

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

Mauricio Bustamante

Niels Bohr Institute, University of Copenhagen

Sydney-CCPC seminar

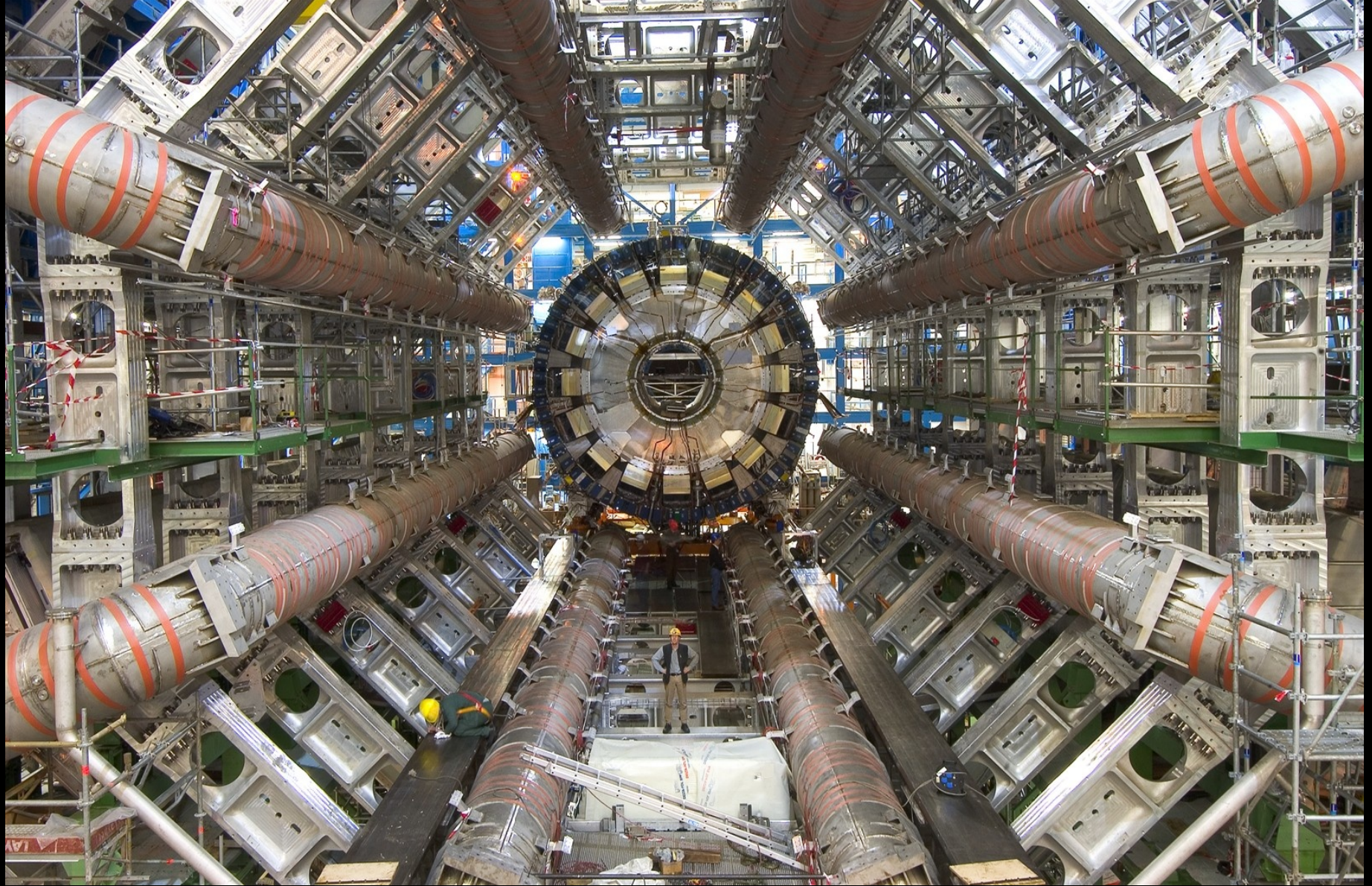
July 30, 2026

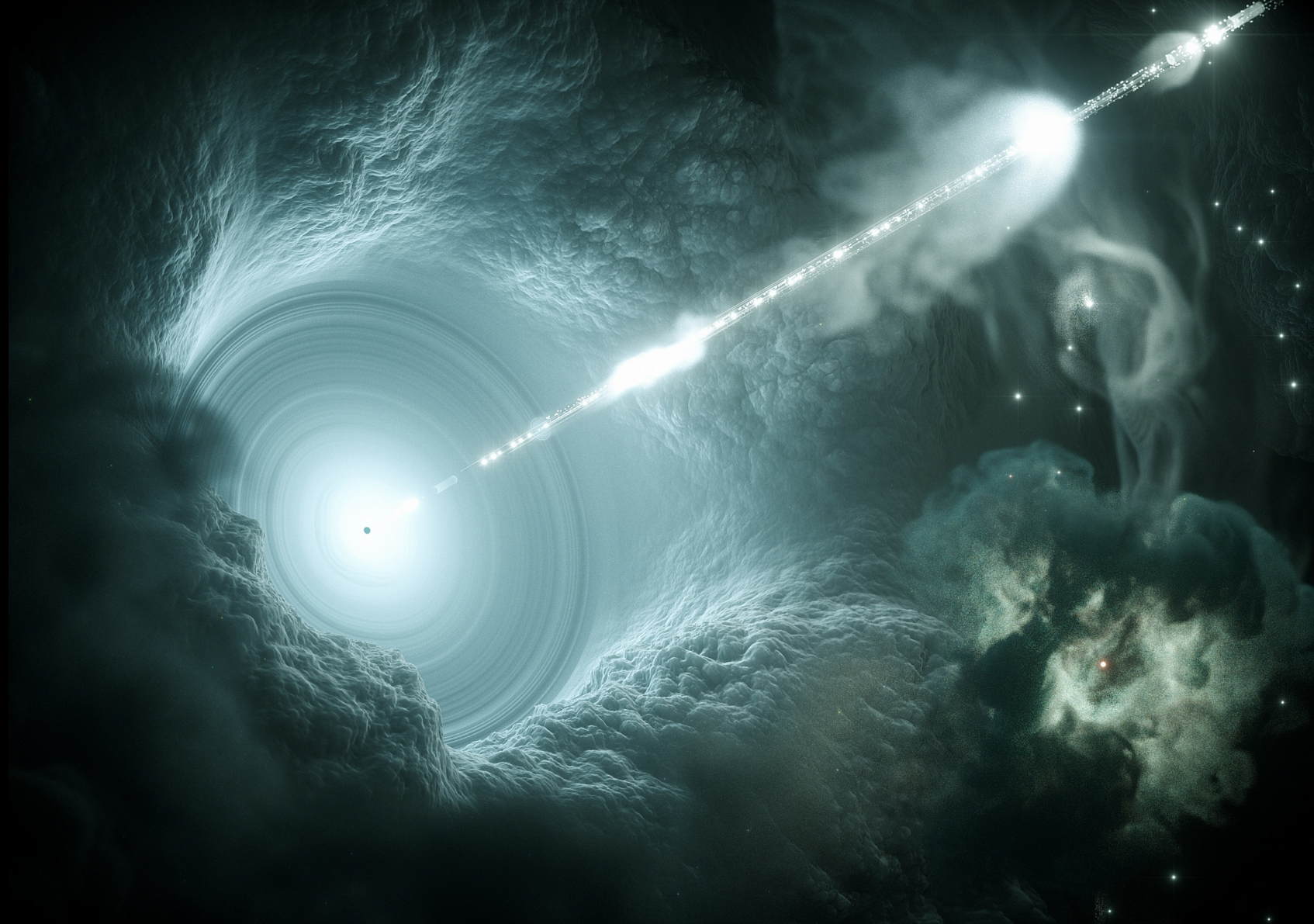
UNIVERSITY OF
COPENHAGEN

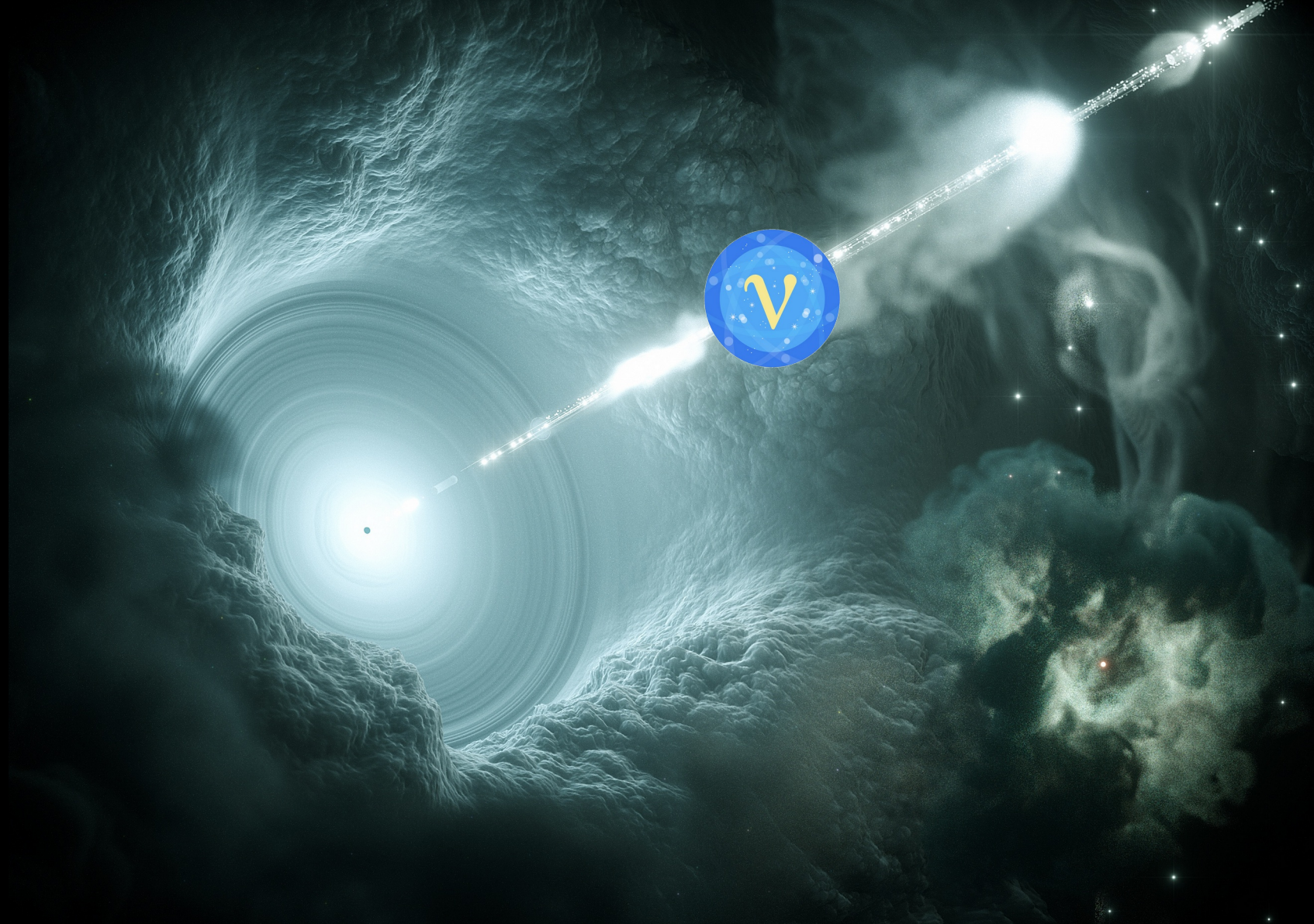


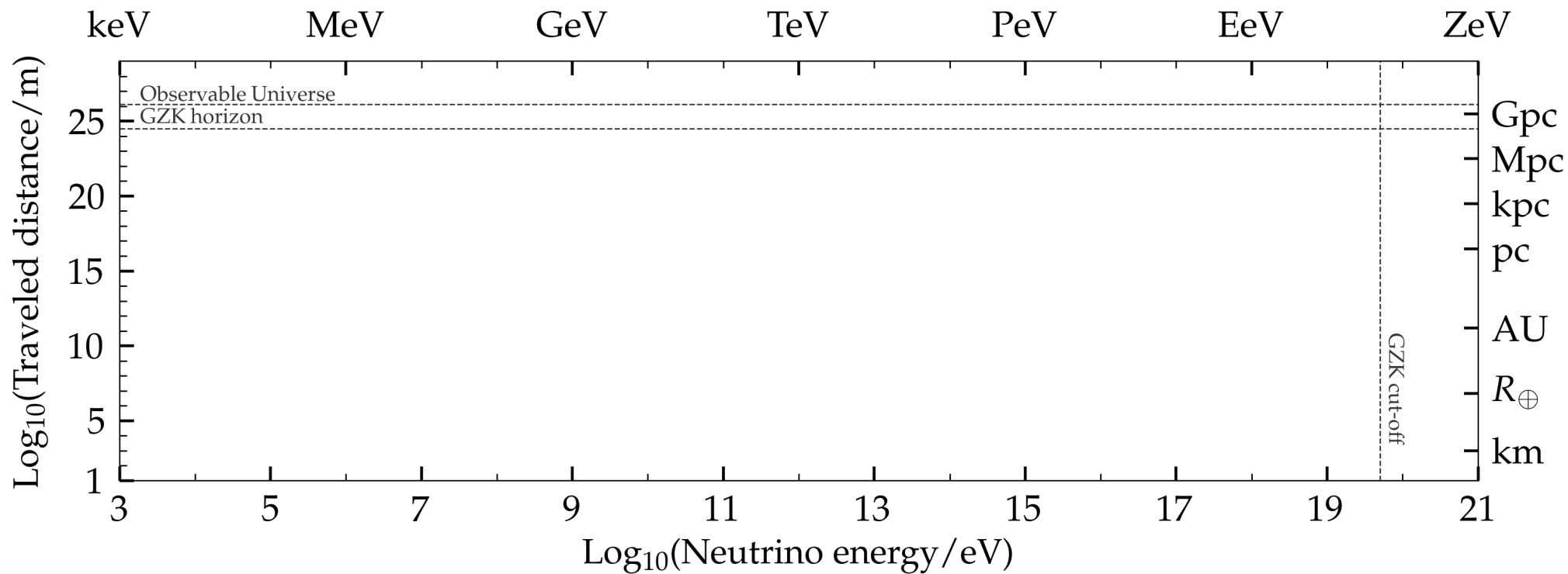
VILLUM FONDEN

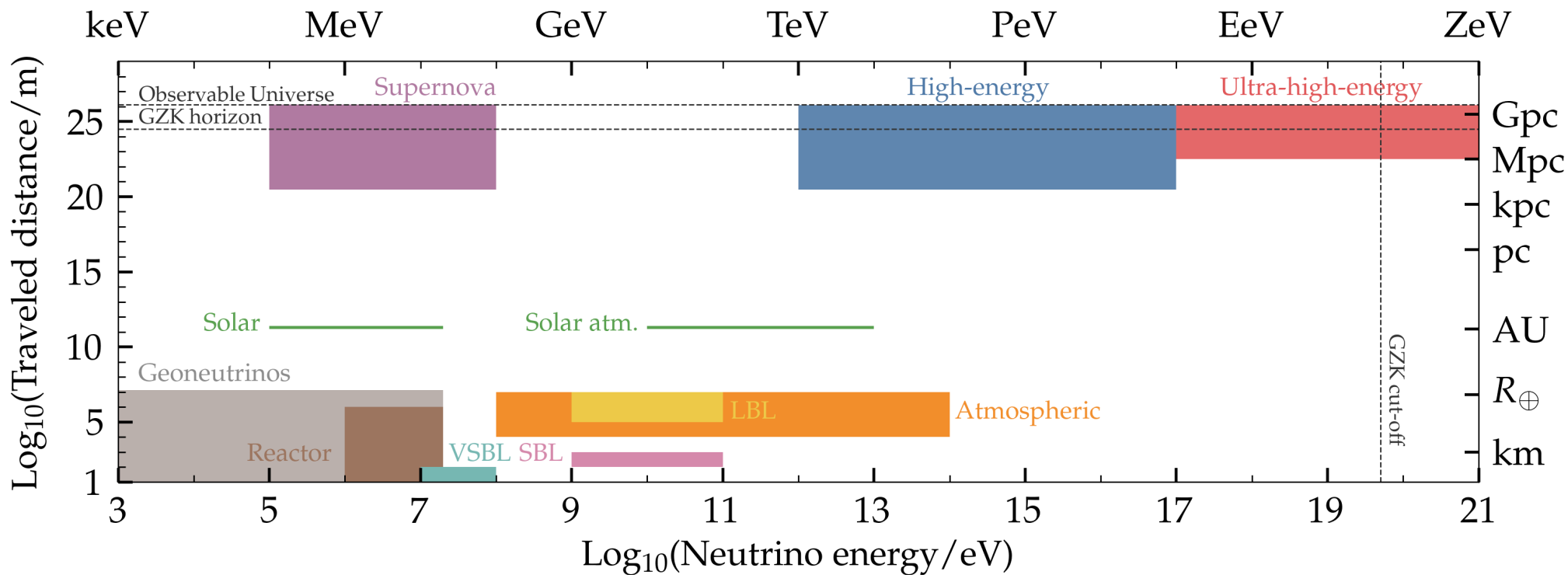




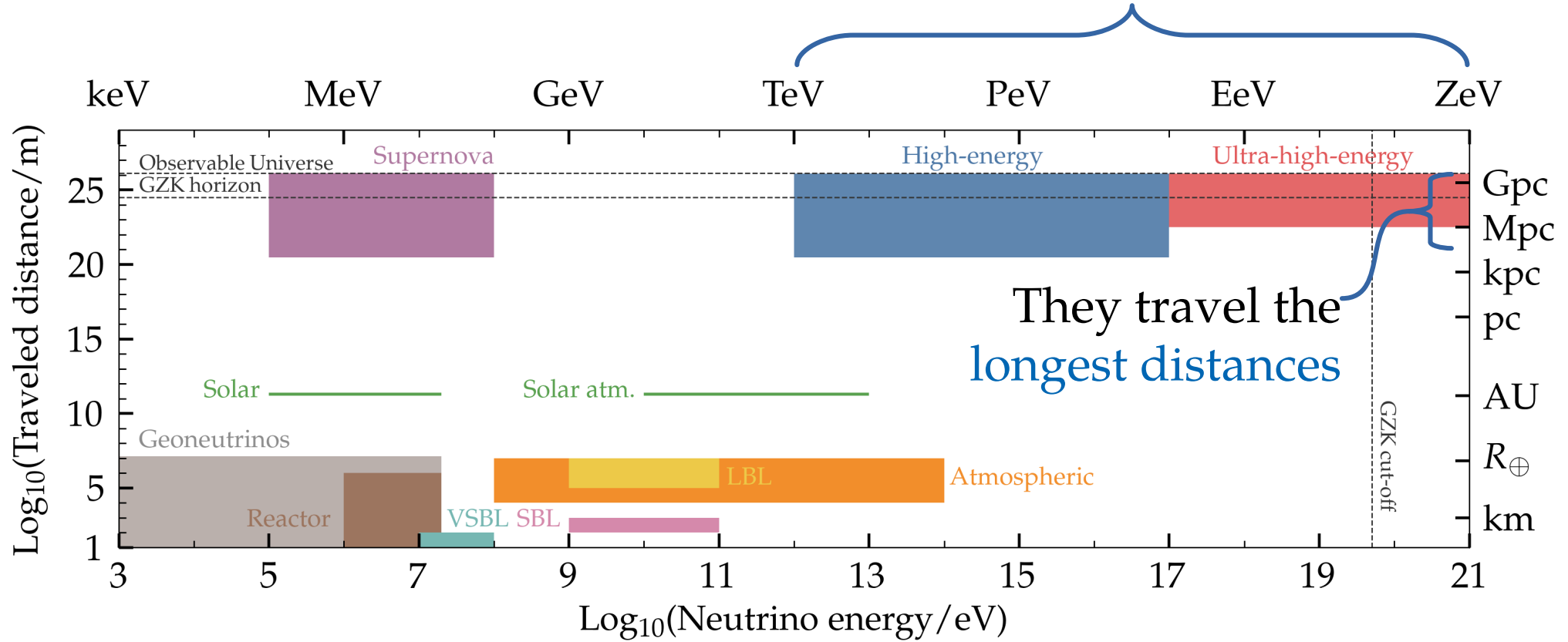




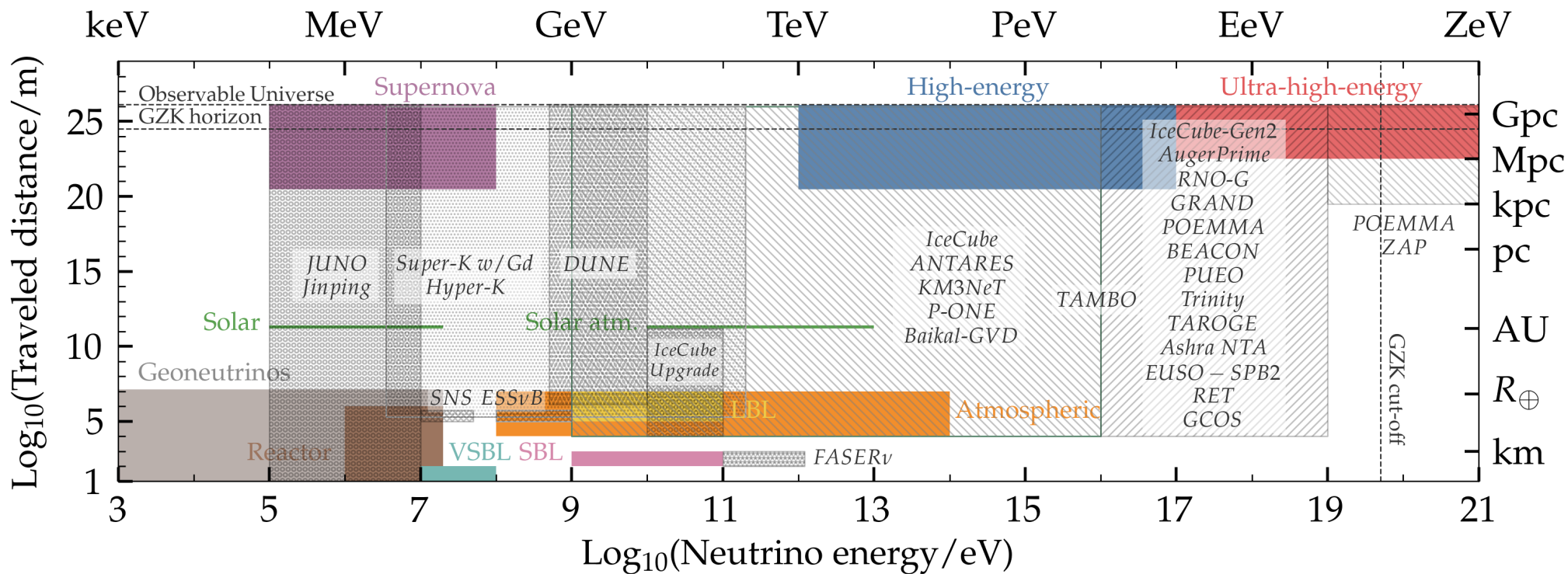


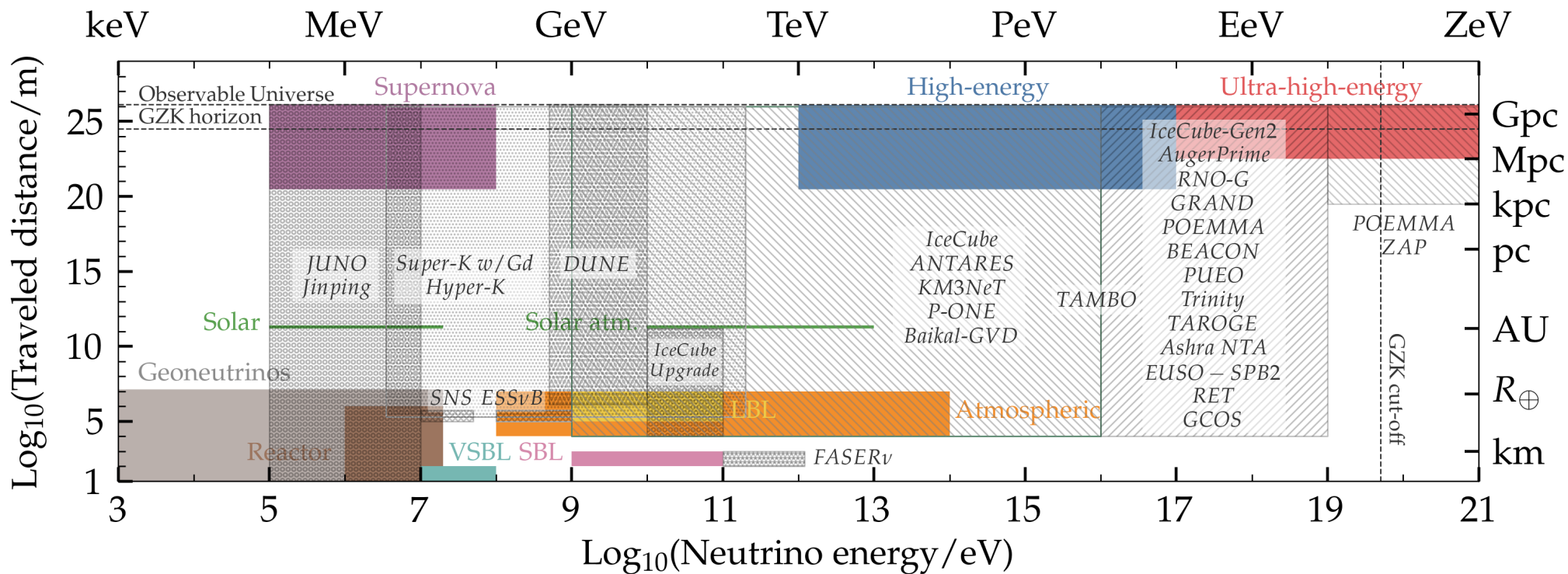


They have the **highest energies**



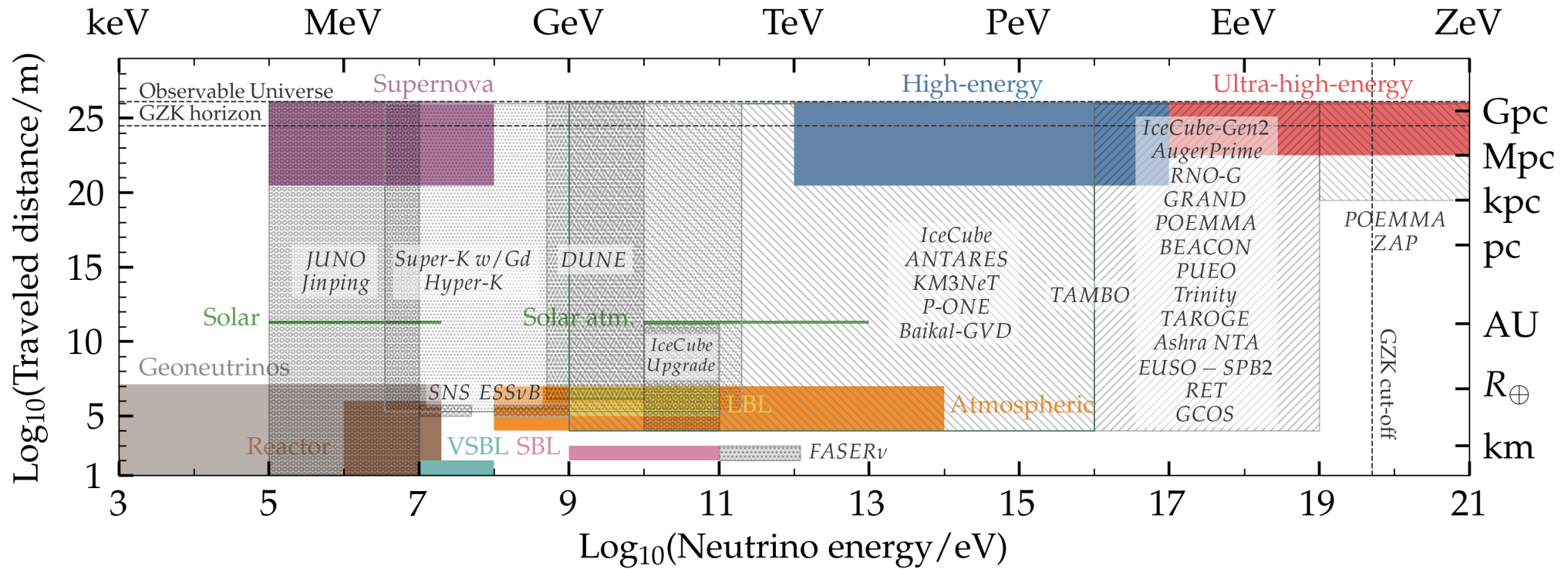
They travel the **longest distances**





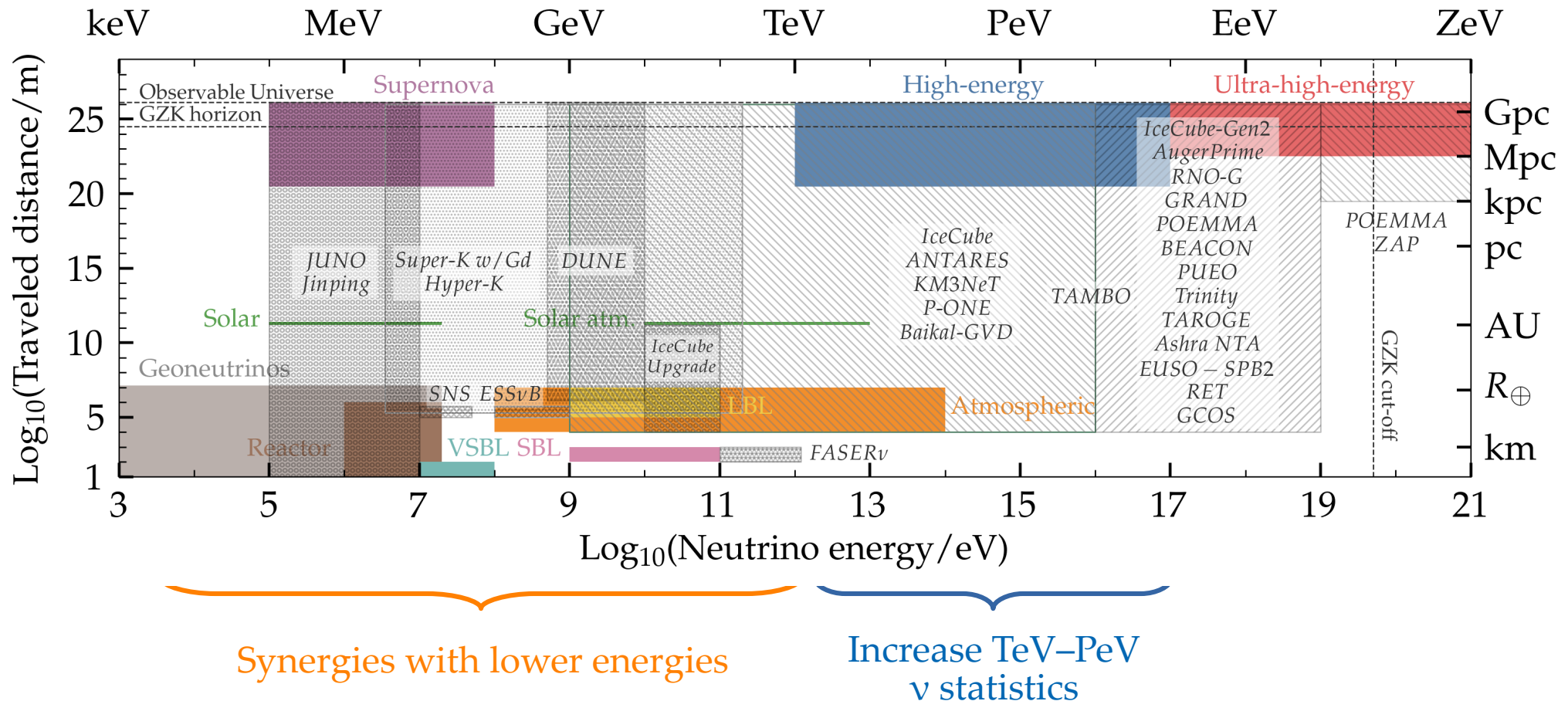
Synergies with lower energies

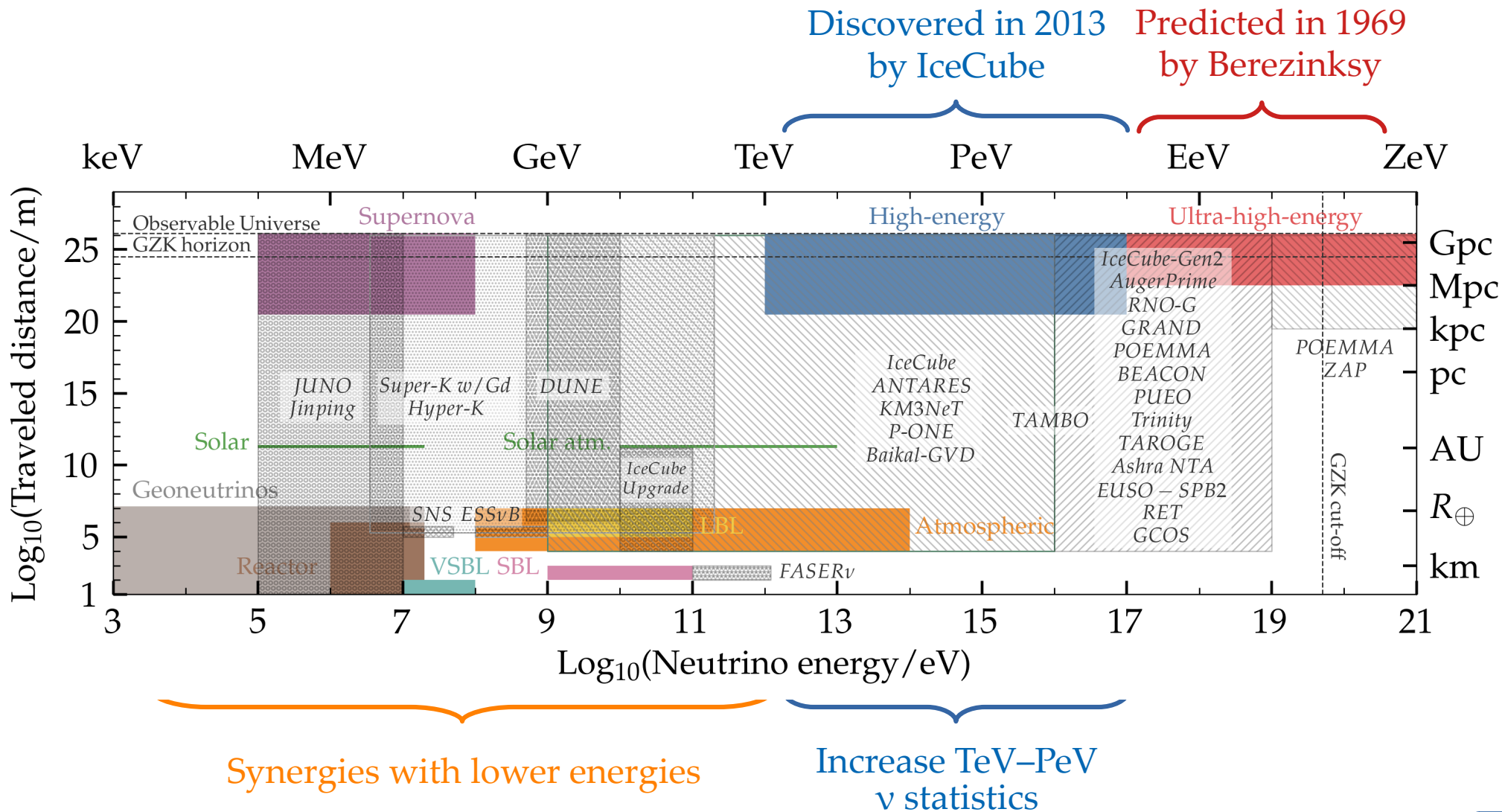
Discovered in 2013
by IceCube

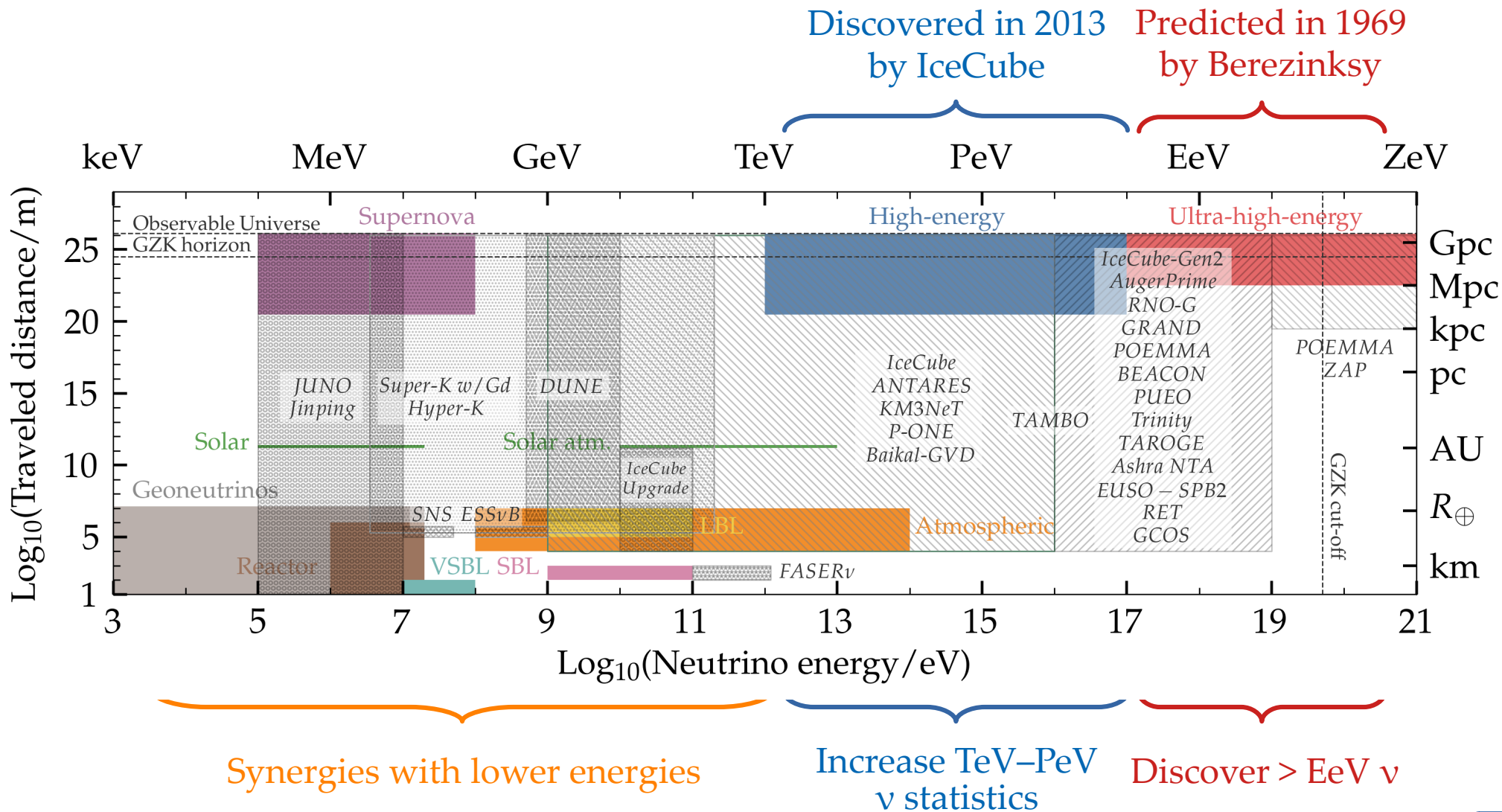


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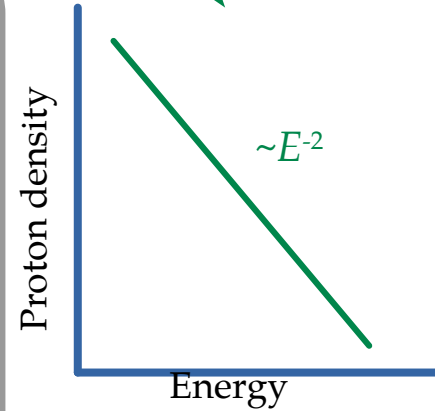
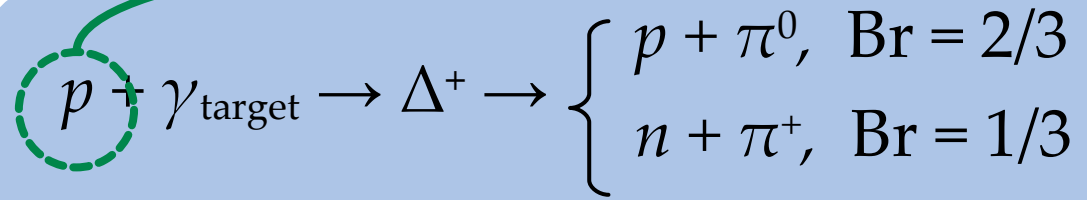
The multi-messenger connection: a simple picture

(or $p + p$)

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

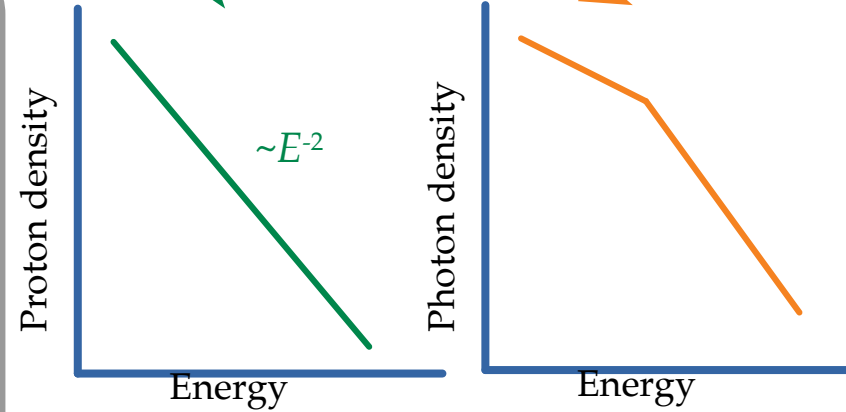
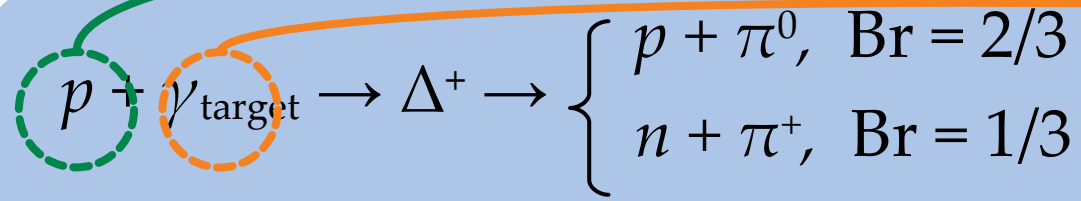
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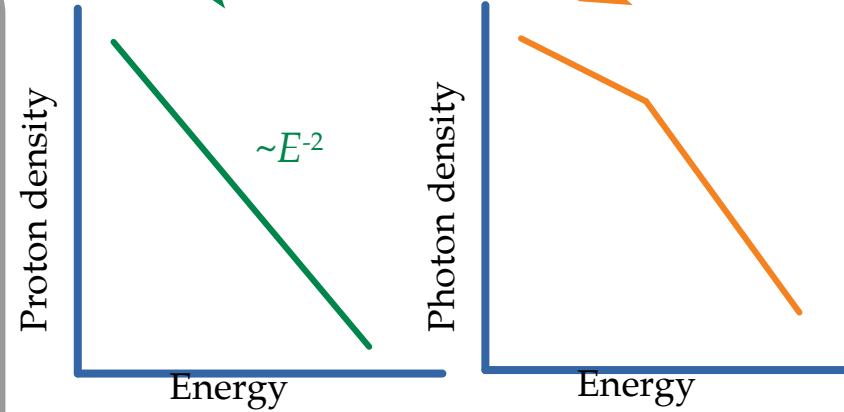
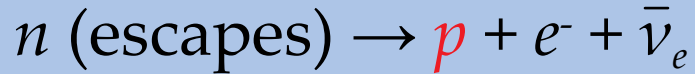
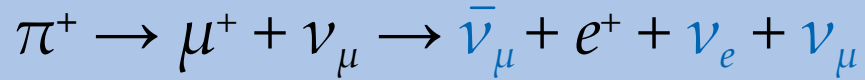
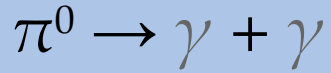
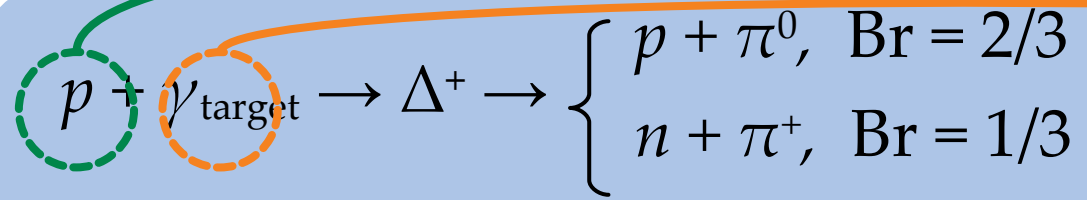
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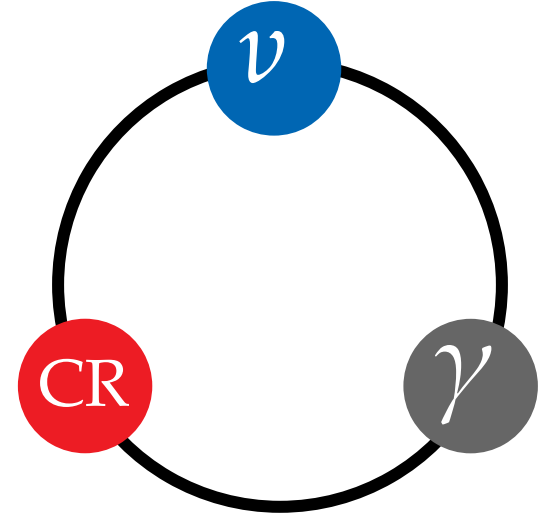
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$$\pi^0 \rightarrow \gamma + \gamma$$

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

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



Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 10

The multi-messenger connection: a simple picture

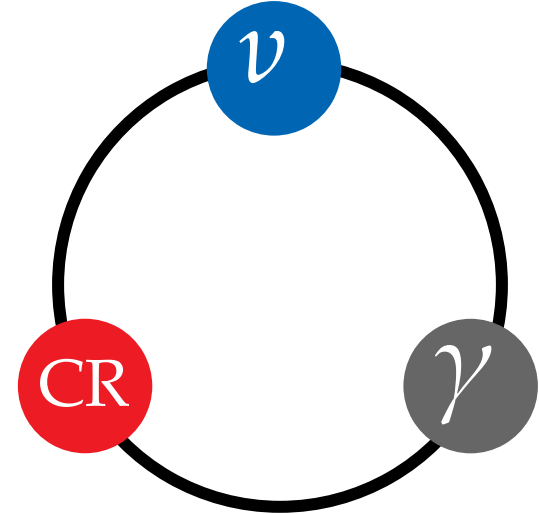
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1 PeV

20 PeV

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Gamma-ray energy = Proton energy / 10

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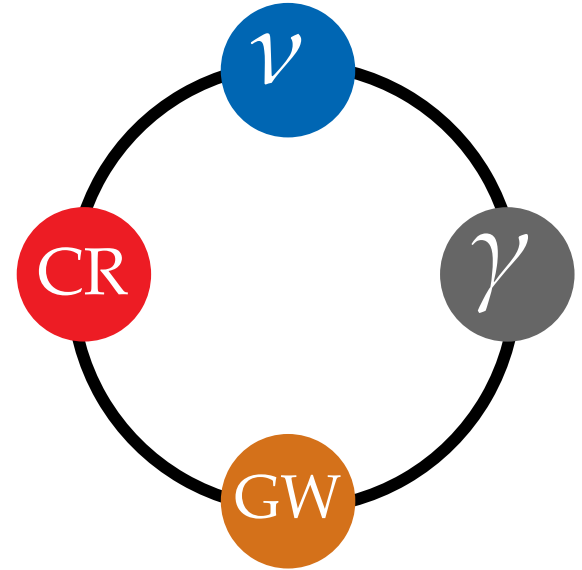
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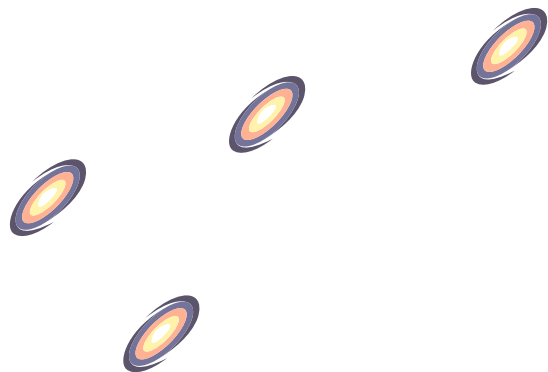
Gamma-ray energy = Proton energy / 10

Redshift



$z = 0$

Note: ν sources can be steady-state or transient



Redshift

$z = 0$

Note: ν sources can be steady-state or transient

MeV γ

Discovered

TeV–PeV ν

“High-energy”

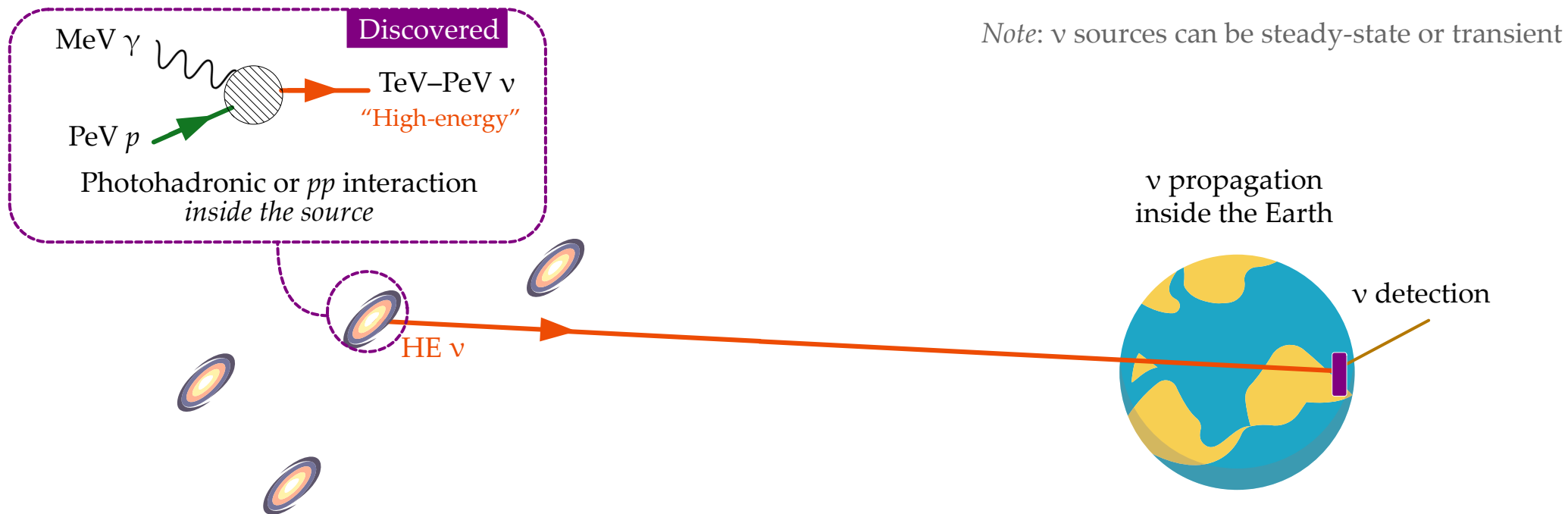
PeV p

Photohadronic or pp interaction
inside the source

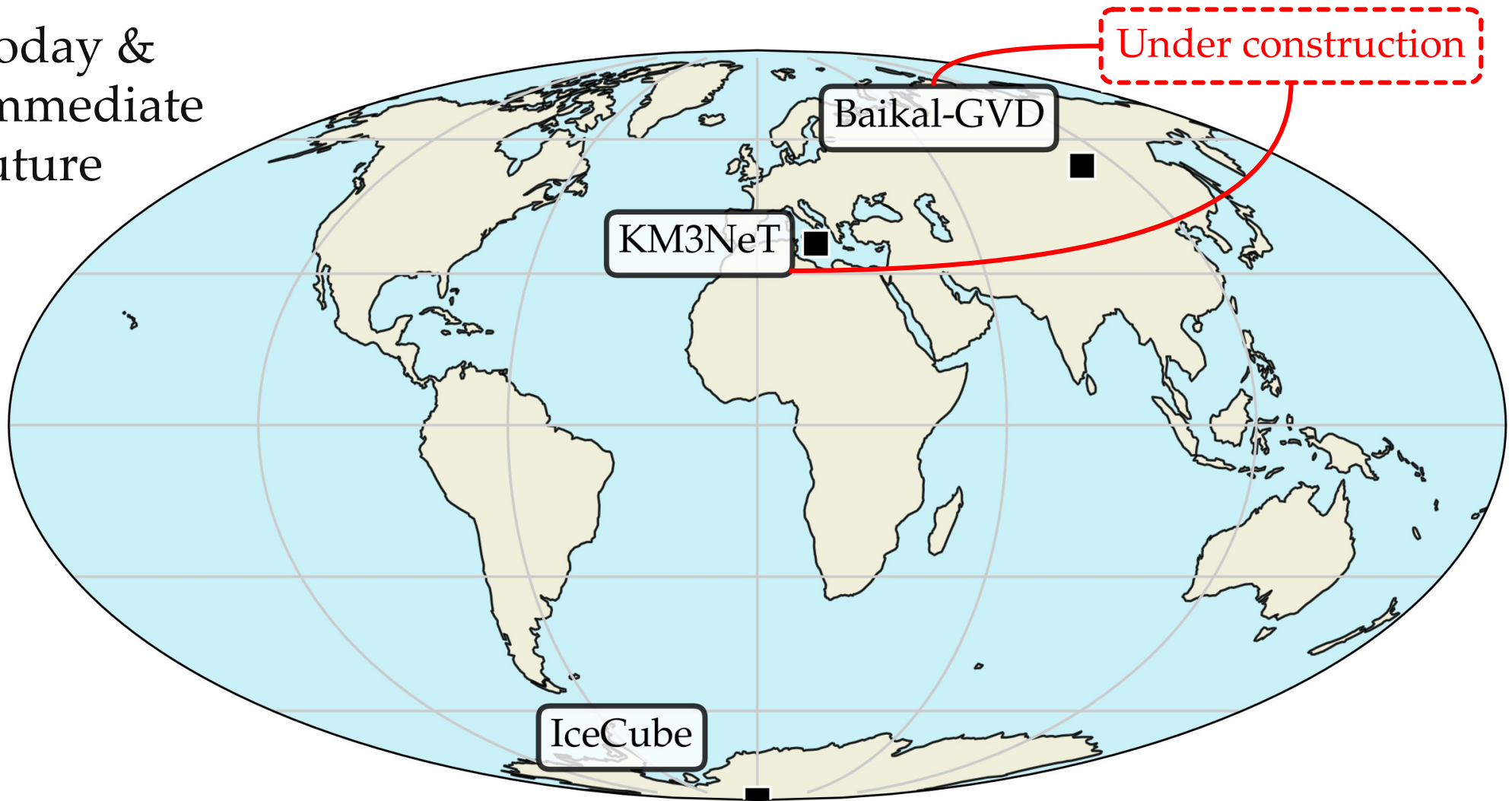
HE ν

ν propagation
inside the Earth

ν detection



Today &
immediate
future



IceCube





ICECUBE

SOUTH POLE NEUTRINO OBSERVATORY



IceCube Laboratory

Data is collected here and sent by satellite to the data warehouse at UW-Madison



Digital Optical Module (DOM)

5,160 DOMs deployed in the ice

50 m

IceTop

1450 m

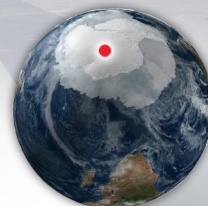
2450 m

86 strings of DOMs,
set 125 meters apart

IceCube
detector

DeepCore

Antarctic bedrock



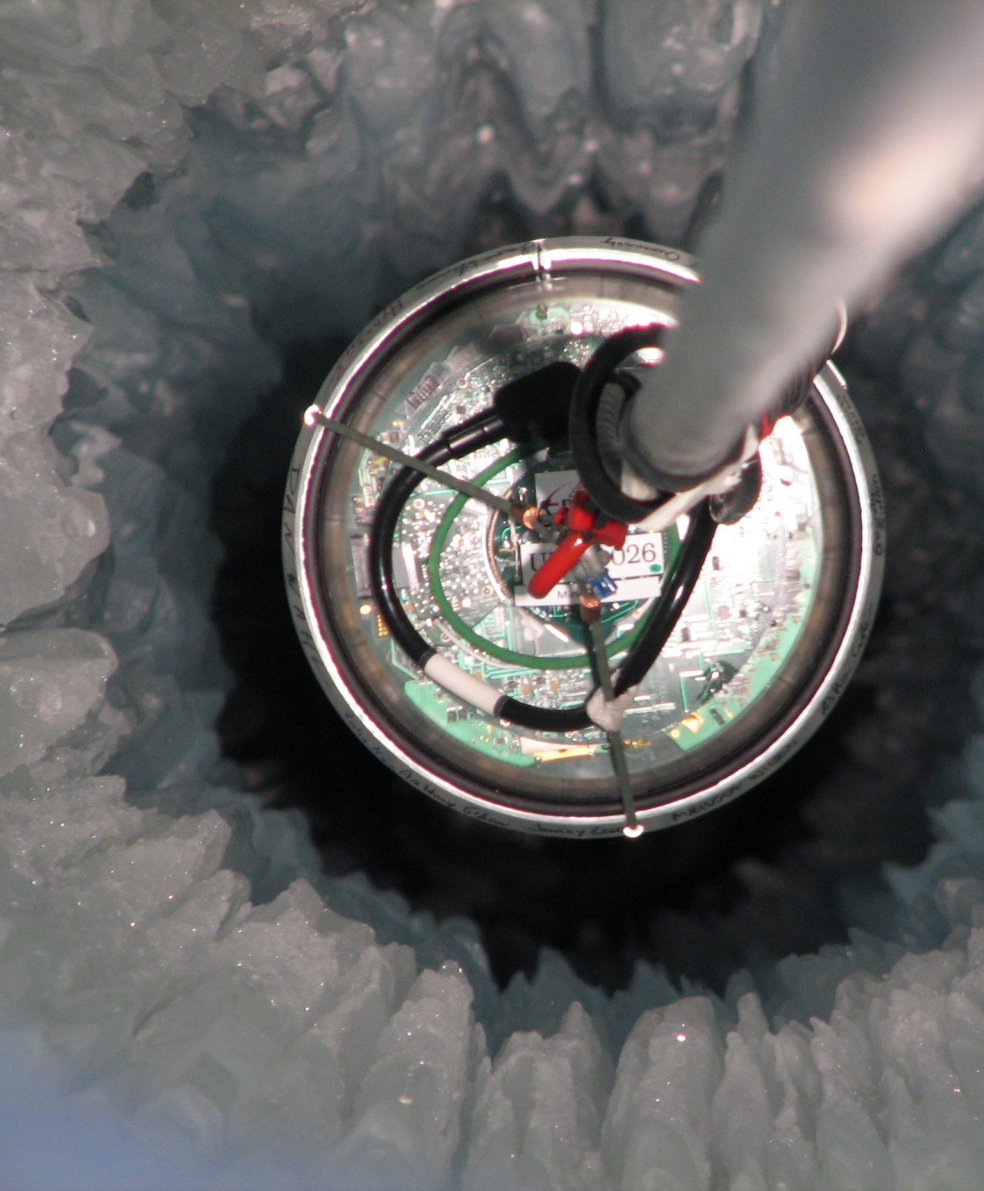
Amundsen-Scott South Pole Station, Antarctica

A National Science Foundation-managed research facility

60 DOMs
on each
string

DOMs
are 17
meters
apart



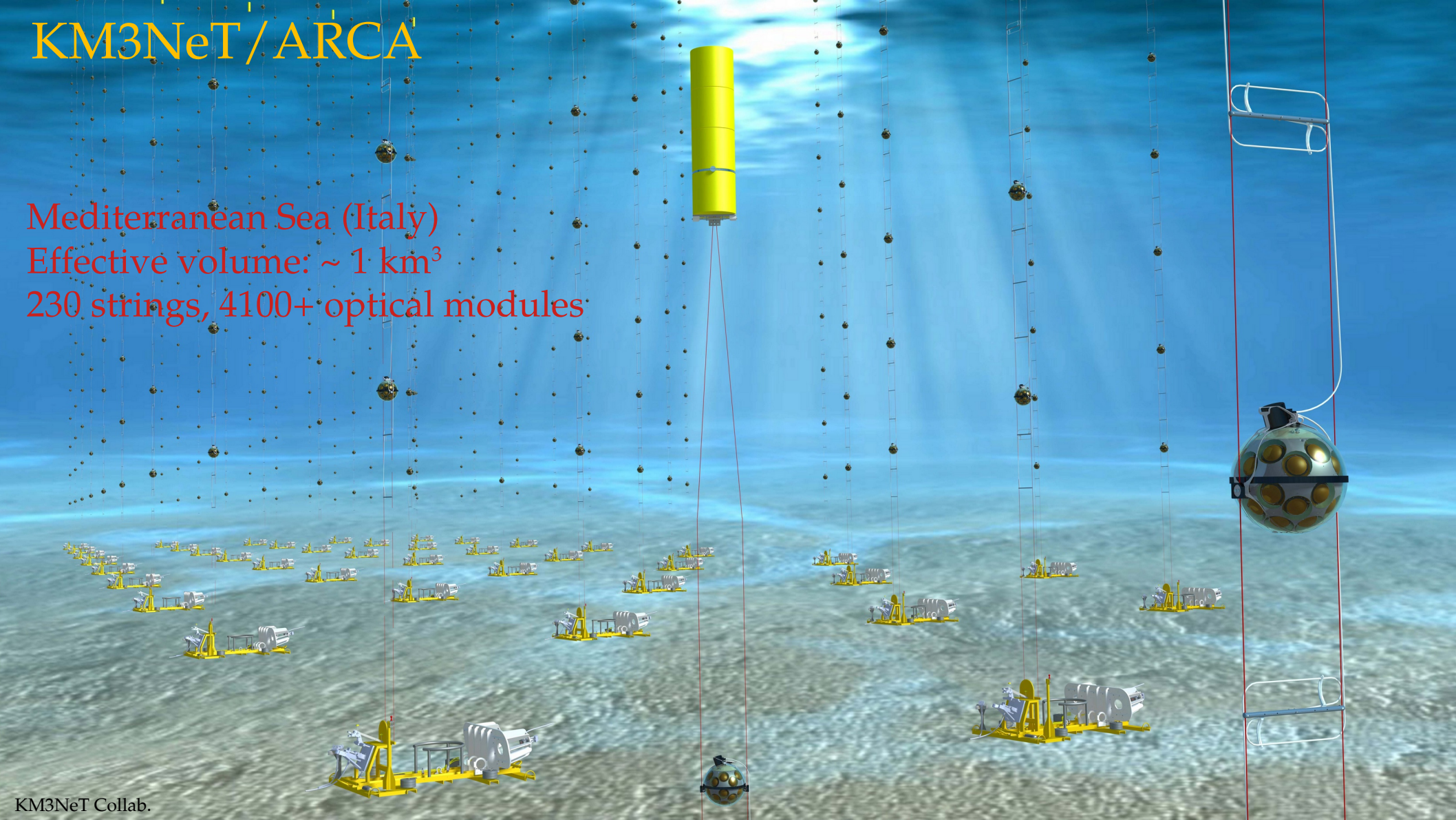


KM3NeT/ARCA

Mediterranean Sea (Italy)

Effective volume: $\sim 1 \text{ km}^3$

230 strings, 4100+ optical modules



Baikal-GVD

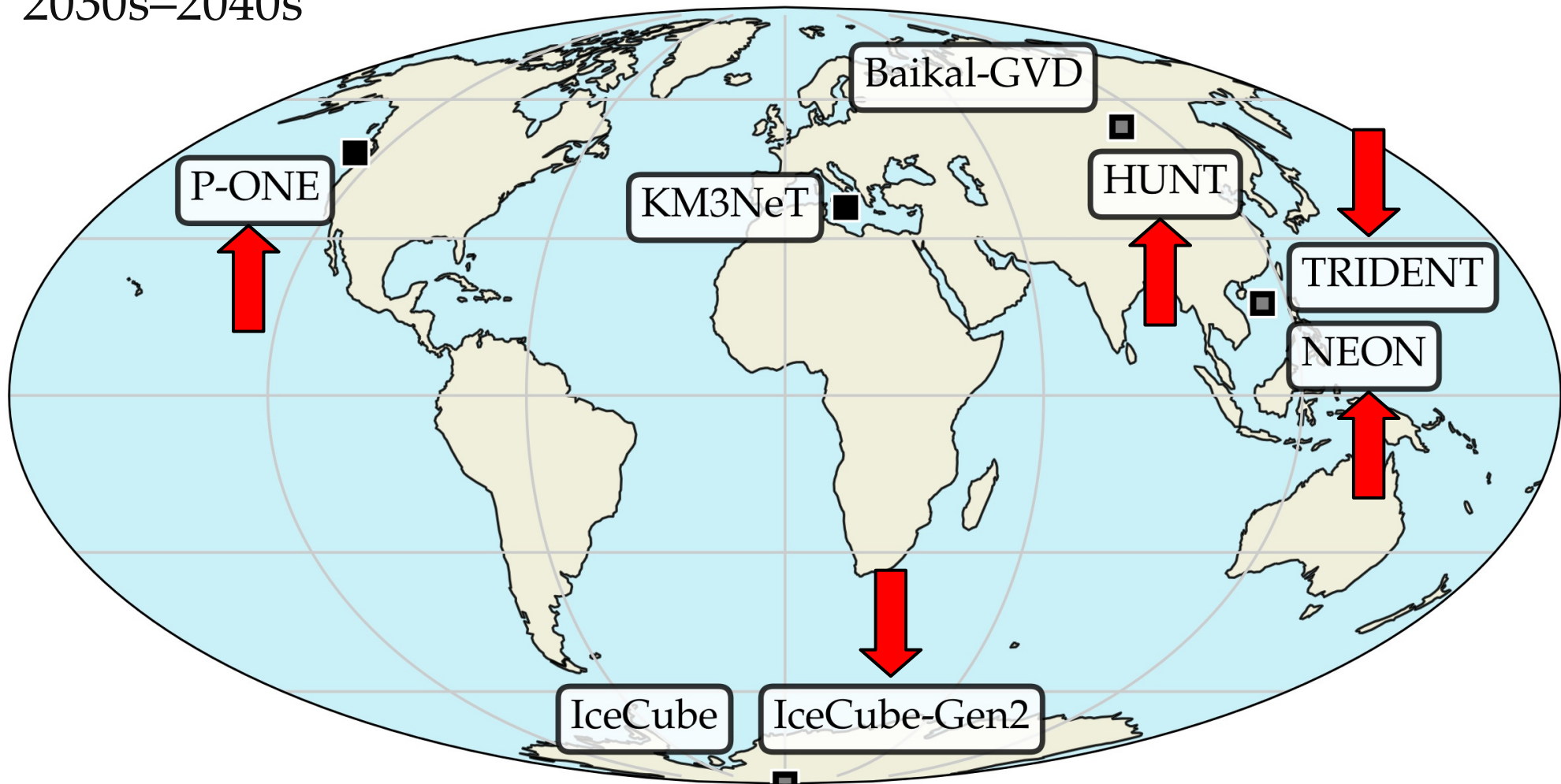
Lake Baikal, Russia

Effective volume: $\sim 1.5 \text{ km}^3$

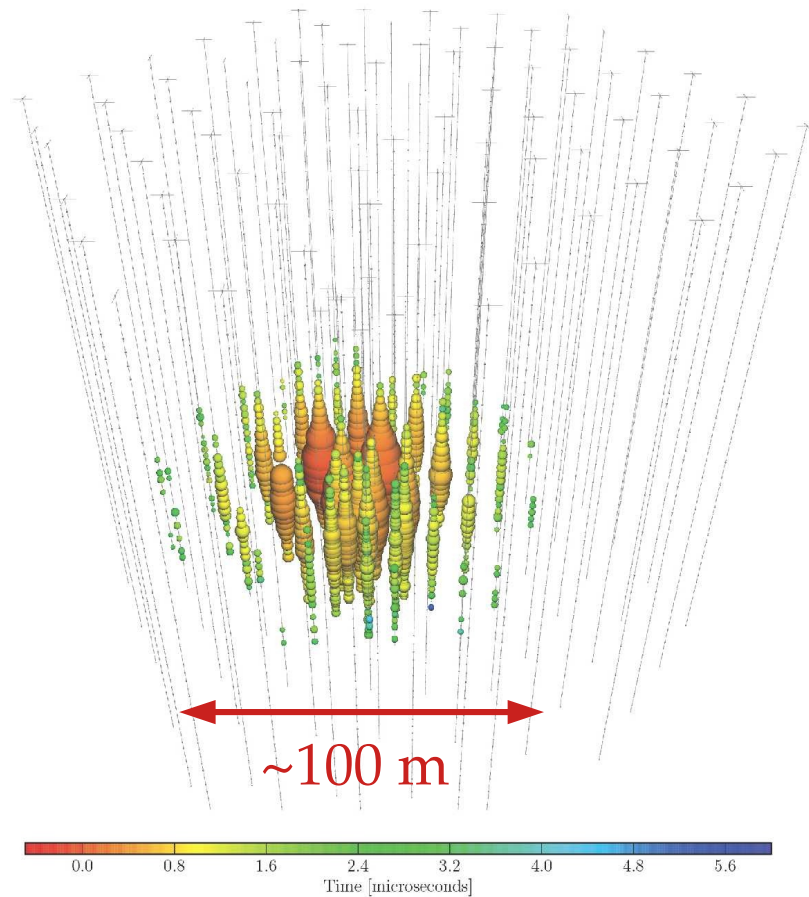
90 strings, 1000+ optical modules



2030s–2040s

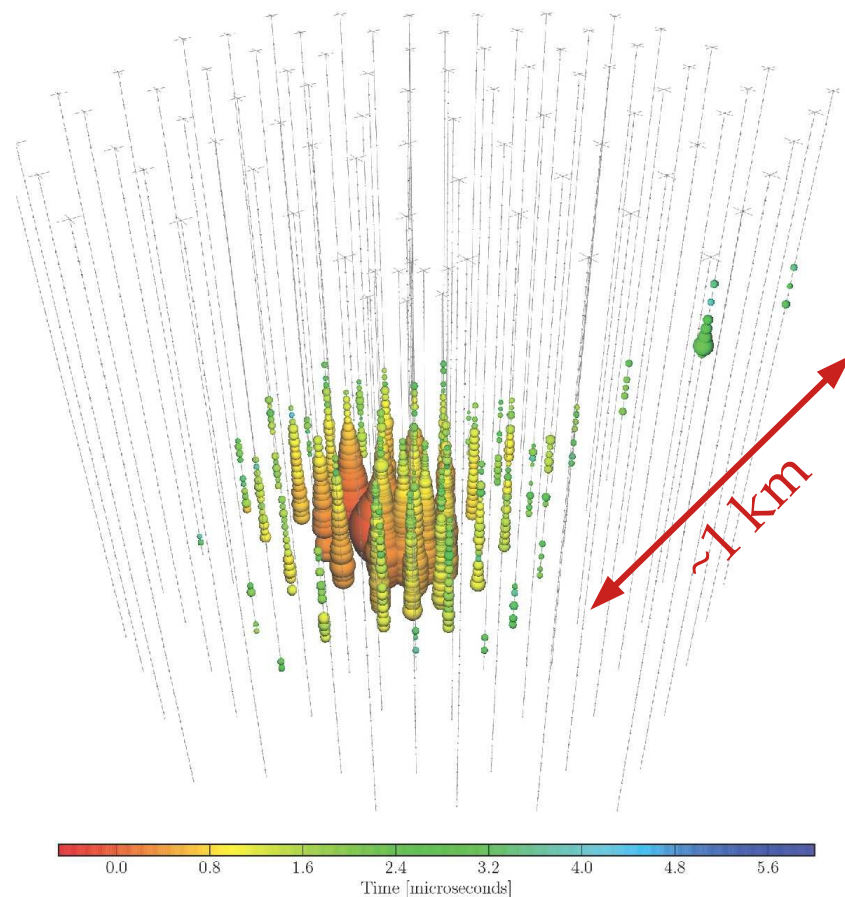


Shower
(mainly from ν_e and ν_τ)

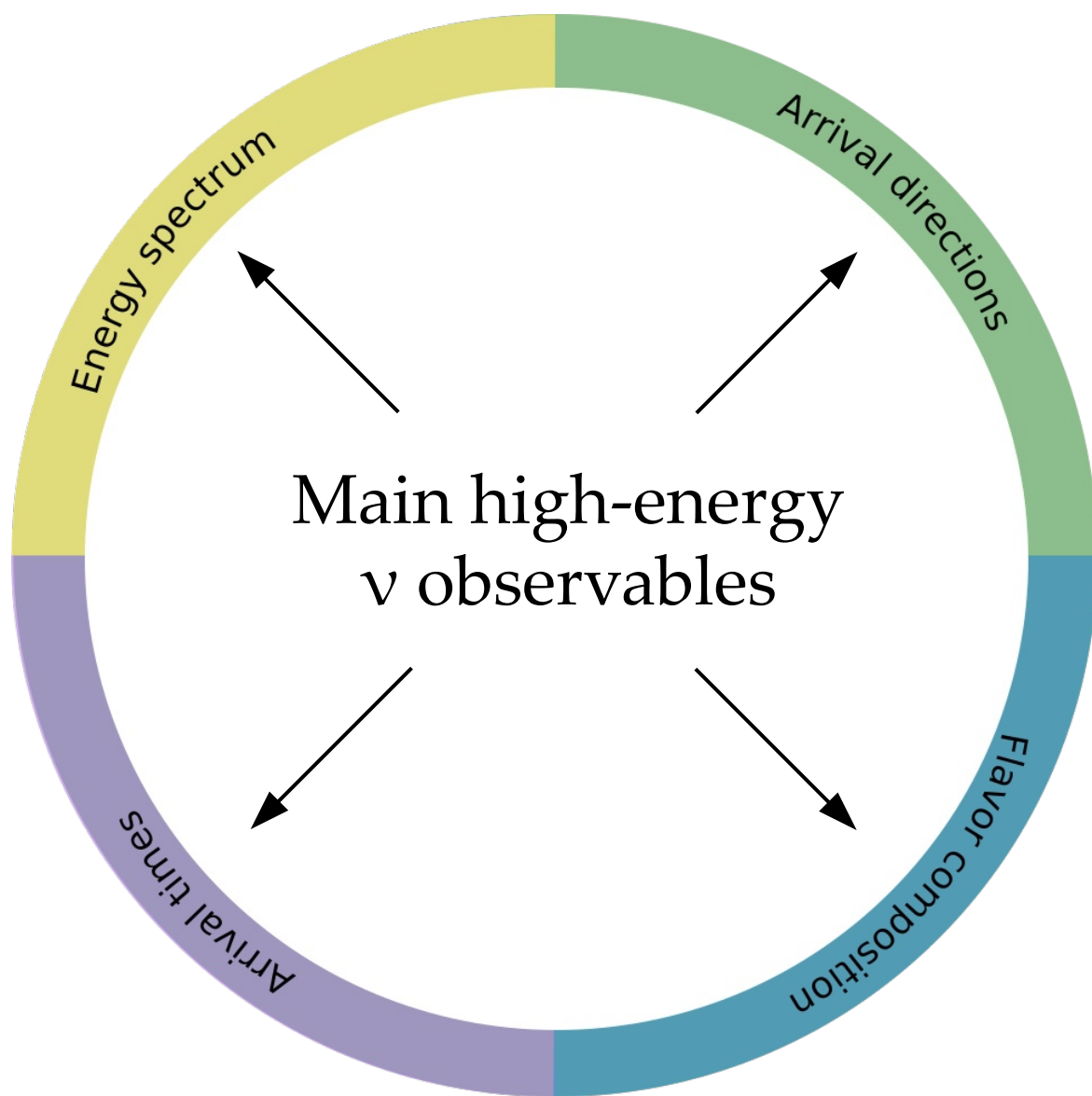


Poor angular resolution: $< 5^\circ$

Track
(mainly from ν_μ)

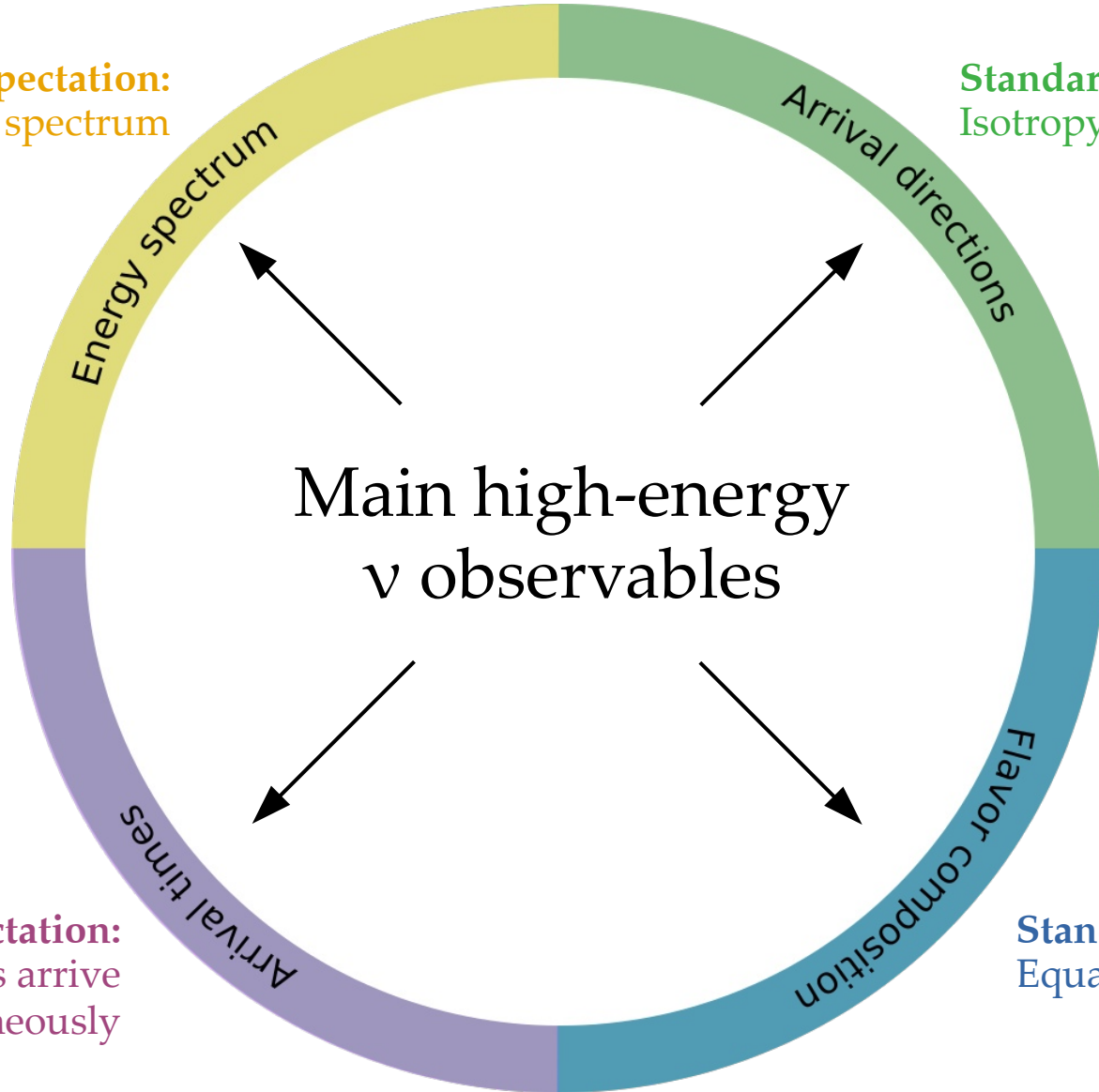


Angular resolution: $< 1^\circ$



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

Energy spectrum

Standard expectation:
Isotropy (for diffuse flux)

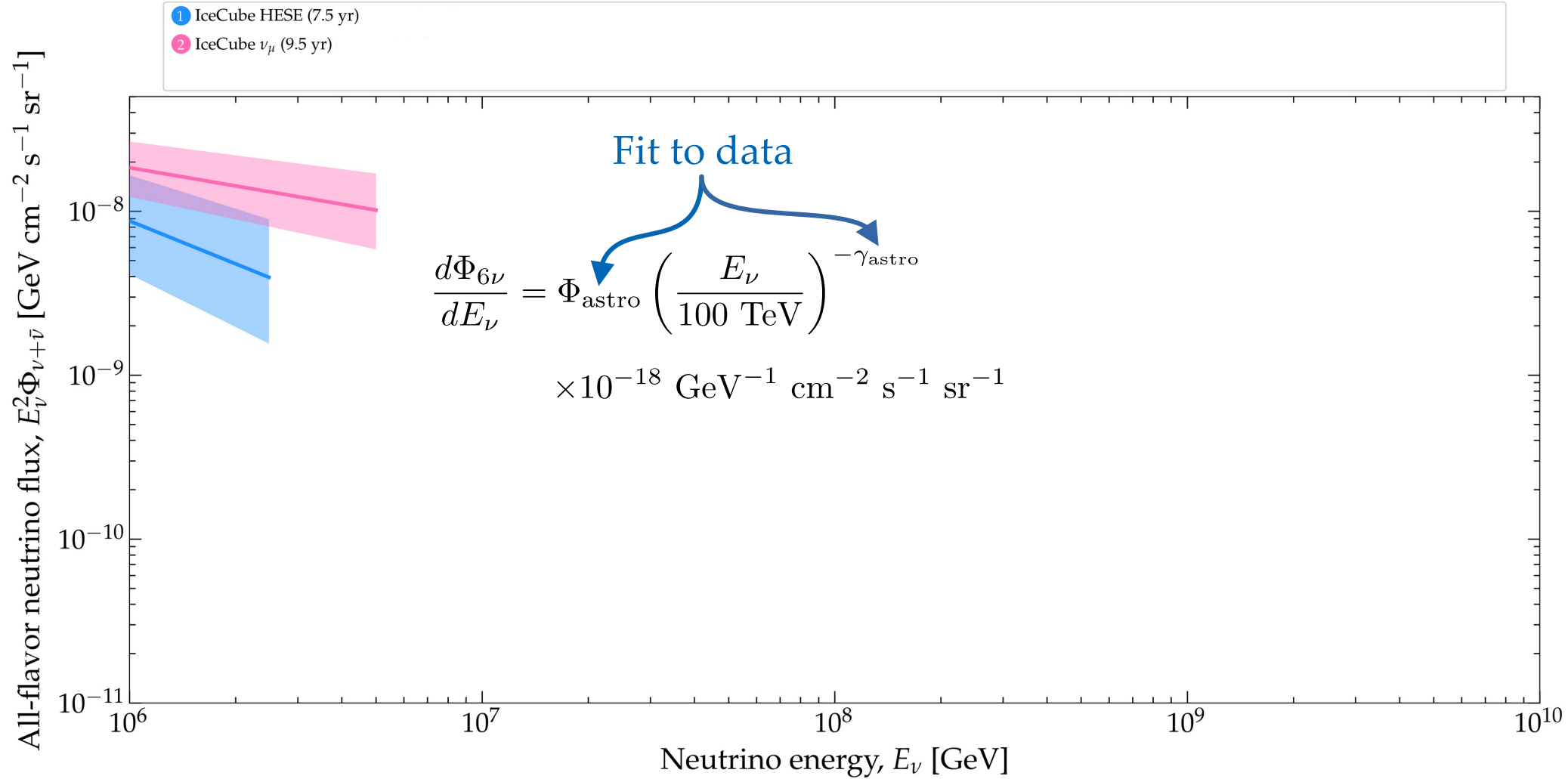
Arrival directions

Standard expectation:
Equal number of ν_e , ν_μ , ν_τ

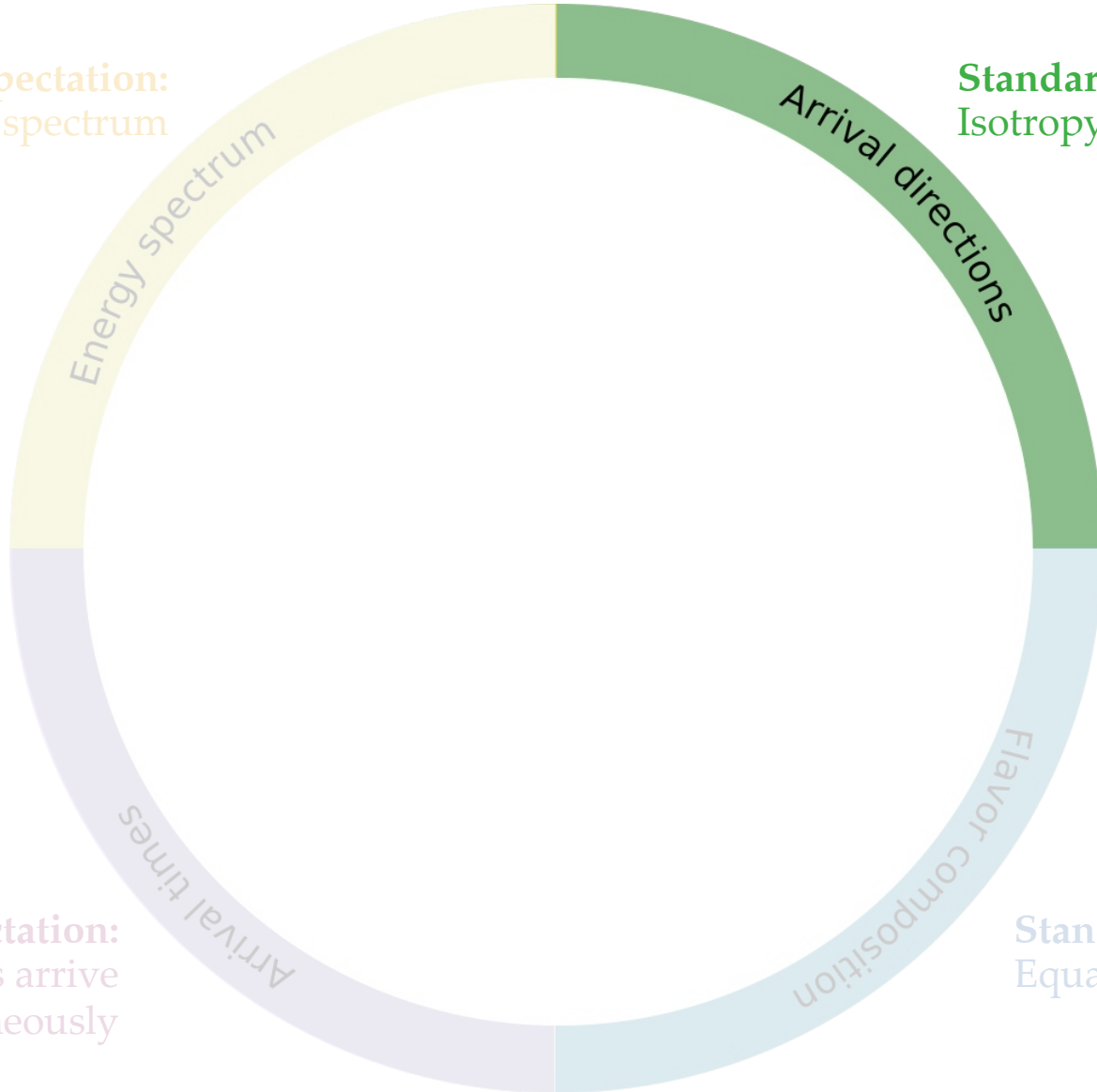
Flavor composition

Standard expectation:
 ν and γ from transients arrive
simultaneously

Arrival times



Standard expectation:
Power-law energy spectrum



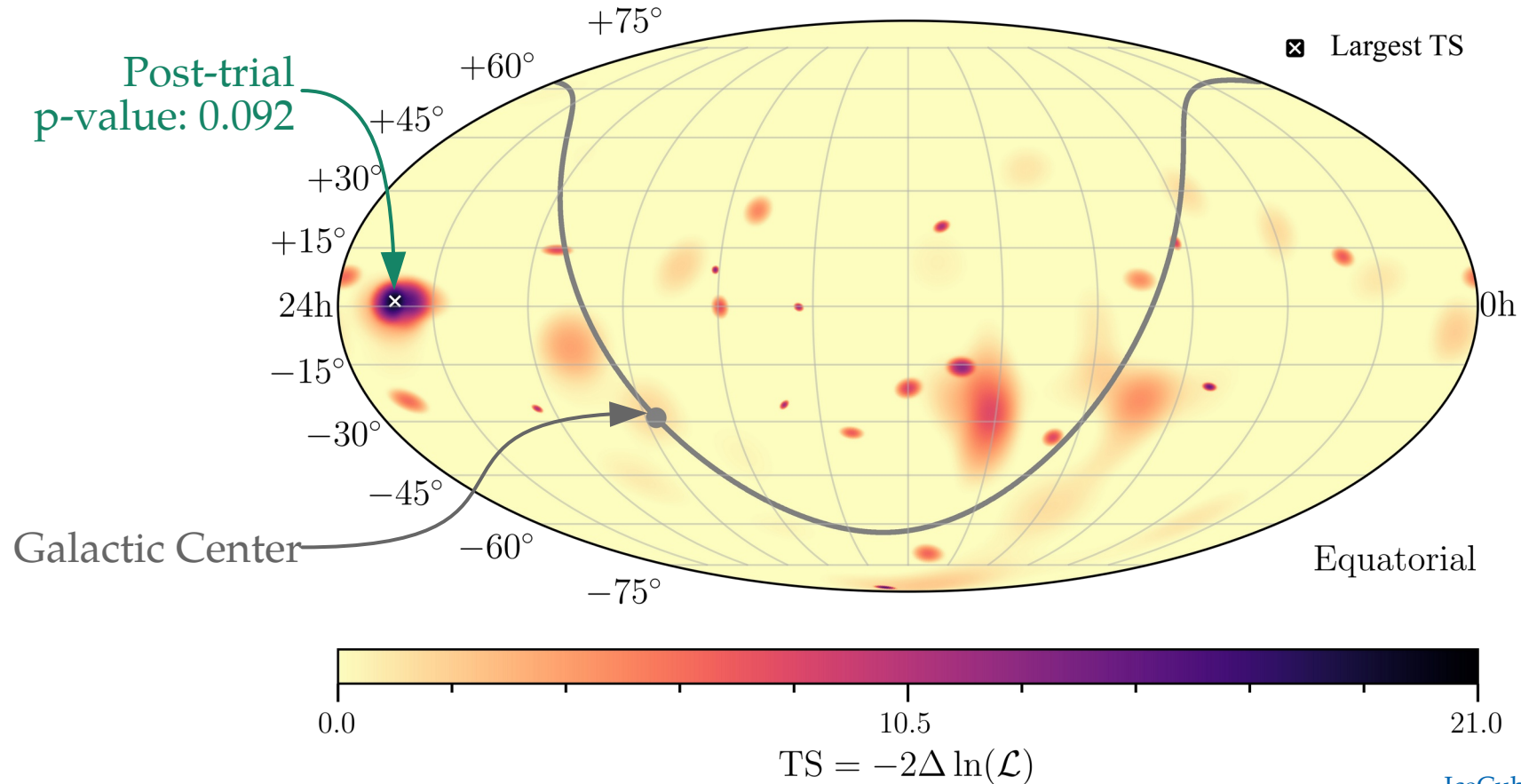
Standard expectation:
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Equal number of ν_e , ν_μ , ν_τ

Standard expectation:
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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

Energy spectrum

Standard expectation:
Isotropy (for diffuse flux)

Arrival directions

Standard expectation:
Equal number of ν_e , ν_μ , ν_τ

Flavor composition

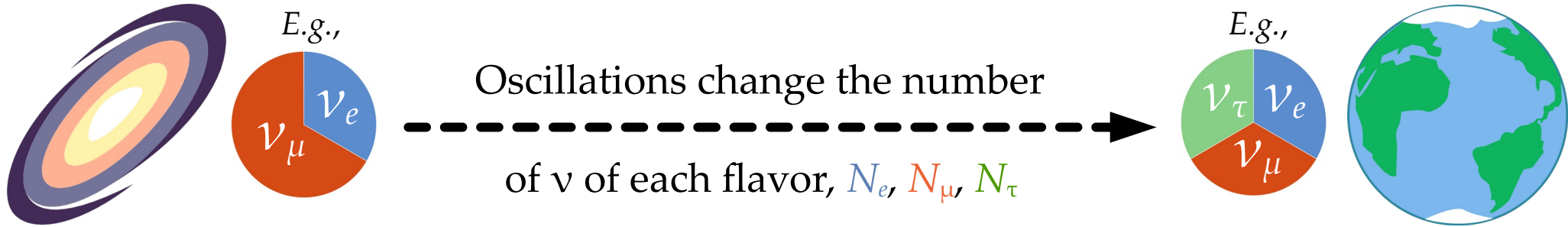
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Arrival times

Astrophysical sources

Earth

Up to a few Gpc



Different production mechanisms yield different flavor ratios:

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

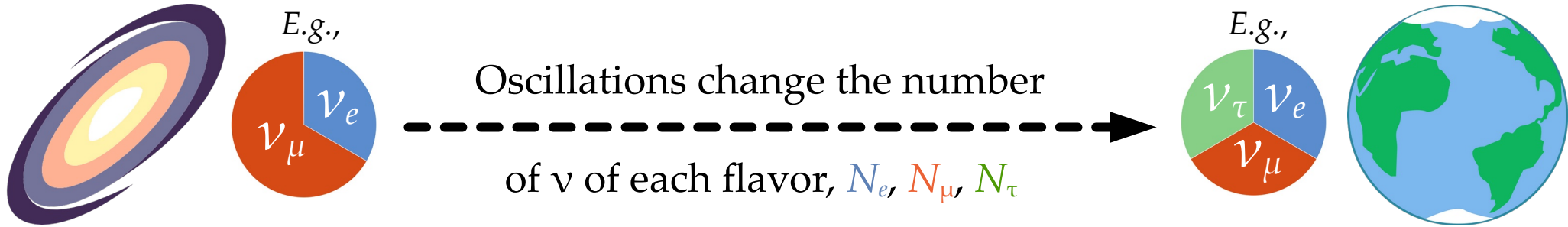
Flavor ratios at Earth ($\alpha = e, \mu, \tau$):

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

Astrophysical sources

Earth

Up to a few Gpc



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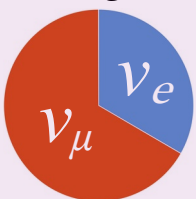
Standard oscillations
or
new physics

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

Sources



E.g.,



$(f_{e,S}, f_{\mu,S}, f_{\tau,S})$

Oscillations

$(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{CP})$

Earth



$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$

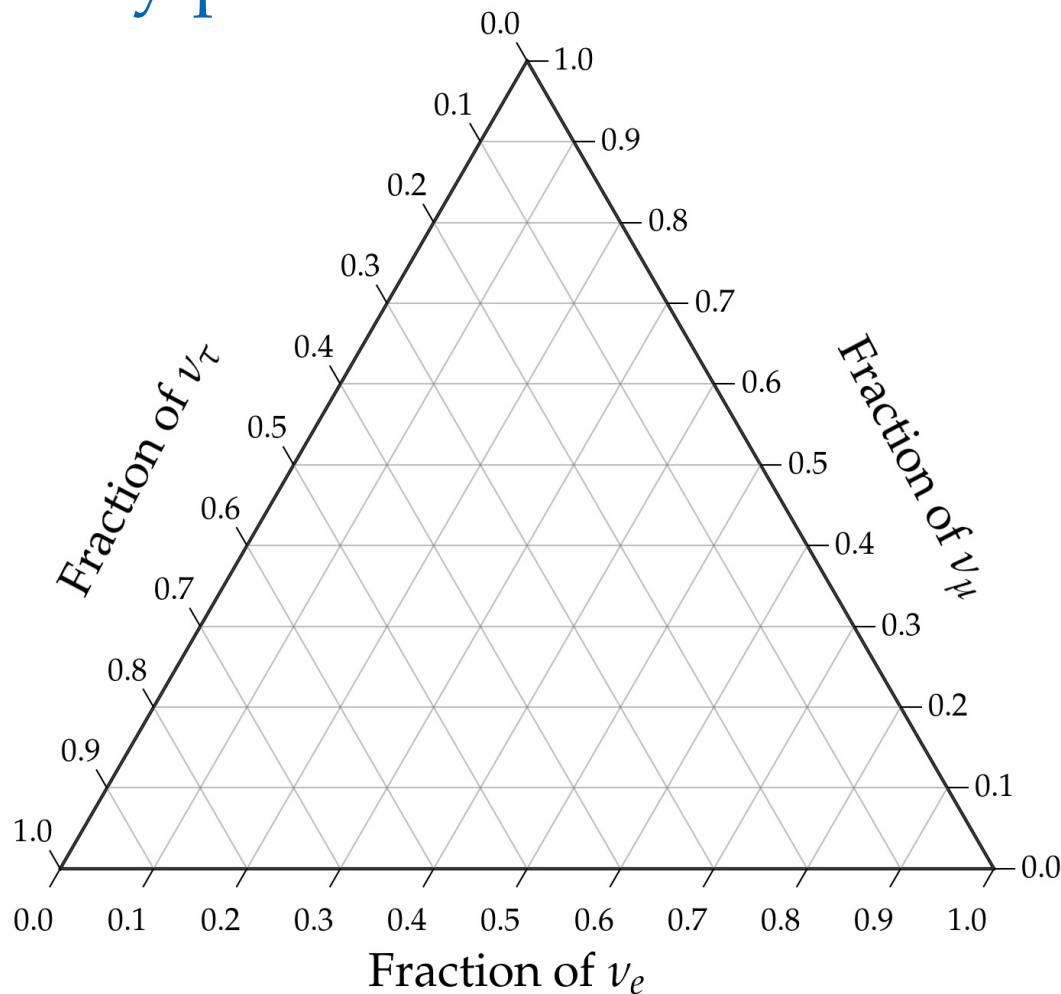
Quick aside: how to read a ternary plot

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

How to read it:

Follow the tilt of the tick marks

Always in this order: (f_e, f_μ, f_τ)



