Tau neutrinos from GeV to EeV

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VILLUM FONDEN

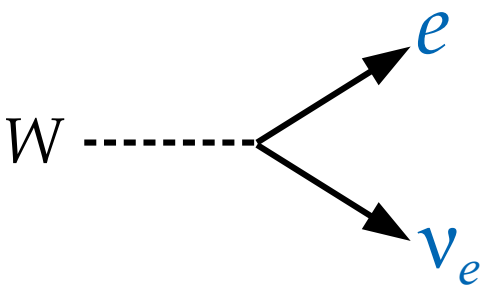
13th CRIS-MAC
Trapani, June 18, 2024

e

electron

ν_e

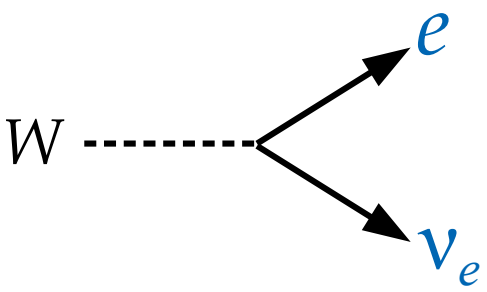
electron neutrino

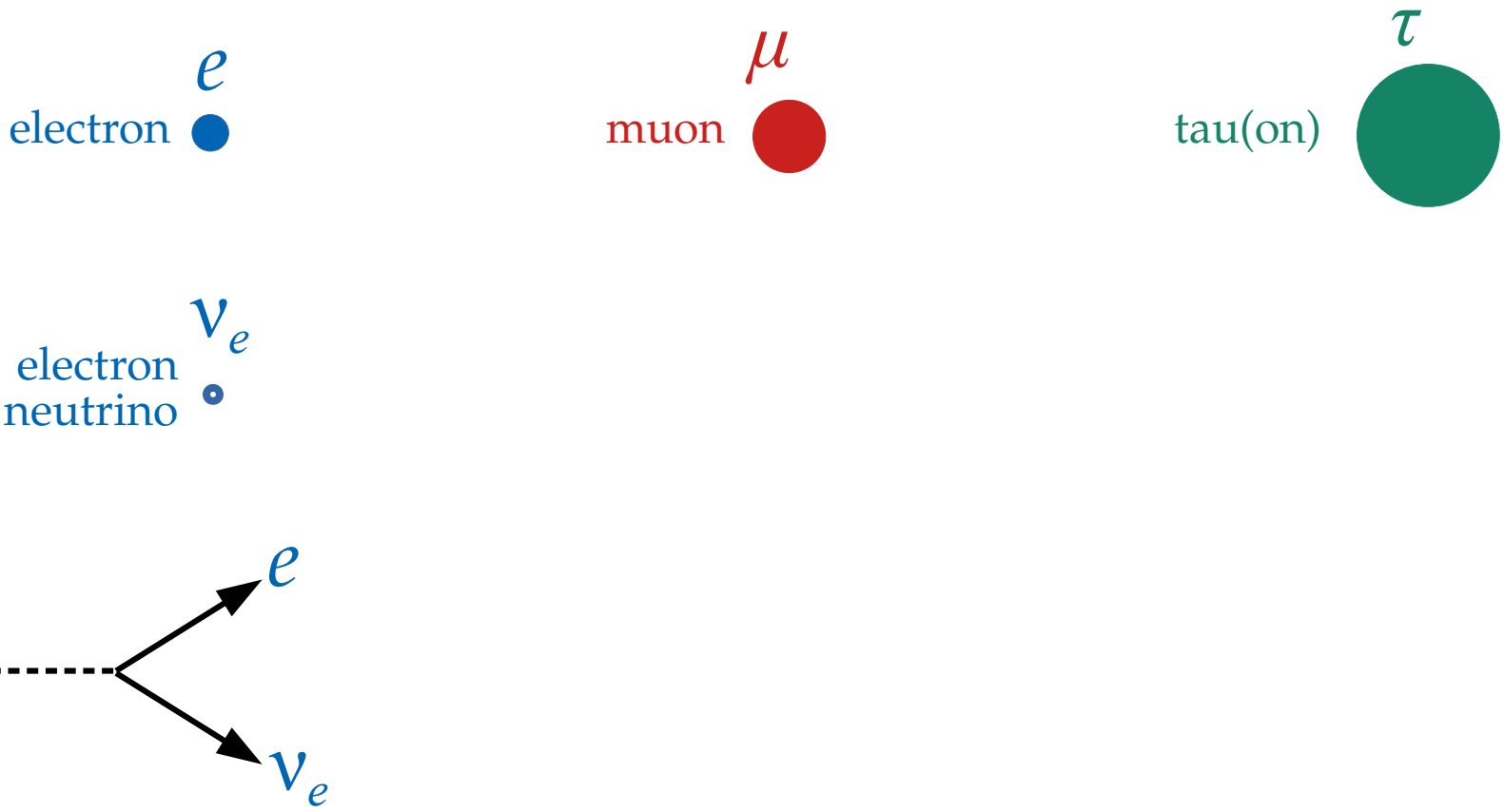



e
electron


μ
muon


ν_e
electron
neutrino


W
e
ν_e


e
electron
μ
muon
τ
tau(on)
ν_e
electron
neutrino
e
W
ν_e

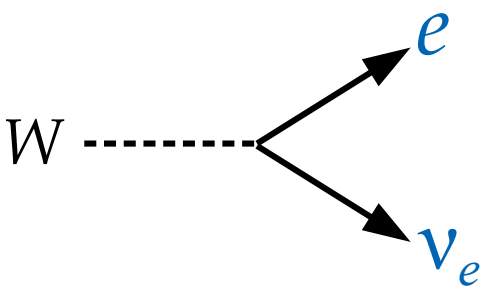
e
electron

μ
muon

200 × electron mass

τ
tau(on)

ν_e
electron
neutrino



e

electron

μ

muon

200 × electron mass

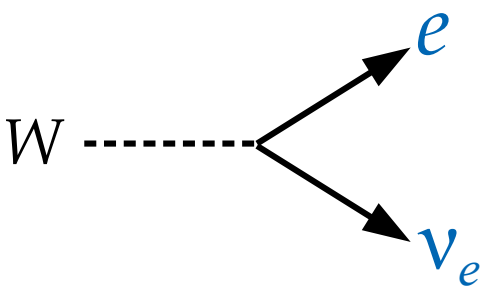
τ

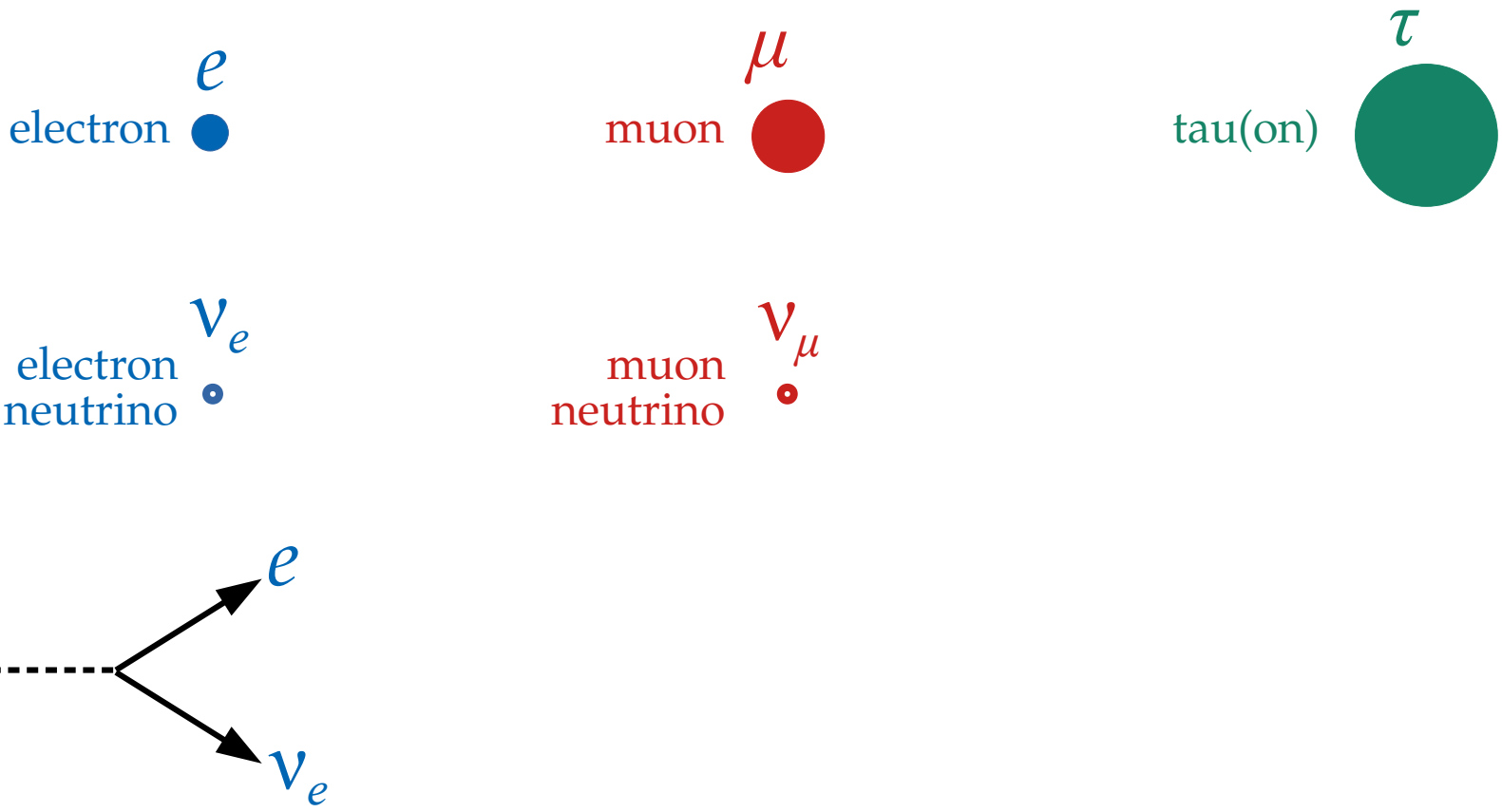
tau(on)

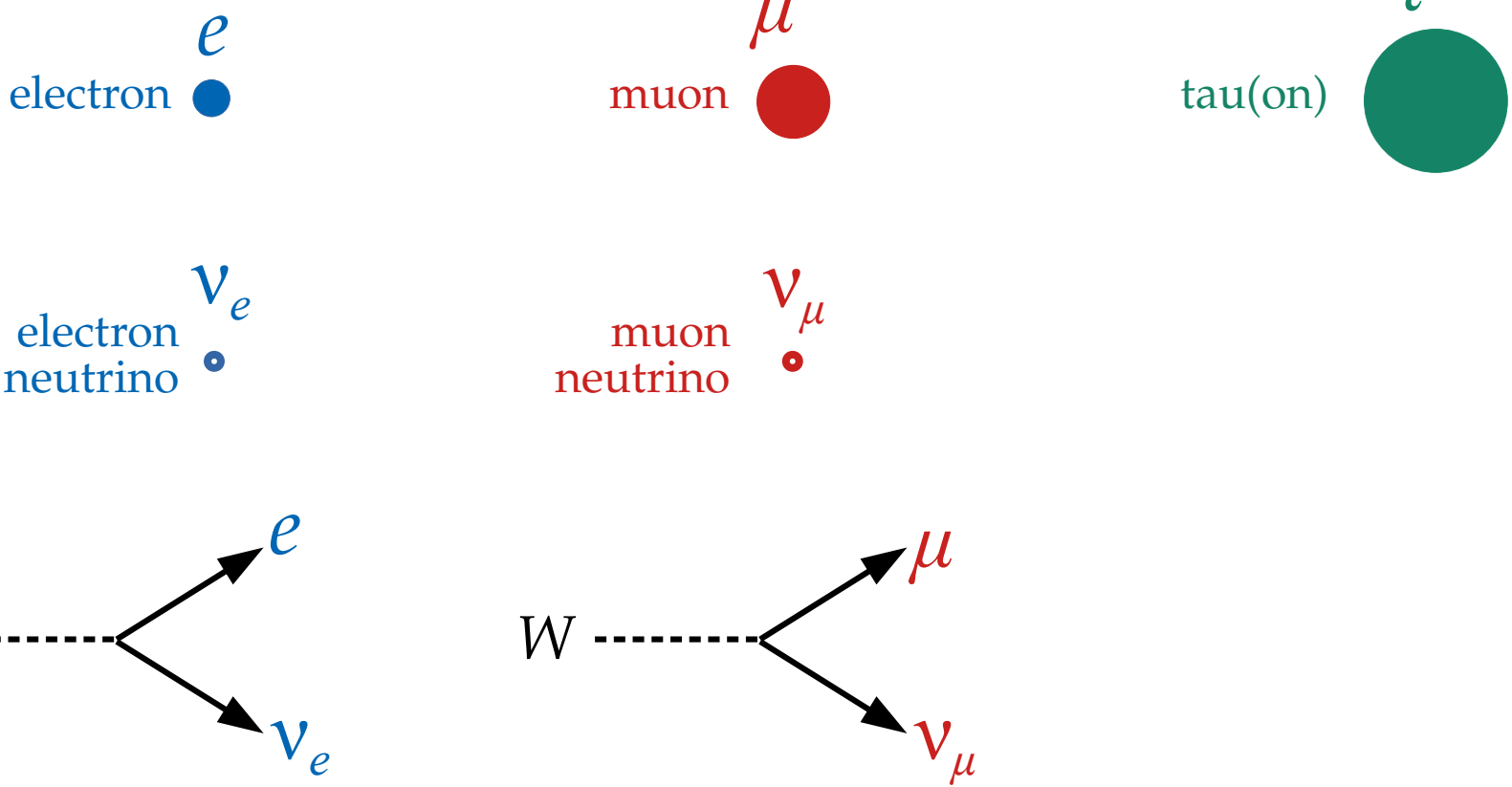
3500 × electron mass

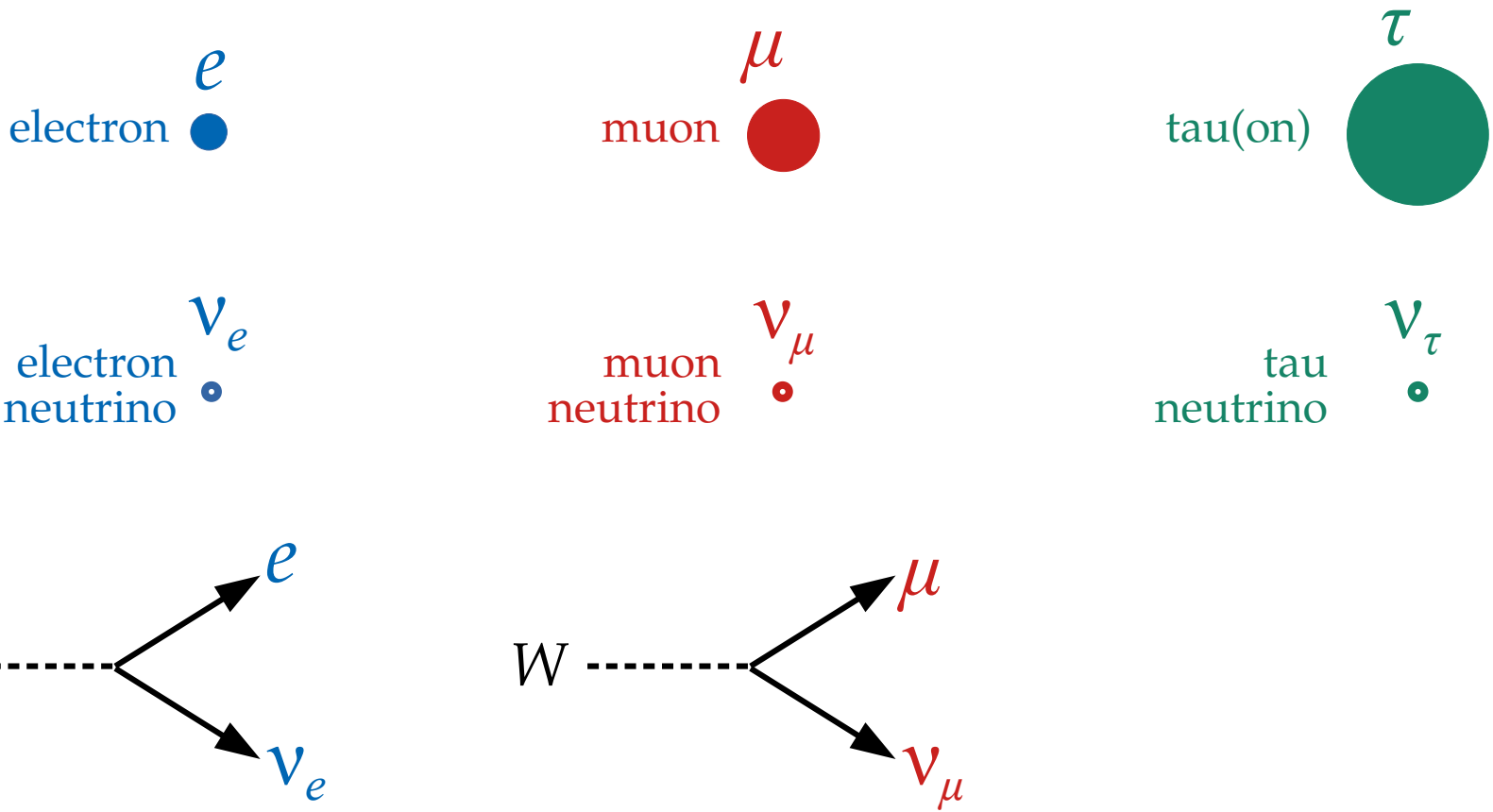
ν_e

electron neutrino



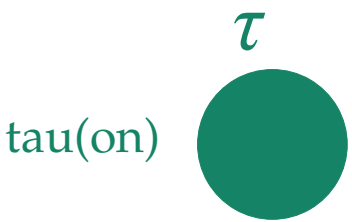

e
electron
μ
muon
τ
tau(on)
ν_e
electron
neutrino
ν_μ
muon
neutrino
W
e
ν_e


e
electron
μ
muon
τ
tau(on)
ν_e
electron
neutrino
ν_μ
muon
neutrino
W
e
ν_e
W
μ
ν_μ


e
electron
μ
muon
τ
tau(on)
ν_e
electron neutrino
ν_μ
muon neutrino
ν_τ
tau neutrino
W
e
ν_e
W
μ
ν_μ


e
electron

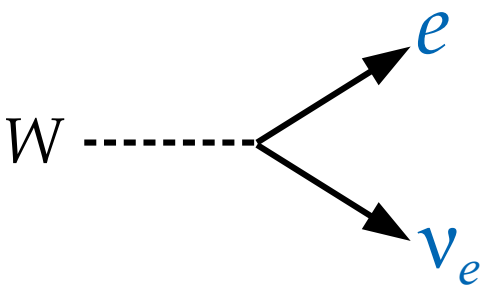

μ
muon

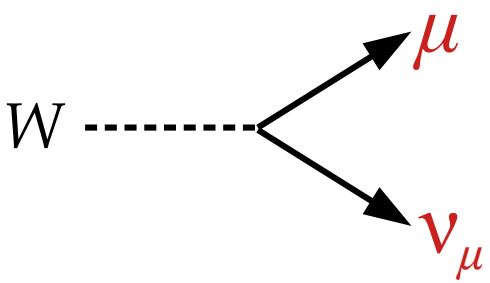

τ
tau(on)

