The flavor composition of high-energy cosmic neutrinos: *towards high statistics and ultra-high energies*

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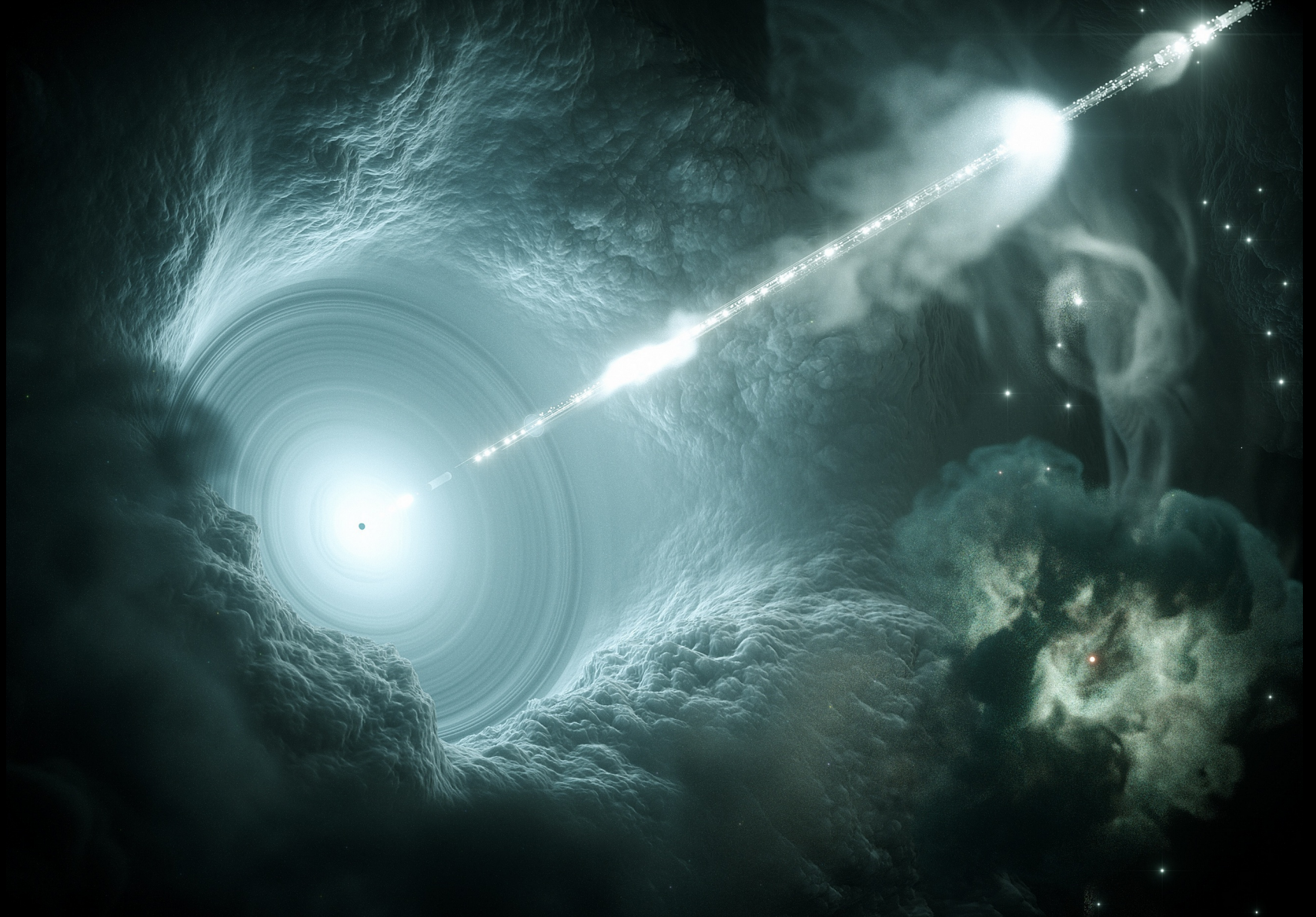
UNIVERSITY OF COPENHAGEN

VILLUM FONDEN

DESY Astroparticle Seminar
Zeuthen, February 16, 2024



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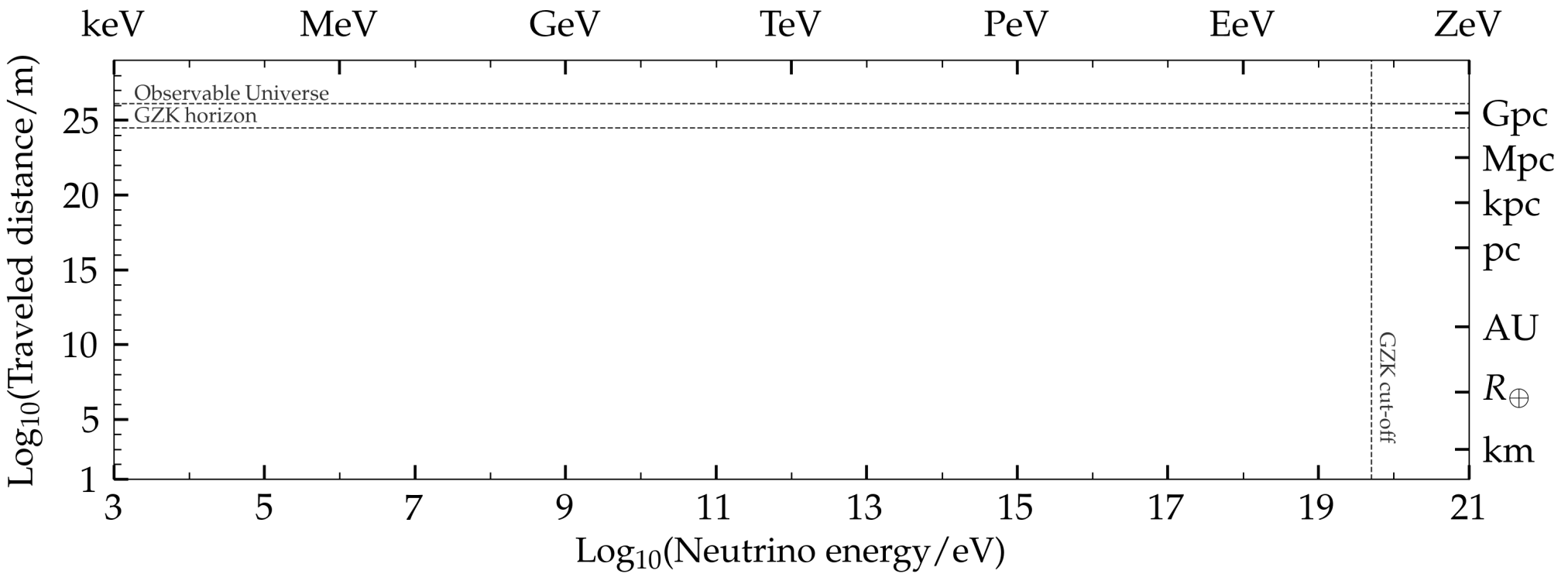
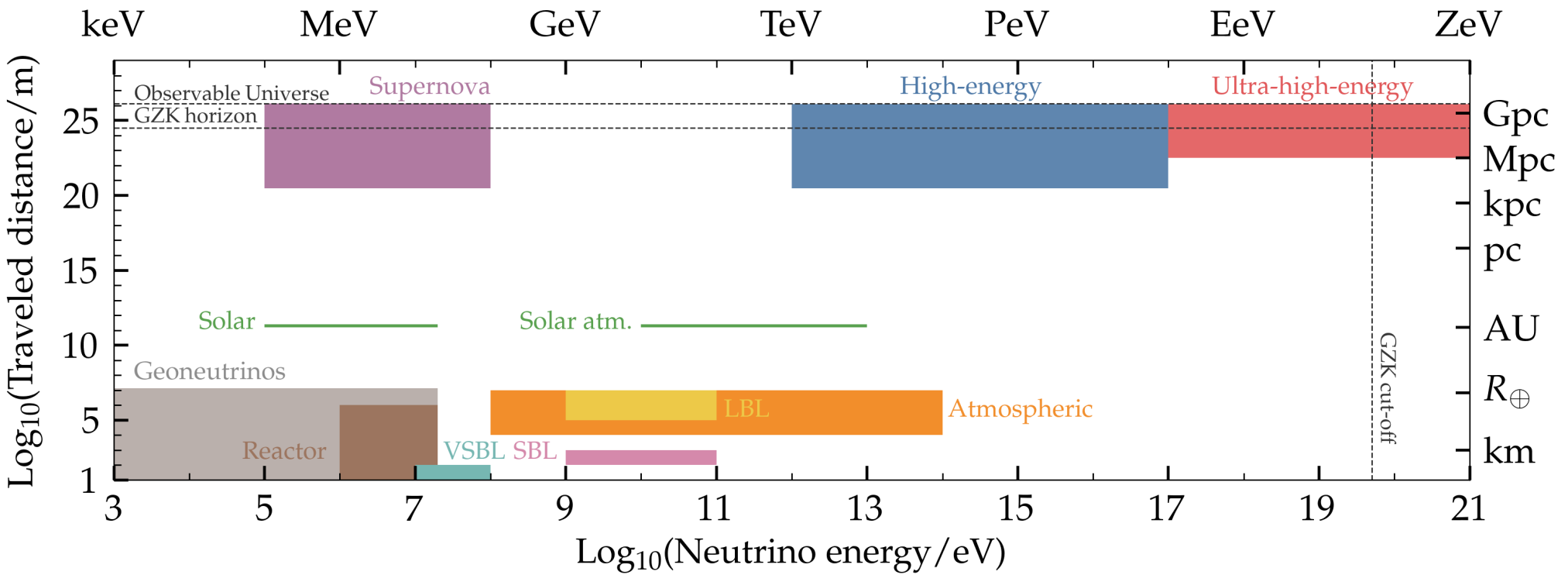


Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333), adapted



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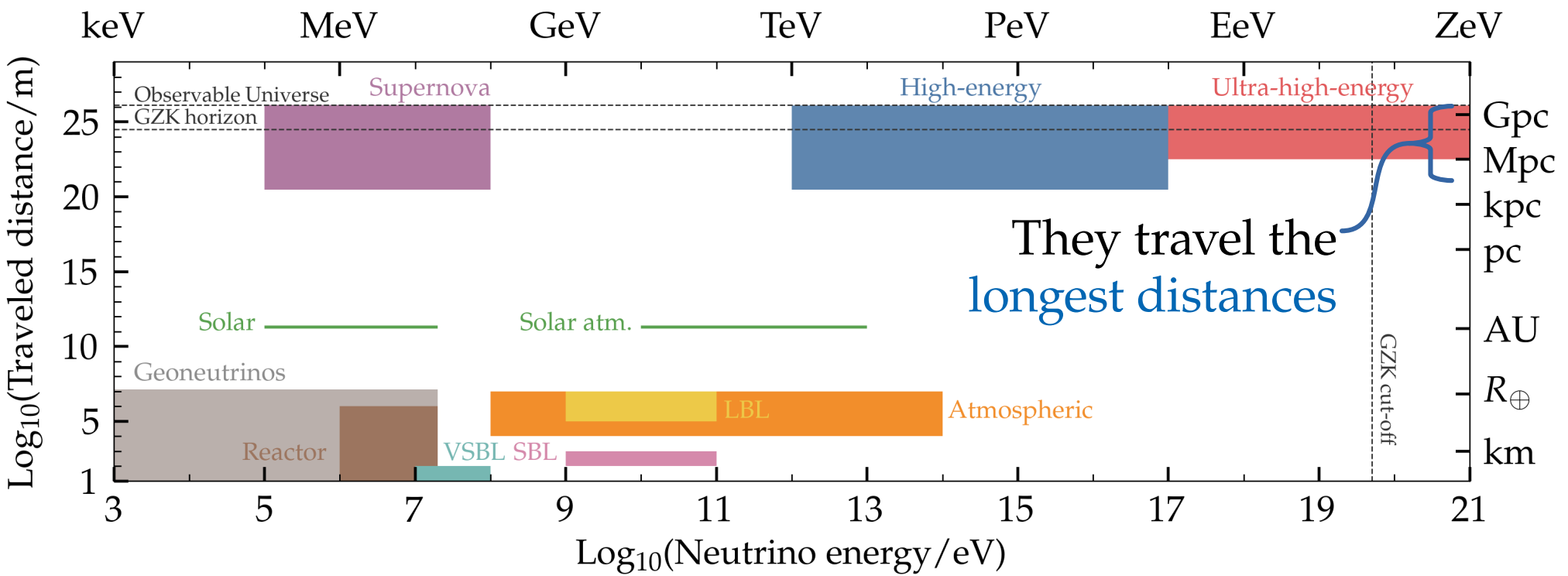
They have the highest energies



They travel the longest distances

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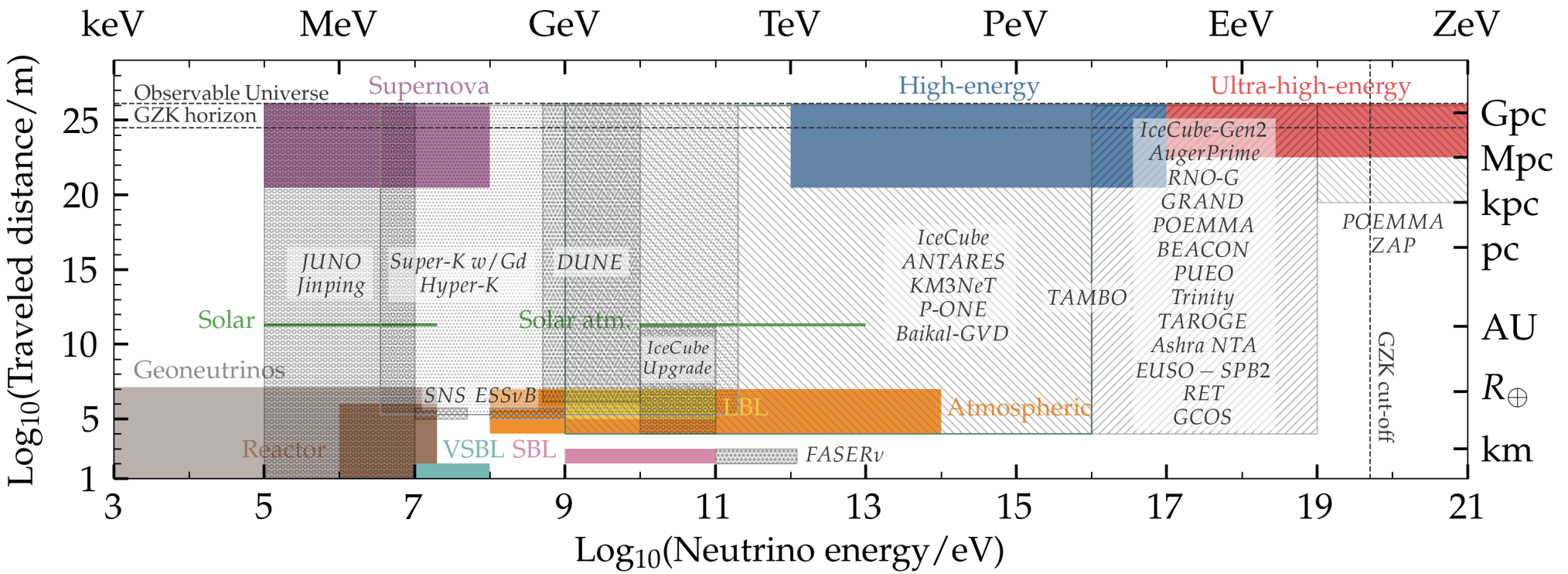

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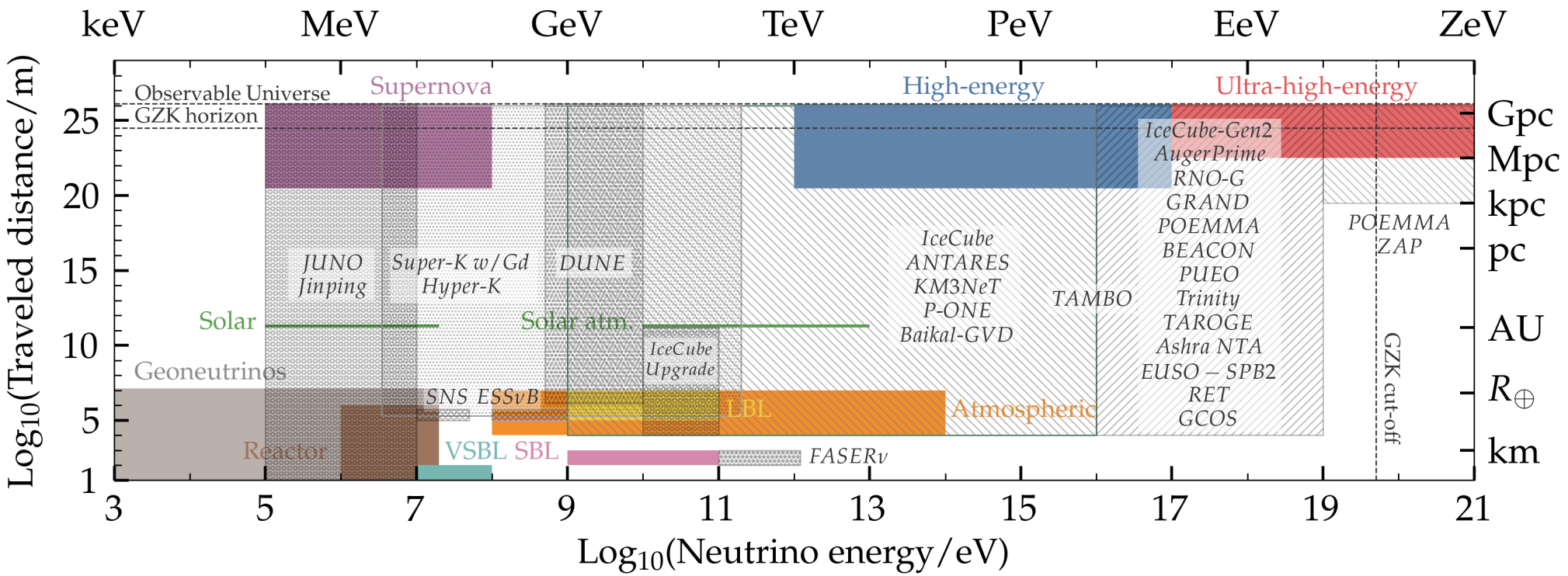
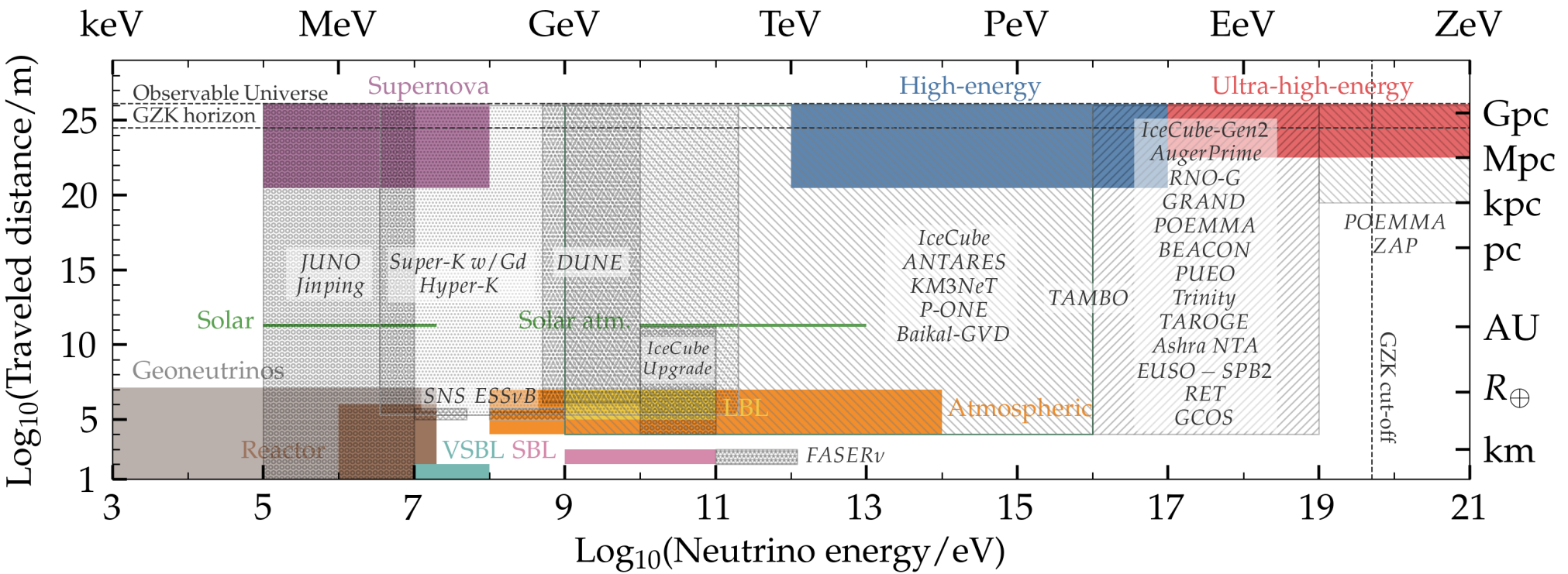


Synergies with lower energies

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

Discovered in 2013
by IceCube



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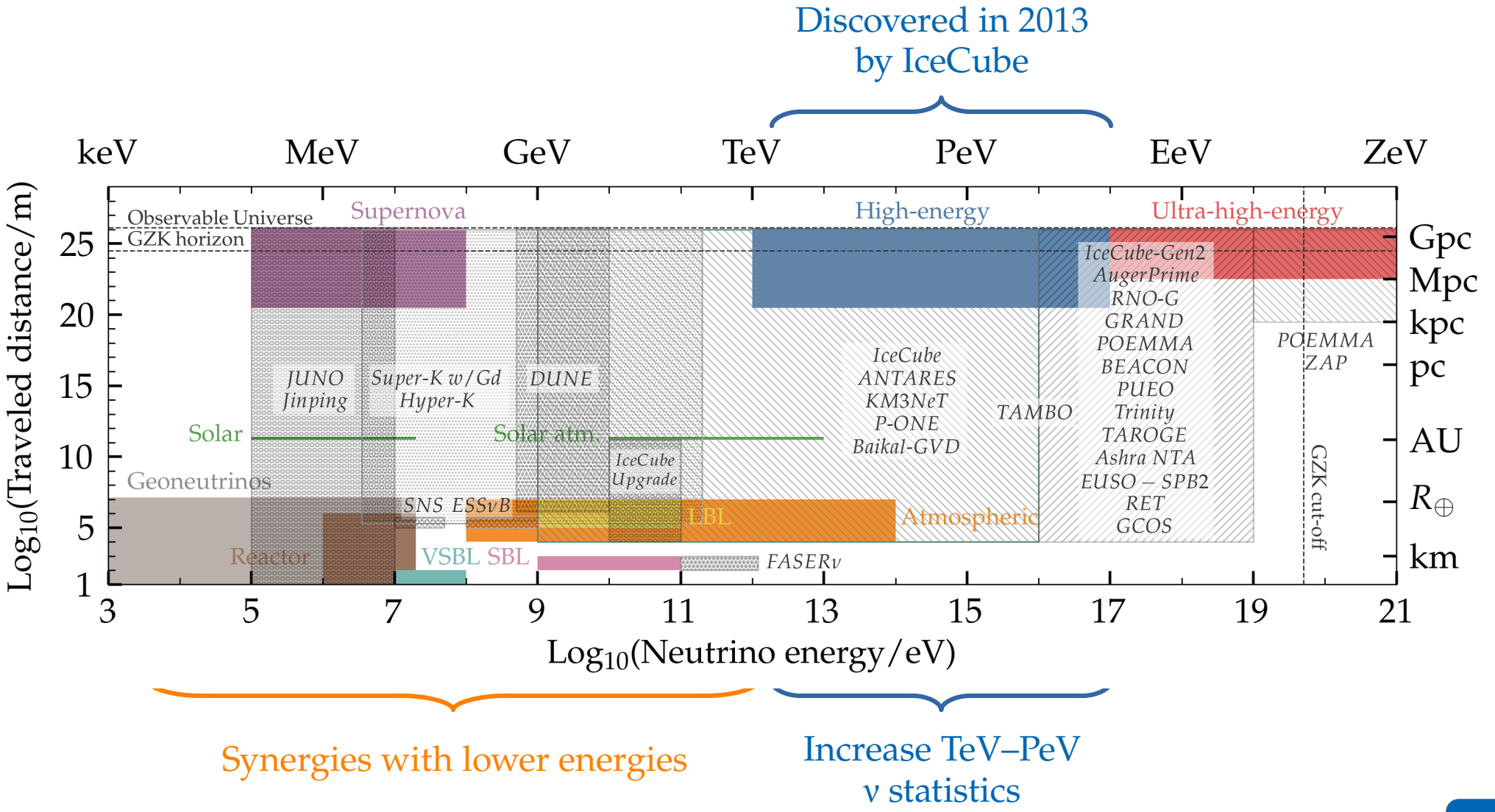

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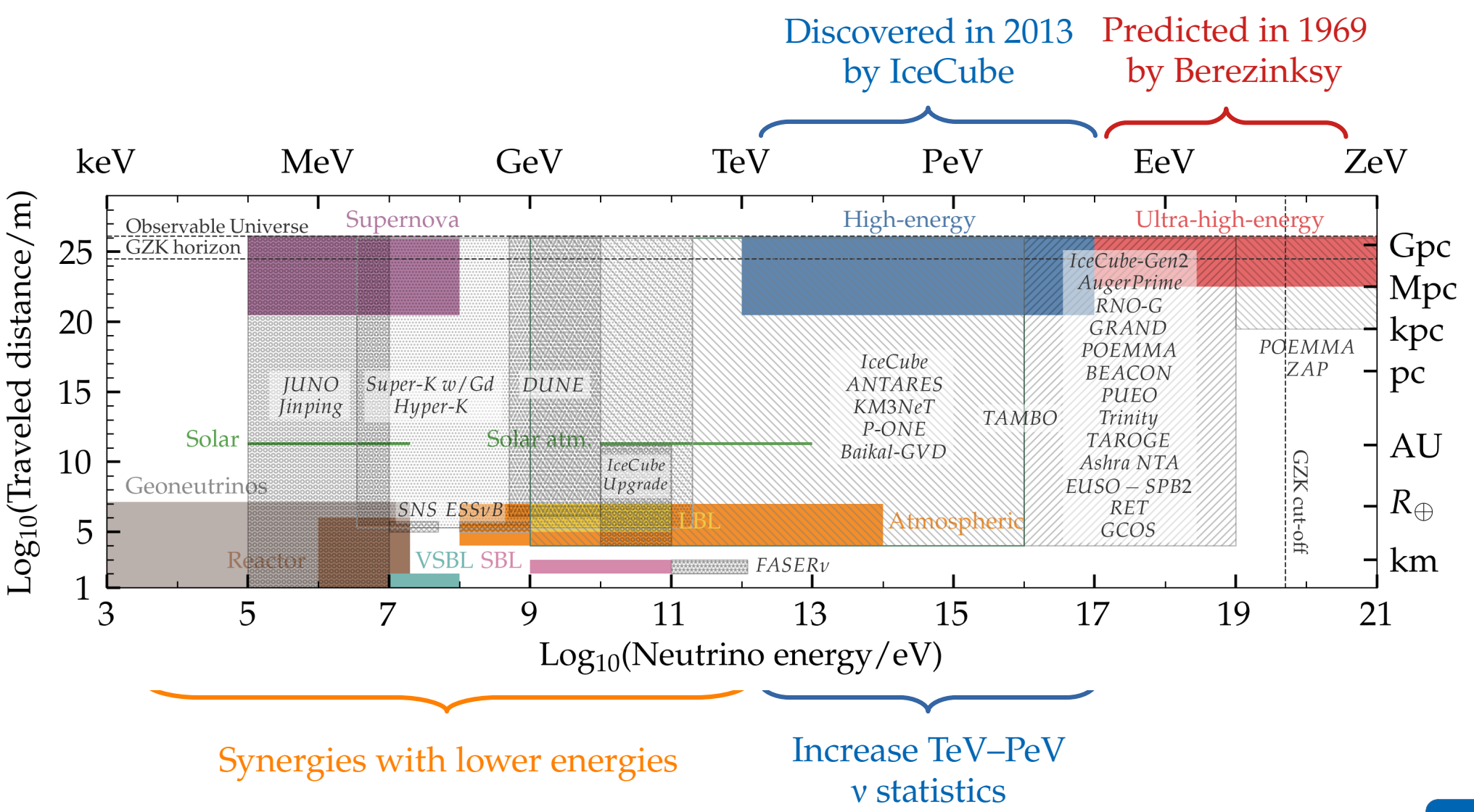

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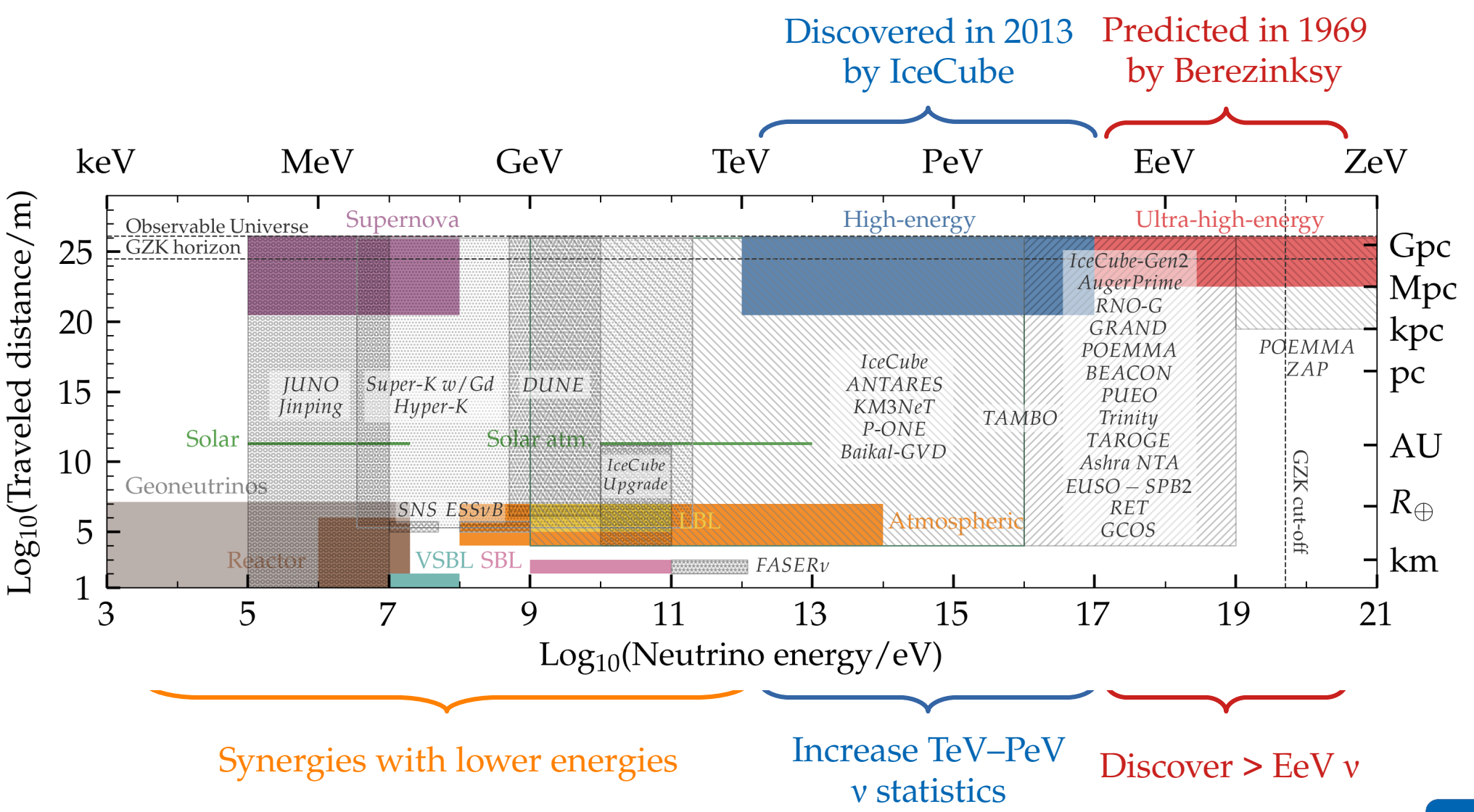

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Making high-energy astrophysical neutrinos: a toy model

(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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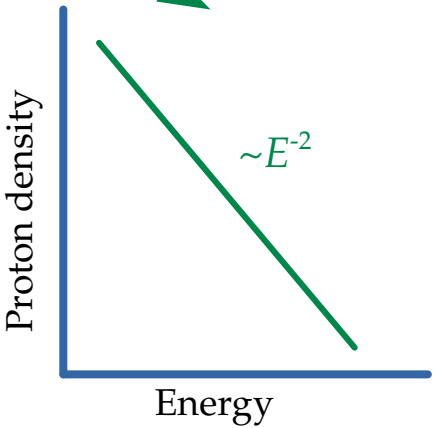

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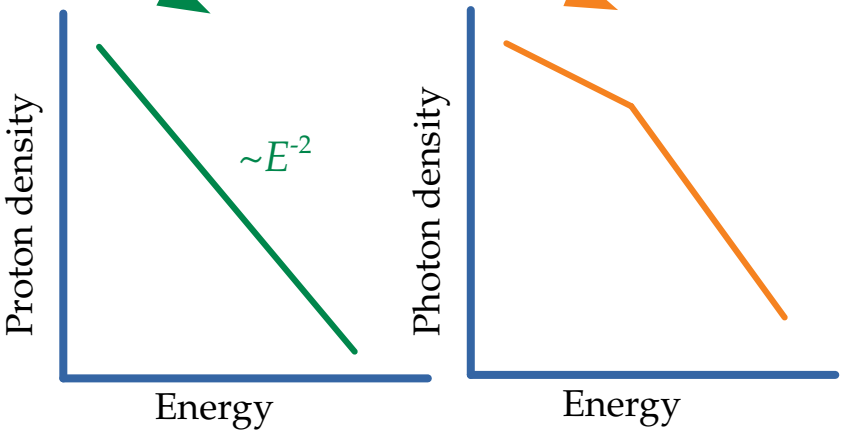

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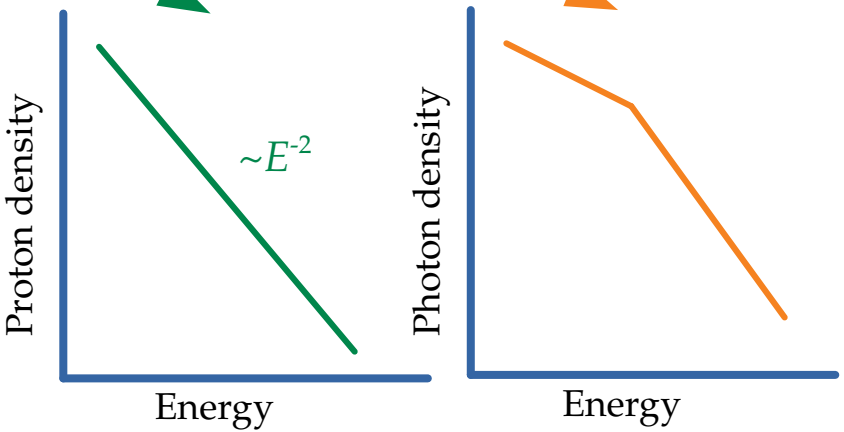
$$\pi^{0} \rightarrow \gamma + \gamma$$

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

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



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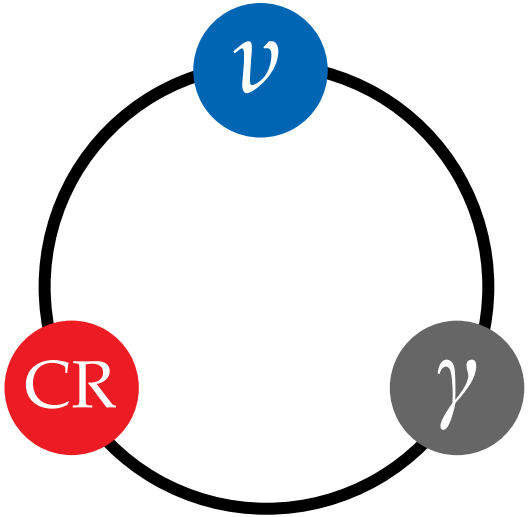
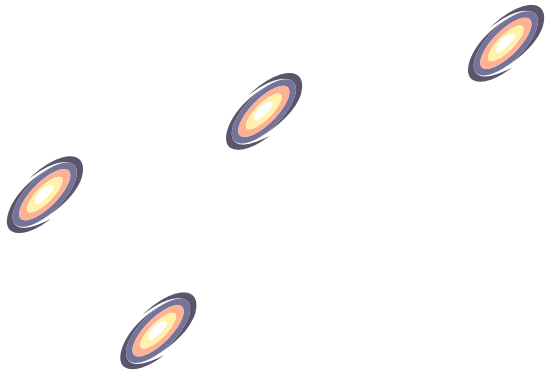


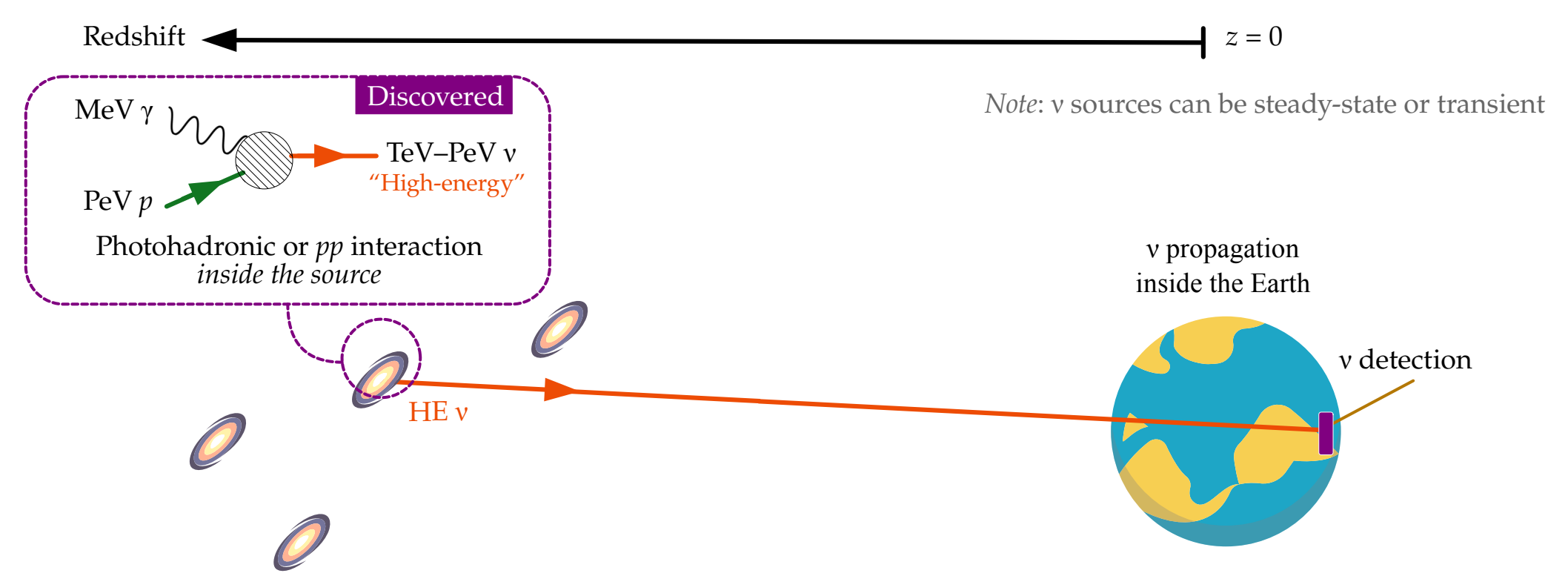
Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 10

Redshift $z = 0$

Note: ν sources can be steady-state or transient





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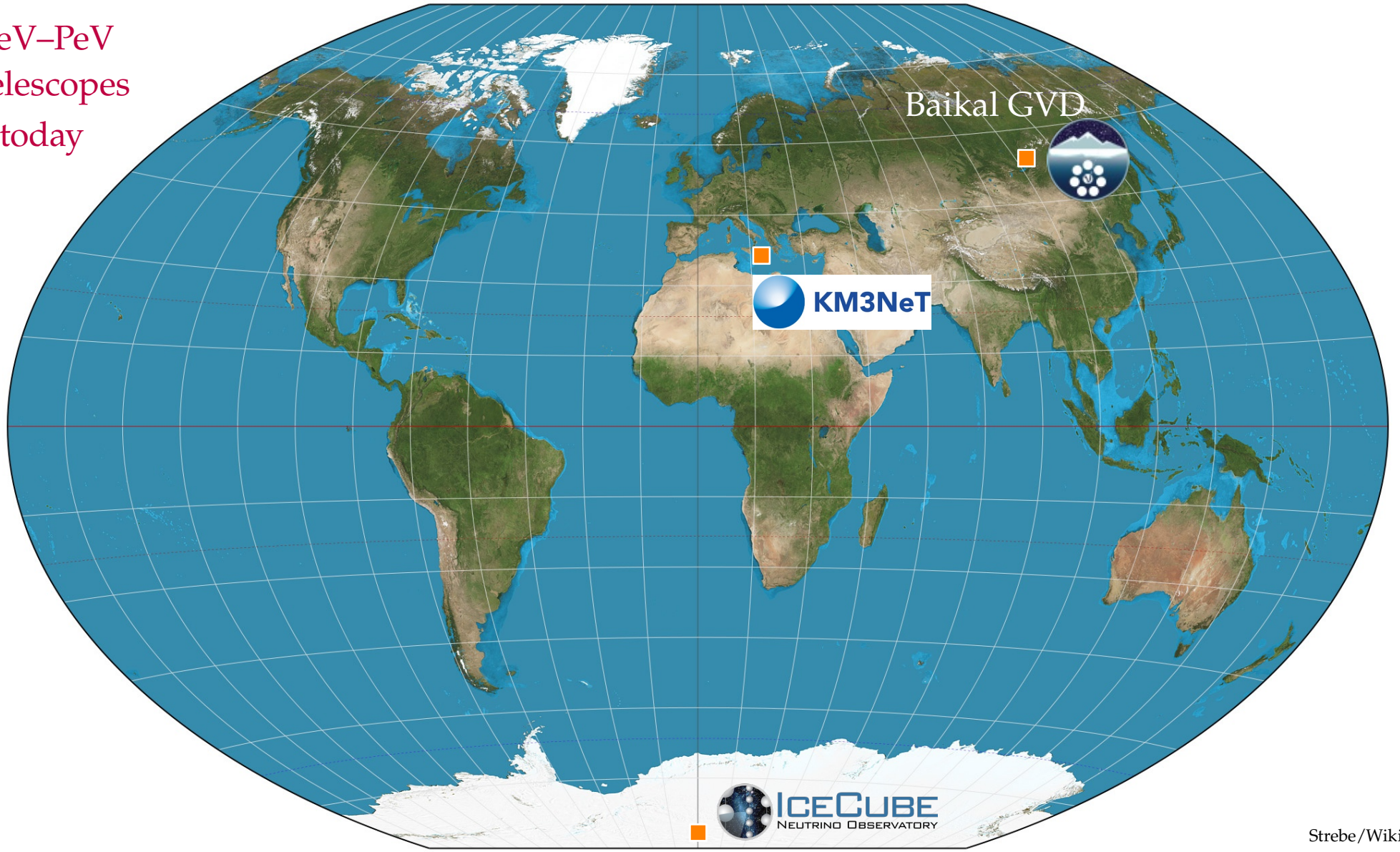
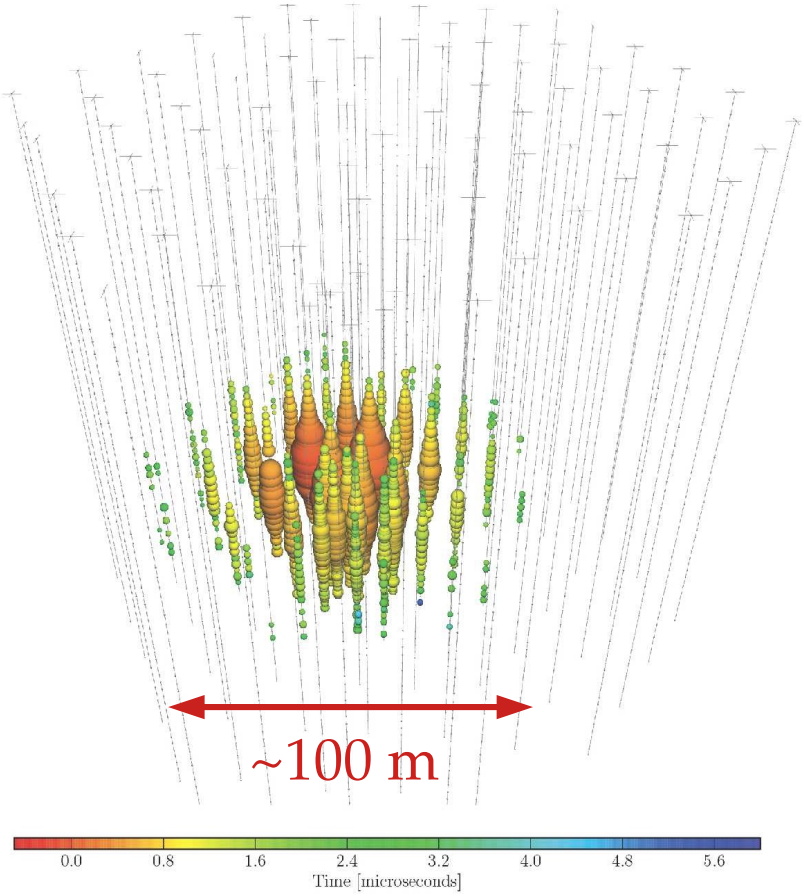
TeV–PeV ν telescopes today



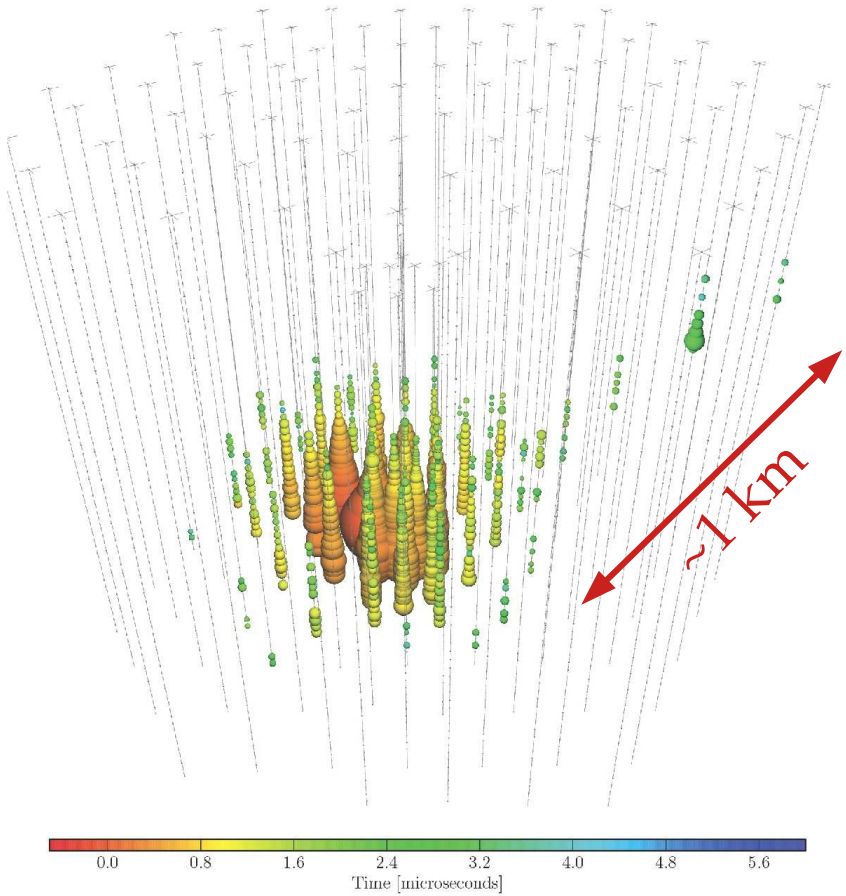
Strebe/Wikipedia

Shower
(mainly from ν_e and ν_τ)

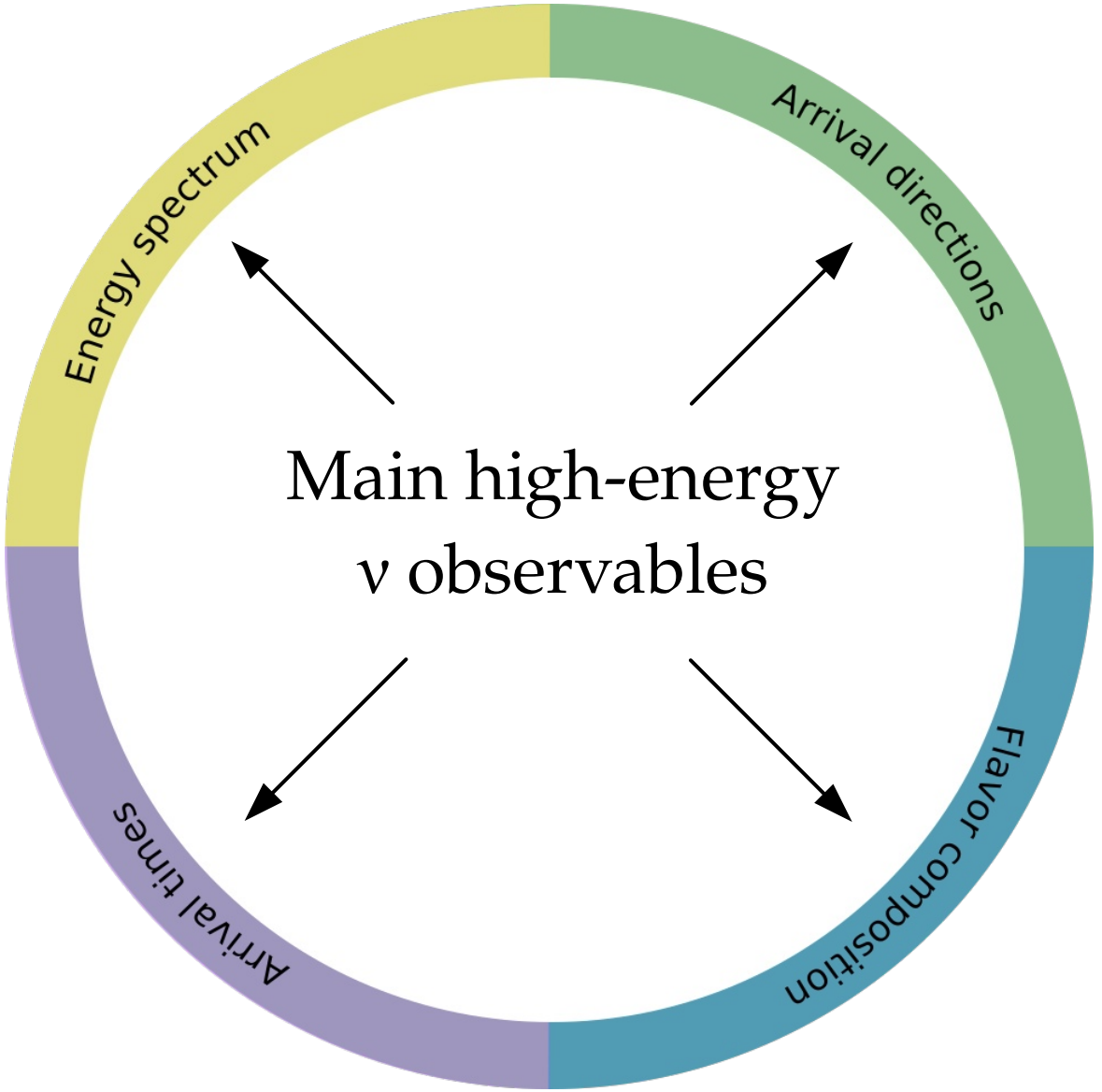


Poor angular resolution: ~10°

Track
(mainly from ν_μ)

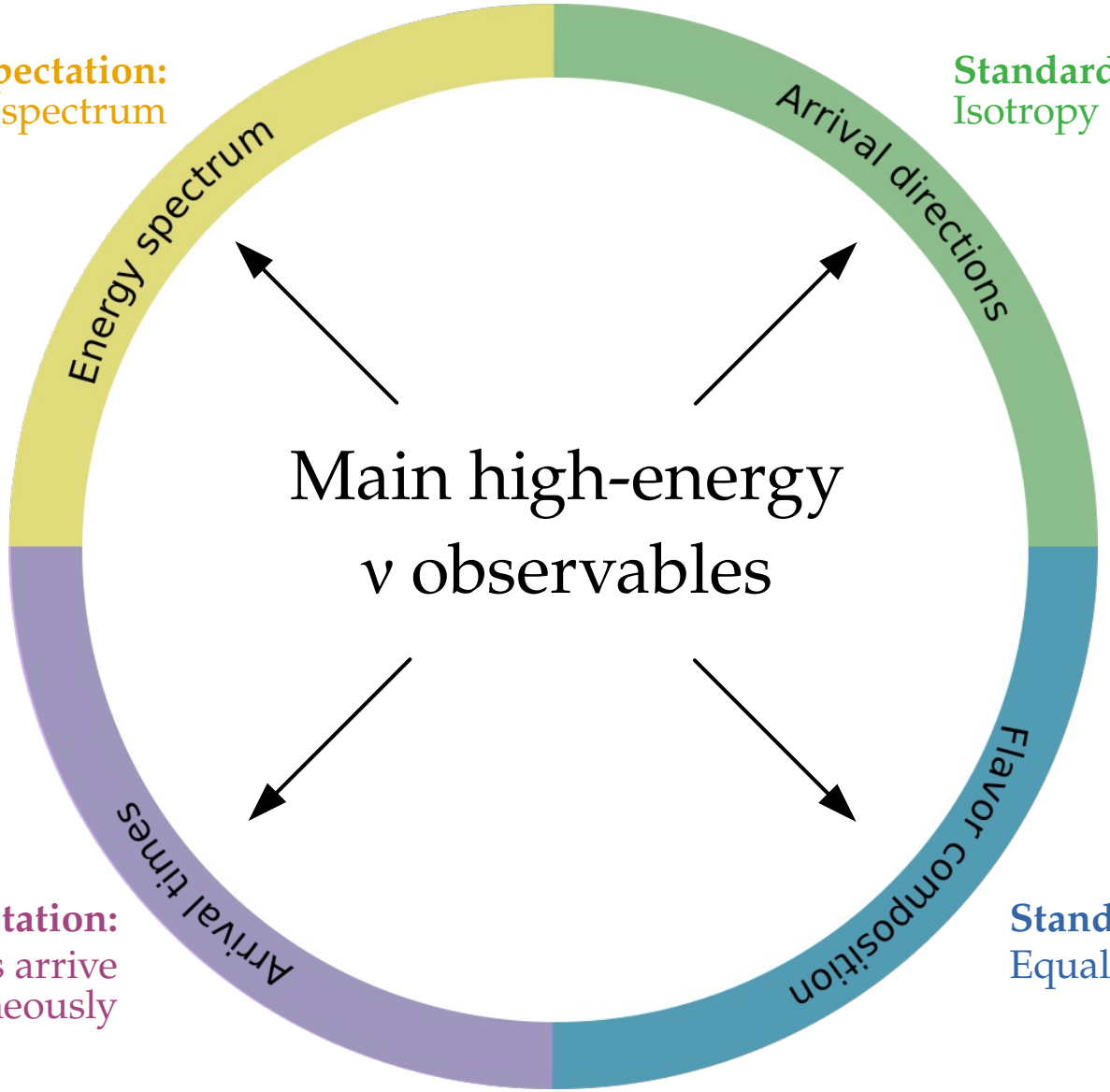


Angular resolution: < 1°


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

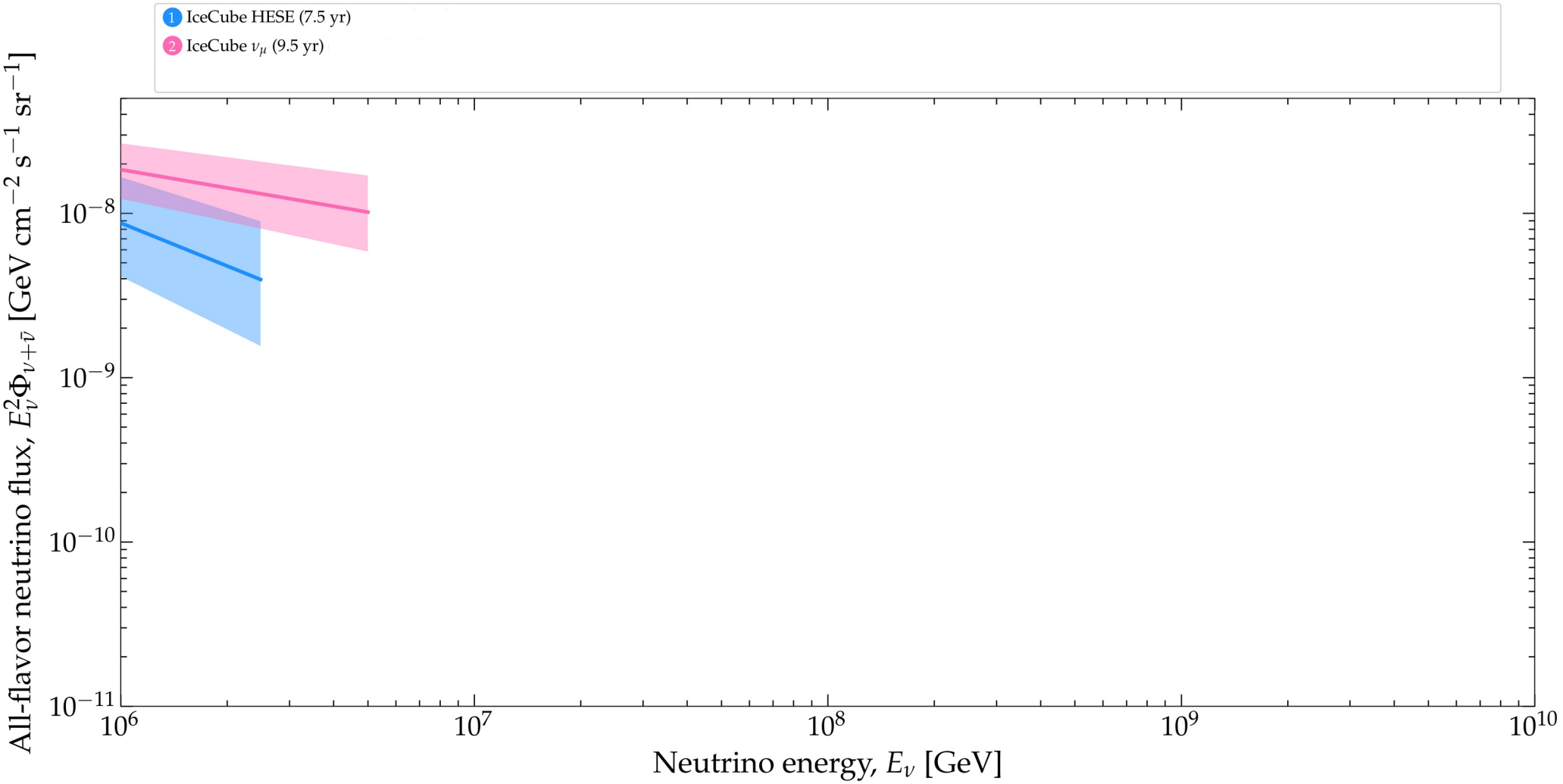
Standard expectation:
Power-law energy spectrum

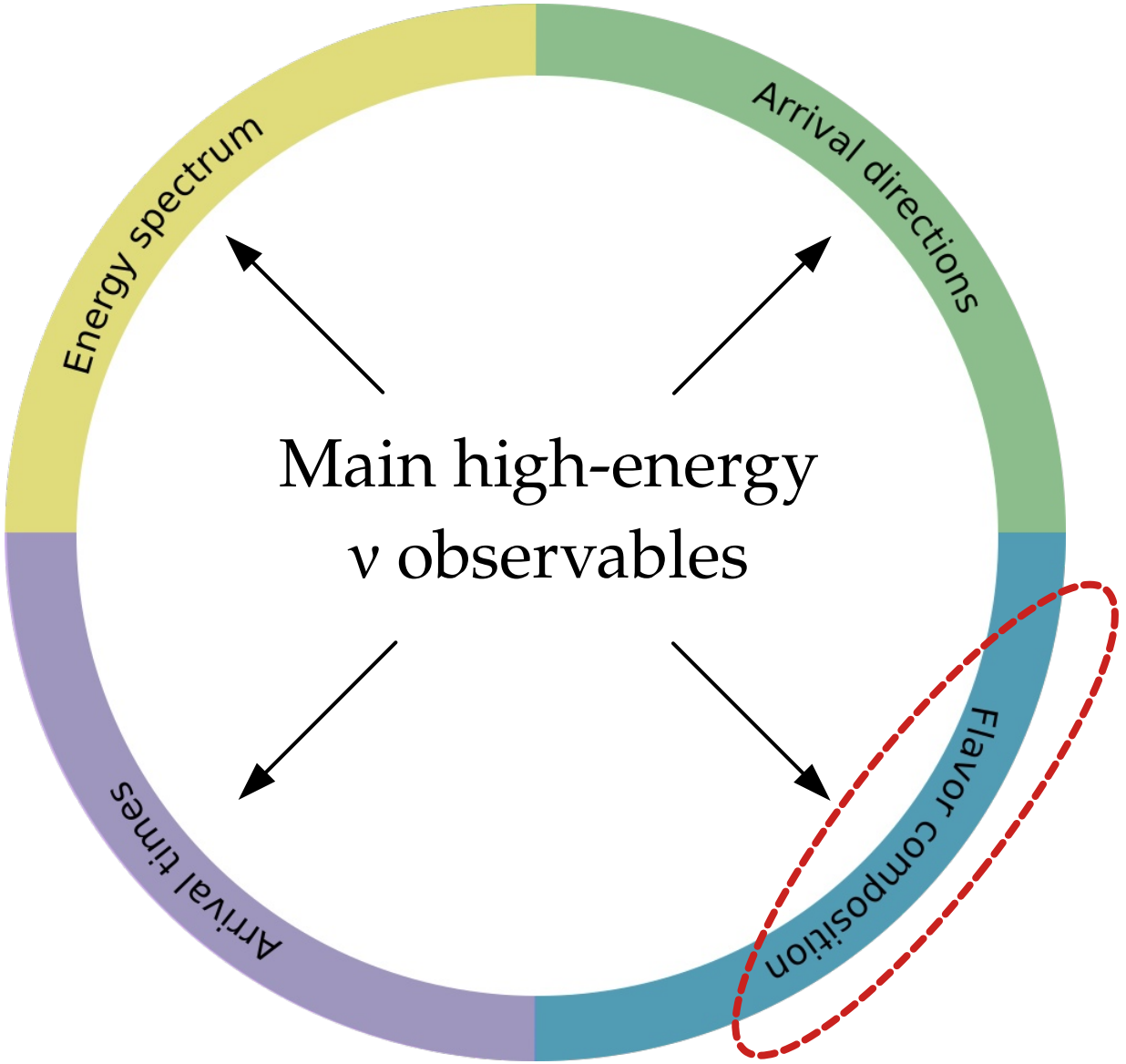
Standard expectation:
Isotropy (for diffuse flux)



Standard expectation:
ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ


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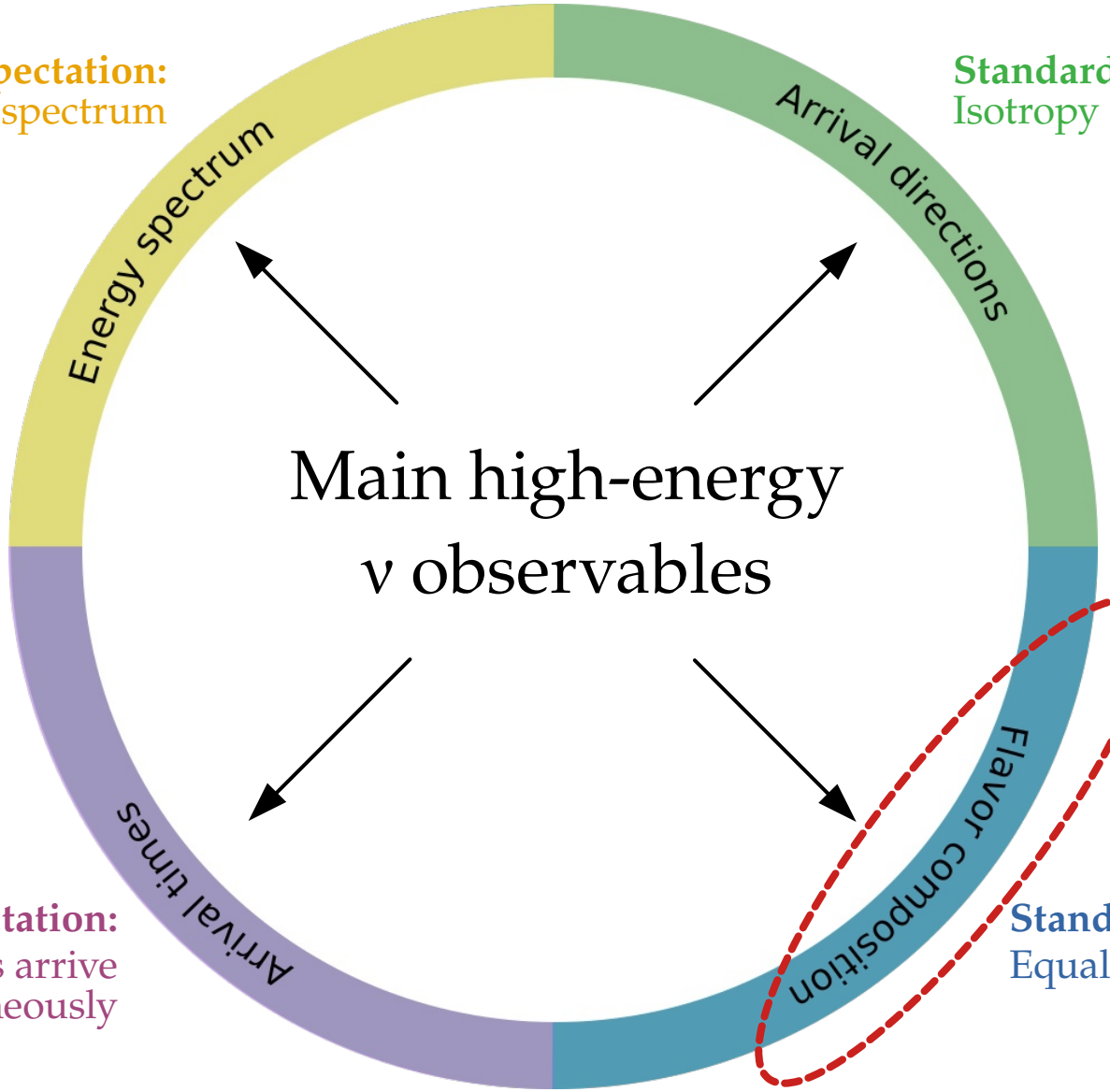

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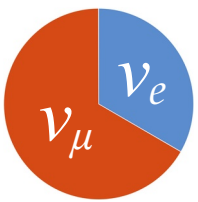
Astrophysical sources

Earth

Up to a few Gpc

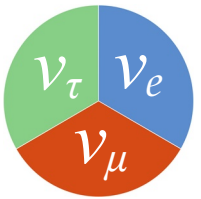
E.g.,



Oscillations change the number

of ν of each flavor, N_e, N_μ, N_τ

E.g.,



Different production mechanisms yield different flavor ratios:

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

Flavor ratios at Earth (α = e, μ, τ):

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

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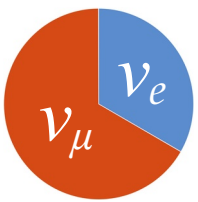

Oscillations change the number

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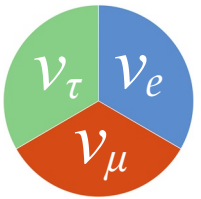

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Flavor ratios at Earth ($\alpha = e, \mu, \tau$):

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Standard oscillations
or
new physics

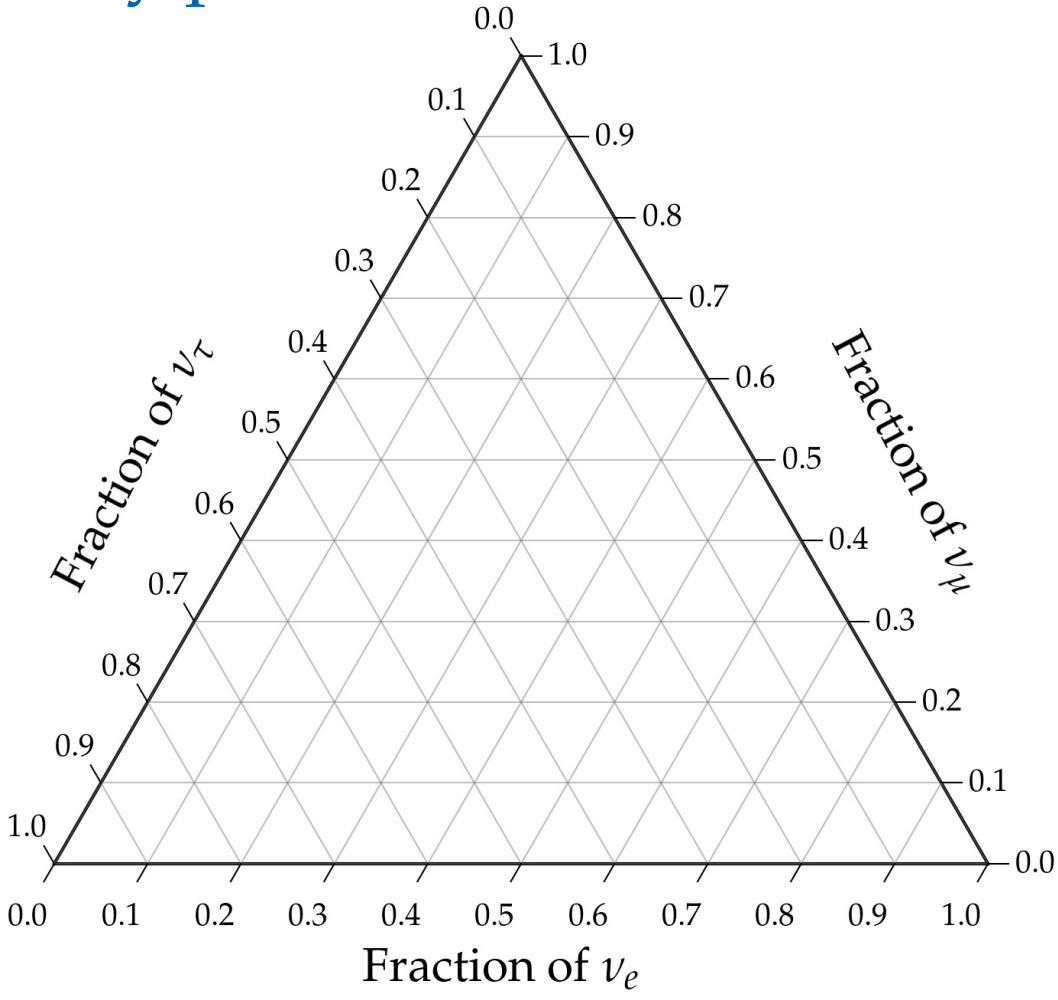
Quick aside: how to read a ternary plot

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

How to read it:

Follow the tilt of the tick marks

Always in this order: (f_e, f_μ, f_τ)



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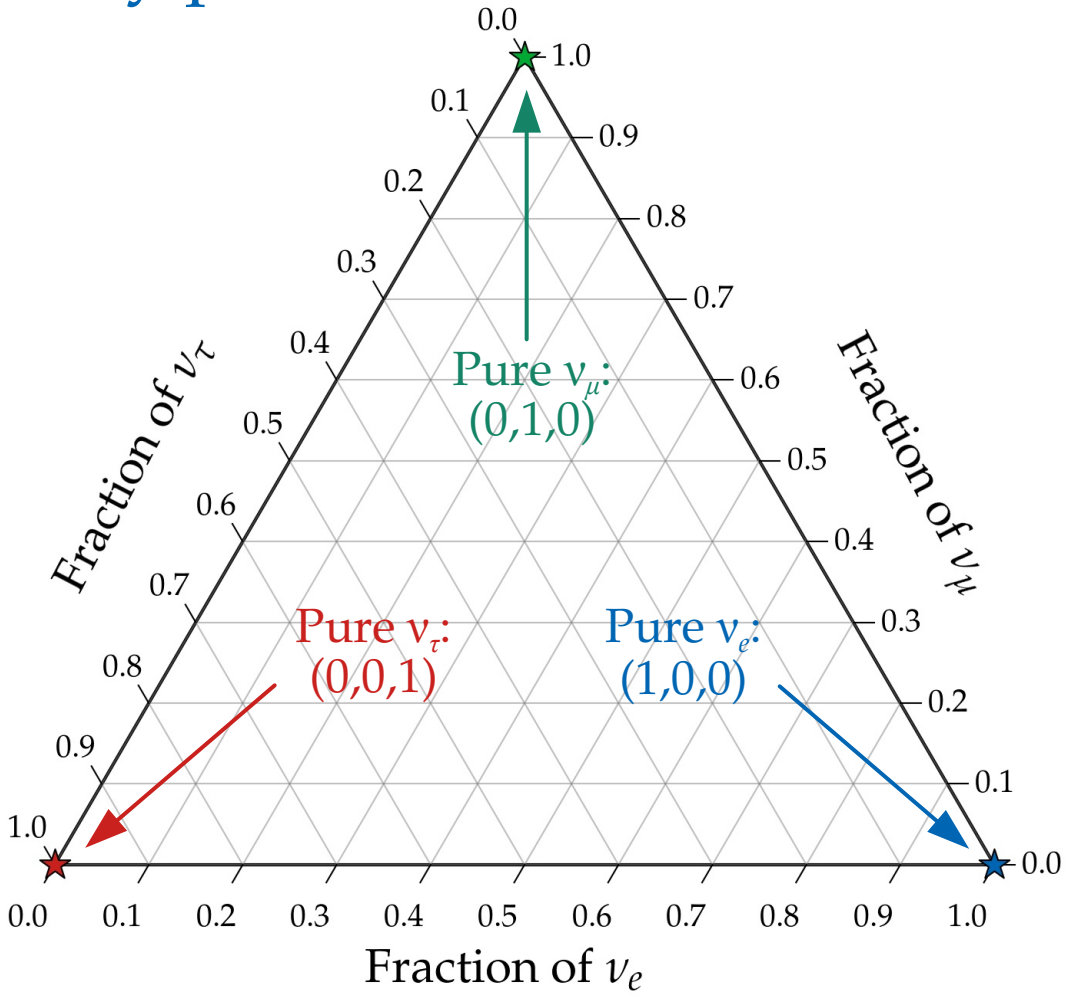

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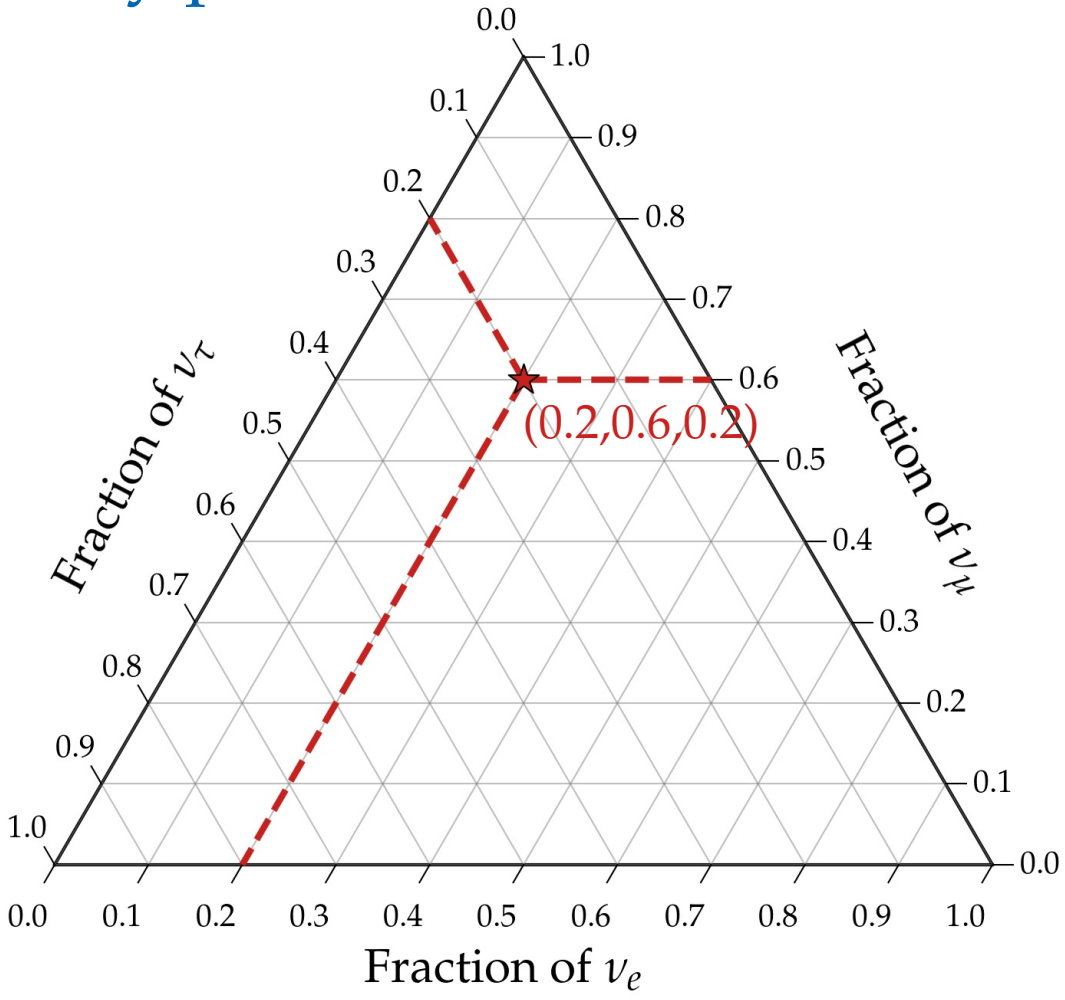

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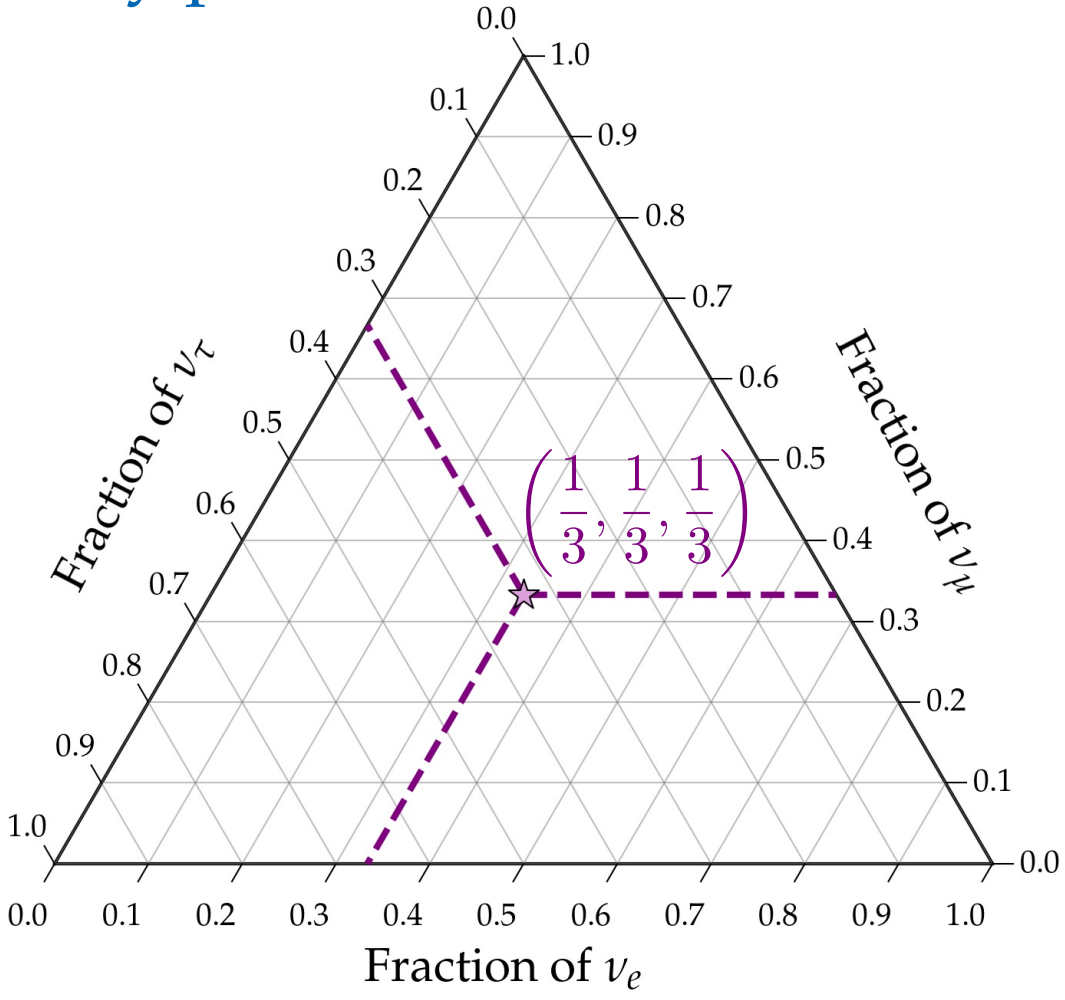
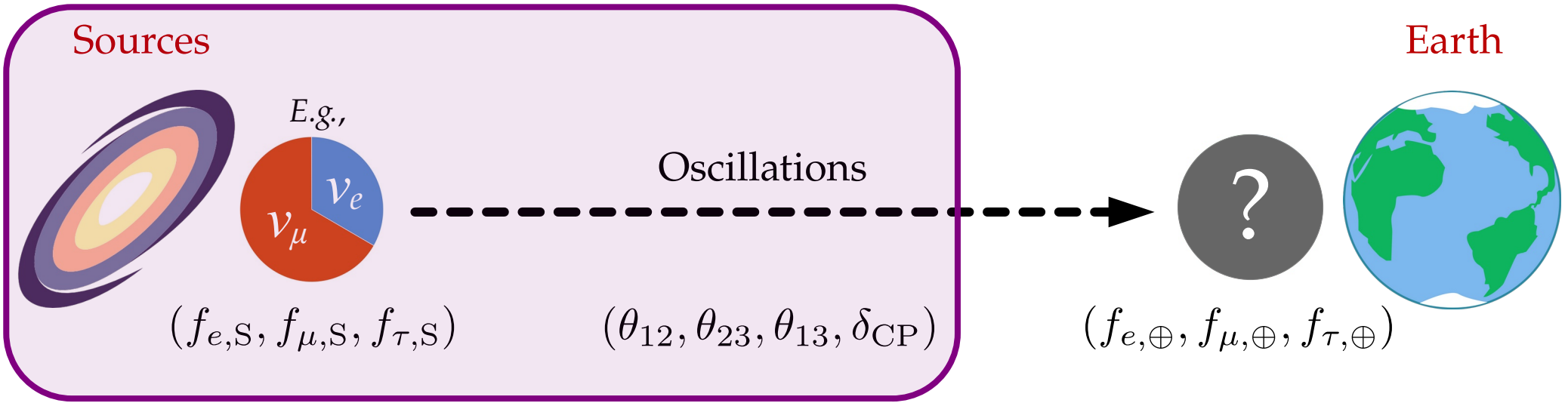


From sources to Earth: we learn what to expect when measuring $f_{\alpha,\oplus}$



One likely TeV–PeV ν production scenario:

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

Full π decay chain

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

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

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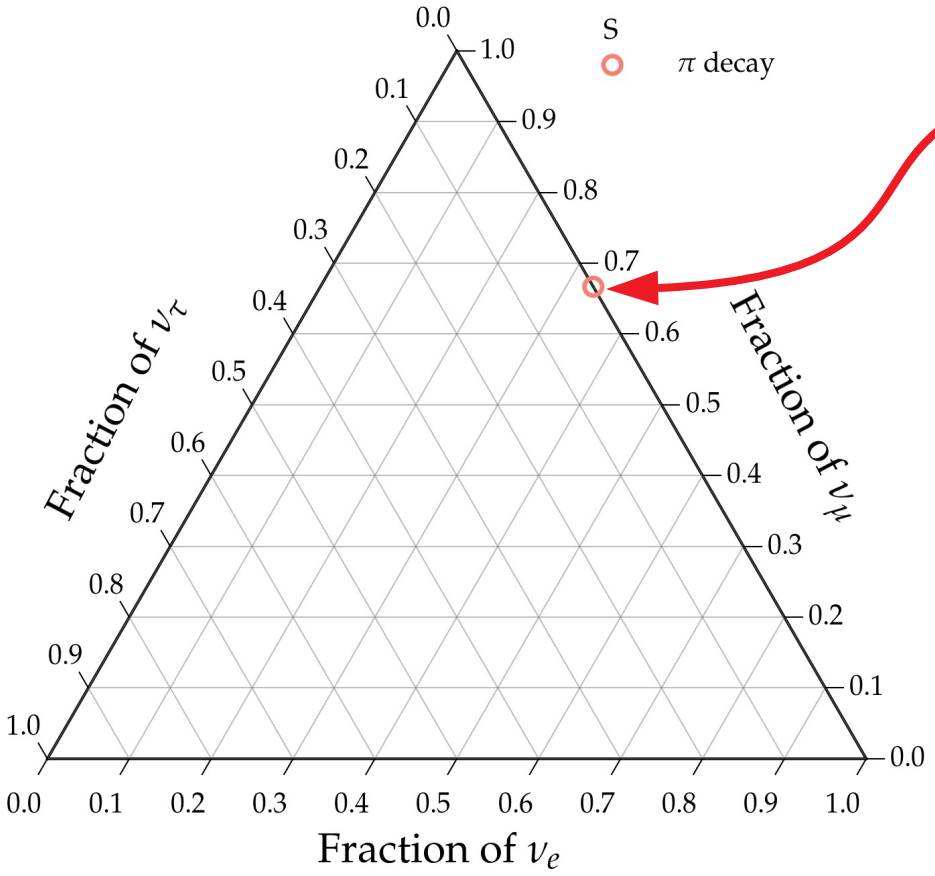

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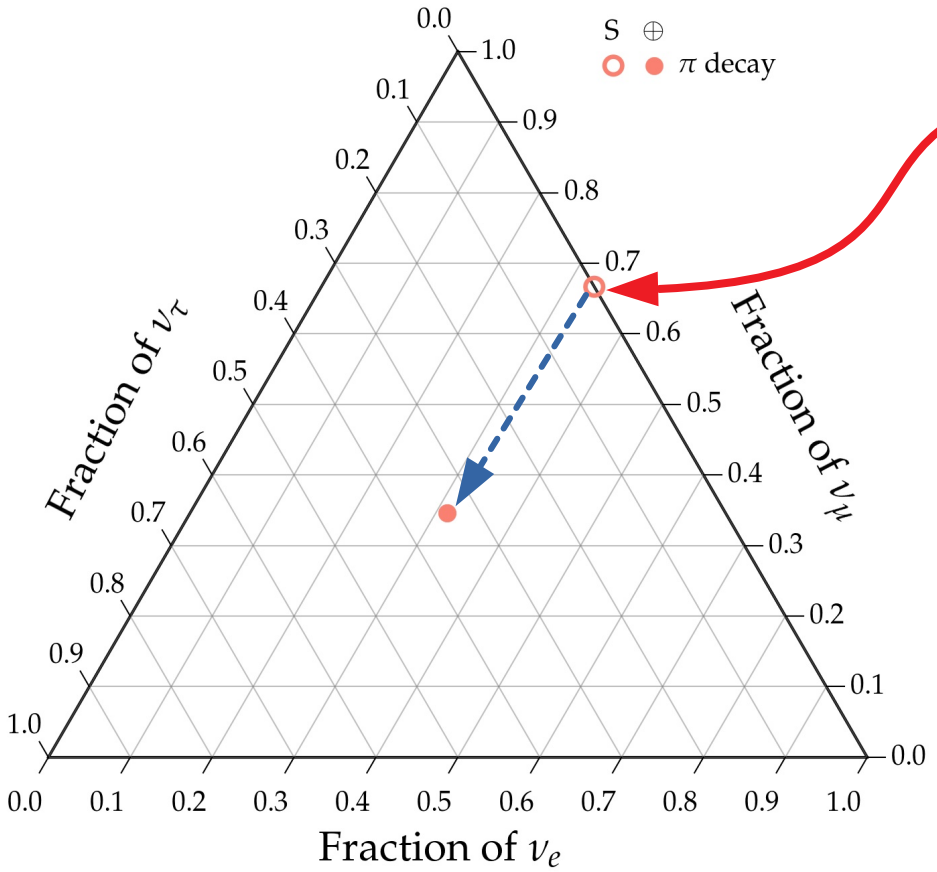

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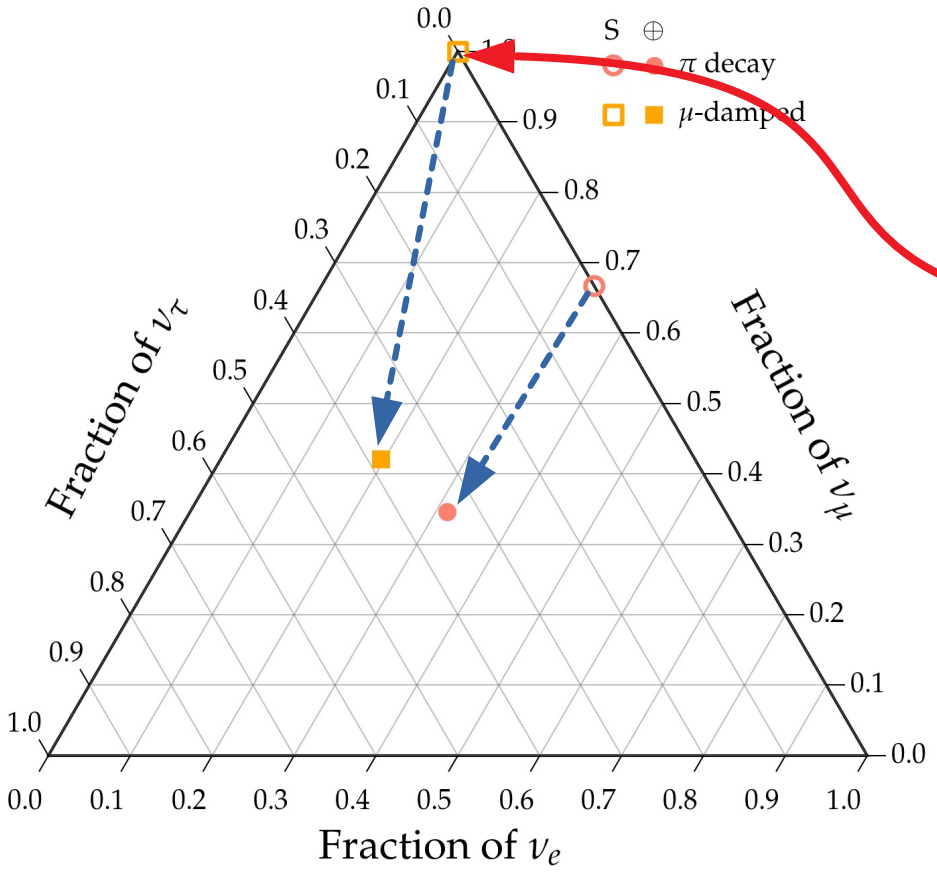

Full π decay chain

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

Muon damped

$(0:1:0)_S$

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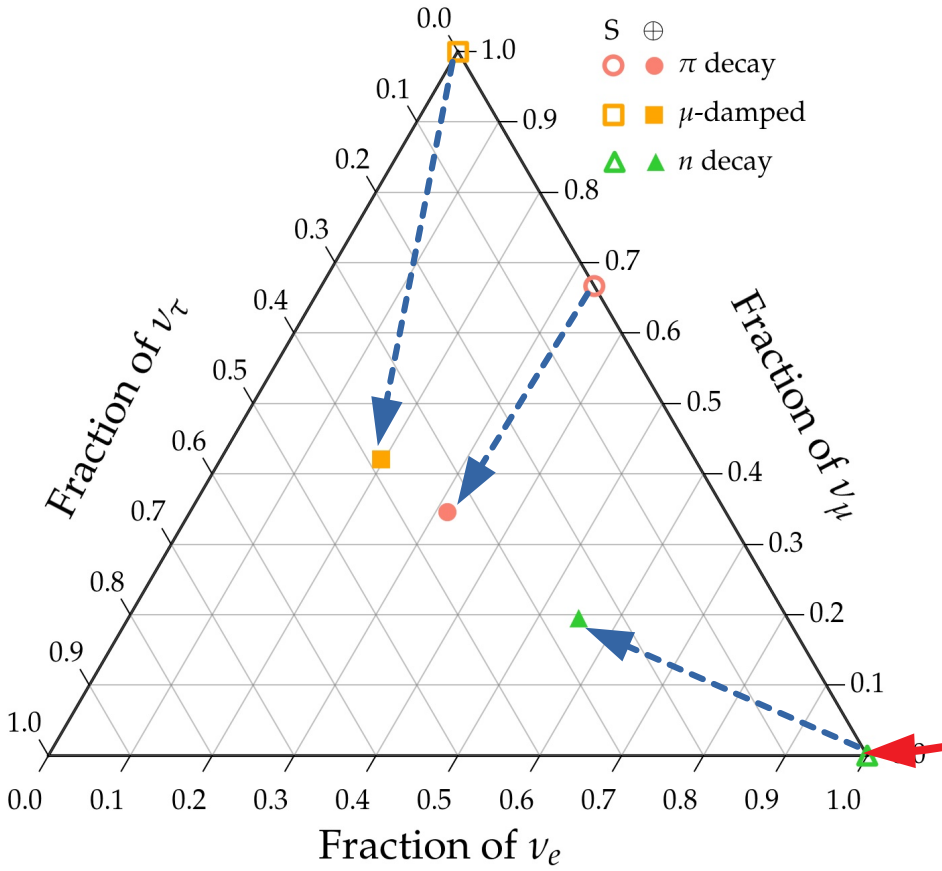