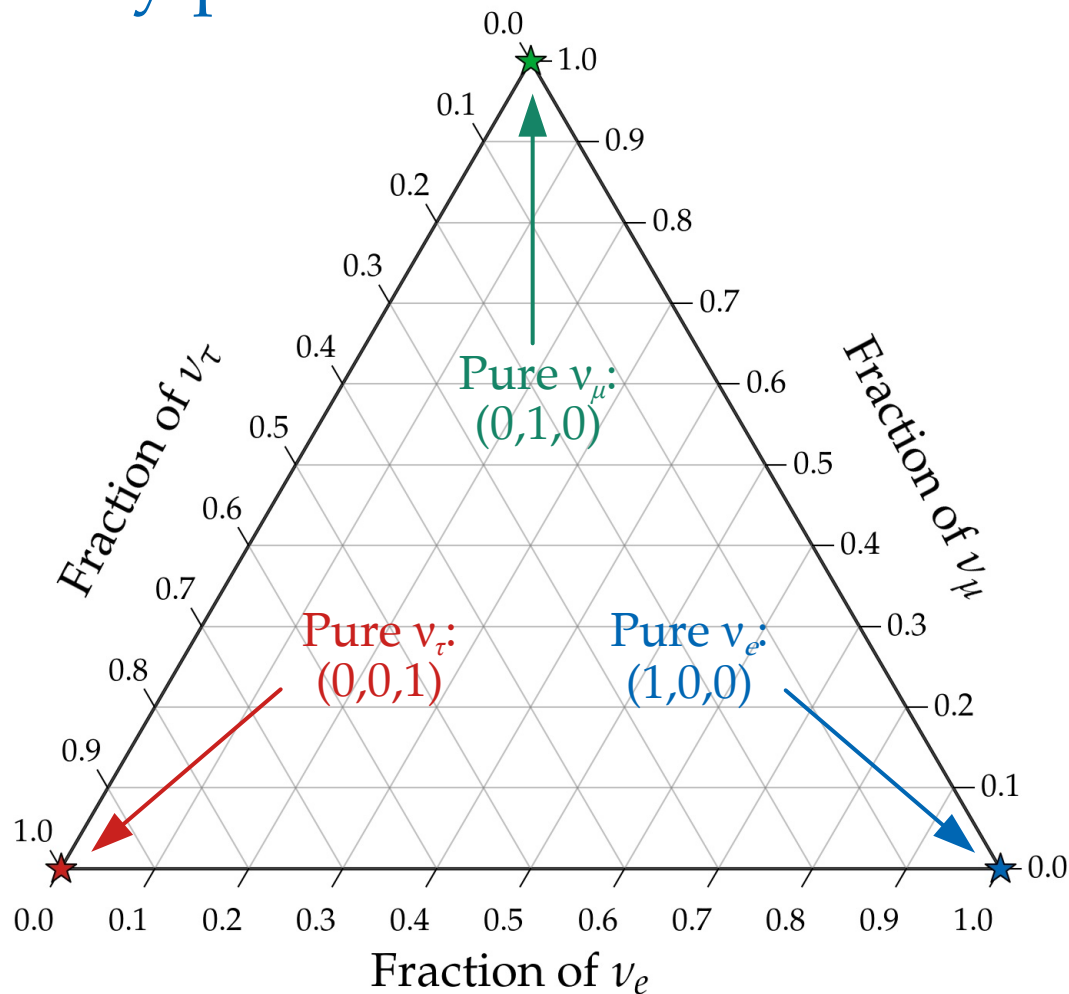
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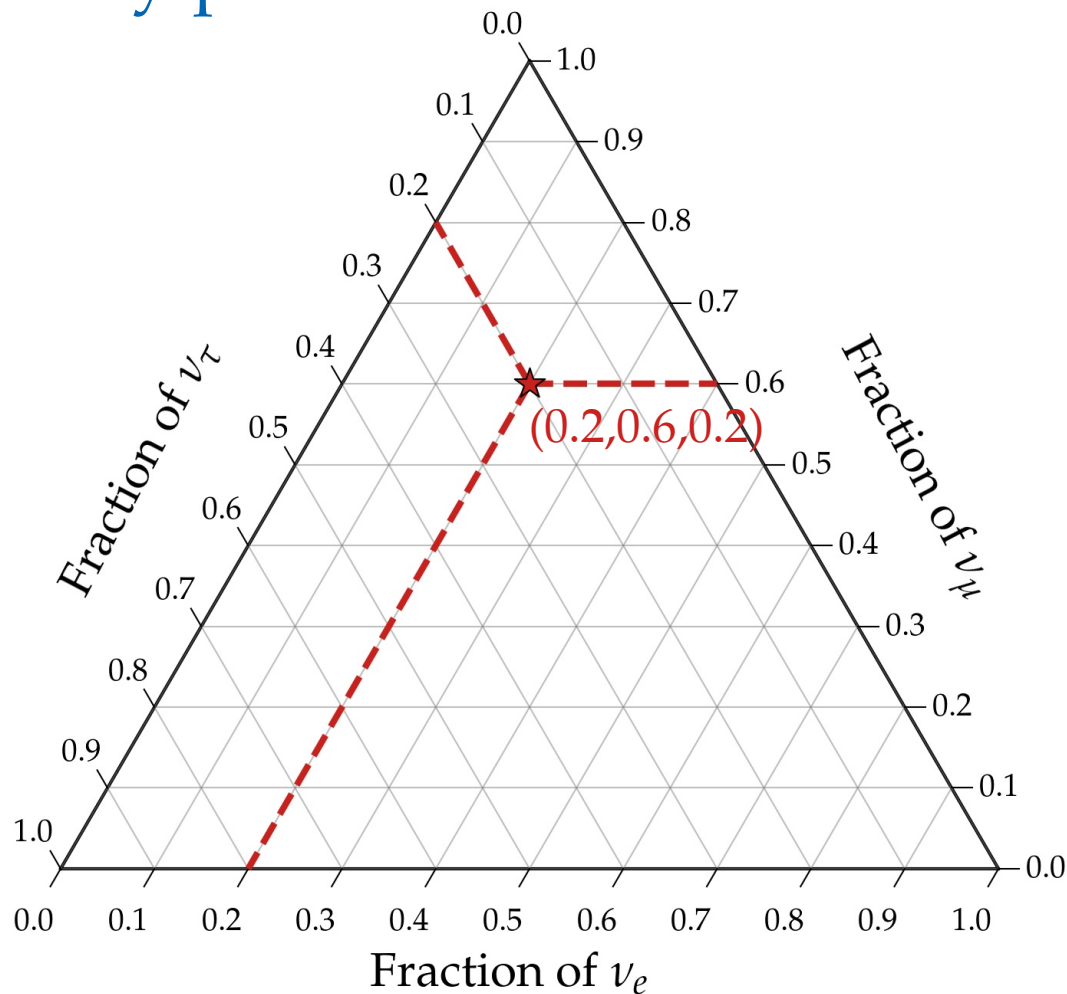
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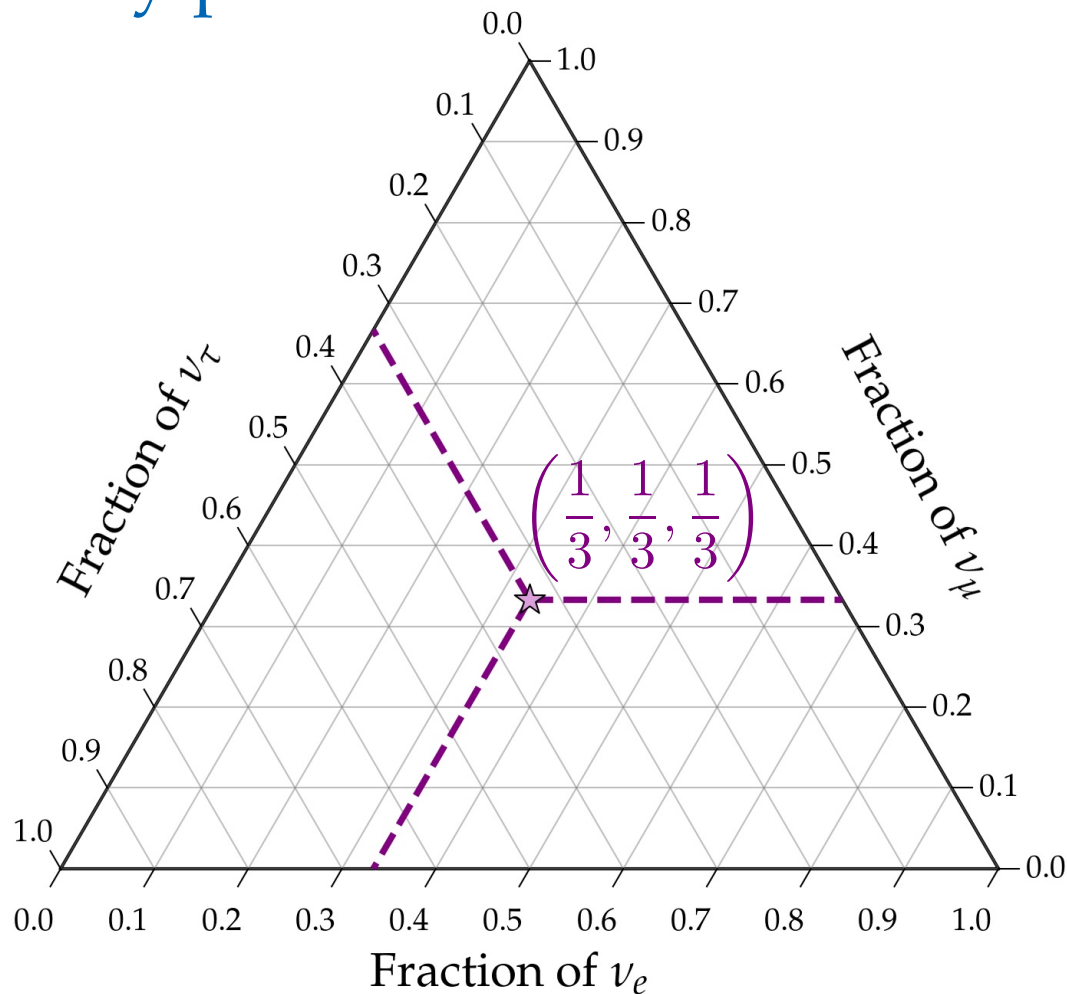
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One likely TeV–PeV ν production scenario:

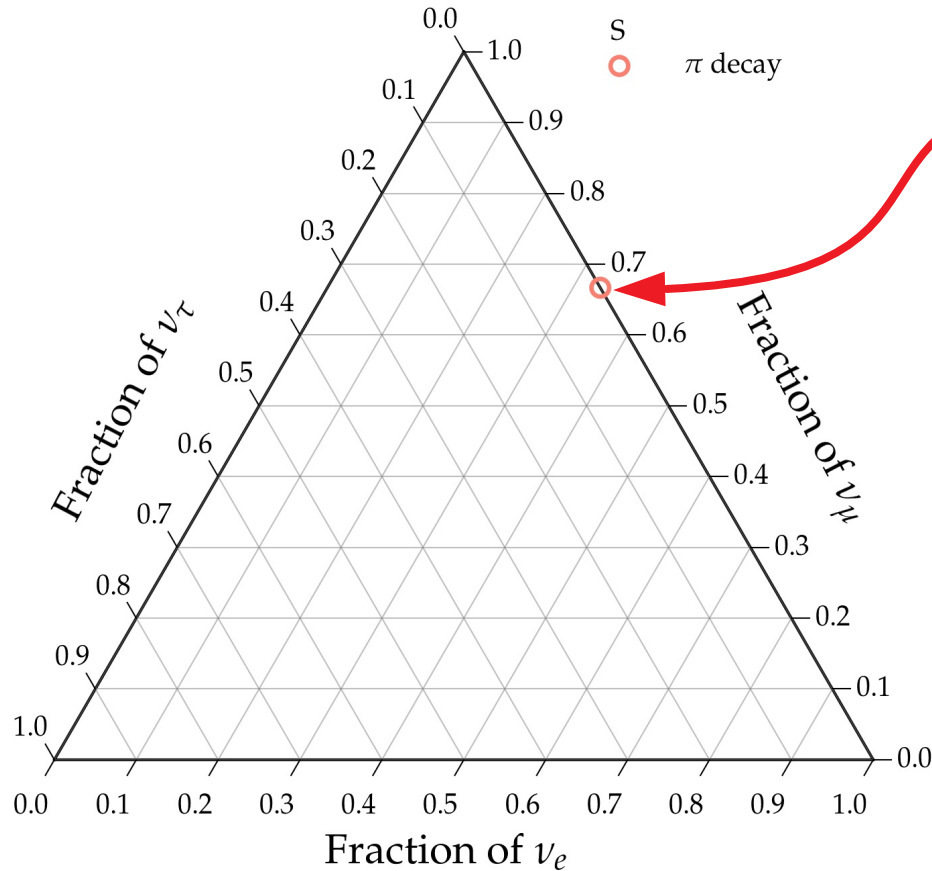
$$p + \gamma \rightarrow \pi^+ \rightarrow \mu^+ + \nu_\mu \text{ followed by } \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

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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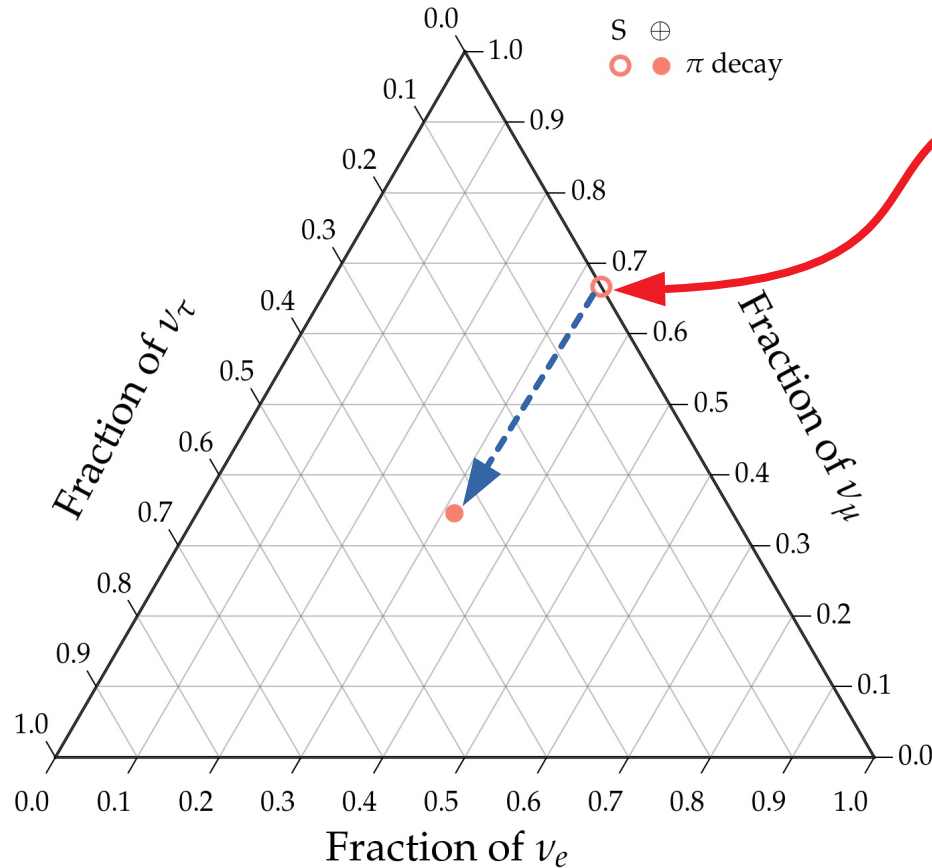


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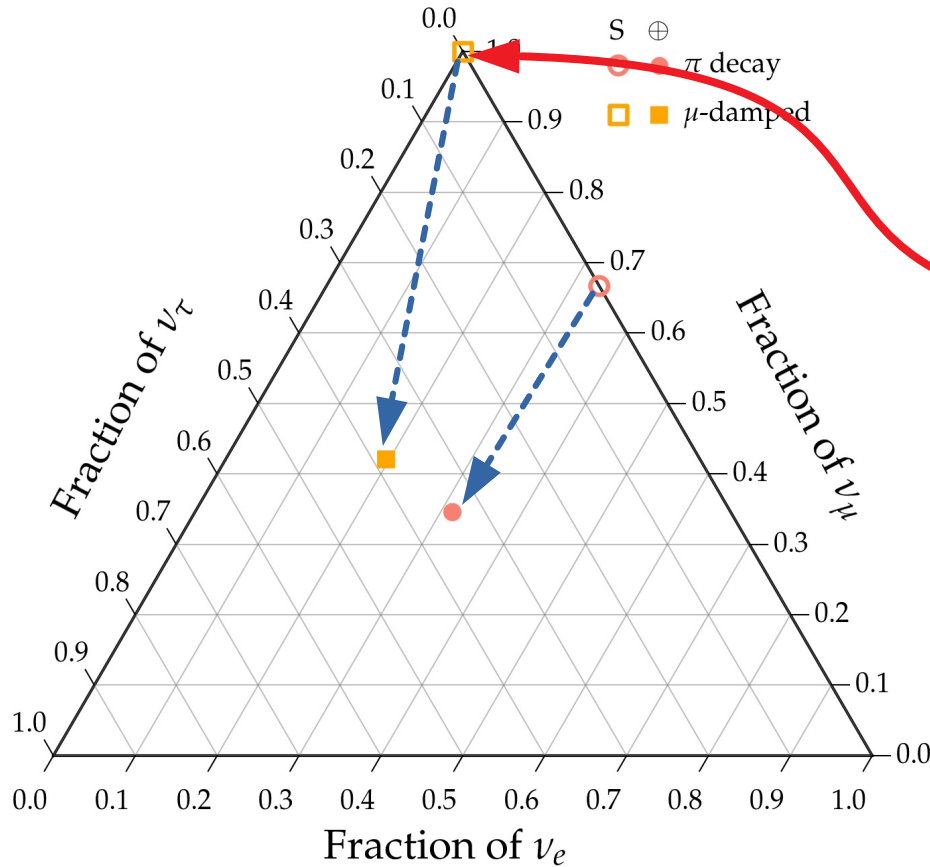


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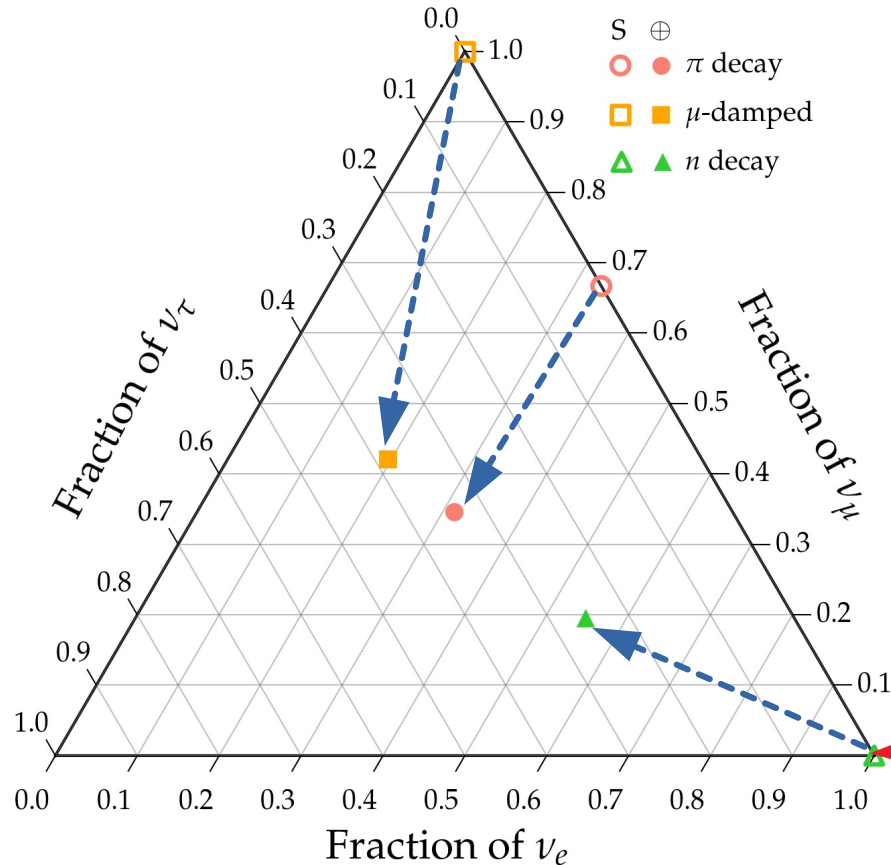
$(1/3:2/3:0)_S$

Muon damped

$(0:1:0)_S$

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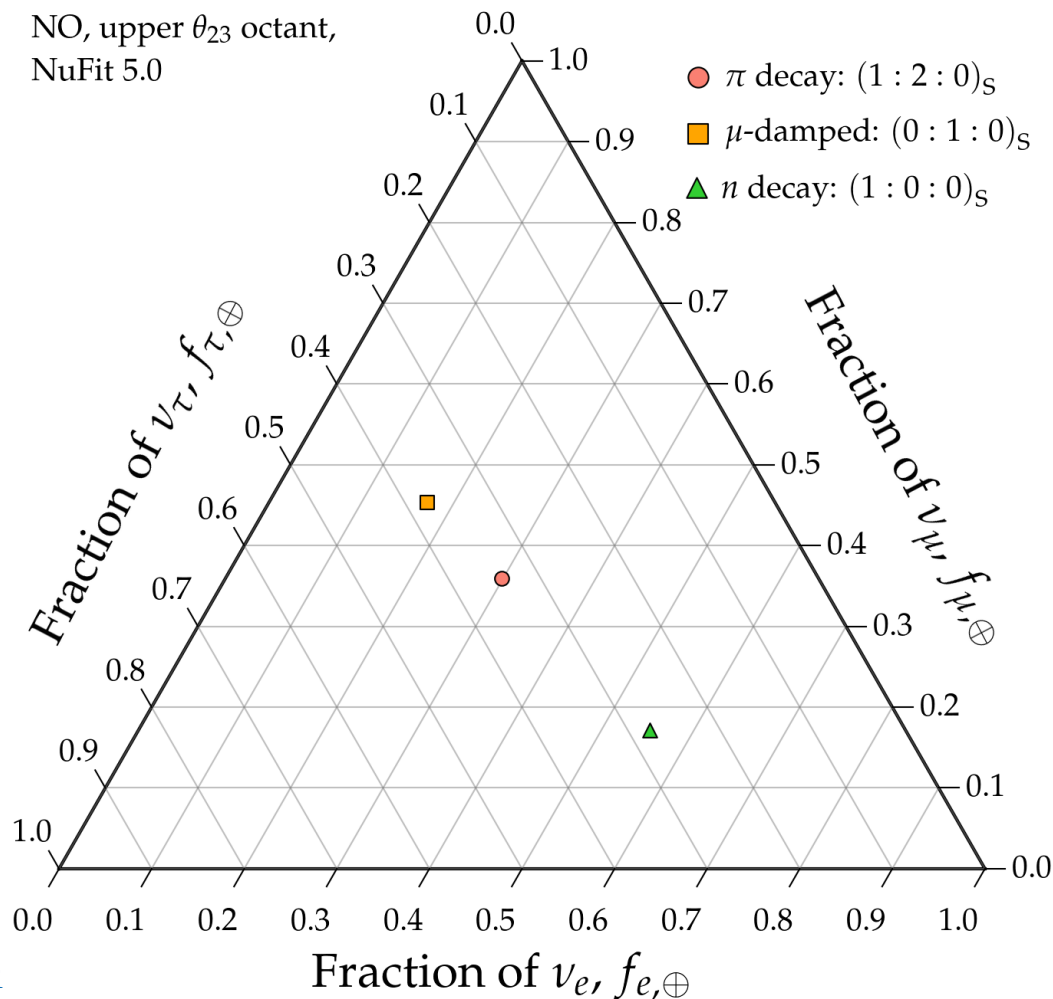
Neutron decay

$(1:0:0)_S$

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Theoretically palatable regions: today

NO, upper θ_{23} octant,
NuFit 5.0



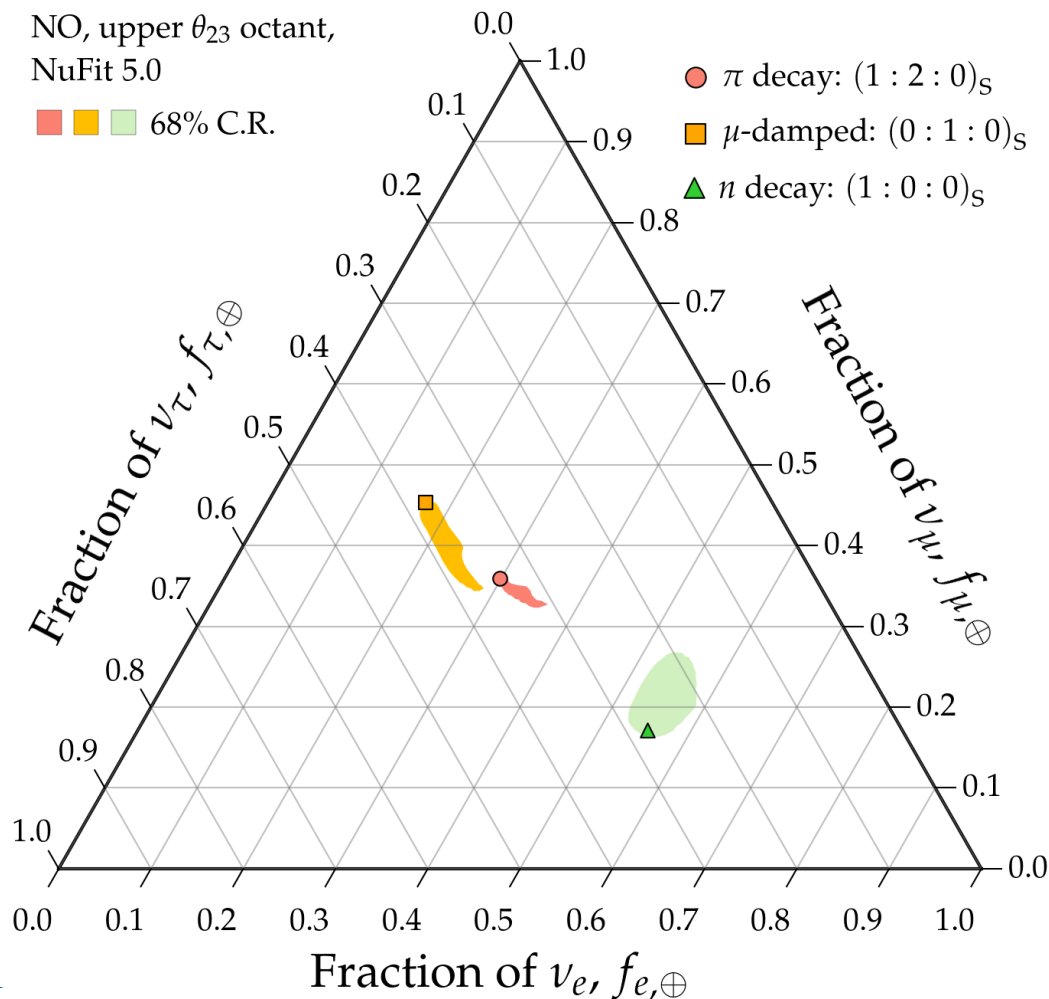
Note:

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

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

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

Theoretically palatable regions: today



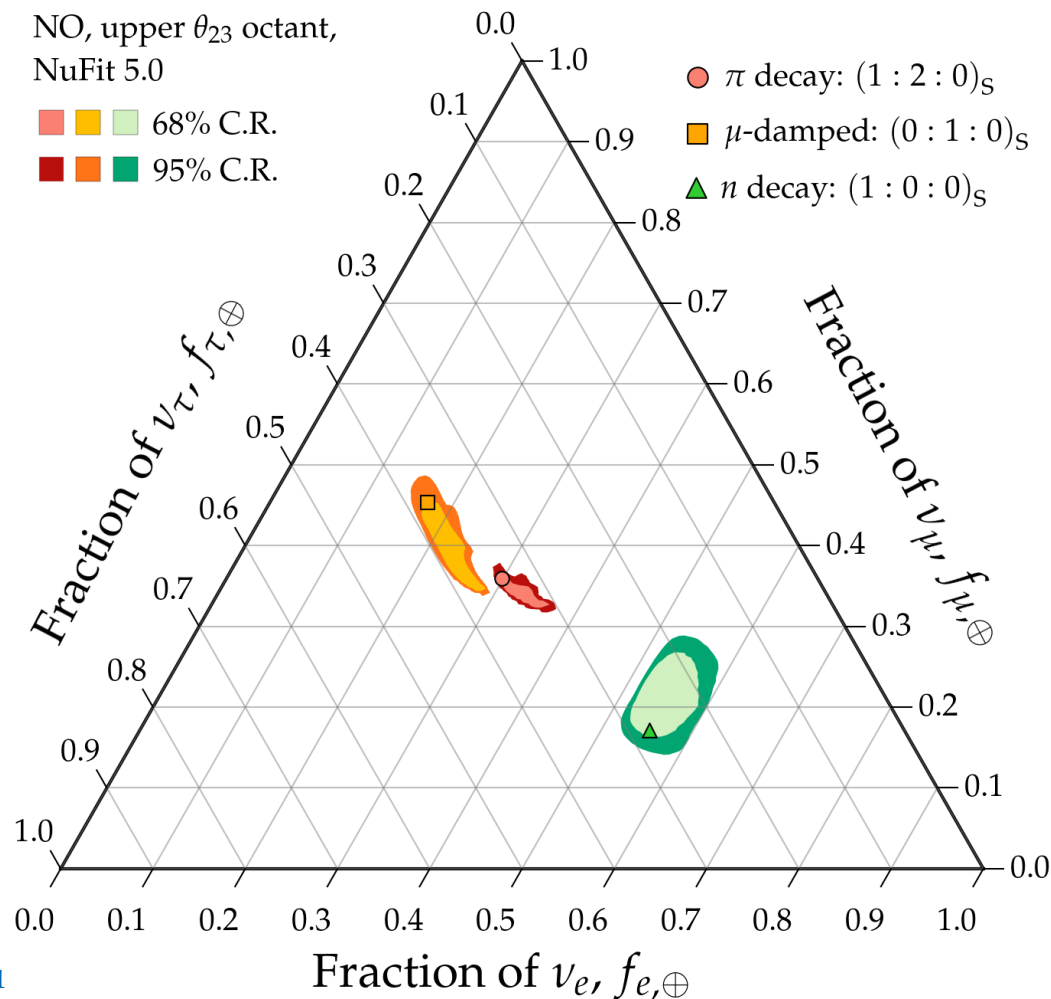
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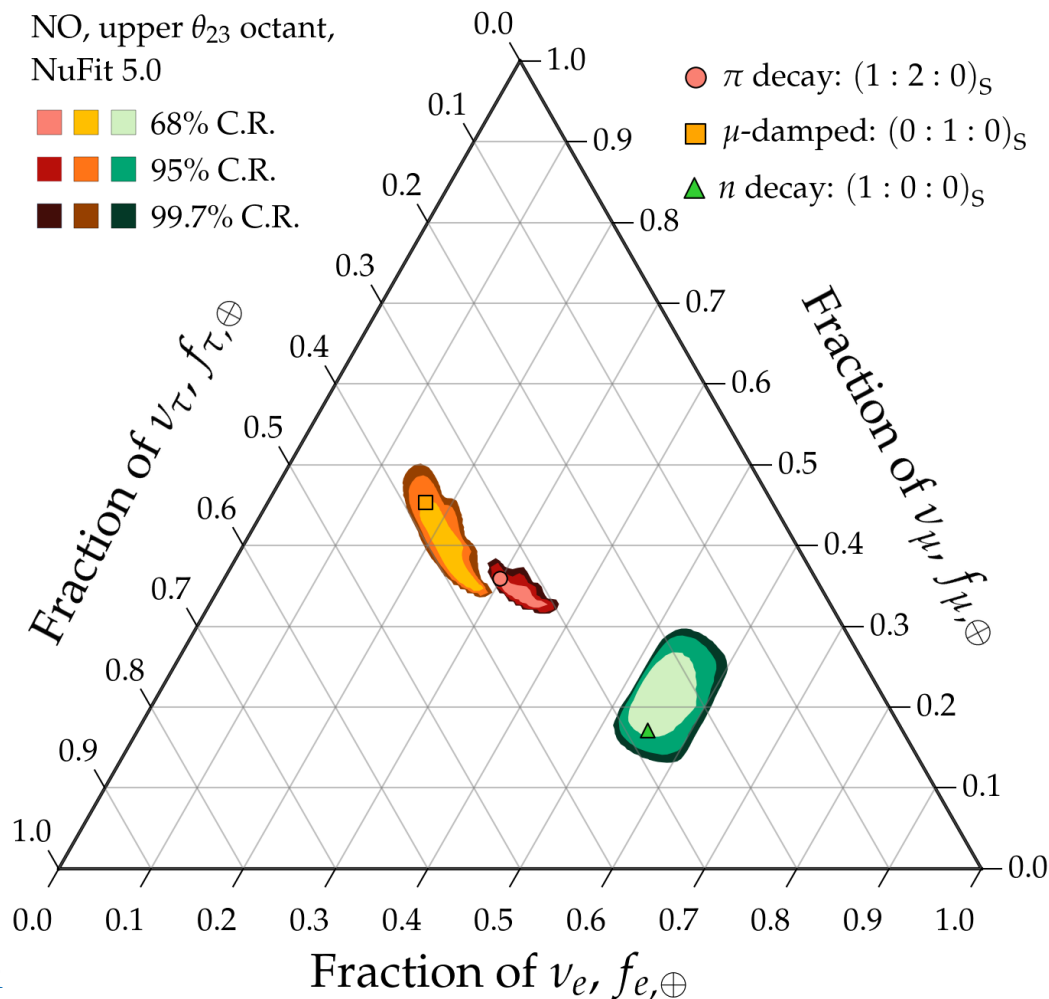
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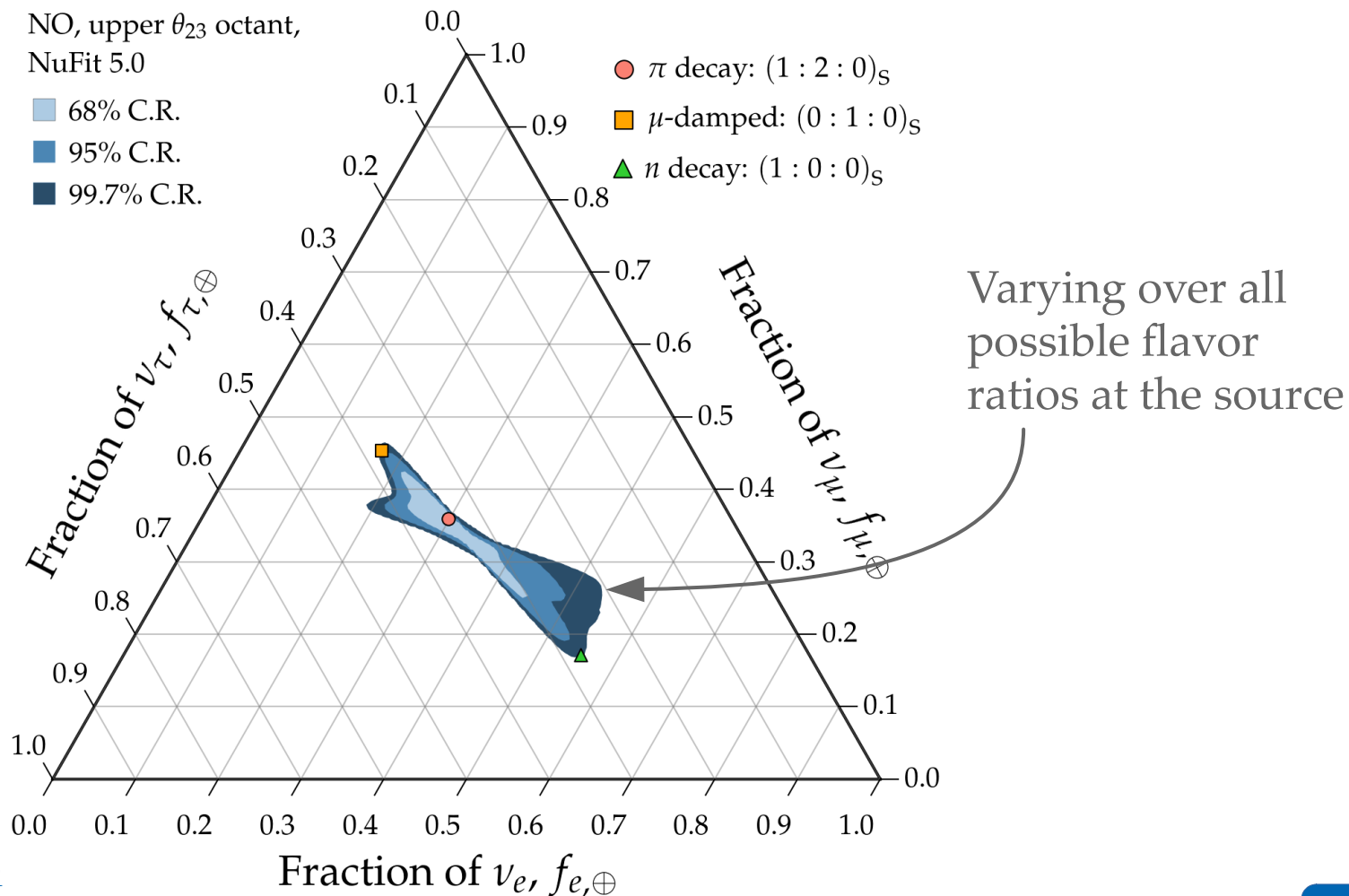
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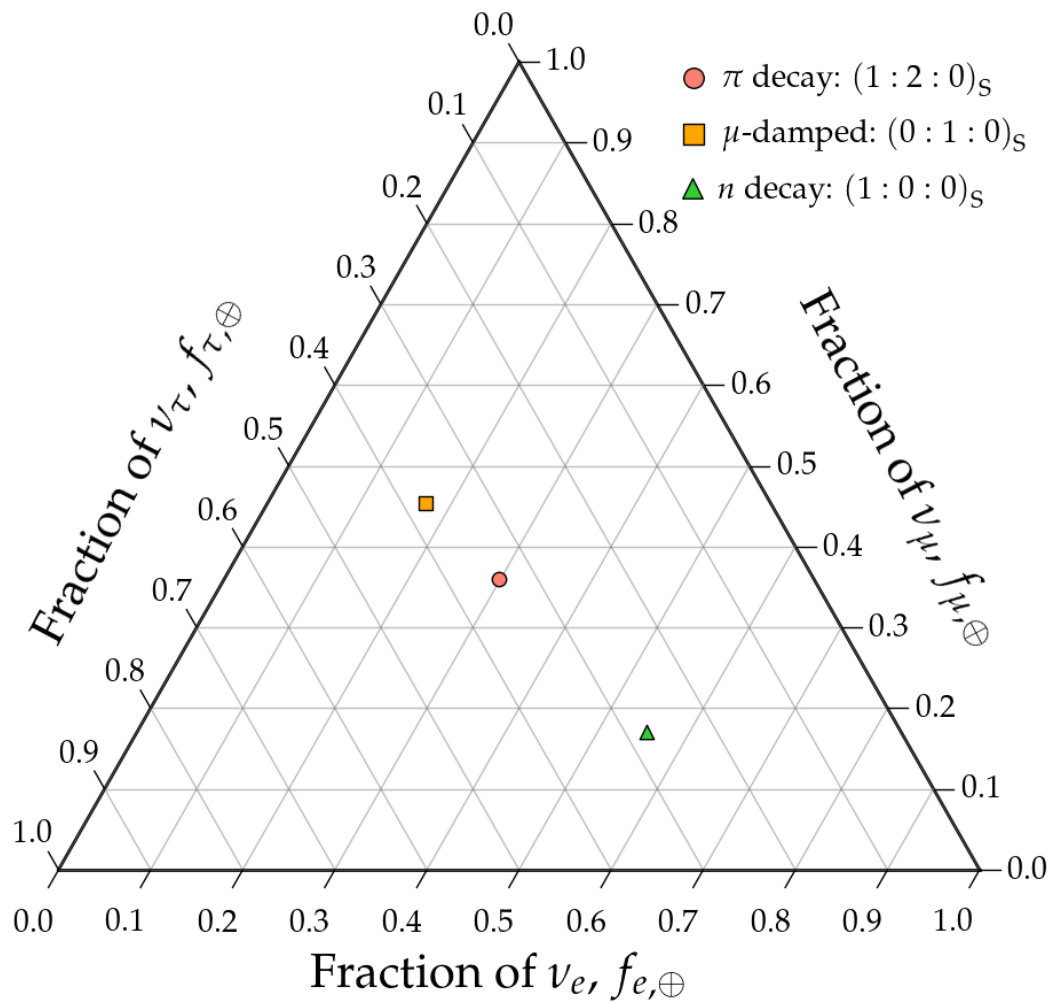
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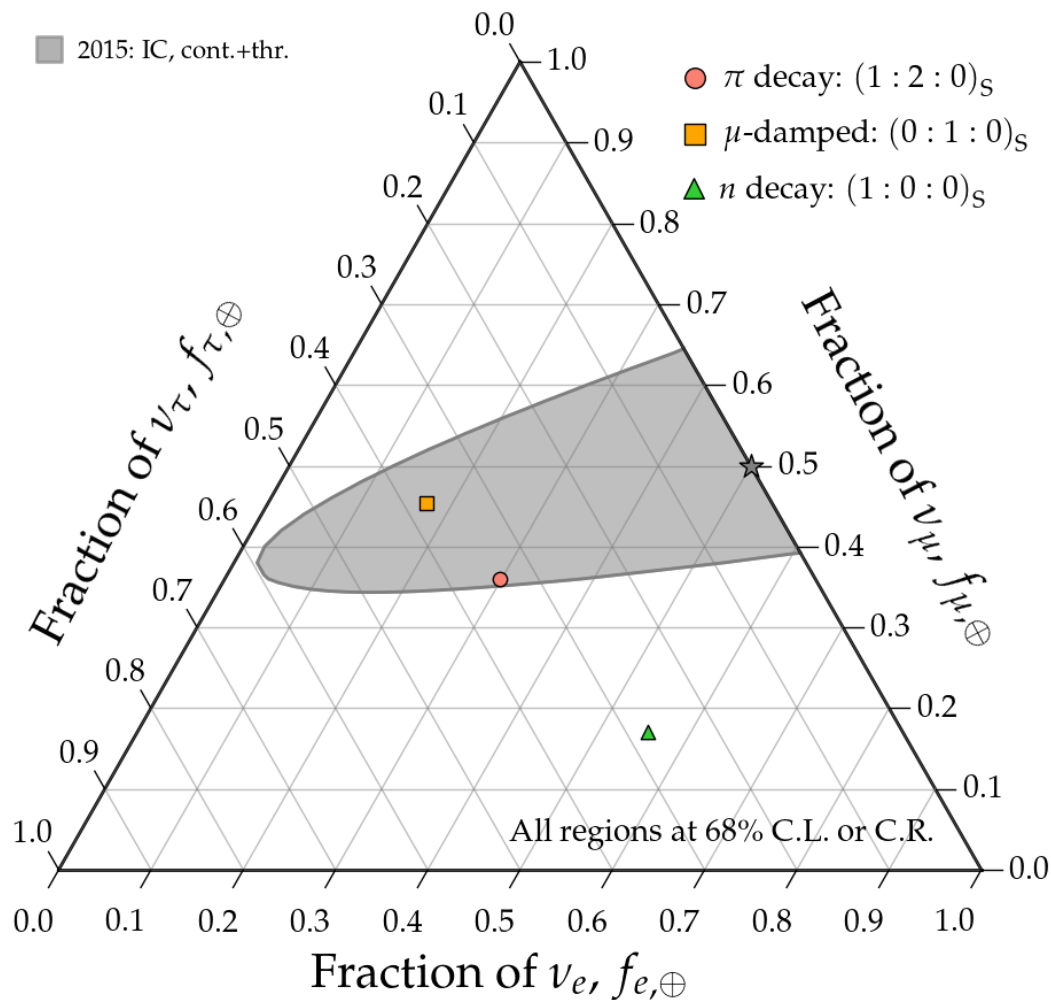
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Measuring flavor composition

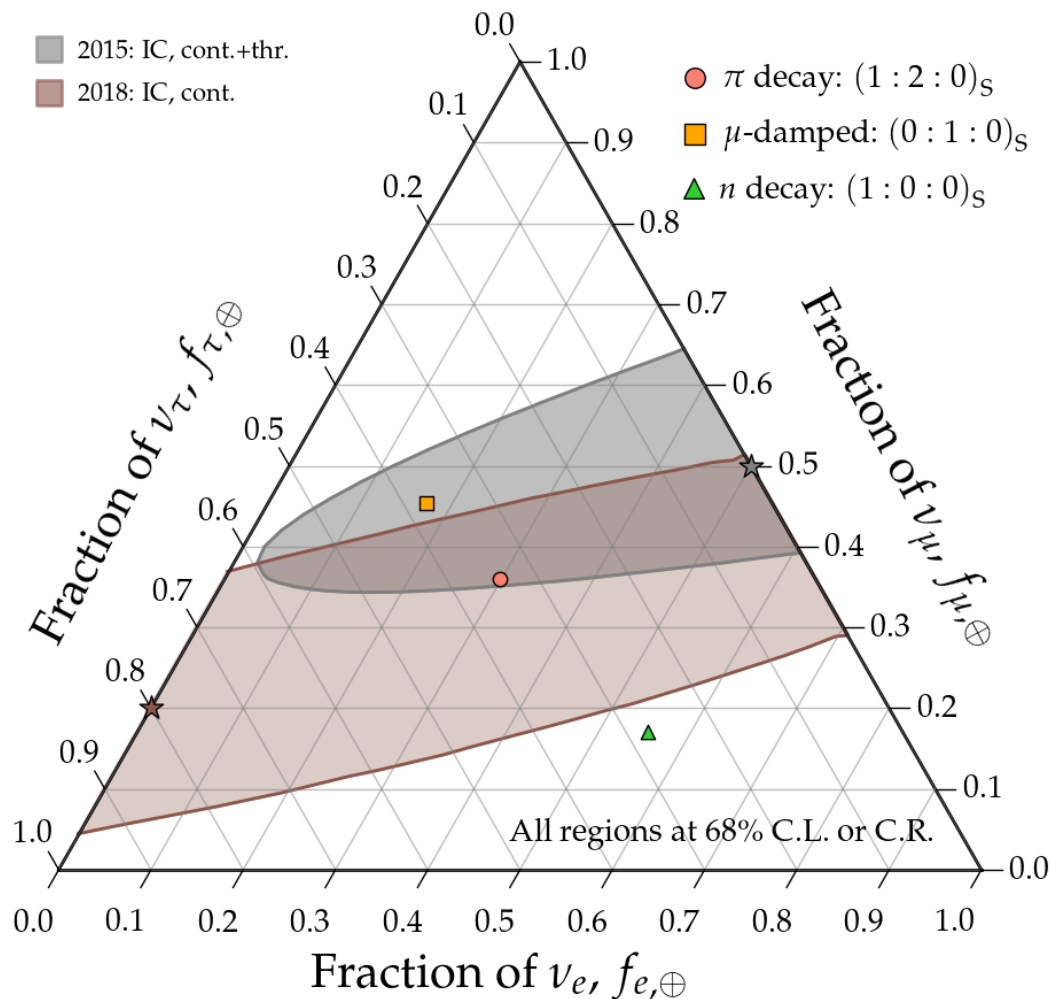
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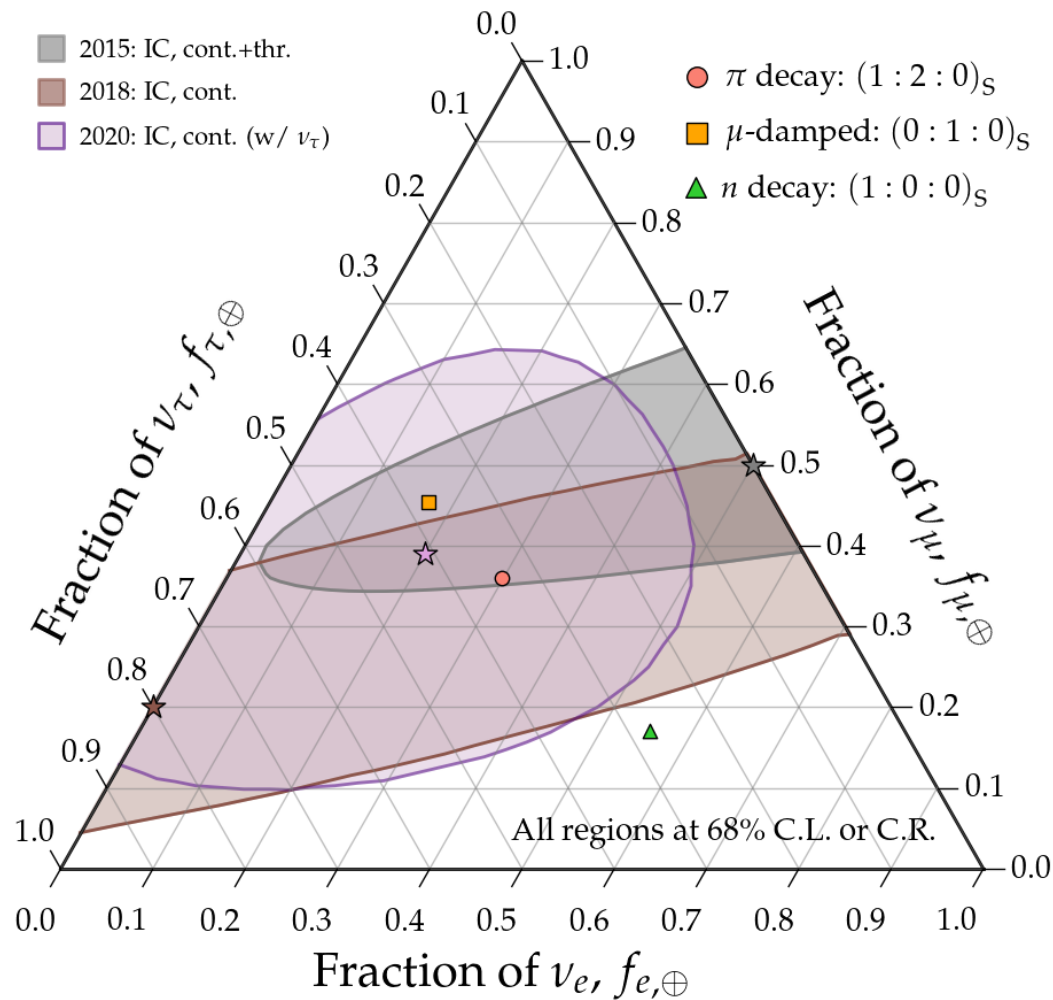
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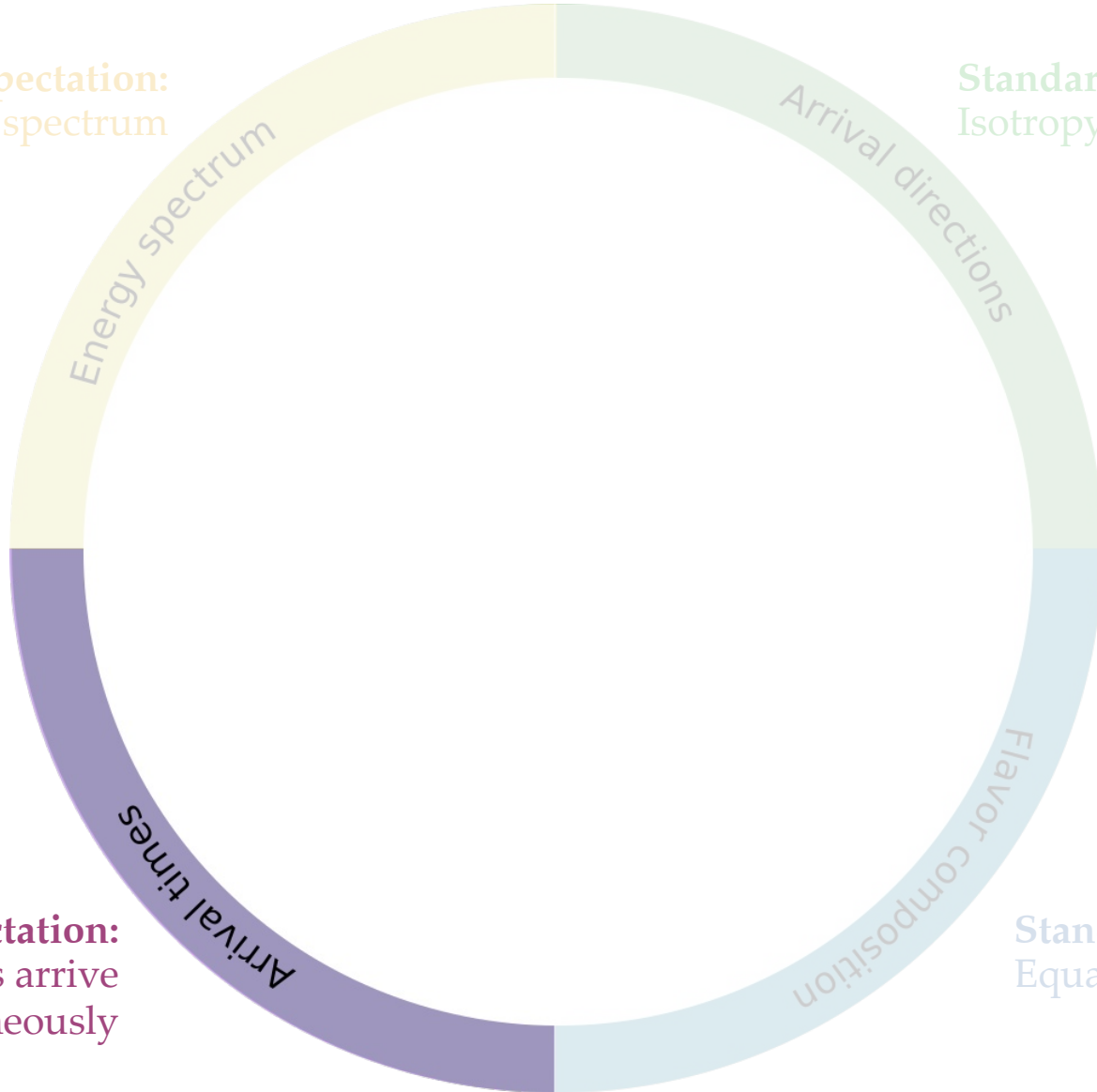


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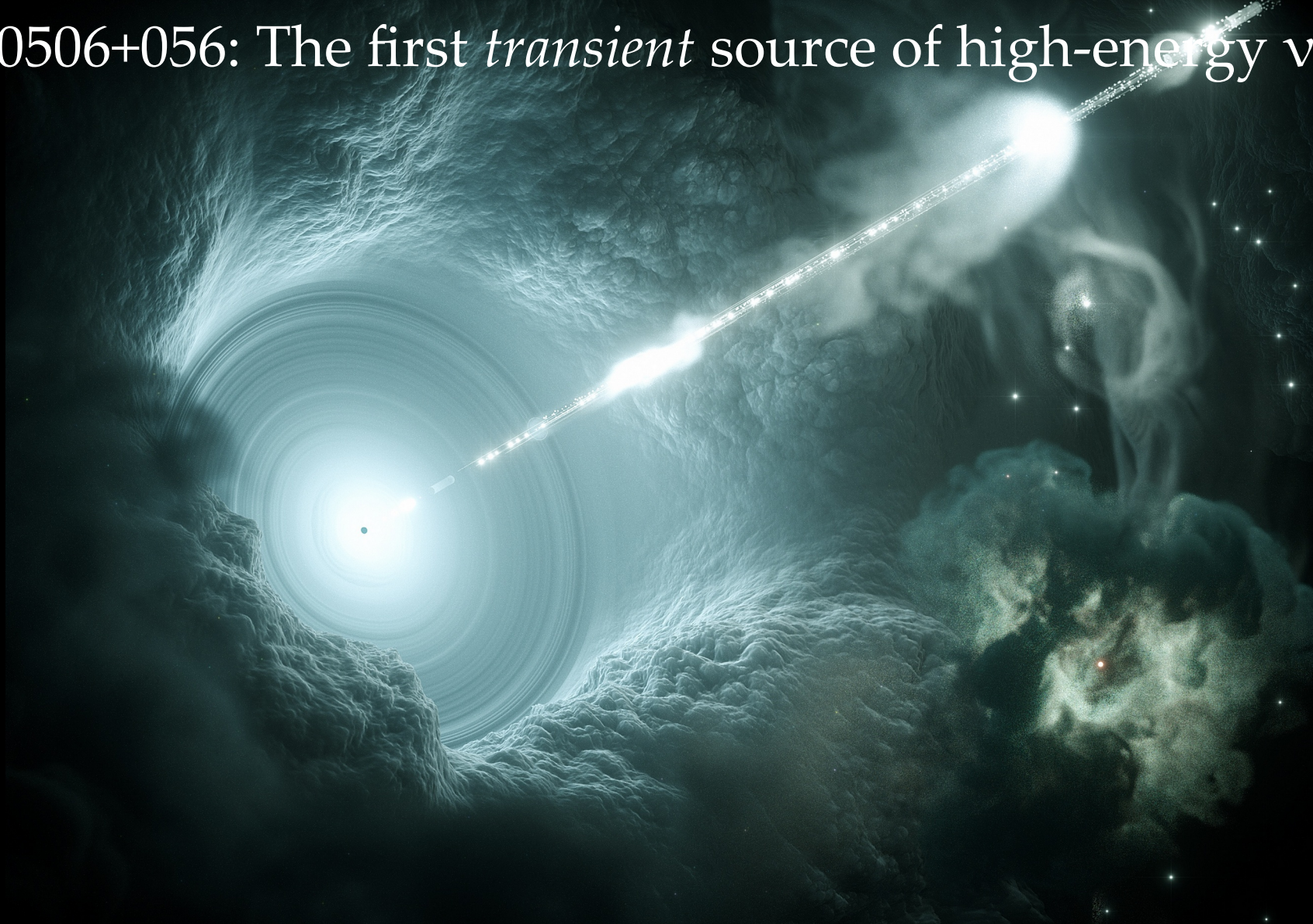
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Standard expectation:
Equal number of ν_e , ν_μ , ν_τ

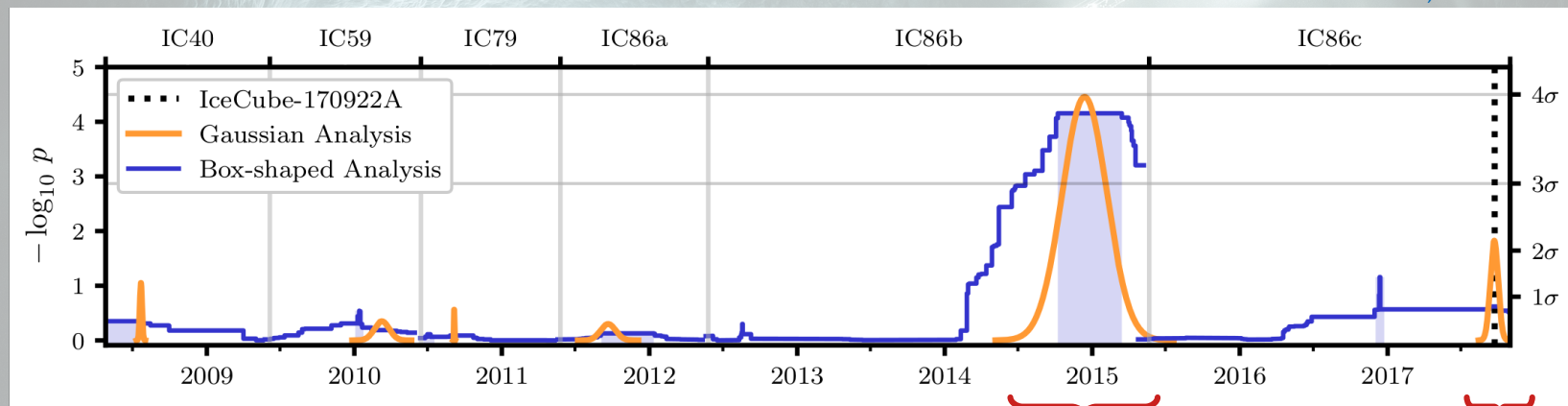
TXS 0506+056: The first *transient* source of high-energy ν



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 $p=7\times 10^{-5}$ to $p=8\times 10^{-3}$

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

Pushing ν physics
to the cosmic frontier

Fundamental physics with high-energy cosmic neutrinos

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

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

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

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

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



Orders-of-magnitude improvement

Fundamental physics with high-energy cosmic neutrinos

Numerous new ν physics effects grow as $\sim \kappa_n \cdot E^n \cdot L$ $\left\{ \begin{array}{l} \text{E.g.,} \\ n = -1: \text{neutrino decay} \\ n = 0: \text{CPT-odd Lorentz violation} \\ n = +1: \text{CPT-even Lorentz violation} \end{array} \right.$

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

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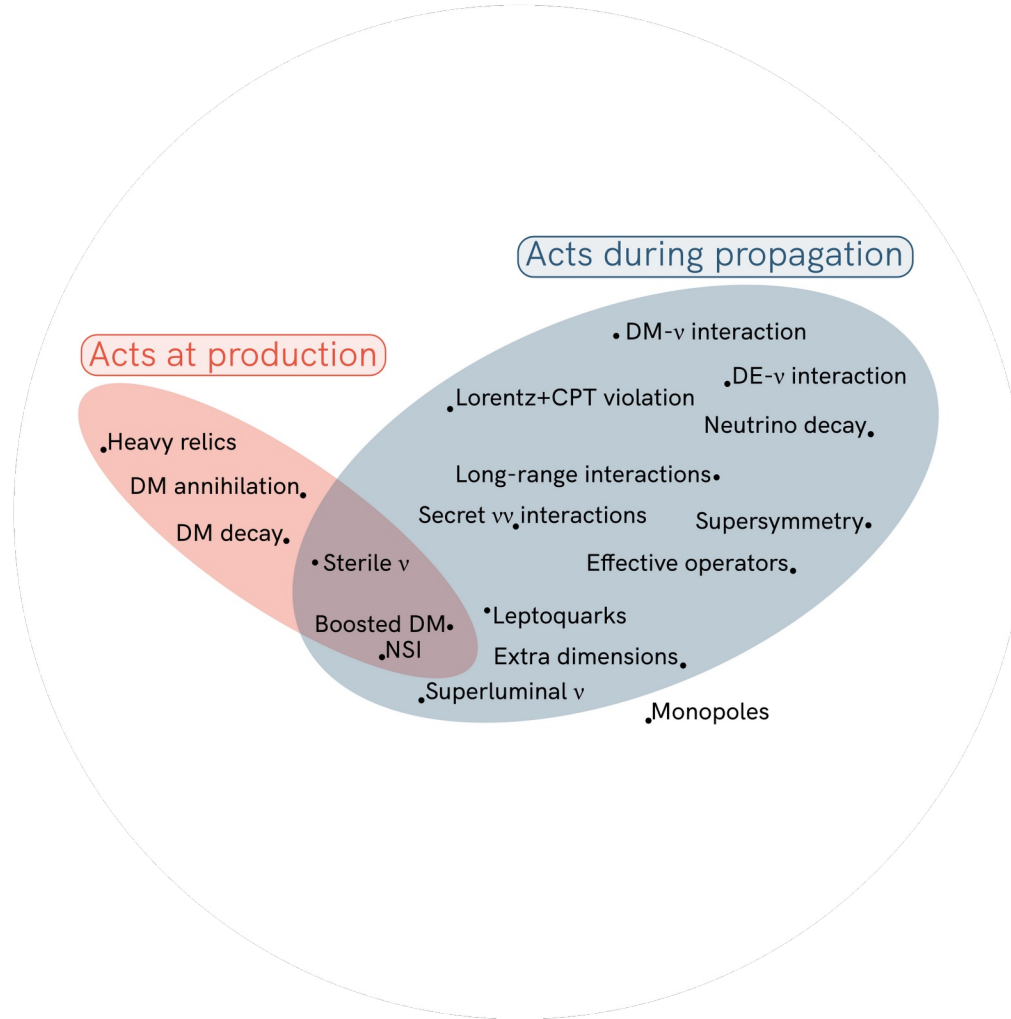
Orders-of-magnitude improvement



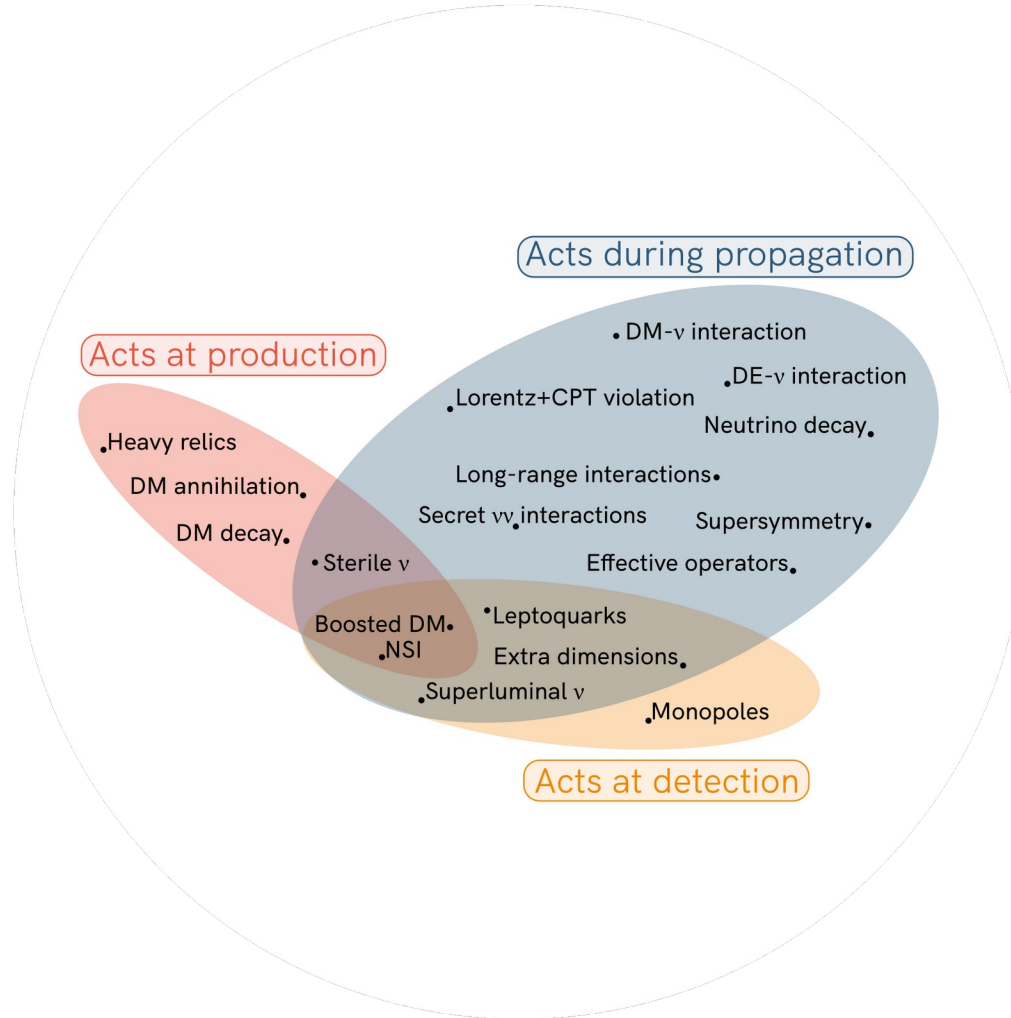
Note: Not an exhaustive list



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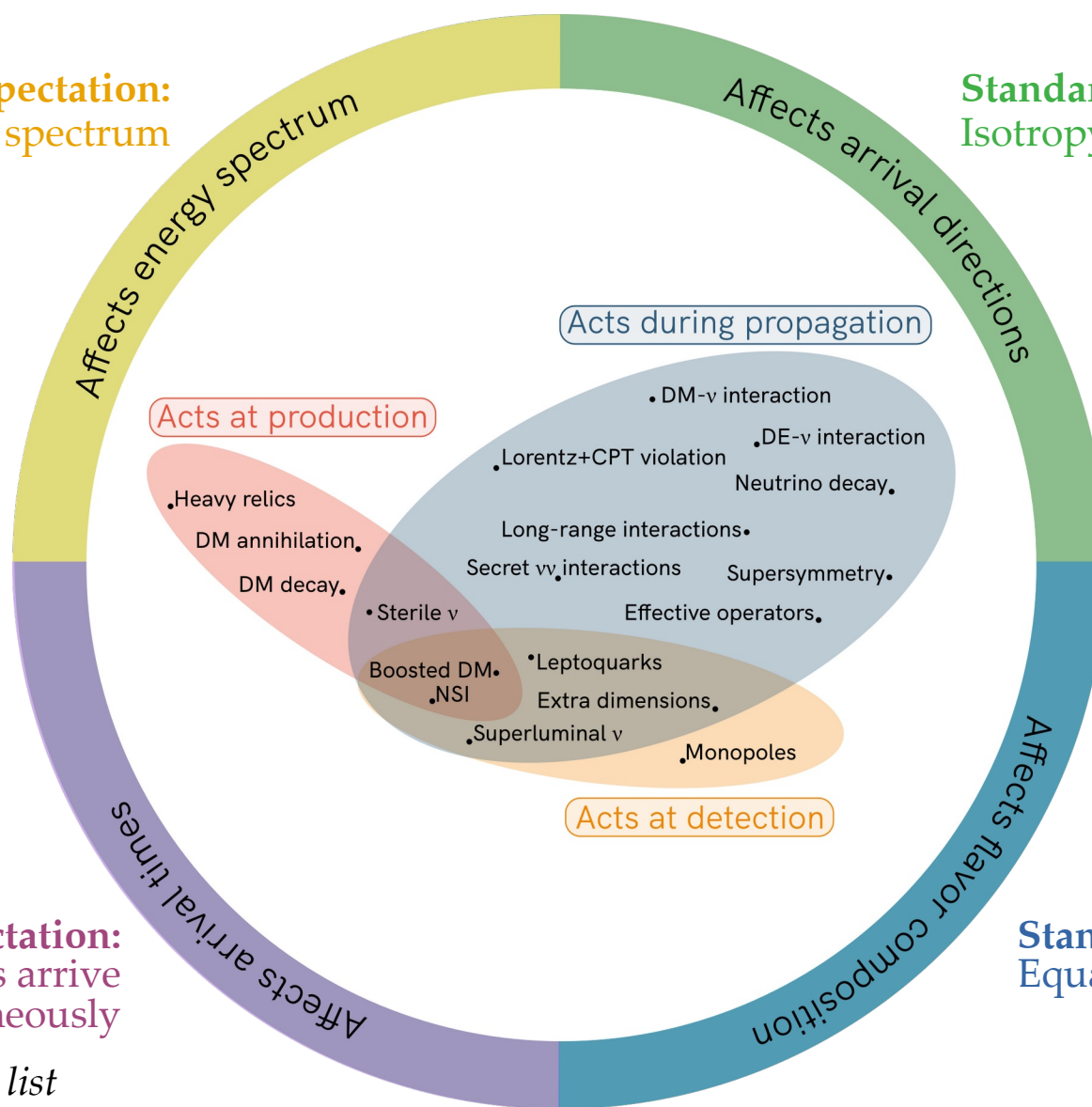
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Standard expectation:
Power-law energy spectrum

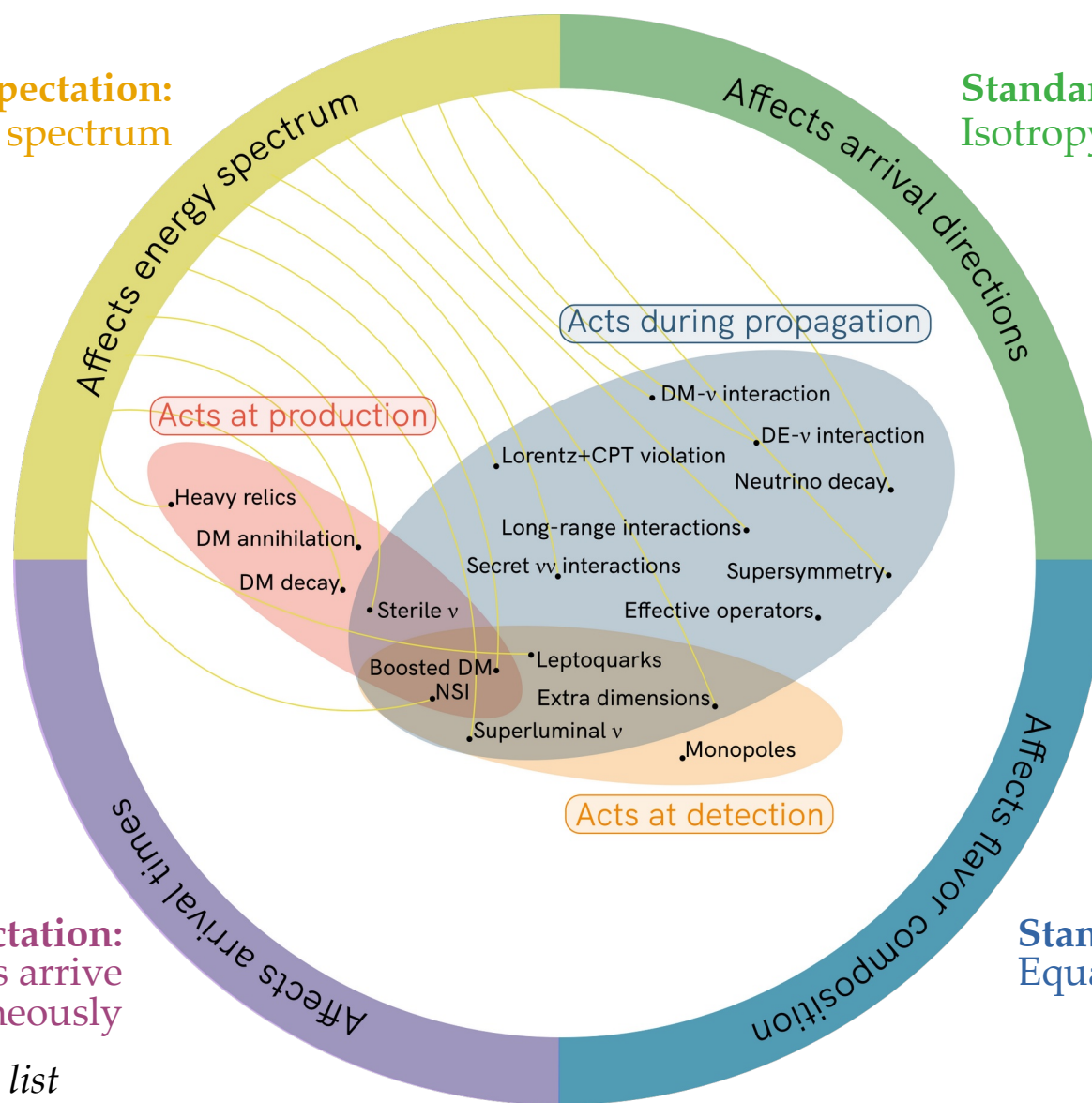
Standard expectation:
Isotropy (for diffuse flux)



Note: Not an exhaustive list

Standard expectation:
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Standard expectation:
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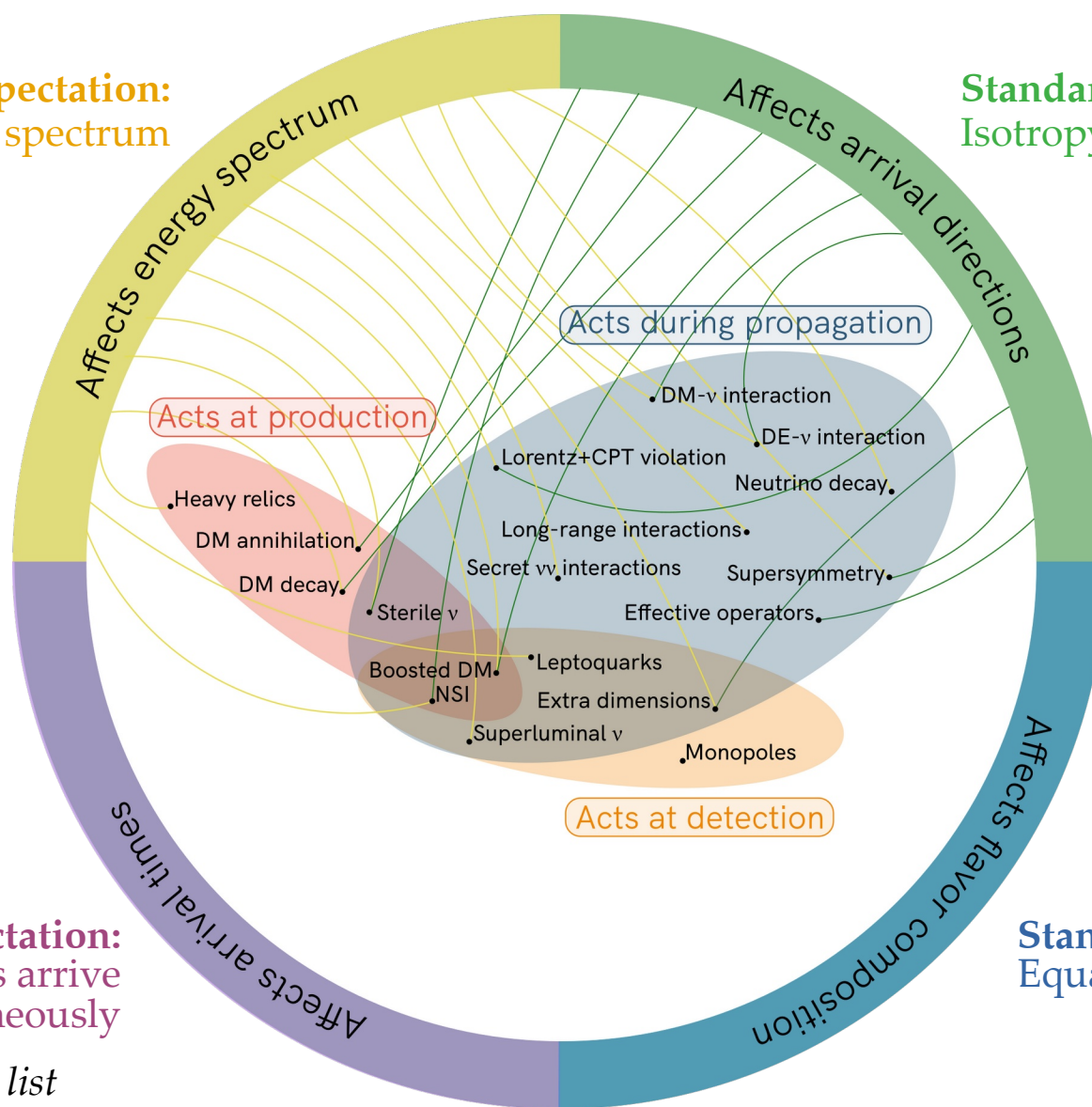
Standard expectation:
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Standard expectation:
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Note: Not an exhaustive list

Standard expectation:
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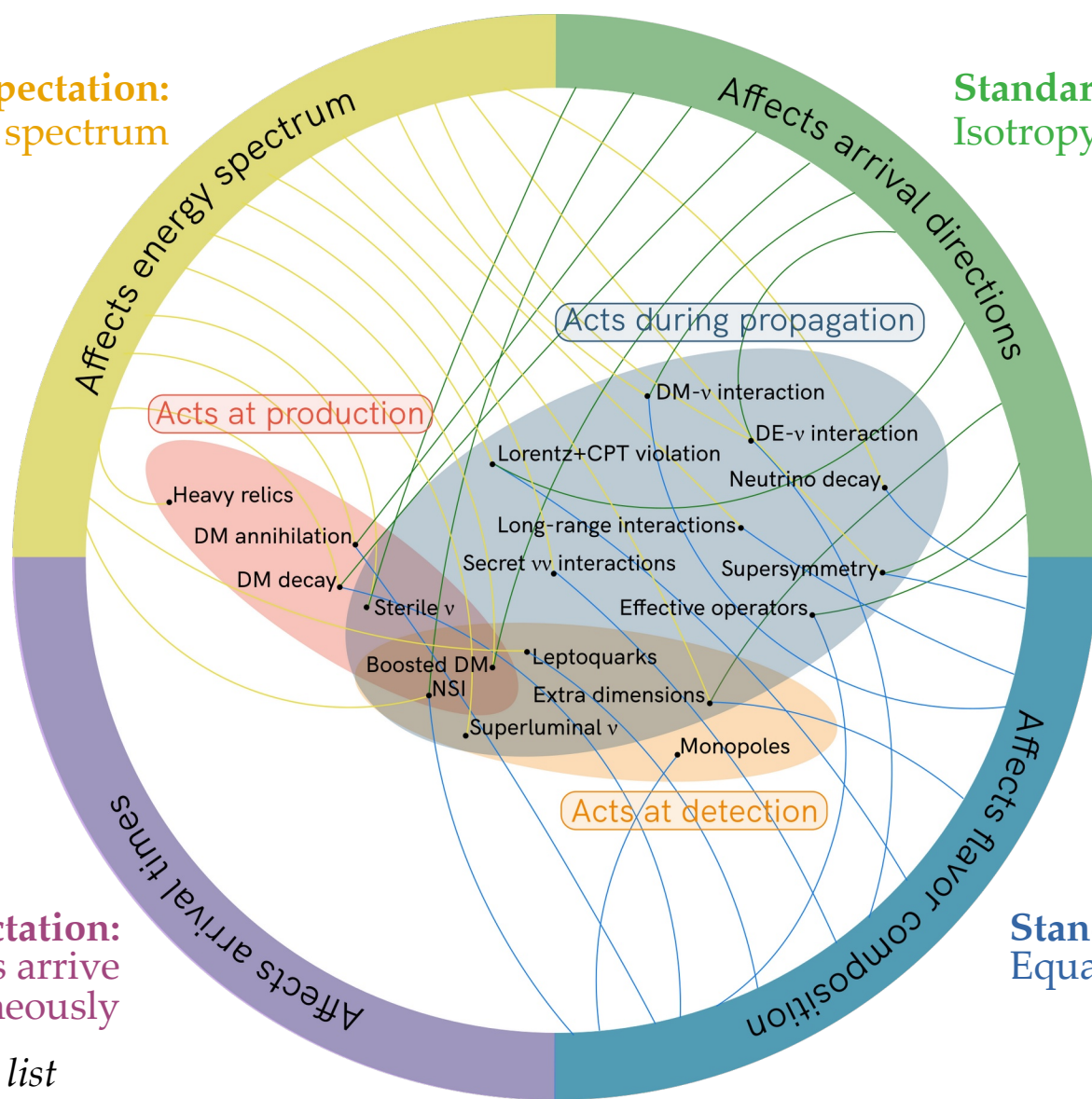
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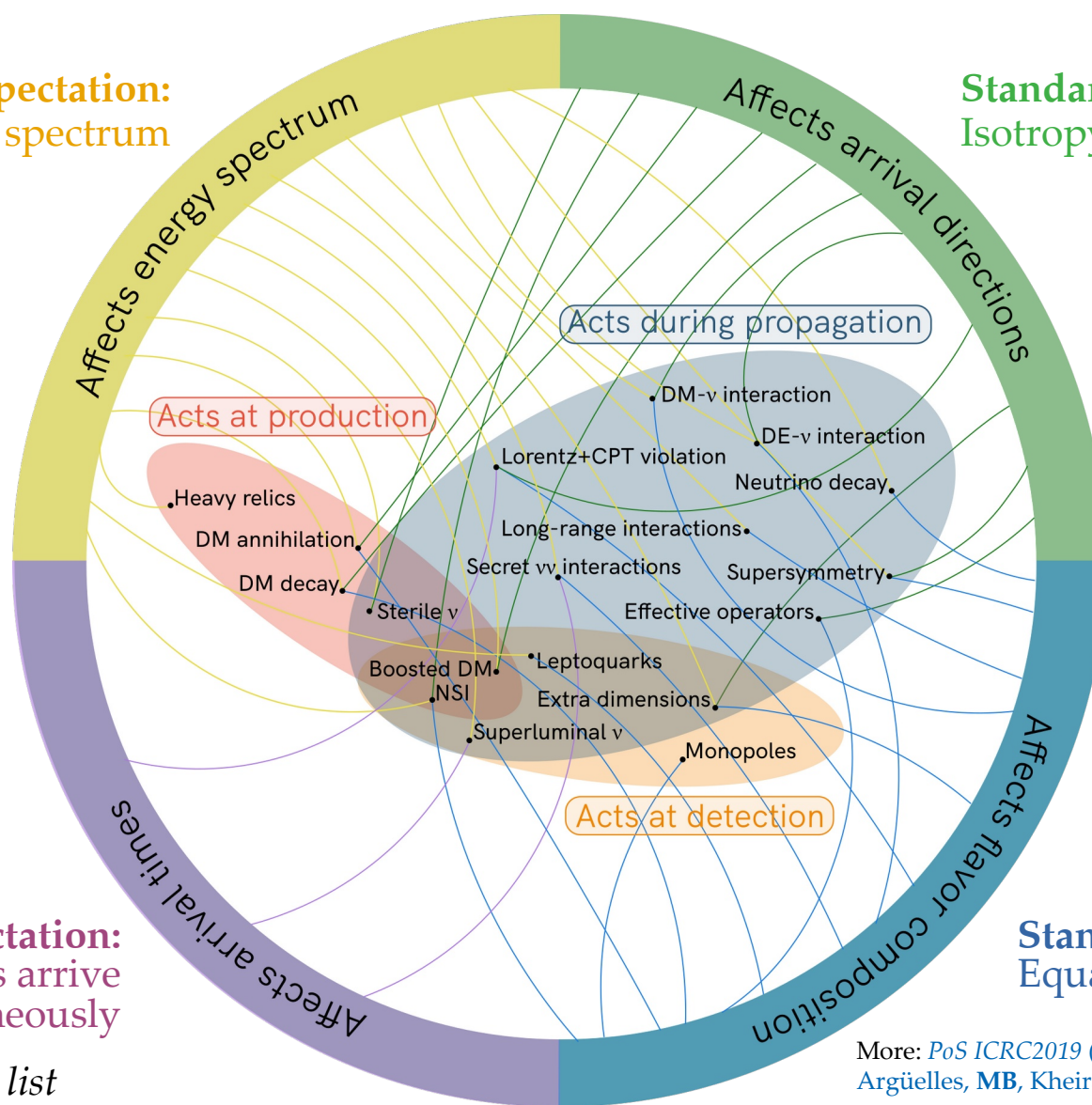
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Power-law energy spectrum

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More: *PoS ICRC2019* (1907.08690)

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

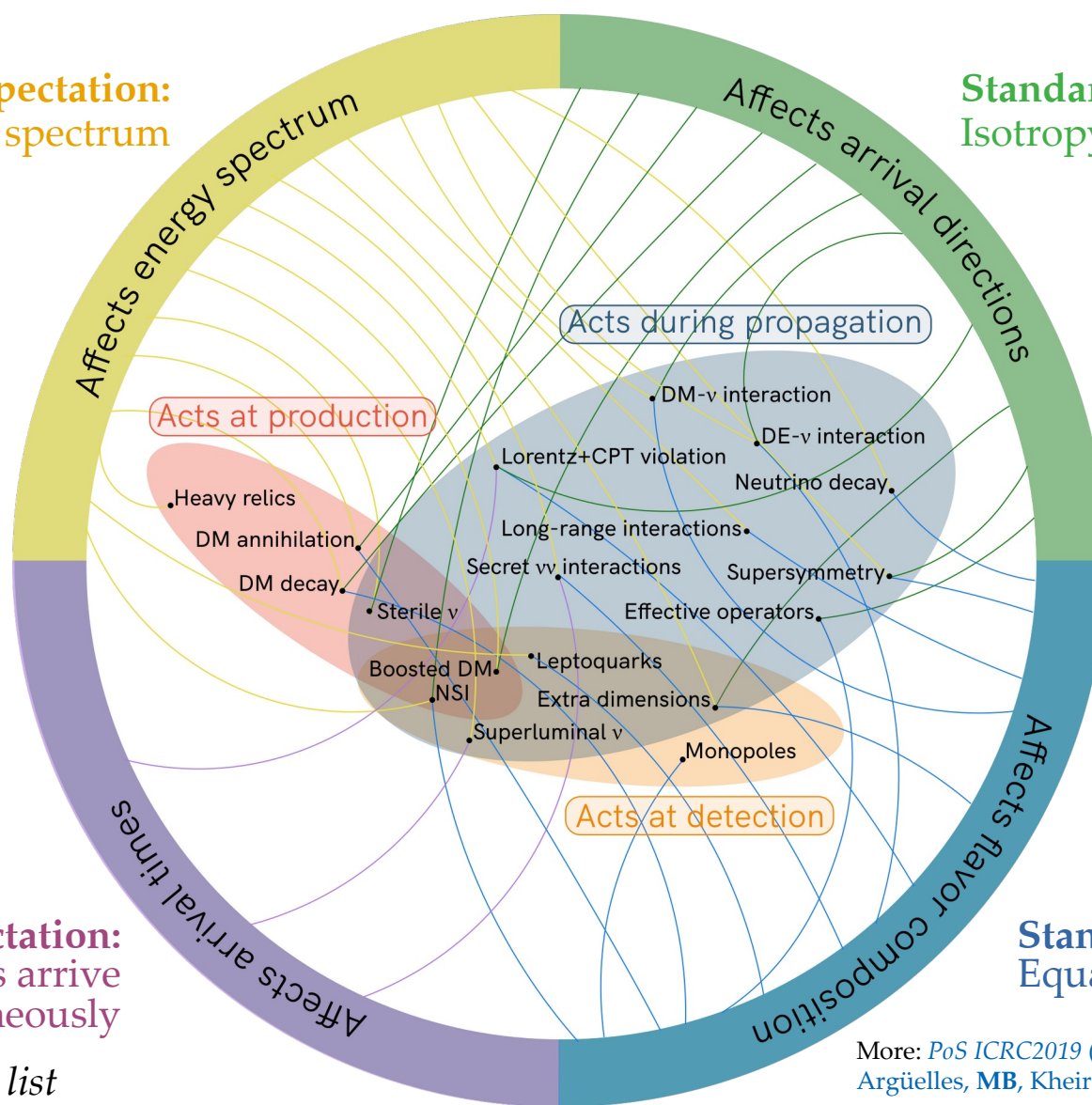
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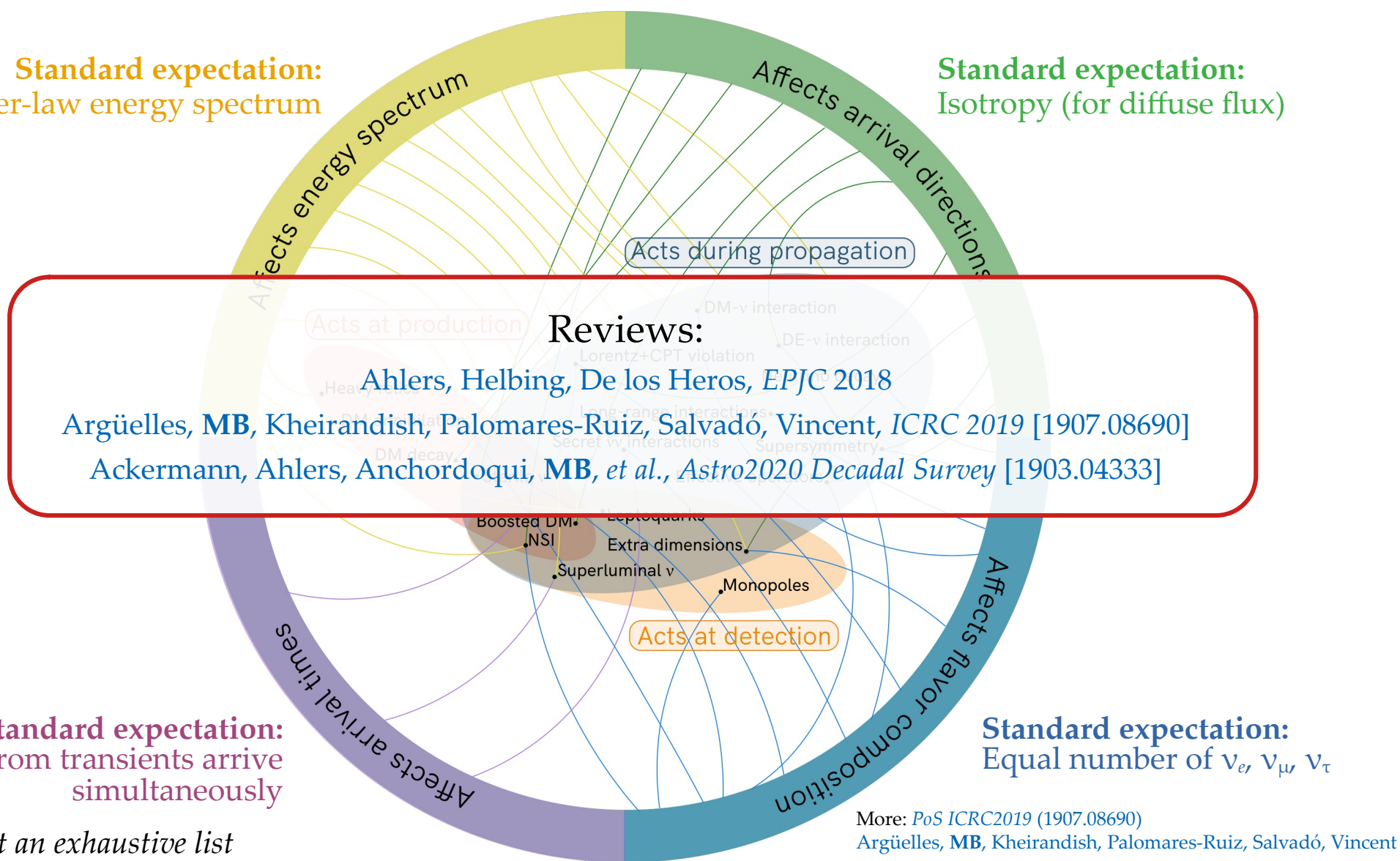
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A warning

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

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

Evidence for BSM

Evidence for BSM

Evidence for SM

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

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If $B \ll 1$: SM is favored

If $B \gg 1$: BSM is favored

If $B \sim 1$: No preference

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

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

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

Account for **particle-physics** + **astrophysical** + **detector** uncertainties

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

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

Account for **particle-physics** + **astrophysical** + **detector** uncertainties

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

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Account for **particle-physics** + **astrophysical** + **detector** uncertainties

A selection of neutrino physics

- 1 Discovering the Glashow resonance
- 2 Neutrino-matter cross section
- 3 Secret neutrino interactions
- 4 New physics via flavor

More in backup slides (ν decay, flavor anisotropy, *etc.*)

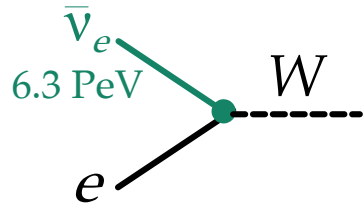
Discovering the Glashow resonance

First observation of a Glashow resonance

Predicted in 1960:

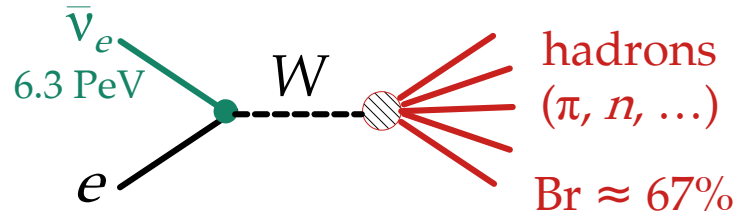
First observation of a Glashow resonance

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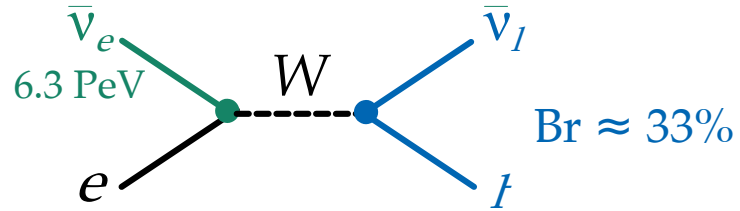
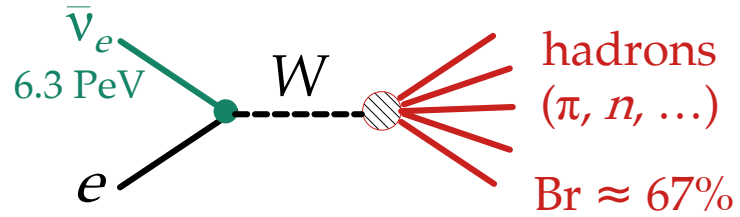
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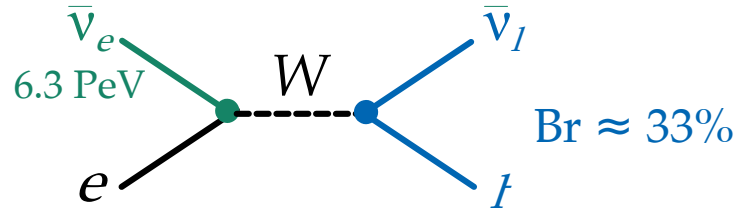
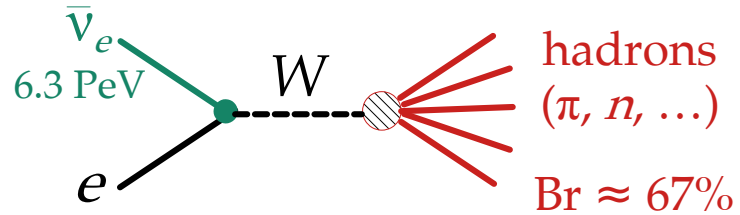
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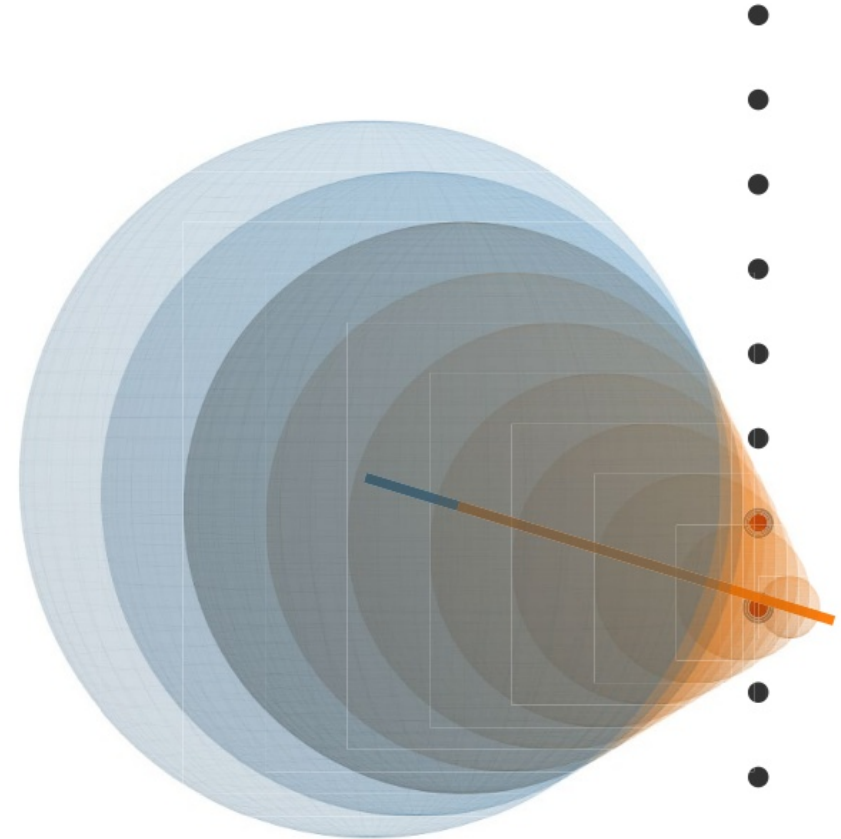


First observation of a Glashow resonance

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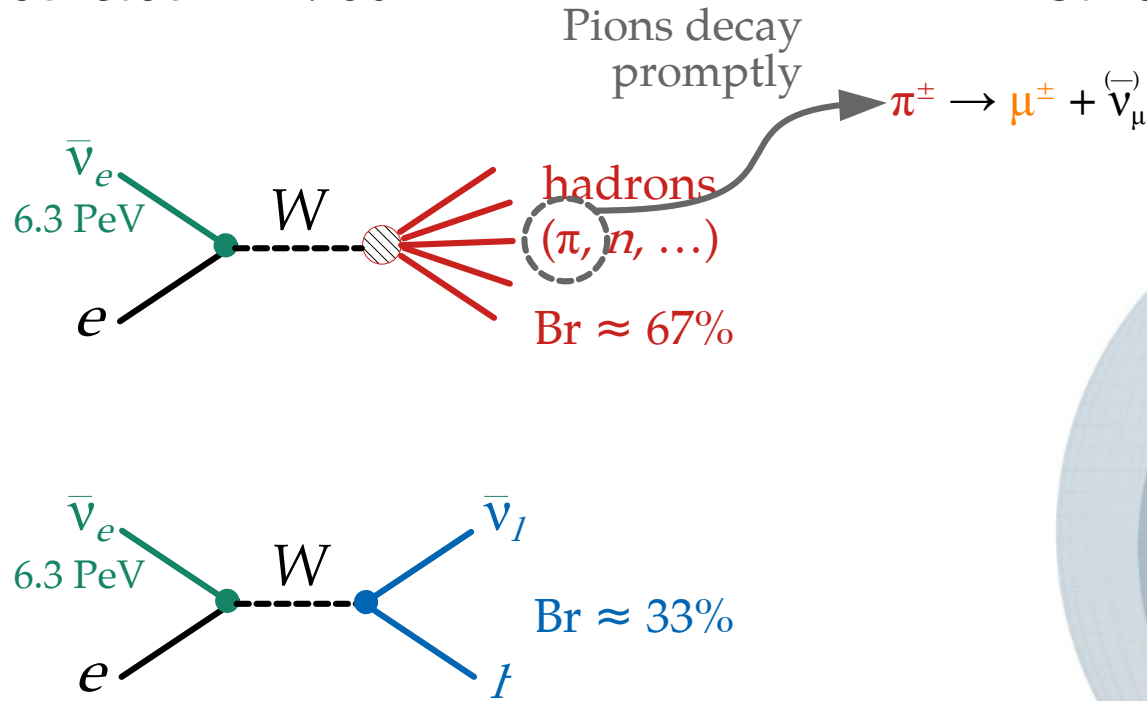


First reported by IceCube in 2021:

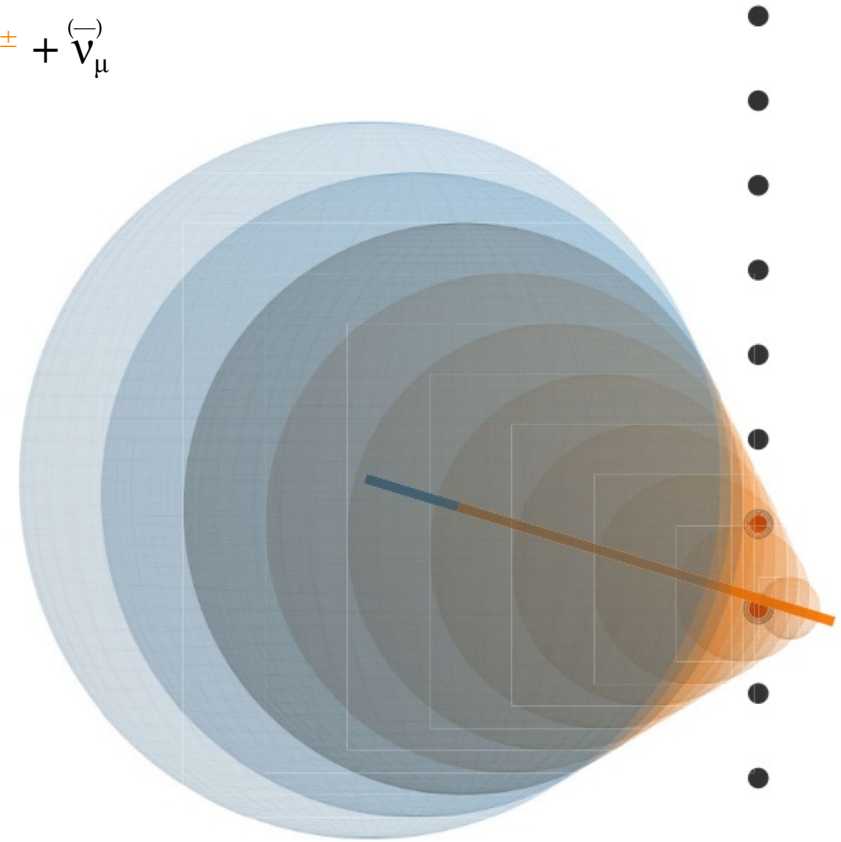


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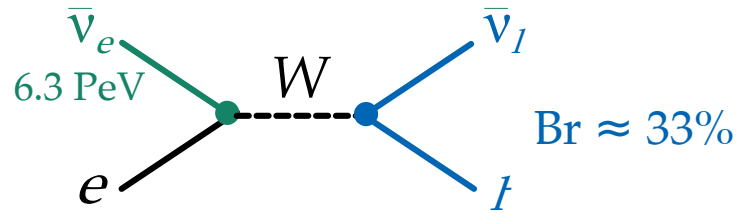
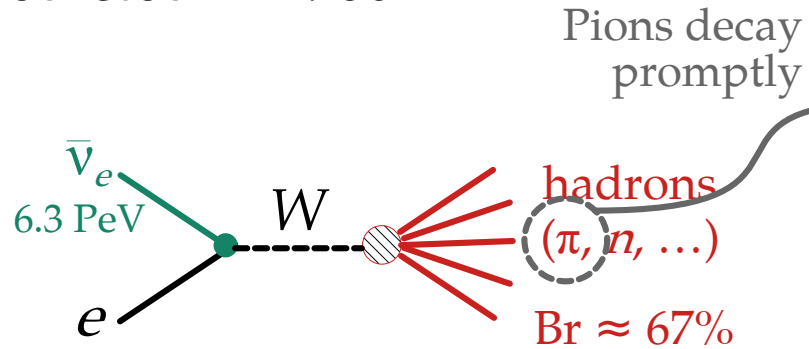


