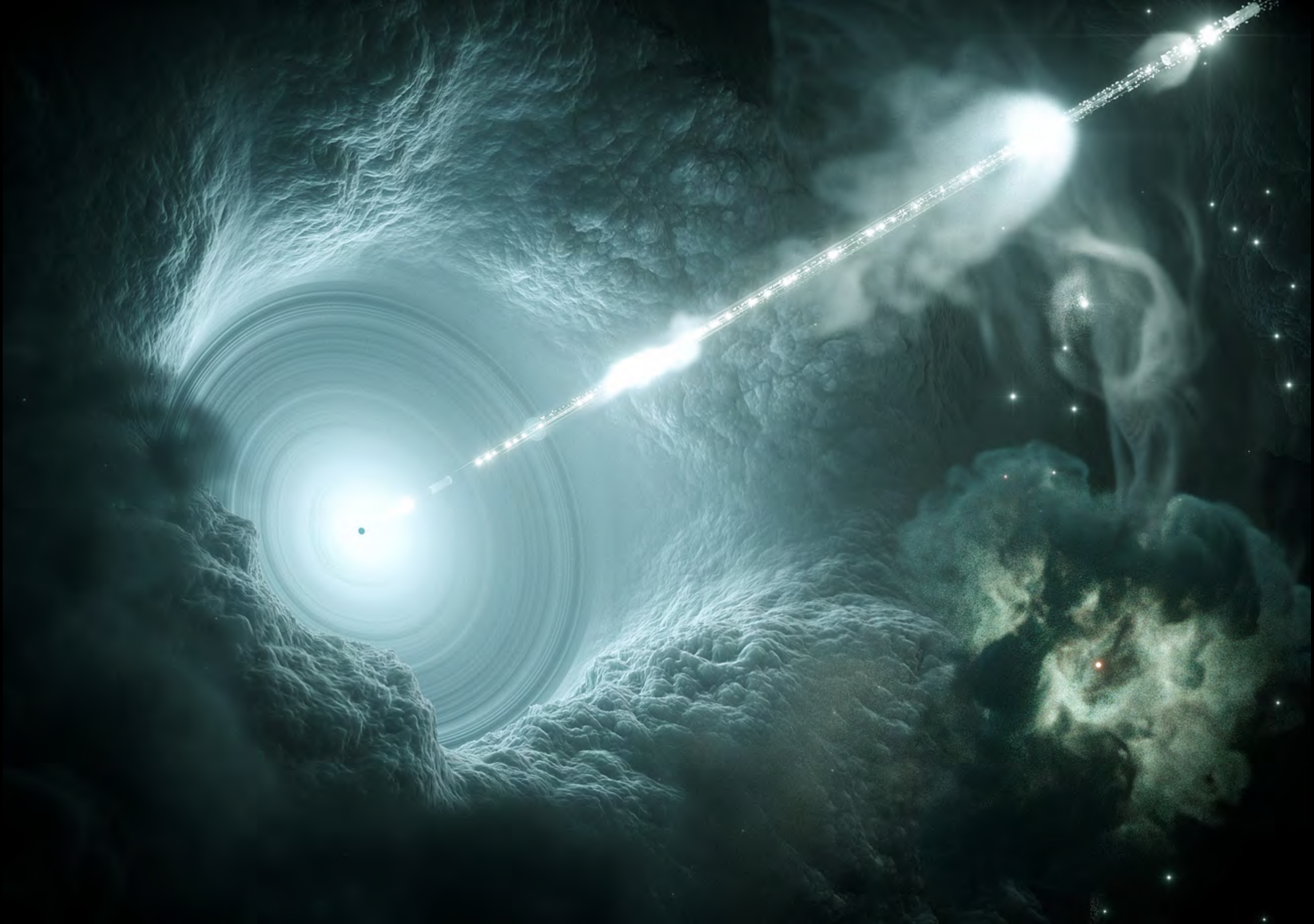
The present and future of flavor in high-energy cosmic neutrinos

Mauricio Bustamante
Niels Bohr Institute, University of Copenhagen

N3AS Seminar
March 26, 2024

UNIVERSITY OF COPENHAGEN

VILLUM FONDEN



DESY

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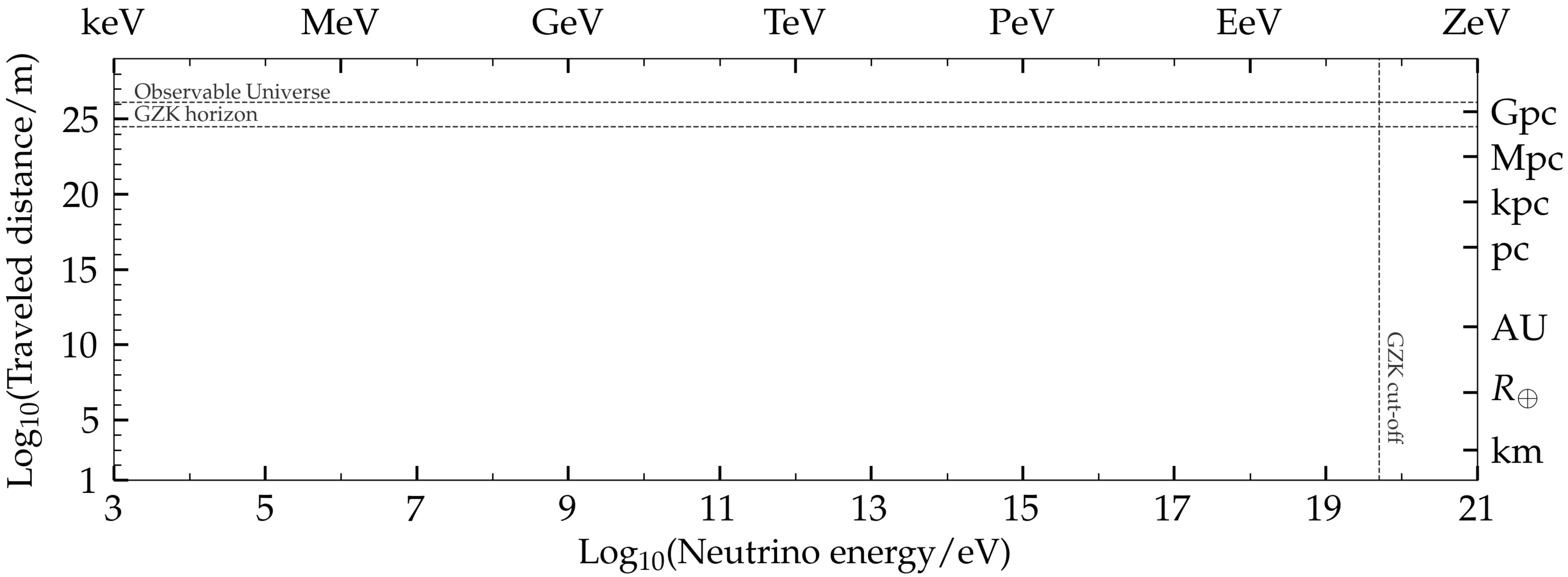
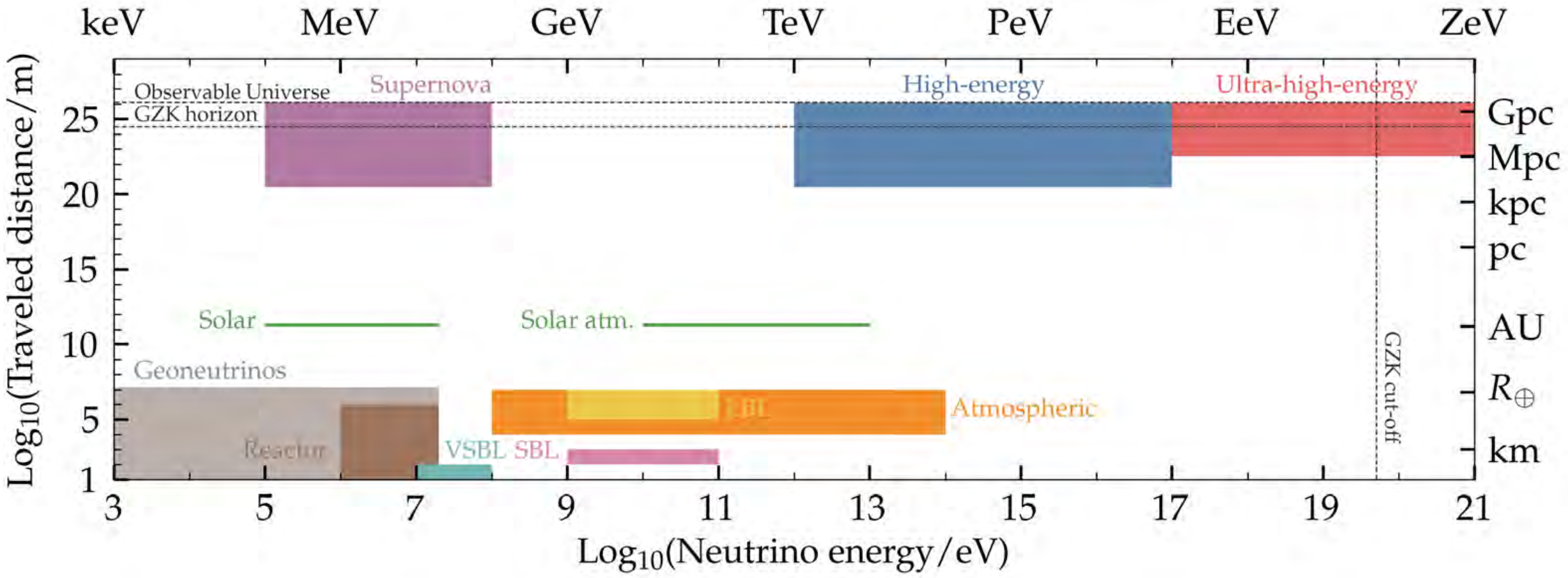
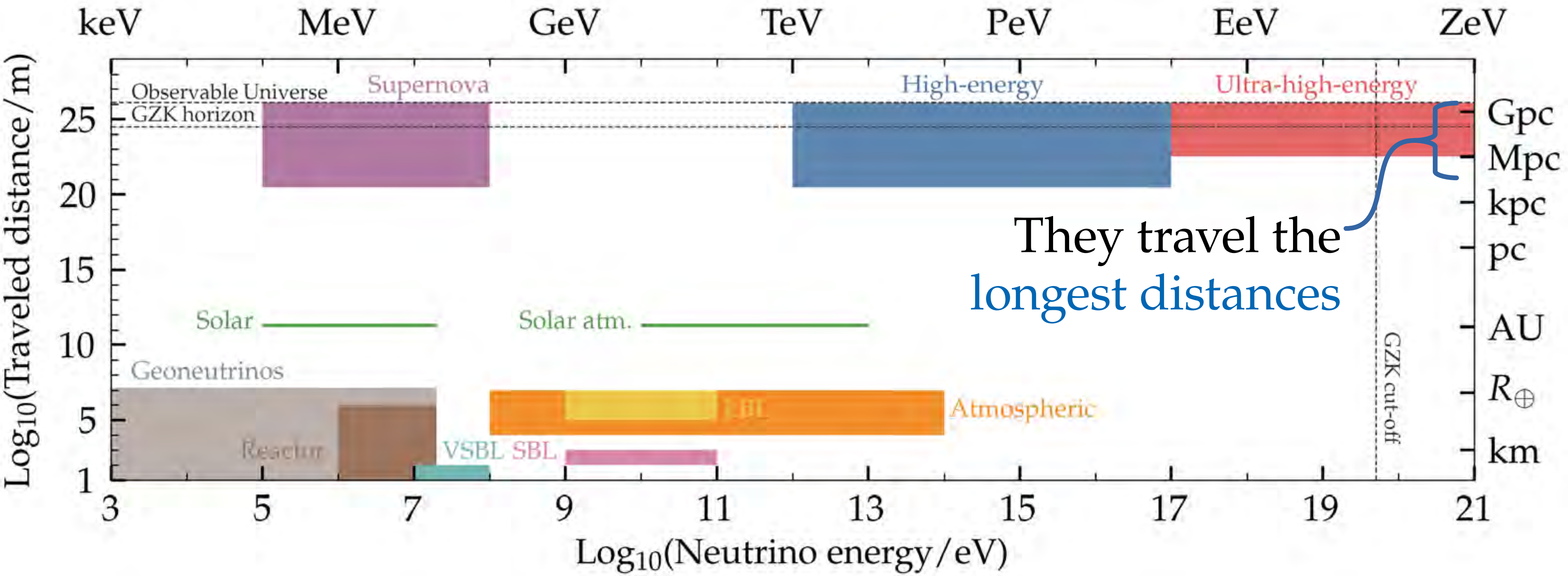


Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333), adapted


keV
MeV
GeV
TeV
PeV
EeV
ZeV
Log10(Traveled distance / m)
25
20
15
10
5
1
Observable Universe
GZK horizon
Supernova
High-energy
Ultra-high-energy
Gpc
Mpc
kpc
pc
AU
R⊕
km
Solar
Solar atm.
Geoneutrinos
Reactor
VSBL
SBL
LBL
Atmospheric
GZK cut-off
3
5
7
9
11
13
15
17
19
21
Log10(Neutrino energy / eV)

They have the highest energies



They travel the longest distances

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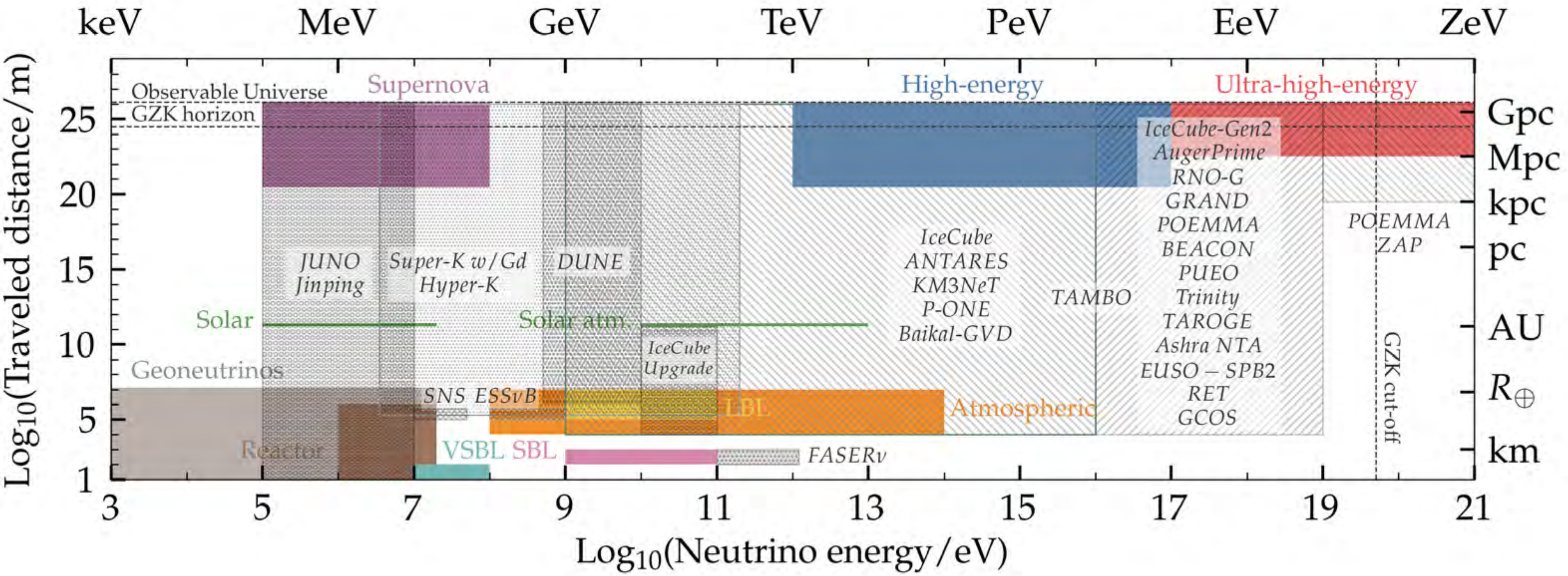

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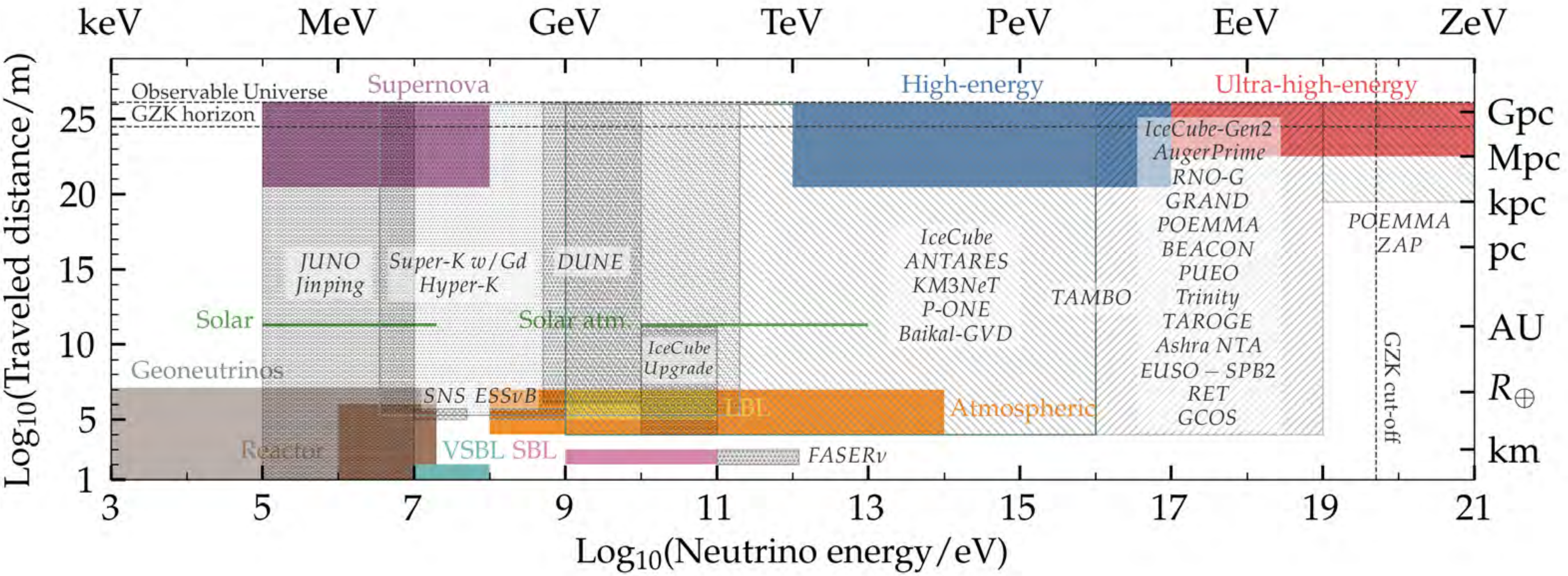

Synergies with lower energies

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Discovered in 2013
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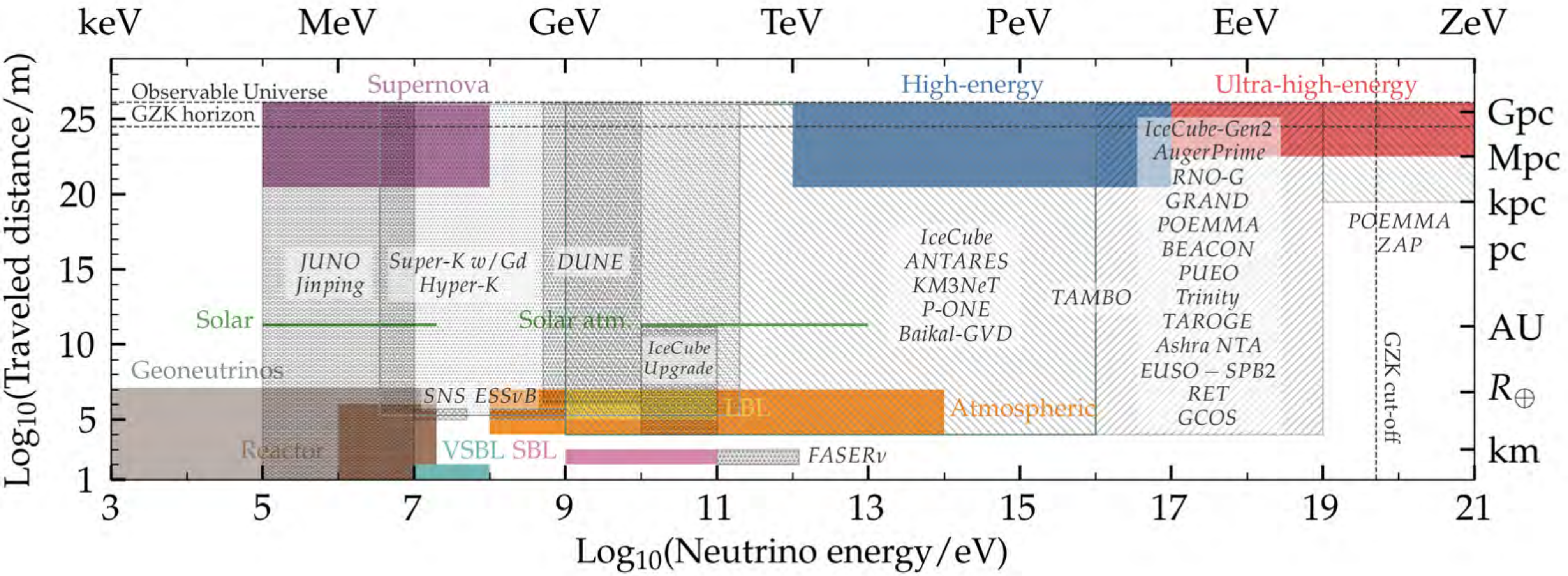

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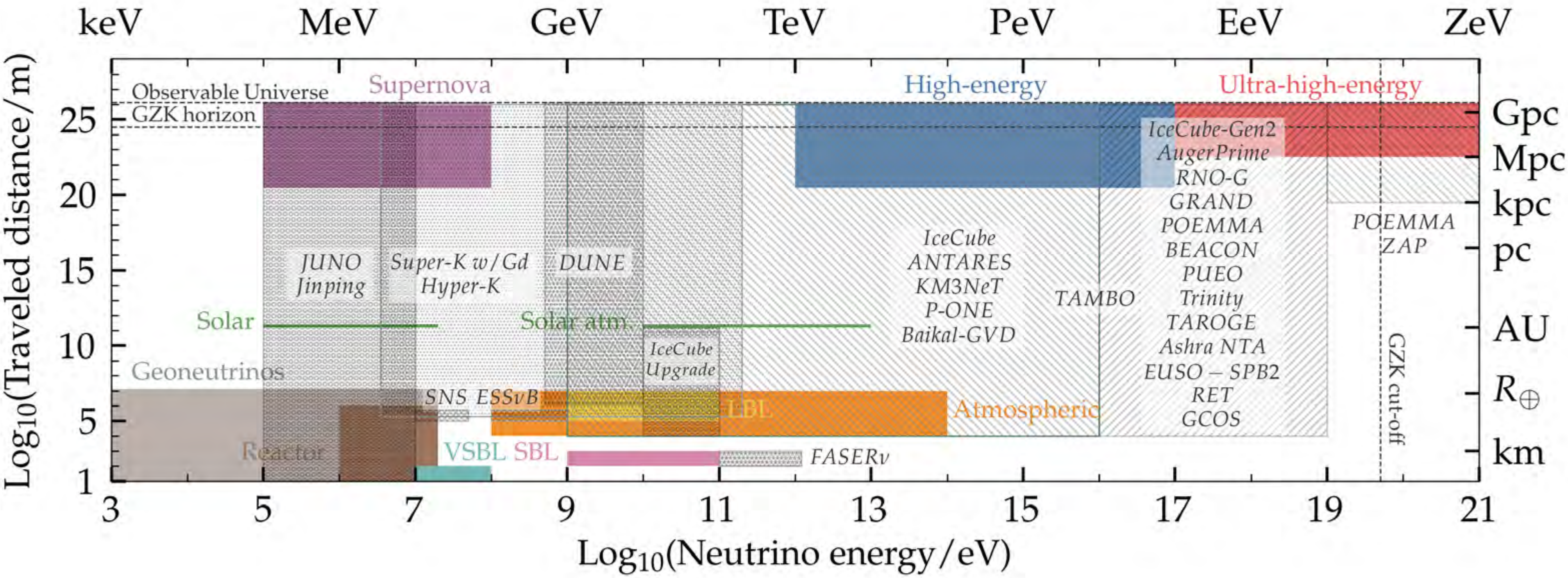

Synergies with lower energies

Increase TeV–PeV
ν statistics

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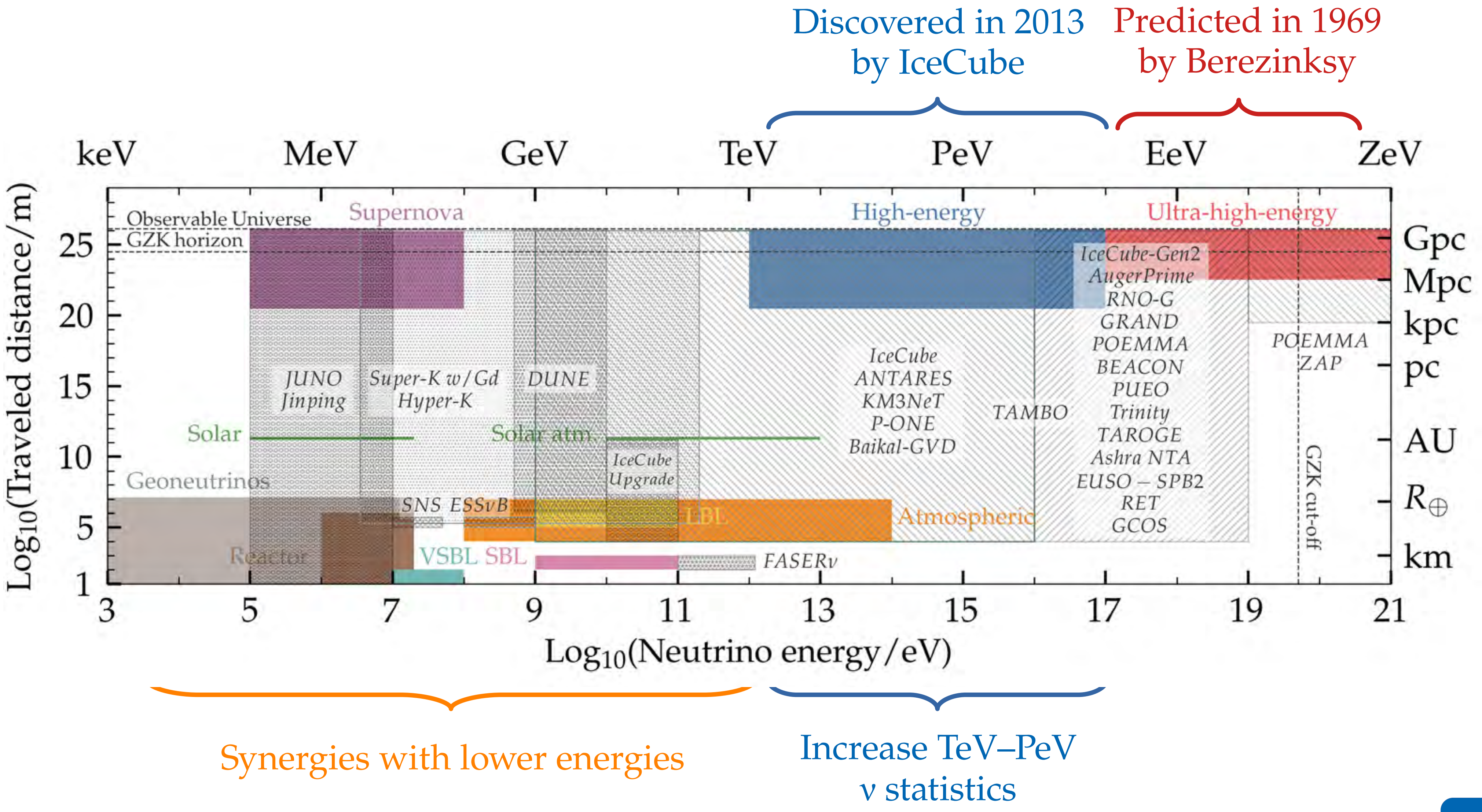

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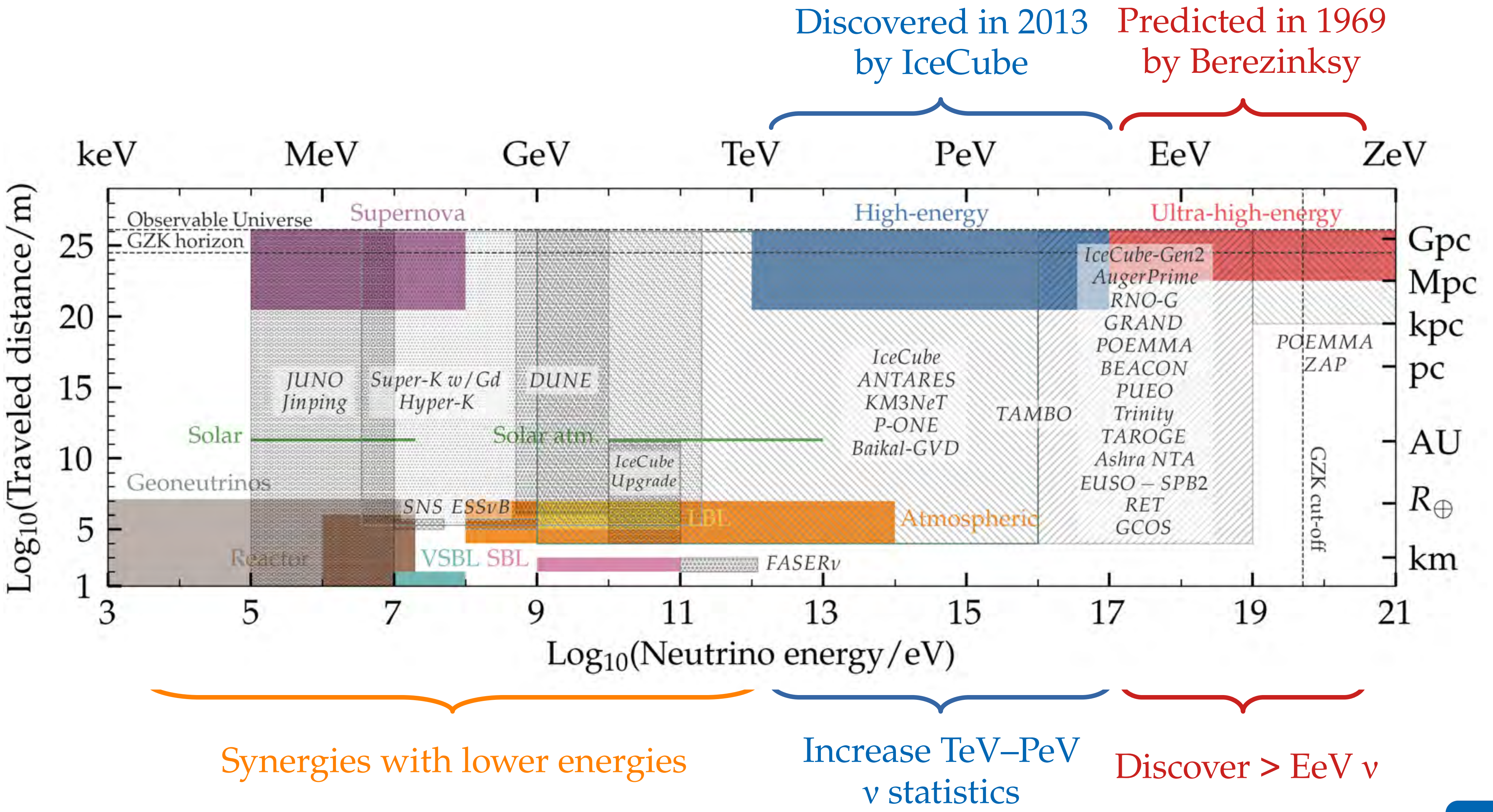

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Making high-energy astrophysical neutrinos: a toy model

(or $p + p$)

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

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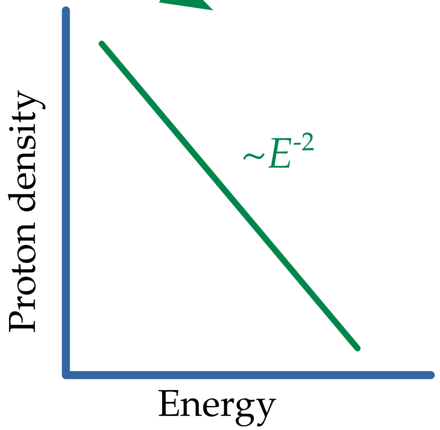

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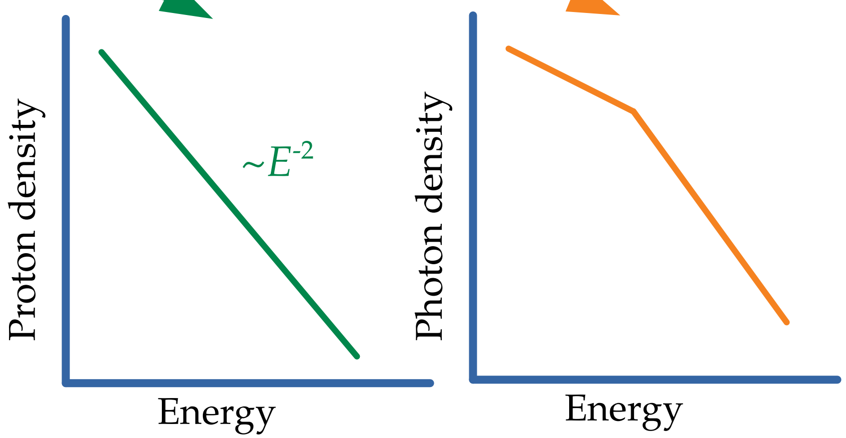

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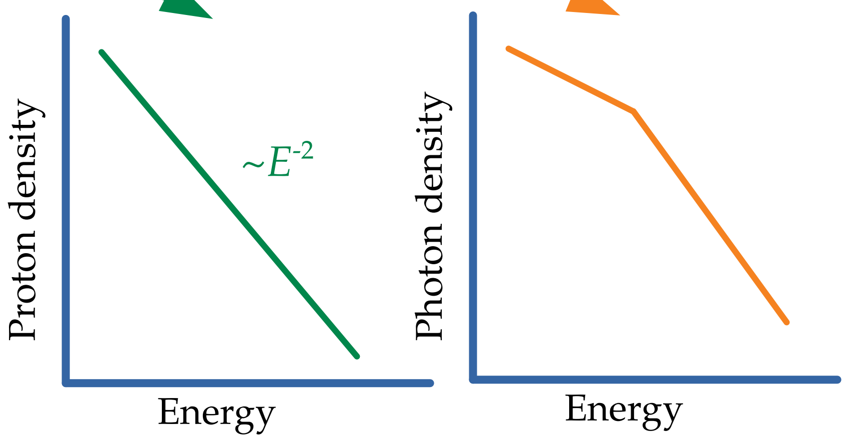
$$\pi^0 \longrightarrow \gamma + \gamma$$

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

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



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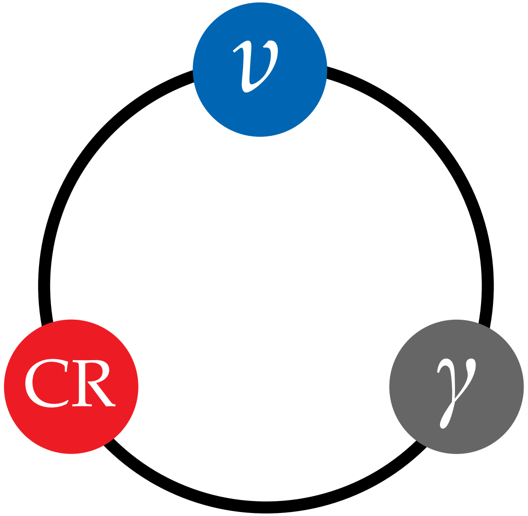
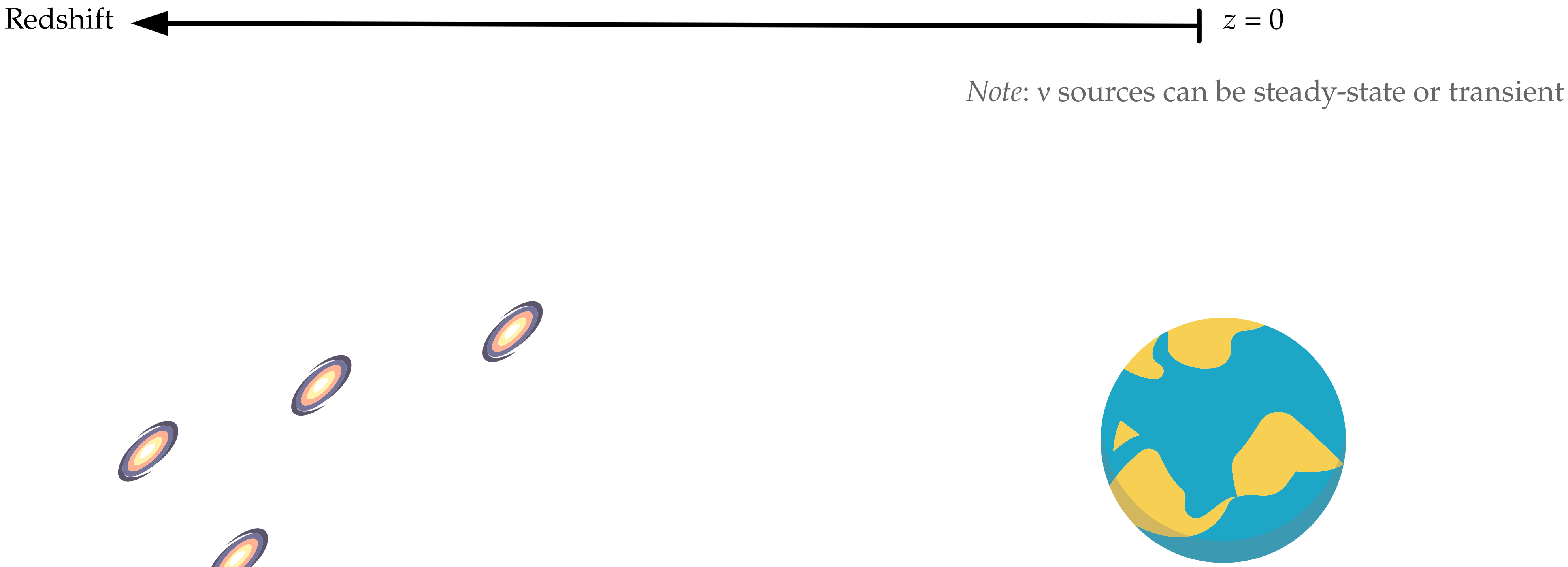
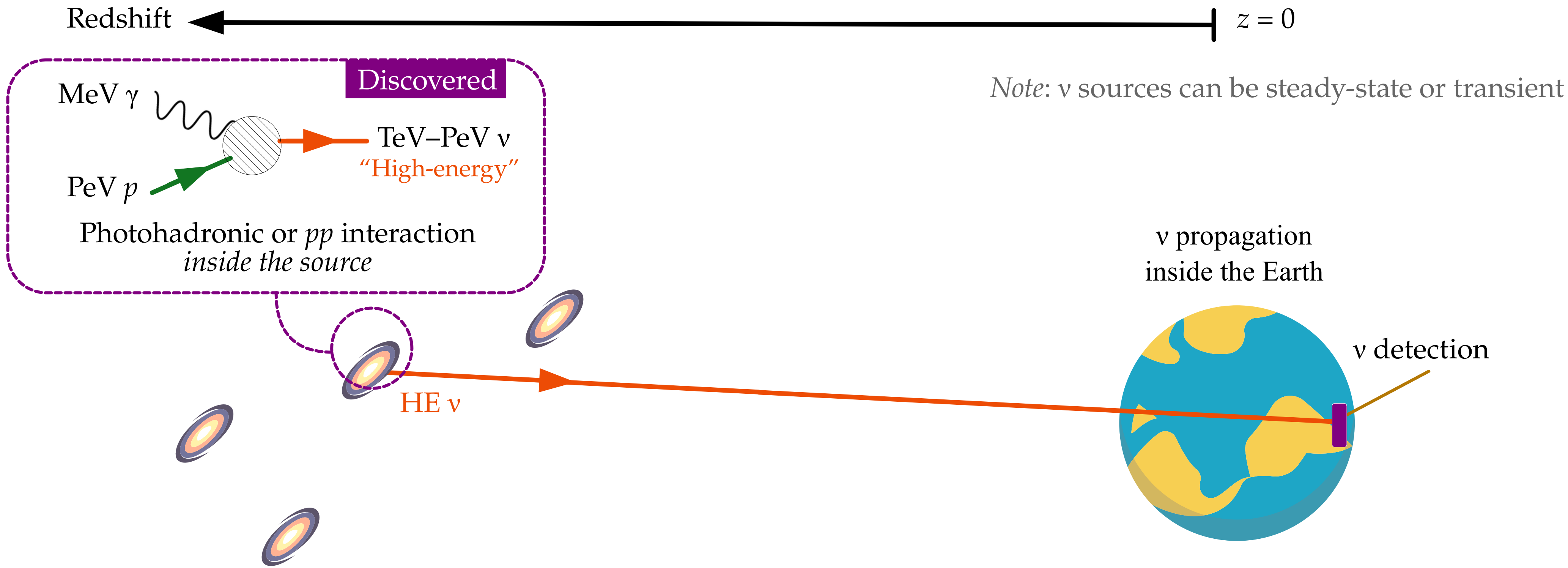


Neutrino energy = Proton energy / 20

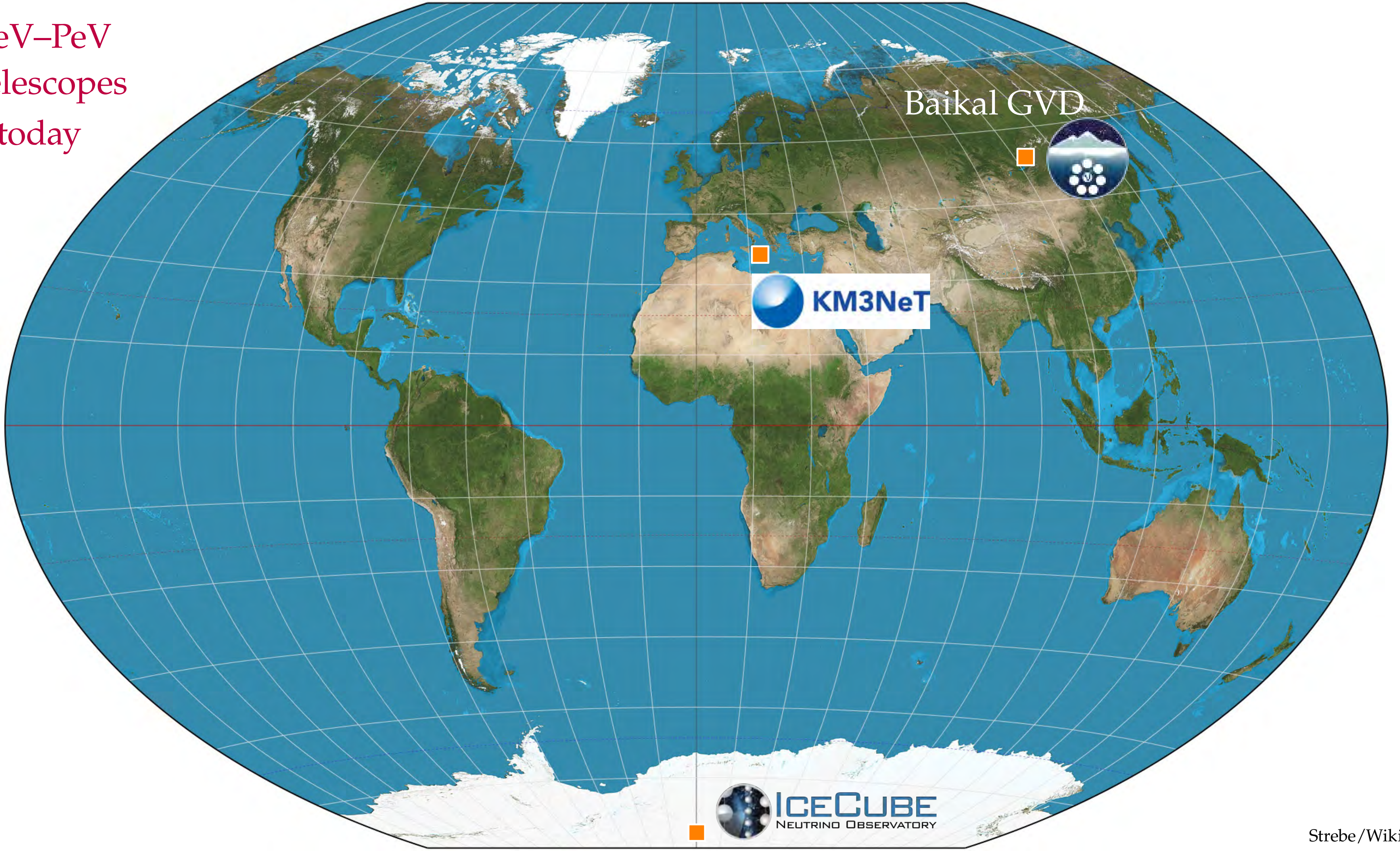
Gamma-ray energy = Proton energy / 10



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

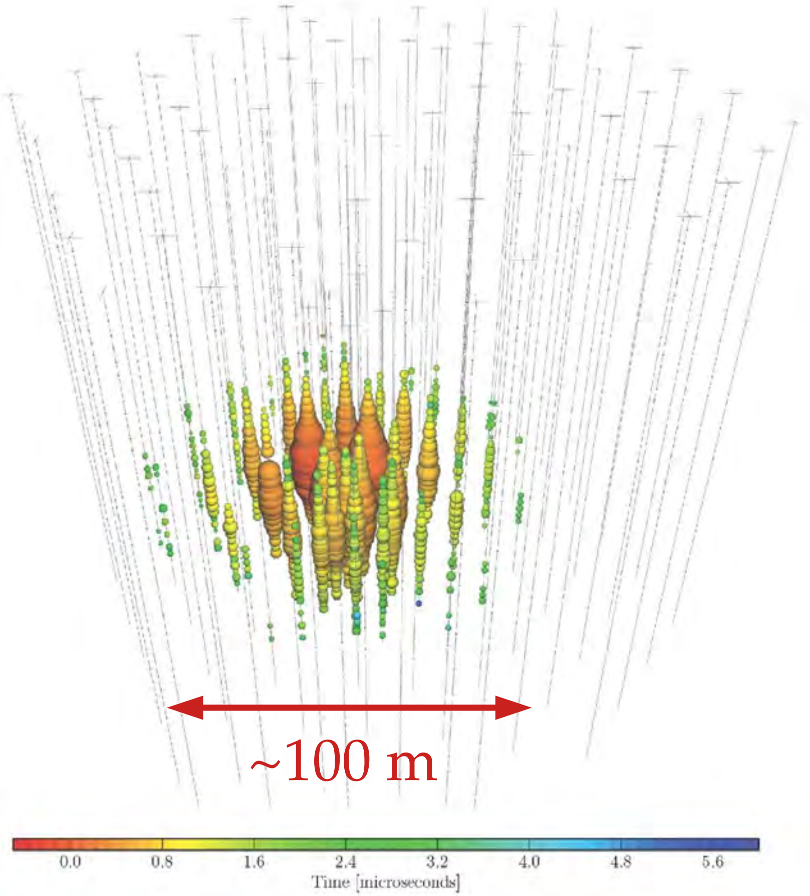

Redshift
$z = 0$
Discovered
MeV γ
TeV–PeV ν
"High-energy"
PeV p
Photohadronic or pp interaction
inside the source
Note: ν sources can be steady-state or transient
ν propagation
inside the Earth
ν detection
HE ν

TeV–PeV
ν telescopes
today



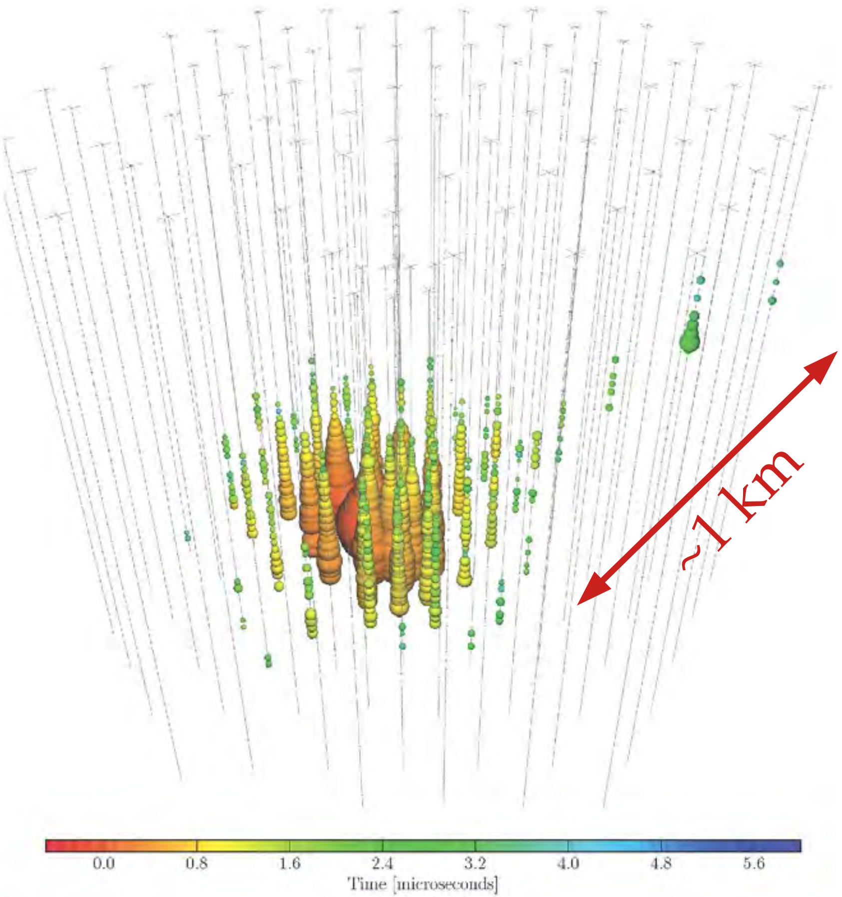
Strebe/Wikipedia

Shower
(mainly from ν_e and ν_τ)

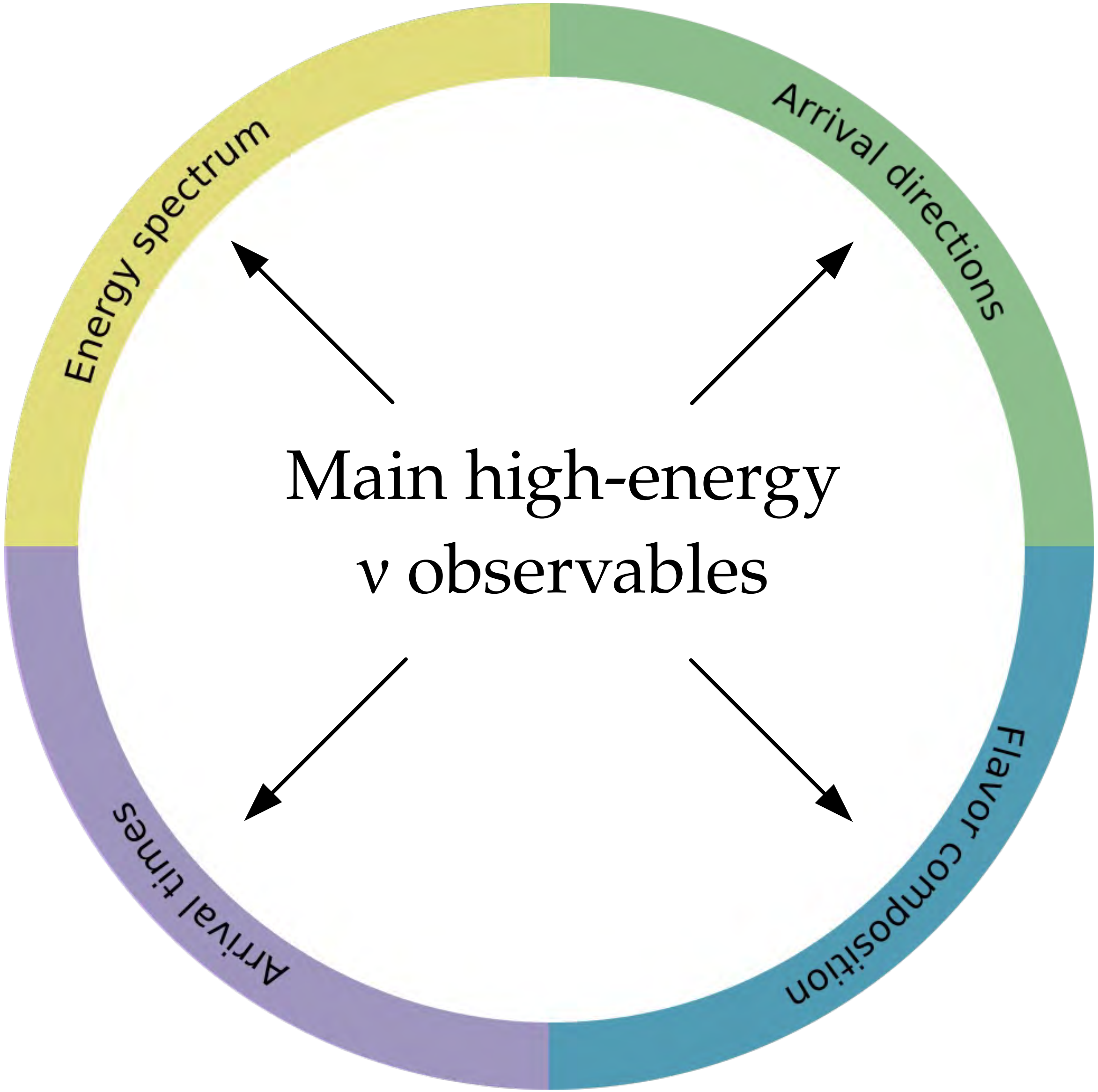


Poor angular resolution: ~10°

Track
(mainly from ν_μ)

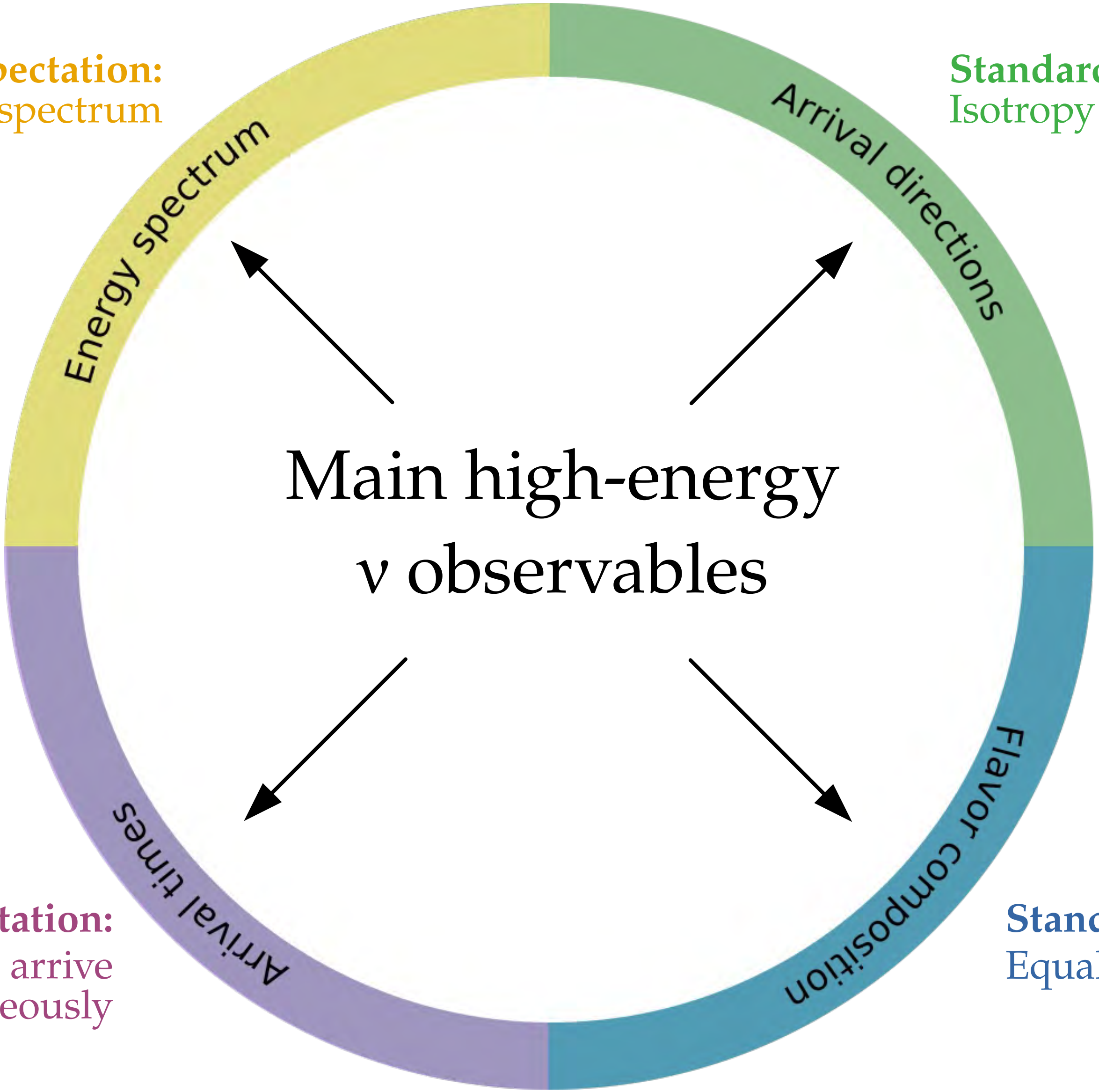


Angular resolution: < 1°


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

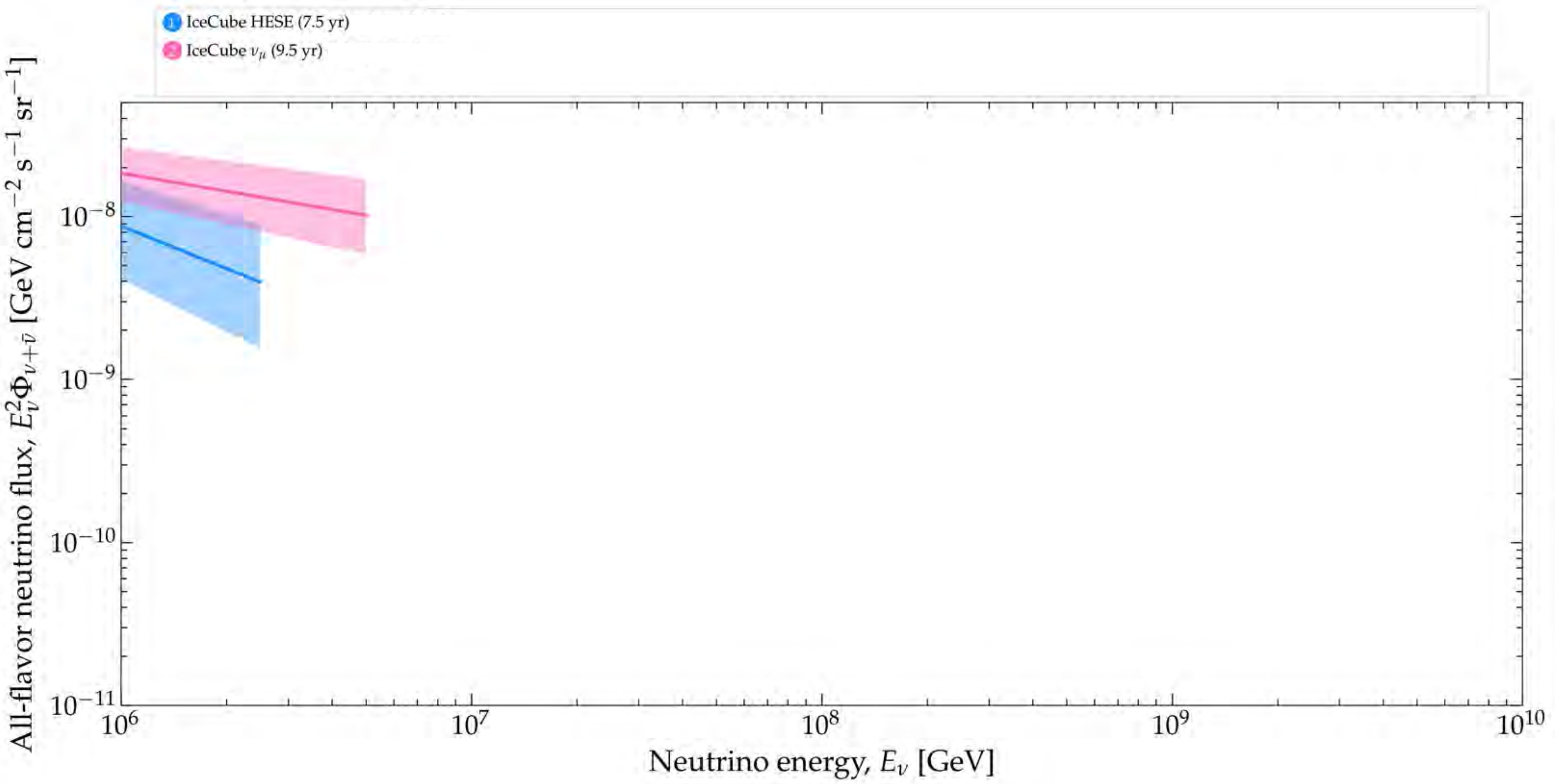
Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)

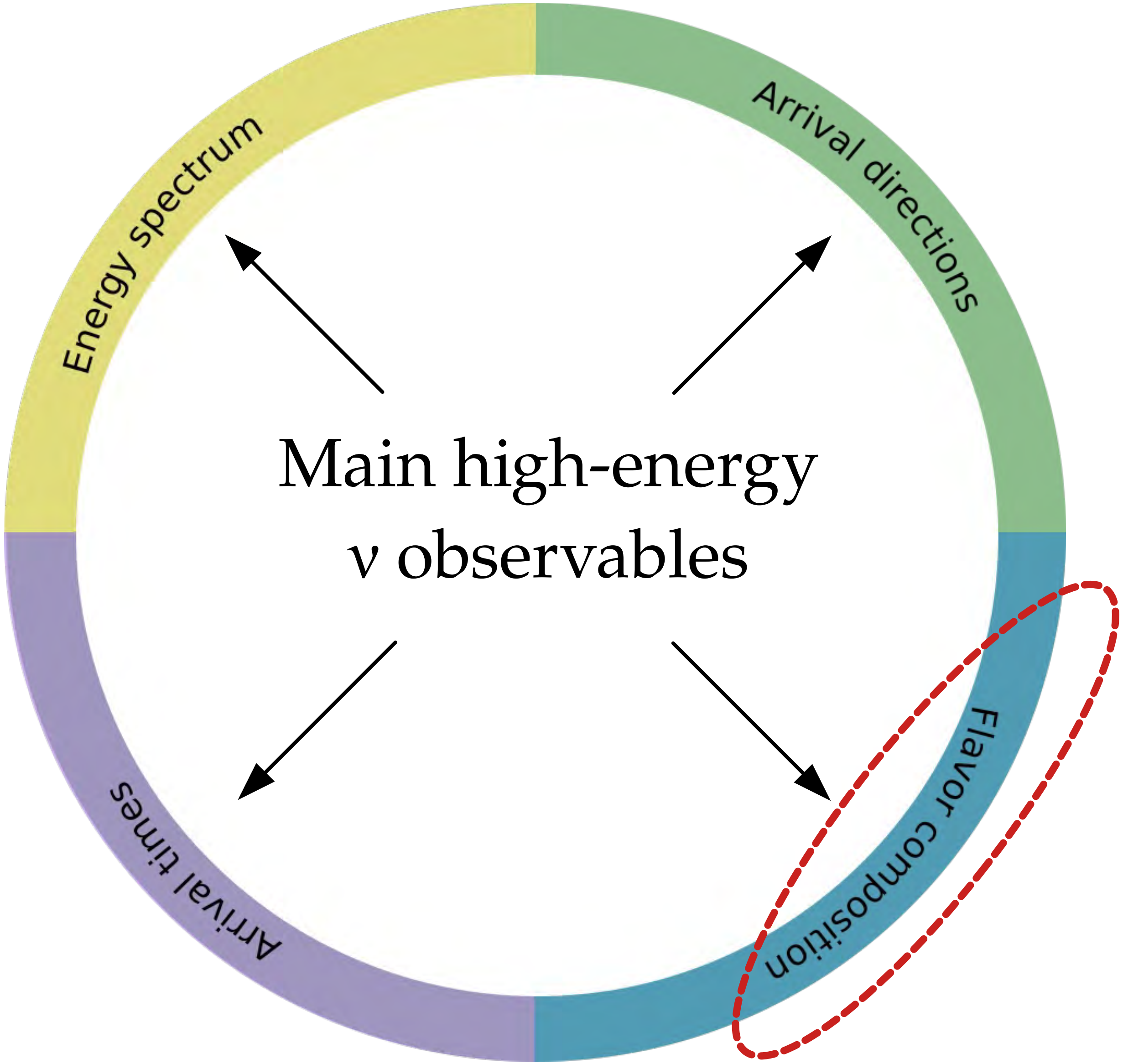


Standard expectation:
ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ



IceCube HESE (7.5 yr)
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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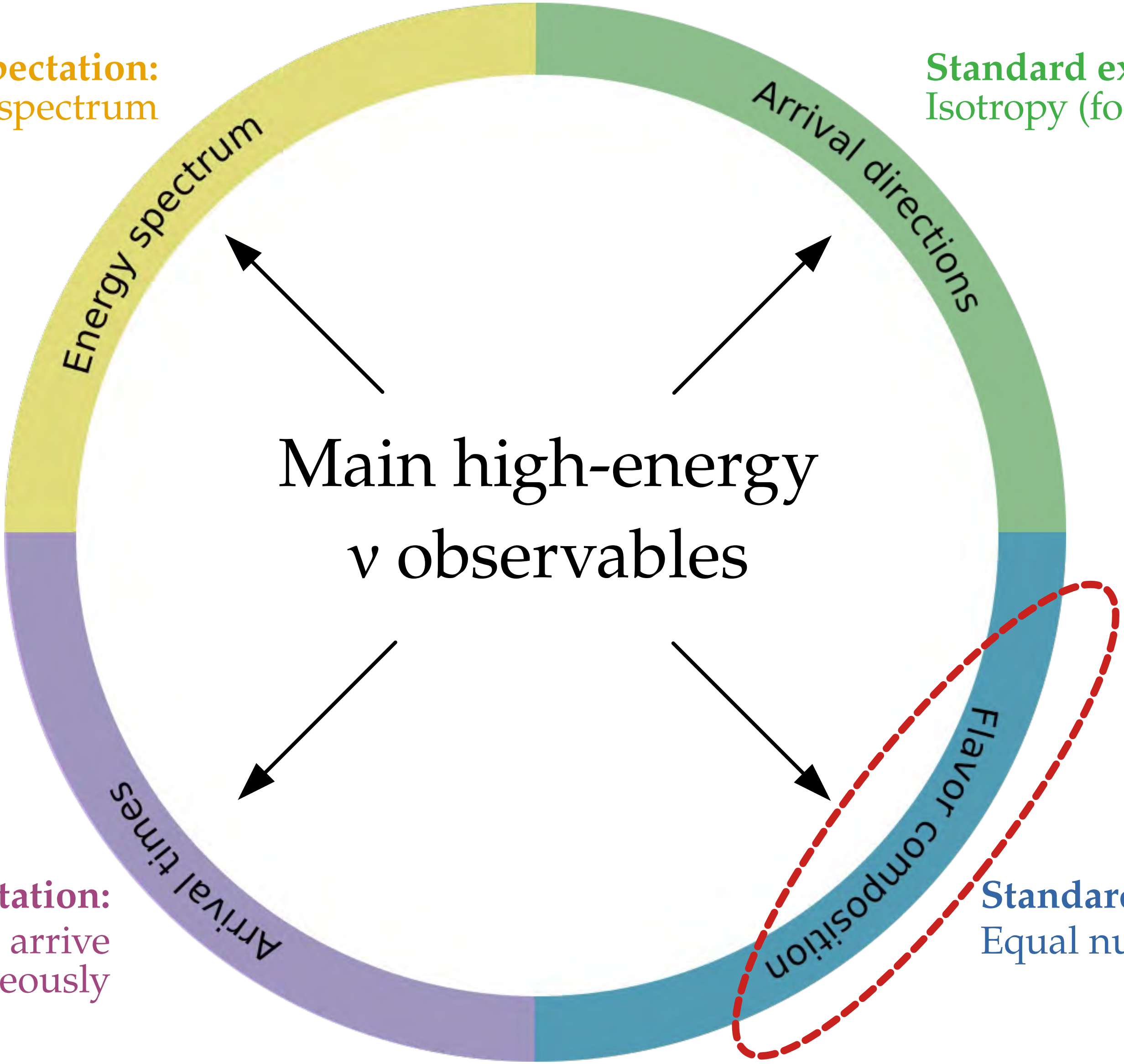

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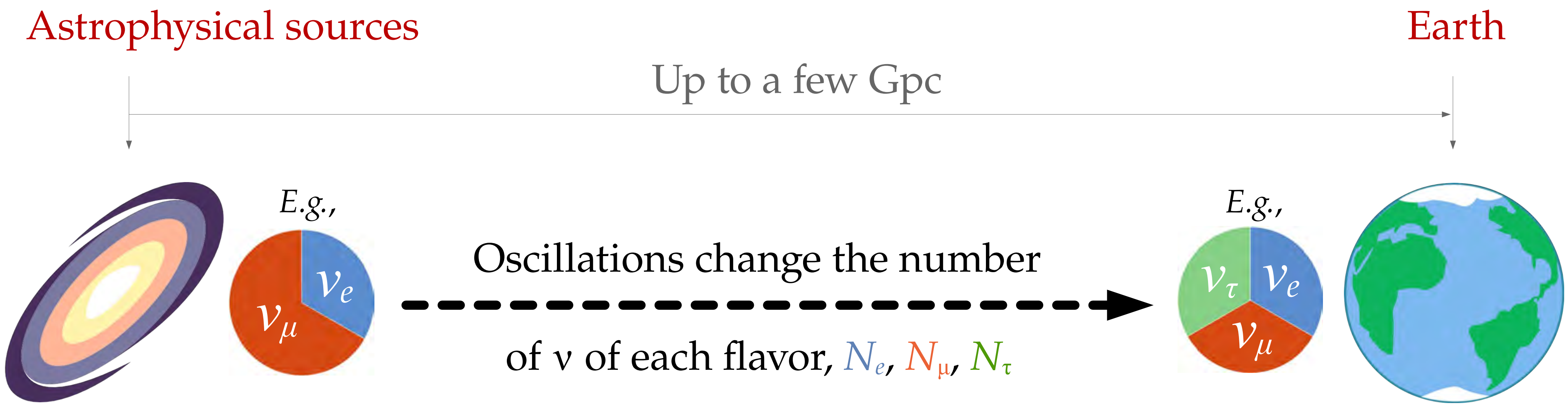
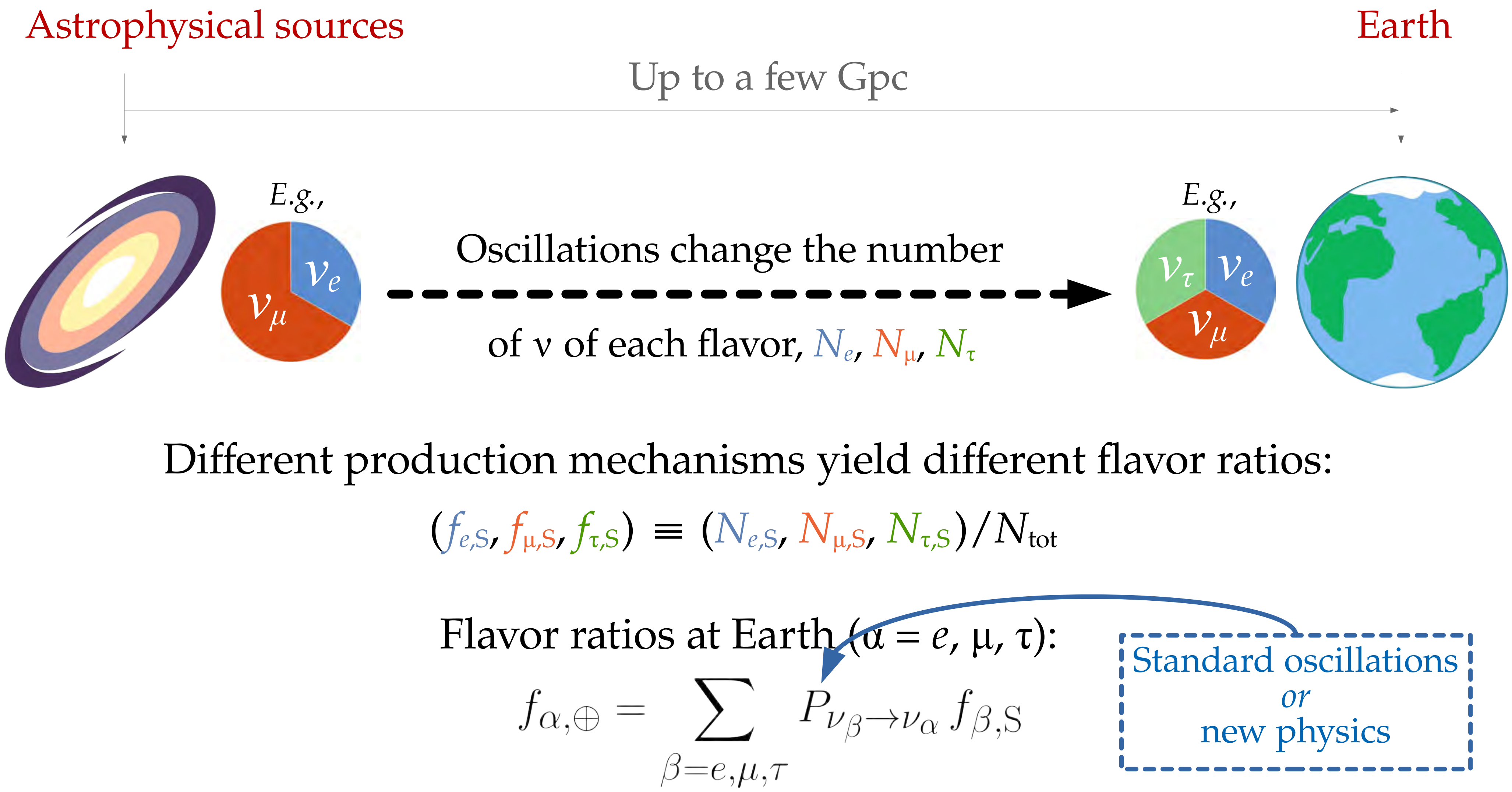


Different production mechanisms yield different flavor ratios:

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

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

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


Astrophysical sources
Earth
Up to a few Gpc
E.g.,
ν_e
ν_μ
Oscillations change the number
of ν of each flavor, N_e, N_μ, N_τ
E.g.,
ν_τ
ν_e
ν_μ
Different production mechanisms yield different flavor ratios:
$(f_{e,S}, f_{\mu,S}, f_{\tau,S}) \equiv (N_{e,S}, N_{\mu,S}, N_{\tau,S})/N_{tot}$
Flavor ratios at Earth ($\alpha = e, \mu, \tau$):
$f_{\alpha,\oplus} = \sum_{\beta=e,\mu,\tau} P_{\nu_\beta\to\nu_\alpha} f_{\beta,S}$
Standard oscillations
or
new physics

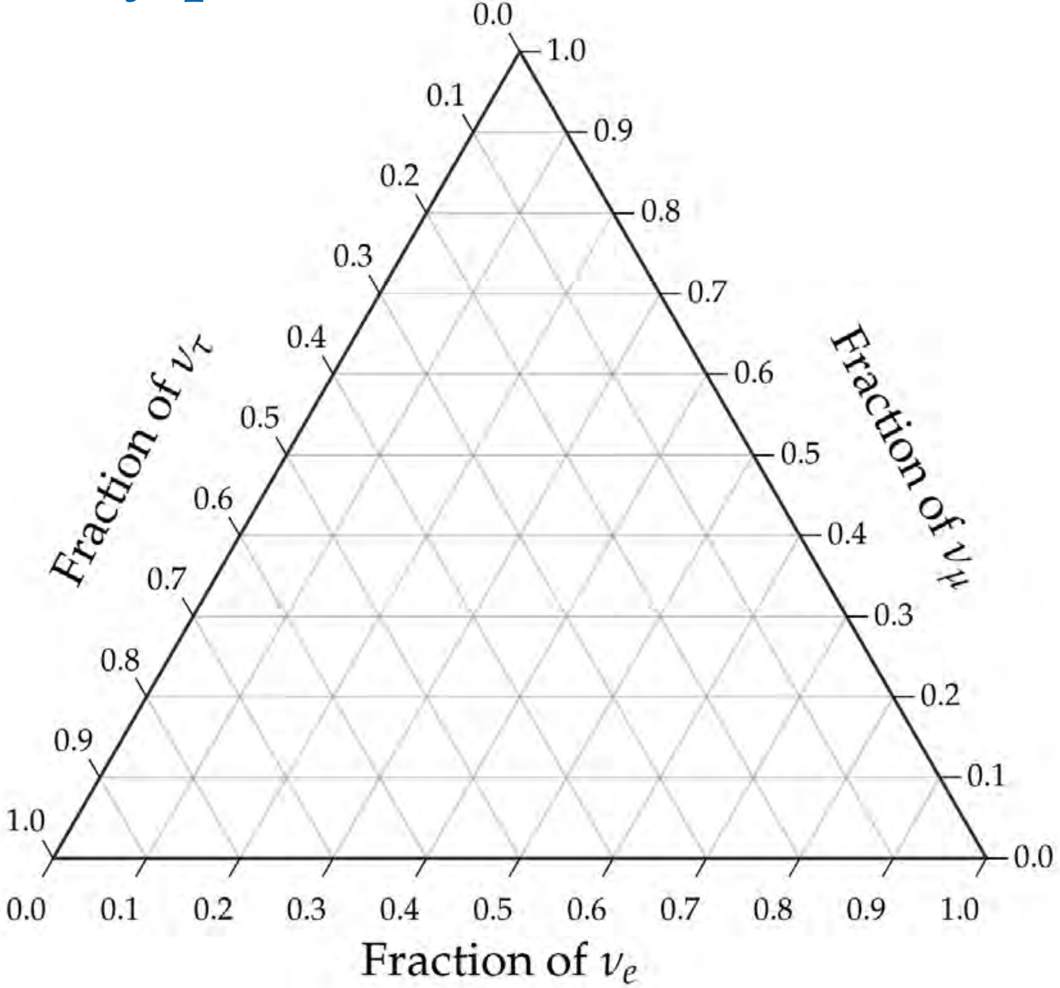
Quick aside: how to read a ternary plot

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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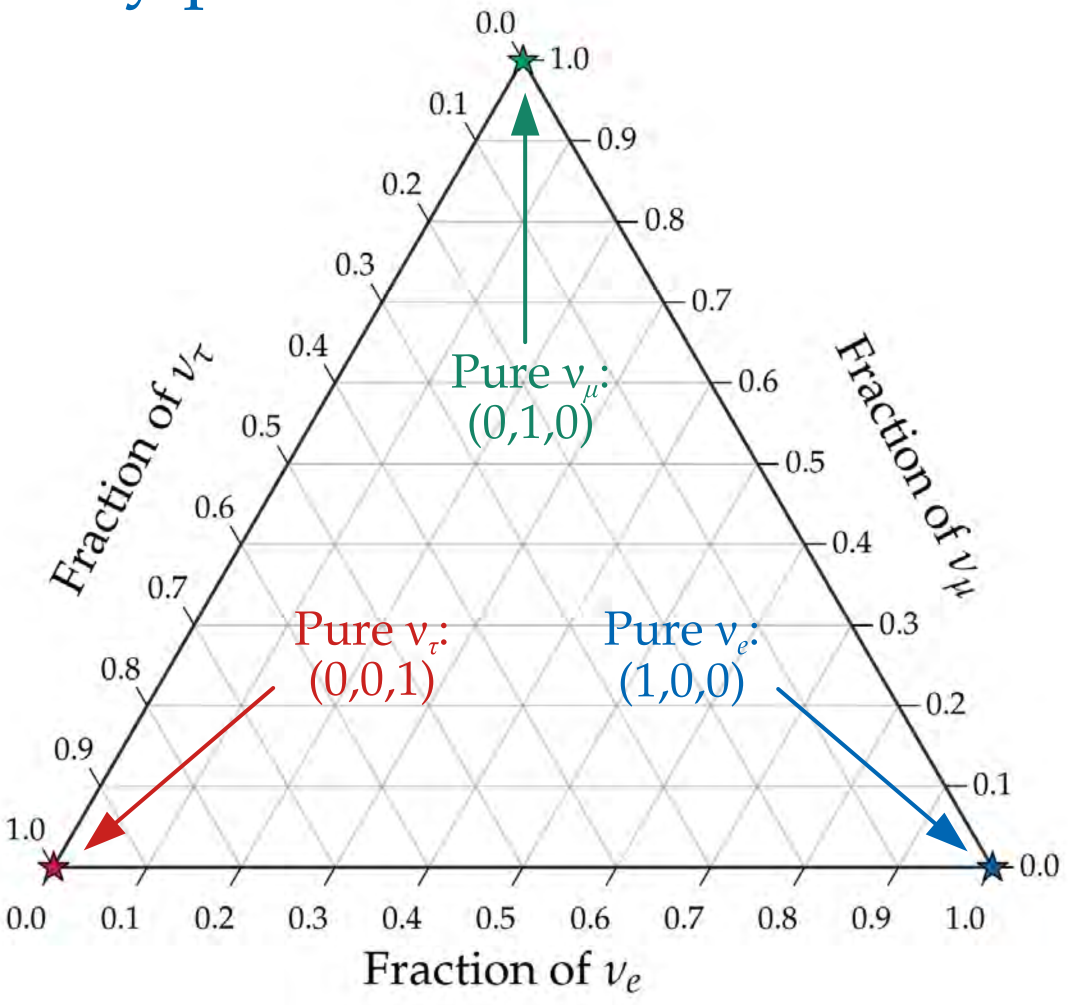

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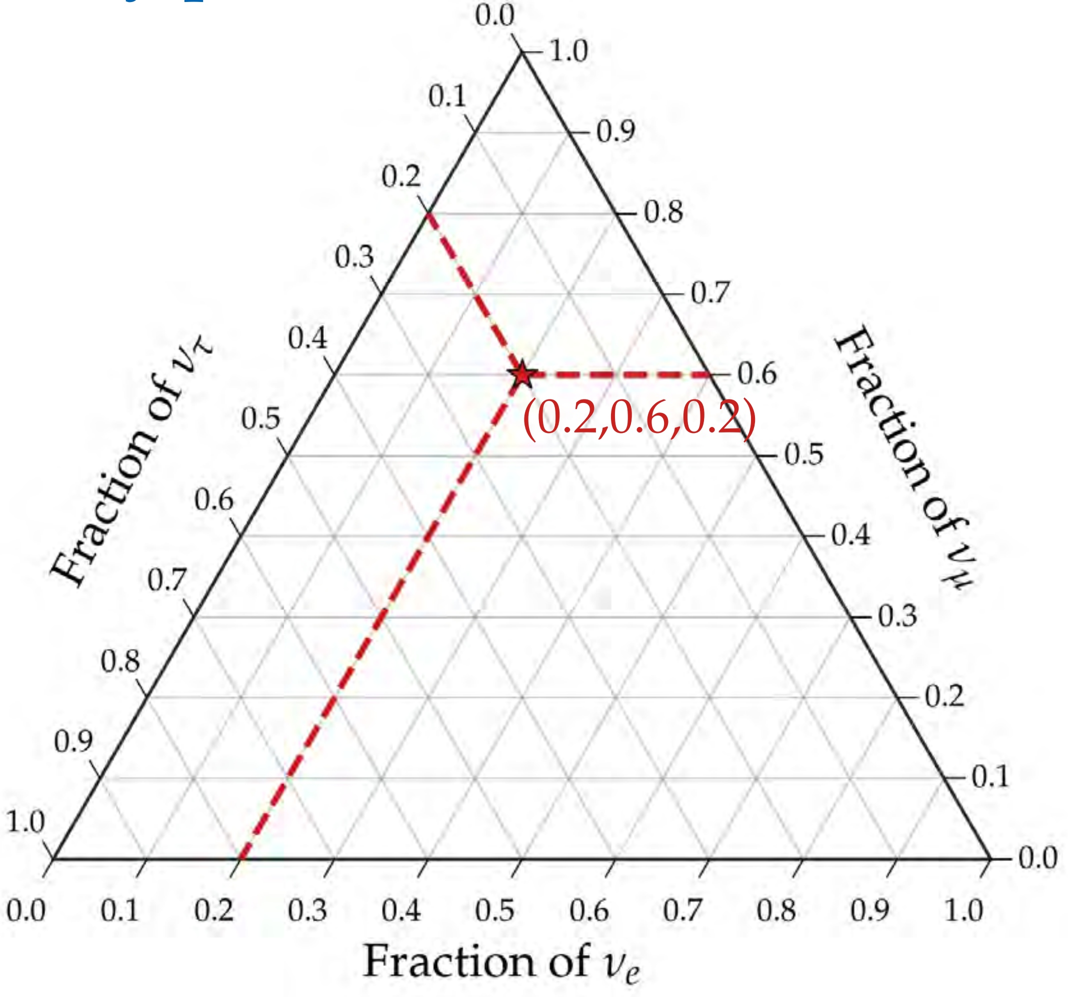

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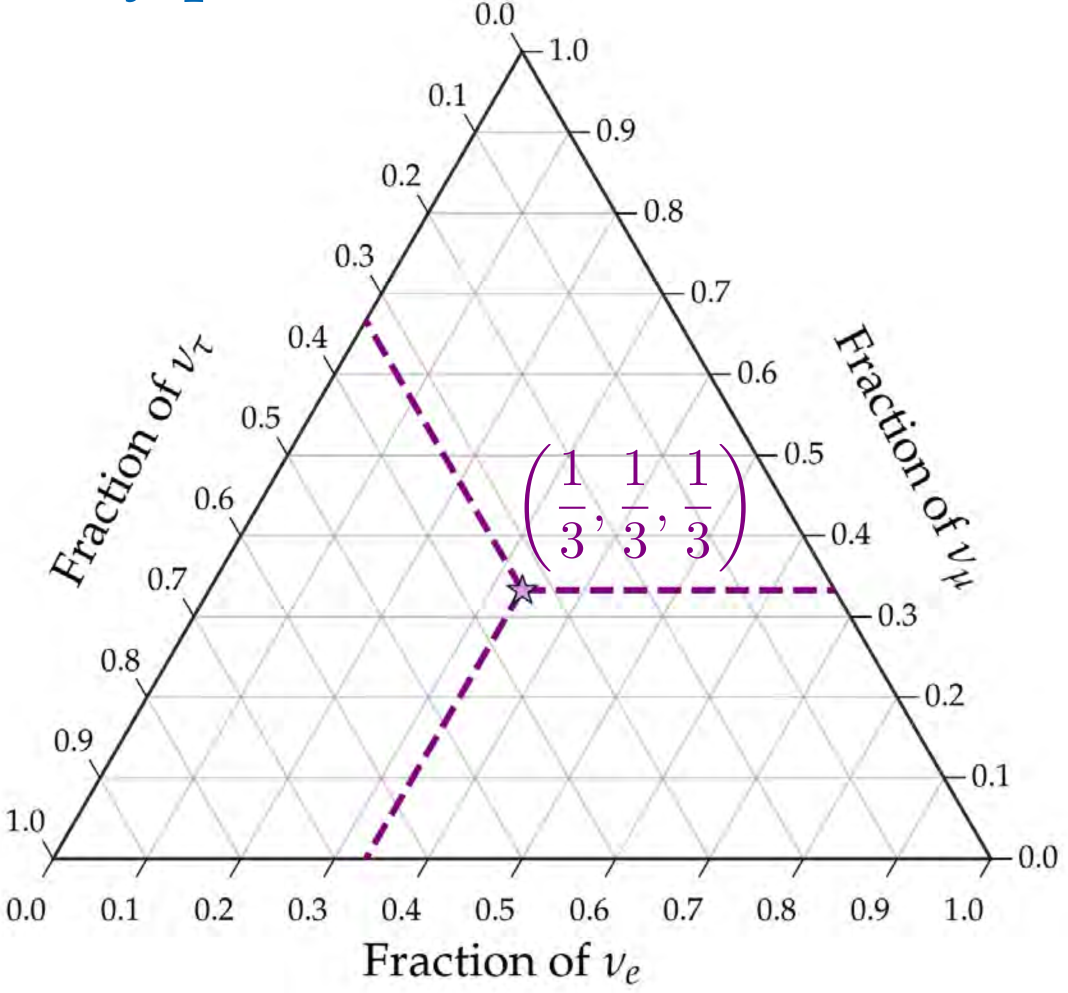

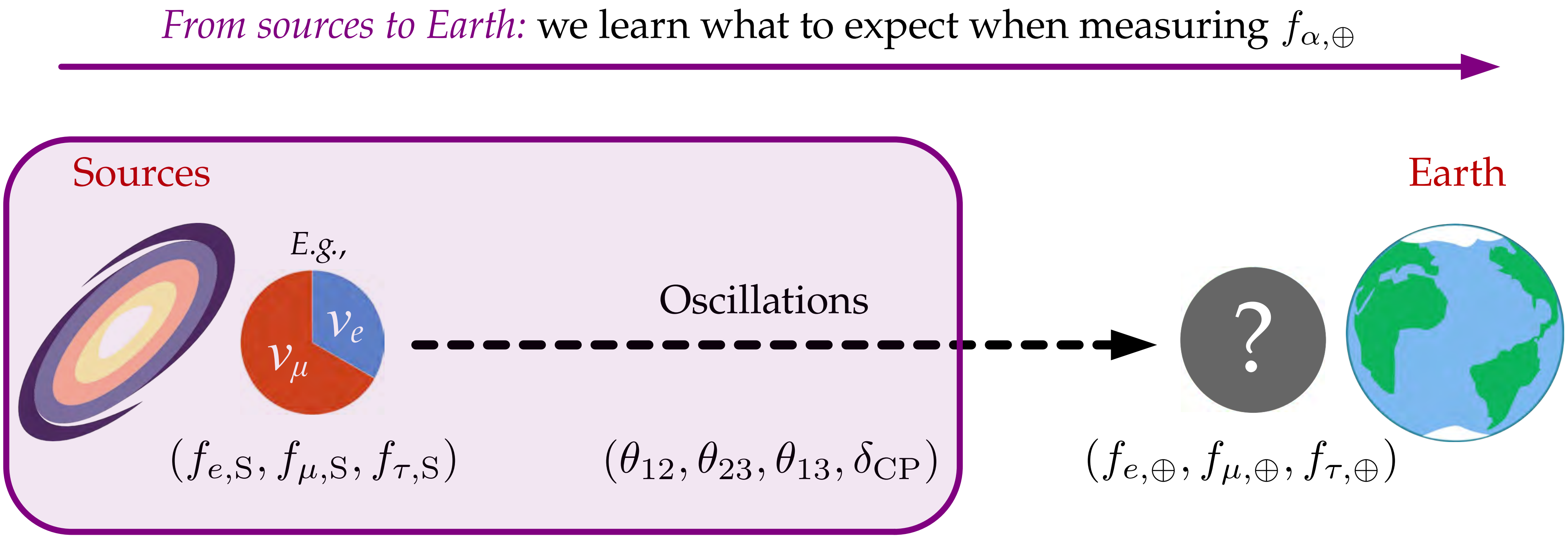
From sources to Earth: we learn what to expect when measuring $f_{\alpha,\oplus}$
Sources
E.g.,
ν_e
ν_μ
Oscillations
$(f_{e,\mathrm{S}}, f_{\mu,\mathrm{S}}, f_{\tau,\mathrm{S}})$
$(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\mathrm{CP}})$
?
Earth
$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$

One likely TeV–PeV ν production scenario:

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

Full π decay chain

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

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

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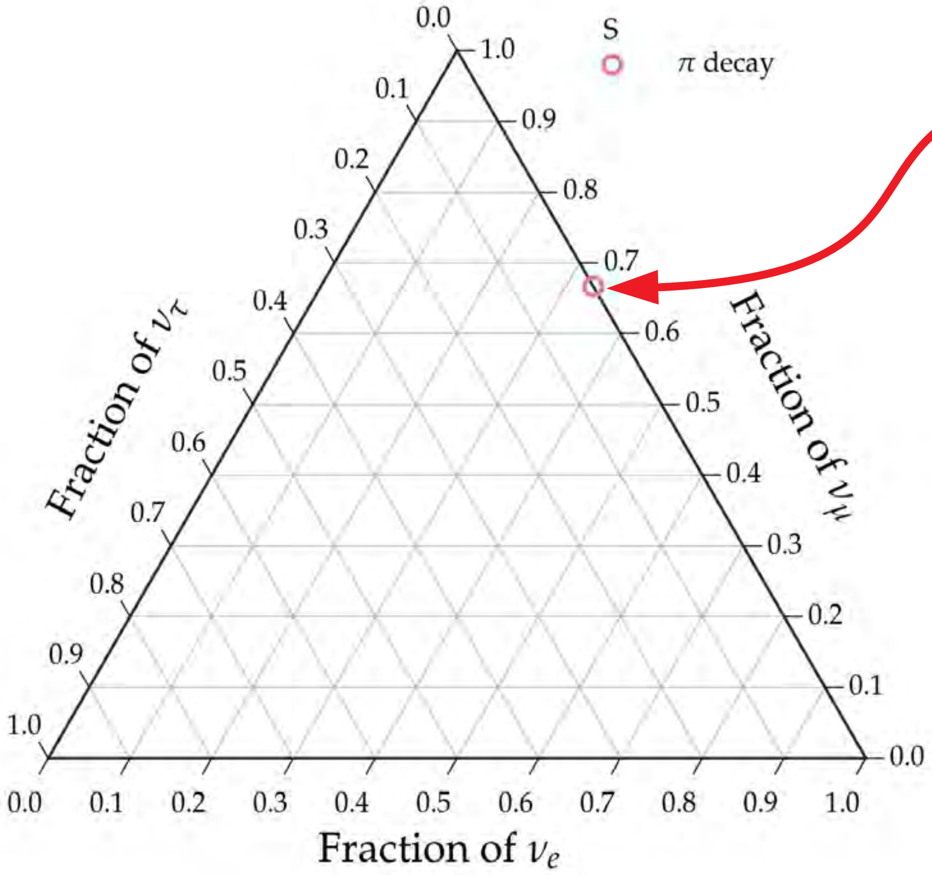

