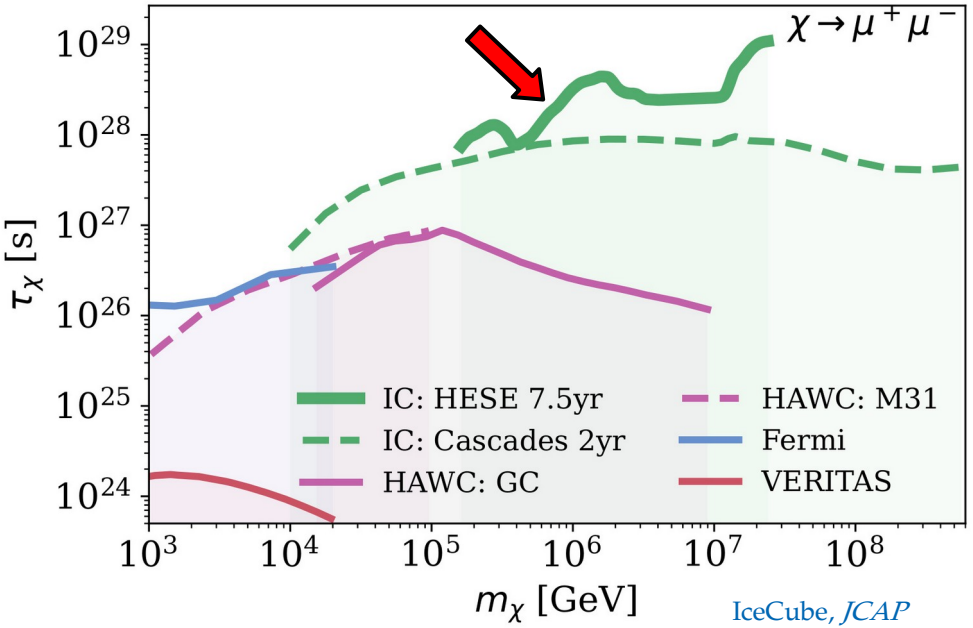


Limits on dark matter decay

Per annihilation channel
(assuming 100% branching ratio)



Compared to other limits
(assuming decay into muons)



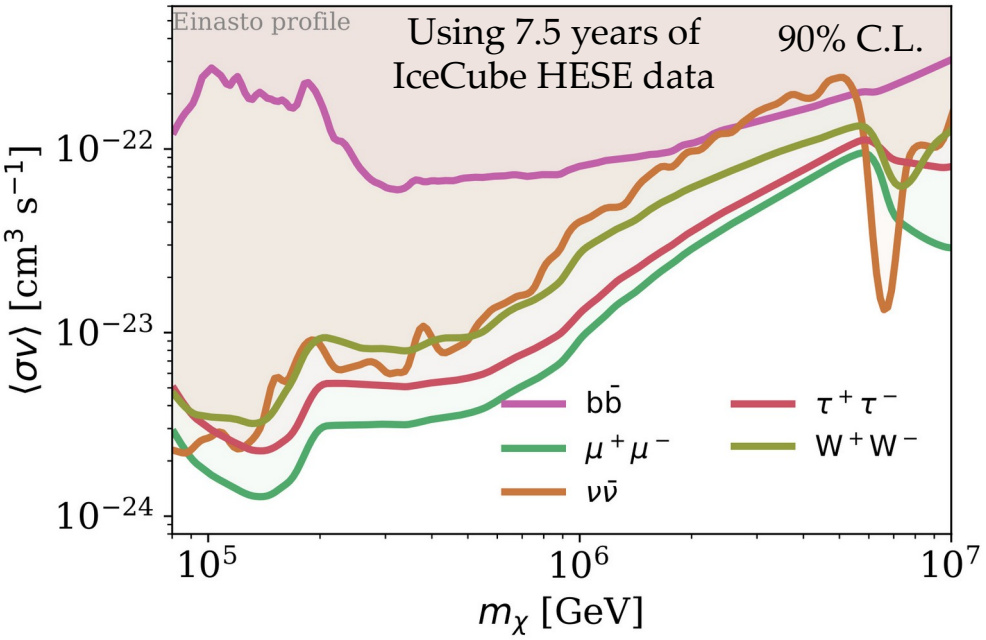
IceCube, *JCAP* 2023

Two DM contributions: Galactic (anisotropic) + extragalactic (isotropic)

Plus background of atmospheric neutrinos (anisotropic, but different)

Limits on dark matter annihilation

Per annihilation channel
(assuming 100% branching ratio)



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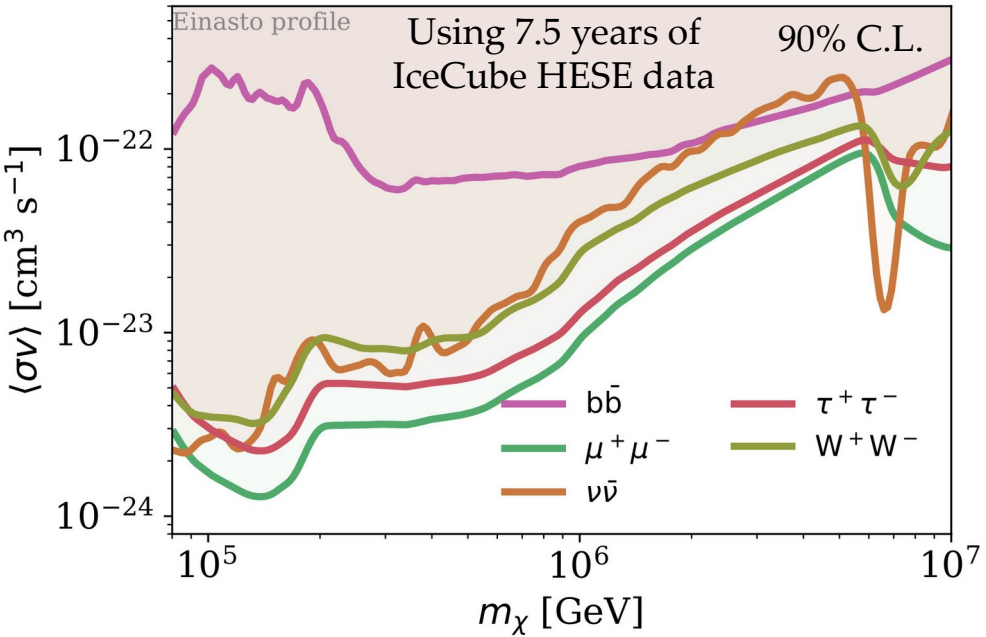
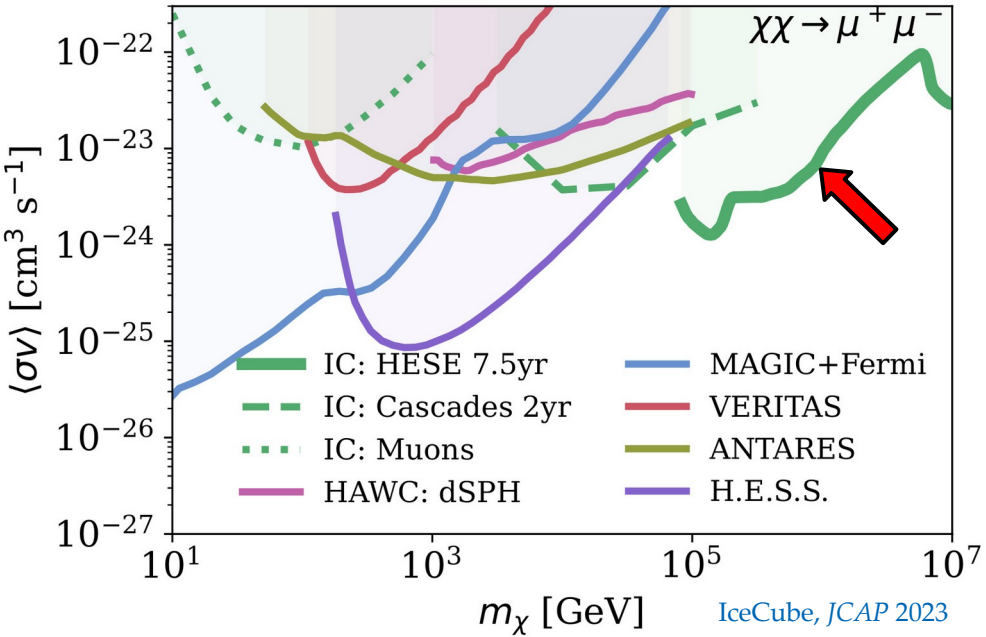
Per annihilation channel
(assuming 100% branching ratio)



Compared to other limits
(assuming annihilation to muons)



IceCube, *JCAP* 2023

Two DM contributions: Galactic (anisotropic) + extragalactic (isotropic)

Plus background of atmospheric neutrinos (anisotropic, but different)

6. Unstable neutrinos:
Are neutrinos for ever?

Are neutrinos forever?

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

  } » Age of Universe (~ 14.5 Gyr)

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

- We work in a model-independent way:
  the nature of φ is unimportant if it is invisible to neutrino detectors

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  } » Age of Universe (~ 14.5 Gyr)

- BSM decays may have significantly higher rates: $\nu_i \to \nu_j + \varphi$ — Nambu-Goldstone boson of a broken symmetry

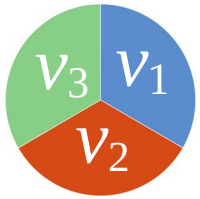
- We work in a model-independent way:
  the nature of φ is unimportant if it is invisible to neutrino detectors

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 $\exp[-(L/E) \cdot (m_i/\tau_i)]$

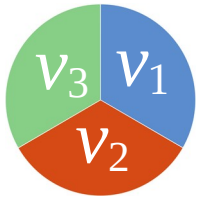
Mass of ν_i Lifetime of ν_i

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 $\exp[-(L/E)\cdot(m_i/\tau_i)]$

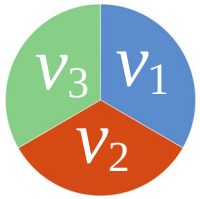
Mass of ν_i Lifetime of ν_i

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 $\exp[-(L/E)\cdot(m_i/\tau_i)]$

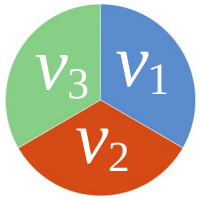
… but ν that travel longer L are more attenuated!

Astrophysical sources

Earth

L ~ up to a few Gpc

E.g.,



Astrophysical sources

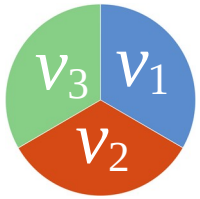
Earth

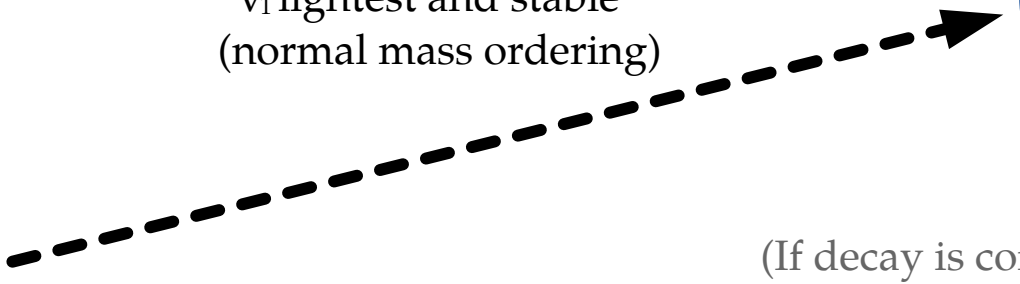
$L \sim$ up to a few Gpc

$\nu_2, \nu_3 \rightarrow \nu_1$

ν_1 lightest and stable
(normal mass ordering)

E.g.,





(If decay is complete)

Astrophysical sources

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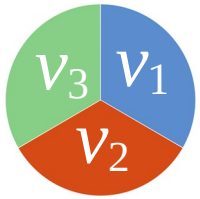

(If decay is complete)

$\nu_1, \nu_2 \rightarrow \nu_3$

ν_3 lightest and stable
(inverted mass
ordering)

Astrophysical sources

Earth

$L \sim$ up to a few Gpc

$\nu_2, \nu_3 \rightarrow \nu_1$

ν_1 lightest and stable
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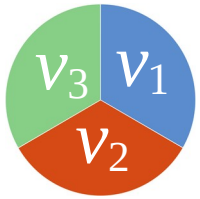

(If decay is complete)

$\nu_1, \nu_2 \rightarrow \nu_3$

ν_3 lightest and stable
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Fine print:

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

Astrophysical sources

Earth

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(normal mass ordering)

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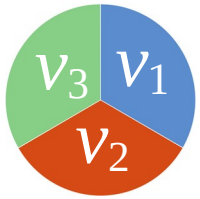

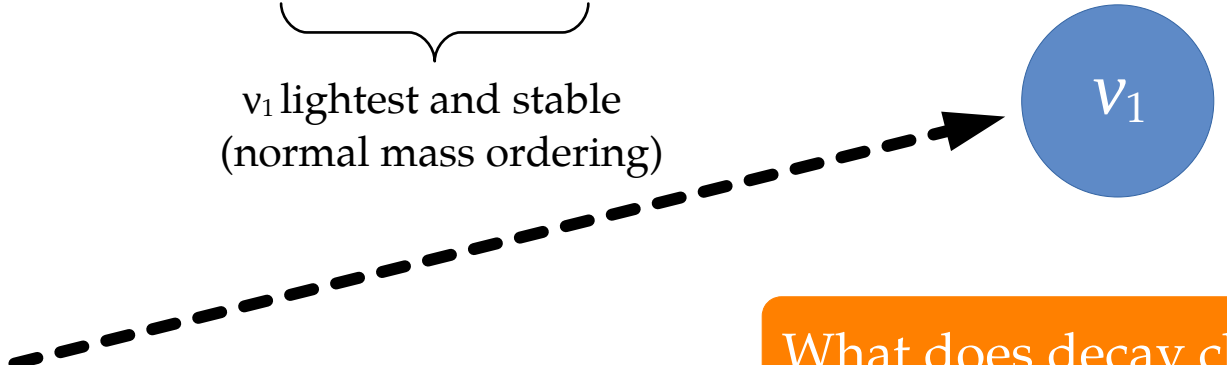

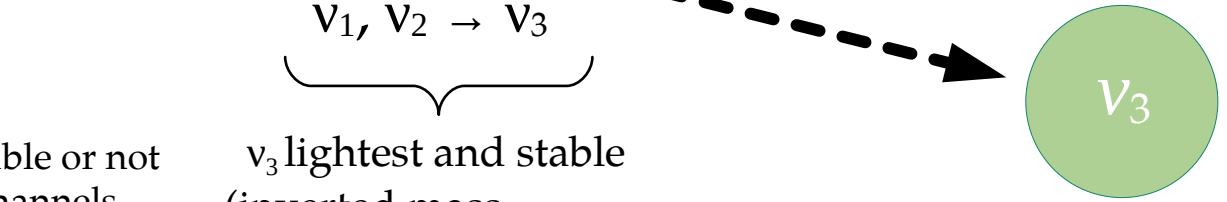

What does decay change?

$\nu_1, \nu_2 \rightarrow \nu_3$

ν_3 lightest and stable
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Fine print:

- Decay can be incomplete
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What does neutrino decay change?

Flavor composition ⟺ Spectrum shape ⟺ Event rate

What does neutrino decay change?