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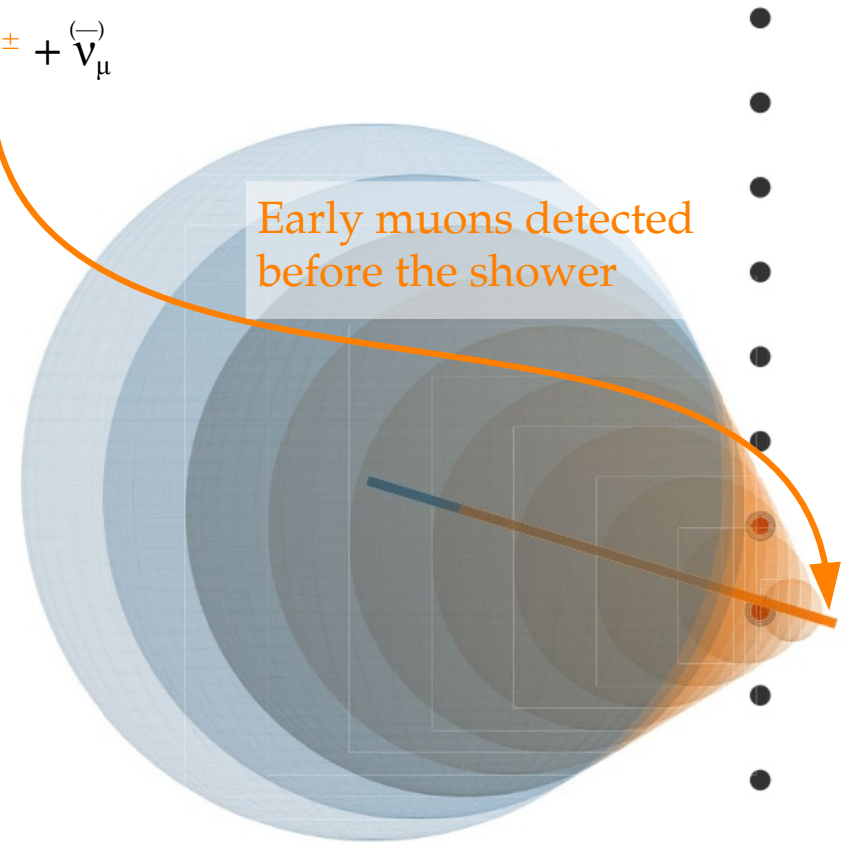


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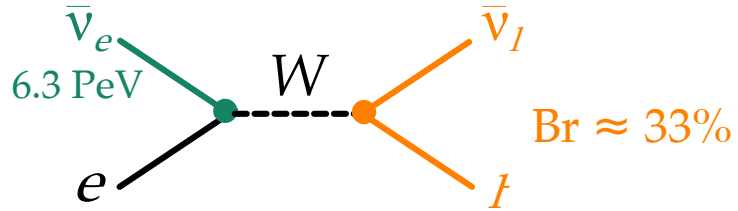
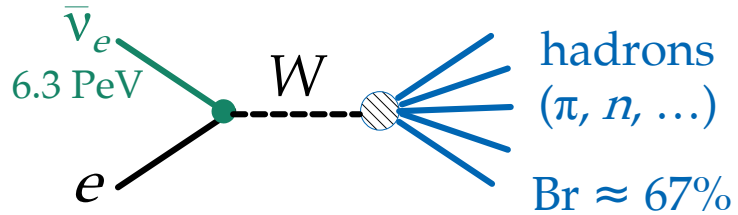


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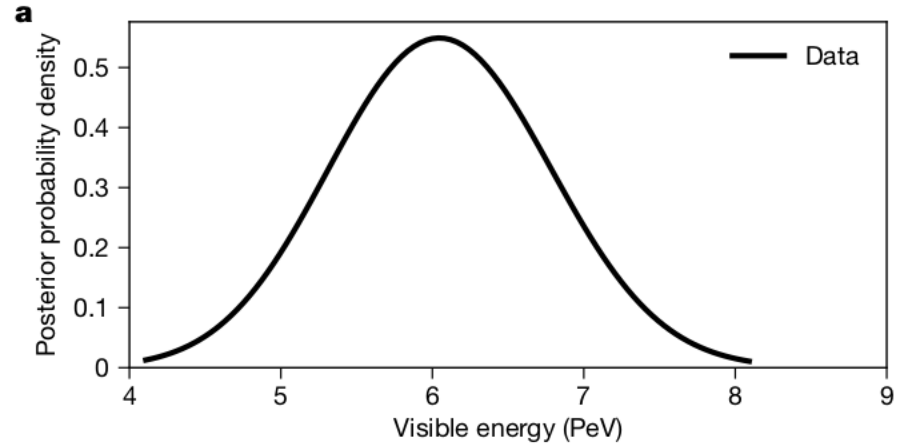


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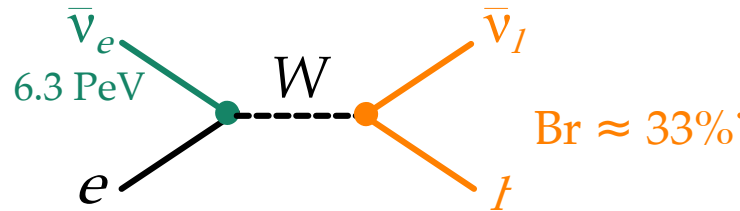
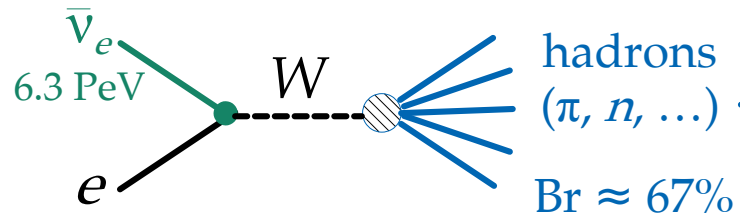


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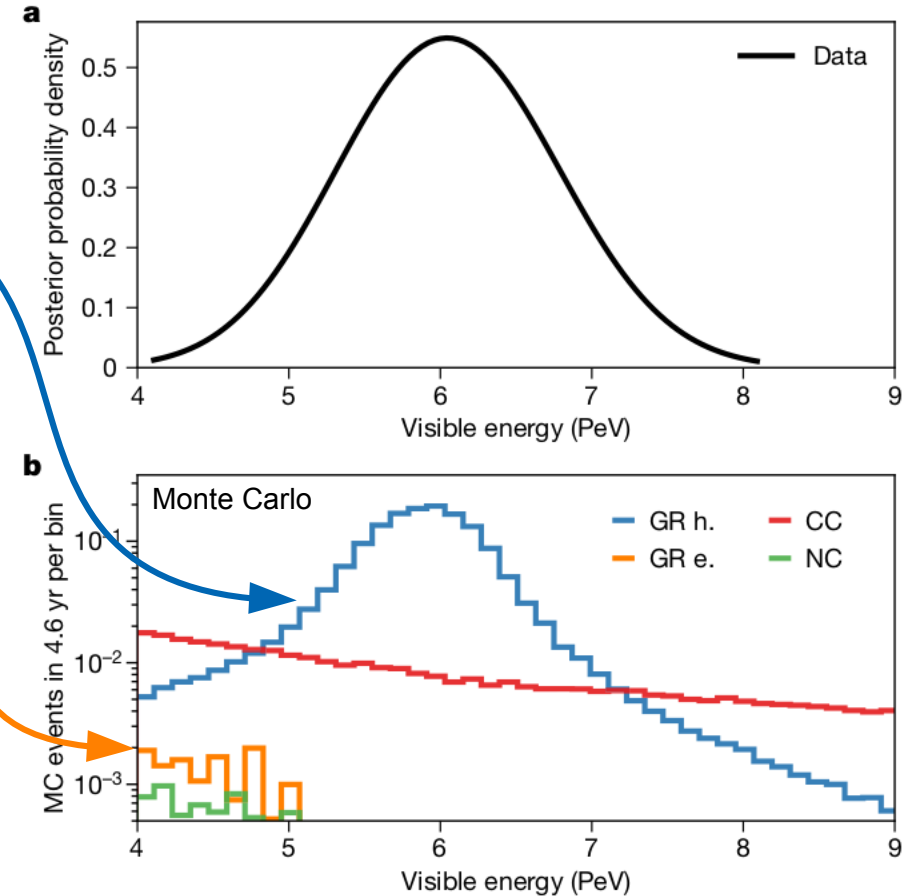


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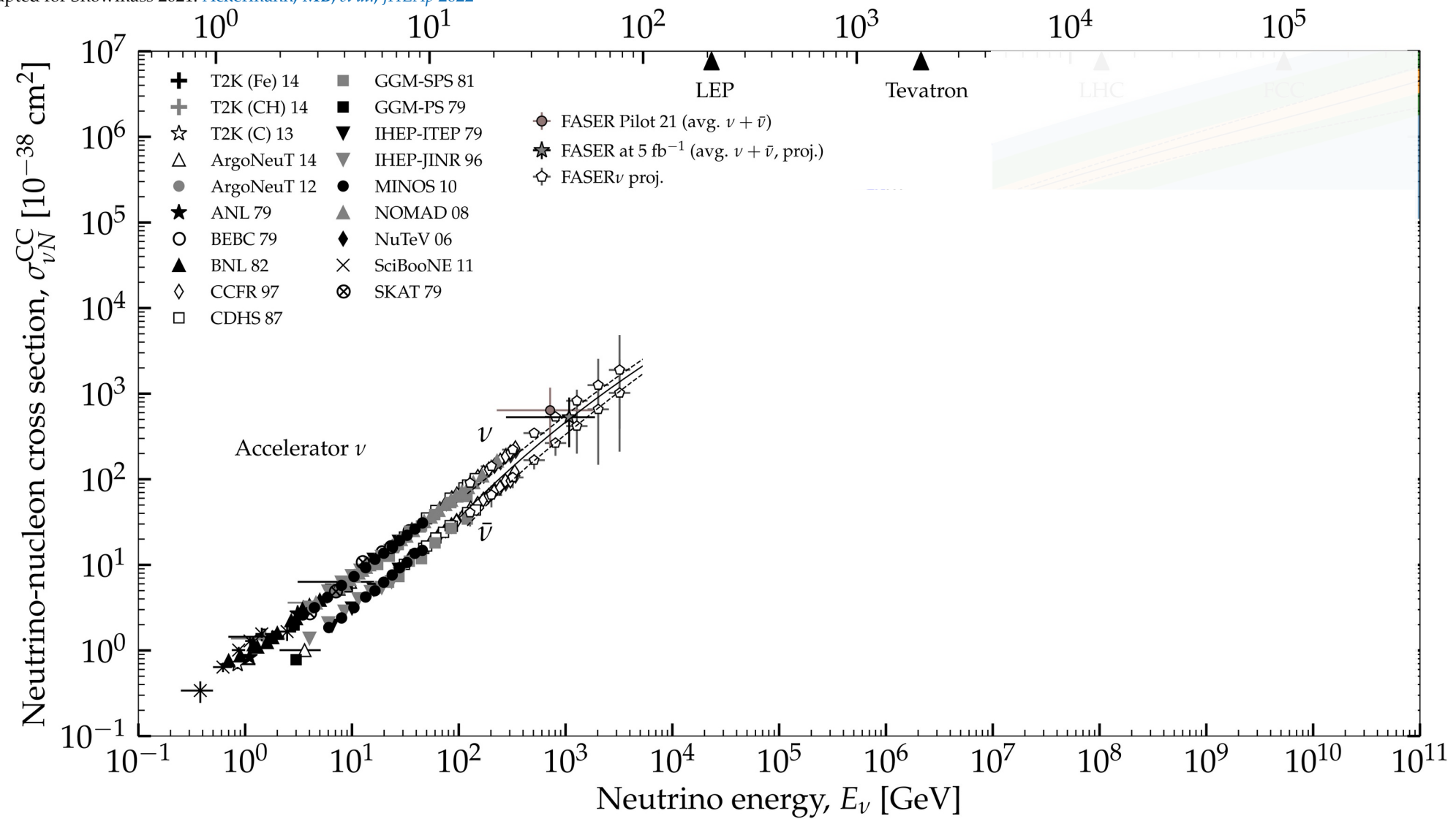


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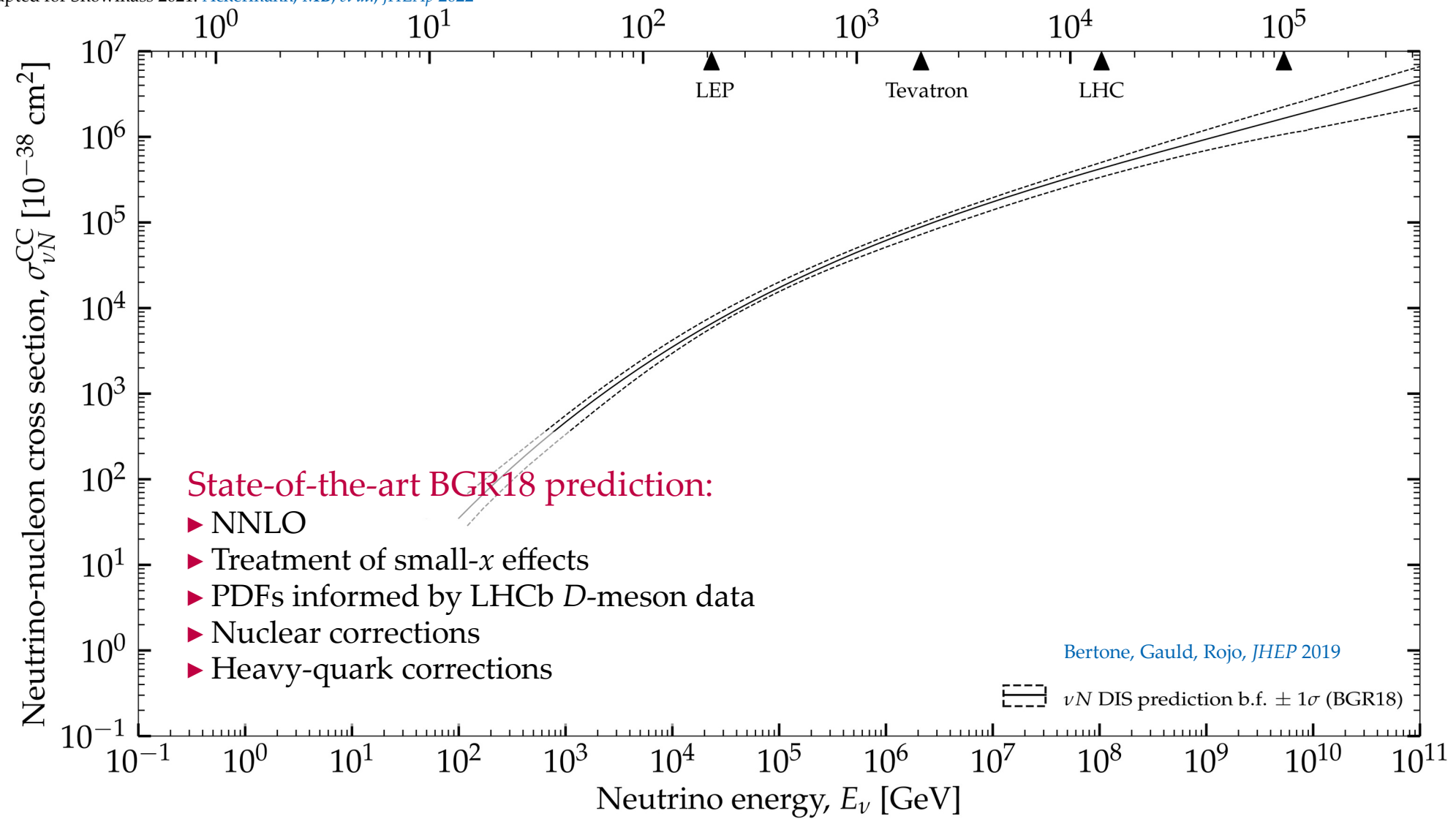


Neutrino-nucleon cross sections

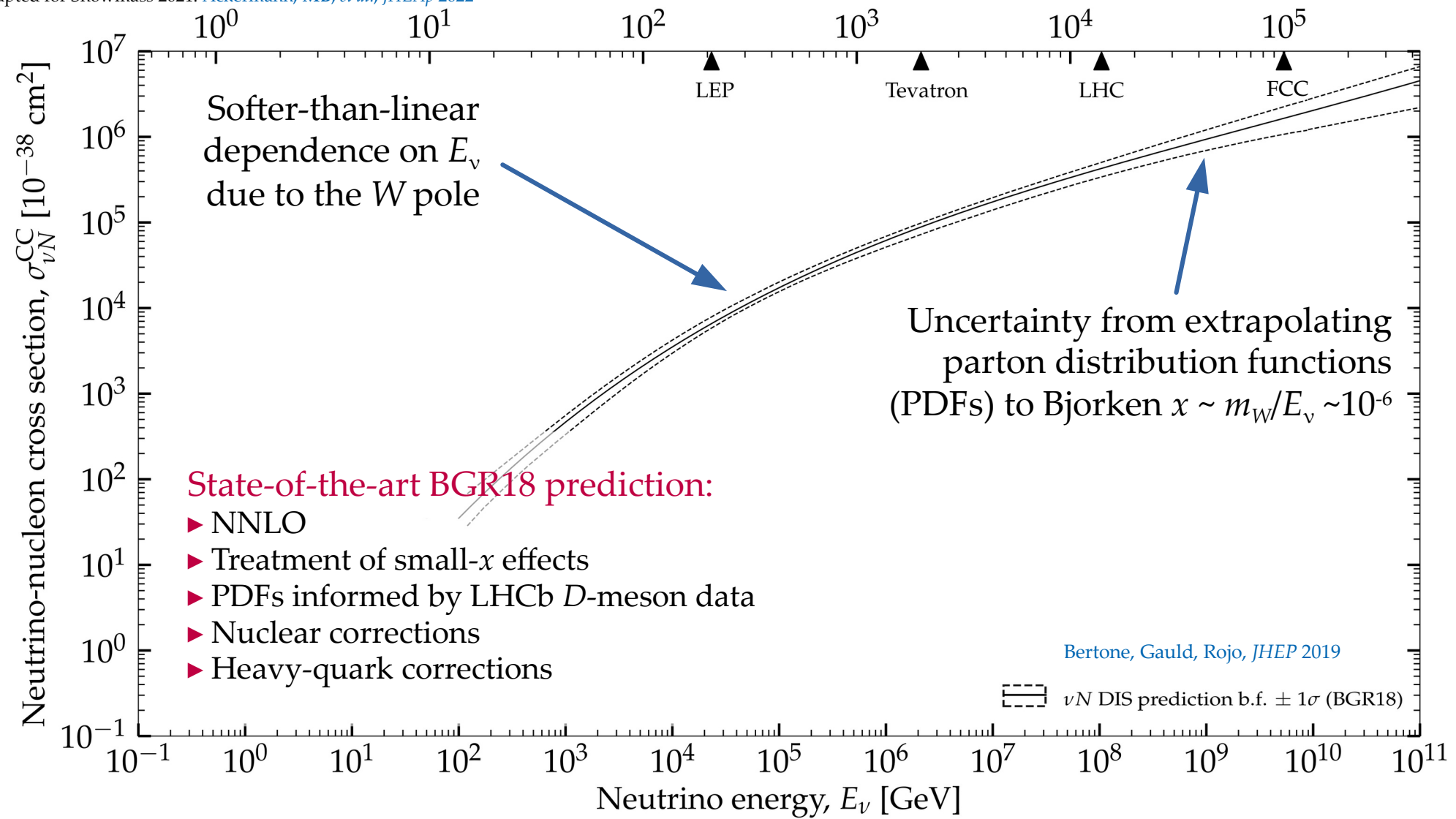
Center-of-mass energy $\sqrt{s}$ [GeV]

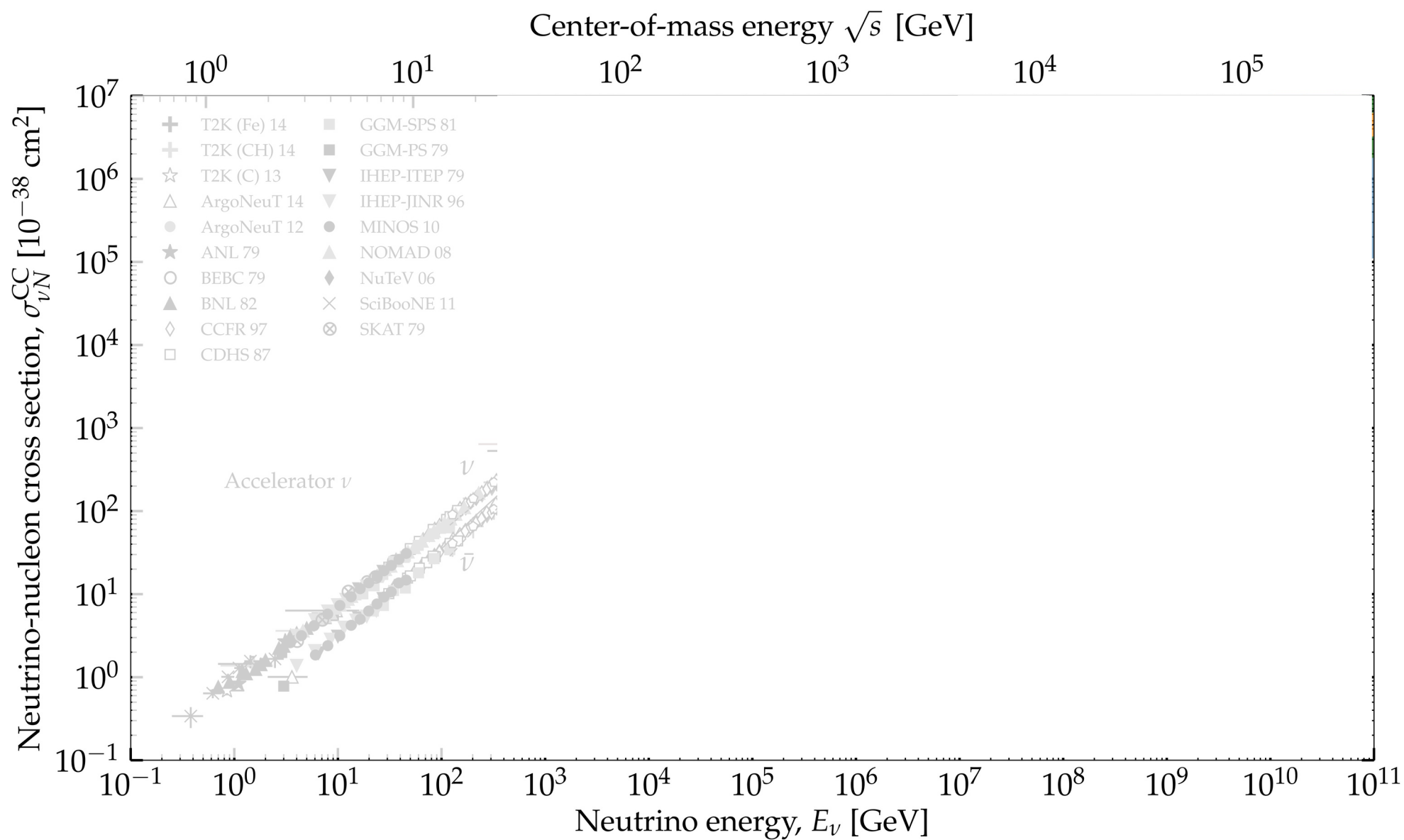


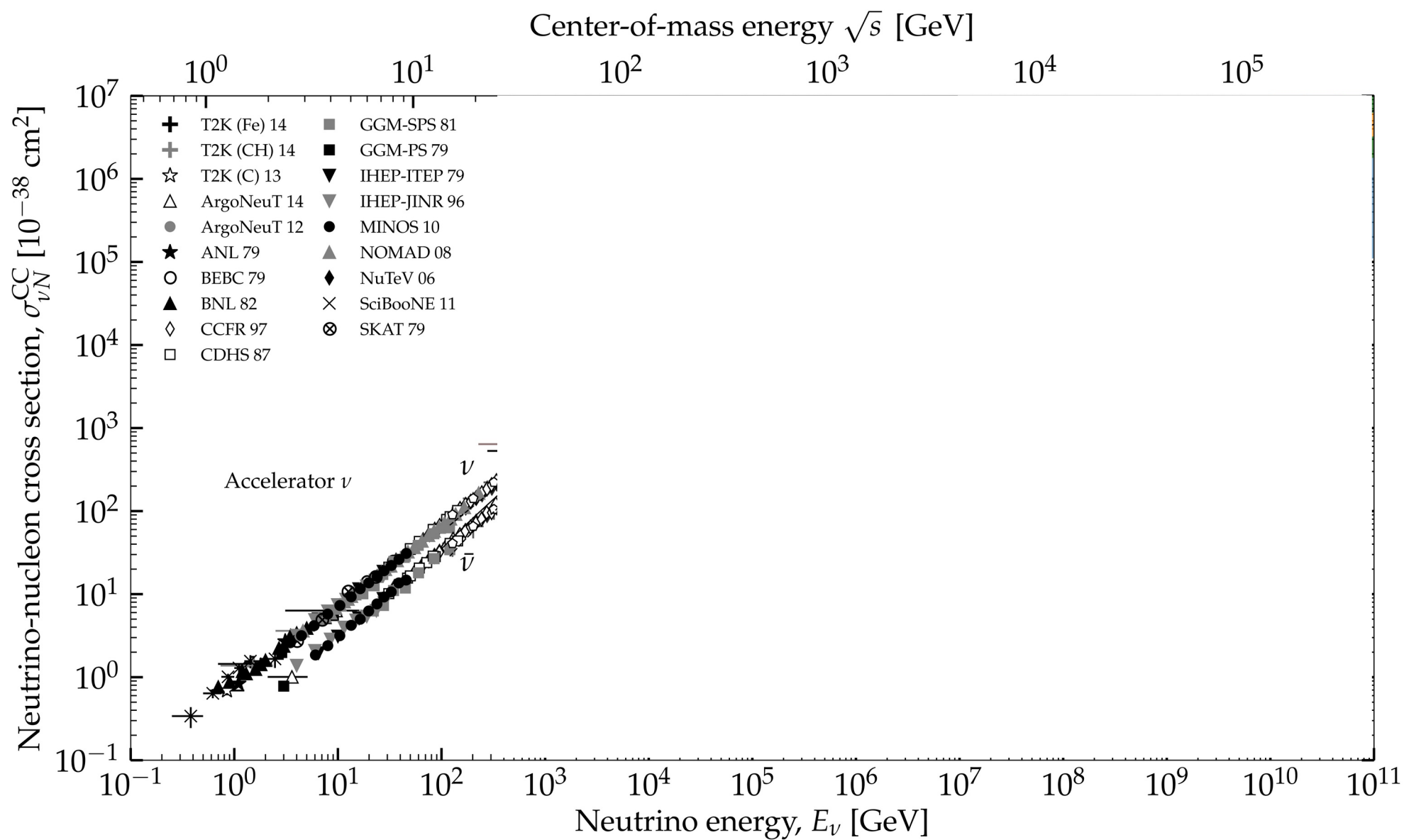
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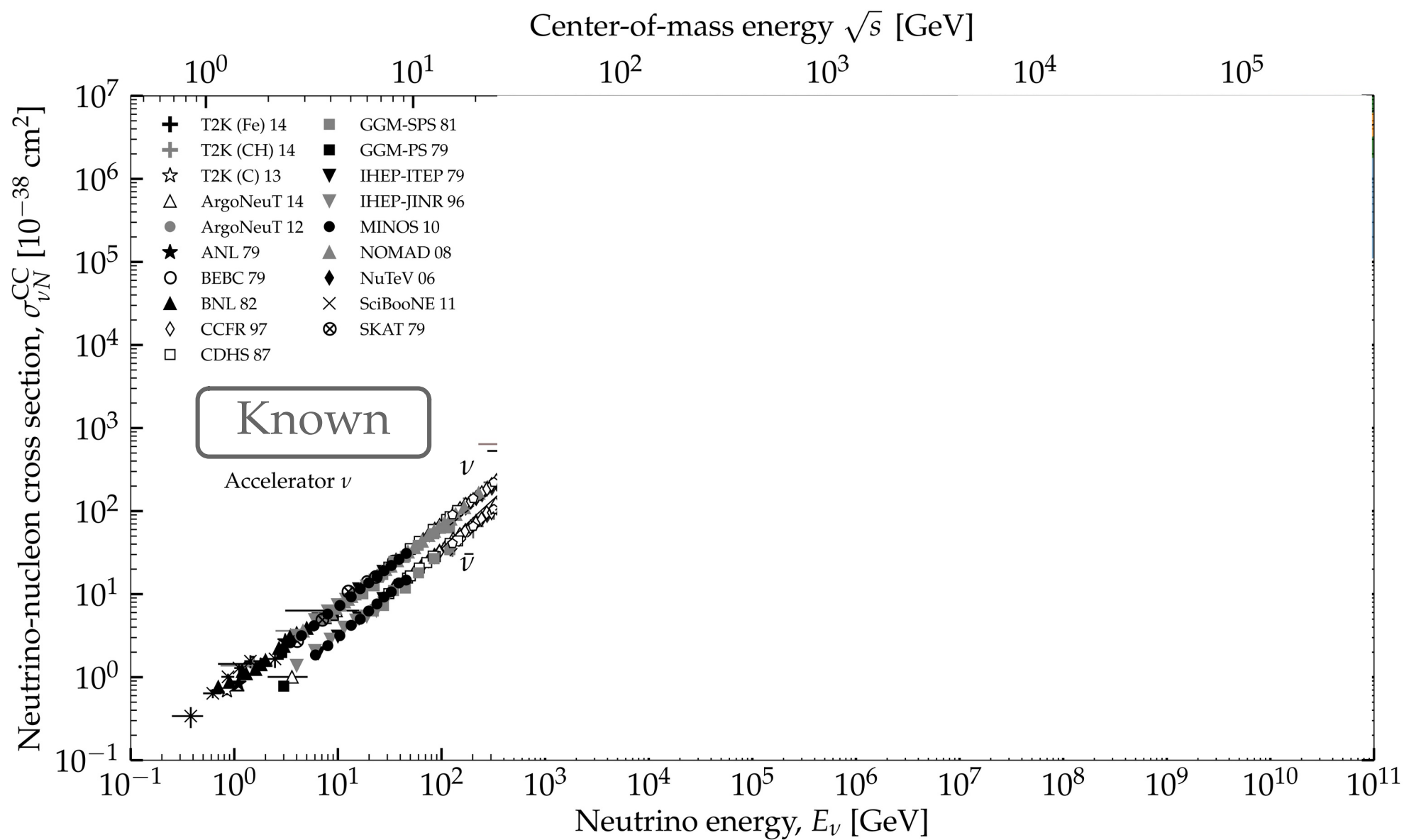


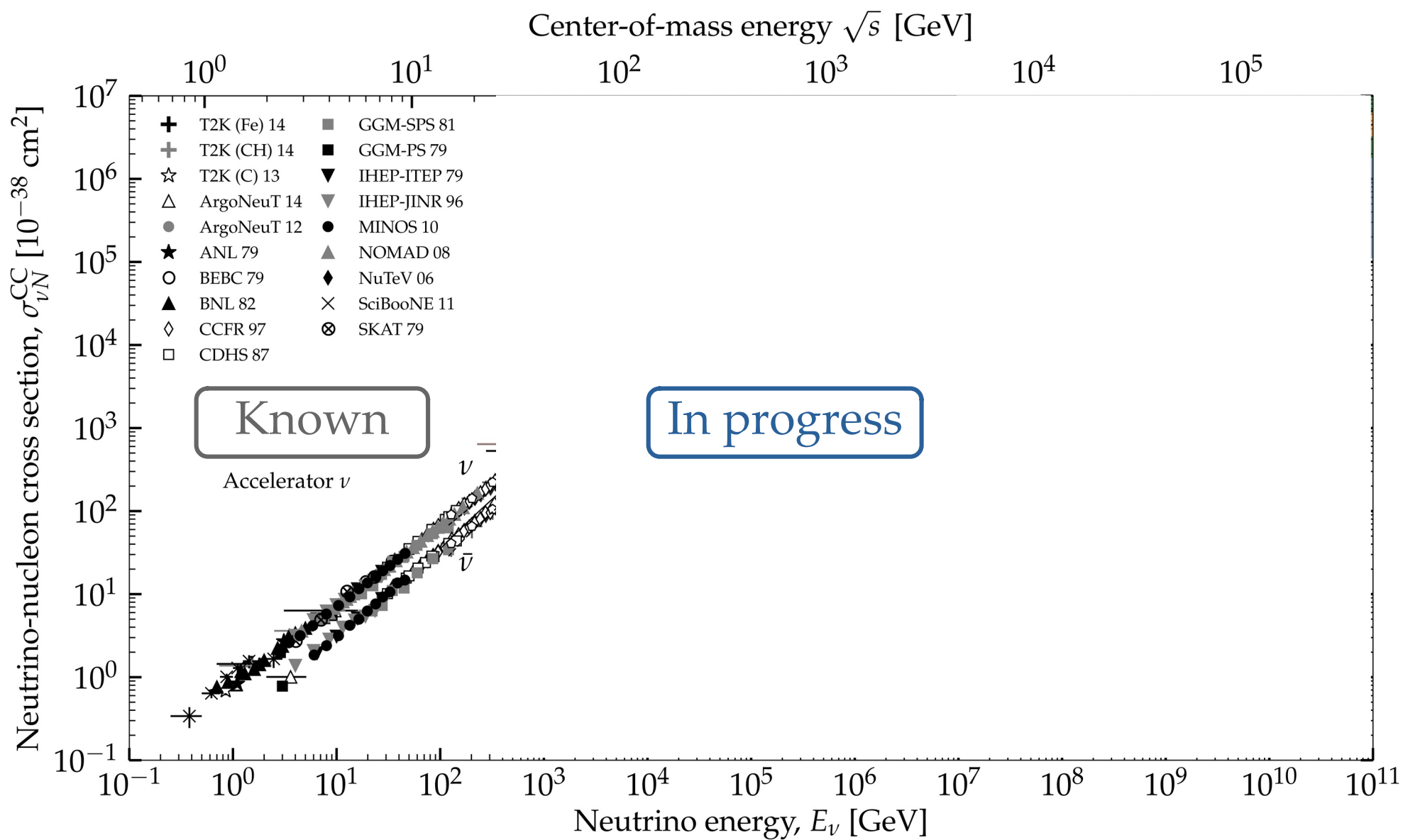
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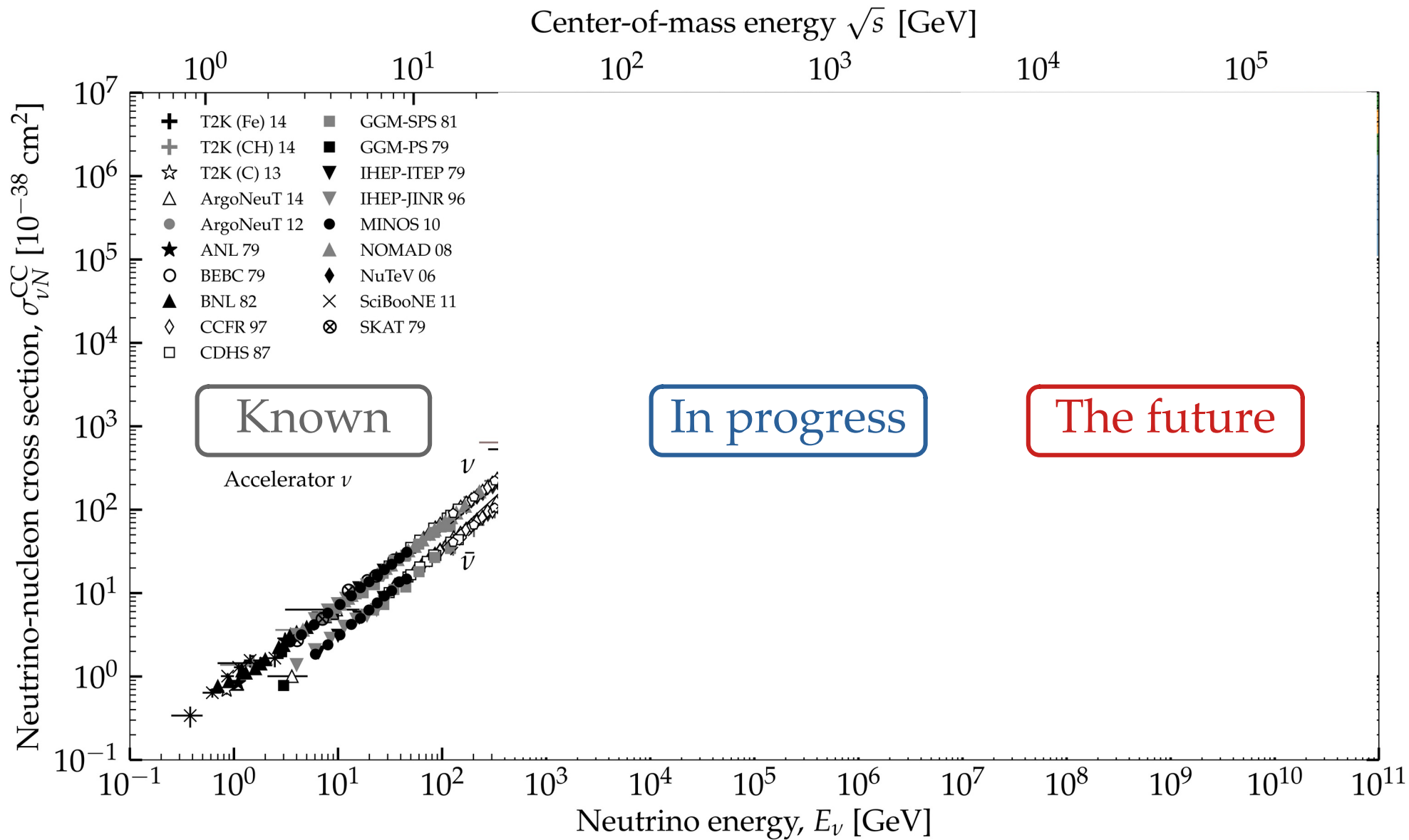






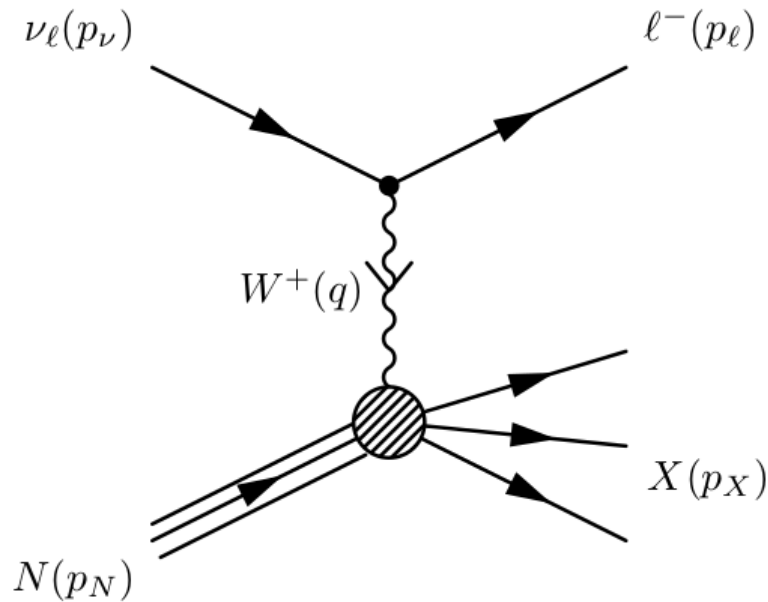




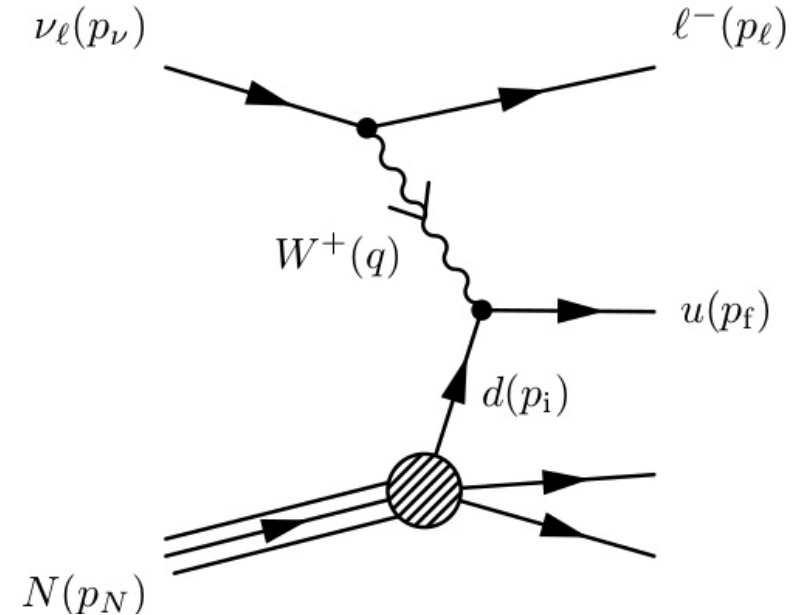


Neutrino-nucleon deep inelastic scattering

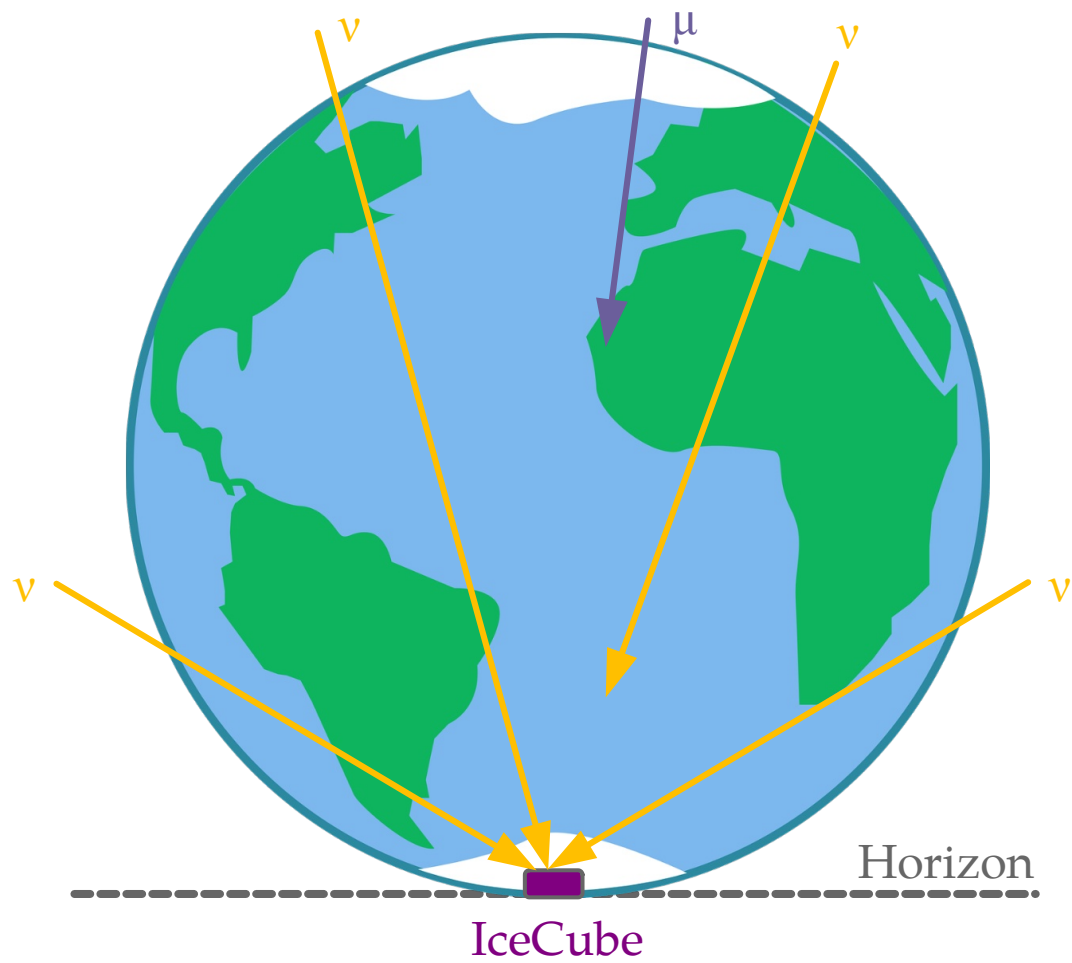
What you see

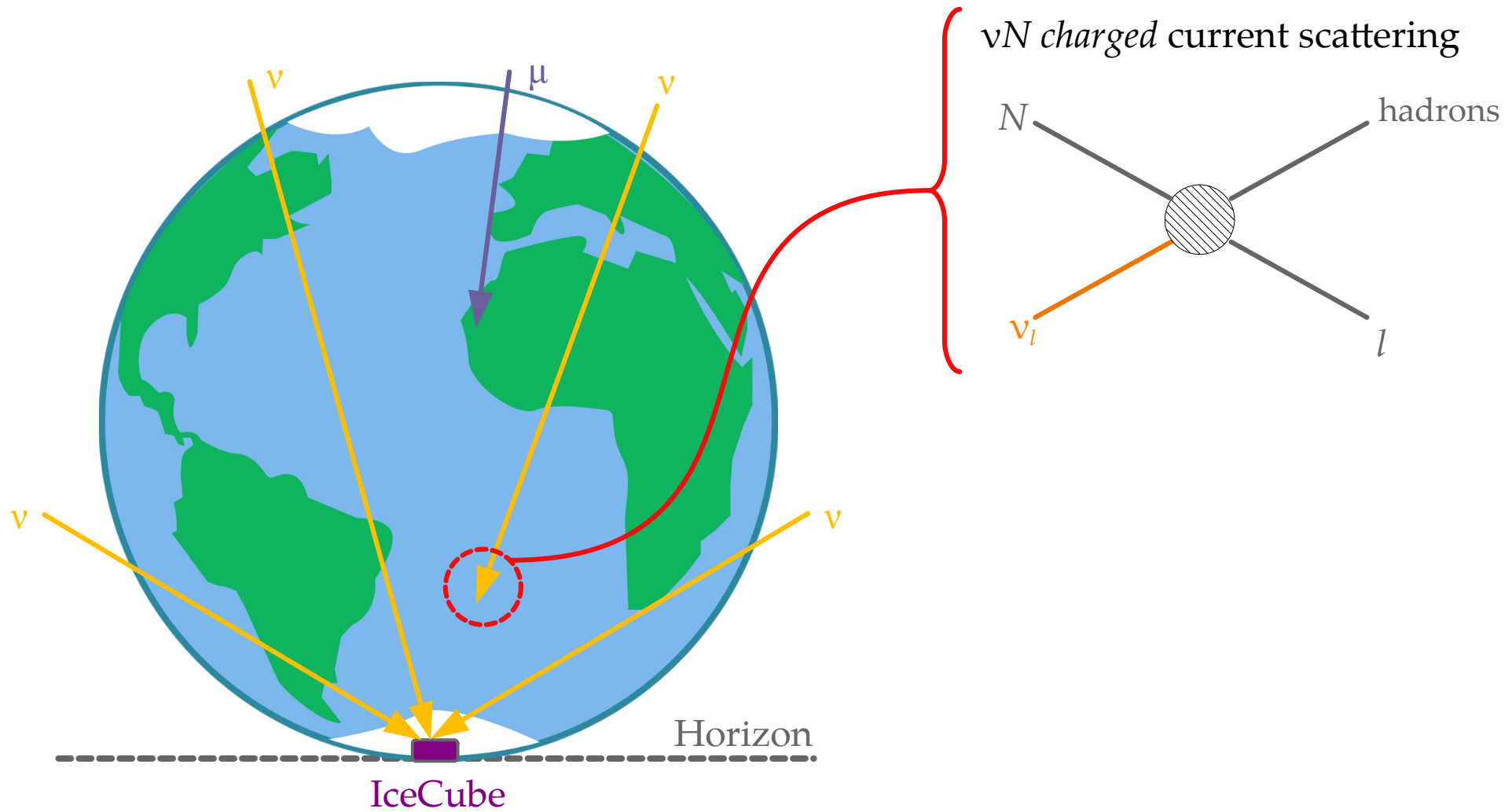


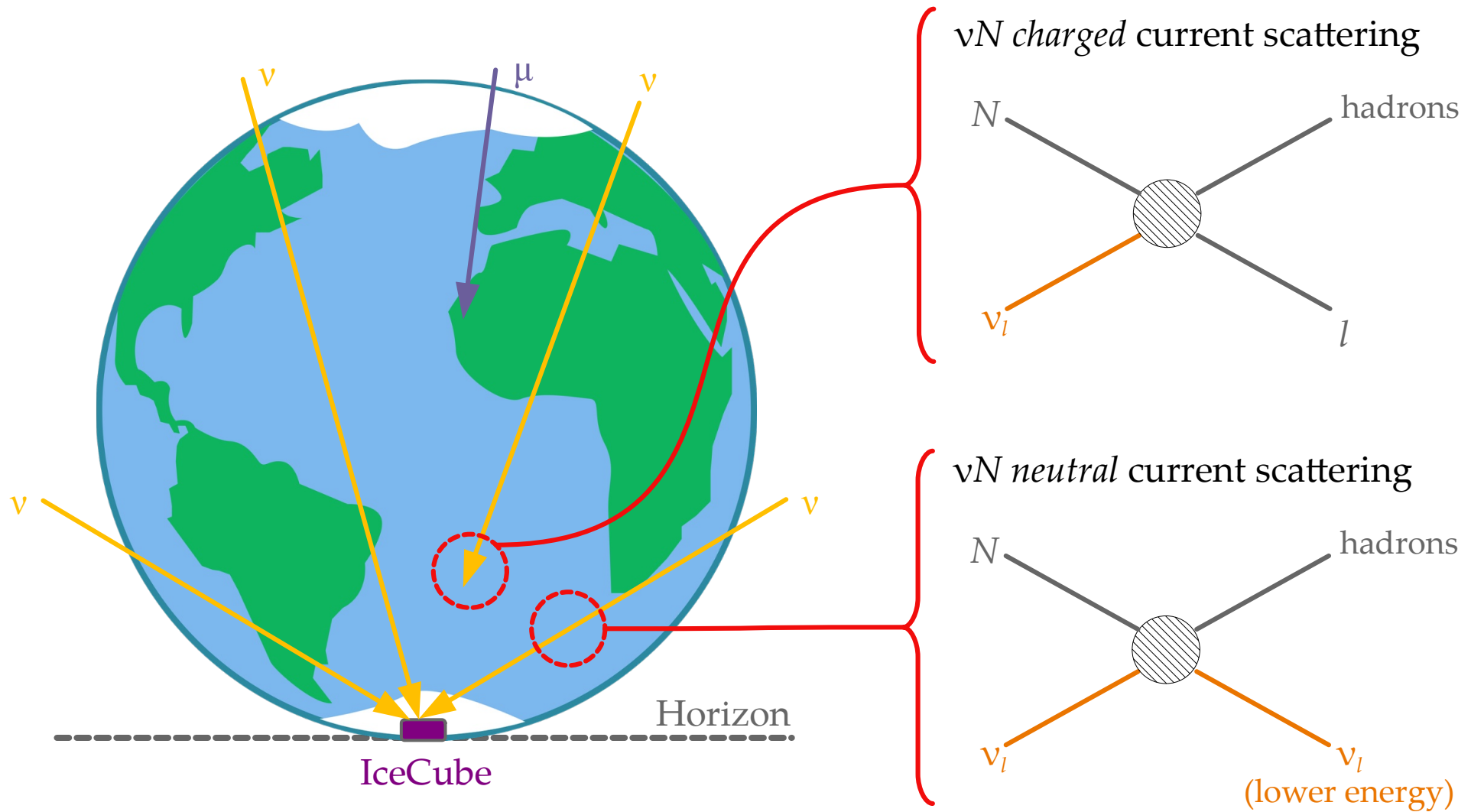
Beneath the hood

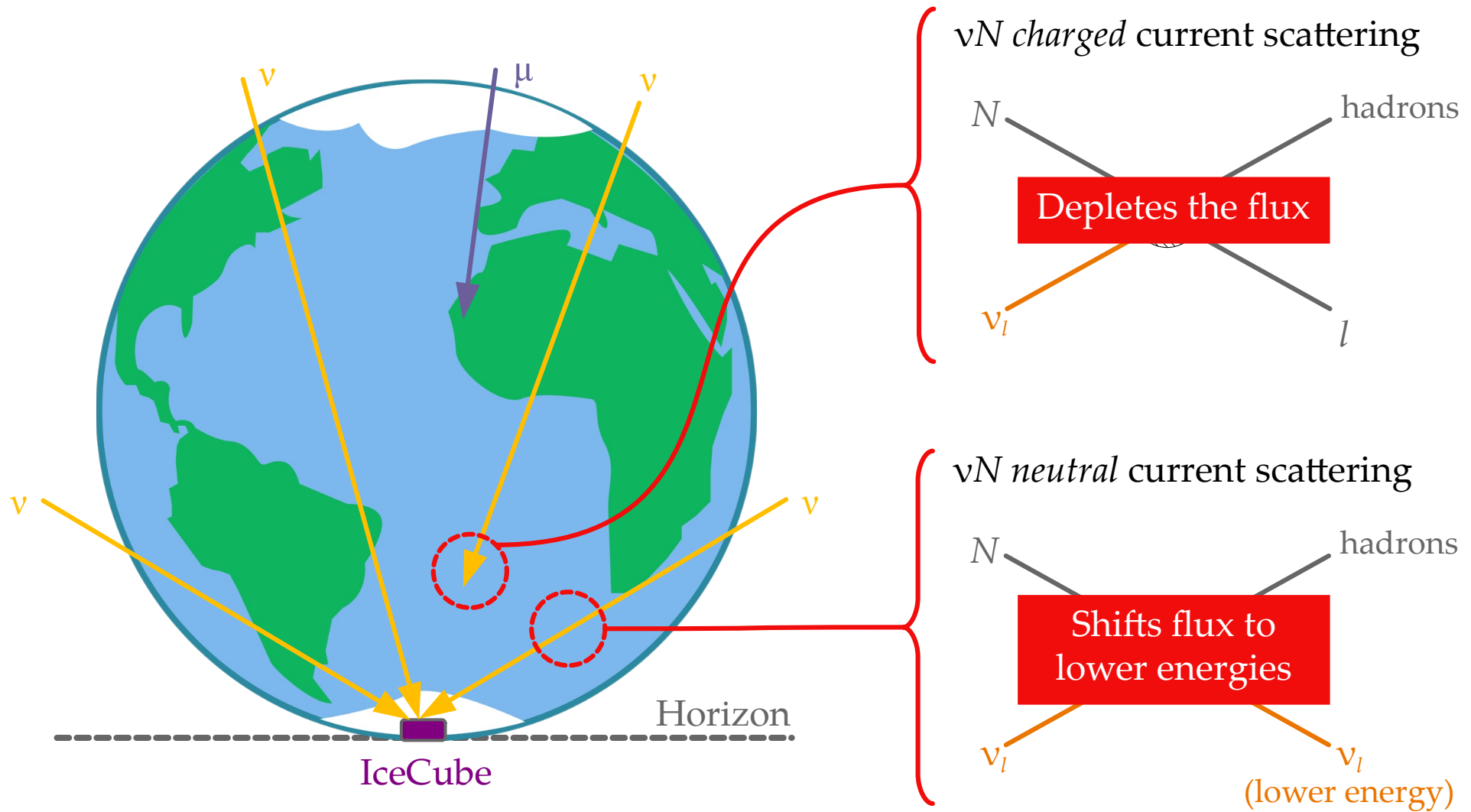


(Plus the equivalent neutral-current process (Z-exchange))



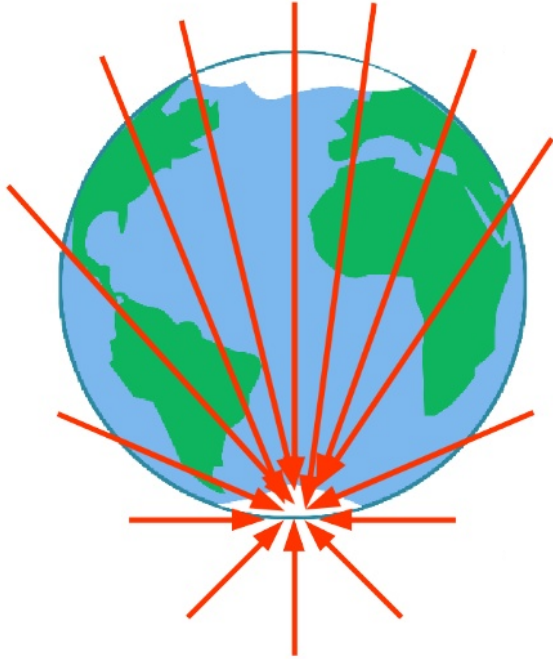




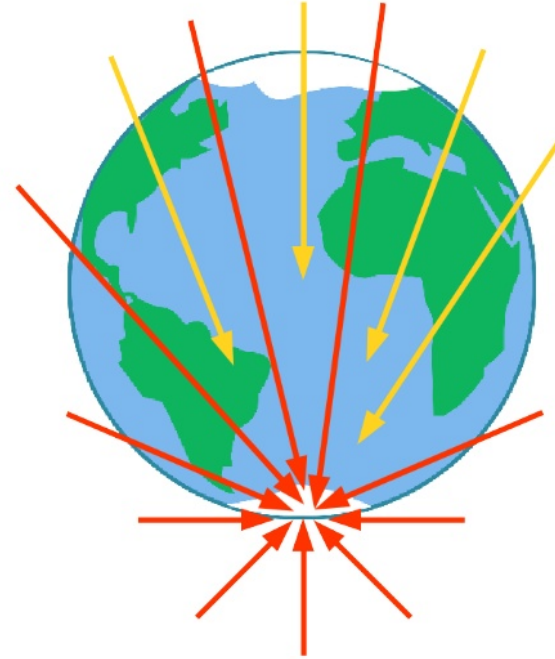


Measuring the high-energy νN cross section

Below ~ 10 TeV: Earth is transparent

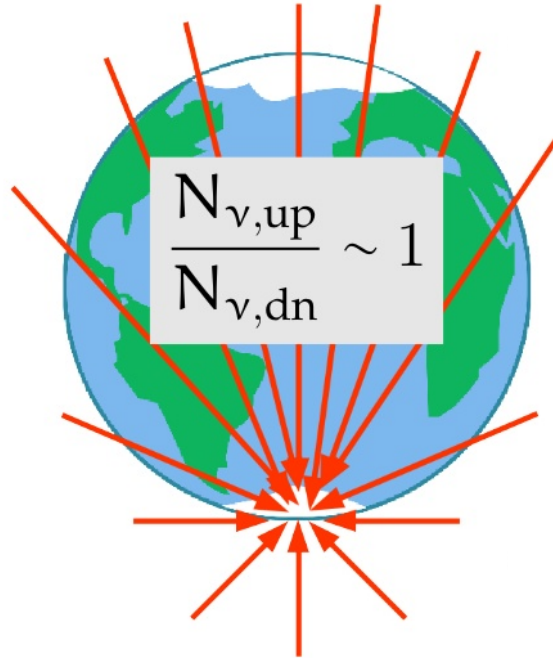


Above ~ 10 TeV: Earth is opaque

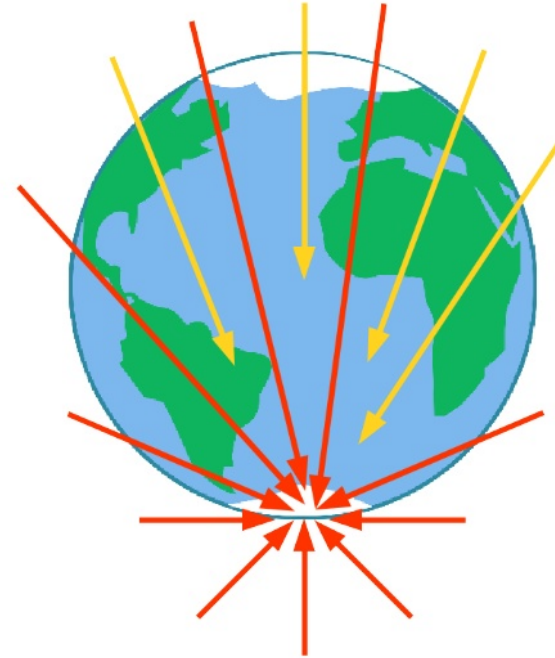


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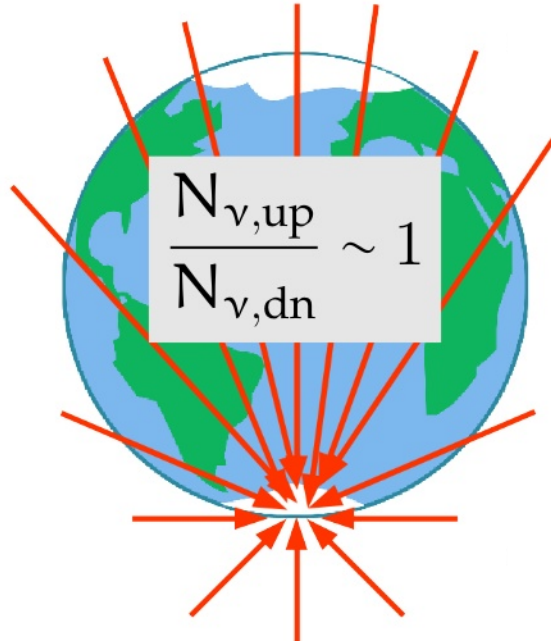


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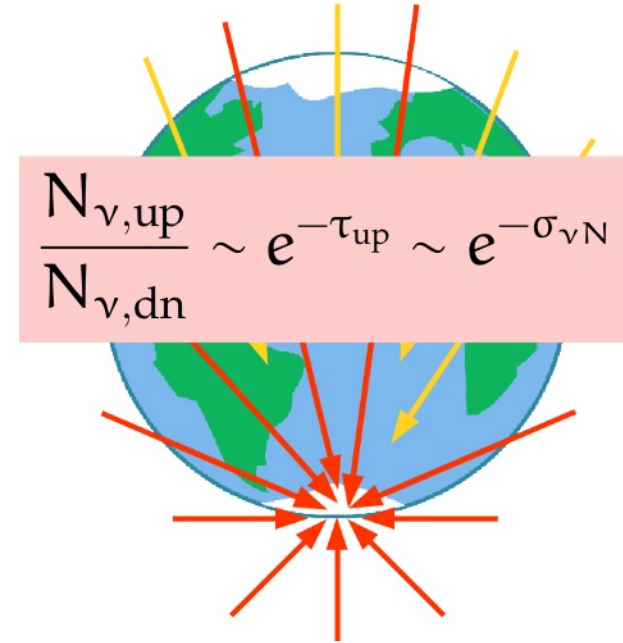


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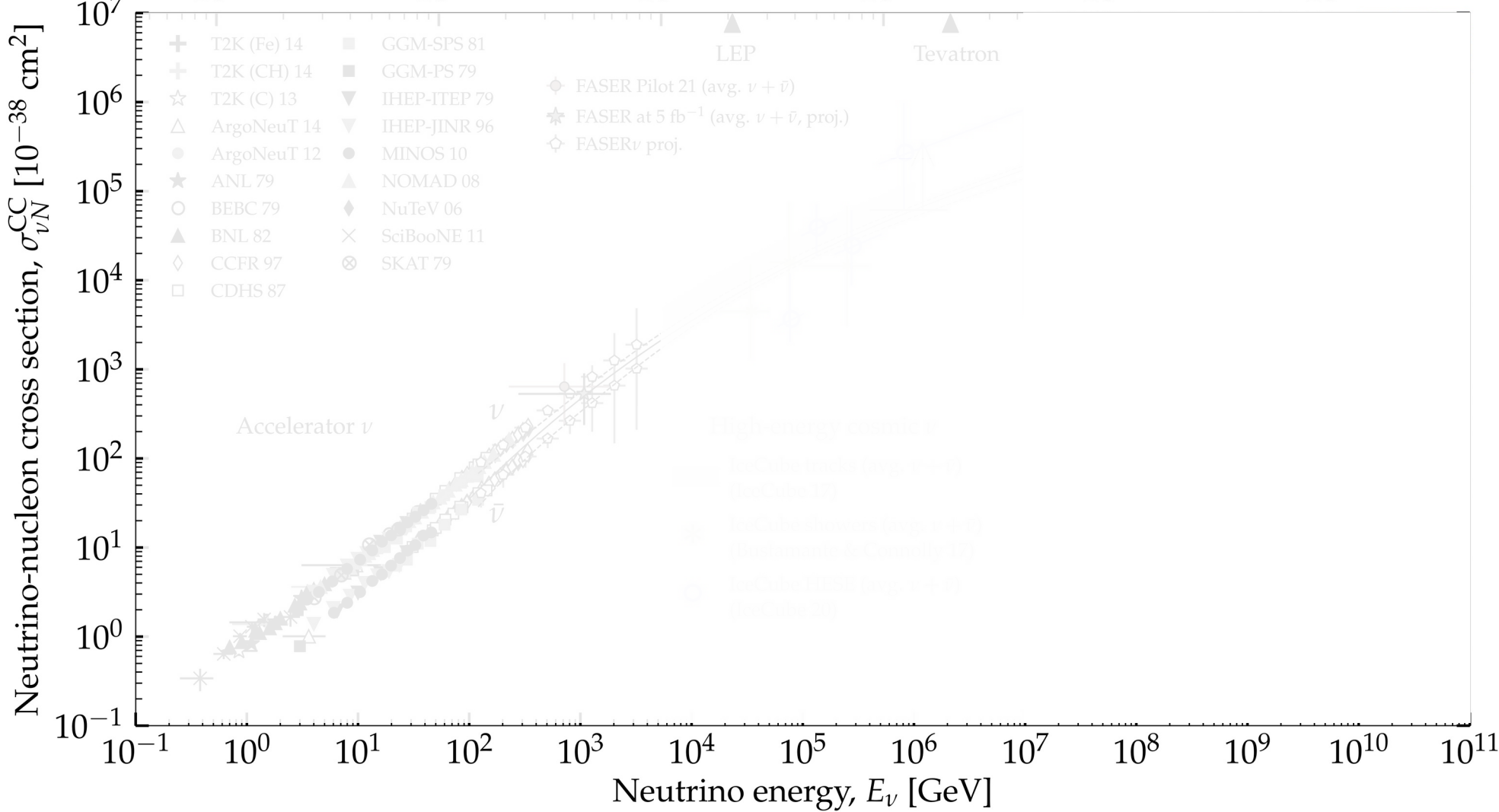
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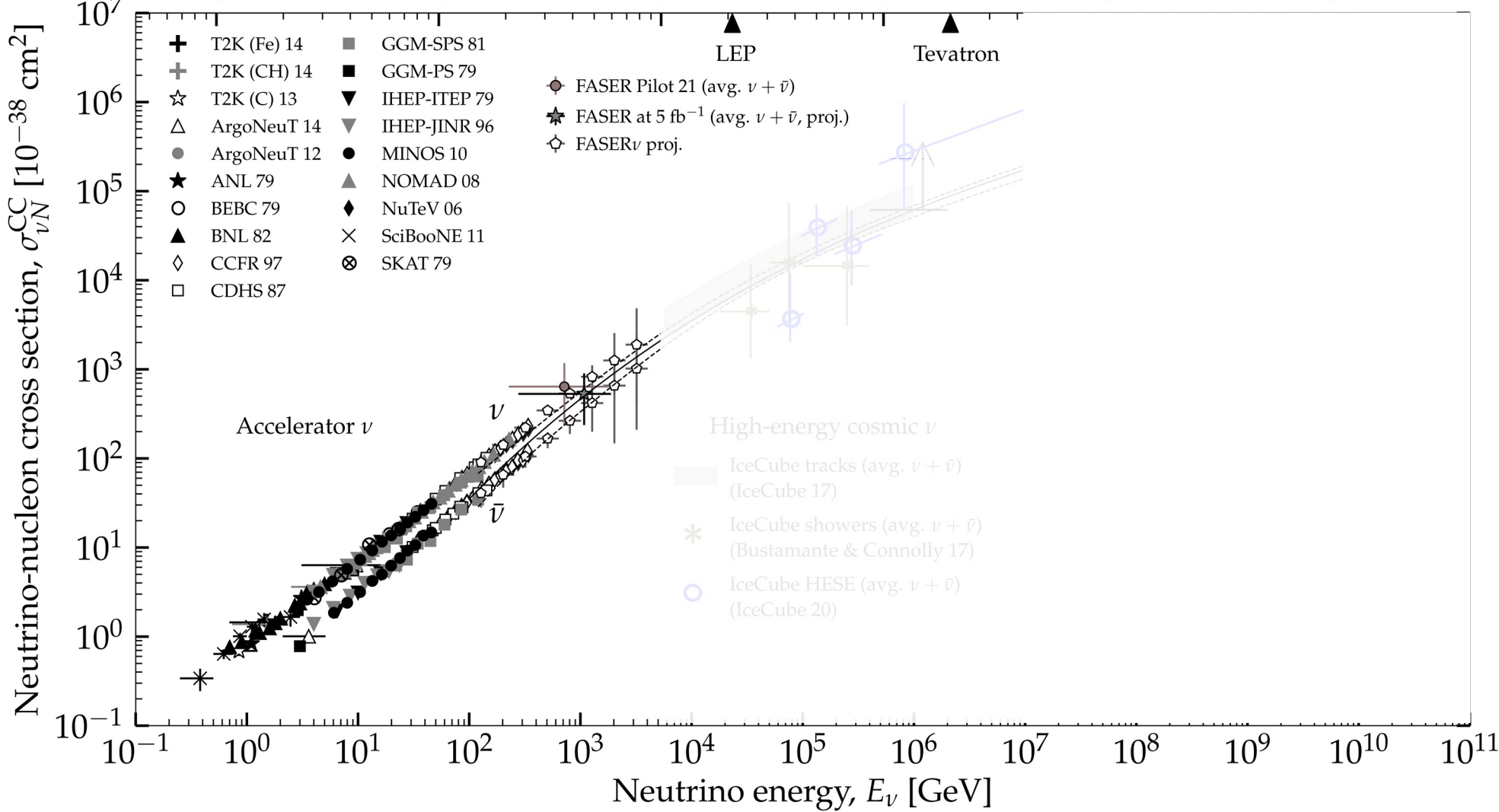
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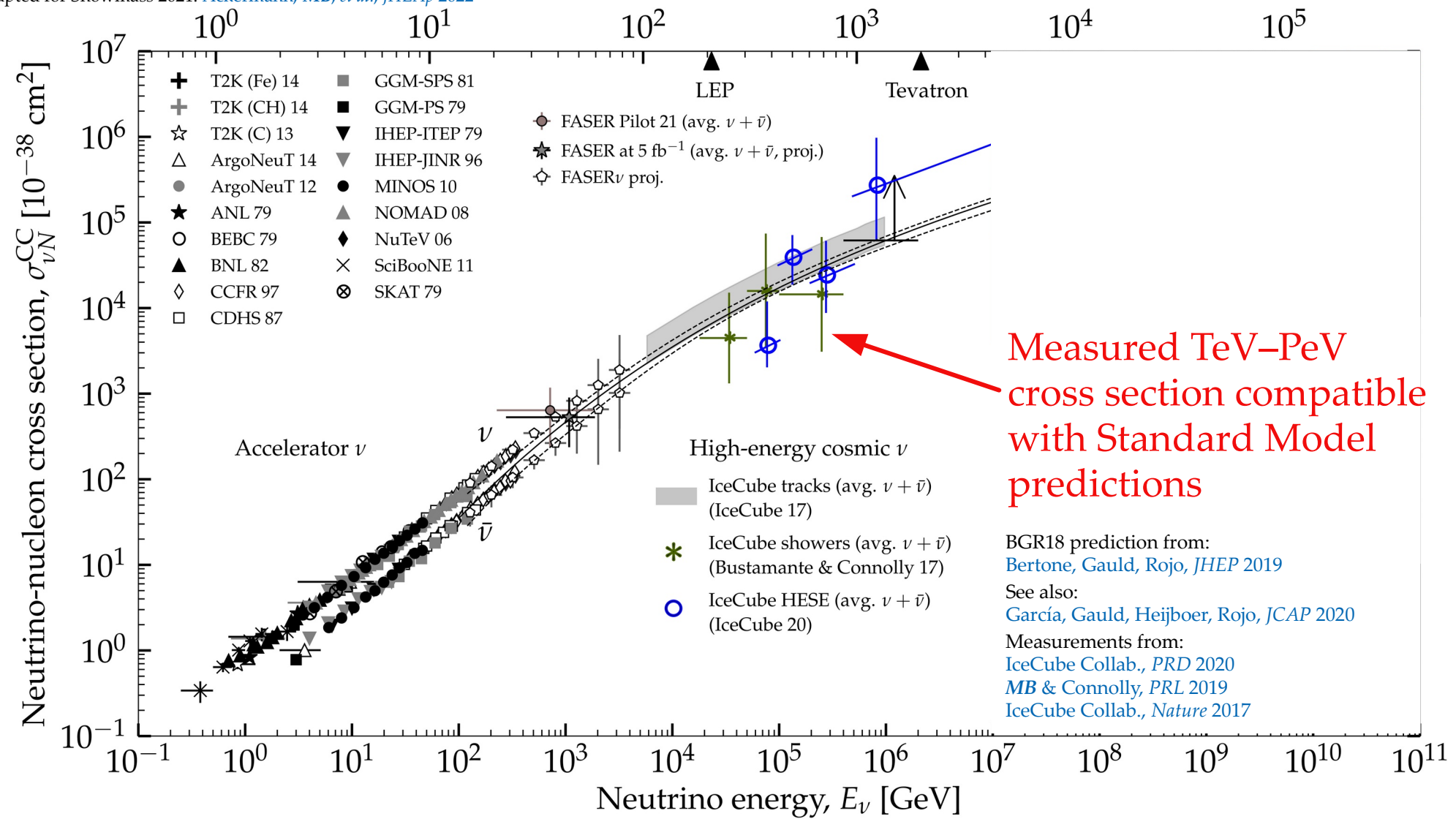
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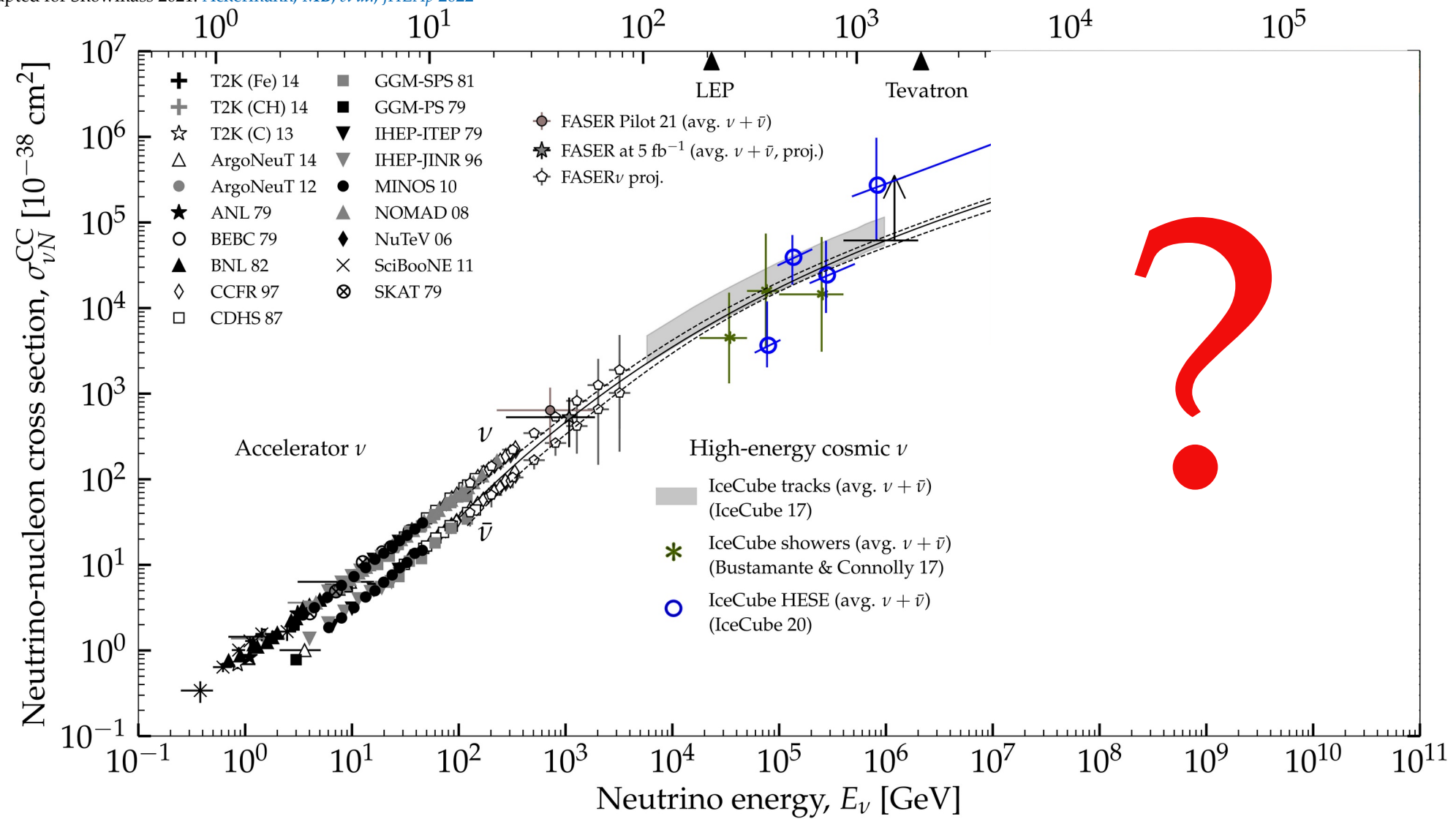
Center-of-mass energy $\sqrt{s}$ [GeV]



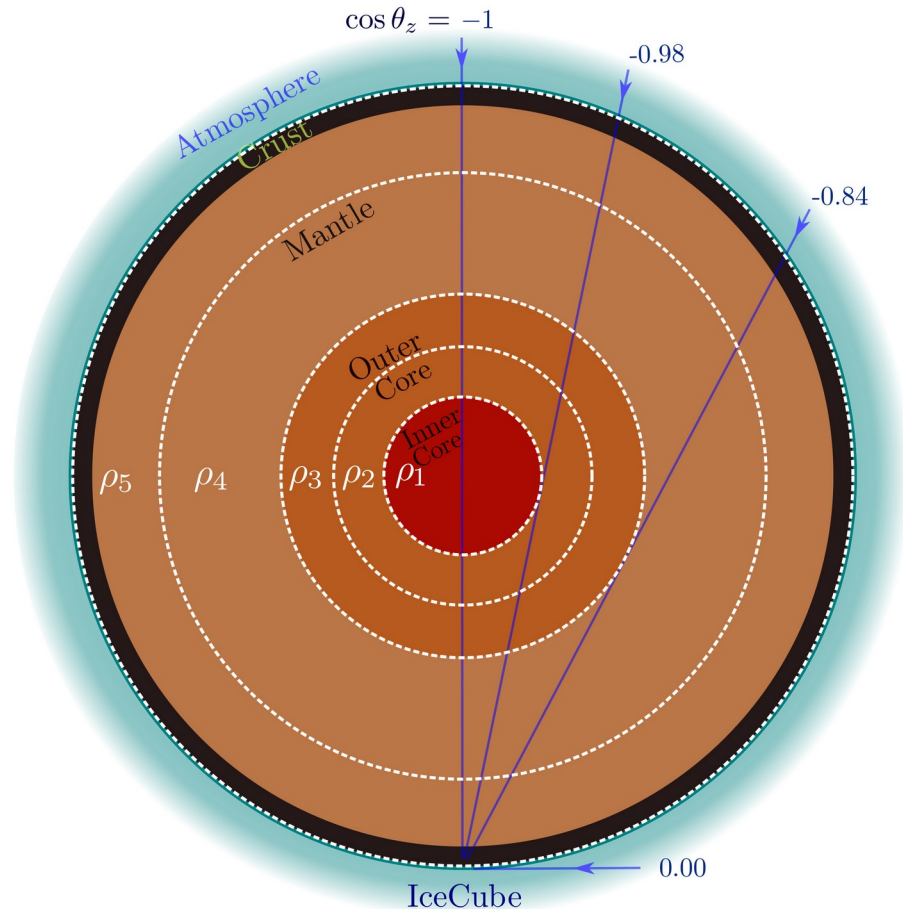
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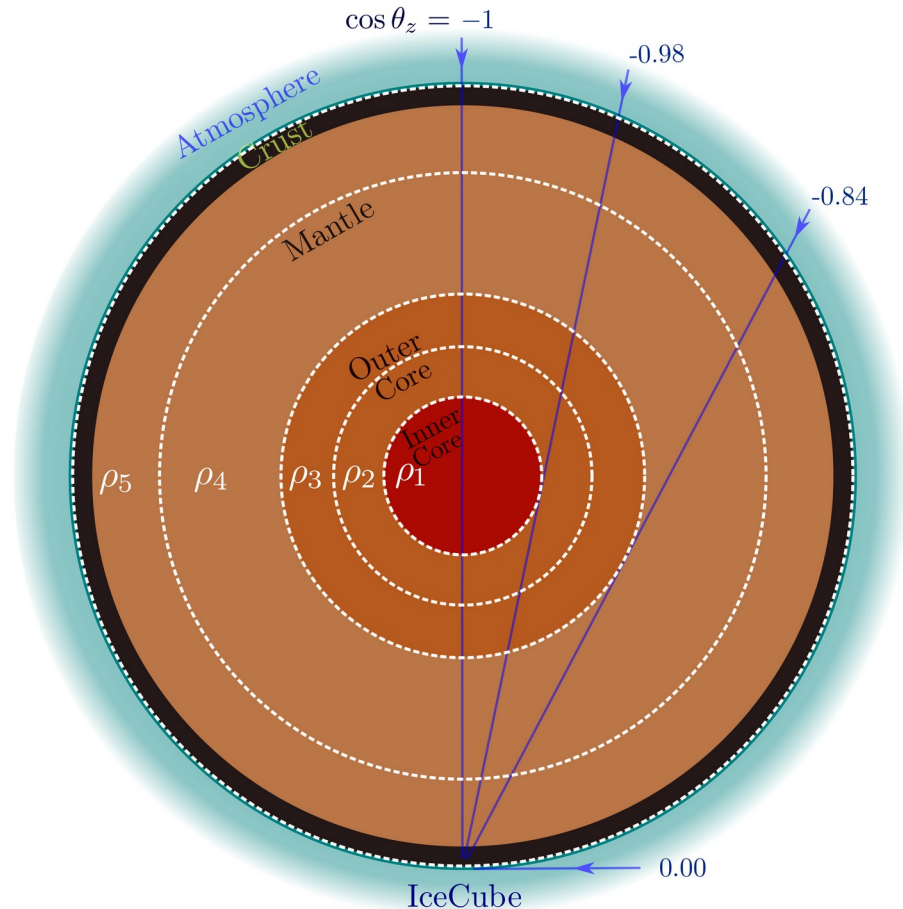


Tomography of the Earth



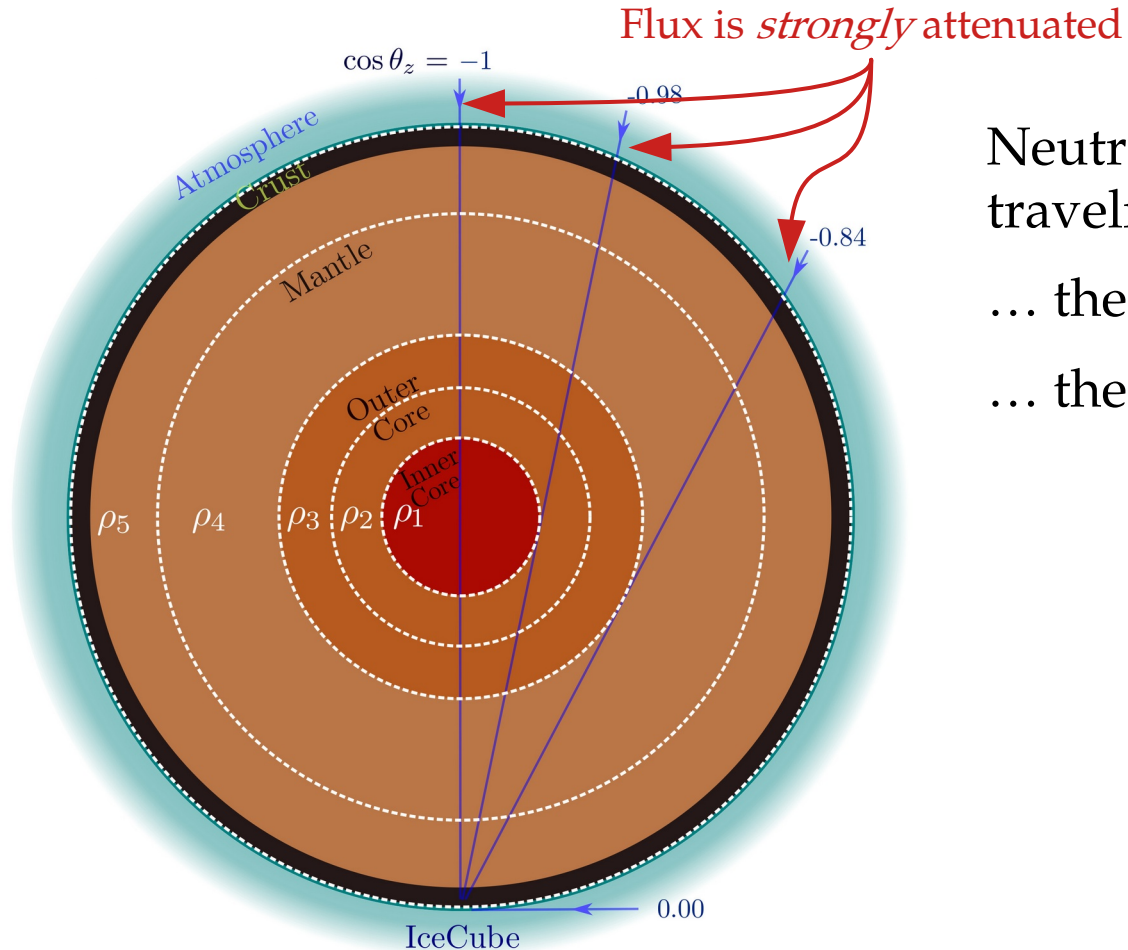
Neutrinos are more likely to interact while traveling inside the Earth ...
... the higher their energy, and
... the longer the distance they travel.