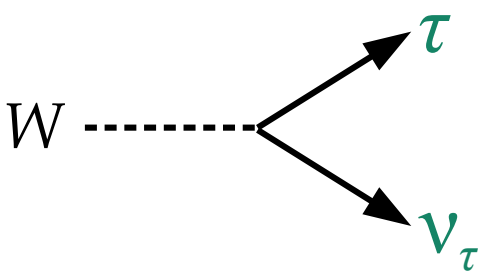

ν_e
electron
neutrino

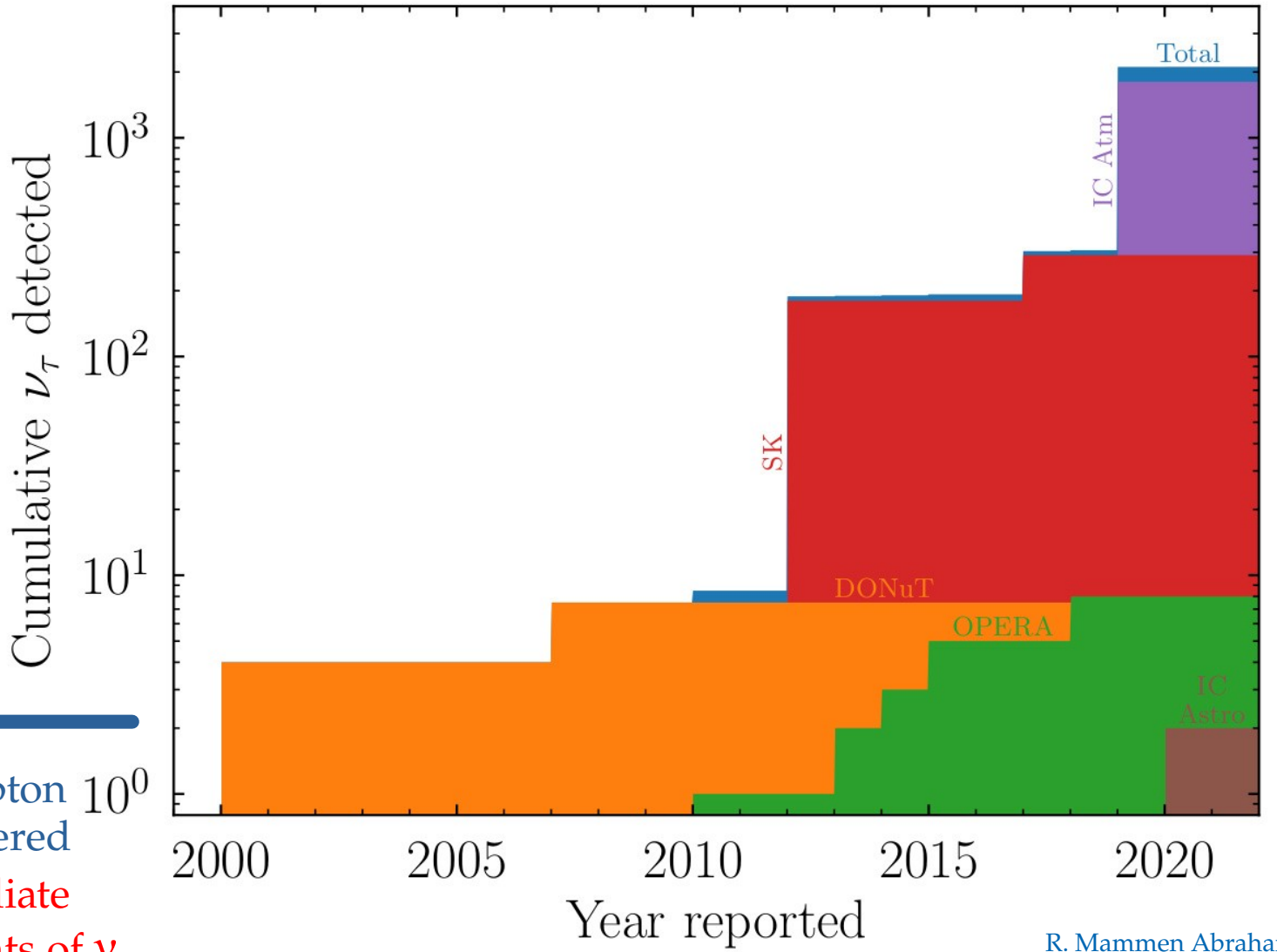

ν_μ
muon
neutrino


ν_τ
tau
neutrino


W
e
ν_e


W
μ
ν_μ

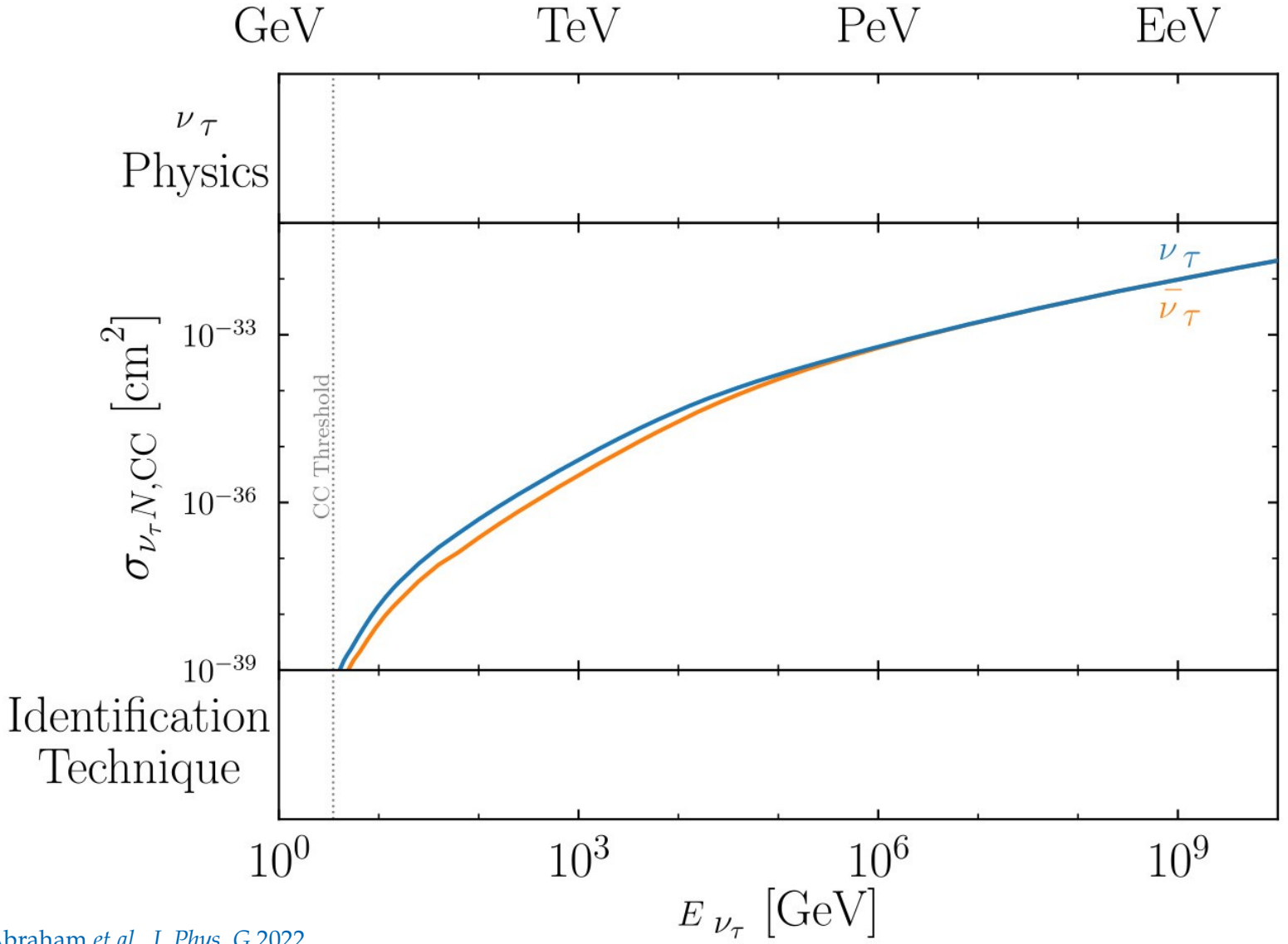

W
τ
ν_τ



1975: Tau lepton discovered

Immediate thoughts of ν_τ

R. Mammen Abraham *et al.*, *J. Phys. G* 2022



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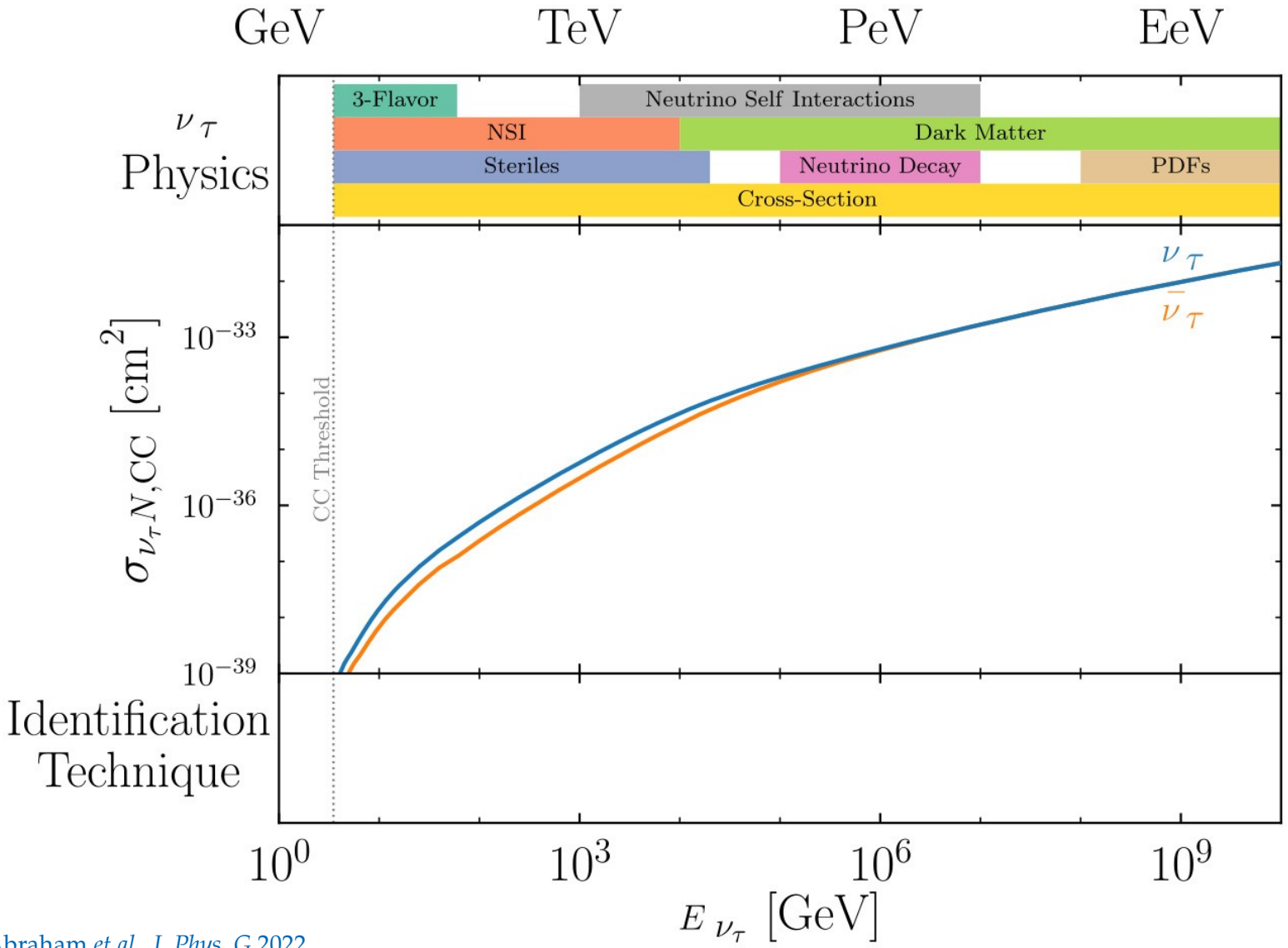

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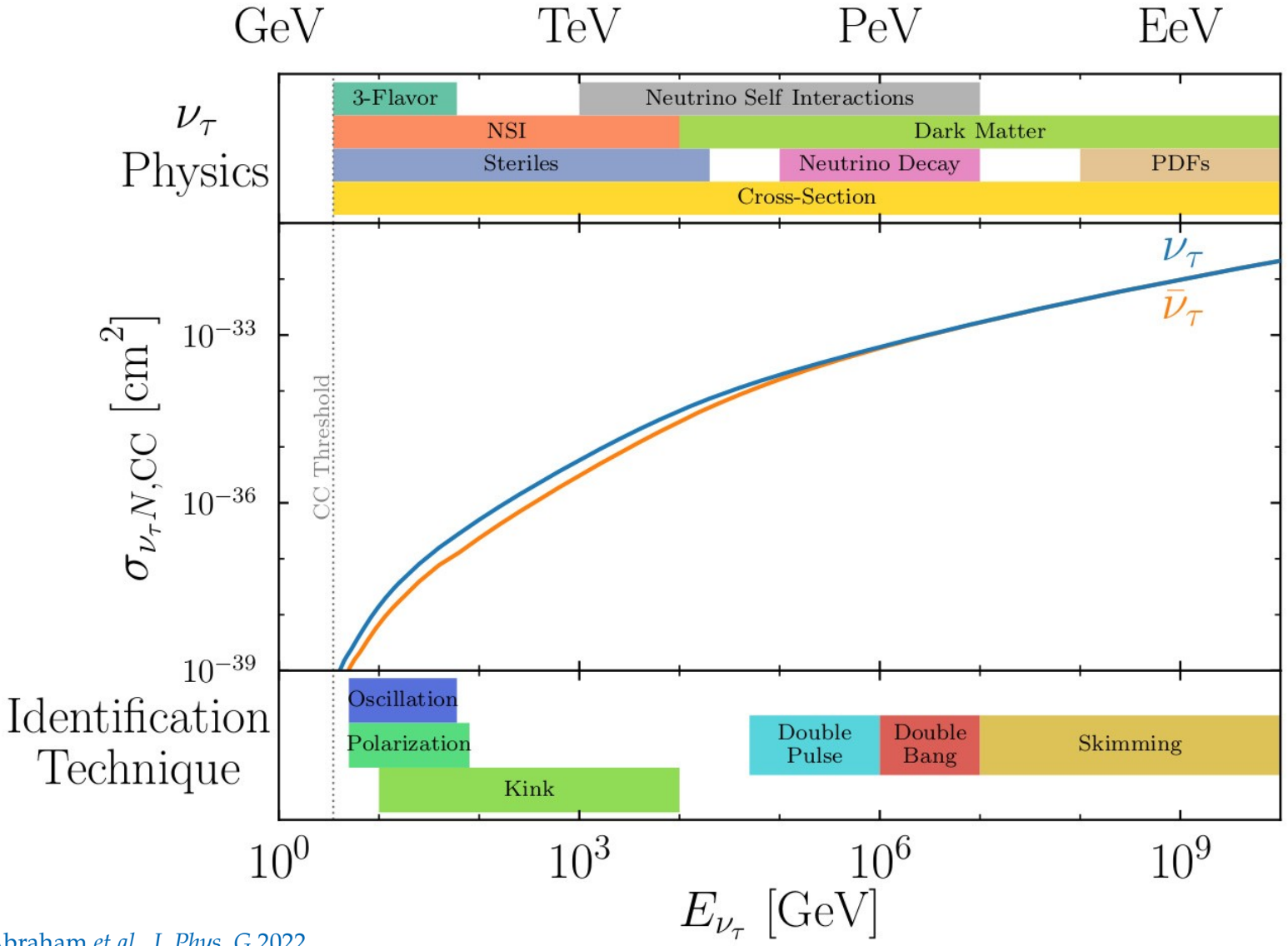

R. Mammen Abraham *et al., J. Phys. G* 2022

1

Neutrino oscillations is a three-state system (ν_e, ν_μ, ν_τ), but we study them using mainly two (ν_e and ν_μ)

2

The **flavor composition** of high-energy cosmic neutrinos reflects the physical conditions inside cosmic accelerators

3

At **ultra-high energies** ($> 10^{18}$ eV), ν_τ provide unique detection opportunities (ν_τ regeneration, Earth-skimming ν_τ)

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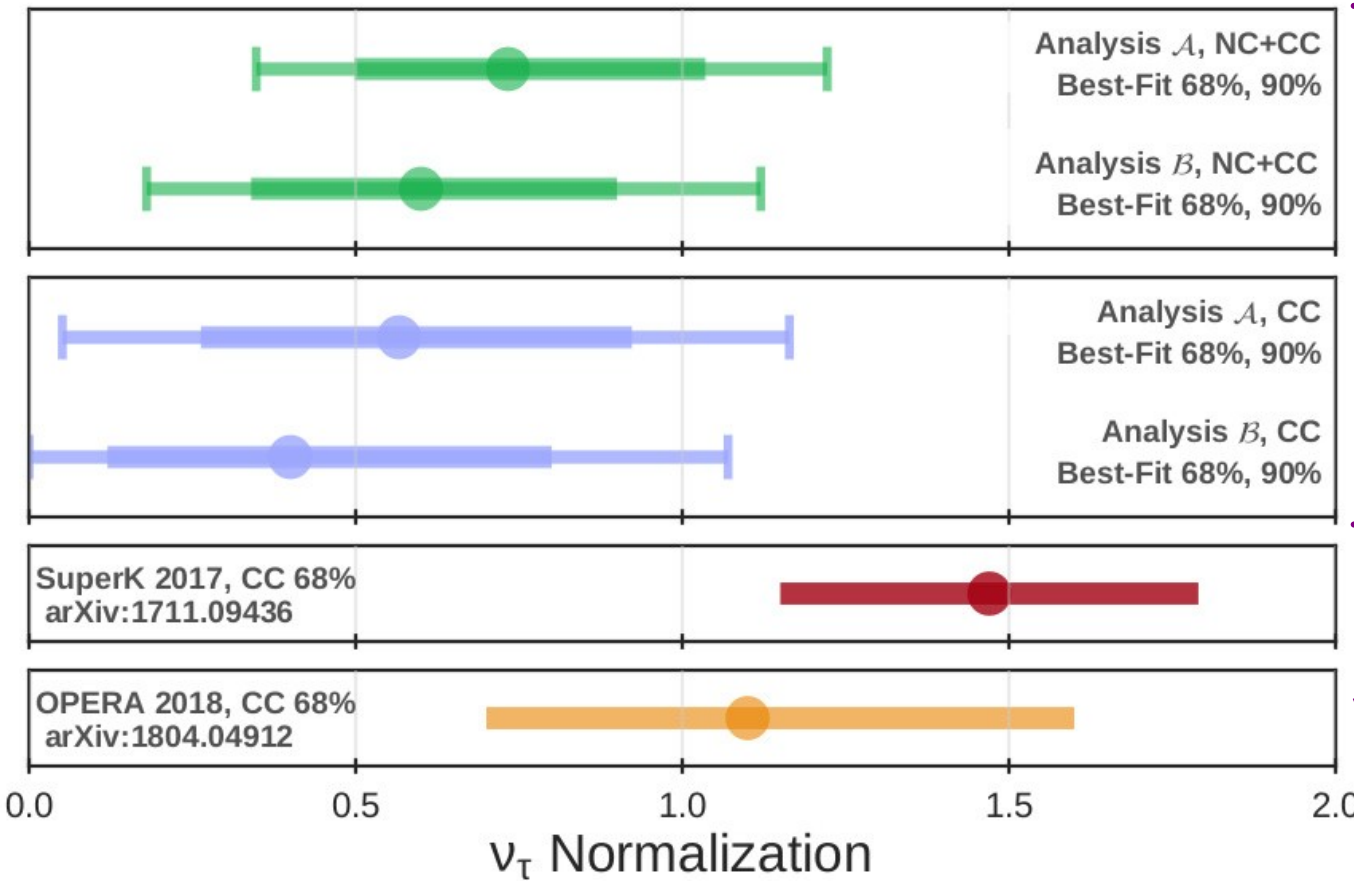
Do GeV ν_τ interact as expected?