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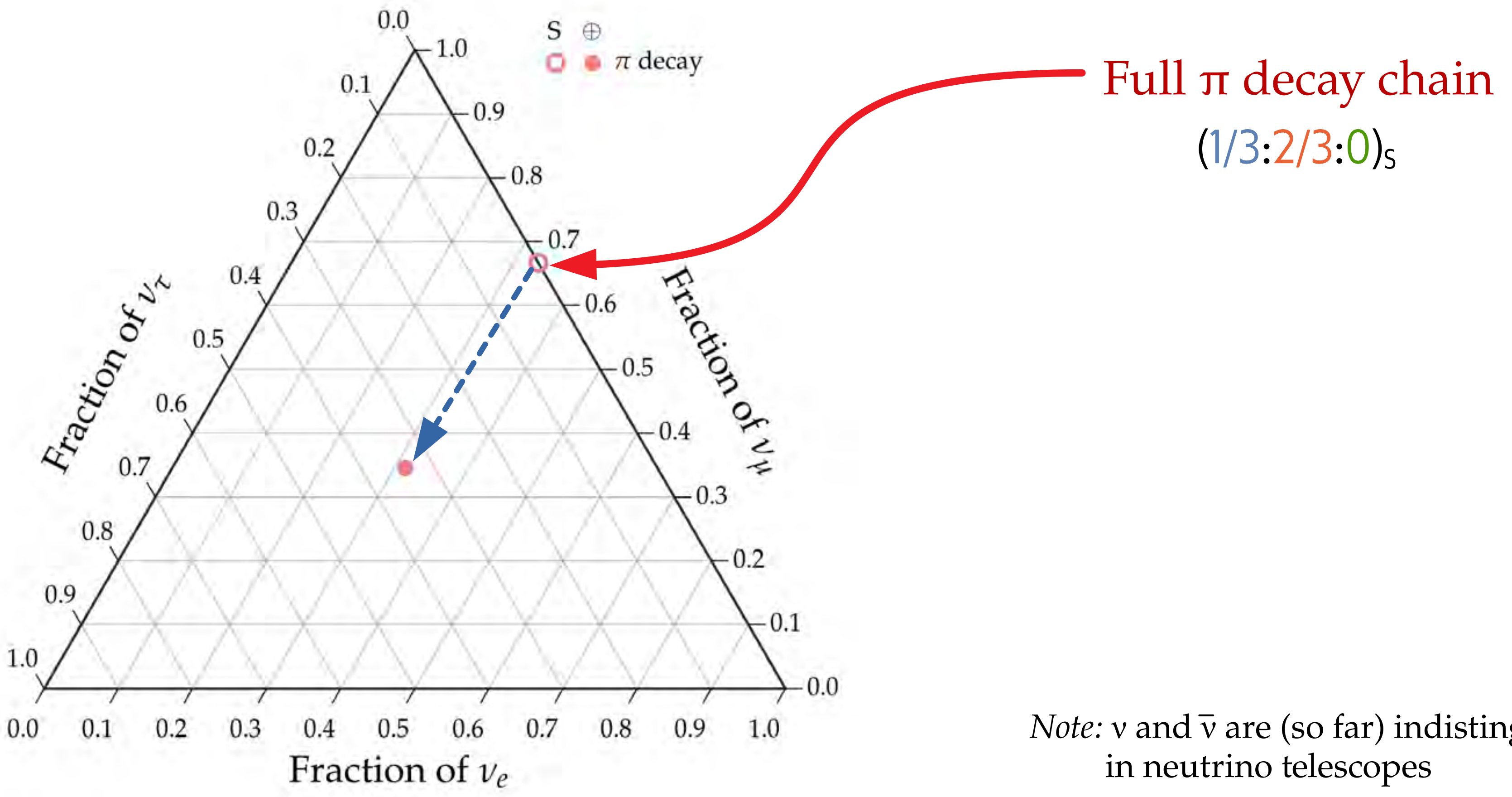

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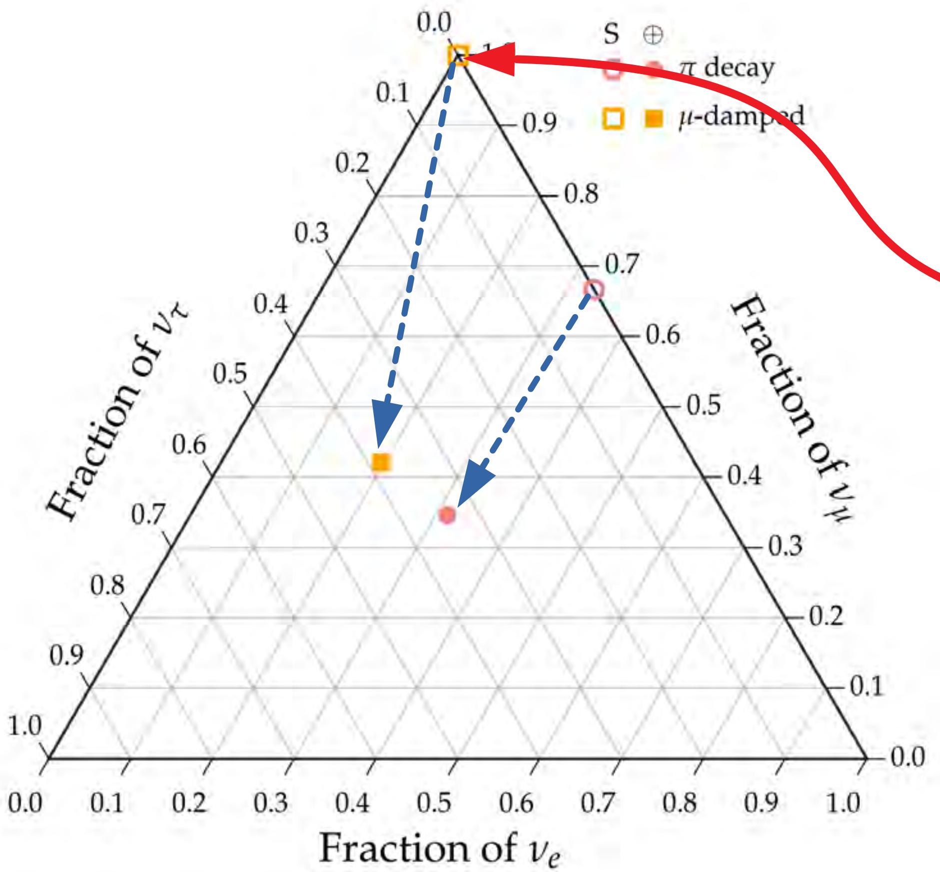

Full π decay chain

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

Muon damped

$(0:1:0)_S$

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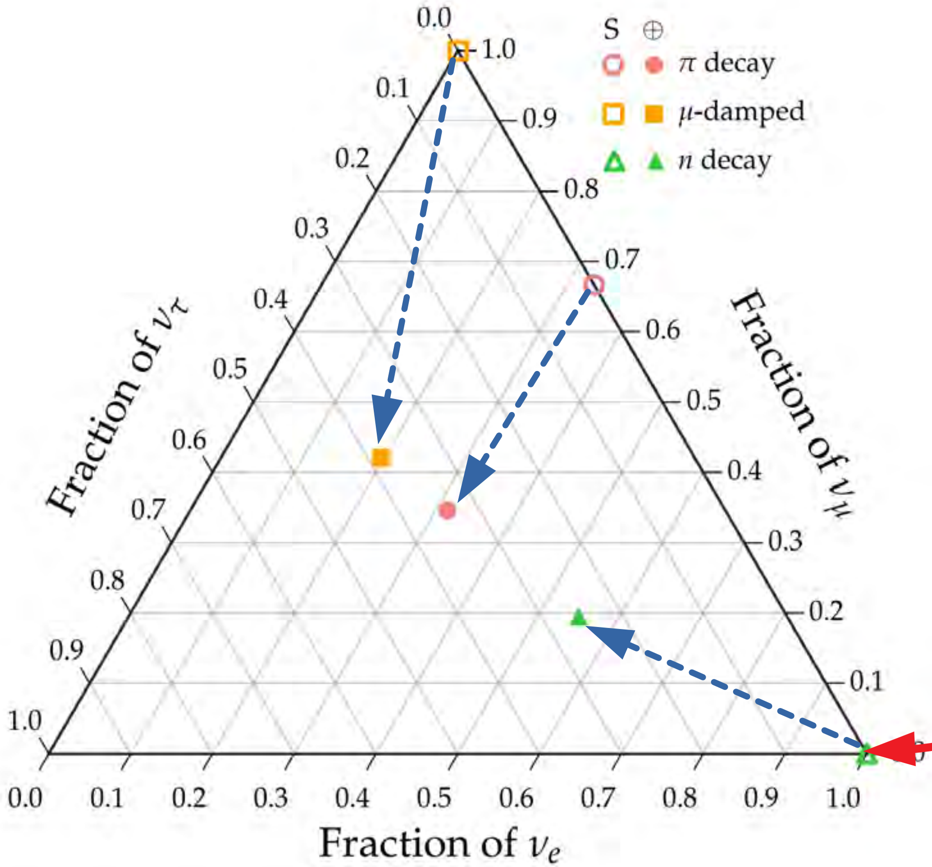

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Neutron decay

$(1:0:0)_S$

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Measuring flavor composition: 2015–2020

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

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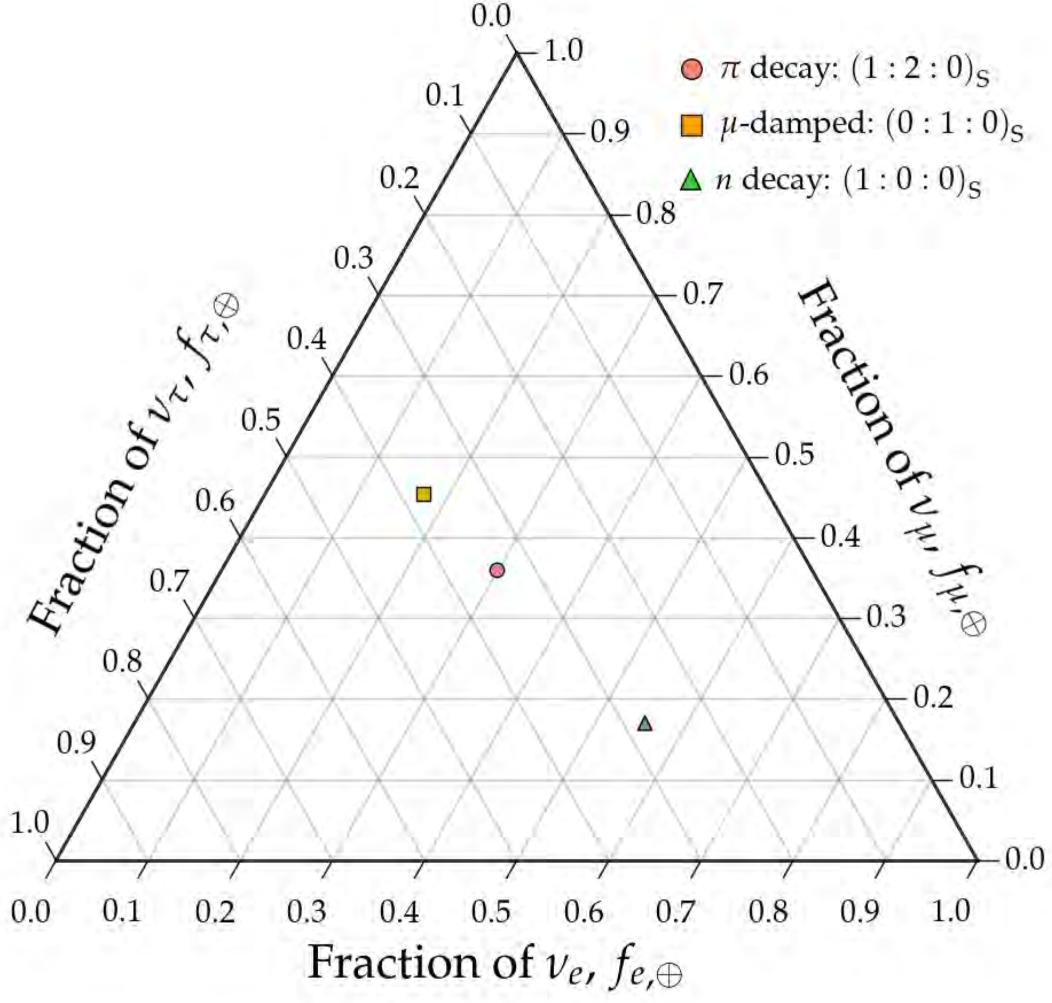

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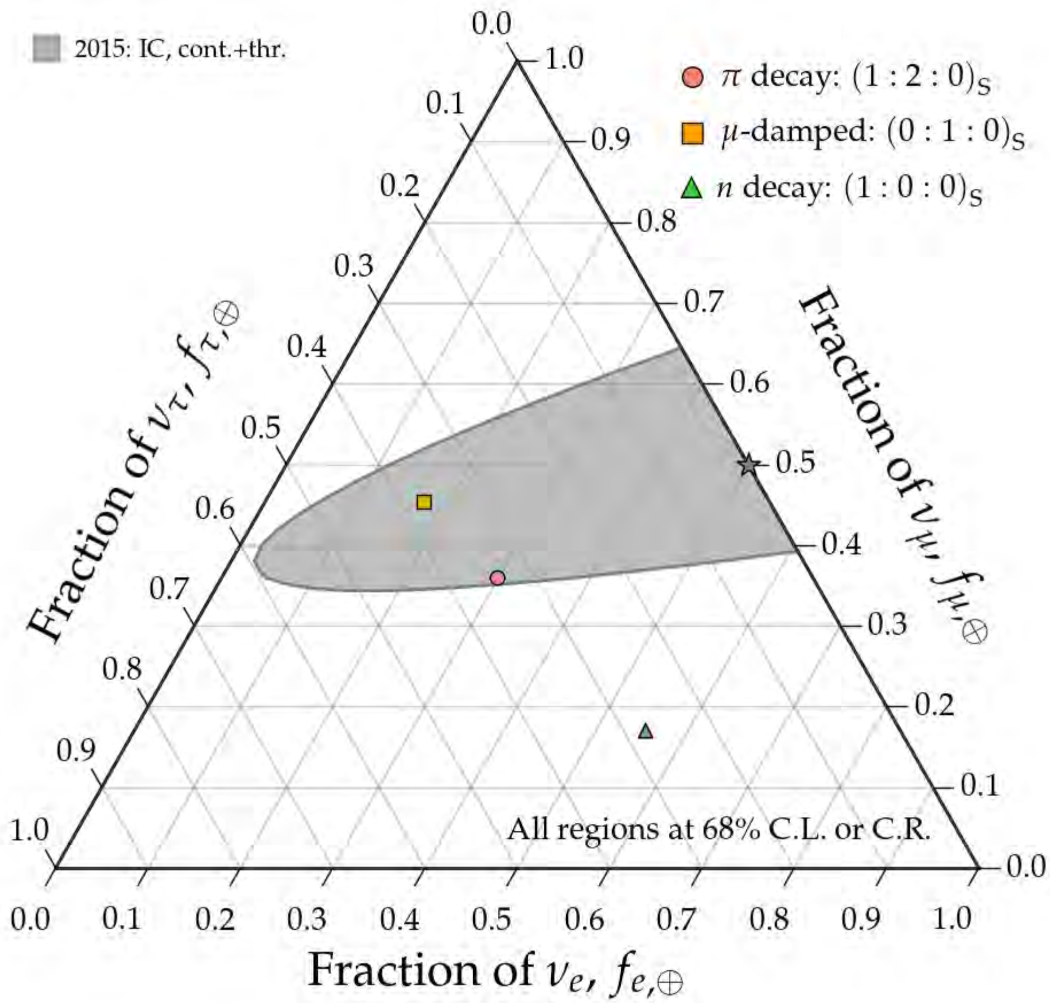

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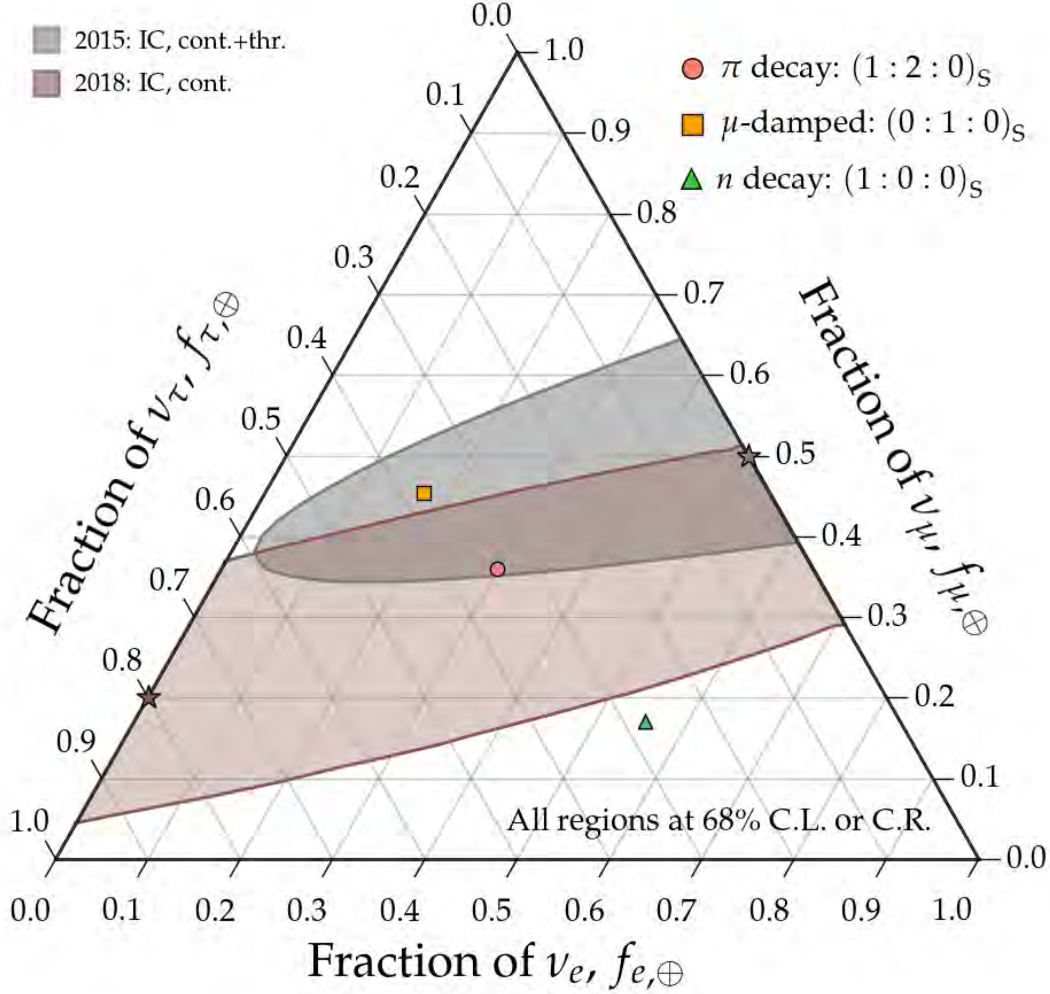

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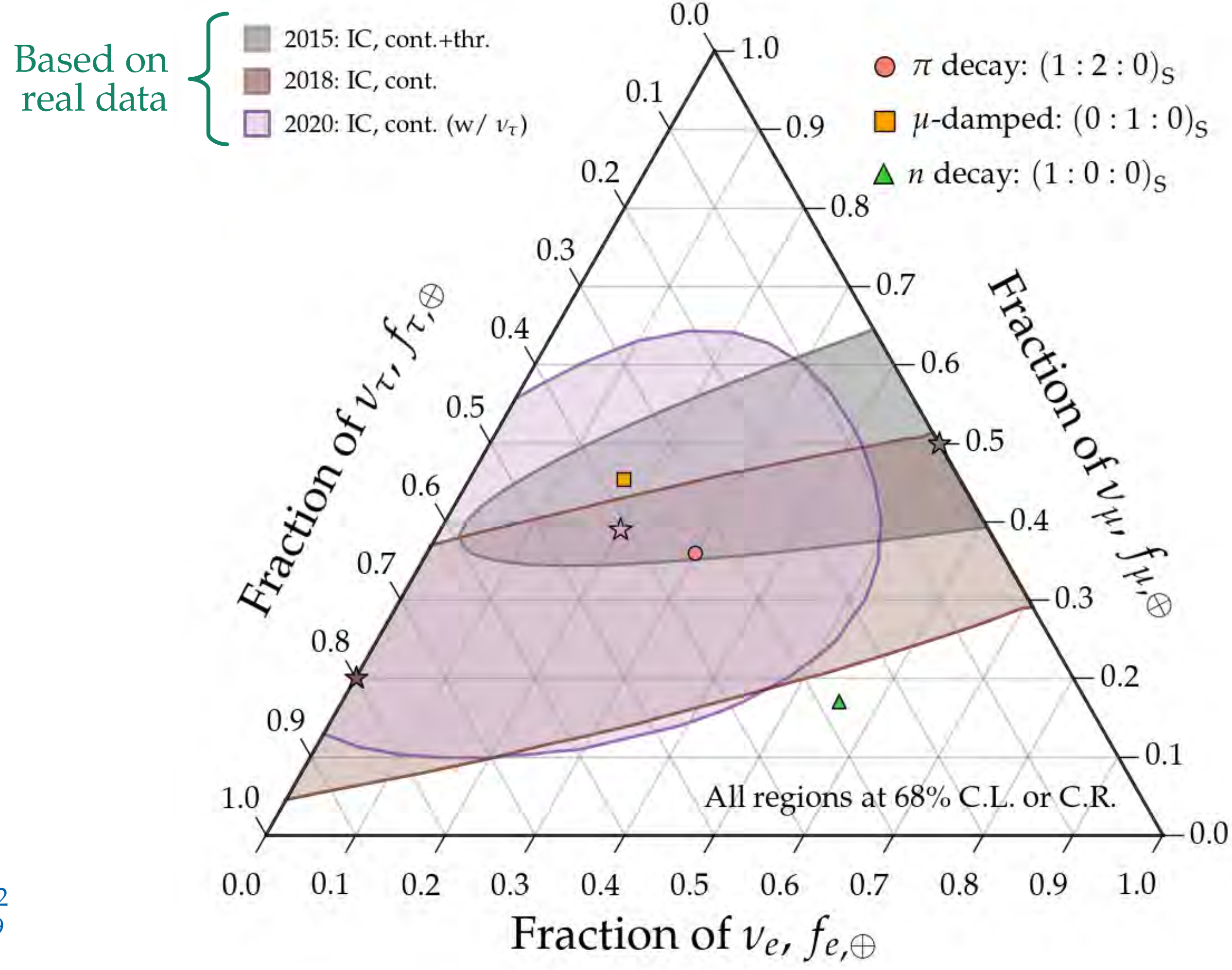

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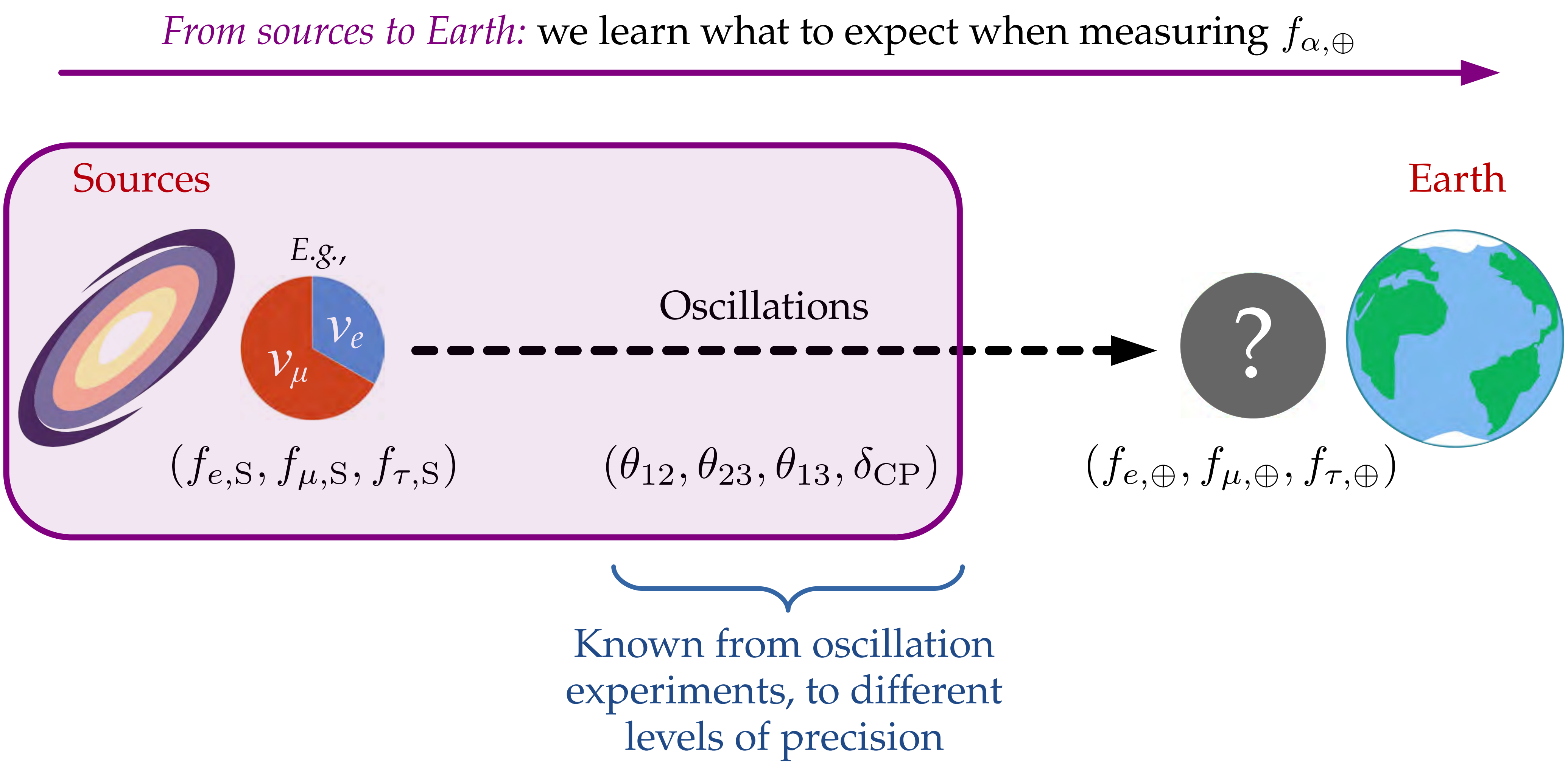
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Oscillations
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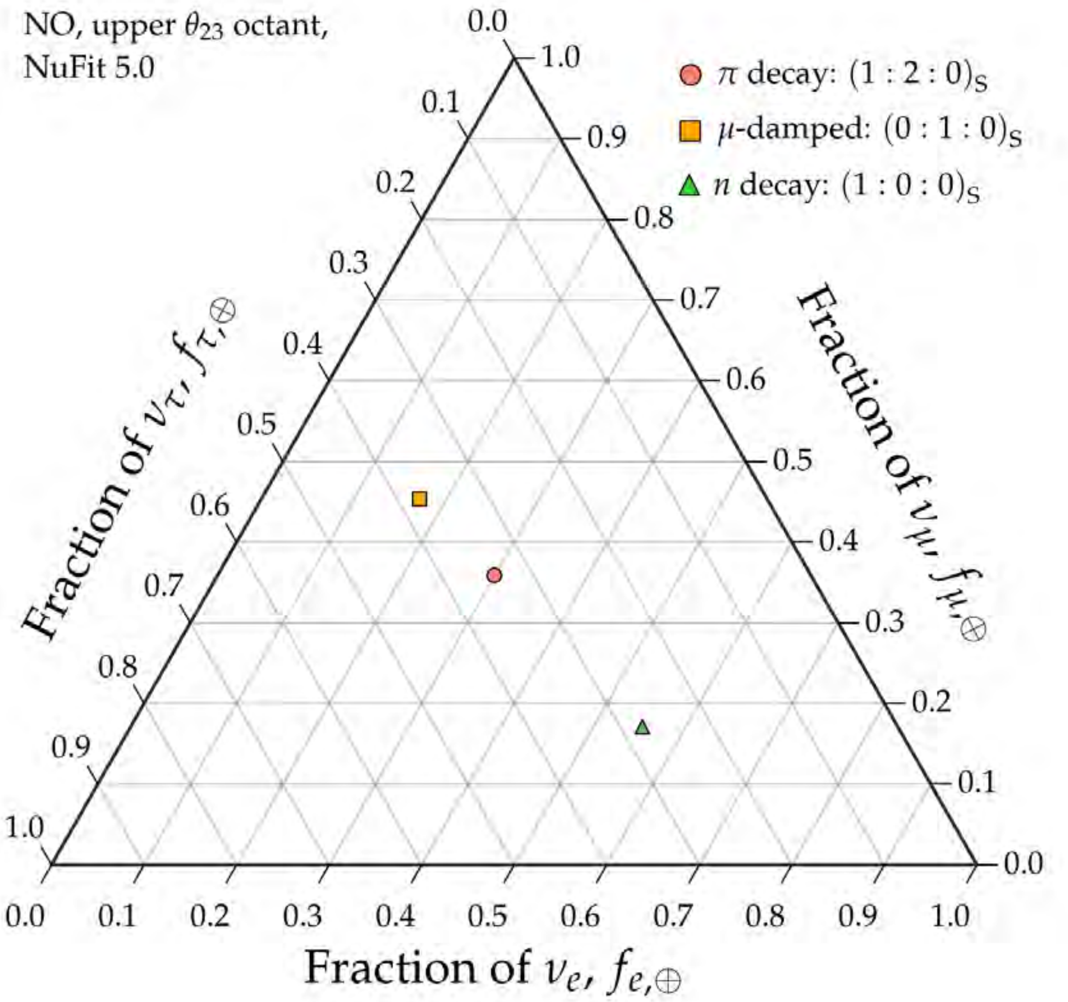
Earth
?
$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$
Known from oscillation experiments, to different levels of precision

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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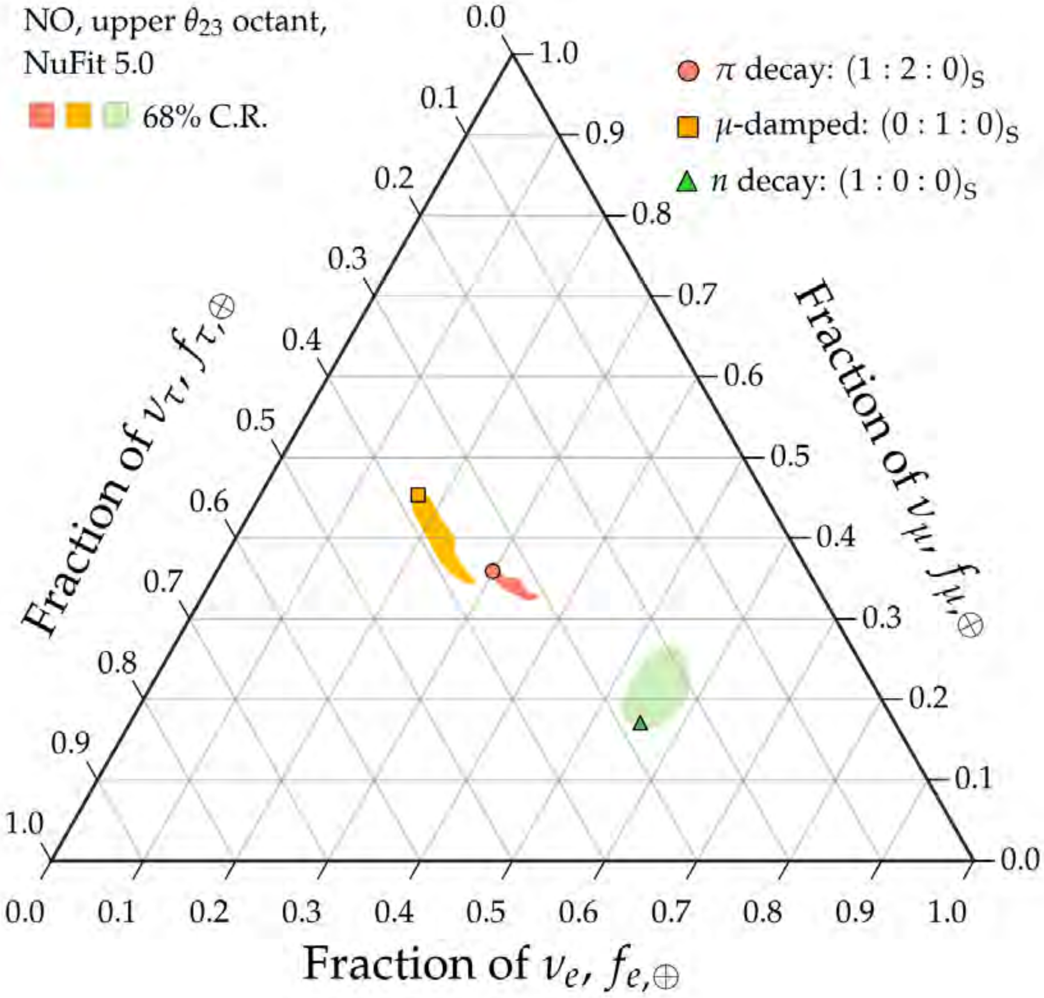

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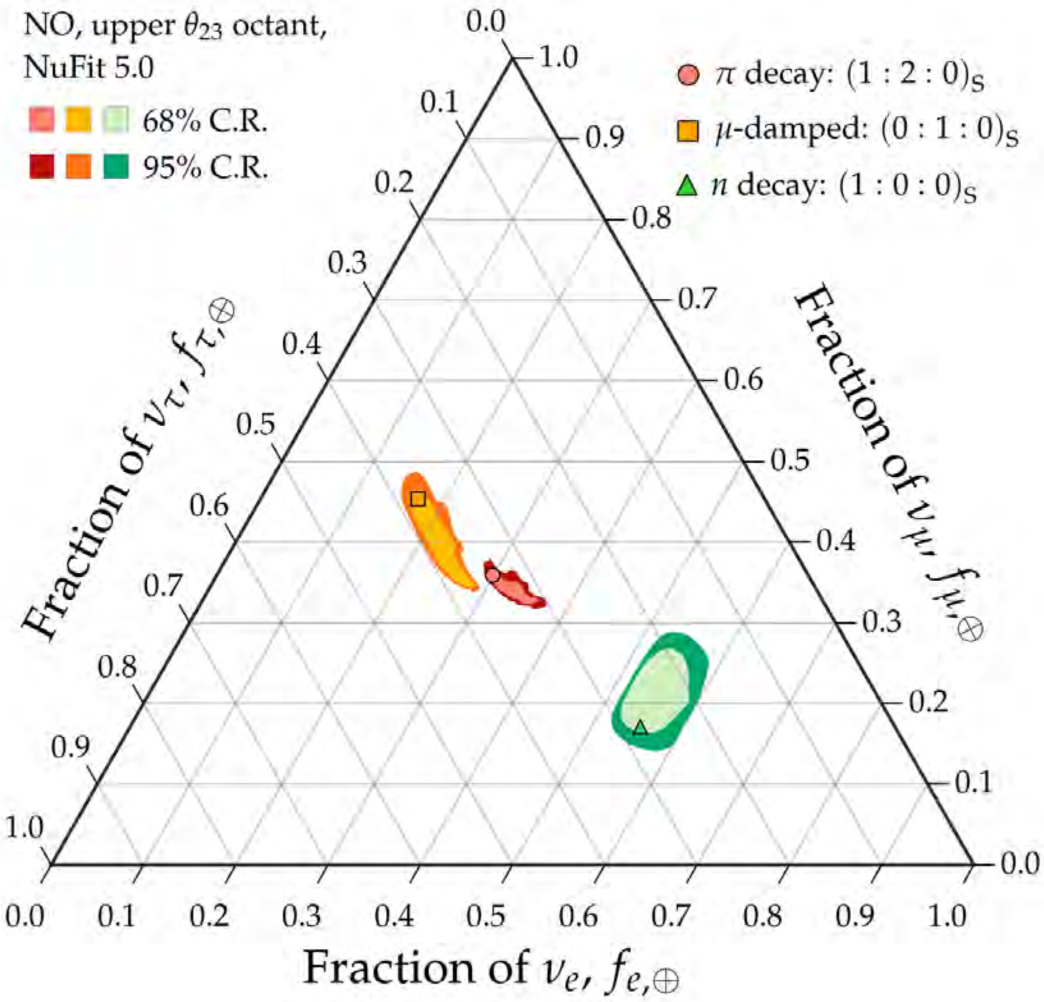

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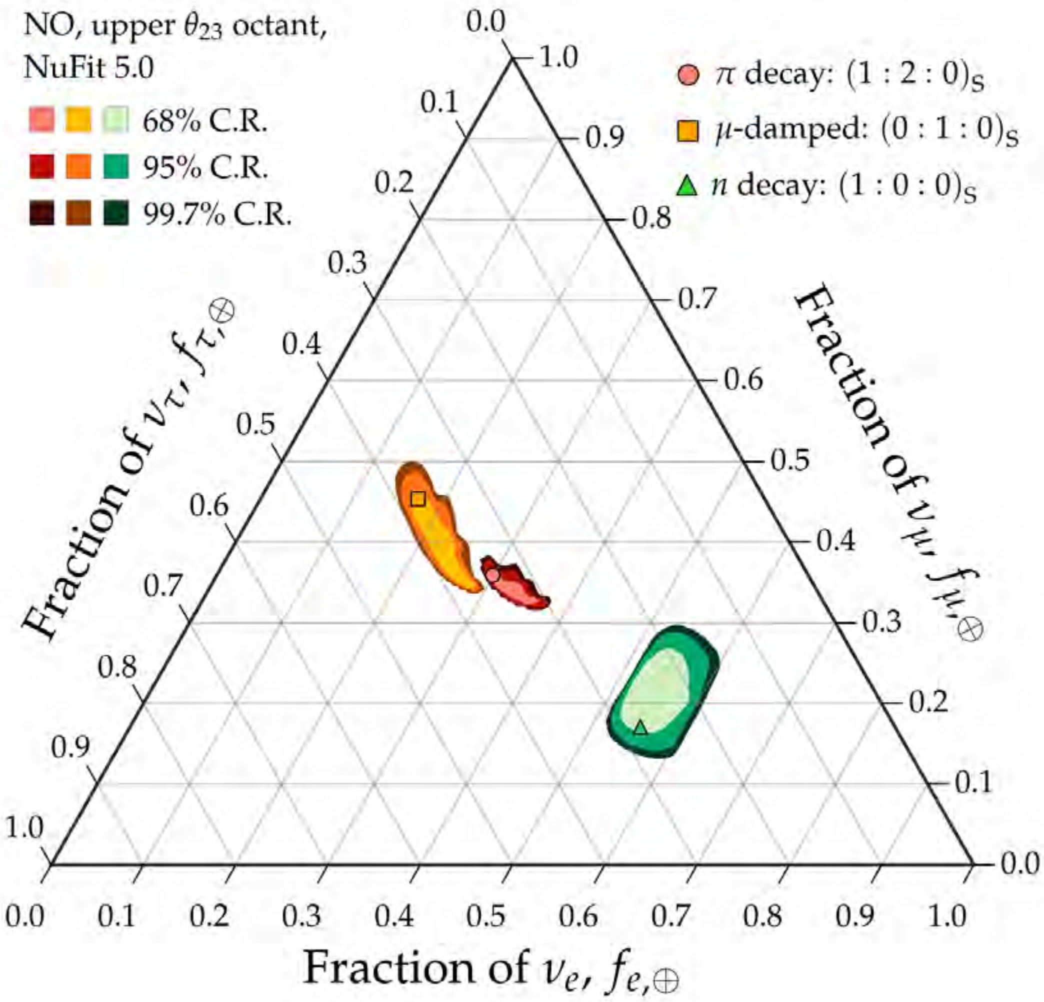

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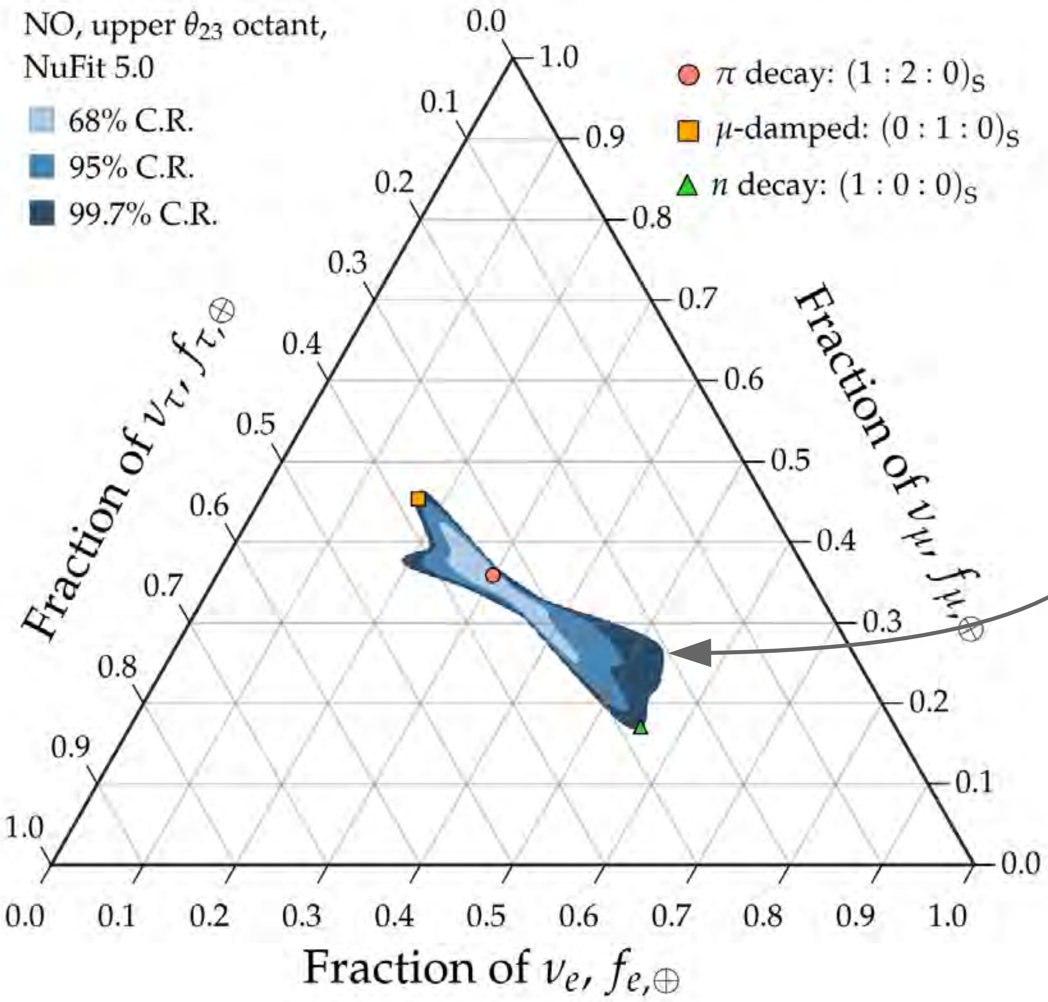

Varying over all possible flavor ratios at the source

Note:
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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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:

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

$$\pi^0 \longrightarrow \gamma + \gamma$$

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

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

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

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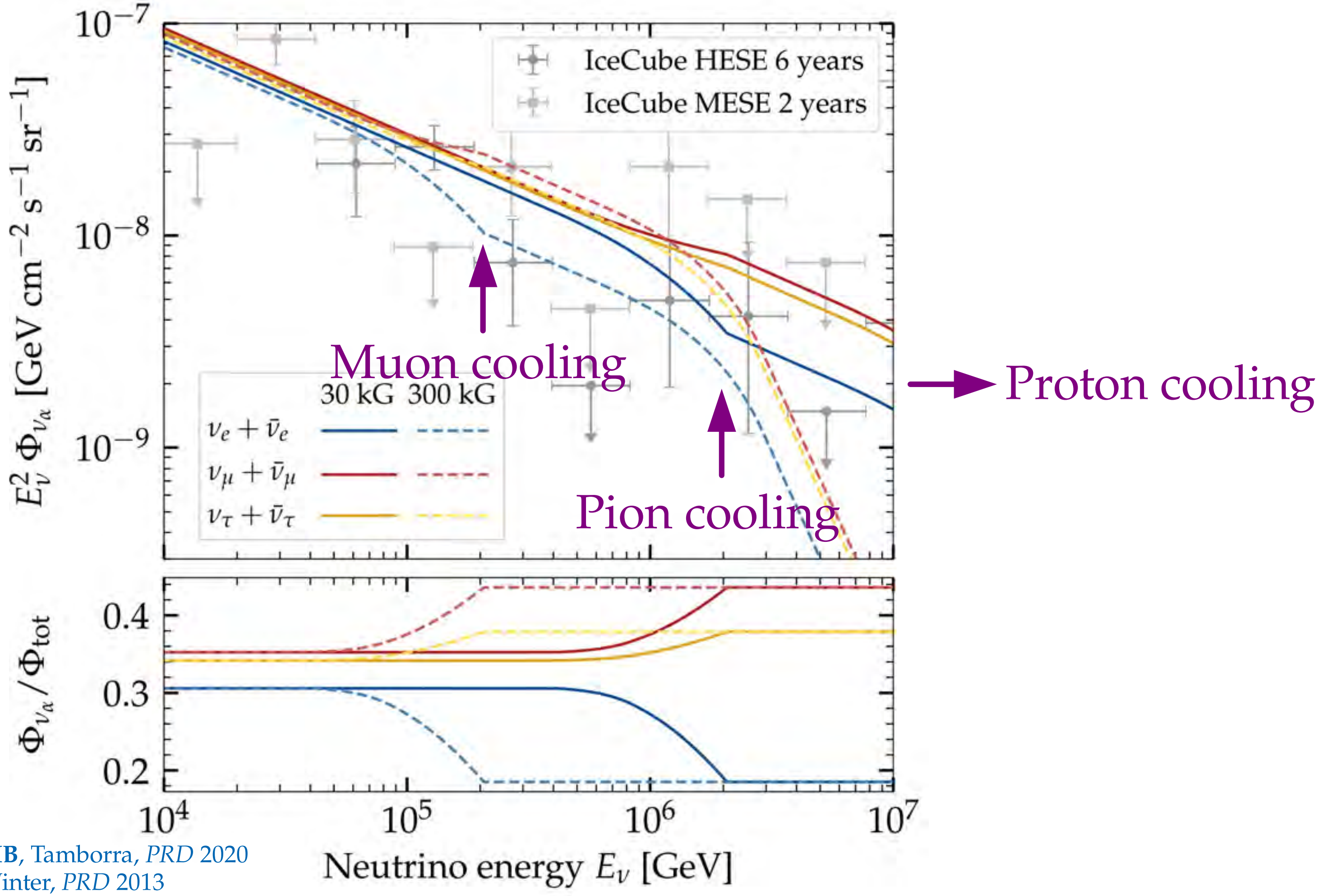

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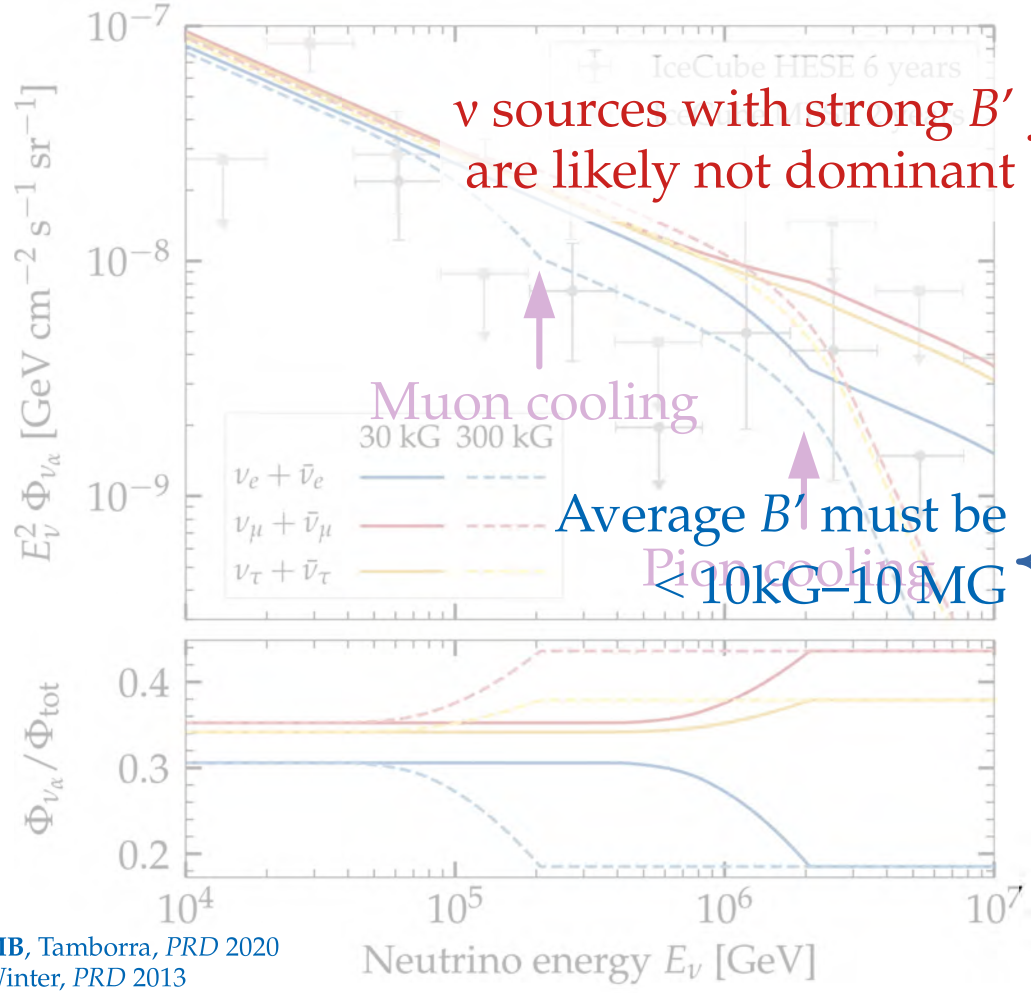
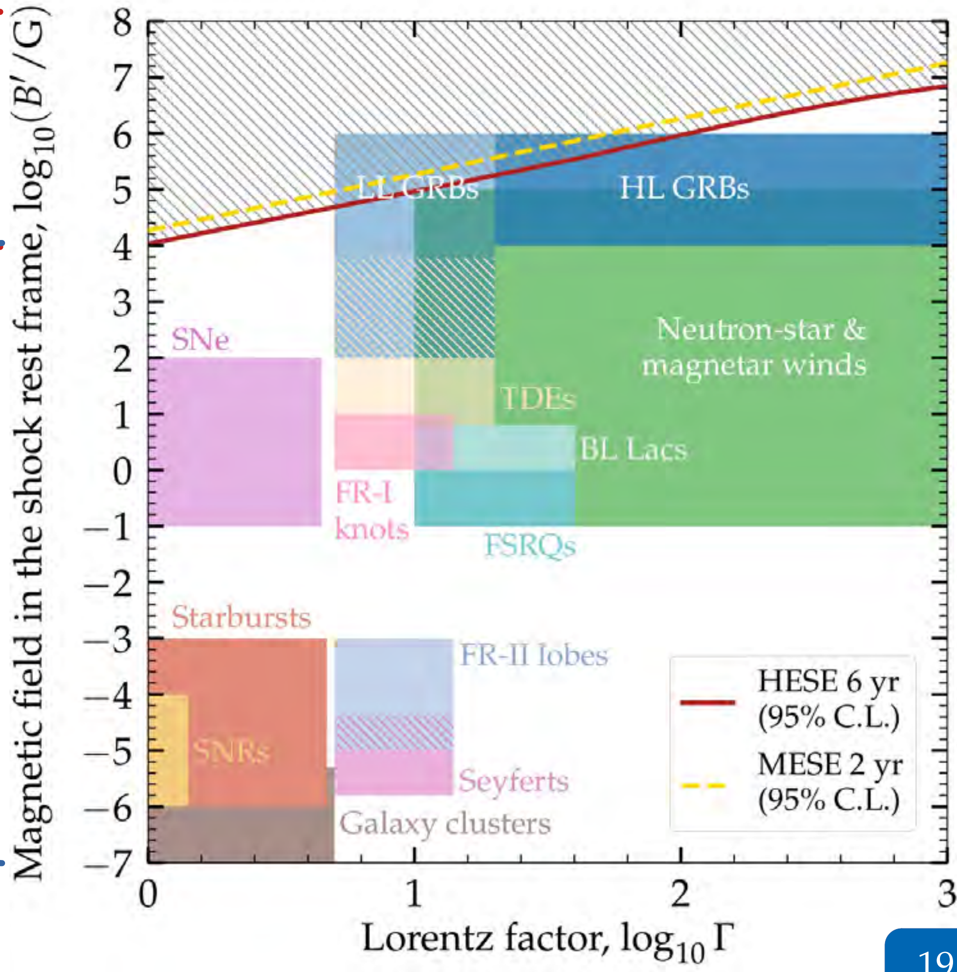


ν sources with strong B' are likely not dominant

Average B' must be $<$ 10kG–10 MG



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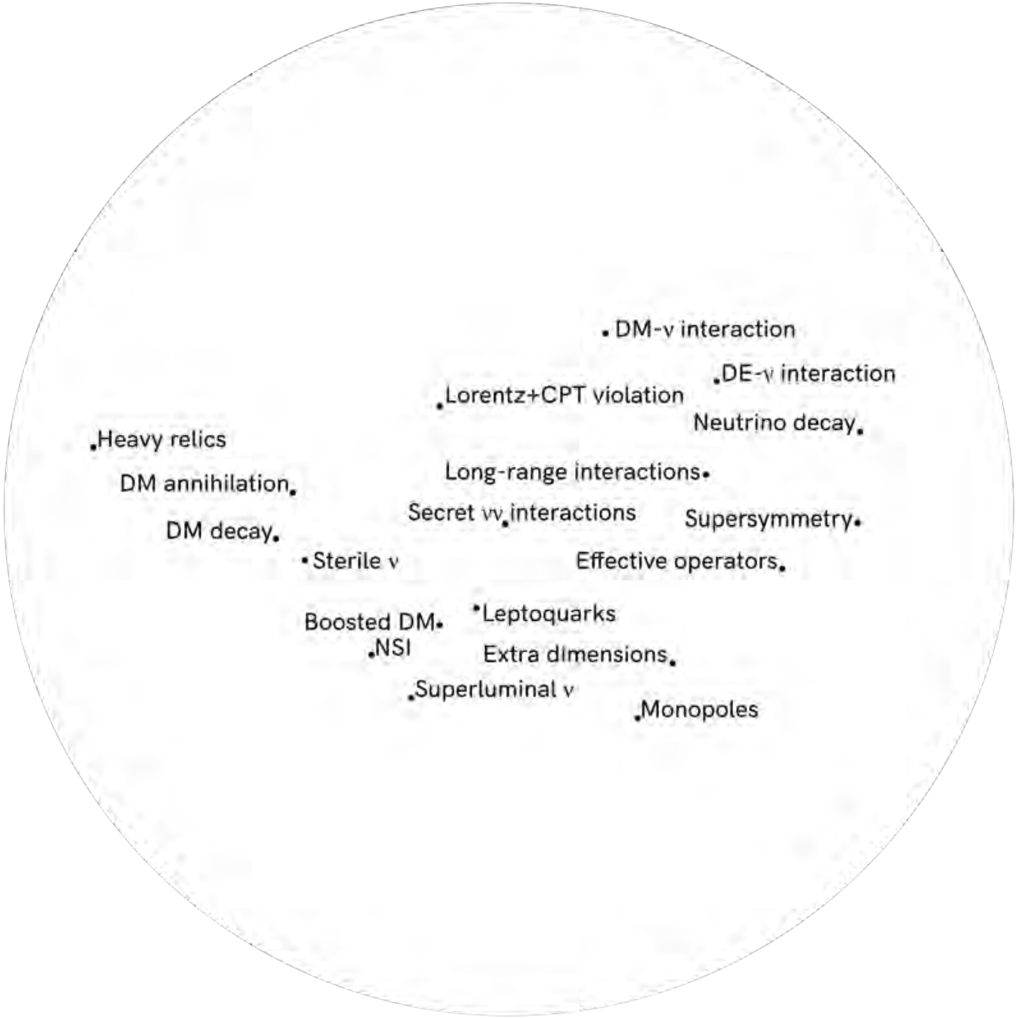
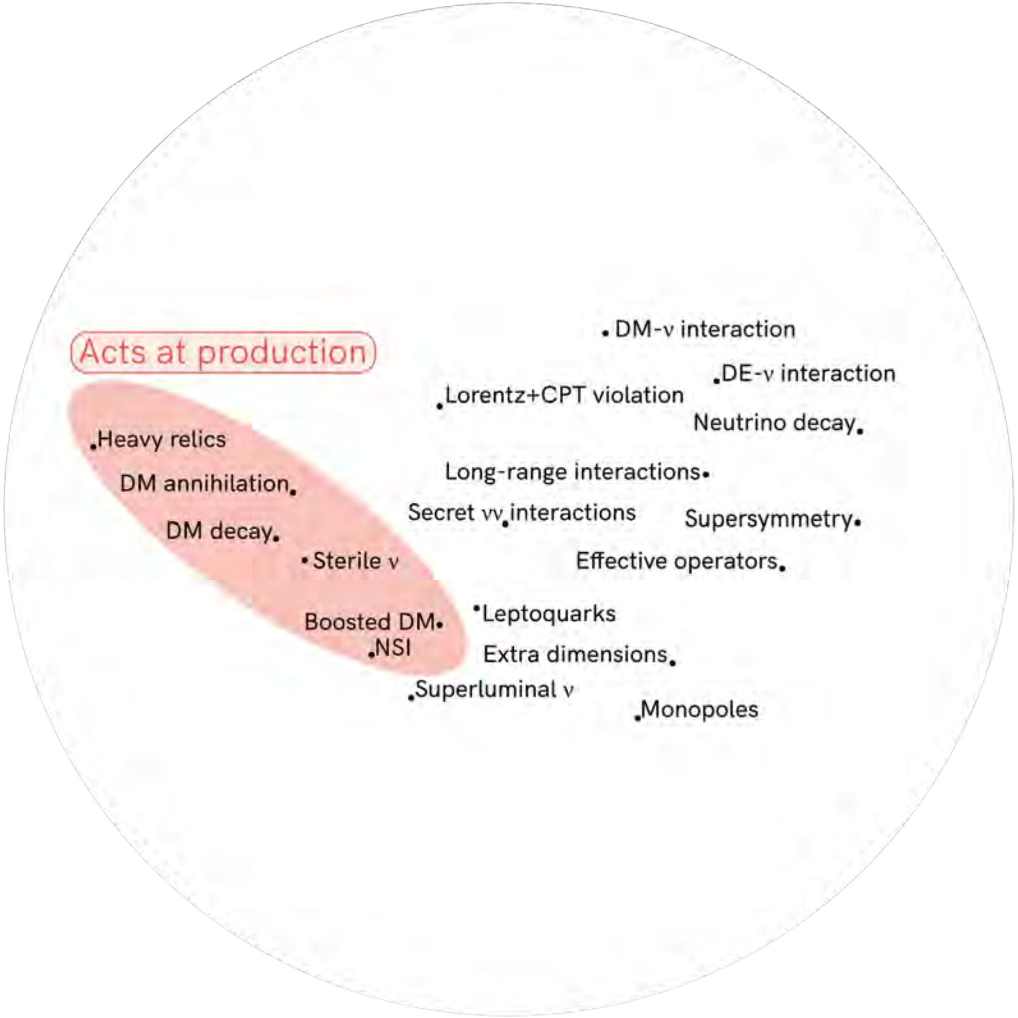


Note: Not an exhaustive list



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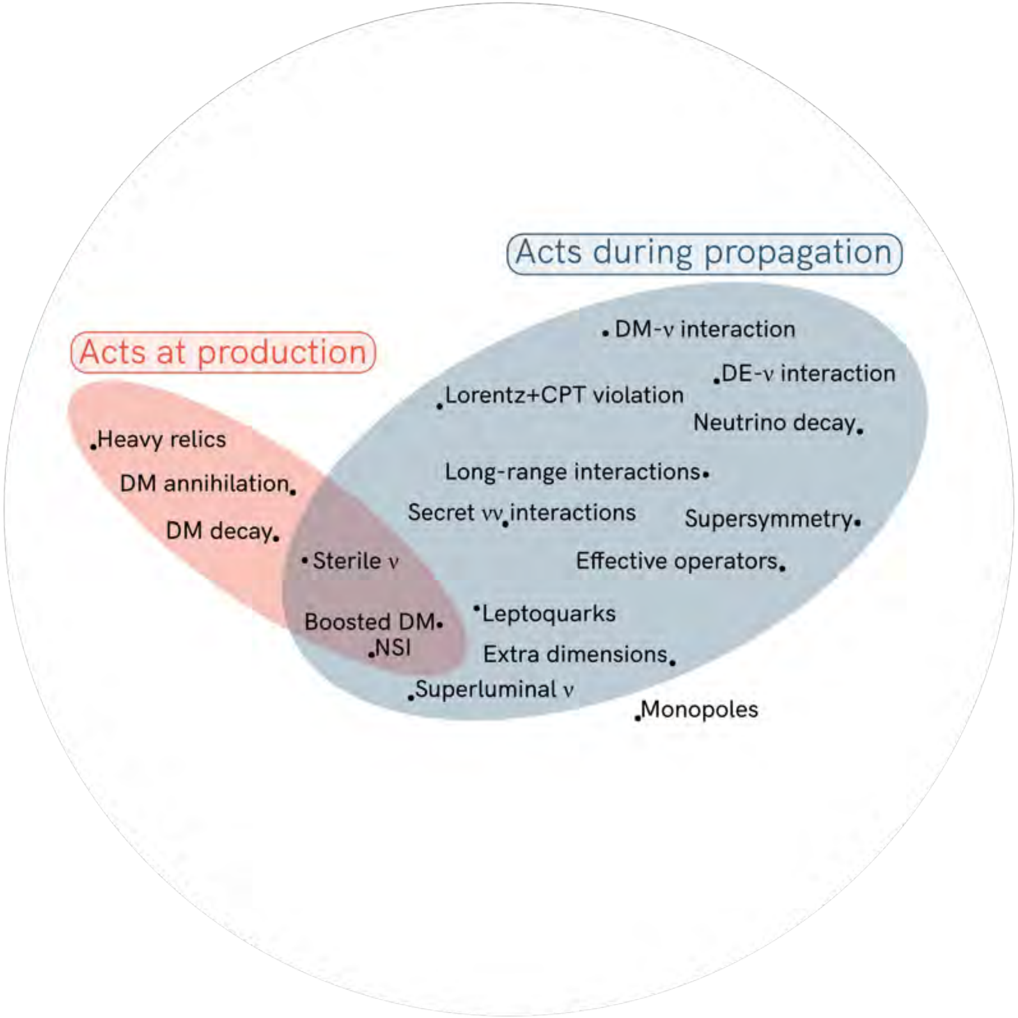

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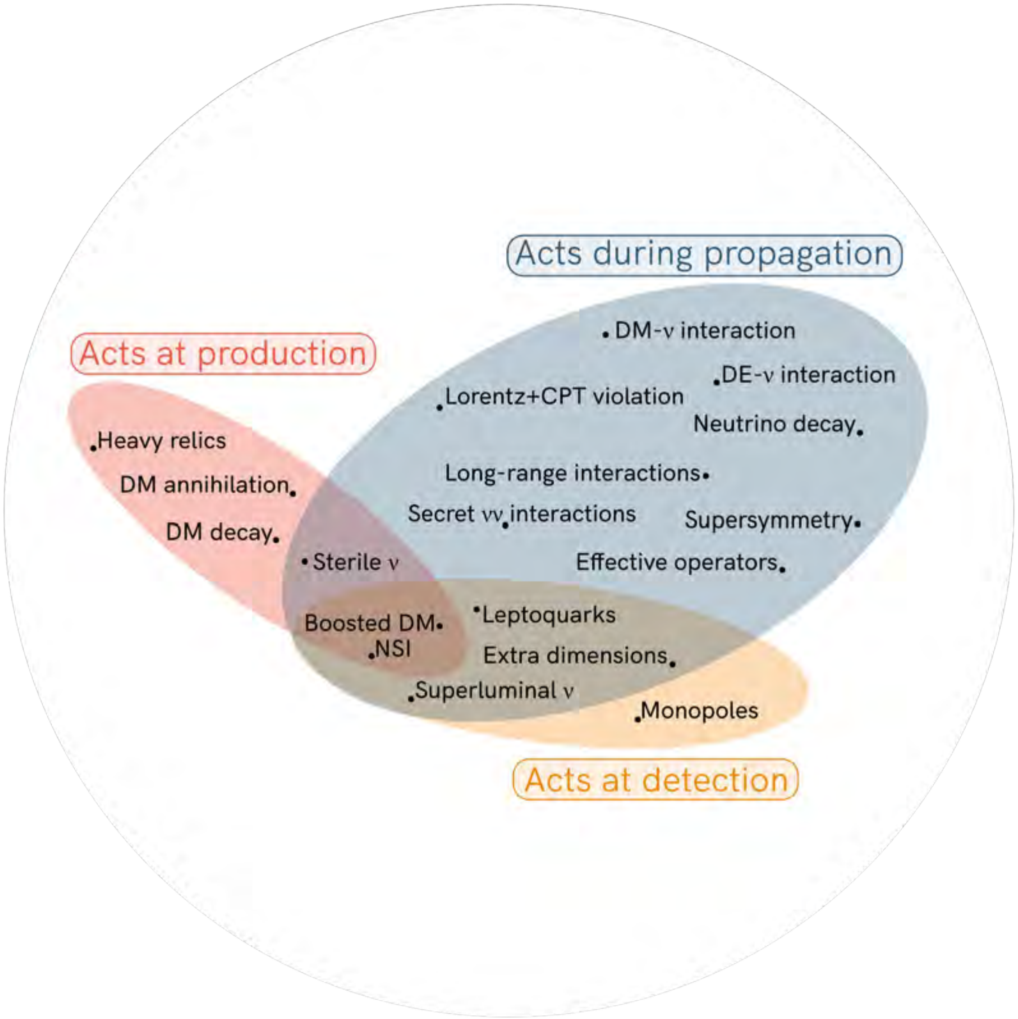
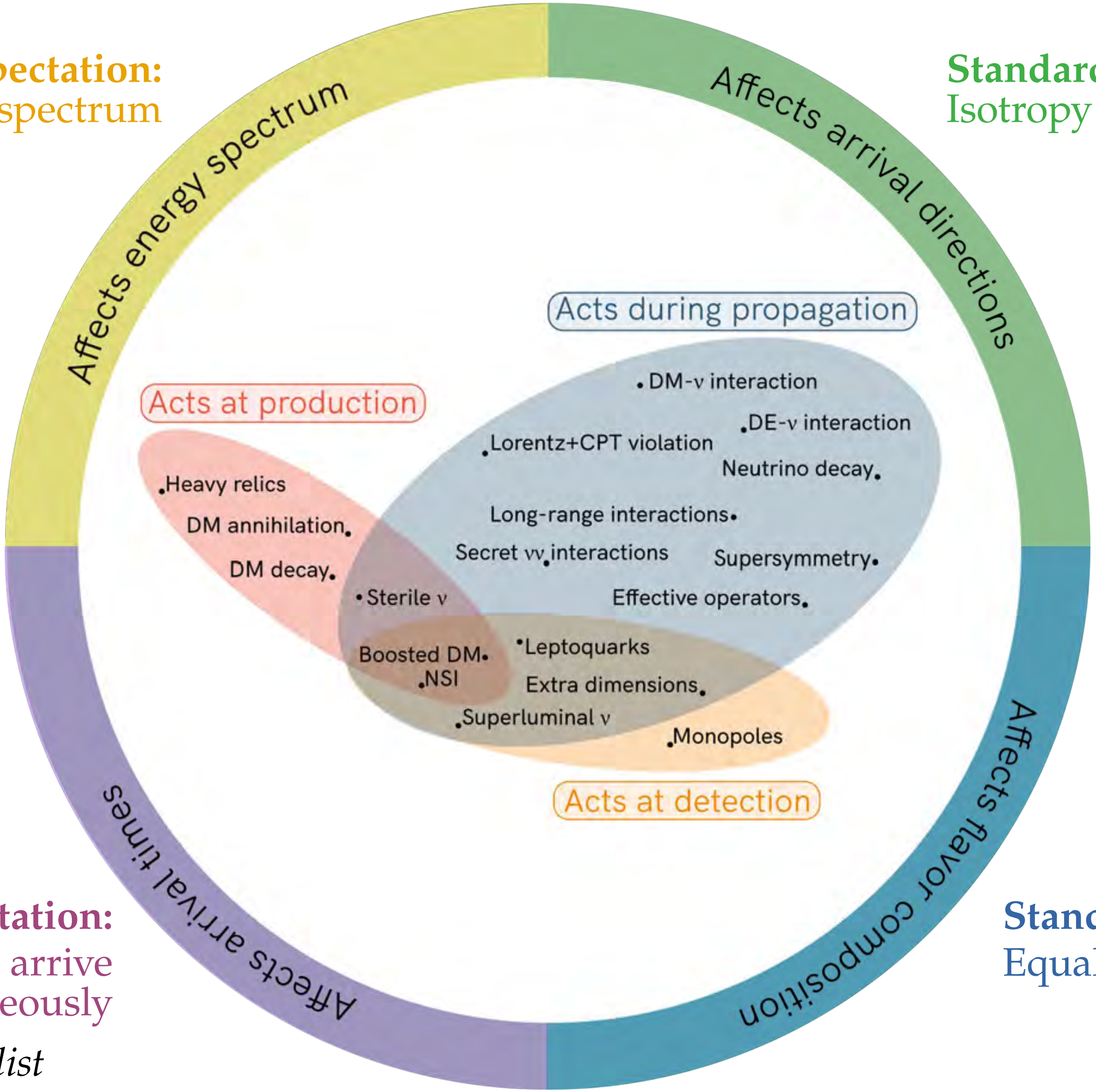


Note: Not an exhaustive list

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



Standard expectation:
ν and γ from transients arrive simultaneously

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Equal number of ν_e, ν_μ, ν_τ

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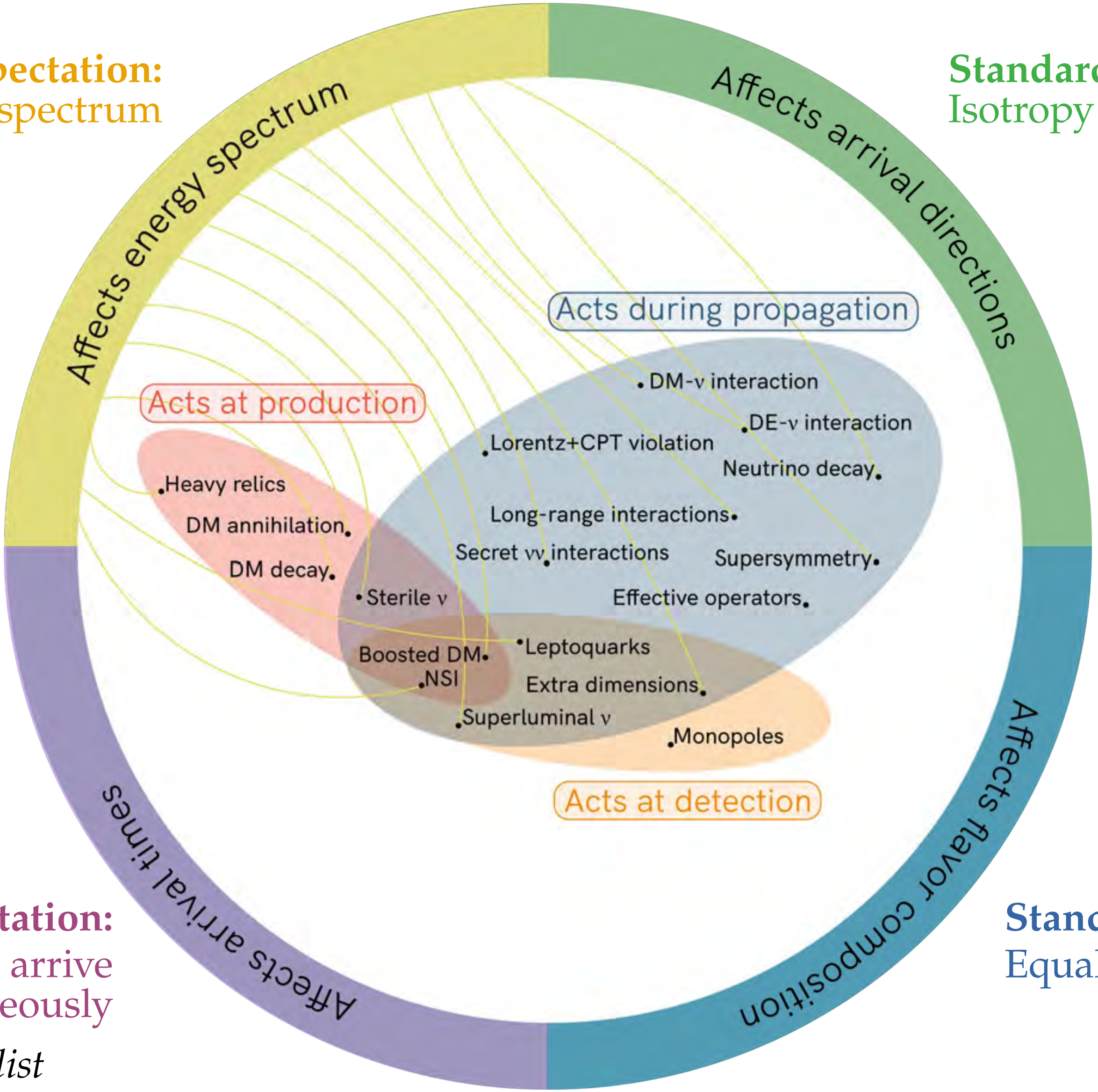

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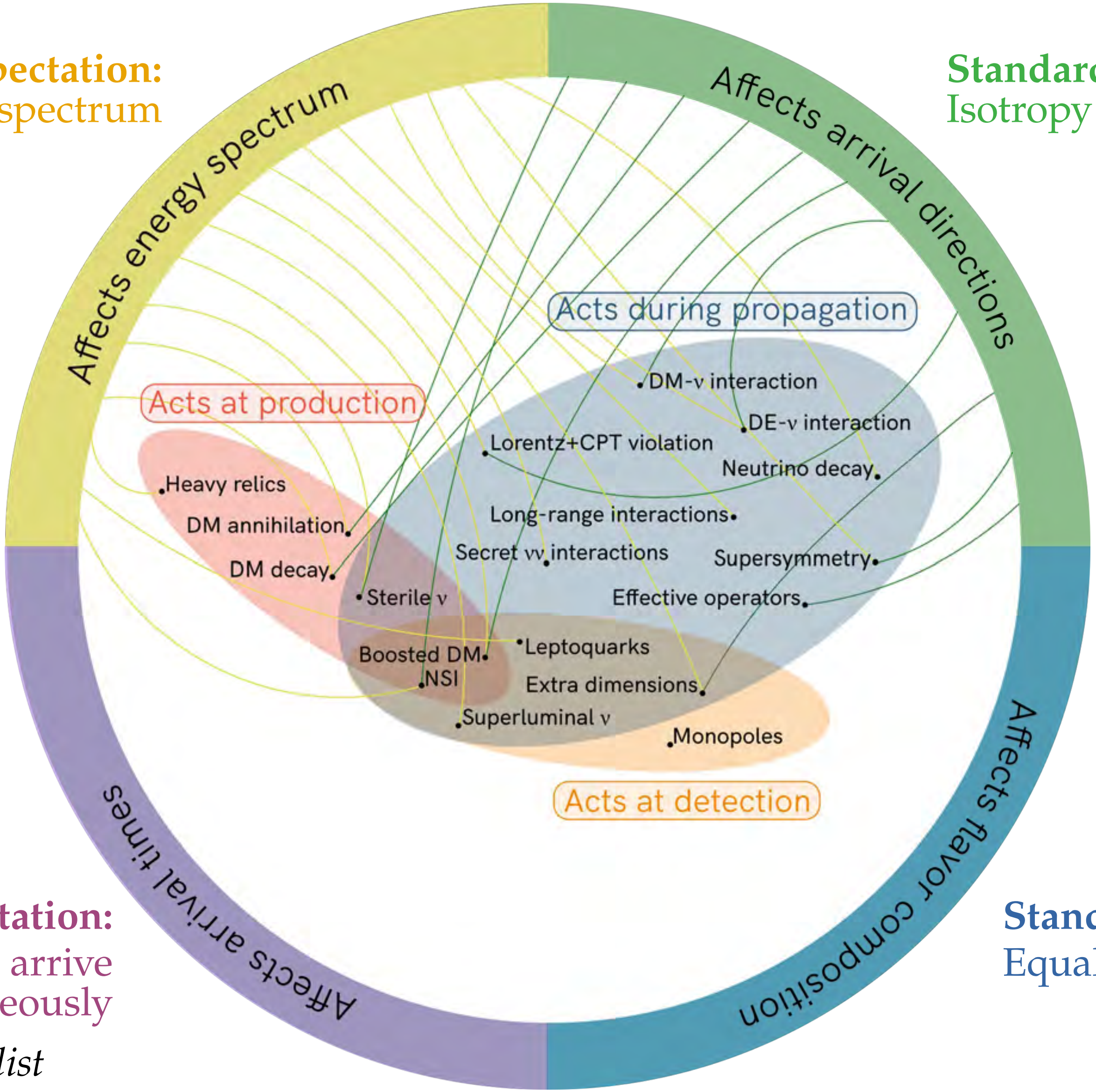

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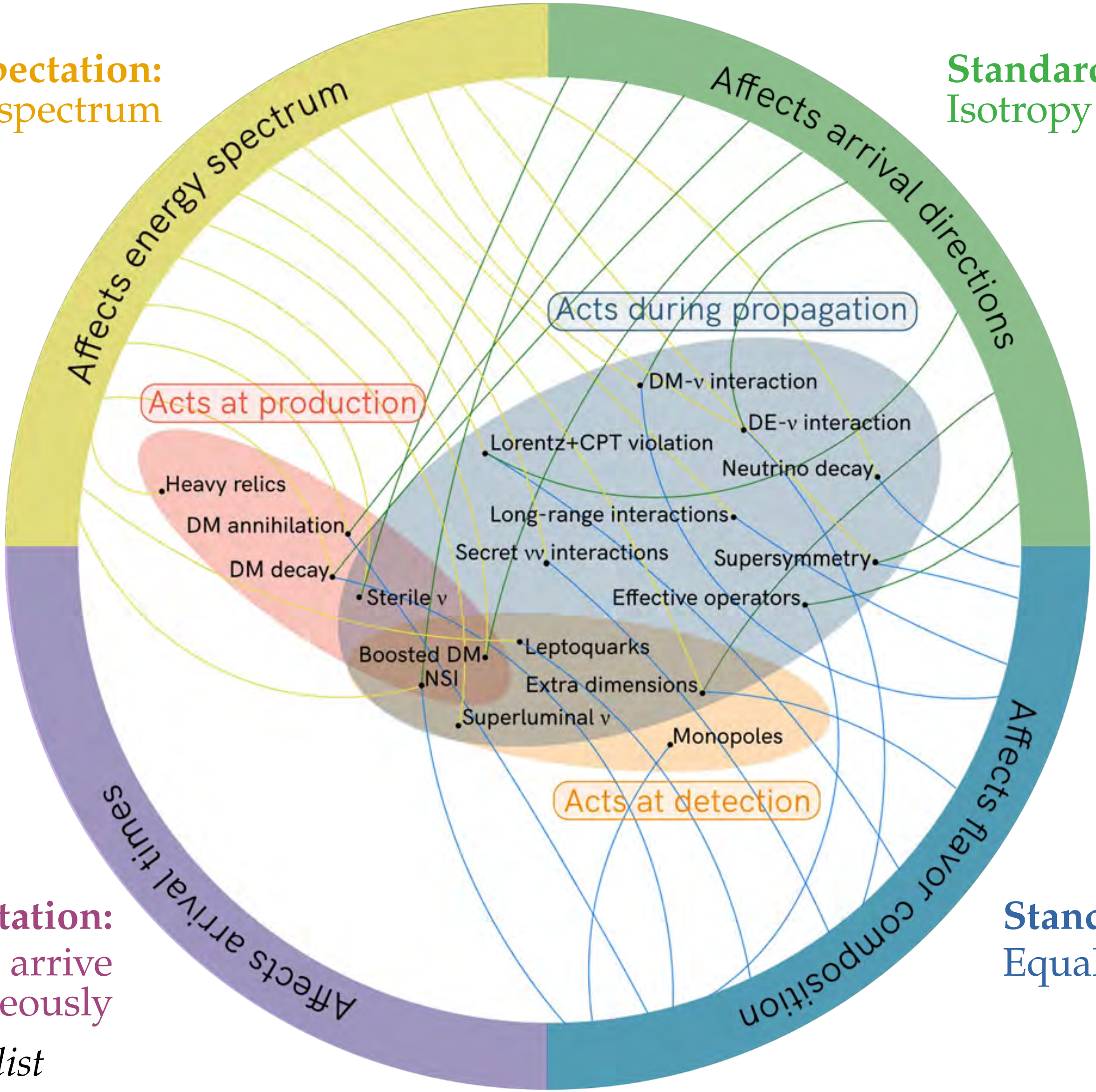

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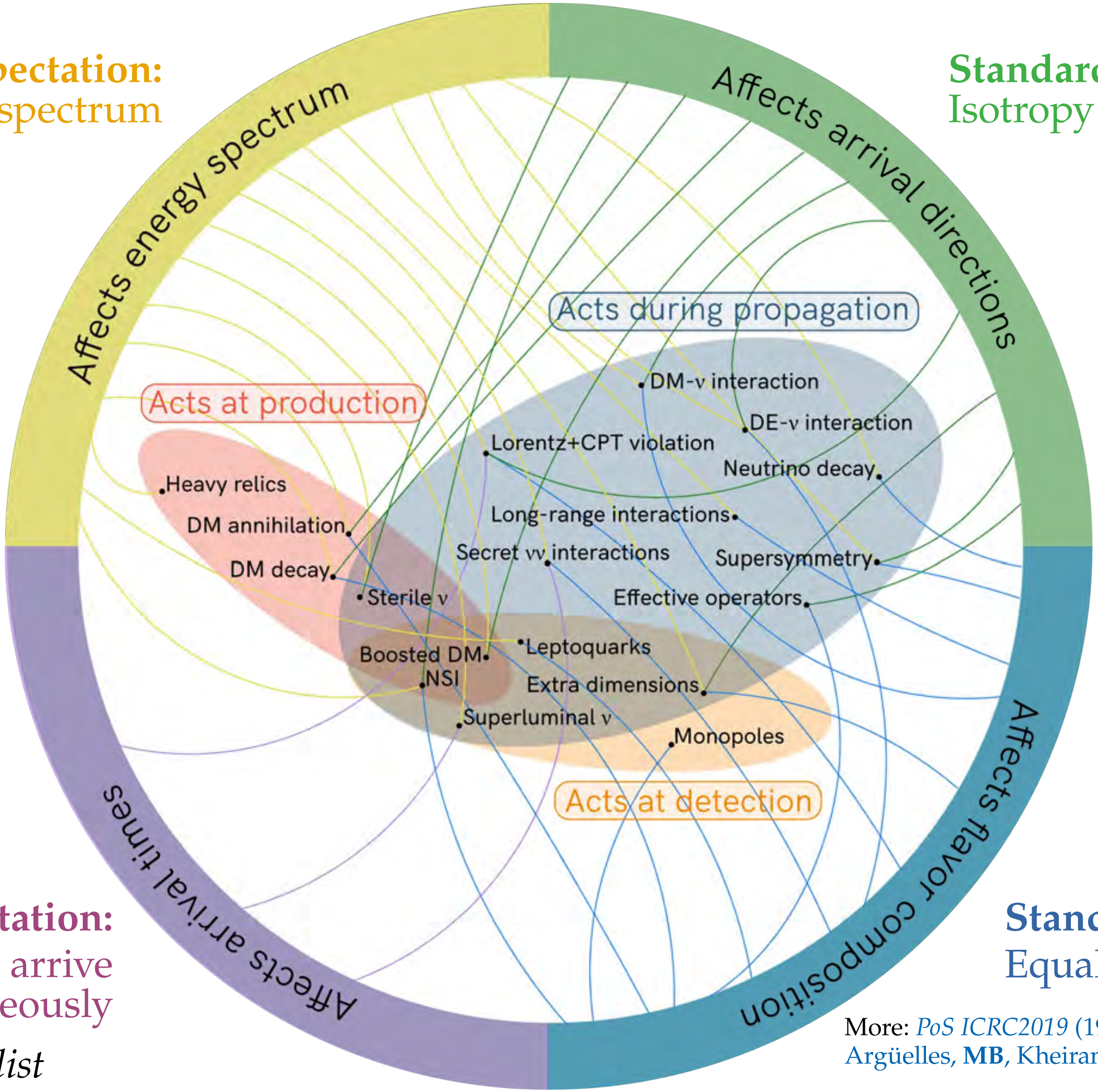

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More: *PoS ICRC2019* (1907.08690)
Argüelles, **MB**, Kheirandish, Palomares-Ruiz, Salvadó, Vincent

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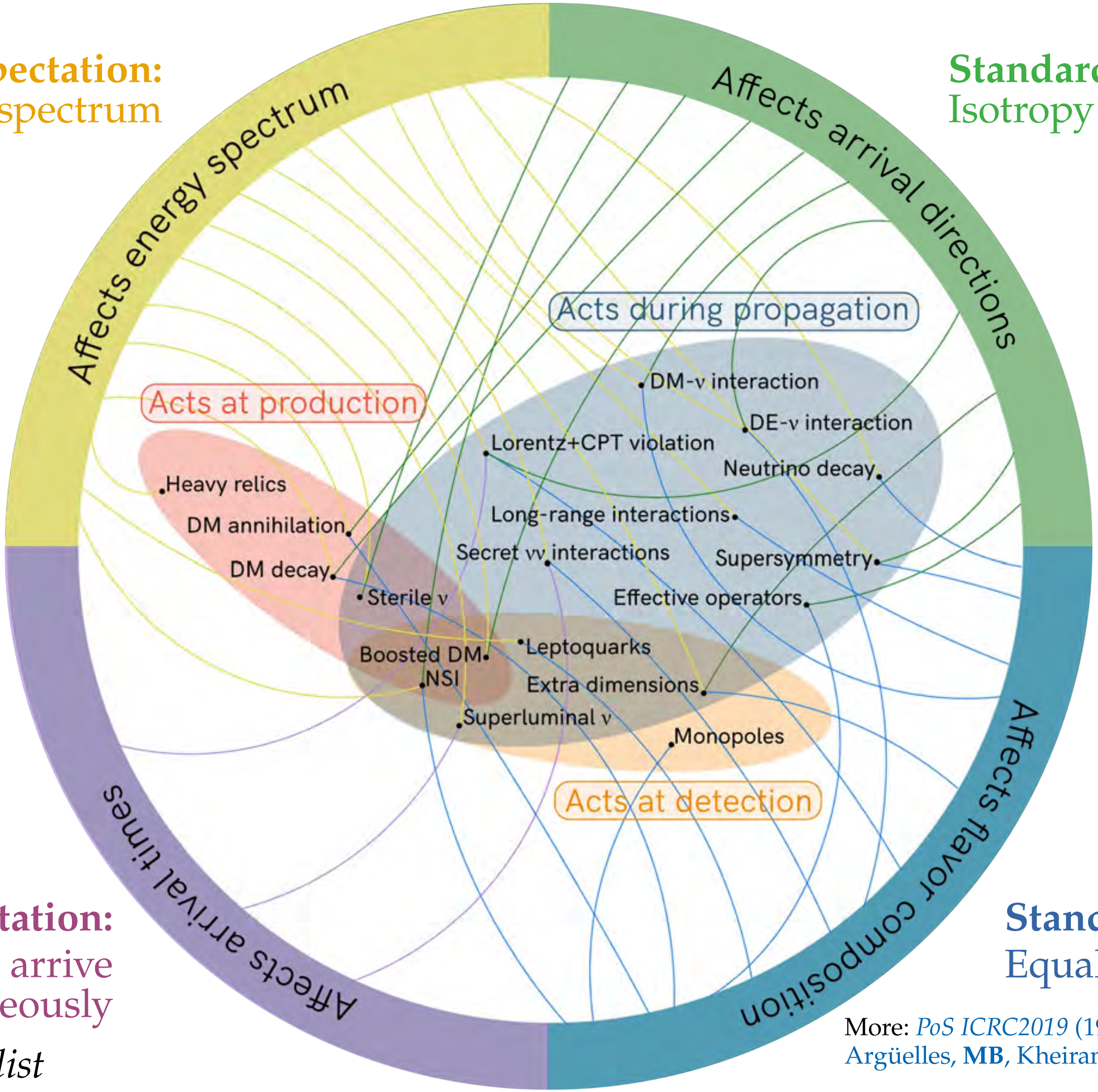

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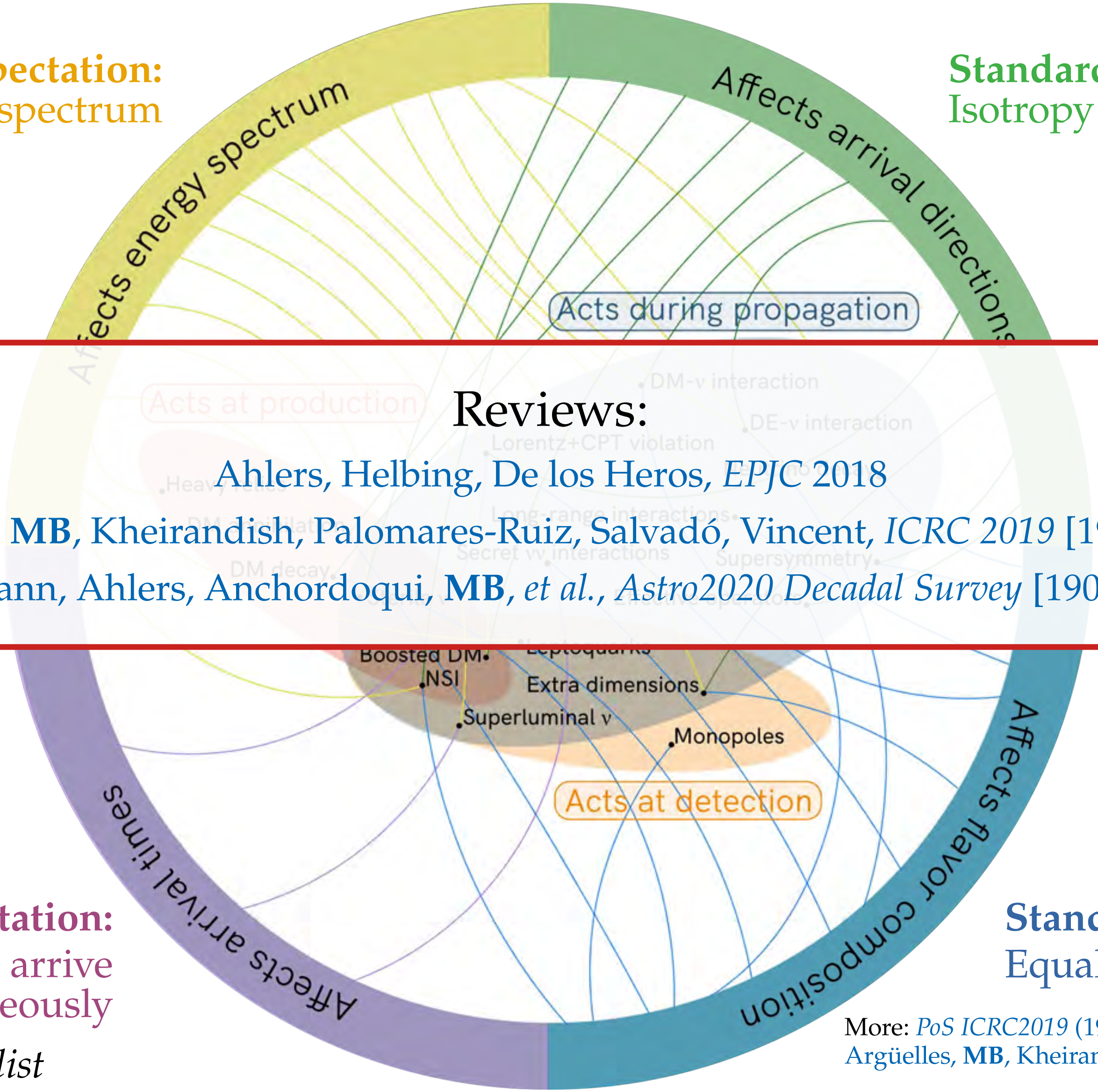

Reviews:

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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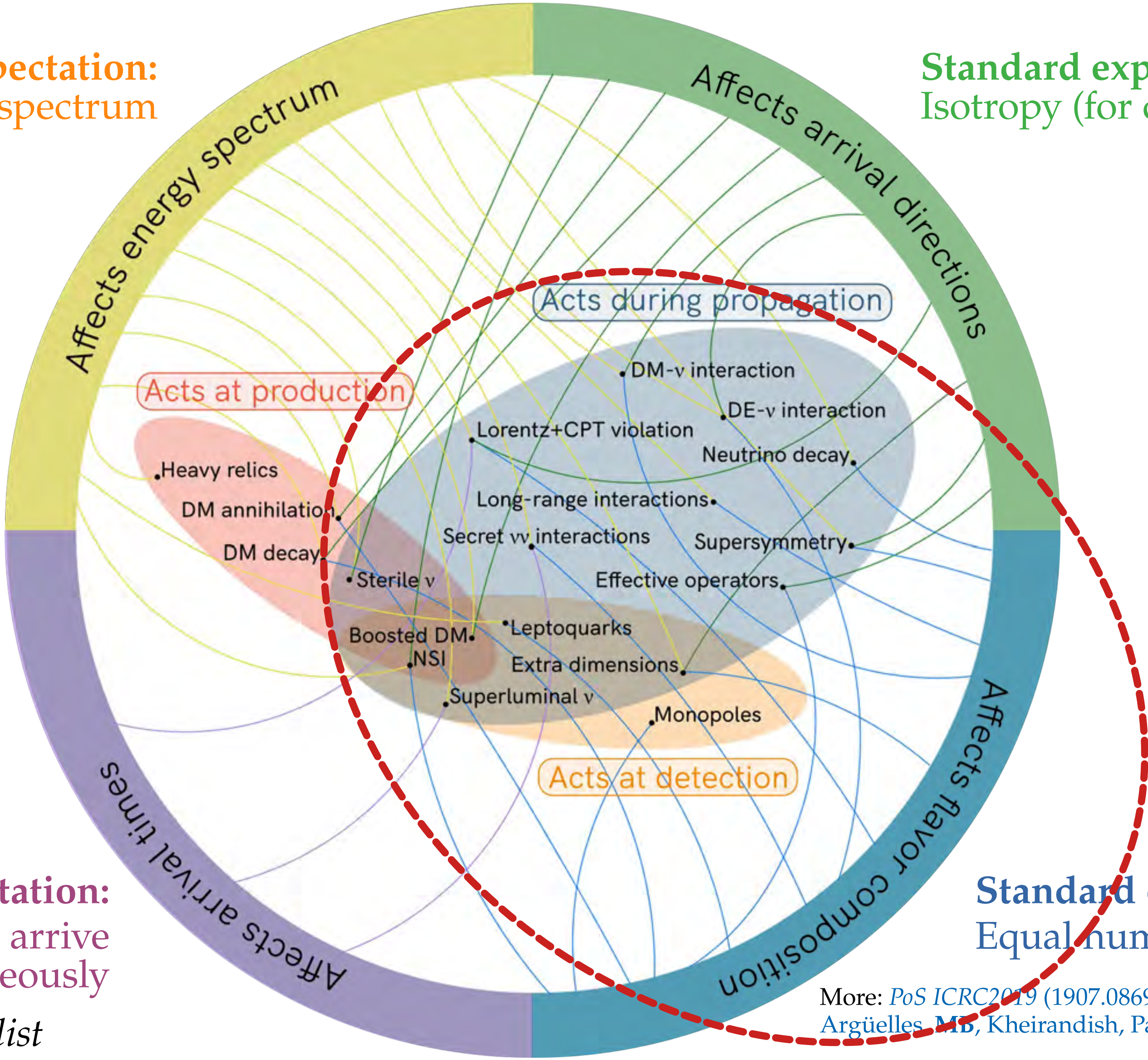

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New physics in flavor composition

Use the flavor sensitivity to test new physics:

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

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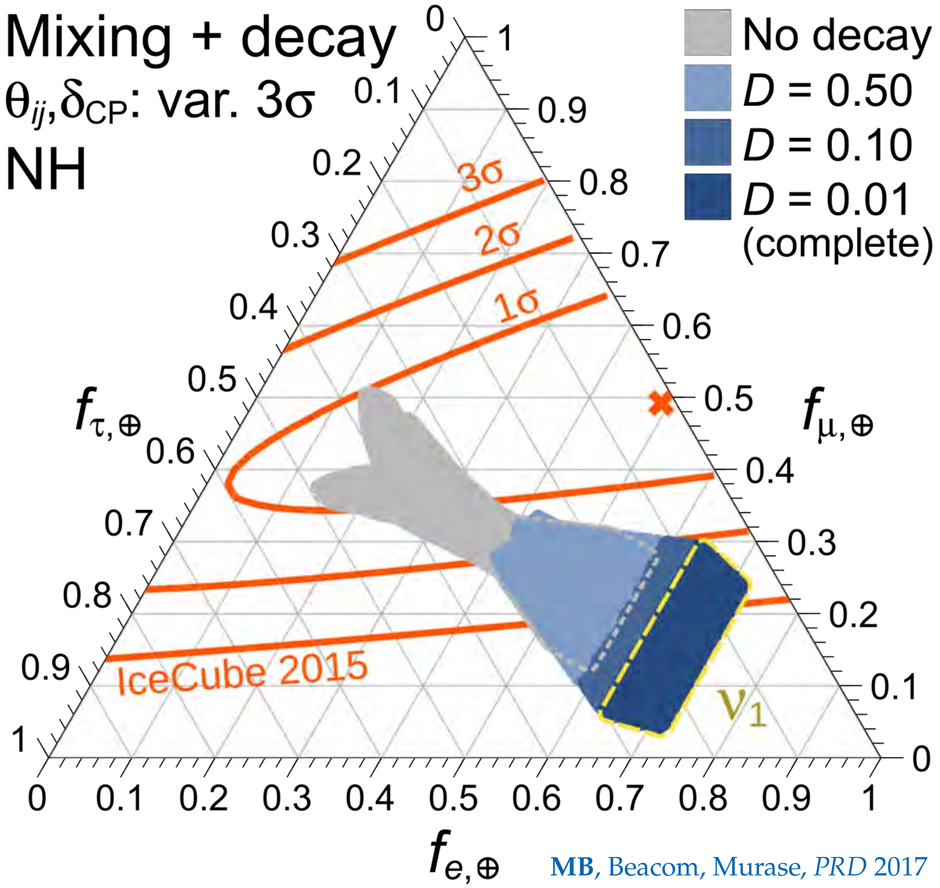