Tomography of the Earth



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Tomography of the Earth

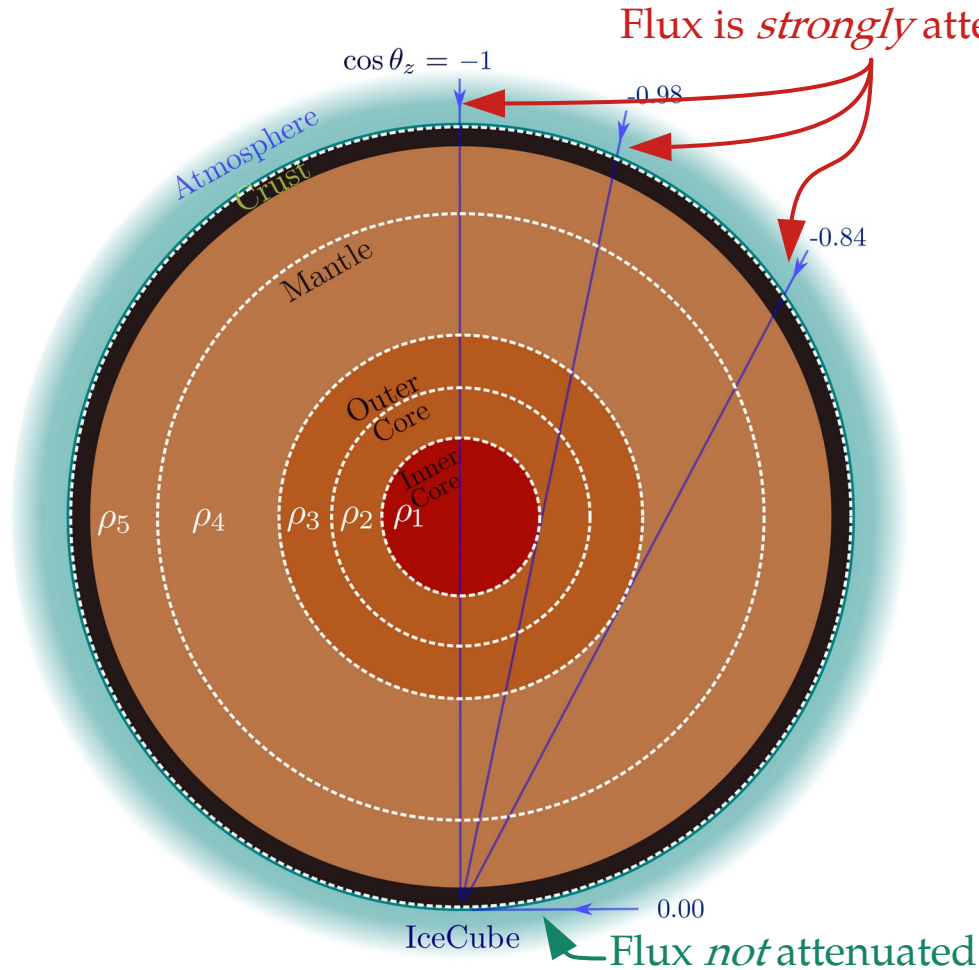


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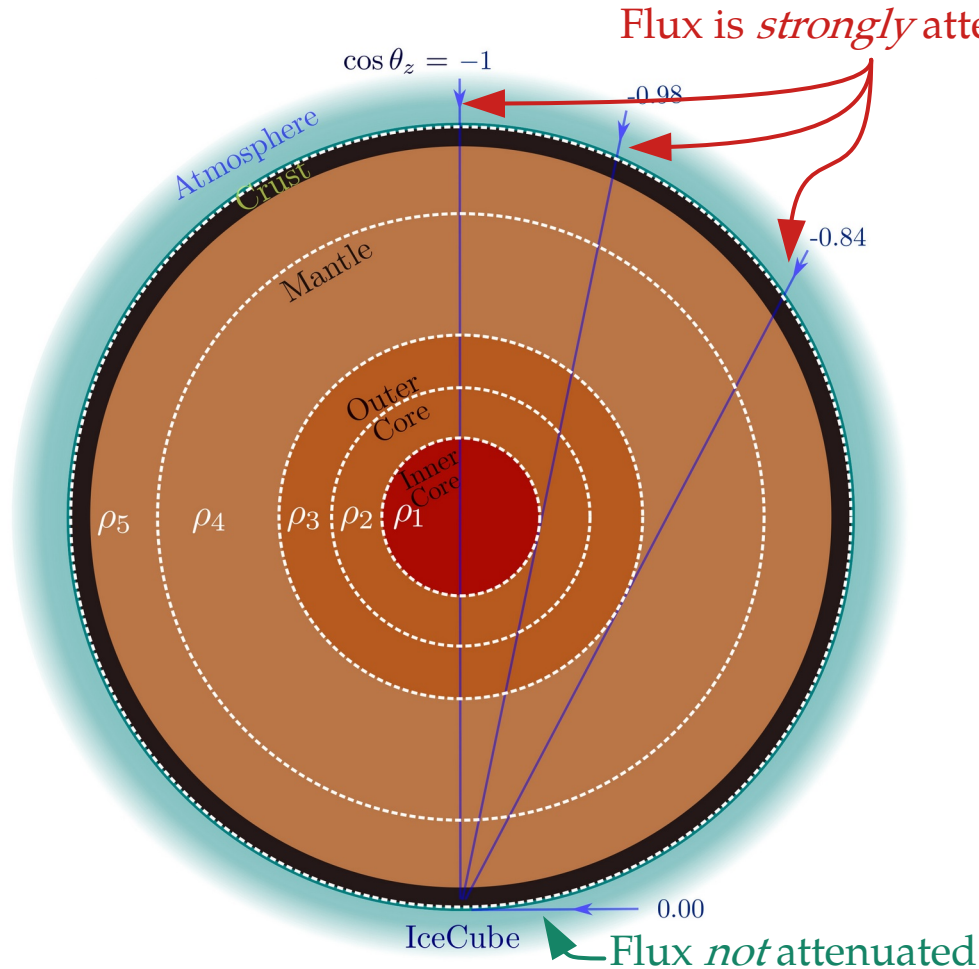
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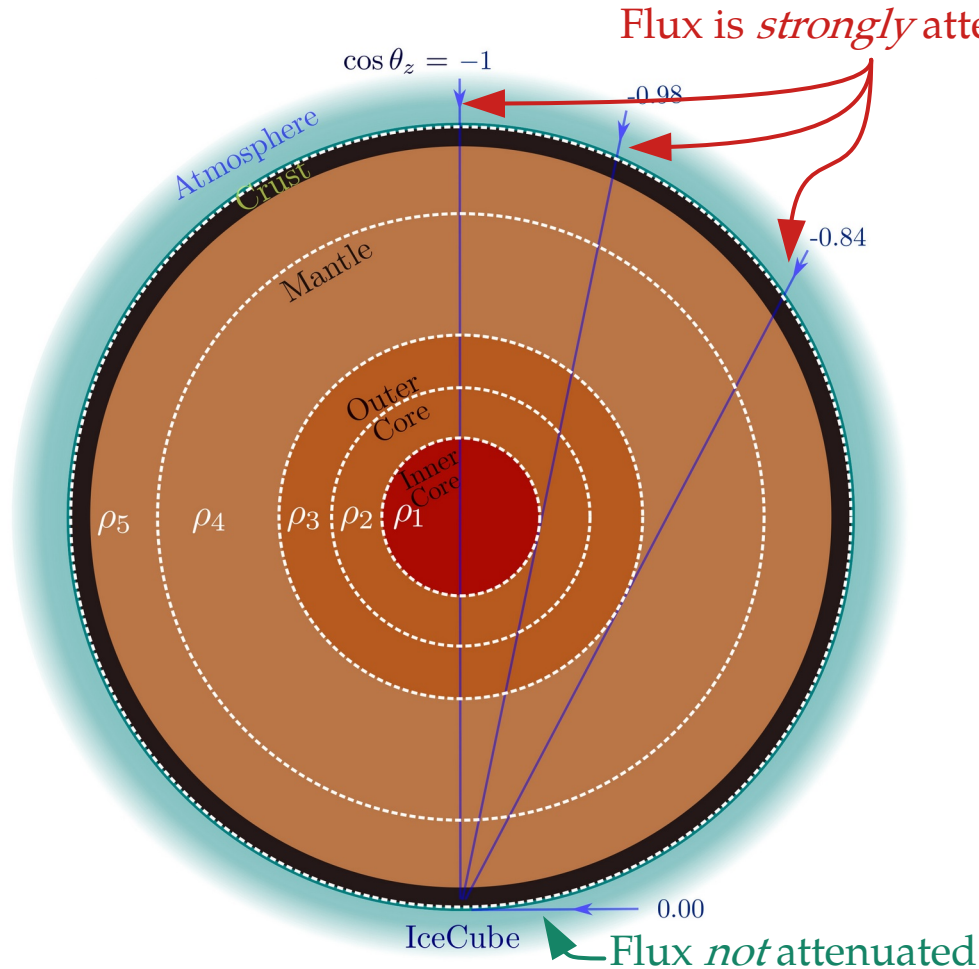
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Comparing atmospheric neutrino fluxes reaching IceCube from different directions:

$$\text{Earth's mass} = 6.0^{+1.6}_{-1.3} \times 10^{24} \text{ kg}$$

Tomography of the Earth



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$$\text{Earth's mass} = 6.0^{+1.6}_{-1.3} \times 10^{24} \text{ kg}$$

$$\left[\text{Vs. gravitational measurements:} \right. \\ \left. (5.9722 \pm 0.0006) \times 10^{24} \text{ kg} \right]$$

Secret neutrino interactions

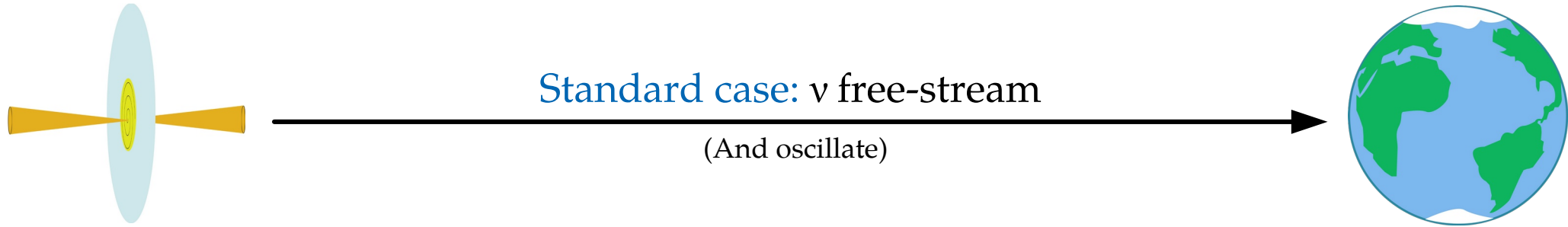


Galactic (kpc) or extragalactic (Mpc – Gpc) distance

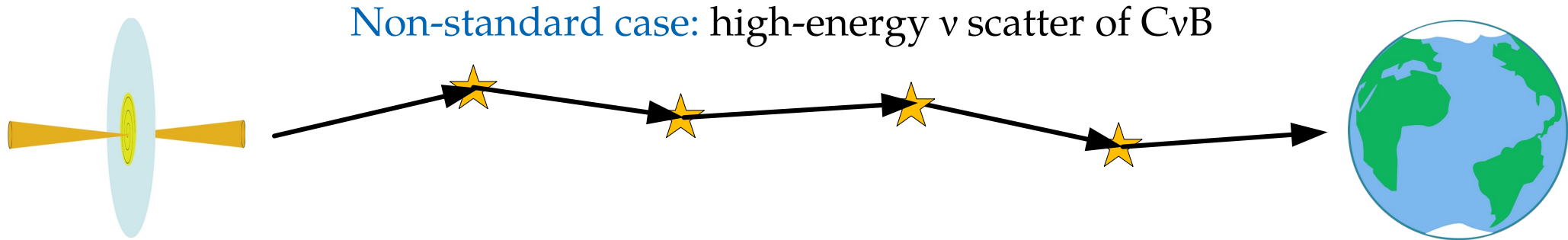
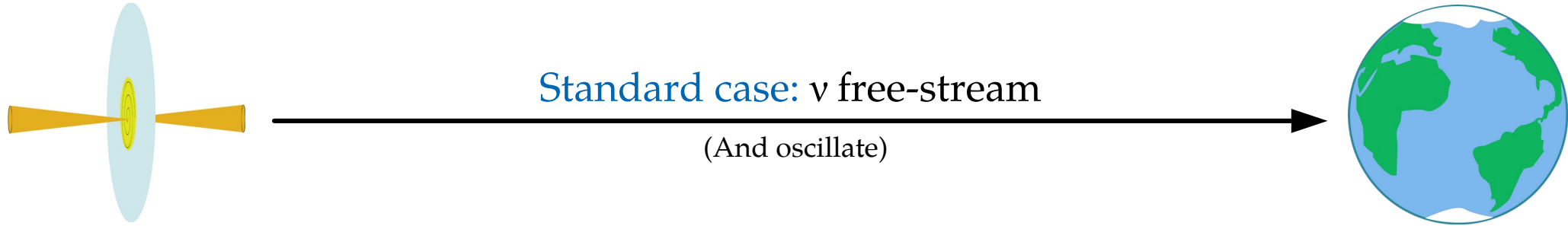
Astrophysical neutrino sources

Earth

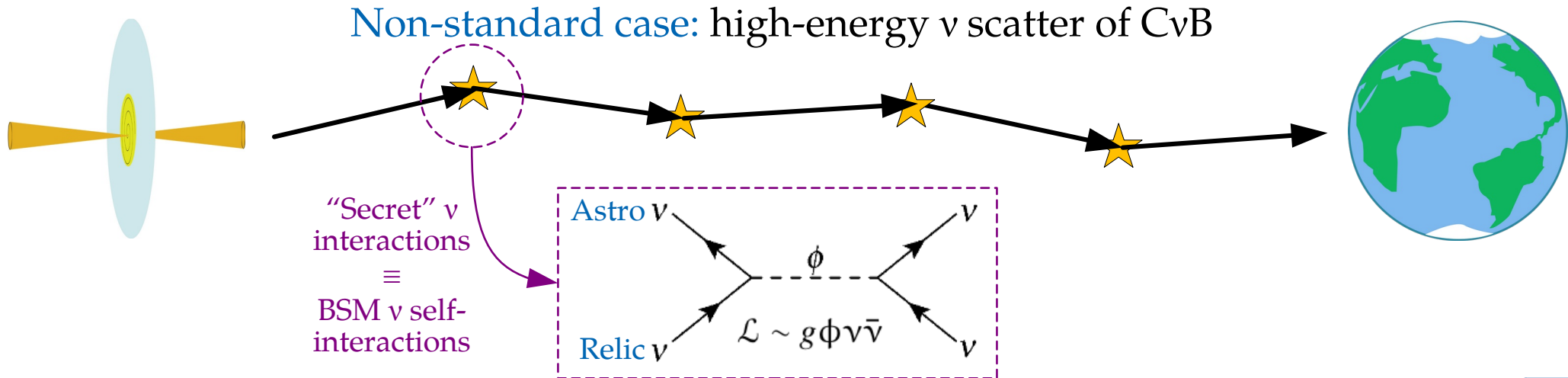
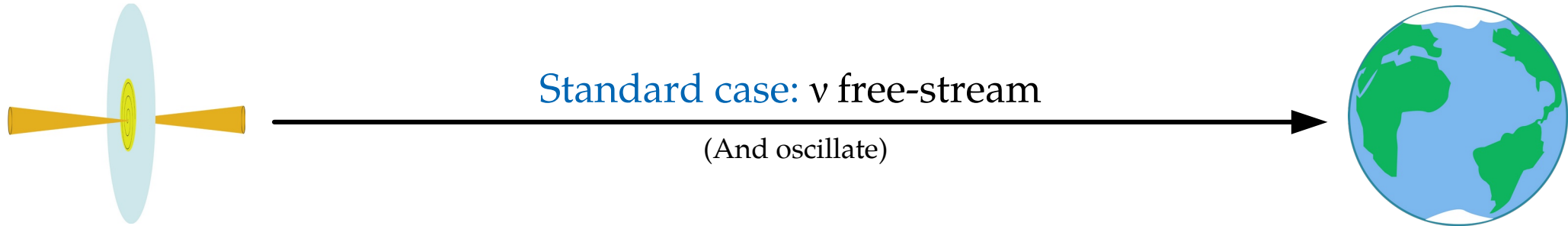
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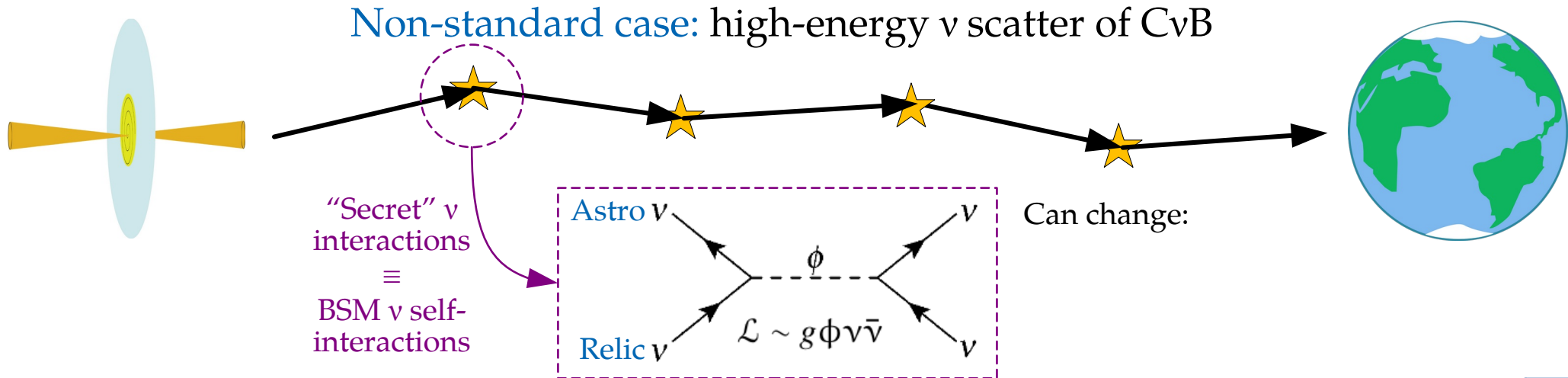
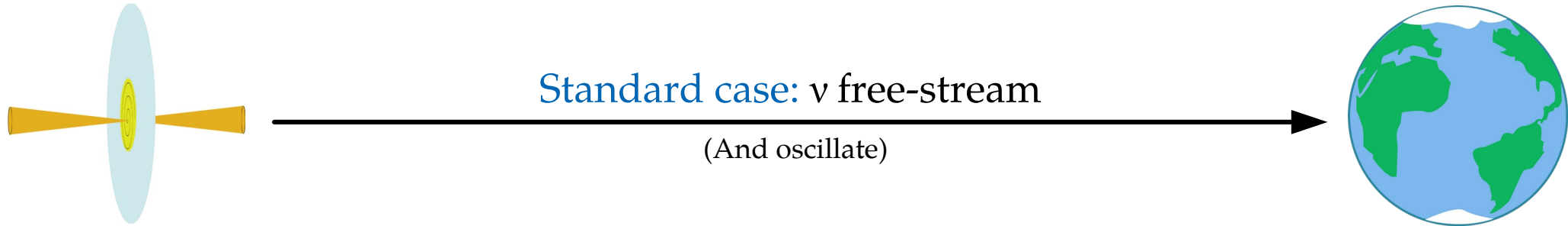
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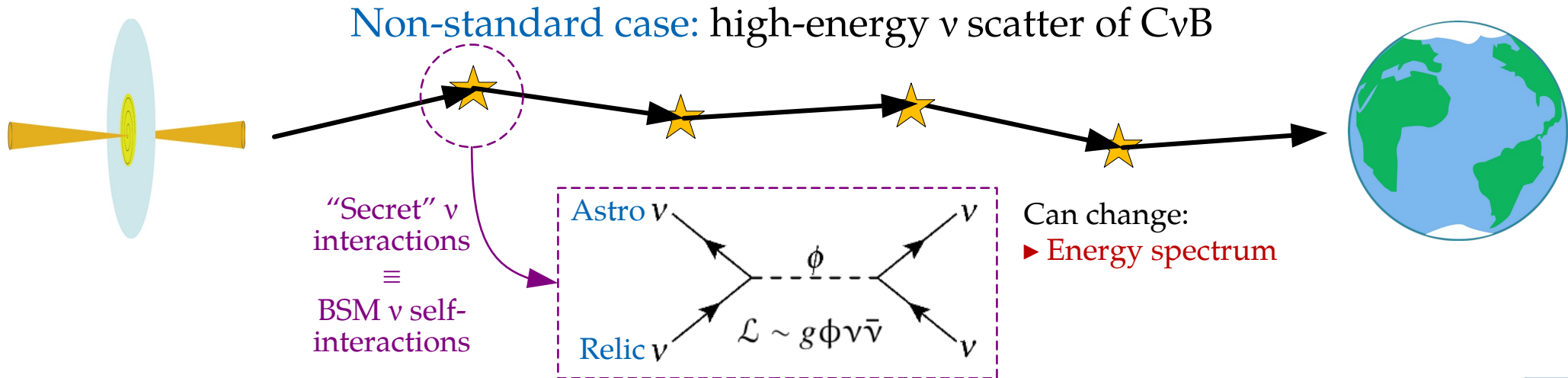
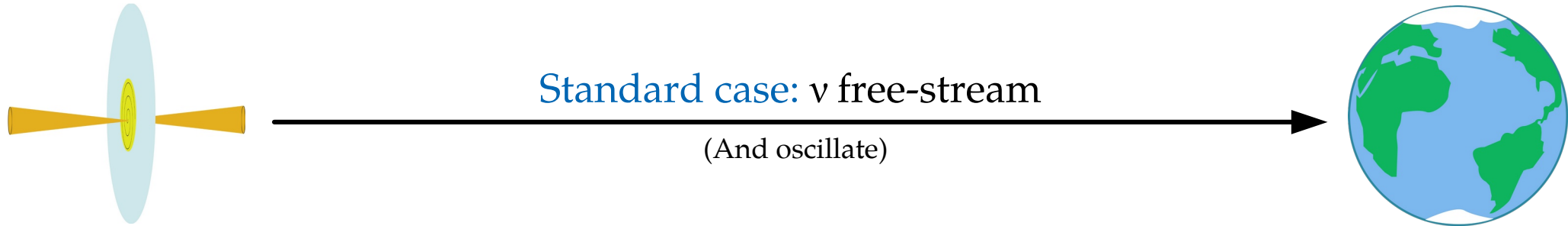
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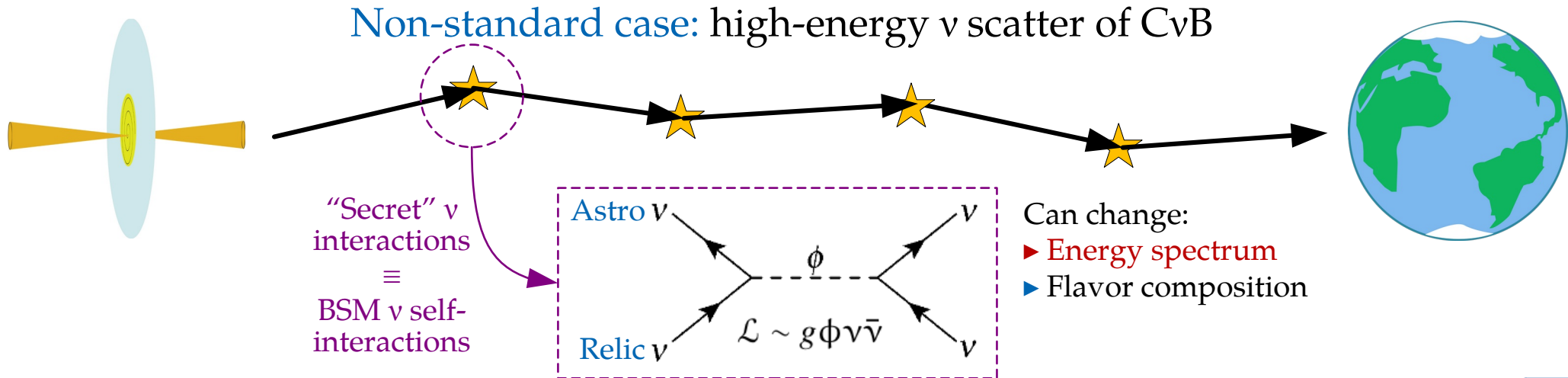
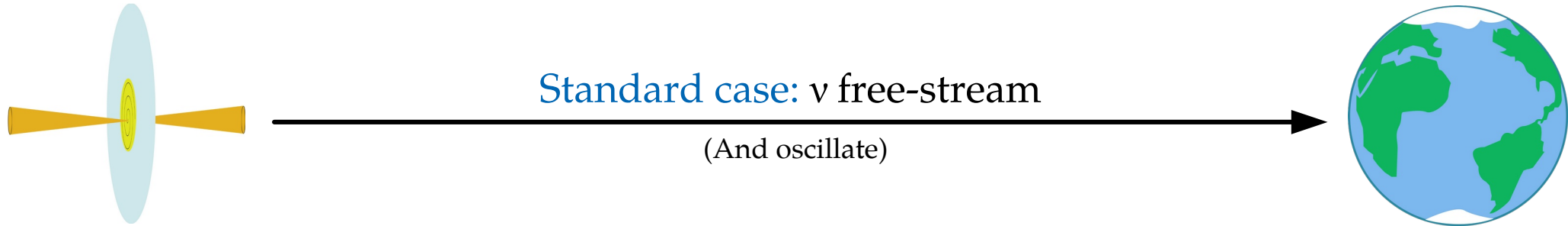
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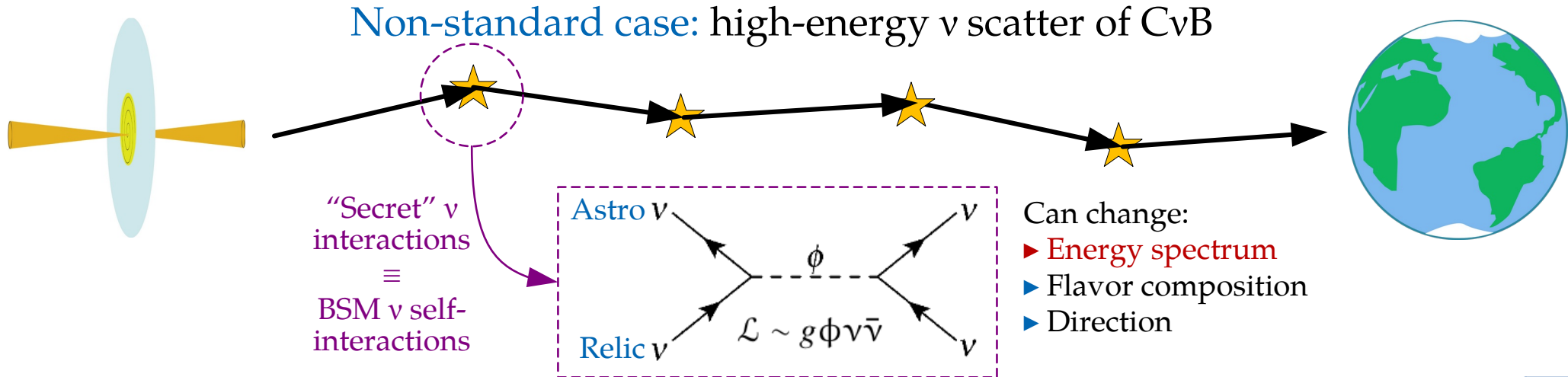
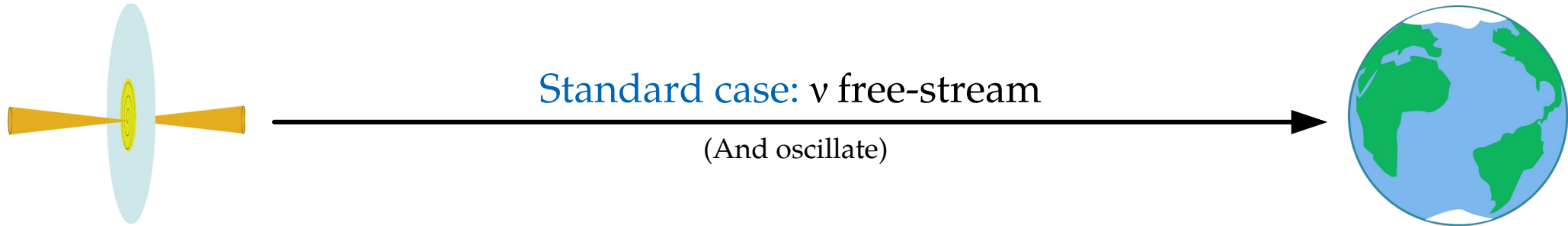
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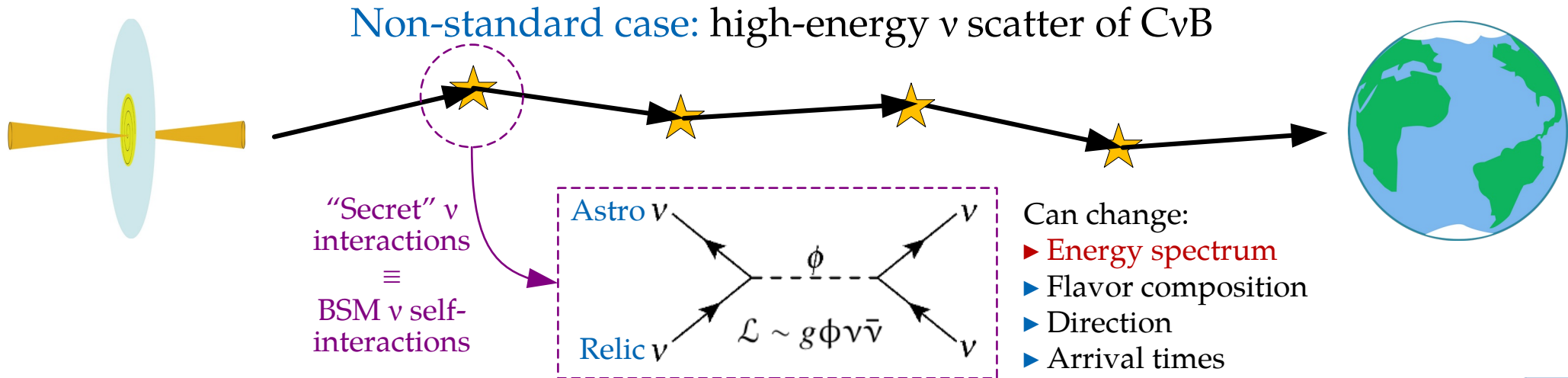
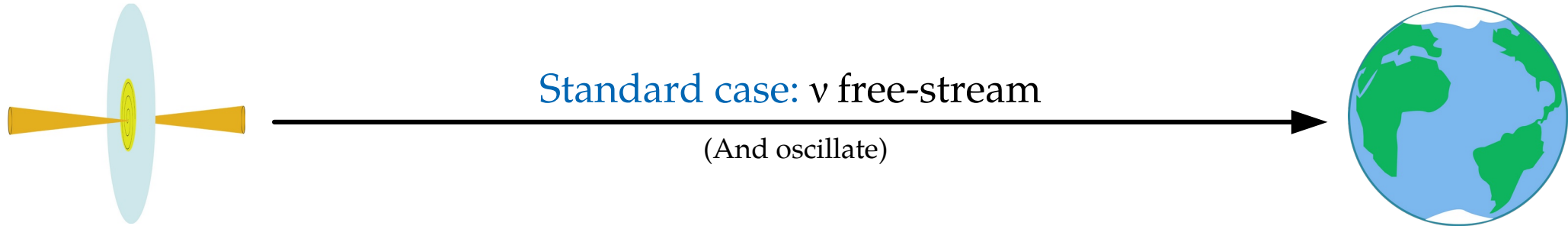
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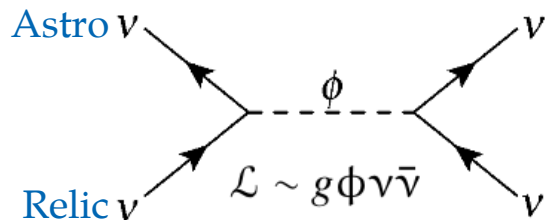


Galactic (kpc) or extragalactic (Mpc – Gpc) distance



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:
$$E_{\text{res}} = \frac{M^2}{2m_\nu}$$

MB, Rosenstroem, Shalgar, Tamborra, *PRD* 2020

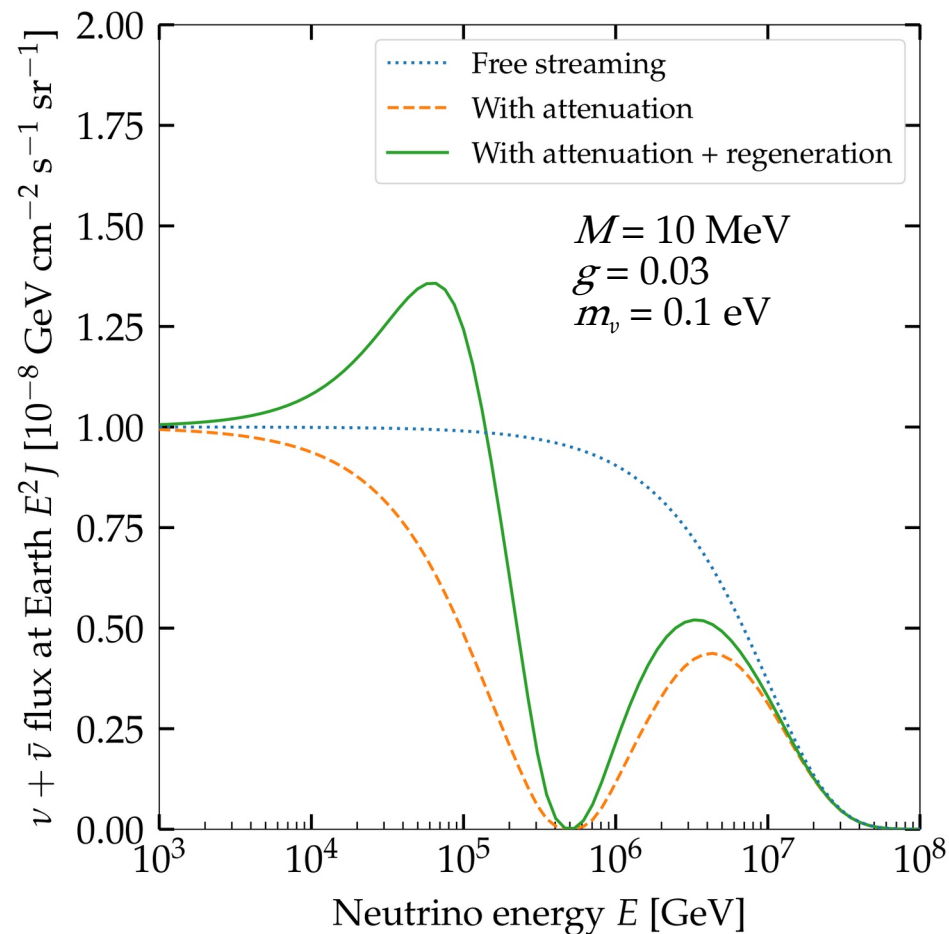
See also: Esteban, Pandey, Brdar, Beacom, *PRD* 2021

Creque-Sarbinowski, Hyde, Kamionkowski, *PRD* 2021

Ng & Beacom, *PRD* 2014

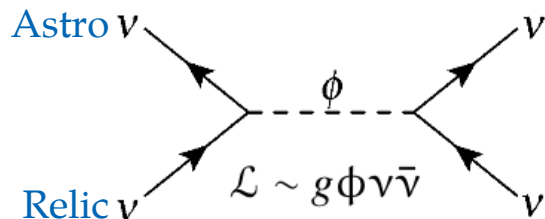
Cherry, Friedland, Shoemaker, 1411.1071

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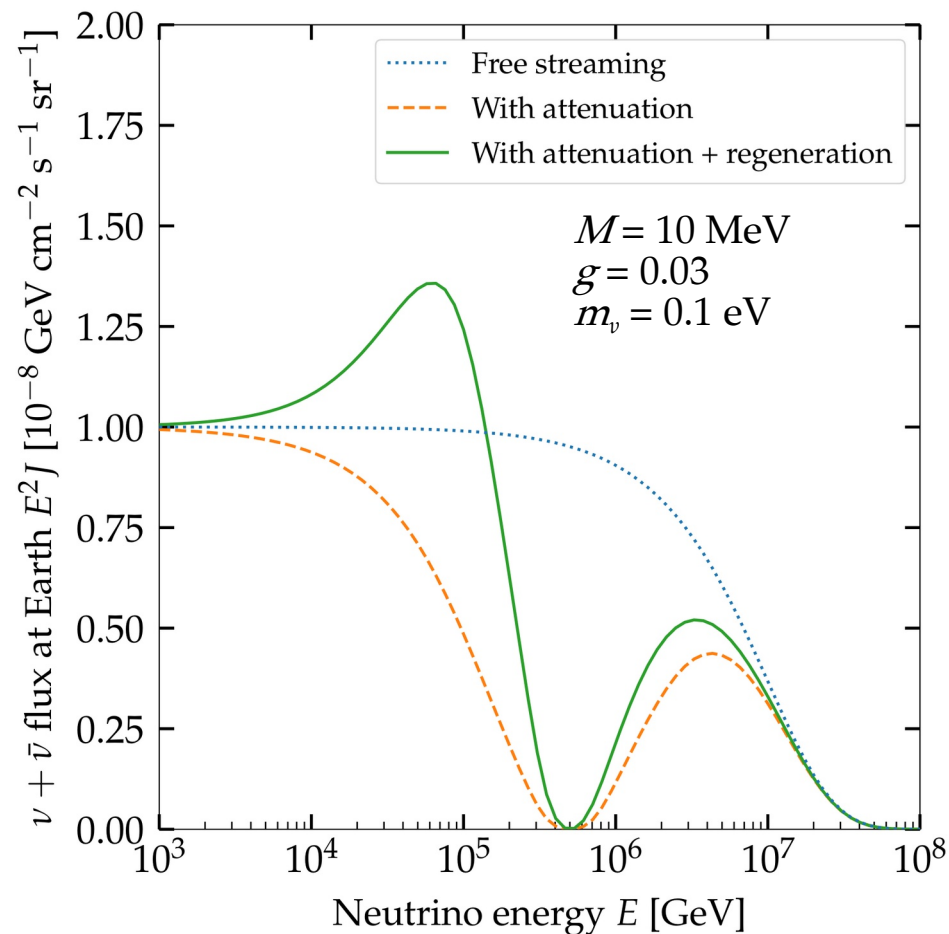


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New coupling Mediator mass

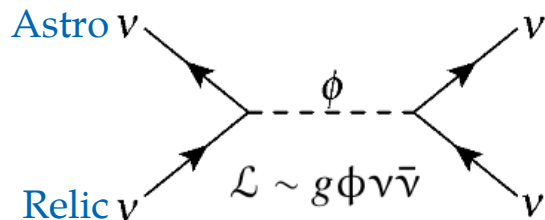
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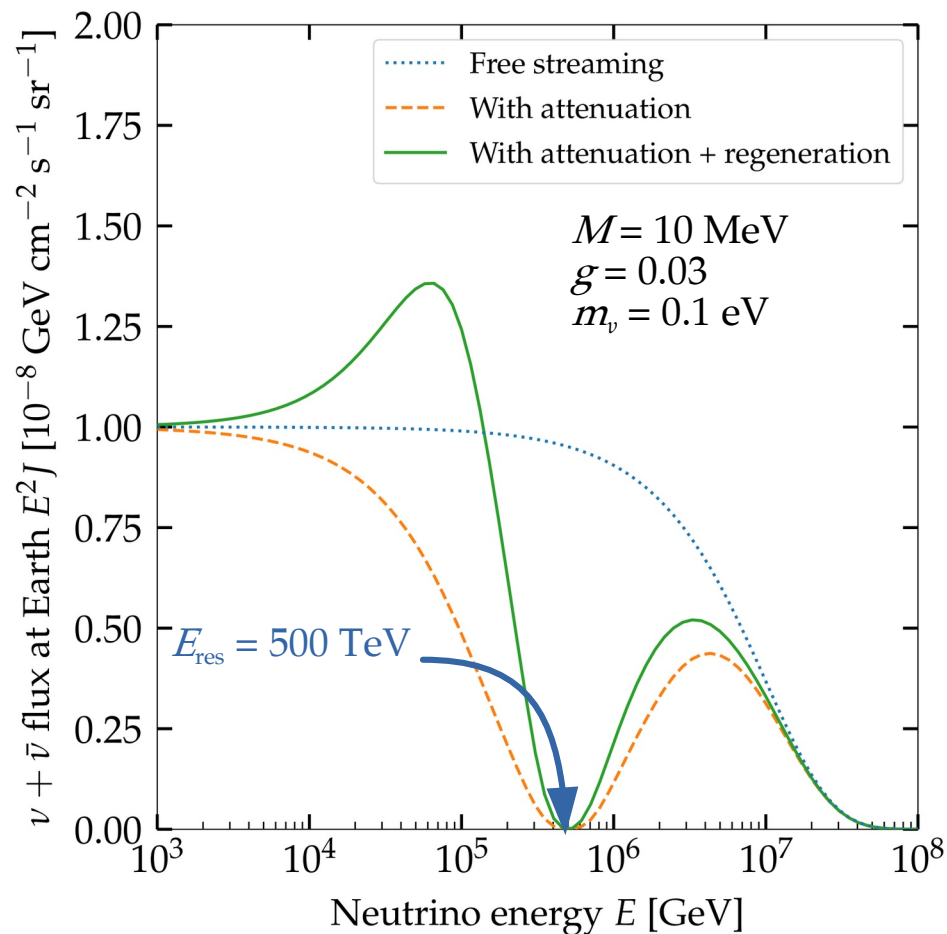


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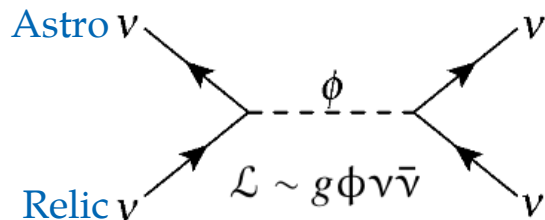
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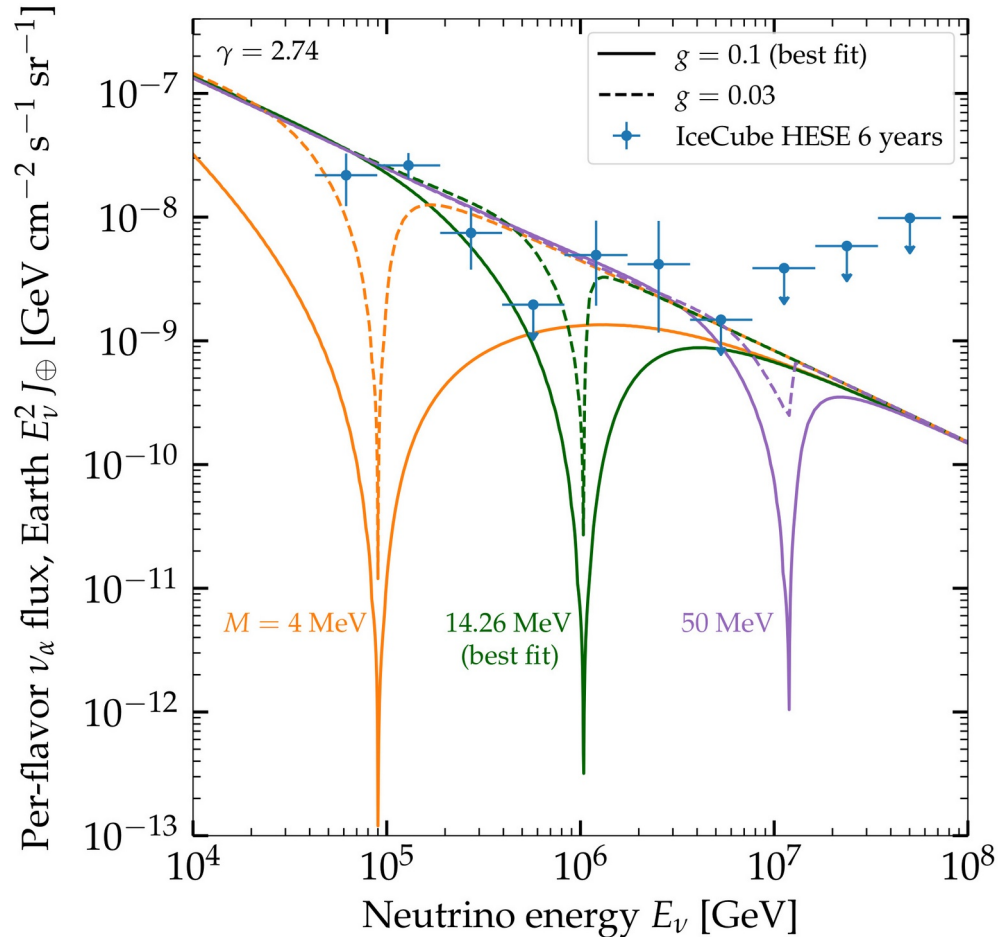


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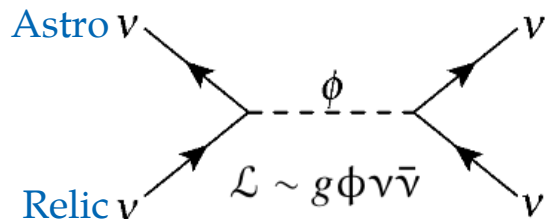
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New coupling g^4 (circled in red)

Mediator mass M^2 (circled in green)

Resonance energy:
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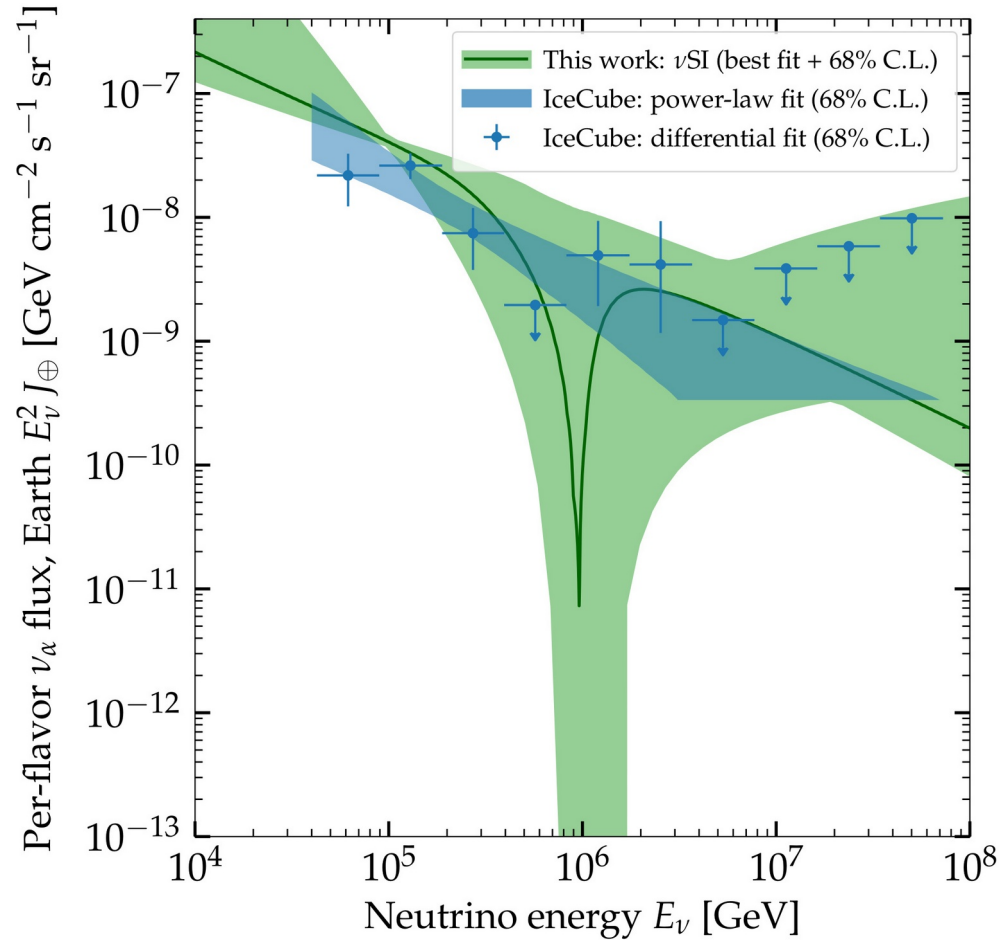
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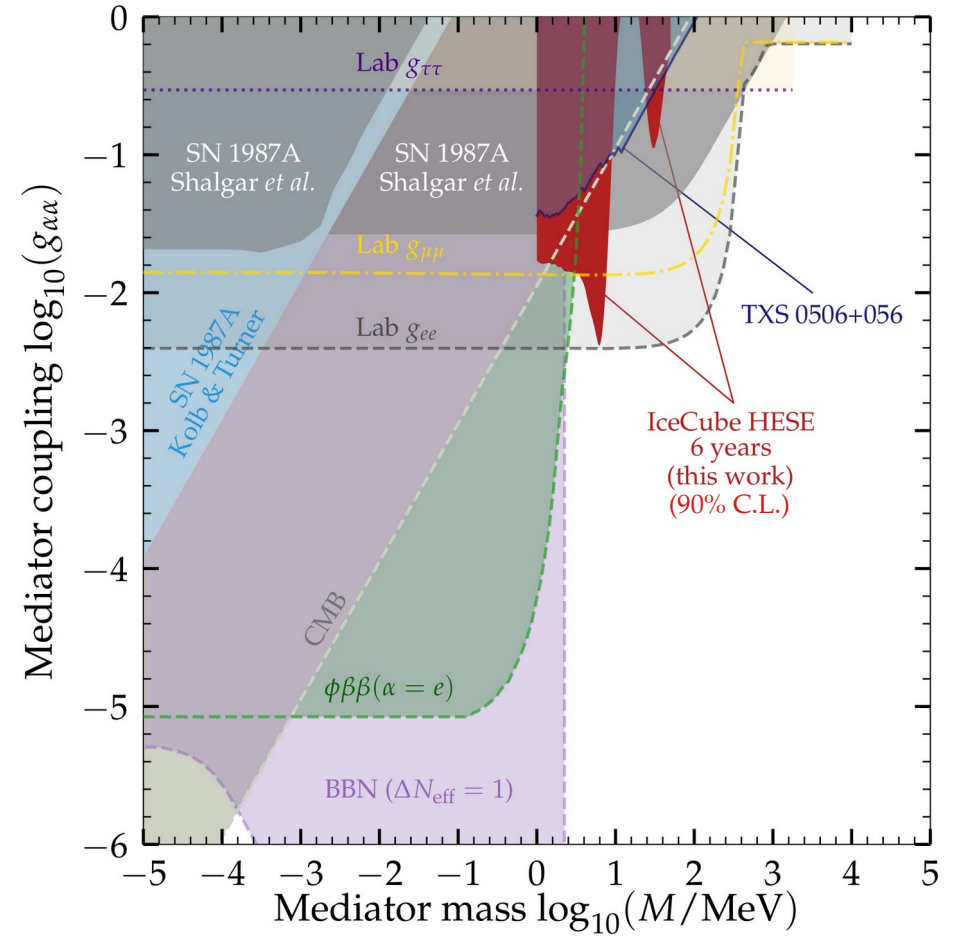
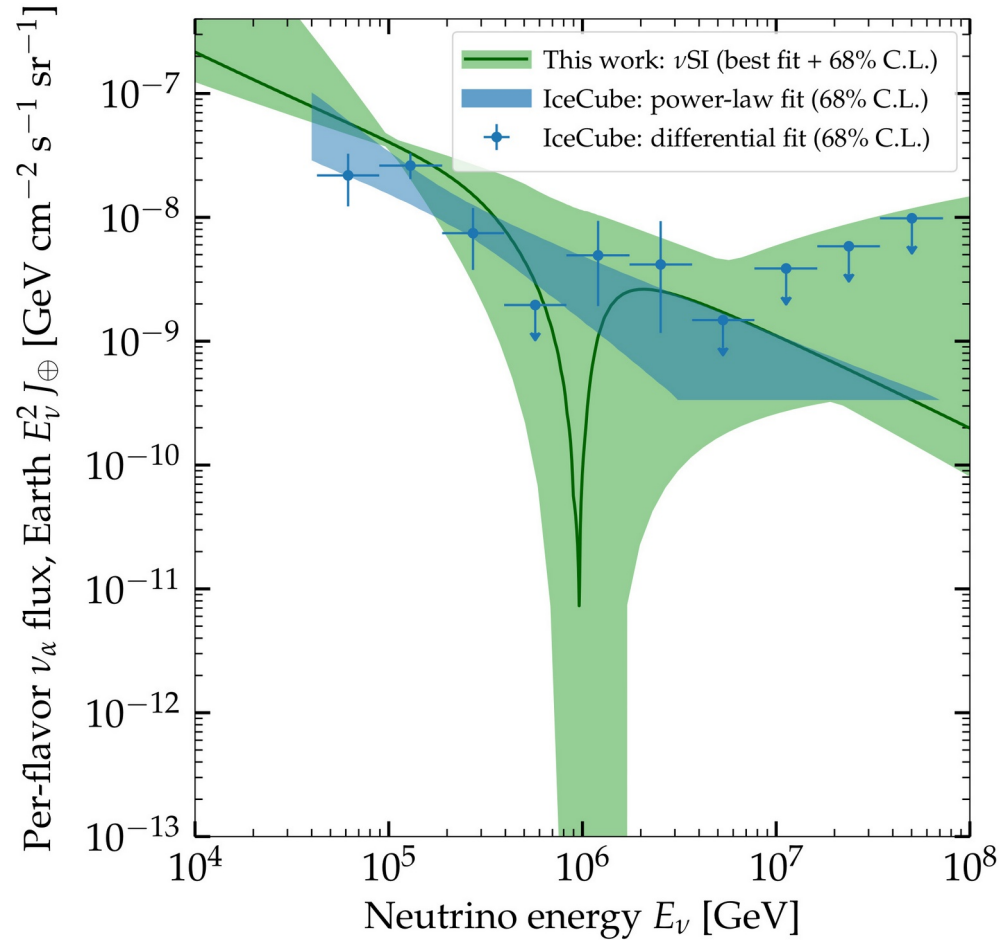
Looking for evidence of ν SI

- ▶ 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

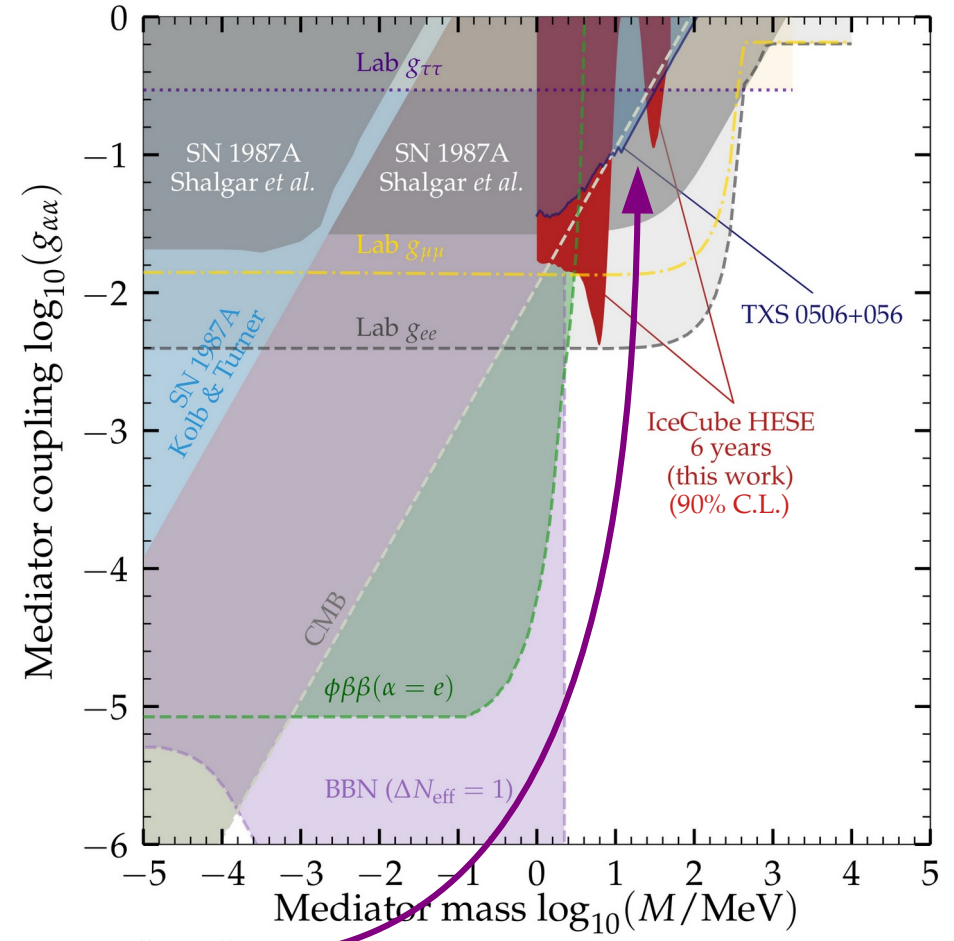
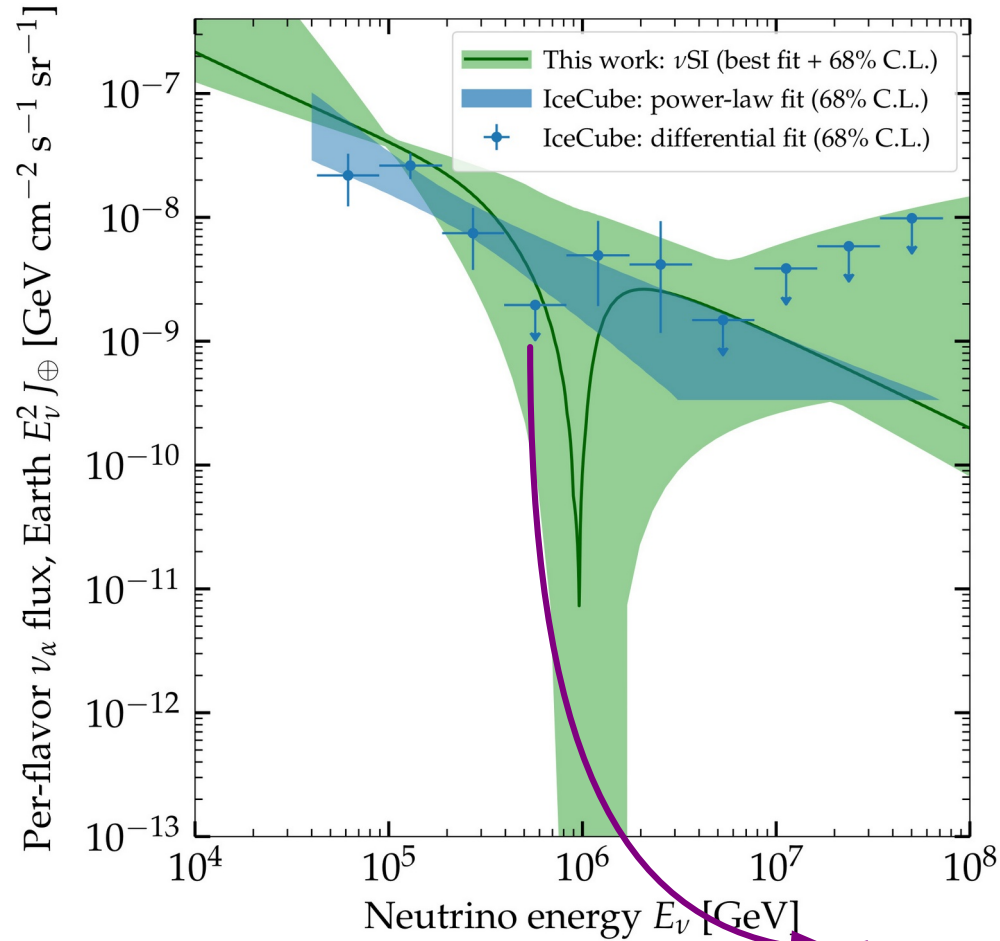
No significant ($> 3\sigma$) evidence for a spectral dip ...



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



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



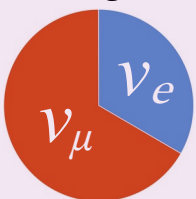
Testing new physics
via flavor

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

Sources



E.g.,



$(f_{e,S}, f_{\mu,S}, f_{\tau,S})$

Oscillations

$(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{CP})$

$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$

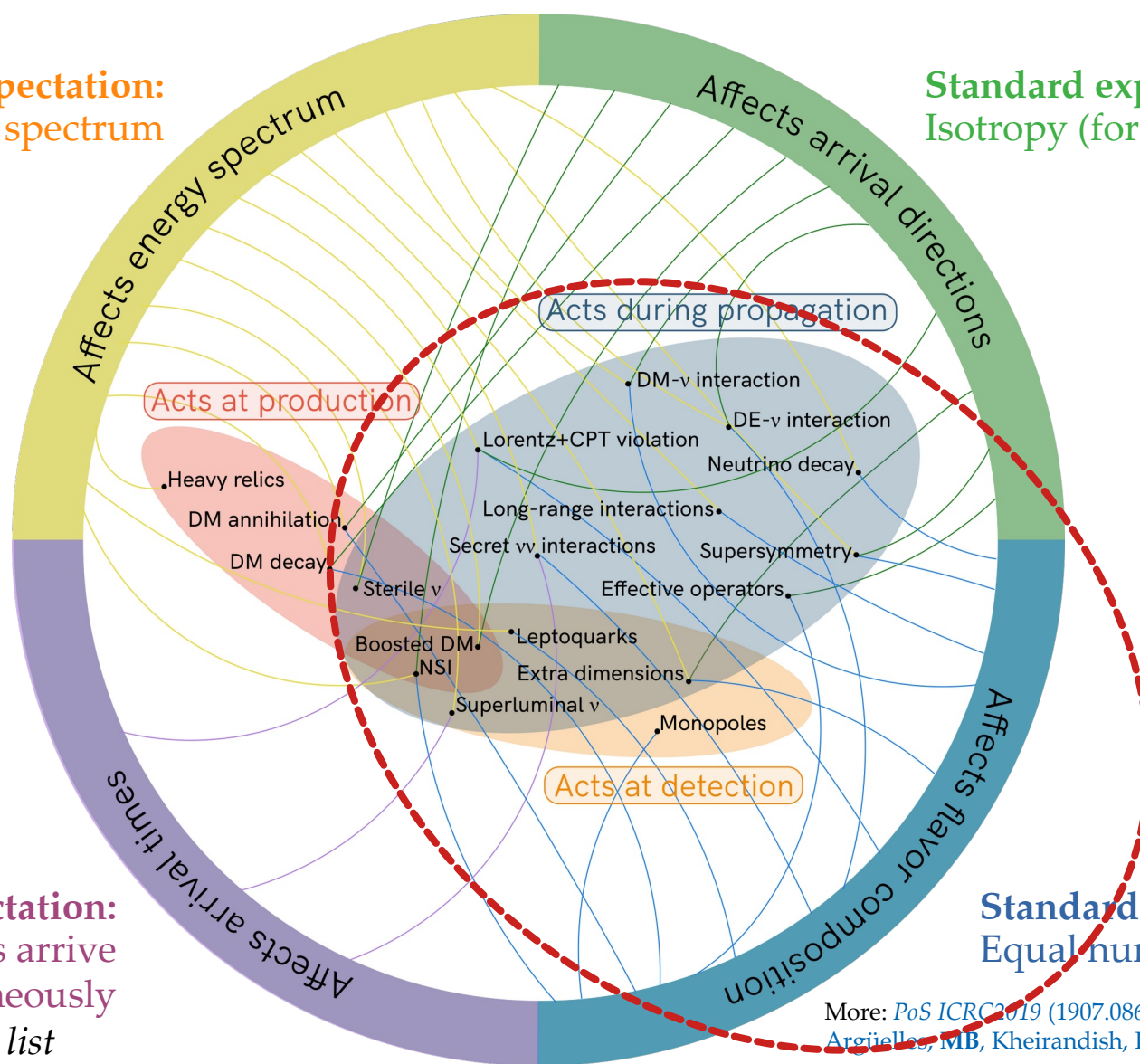
Earth



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

Standard expectation:
Equal number of ν_e , ν_μ , ν_τ

Note: Not an exhaustive list

More: *PoS ICRC2019* (1907.08690)

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

New physics in flavor composition

Use the flavor sensitivity to test new physics:

New physics in flavor composition

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Reviews:

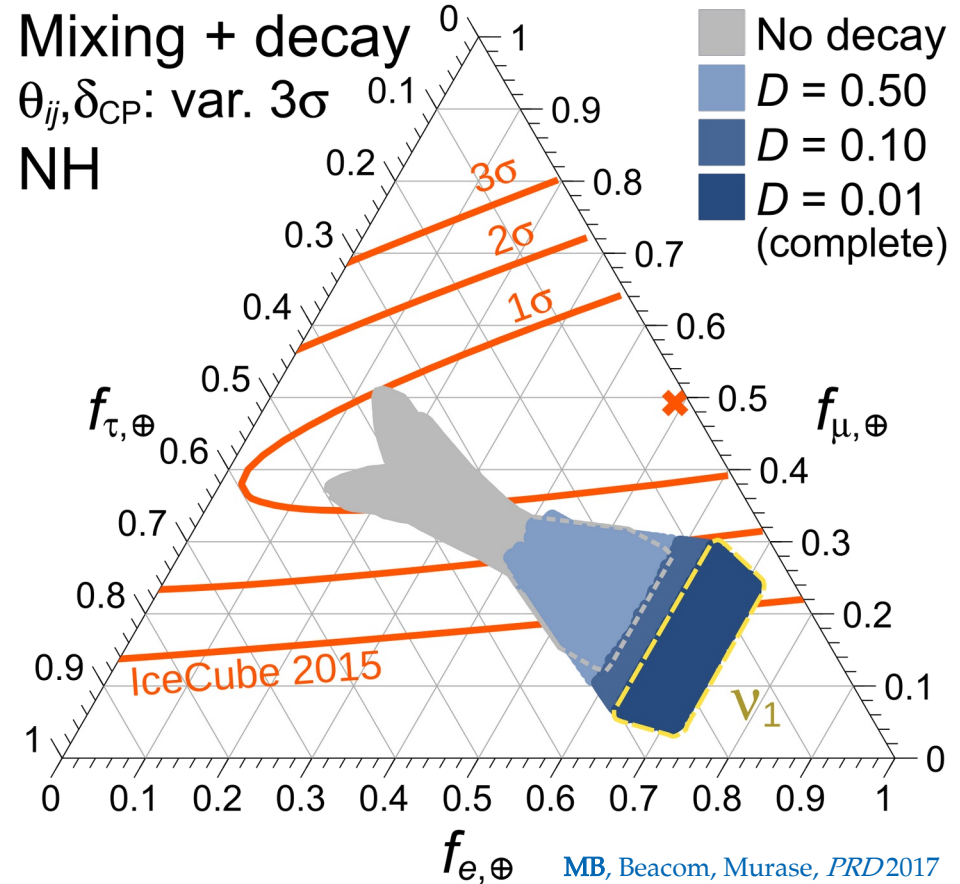
Argüelles *et al.* (inc. *MB*), *EPJC* 2023; Mehta & Winter, *JCAP* 2011; Rasmussen *et al.*, *PRD* 2017

New physics in flavor composition

Use the flavor sensitivity to test new physics:

► Neutrino decay

[Beacom *et al.*, *PRL* 2003; Baerwald, *MB*, Winter, *JCAP* 2010;
MB, Beacom, Winter, *PRL* 2015; *MB*, Beacom, Murase, *PRD* 2017]



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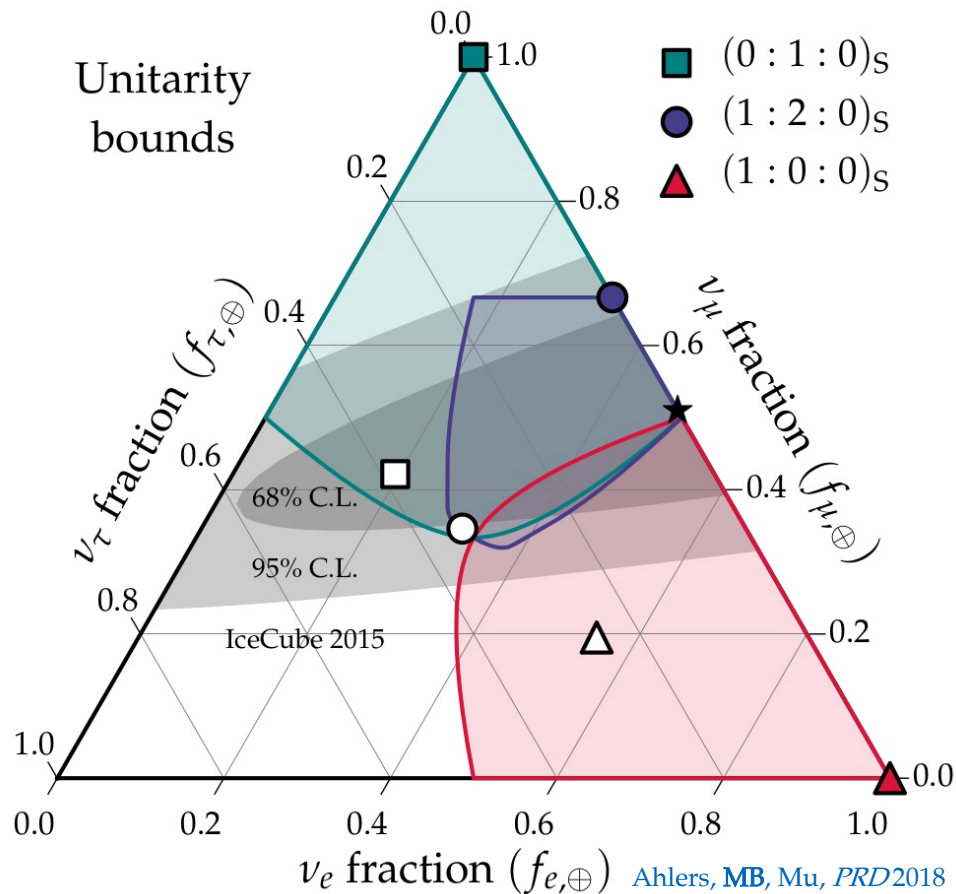
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- ▶ Tests of unitarity at high energy

[Xu, He, Rodejohann, *JCAP* 2014; Ahlers, *MB*, Mu, *PRD* 2018;
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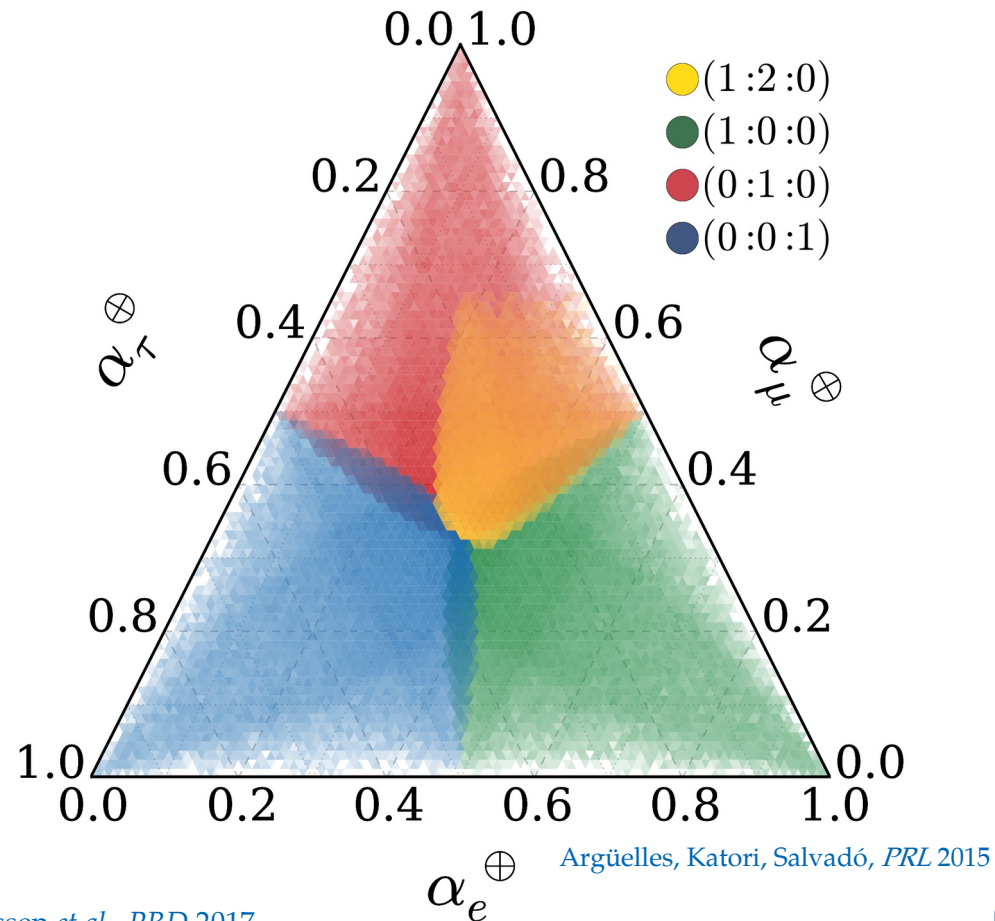
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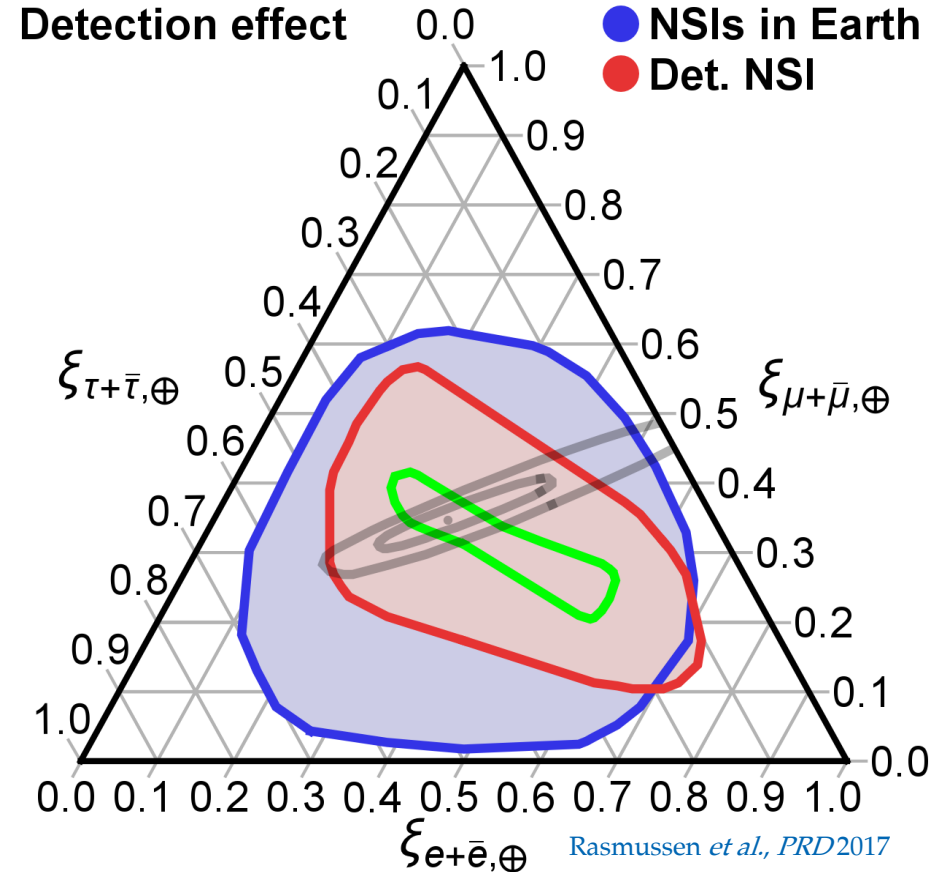
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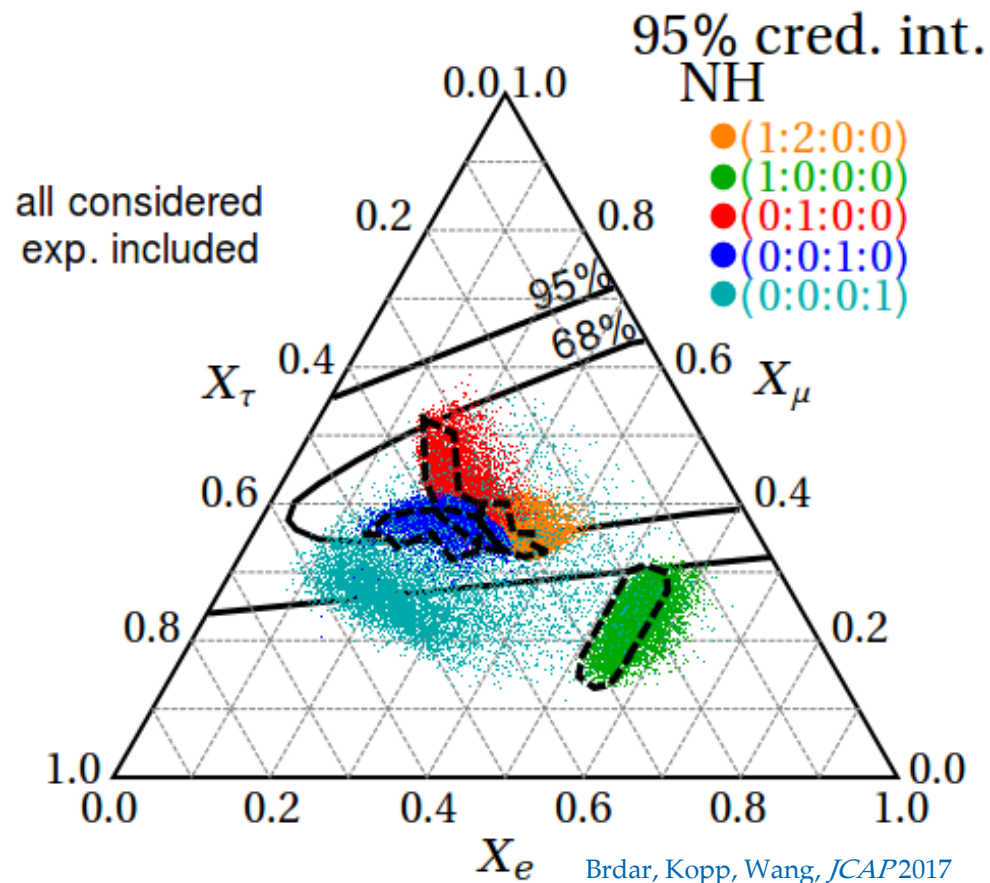
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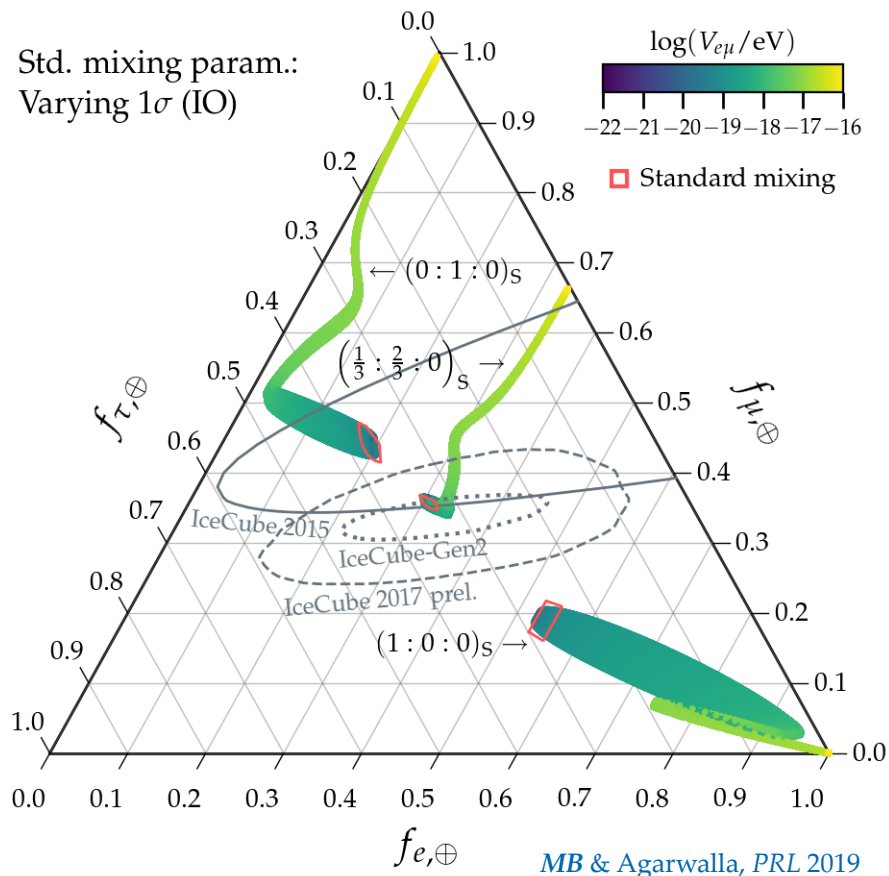
[Aeikens *et al.*, *JCAP* 2015; Brdar, Kopp, Wang, *JCAP* 2017;
Argüelles *et al.*, *JCAP* 2020; Ahlers, *MB*, *JCAP* 2021]

- ▶ Long-range $e\nu$ interactions

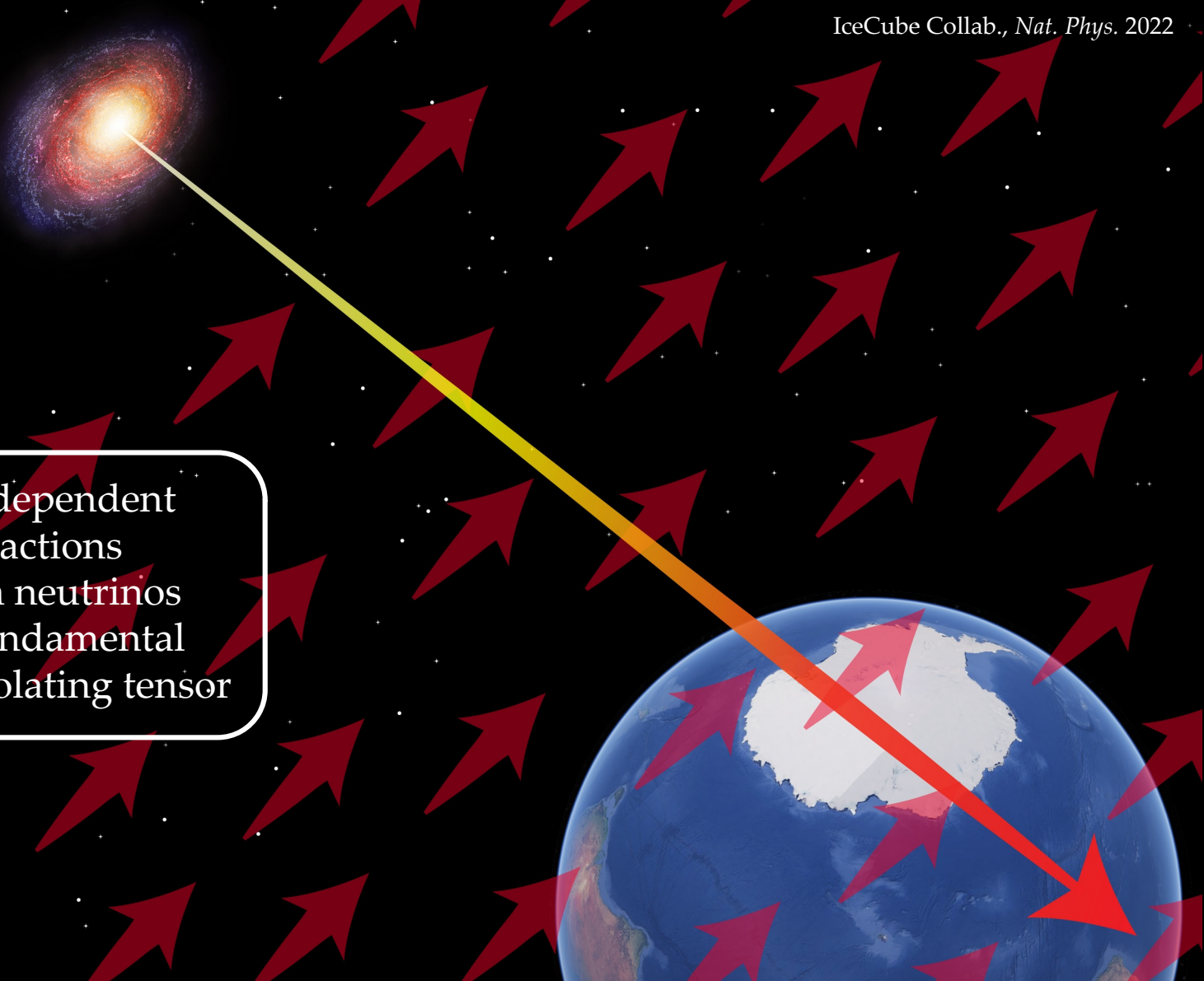
[*MB* & Agarwalla, *PRL* 2019]

Reviews:

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



Flavor-dependent
interactions
between neutrinos
and a fundamental
Lorentz-violating tensor



Standard oscillations:

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

Lorentz-violating interactions (Standard Model Extension):

Kostelecky, Mewes, PRD 2004

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

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

Total Hamiltonian:

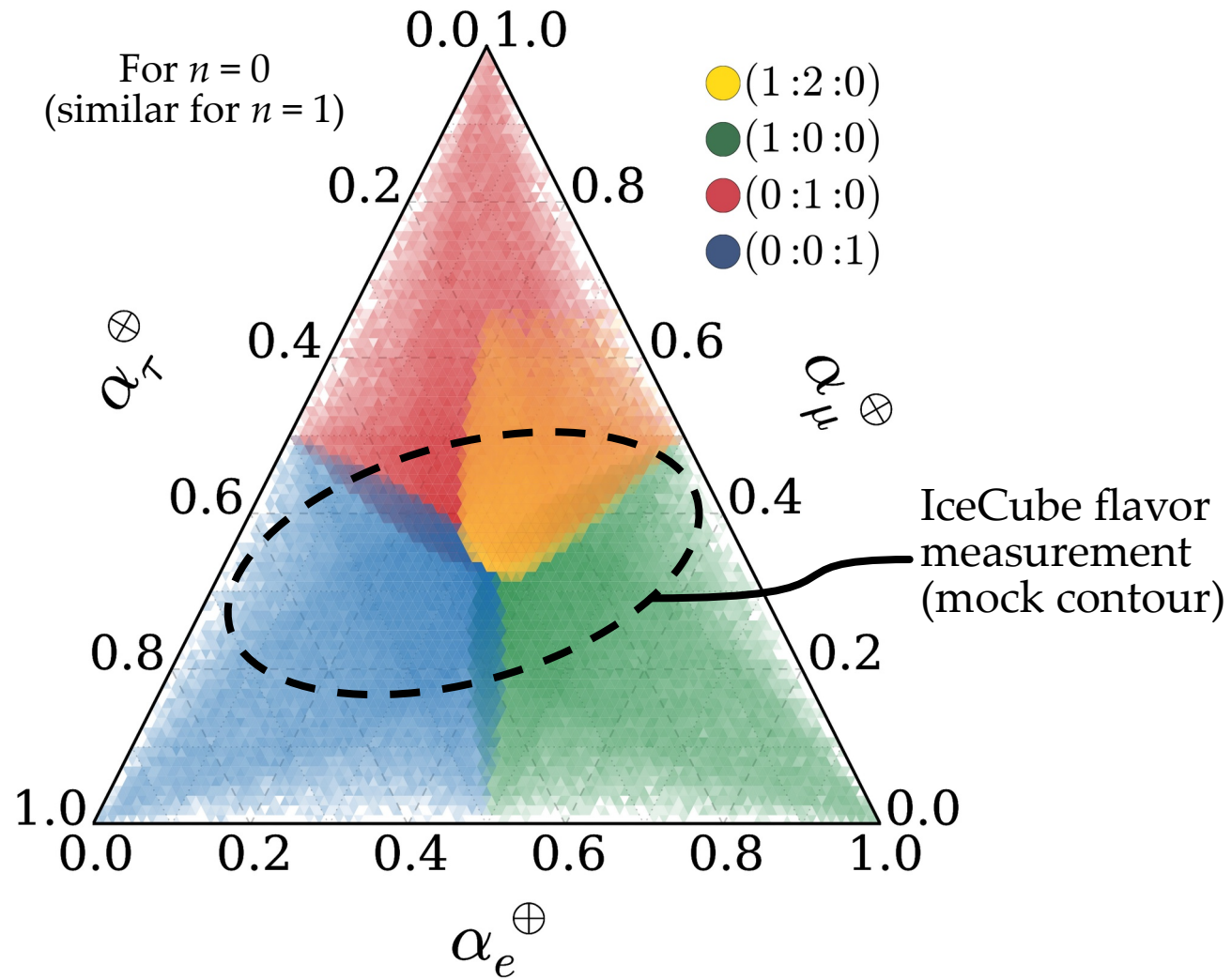
$$H_{\text{tot}} = H_{\text{std}} + H_{\text{new}}$$

The flavor-transition probabilities are calculated as before,

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

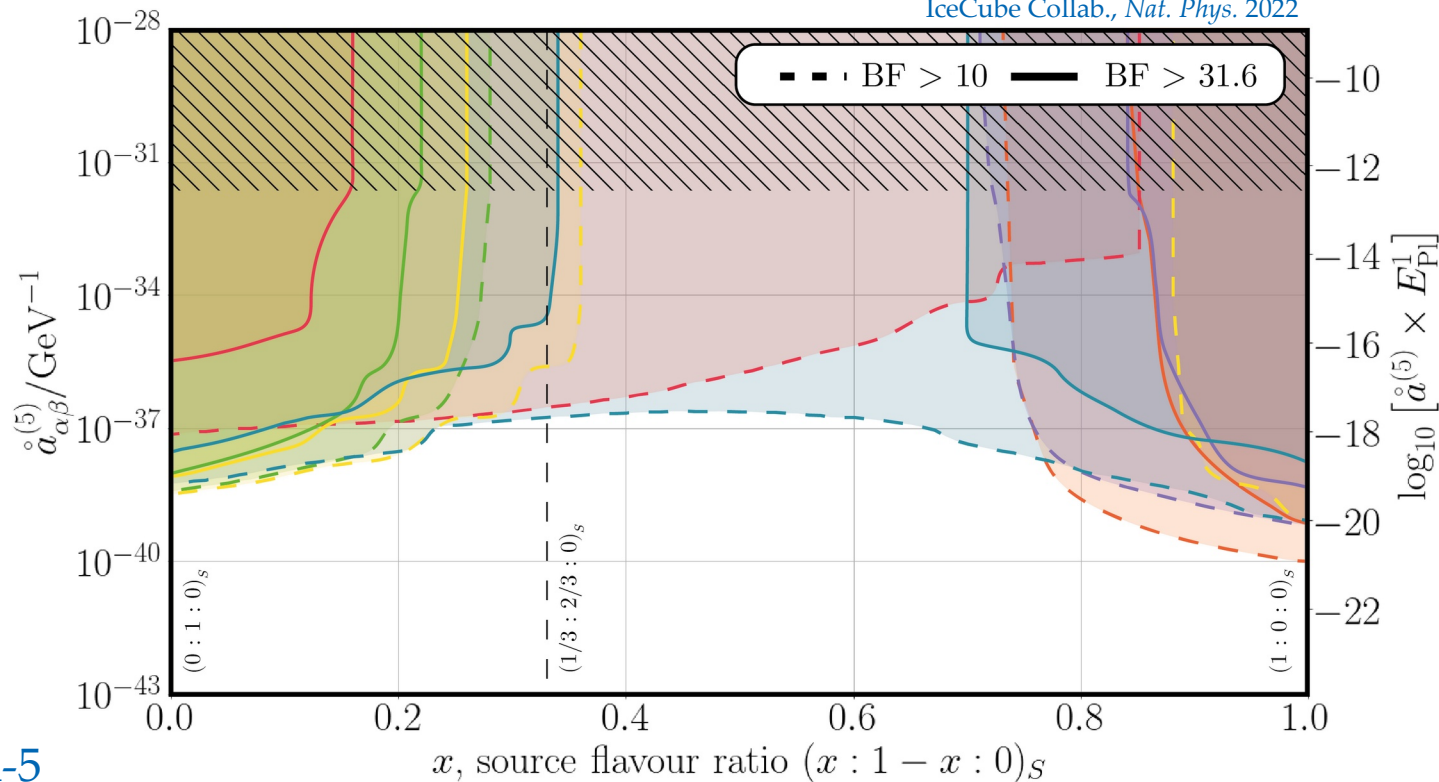
Depends on standard & new parameters

but now the lepton mixing matrix, $\mathbf{U}_{\text{tot}}$, is the one that diagonalizes H_{tot}

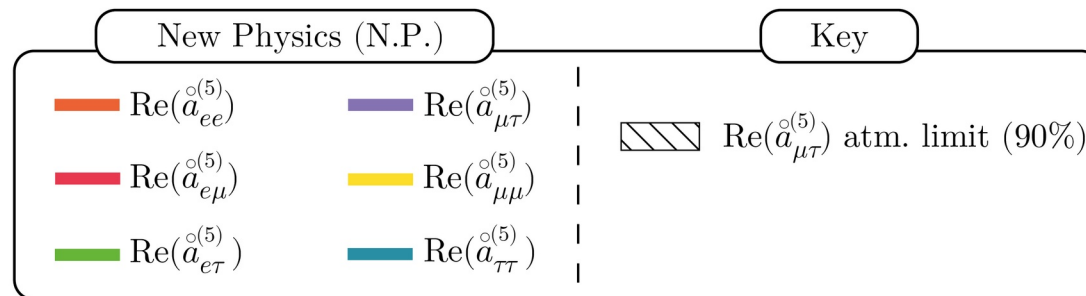


Argüelles, Katori, Salvadó, *PRL* 2015

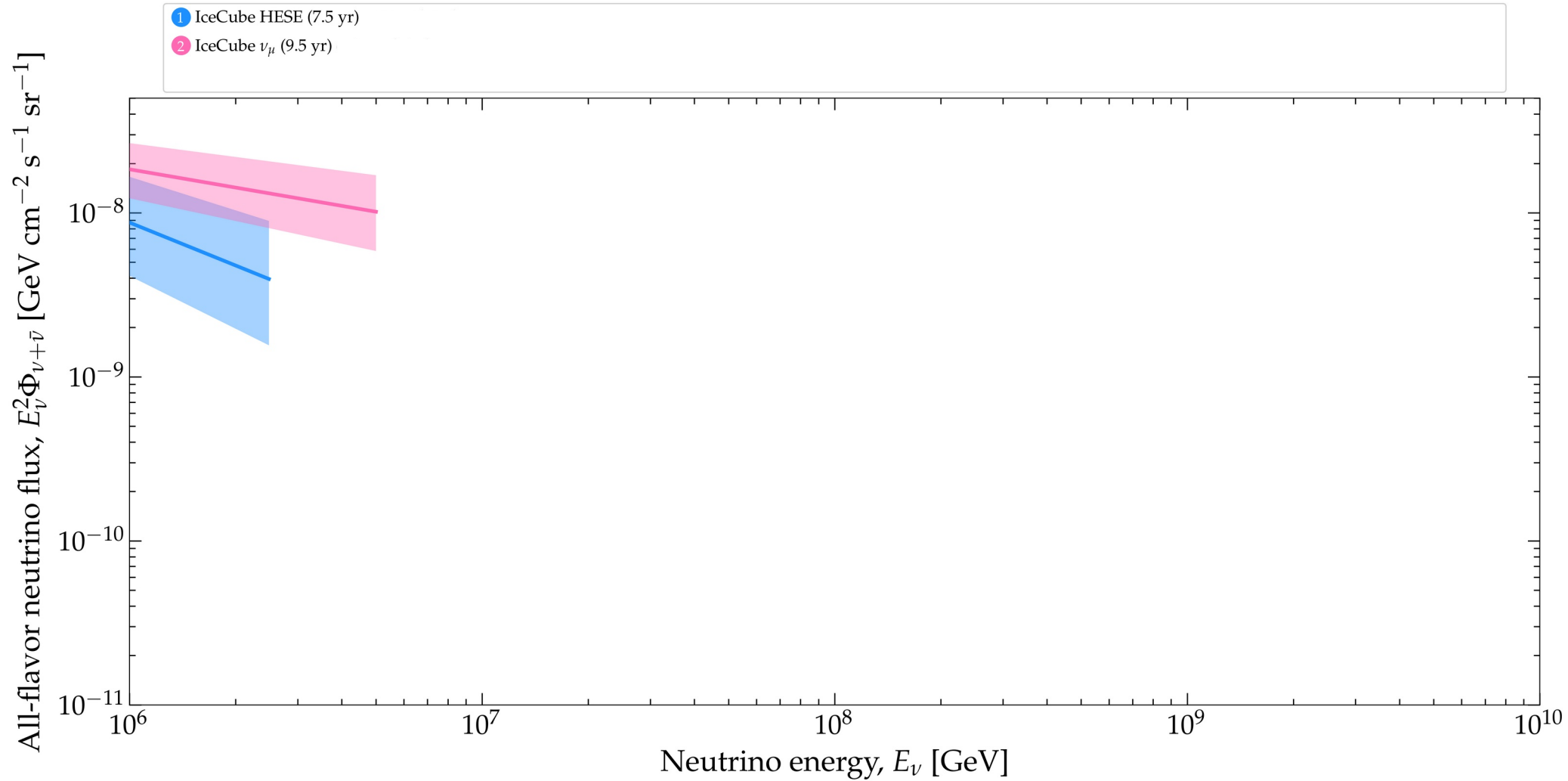
See also Ahlers, **MB**, Mu, *PRD* 2018; Rasmussen *et al.*, *PRD* 2017; **MB**, Beacom, Winter *PRL* 2015;
MB, Gago, Peña-Garay *JCAP* 2010; Bazo, **MB**, Gago, Miranda *IJMPA* 2009; + many others

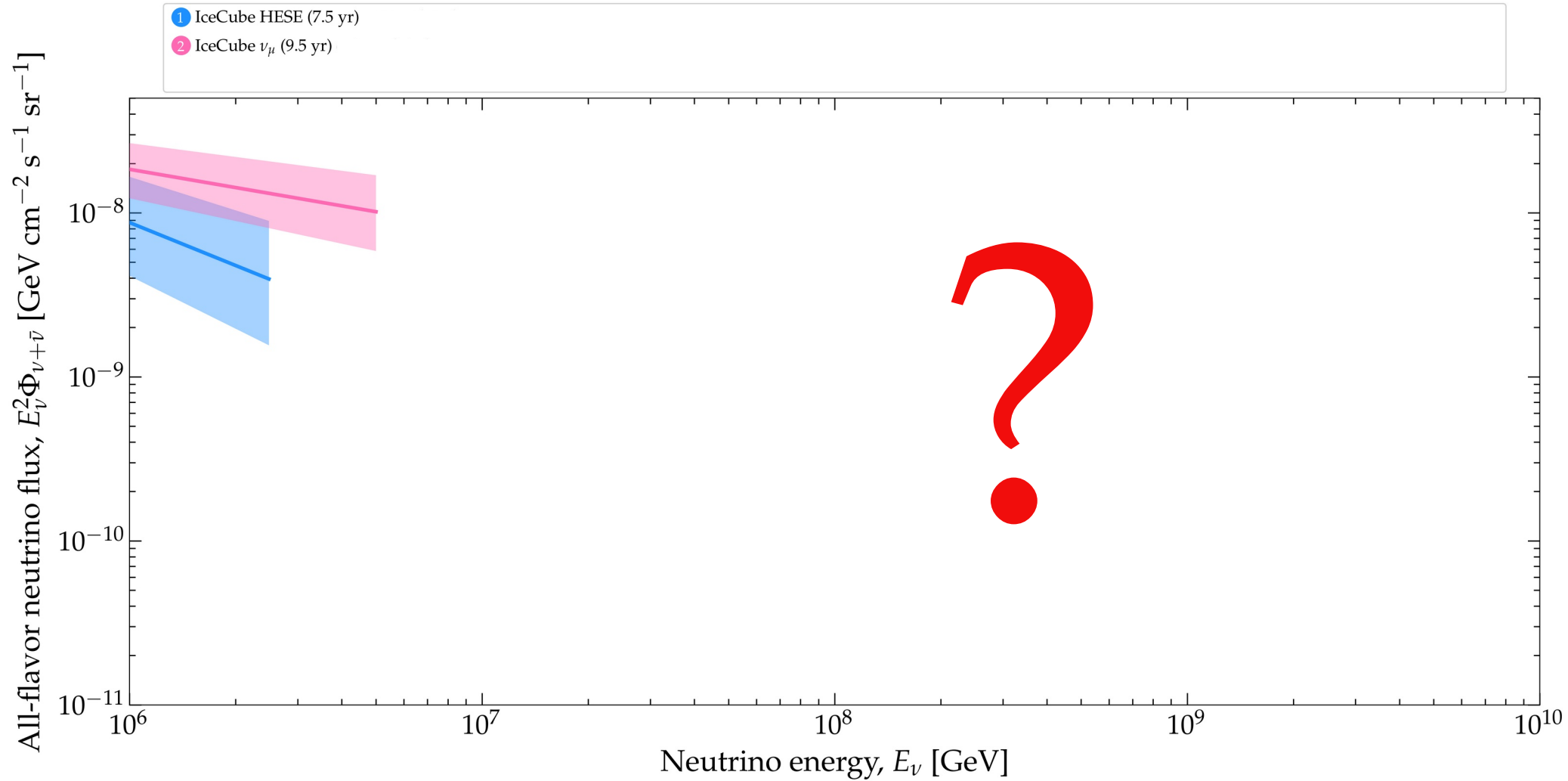


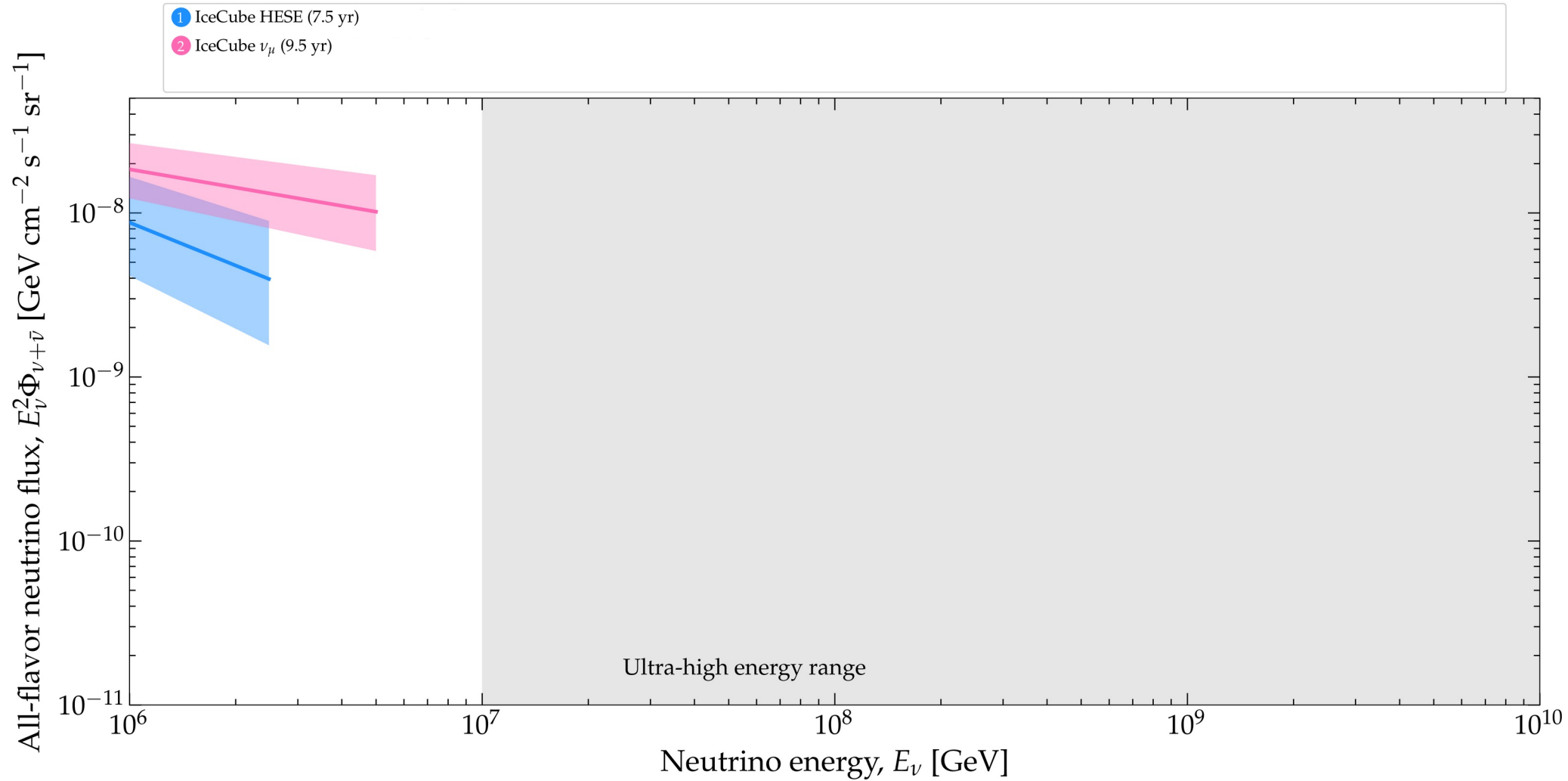
Dimension-5
CPT-odd
isotropic
Lorentz-invariance
-violating
coefficient

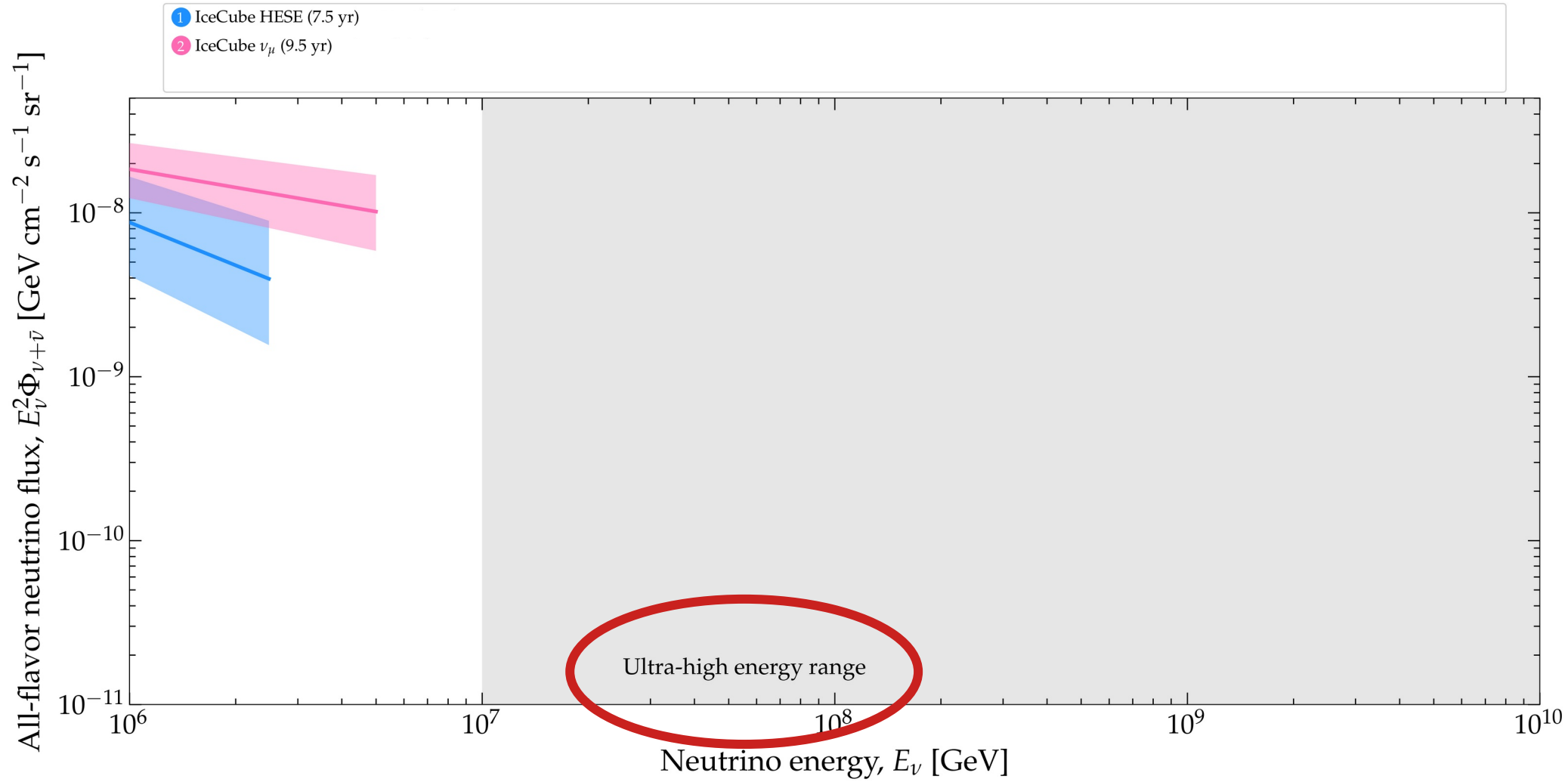


Ultra-high
energies (> 100 PeV)



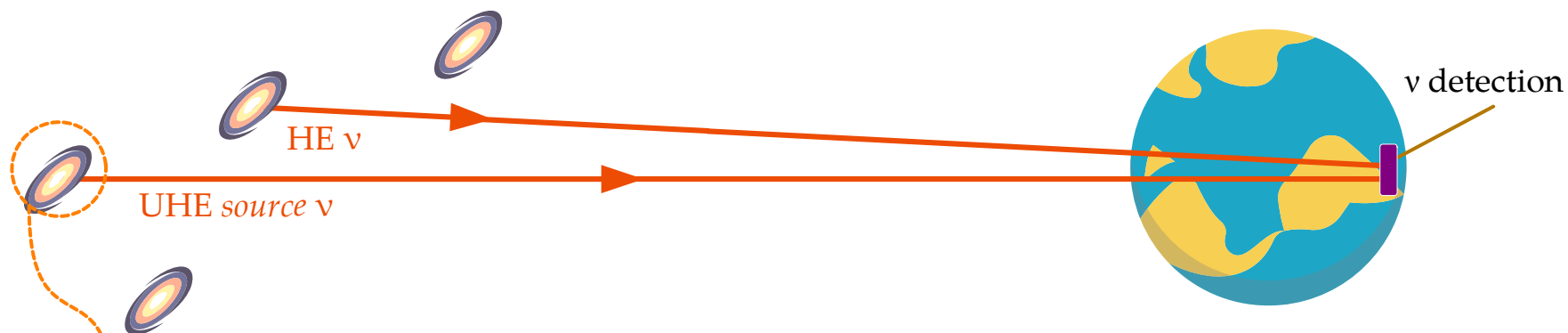






Redshift

$z = 0$



meV γ

Undiscovered

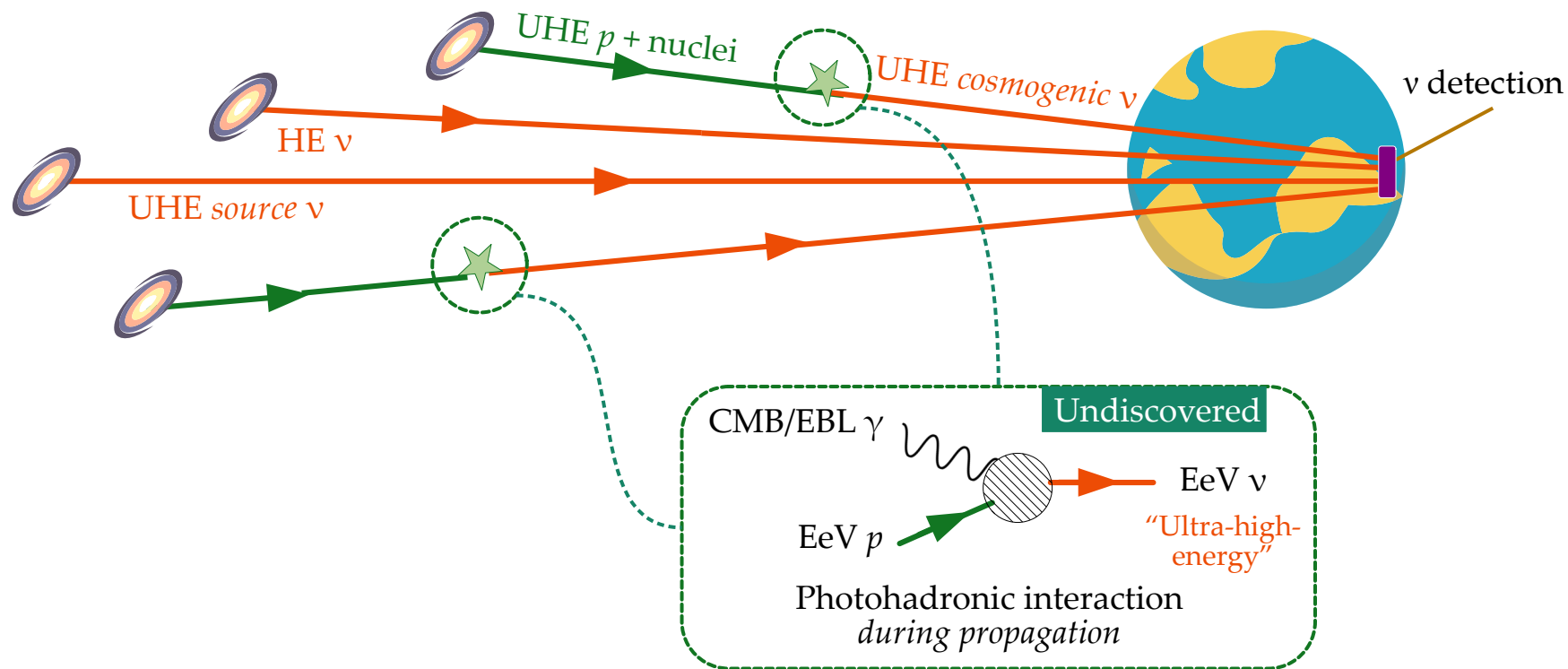
EeV p

EeV ν

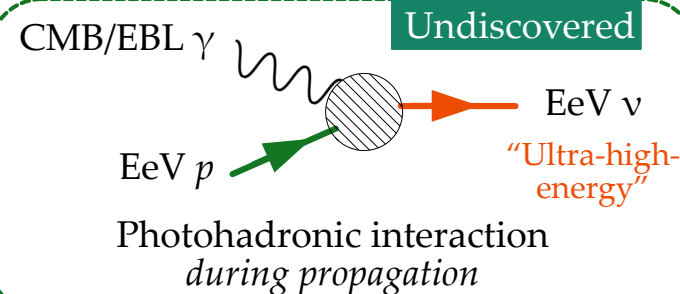
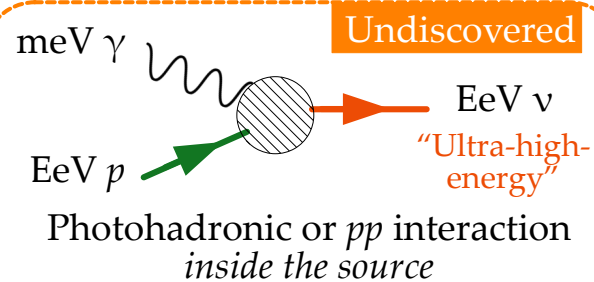
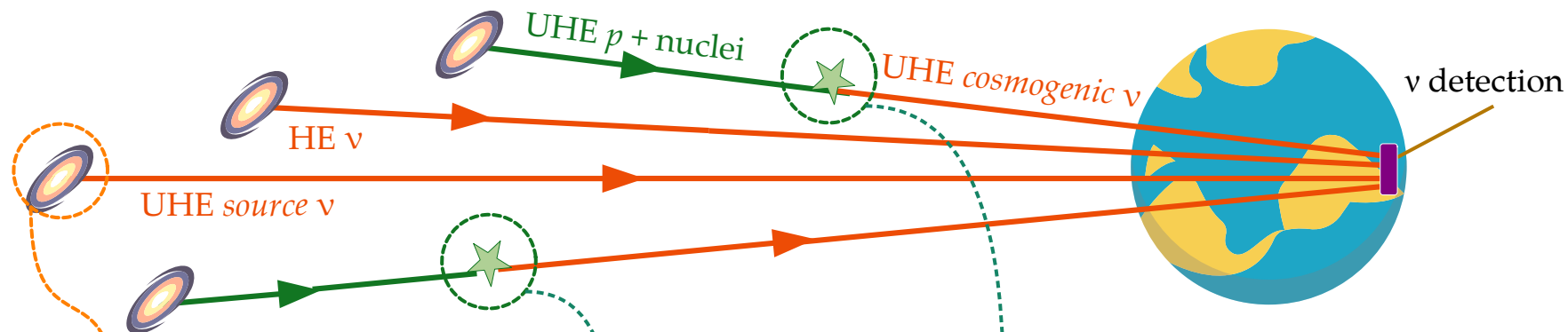
"Ultra-high-energy"

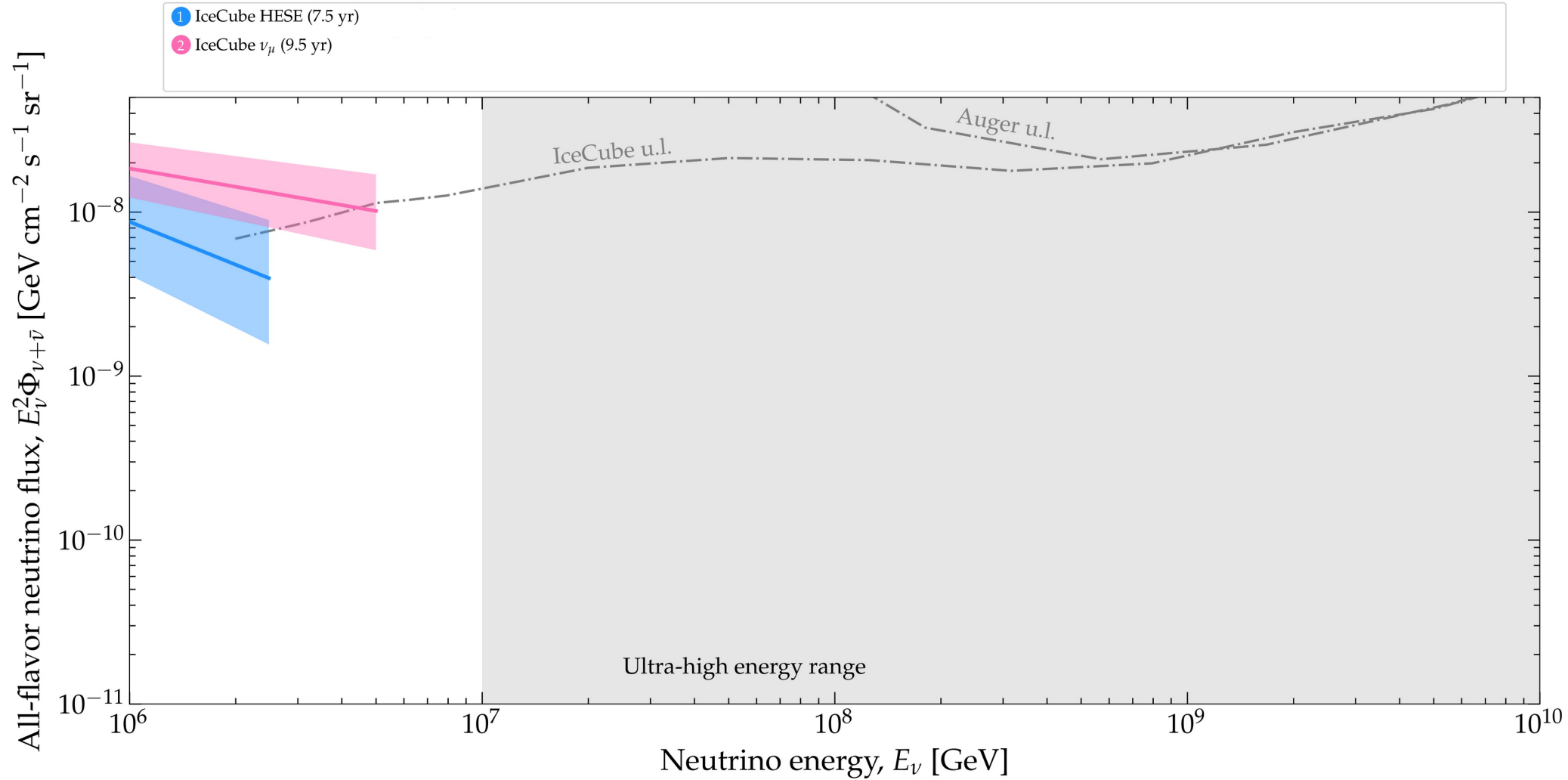
Photohadronic or pp interaction
inside the source

Redshift ← $z = 0$



Redshift ← $z = 0$





The international journal of science / 13 February 2025

nature

COSMIC CATCHER

Deep-sea telescope detects
neutrino with highest
energy ever recorded

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

The international journal of science / 13 February 2025

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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

But is it due to a neutrino?