Full π decay chain

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

Muon damped

$(0:1:0)_S$

Neutron decay

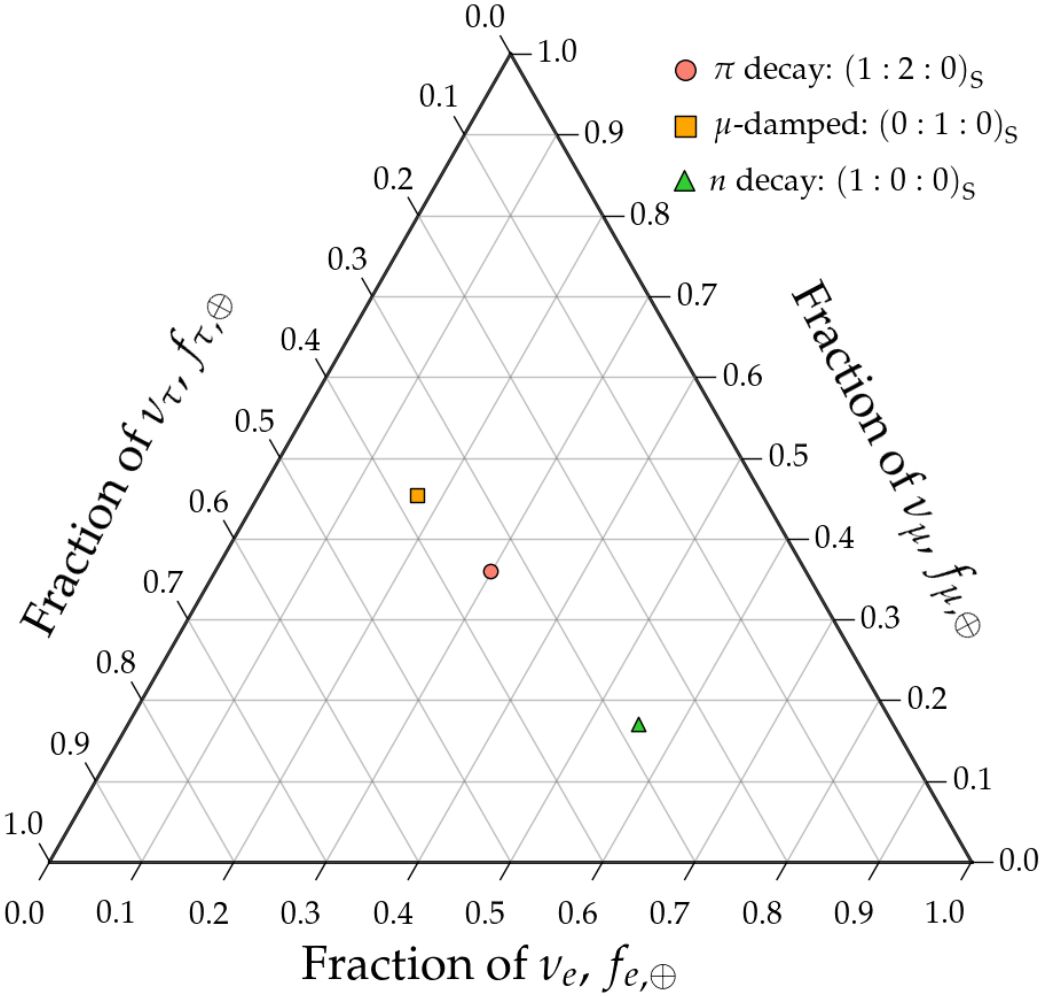
$(1:0:0)_S$

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

Measuring flavor composition: 2015–2020

IceCube Collab., *EPJC* 2022
IceCube Collab., *PRD* 2019
IceCube Collab., *ApJ* 2015

Measuring flavor composition: 2015–2020



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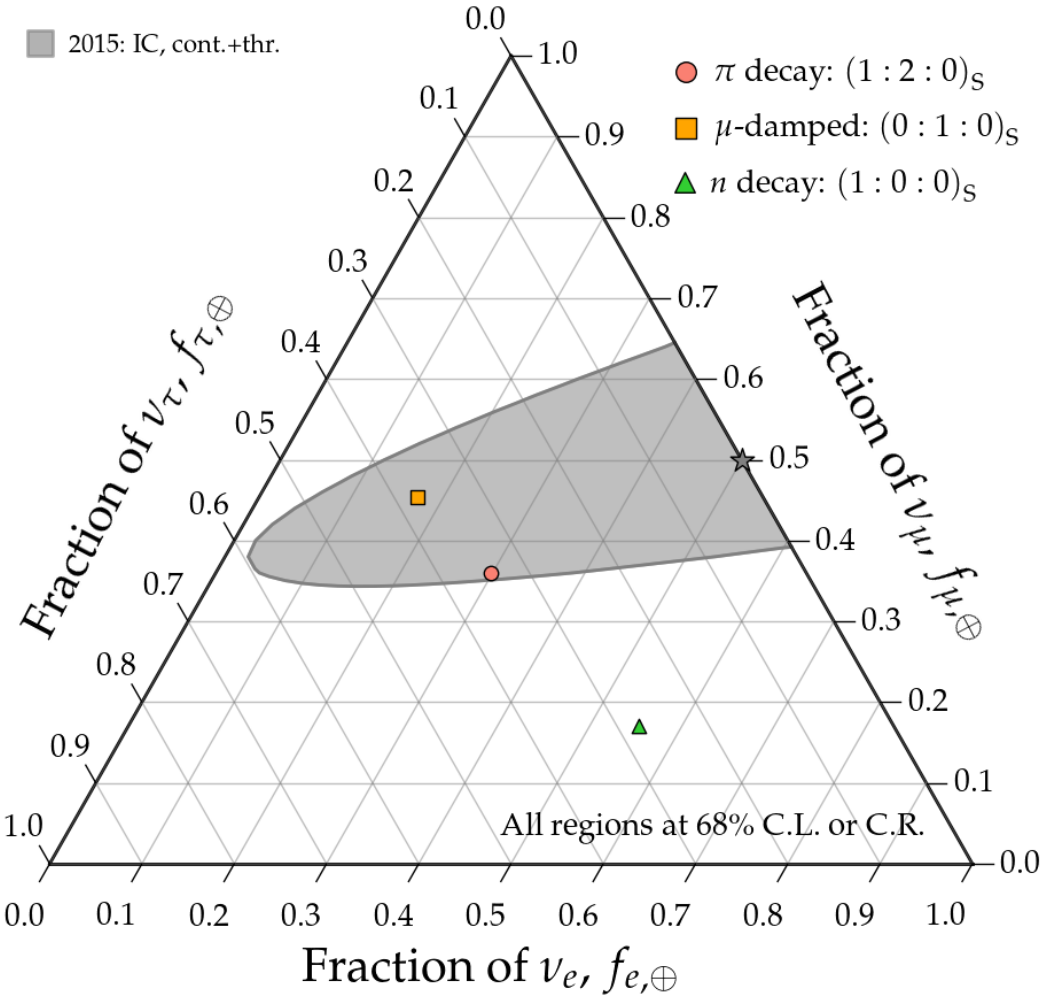

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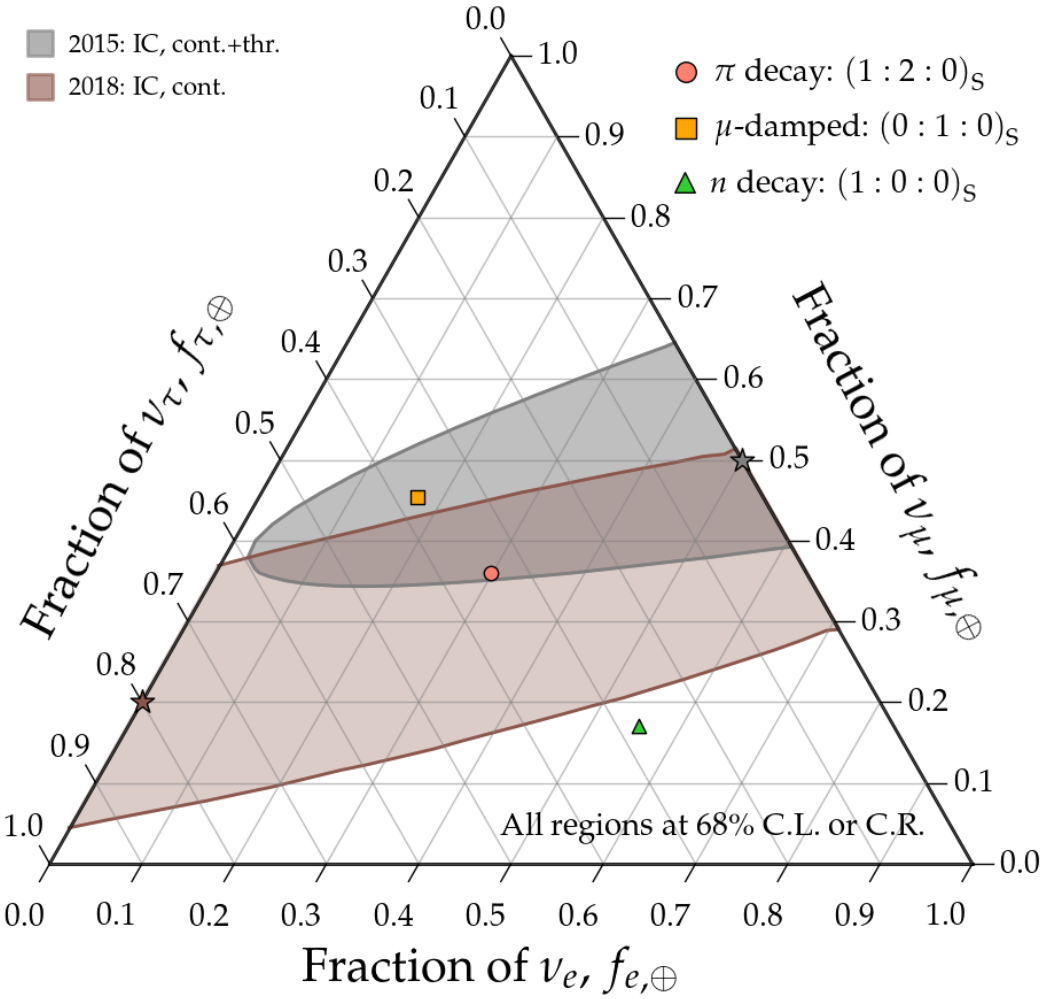

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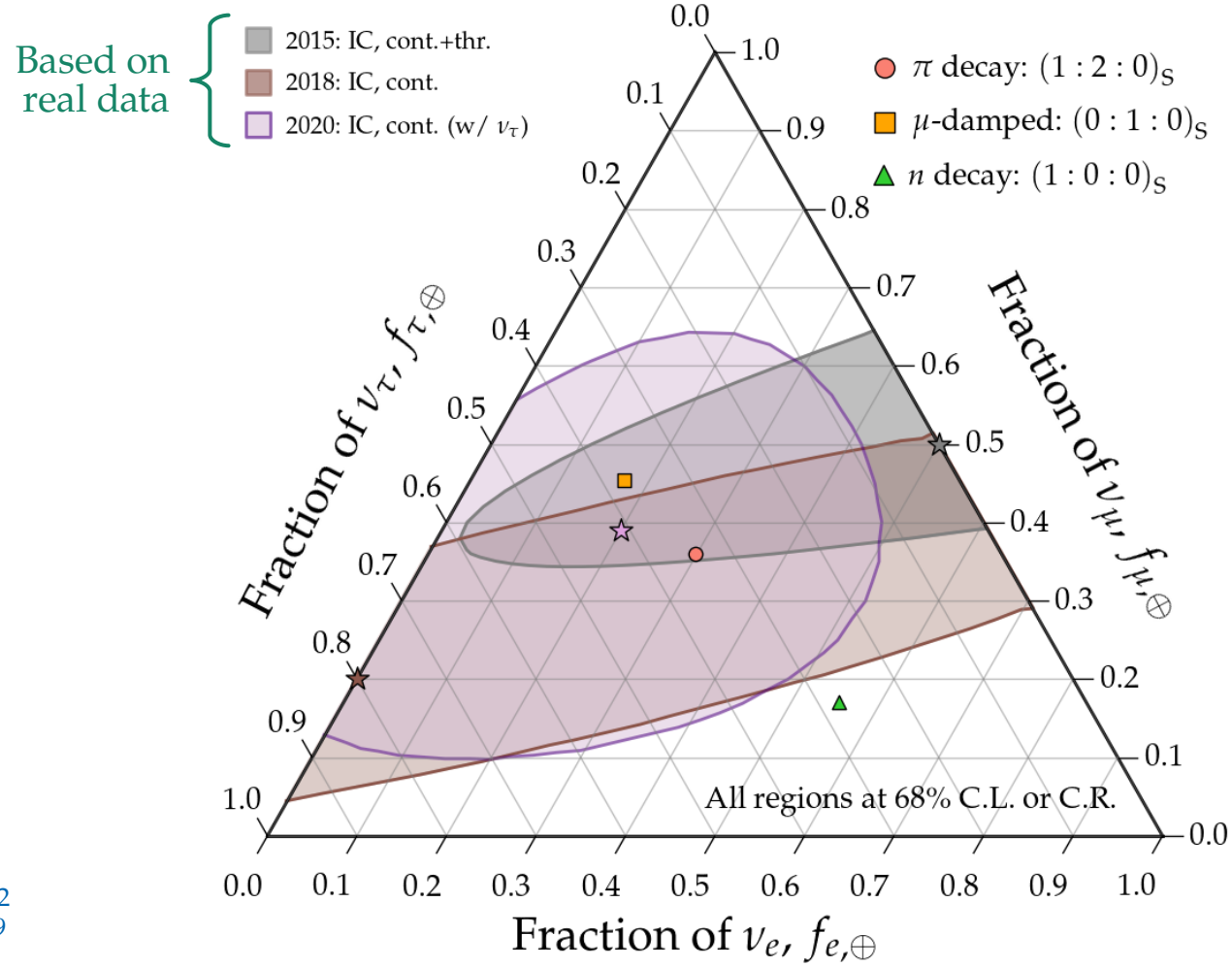

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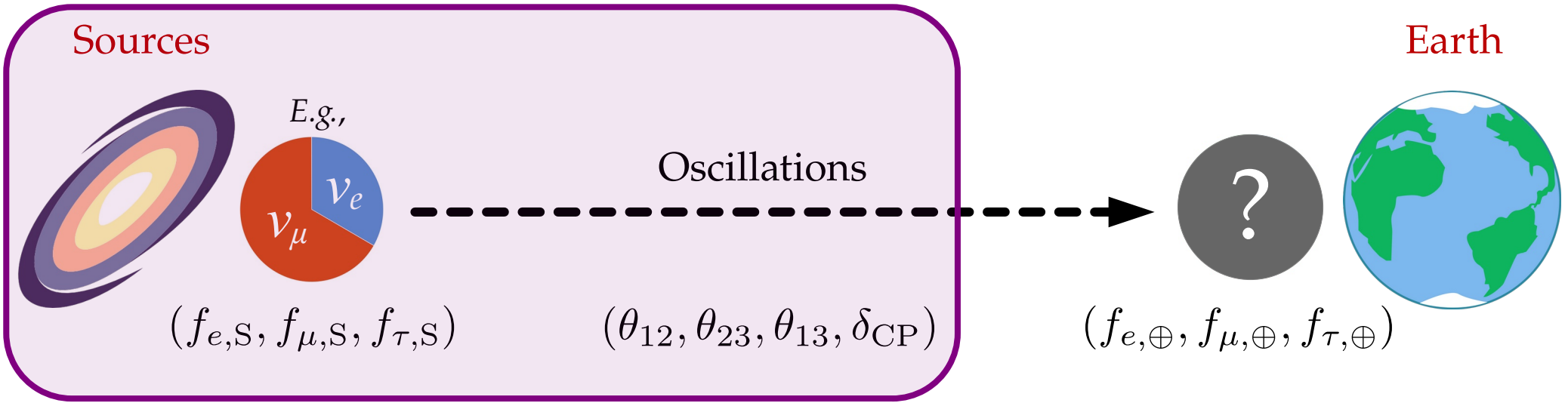
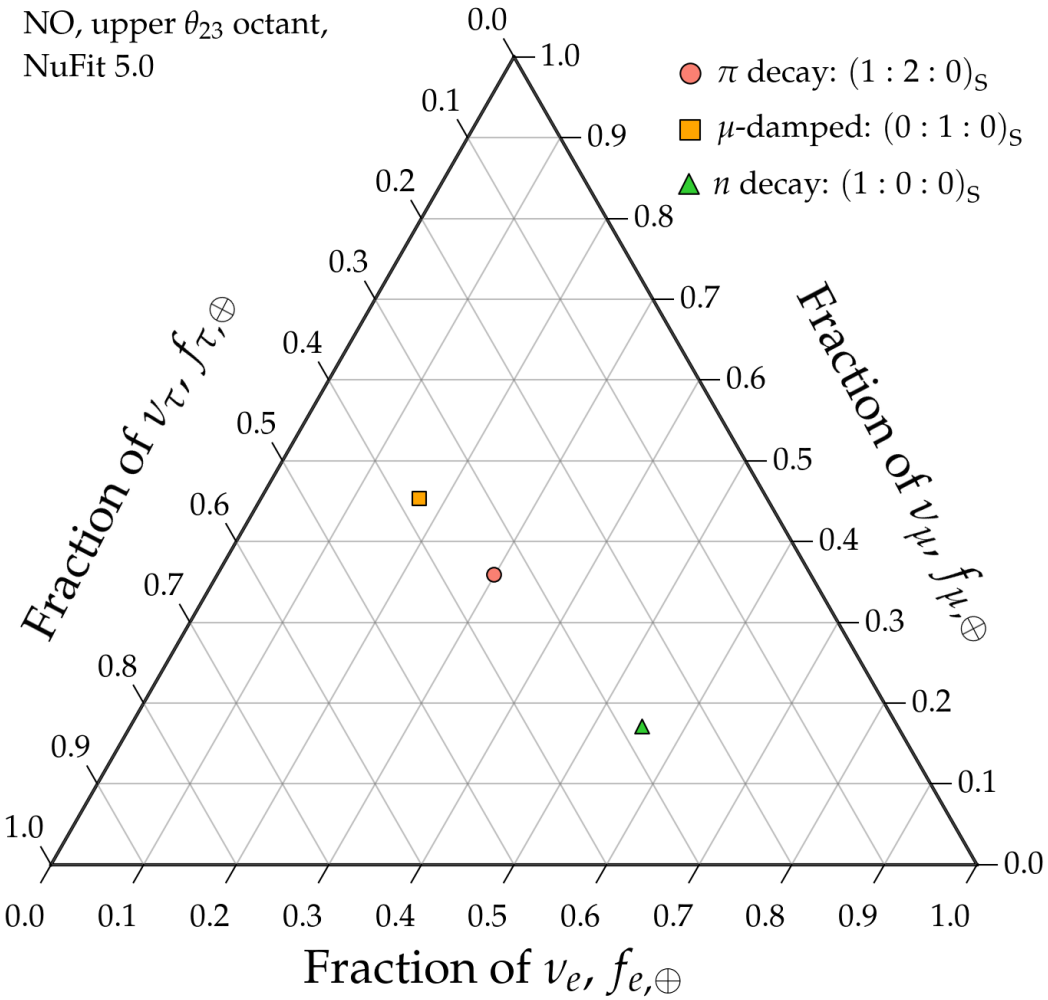
IceCube Collab., *ApJ* 2015

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



Known from oscillation experiments, to different levels of precision

Theoretically palatable regions: today



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

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

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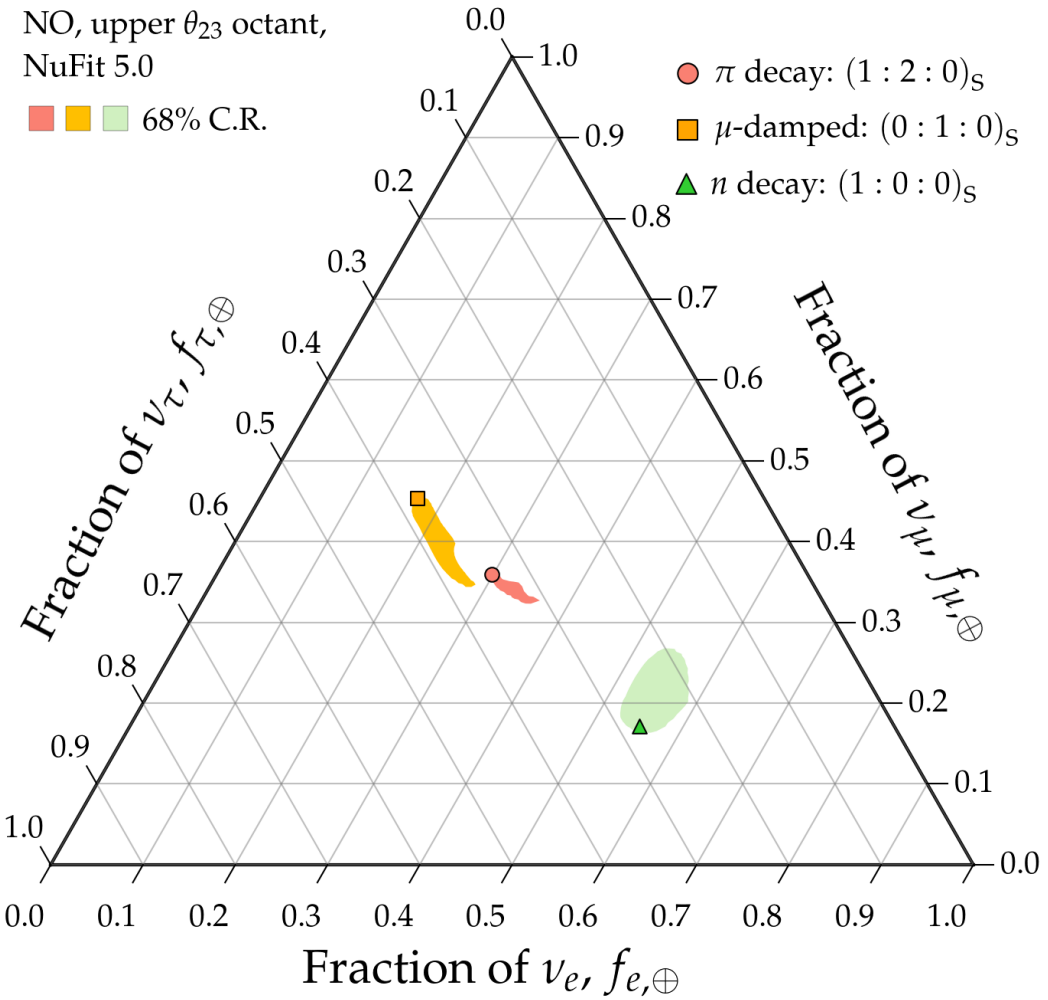

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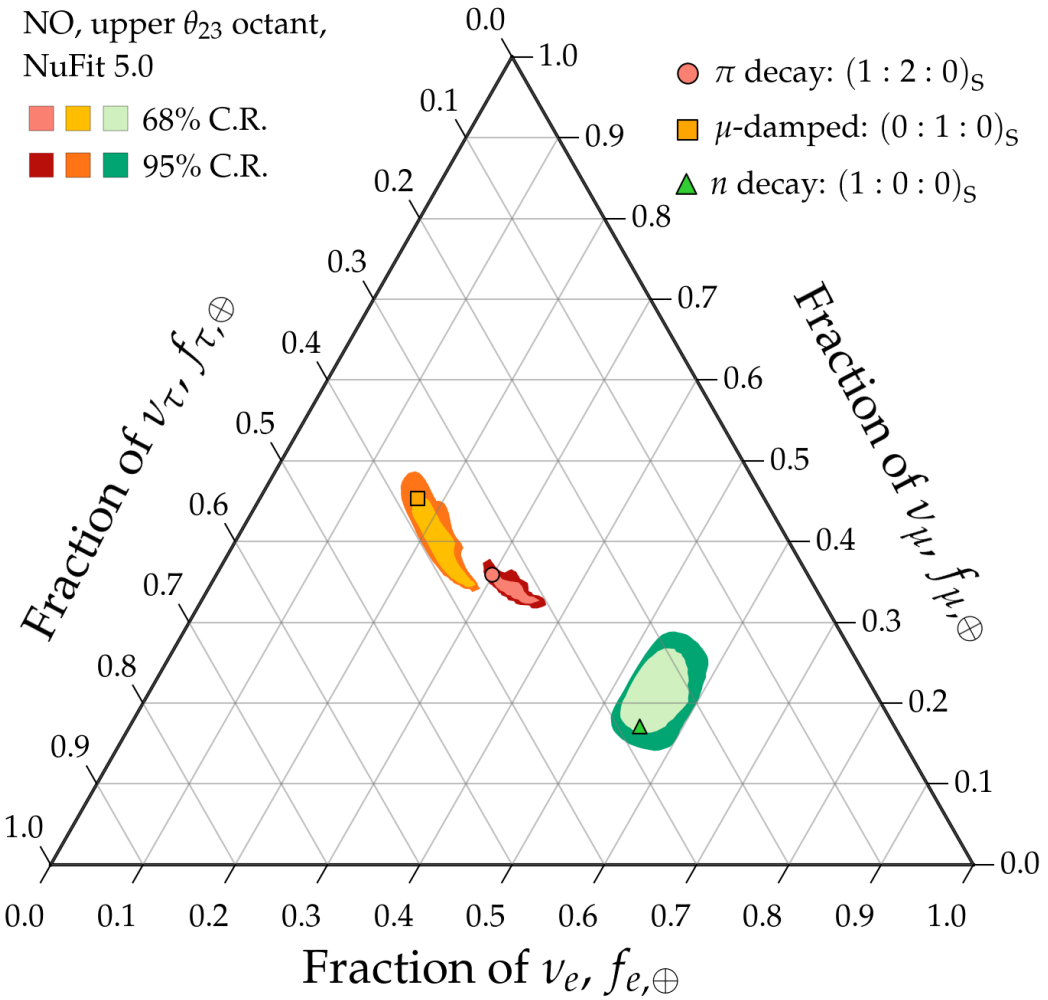

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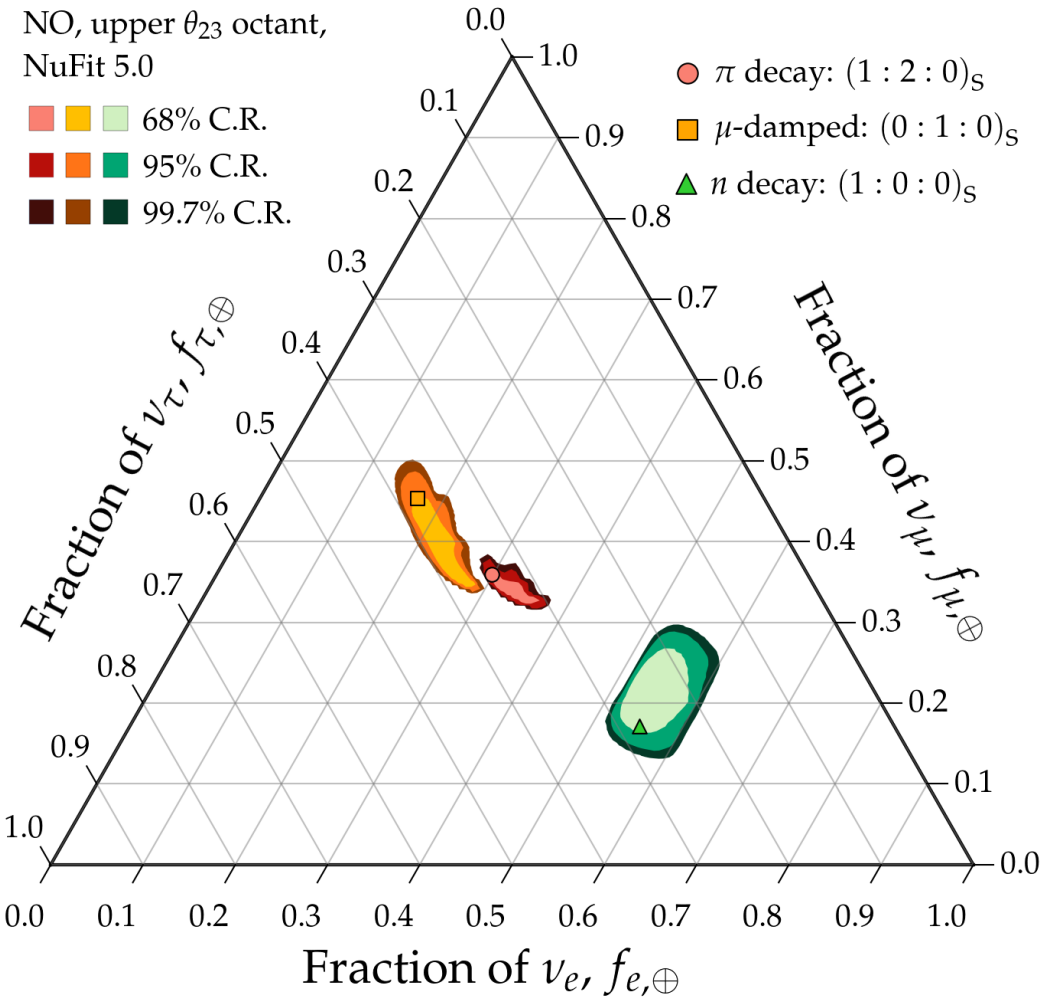

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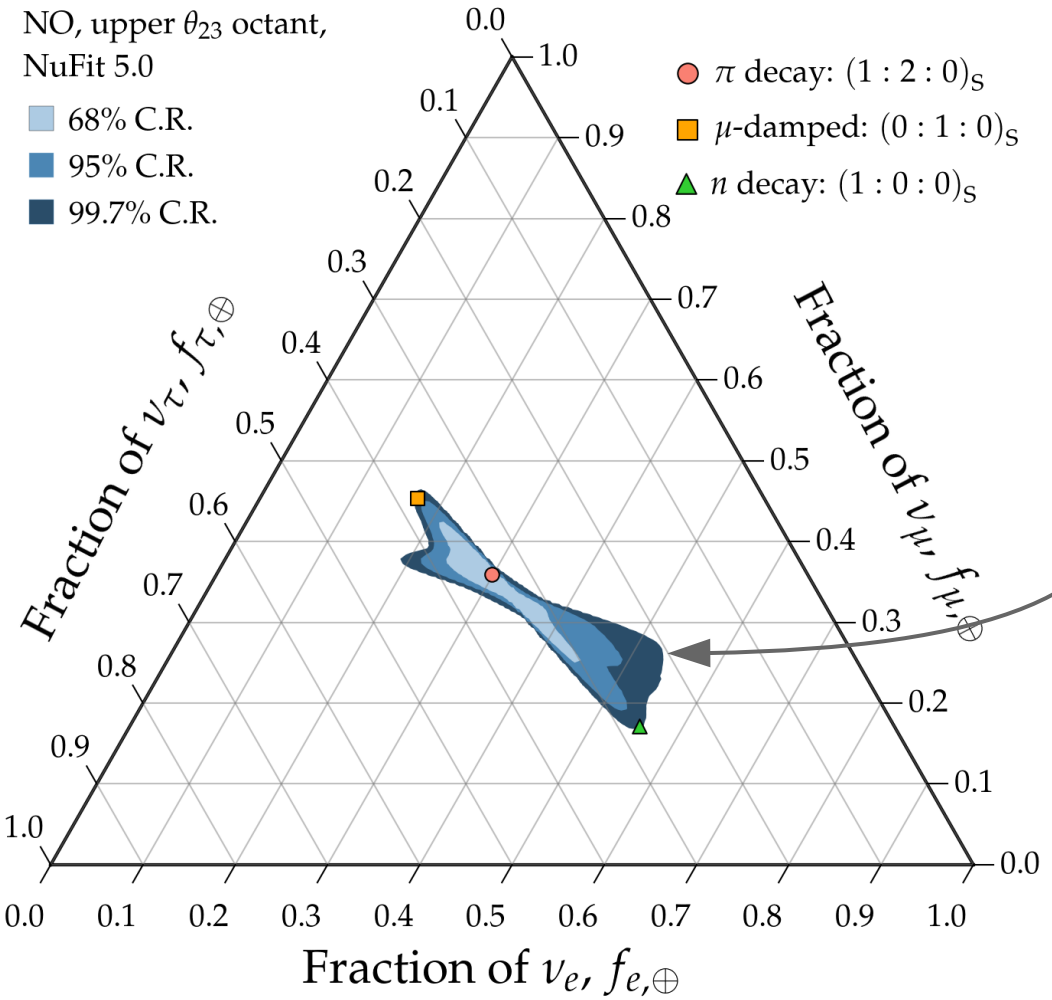

Varying over all possible flavor ratios at the source

Note:
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Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
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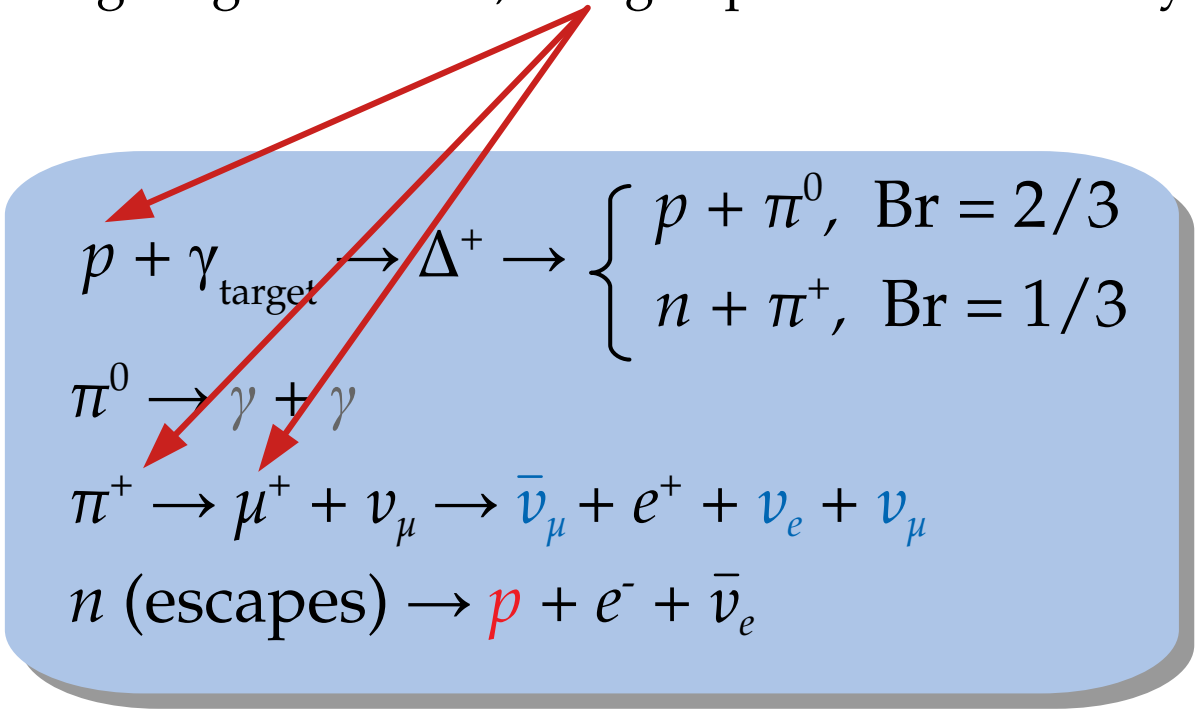
Using high-energy neutrinos as magnetometers

If sources have strong magnetic fields, charged particles cool via synchrotron:



MB, Tamborra, *PRD* 2020
Winter, *PRD* 2013

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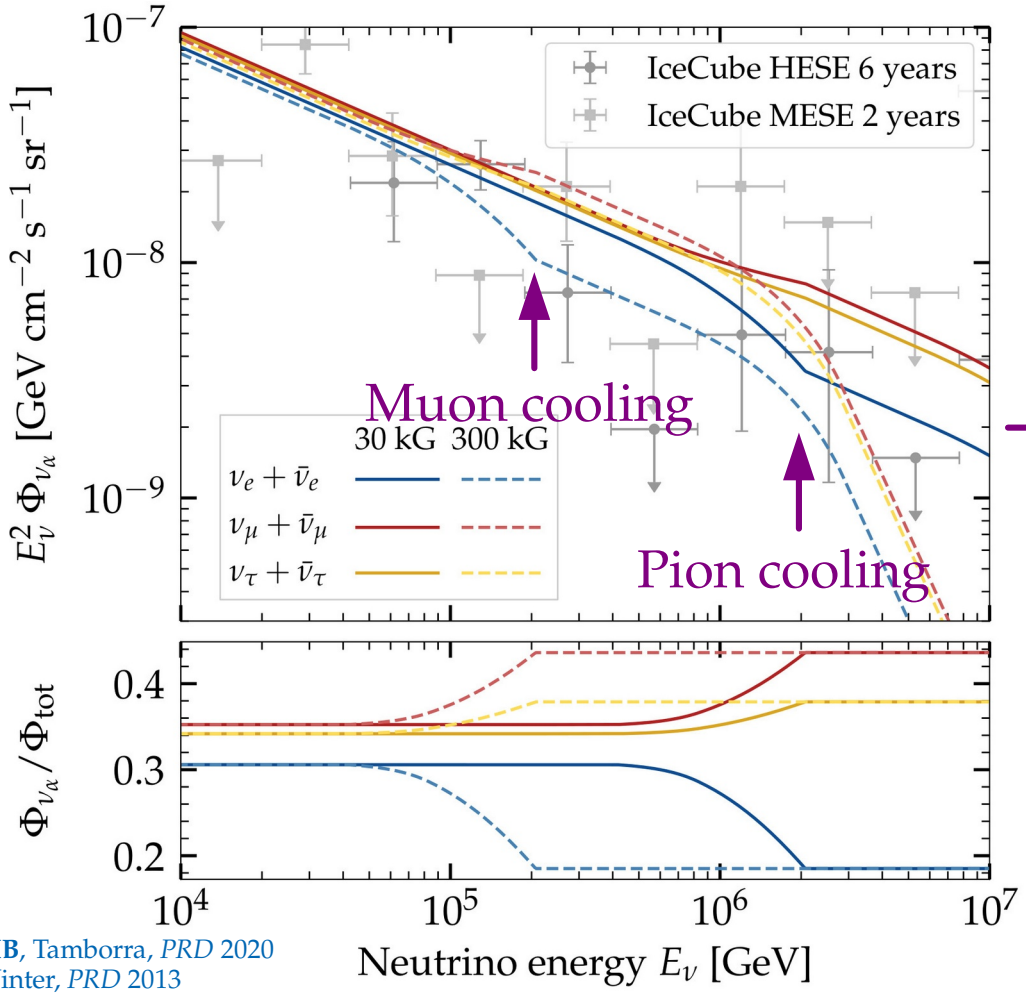

→ Proton cooling

MB, Tamborra, *PRD* 2020
Winter, *PRD* 2013

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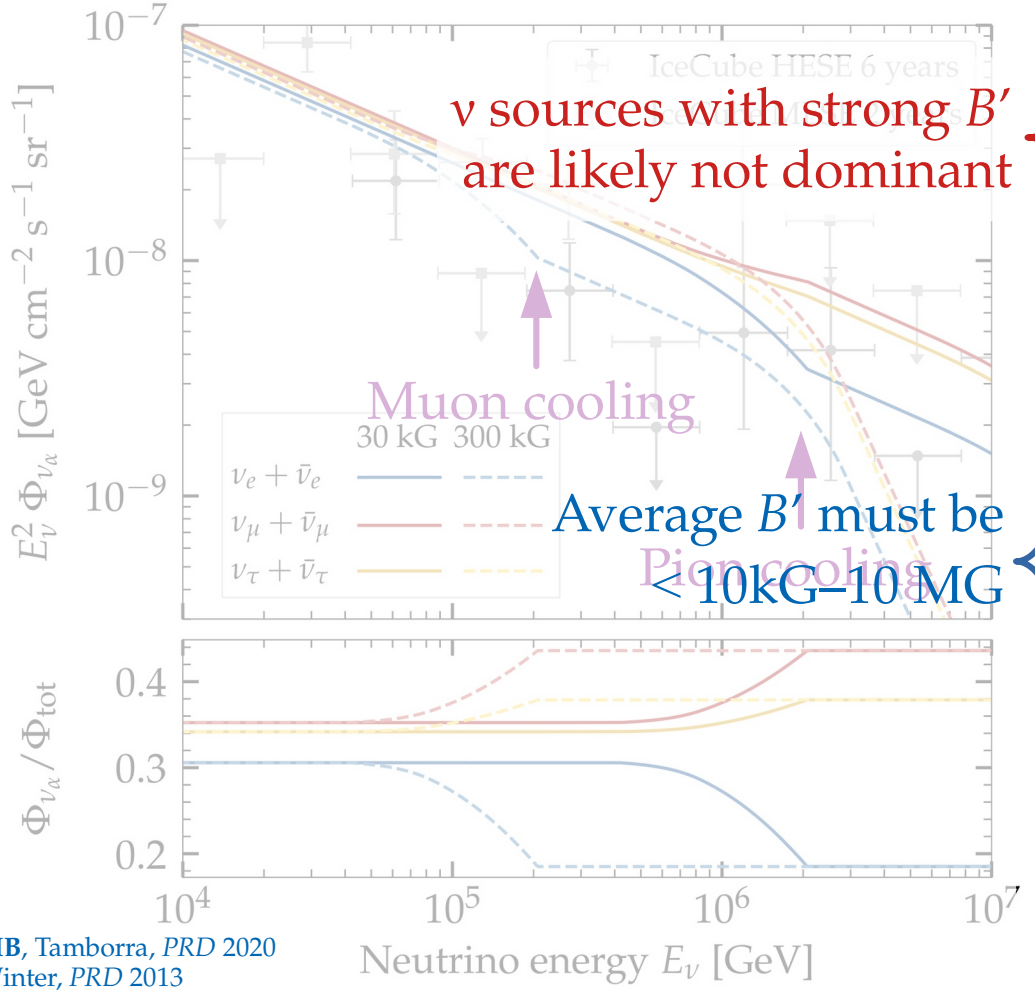

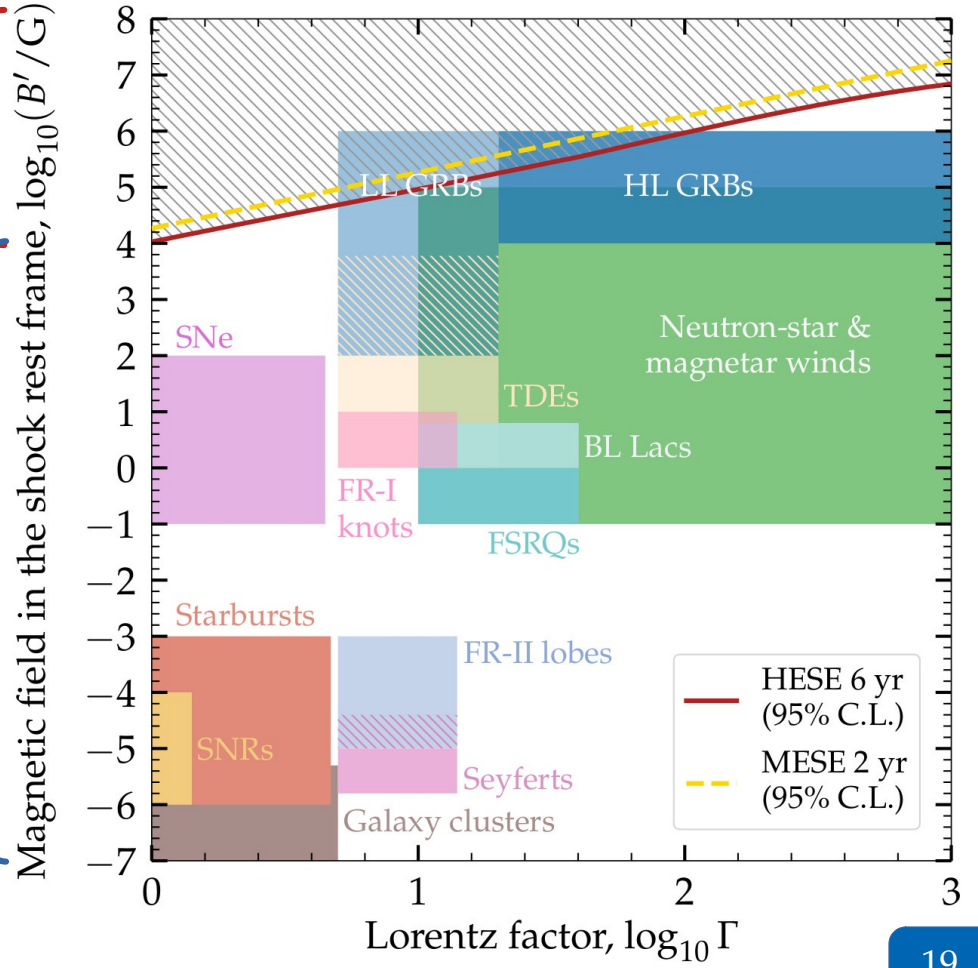

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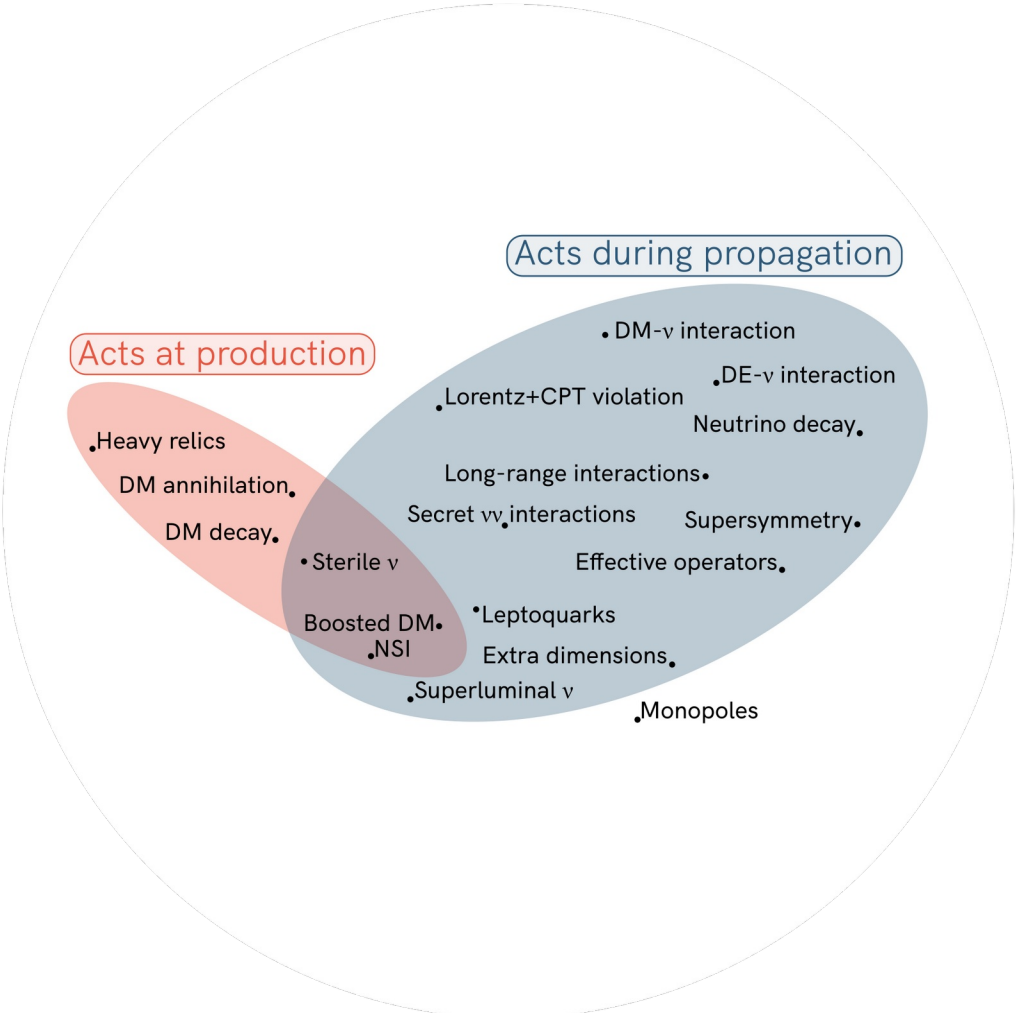

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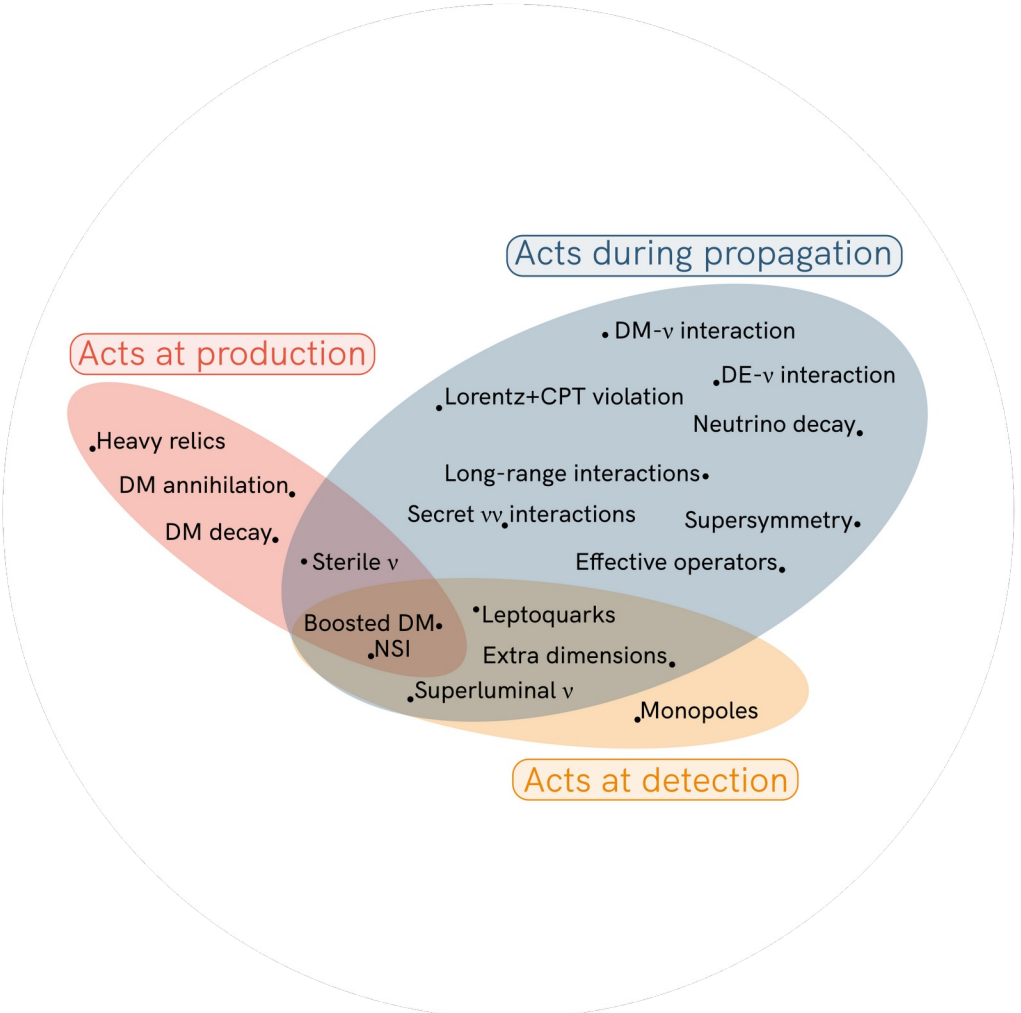
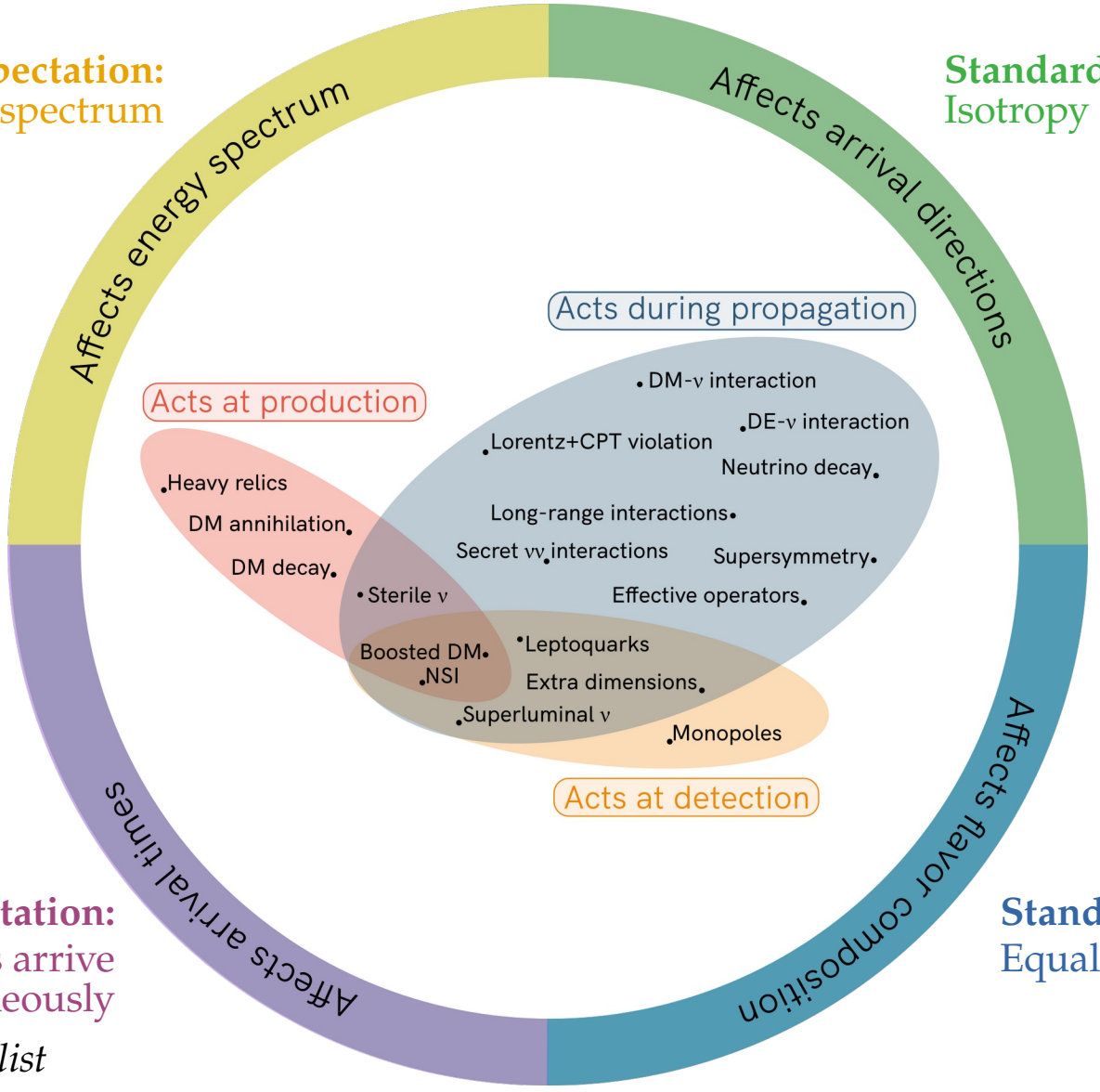


Note: Not an exhaustive list

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



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ν and γ from transients arrive simultaneously

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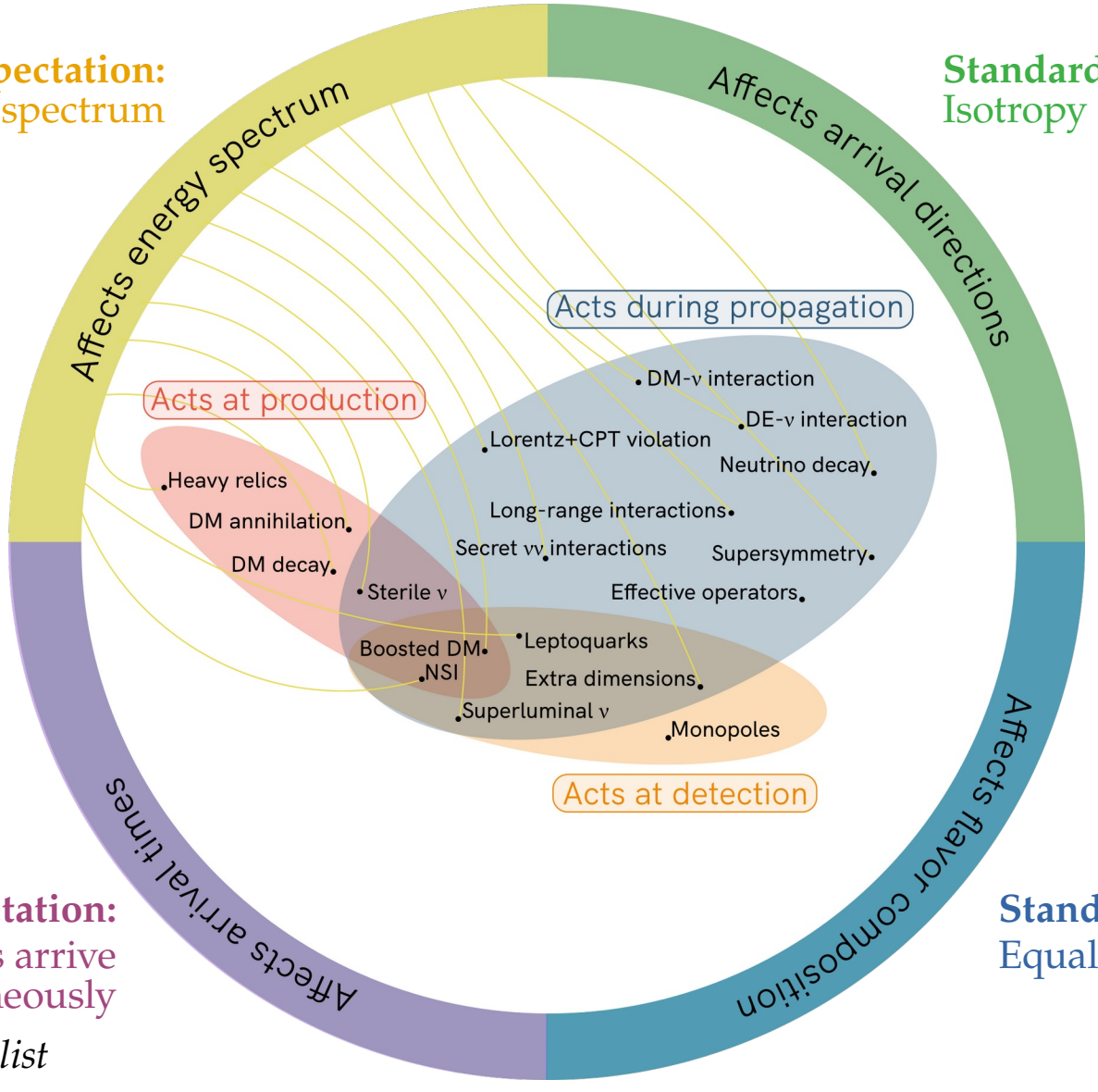

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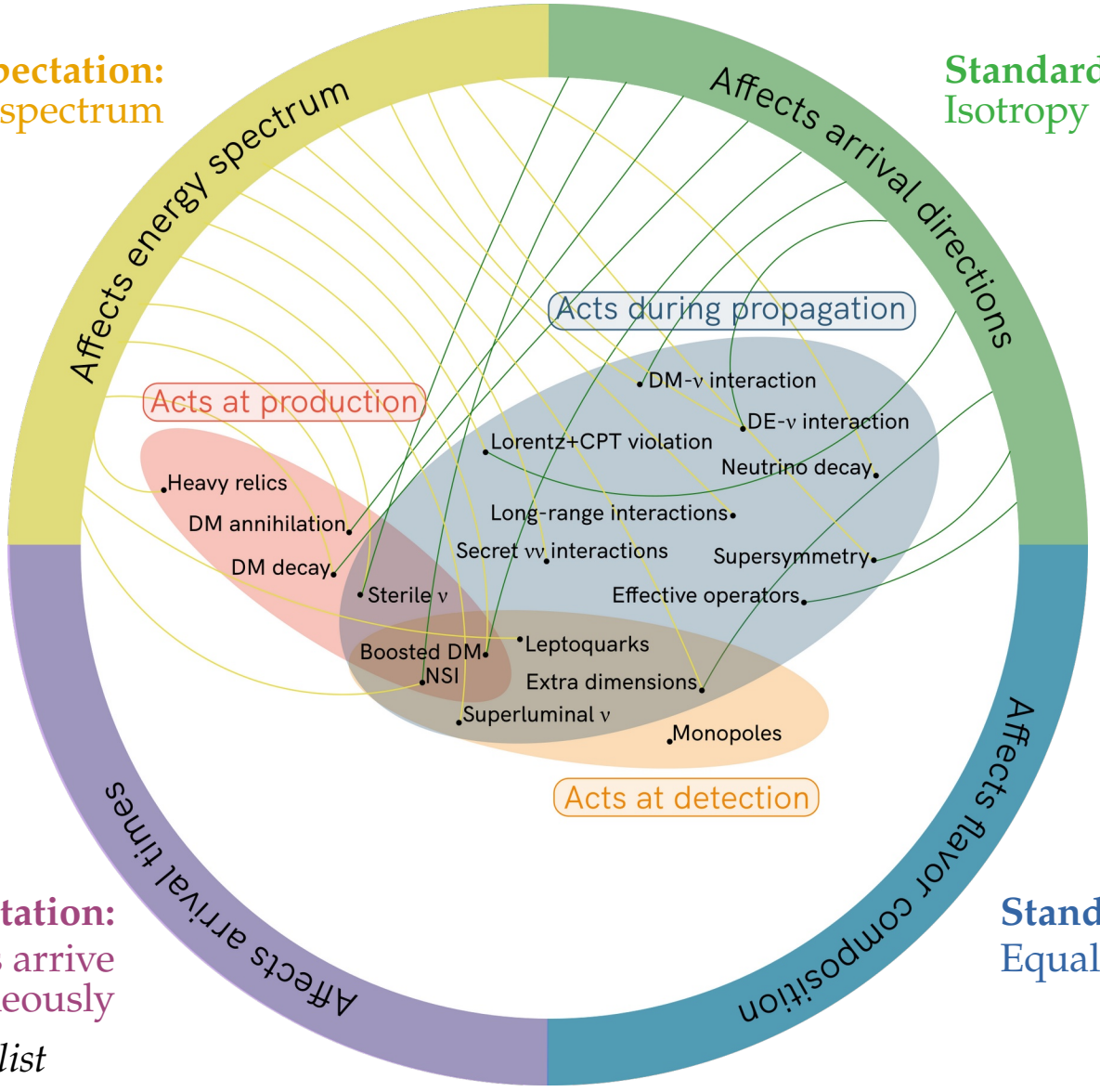

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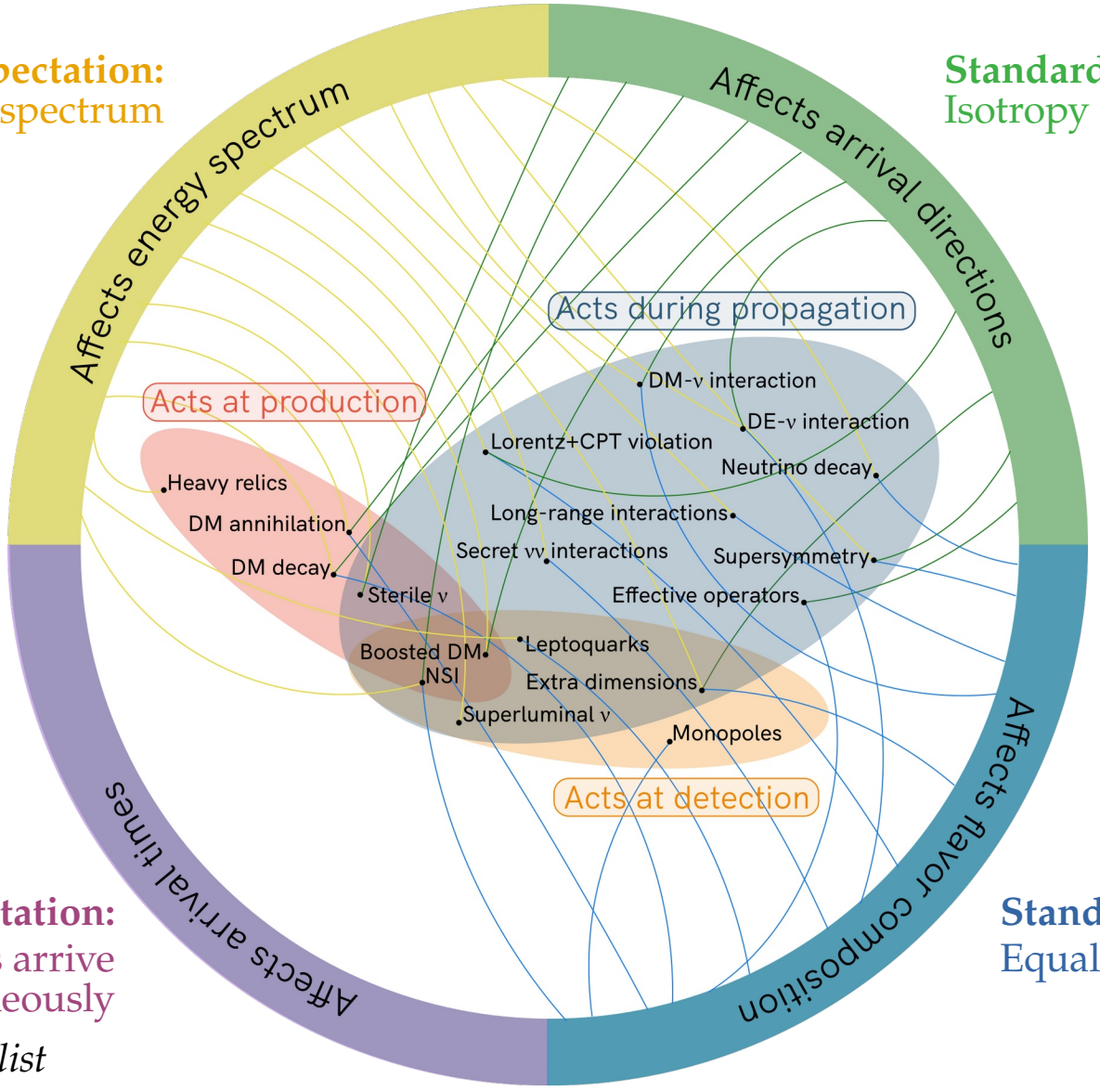

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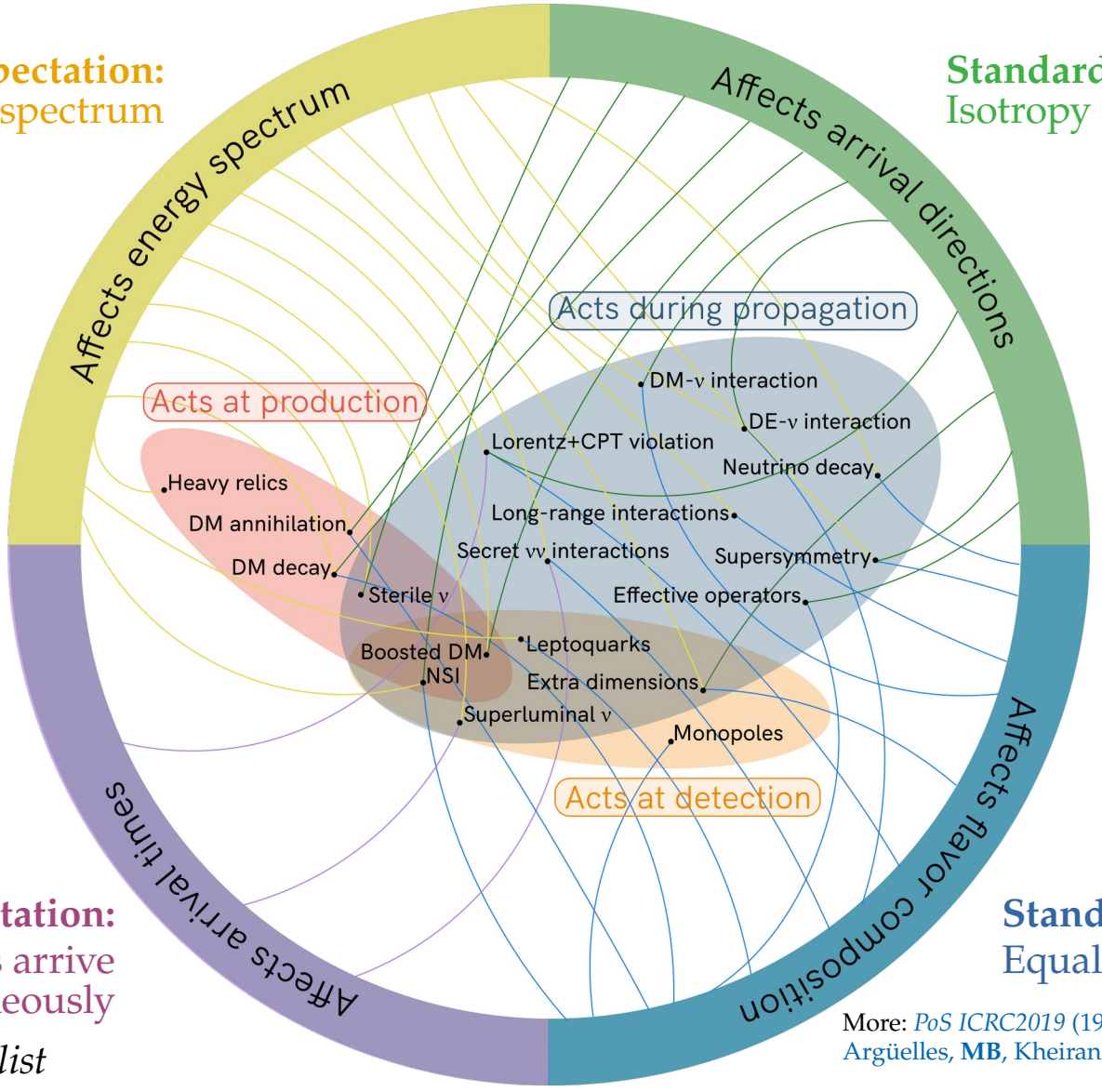

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More: *PoS ICRC2019* (1907.08690)
Argüelles, **MB**, Kheirandish, Palomares-Ruiz, Salvadó, Vincent

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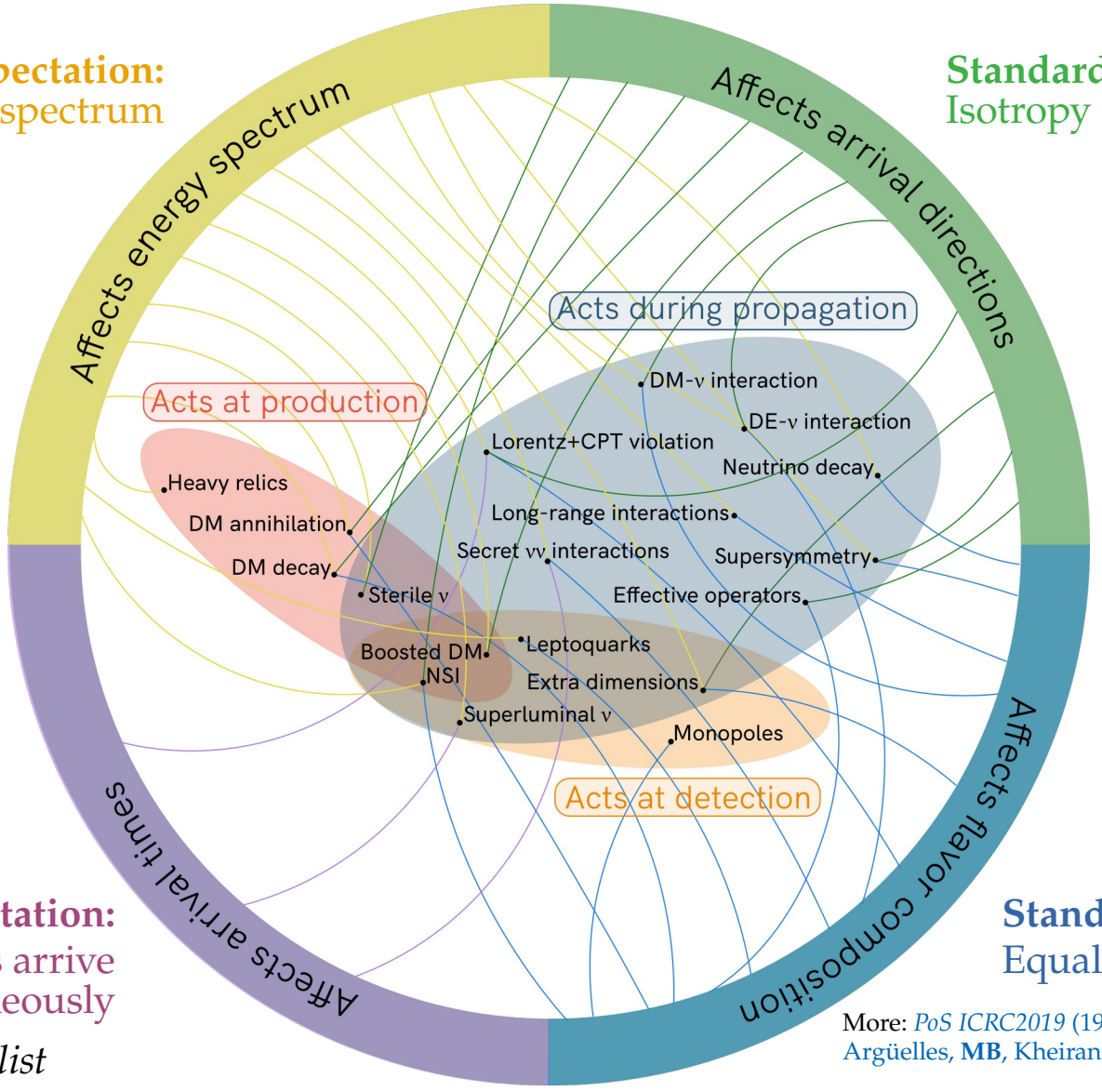

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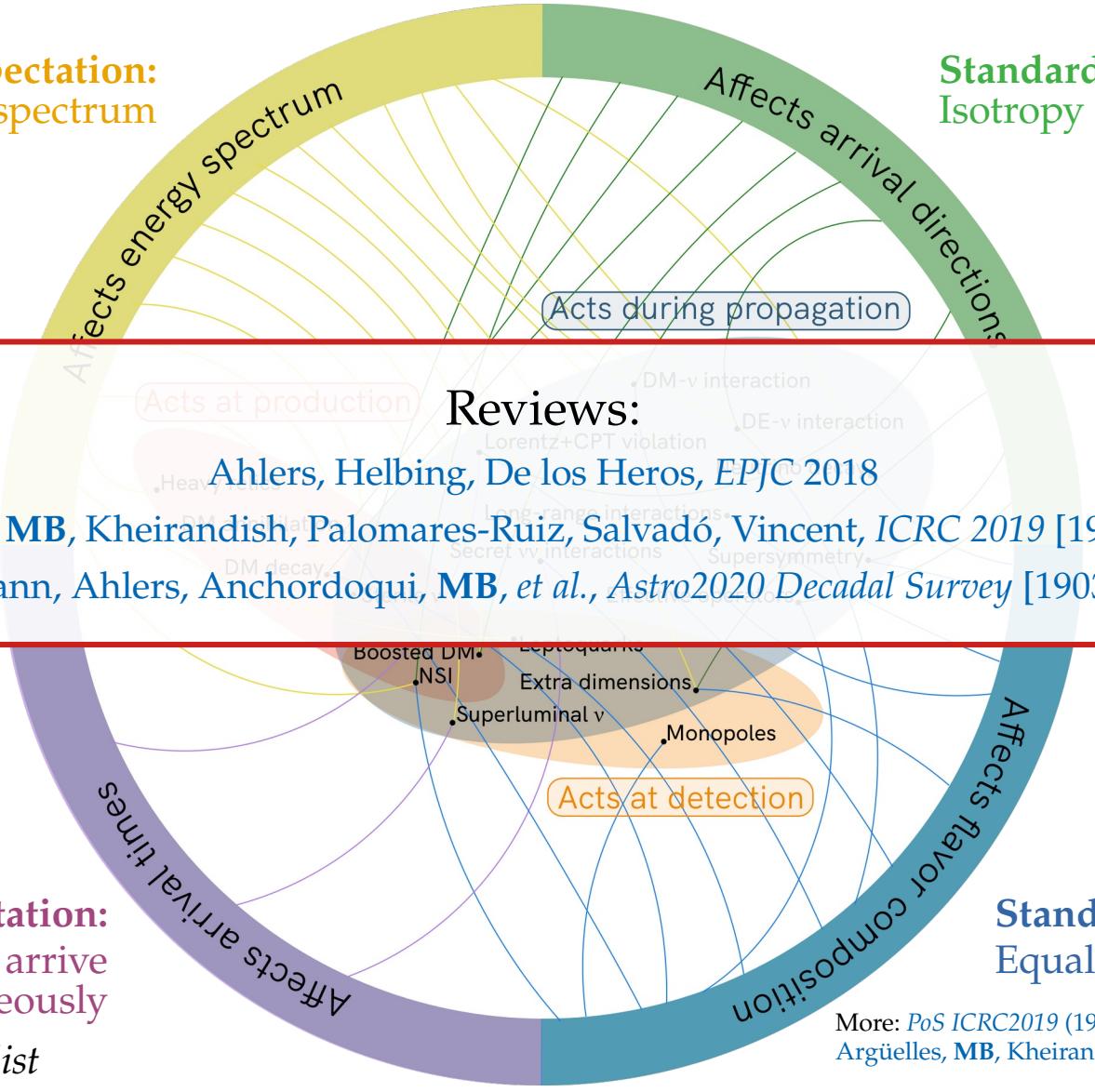

Reviews:

Ahlers, Helbing, De los Heros, *EPJC* 2018

Argüelles, **MB**, Kheirandish, Palomares-Ruiz, Salvadó, Vincent, *ICRC 2019* [1907.08690]

Ackermann, Ahlers, Anchordoqui, **MB**, *et al.*, *Astro2020 Decadal Survey* [1903.04333]

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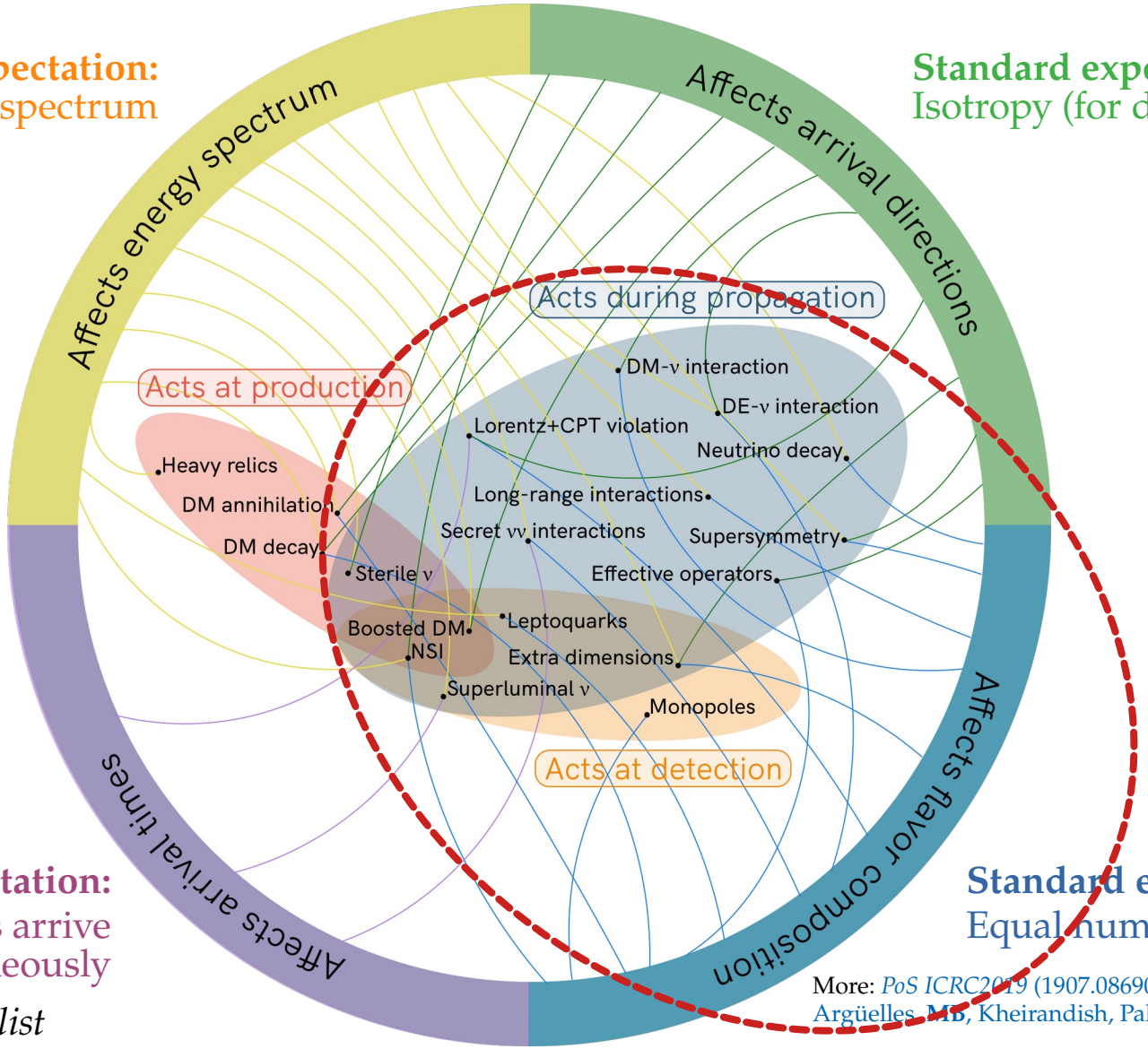

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New physics in flavor composition

Use the flavor sensitivity to test new physics:

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Reviews:
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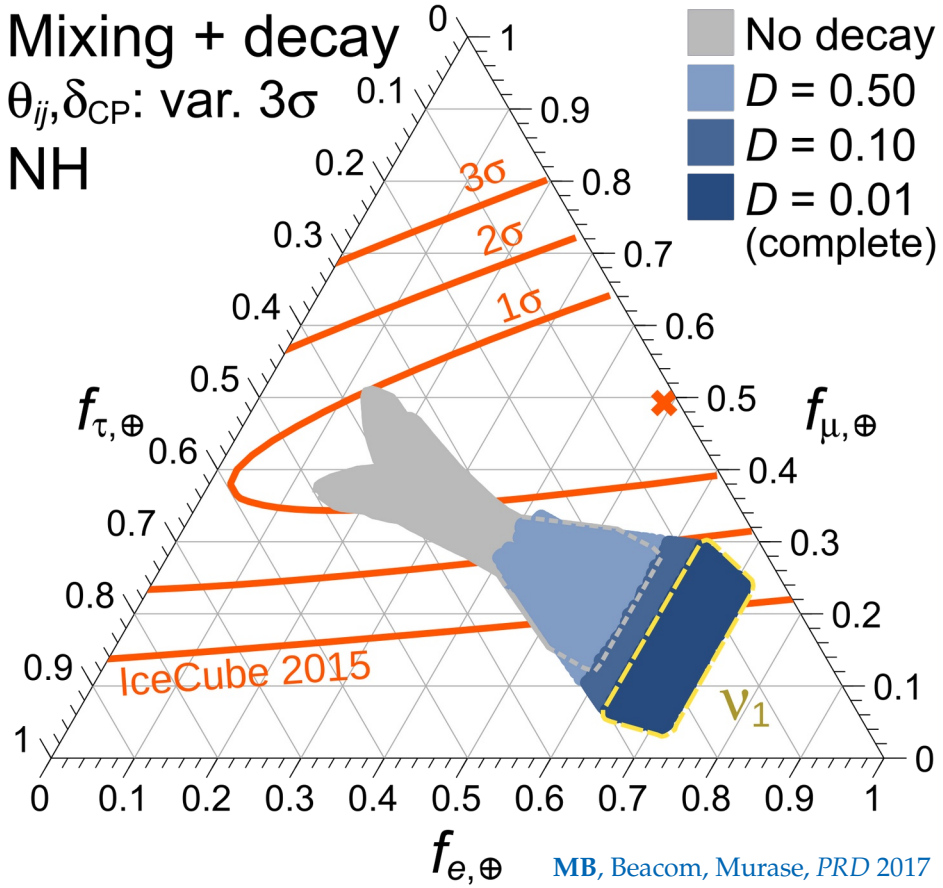

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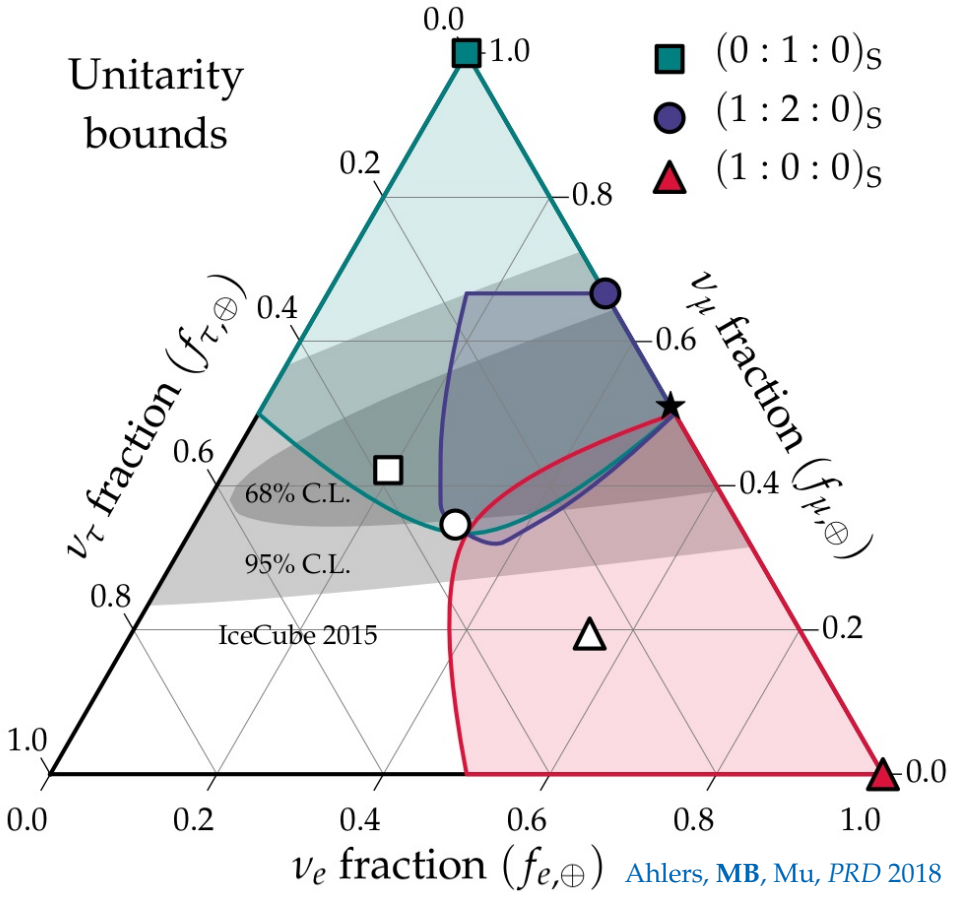

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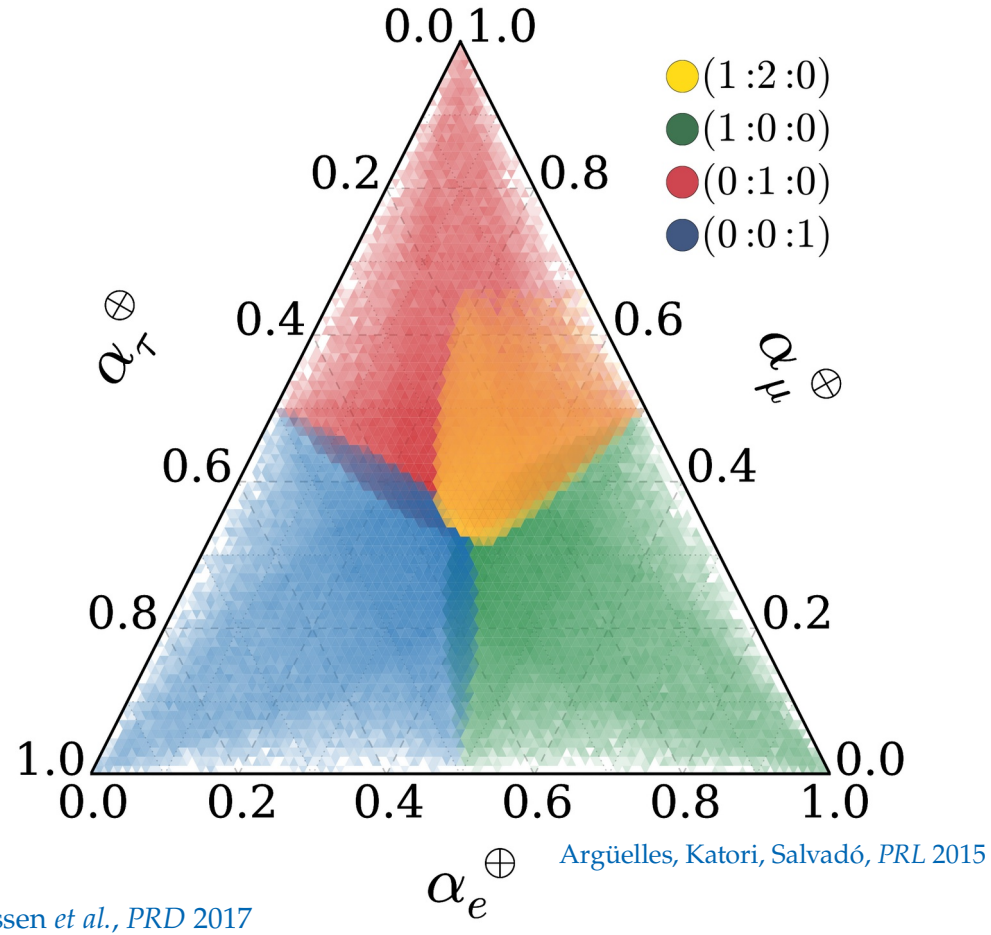

Argüelles, Katori, Salvadó, *PRL* 2015

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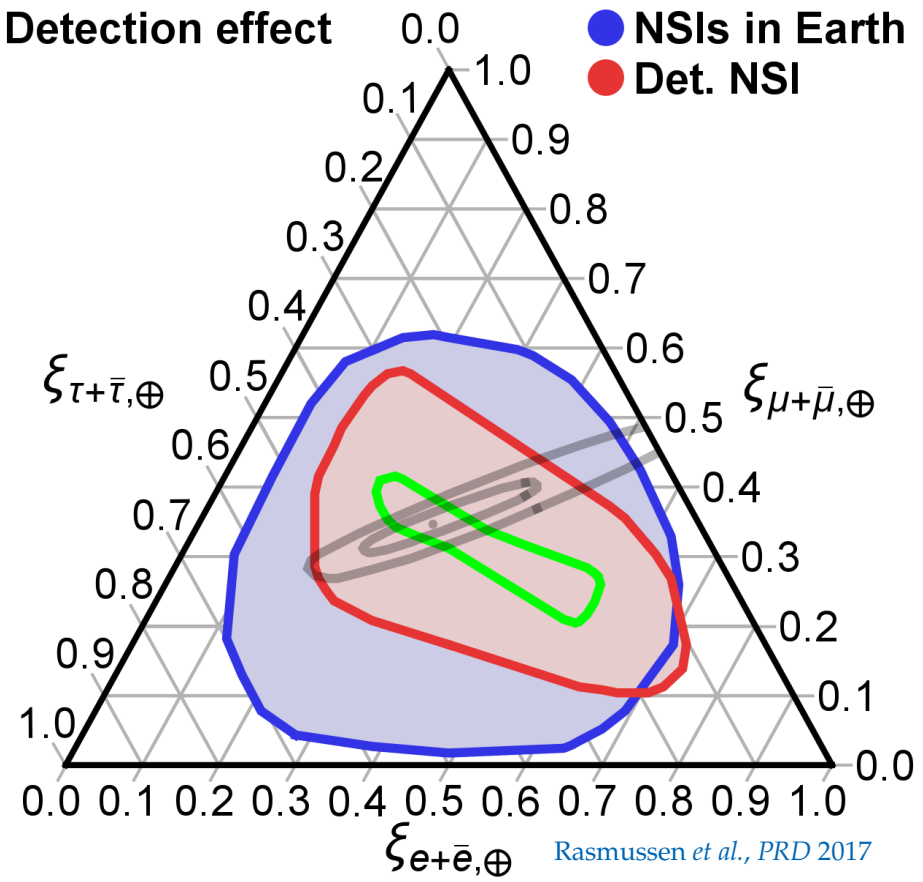