MB, Beacom, Murase, *PRD* 2017

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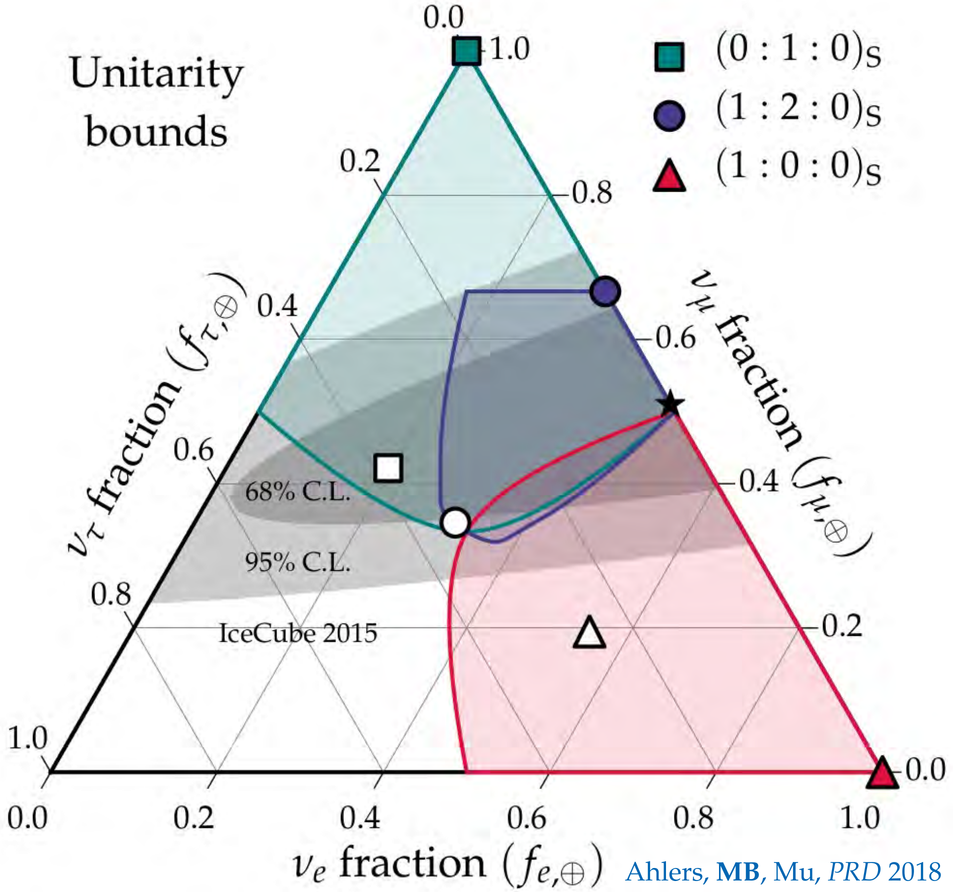

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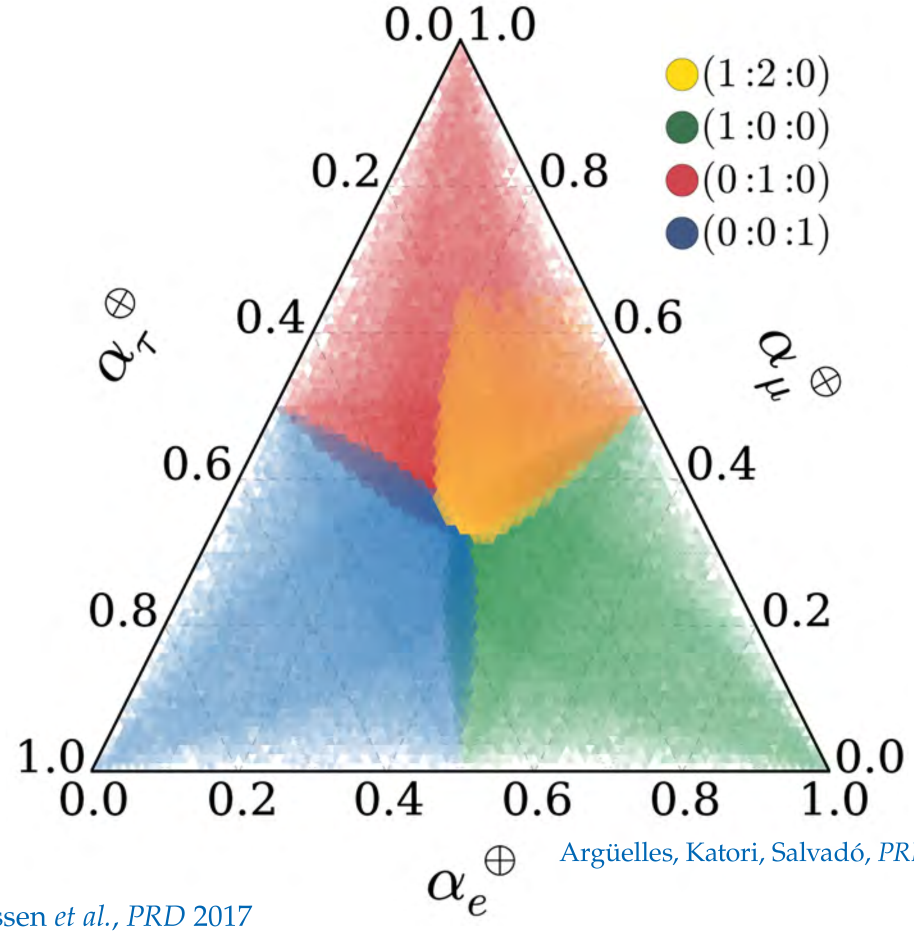

Argüelles, Katori, Salvadó, *PRL* 2015

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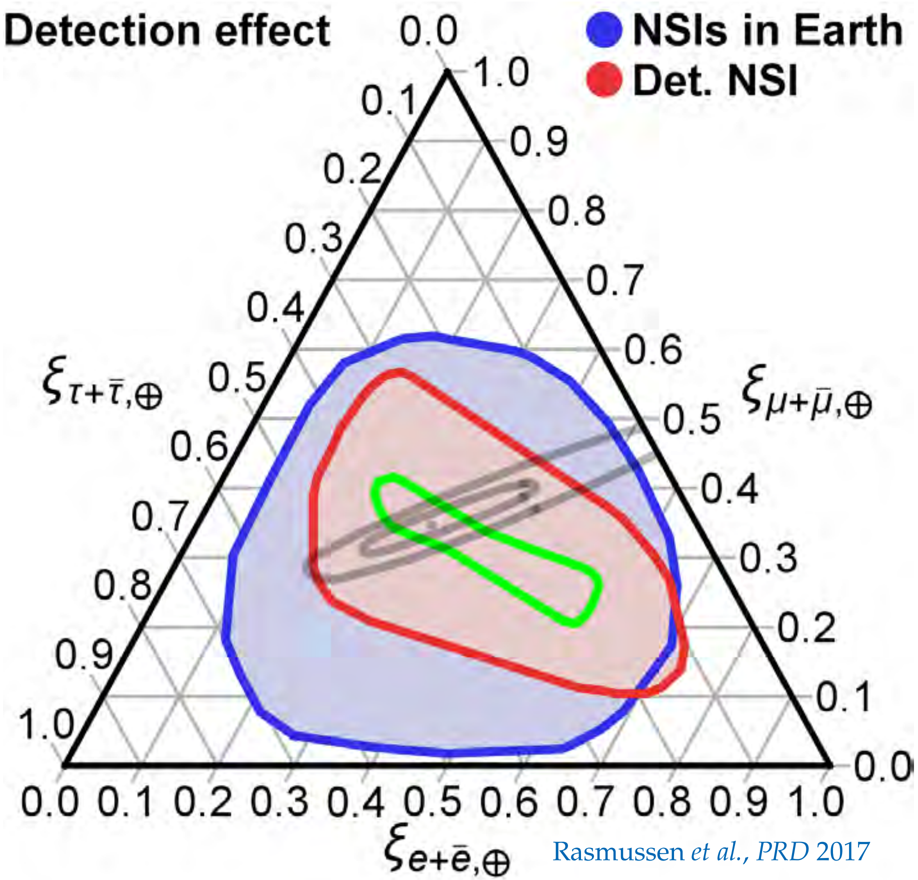

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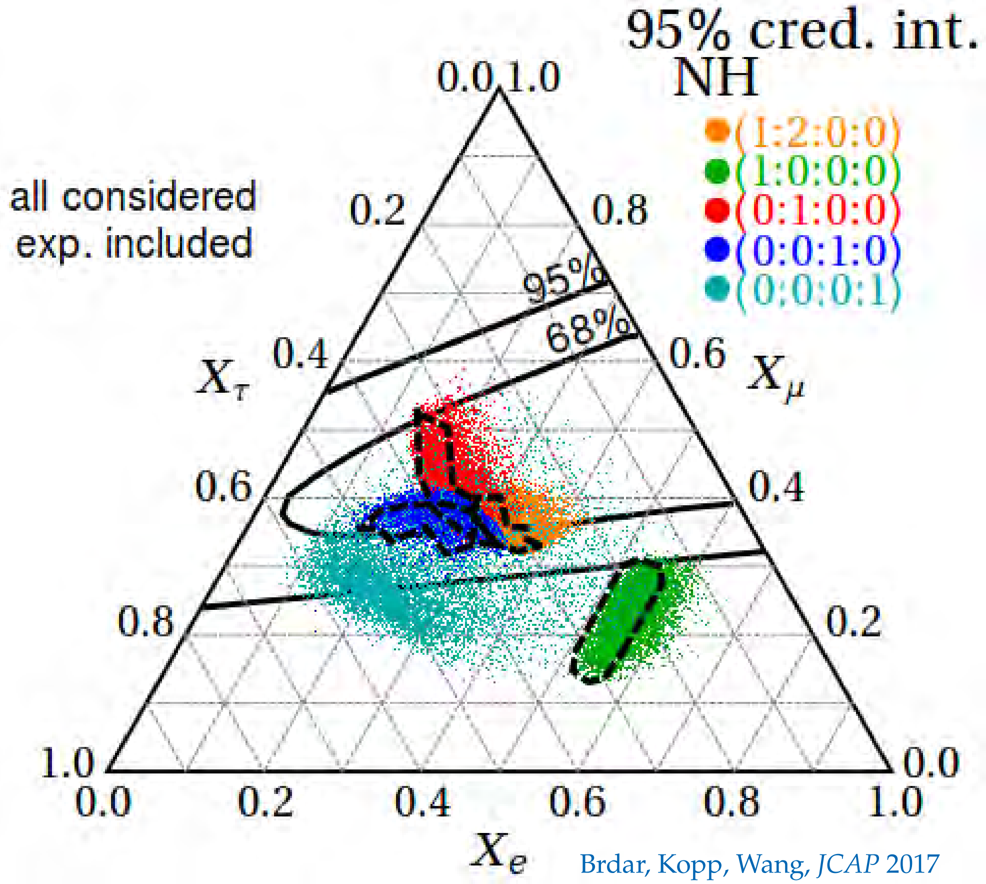

Brdar, Kopp, Wang, *JCAP* 2017

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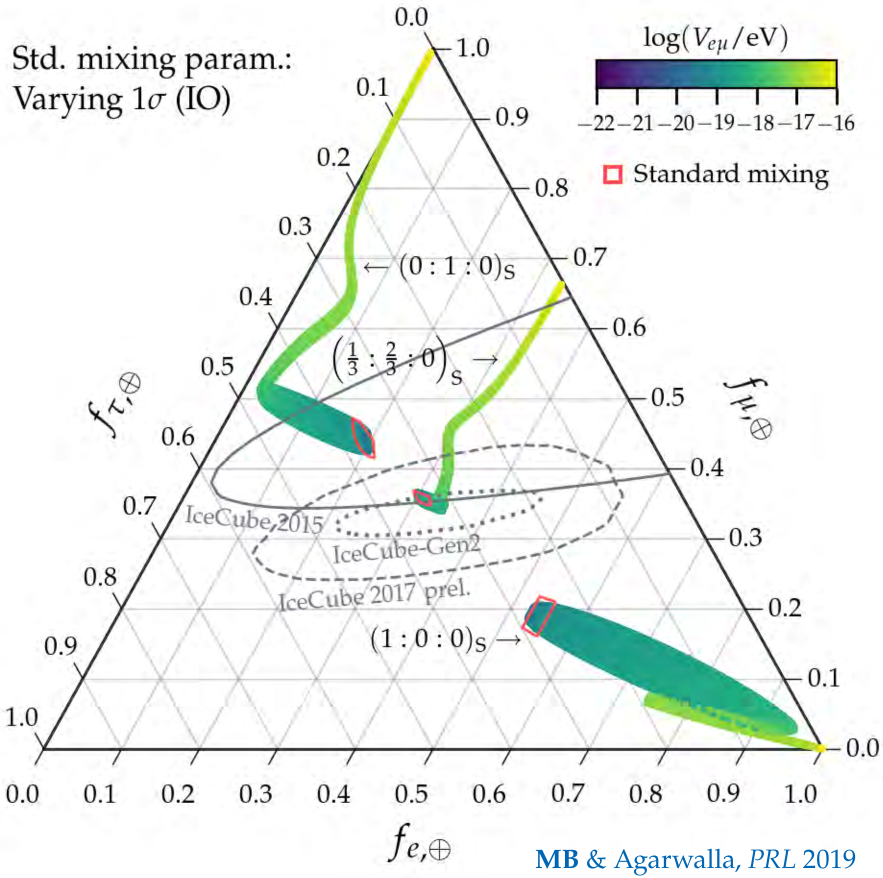
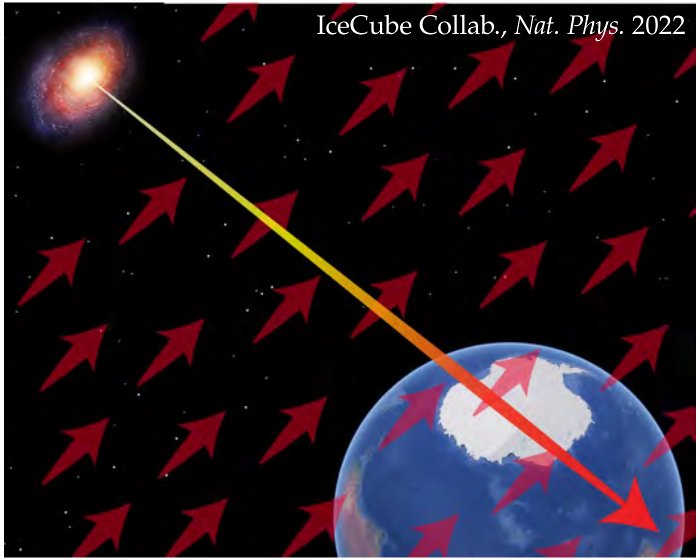
- ▸ Long-range *e*ν interactions
  [**MB** & Agarwalla, *PRL* 2019]



MB & Agarwalla, *PRL* 2019

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

Lorentz-invariance violation can fill up the flavor triangle

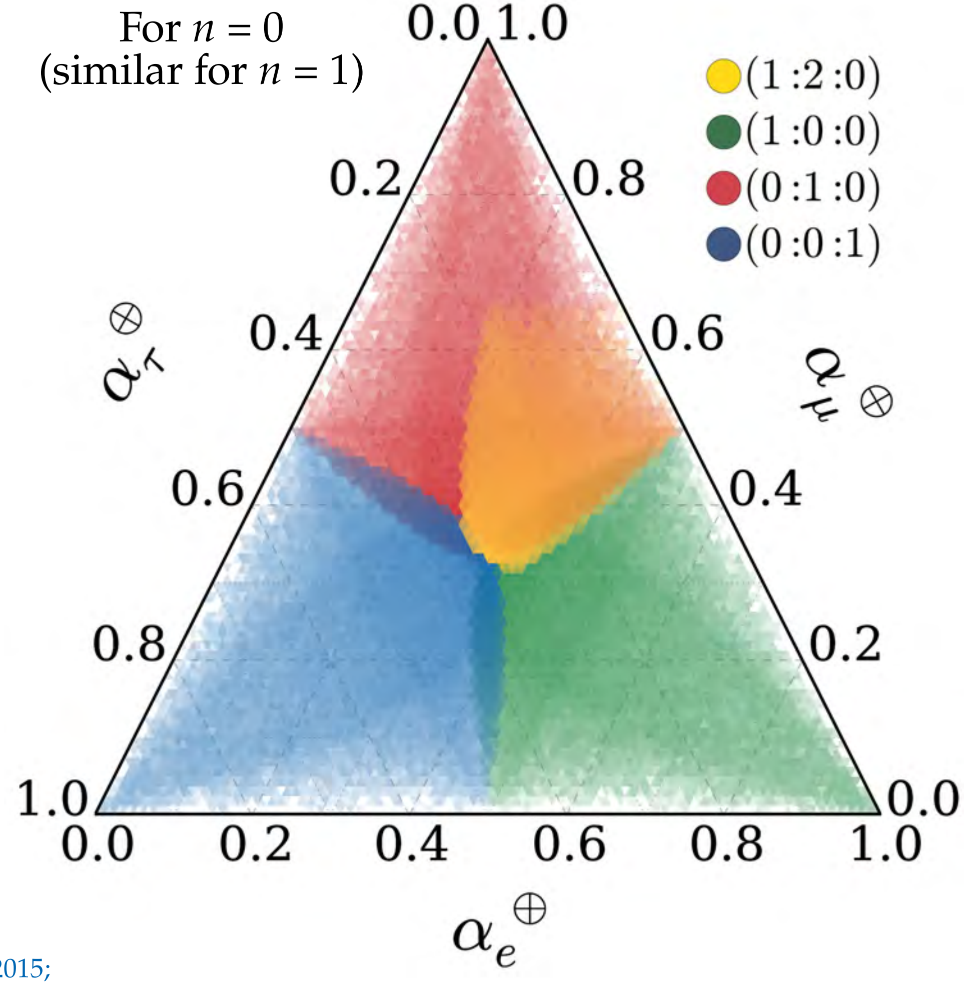


$$H_{\rm tot} = H_{\rm std} + H_{\rm NP}$$

$$H_{\rm std} = \frac{1}{2E} U^\dagger_{\rm PMNS}\, \mathrm{diag}\left(0, \Delta m^2_{21}, \Delta m^2_{31}\right) U_{\rm PMNS}$$

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

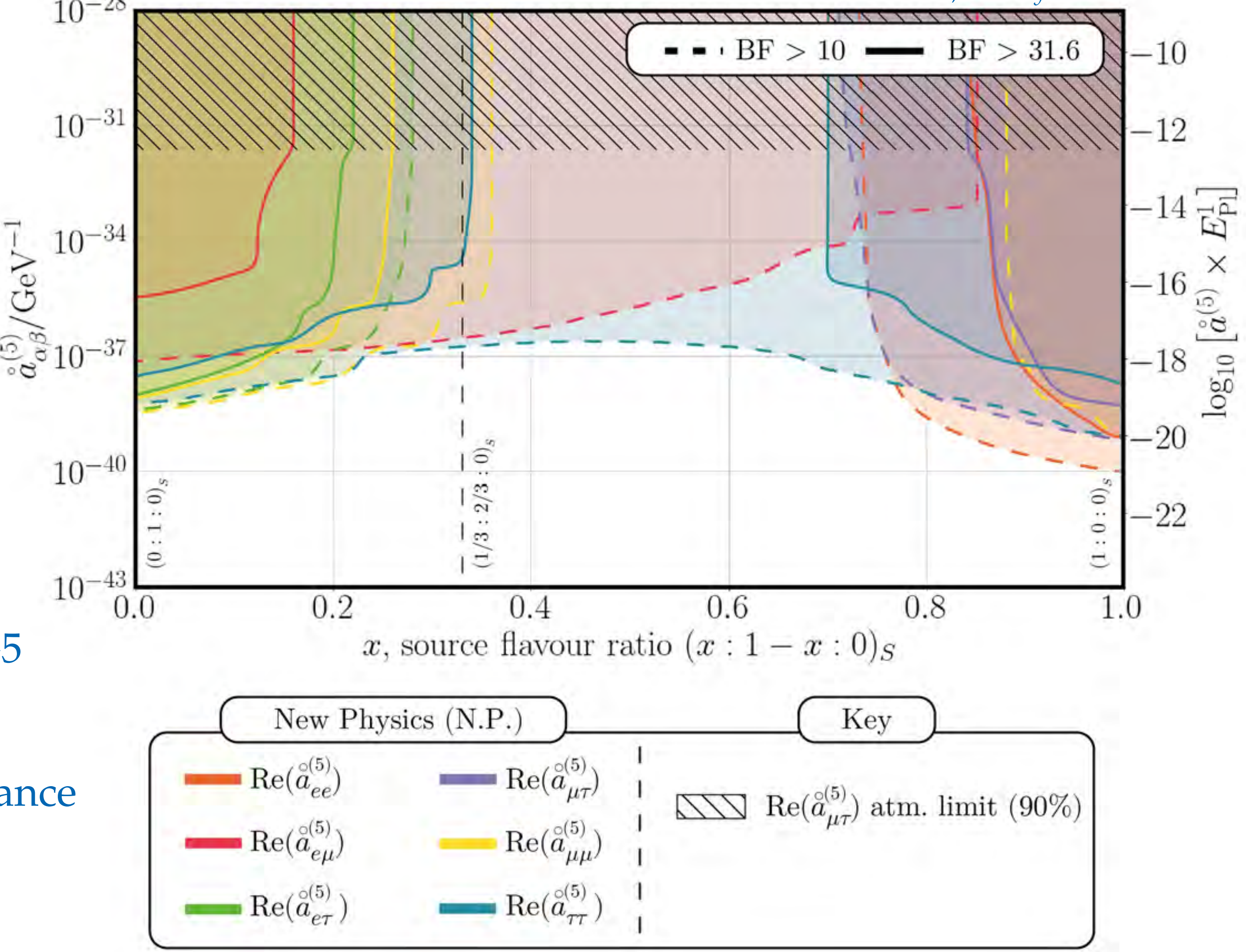
For $n = 0$
(similar for $n = 1$)



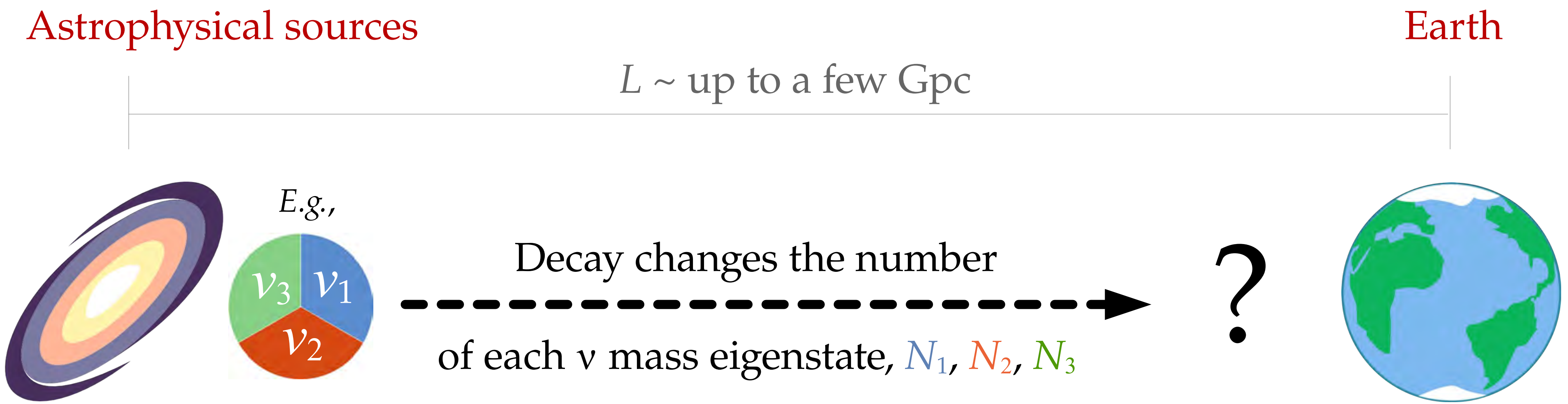
Argüelles, Katori, Salvadó, *PRL* 2015

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

IceCube Collab., *Nat. Phys.* 2022



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



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

Mass of ν_i Lifetime of ν_i

Astrophysical sources

Earth

L ~ up to a few Gpc

E.g.,

Decay changes the number

of each ν mass eigenstate, N_1, N_2, N_3

?

Only sensitive to their ratio

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

Mass of ν_i Lifetime of ν_i

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E.g.,

Decay changes the number

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?

Lower-E ν are longer-lived…

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

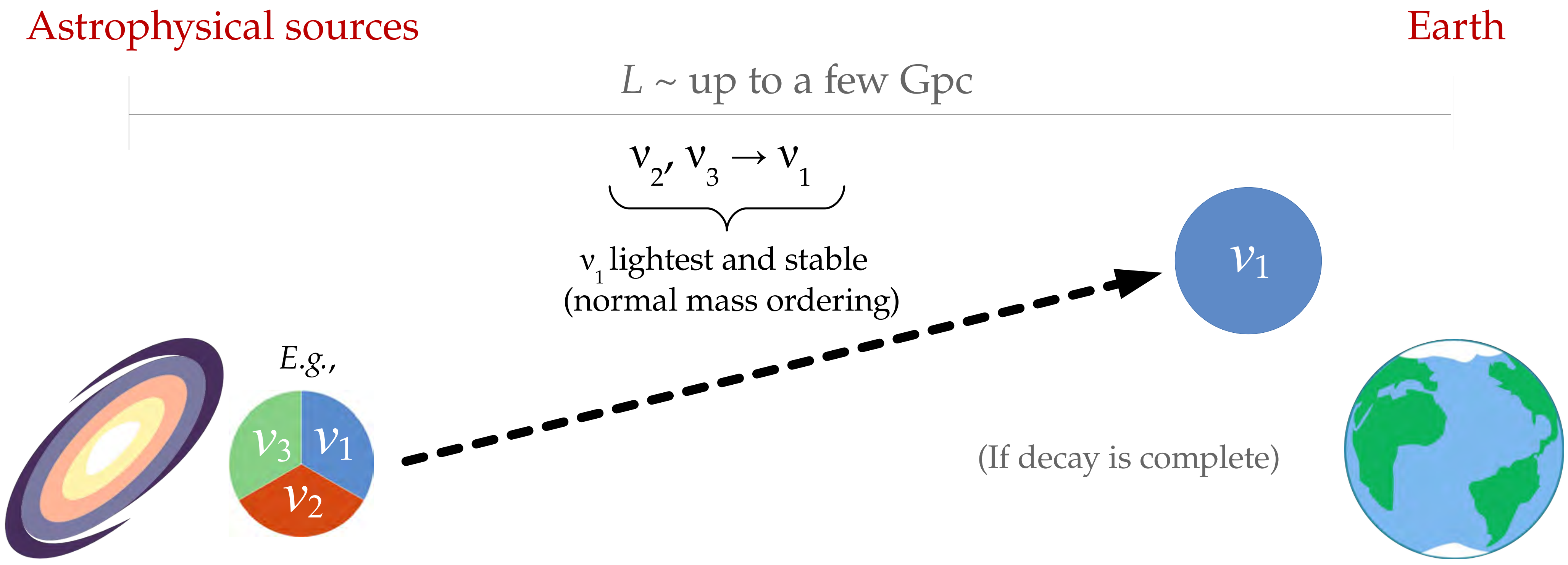
… but ν that travel longer L are more attenuated!

Astrophysical sources

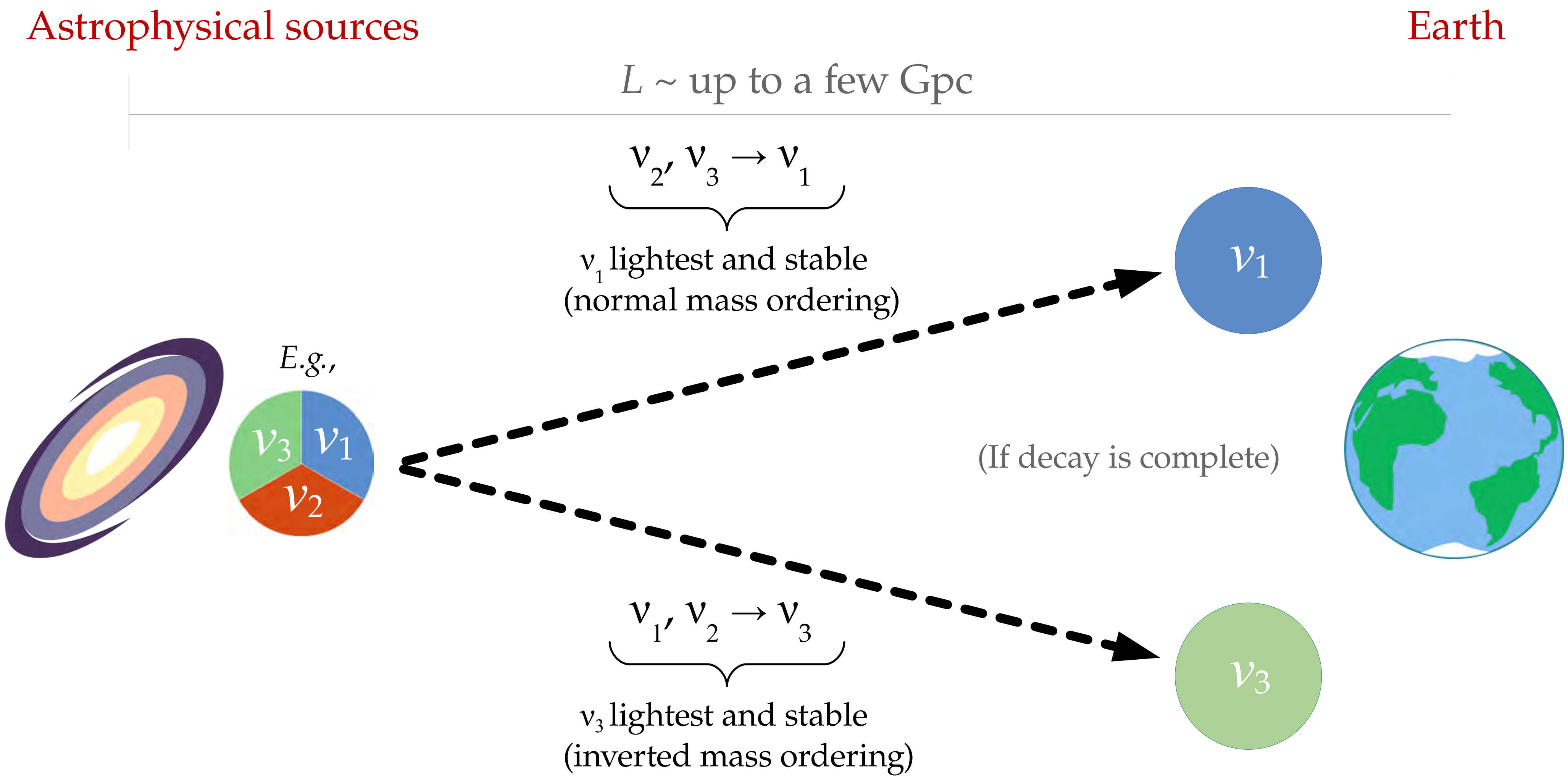
Earth

$L \sim$ up to a few Gpc

E.g.,



Astrophysical sources
Earth
L ~ up to a few Gpc
ν2, ν3 → ν1
ν1 lightest and stable
(normal mass ordering)
E.g.,
ν3
ν1
ν2
ν1
(If decay is complete)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ν_3 lightest and stable
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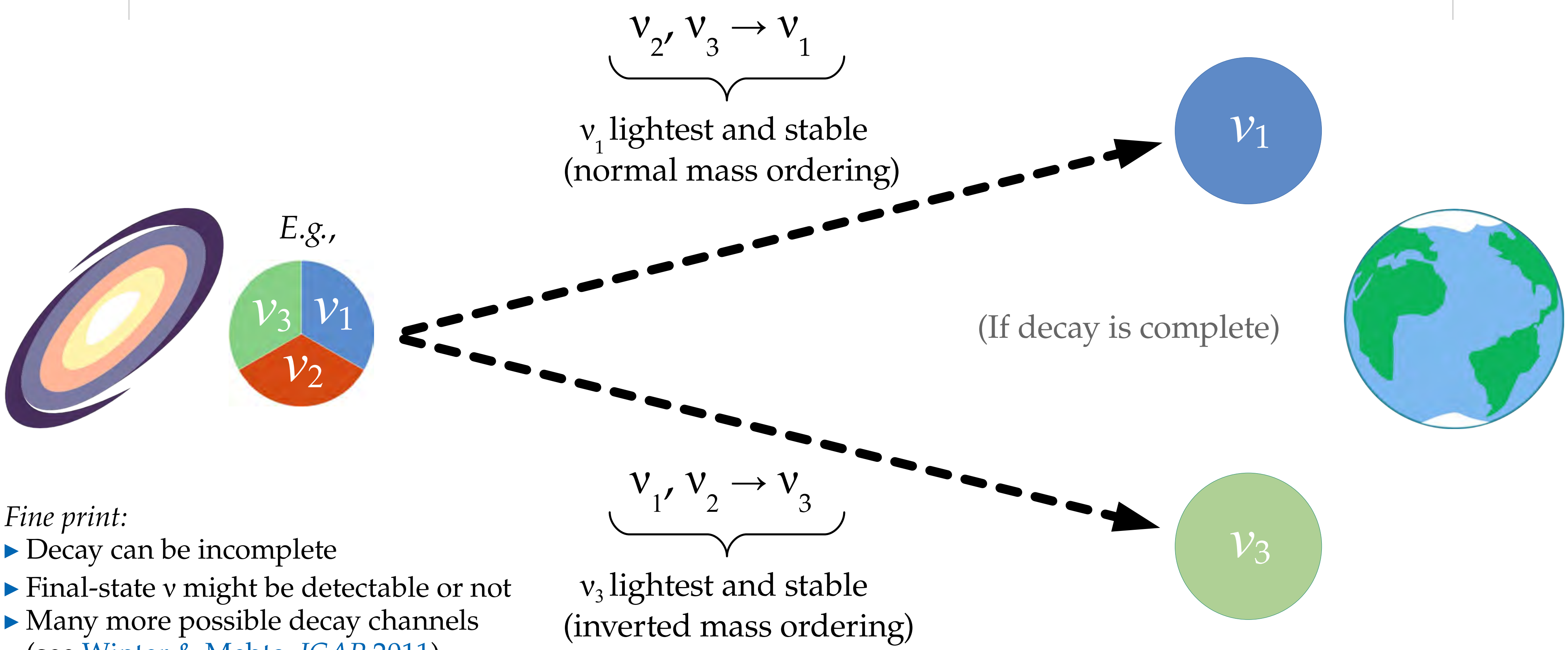
Astrophysical sources → Earth

$L \sim$ up to a few Gpc



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

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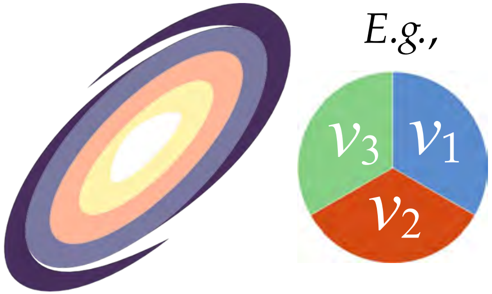
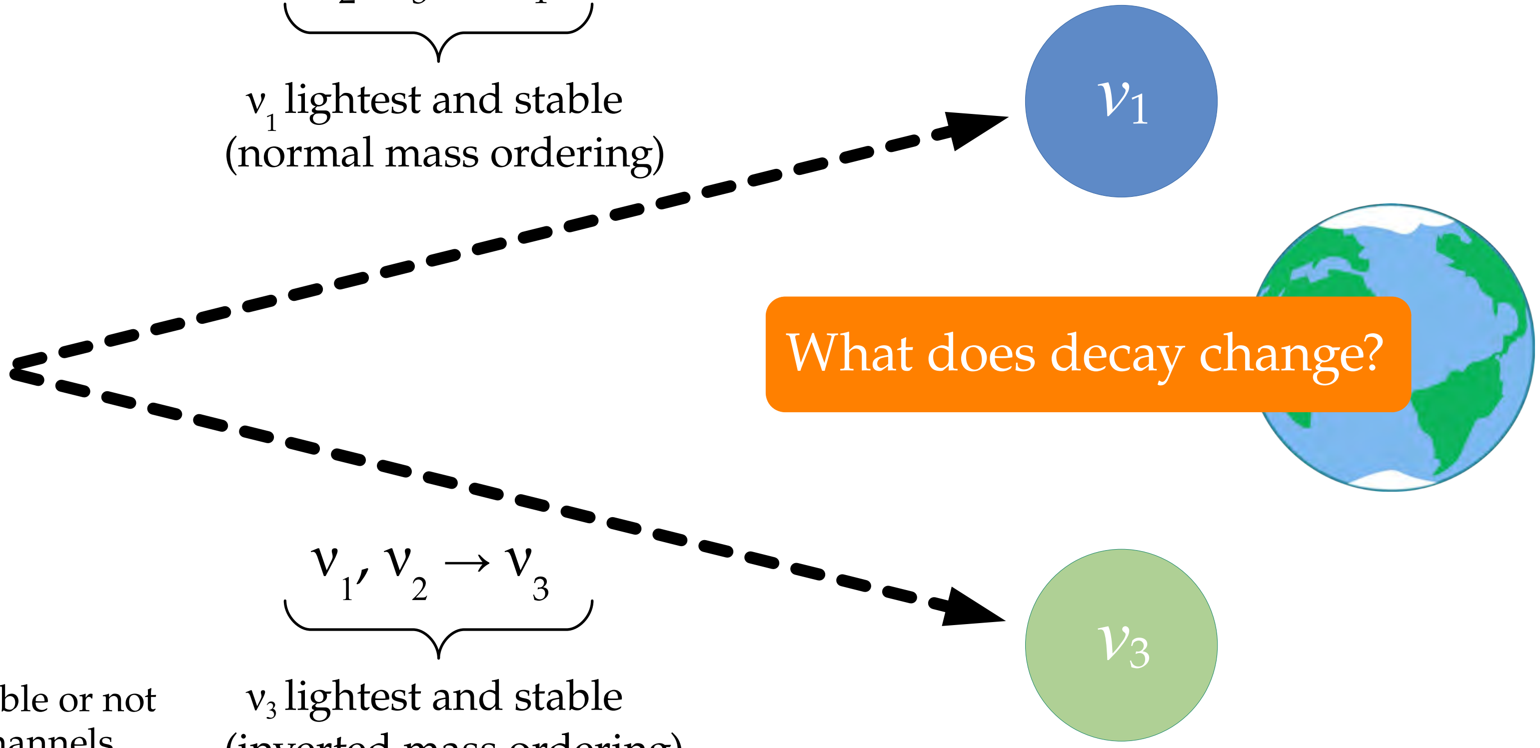
$\nu_2, \nu_3 \to \nu_1$

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)

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What does neutrino decay change?

Flavor composition ⟺ Spectrum shape ⟺ Event rate

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Flavor composition ⟺ Spectrum shape ⟺ Event rate

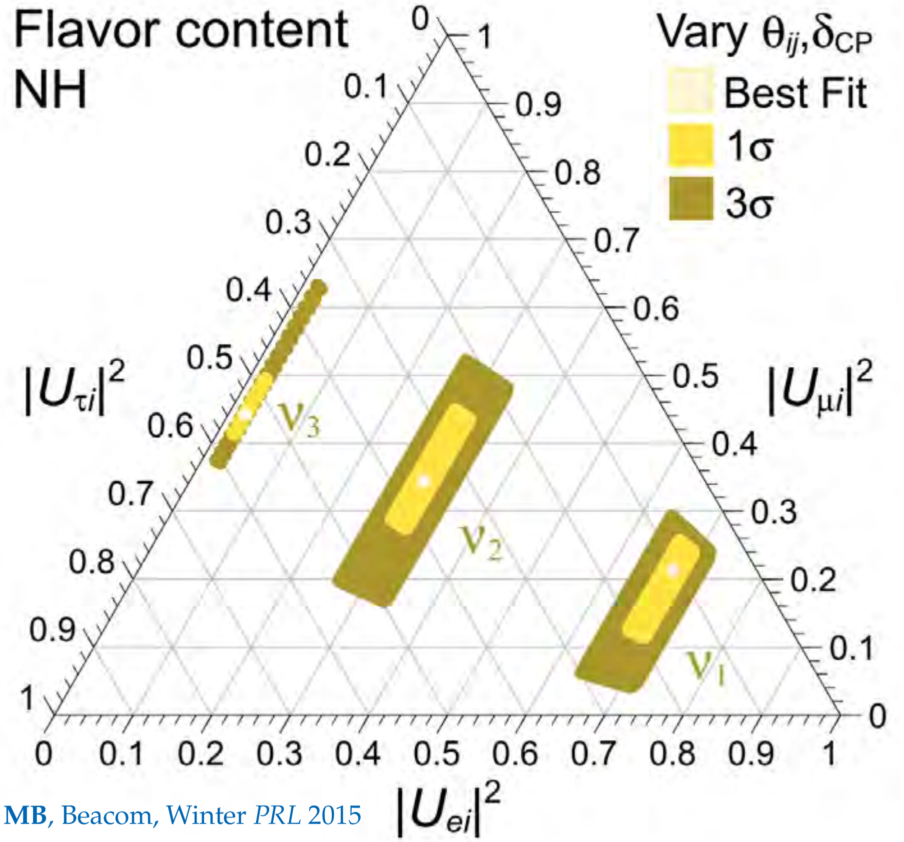
Flavor content of mass eigenstates:

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

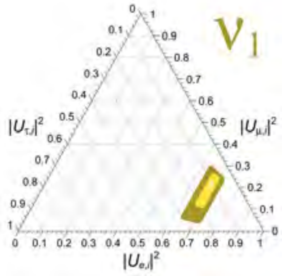
What does neutrino decay change?

Flavor composition ⟺ Spectrum shape ⟺ Event rate

E.g.,

$$\underbrace{\nu_2, \nu_3 \to \nu_1}$$

ν_1 lightest and stable
(normal mass ordering)



$$\underbrace{\nu_1, \nu_2 \to \nu_3}$$

ν_3 lightest and stable
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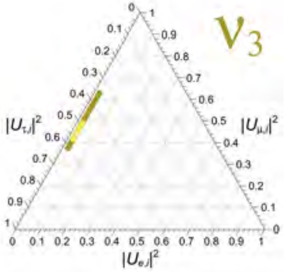
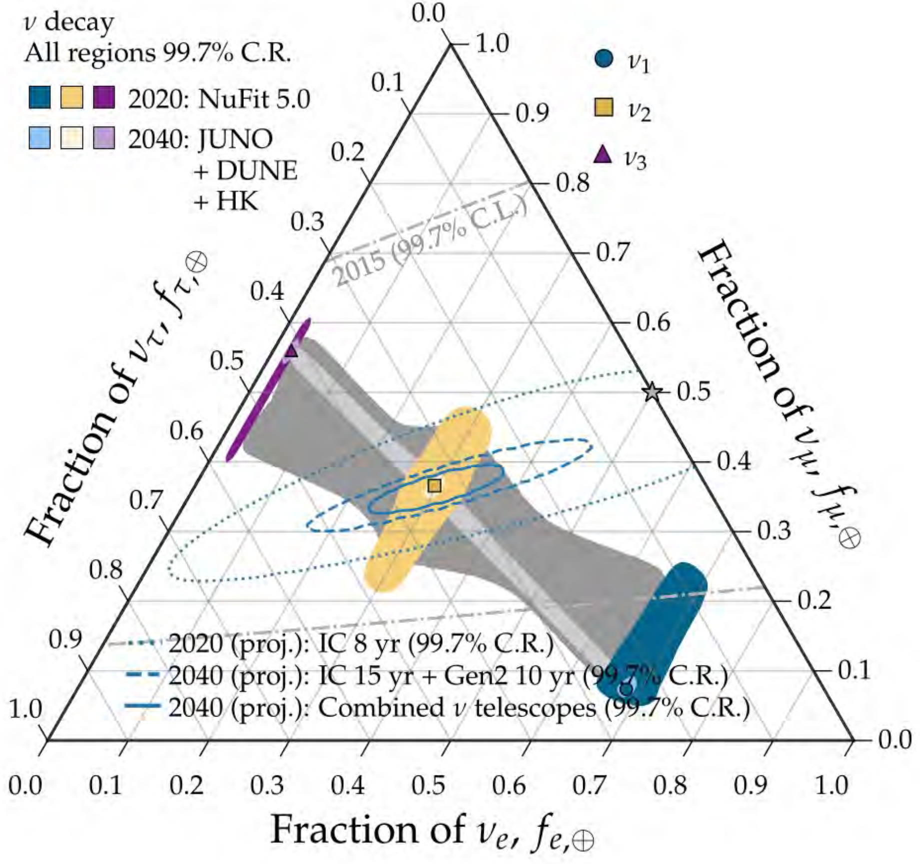


What does neutrino decay change?

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

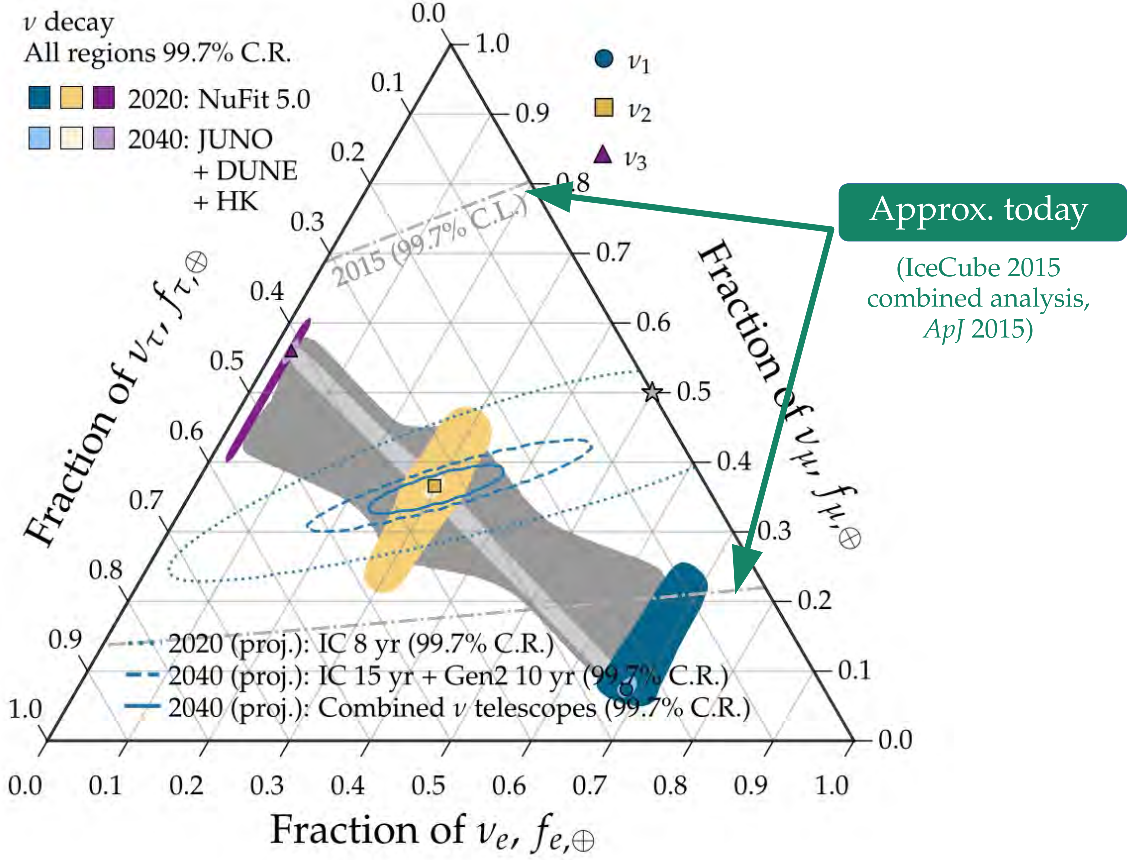
Flavor composition ⟷ Spectrum shape ⟷ Event rate



What does neutrino decay change?

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

Flavor composition ⟺ Spectrum shape ⟺ Event rate



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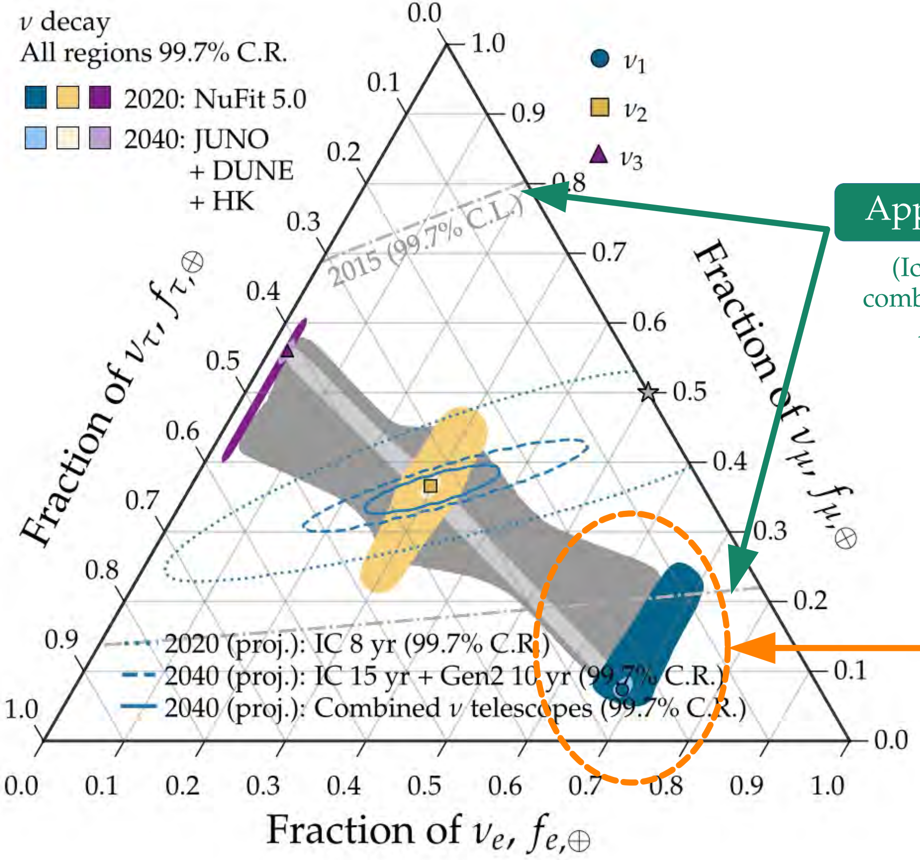
Flavor composition ⟺ Spectrum shape ⟺ Event rate



Approx. today

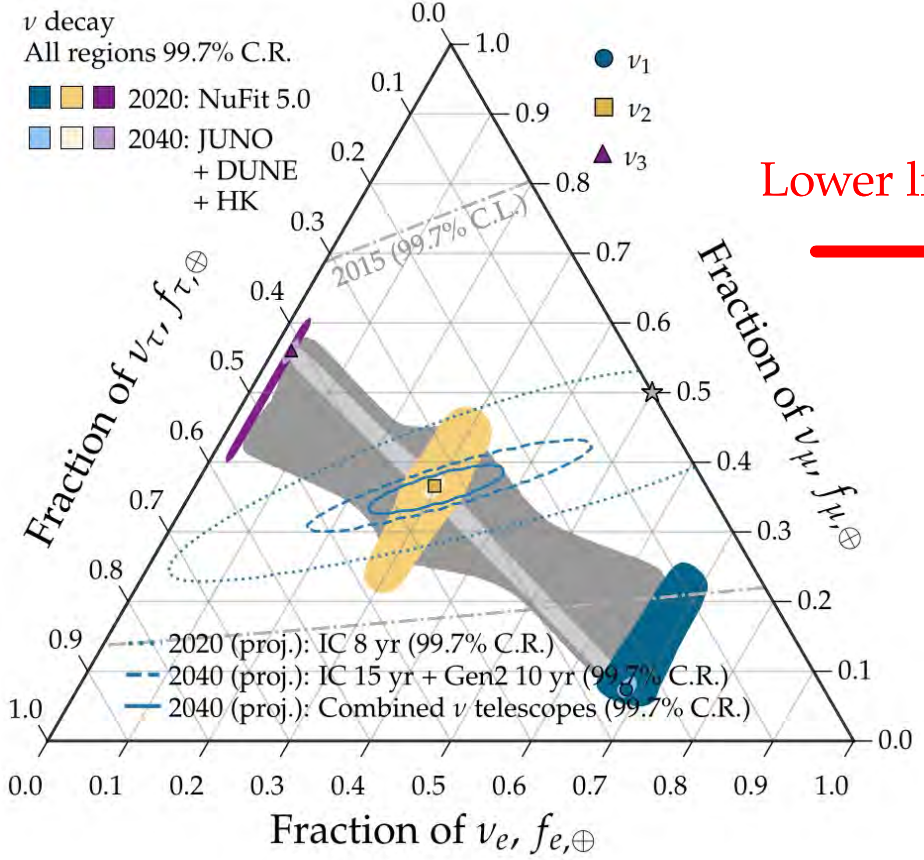
(IceCube 2015 combined analysis, *ApJ* 2015)

Complete decay into ν_1 disfavored by 2015 IceCube flavor measurement

What does neutrino decay change?

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

Flavor composition ⟺ Spectrum shape ⟺ Event rate

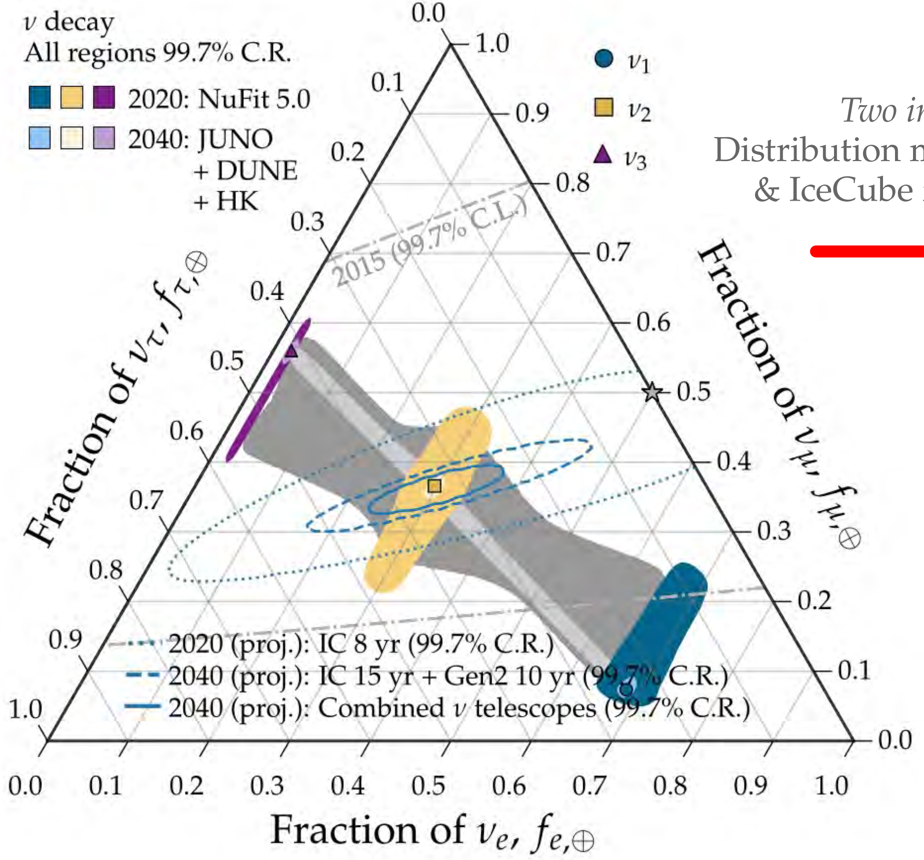


Lower limit on τ/m →

What does neutrino decay change?

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

Flavor composition ⟺ Spectrum shape ⟺ Event rate

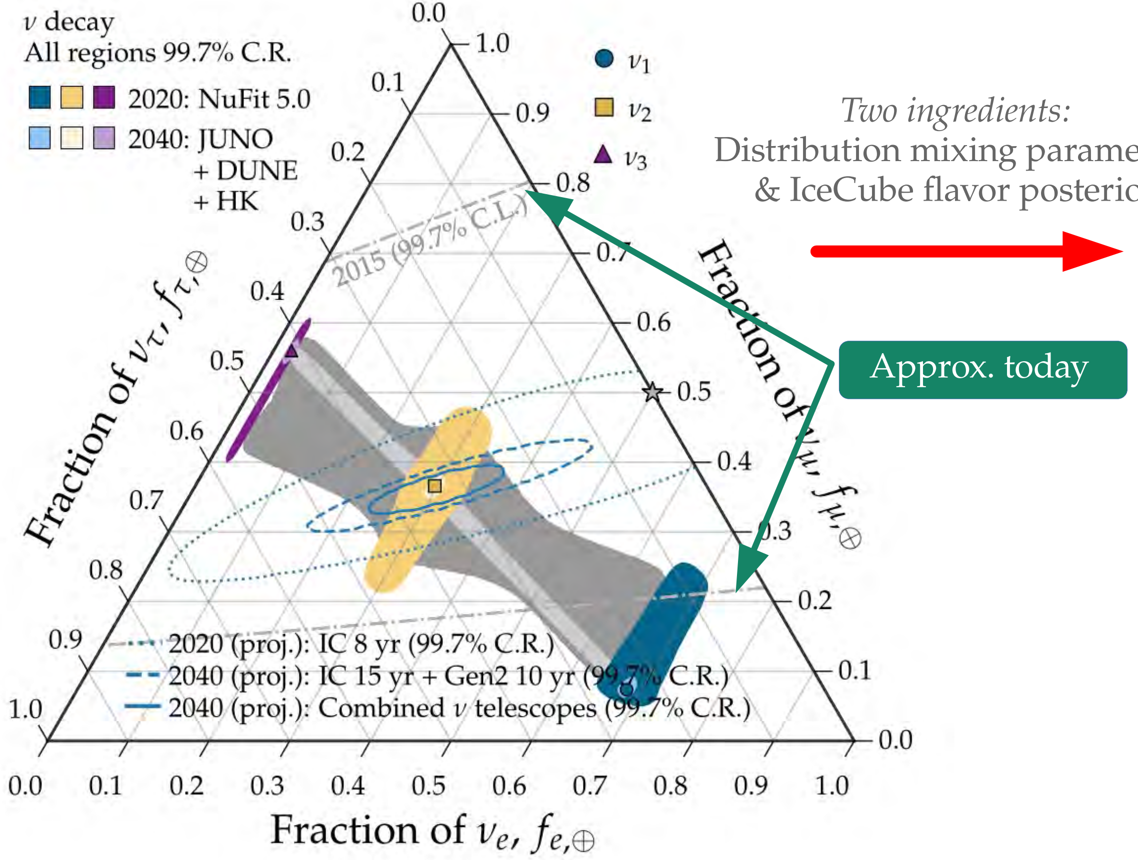


Two ingredients:
Distribution mixing parameters
& IceCube flavor posterior

What does neutrino decay change?

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

Flavor composition ⟺ Spectrum shape ⟺ Event rate



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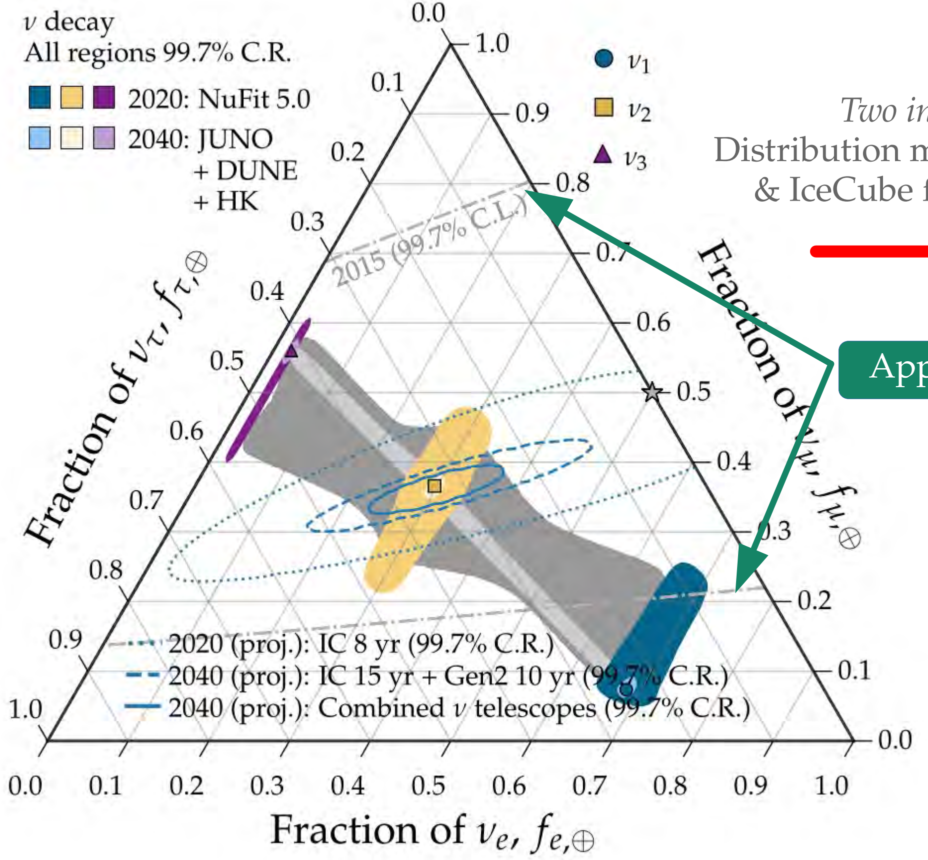
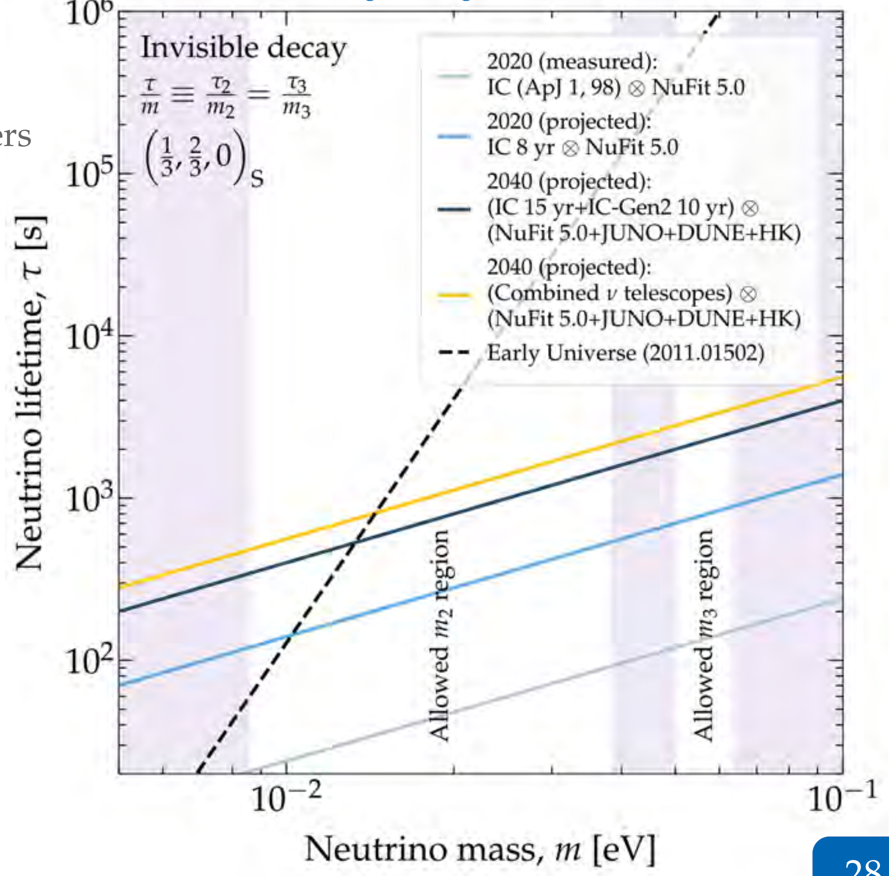
Flavor composition ⇔ Spectrum shape ⇔ Event rate



Two ingredients:
Distribution mixing parameters
& IceCube flavor posterior

Approx. today

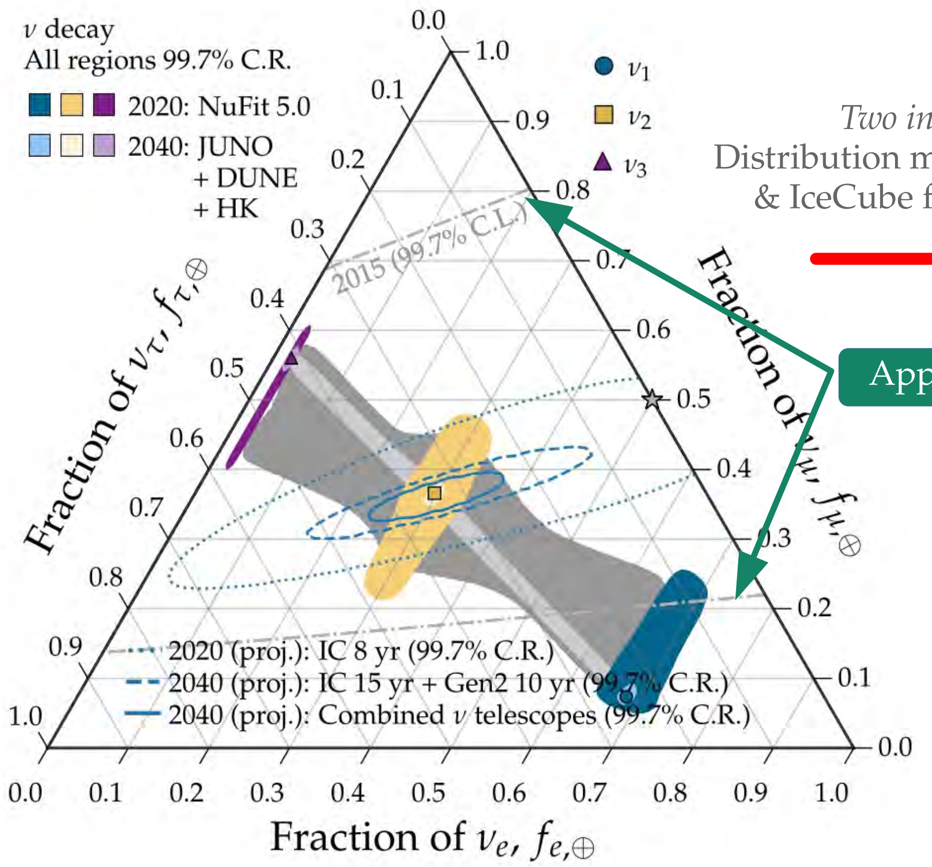
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



What does neutrino decay change?

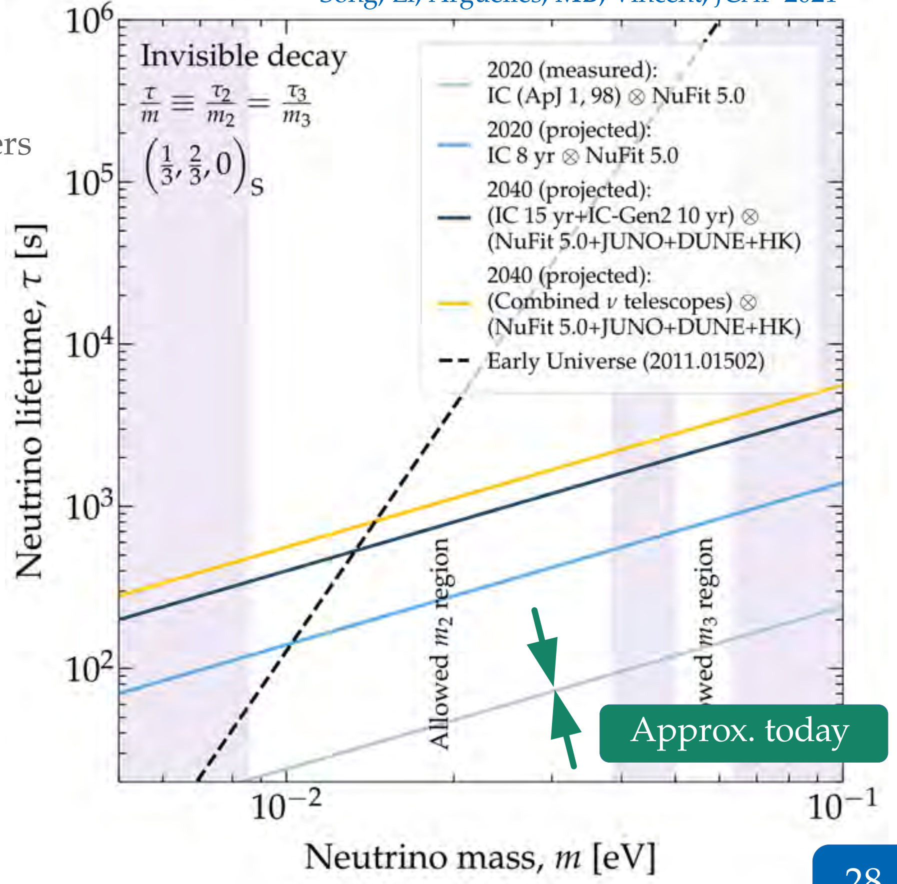
See also: Beacom *et al.*, *PRL* 2002 / Baerwald, **MB**, Winter, *JCAP* 2012 / **MB**, Beacom, Murase, *PRD* 2017 / Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / **MB**, 2004.06844

Flavor composition ⟺ Spectrum shape ⟺ Event rate



Two ingredients:
Distribution mixing parameters & IceCube flavor posterior

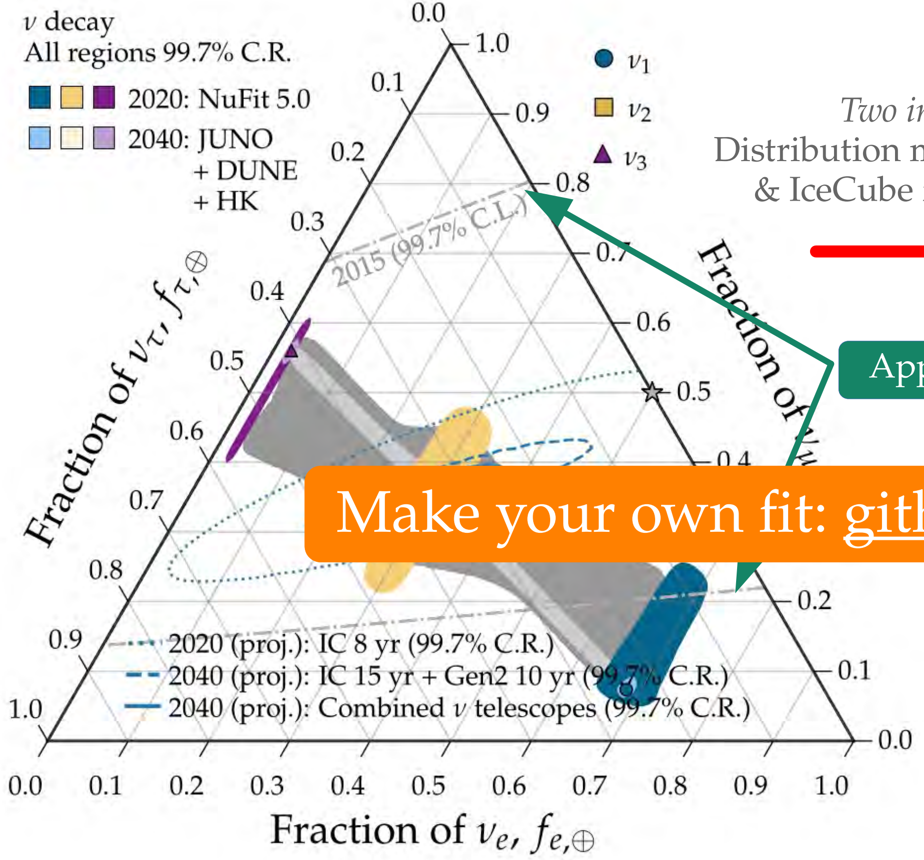
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



What does neutrino decay change?

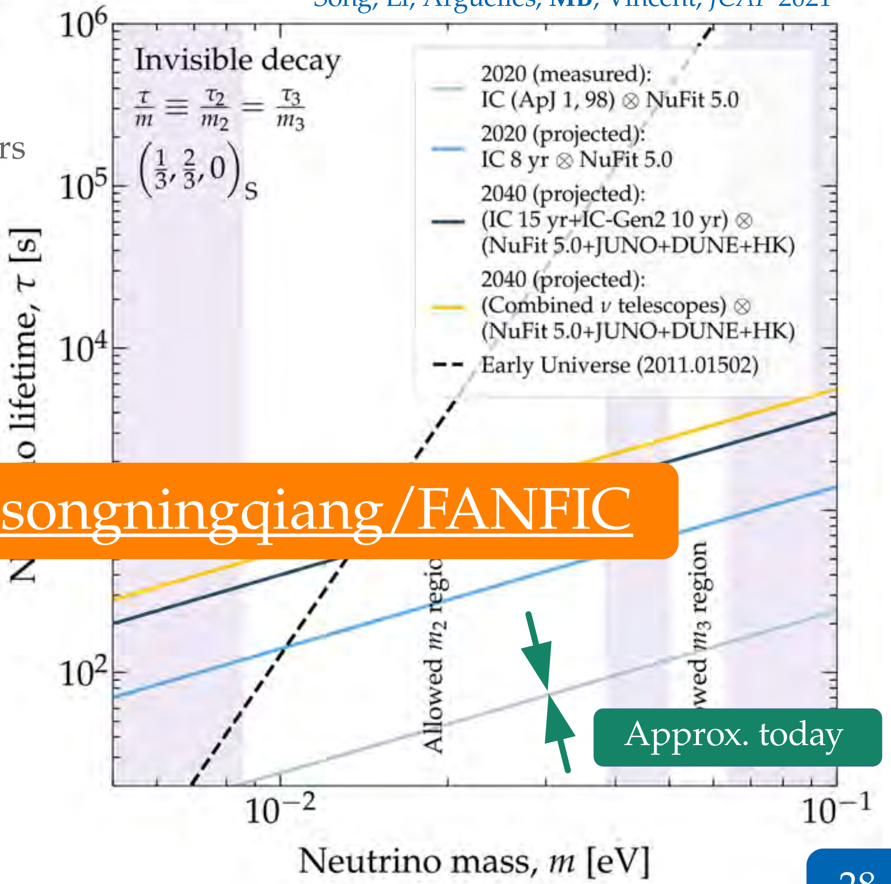
See also: Beacom *et al.*, *PRL* 2002 / Baerwald, **MB**, Winter, *JCAP* 2012 / **MB**, Beacom, Murase, *PRD* 2017 / Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / **MB**, 2004.06844

Flavor composition ⟺ Spectrum shape ⟺ Event rate



Two ingredients:
Distribution mixing parameters & IceCube flavor posterior

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



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

Towards
high statistics

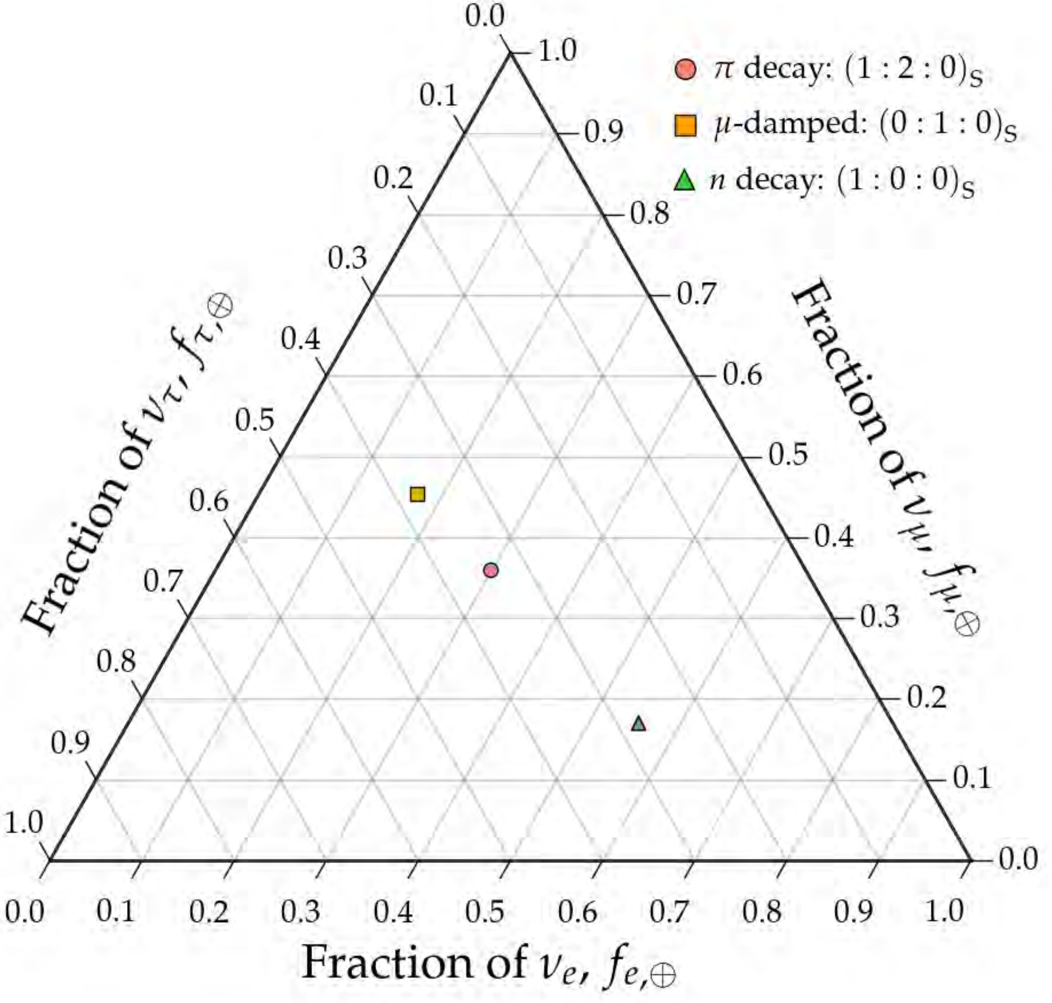
TeV–PeV
ν telescopes
2030s

Strebe/Wikipedia

Measuring flavor composition: 2015–2040

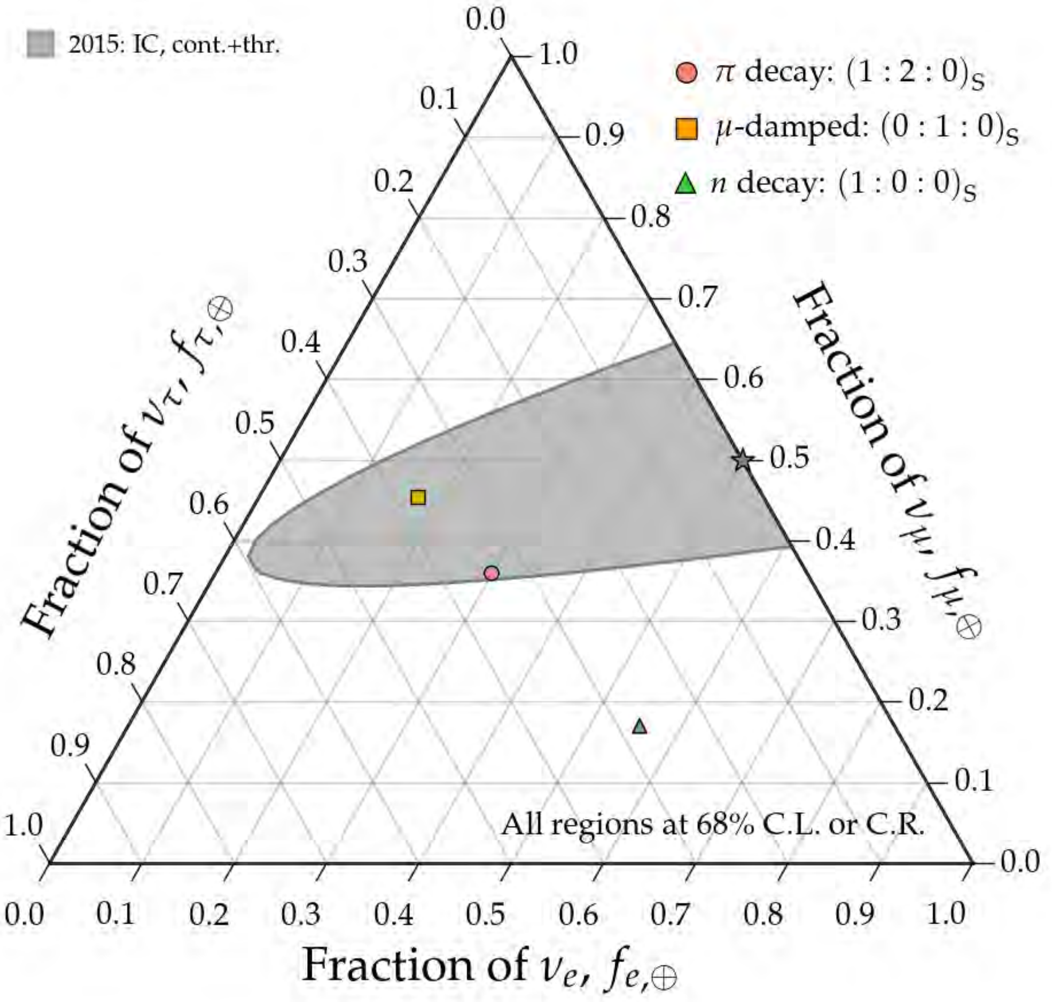
IceCube Collab., *EPJC* 2022
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
IceCube Collab., *PRD* 2019
IceCube Collab., *ApJ* 2015

Measuring flavor composition: 2015–2040



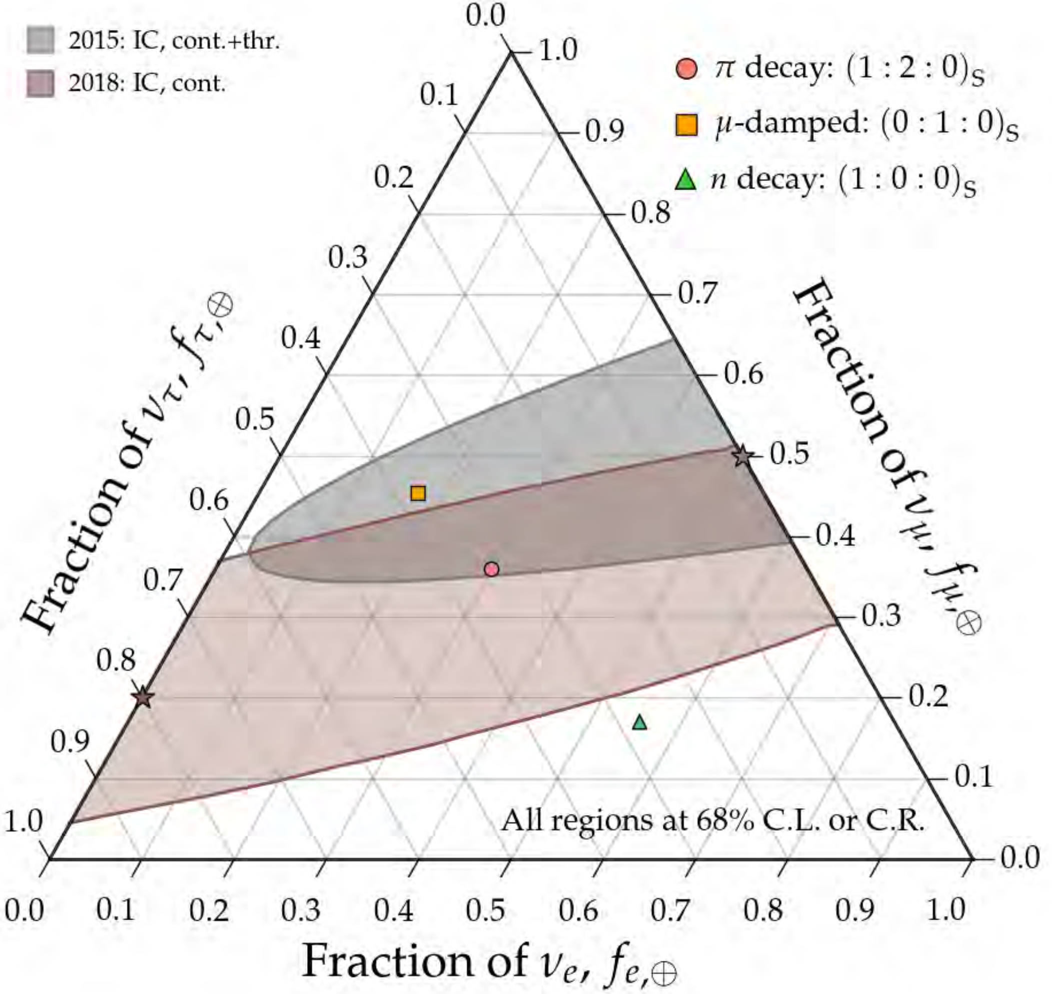
IceCube Collab., *EPJC* 2022
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
IceCube Collab., *PRD* 2019
IceCube Collab., *ApJ* 2015

Measuring flavor composition: 2015–2040



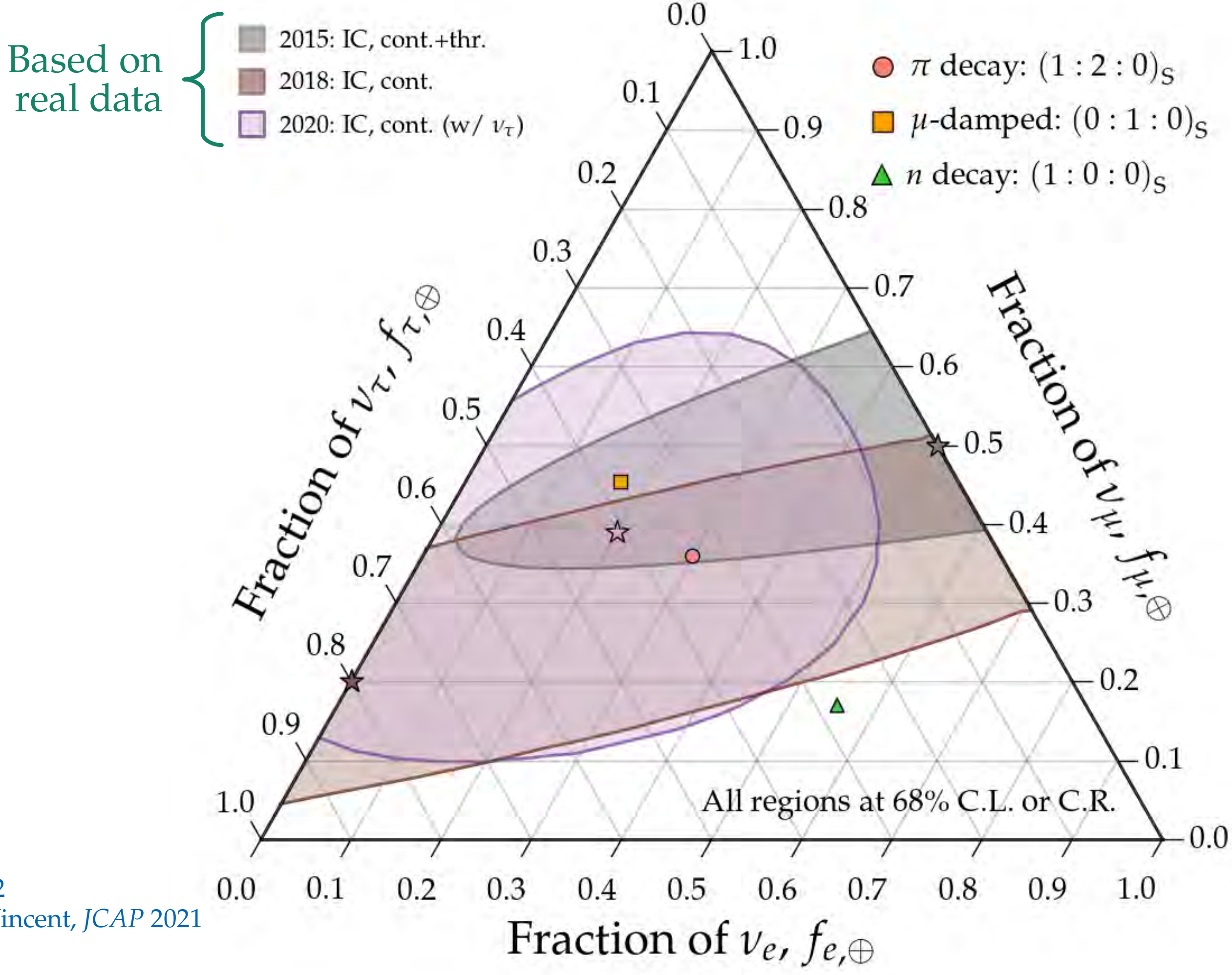
IceCube Collab., *EPJC* 2022
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
IceCube Collab., *PRD* 2019
IceCube Collab., *ApJ* 2015

Measuring flavor composition: 2015–2040



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

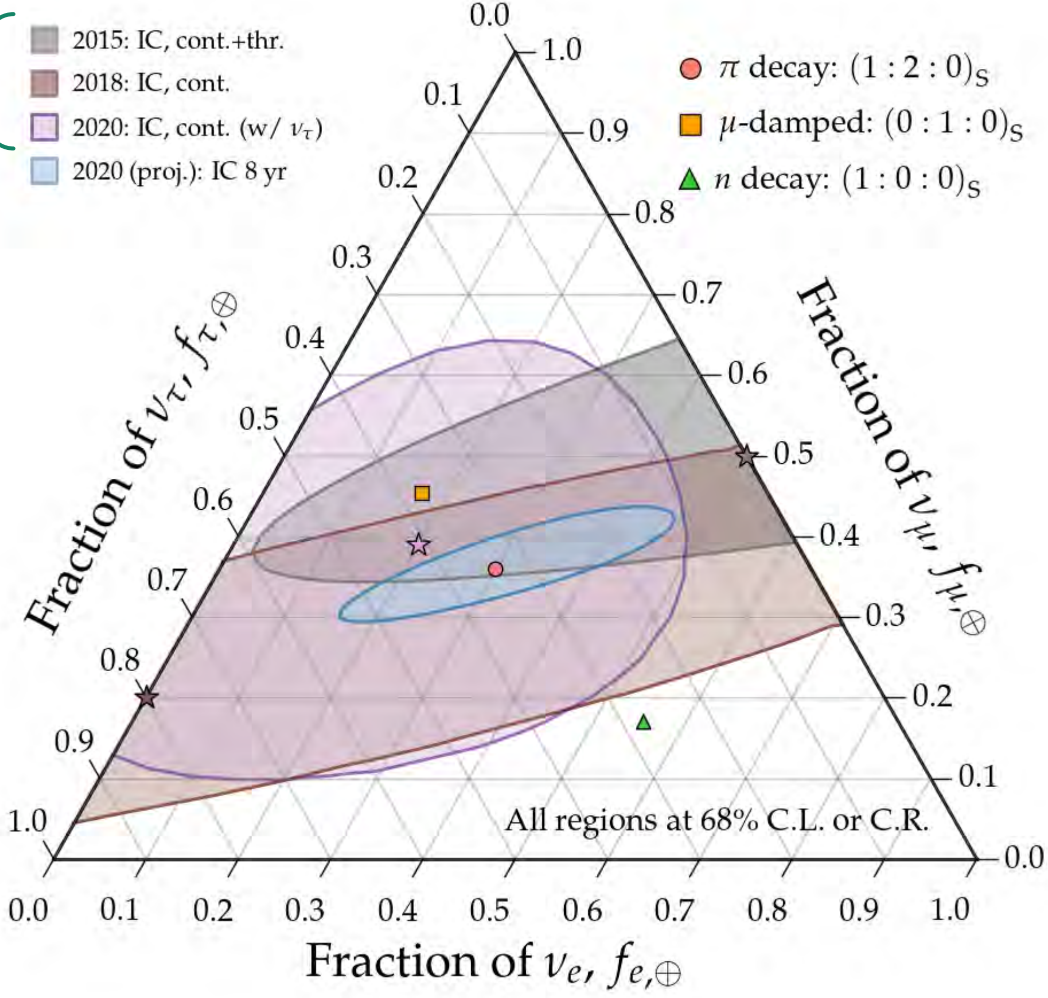
Measuring flavor composition: 2015–2040



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

Measuring flavor composition: 2015–2040

Based on real data



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

Measuring flavor composition: 2015–2040

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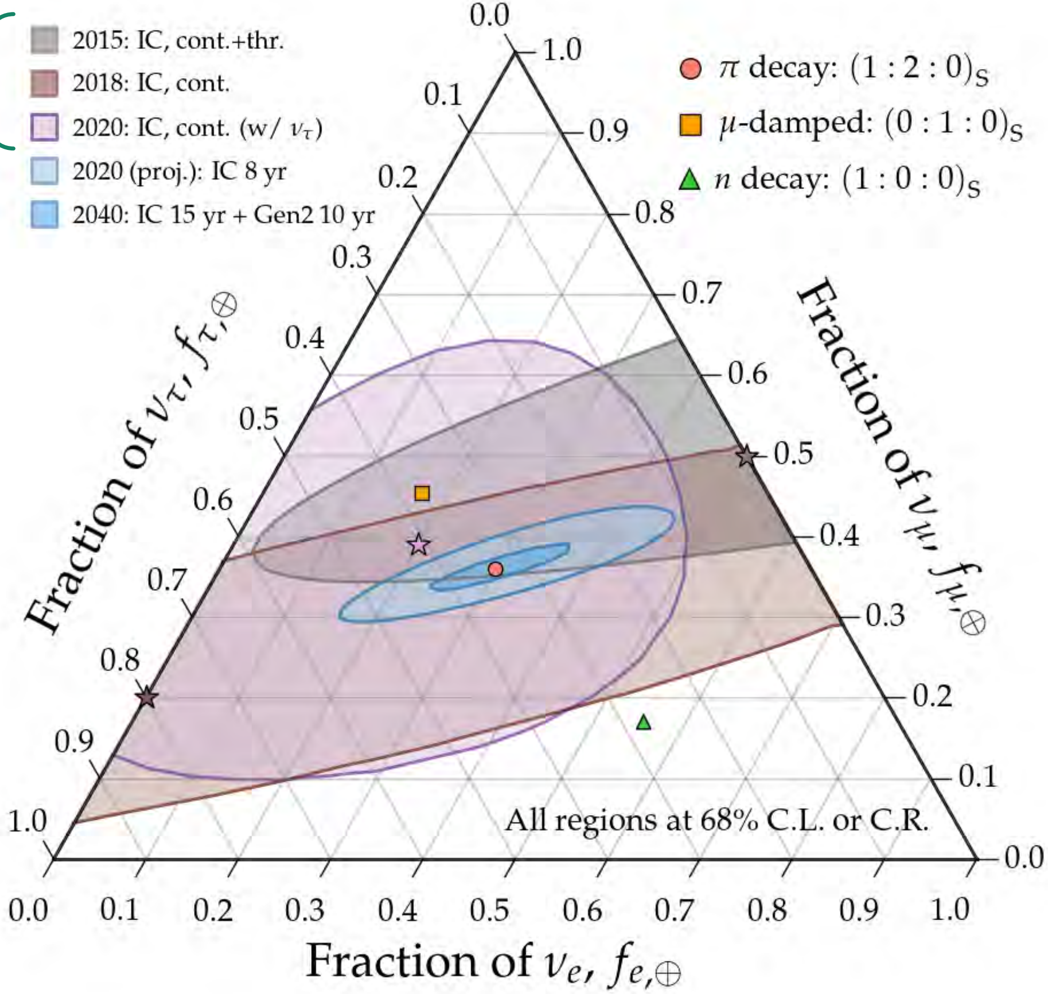