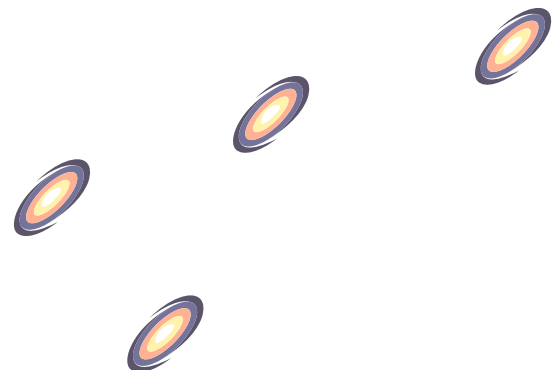
Yes! Direction points underground,
after traveling 150 km through Earth

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

Redshift



$z = 0$



Redshift



$z = 0$

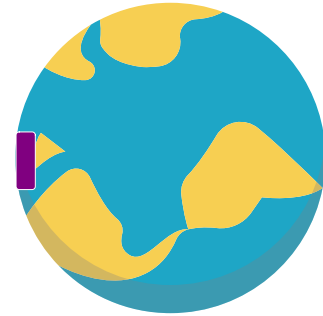
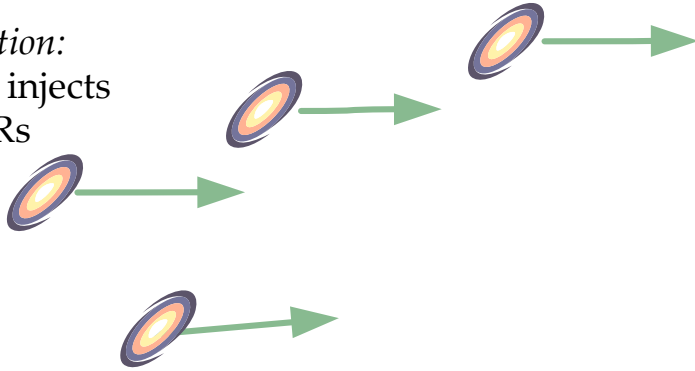
At production:
Each source injects
UHECRs



Redshift ←  $z = 0$

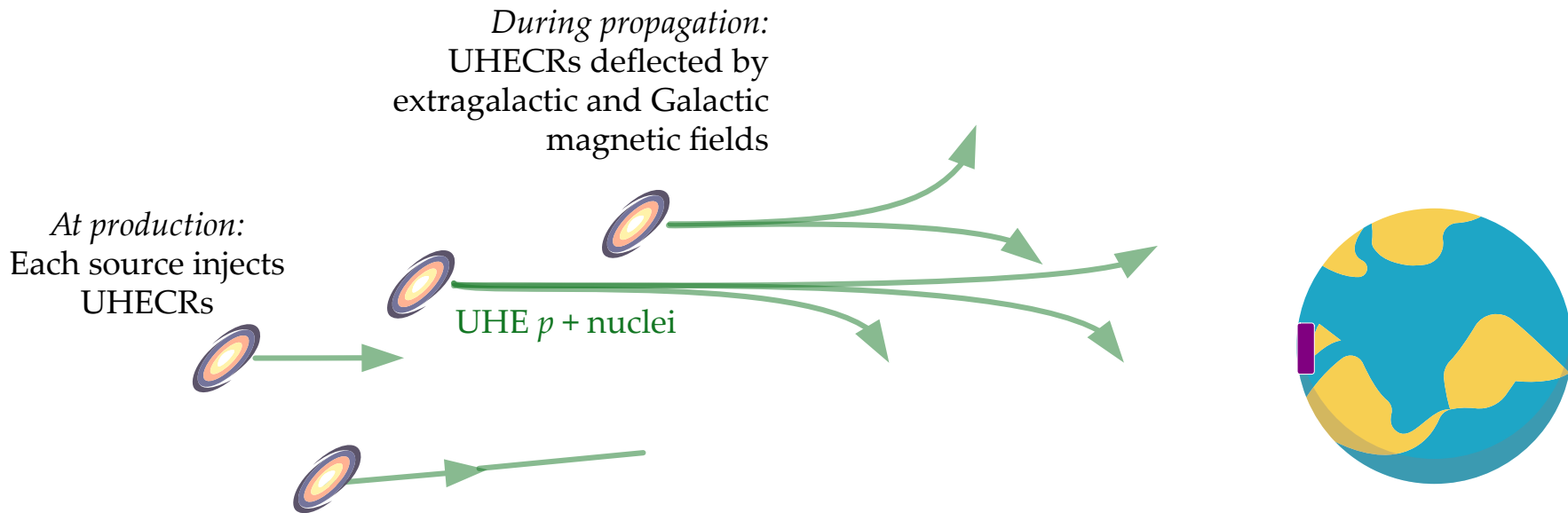
UHECR sources distributed in redshift (e.g., as star-formation rate)

At production:
Each source injects
UHECRs



Redshift ← $z = 0$

UHECR sources distributed in redshift (e.g., as star-formation rate)



Redshift ← $z = 0$

UHECR sources distributed in redshift (e.g., as star-formation rate)

During propagation:
UHECRs deflected by
extragalactic and Galactic
magnetic fields

At production:
Each source injects
UHECRs

UHE $p + \text{nuclei}$



During propagation:
UHECRs lose energy
and photodisintegrate
by interacting with cosmic
photon backgrounds

CMB/EBL γ

e^+, e^-

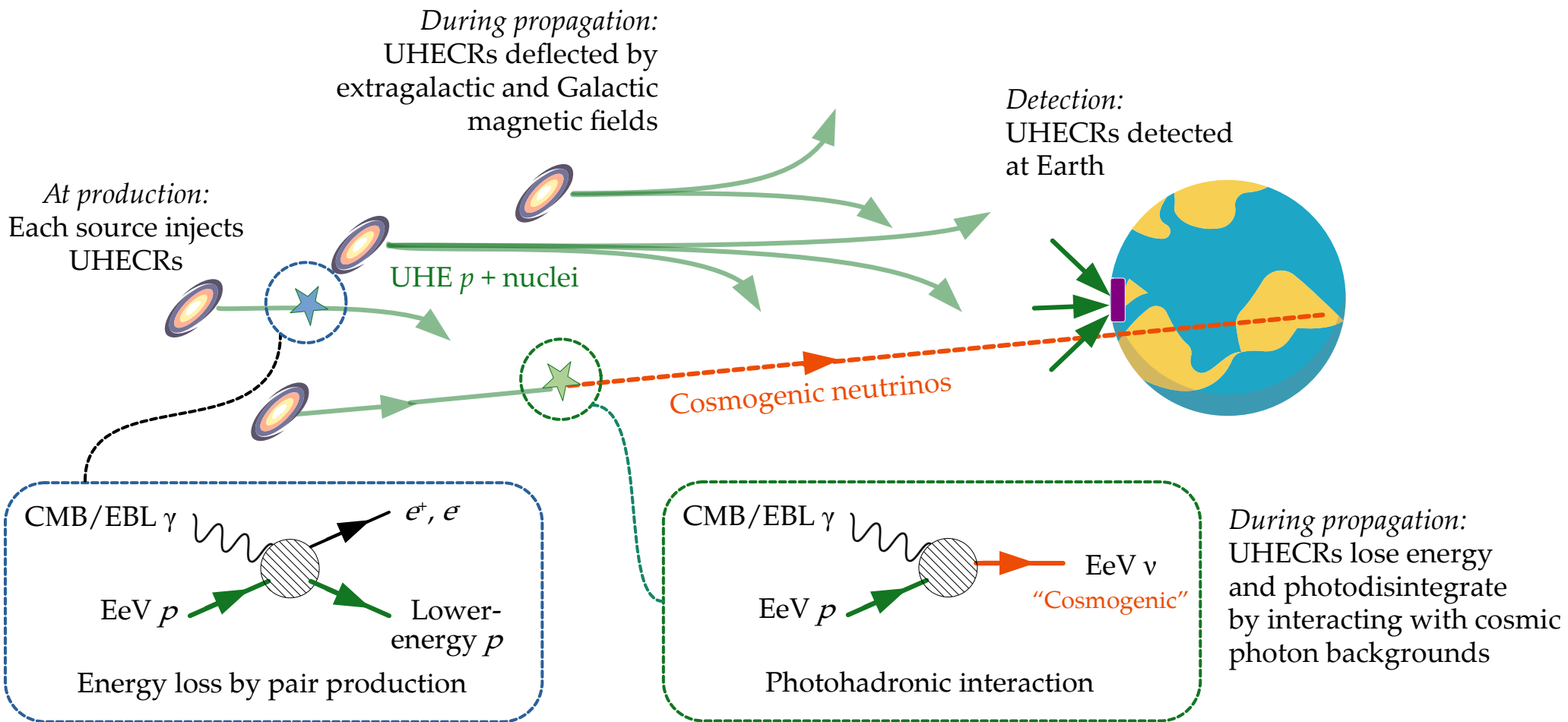
EeV p

Lower-energy p

Energy loss by pair production

Redshift $\longleftarrow$ $\longrightarrow$ $z = 0$

UHECR sources distributed in redshift (e.g., as star-formation rate)



Tests at ultra-high
energies (> 100 PeV)

Lorentz-invariance violation — from superluminal speeds

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

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

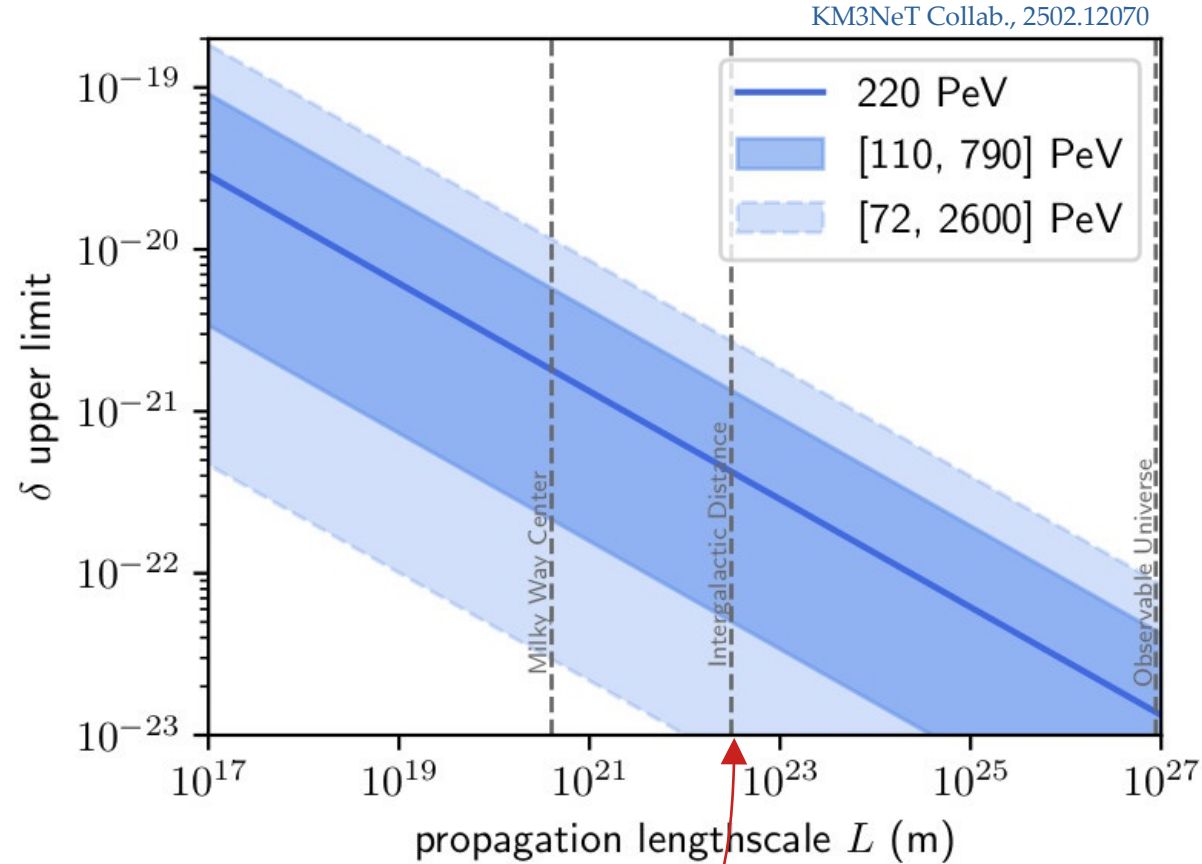
Cohen & Glashow, *PRL* 2011

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

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

Decay width

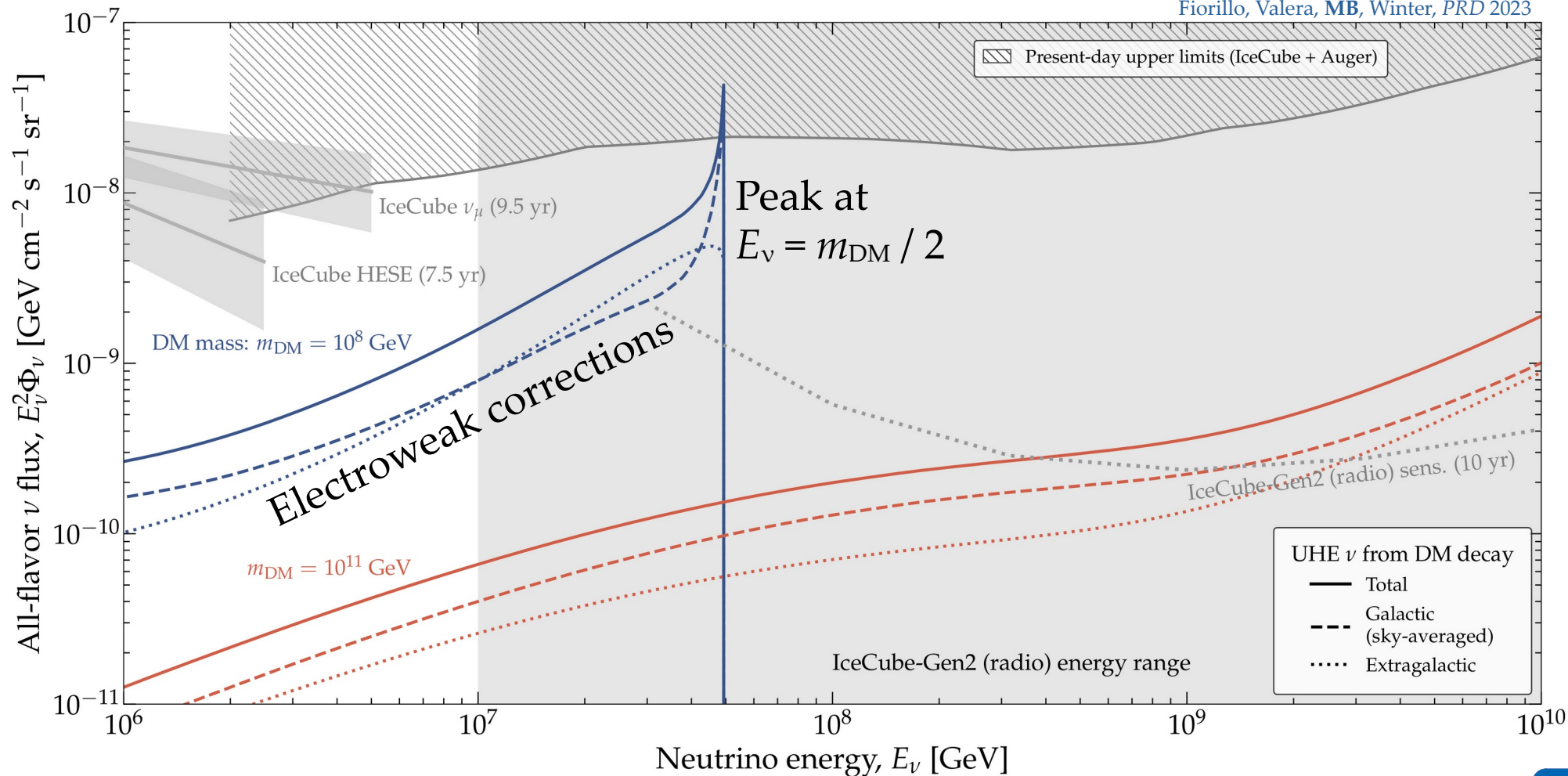
Demanding that the travel distance $L < 10 L_{\text{dec}}$ sets upper limits on δ



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

Decay of heavy dark matter ($\text{DM} \rightarrow \nu + \nu$)

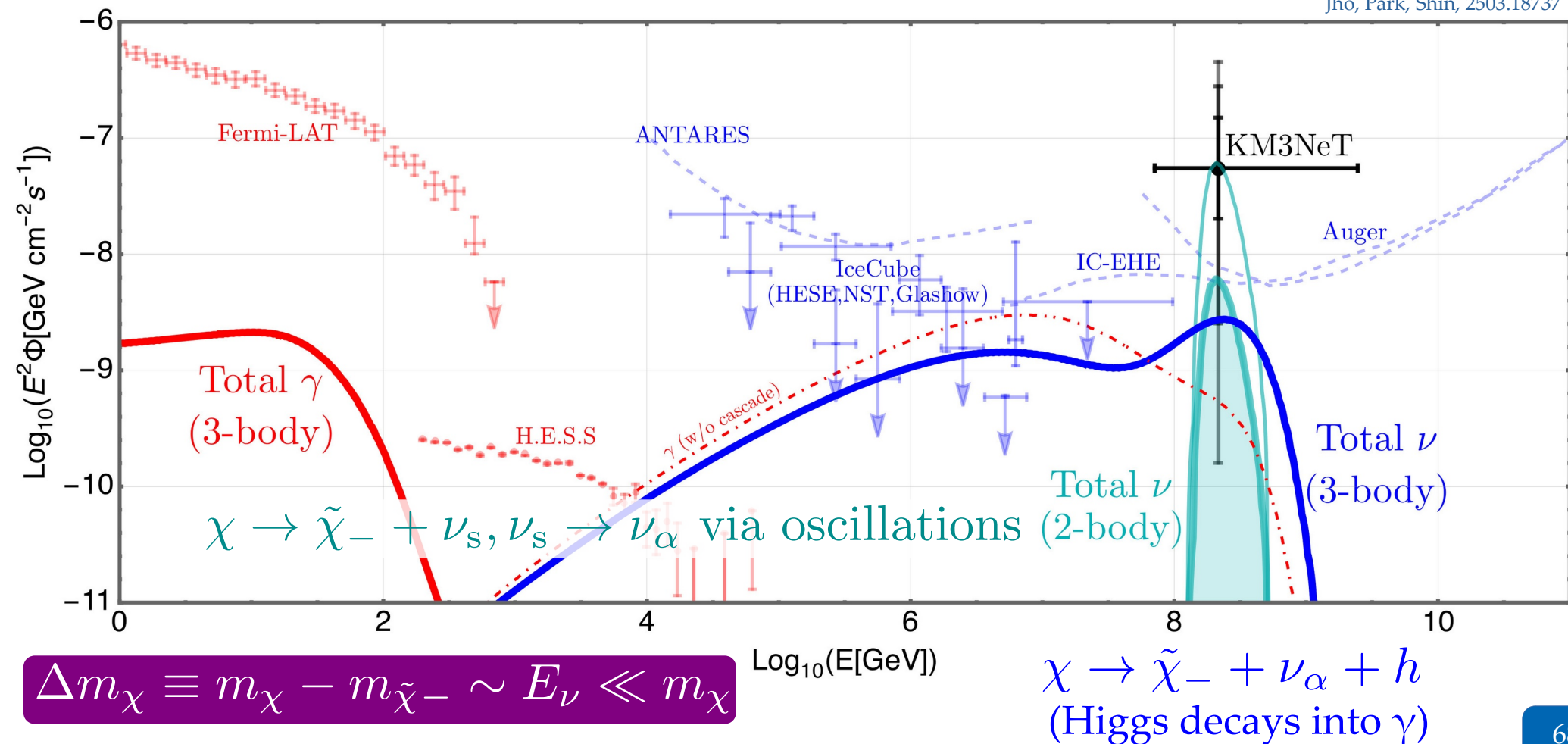
Fiorillo, Valera, MB, Winter, *PRD* 2023



Decay of heavy dark matter — supersymmetric

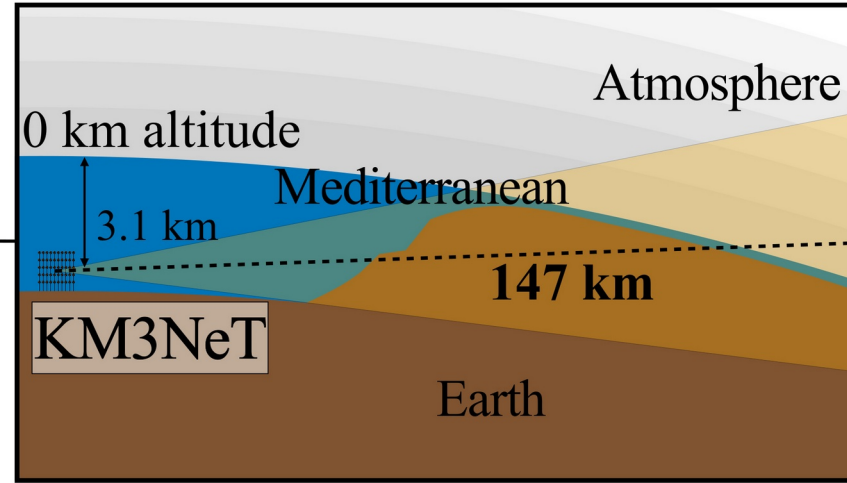
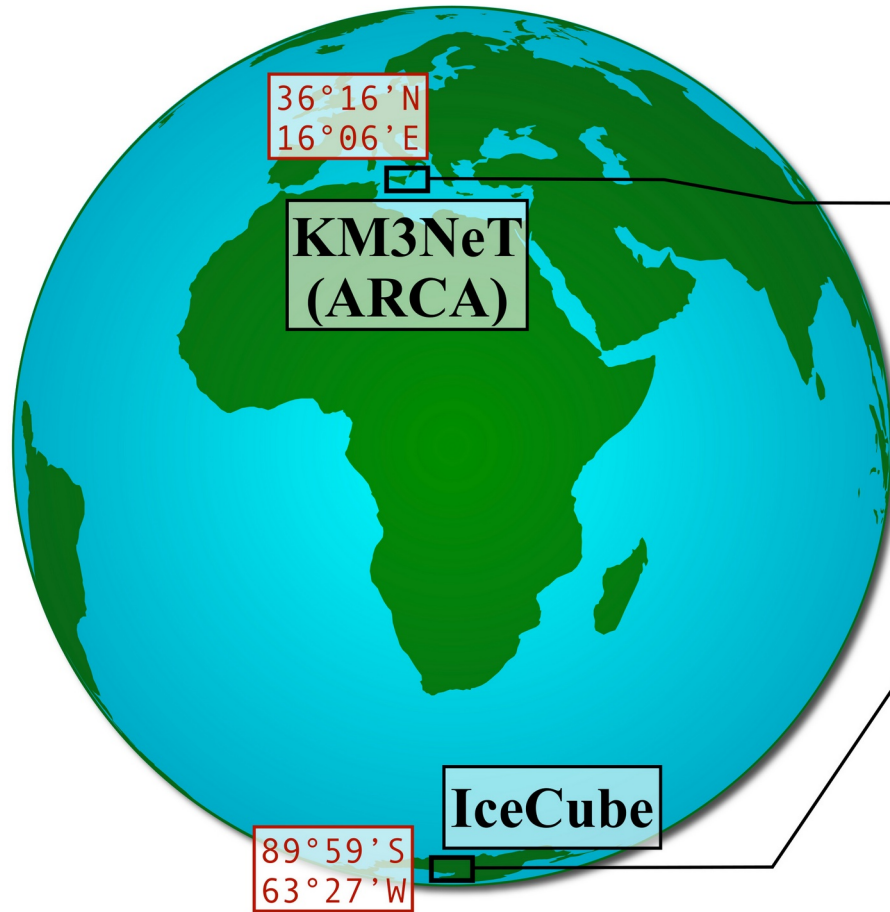
Multi-component DM: heavy (χ , unstable) & lighter ($\tilde{\chi}_-$, stable)

Jho, Park, Shin, 2503.18737

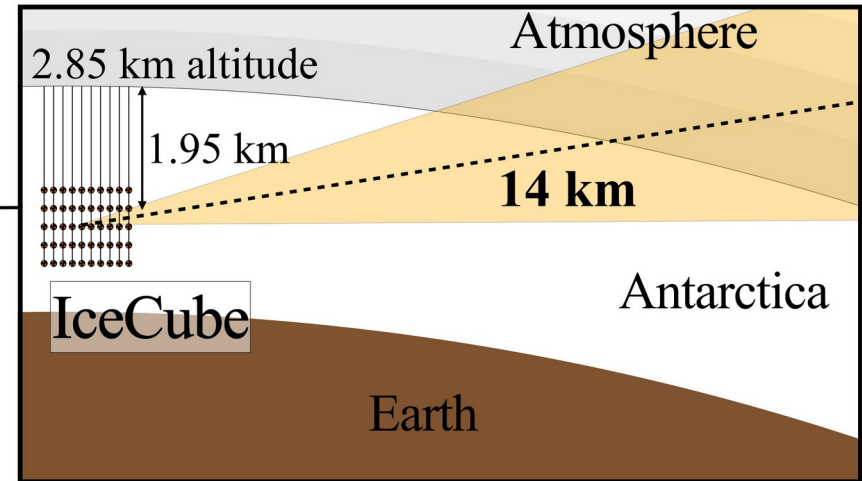


Sterile-active ν transitions

Brdar & Chattopadhyay, 2502.21299



High-energy
keV-scale
sterile
neutrino
 ν_s

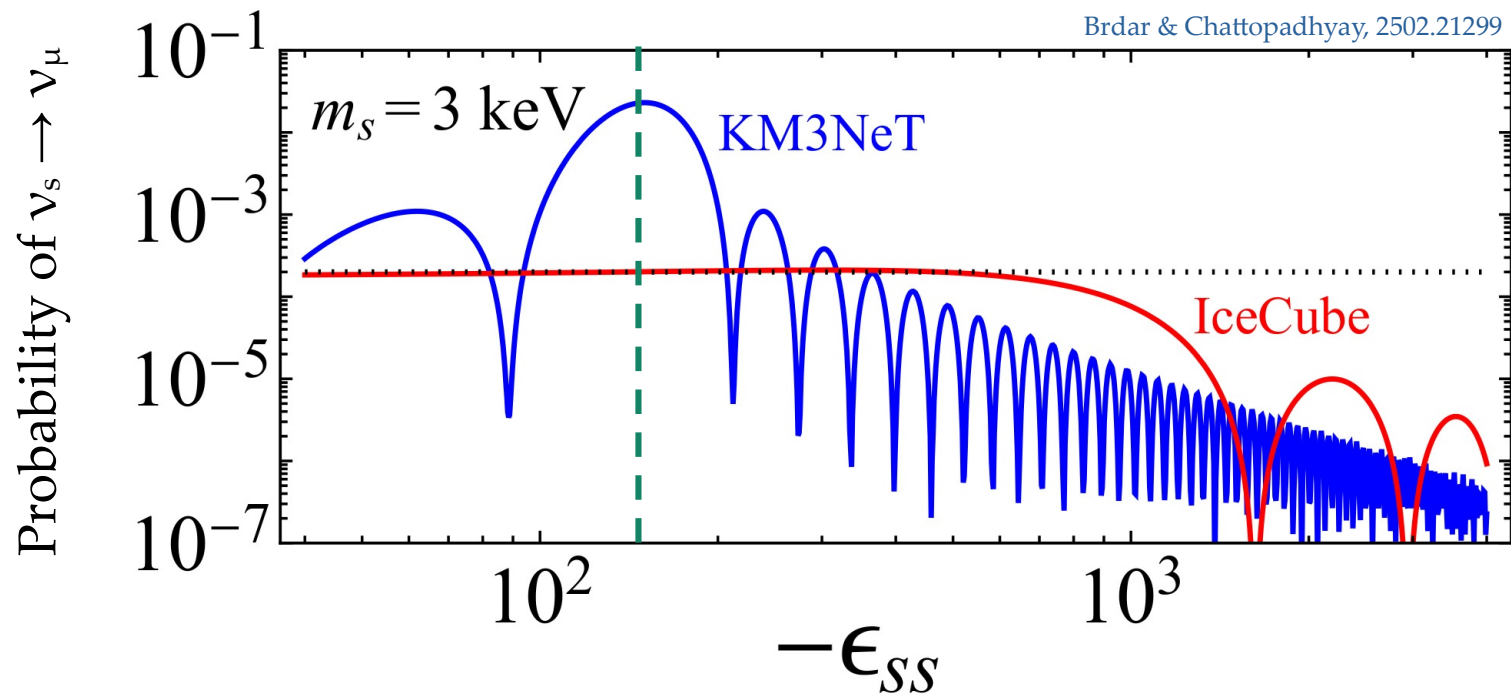


Sterile-active ν transitions

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 $-\epsilon_{ss} = 150$, transitions are resonant in KM3NeT,
but not in IceCube



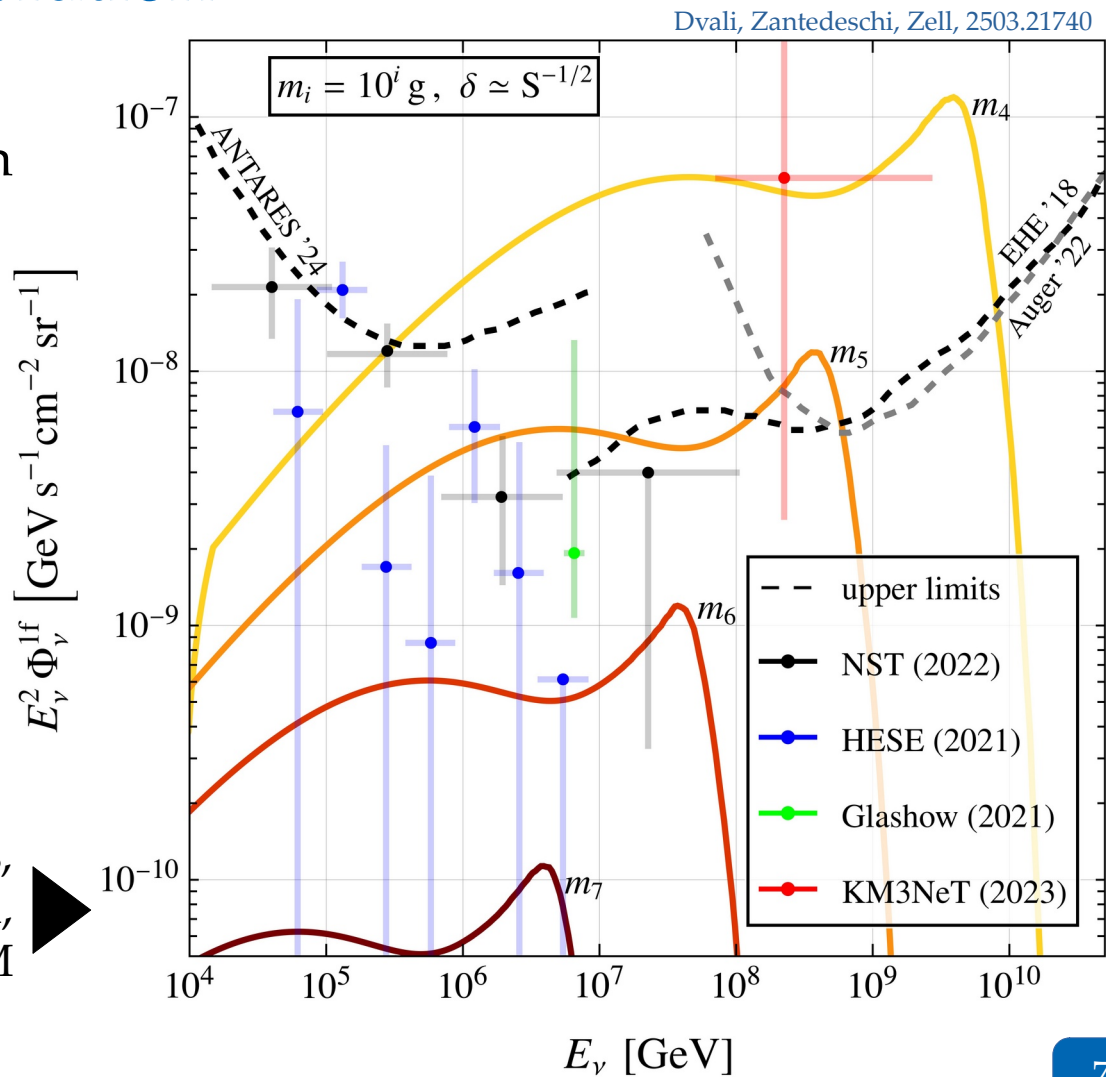
Primordial black hole evaporation

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

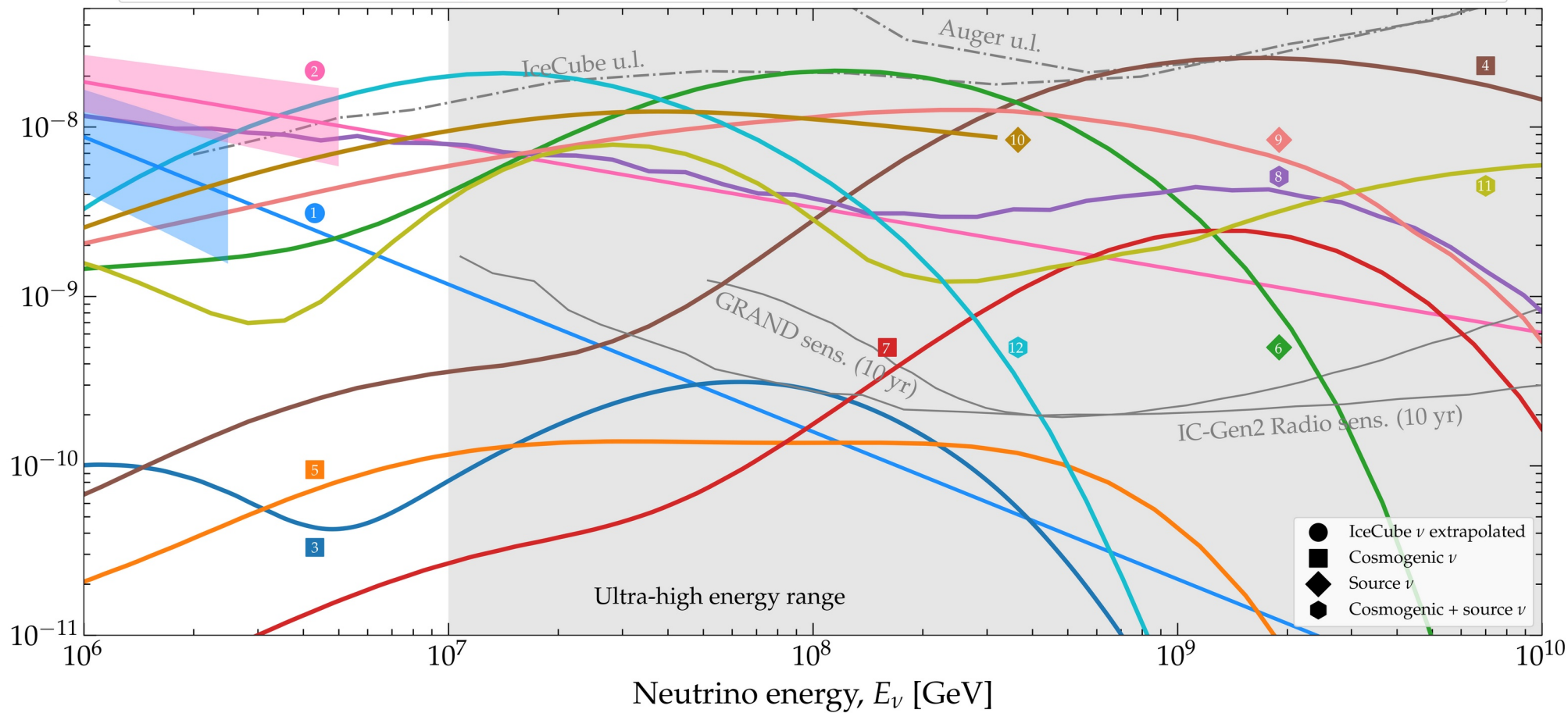
Galactic + extragalactic contributions,
monochromatic mass spectrum,
PBHs make up all of DM

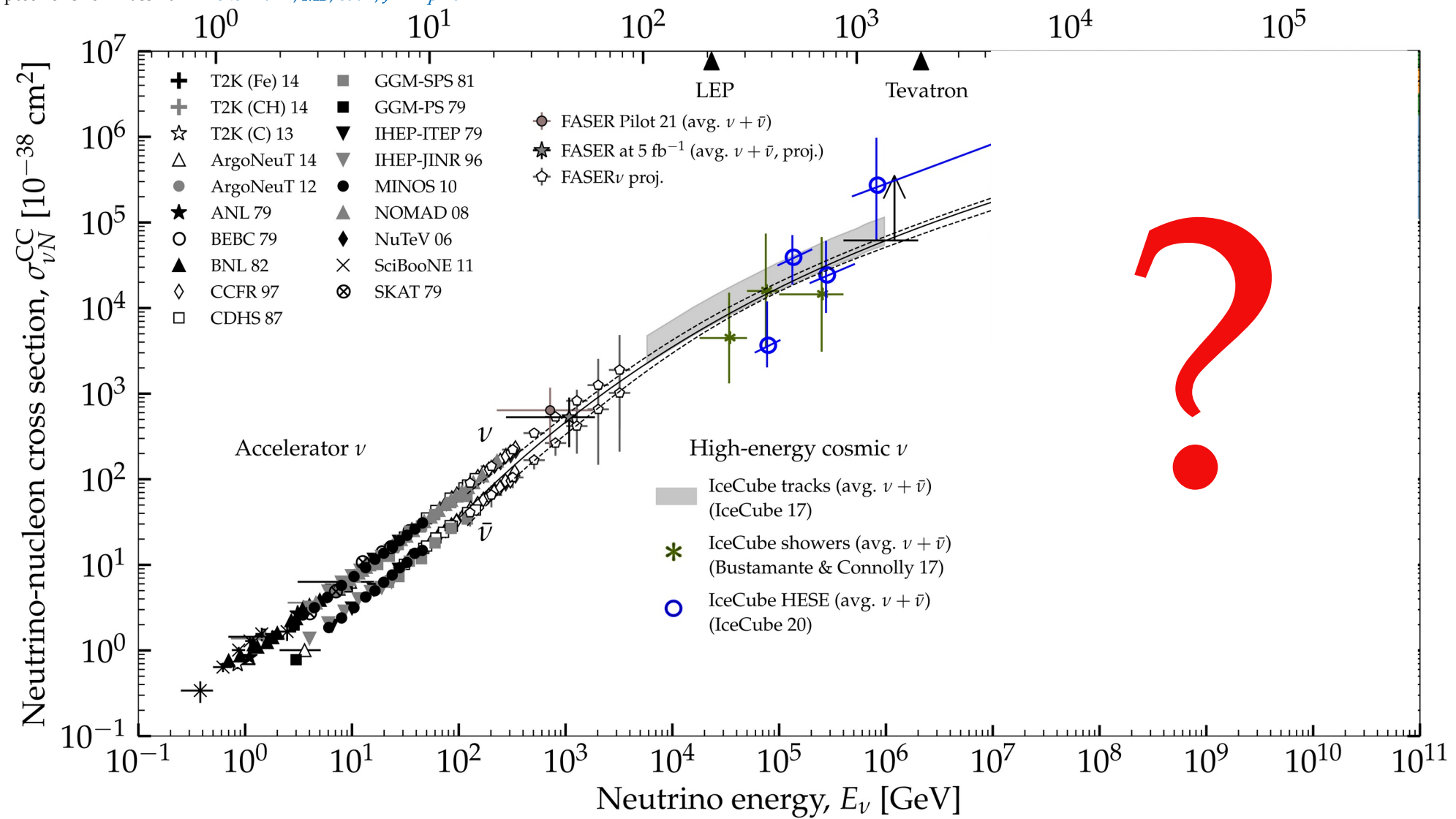


Cross sections at UHE

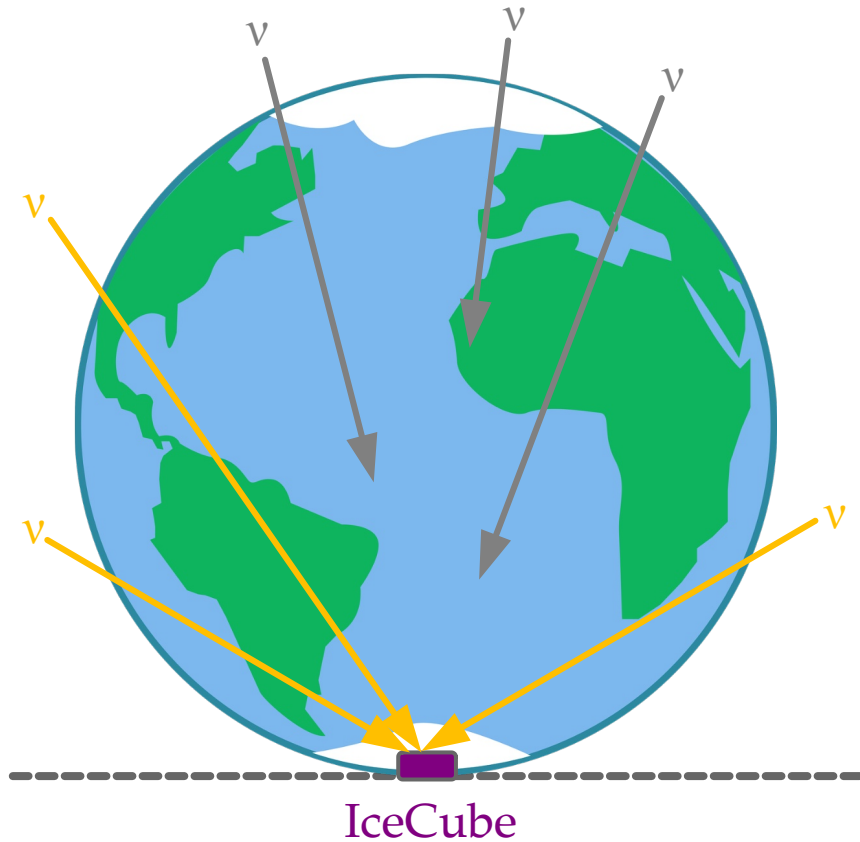
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [$\text{GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$]

- | | | | |
|--|---|--|--|
| 1 IceCube HESE (7.5 yr) extrapolated | 4 Bergman & van Vliet, fit to TA UHECRs | 7 Rodrigues <i>et al.</i> , HL BL Lacs | 10 Padovani <i>et al.</i> , BL Lacs |
| 2 IceCube ν_μ (9.5 yr) extrapolated | 5 Rodrigues <i>et al.</i> , all AGN | 8 Fang & Murase, cosmic-ray reservoirs | 11 Muzio <i>et al.</i> , maximum extra p component |
| 3 Heinze <i>et al.</i> , fit to Auger UHECRs | 6 Rodrigues <i>et al.</i> , all AGN | 9 Fang <i>et al.</i> , newborn pulsars | 12 Muzio <i>et al.</i> , fit to Auger & IceCube |



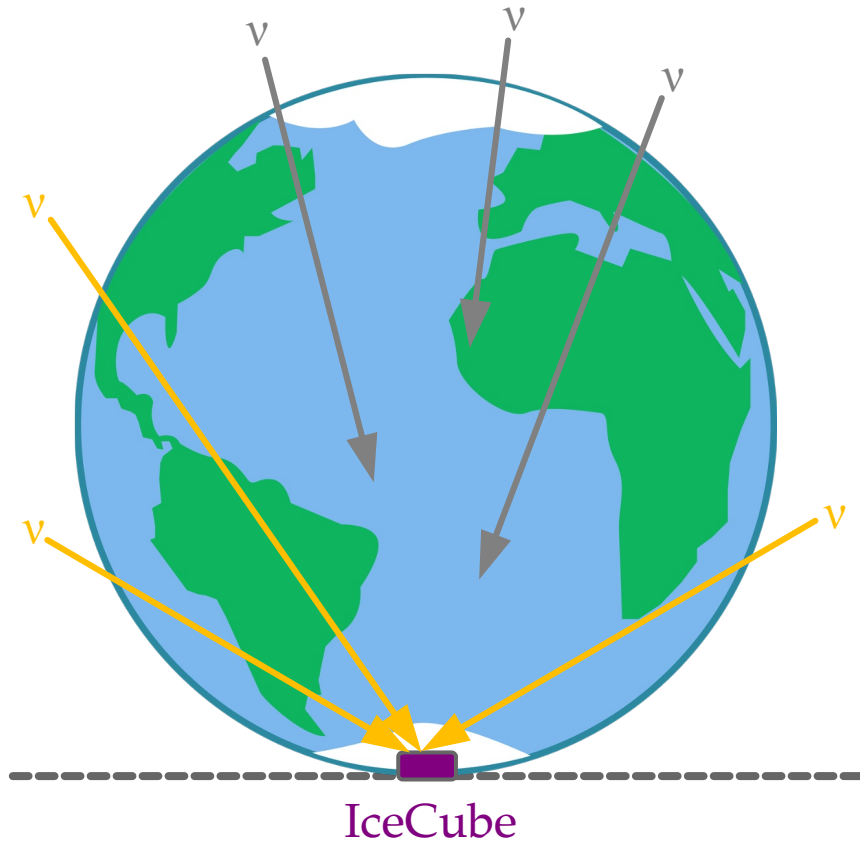


TeV–PeV:



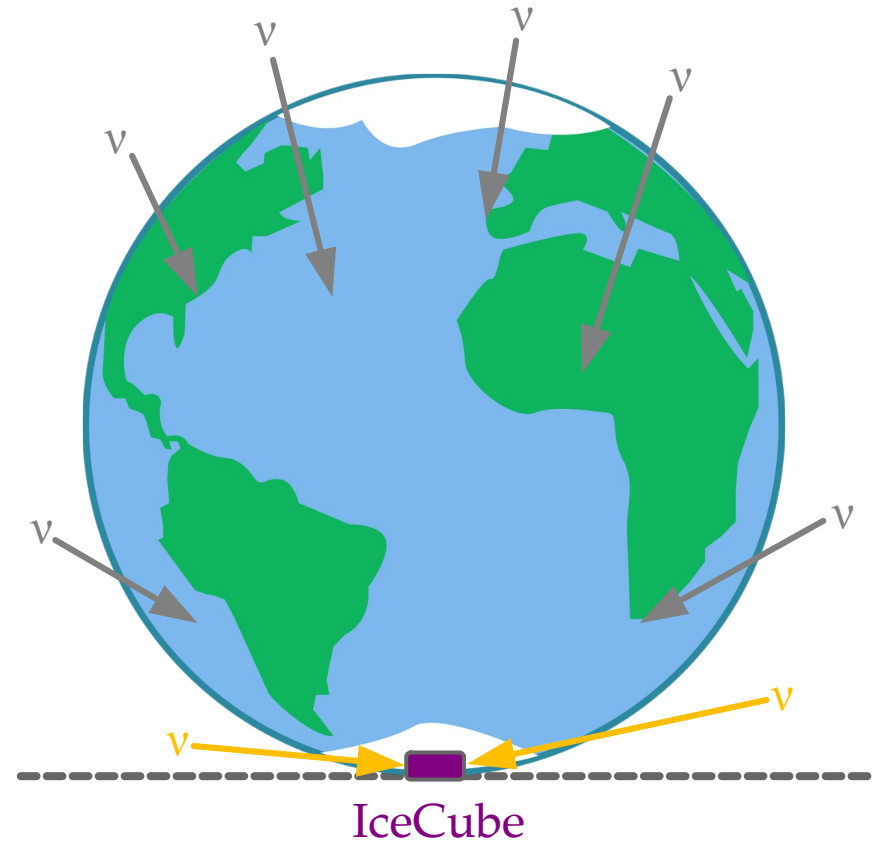
Earth is *almost fully* opaque,
some upgoing ν still make it through

TeV–PeV:



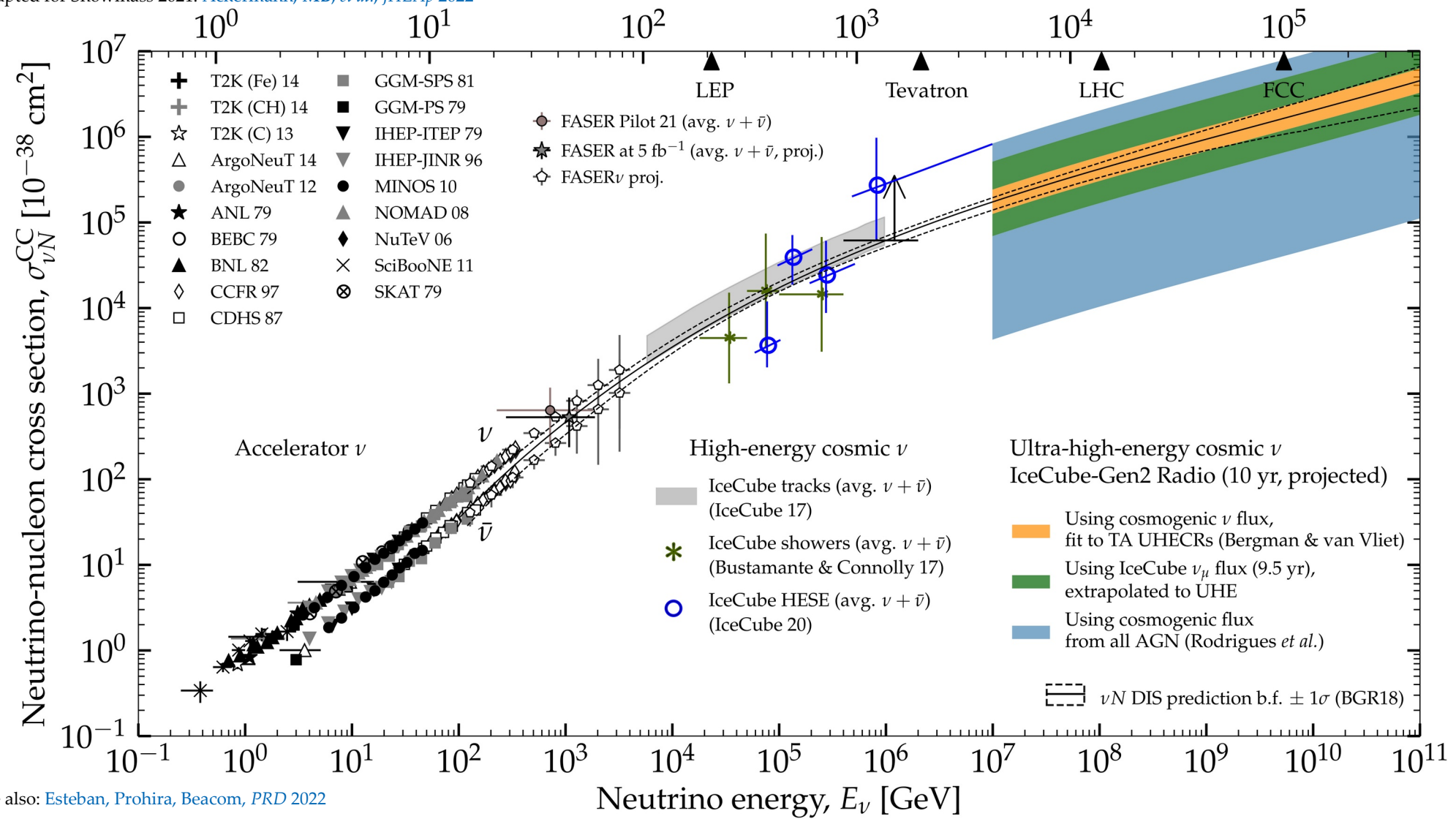
Earth is *almost fully* opaque,
some upgoing ν still make it through

> 100 PeV:

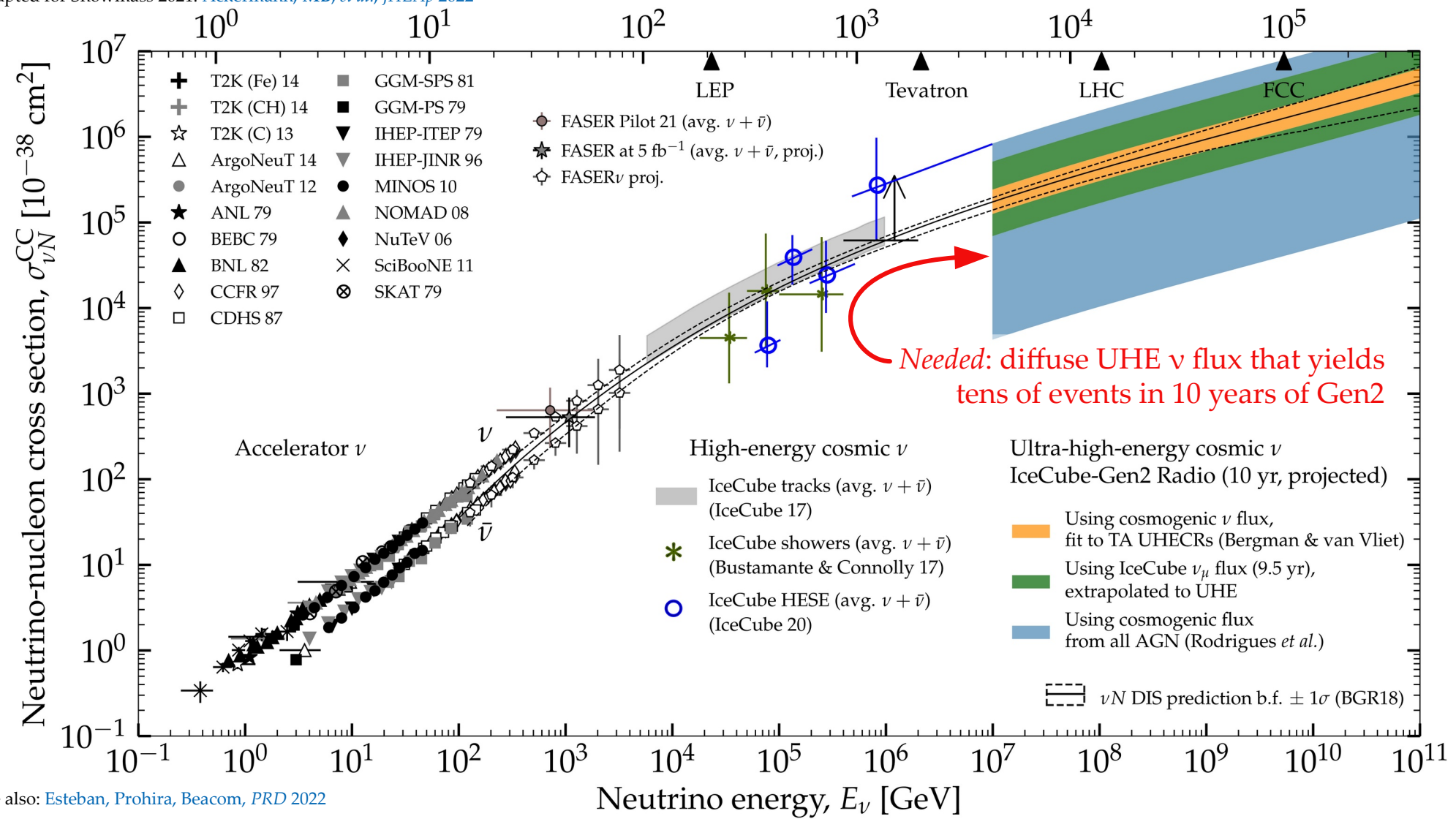


Earth is *completely* opaque,
but horizontal ν still make it through

Center-of-mass energy $\sqrt{s}$ [GeV]



Center-of-mass energy $\sqrt{s}$ [GeV]



So...

Today TeV–PeV ν

Turn predictions
into data-driven tests

Key developments:

Bigger detectors $\rightarrow$ larger statistics

Better reconstruction

Smaller astrophysical uncertainties

Today
TeV–PeV ν

Turn predictions
into data-driven tests

Key developments:

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Next decade
> 100-PeV ν

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TeV–PeV ν

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New detection techniques

Better UHE ν flux predictions

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Made robust and meaningful by accounting
for all relevant particle and astrophysics uncertainties

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TeV–PeV ν

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Bigger detectors $\rightarrow$ larger statistics

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Next decade
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Make predictions for
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Key developments:

Discovery

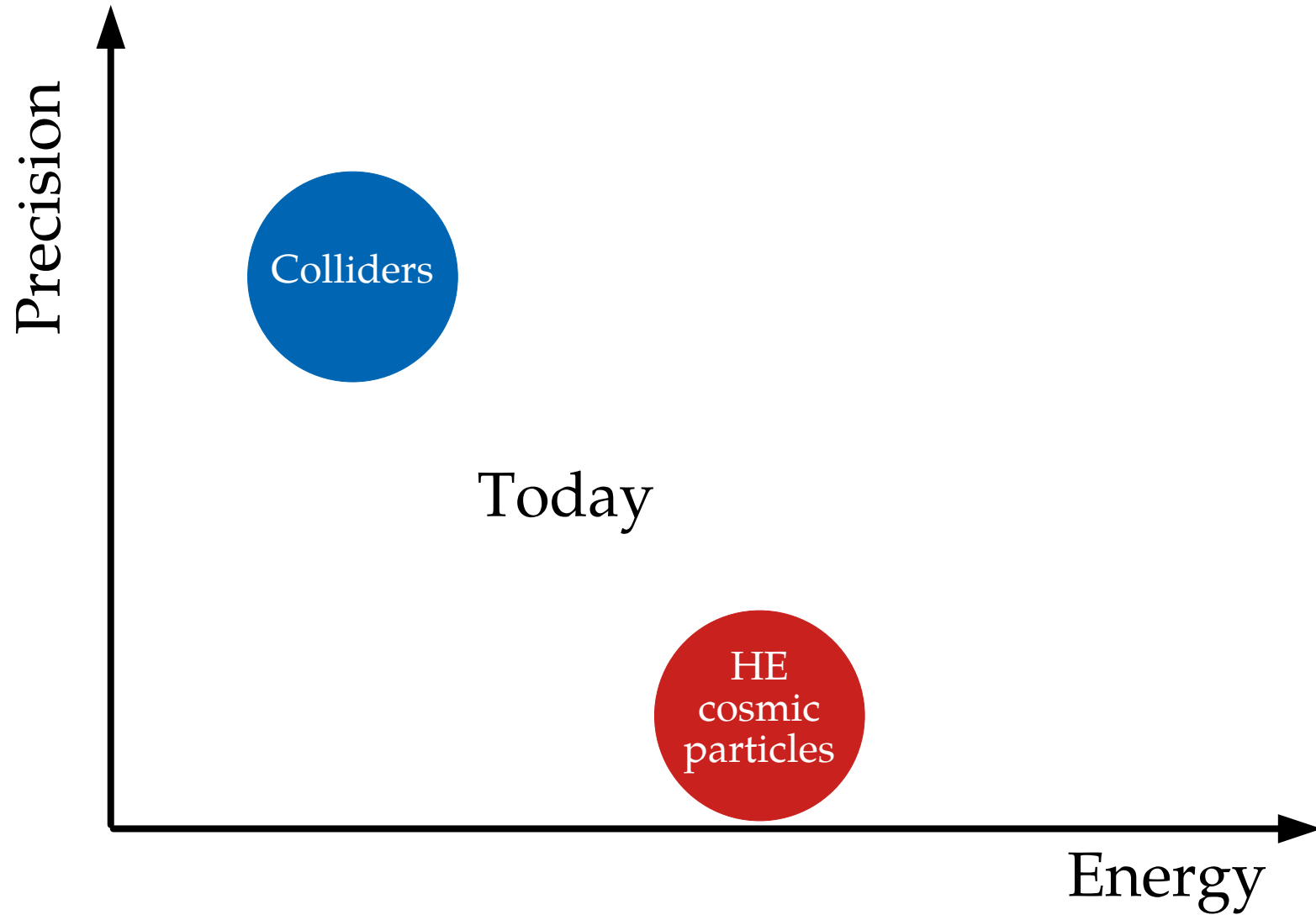
New detection techniques

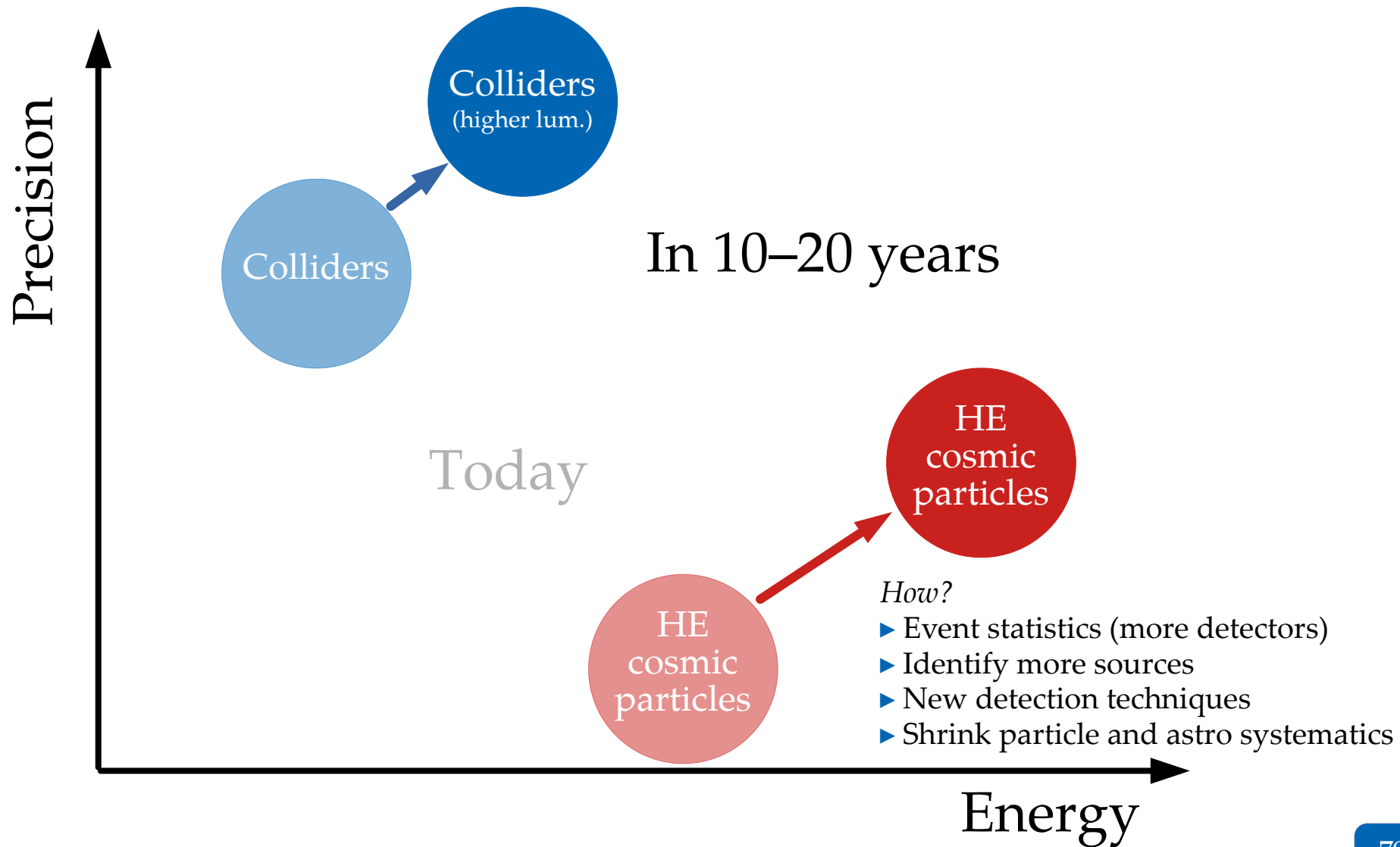
Better UHE ν flux predictions

Similar to the evolution of cosmology to a
high-precision field in the 1990s



Made robust and meaningful by accounting
for all relevant particle and astrophysics uncertainties





How it
started

How it's
going

10–20 years
from now



How it
started

How it's
going

10–20 years
from now

First predictions
of high-energy
cosmic ν



How it
started

How it's
going

10–20 years
from now

First predictions
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cosmic ν

PeV ν
discovered

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Hints of sources
First tests of ν
physics

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EeV ν discovered
Precision tests w/ PeV ν
First tests with EeV ν

How it
started

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going

10–20 years
from now

First predictions
of high-energy
cosmic ν

PeV ν
discovered

Hints of sources
First tests of ν
physics

How do we get there?

EeV ν discovered
Precision tests w/ PeV ν
First tests with EeV ν

Thank you!

Backup slides

In-Earth neutrino attenuation

Measuring the high-energy νN cross section

Number of detected neutrinos (simplified for presentation):

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

Measuring the high-energy νN cross section

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

$$N \propto \Phi_\nu \sigma_{\nu N}$$

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$$N \propto \underbrace{\Phi_\nu \sigma_{\nu N}}_{\text{Degeneracy}}$$

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Downgoing neutrinos
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$$N \propto \underbrace{\Phi_\nu \sigma_{\nu N}}_{\text{Degeneracy}}$$

Upgoing neutrinos
(L long $\rightarrow$ lots of matter)

$$N \propto \Phi_\nu \sigma_{\nu N} e^{-L \sigma_{\nu N} n_N}$$

Measuring the high-energy νN cross section

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

$$N \propto \underbrace{\Phi_\nu \sigma_{\nu N}}_{\text{Degeneracy}}$$

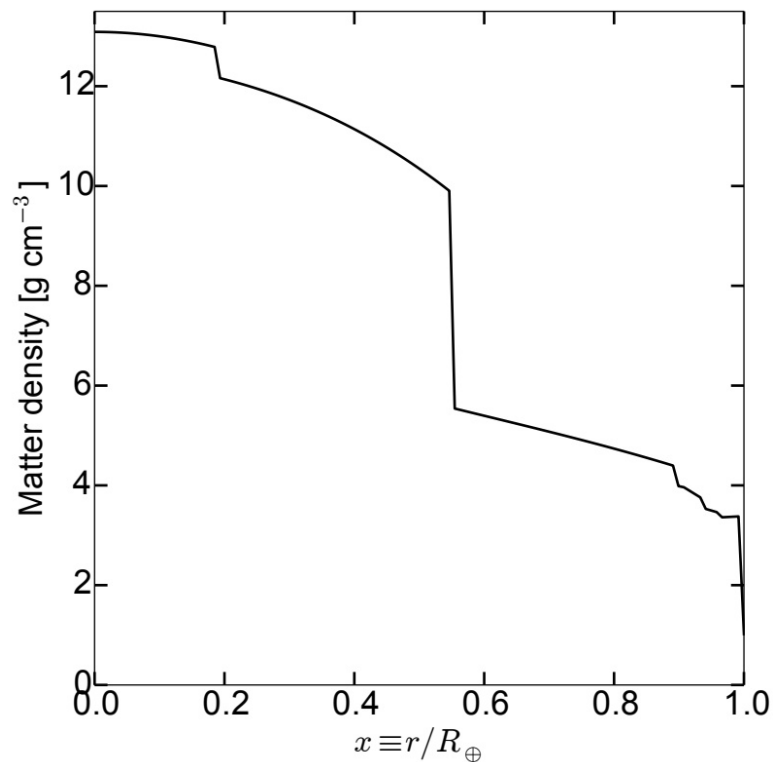
Upgoing neutrinos
(L long $\rightarrow$ lots of matter)

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

A feel for the in-Earth attenuation

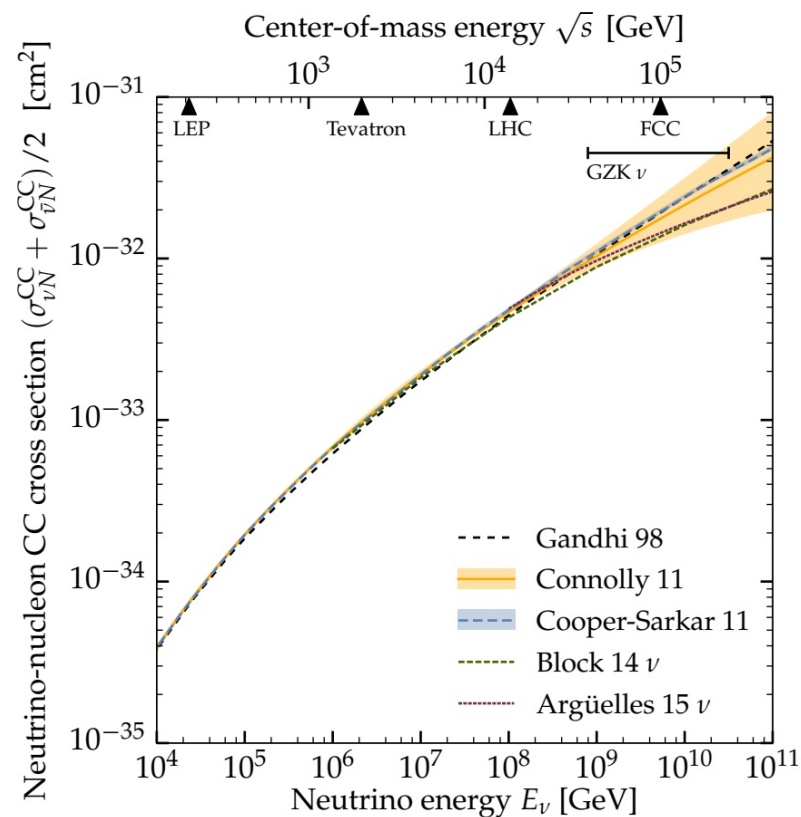
Earth matter density

(Preliminary Reference Earth Model)

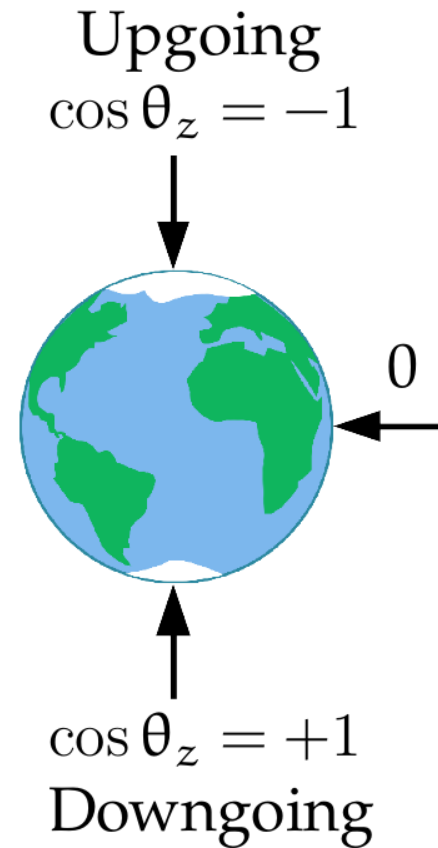
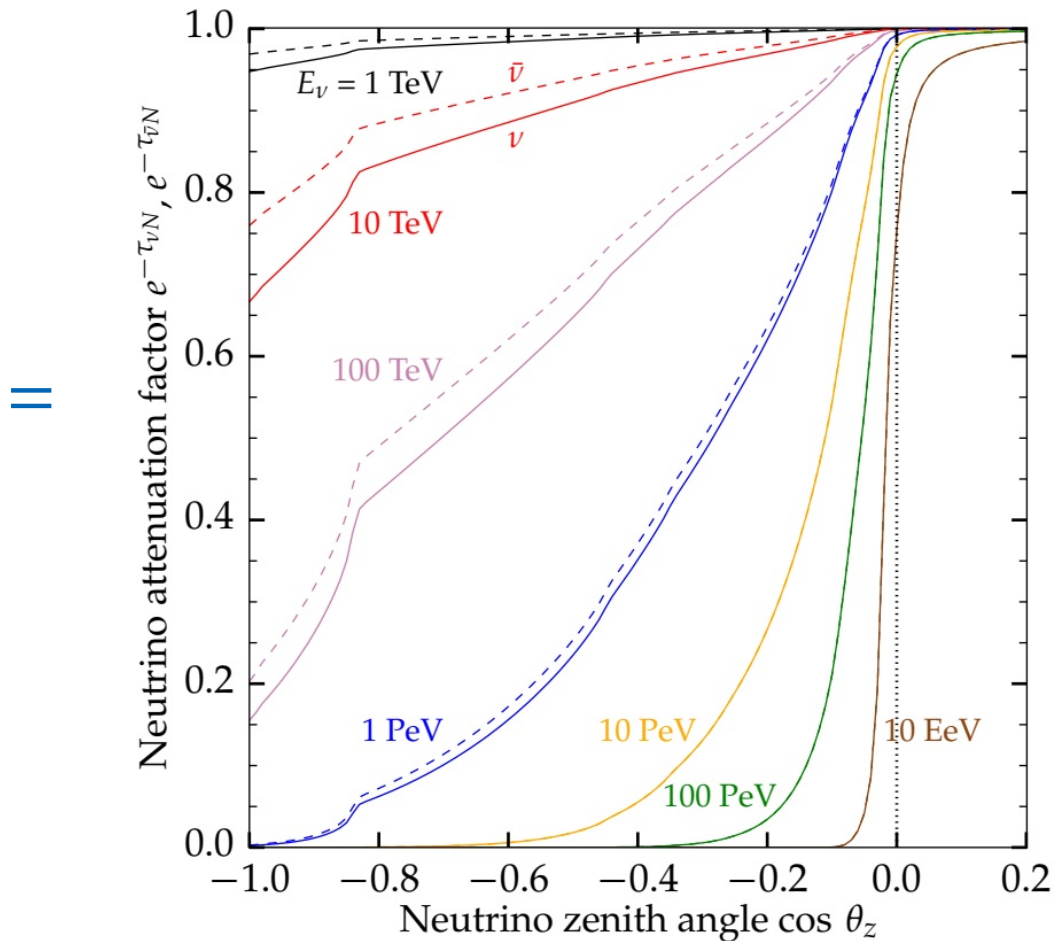


+

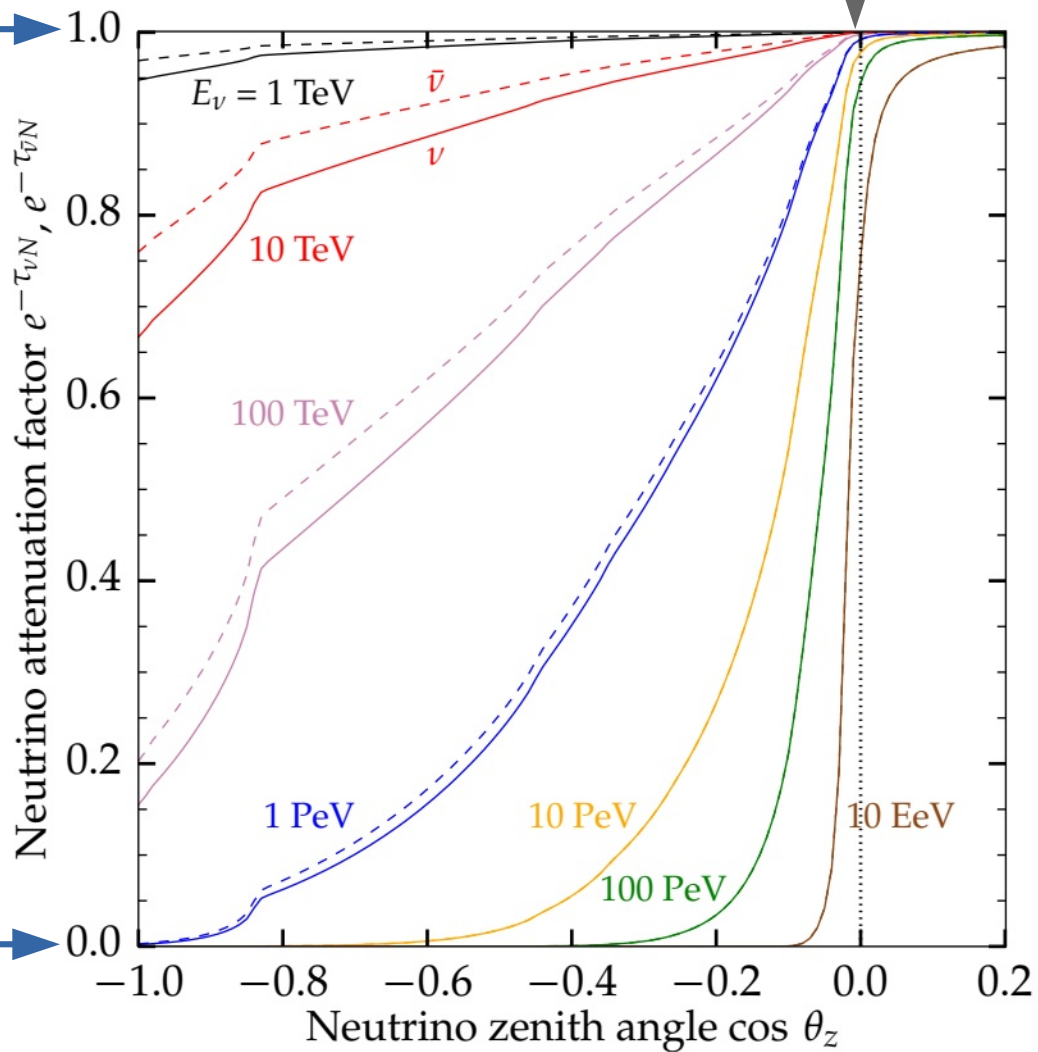
Neutrino-nucleon cross section



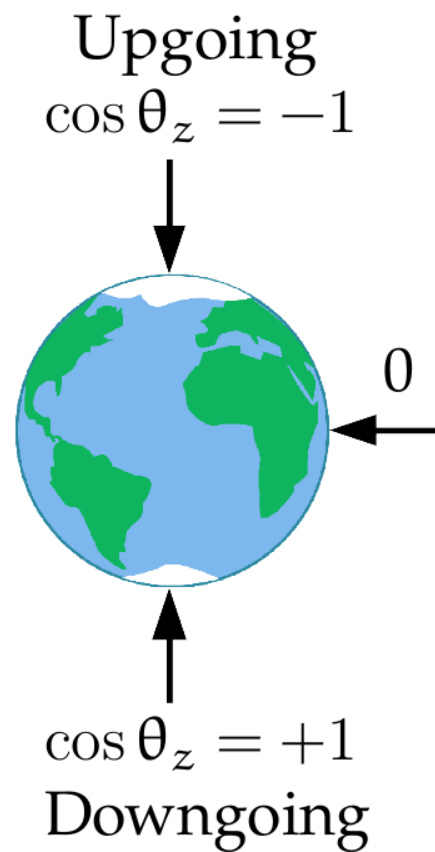
A feel for the in-Earth attenuation



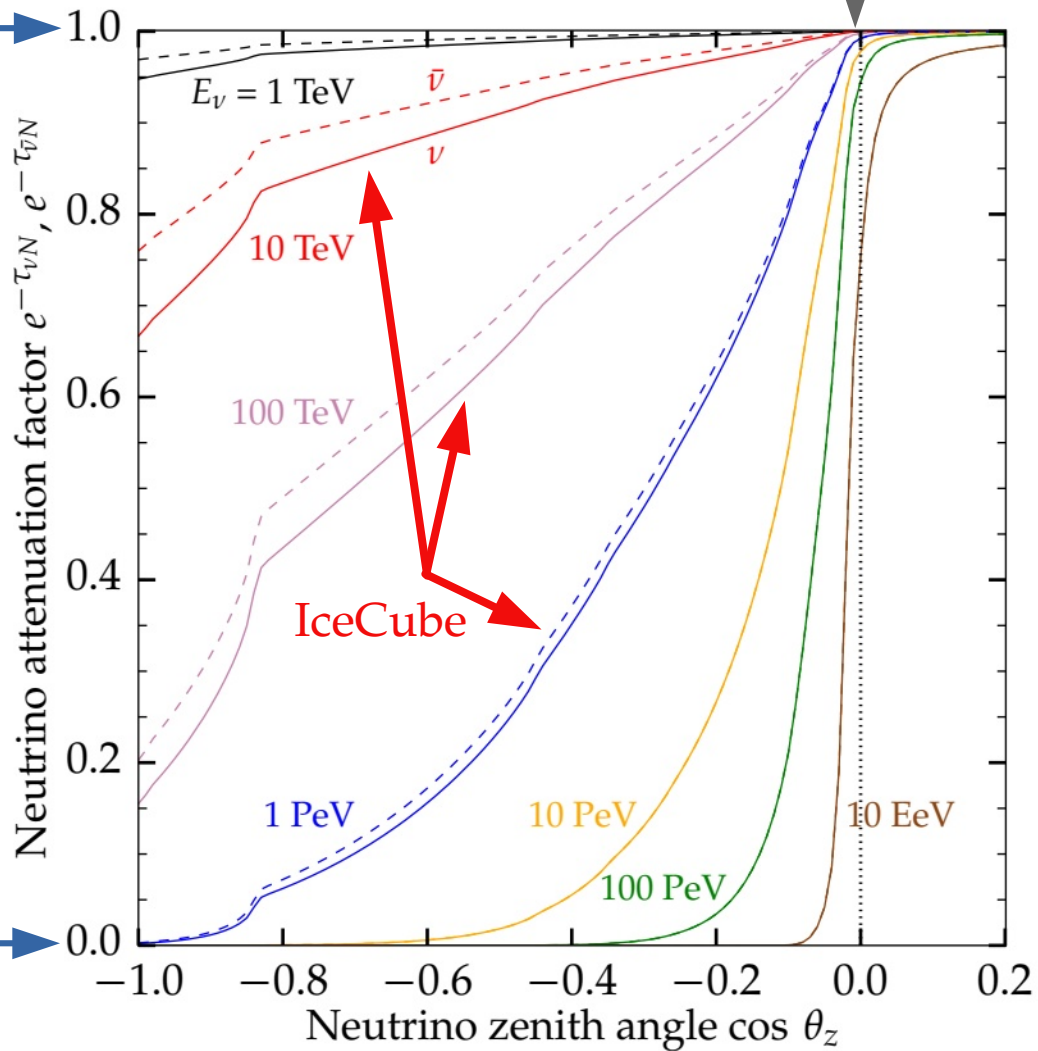
No
attenuation



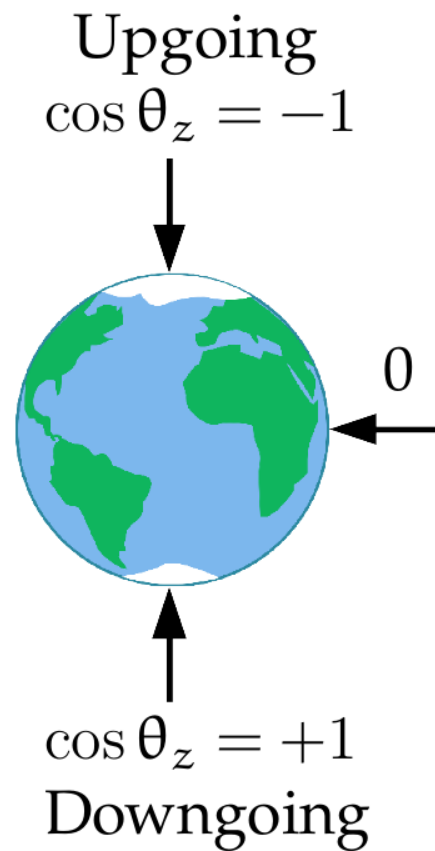
Full
attenuation

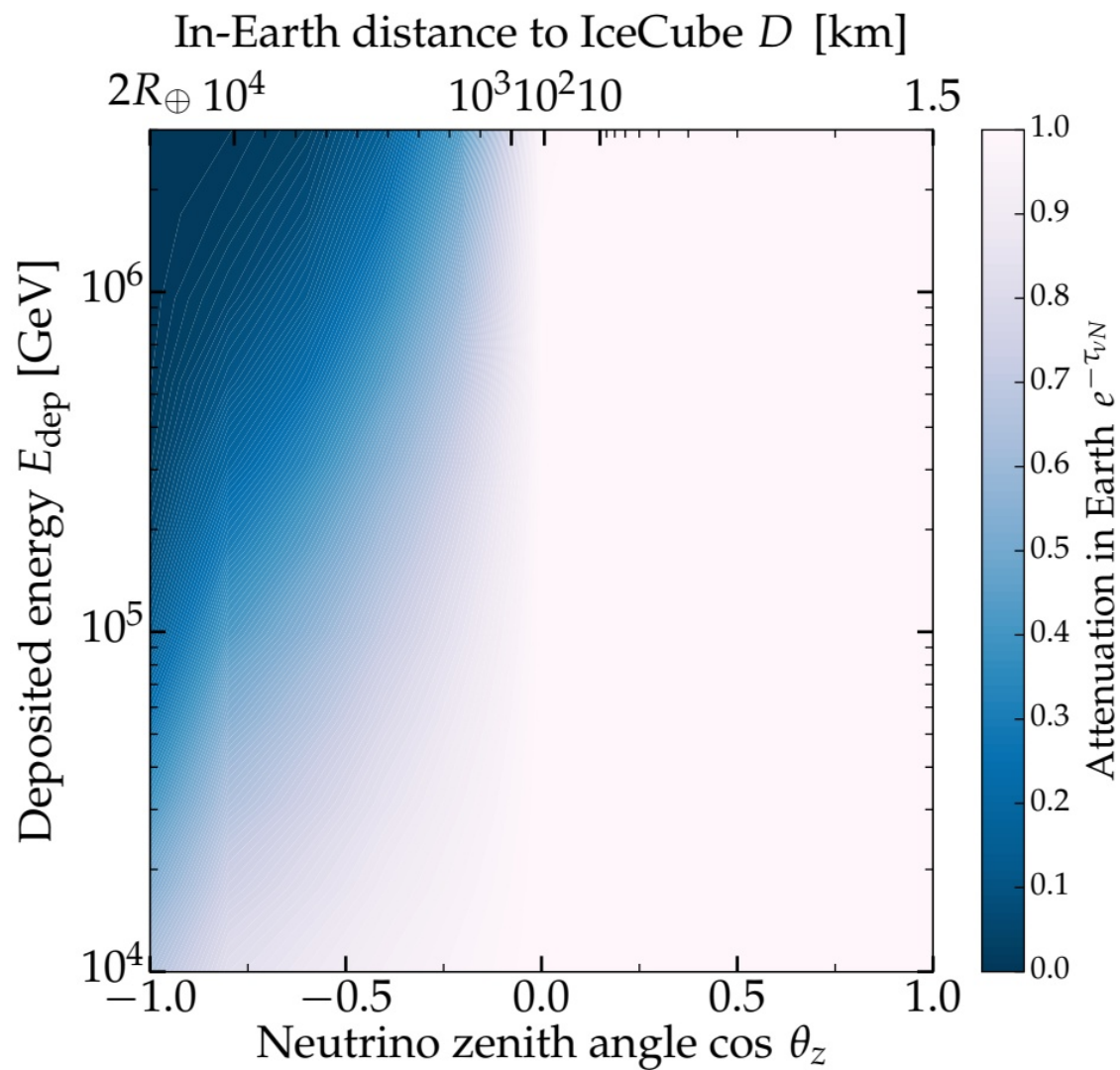


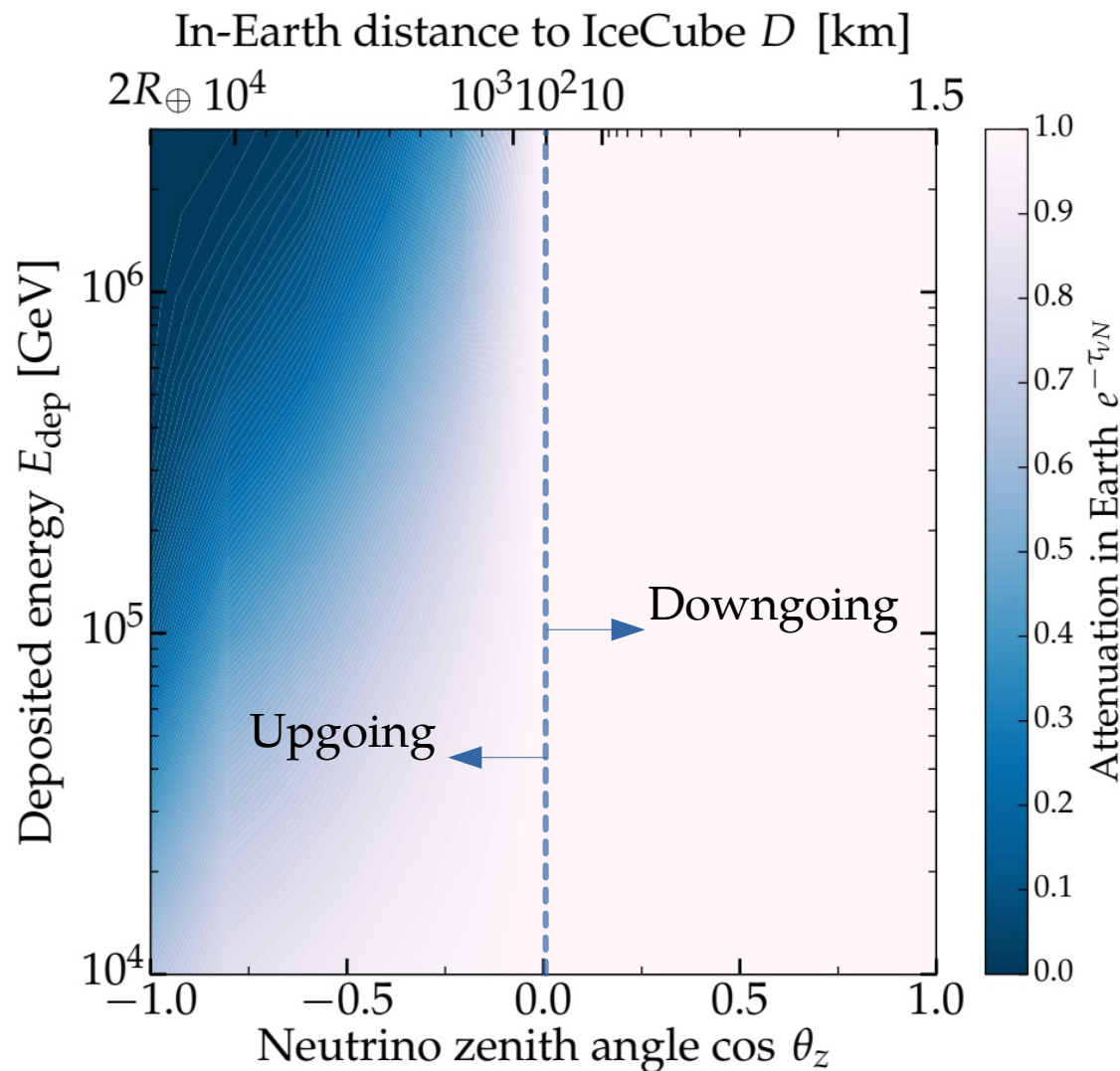
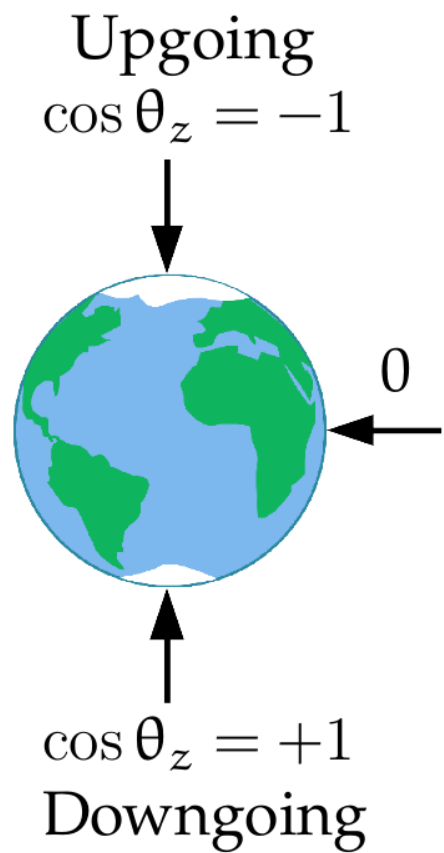
No
attenuation

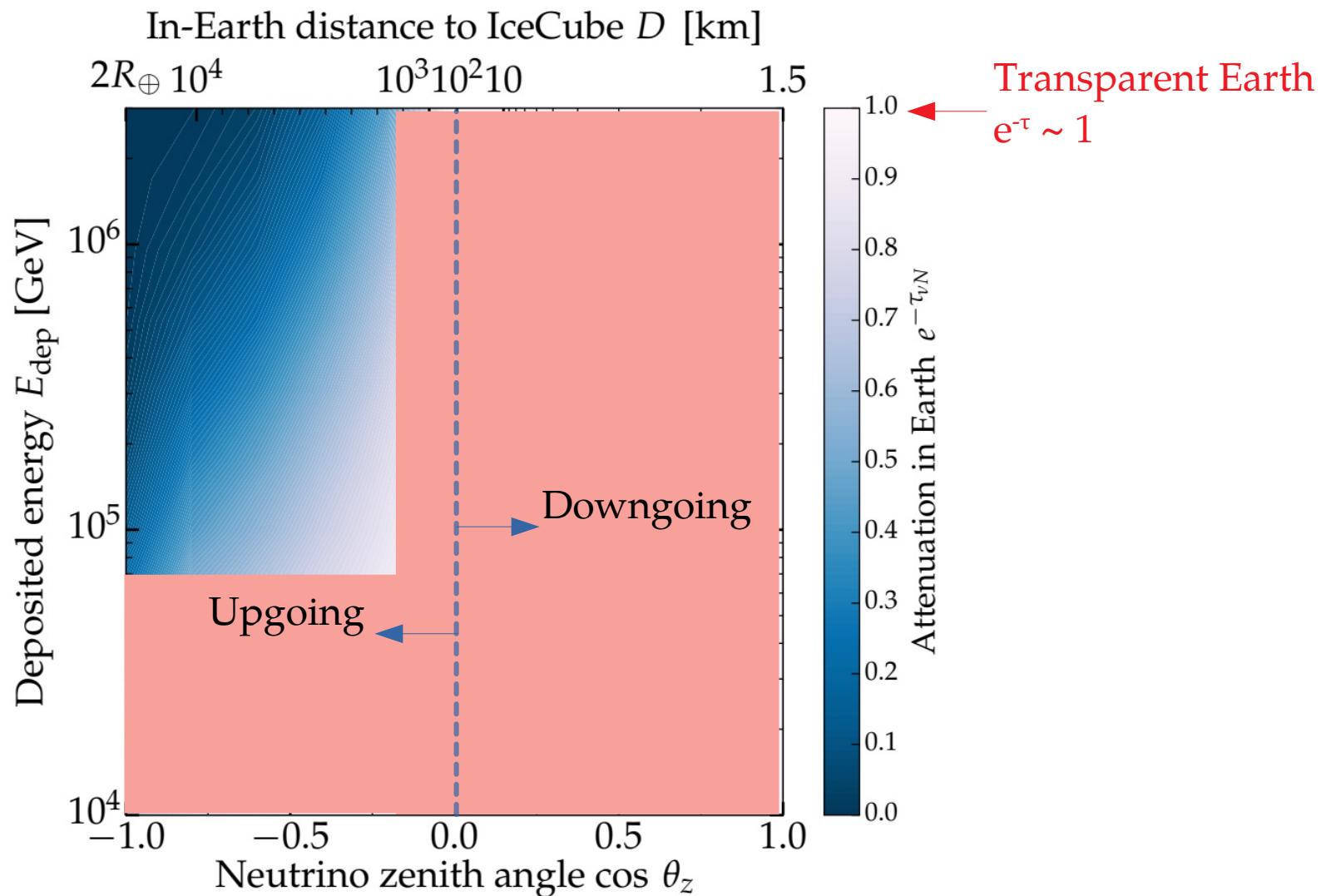
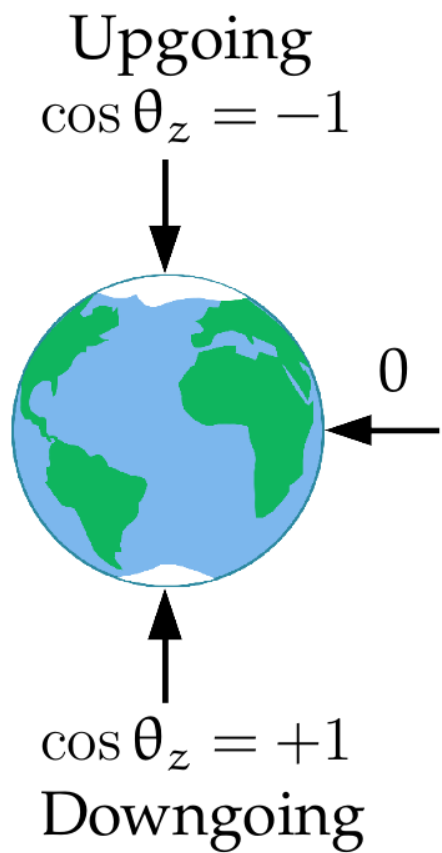


