

Neutrino physics at the cosmic and energy frontiers

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Niels Bohr Institute, University of Copenhagen

GAPP Seminar

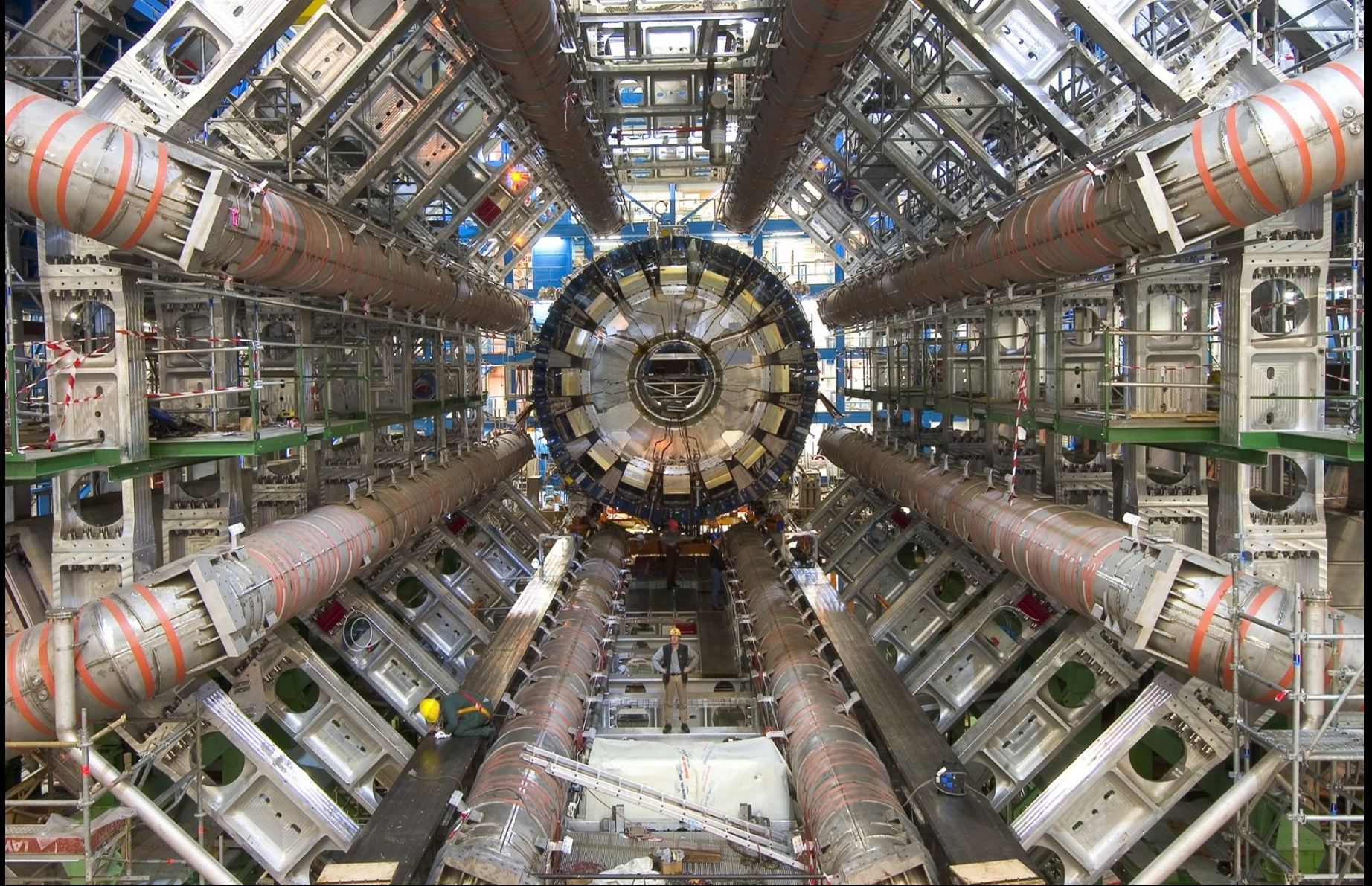
Penn State, January 30, 2024

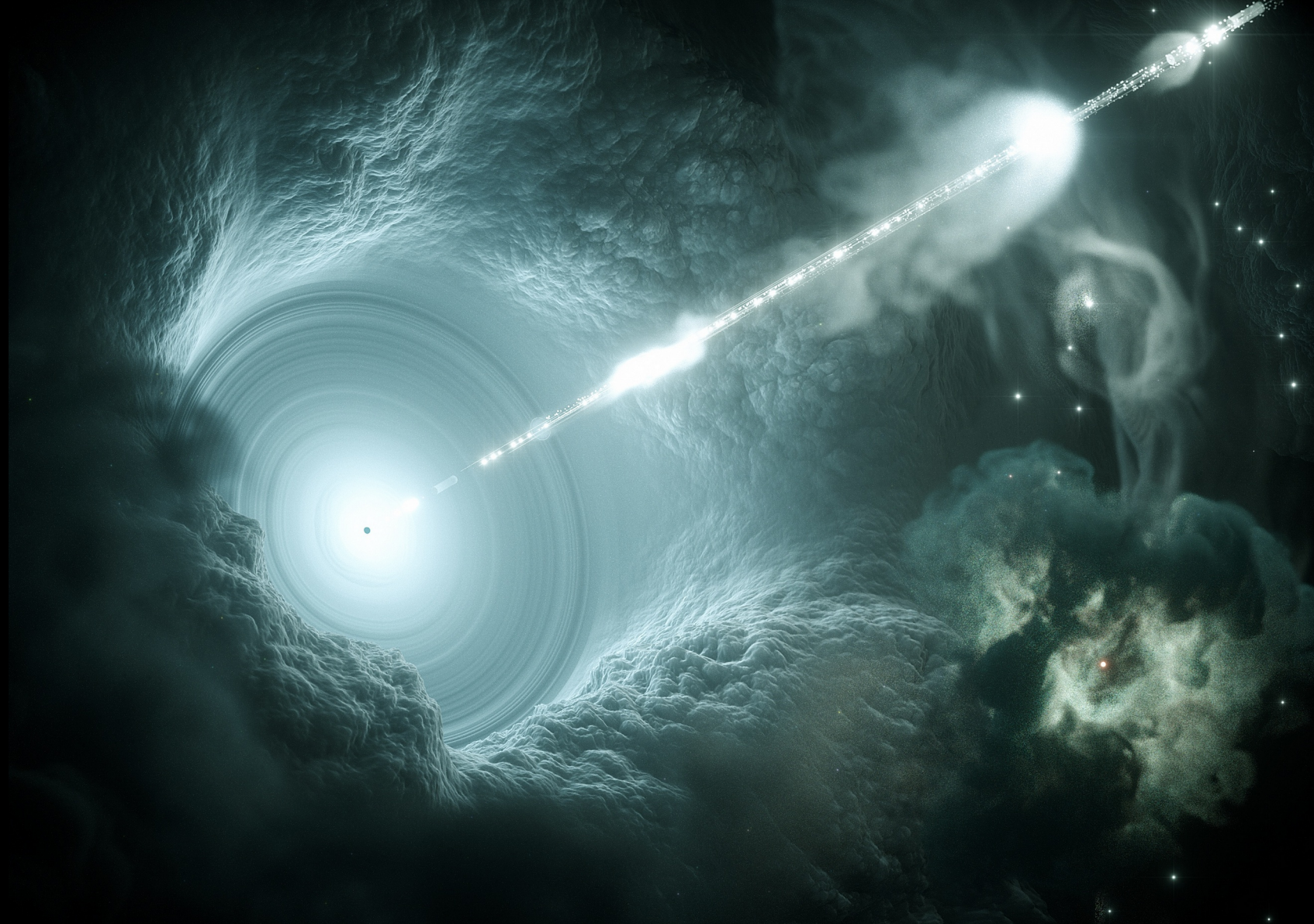
UNIVERSITY OF
COPENHAGEN

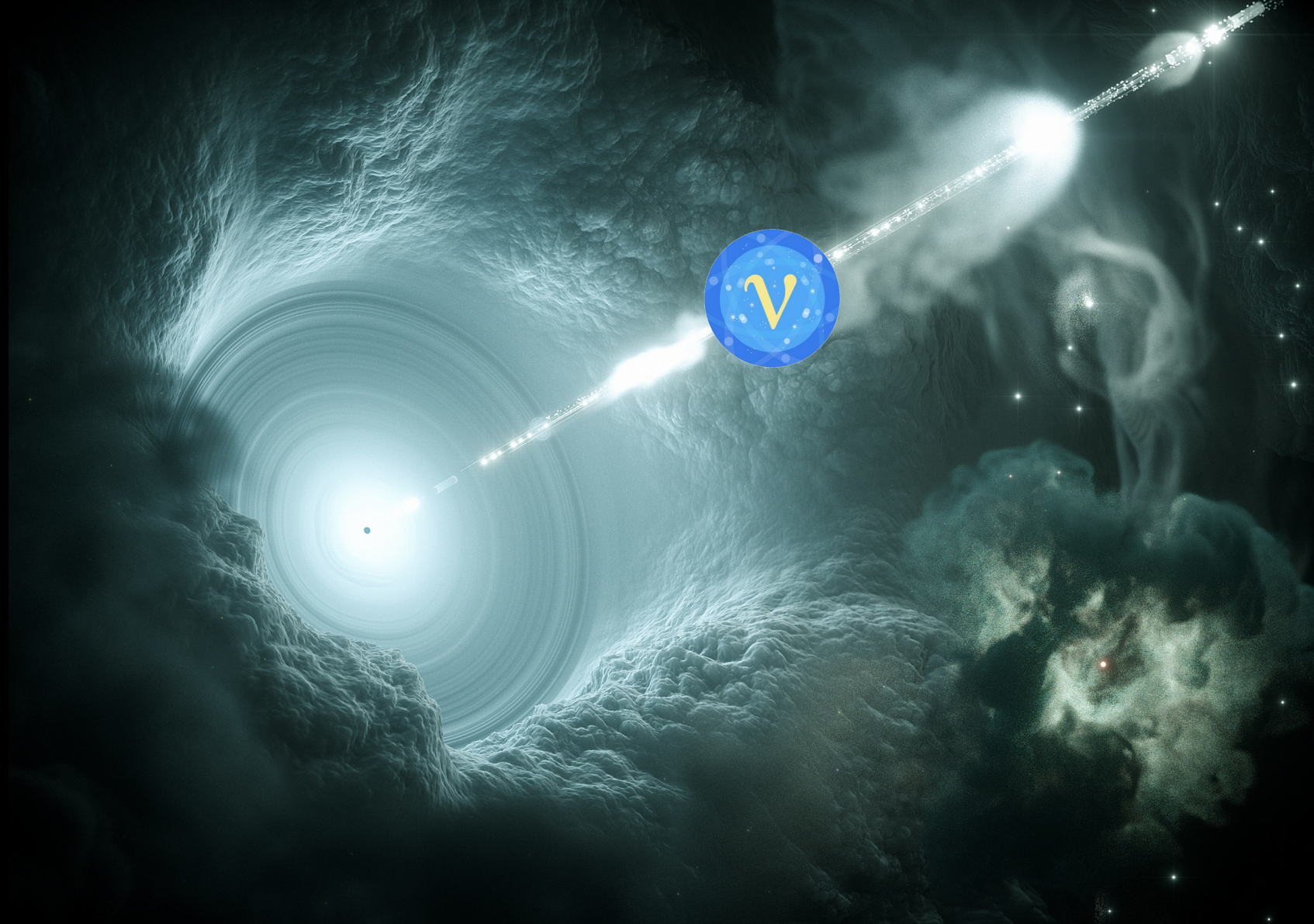


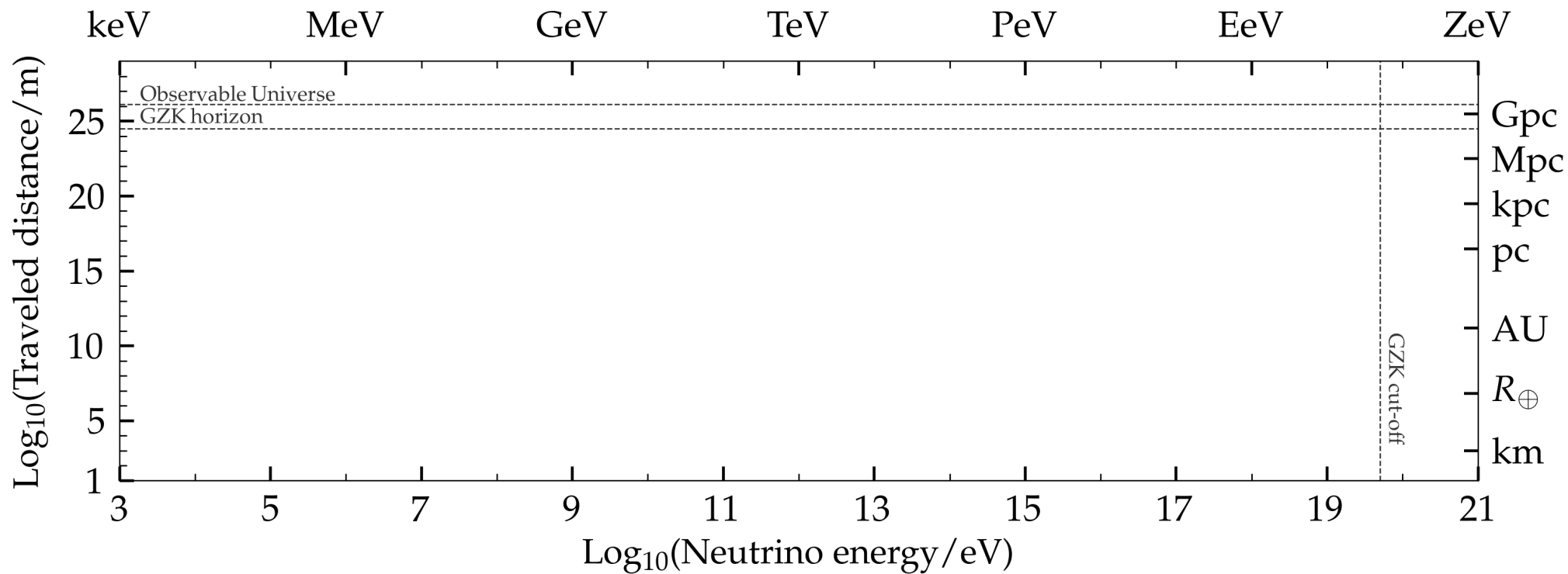
VILLUM FONDEN

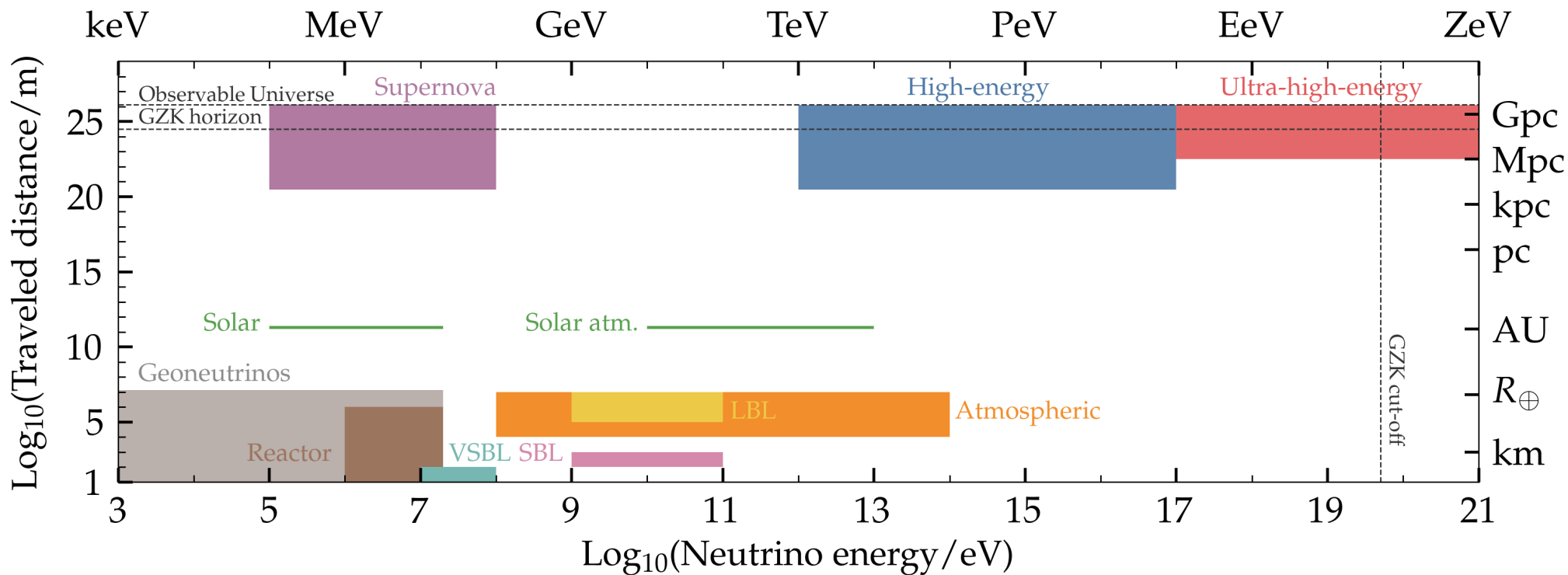




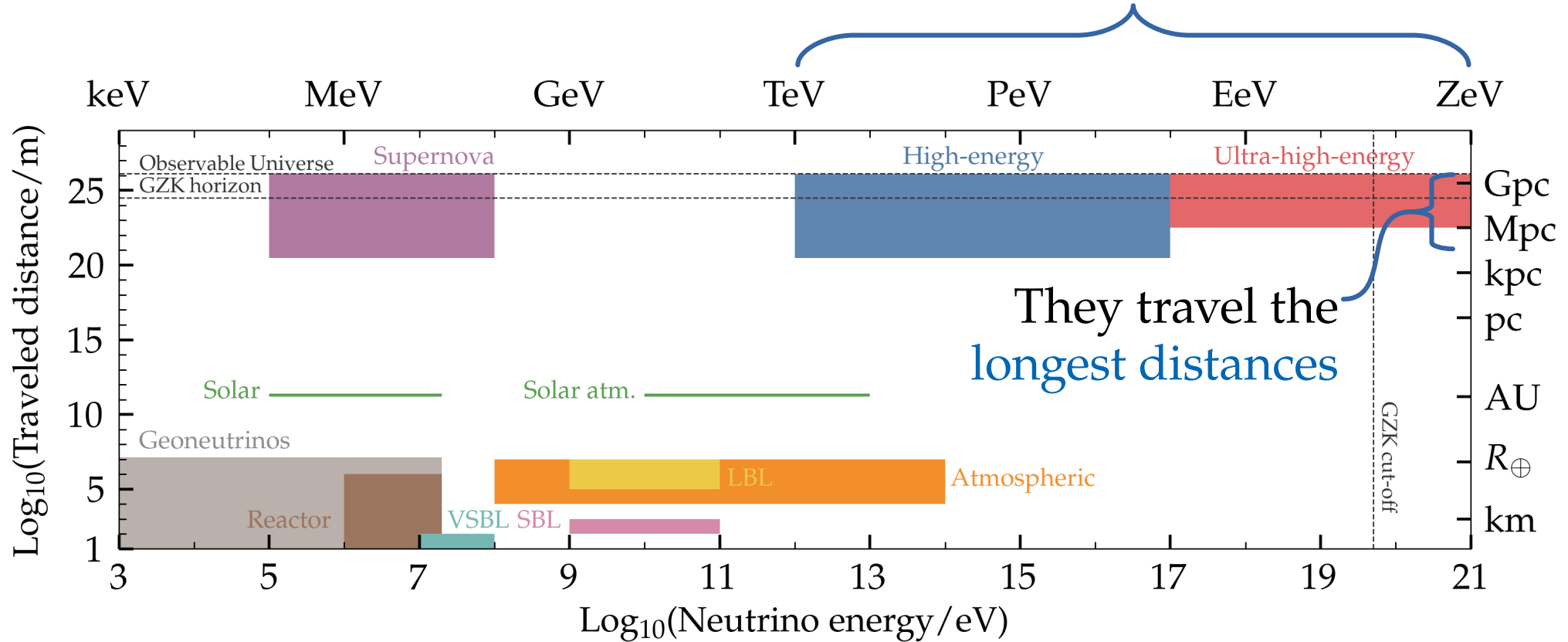


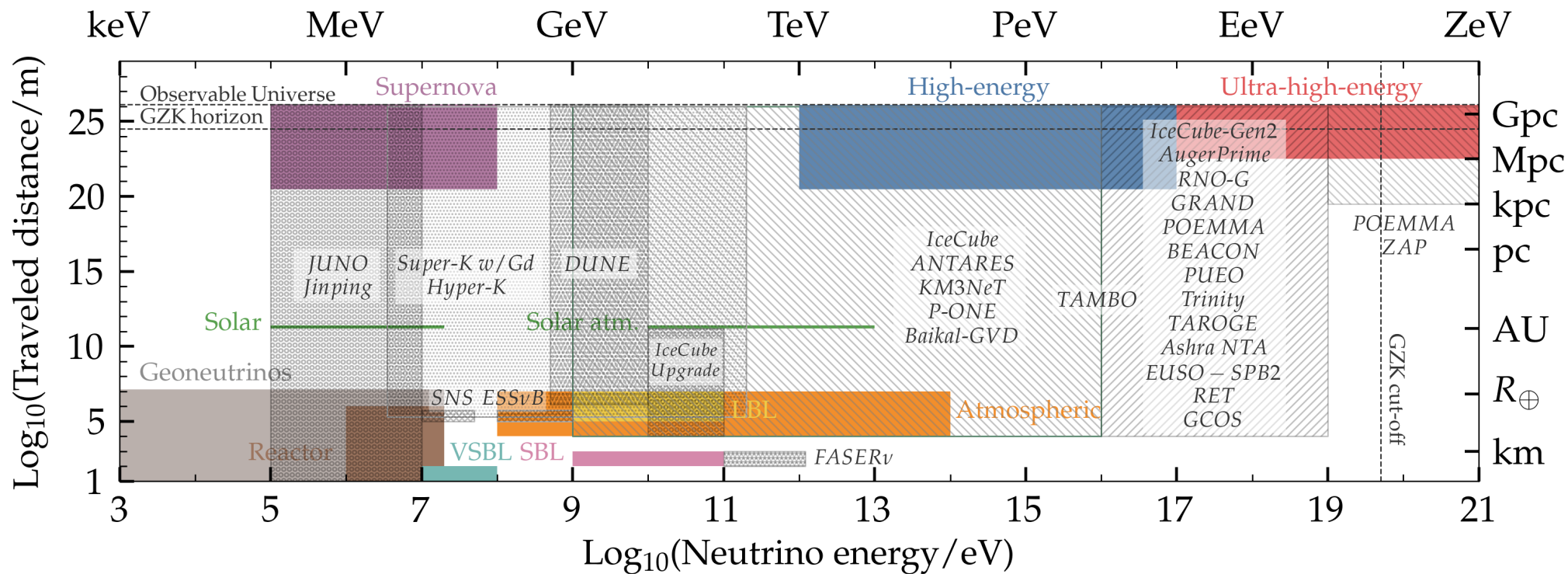


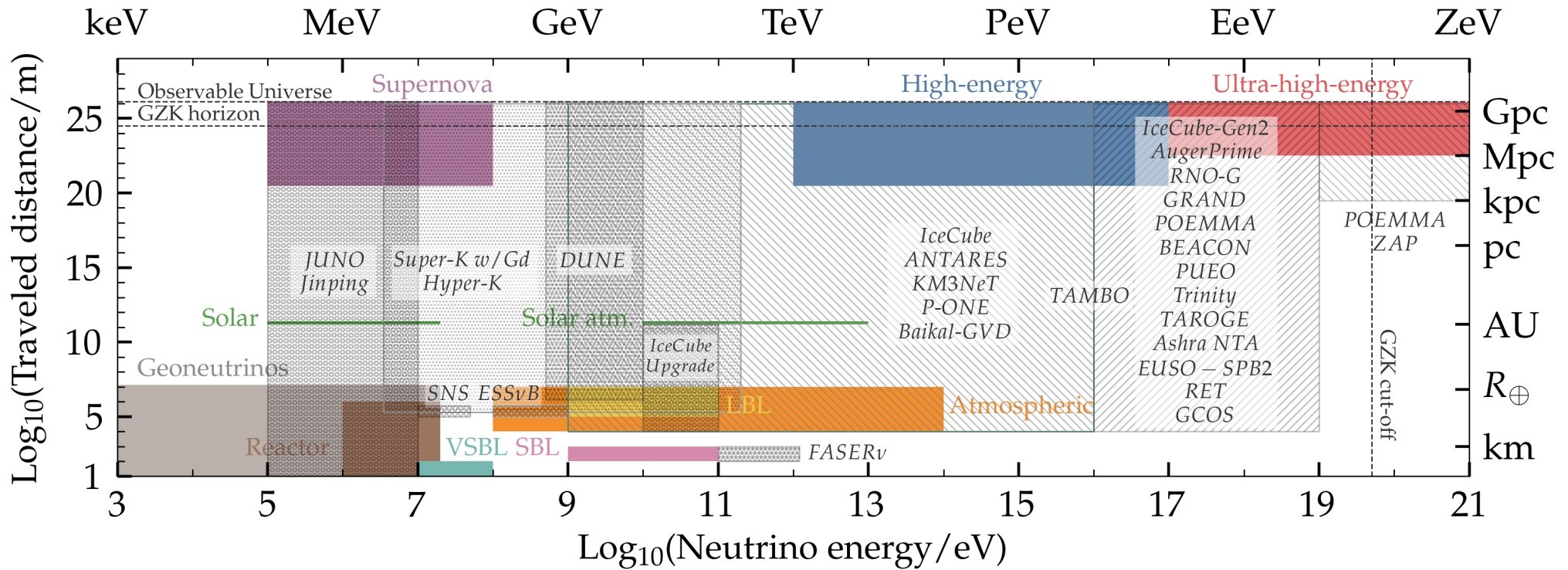




They have the **highest energies**

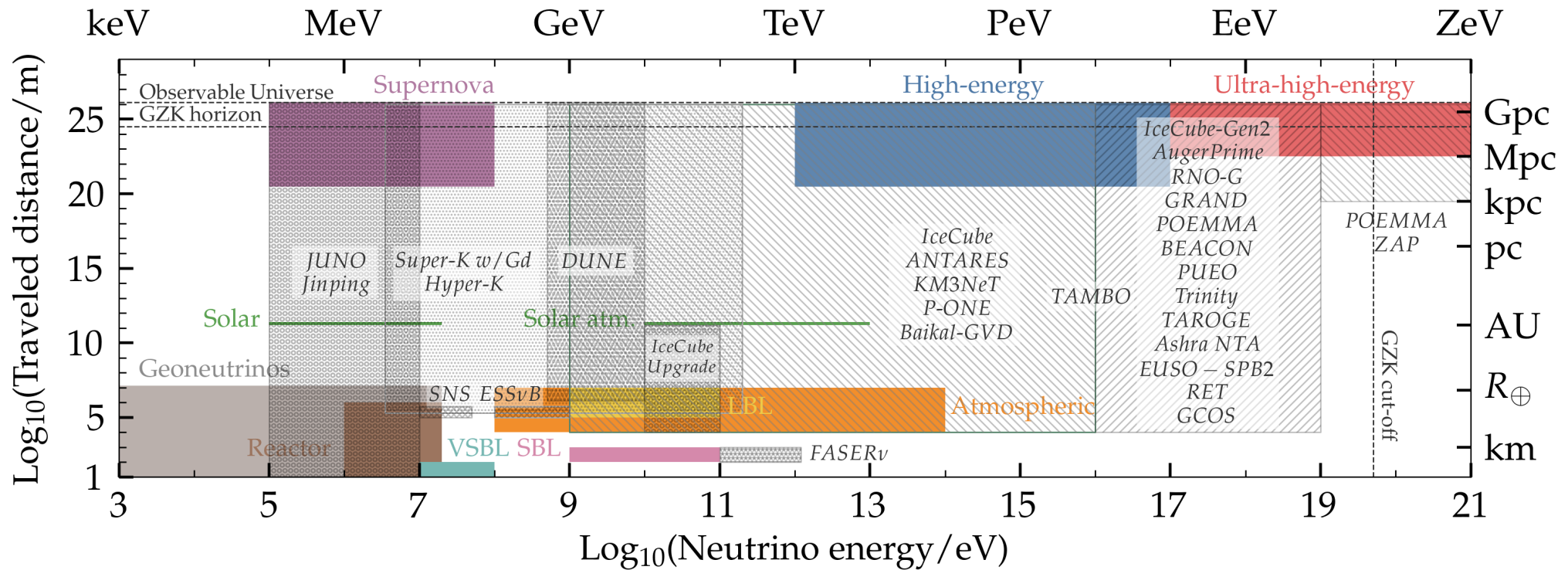




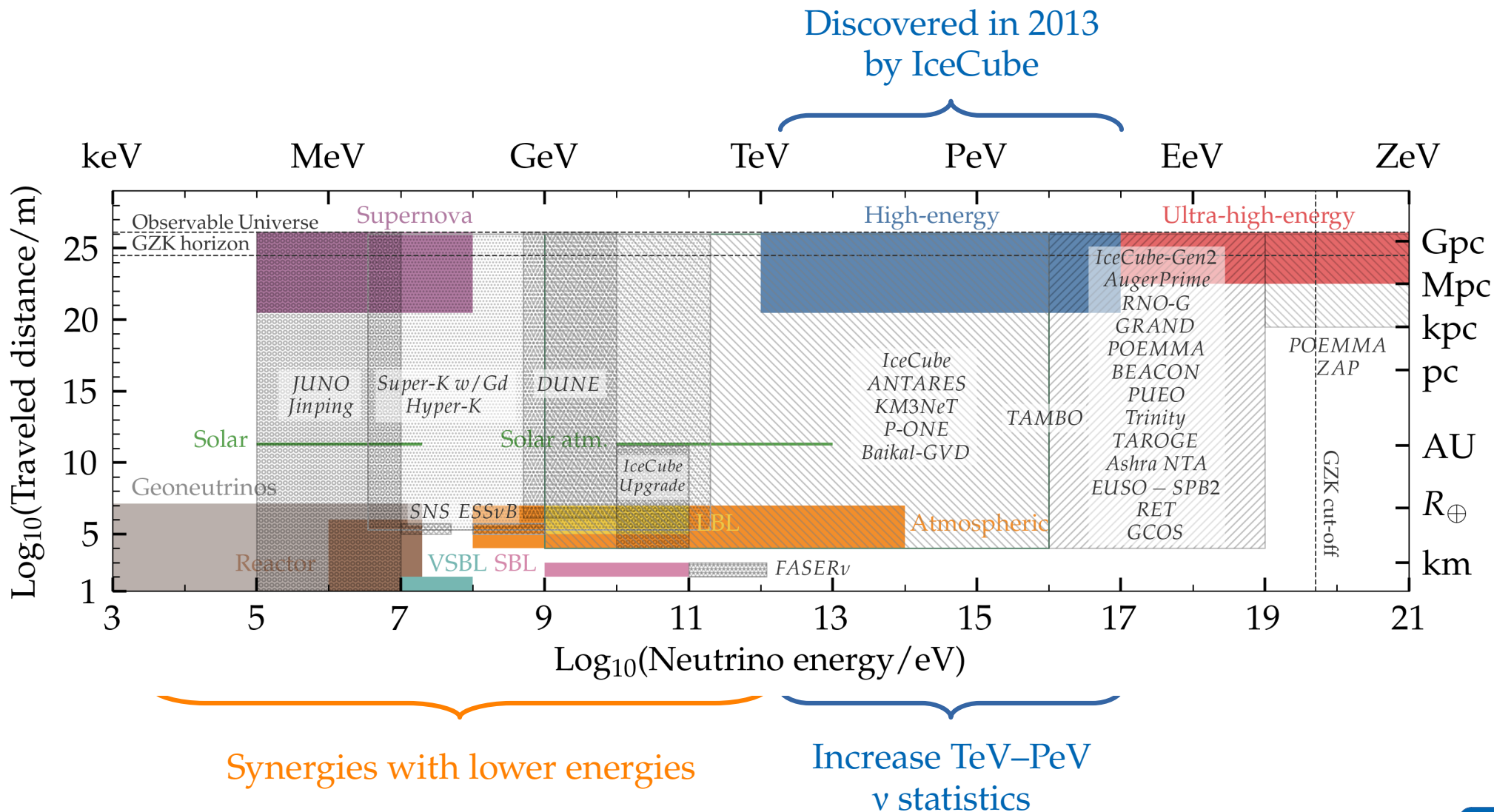


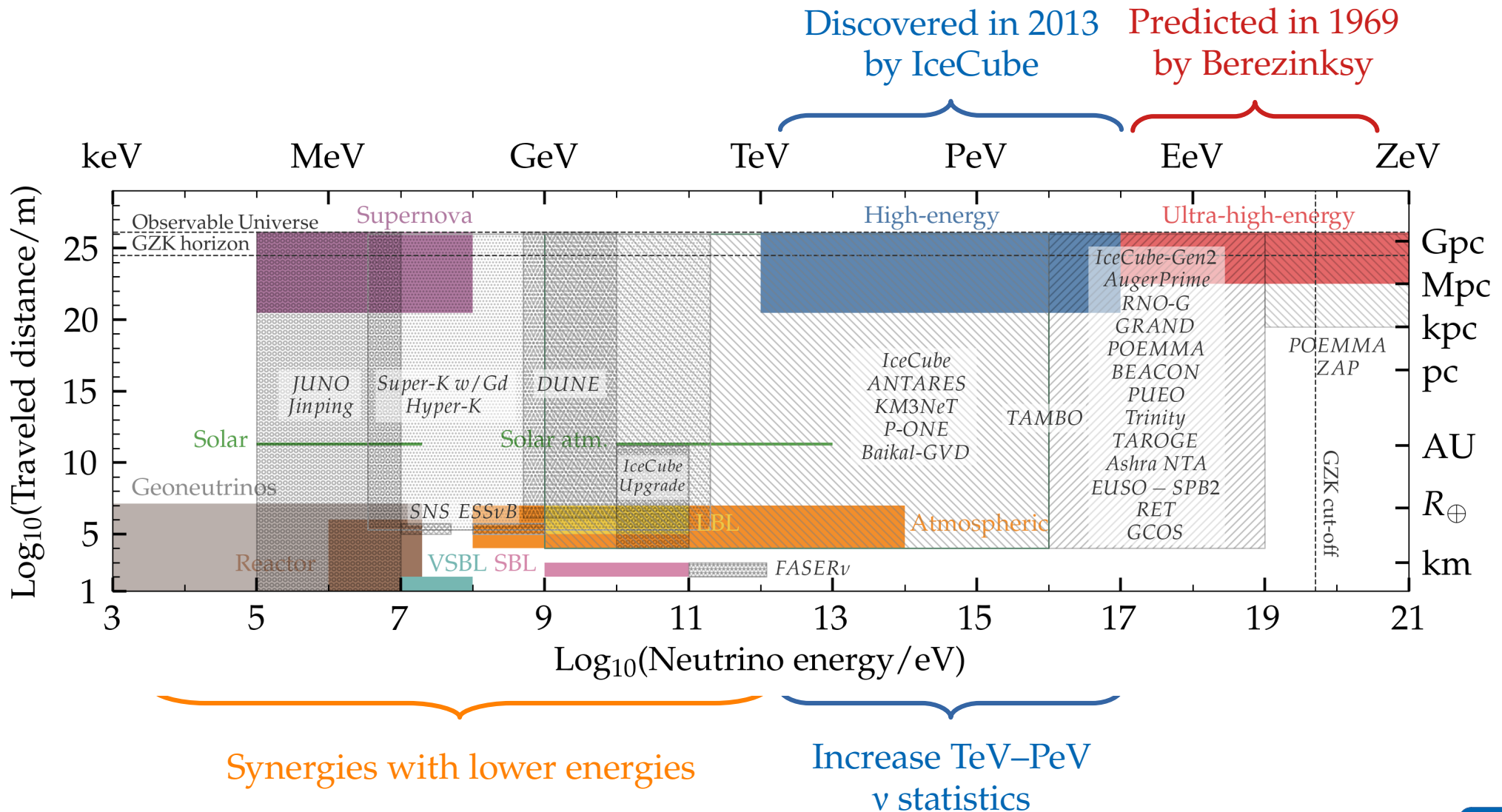
Synergies with lower energies

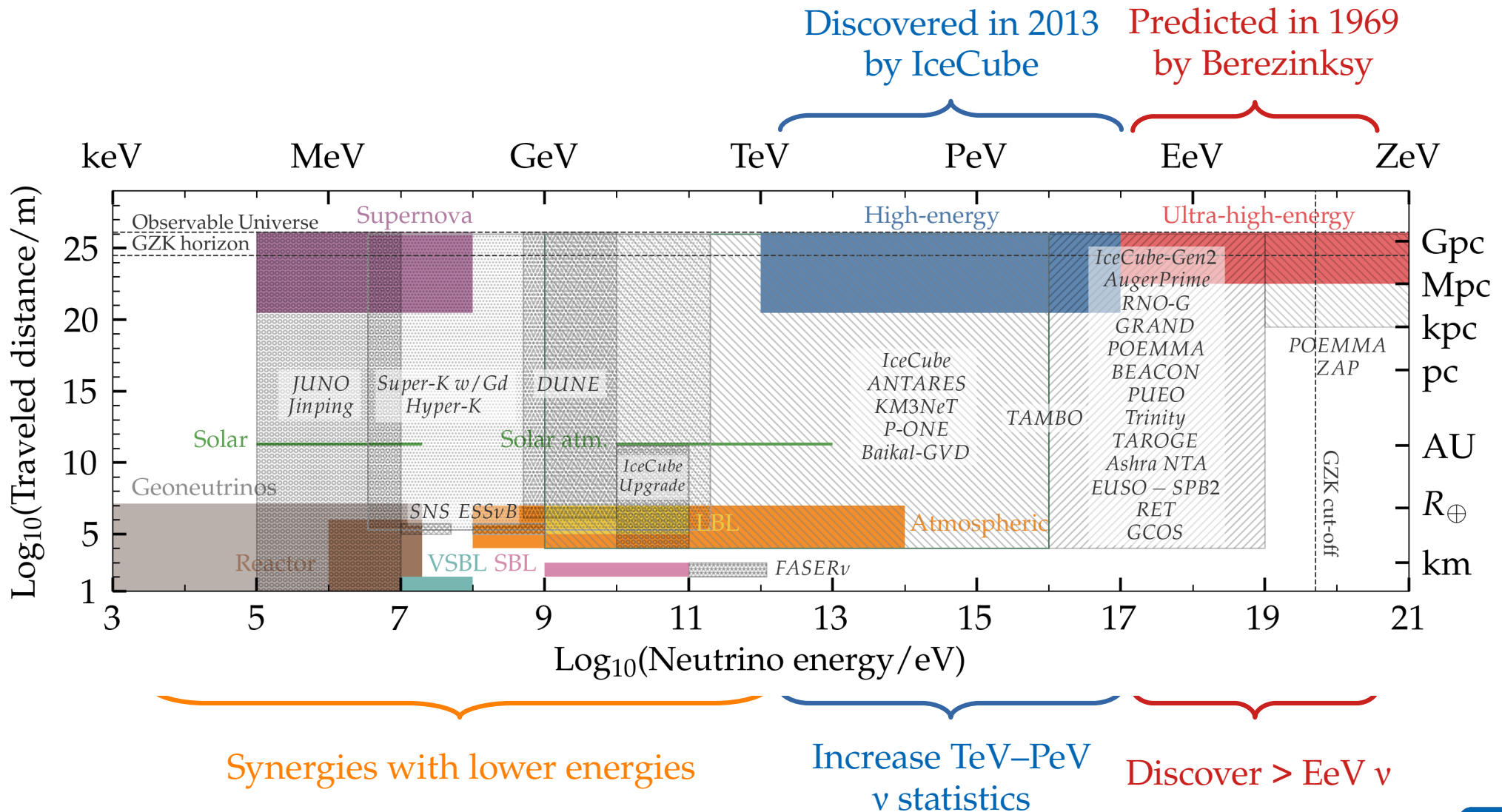
Discovered in 2013
by IceCube



Synergies with lower energies



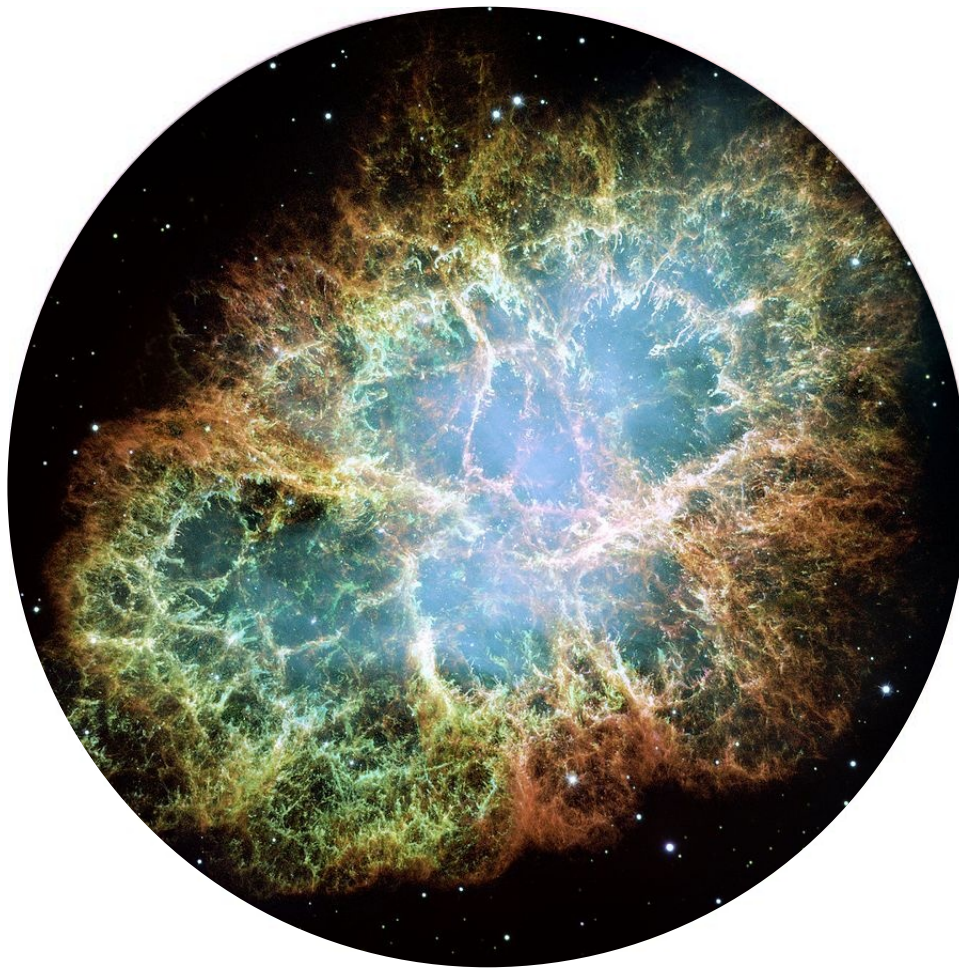


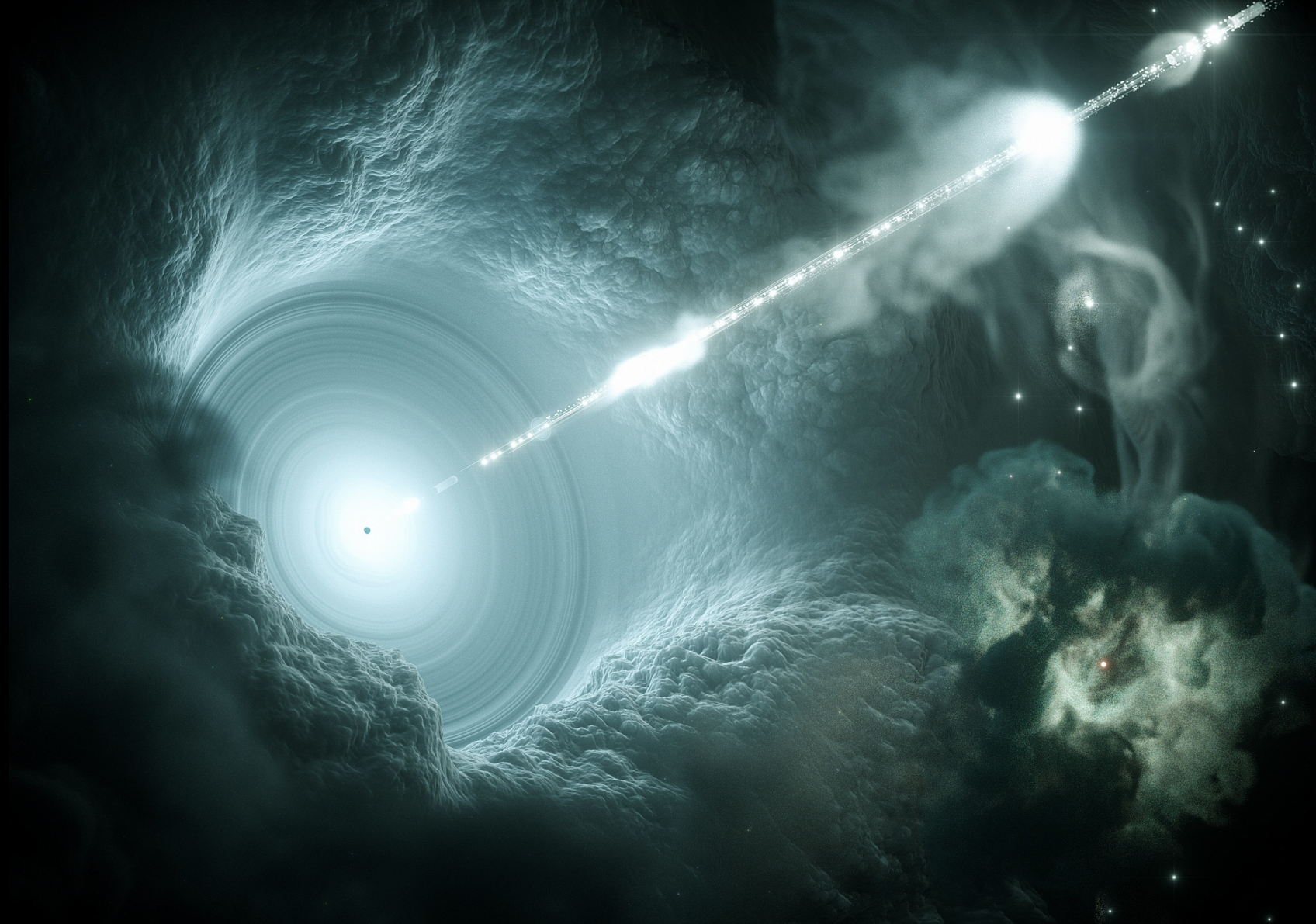


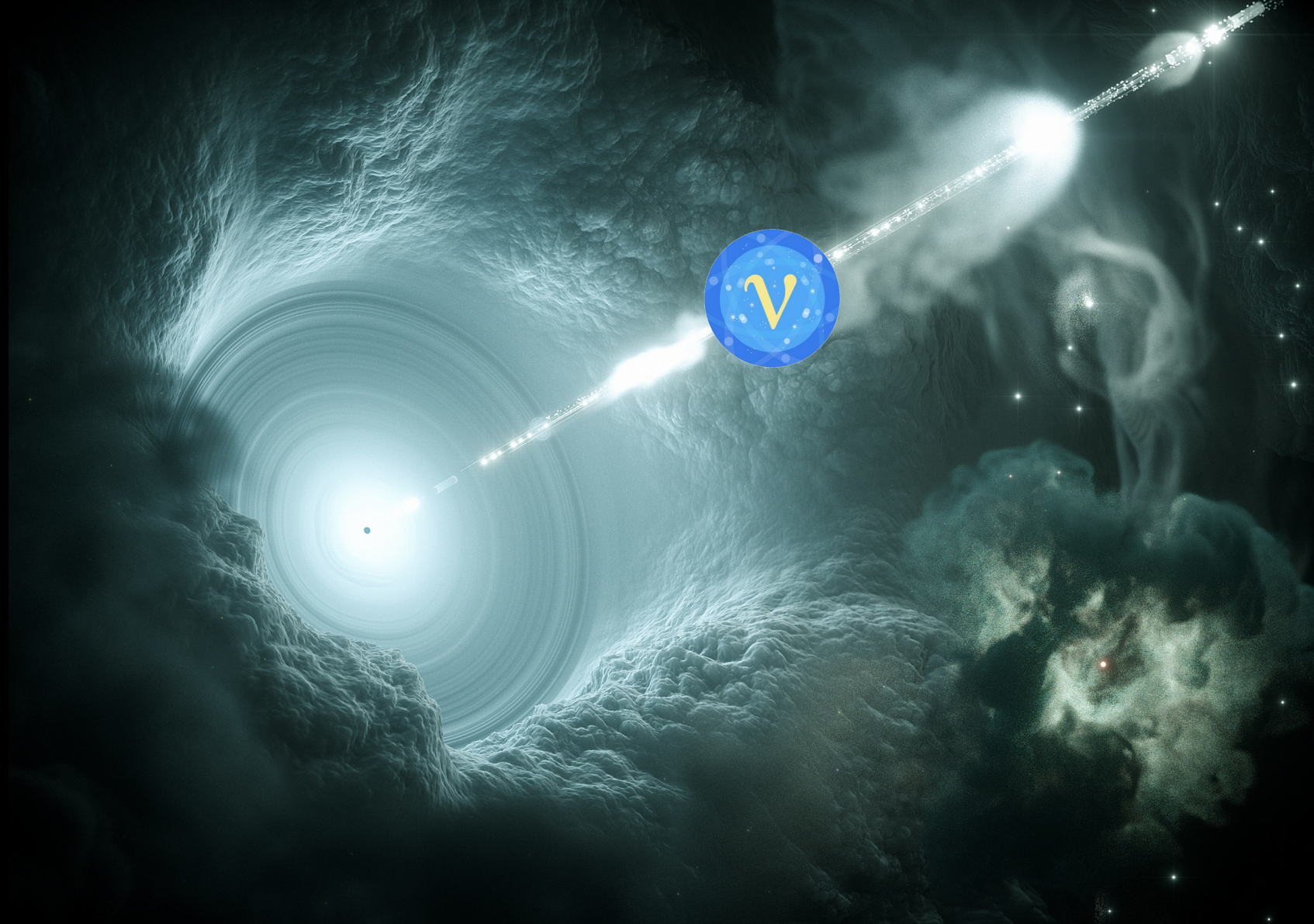
Today
TeV–PeV ν

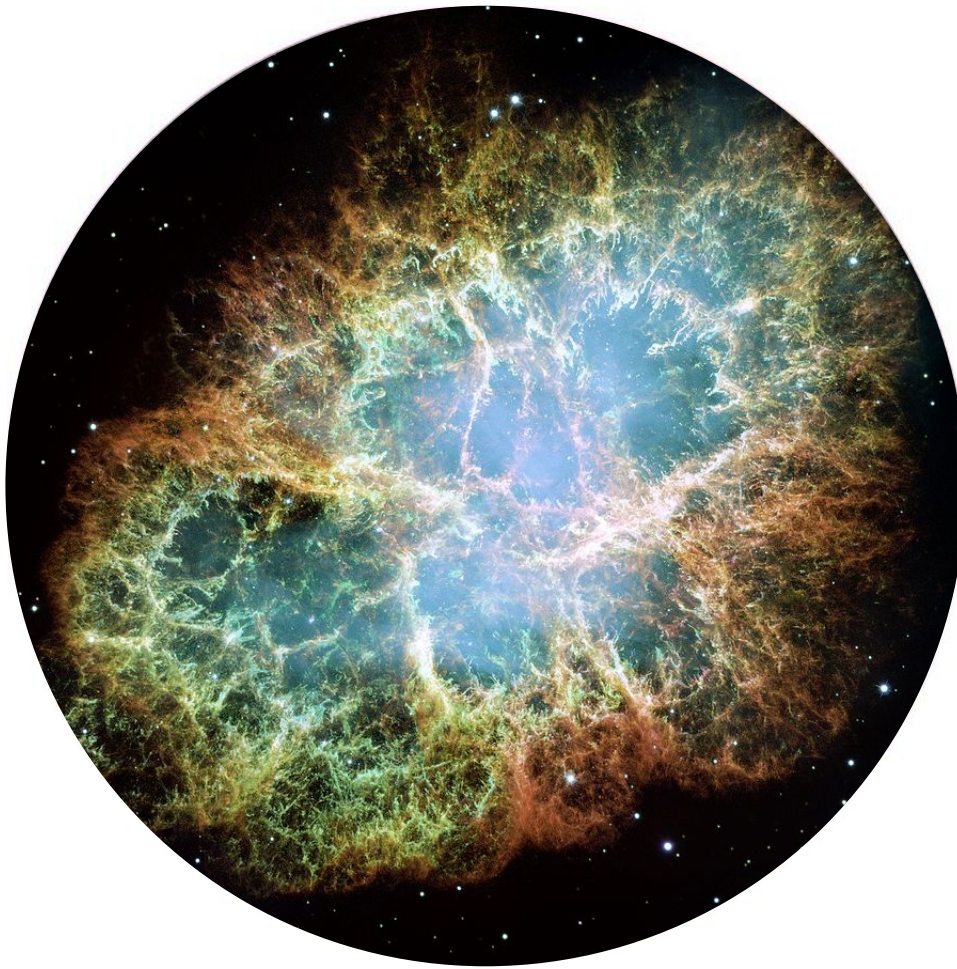
Next decade
> 100-PeV ν

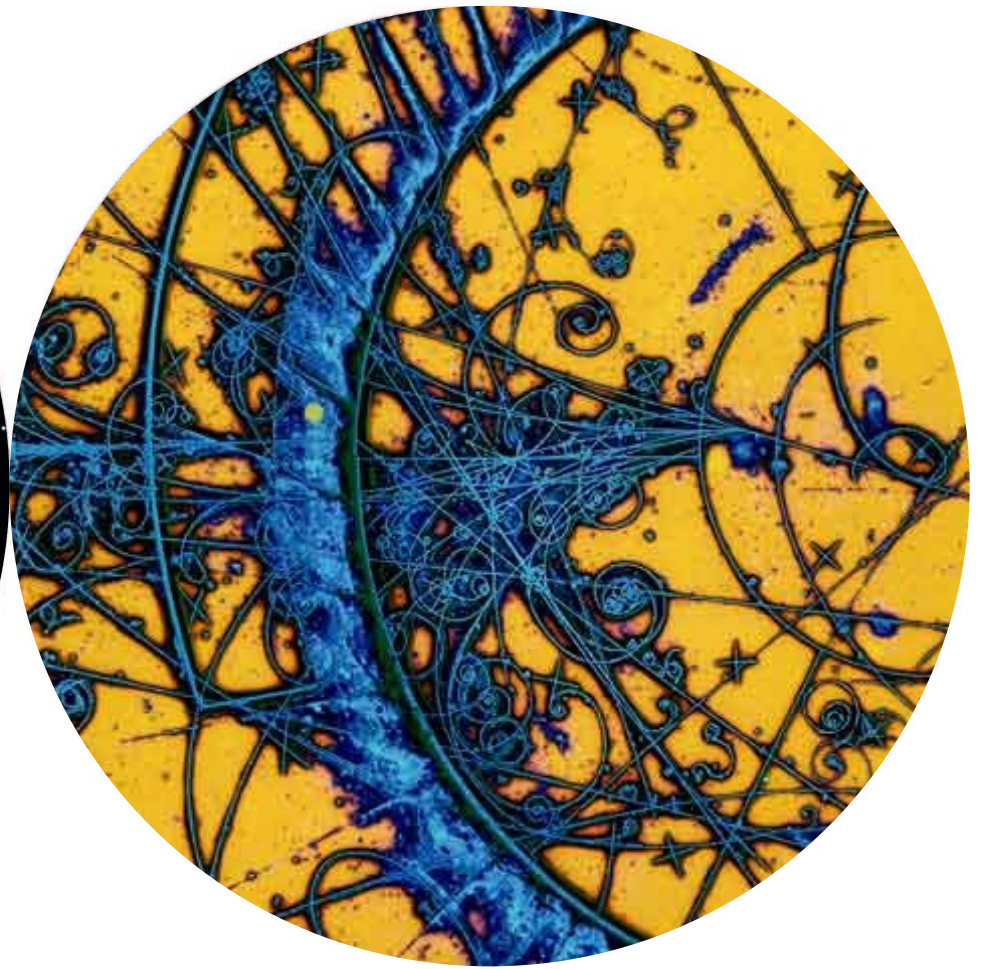
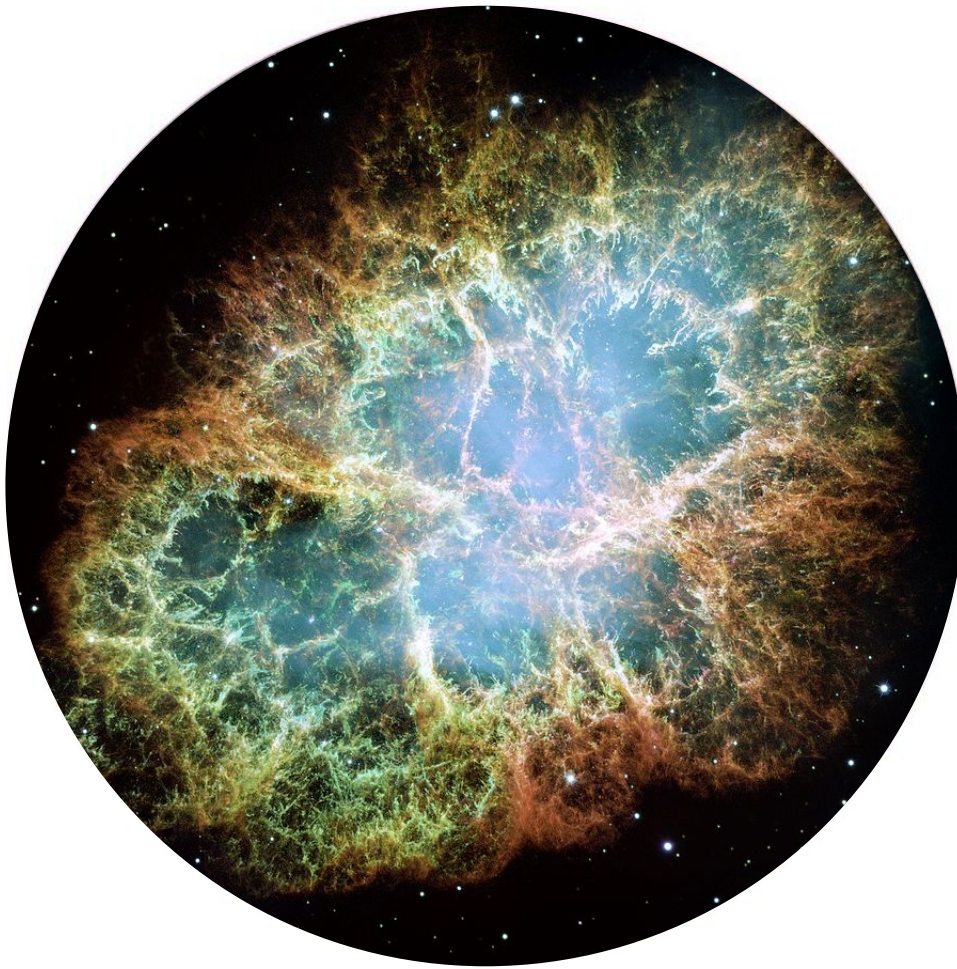




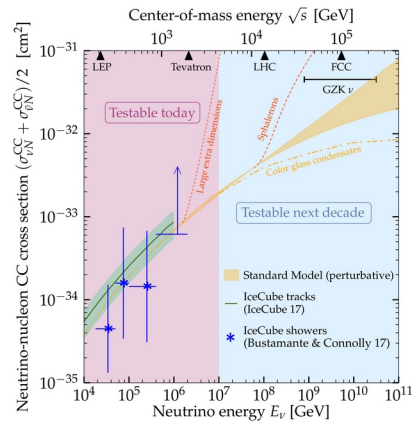






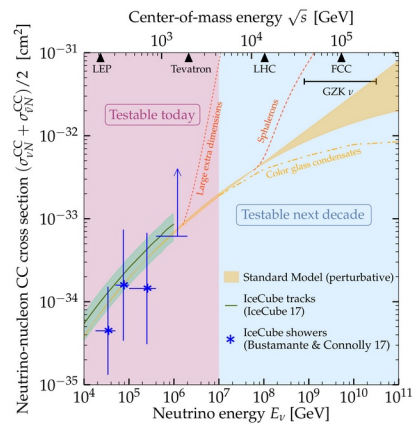


TeV–EeV ν cross sections



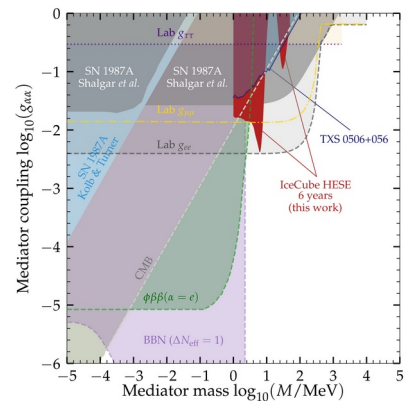
MB & Connolly, *PRL* 2019

TeV–EeV ν cross sections



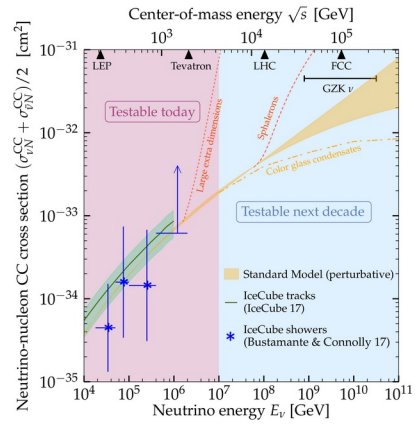
MB & Connolly, *PRL* 2019

ν self-interactions



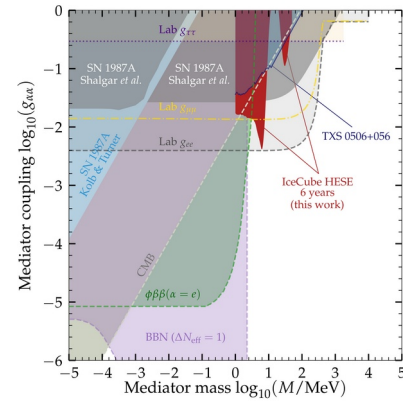
MB, Rosenström, Shalgar, Tamborra, *PRD* 2020

TeV–EeV ν cross sections



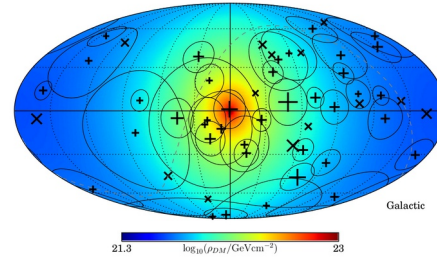
MB & Connolly, PRL 2019

ν self-interactions



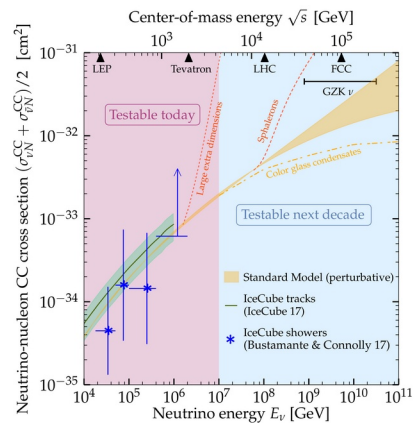
MB, Rosenström, Shalgar, Tamborra, PRD 2020

ν scattering on Galactic DM



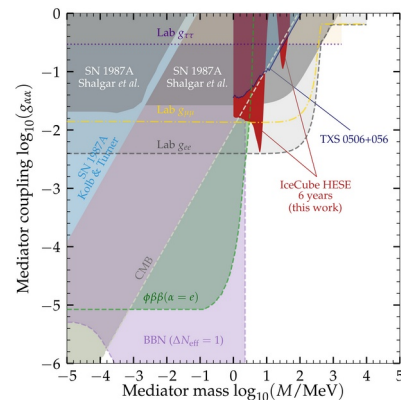
Argüelles, Kheirandish, Vincent, PRL 2017

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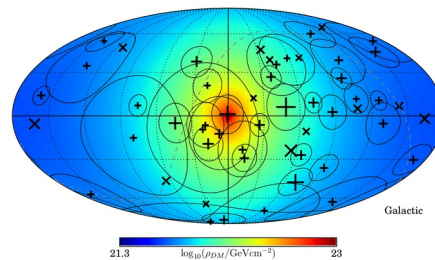
MB & Connolly, PRL 2019

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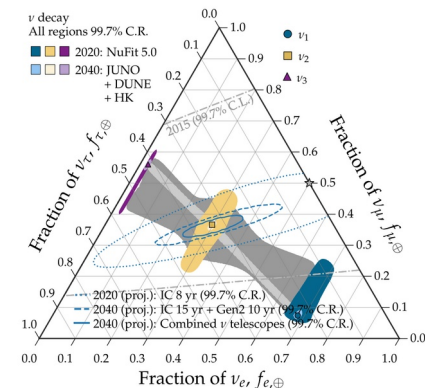
MB, Rosenström, Shalgar, Tamborra, PRD 2020

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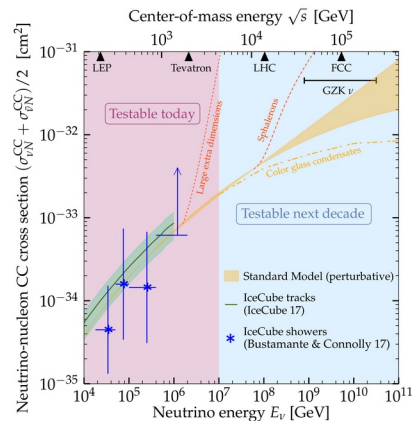
Argüelles, Kheirandish, Vincent, PRL 2017

ν decay



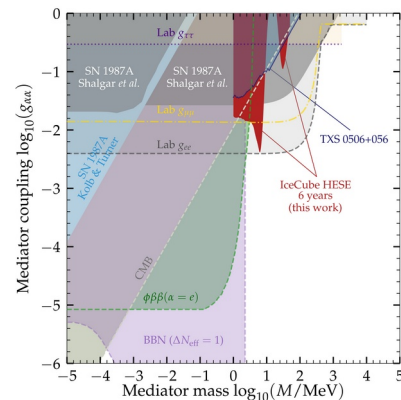
Song, Li, Argüelles, MB, Vincent, JCAP 2021

TeV–EeV ν cross sections



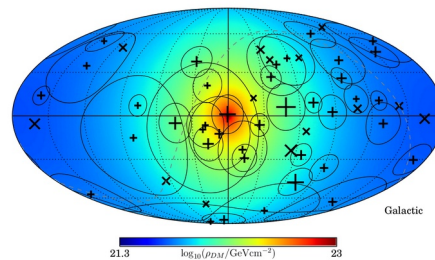
MB & Connolly, PRL 2019

ν self-interactions



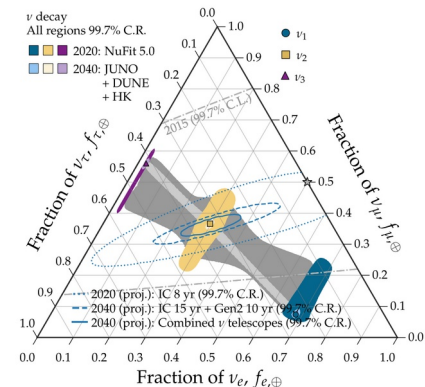
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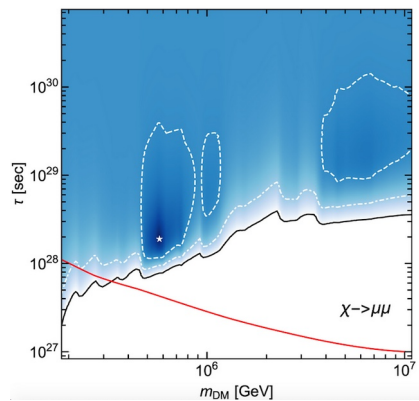
Argüelles, Kheirandish, Vincent, PRL 2017

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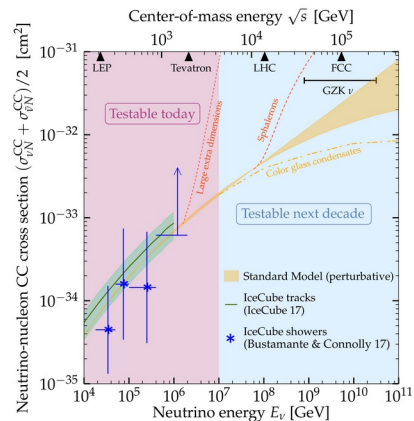
Song, Li, Argüelles, MB, Vincent, JCAP 2021

Dark matter decay



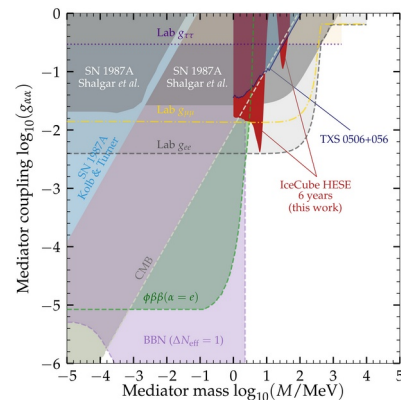
Chianese, Fiorillo, Miele, Morisi, Pisanti, JCAP 2019

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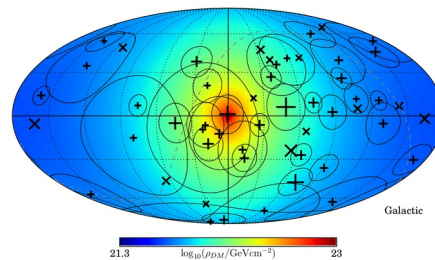
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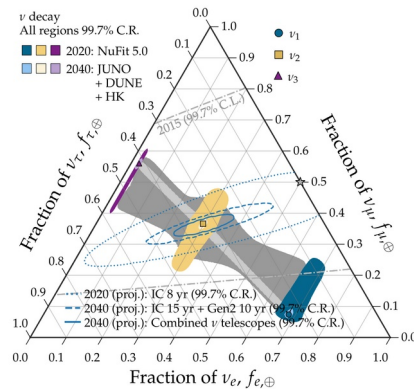
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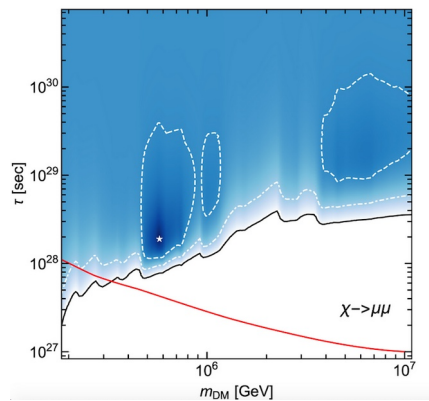
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ν decay



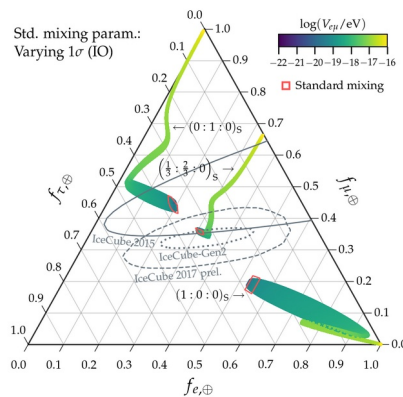
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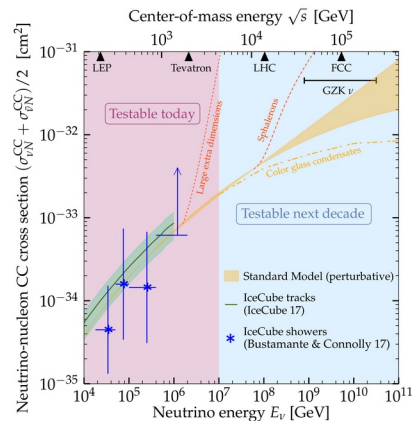
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ν -electron interaction



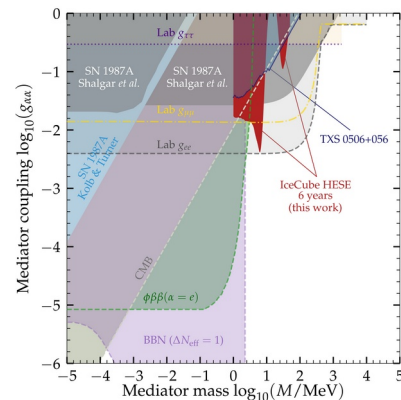
MB & Agarwalla, PRL 2019

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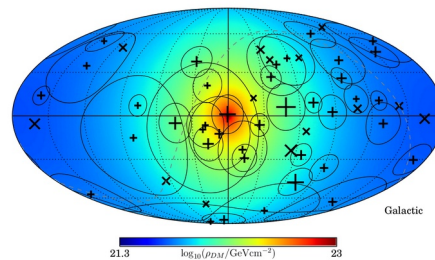
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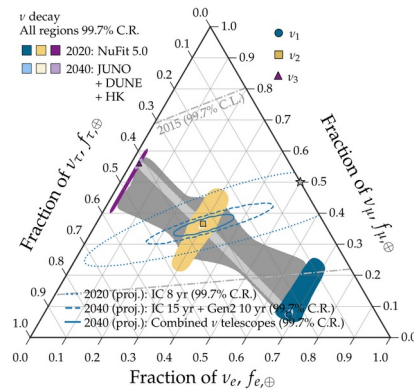
MB, Rosenström, Shalgar, Tamborra, PRD 2020

ν scattering on Galactic DM



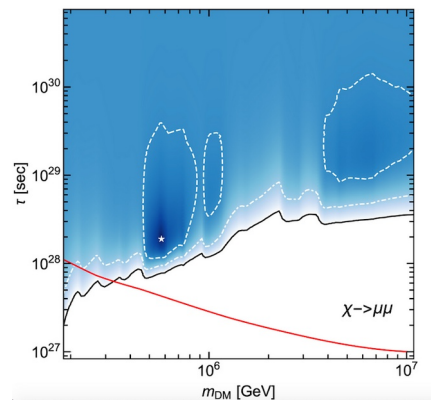
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ν decay



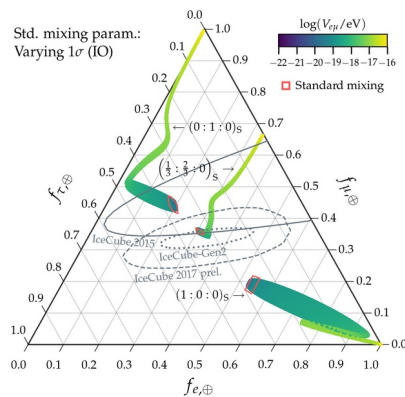
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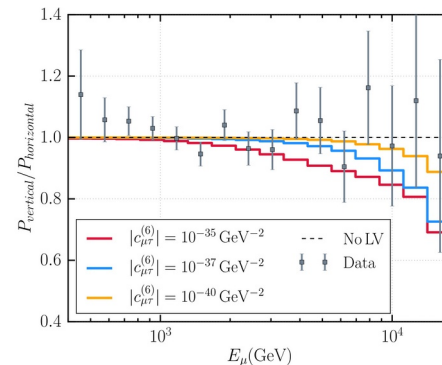
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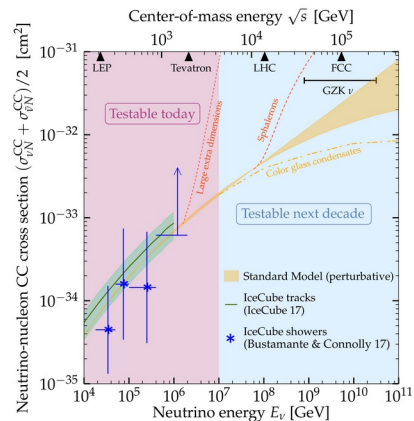
MB & Agarwalla, PRL 2019

Lorentz-invariance violation



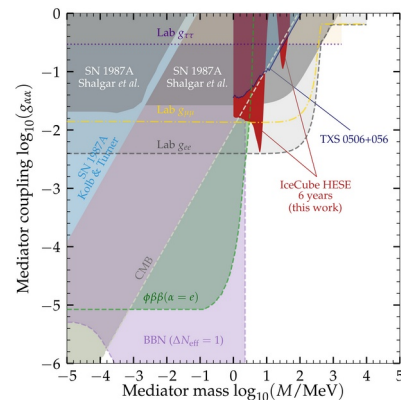
IceCube, Nature Phys. 2018

TeV–EeV ν cross sections



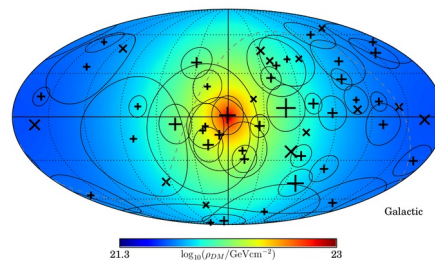
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ν self-interactions



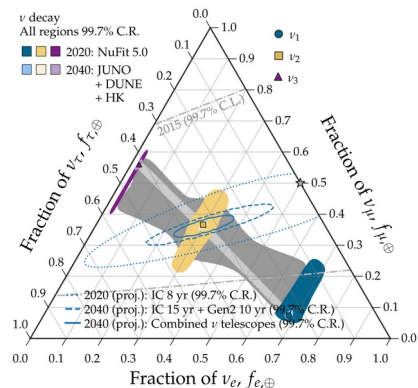
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ν scattering on Galactic DM



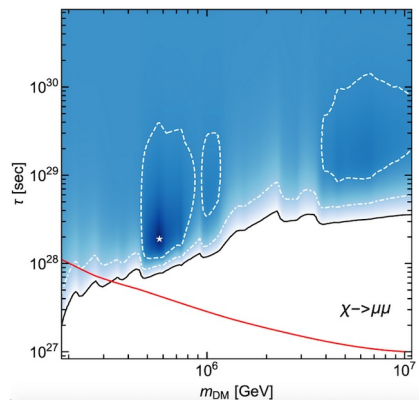
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ν decay



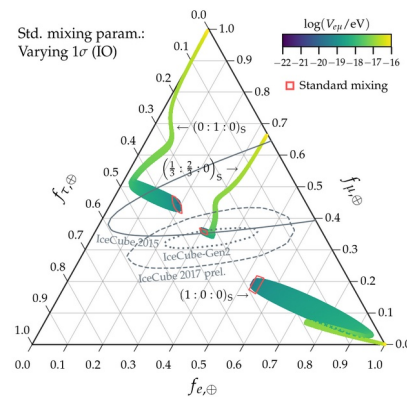
Song, Li, Argüelles, MB, Vincent, JCAP 2021

Dark matter decay



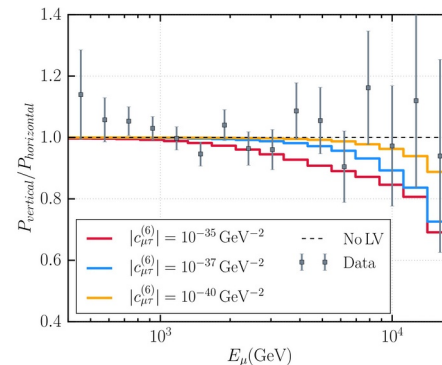
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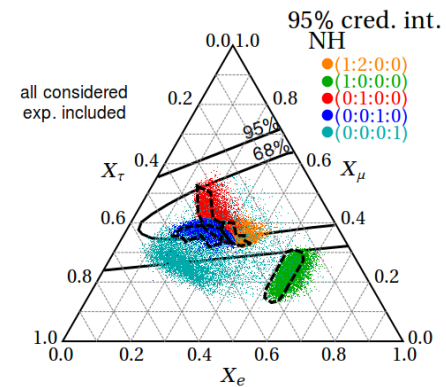
MB & Agarwalla, PRL 2019

Lorentz-invariance violation



IceCube, Nature Phys. 2018

Sterile neutrinos



Brdar, Kopp, Wang, JCAP 2017

Fundamental physics with high-energy cosmic neutrinos

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

Fundamental physics with high-energy cosmic neutrinos

- ▶ Numerous new ν physics effects grow as $\sim \kappa_n \cdot E^n \cdot L$ $\left. \vphantom{\begin{matrix} \kappa_n \\ E^n \\ L \end{matrix}} \right\} \begin{array}{l} \text{E.g.,} \\ n = -1: \text{neutrino decay} \\ n = 0: \text{CPT-odd Lorentz violation} \\ n = +1: \text{CPT-even Lorentz violation} \end{array}$
- ▶ So we can probe $\kappa_n \sim 4 \cdot 10^{-47} (E/\text{PeV})^{-n} (L/\text{Gpc})^{-1} \text{PeV}^{1-n}$
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High-energy cosmic neutrinos:

Basics and current status

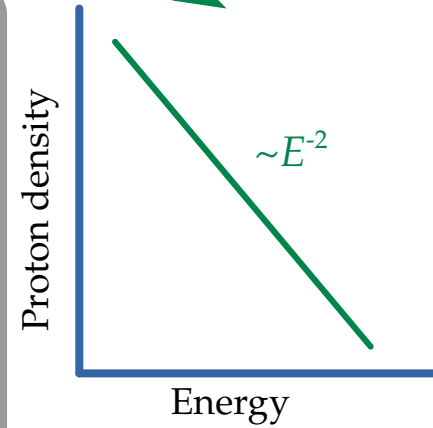
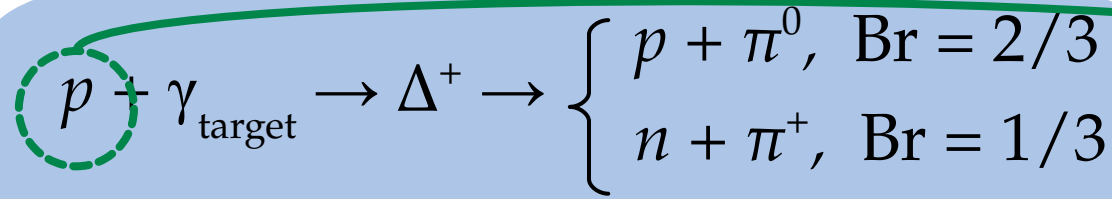
Making high-energy astrophysical neutrinos: a toy model

(or $p + p$)

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

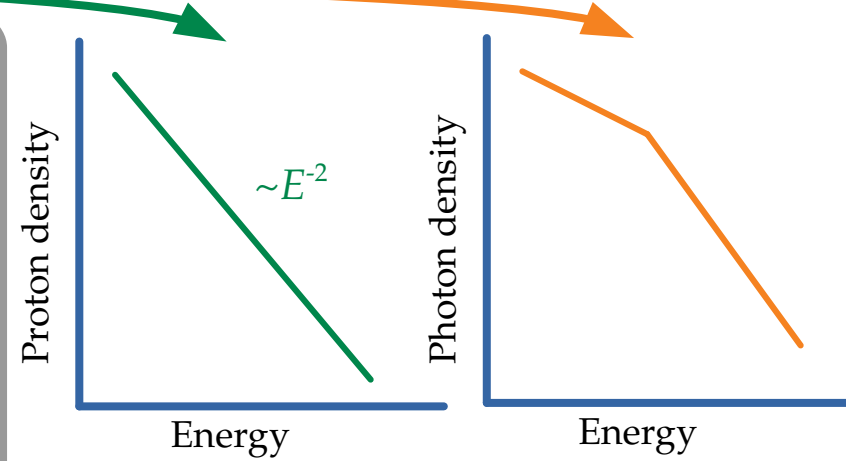
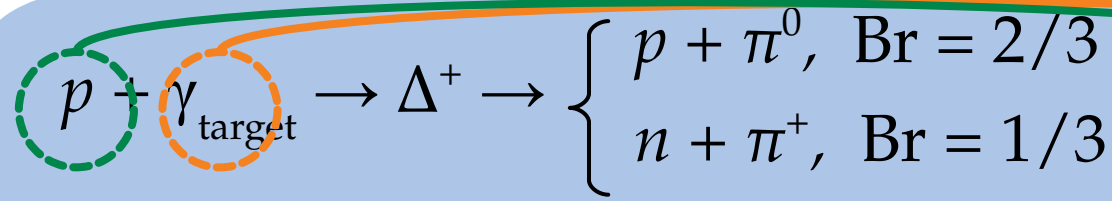
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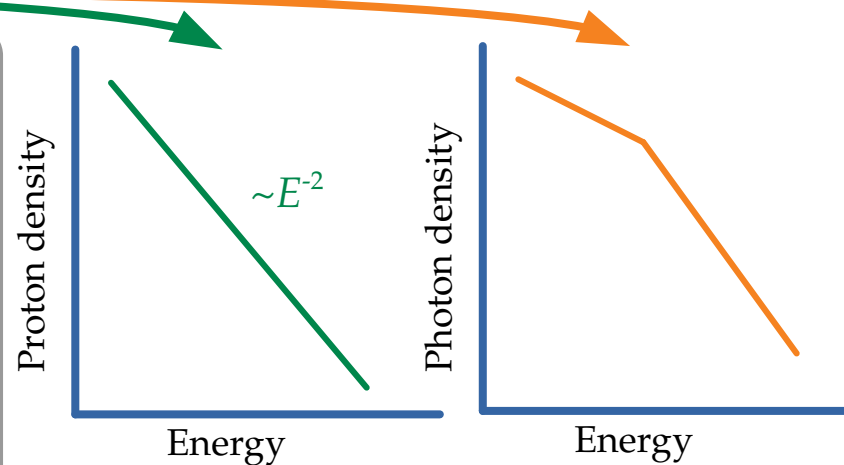
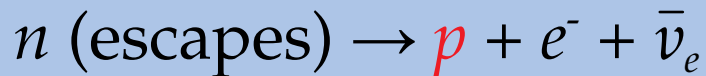
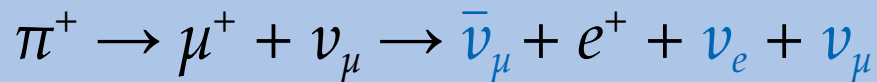
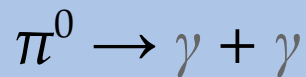
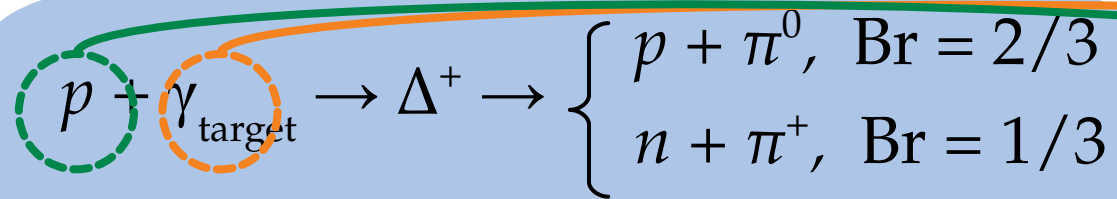
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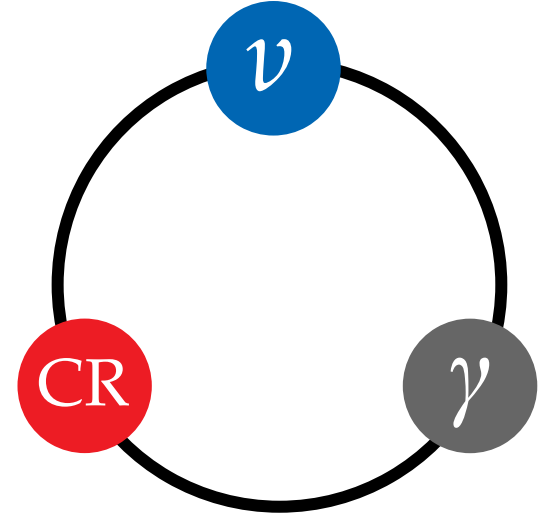
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$$\pi^0 \rightarrow \gamma + \gamma$$

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

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



Neutrino energy = Proton energy / 20

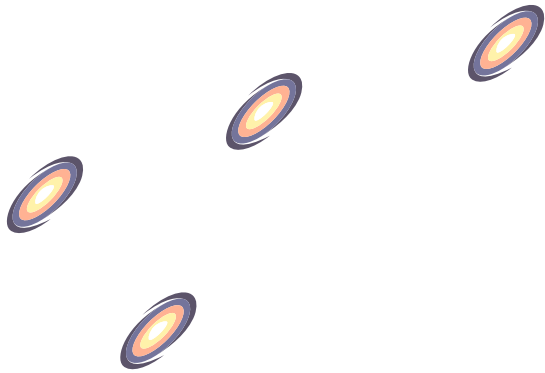
Gamma-ray energy = Proton energy / 10

Redshift



$z = 0$

Note: v sources can be steady-state or transient



Redshift

$z = 0$

Discovered

MeV γ

PeV p

TeV–PeV ν

“High-energy”

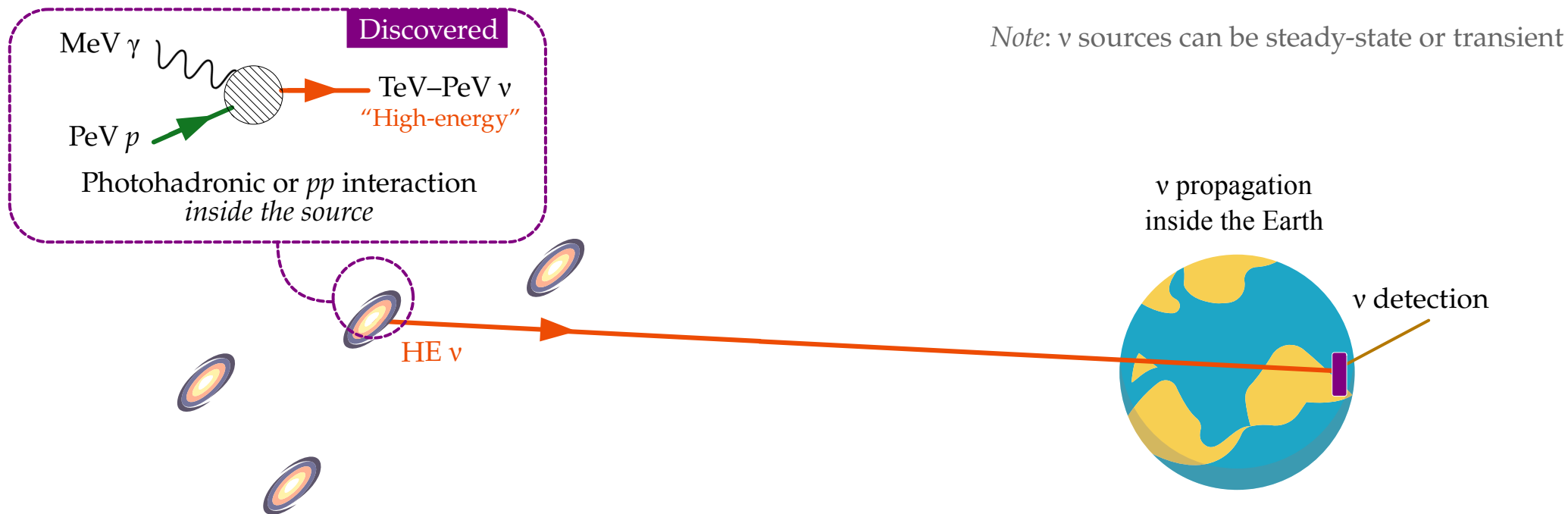
Photohadronic or pp interaction
inside the source