IceCube Collab., *EPJC* 2022
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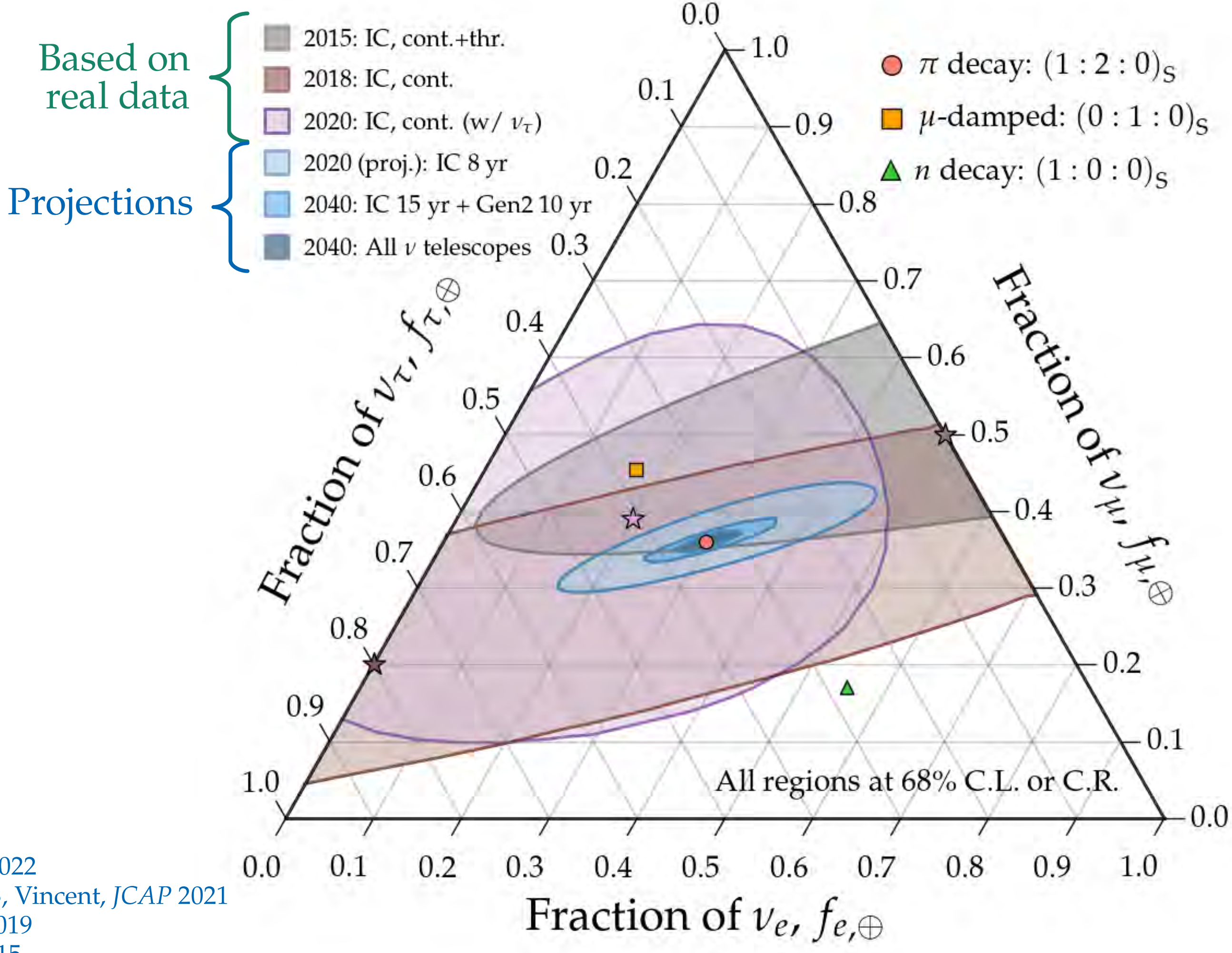
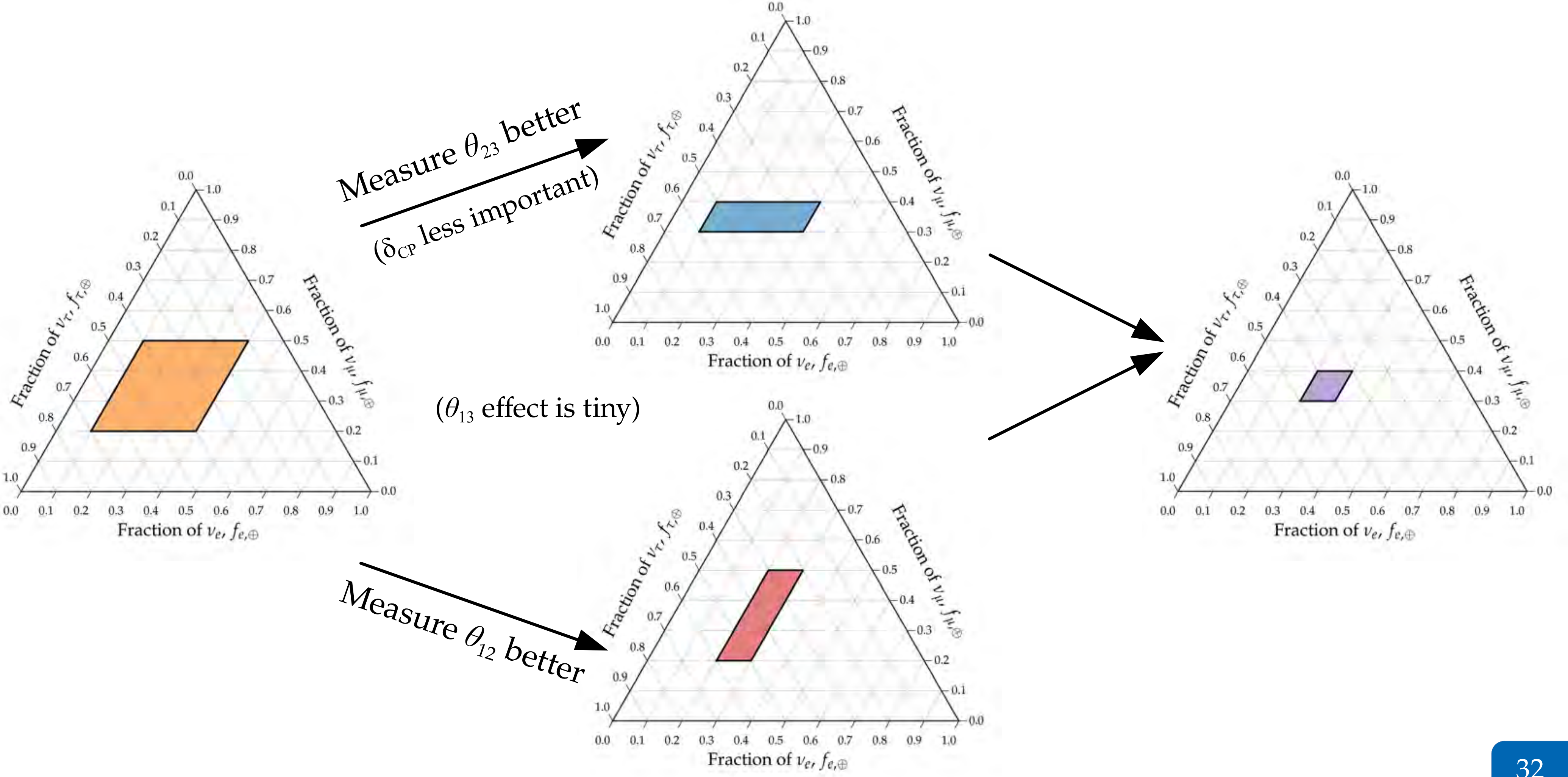


IceCube Collab., *EPJC* 2022
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
IceCube Collab., *PRD* 2019
IceCube Collab., *ApJ* 2015

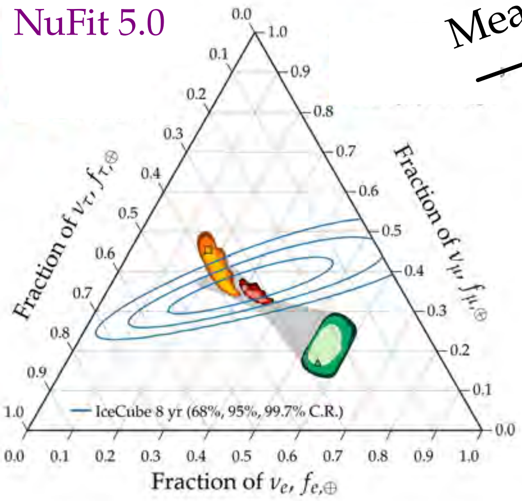
How knowing the mixing parameters better helps



How knowing the mixing parameters better helps

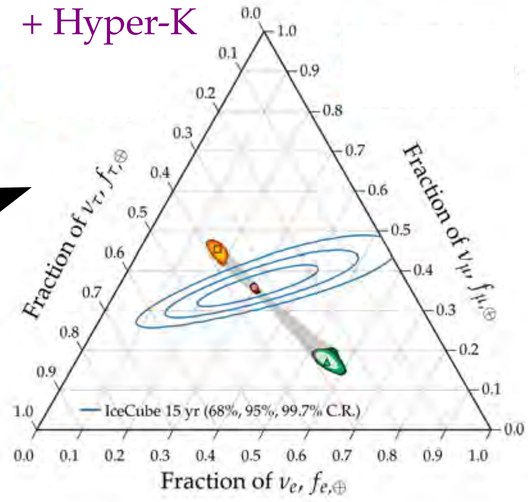
2020

NuFit 5.0



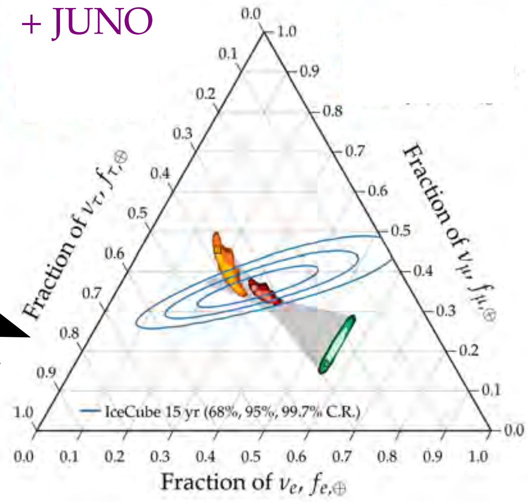
Measure θ_{23} better

+ Hyper-K



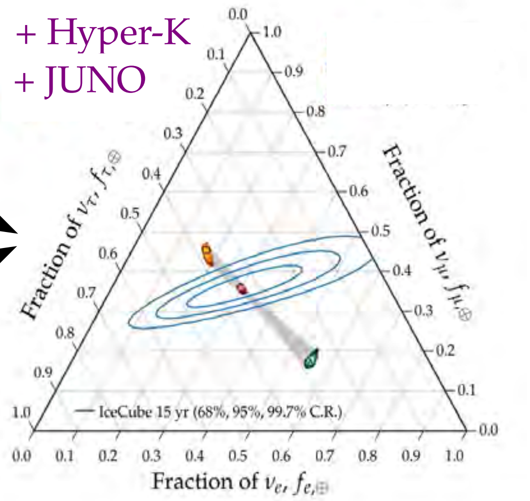
Measure θ_{12} better

+ JUNO



~2030

+ Hyper-K
+ JUNO

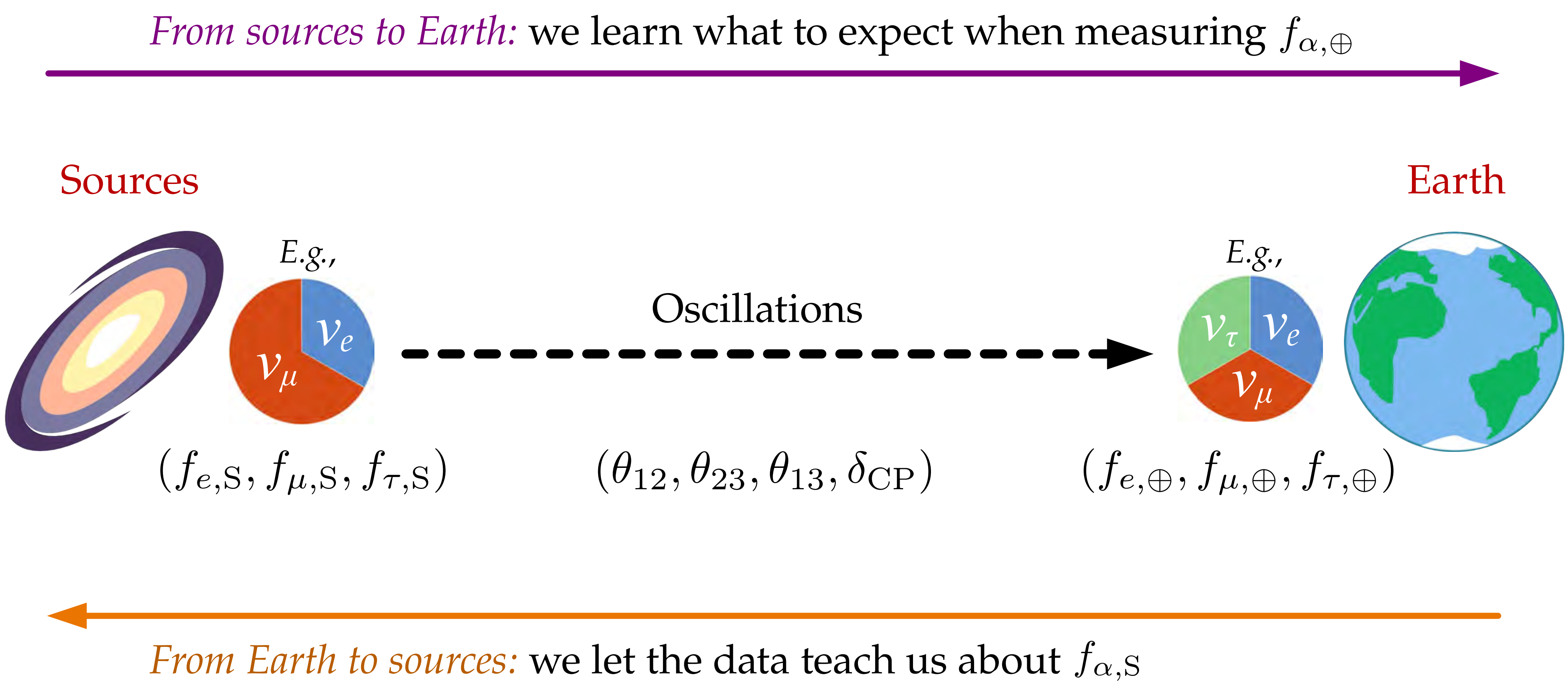


In our results:
JUNO + Hyper-K + DUNE

Marginal improvement til 2040

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

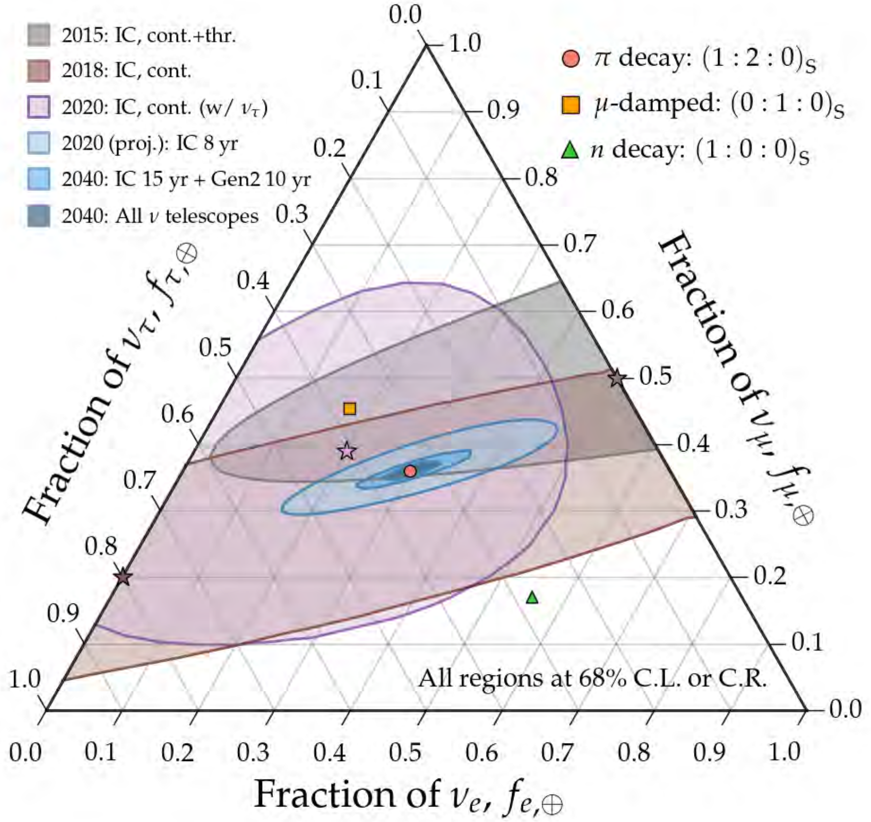
Back to the sources



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

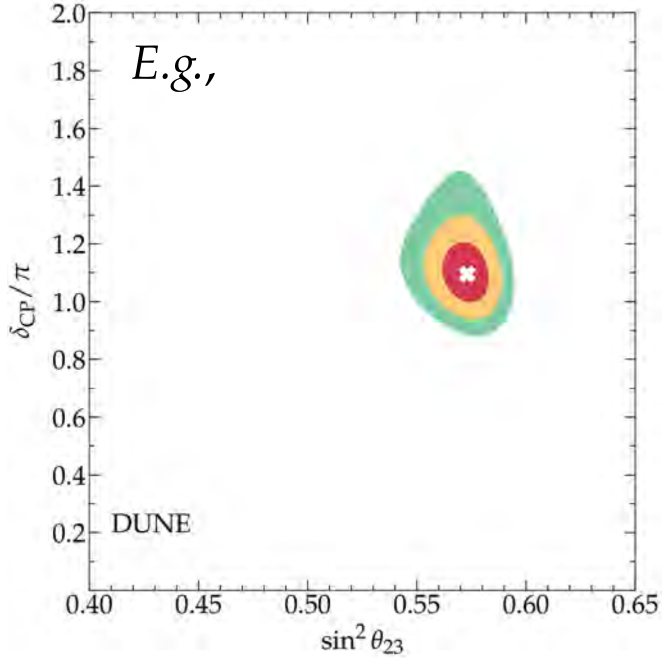
Inferring the flavor composition at the sources

Ingredient #1:
Flavor ratios measured at Earth,
$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$



Ingredient #2:
Probability density of mixing parameters $(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{CP})$

$\mathcal{L}(\boldsymbol{\vartheta})$



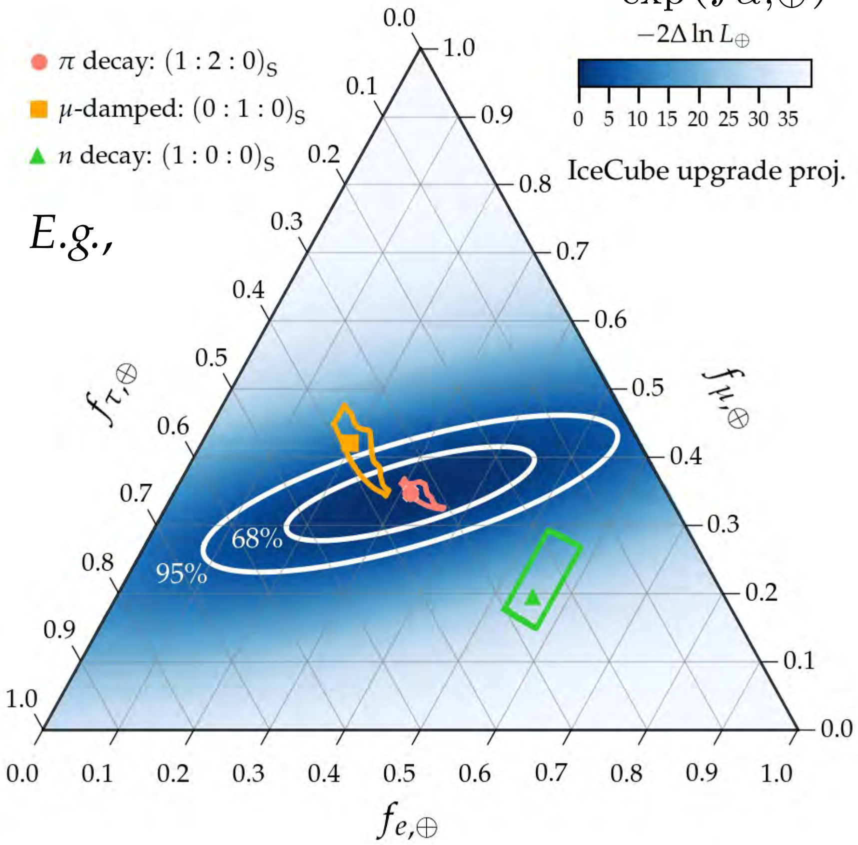
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
MB & Ahlers, *PRL* 2019

Inferring the flavor composition at the sources

Ingredient #1:
Flavor ratios measured at Earth,
$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$

$\mathcal{P}_{\rm exp}(f_{\alpha,\oplus})$

E.g.,



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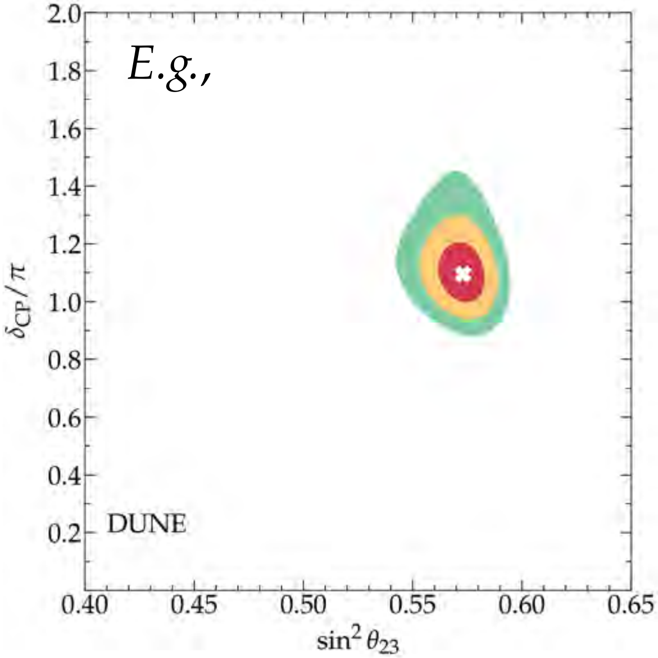
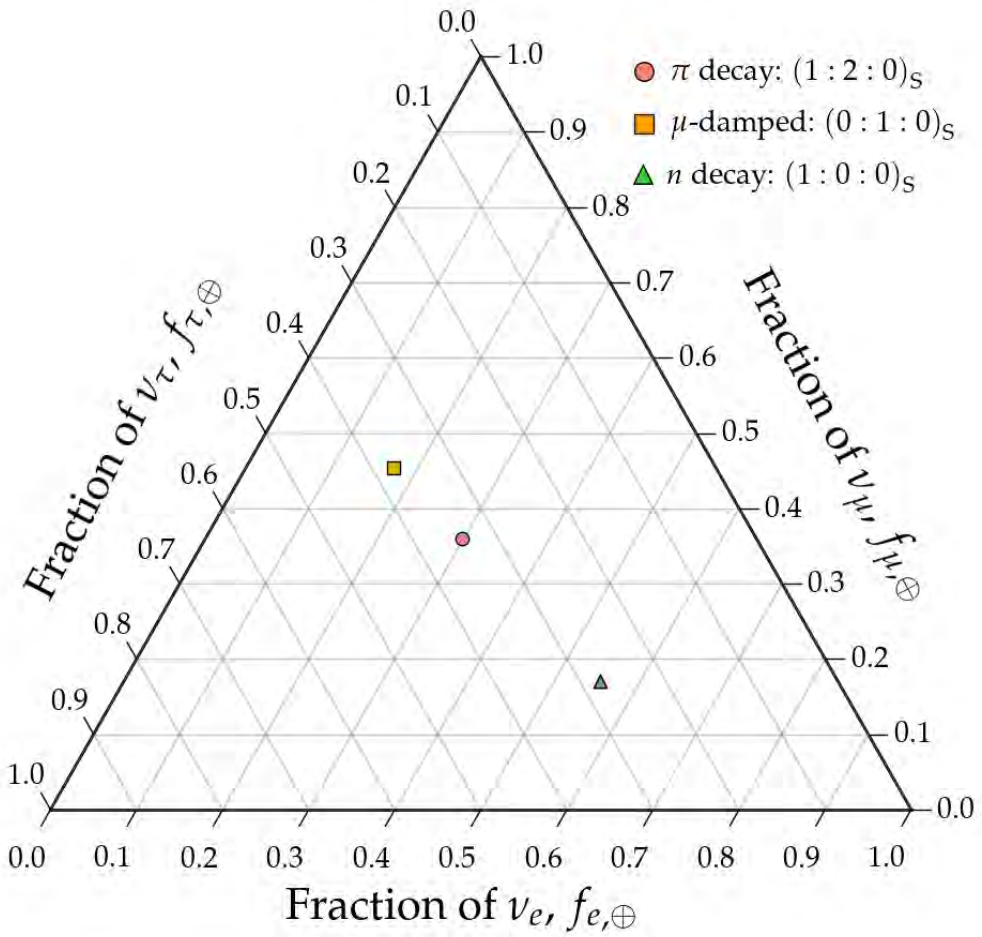


Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
MB & Ahlers, *PRL* 2019

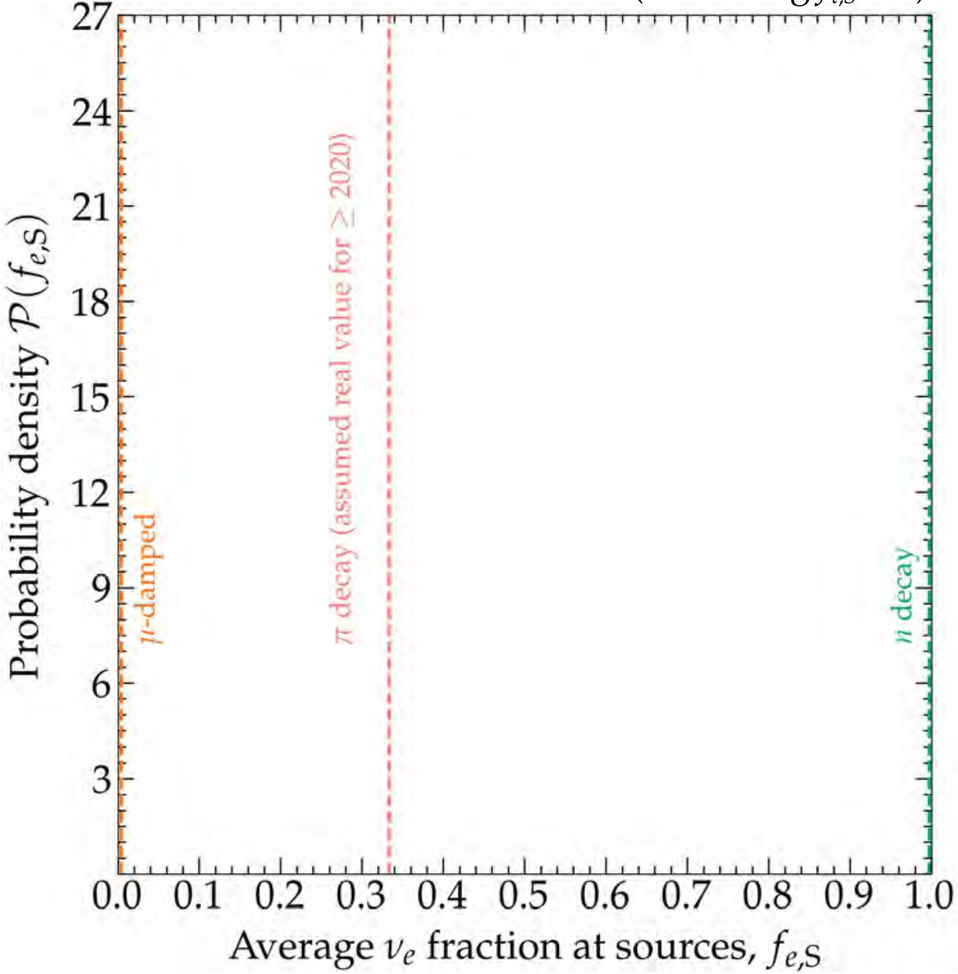
Inferring the flavor composition at the sources

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

Inferring the flavor composition at the sources



(Assuming $f_{\tau,S} = 0$)



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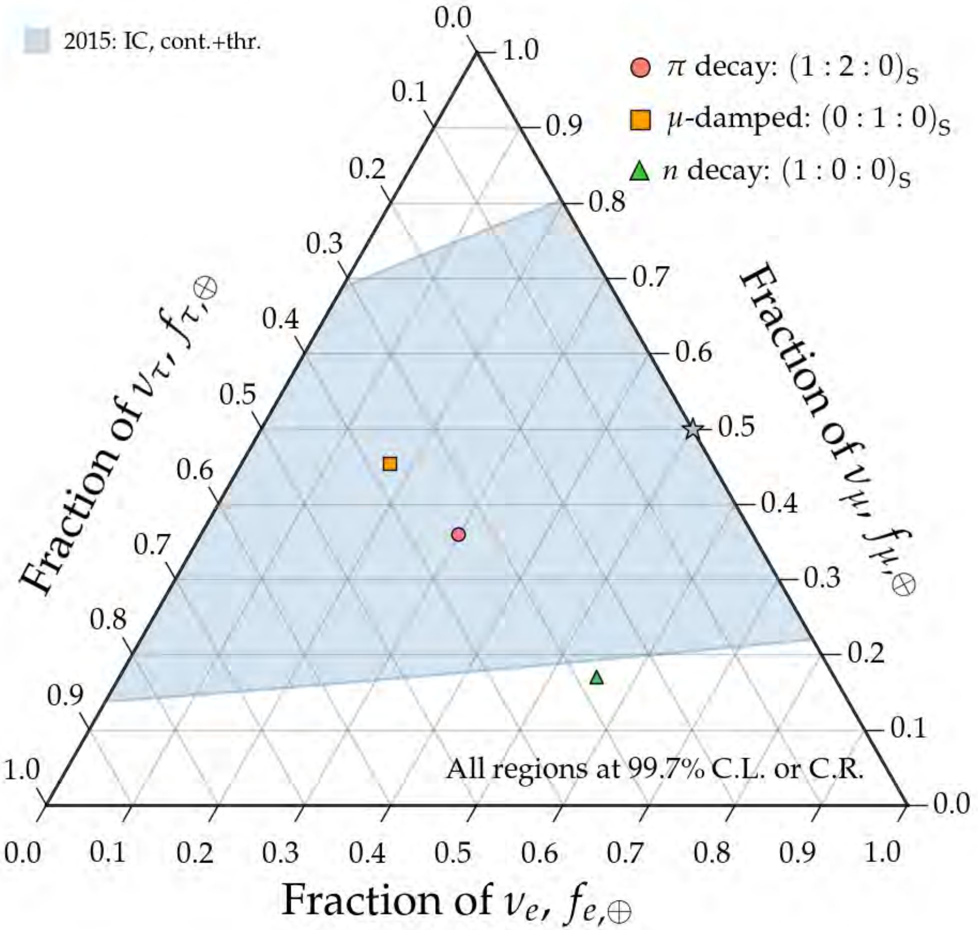

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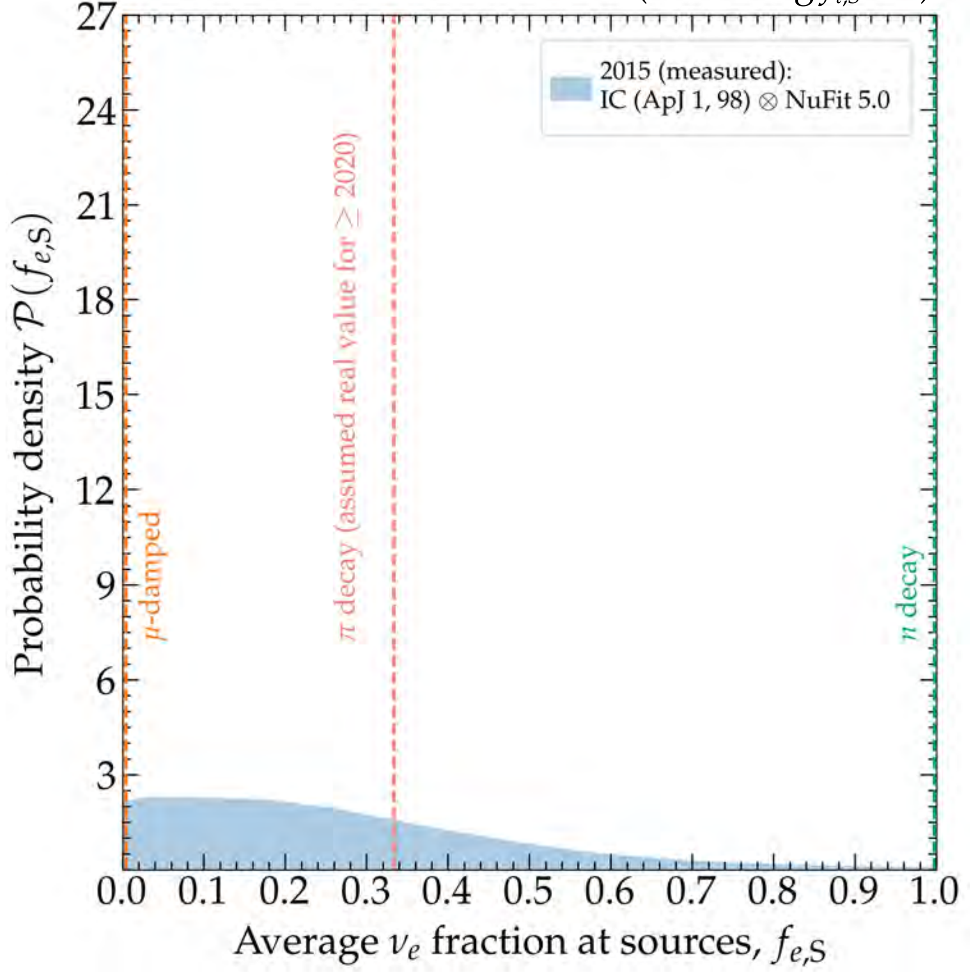

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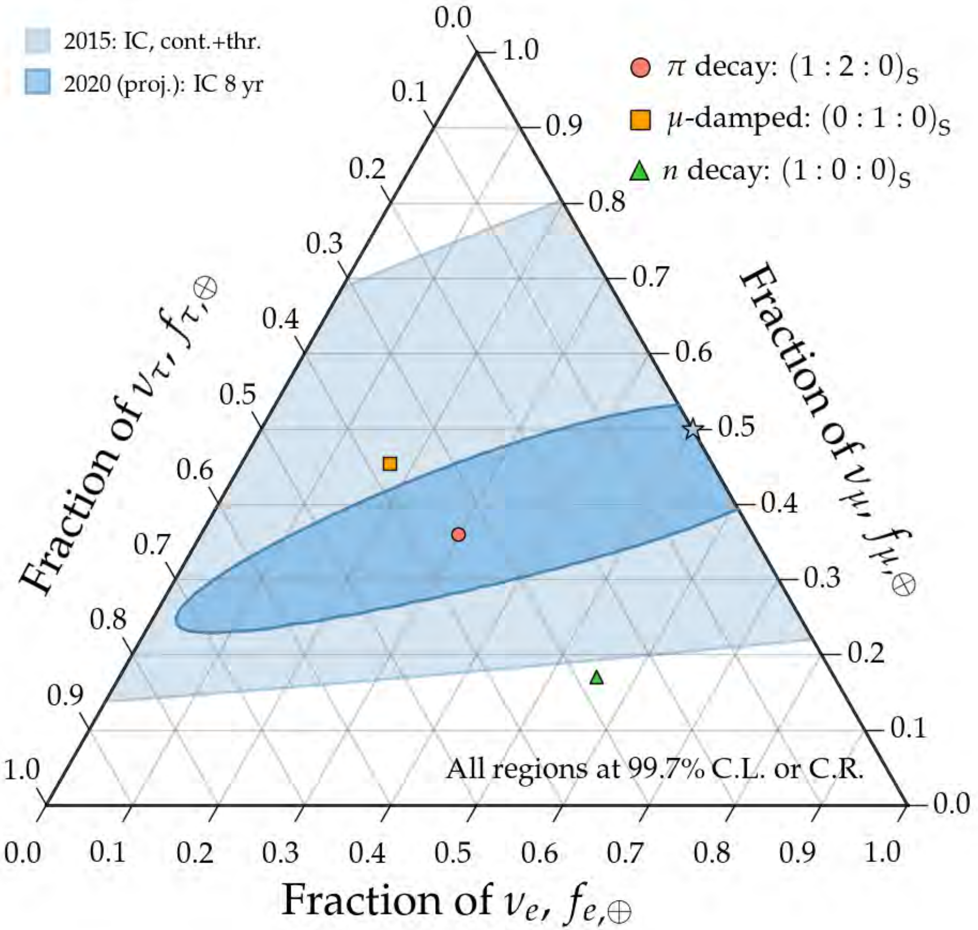
MB & Ahlers, *PRL* 2019

Inferring the flavor composition at the sources



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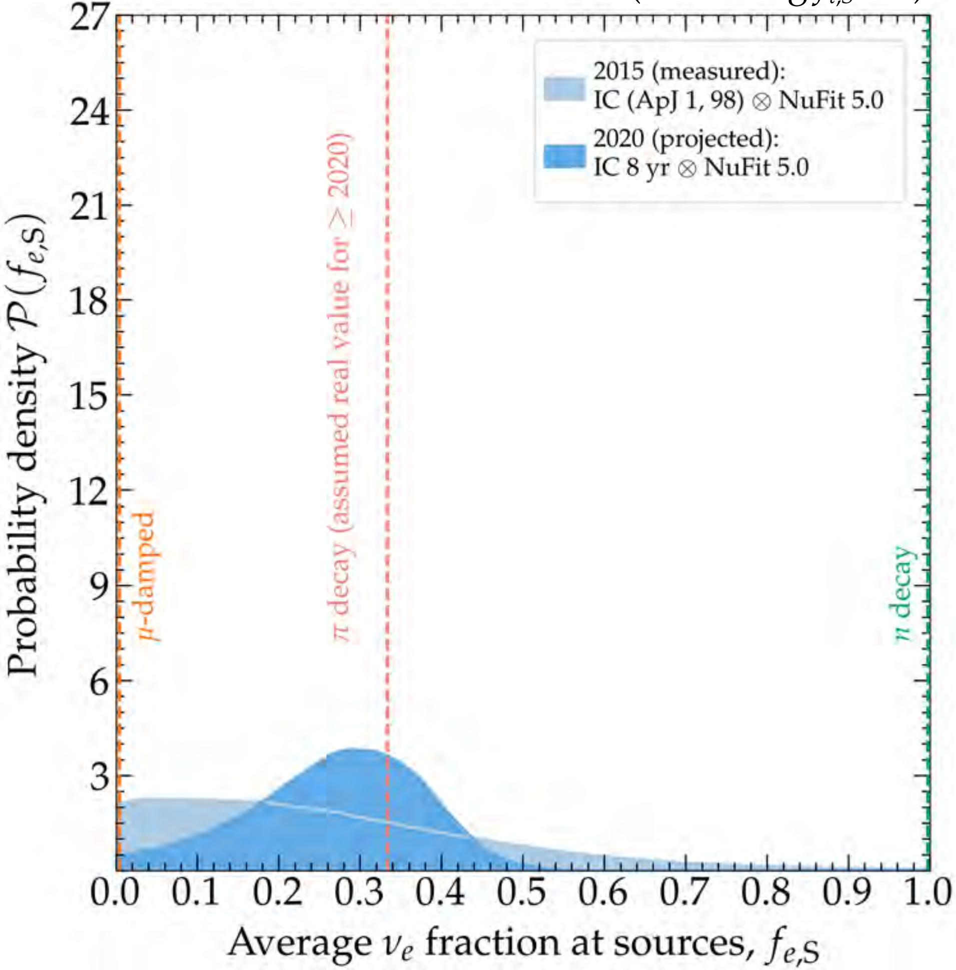

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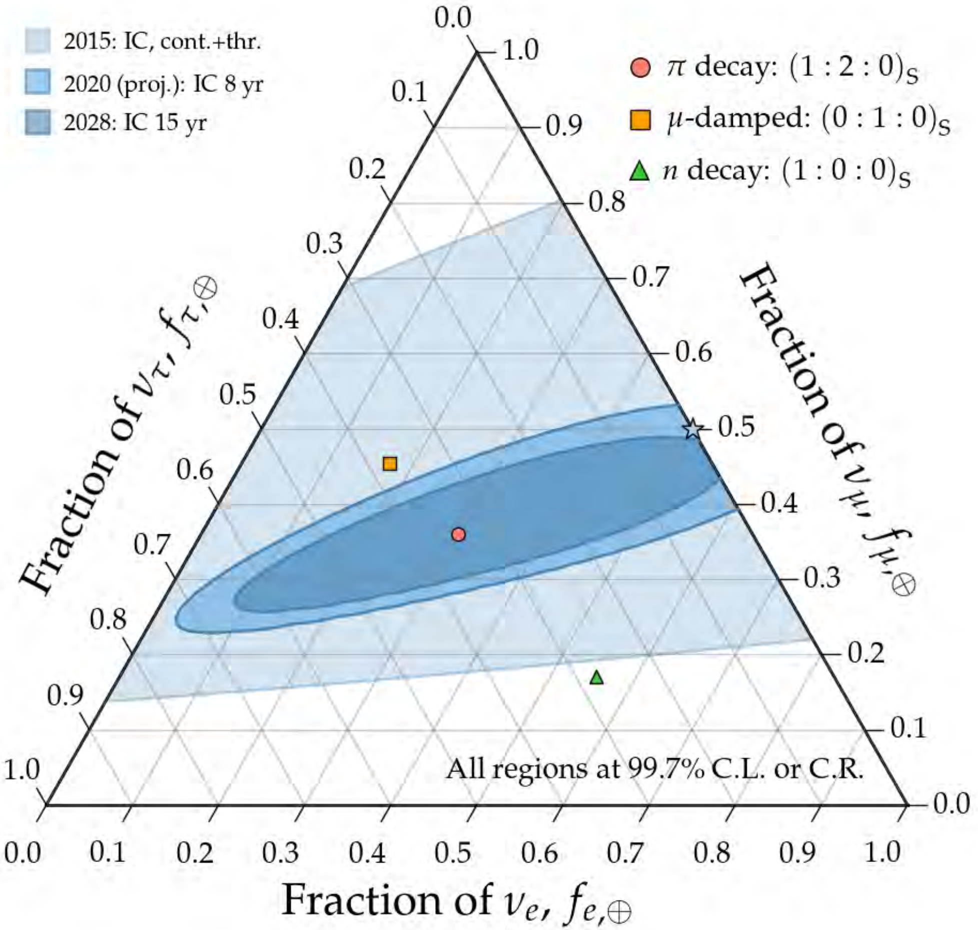

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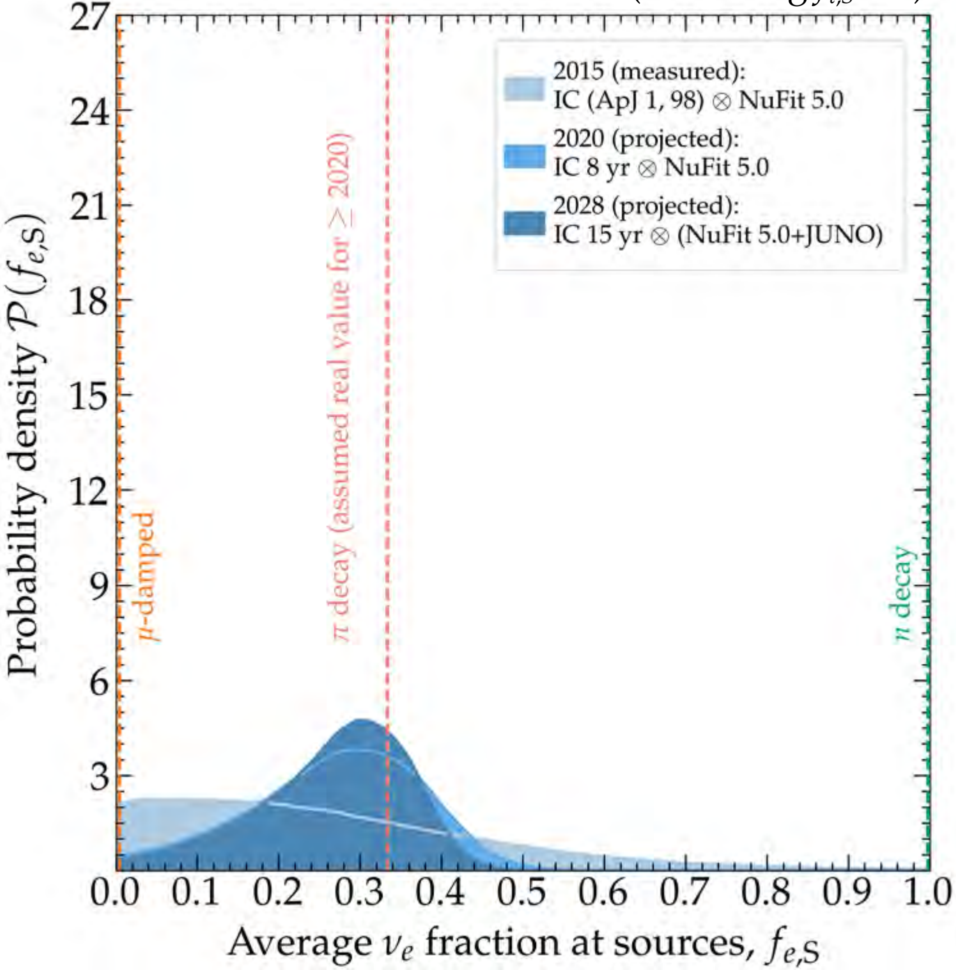

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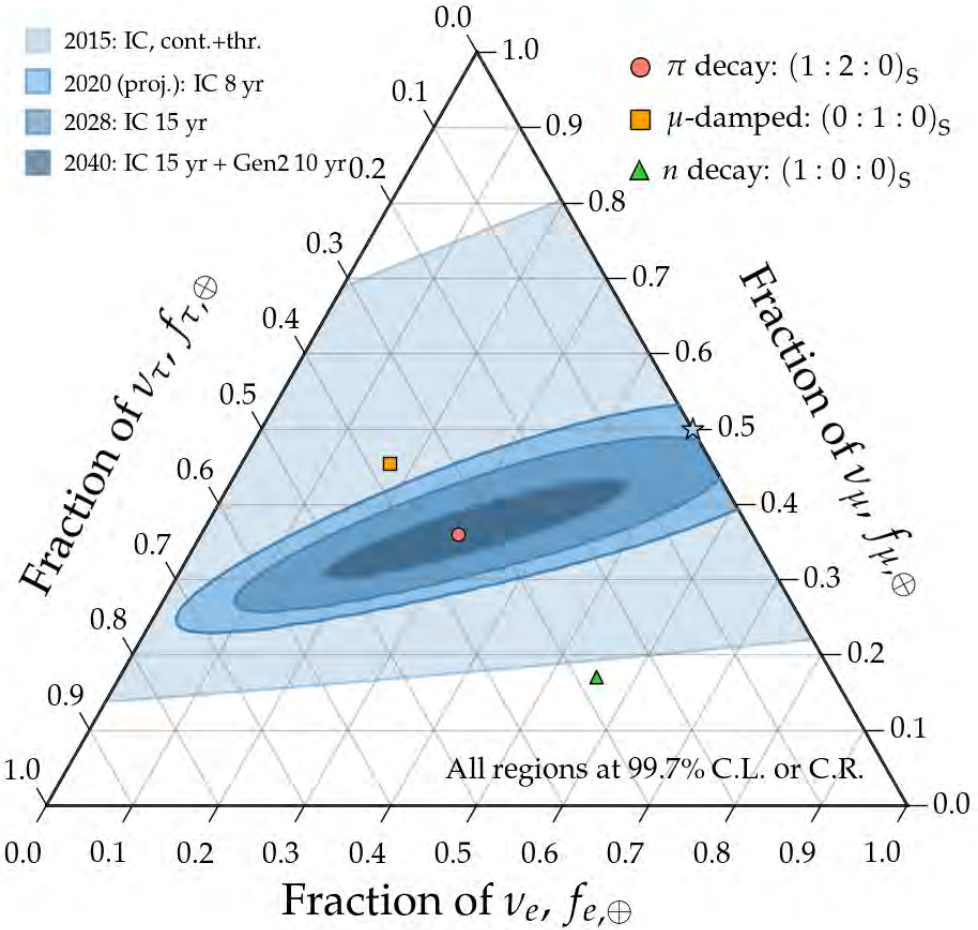

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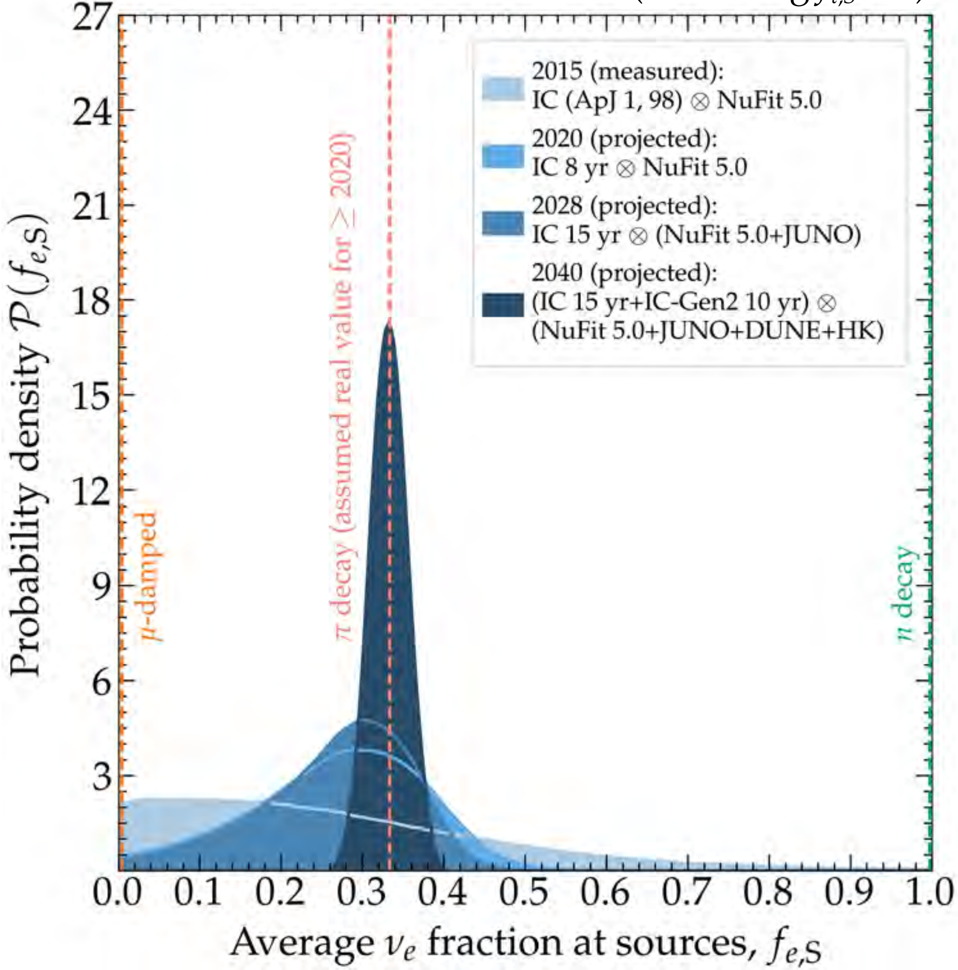

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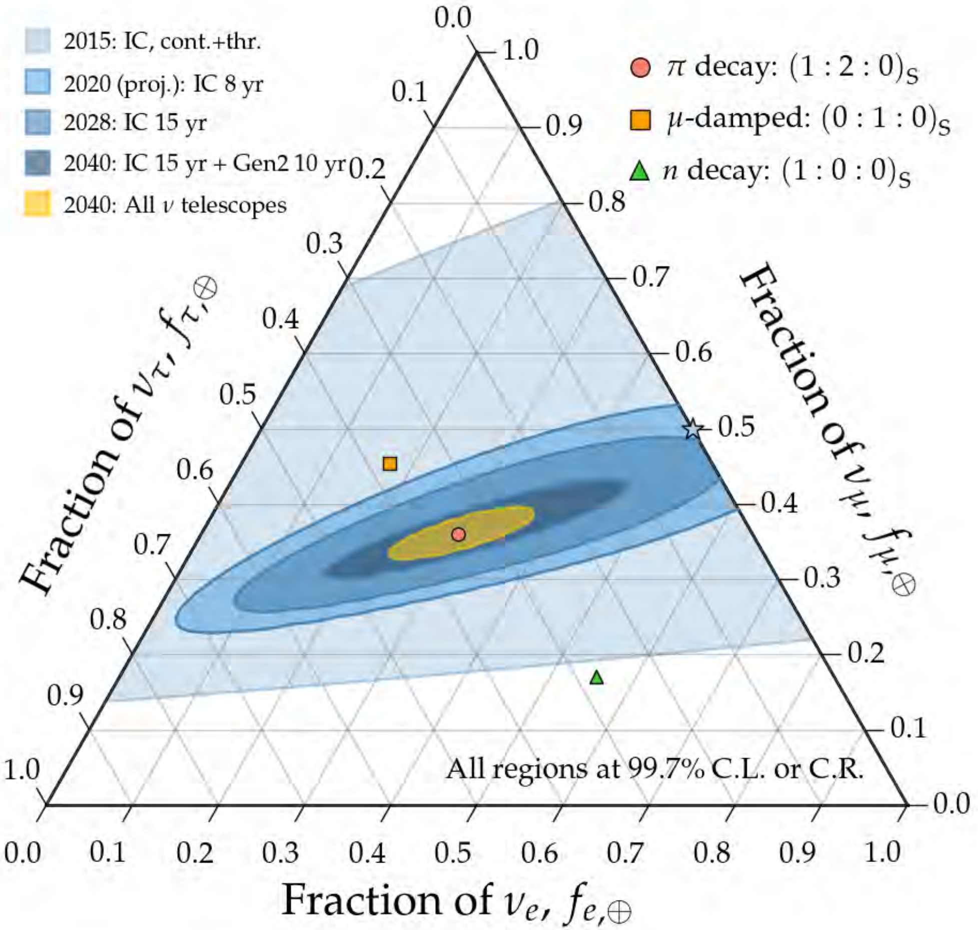
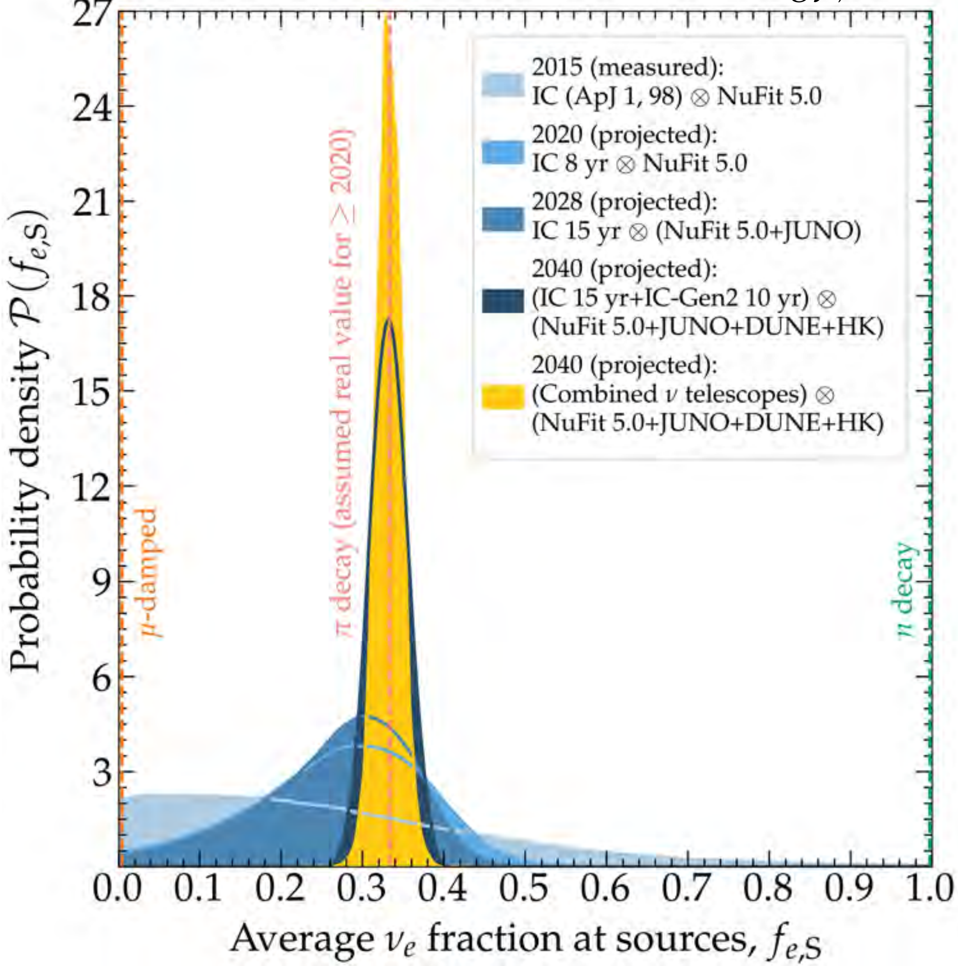


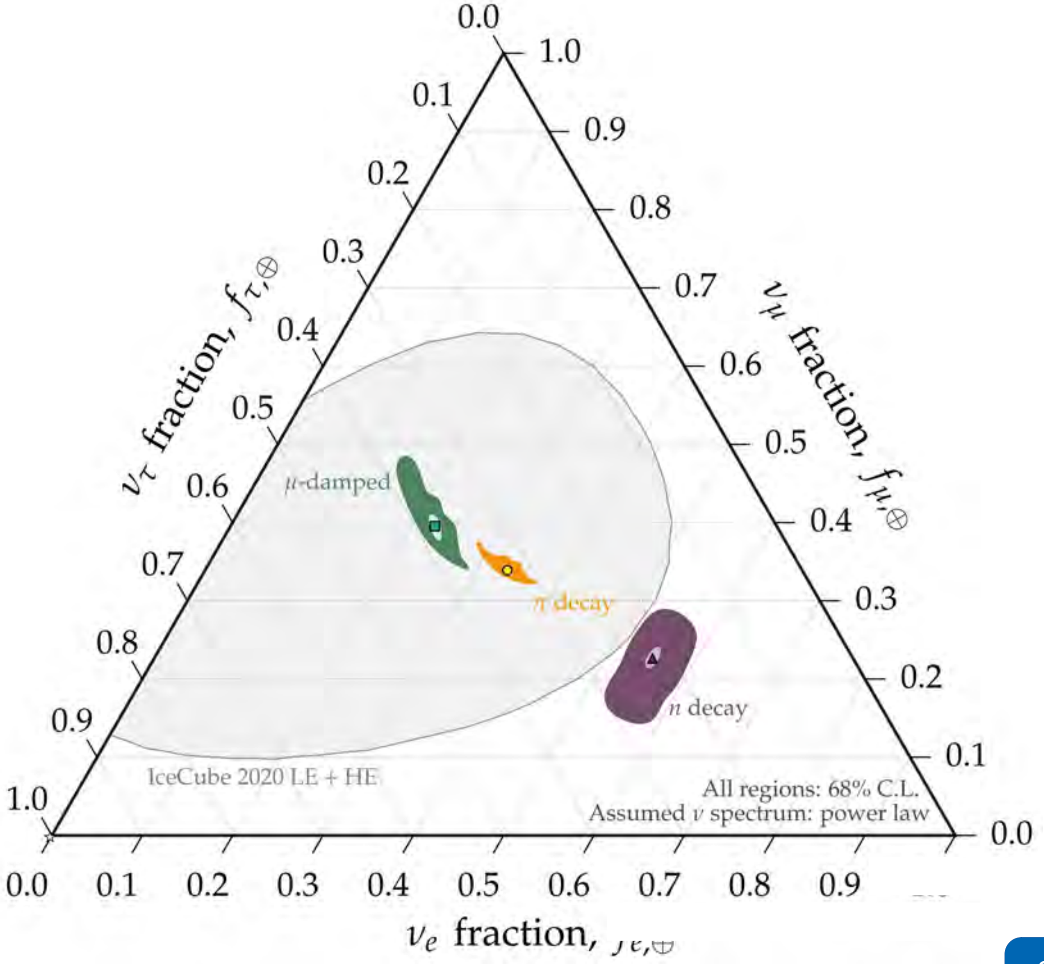
(Assuming $f_{\tau,S} = 0$)



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

Measuring energy-dependent flavor composition

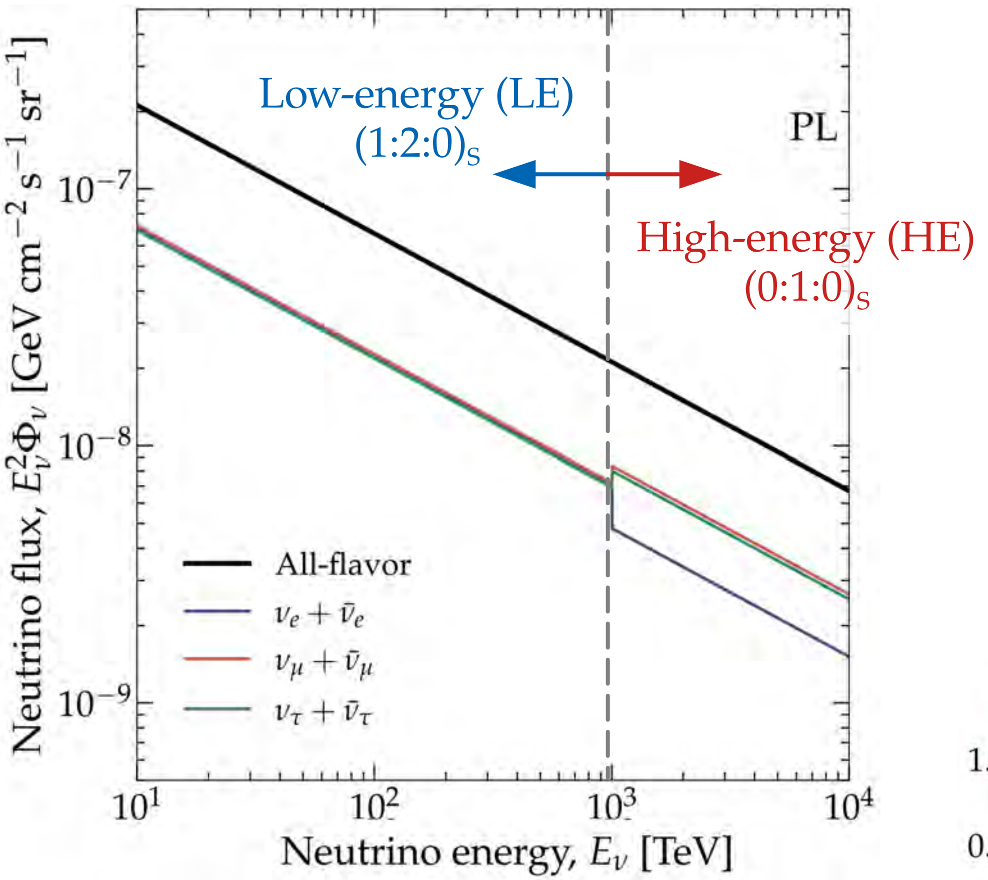
Flavor composition: measuring the energy dependence



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

Flavor composition: measuring the energy dependence

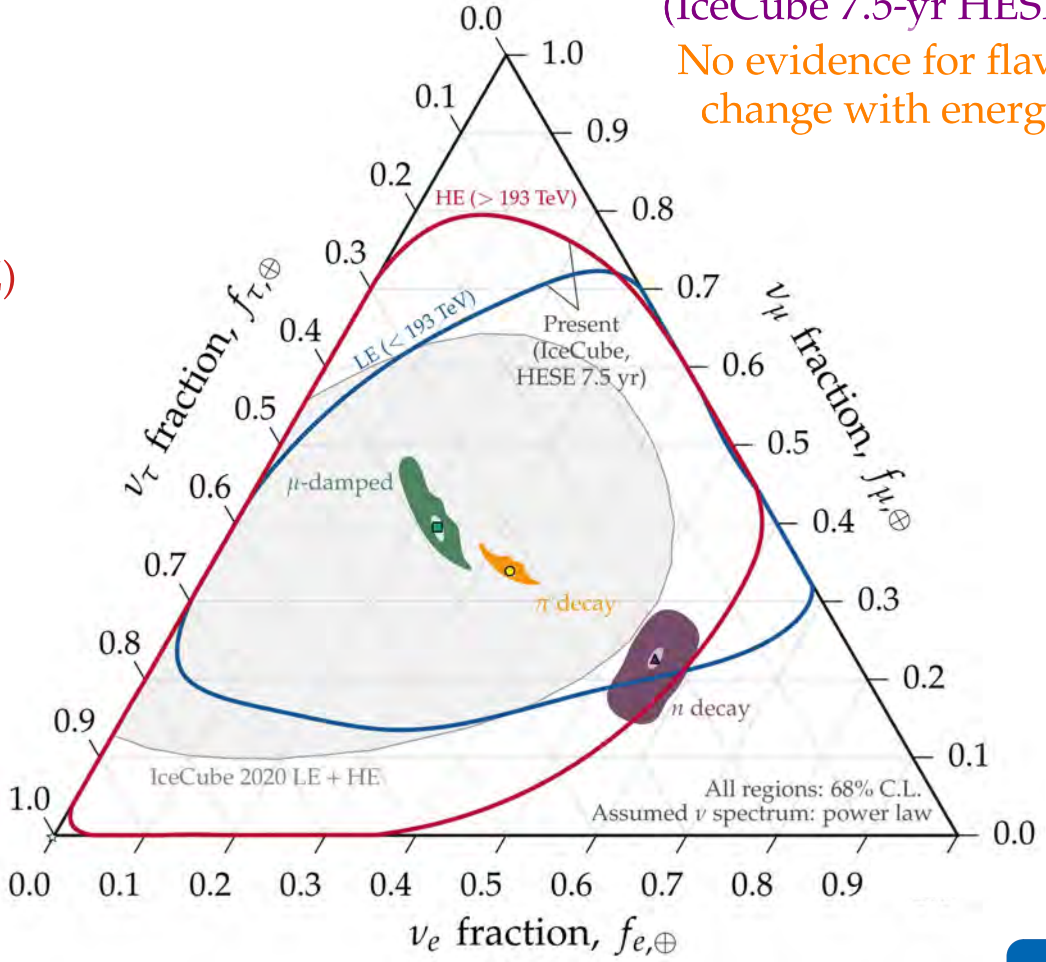
Power-law (PL) diffuse ν flux



Today

(IceCube 7.5-yr HESE):

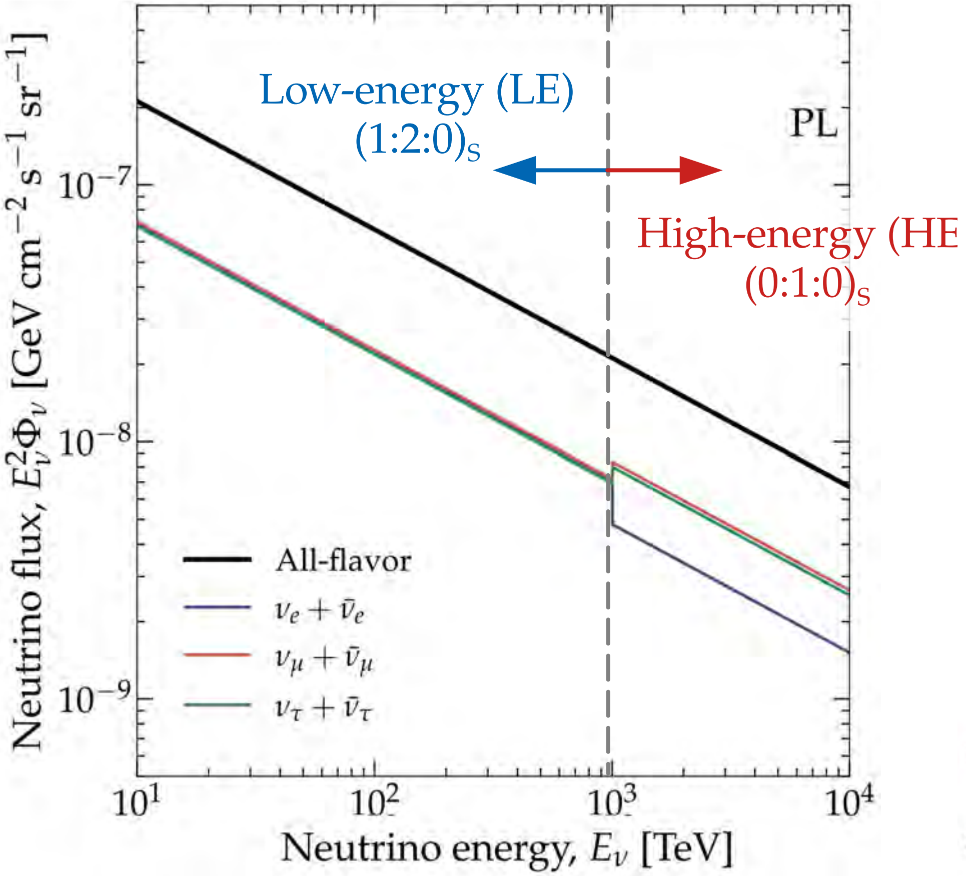
No evidence for flavor change with energy



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

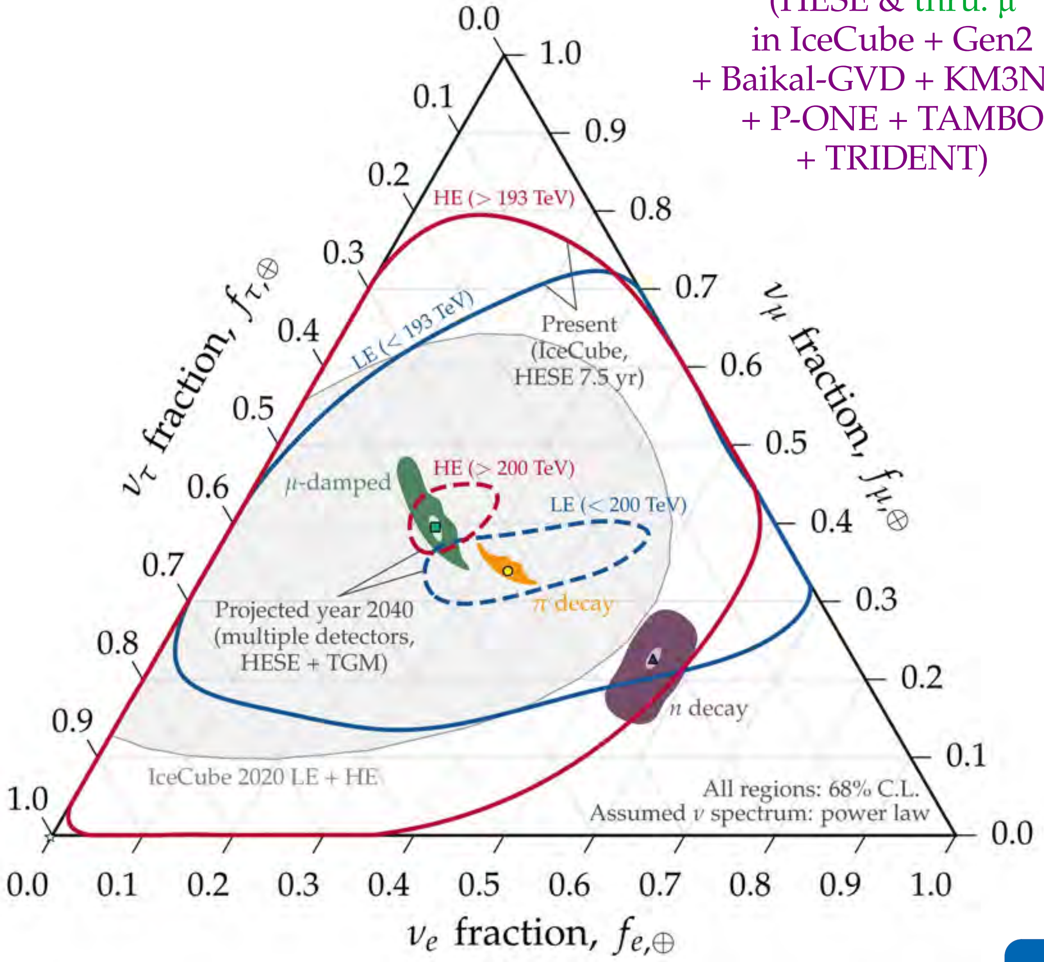
Flavor composition: measuring the energy dependence

Power-law (PL) diffuse ν flux



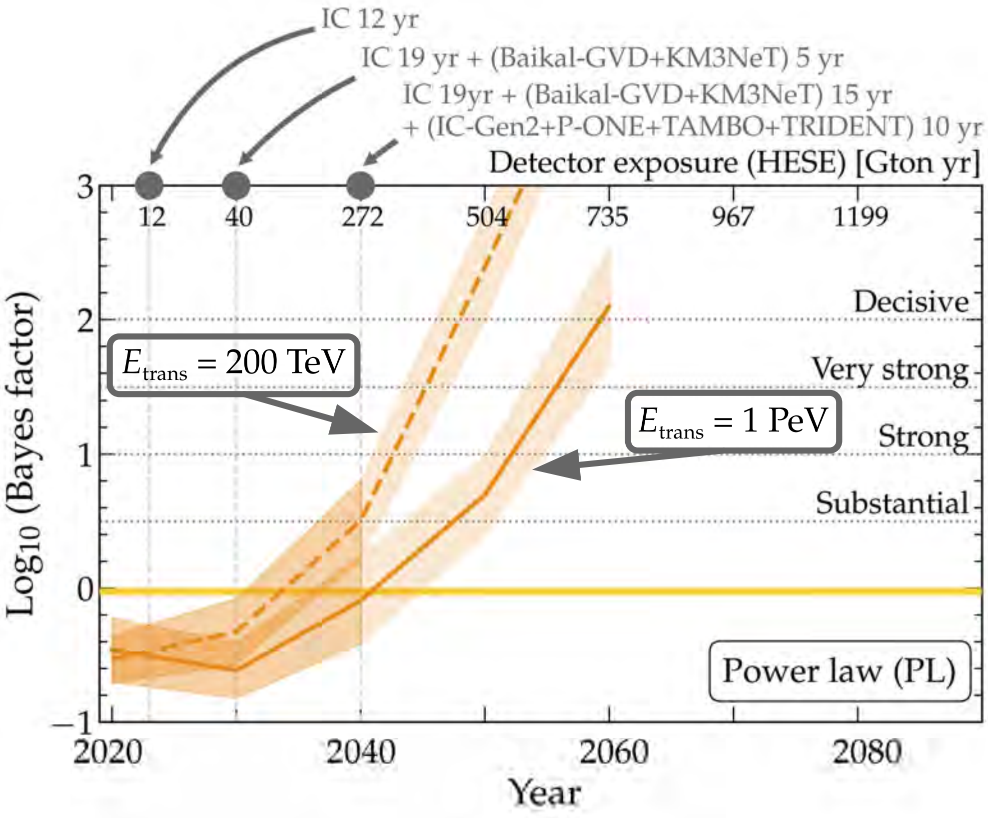
Future

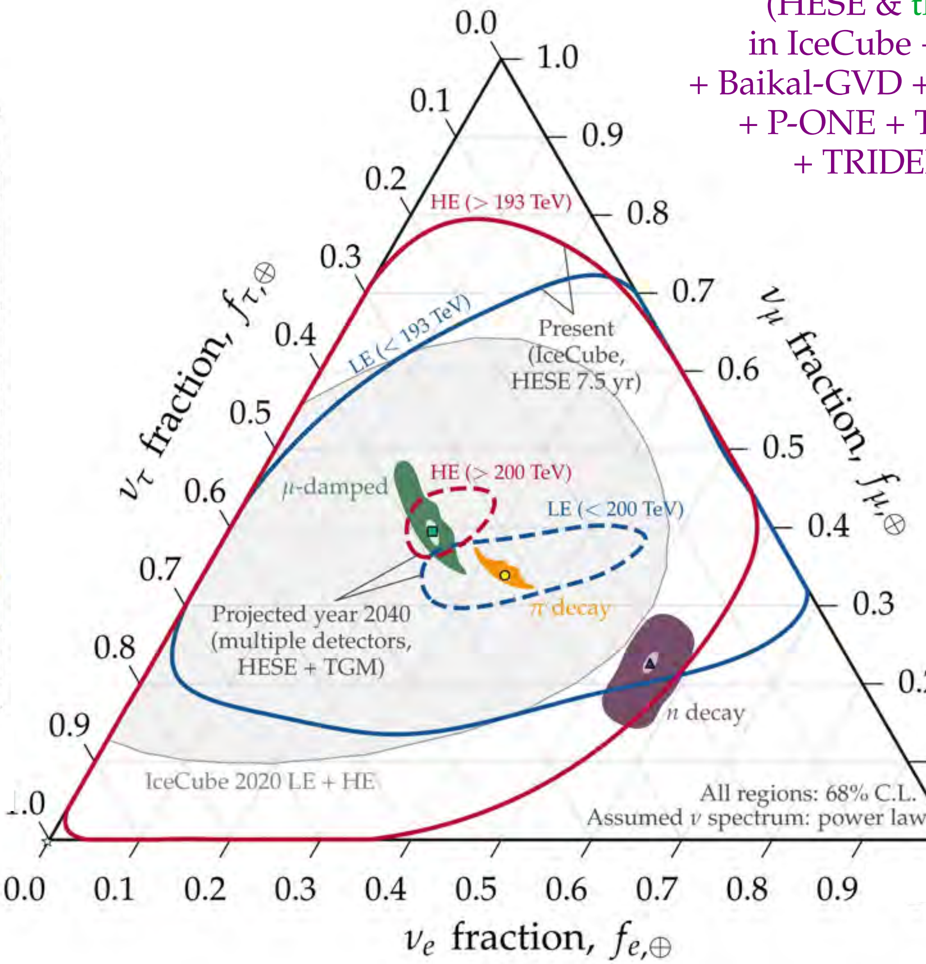
(HESE & thru. μ
in IceCube + Gen2
+ Baikal-GVD + KM3NeT
+ P-ONE + TAMBO
+ TRIDENT)



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

Flavor composition: measuring the energy dependence

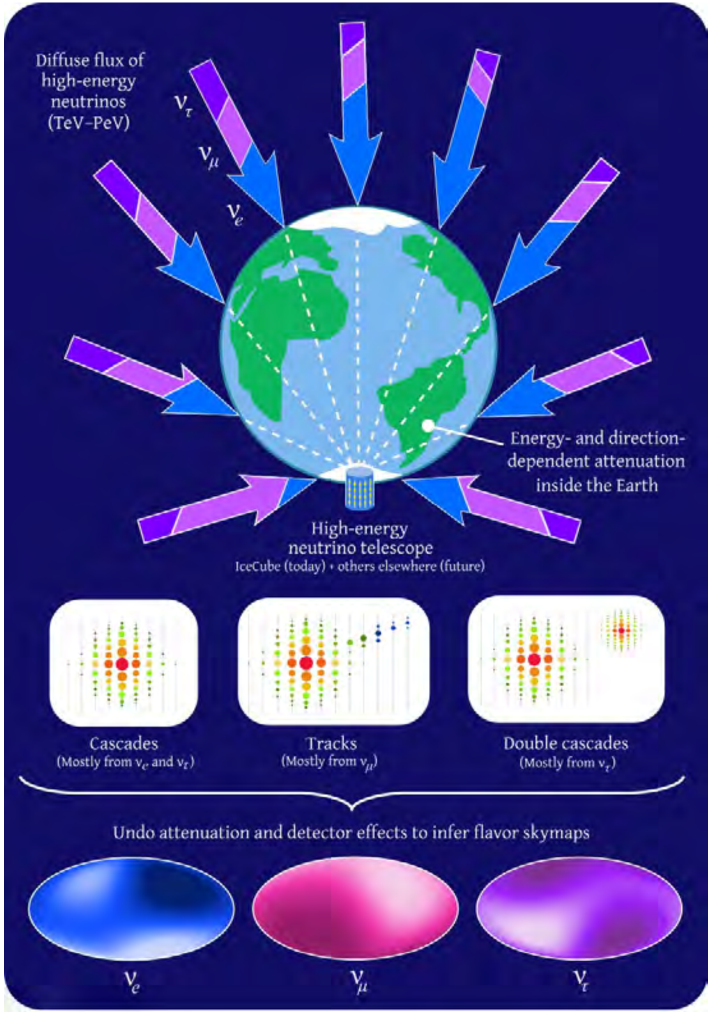




Liu, Fiorillo, Argüelles, **MB**, Song, Vincent, 2312.07649

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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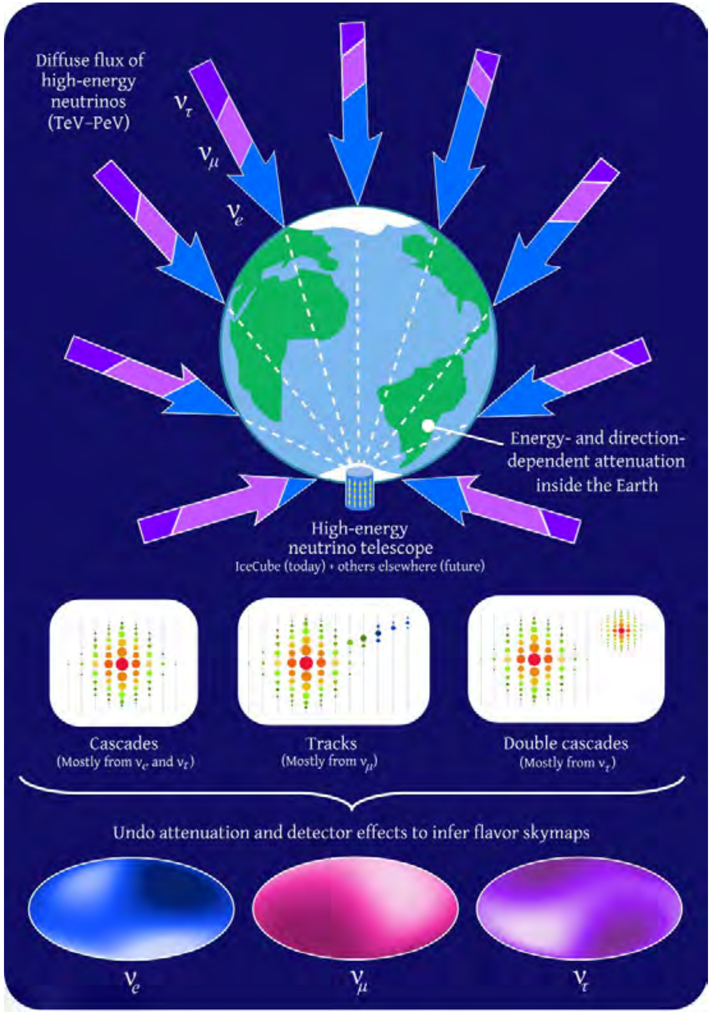

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From the angular distribution of detected events in neutrino telescopes (HESE cascades, tracks, double cascades) …

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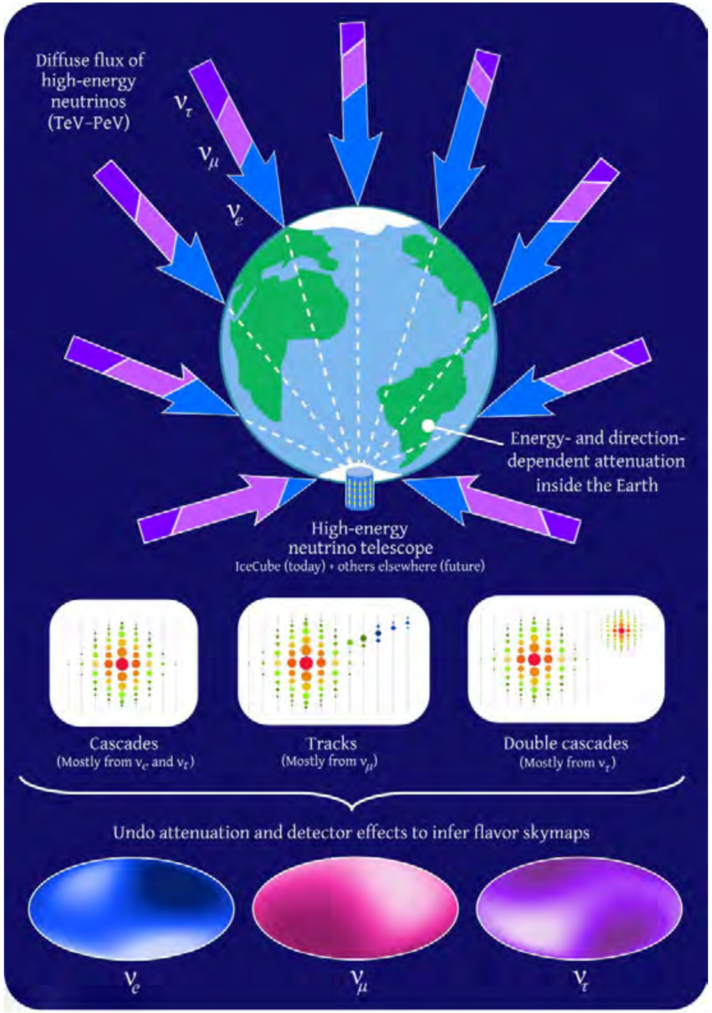

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… we infer the directional dependence of the diffuse fluxes of ν_e, ν_μ, ν_τ

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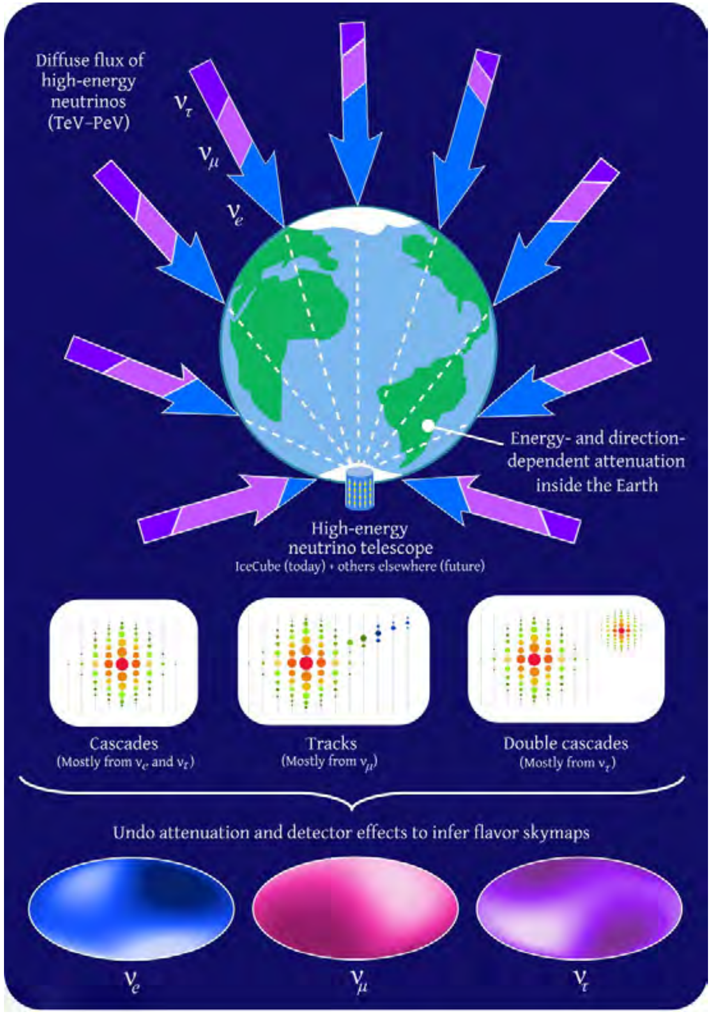
Flavor anisotropy in the high-energy neutrino sky



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

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

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

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

Telalovic, **MB**, 2310.15224

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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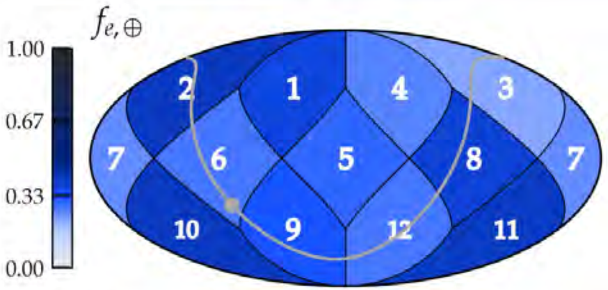

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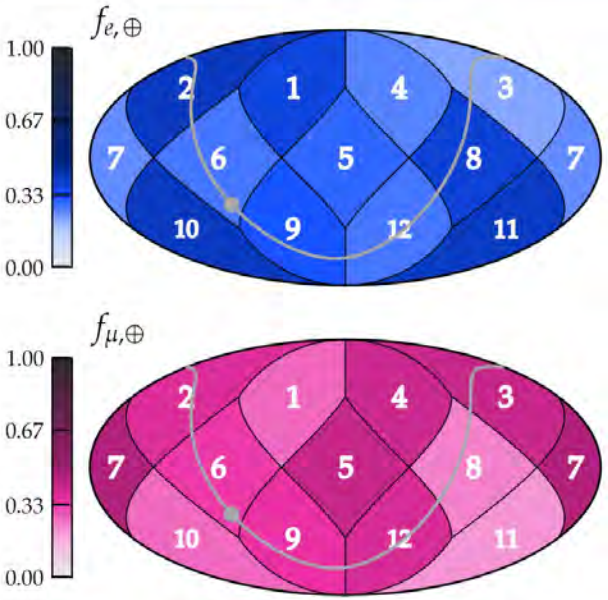

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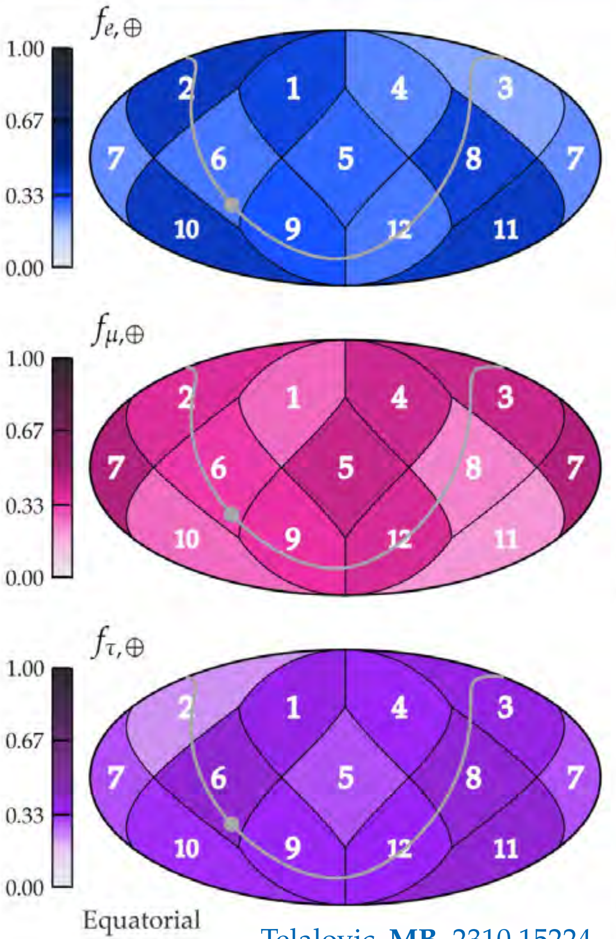

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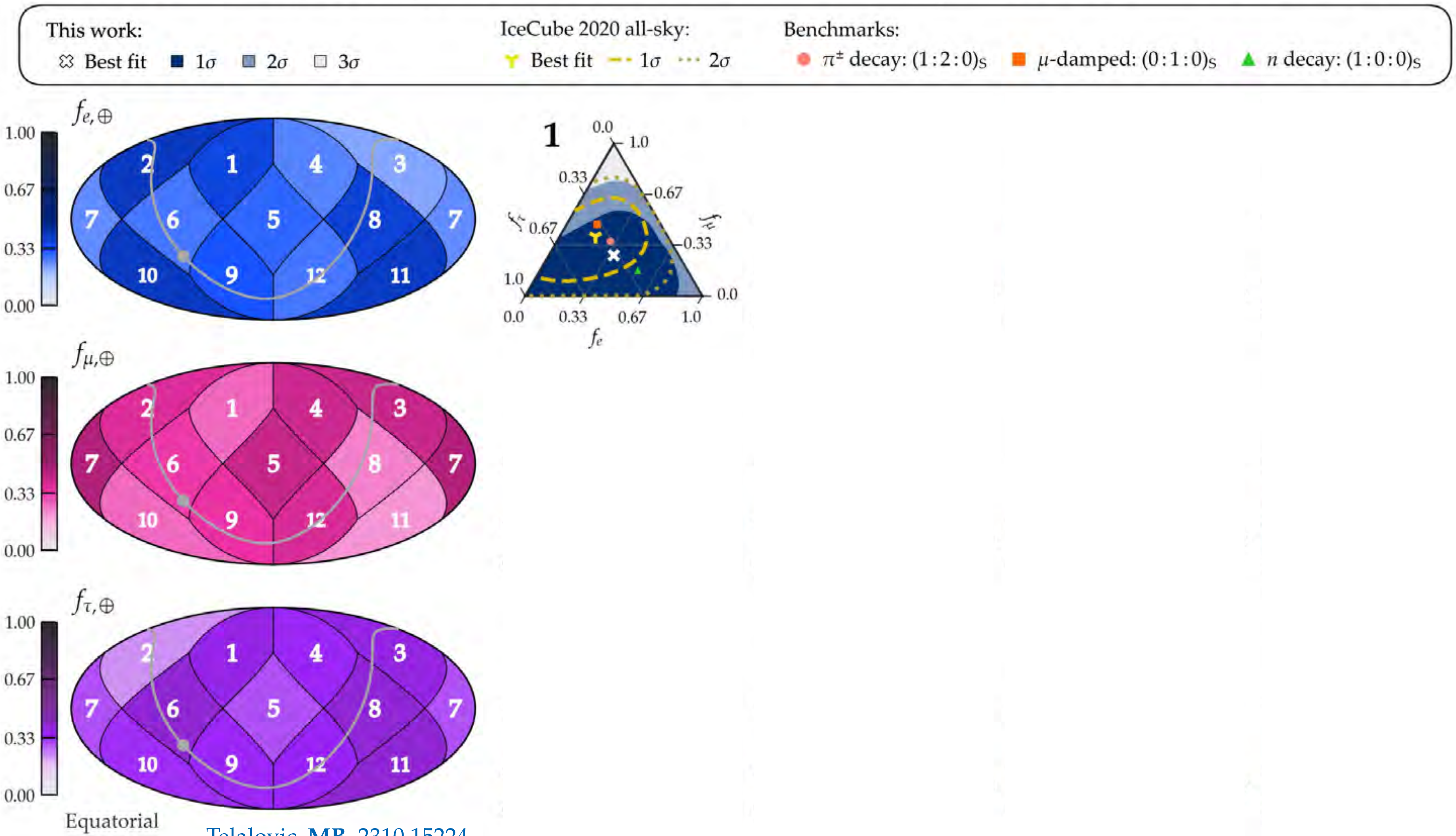