Flavor composition ⟺ Spectrum shape ⟺ Event rate

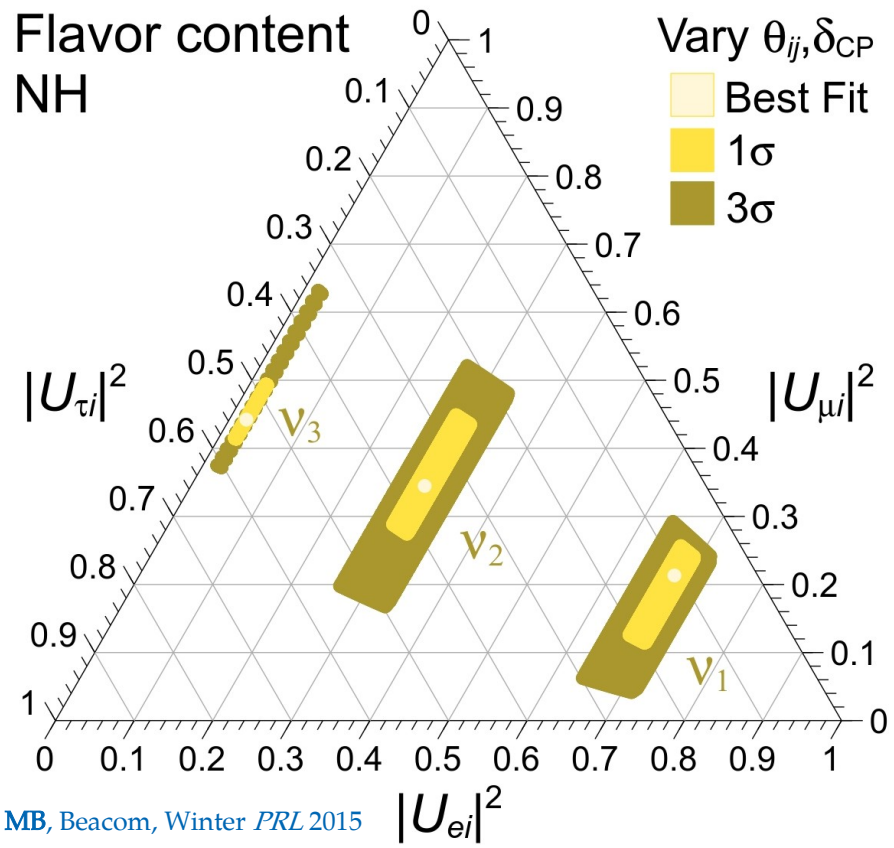
Flavor content of mass eigenstates:

Known to within 2%

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

Known to within 8%

Known to within 20% (or worse)



MB, Beacom, Winter *PRL* 2015

What does neutrino decay change?

Flavor composition ⟺ Spectrum shape ⟺ Event rate

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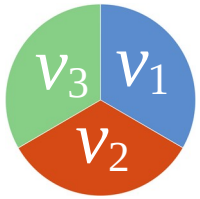
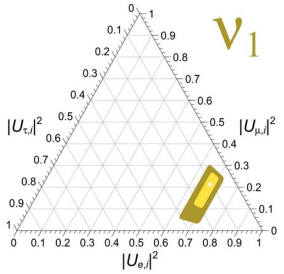
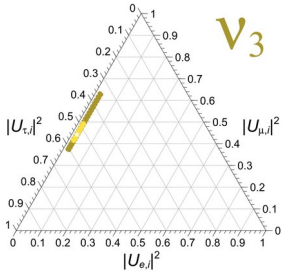






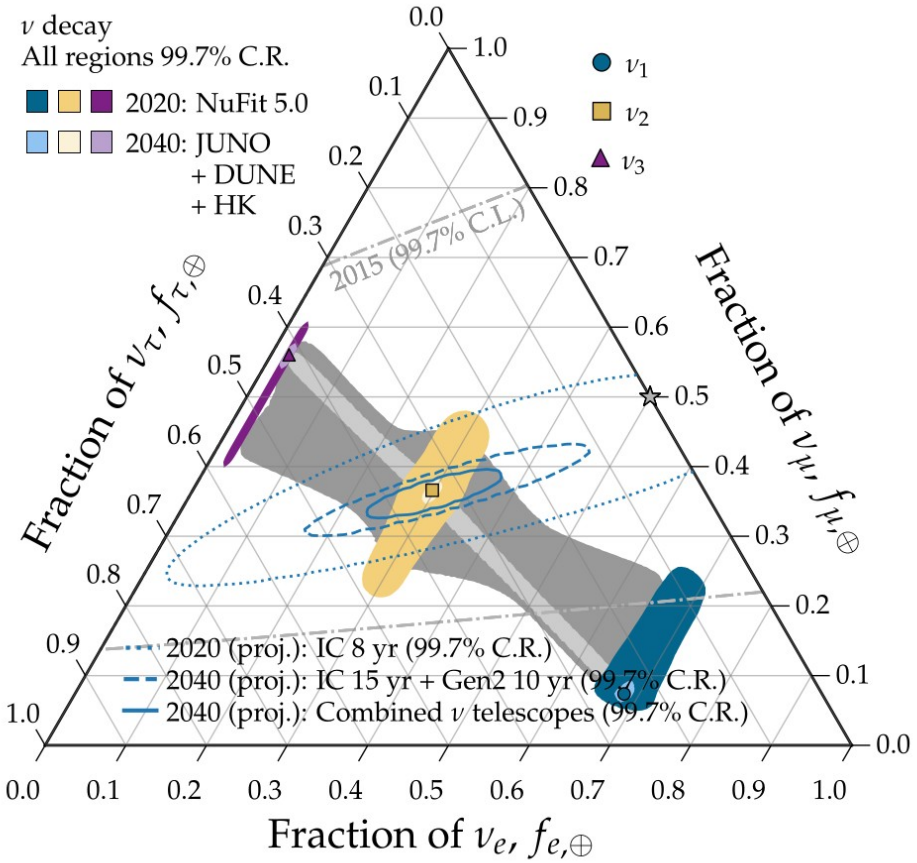
$\nu_1, \nu_2 \rightarrow \nu_3$

ν_3 lightest and stable (inverted mass ordering)

What does neutrino decay change?

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

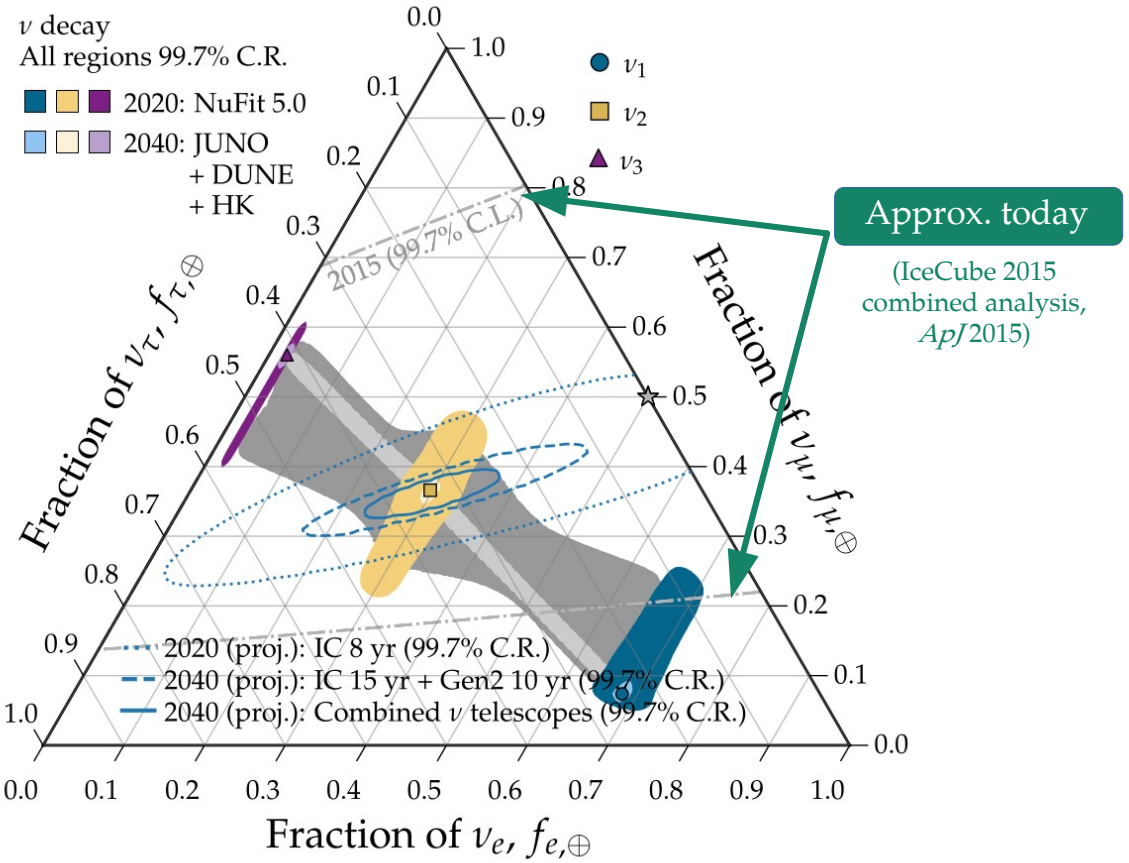
Flavor composition ⟺ Spectrum shape ⟺ Event rate



What does neutrino decay change?

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

Flavor composition ⟺ Spectrum shape ⟺ Event rate



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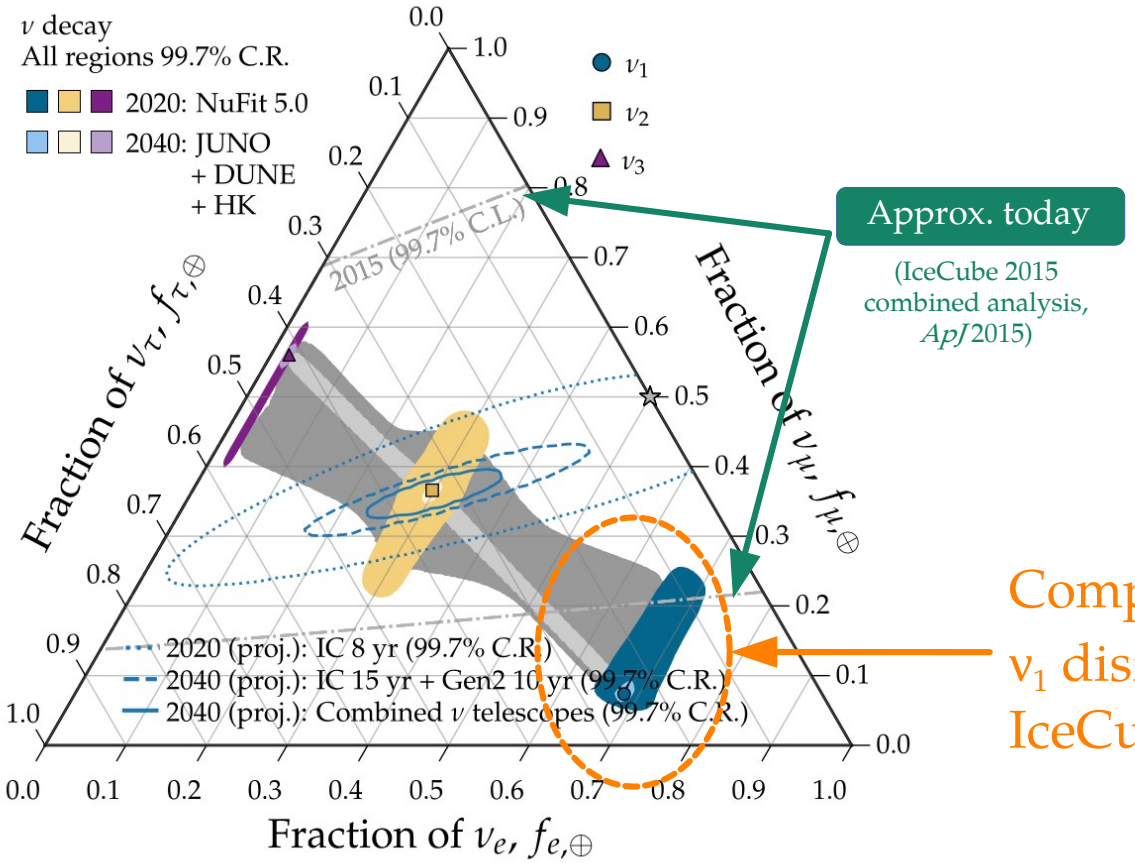
Flavor composition ⟺ Spectrum shape ⟺ Event rate



Approx. today

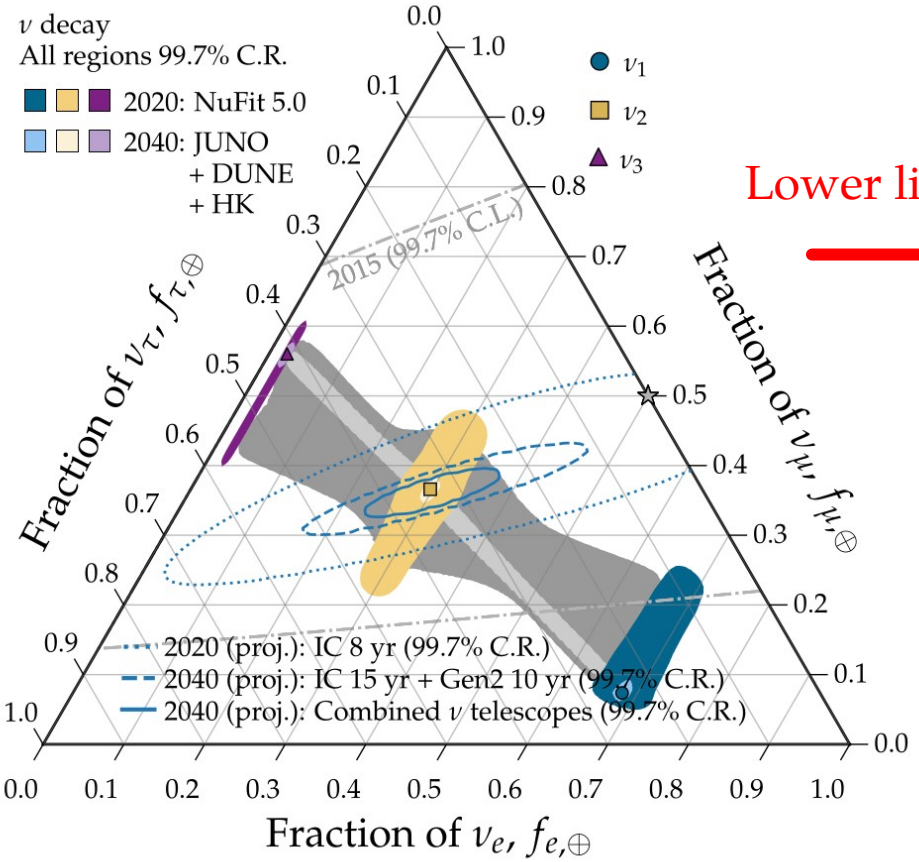
(IceCube 2015 combined analysis, *ApJ* 2015)

Complete decay into ν_1 disfavored by 2015 IceCube flavor measurement

What does neutrino decay change?

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

Flavor composition ⟺ Spectrum shape ⟺ Event rate

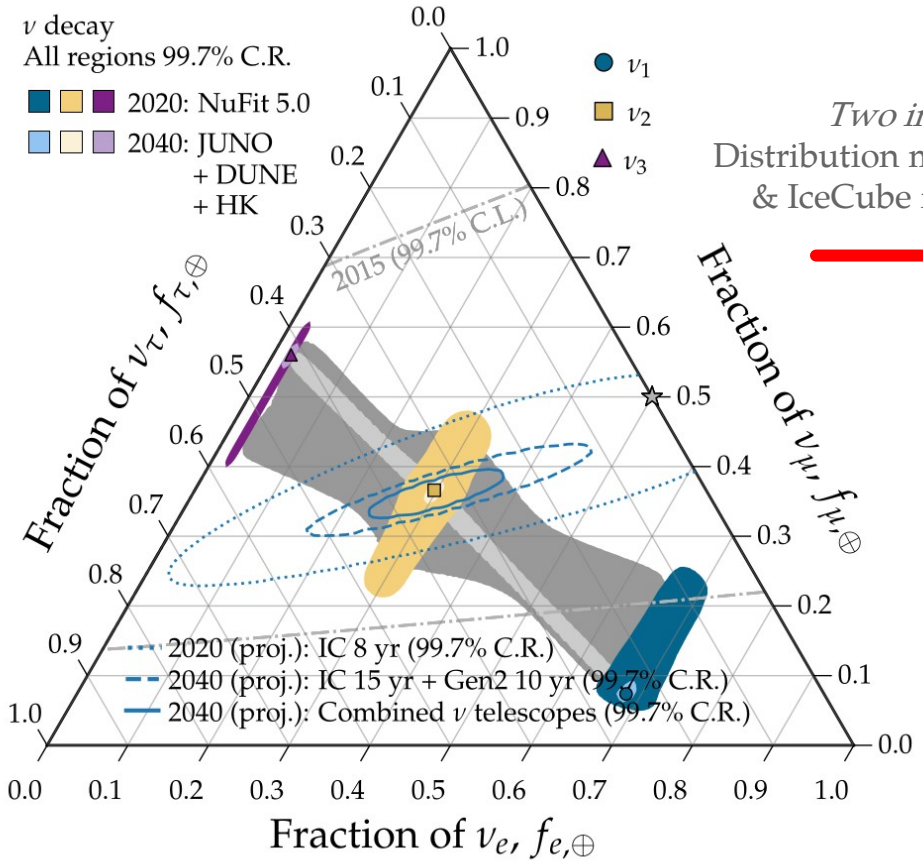


Lower limit on τ/m →

What does neutrino decay change?