Note: ν sources can be steady-state or transient

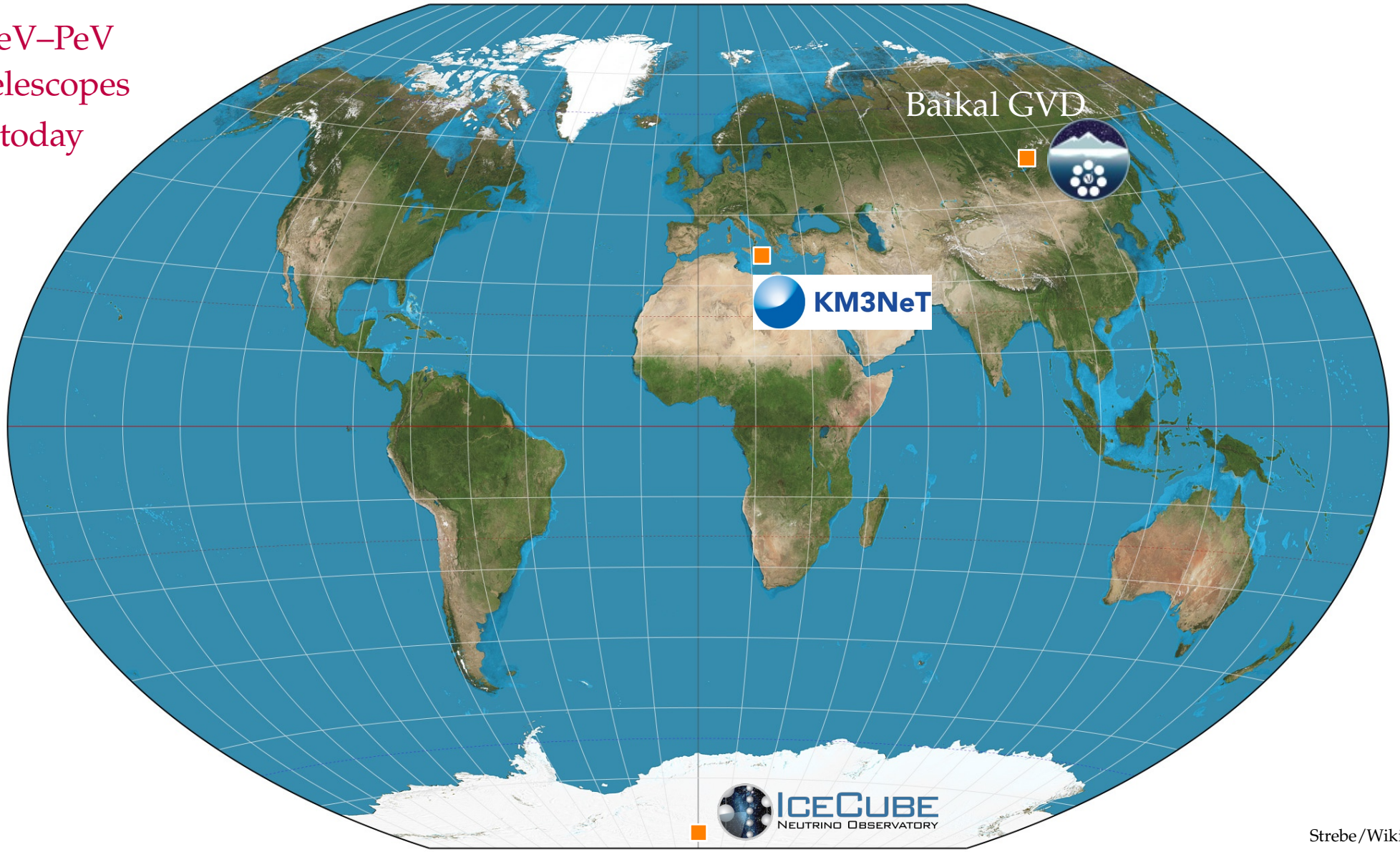
ν propagation
inside the Earth

ν detection

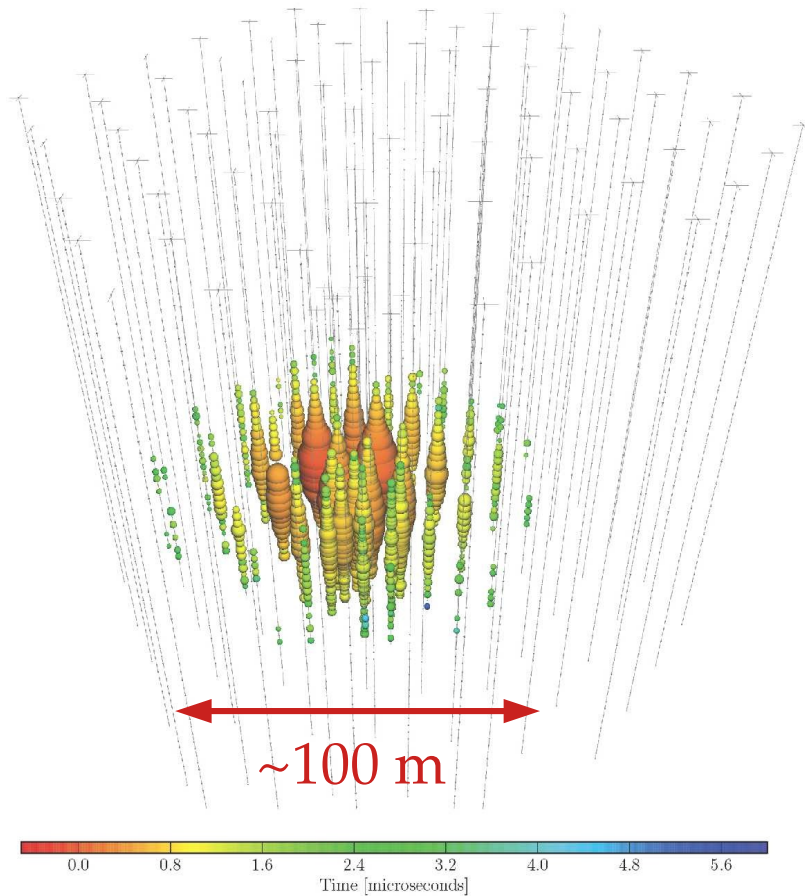
HE ν



TeV–PeV
 ν telescopes
today

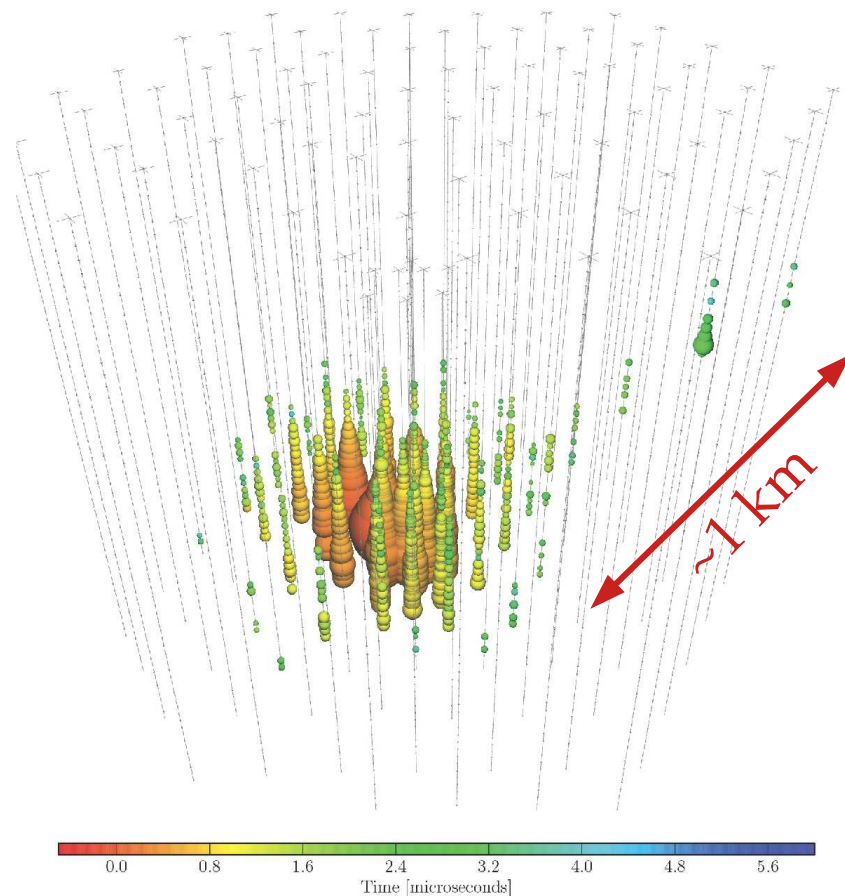


Shower (mainly from ν_e and ν_τ)

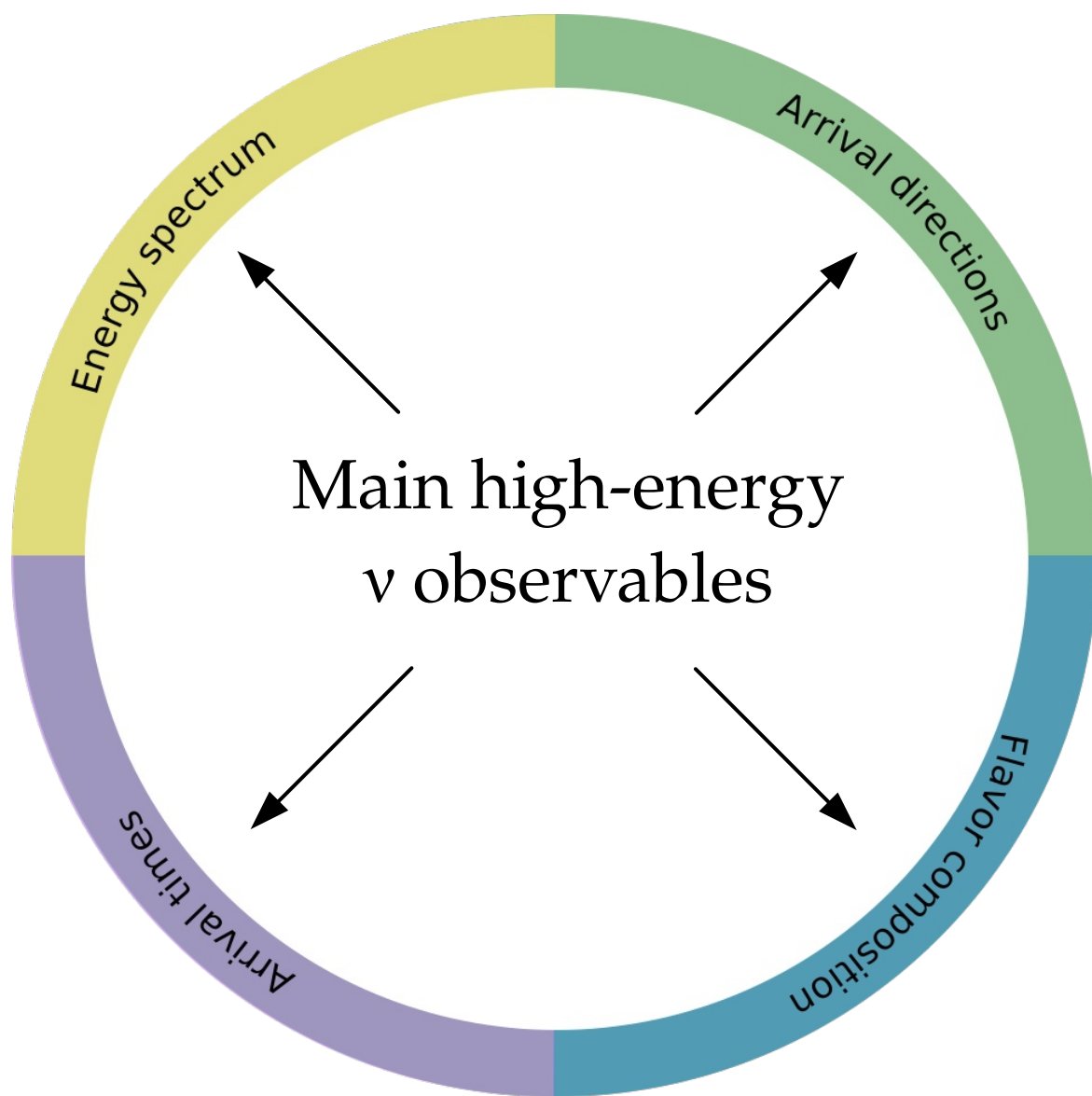


Poor angular resolution: $\sim 10^\circ$

Track (mainly from ν_μ)



Angular resolution: $< 1^\circ$

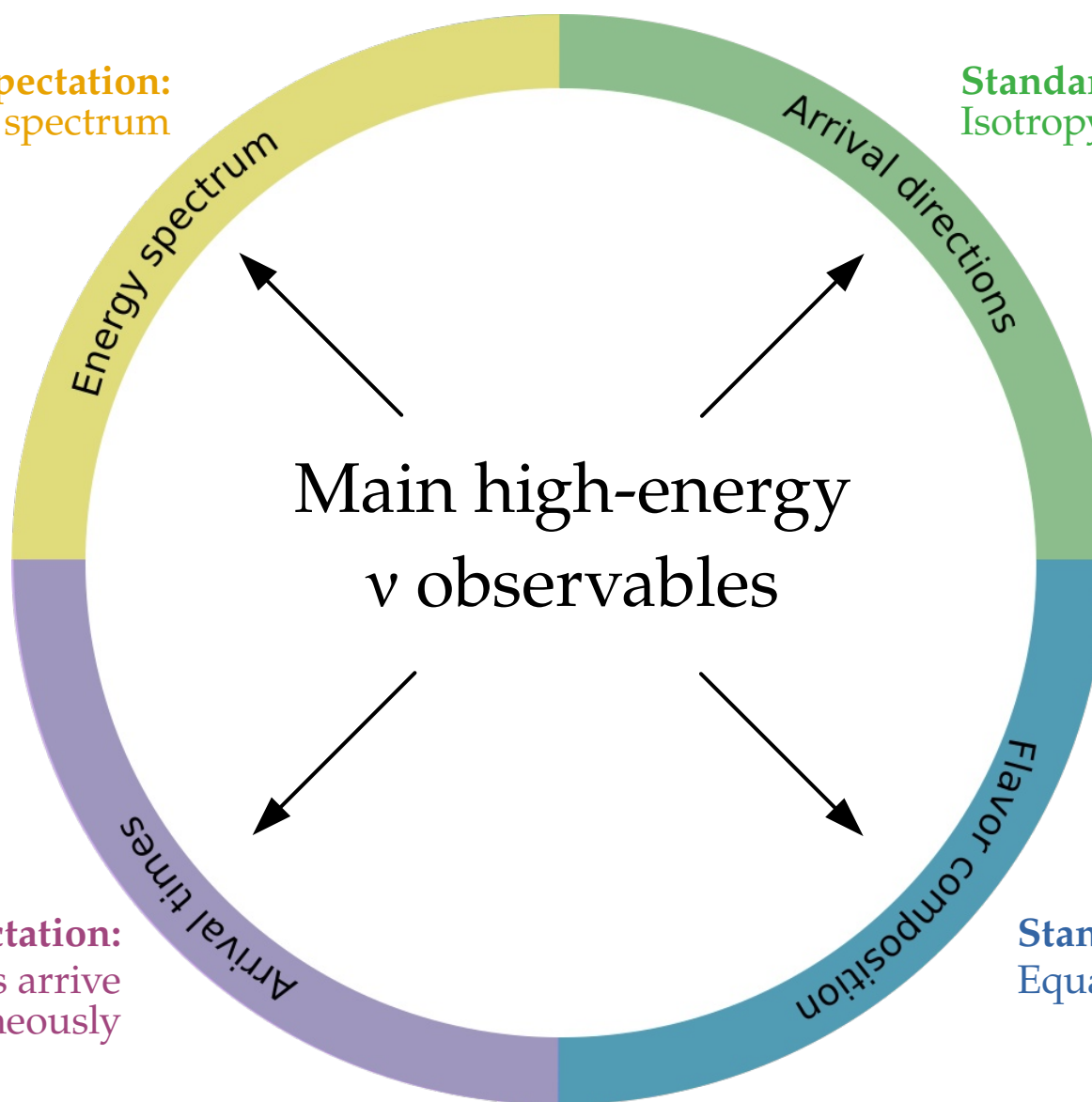


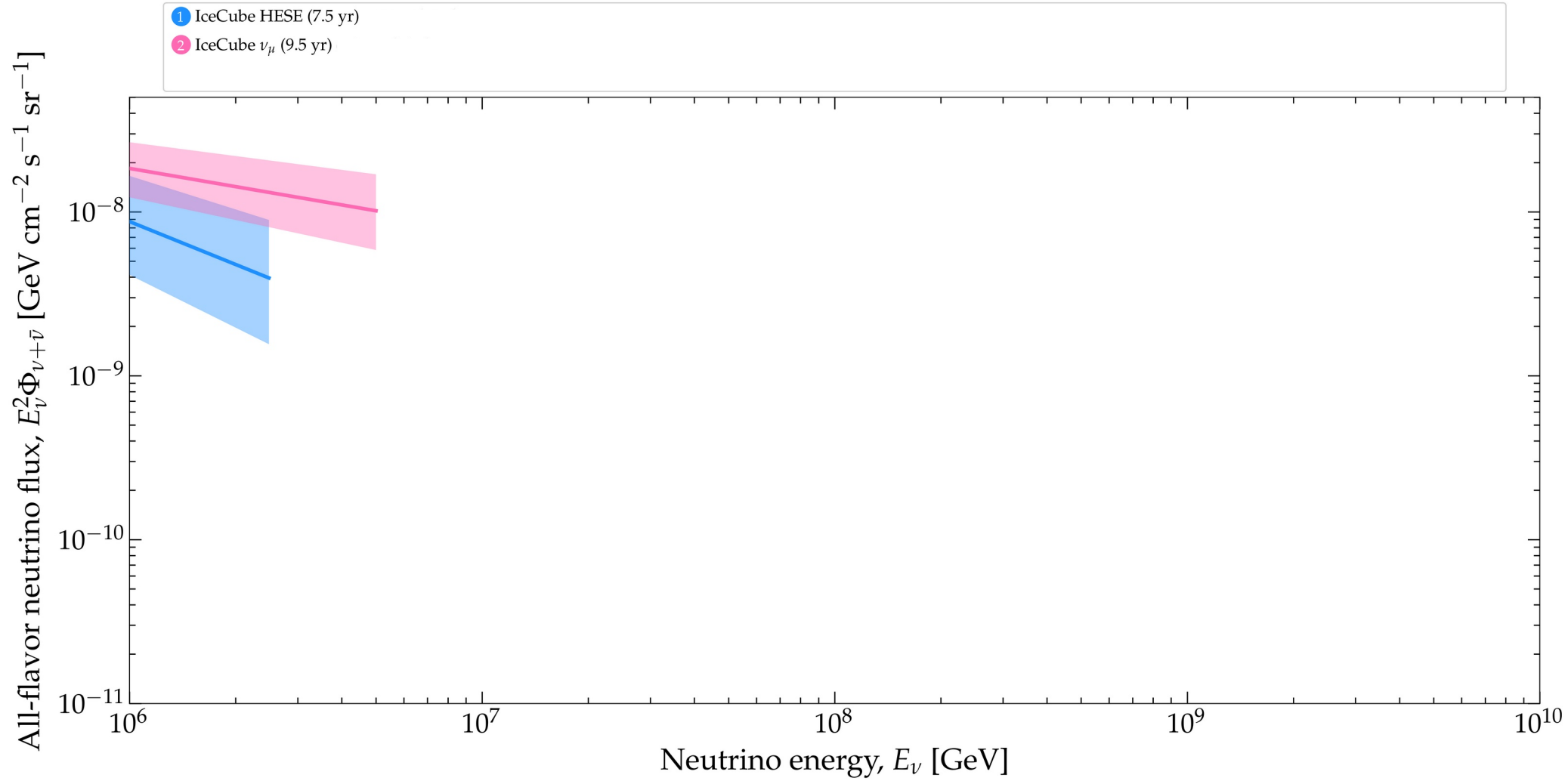
Standard expectation:
Power-law energy spectrum

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





Today
TeV–PeV ν

Today
TeV–PeV ν

Turn predictions
into data-driven tests

Today

TeV–PeV ν

Turn predictions
into data-driven tests

Key developments:

Bigger detectors $\rightarrow$ larger statistics

Better reconstruction

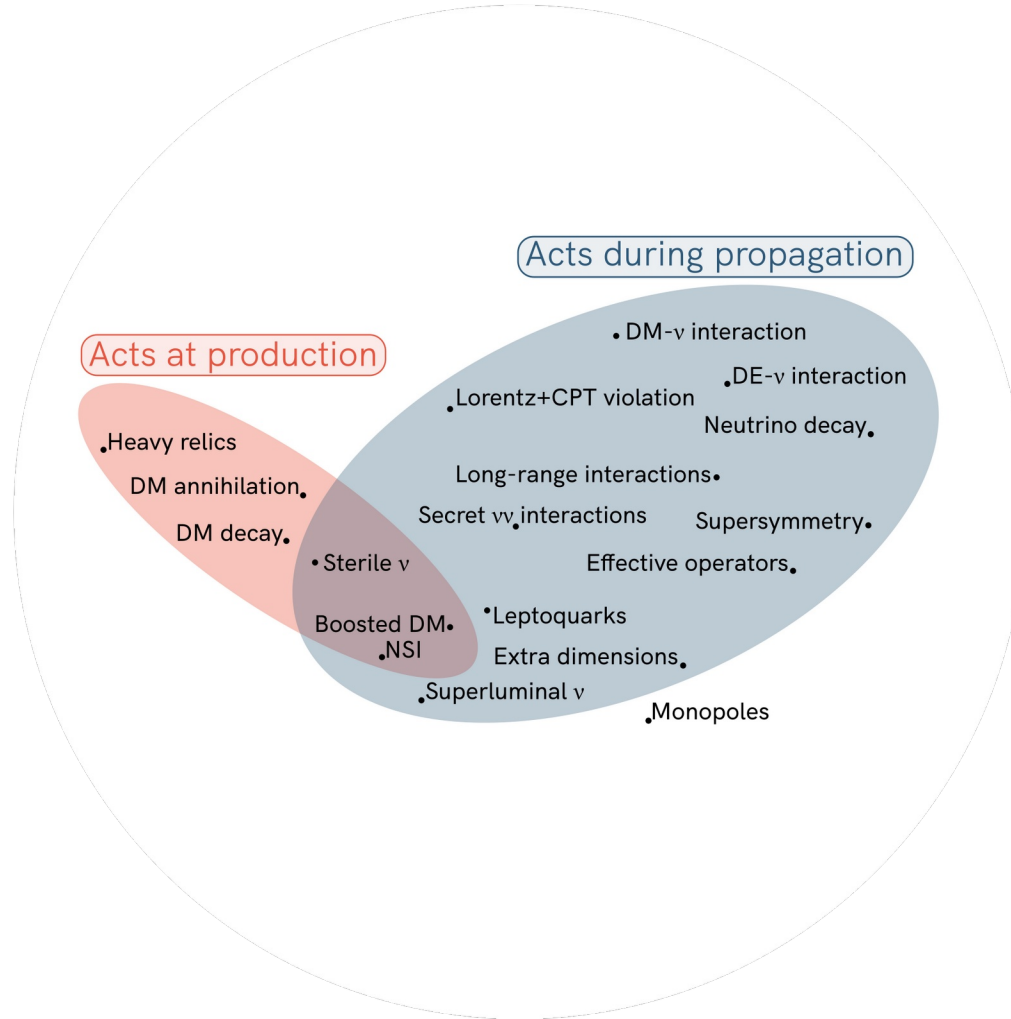
Smaller astrophysical uncertainties



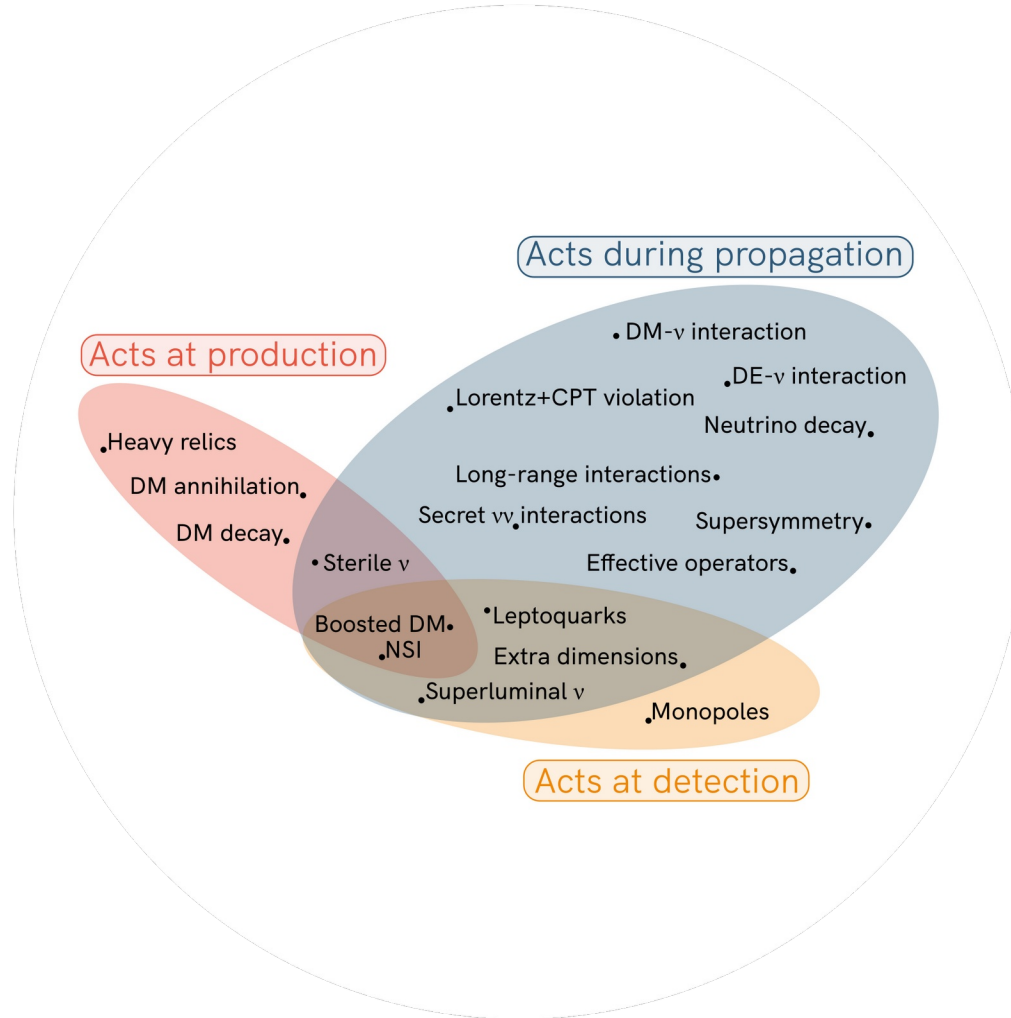
Note: Not an exhaustive list



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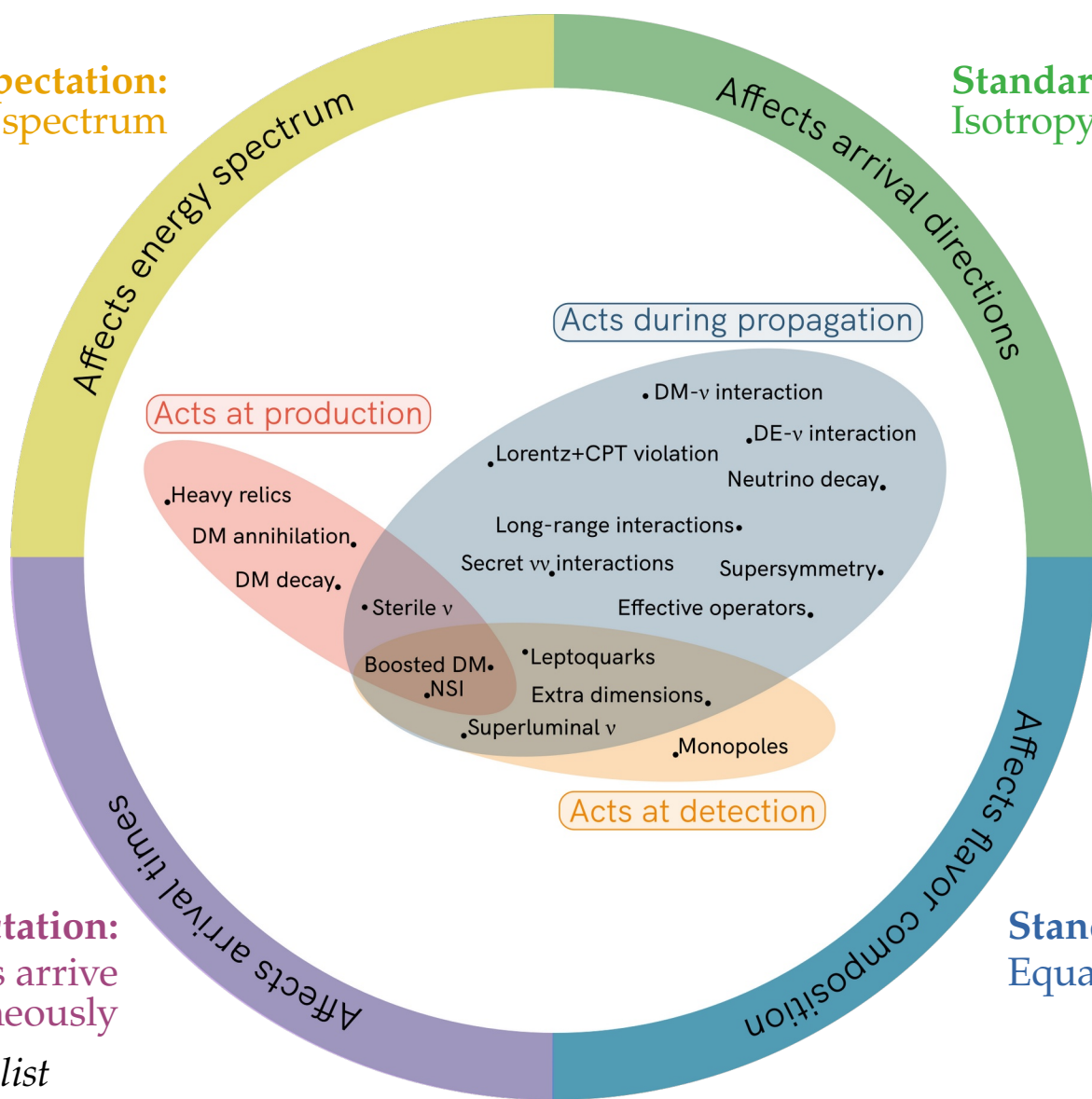
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Standard expectation:
Equal number of ν_e , ν_μ , ν_τ

Note: Not an exhaustive list



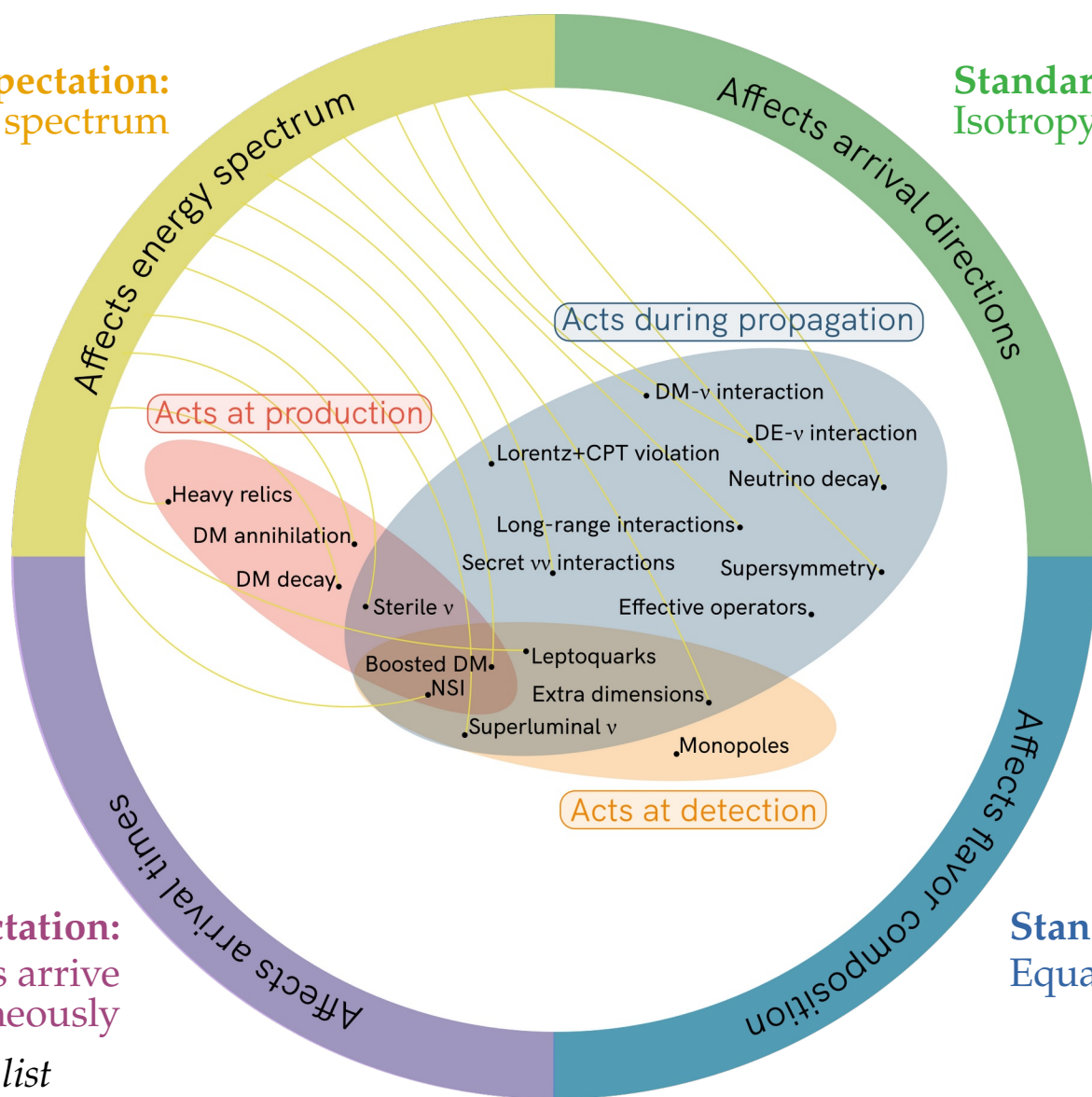
Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)

Standard expectation:
 ν and γ from transients arrive
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Equal number of ν_e, ν_μ, ν_τ

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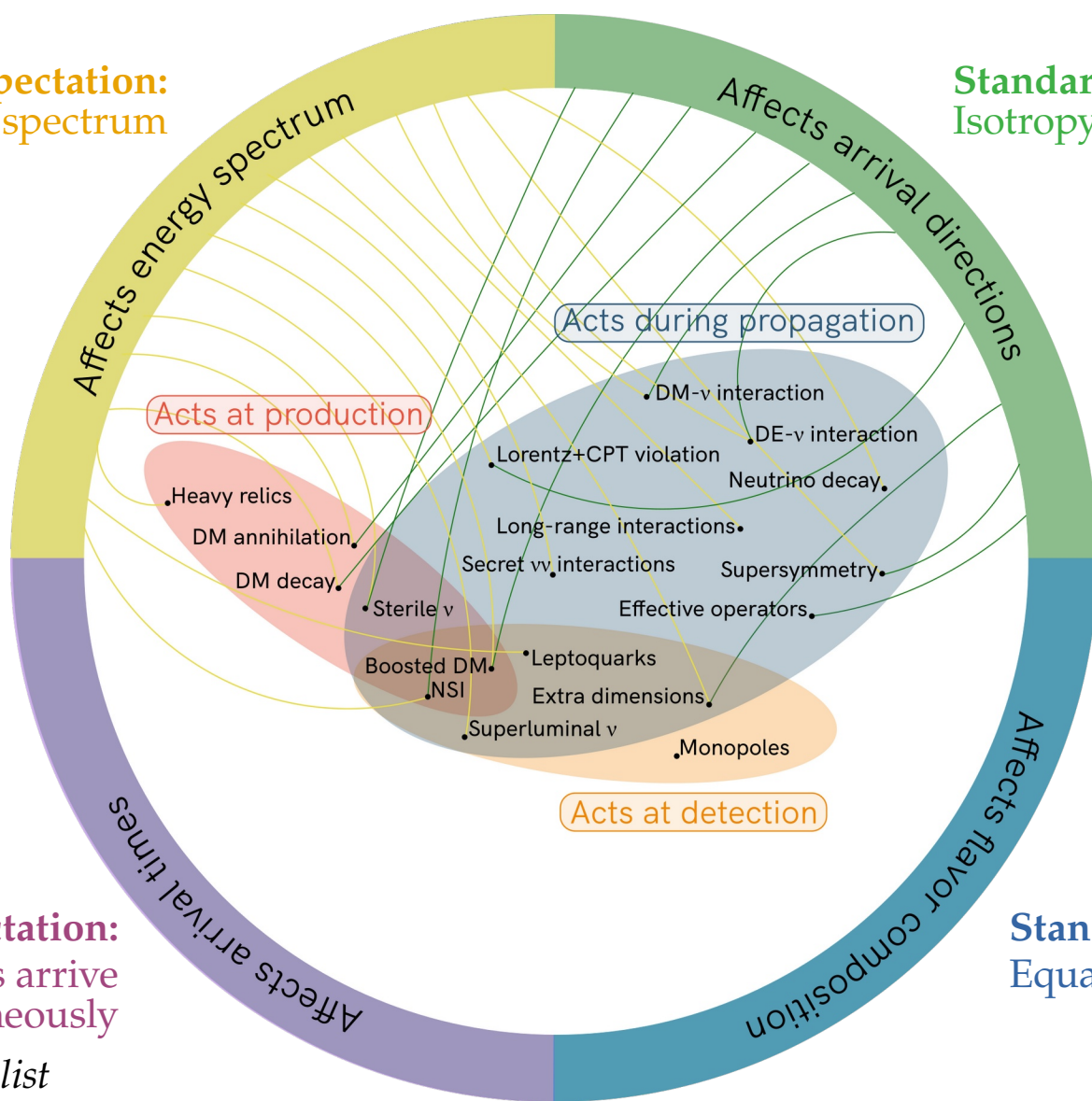
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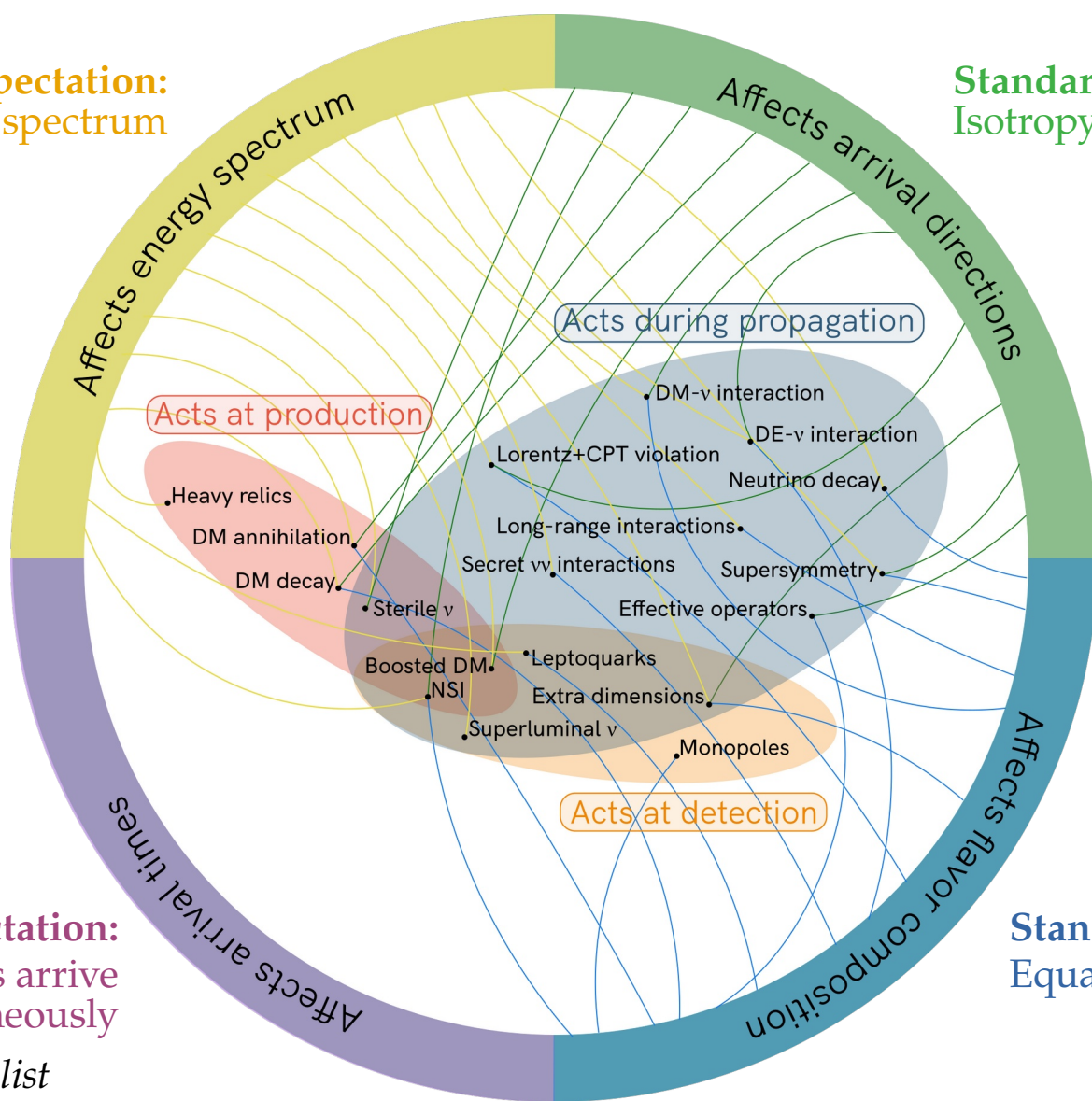
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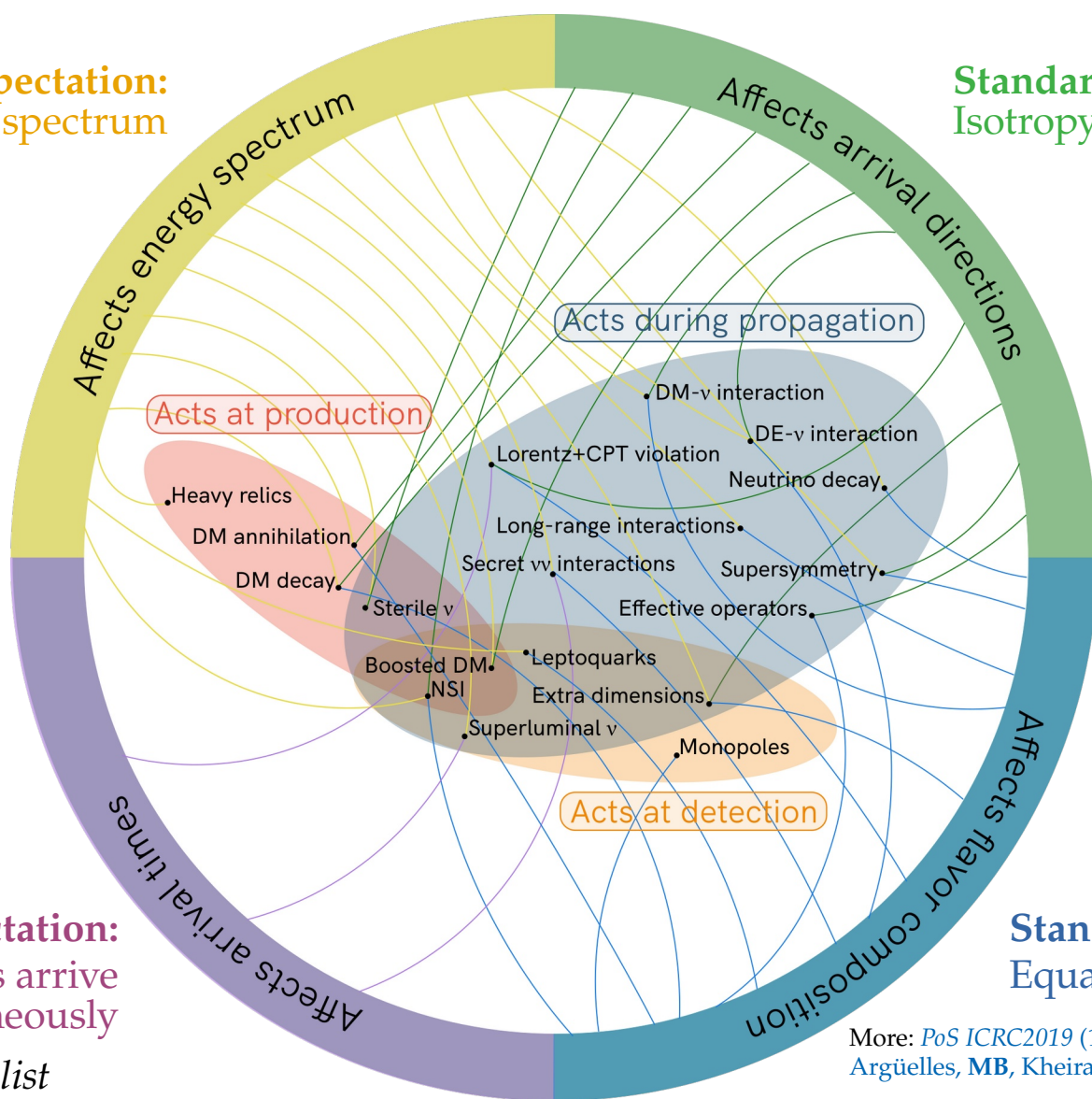
Standard expectation:
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More: *PoS ICRC2019* (1907.08690)

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

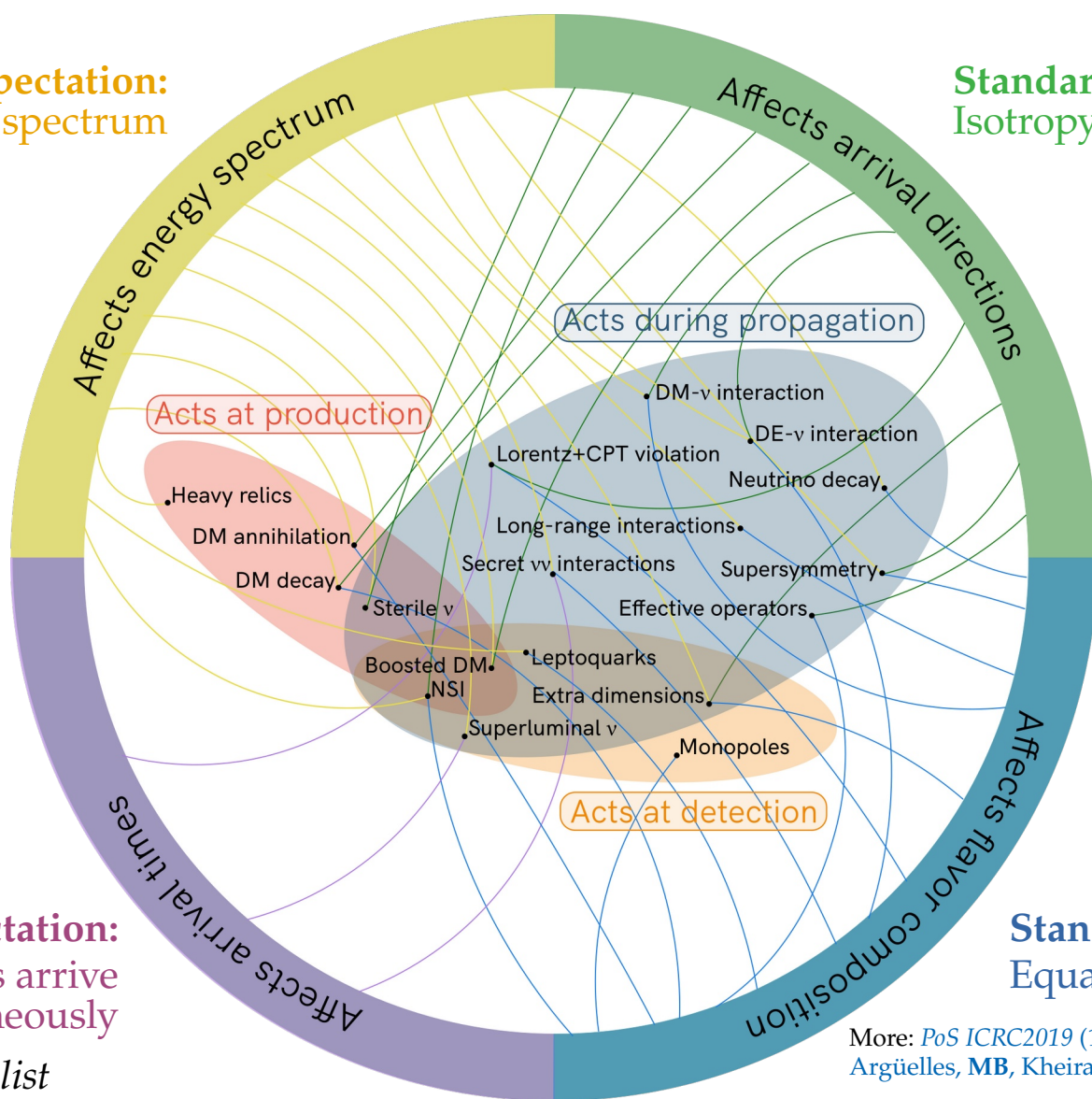
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Reviews:
Ahlers, Helbing, De los Heros, *EPJC* 2018
Argüelles, MB, Kheirandish, Palomares-Ruiz, Salvadó, Vincent, *ICRC* 2019 [1907.08690]
Ackermann, Ahlers, Anchordoqui, MB, et al., *Astro2020 Decadal Survey* [1903.04333]

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

Three examples

- 1 Glashow resonance
- 2 Neutrino-matter cross section
- 3 New physics via flavor

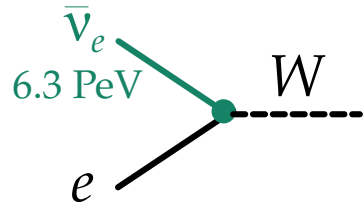
1. Glashow resonance:
Long-sought, finally seen

First observation of a Glashow resonance

Predicted in 1960:

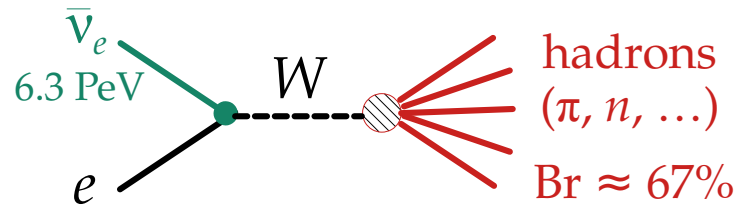
First observation of a Glashow resonance

Predicted in 1960:



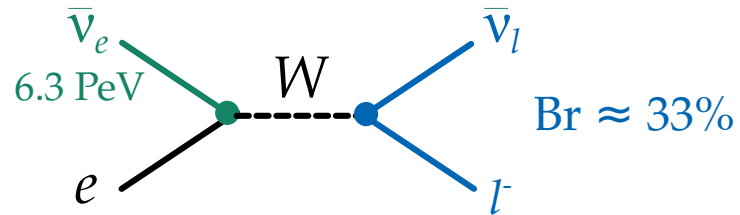
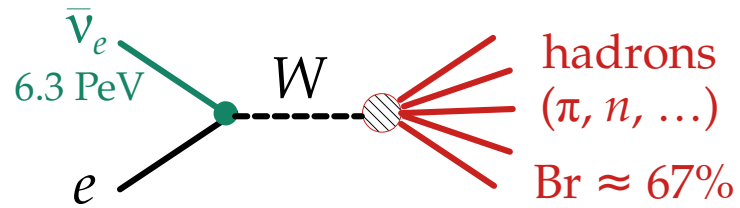
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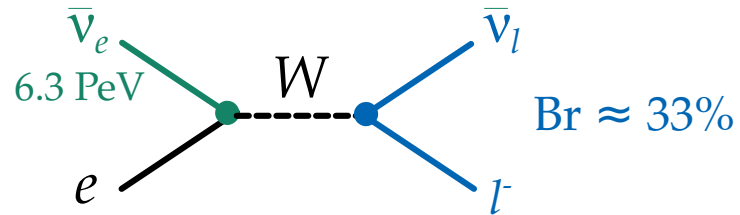
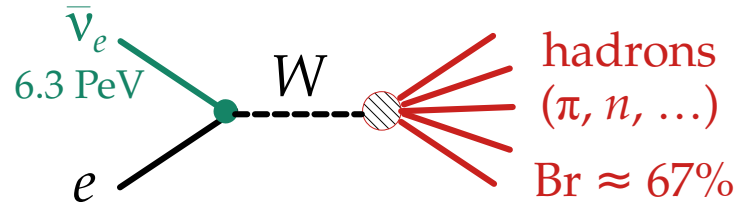
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Predicted in 1960:

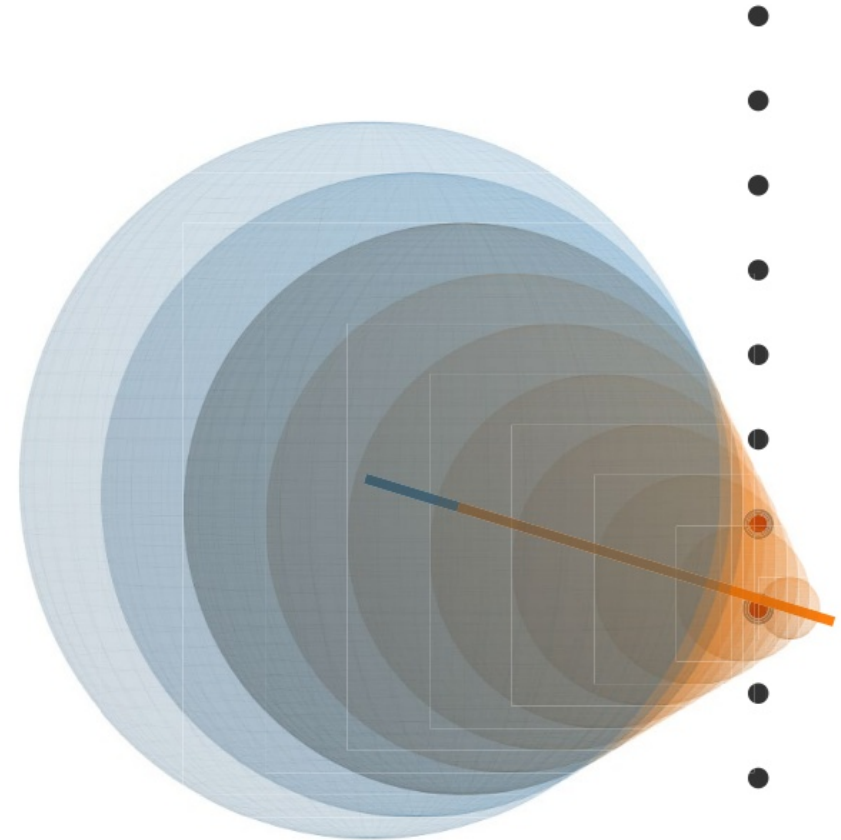


First observation of a Glashow resonance

Predicted in 1960:

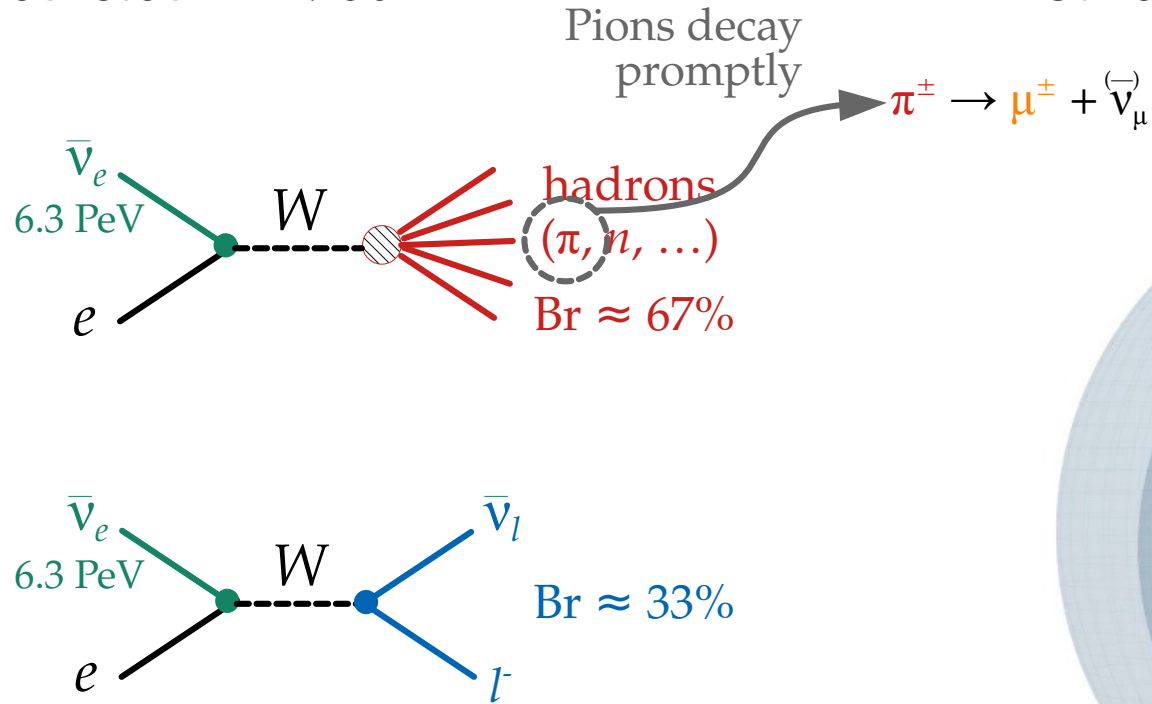


First reported by IceCube in 2021:

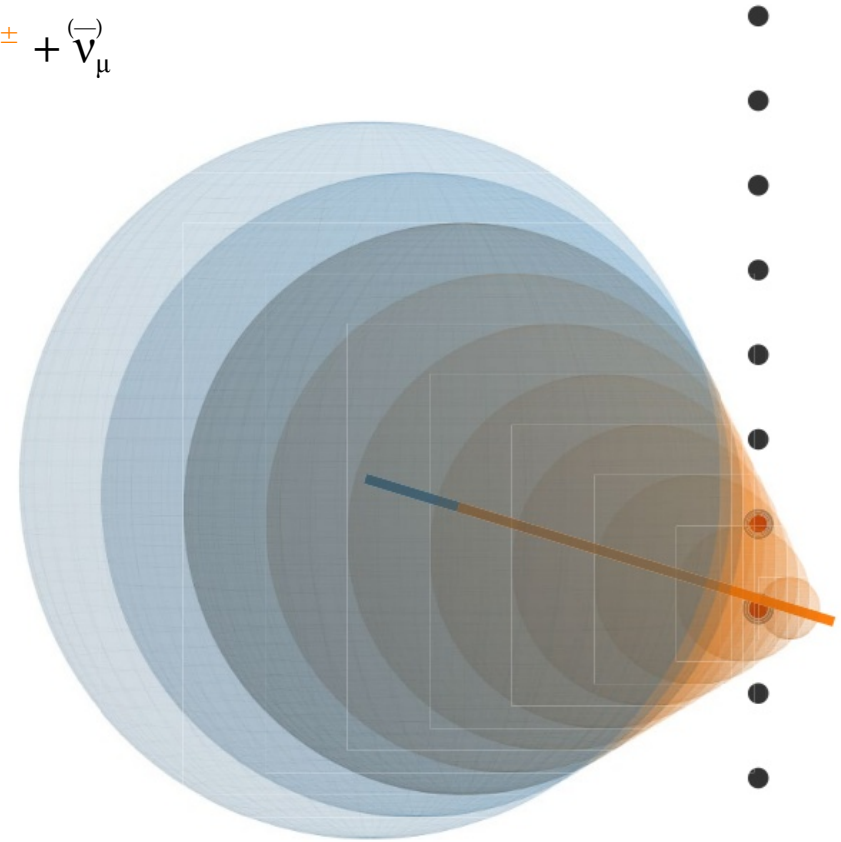


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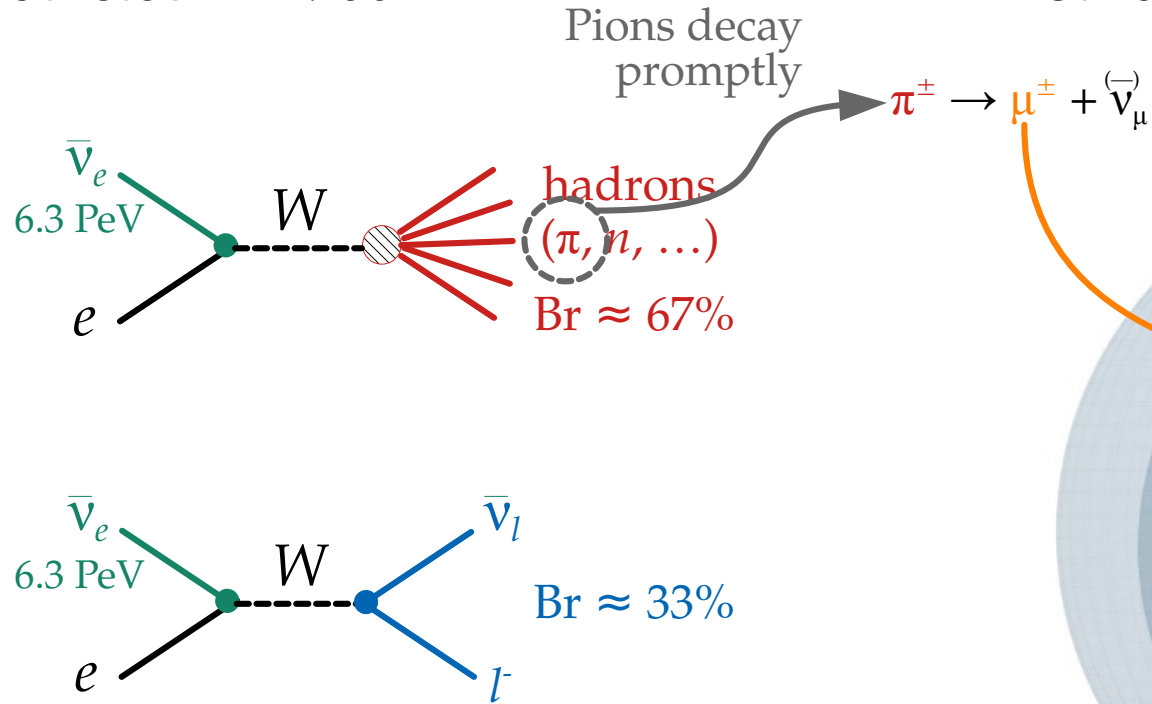


First reported by IceCube in 2021:

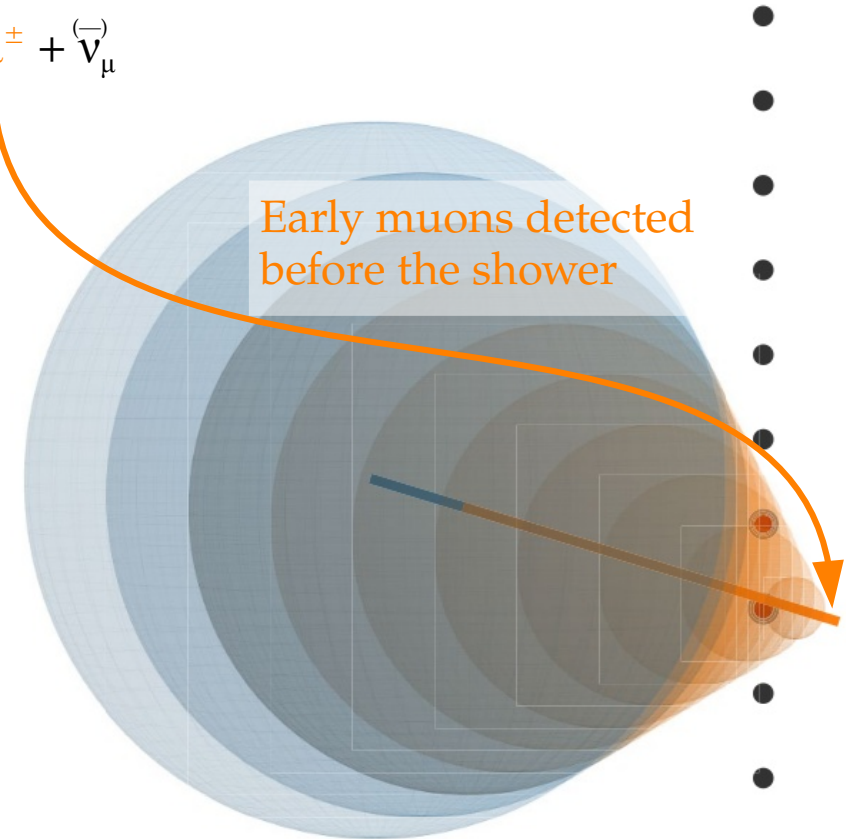


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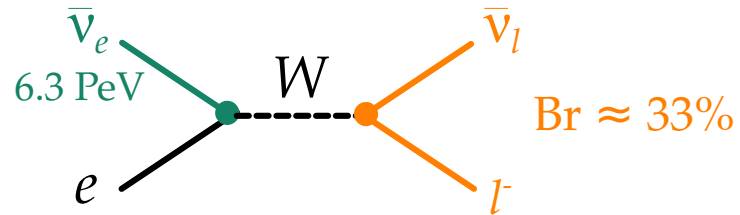
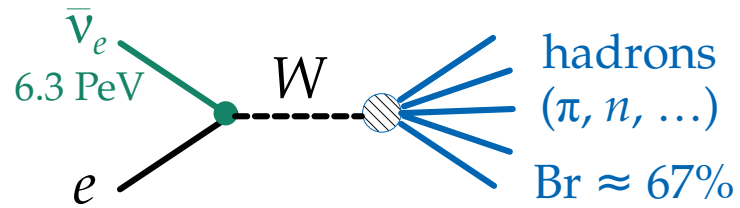


First reported by IceCube in 2021:

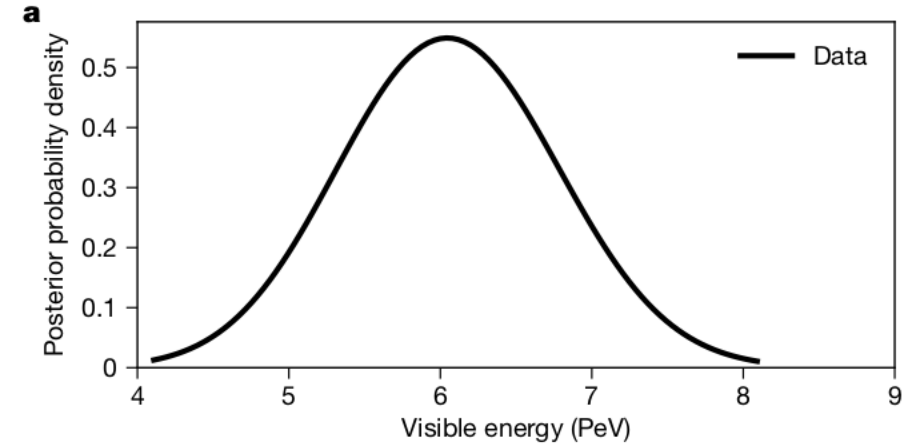


First observation of a Glashow resonance

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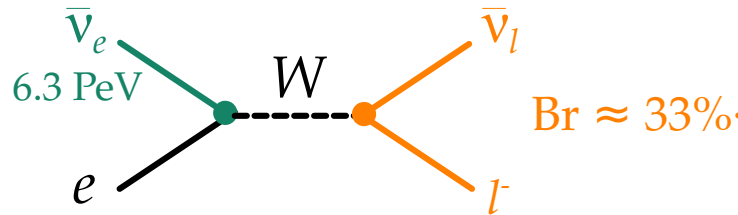
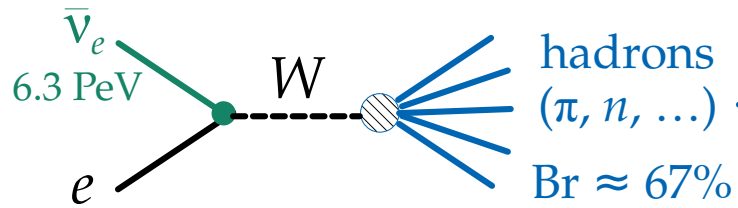


First reported by IceCube in 2021:

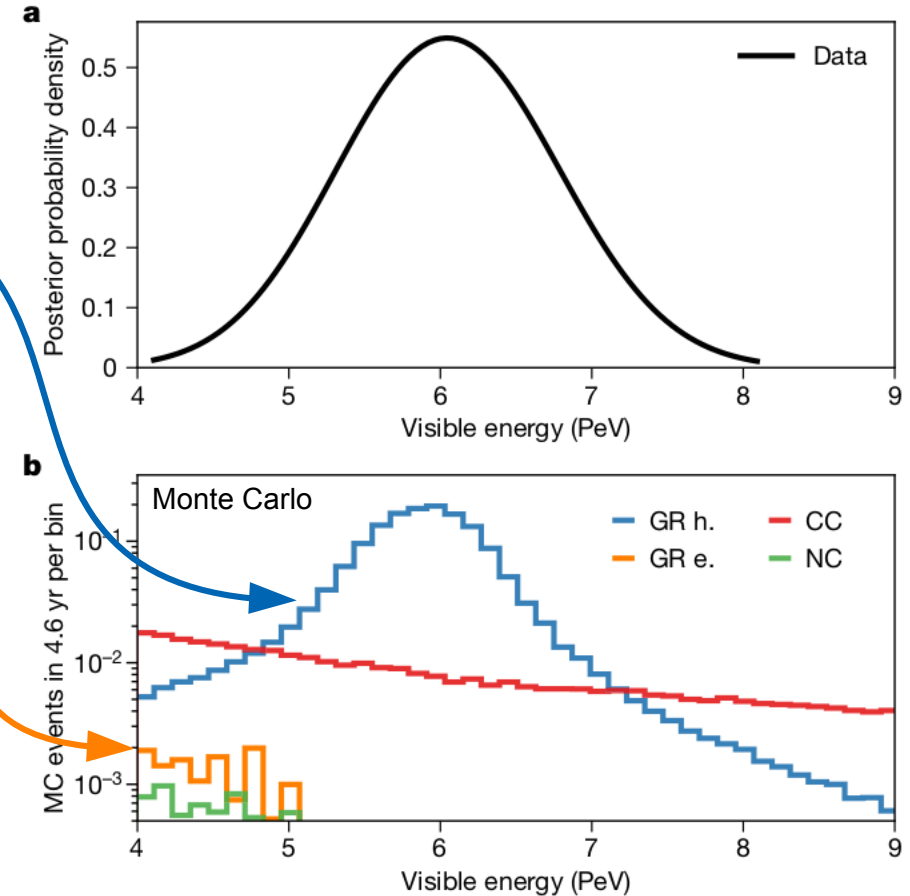


First observation of a Glashow resonance

Predicted in 1960:

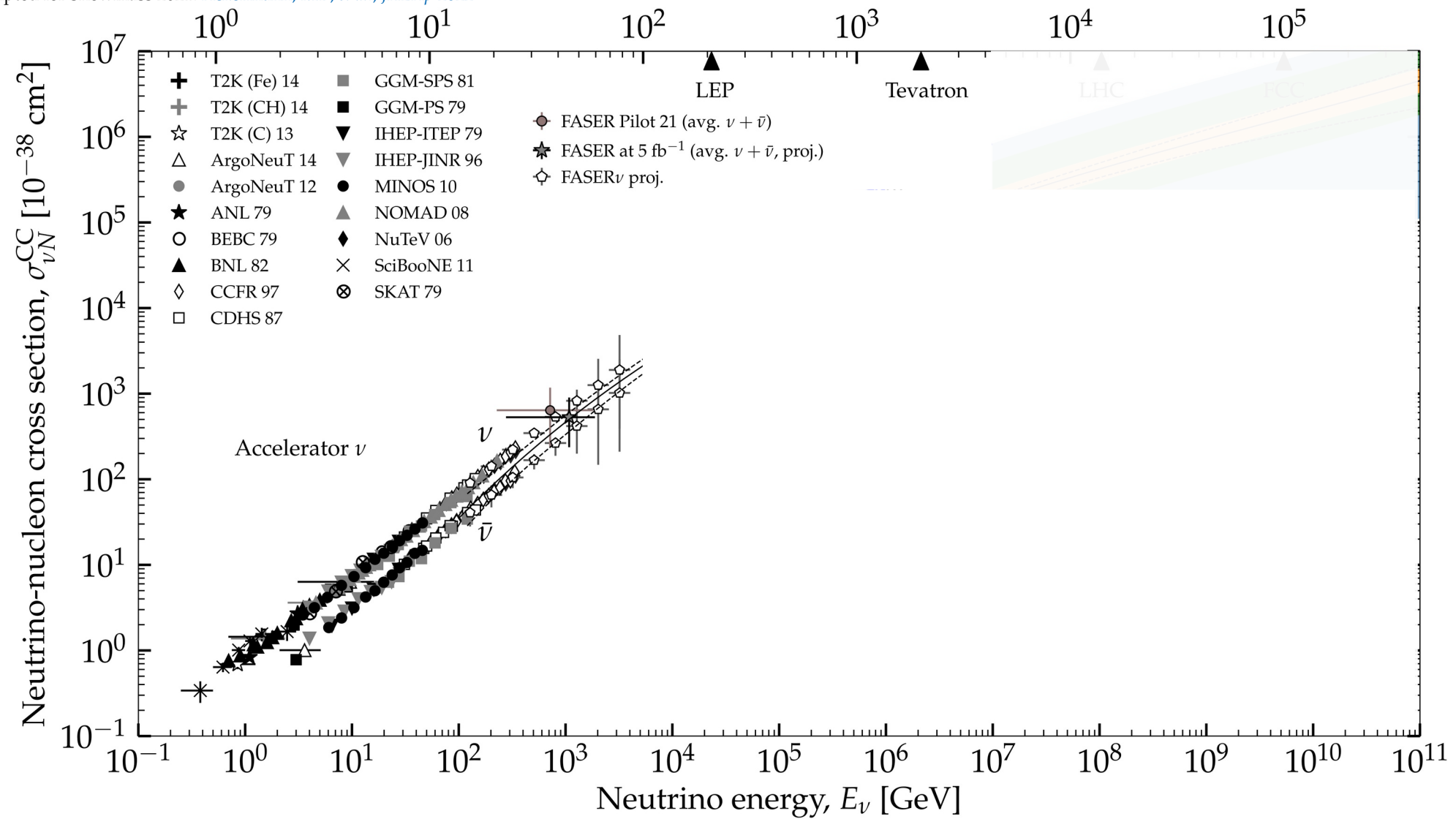


First reported by IceCube in 2021:

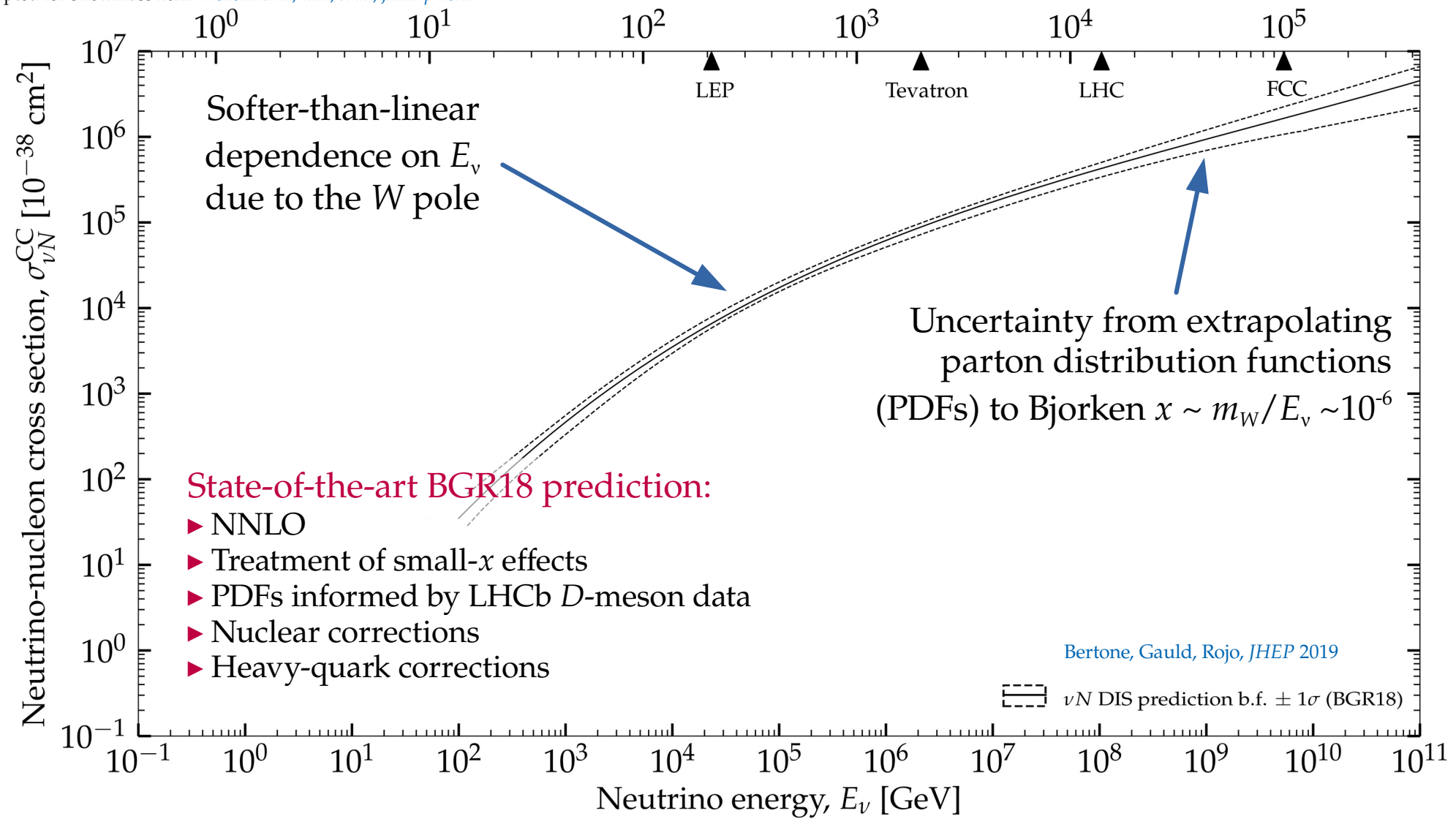


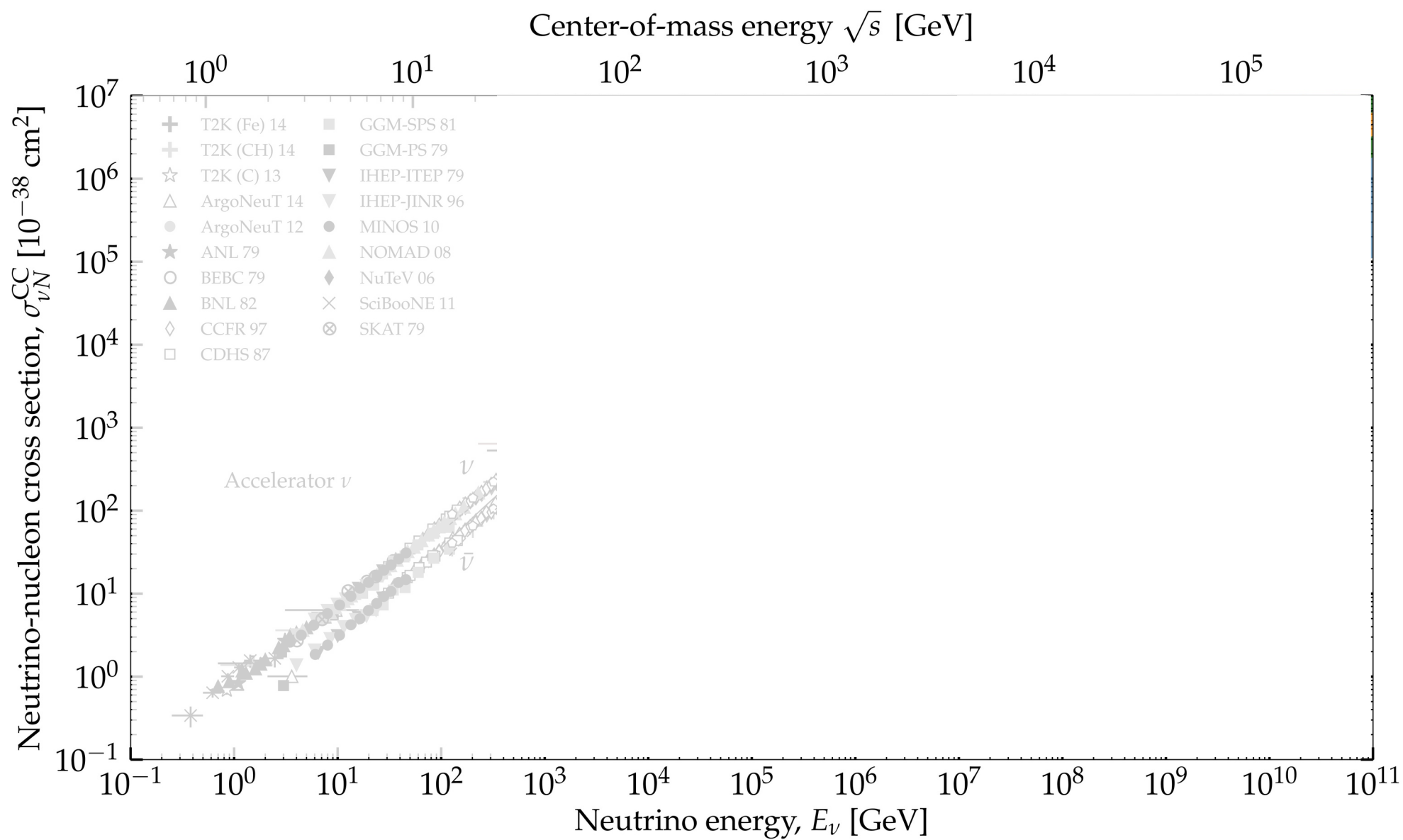
2. Neutrino-matter cross section: *From TeV to EeV*

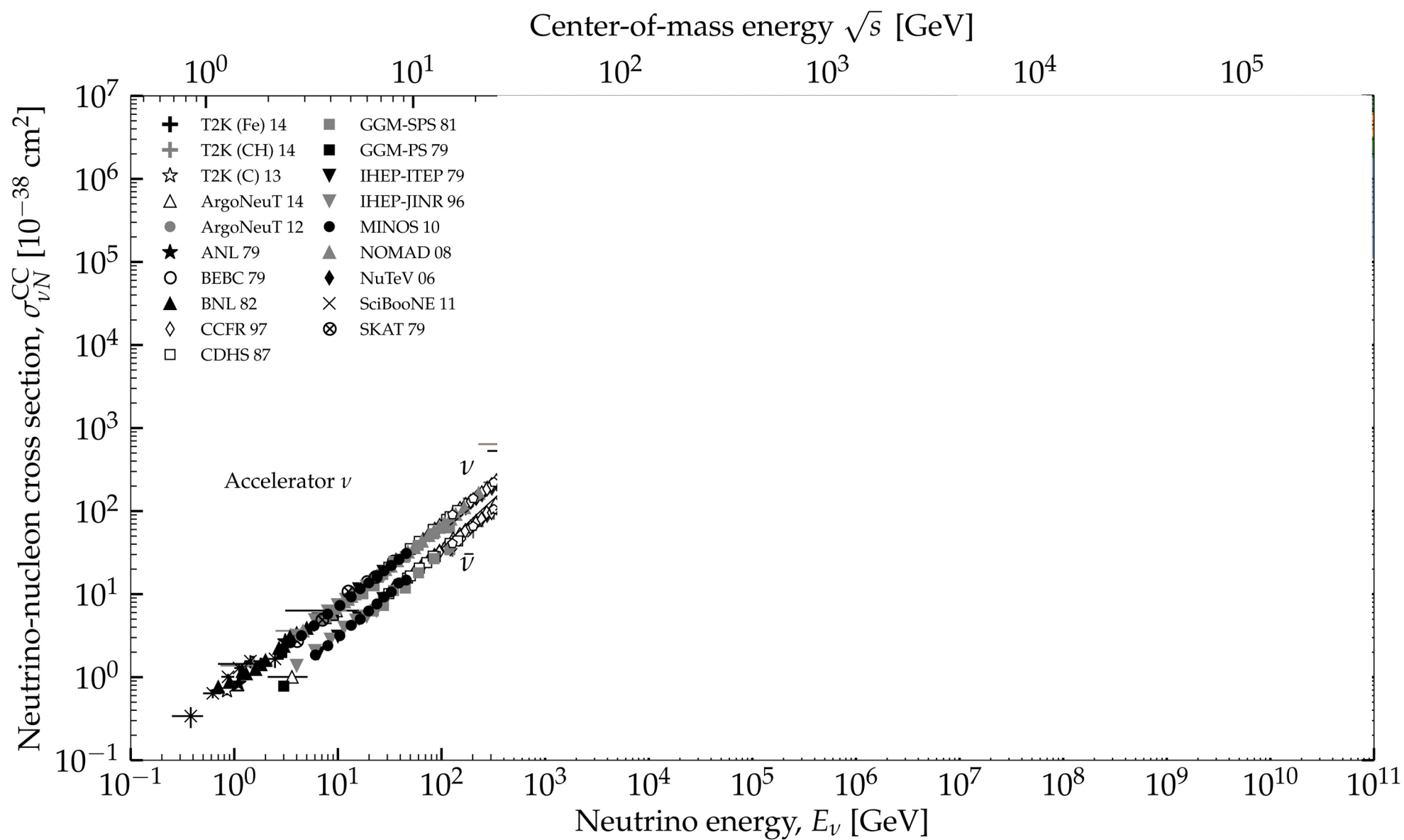
Center-of-mass energy $\sqrt{s}$ [GeV]

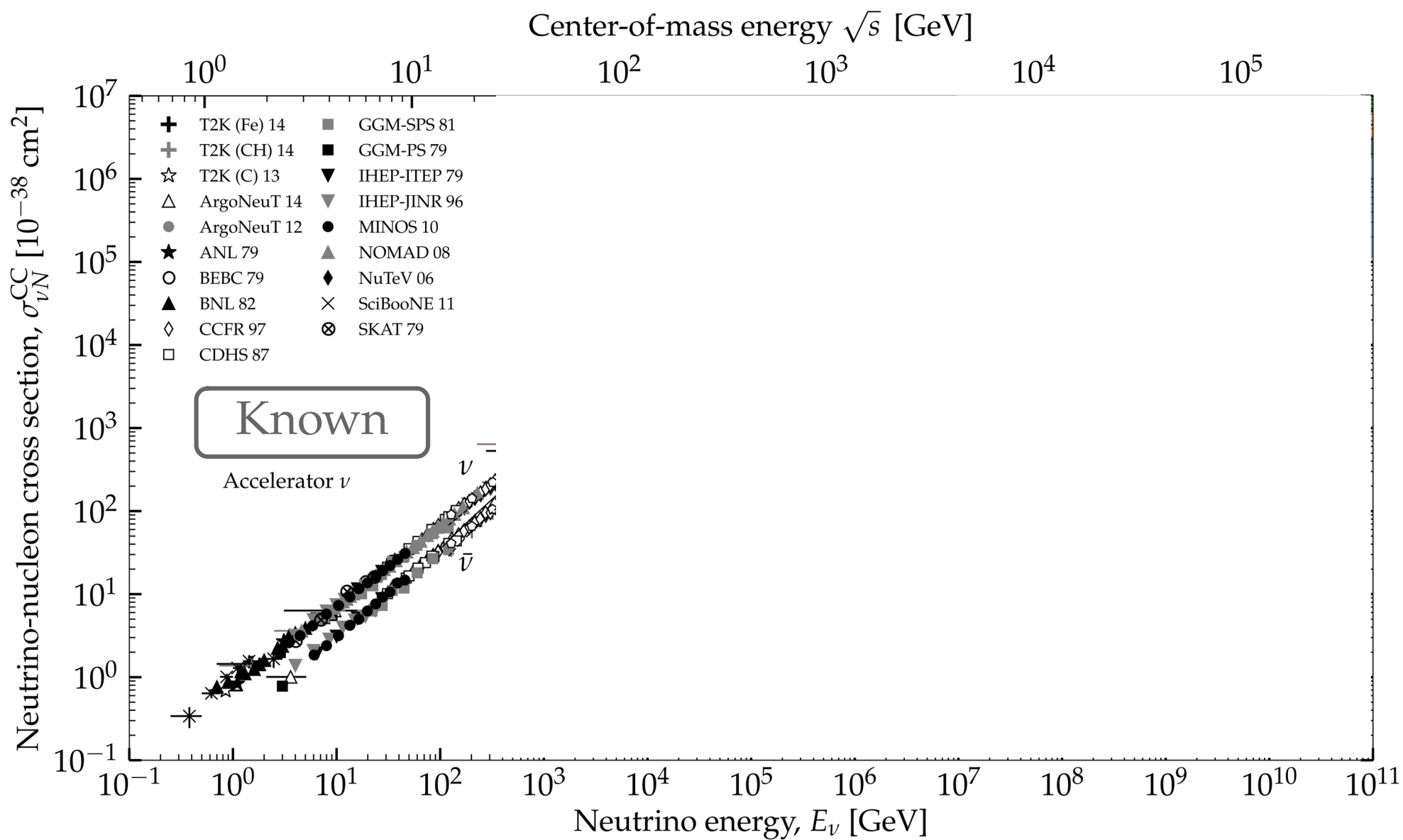


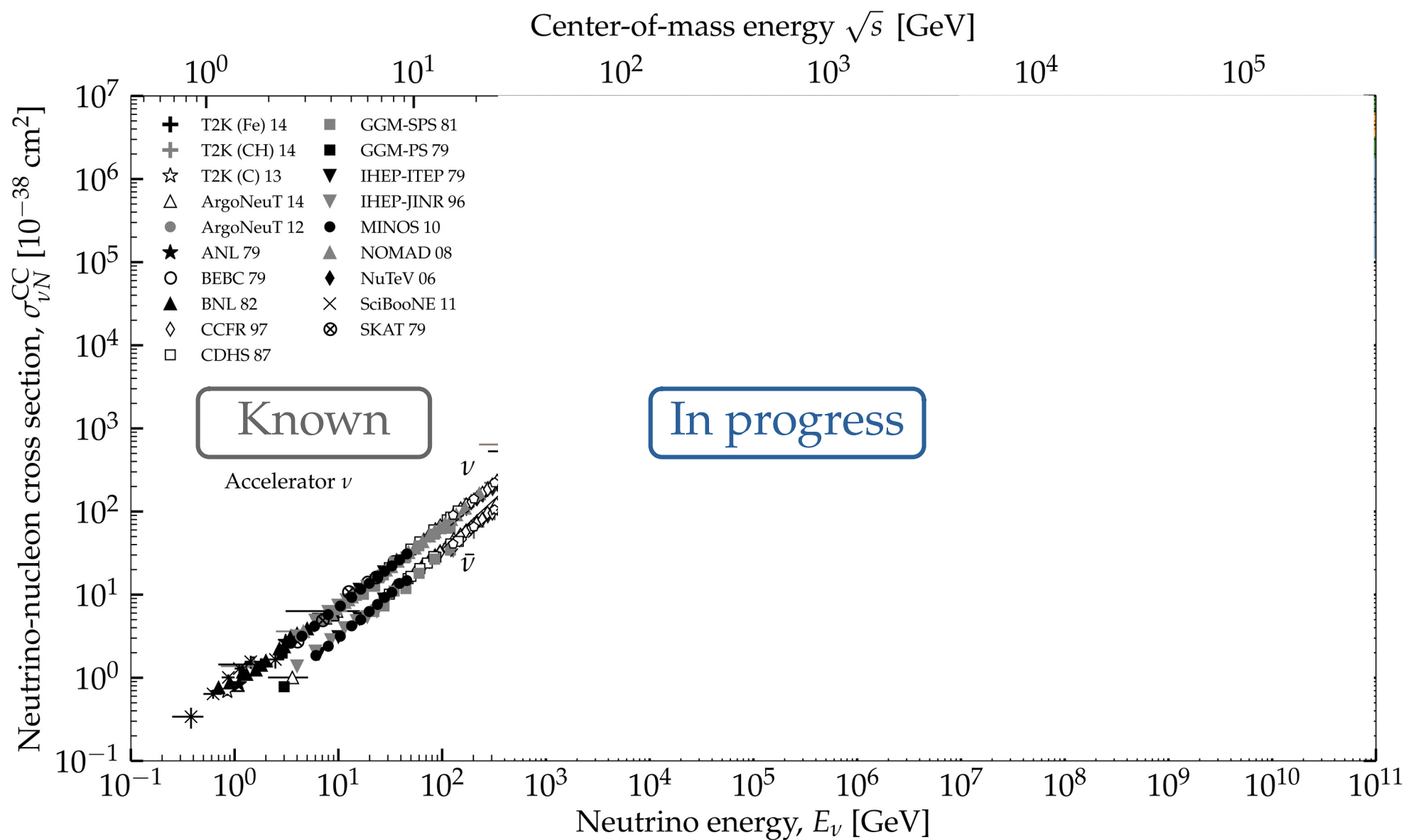
Center-of-mass energy $\sqrt{s}$ [GeV]