Using GeV-scale atmospheric and accelerator ν_τ:



IceCube/ DeepCore ~1800 CC ν_τ

~340 CC ν_τ

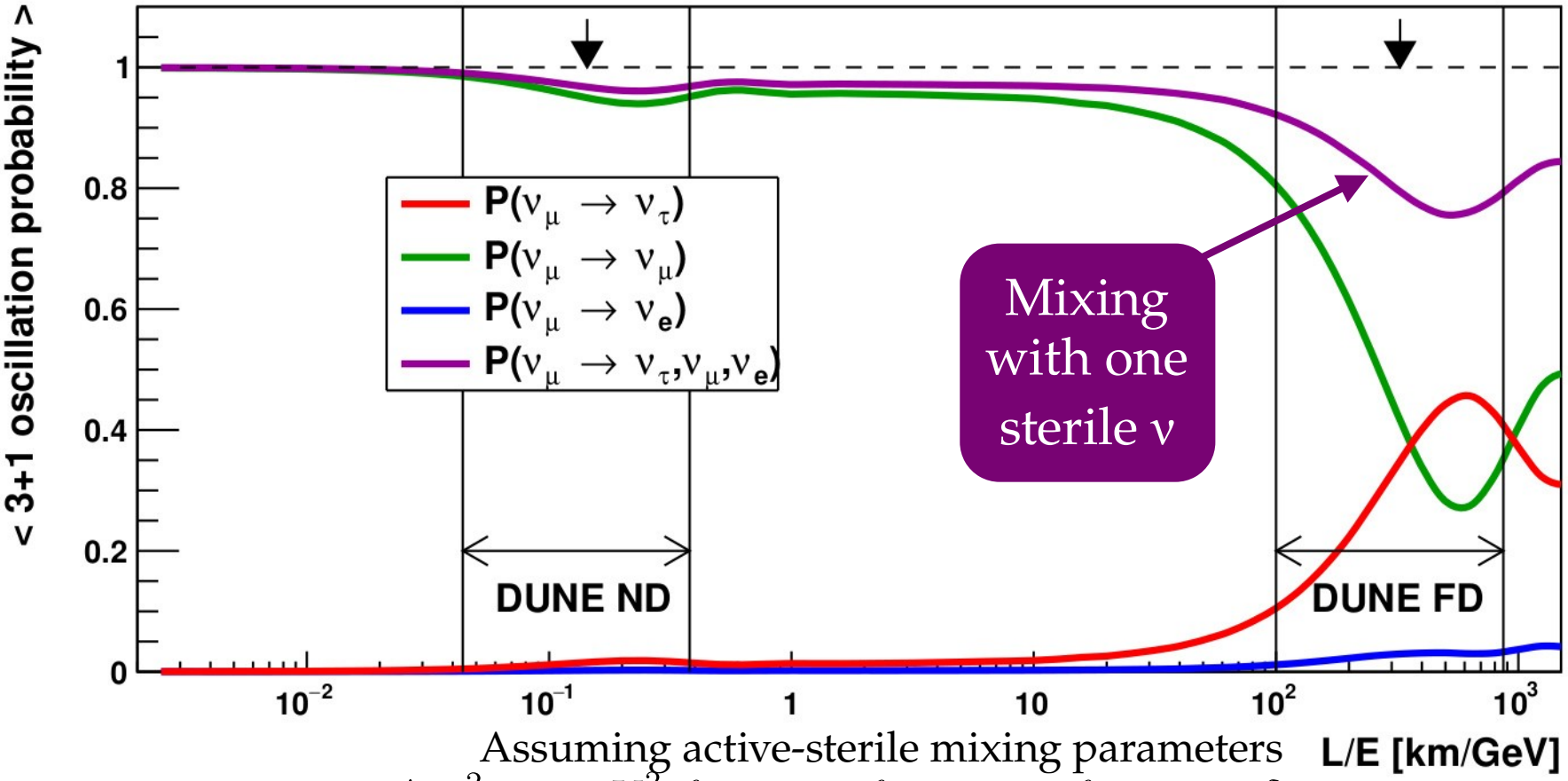
5 CC ν_τ (identified)

(to the Standard- Model expectation)

IceCube Collab., *PRD* 2019

Tau neutrinos can test the three-neutrino paradigm

Flavor-transition probabilities change if there are additional, sterile flavors:

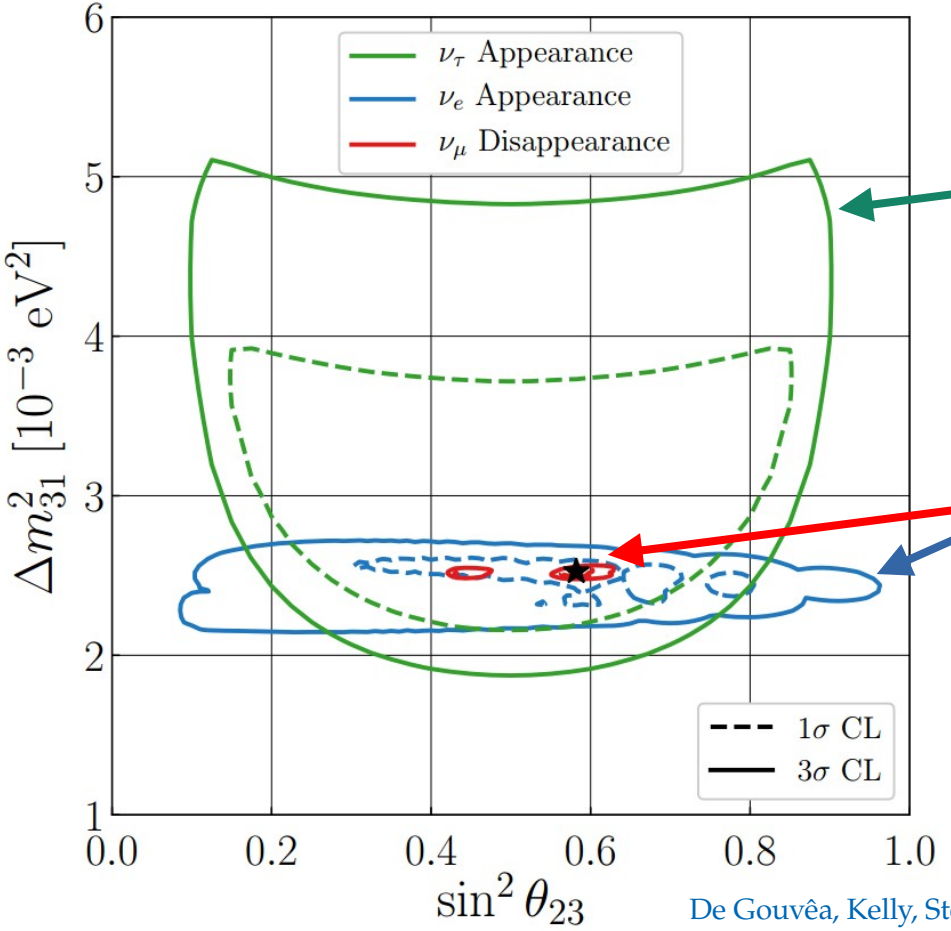


Assuming active-sterile mixing parameters $\Delta m^2_{41} = 6\ \mathrm{eV}^2, \theta_{14} = 0.2, \theta_{24} = 0.15, \theta_{34} = 0.6, \delta_i = 0$

R. Mammen Abraham *et al., J. Phys. G* 2022

DUNE: identifying many more GeV-scale ν_τ

No improvement to measurements of the neutrino mixing parameters…



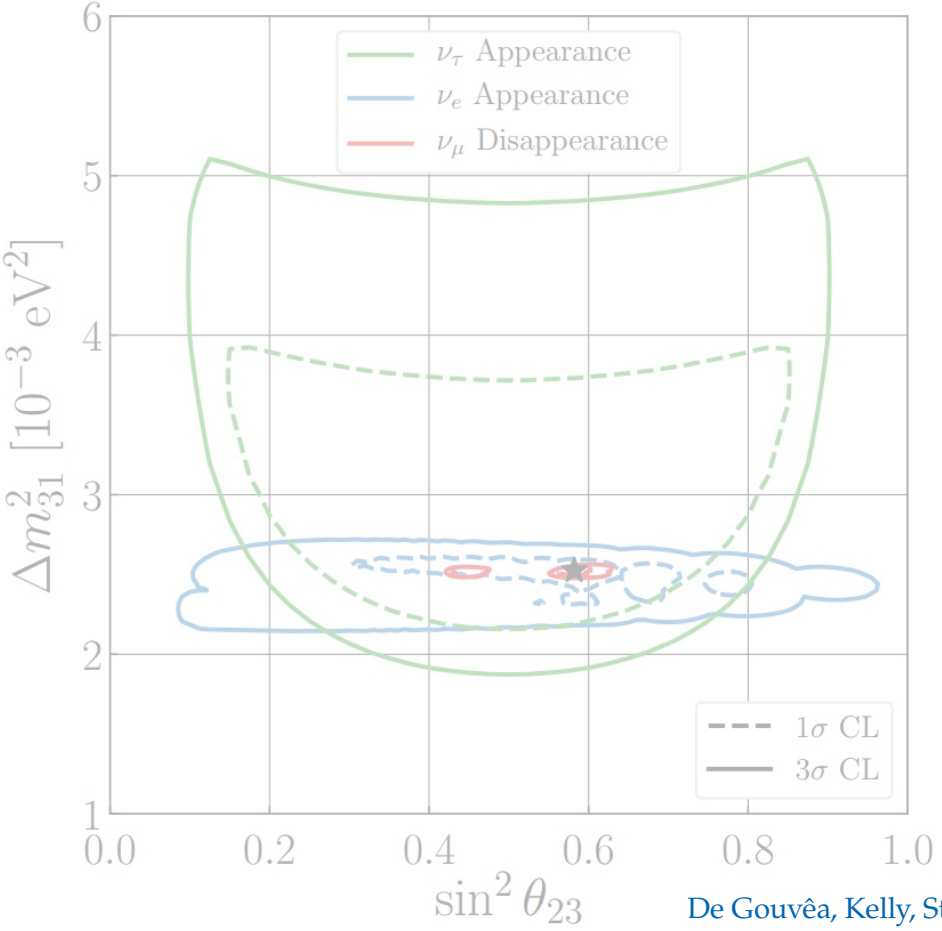
Using identified ν_τ

Usual method:
using only ν_e (appearance)
and ν_μ (disappearance)

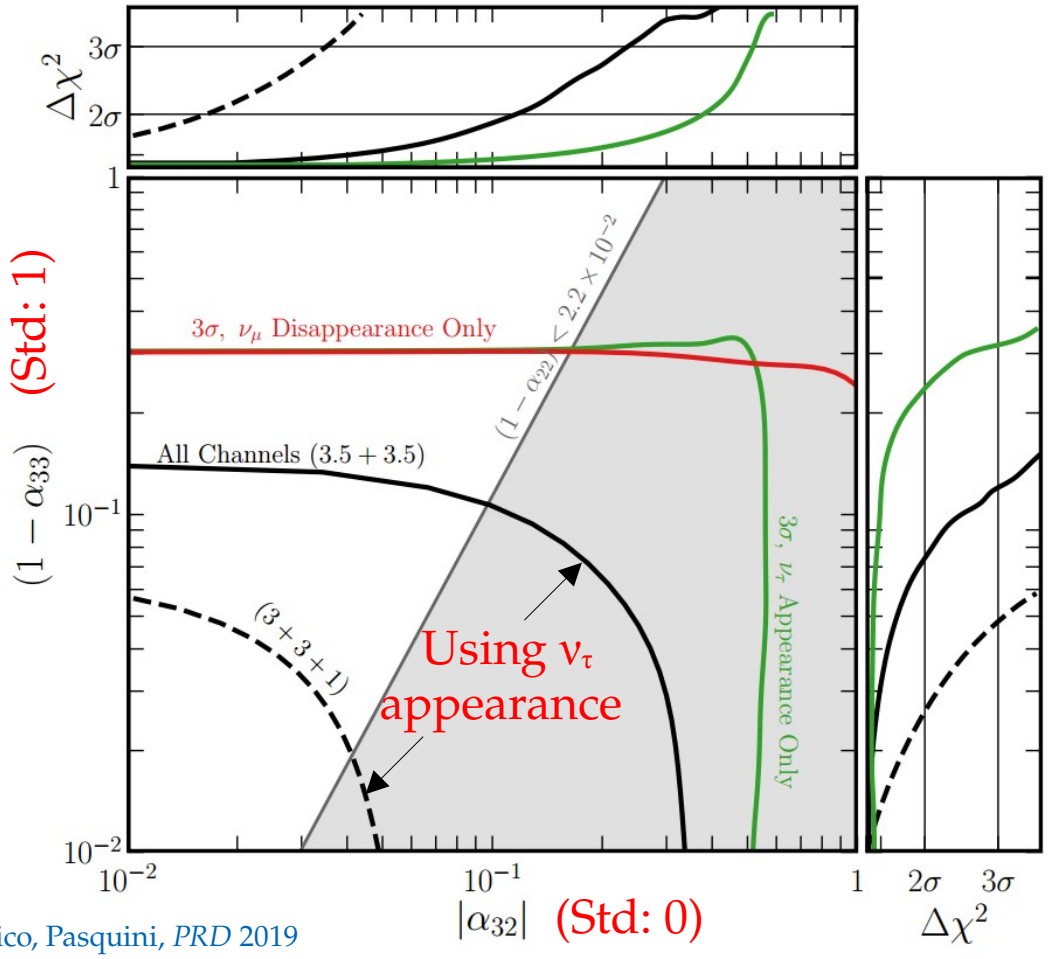
De Gouvêa, Kelly, Stenico, Pasquini, *PRD* 2019

DUNE: identifying many more GeV-scale ν_τ

No improvement to measurements of the neutrino mixing parameters…



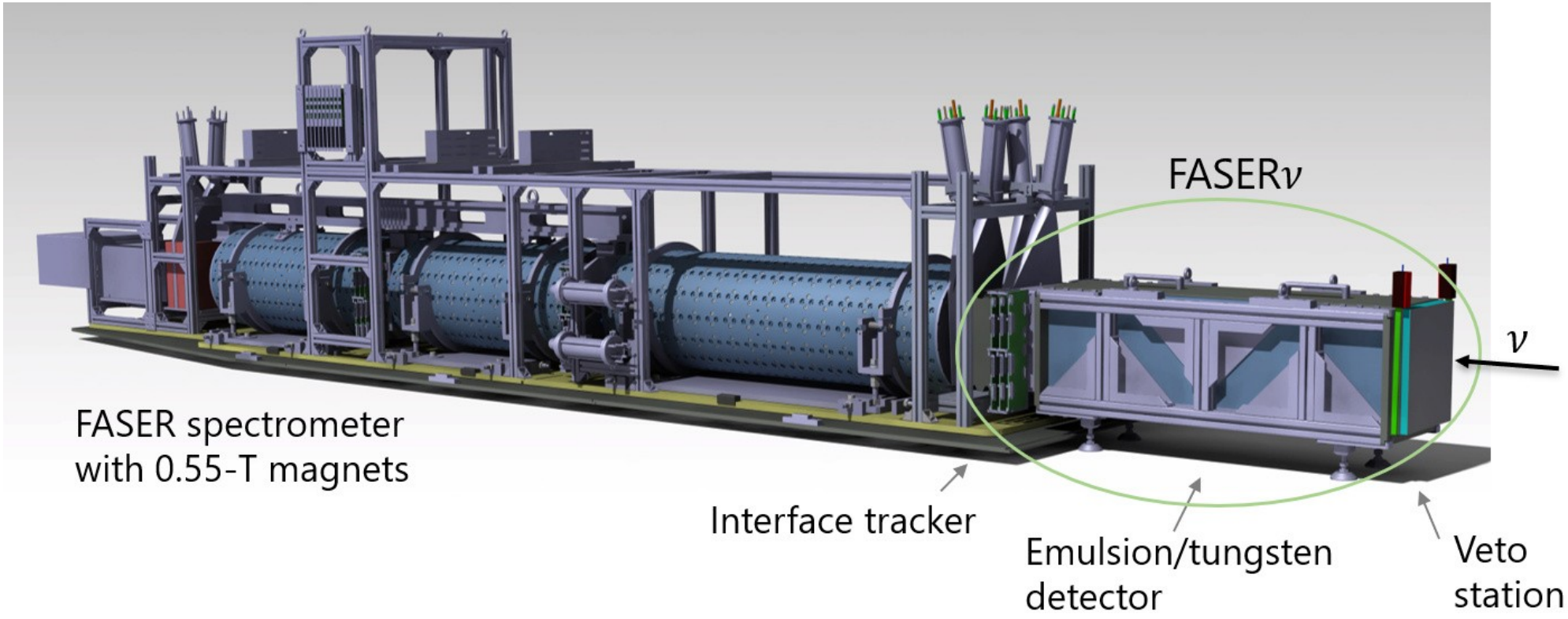
… but improved testing of the 3ν paradigm