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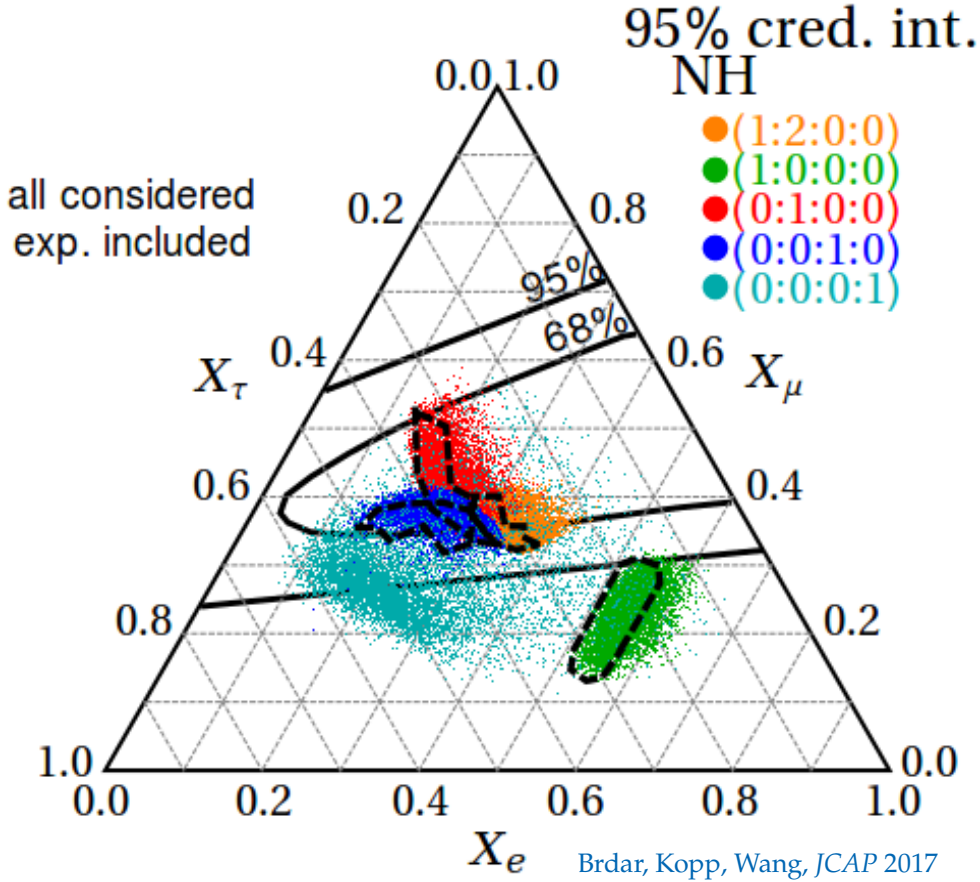

Brdar, Kopp, Wang, *JCAP* 2017

Reviews:
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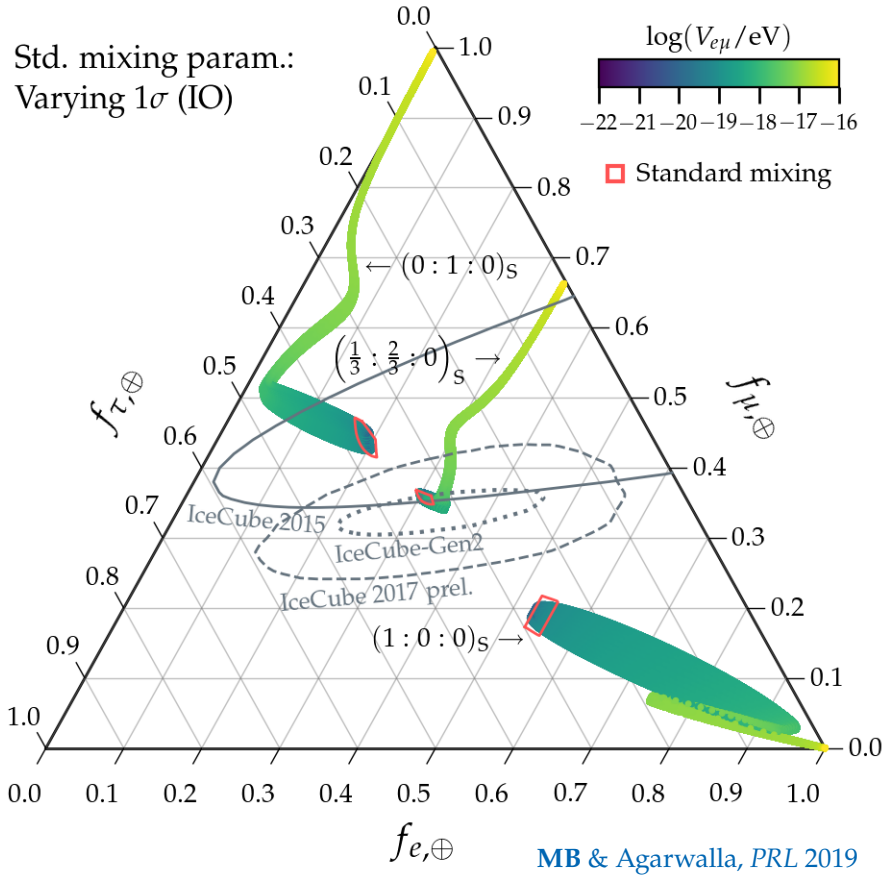
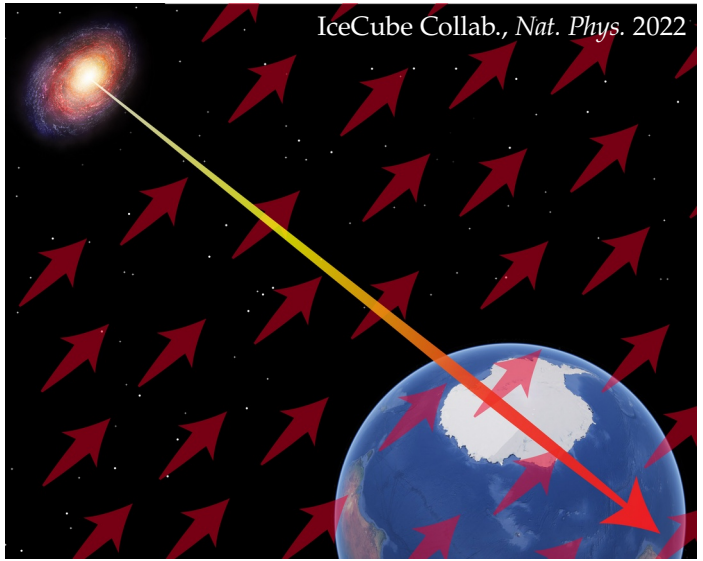
- Long-range *eν* interactions
  [**MB** & Agarwalla, *PRL* 2019]



MB & Agarwalla, *PRL* 2019

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

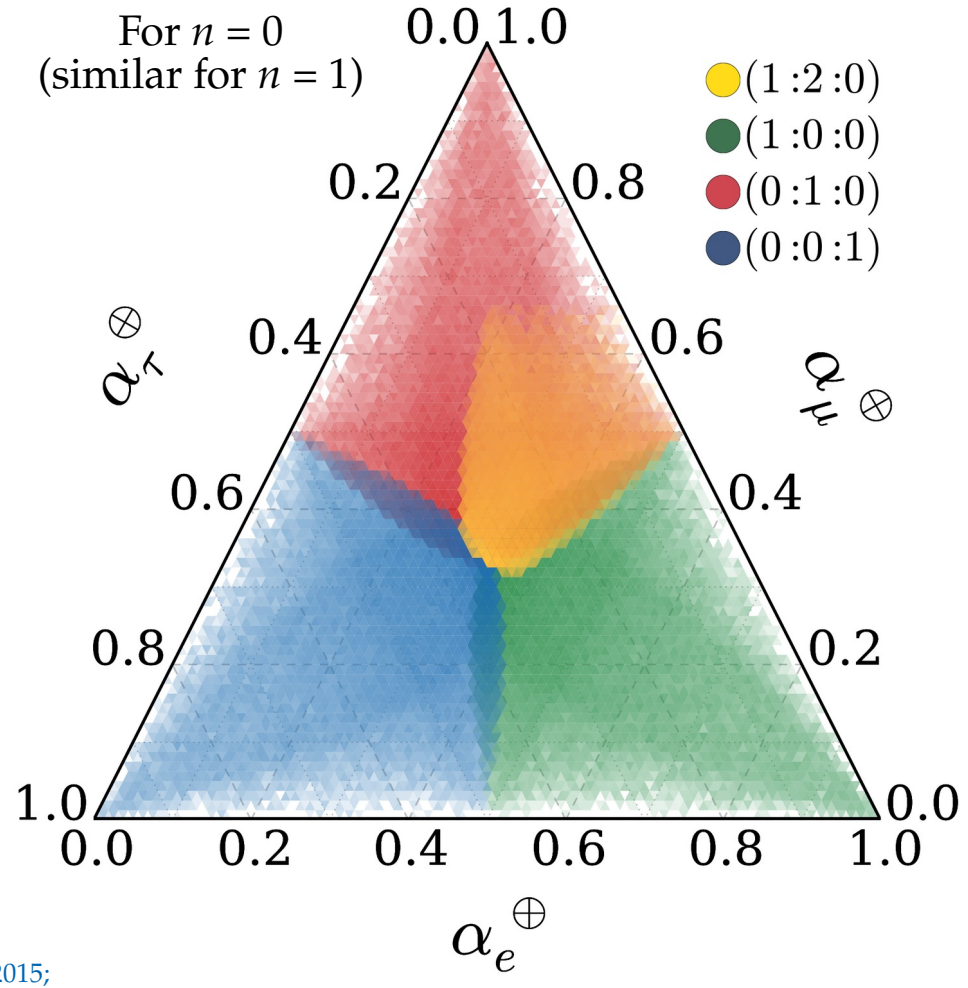
Lorentz-invariance violation can fill up the flavor triangle



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

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

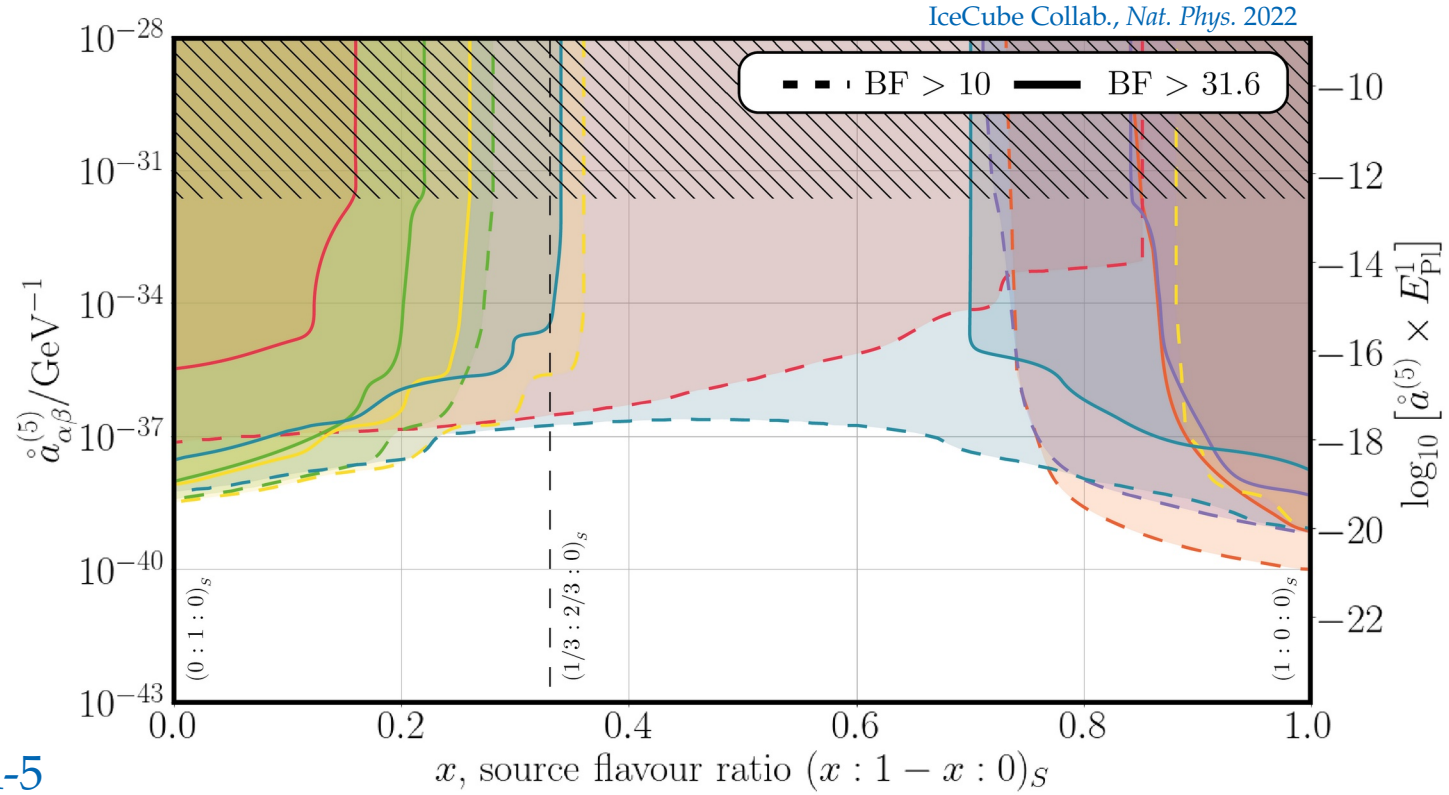
$$H_{\text{NP}} = \sum_n \left(\frac{E}{\Lambda_n}\right)^n U_n^{\dagger}\, \text{diag}\left(O_{n,1}, O_{n,2}, O_{n,3}\right) U_n$$



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

Argüelles, Katori, Salvadó, *PRL* 2015

IceCube Collab., *Nat. Phys.* 2022



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

Astrophysical sources

Earth

L ~ up to a few Gpc

E.g.,

Decay changes the number

of each ν mass eigenstate, N_1, N_2, N_3

?

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

Mass of ν_i Lifetime of ν_i

Astrophysical sources

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L ~ up to a few Gpc

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Decay changes the number

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Only sensitive to their ratio

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

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?

Lower-E ν are longer-lived…

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

… but ν that travel longer L are more attenuated!

Astrophysical sources

Earth

L ~ up to a few Gpc

E.g.,

Astrophysical sources

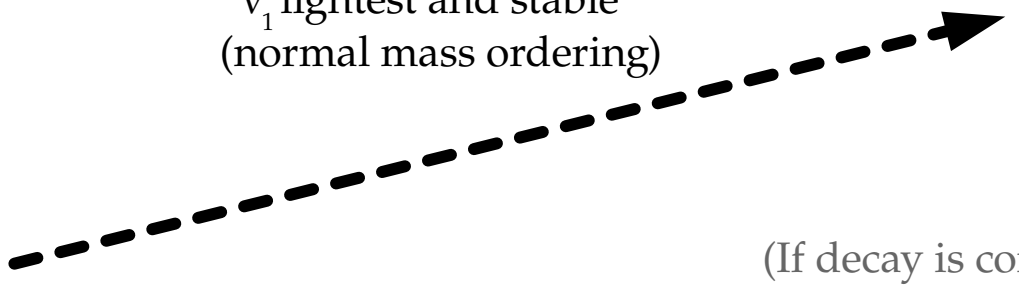
Earth

L ~ up to a few Gpc

$\nu_2, \nu_3 \rightarrow \nu_1$

ν_1 lightest and stable
(normal mass ordering)

E.g.,



(If decay is complete)

Astrophysical sources

Earth

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E.g.,

(If decay is complete)

$\nu_1, \nu_2 \rightarrow \nu_3$

ν_3 lightest and stable
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E.g.,

(If decay is complete)

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ν_3 lightest and stable
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Fine print:

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

Astrophysical sources

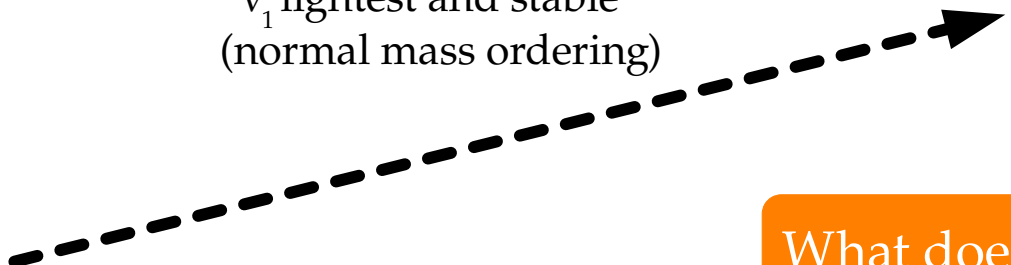
Earth

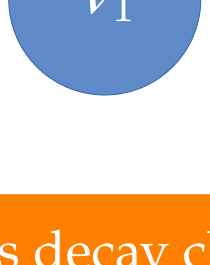
L ~ up to a few Gpc

$\nu_2, \nu_3 \rightarrow \nu_1$

ν_1 lightest and stable
(normal mass ordering)

E.g.,





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 ⟺ Spectrum shape ⟺ Event rate

What does neutrino decay change?

Flavor composition ⟺ Spectrum shape ⟺ Event rate

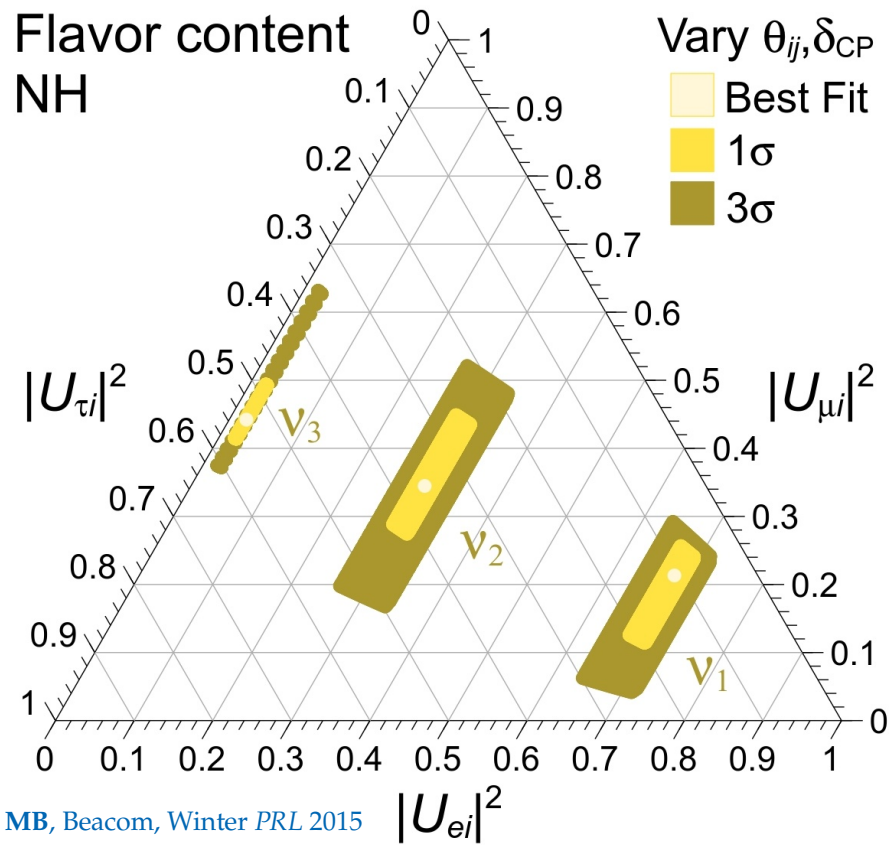
Flavor content of mass eigenstates:

Known to within 2%

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

Known to within 8%

Known to within 20% (or worse)



MB, Beacom, Winter *PRL* 2015

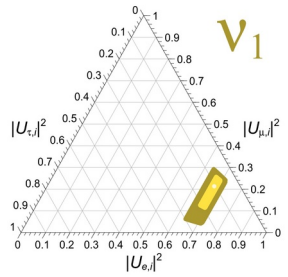
What does neutrino decay change?

Flavor composition ⟺ Spectrum shape ⟺ Event rate

$\nu_2, \nu_3 \to \nu_1$

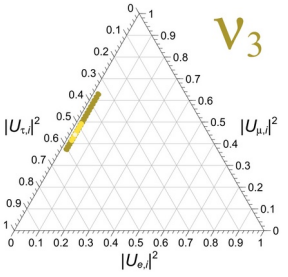
ν_1 lightest and stable
(normal mass ordering)

E.g.,



$\nu_1, \nu_2 \to \nu_3$

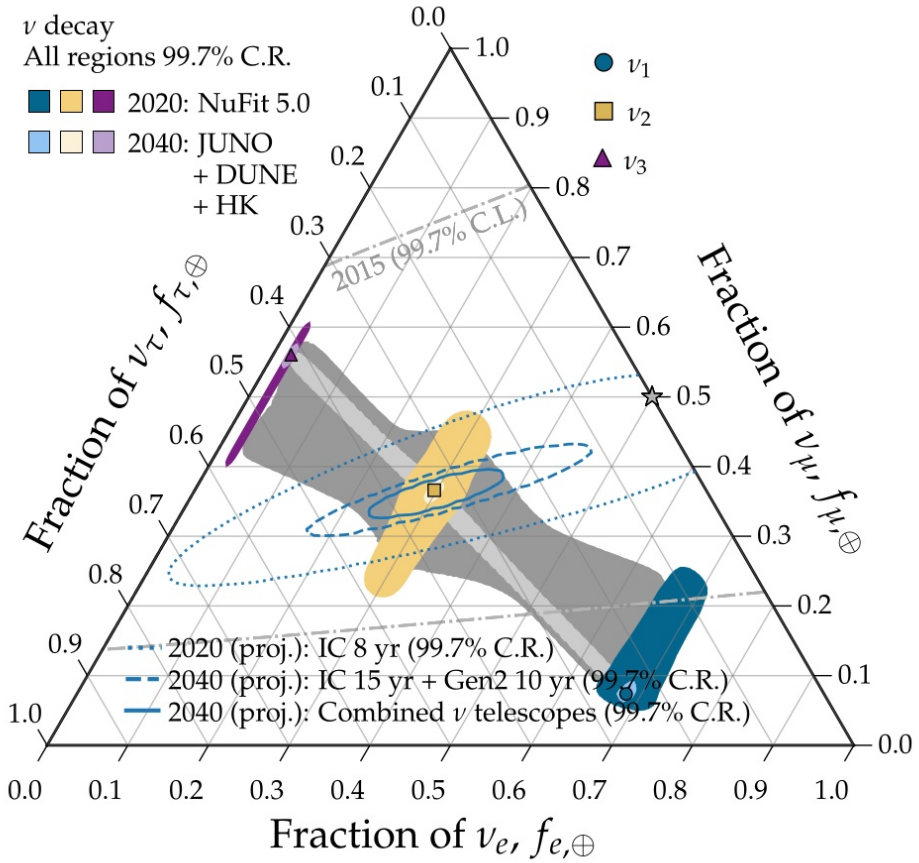
ν_3 lightest and stable
(inverted mass ordering)



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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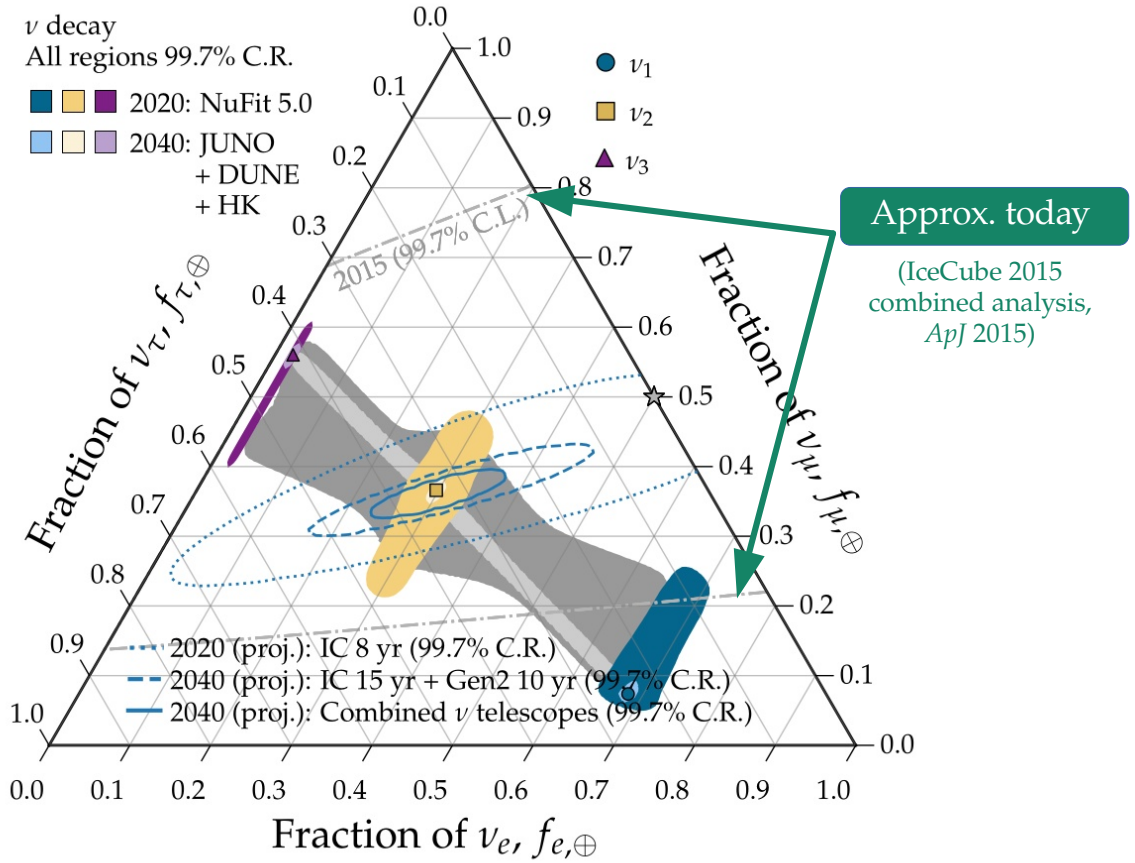
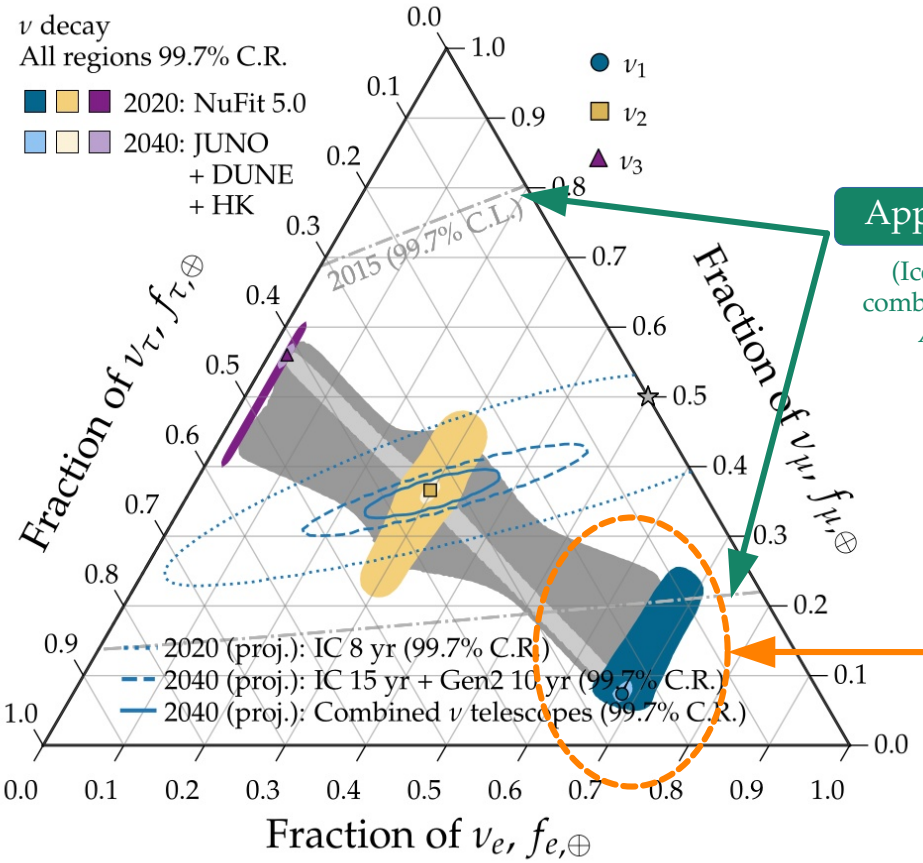
Flavor composition ⟺ Spectrum shape ⟺ Event rate



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

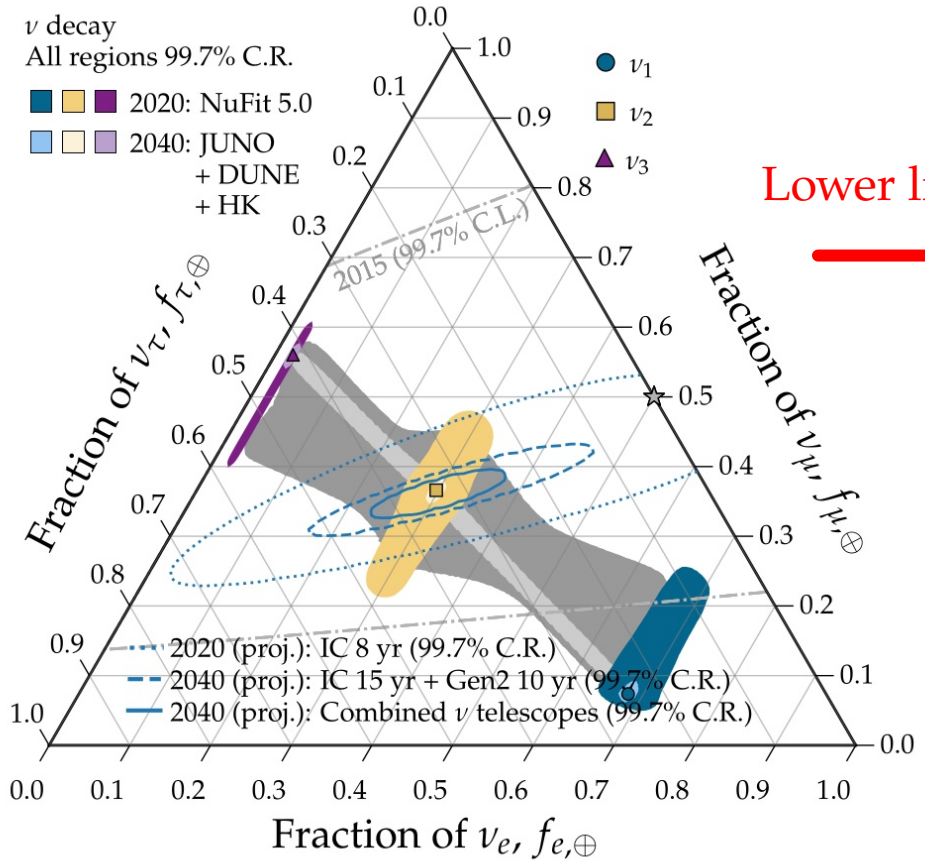
(IceCube 2015 combined analysis, *ApJ* 2015)

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

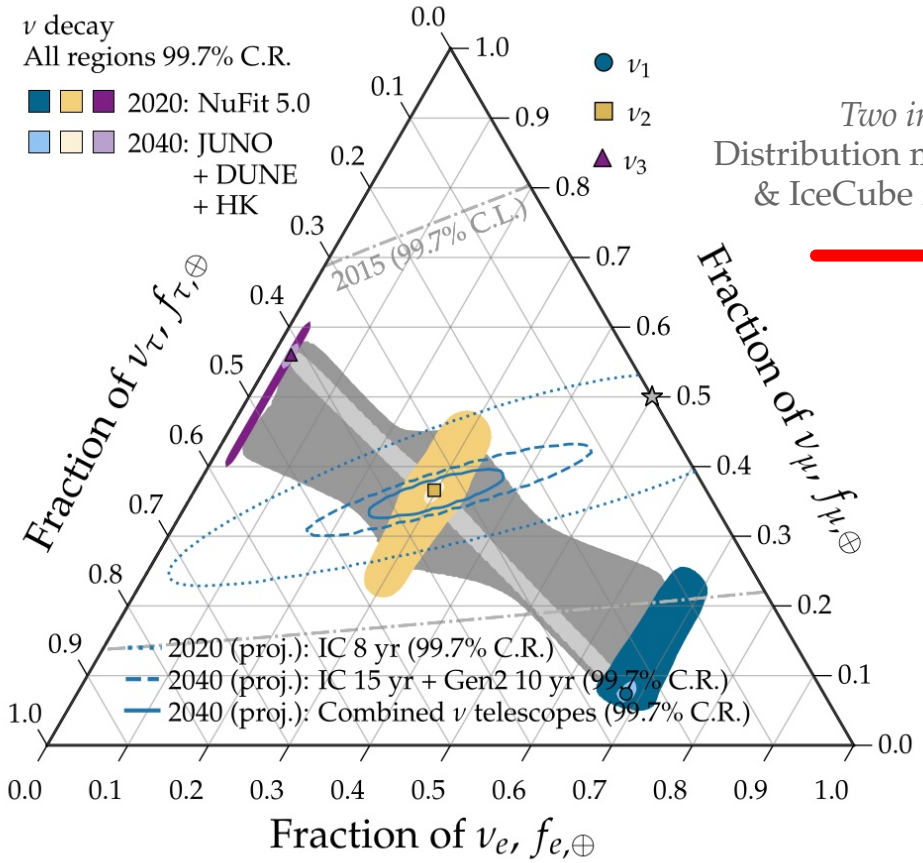


Lower limit on τ/m →

What does neutrino decay change?

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

Flavor composition ⟺ Spectrum shape ⟺ Event rate

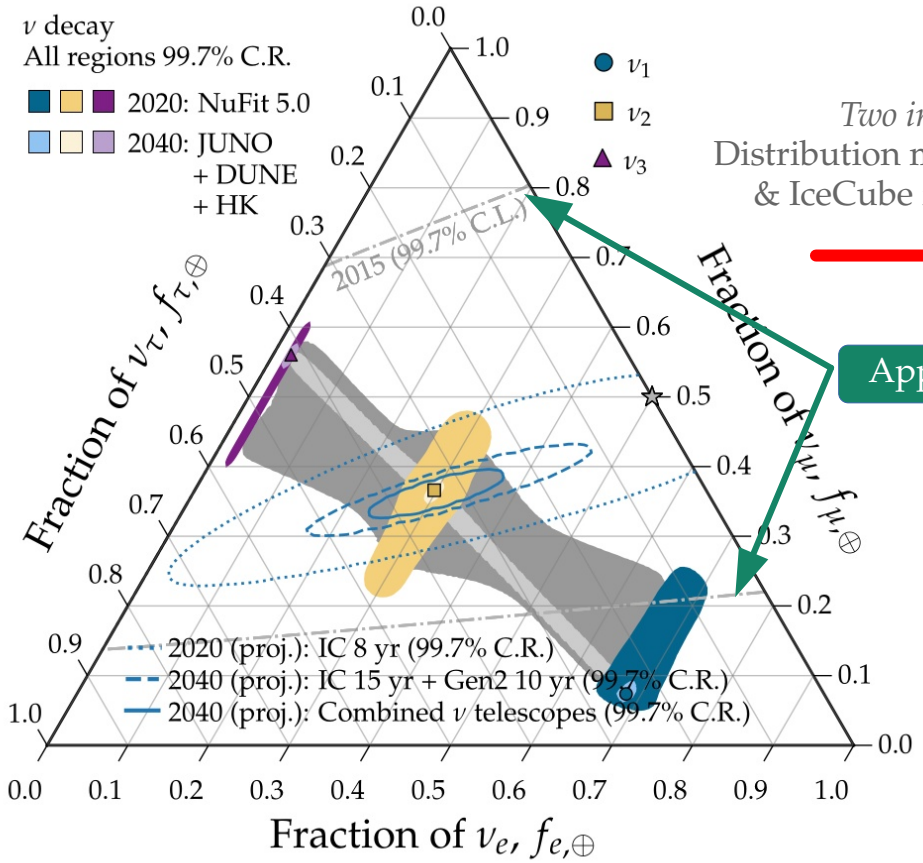


Two ingredients:
Distribution mixing parameters
& IceCube flavor posterior

What does neutrino decay change?

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

Flavor composition ⟺ Spectrum shape ⟺ Event rate



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Approx. today

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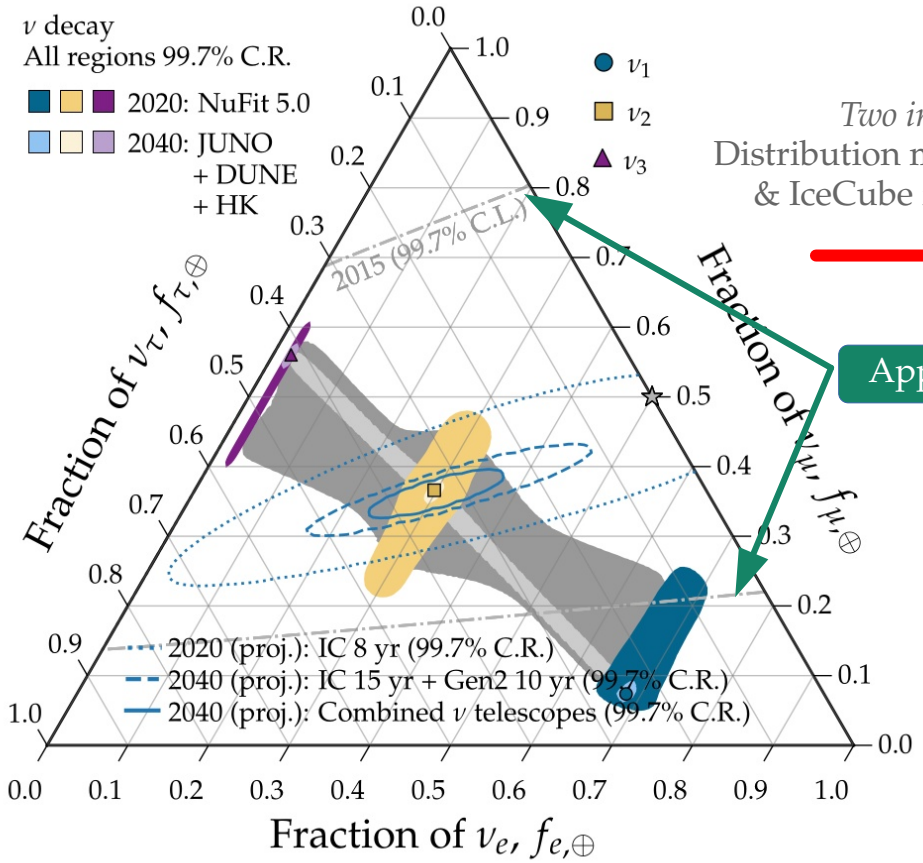
See also: Beacom *et al.*, *PRL* 2002 / Baerwald, **MB**, Winter, *JCAP* 2012 / **MB**, Beacom, Murase, *PRD* 2017 / Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 /Abdullahi & Denton, *PRD* 2020 / **MB**, 2004.06844

Flavor composition ⟺ Spectrum shape ⟺ Event rate



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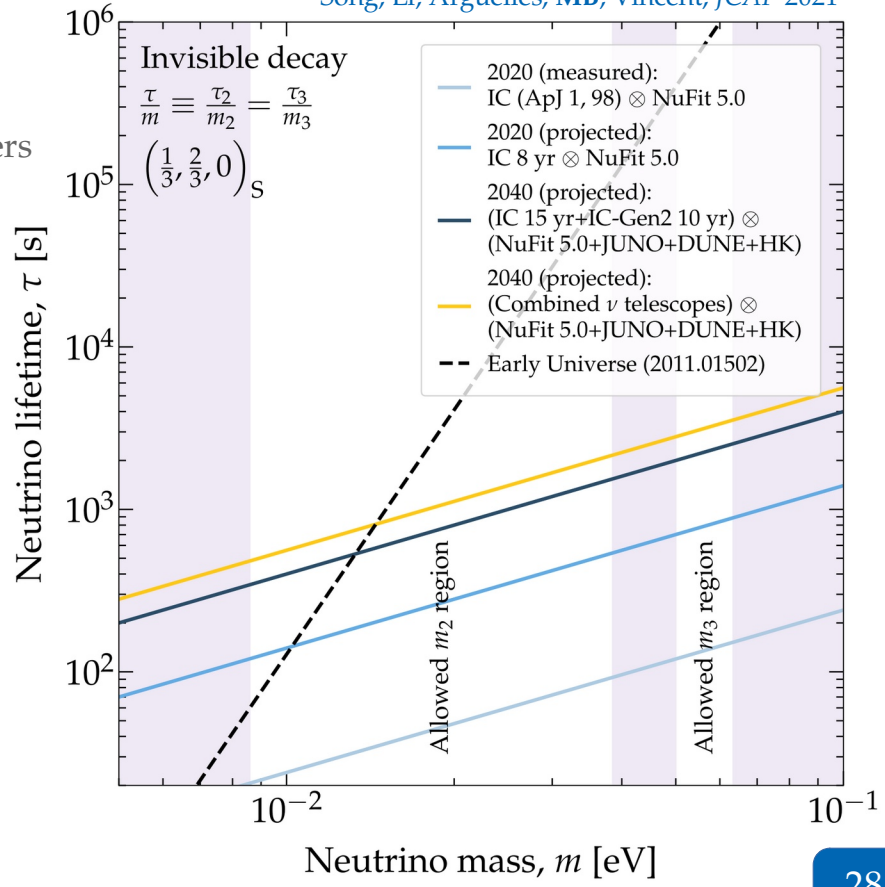
Approx. today

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



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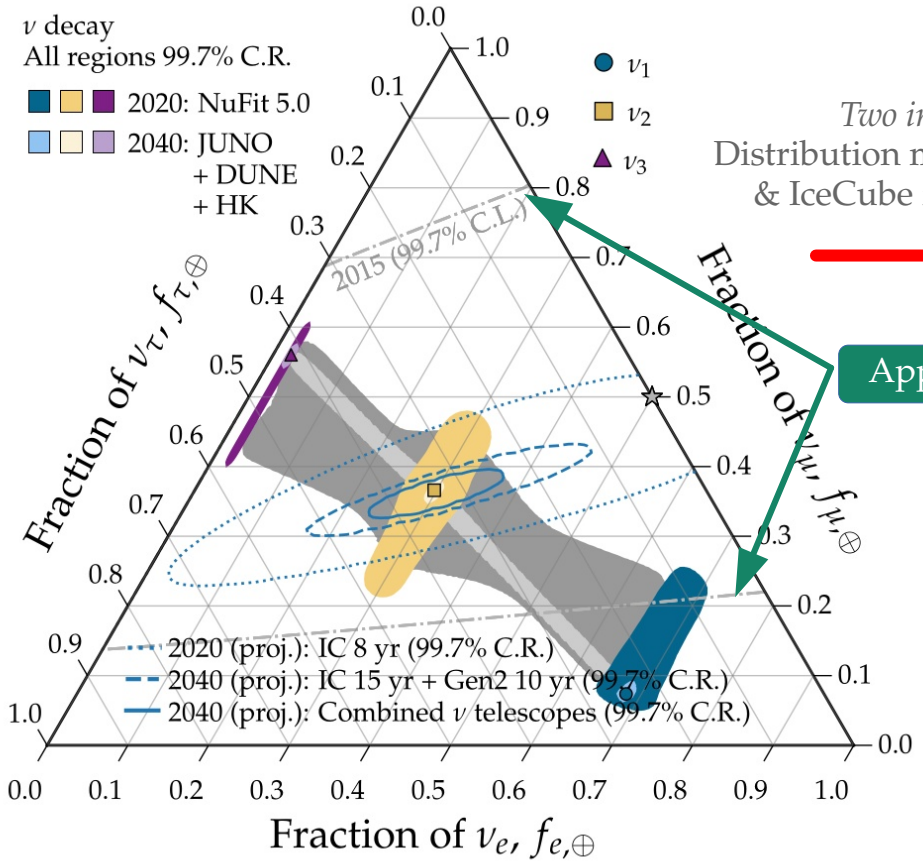
Flavor composition ⟺ Spectrum shape ⟺ Event rate



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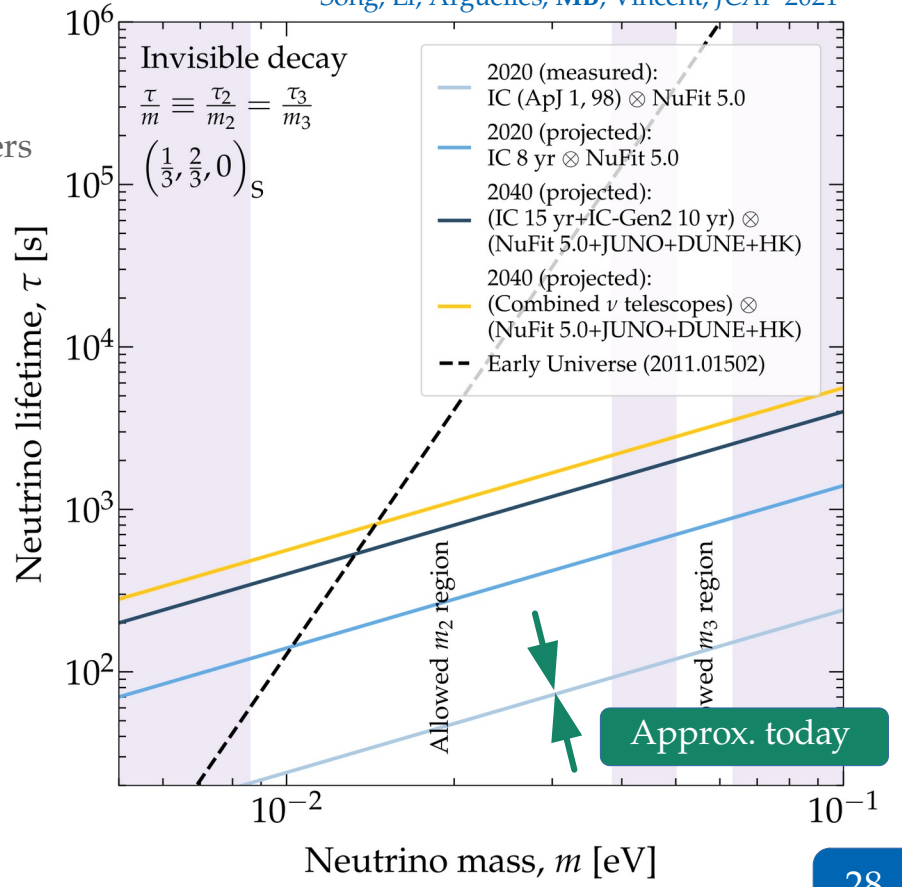
Approx. today

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



Approx. today

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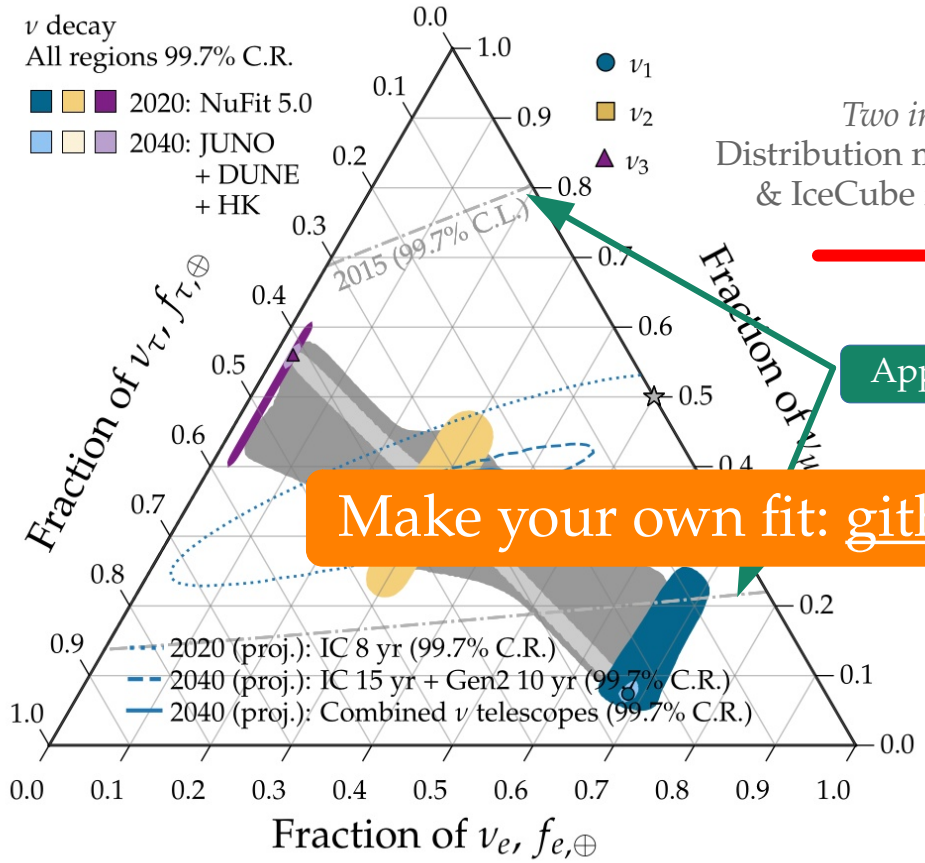
Flavor composition ⟺ Spectrum shape ⟺ Event rate



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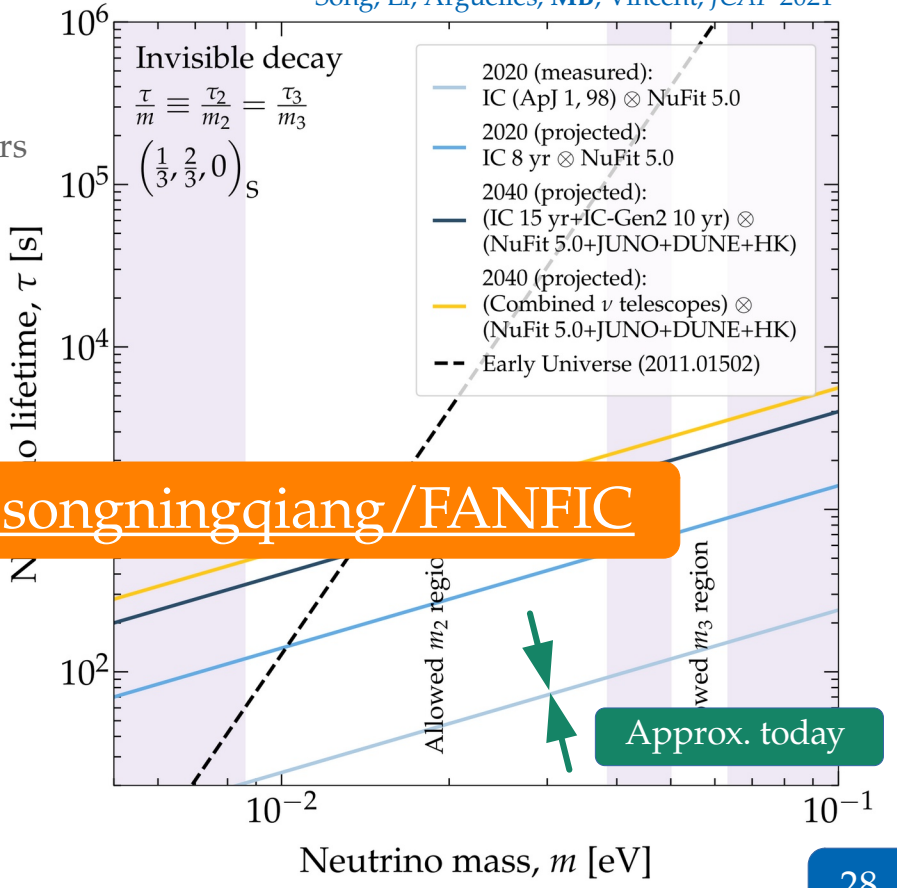
Approx. today

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



Approx. today

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

Towards high statistics

Strebe/Wikipedia

Measuring flavor composition: 2015–2040

IceCube Collab., *EPJC* 2022
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
IceCube Collab., *PRD* 2019
IceCube Collab., *ApJ* 2015

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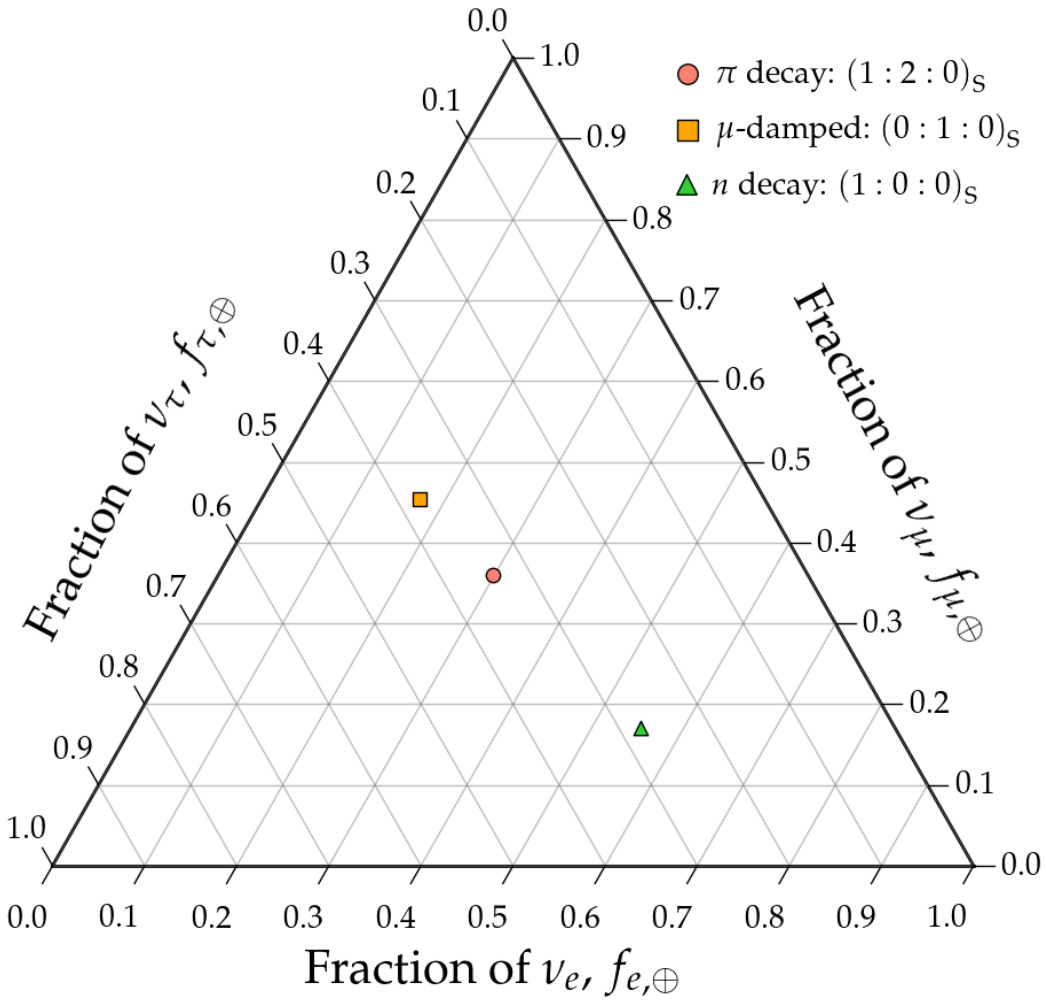

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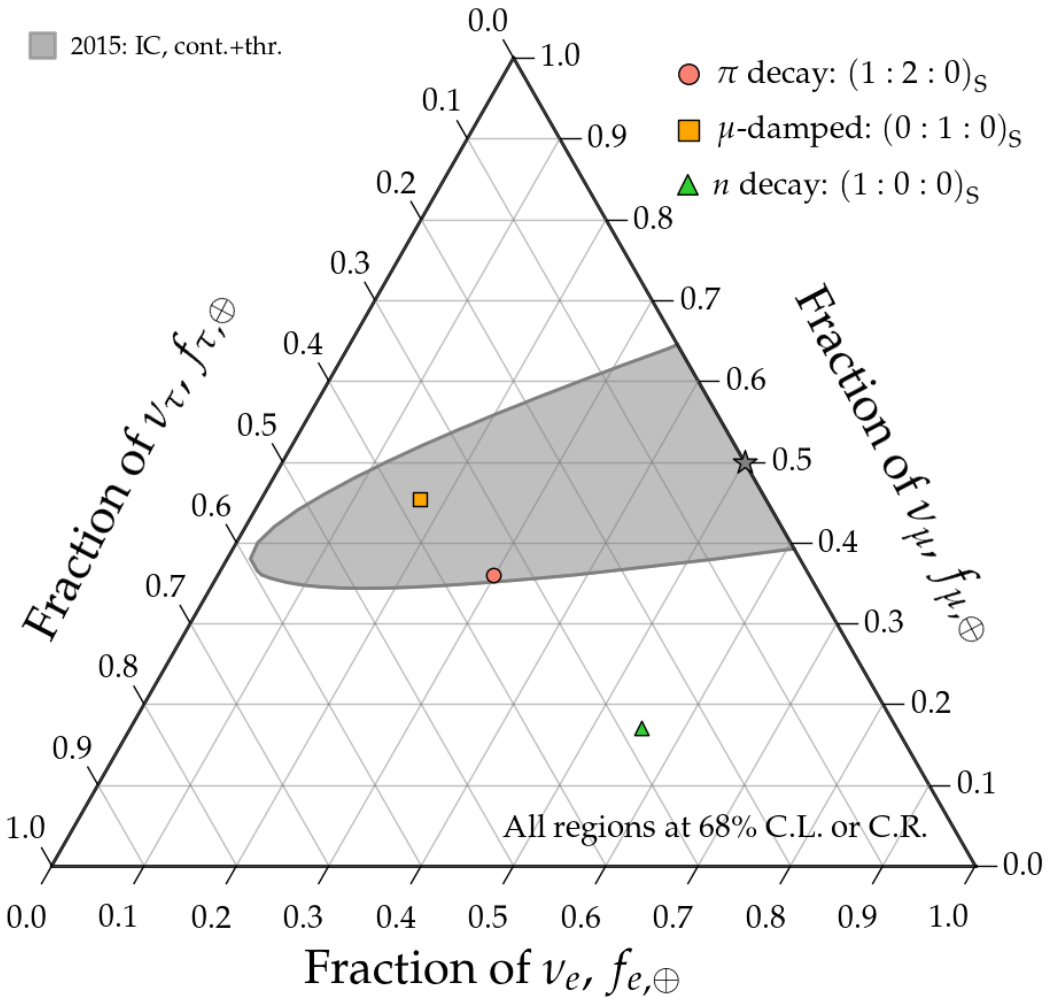

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Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
IceCube Collab., *PRD* 2019
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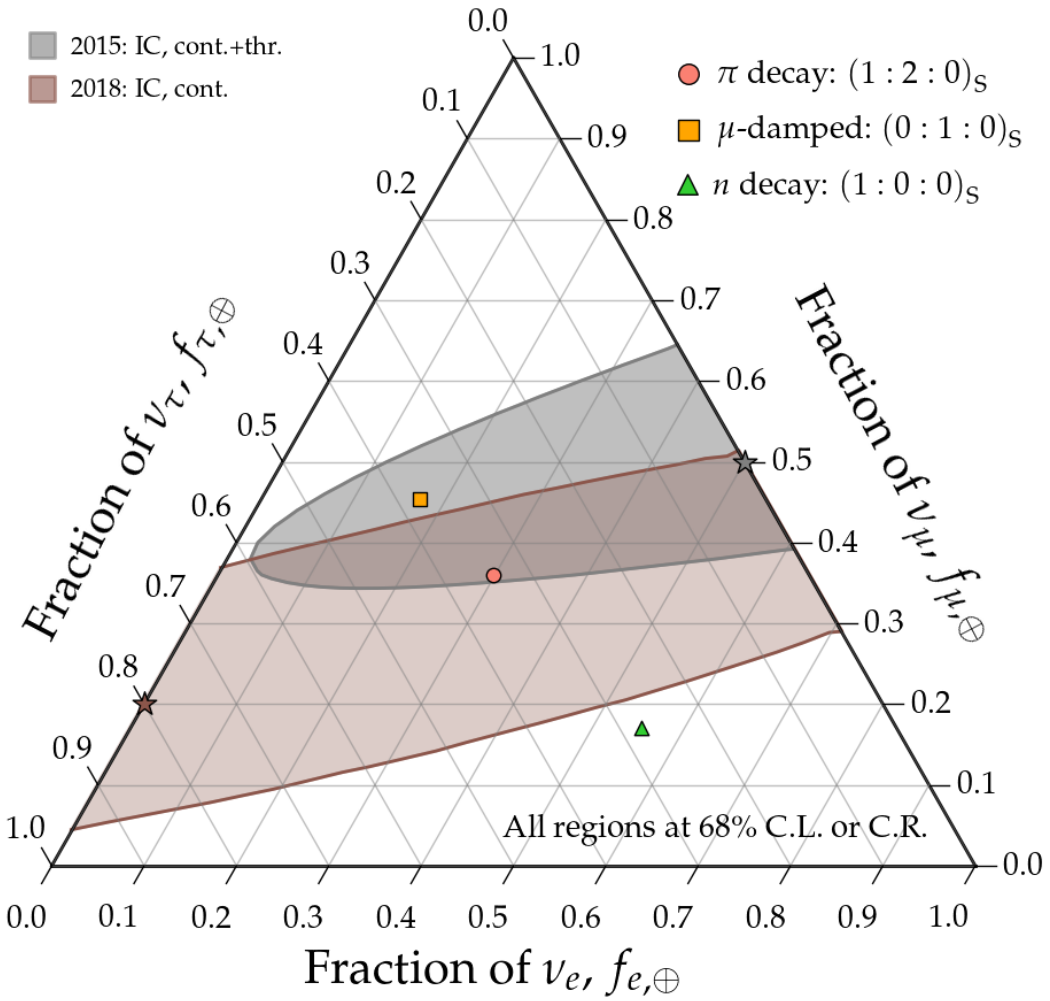

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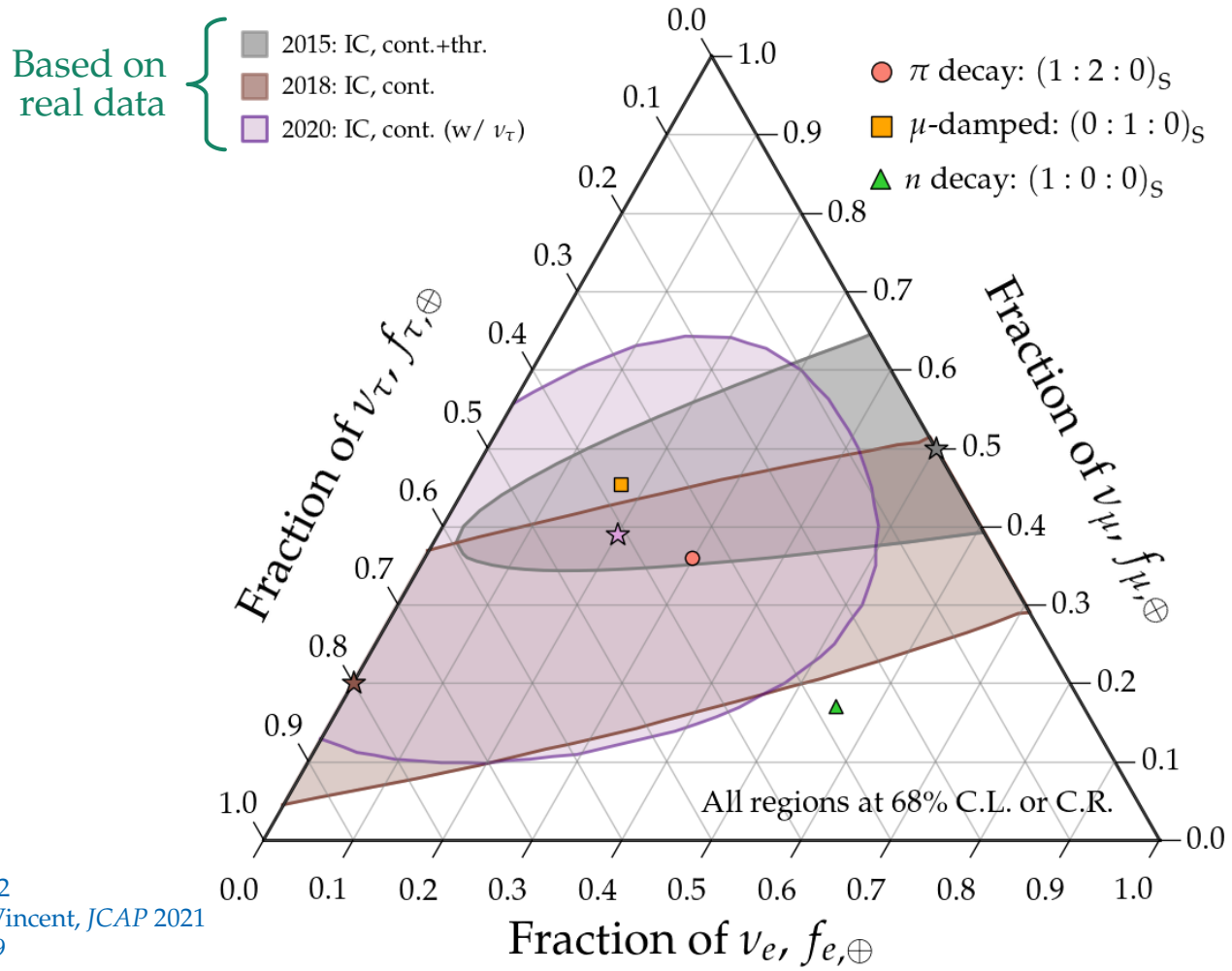

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IceCube Collab., *PRD* 2019
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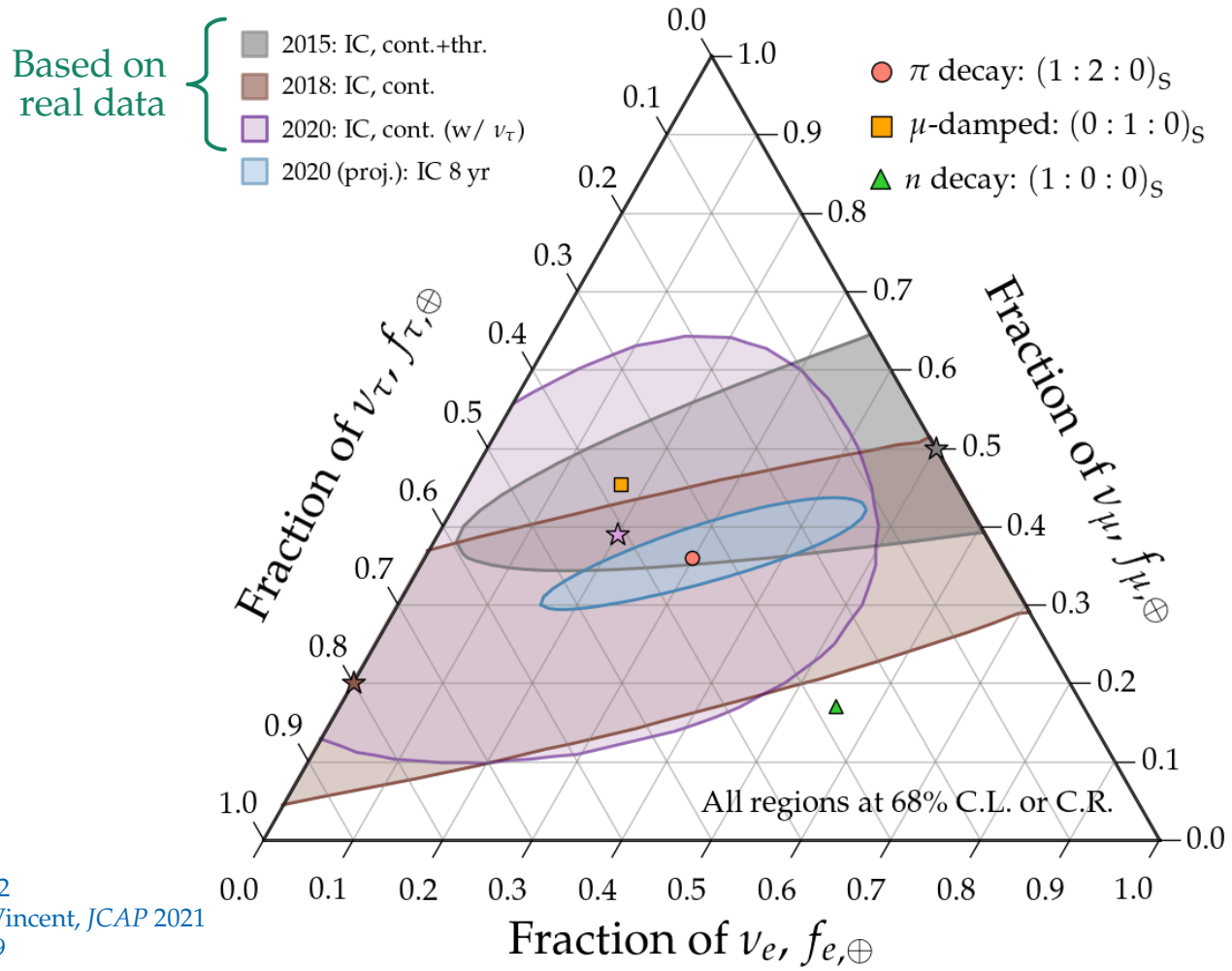

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IceCube Collab., *PRD* 2019
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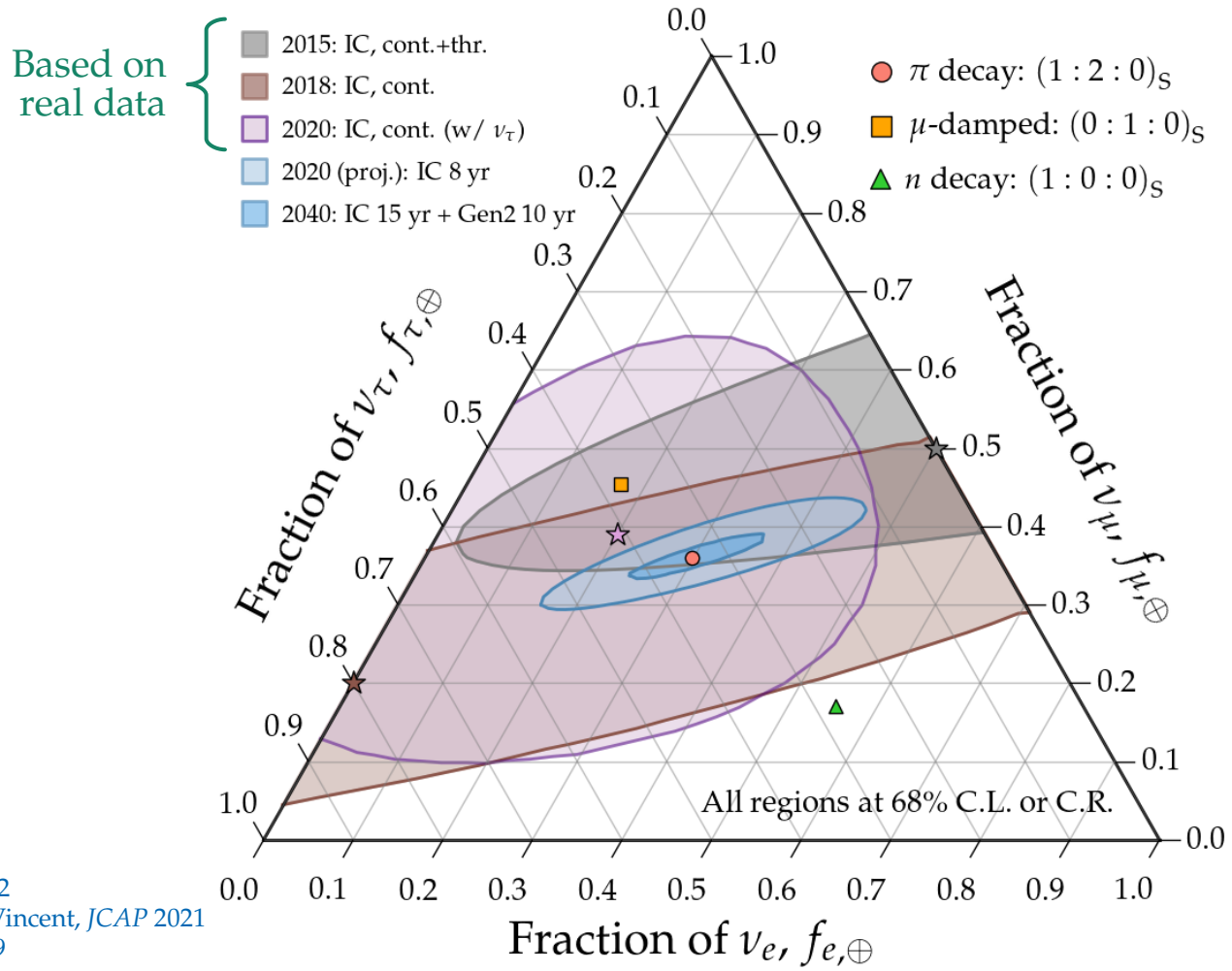

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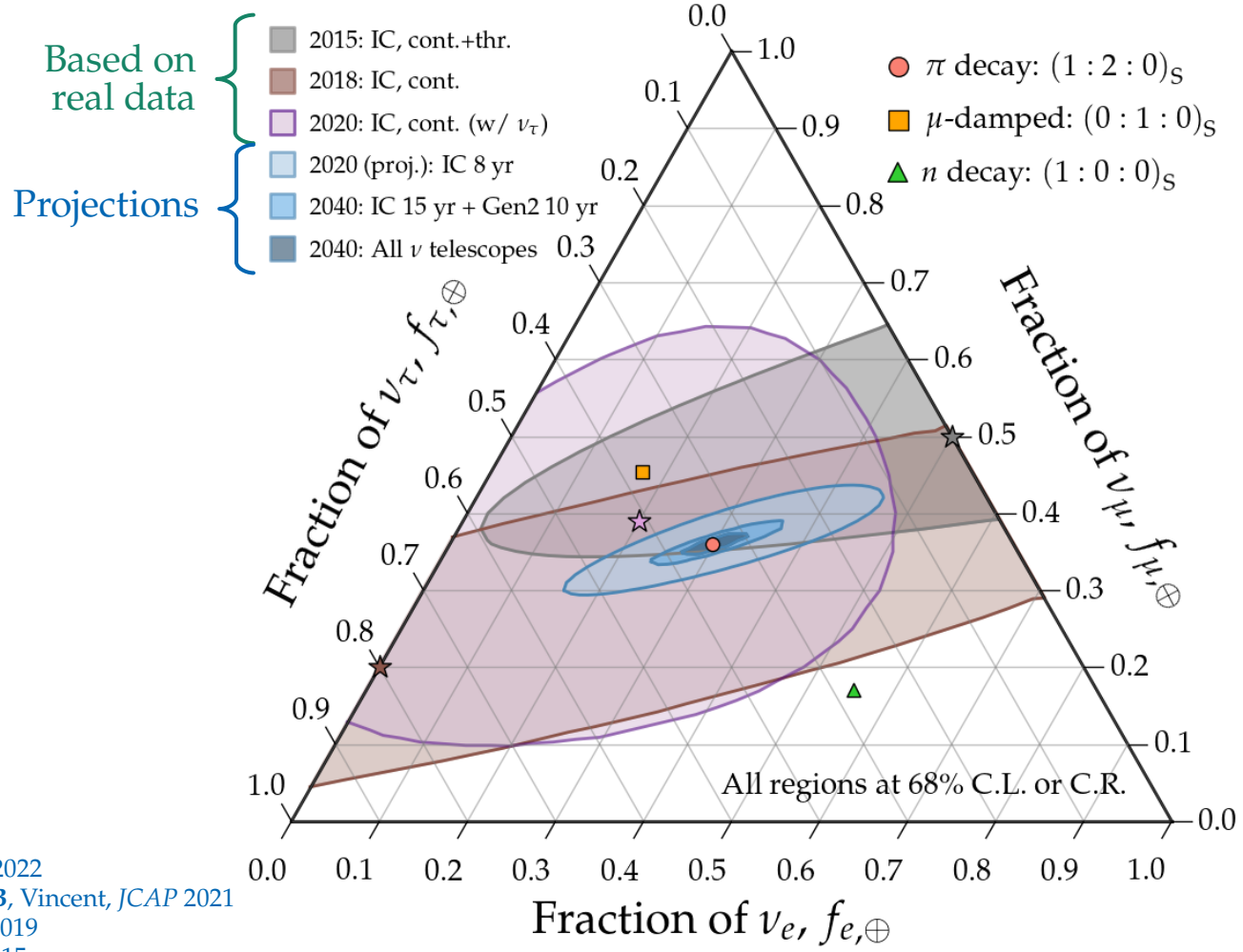

IceCube Collab., *EPJC* 2022
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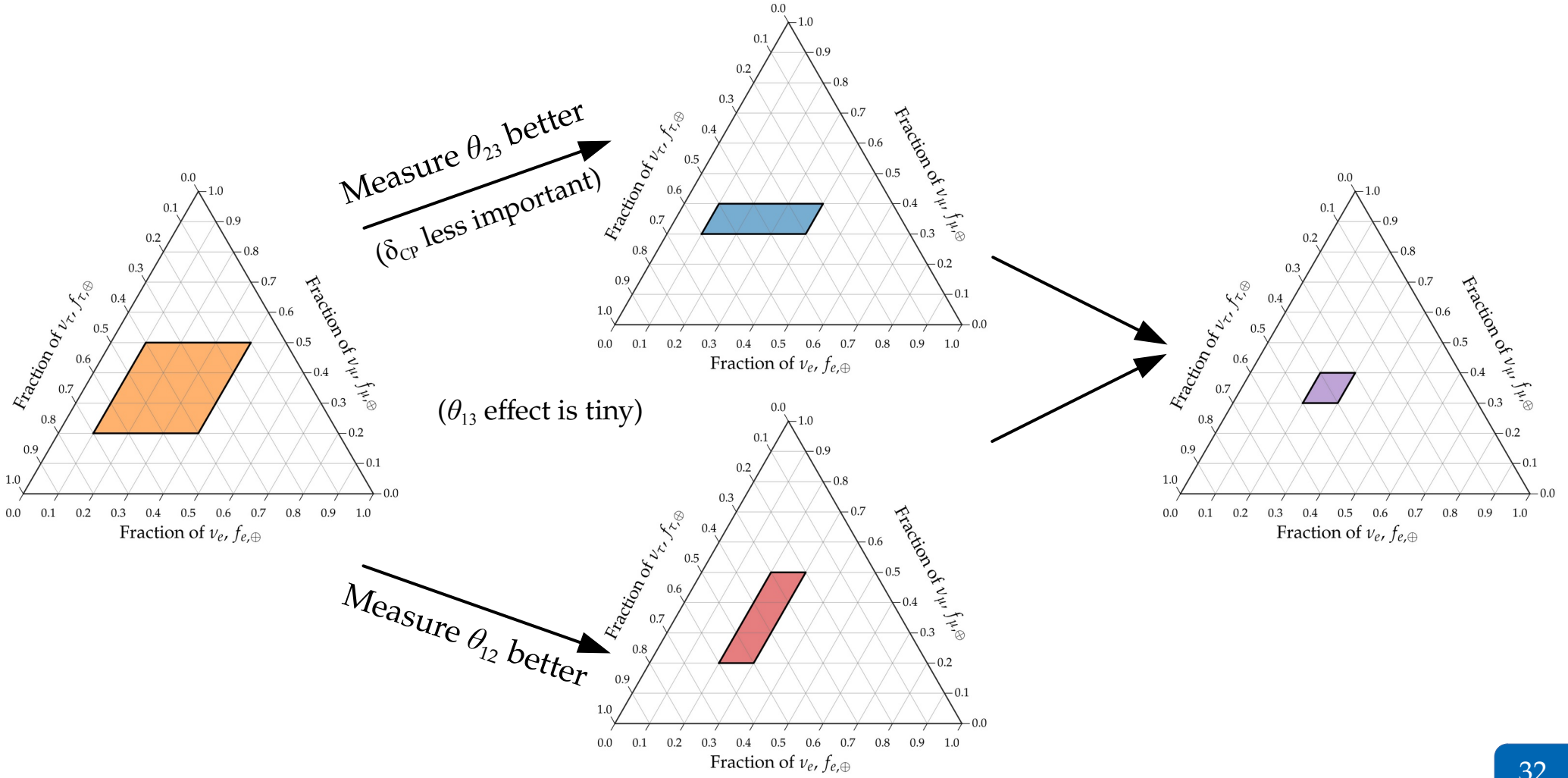
IceCube Collab., *PRD* 2019
IceCube Collab., *ApJ* 2015

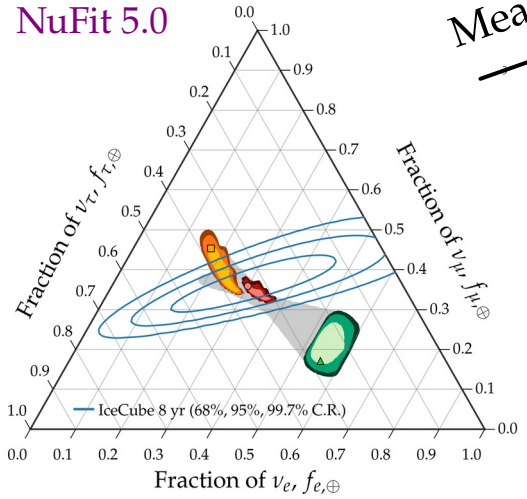
How knowing the mixing parameters better helps



How knowing the mixing parameters better helps

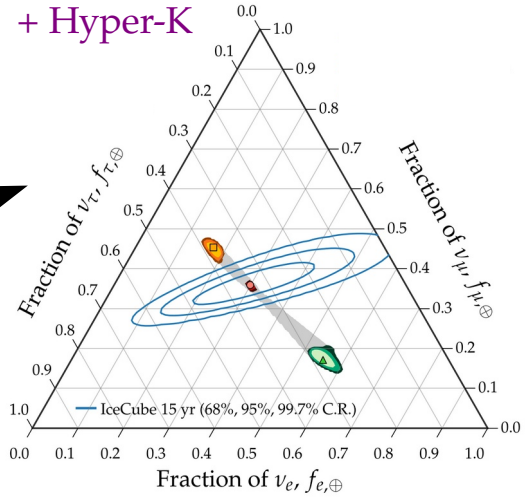
2020

NuFit 5.0

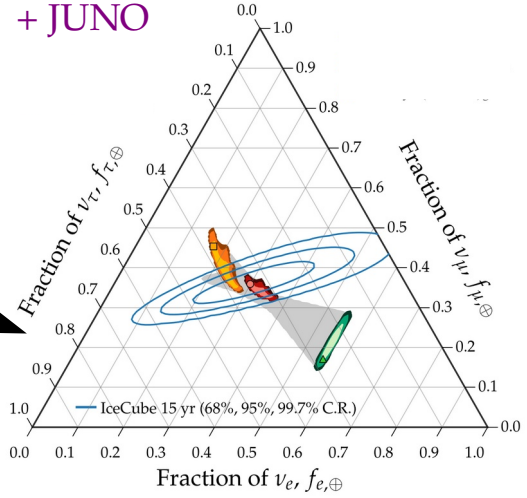


Measure θ_{23} better

+ Hyper-K



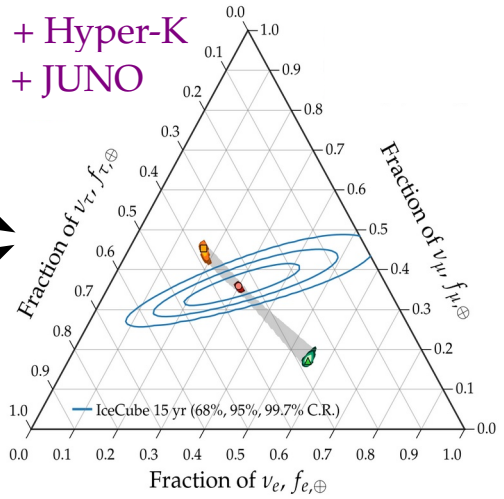
+ JUNO



Measure θ_{12} better

~2030

+ Hyper-K
+ JUNO



In our results:
JUNO + Hyper-K + DUNE

Marginal improvement til 2040

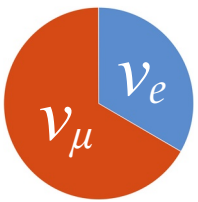
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Back to the sources

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

Sources

E.g.,



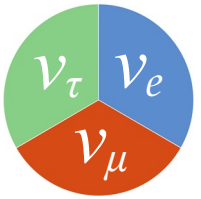
Oscillations

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

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

Earth

E.g.,



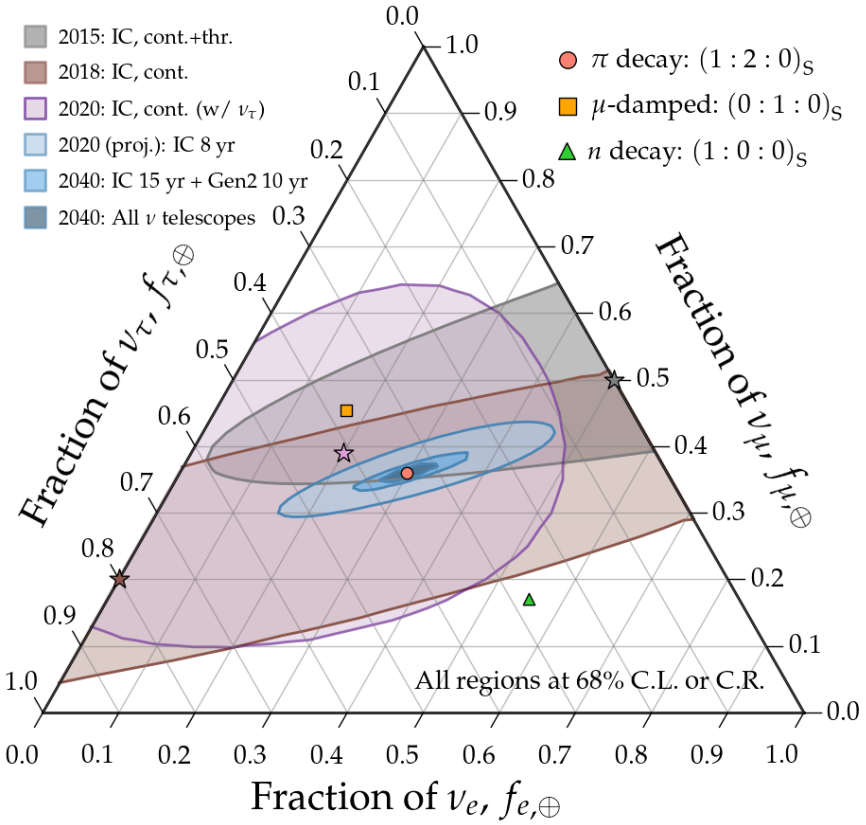
$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$

From Earth to sources: we let the data teach us about $f_{\alpha,\mathrm{S}}$

Inferring the flavor composition at the sources

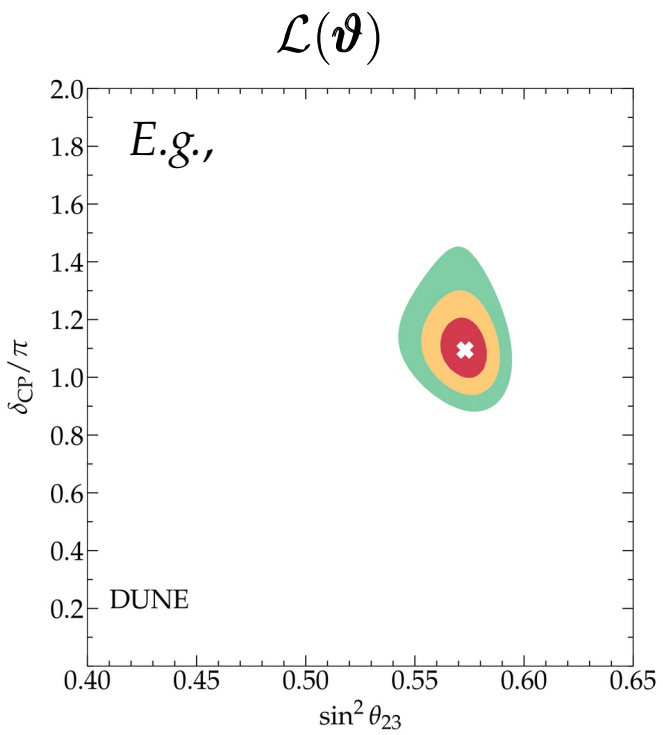
Ingredient #1:

Flavor ratios measured at Earth, $(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$



Ingredient #2:

Probability density of mixing parameters $(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{CP})$



Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
MB & Ahlers, *PRL* 2019

Inferring the flavor composition at the sources

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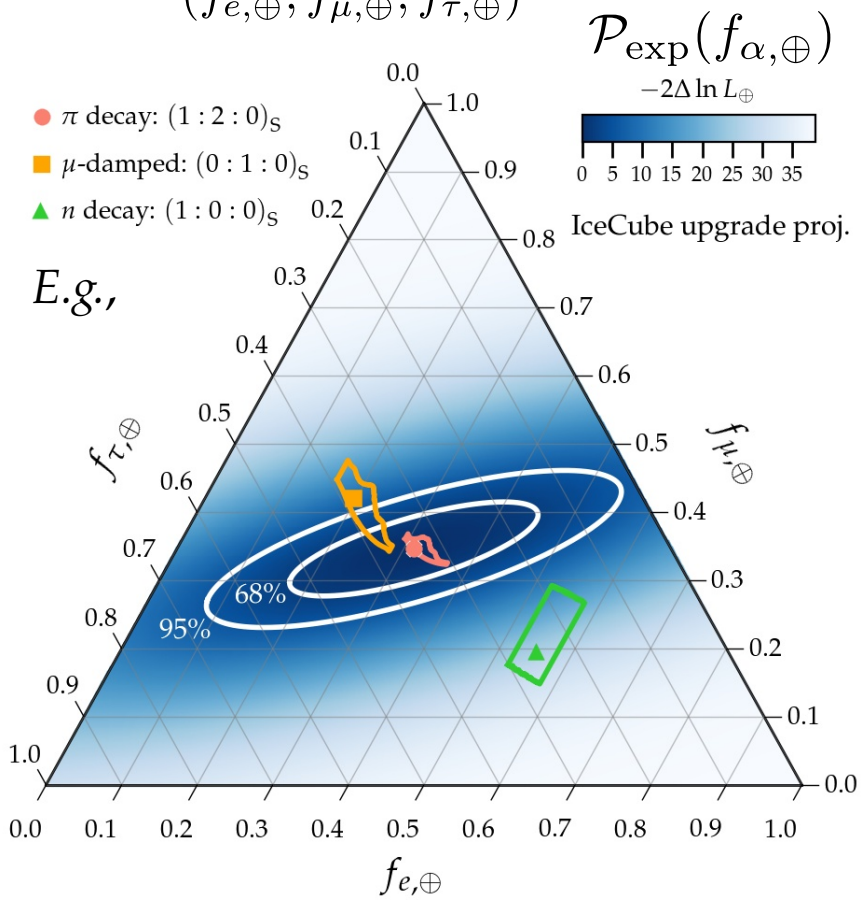
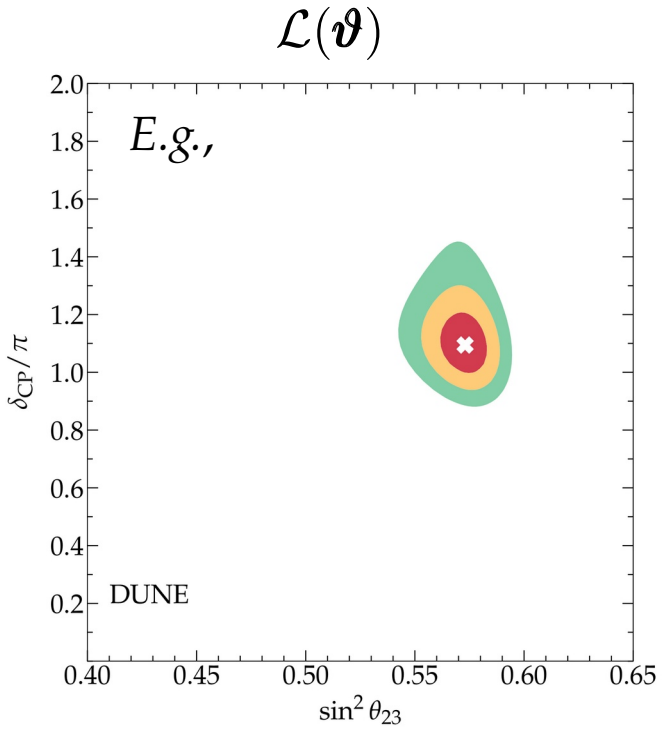


Ingredient #2:

Probability density of mixing parameters $(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\rm CP})$



Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
MB & Ahlers, *PRL* 2019

Inferring the flavor composition at the sources

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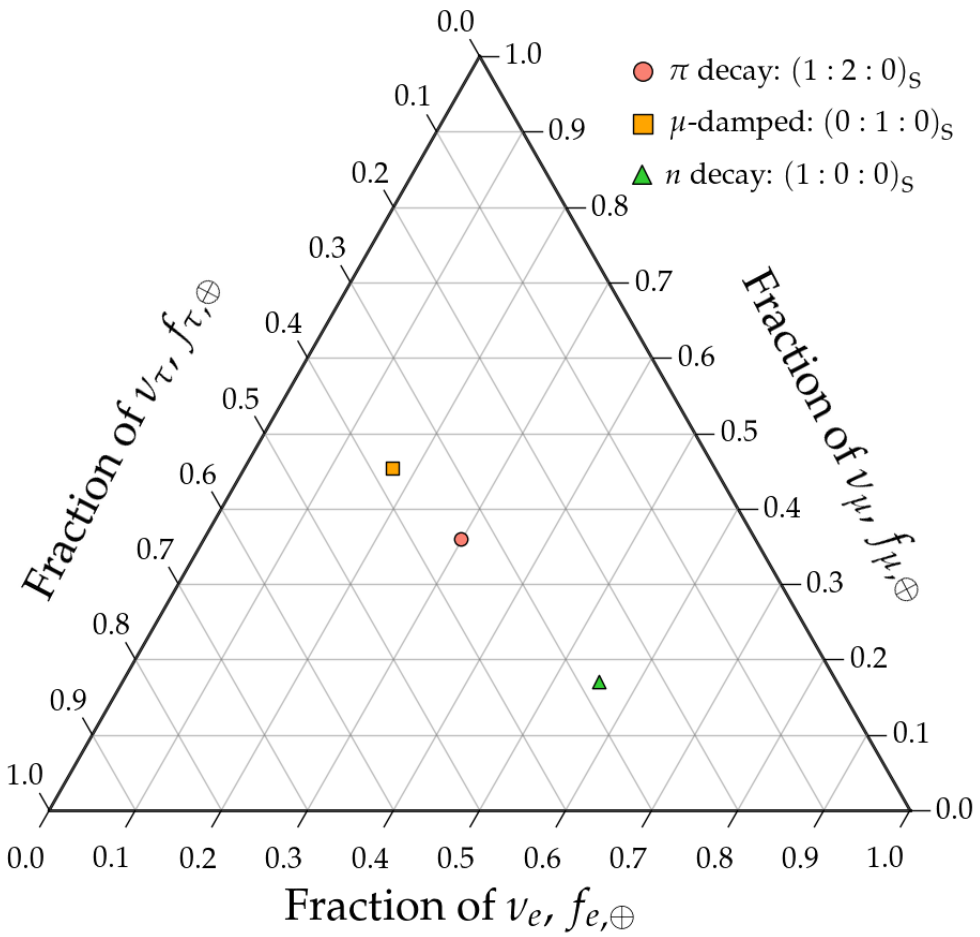

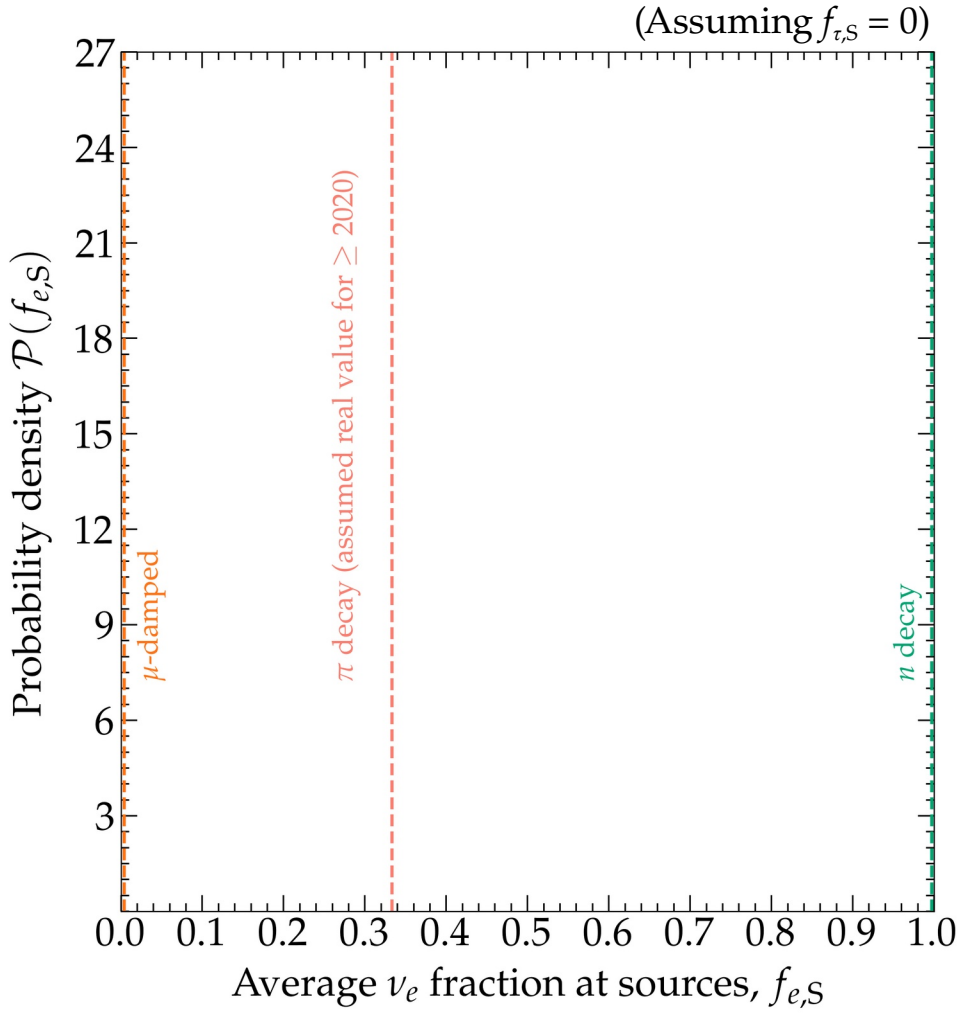

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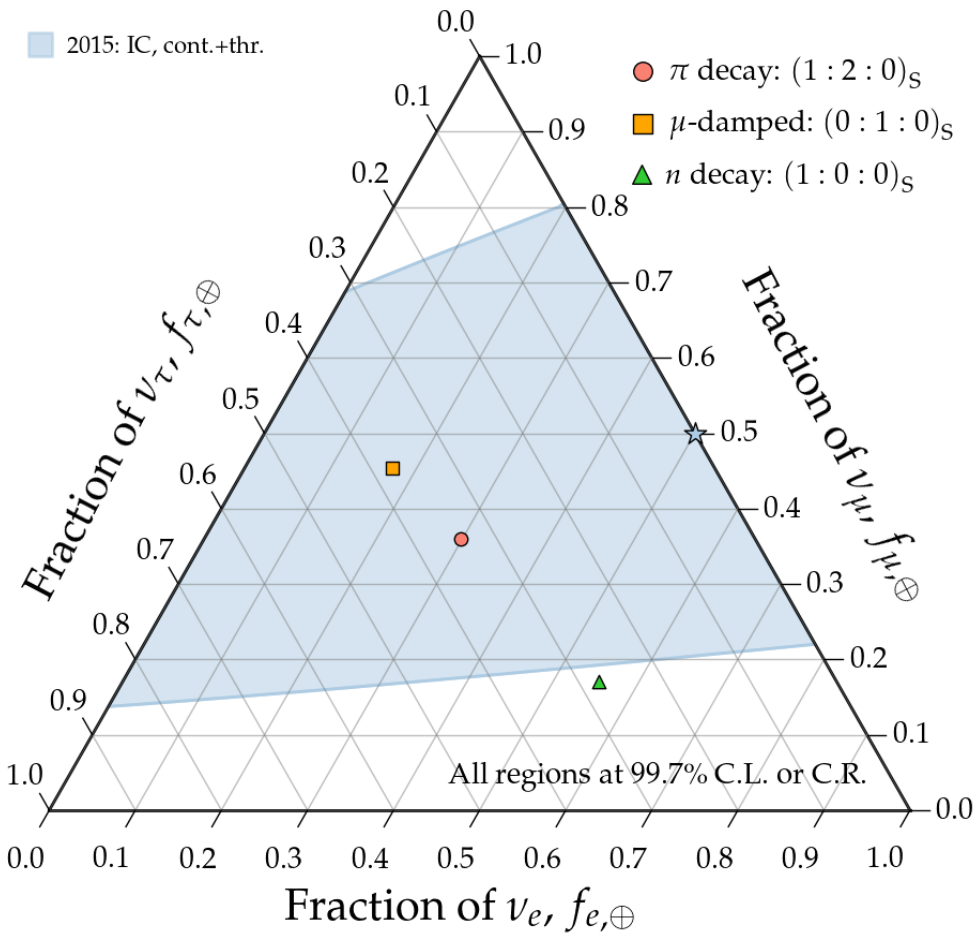
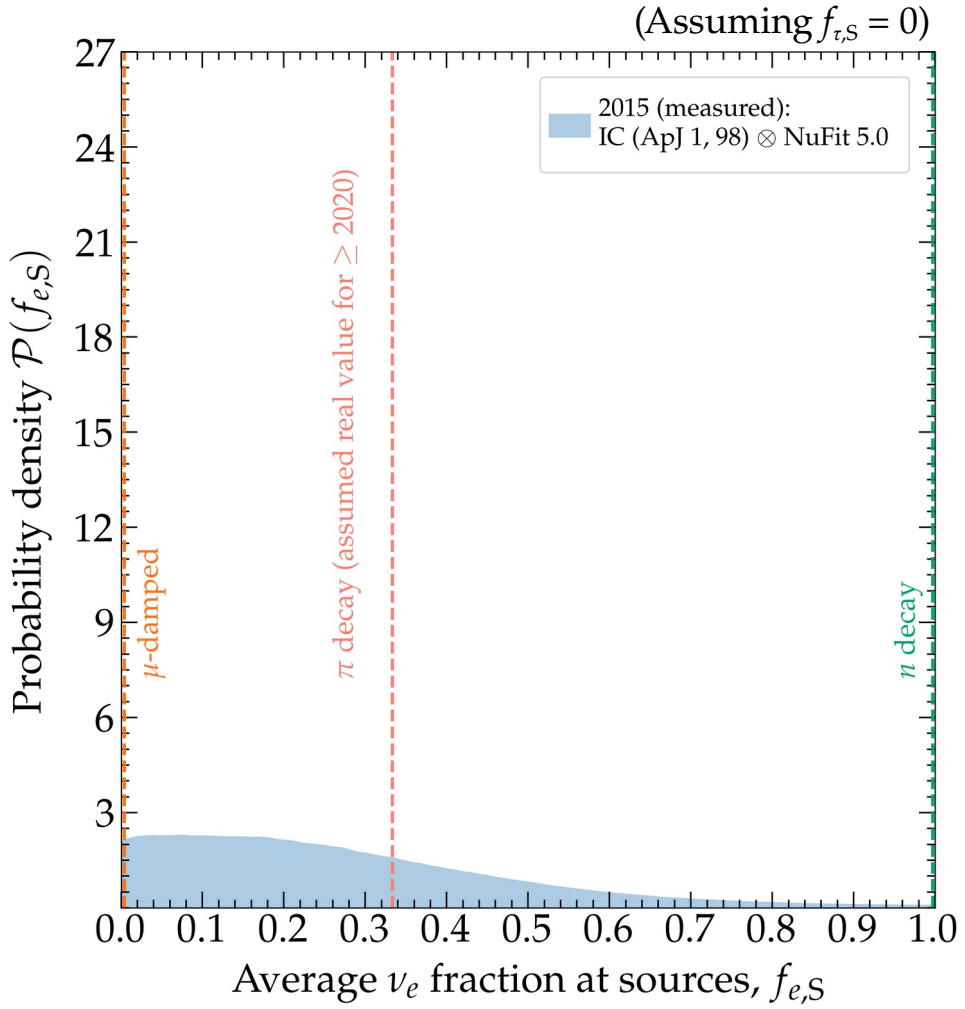
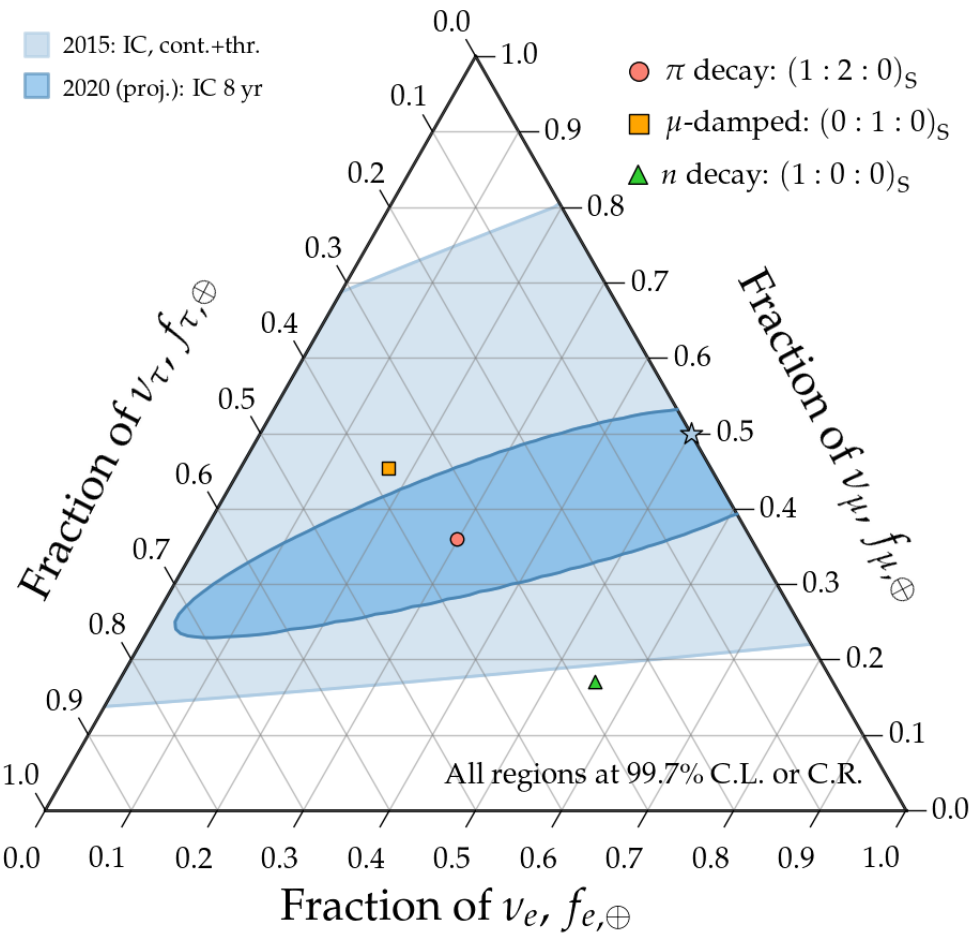
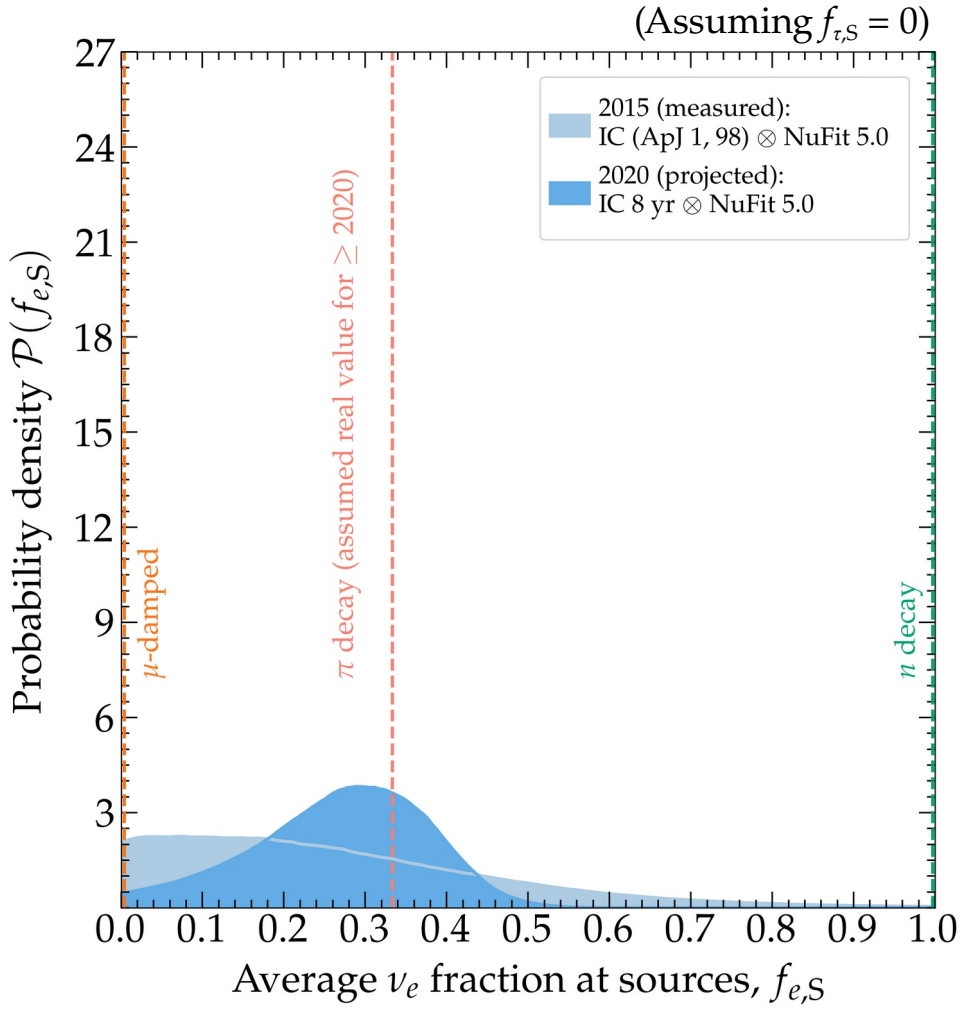




Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
MB & Ahlers, *PRL* 2019

Inferring the flavor composition at the sources





Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
MB & Ahlers, *PRL* 2019

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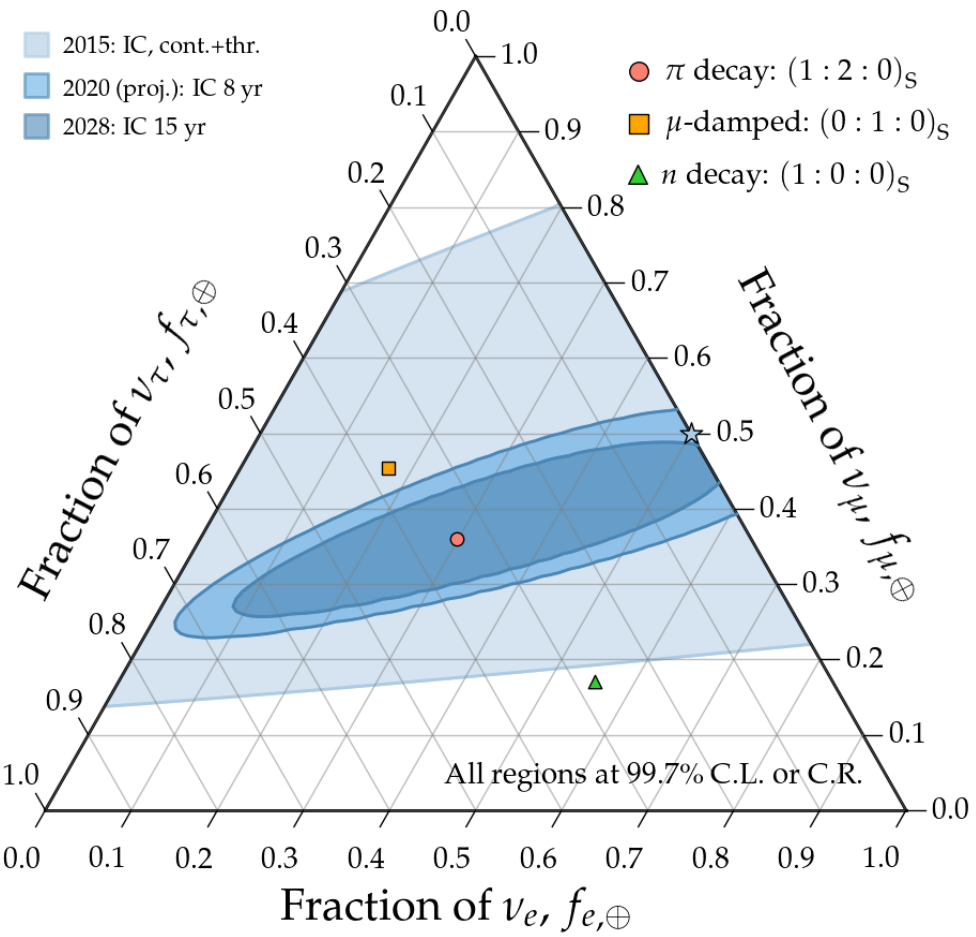

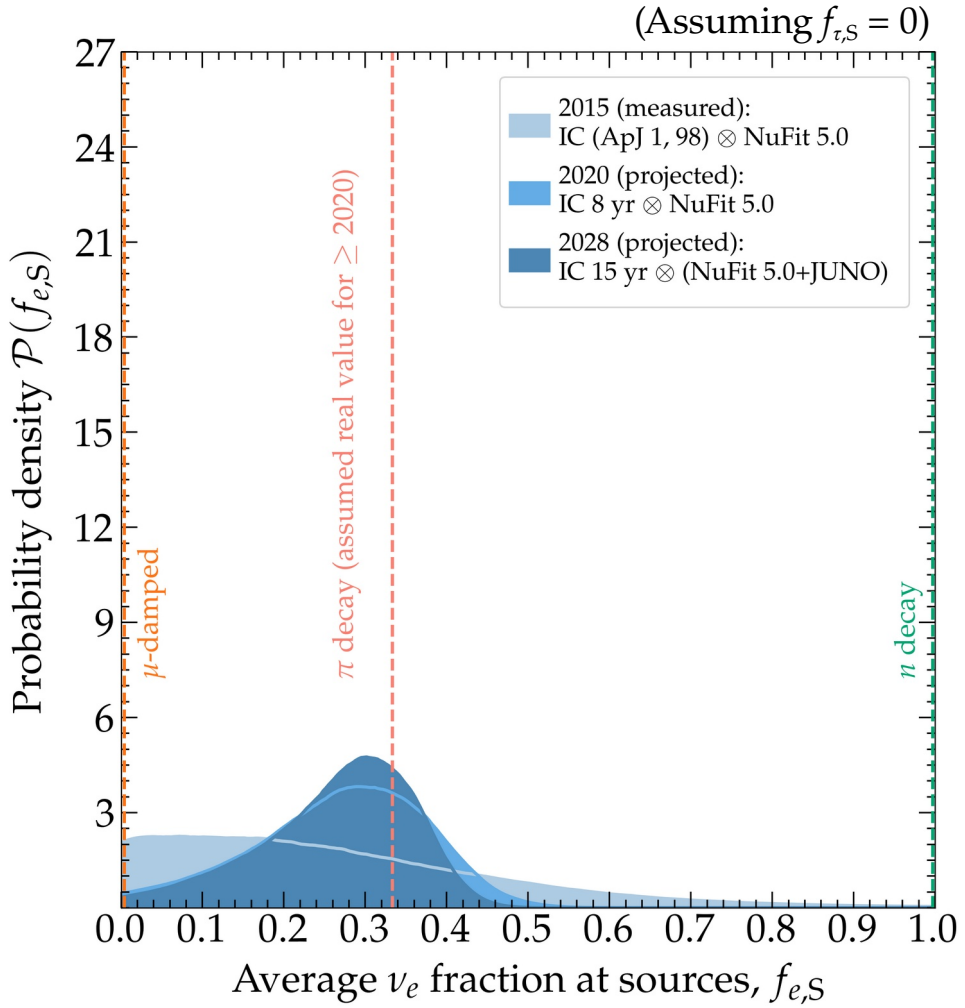

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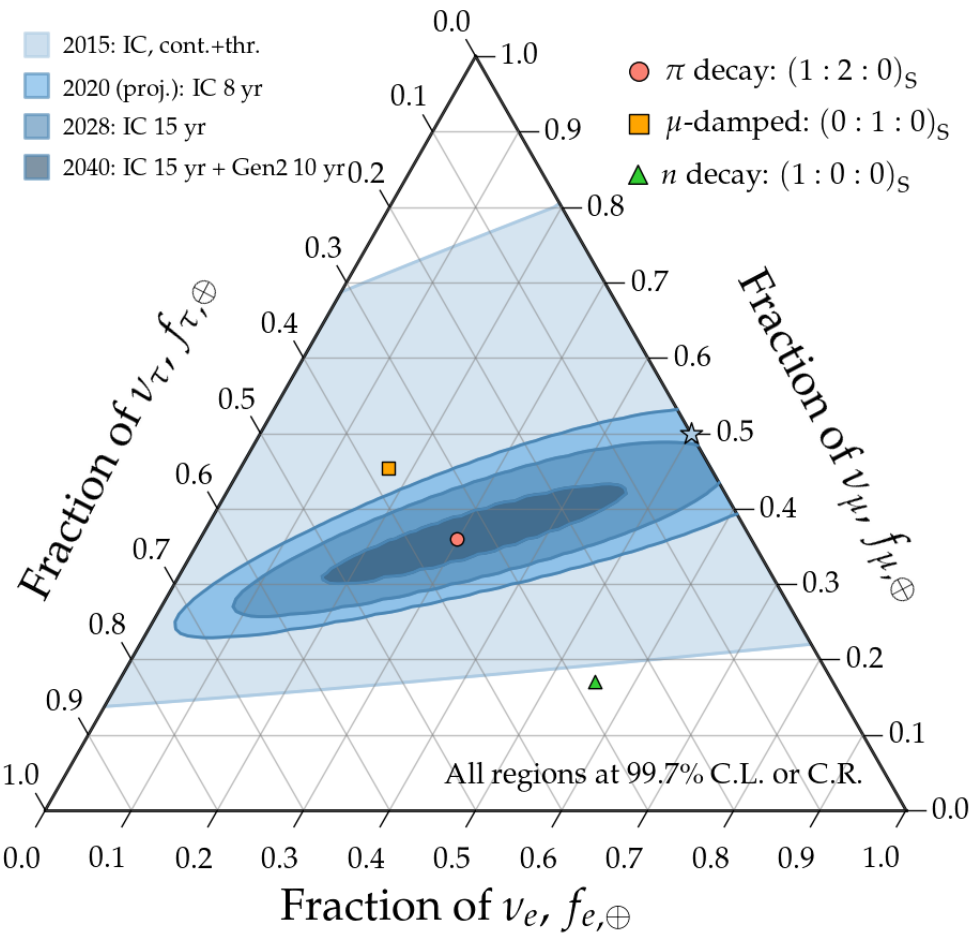

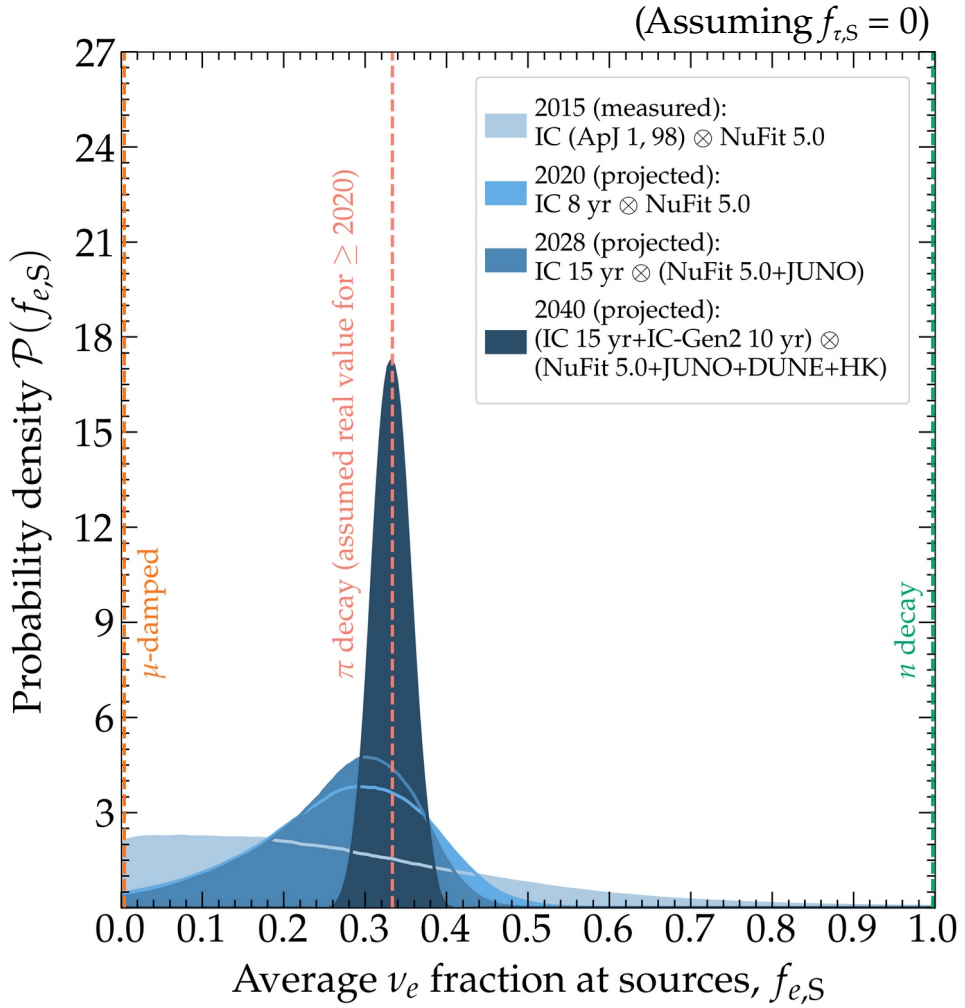

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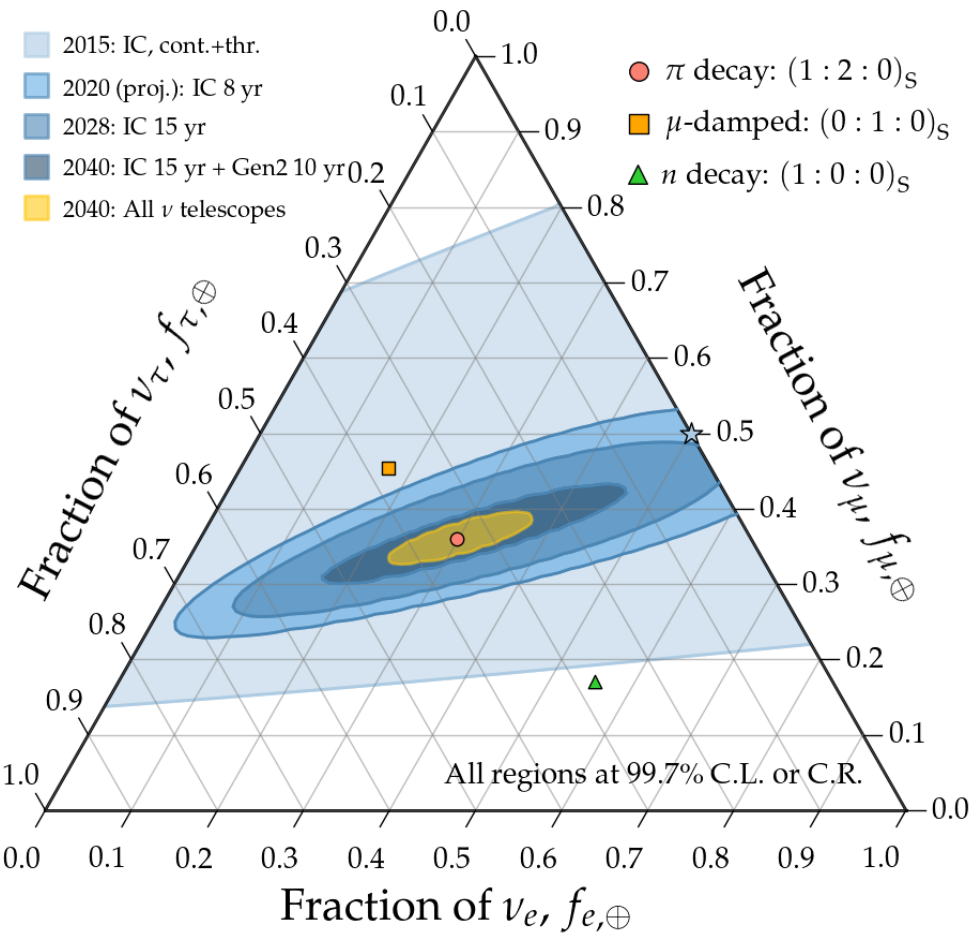
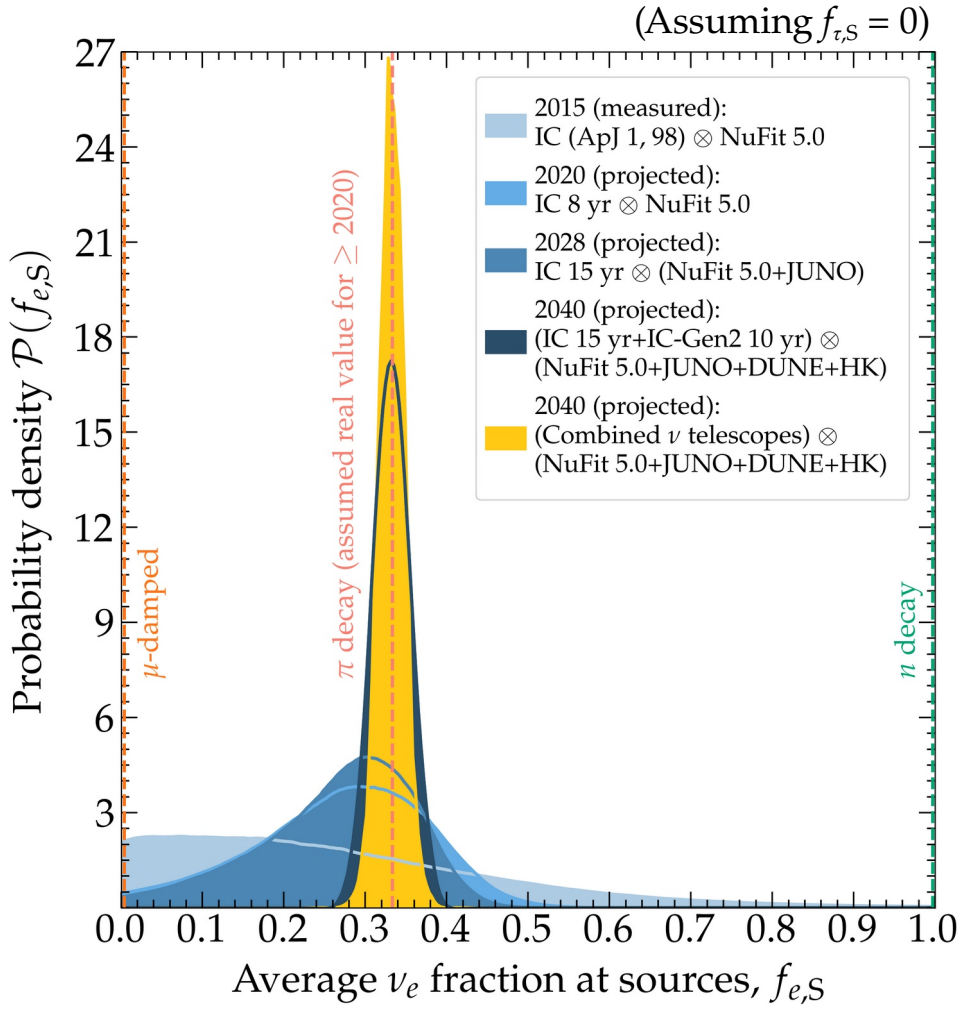
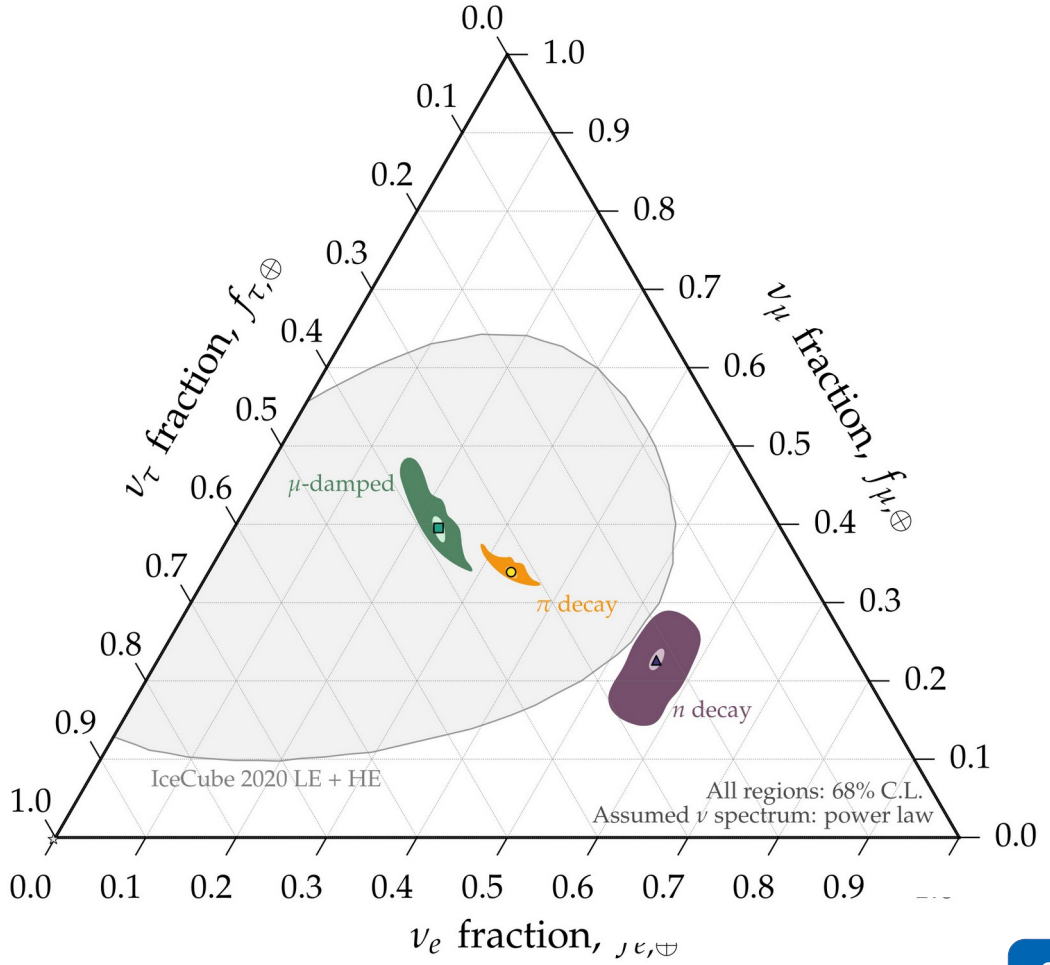




Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
MB & Ahlers, *PRL* 2019

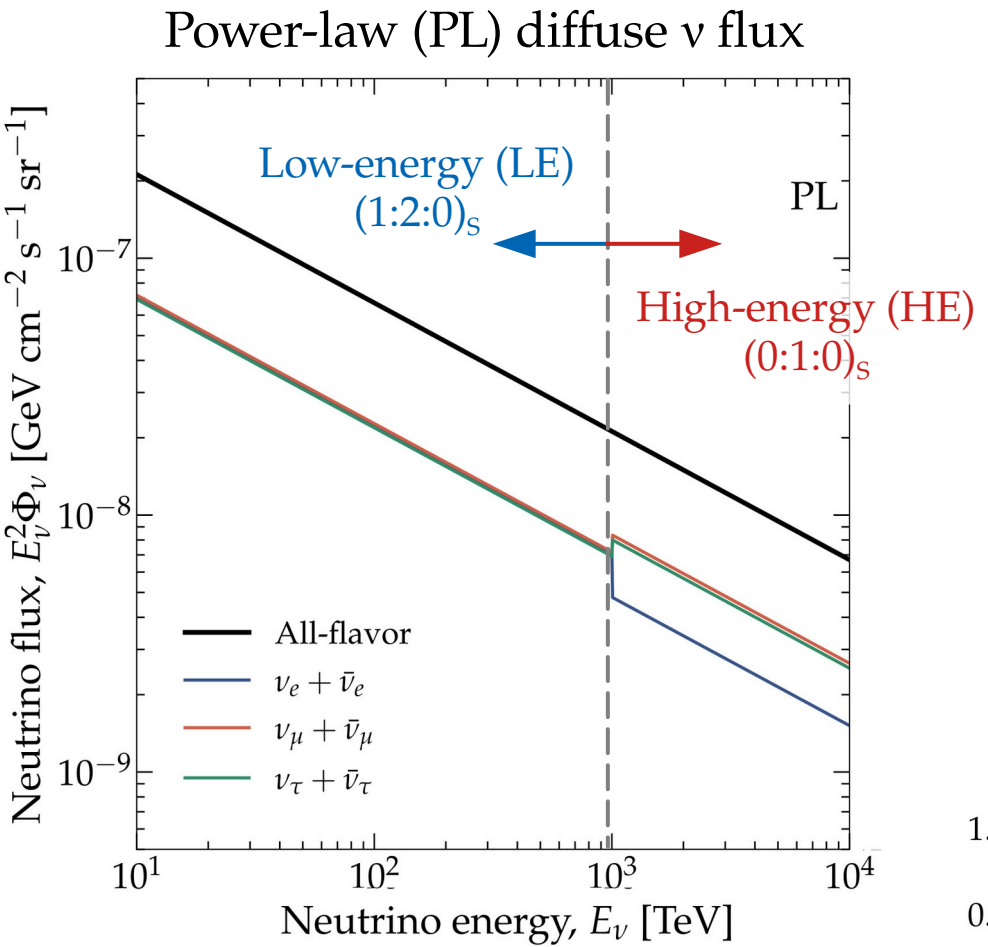
Measuring energy-dependent flavor composition

Flavor composition: measuring the energy dependence

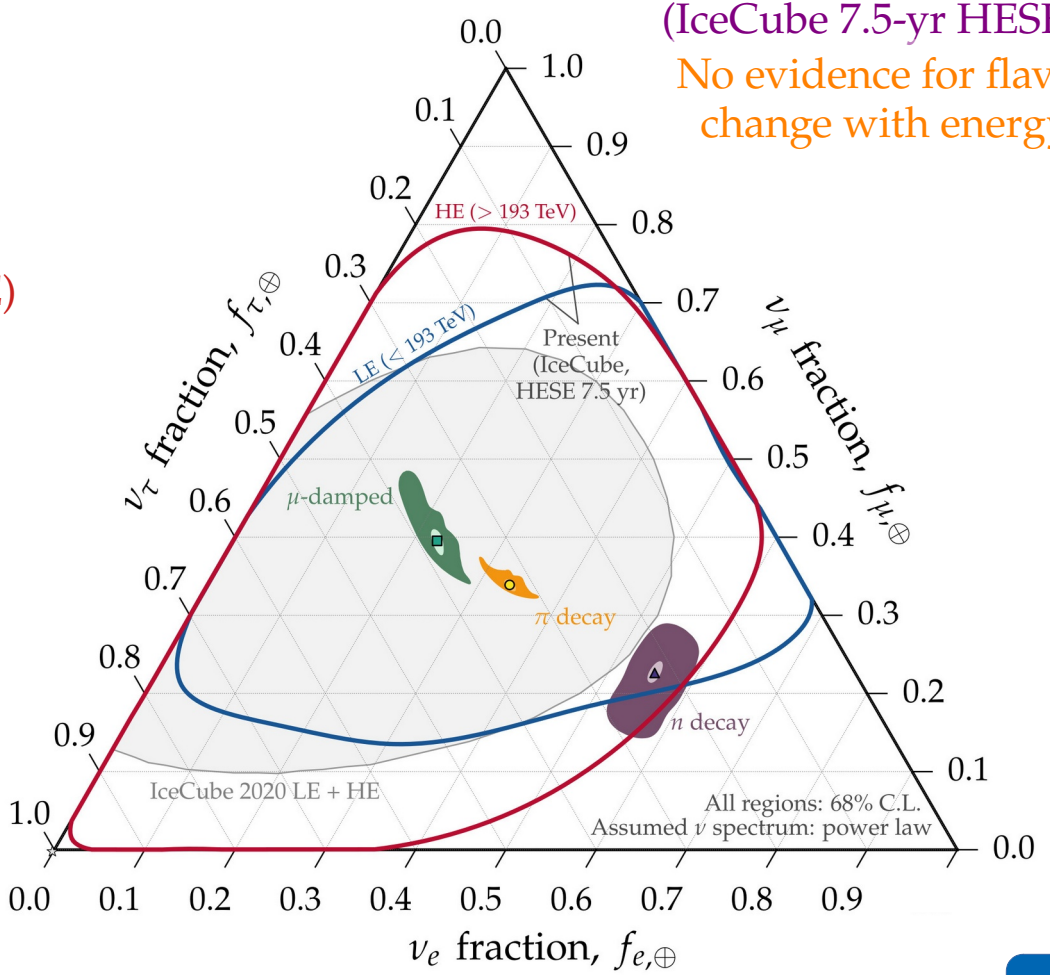


Liu, Fiorillo, Argüelles, **MB**, Song, Vincent, 2312.07649

Flavor composition: measuring the energy dependence

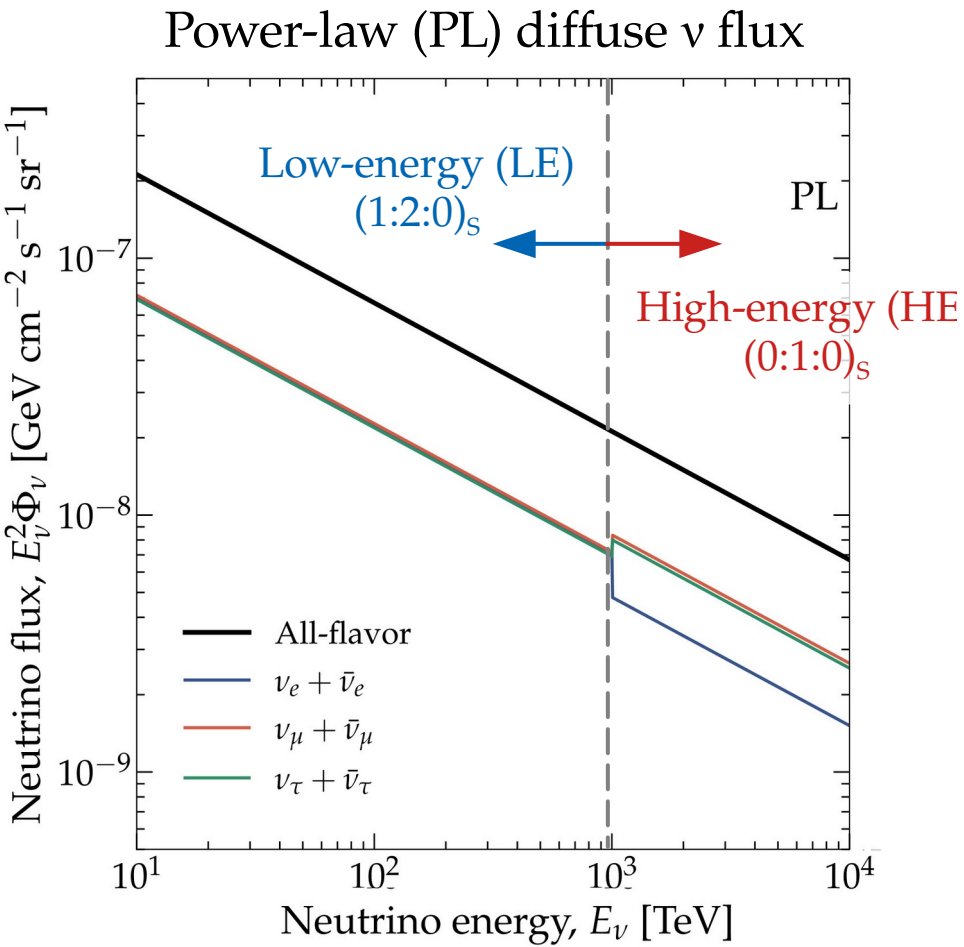


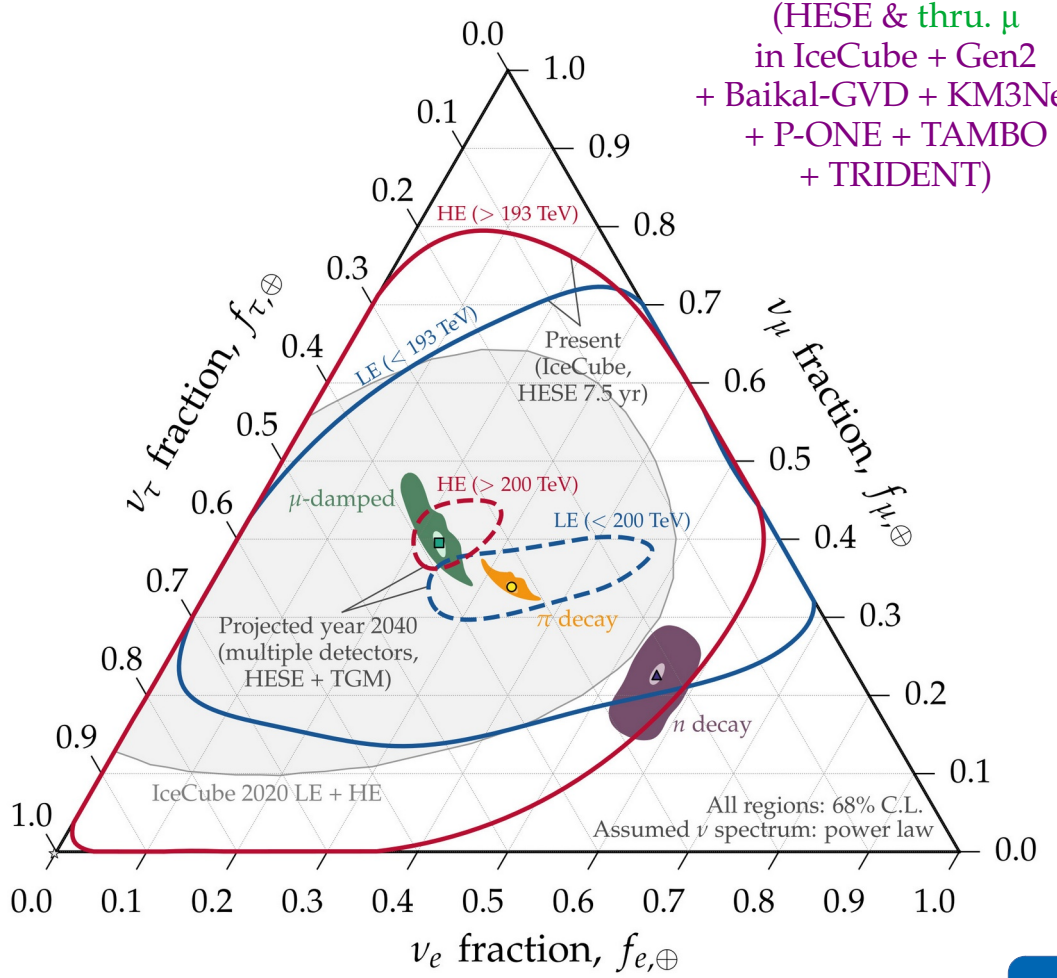
Today
(IceCube 7.5-yr HESE):
No evidence for flavor change with energy



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

Flavor composition: measuring the energy dependence





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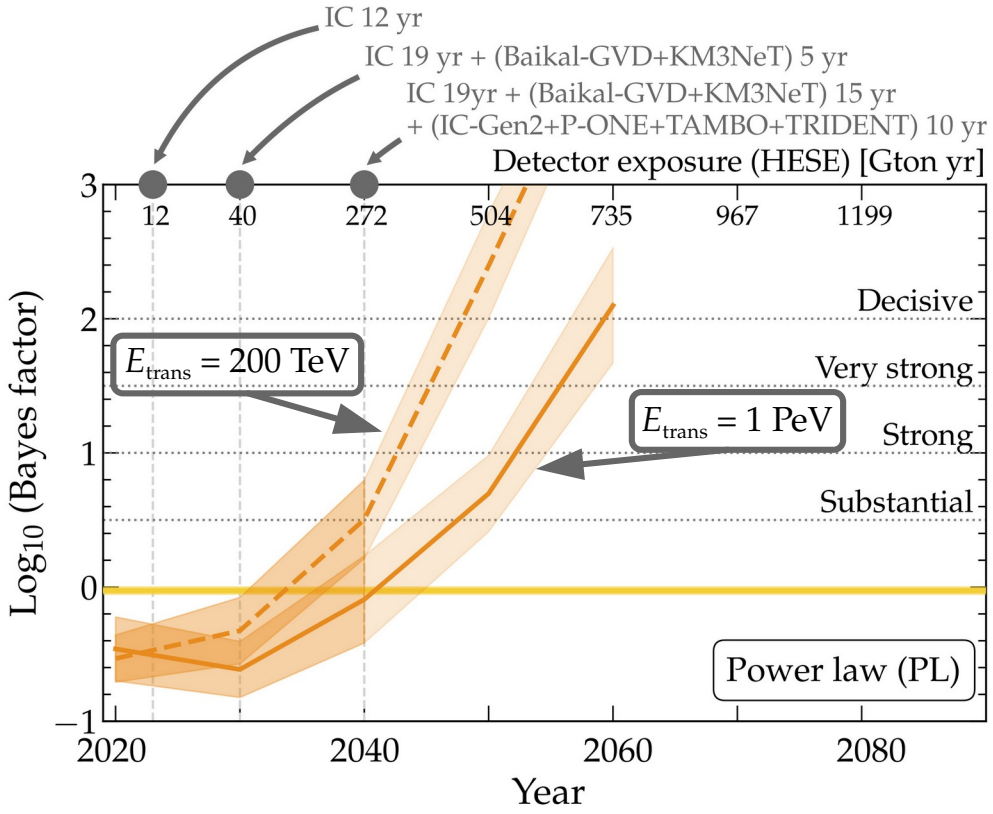
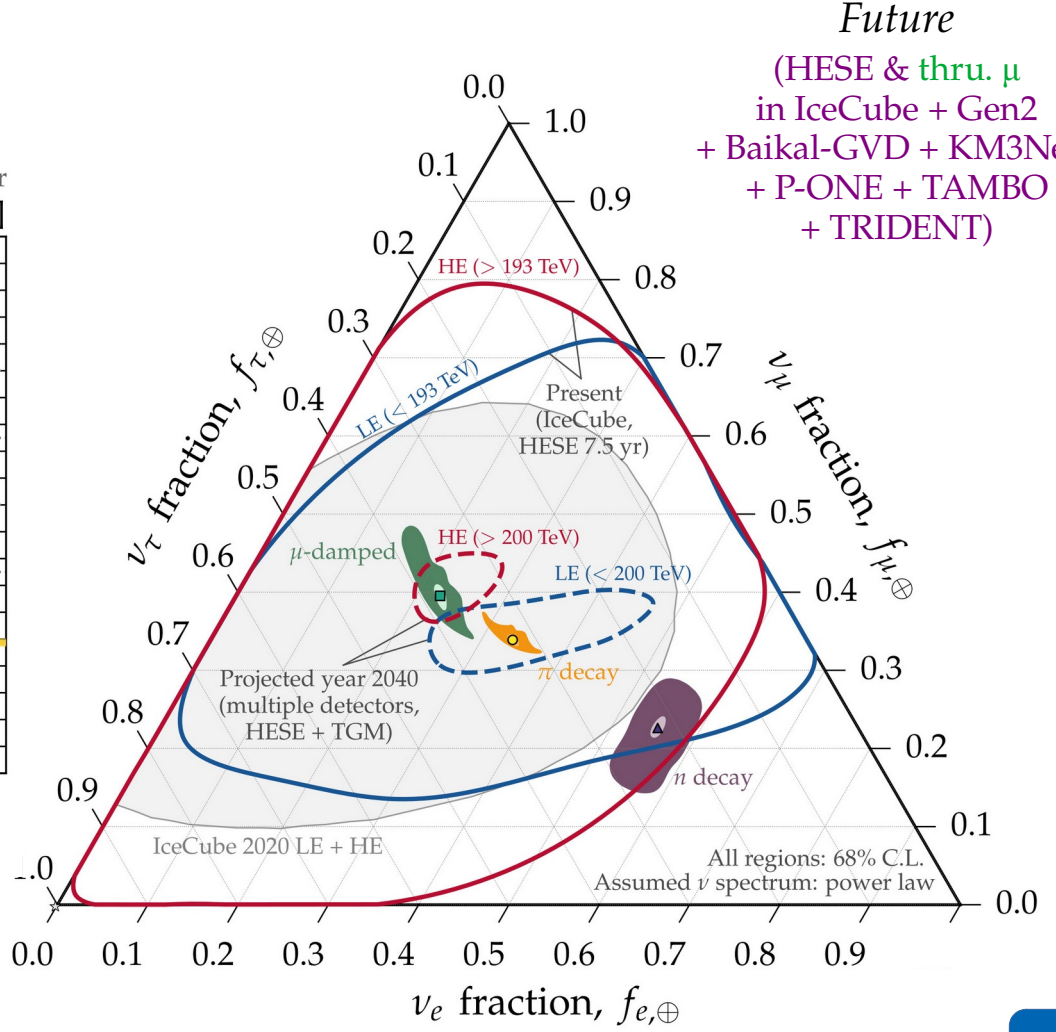
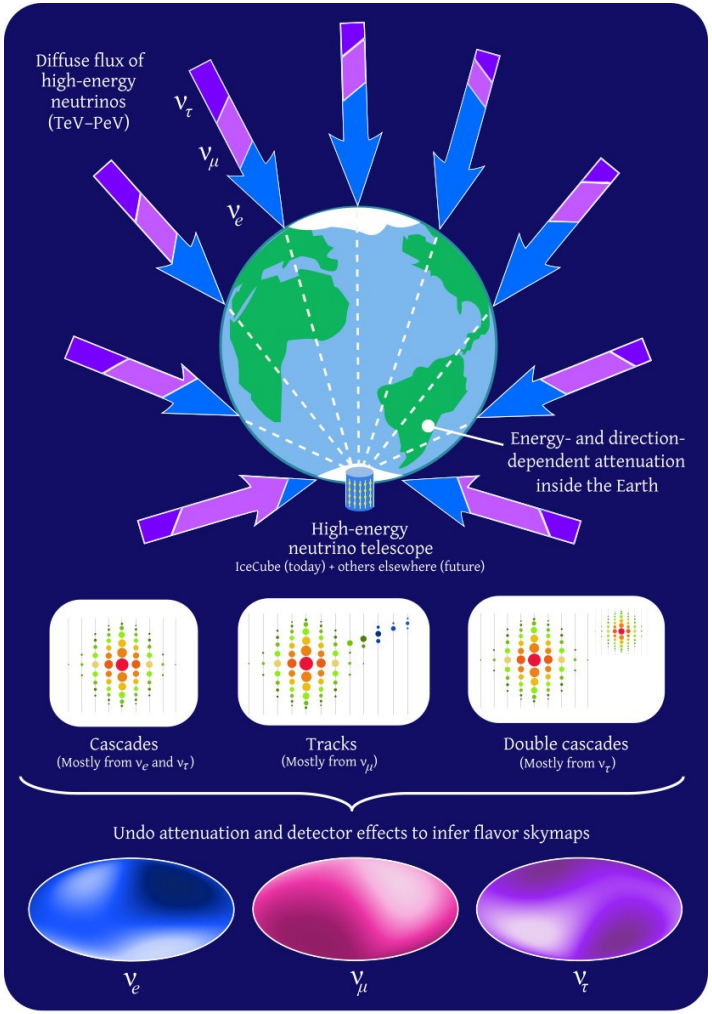




Liu, Fiorillo, Argüelles, **MB**, Song, Vincent, 2312.07649

Measuring flavor anisotropy

Flavor anisotropy in the high-energy neutrino sky



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

Telalovic, **MB**, 2310.15224

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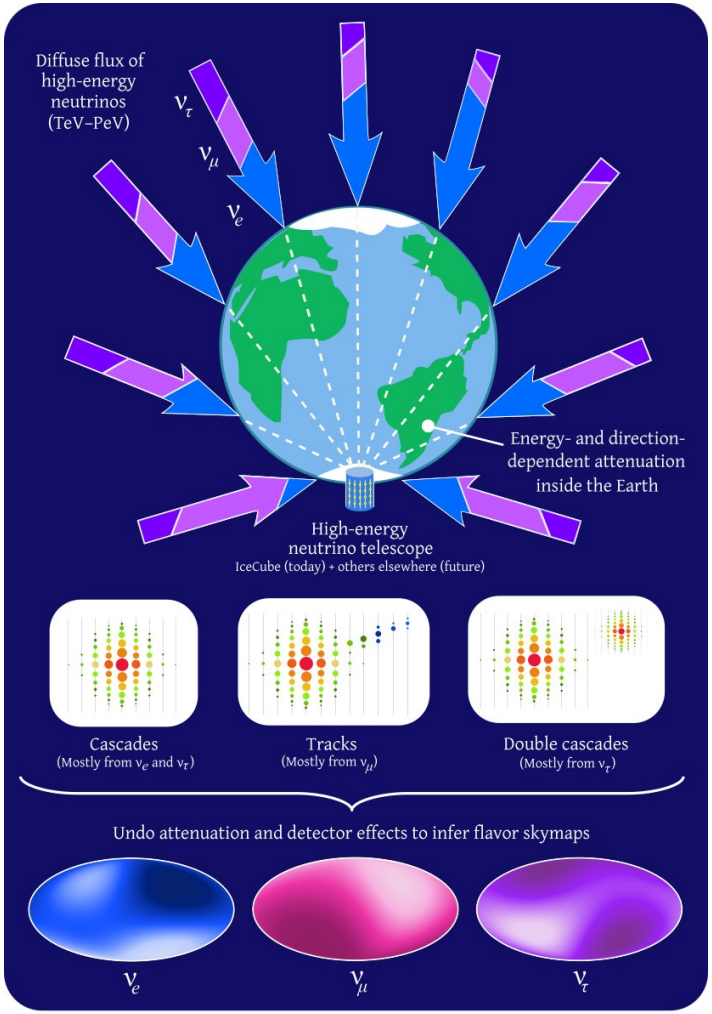

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From the angular distribution of detected events in neutrino telescopes (HESE cascades, tracks, double cascades) …

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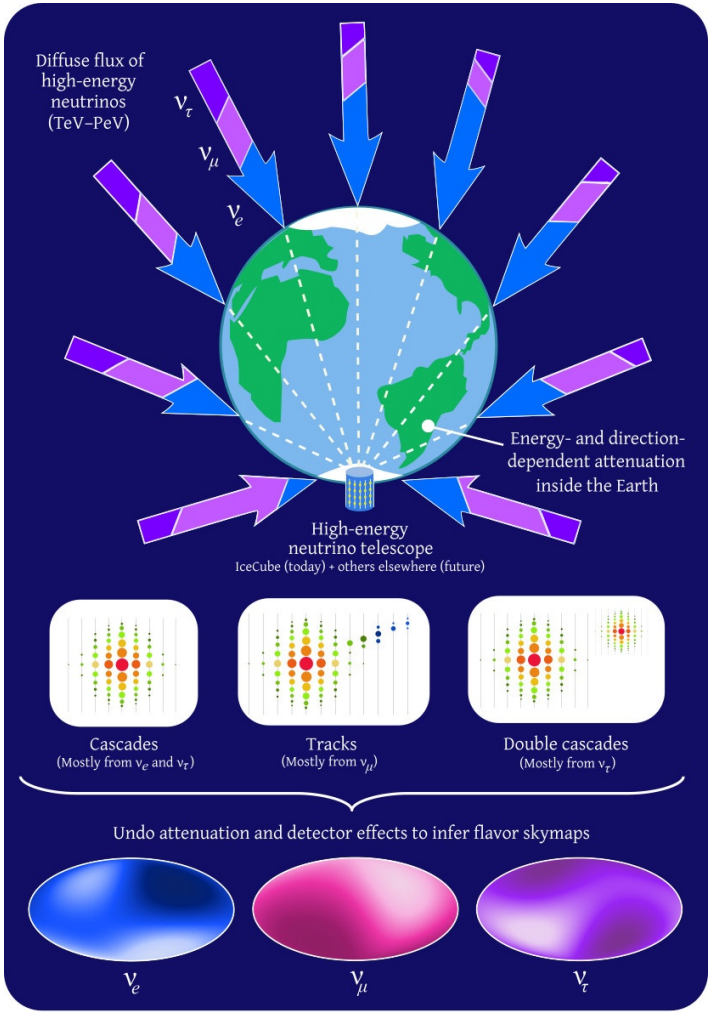

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… we infer the directional dependence of the diffuse fluxes of ν_e, ν_μ, ν_τ

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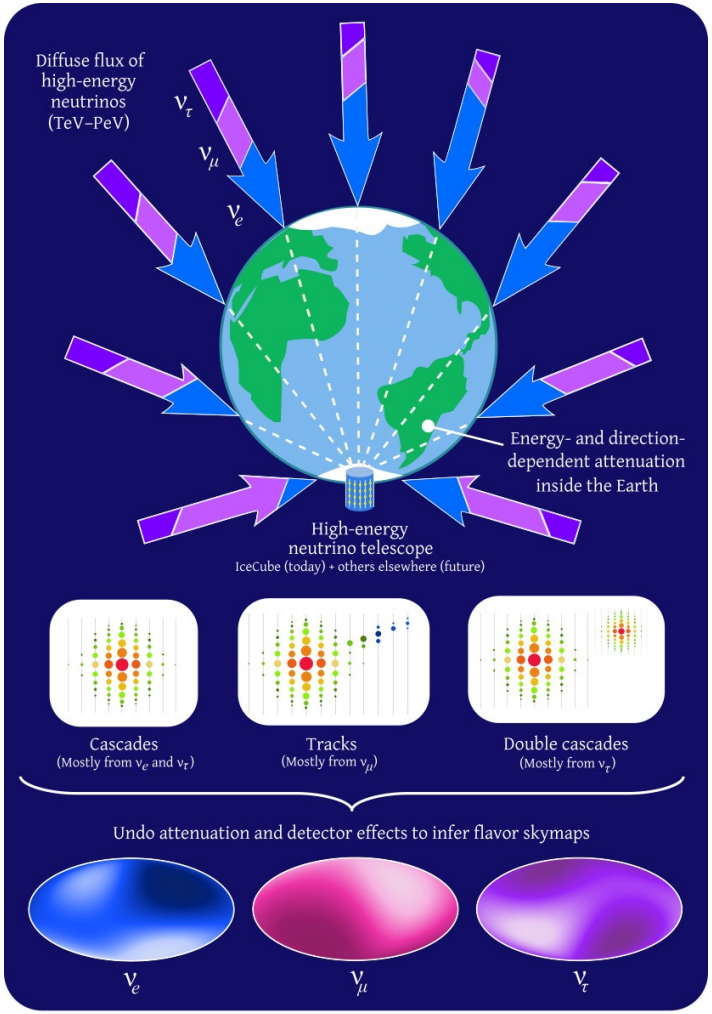

Does the high-energy sky shine equally brightly In neutrinos of all flavors?

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

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

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

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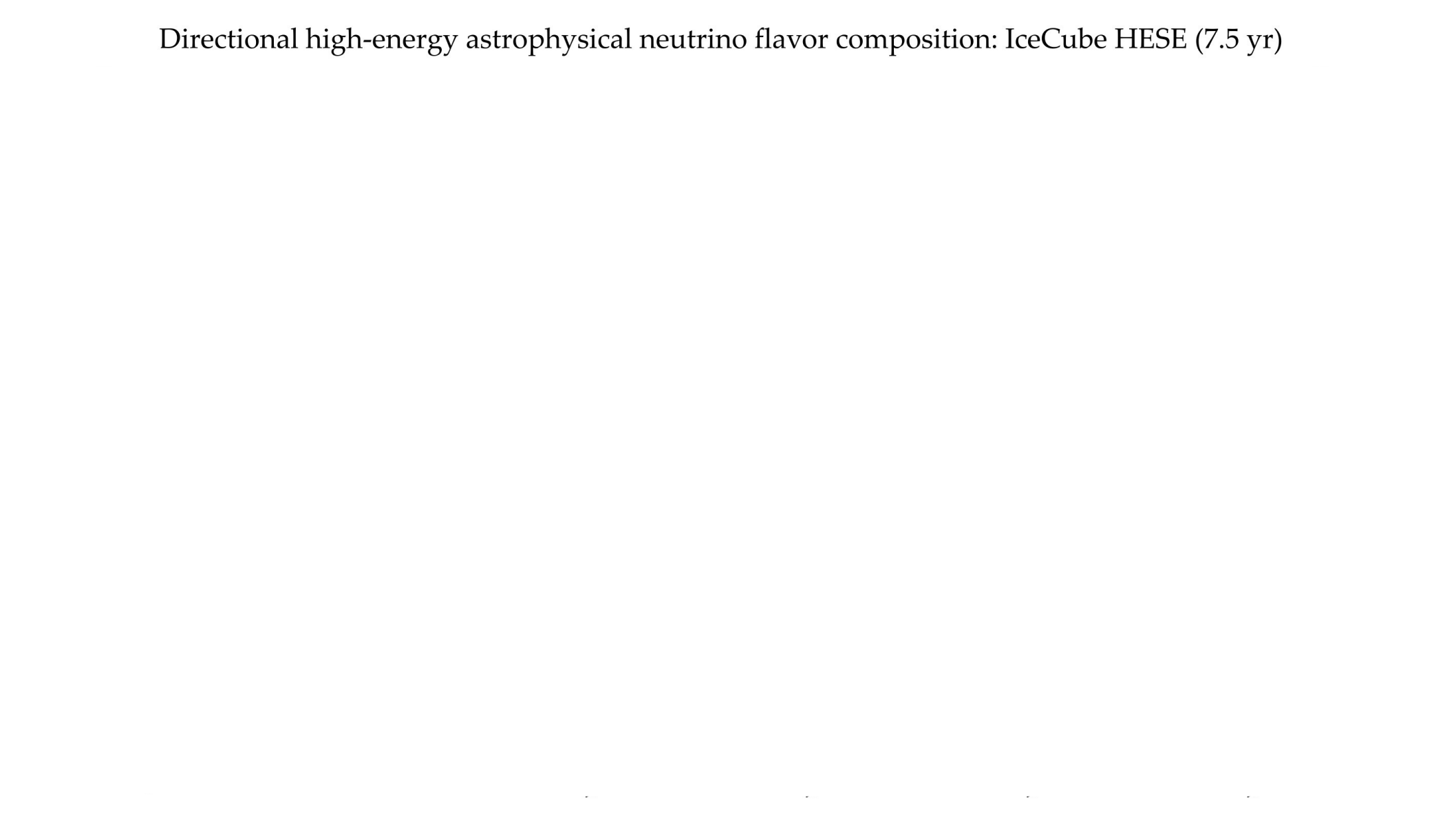
Directional high-energy astrophysical neutrino flavor composition: IceCube HESE (7.5 yr)

Real, public data

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



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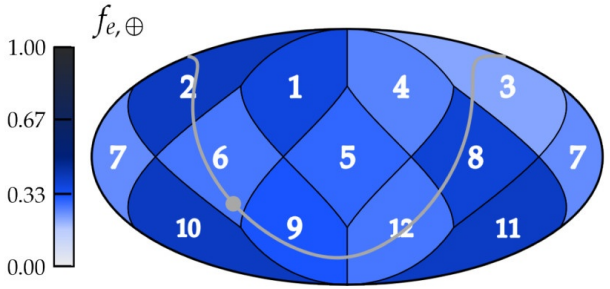

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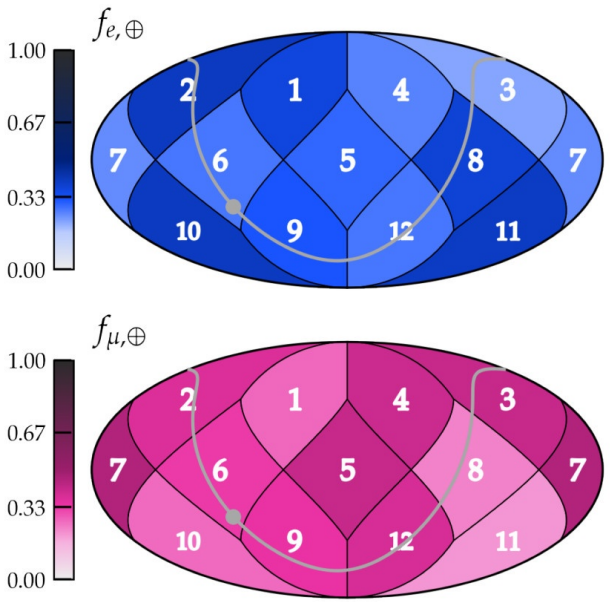

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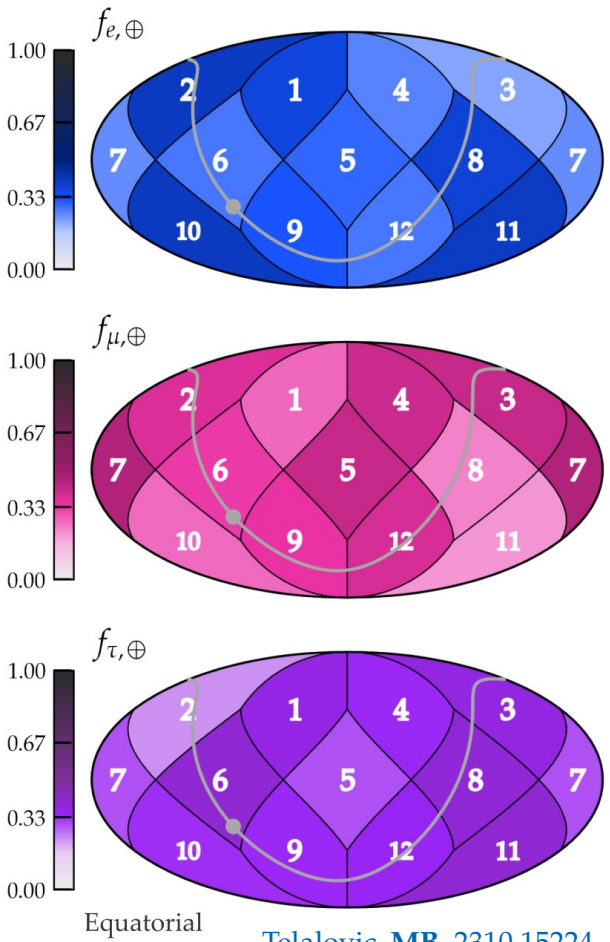

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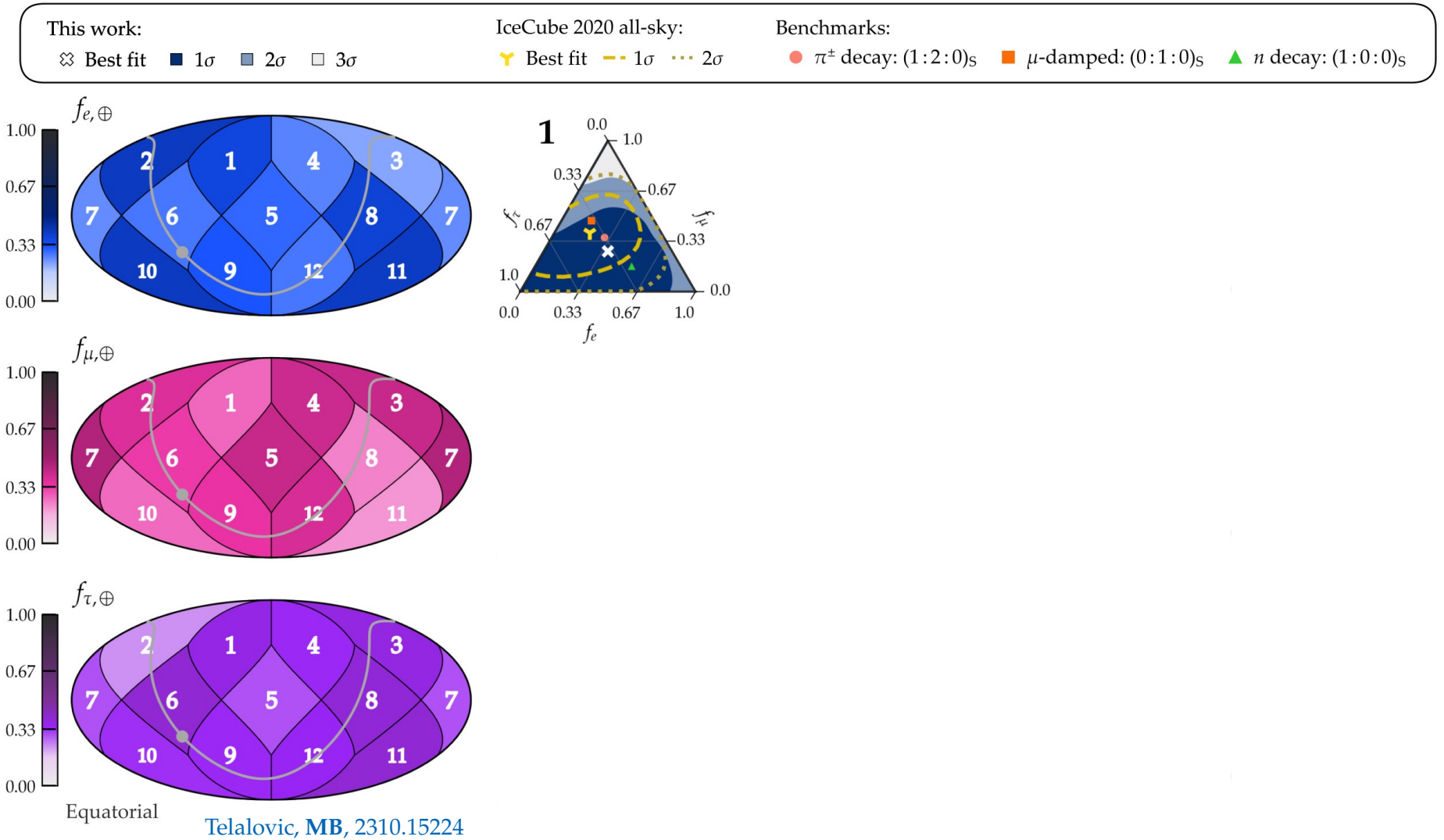

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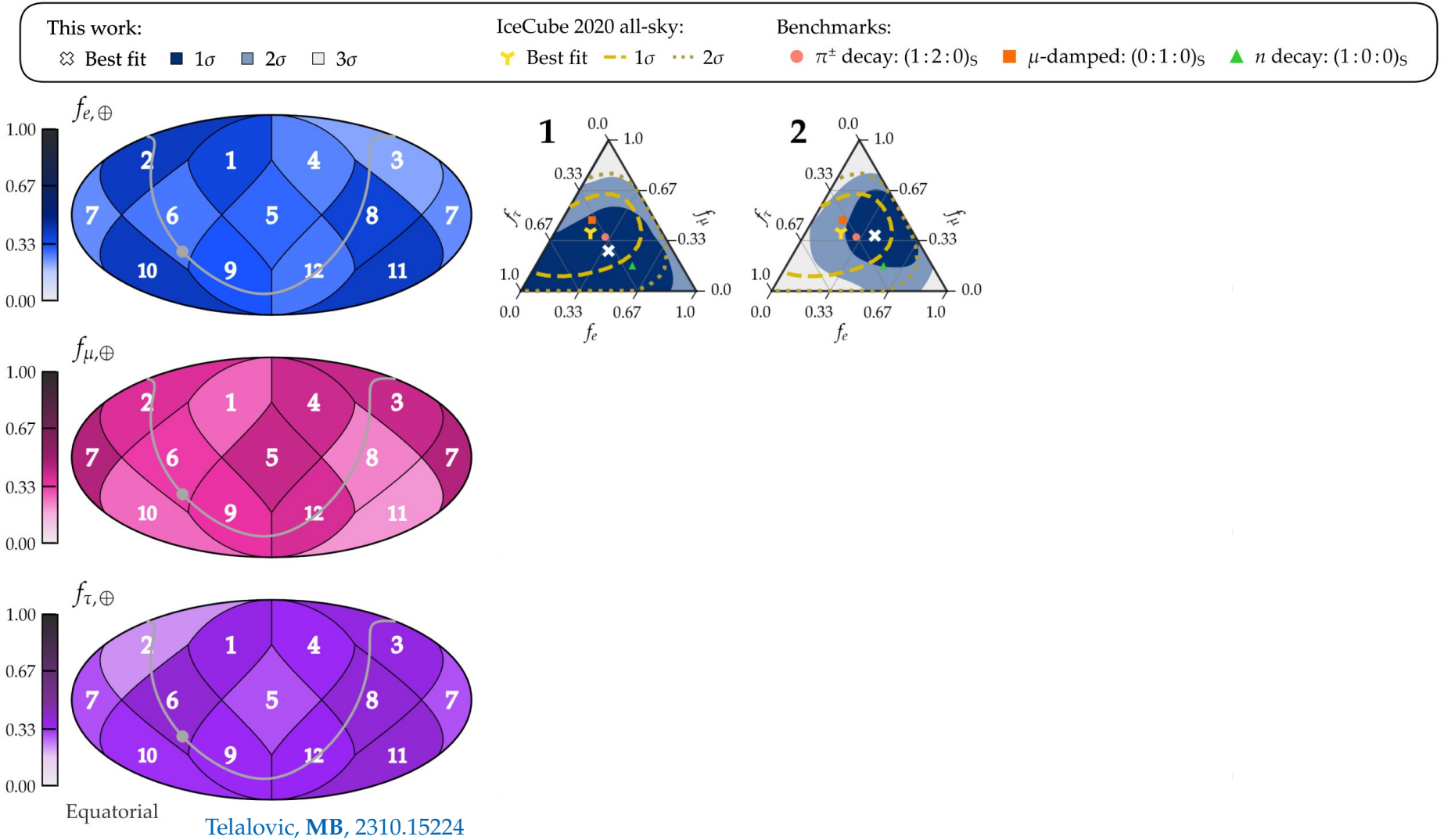

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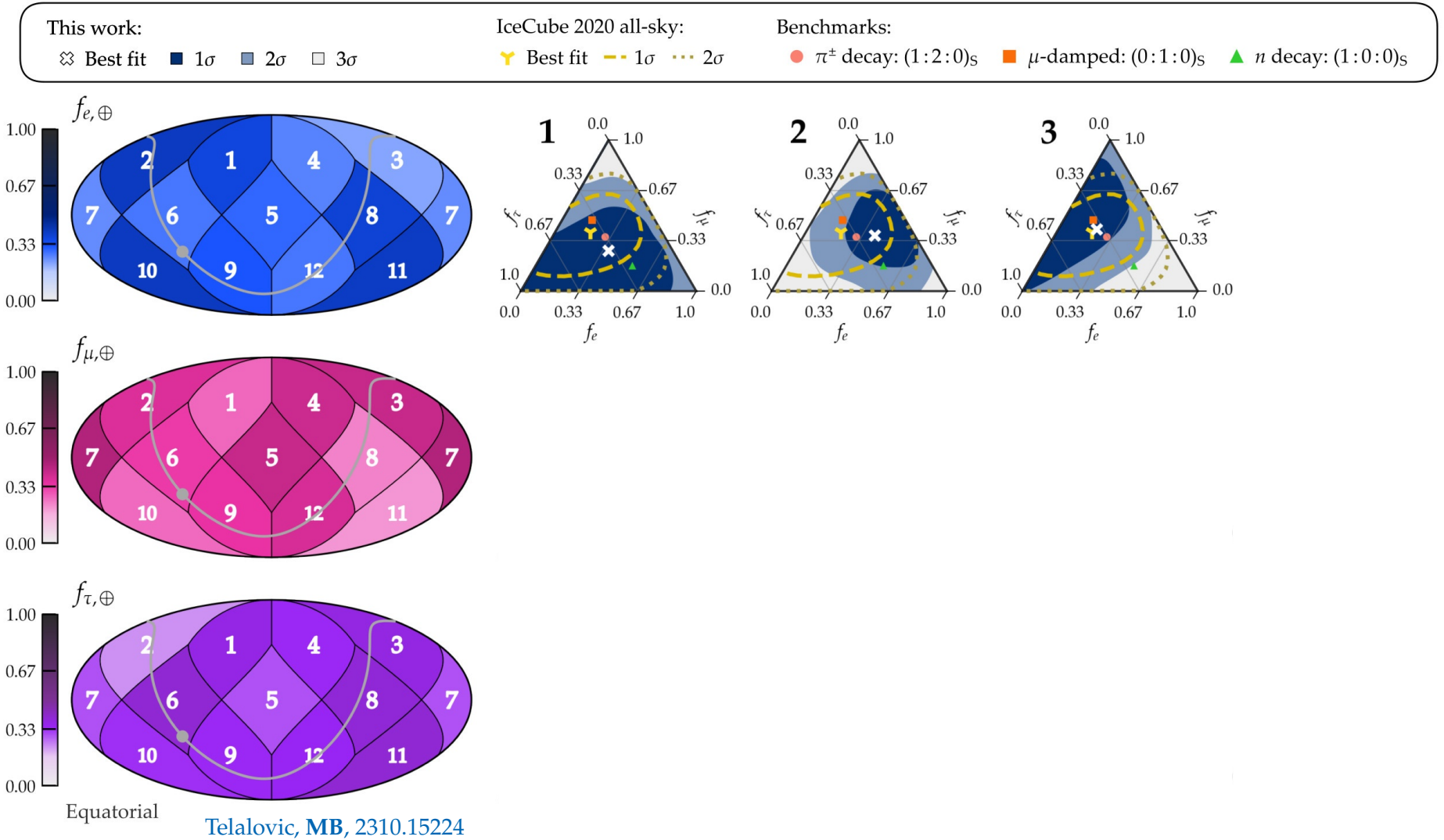

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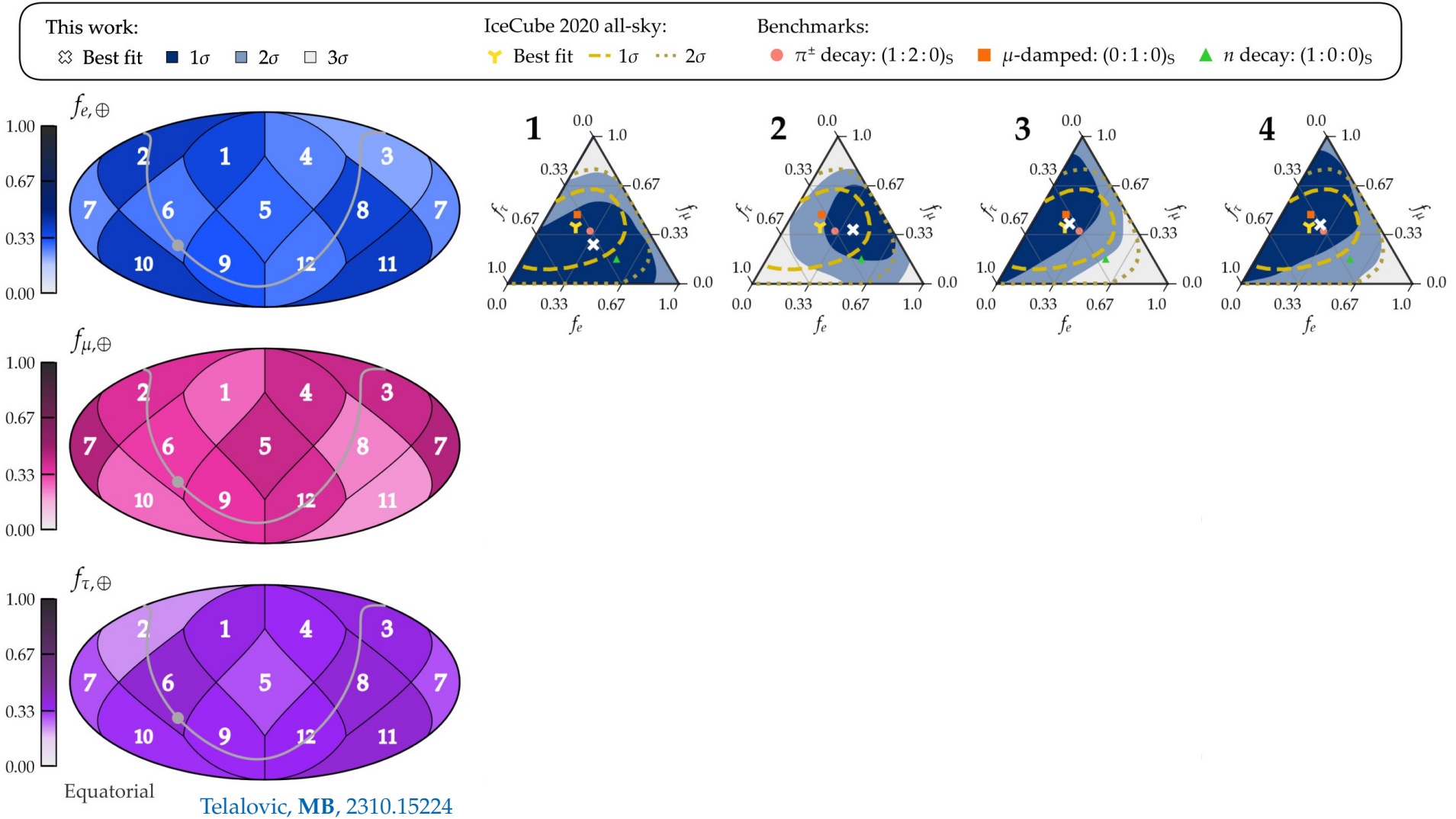

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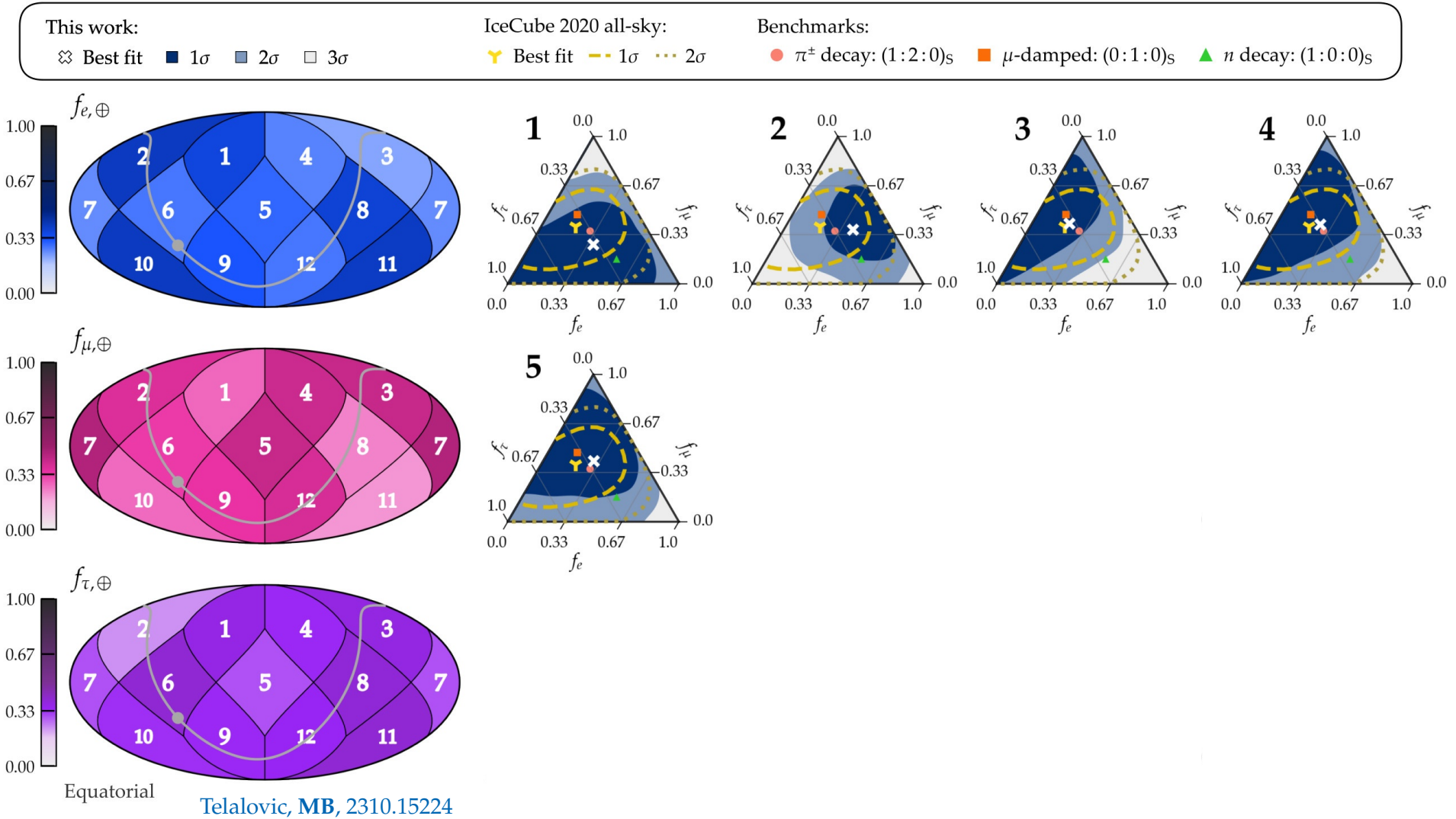