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

Flavor composition ⟺ Spectrum shape ⟺ Event rate



Two ingredients:
Distribution mixing parameters
& IceCube flavor posterior

What does neutrino decay change?

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

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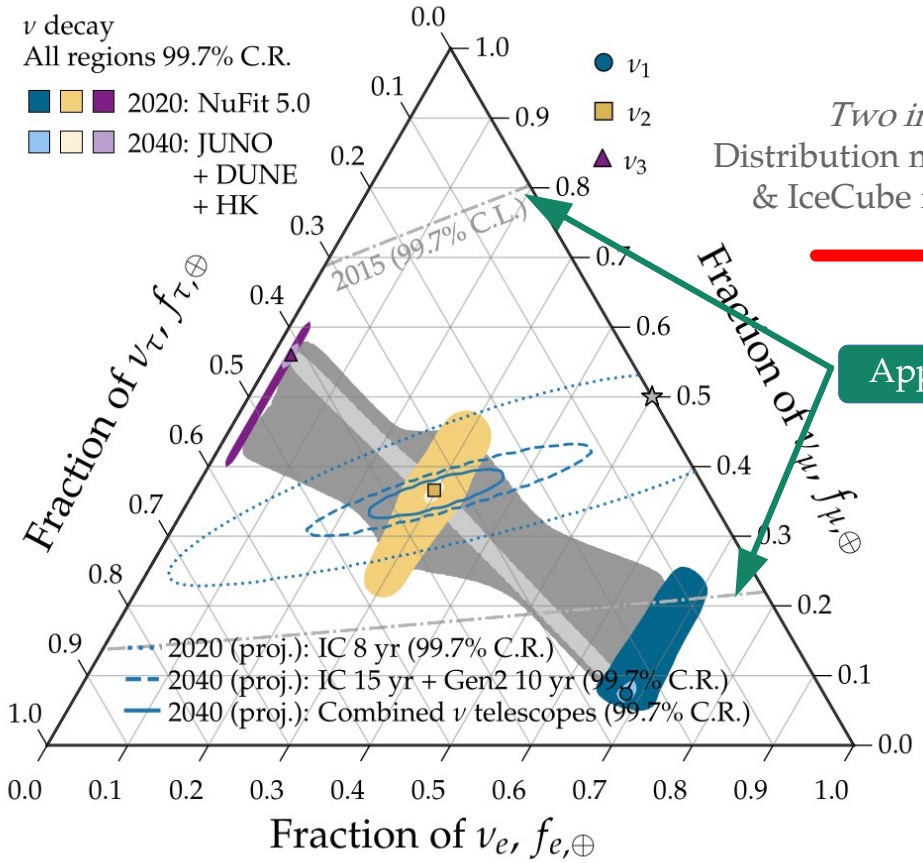

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Approx. today

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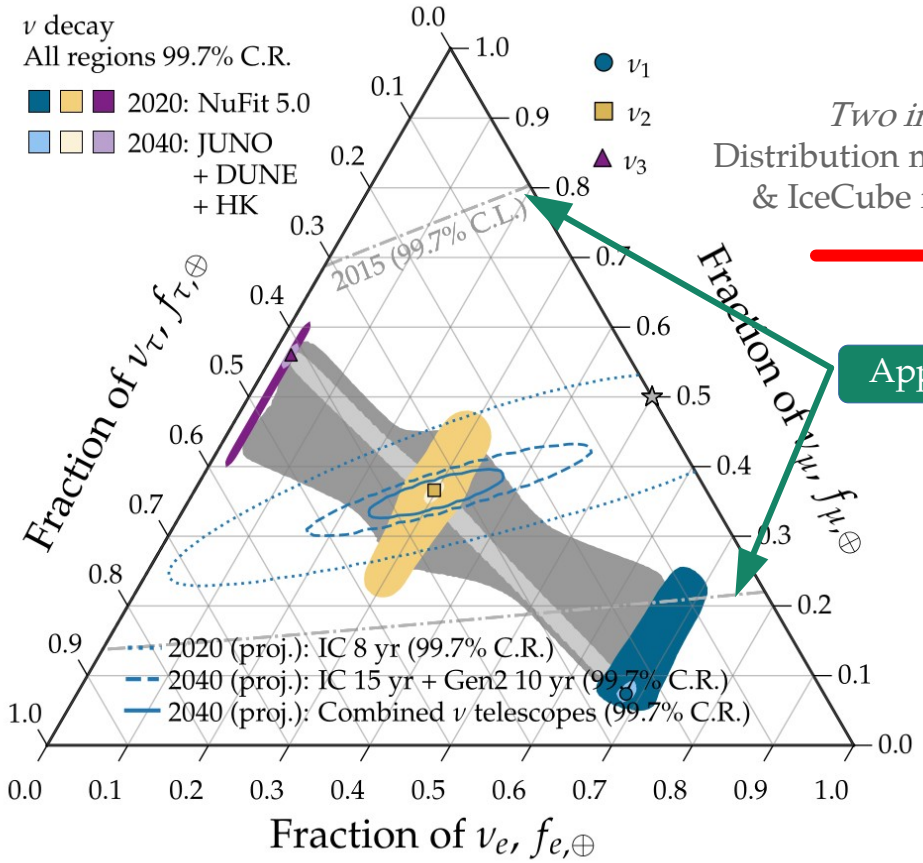

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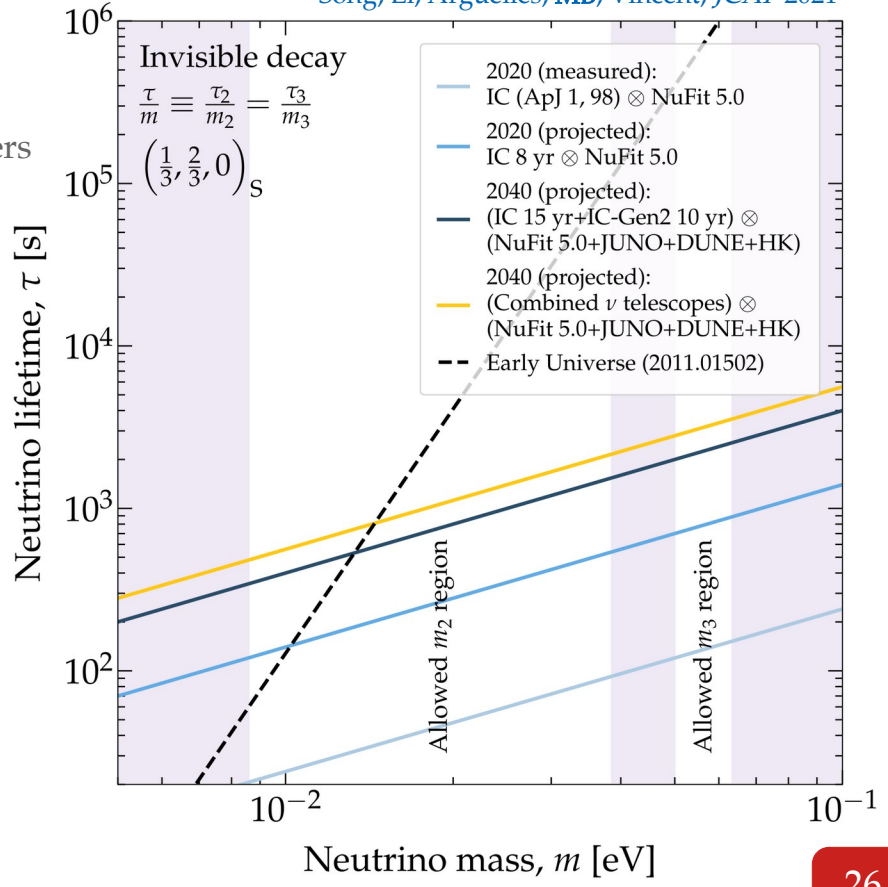
Approx. today

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



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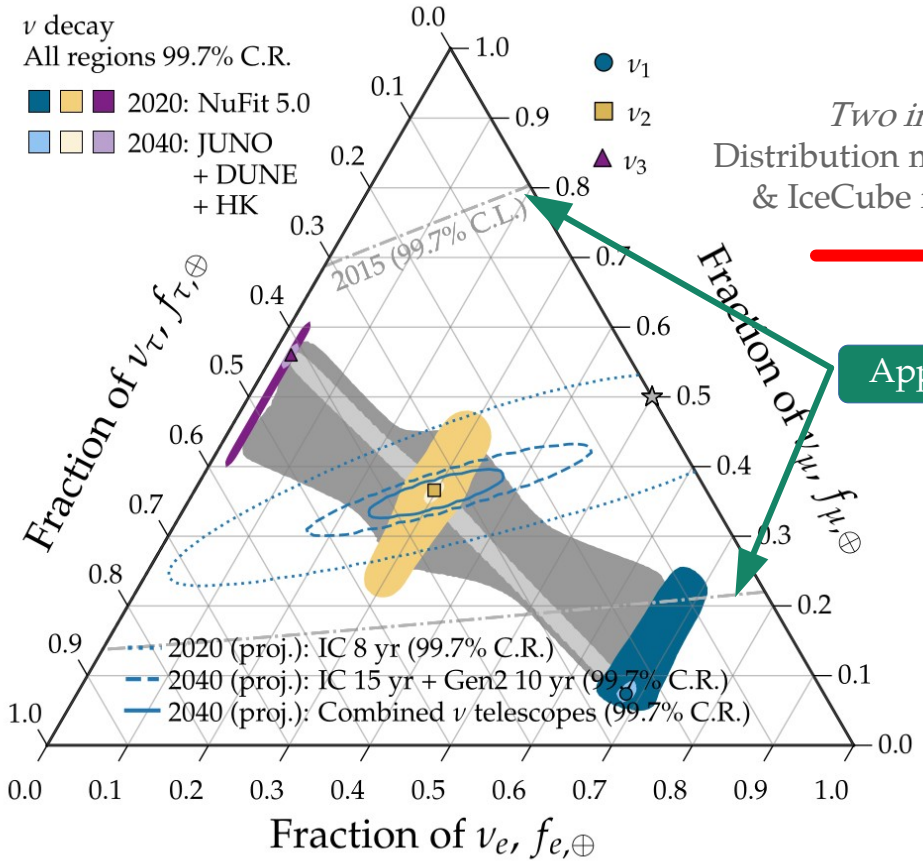

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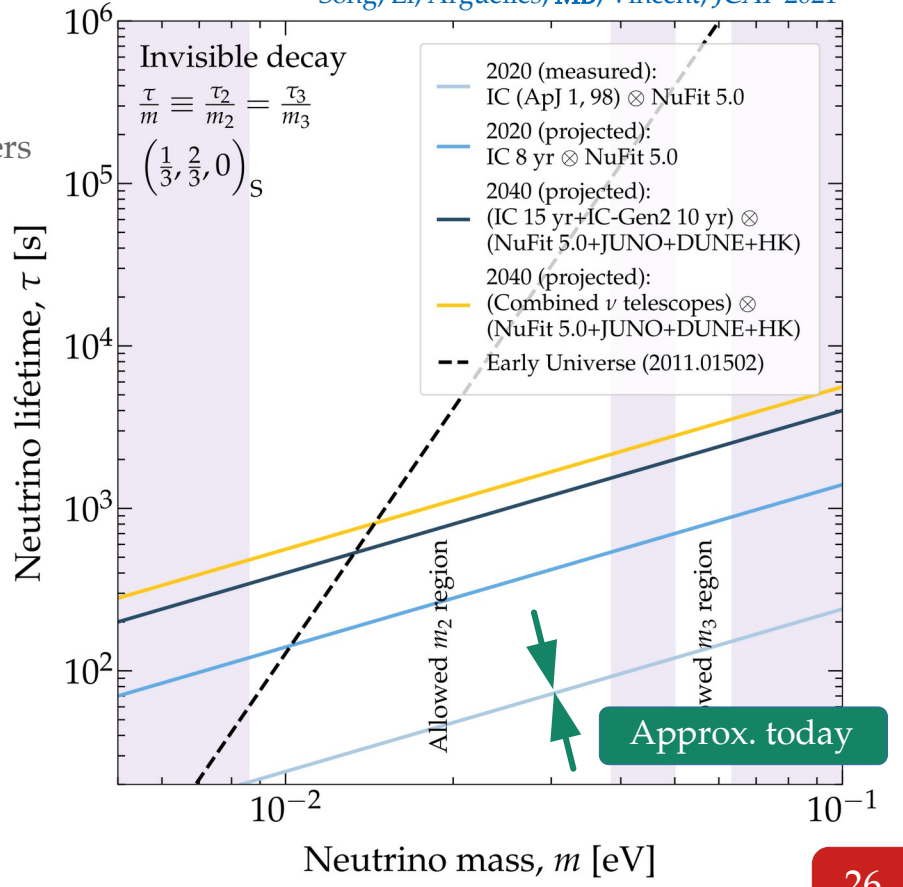
Approx. today

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



Approx. today

What does neutrino decay change?

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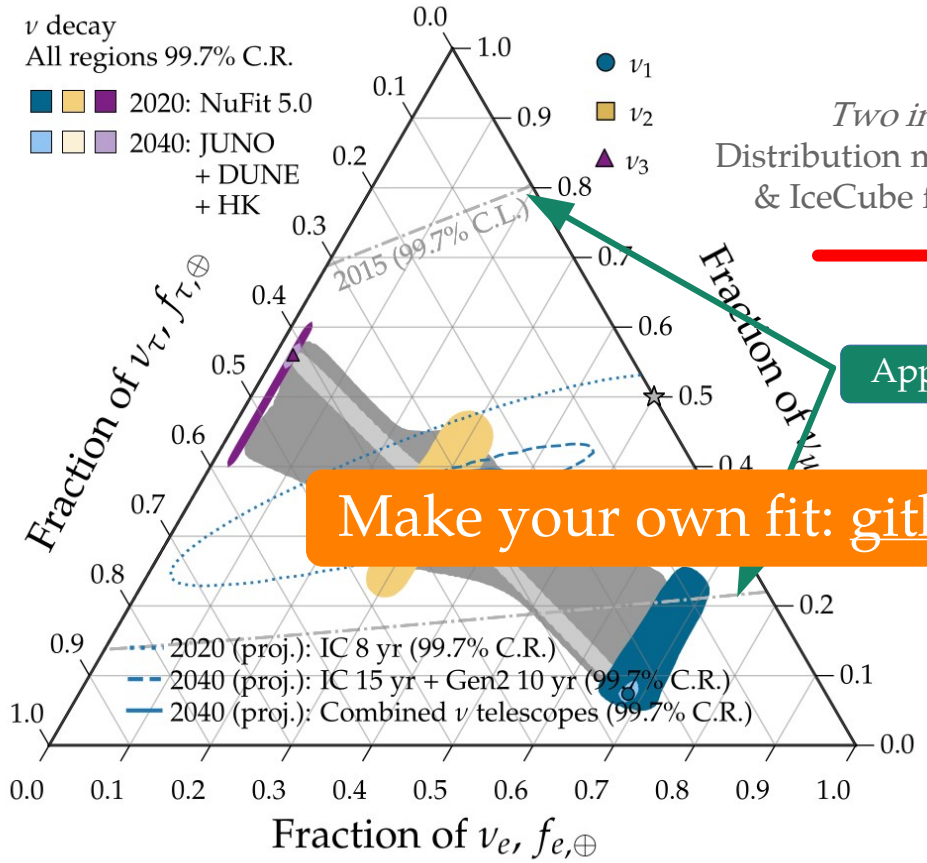
Flavor composition ⟺ Spectrum shape ⟺ Event rate