De Gouvêa, Kelly, Stenico, Pasquini, *PRD* 2019

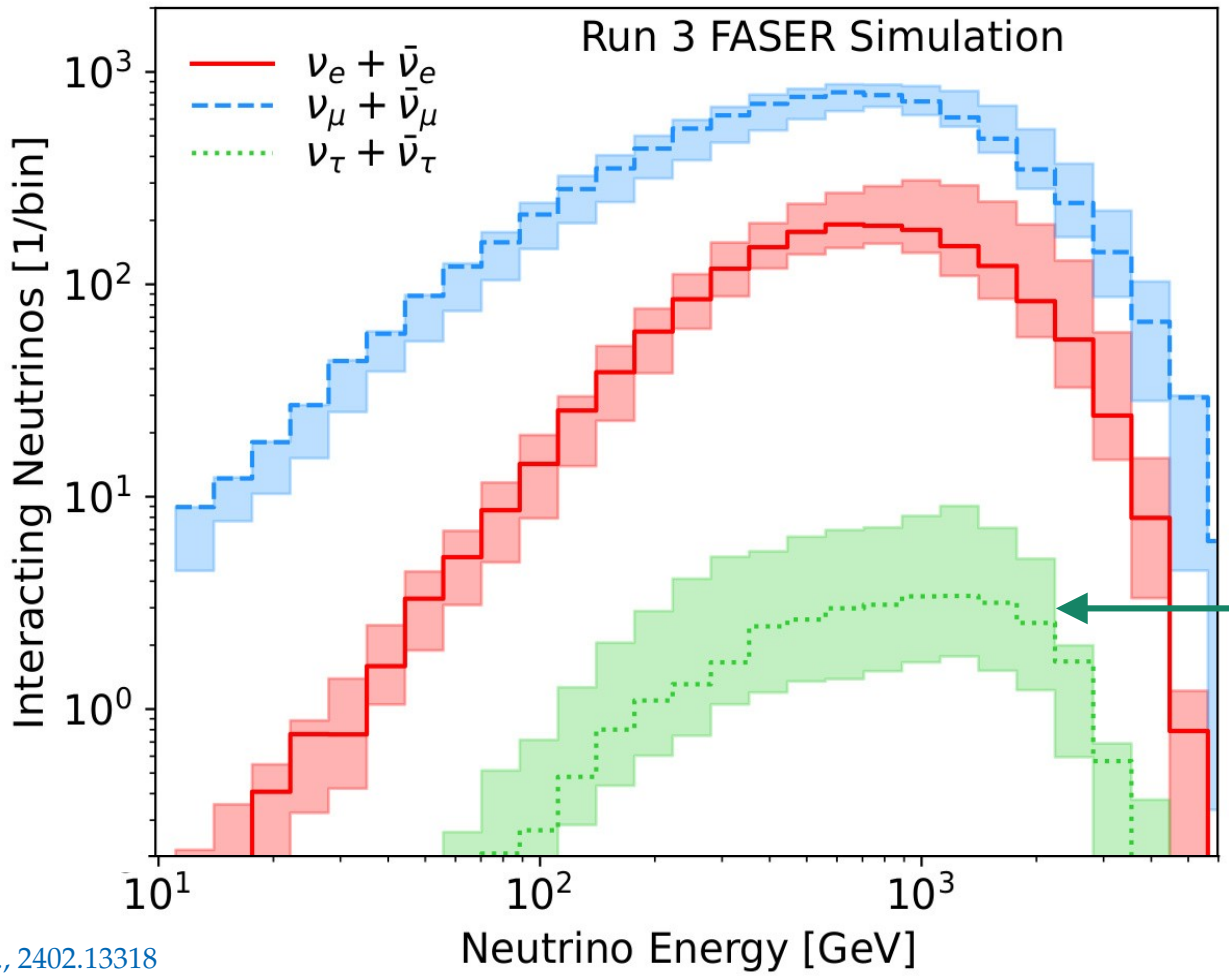
The intermediate energy range: TeV-scale ν_τ

Place a neutrino detector on the path of the LHC beam:



FASER Collab., 2402.13318

The intermediate energy range: TeV-scale ν_τ



20–100 tagged ν_τ during LHC Run 3

FASER Collab., 2402.13318

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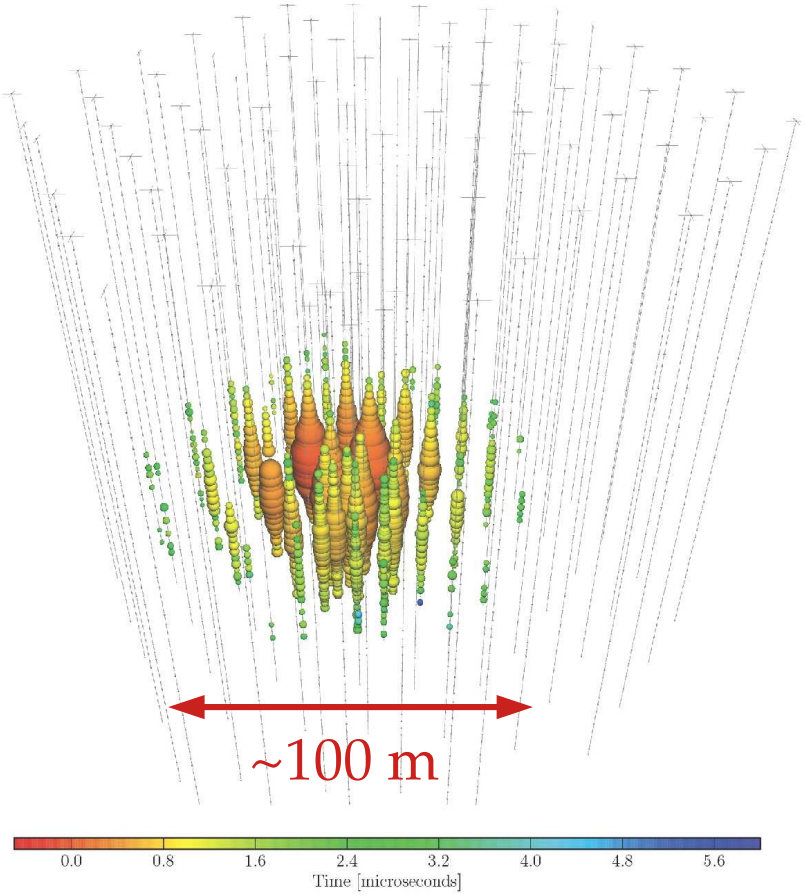
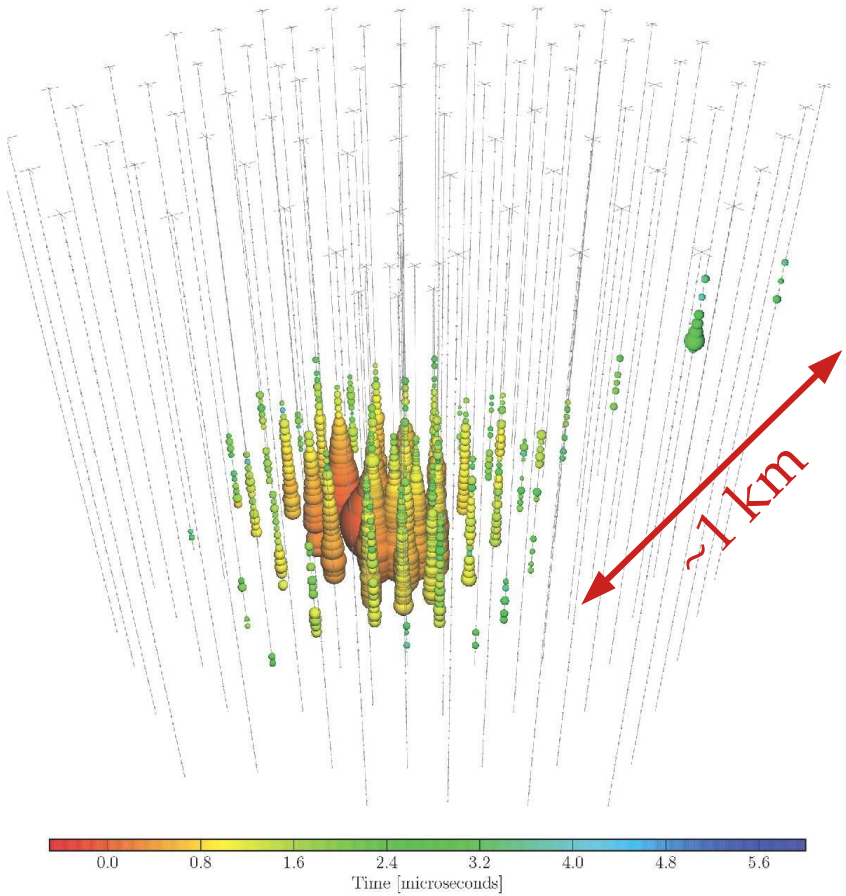
Shower
(mainly from ν_e and ν_τ)

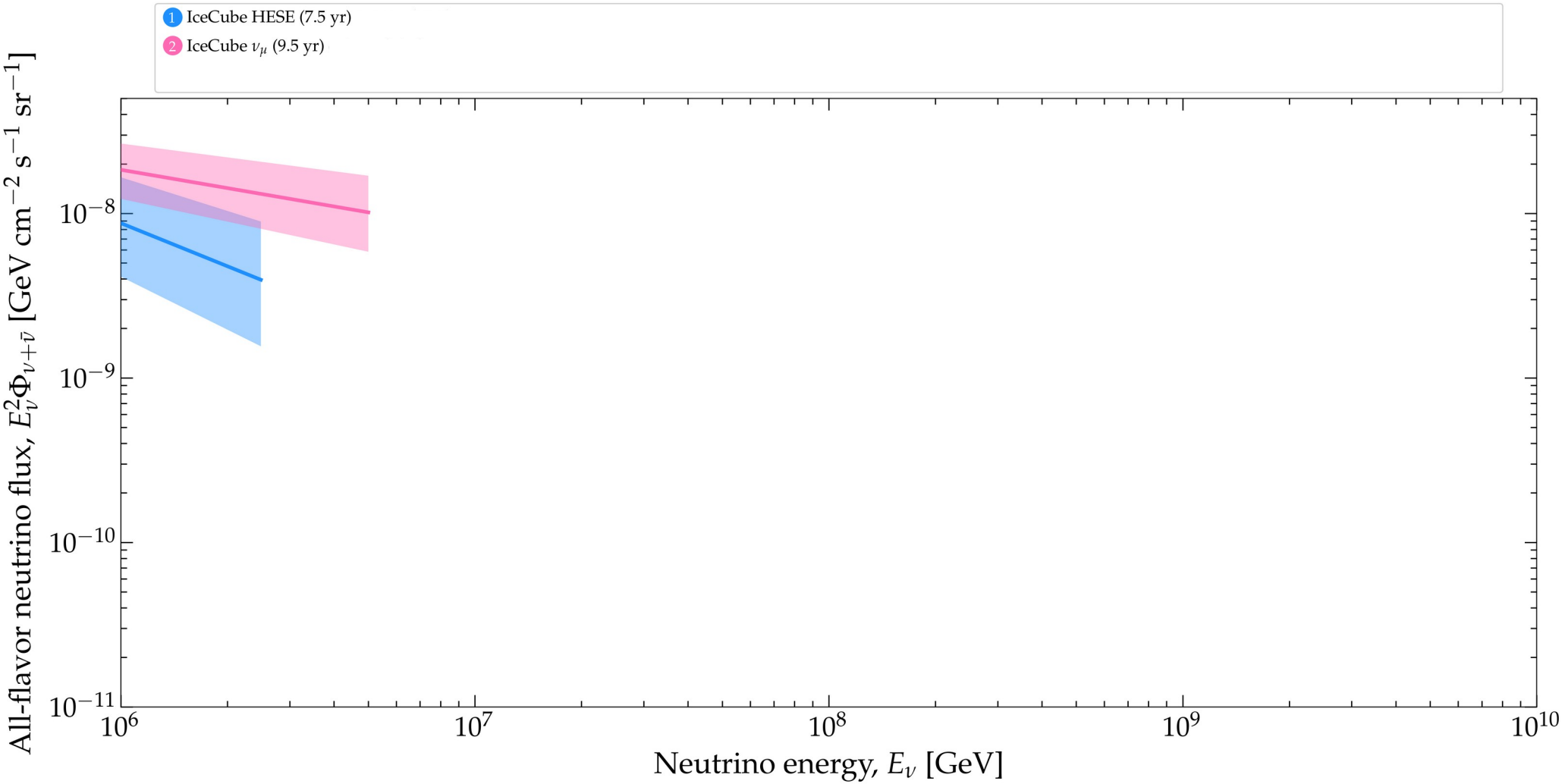


Poor angular resolution: ~10°

Track
(mainly from ν_μ)



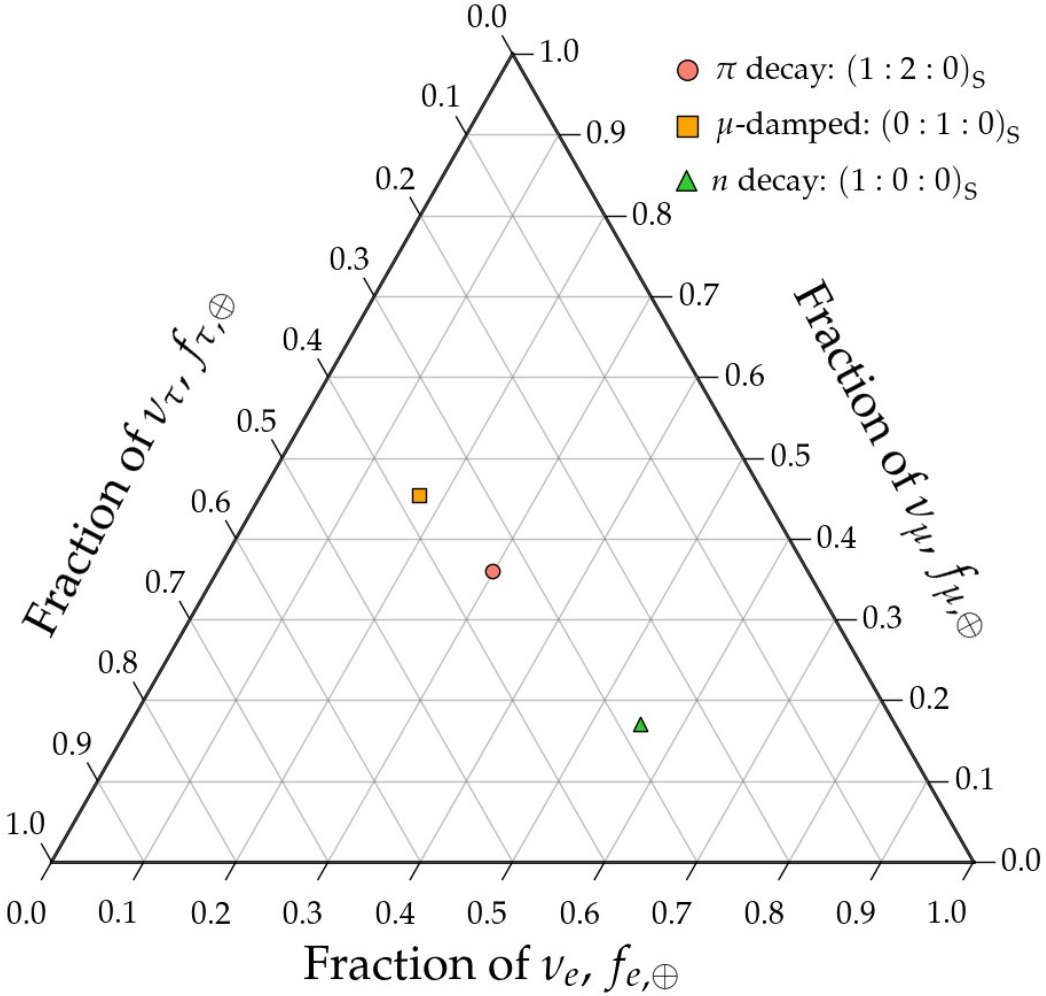
Angular resolution: < 1°


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]

Measuring flavor composition: 2015–2020

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

Measuring flavor composition: 2015–2020



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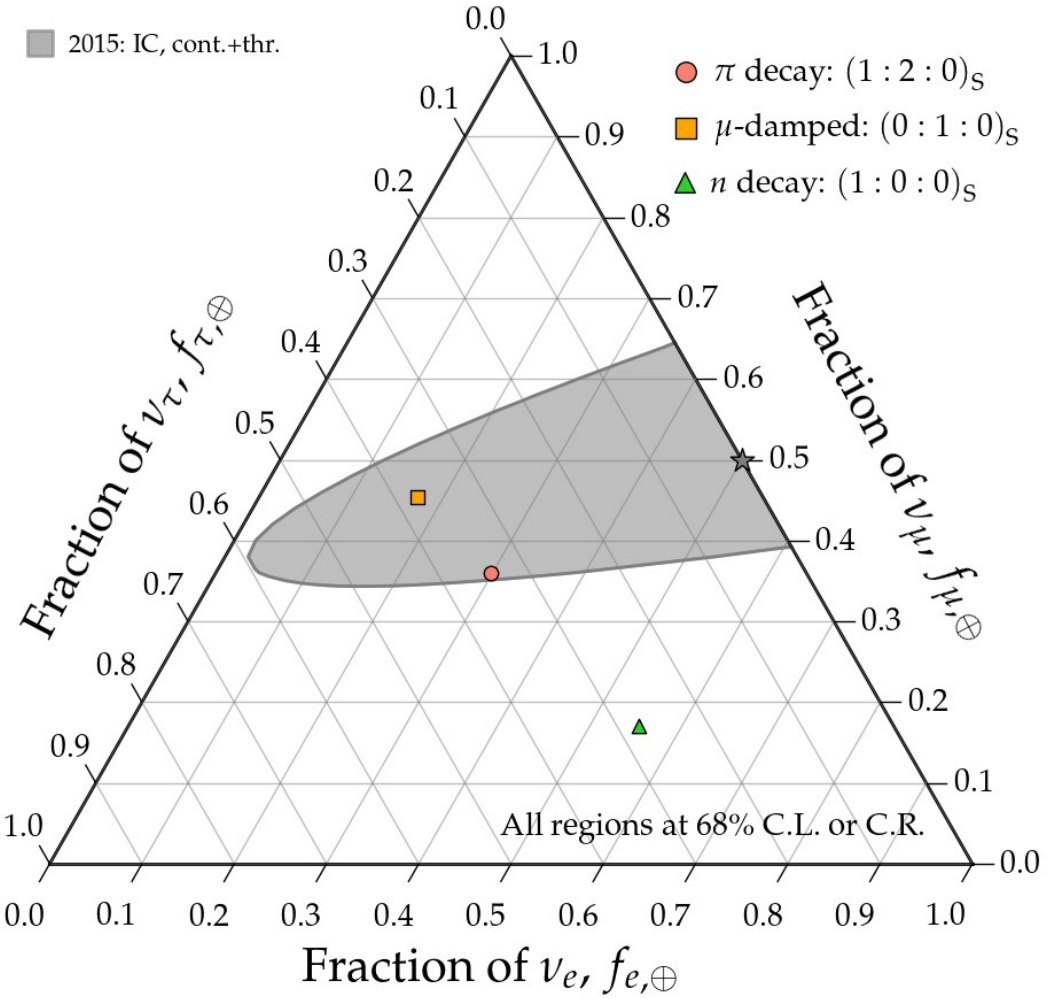