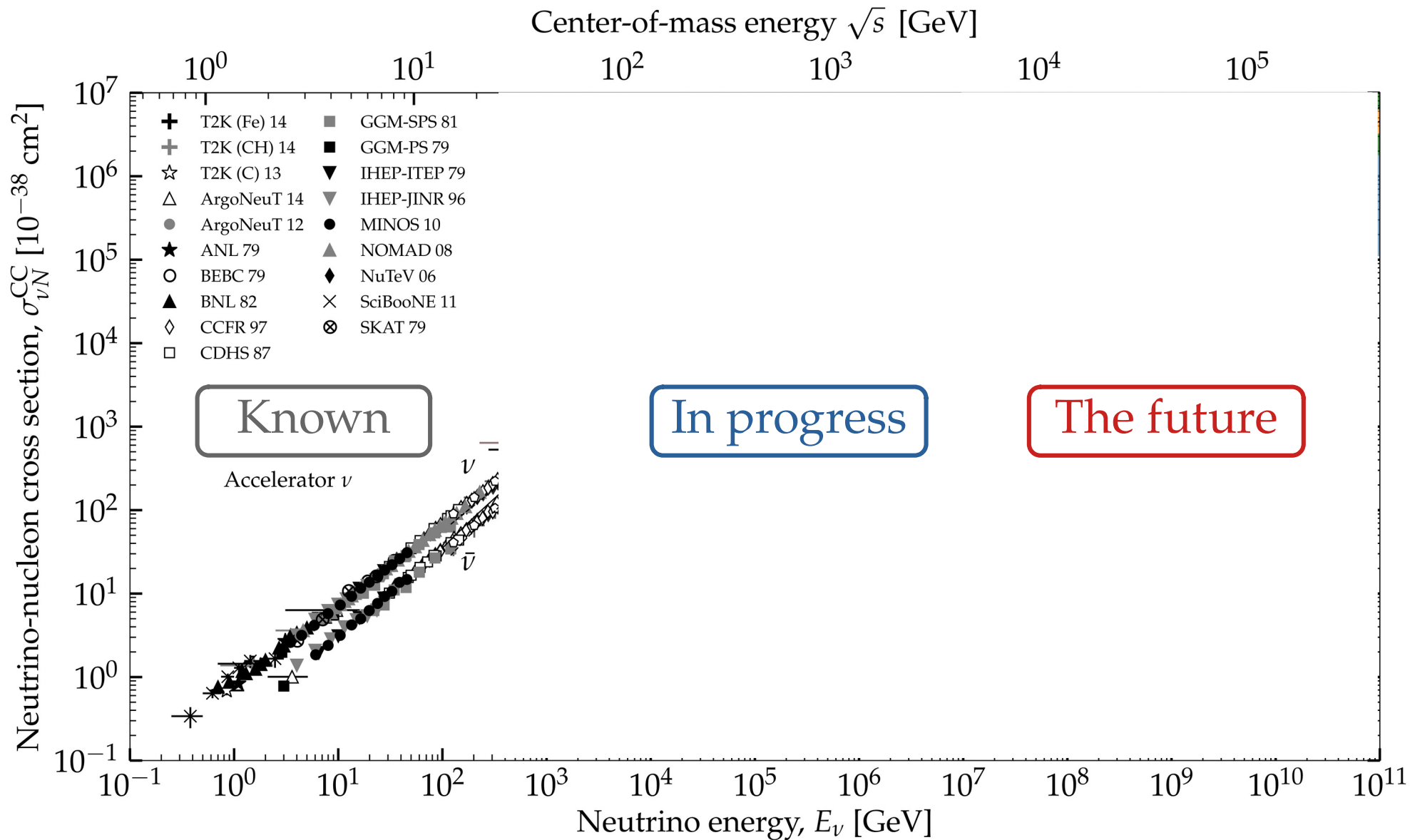


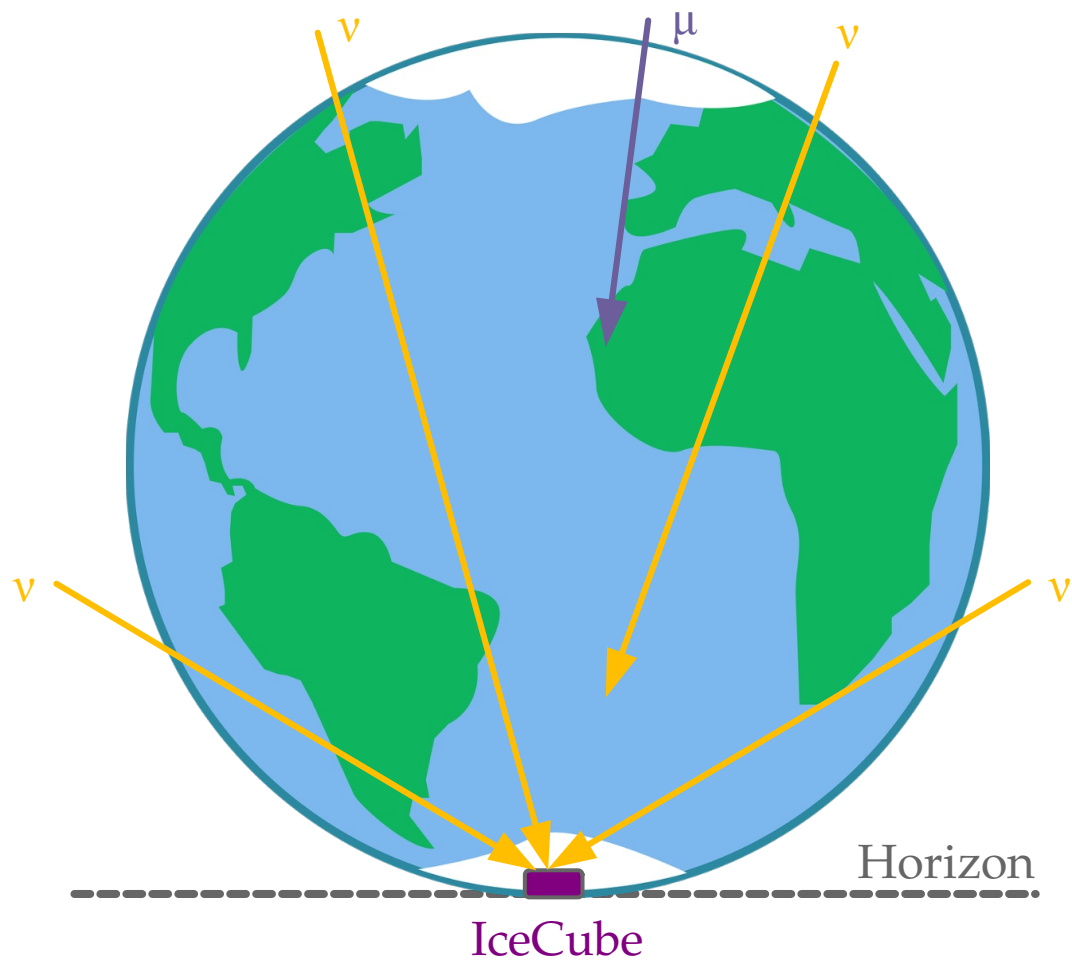


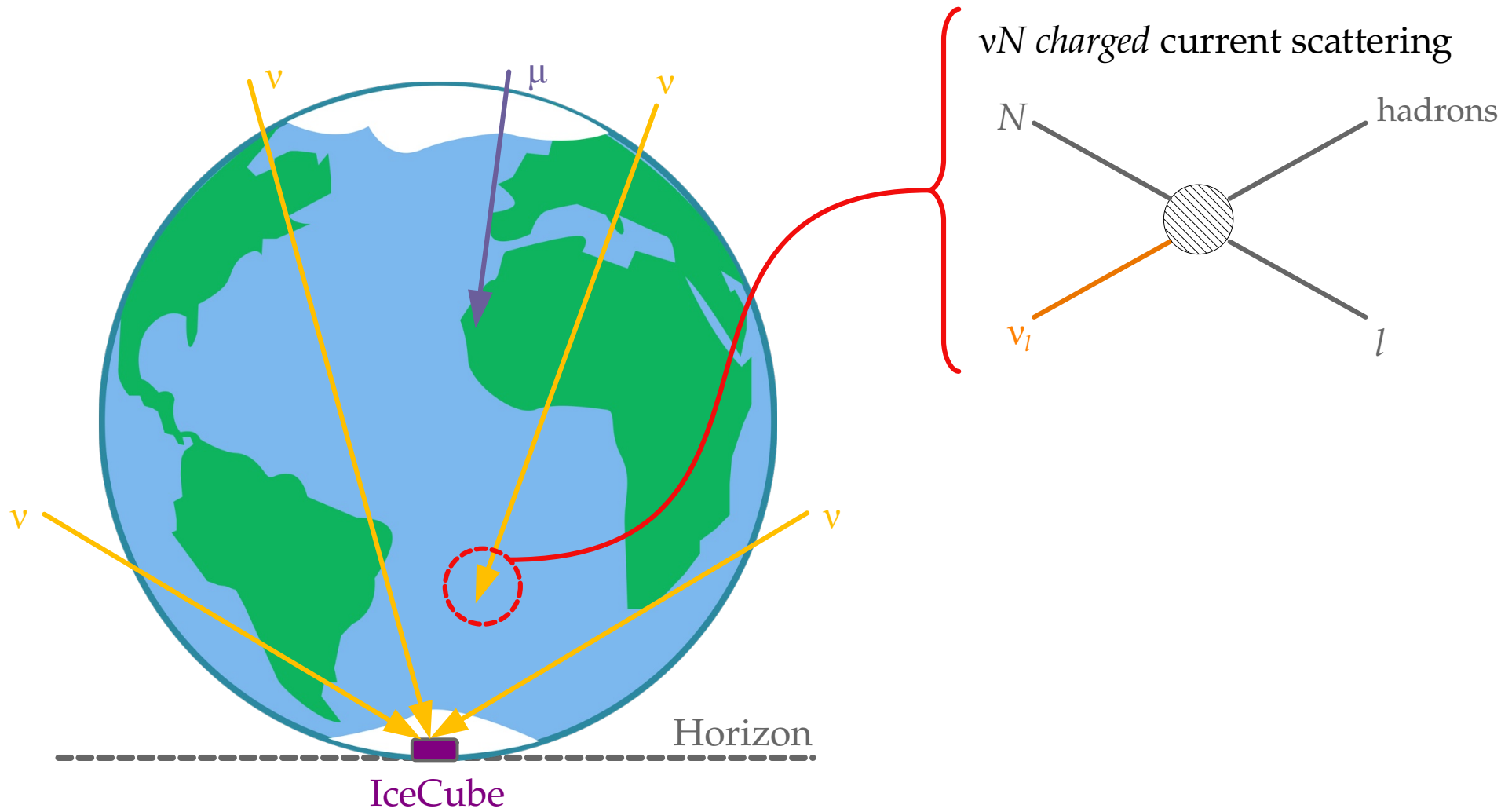


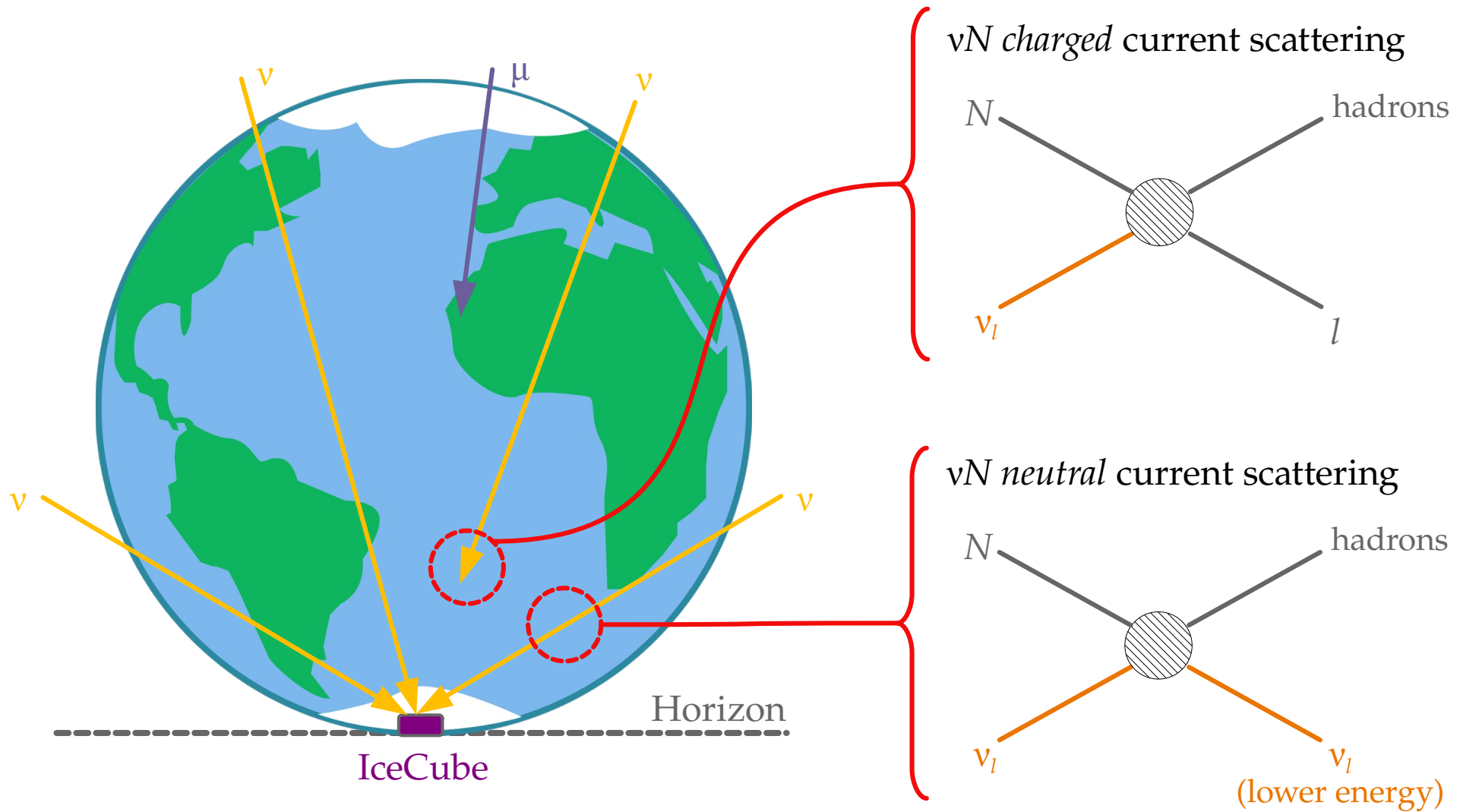


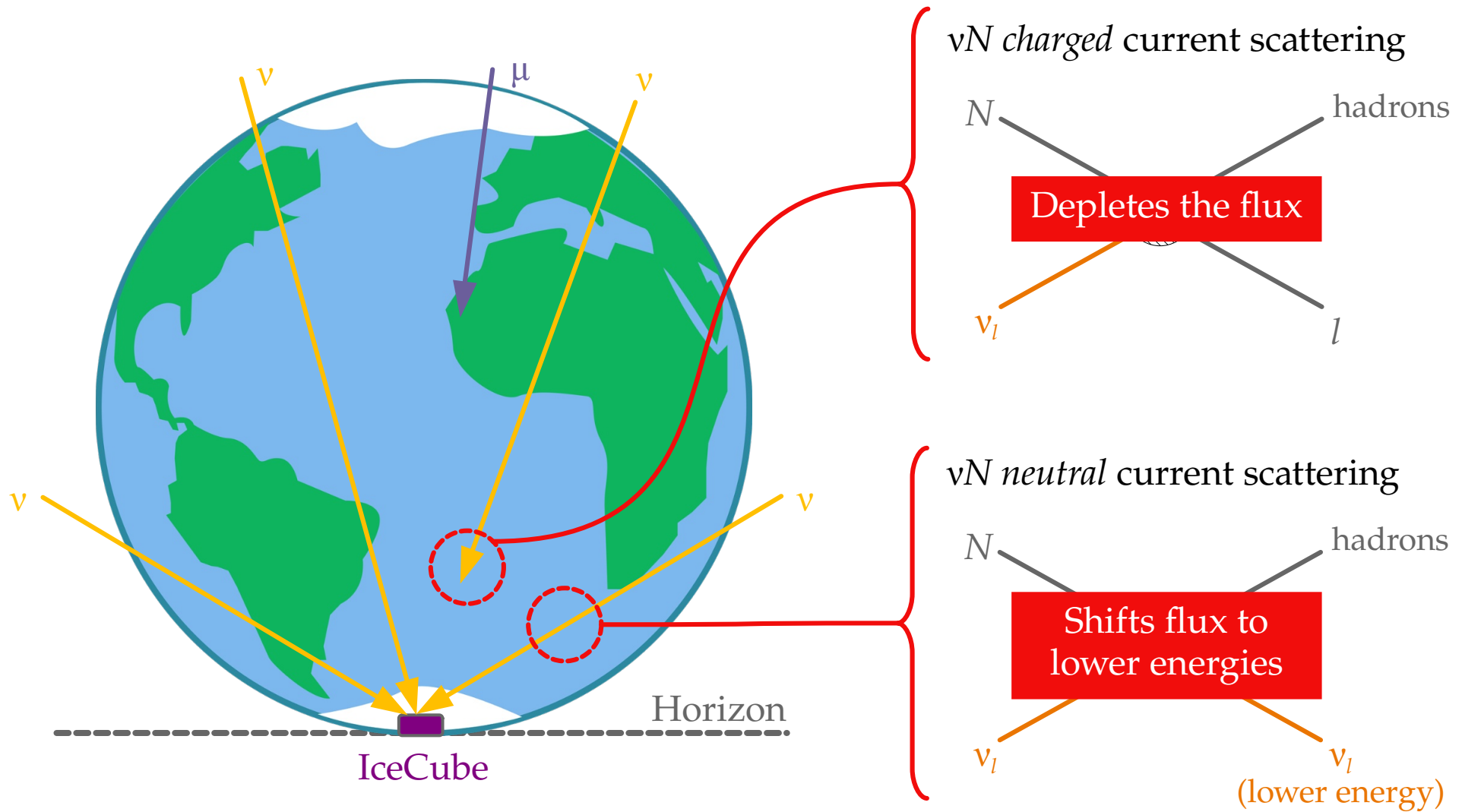








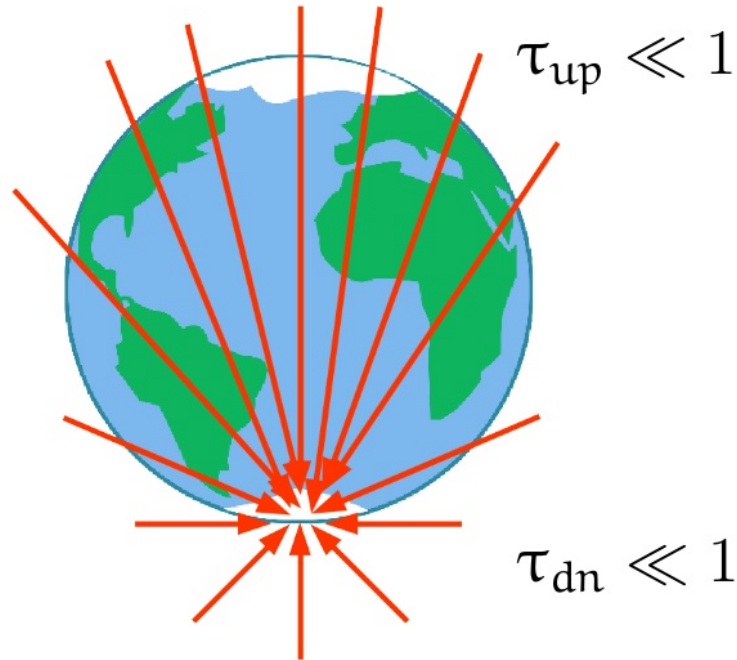




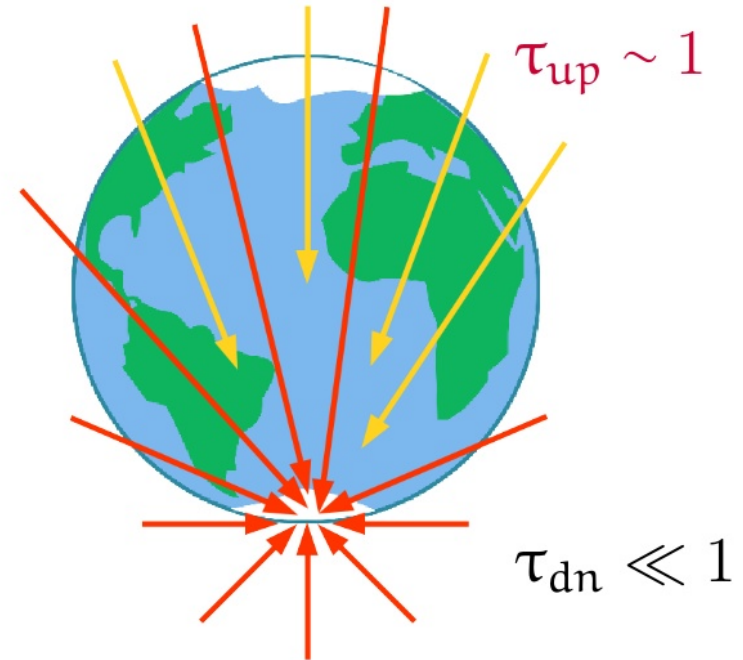
Measuring the high-energy νN cross section

$$\text{Optical depth to } \nu N \text{ int's} = \frac{\text{Distance from Earth's surface to IceCube}}{\text{Mean free path inside Earth}} \equiv \tau(E_\nu, \theta_z) \propto \sigma_{\nu N}$$

Below ~ 10 TeV: Earth is transparent



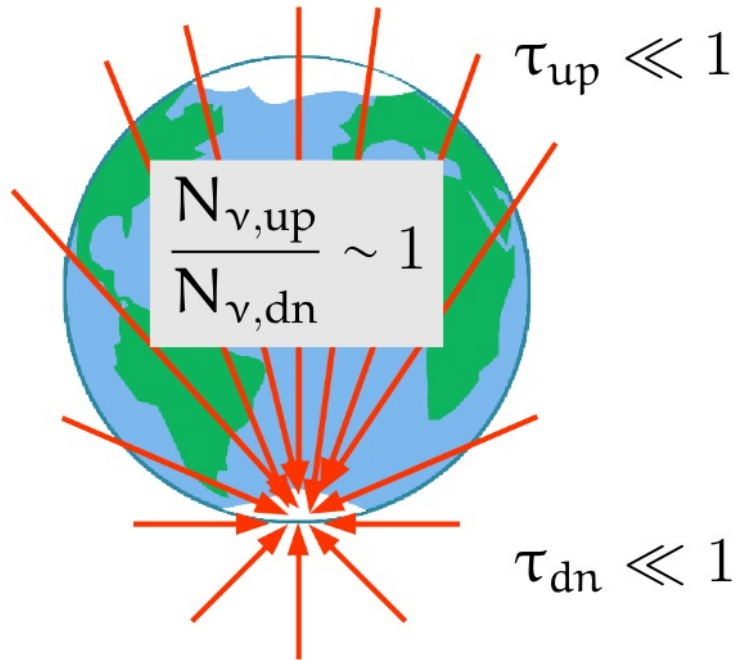
Above ~ 10 TeV: Earth is opaque



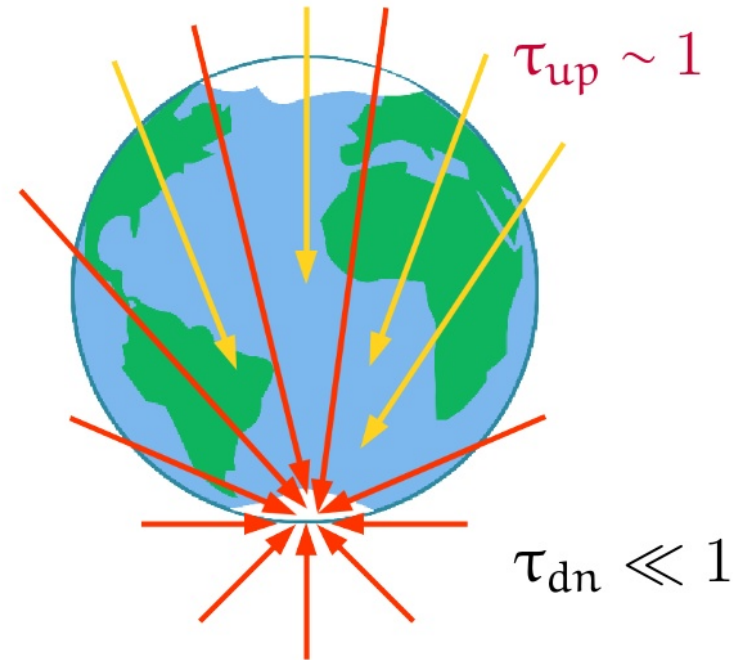
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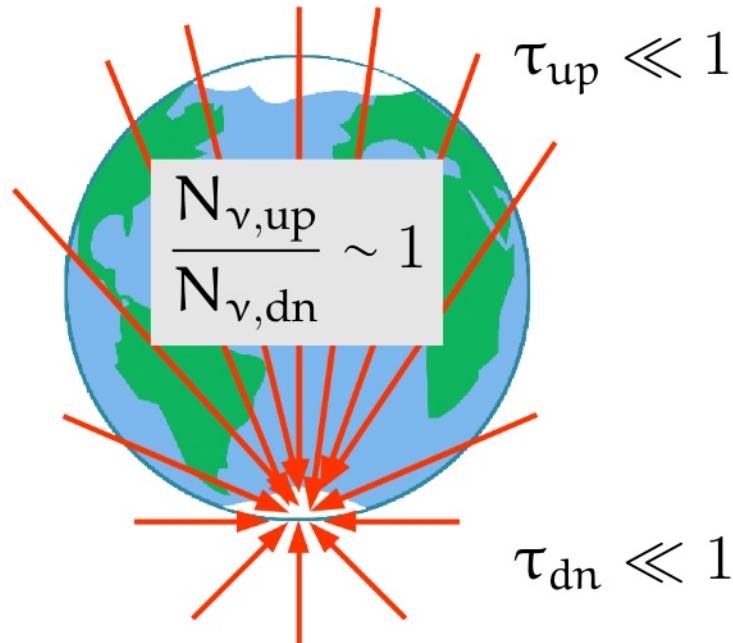
Above ~ 10 TeV: Earth is opaque



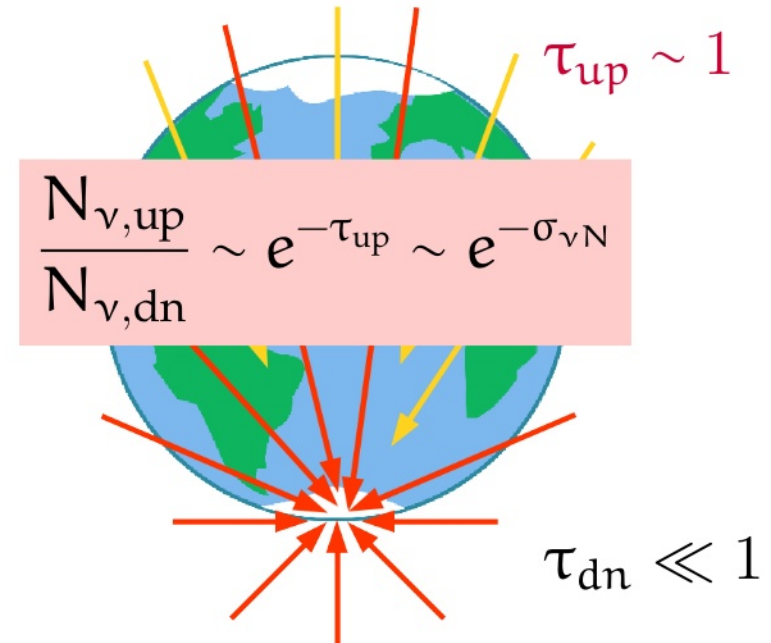
Measuring the high-energy νN cross section

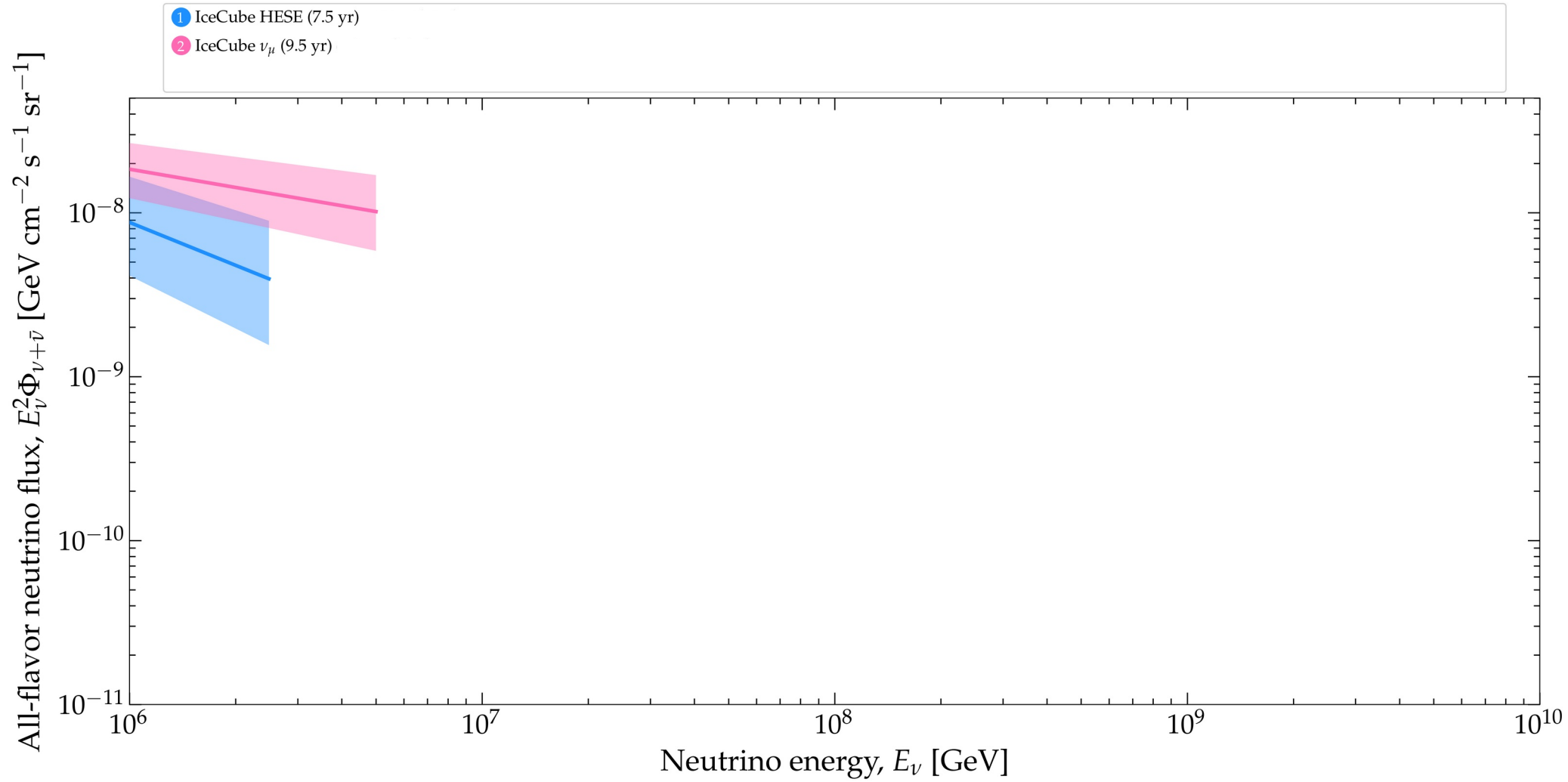
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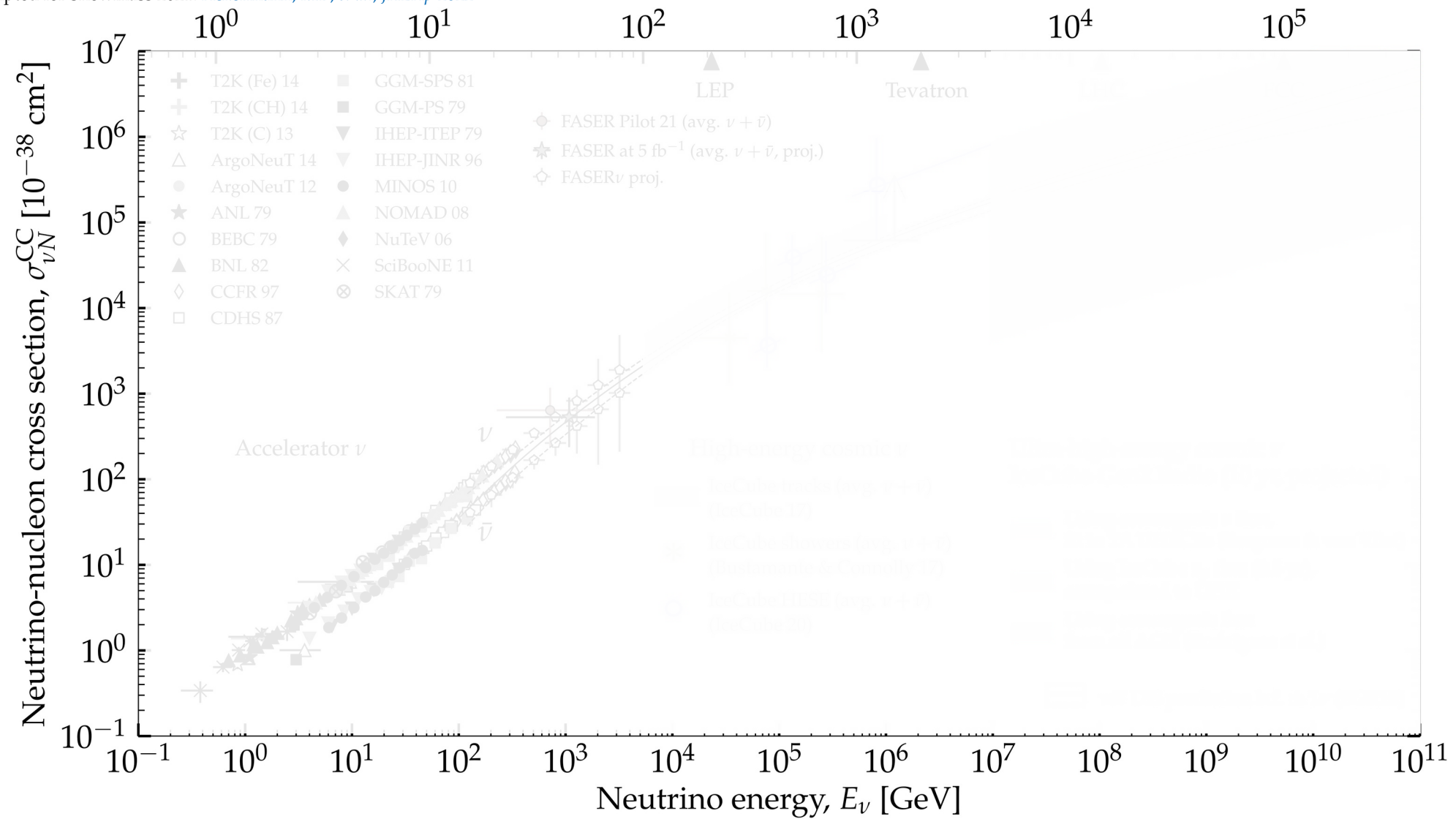


Above ~ 10 TeV: Earth is opaque

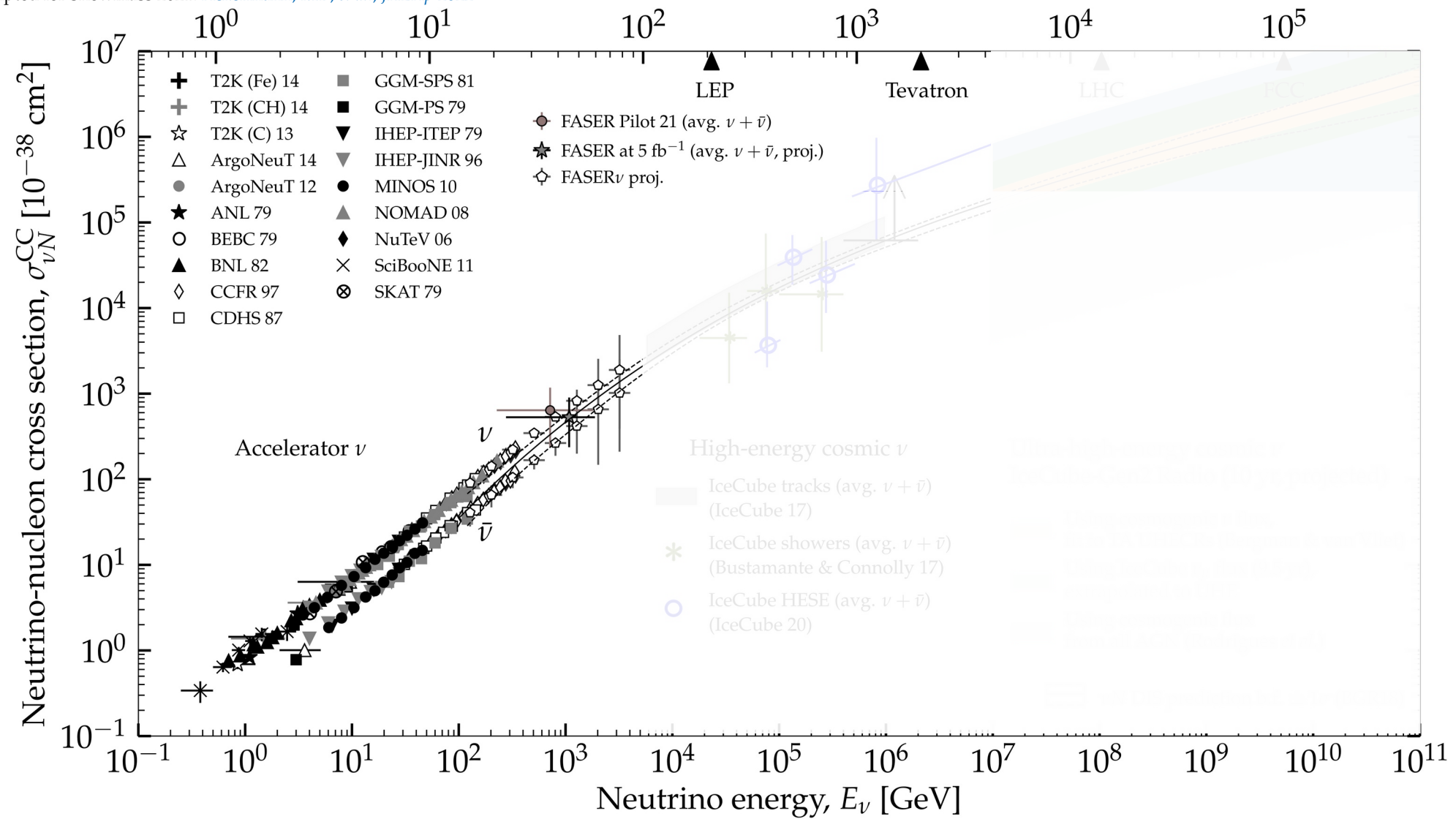




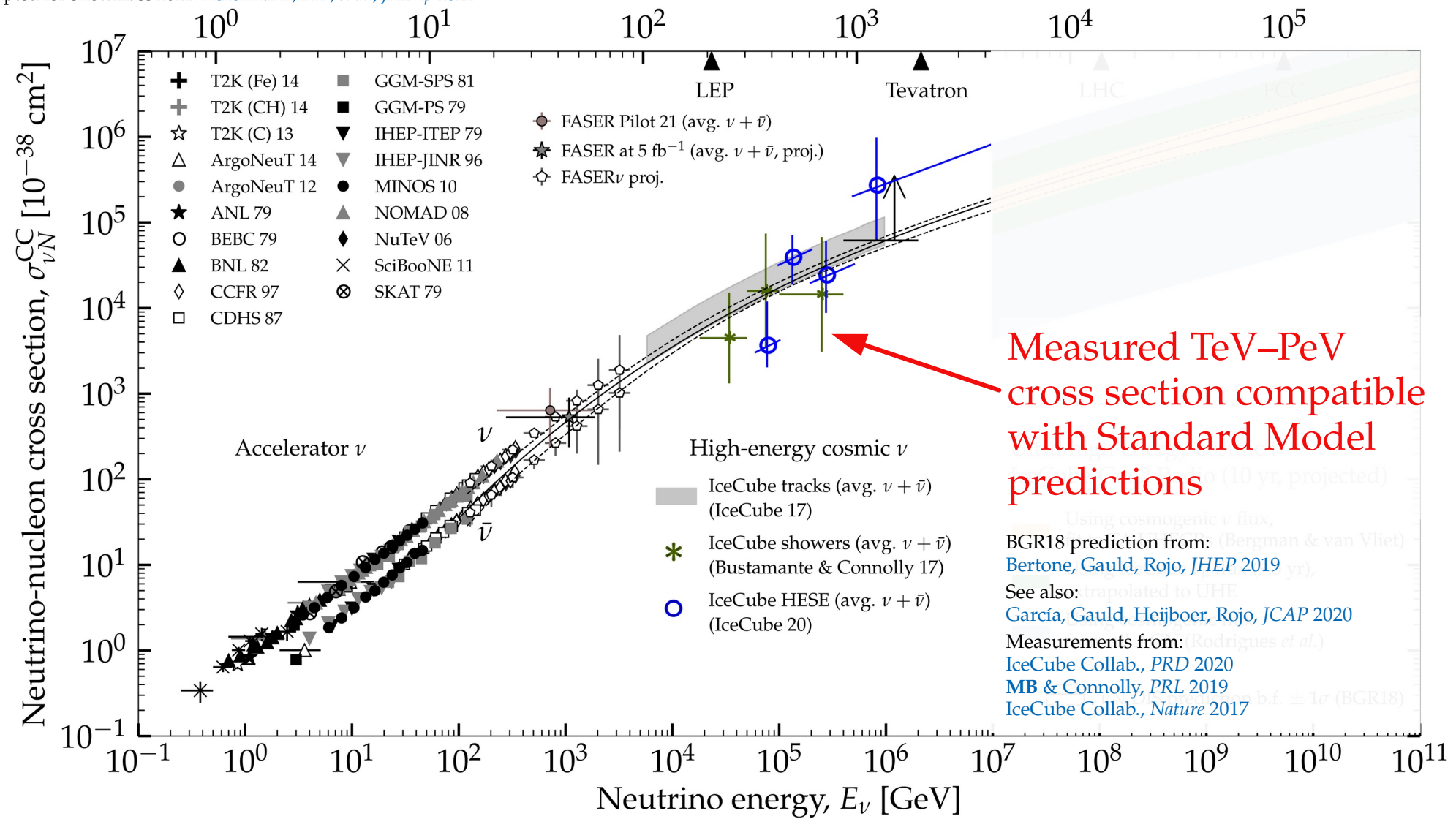
Center-of-mass energy $\sqrt{s}$ [GeV]



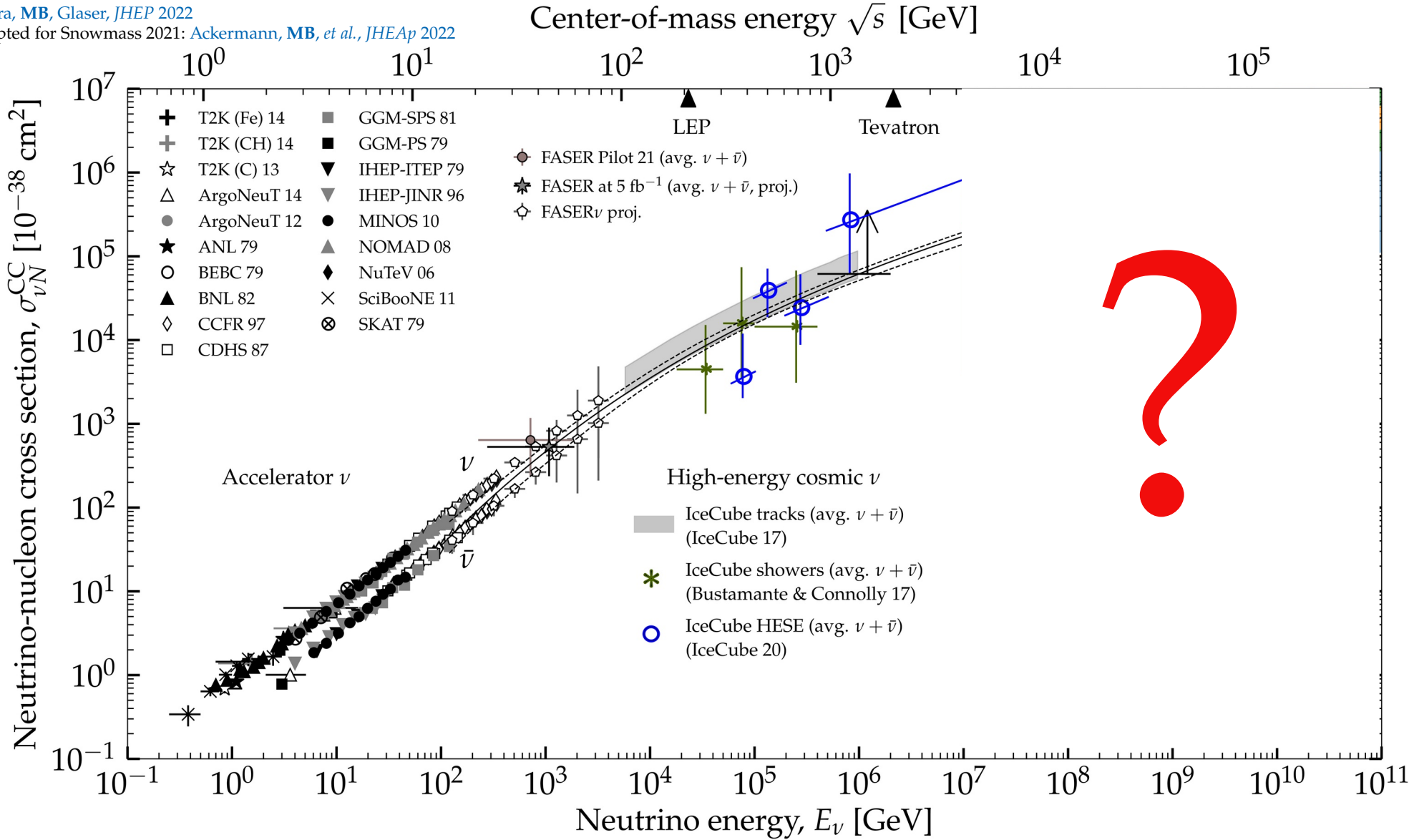
Center-of-mass energy $\sqrt{s}$ [GeV]



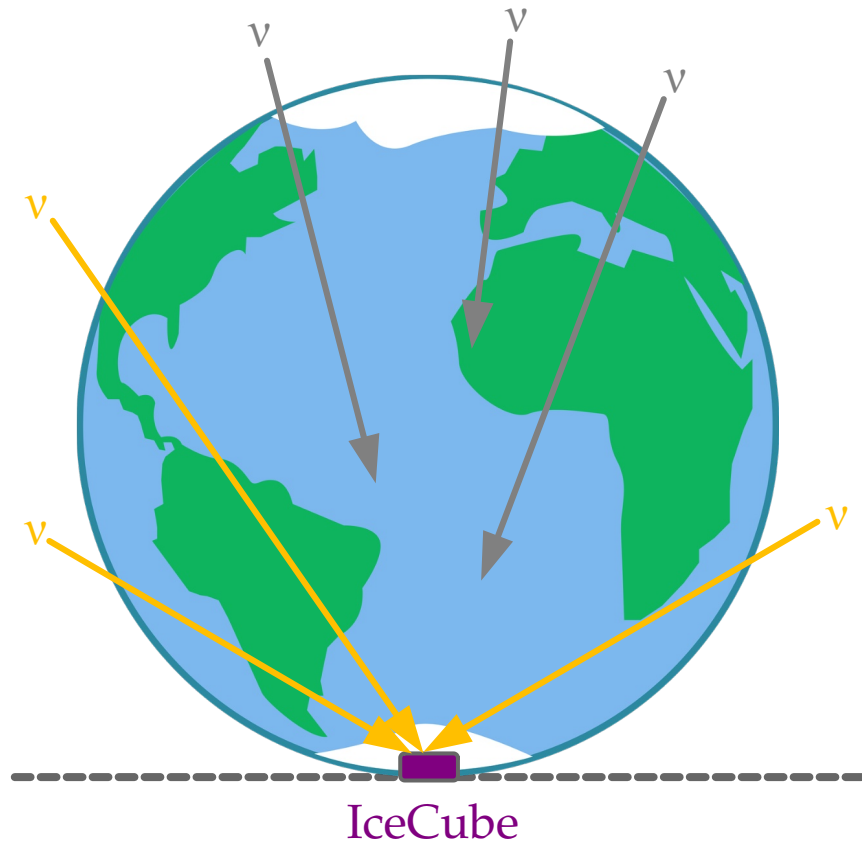
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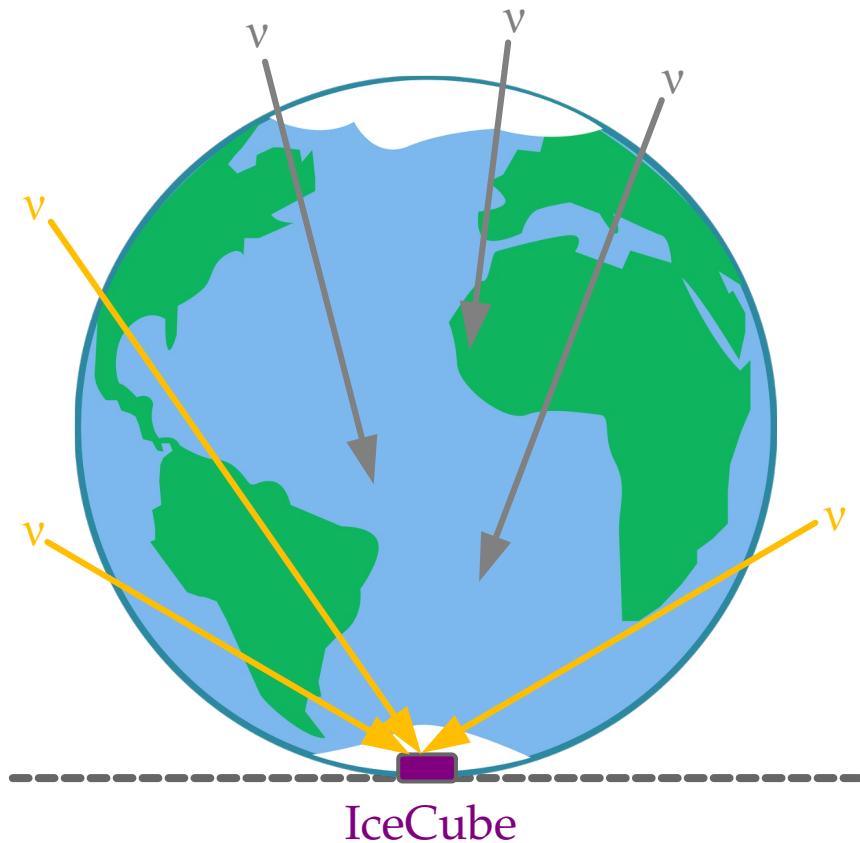


TeV–PeV:



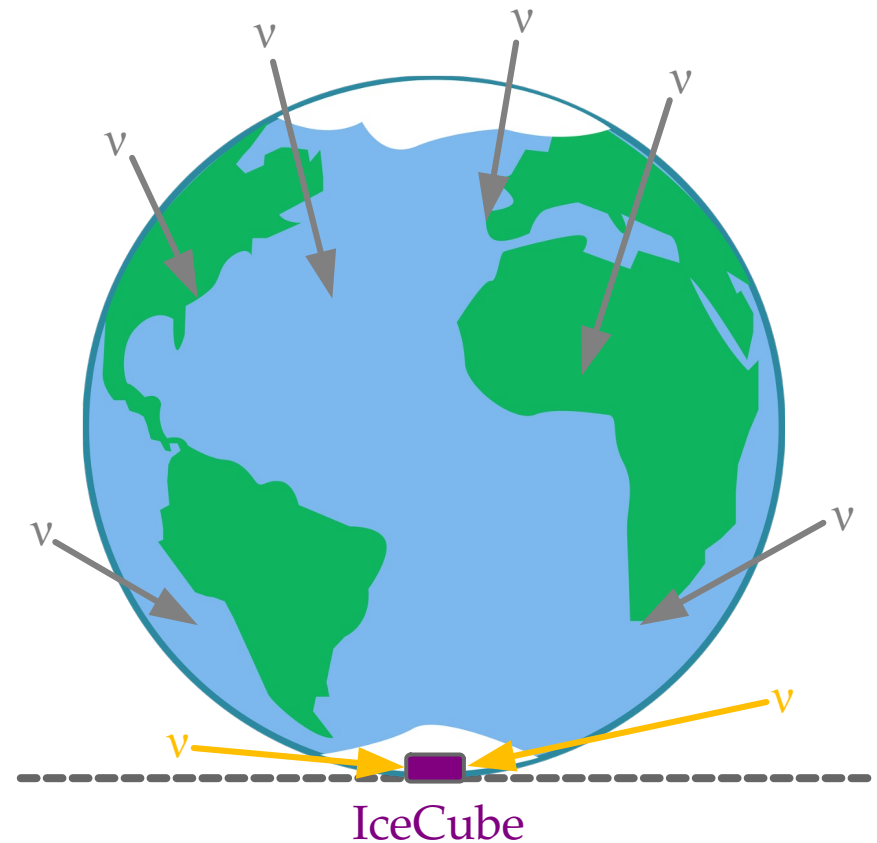
Earth is *almost fully* opaque,
some upgoing ν still make it through

TeV–PeV:

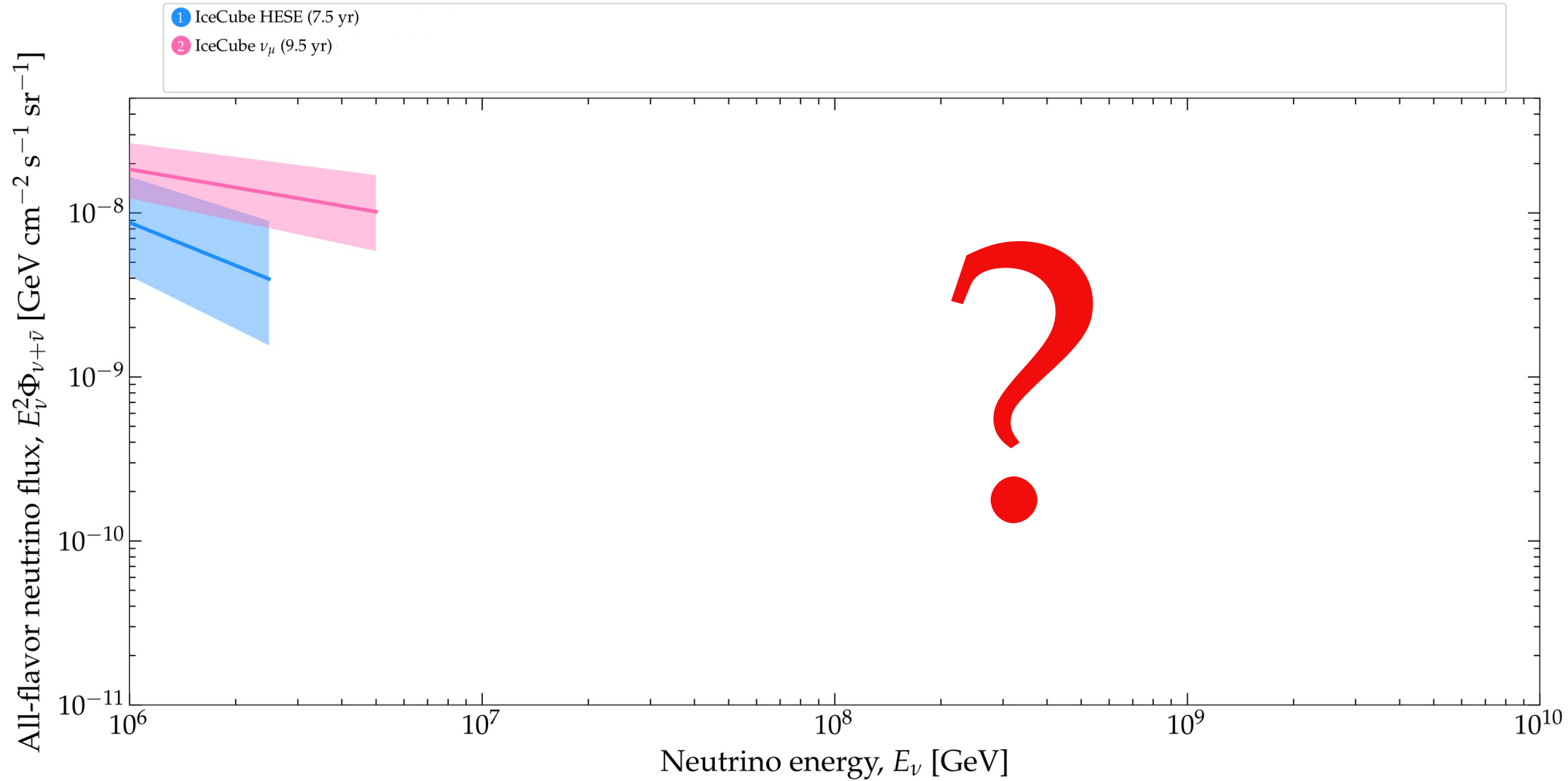


Earth is *almost fully* opaque,
some upgoing ν still make it through

> 100 PeV:



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



Redshift

$z = 0$

Discovered

MeV γ

PeV p

TeV–PeV ν

“High-energy”

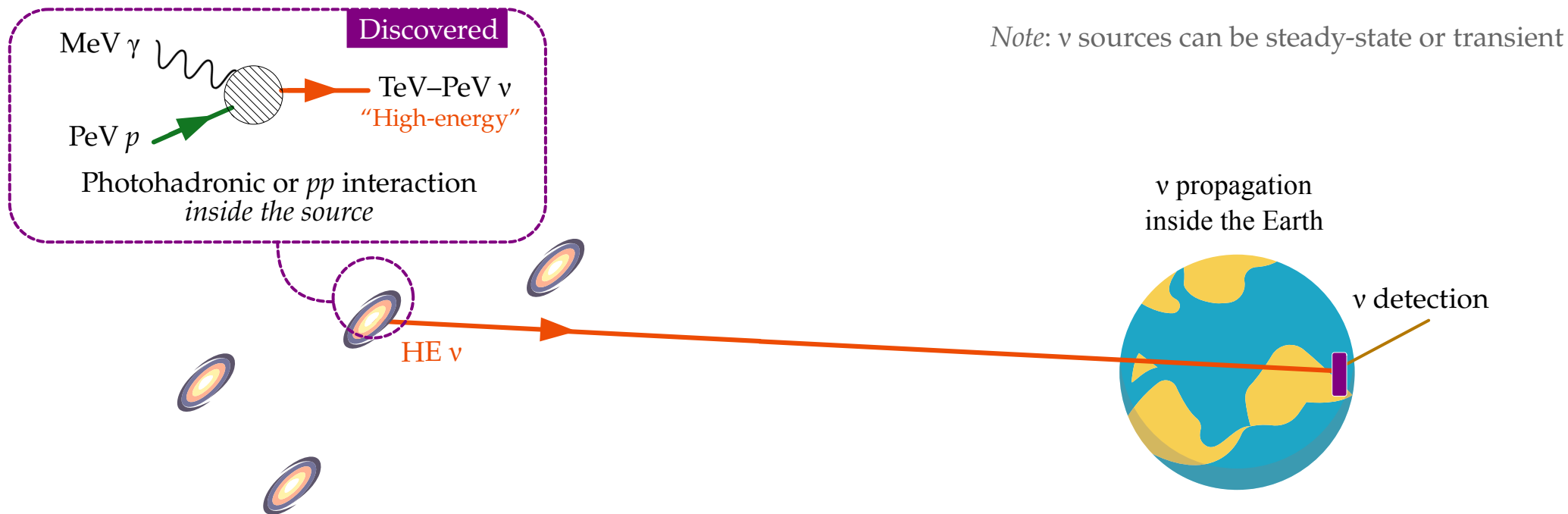
Photohadronic or pp interaction
inside the source

Note: ν sources can be steady-state or transient

ν propagation
inside the Earth

ν detection

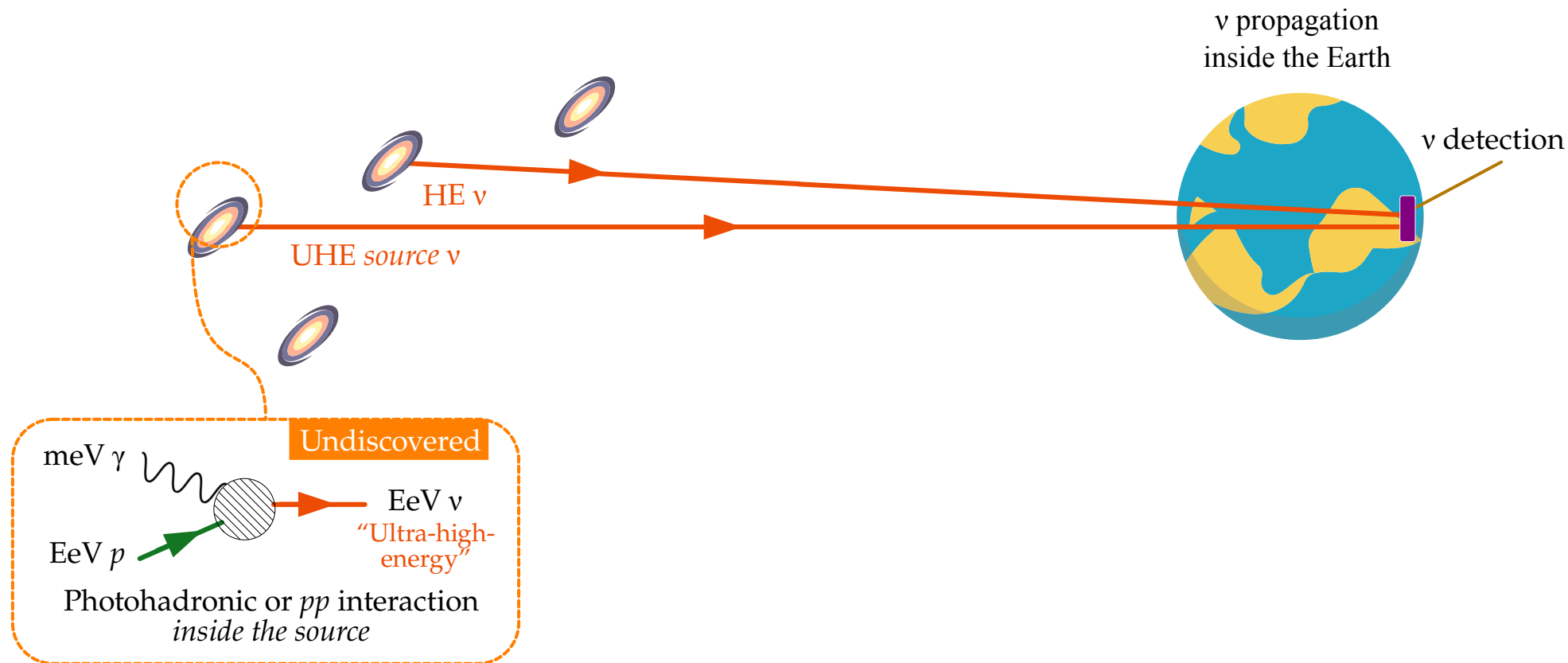
HE ν



Redshift

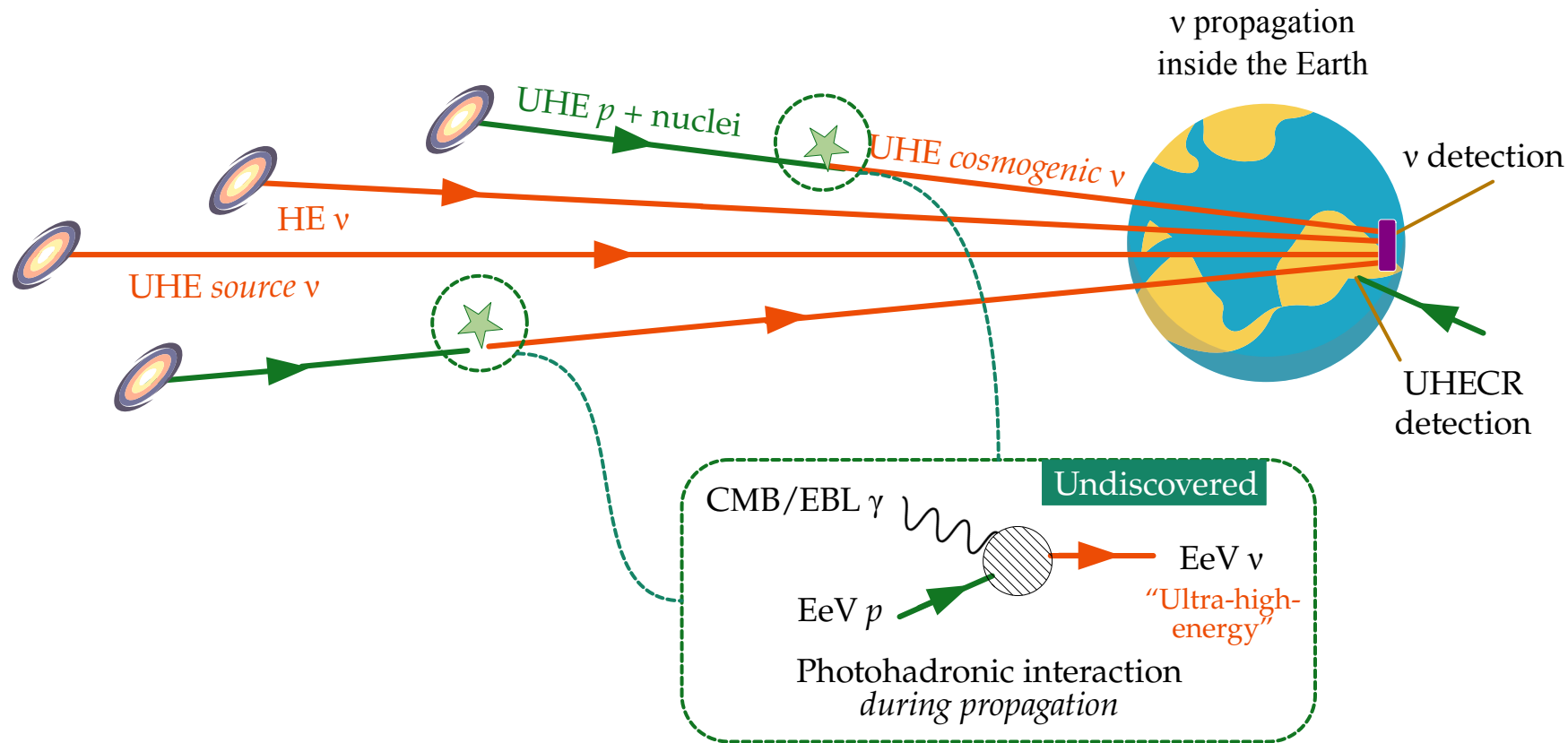
$z = 0$

Note: ν sources can be steady-state or transient



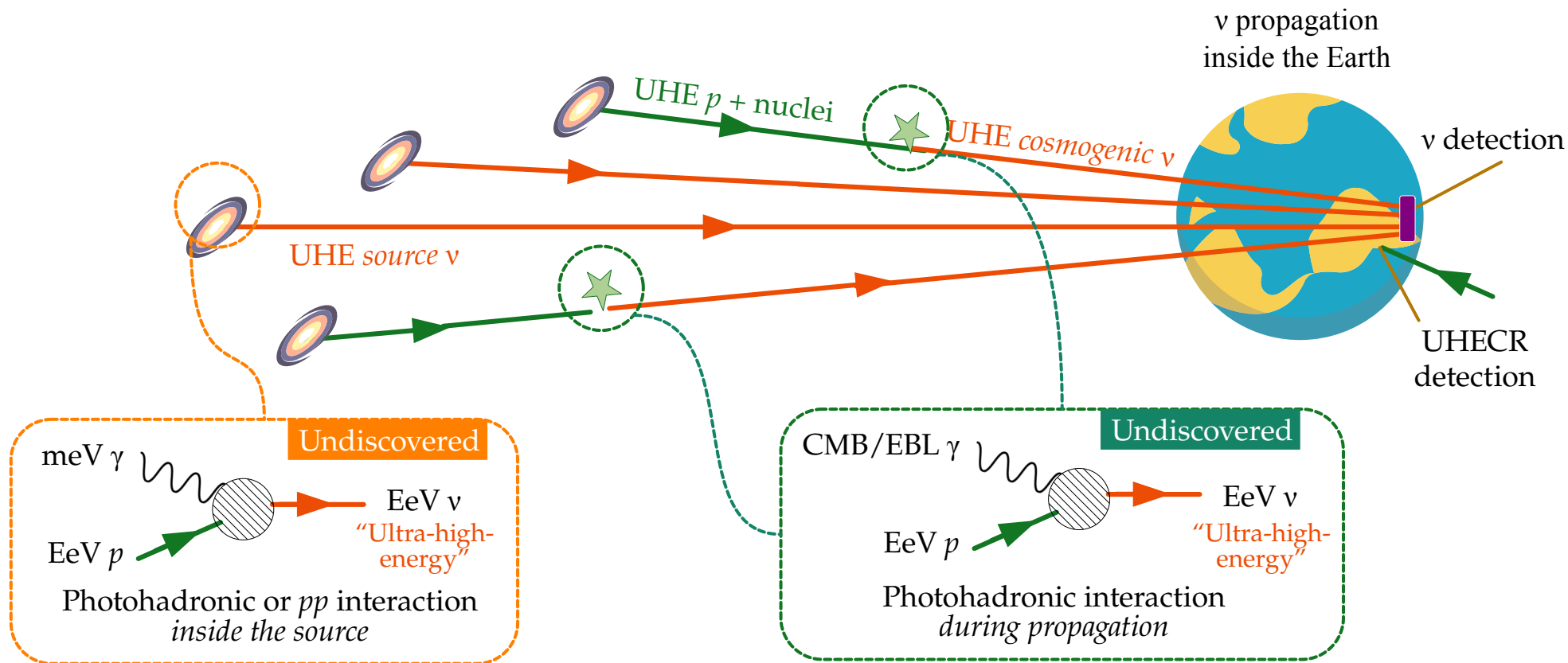
Redshift ← $z = 0$

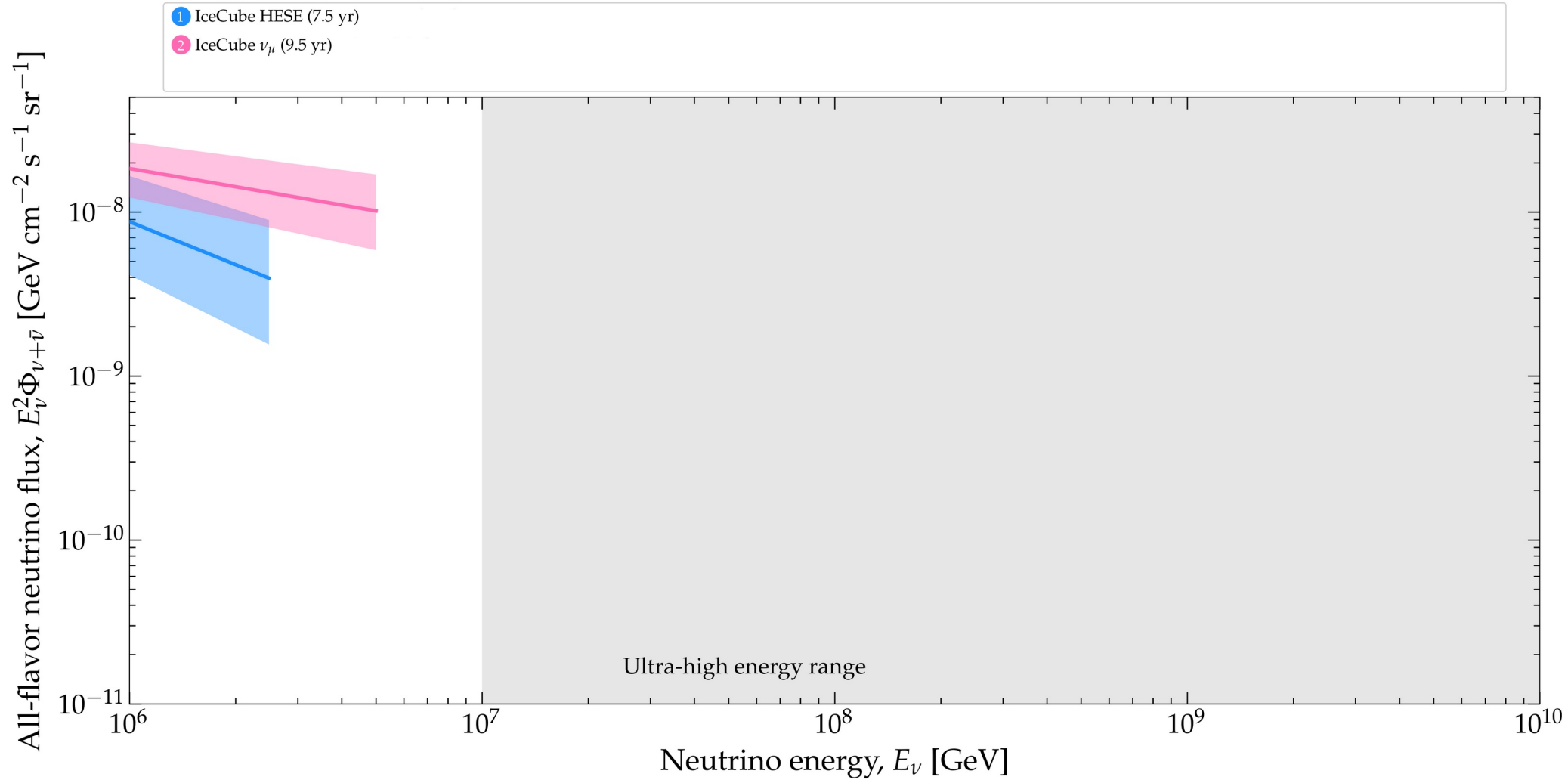
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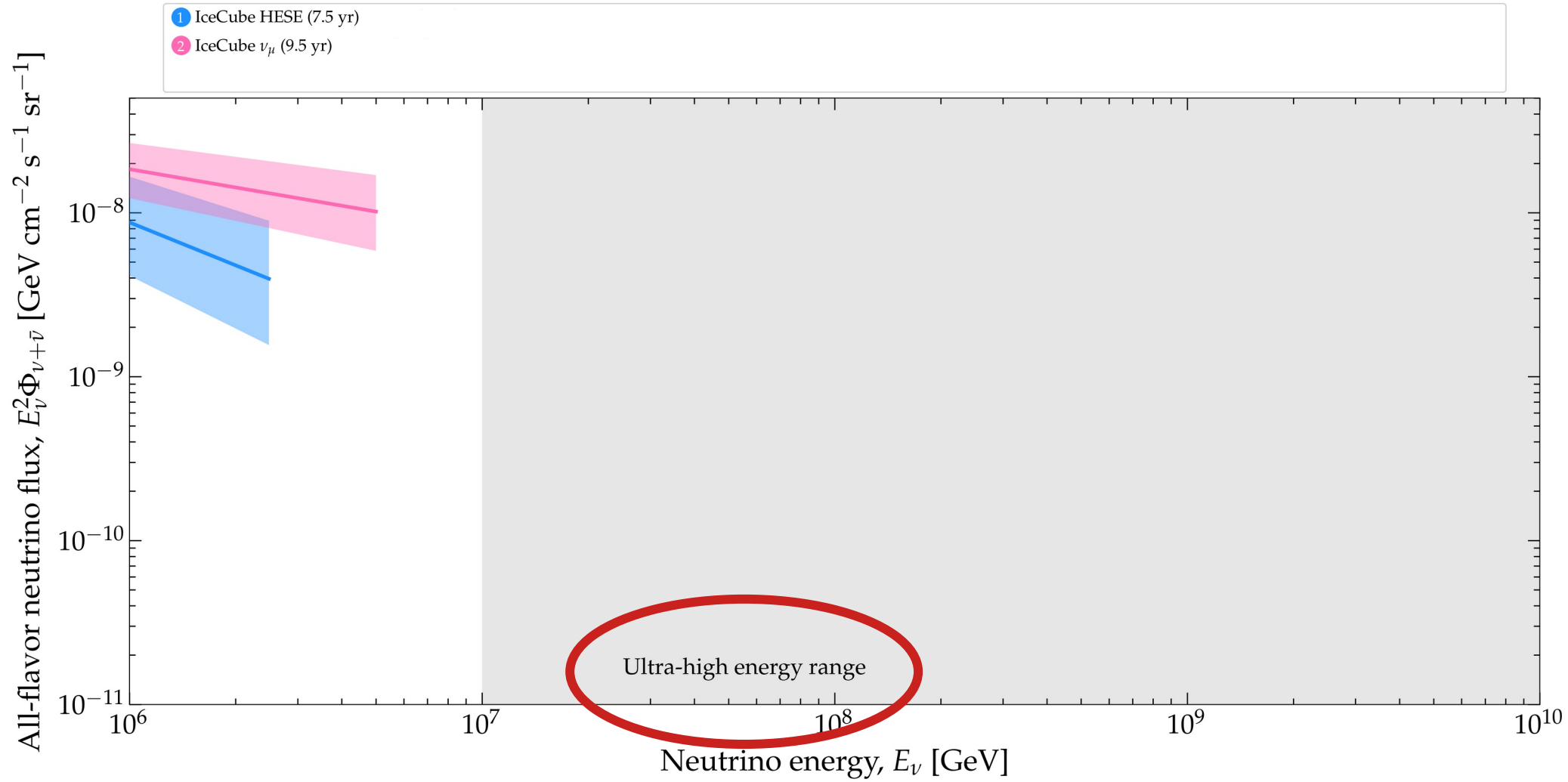


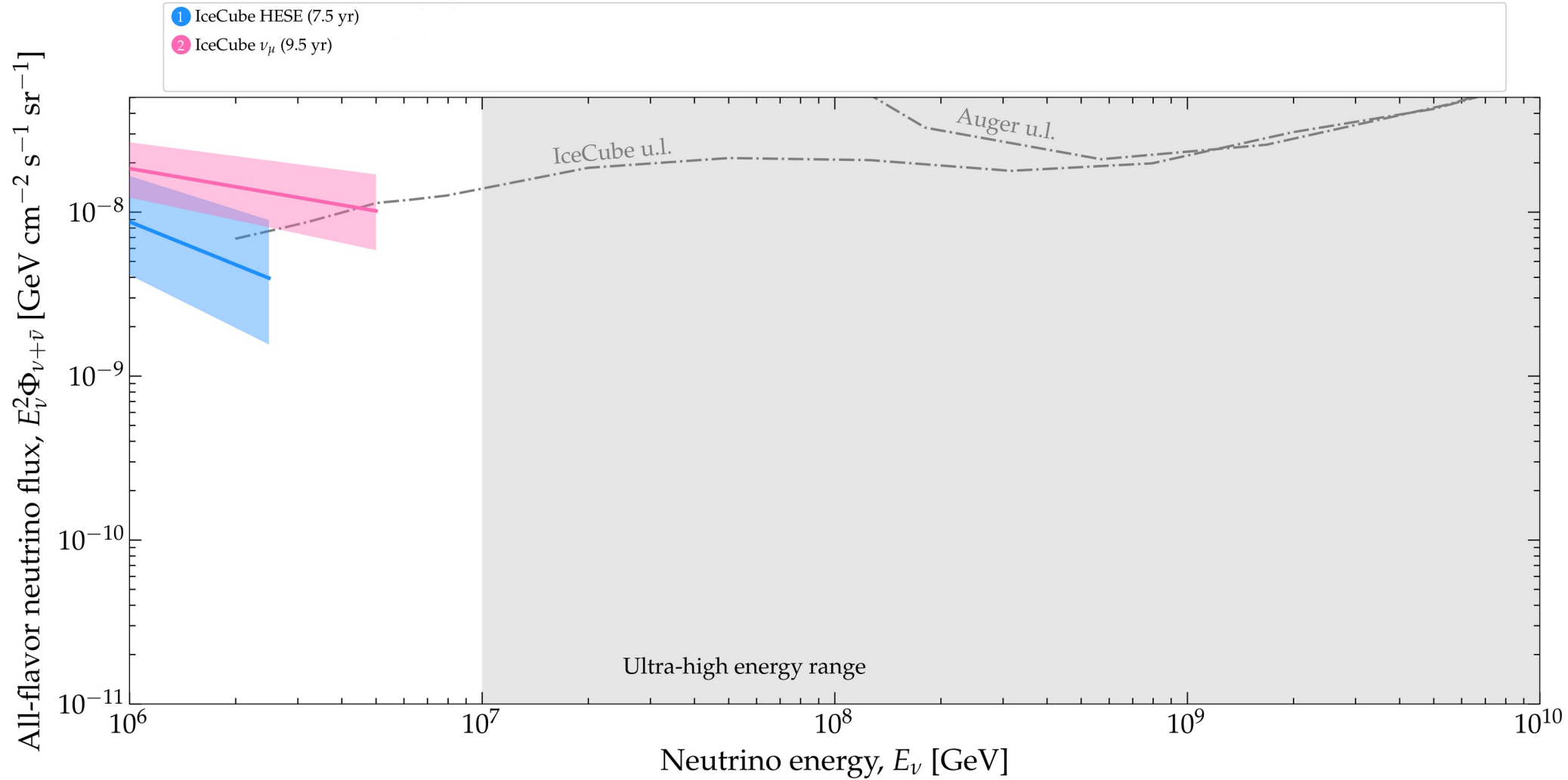
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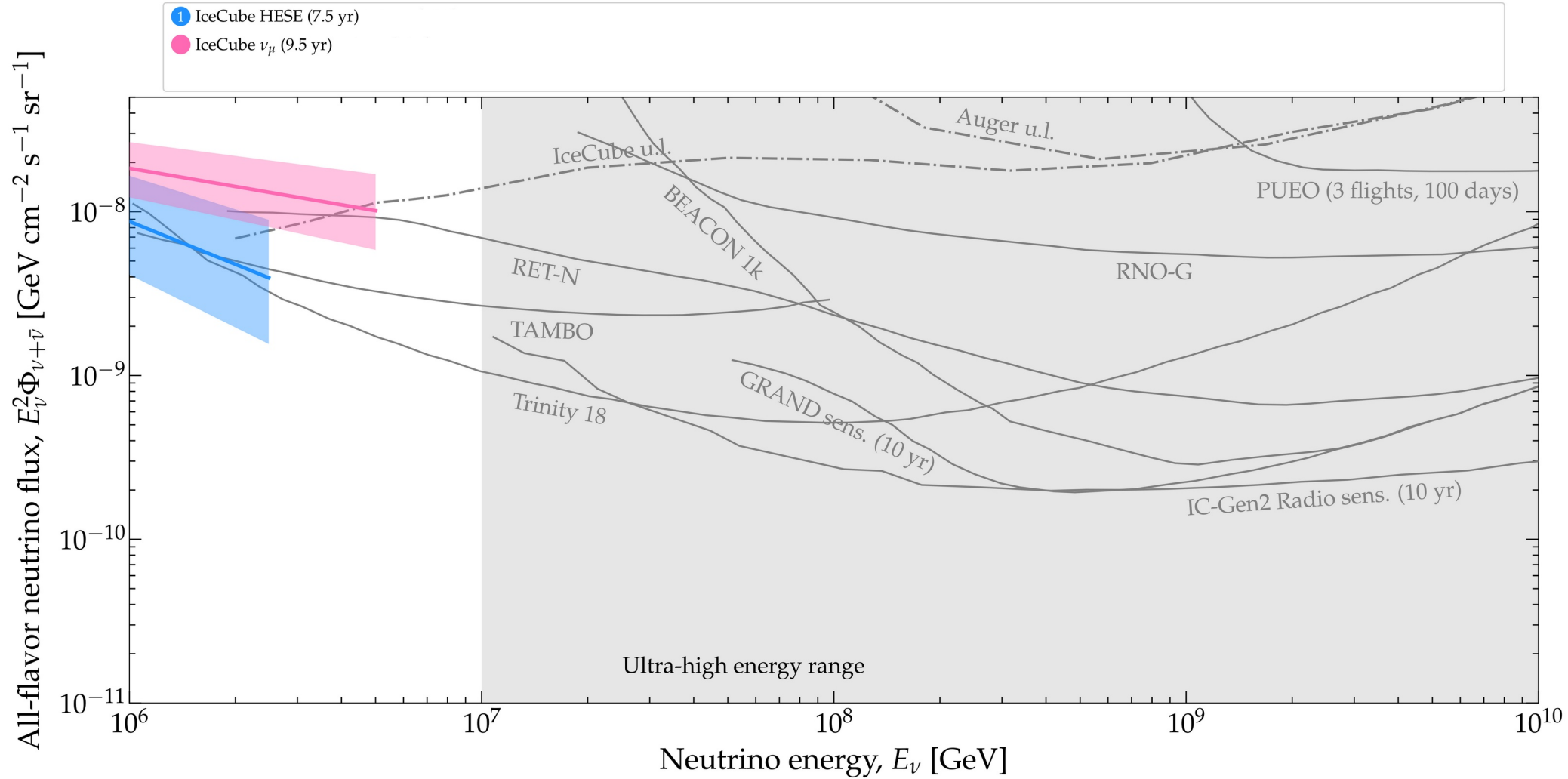
Note: ν sources can be steady-state or transient