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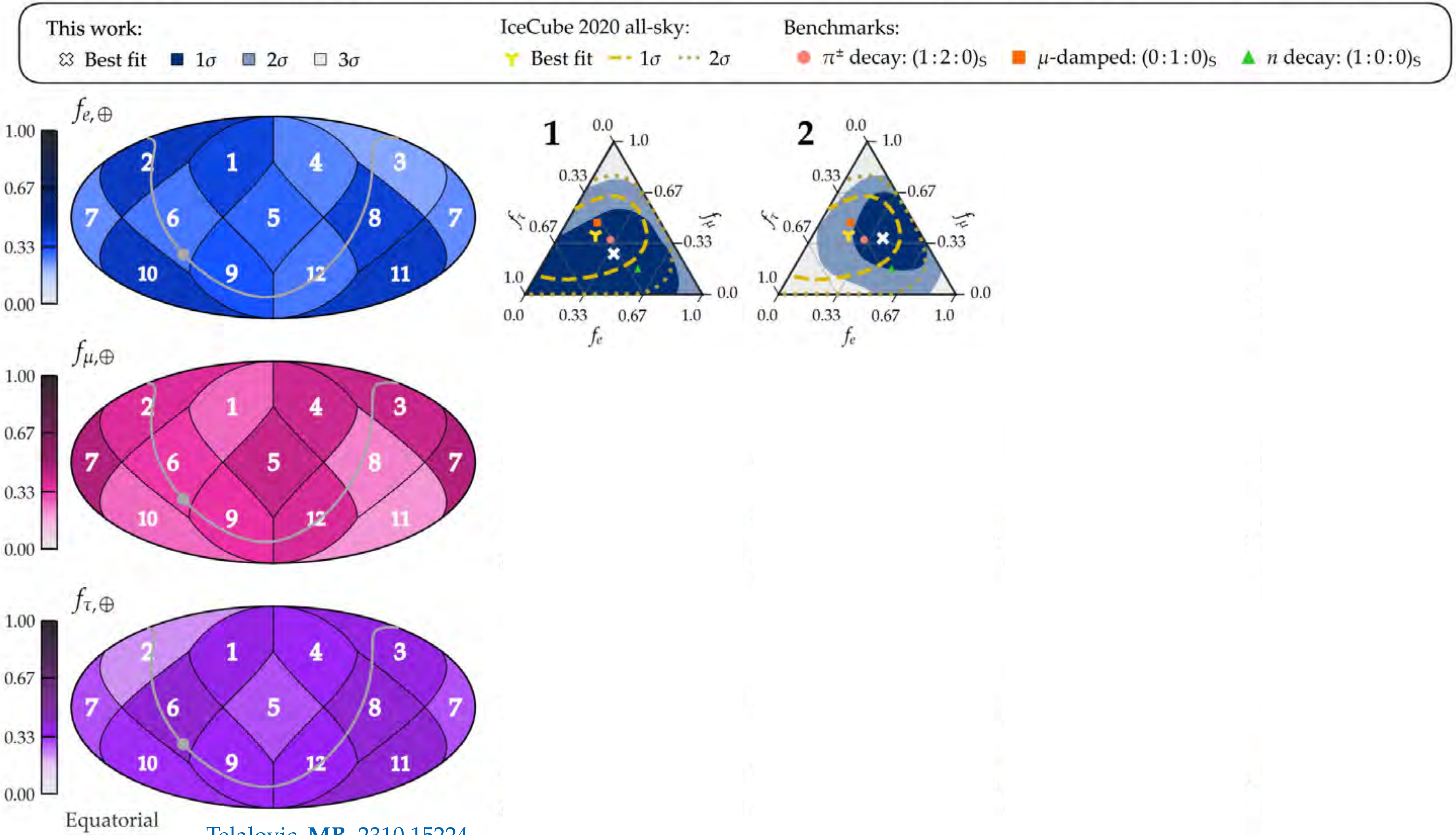

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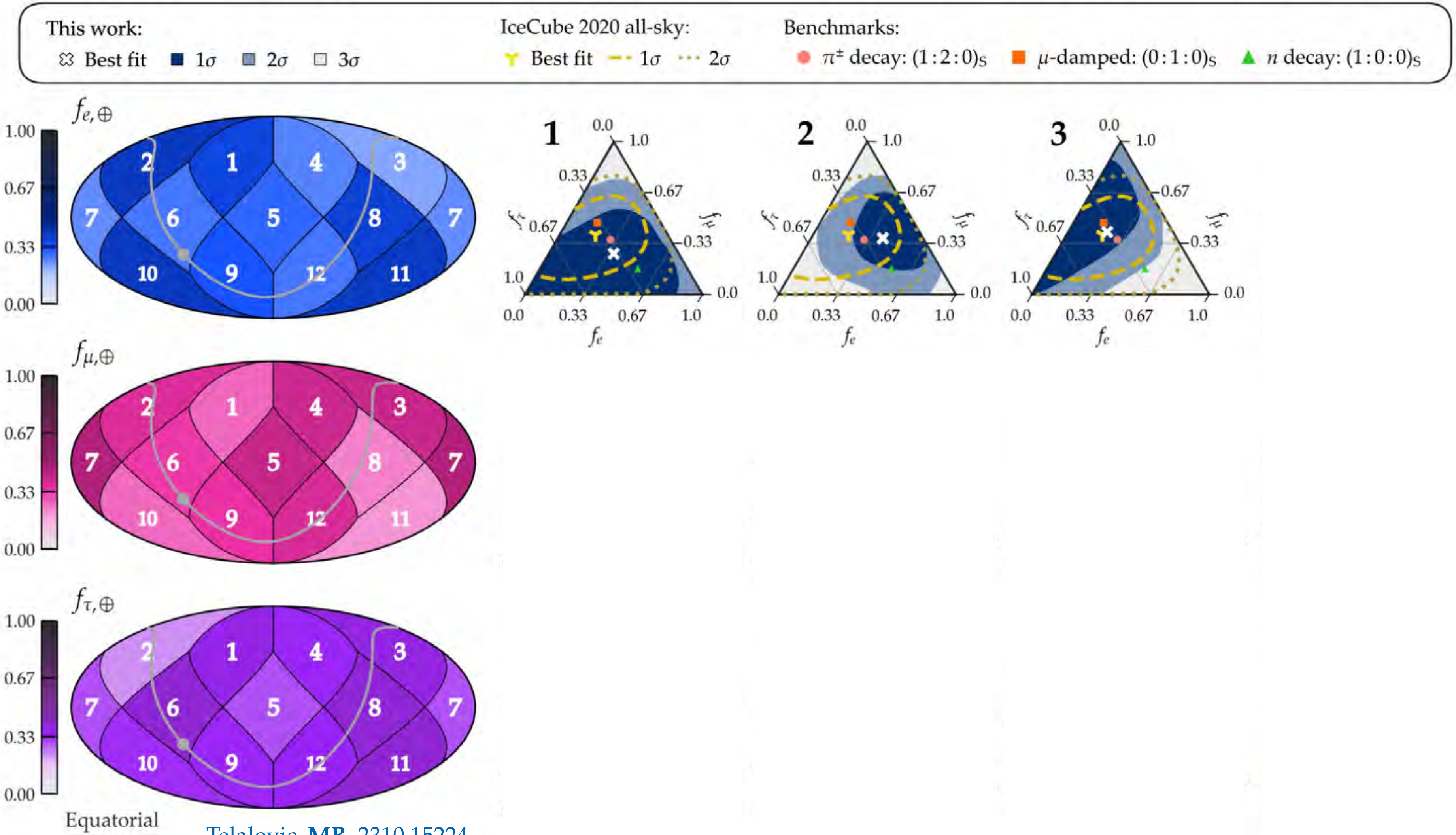

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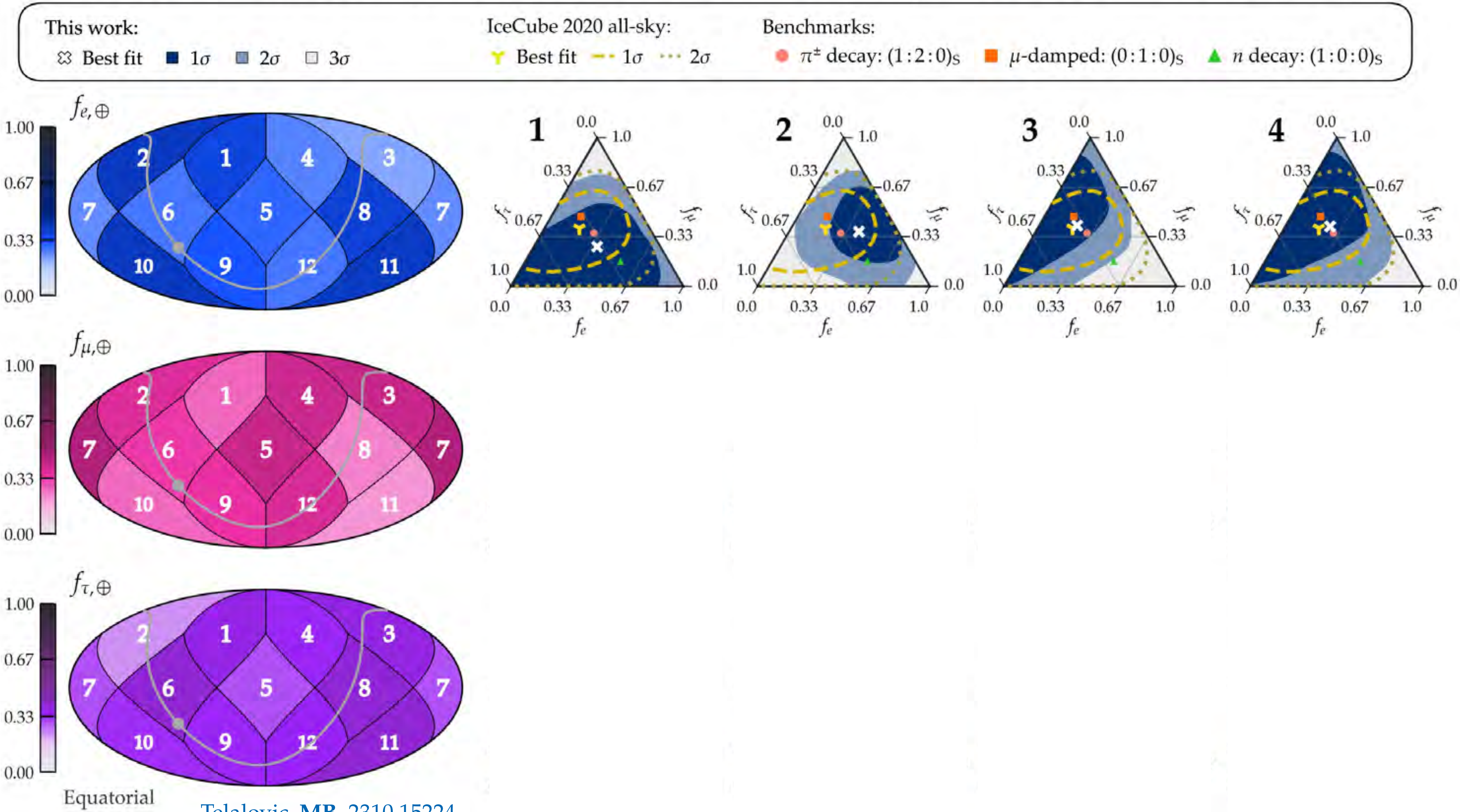

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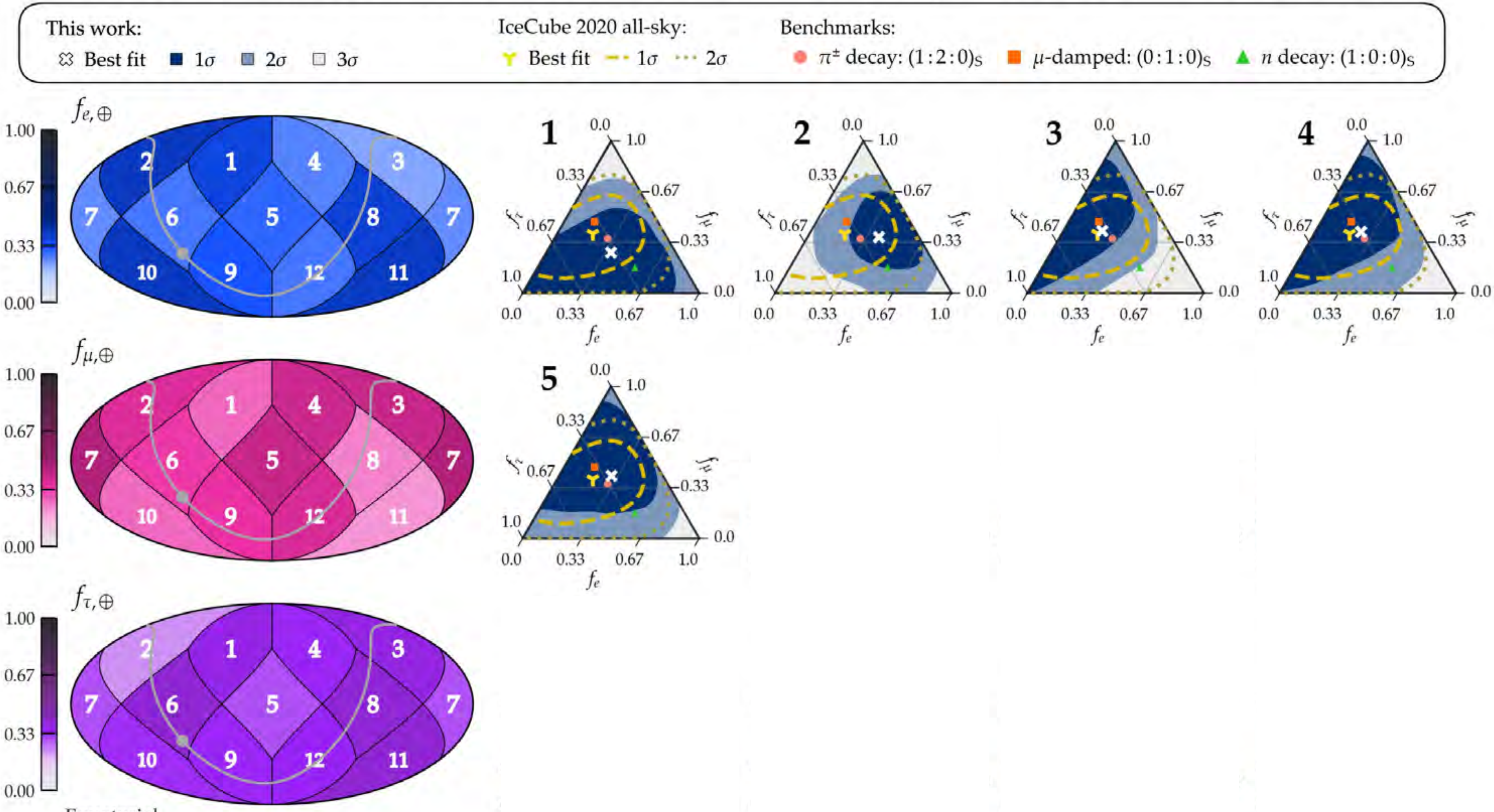

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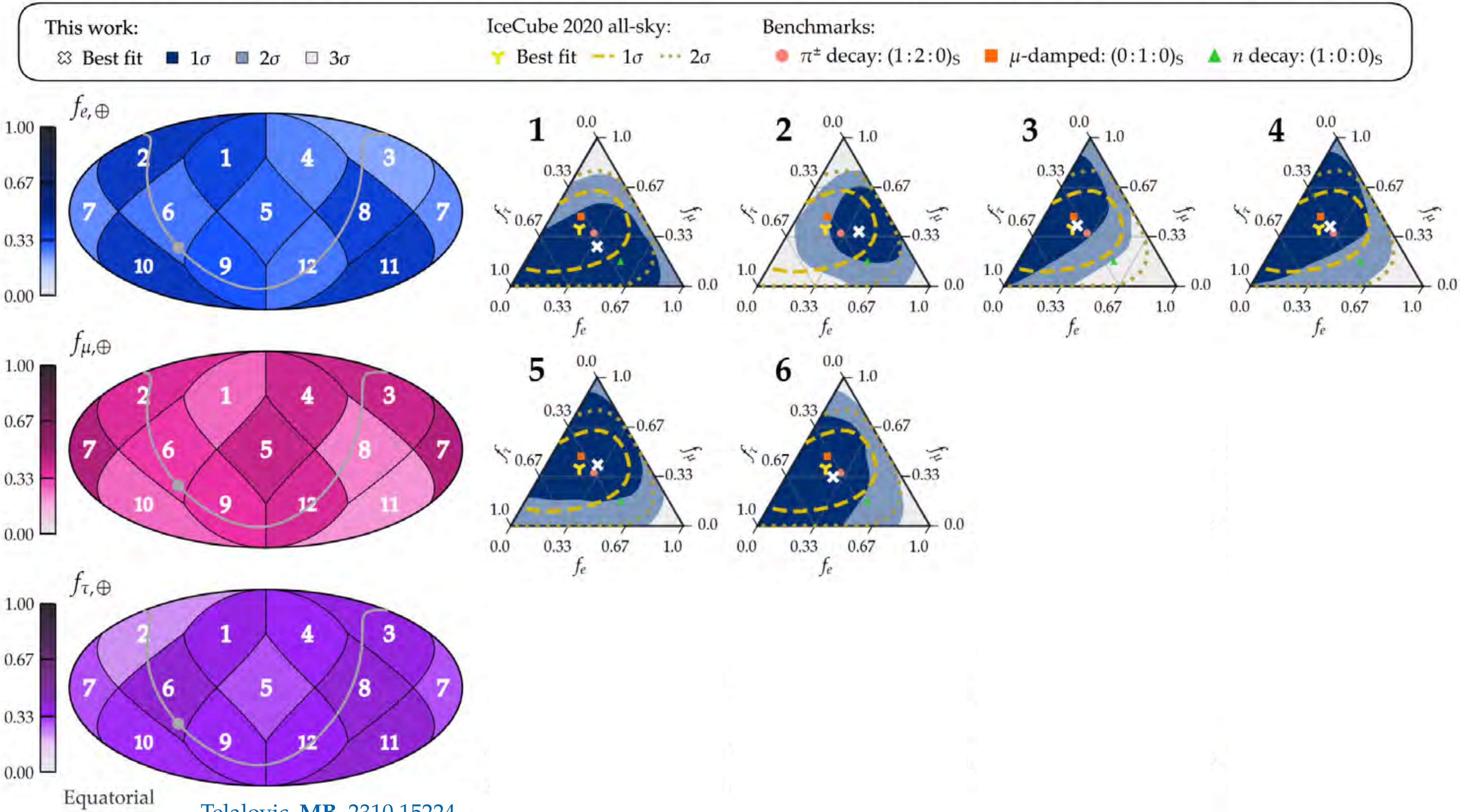

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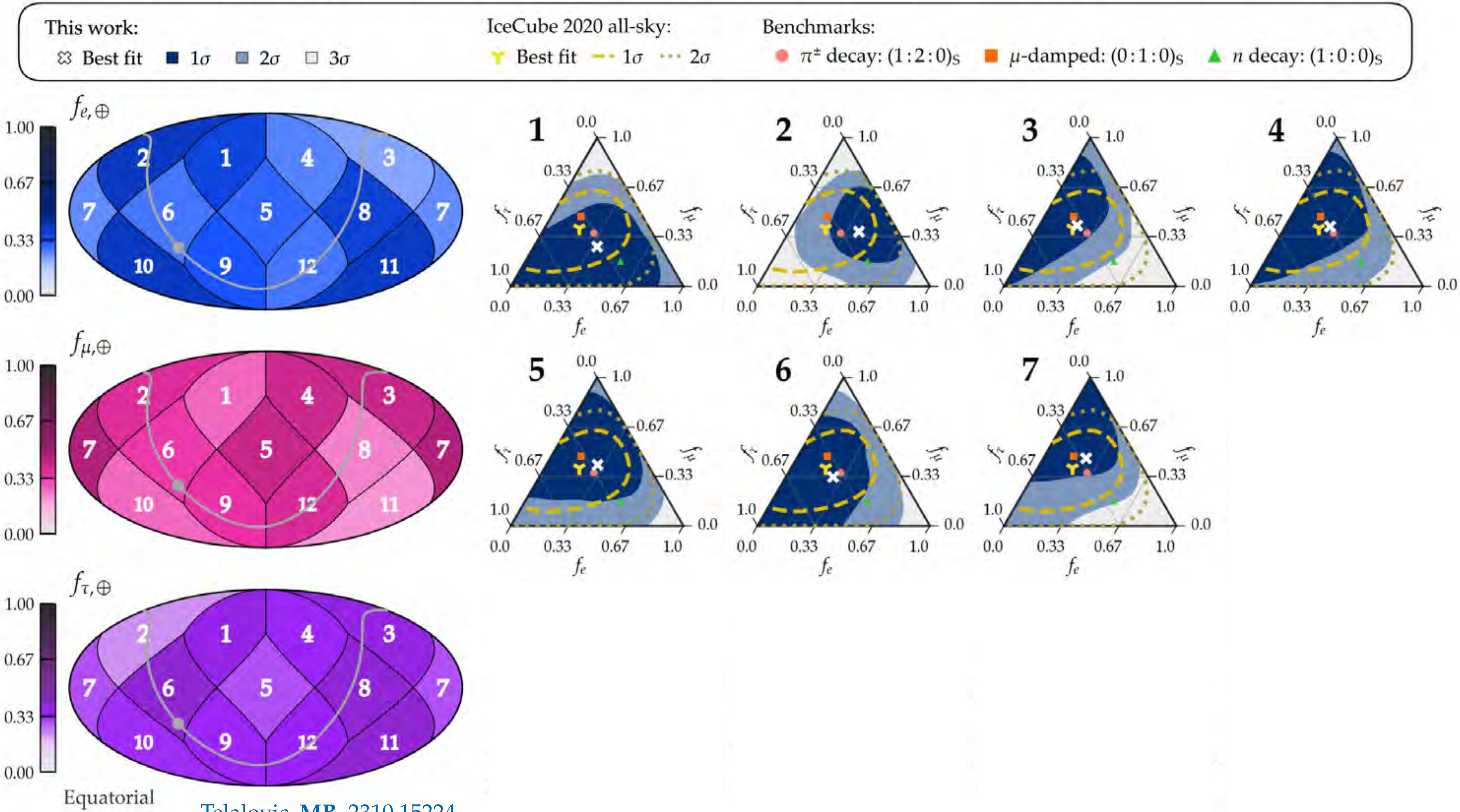

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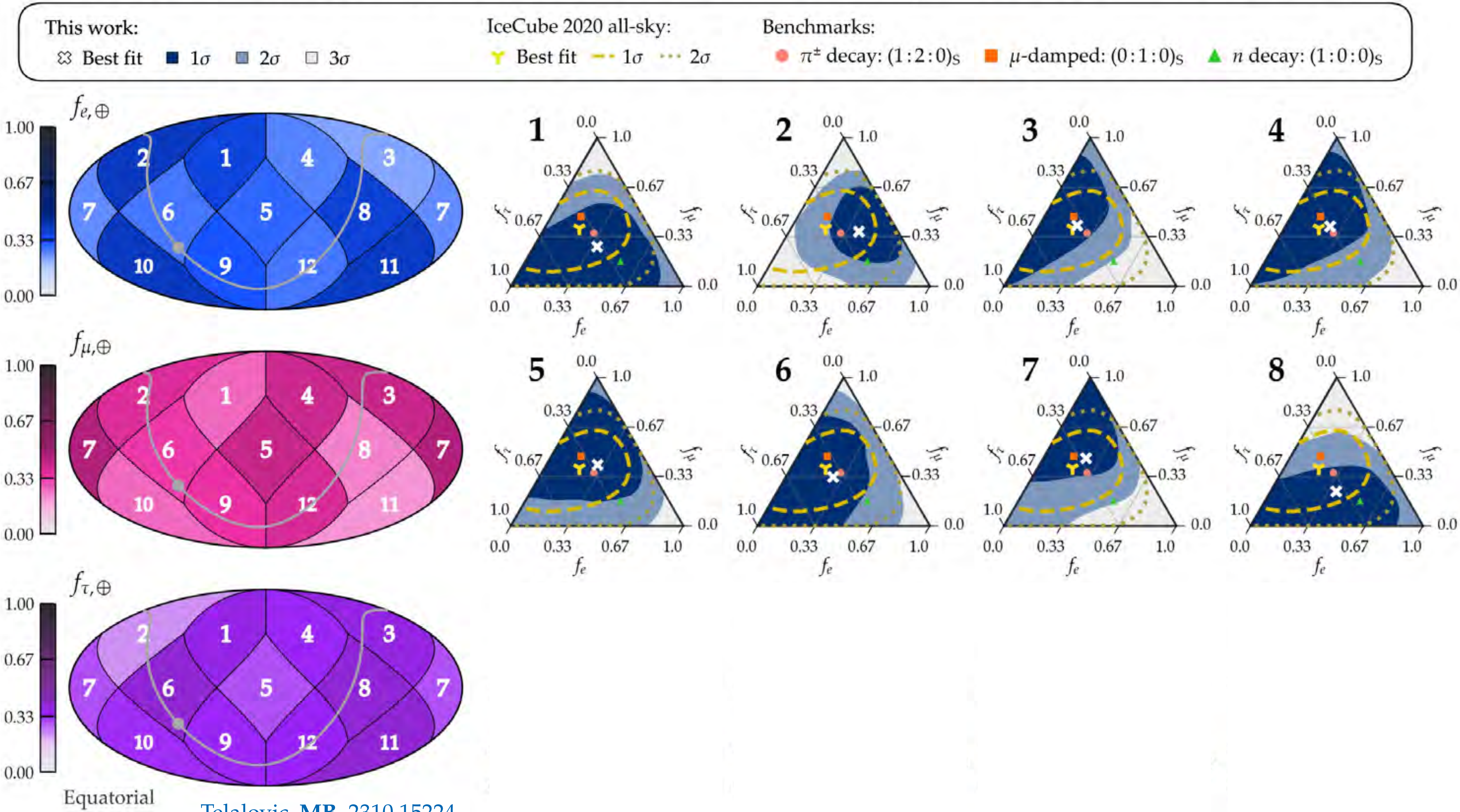

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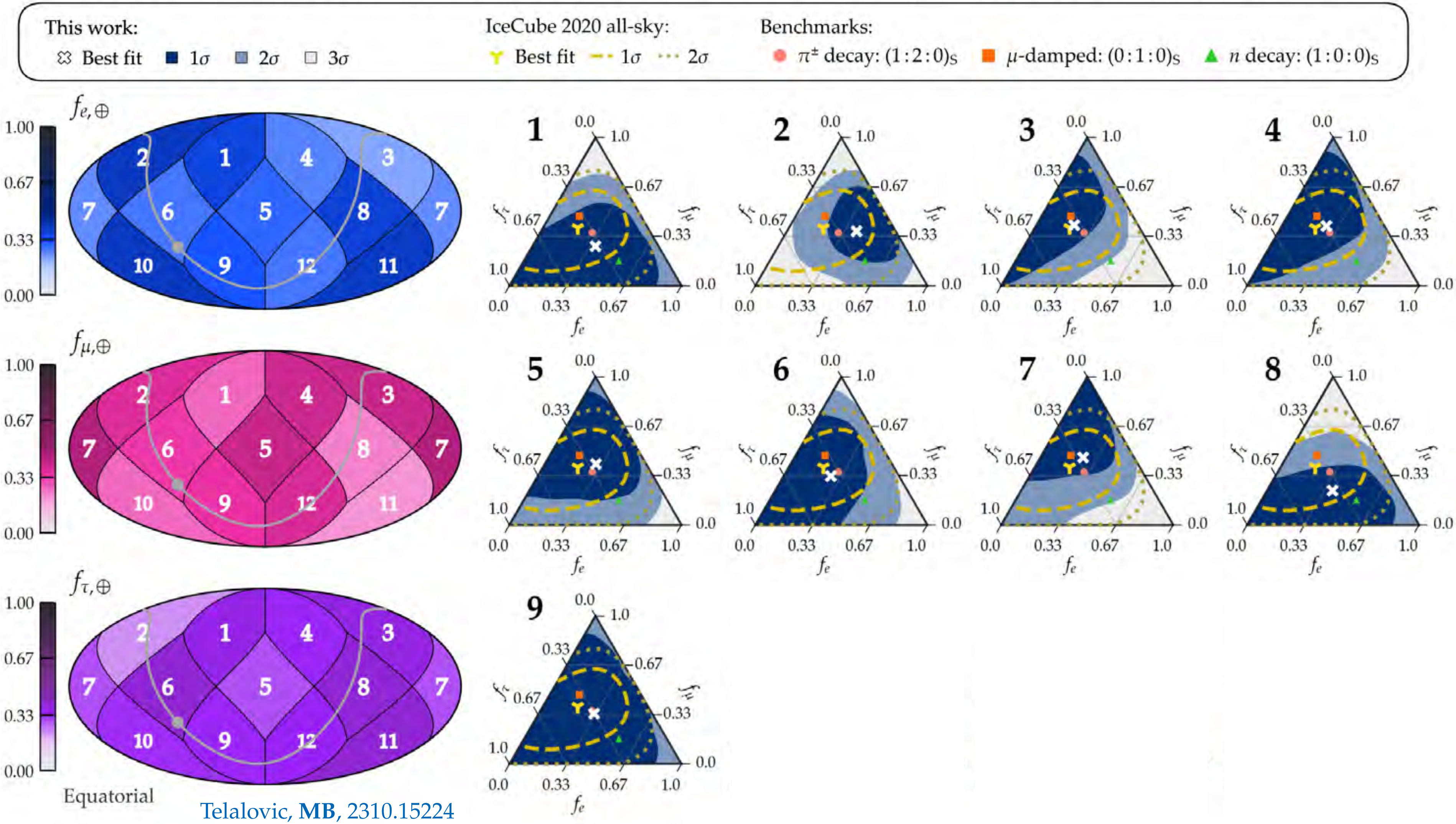

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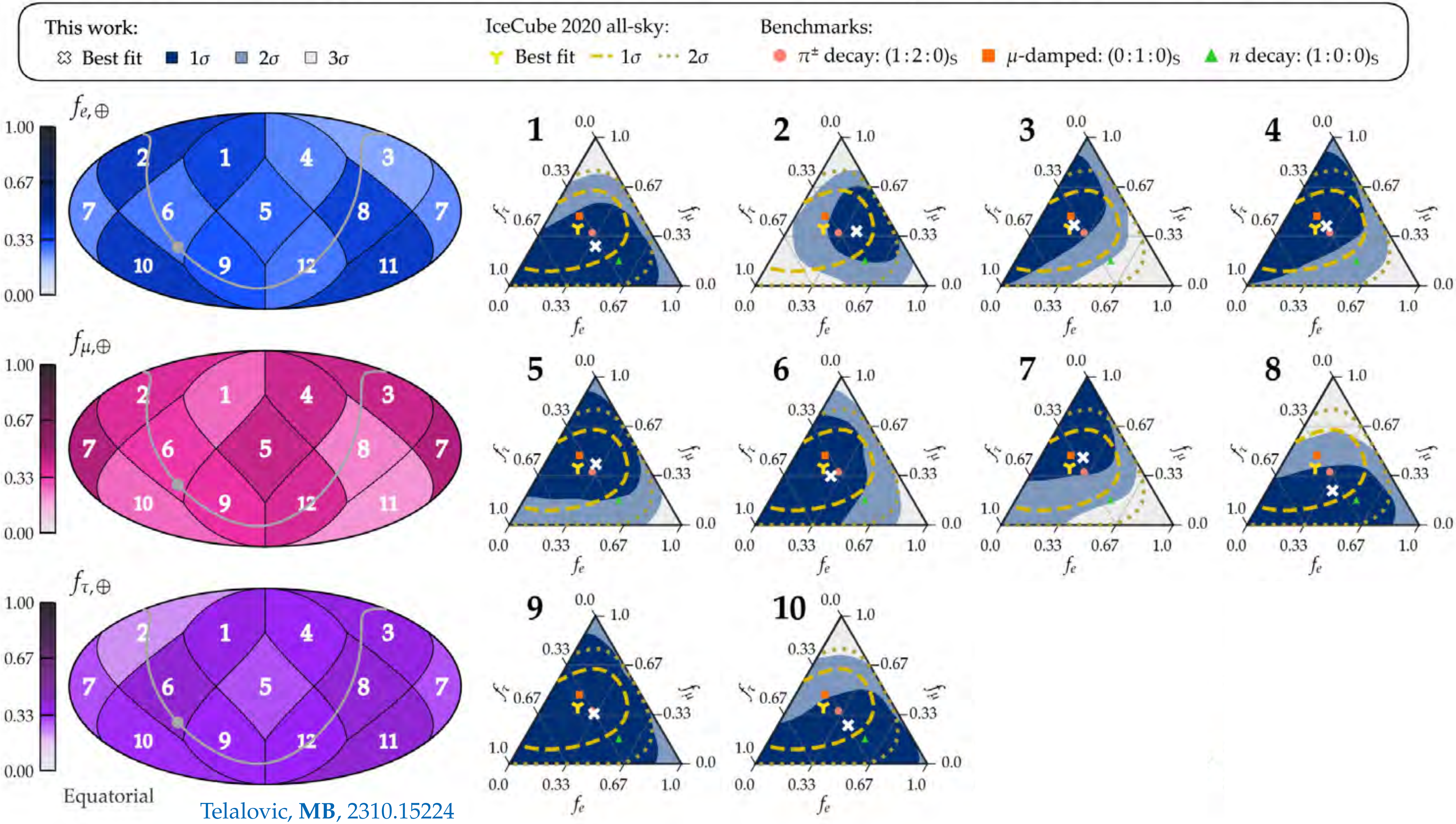

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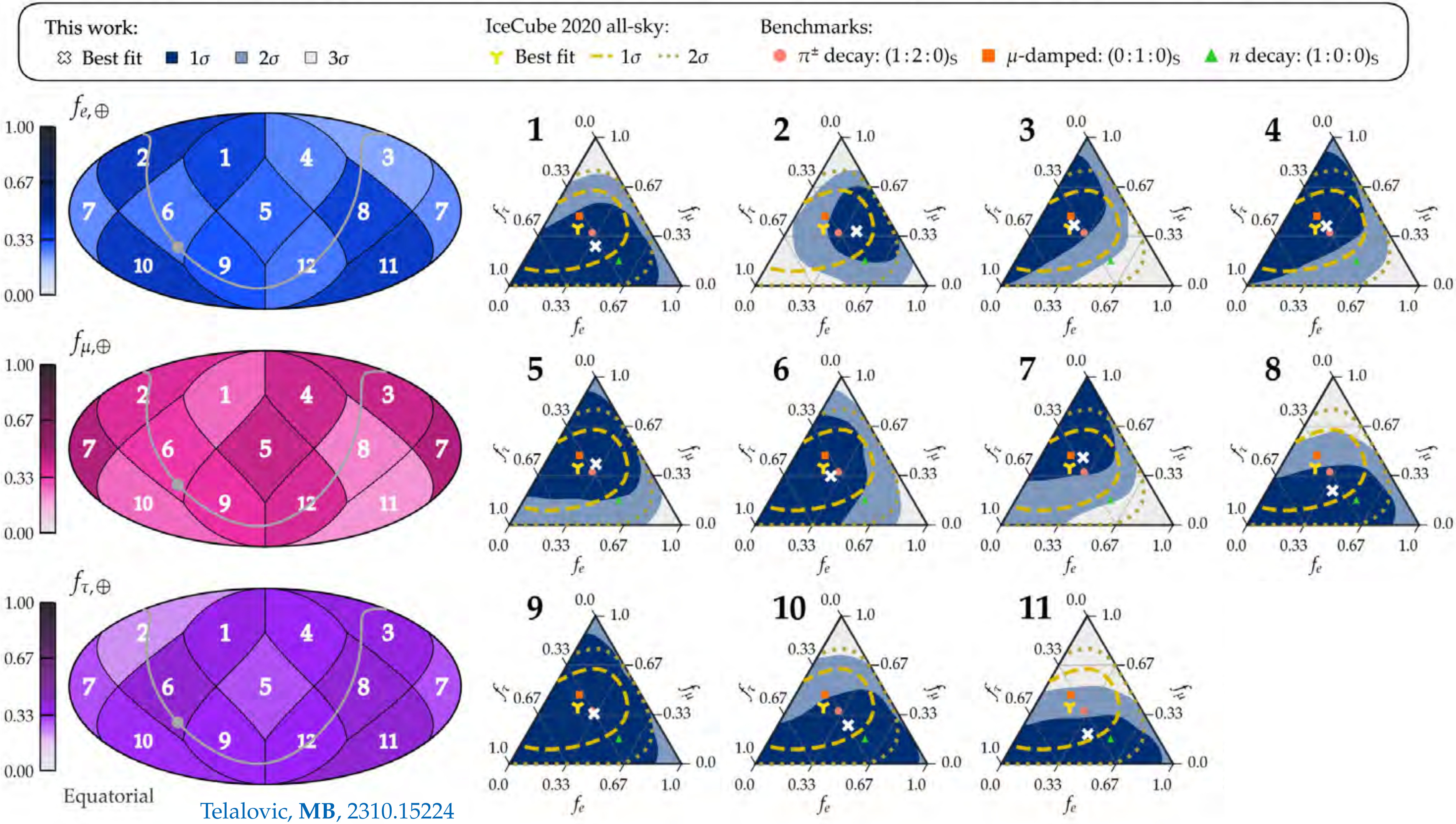

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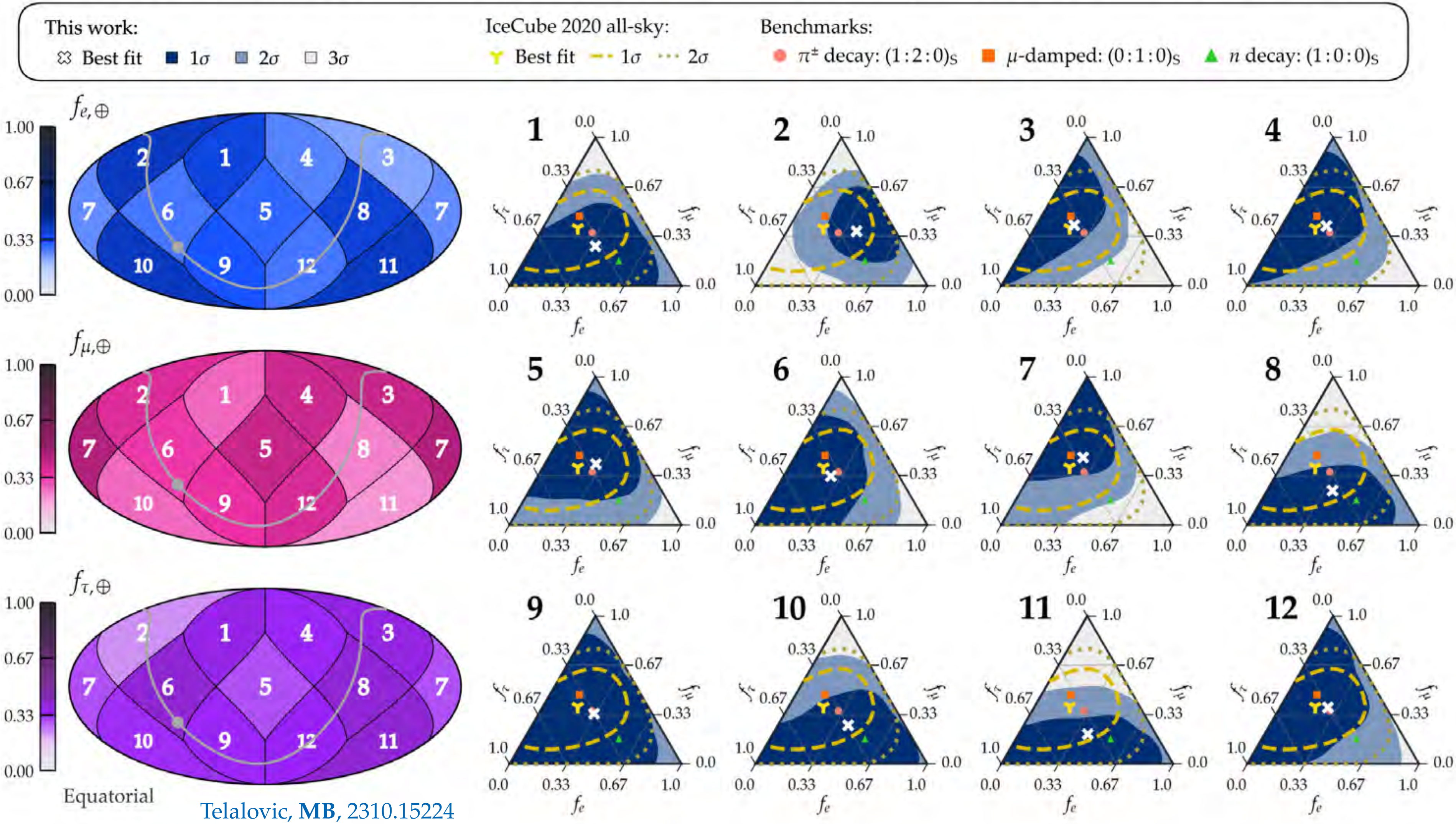

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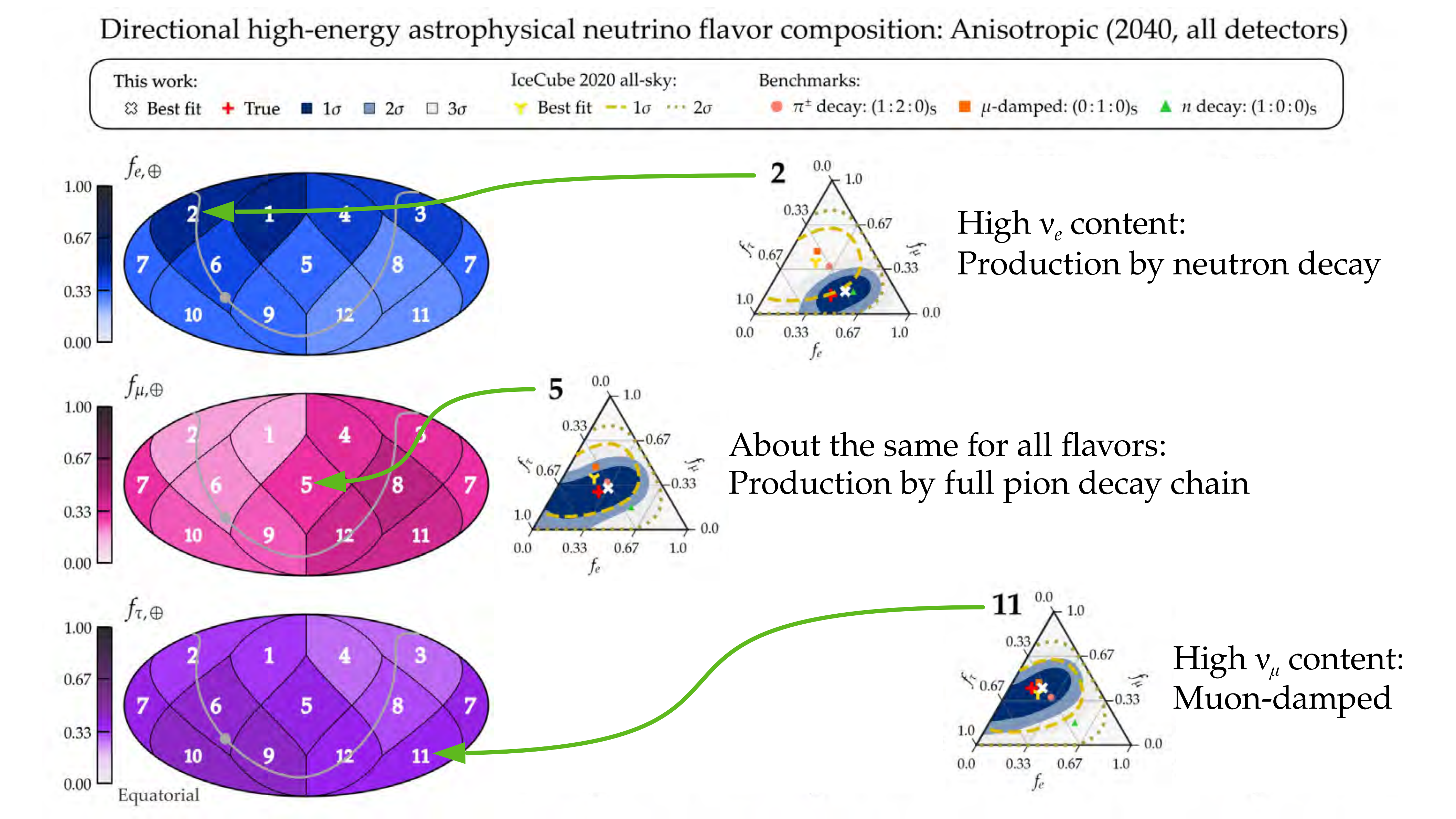

Directional high-energy astrophysical neutrino flavor composition: Anisotropic (2040, all detectors)
This work: Best fit True 1σ 2σ 3σ
IceCube 2020 all-sky: Best fit 1σ 2σ
Benchmarks: π± decay: (1:2:0)S μ-damped: (0:1:0)S n decay: (1:0:0)S
fe,⊕
fμ,⊕
fτ,⊕
Equatorial
High νe content:
Production by neutron decay
About the same for all flavors:
Production by full pion decay chain
High νμ content:
Muon-damped

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

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

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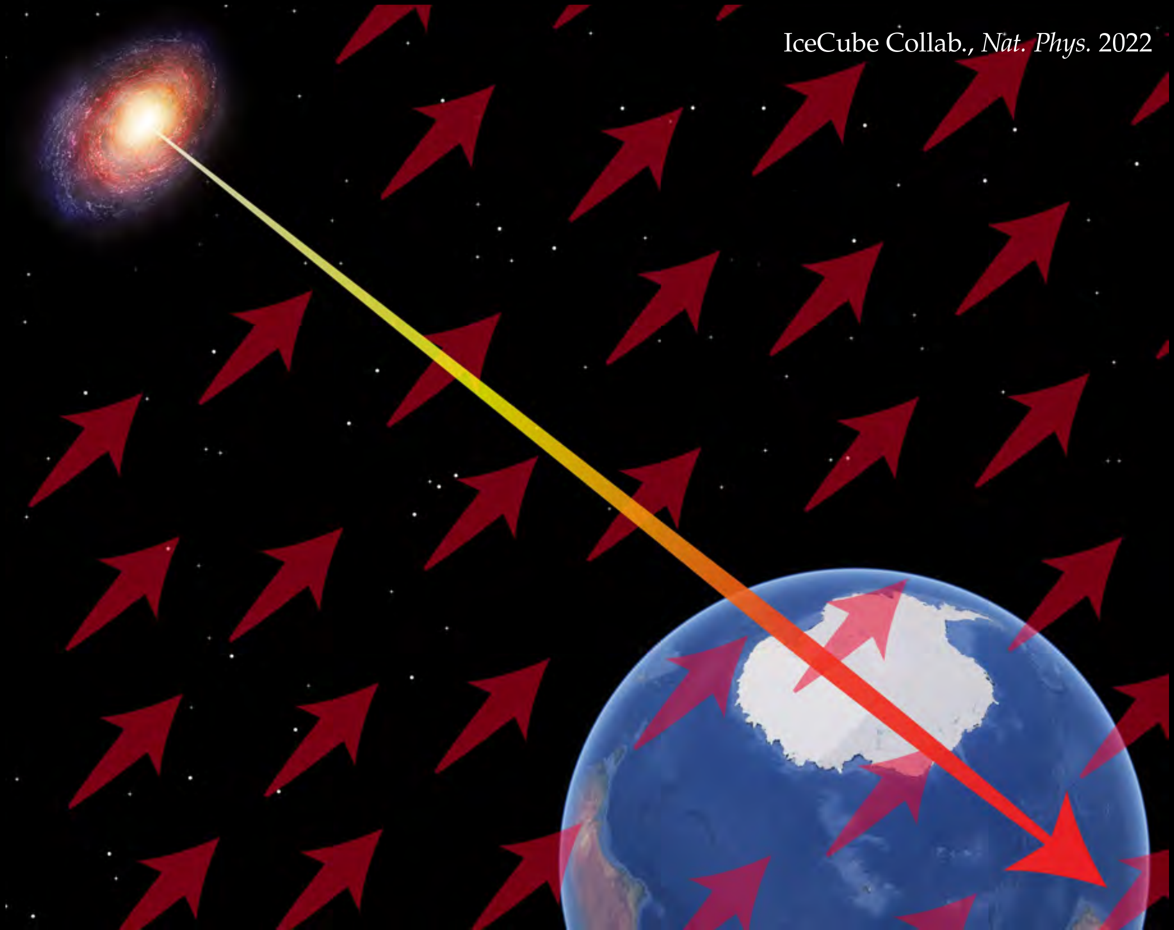
Why is this interesting for neutrino physics?

Because new physics can introduce preferred directions for different flavors



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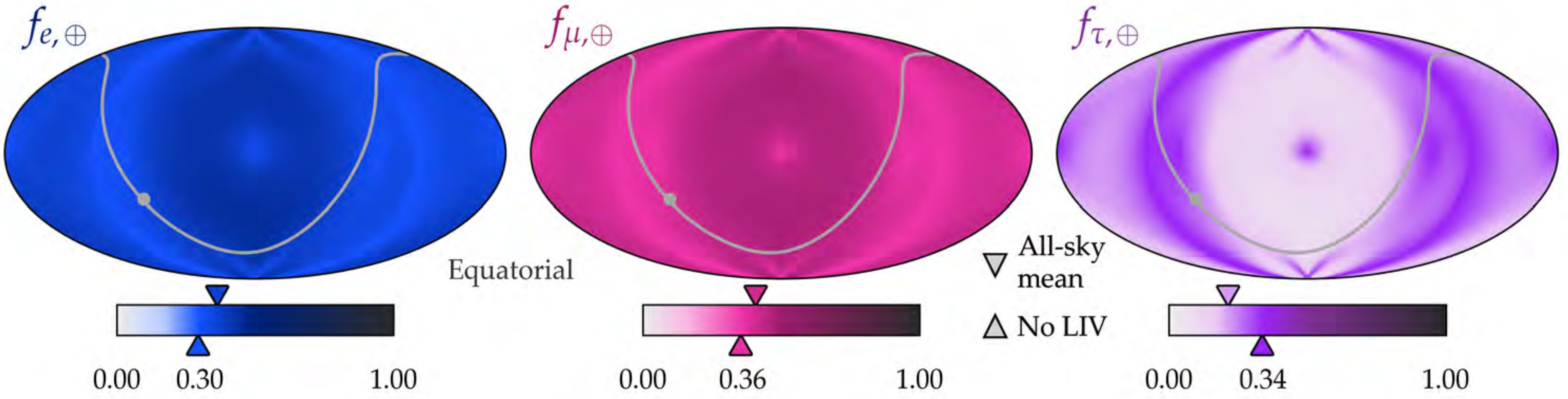

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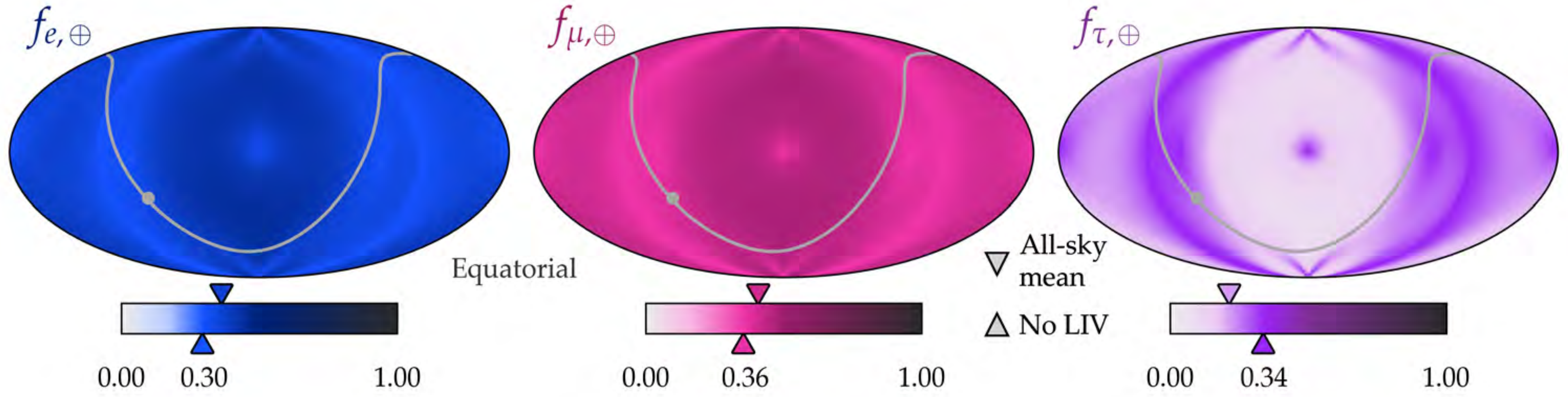

For dimension-5 CPT-odd LIV coefficient

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

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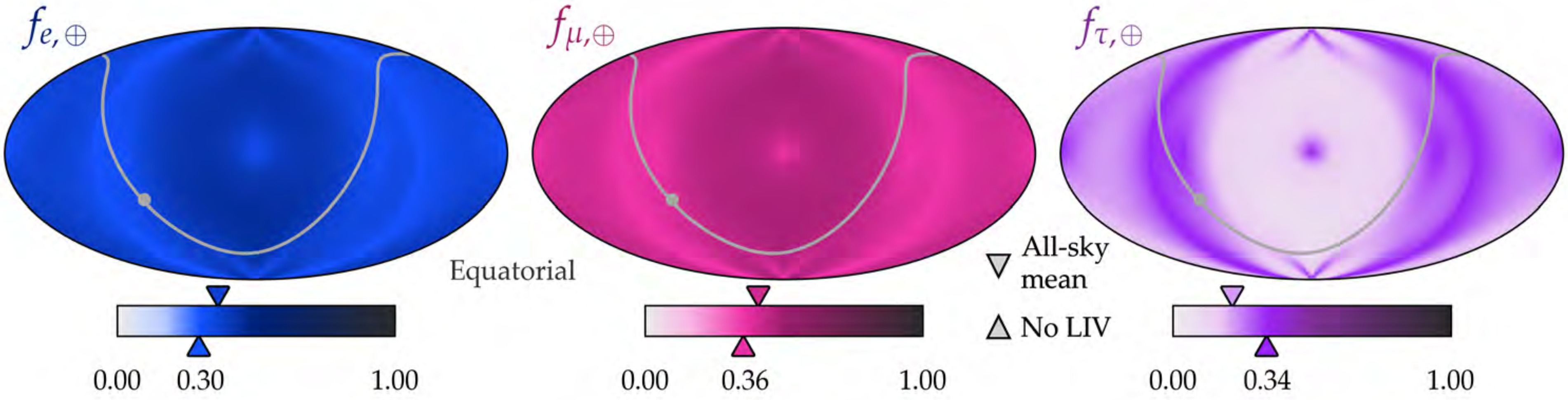

For dimension-5 CPT-odd LIV coefficient

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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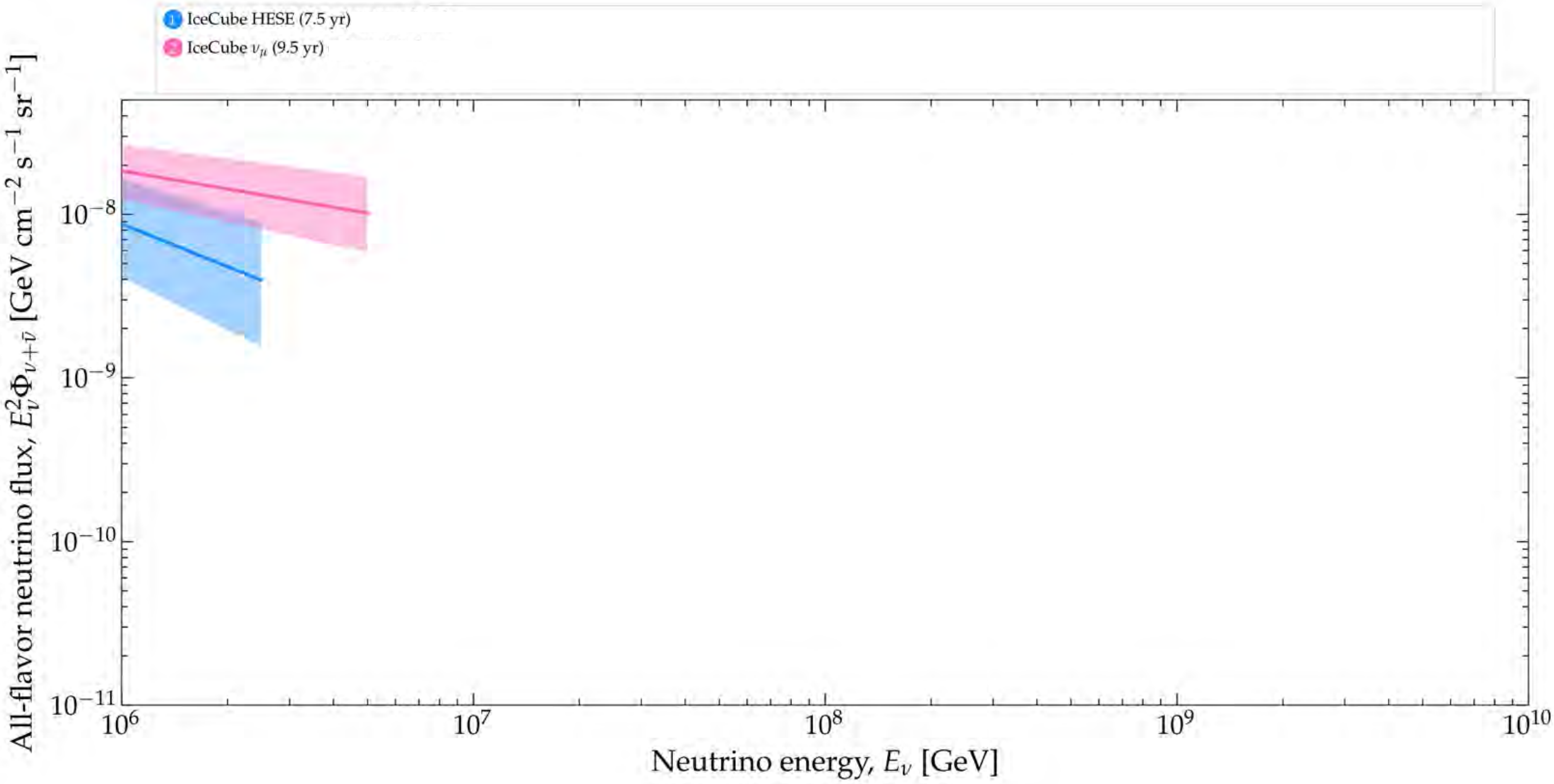
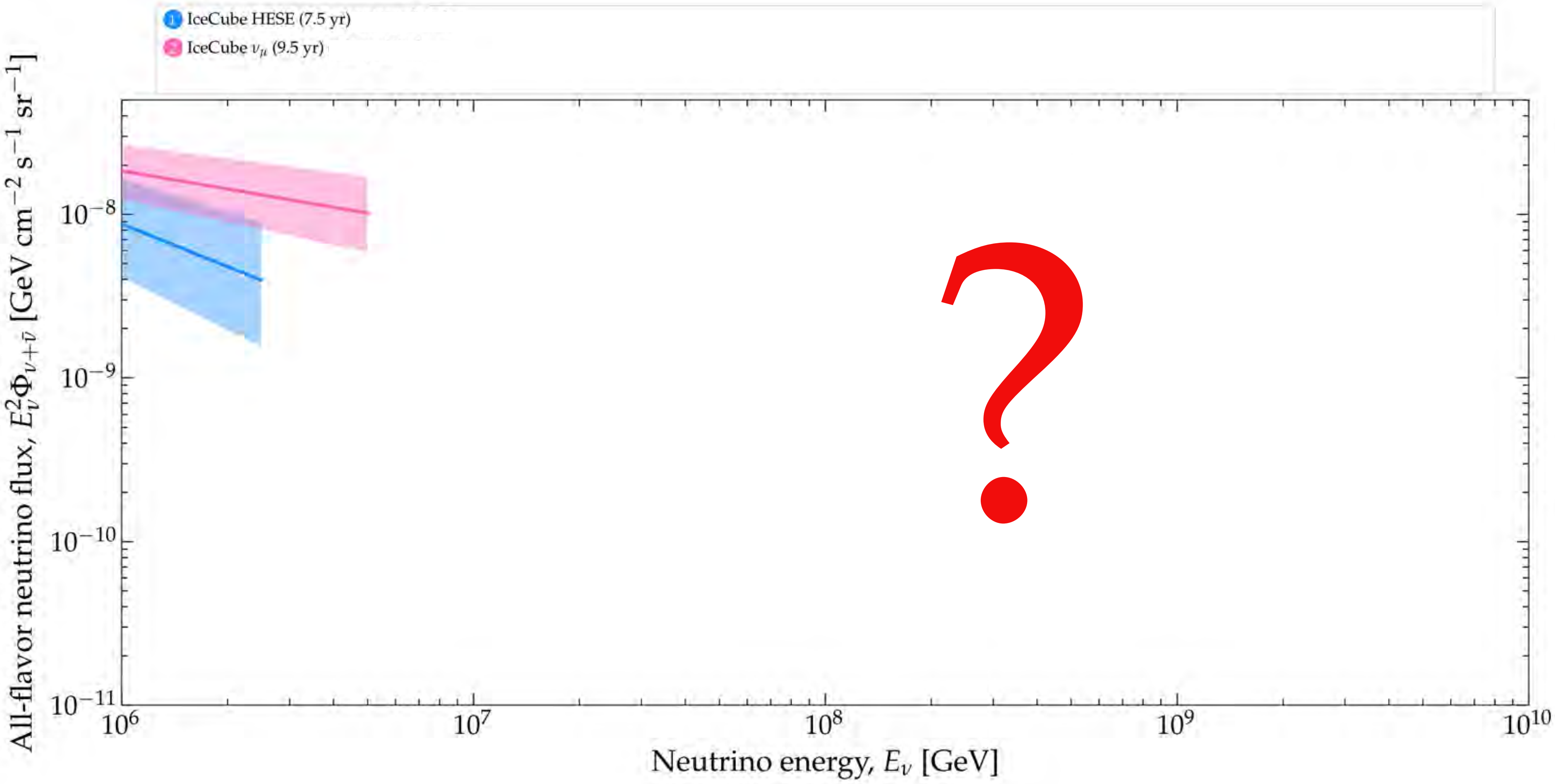
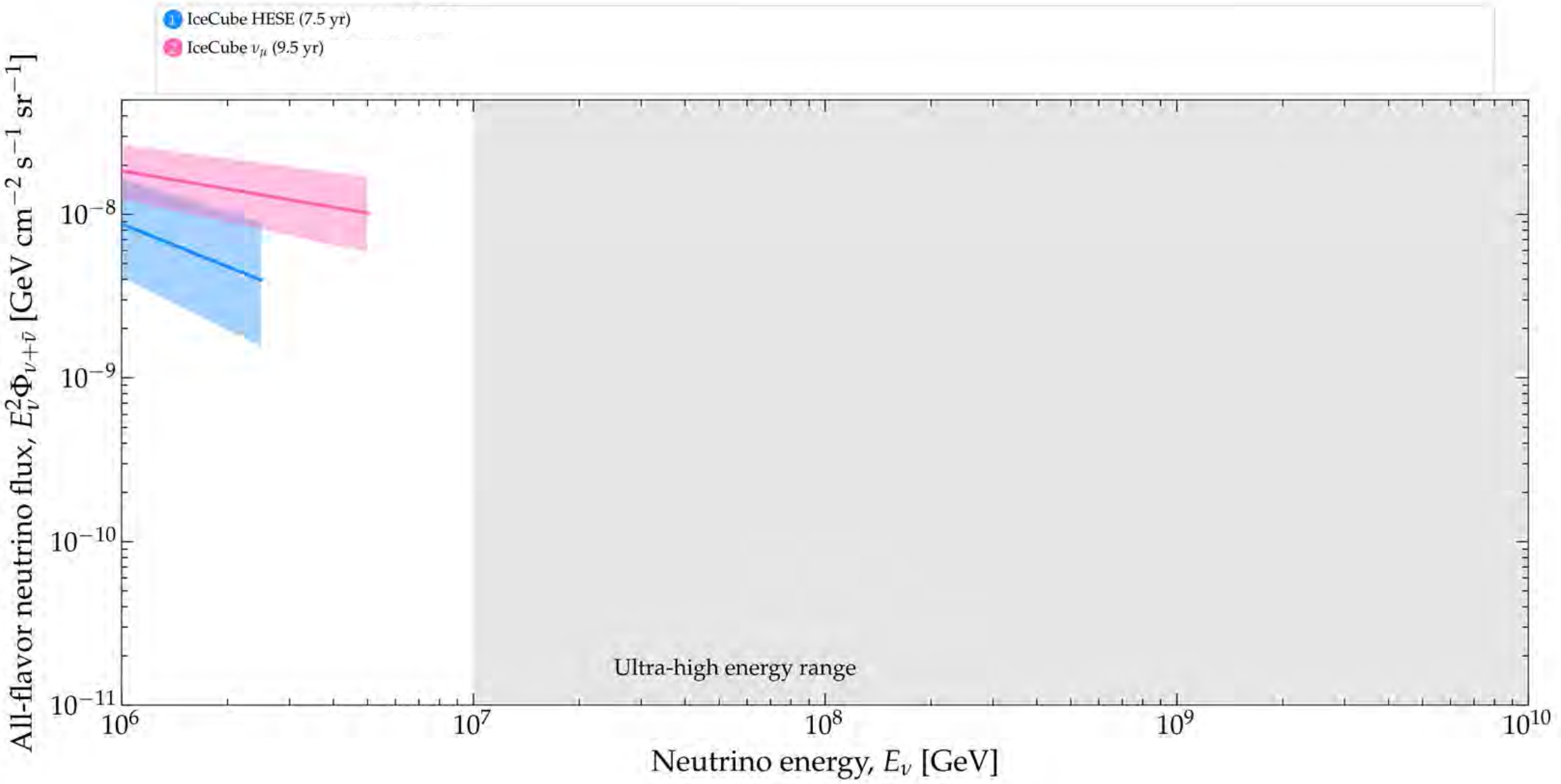
Towards ultra-high energies

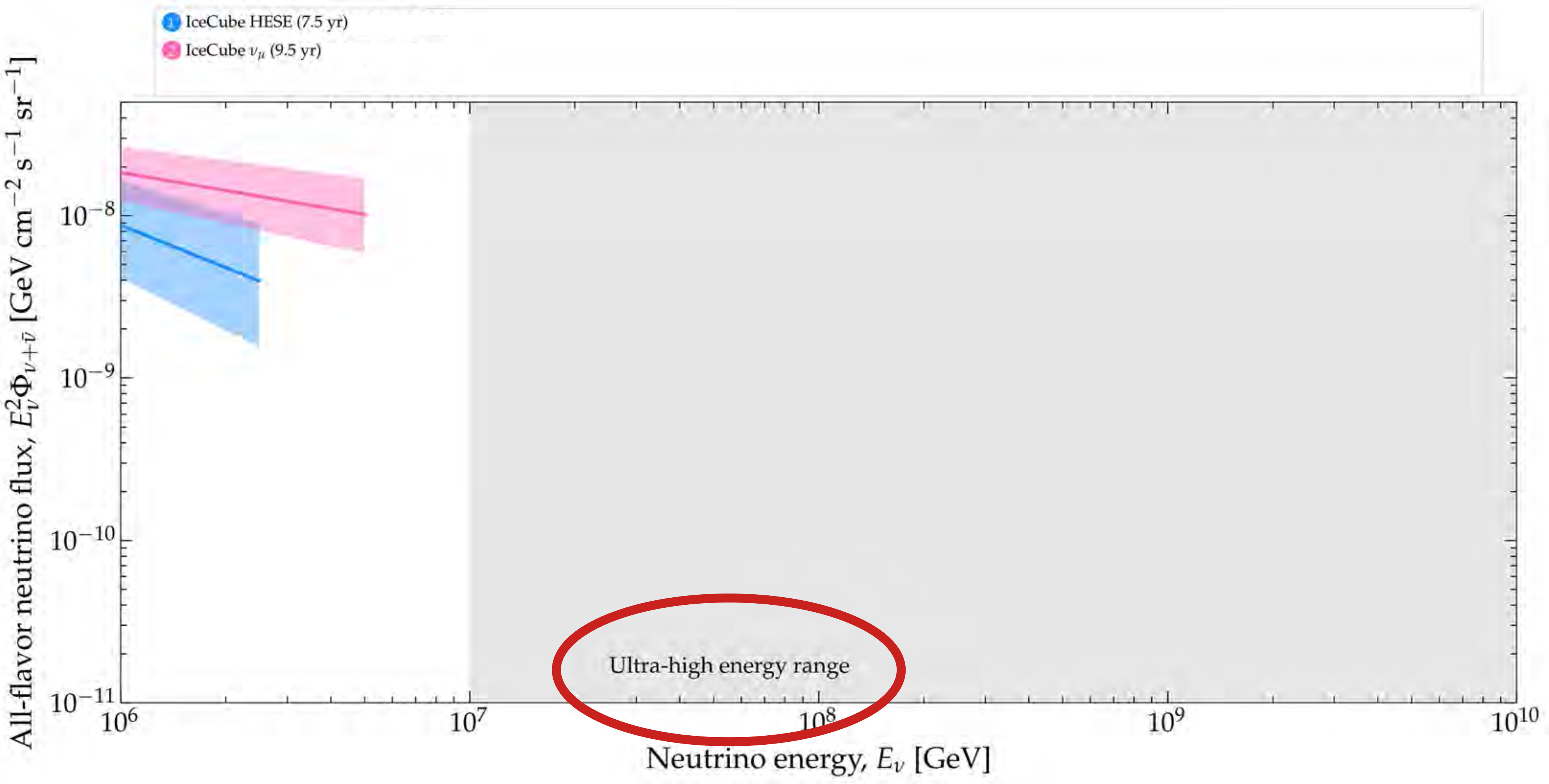


1 IceCube HESE (7.5 yr)
2 IceCube ν_μ (9.5 yr)
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]



IceCube HESE (7.5 yr)
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]
?


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



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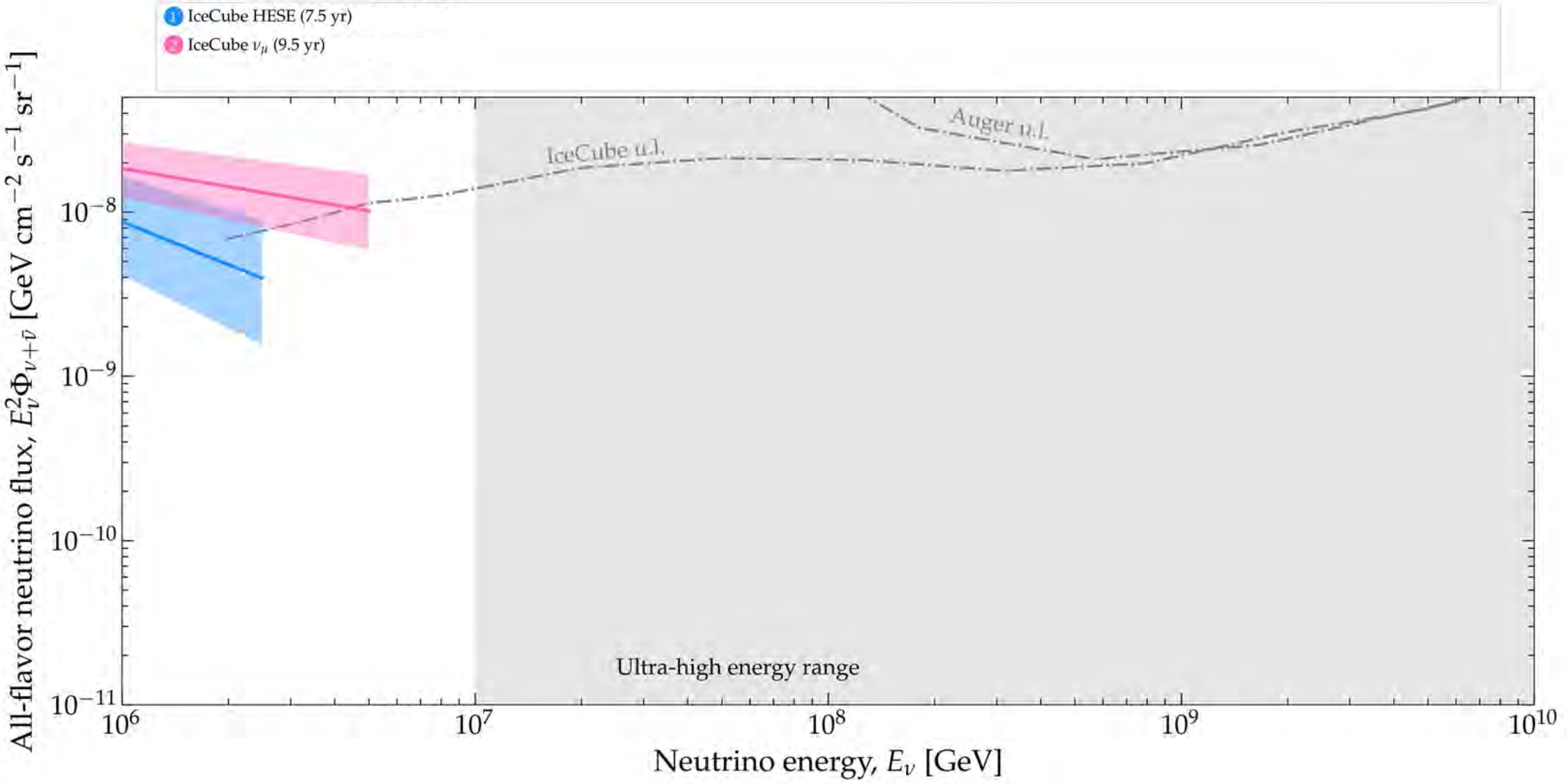
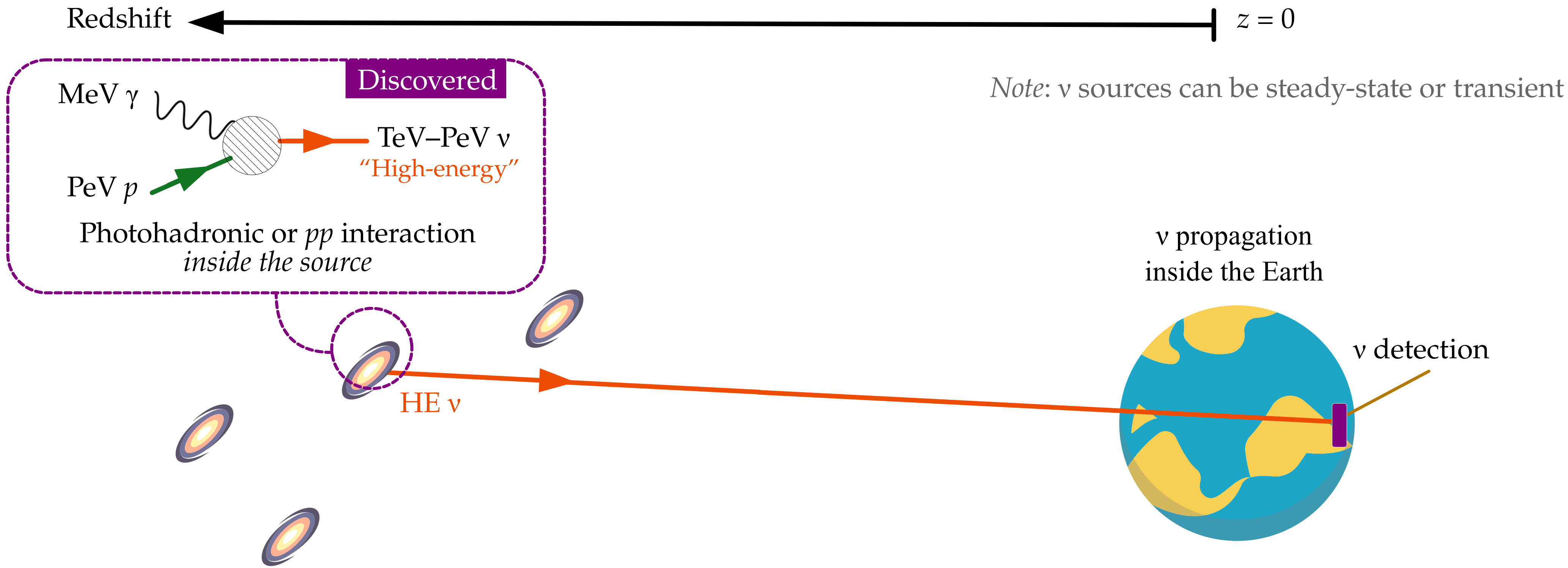
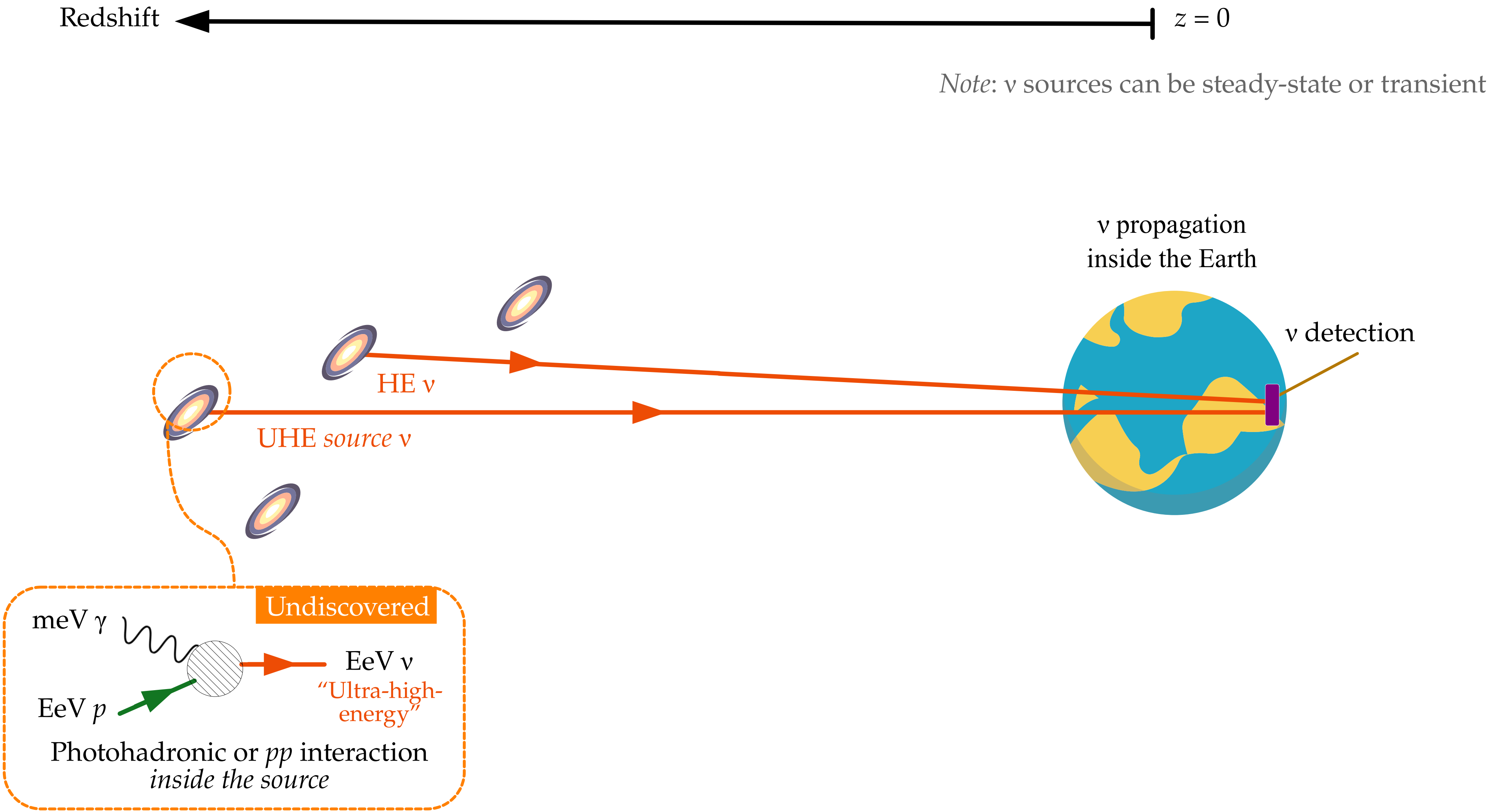
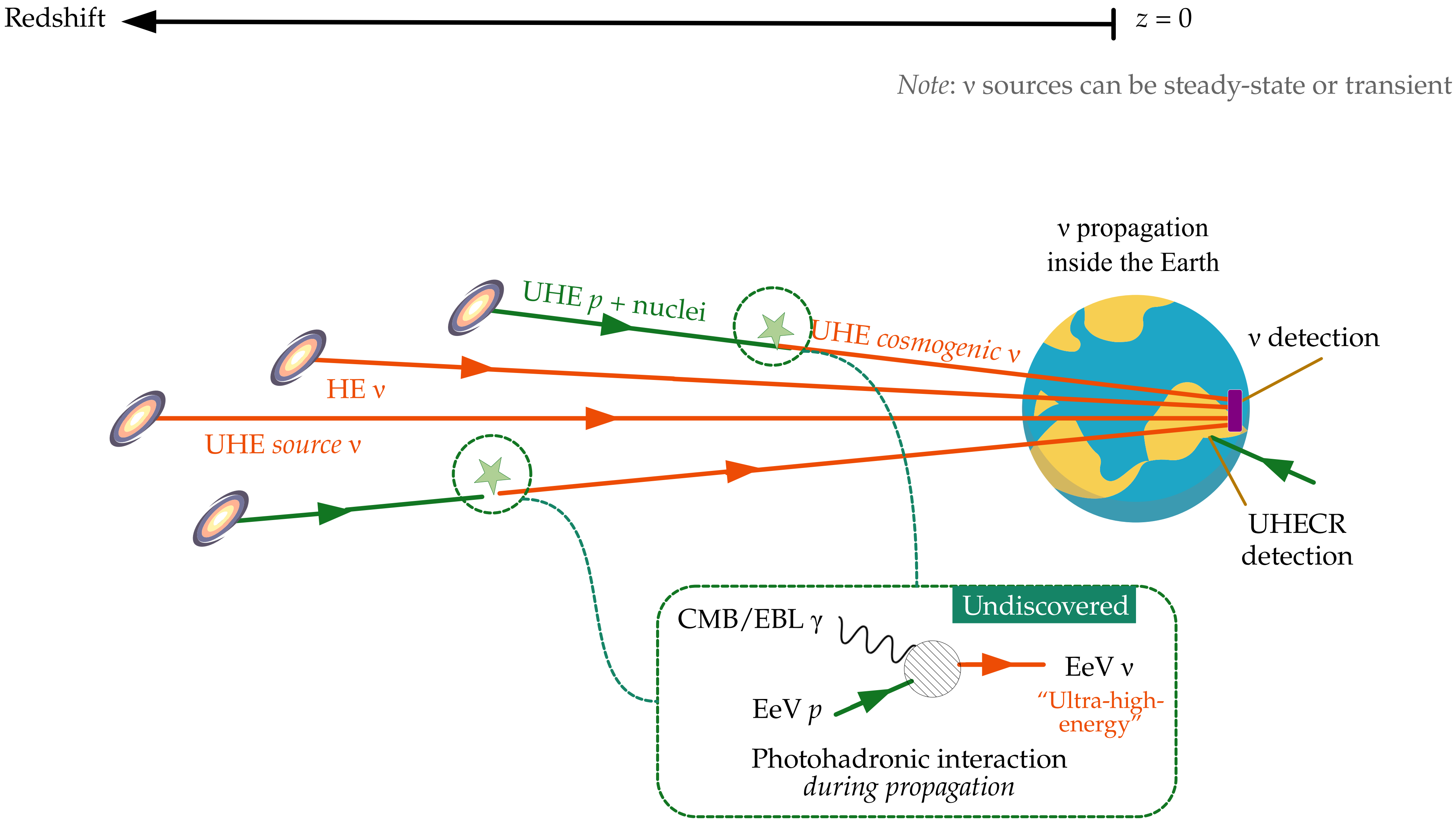
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}
Neutrino energy, E_ν [GeV]
Ultra-high energy range



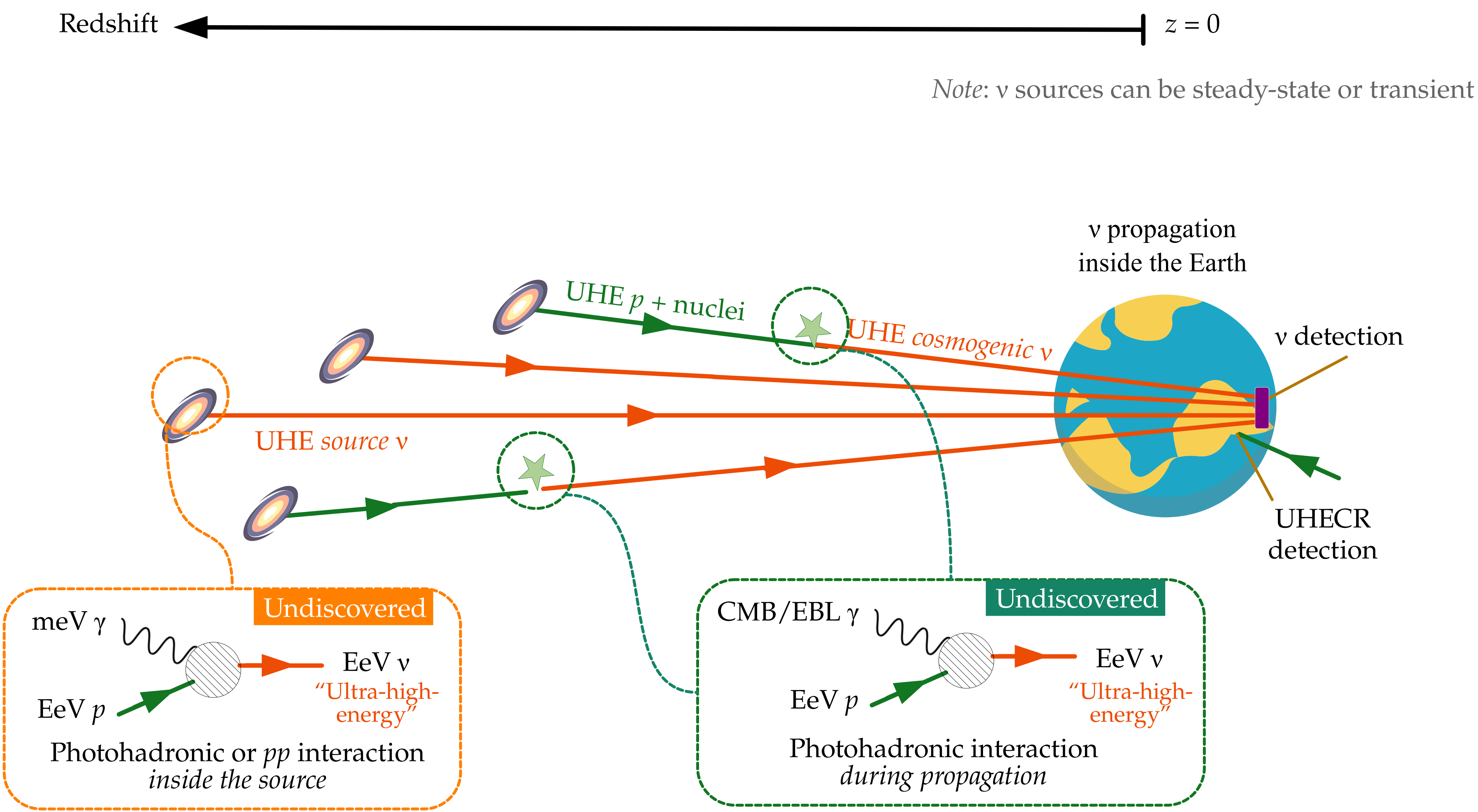
1 IceCube HESE (7.5 yr)
2 IceCube ν_μ (9.5 yr)
Auger u.l.
IceCube u.l.
Ultra-high energy range
10^{-8}
10^{-9}
10^{-10}
10^{-11}
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]


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

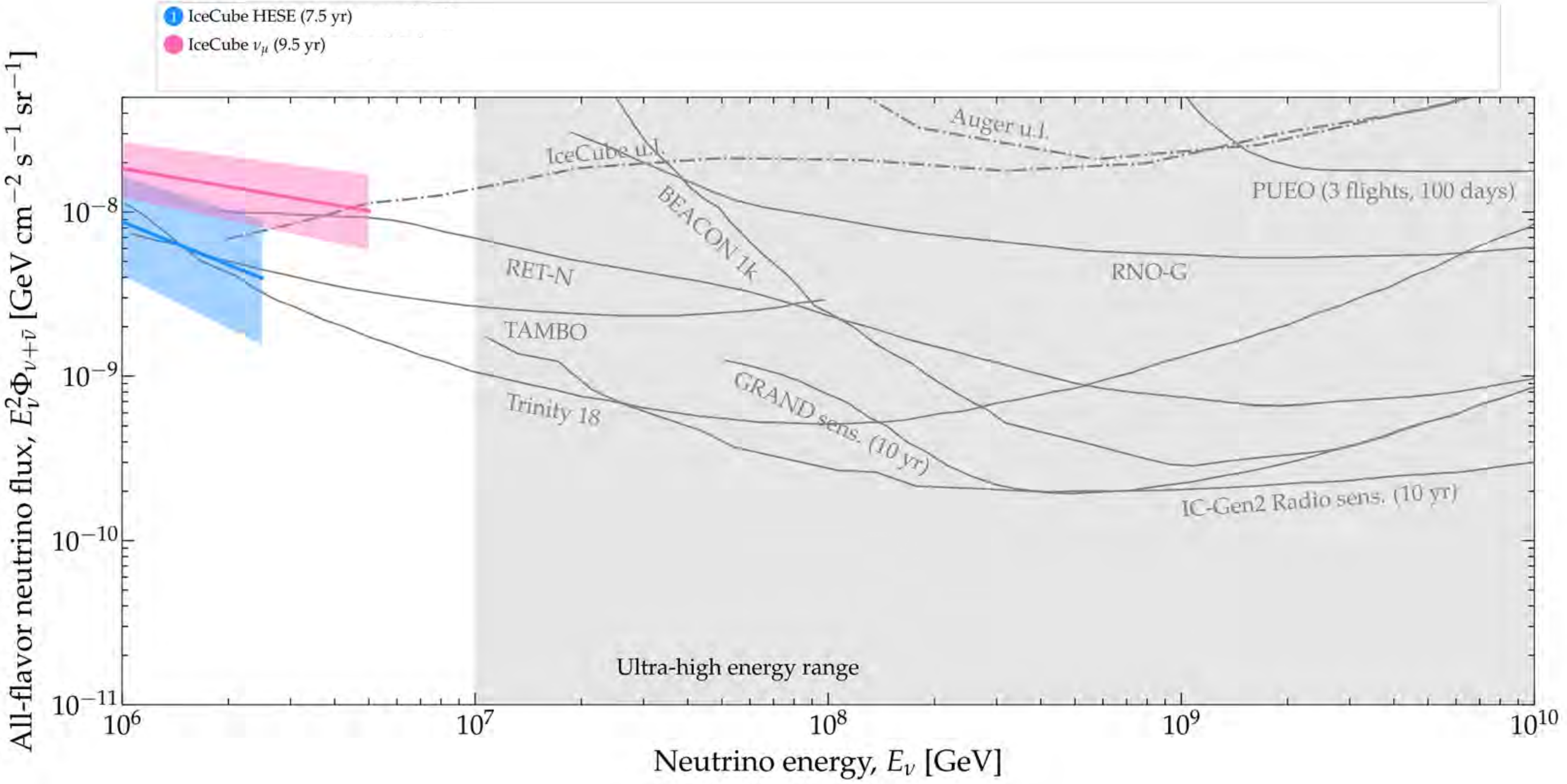

Redshift
z = 0
Note: ν sources can be steady-state or transient
ν propagation
inside the Earth
ν detection
HE ν
UHE source ν
Undiscovered
meV γ
EeV ν
"Ultra-high-
energy"
EeV p
Photohadronic or pp interaction
inside the source

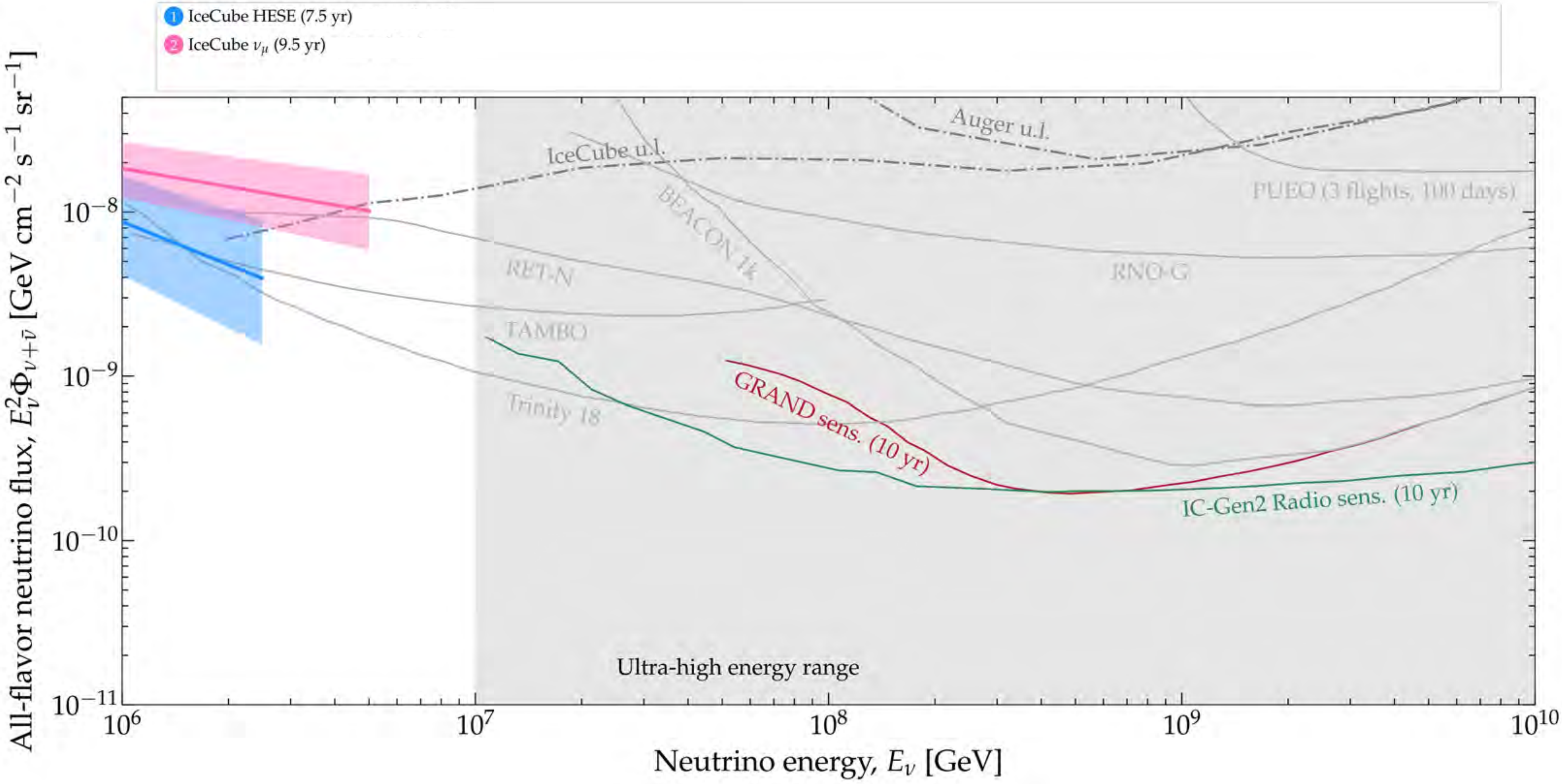


Redshift
z = 0
Note: ν sources can be steady-state or transient
ν propagation
inside the Earth
UHE p + nuclei
UHE cosmogenic ν
ν detection
HE ν
UHE source ν
UHECR
detection
Undiscovered
CMB/EBL γ
EeV ν
"Ultra-high-energy"
EeV p
Photohadronic interaction
during propagation



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
UHE *source* ν
UHECR detection
Undiscovered
meV γ
EeV ν
"Ultra-high-energy"
EeV *p*
Photohadronic or *pp* interaction
inside the source
Undiscovered
CMB/EBL γ
EeV ν
"Ultra-high-energy"
EeV *p*
Photohadronic interaction
during propagation