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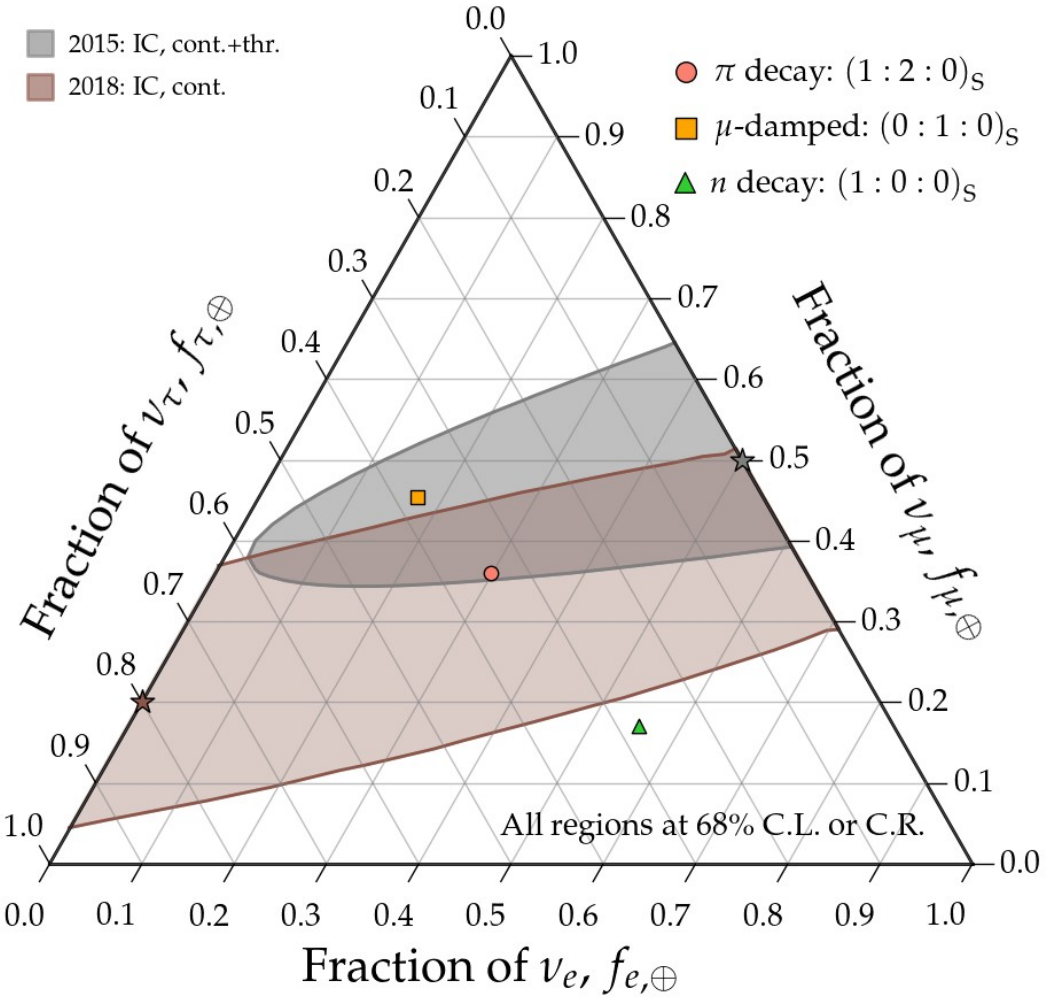

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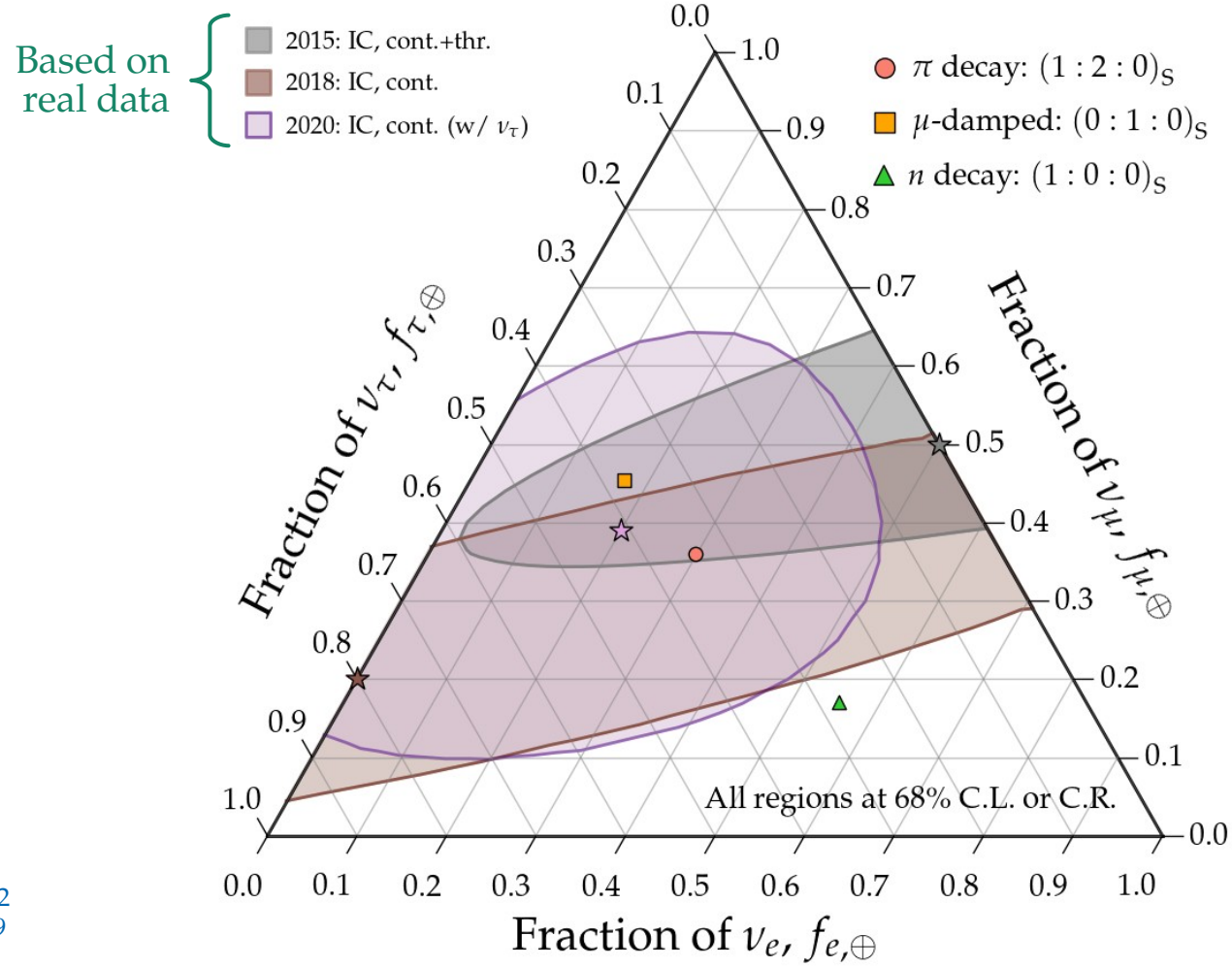


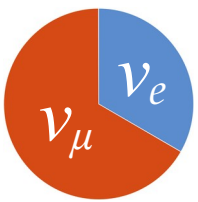
IceCube Collab., *EPJC* 2022
IceCube Collab., *PRD* 2019
IceCube Collab., *ApJ* 2015

Astrophysical sources

Earth

Up to a few Gpc

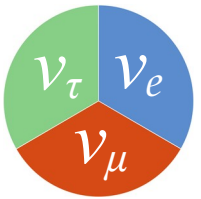
E.g.,



Oscillations change the number

of ν of each flavor, N_e, N_μ, N_τ

E.g.,



Different production mechanisms yield different flavor ratios:

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

Flavor ratios at Earth (α = e, μ, τ):

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

Astrophysical sources

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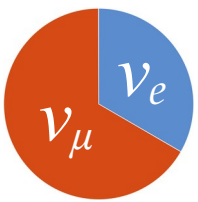
Up to a few Gpc

E.g.,



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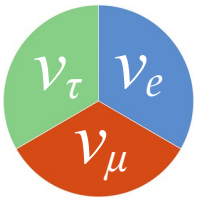

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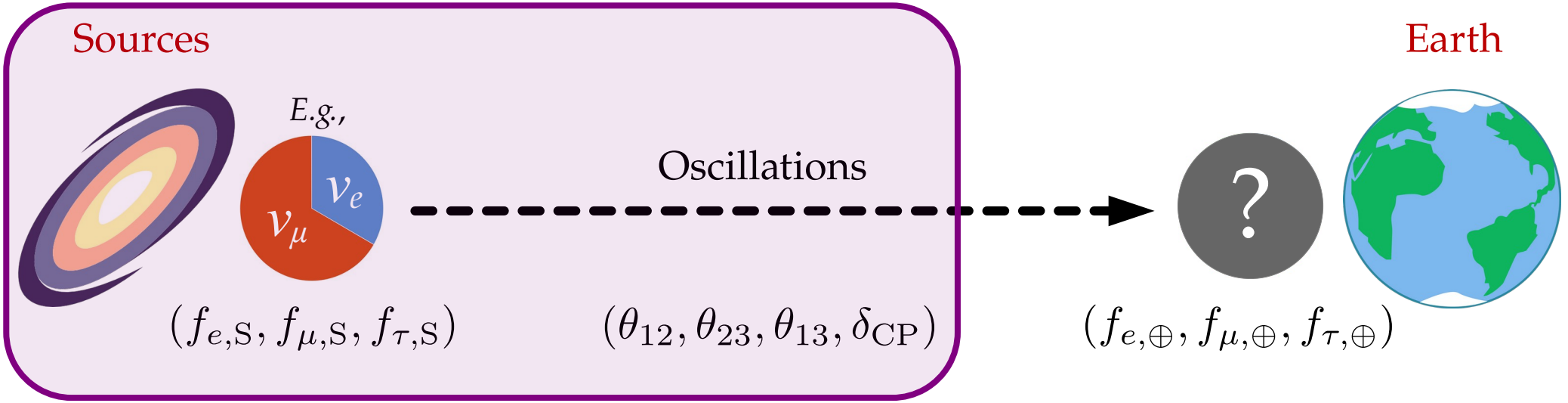
Standard oscillations
or
new physics

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



One likely TeV–PeV ν production scenario:

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

Full π decay chain

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

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

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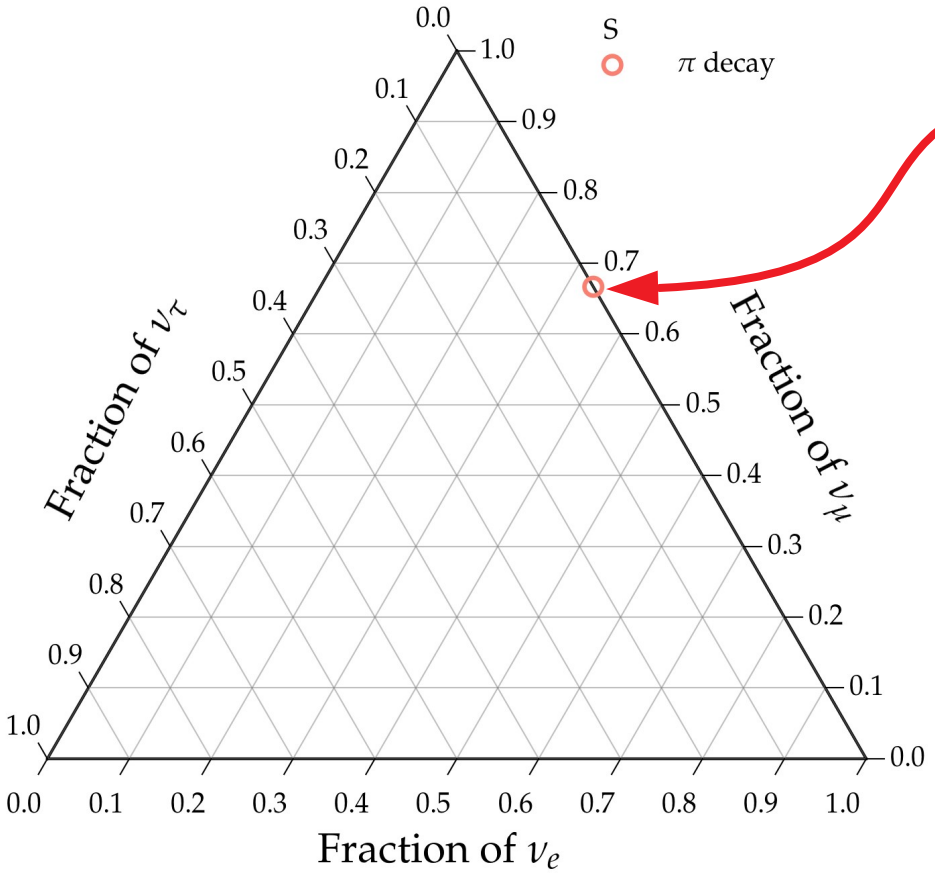

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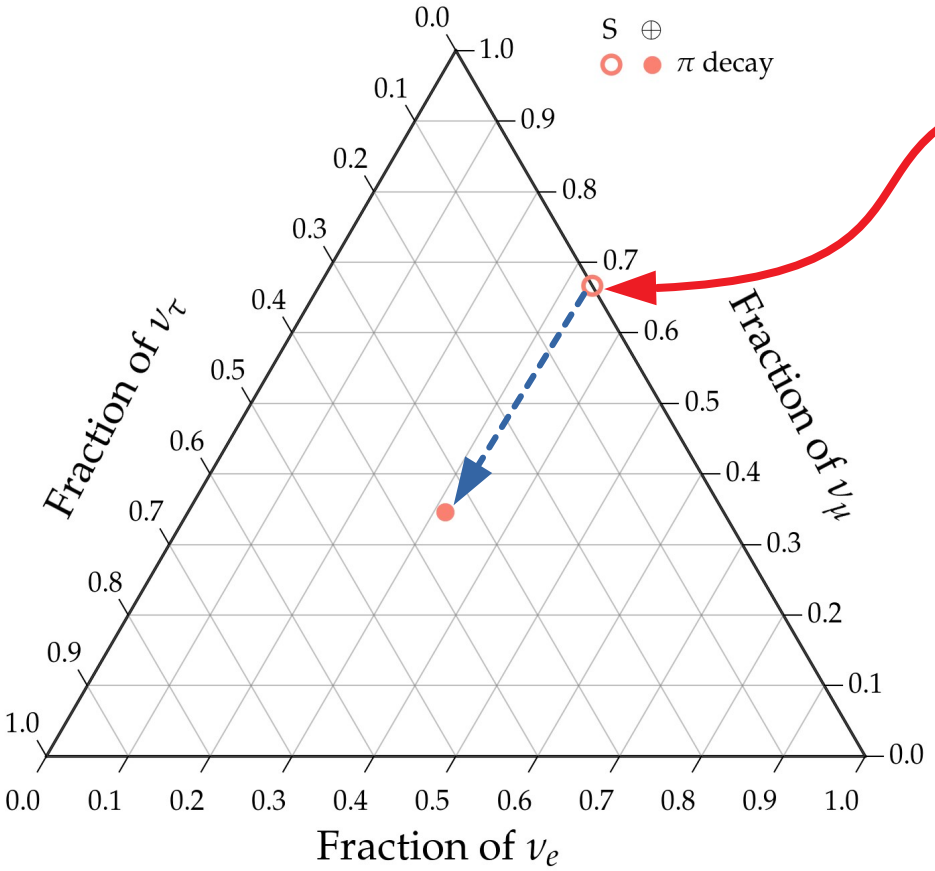

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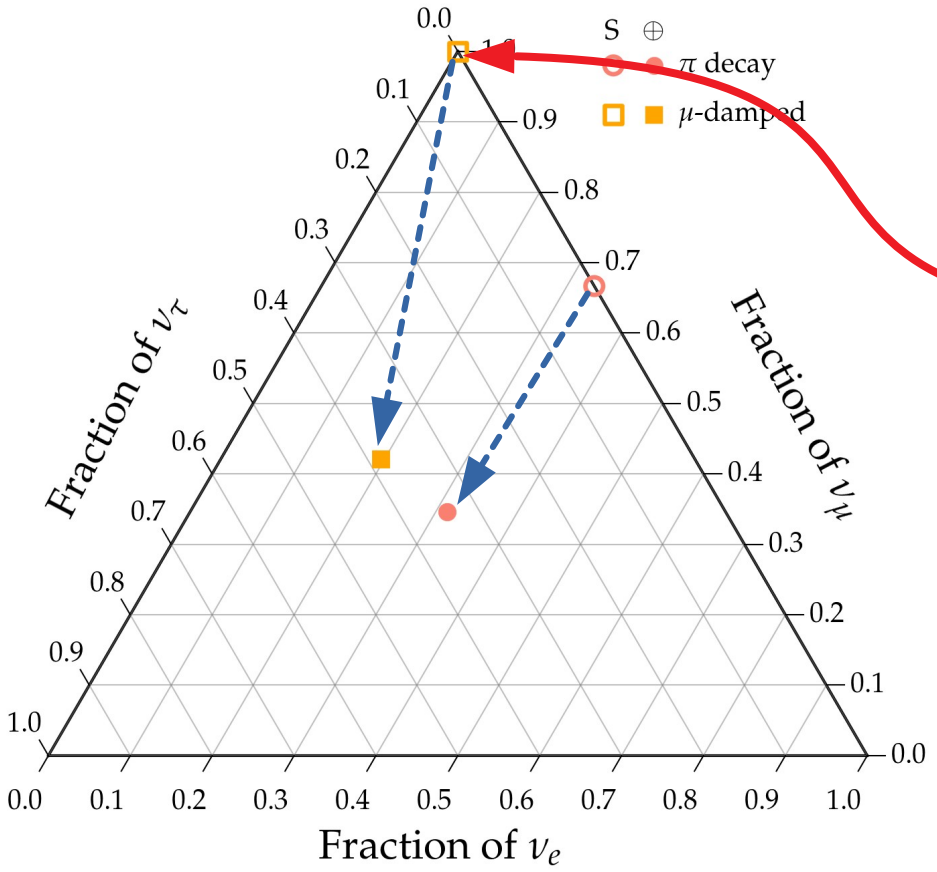