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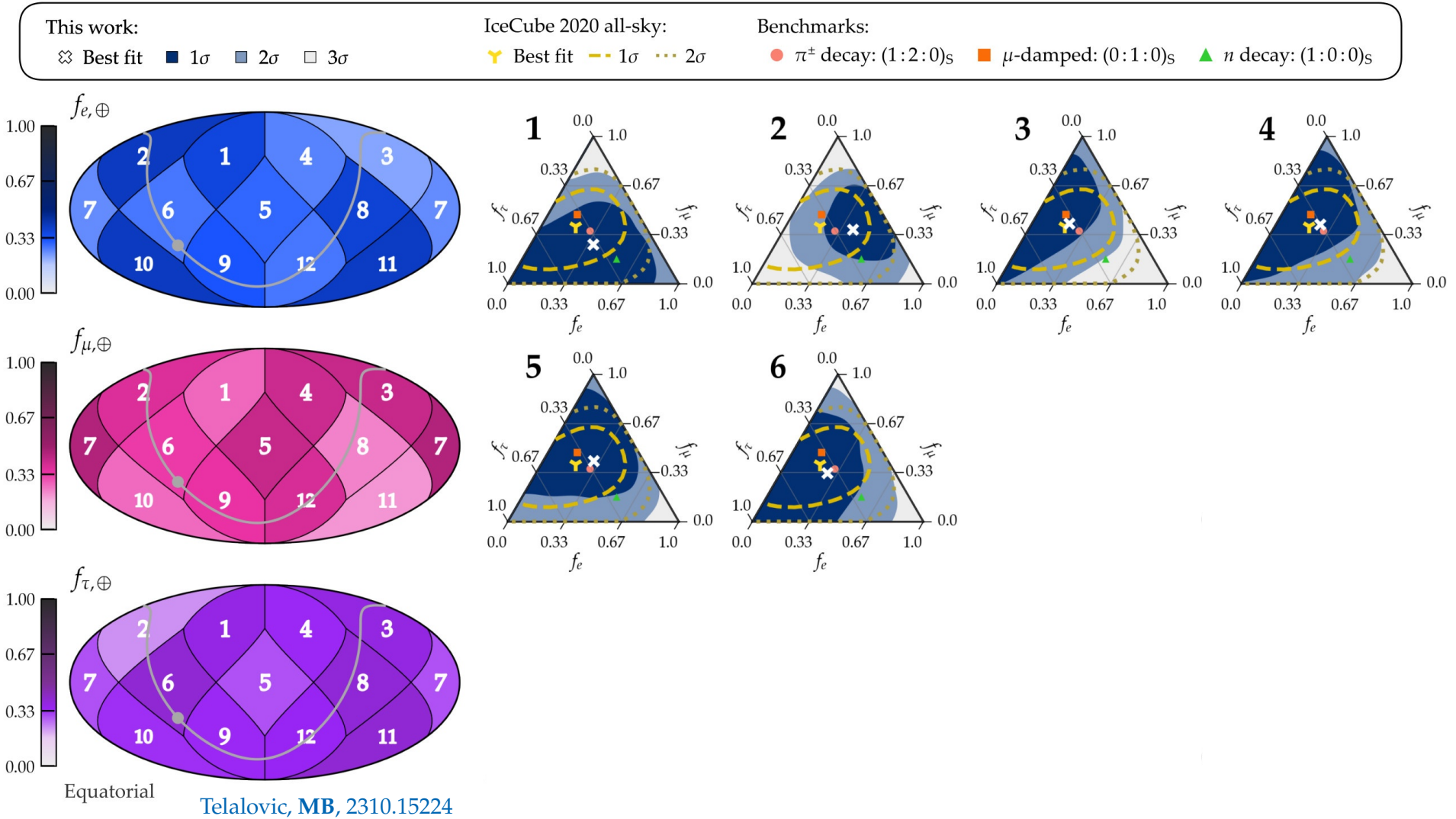

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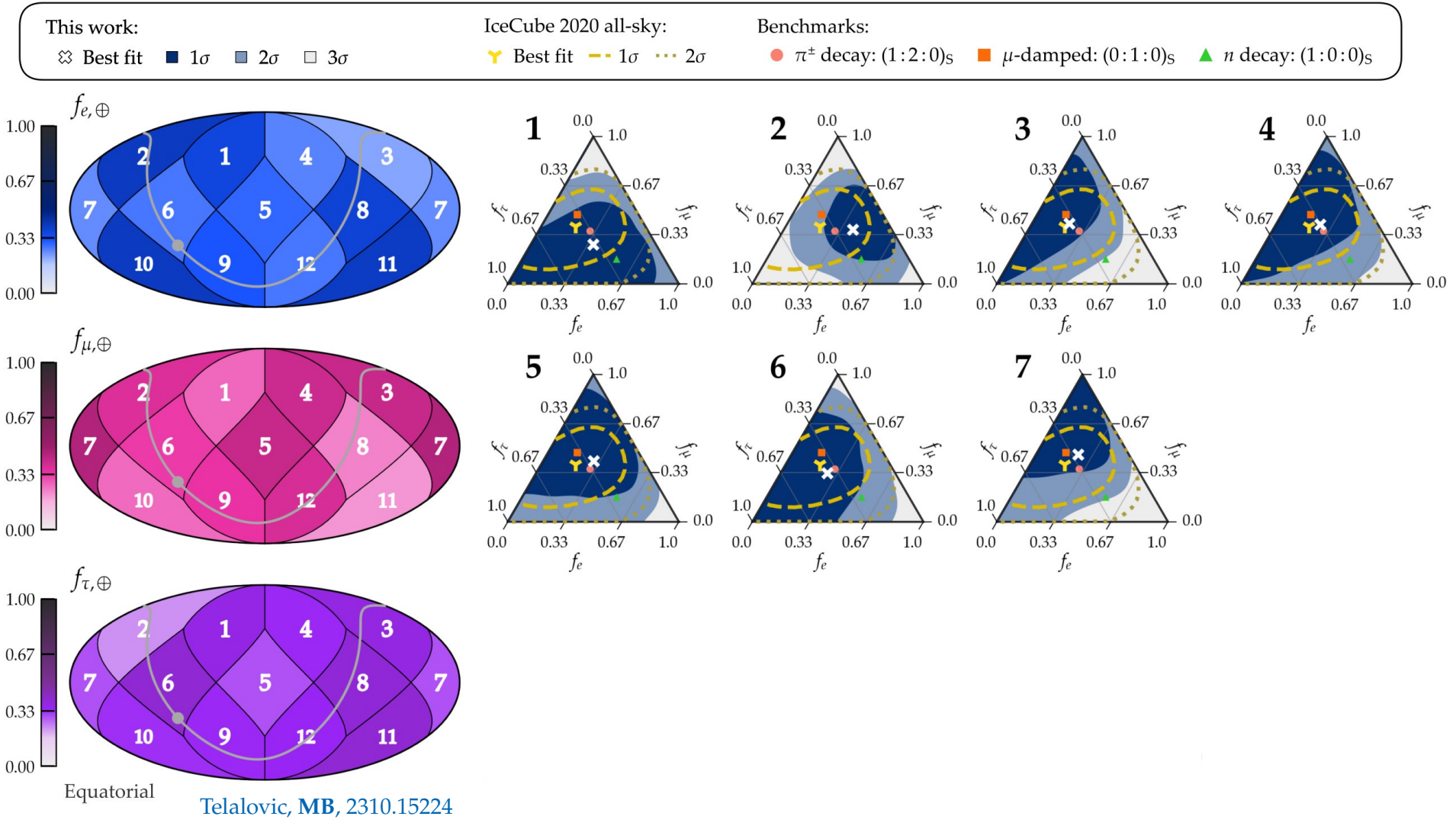

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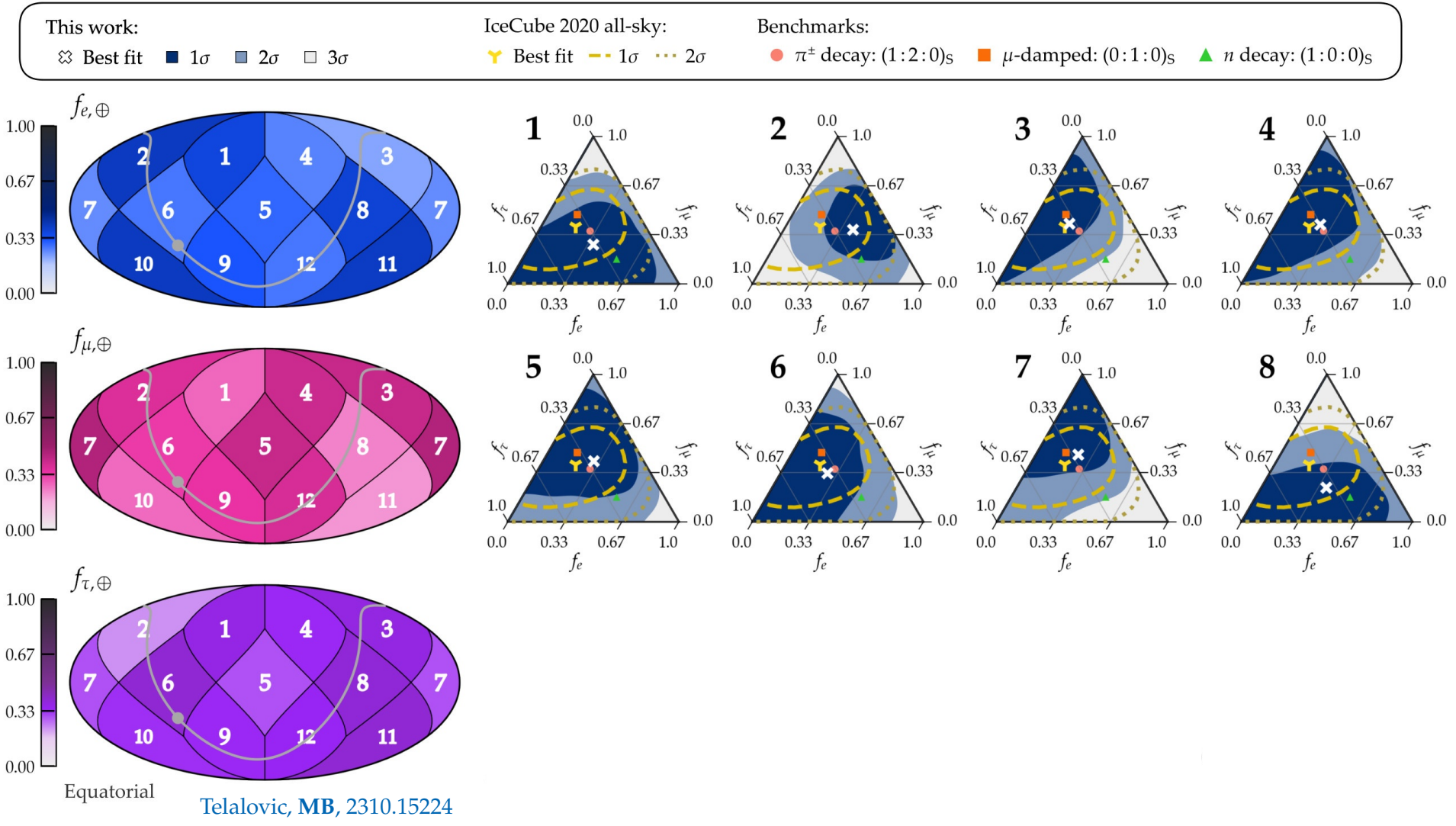

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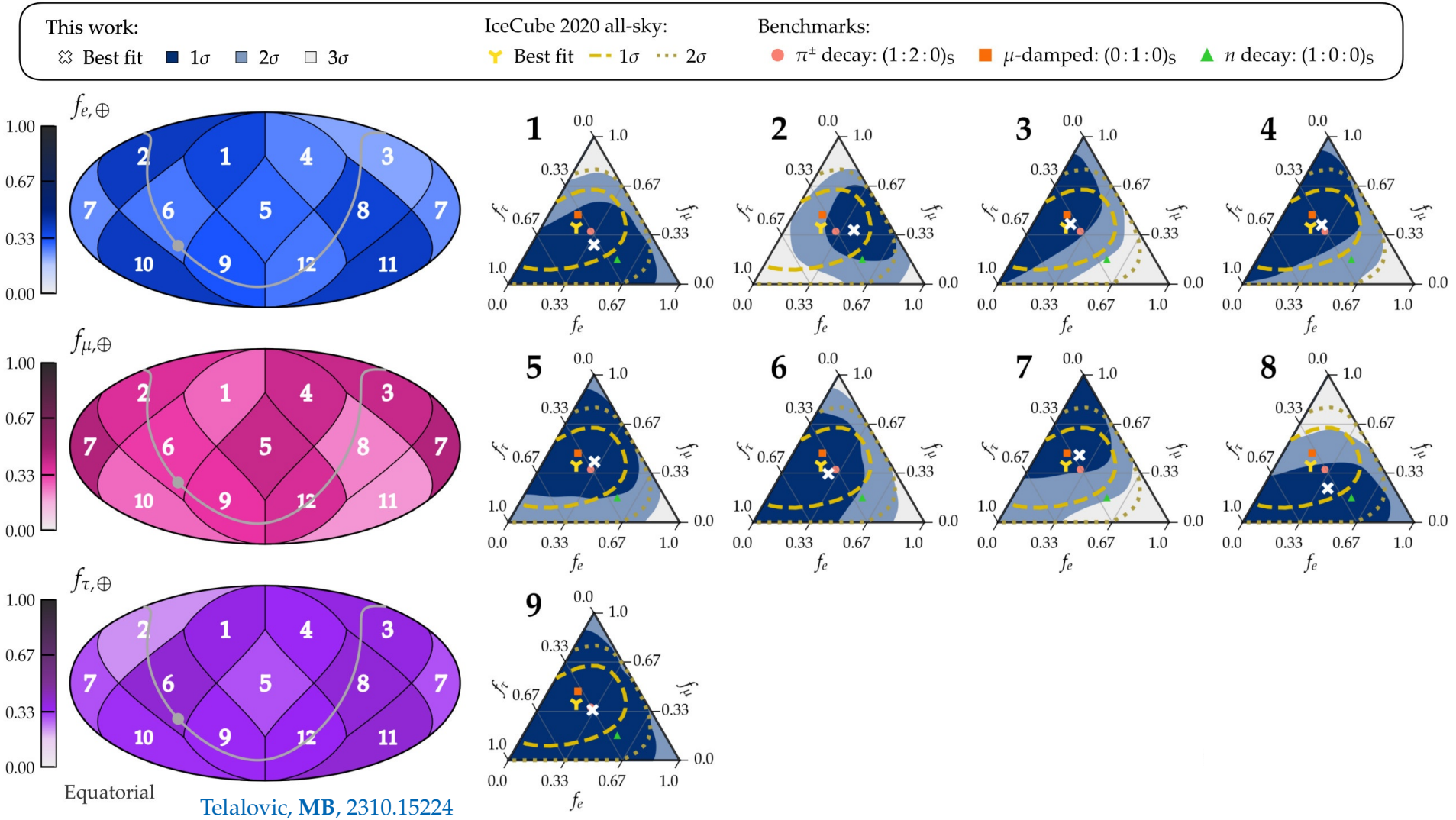

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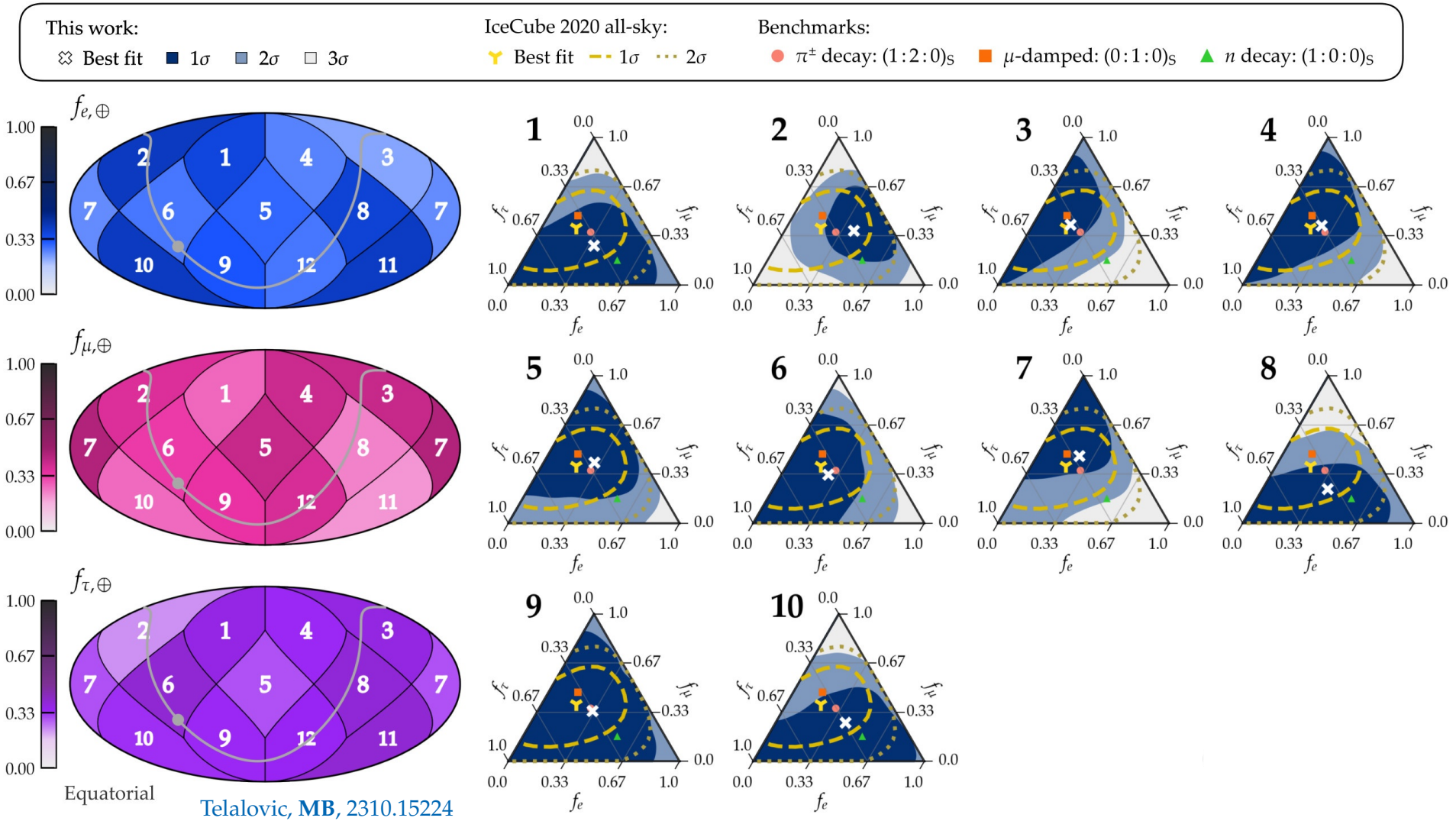

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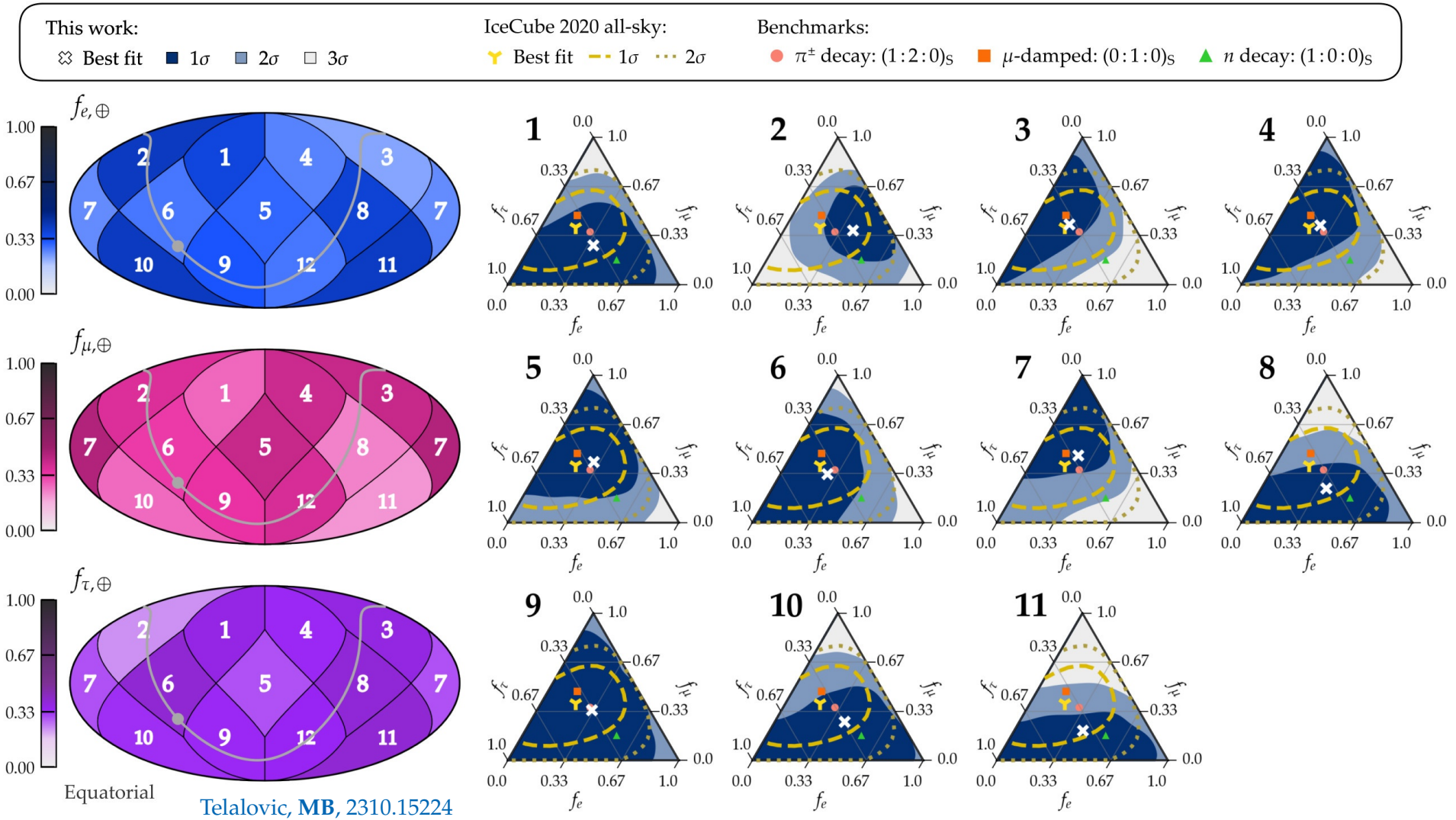

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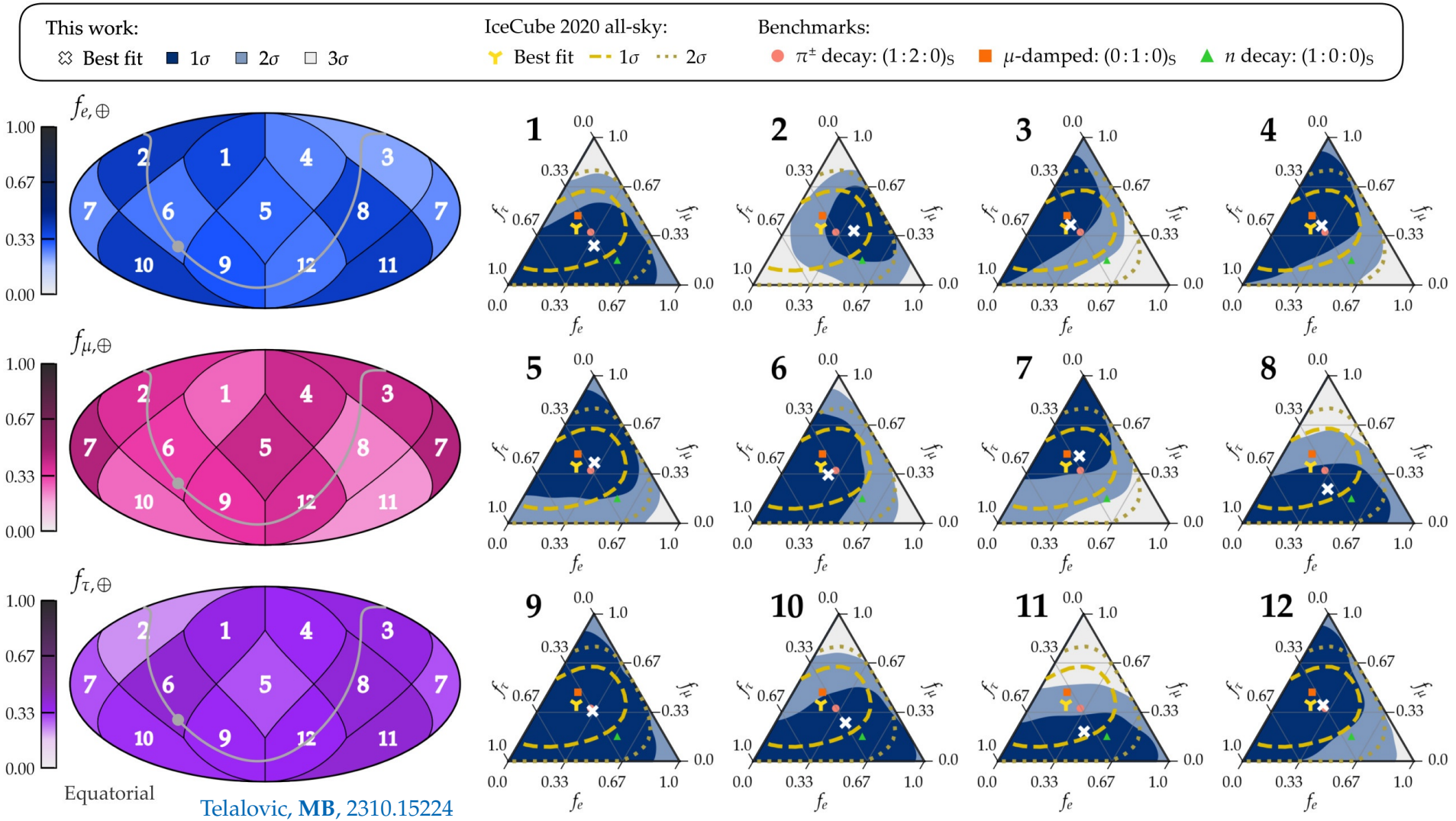

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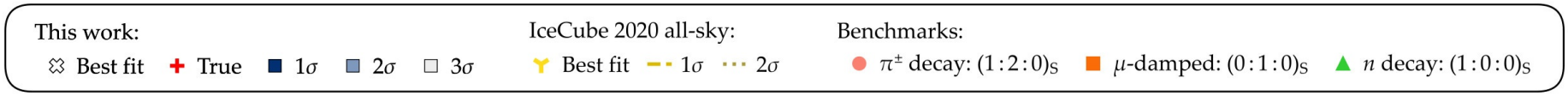
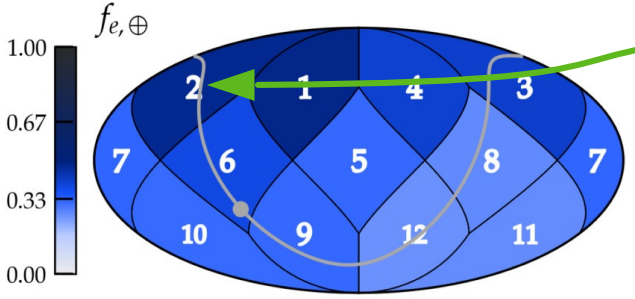
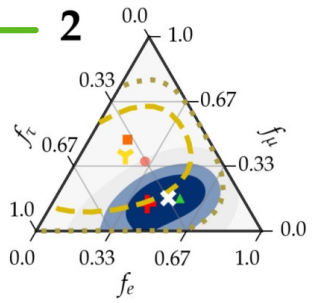
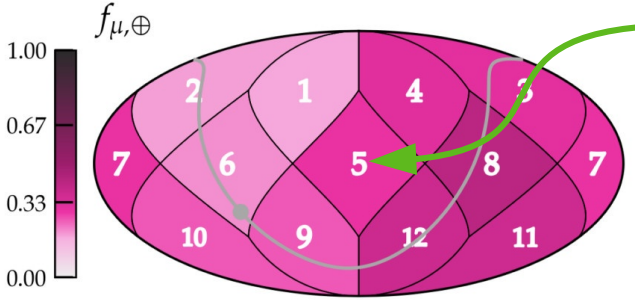
Directional high-energy astrophysical neutrino flavor composition: Anisotropic (2040, all detectors)

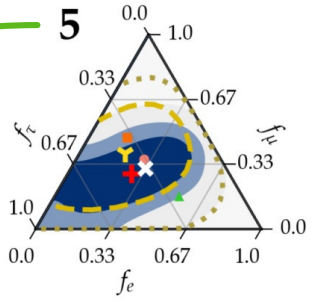




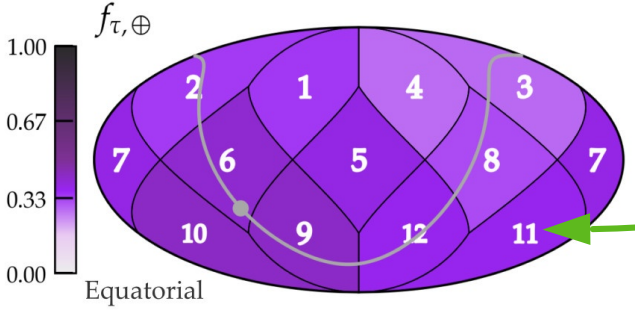


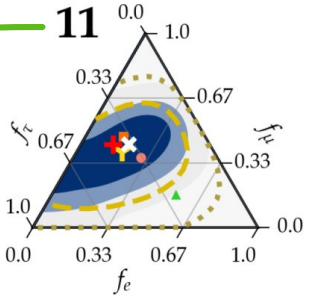
High ν_e content:
Production by neutron decay





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





High ν_μ content:
Muon-damped

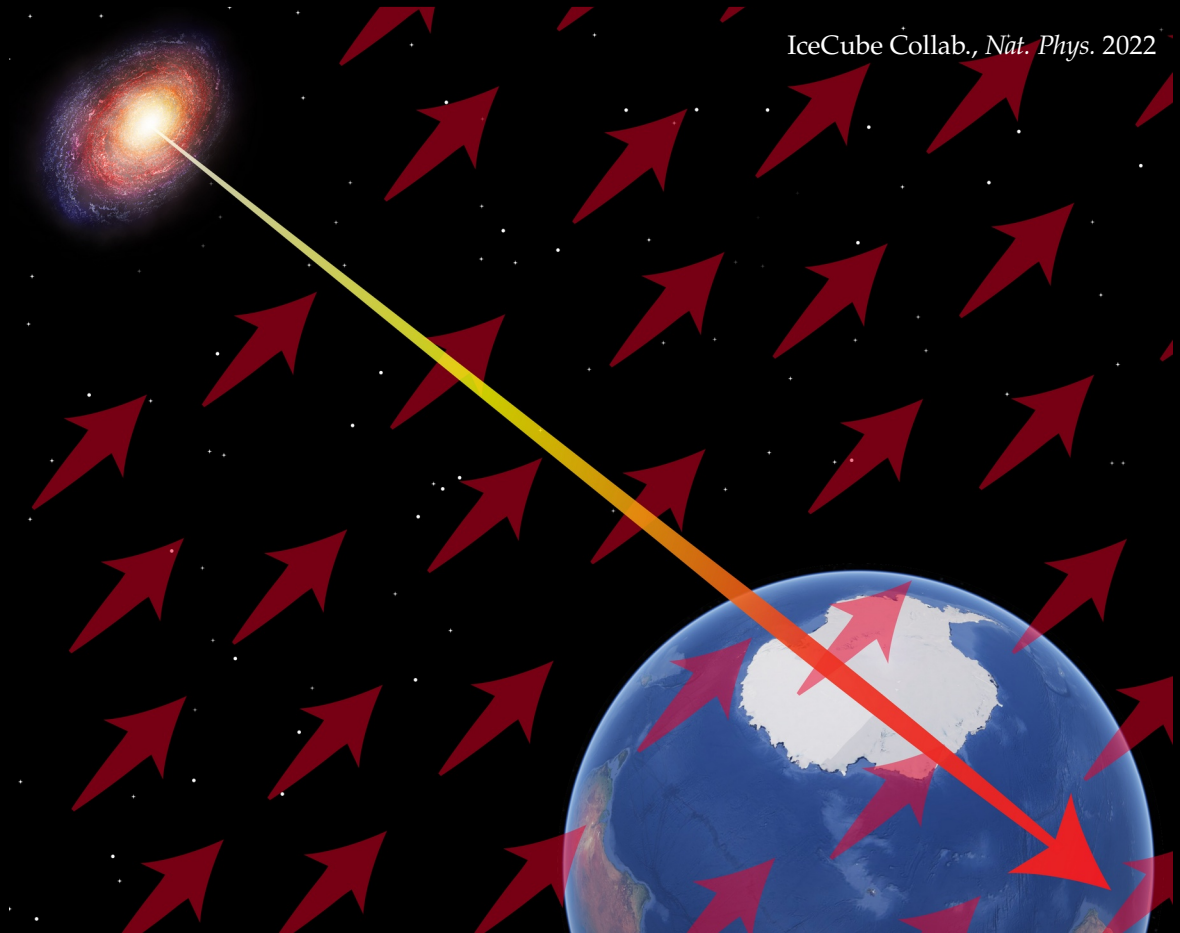
There is no sign of flavor anisotropy in present-day IceCube data (Bayes factor is ~1)

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

Work led by Bernanda Telalovic

Why is this interesting for neutrino physics?

Because new physics can introduce preferred directions for different flavors



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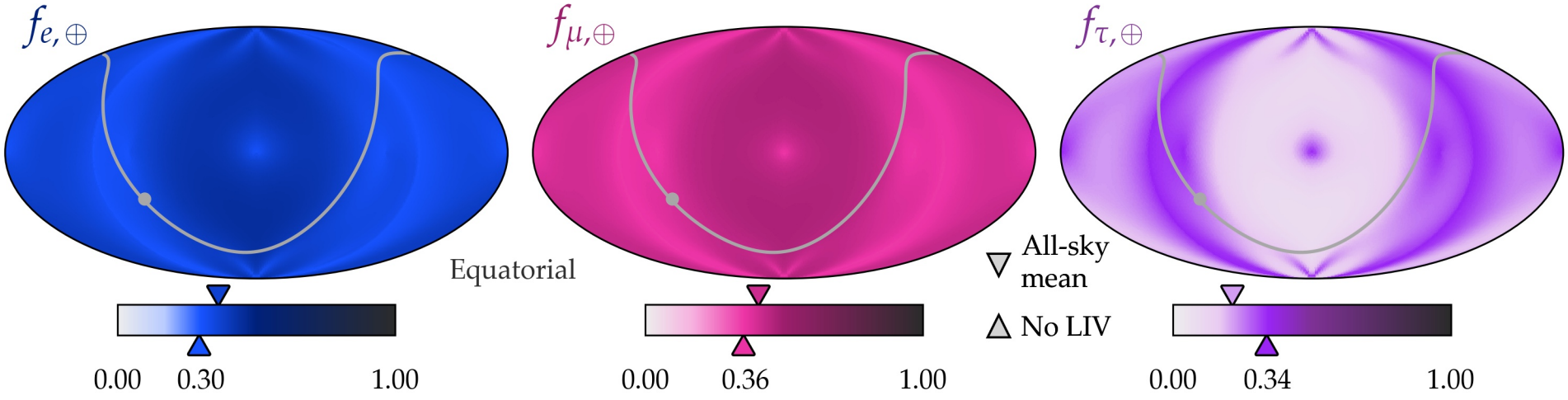

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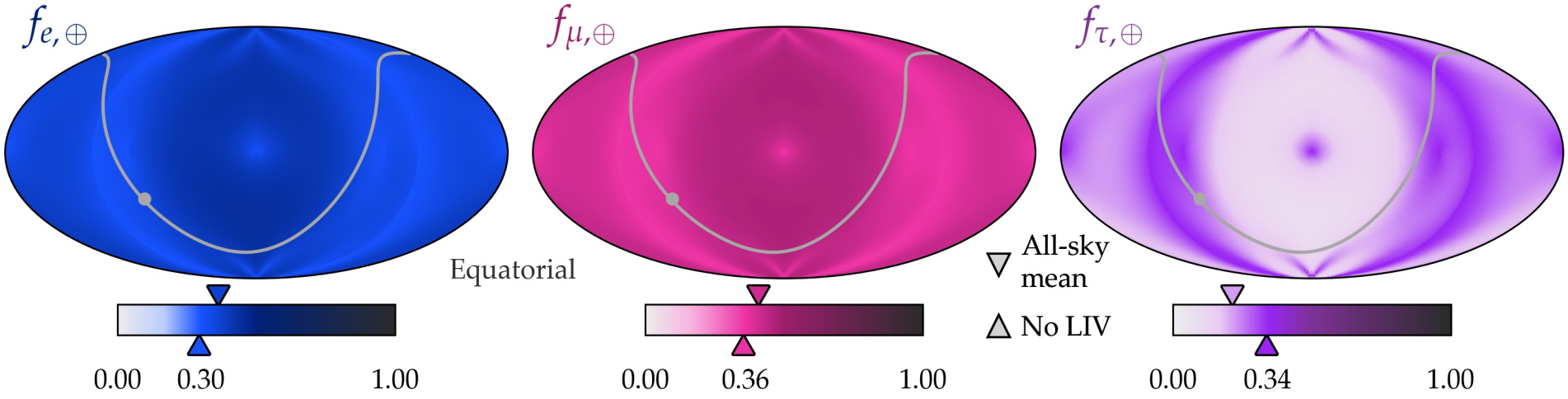

For dimension-5 CPT-odd LIV coefficient

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

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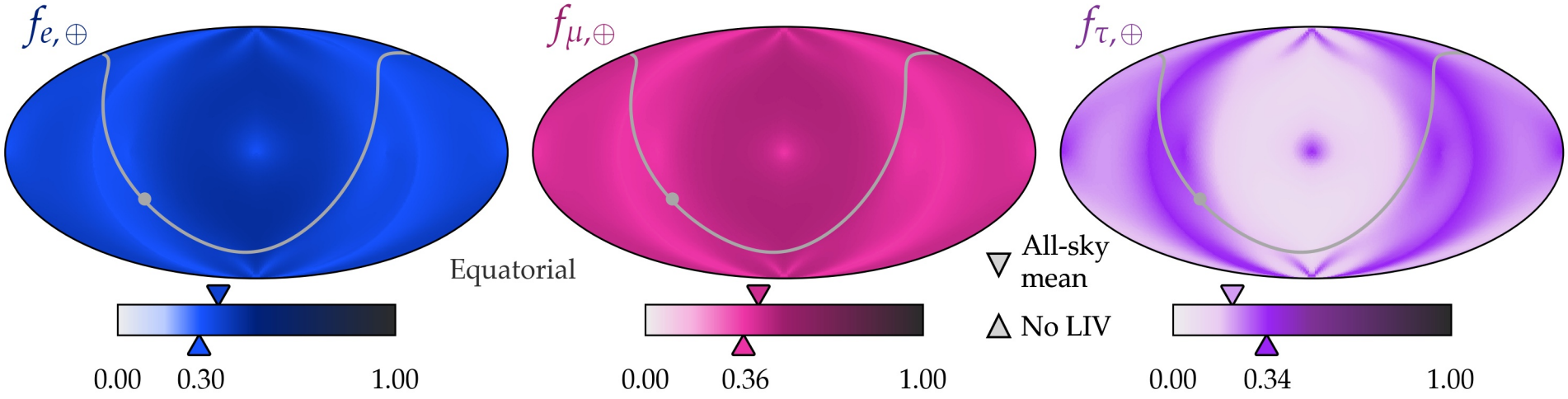

For dimension-5 CPT-odd LIV coefficient

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

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

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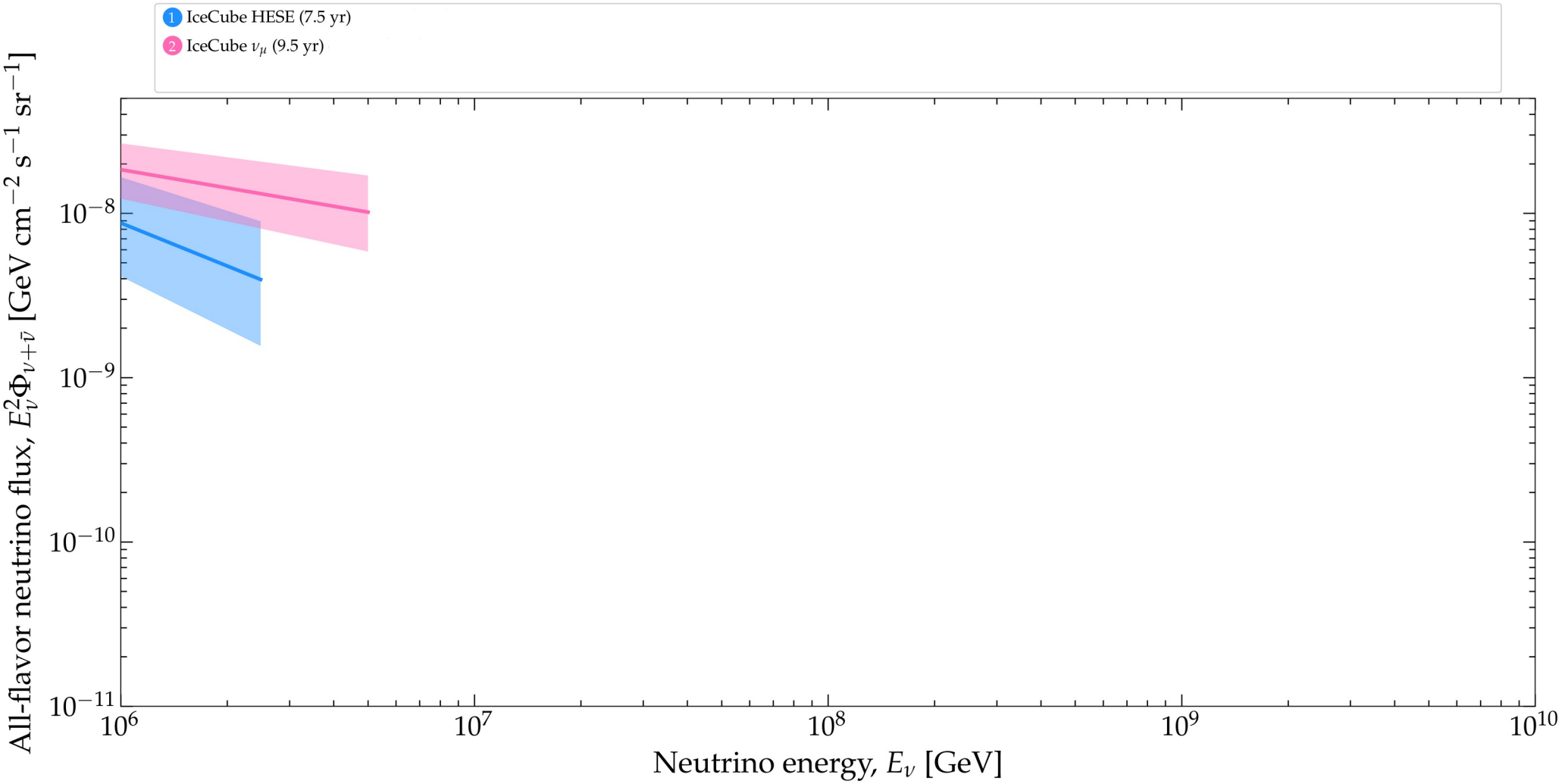
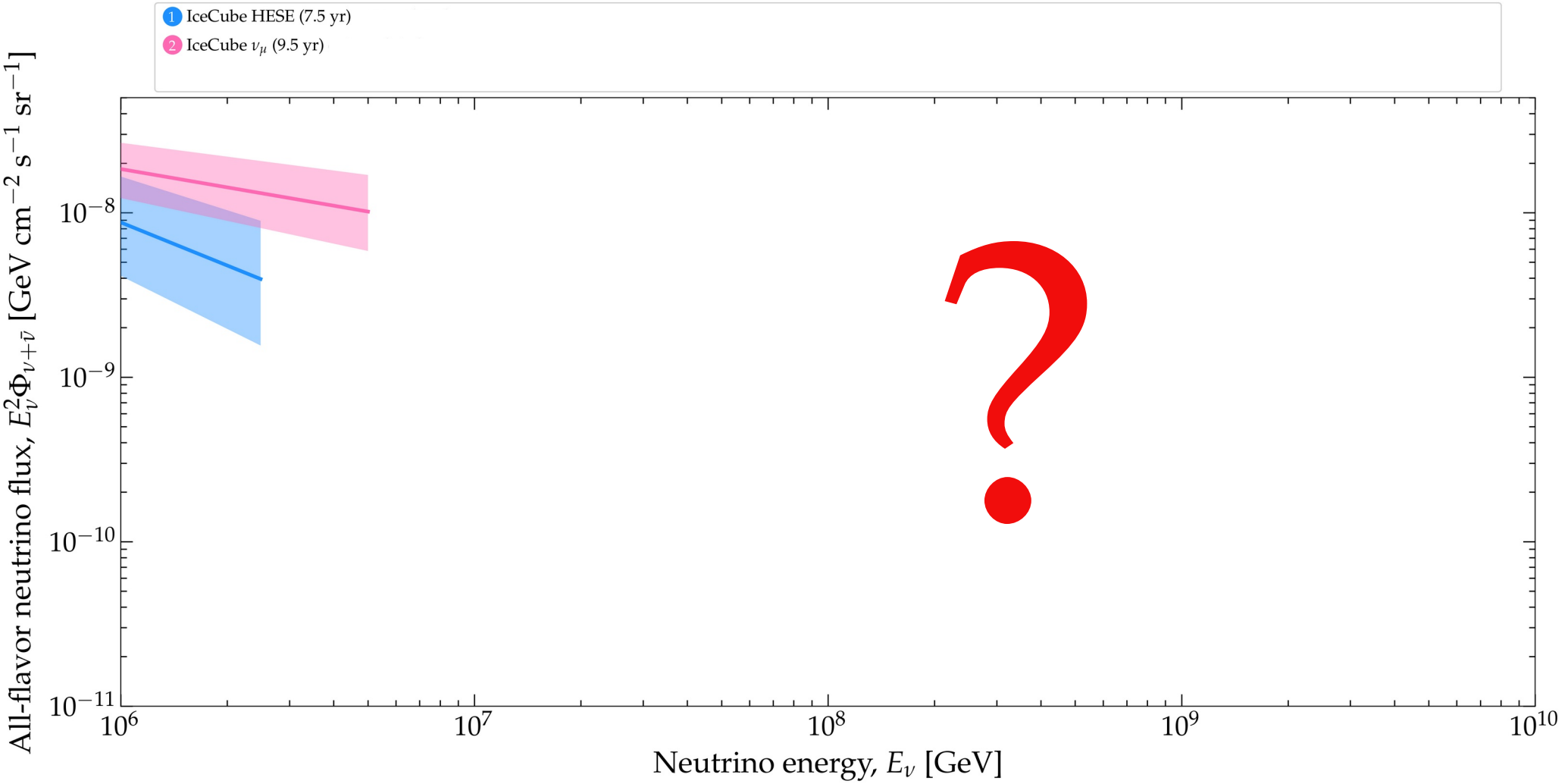
Towards ultra-high energies


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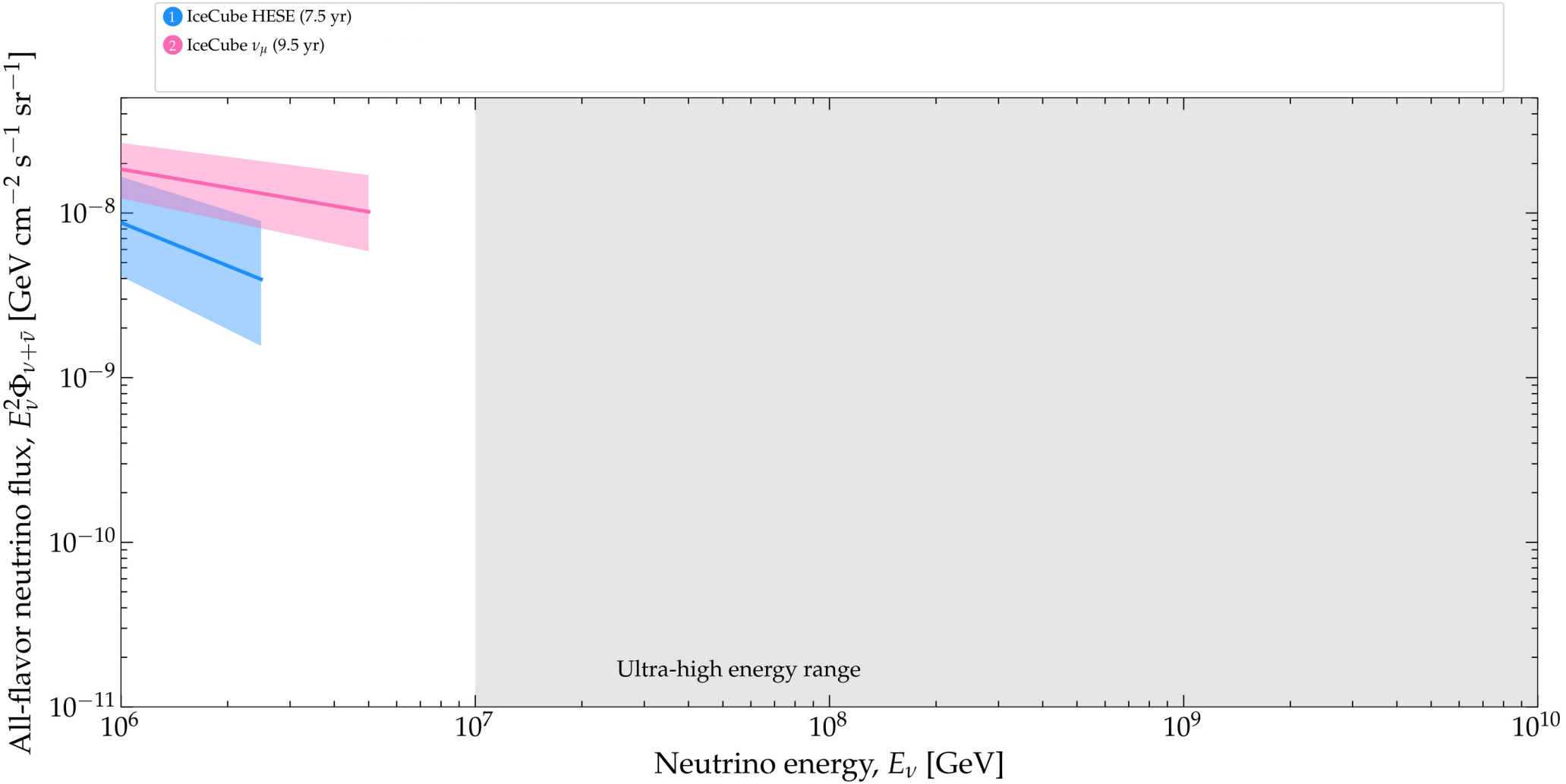
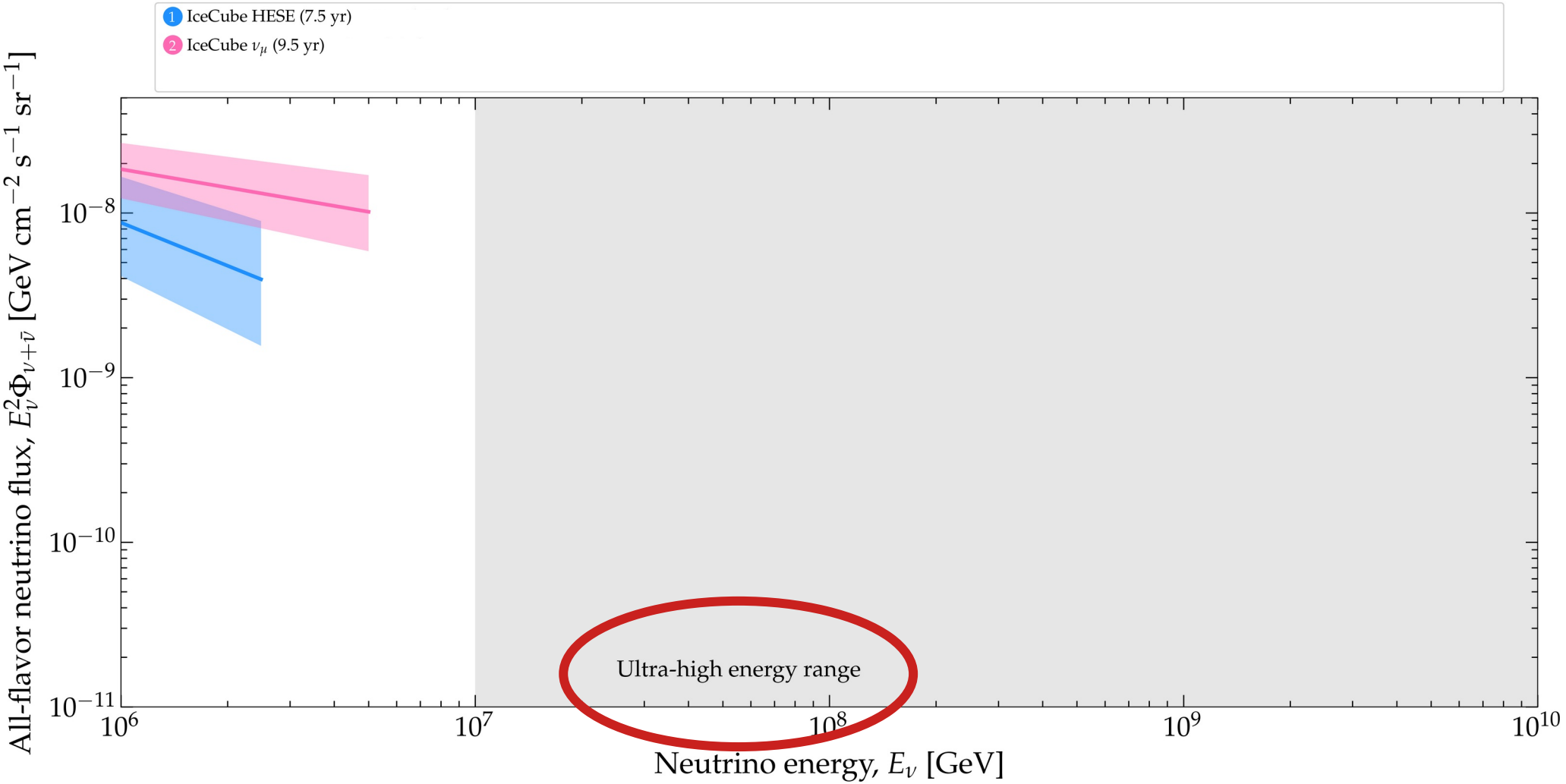
10^{-11}
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]
?


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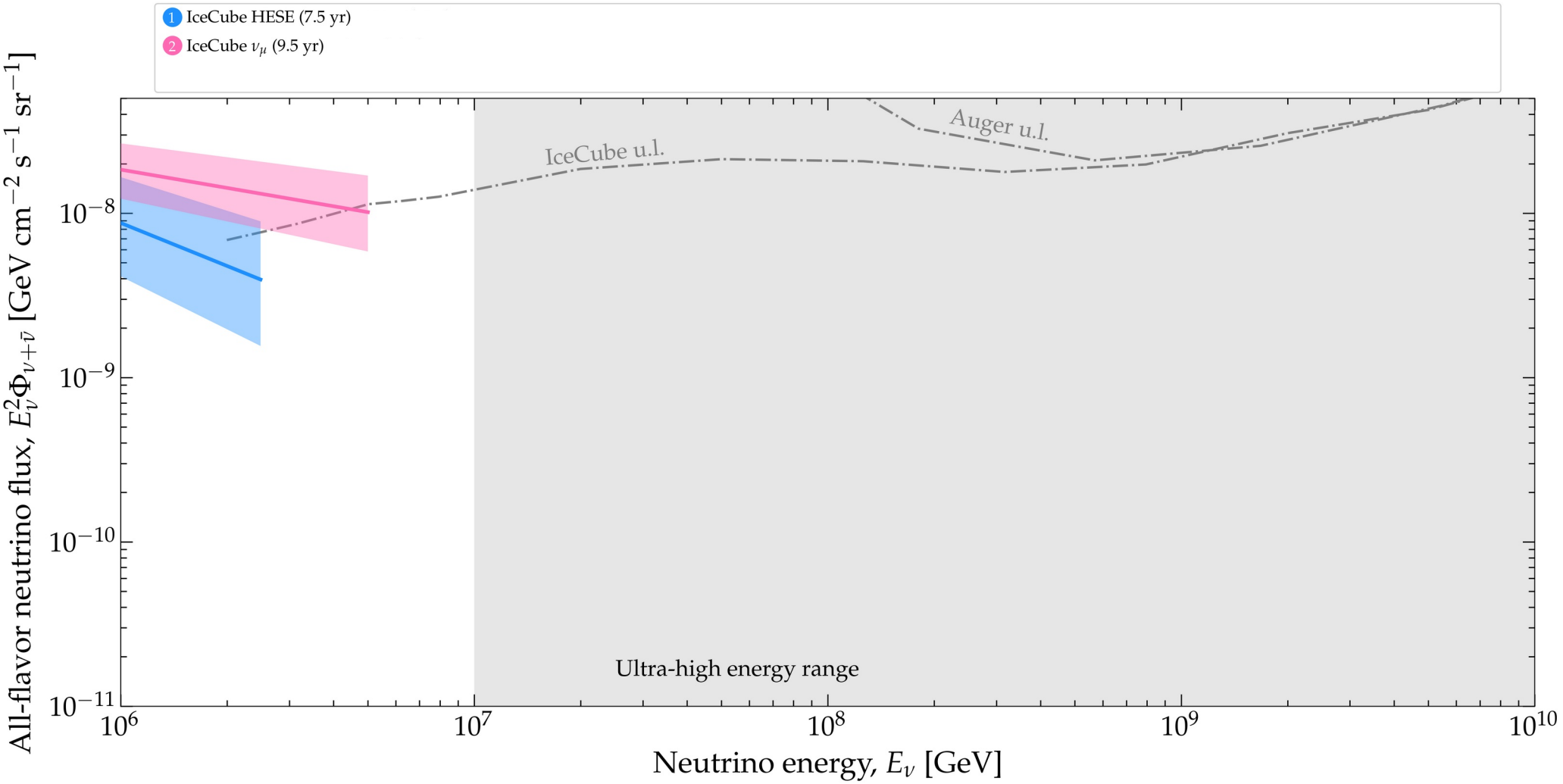
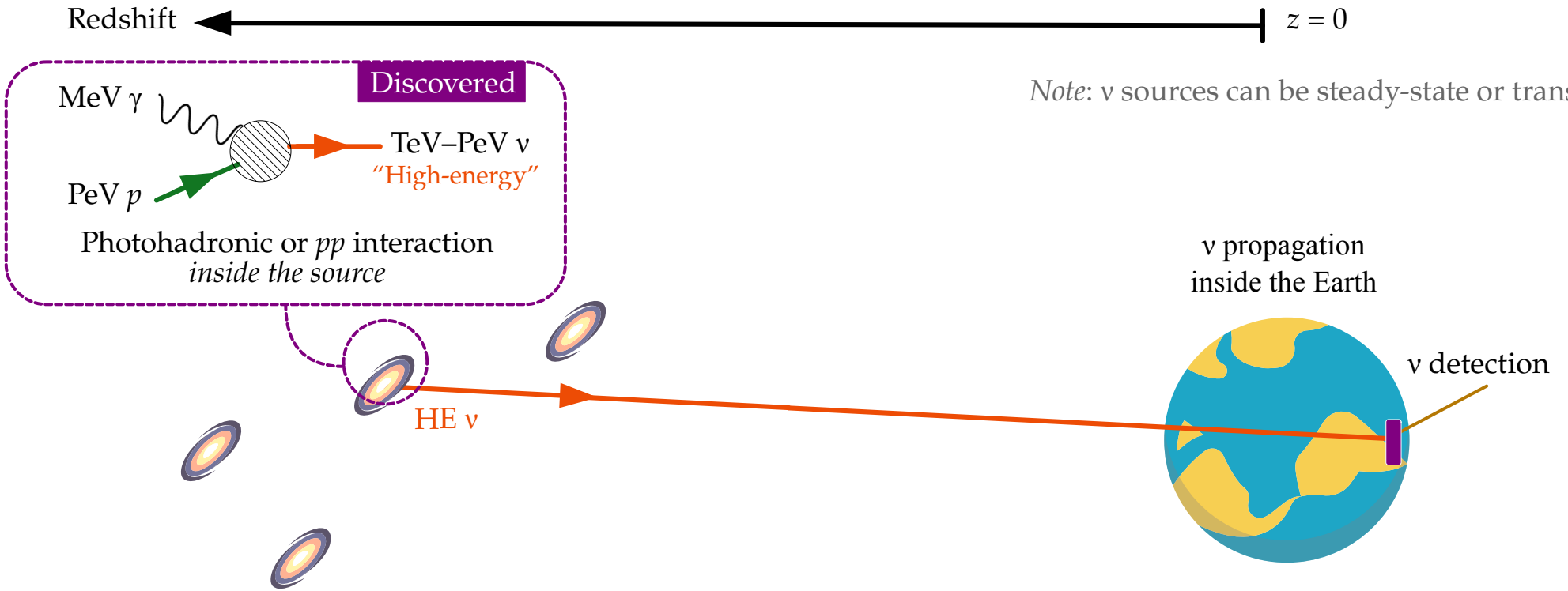
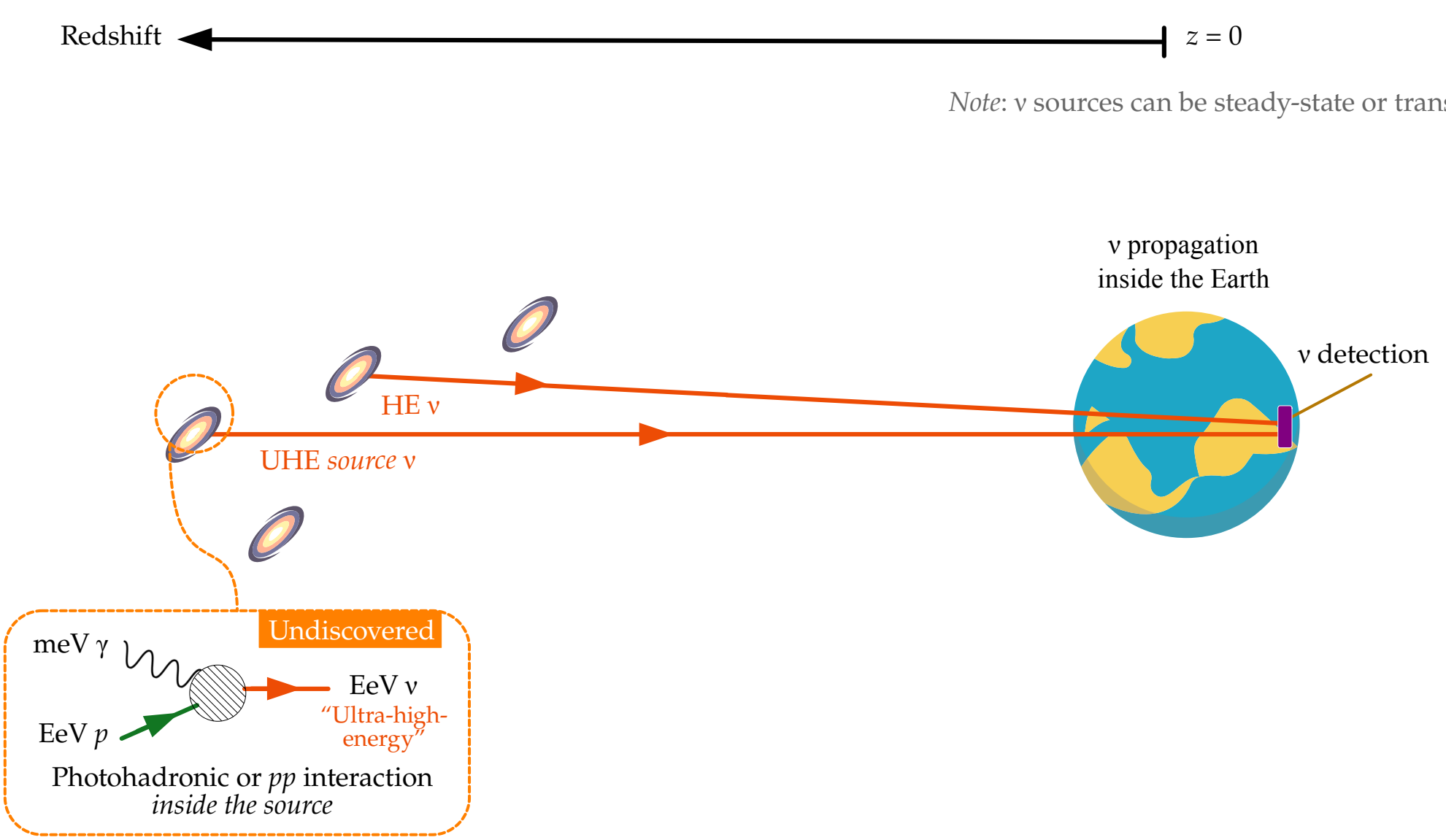
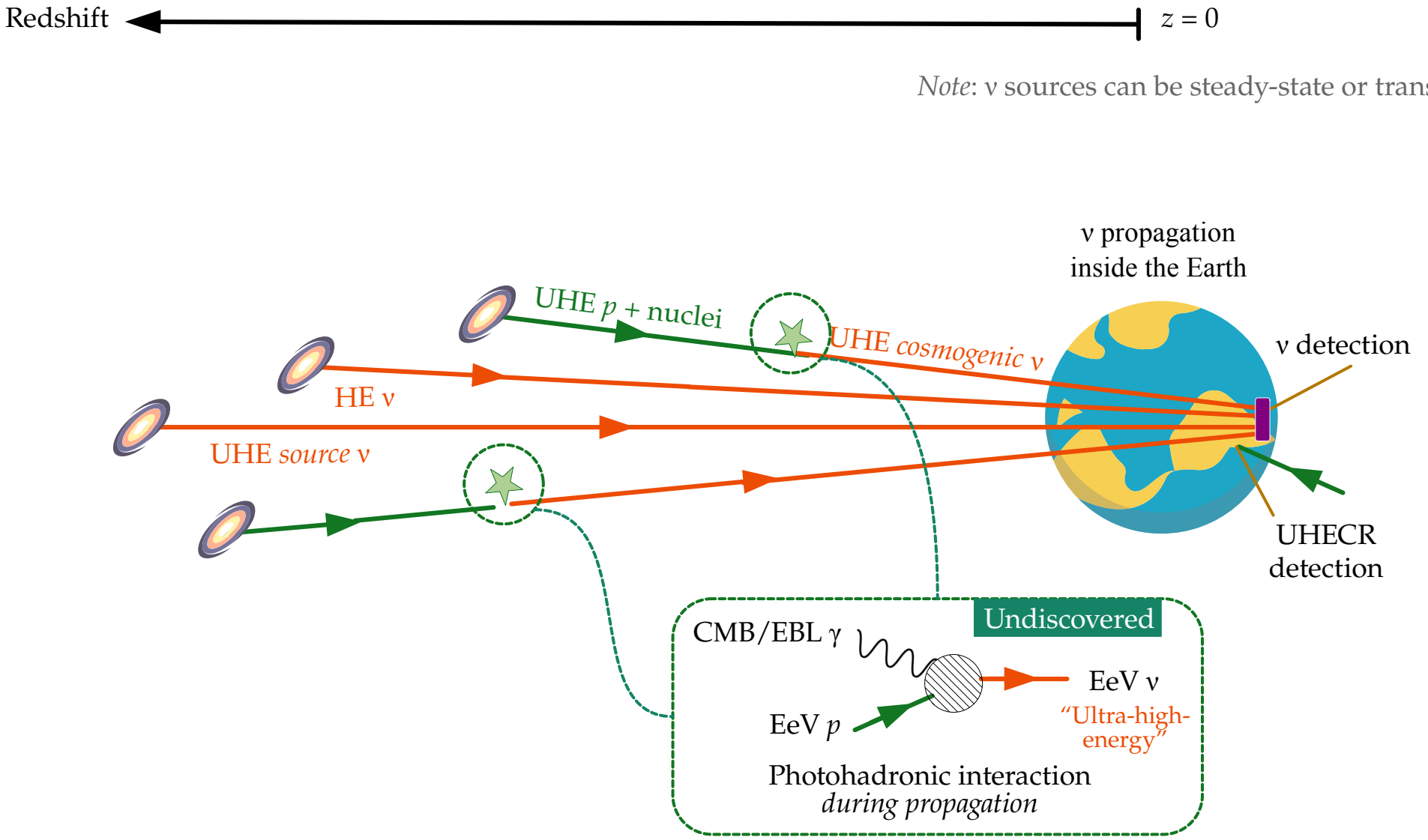
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
Ultra-high energy range
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]

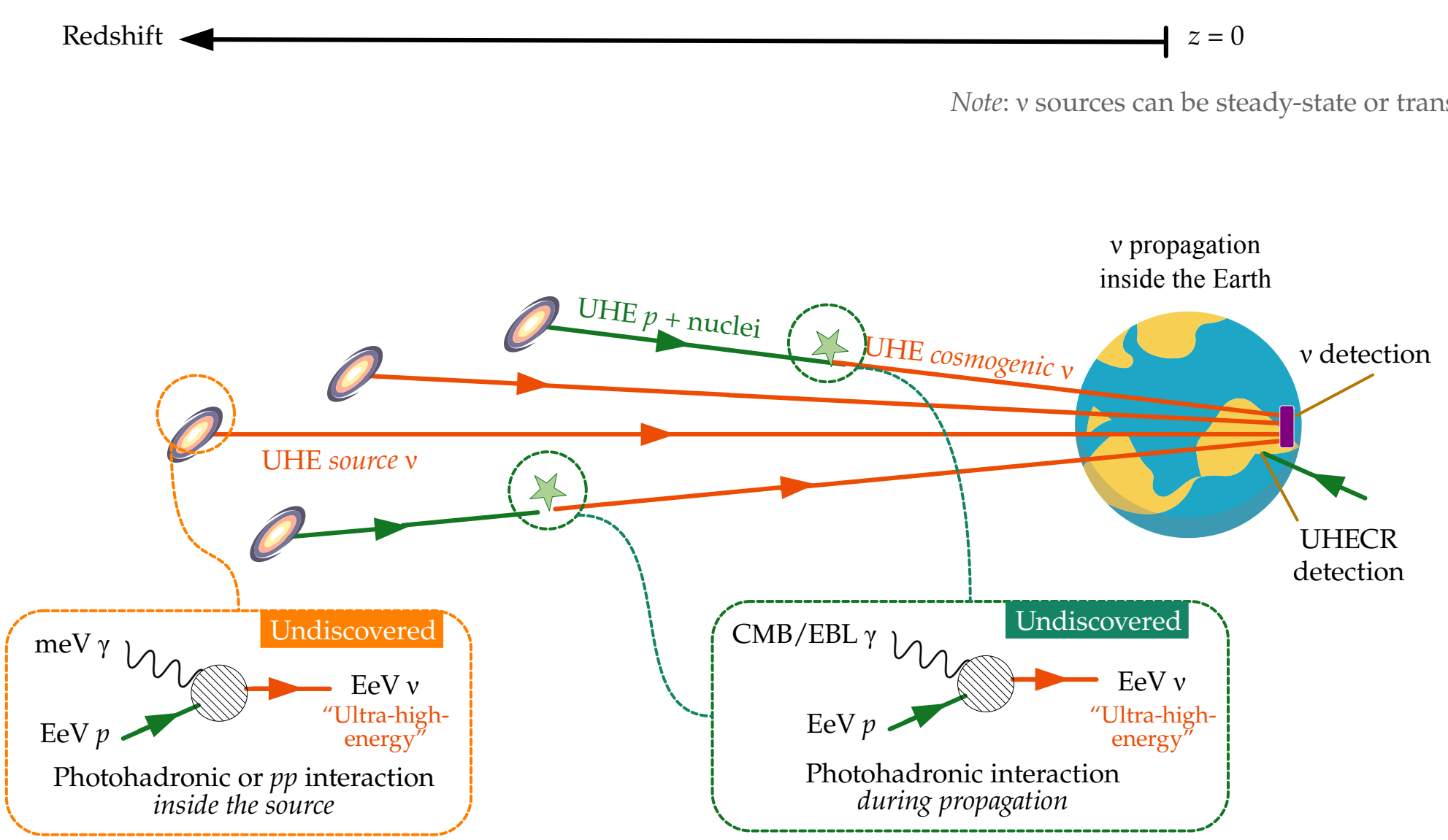

1 IceCube HESE (7.5 yr)
2 IceCube ν_μ (9.5 yr)
IceCube u.l.
Auger u.l.
Ultra-high energy range
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy, E_ν [GeV]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}



Note: ν sources can be steady-state or transient


Redshift
z = 0
Note: ν sources can be steady-state or transient
ν propagation
inside the Earth
ν detection
HE ν
UHE source ν
Undiscovered
meV γ
EeV ν
"Ultra-high-
energy"
EeV p
Photohadronic or pp interaction
inside the source


Redshift
z = 0
Note: ν sources can be steady-state or transient
ν propagation
inside the Earth
UHE p + nuclei
UHE cosmogenic ν
ν detection
HE ν
UHE source ν
UHECR
detection
Undiscovered
CMB/EBL γ
EeV ν
"Ultra-high-
energy"
EeV p
Photohadronic interaction
during propagation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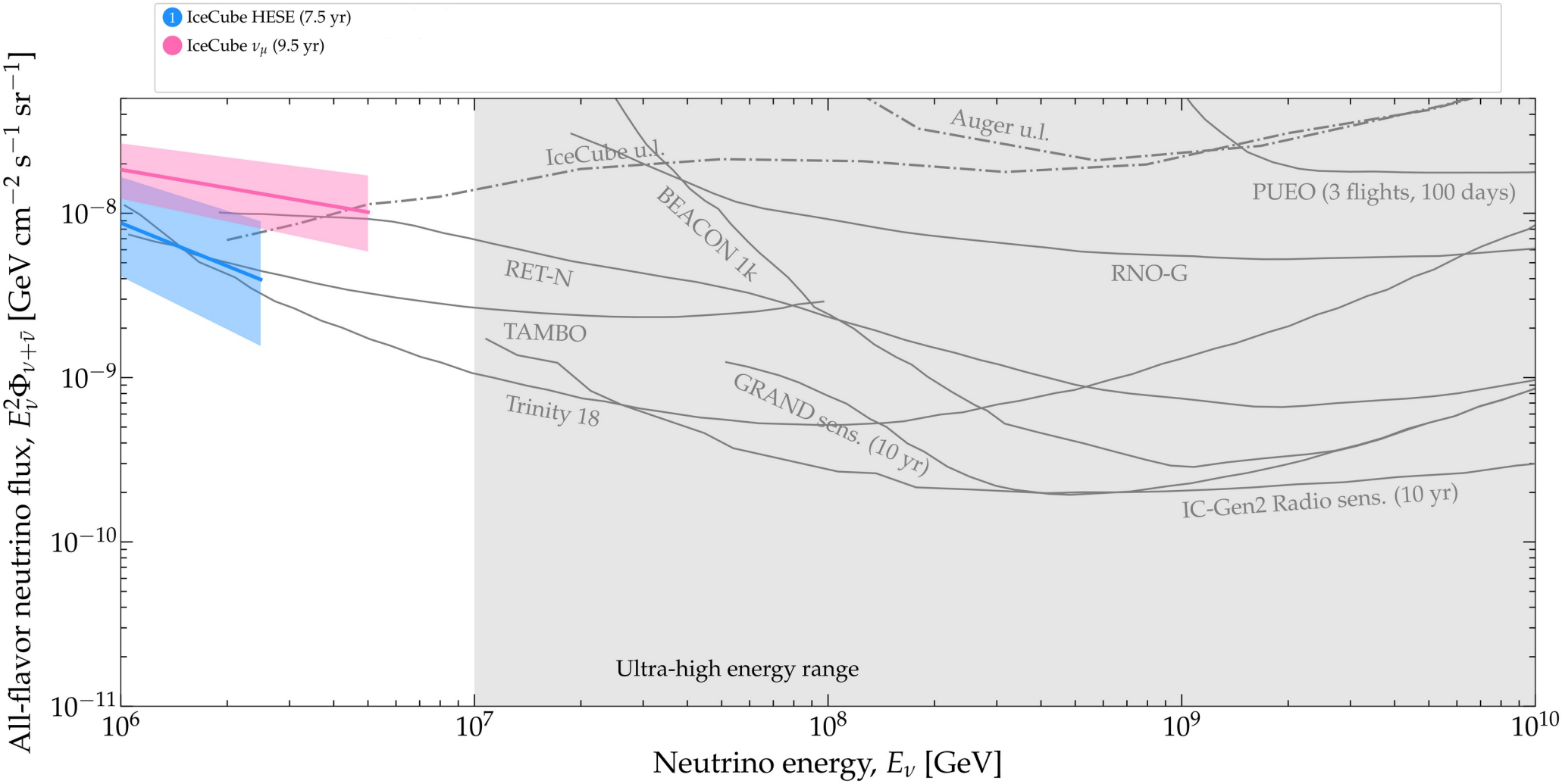
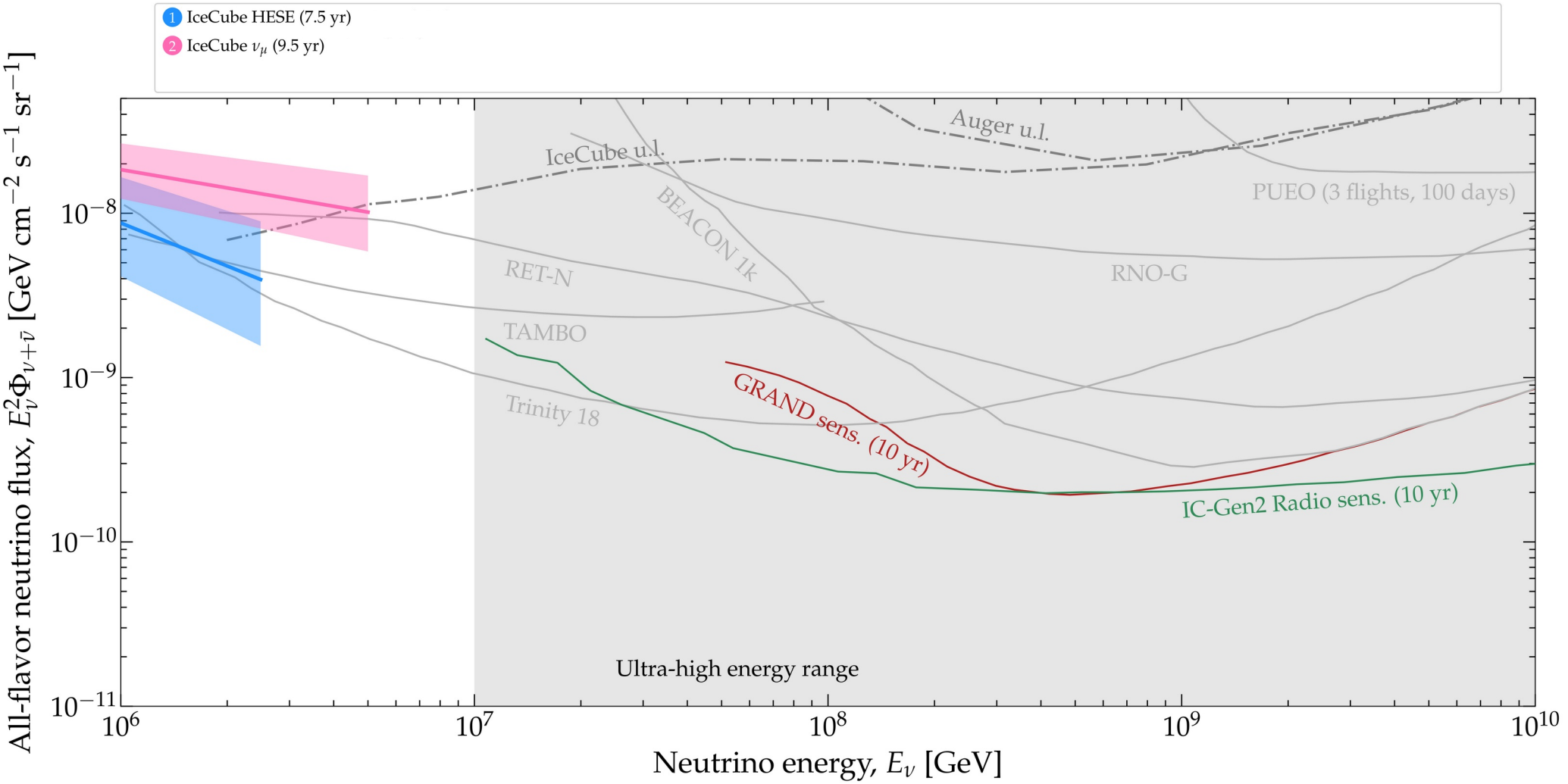

1 IceCube HESE (7.5 yr)
IceCube ν_μ (9.5 yr)
Auger u.l.
IceCube u.l.
BEACON 1k
PUEO (3 flights, 100 days)
RET-N
RNO-G
TAMBO
Trinity 18
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy, E_ν [GeV]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}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Auger u.l.
IceCube u.l.
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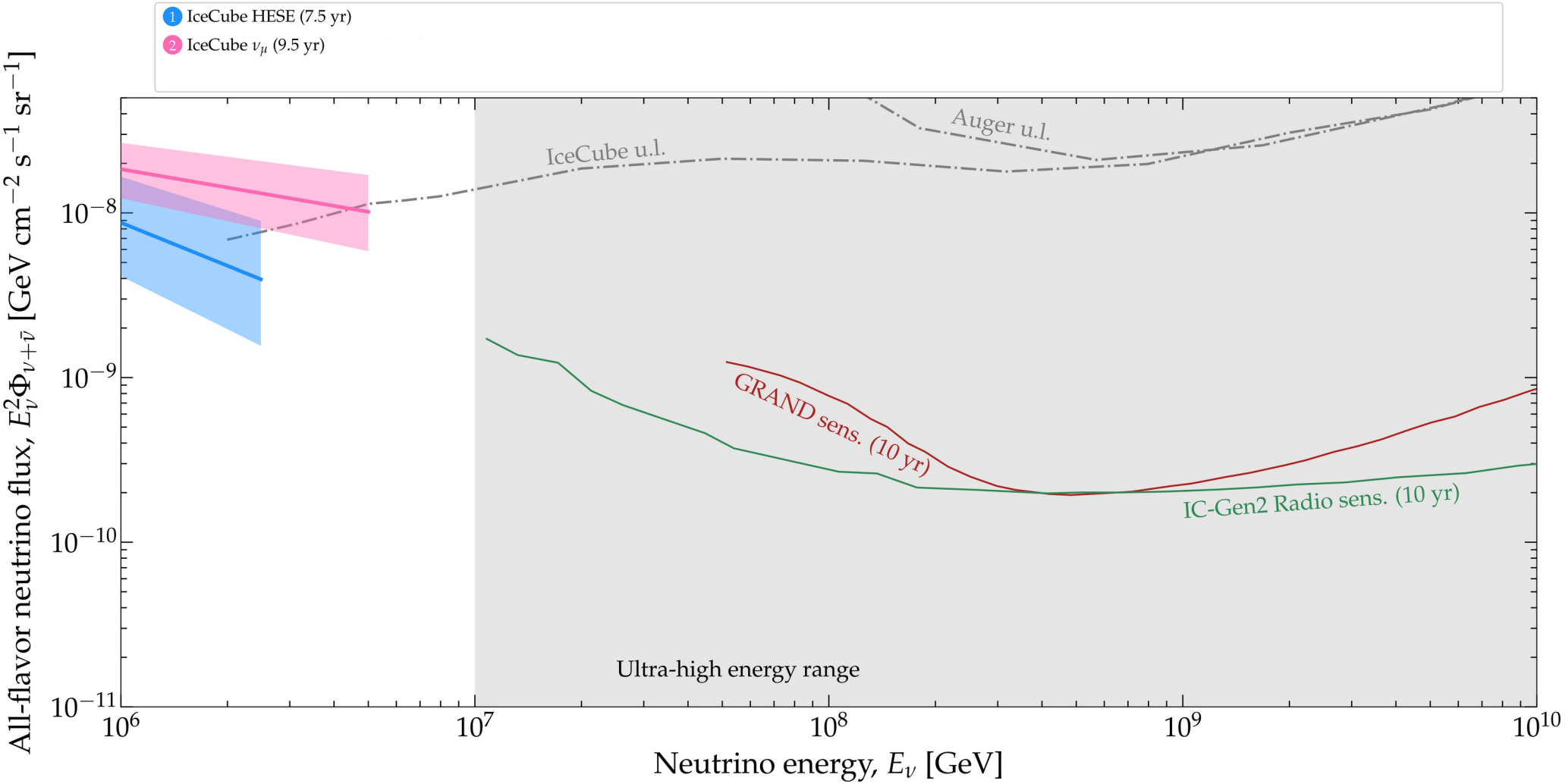
10^6
10^7
10^8
10^9
10^{10}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Auger u.l.
IceCube u.l.
GRAND sens. (10 yr)
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10^{-8}
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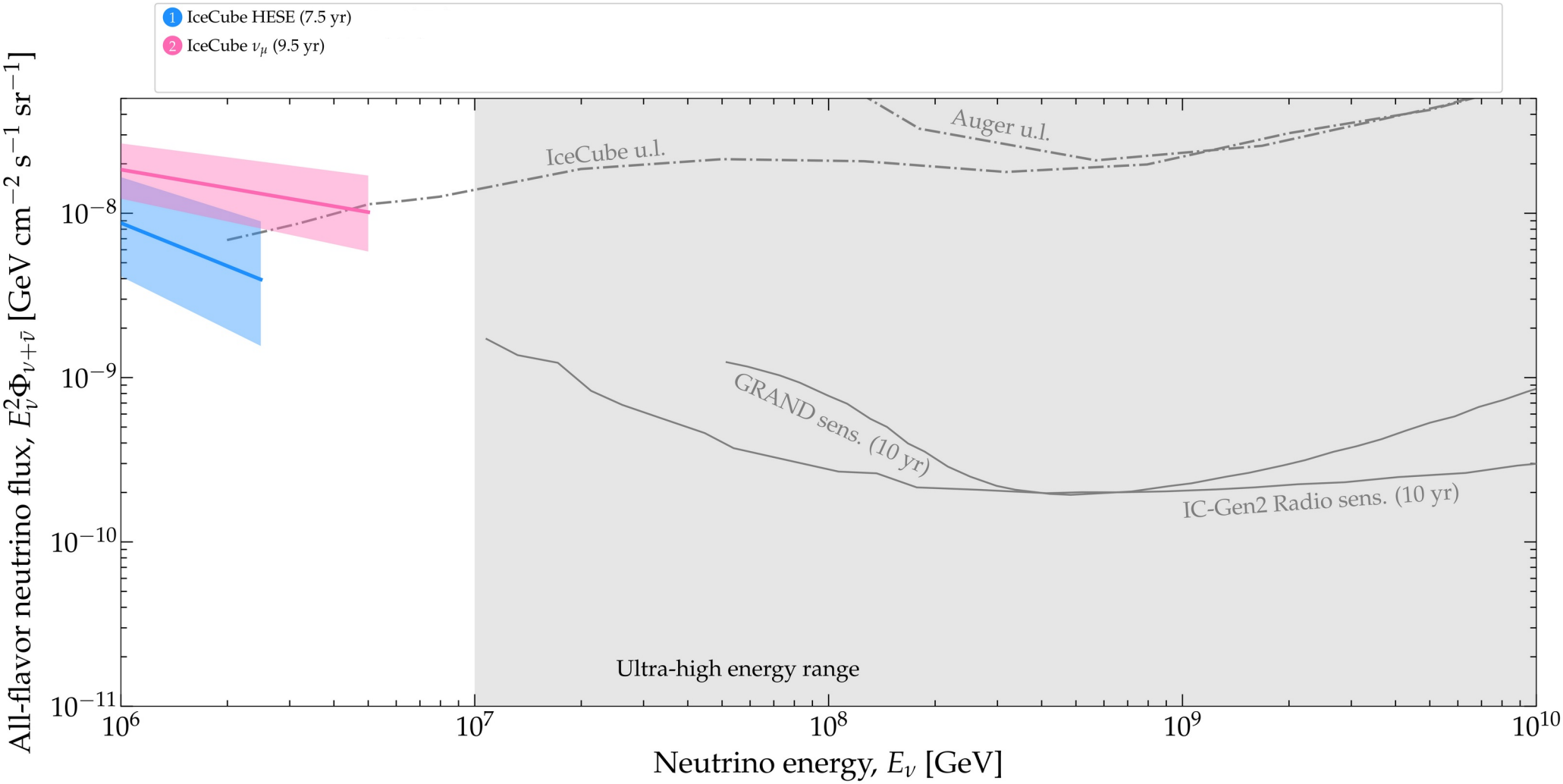
10^6
10^7
10^8
10^9
10^{10}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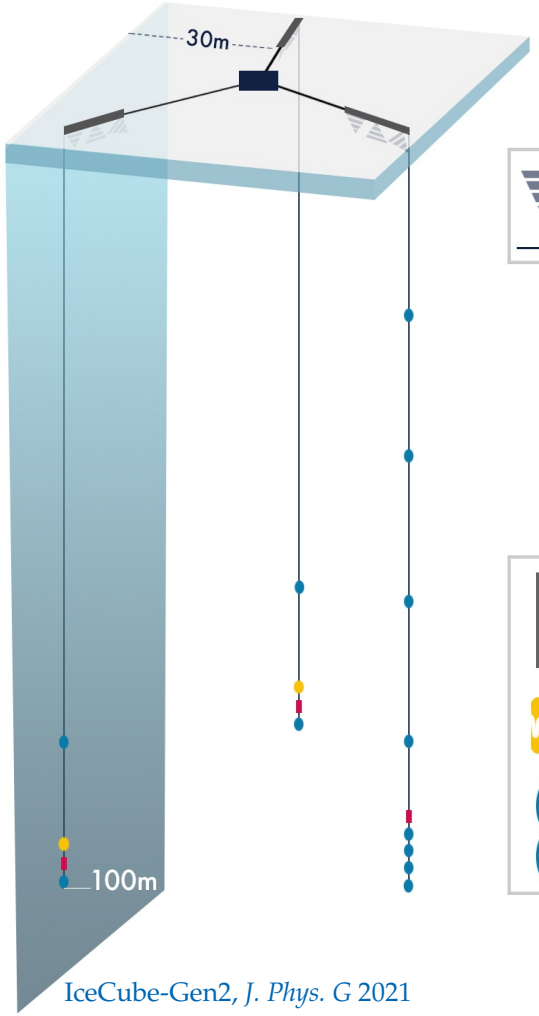
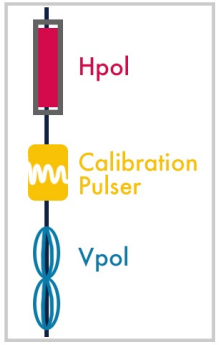
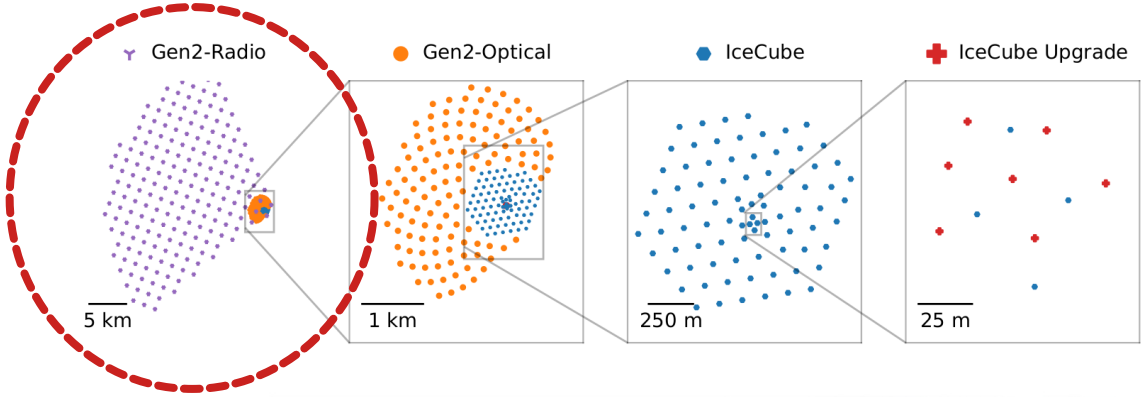
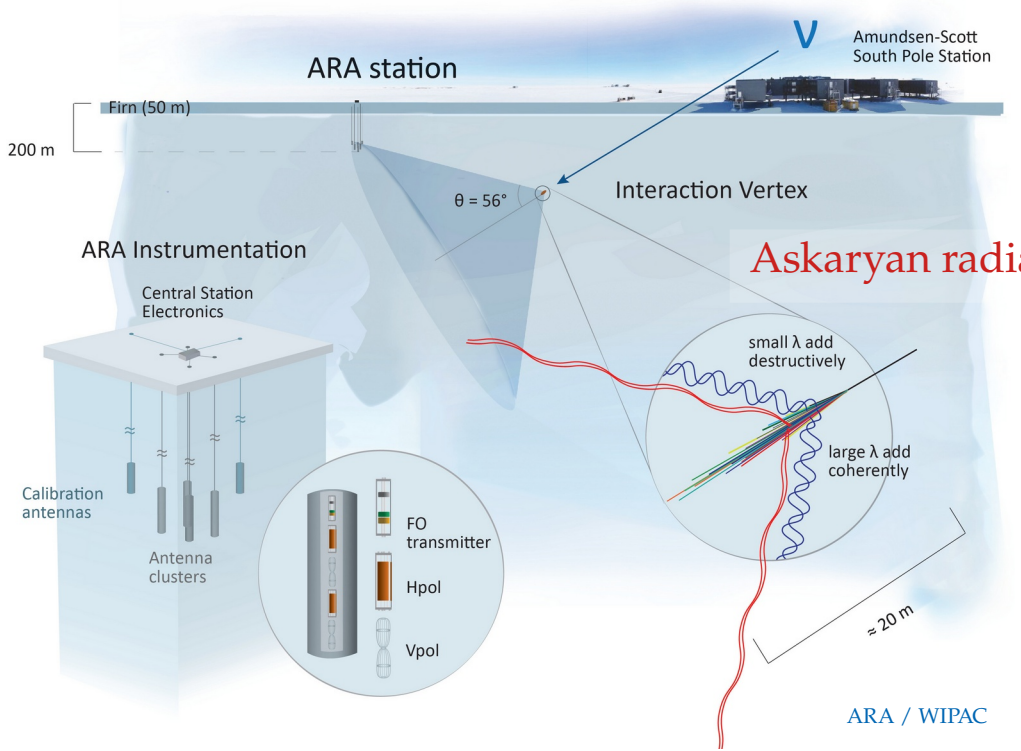
Auger u.l.
IceCube u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy, E_ν [GeV]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}