Two ingredients:
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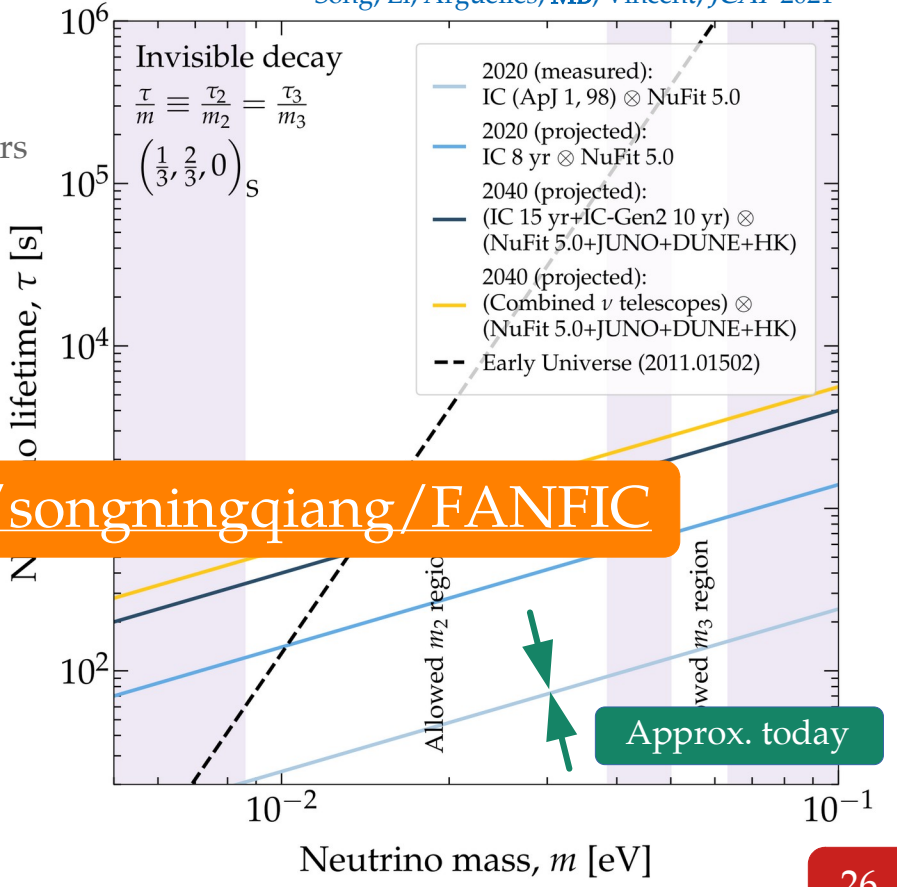
Approx. today

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



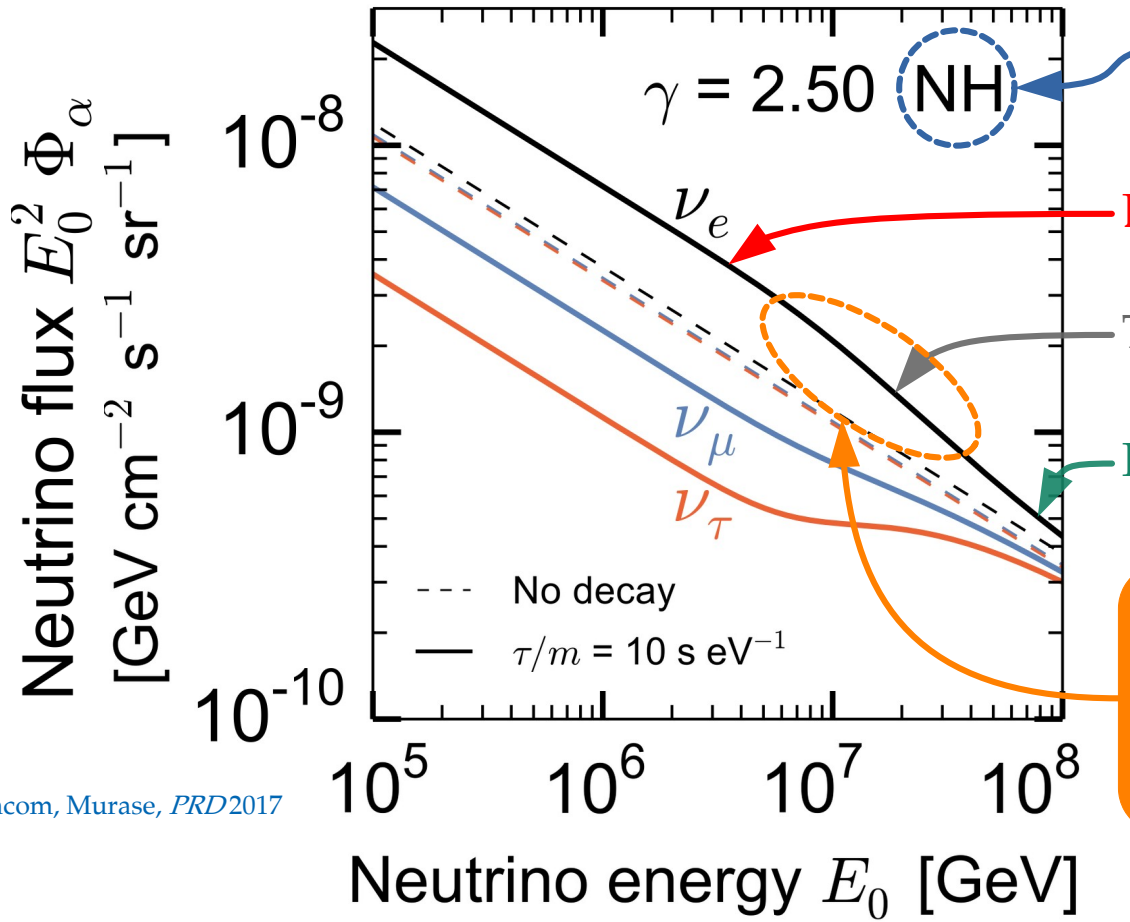
Approx. today

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

What does neutrino decay change?

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

Flavor composition ⟺ Spectrum shape ⟺ Event rate



$\nu_2, \nu_3 \rightarrow \nu_1$

Low energy: decay evident

Transition region

High energy: no decay

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

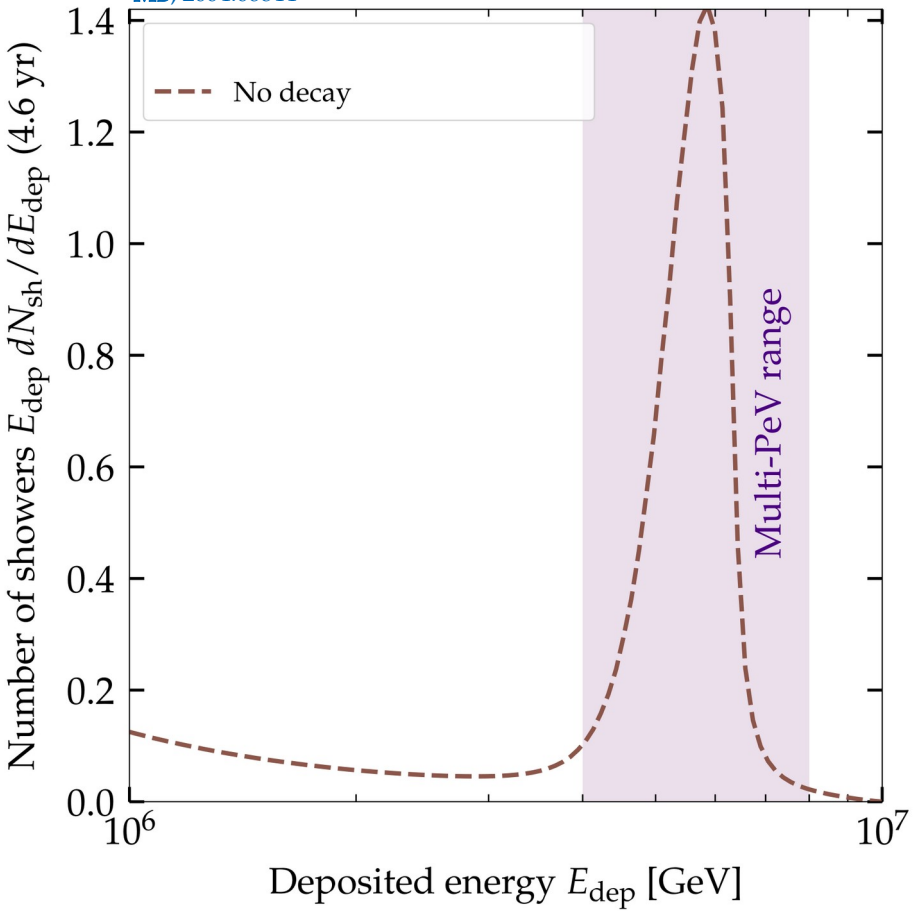
MB, Beacom, Murase, *PRD* 2017

What does neutrino decay change?

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

Flavor composition ⟺ Spectrum shape ⟺ Event rate

MB, 2004.06844



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Flavor composition ⟺ Spectrum shape ⟺ Event rate

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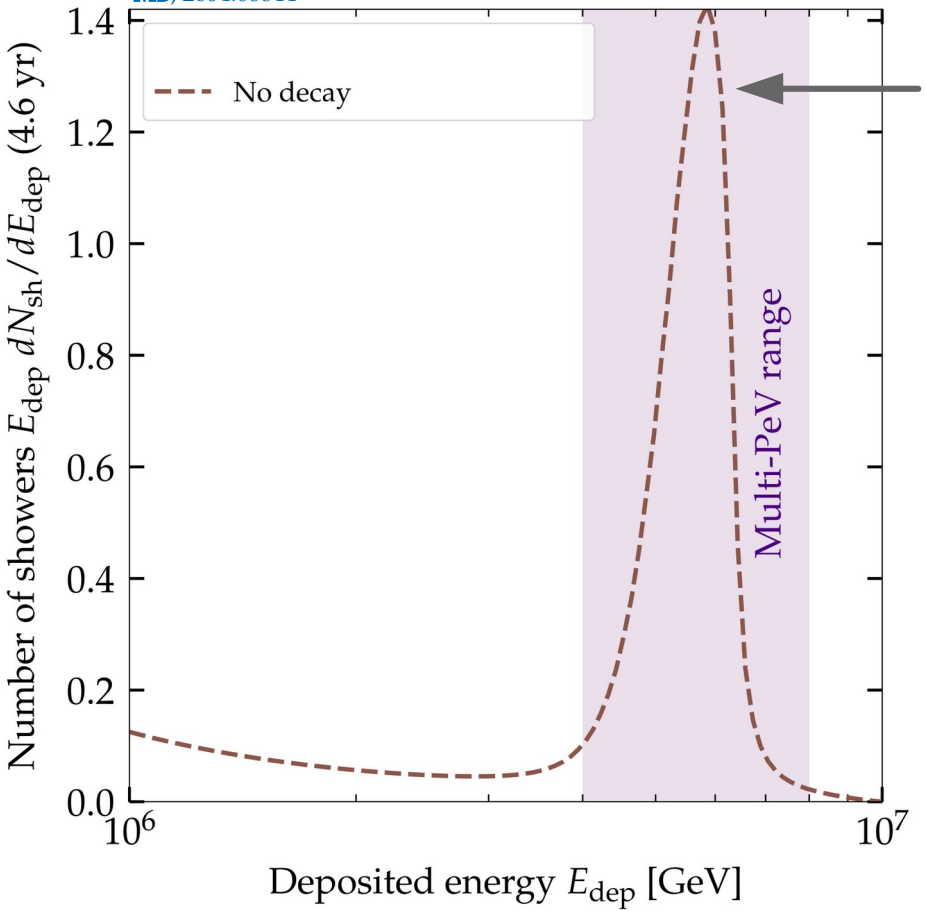

Glashow resonance (GR):
$\bar{\nu}_e + e \rightarrow W \rightarrow$ hadrons $\rightarrow$ shower

What does neutrino decay change?

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Flavor composition ⟺ Spectrum shape ⟺ Event rate

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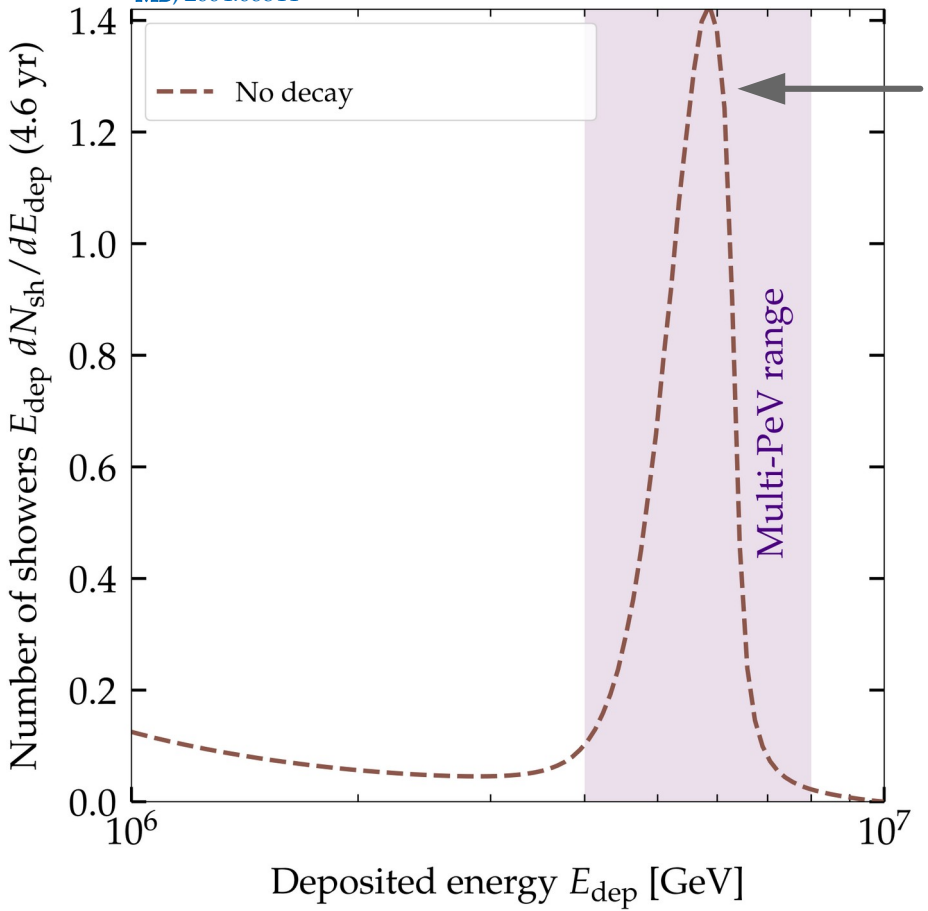
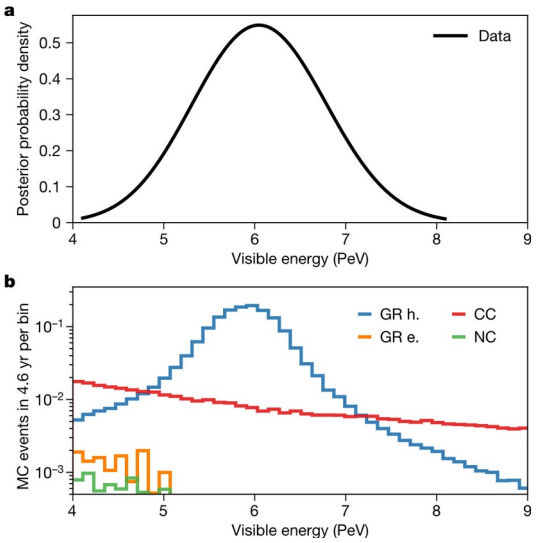
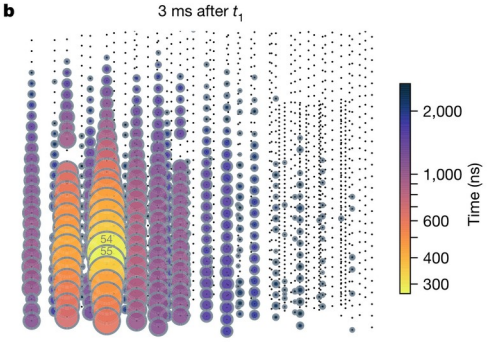


Glashow resonance (GR):
$\bar{\nu}_e + e \rightarrow W \rightarrow$ hadrons $\rightarrow$ shower

IceCube has seen one GR candidate in 4.6 years:





IceCube Collab., *Nature* 2021

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

Flavor composition ⟺ Spectrum shape ⟺ Event rate

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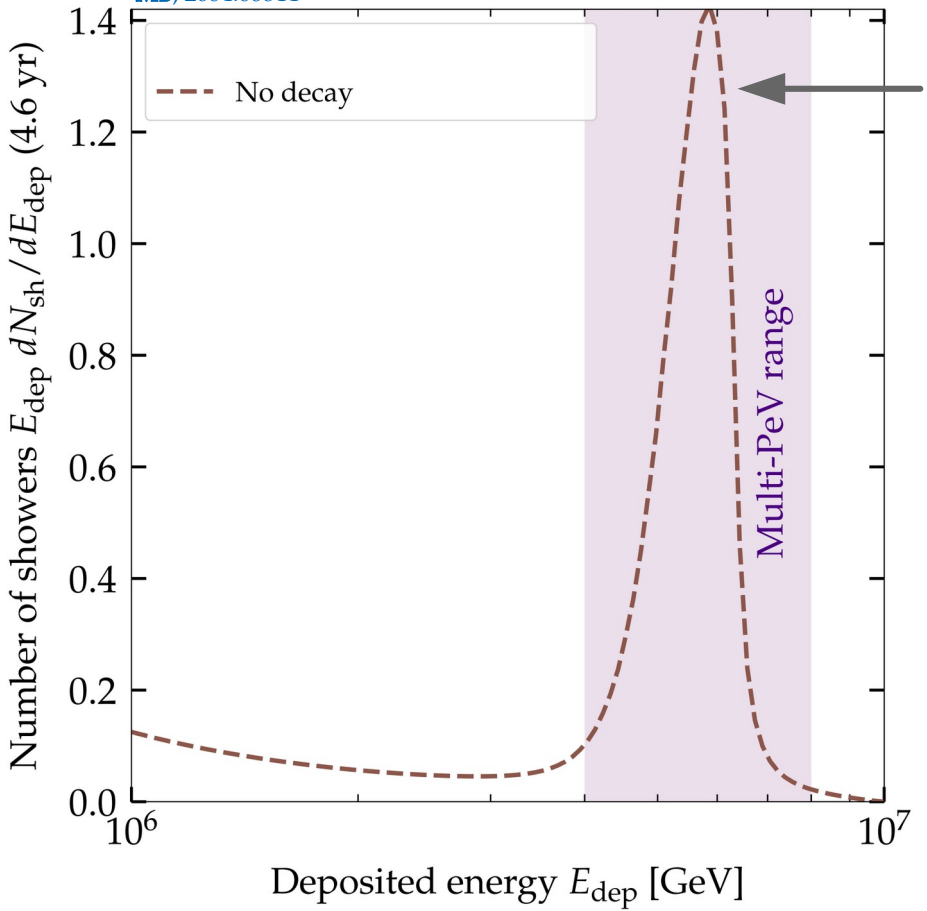
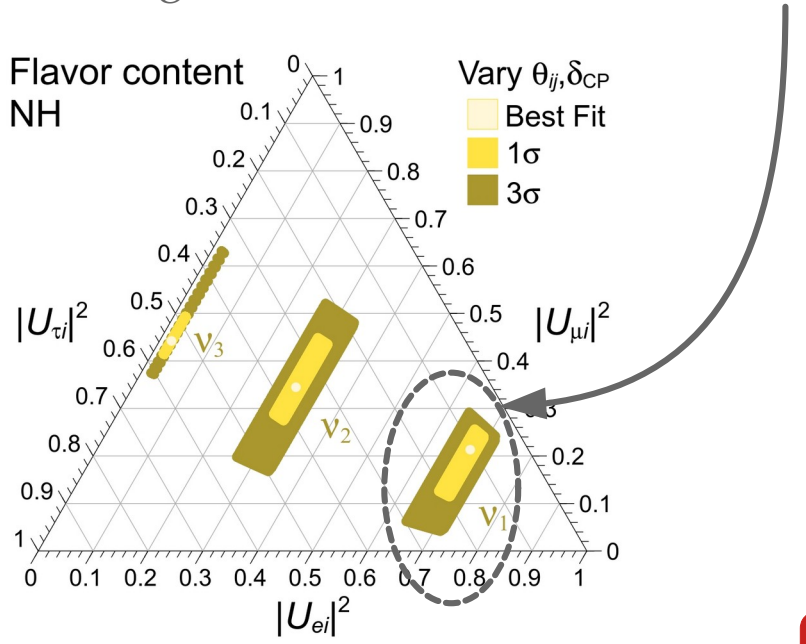


Glashow resonance (GR):
$\bar{\nu}_e + e \rightarrow W \rightarrow$ hadrons $\rightarrow$ shower

ν_1 is the mass eigenstate with the most e flavor



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Flavor composition ⟺ Spectrum shape ⟺ Event rate

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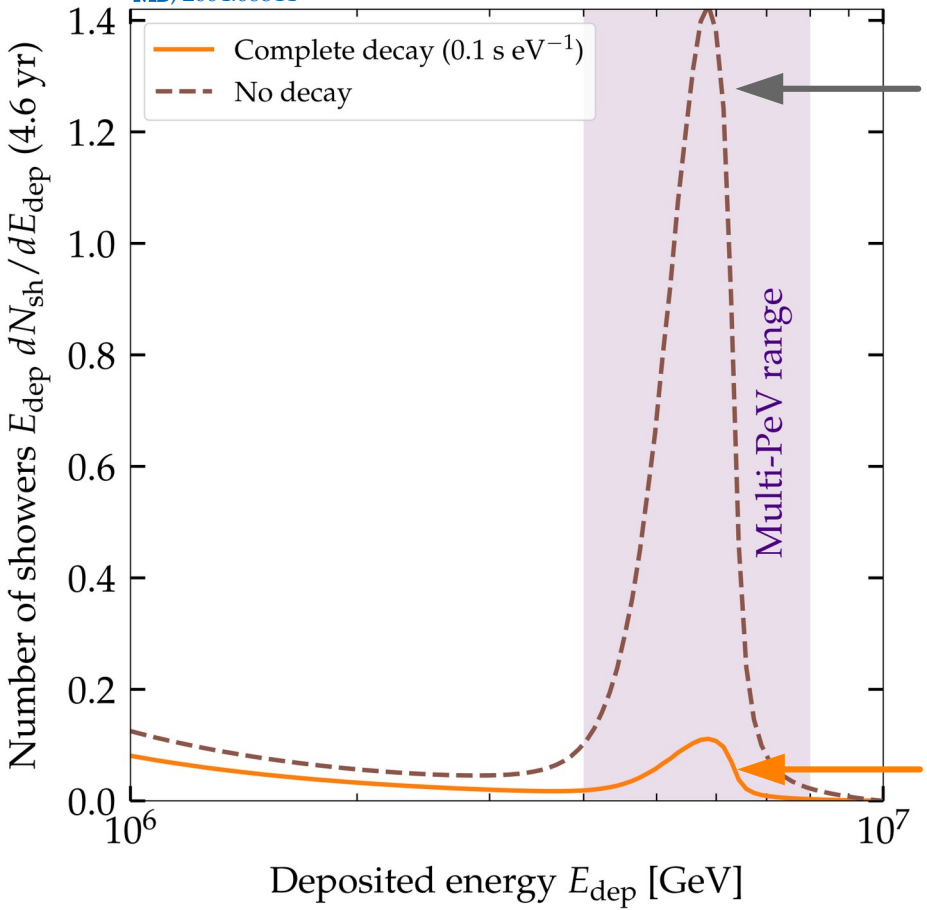

Glashow resonance (GR):
$\bar{\nu}_e + e \rightarrow W \rightarrow$ hadrons $\rightarrow$ shower

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

What does neutrino decay change?

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

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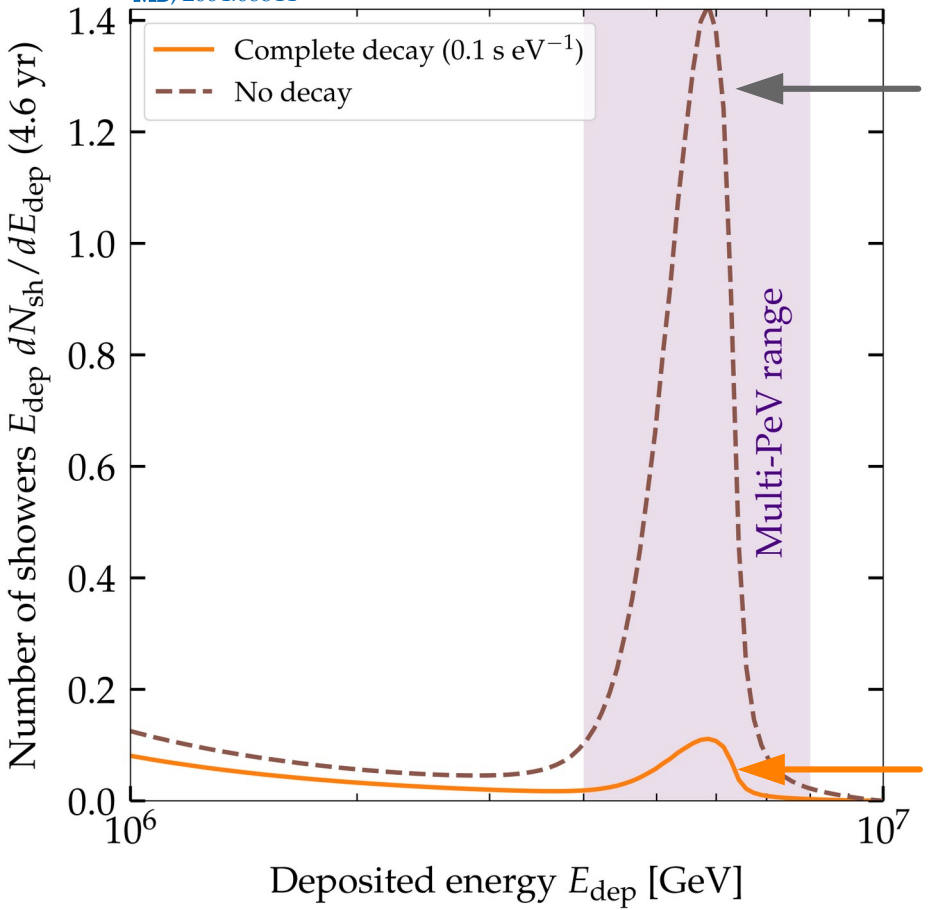

Glashow resonance (GR):
$\bar{\nu}_e + e \rightarrow W \rightarrow$ hadrons $\rightarrow$ shower

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

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

What does neutrino decay change?

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

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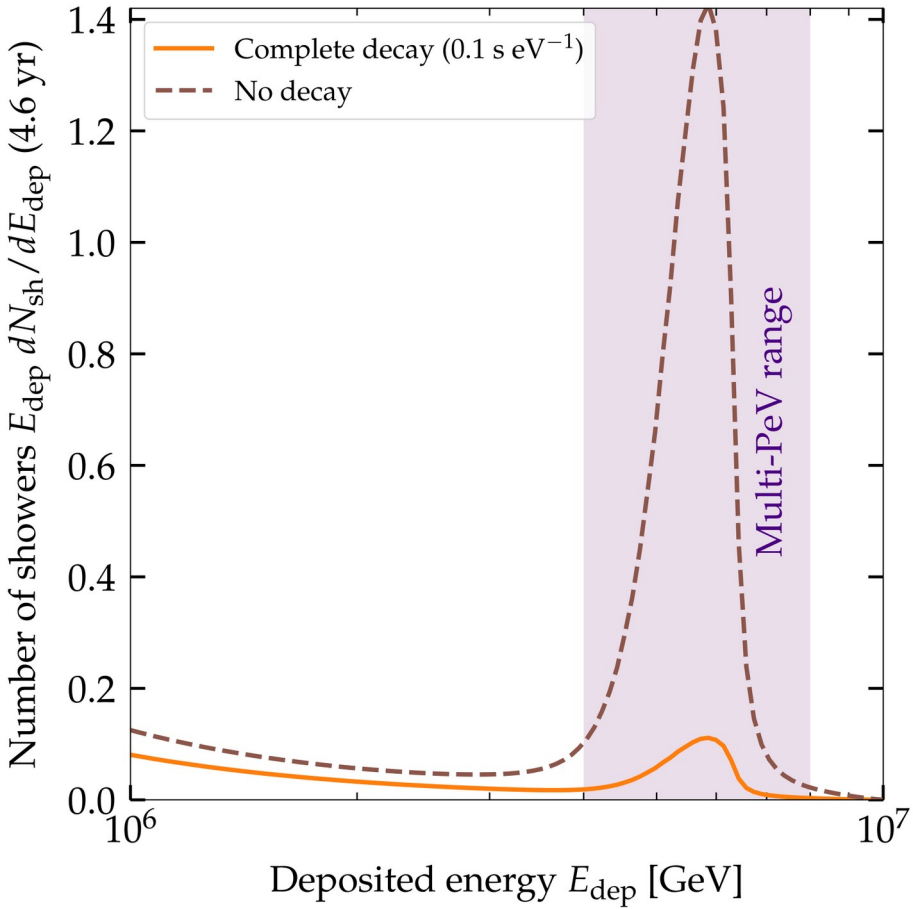

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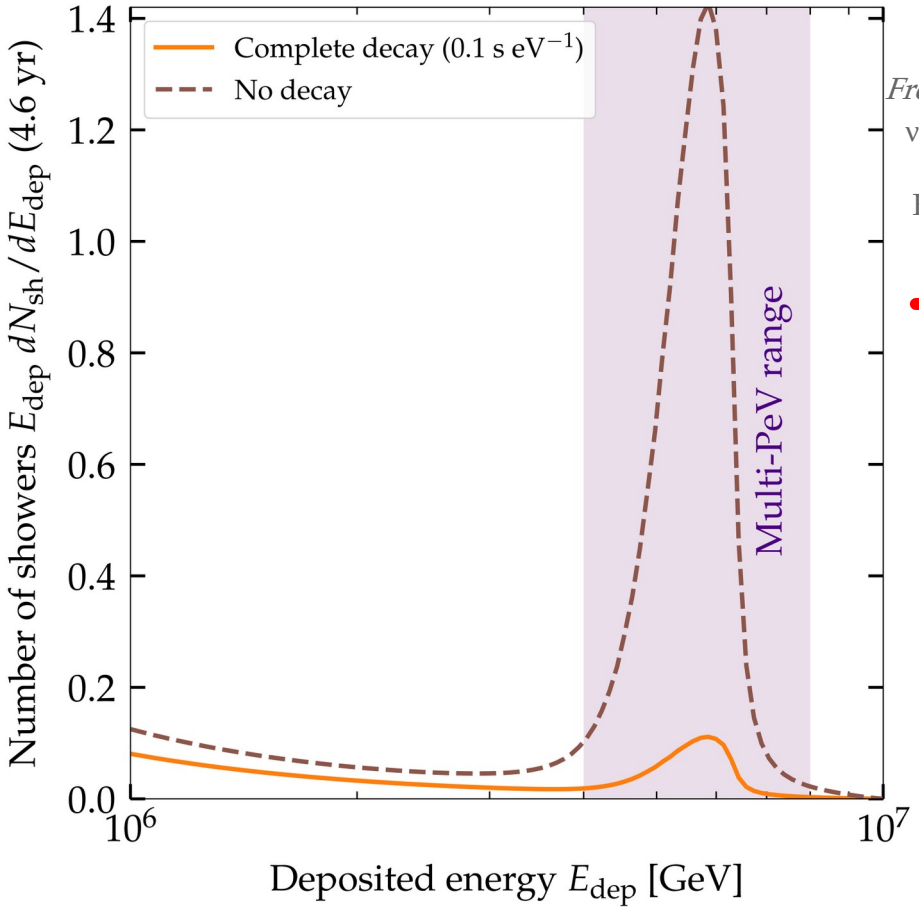

Free parameters:
ν_1, ν_2 lifetimes
Mix. par.
Flavor ratios
$\bar{\nu}/\nu$ ratio

What does neutrino decay change?