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



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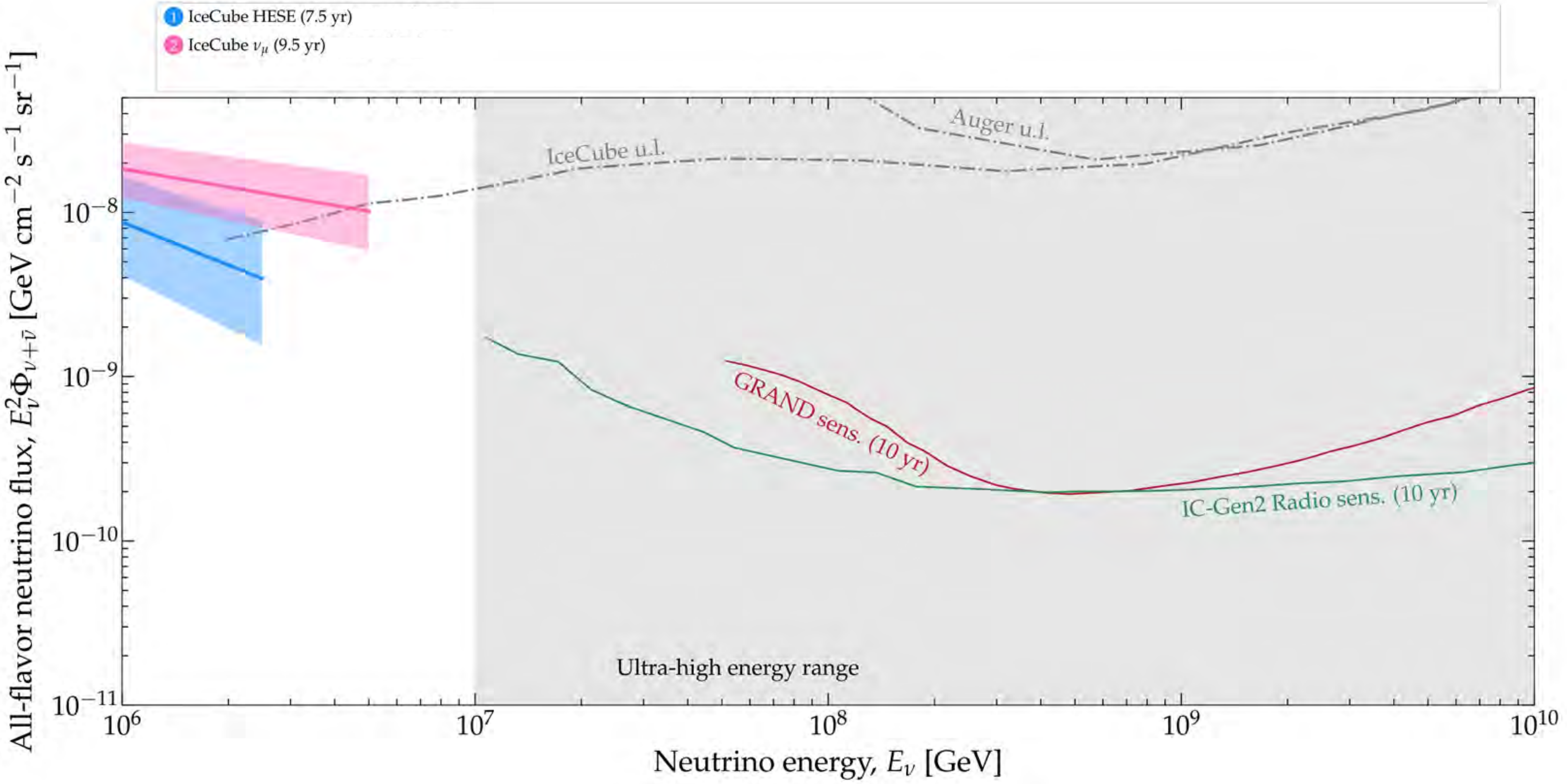
Ultra-high energy range
All-flavor neutrino flux, $E_\nu^2\Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy, E_ν [GeV]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}



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IceCube ν_μ (9.5 yr)
IceCube u.l.
Auger u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
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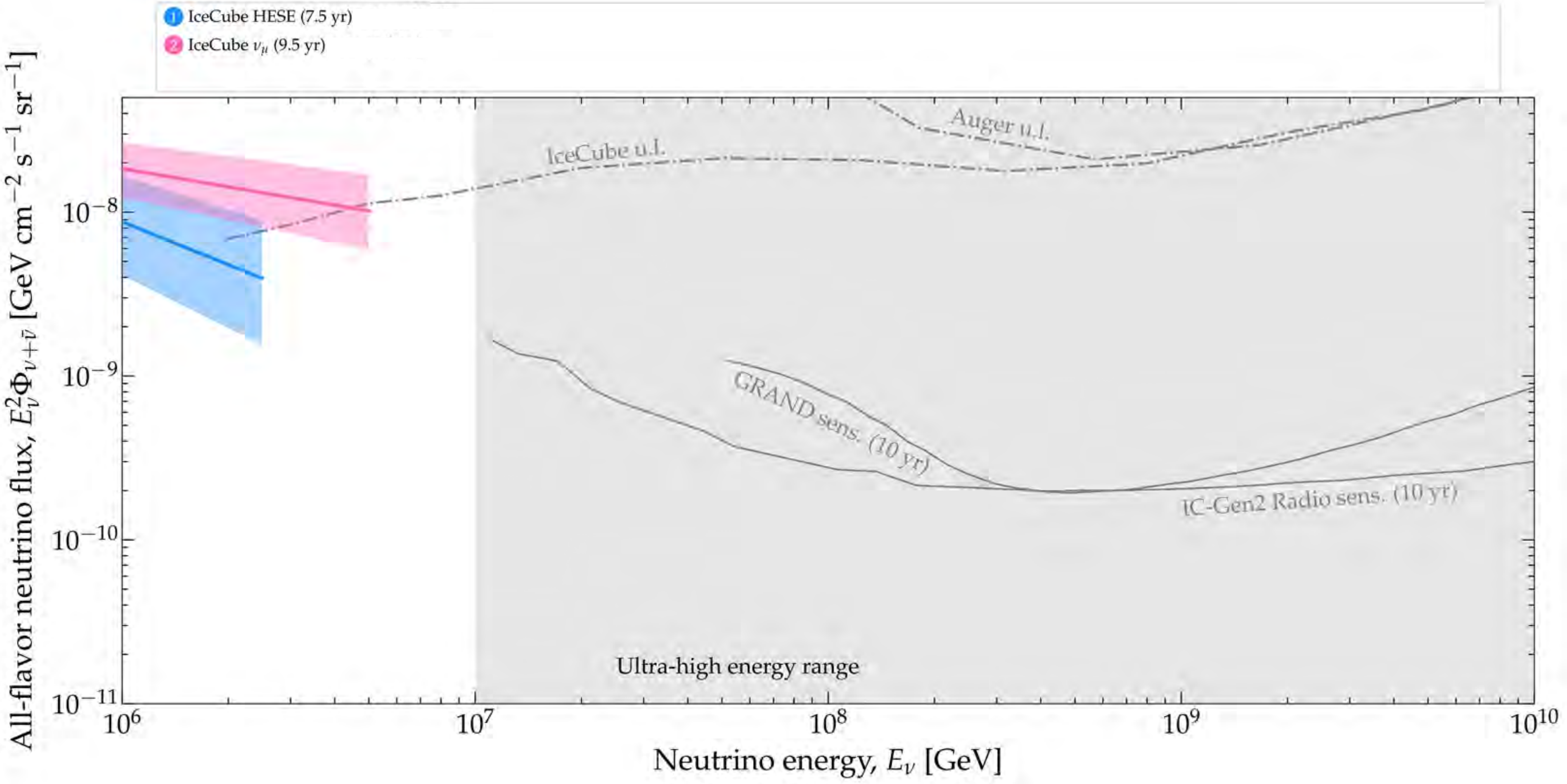
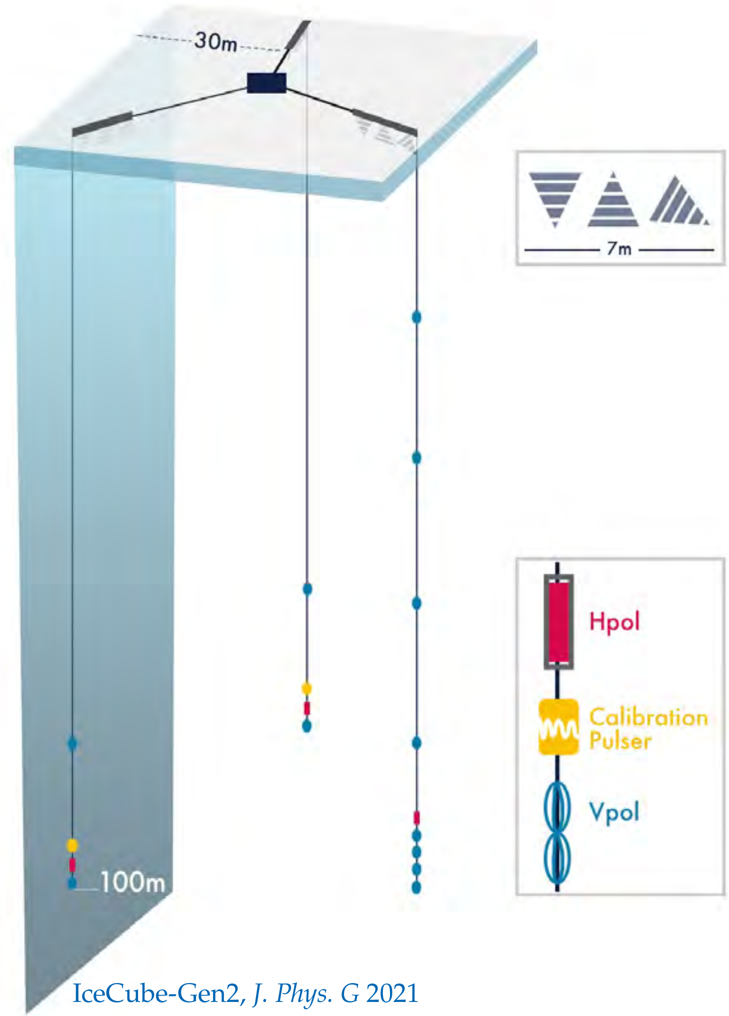
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]

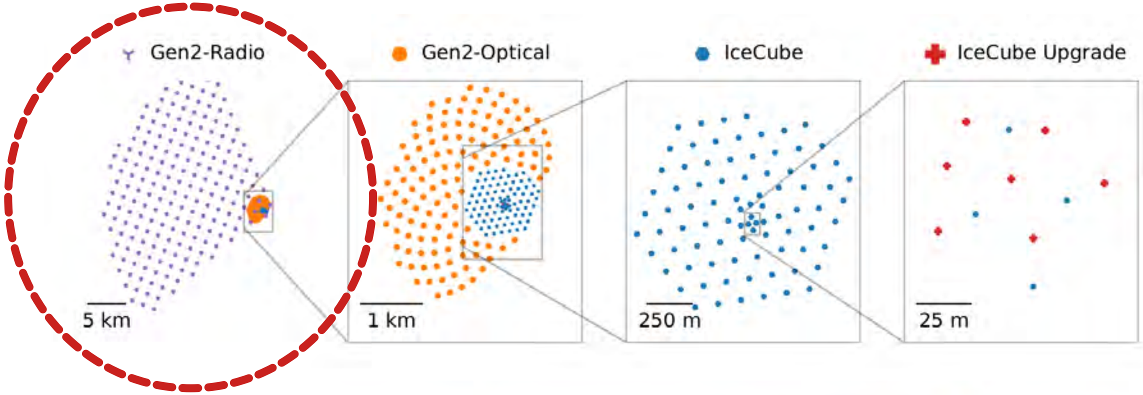


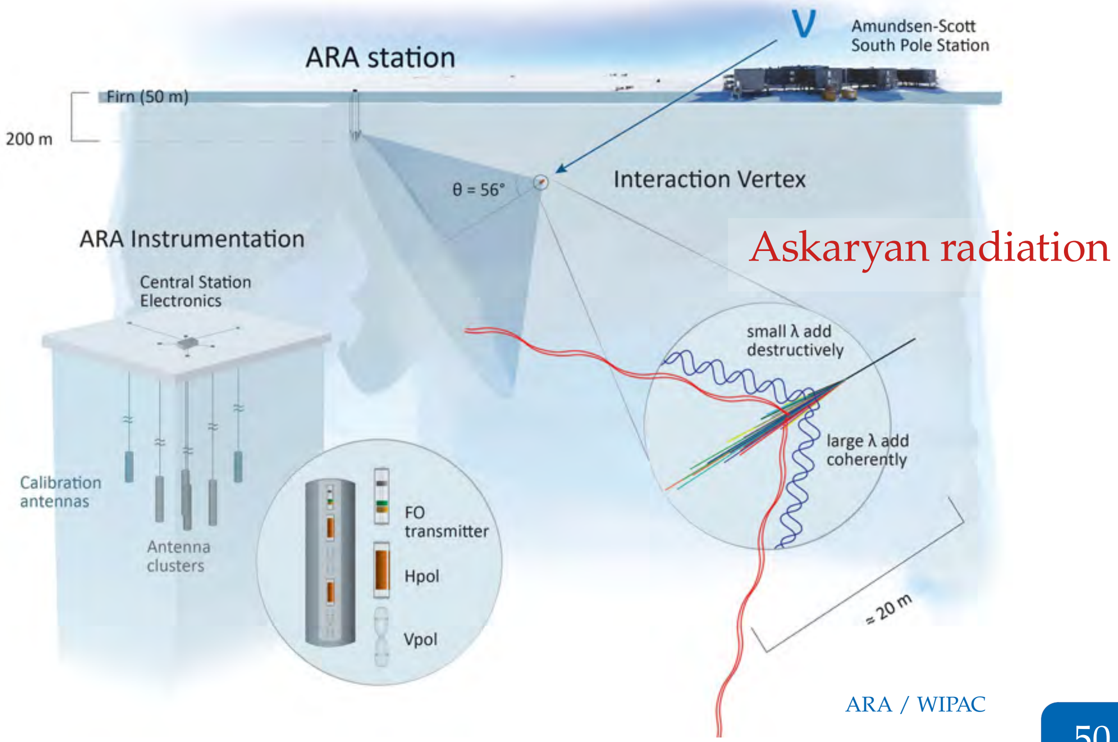
IceCube HESE (7.5 yr)
IceCube ν_μ (9.5 yr)
Auger u.l.
IceCube u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
All-flavor neutrino flux, $E_\nu^2\Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}
Neutrino energy, E_ν [GeV]

IceCube-Gen2 Radio

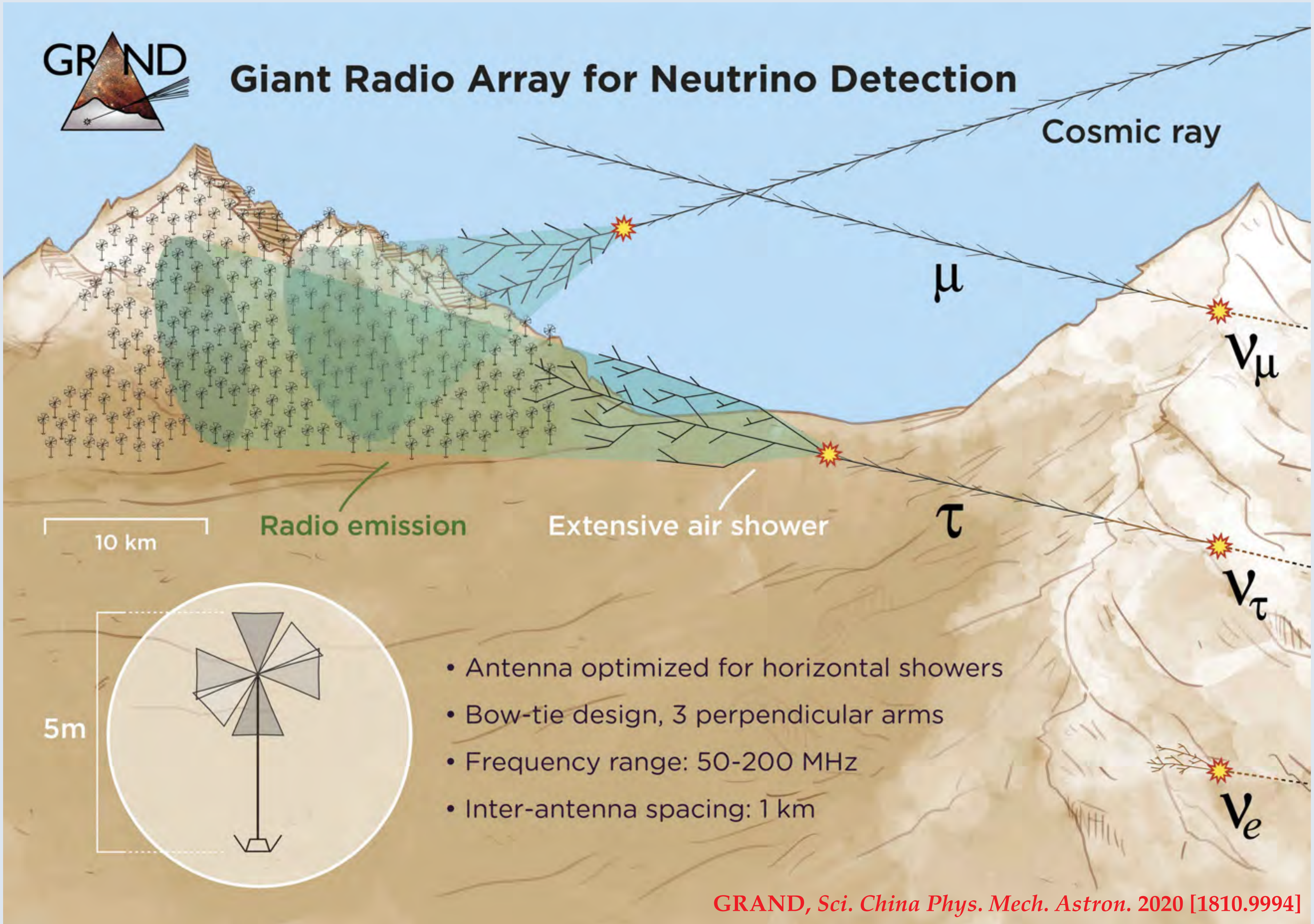


IceCube-Gen2, *J. Phys. G* 2021





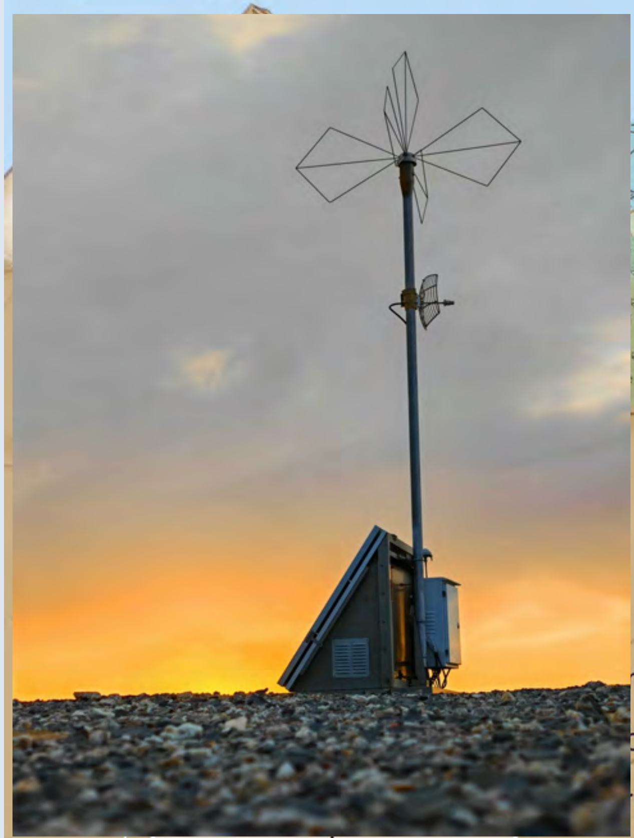
ARA / WIPAC



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

Giant Radio Array for Neutrino Detection

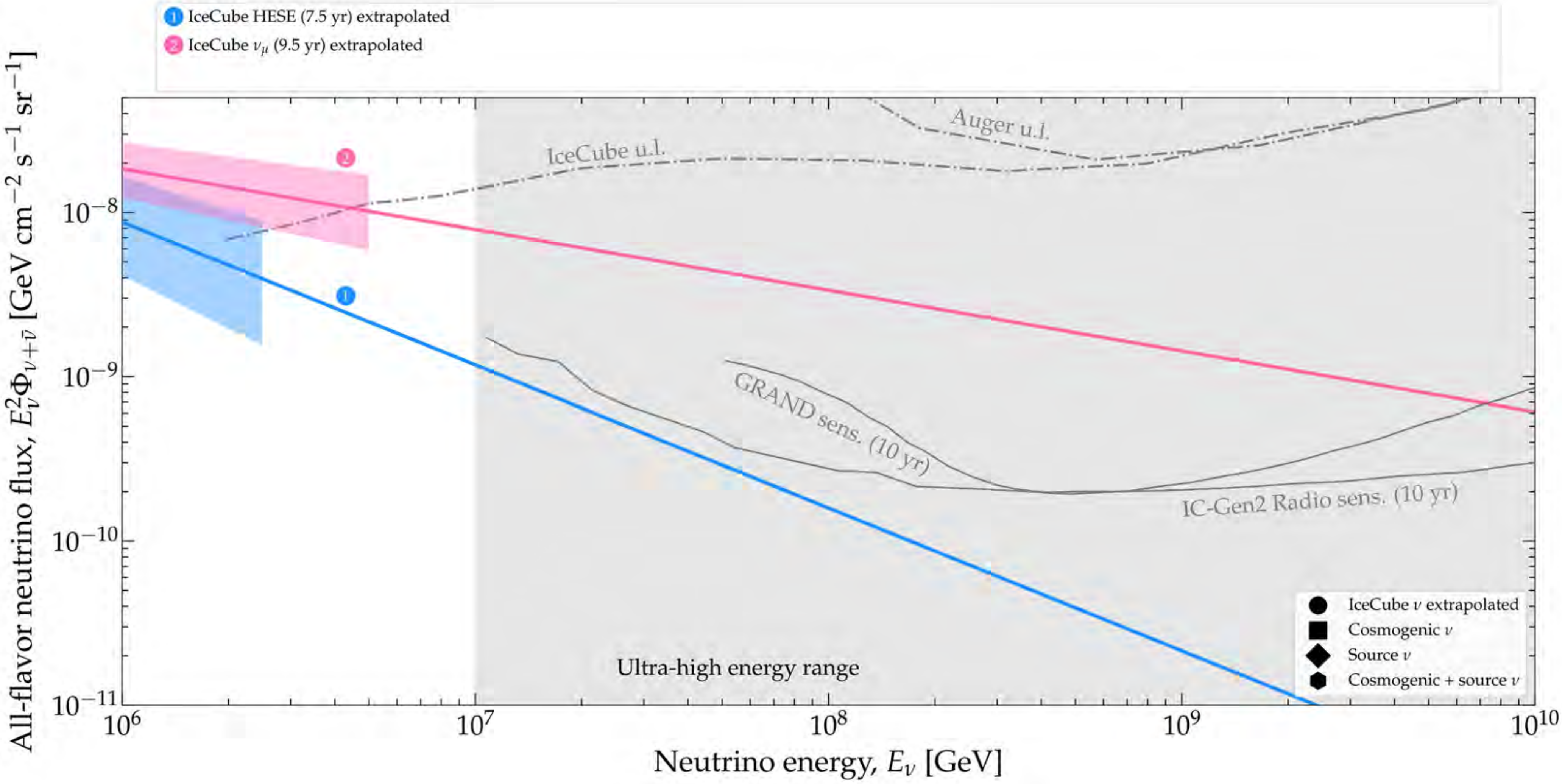
Cosmic ray



- Inter-antenna spacing: 1 km

ν_e

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



IceCube HESE (7.5 yr) extrapolated
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}]
Neutrino energy, E_ν [GeV]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{6}
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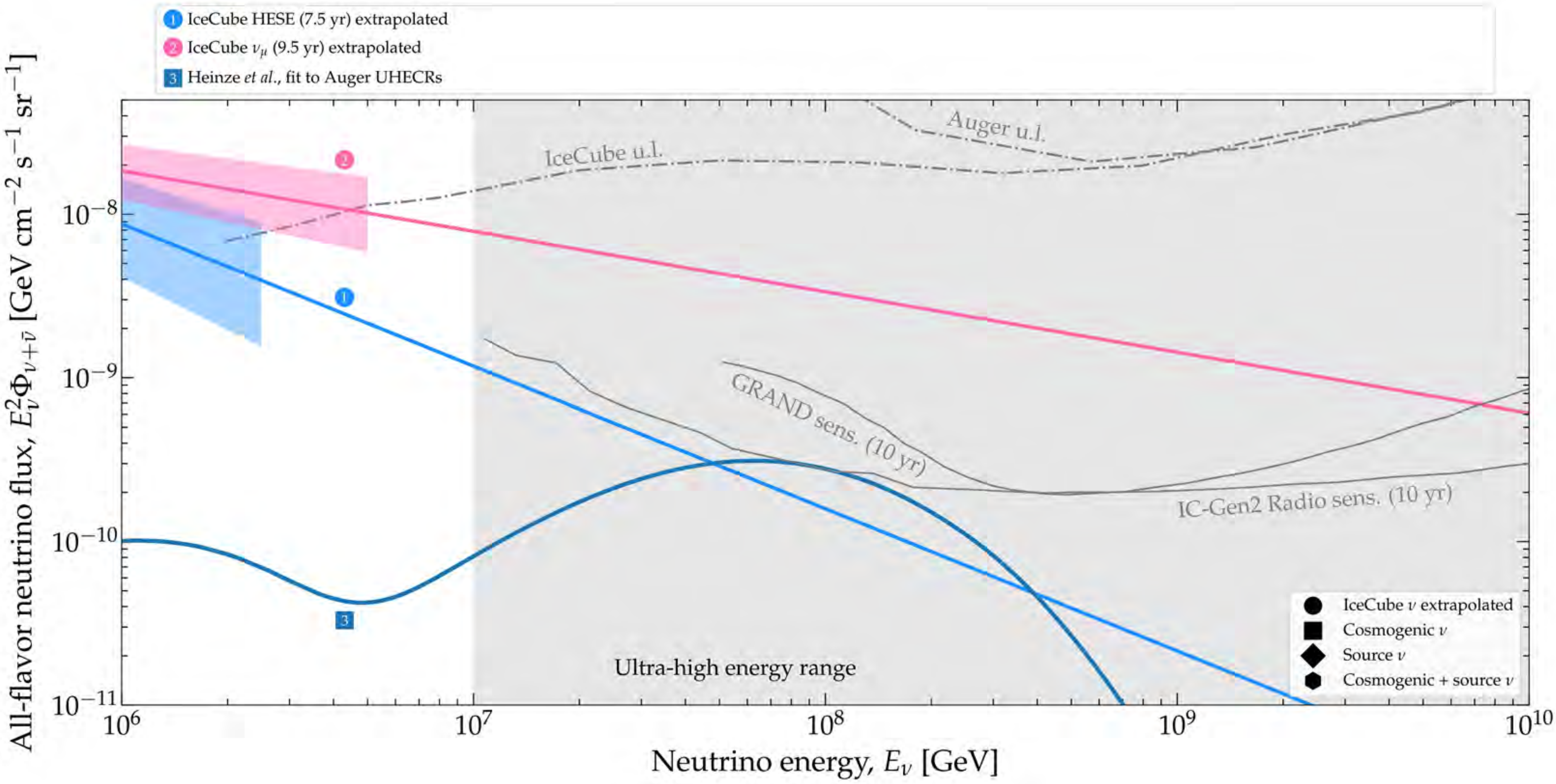

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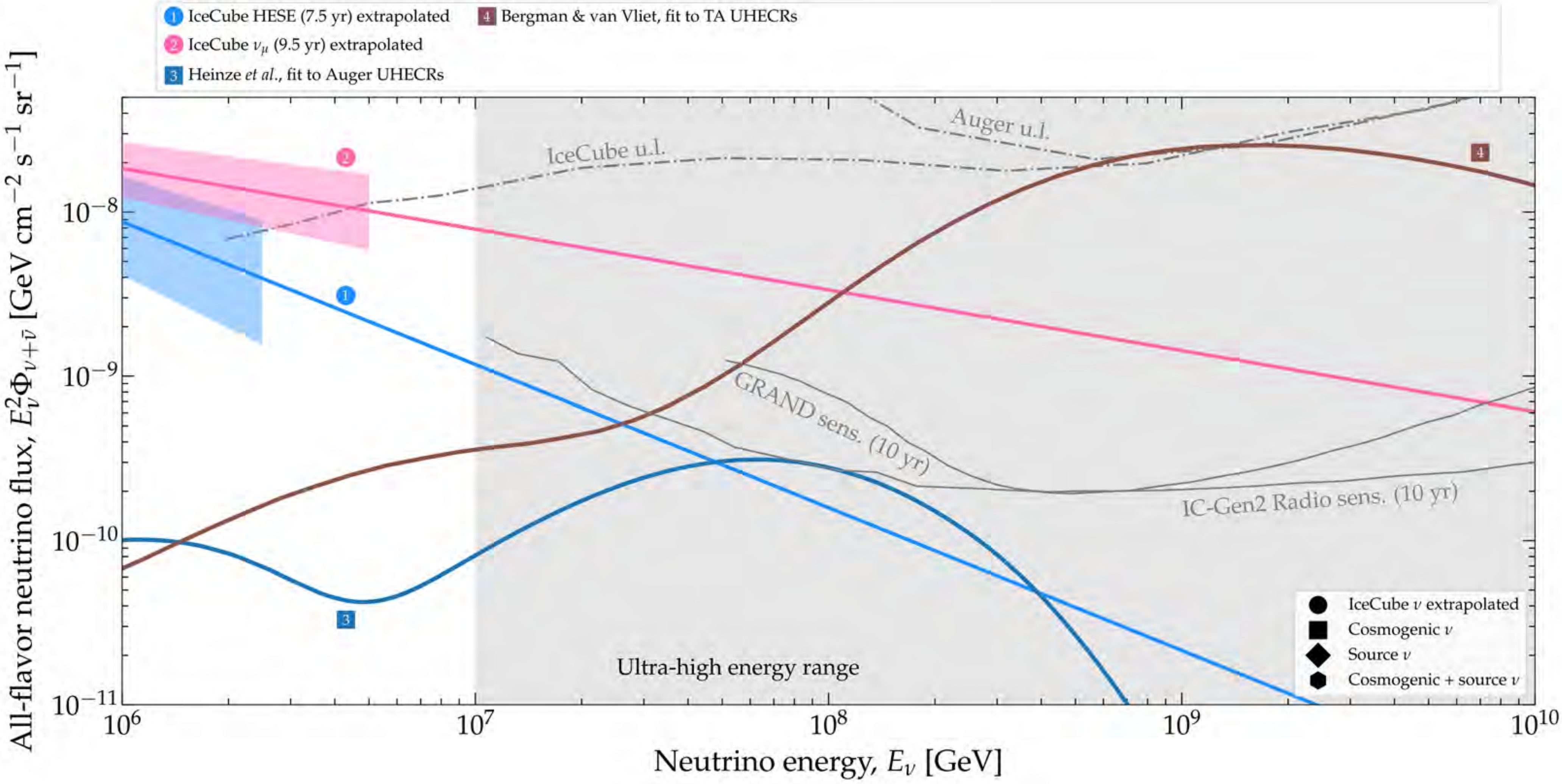

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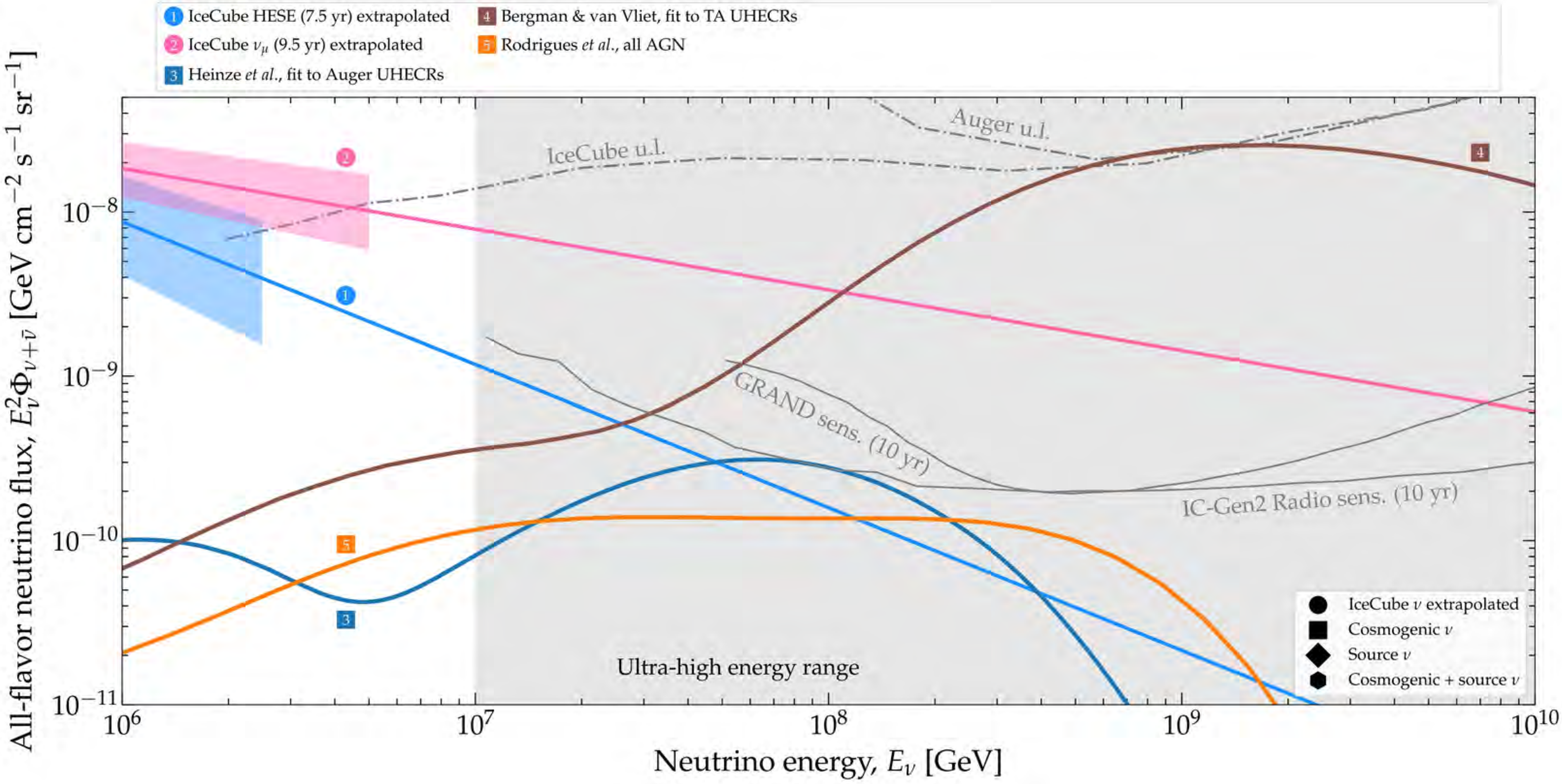

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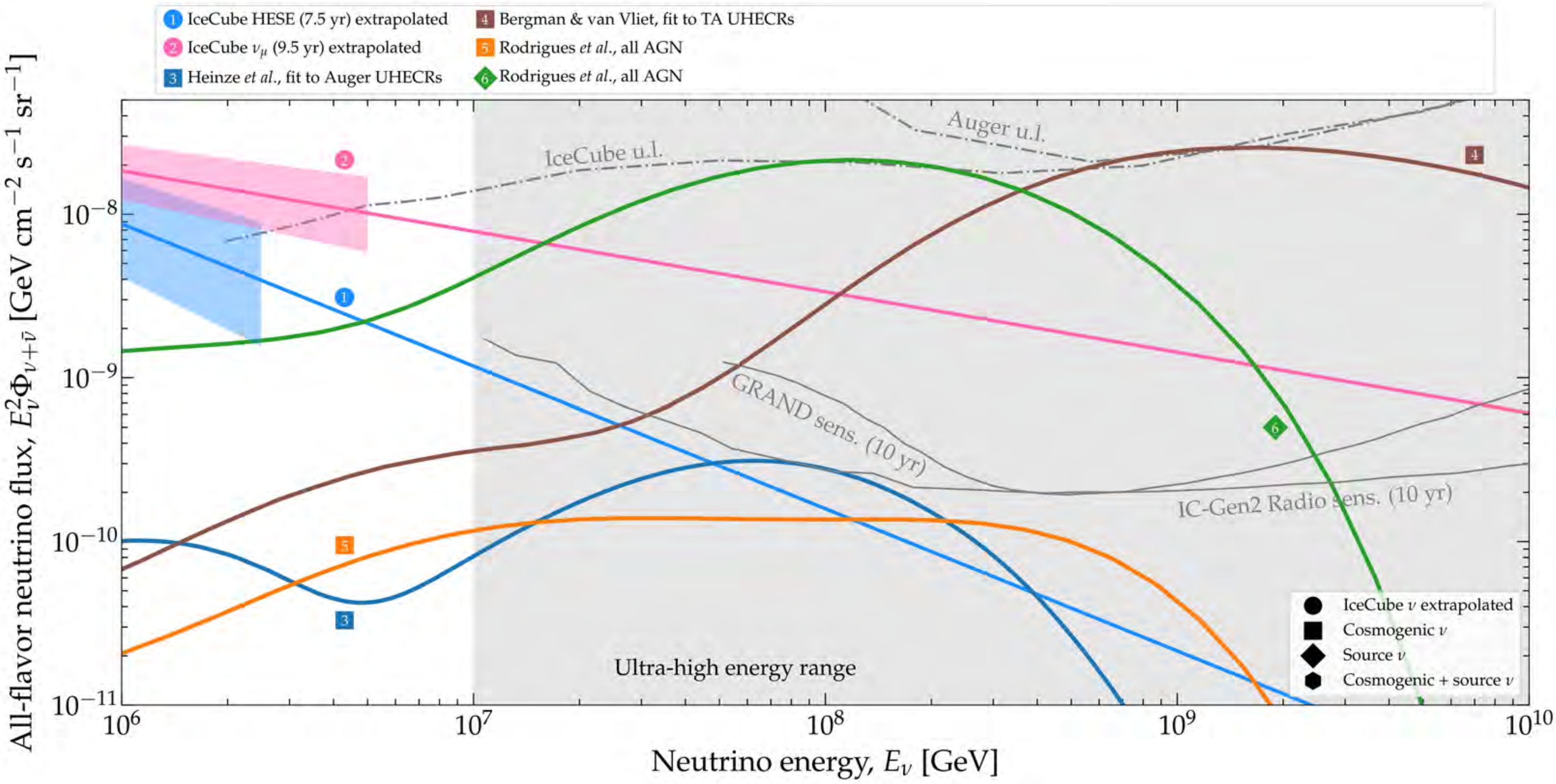

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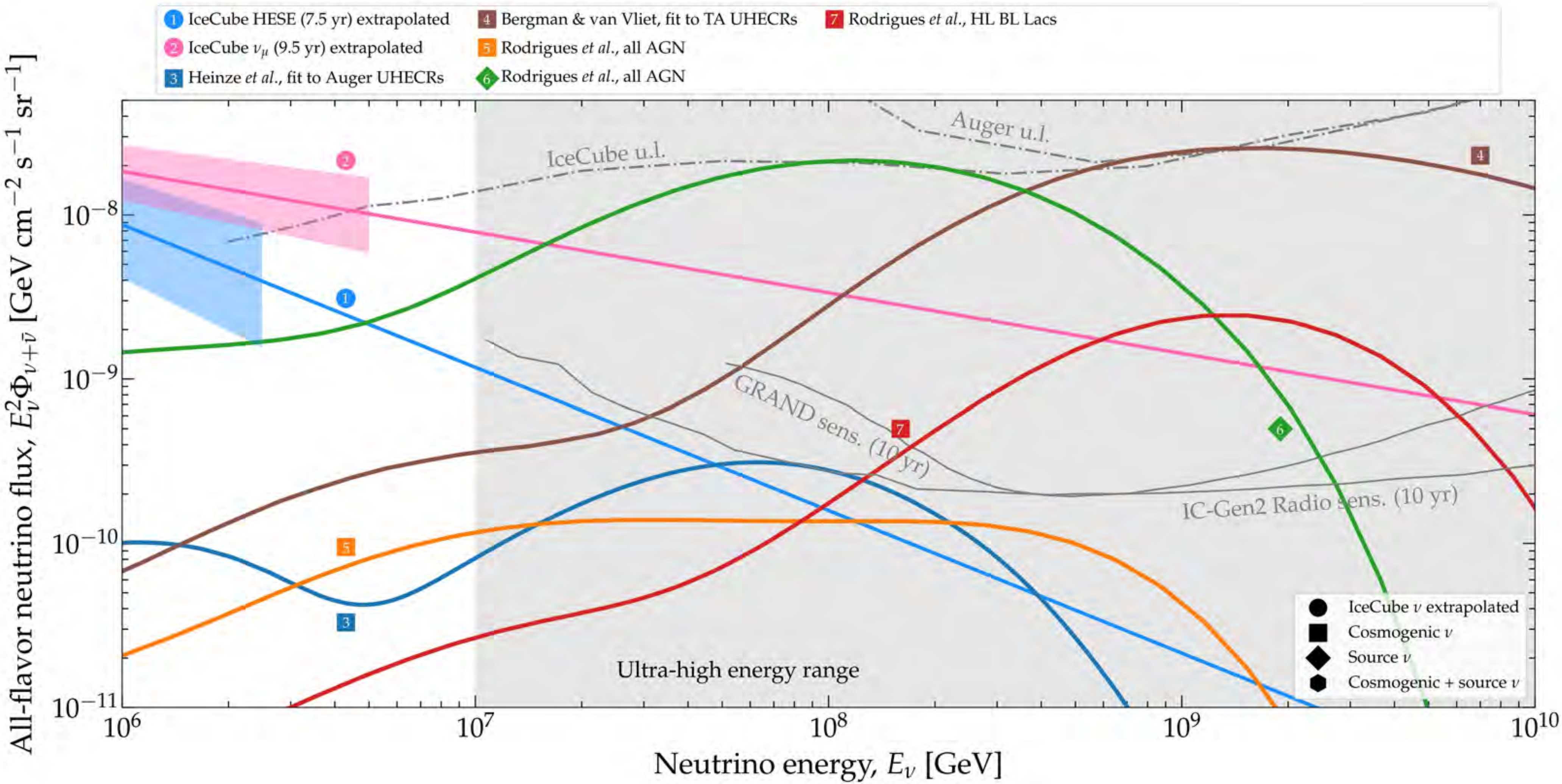

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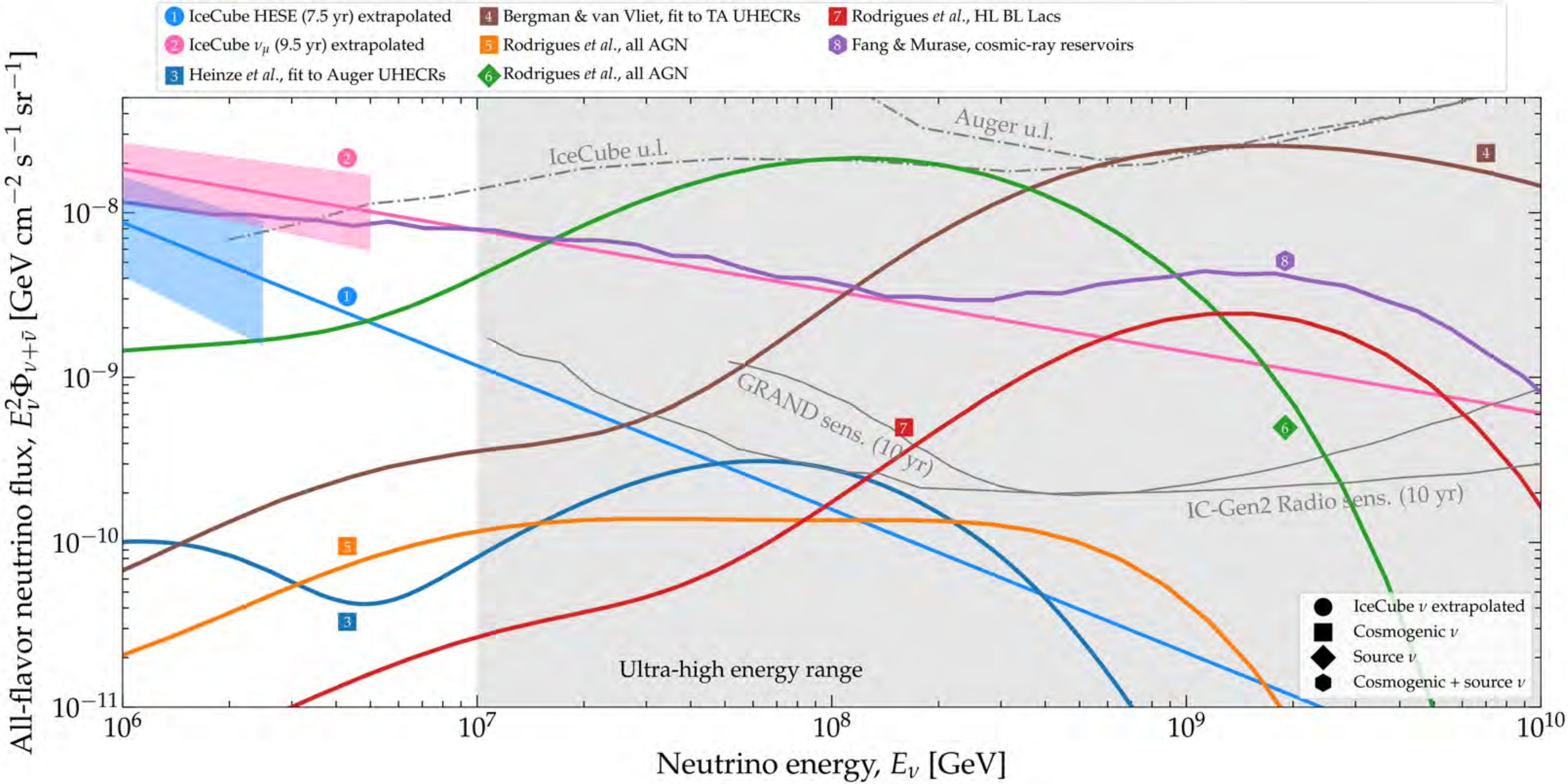

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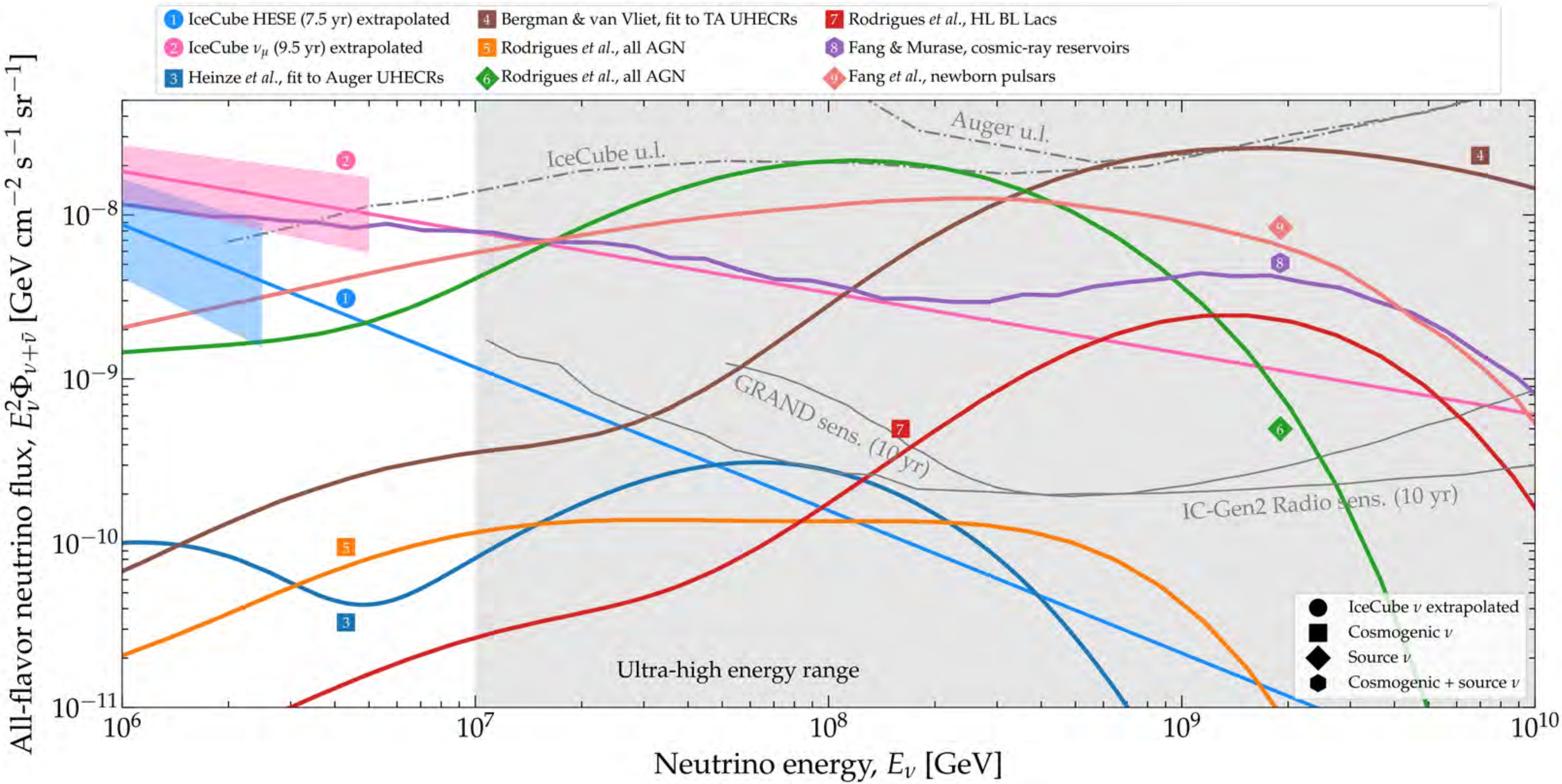

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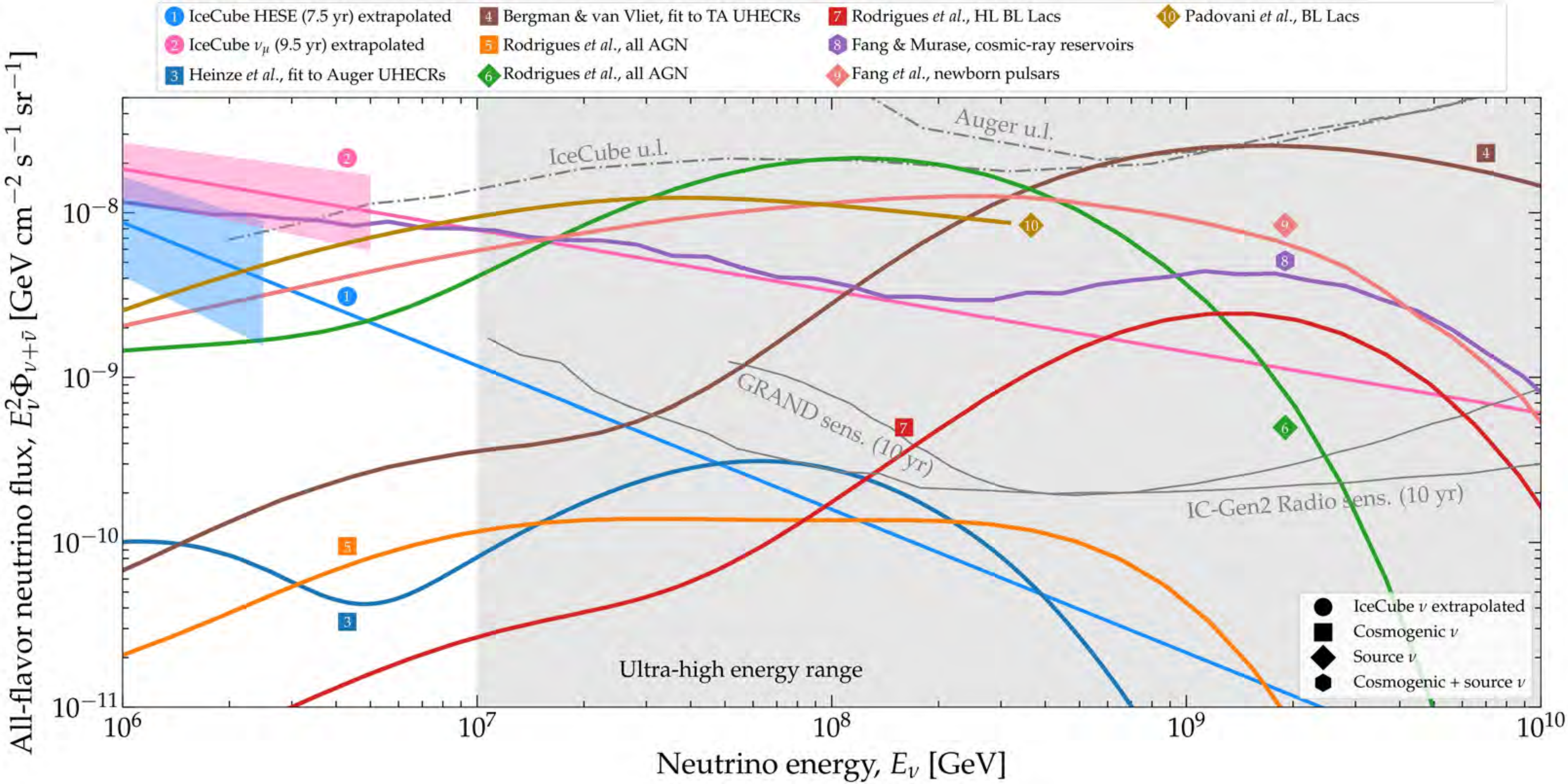

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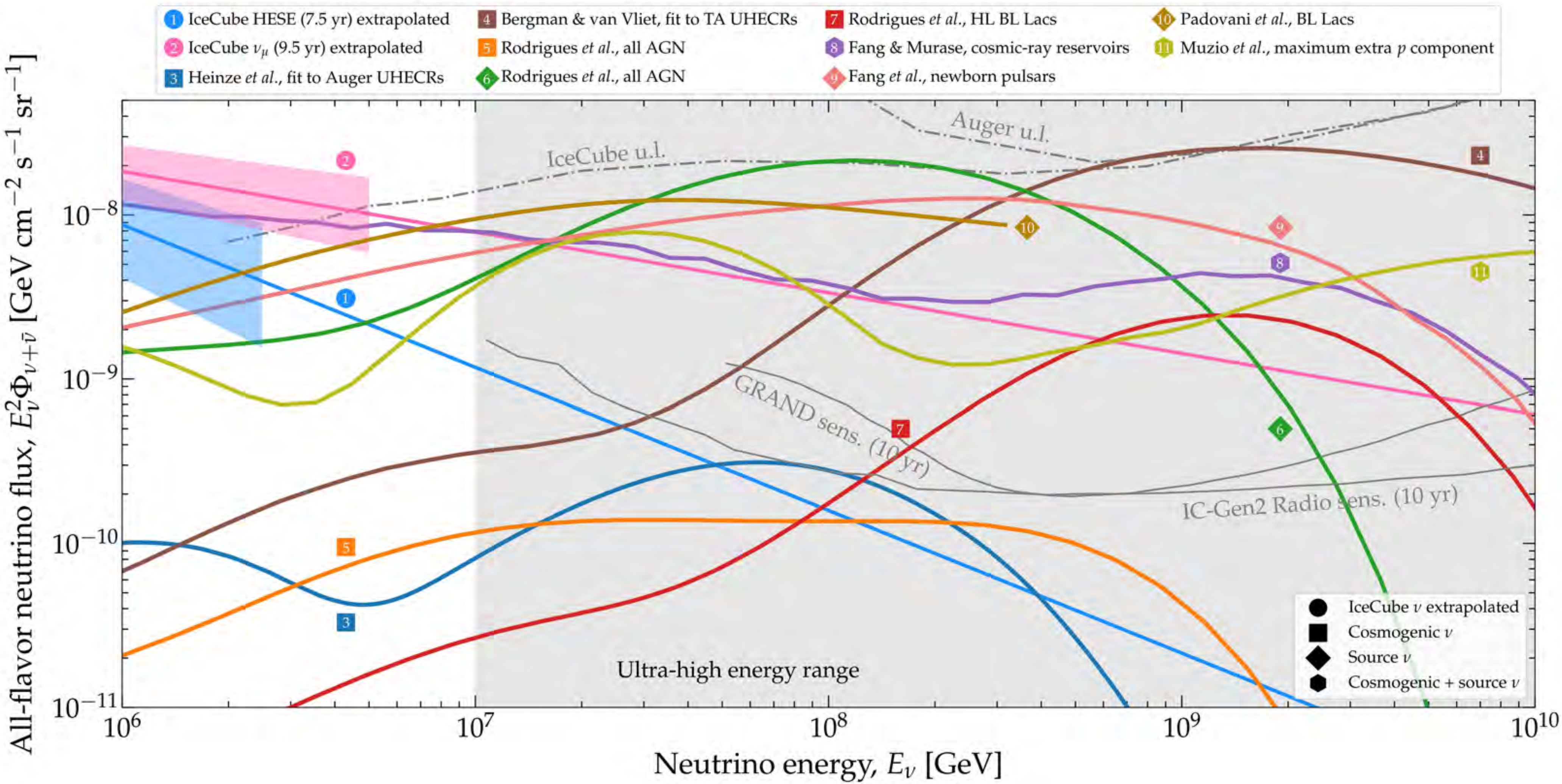

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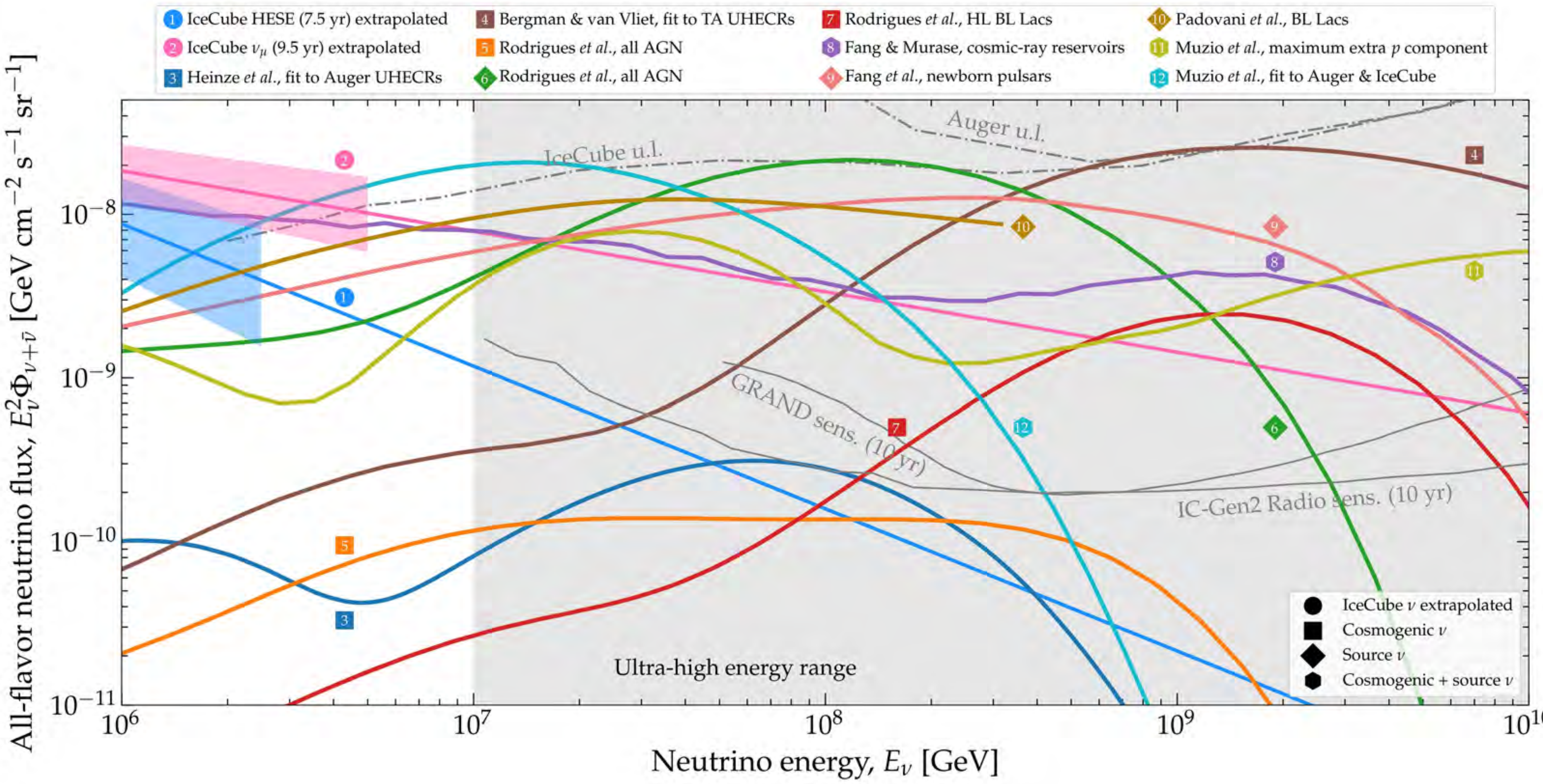

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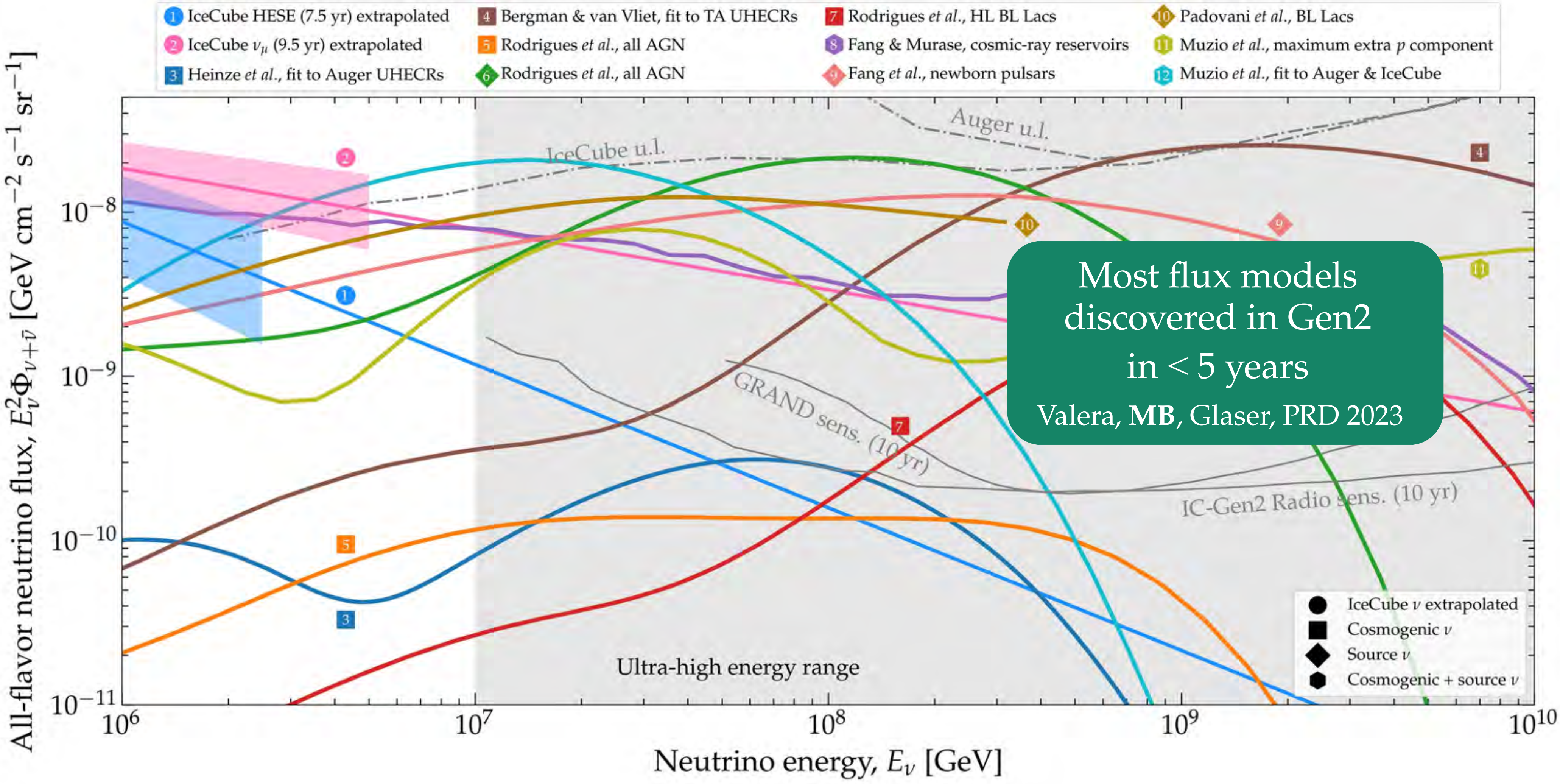


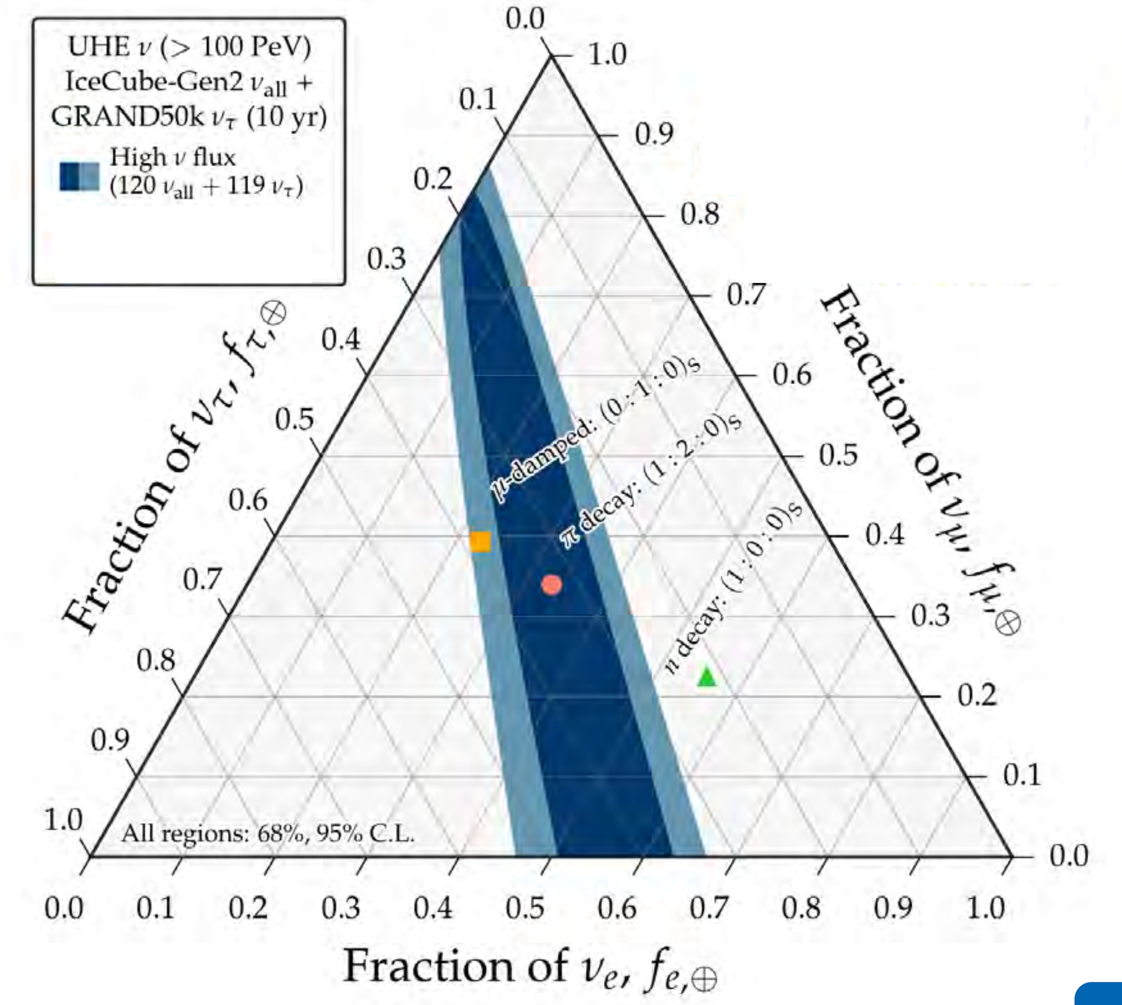
Most flux models discovered in Gen2 in < 5 years

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

Manufacturing UHE flavor sensitivity with two detectors

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

Then we combine two detectors:



Testagrossa, Fiorillo, **MB**, 2310.12215

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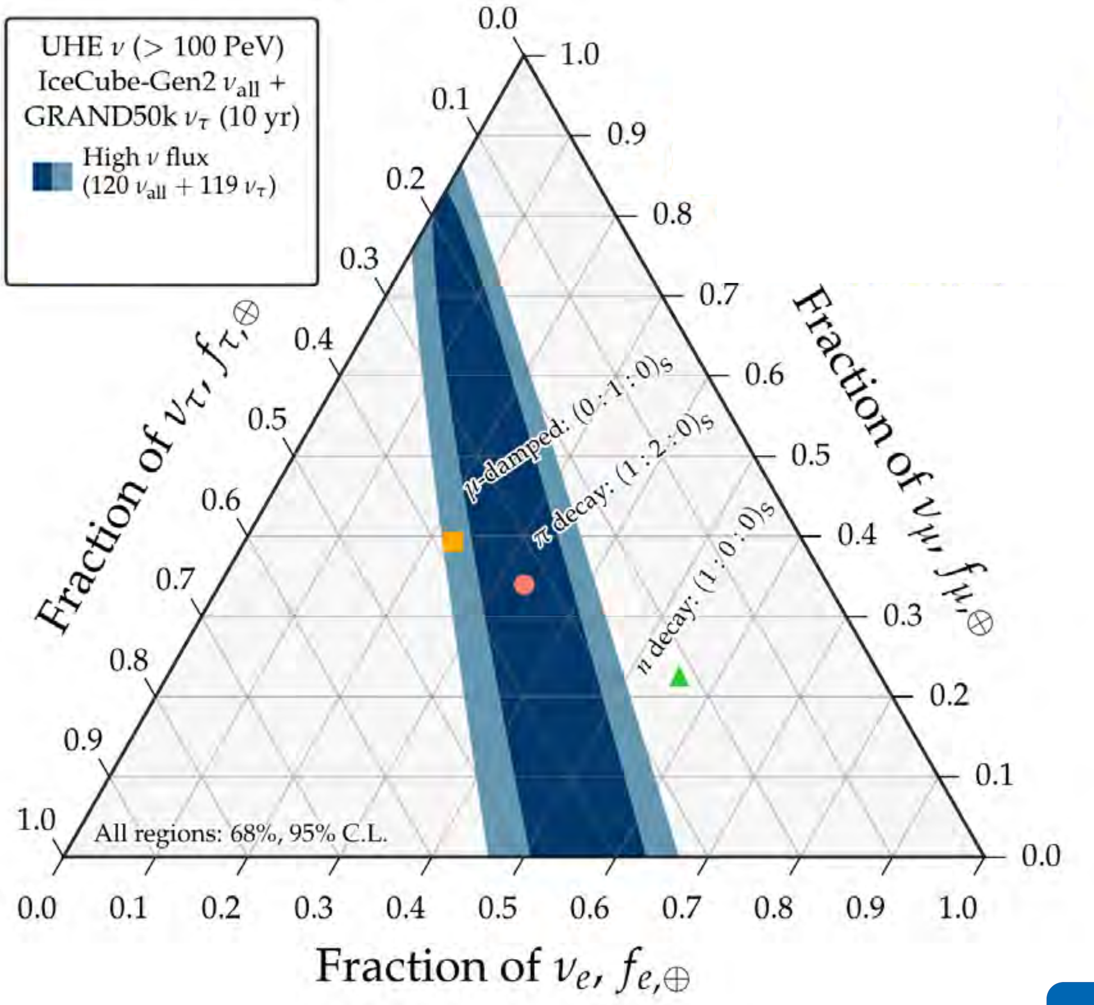

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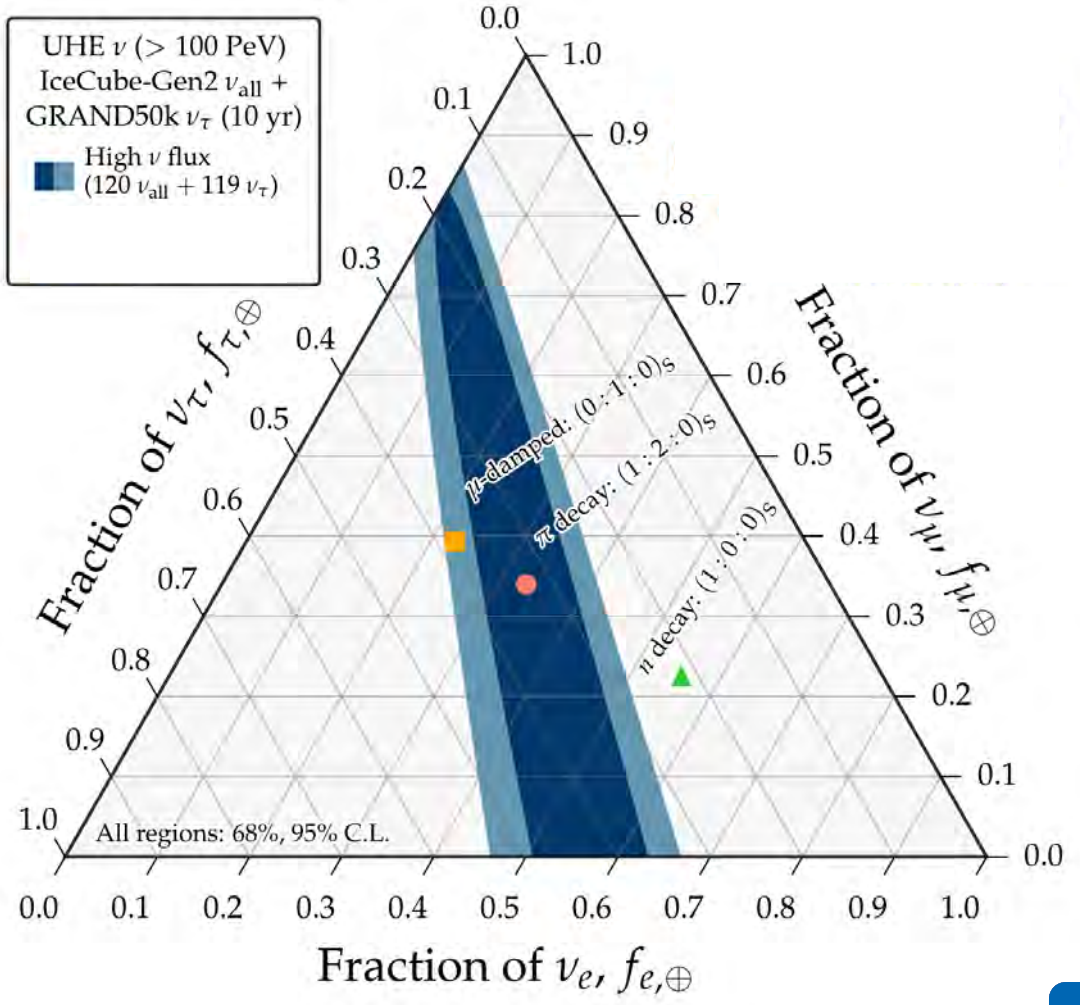

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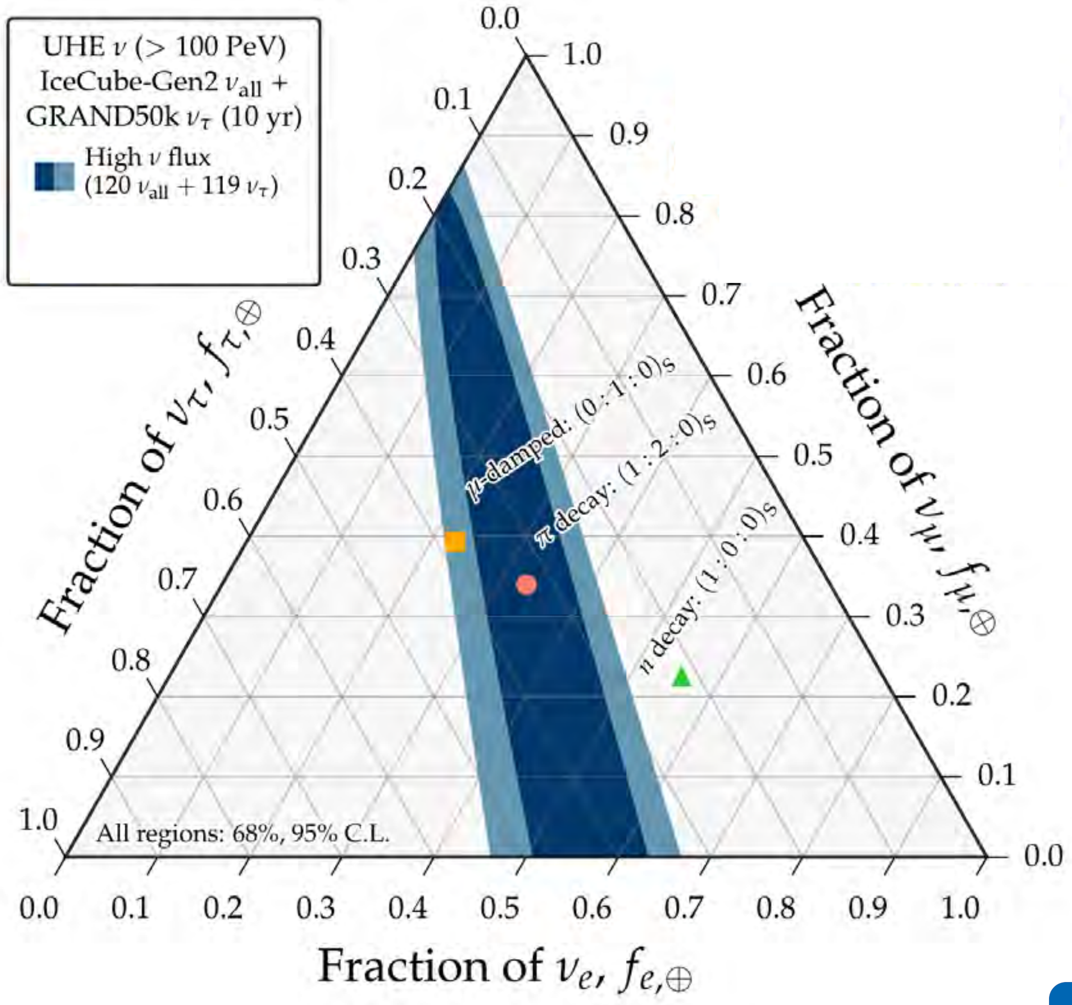

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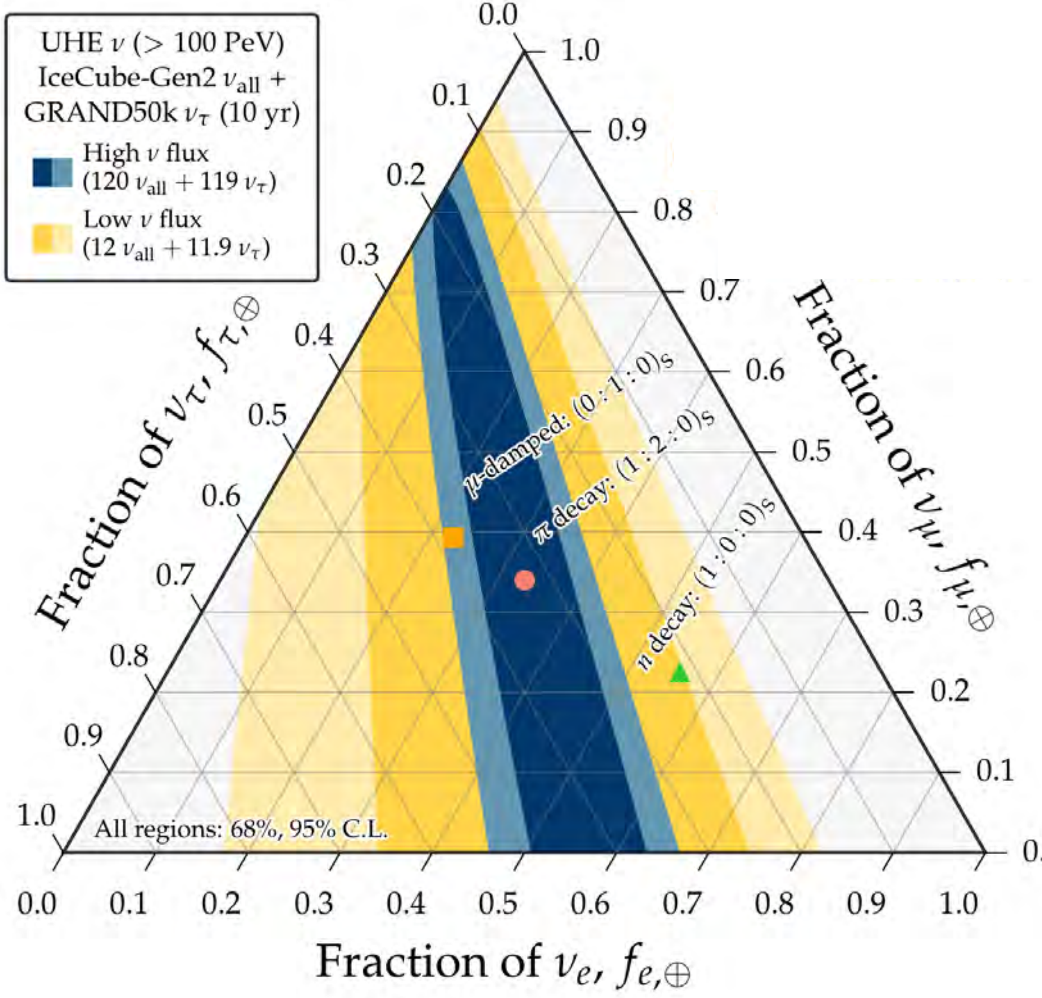

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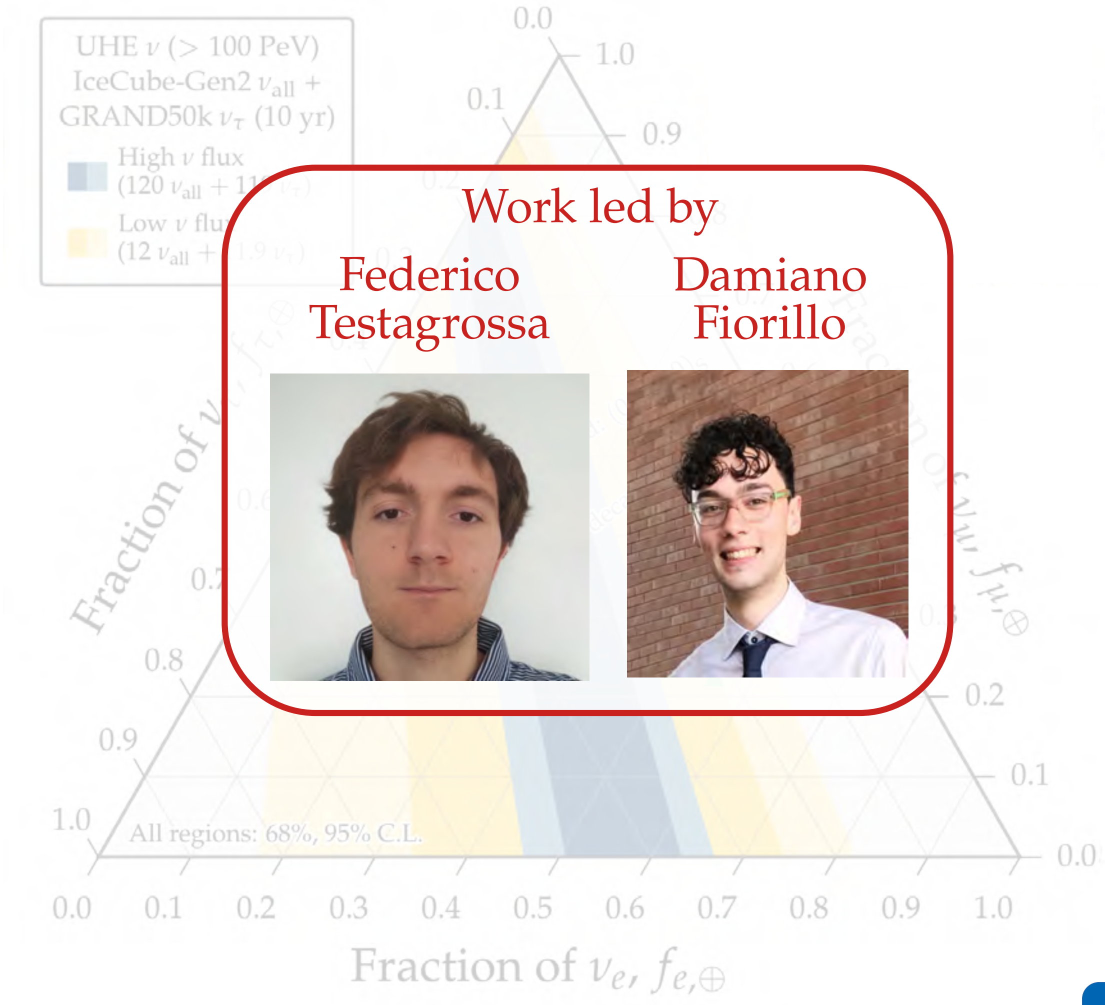

Work led by

Federico Testagrossa

Damiano Fiorillo

Testagrossa, Fiorillo, **MB**, 2310.12215

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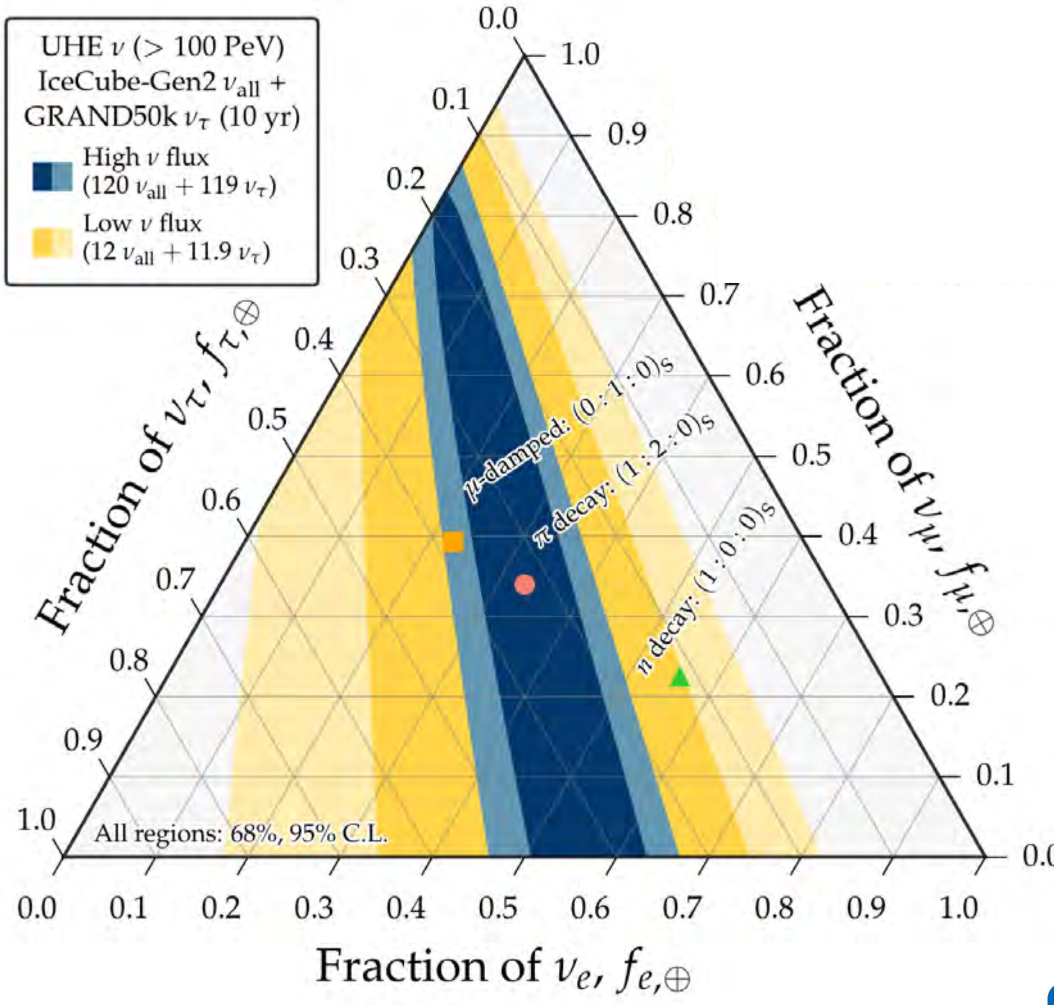

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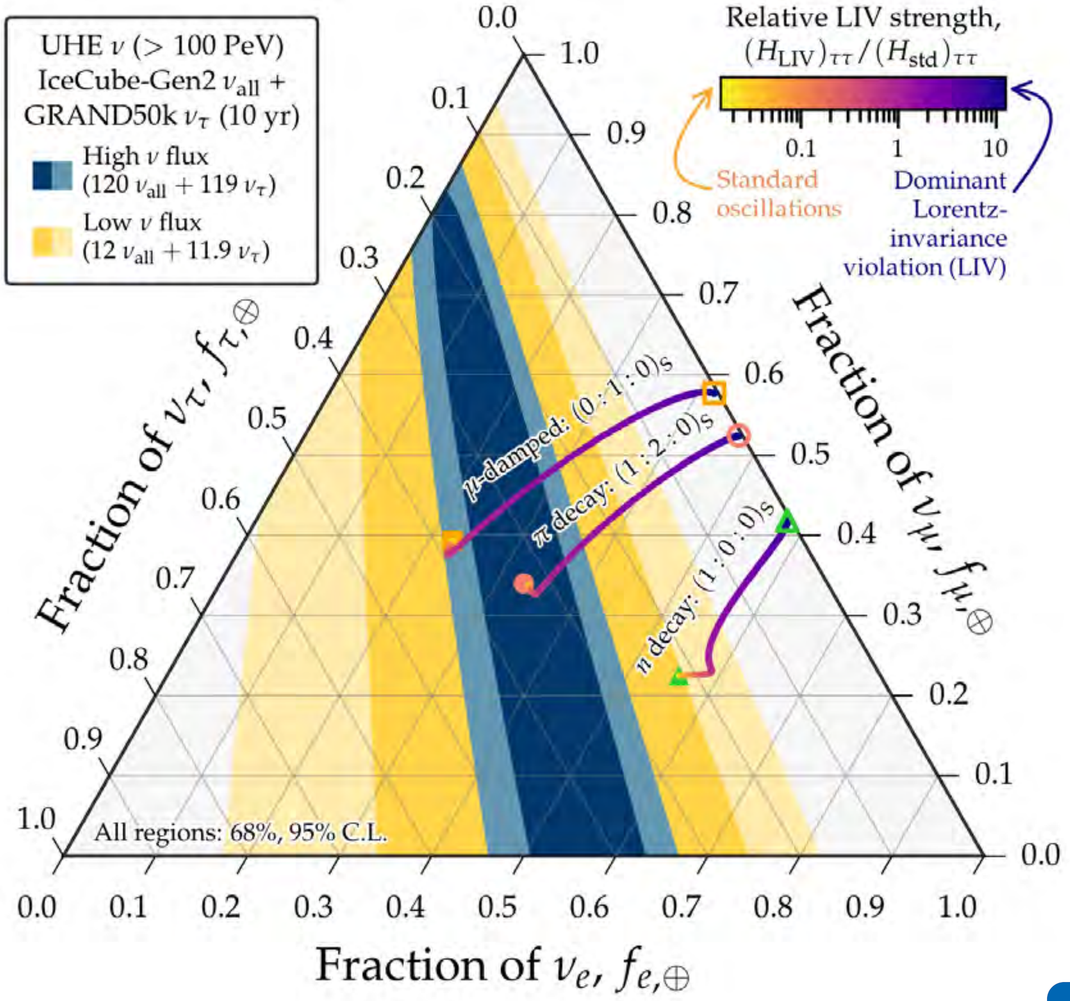
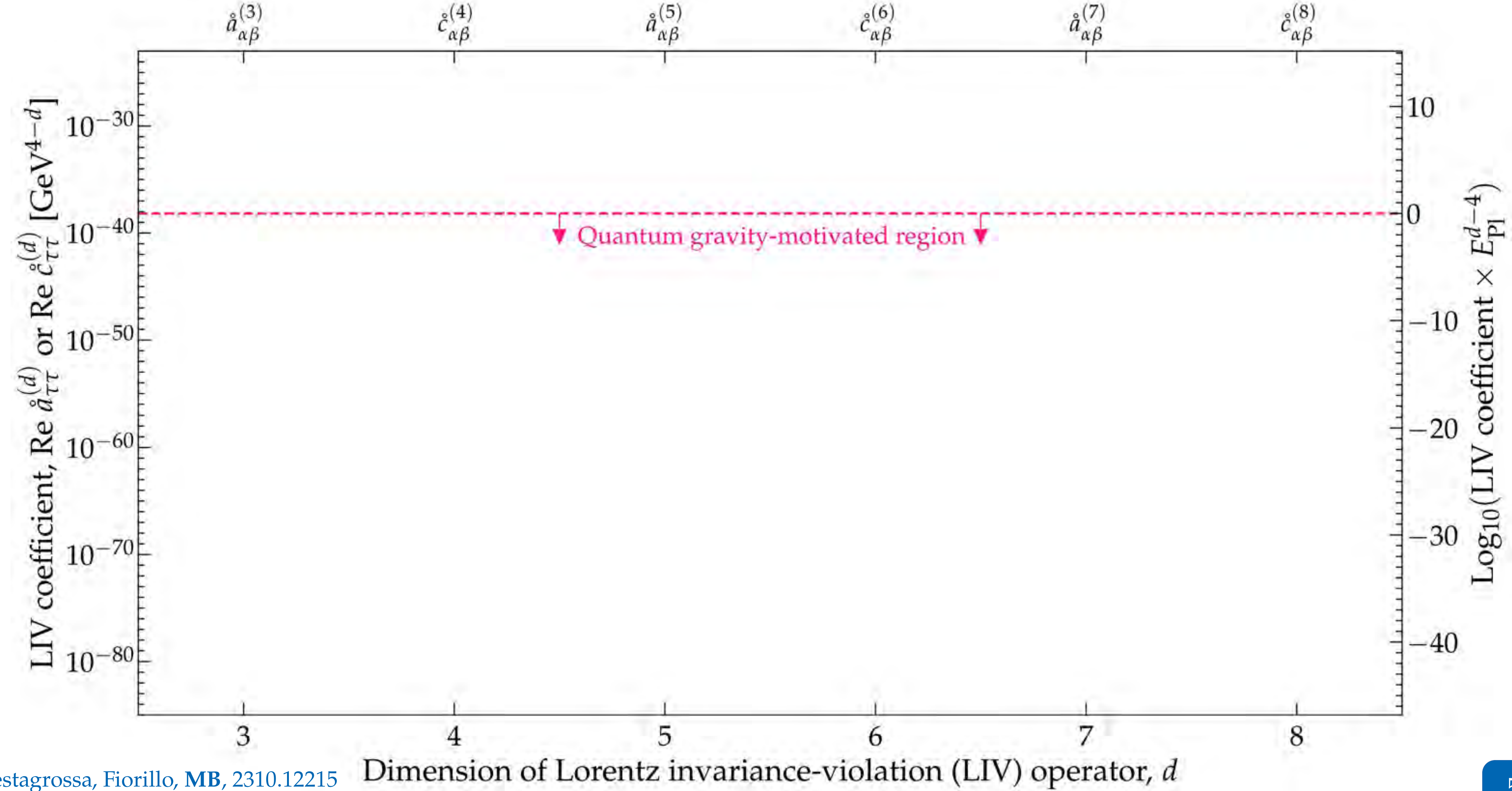