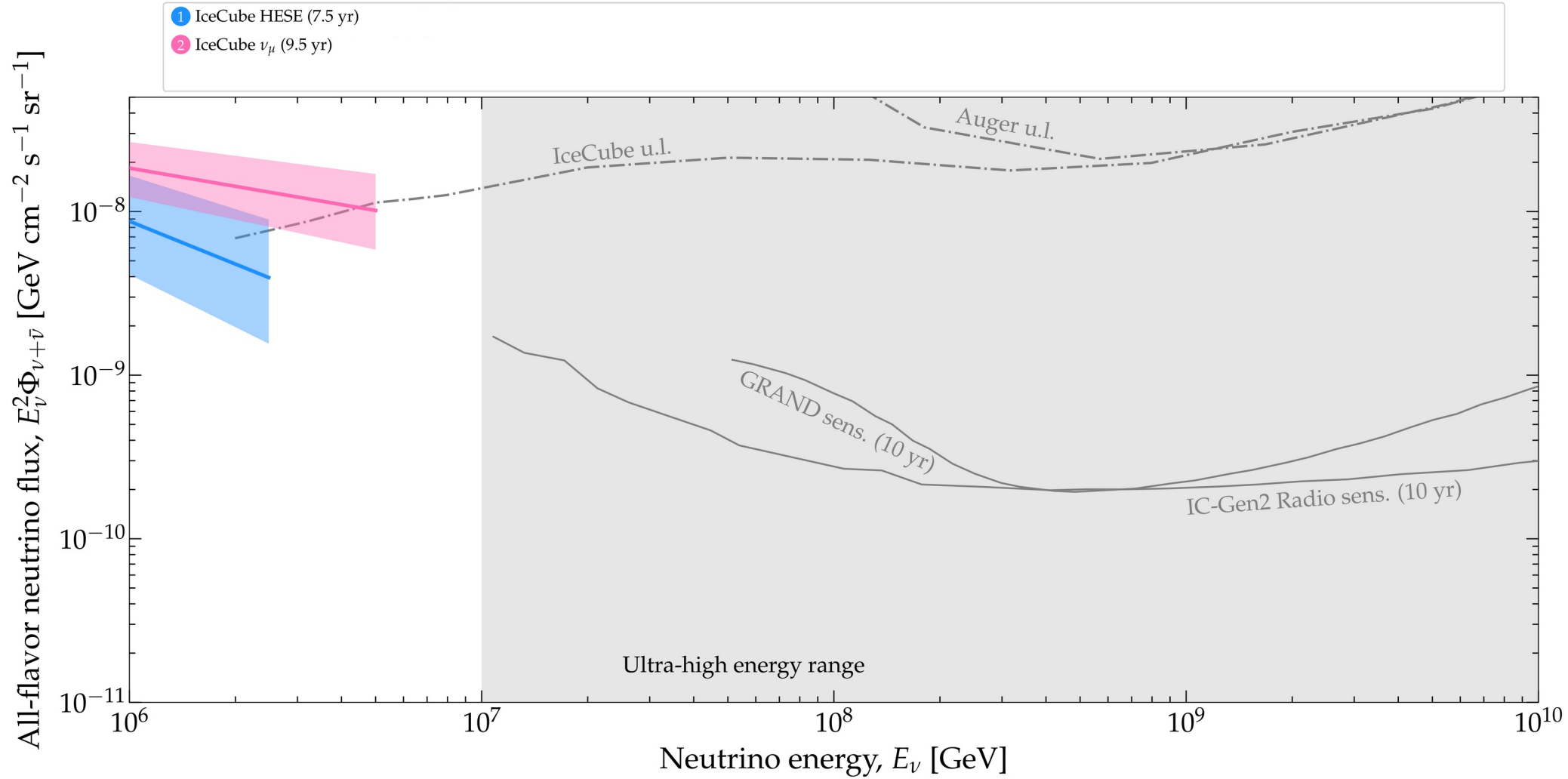


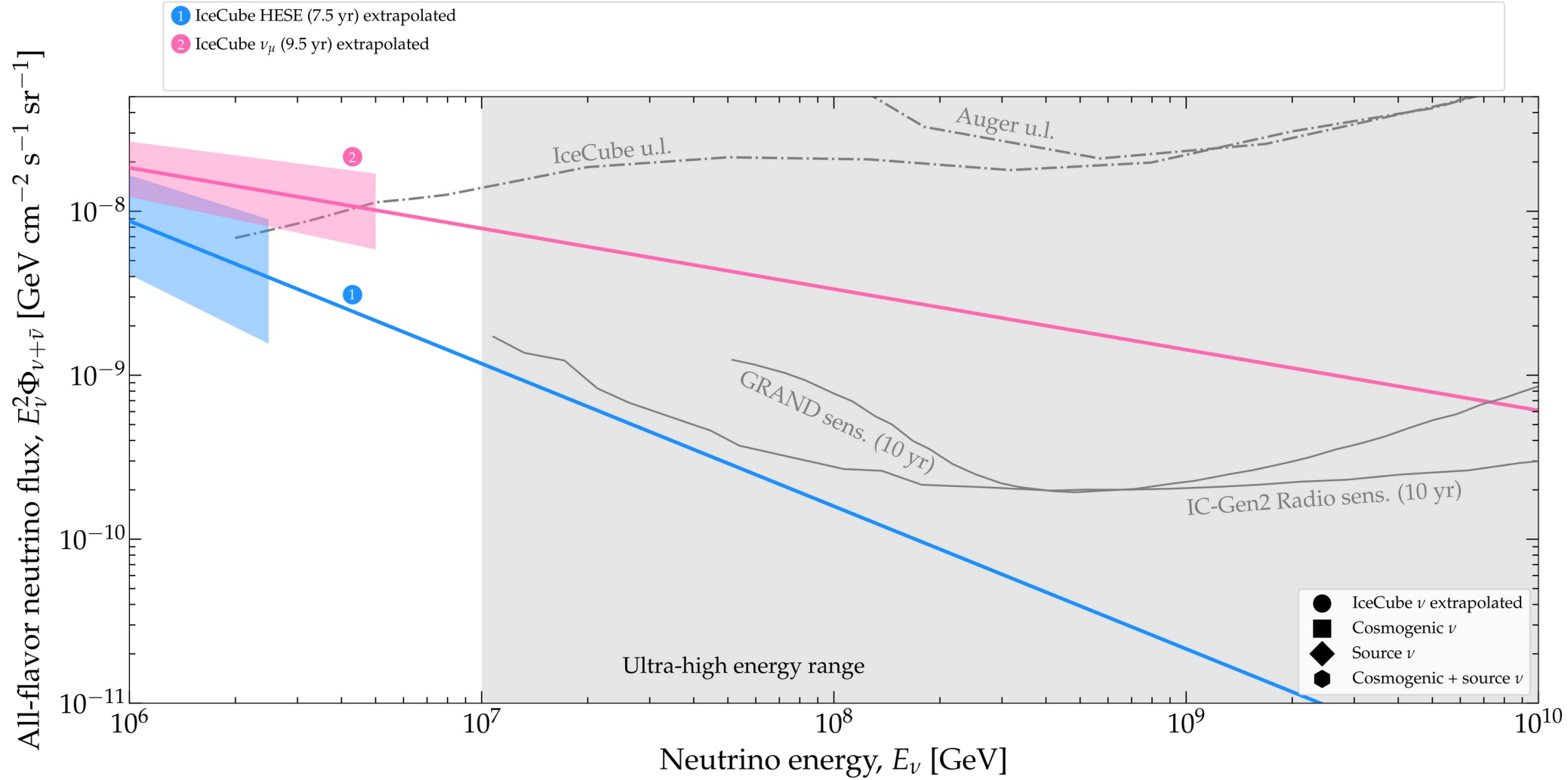


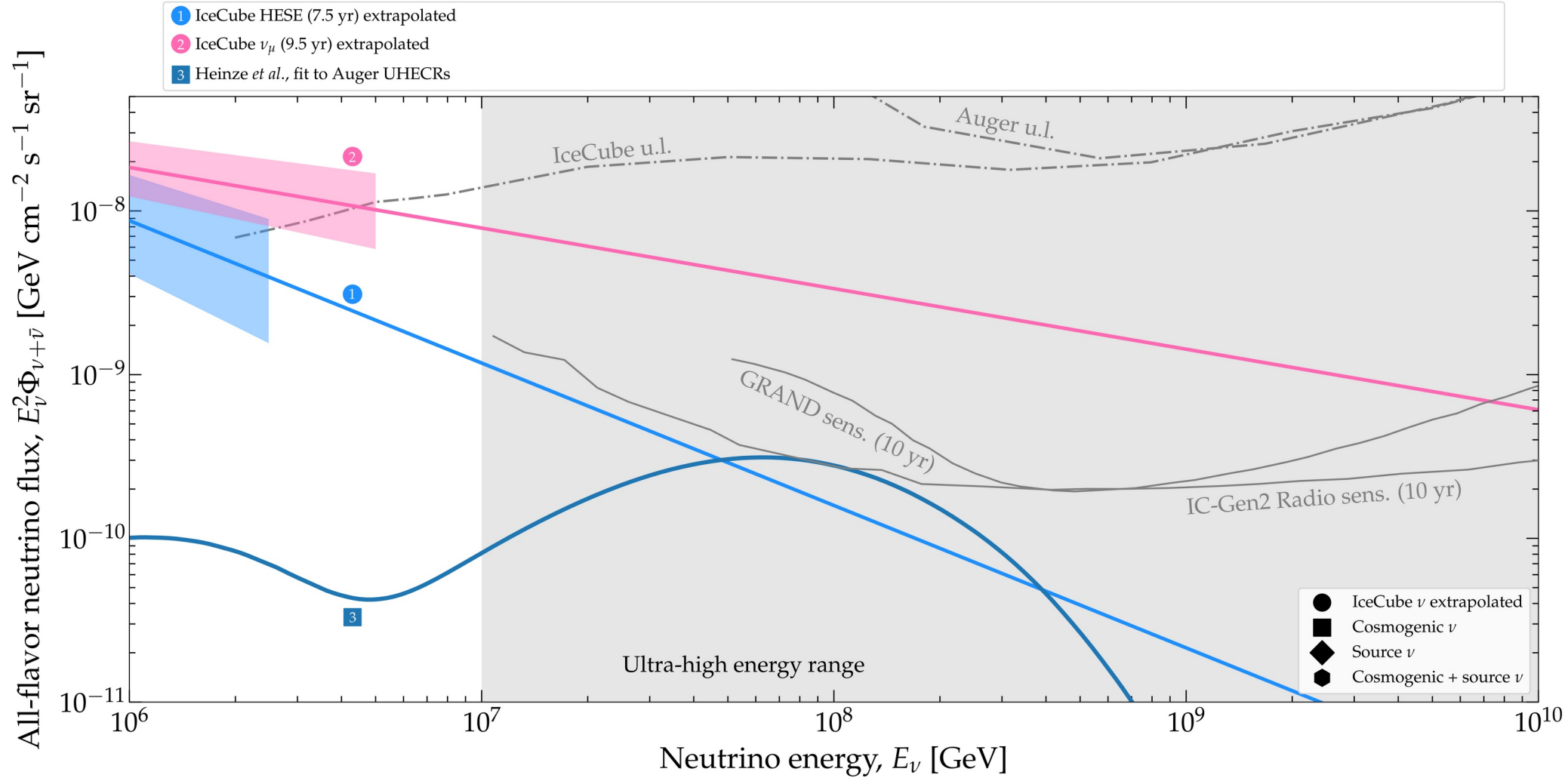


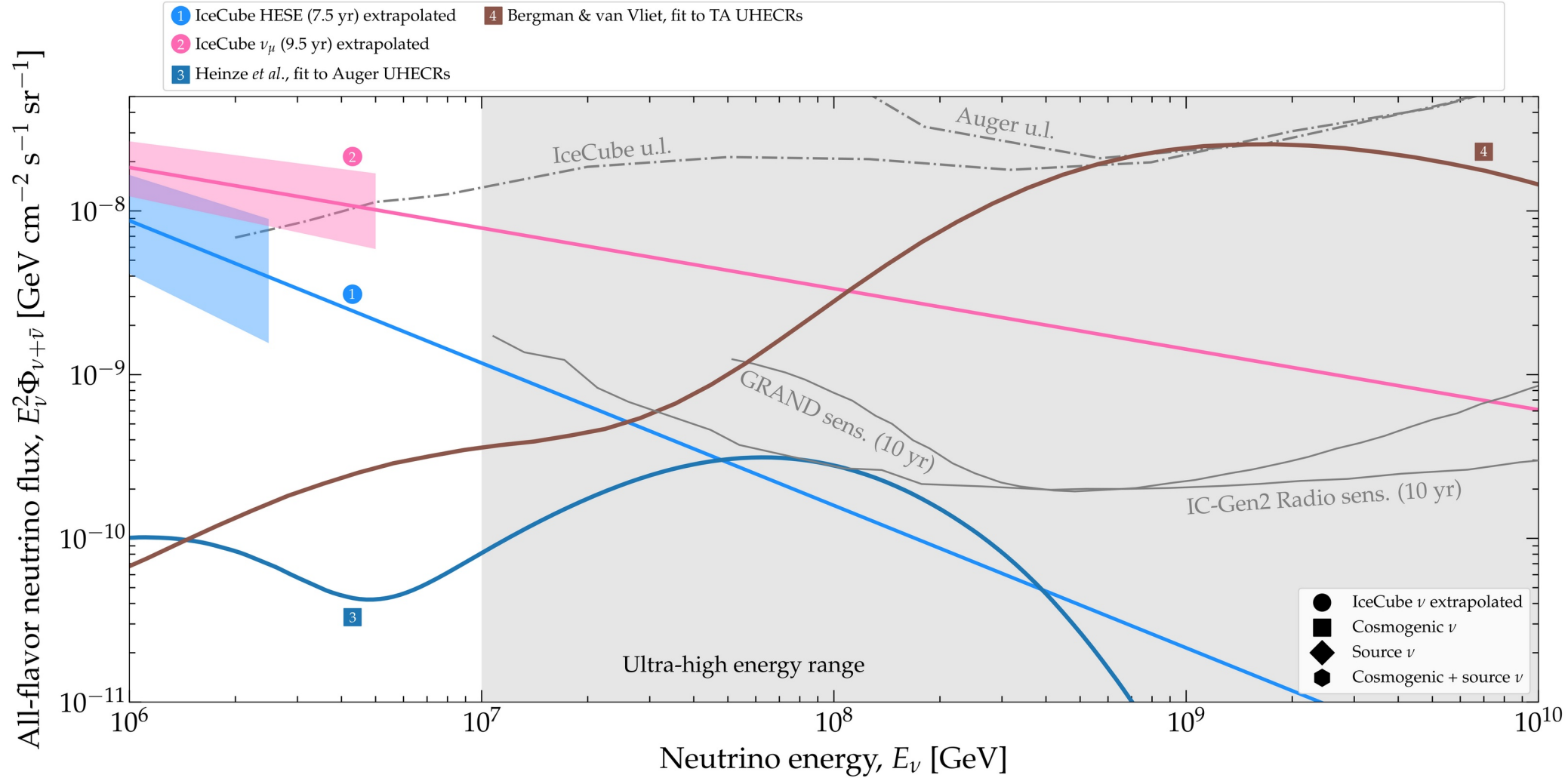


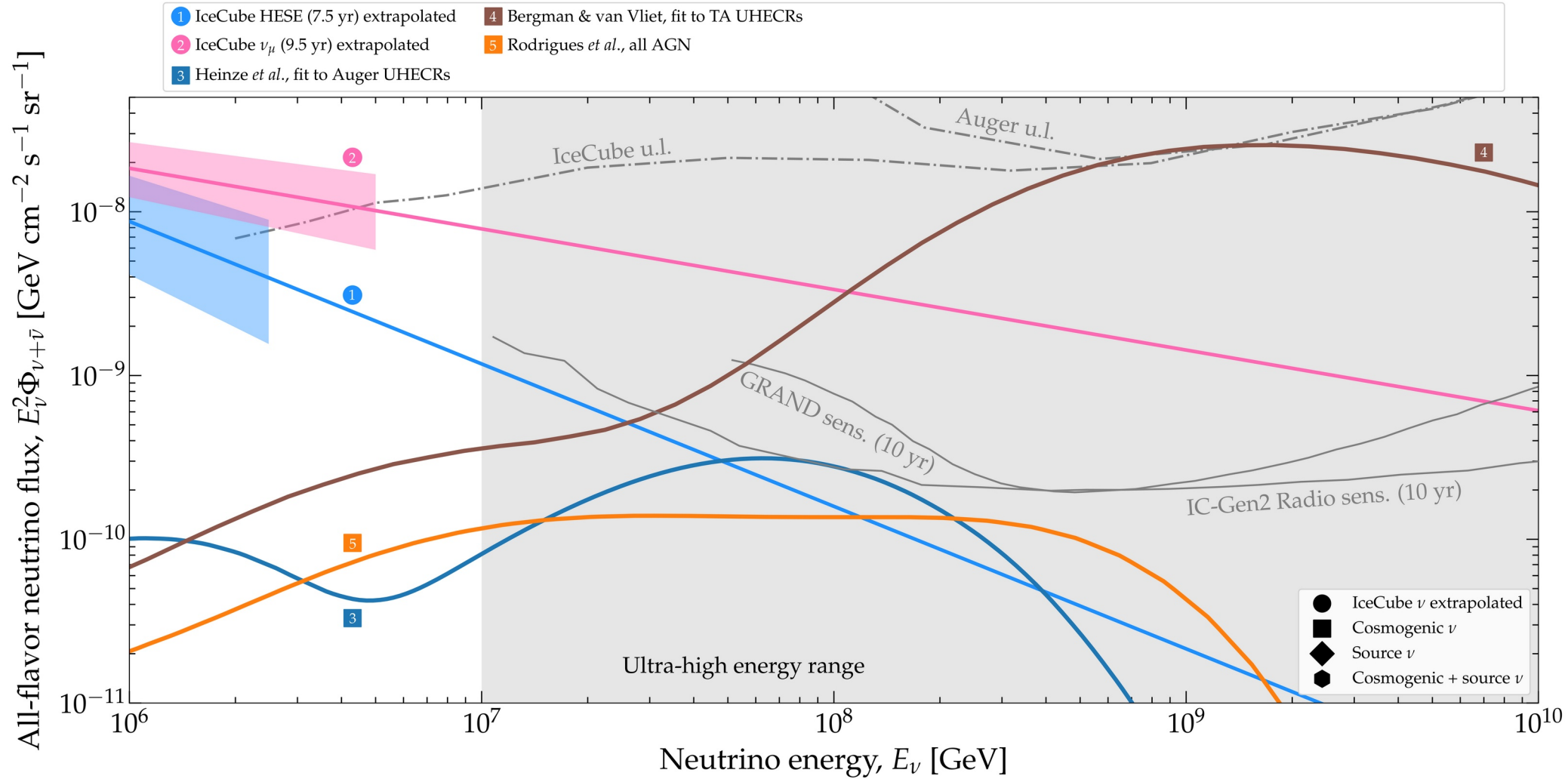






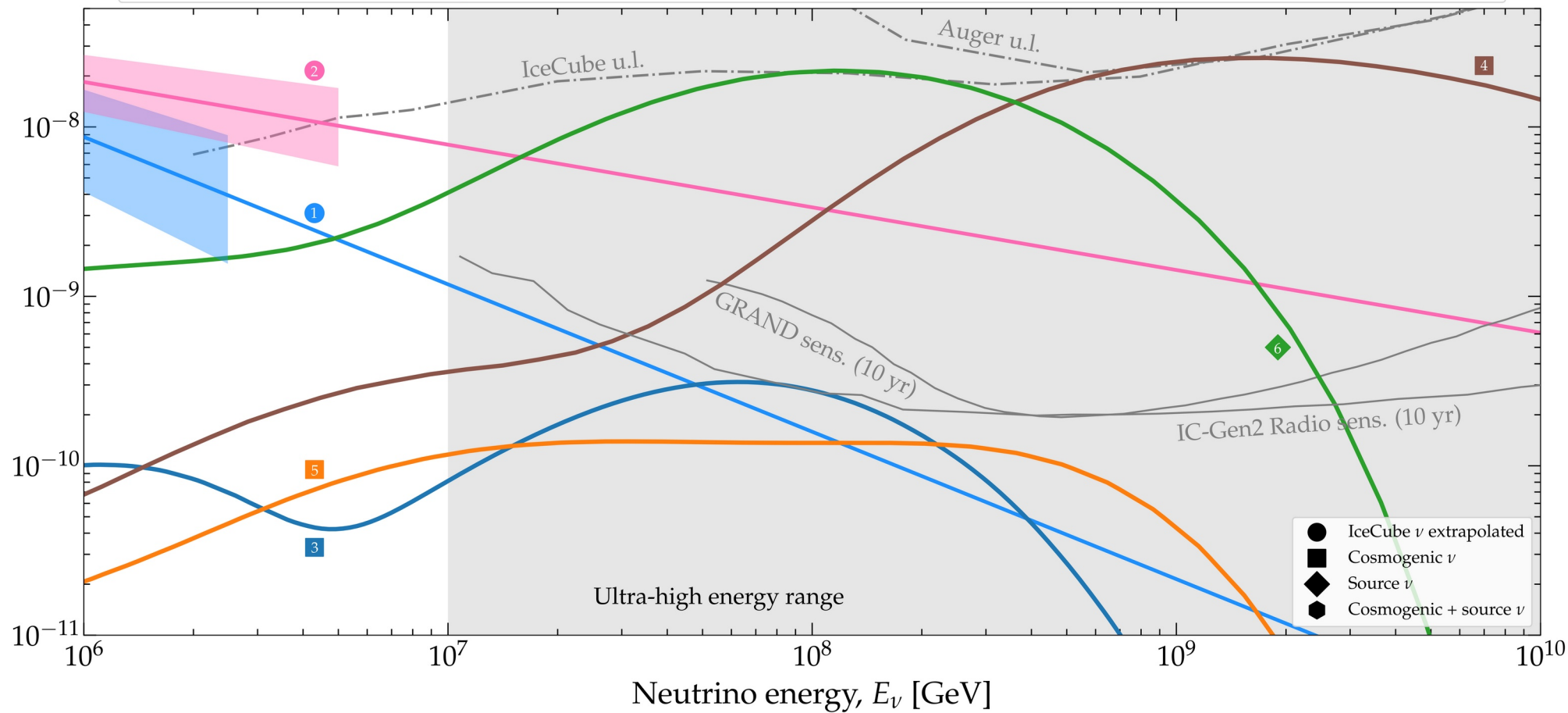


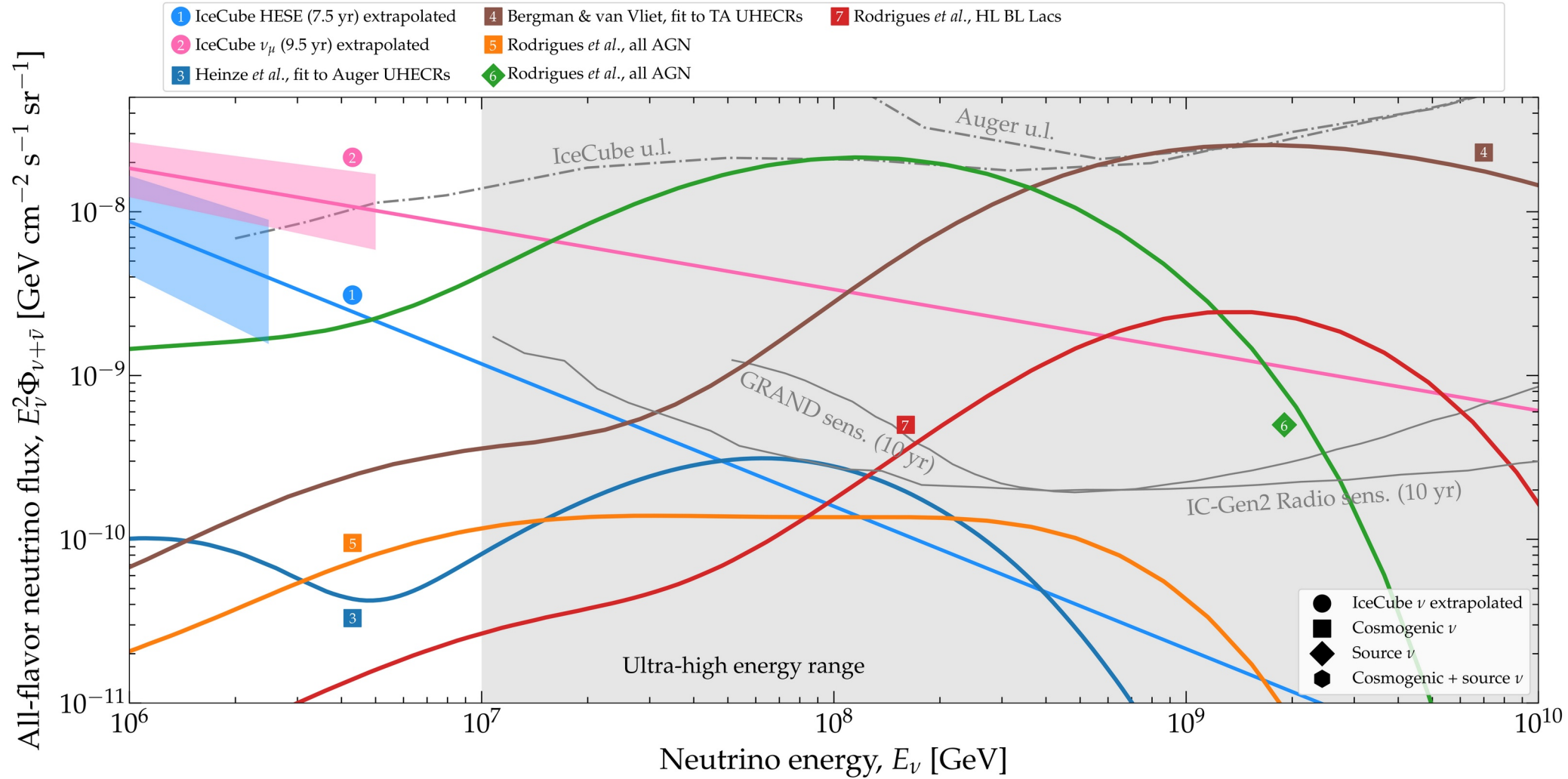


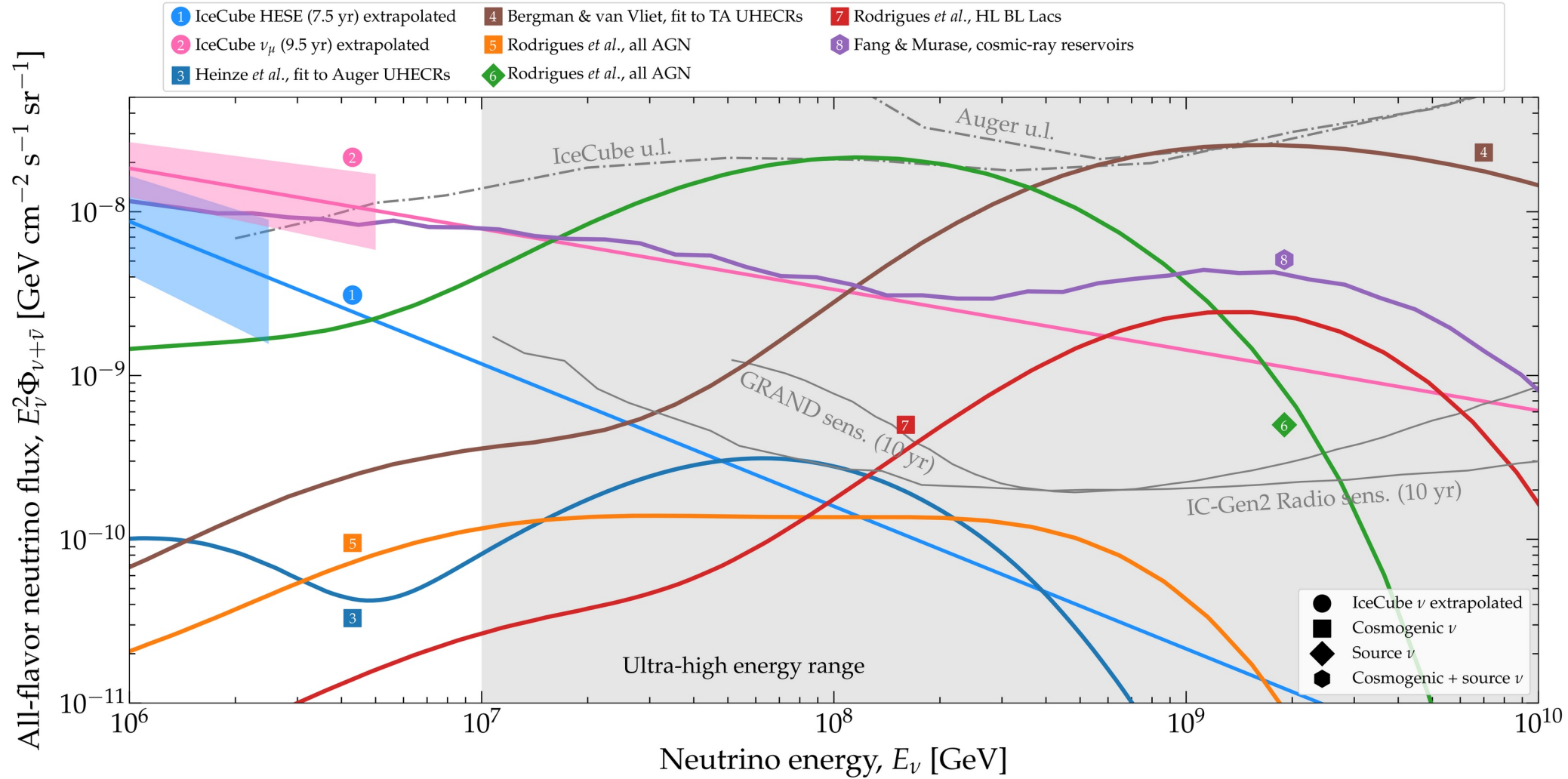


All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [$\text{GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$]

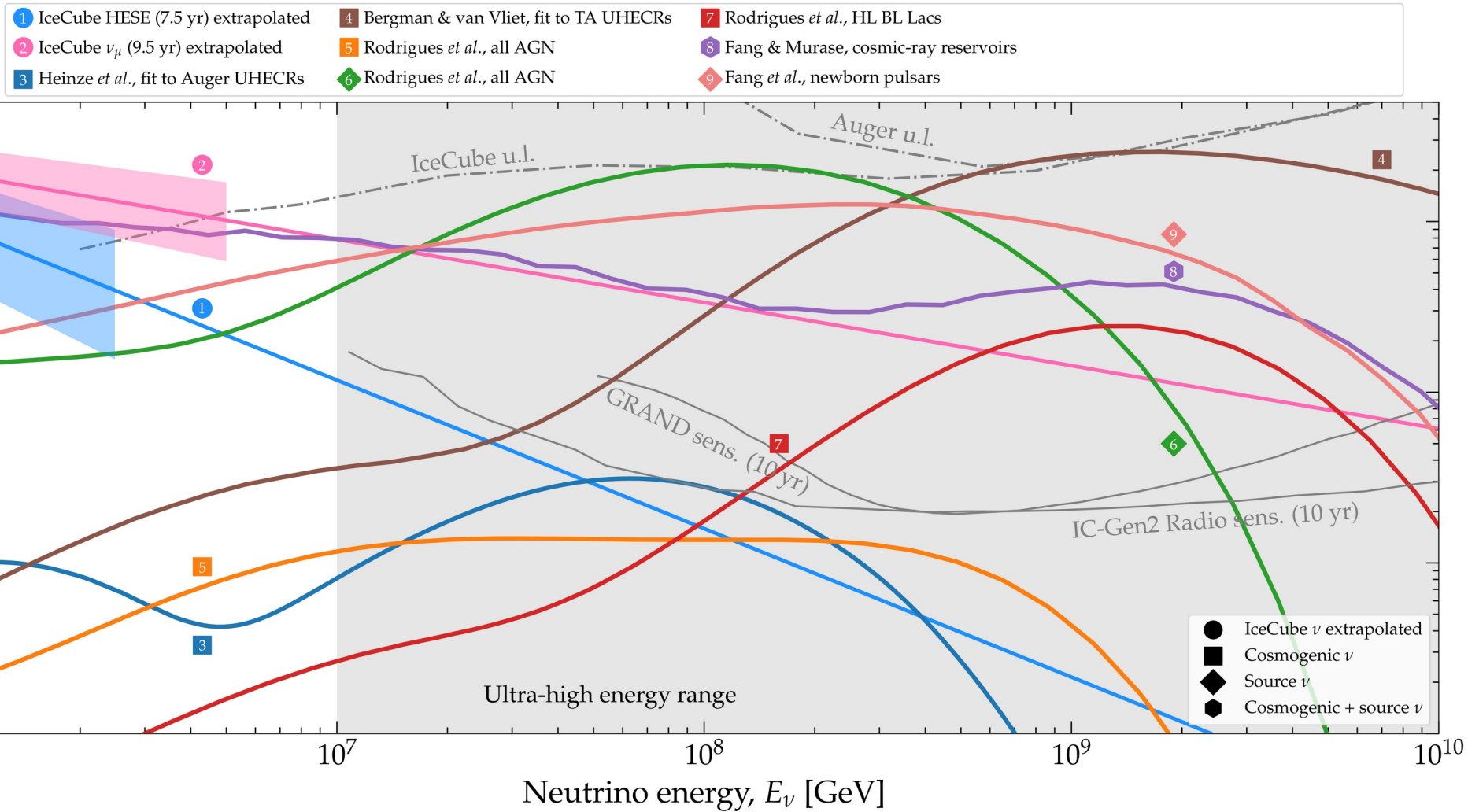
- 1 IceCube HESE (7.5 yr) extrapolated
- 2 IceCube ν_μ (9.5 yr) extrapolated
- 3 Heinze *et al.*, fit to Auger UHECRs
- 4 Bergman & van Vliet, fit to TA UHECRs
- 5 Rodrigues *et al.*, all AGN
- 6 Rodrigues *et al.*, all AGN

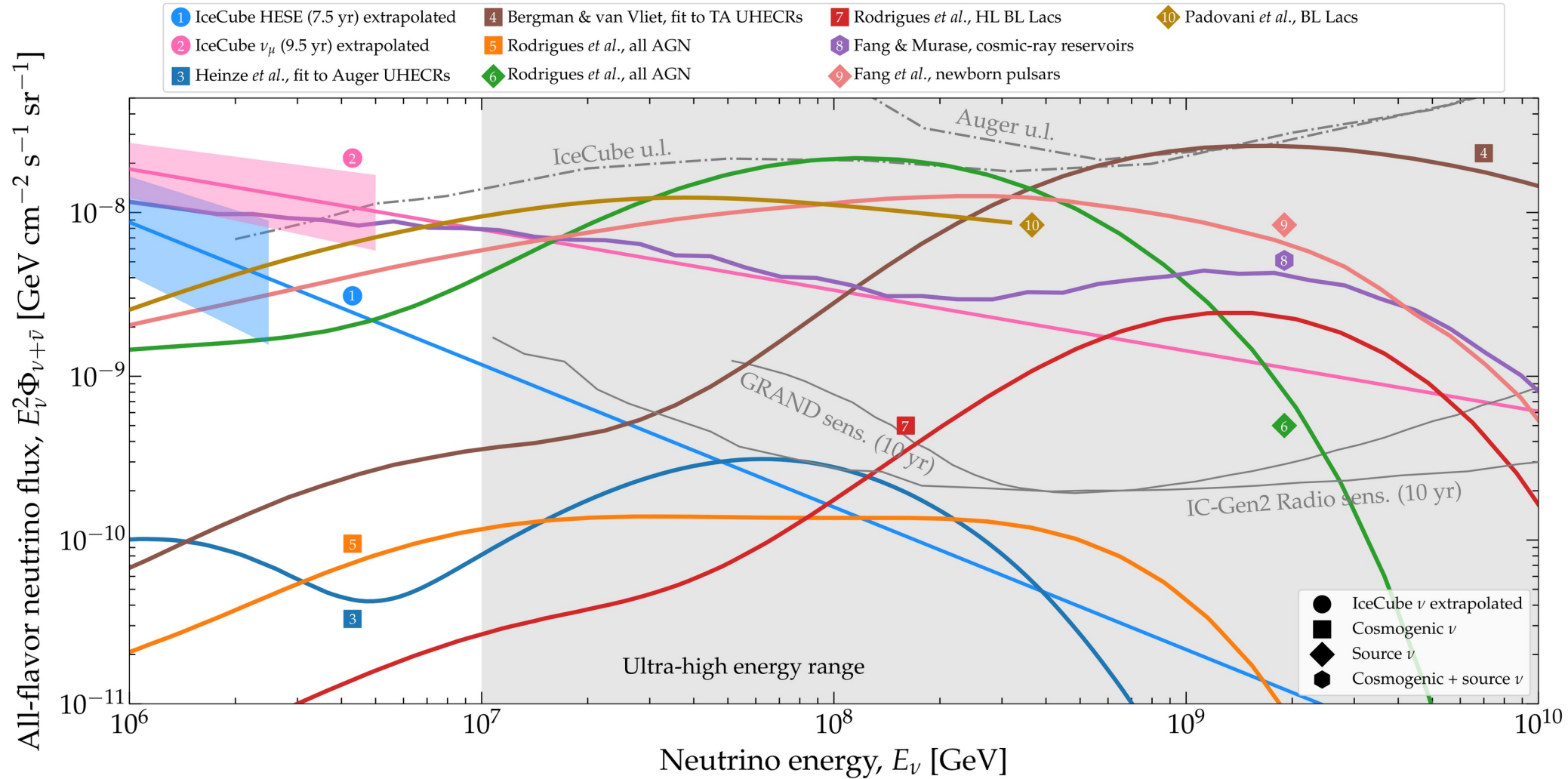






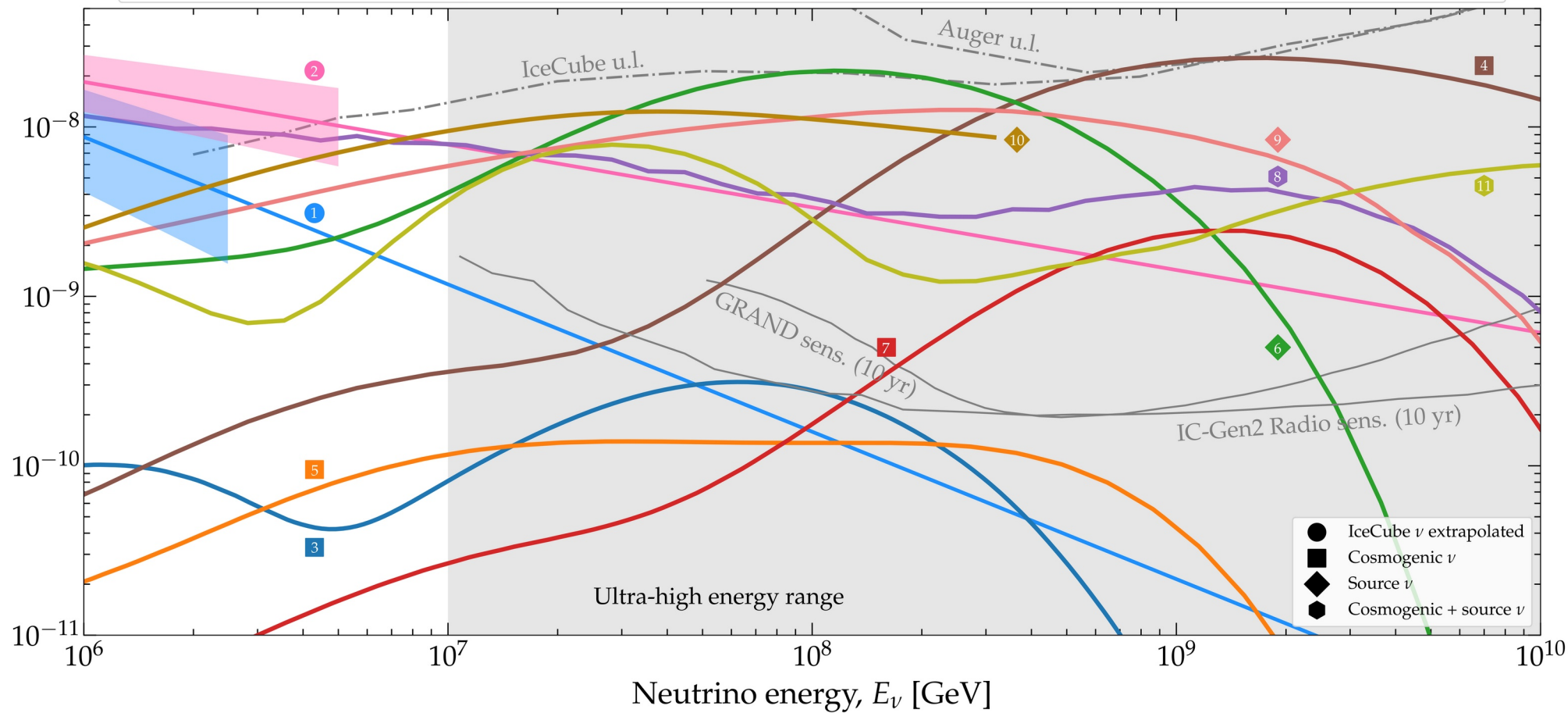
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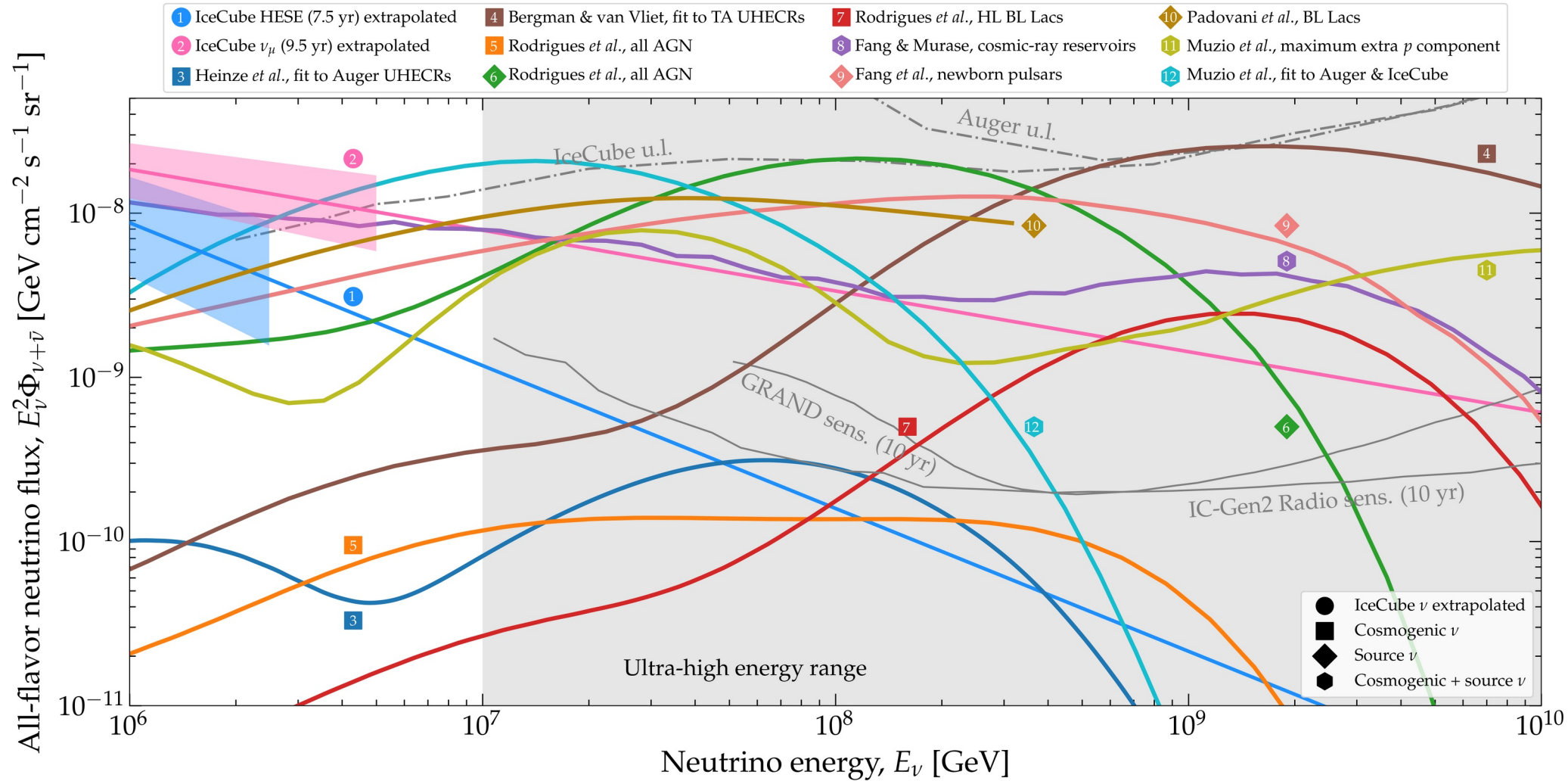




All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [$\text{GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$]

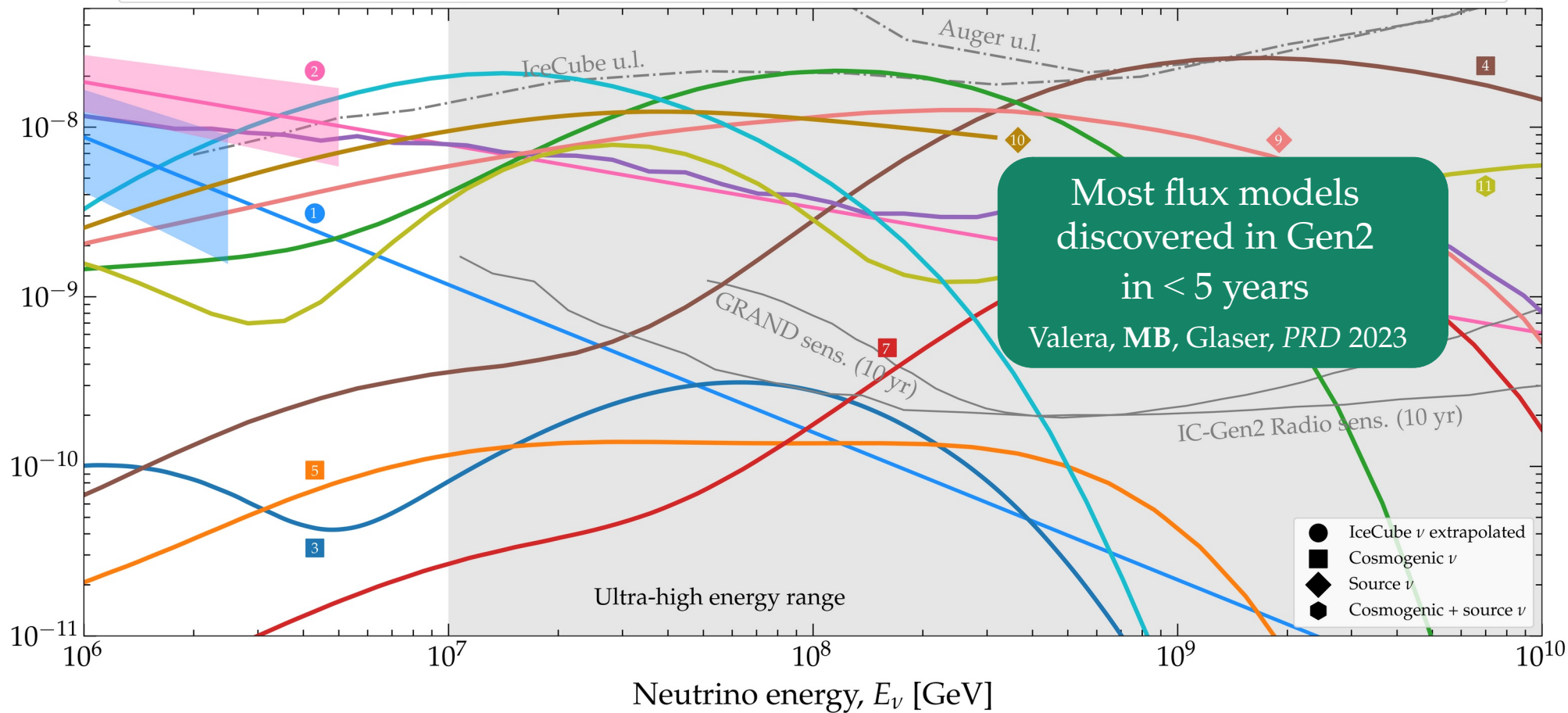
- | | | | |
|--|---|--|--|
| 1 IceCube HESE (7.5 yr) extrapolated | 4 Bergman & van Vliet, fit to TA UHECRs | 7 Rodrigues <i>et al.</i> , HL BL Lacs | 10 Padovani <i>et al.</i> , BL Lacs |
| 2 IceCube ν_μ (9.5 yr) extrapolated | 5 Rodrigues <i>et al.</i> , all AGN | 8 Fang & Murase, cosmic-ray reservoirs | 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 | |



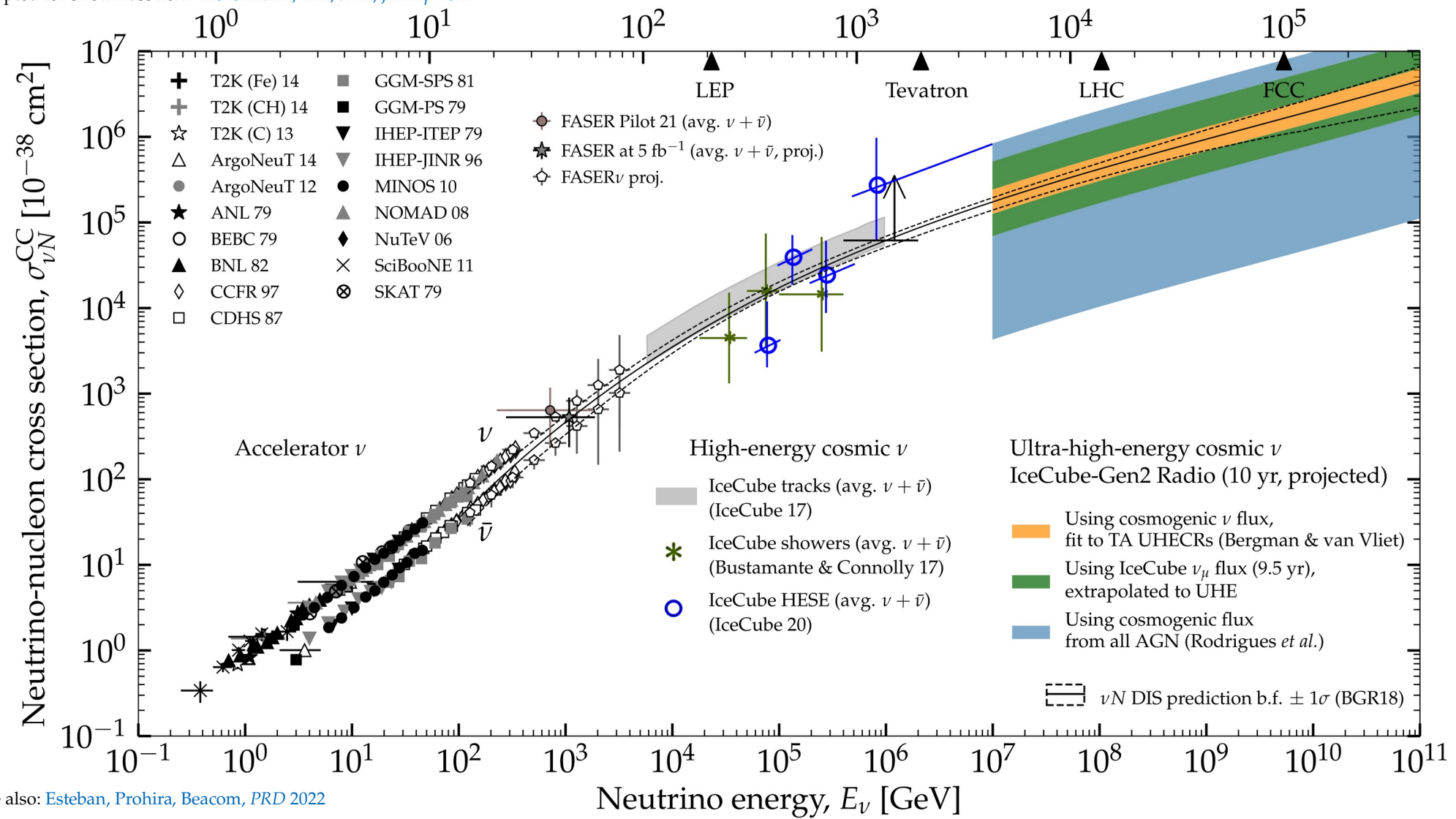


All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [$\text{GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$]

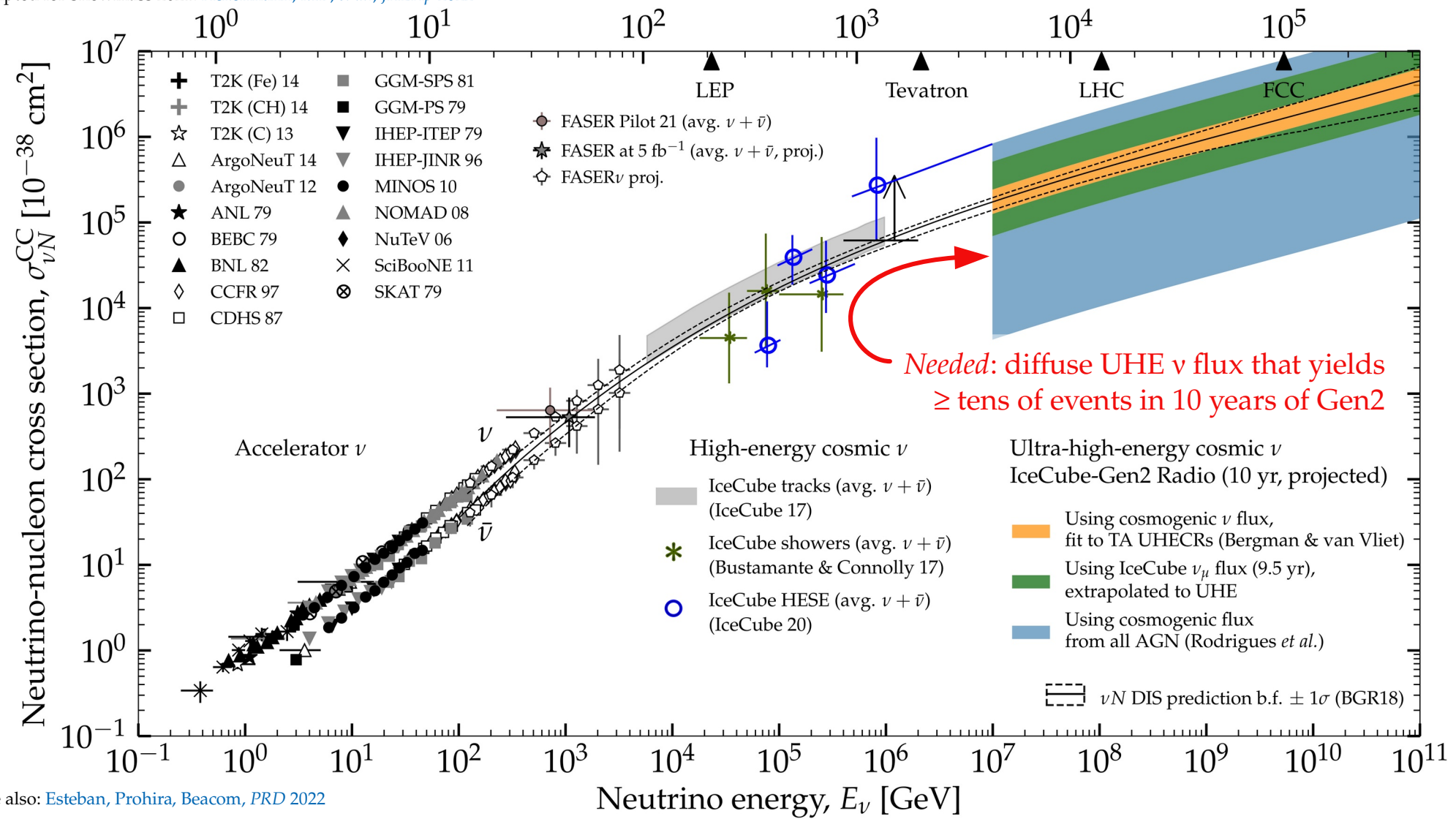
- | | | | |
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| 3 Heinze <i>et al.</i> , fit to Auger UHECRs | 6 Rodrigues <i>et al.</i> , all AGN | 9 Fang <i>et al.</i> , newborn pulsars | 12 Muzio <i>et al.</i> , fit to Auger & IceCube |



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



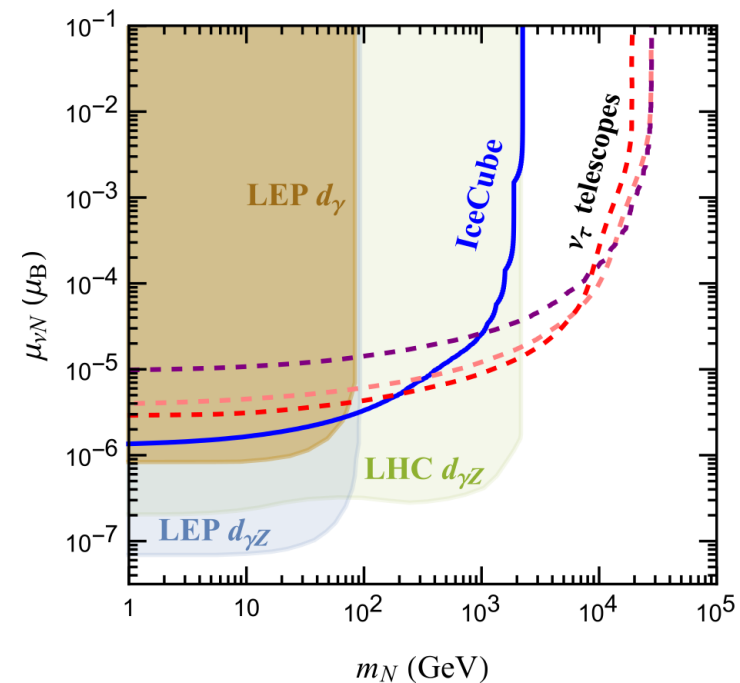
Center-of-mass energy $\sqrt{s}$ [GeV]



New physics in the UHE νN cross section

New physics in the UHE νN cross section

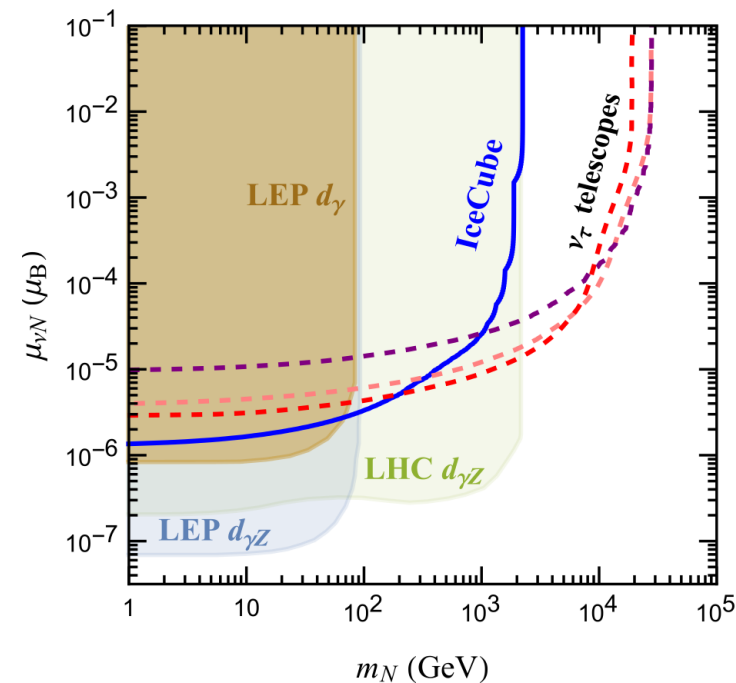
Heavy sterile neutrinos
via the dipole portal



Huang, Jana, Lindner, Rodejohann, *PLB* 2023 [2204.10347]

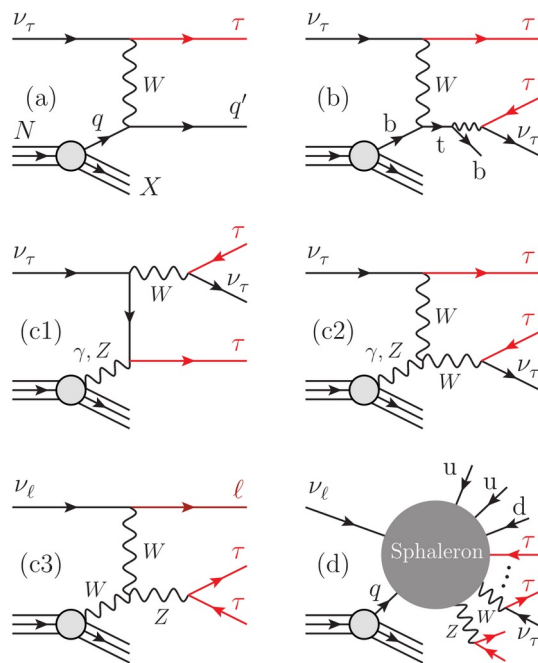
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Huang, Jana, Lindner, Rodejohann, *PLB* 2023 [2204.10347]

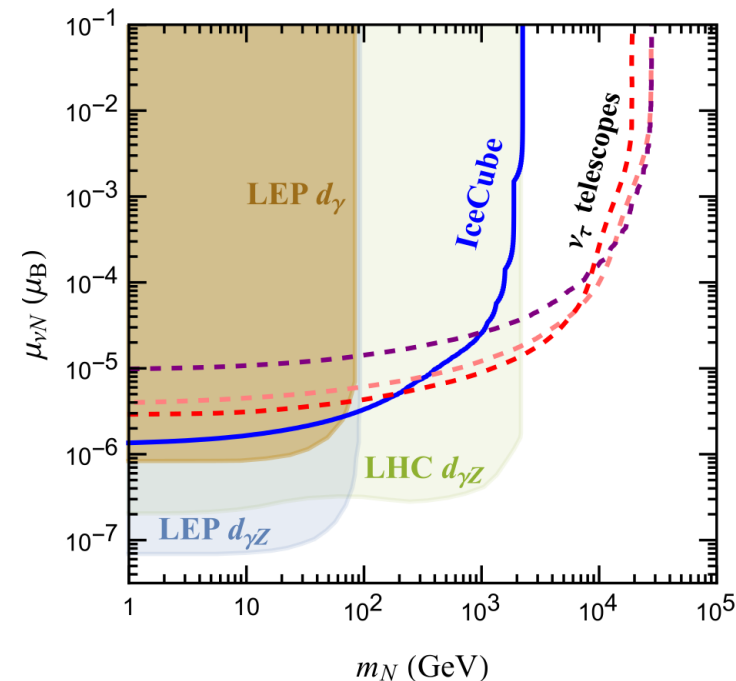
Multiple ν_τ -induced
bangs



Huang, *EPJC* 2022 [2207.02222]

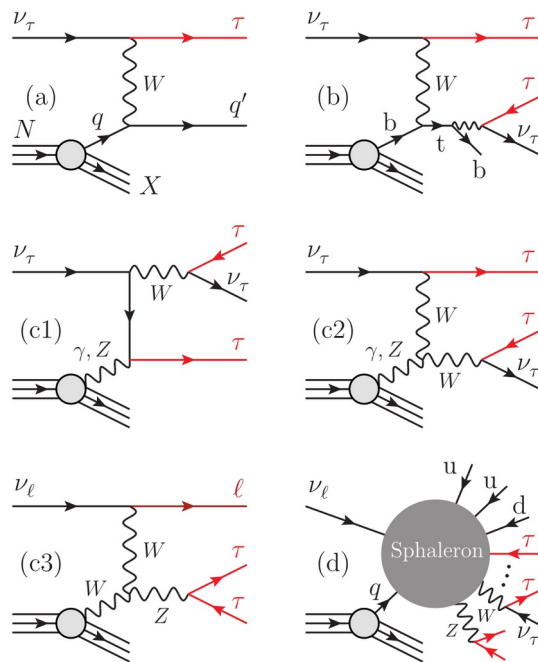
New physics in the UHE νN cross section

Heavy sterile neutrinos
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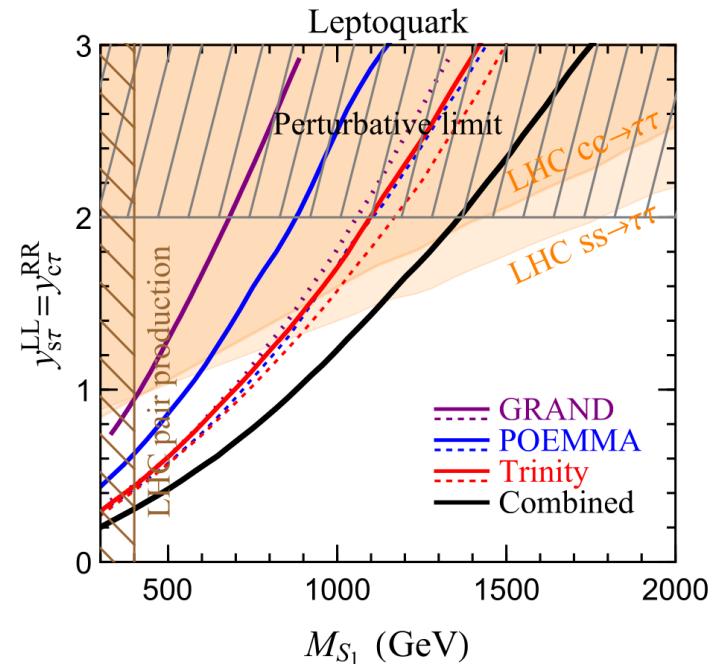
Huang, Jana, Lindner, Rodejohann, *PLB* 2023 [2204.10347]

Multiple ν_τ -induced
bangs



Huang, *EPJC* 2022 [2207.02222]

Leptoquarks,
charged Higgs, etc.



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

Today

TeV–PeV ν

Turn predictions
into data-driven tests

Key developments:

Bigger detectors $\rightarrow$ larger statistics

Better reconstruction

Smaller astrophysical uncertainties

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TeV–PeV ν

Turn predictions
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Next decade
 > 100 -PeV ν

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 $> 100\text{-PeV } \nu$

Make predictions for
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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

Turn predictions
into data-driven tests

Key developments:

Bigger detectors $\rightarrow$ larger statistics

Better reconstruction

Smaller astrophysical uncertainties

Next decade
 > 100 -PeV ν

Make predictions for
a new energy regime

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

3. Flavor:

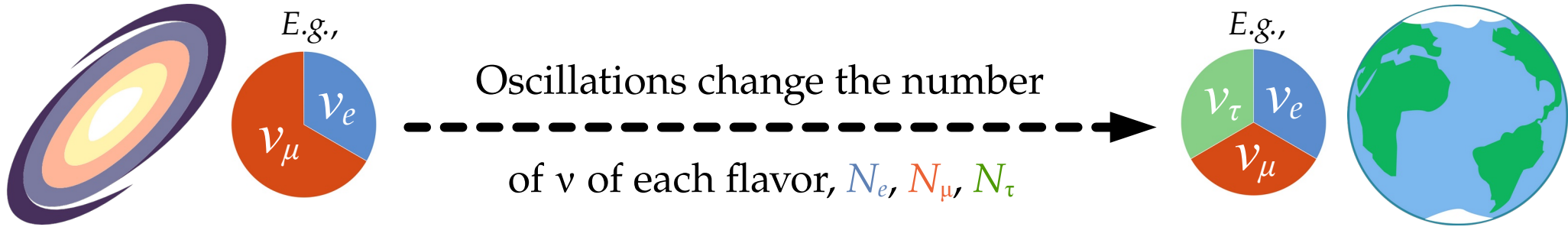
Towards precision, finally

(with the help of lower-energy experiments)

Astrophysical sources

Earth

Up to a few Gpc



Different production mechanisms yield different flavor ratios:

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

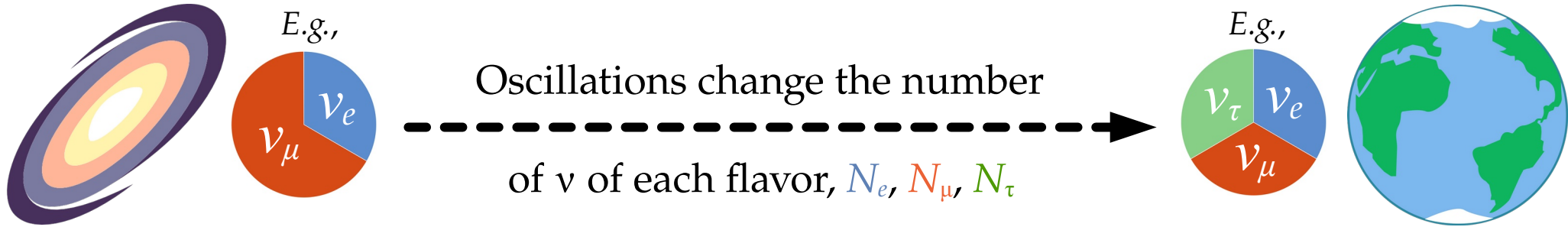
Flavor ratios at Earth ($\alpha = e, \mu, \tau$):

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

Astrophysical sources

Earth

Up to a few Gpc



Different production mechanisms yield different flavor ratios:

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

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

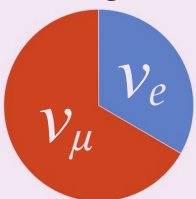
Standard oscillations
or
new physics

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



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

One likely TeV–PeV ν production scenario:

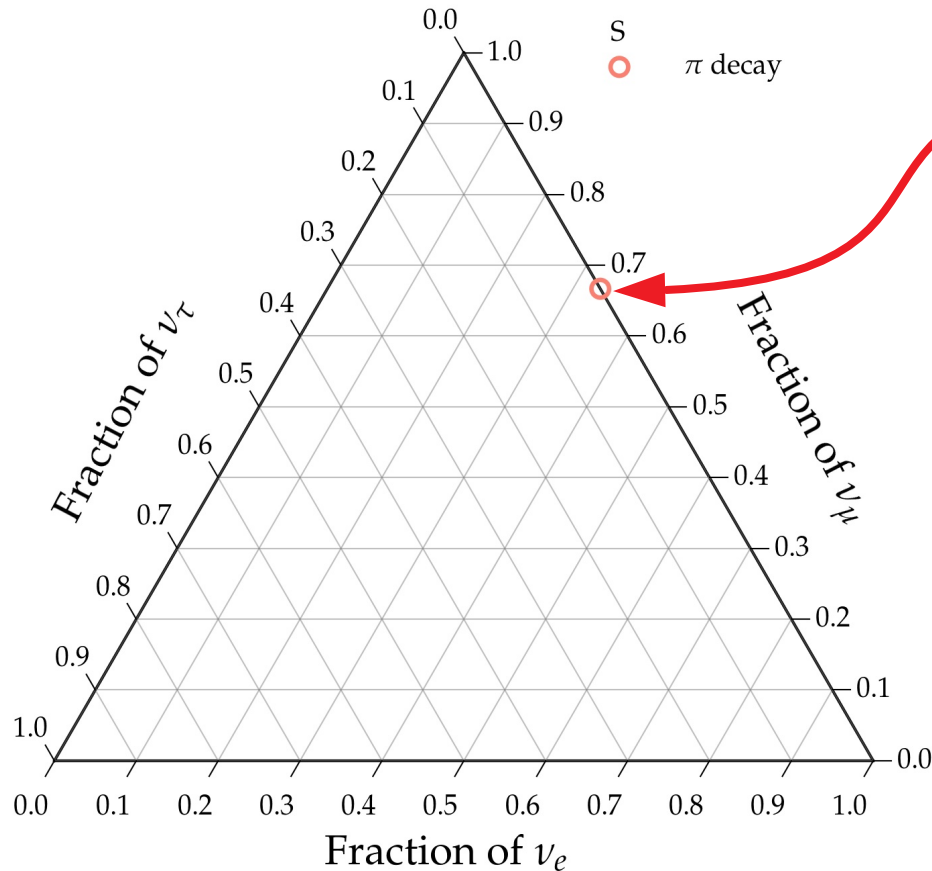
$$p + \gamma \rightarrow \pi^+ \rightarrow \mu^+ + \nu_\mu \text{ followed by } \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

Full π decay chain

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

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

One likely TeV–PeV ν production scenario:



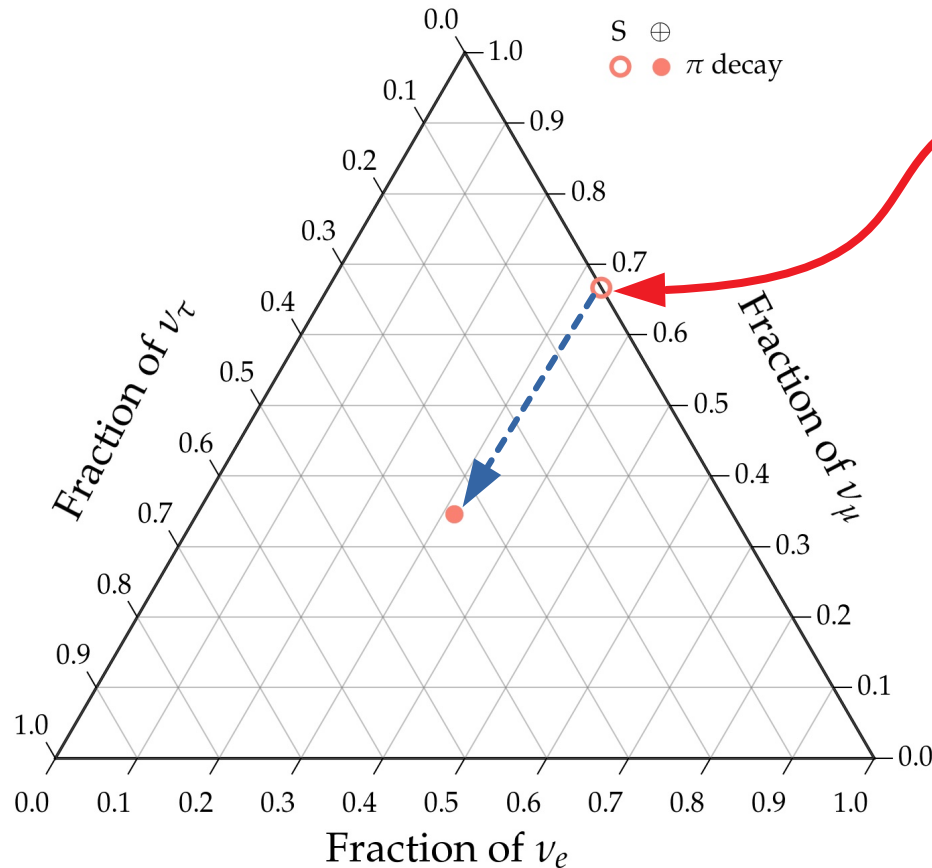
Full π decay chain

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

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

One likely TeV–PeV ν production scenario:

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

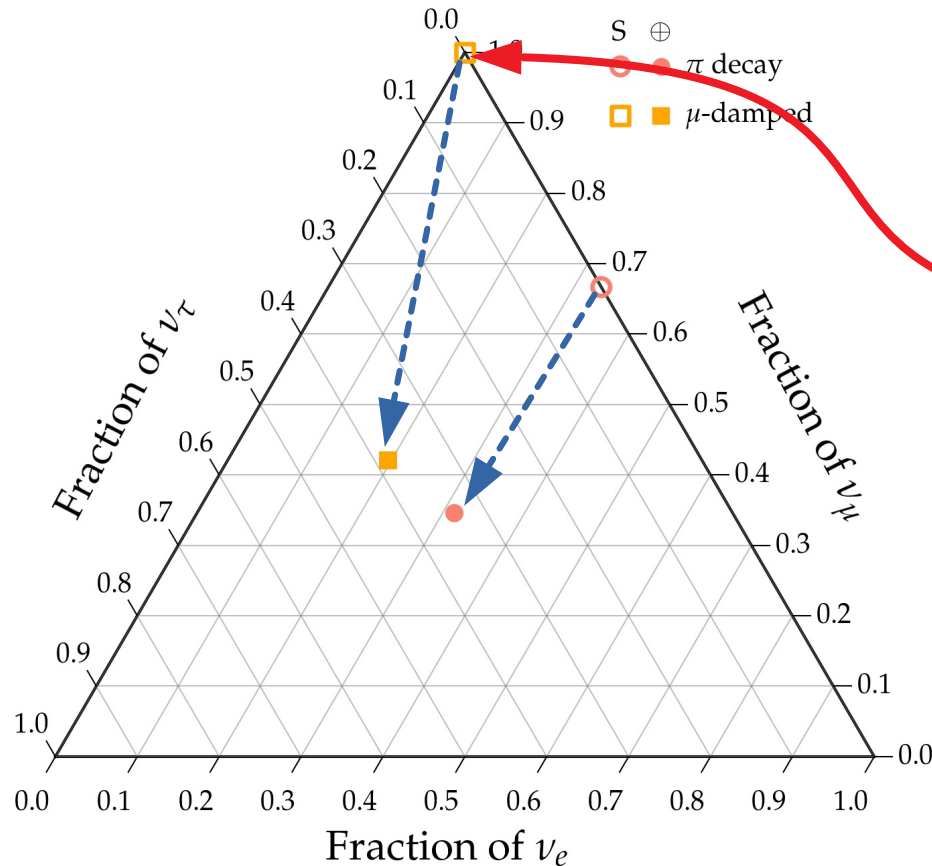


Full π decay chain

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One likely TeV–PeV ν production scenario:



Full π decay chain

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

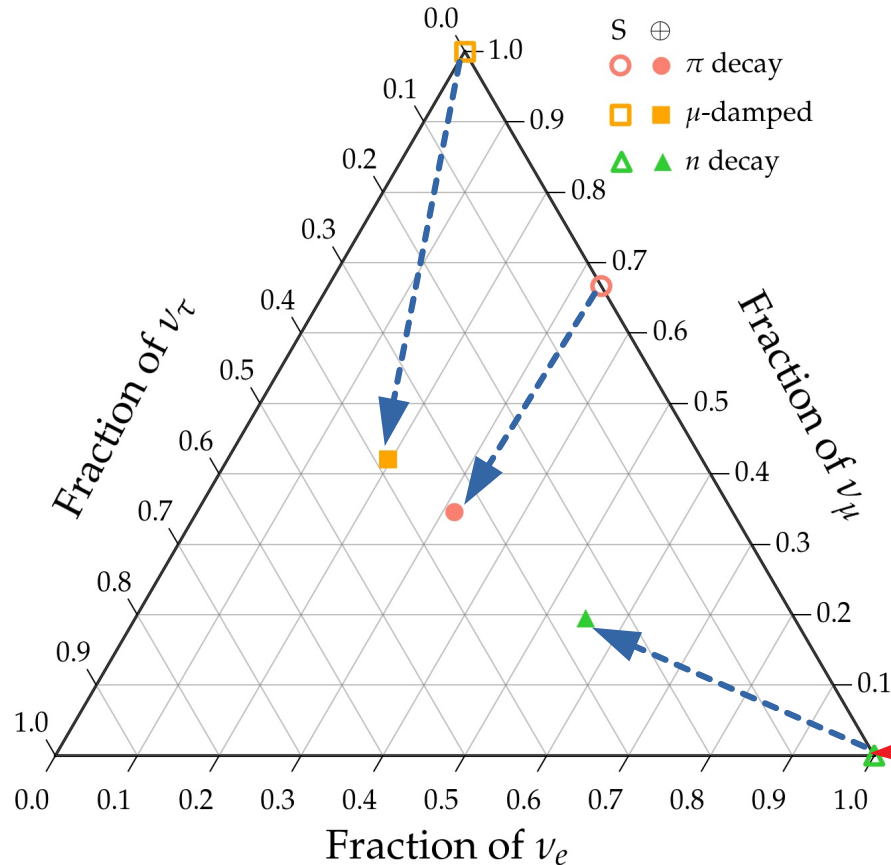
Muon damped

$(0:1:0)_S$

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

One likely TeV–PeV ν production scenario:

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



Full π decay chain

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

Muon damped

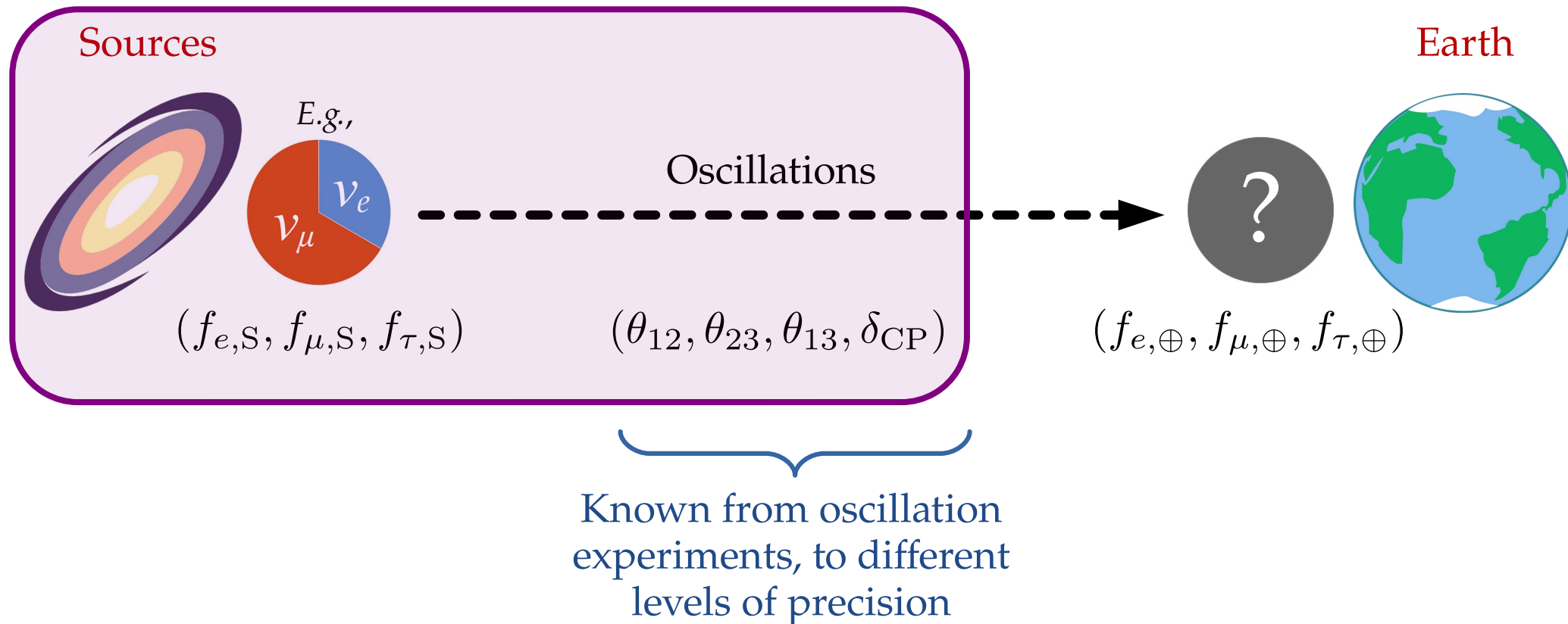
$$(0:1:0)_S$$

Neutron decay

$$(1:0:0)_S$$

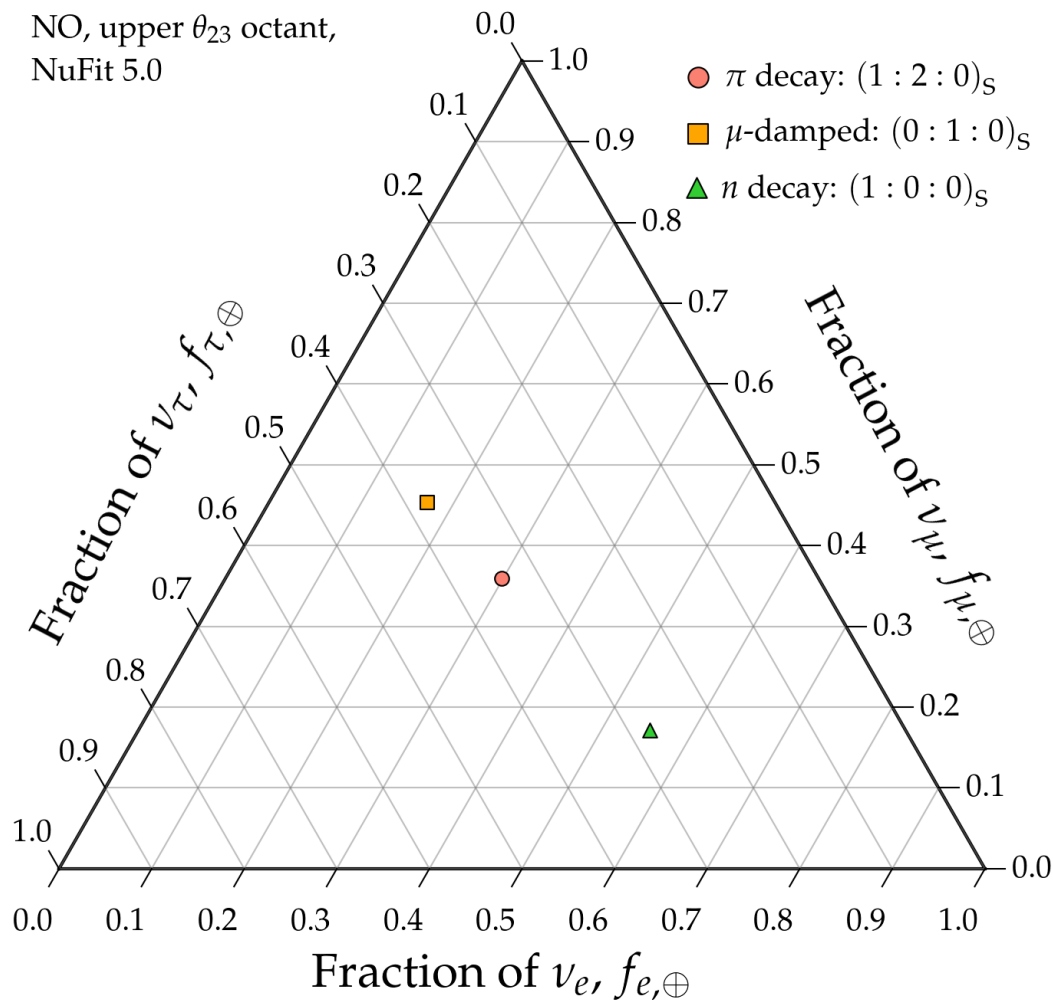
Note: ν and $\bar{\nu}$ are (so far) indistinguishable in neutrino telescopes

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



Theoretically palatable regions: today

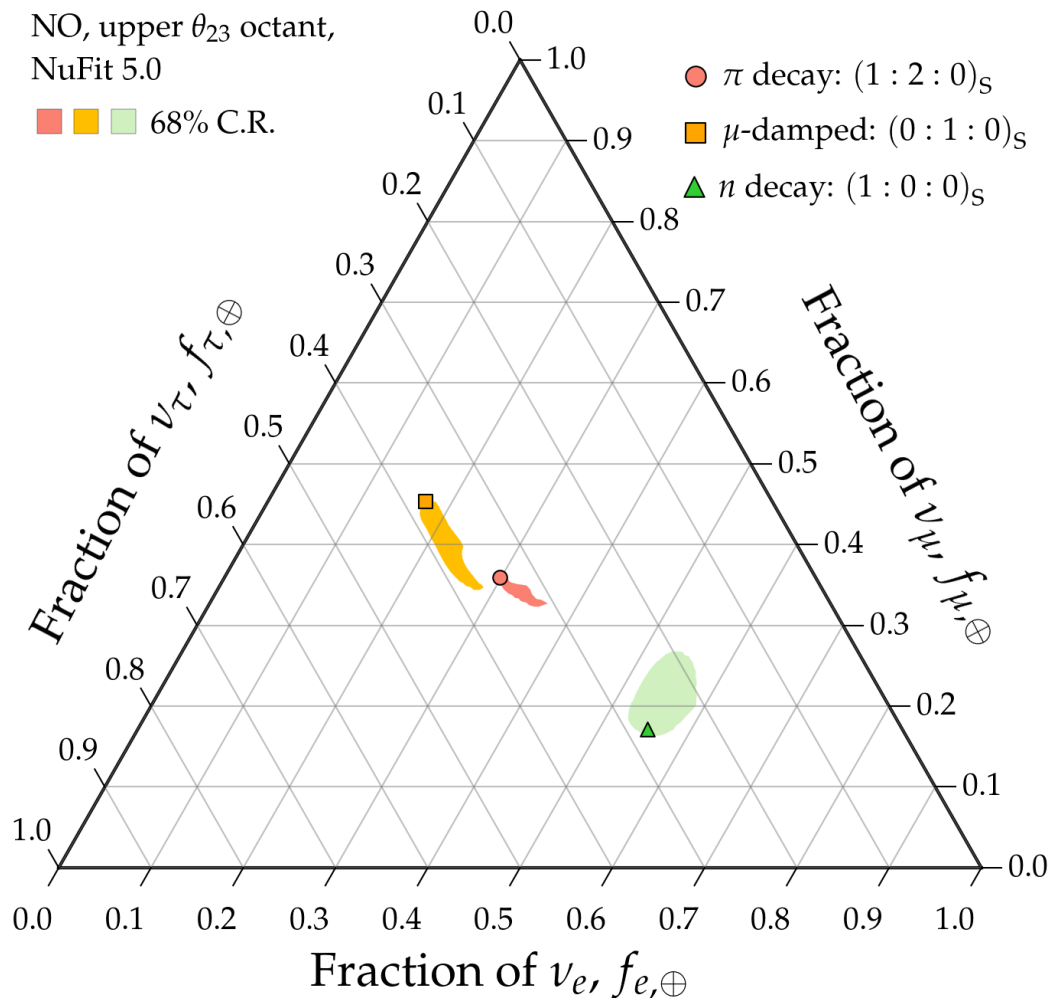
NO, upper θ_{23} octant,
NuFit 5.0



Note:

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

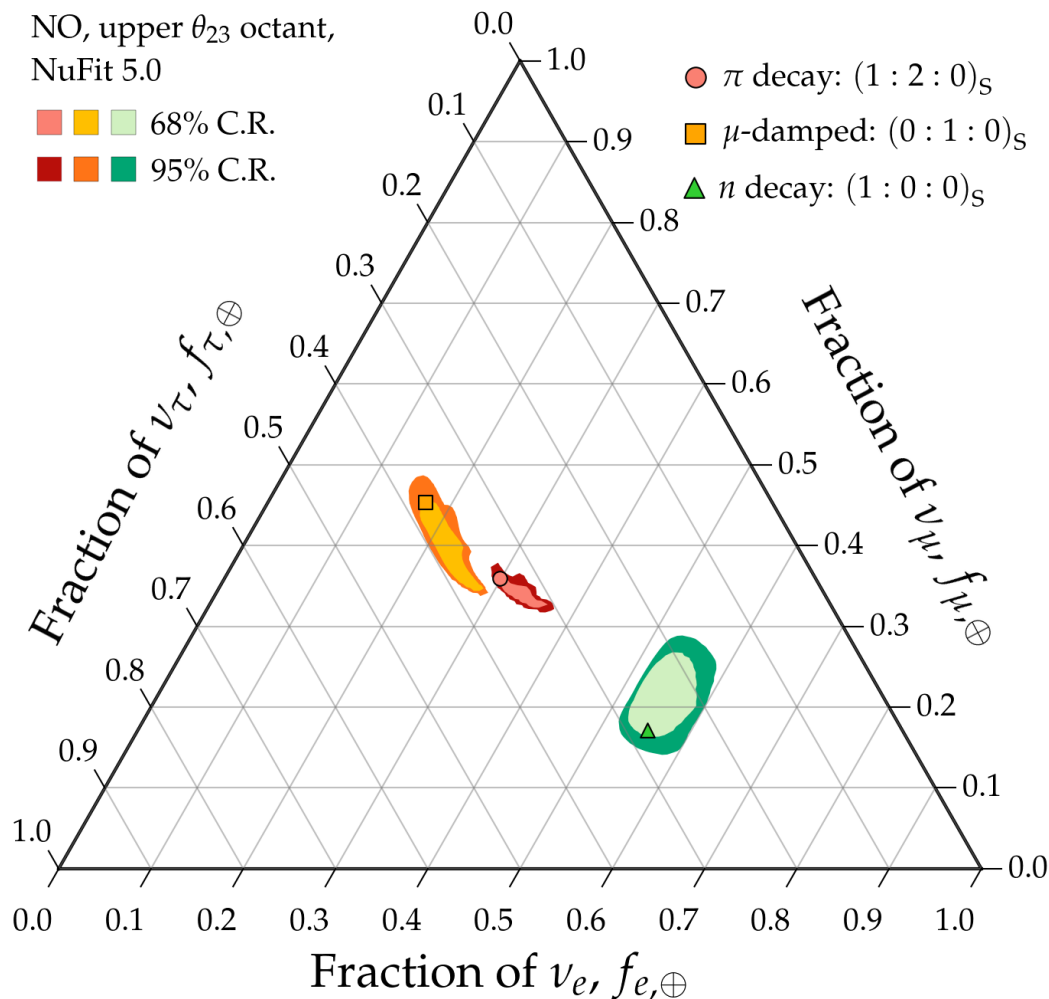
Theoretically palatable regions: today



Note:

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

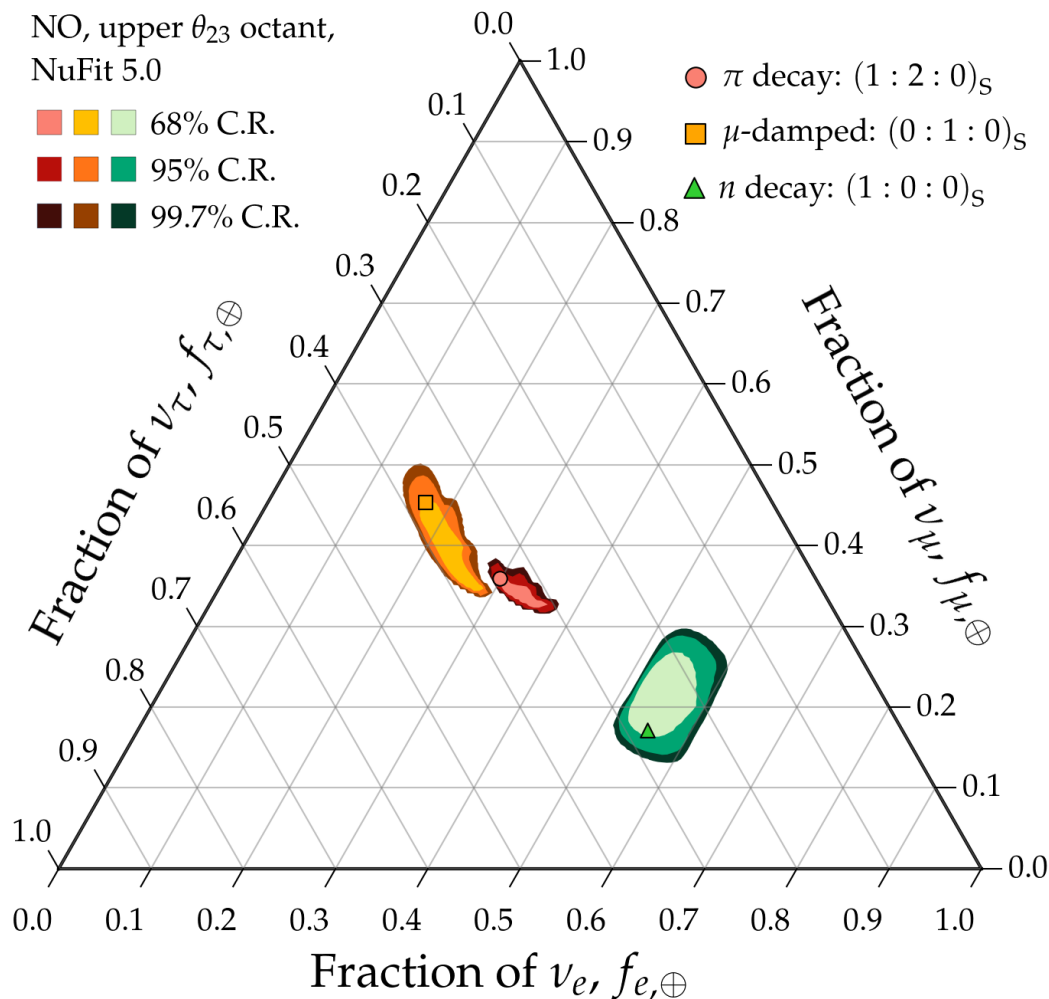
Theoretically palatable regions: today



Note:

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neutrino mass ordering (NO);
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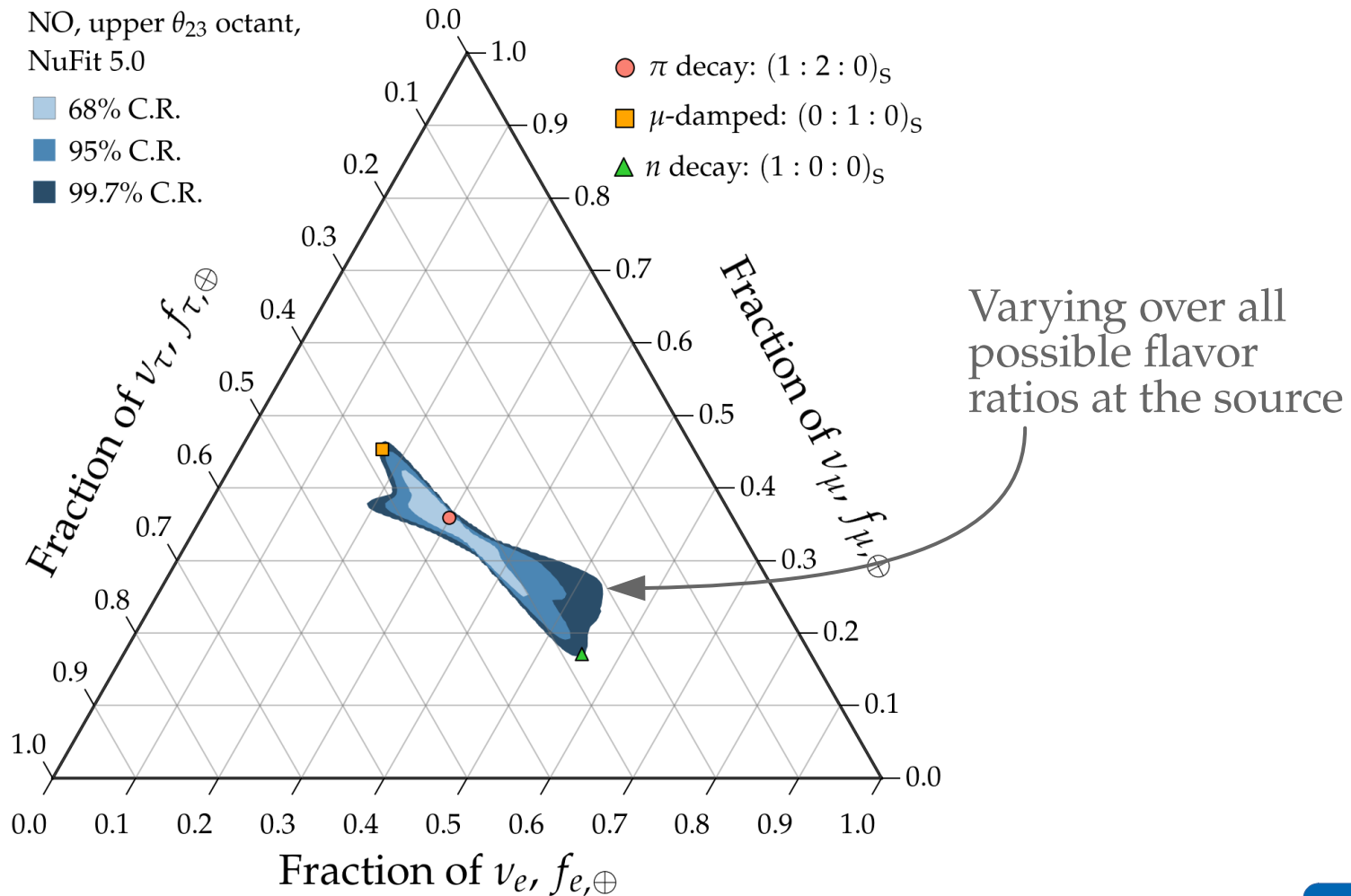
Theoretically palatable regions: today