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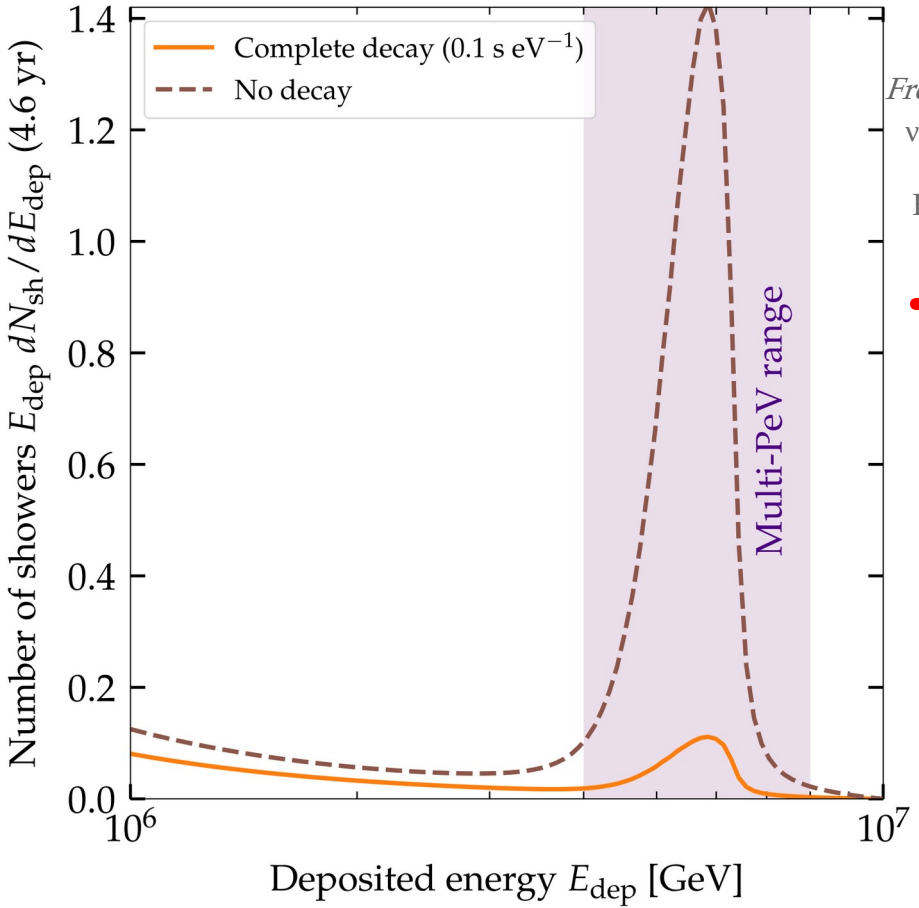

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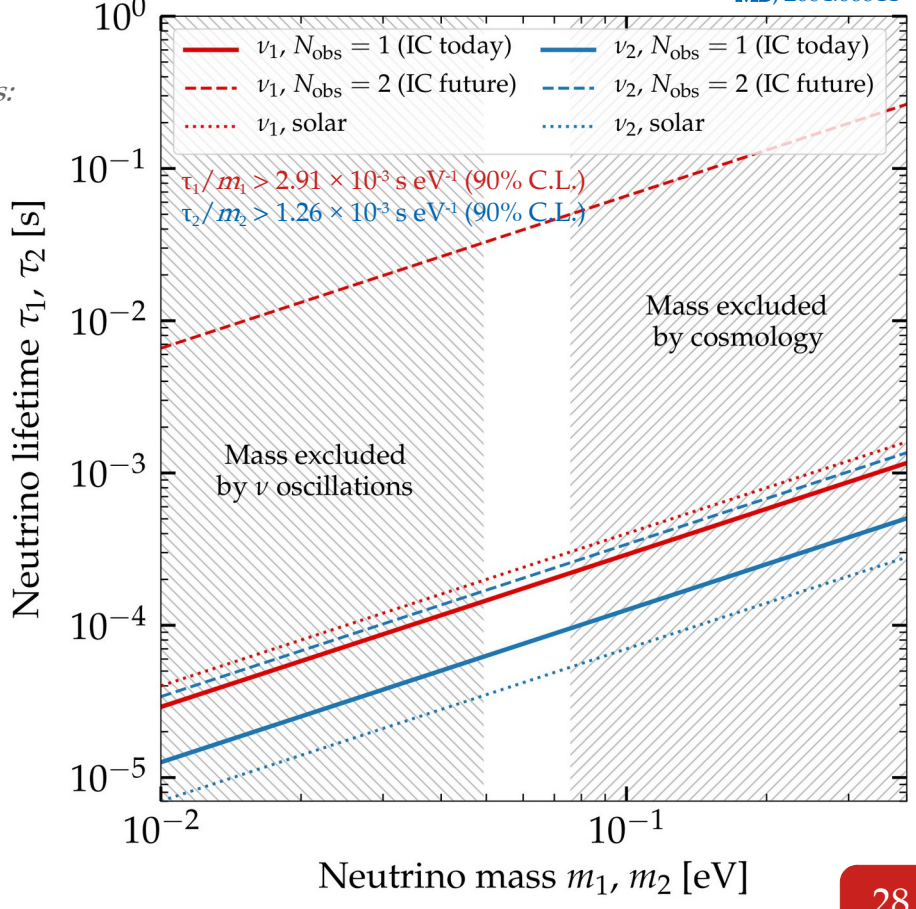

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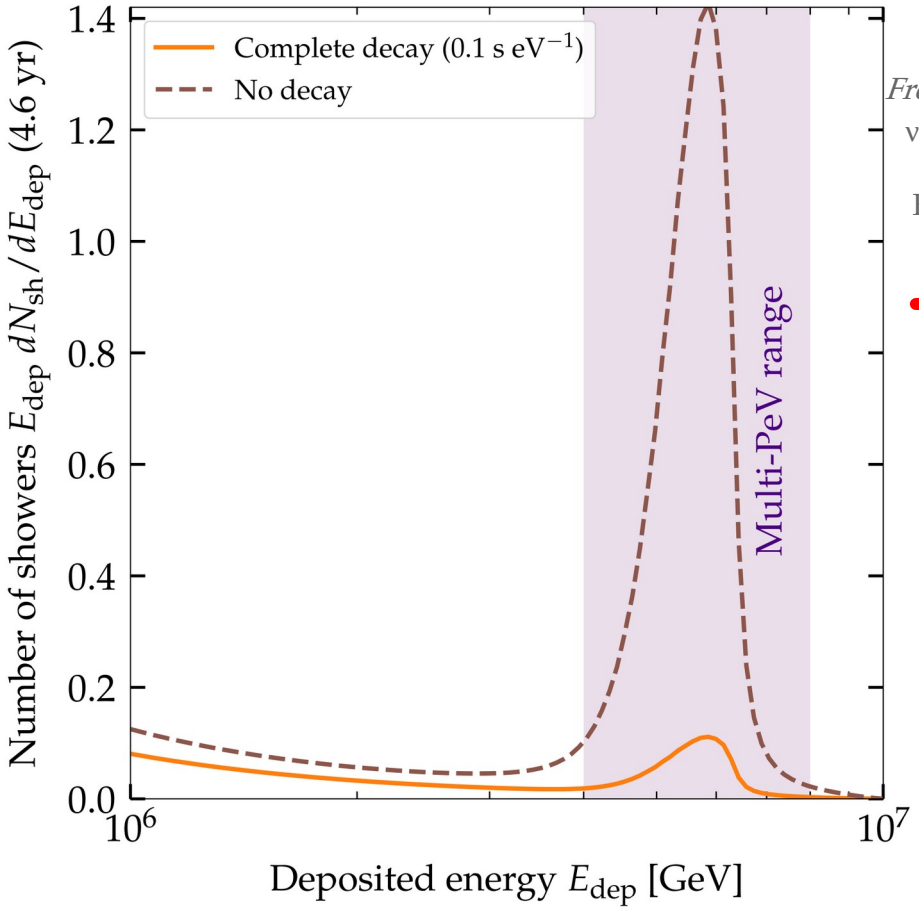

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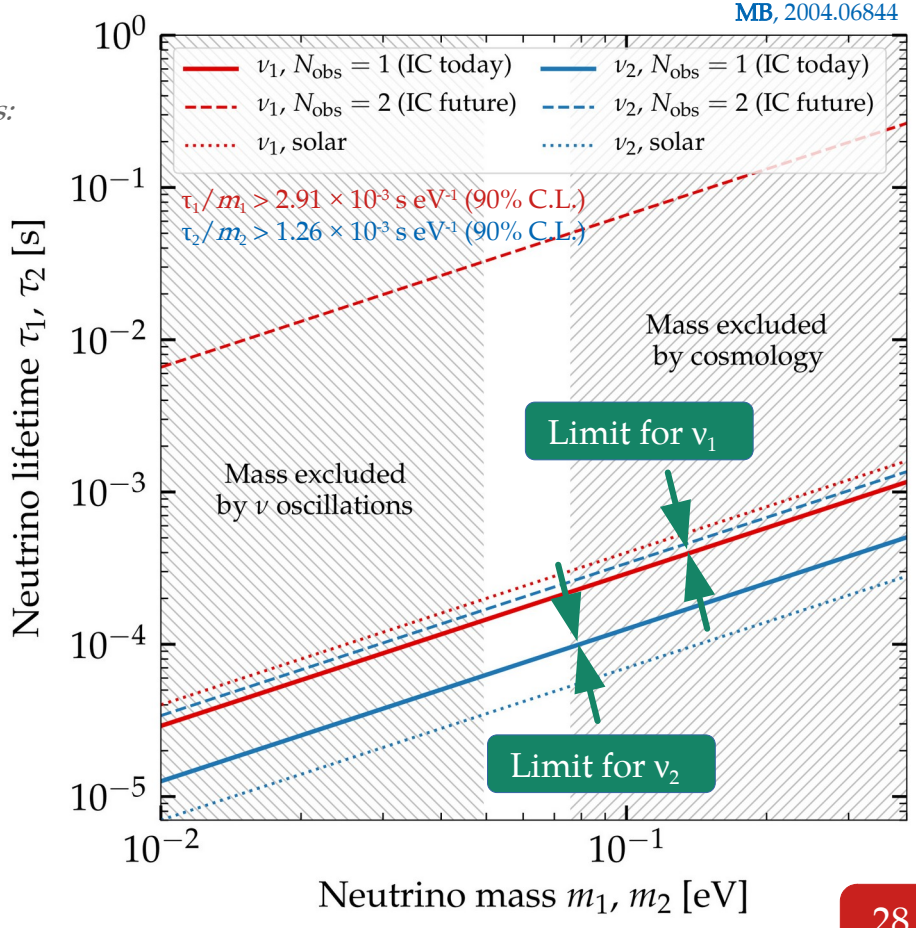
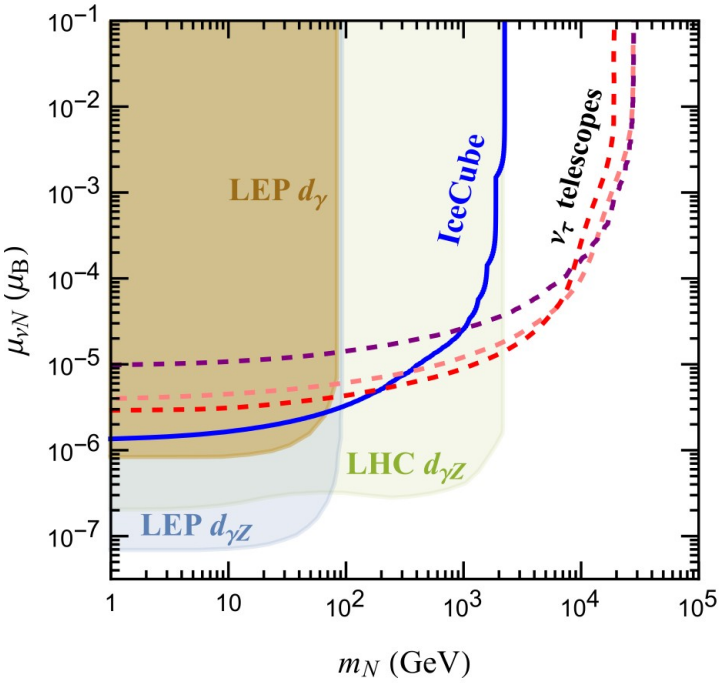


New physics in the UHE νN cross section

New physics in the UHE νN cross section

Heavy sterile neutrinos
via the dipole portal



Huang, Jana, Lindner, Rodejohann, 2204.10347

New physics in the UHE νN cross section

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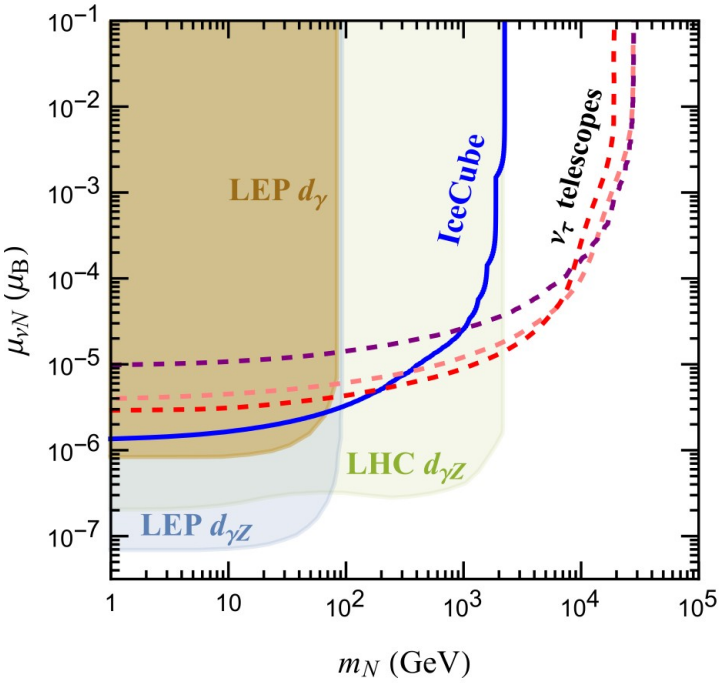
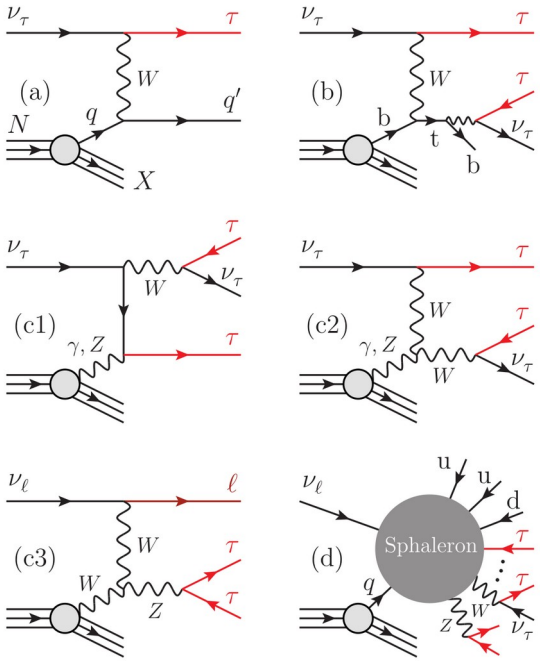


Huang, Jana, Lindner, Rodejohann, 2204.10347

Multiple ν_τ-induced bangs



Huang, *EPJC* 2022 [2207.02222]

New physics in the UHE νN cross section

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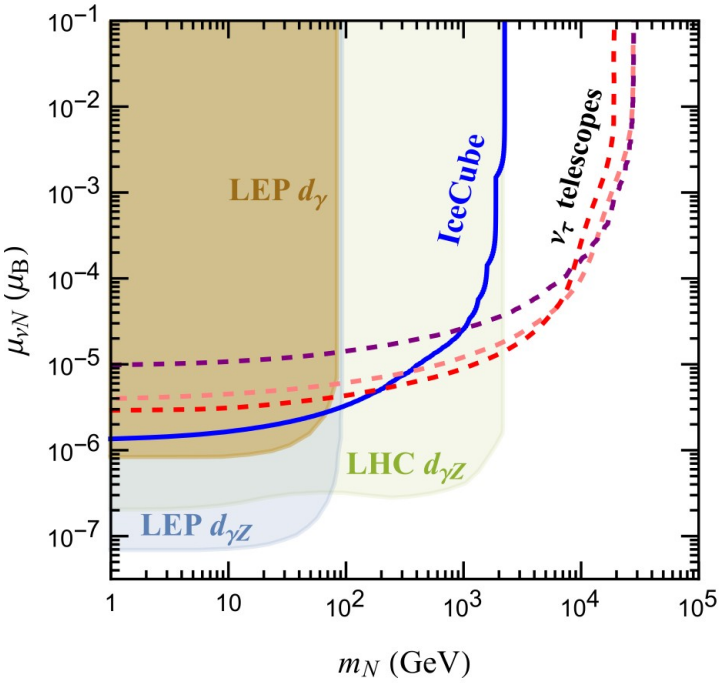
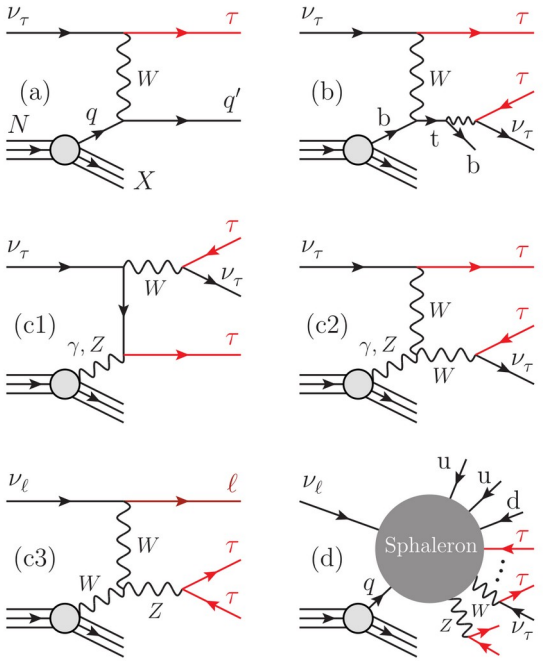