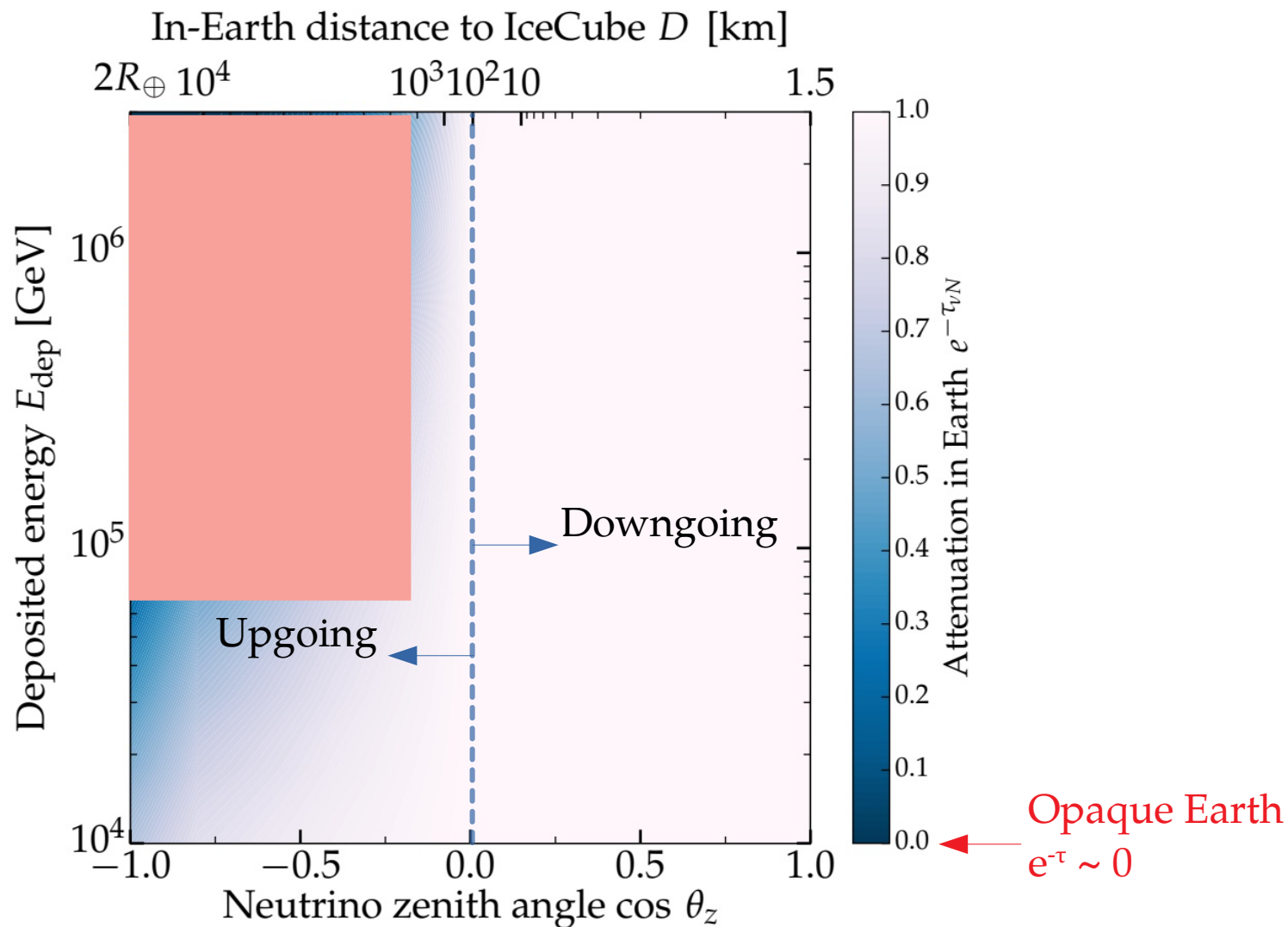
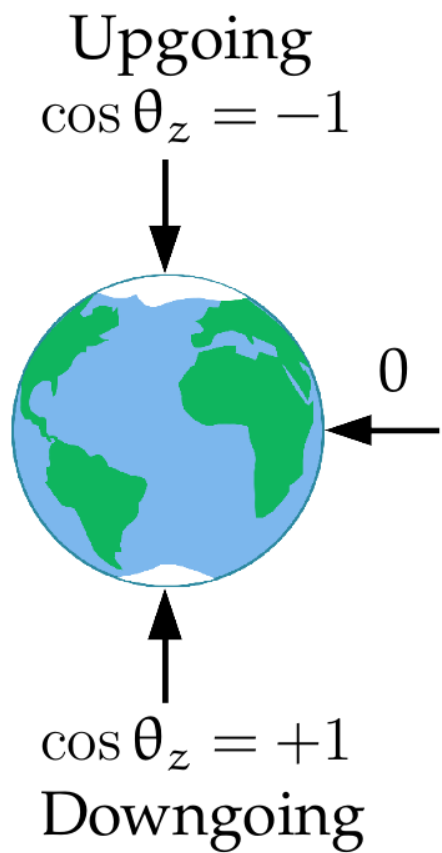
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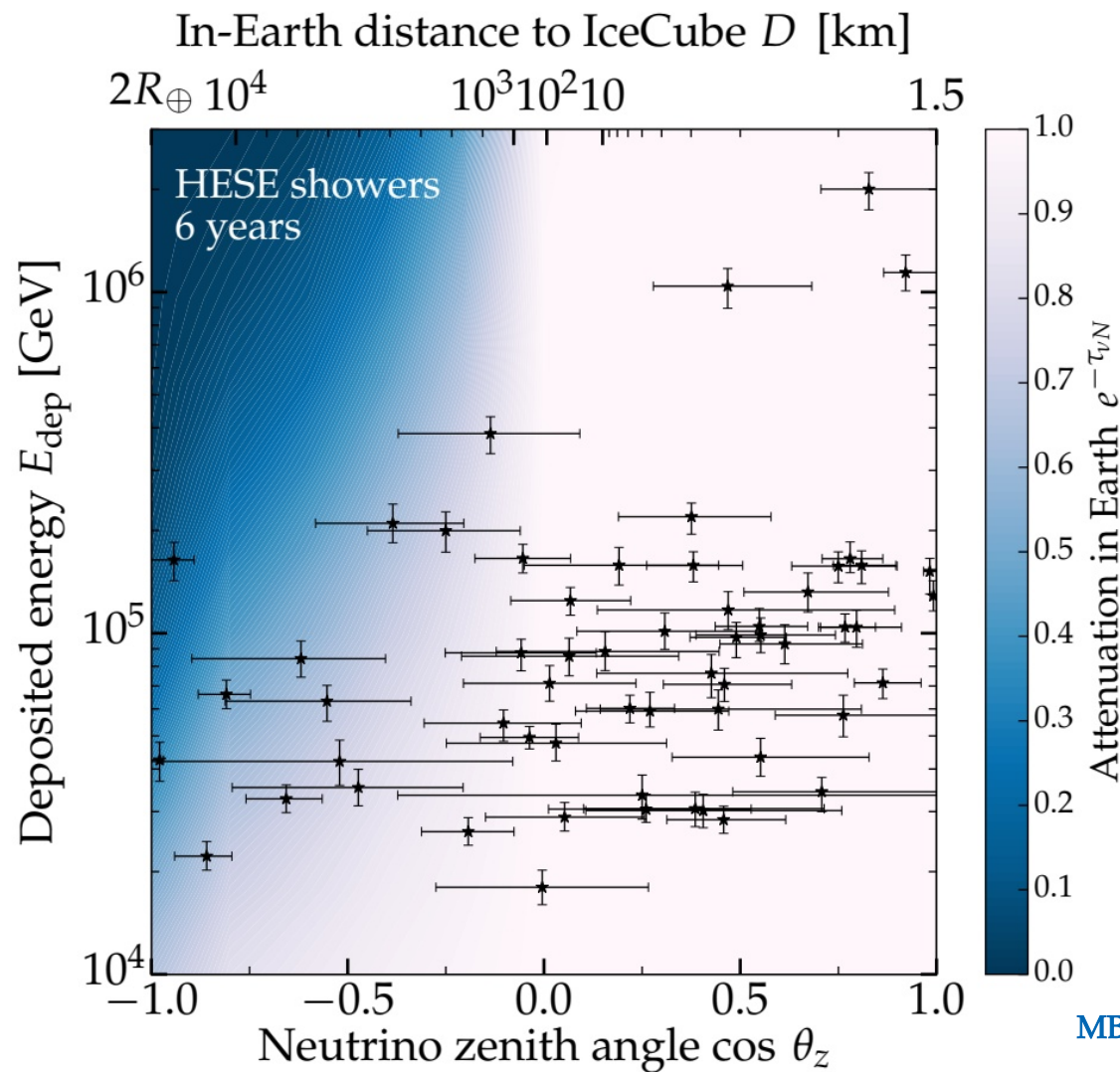




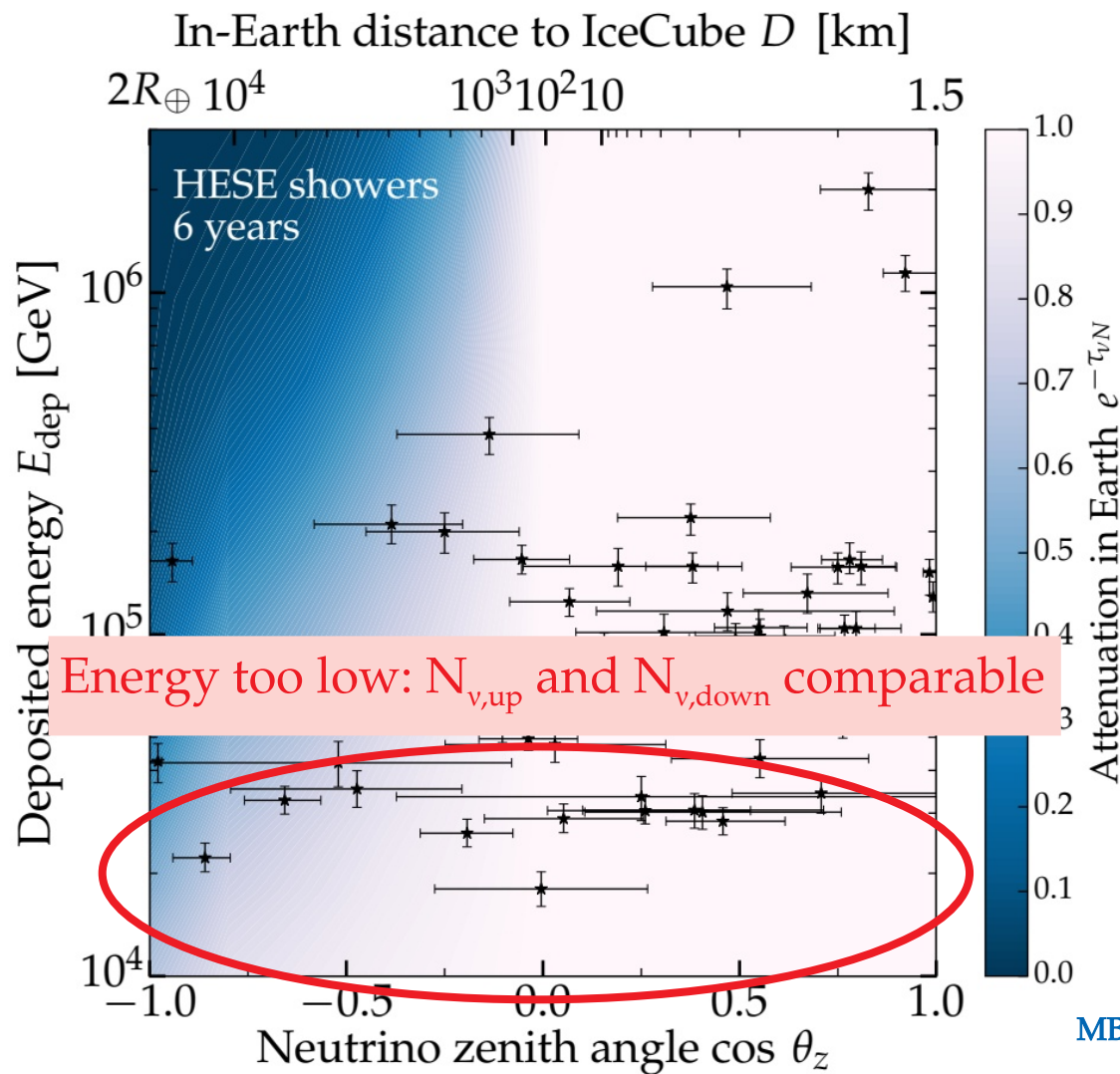




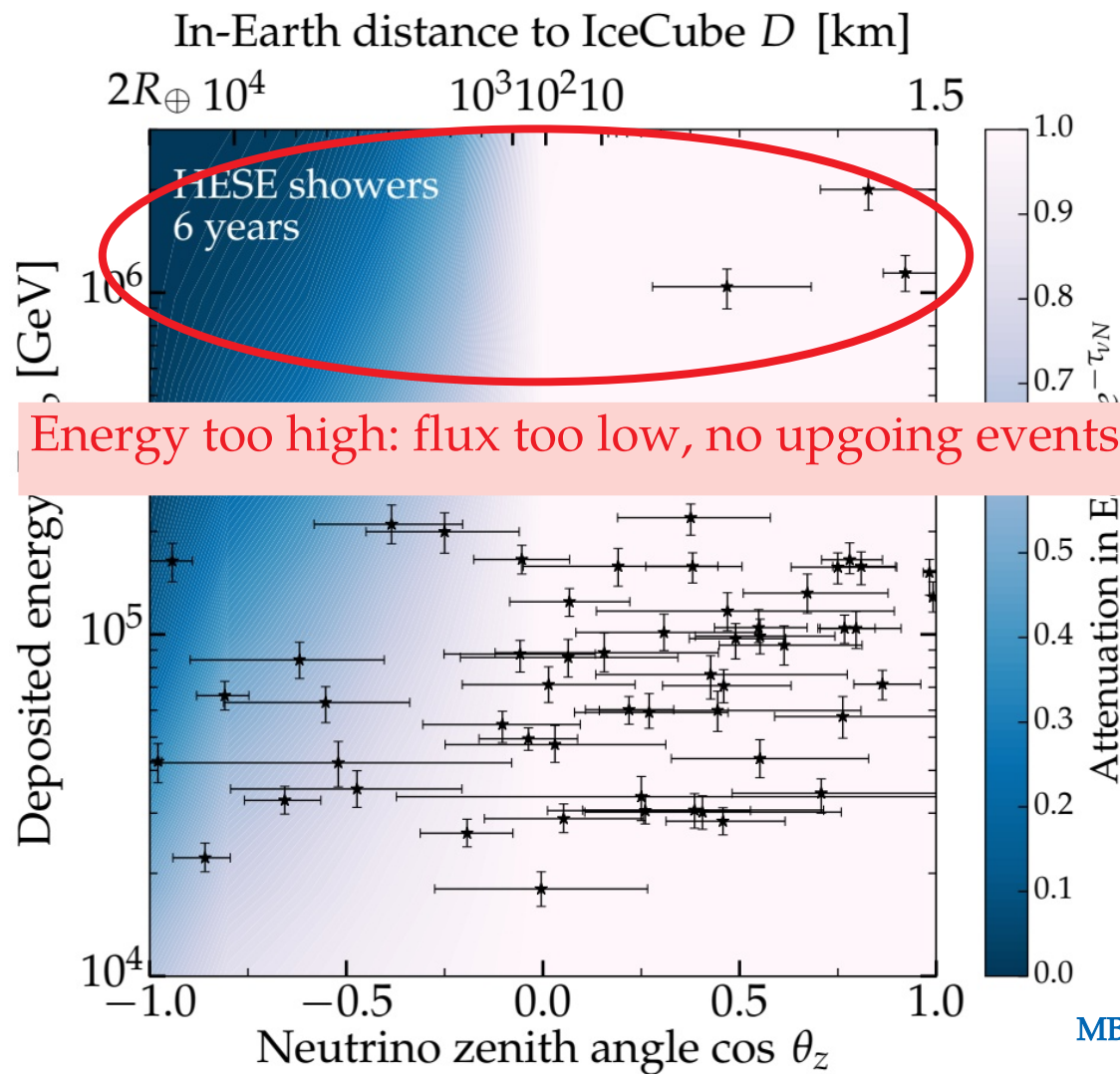




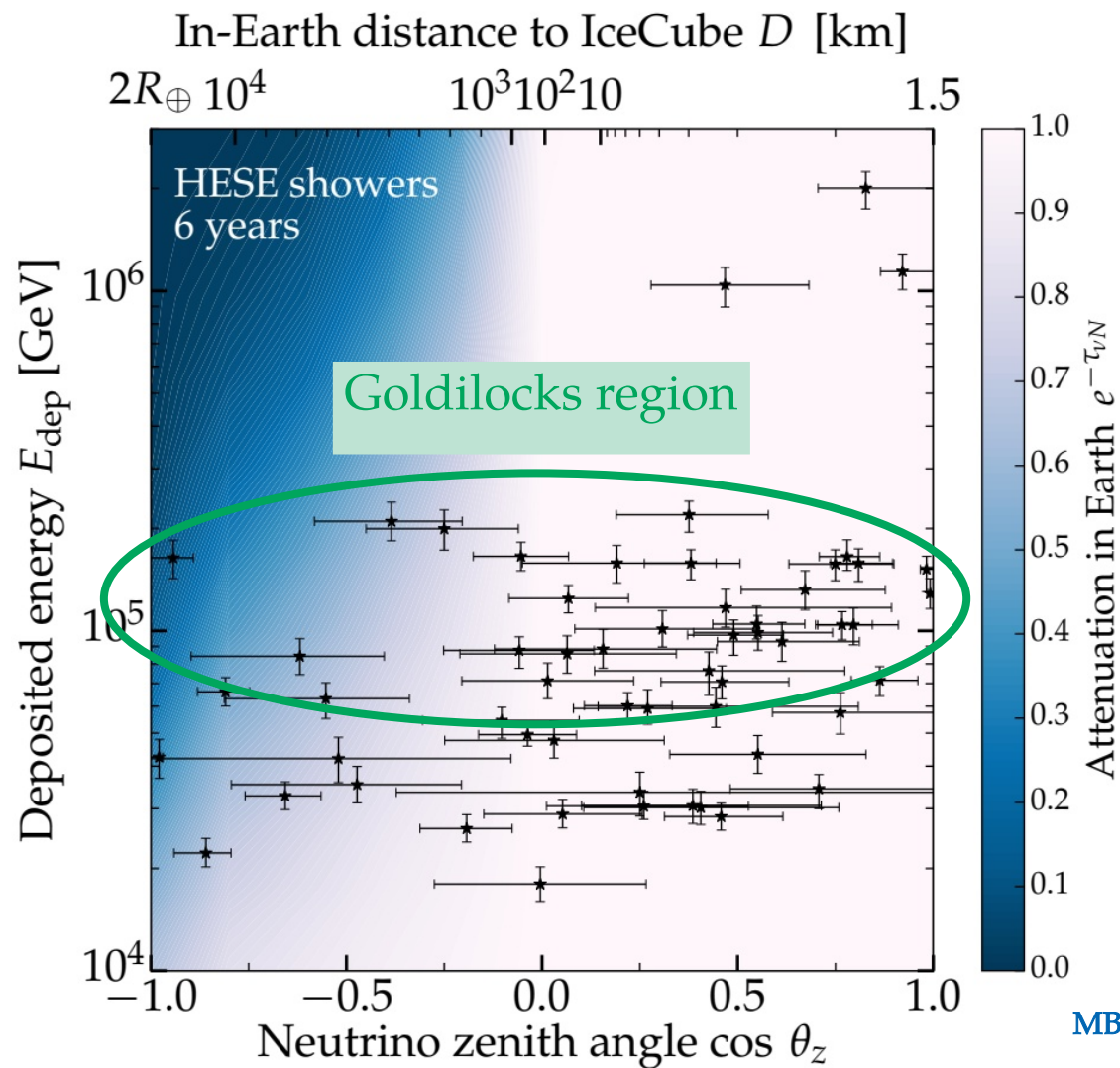
MB & Connolly, *PRL* 2019



MB & Connolly, *PRL* 2019



MB & Connolly, *PRL* 2019



MB & Connolly, *PRL* 2019

Dark matter decay and annihilation

High-energy neutrinos from dark matter

Dark matter co-annihilation:

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

$$\chi + \chi \rightarrow \dots \rightarrow \nu + \bar{\nu} + \dots$$

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

Dark matter decay:

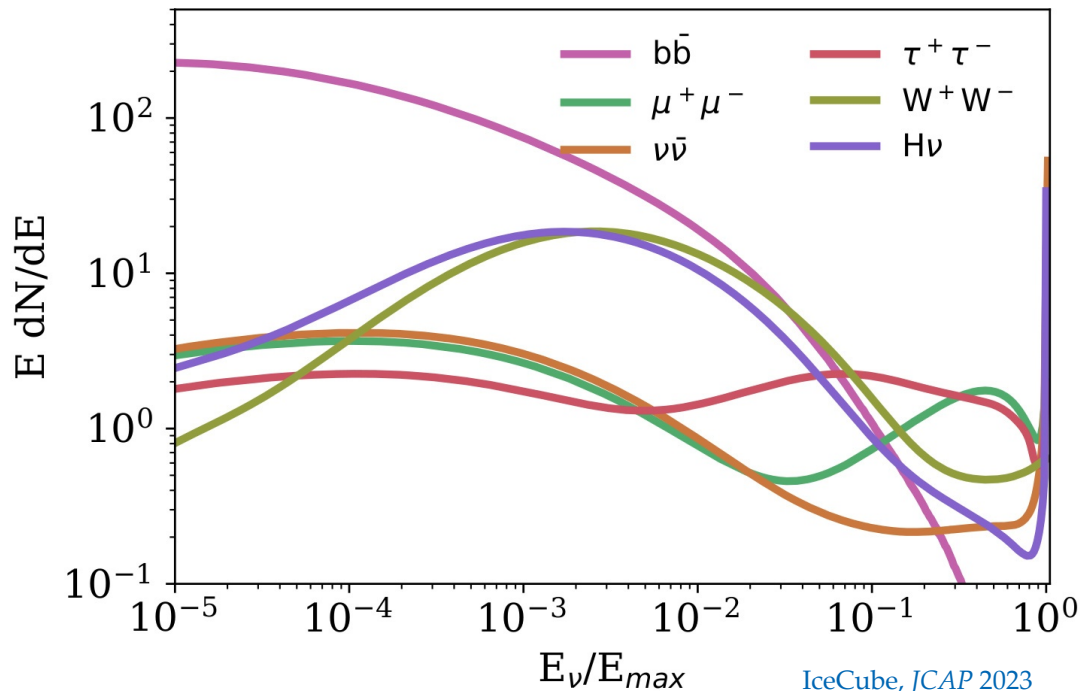
$$\chi \rightarrow \nu + \bar{\nu}$$

$$\chi \rightarrow \dots \rightarrow \nu + \bar{\nu} + \dots$$

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

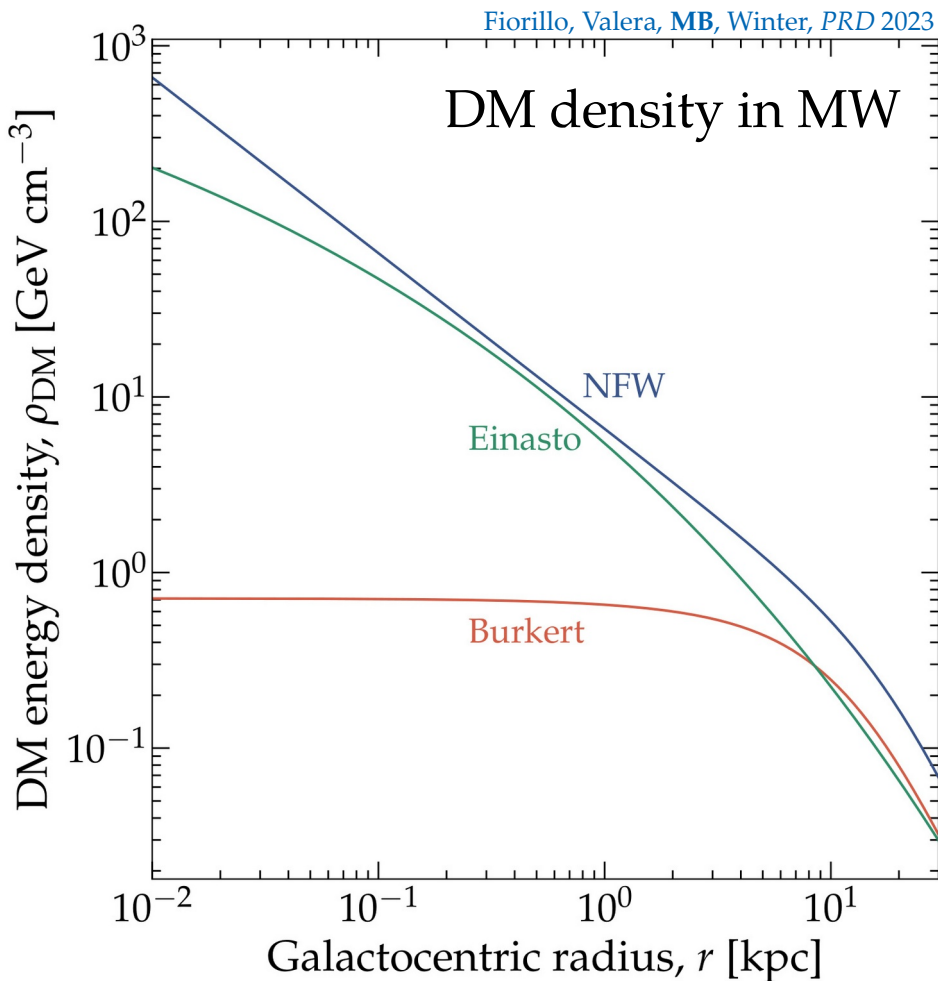
Electroweak corrections (off-shell W and Z emission) broaden the ν spectrum

$\nu + \nu$ yield from DM (at source)



Approximate independence on m_{χ}
valid for $m_{\chi} \approx 100 \text{ TeV} - 10 \text{ PeV}$

Dark matter in the Milky Way

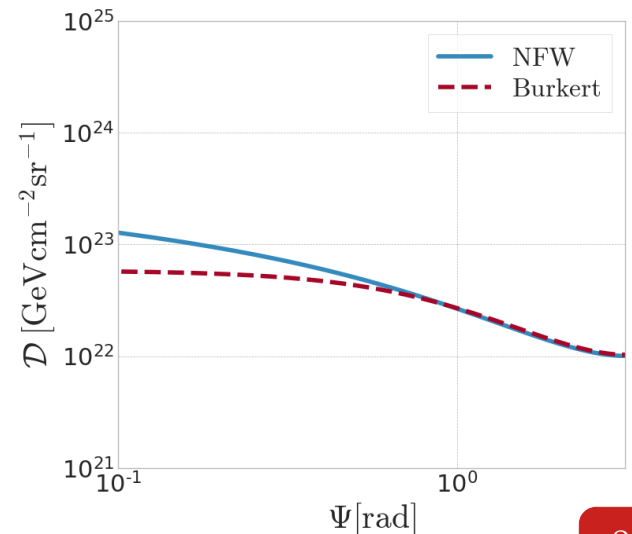
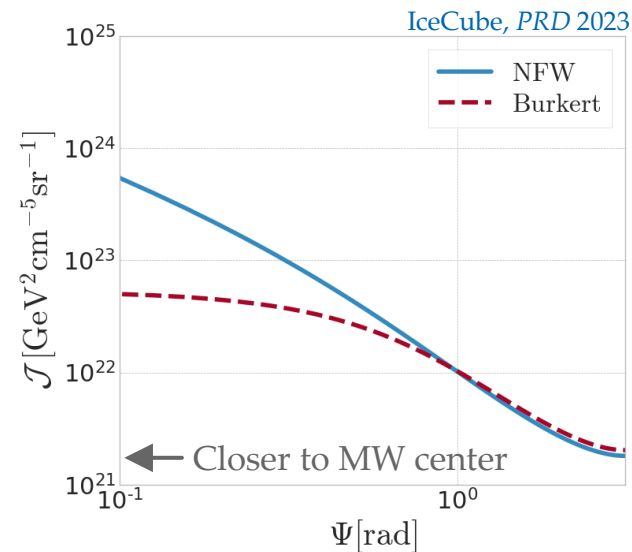


DM annihilation

$$\Phi_\nu \propto \mathcal{I} \propto \rho_{\text{DM}}^2$$

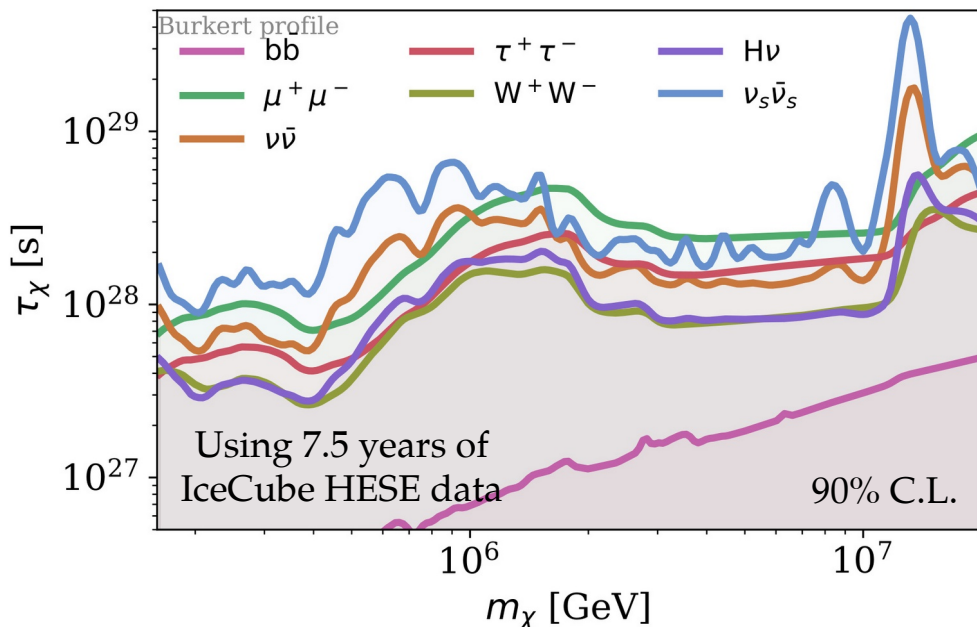
DM decay

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

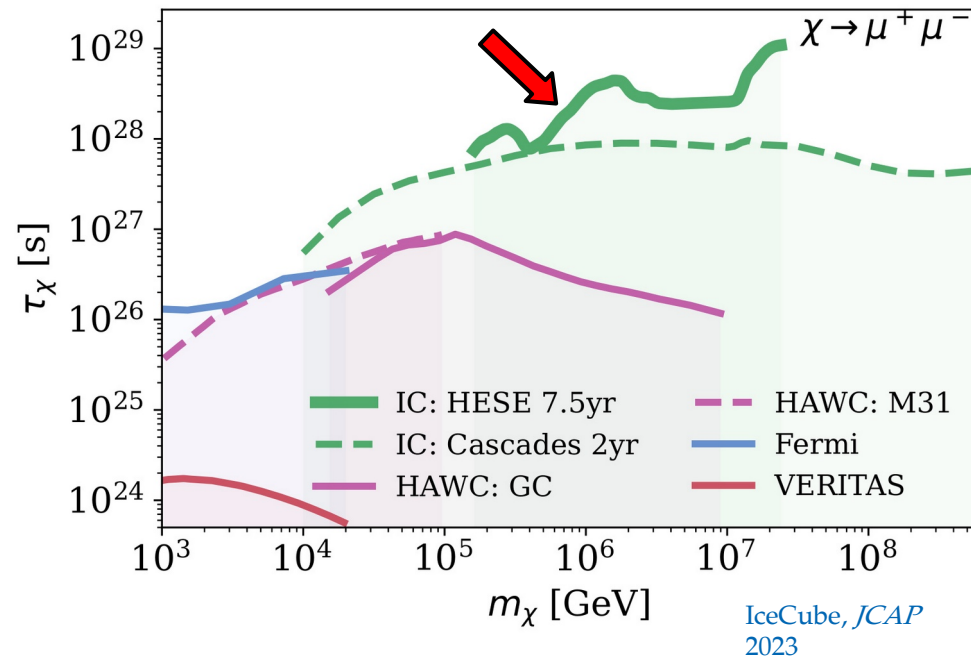


Limits on dark matter decay

Per annihilation channel
(assuming 100% branching ratio)



Compared to other limits
(assuming decay into muons)

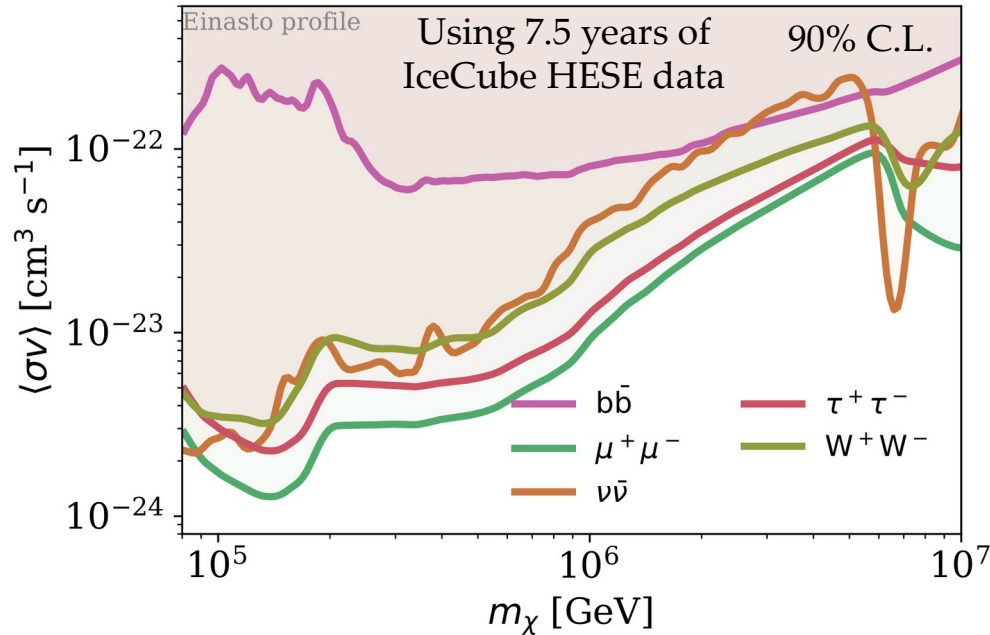


IceCube, JCAP
2023

Two DM contributions: Galactic (anisotropic) + extragalactic (isotropic)
Plus background of atmospheric neutrinos (anisotropic, but different)

Limits on dark matter annihilation

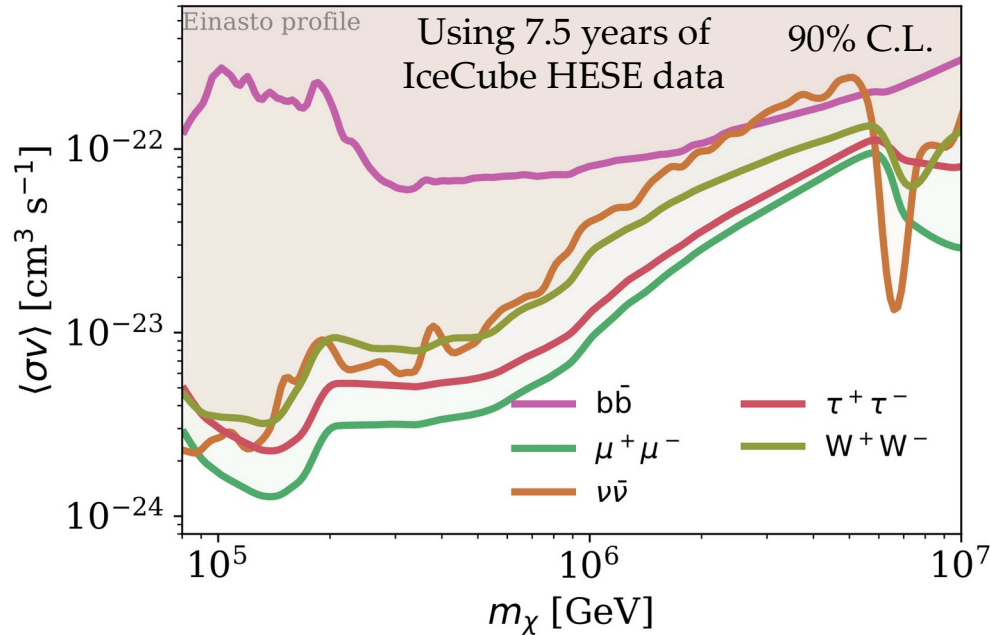
Per annihilation channel
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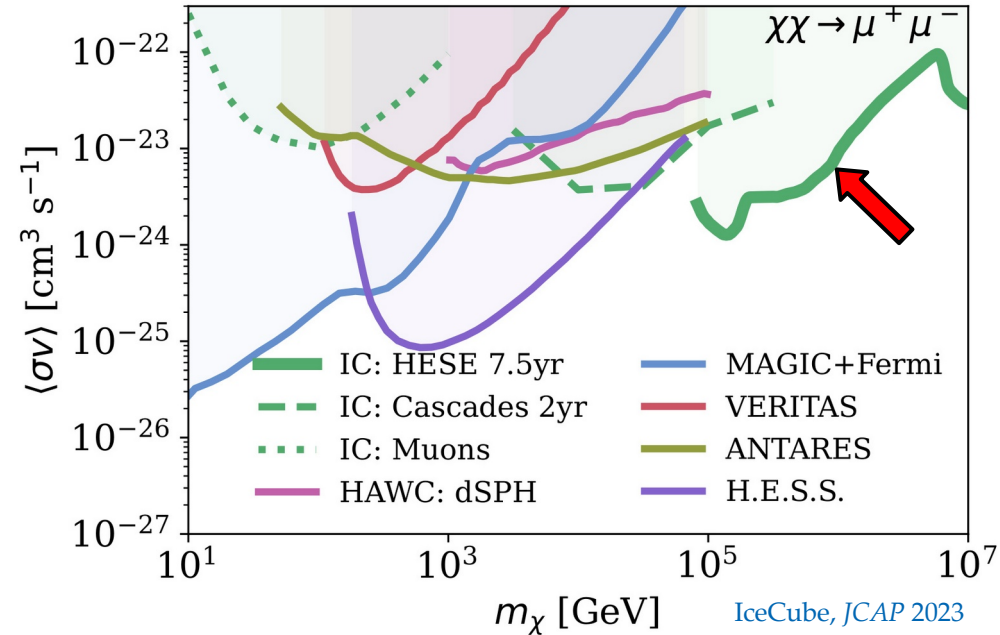
Two DM contributions: **Galactic** (anisotropic) + **extragalactic** (isotropic)
Plus background of **atmospheric** neutrinos (anisotropic, but different)

Limits on dark matter annihilation

Per annihilation channel
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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)

Neutrino decay

Are neutrinos forever?

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

» Age of Universe (~ 14.5 Gyr)
- ▶ BSM decays may have significantly higher rates: $\nu_i \rightarrow \nu_j + \varphi$
- ▶ We work in a model-independent way:
the nature of φ is unimportant if it is invisible to neutrino detectors

Are neutrinos forever?

- ▶ In the Standard Model (vSM), neutrinos are essentially stable ($\tau > 10^{36}$ yr):

- ▶ One-photon decay ($\nu_i \rightarrow \nu_j + \gamma$): $\tau > 10^{36} (m_i/\text{eV})^{-5}$ yr

- ▶ Two-photon decay ($\nu_i \rightarrow \nu_j + \gamma + \gamma$): $\tau > 10^{57} (m_i/\text{eV})^{-9}$ yr

- ▶ Three-neutrino decay ($\nu_i \rightarrow \nu_j + \nu_k + \bar{\nu}_k$): $\tau > 10^{55} (m_i/\text{eV})^{-5}$ yr

» Age of Universe
(~ 14.5 Gyr)

- ▶ BSM decays may have significantly higher rates: $\nu_i \rightarrow \nu_j$  Nambu-Goldstone boson of a broken symmetry

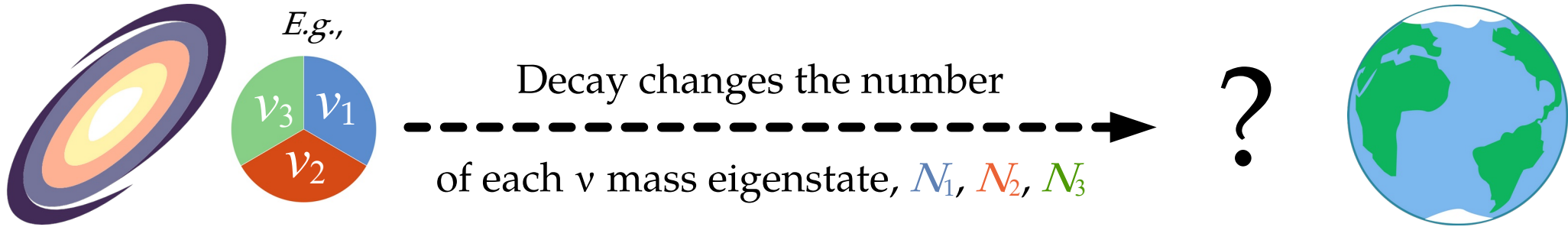
- ▶ We work in a model-independent way:

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

Astrophysical sources

Earth

$L \sim$ up to a few Gpc

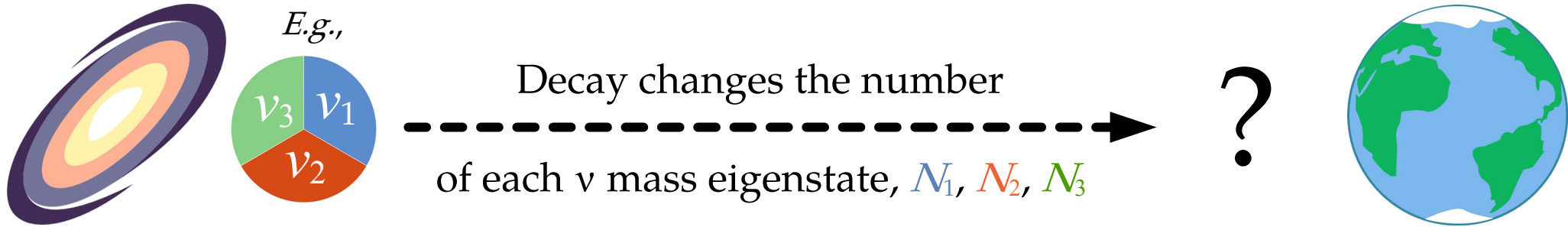


The flux of ν_i is attenuated by $\exp[- (L/E) \cdot (\underbrace{m_i}_{\text{Mass of } \nu_i} / \underbrace{\tau_i}_{\text{Lifetime of } \nu_i})]$

Astrophysical sources

Earth

$L \sim$ up to a few Gpc



Only sensitive to their ratio

The flux of ν_i is attenuated by $\exp[- (L/E) \cdot \overbrace{(m_i/\tau_i)}^{\text{Mass of } \nu_i \text{ Lifetime of } \nu_i}]$

Astrophysical sources

Earth

$L \sim$ up to a few Gpc



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

?



Lower- $E \nu$ are longer-lived...

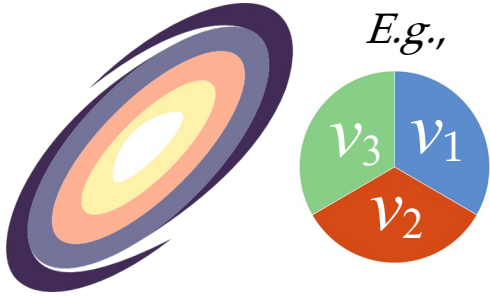
The flux of ν_i is attenuated by $\exp[-(L/E) \cdot (m_i/\tau_i)]$

... but ν that travel longer L are more attenuated!

Astrophysical sources

Earth

$L \sim$ up to a few Gpc



Astrophysical sources

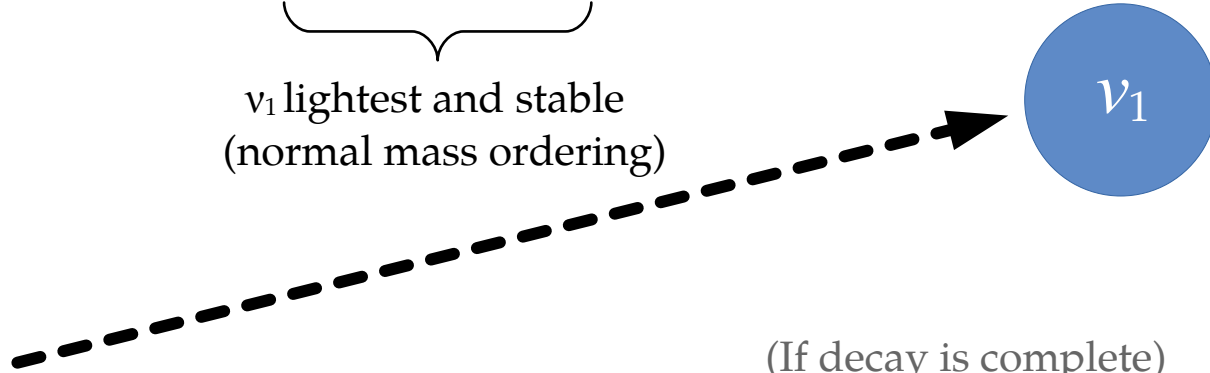
Earth

$L \sim \text{up to a few Gpc}$

$$\nu_2, \nu_3 \rightarrow \nu_1$$

ν_1 lightest and stable
(normal mass ordering)

E.g.,



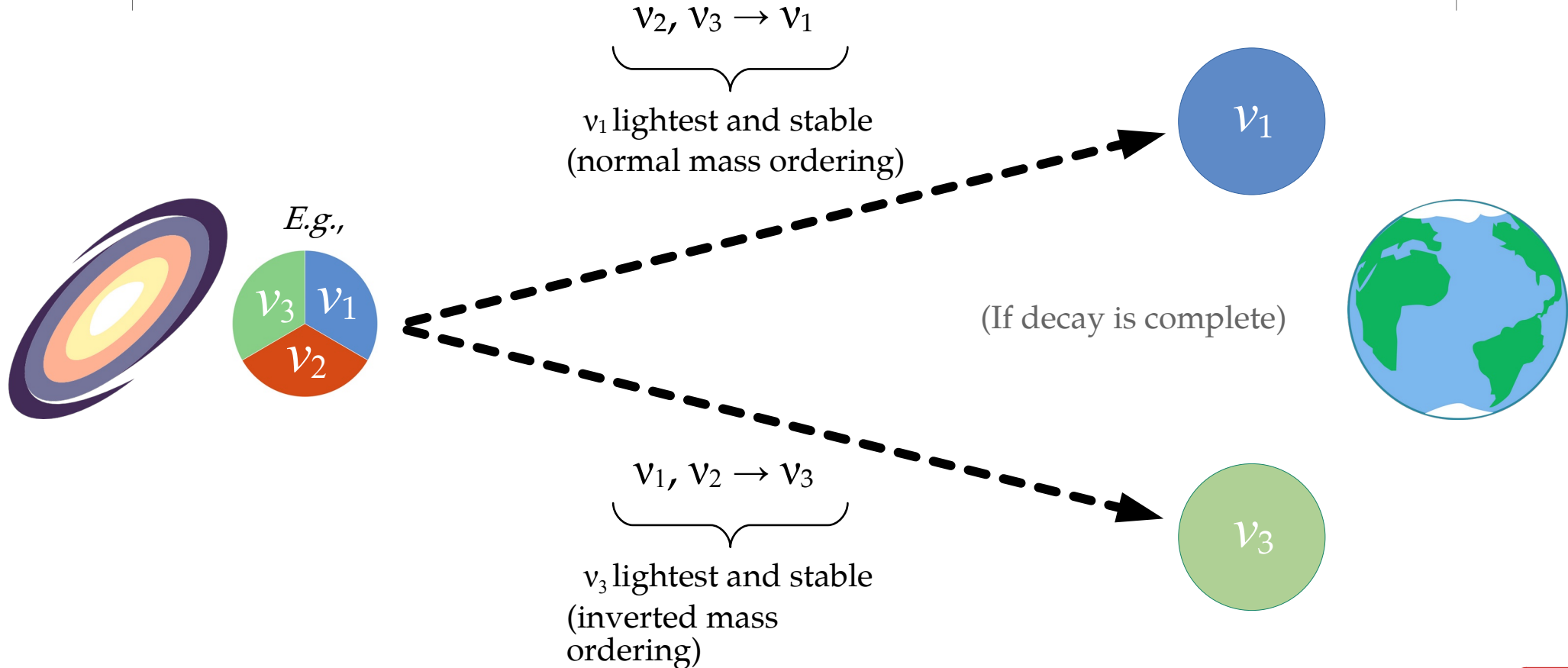
(If decay is complete)

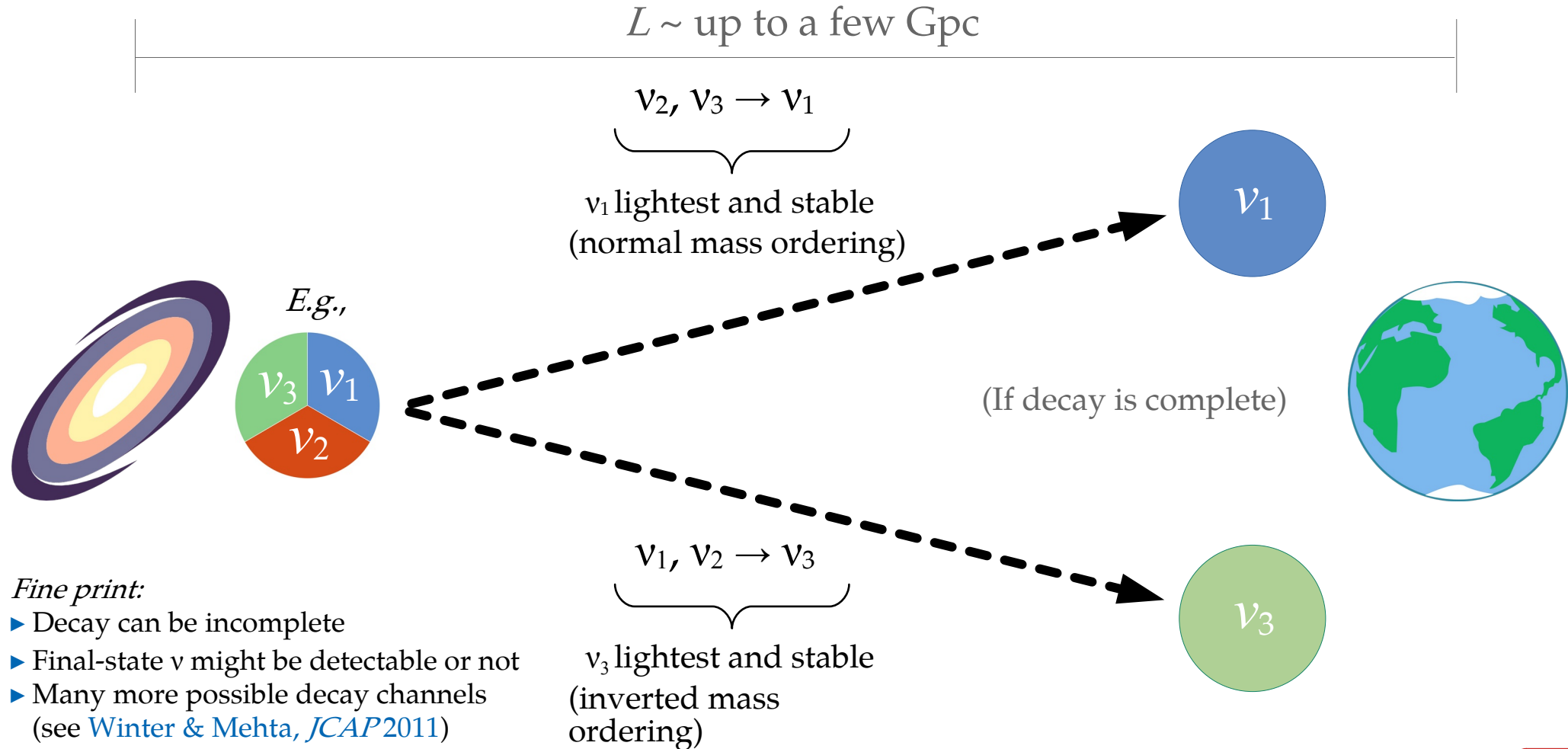


Astrophysical sources

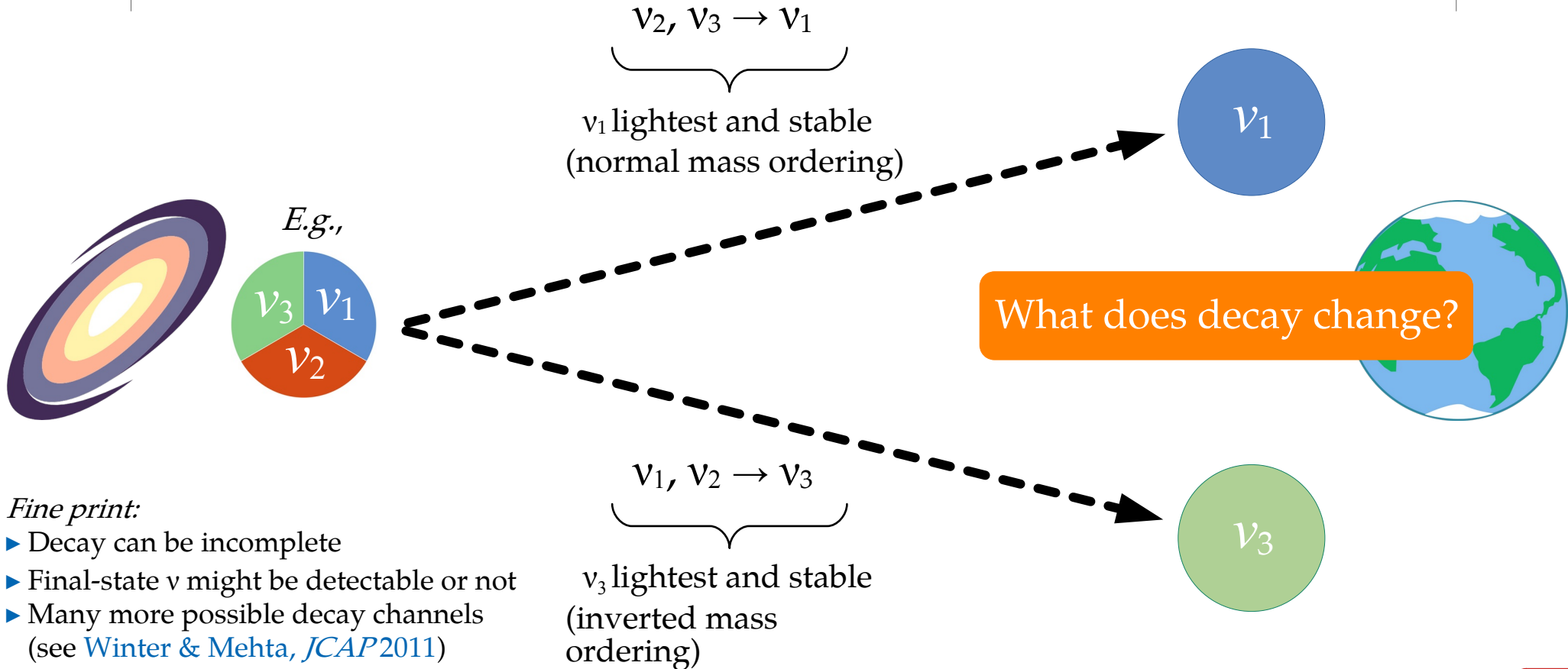
Earth

$L \sim$ up to a few Gpc





$L \sim \text{up to a few Gpc}$



What does neutrino decay change?

Flavor composition $\longleftrightarrow$ Spectrum shape $\longleftrightarrow$ Event rate

What does neutrino decay change?

Flavor composition $\longleftrightarrow$ Spectrum shape $\longleftrightarrow$ Event rate

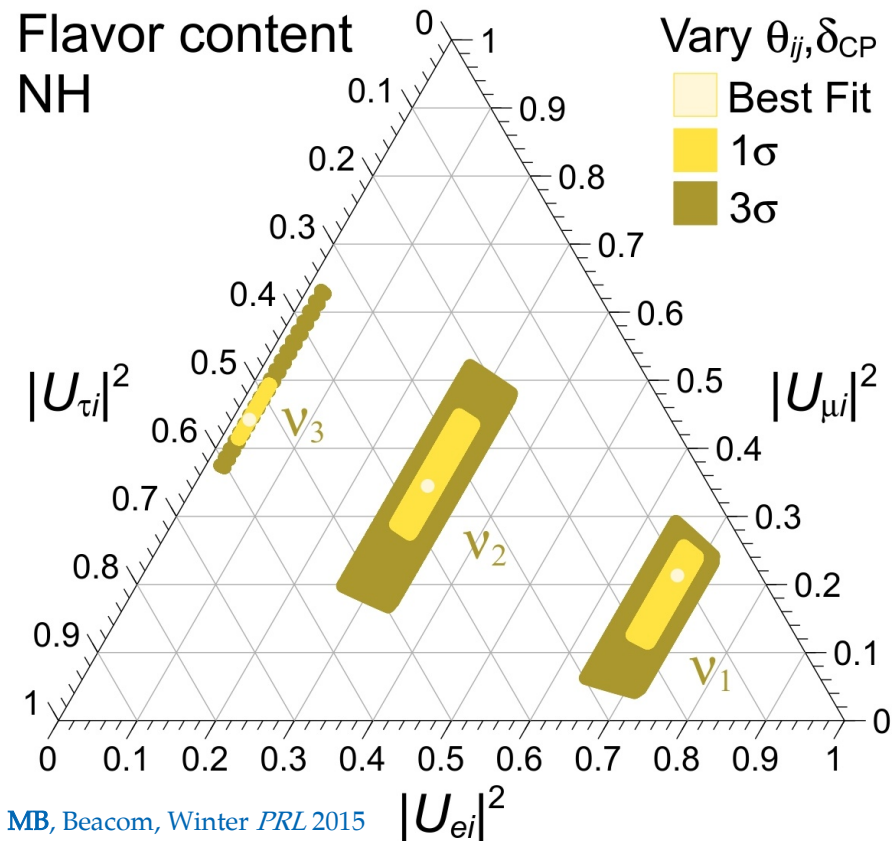
Flavor content of mass eigenstates:

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

Known to within 2%

Known to within 8%

Known to within 20% (or worse)



What does neutrino decay change?

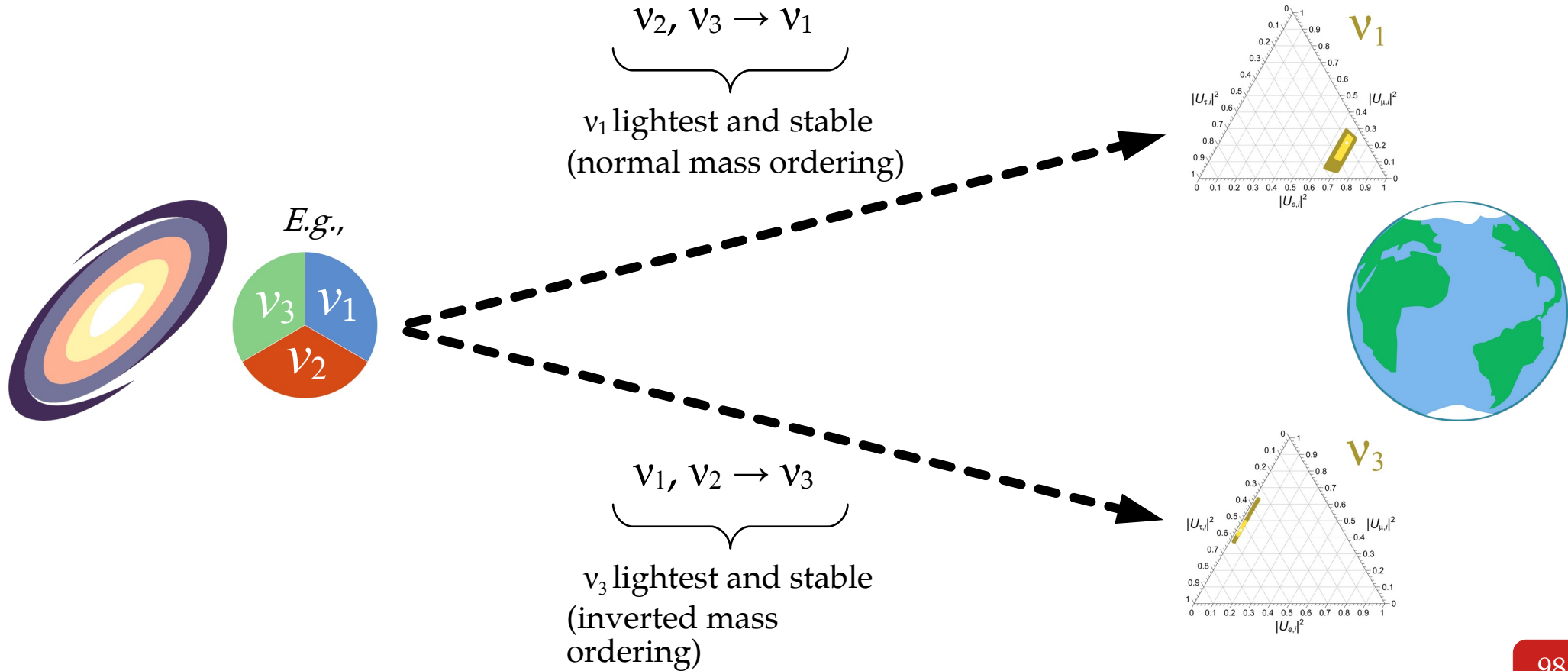
Flavor composition



Spectrum shape



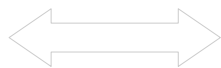
Event rate



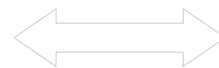
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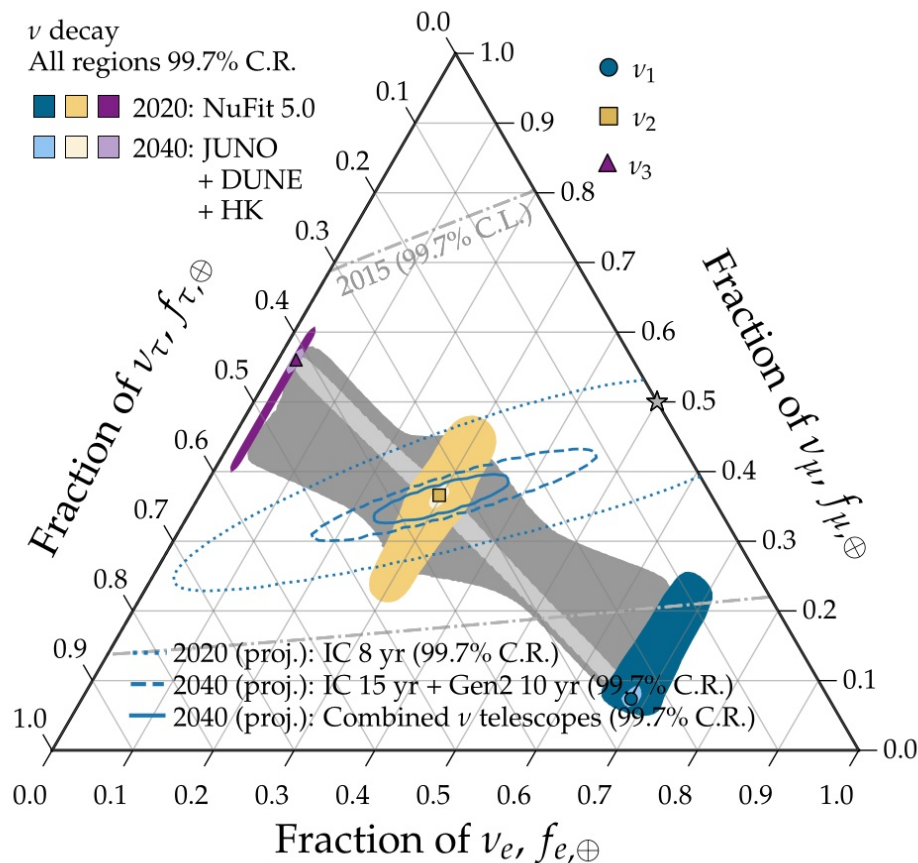
Flavor composition



Spectrum shape



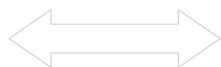
Event rate



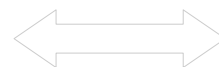
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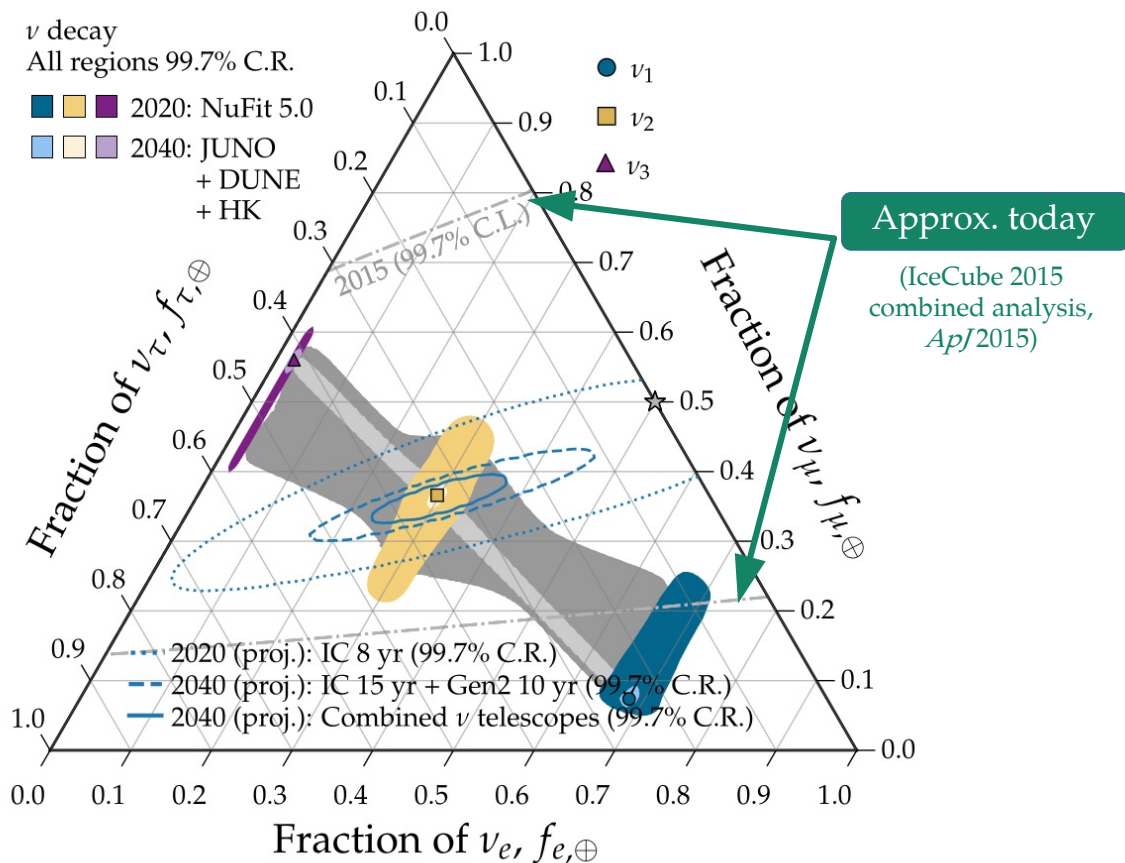
Flavor composition



Spectrum shape



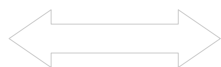
Event rate



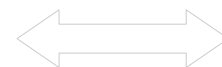
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See also: Beacom *et al.*, *PRL* 2002 / Baerwald, **MB**, Winter, *JCAP* 2012 / **MB**, Beacom, Murase, *PRD* 2017 / Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / **MB**, 2004.06844

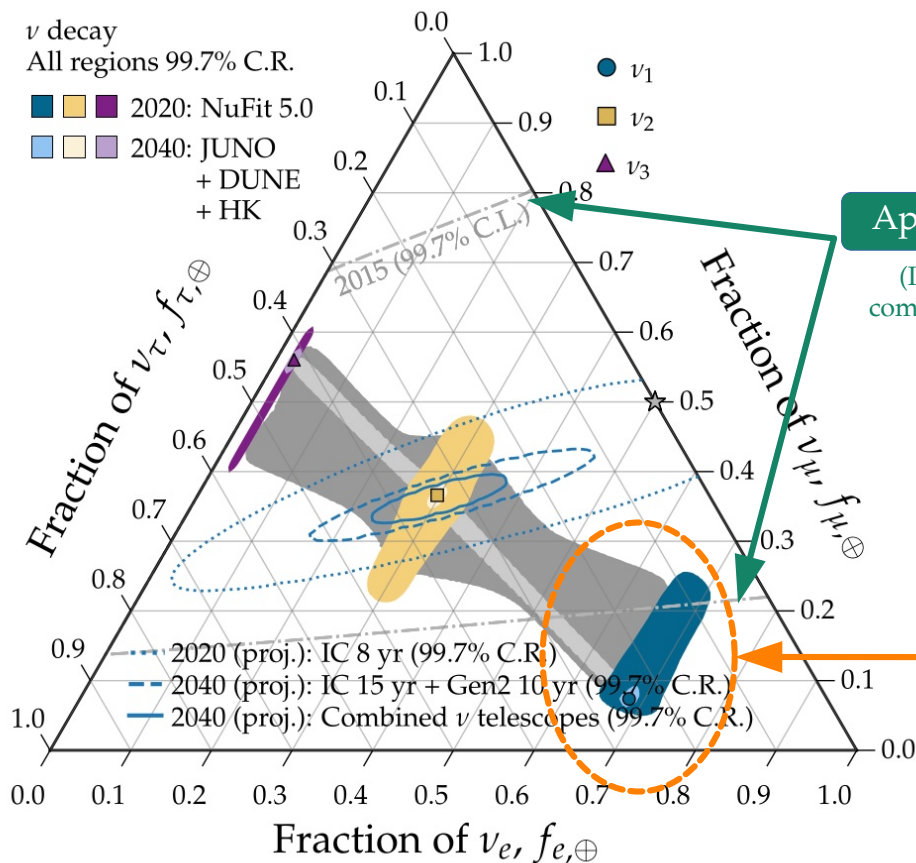
Flavor composition



Spectrum shape



Event rate



Approx. today

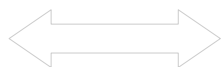
(IceCube 2015
combined analysis,
ApJ 2015)

Complete decay into
 ν_1 disfavored by 2015
IceCube flavor measurement

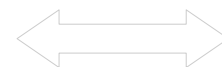
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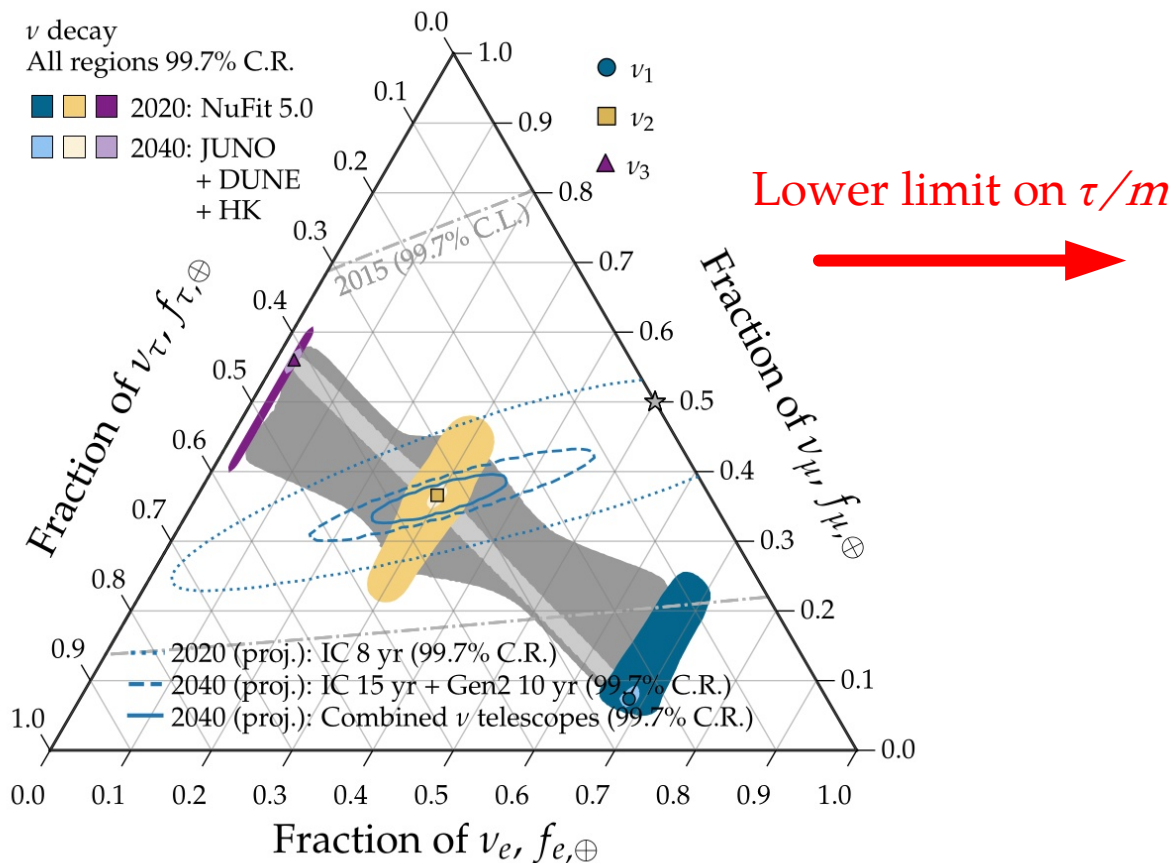
Flavor composition



Spectrum shape



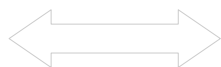
Event rate



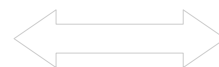
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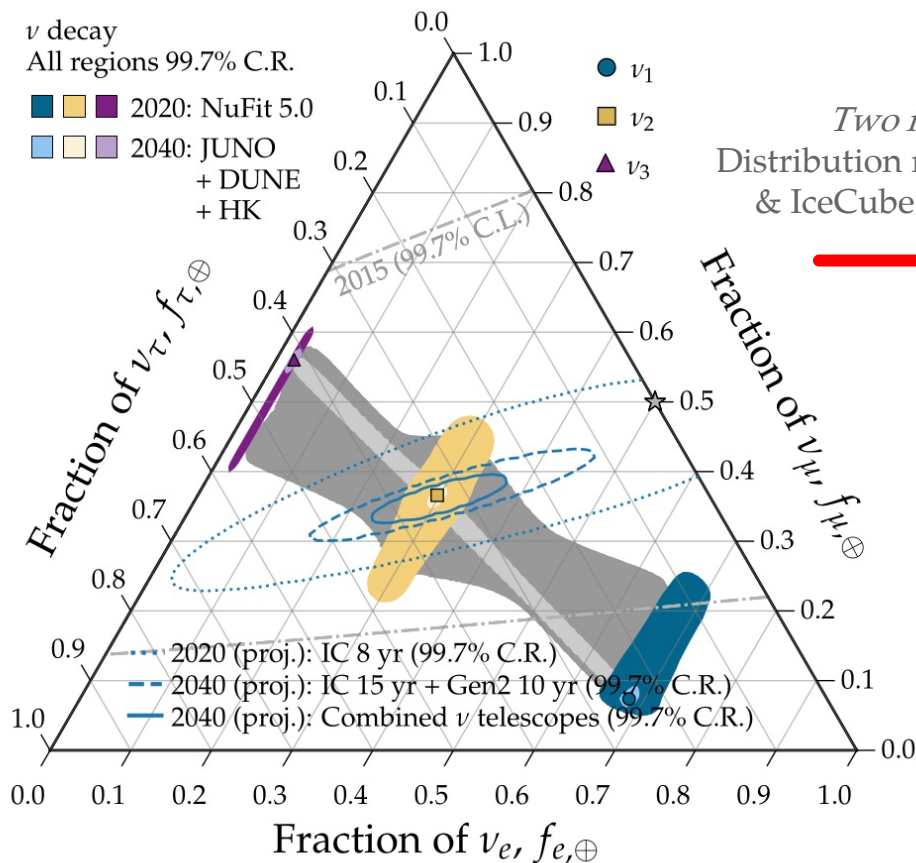
Flavor composition



Spectrum shape



Event rate



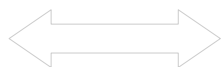
Two ingredients:
Distribution mixing parameters
& IceCube flavor posterior



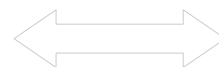
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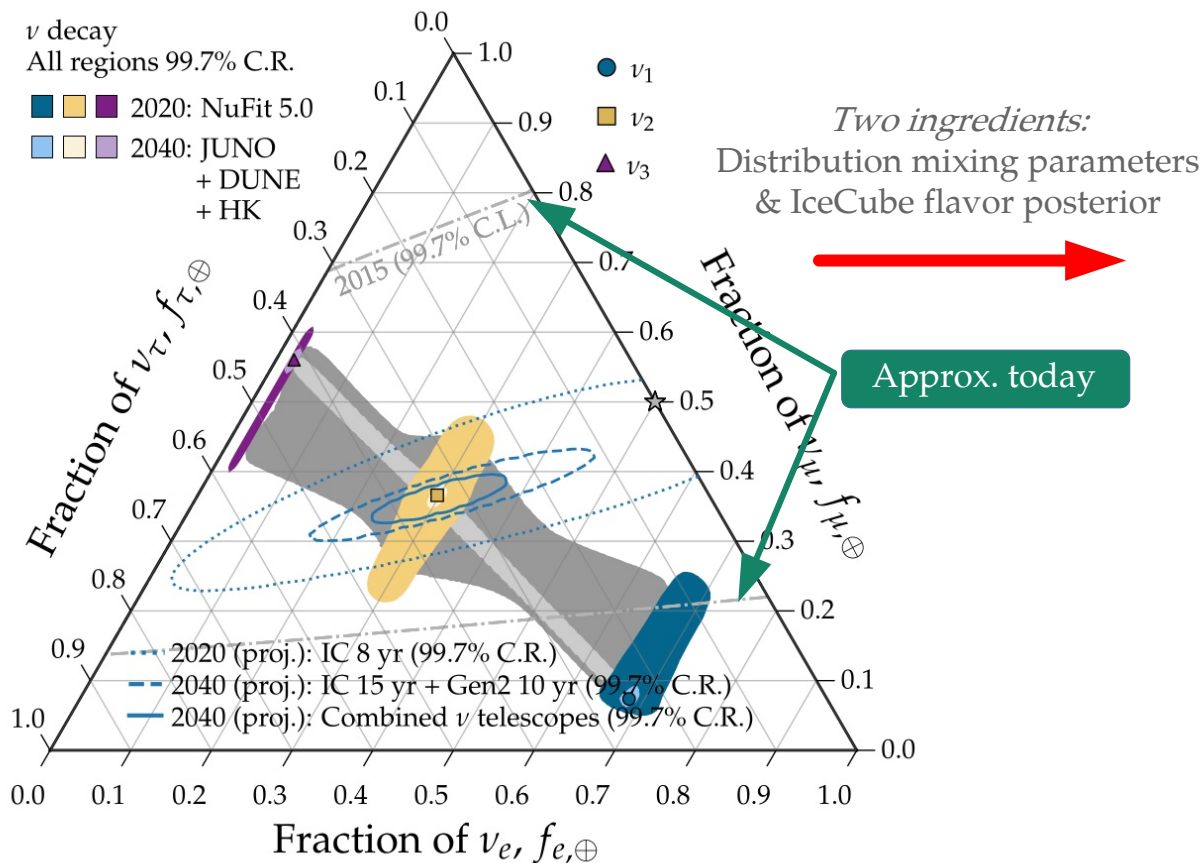
Flavor composition



Spectrum shape



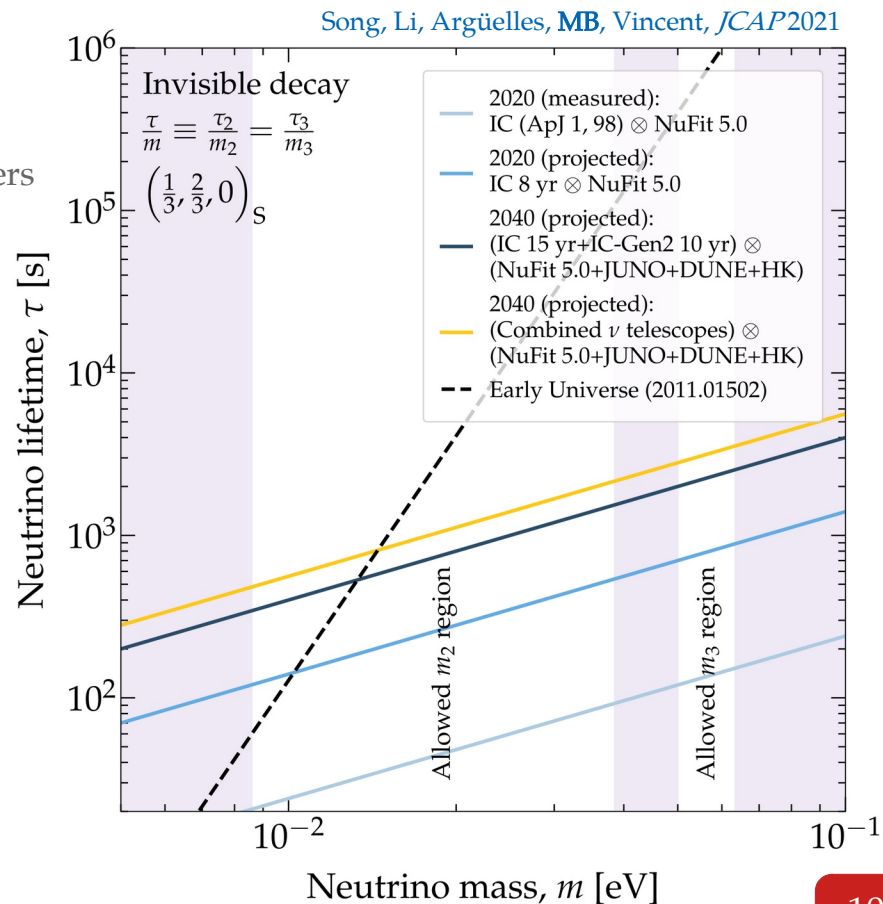
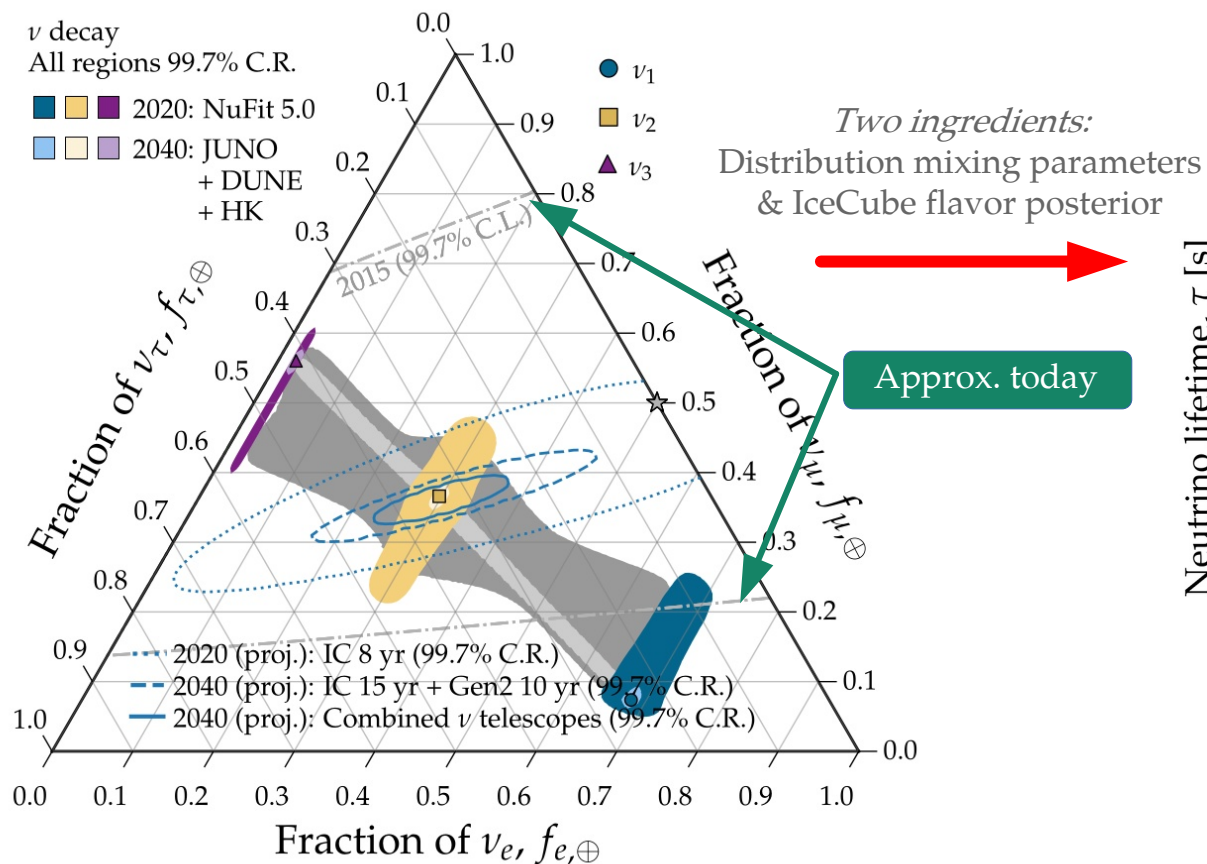
Event rate



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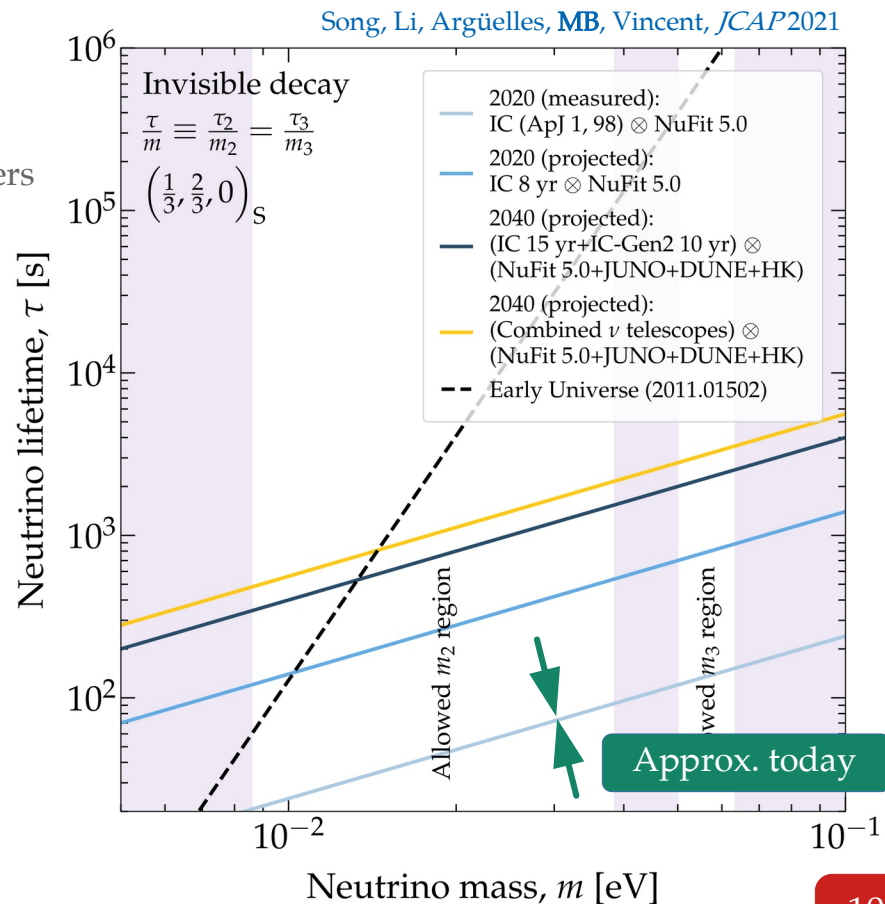
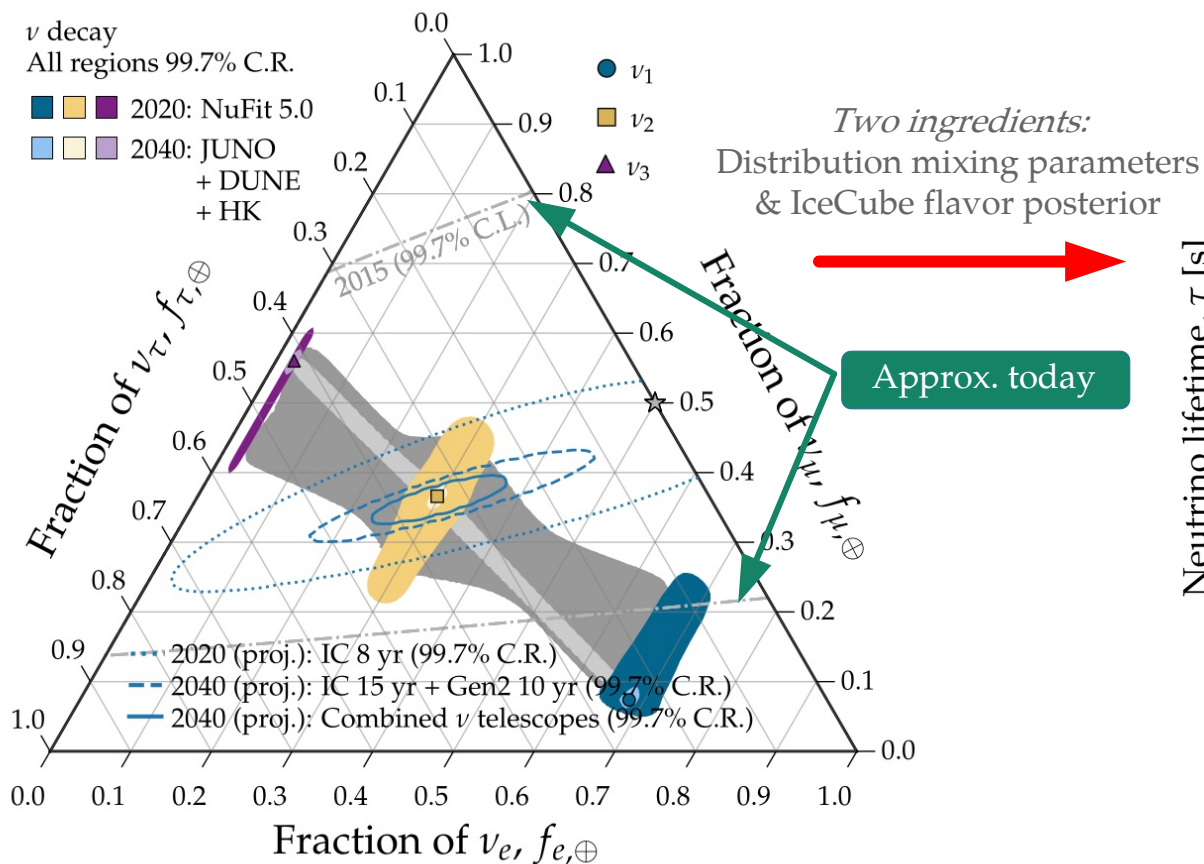
Flavor composition $\longleftrightarrow$ Spectrum shape $\longleftrightarrow$ Event rate



What does neutrino decay change?

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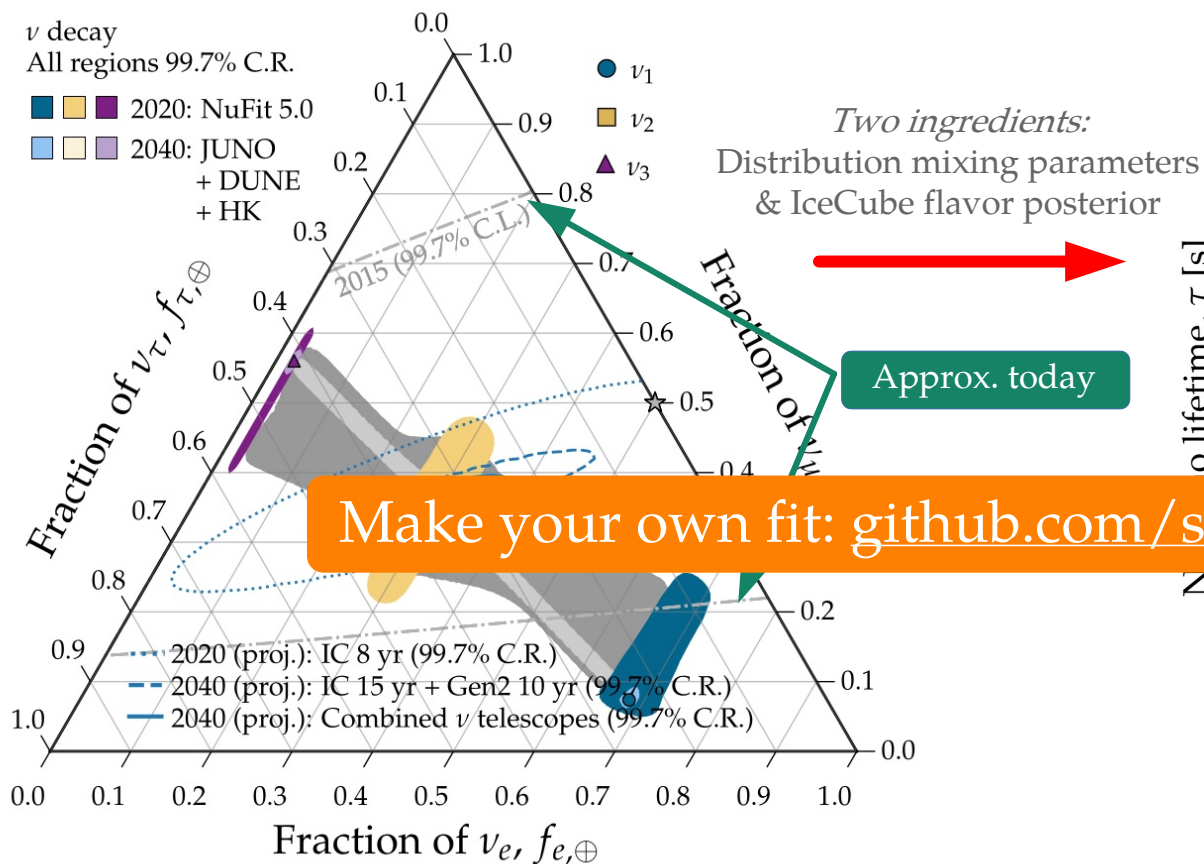
Flavor composition $\longleftrightarrow$ Spectrum shape $\longleftrightarrow$ Event rate



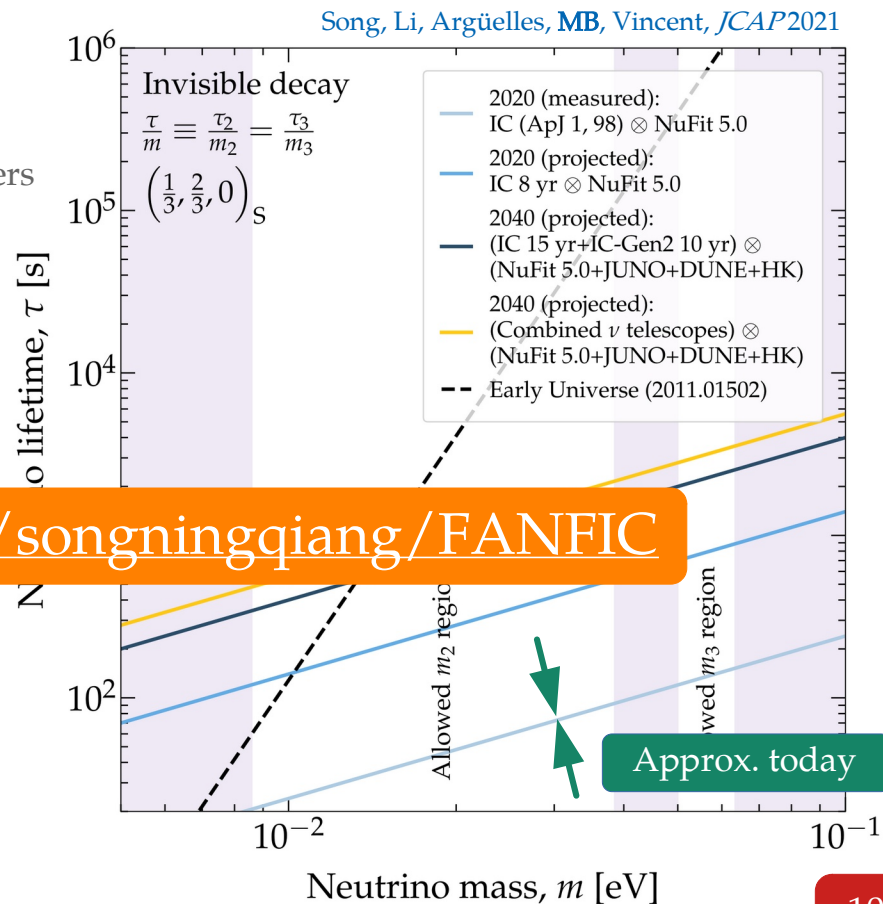
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Flavor composition $\longleftrightarrow$ Spectrum shape $\longleftrightarrow$ Event rate



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



What does neutrino decay change?