Note:

All plots shown are for normal
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Theoretically palatable regions: today



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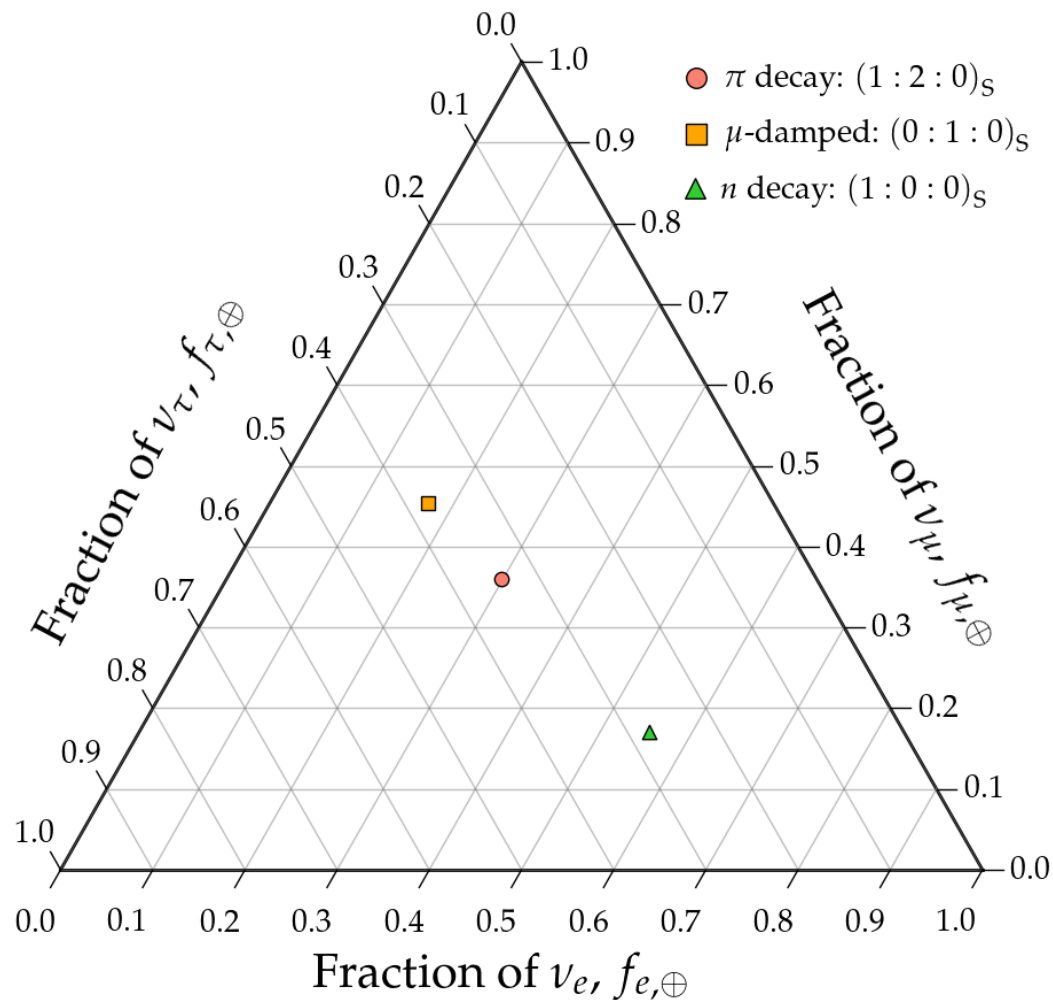
Theoretically palatable regions: today

Note:

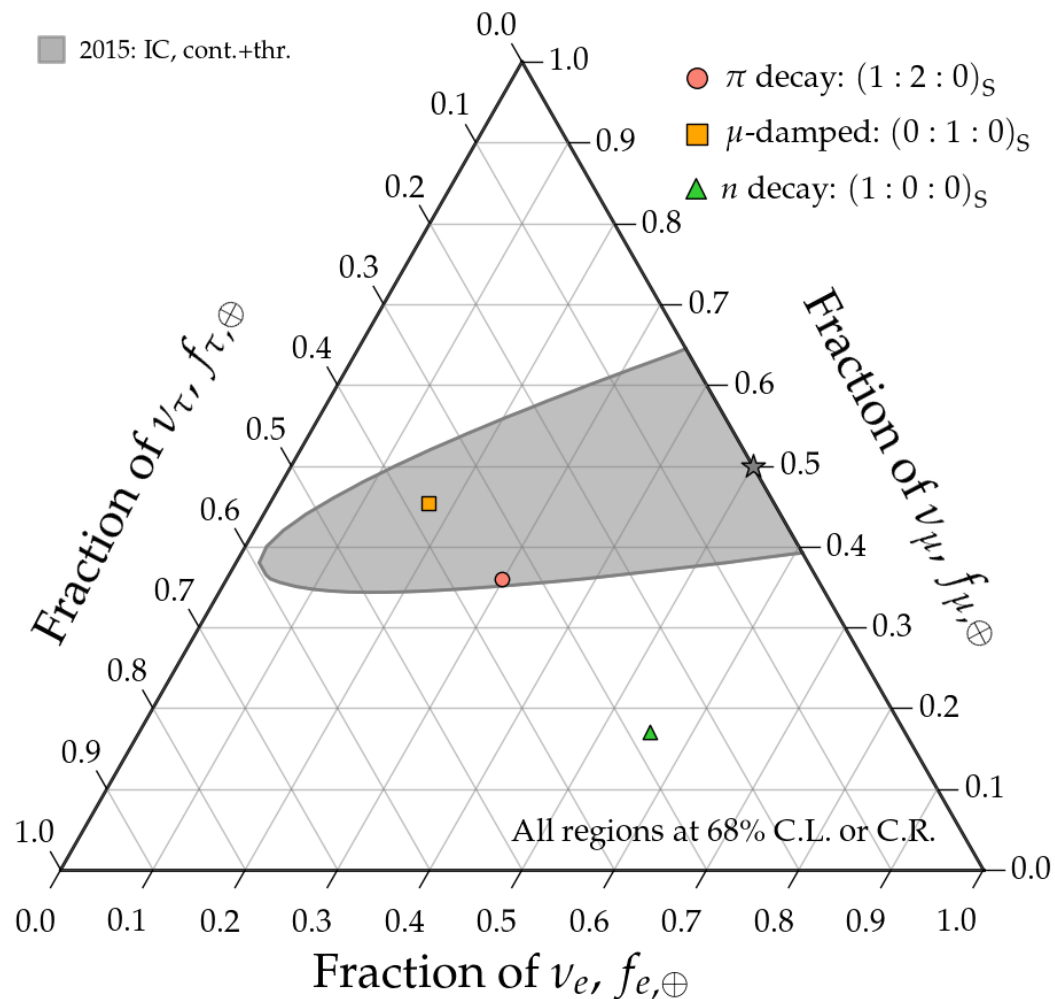
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Measuring flavor composition: 2015–2020

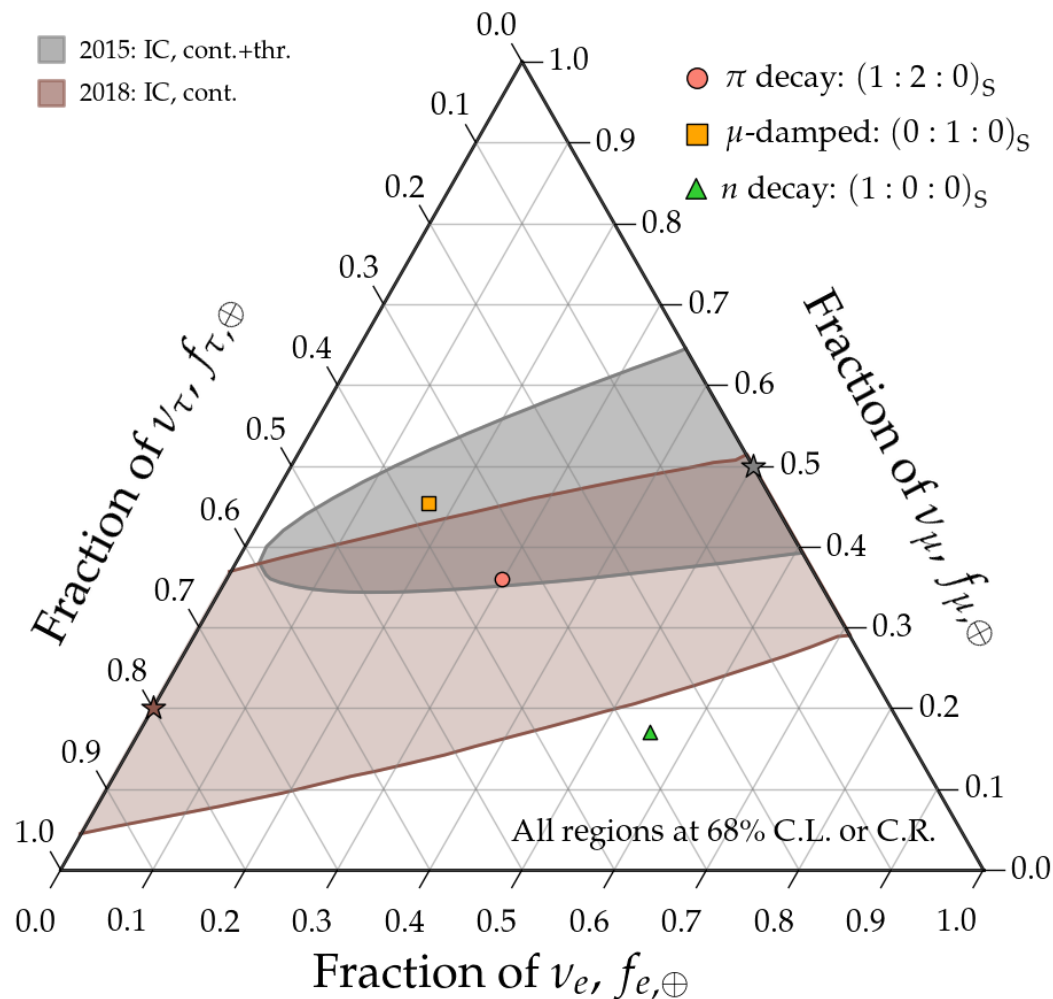
Measuring flavor composition: 2015–2020



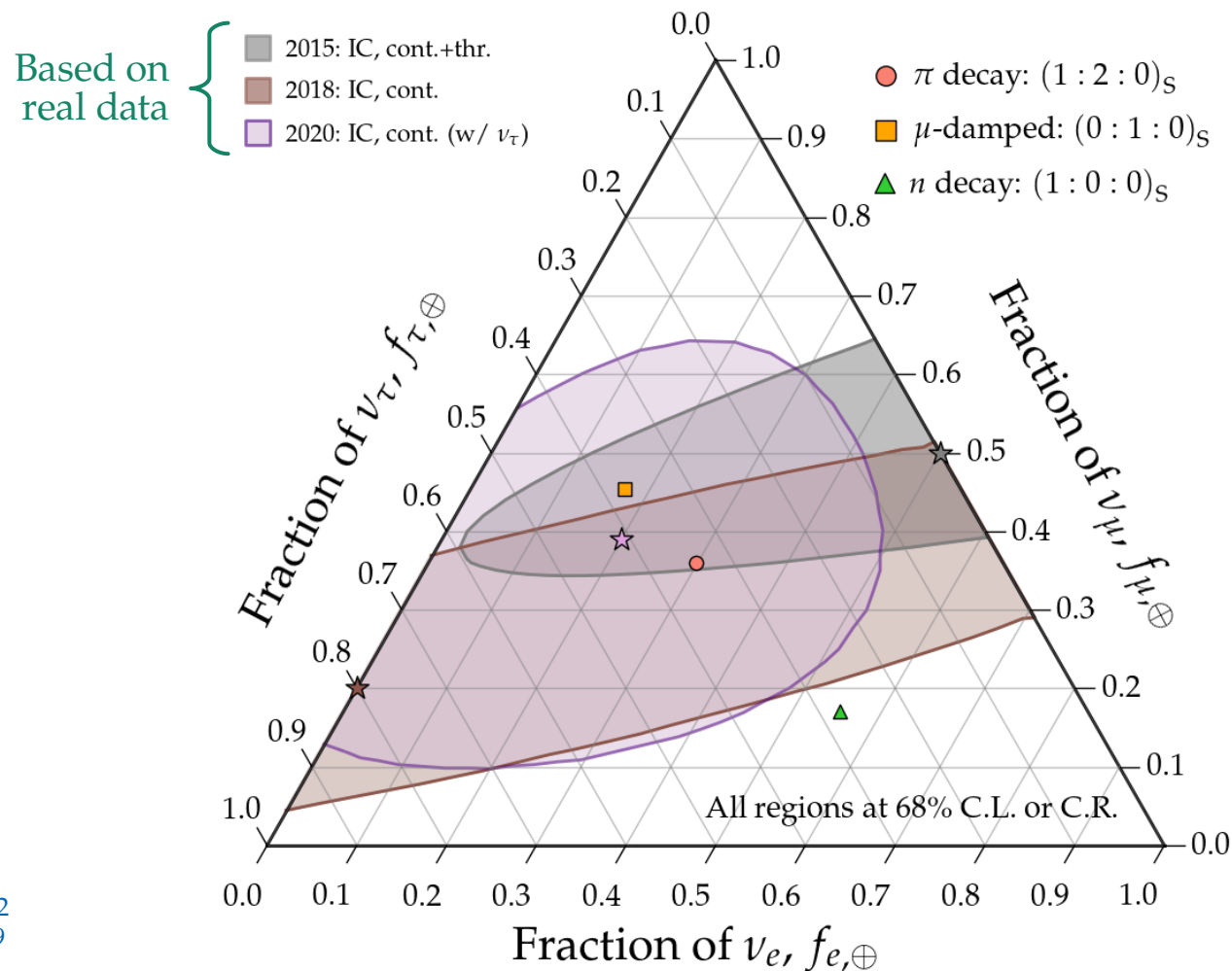
Measuring flavor composition: 2015–2020



Measuring flavor composition: 2015–2020



Measuring flavor composition: 2015–2020



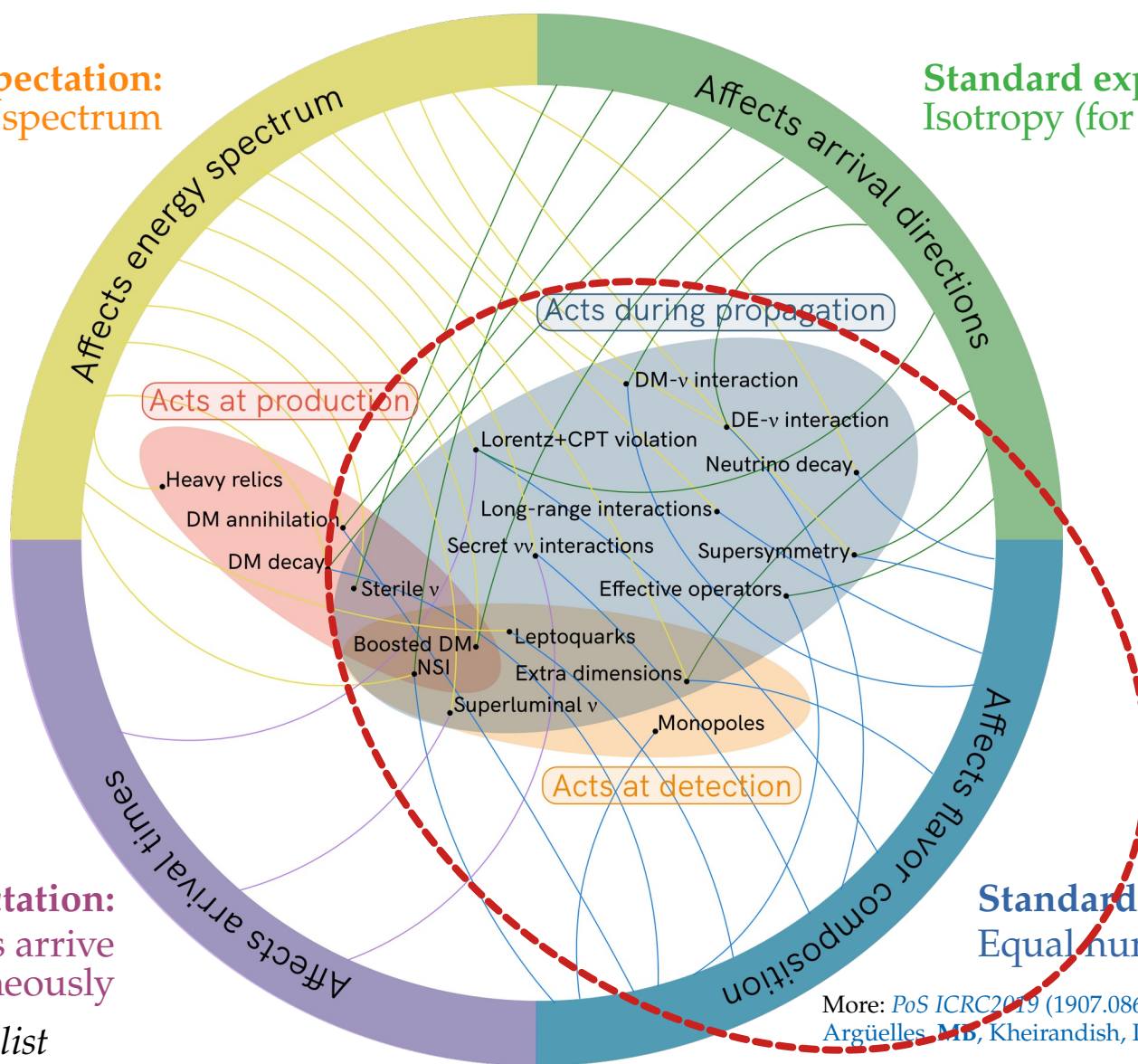
Standard expectation:
Power-law energy spectrum

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, M.B., Kheirandish, Palomares-Ruiz, Salvadó, Vincent

New physics in flavor composition

Use the flavor sensitivity to test new physics:

New physics in flavor composition

Use the flavor sensitivity to test new physics:

Reviews:

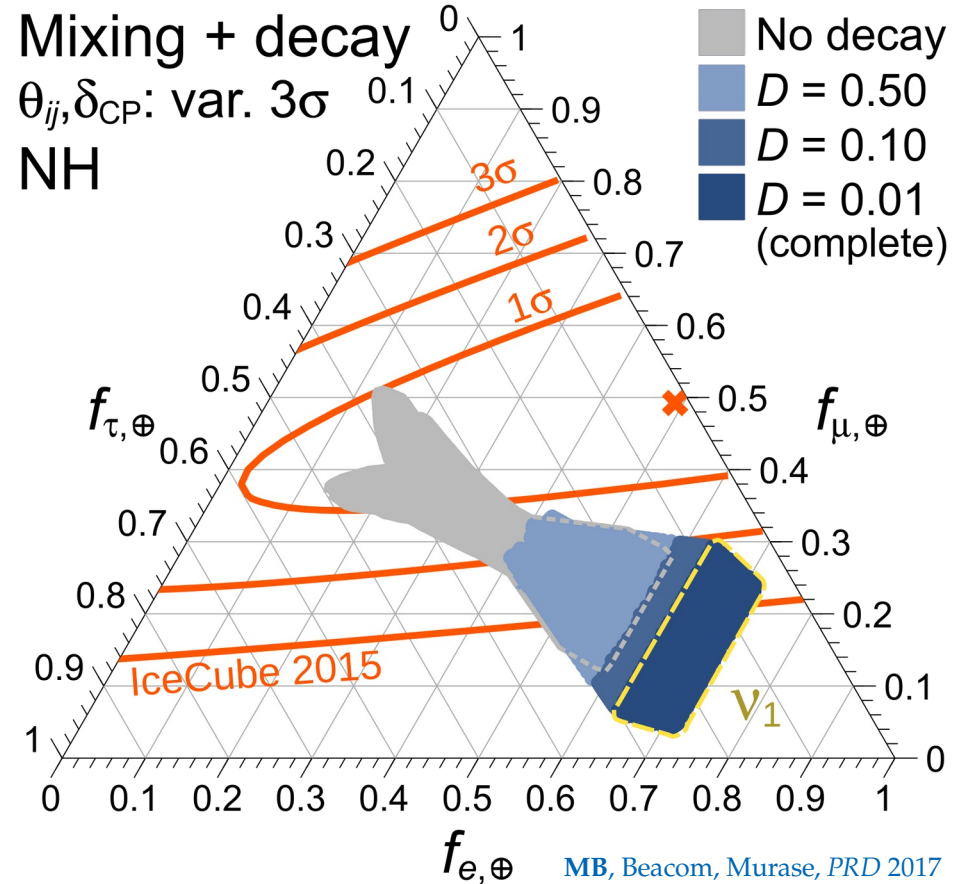
Argüelles *et al.* (inc. **MB**), *EPJC* 2023; Mehta & Winter, *JCAP* 2011; Rasmussen *et al.*, *PRD* 2017

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]



Reviews:

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

New physics in flavor composition

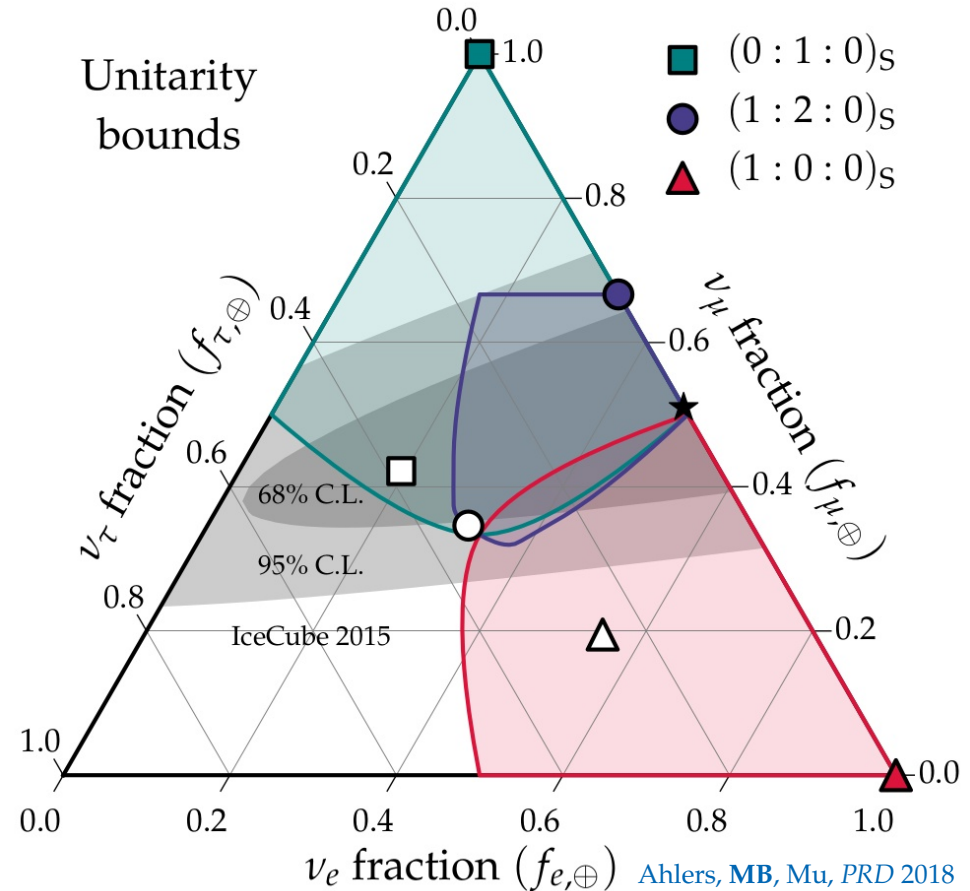
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- Tests of unitarity at high energy

[Xu, He, Rodejohann, *JCAP* 2014; Ahlers, **MB**, Mu, *PRD* 2018;
Ahlers, **MB**, Nortvig, *JCAP* 2021]



Reviews:

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

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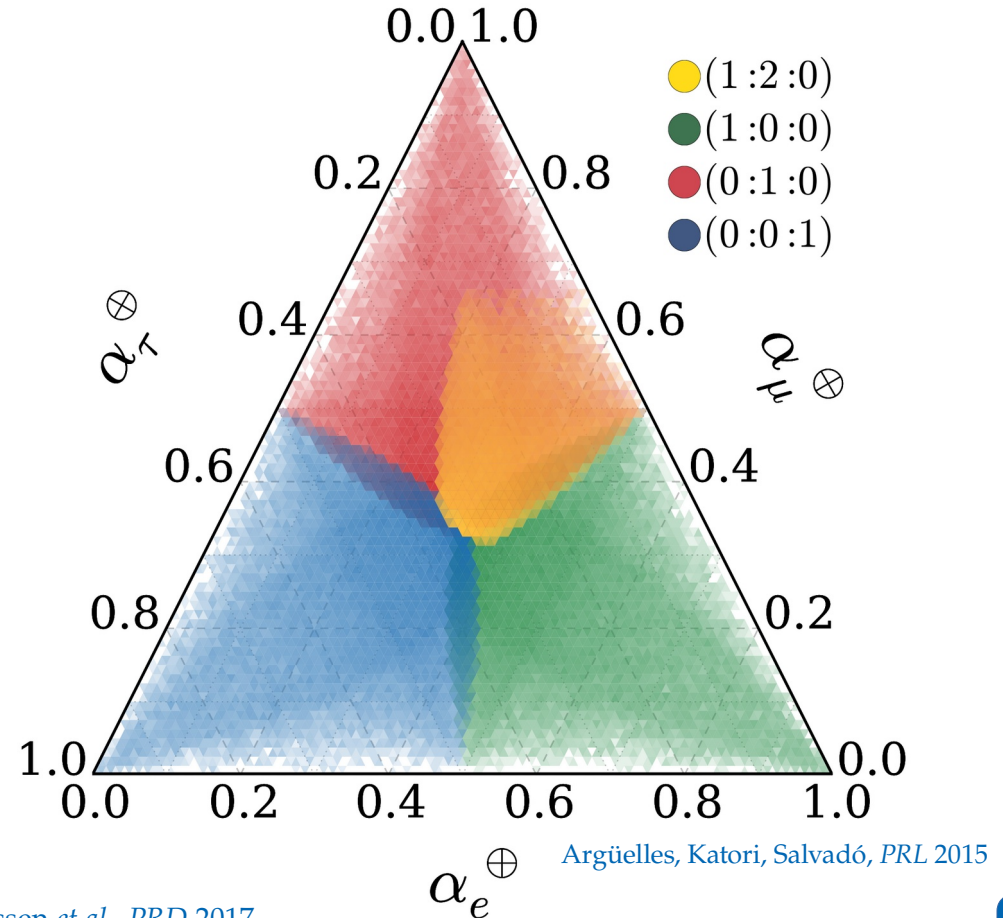
[Beacom *et al.*, *PRL* 2003; Baerwald, **MB**, Winter, *JCAP* 2010;
MB, Beacom, Winter, *PRL* 2015; **MB**, Beacom, Murase, *PRD* 2017]

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- Lorentz- and CPT-invariance violation

[Barenboim & Quigg, *PRD* 2003; **MB**, Gago, Peña-Garay, *JHEP* 2010;
Kostelecky & Mewes 2004; Argüelles, Katori, Salvadó, *PRL* 2015]



Reviews:

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

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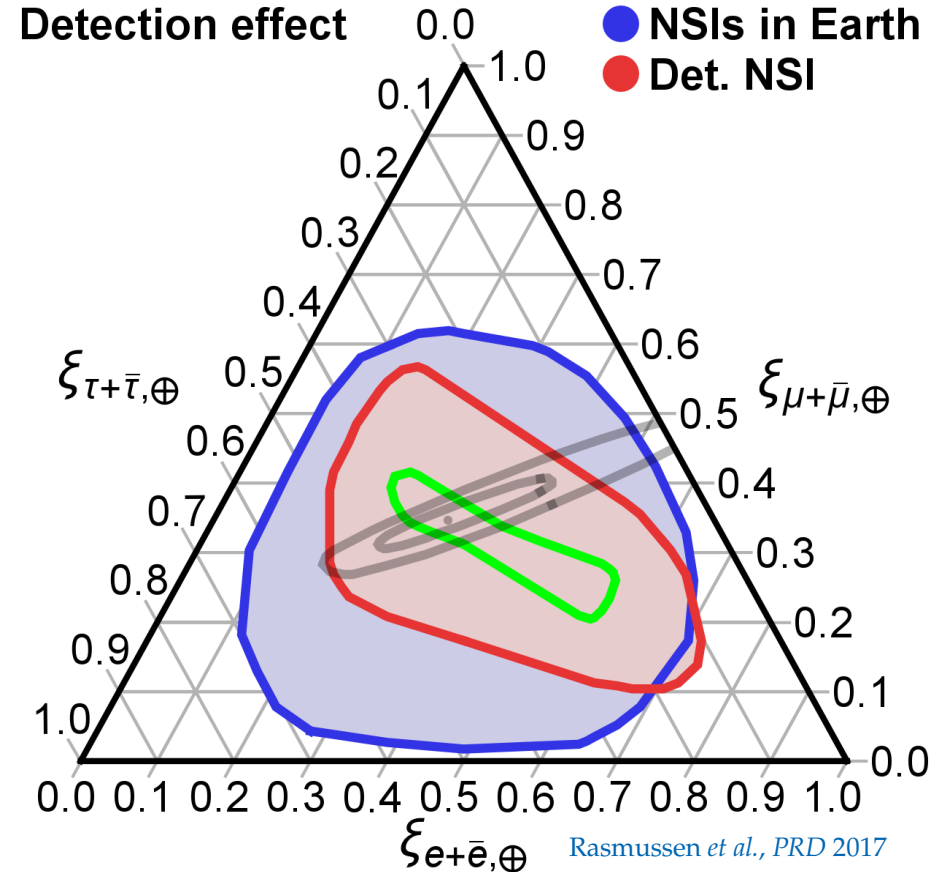
[Barenboim & Quigg, *PRD* 2003; **MB**, Gago, Peña-Garay, *JHEP* 2010;
Kostelecky & Mewes 2004; Argüelles, Katori, Salvadó, *PRL* 2015]

- ▶ Non-standard interactions

[González-García *et al.*, *Astropart. Phys.* 2016;
Rasmussen *et al.*, *PRD* 2017]

Reviews:

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



New physics in flavor composition

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

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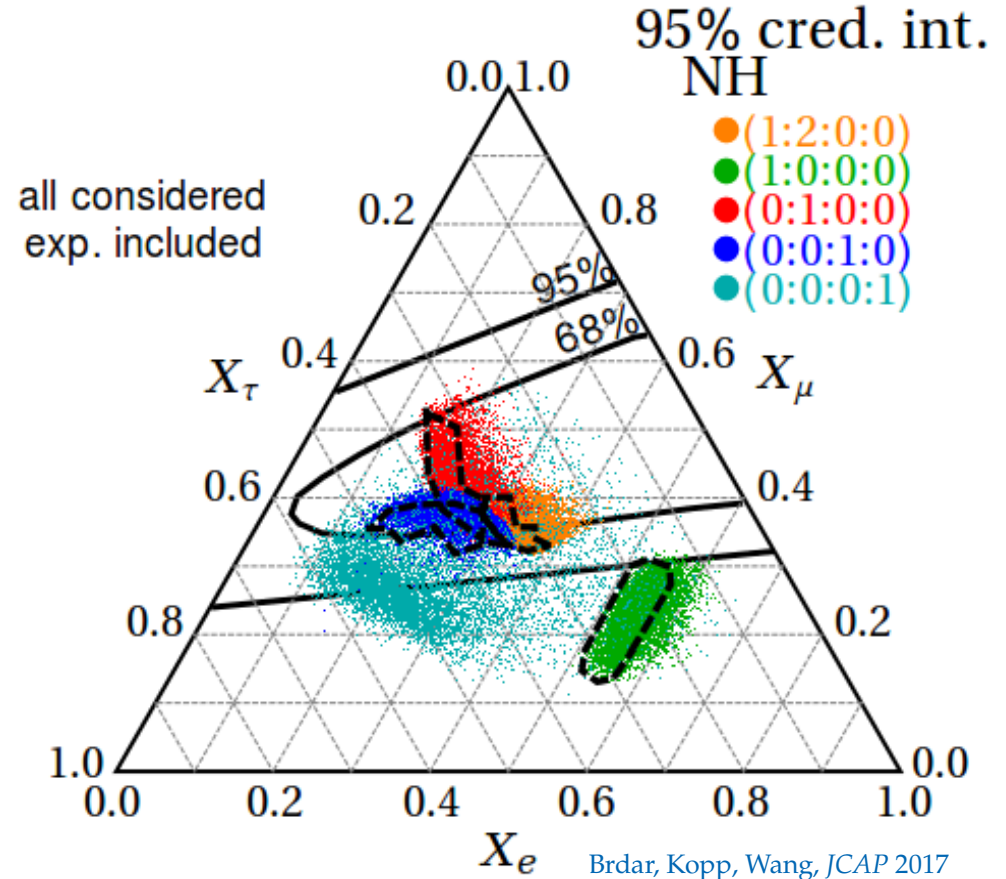
[González-García *et al.*, *Astropart. Phys.* 2016;
Rasmussen *et al.*, *PRD* 2017]

- ▶ Active-sterile ν mixing

[Aeikens *et al.*, *JCAP* 2015; Brdar, Kopp, Wang, *JCAP* 2017;
Argüelles *et al.*, *JCAP* 2020; Ahlers, **MB**, *JCAP* 2021]

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;
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Rasmussen *et al.*, *PRD* 2017]

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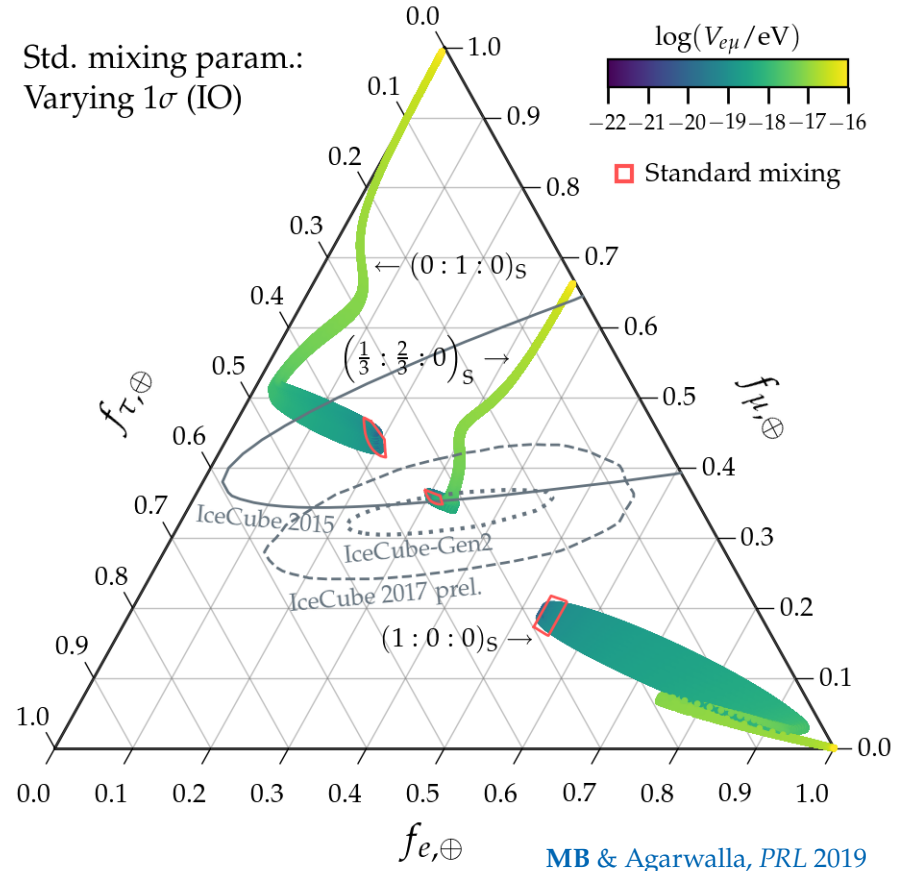
[Aeikens *et al.*, *JCAP* 2015; Brdar, Kopp, Wang, *JCAP* 2017;
Argüelles *et al.*, *JCAP* 2020; Ahlers, **MB**, *JCAP* 2021]

- Long-range $e\nu$ interactions

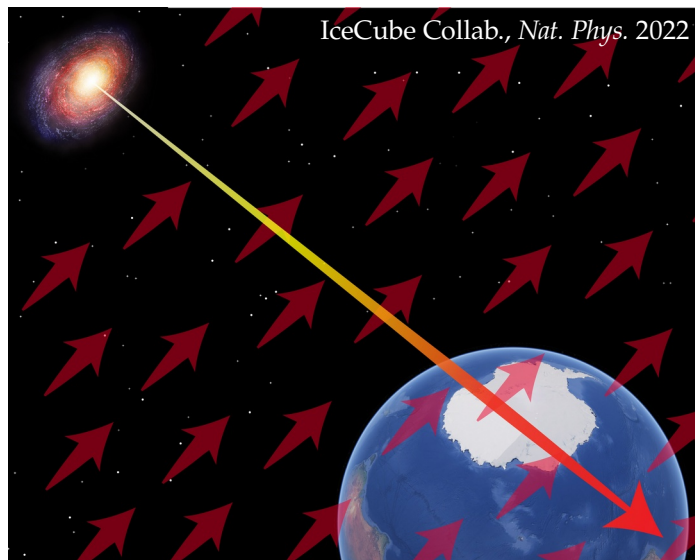
[**MB** & Agarwalla, *PRL* 2019]

Reviews:

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



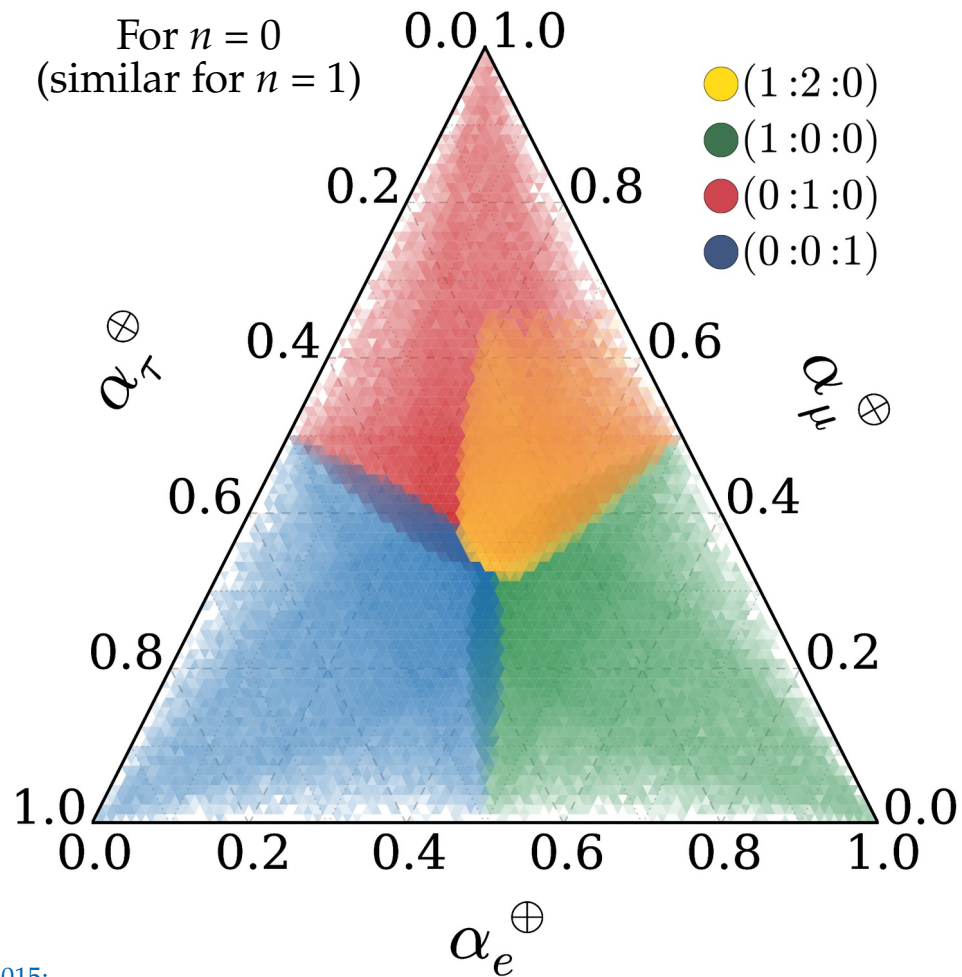
Lorentz-invariance violation can fill up the flavor triangle



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

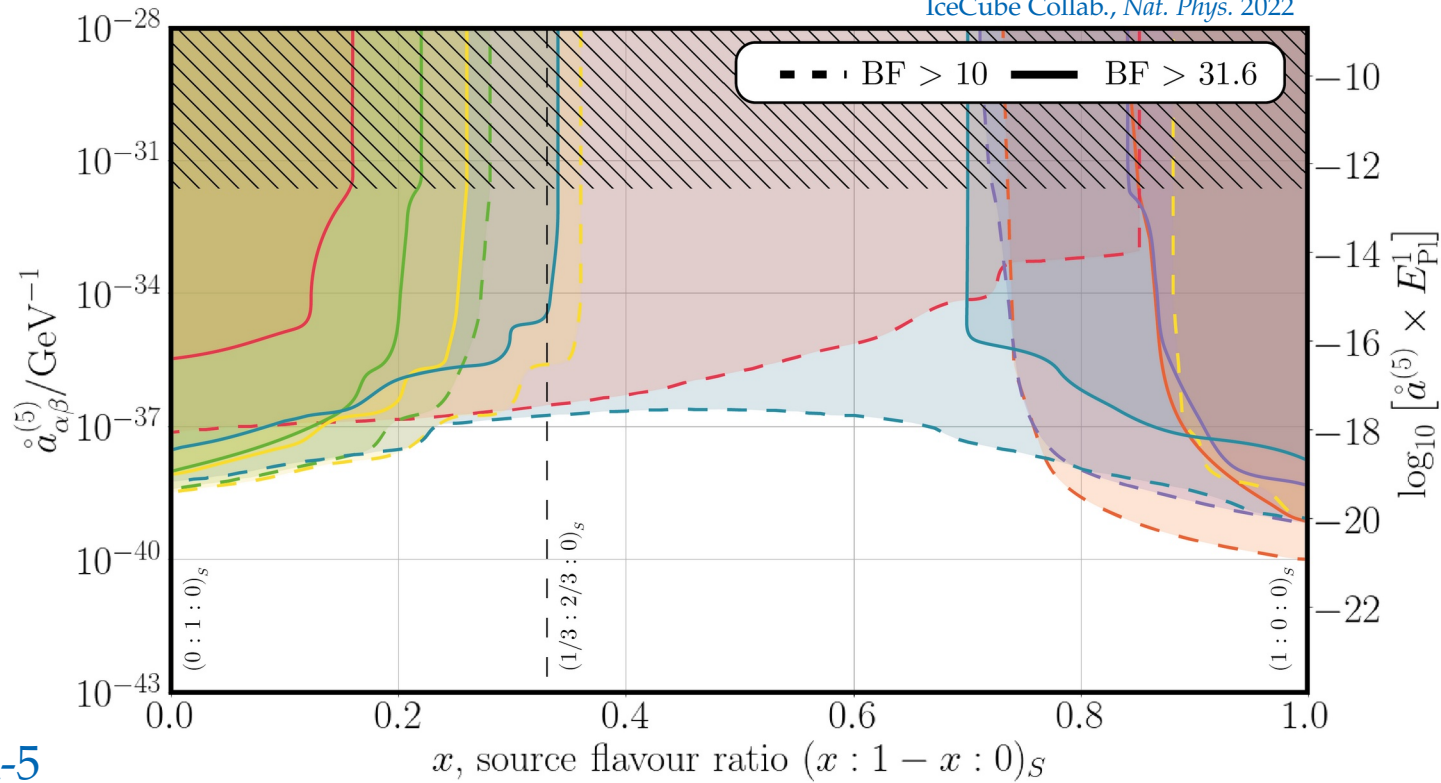
$$H_{\text{std}} = \frac{1}{2E} U_{\text{PMNS}}^\dagger \text{diag} (0, \Delta m_{21}^2, \Delta m_{31}^2) U_{\text{PMNS}}$$

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

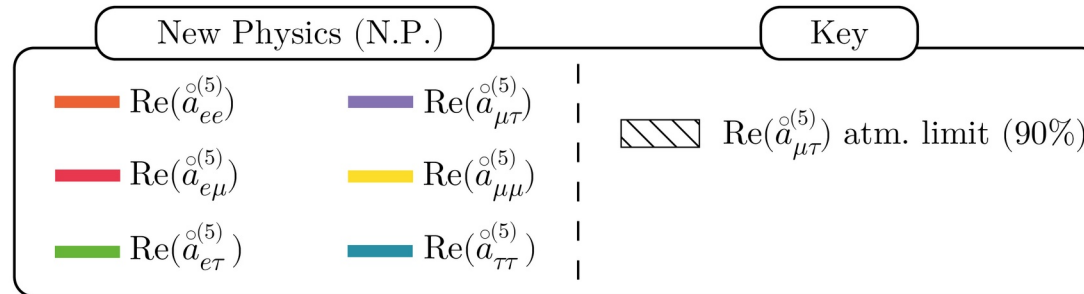


See also: Ahlers, **MB**, Mu, *PRD* 2018; Rasmusen *et al.*, *PRD* 2017; **MB**, Beacom, Winter *PRL* 2015; **MB**, Gago, Peña-Garay *JCAP* 2010; Bazo, **MB**, Gago, Miranda *IJMPA* 2009; + many others

Argüelles, Katori, Salvadó, *PRL* 2015

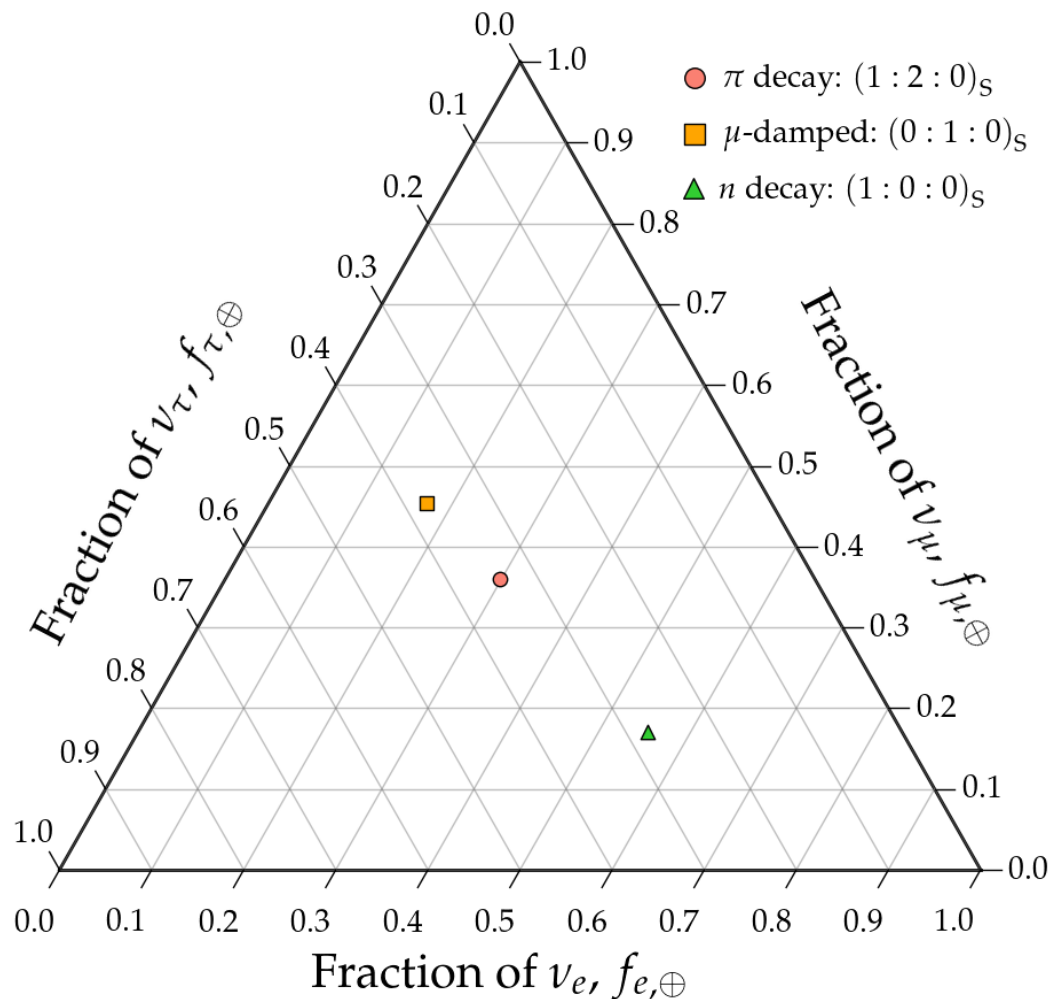


Dimension-5
 CPT-odd
 Isotropic
 Lorentz-invariance
 -violating
 coefficient

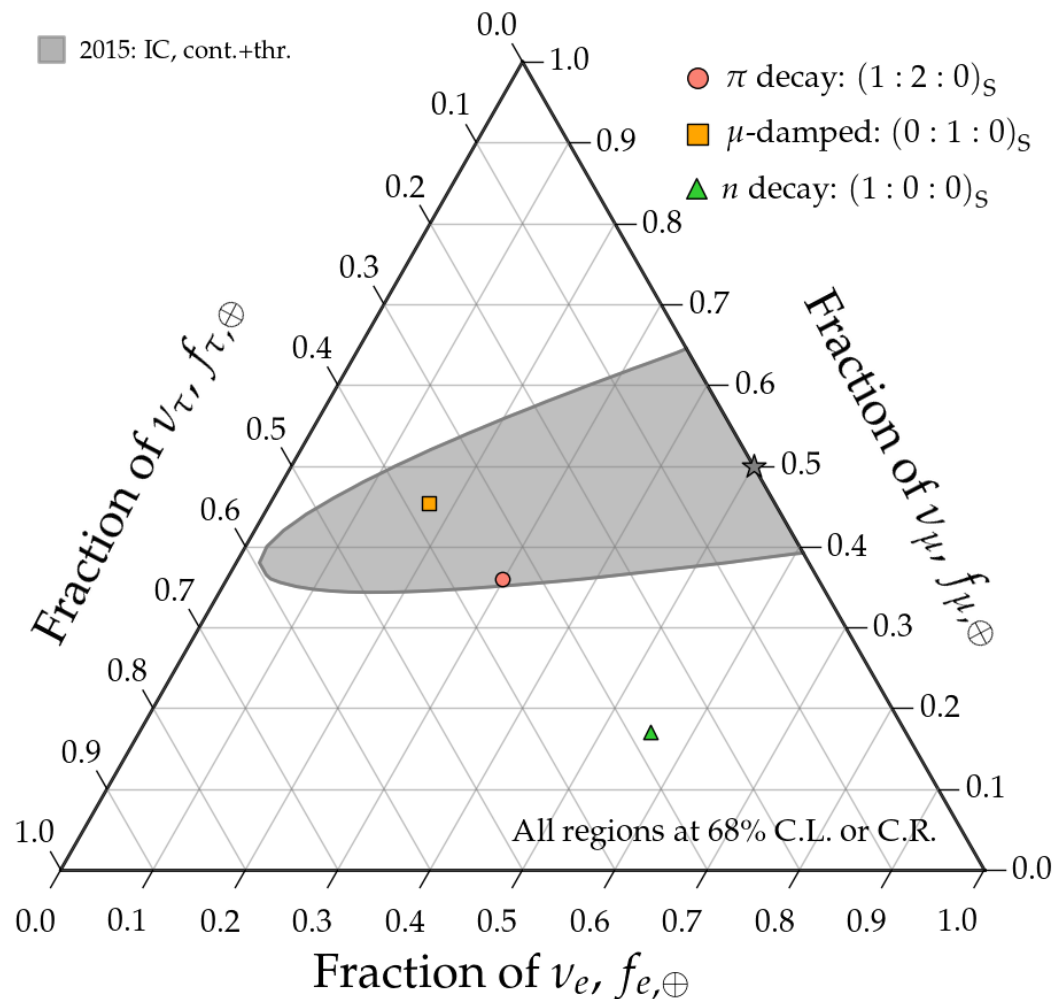


Measuring flavor composition: 2015–2040

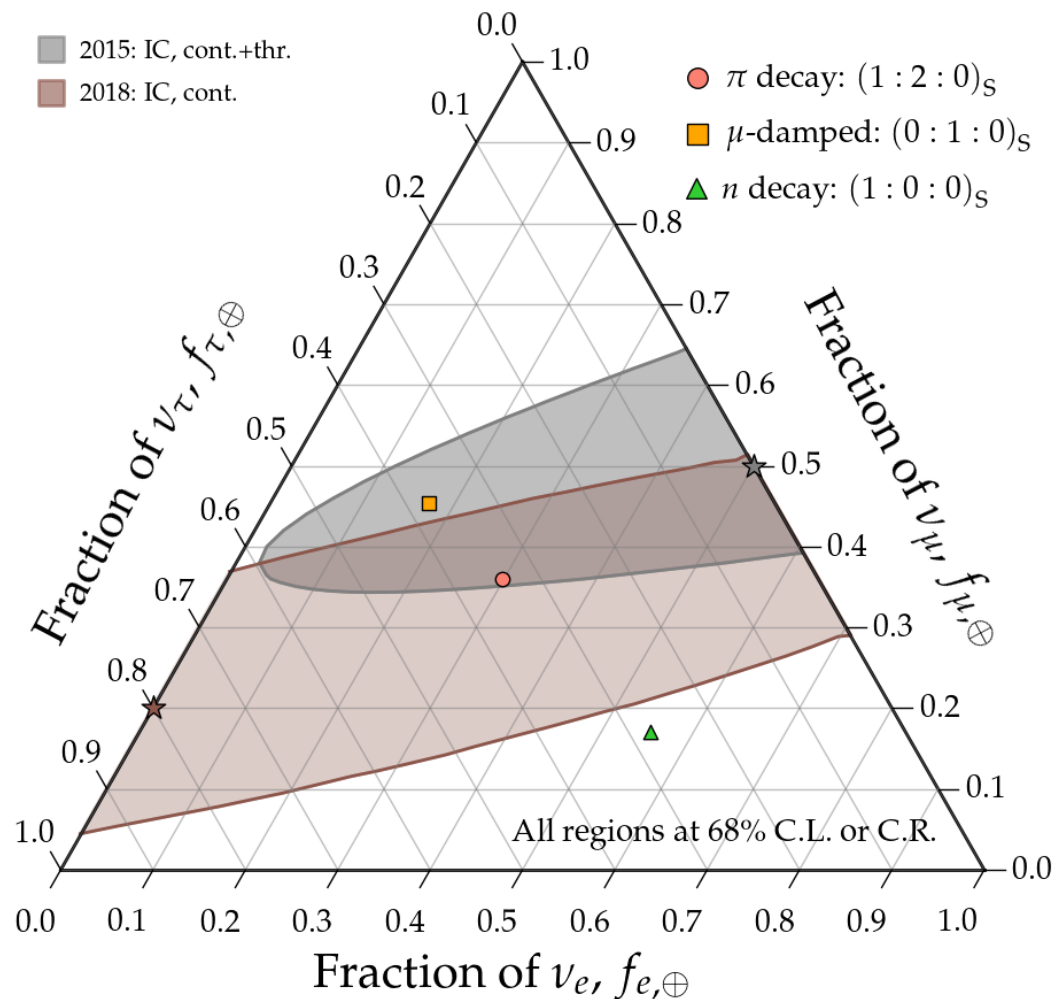
Measuring flavor composition: 2015–2040



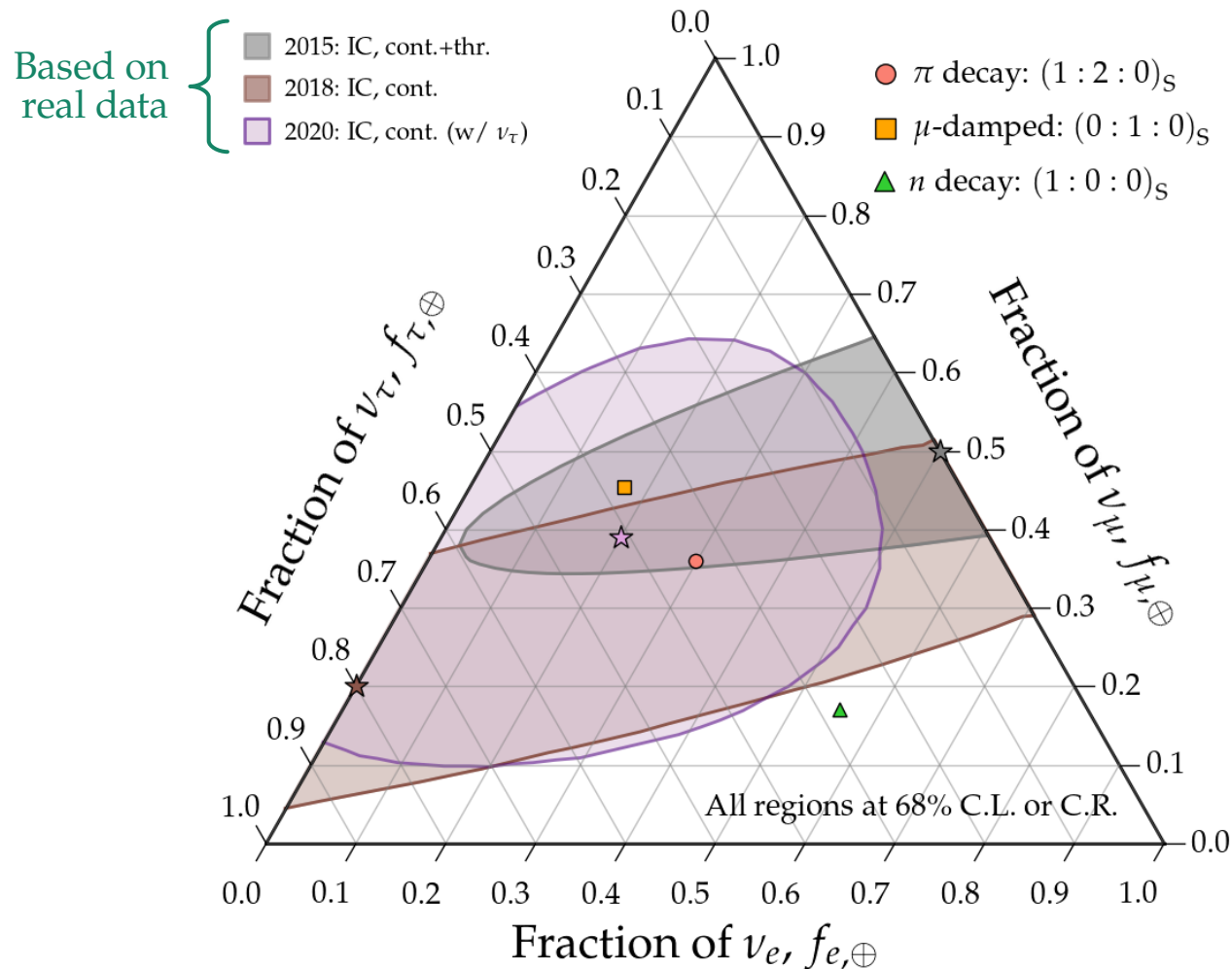
Measuring flavor composition: 2015–2040



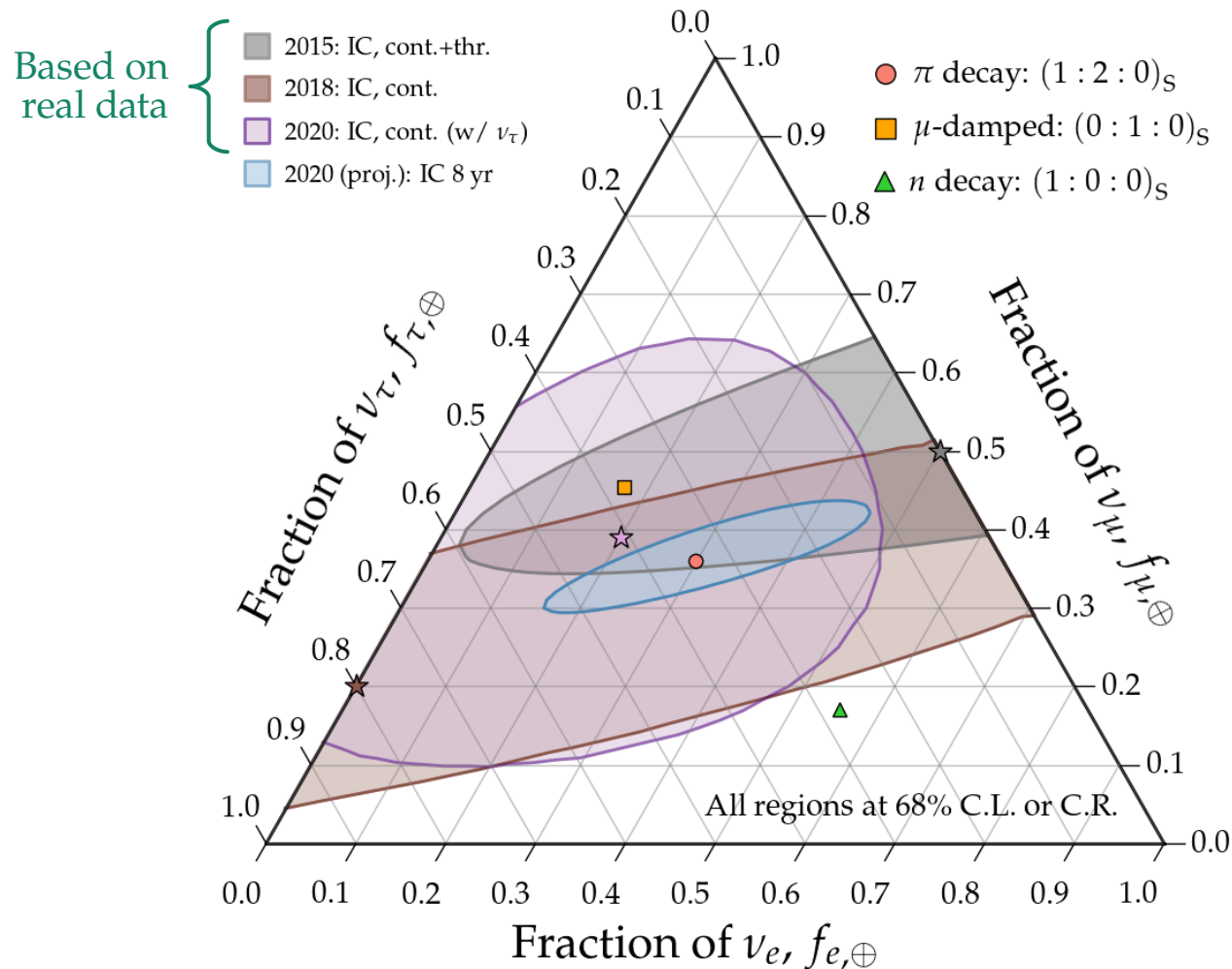
Measuring flavor composition: 2015–2040



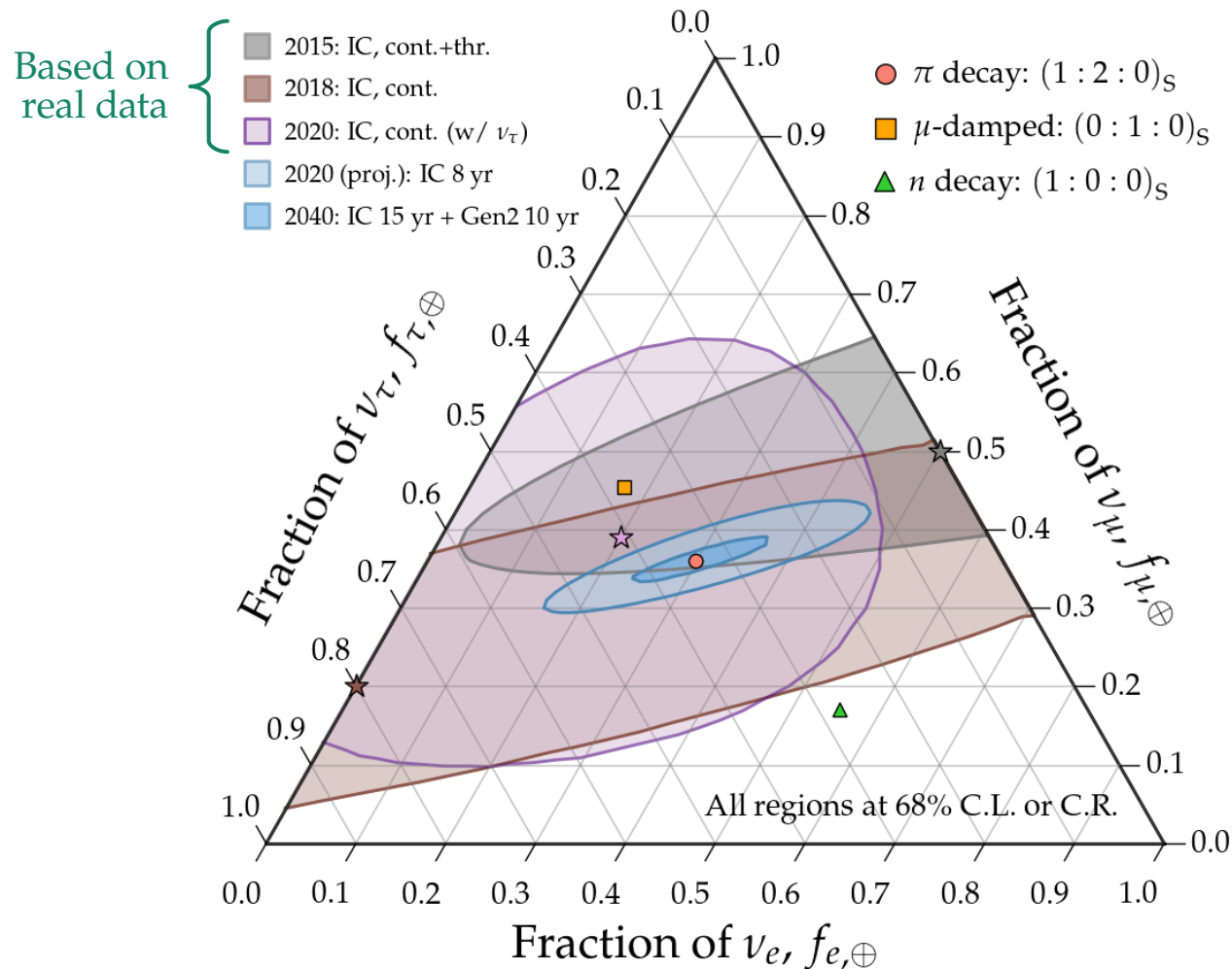
Measuring flavor composition: 2015–2040



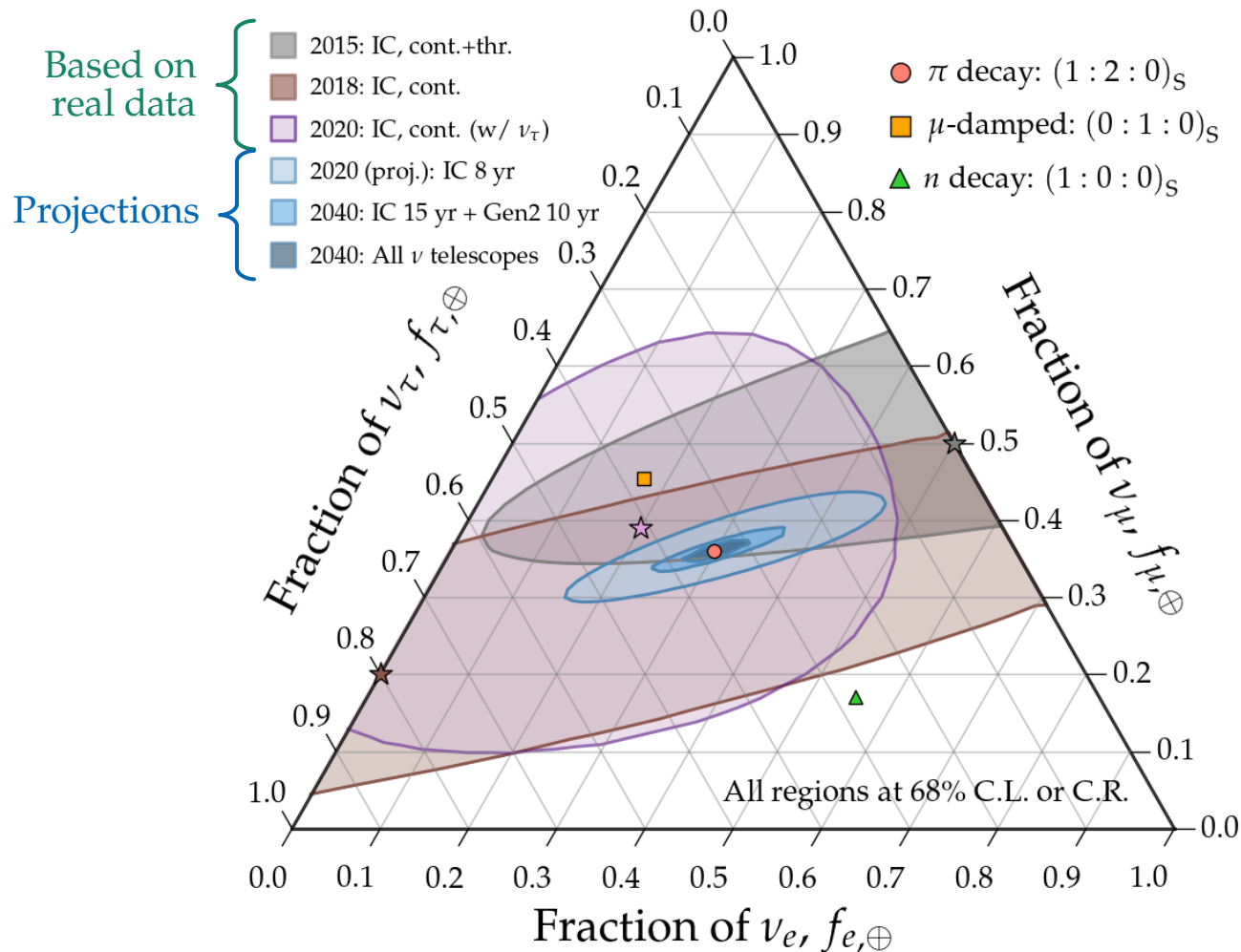
Measuring flavor composition: 2015–2040



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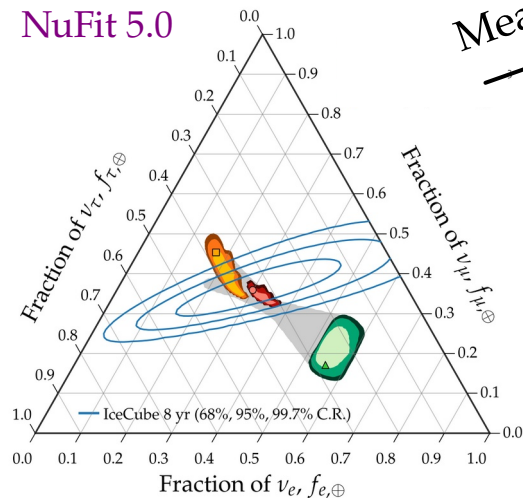
Measuring flavor composition: 2015–2040



How knowing the mixing parameters better helps

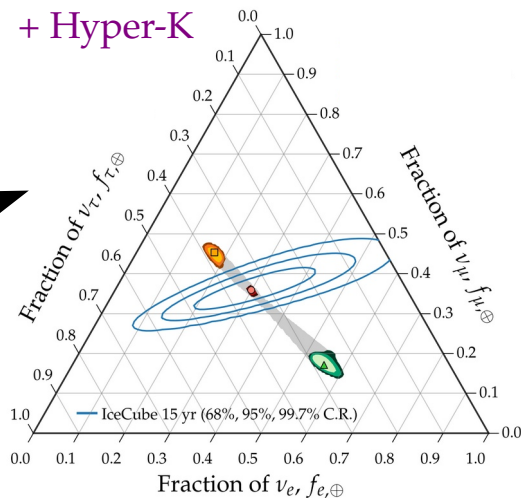
2020

NuFit 5.0

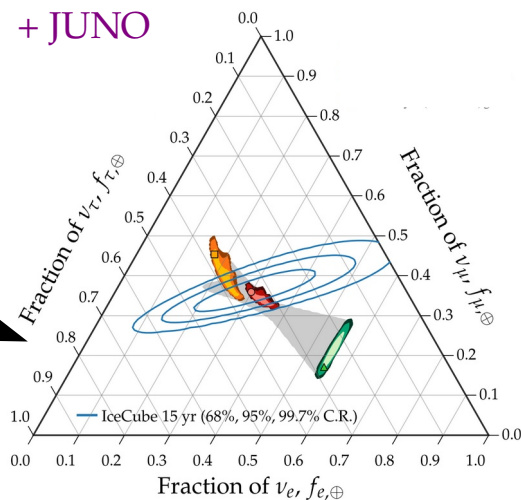


Measure θ_{23} better

+ Hyper-K



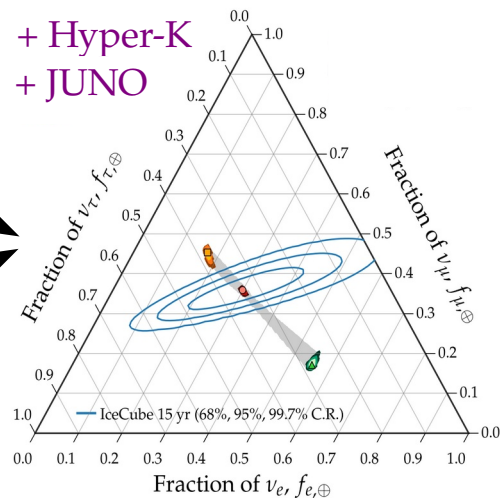
+ JUNO



Measure θ_{12} better

~2030

+ Hyper-K
+ JUNO



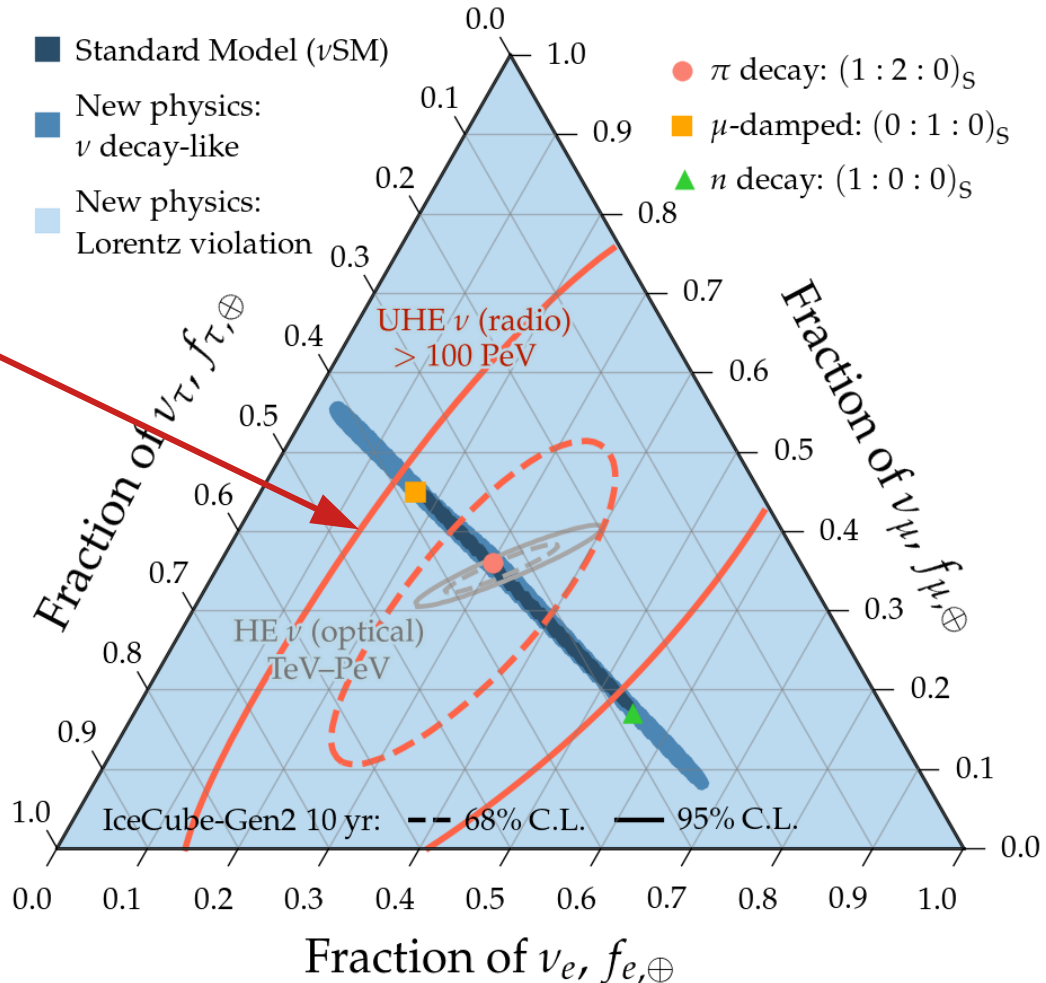
In our results:
JUNO + Hyper-K + DUNE

Marginal improvement til 2040

Flavor composition at ultra-high energies

First measurement forecasts of the UHE flavor composition in in-ice radio detectors (IceCube-Gen2, 10 yr)

Coleman, Ericsson, MB, Glaser, 2401.XXXXX



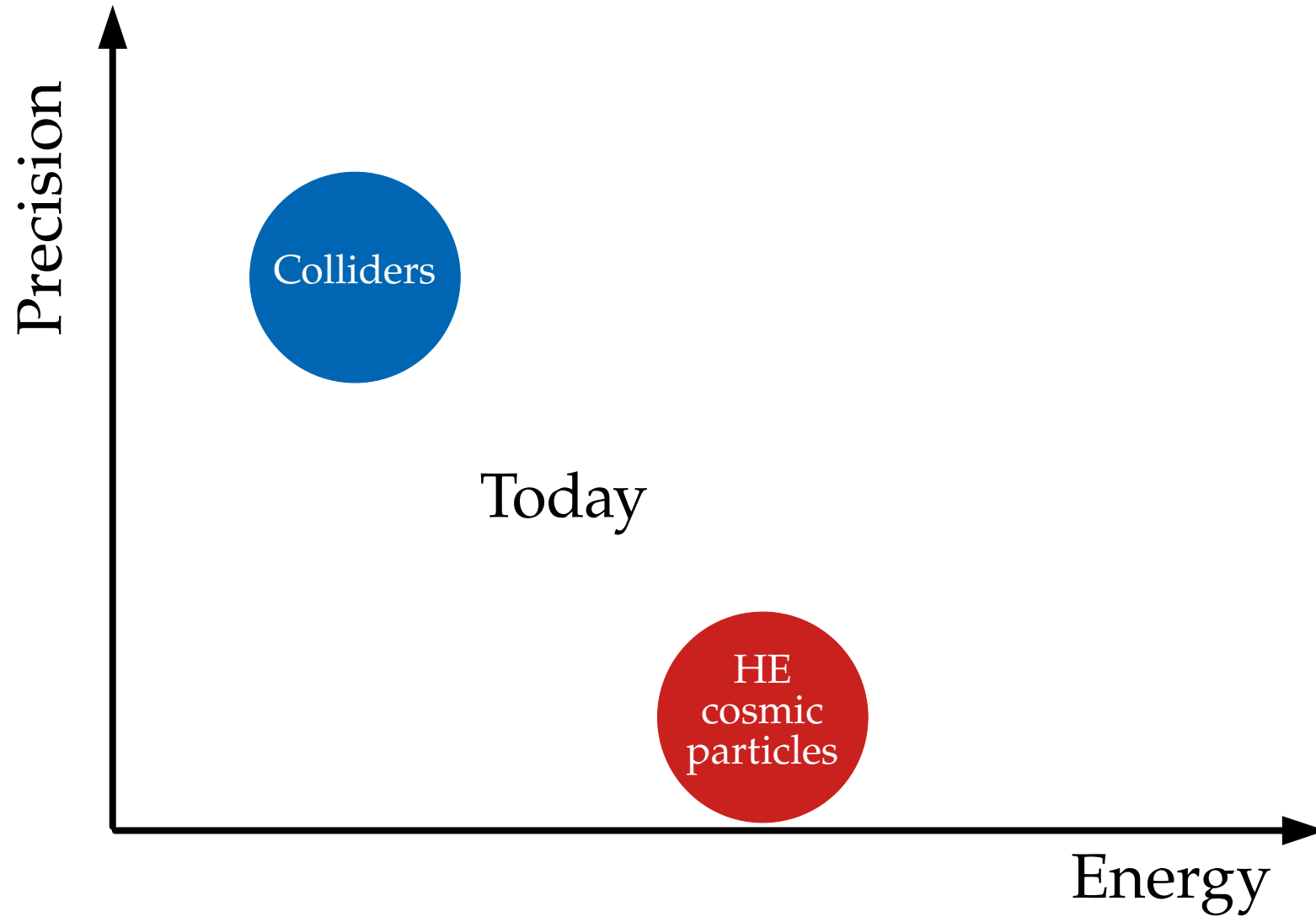
What's next?

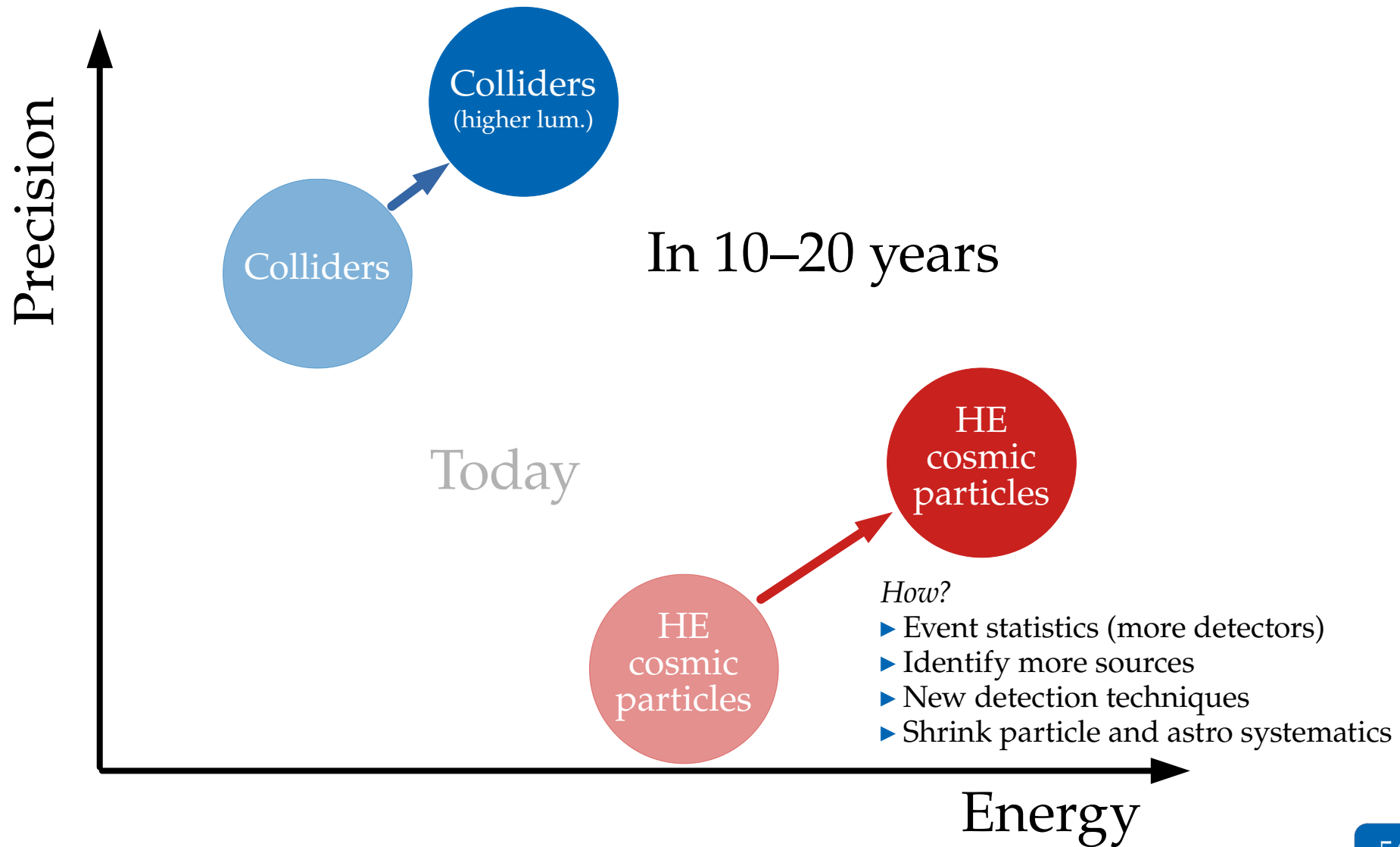
Many TeV–EeV
v telescopes
in planning for
2020–2040

				Flavor	Technique		Neutrino Target			Geometry			
Experiments	Phase & Online Date	Energy Range	Site	All Flavor Tau	Optical / UV	Showers Radio	H ₂ O Atmosphere	Earth's limb Topography	Lunar Regolith	Planar Arrays Embedded	Valley Mountains	Balloon	Satellite
IceCube	2010	TeV-EeV	South Pole	✓	✓		✓			✓			
KM3NeT	2021	TeV-PeV	Mediterranean	✓	✓		✓			✓			
Baikal-GVD	2021	TeV-PeV	Lake Baikal	✓	✓		✓			✓			
P-ONE	2020	TeV-PeV	Pacific Ocean	✓	✓		✓			✓			
IceCube-Gen2	2030+	TeV-EeV	South Pole	✓	✓	✓	✓			✓			
ARIANNA	2014	>30 PeV	Moore's Bay	✓		✓	✓			✓			
ARA	2011	>30 PeV	South Pole	✓		✓	✓			✓			
RNO-G	2021	>30 PeV	Greenland	✓		✓	✓			✓			
RET-N	2024	PeV-EeV	Antarctica	✓		✓	✓			✓			
ANITA	2008,2014,2016	EeV	Antarctica	✓	✓		✓	✓					✓
PUEO	2024	EeV	Antarctica	✓	✓		✓	✓					✓
GRAND	2020	EeV	China / Worldwide	✓		✓	✓	✓	✓	✓	✓		
BEACON	2018	EeV	CA, USA/ Worldwide	✓		✓		✓	✓		✓		
TAROG-M	2018	EeV	Antarctica	✓		✓		✓	✓		✓		
SKA	2029	>100 EeV	Australia	✓		✓			✓	✓			
Trinity	2022	PeV-EeV	Utah, USA	✓		✓		✓			✓		
POEMMA		>20 PeV	Satellite	✓	✓	✓	✓	✓					✓
EUSO-SPB	2022	EeV	New Zealand	✓		✓		✓				✓	
Pierre Auger	2008	EeV	Argentina	✓	✓		✓	✓	✓	✓			
AugerPrime	2022	EeV	Argentina	✓	✓	✓	✓	✓	✓	✓			
Telescope Array	2008	EeV	Utah, USA	✓	✓		✓			✓			
TAx4		EeV	Utah, USA	✓	✓								
TAMBO	2025-2026	PeV-EeV	Peru	✓		✓			✓		✓		

Operational		Date full operations began
Prototype		Date prototype operations began or begin
Planning		Projected full operations

Abraham *et al.* (inc. MB),
J. Phys. G: Nucl. Part. Phys. 59, 11 (2022) [2203.05591]





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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PeV ν
discovered



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Hints of sources
First tests of ν physics

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How it's
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Hints of sources
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EeV ν discovered
Precision tests with PeV ν
First tests with EeV ν

How it
started

How it's
going

10–20 years
from now

First predictions
of high-energy
cosmic ν

PeV ν
discovered

Hints of sources
First tests of ν physics

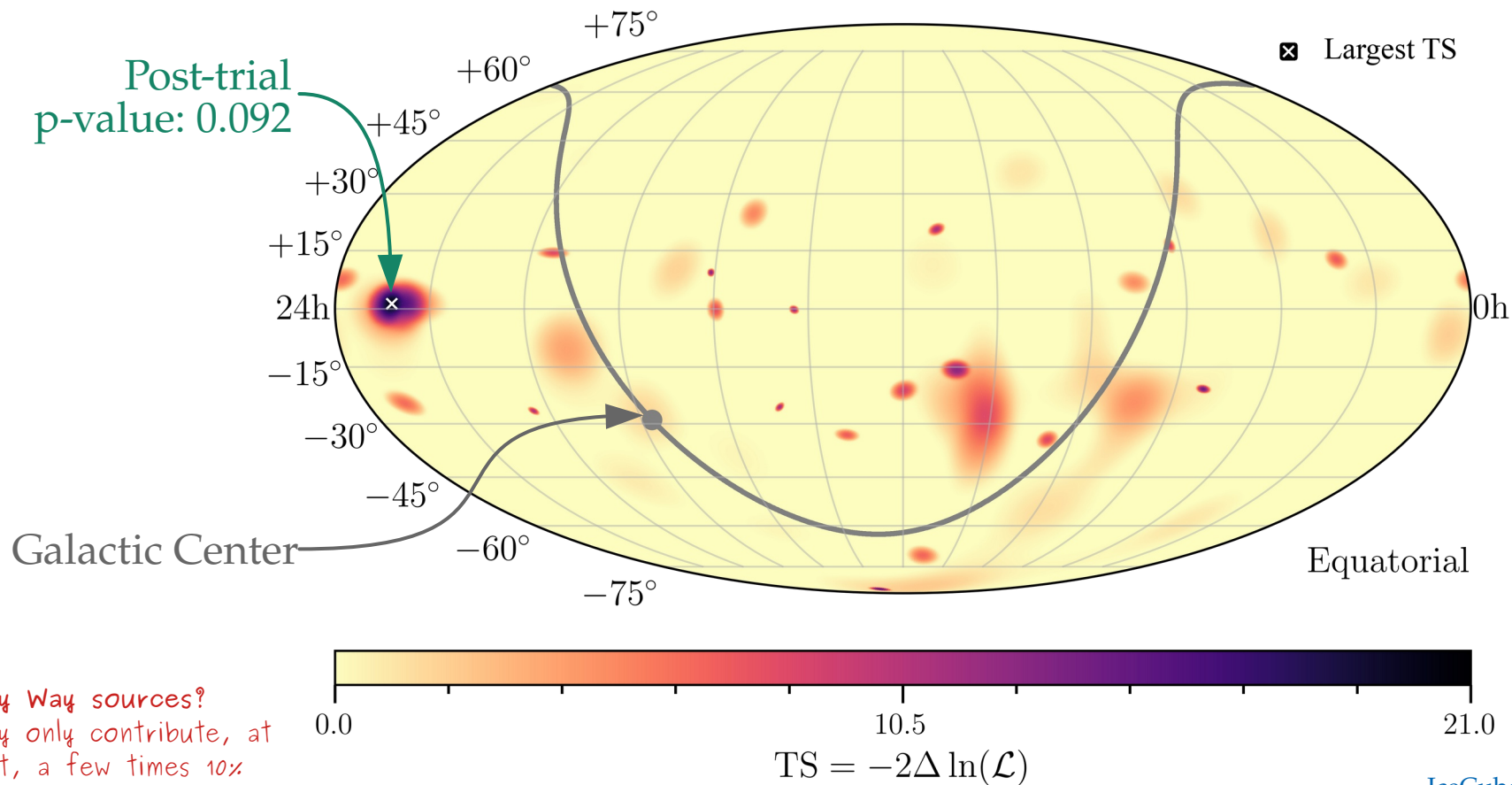
How do we get there?