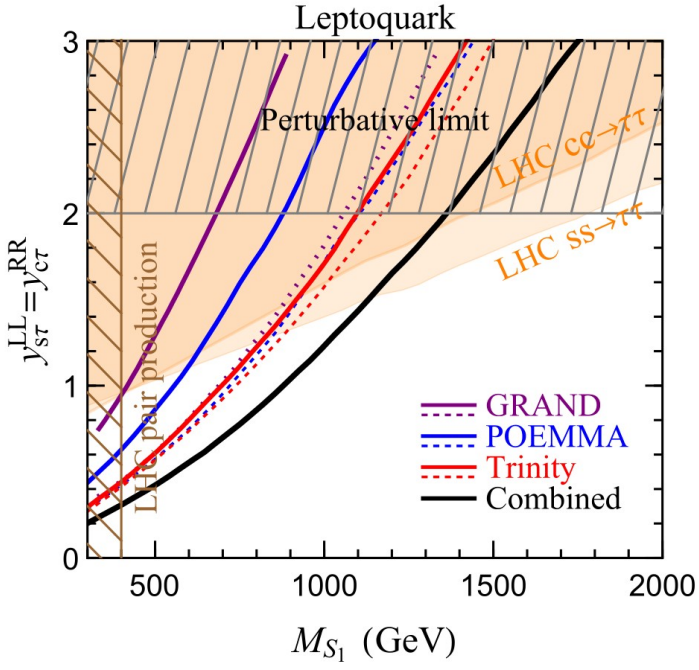
Huang, Jana, Lindner, Rodejohann, 2204.10347

Multiple ν_τ-induced bangs



Huang, *EPJC* 2022 [2207.02222]

Leptoquarks, charged Higgs, *etc.*



Huang, Jana, Lindner, Rodejohann, *JCAP* 2022 [2112.09476]

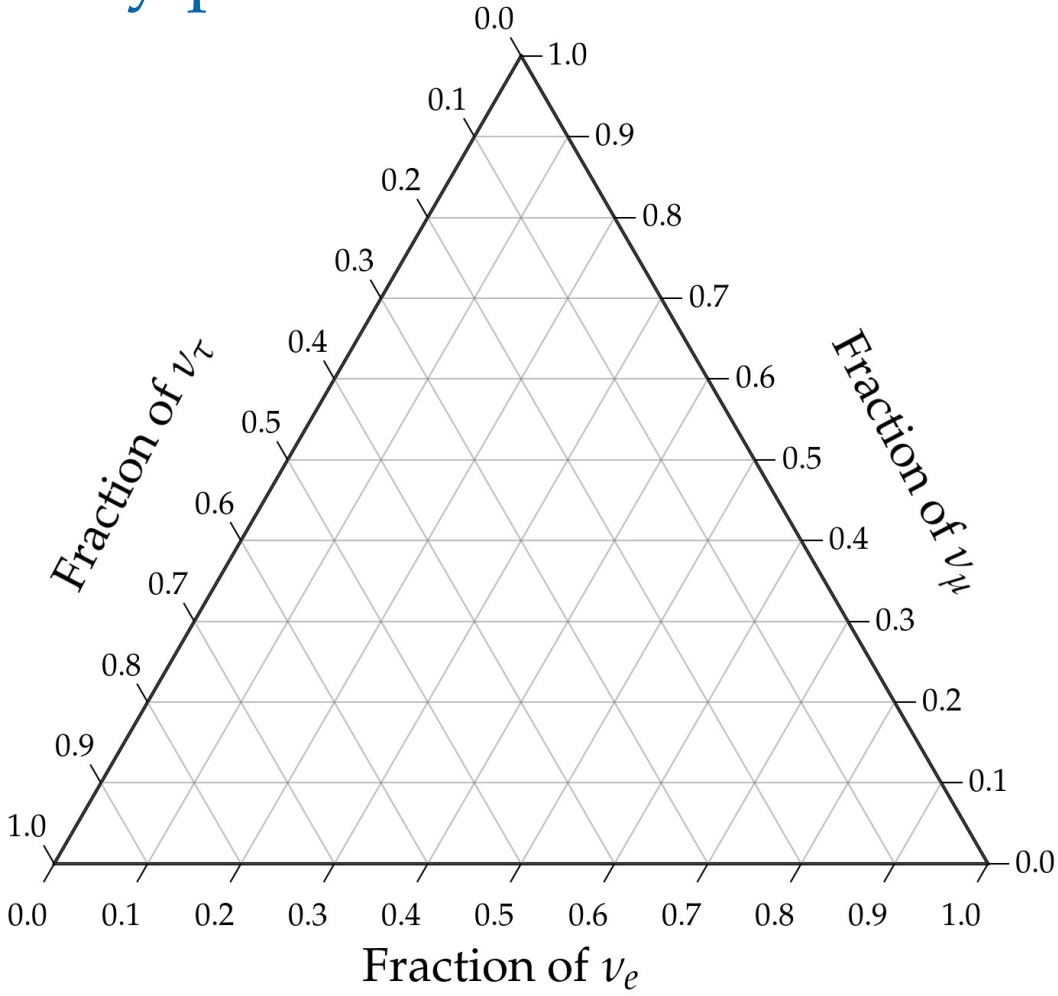
Quick aside: how to read a ternary plot

Assumes underlying unitarity –
sum of projections on each axis is 1

How to read it:

Follow the tilt of the tick marks

Always in this order: (f_e, f_μ, f_τ)



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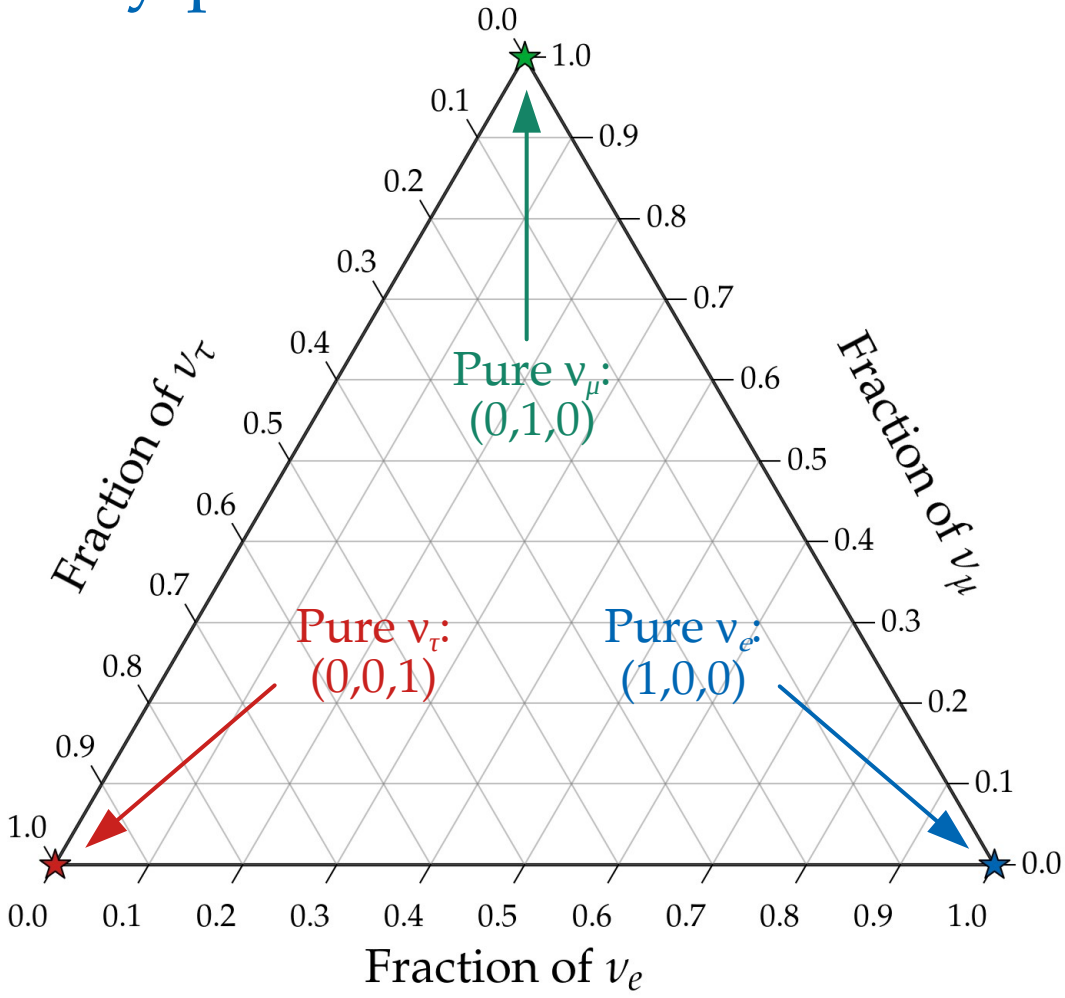


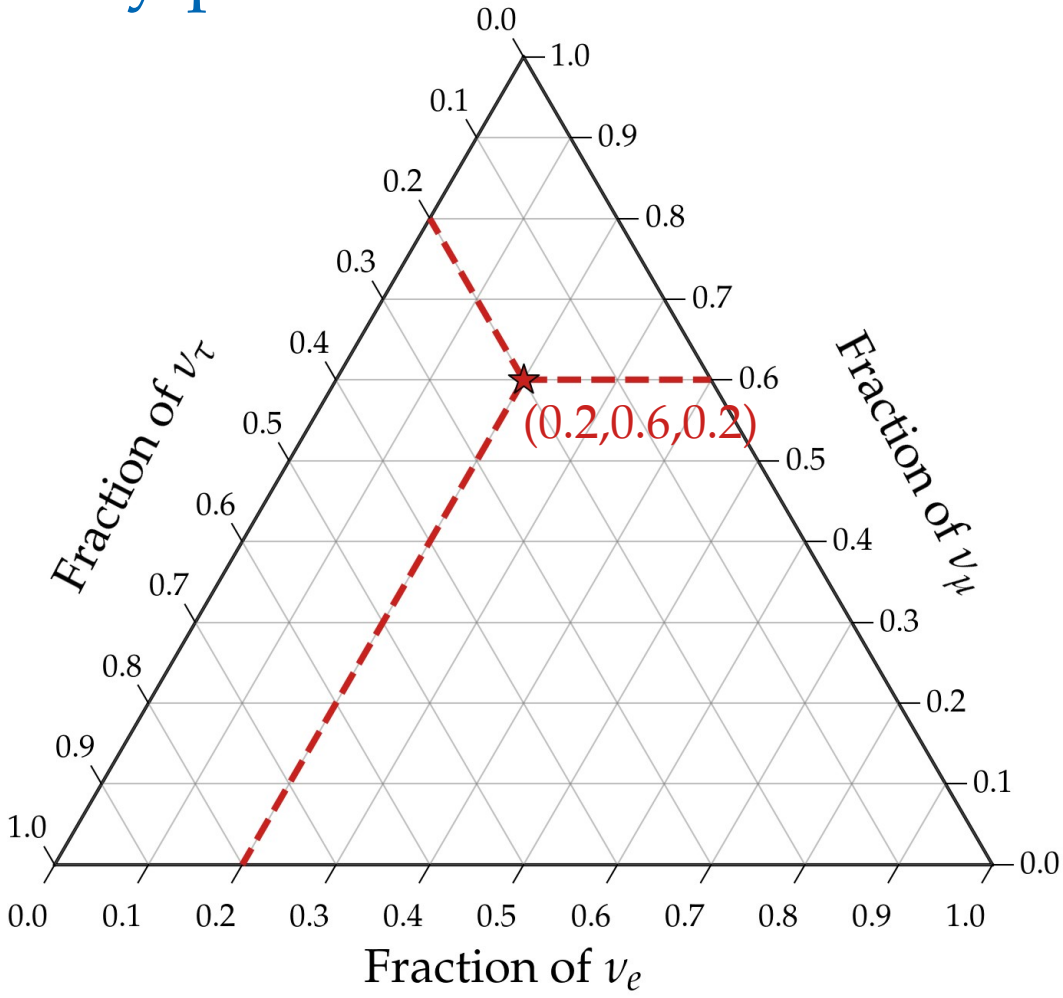
Quick aside: how to read a ternary plot

Assumes underlying unitarity –
sum of projections on each axis is 1

How to read it:

Follow the tilt of the tick marks

Always in this order: (f_e, f_μ, f_τ)



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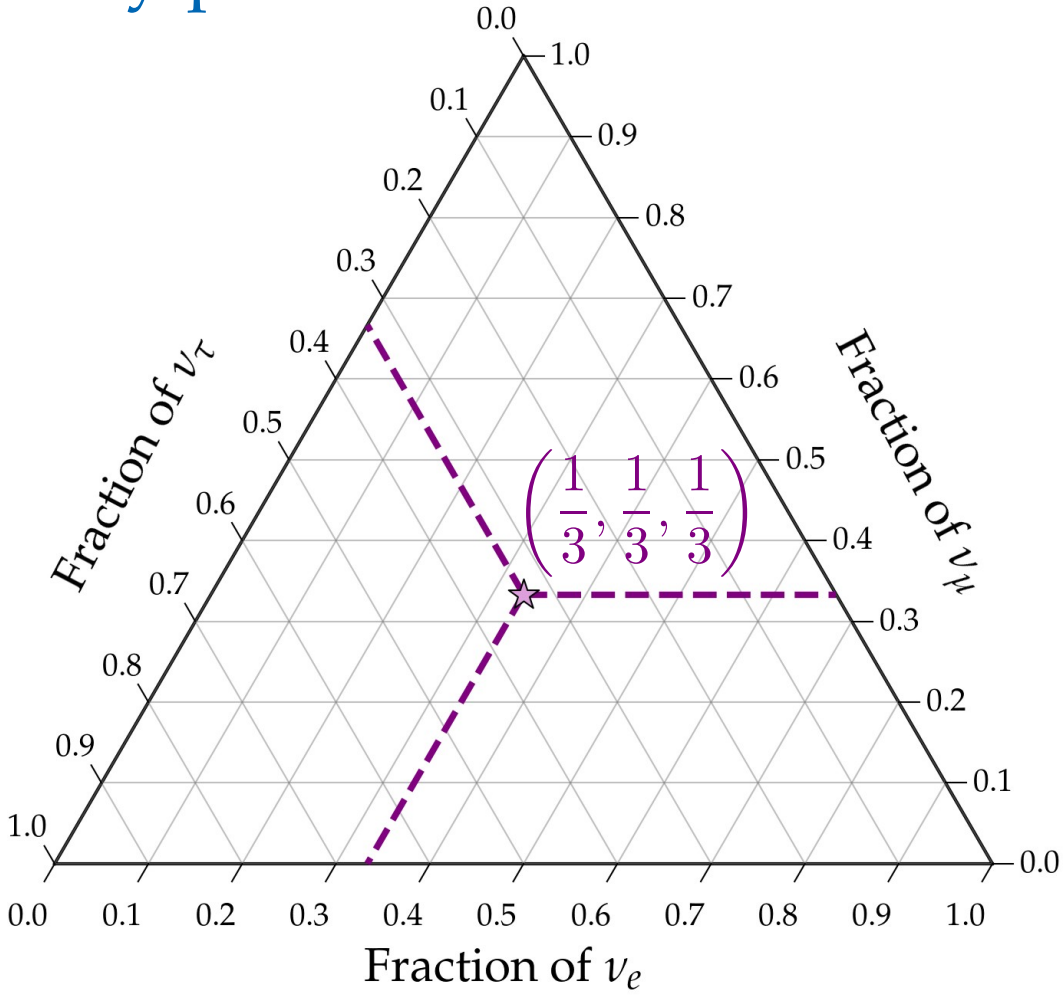
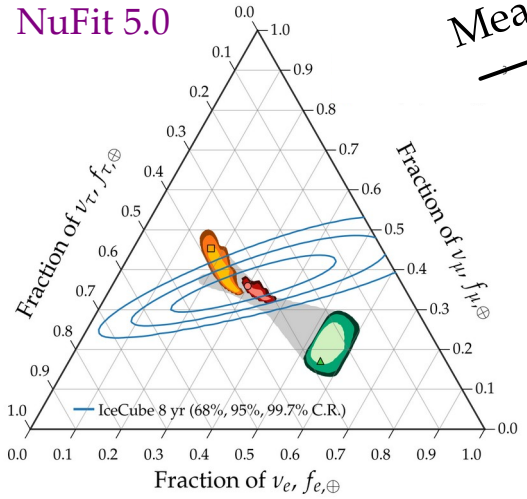