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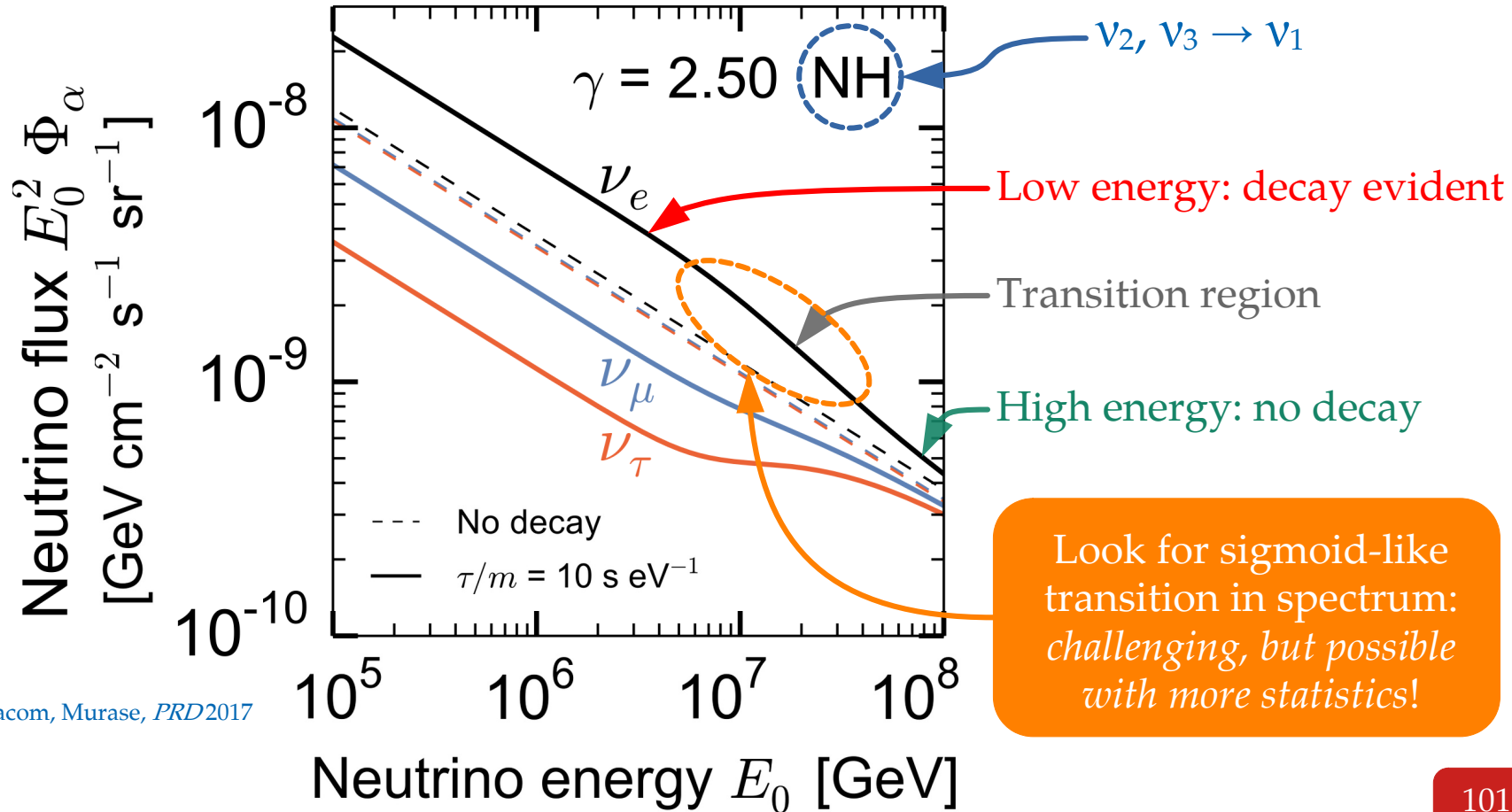
Flavor composition



Spectrum shape



Event rate

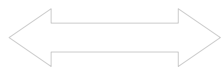


MB, Beacom, Murase, *PRD* 2017

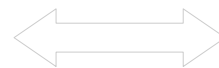
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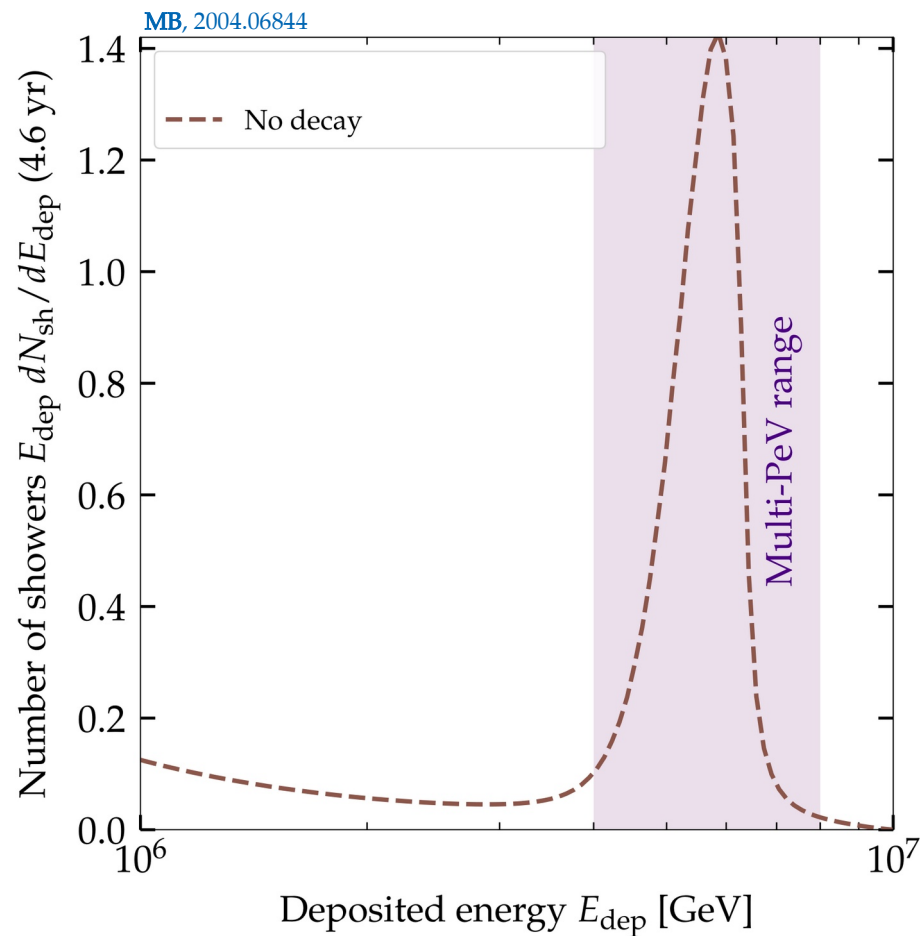
Flavor composition



Spectrum shape



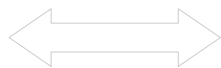
Event rate



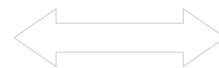
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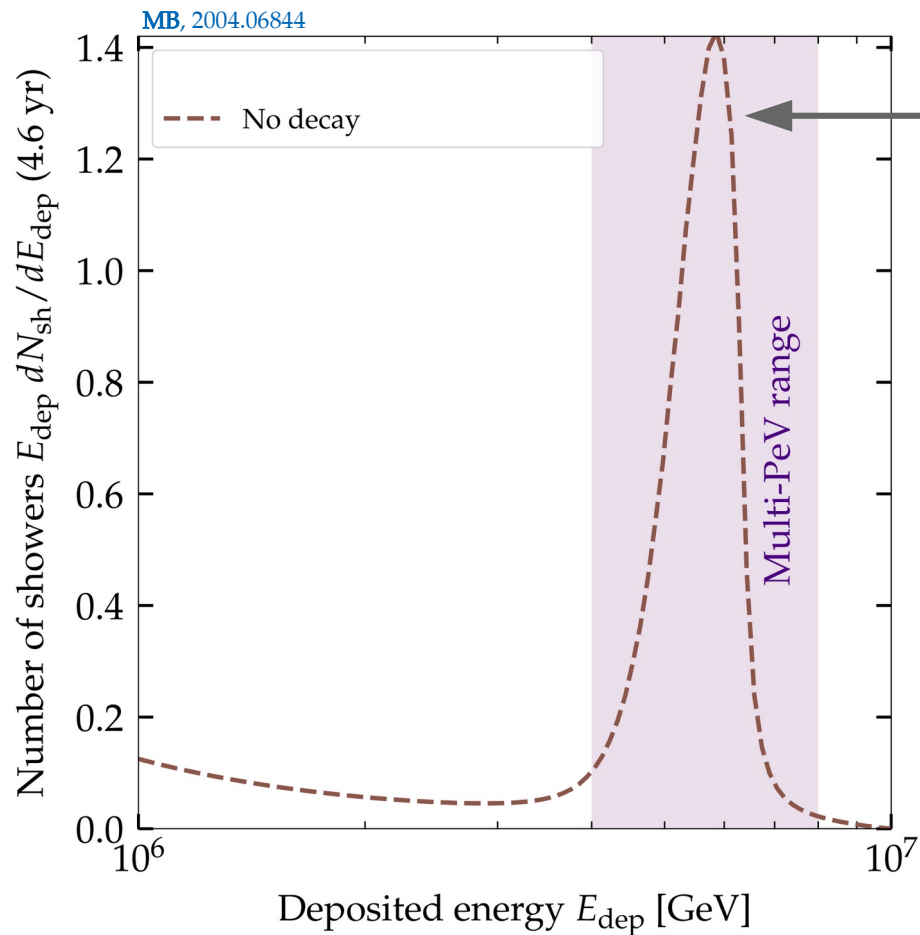
Flavor composition



Spectrum shape



Event rate



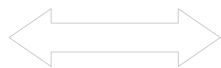
Glashow resonance (GR):

$\bar{\nu}_e + e \rightarrow W \rightarrow \text{hadrons} \rightarrow \text{shower}$

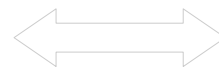
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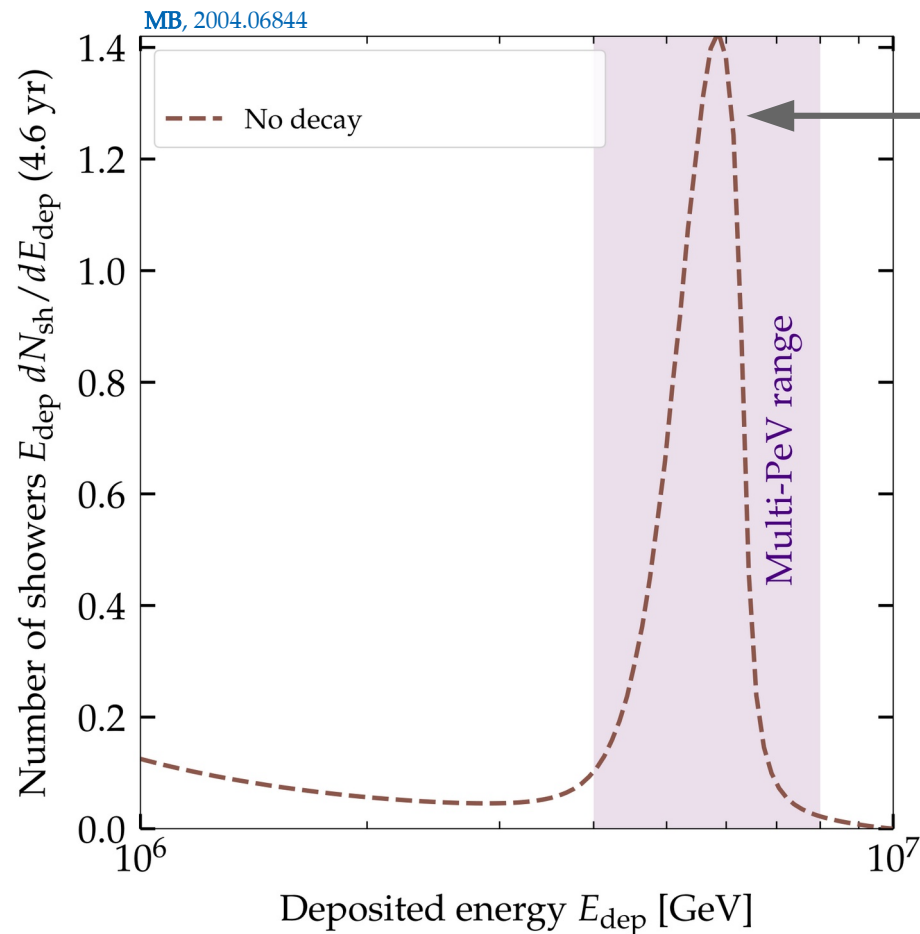
Flavor composition



Spectrum shape



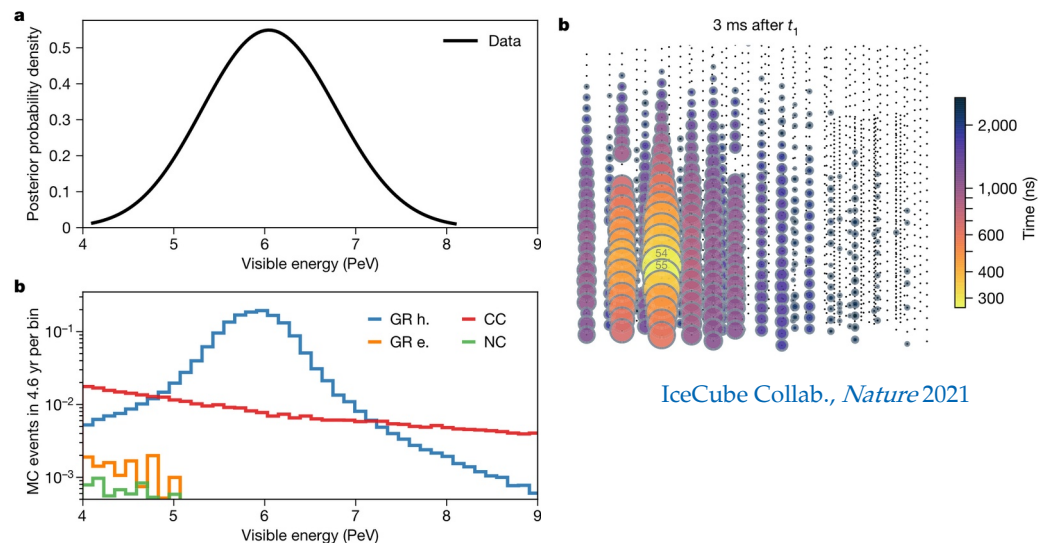
Event rate



Glashow resonance (GR):

$$\bar{\nu}_e + e \rightarrow W \rightarrow \text{hadrons} \rightarrow \text{shower}$$

IceCube has seen one GR candidate in 4.6 years:

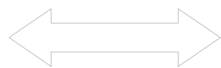


IceCube Collab., *Nature* 2021

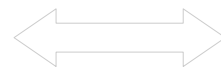
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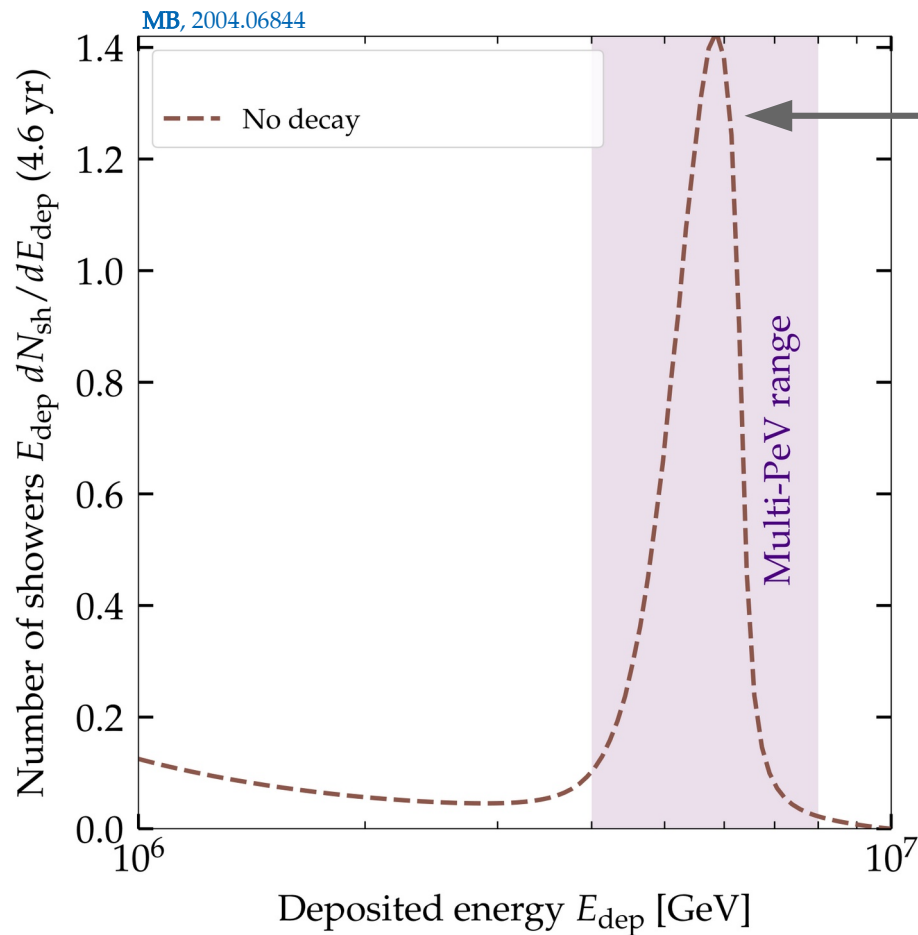
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Spectrum shape



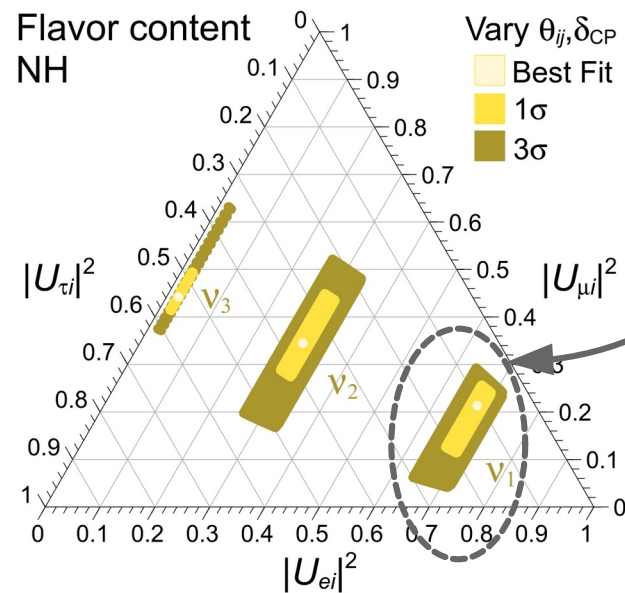
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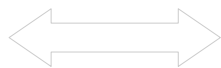
ν_1 is the mass eigenstate with the most e flavor



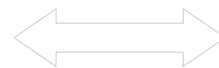
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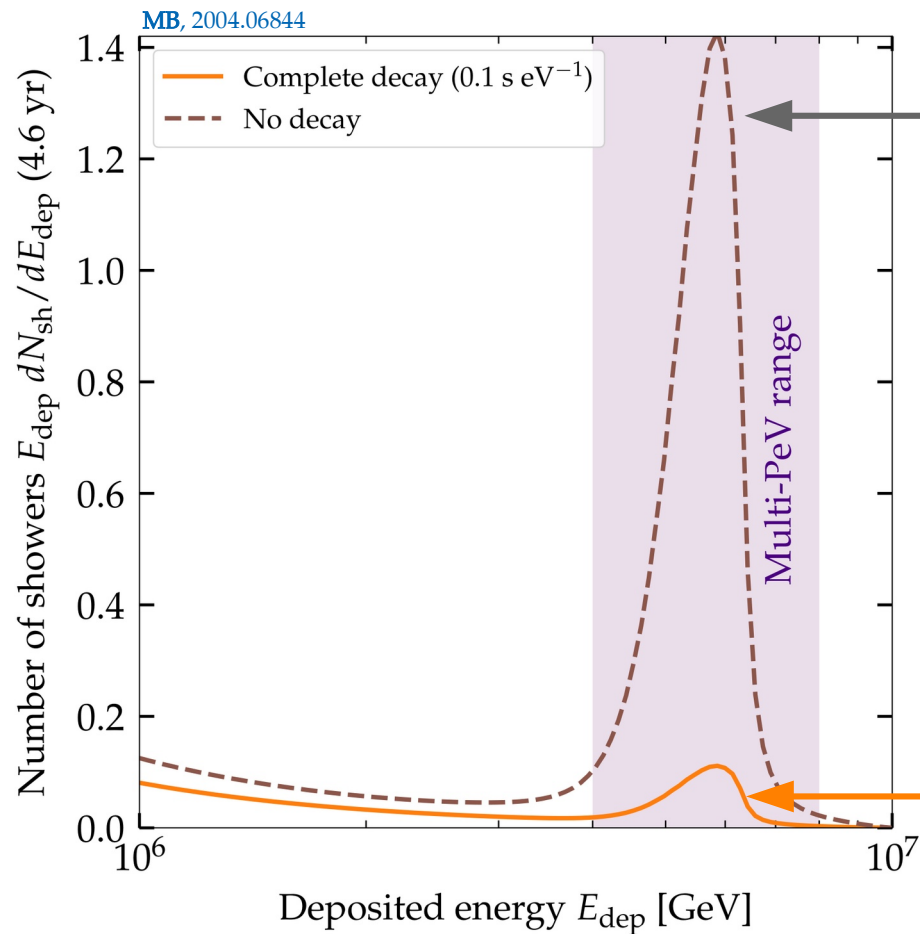
Flavor composition



Spectrum shape



Event rate



Glashow resonance (GR):

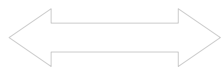
$$\bar{\nu}_e + e \rightarrow W \rightarrow \text{hadrons} \rightarrow \text{shower}$$

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

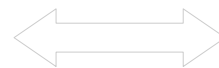
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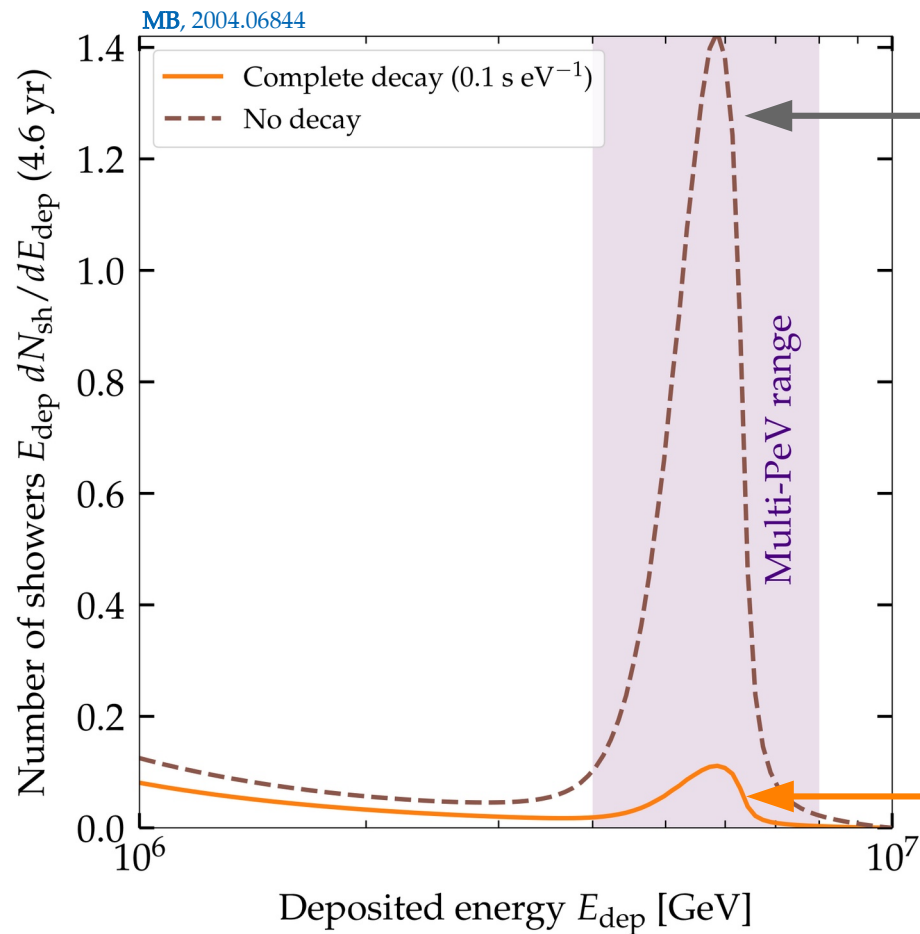
Flavor composition



Spectrum shape



Event rate



Glashow resonance (GR):

$\bar{\nu}_e + e \rightarrow W \rightarrow \text{hadrons} \rightarrow \text{shower}$

So by having observed 1 GR event we can place a *lower* limit on the lifetime of $\bar{\nu}_1$ ($= \nu_1$)

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

What does neutrino decay change?

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

Flavor composition

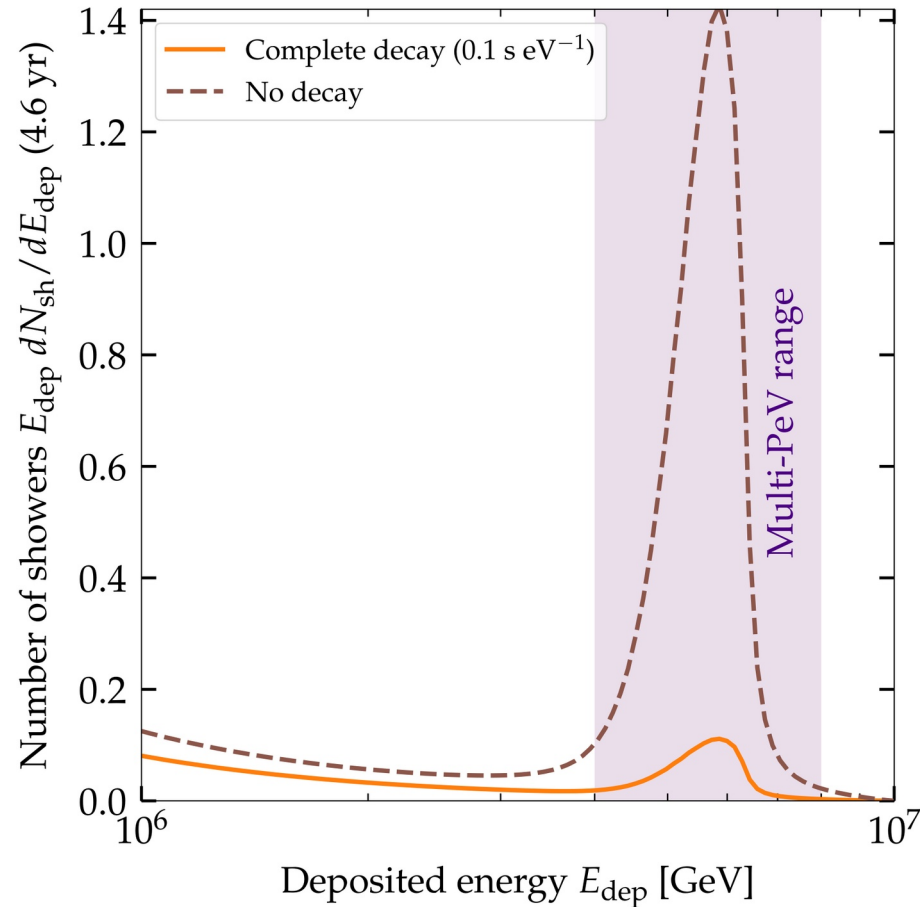


Spectrum shape



Event rate

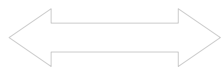
MB, 2004.06844



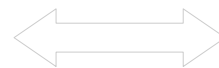
What does neutrino decay change?

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

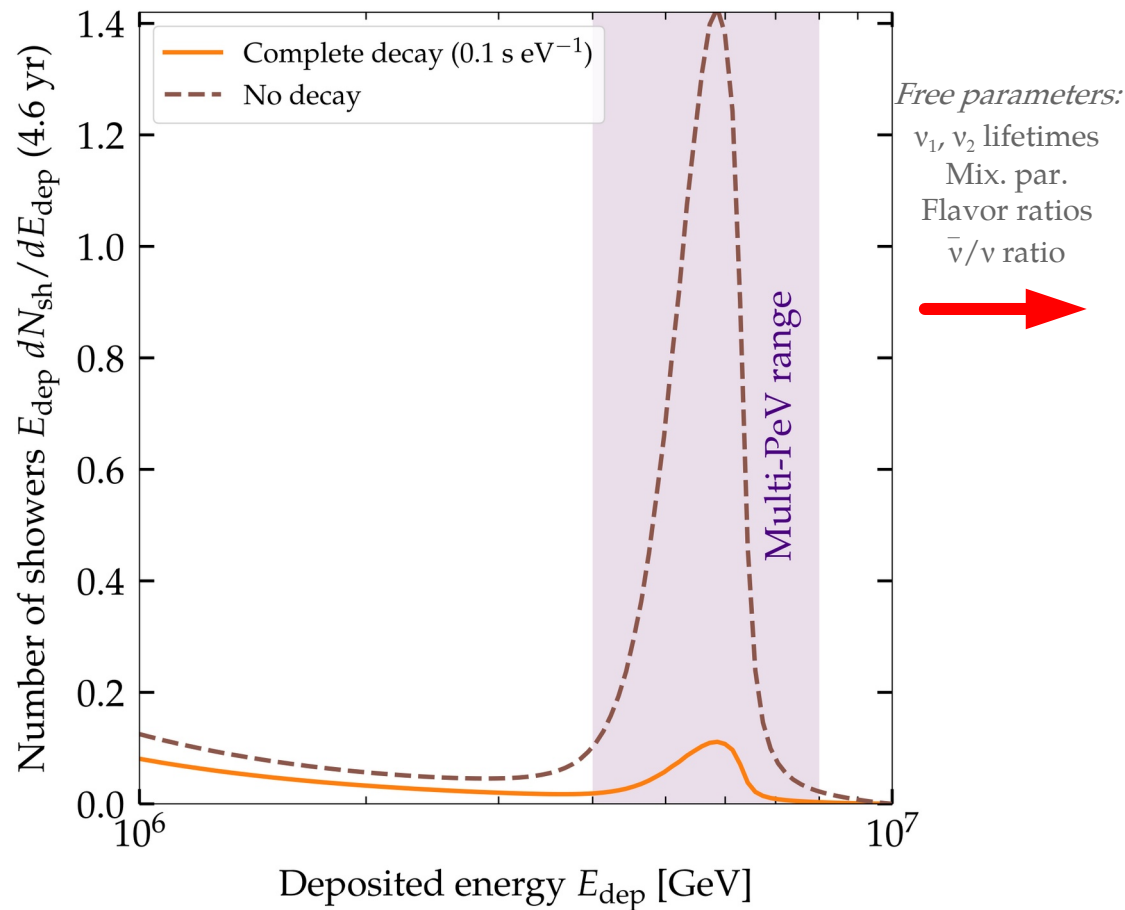


Spectrum shape



Event rate

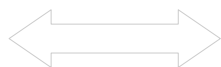
MB, 2004.06844



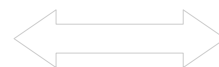
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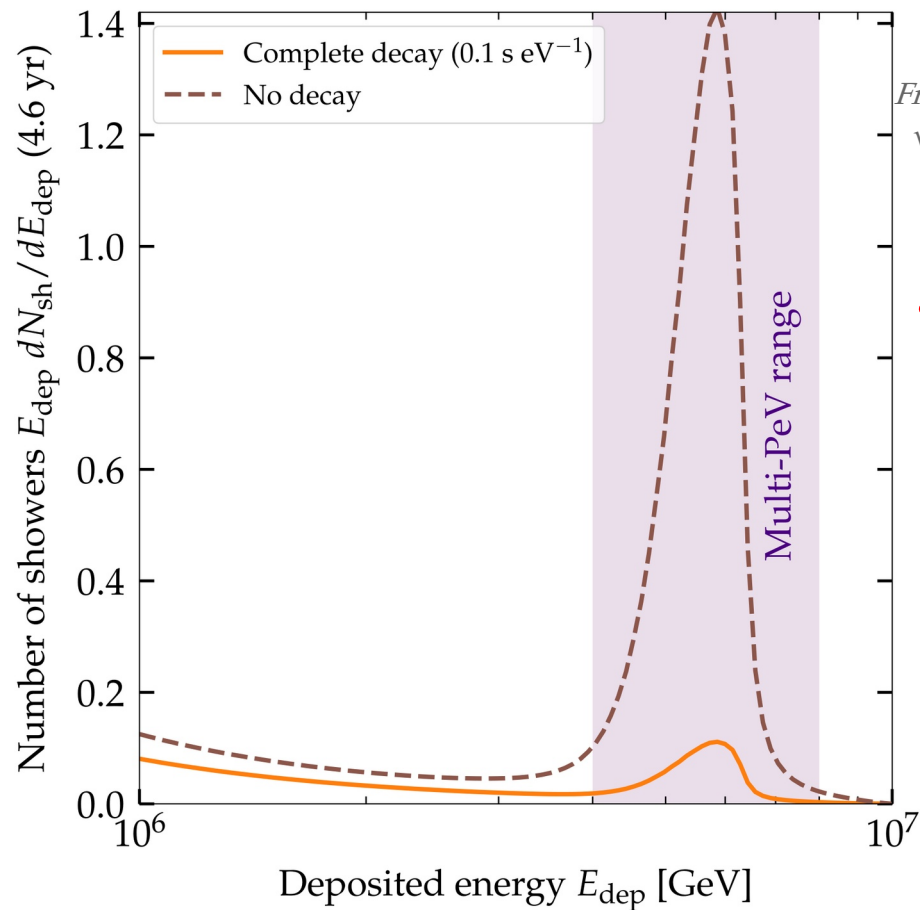
Flavor composition



Spectrum shape

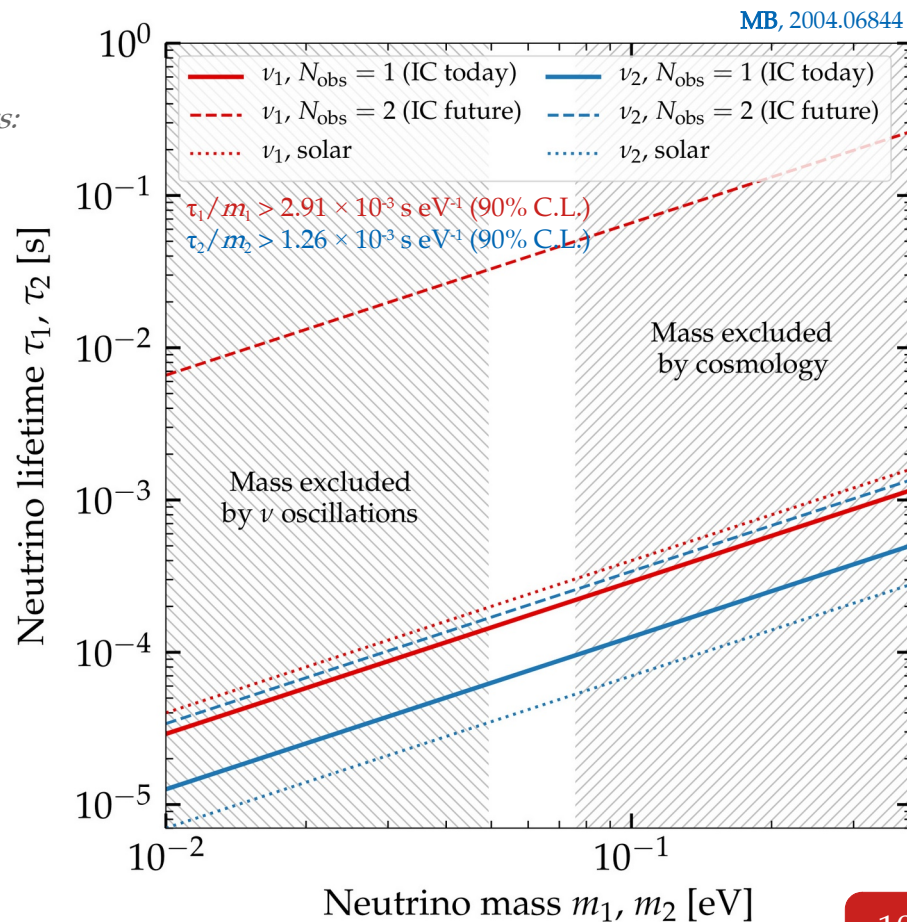


Event rate



Free parameters:

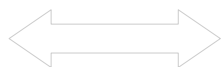
ν_1, ν_2 lifetimes
Mix. par.
Flavor ratios
 $\bar{\nu}/\nu$ ratio



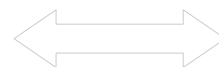
What does neutrino decay change?

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

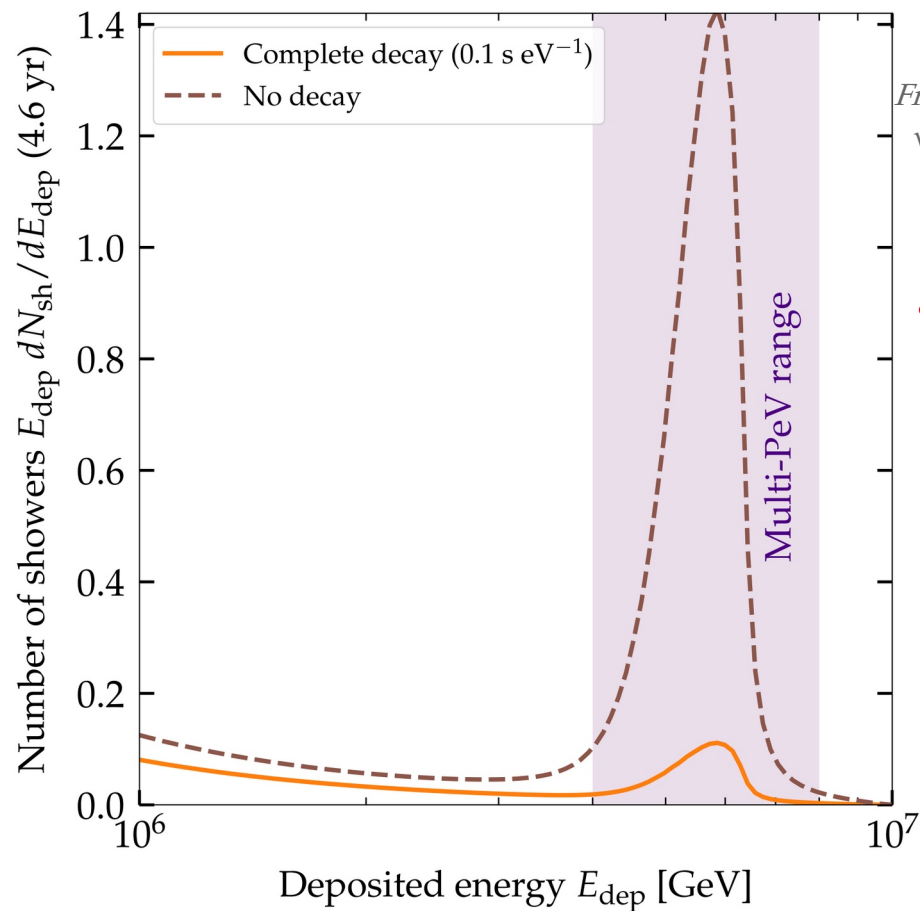
Flavor composition



Spectrum shape

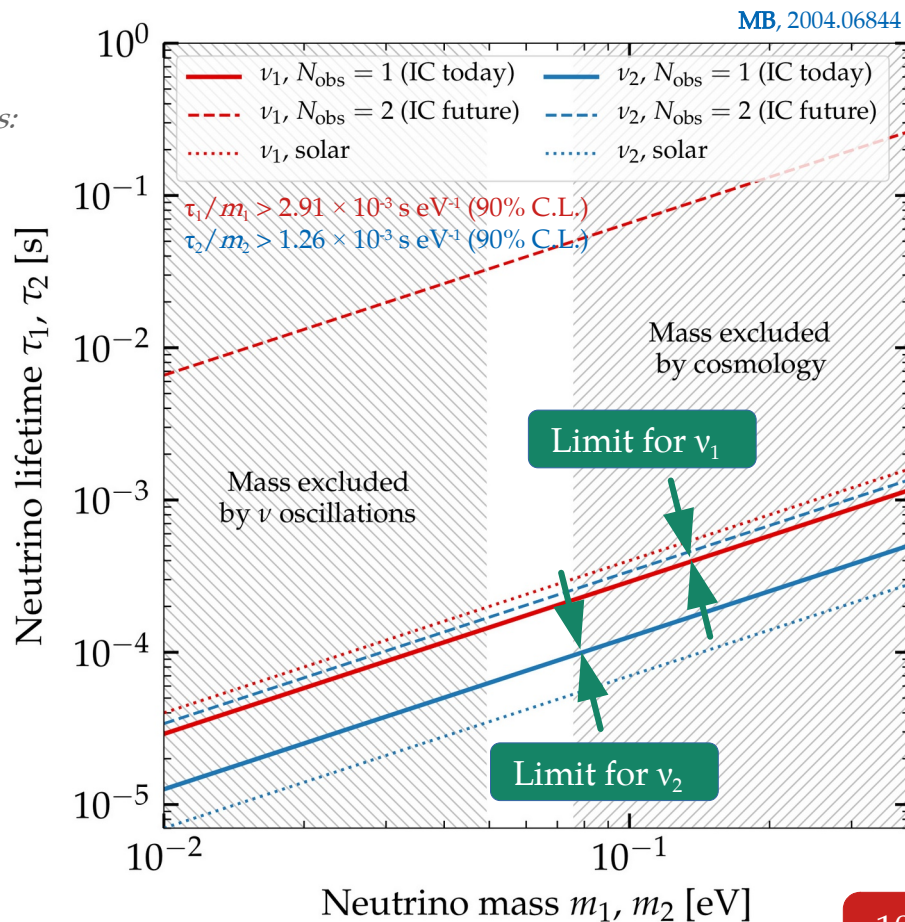


Event rate



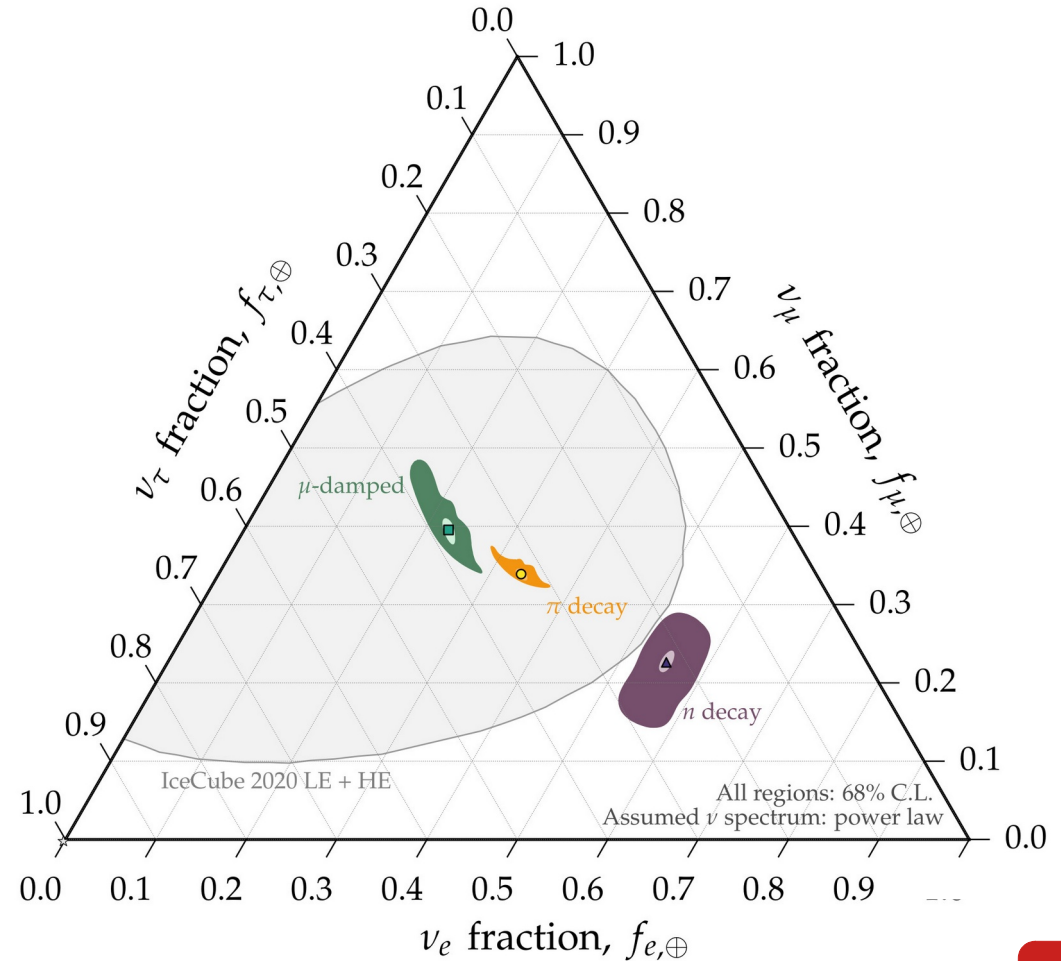
Free parameters:

ν_1, ν_2 lifetimes
Mix. par.
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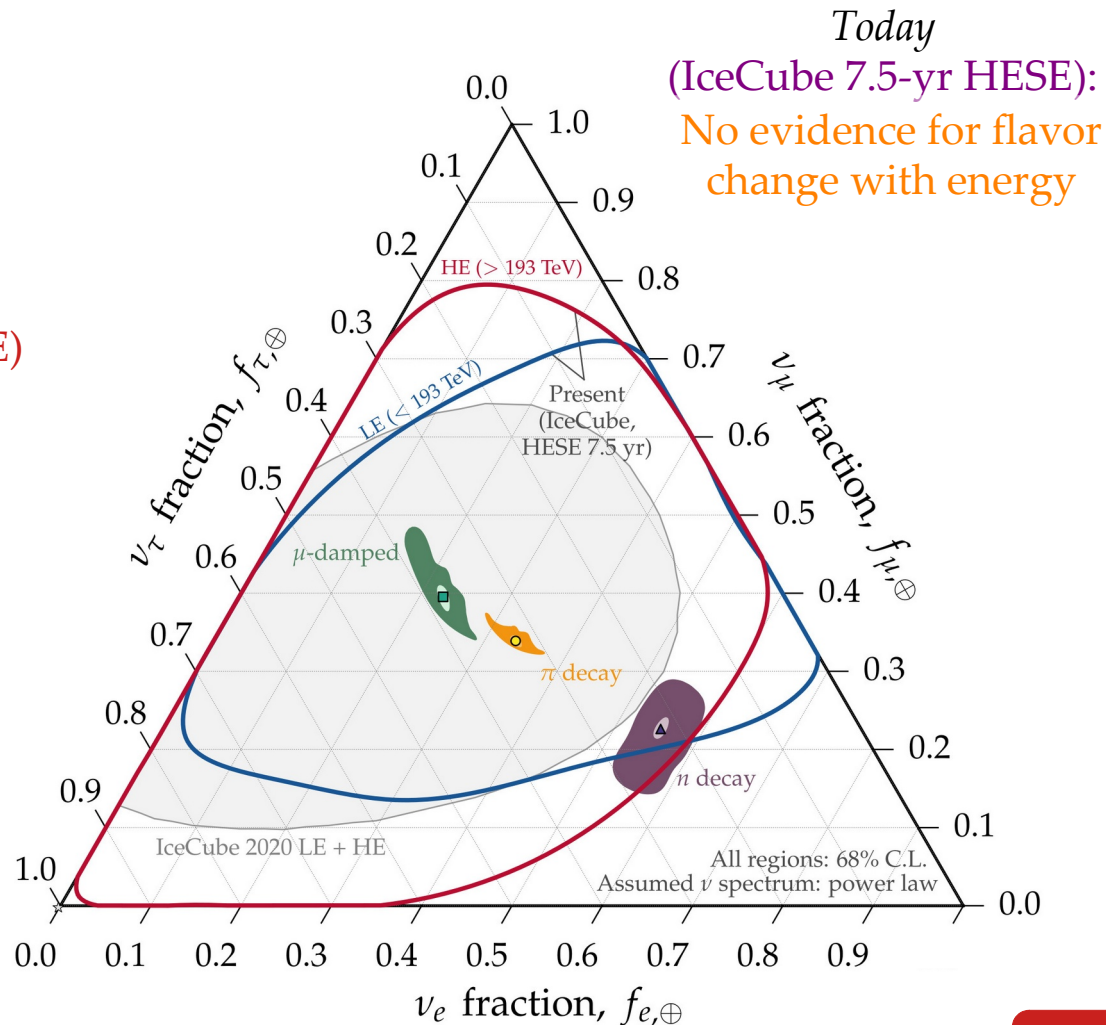
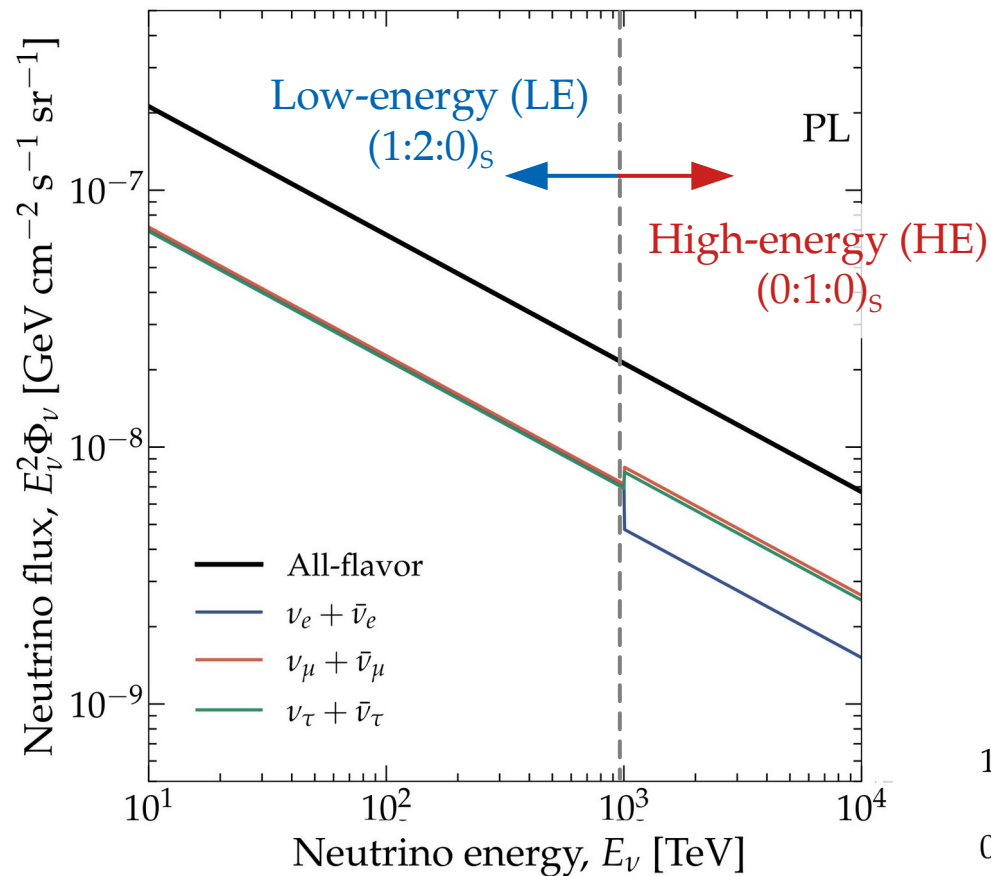
Energy-dependent
flavor composition

Flavor composition: measuring the energy dependence



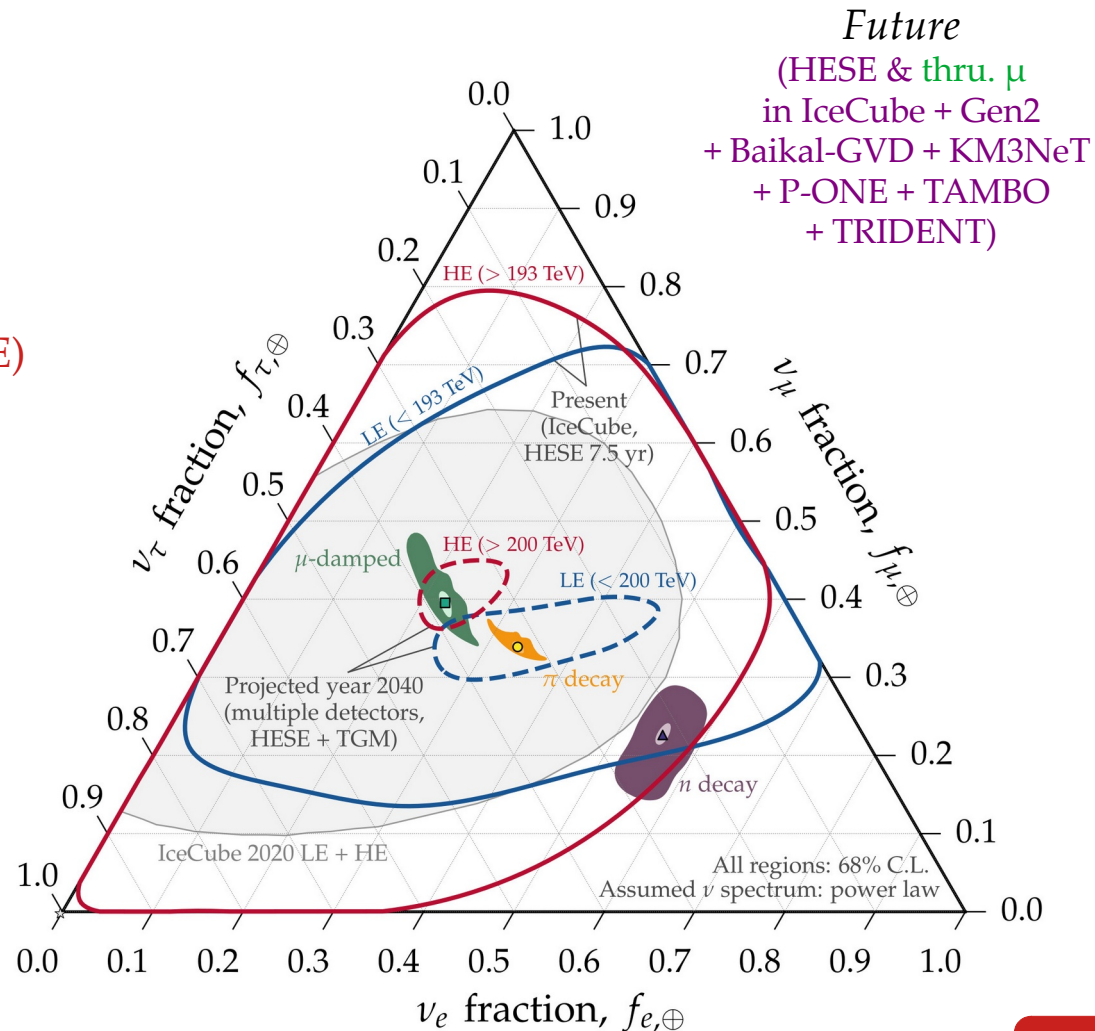
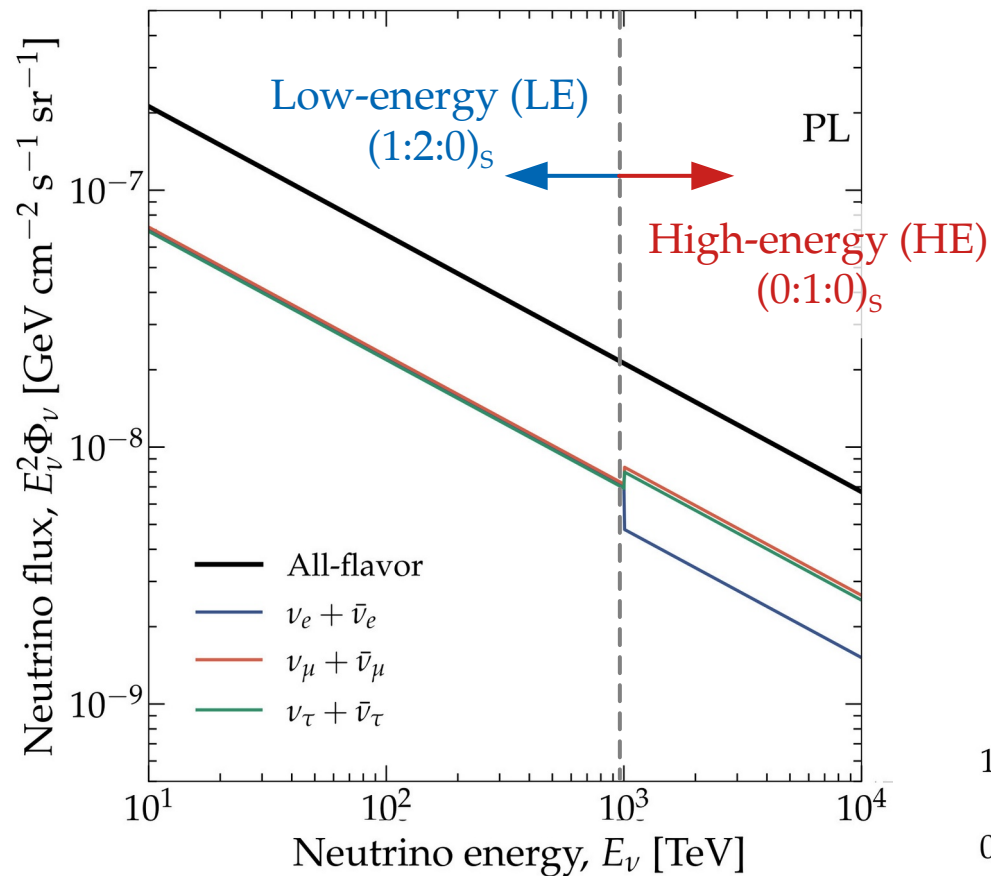
Flavor composition: measuring the energy dependence

Power-law (PL) diffuse ν flux



Flavor composition: measuring the energy dependence

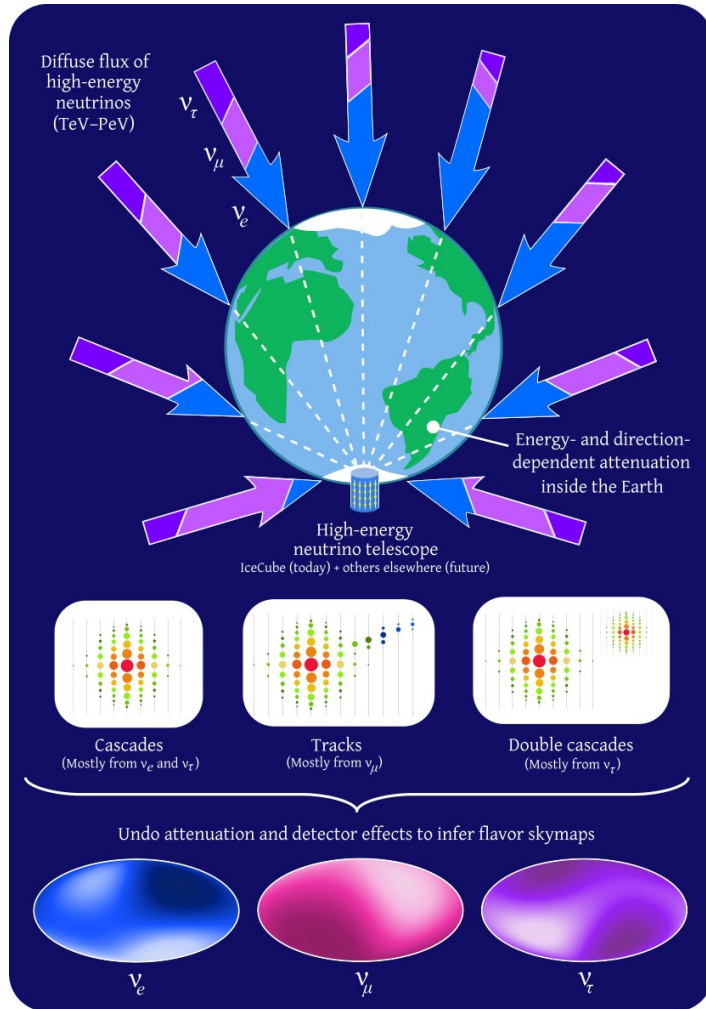
Power-law (PL) diffuse ν flux



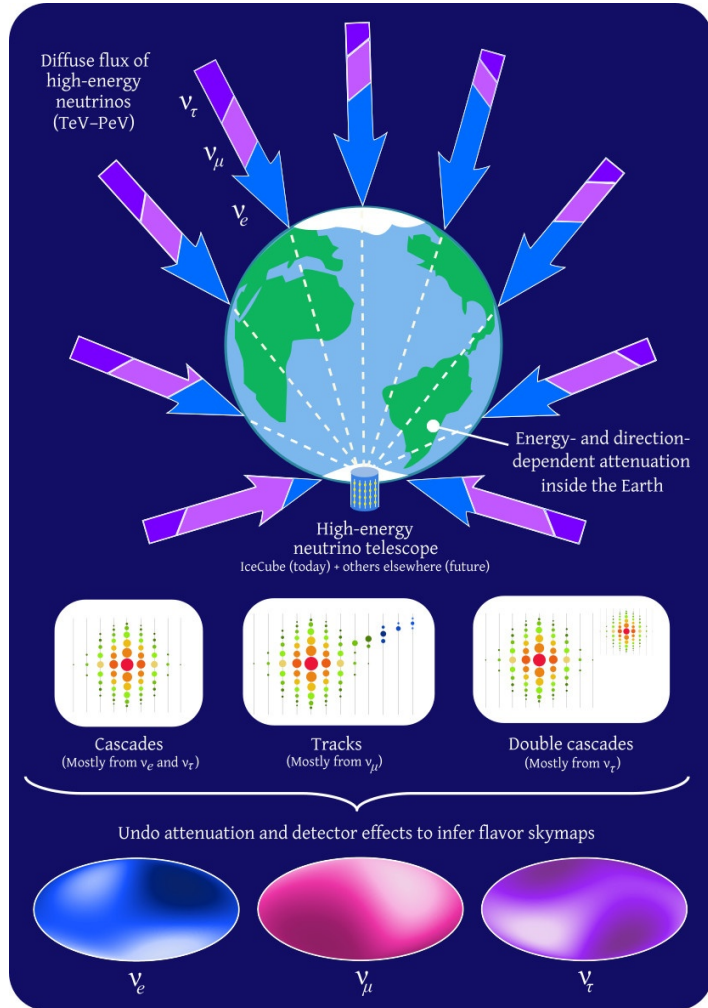
High-energy
flavor anisotropy

Flavor anisotropy in the high-energy neutrino sky

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



Flavor anisotropy in the high-energy neutrino sky

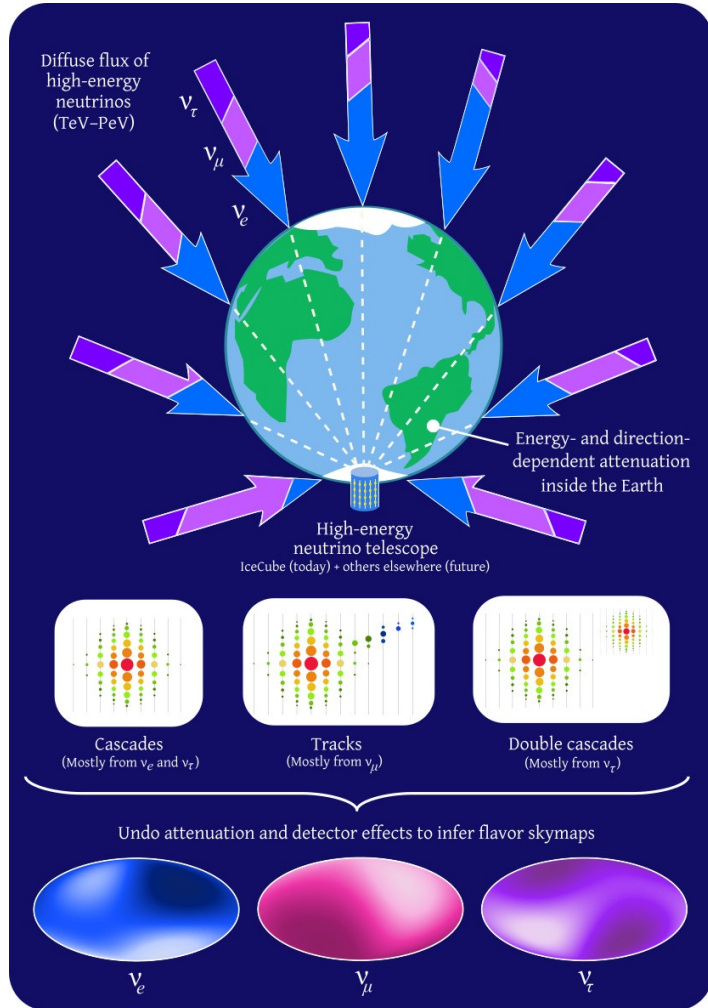


*Does the high-energy sky shine equally brightly
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From the angular distribution of detected
events in neutrino telescopes
(HESE cascades, tracks, double cascades) ...



Flavor anisotropy in the high-energy neutrino sky

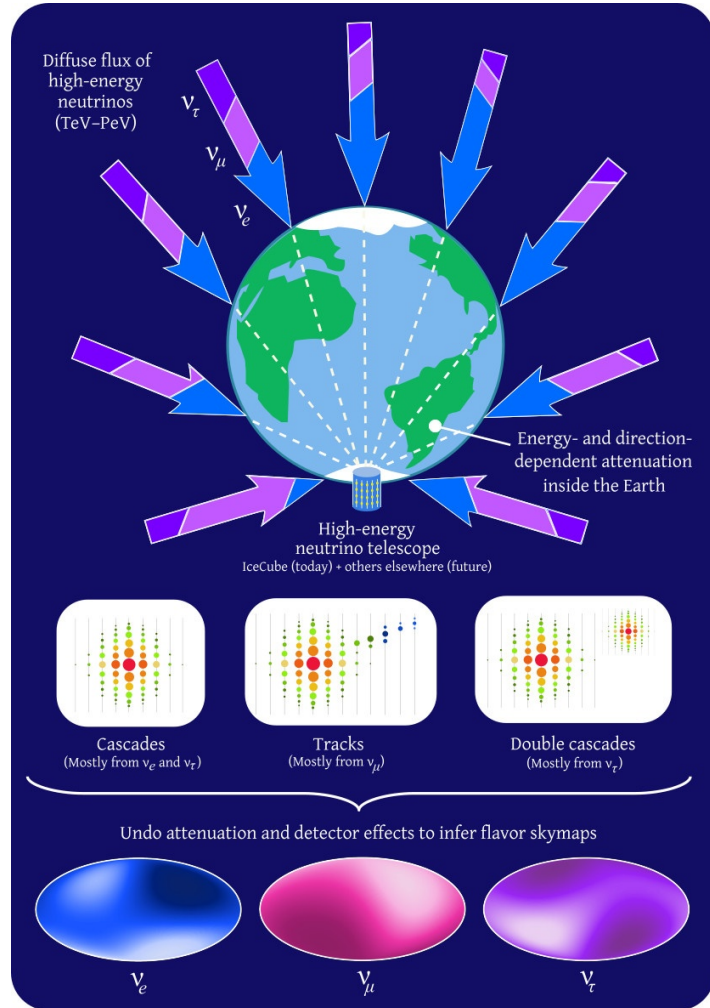


*Does the high-energy sky shine equally brightly
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From the angular distribution of detected
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(HESE cascades, tracks, double cascades) ...

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

Flavor anisotropy in the high-energy neutrino sky



*Does the high-energy sky shine equally brightly
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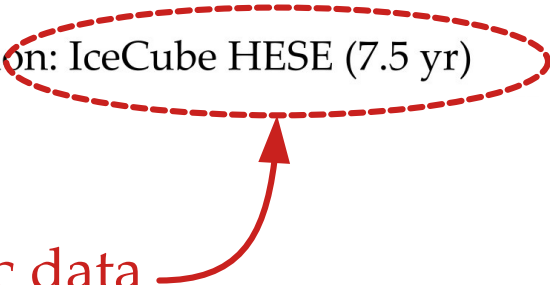
*From the angular distribution of detected
events in neutrino telescopes
(HESE cascades, tracks, double cascades) ...*

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

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

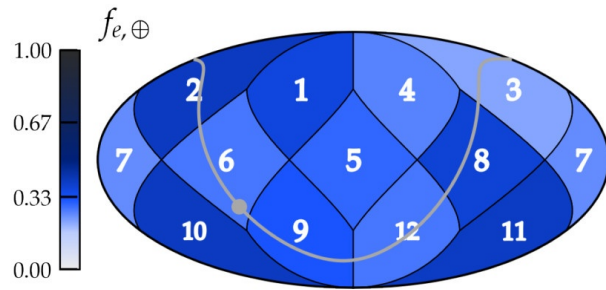
Directional high-energy astrophysical neutrino flavor composition: IceCube HESE (7.5 yr)

Real, public data

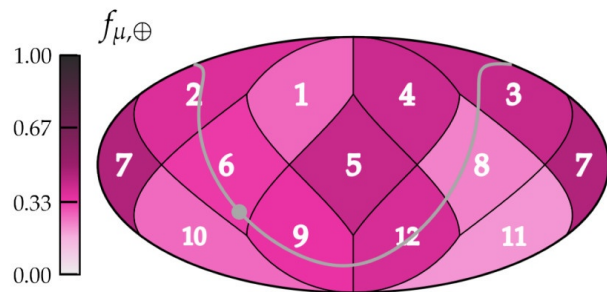
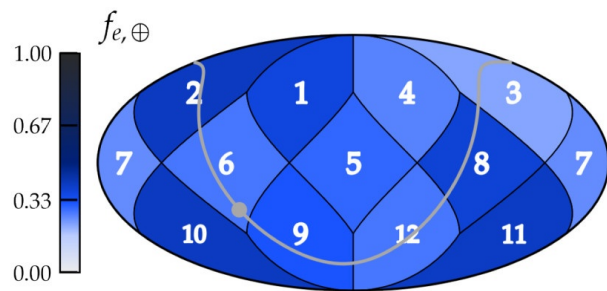


Directional high-energy astrophysical neutrino flavor composition: IceCube HESE (7.5 yr)

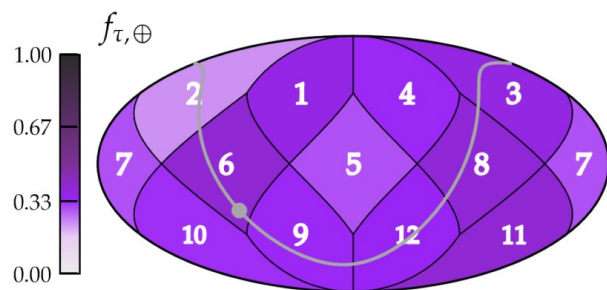
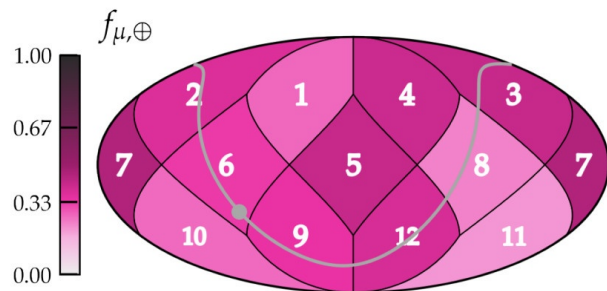
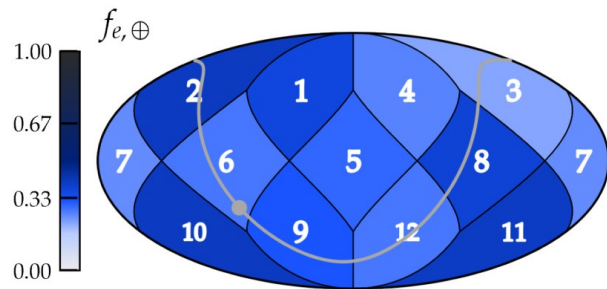
Directional high-energy astrophysical neutrino flavor composition: IceCube HESE (7.5 yr)



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Equatorial

Telalovic, MB, JCAP 2025

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

This work:

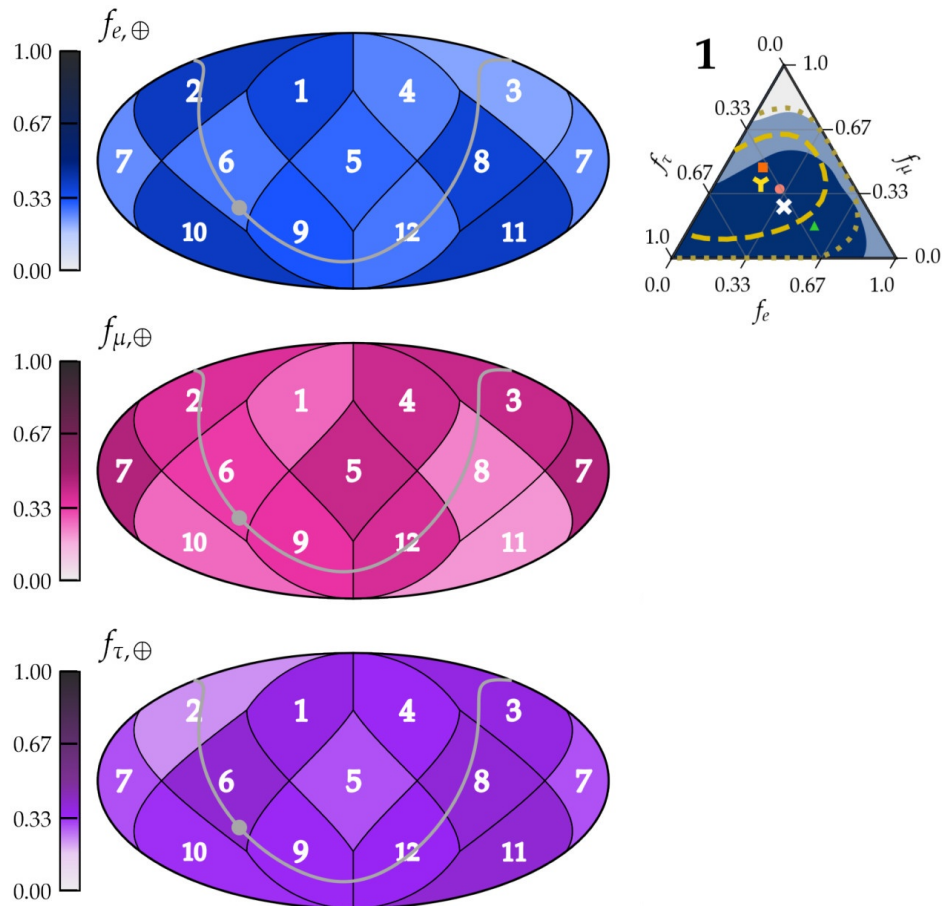
⊗ Best fit ■ 1σ ■ 2σ □ 3σ

IceCube 2020 all-sky:

Y Best fit - - 1σ ··· 2σ

Benchmarks:

● $\pi^\pm$ decay: (1:2:0)_S ■ μ -damped: (0:1:0)_S ▲ n decay: (1:0:0)_S



Equatorial

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

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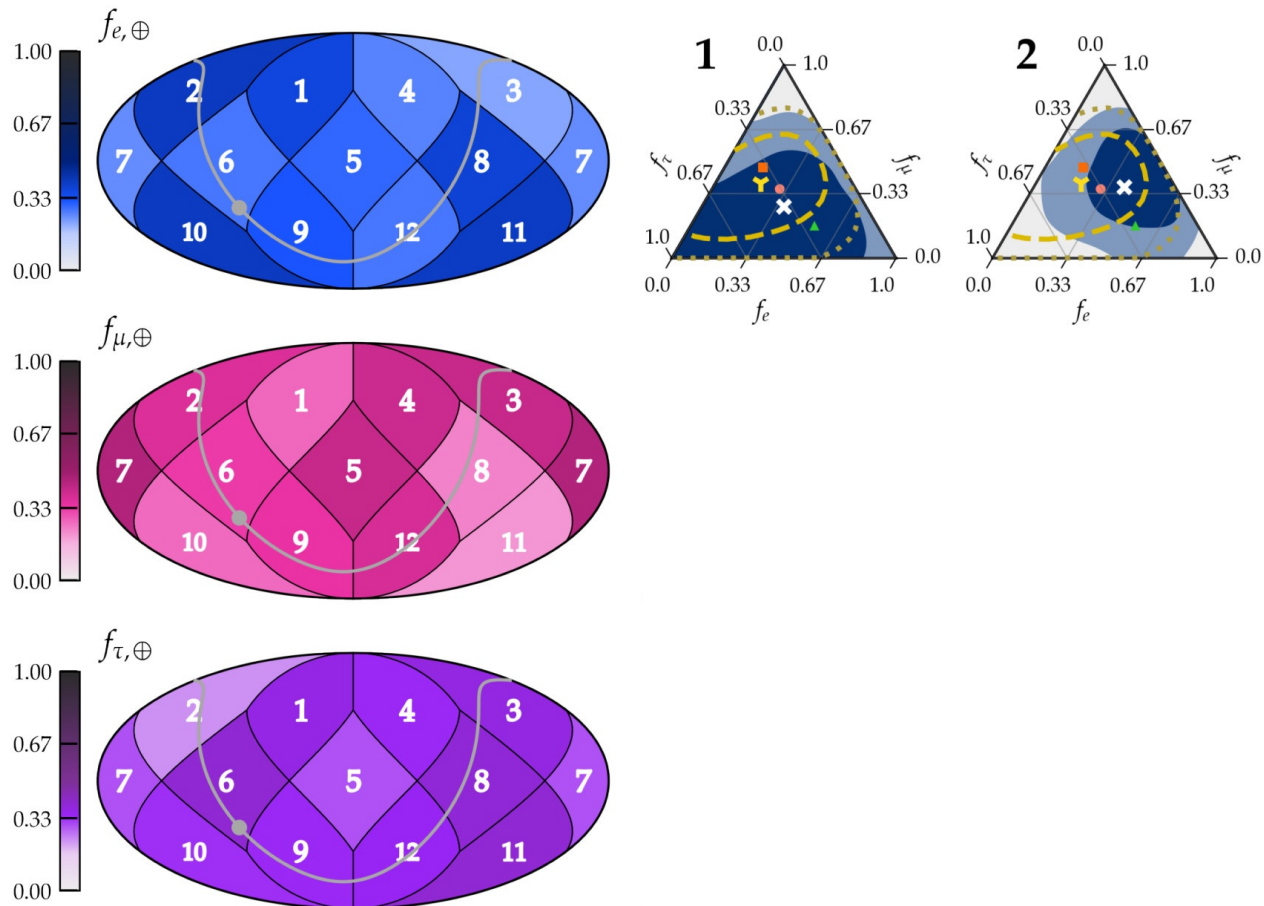
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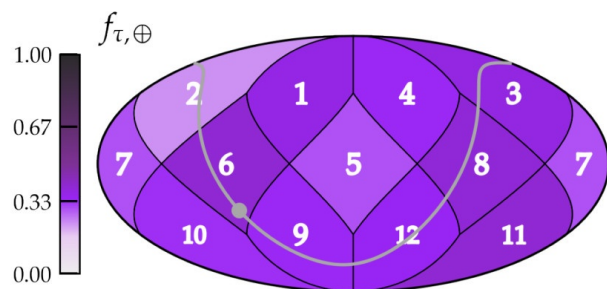
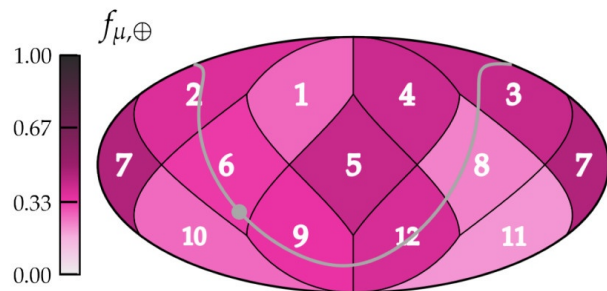
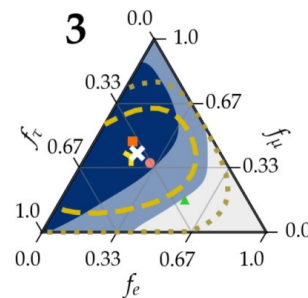
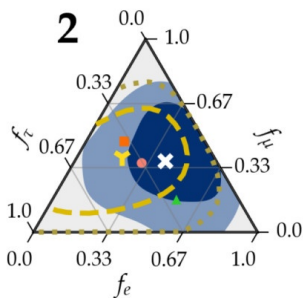
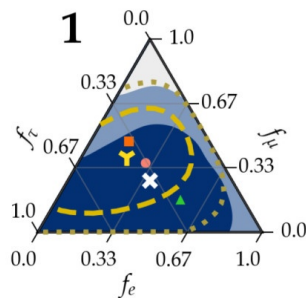
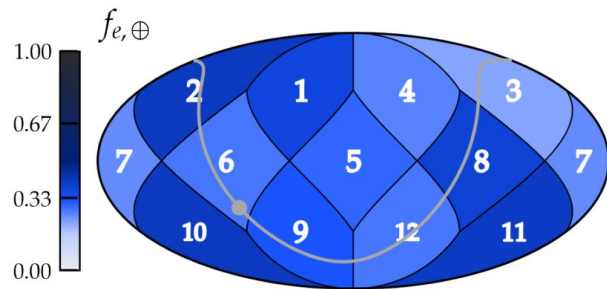
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Equatorial

Telalovic, MB, JCAP 2025

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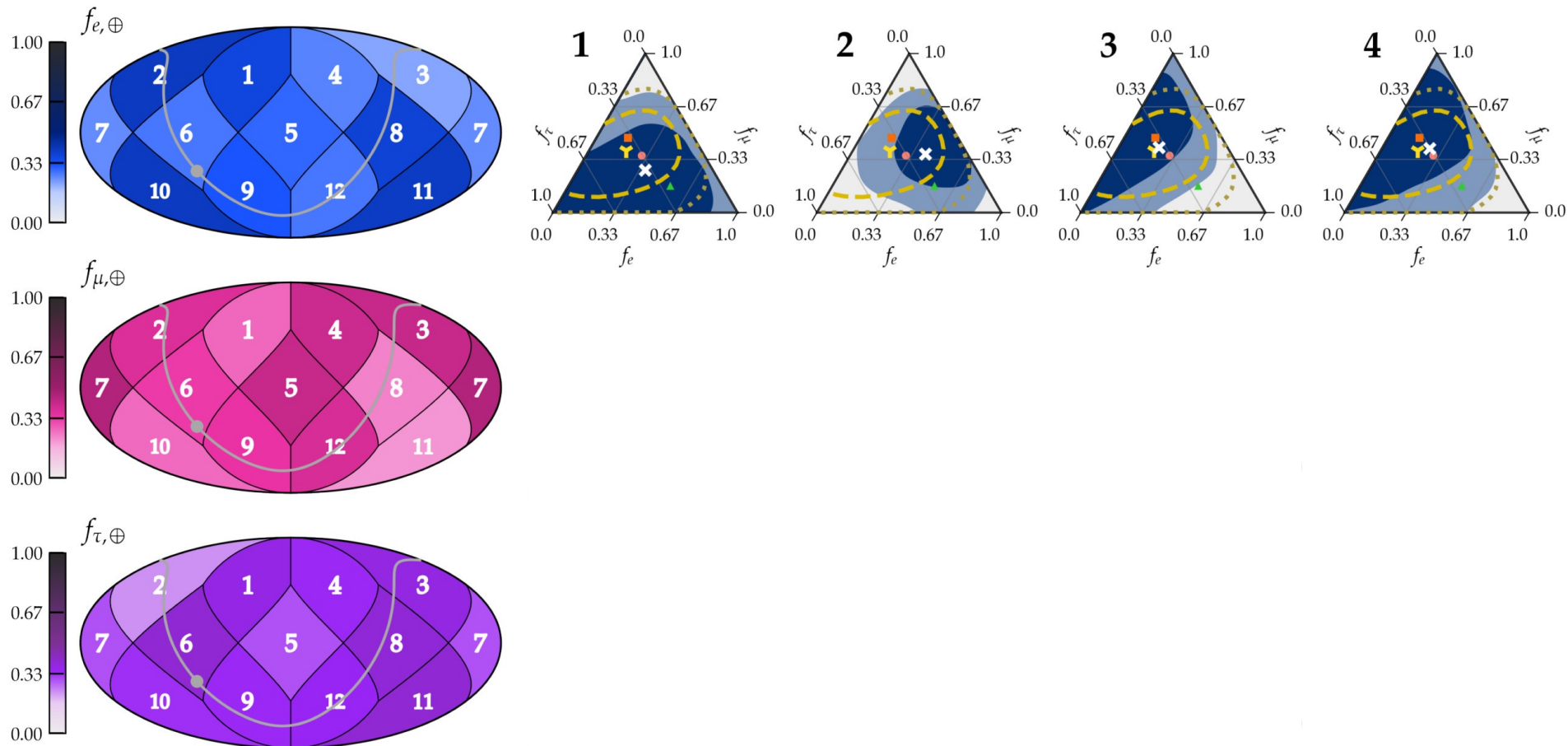
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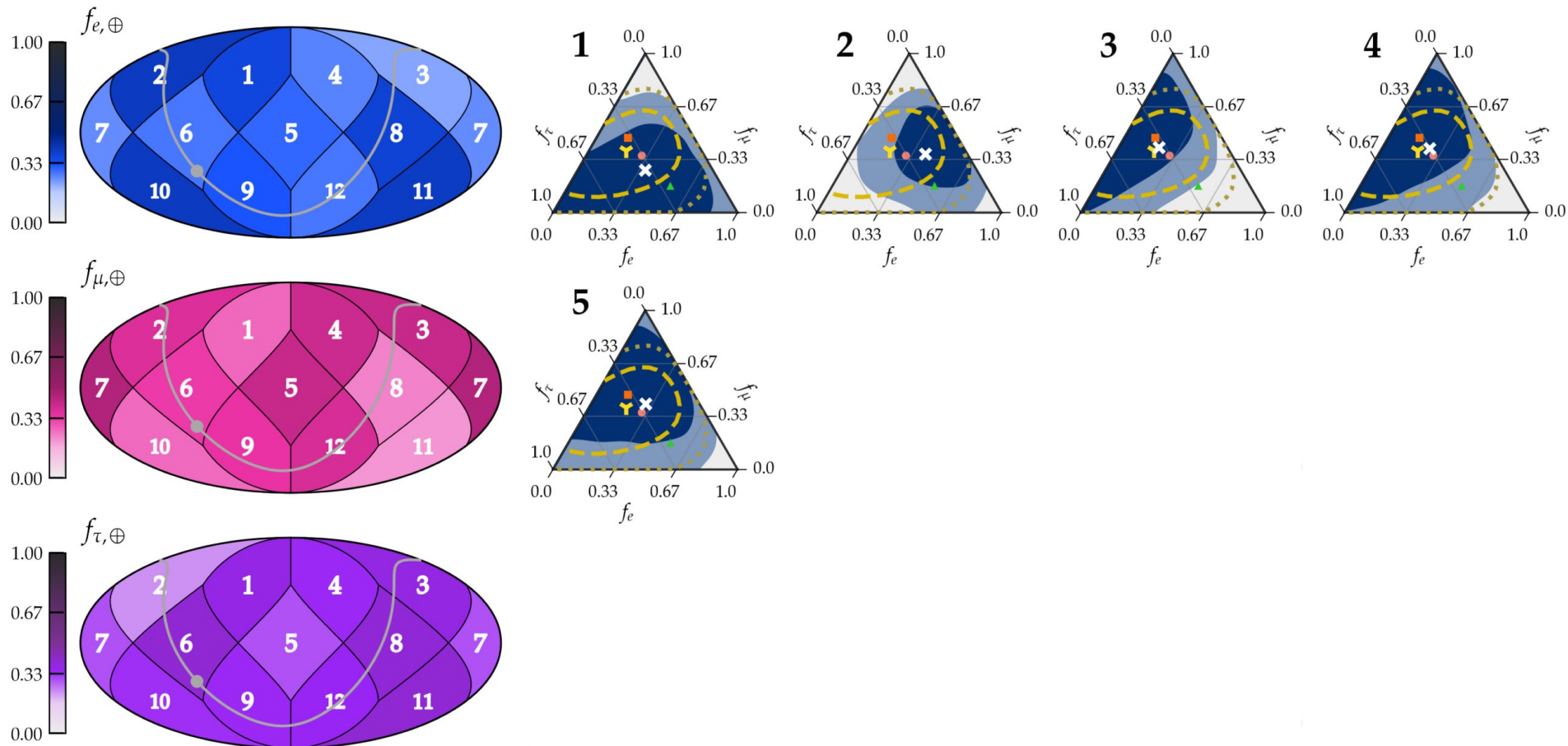
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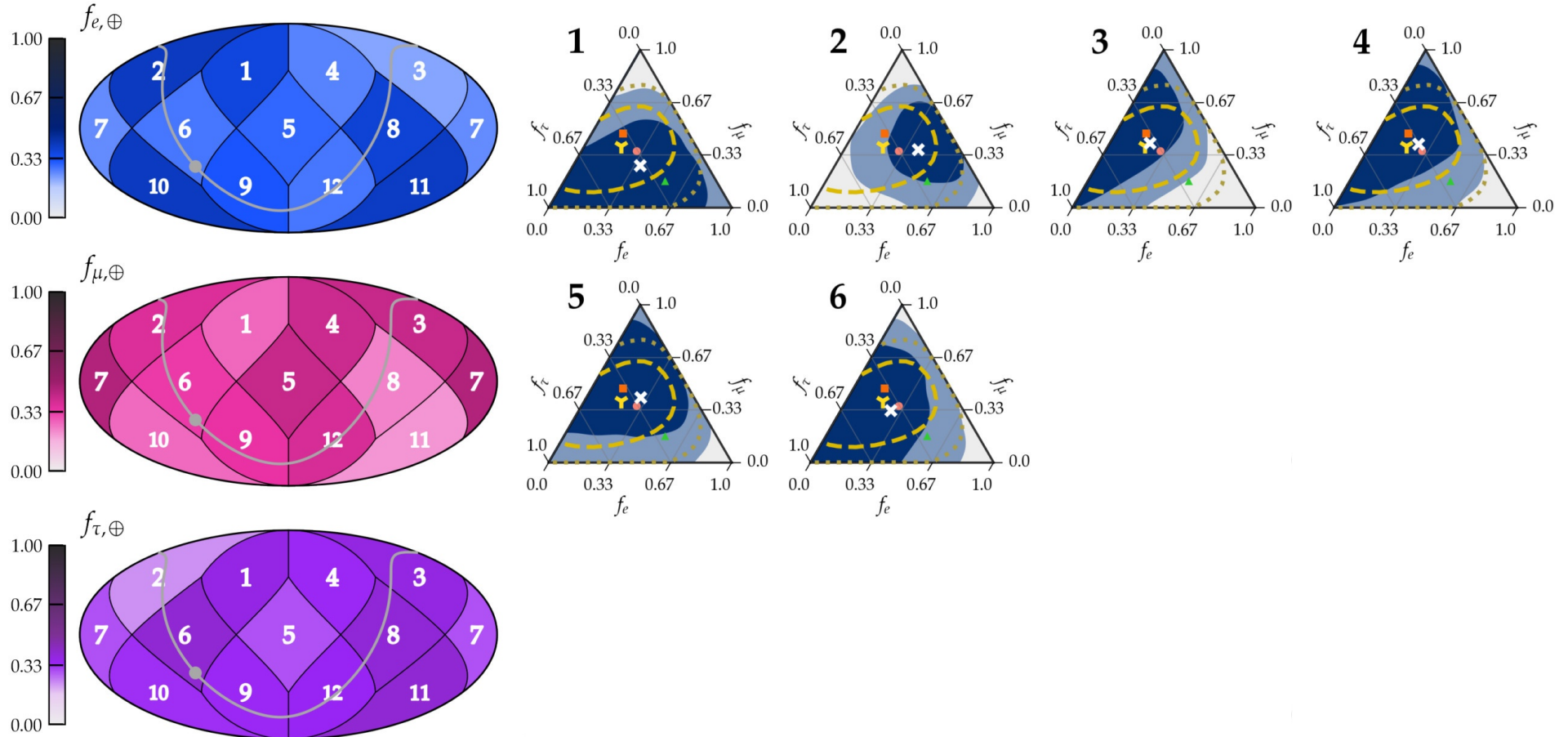
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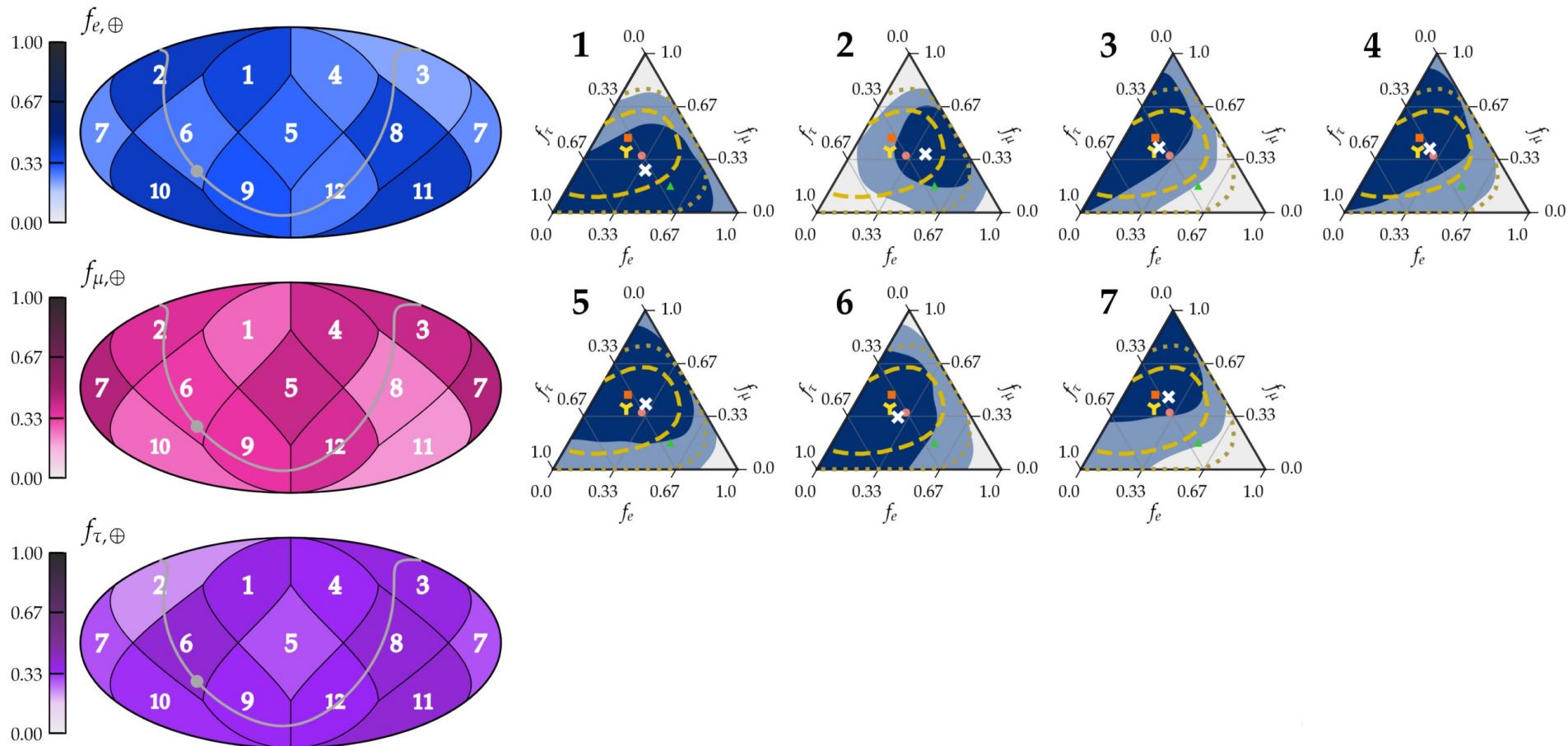
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Equatorial

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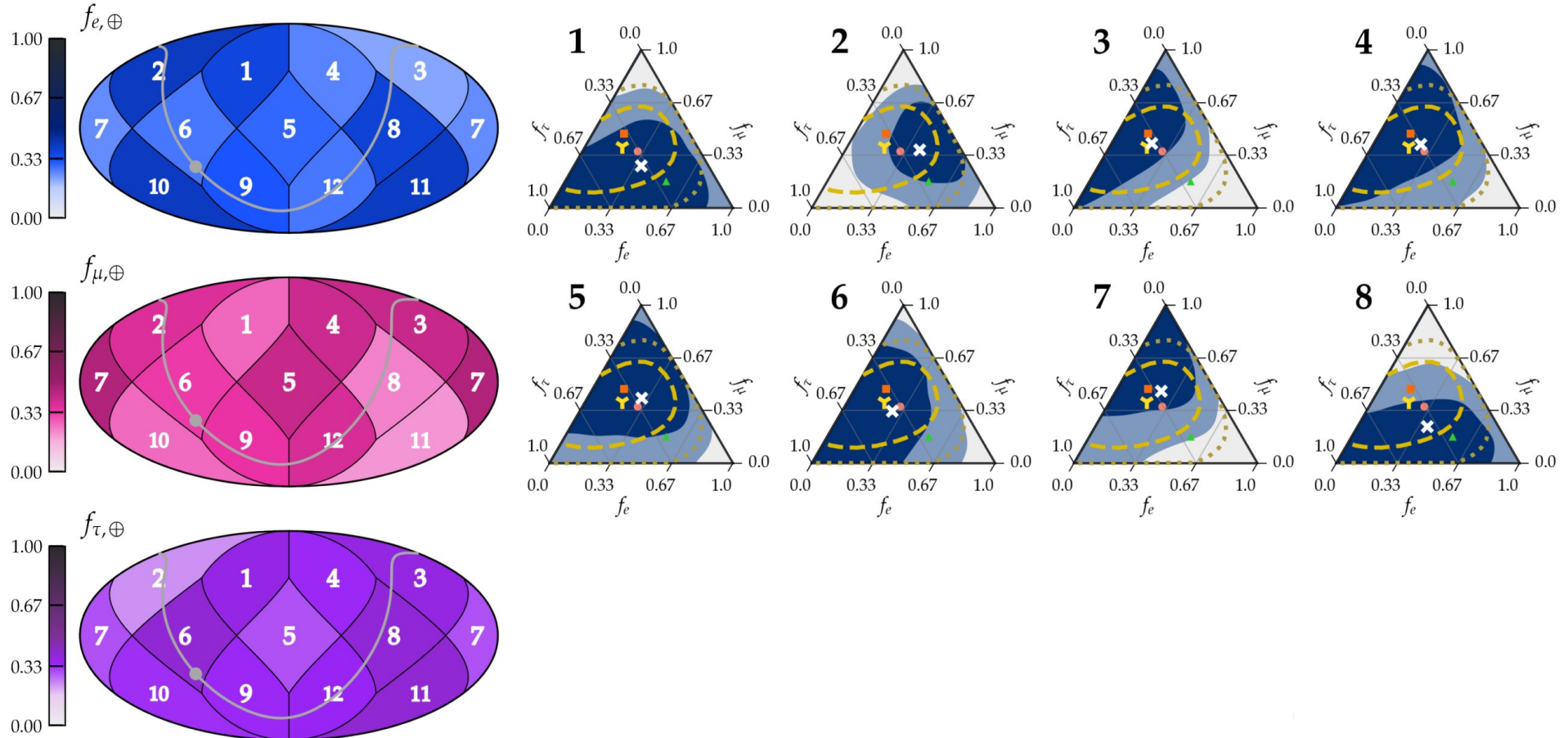
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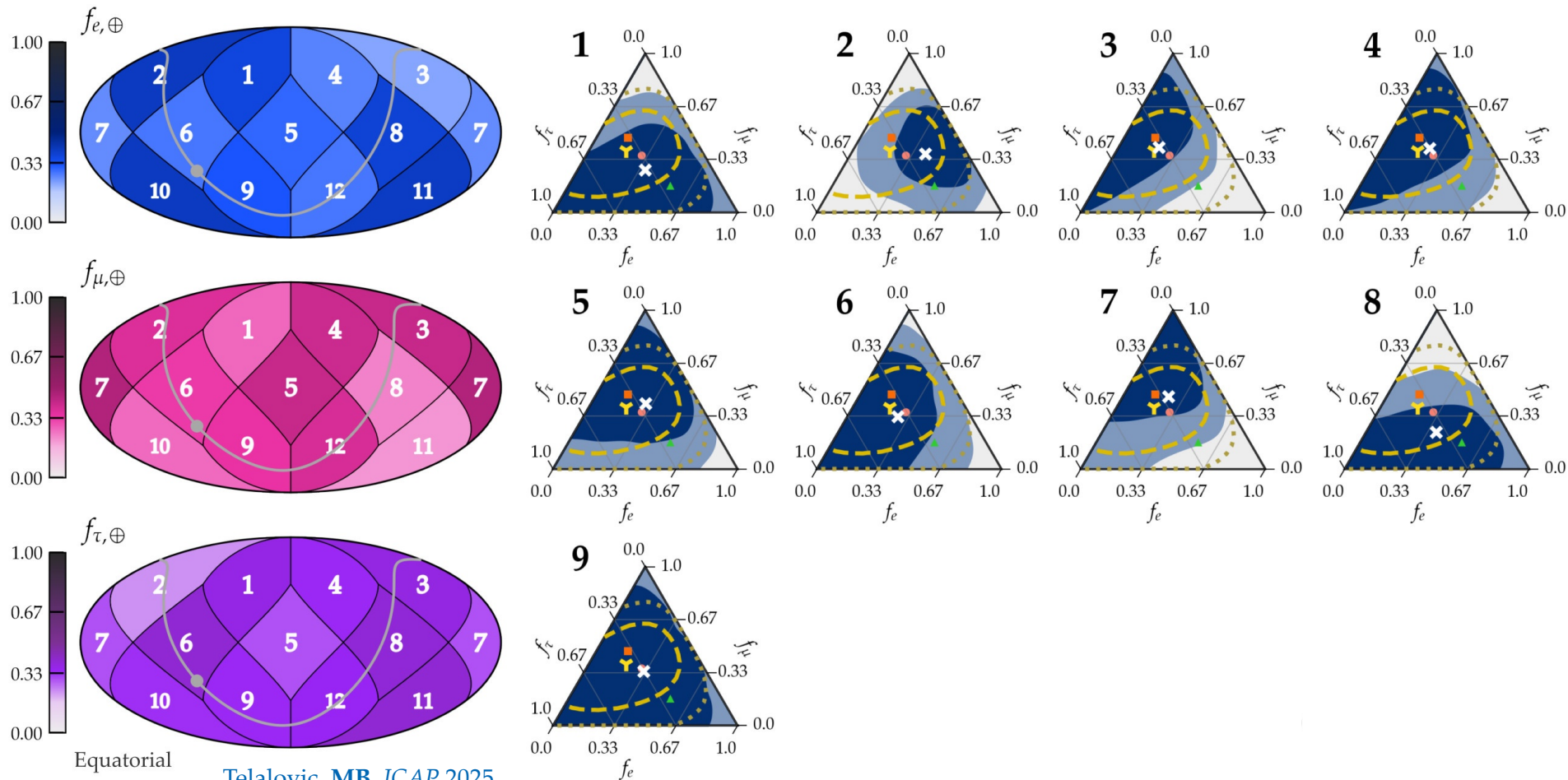
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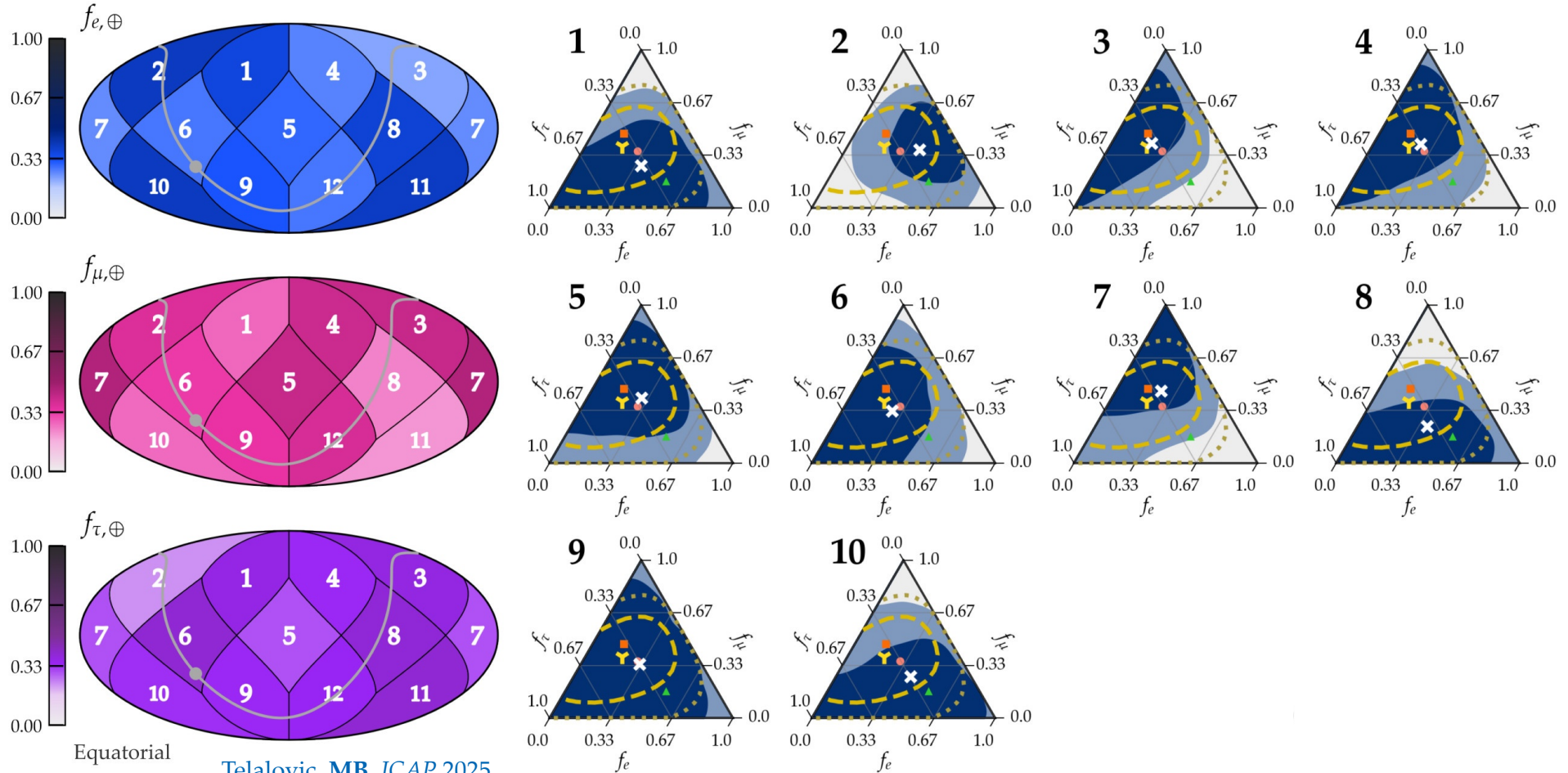
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IceCube 2020 all-sky:

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

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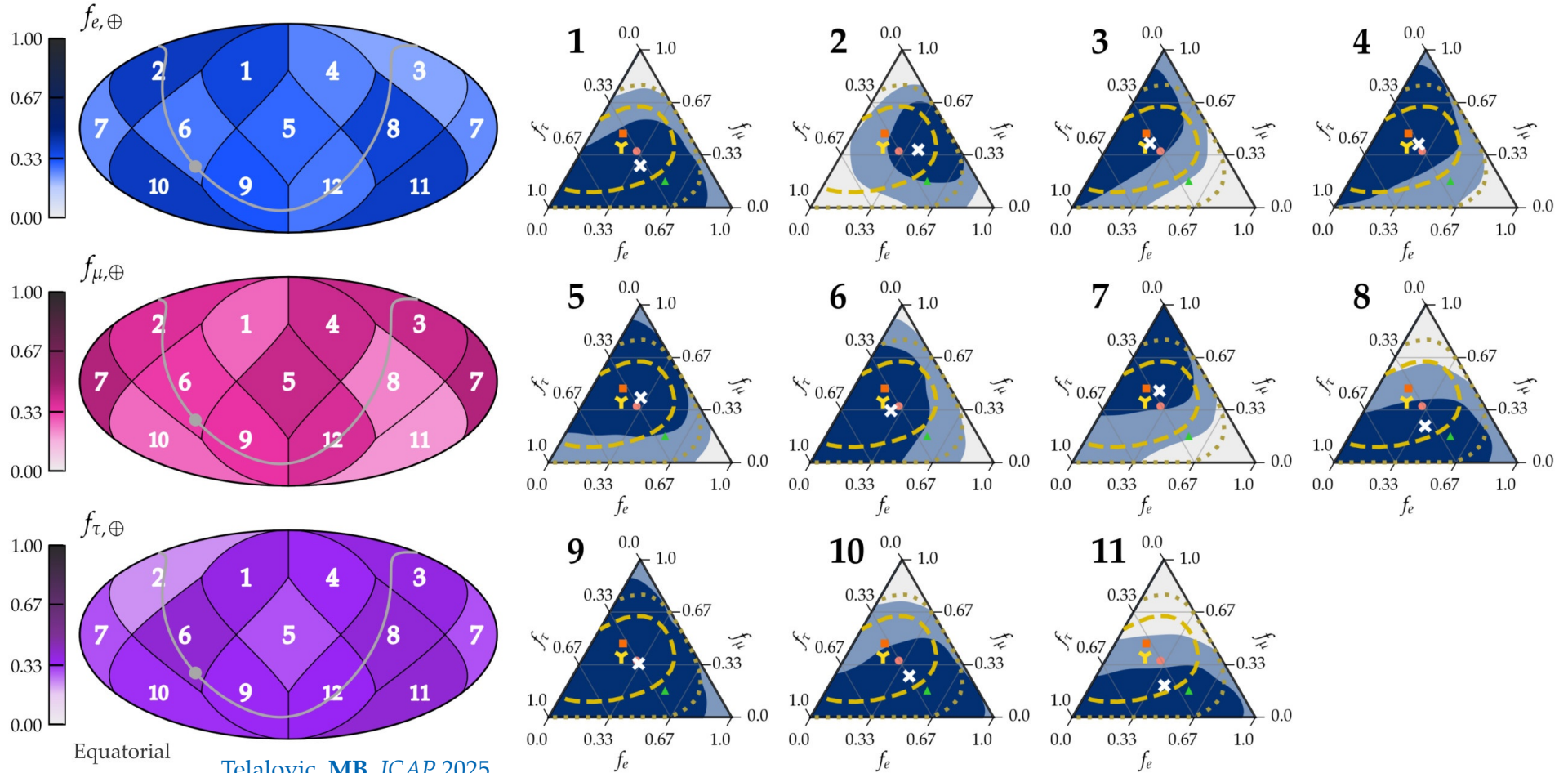
✖ Best fit ■ 1 σ ■ 2 σ □ 3 σ

IceCube 2020 all-sky:

✖ Best fit - - 1 σ - - - 2 σ

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Equatorial

Telaviv, MB, JCAP 2025

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

This work:

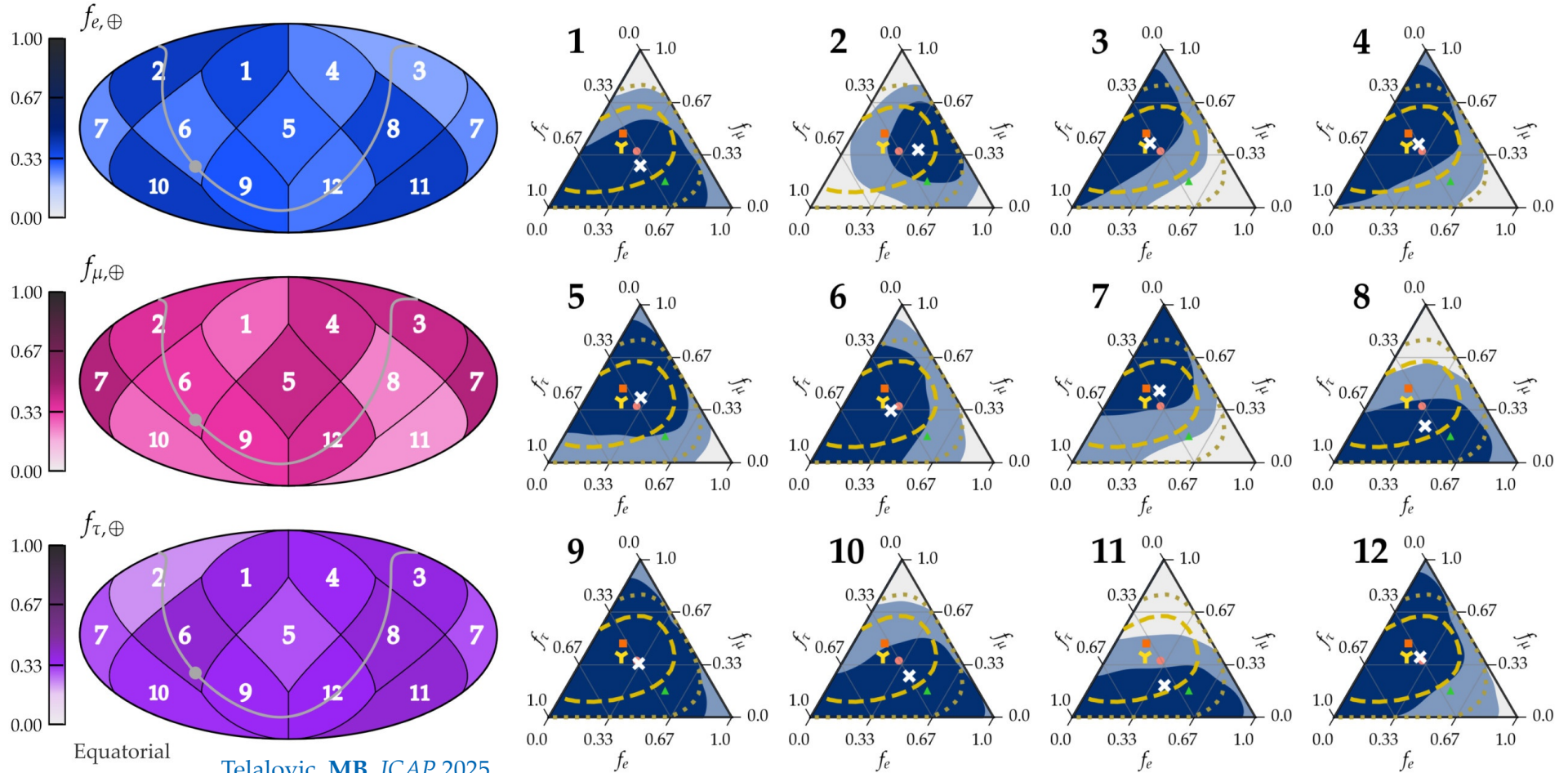
✖ Best fit ■ 1 σ ■ 2 σ □ 3 σ

IceCube 2020 all-sky:

Y Best fit - - 1 σ - - - 2 σ

Benchmarks:

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This work:

⊗ Best fit ■ 1σ ■ 2σ □ 3σ

IceCube 2020 all-sky:

⋄ Best fit - - 1σ ... 2σ

Benchmarks:

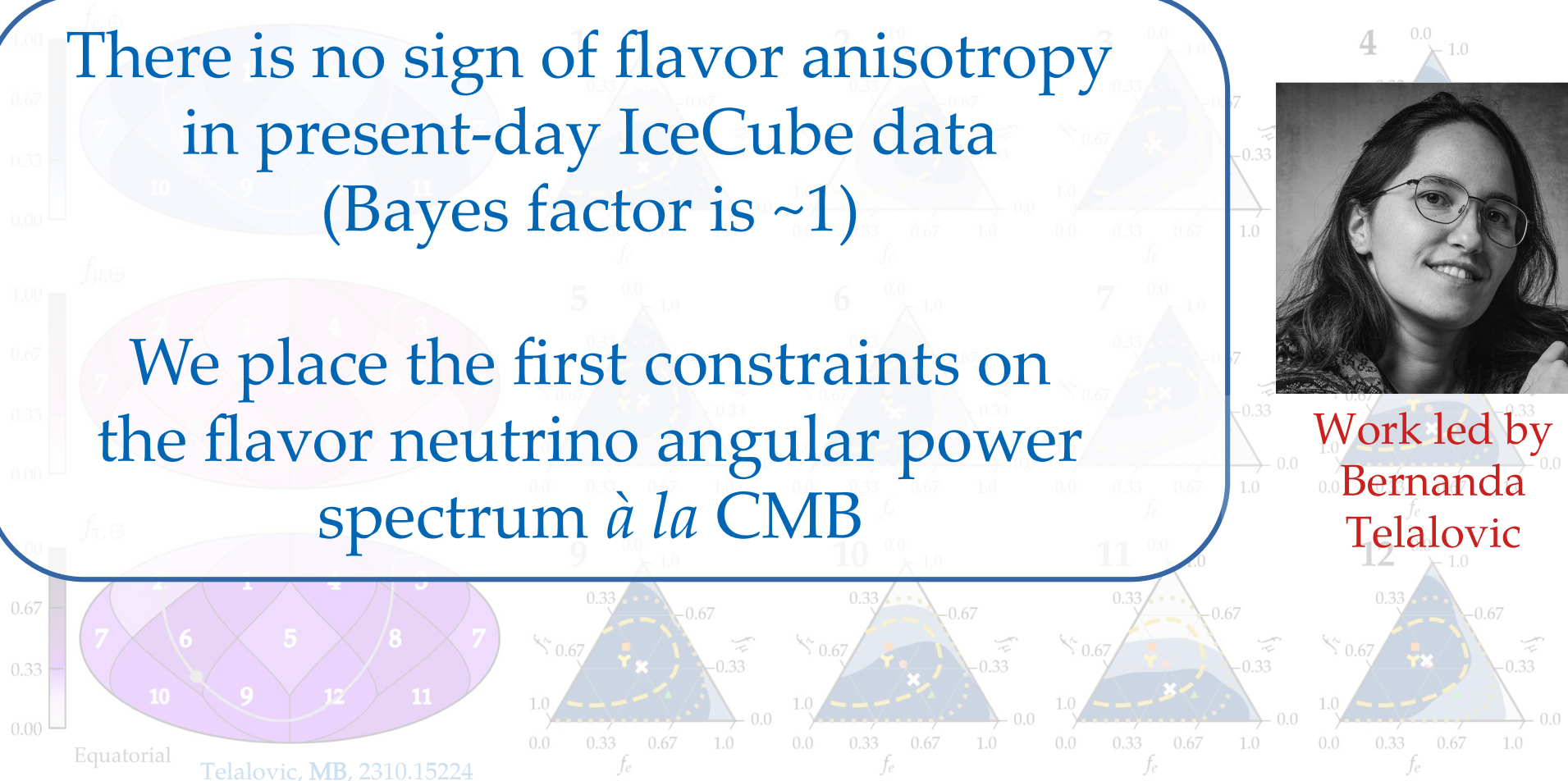
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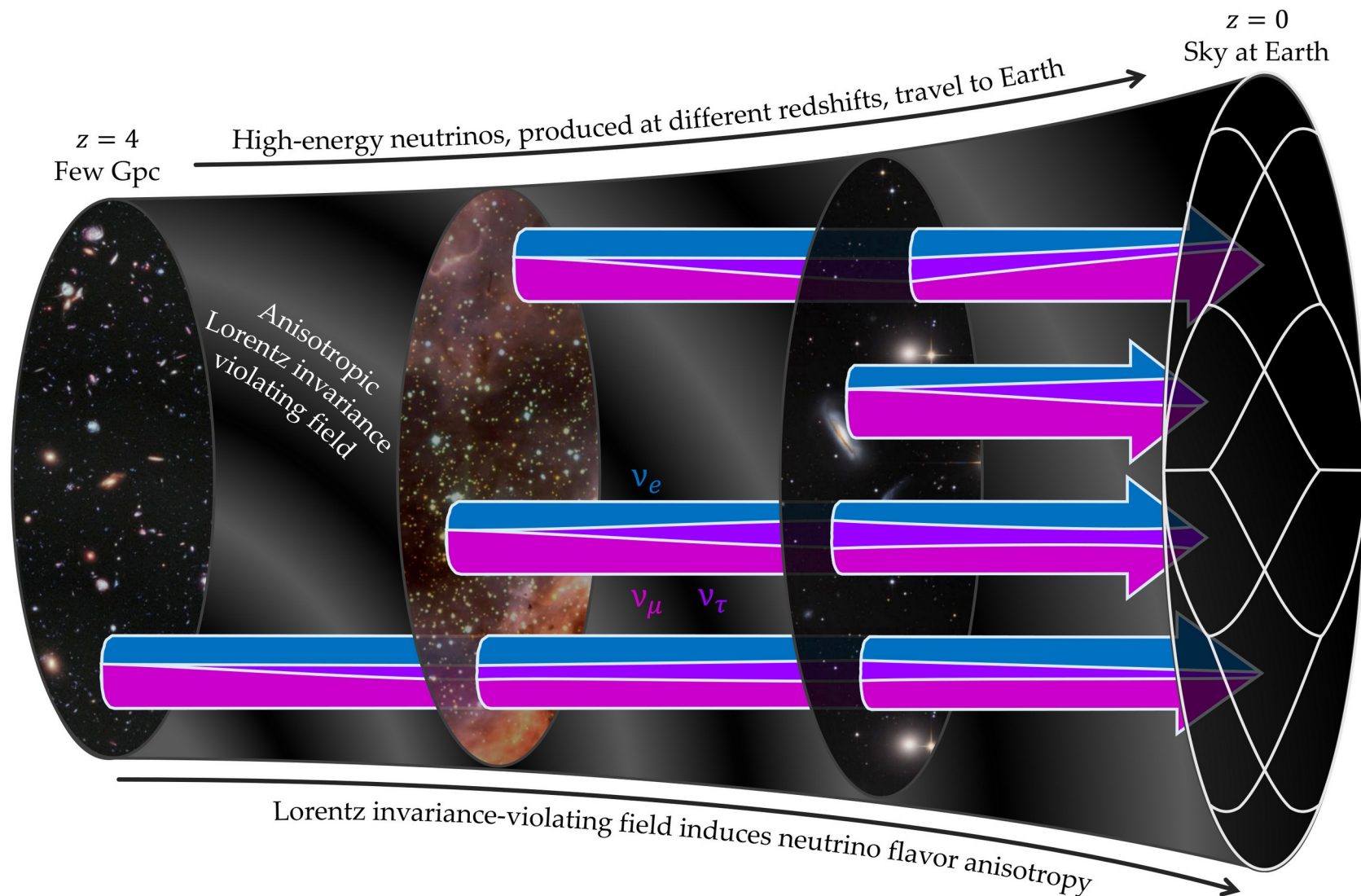
There is no sign of flavor anisotropy
in present-day IceCube data
(Bayes factor is ~ 1)

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



Work led by
Bernanda
Telalovic





Anisotropic Lorentz-invariance violation makes the flavor sky anisotropic:

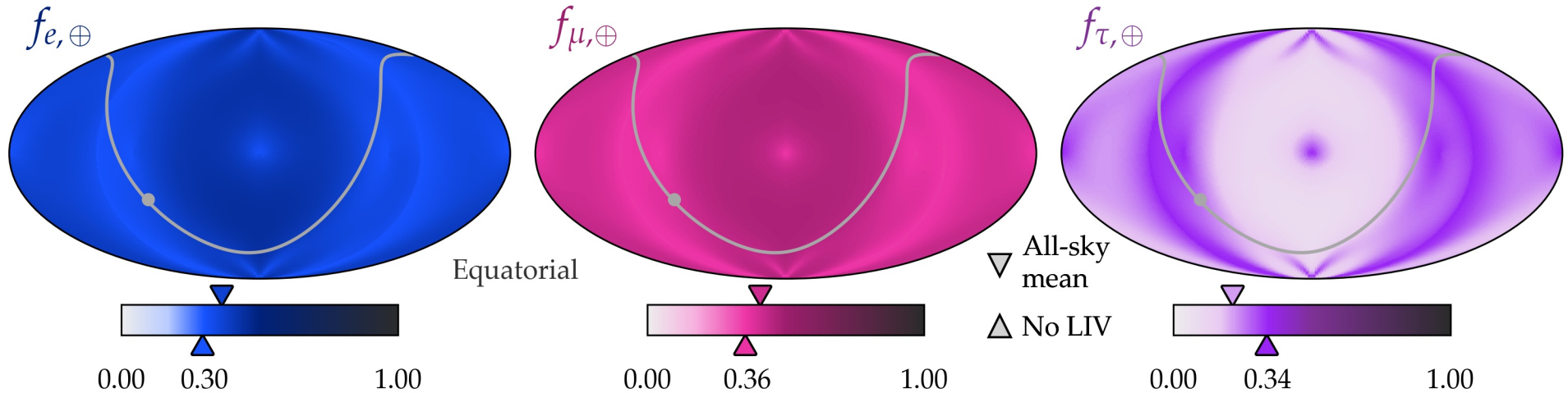
$$H_{\text{tot}} = H_{\text{vac}} + \sum_{d=2}^{\infty} H_{\text{LIV}}^{(d)} = H_{\text{vac}} + E^{d-3} \sum_{\ell=0}^{d-1} \sum_{m=-\ell}^{\ell} Y_{\ell}^m(\hat{\mathbf{p}}) (a_{\text{eff}}^{(d)})_{\ell m}^{\alpha\beta}$$

Neutrino oscillation probability becomes direction-dependent 

Anisotropic Lorentz-invariance violation makes the flavor sky anisotropic:

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

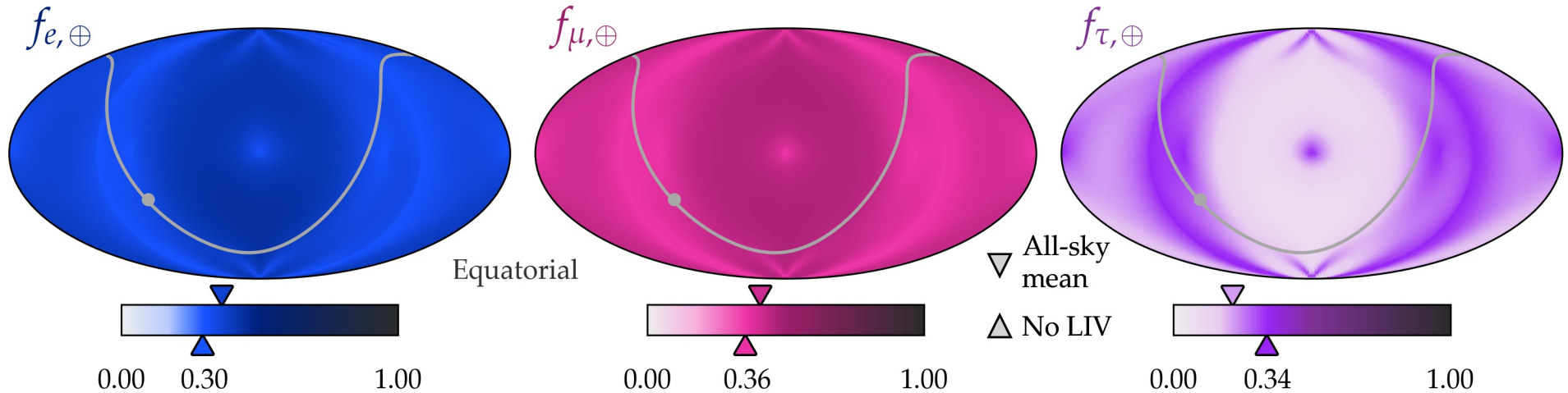
Neutrino oscillation probability becomes direction-dependent



Anisotropic Lorentz-invariance violation makes the flavor sky anisotropic:

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

Neutrino oscillation probability becomes direction-dependent



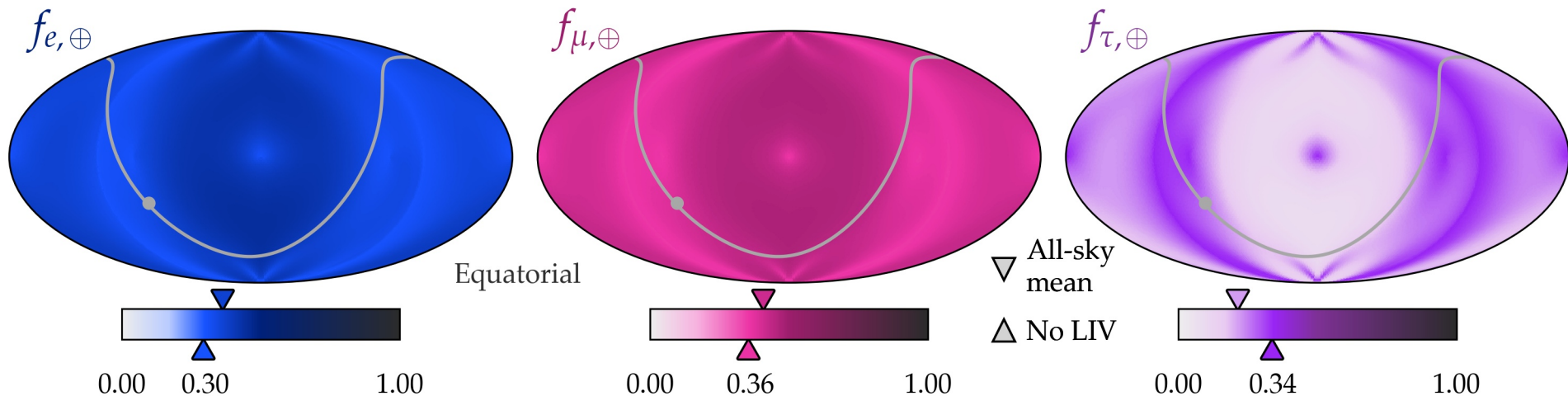
Upper limits from accelerator ν (MINOS): $< 10^{-20} - 10^{-15} \text{ GeV}^{-1}$

For dimension-5
CPT-odd LIV coefficient

Anisotropic Lorentz-invariance violation makes the flavor sky anisotropic:

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

Neutrino oscillation probability becomes direction-dependent

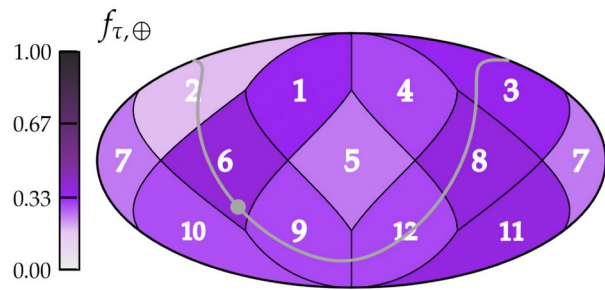
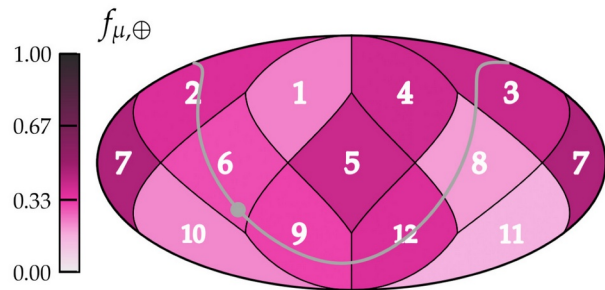
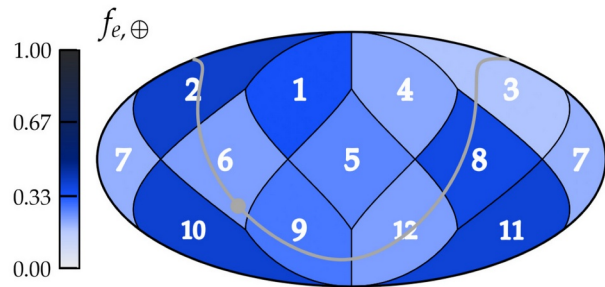
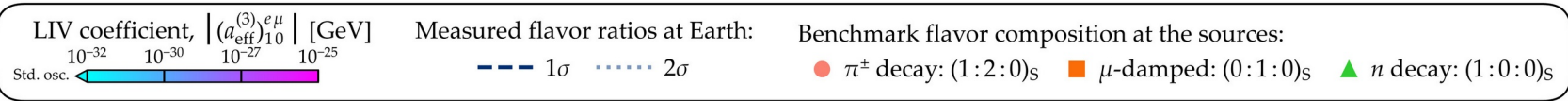


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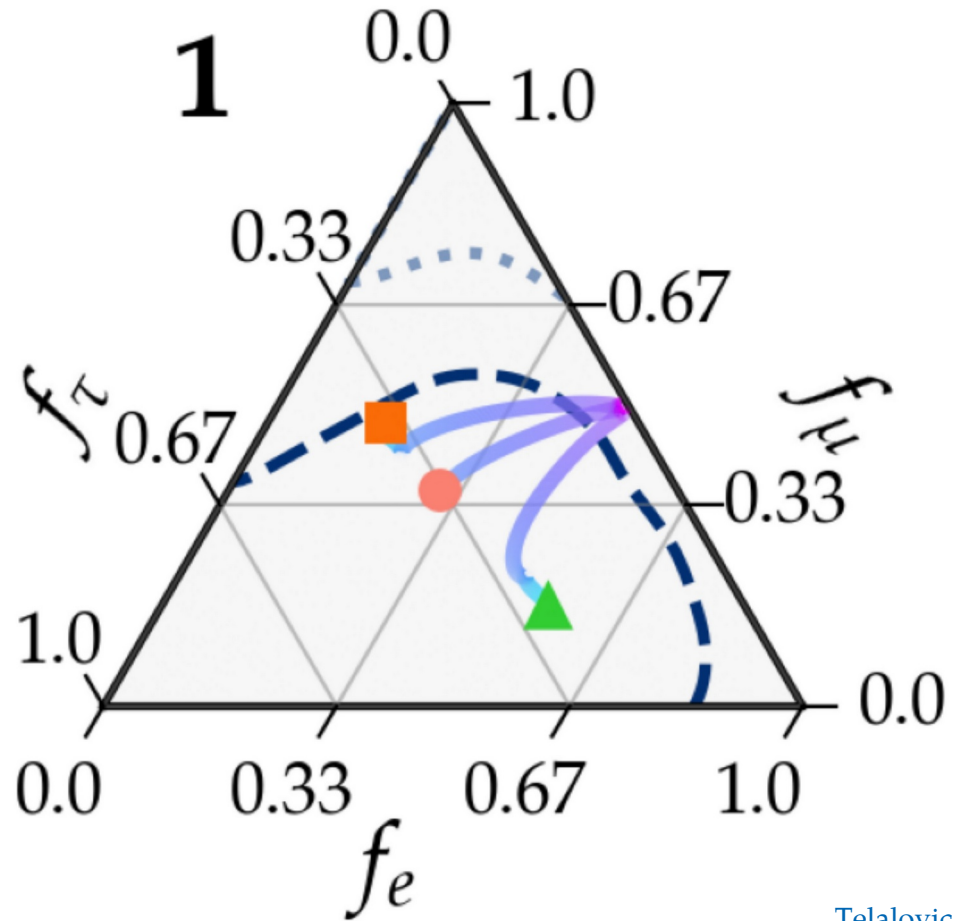
Upper limits from 7.5-year HES: $< 10^{-34} \text{ GeV}^{-1}$

For dimension-5
CPT-odd LIV coefficient

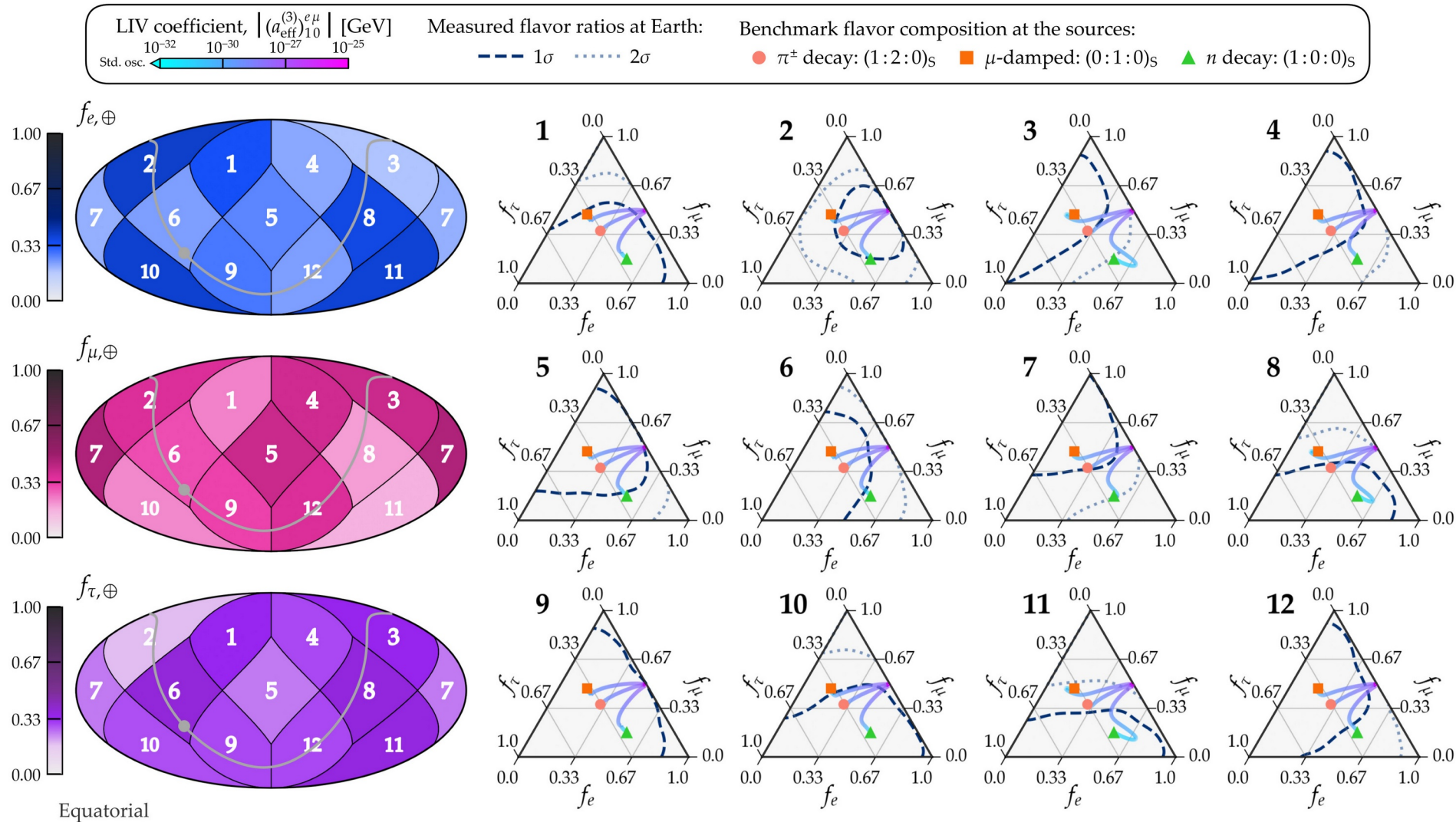
Lorentz-violating high-energy neutrino flavor anisotropy (IceCube HESE 7.5 years)



Equatorial



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



Disfavored at 95% C.L. from flavor isotropy (this work, using IceCube 7.5-year HESE)

$l=0$
 $m=0$

$l=1$
 $m \in [-1,1]$

$l=2$
 $m \in [-2,2]$

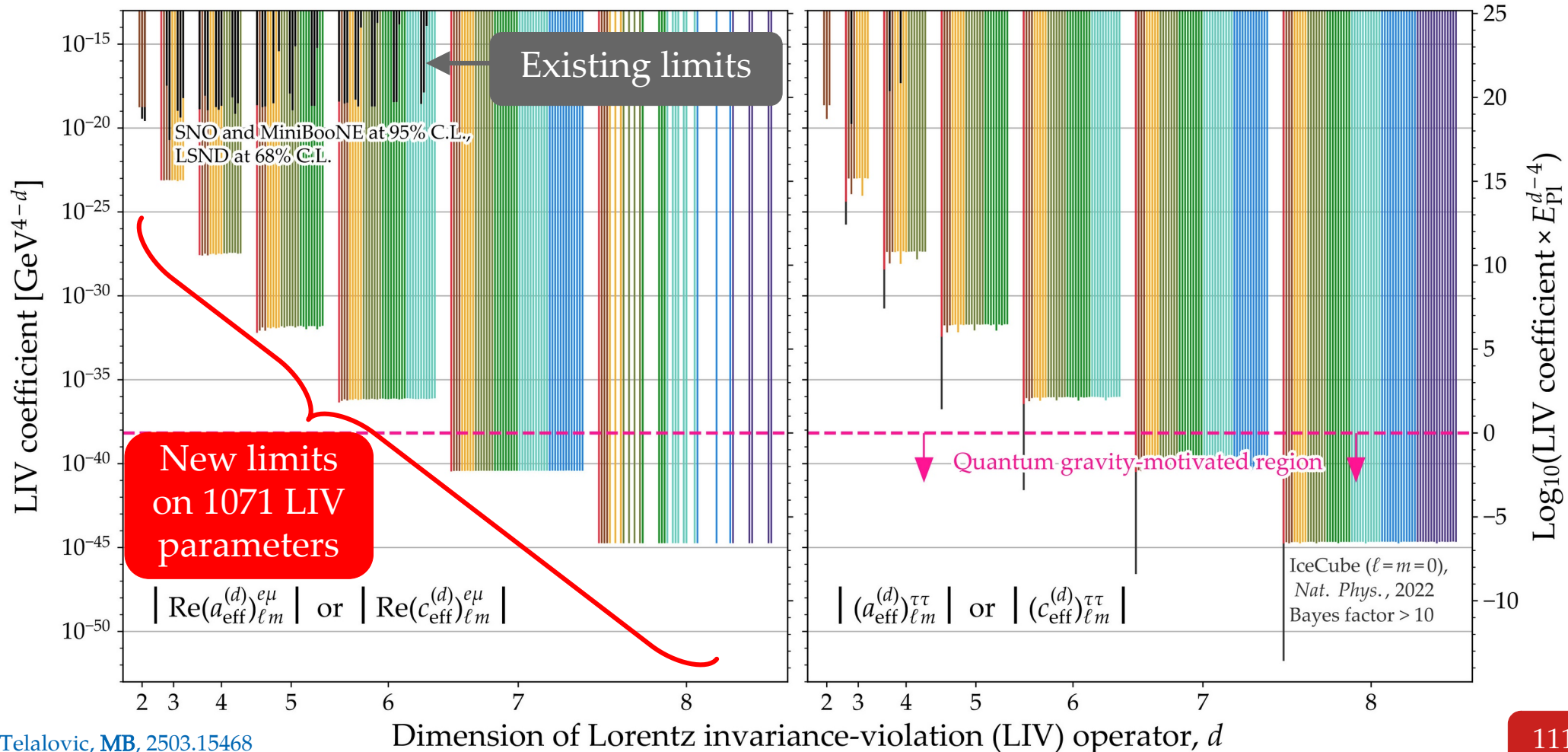
$l=3$
 $m \in [-3,3]$

$l=4$
 $m \in [-4,4]$

$l=5$
 $m \in [-5,5]$

$l=6$
 $m \in [-6,6]$

$l=7$
 $m \in [-7,7]$



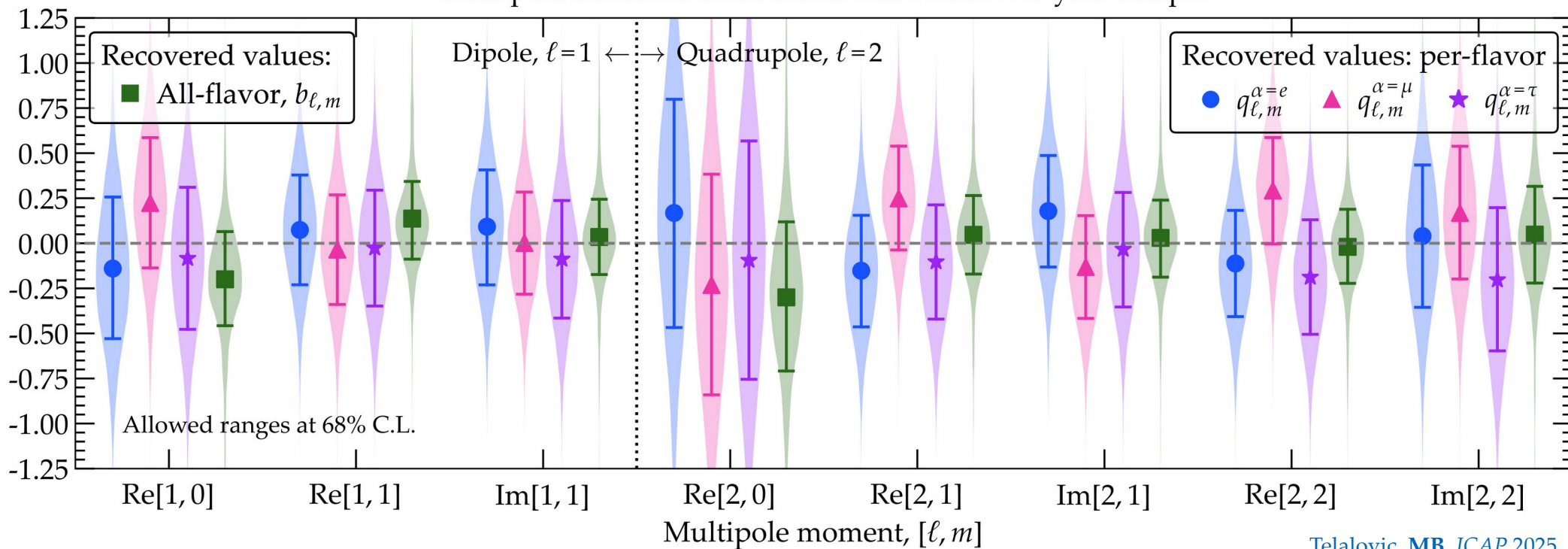
Flavor dipoles and quadrupoles in the sky?

Flavor-dependent
multipole expansion

Isotropic flux

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

Multipole moments from the IceCube HESE 7.5-year sample



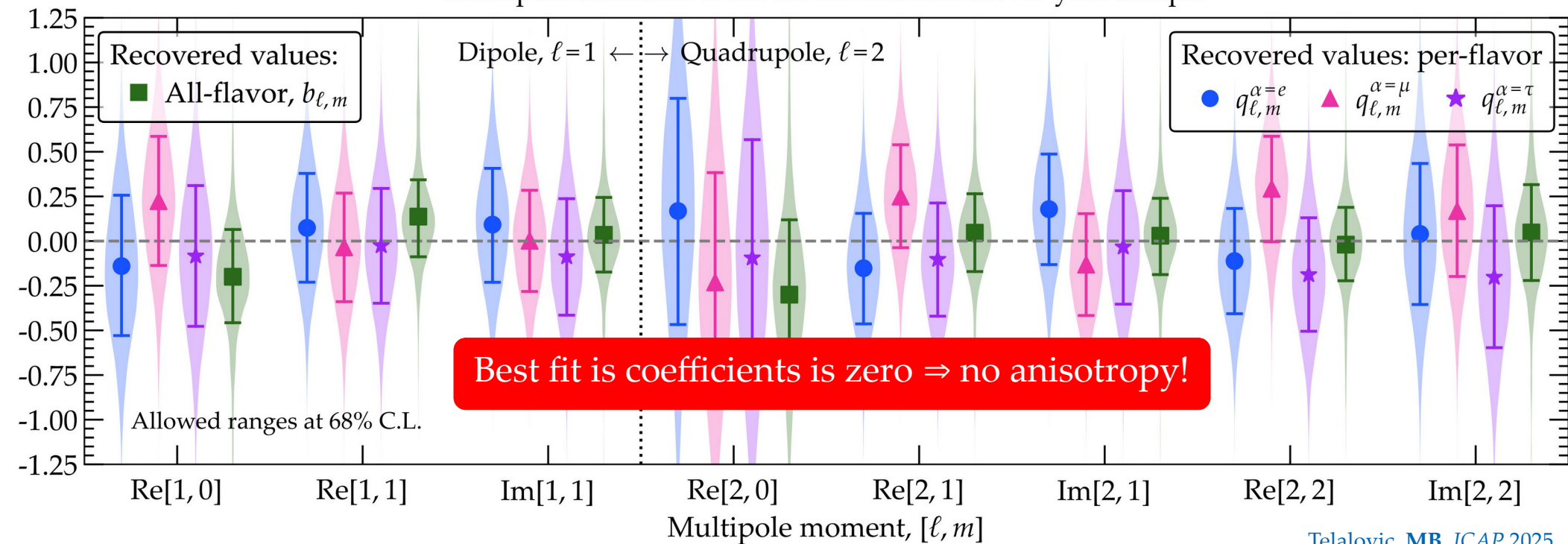
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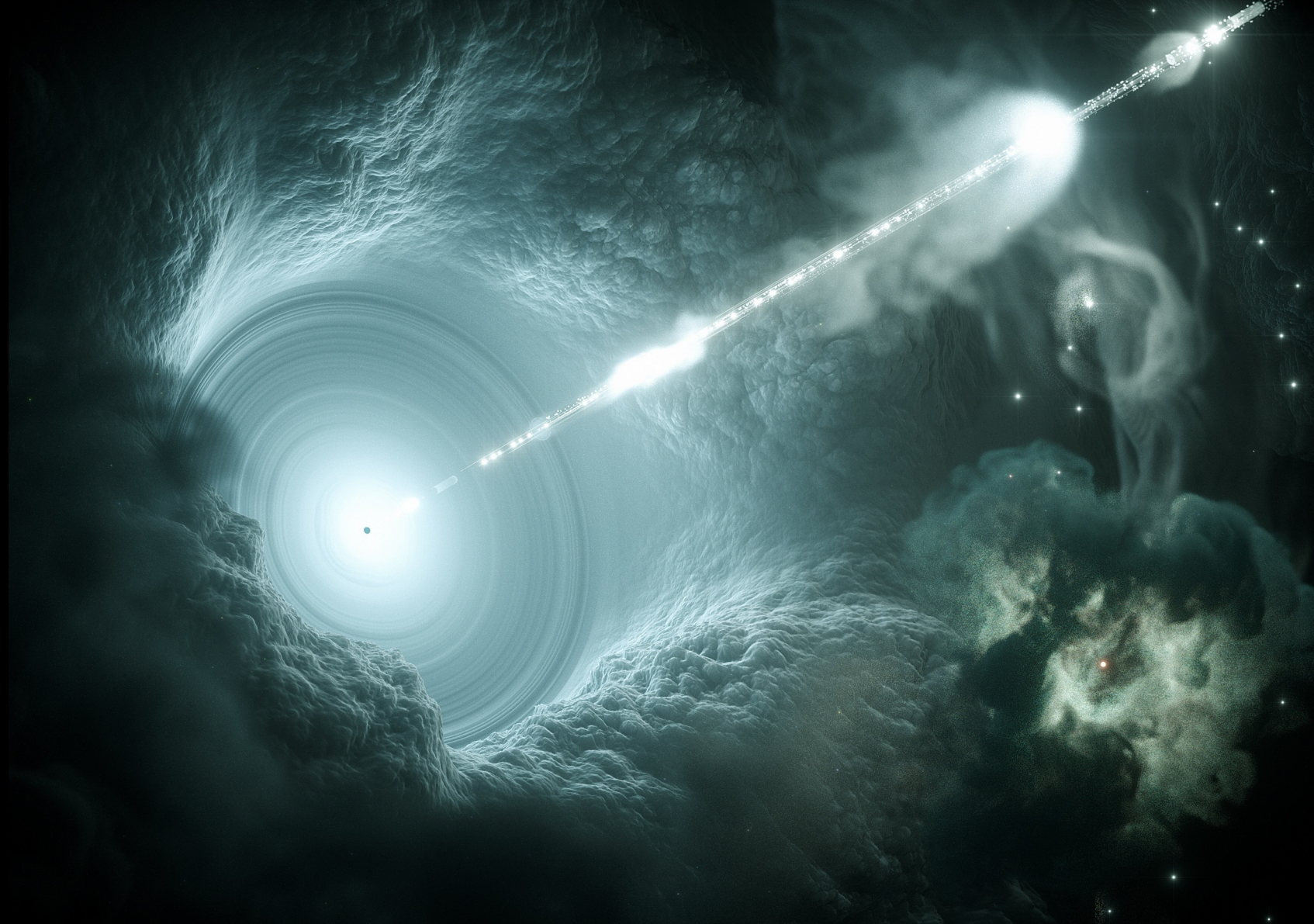
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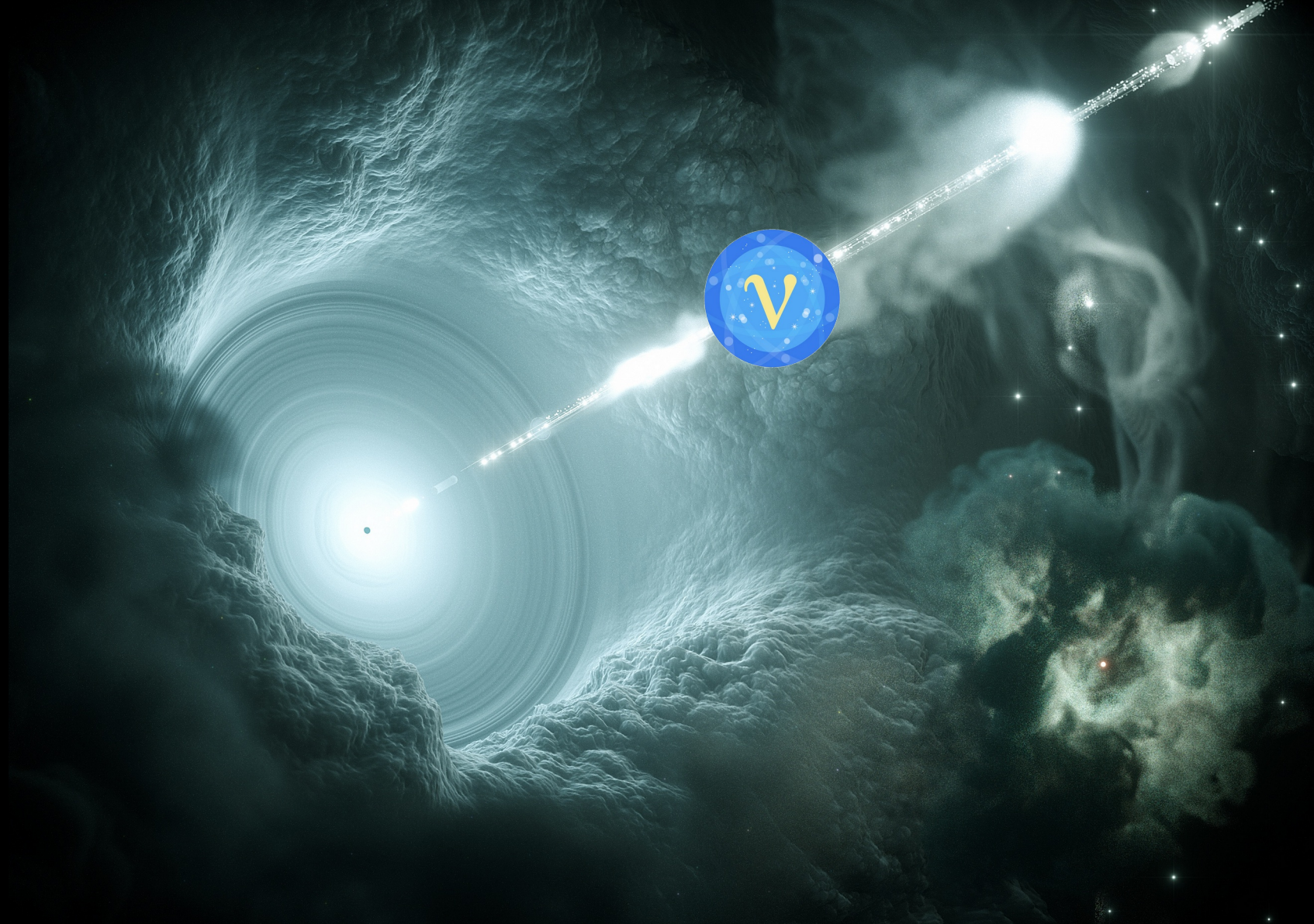
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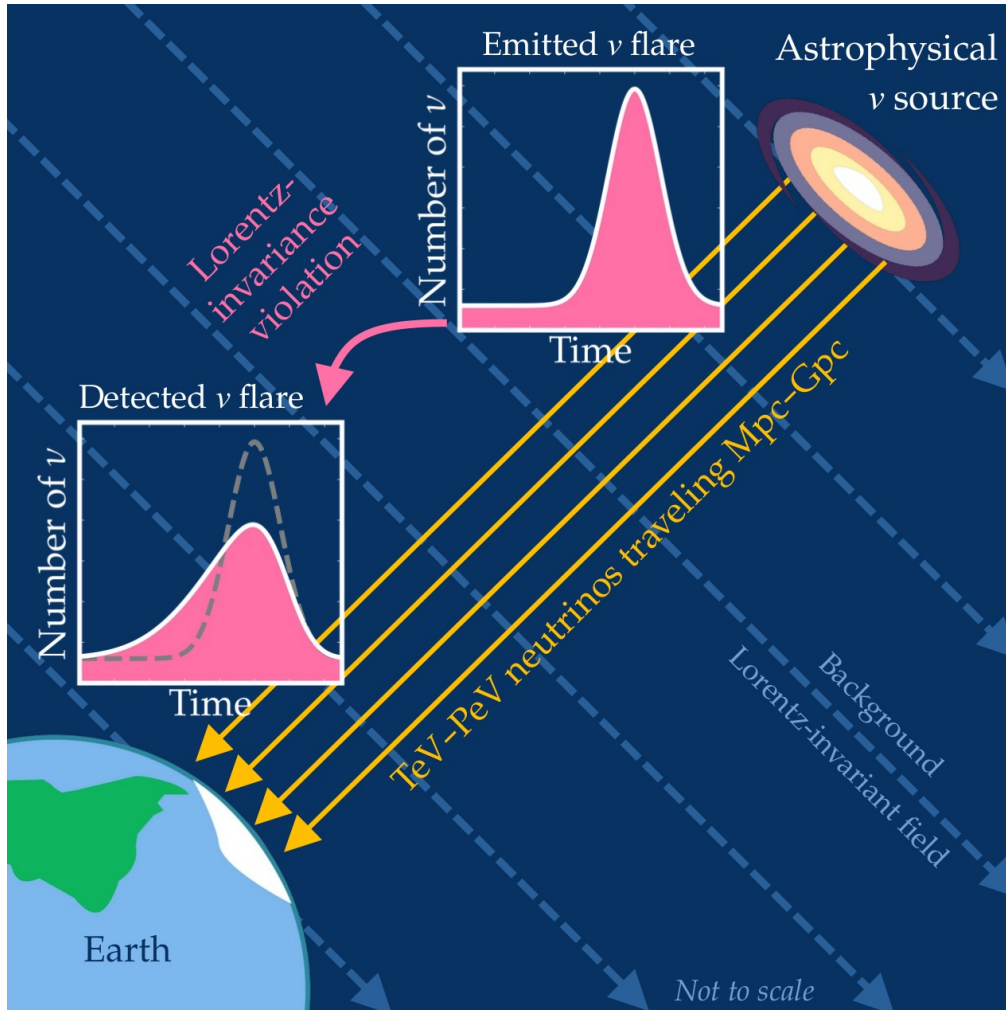


Lorentz-invariance
violation from a
neutrino flare





New physics from high-energy neutrino flares



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

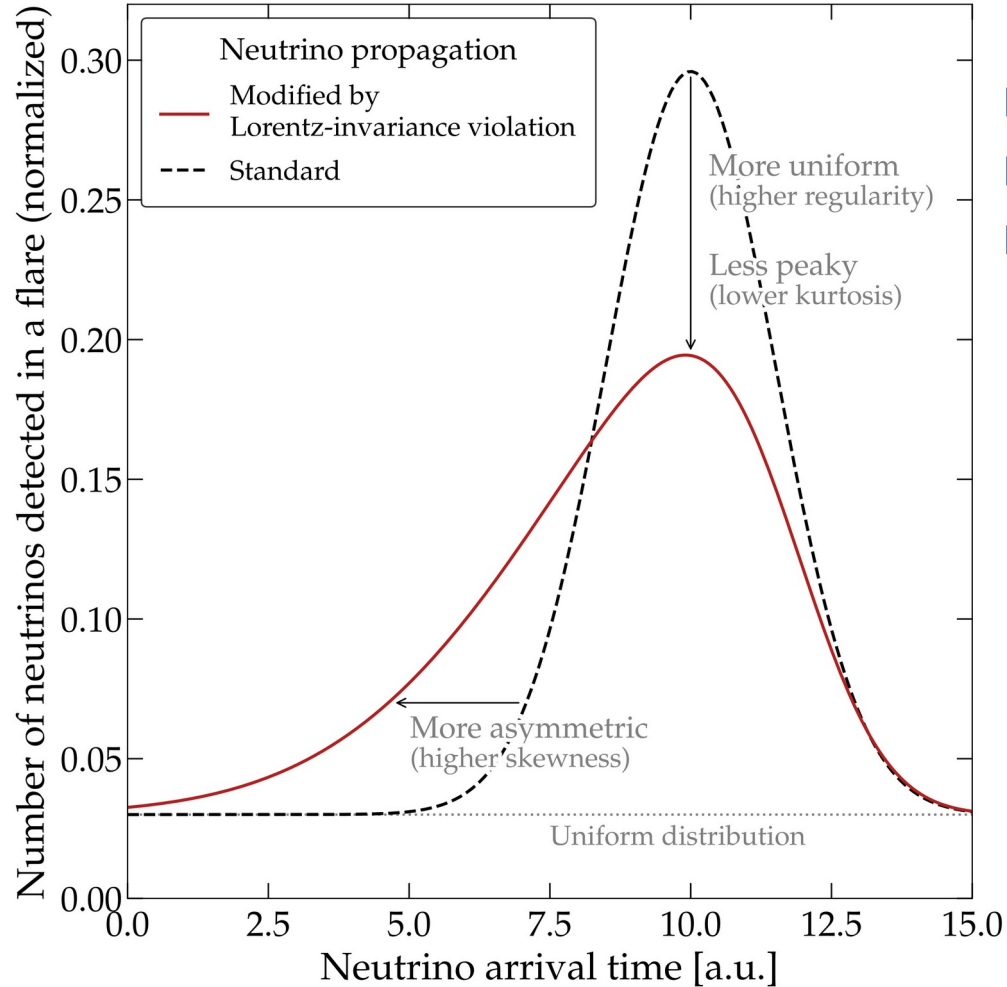
$$v(E_\nu) = \left[1 - \frac{n+1}{2} \left(\frac{E_\nu}{M_n} \right)^n \right] \equiv 1 - \Delta v(E_\nu)$$

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*

New physics from high-energy neutrino flares

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



LIV makes the ν flare time-distribution...

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

For a detected neutrino with E_ν in a flare:

$$t_{\text{obs}}(E_\nu) = b_s(E_\nu)(1 + z_{\text{src}}) + \tau_n(z_{\text{src}})E_\nu^n$$

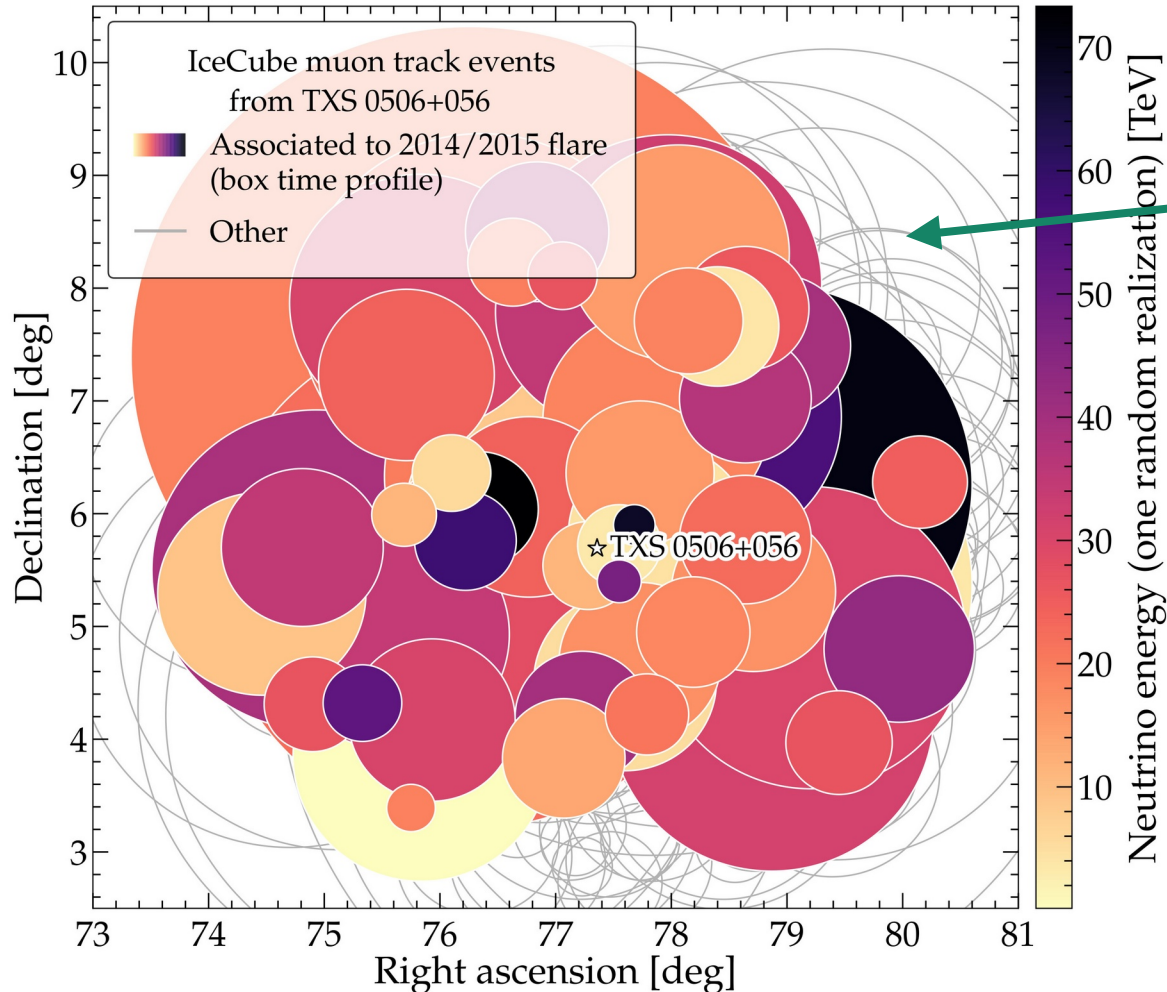
Detection time
of a at Earth

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

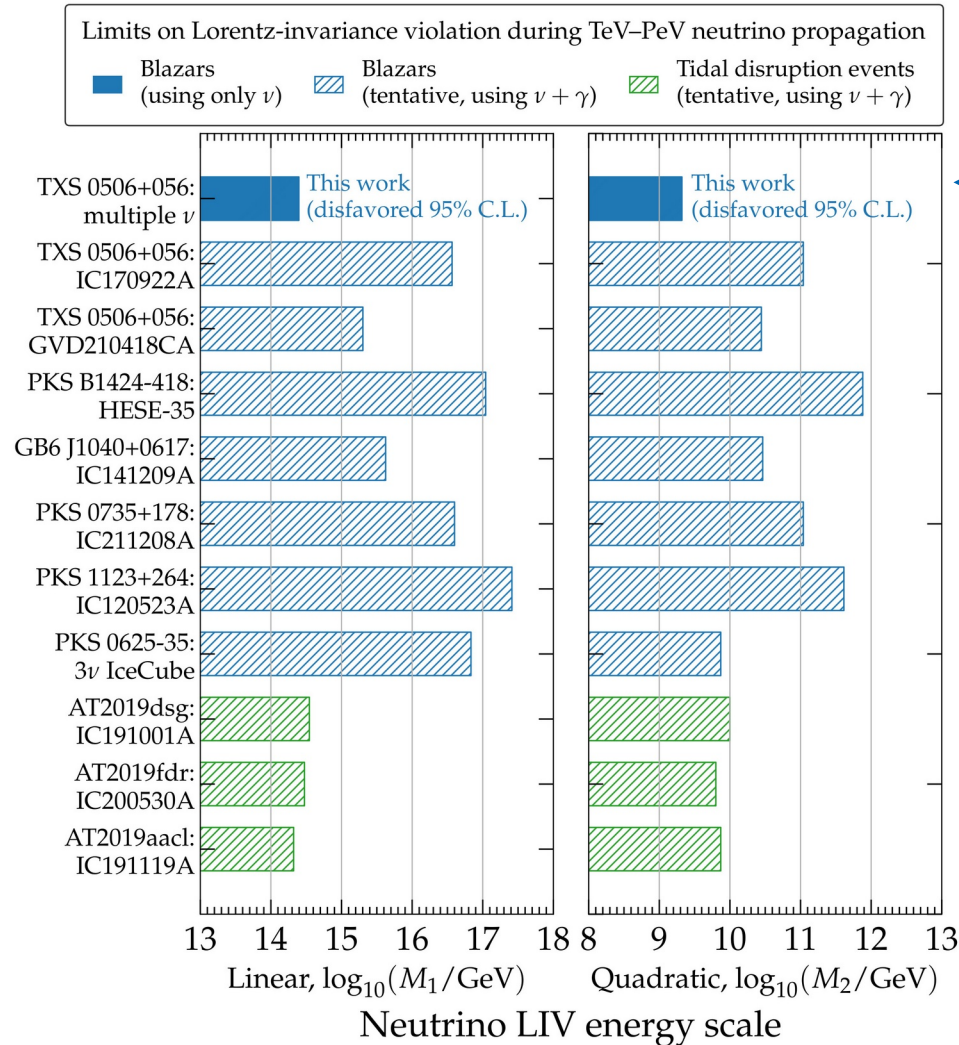


Use IceCube through-going muons associated to the 2015/2015 flare of TXS 0506+056

- ▶ 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)

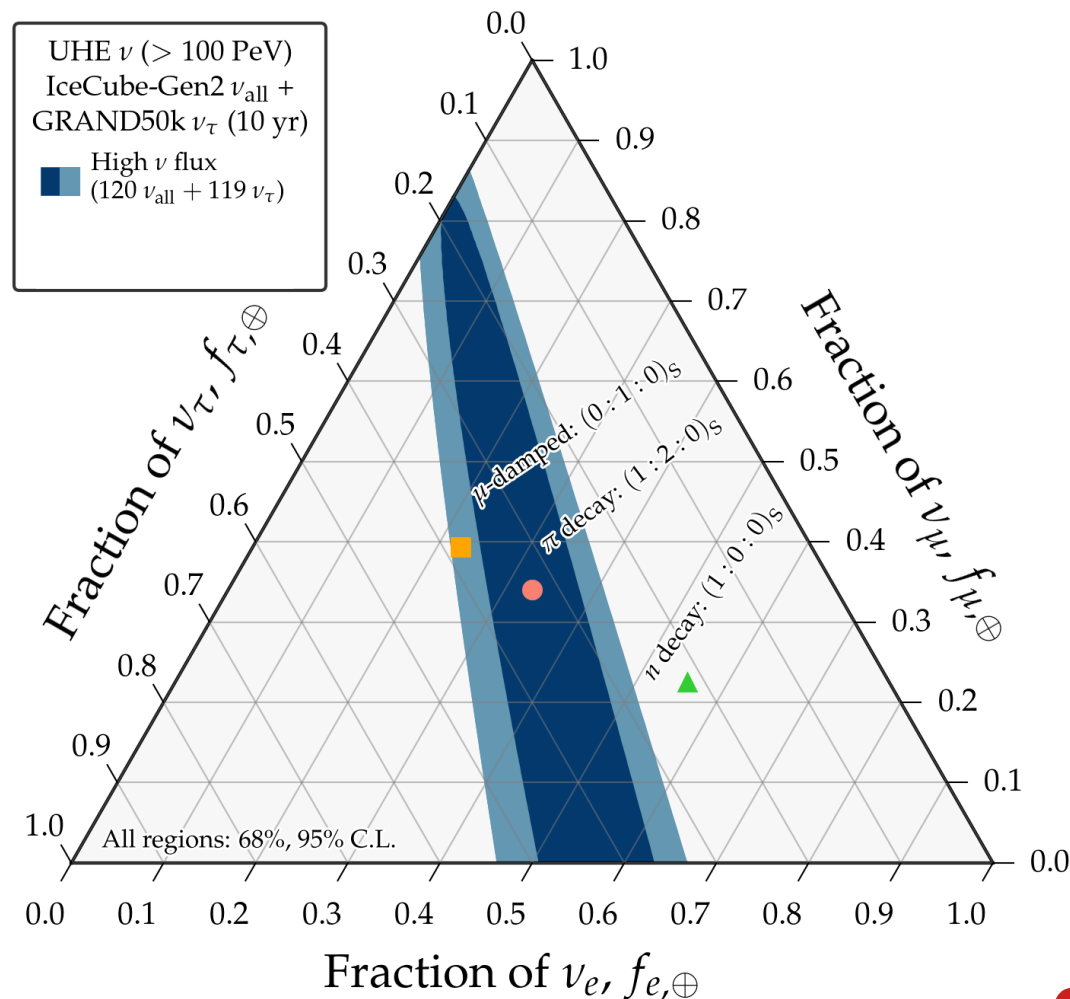
MB, Ellis, Konoplich, Sakharov, *PRD* 2025

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:

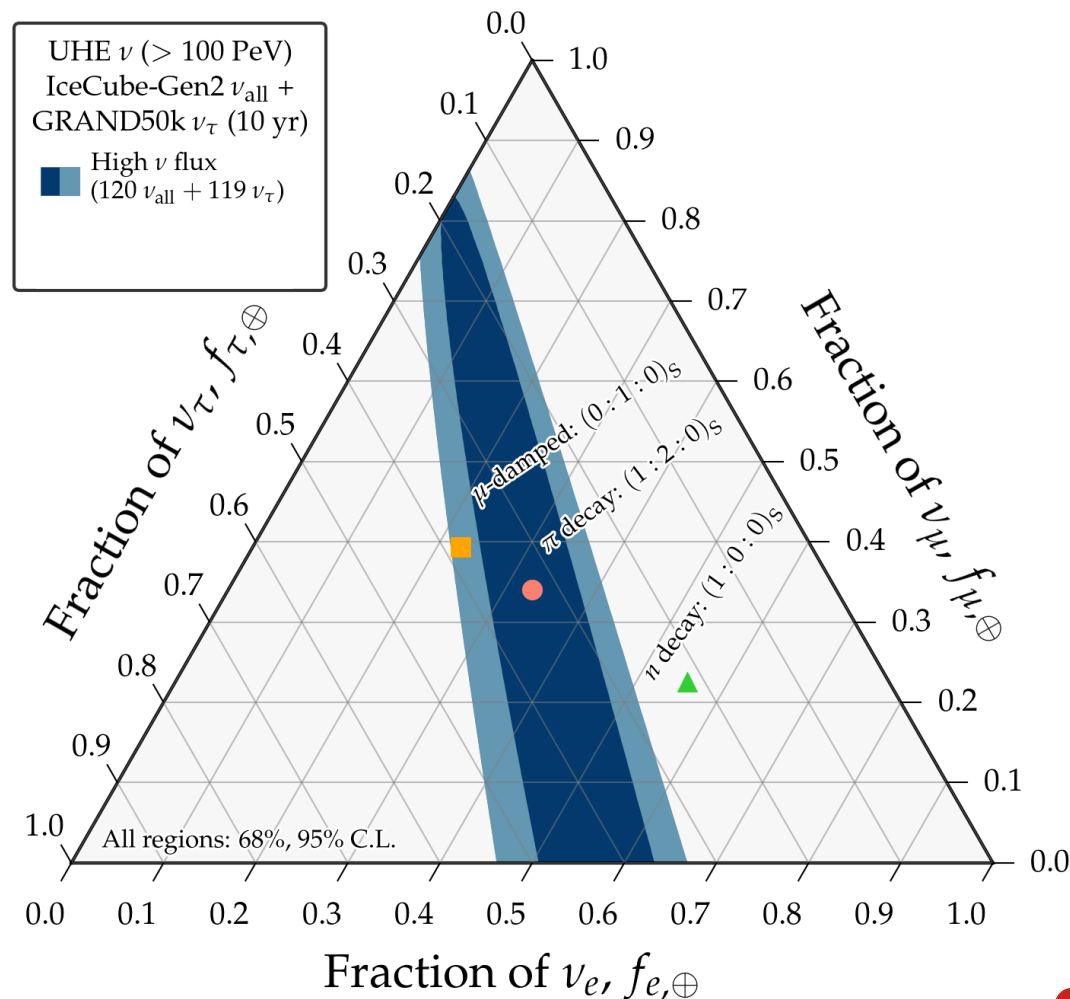


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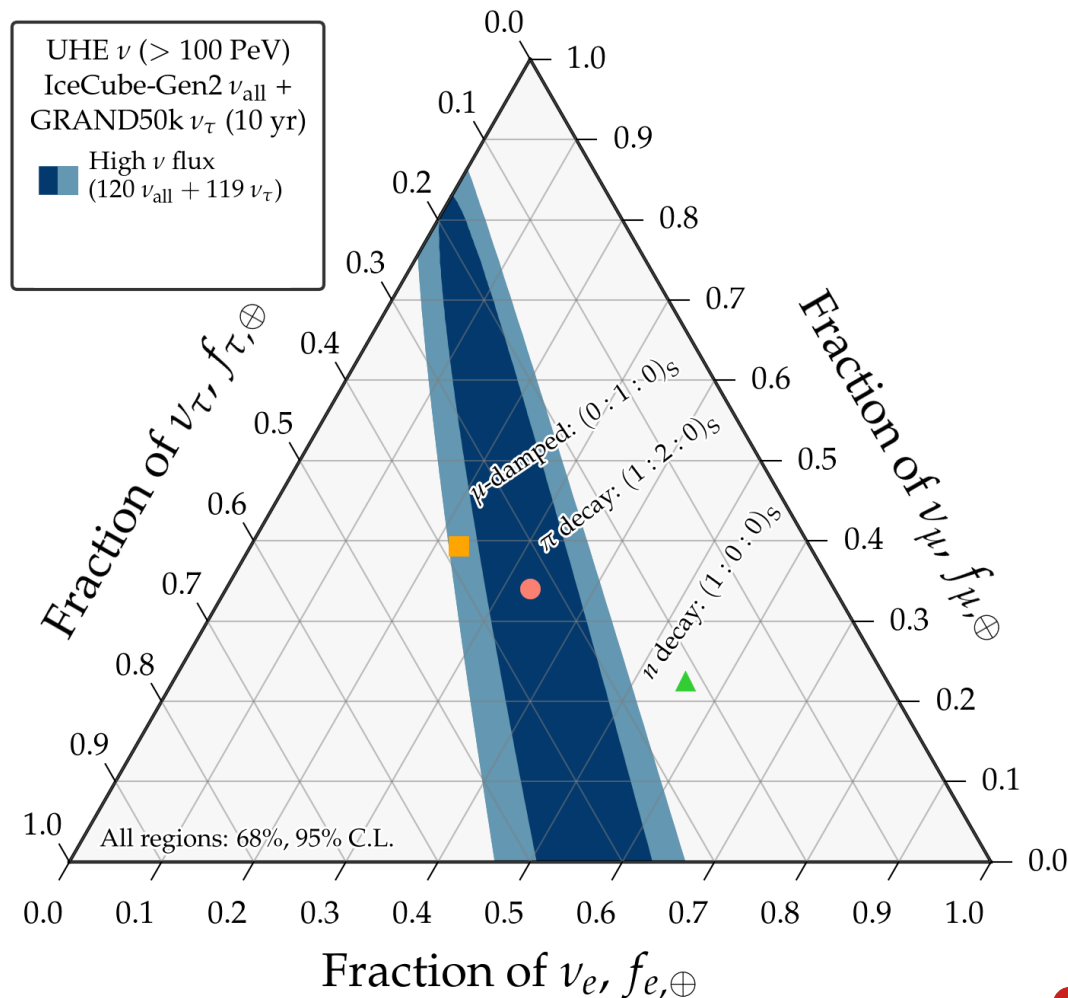
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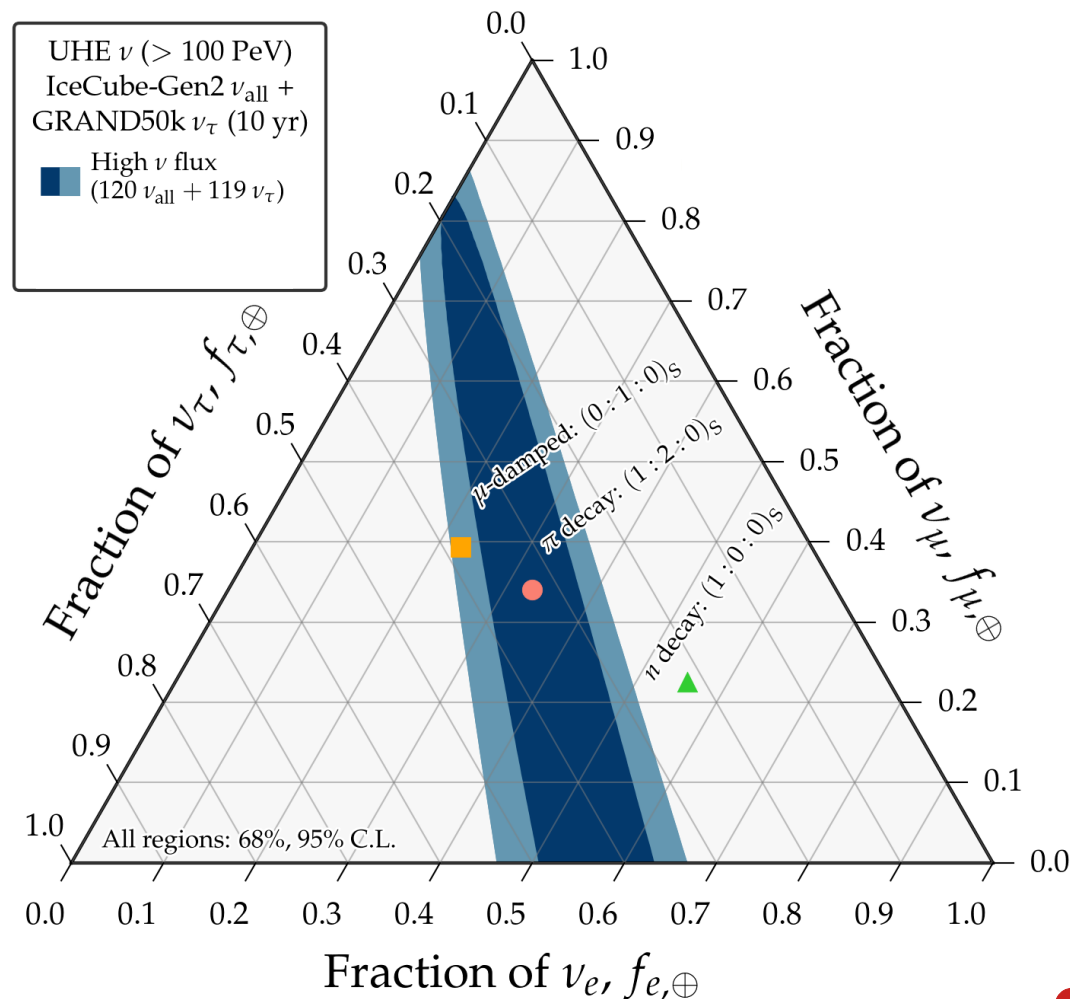
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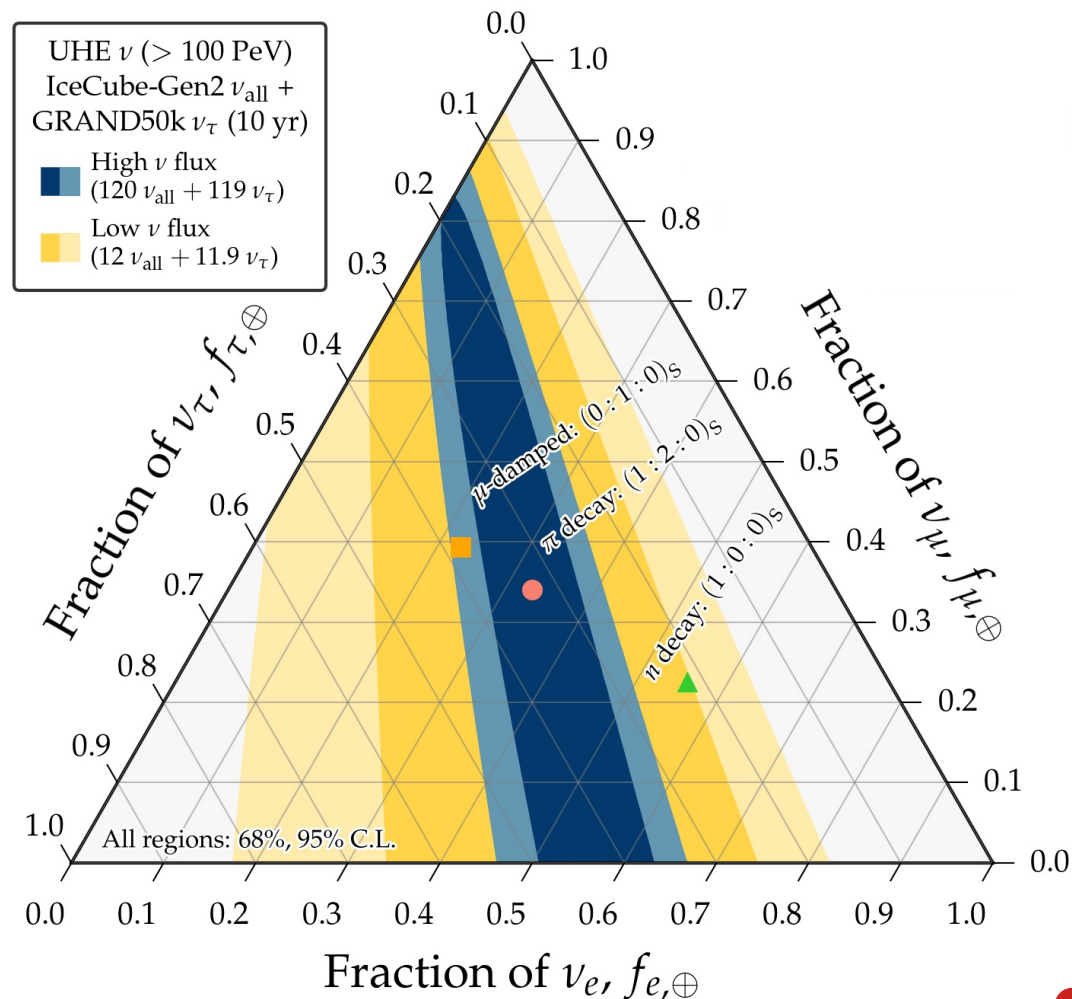
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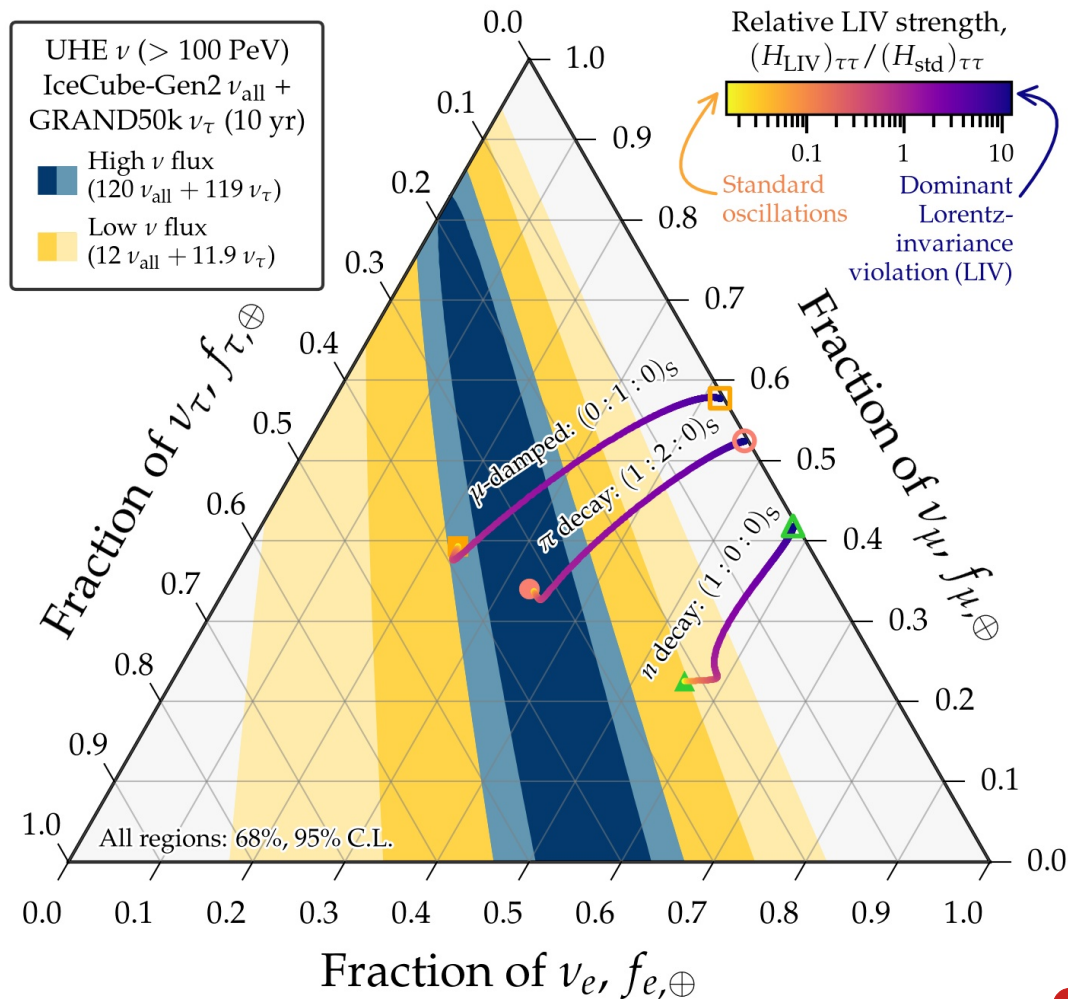
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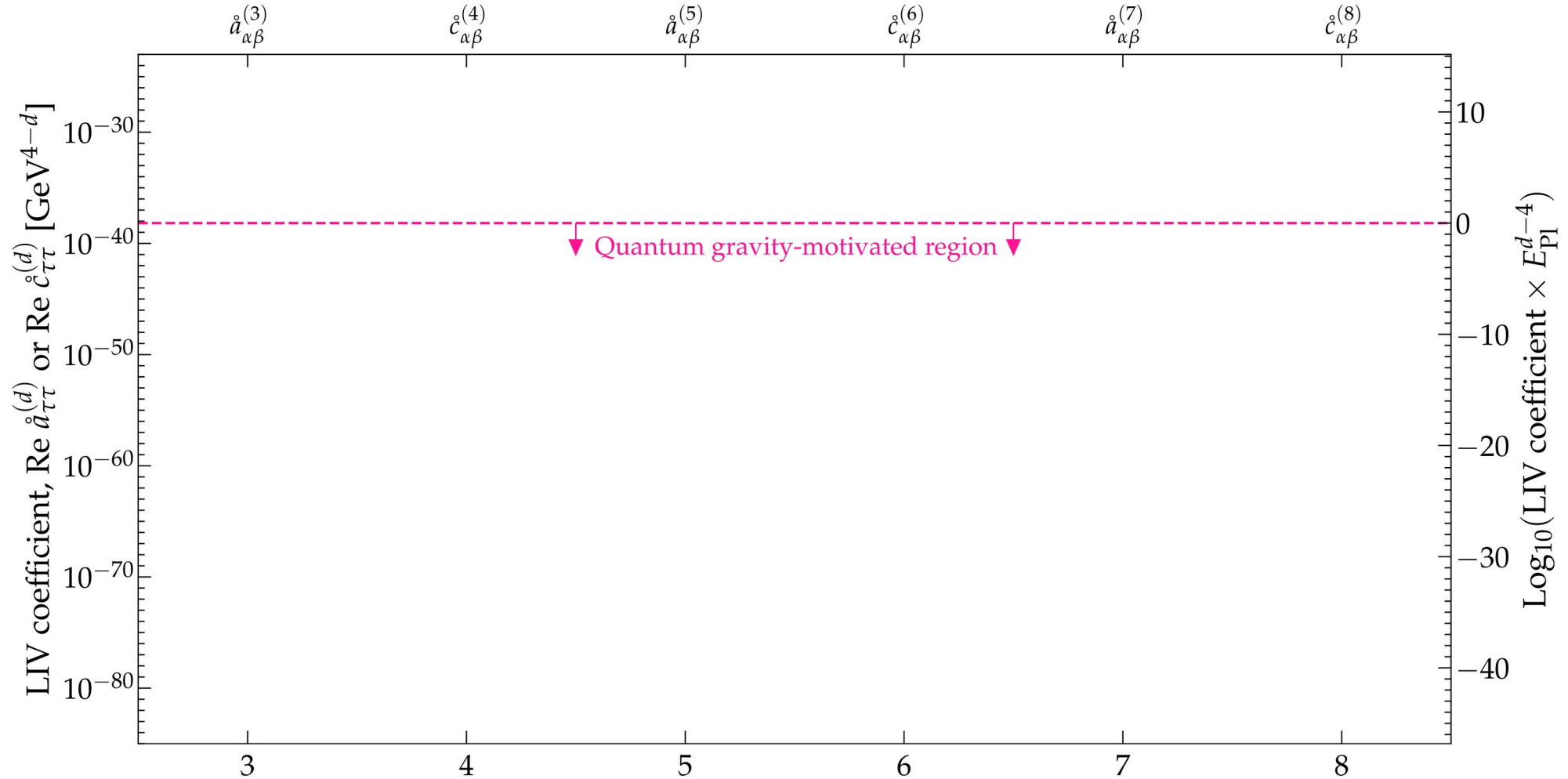
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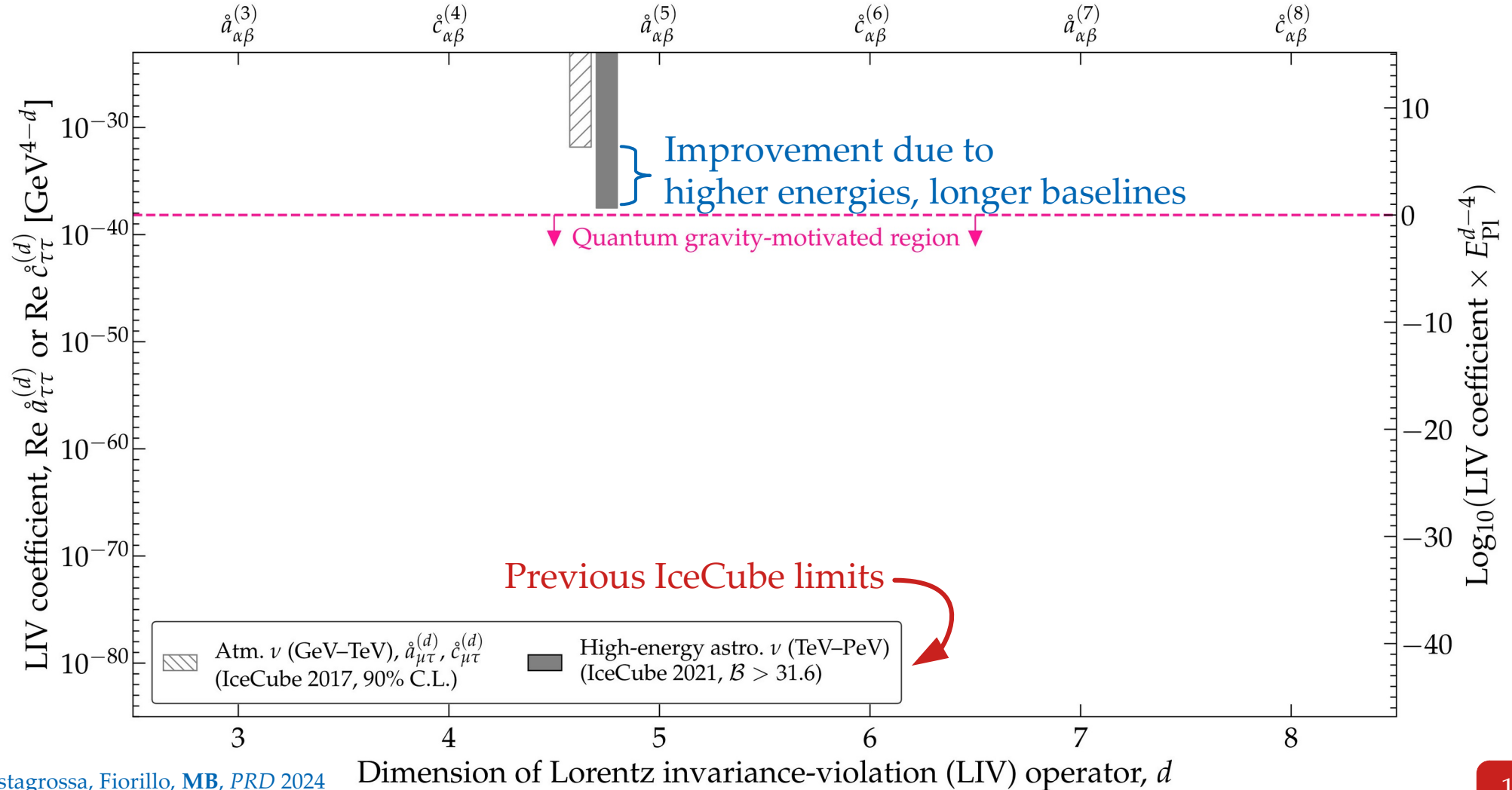
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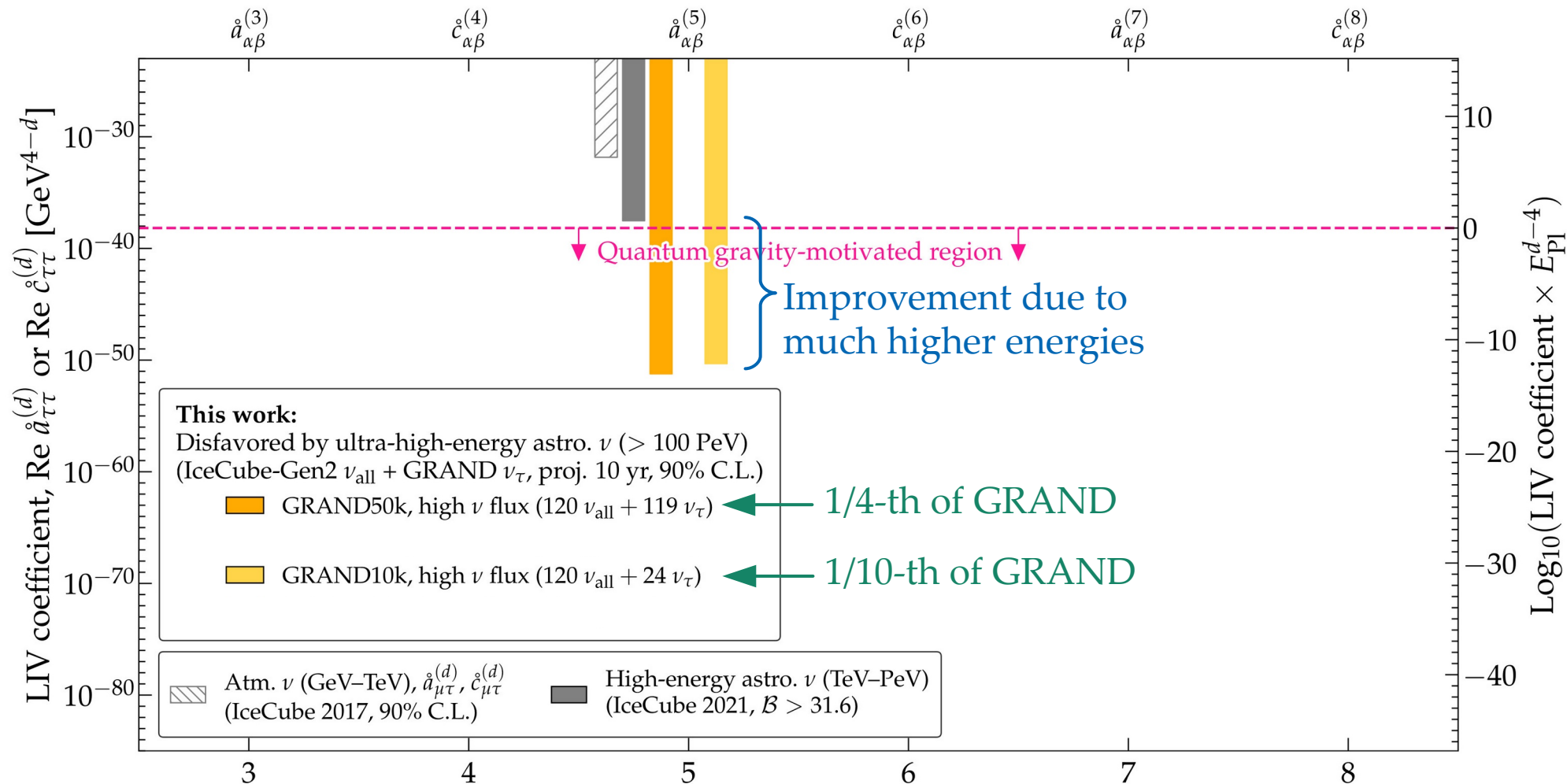
Lorentz-invariance violation at ultra-high energies



Lorentz-invariance violation at ultra-high energies

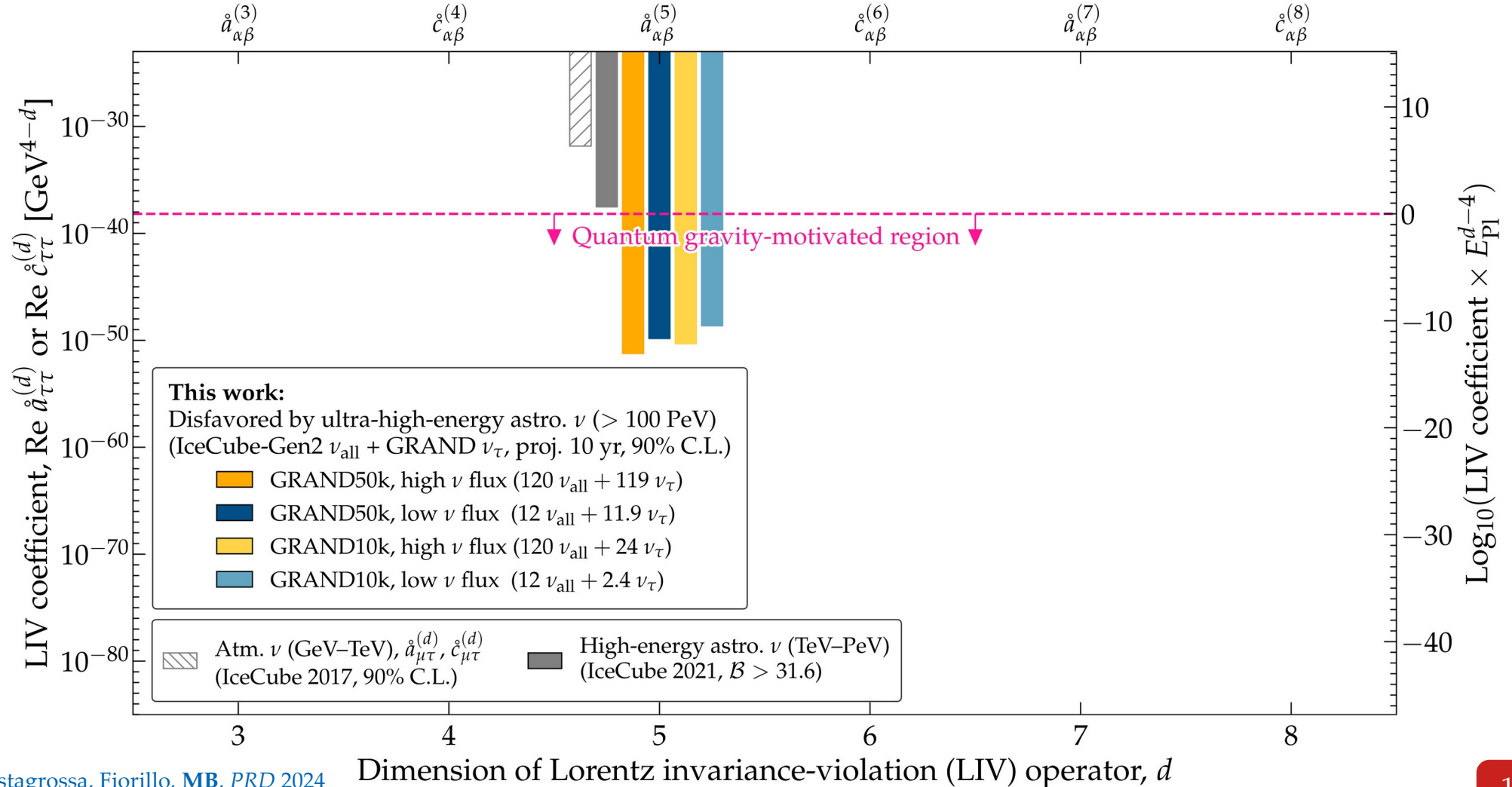


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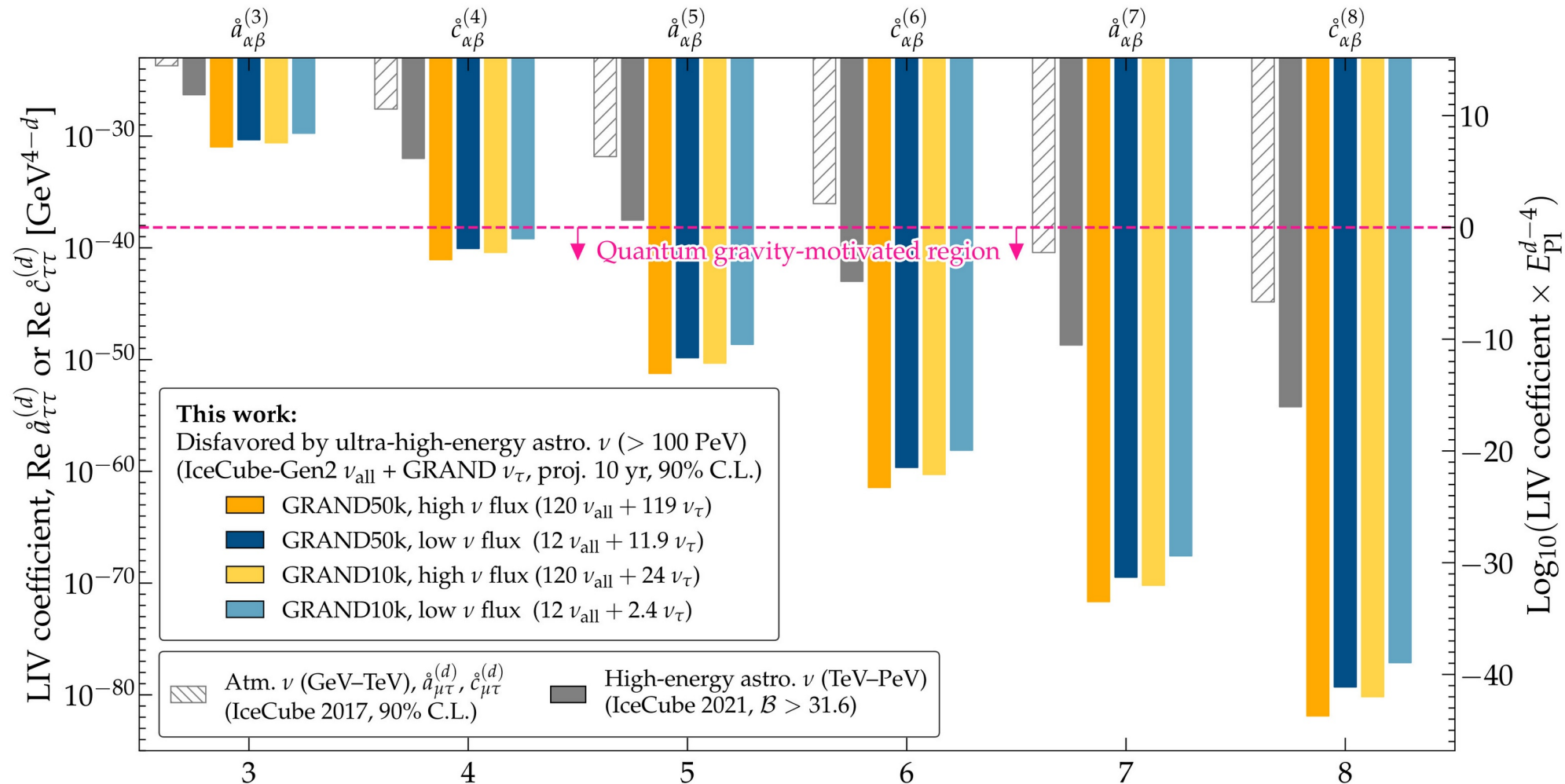


Dimension of Lorentz invariance-violation (LIV) operator, d

Lorentz-invariance violation at ultra-high energies



Lorentz-invariance violation at ultra-high energies



Dimension of Lorentz invariance-violation (LIV) operator, d

IceCube-Gen2 (radio) alone might measure flavor