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

Backup slides

Arrival directions (7.5 yr)

No significant excess in the neutrino sky map:



Milky Way sources?
They only contribute, at
most, a few times 10%
of the total diffuse flux

Measuring the high-energy νN cross section

Number of detected neutrinos (simplified for presentation):

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

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

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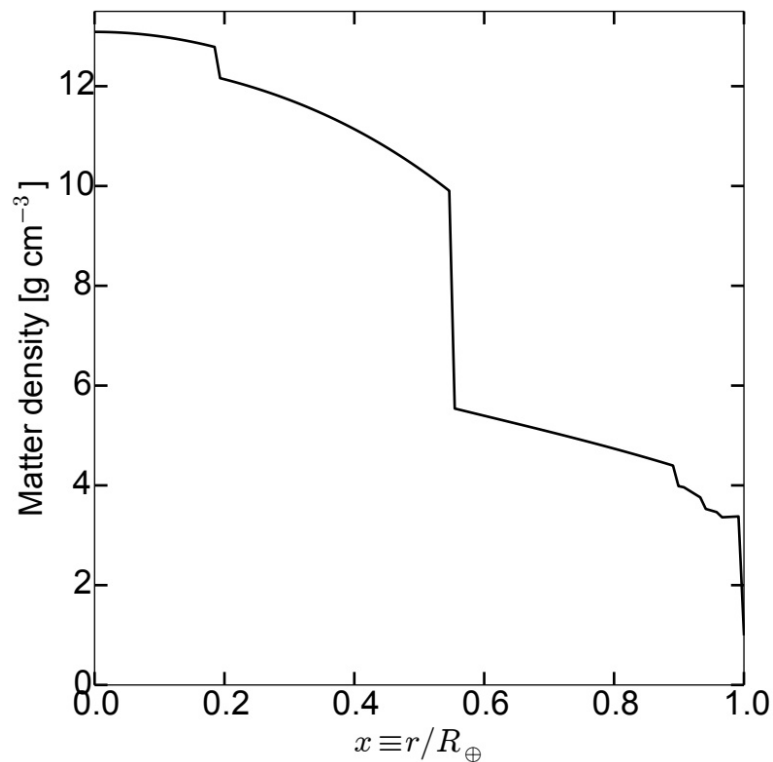
Upgoing neutrinos
(L long $\rightarrow$ lots of matter)

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

A feel for the in-Earth attenuation

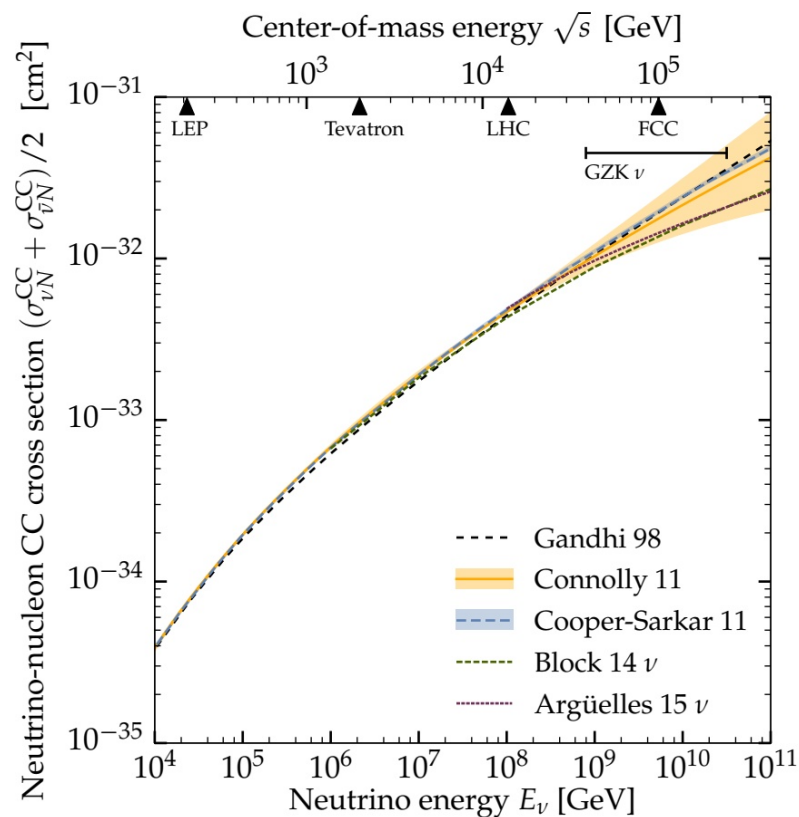
Earth matter density

(Preliminary Reference Earth Model)

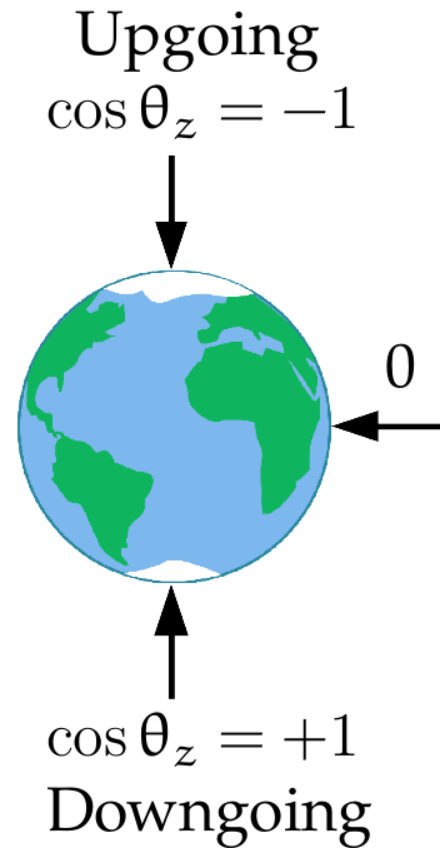
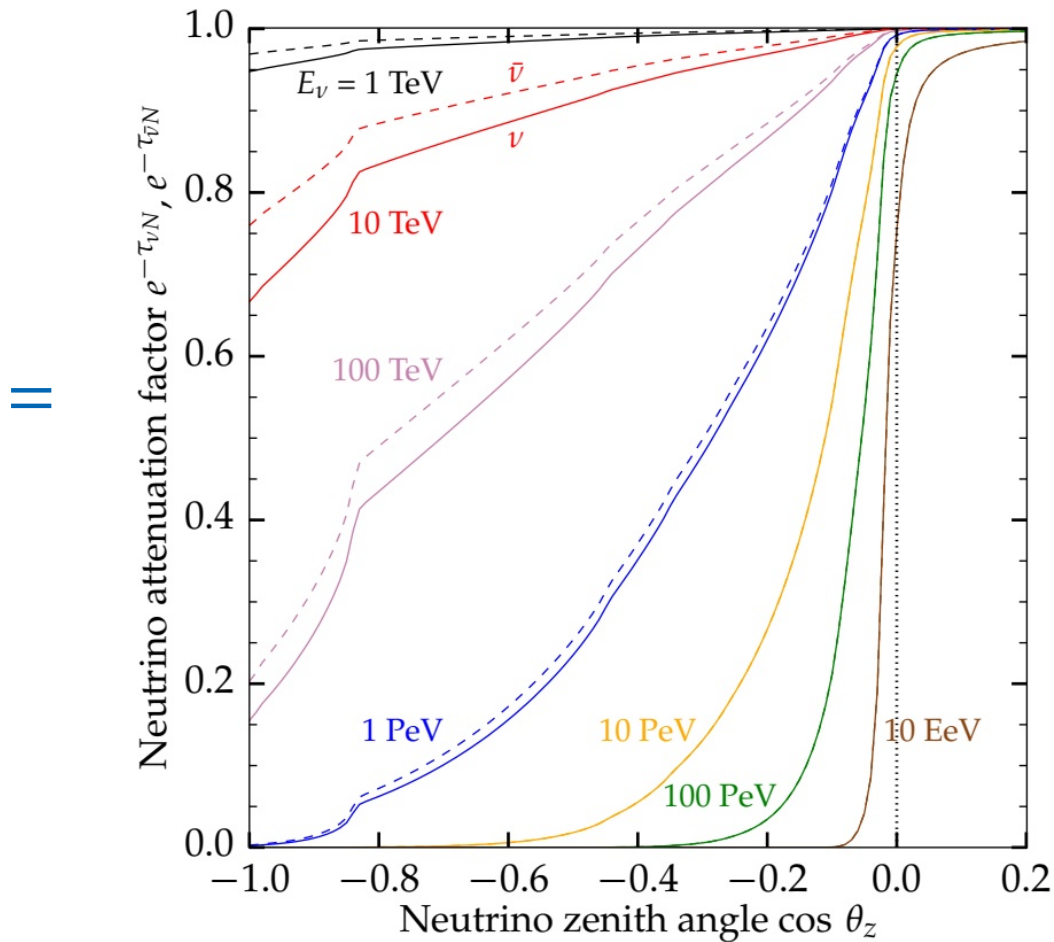


+

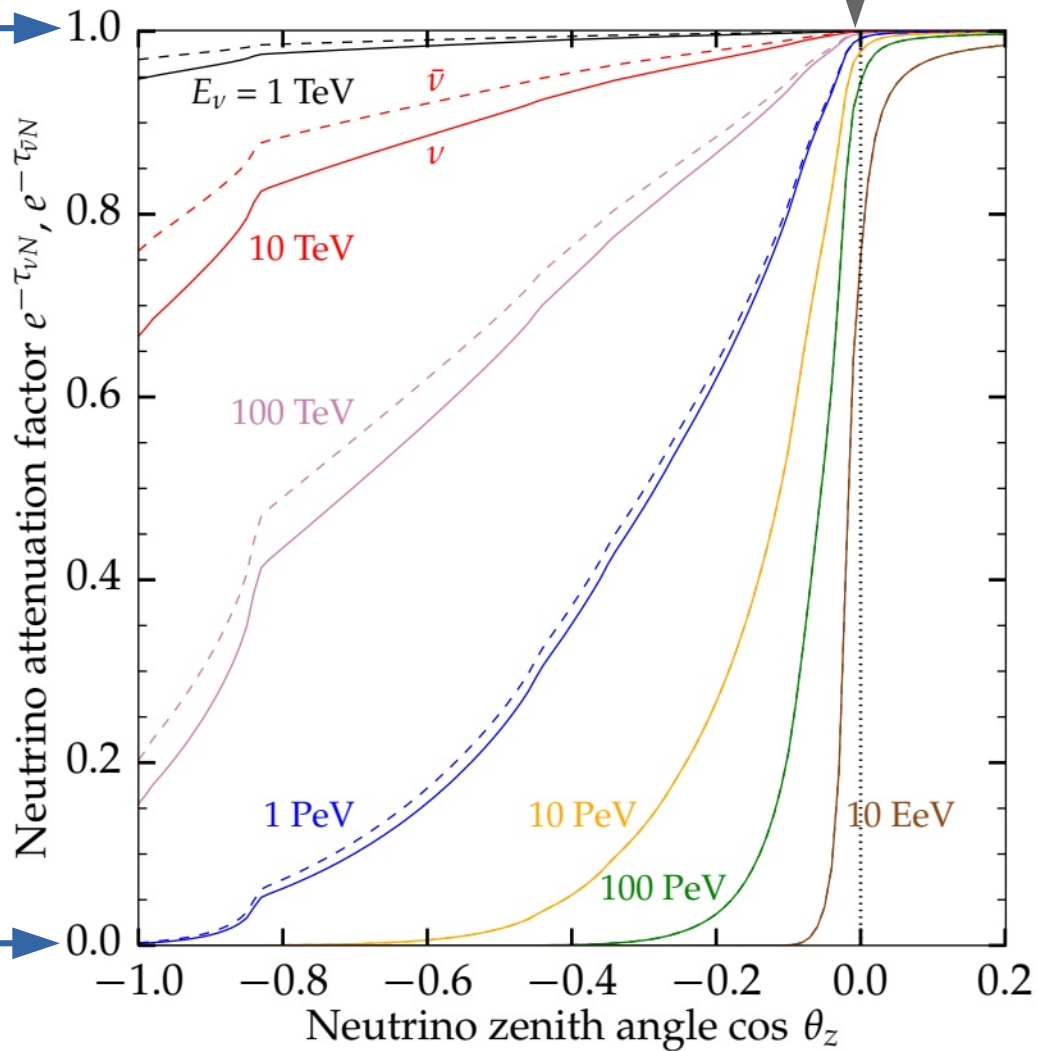
Neutrino-nucleon cross section



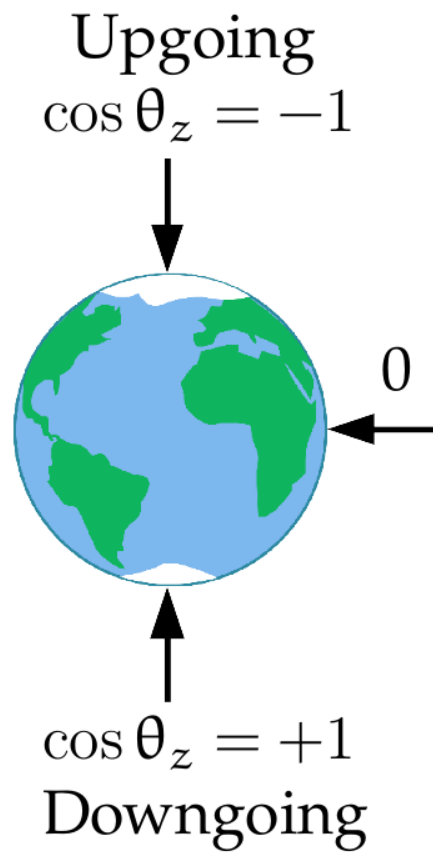
A feel for the in-Earth attenuation



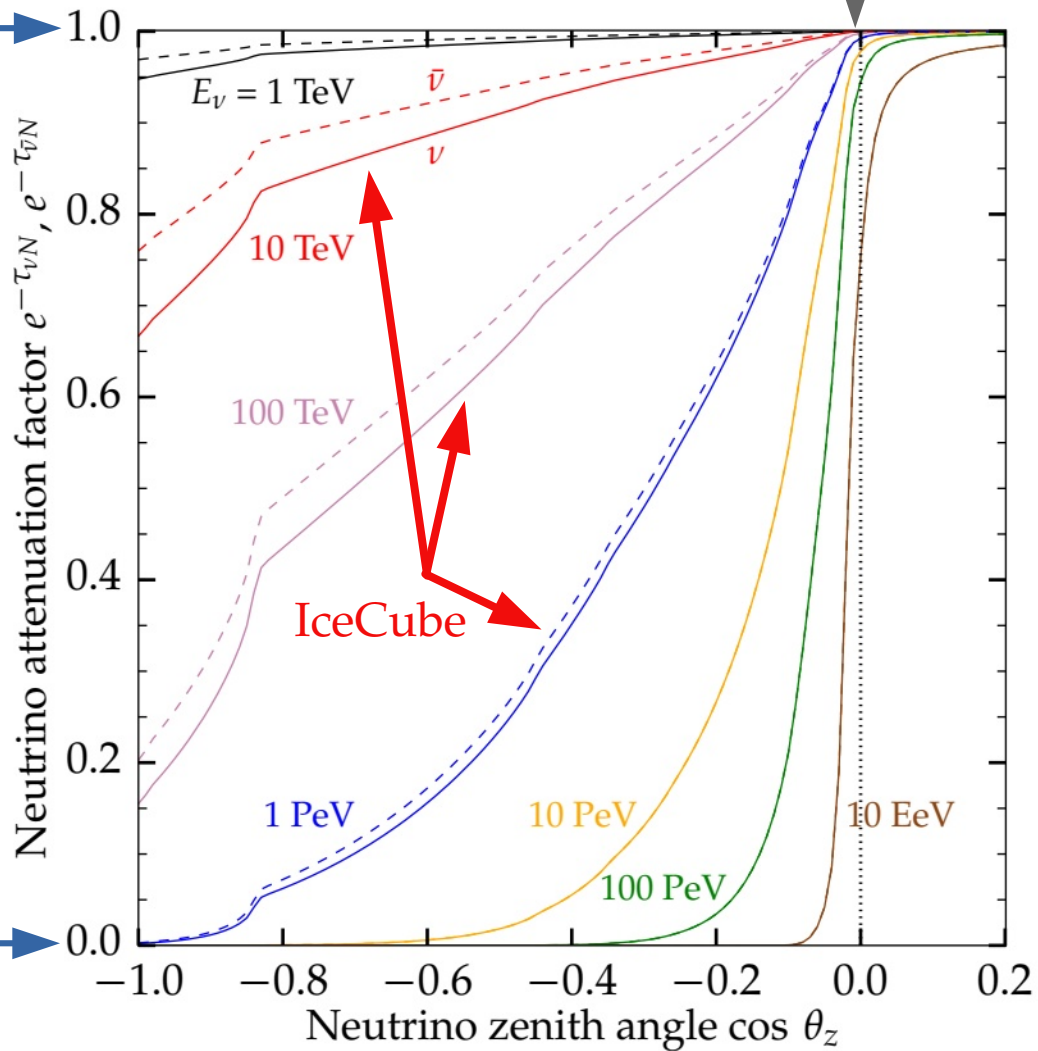
No
attenuation



Full
attenuation

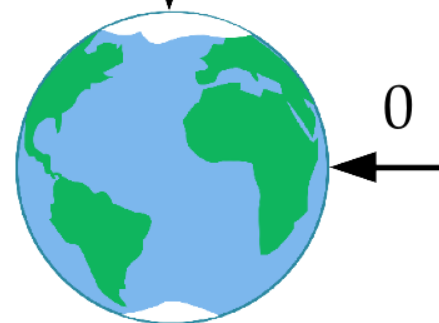


No
attenuation

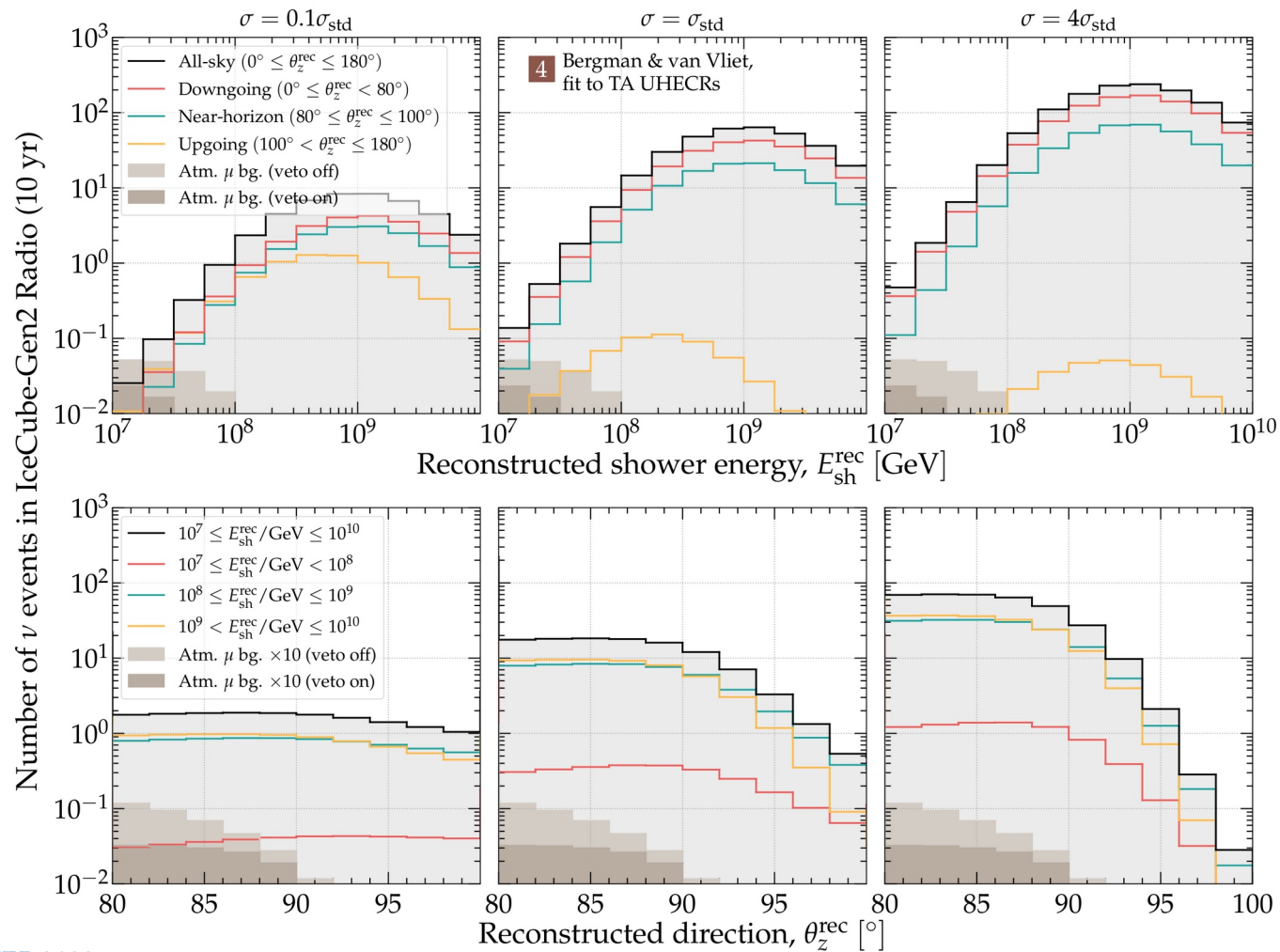


Full
attenuation

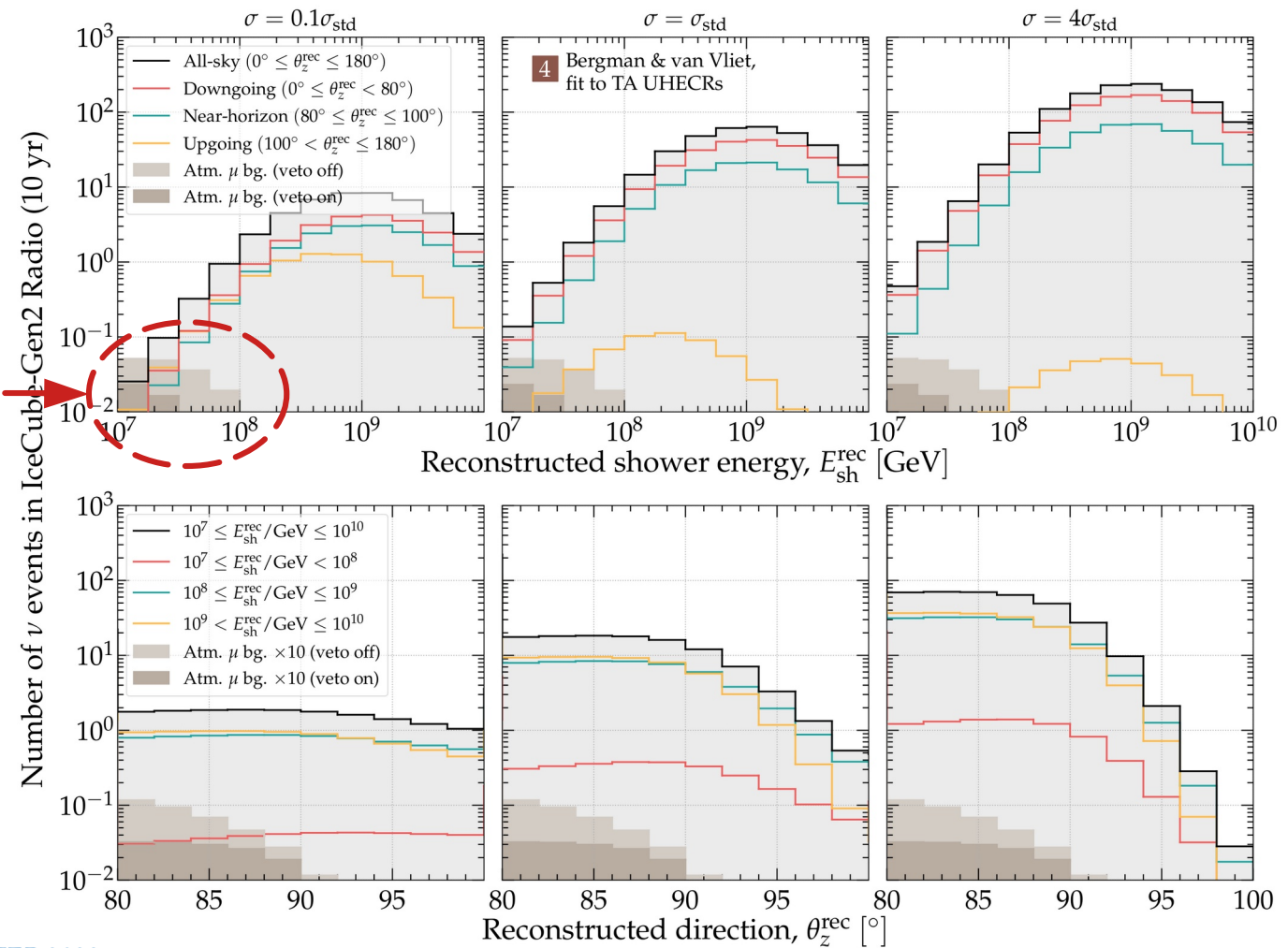
Upgoing
 $\cos \theta_z = -1$



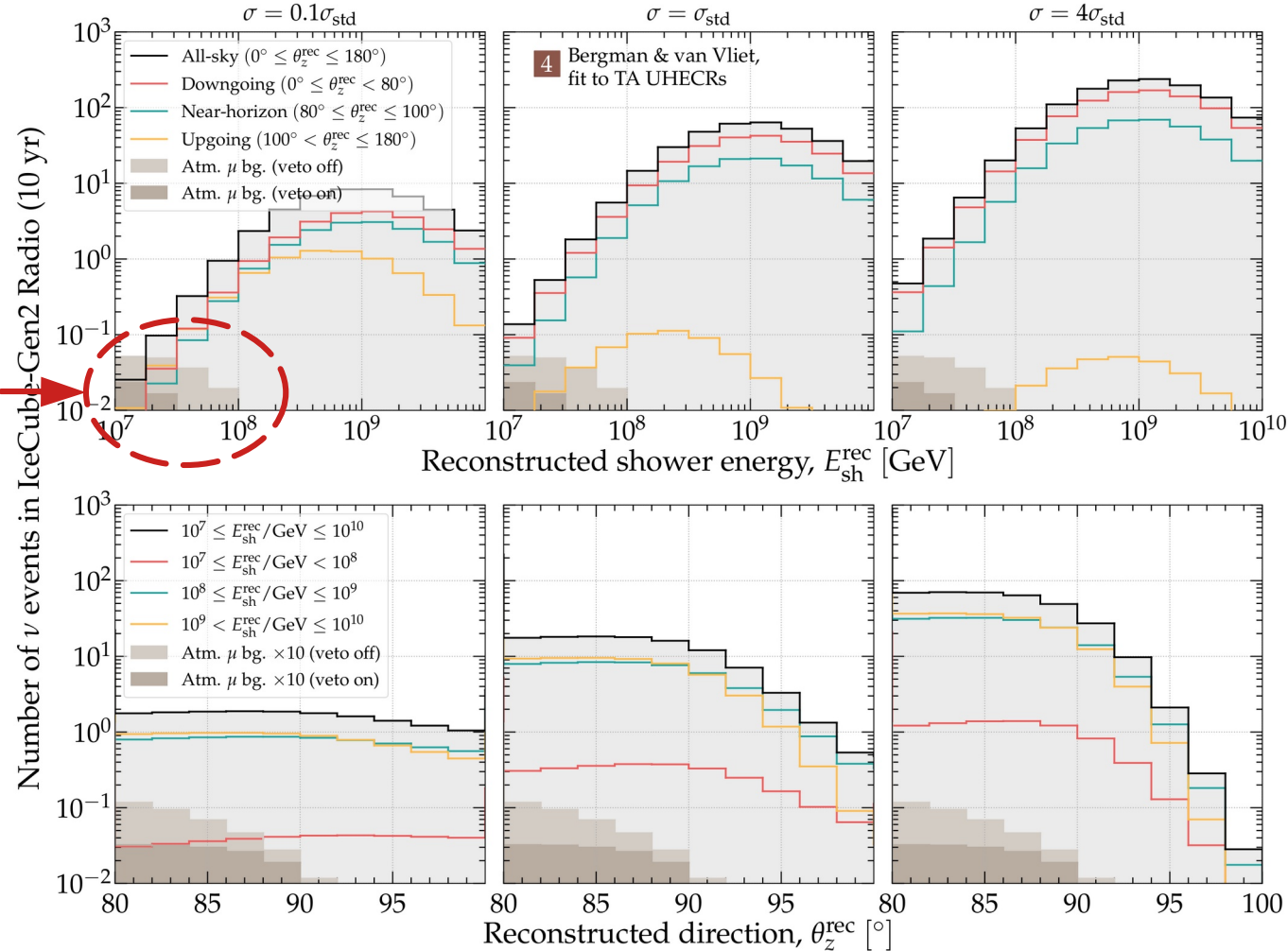
$\cos \theta_z = +1$
Downgoing



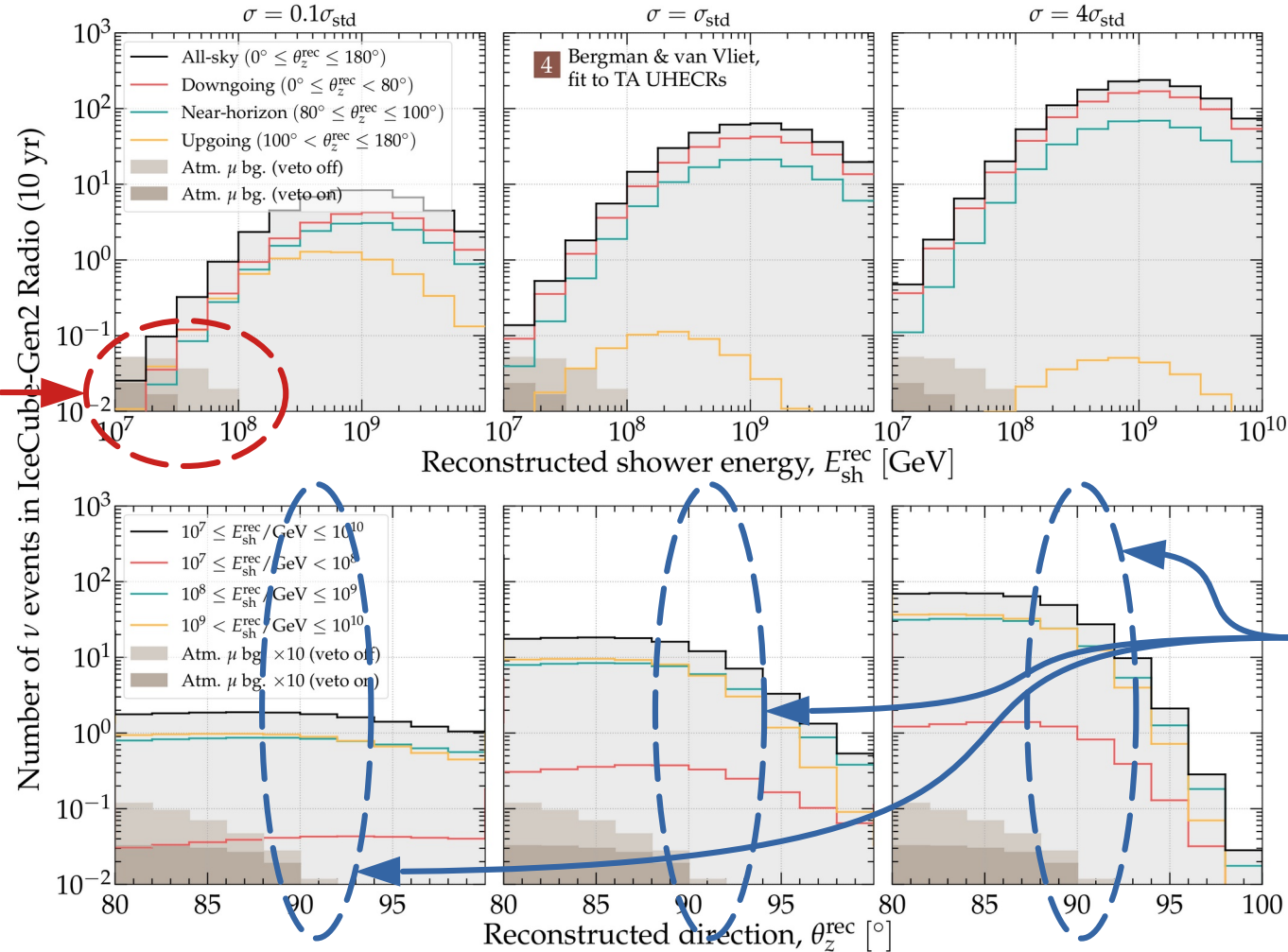
Atmospheric
muon
background



Larger neutrino-nucleon cross section



Larger neutrino-nucleon cross section

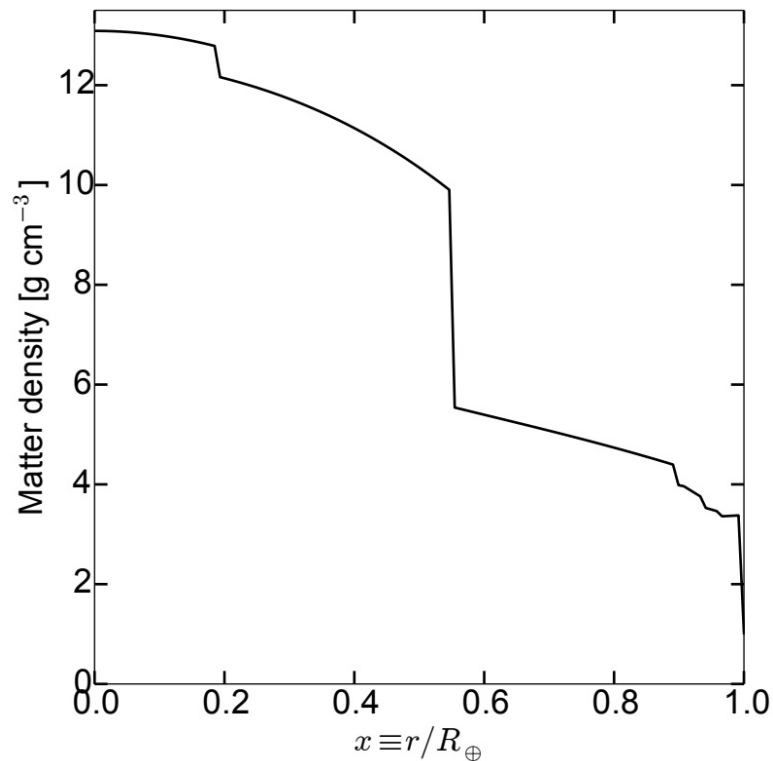


Sensitivity to cross section comes from horizontal neutrinos

A feel for the in-Earth attenuation

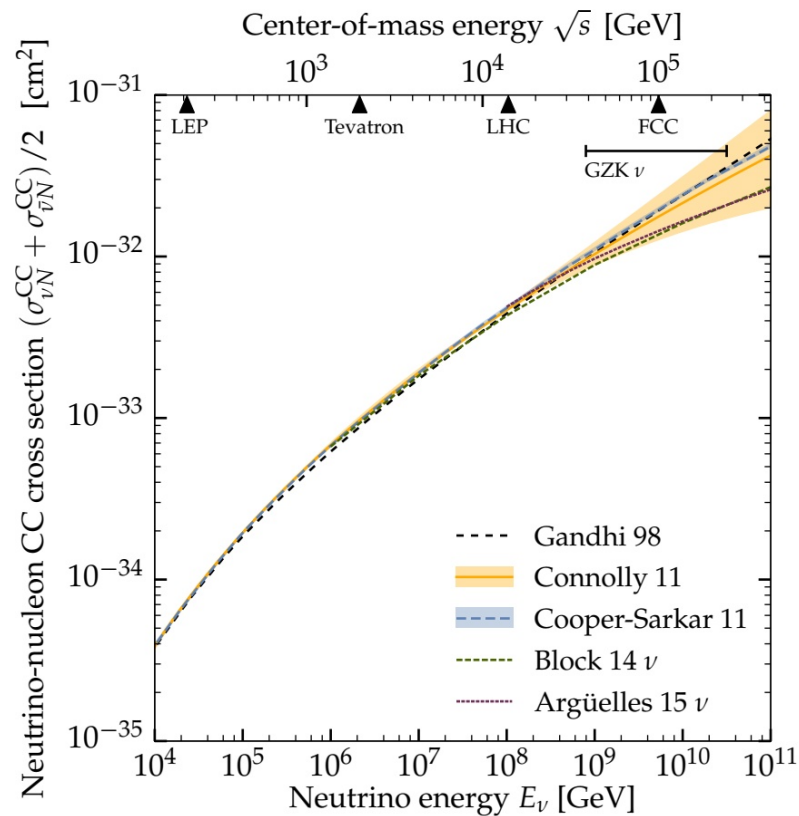
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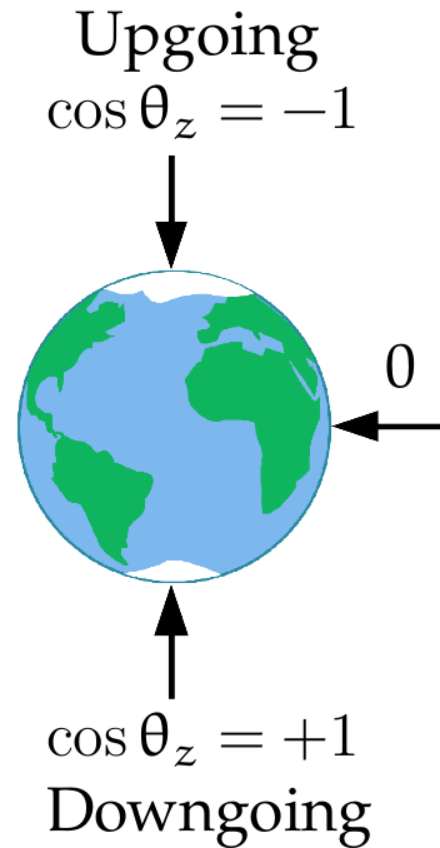
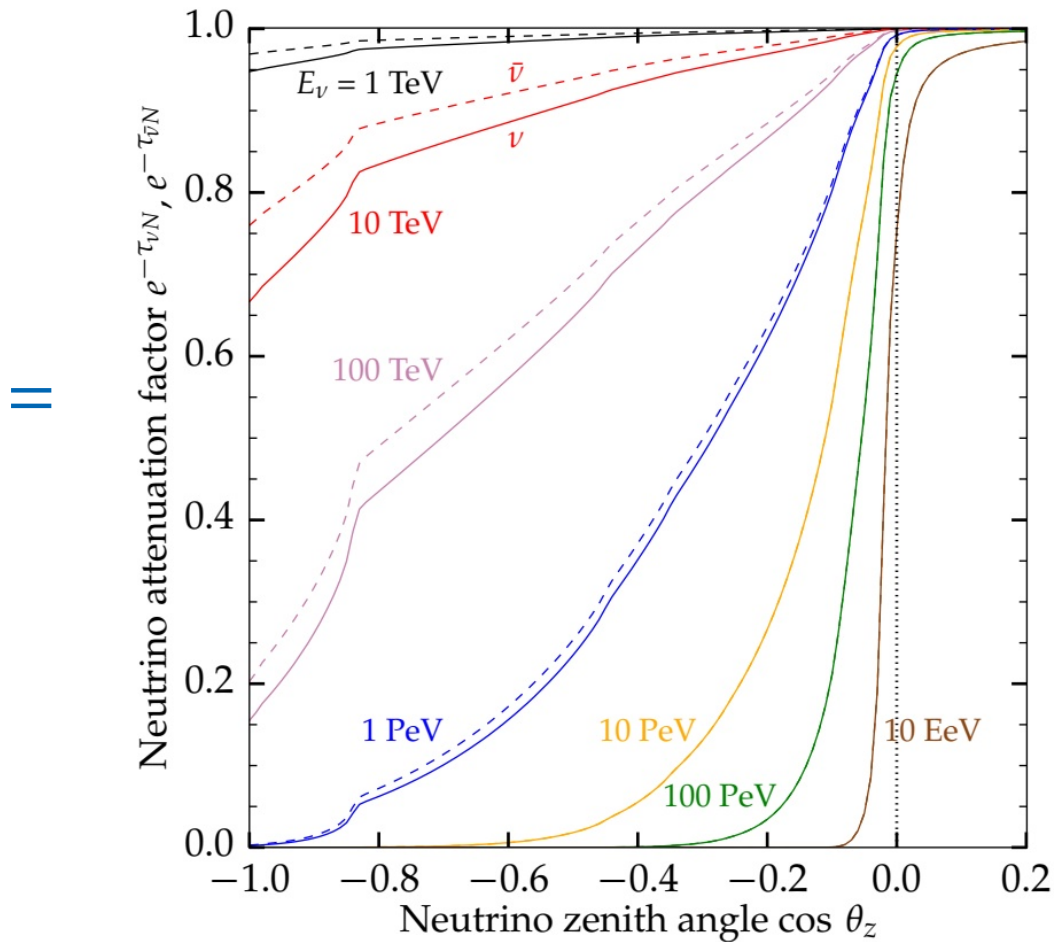


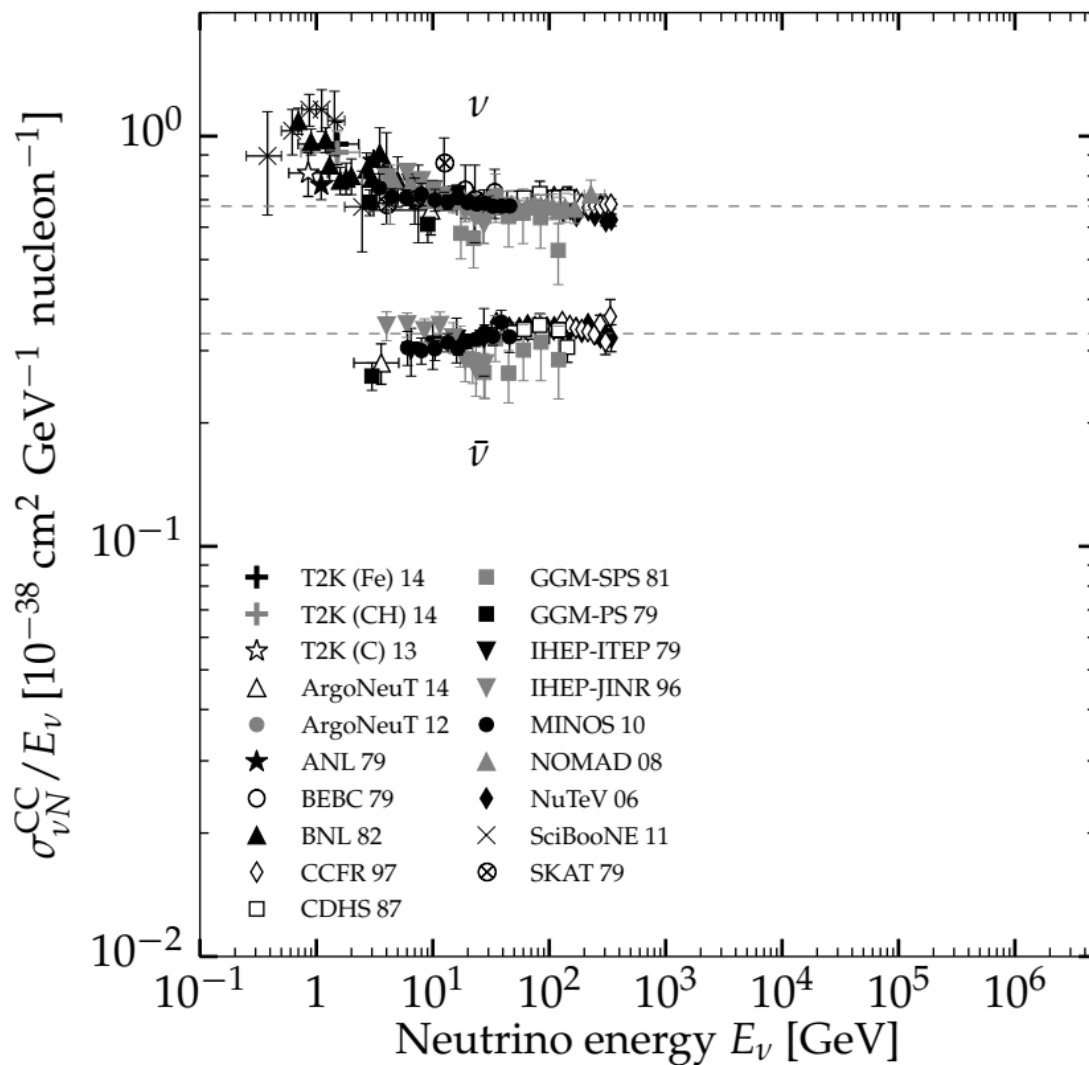
+

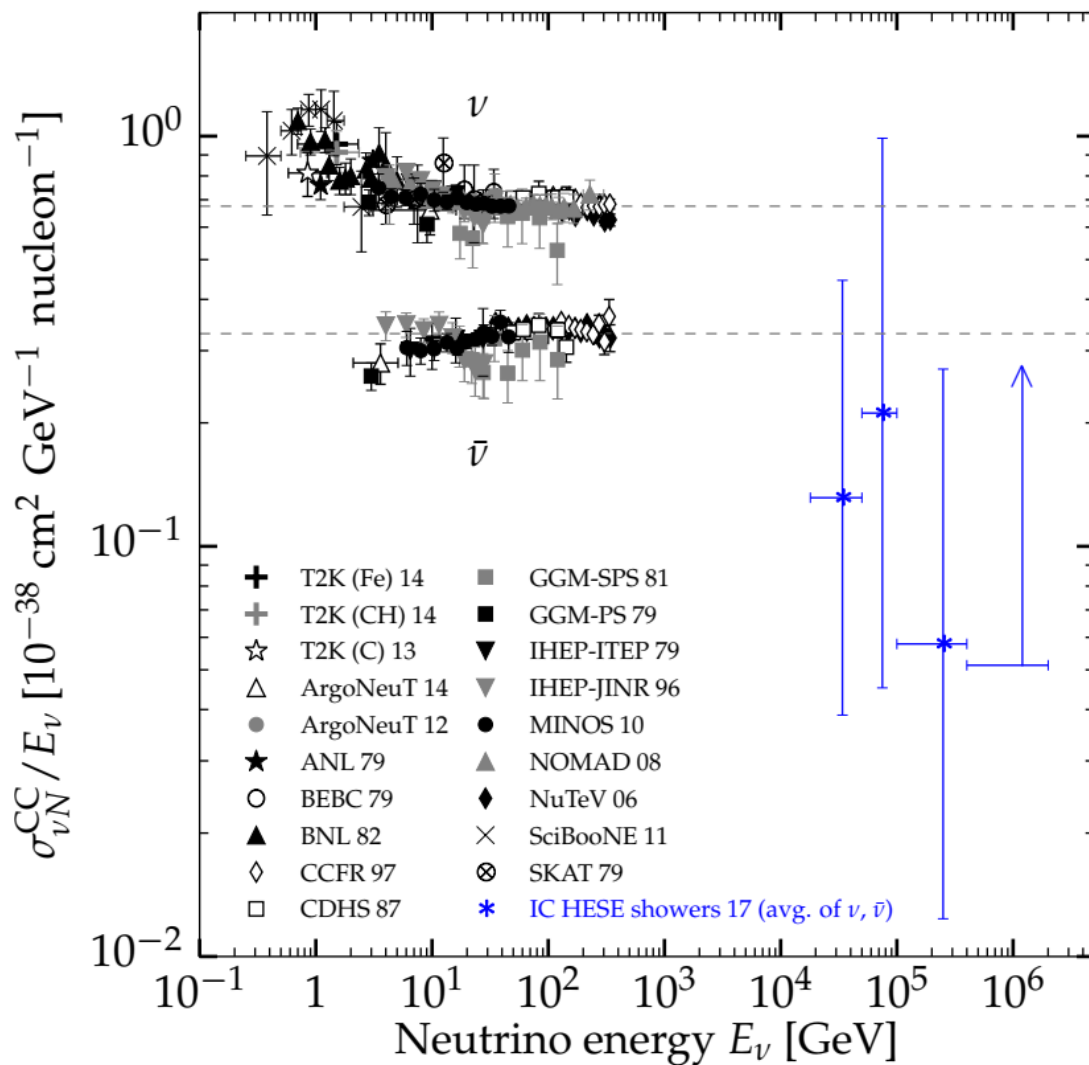
Neutrino-nucleon cross section

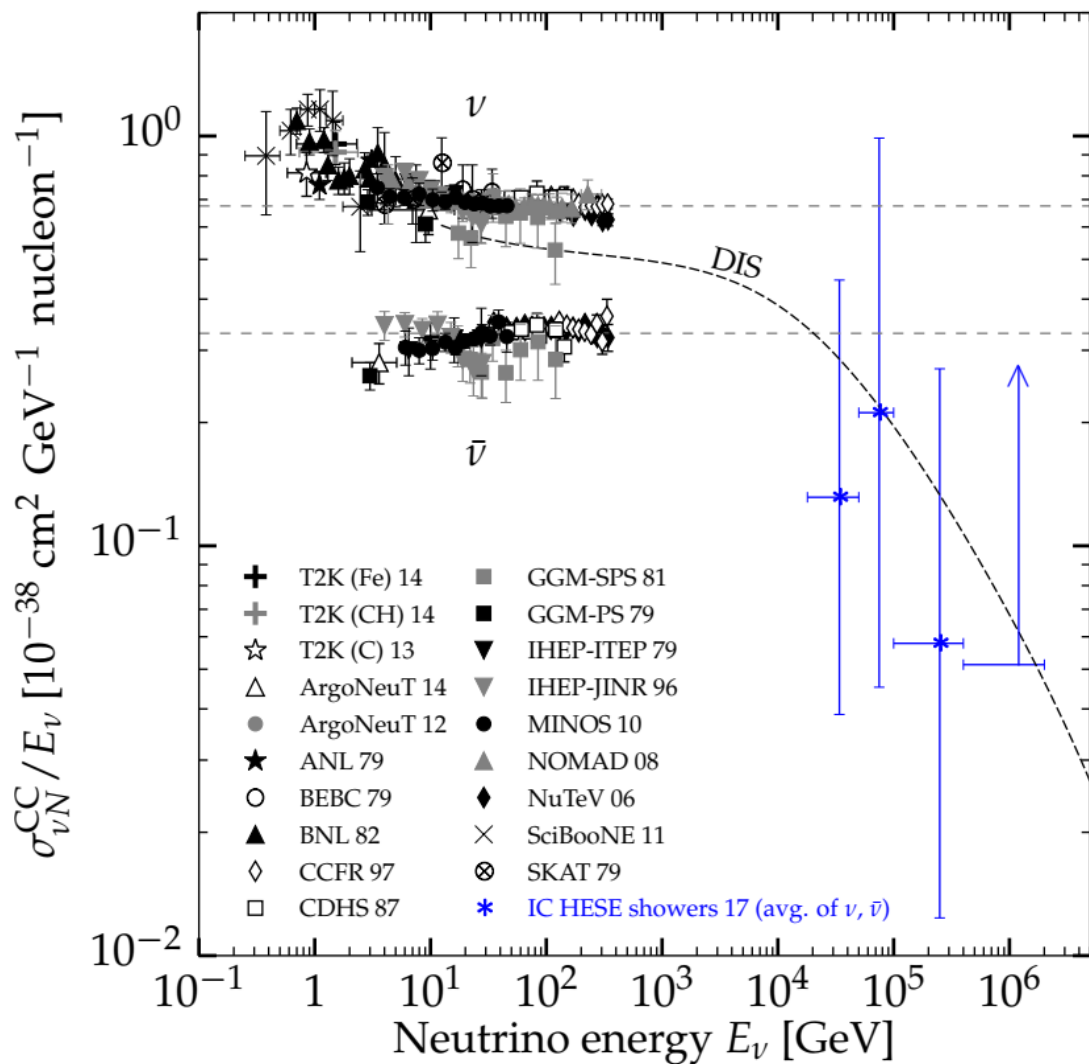


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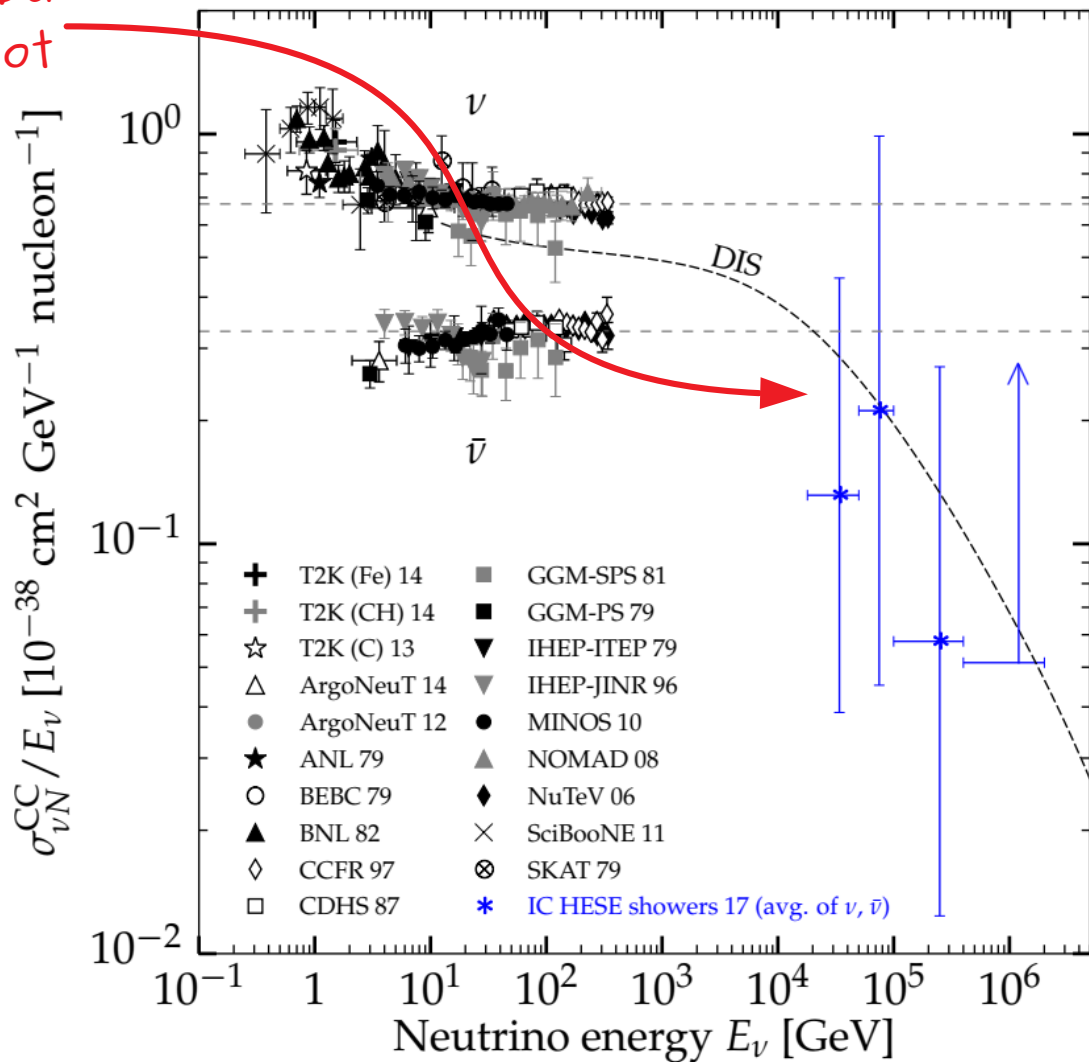








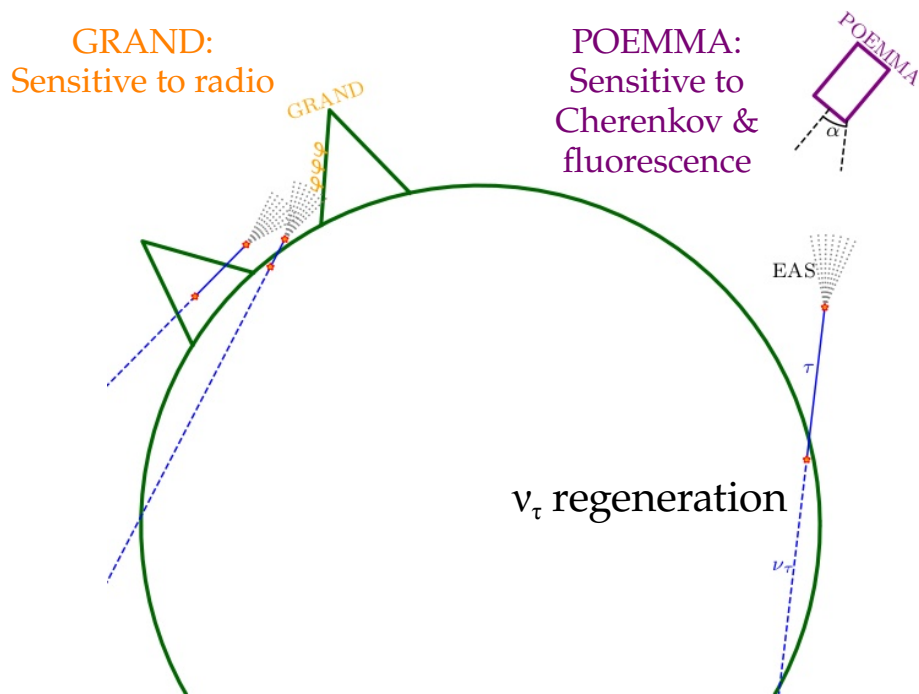
Extending the PDG
cross-section plot



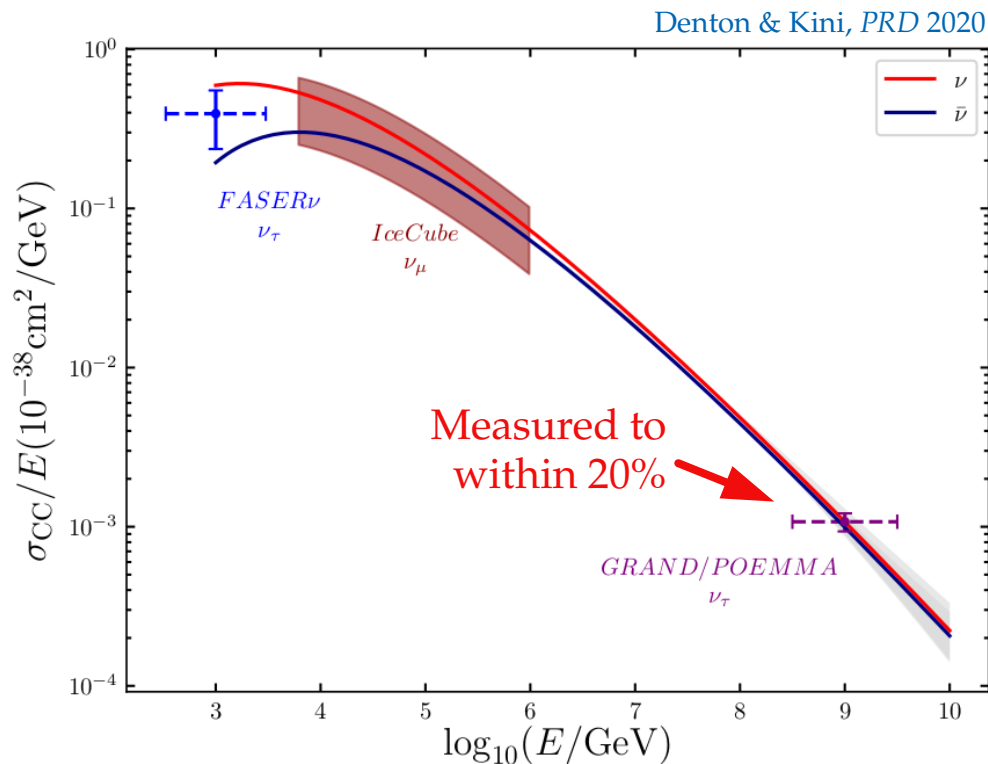
MB & Connolly PRL 2019
See also: IceCube, Nature 2017

GRAND & POEMMA

Both sensitive to extensive air showers induced by Earth-skimming UHE ν_τ



If they see 100 events from ν_τ with initial energy of 10^9 GeV (pre-attenuation):



Flux normalization

Cross section

All-flavor ν flux (10^8 GeV), $\log_{10}(E_{\nu,0}^2 \Phi_0 / [\text{GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}])$

IceCube-Gen2 Radio, 10 years

UHE ν flux model

- Rodrigues *et al.*, HL BL Lacs
- IceCube ν_μ (9.5 yr) extrapolated
- Rodrigues *et al.*, all AGN
- Bergman & van Vliet, fit to TA UHECRs

UHE νN cross section, $\log_{10} f_\sigma \equiv \log_{10}(\sigma / \sigma_{\text{std}})$

○ Real value
☆ Best fit
68% C.L.
95% C.L.
99.7% C.L.

$\log_{10} \sigma / \sigma_{\text{std}}$

- 0.09^{+0.75}_{-0.37}
- 0.07^{+0.54}_{-0.33}
- 0.01^{+0.18}_{-0.15}
- 0.01^{+0.16}_{-0.13}

$\log_{10} E_{\nu,0}^2 \Phi_0$

- 9.66^{+0.36}_{-0.74}
- 8.41^{+0.32}_{-0.53}
- 7.66^{+0.15}_{-0.18}
- 8.54^{+0.12}_{-0.15}

Needed to measure the cross section?

~30–300 events

In this work:
We fix the energy dependence of flux and cross section (but explore many alternatives)

Soon to come:
Measure the energy dependence of the flux and cross section

Flavor at the Earth: *theoretically palatable regions*

Theoretically palatable flavor regions

≡

MB, Beacom, Winter, PRL 2015

Allowed regions of flavor ratios at Earth derived from oscillations

Note:

The original palatable regions were
frequentist [MB, Beacom, Winter, PRL 2015];
the new ones are Bayesian

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Ingredient #1:

Flavor ratios at the source,

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

Fix at one of the benchmarks
(pion decay, muon-damped, neutron decay)

or

Explore all possible combinations

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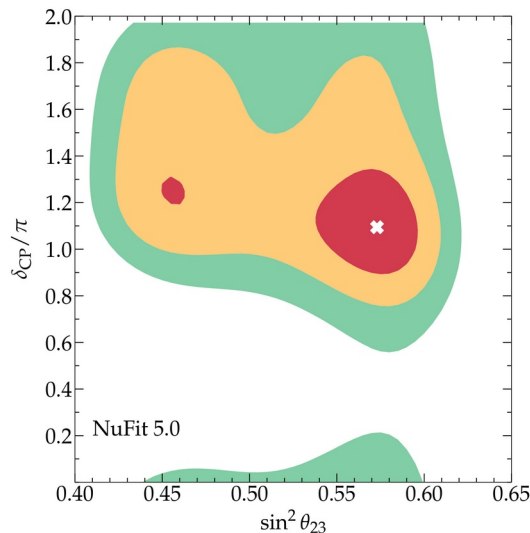
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Explore all possible combinations

2020: Use χ^2 profiles from
the NuFit 5.0 global fit
(solar + atmospheric
+ reactor + accelerator)

Esteban *et al.*, *JHEP* 2020
www.nu-fit.org



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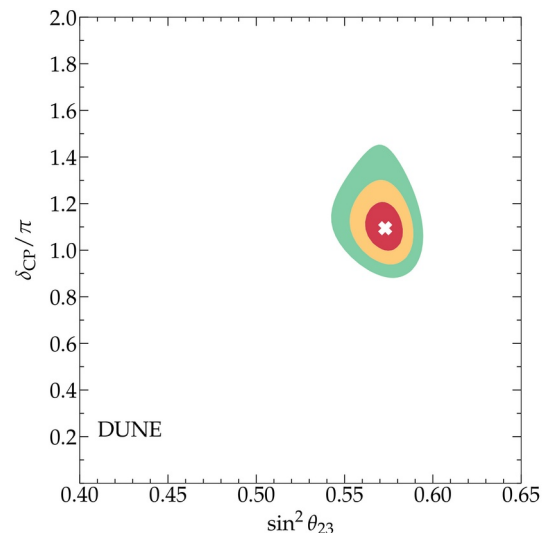
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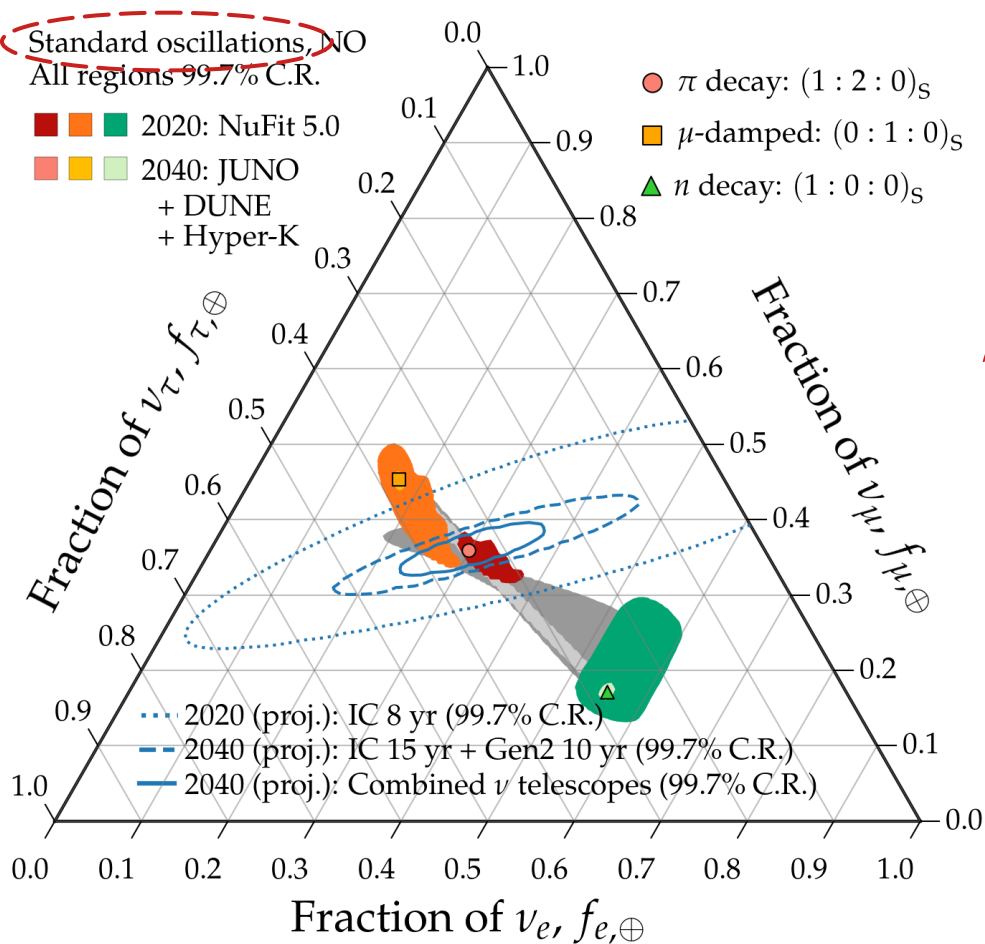
Post-2020: Build our own profiles using simulations of JUNO, DUNE, Hyper-K

An *et al.*, *J. Phys. G* 2016
DUNE, 2002.03005

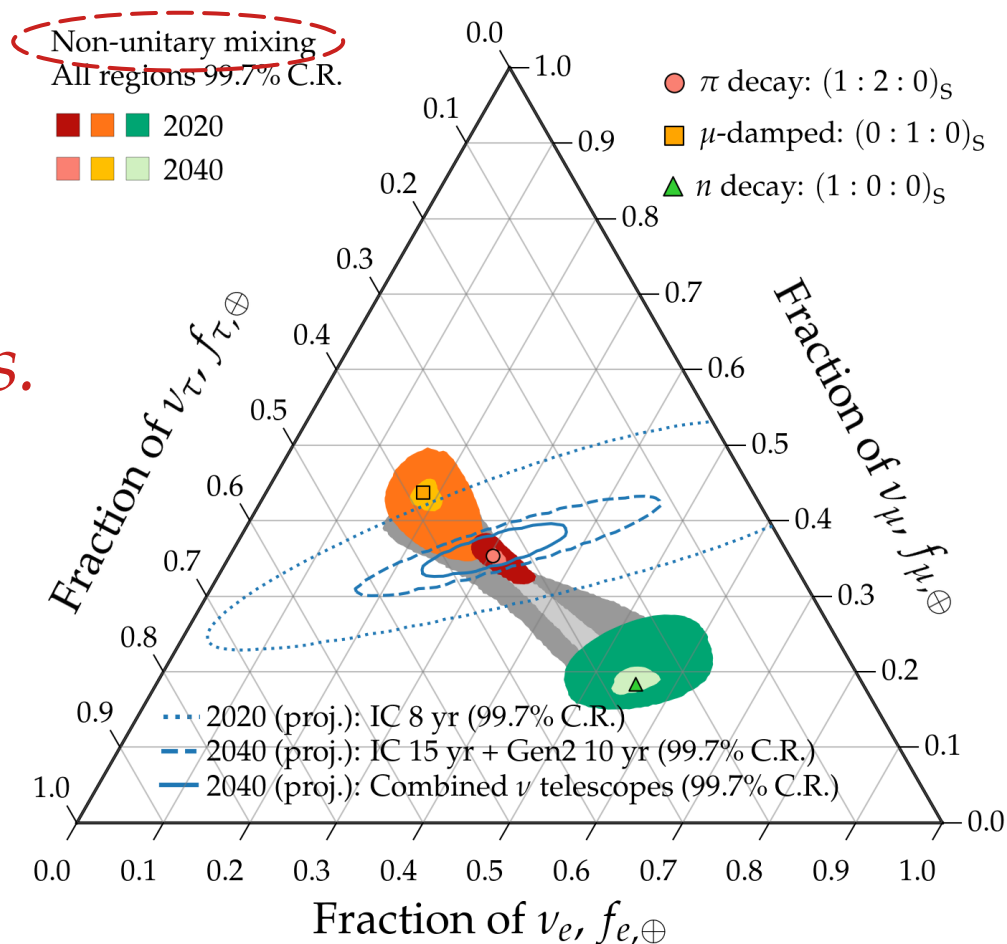
Huber, Lindner, Winter, *Nucl. Phys. B* 2002



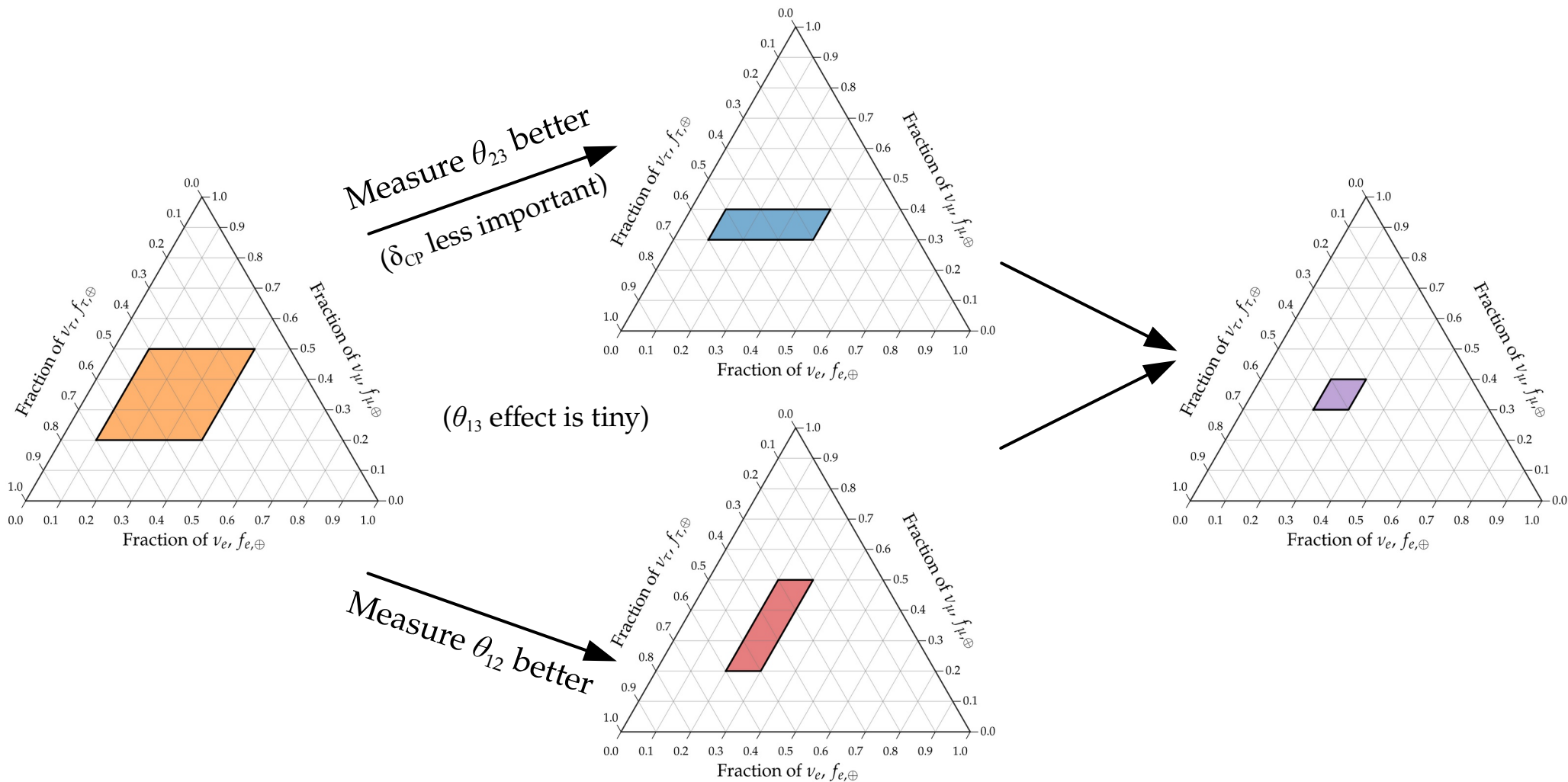
No unitarity? *No problem*



vs.



How knowing the mixing parameters better helps



Unstable neutrinos:
Are neutrinos for ever?

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
- ▶ BSM decays may have significantly higher rates: $\nu_i \rightarrow \nu_j + \phi$
- ▶ We work in a model-independent way:
the nature of ϕ is unimportant if it is invisible to neutrino detectors

» Age of Universe
(~ 14.5 Gyr)

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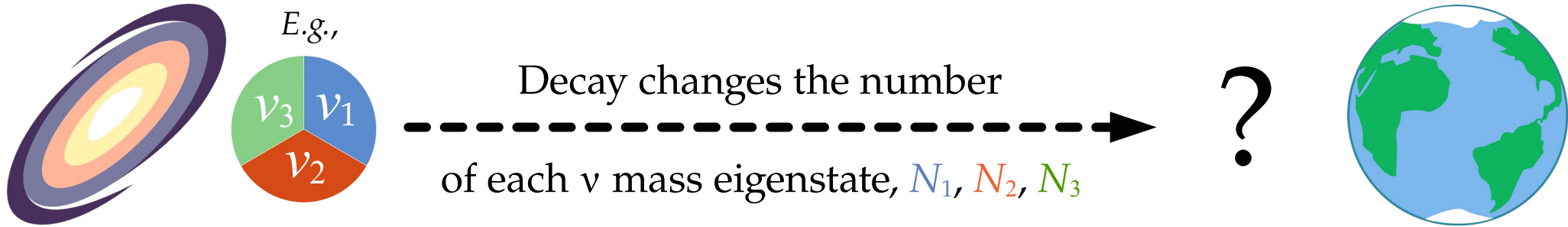
Nambu-Goldstone
boson of a broken
symmetry

- ▶ 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



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

?



Only sensitive to their ratio

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

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 ν are longer-lived...

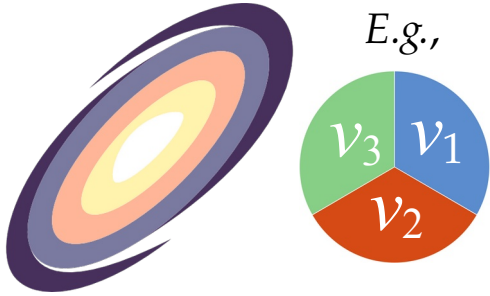
The flux of ν_i is attenuated by $\exp[- (L/E) \cdot (m_i/\tau_i)]$

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

Astrophysical sources

Earth

$L \sim$ up to a few Gpc



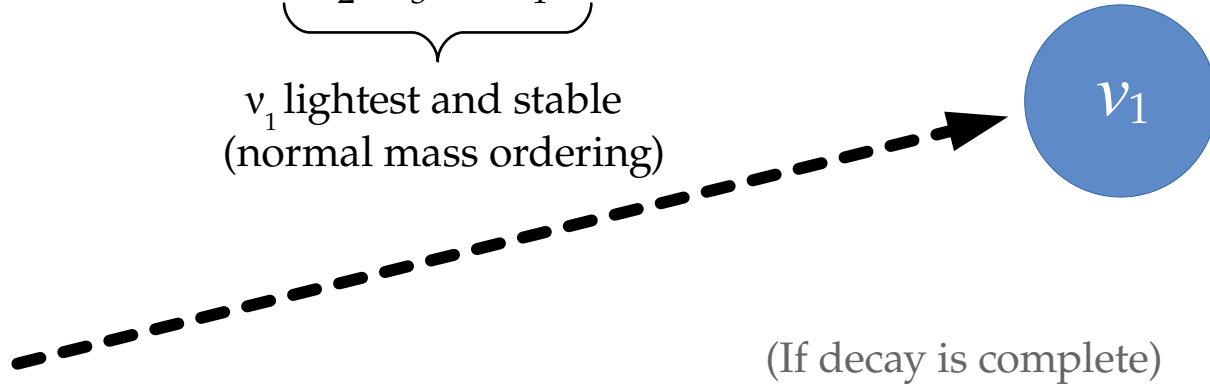
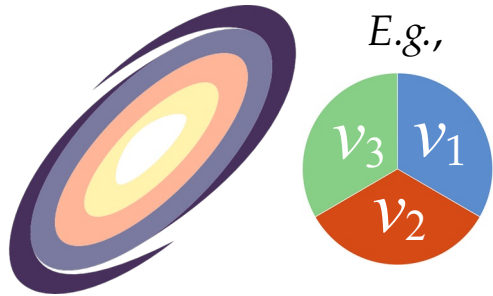
Astrophysical sources

Earth

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

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

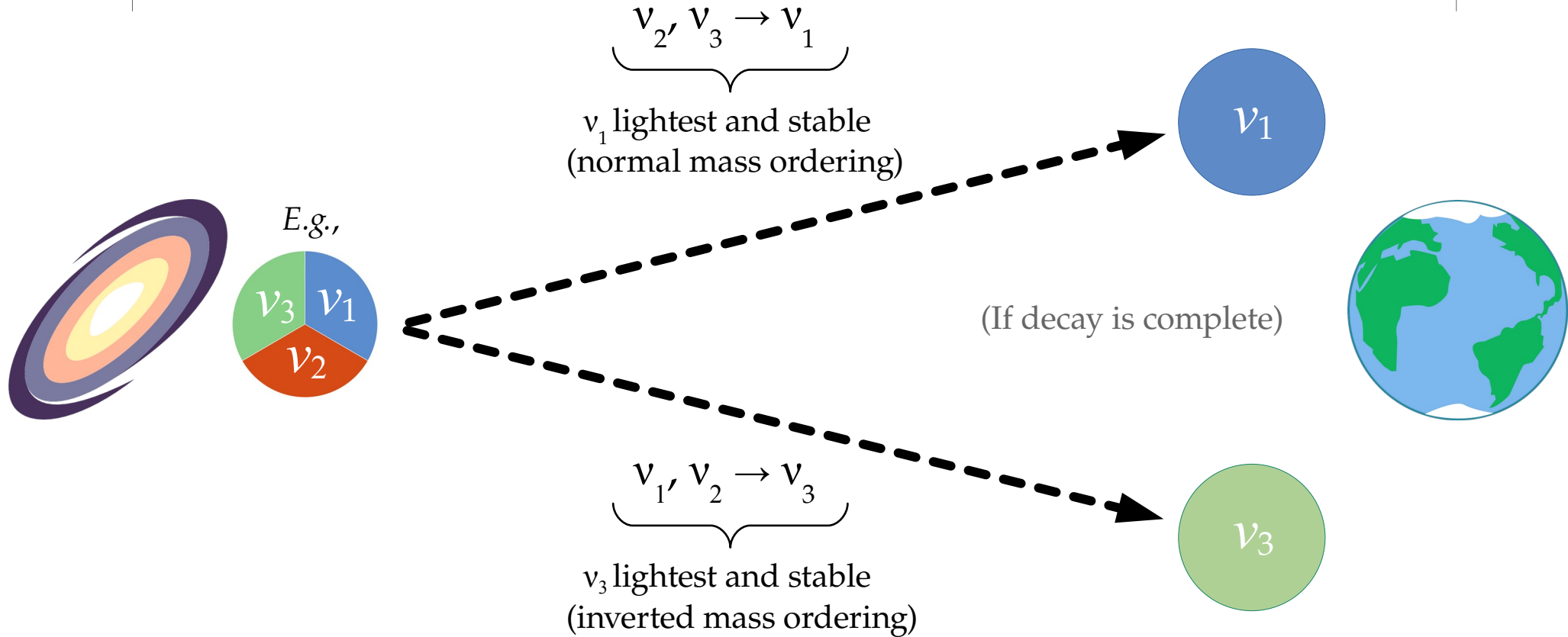
ν_1 lightest and stable
(normal mass ordering)



Astrophysical sources

Earth

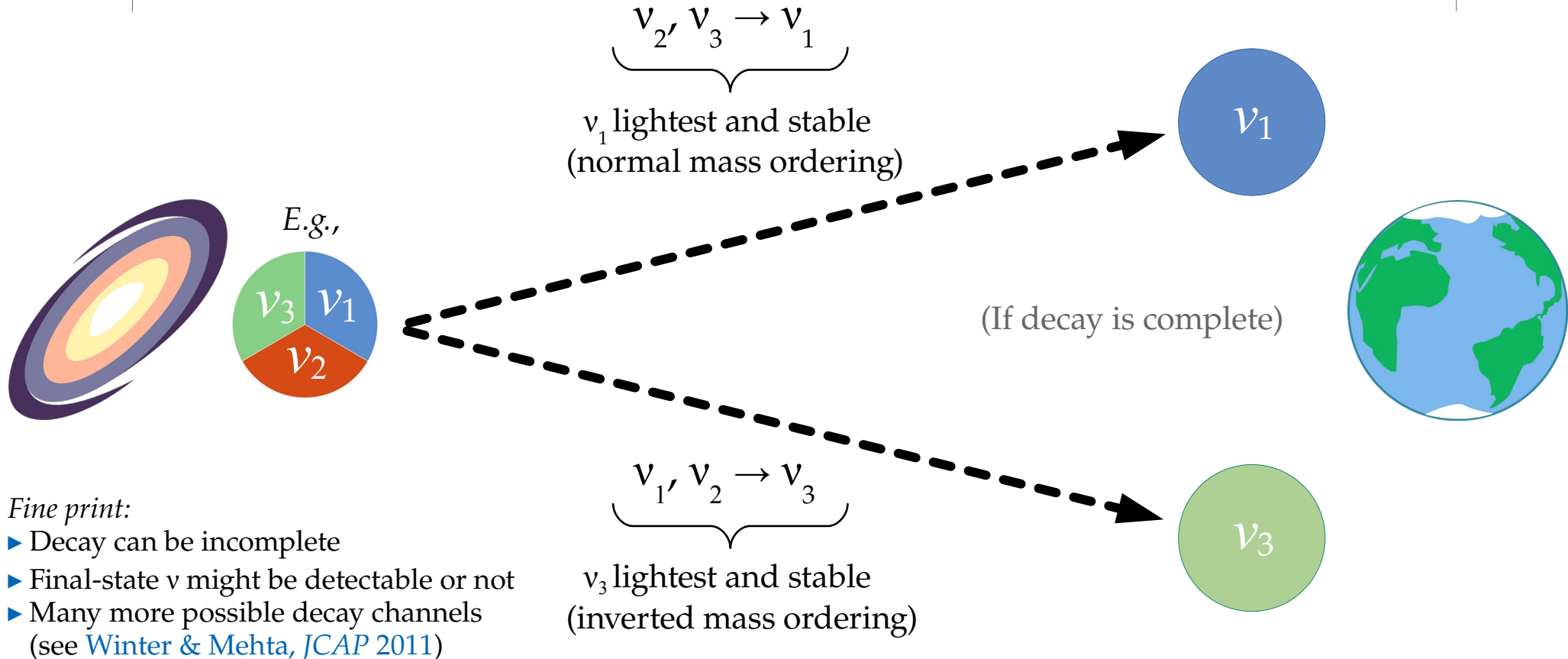
$L \sim$ up to a few Gpc



Astrophysical sources

Earth

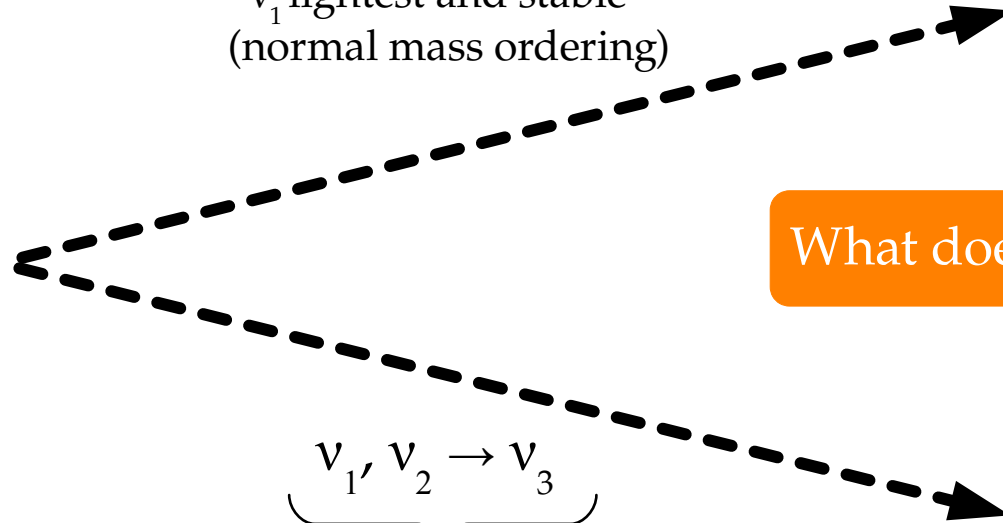
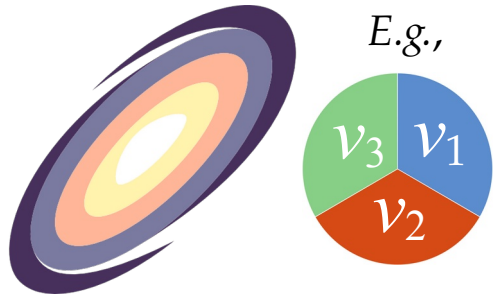
$L \sim \text{up to a few Gpc}$



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

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

ν_1 lightest and stable
(normal mass ordering)



What does decay change?



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

ν_3 lightest and stable
(inverted mass ordering)

Fine print:

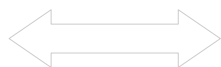
- ▶ Decay can be incomplete
- ▶ Final-state ν might be detectable or not
- ▶ Many more possible decay channels
(see [Winter & Mehta, JCAP 2011](#))

What does neutrino decay change?

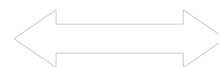
Flavor composition $\longleftrightarrow$ Spectrum shape $\longleftrightarrow$ Event rate

What does neutrino decay change?

Flavor composition



Spectrum shape



Event rate

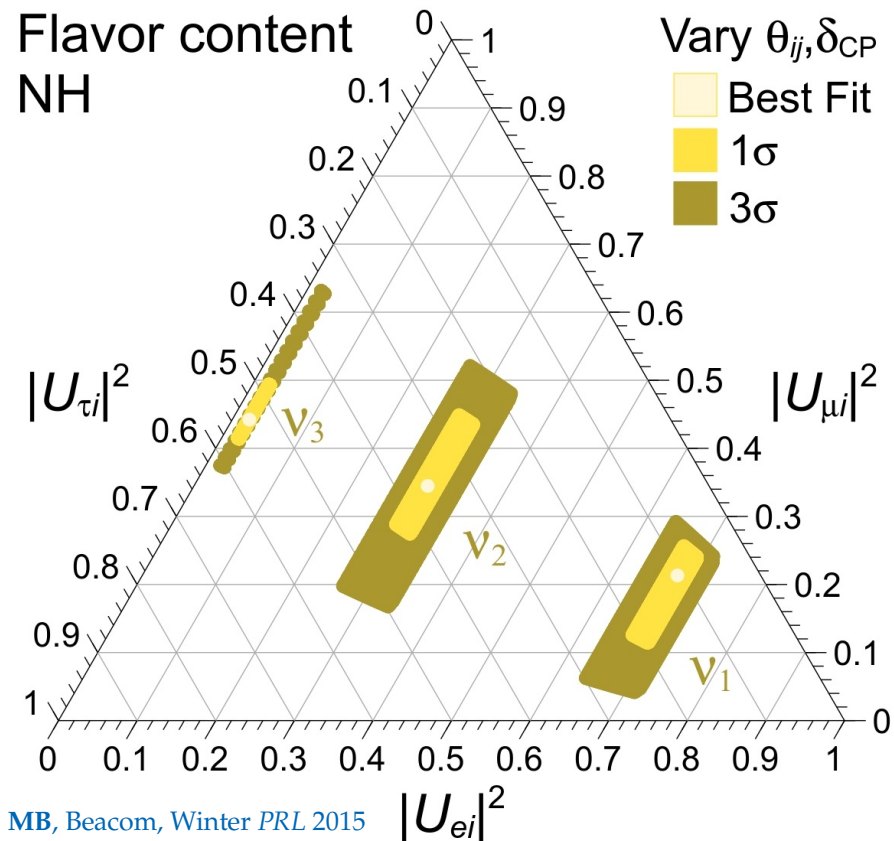
Flavor content of mass eigenstates:

Known to within 2%

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

Known to within 8%

Known to within 20%
(or worse)



What does neutrino decay change?

Flavor composition



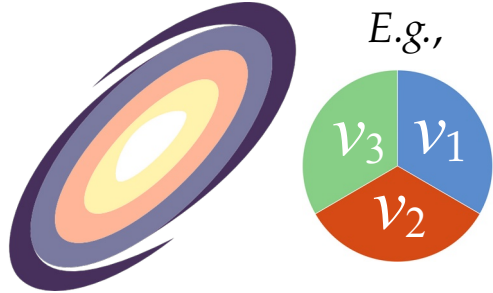
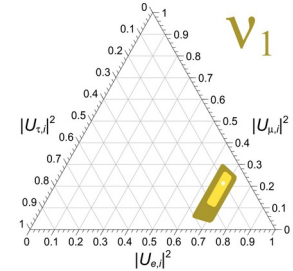
Spectrum shape



Event rate

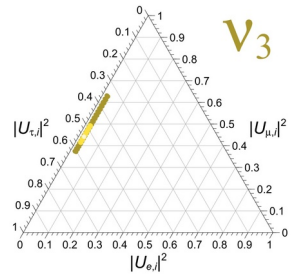
$$\nu_{2'}, \nu_3 \rightarrow \nu_1$$

ν_1 lightest and stable
(normal mass ordering)



$$\nu_{1'}, \nu_2 \rightarrow \nu_3$$

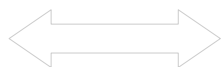
ν_3 lightest and stable
(inverted mass ordering)



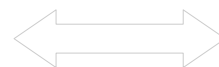
What does neutrino decay change?