Testagrossa, Fiorillo, **MB**, 2310.12215

Lorentz-invariance violation at ultra-high energies



Testagrossa, Fiorillo, **MB**, 2310.12215

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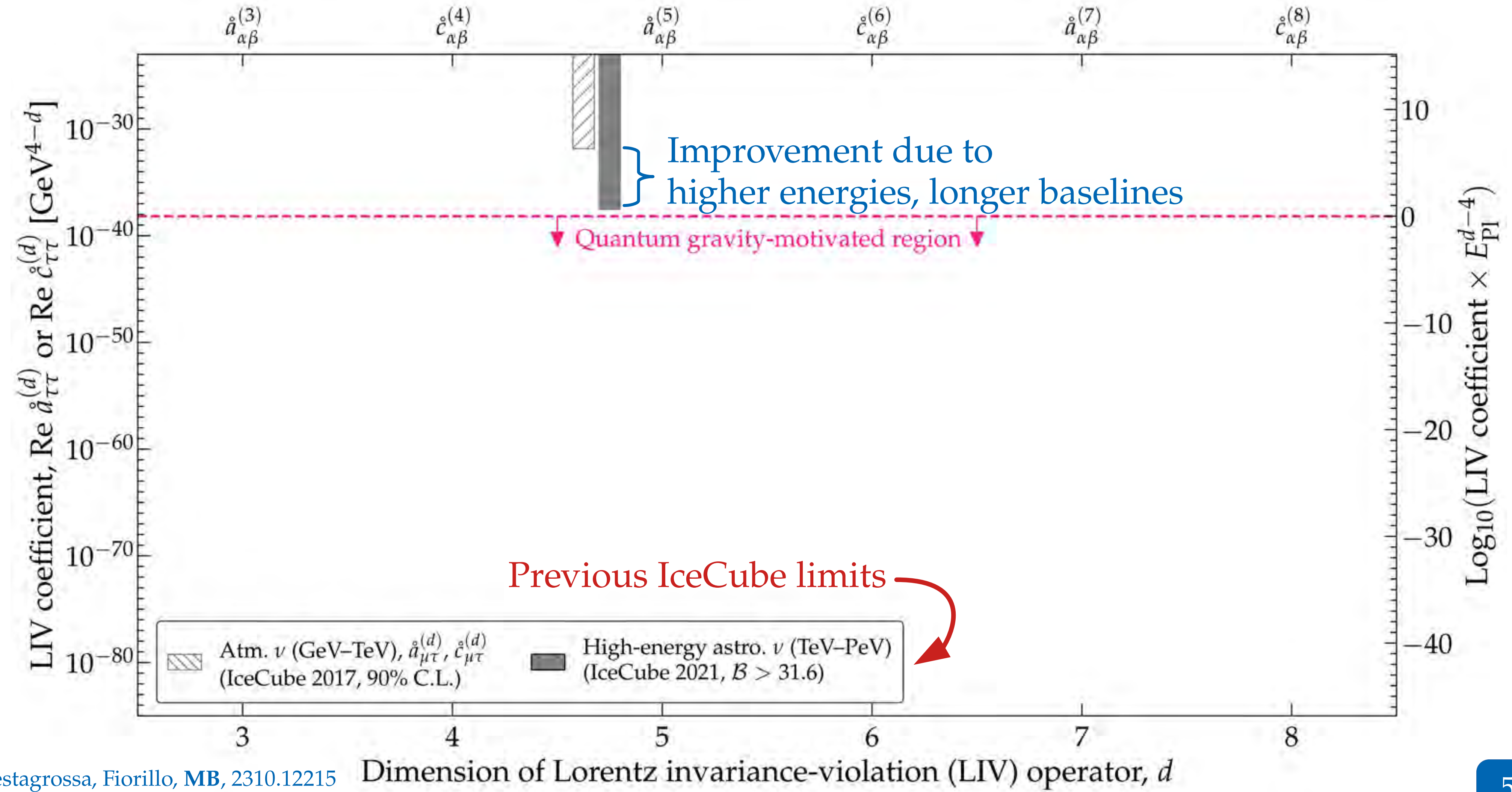

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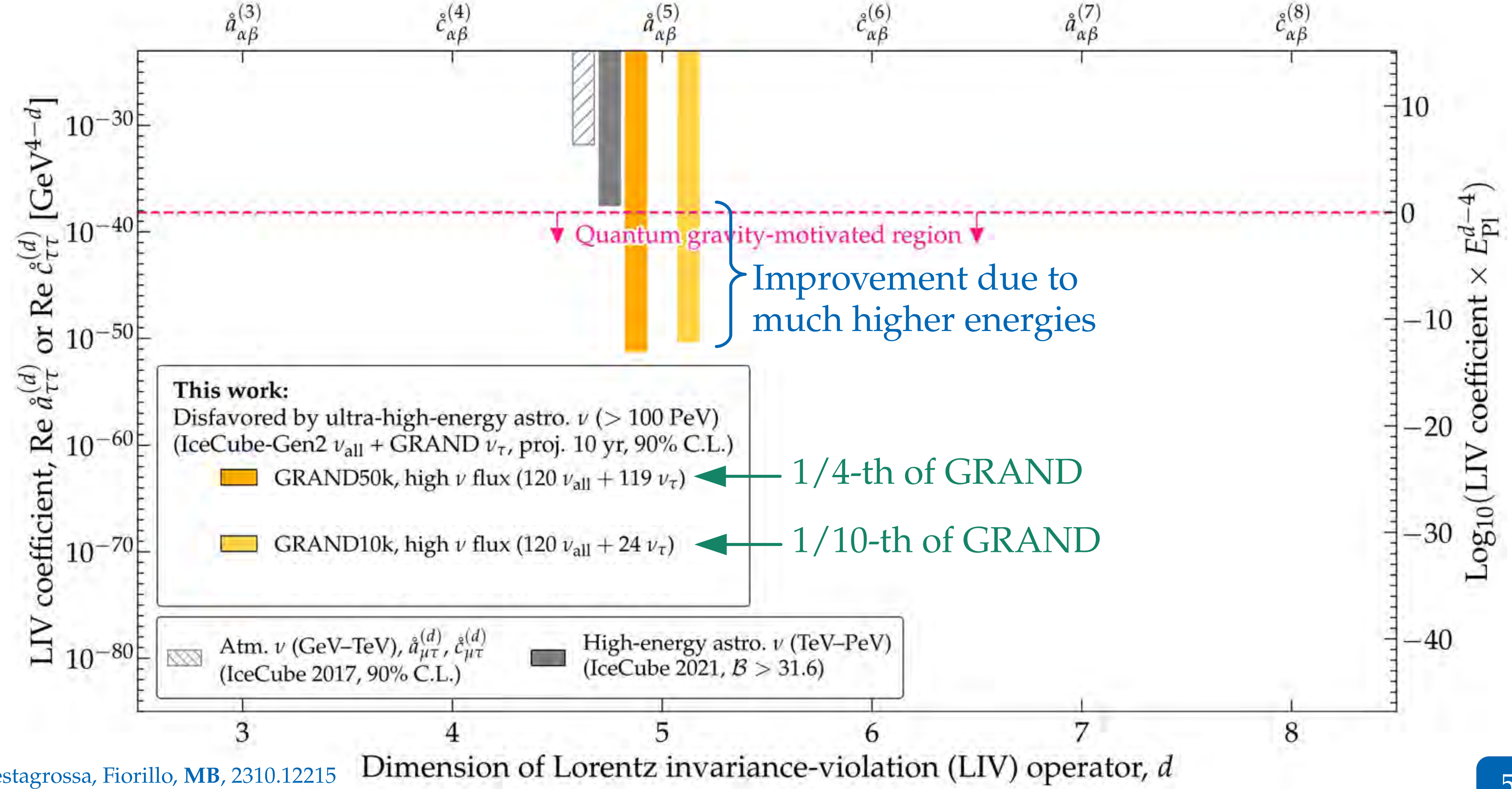

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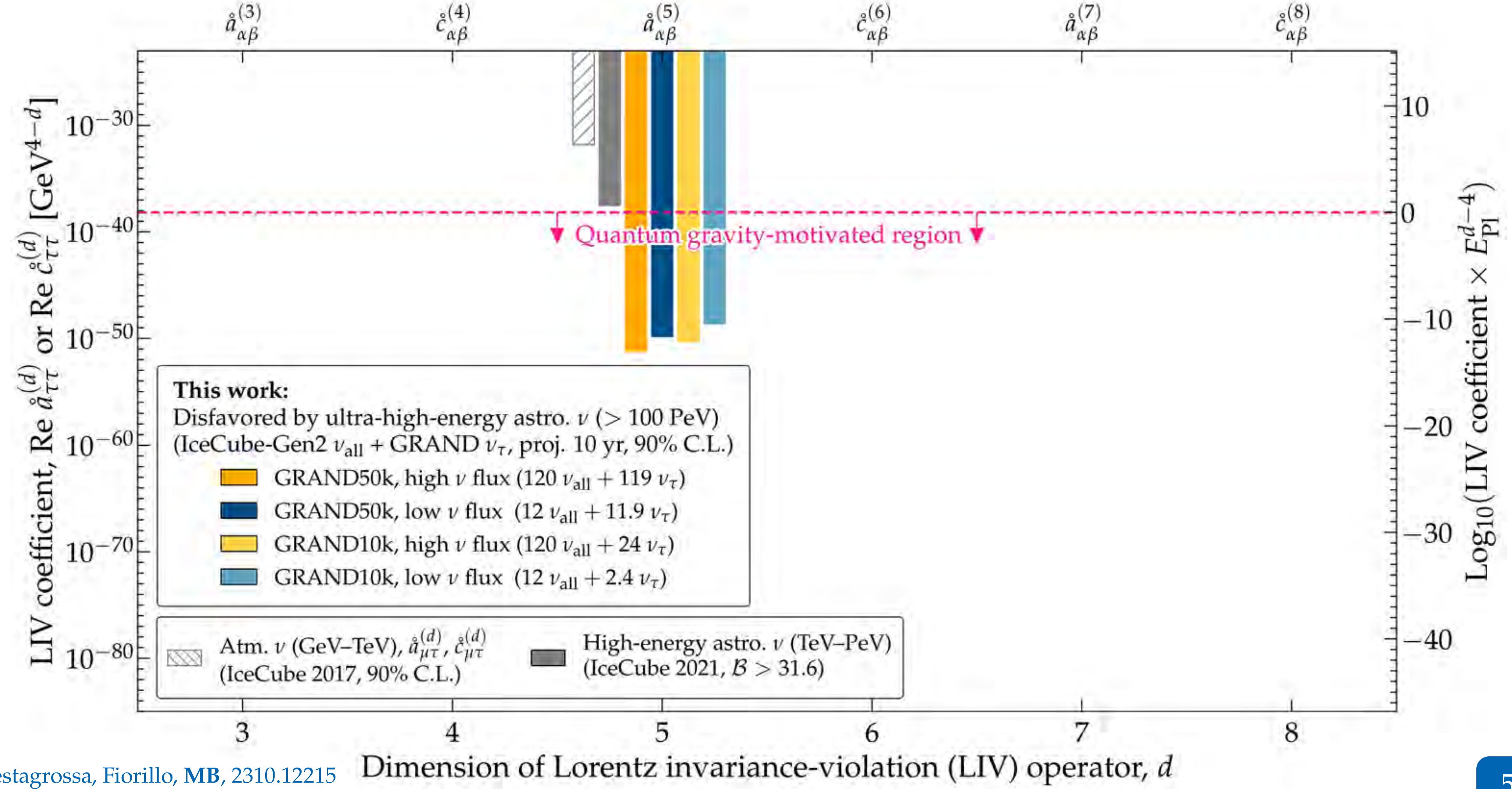

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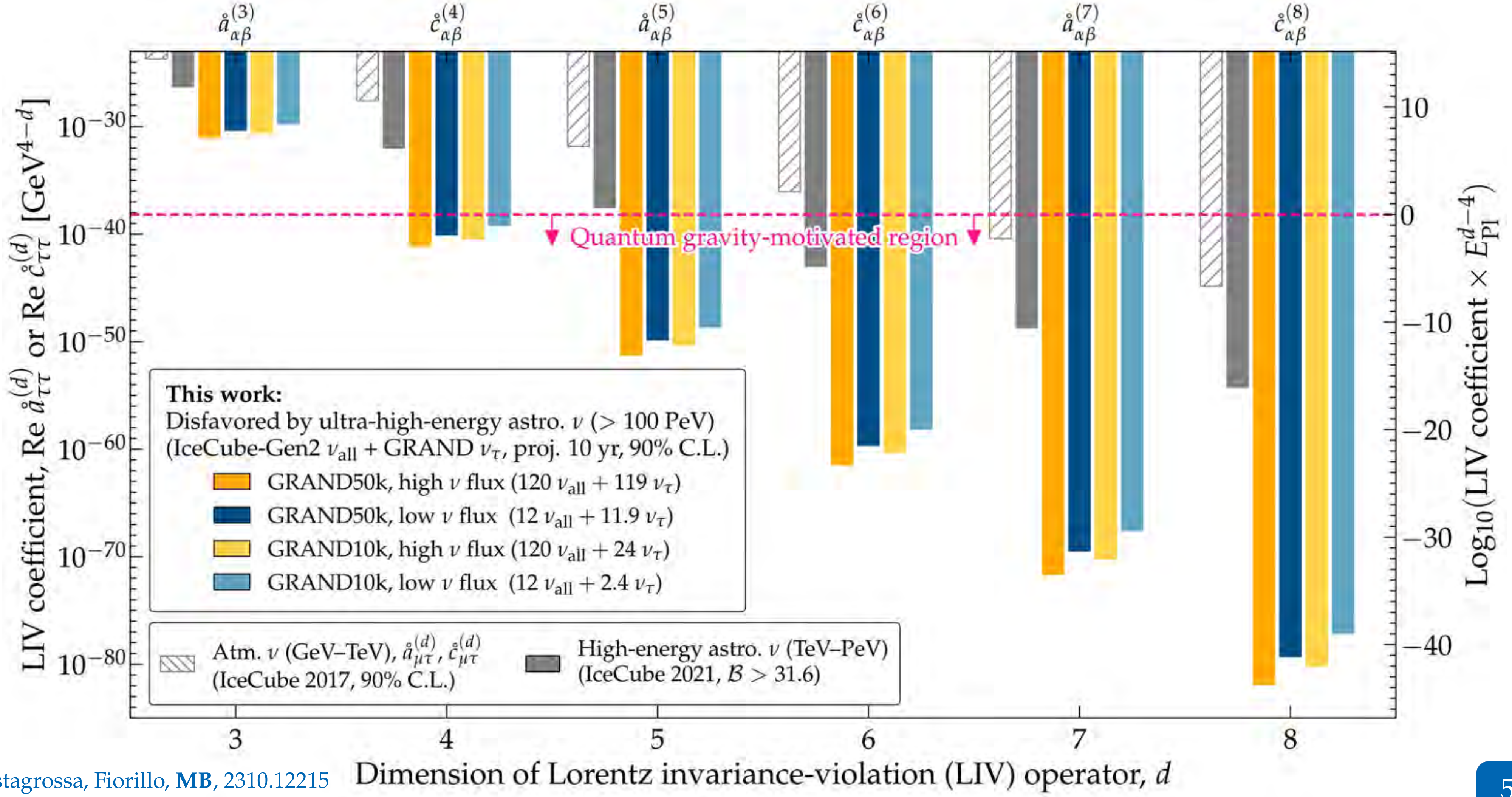
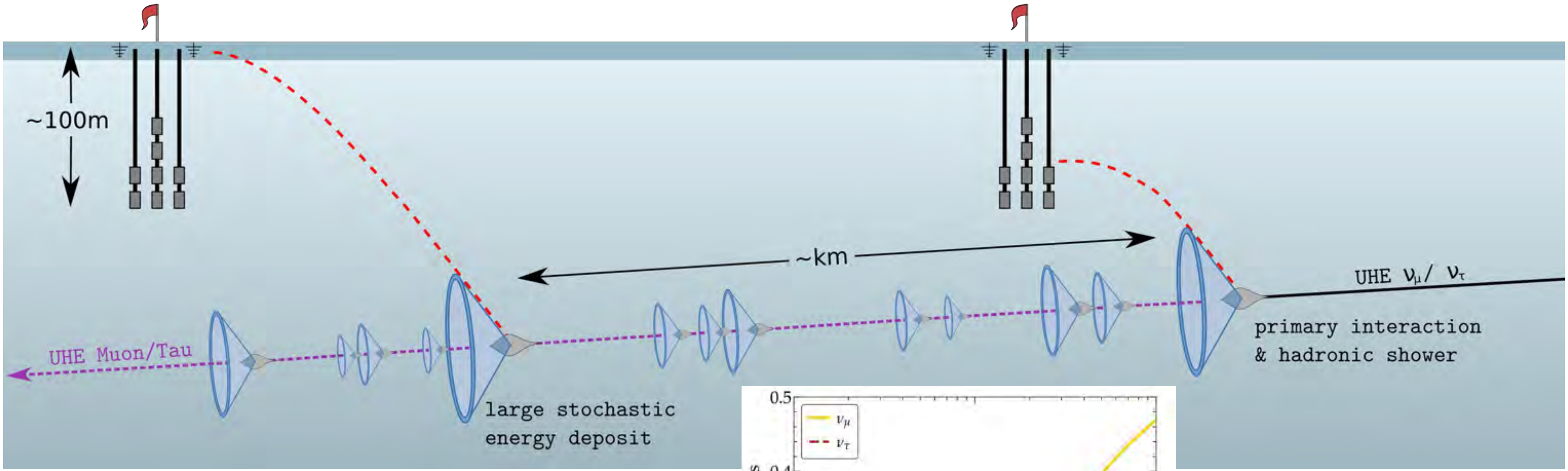
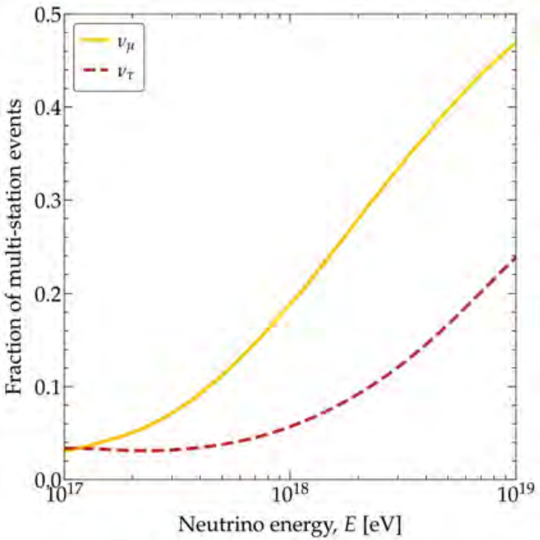


Testagrossa, Fiorillo, **MB**, 2310.12215

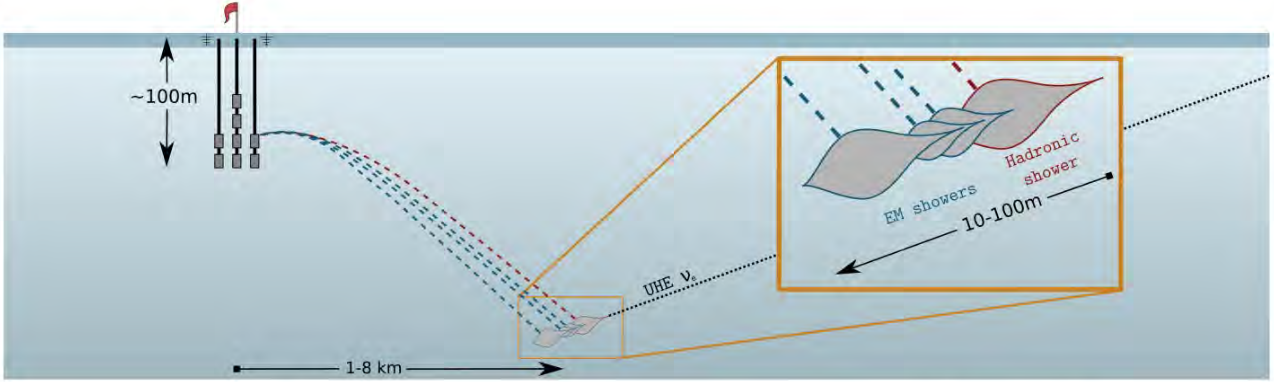
Multi-shower events from $\nu_\mu + \nu_\tau$ in IceCube-Gen2 (radio)

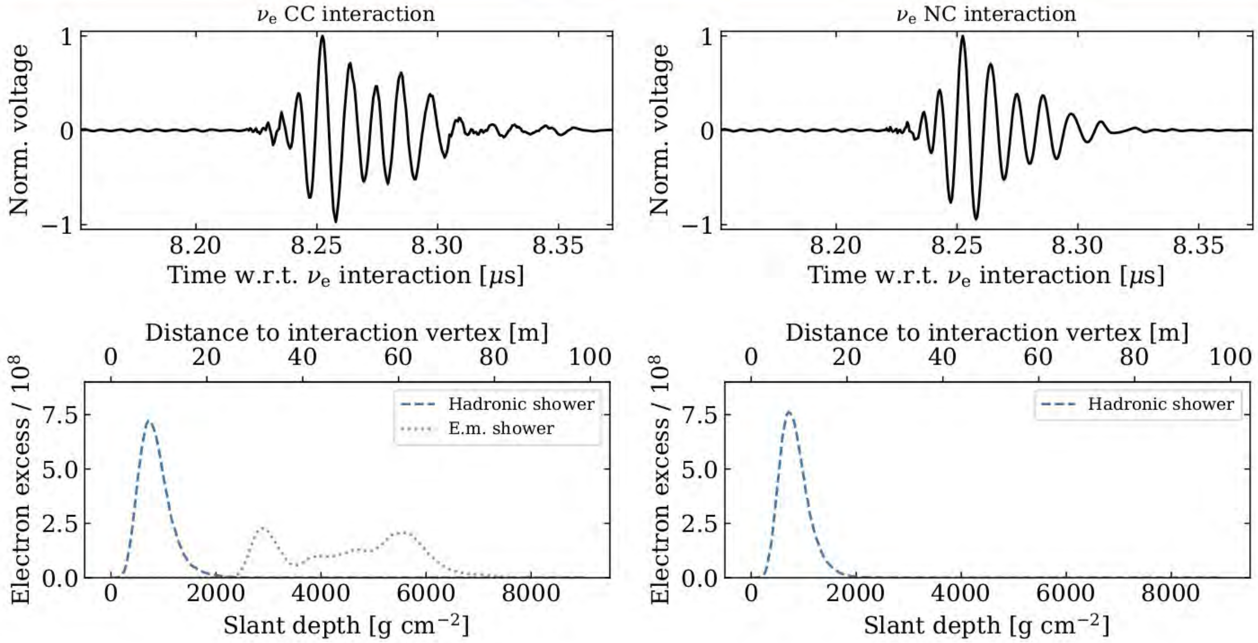


Coleman, Ericsson, **MB**, Glaser, 2402.02432



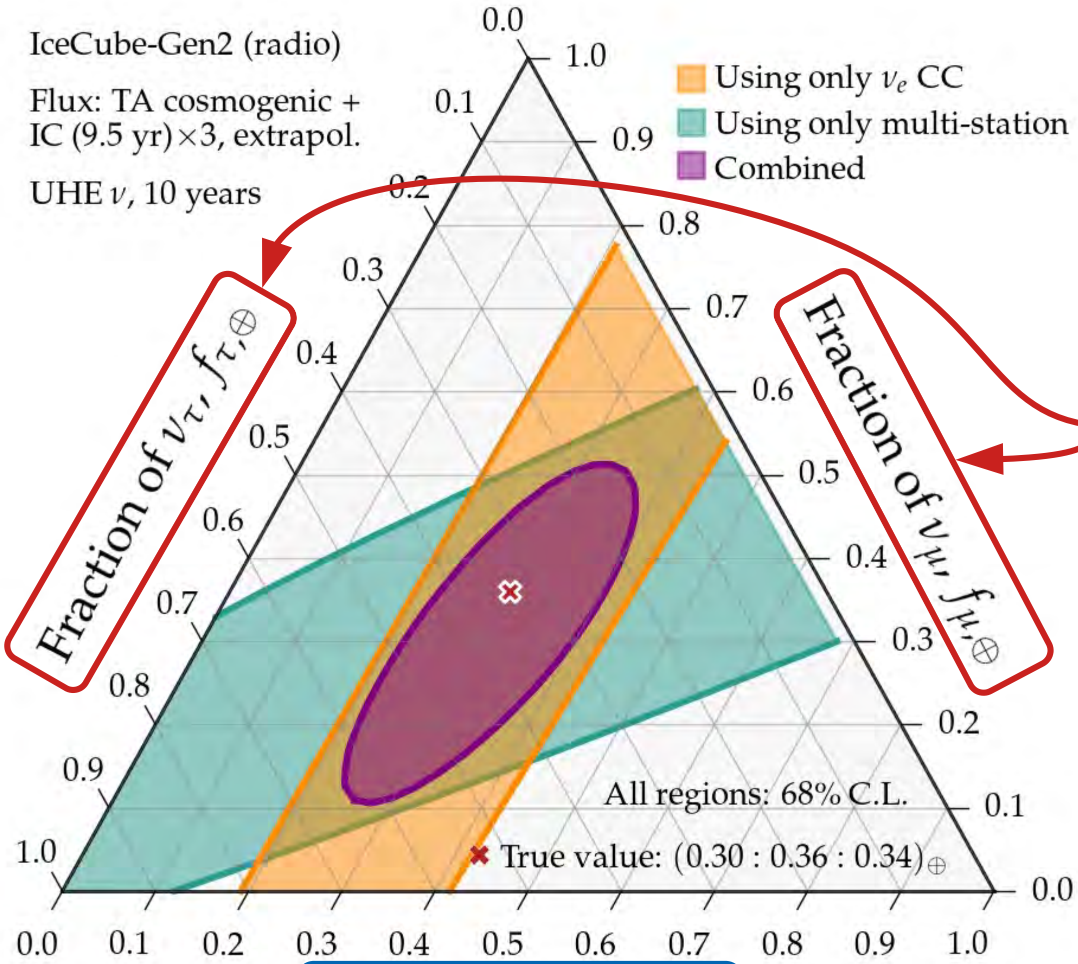
Multi-shower ν_e CC interactions in IceCube-Gen2 (radio)





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

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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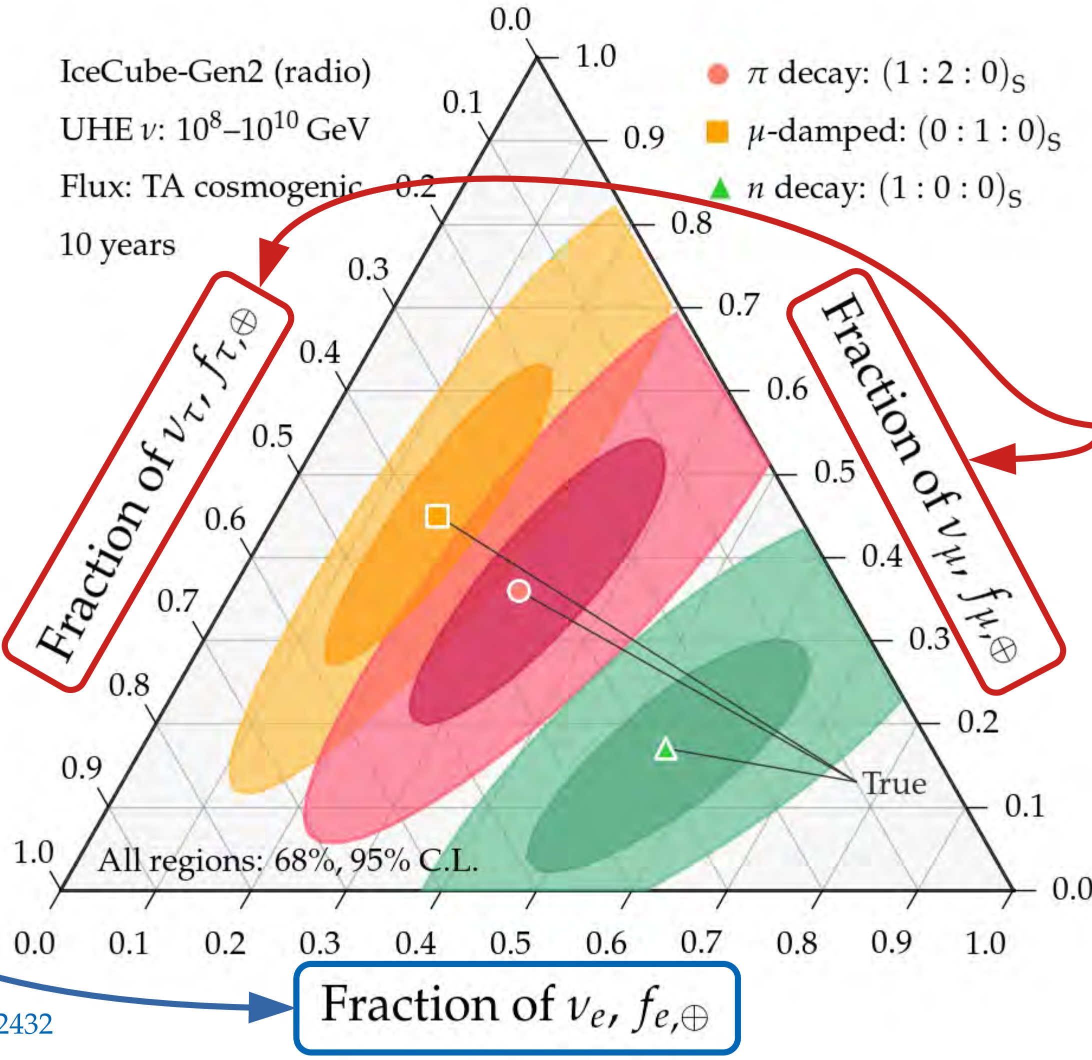

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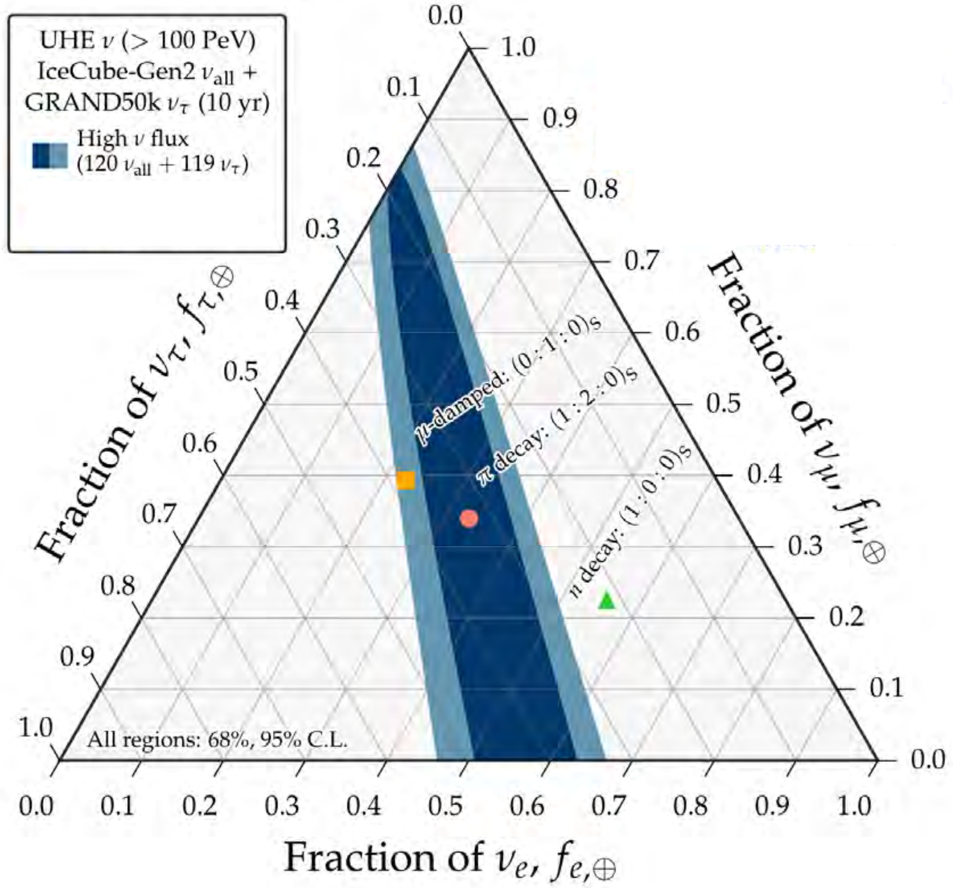
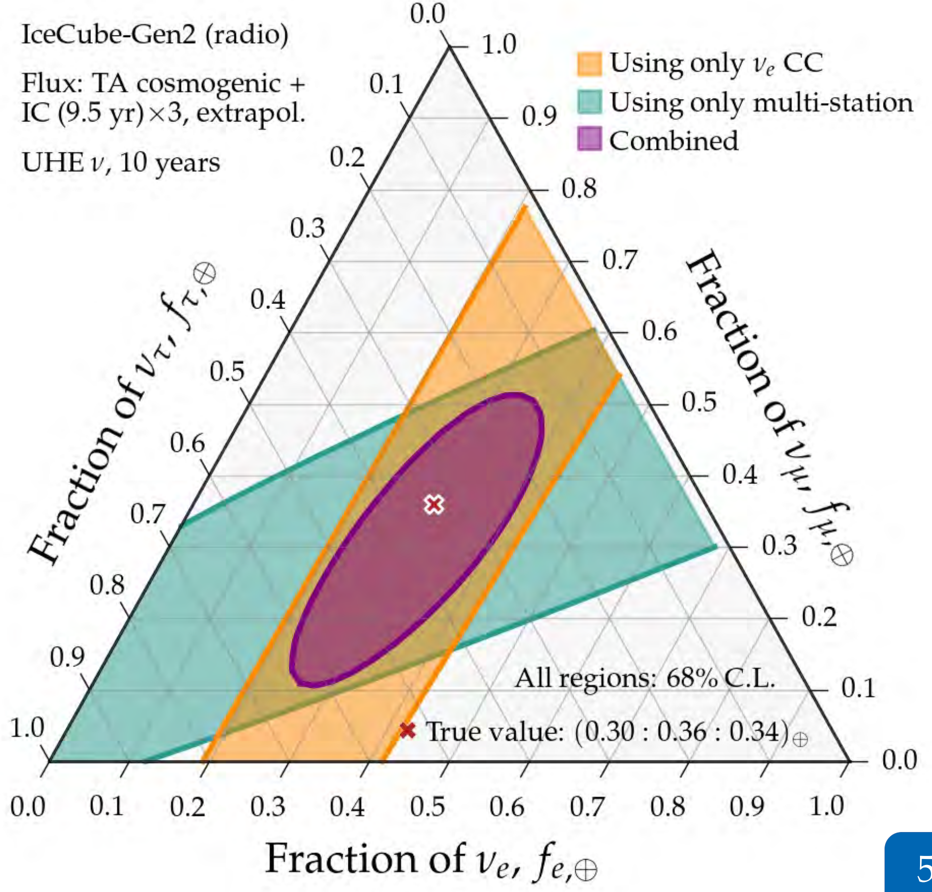
Coleman, Ericsson, **MB**, Glaser, 2402.02432

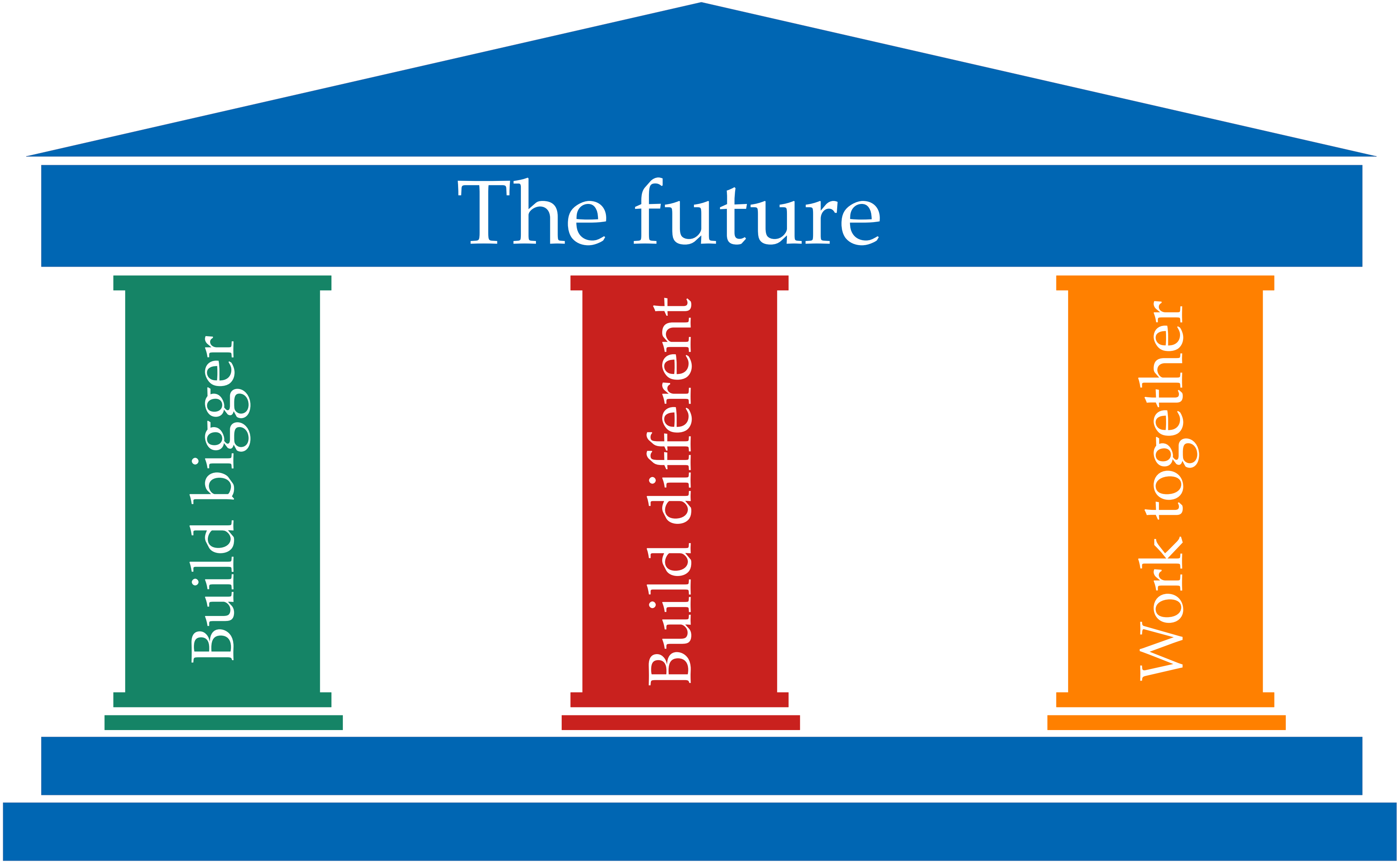
Accessing the full UHE flavor information

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)

$$\nu_l + N \rightarrow l + X$$

How does IceCube see TeV–PeV neutrinos?

Deep inelastic neutrino-nucleon scattering

Neutral current (NC)

Charged current (CC)

Receives $(1-\langle y \rangle)E_\nu$

Receives $\langle y \rangle E_\nu$

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

$\nu_l + N \rightarrow l + X$

At TeV–PeV, the average inelasticity $\langle y \rangle$ = 0.25–0.30

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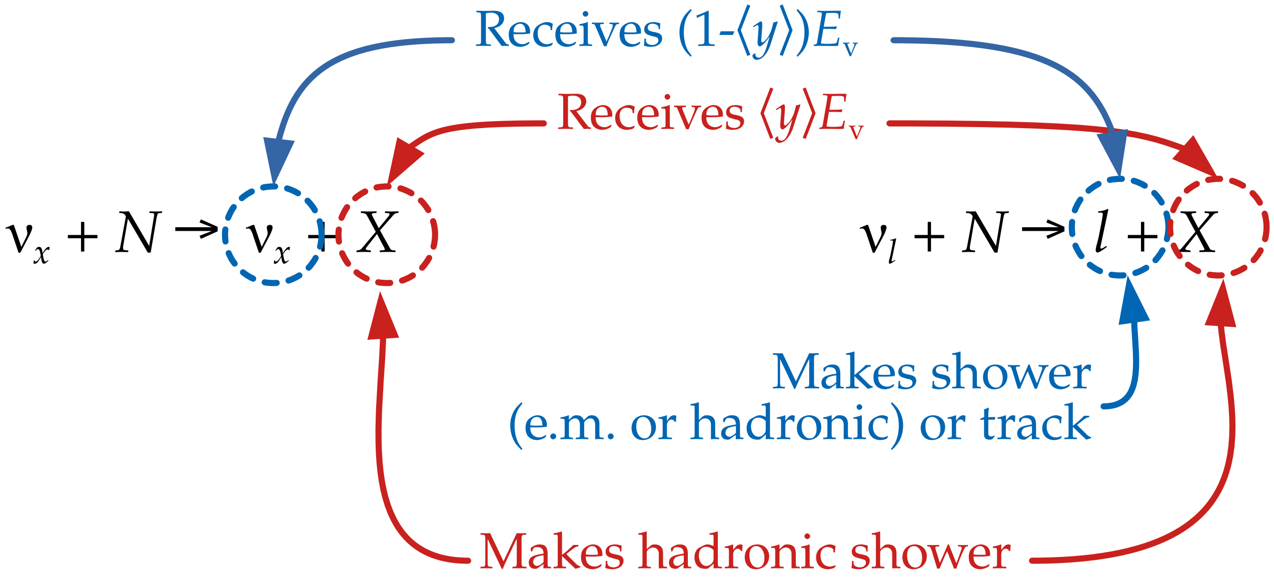

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Flavor at the Earth: *theoretically palatable regions*

Theoretically palatable flavor regions

≡

MB, Beacom, Winter, *PRL* 2015

Allowed regions of flavor ratios at Earth derived from oscillations

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

Flavor at the Earth: *theoretically palatable regions*

Theoretically palatable flavor regions

≡

MB, Beacom, Winter, *PRL* 2015

Allowed regions of flavor ratios at Earth derived from oscillations

Ingredient #1:

Flavor ratios at the source,

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

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

or

Explore all possible combinations

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

Flavor at the Earth: *theoretically palatable regions*

Theoretically palatable flavor regions

$\equiv$

MB, Beacom, Winter, *PRL* 2015

Allowed regions of flavor ratios at Earth derived from oscillations

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

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(pion decay, muon-damped, neutron decay)

or

Explore all possible combinations

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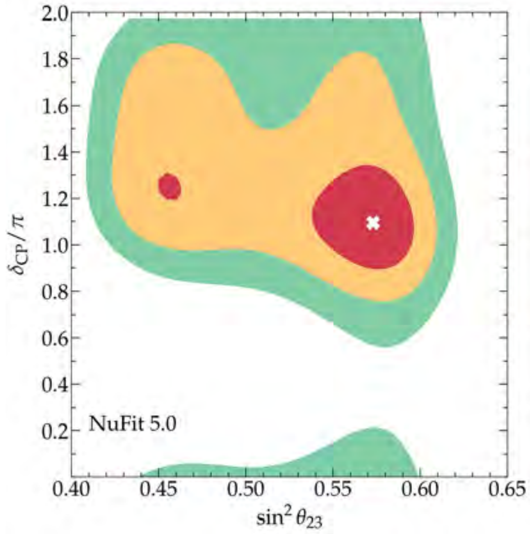
Esteban *et al.*, *JHEP* 2020
www.nu-fit.org



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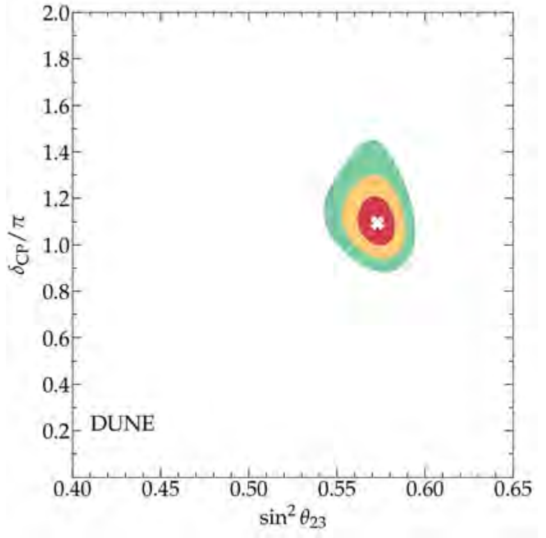
Post-2020: Build our own profiles using simulations of JUNO, DUNE, Hyper-K

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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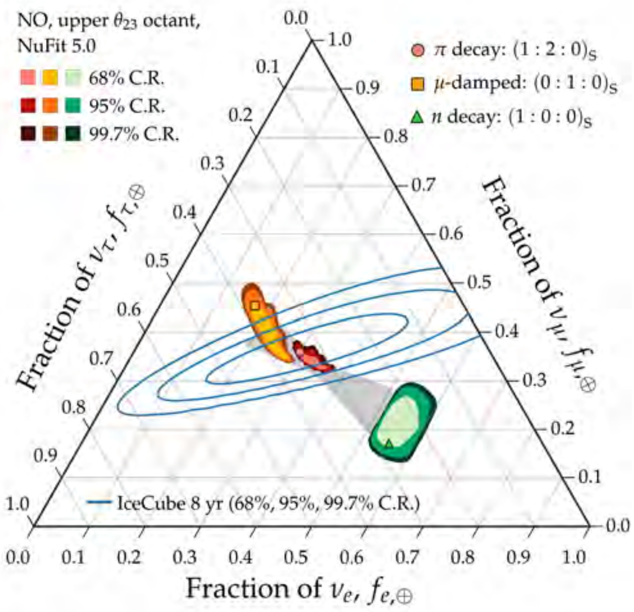

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Measurement: imprecise

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

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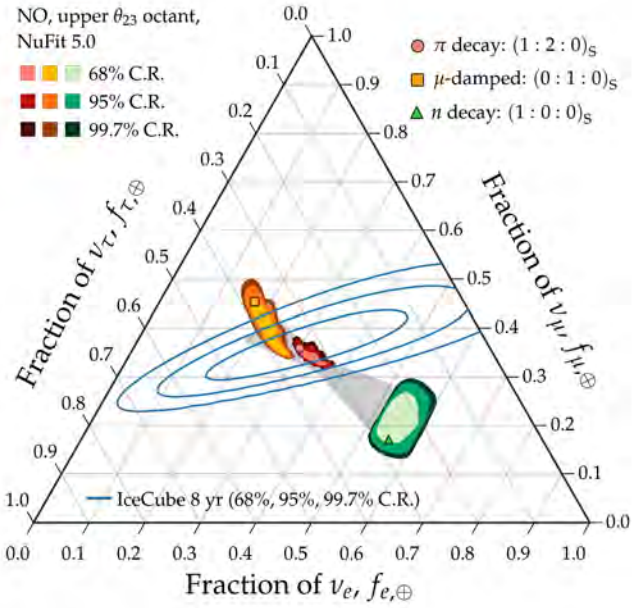

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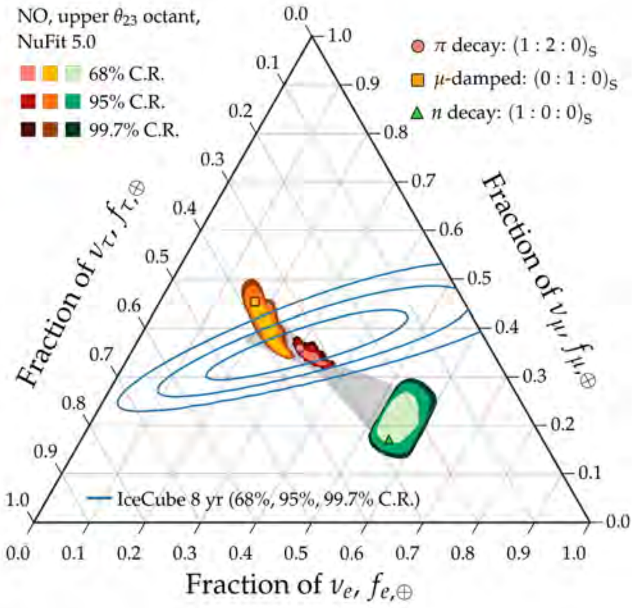

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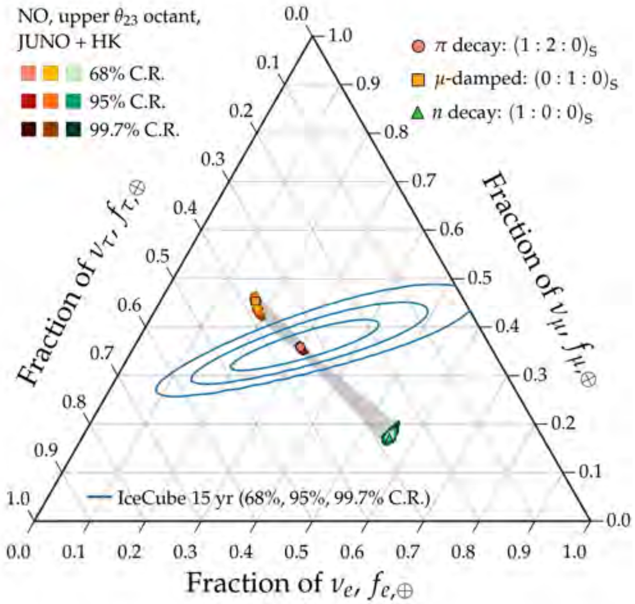

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Measurement: improving

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

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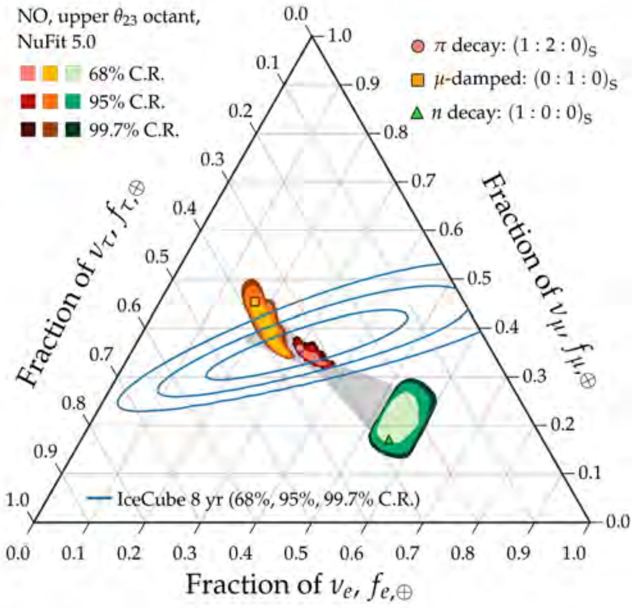

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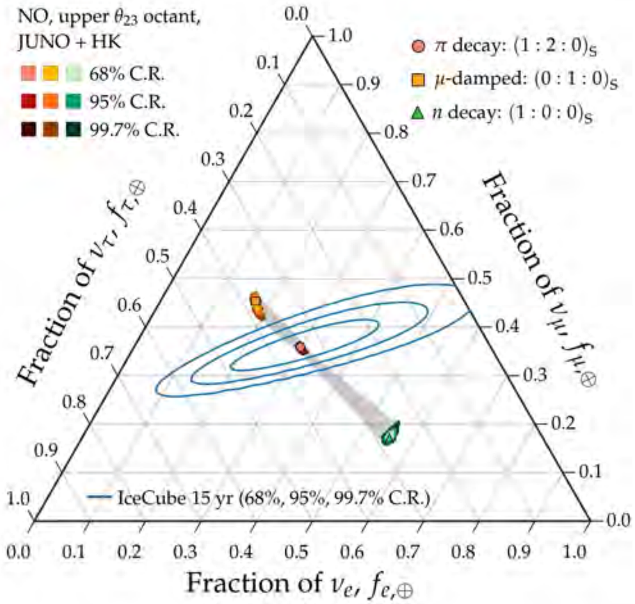

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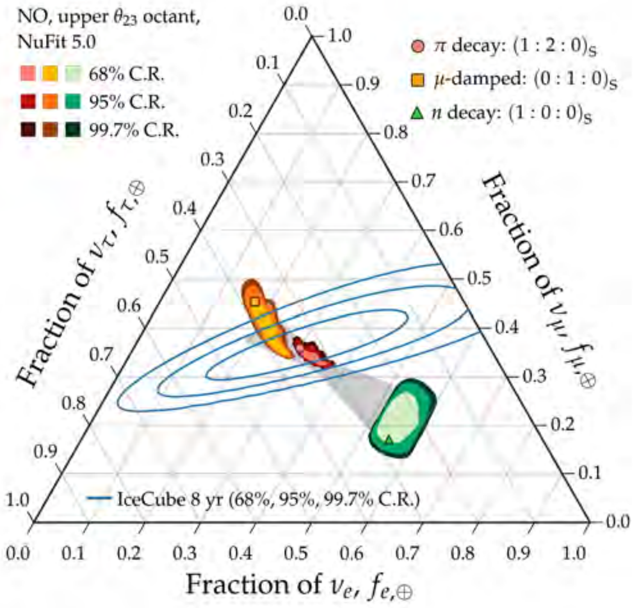

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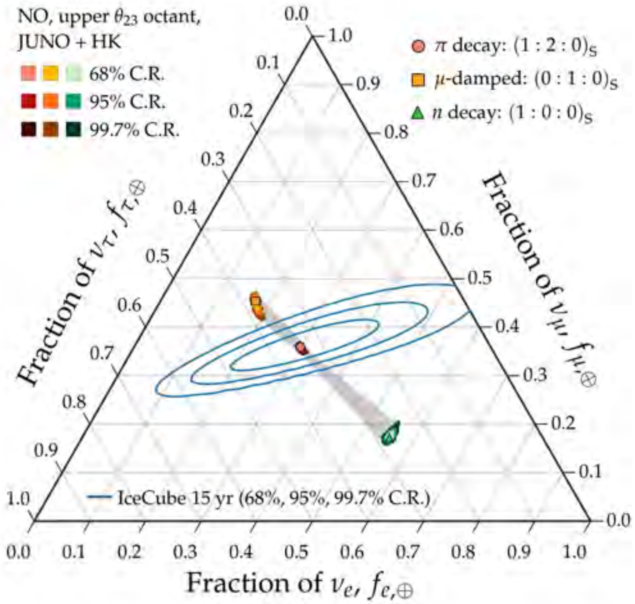

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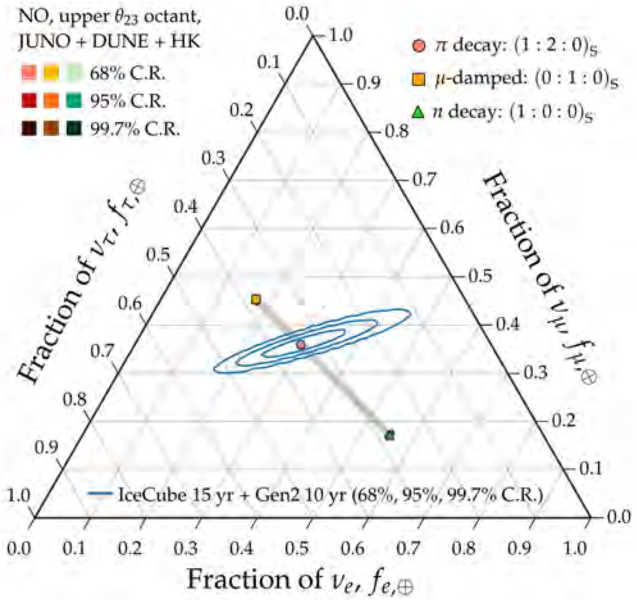

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Measurement: precise

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

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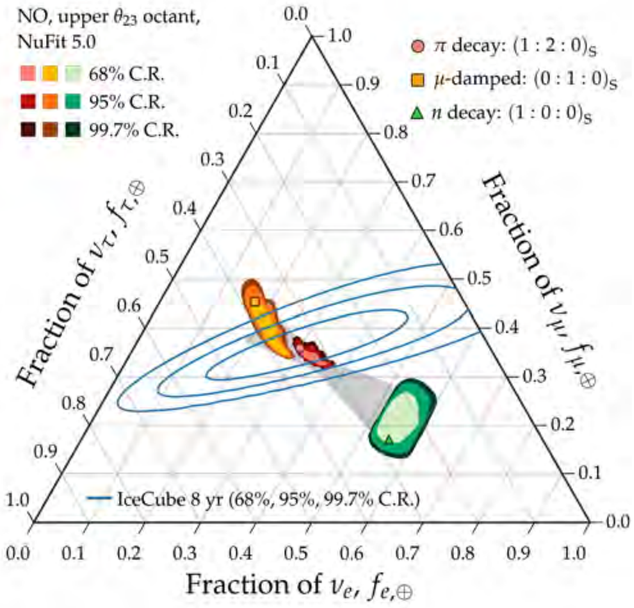

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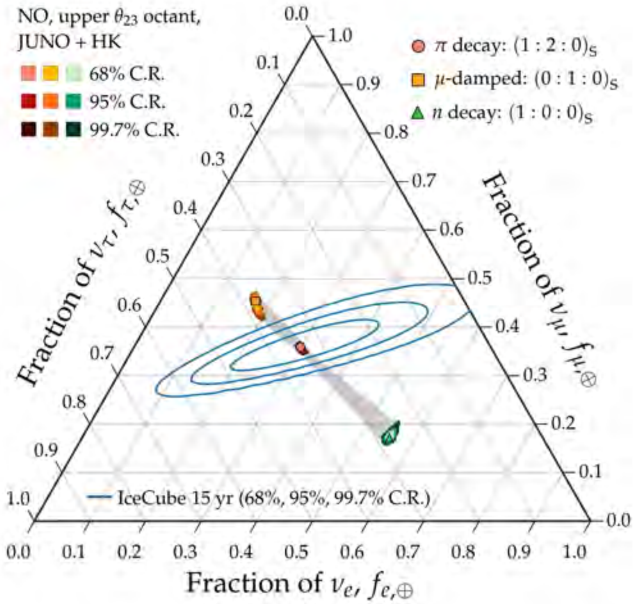

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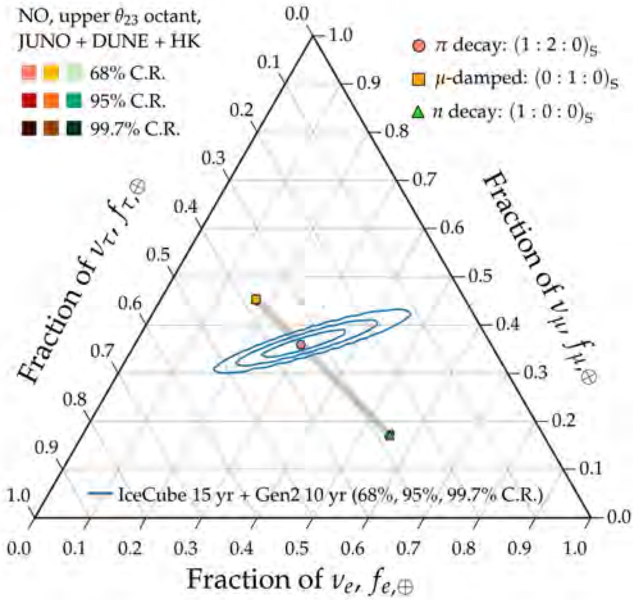

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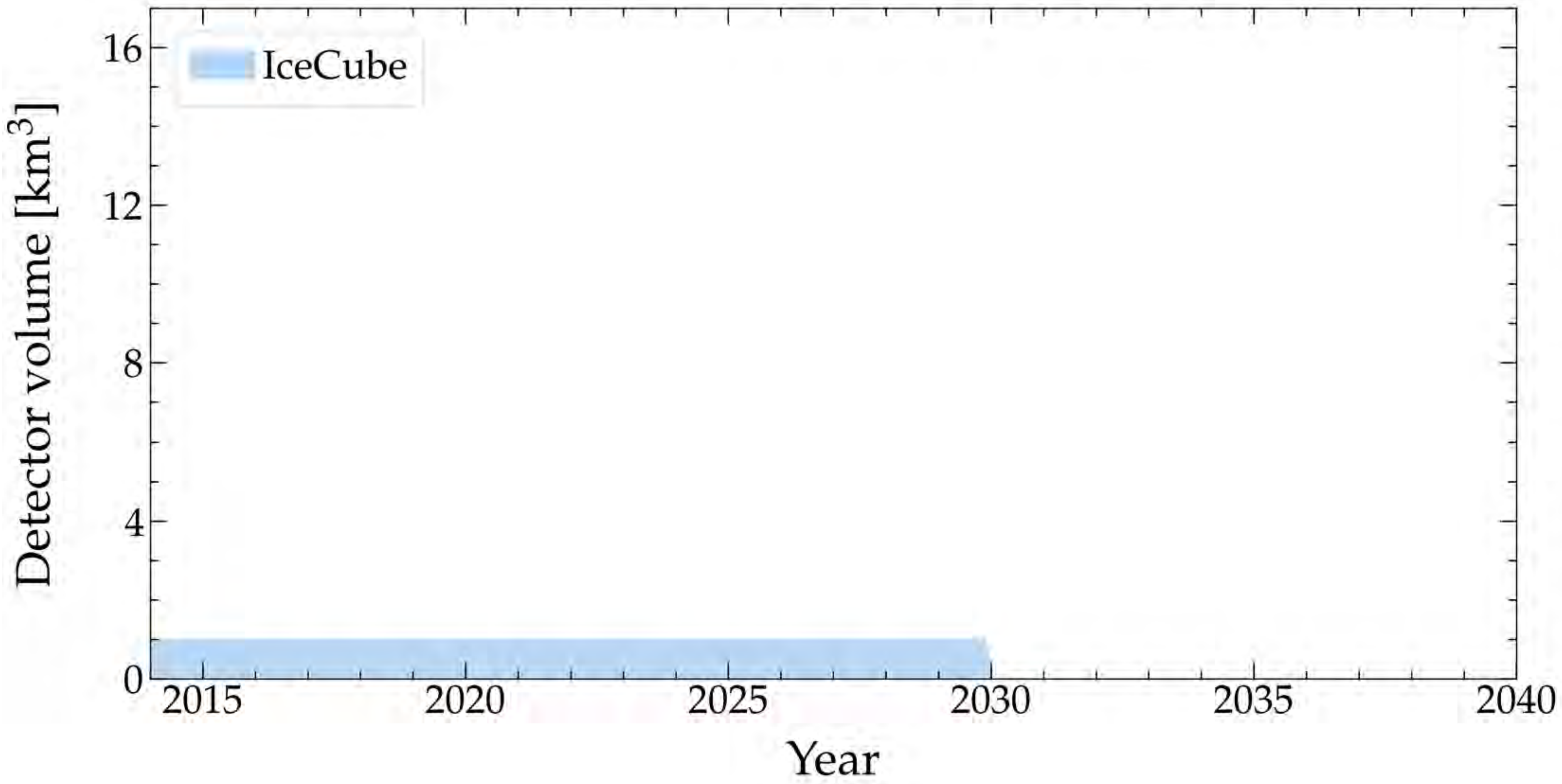
Success

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



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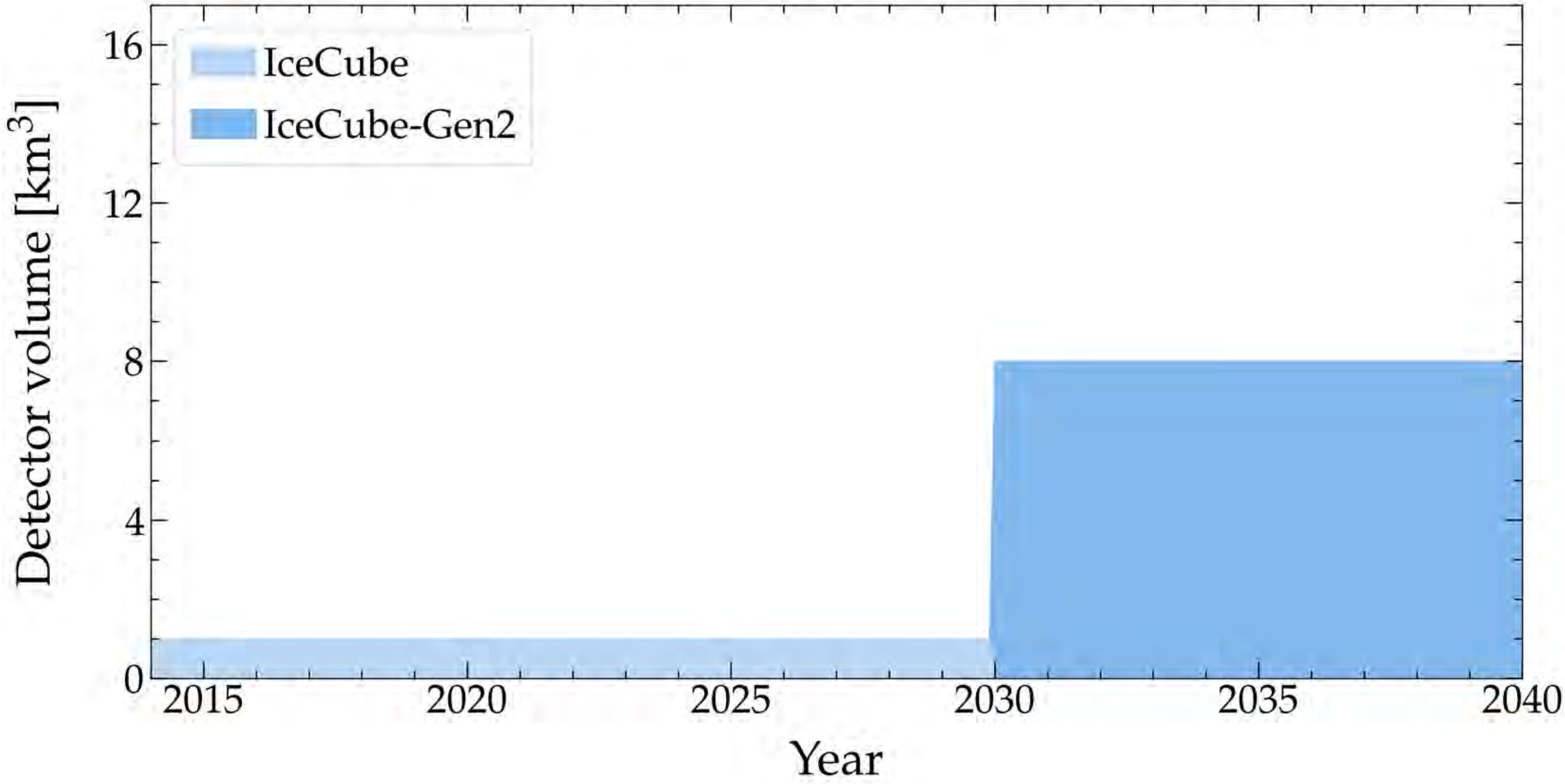

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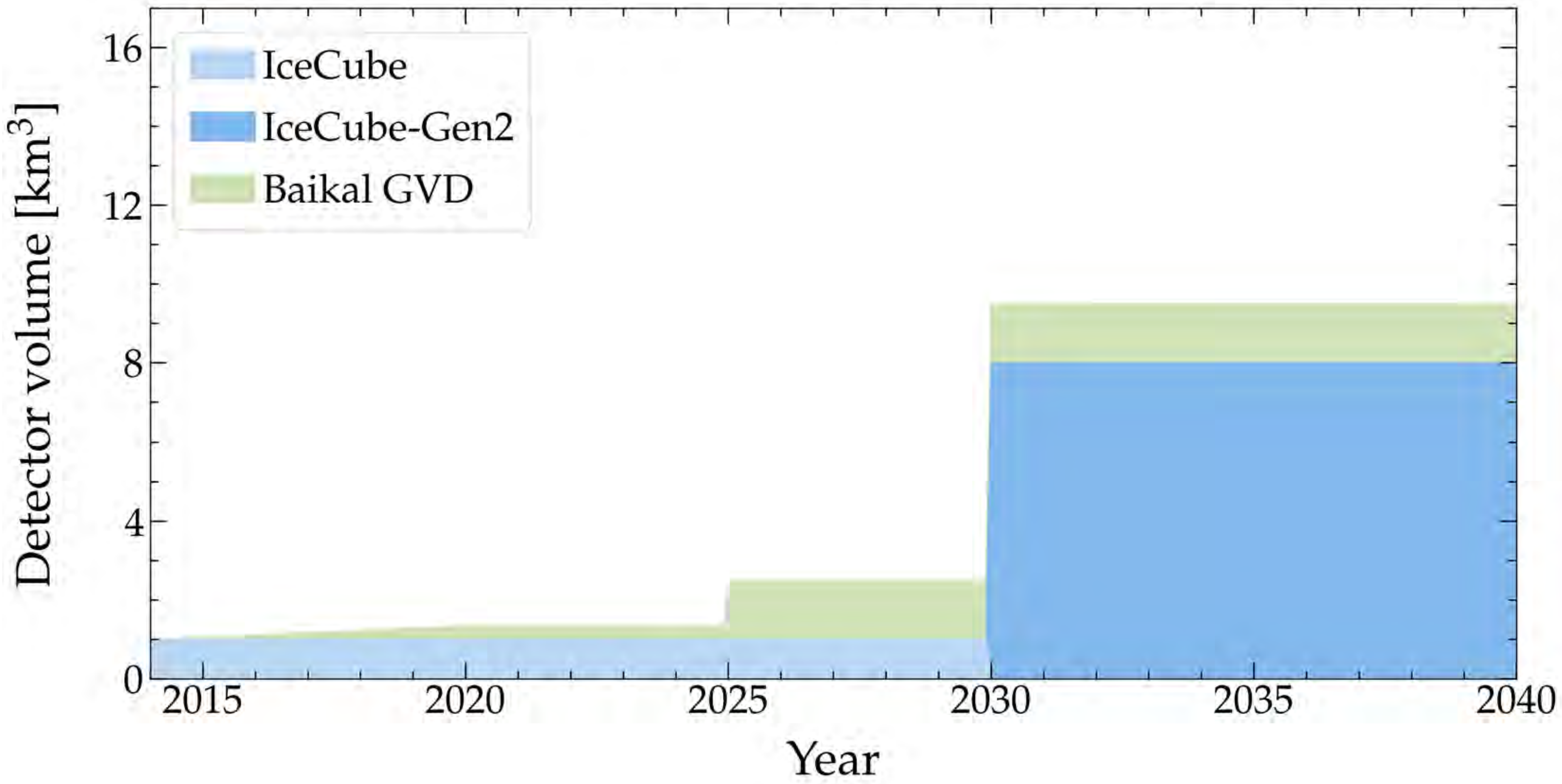

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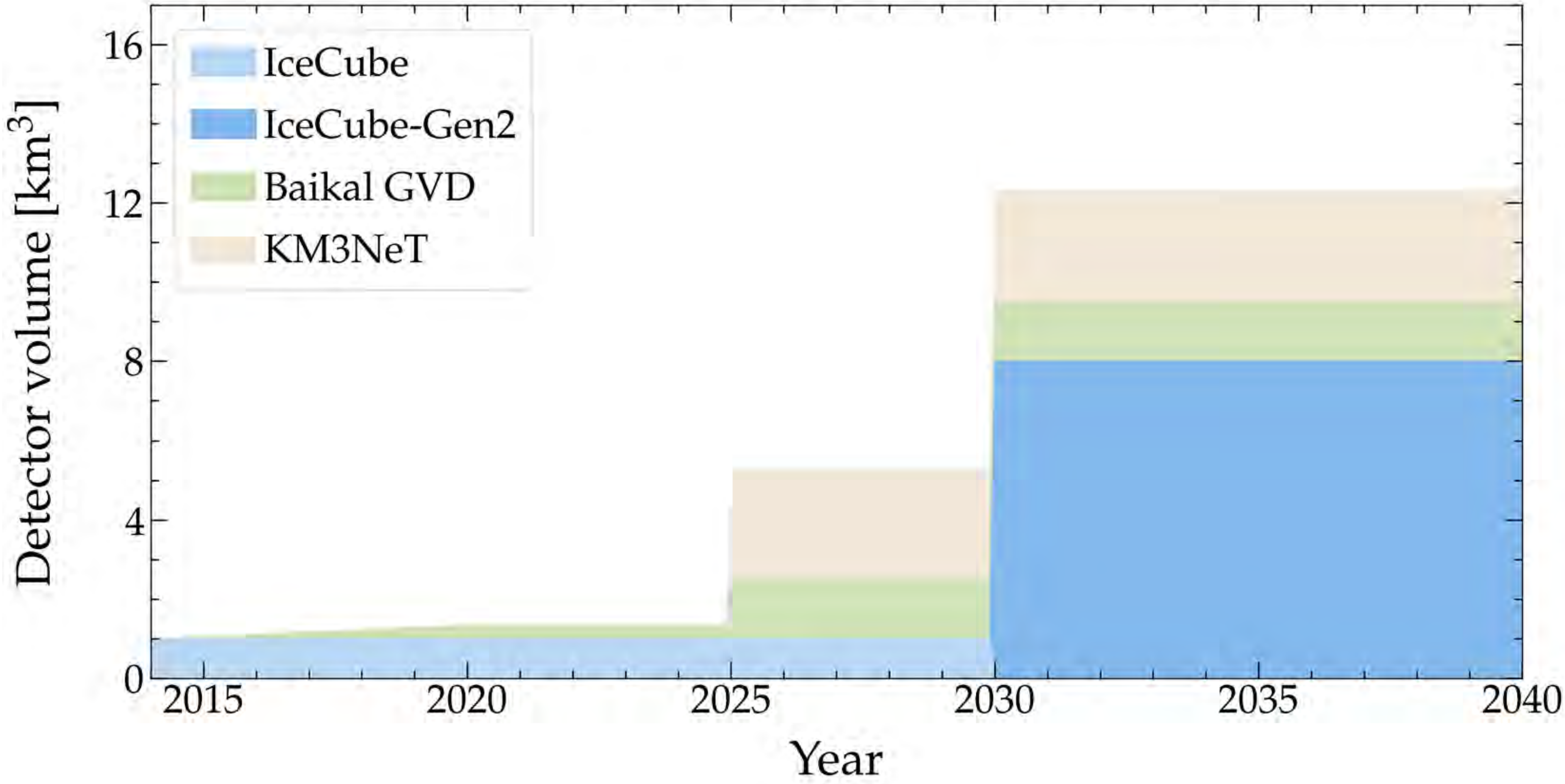

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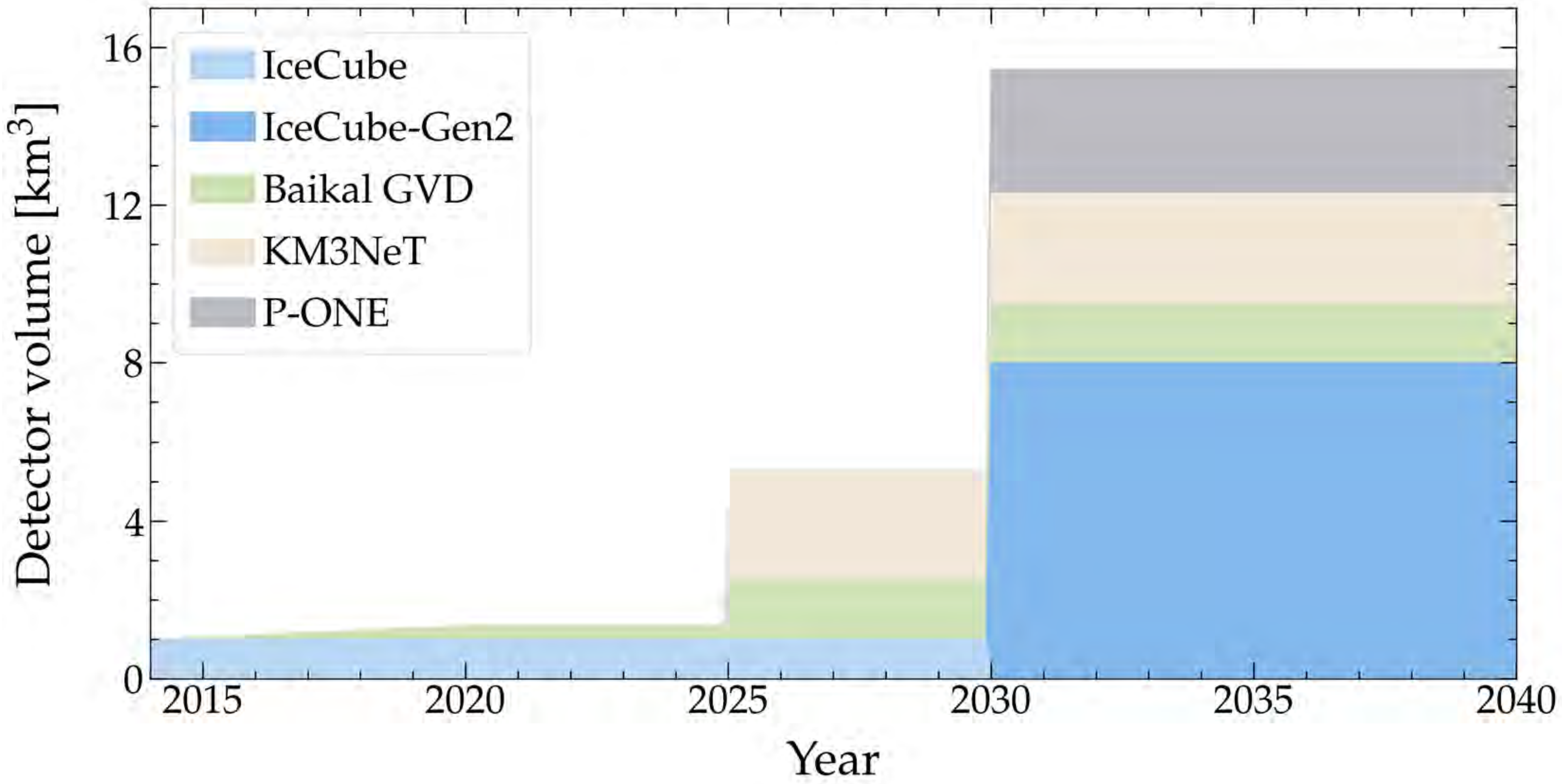

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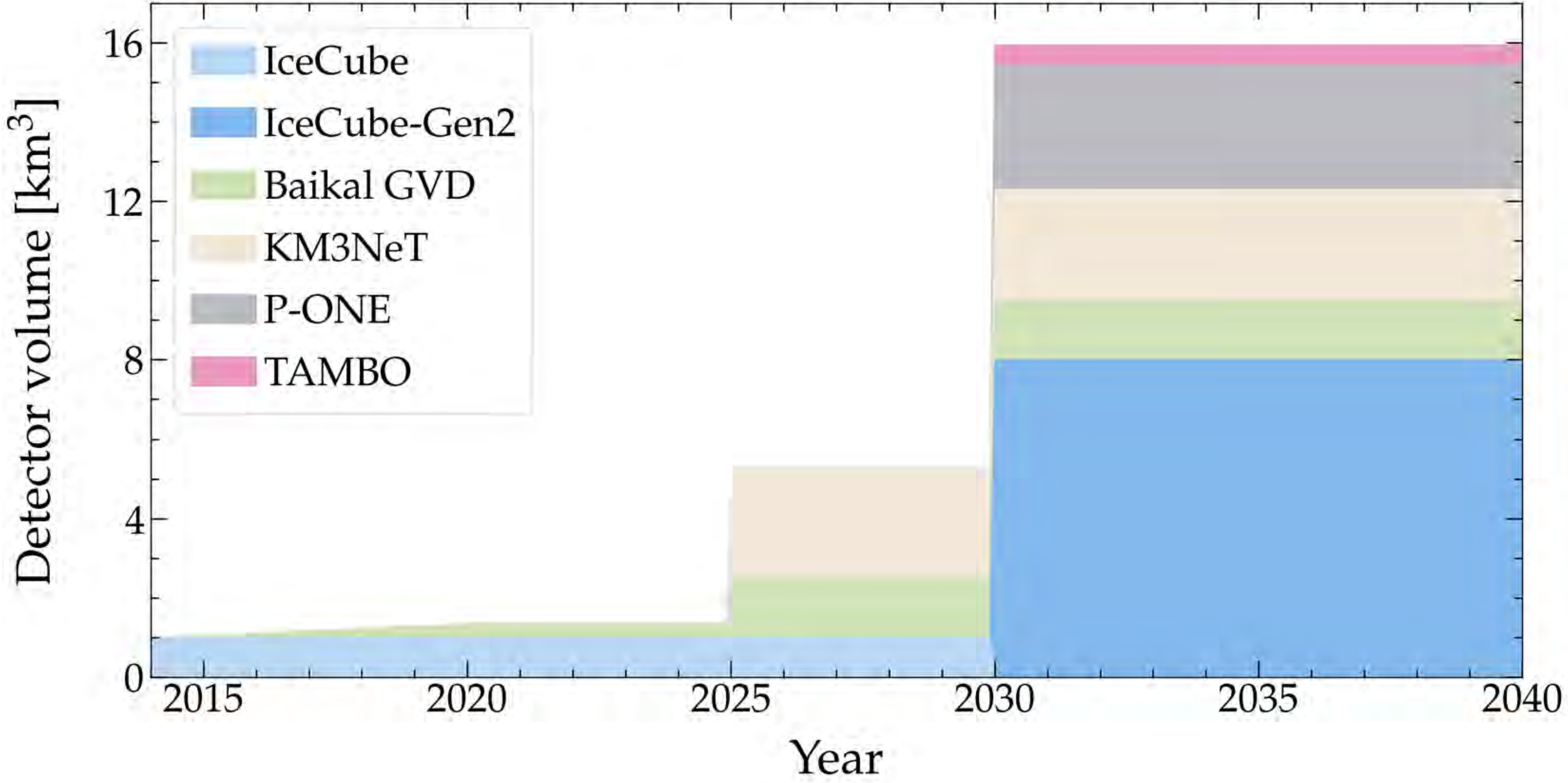

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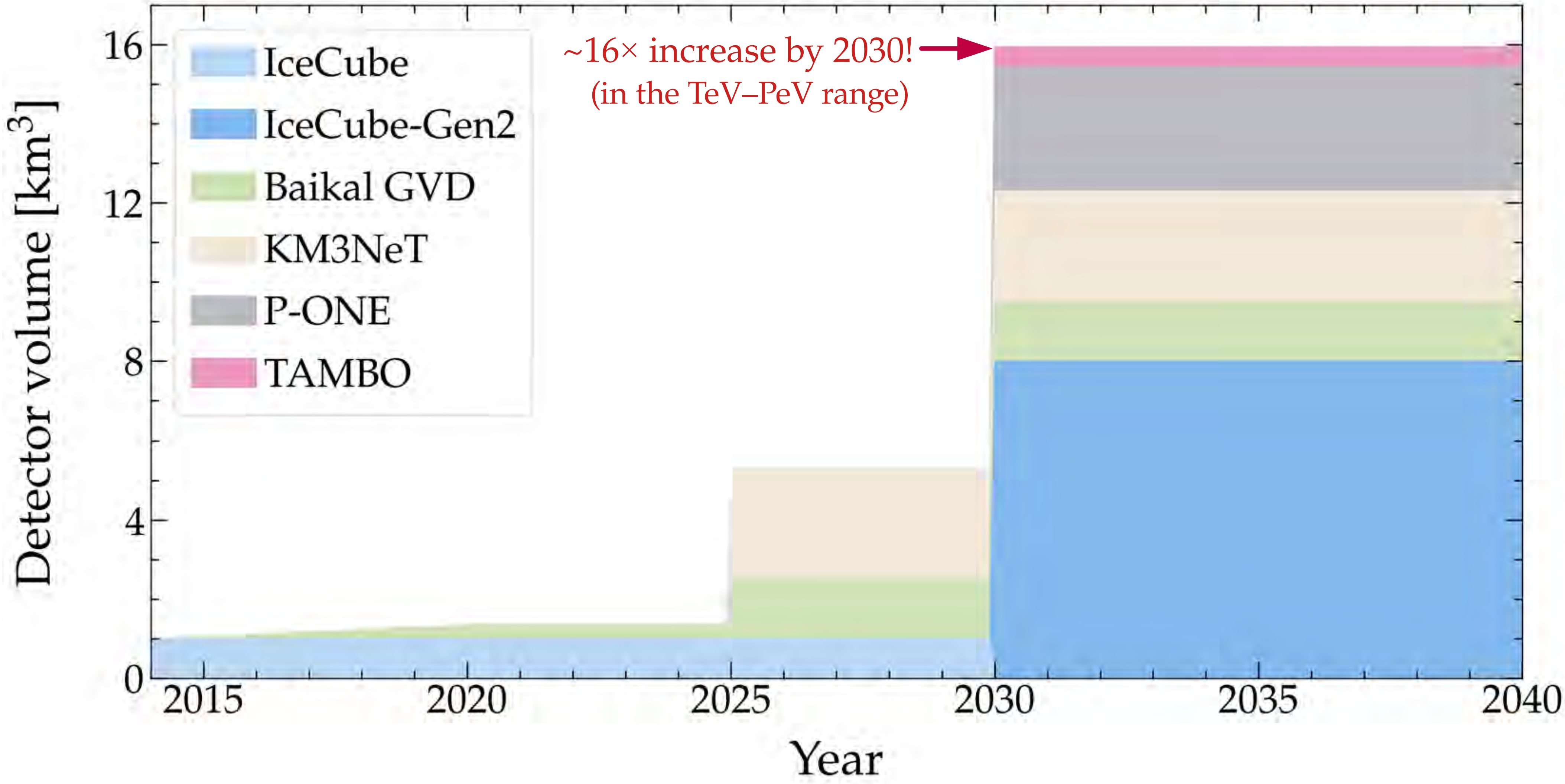

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

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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  E.g.,
  n = -1: neutrino decay
  n = 0: CPT-odd Lorentz violation
  n = +1: CPT-even Lorentz violation

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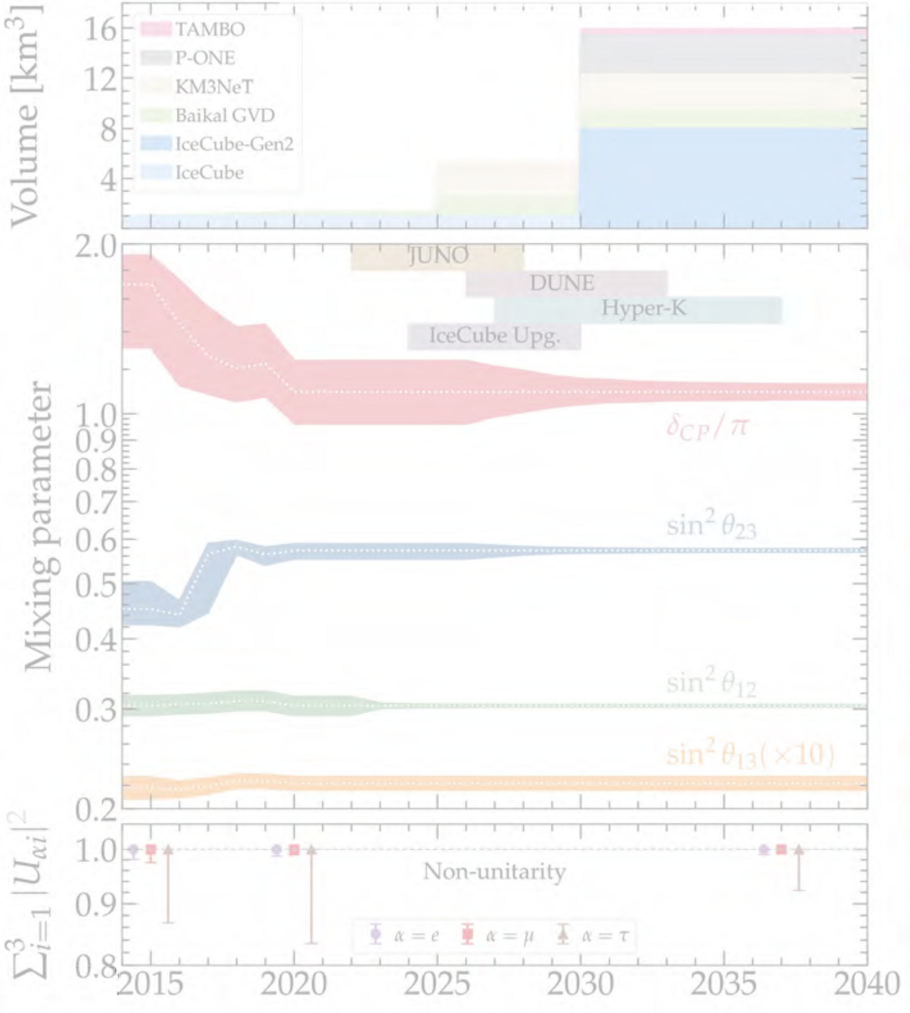
Three reasons to be excited

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



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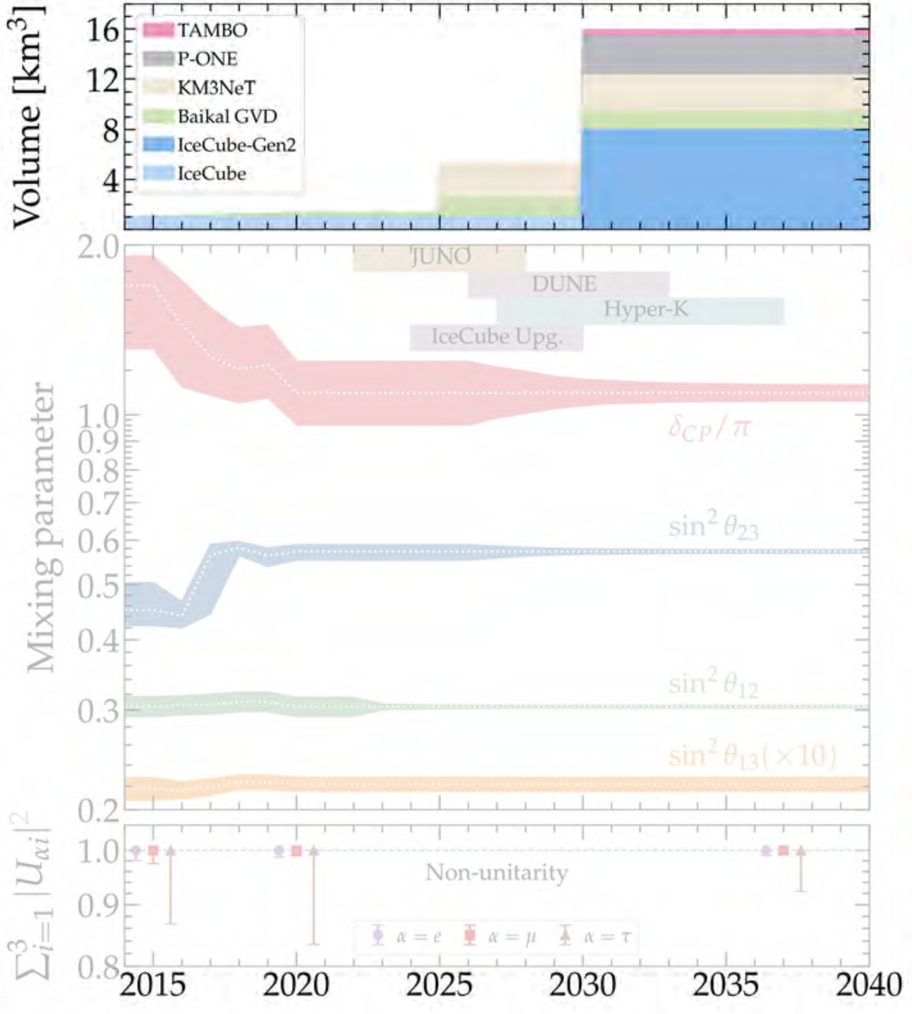

Flavor measurements:

New neutrino telescopes = more events, better flavor measurement

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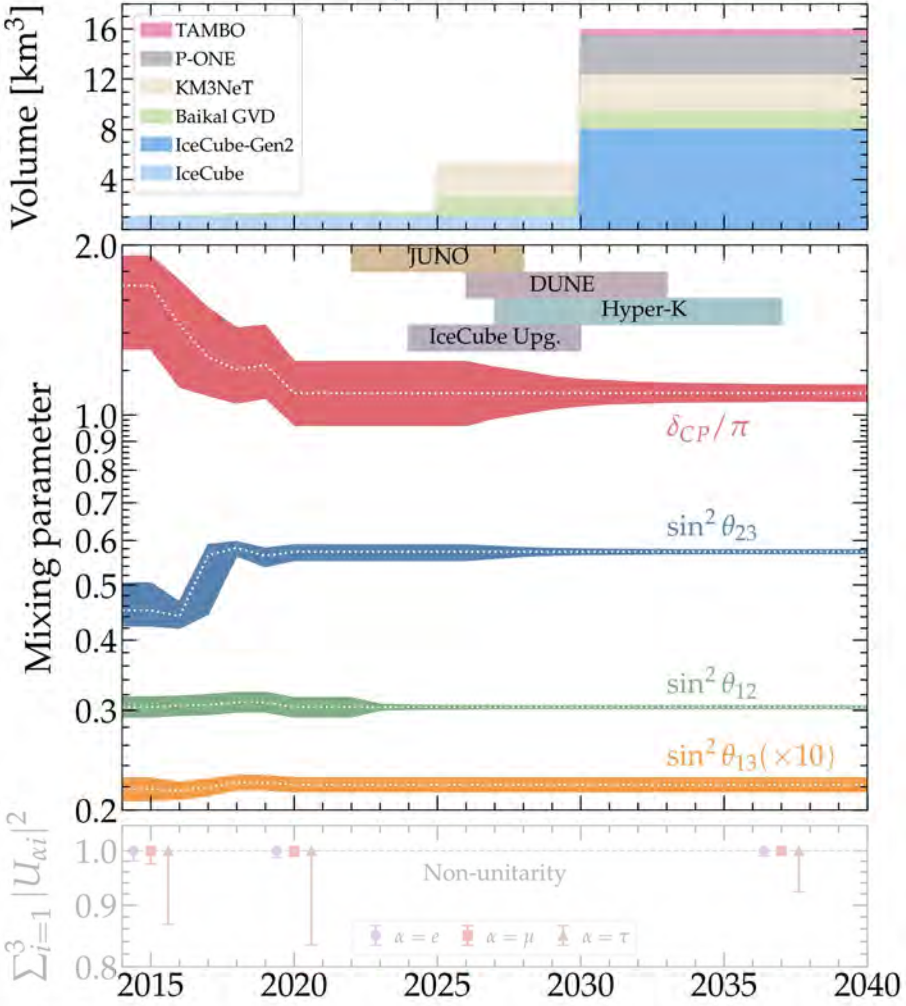

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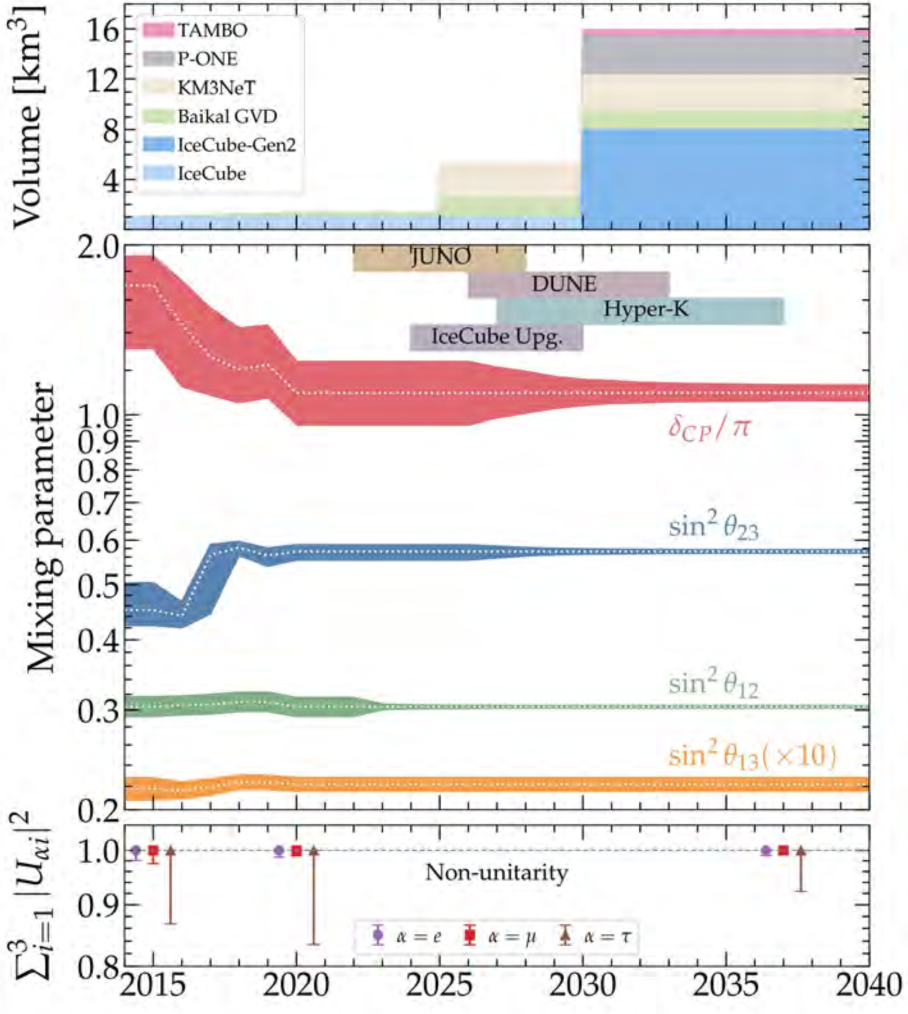

Flavor measurements:
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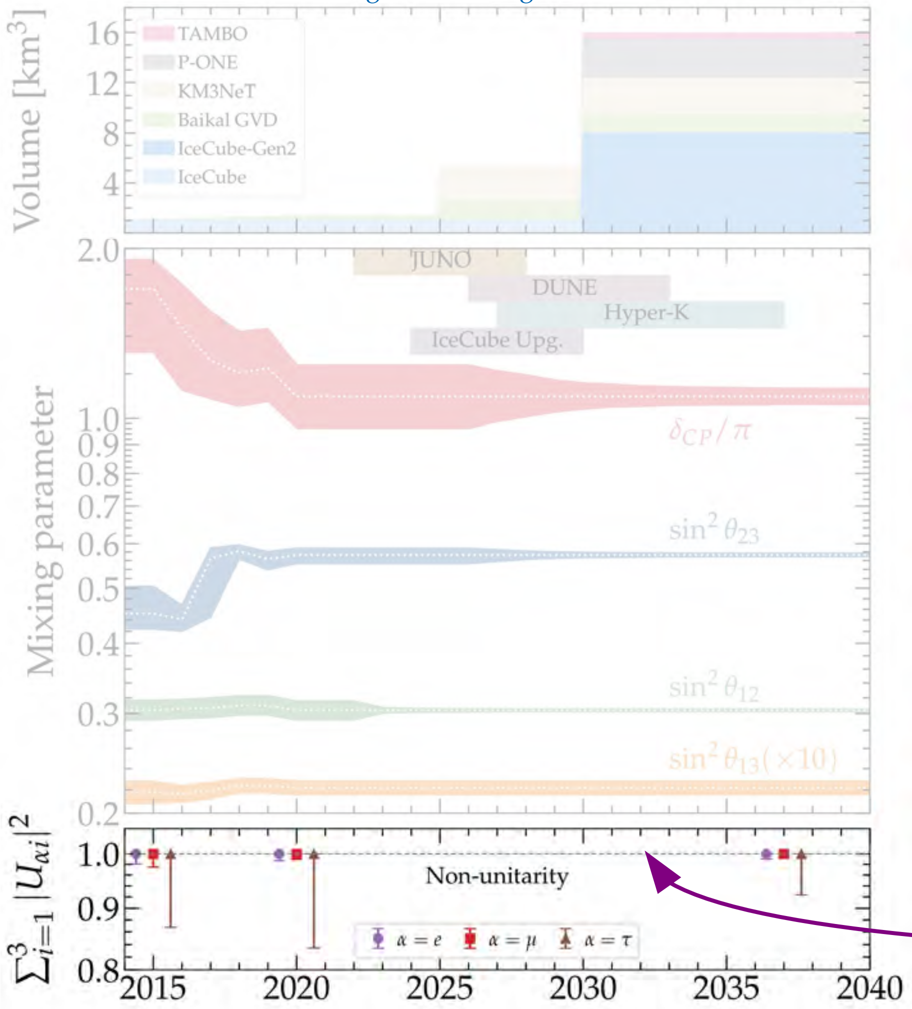
Oscillation physics:
We will know the mixing parameters better (JUNO, DUNE, Hyper-K, IceCube Upgrade)

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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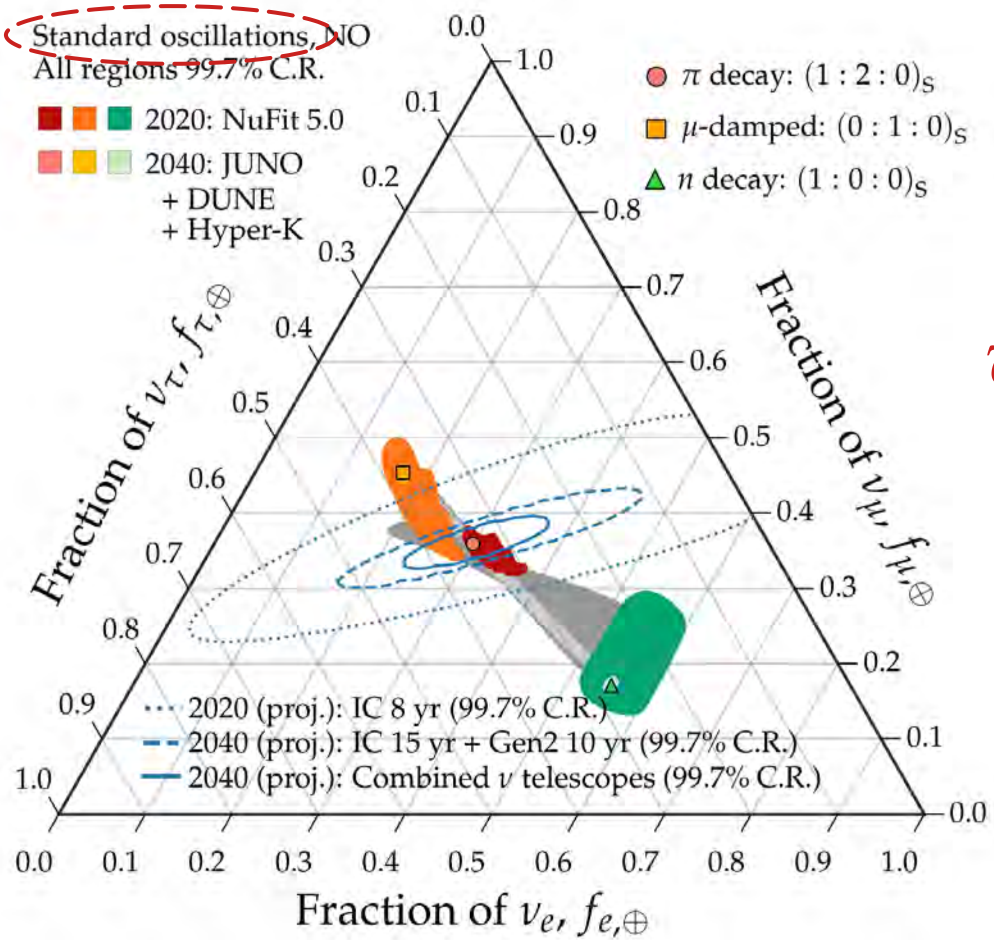
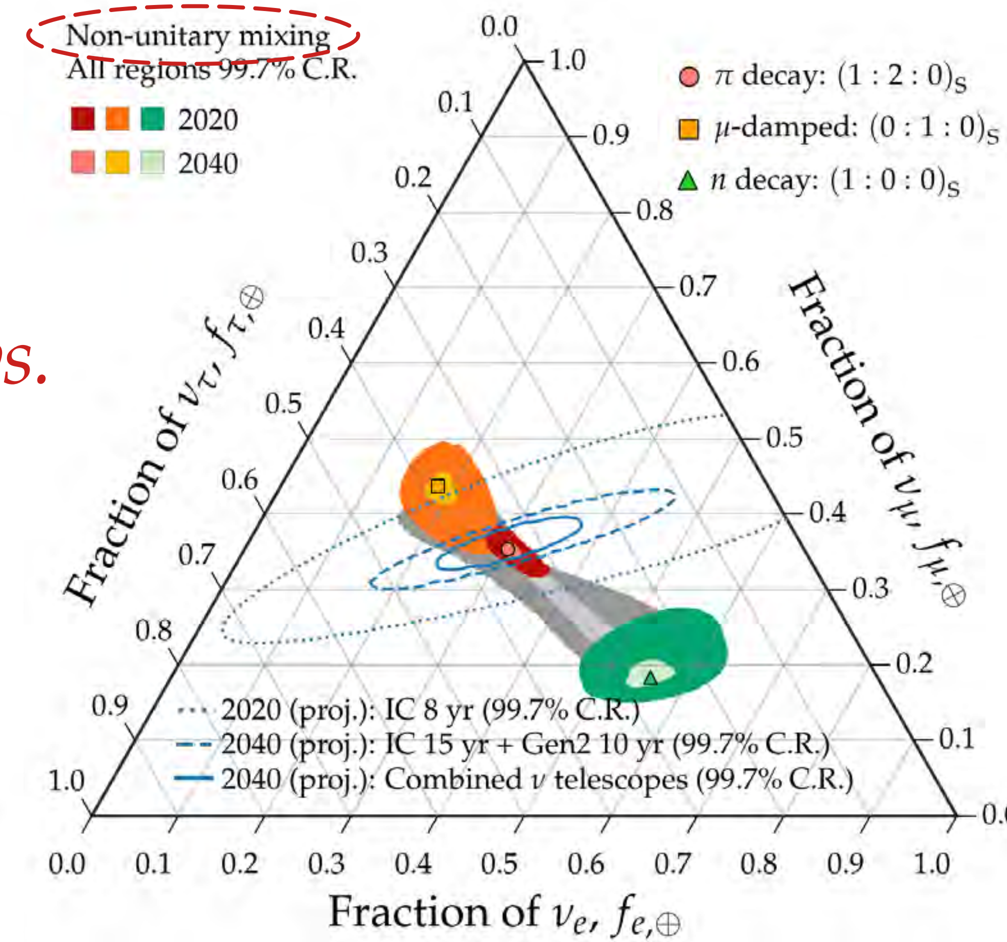


vs.