IceCube-Gen2 Radio



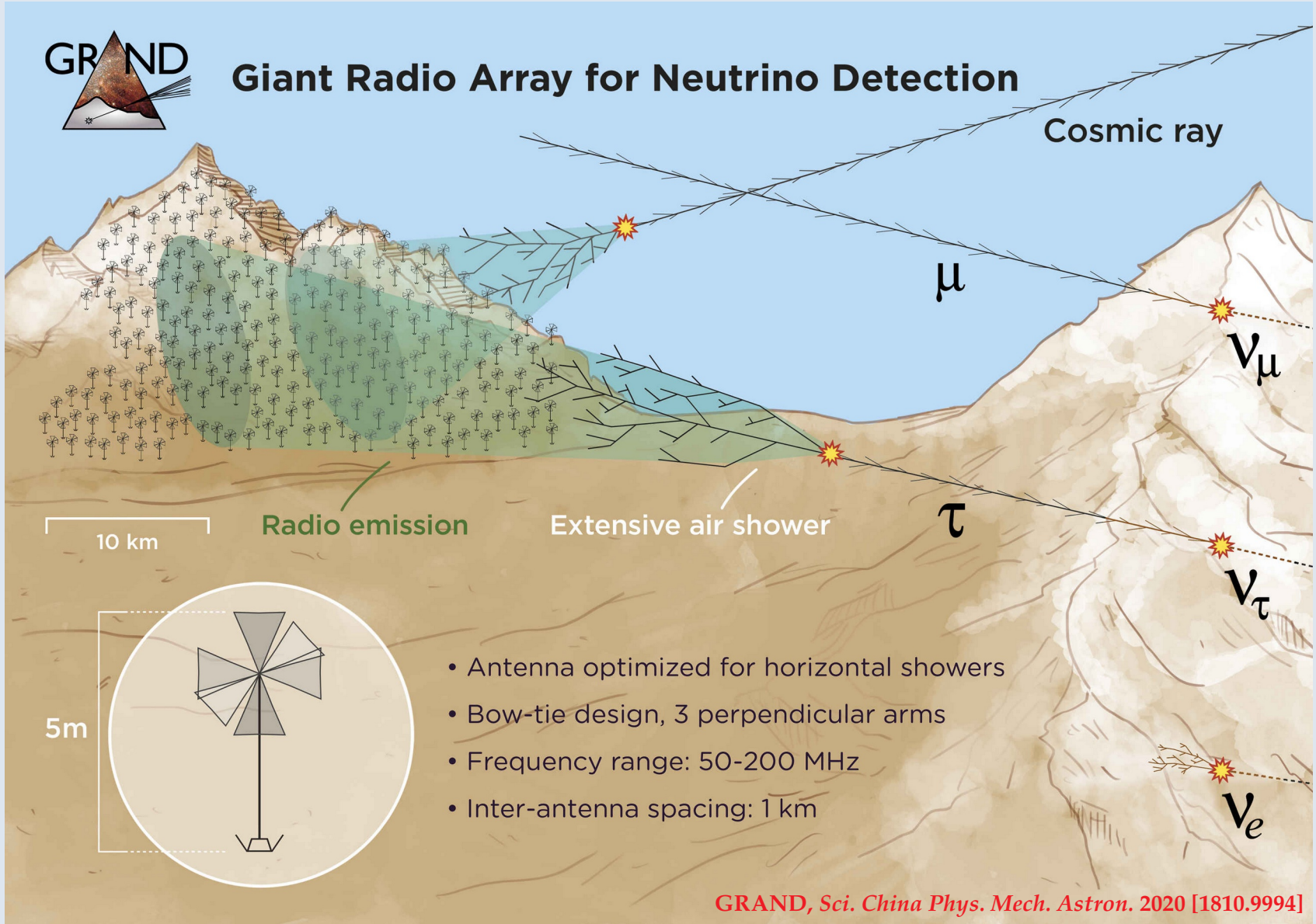






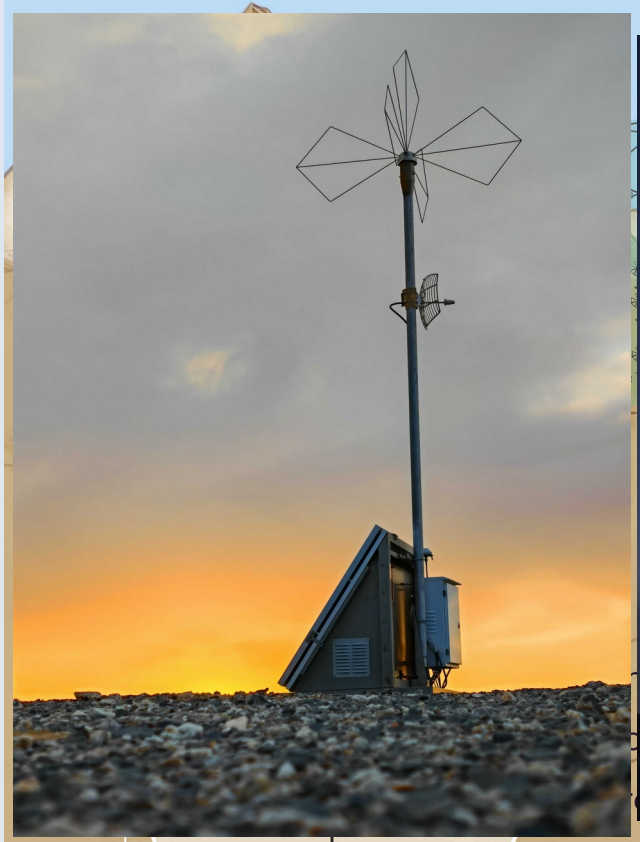
IceCube-Gen2, *J. Phys. G* 2021

ARA / WIPAC


GRAND
Giant Radio Array for Neutrino Detection
Cosmic ray
μ
τ
ν_μ
ν_τ
ν_e
10 km
Radio emission
Extensive air shower
5m
• Antenna optimized for horizontal showers
• Bow-tie design, 3 perpendicular arms
• Frequency range: 50-200 MHz
• Inter-antenna spacing: 1 km
GRAND, *Sci. China Phys. Mech. Astron.* 2020 [1810.9994]

Giant Radio Array for Neutrino Detection

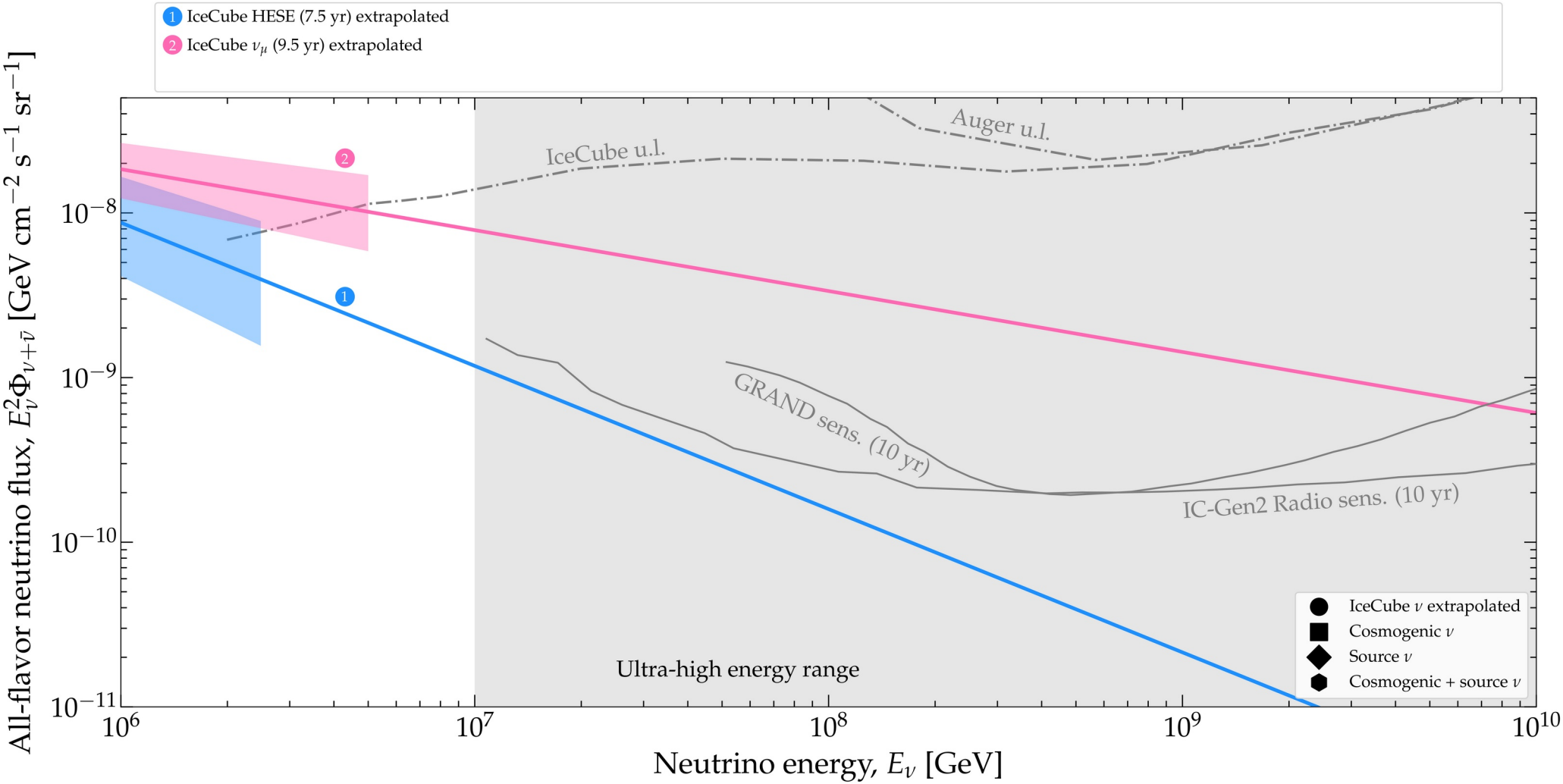
Cosmic ray

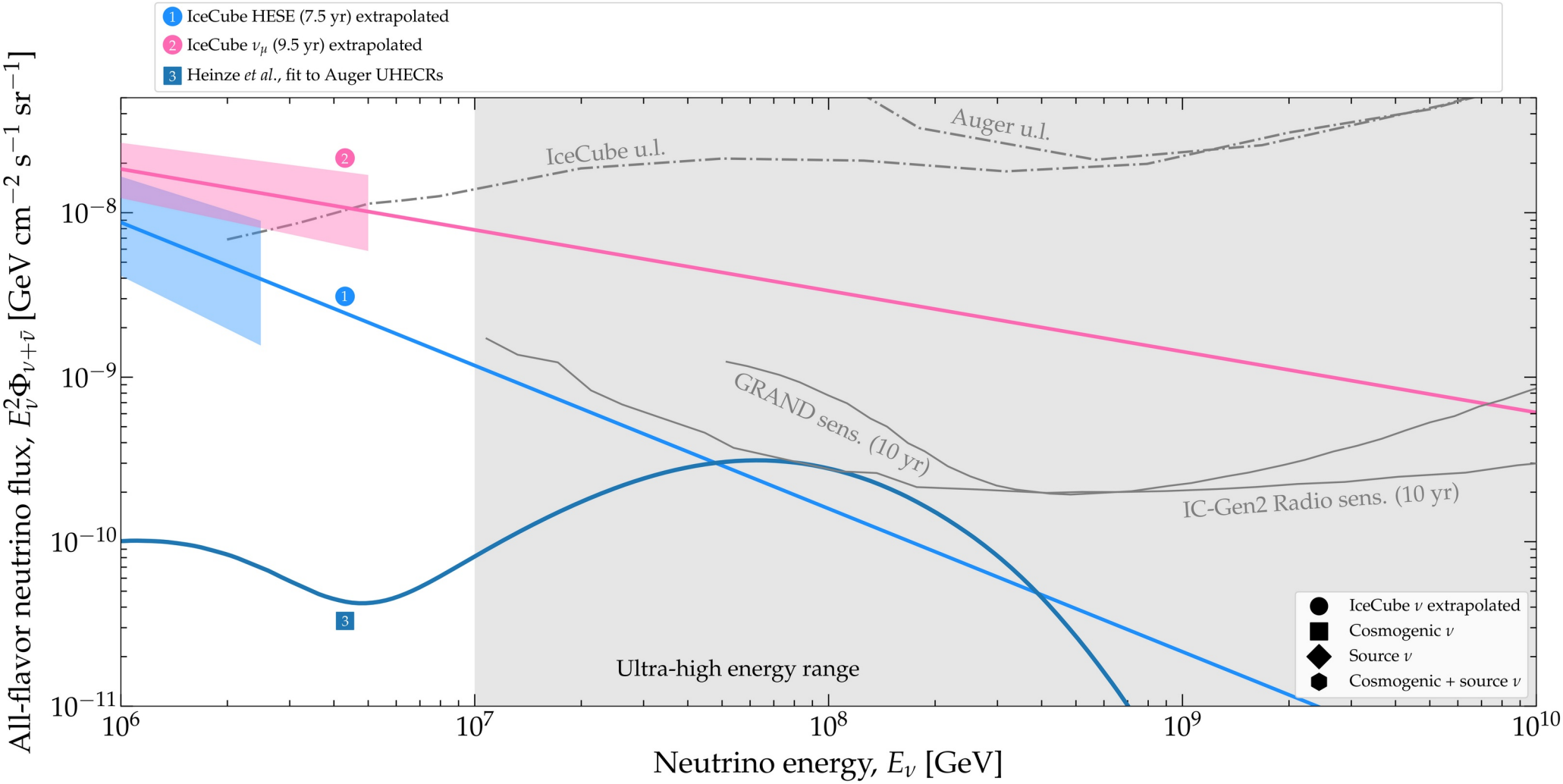


- Inter-antenna spacing: 1 km

ν_e

GRAND, *Sci. China Phys. Mech. Astron.* 2020 [1810.9994]


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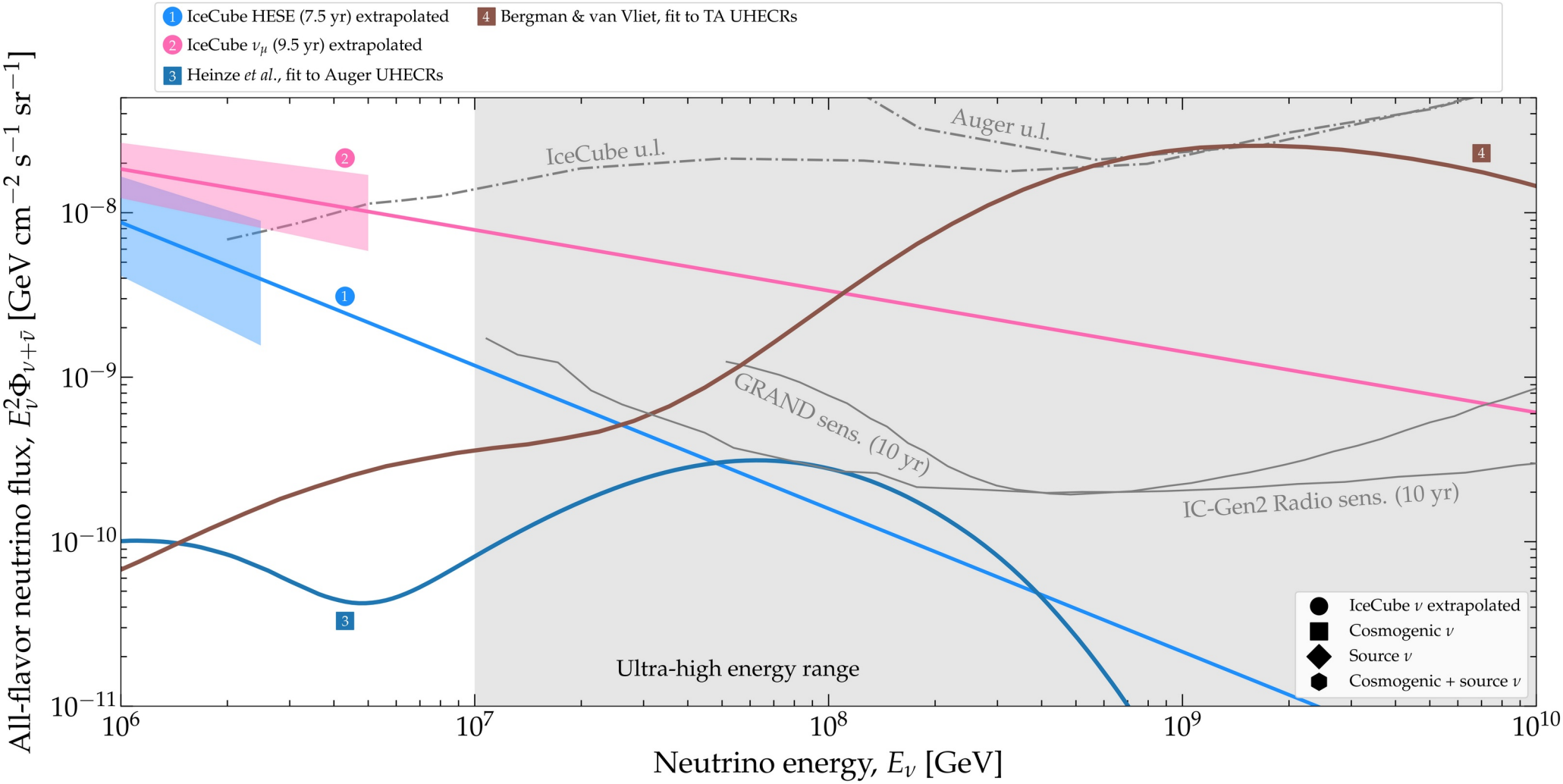
10^9
10^{10}
Neutrino energy, E_ν [GeV]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IceCube u.l.
Auger u.l.
GRAND sens. (10 yr)
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Ultra-high energy range
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10^6
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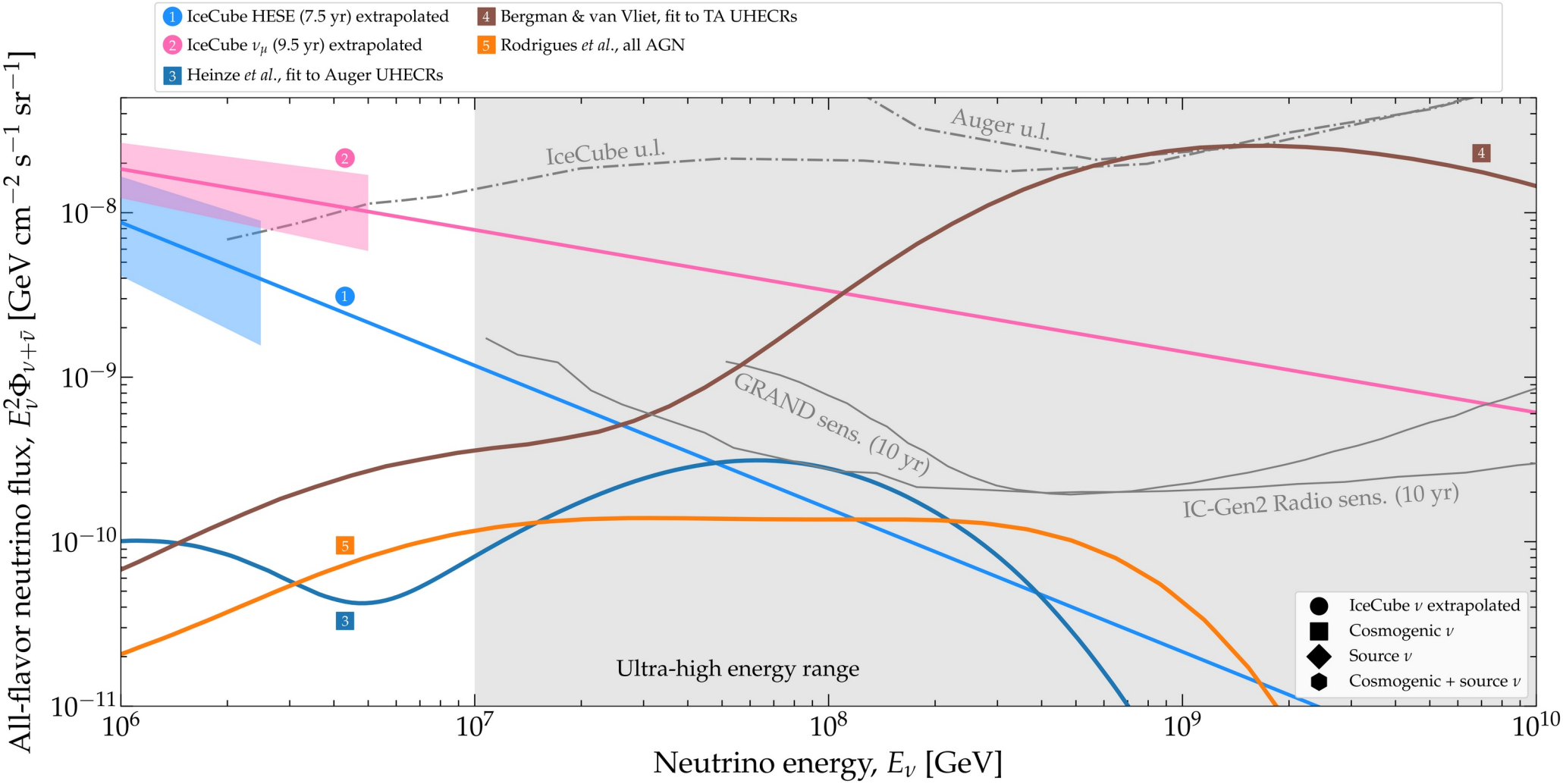
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Auger u.l.
IceCube u.l.
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Ultra-high energy range
IceCube ν extrapolated
Cosmogenic ν
Source ν
Cosmogenic + source ν
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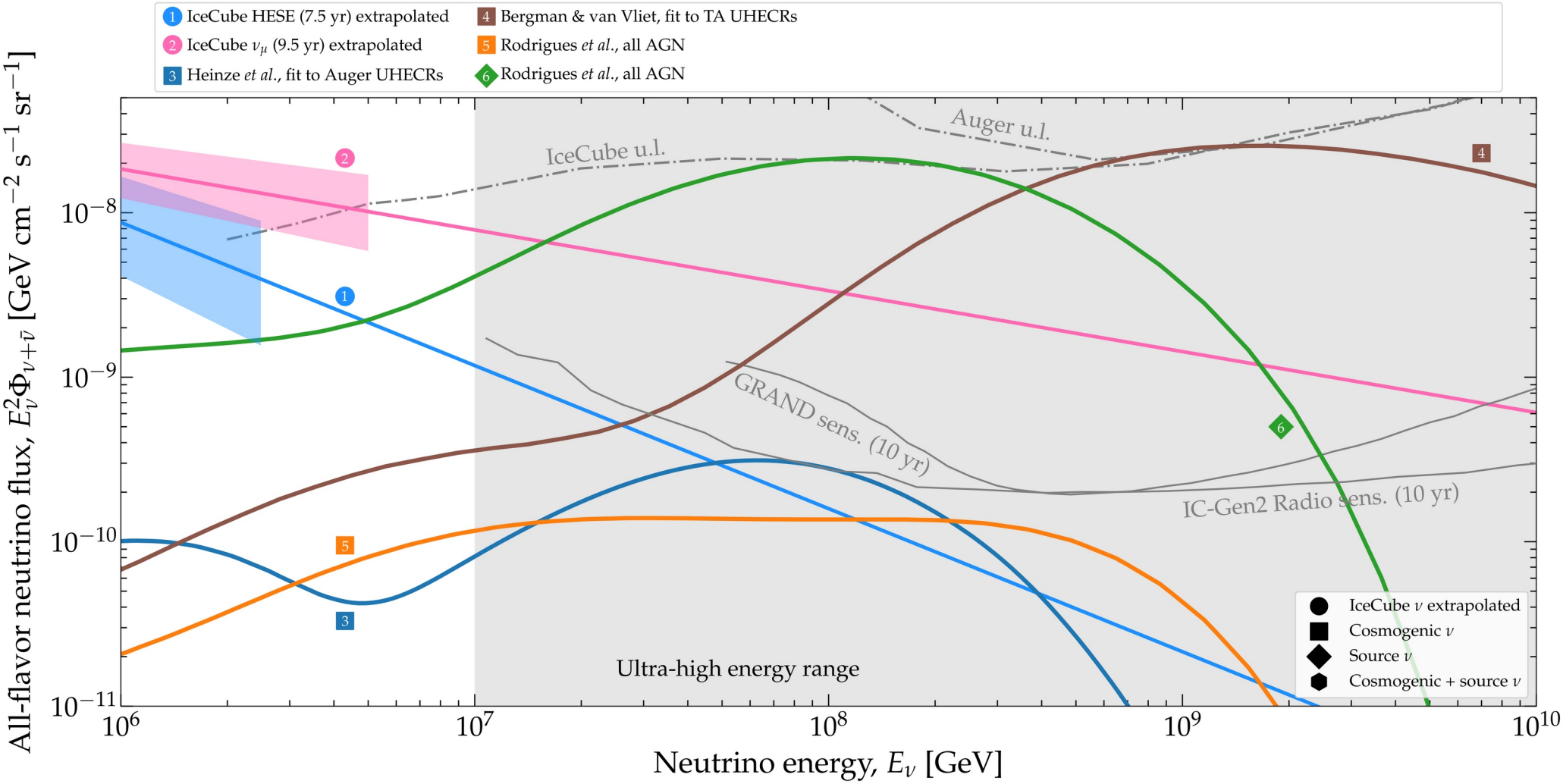
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IceCube u.l.
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GRAND sens. (10 yr)
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Ultra-high energy range
IceCube ν extrapolated
Cosmogenic ν
Source ν
Cosmogenic + source ν
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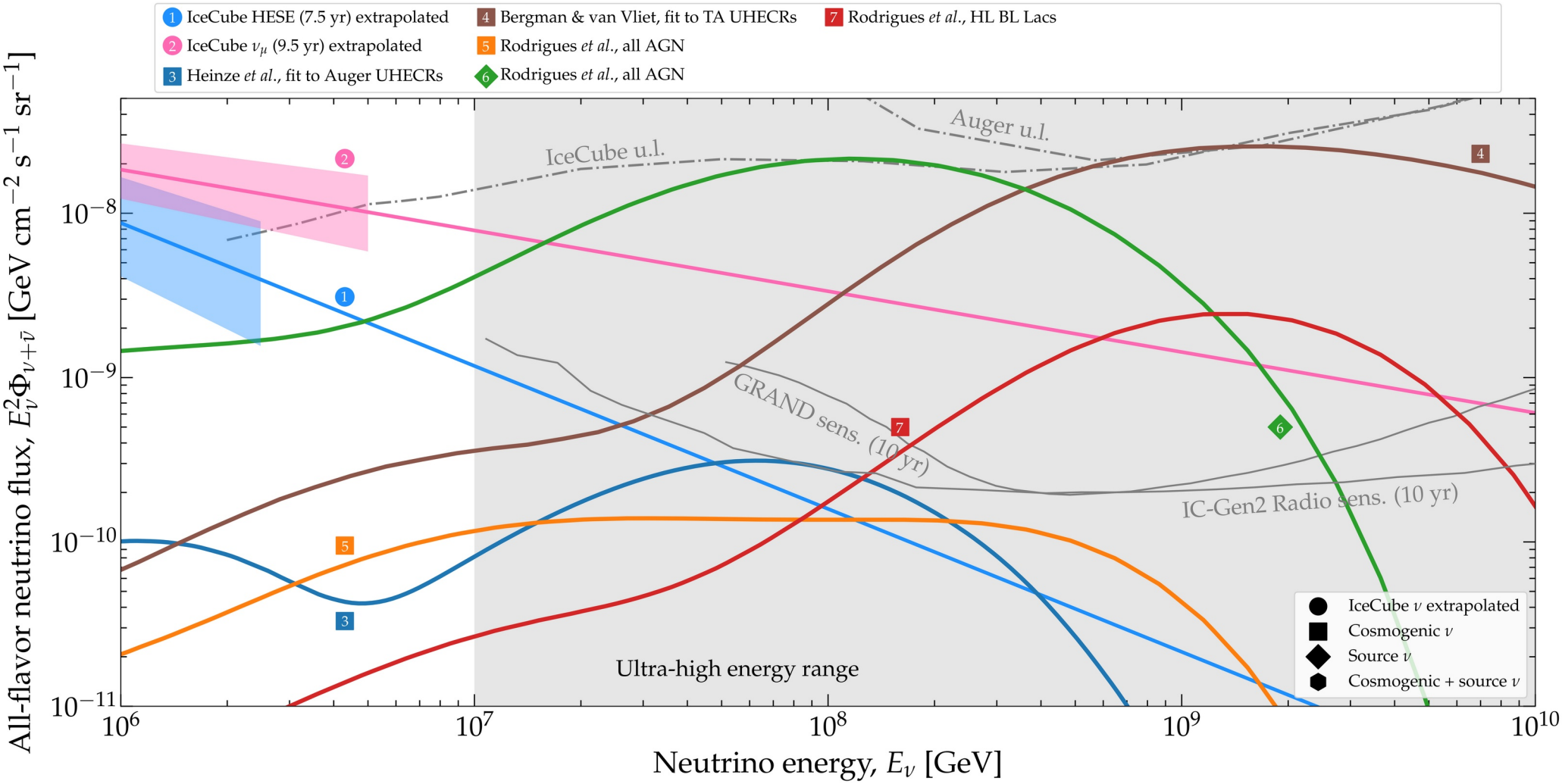
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IceCube u.l.
Auger u.l.
GRAND sens. (10 yr)
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Ultra-high energy range
IceCube ν extrapolated
Cosmogenic ν
Source ν
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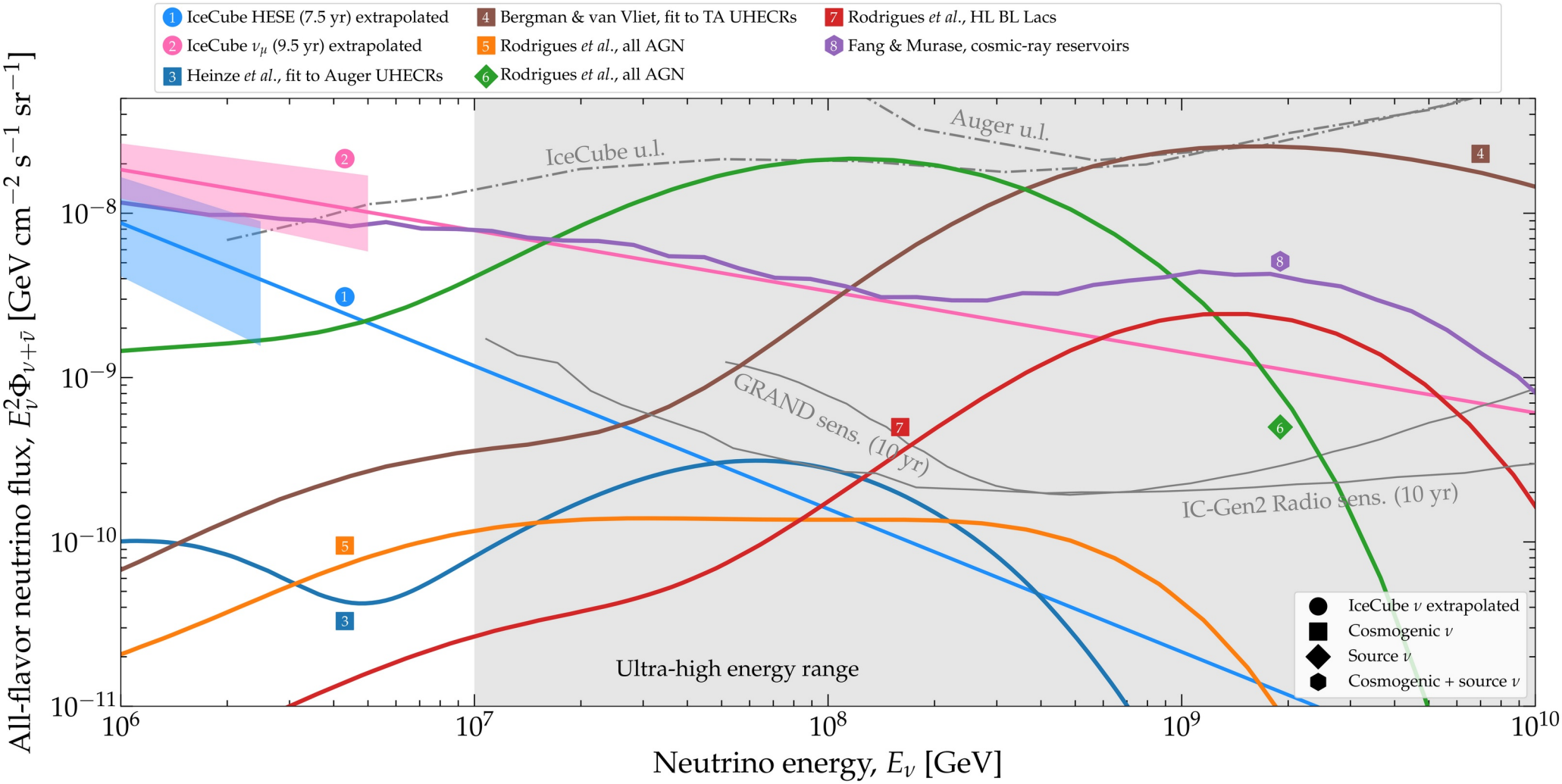
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8 Fang & Murase, cosmic-ray reservoirs
IceCube u.l.
Auger u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
IceCube ν extrapolated
Cosmogenic ν
Source ν
Cosmogenic + source ν
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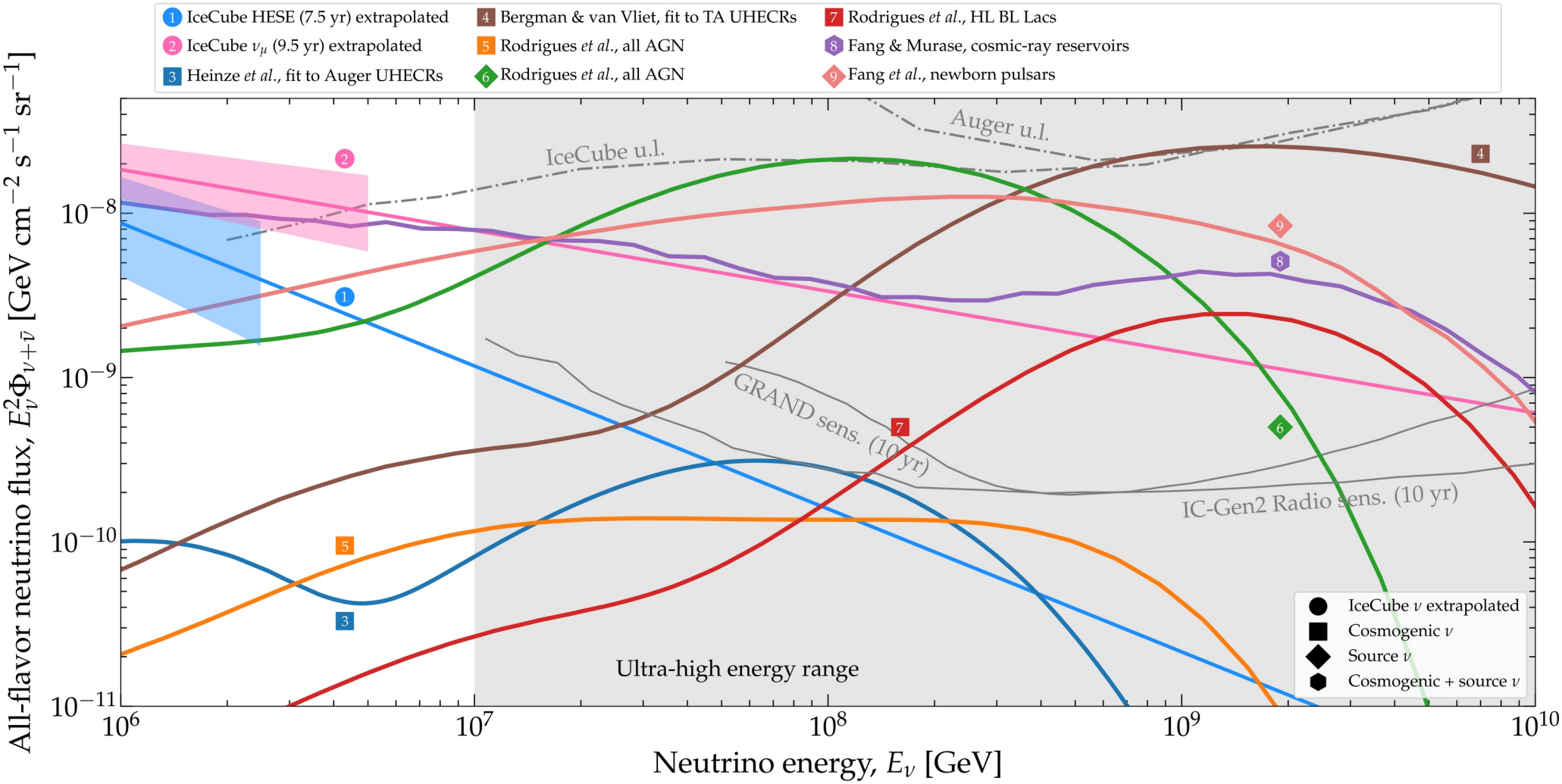
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IceCube u.l.
Auger u.l.
GRAND sens. (10 yr)
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IceCube ν extrapolated
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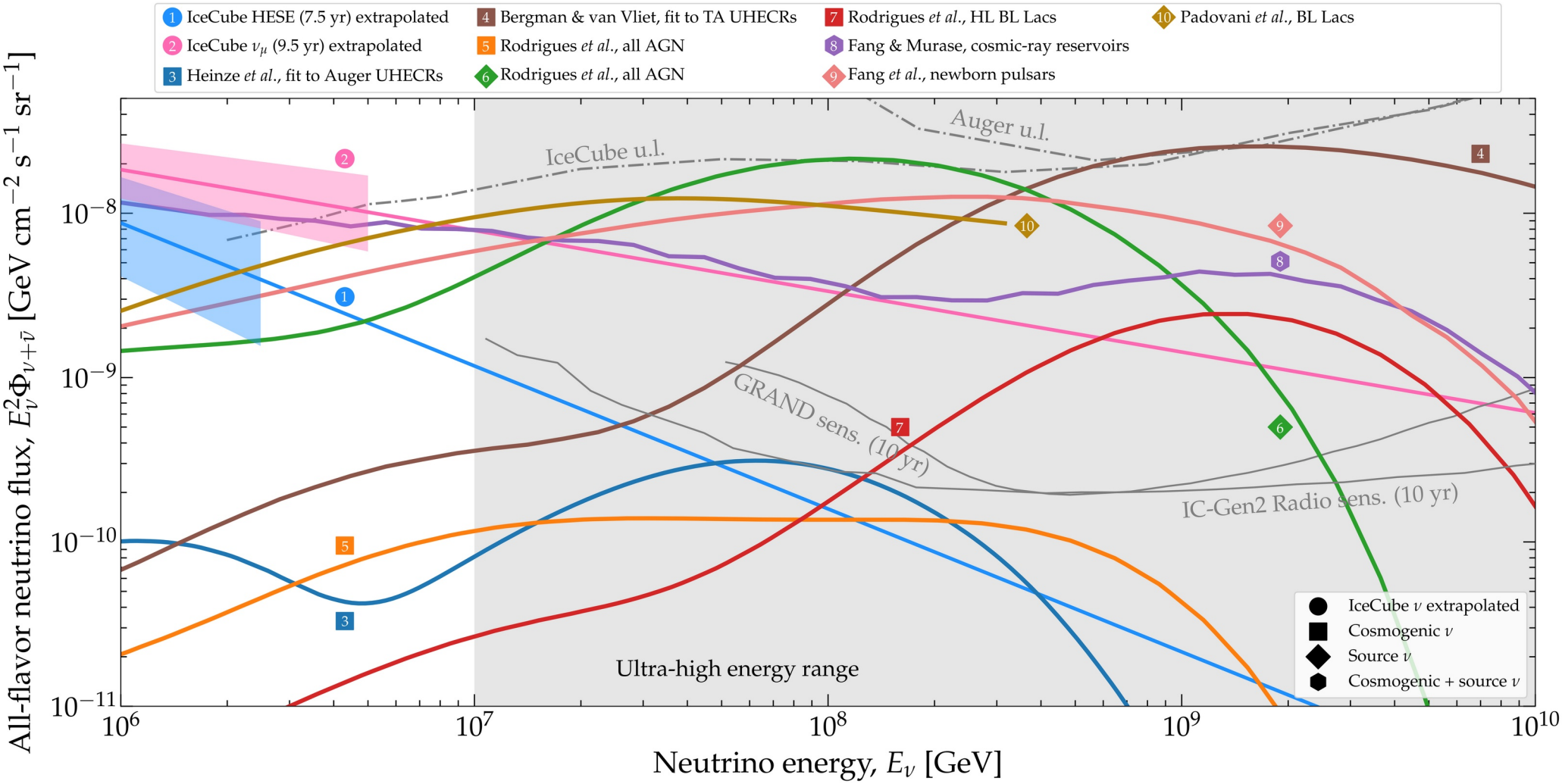
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IceCube u.l.
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GRAND sens. (10 yr)
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Ultra-high energy range
IceCube ν extrapolated
Cosmogenic ν
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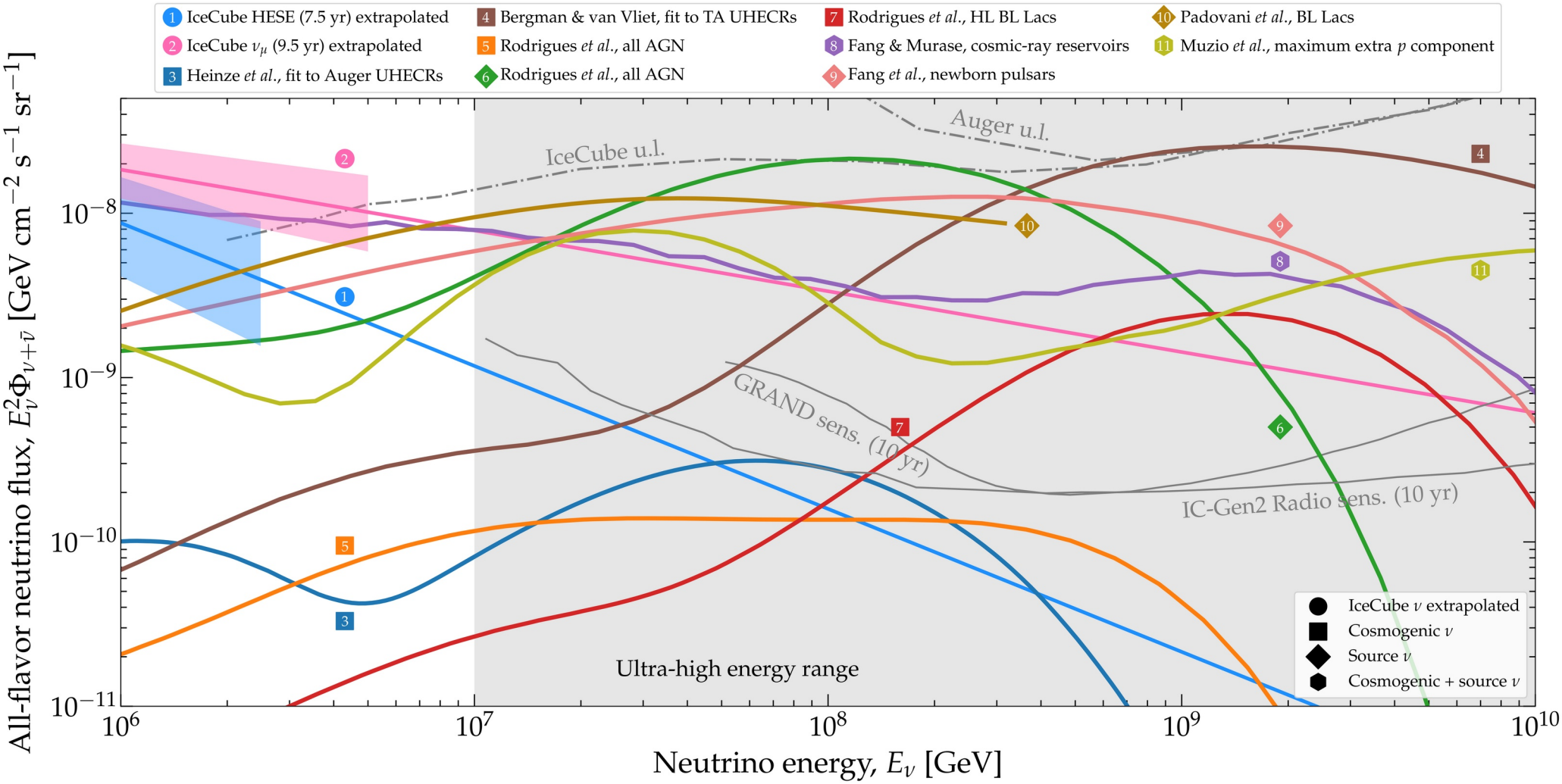
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11 Muzio et al., maximum extra p component
IceCube u.l.
Auger u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
IceCube ν extrapolated
Cosmogenic ν
Source ν
Cosmogenic + source ν
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$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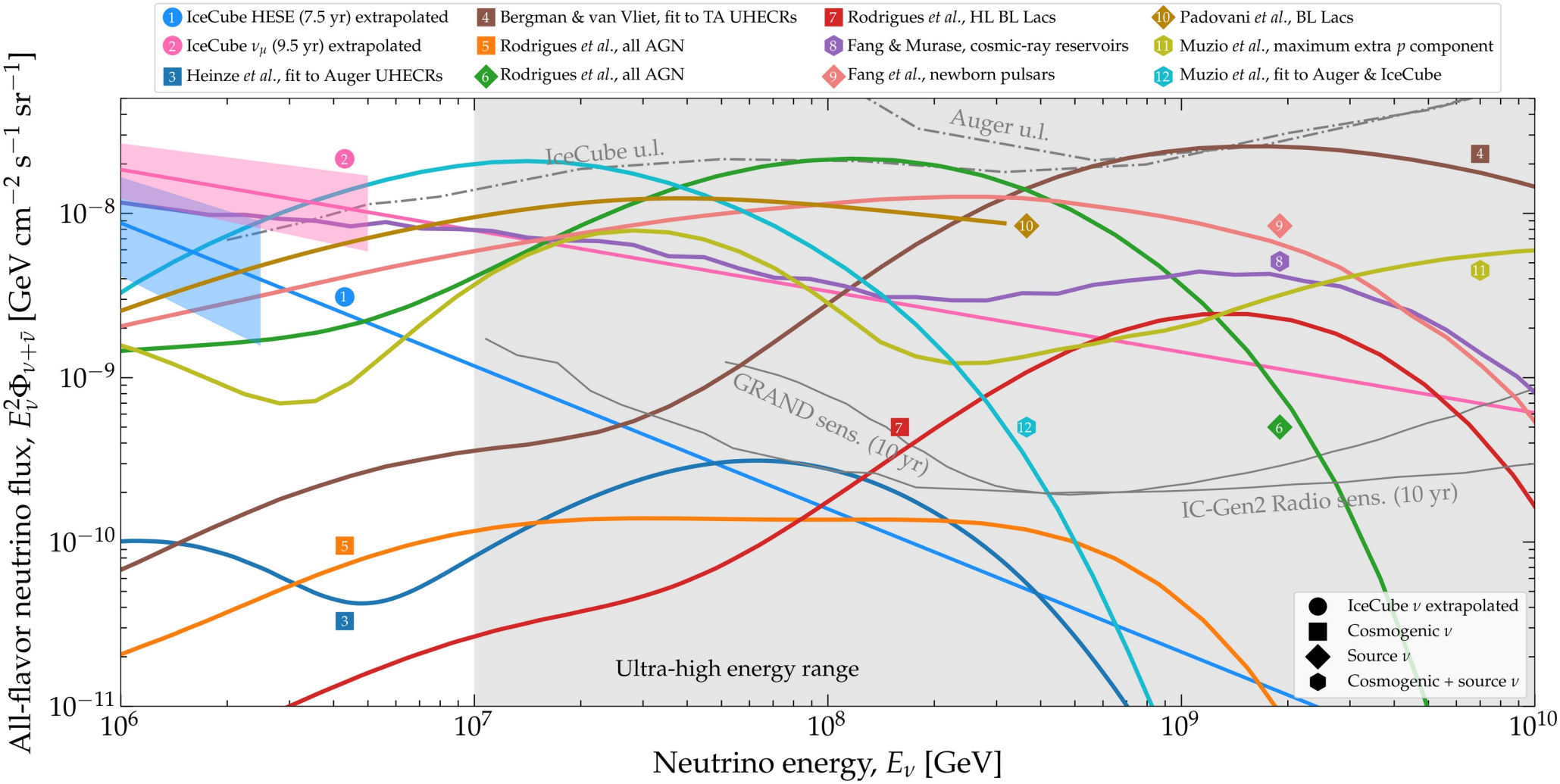
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5 Rodrigues et al., all AGN
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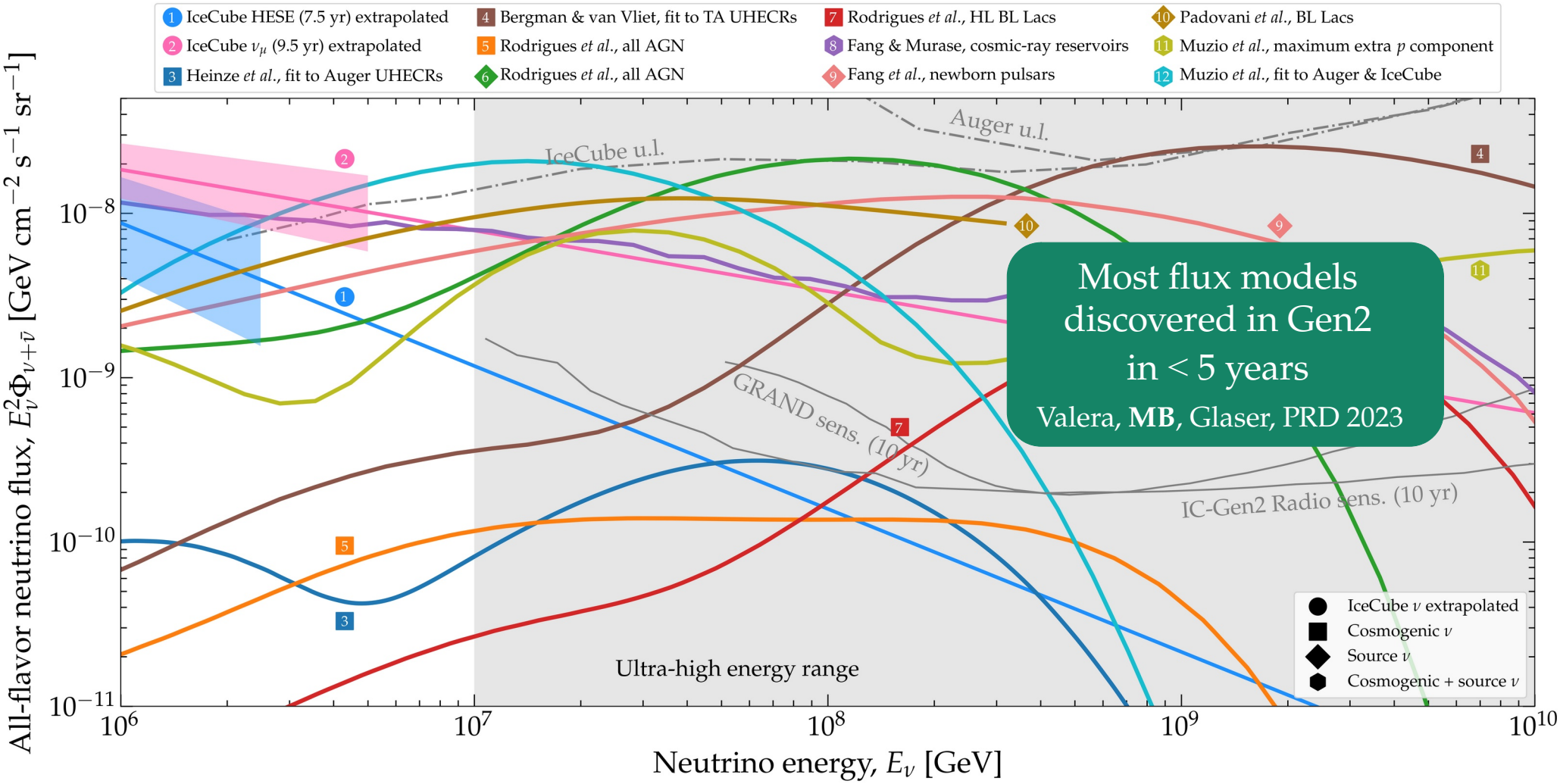
11 Muzio et al., maximum extra p component
12 Muzio et al., fit to Auger & IceCube
IceCube u.l.
Auger u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
IceCube ν extrapolated
Cosmogenic ν
Source ν
Cosmogenic + source ν
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$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


1 IceCube HESE (7.5 yr) extrapolated
2 IceCube ν_μ (9.5 yr) extrapolated
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Ultra-high energy range
Most flux models discovered in Gen2 in < 5 years
Valera, MB, Glaser, PRD 2023
IceCube ν extrapolated
Cosmogenic ν
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All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
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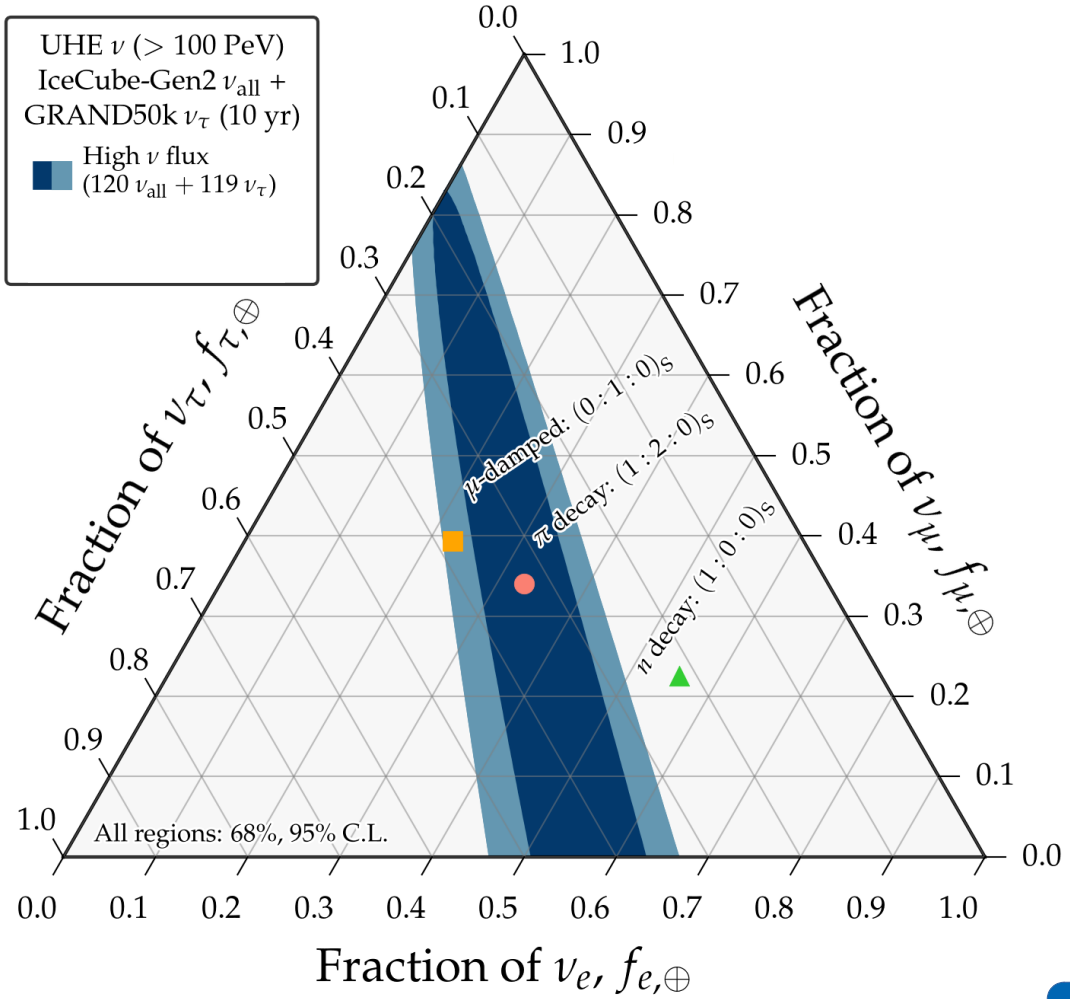
Manufacturing UHE flavor sensitivity with two detectors

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

Then we combine two of detectors:



Testagrossa, Fiorillo, **MB**, 2310.12215

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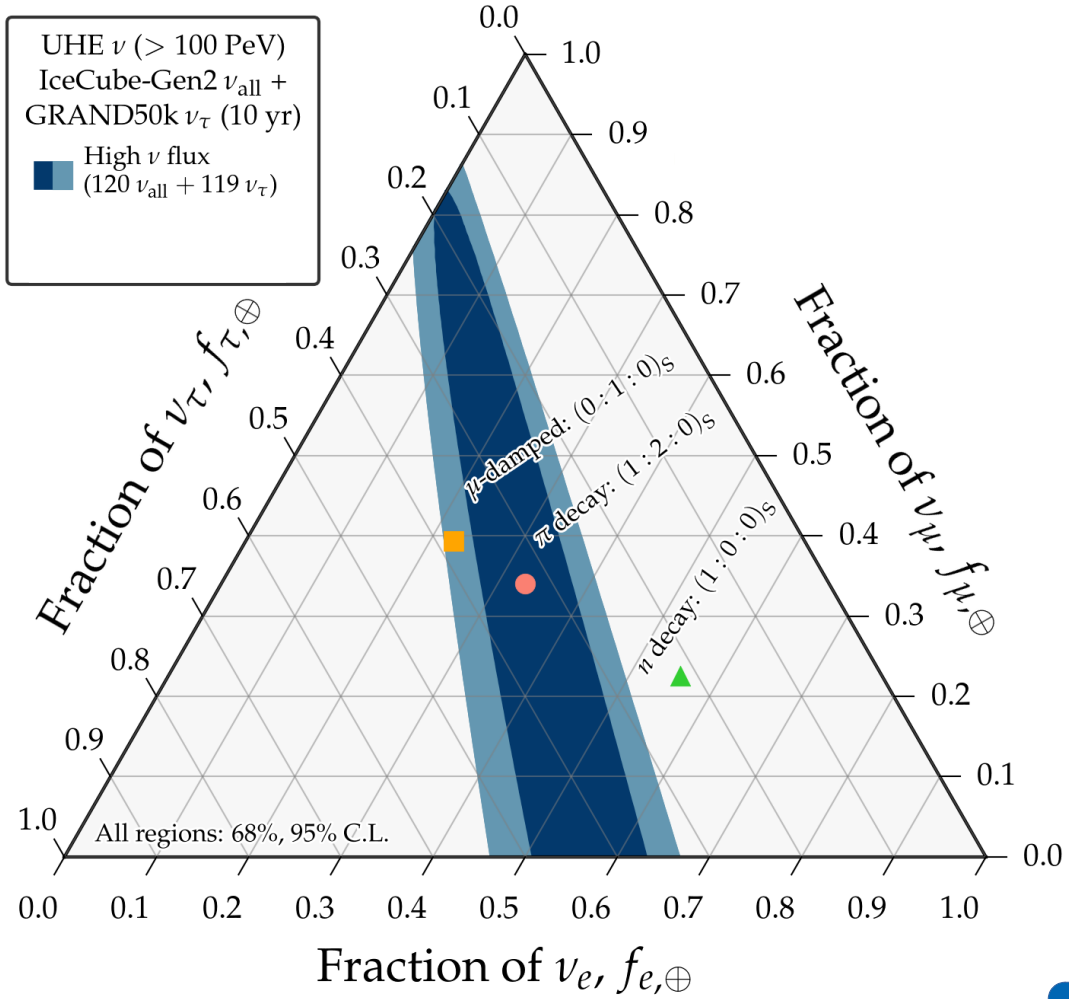

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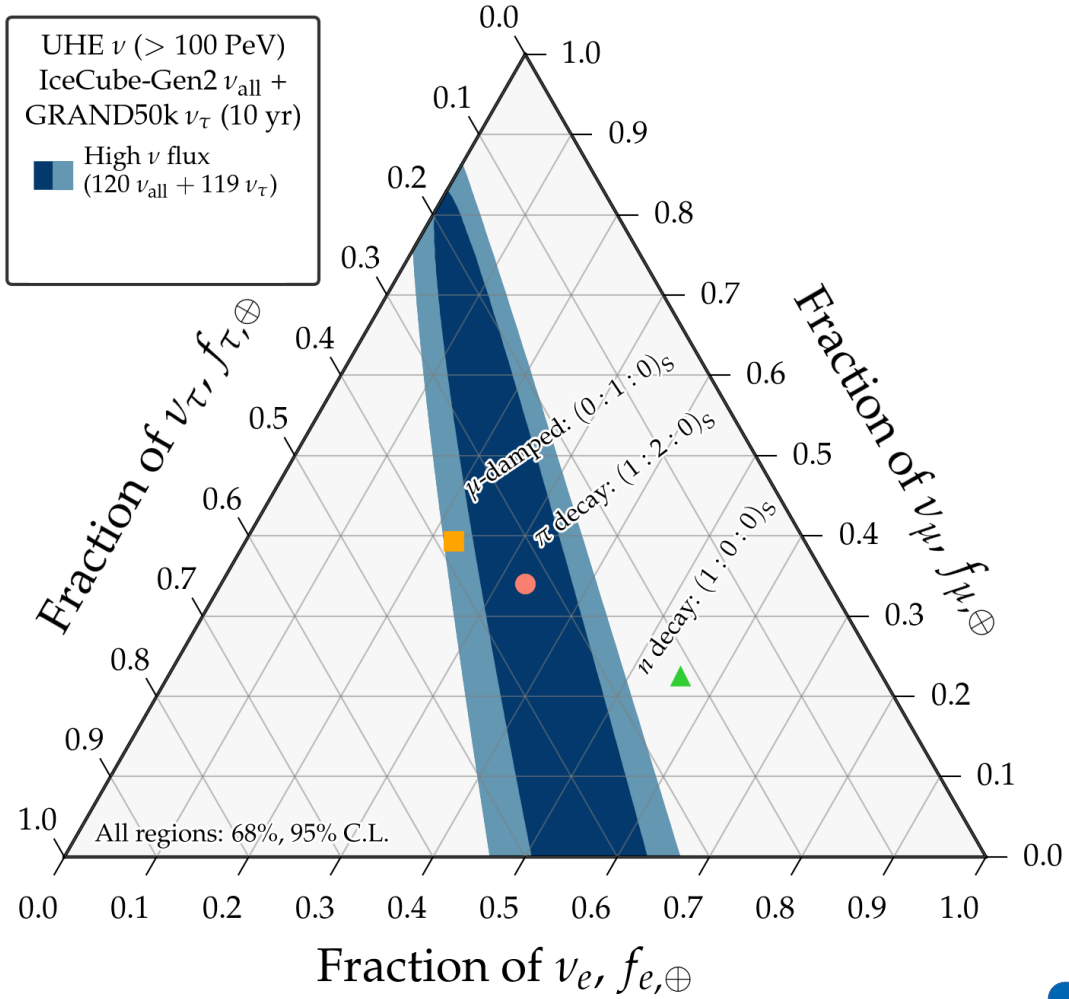

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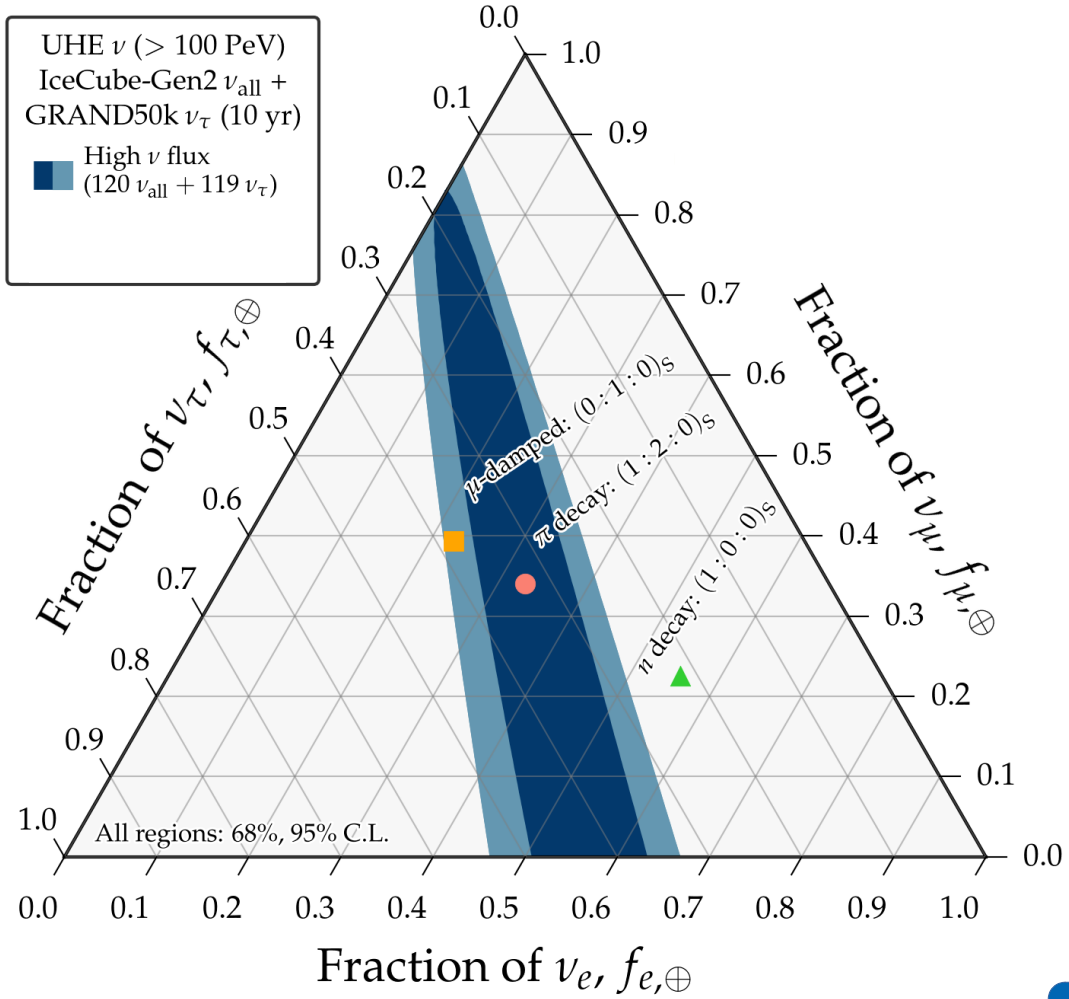

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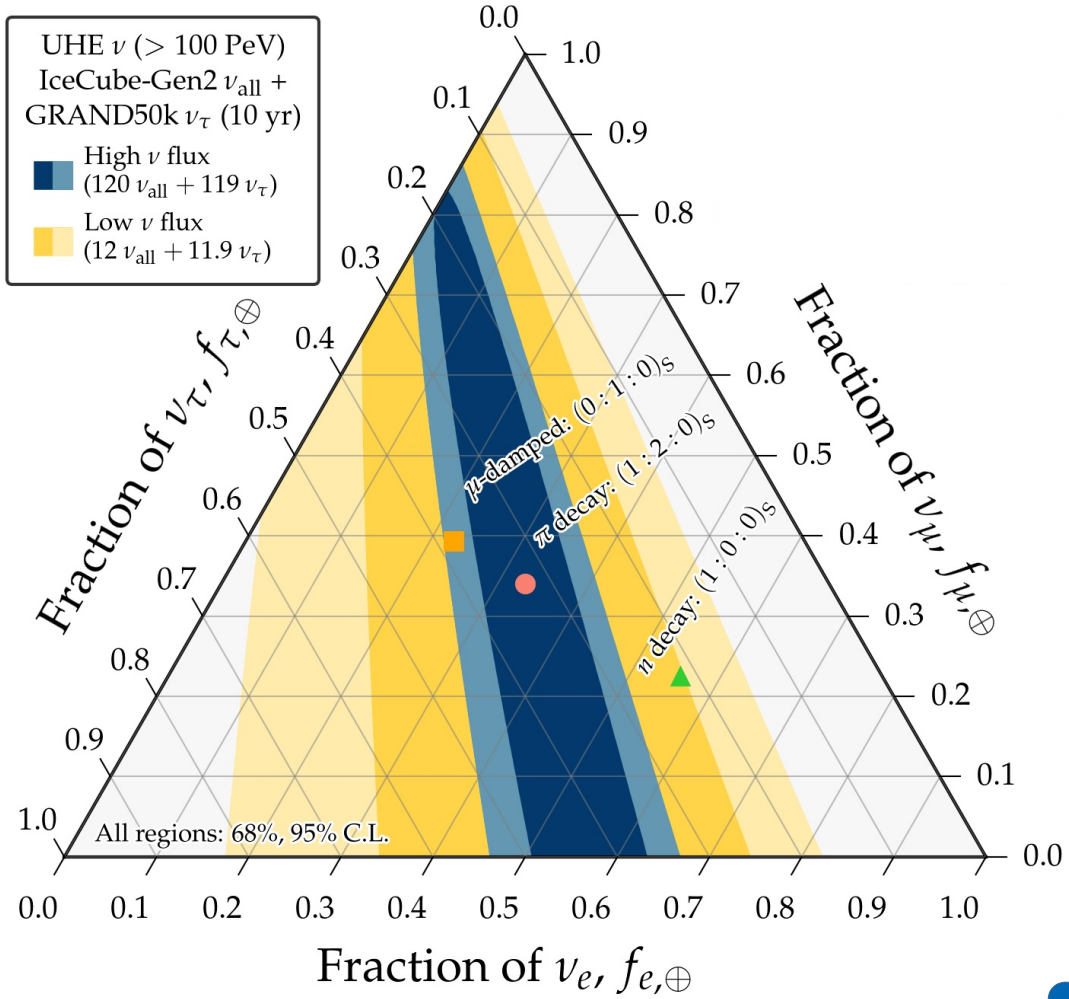

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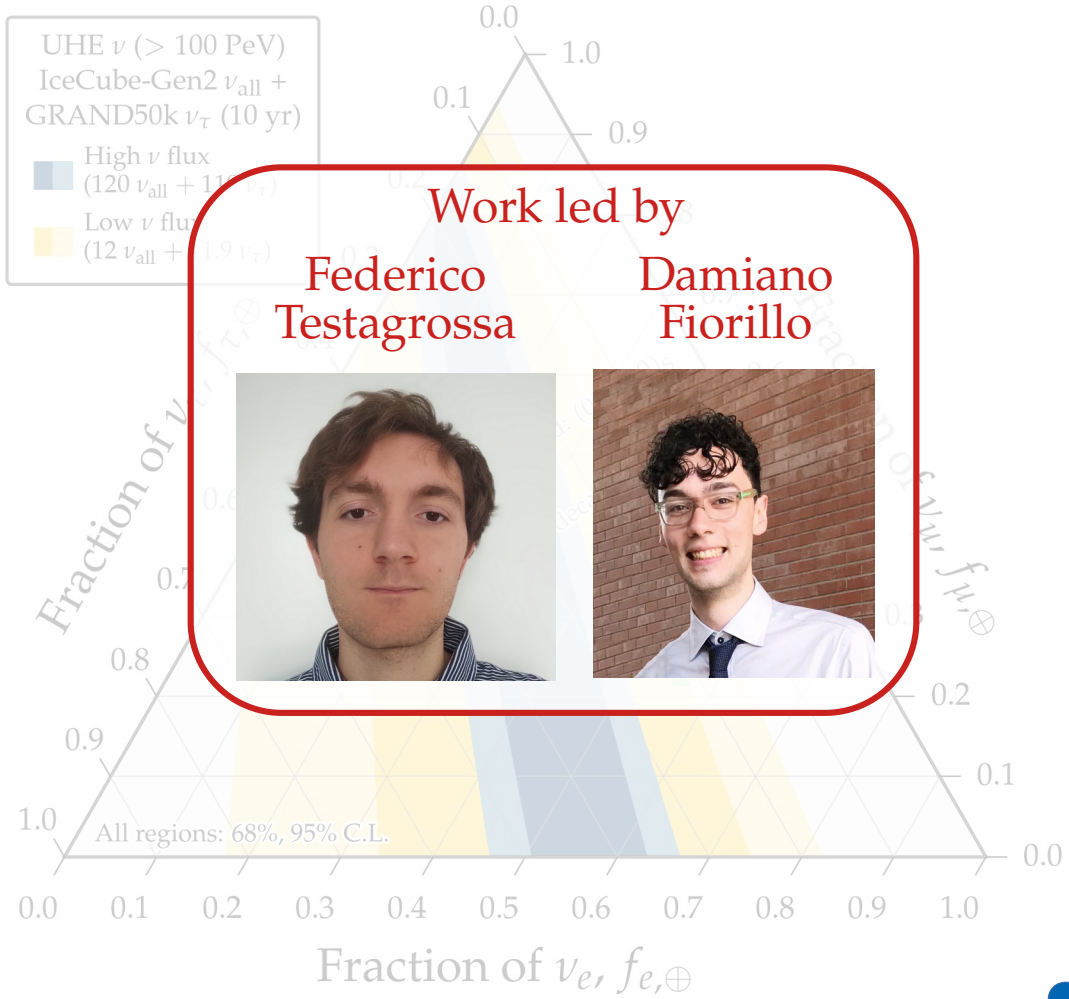

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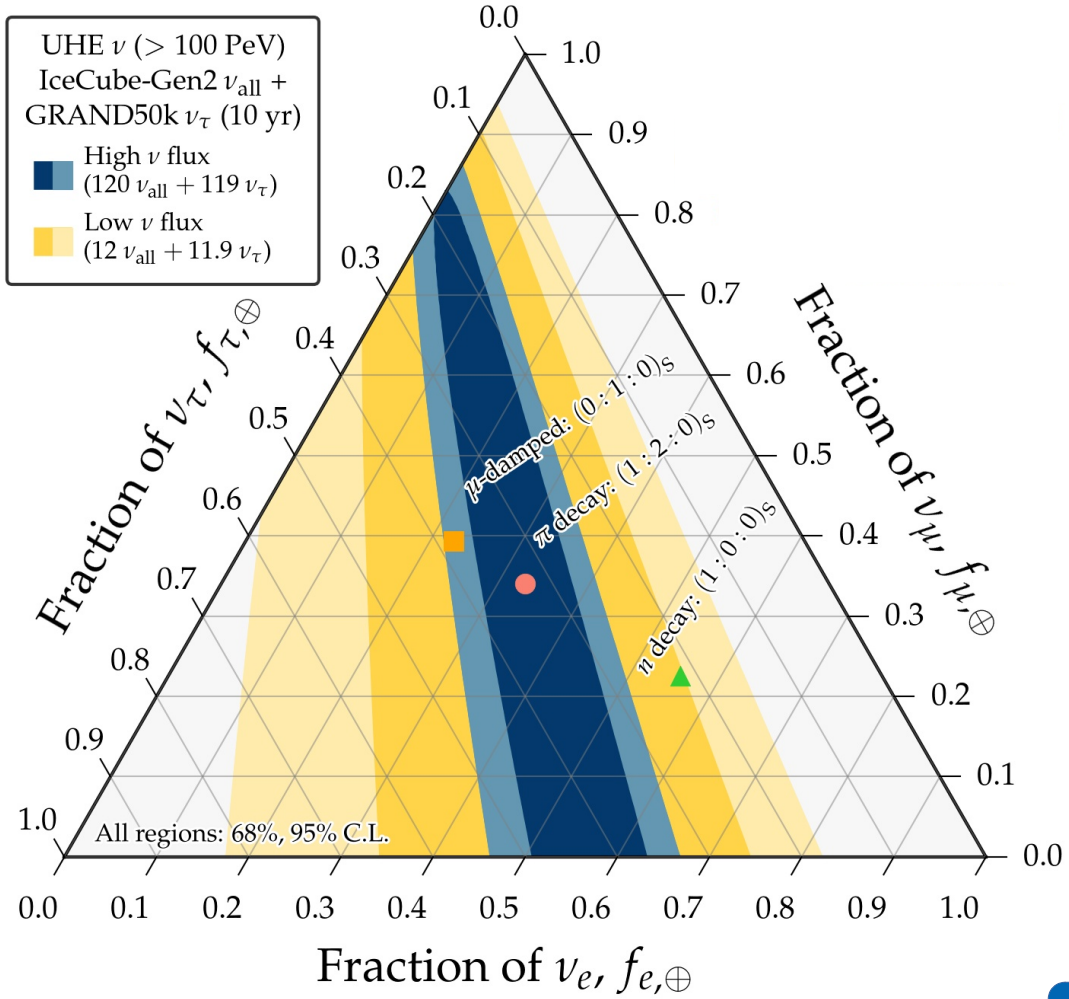

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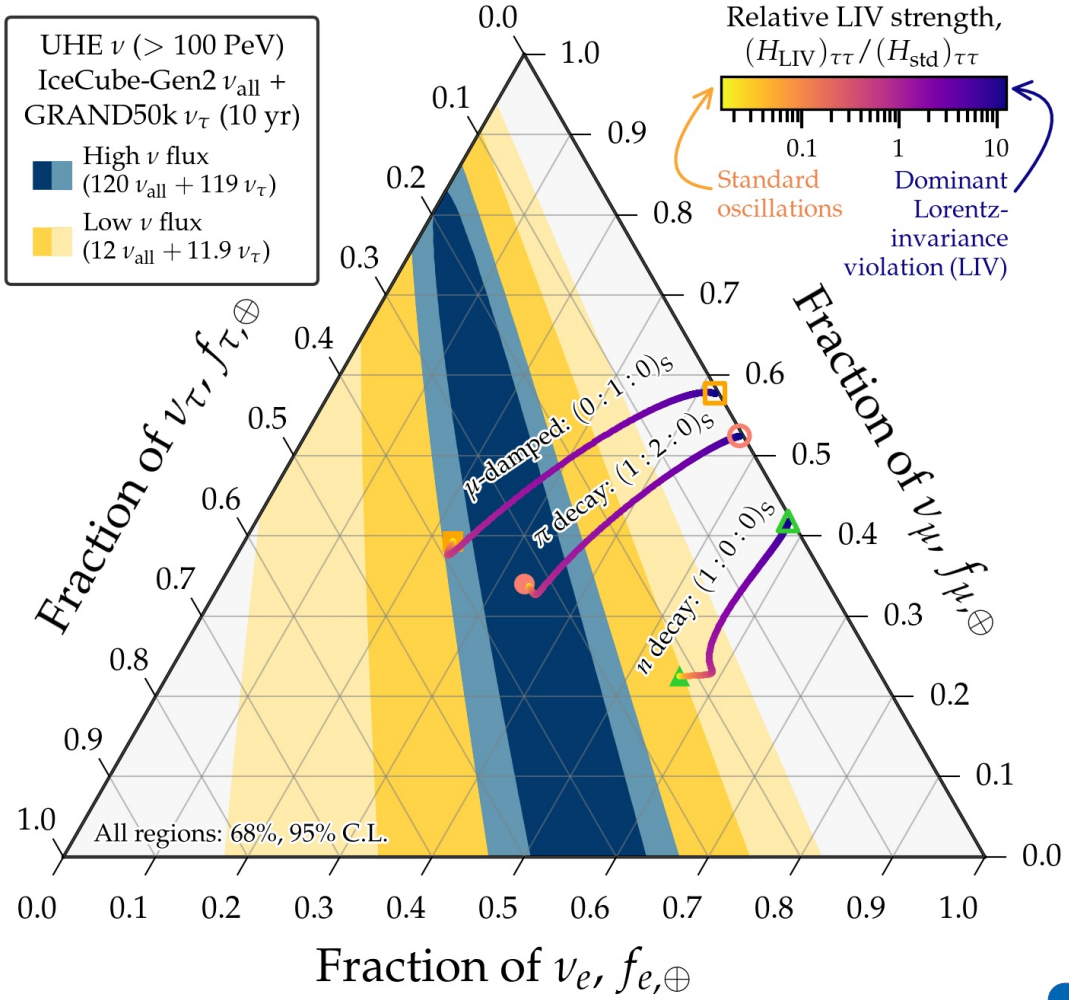
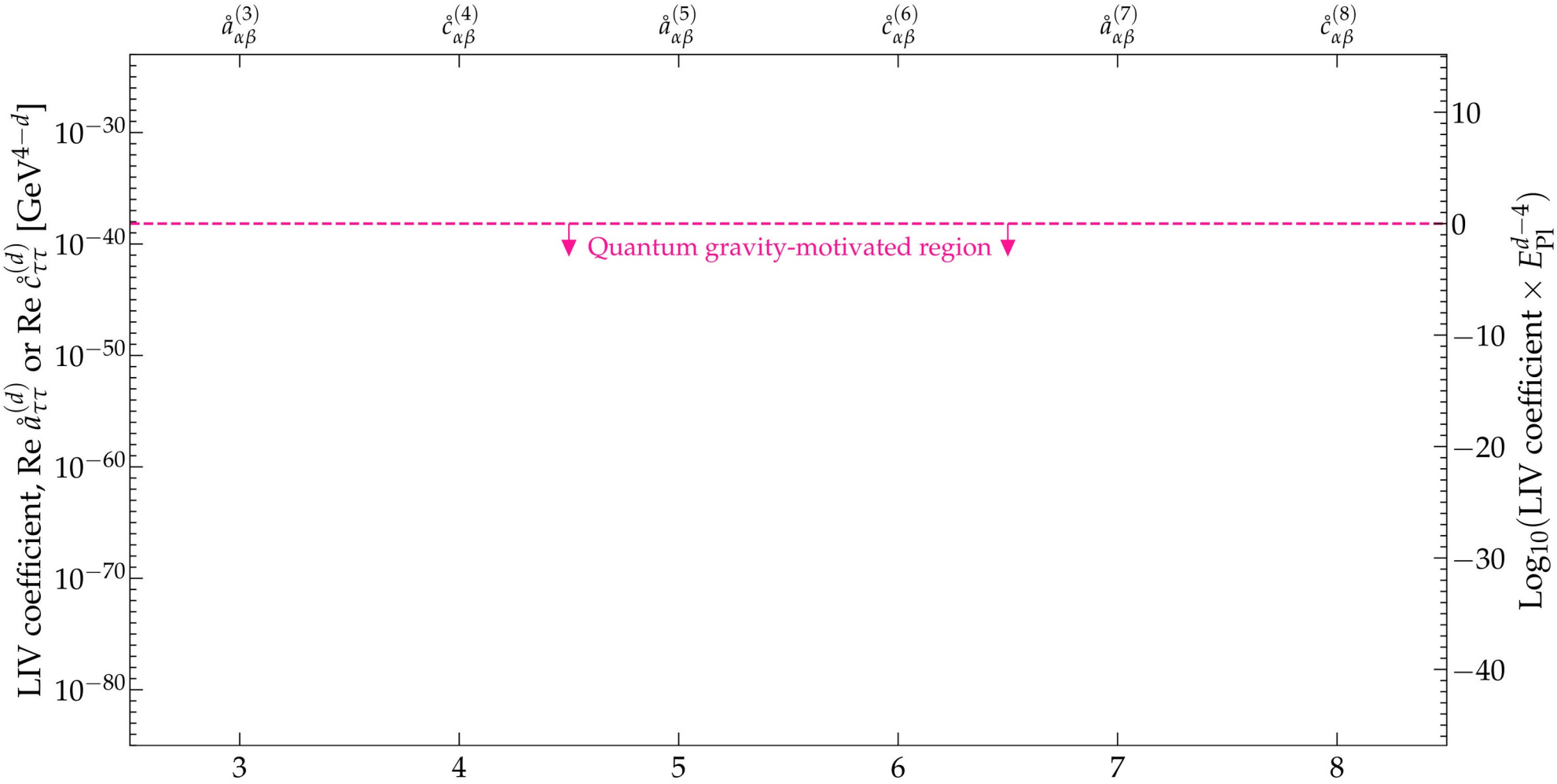


Testagrossa, Fiorillo, **MB**, 2310.12215

Lorentz-invariance violation at ultra-high energies



Testagrossa, Fiorillo, **MB**, 2310.12215

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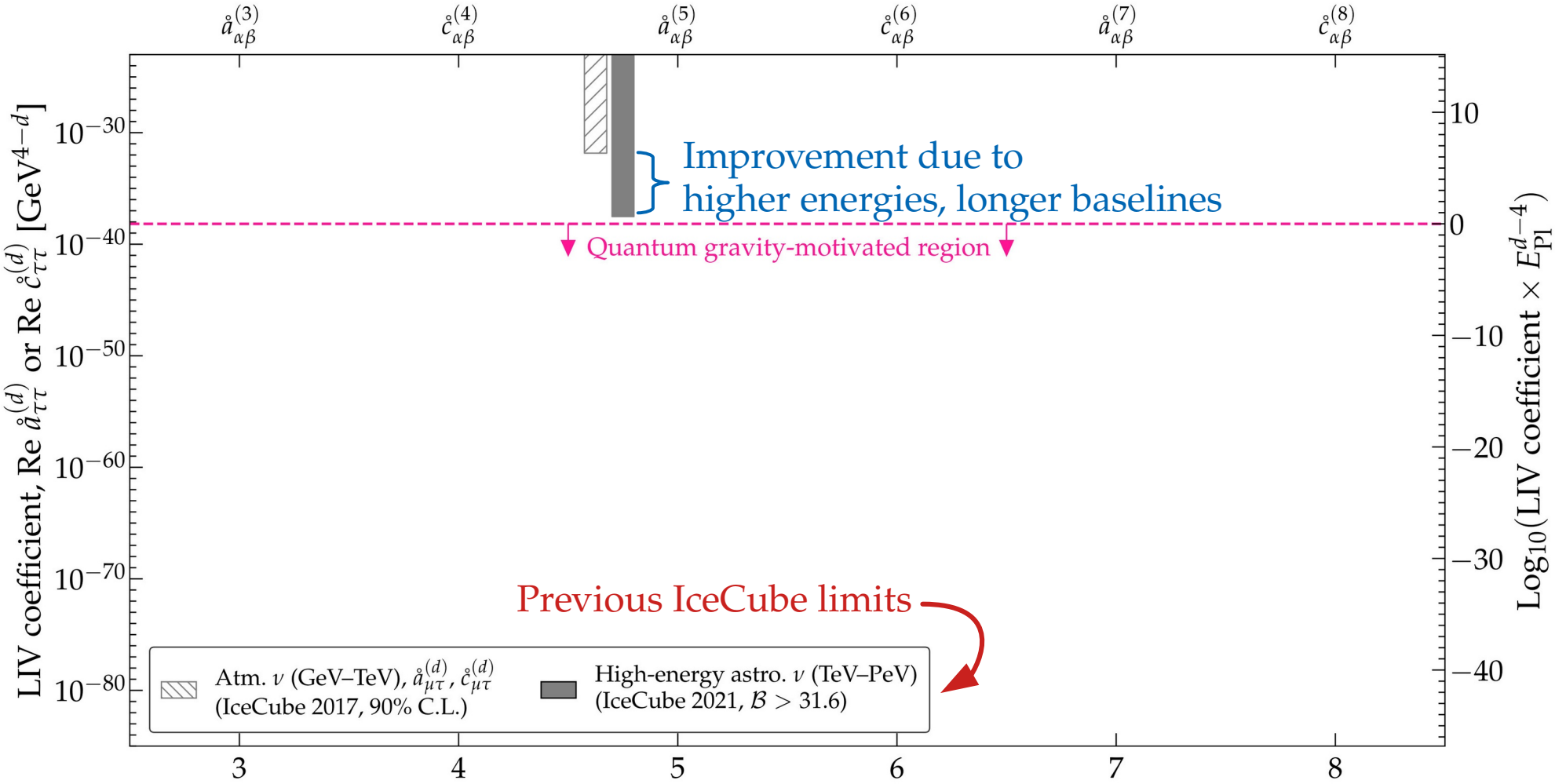

Testagrossa, Fiorillo, **MB**, 2310.12215

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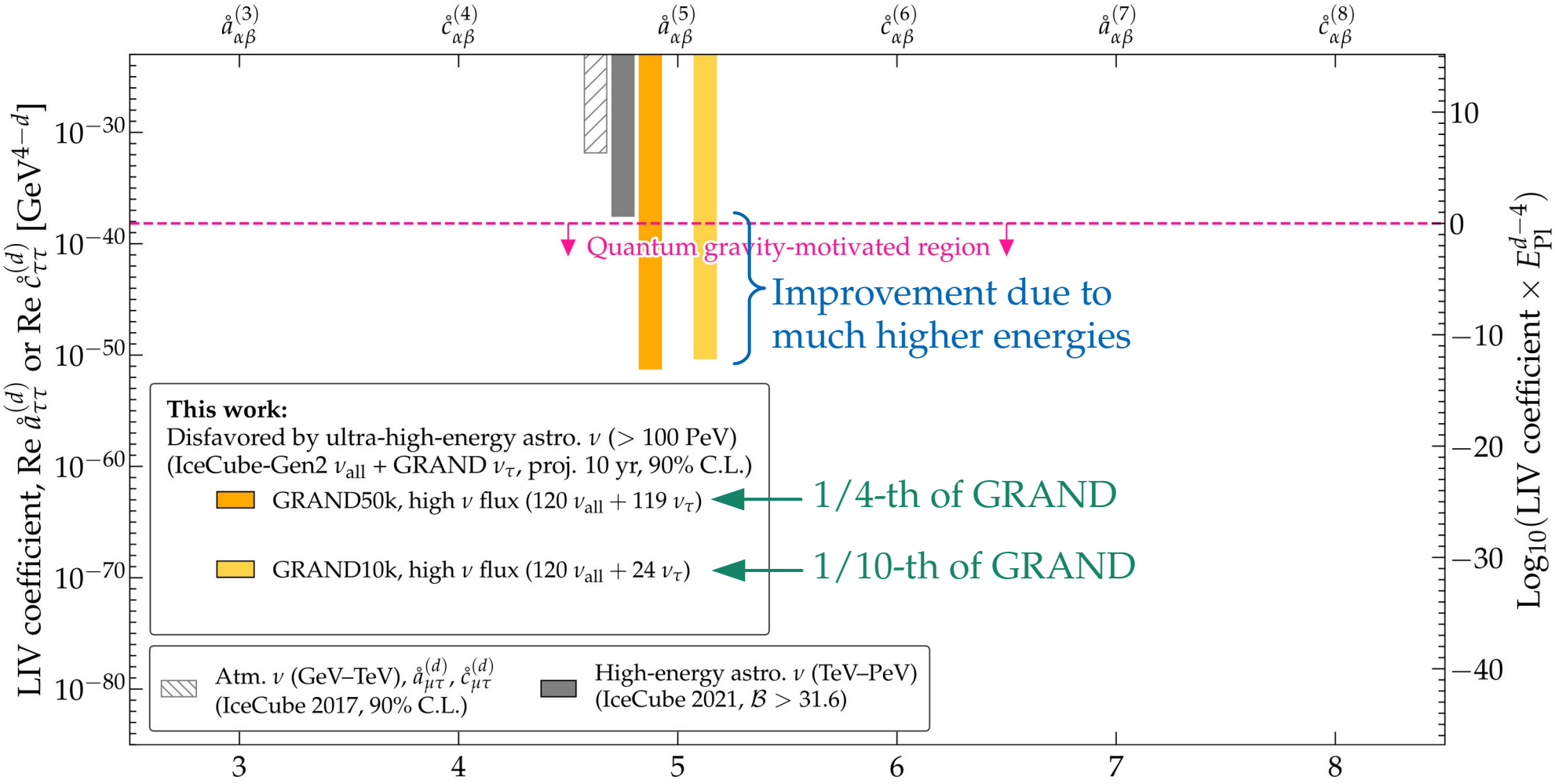