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

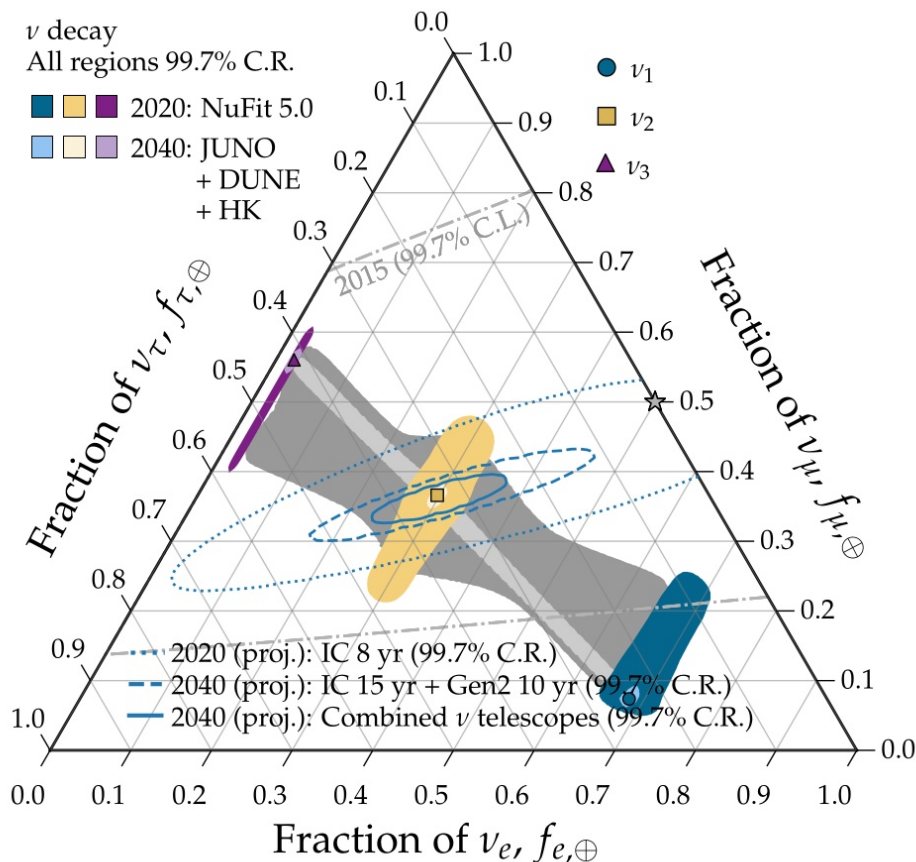
Flavor composition



Spectrum shape



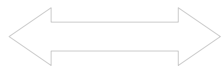
Event rate



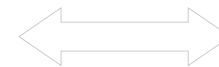
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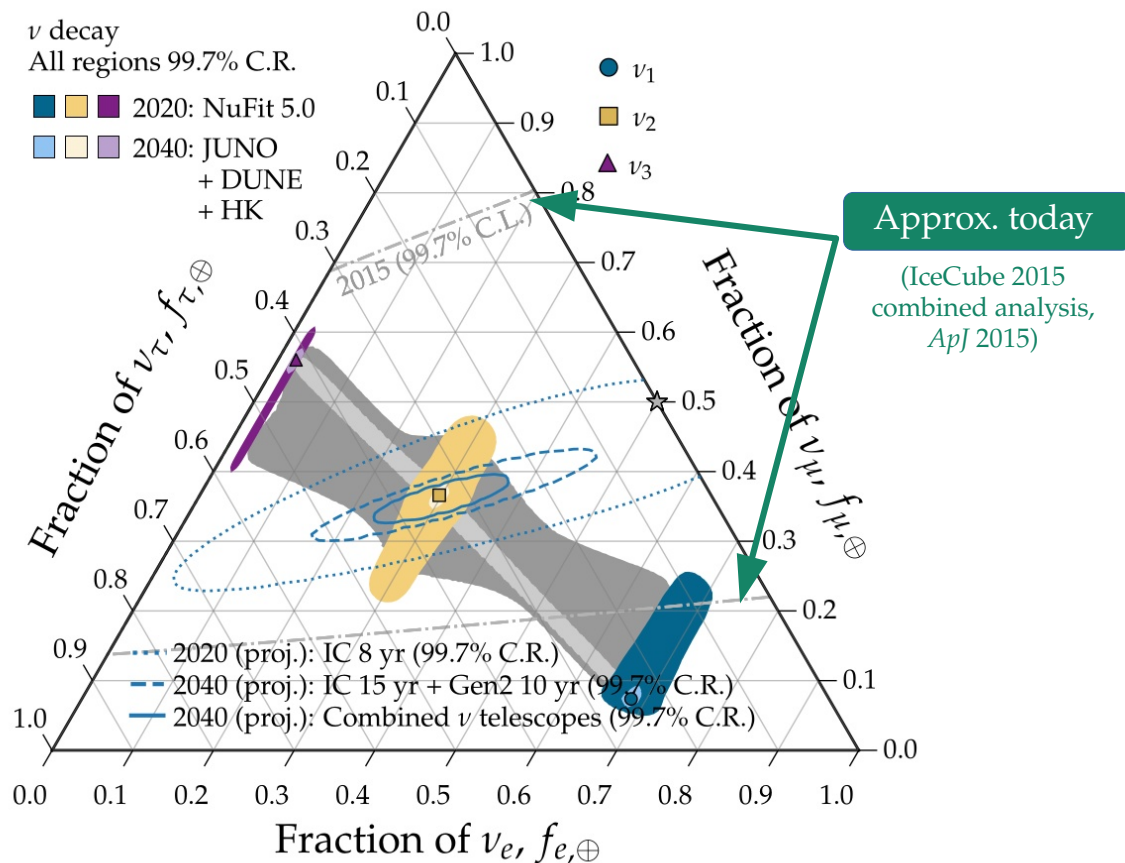
Flavor composition



Spectrum shape



Event rate



What does neutrino decay change?

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

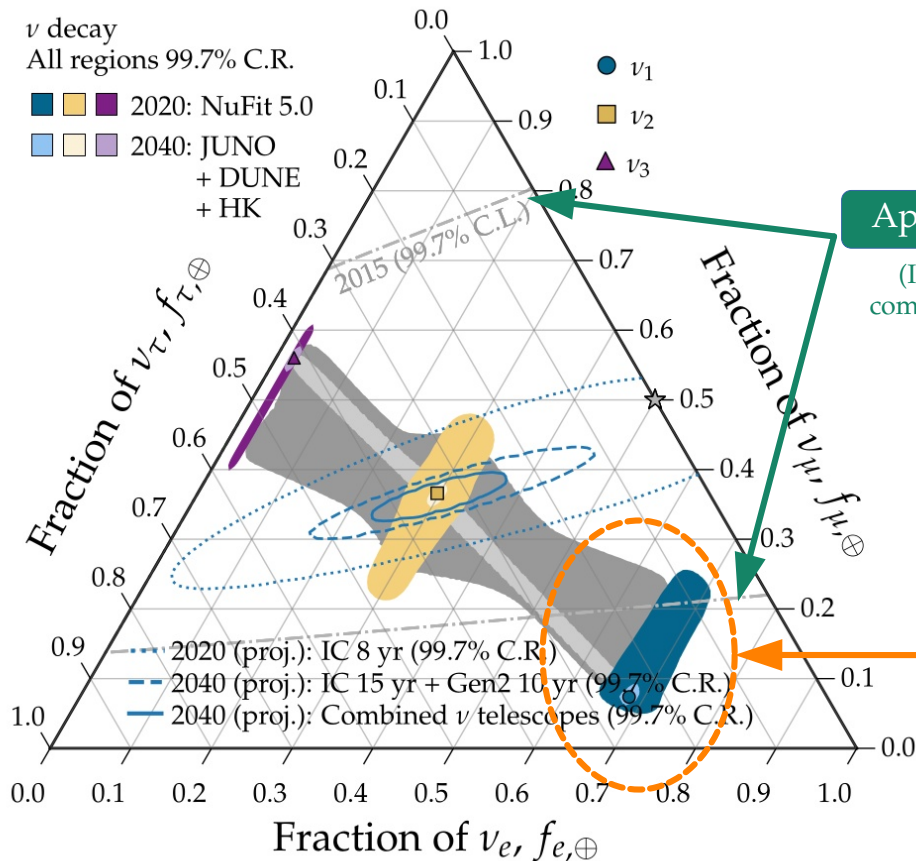
Flavor composition



Spectrum shape



Event rate



Approx. today

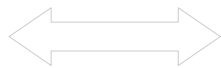
(IceCube 2015
combined analysis,
ApJ 2015)

Complete decay into
 ν_1 disfavored by 2015
IceCube flavor measurement

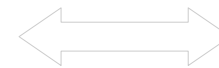
What does neutrino decay change?

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

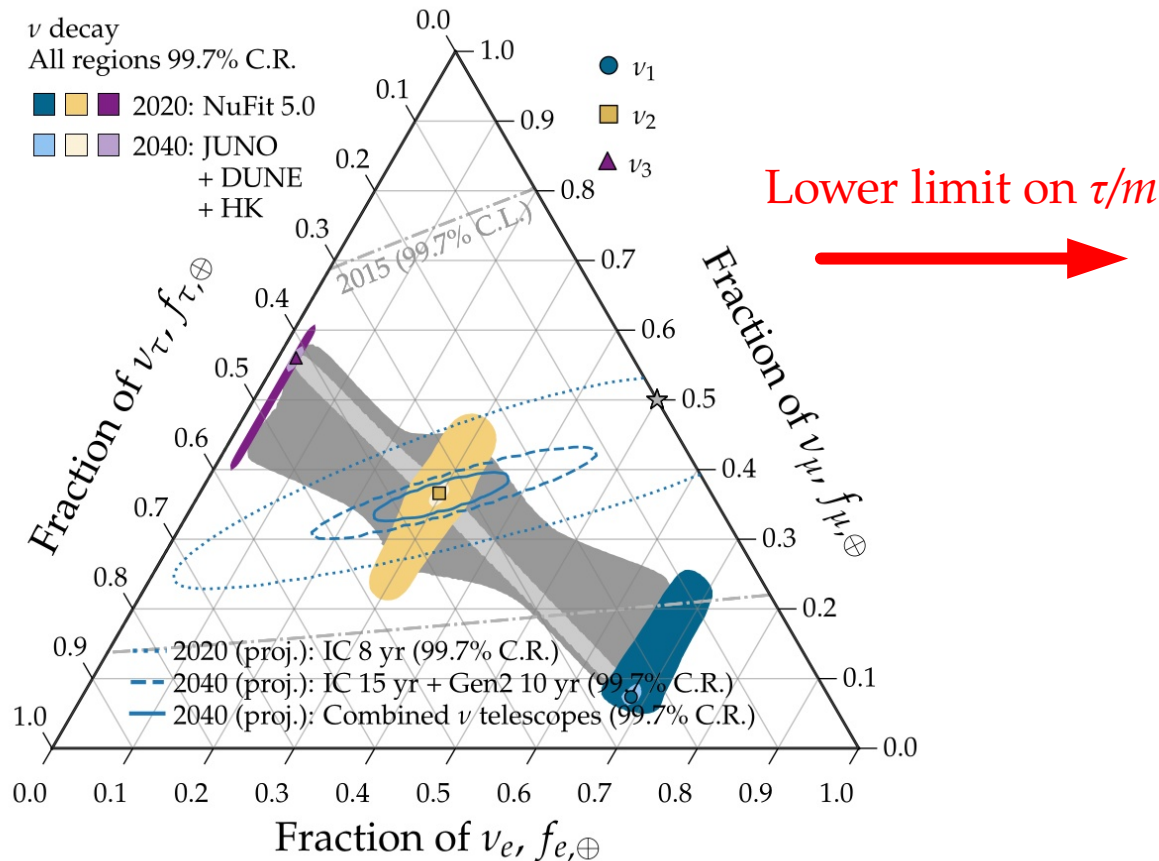
Flavor composition



Spectrum shape



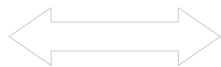
Event rate



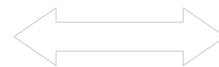
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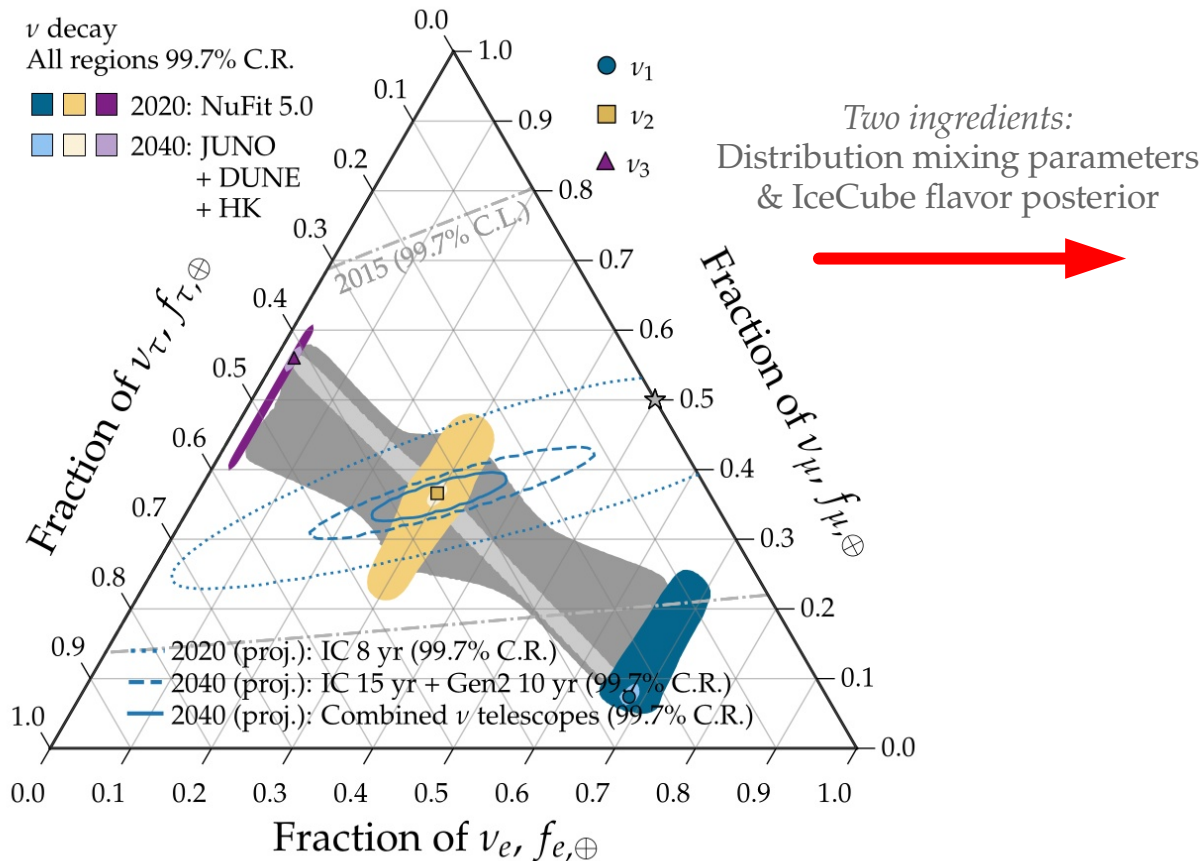
Flavor composition



Spectrum shape



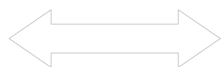
Event rate



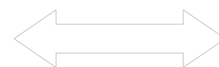
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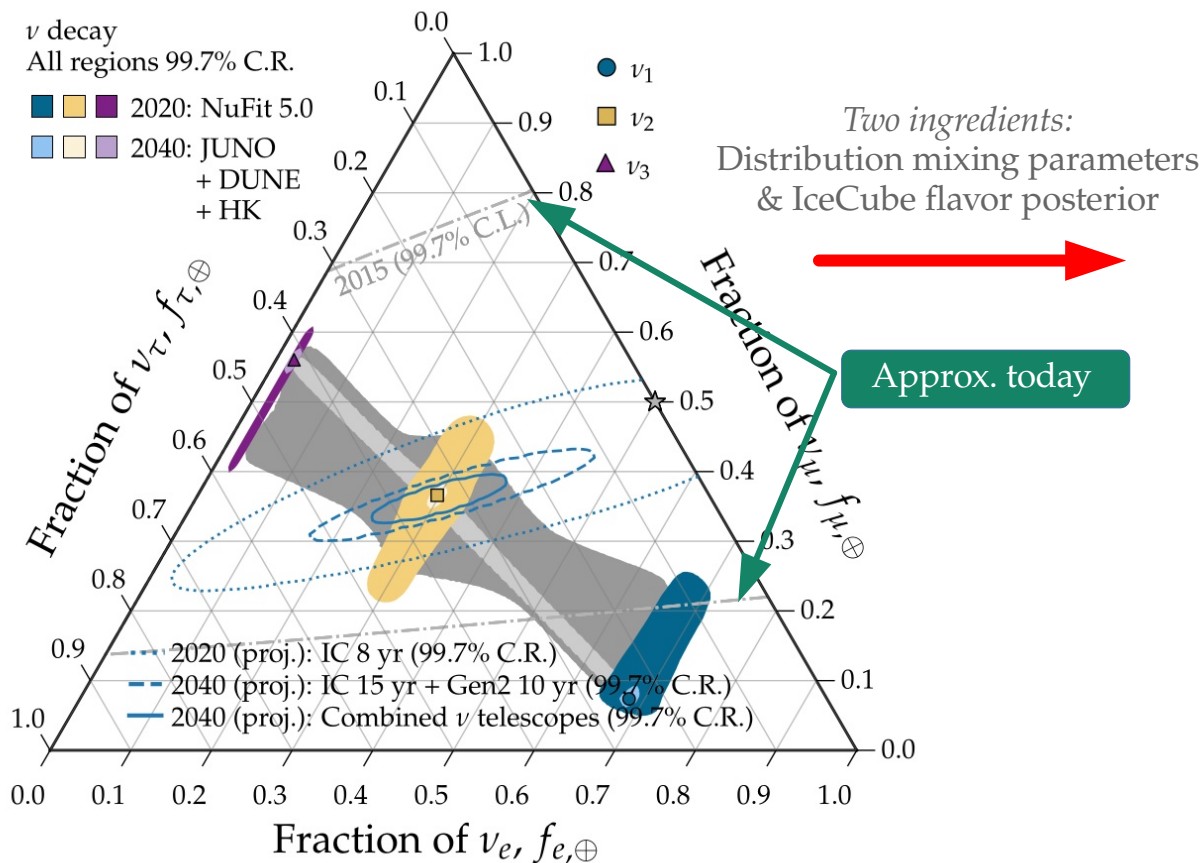
Flavor composition



Spectrum shape



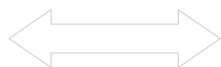
Event rate



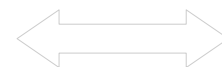
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See also: Beacom *et al.*, *PRL* 2002 / Baerwald, **MB**, Winter, *JCAP* 2012 / **MB**, Beacom, Murase, *PRD* 2017 / Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / **MB**, 2004.06844

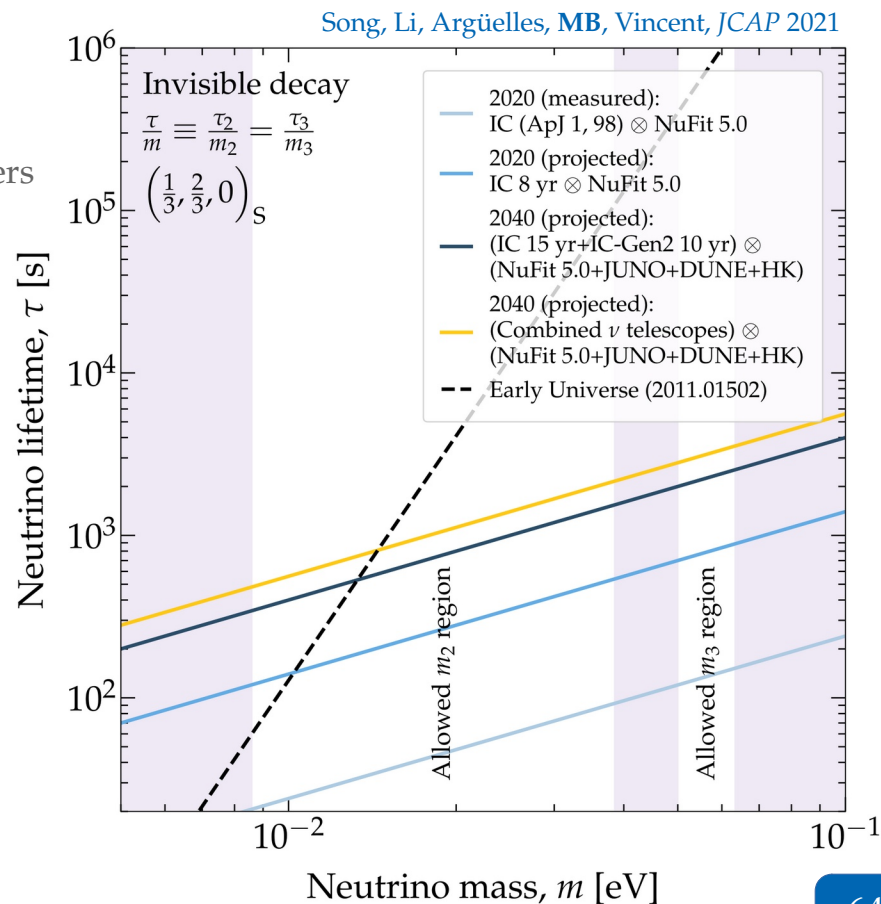
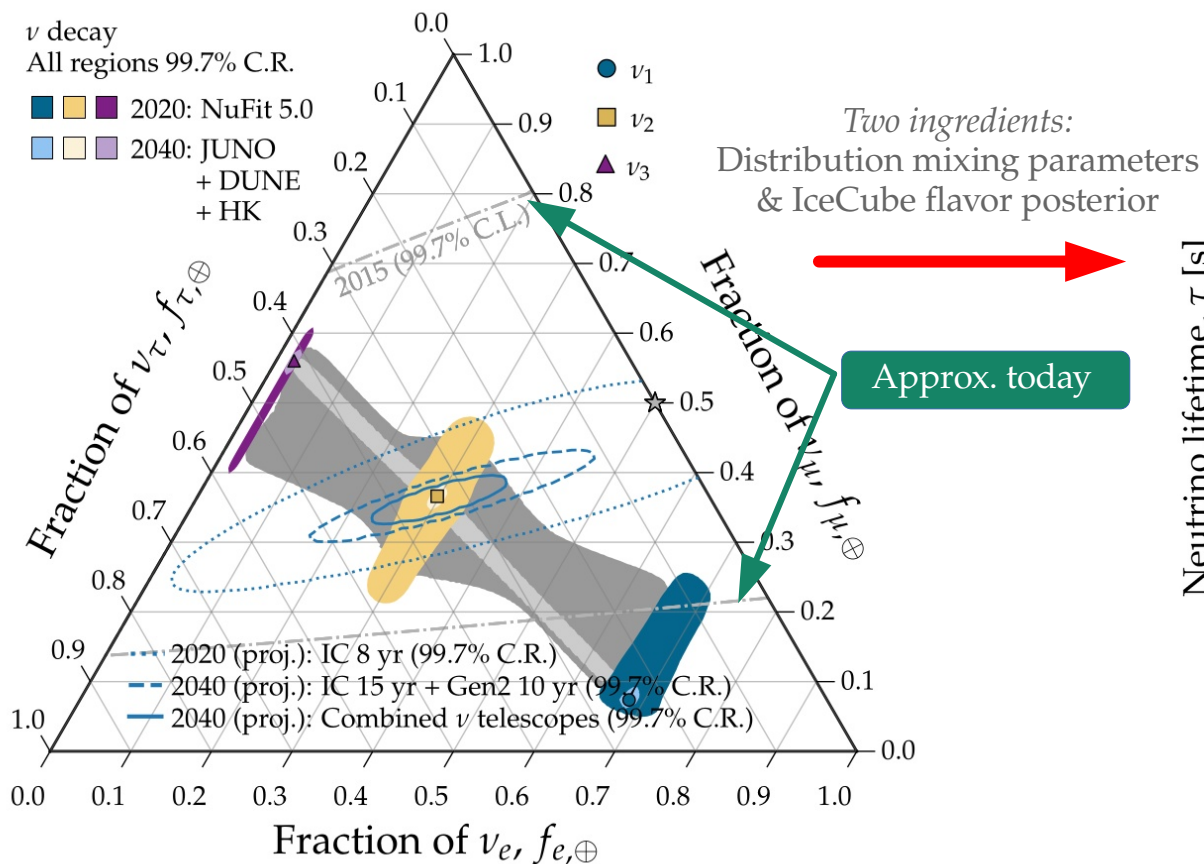
Flavor composition



Spectrum shape



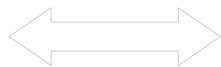
Event rate



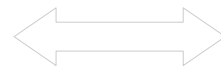
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See also: Beacom *et al.*, *PRL* 2002 / Baerwald, **MB**, Winter, *JCAP* 2012 / **MB**, Beacom, Murase, *PRD* 2017 / Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / **MB**, 2004.06844

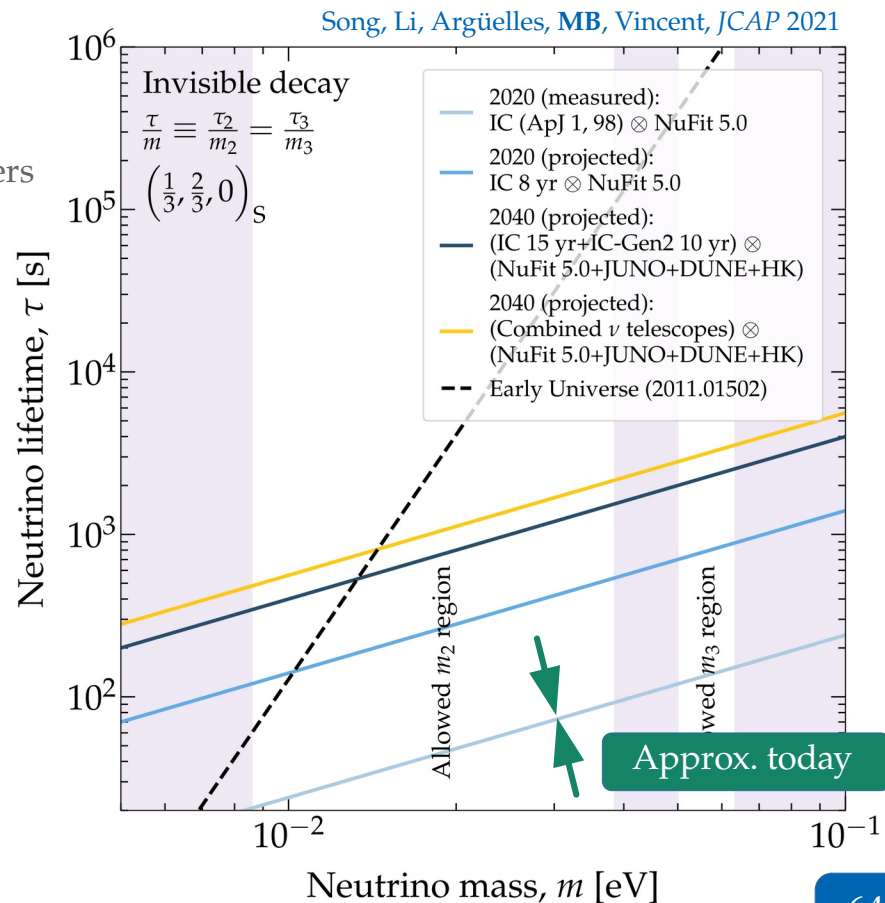
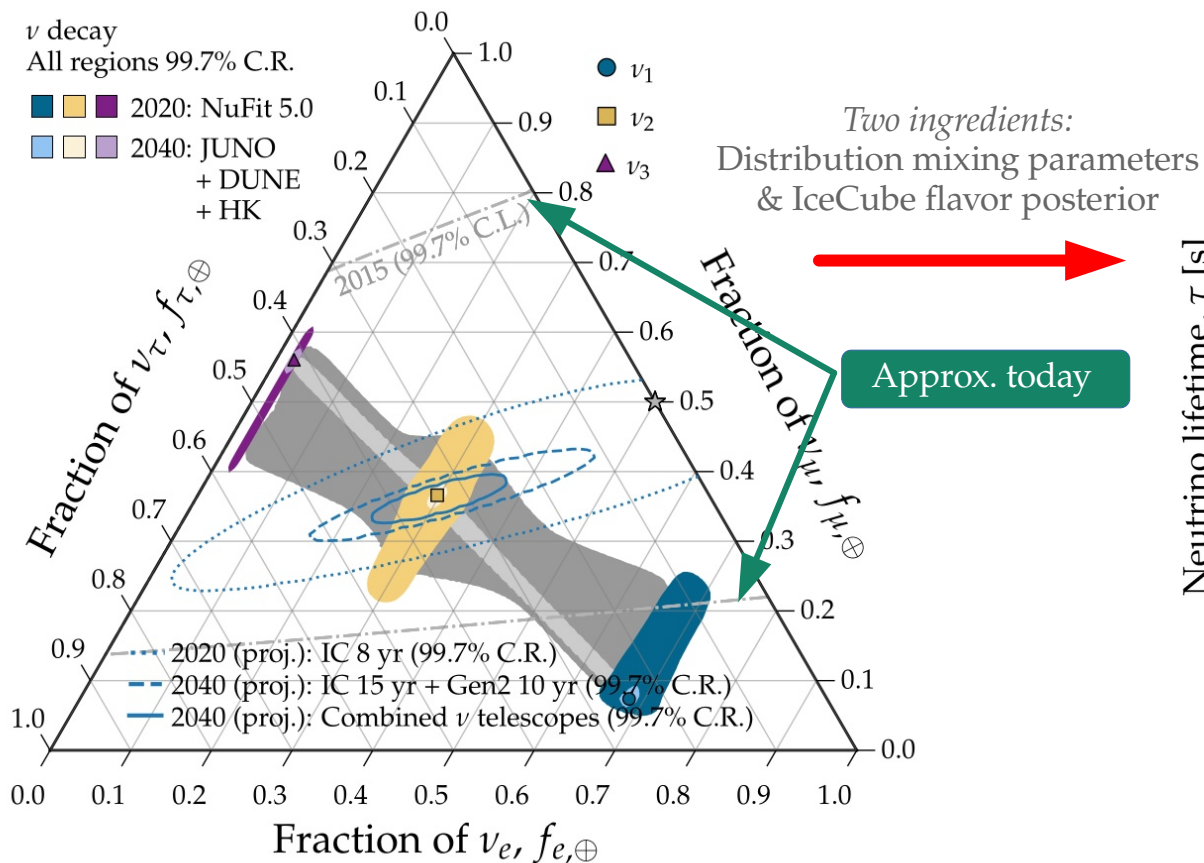
Flavor composition



Spectrum shape



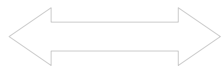
Event rate



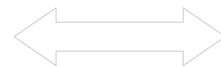
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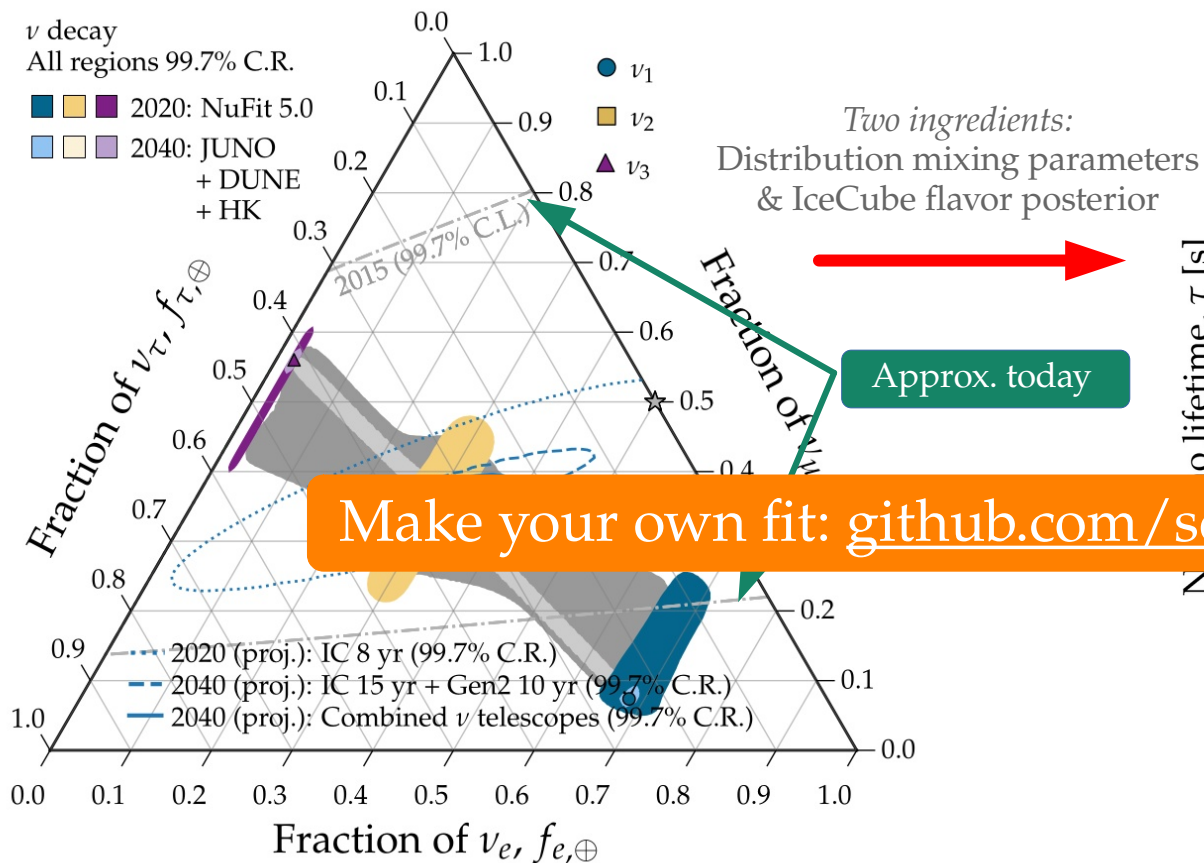
Flavor composition



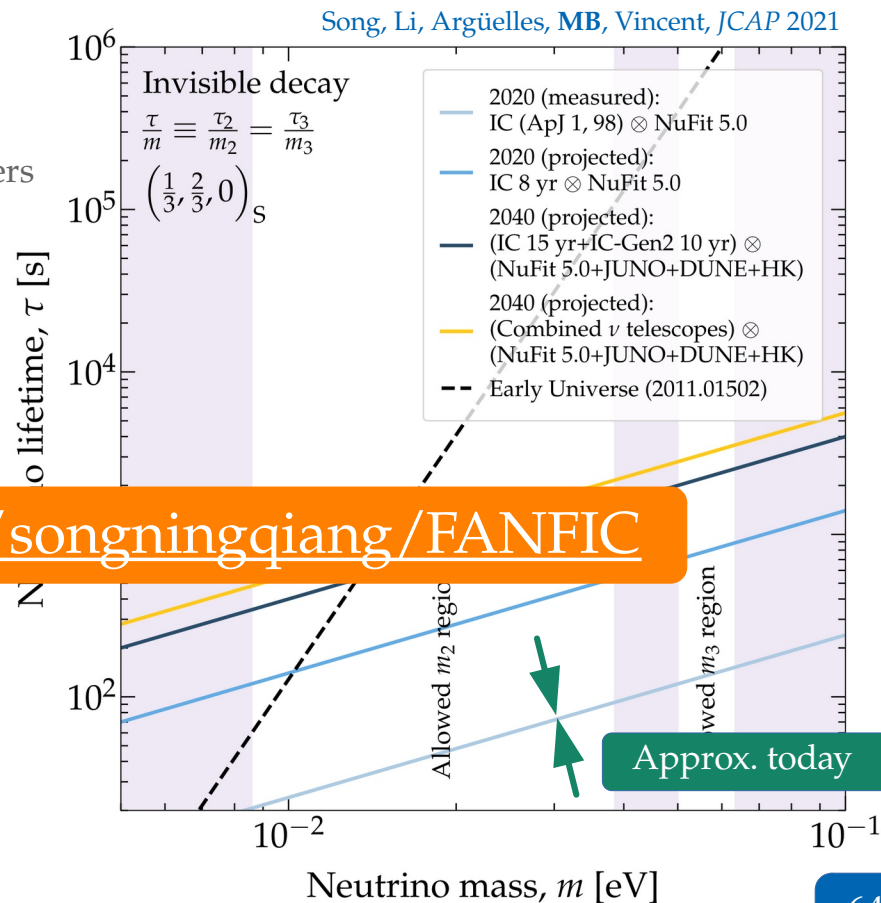
Spectrum shape



Event rate



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



What does neutrino decay change?

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

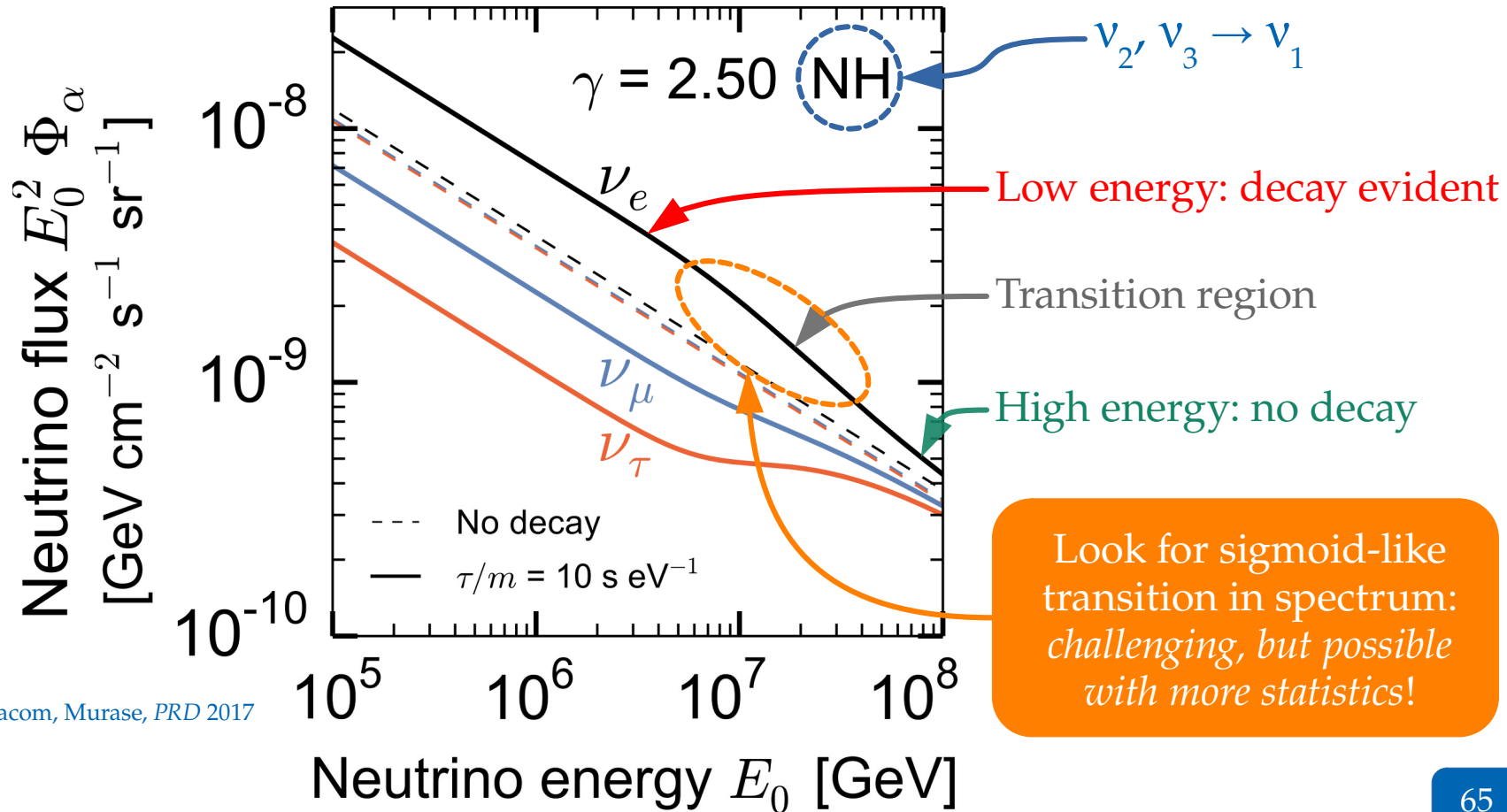
Flavor composition



Spectrum shape



Event rate

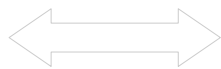


MB, Beacom, Murase, *PRD* 2017

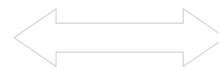
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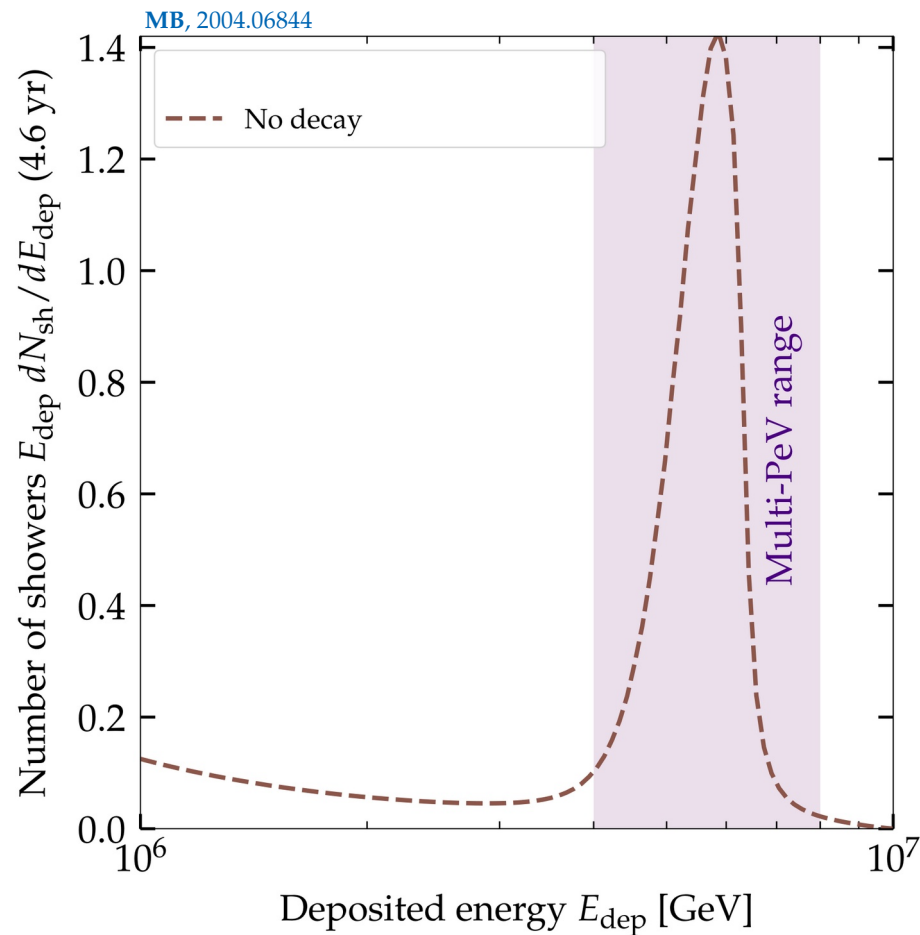
Flavor composition



Spectrum shape



Event rate



What does neutrino decay change?

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

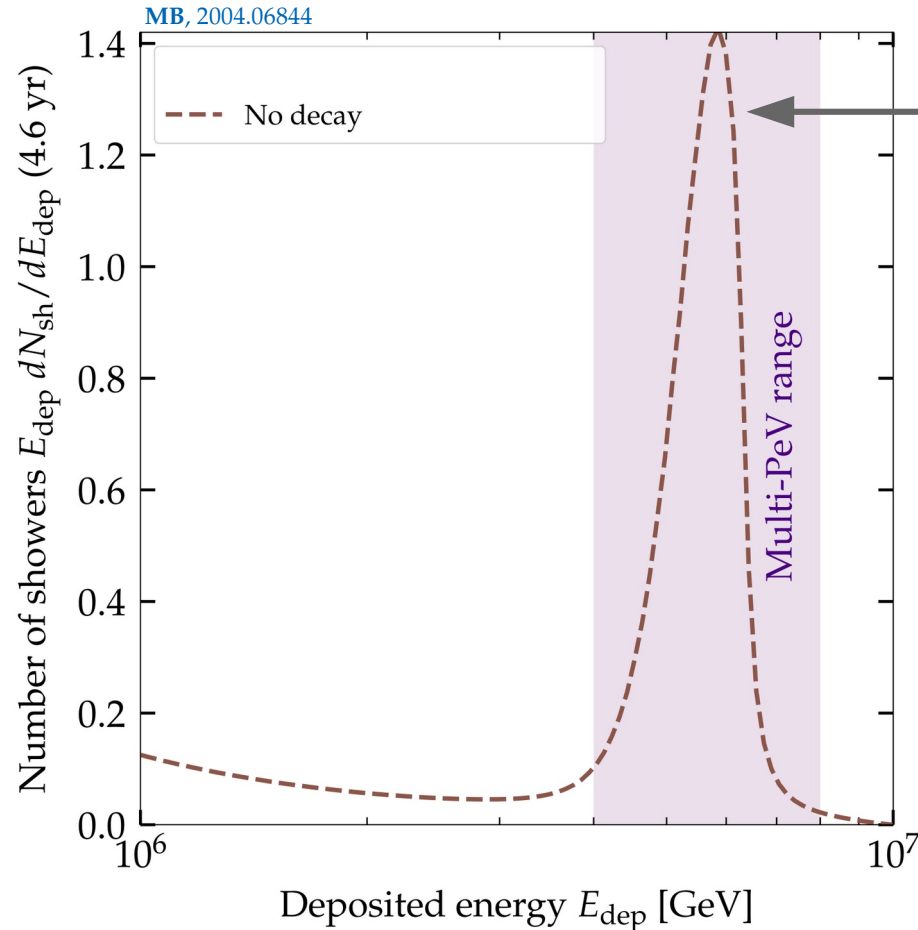
Flavor composition



Spectrum shape



Event rate

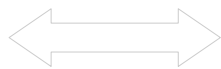


Glashow resonance (GR):
 $\bar{\nu}_e + e \rightarrow W \rightarrow \text{hadrons} \rightarrow \text{shower}$

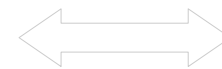
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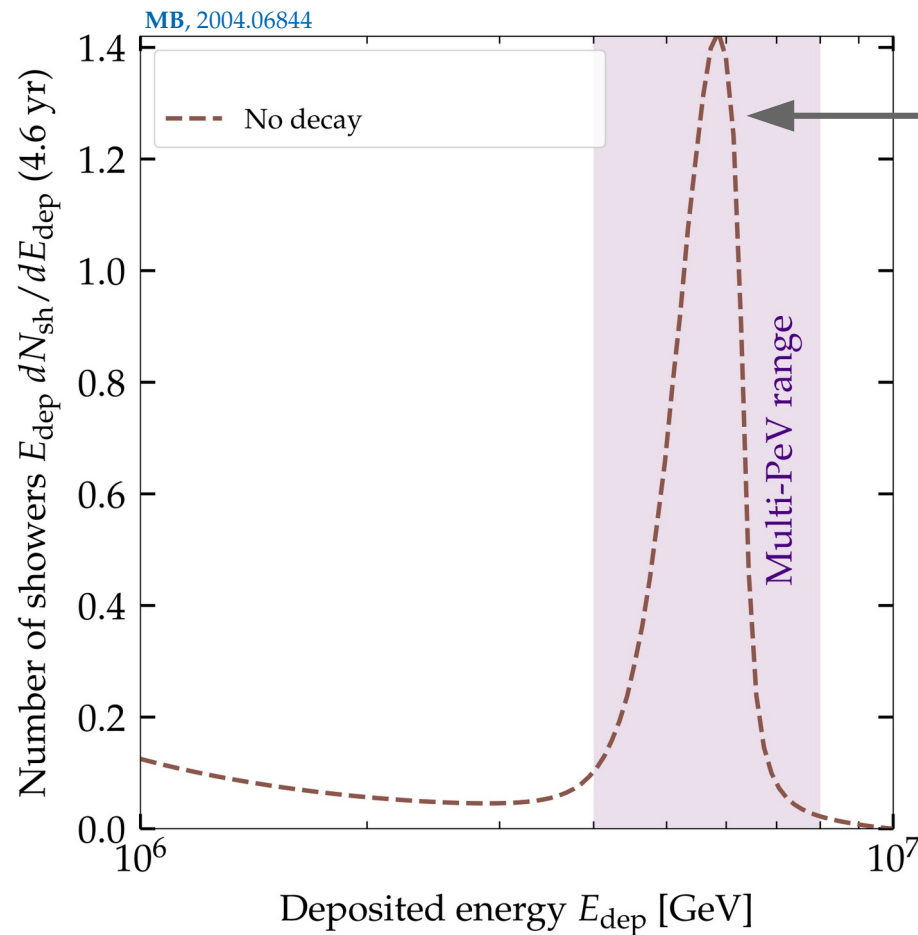
Flavor composition



Spectrum shape

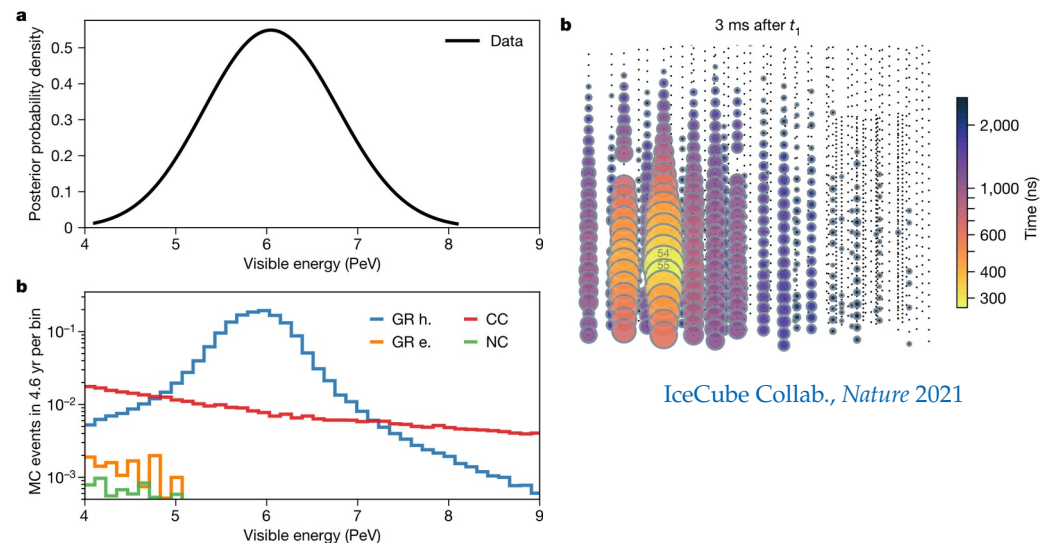


Event rate



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

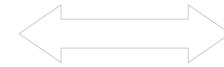
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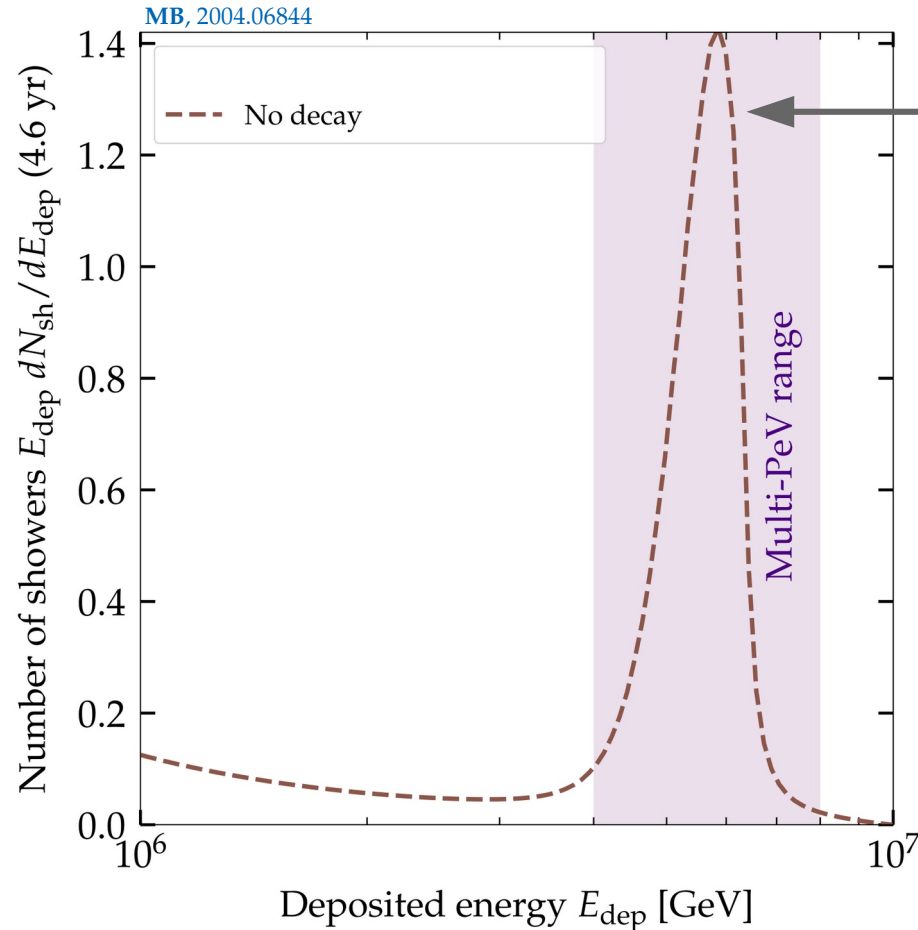
Flavor composition



Spectrum shape



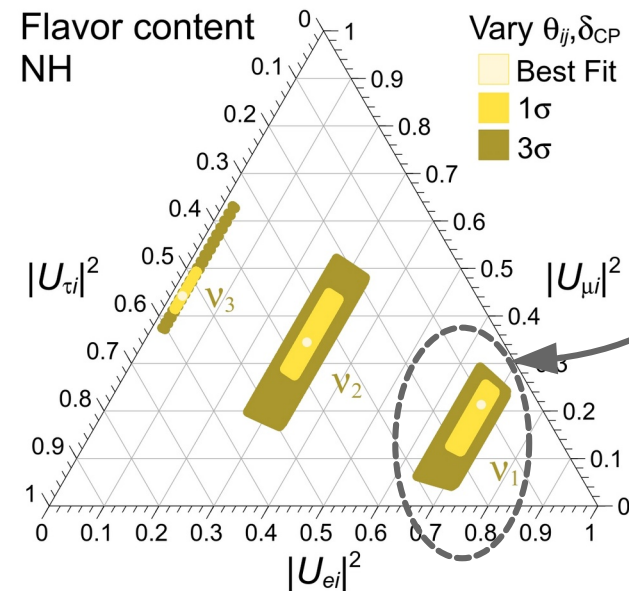
Event rate



Glashow resonance (GR):

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

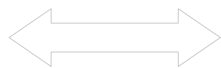
ν_1 is the mass eigenstate with the most e flavor



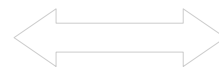
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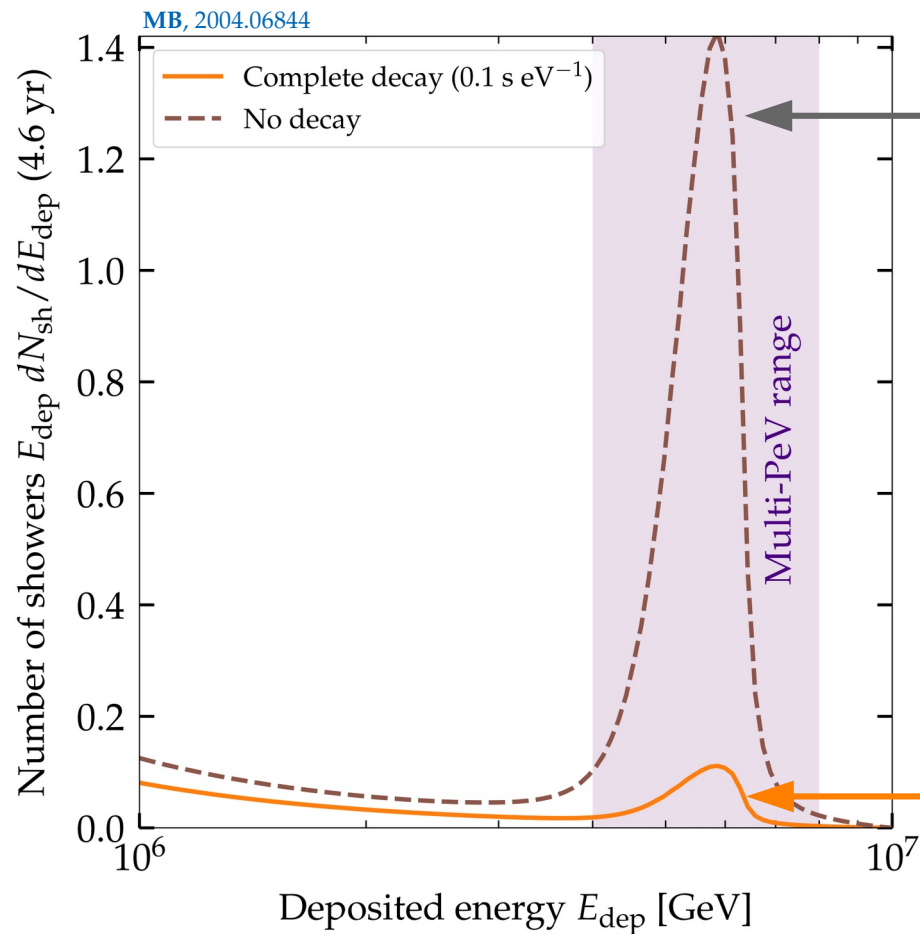
Flavor composition



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

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

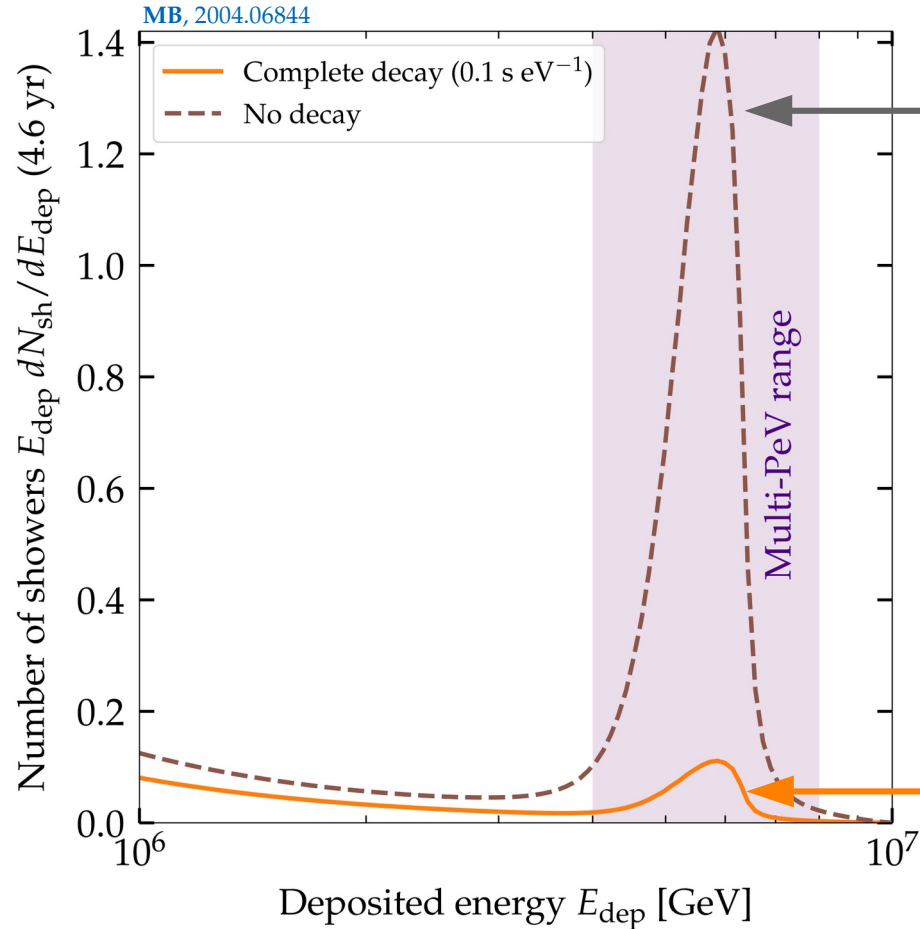
Flavor composition



Spectrum shape



Event rate



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

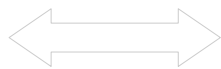
So by having observed 1 GR event we can place a *lower* limit on the lifetime of $\bar{\nu}_1$ ($= \nu_1$)

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

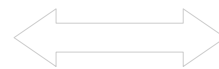
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Flavor composition

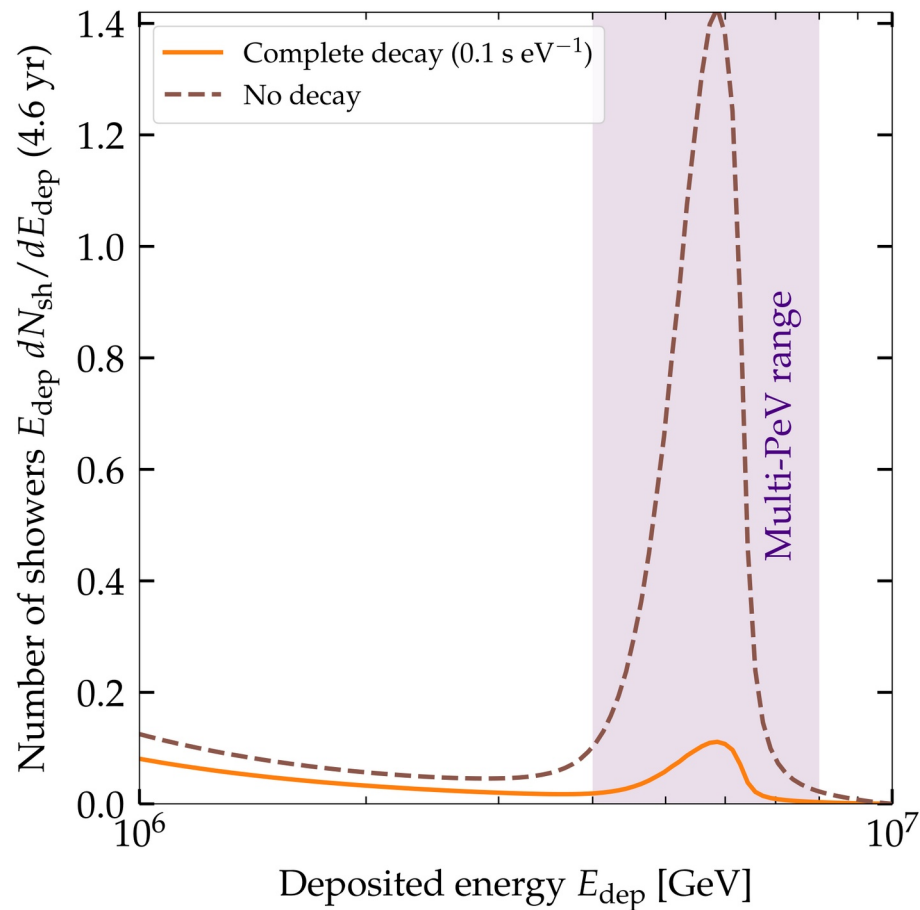


Spectrum shape



Event rate

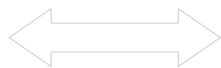
MB, 2004.06844



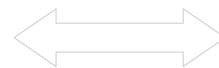
What does neutrino decay change?

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

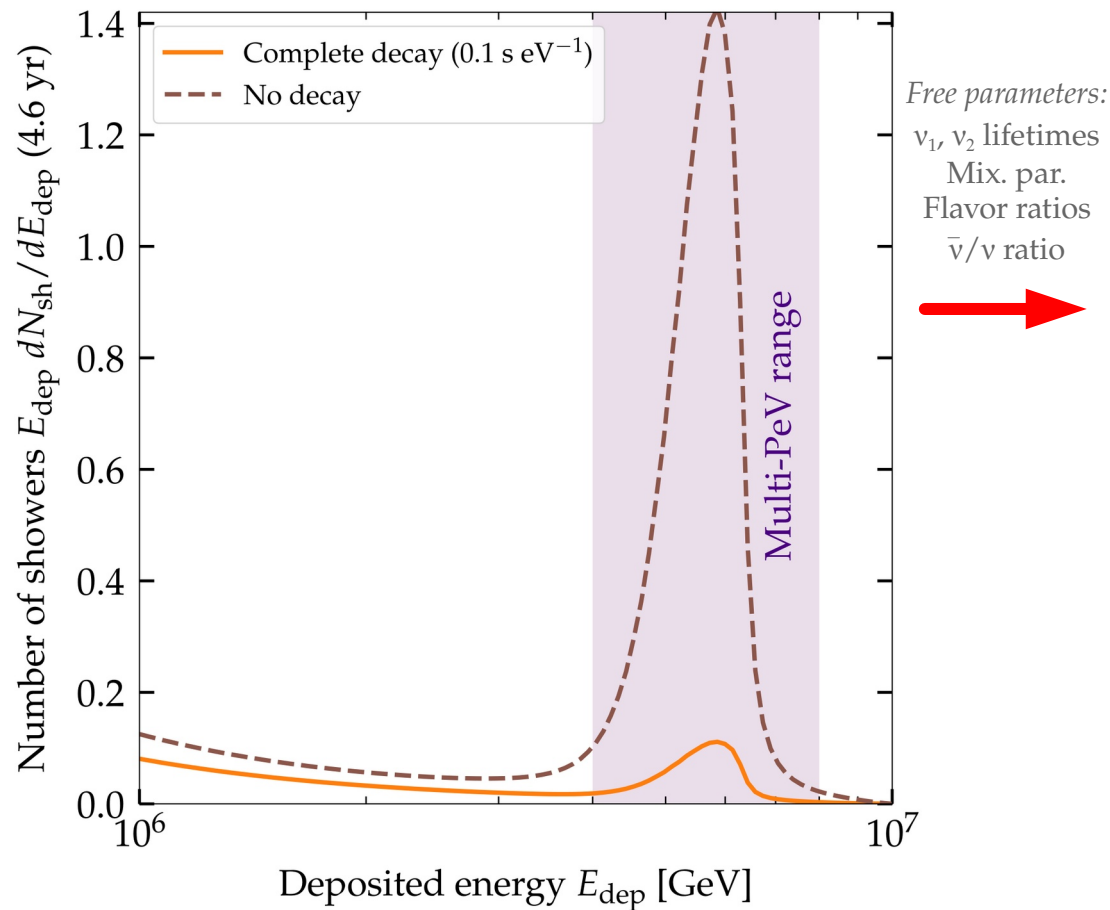


Spectrum shape



Event rate

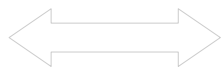
MB, 2004.06844



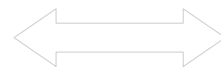
What does neutrino decay change?

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

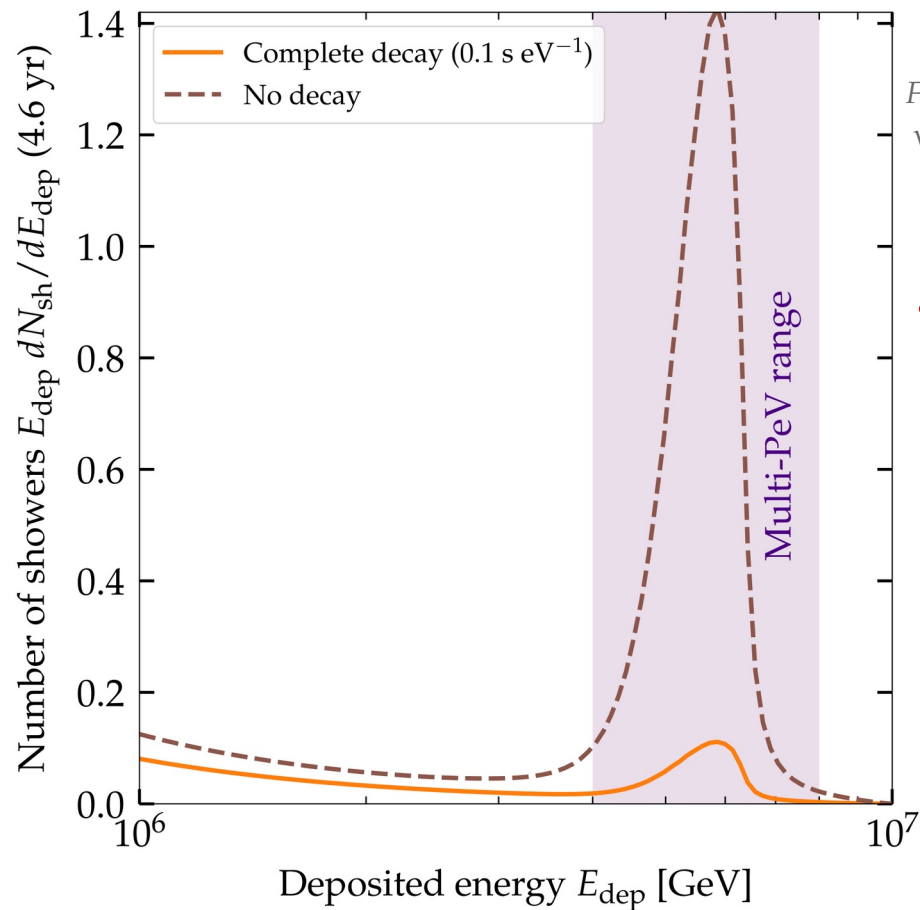
Flavor composition



Spectrum shape



Event rate



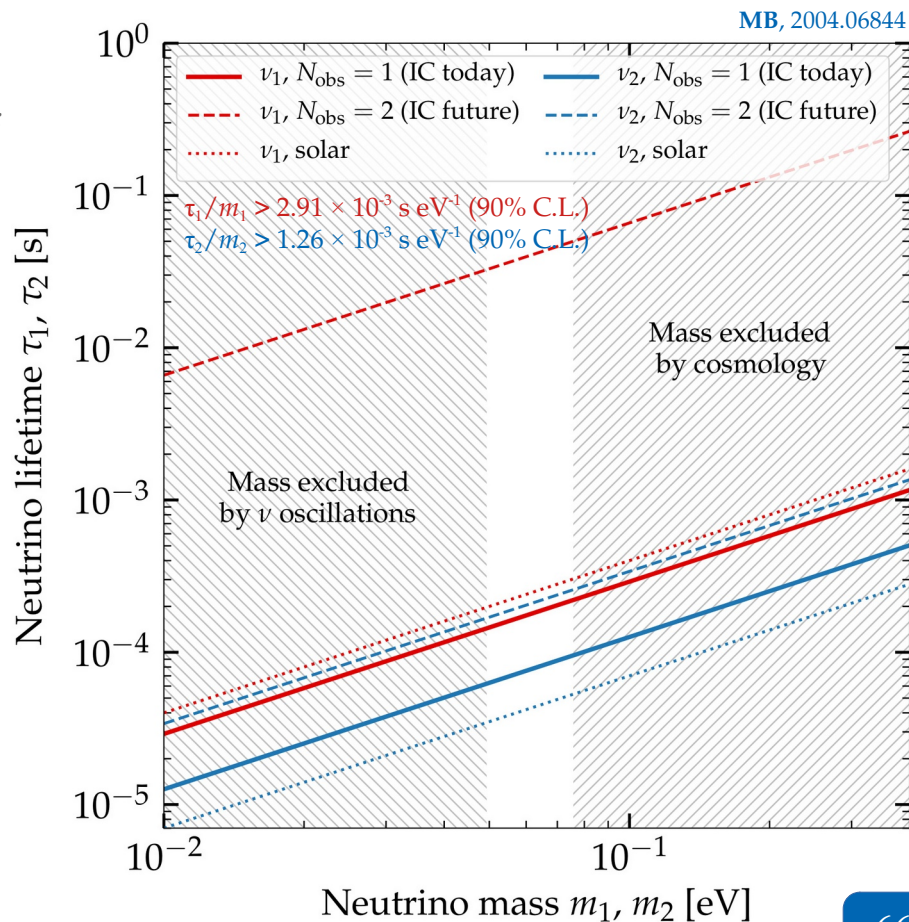
Free parameters:

ν_1, ν_2 lifetimes

Mix. par.

Flavor ratios

$\bar{\nu}/\nu$ ratio

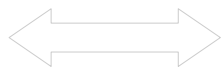


MB, 2004.06844

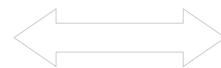
What does neutrino decay change?

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

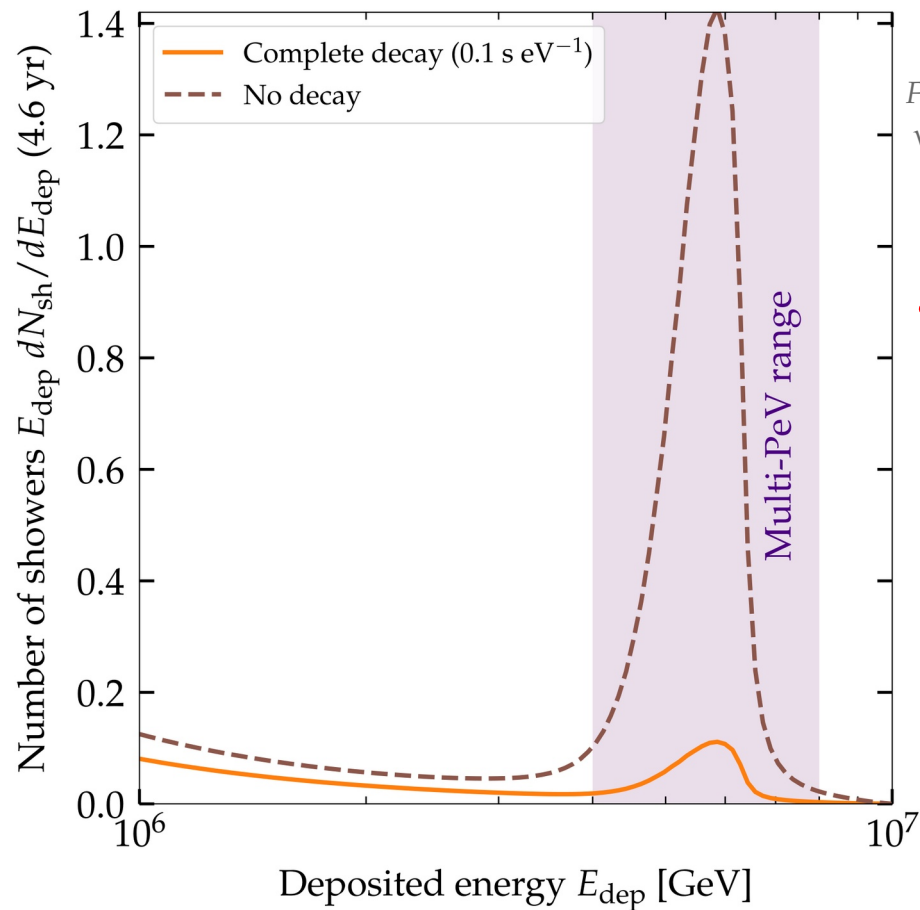
Flavor composition



Spectrum shape



Event rate



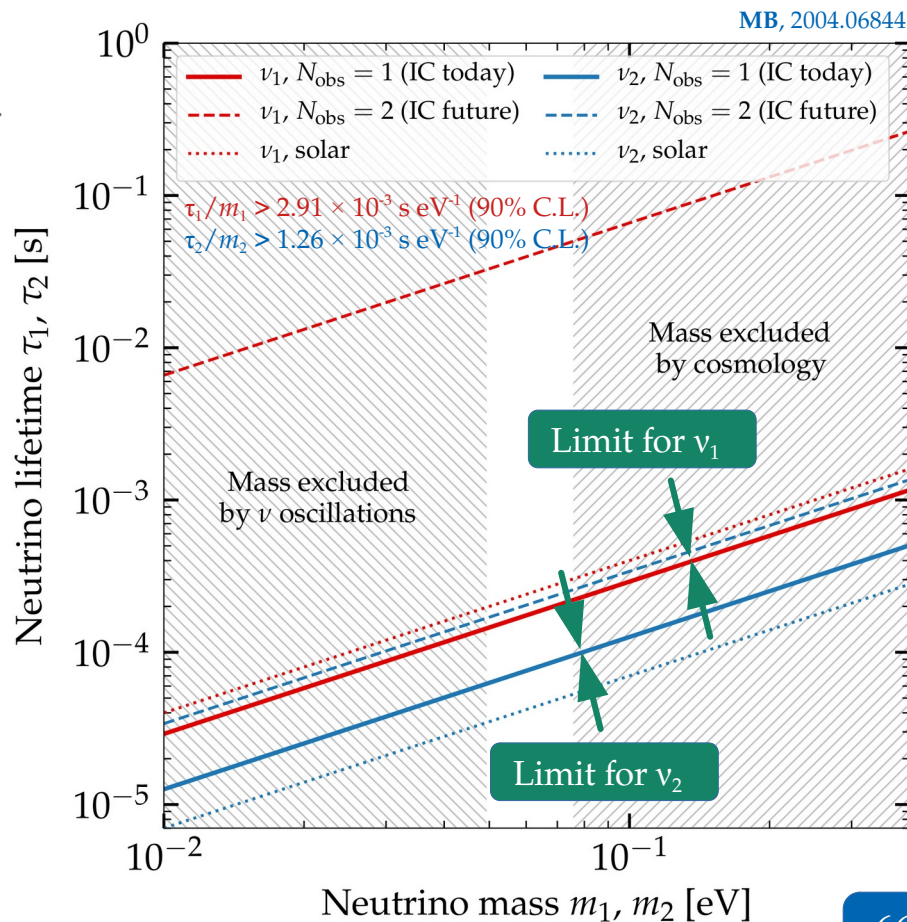
Free parameters:

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Mix. par.

Flavor ratios

$\bar{\nu}/\nu$ ratio



New neutrino interactions:
Are there secret $\nu\nu$ interactions?

Astrophysical neutrino sources

Earth

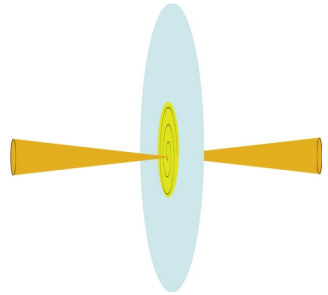


Galactic (kpc) or extragalactic (Mpc – Gpc) distance

Astrophysical neutrino sources

Earth

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

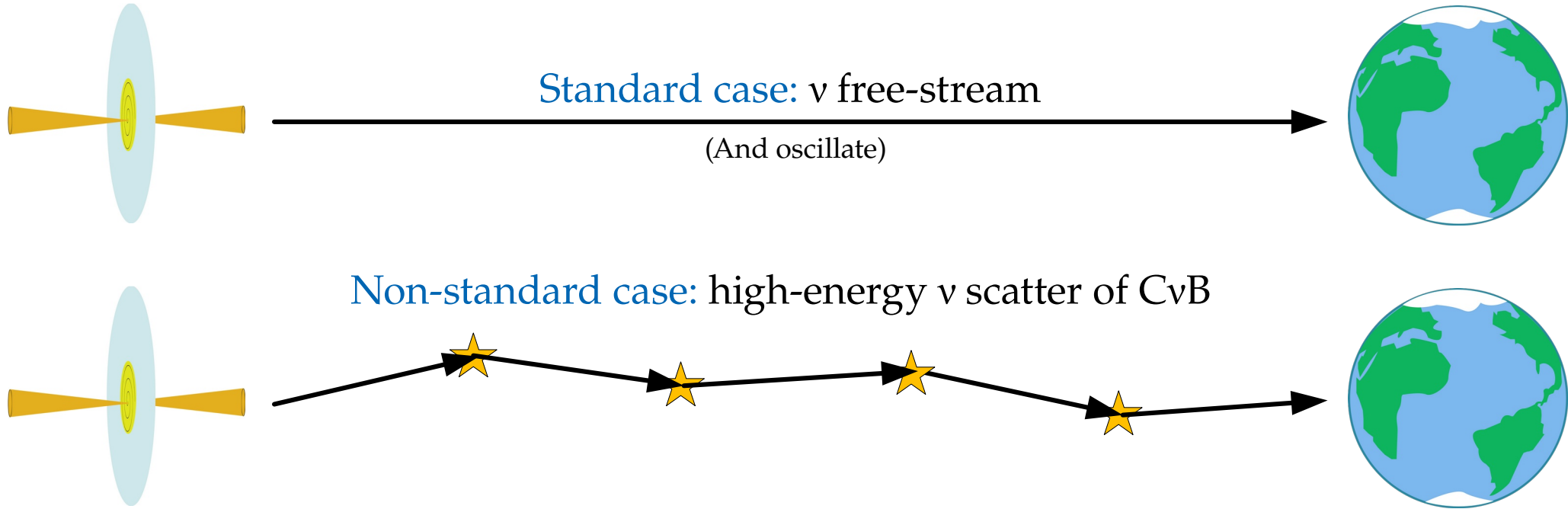


Standard case: ν free-stream

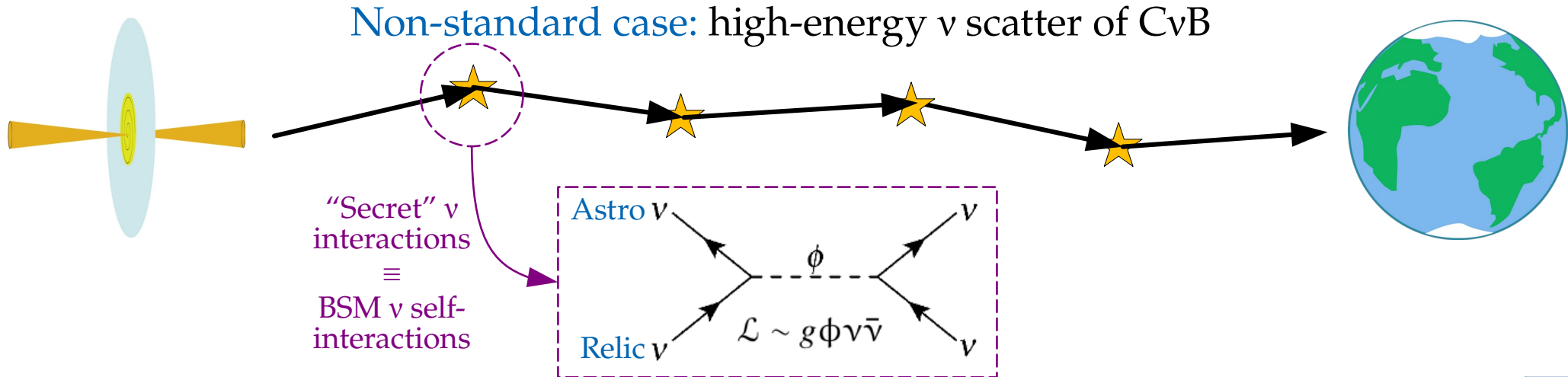
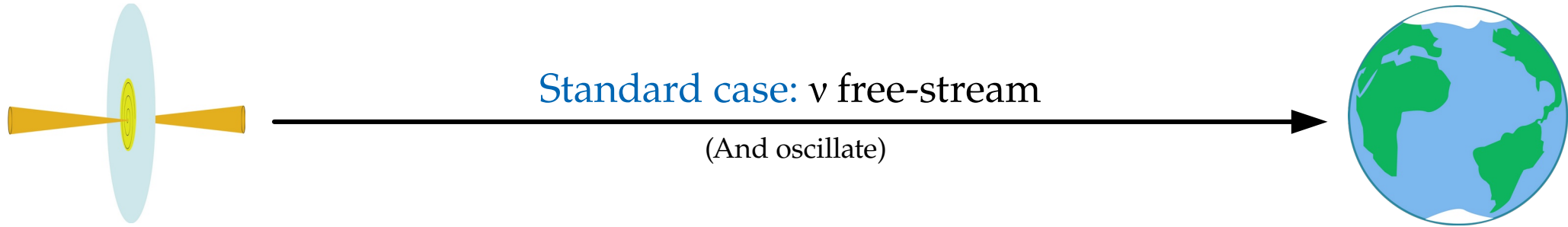
(And oscillate)



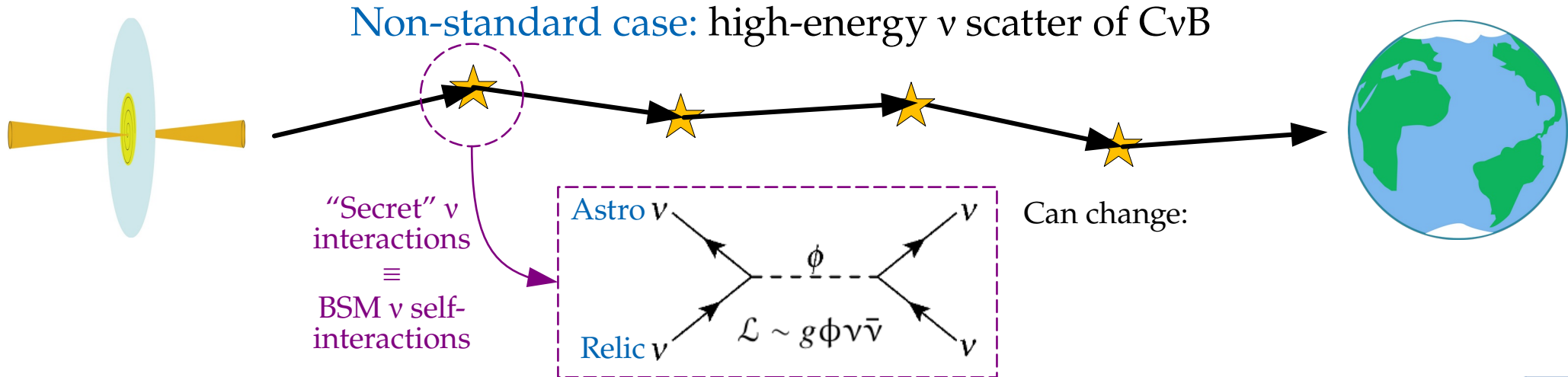
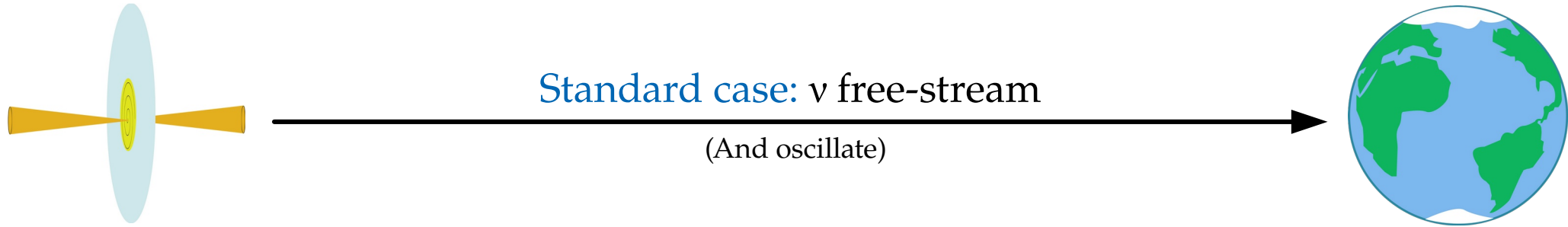
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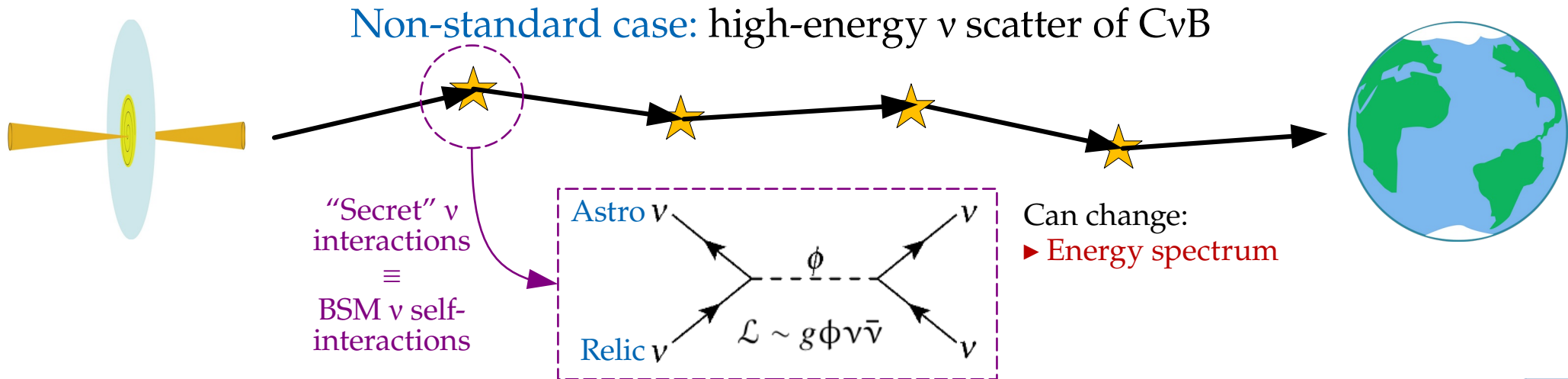
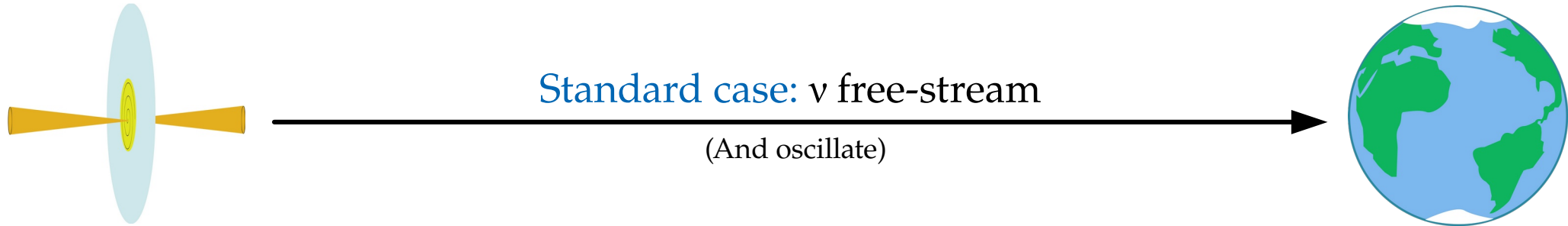
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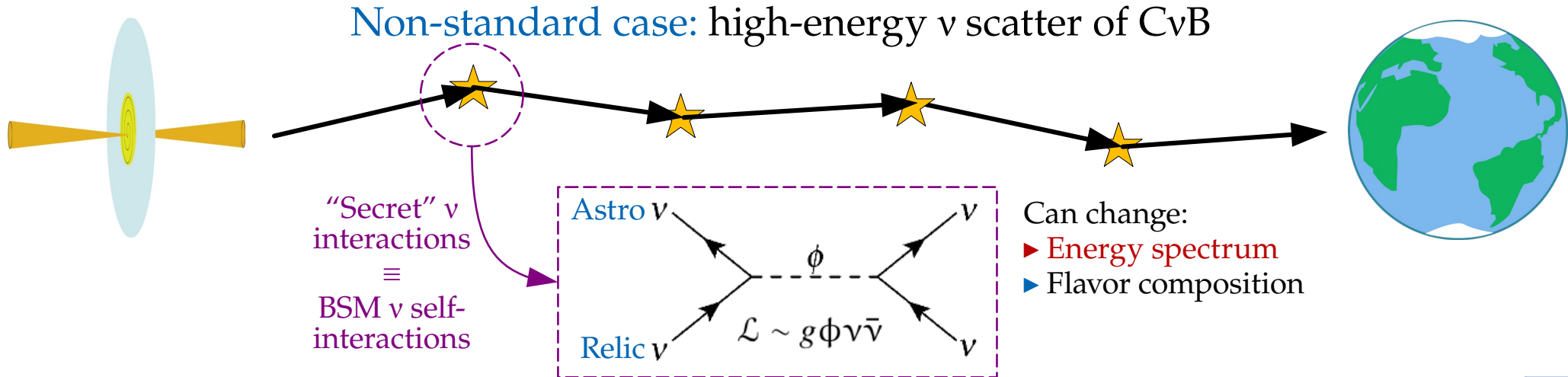
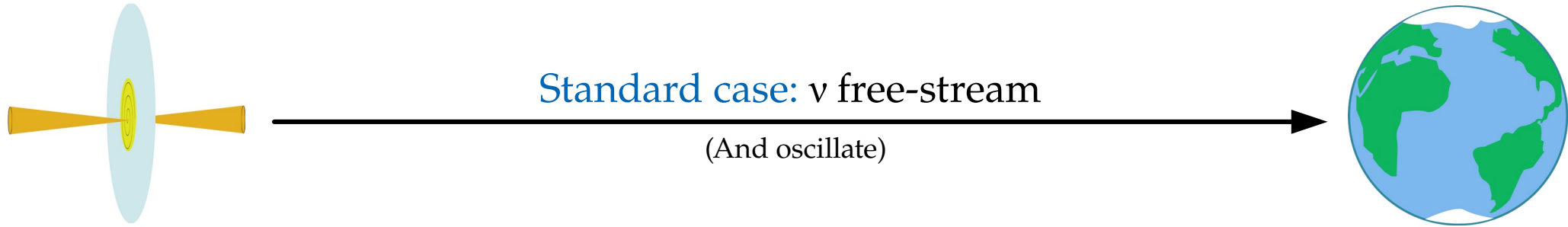
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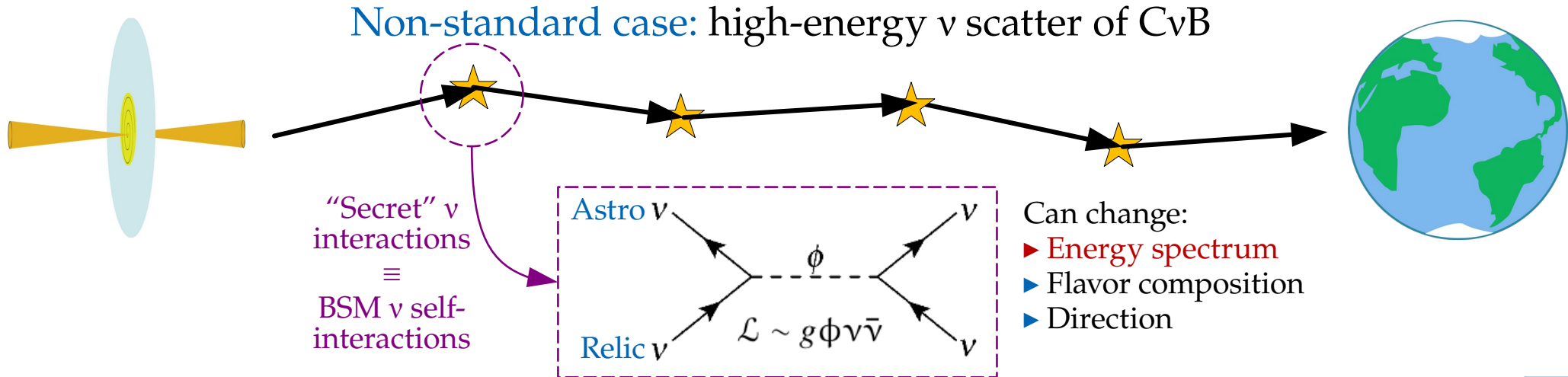
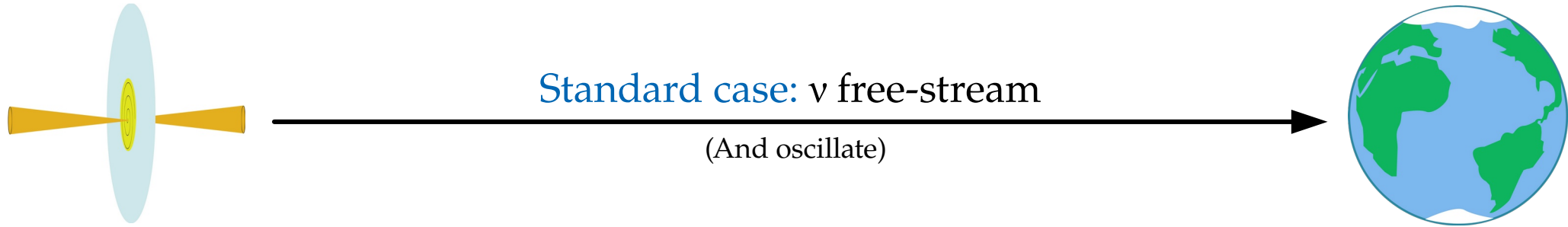
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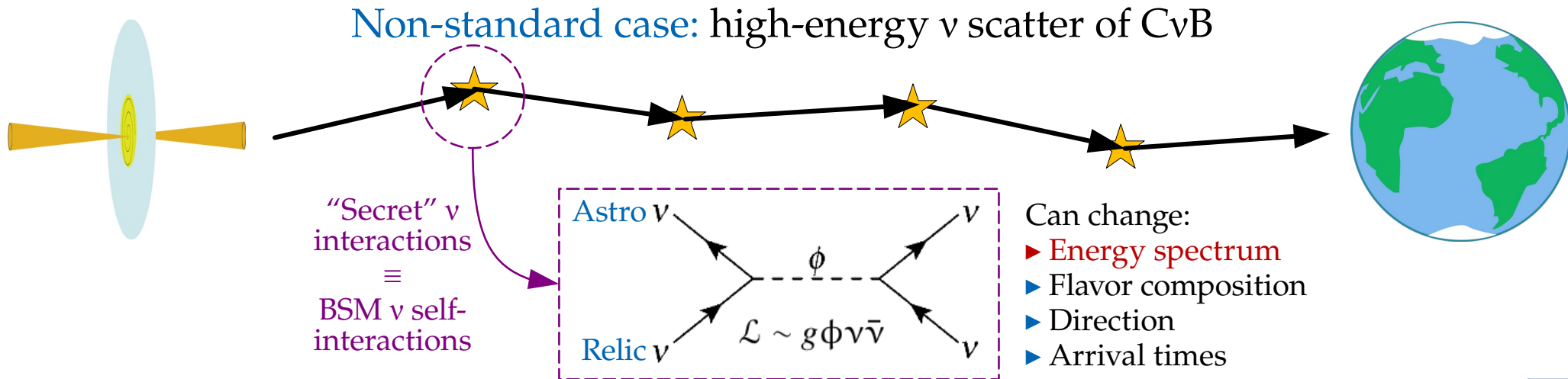
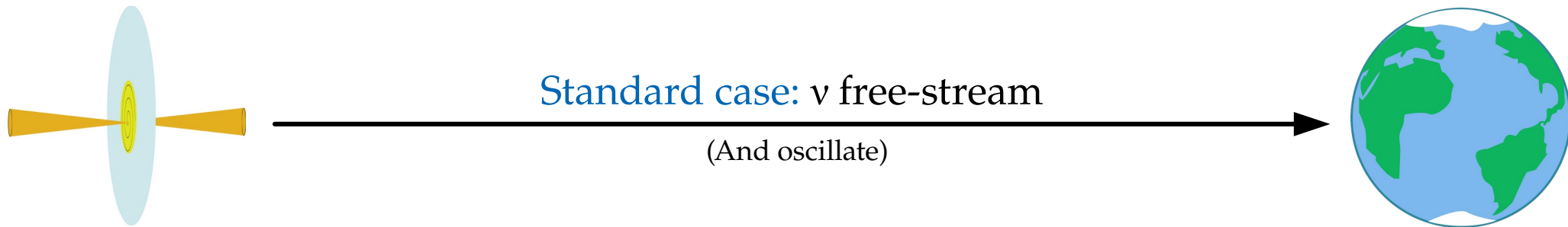
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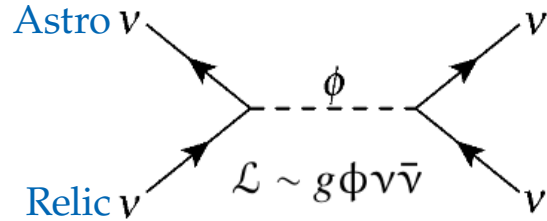