Full π decay chain

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

Muon damped

$(0{:}1{:}0)_S$

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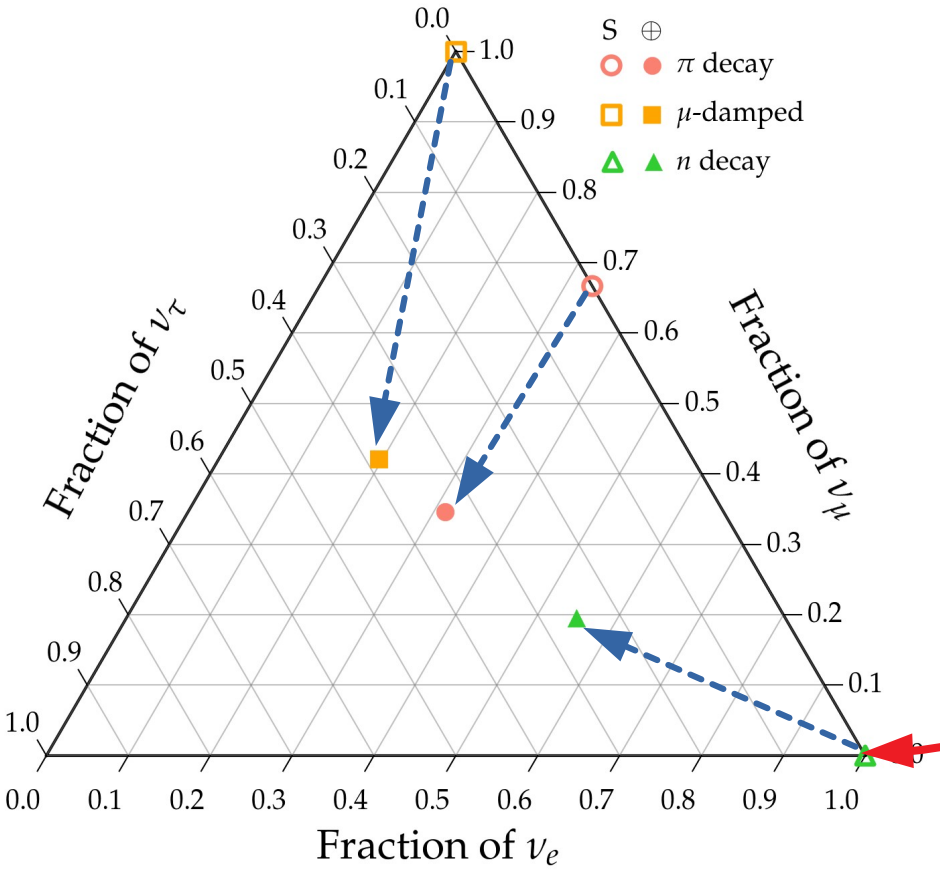

Full π decay chain

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

Muon damped

$(0{:}1{:}0)_S$

Neutron decay

$(1{:}0{:}0)_S$

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

New physics in flavor composition

Use the flavor sensitivity to test new physics:

New physics in flavor composition

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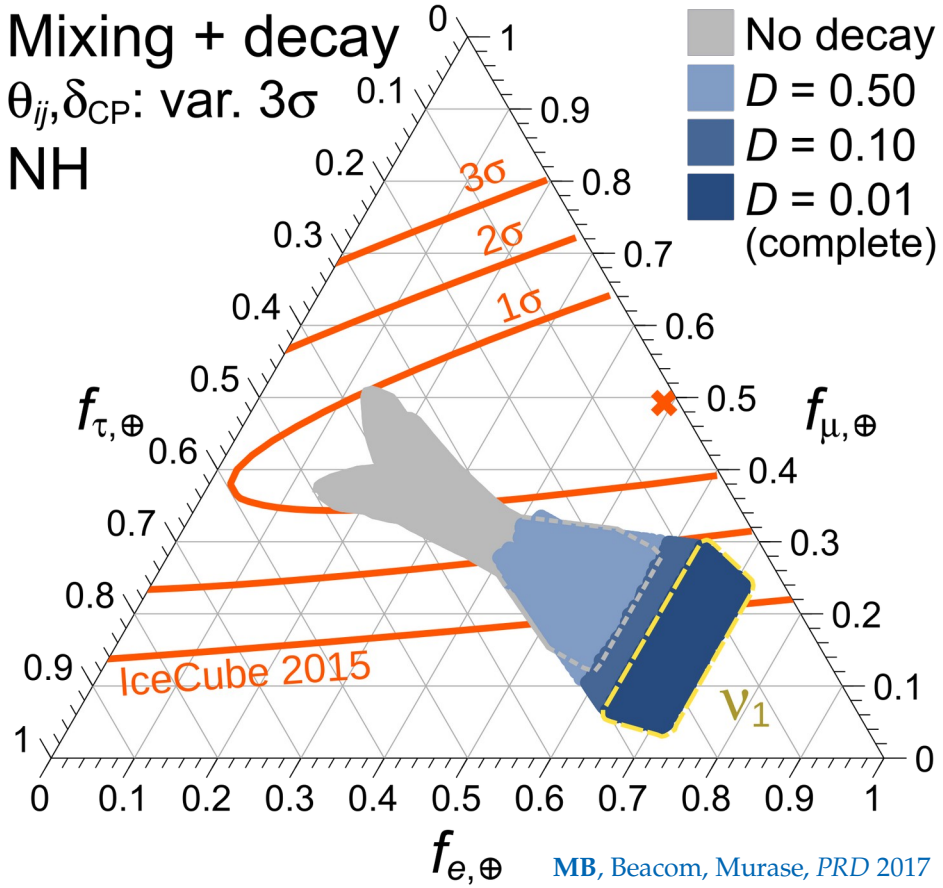
Reviews:
Argüelles *et al.* (inc. **MB**), *EPJC* 2023; Mehta & Winter, *JCAP* 2011; Rasmussen *et al.*, *PRD* 2017

New physics in flavor composition

Use the flavor sensitivity to test new physics:

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



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New physics in flavor composition

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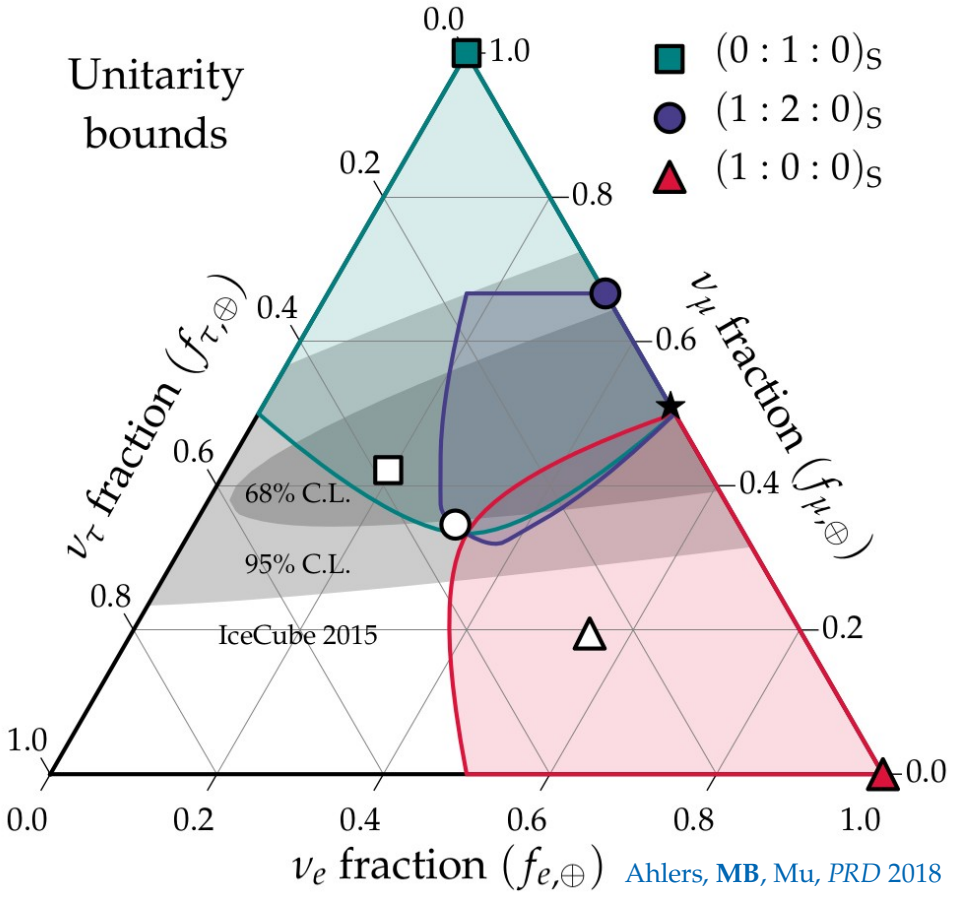

Ahlers, **MB**, Mu, *PRD* 2018

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

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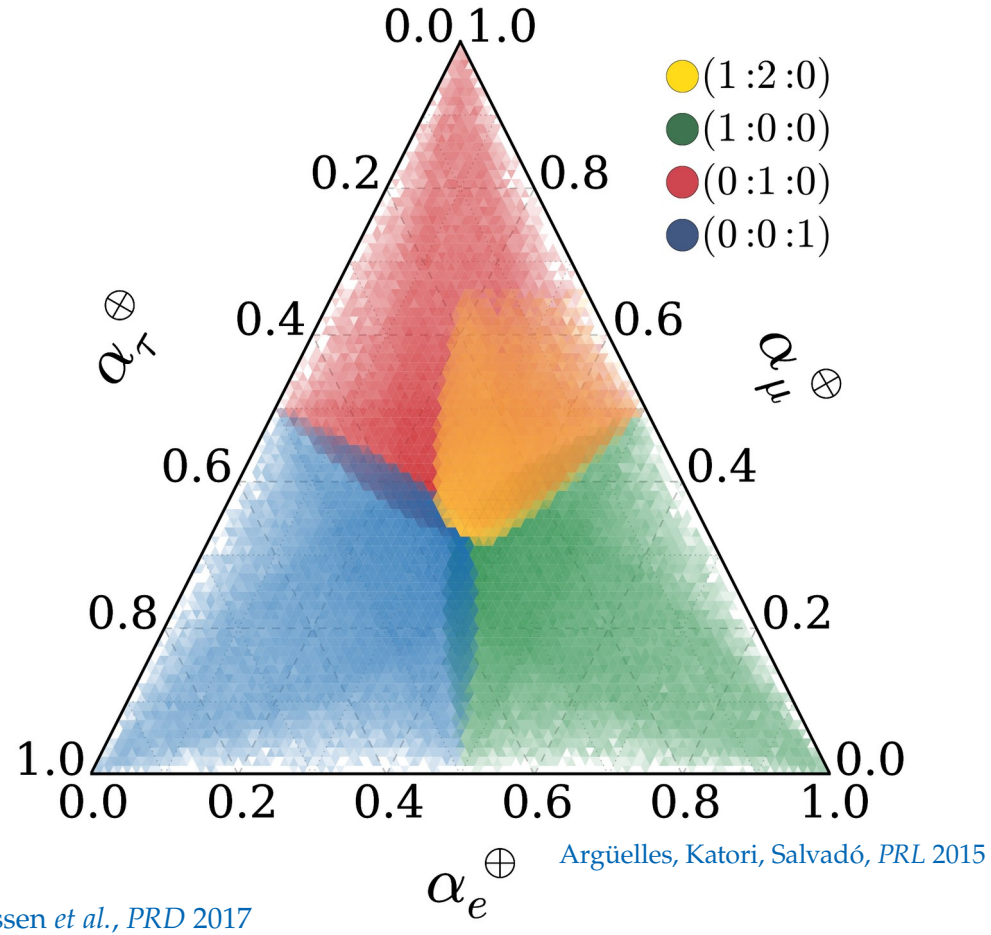

Argüelles, Katori, Salvadó, *PRL* 2015

Reviews:
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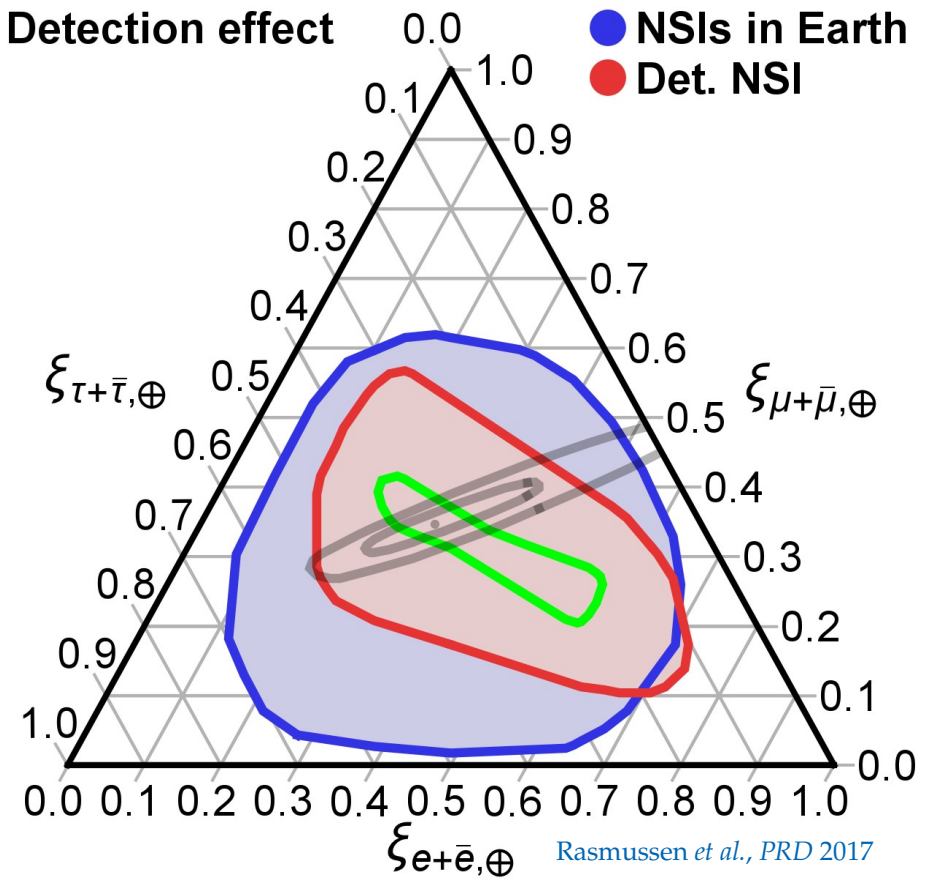

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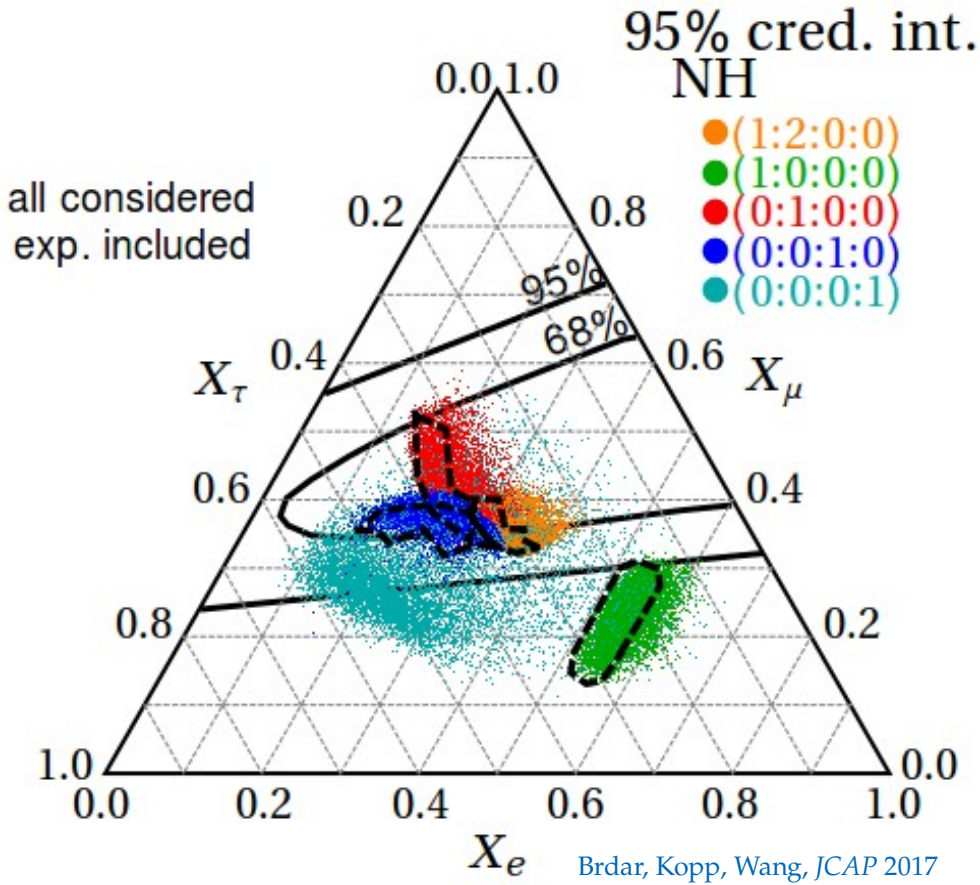

Brdar, Kopp, Wang, *JCAP* 2017

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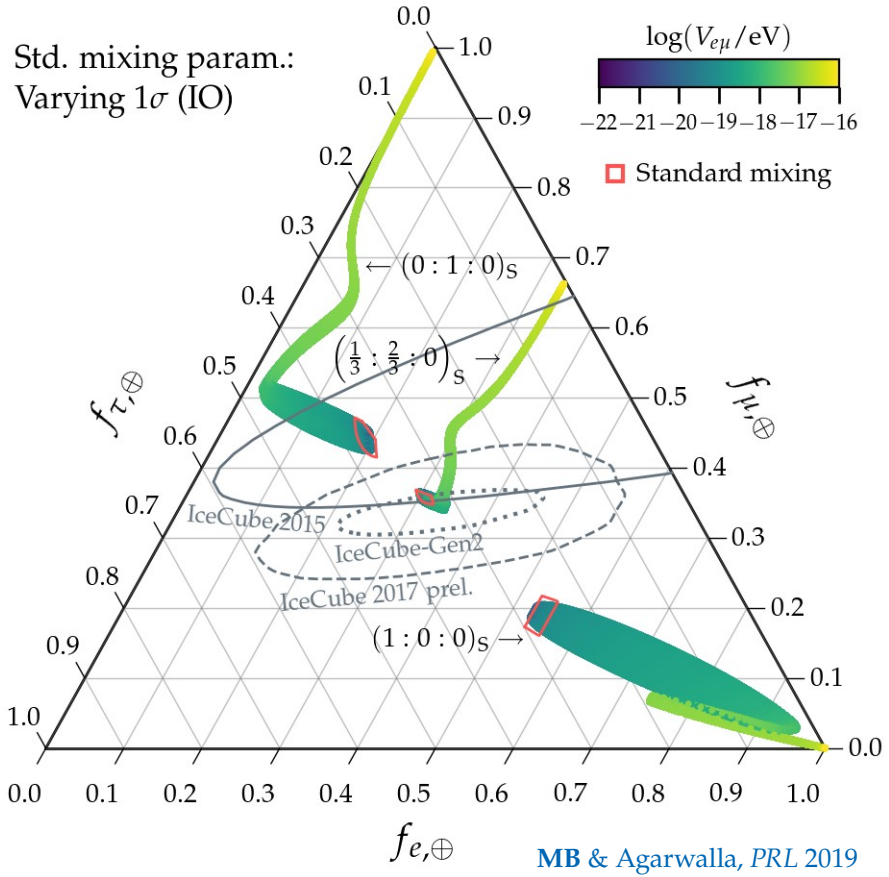
- Long-range *eν* interactions
  [**MB** & Agarwalla, *PRL* 2019]