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
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  » Age of Universe (~ 14.5 Gyr)

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

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  Nambu-Goldstone boson of a broken symmetry

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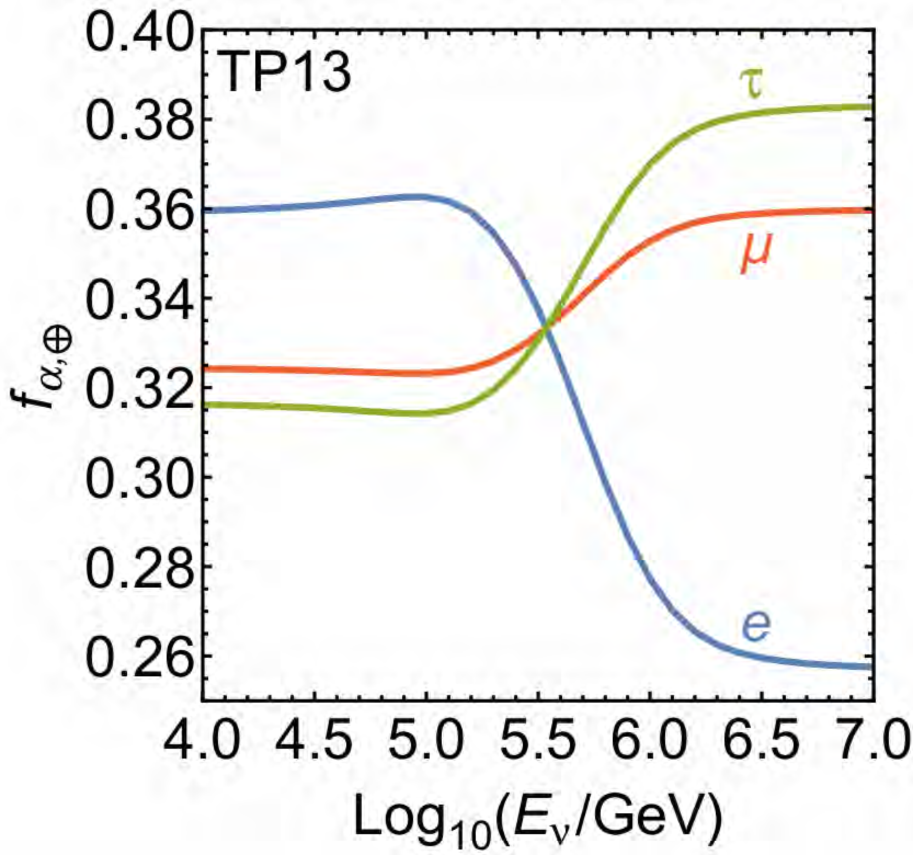
Flavor composition: measuring the energy dependence

Expected from astrophysical processes



MB, Beacom, Winter *PRL* 2015

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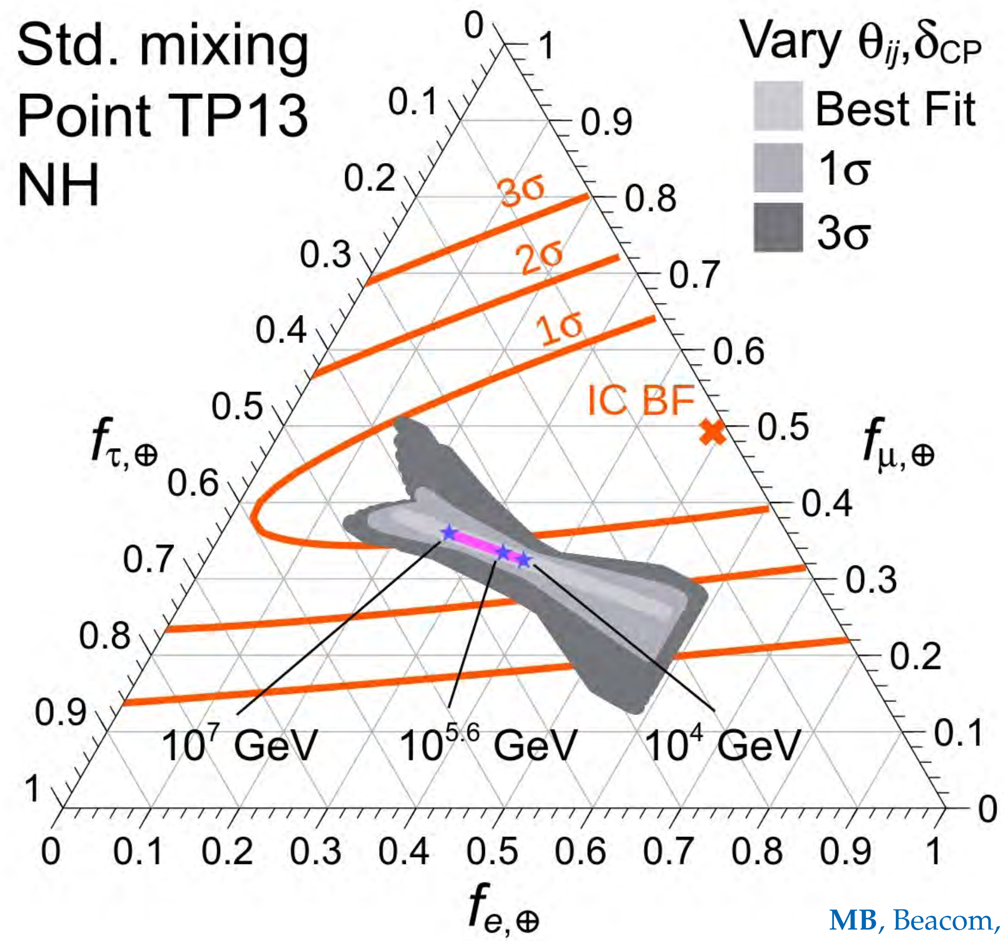

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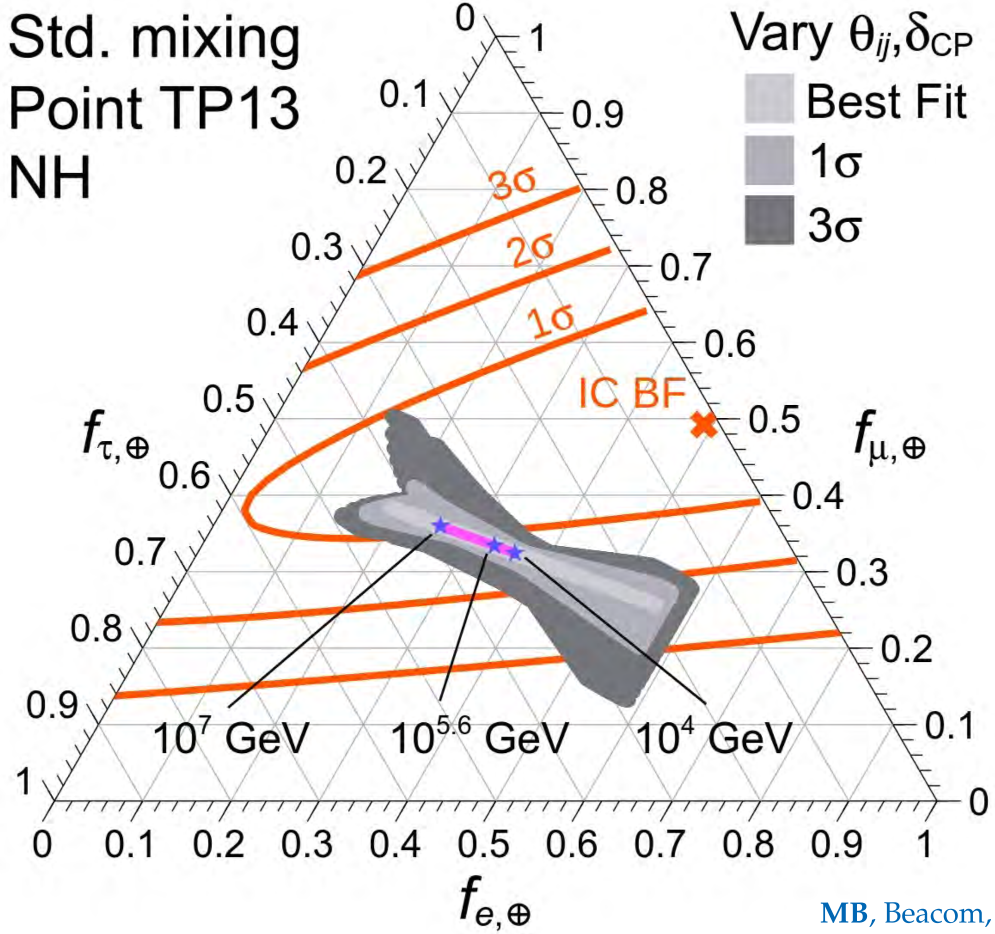

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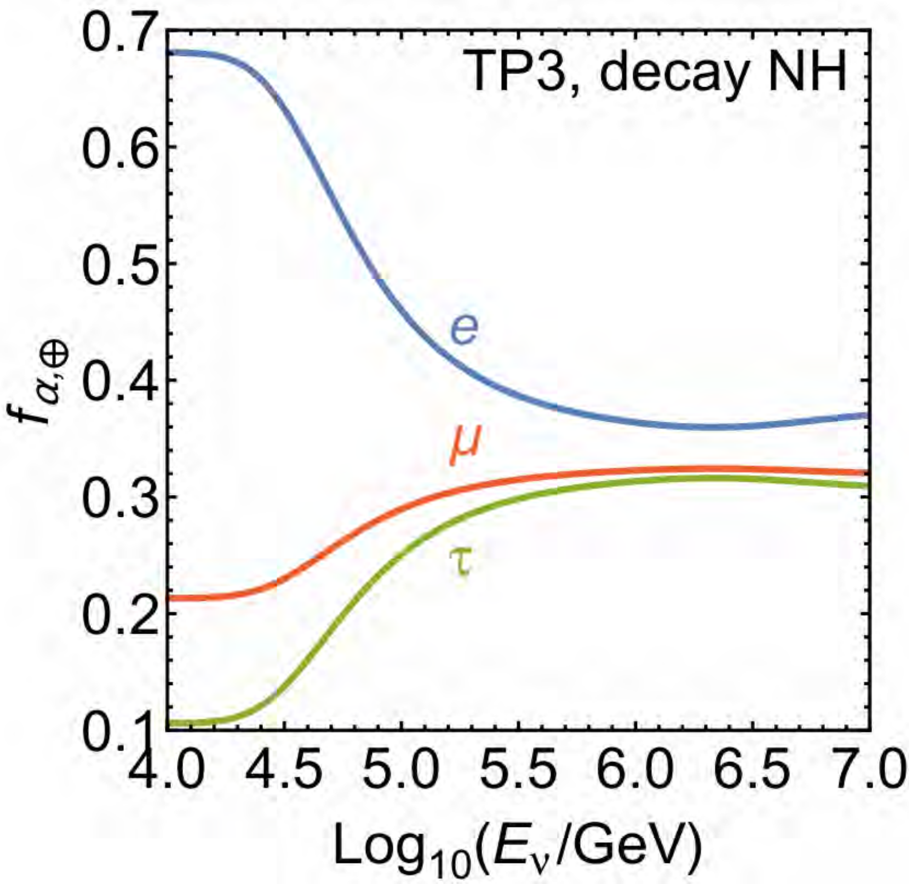

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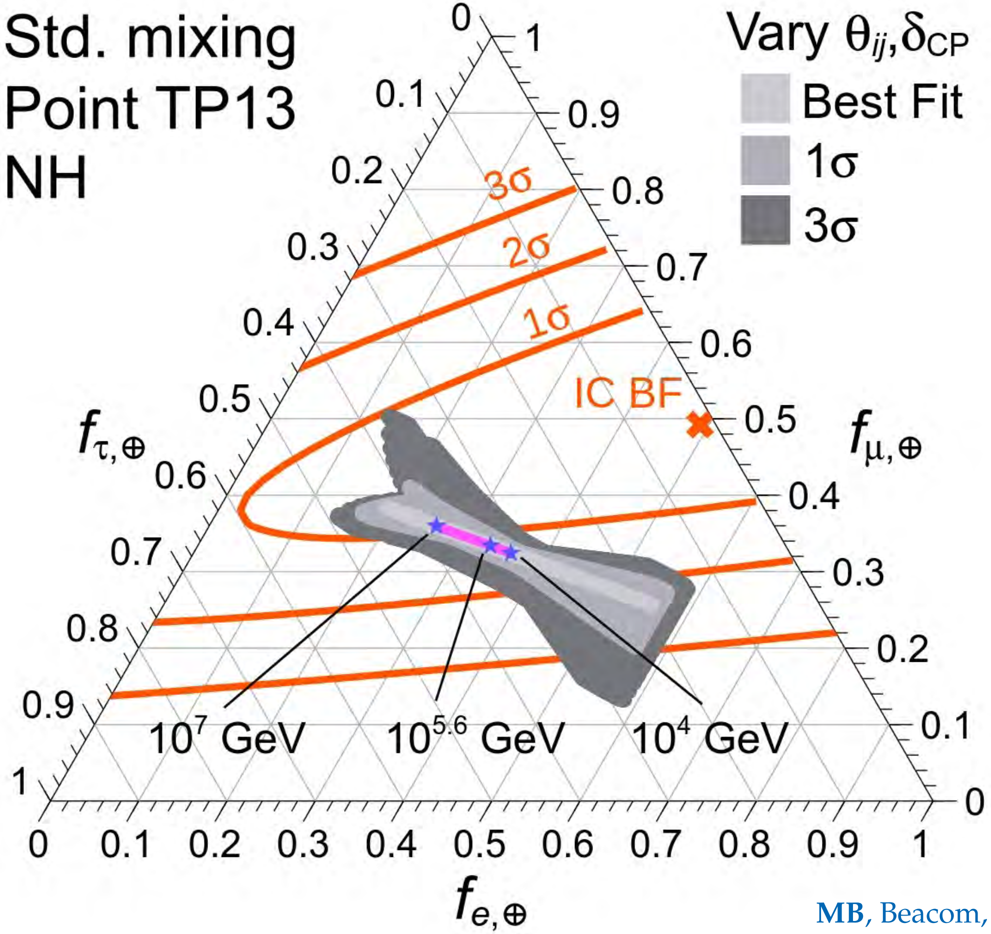

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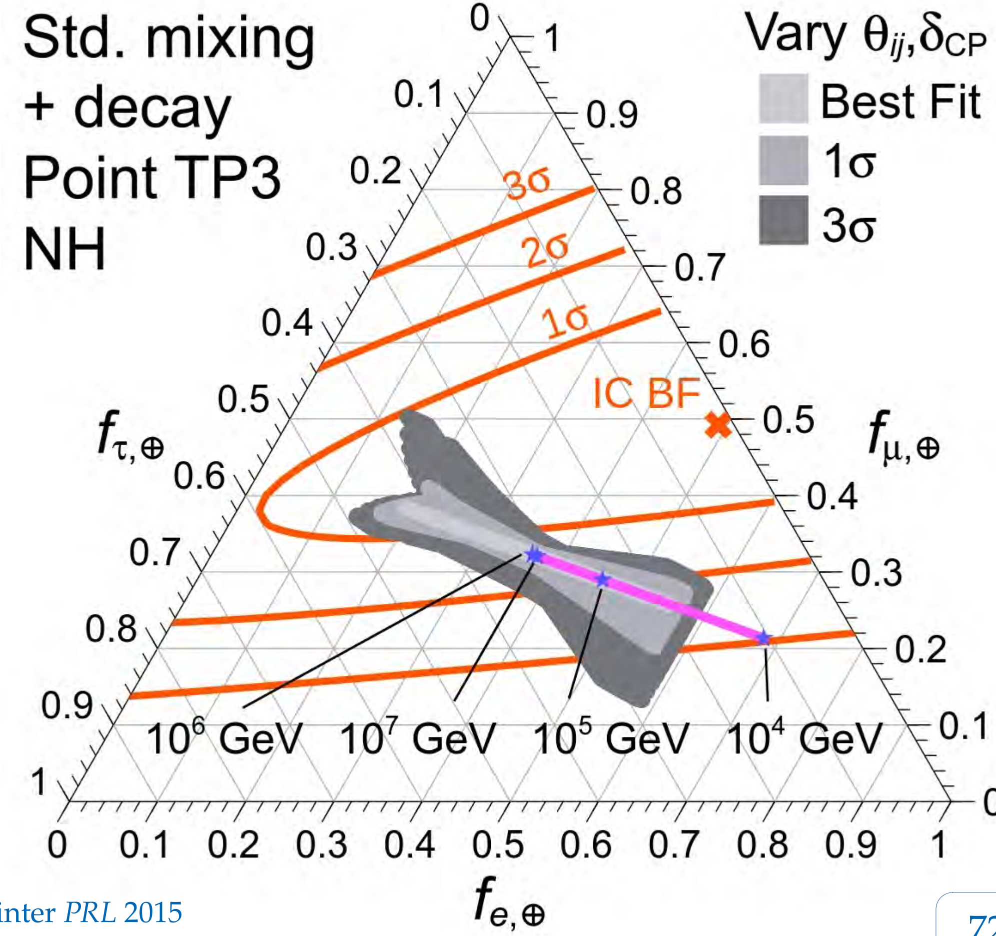

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More than one production mechanism?

Can we detect the contribution of multiple ν production mechanisms?

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

π decay: (1/3, 2/3, 0) μ damped: (0, 1, 0) *n* decay: (1, 0, 0)

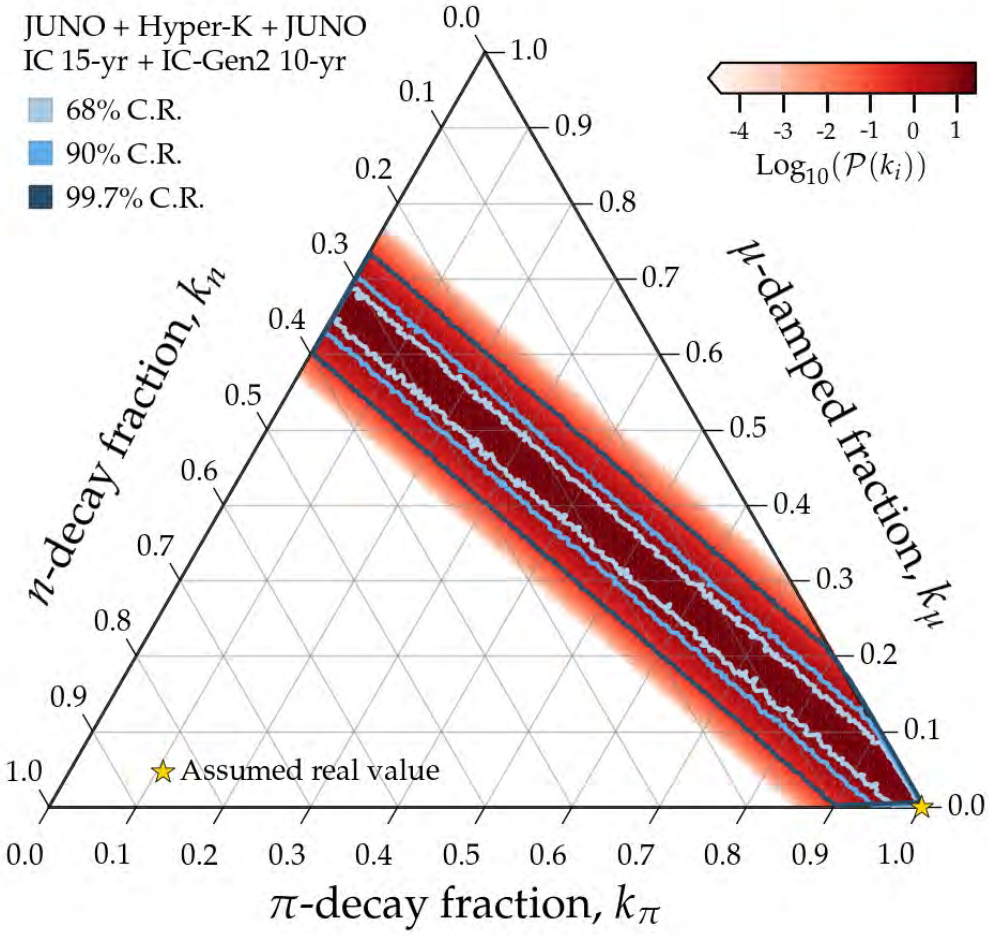
Propagate to Earth

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

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]



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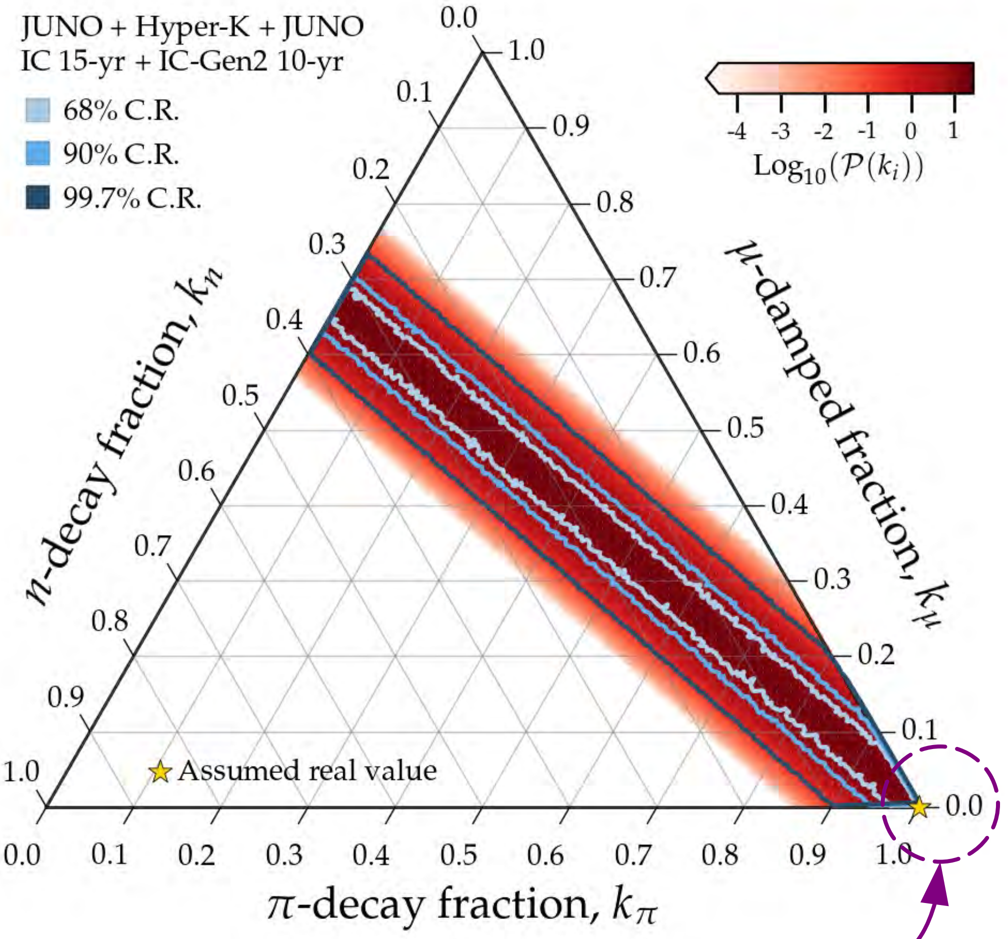

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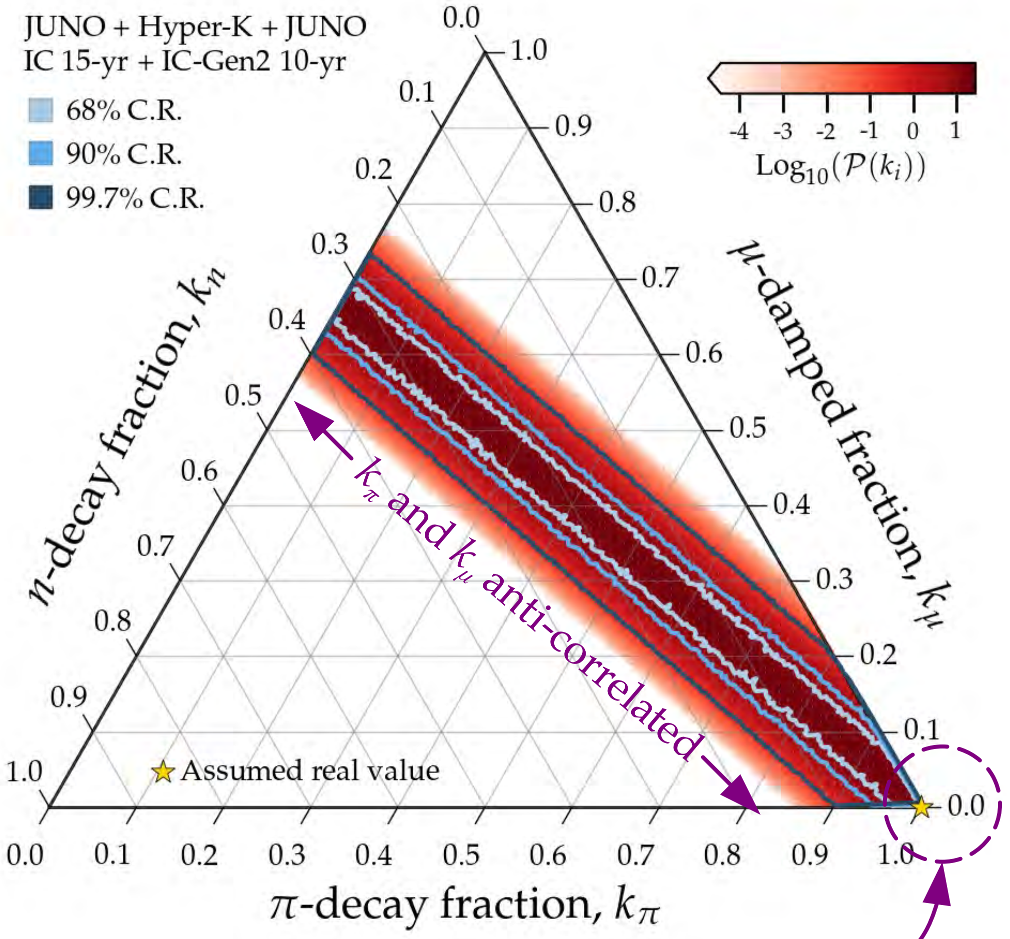

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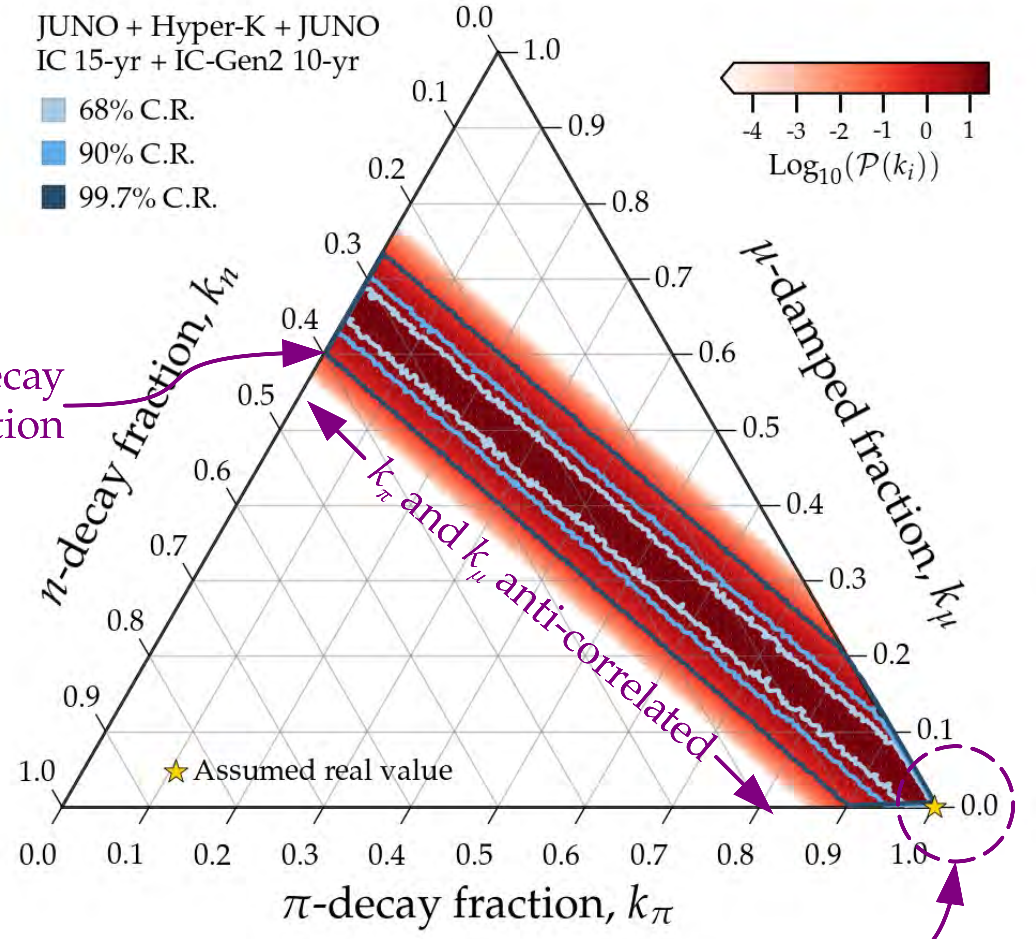

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μ damped: (0, 1, 0)
n decay: (1, 0, 0)

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

More than one production mechanism?

Can we detect the contribution of multiple ν production mechanisms?

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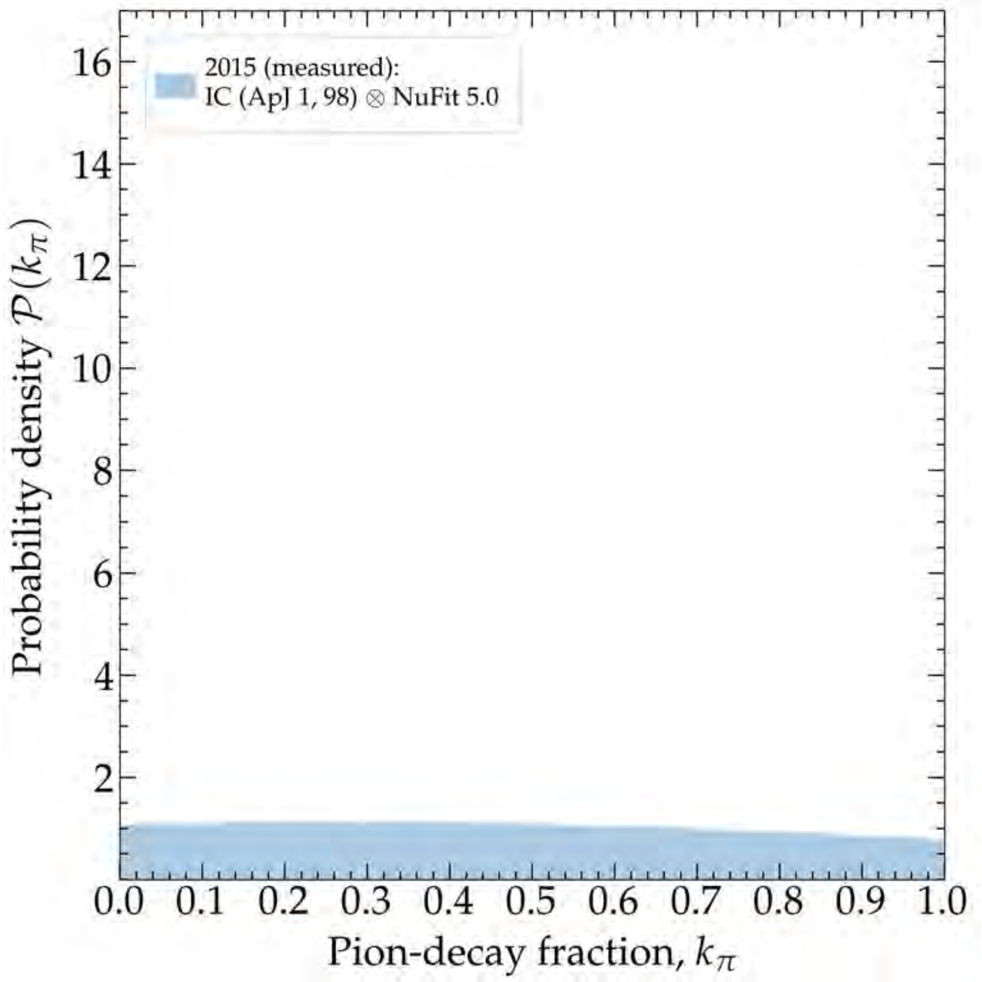

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

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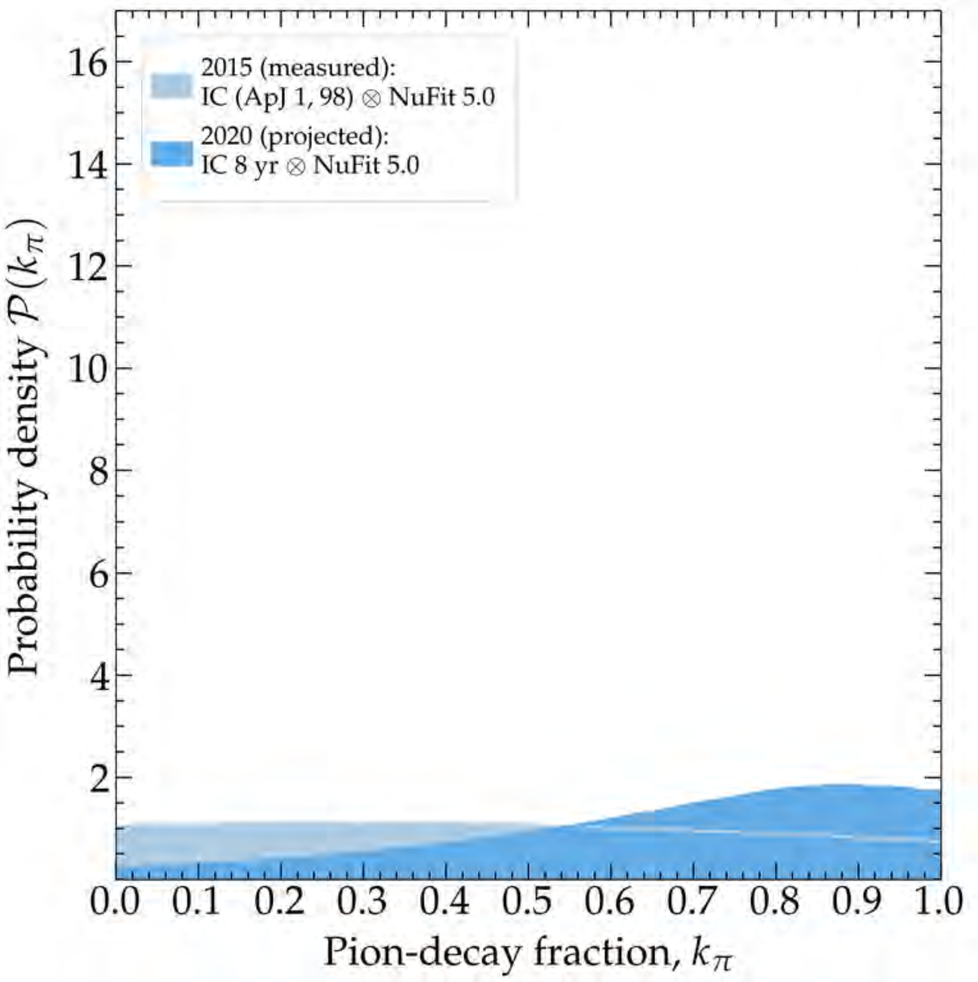

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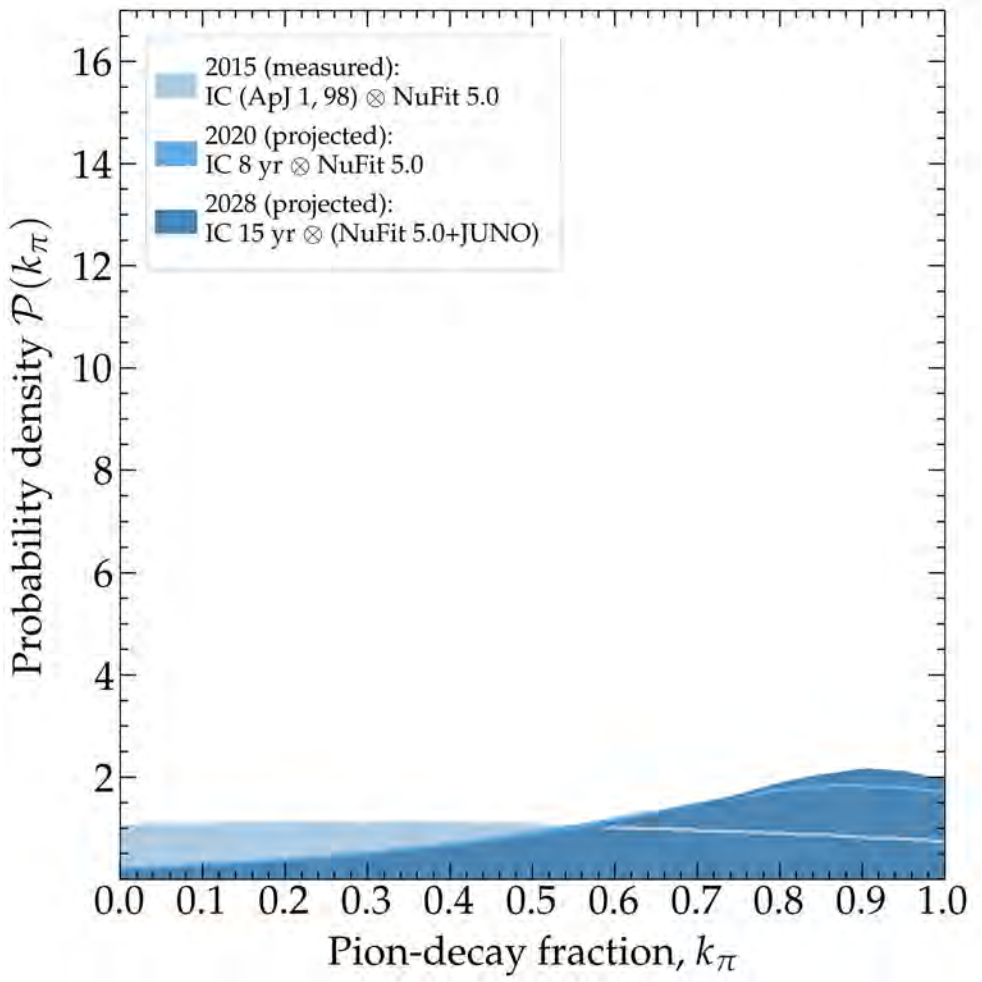

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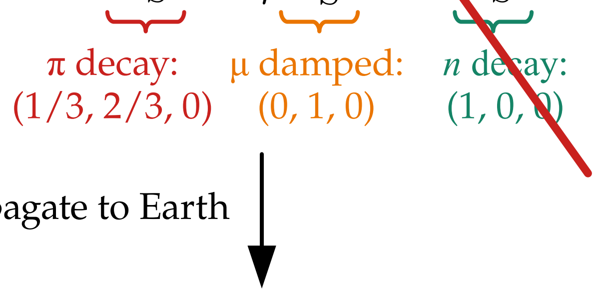

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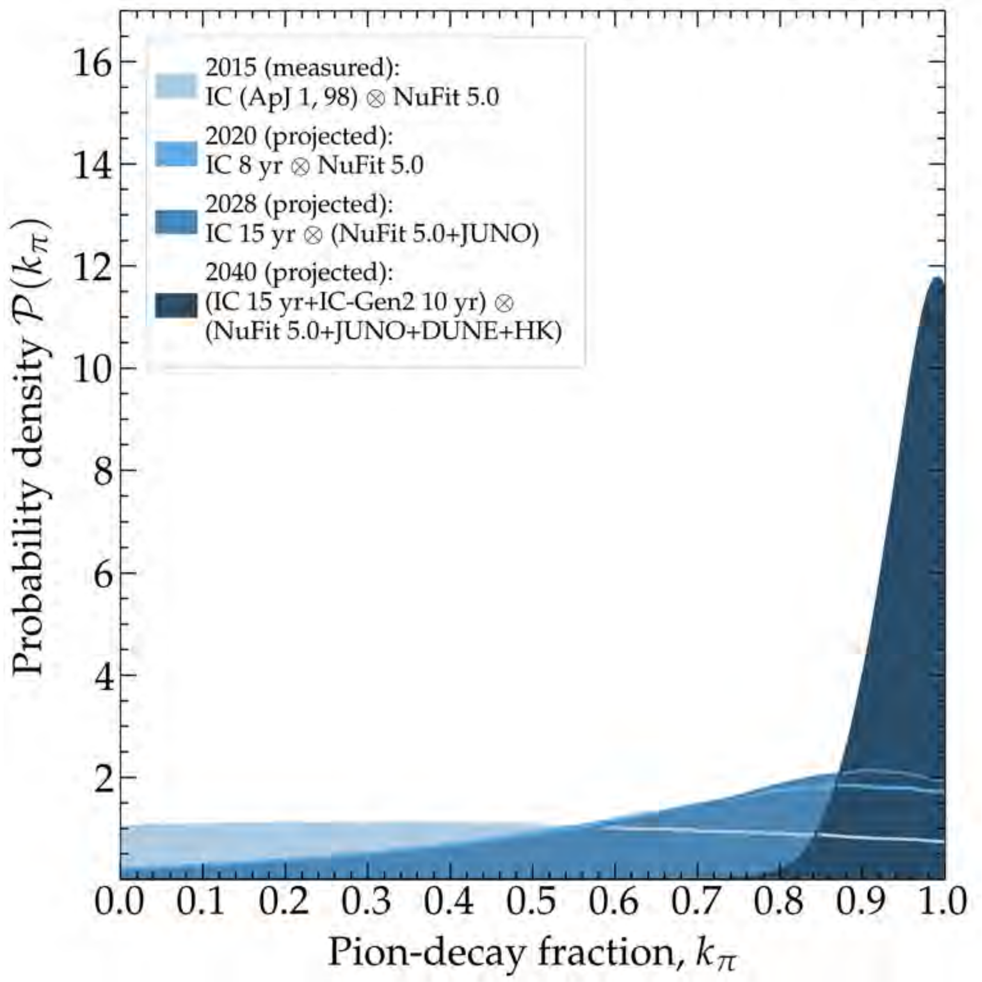

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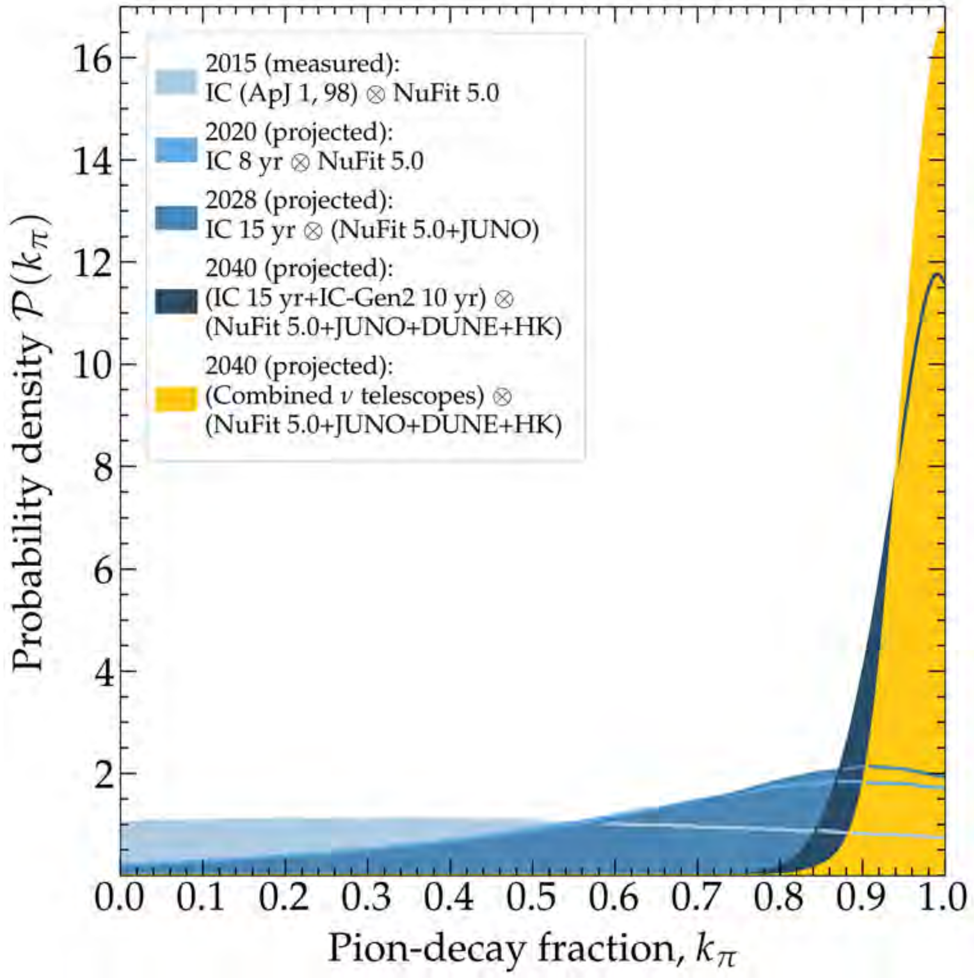
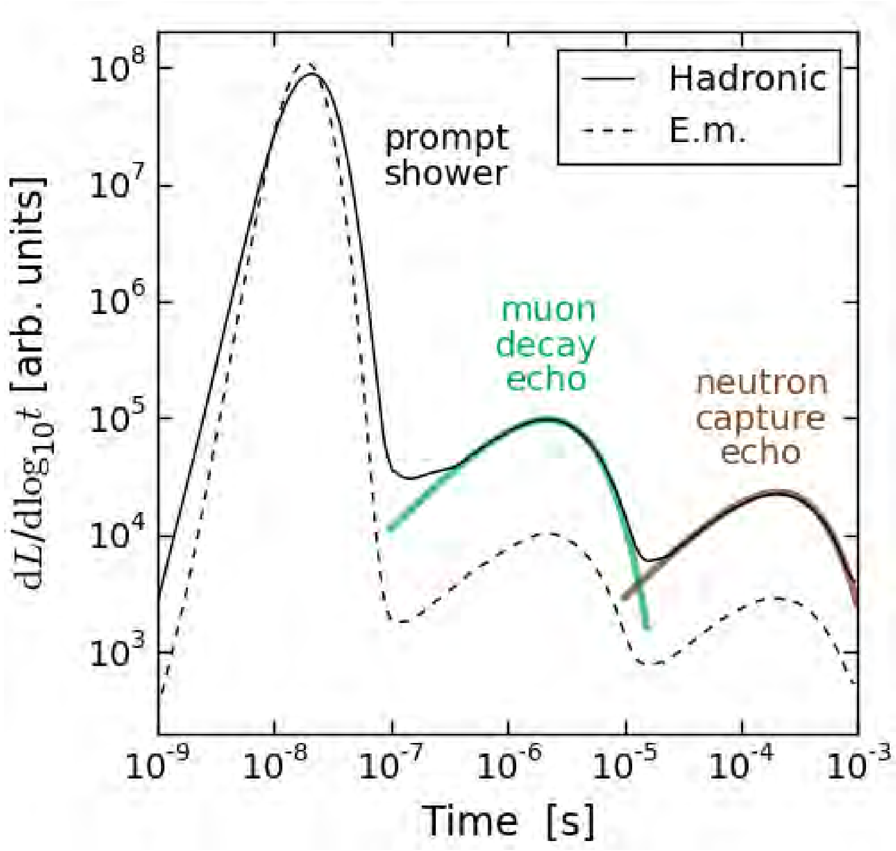
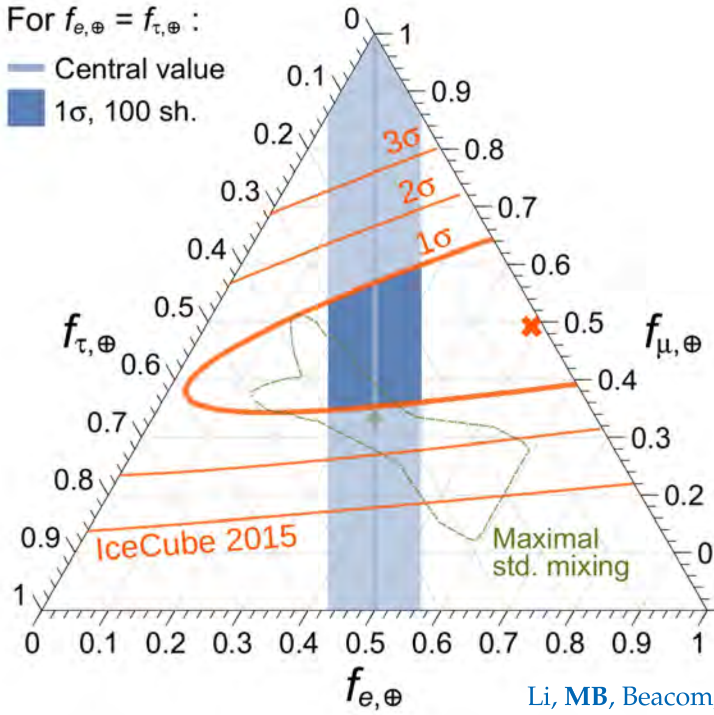


Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

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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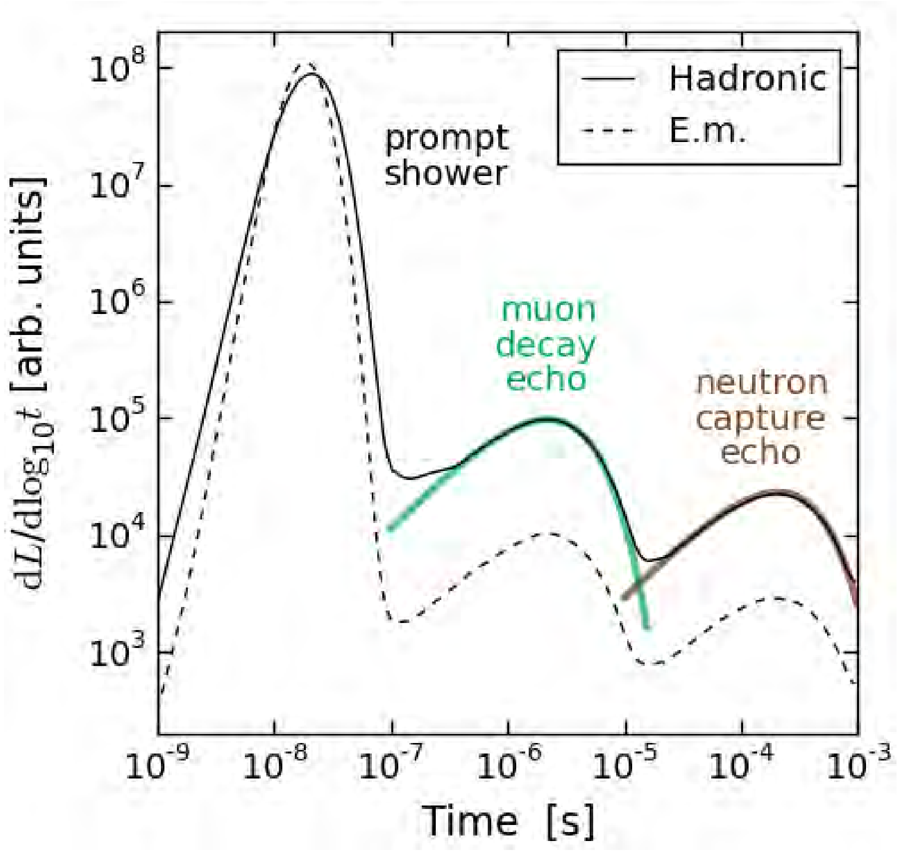
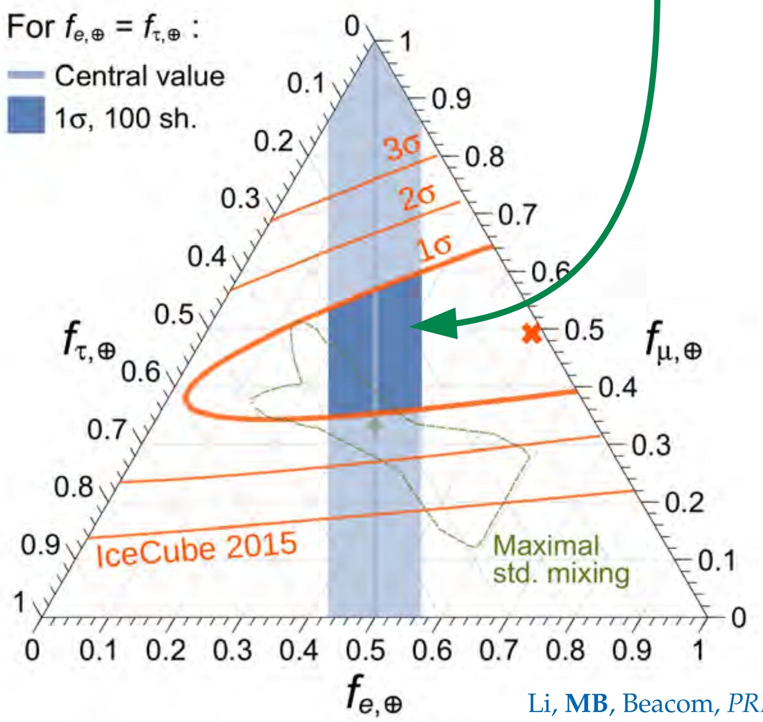


~10 × improvement over current measurement



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

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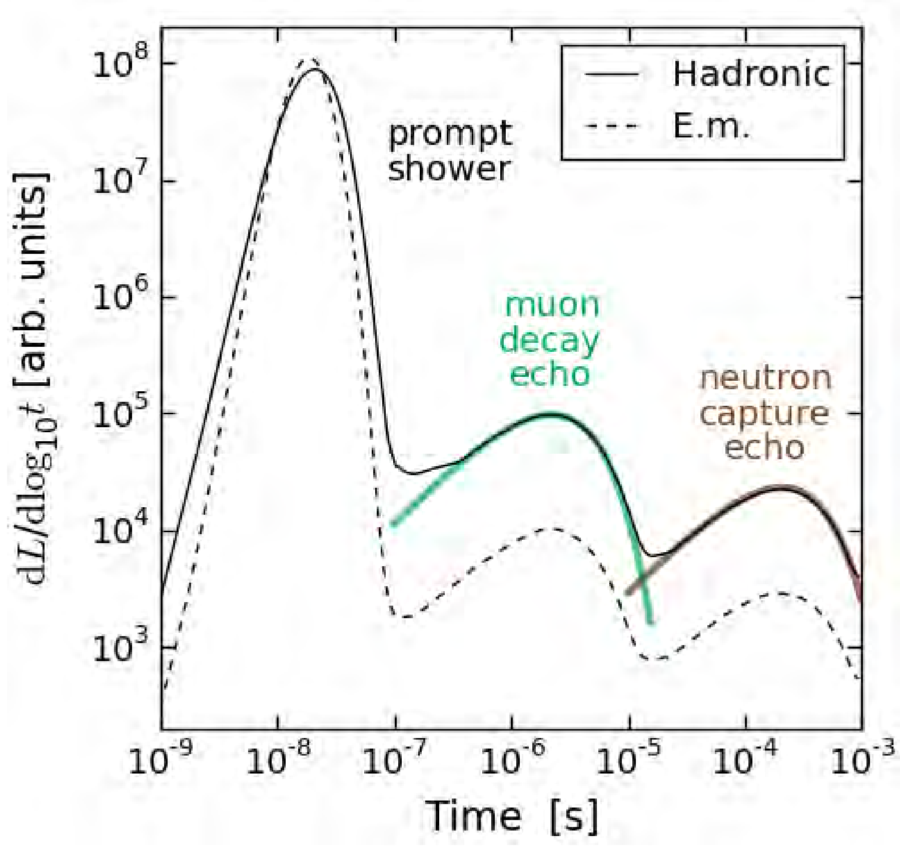

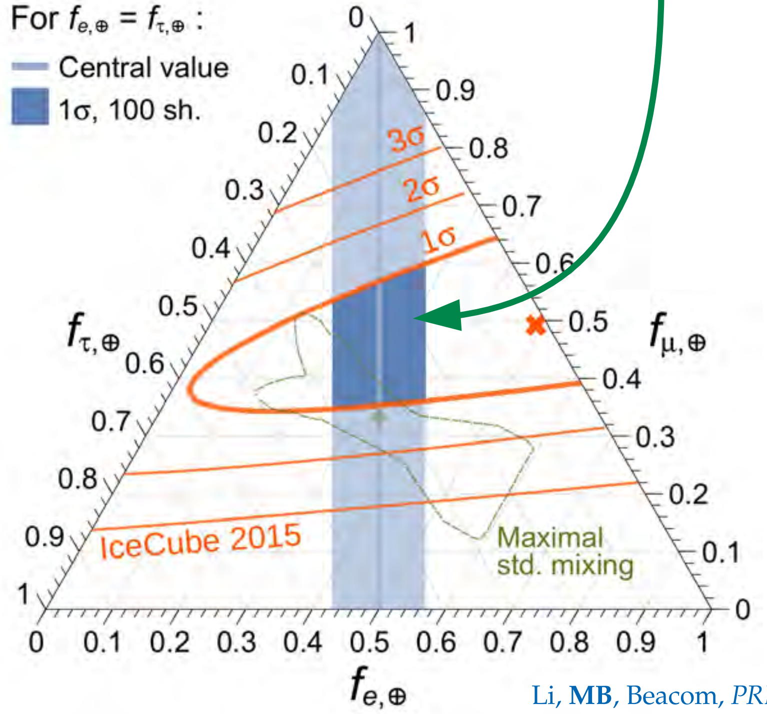

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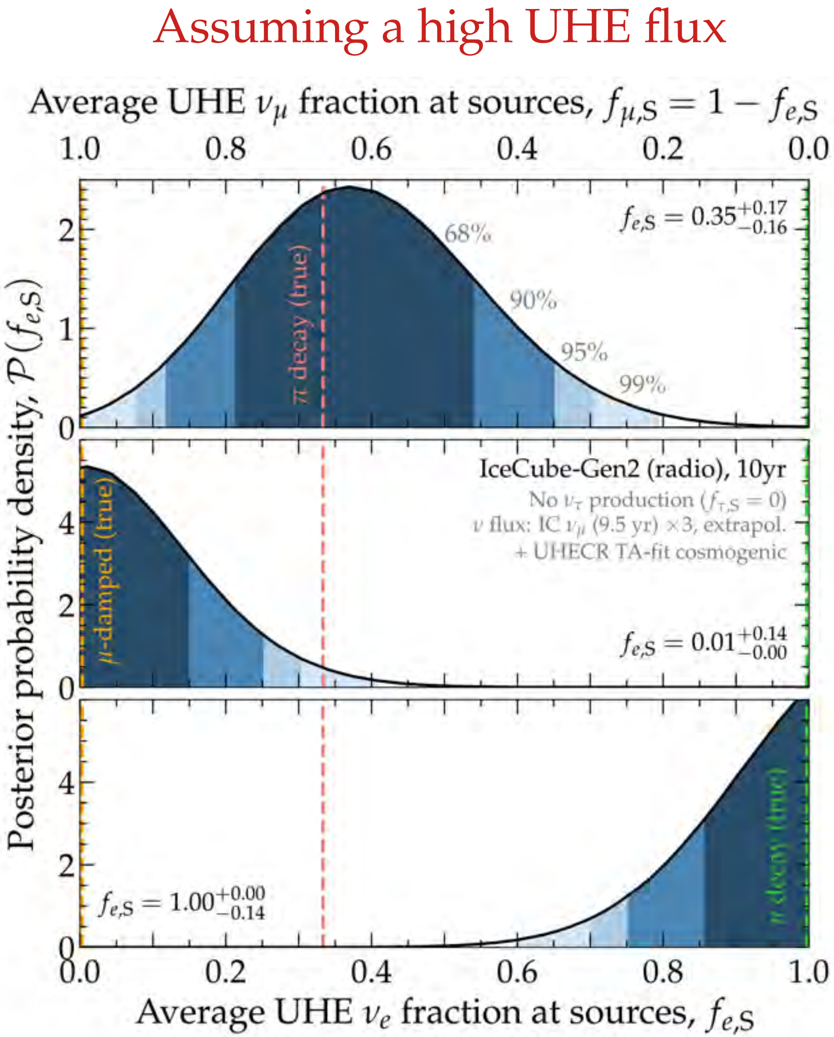
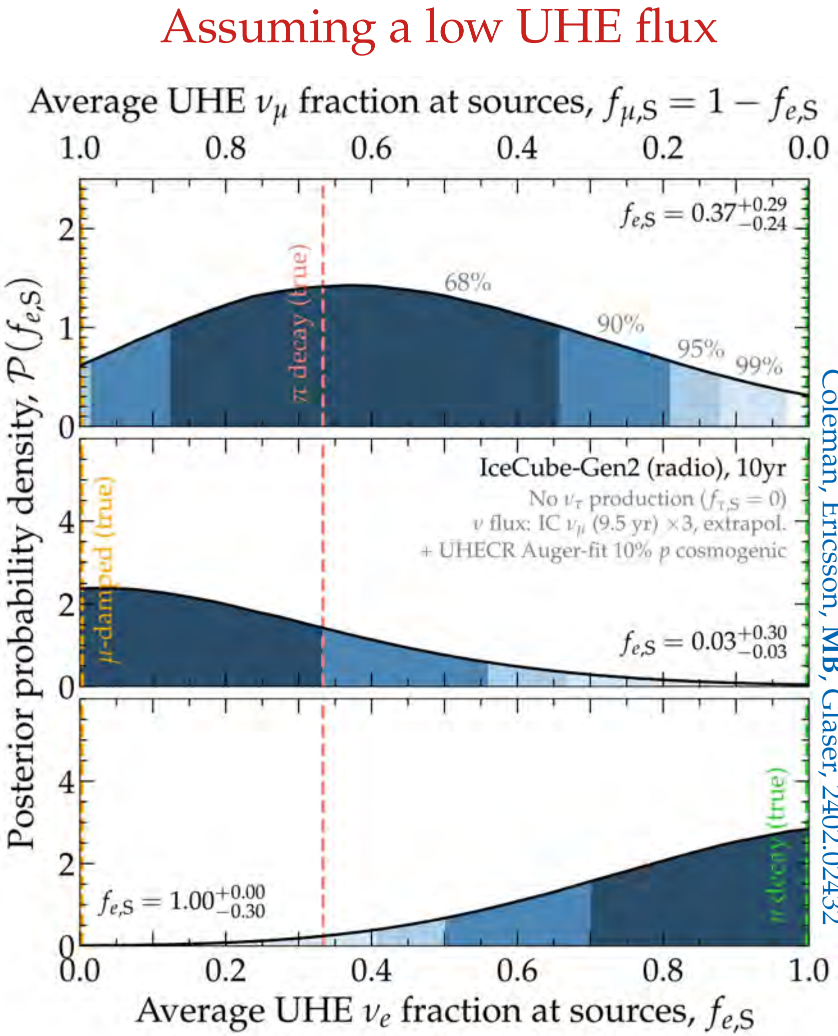
Li, **MB**, Beacom, *PRL* 2019

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

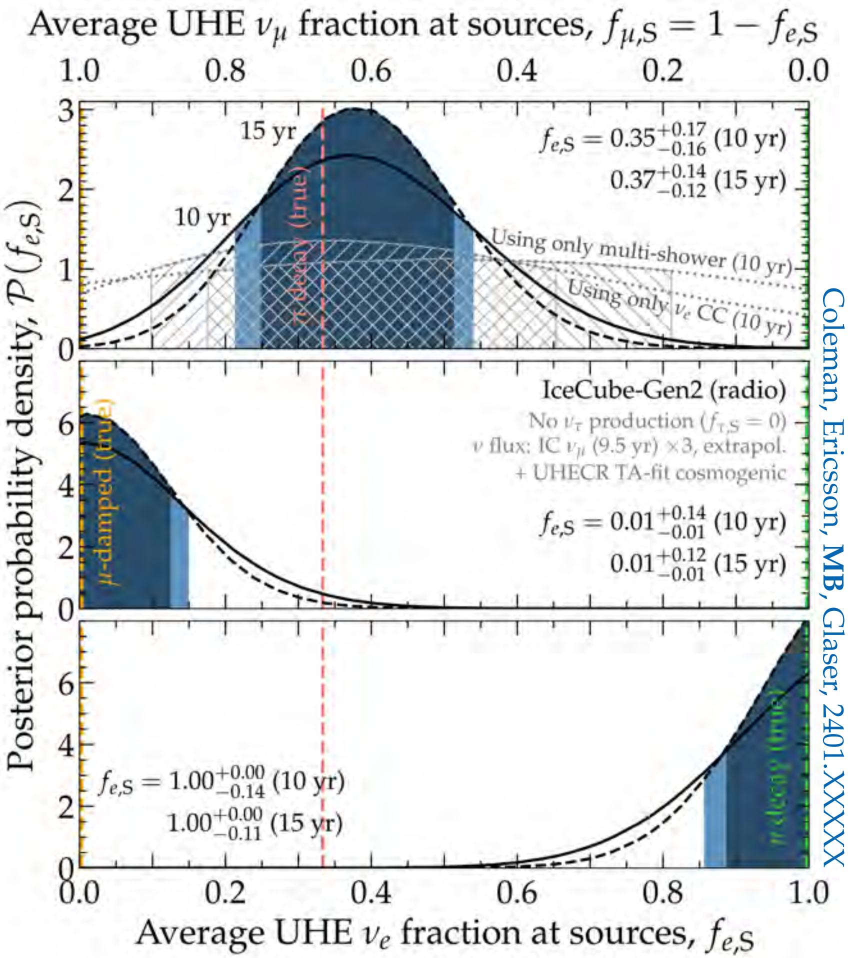




Coleman, Ericsson, **MB**, Glaser, 2402.02432

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

10 yr *vs.* 15 yr, individual channels



Coleman, Ericsson, MB, Glaser, 2401.XXXXX

Flavor composition: measuring the energy dependence

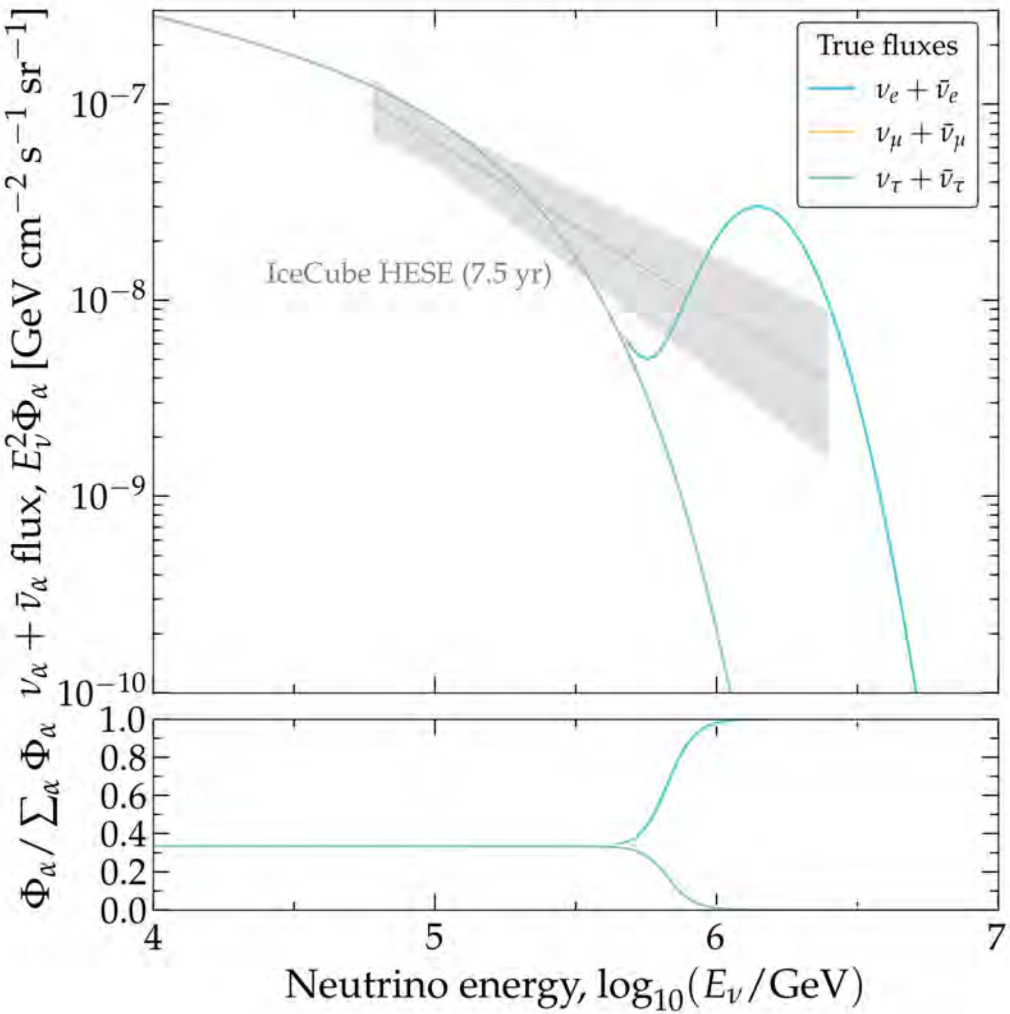
Can we do better?

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



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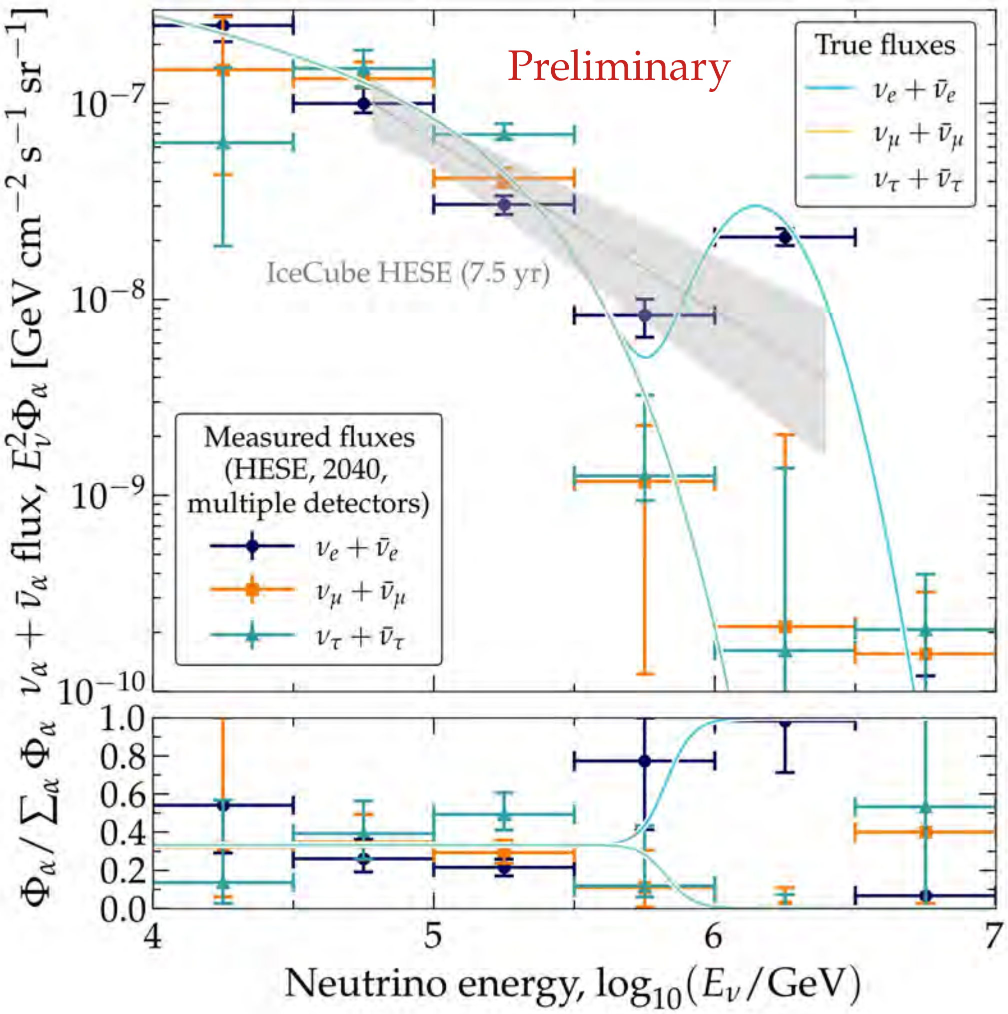
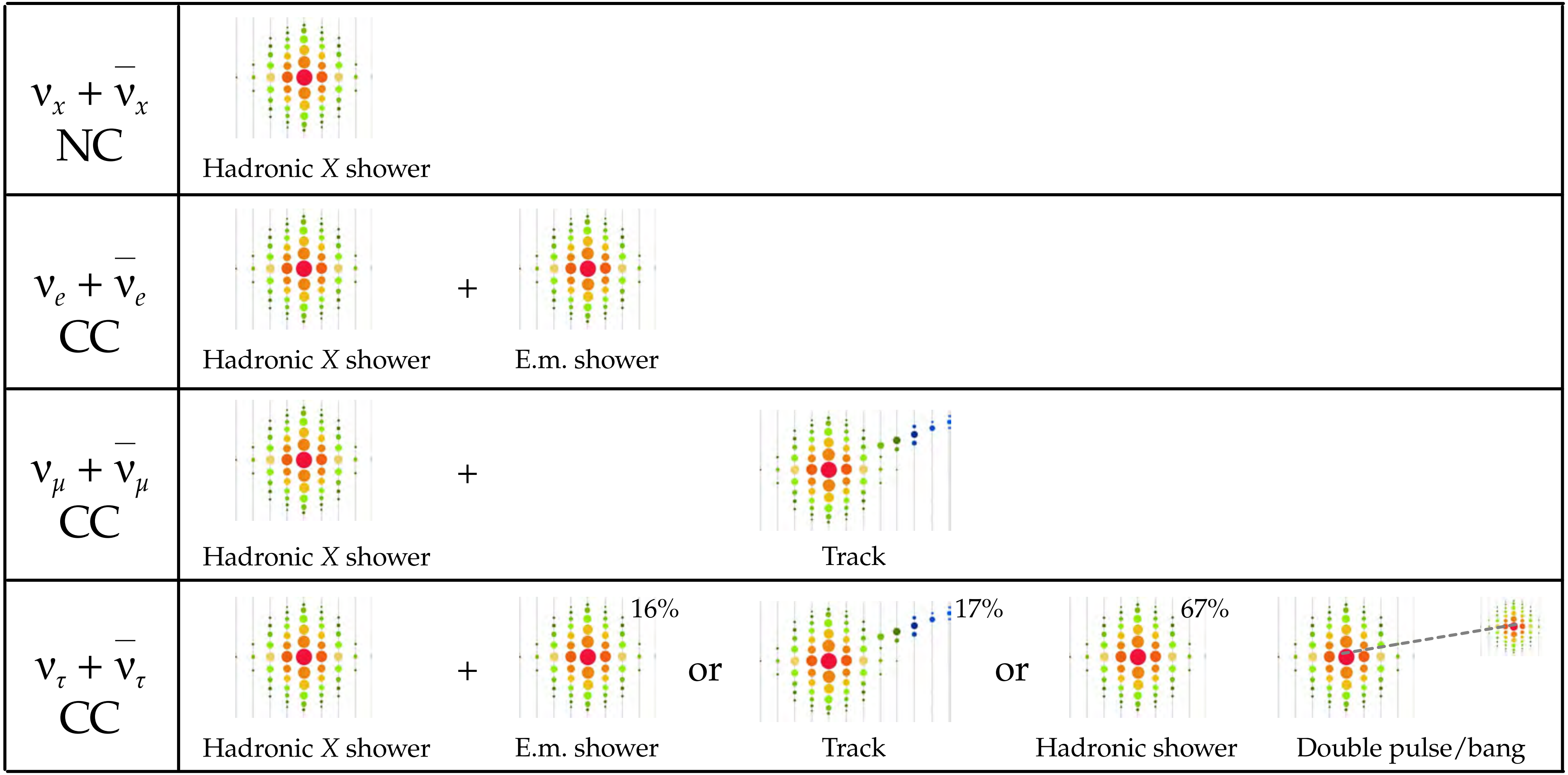
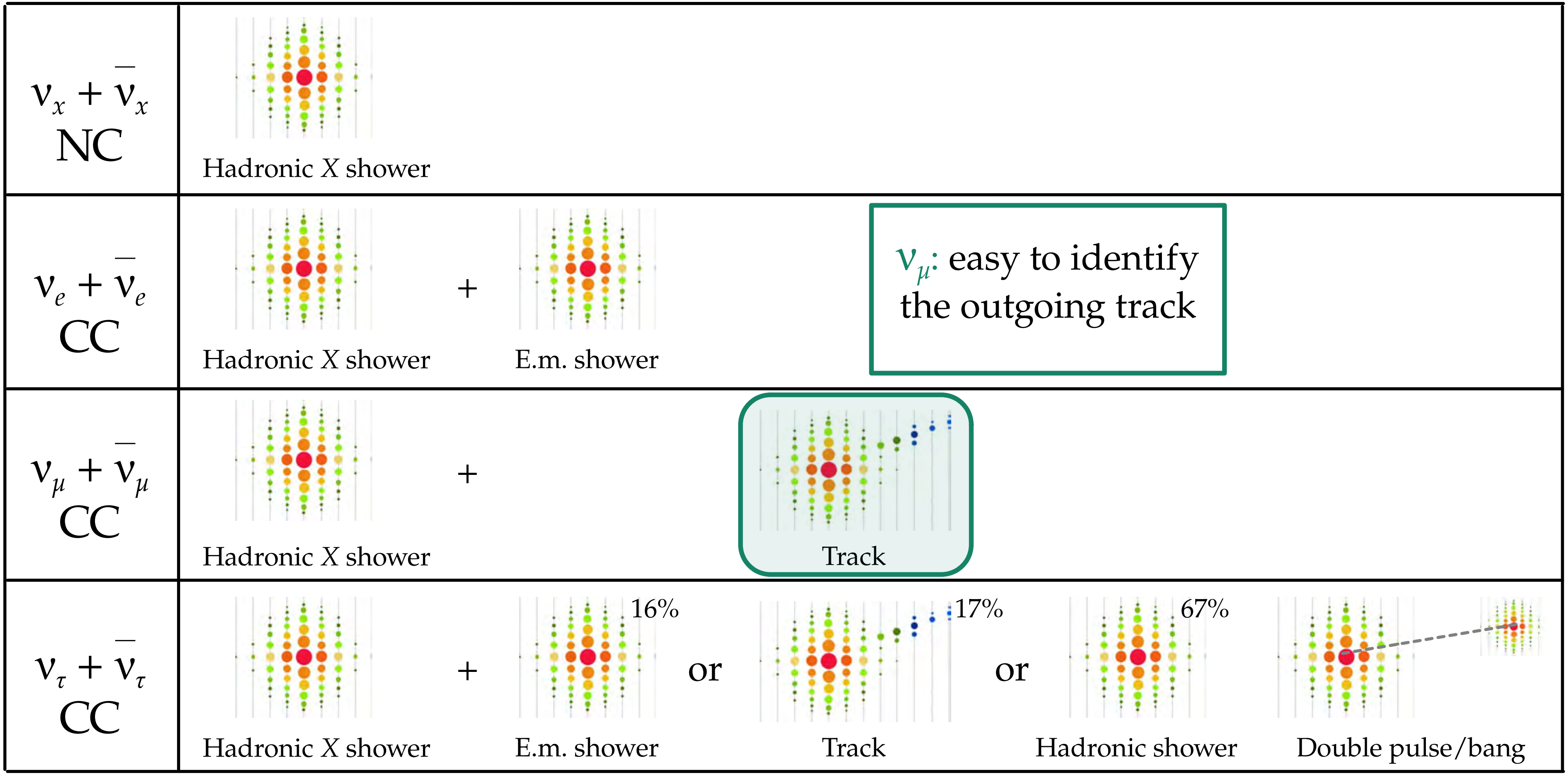


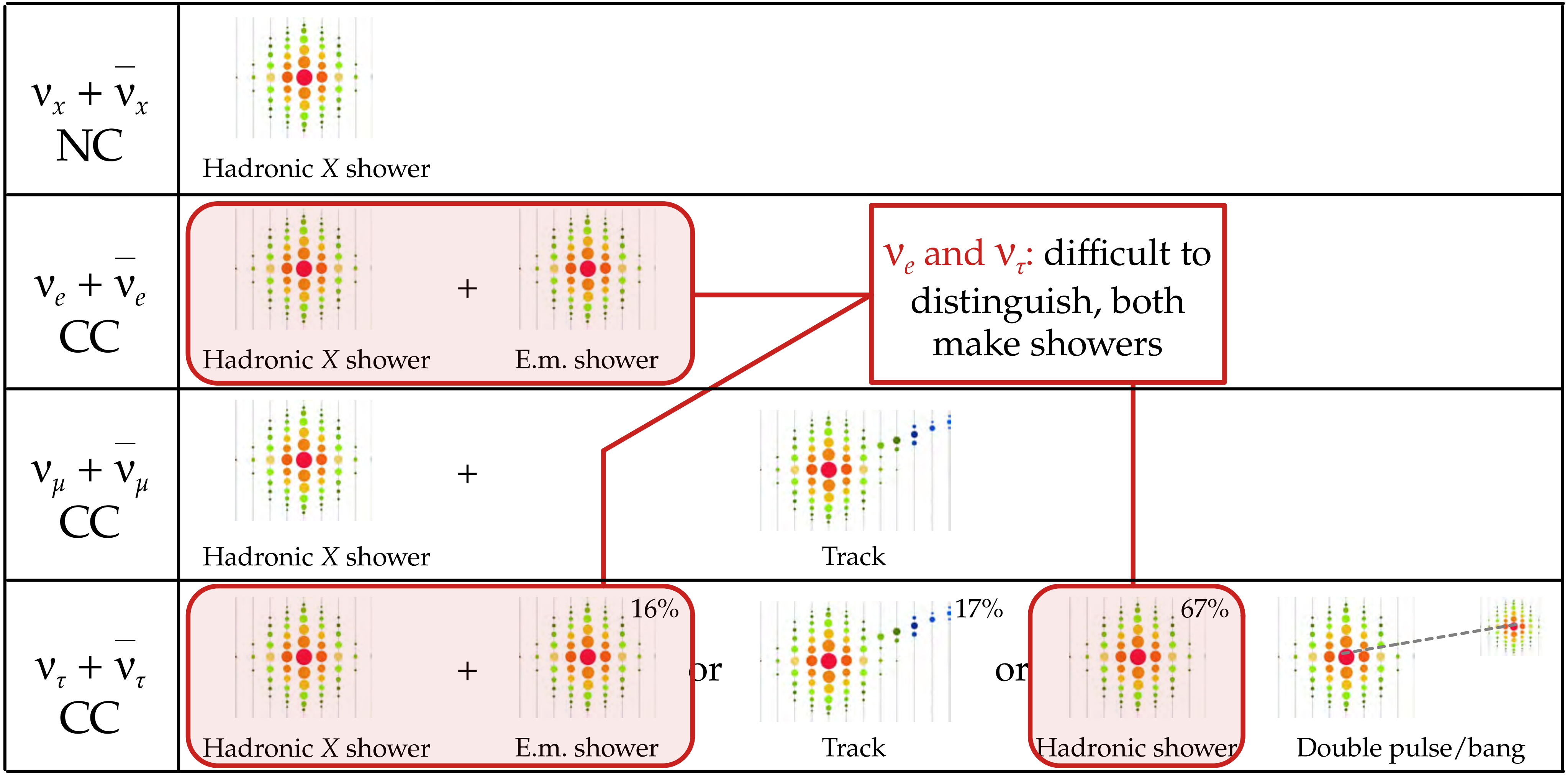
Liu, **MB**, *In prep.*

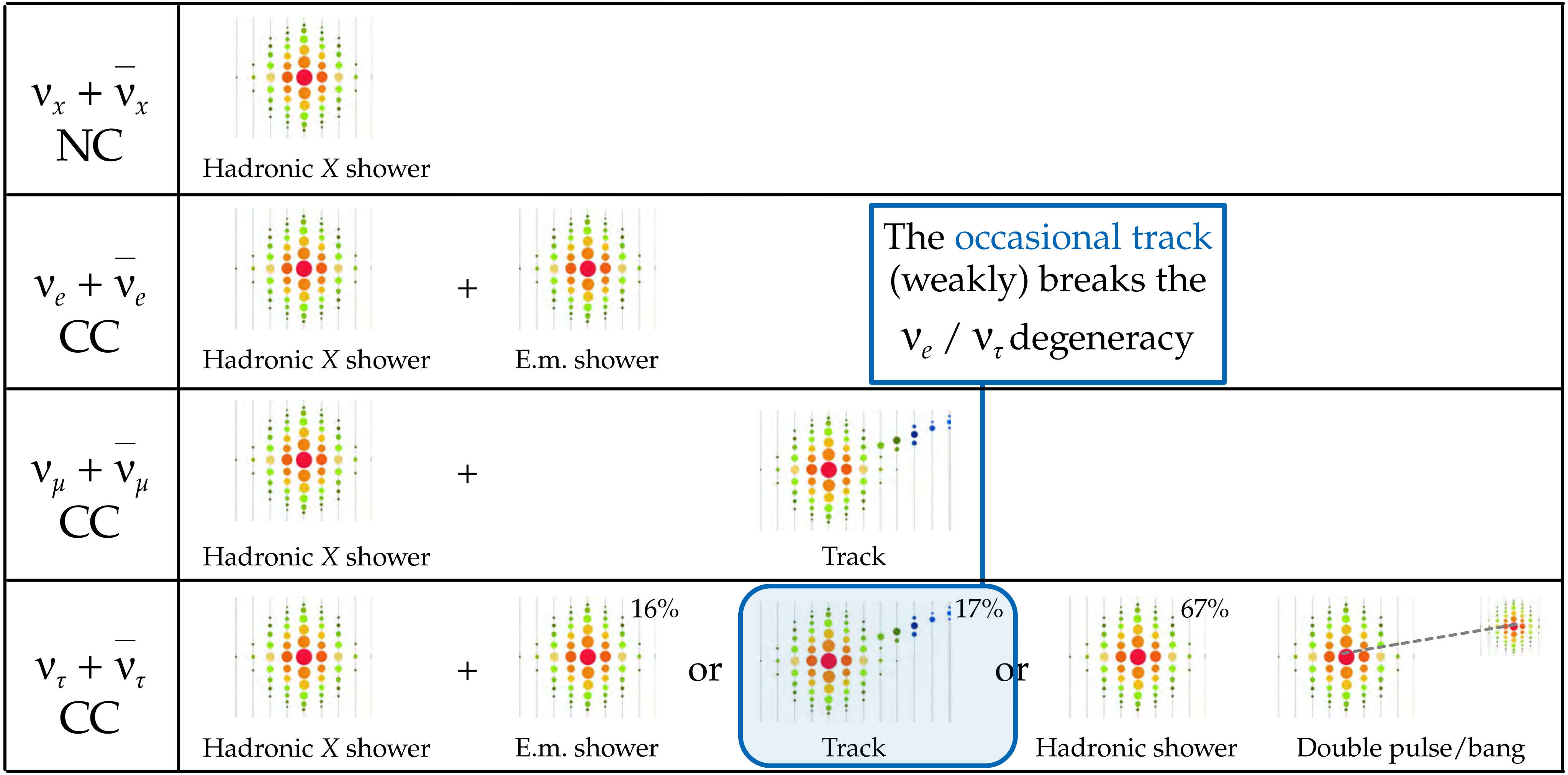


$\nu_x + \bar{\nu}_x$ NC
Hadronic X shower
$\nu_e + \bar{\nu}_e$ CC
Hadronic X shower
+
E.m. shower
$\nu_\mu + \bar{\nu}_\mu$ CC
Hadronic X shower
+
Track
$\nu_\tau + \bar{\nu}_\tau$ CC
Hadronic X shower
+
16%
E.m. shower
or
17%
Track
or
67%
Hadronic shower
Double pulse/bang



$\nu_x + \bar{\nu}_x$ NC
Hadronic X shower
$\nu_e + \bar{\nu}_e$ CC
Hadronic X shower
+
E.m. shower
ν_μ: easy to identify the outgoing track
$\nu_\mu + \bar{\nu}_\mu$ 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
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
+
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
The occasional track (weakly) breaks the ν_e / ν_τ degeneracy
$\nu_\mu + \bar{\nu}_\mu$ 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