Testagrossa, Fiorillo, **MB**, 2310.12215

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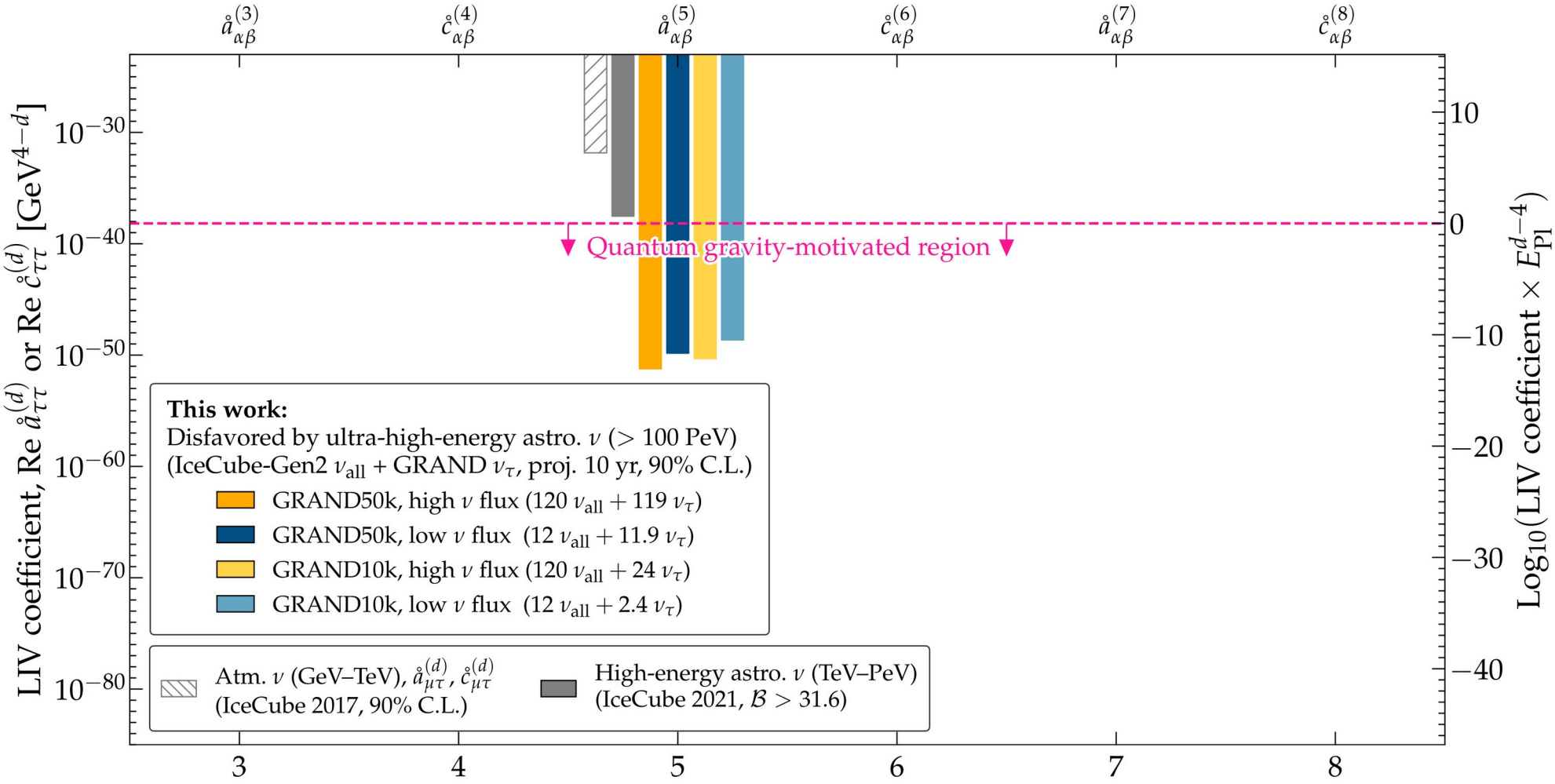

Testagrossa, Fiorillo, **MB**, 2310.12215

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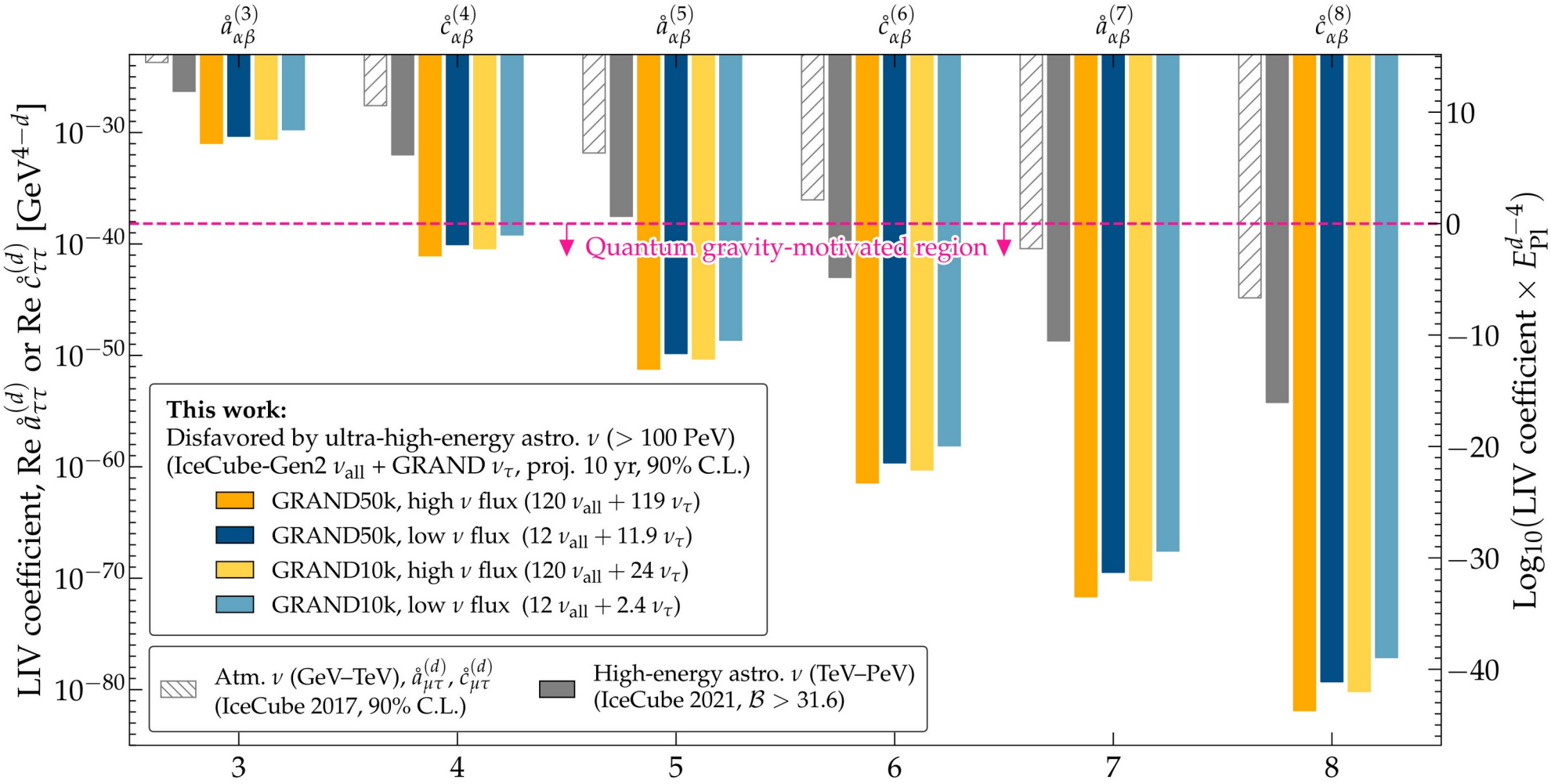
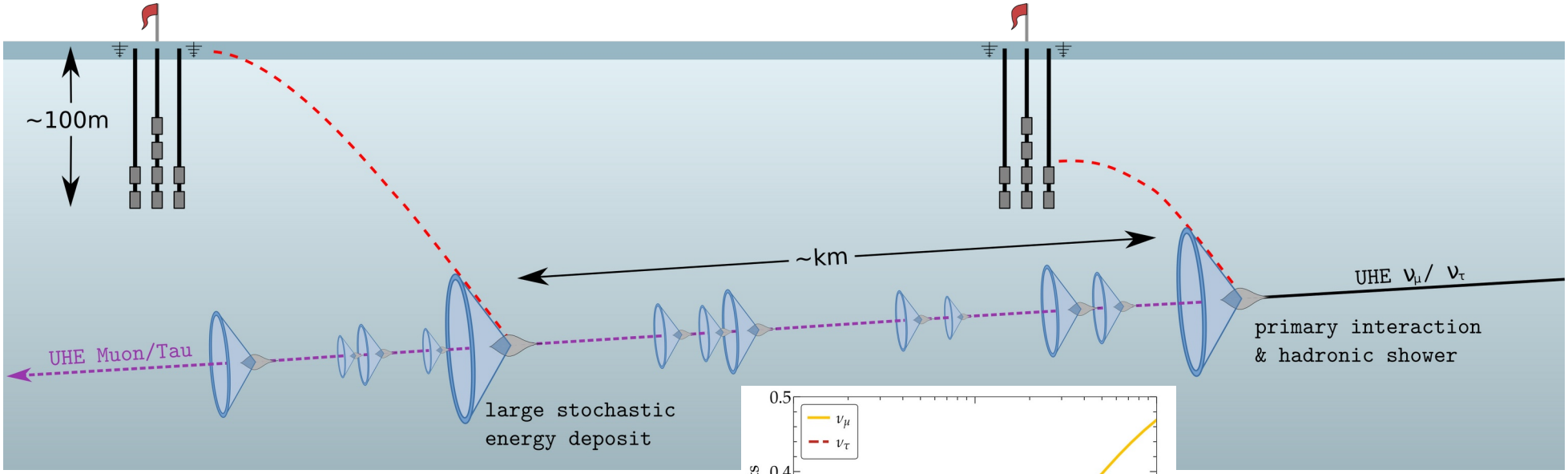
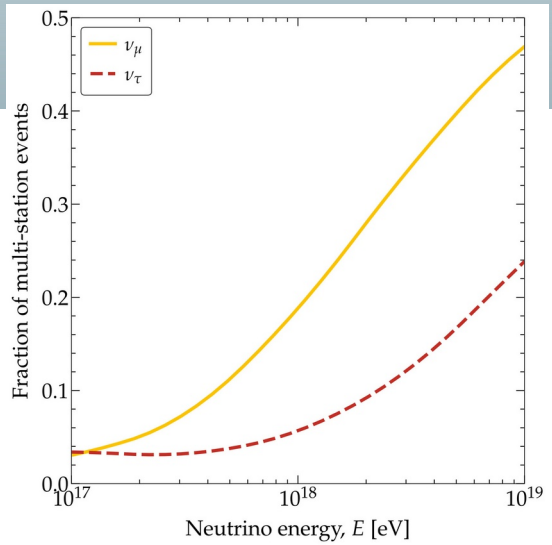


Testagrossa, Fiorillo, **MB**, 2310.12215

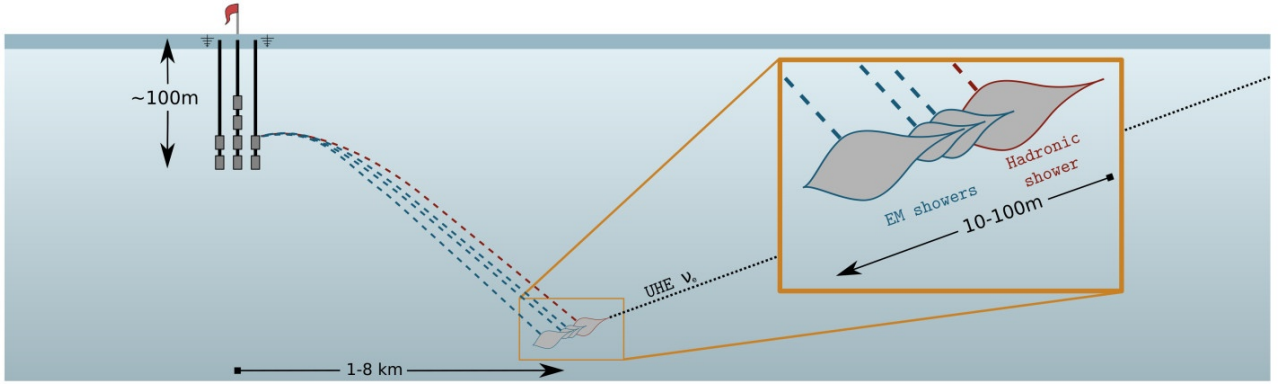
Multi-shower events from $\nu_\mu + \nu_\tau$ in IceCube-Gen2 (radio)

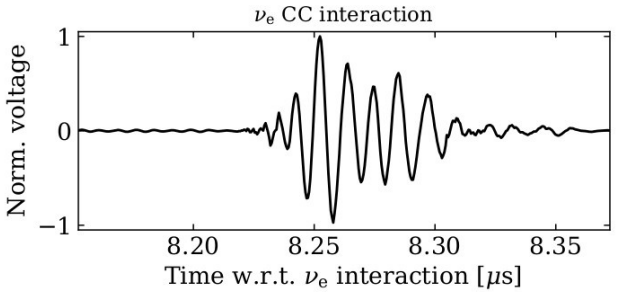


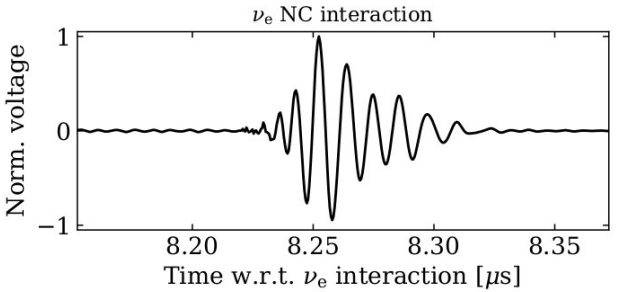
Coleman, Ericsson, **MB**, Glaser, 2402.02432

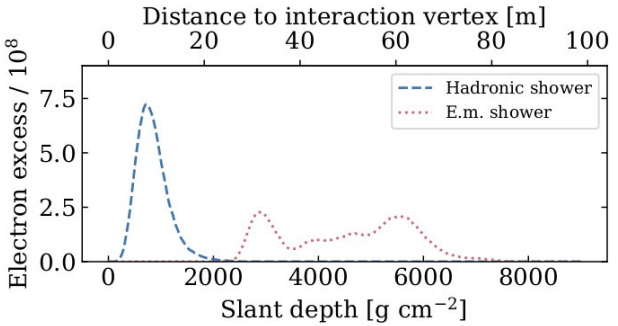


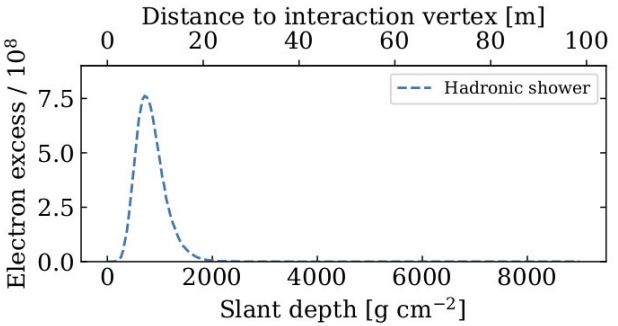
Multi-shower ν_e CC interactions in IceCube-Gen2 (radio)











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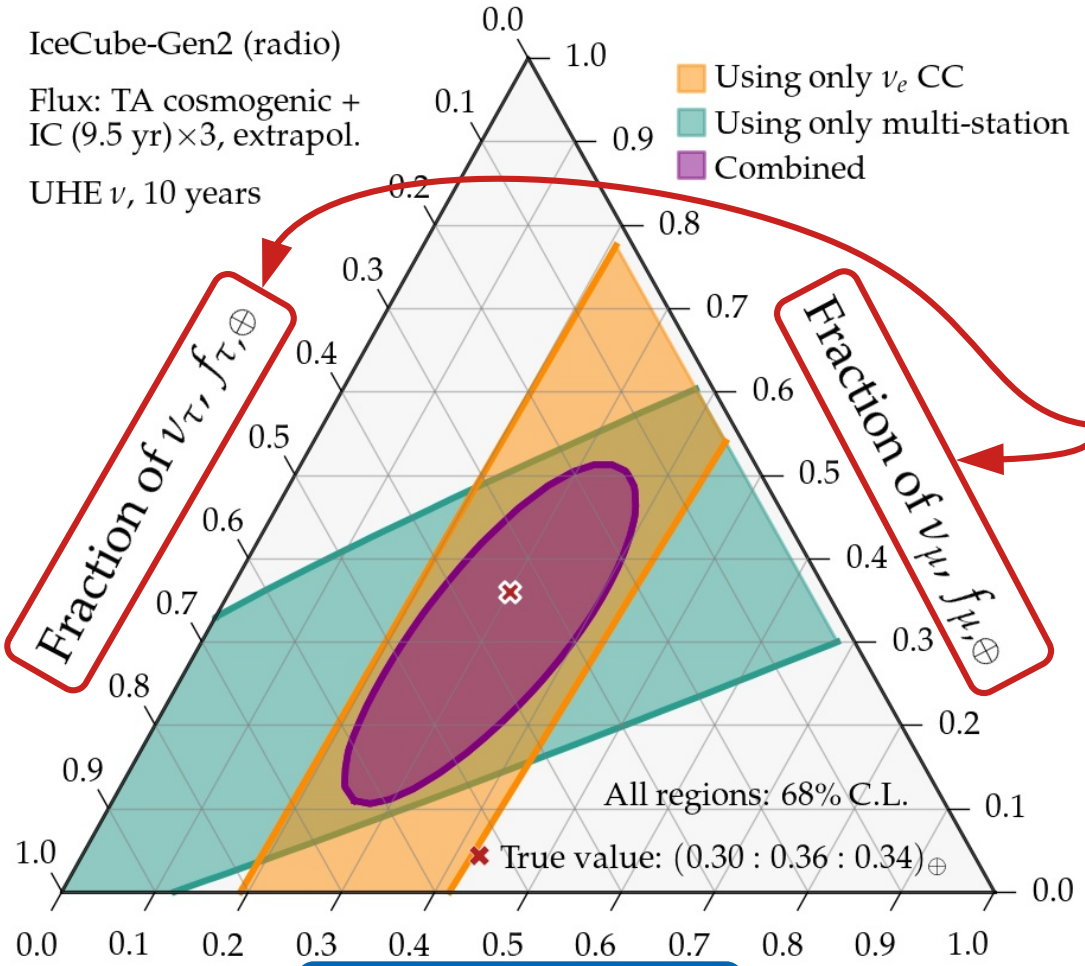
IceCube-Gen2 (radio) alone might measure flavor



Fraction of ν_e

Showers are elongated due to the LPM effect

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

Secondary muons and tauons create multiple showers (hit >1 radio station)

Coleman, Ericsson, **MB**, Glaser, 2402.02432

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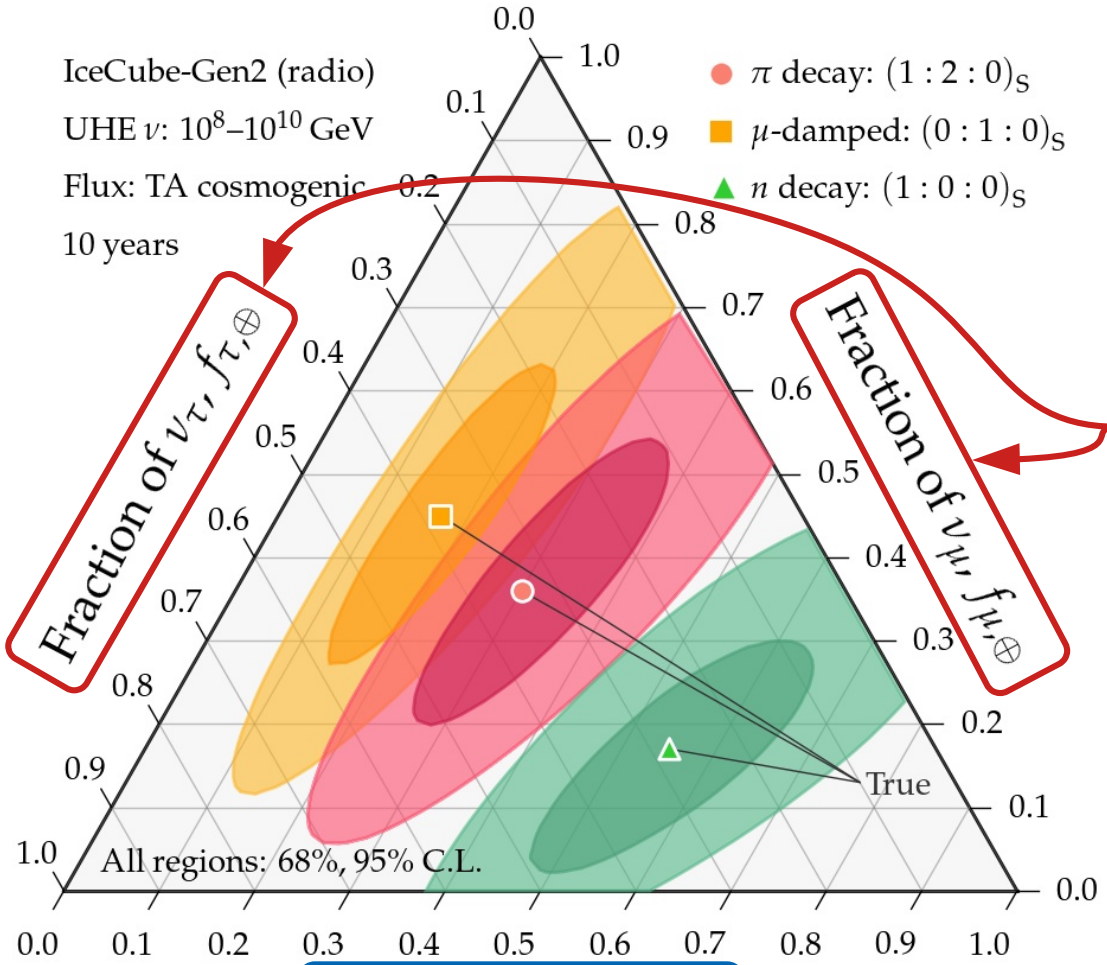

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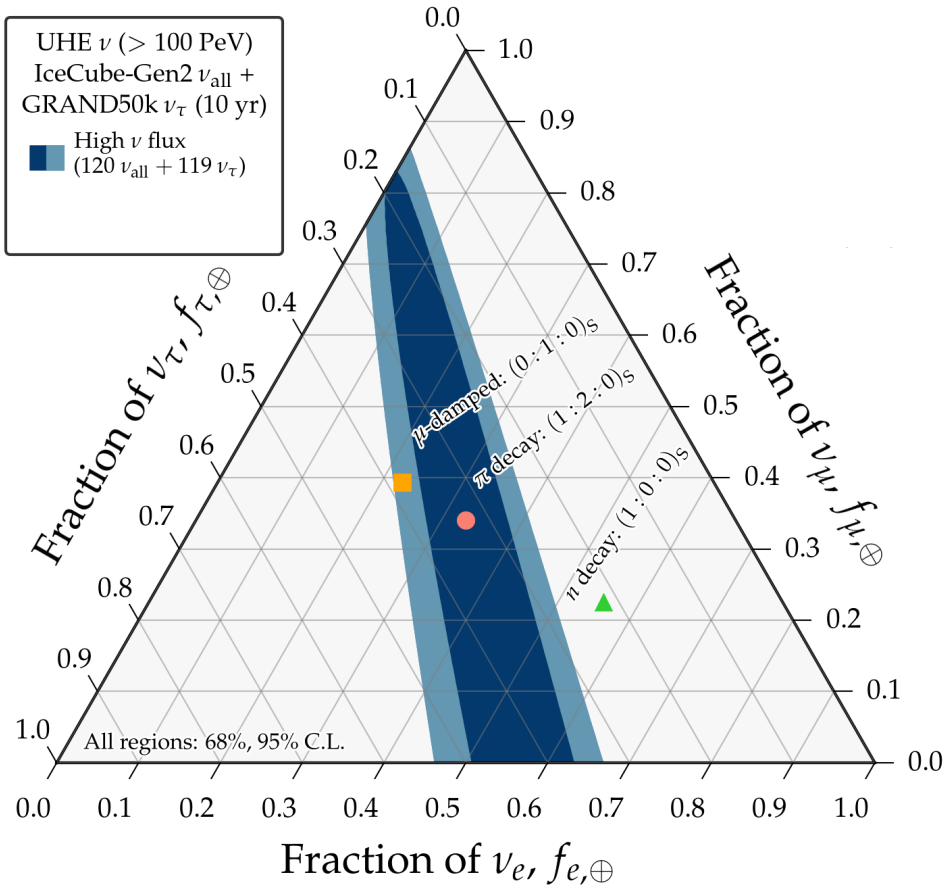
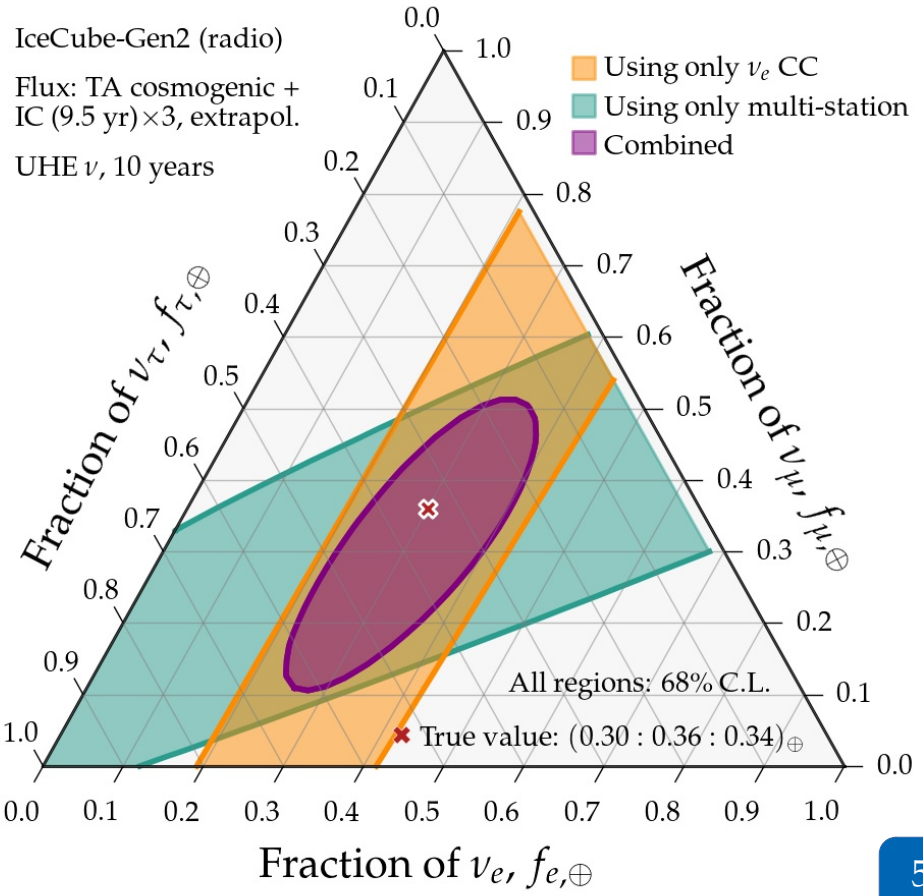
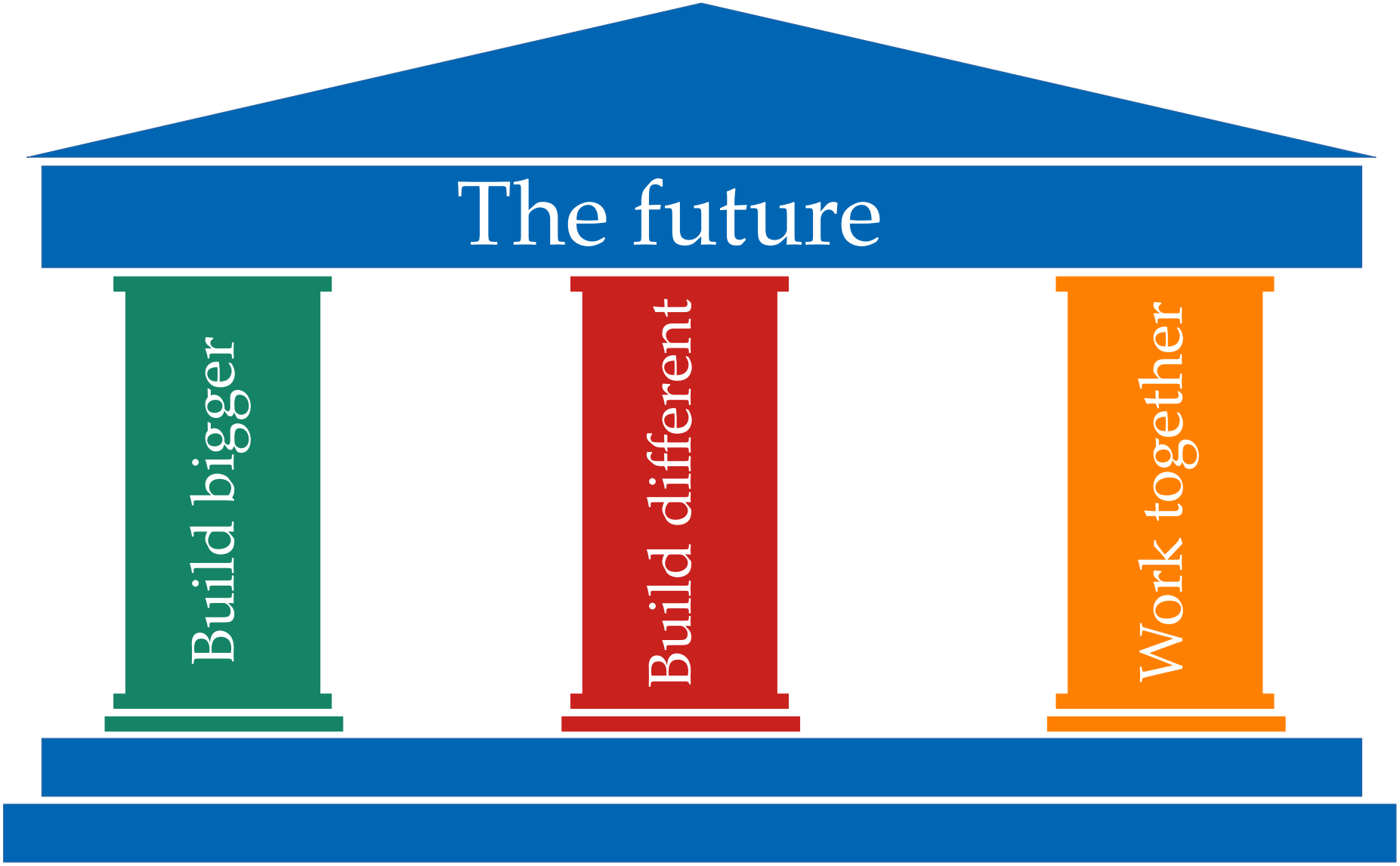
Accessing the full UHE flavor information

IceCube-Gen2 (no flavor-id) + GRAND:
Access to ν_τ fraction



IceCube-Gen2 (with flavor-id):
Access to ν_e fraction and ν_μ+ν_τ fraction




The future
Build bigger
Build different
Work together

Backup slides

How does IceCube see TeV–PeV neutrinos?

Deep inelastic neutrino-nucleon scattering

Neutral current (NC)

$$\nu_x + N \rightarrow \nu_x + X$$

Charged current (CC)

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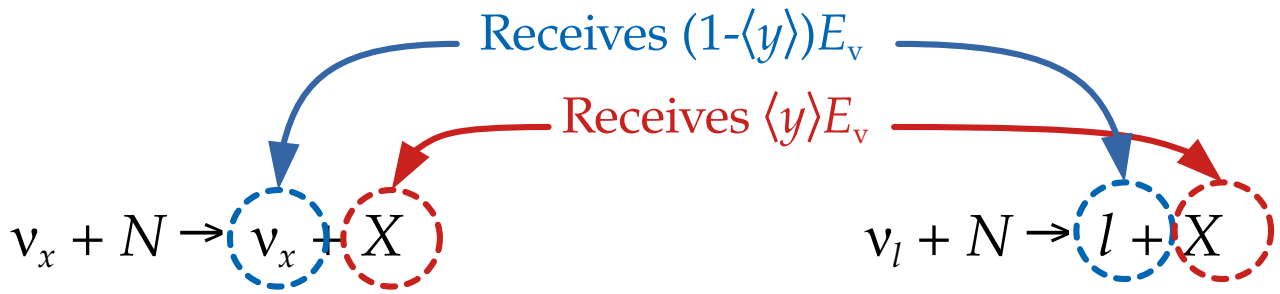

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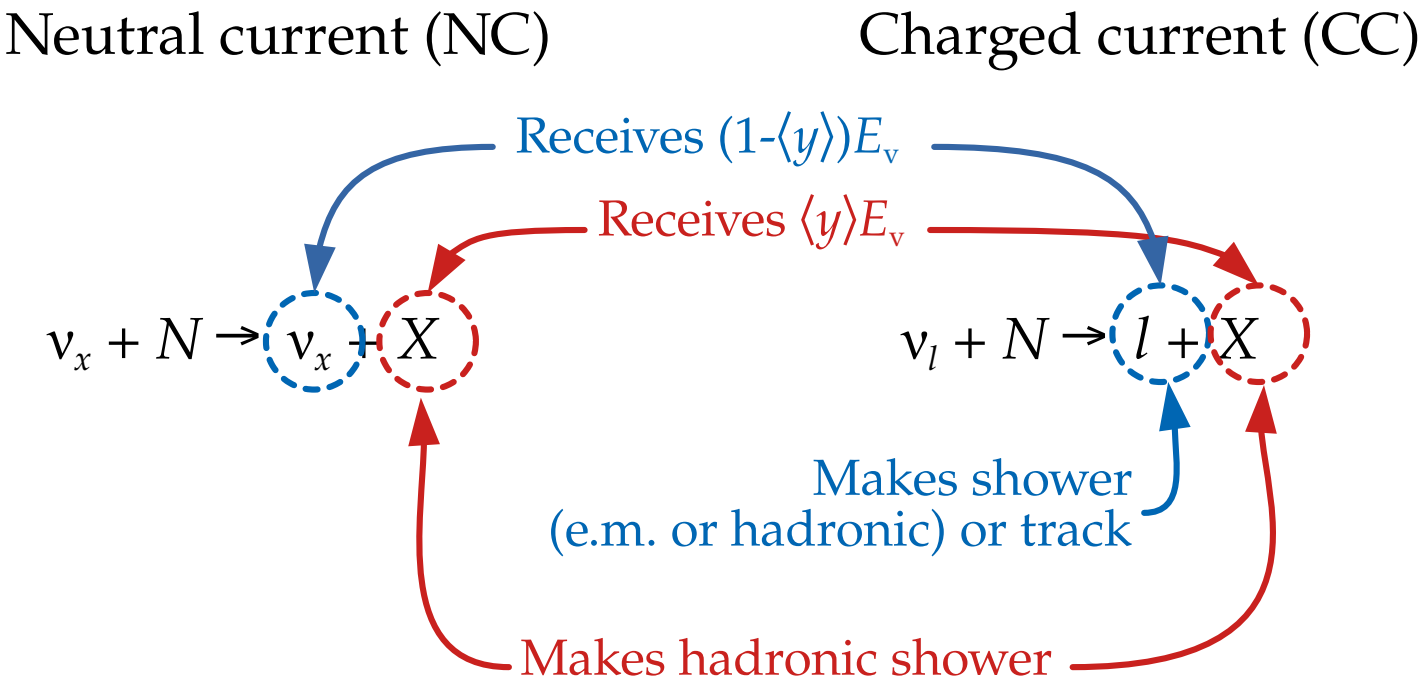

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Flavor at the Earth: *theoretically palatable regions*

Theoretically palatable flavor regions

≡

Allowed regions of flavor ratios at Earth derived from oscillations

MB, Beacom, Winter, *PRL* 2015

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,

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

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(pion decay, muon-damped, neutron decay)

or

Explore all possible combinations

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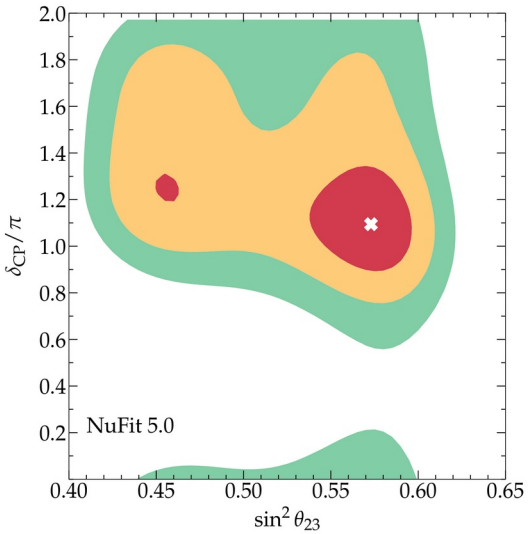
2020: Use χ^2 profiles from the NuFit 5.0 global fit (solar + atmospheric + reactor + accelerator)

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



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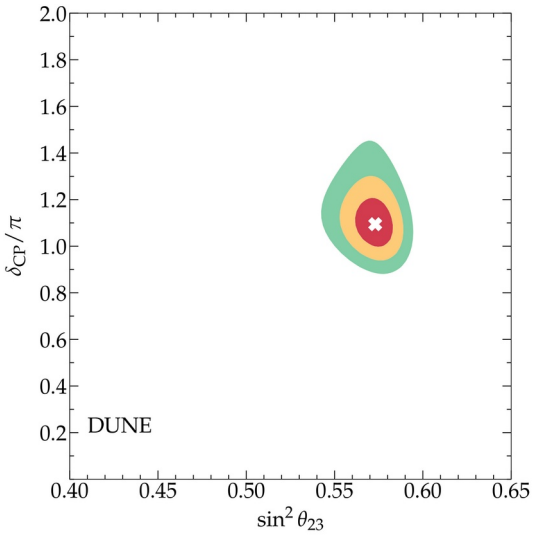
Post-2020: Build our own profiles using simulations of JUNO, DUNE, Hyper-K

An *et al.*, *J. Phys. G* 2016
DUNE, 2002.03005
Huber, Lindner, Winter, *Nucl. Phys. B* 2002



Theoretically palatable regions: 2020 → 2030 → 2040

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

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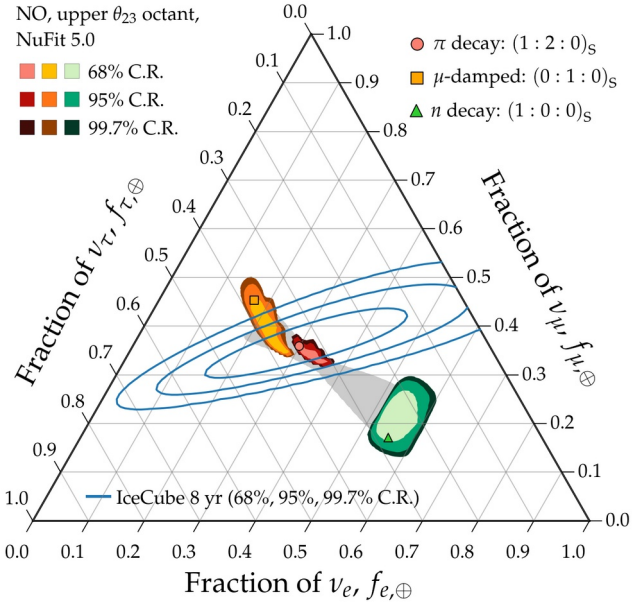

Allowed regions: overlapping

Measurement: imprecise

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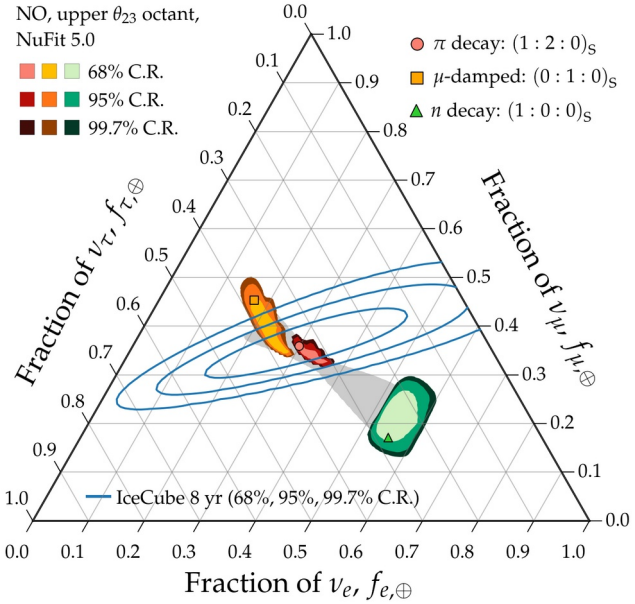

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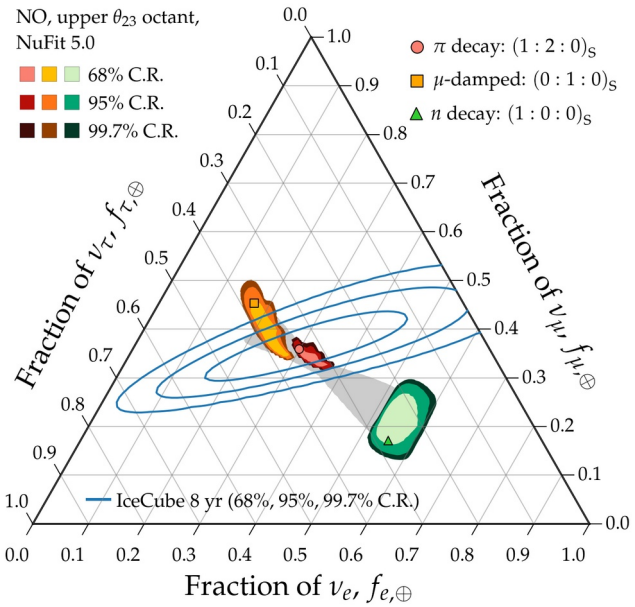
2020



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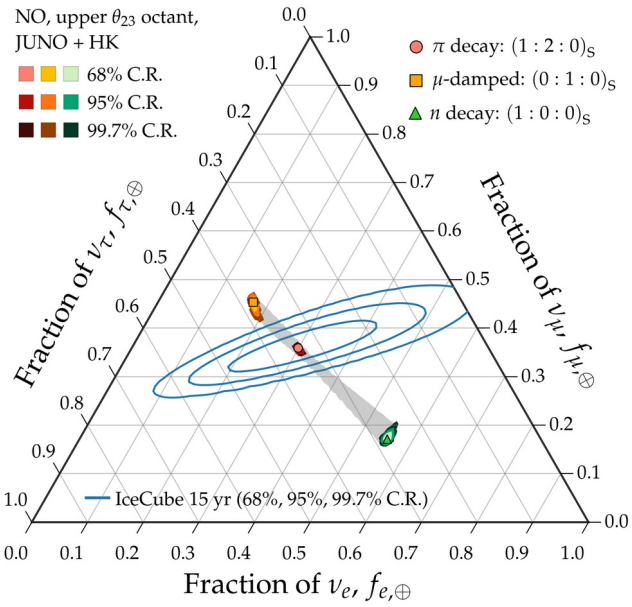
Not ideal

2030



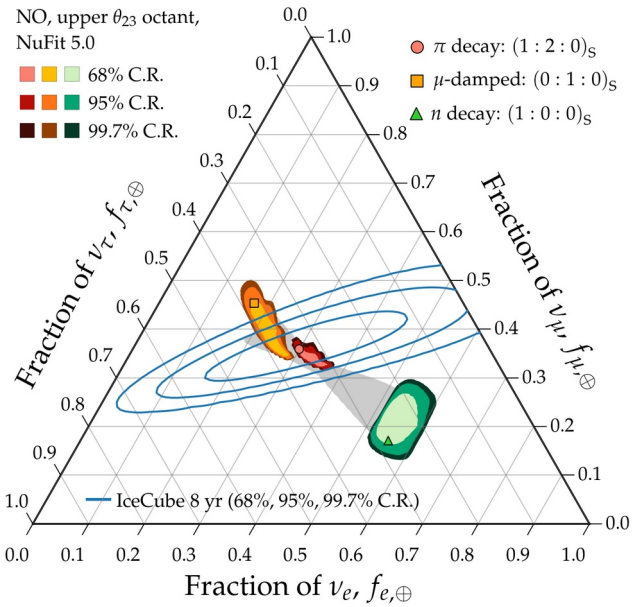
Allowed regions: well separated

Measurement: improving

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

Theoretically palatable regions: 2020 → 2030 → 2040

2020



Allowed regions: overlapping

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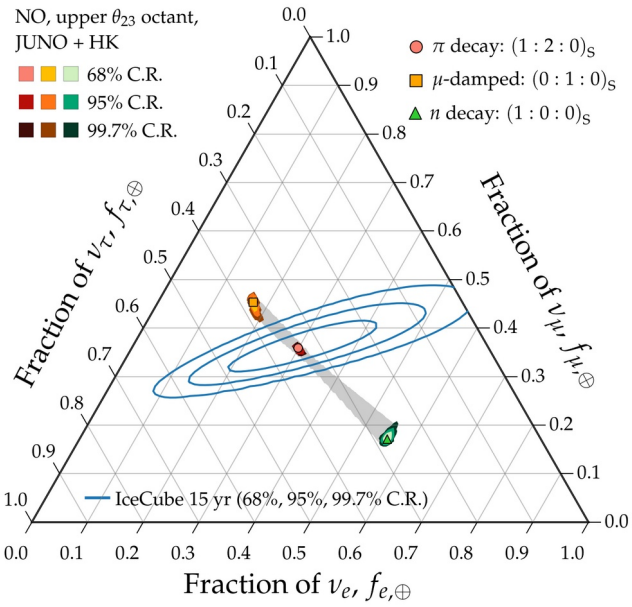
Not ideal

2030



Allowed regions: well separated

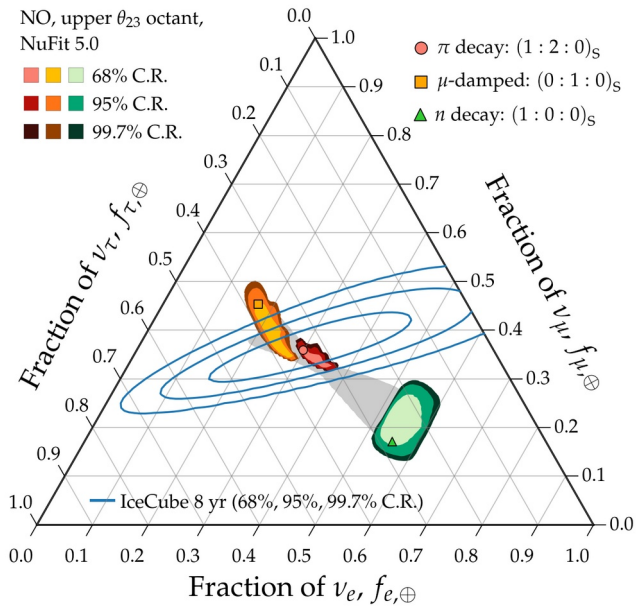
Measurement: improving

Nice

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

Theoretically palatable regions: 2020 → 2030 → 2040

2020

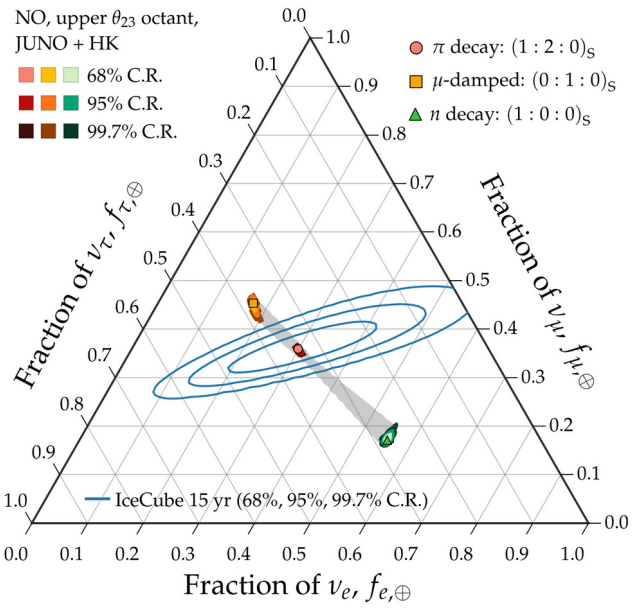


Allowed regions: overlapping

Measurement: imprecise

Not ideal

2030



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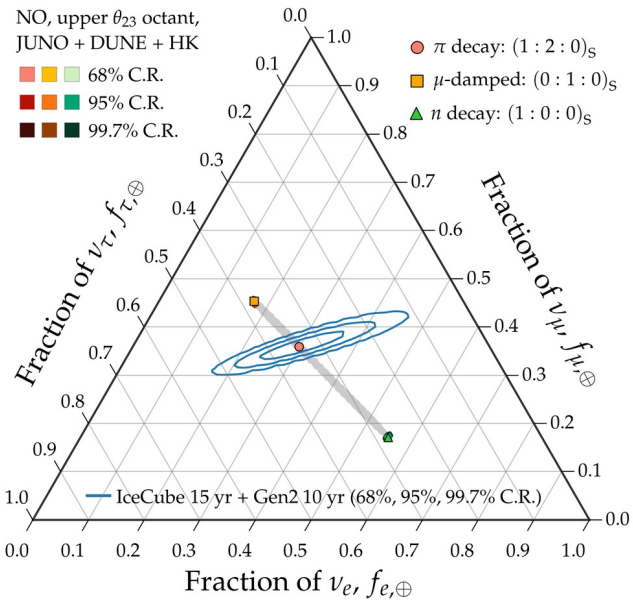

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Measurement: precise

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

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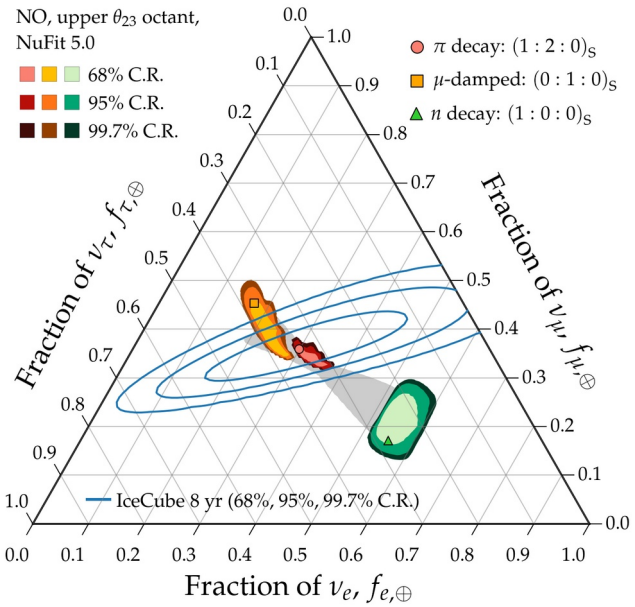

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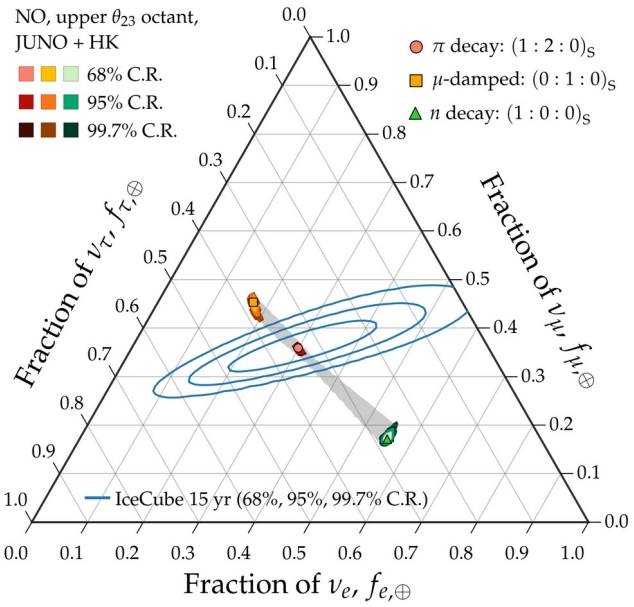

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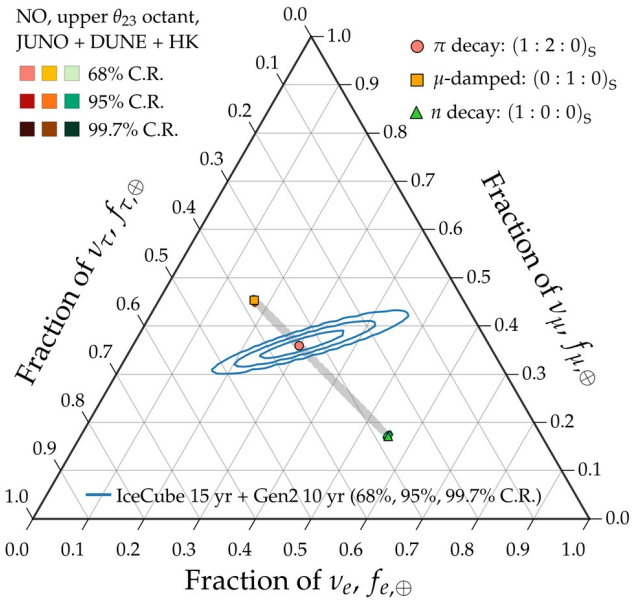

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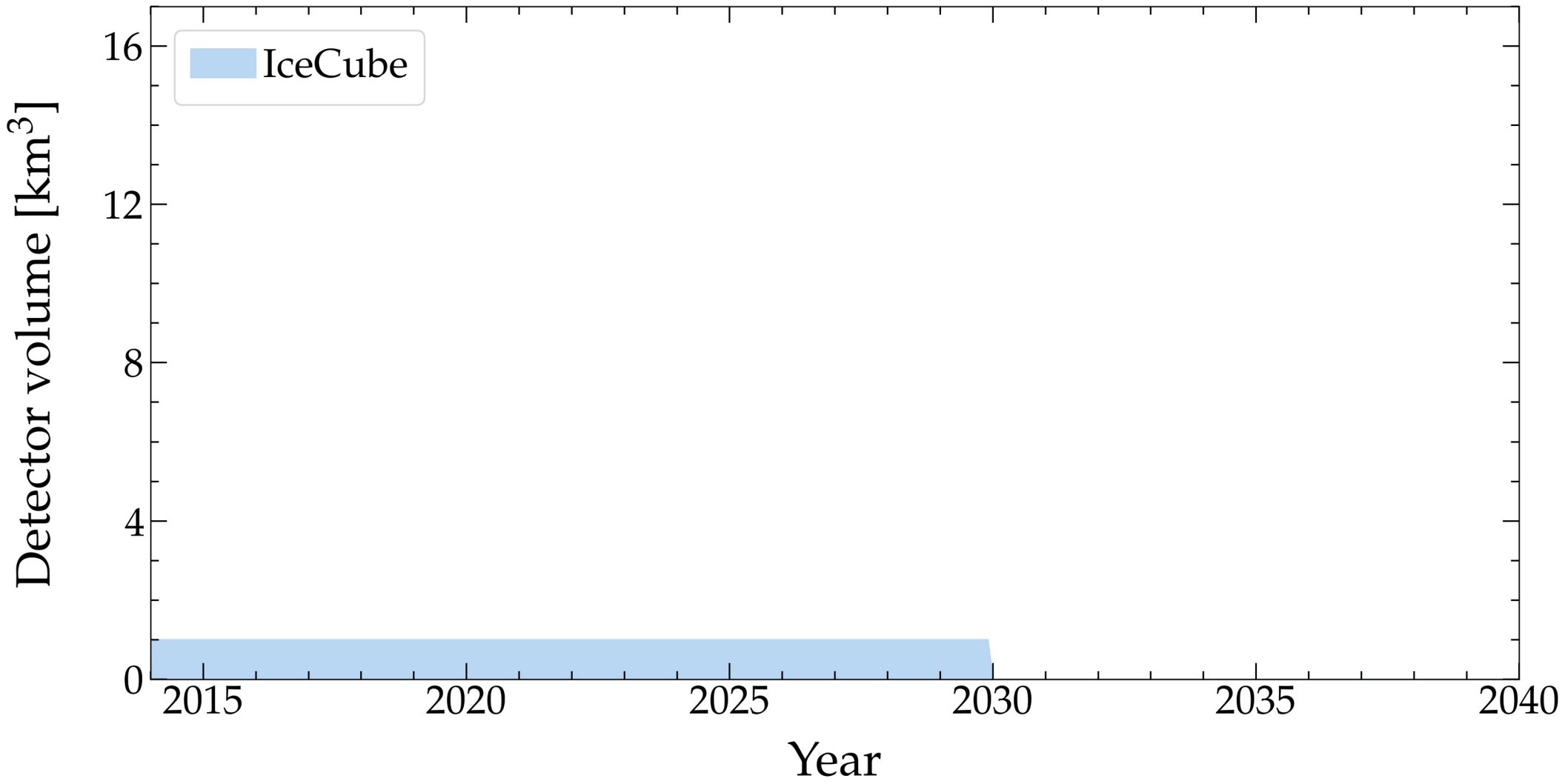
Success

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



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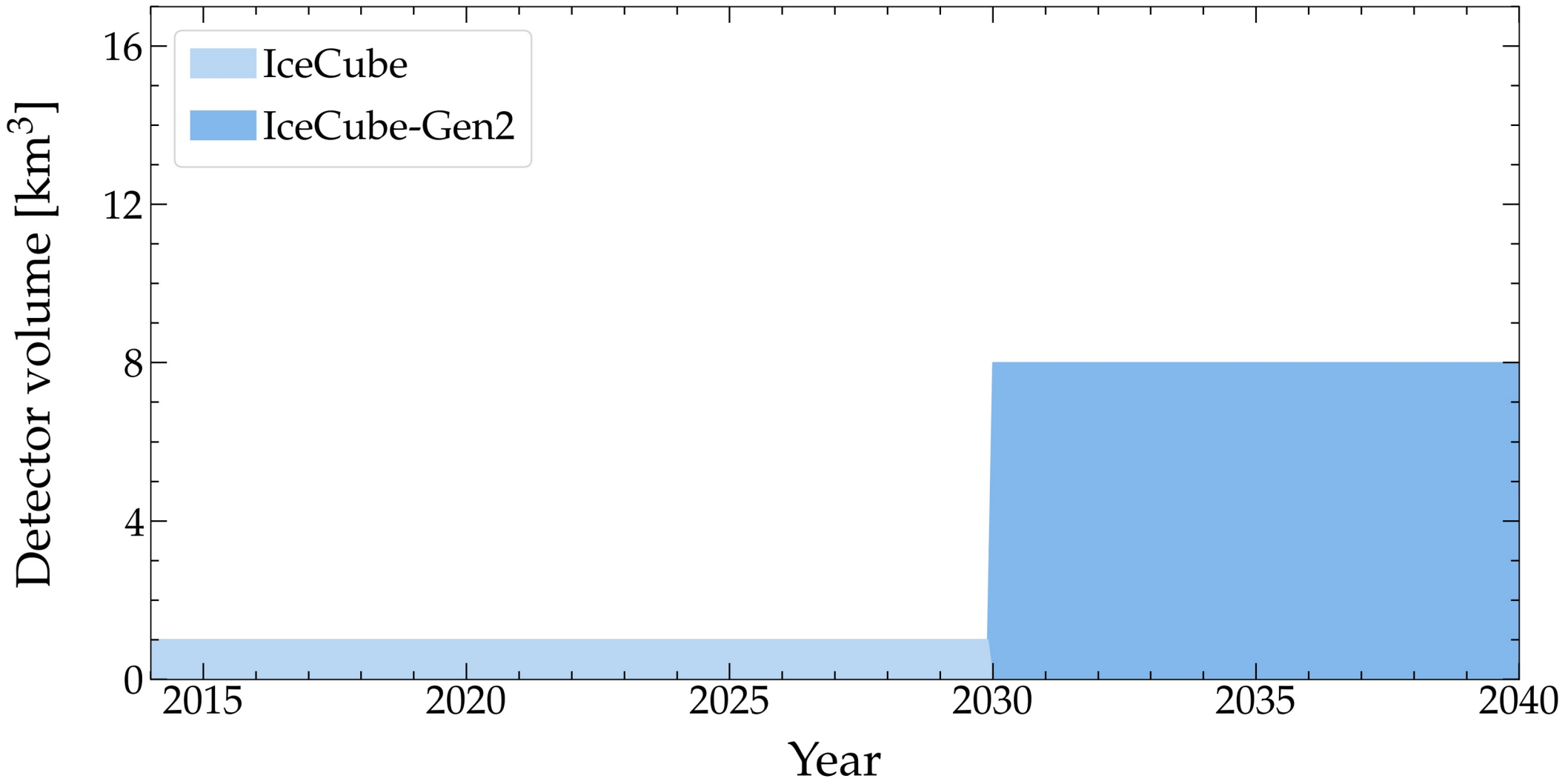

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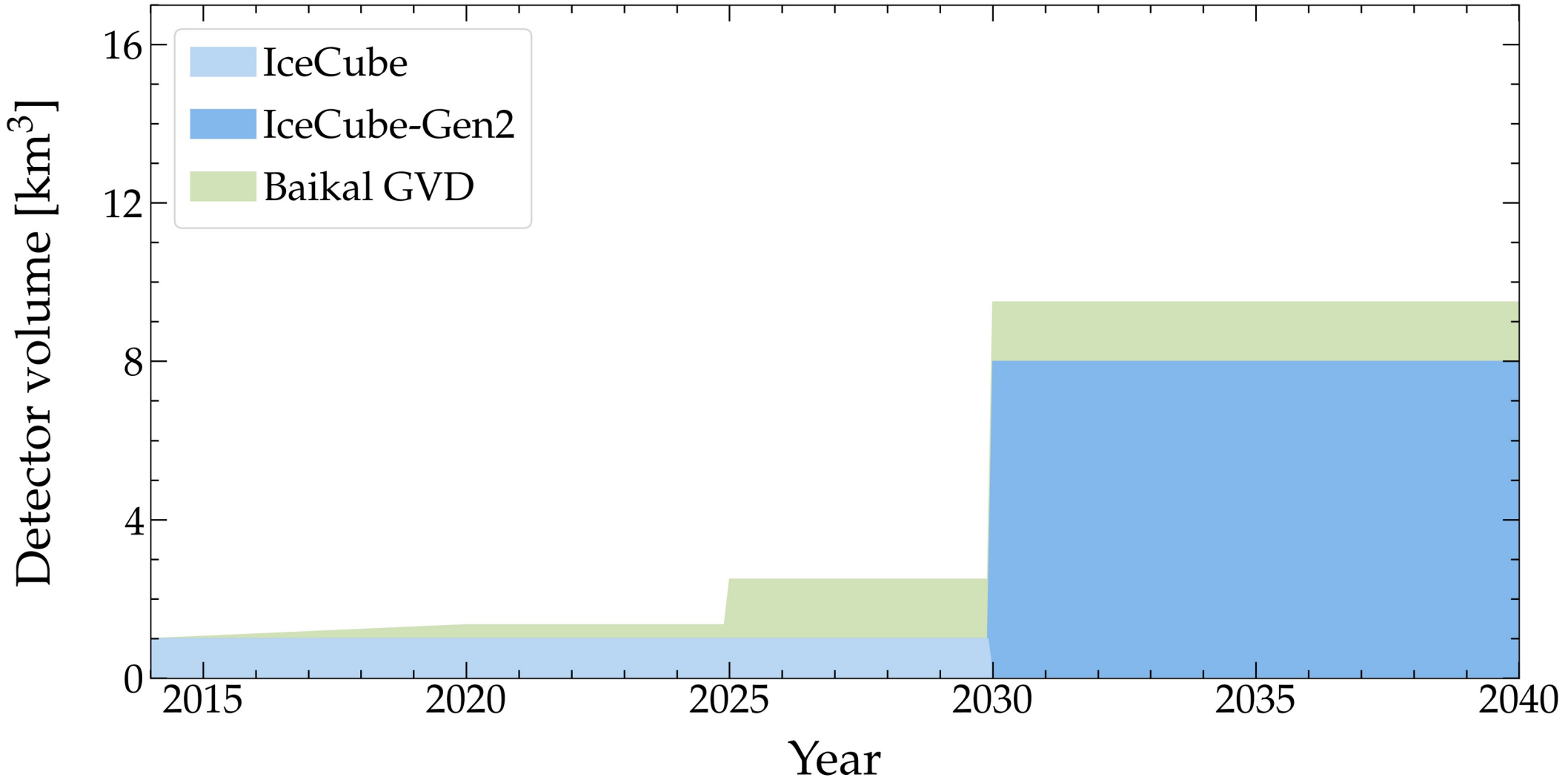

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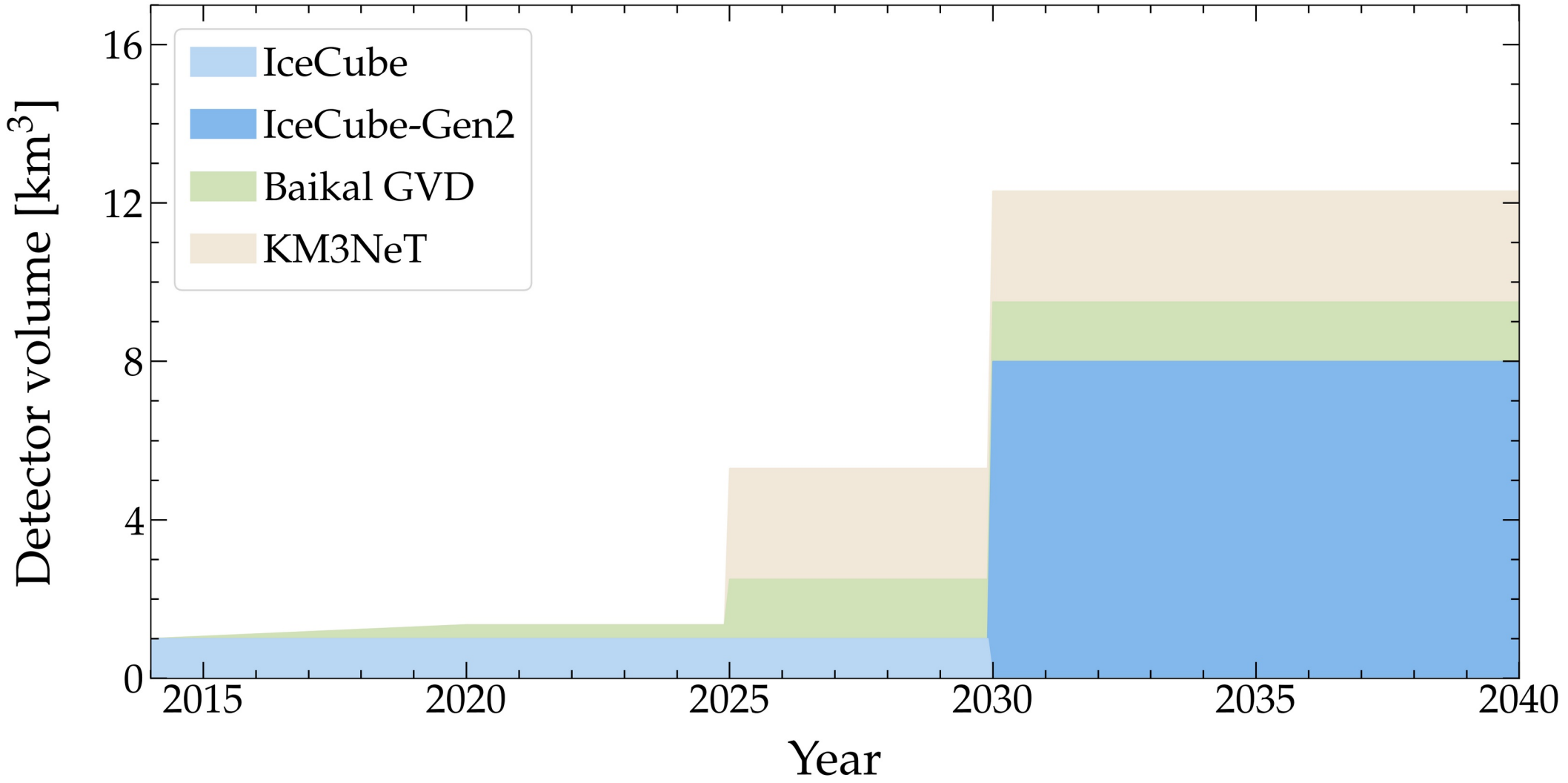

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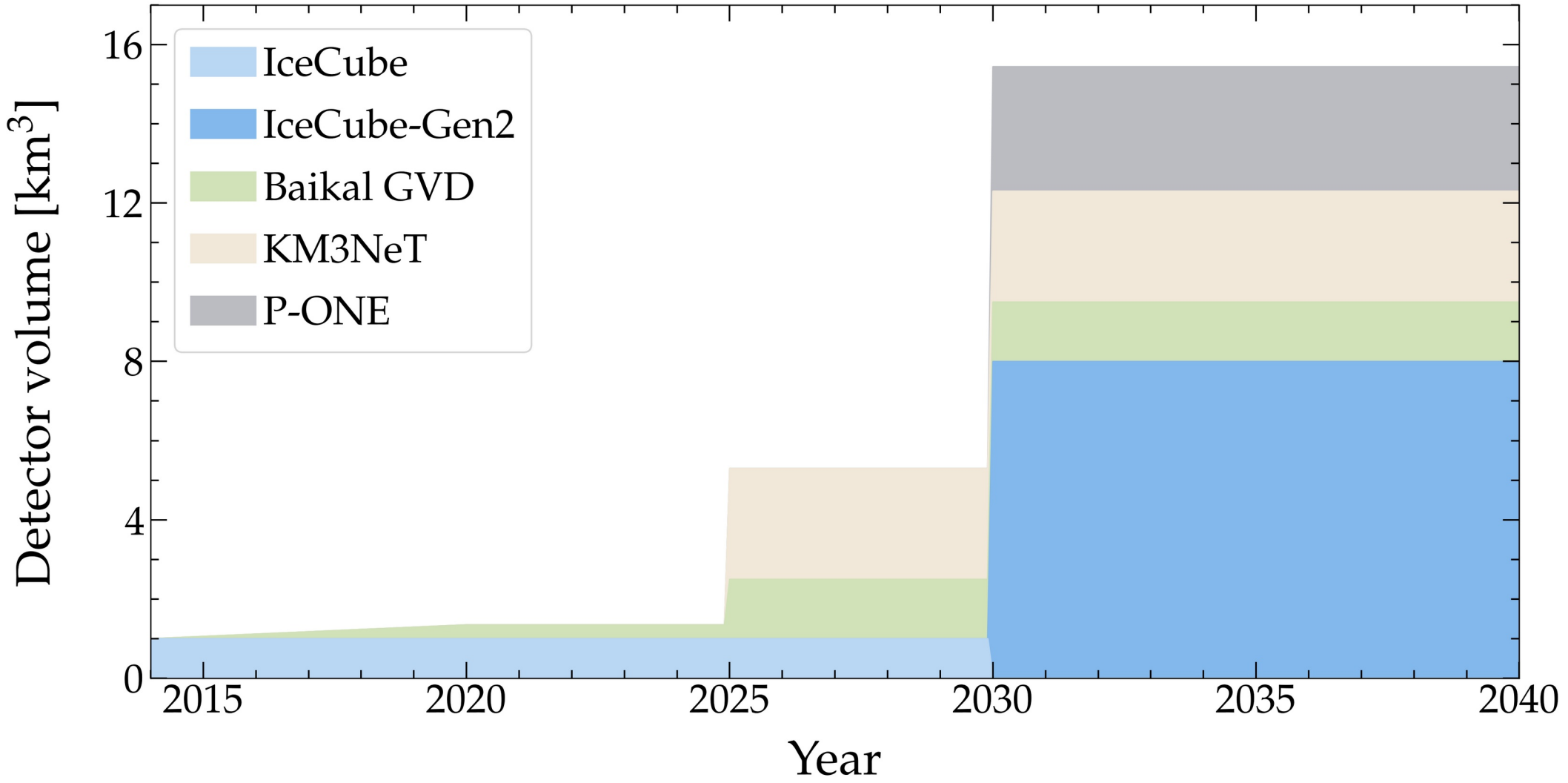

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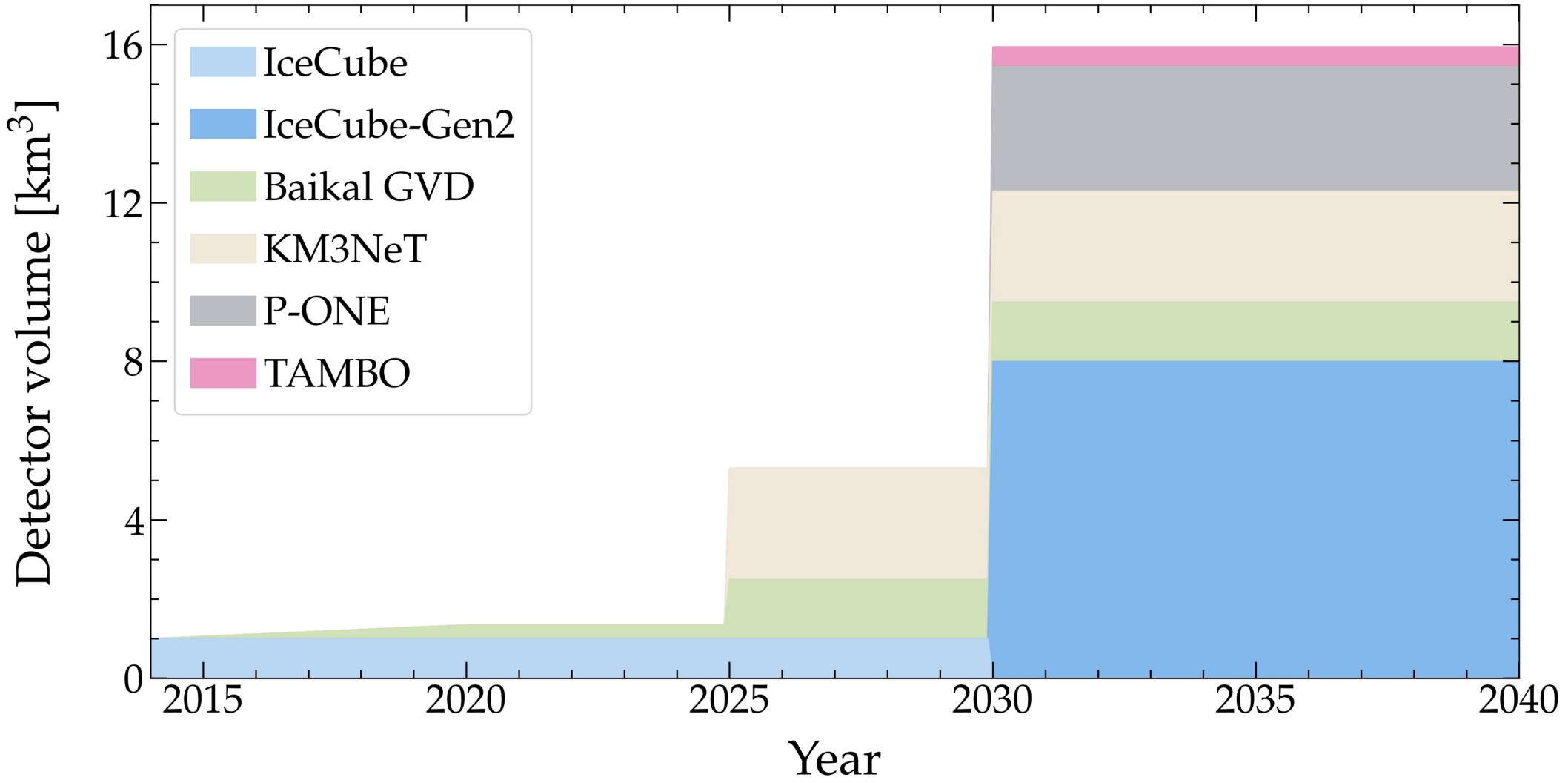

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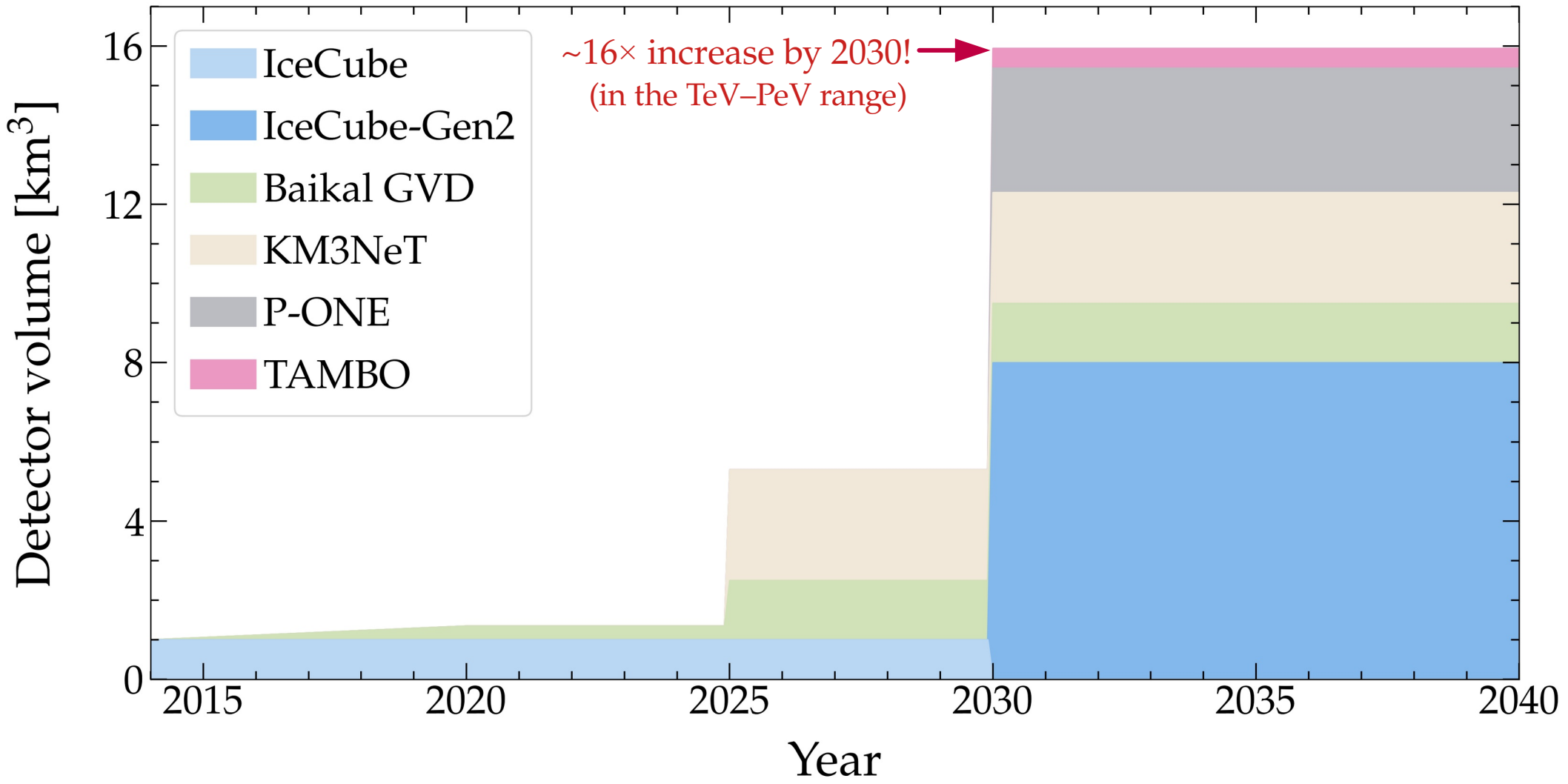

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

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 $\kappa_n \sim 4 \cdot 10^{-47}\ (E/\mathrm{PeV})^{-n}\ (L/\mathrm{Gpc})^{-1}\ \mathrm{PeV}^{1-n}$
- Improvement over limits using atmospheric ν: $\kappa_0 < 10^{-29}$ PeV, $\kappa_1 < 10^{-33}$

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  n = -1: neutrino decay
  n = 0: CPT-odd Lorentz violation
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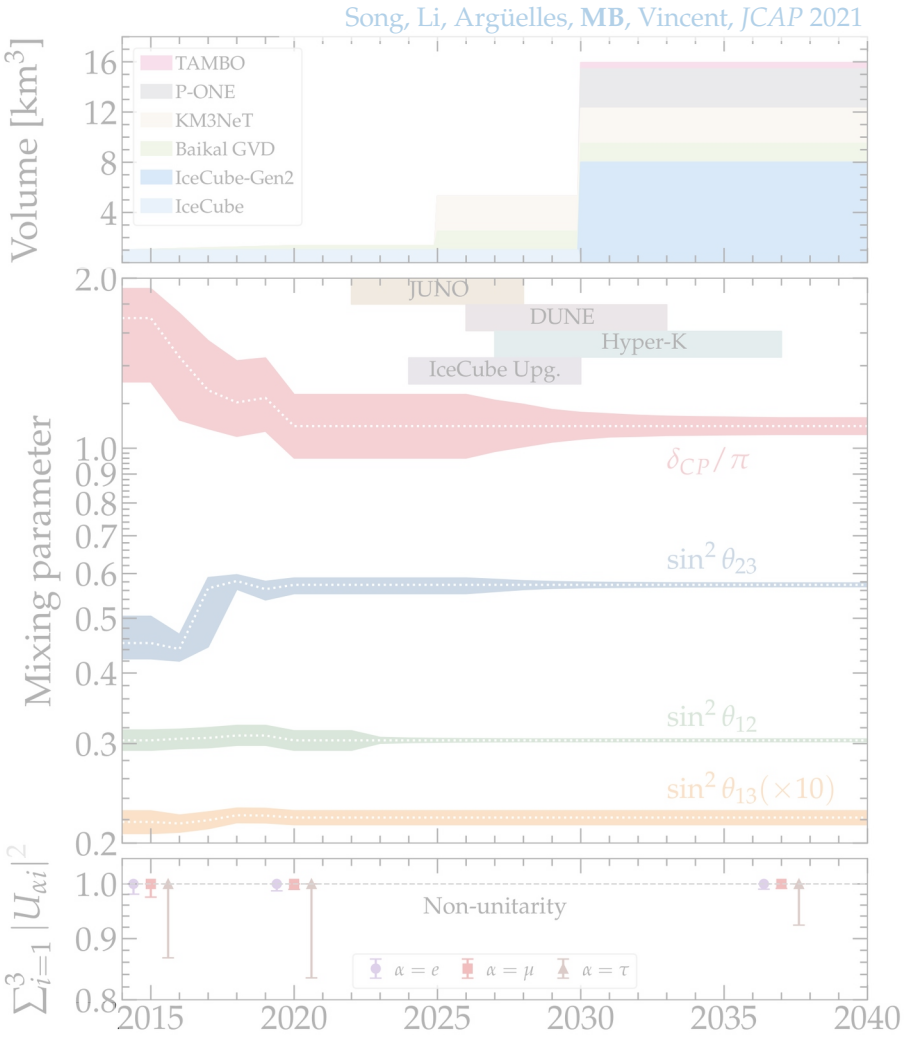
Three reasons to be excited

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



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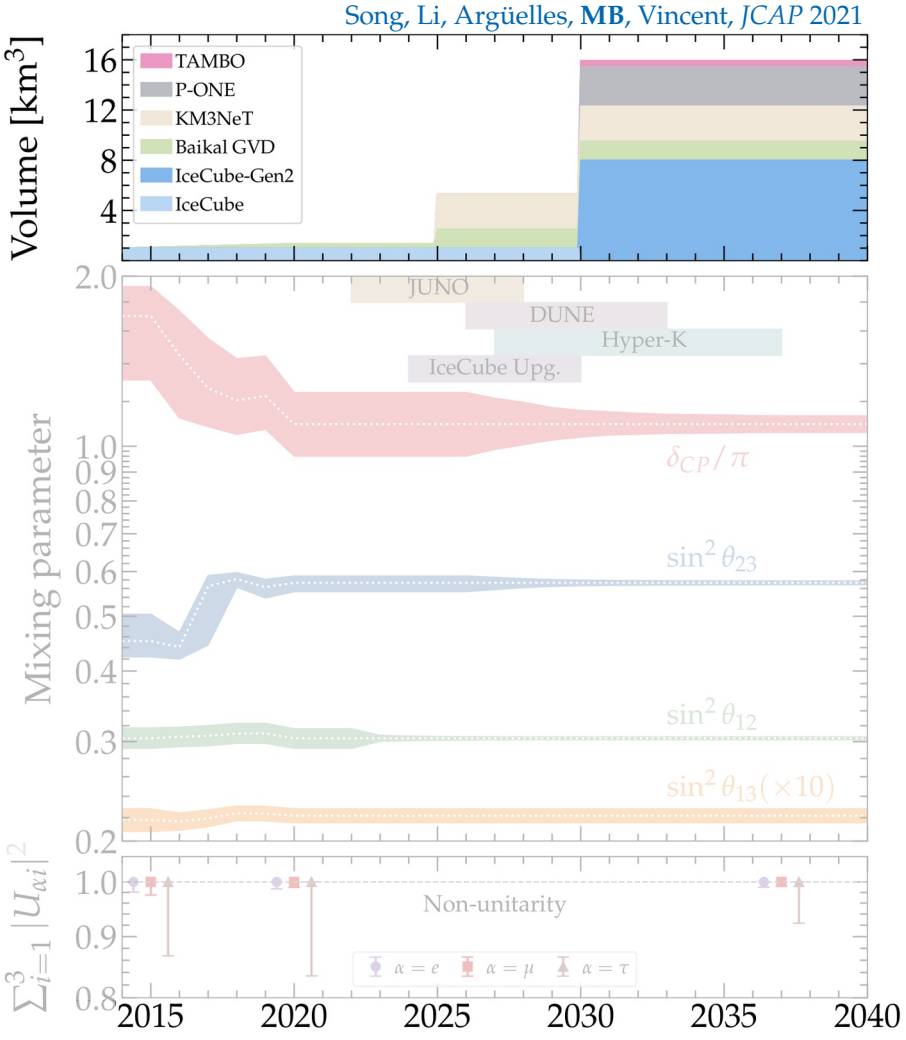

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New neutrino telescopes = more events, better flavor measurement

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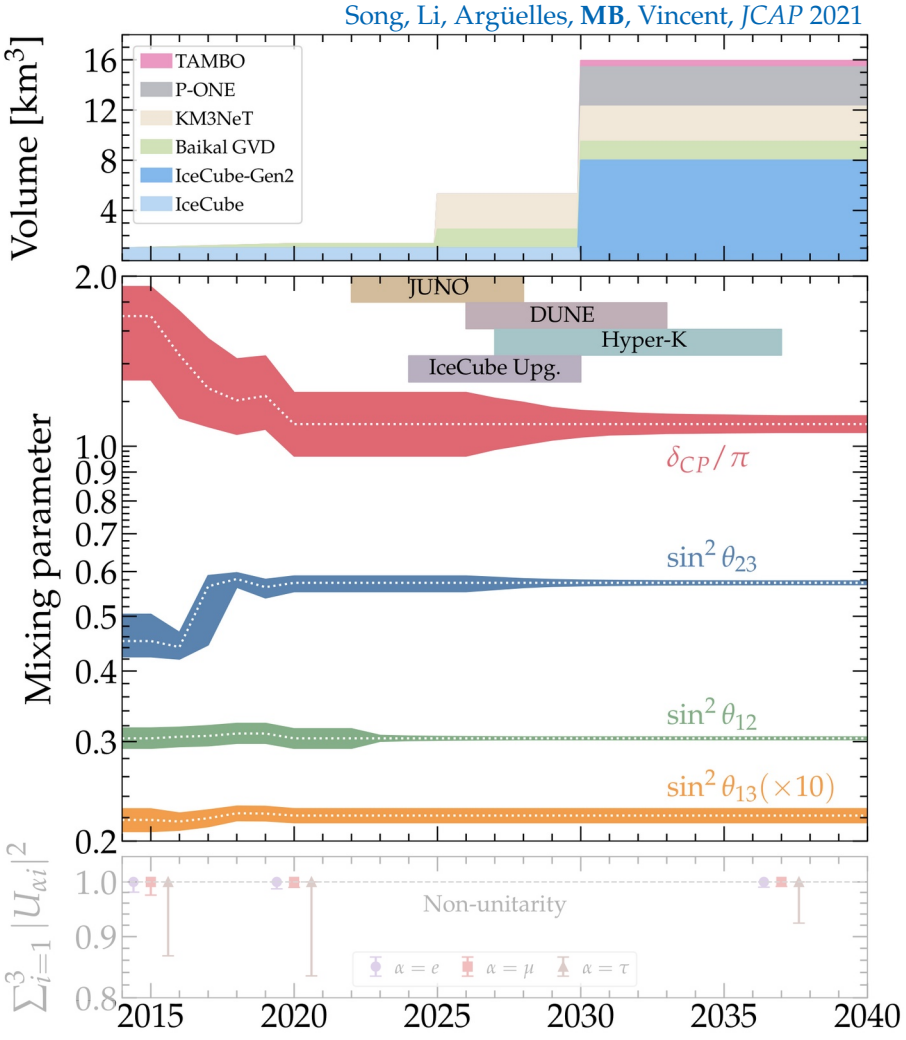

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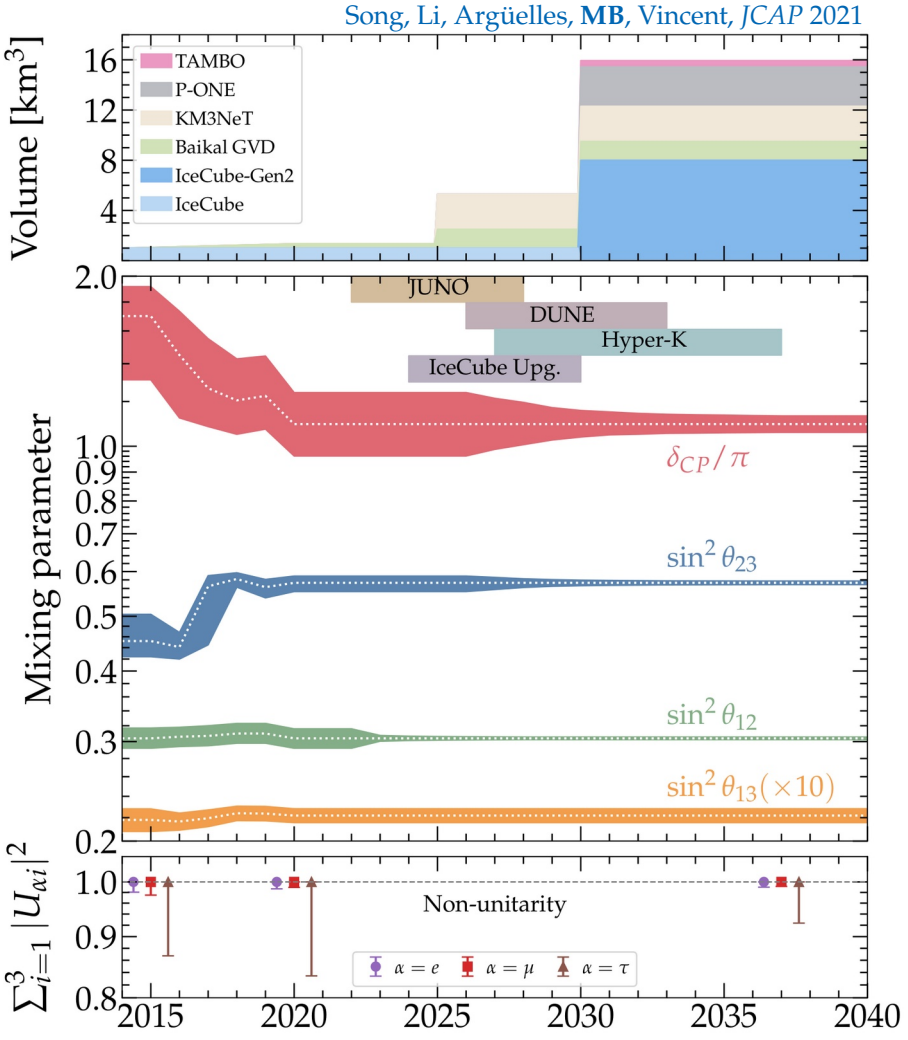

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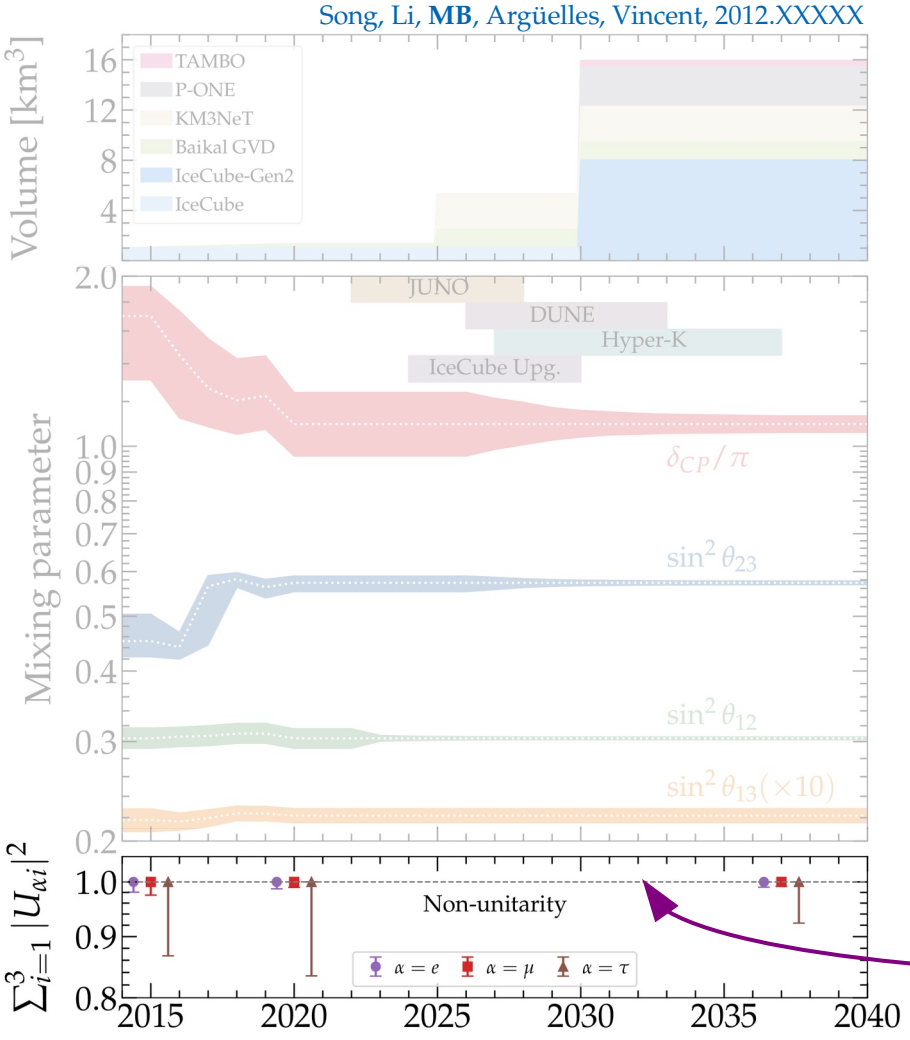
Oscillation physics:
We will know the mixing parameters better (JUNO, DUNE, Hyper-K, IceCube Upgrade)

Test of the oscillation framework:
We will be able to do what we want even if oscillations are non-unitary

No unitarity? *No problem*

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX



The 3×3 active mixing matrix is a non-unitary sub-matrix of a bigger one:

Active flavors

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & \cdots \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & \cdots \\ \cdots & \cdots & \cdots & \ddots \end{pmatrix}$$

Additional sterile flavors

The elements $|U_{\alpha i}|^2$ for active flavors can be measured *without* assuming unitarity

Because the sub-matrix is not-unitary ($U_{3\nu}^{\dagger} U_{3\nu} \neq 1$), the "row sum" may be < 1

Ellis, Kelly, Li, 2008.01088
Parke & Ross-Lonergan, *PRD* 2016

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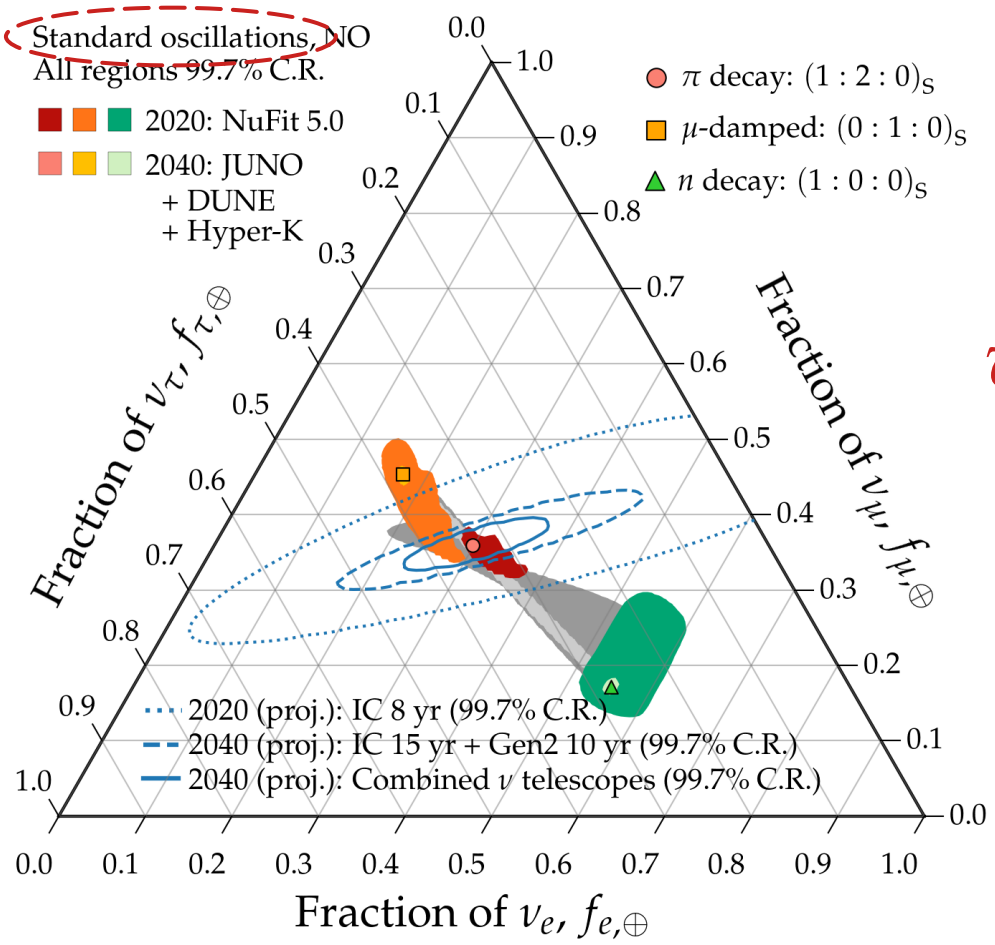
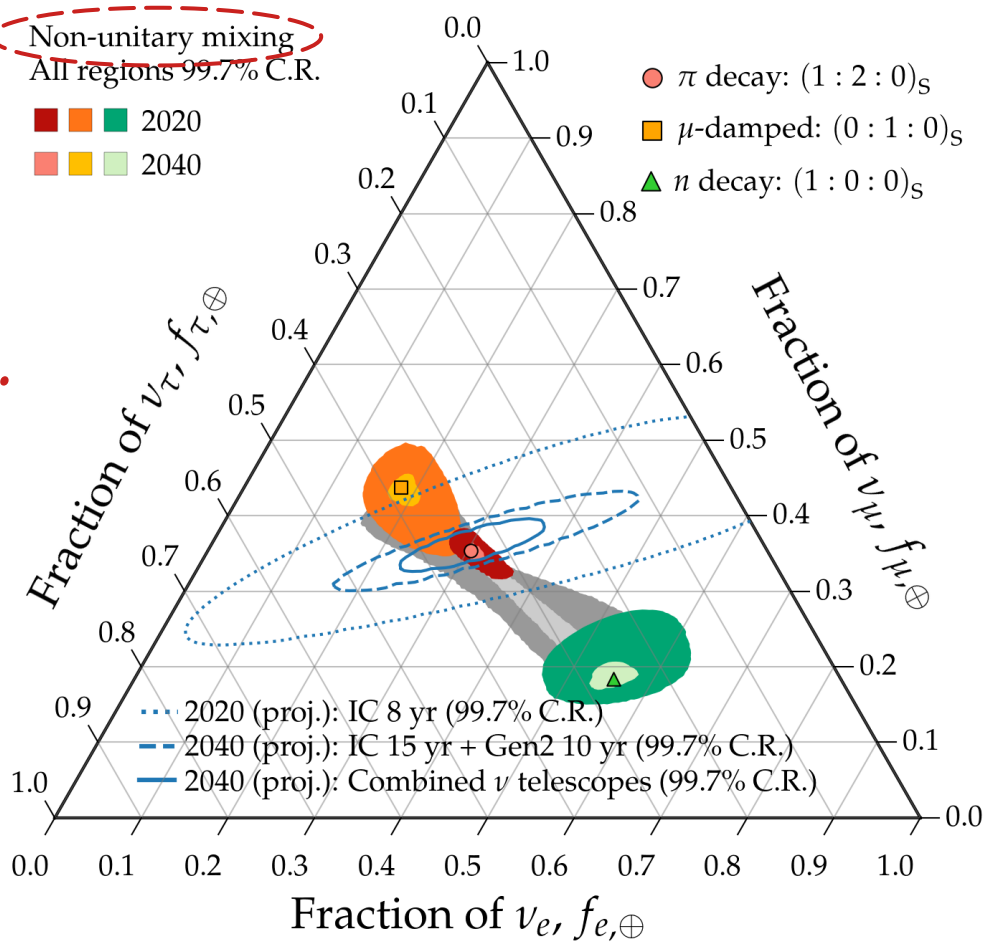


vs.