How knowing the mixing parameters better helps

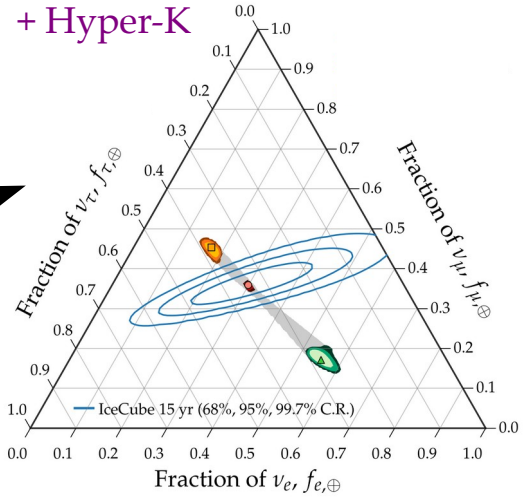
2020

NuFit 5.0



Measure θ_{23} better

+ Hyper-K



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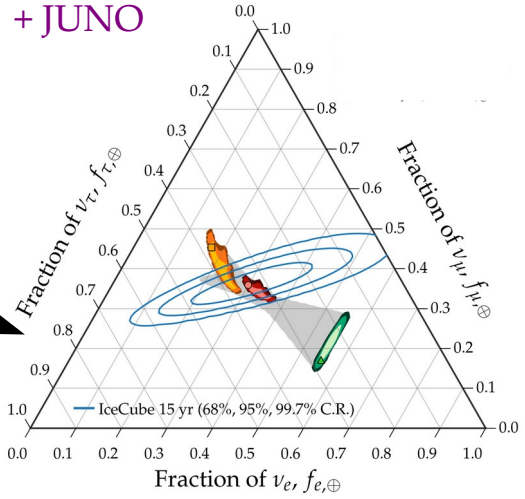
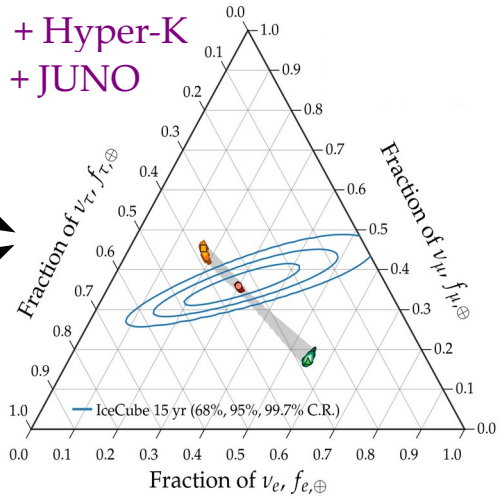


Measure θ_{12} better

~2030

+ Hyper-K
+ JUNO



In our results:
JUNO + Hyper-K + DUNE

Marginal improvement til 2040

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

Flavor composition: measuring the energy dependence

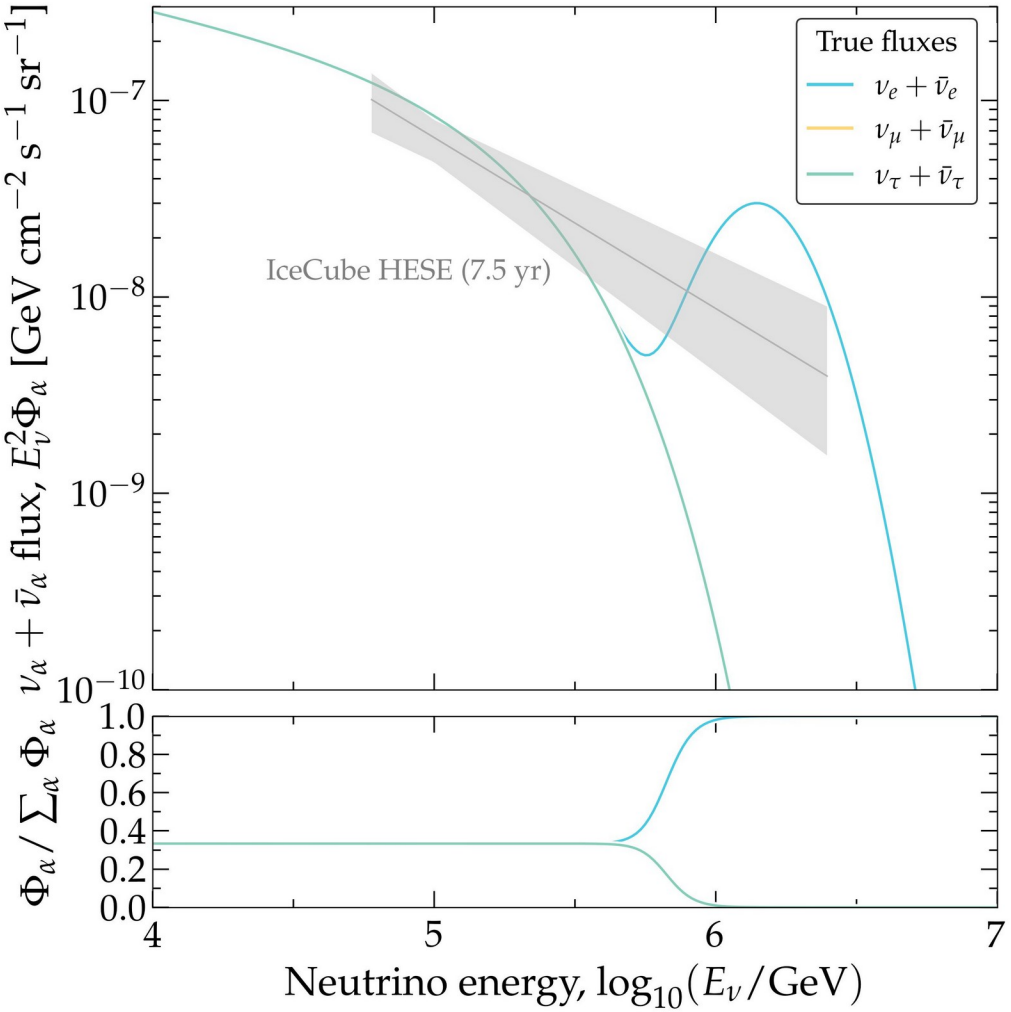
Can we do better?

Maybe

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

How?

—Infer the spectrum of ν_e, ν_μ, ν_τ separately



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

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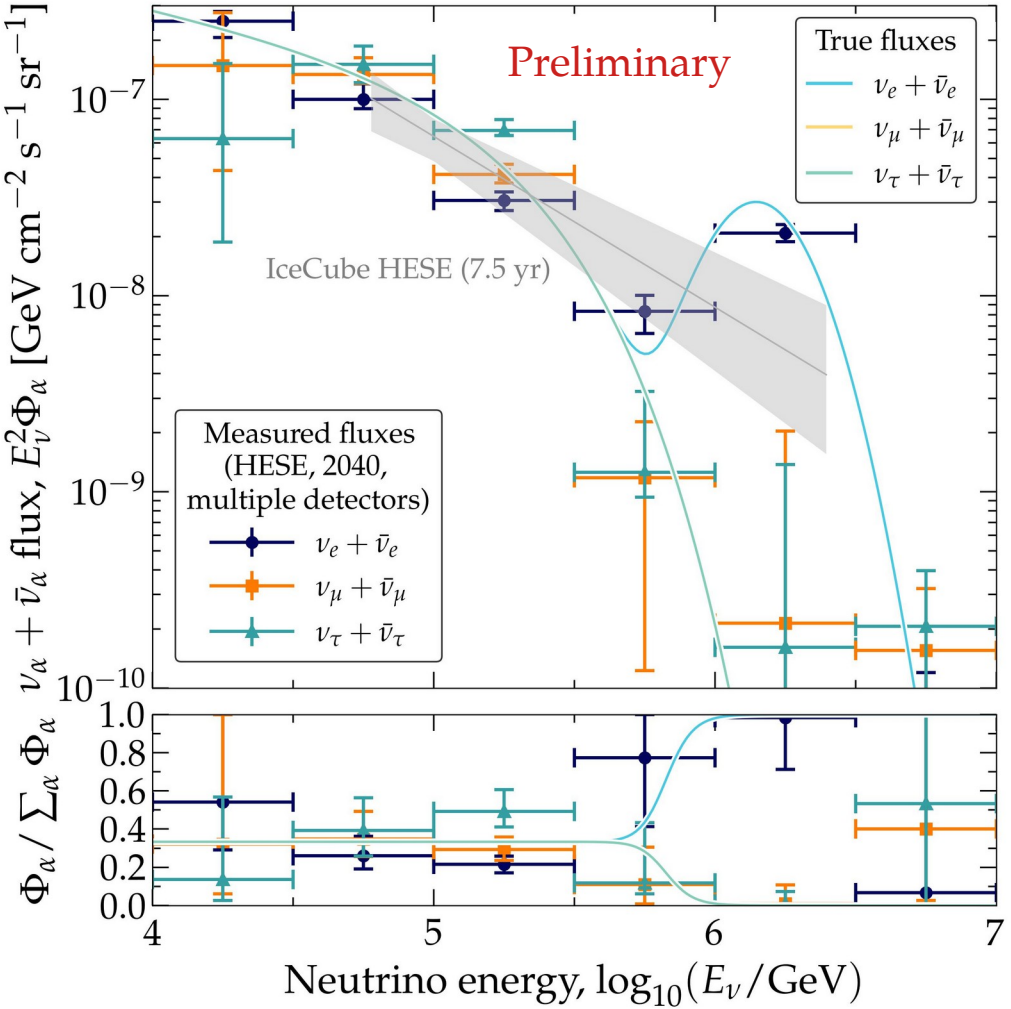


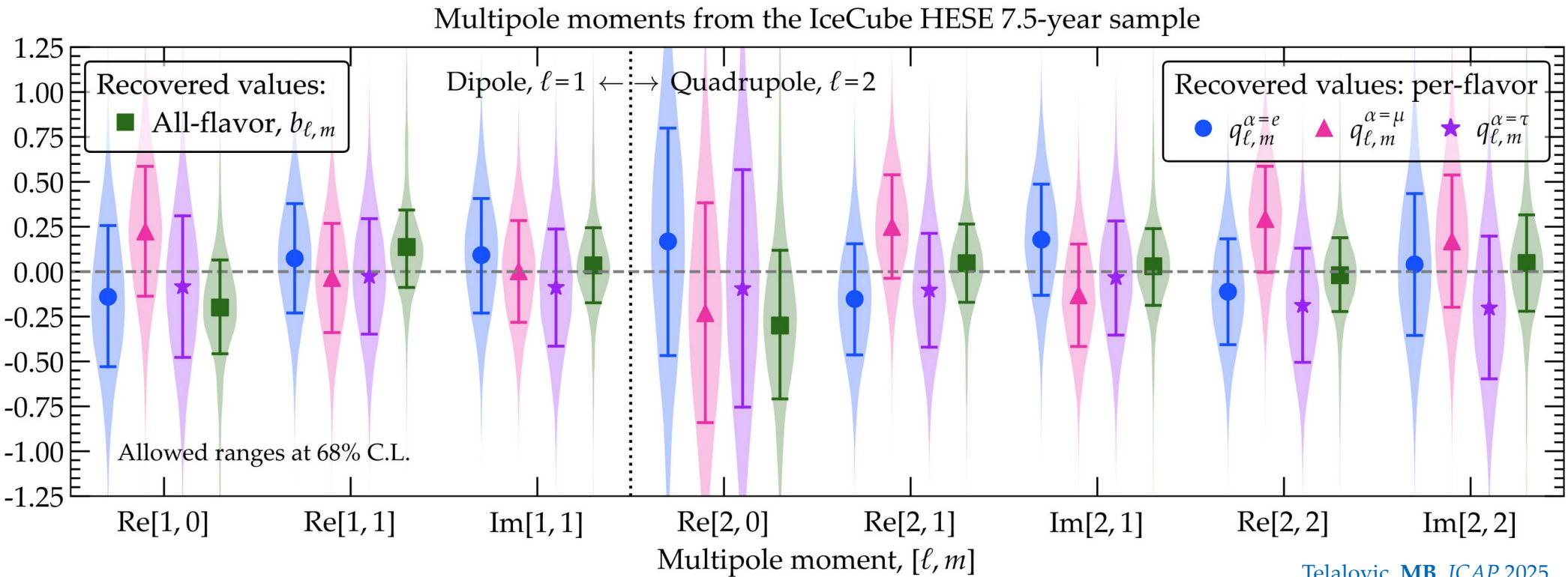
Liu, **MB**, *In prep.*

Flavor dipoles and quadrupoles in the sky?

Flavor-dependent multipole expansion

Isotropic flux

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



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

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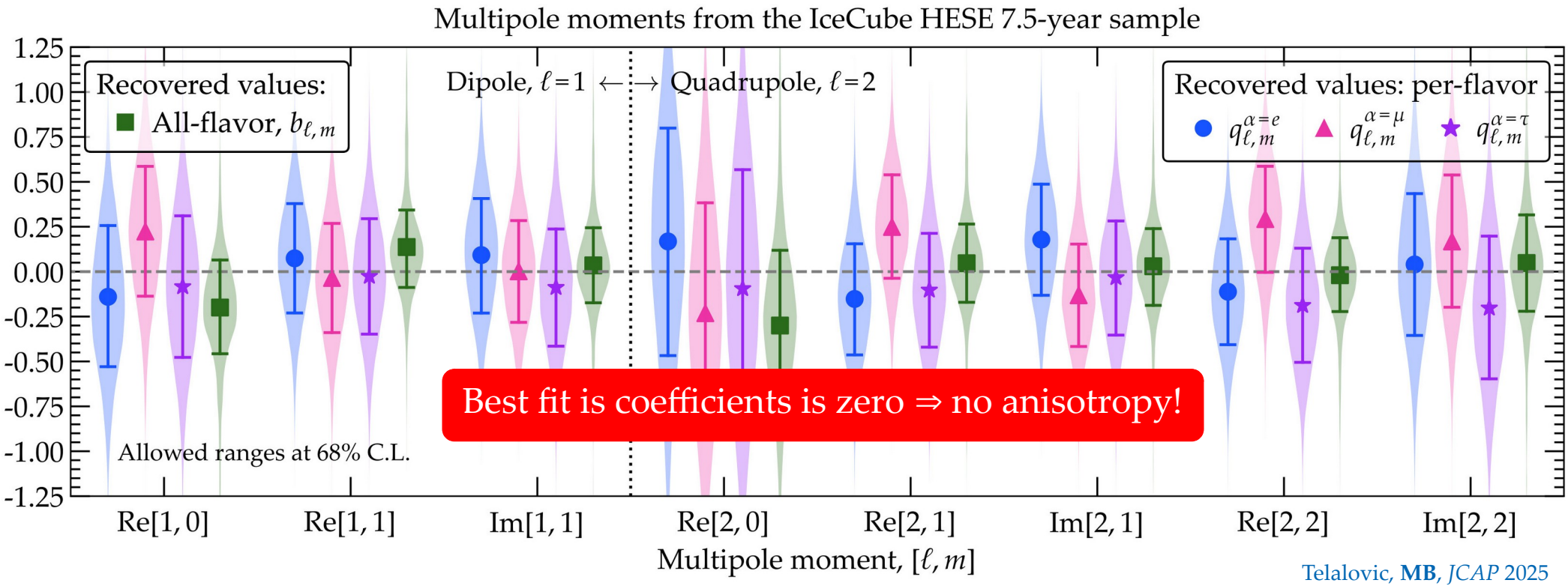

Telalovic, **MB**, *JCAP* 2025