Galactic (kpc) or extragalactic (Mpc – Gpc) distance



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

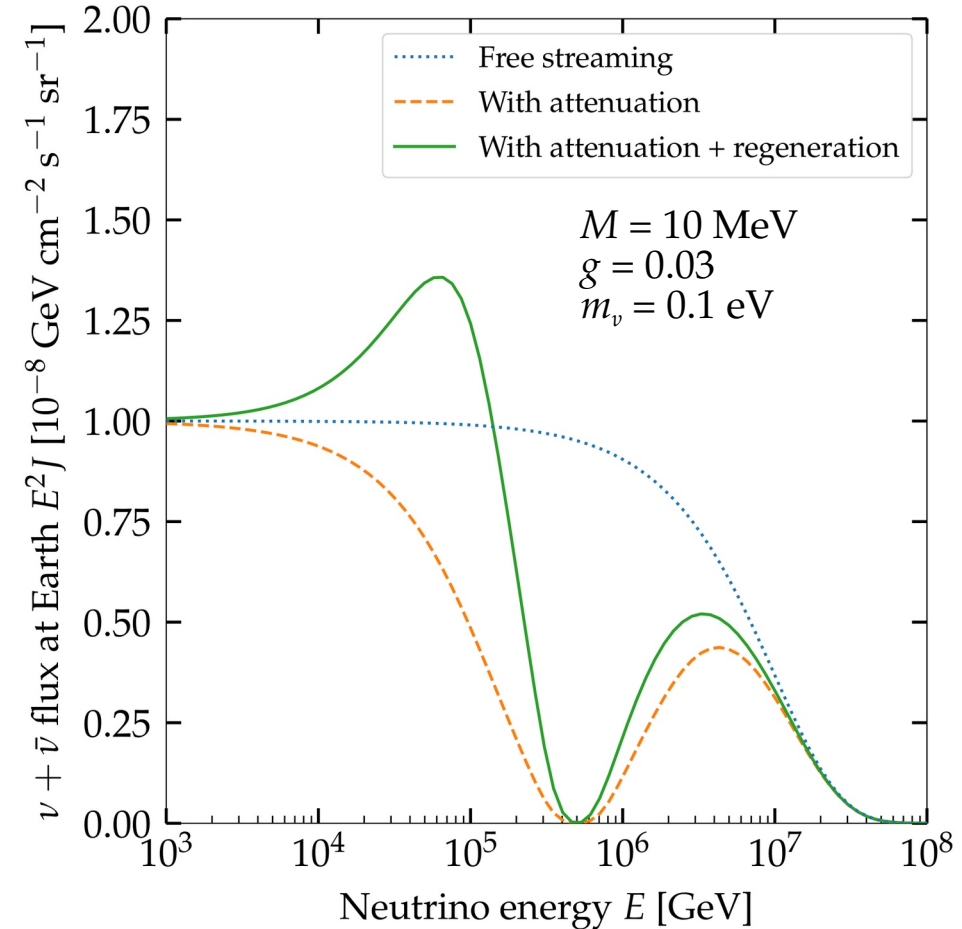
See also: Esteban, Pandey, Brdar, Beacom, *PRD* 2021

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

Ng & Beacom, *PRD* 2014

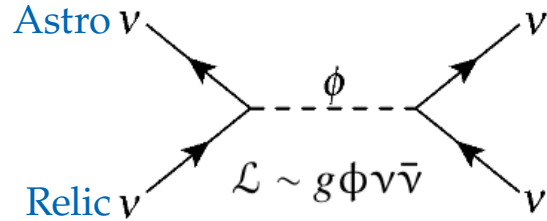
Cherry, Friedland, Shoemaker, 1411.1071

Blum, Hook, Murase, 1408.3799



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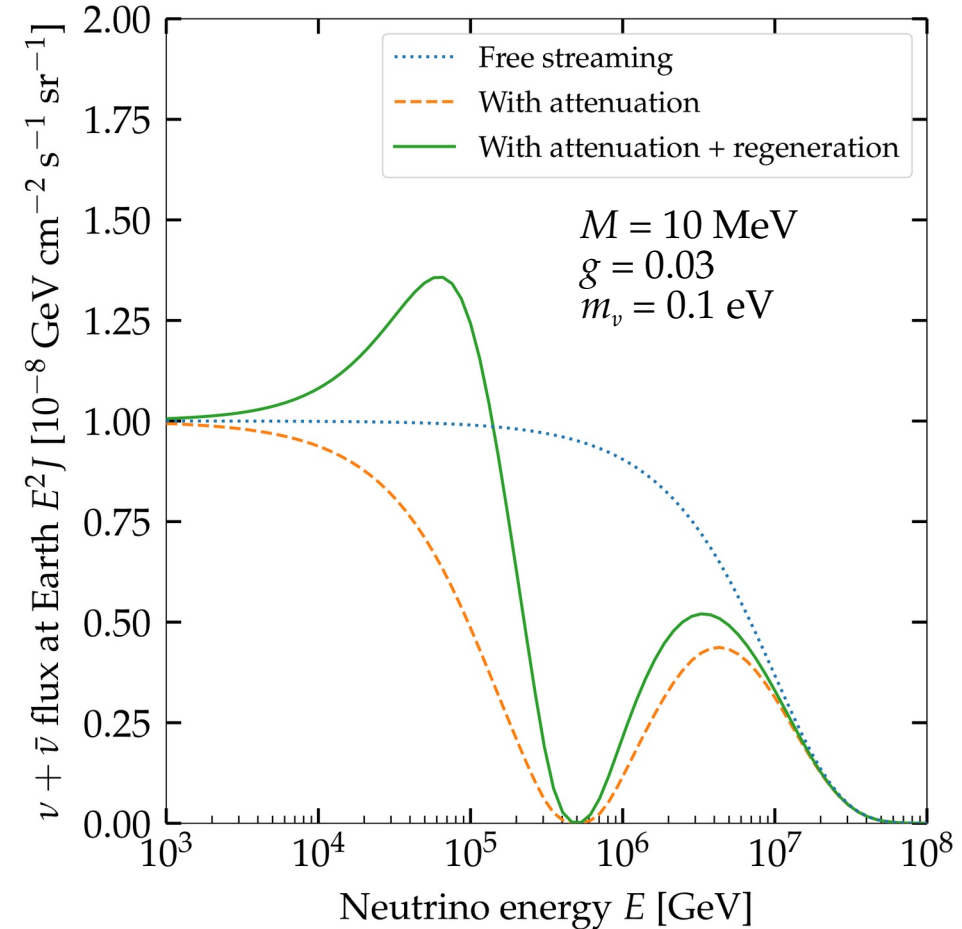


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New coupling Mediator mass

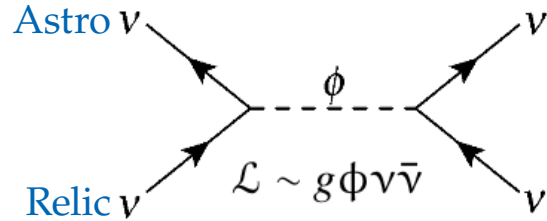
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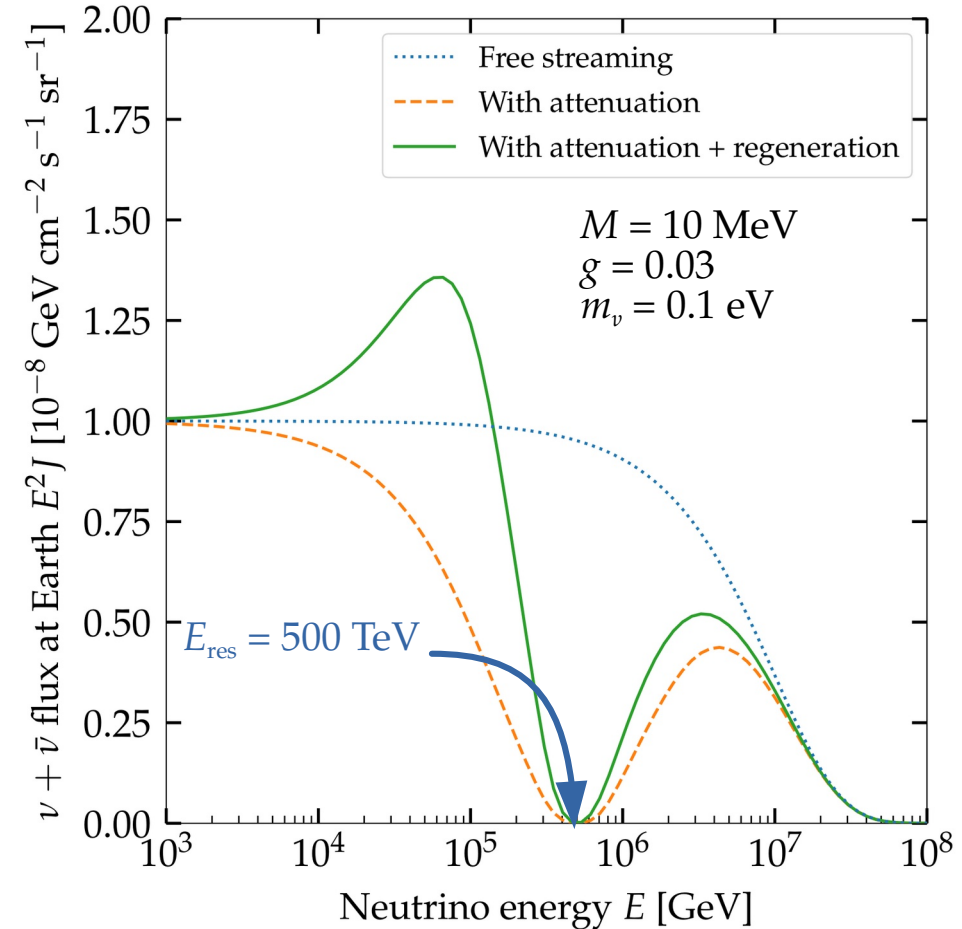


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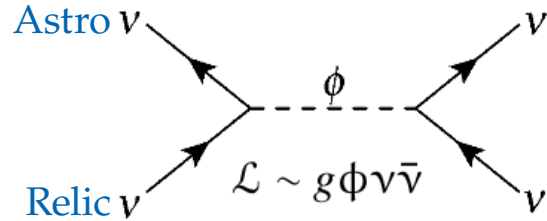
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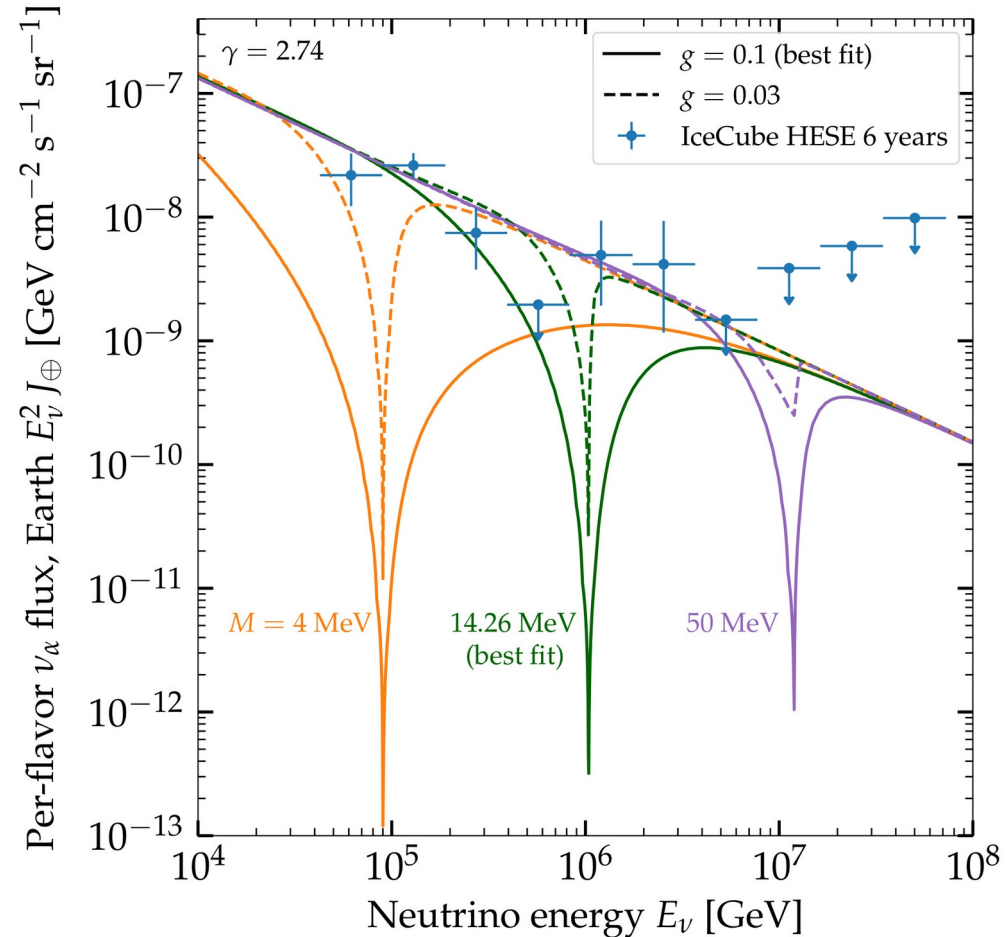


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$$\sigma = \frac{g^4 s}{4\pi (s - M^2)^2 + M^2 \Gamma^2}$$

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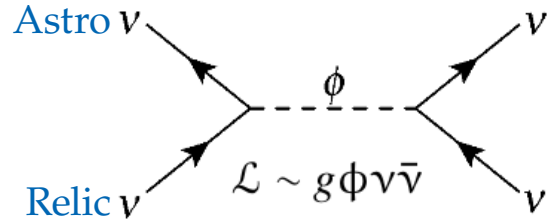
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New coupling (g^4) and Mediator mass (M^2) are highlighted.

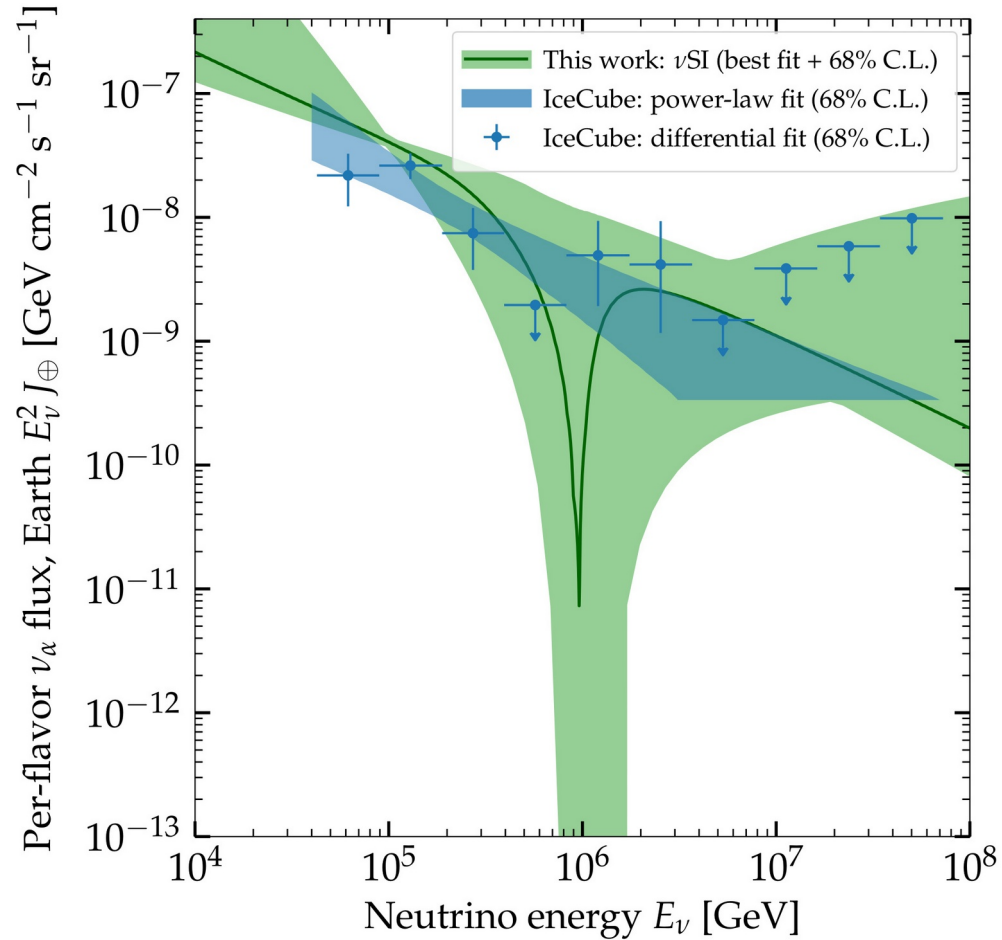
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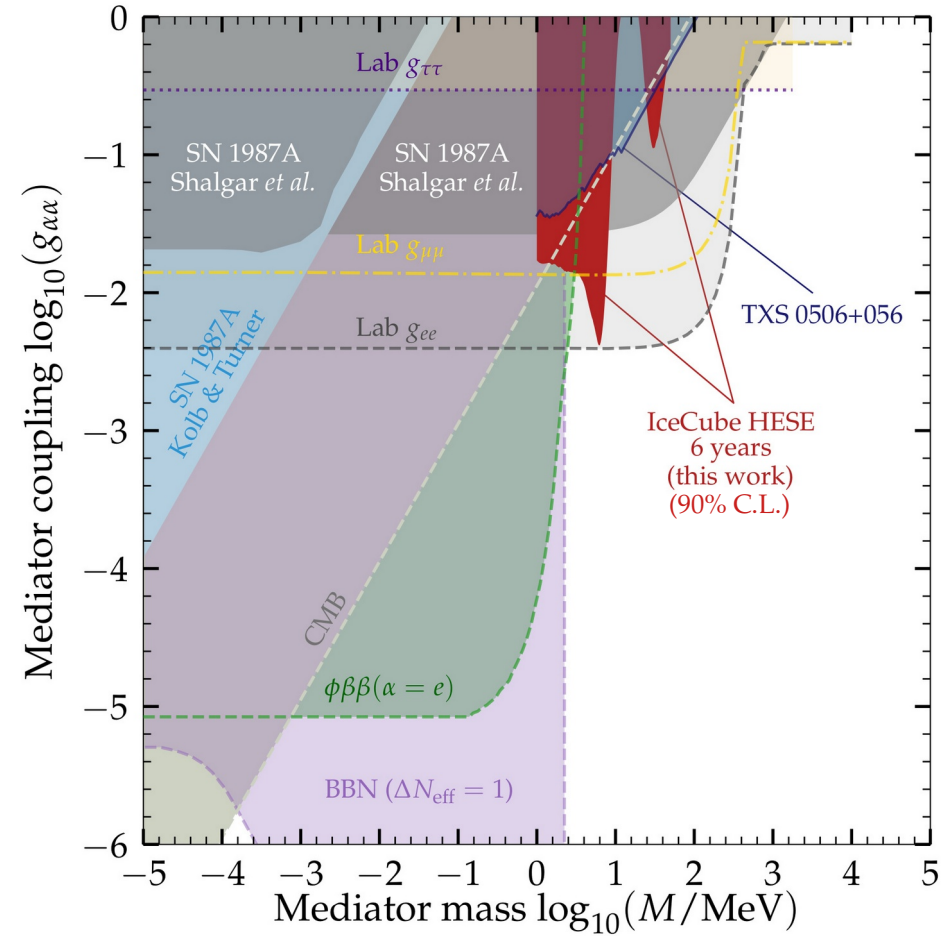
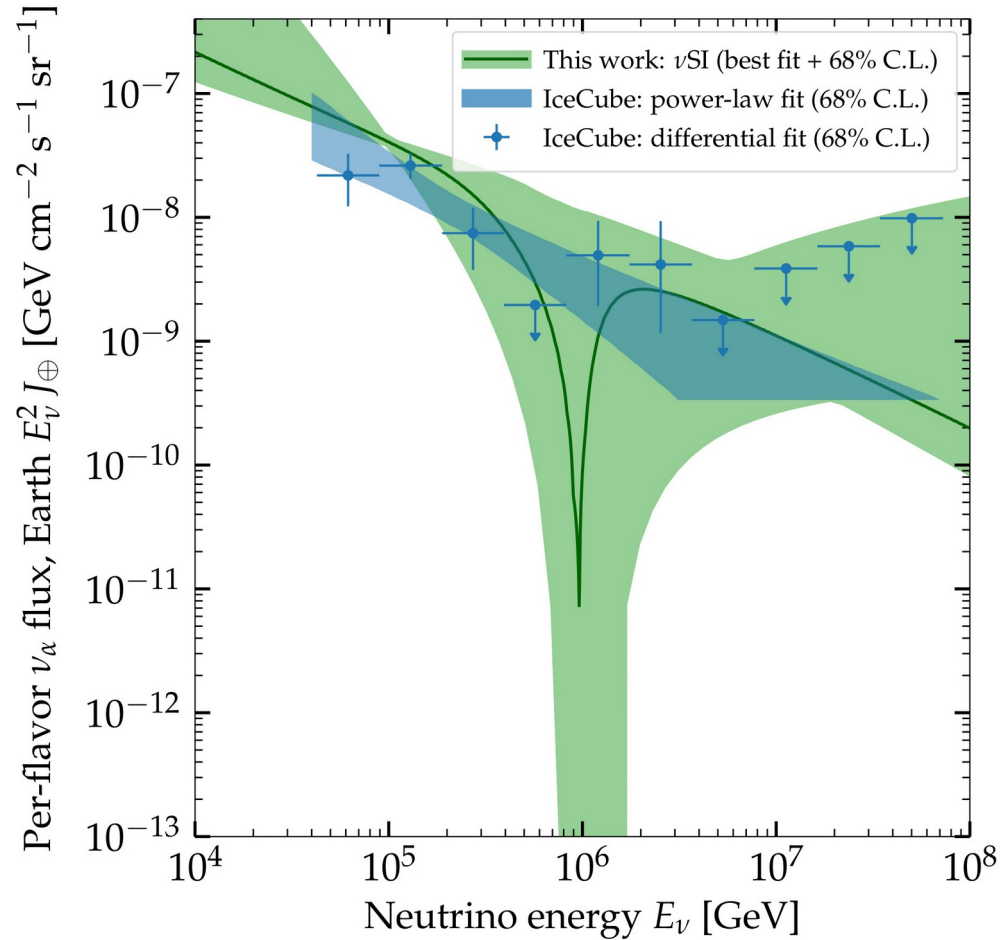
Looking for evidence of ν SI

- ▶ 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

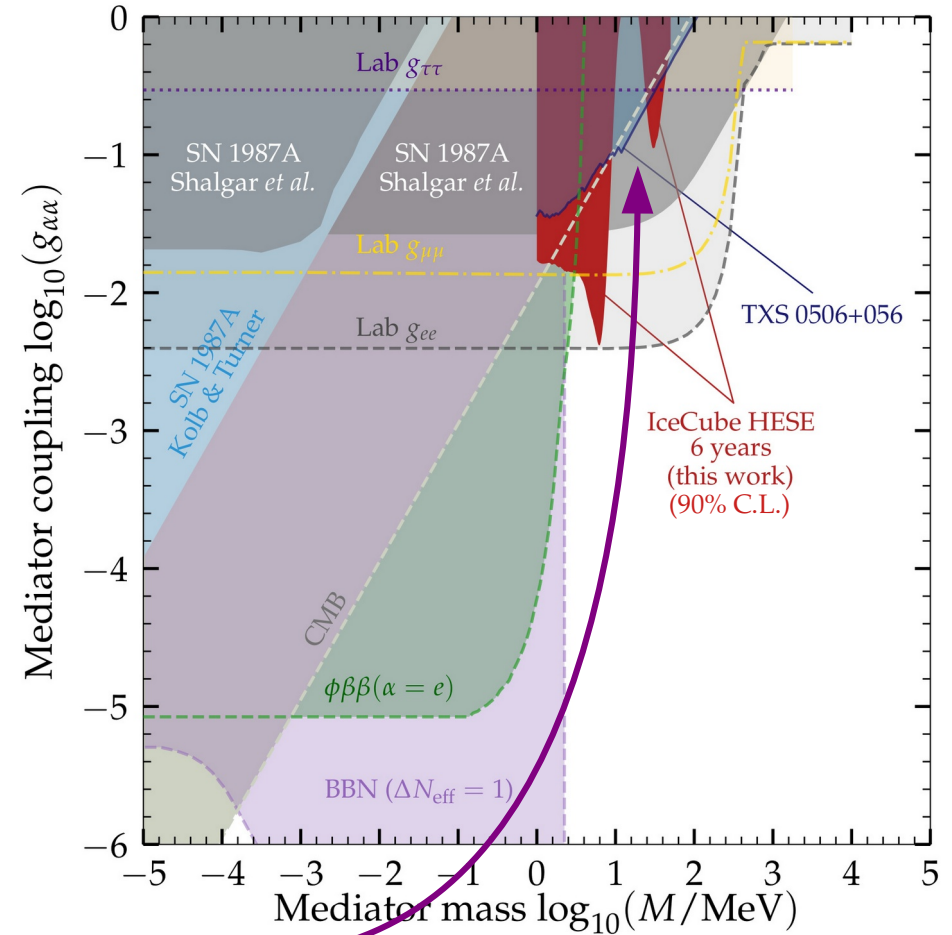
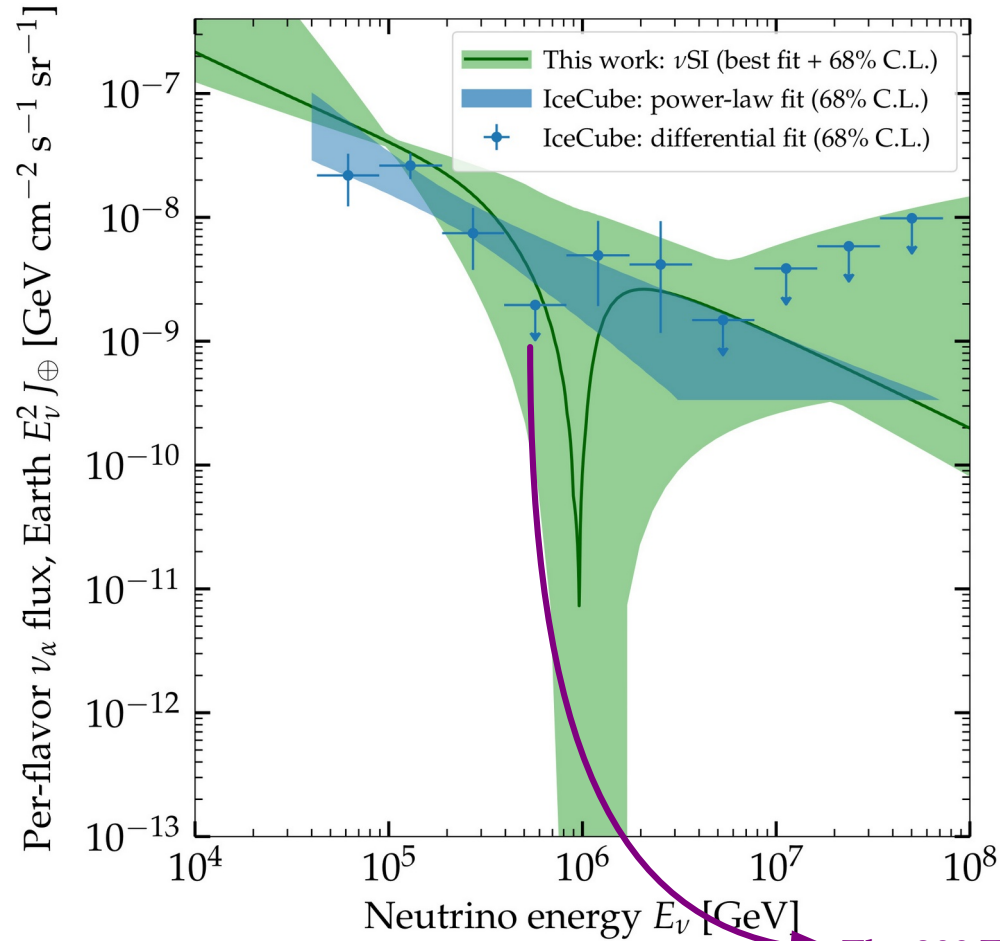
No significant ($> 3\sigma$) evidence for a spectral dip ...



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



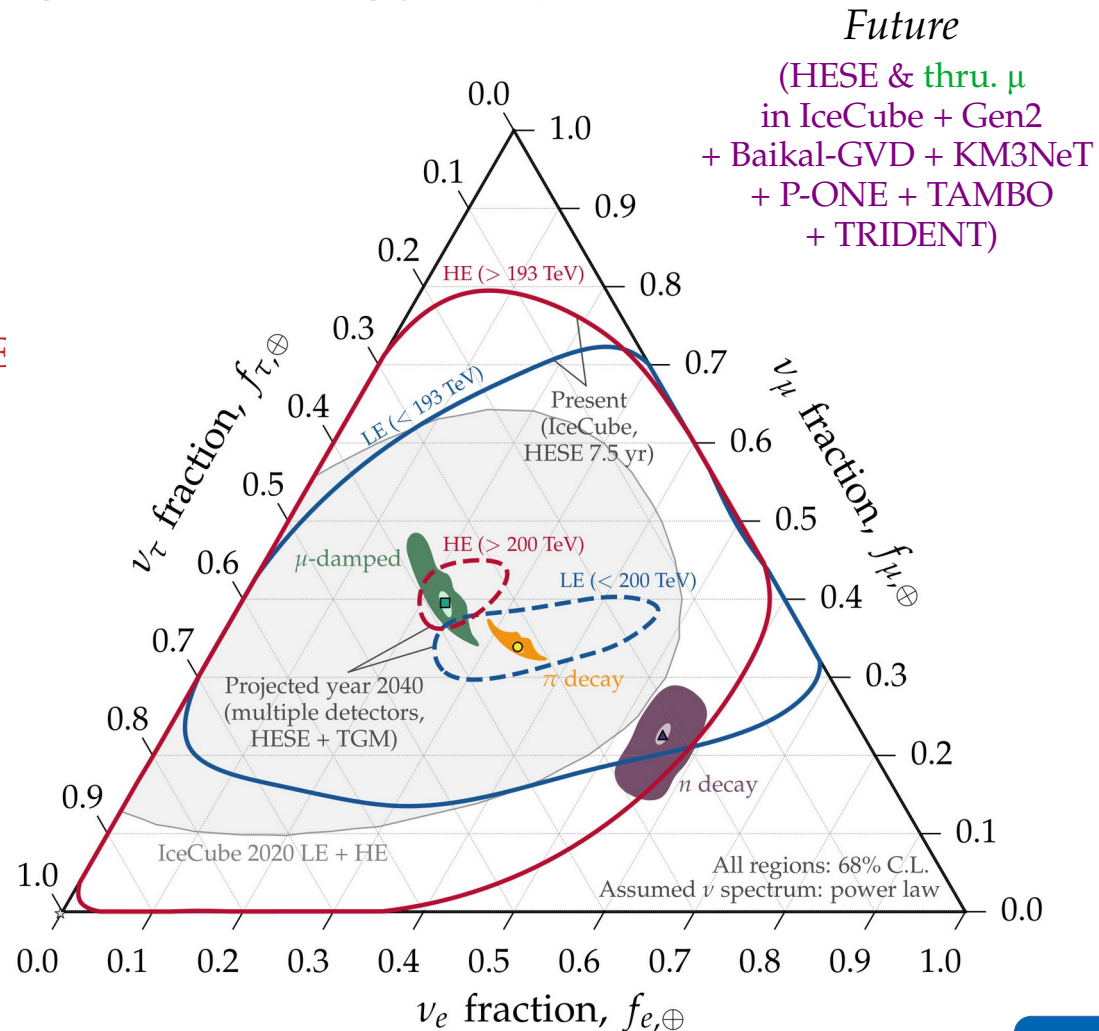
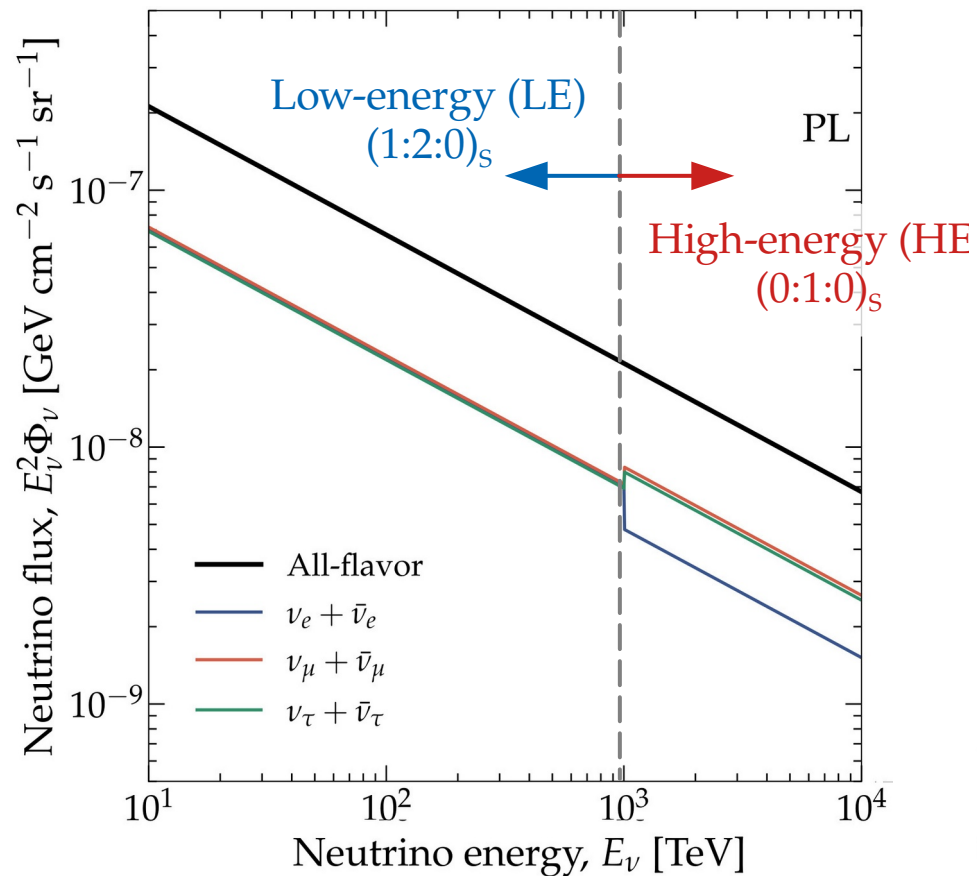
No significant ($> 3\sigma$) evidence for a spectral dip so we set upper limits on the coupling g



Flavor composition:
Beyond basics

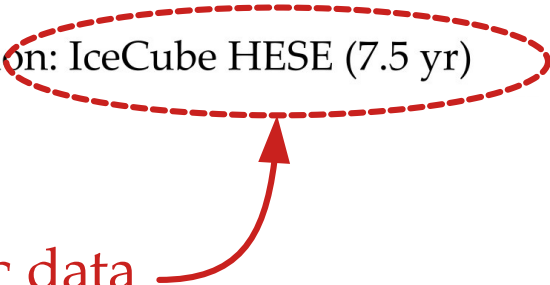
Flavor composition: measuring the energy dependence

Power-law (PL) diffuse ν flux



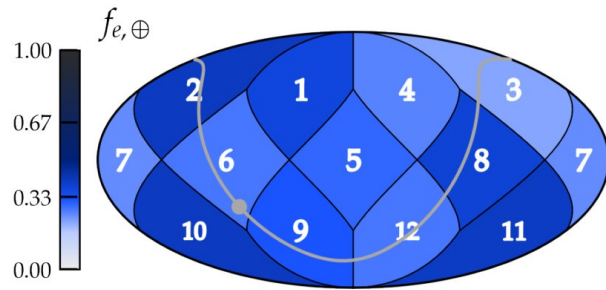
Directional high-energy astrophysical neutrino flavor composition: IceCube HESE (7.5 yr)

Real, public data

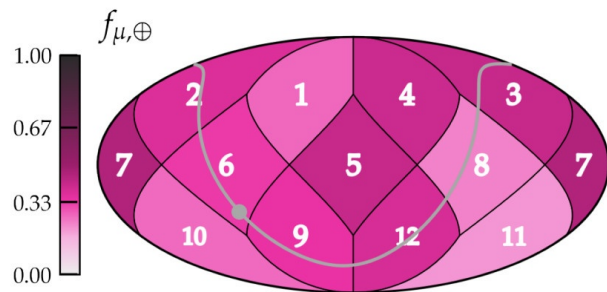
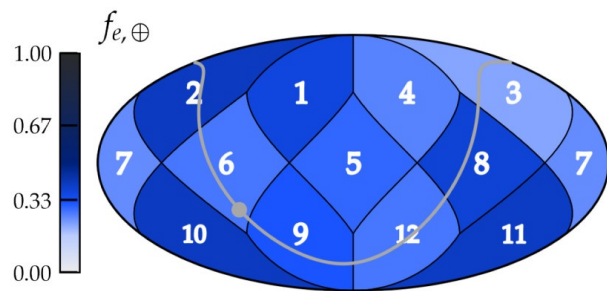


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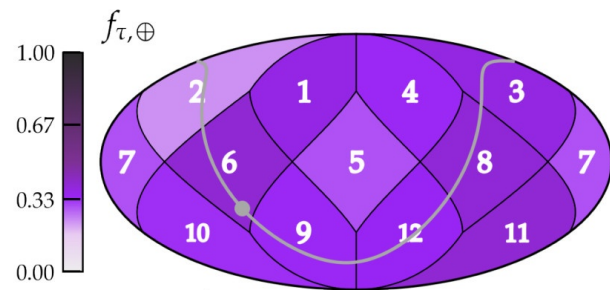
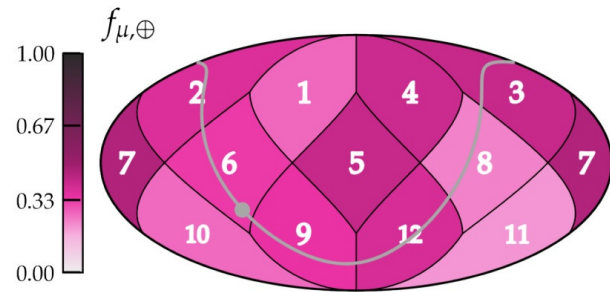
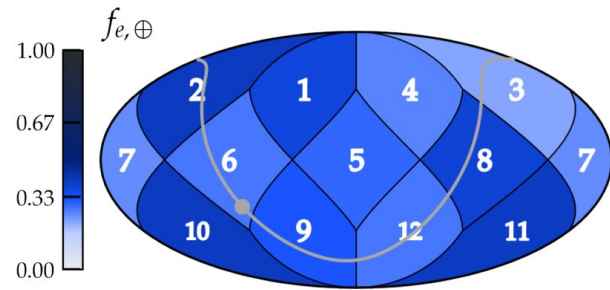
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Directional high-energy astrophysical neutrino flavor composition: IceCube HESE (7.5 yr)



Equatorial

Telalovic, MB, 2310.15224

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

This work:

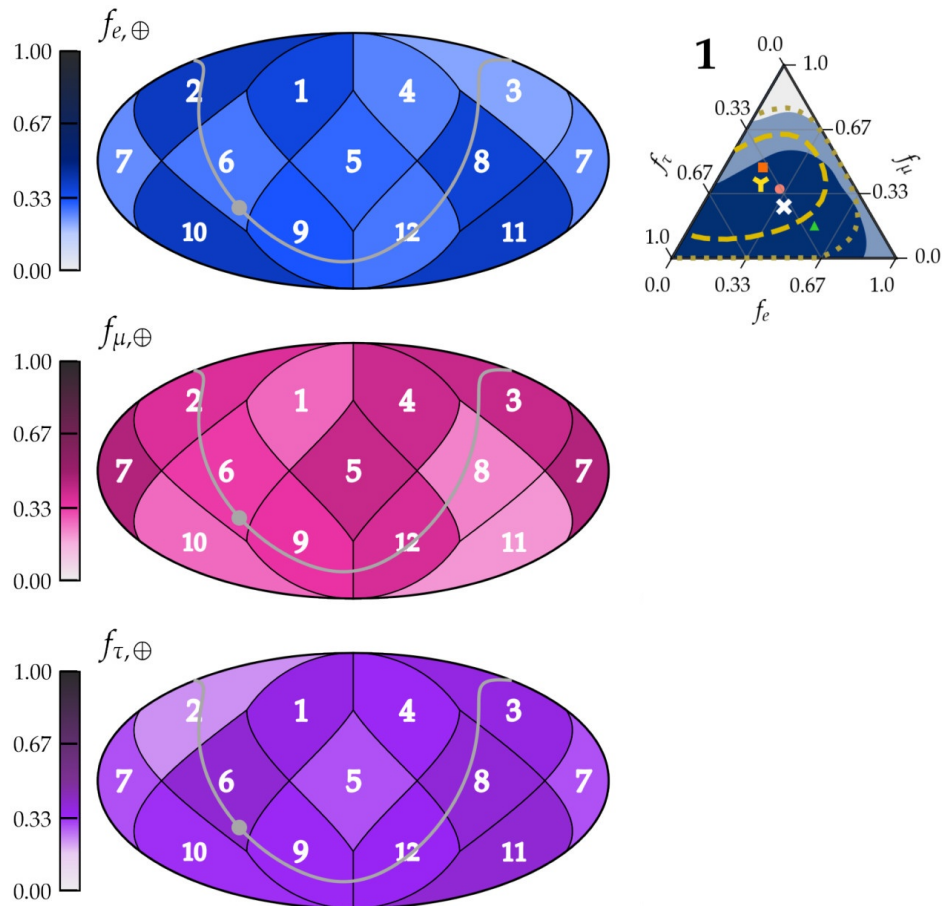
⊗ Best fit ■ 1σ ■ 2σ □ 3σ

IceCube 2020 all-sky:

⊗ Best fit - - 1σ ··· 2σ

Benchmarks:

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



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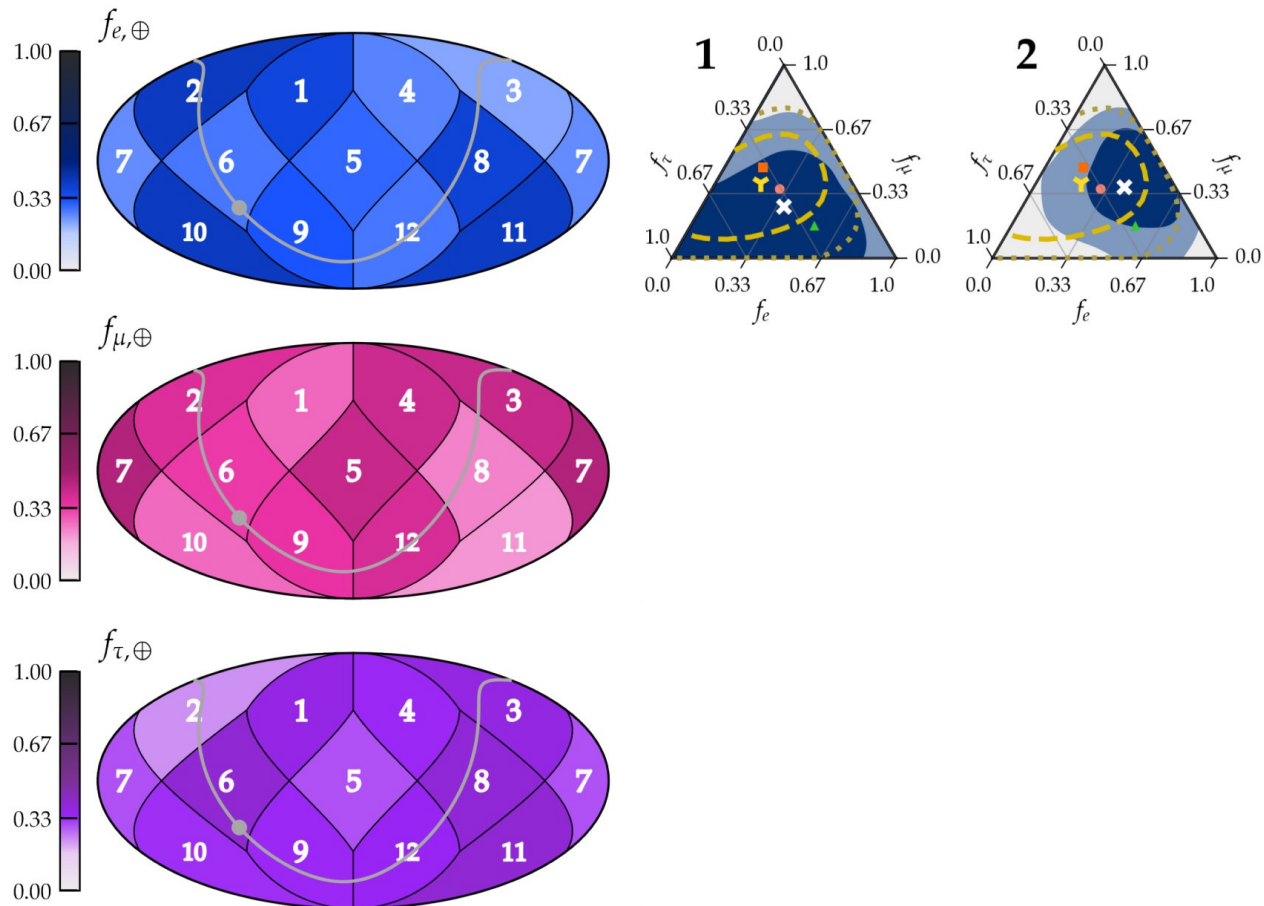
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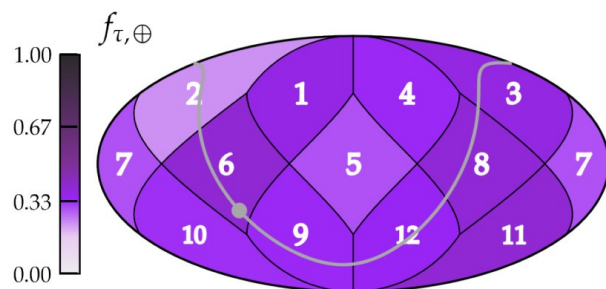
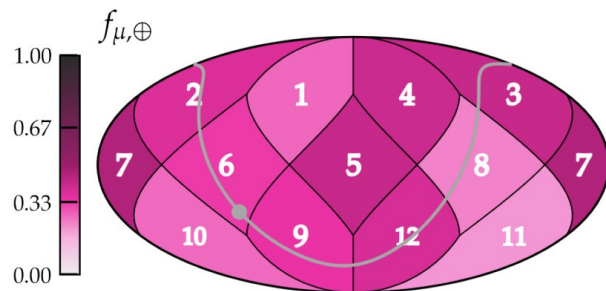
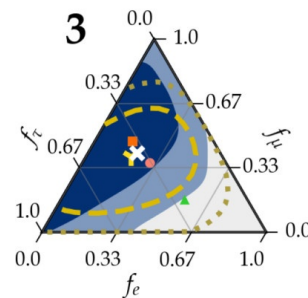
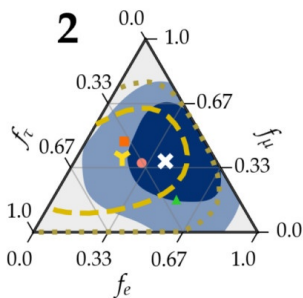
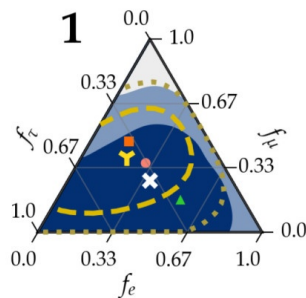
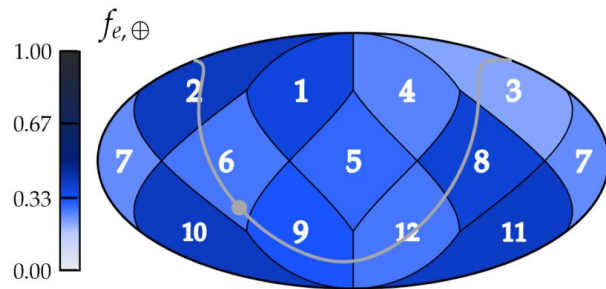
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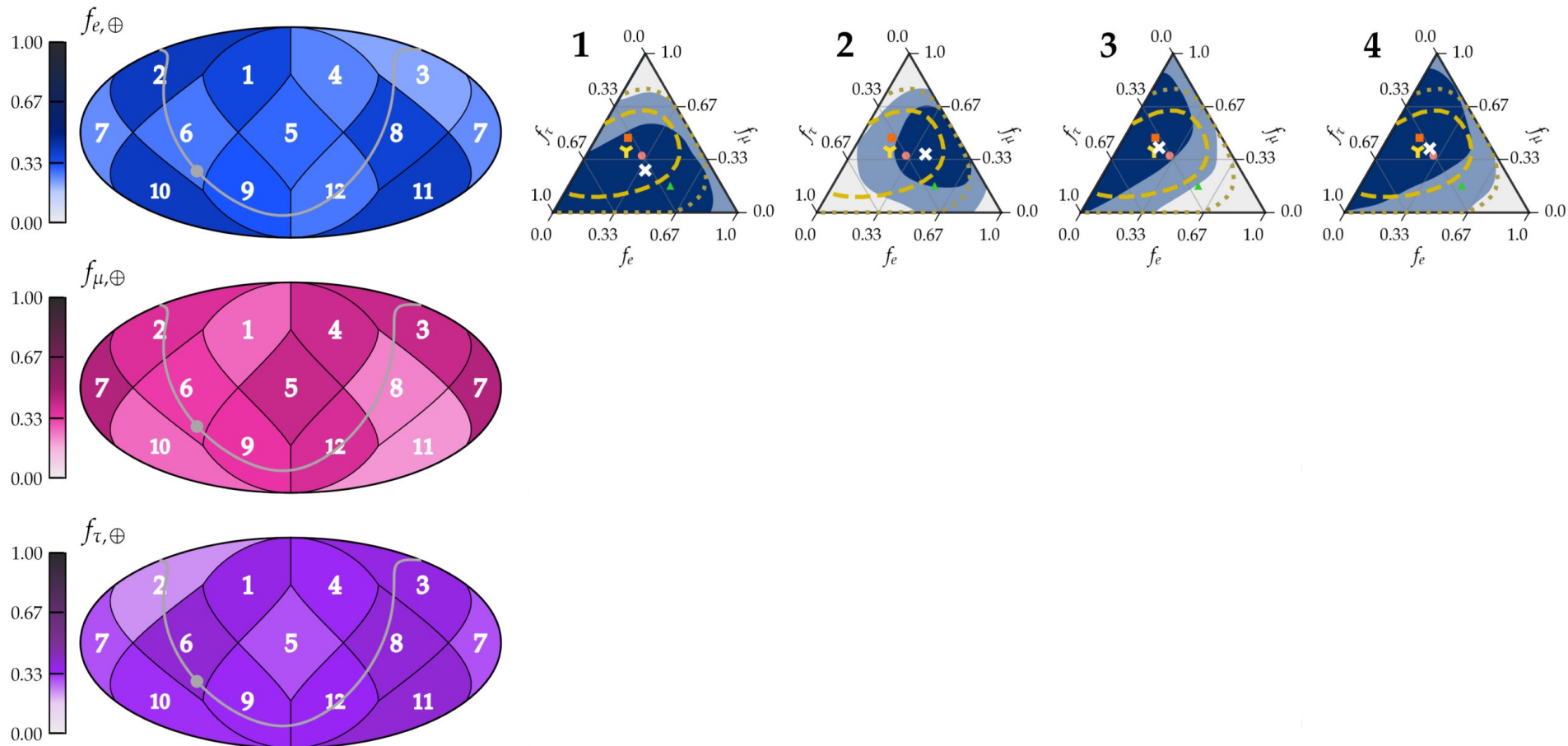
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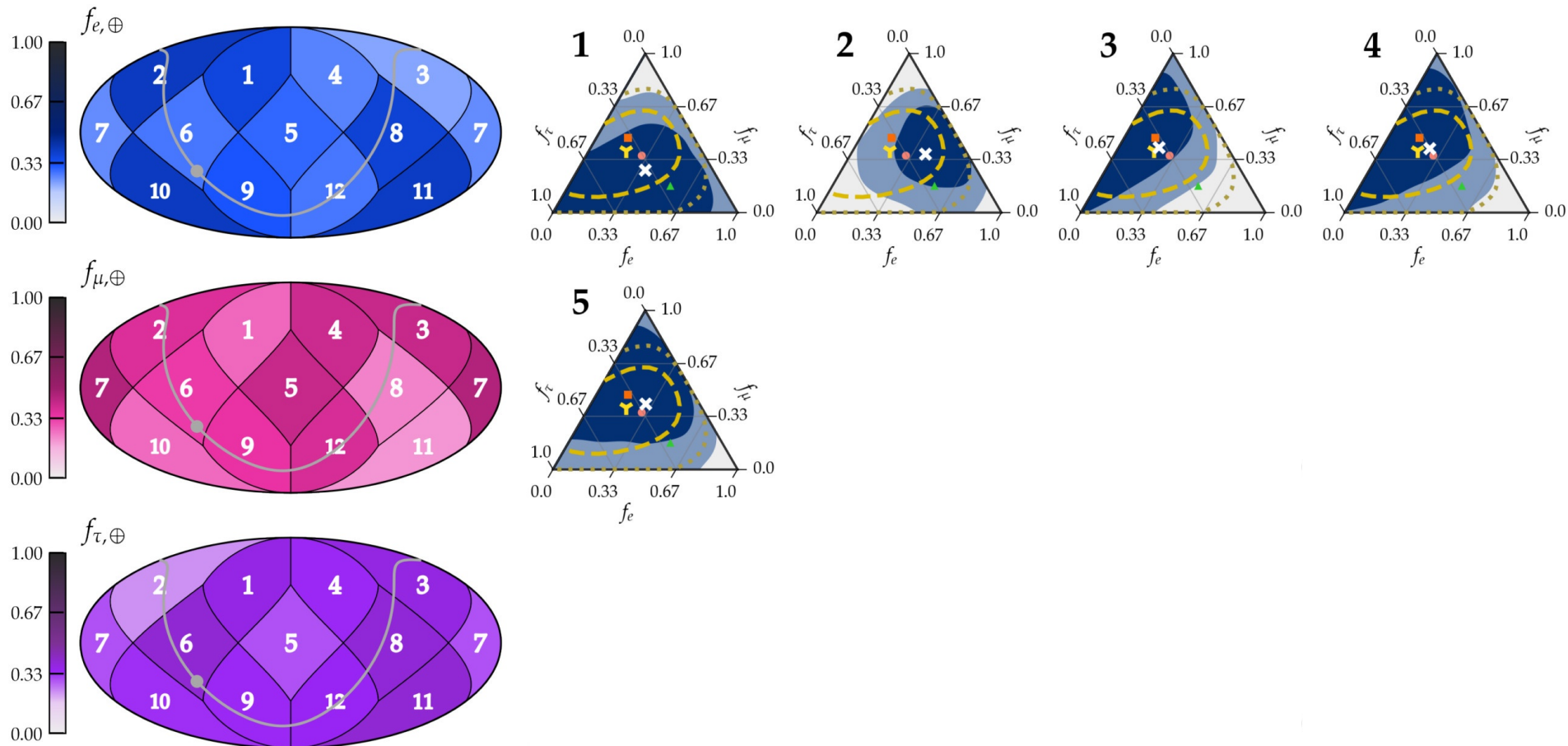
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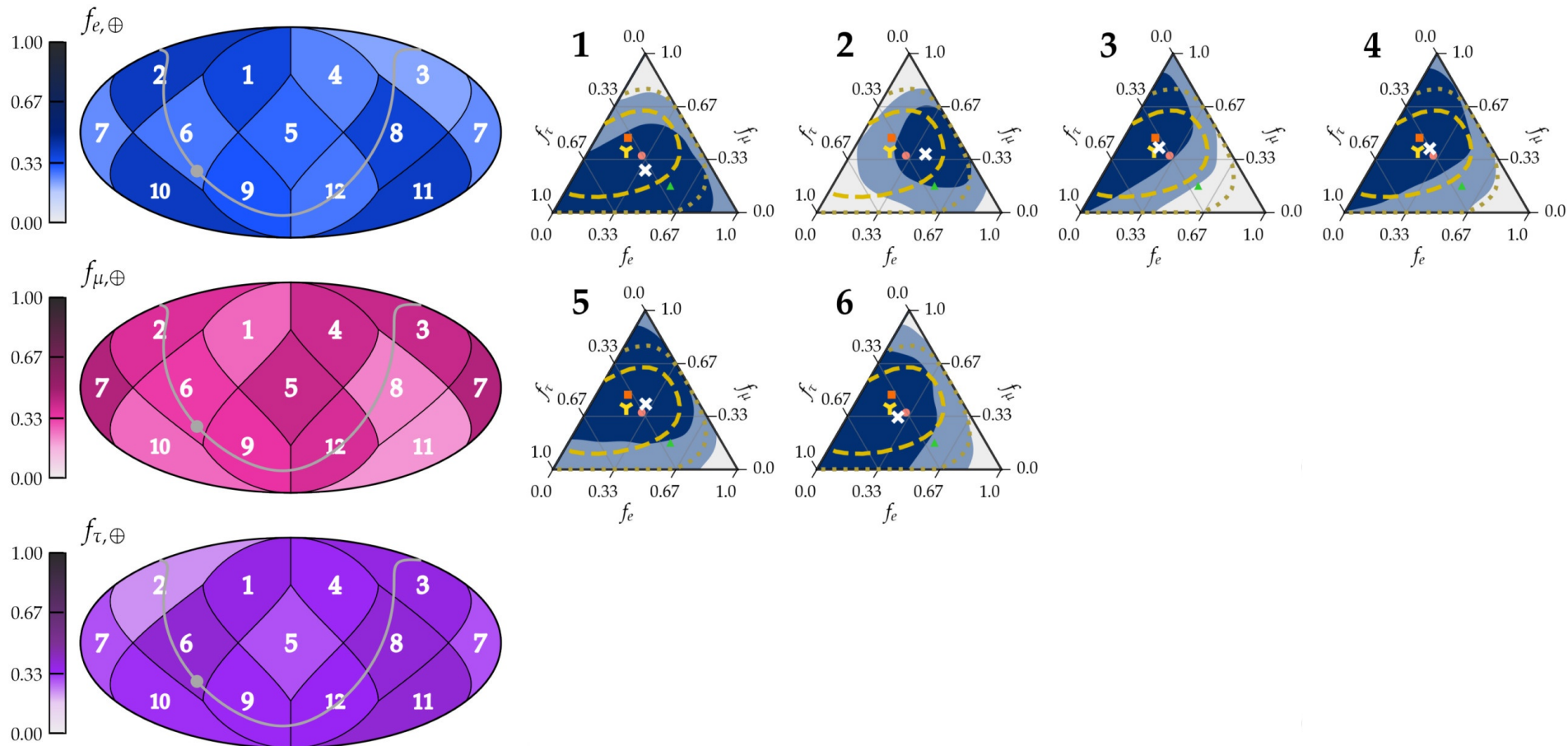
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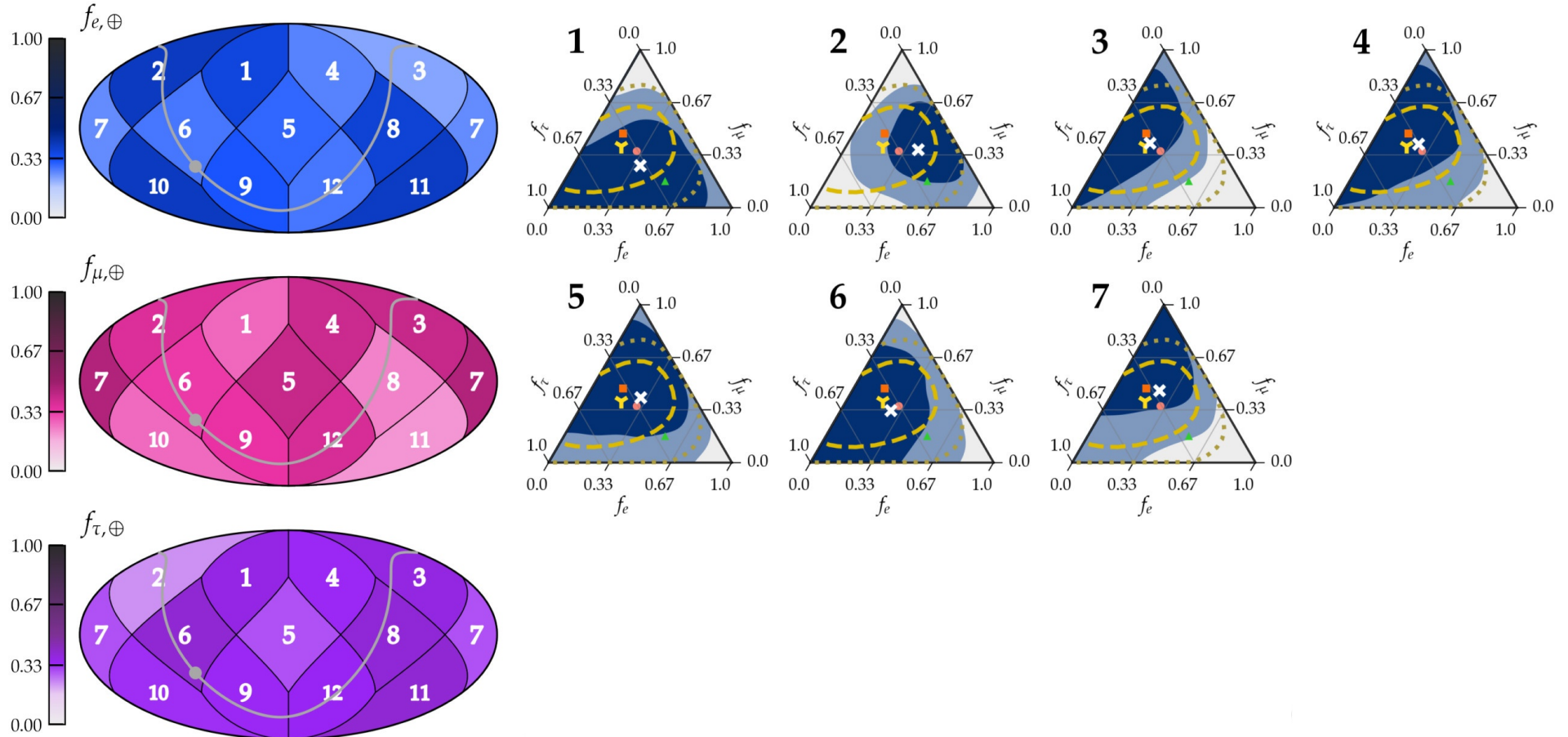
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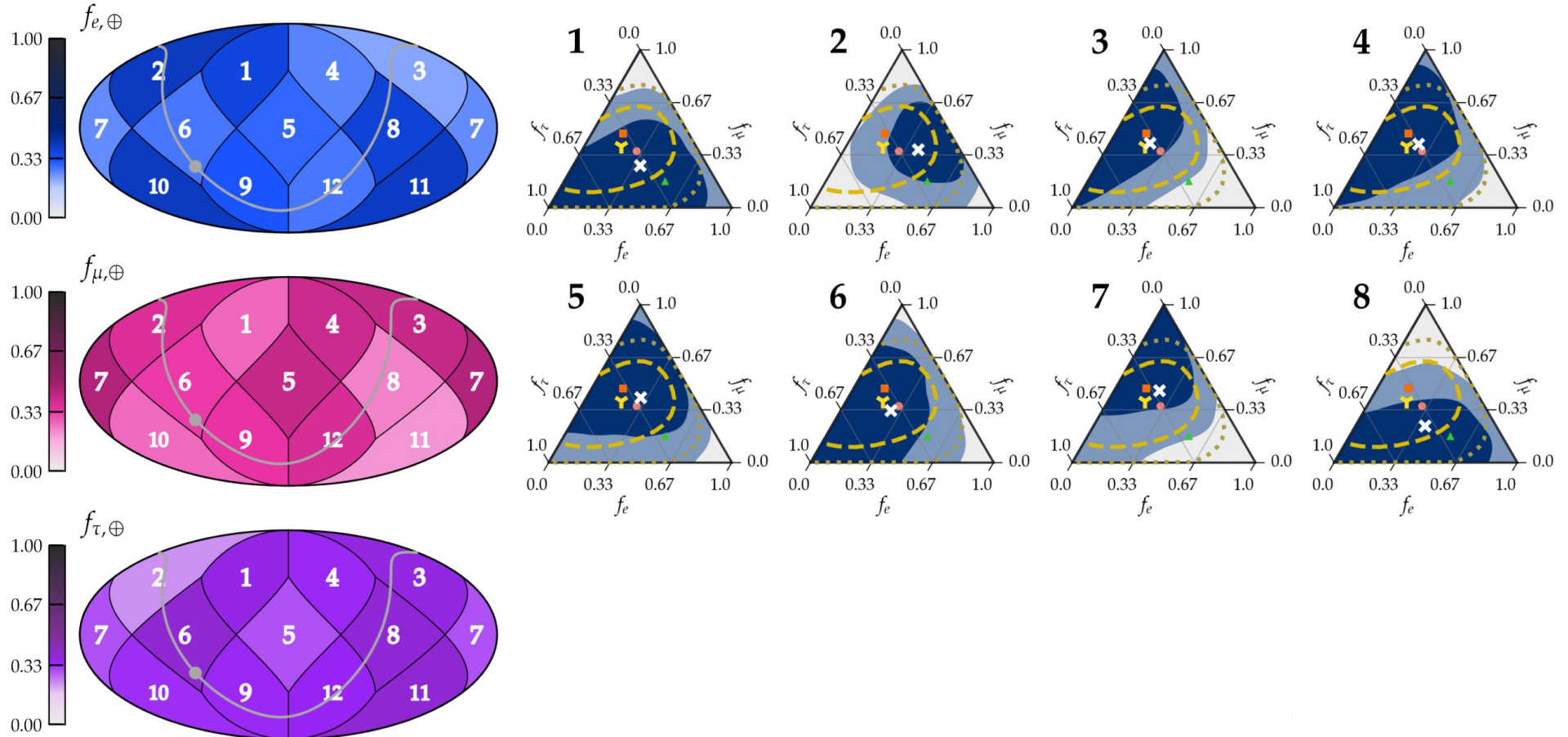
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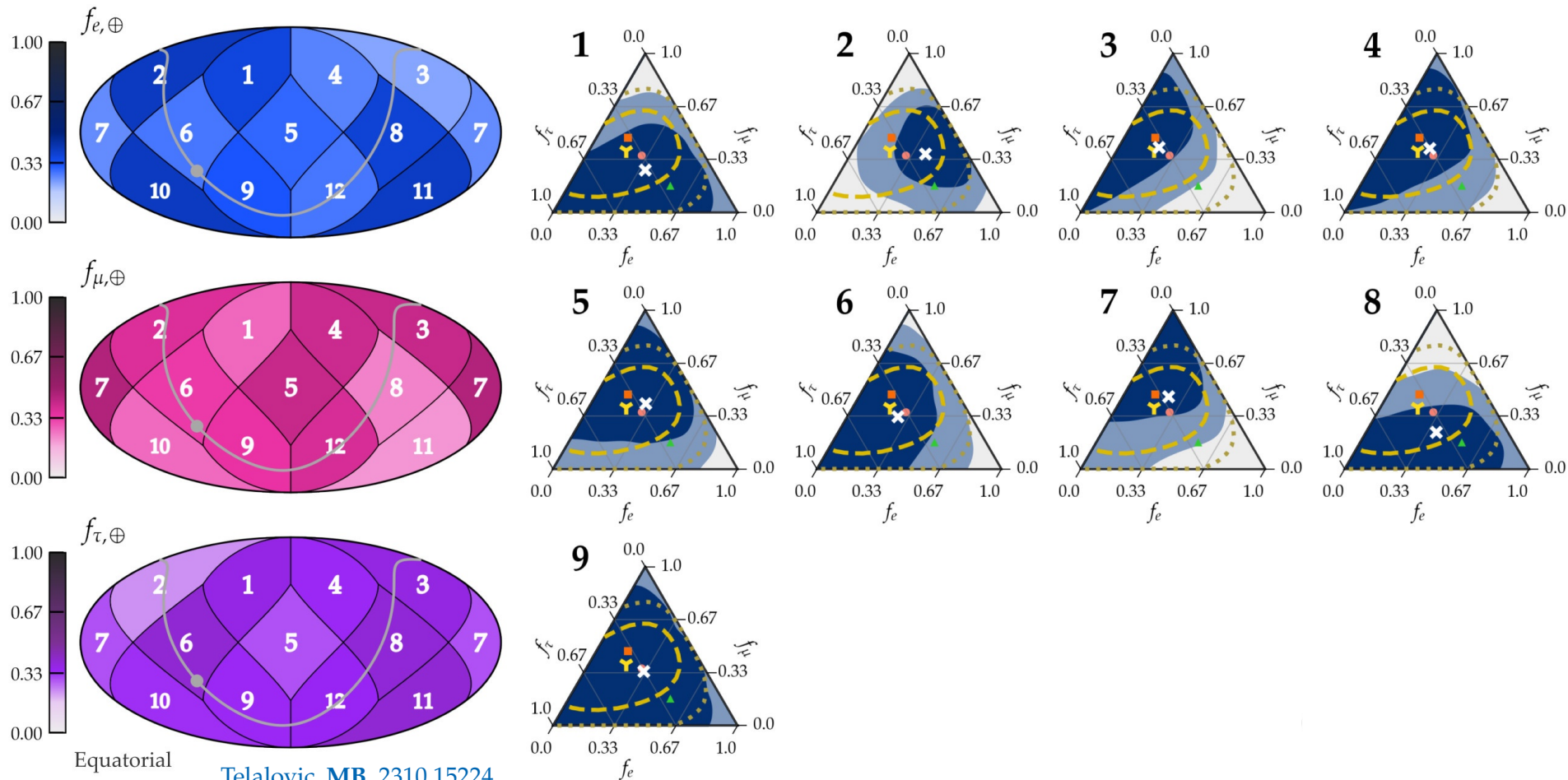
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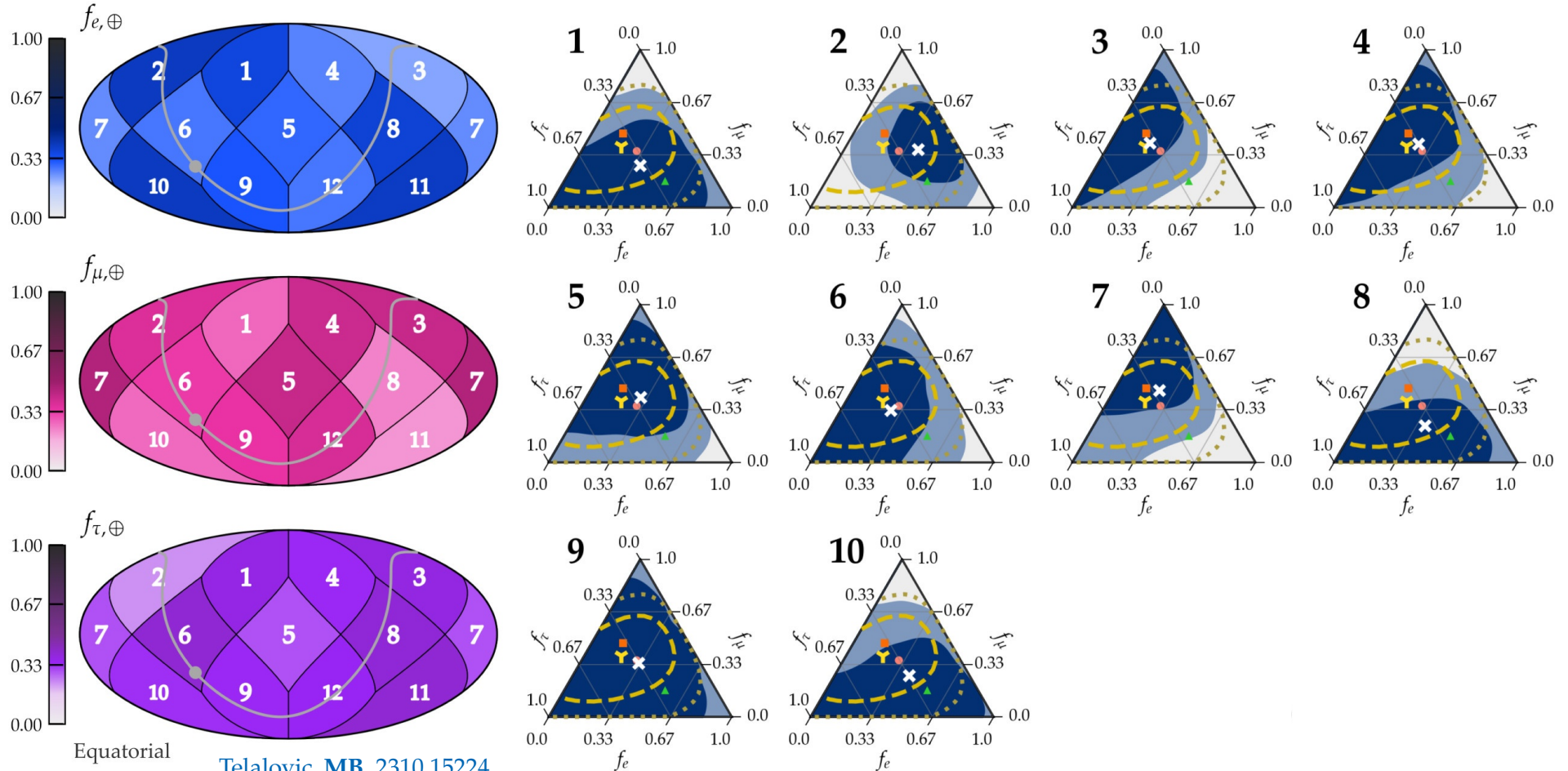
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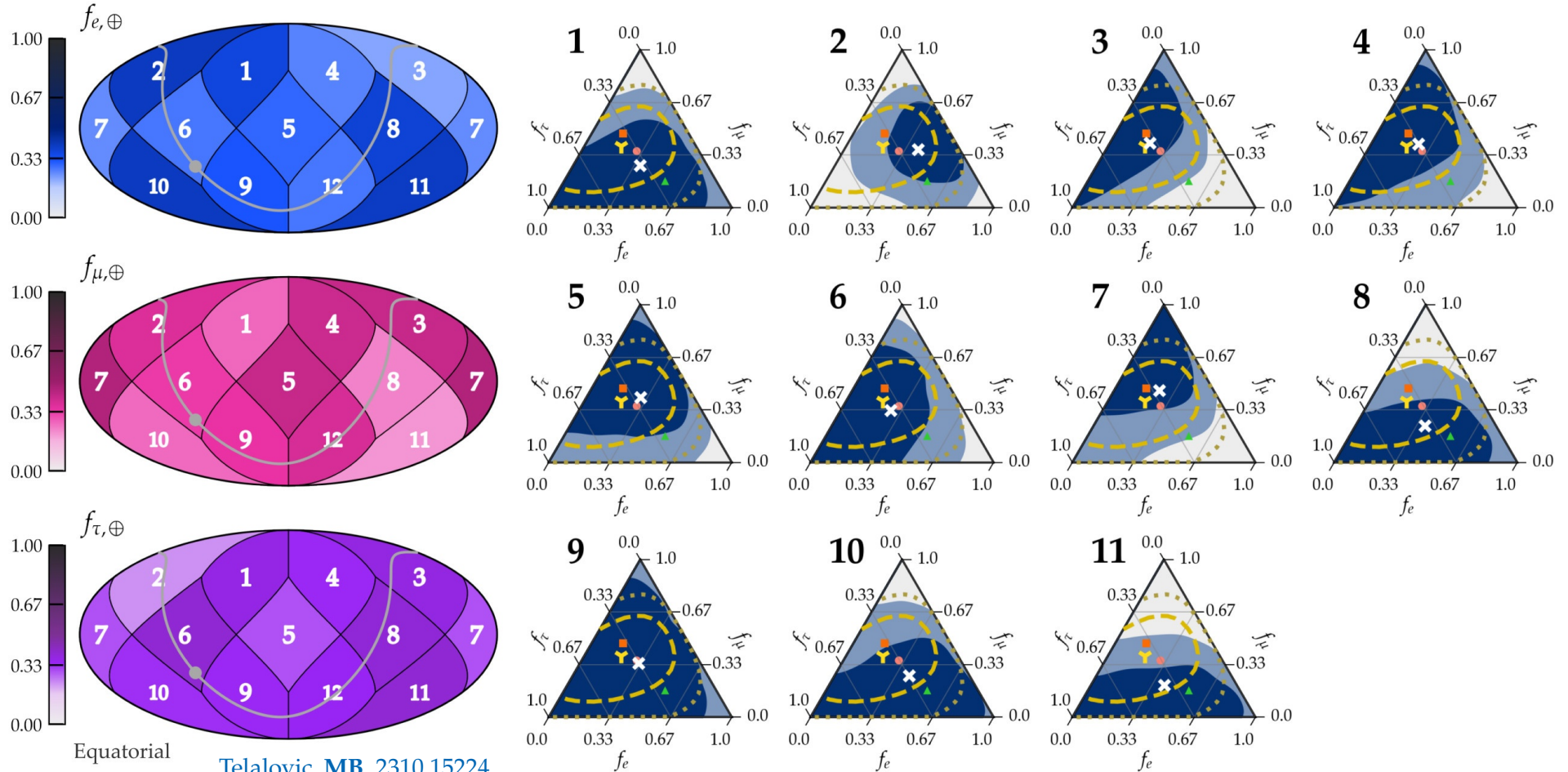
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Directional high-energy astrophysical neutrino flavor composition: IceCube HESE (7.5 yr)

This work:

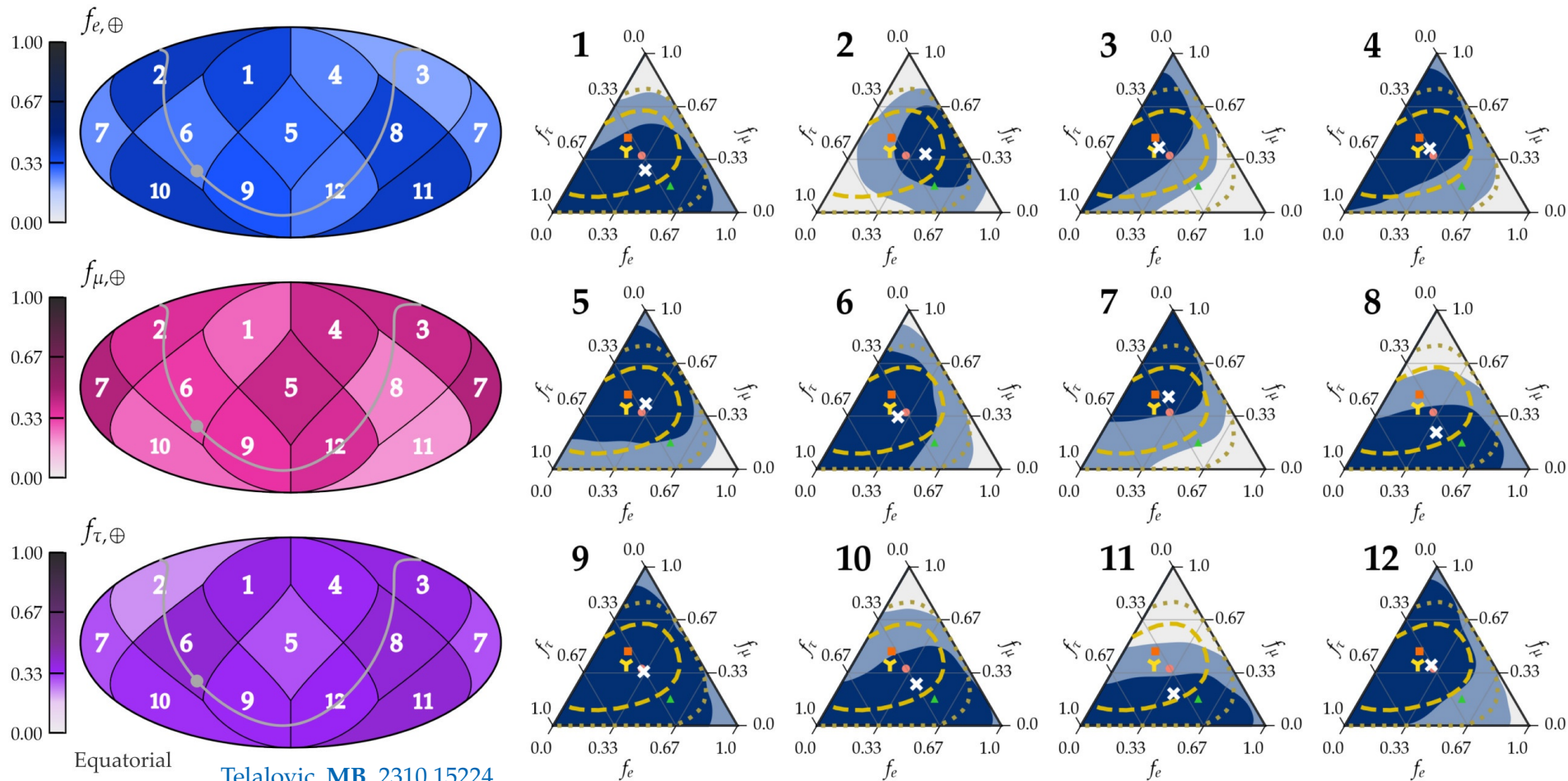
✖ Best fit ■ 1 σ ■ 2 σ □ 3 σ

IceCube 2020 all-sky:

Y Best fit - - 1 σ - - - 2 σ

Benchmarks:

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



Directional high-energy astrophysical neutrino flavor composition: Anisotropic (2040, all detectors)

This work:

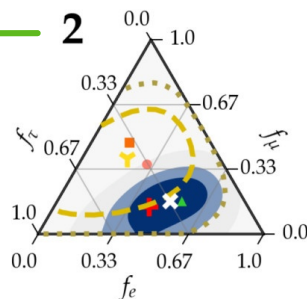
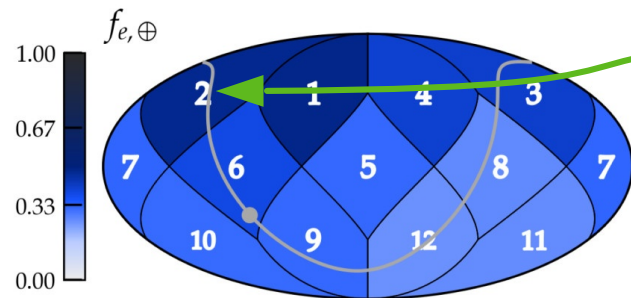
⊗ Best fit + True ■ 1σ ▒ 2σ □ 3σ

IceCube 2020 all-sky:

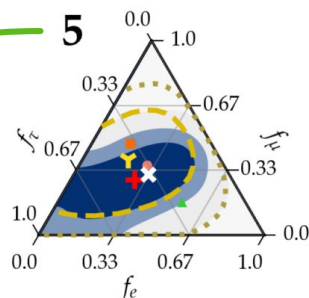
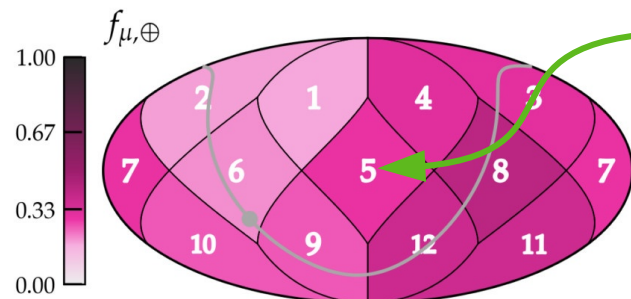
Y Best fit - - 1σ - - - 2σ

Benchmarks:

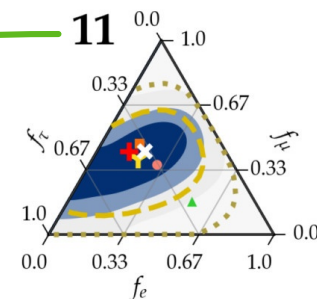
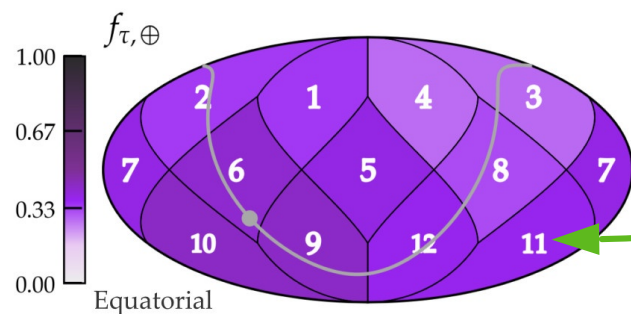
● $\pi^\pm$ decay: (1:2:0)_S ■ μ -damped: (0:1:0)_S ▲ n decay: (1:0:0)_S



High ν_e content:
Production by neutron decay



About the same for all flavors:
Production by full pion decay chain



High ν_μ content:
Muon-damped