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

Are neutrinos forever?

- In the Standard Model (νSM), neutrinos are essentially stable ($\tau > 10^{36}$ yr):
  - One-photon decay ($\nu_i \to \nu_j + \gamma$): $\tau > 10^{36}\ (m_i/\mathrm{eV})^{-5}$ yr
  - Two-photon decay ($\nu_i \to \nu_j + \gamma + \gamma$): $\tau > 10^{57}\ (m_i/\mathrm{eV})^{-9}$ yr
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  } » Age of Universe (~ 14.5 Gyr)

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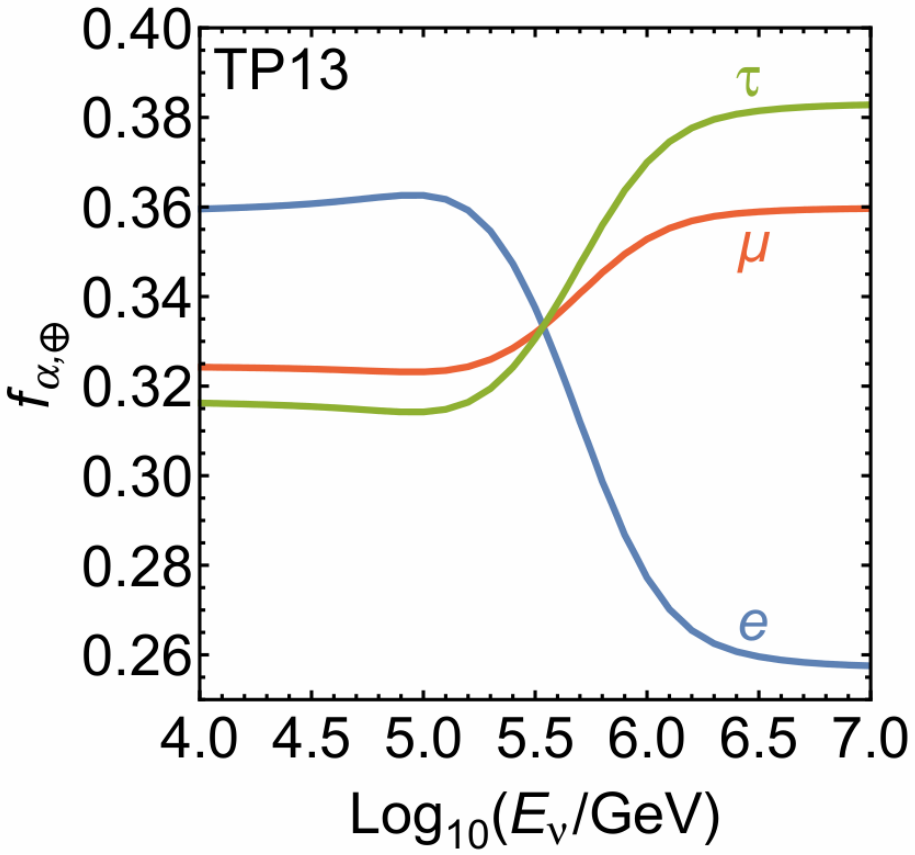
Flavor composition: measuring the energy dependence

Expected from astrophysical processes



MB, Beacom, Winter *PRL* 2015

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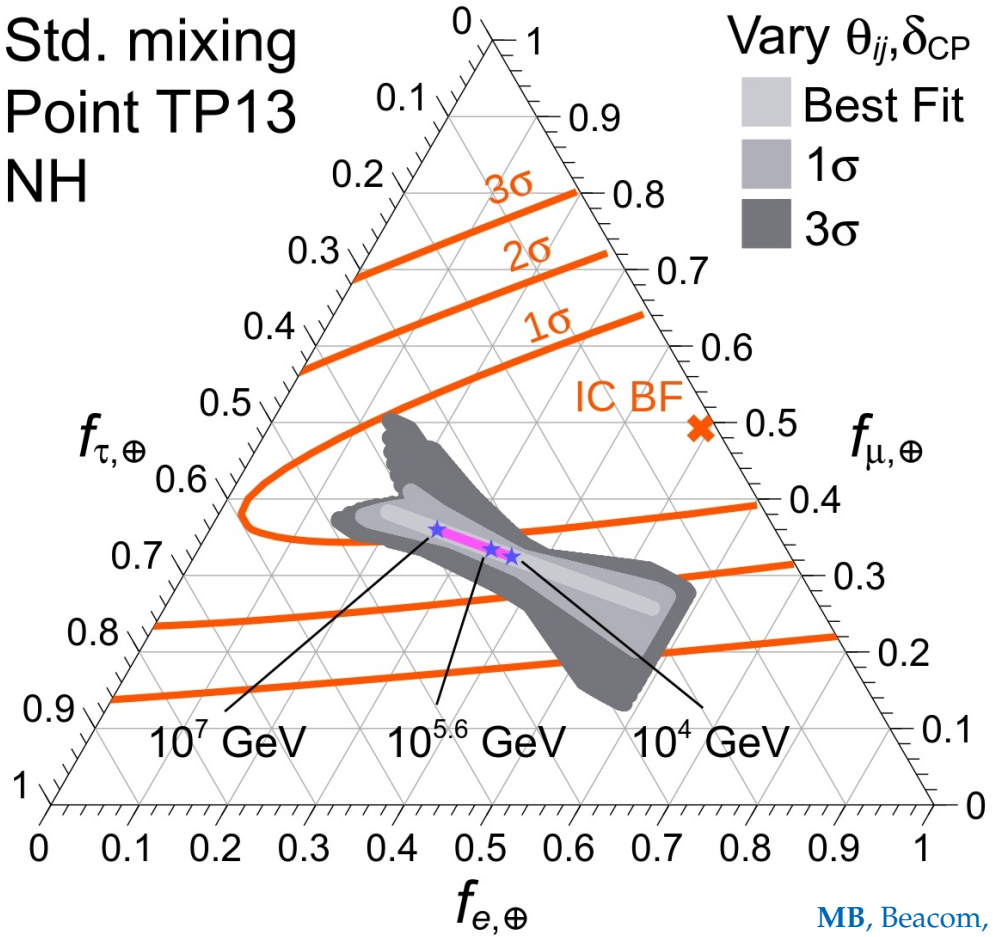

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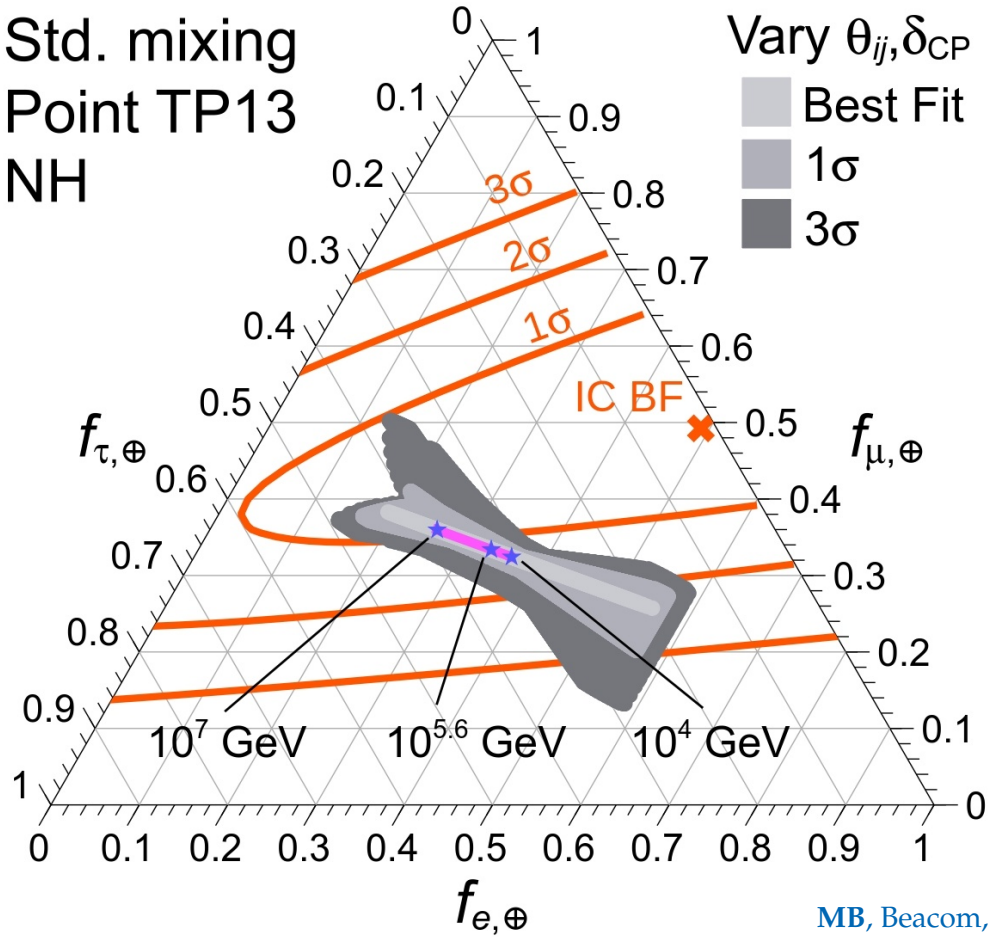

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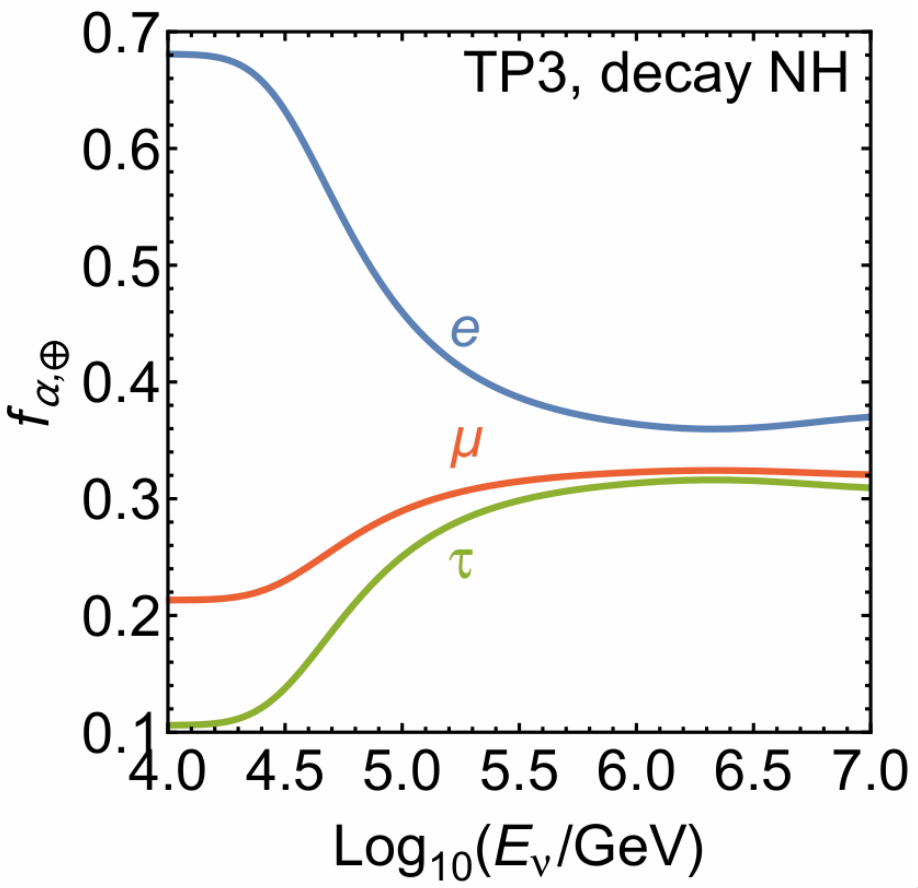

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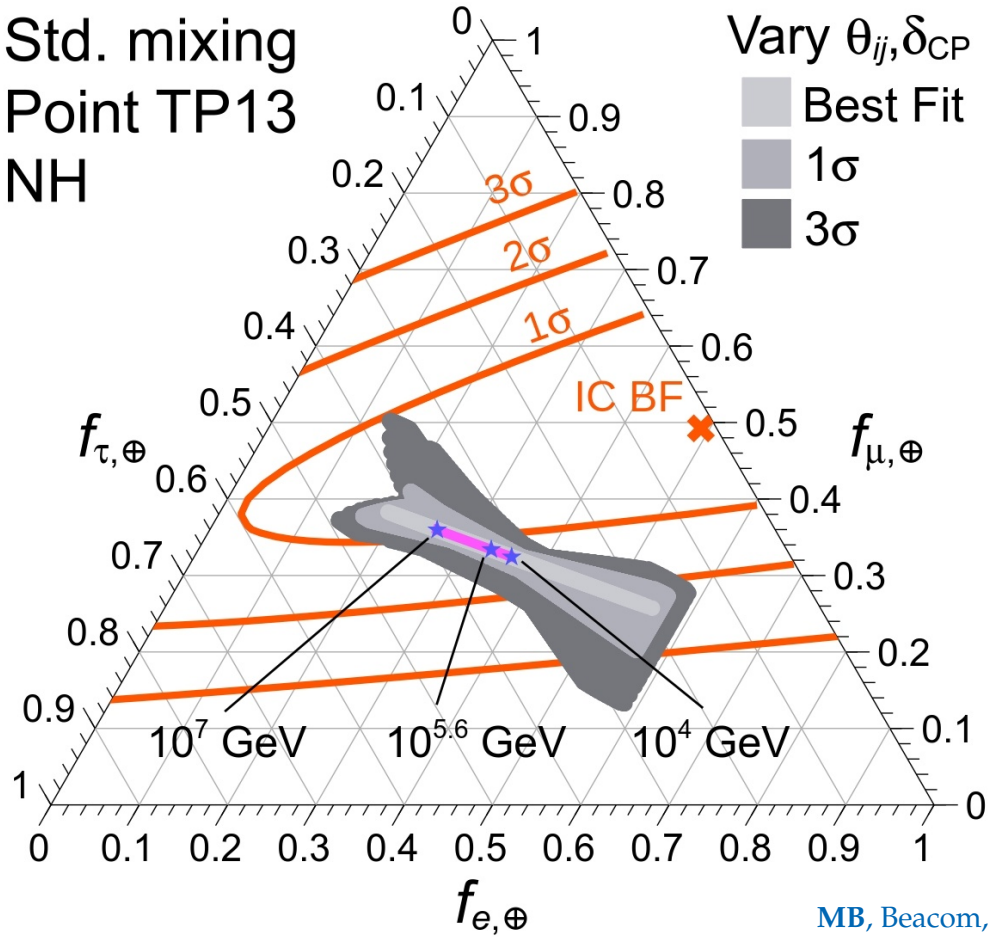

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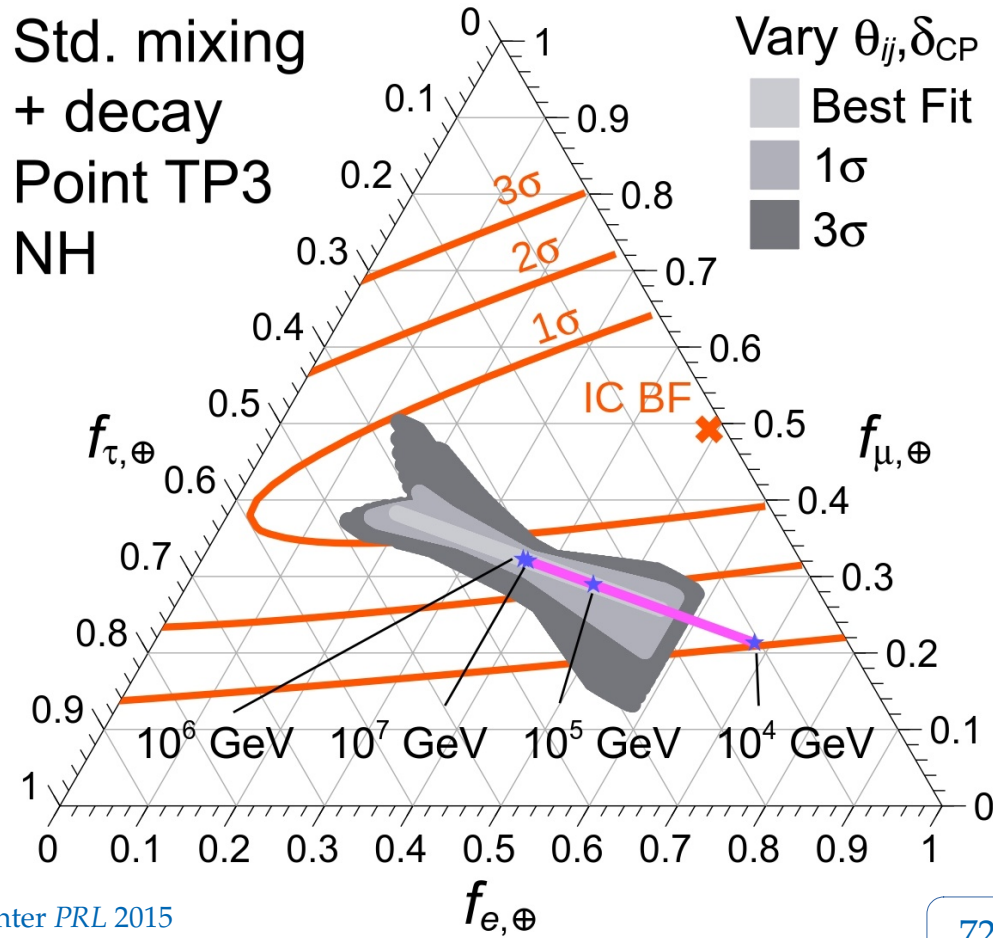

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More than one production mechanism?

Can we detect the contribution of multiple ν production mechanisms?

$$\boldsymbol{f}_{\rm S} = k_\pi \underbrace{\boldsymbol{f}_{\rm S}^{\pi}}_{\pi\text{ decay: }(1/3,\,2/3,\,0)} + k_\mu \underbrace{\boldsymbol{f}_{\rm S}^{\mu}}_{\mu\text{ damped: }(0,\,1,\,0)} + k_n \underbrace{\boldsymbol{f}_{\rm S}^{n}}_{n\text{ decay: }(1,\,0,\,0)}$$

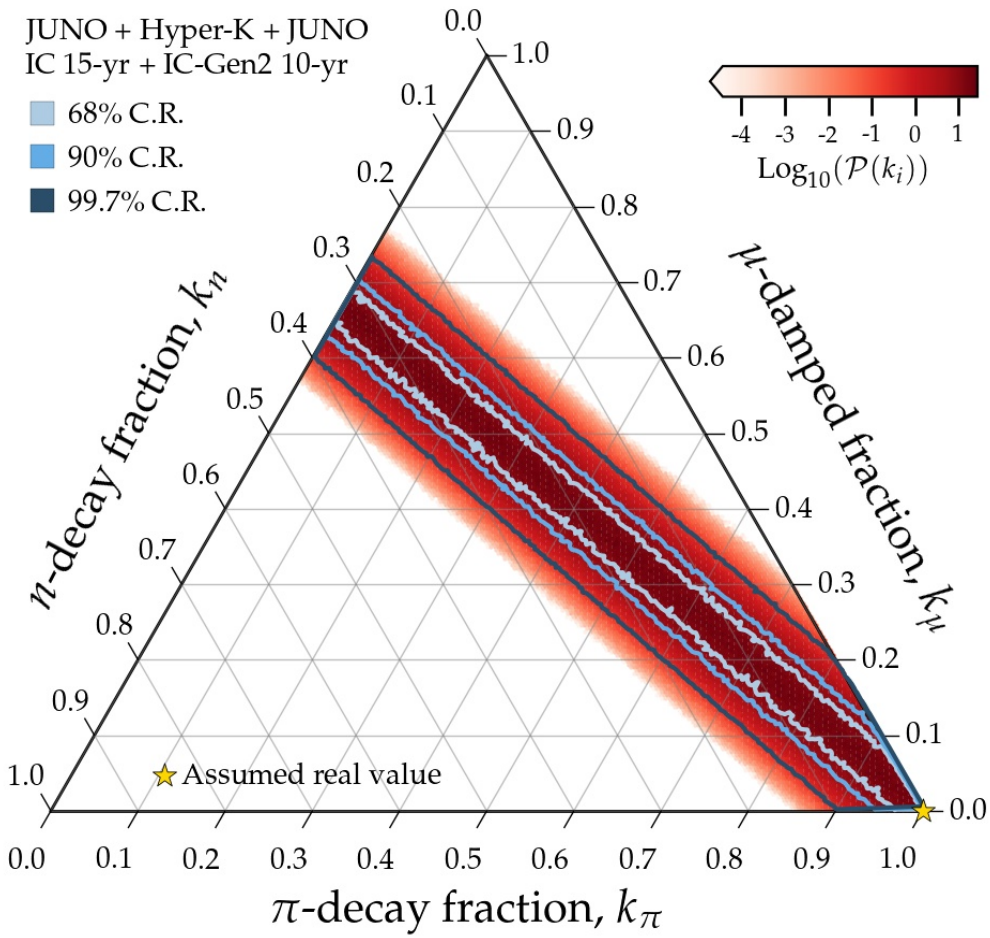
Propagate to Earth ↓

$$\boldsymbol{f}_{\oplus}$$

Assume real value $k_\pi = 1$ ($k_\mu = k_n = 0$)

By 2040, how well will we recover the real value?

[Adding spectrum information (not shown) will likely help]



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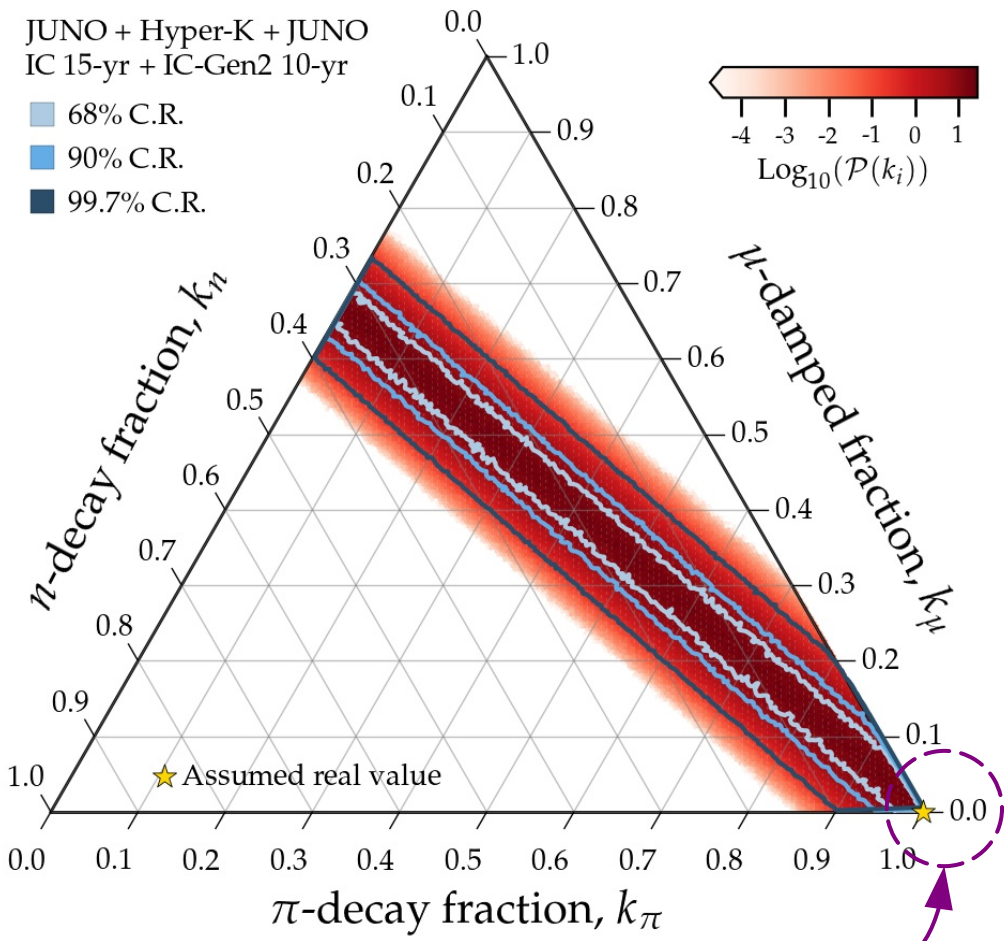

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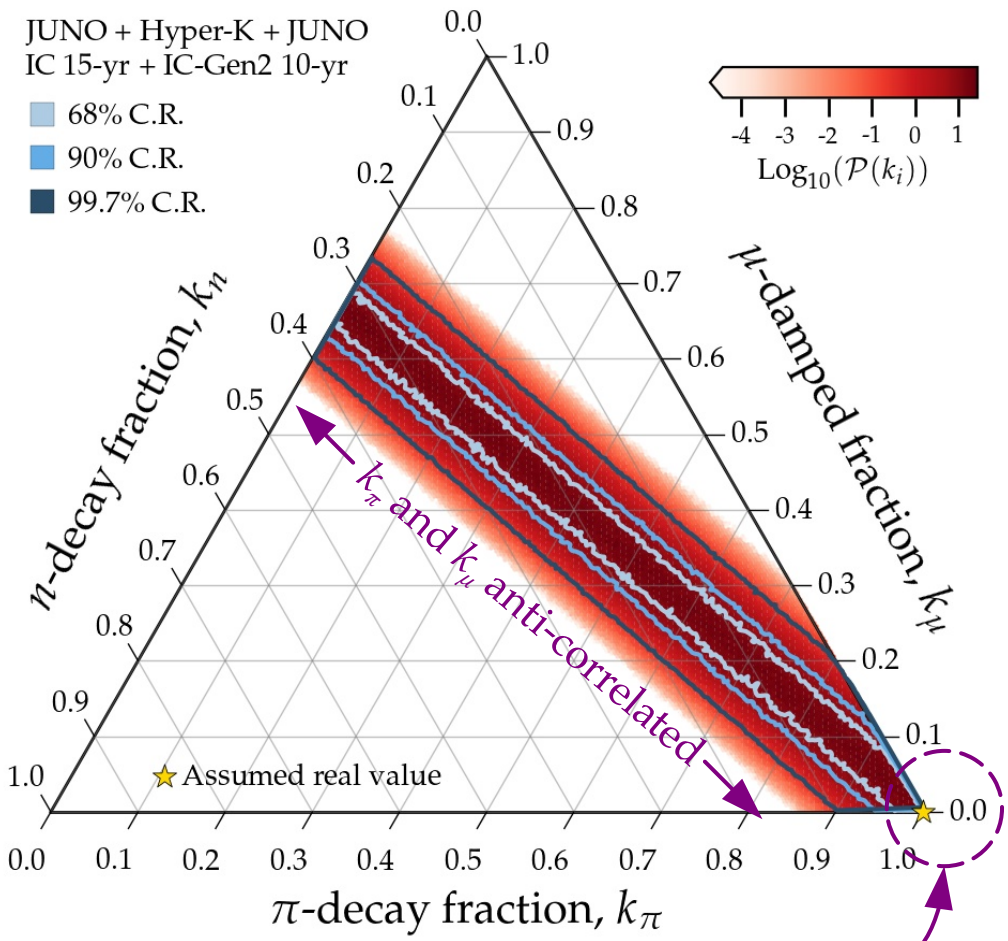

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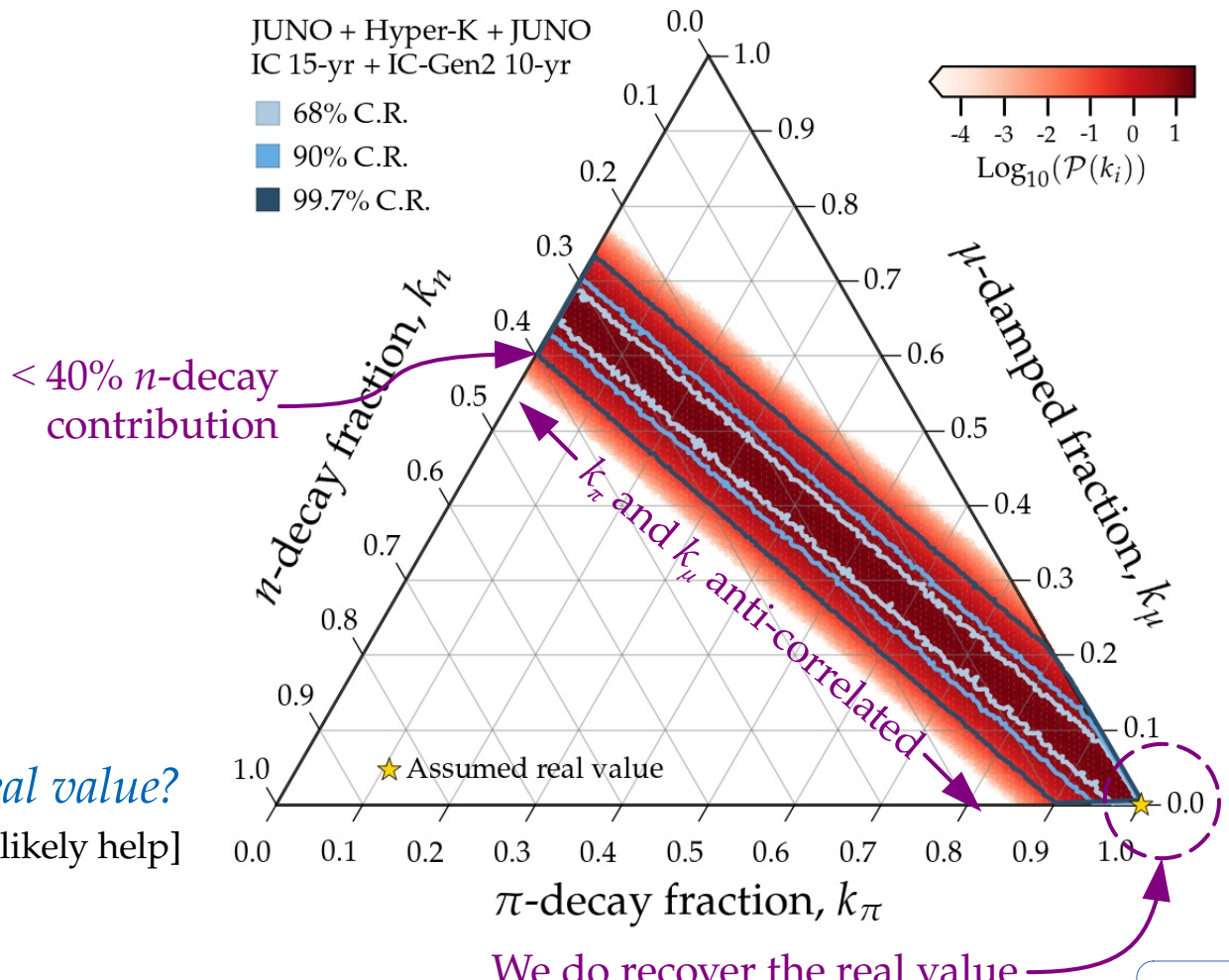

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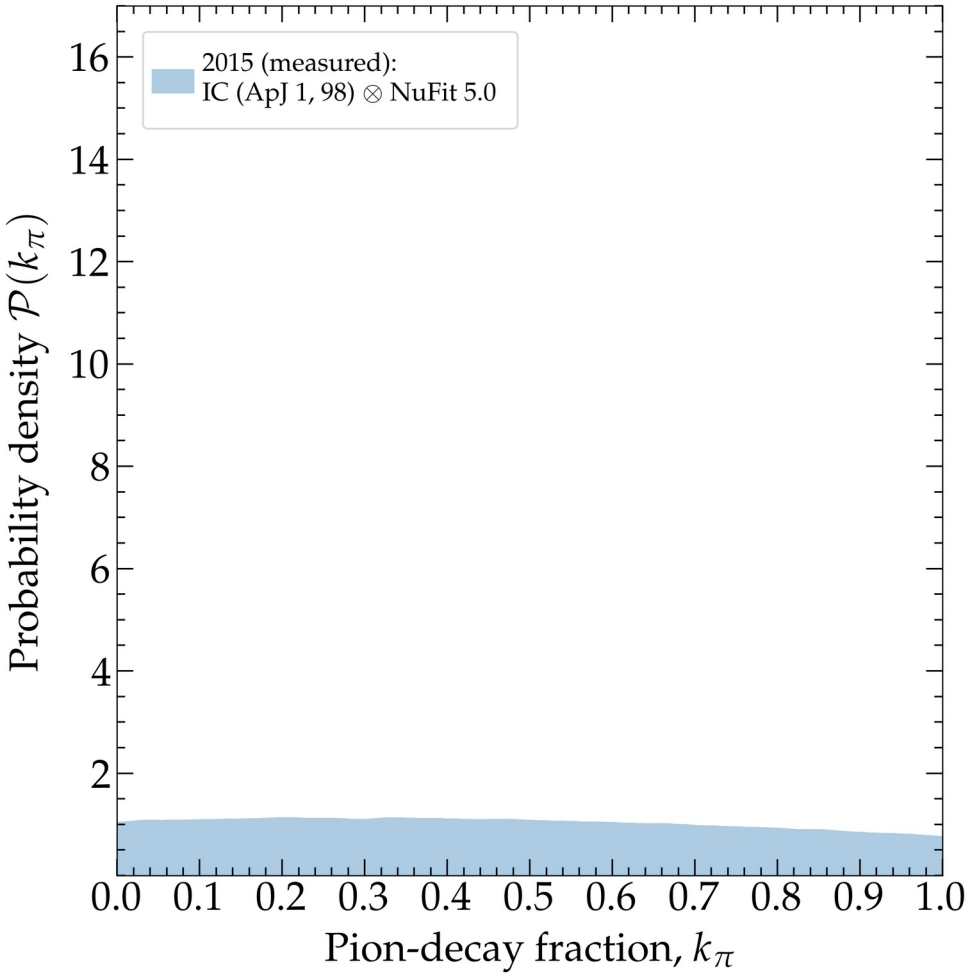

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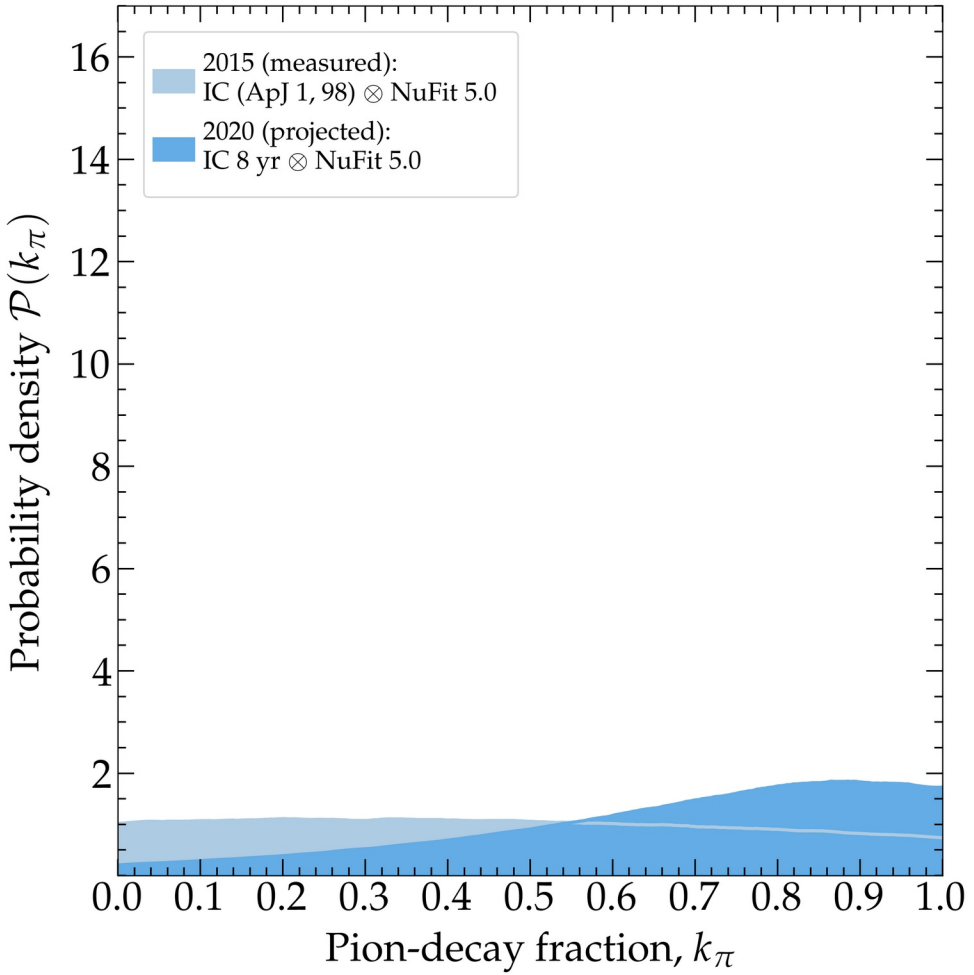

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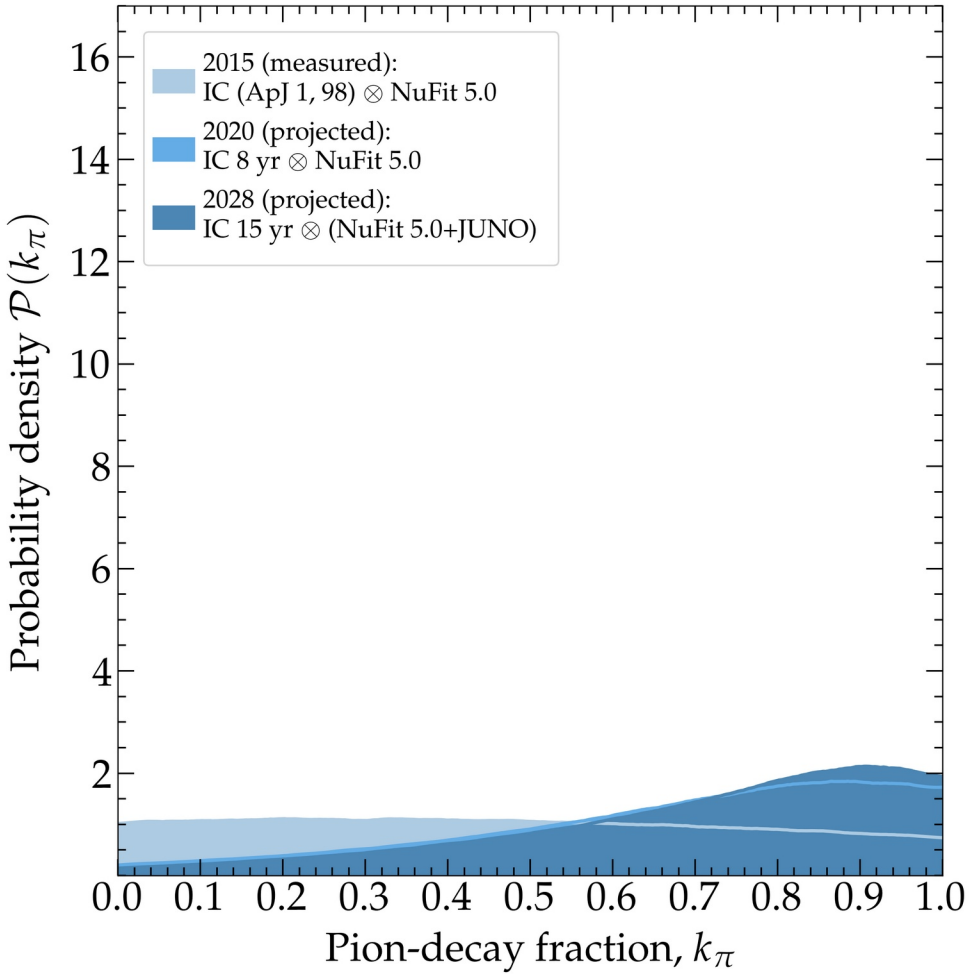

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$$\boldsymbol{f}_{\rm S} = k_\pi \boldsymbol{f}^{\pi}_{\rm S} + k_\mu \boldsymbol{f}^{\mu}_{\rm S} + k_n \boldsymbol{f}^{n}_{\rm S}$$

π decay: (1/3, 2/3, 0)

μ damped: (0, 1, 0)

n decay: (1, 0, 0)

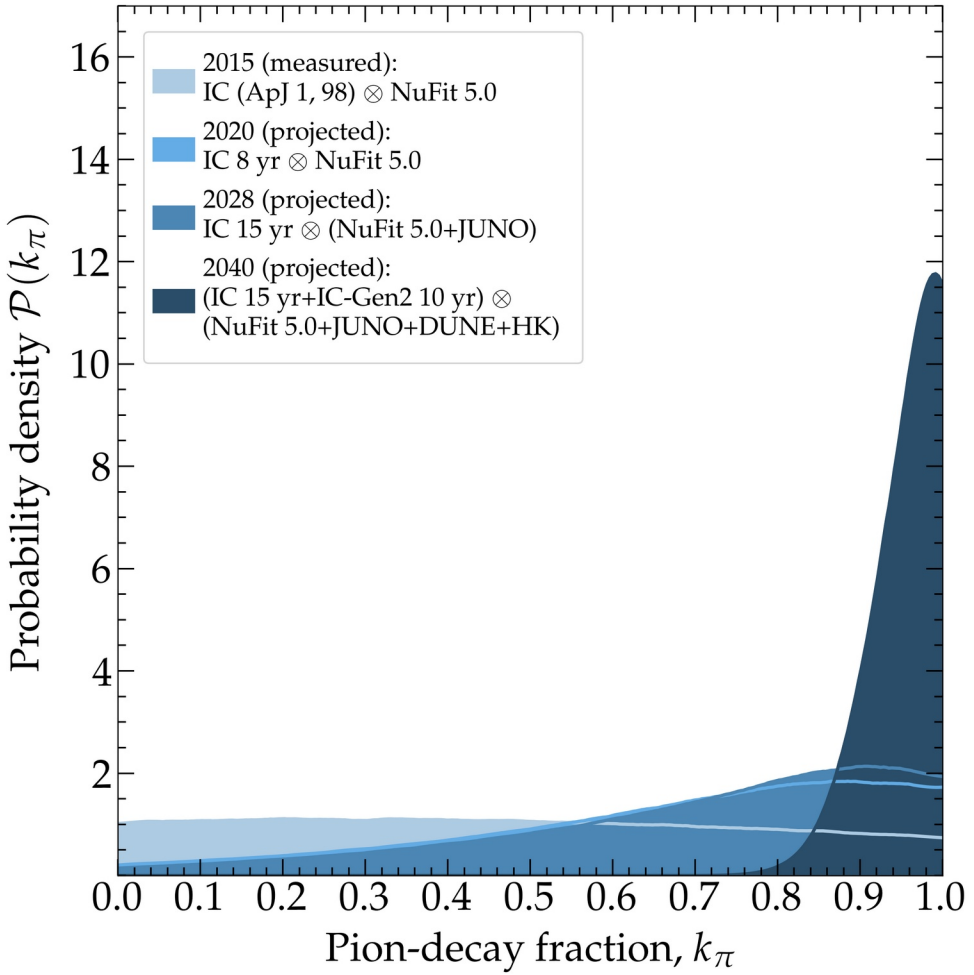
Propagate to Earth

$$\boldsymbol{f}_{\oplus}$$

Assume real value $k_\pi = 1$ ($k_\mu = k_n = 0$)

By 2040, how well will we recover the real value?

[Adding spectrum information (not shown) will likely help]



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

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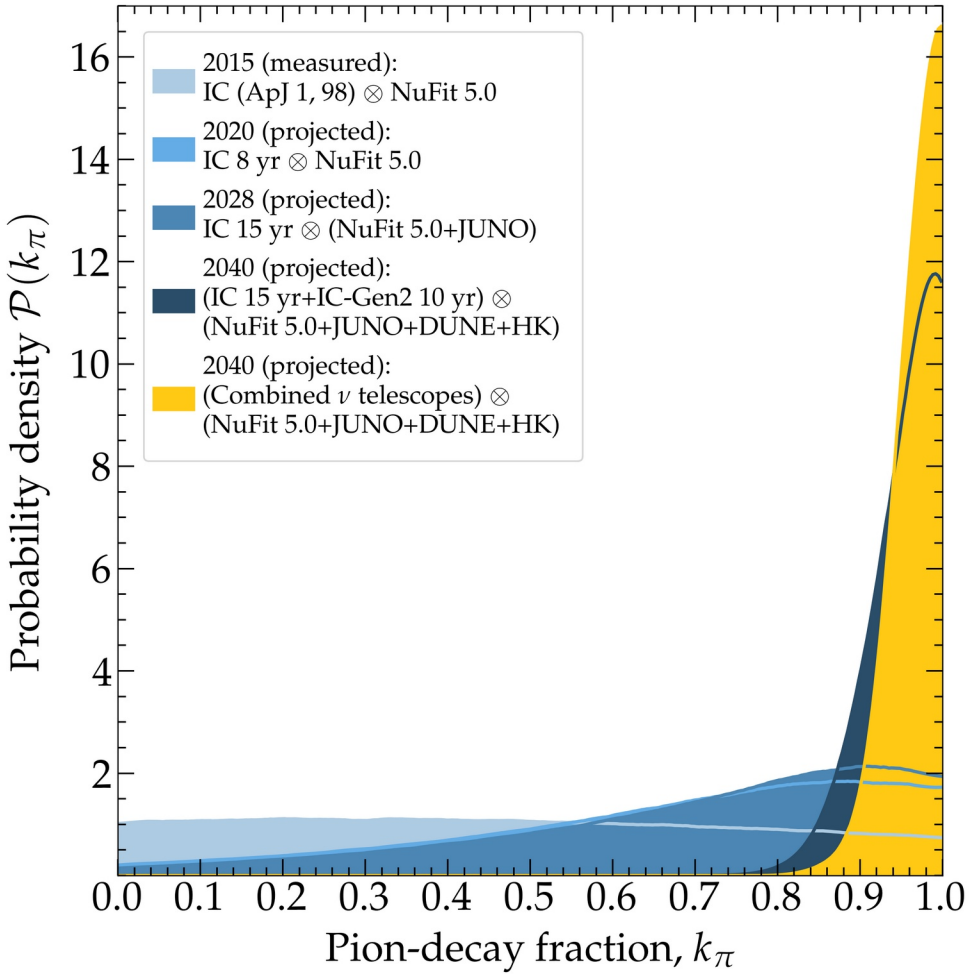
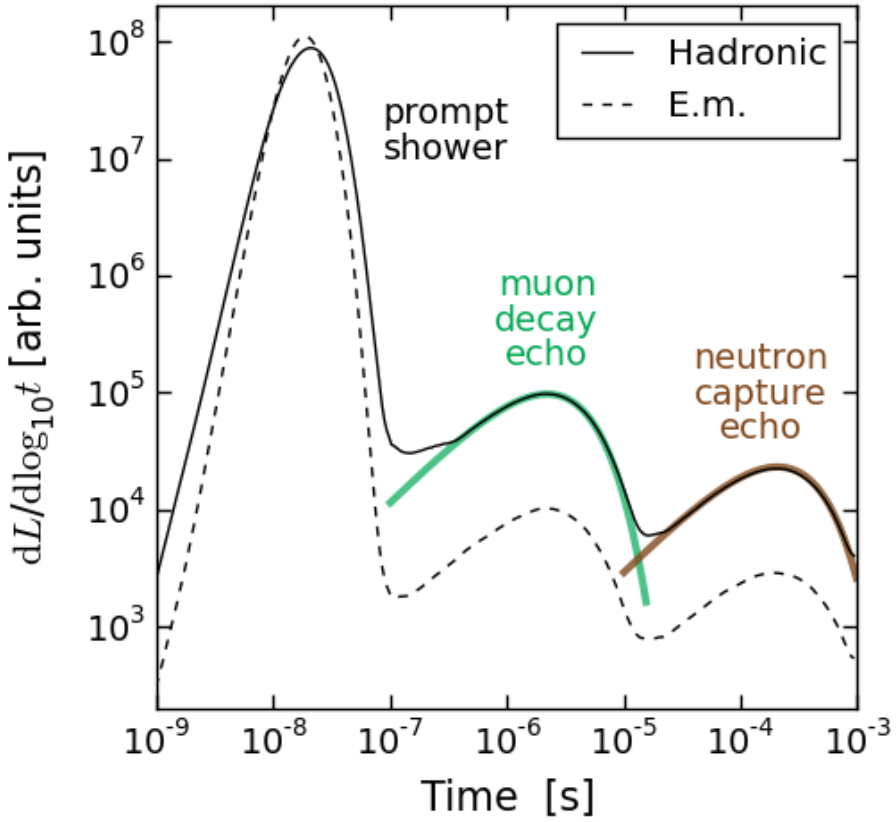
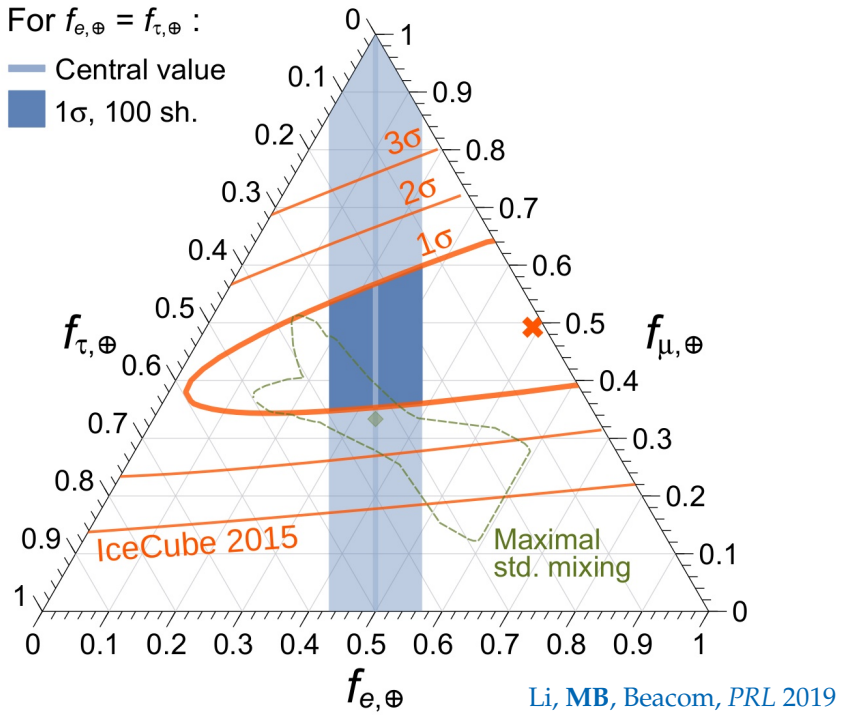


Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Side note: Improving flavor-tagging using *echoes*

Late-time light (*echoes*) from muon decays and neutron captures can separate showers made by ν_e and ν_τ –





Li, **MB**, Beacom, *PRL* 2019

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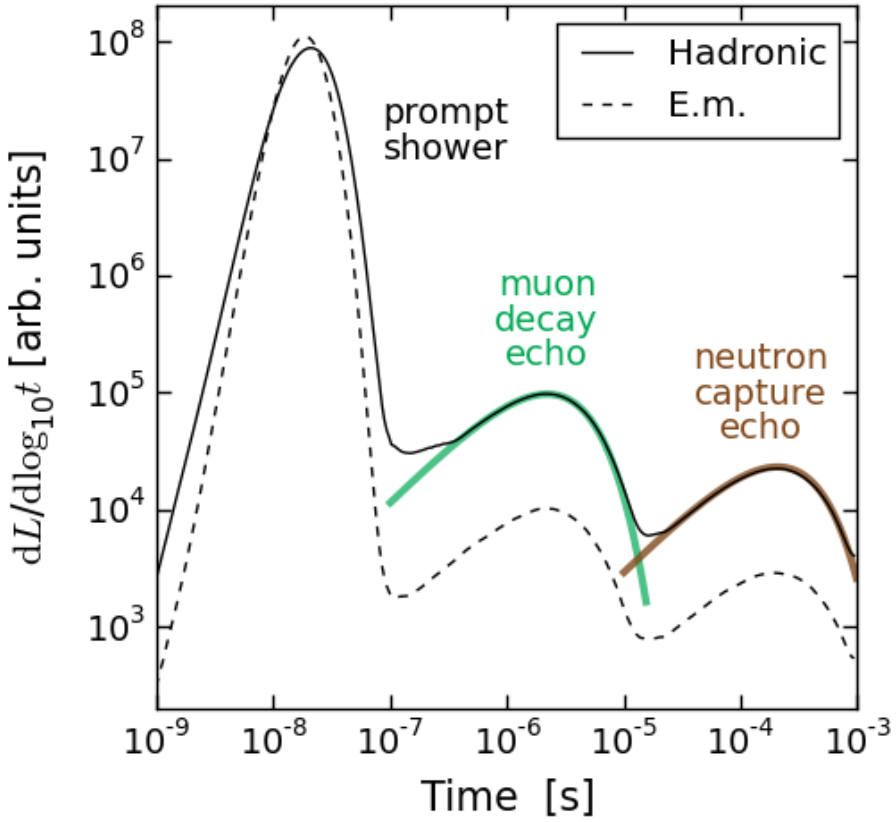

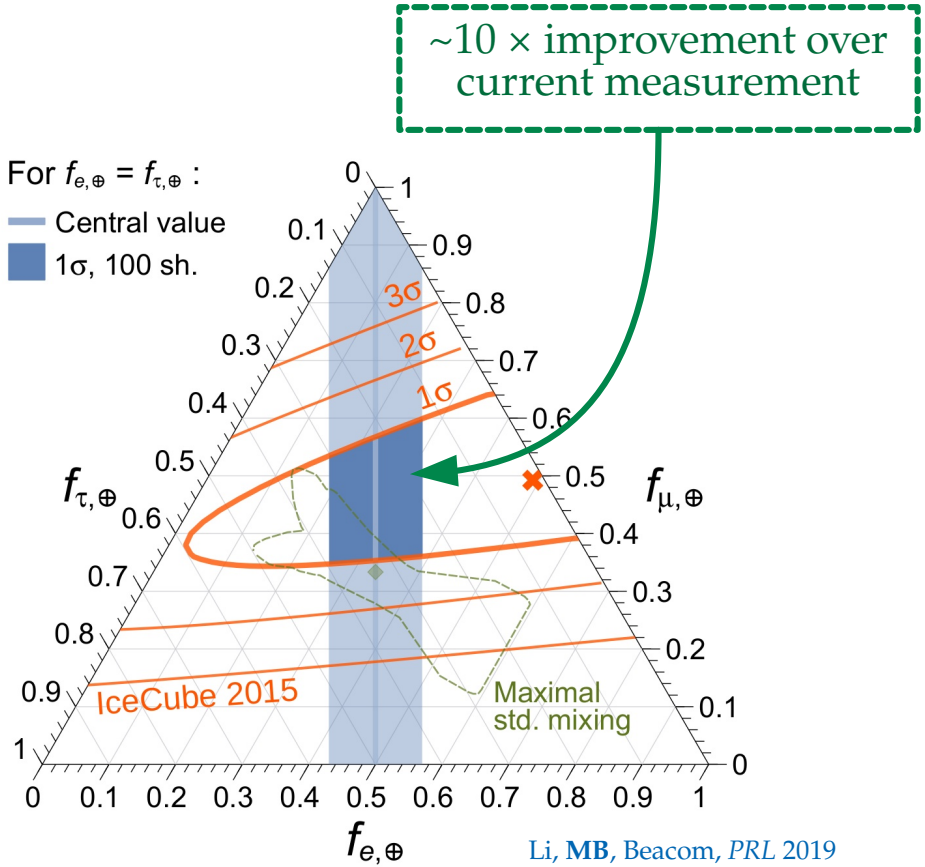

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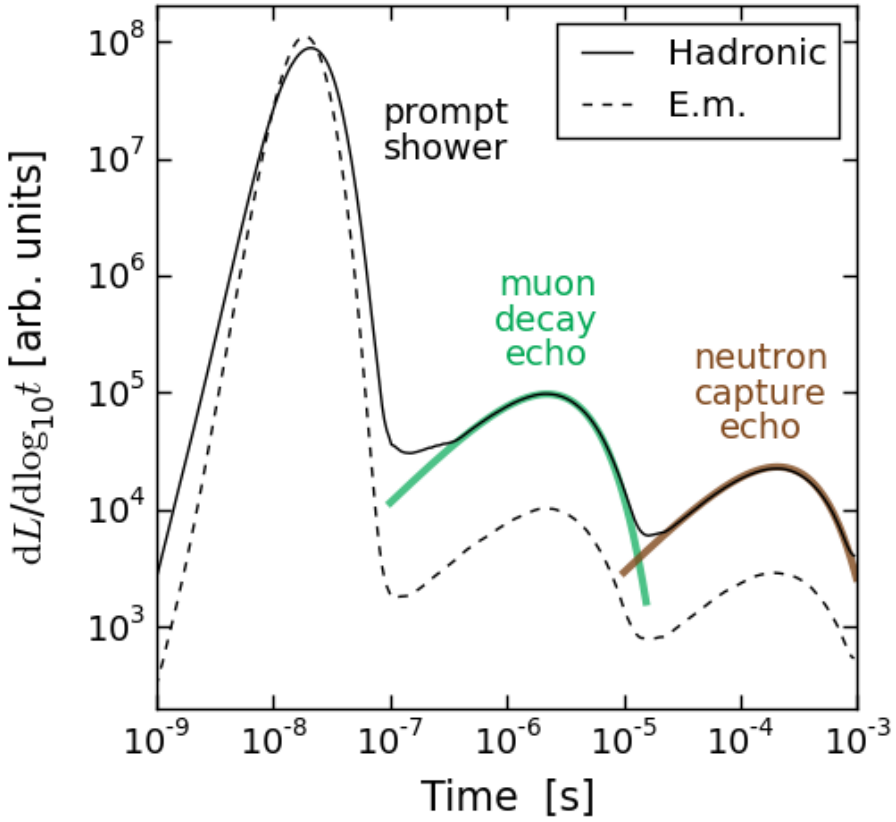
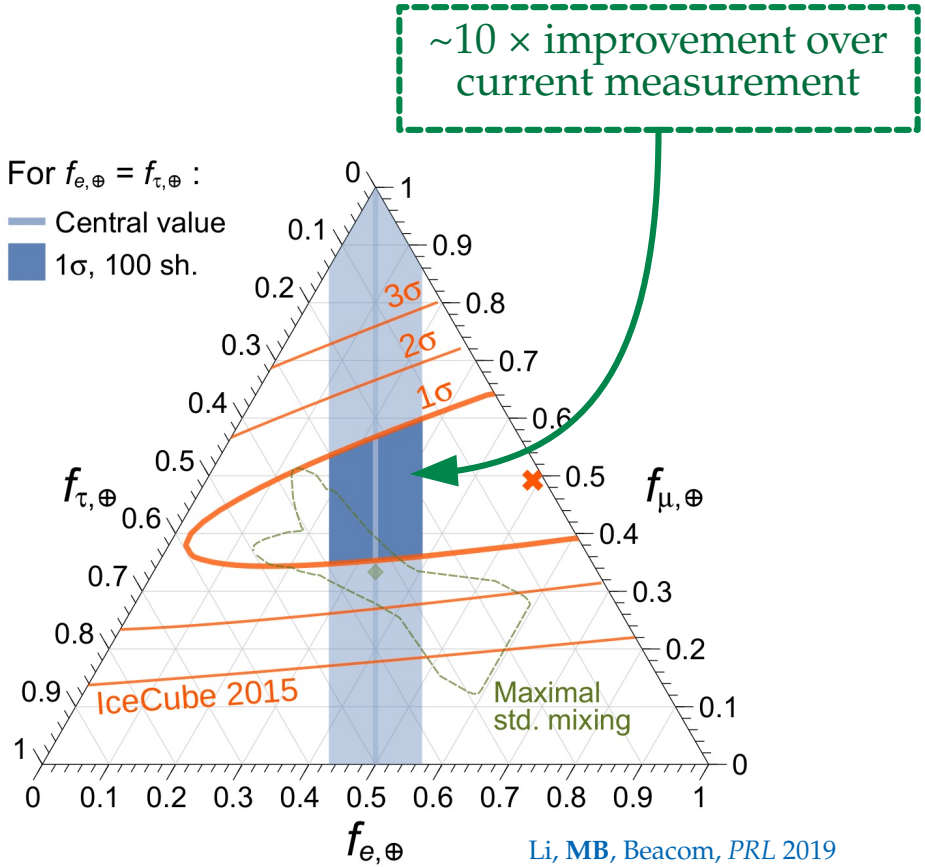
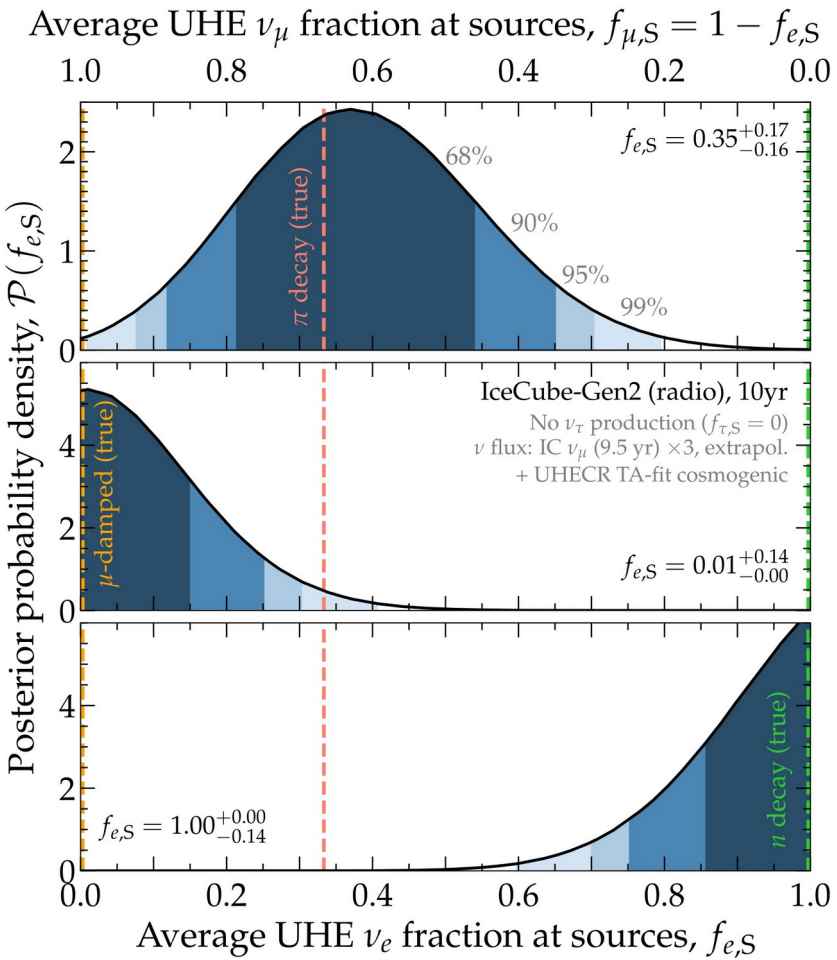




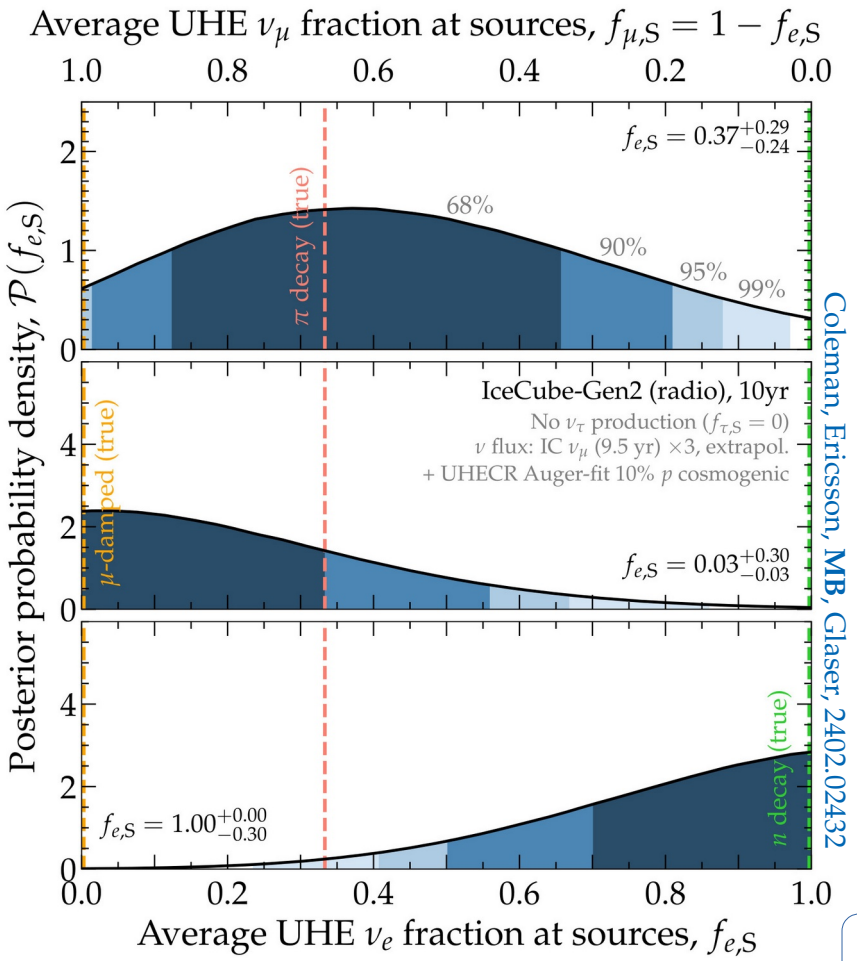
Li, **MB**, Beacom, *PRL* 2019

Inferring the UHE flavor composition at the sources (1/2)

Assuming a high UHE flux



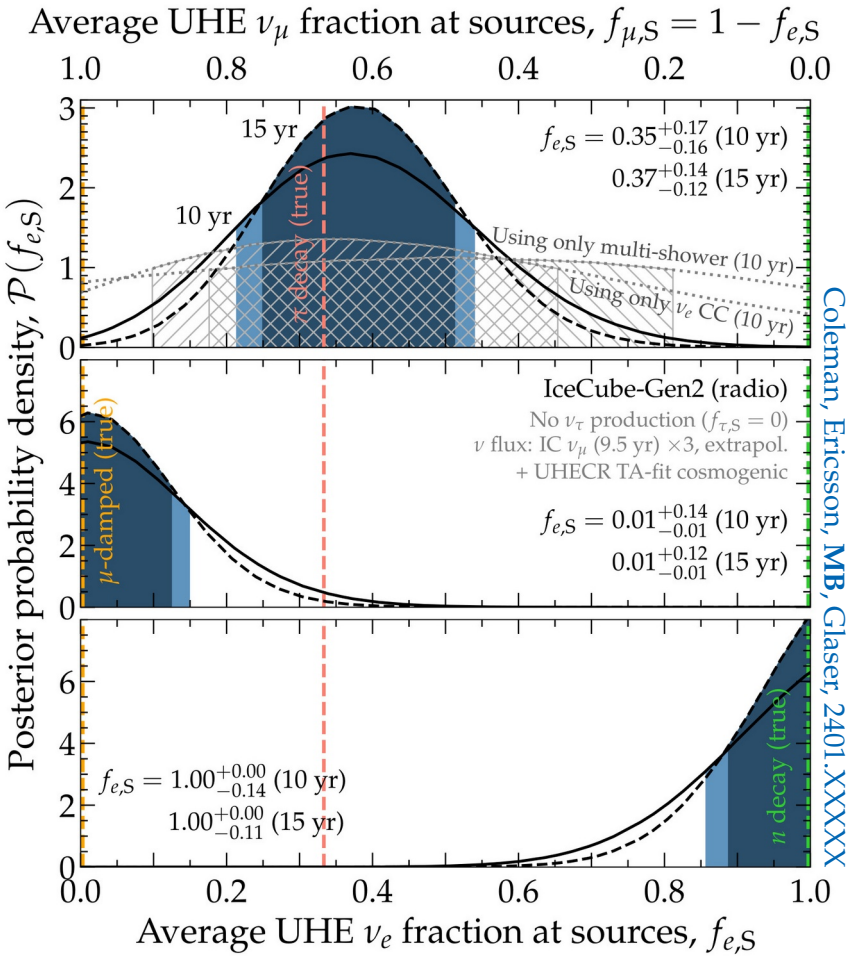
Assuming a low UHE flux



Coleman, Ericsson, **MB**, Glaser, 2402.02432

Inferring the UHE flavor composition at the sources (2/2)

10 yr *vs.* 15 yr, individual channels



Flavor composition: measuring the energy dependence

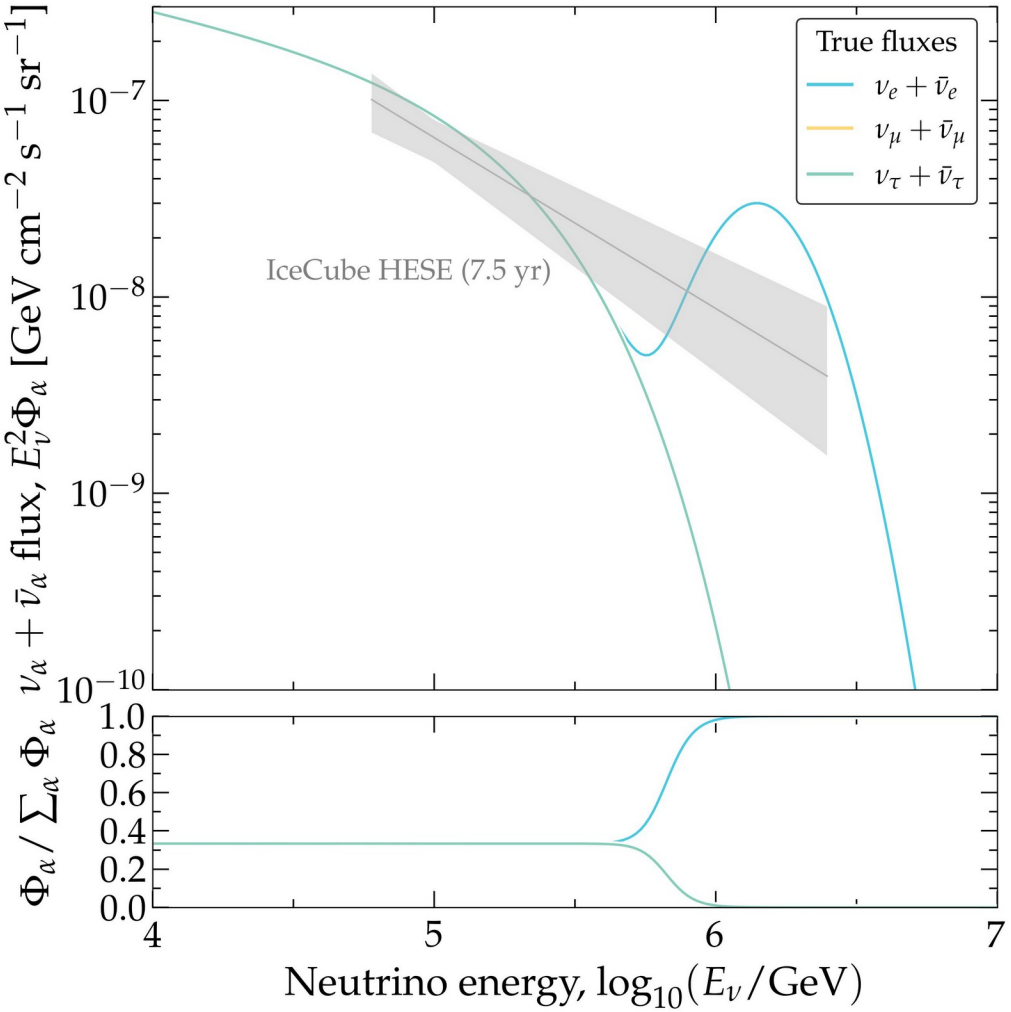
Can we do better?

Maybe

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

How?

—Infer the spectrum of ν_e, ν_μ, ν_τ separately



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

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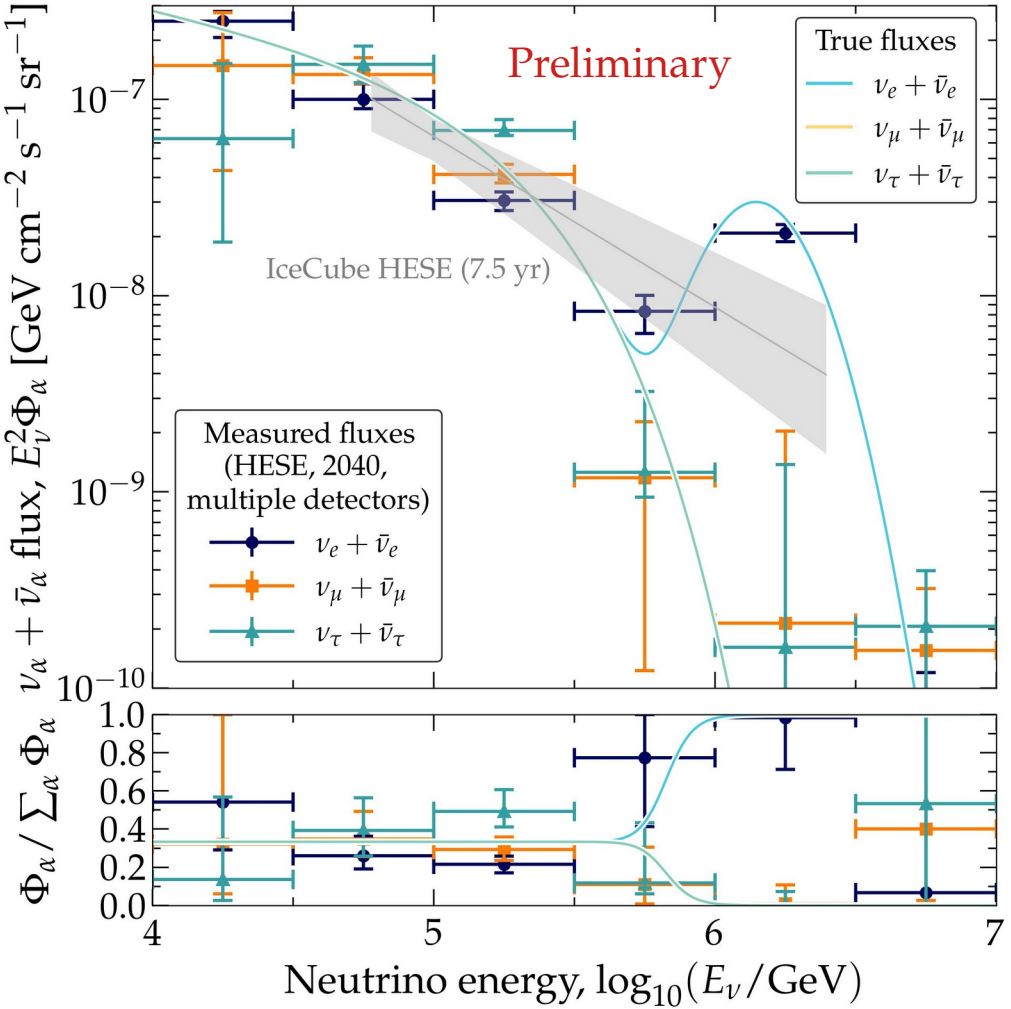
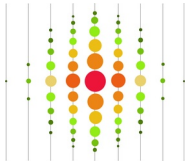
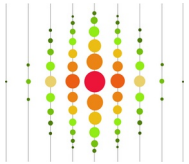
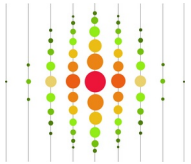
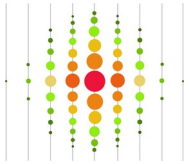
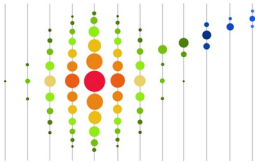
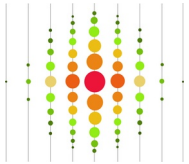
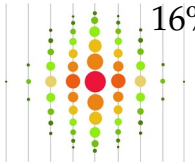
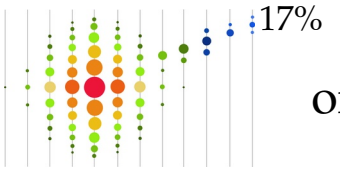
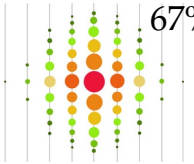
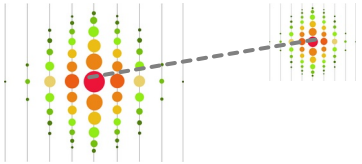
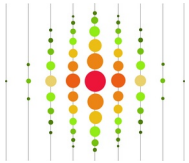
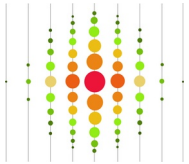
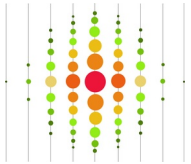
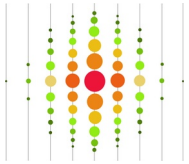
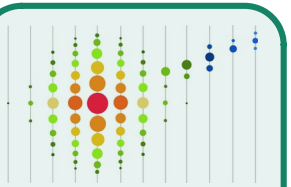
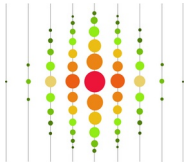
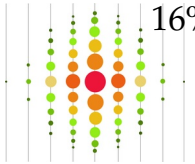
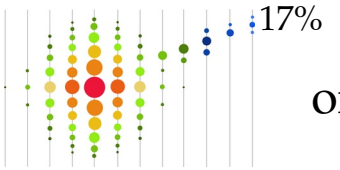
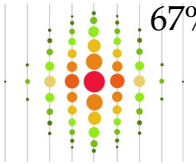
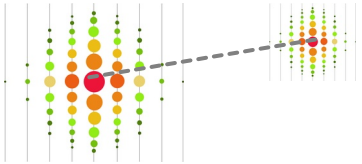
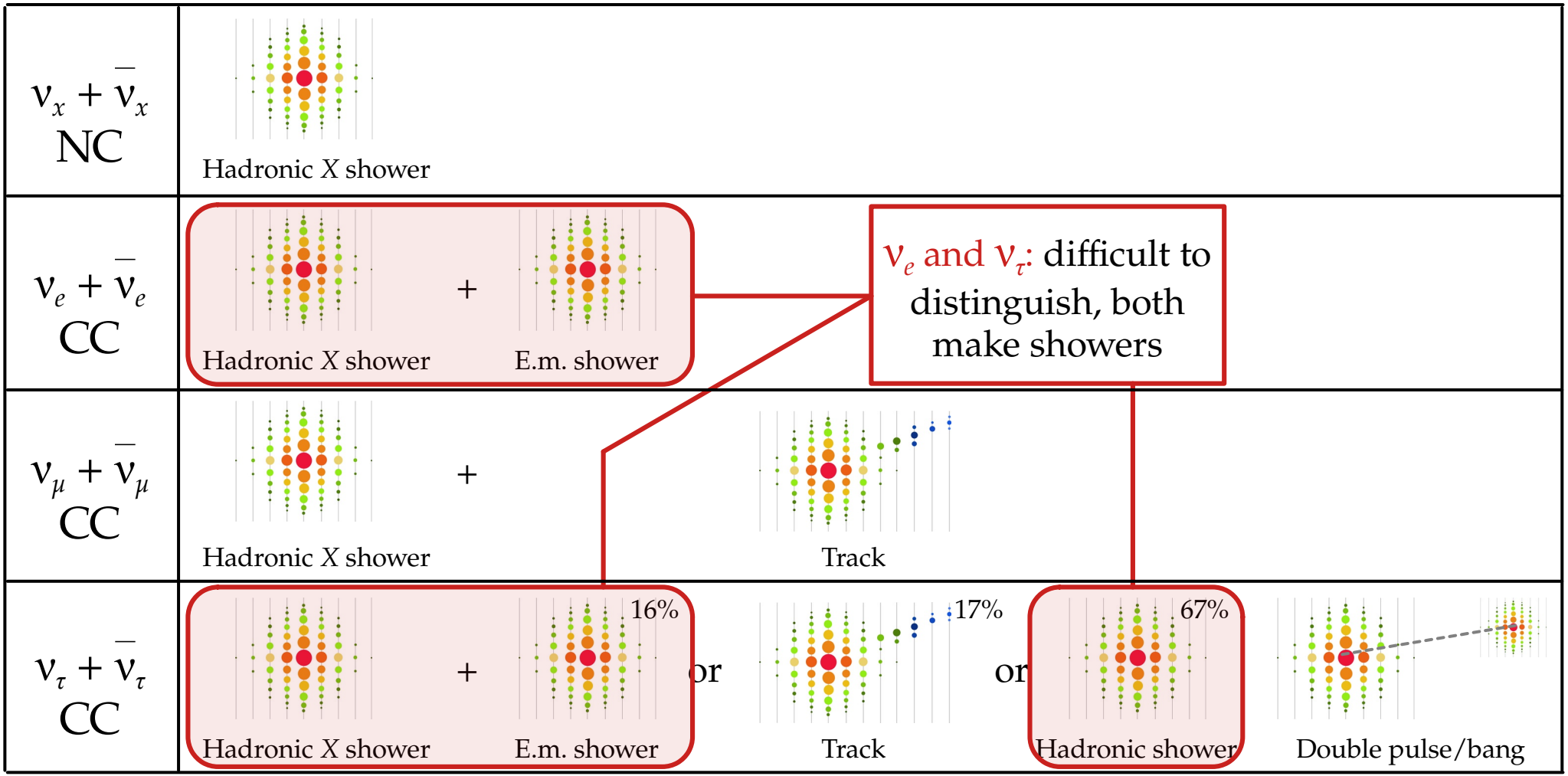


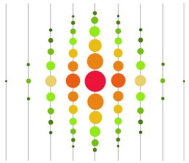
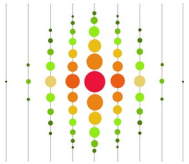
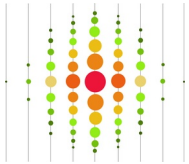
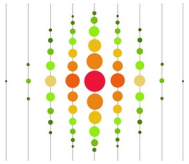
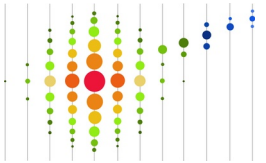
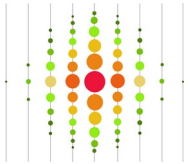
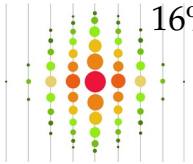
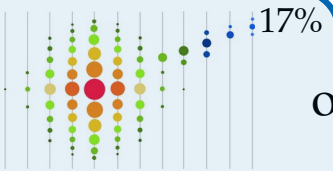
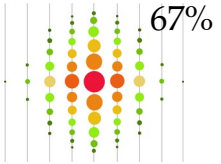
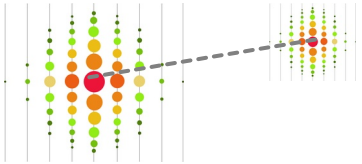
Liu, **MB**, *In prep.*

$\nu_x + \bar{\nu}_x$ NC	 Hadronic X shower
$\nu_e + \bar{\nu}_e$ CC	 Hadronic X shower +  E.m. shower
$\nu_\mu + \bar{\nu}_\mu$ CC	 Hadronic X shower +  Track
$\nu_\tau + \bar{\nu}_\tau$ CC	 Hadronic X shower +  E.m. shower 16% or  Track 17% or  Hadronic shower 67%  Double pulse/bang

$\nu_x + \bar{\nu}_x$ NC	 Hadronic X shower
$\nu_e + \bar{\nu}_e$ CC	 Hadronic X shower +  E.m. shower
$\nu_\mu + \bar{\nu}_\mu$ CC	 Hadronic X shower +  Track
$\nu_\tau + \bar{\nu}_\tau$ CC	 Hadronic X shower +  E.m. shower 16% or  Track 17% or  Hadronic shower 67%  Double pulse/bang

ν_μ: easy to identify the outgoing track


$\nu_x + \bar{\nu}_x$ NC
Hadronic X shower
$\nu_e + \bar{\nu}_e$ CC
Hadronic X shower
+
E.m. shower
ν_e and ν_τ: difficult to distinguish, both make showers
$\nu_\mu + \bar{\nu}_\mu$ CC
Hadronic X shower
+
Track
$\nu_\tau + \bar{\nu}_\tau$ CC
Hadronic X shower
+
16%
E.m. shower
or
17%
Track
or
67%
Hadronic shower
Double pulse/bang

$\nu_x + \bar{\nu}_x$ NC	 Hadronic X shower						
$\nu_e + \bar{\nu}_e$ CC	 Hadronic X shower	+	 E.m. shower				
$\nu_\mu + \bar{\nu}_\mu$ CC	 Hadronic X shower	+		 Track			
$\nu_\tau + \bar{\nu}_\tau$ CC	 Hadronic X shower	+	 E.m. shower 16%	or	 Track 17%	or	 Hadronic shower 67%  Double pulse/bang

The occasional track (weakly) breaks the ν_e / ν_τ degeneracy