MB & Agarwalla, *PRL* 2019

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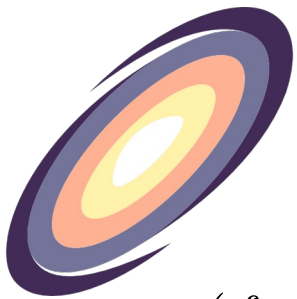
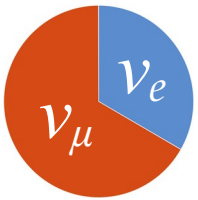
From sources to Earth: we learn what to expect when measuring $f_{\alpha,\oplus}$

Sources



E.g.,

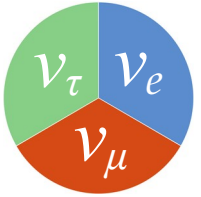


Oscillations

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

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

E.g.,



Earth

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

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

Inferring the flavor composition at the sources

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

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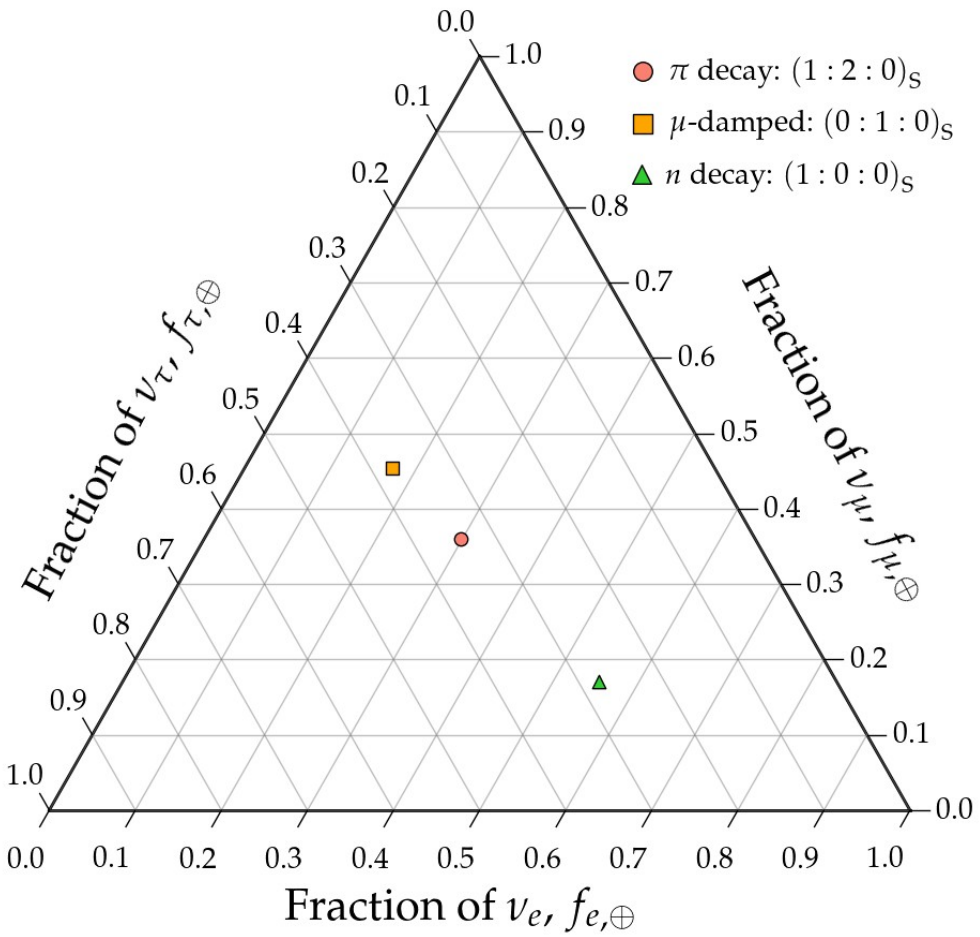

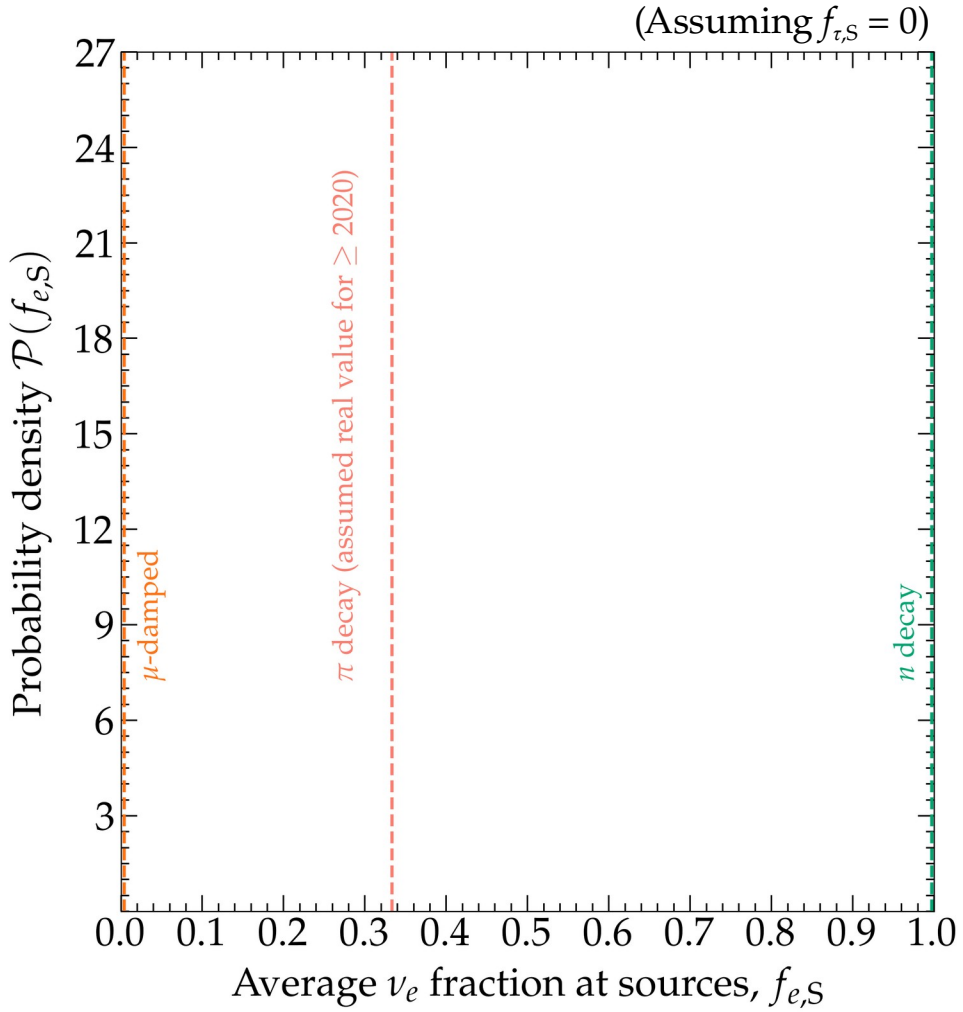

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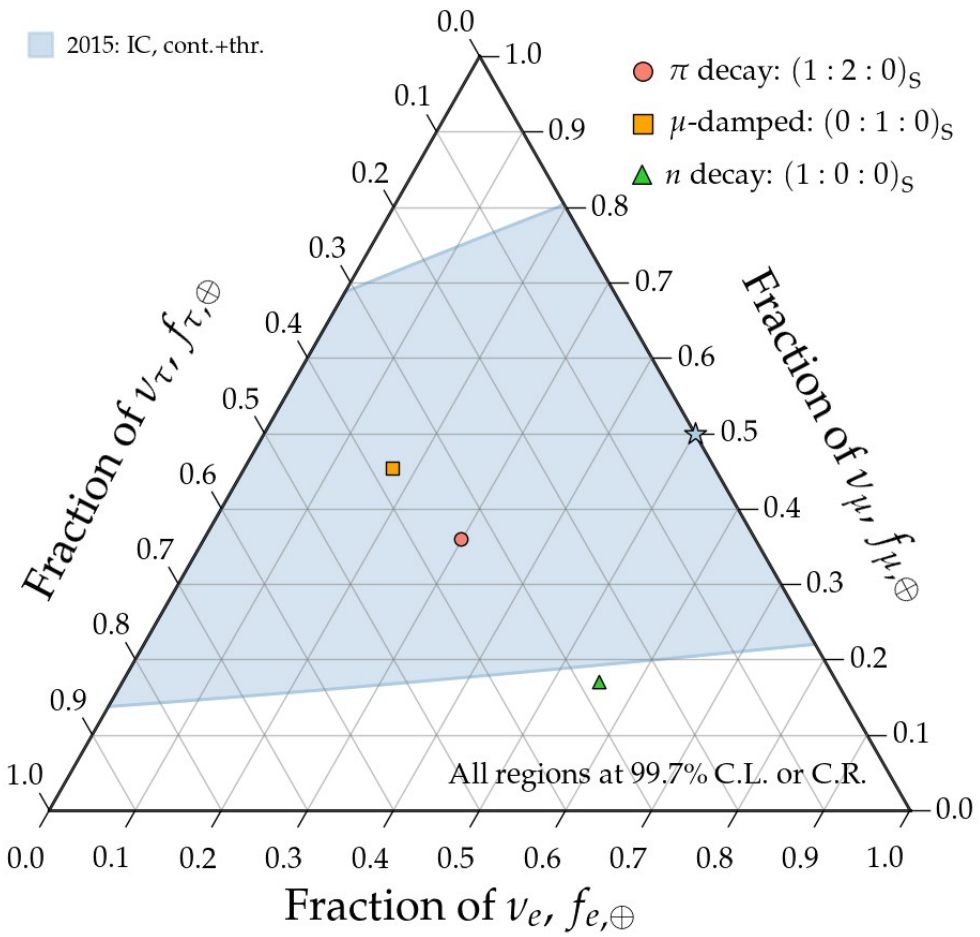

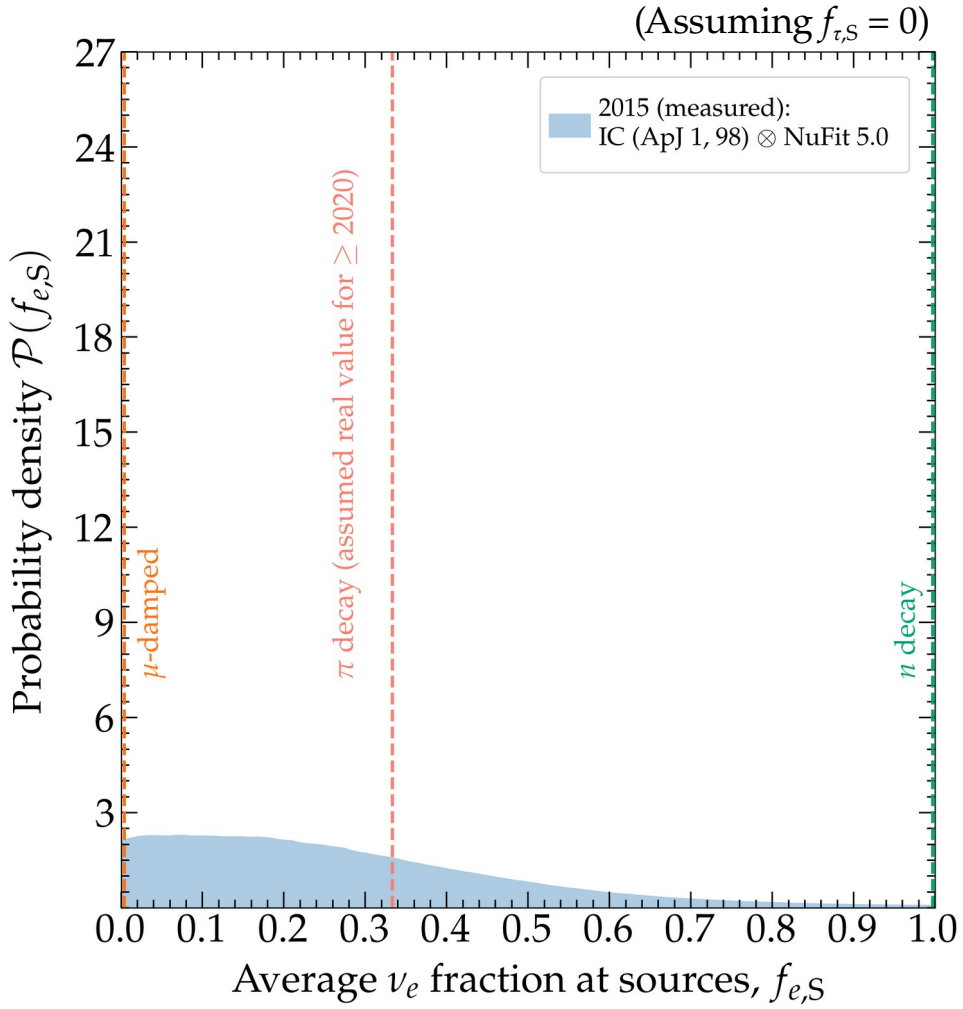

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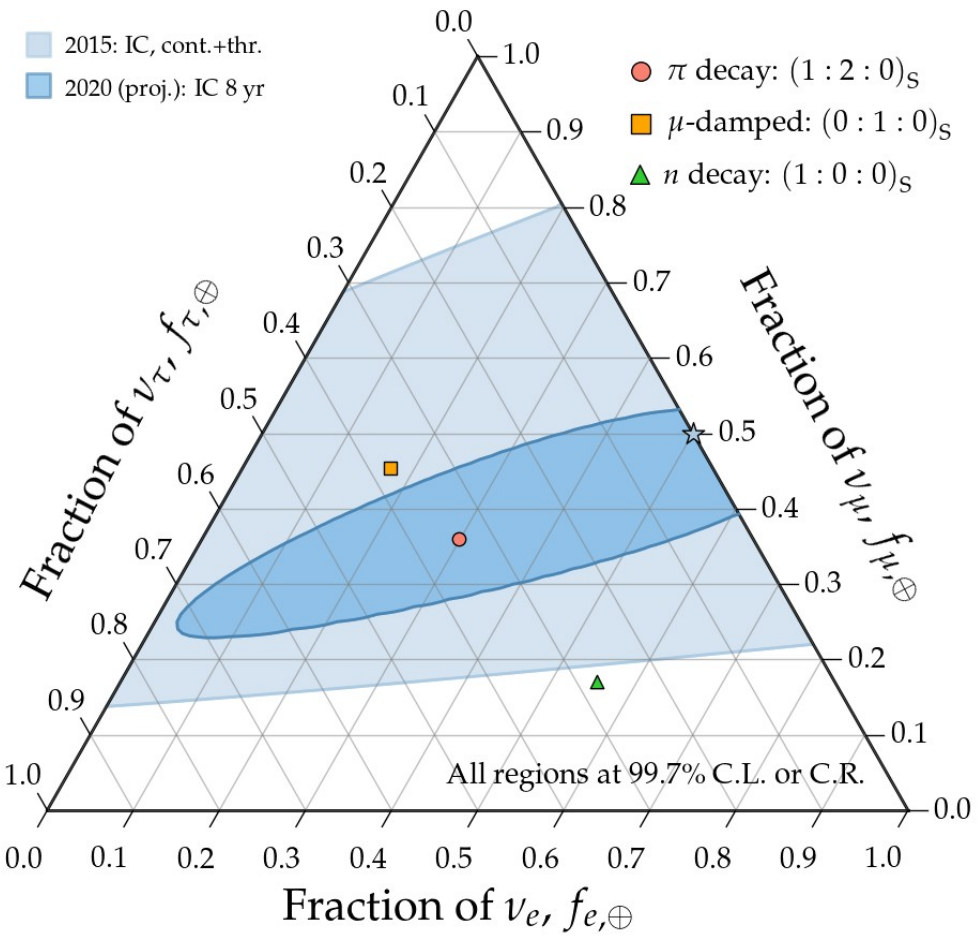

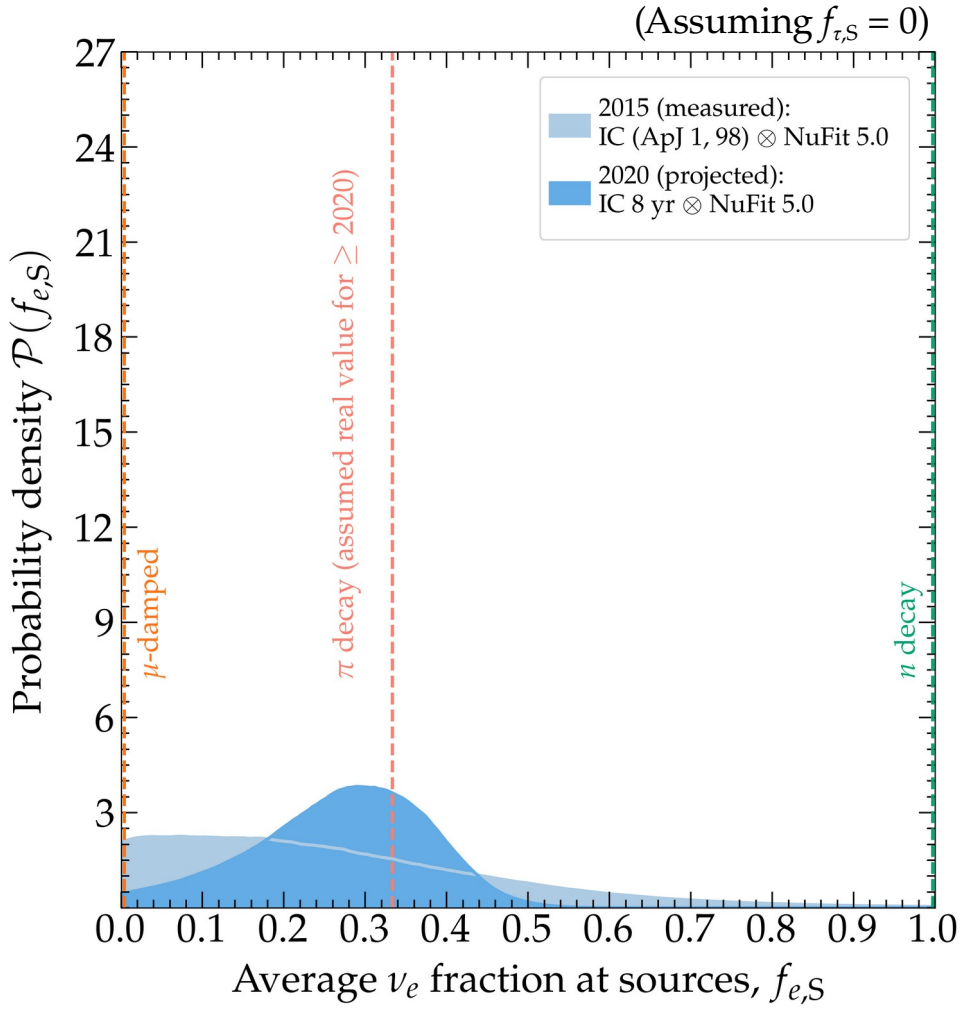

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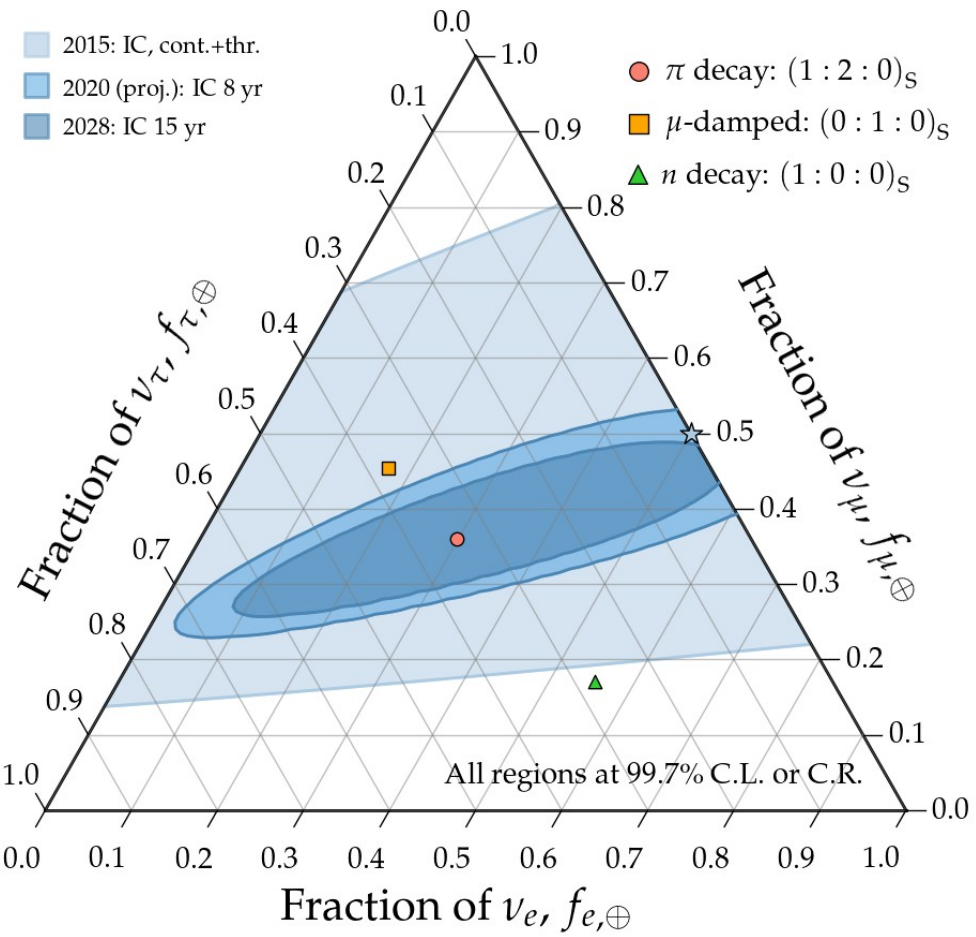

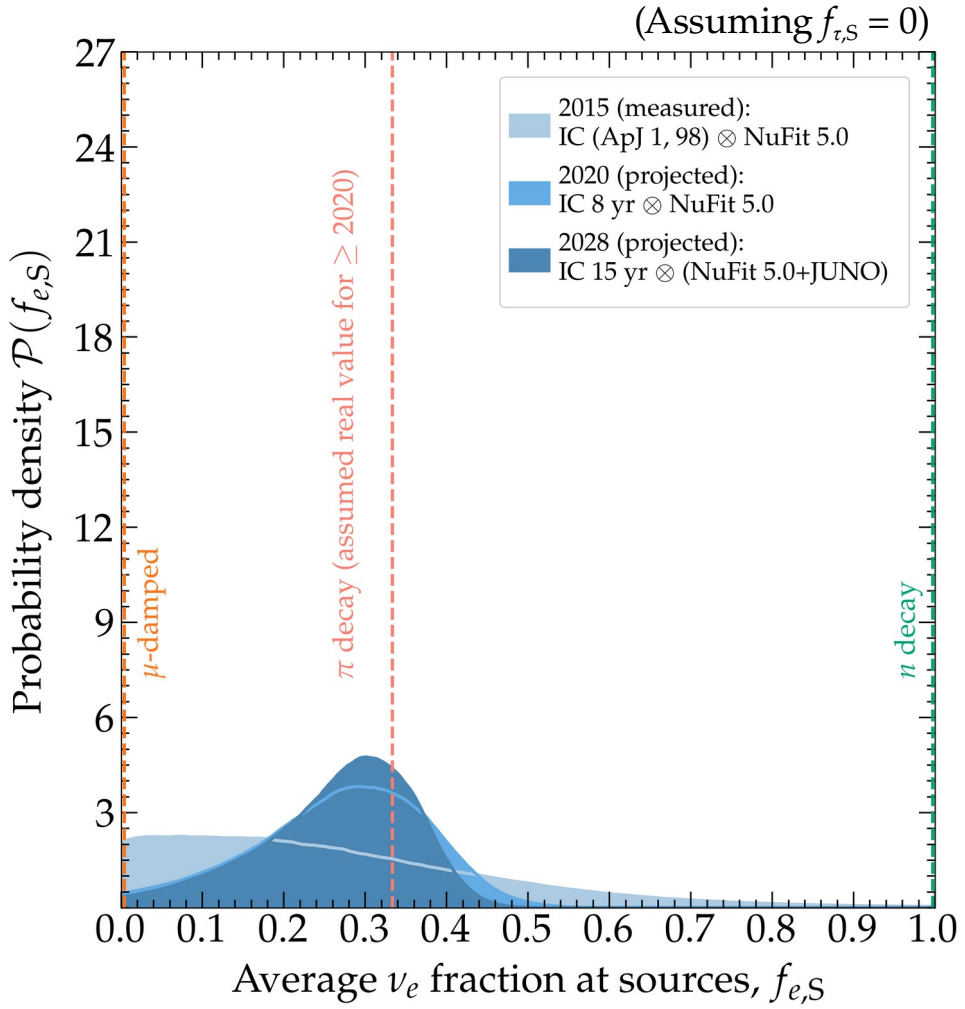

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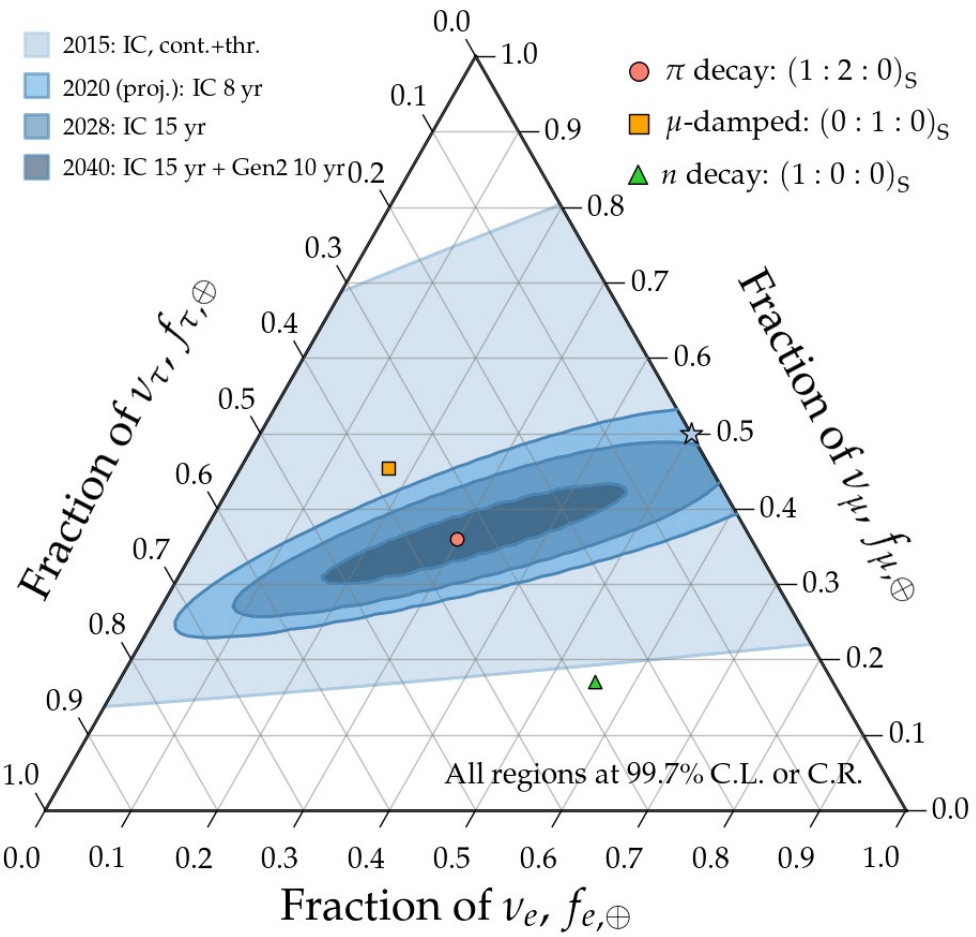

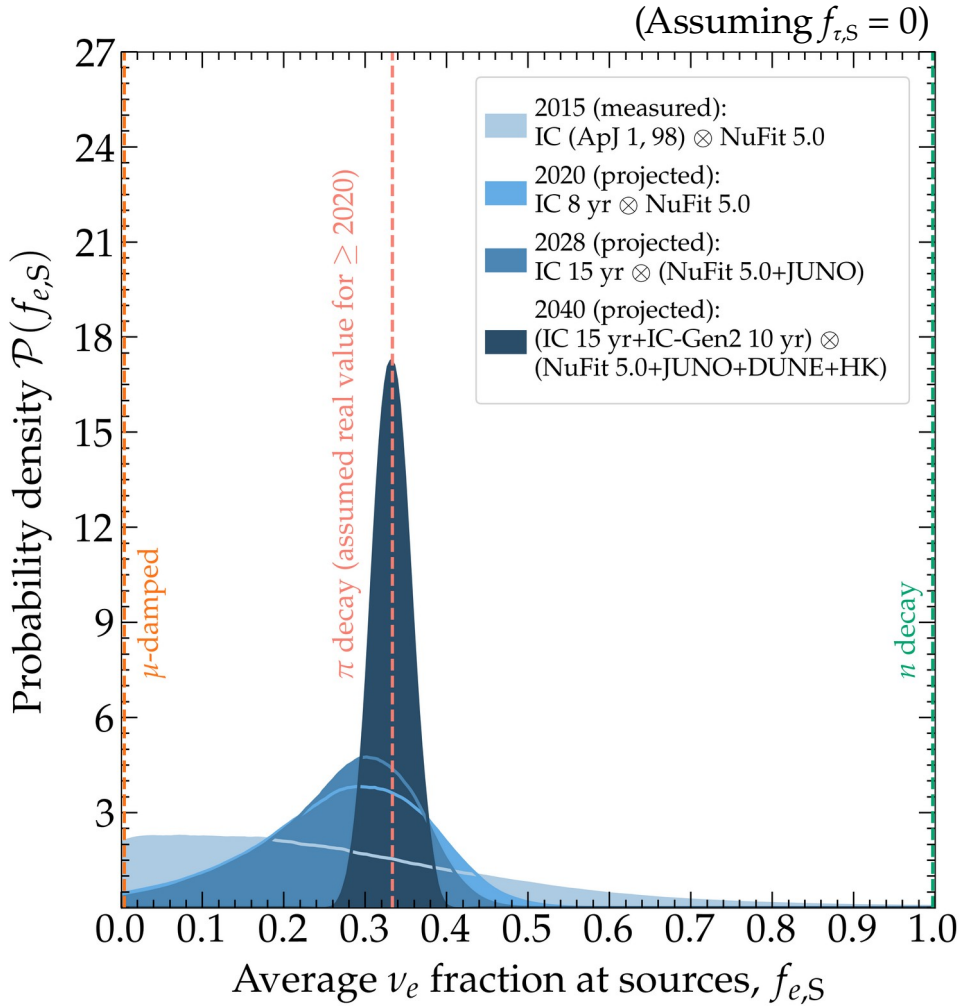

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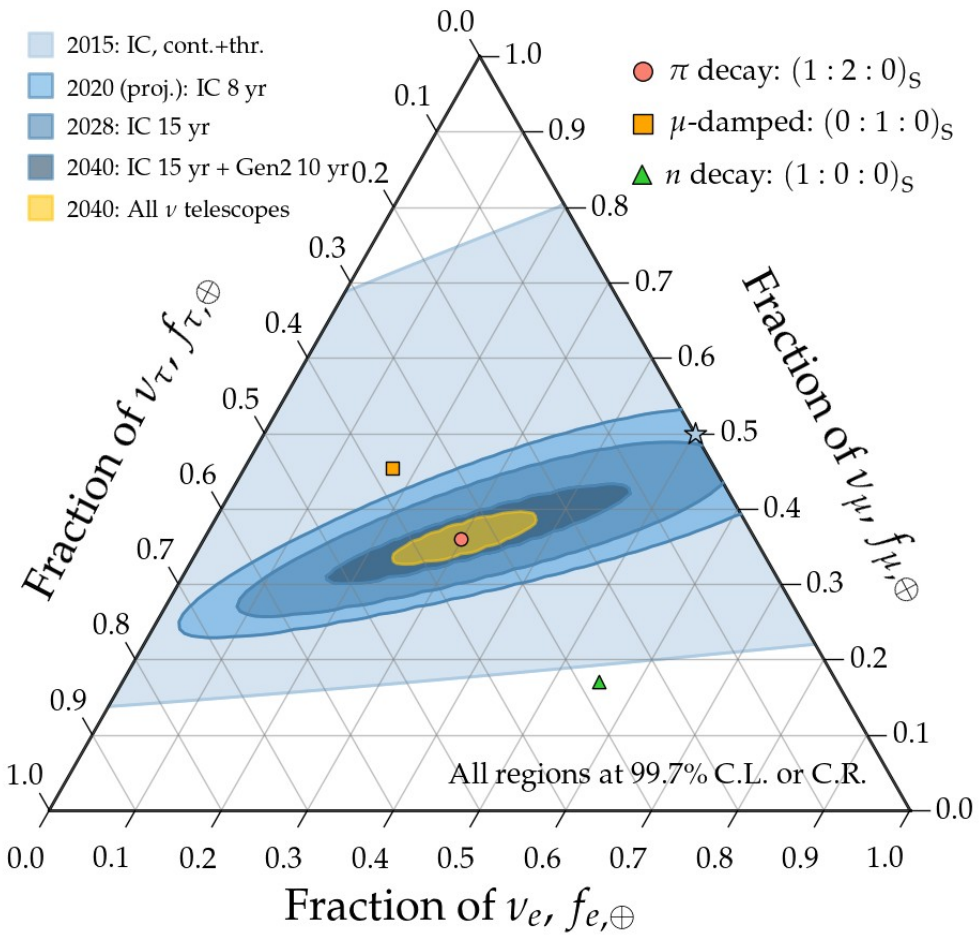

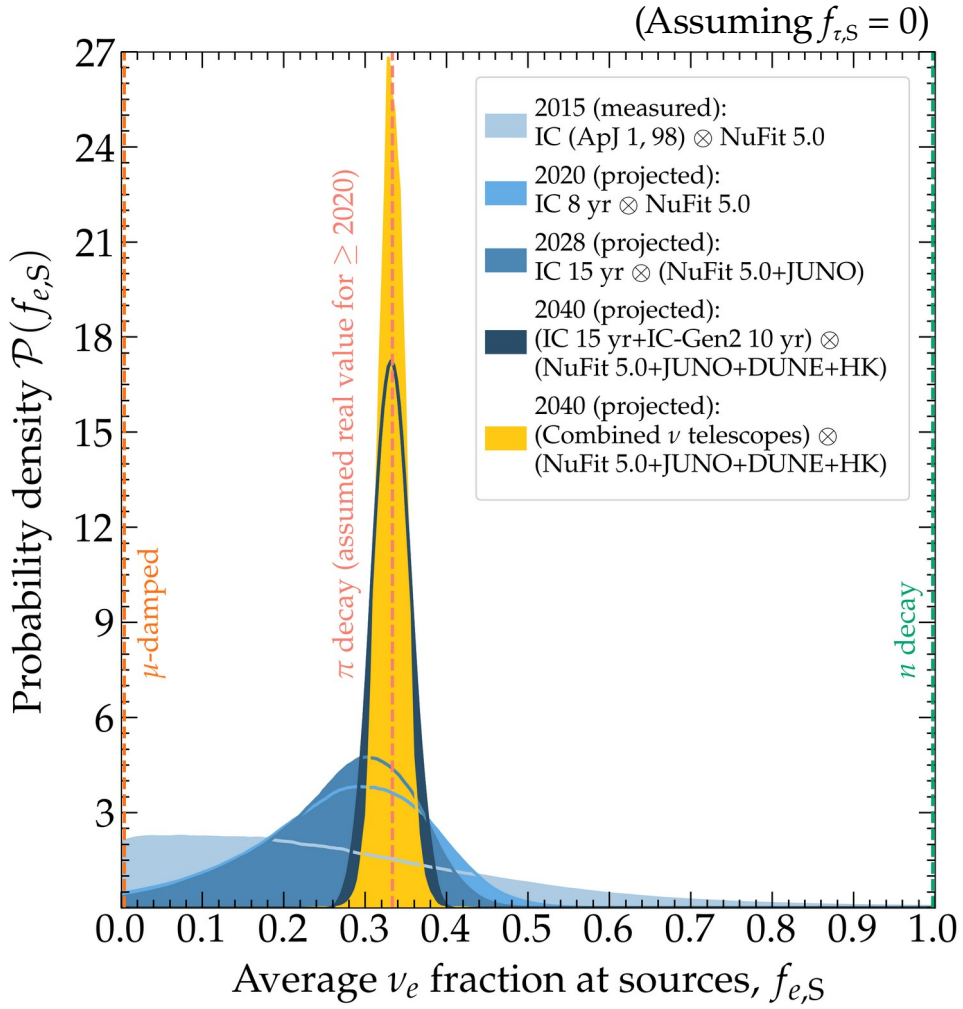

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1

Neutrino oscillations is a three-state system (ν_e, ν_μ, ν_τ), but we study them using mainly two (ν_e and ν_μ)

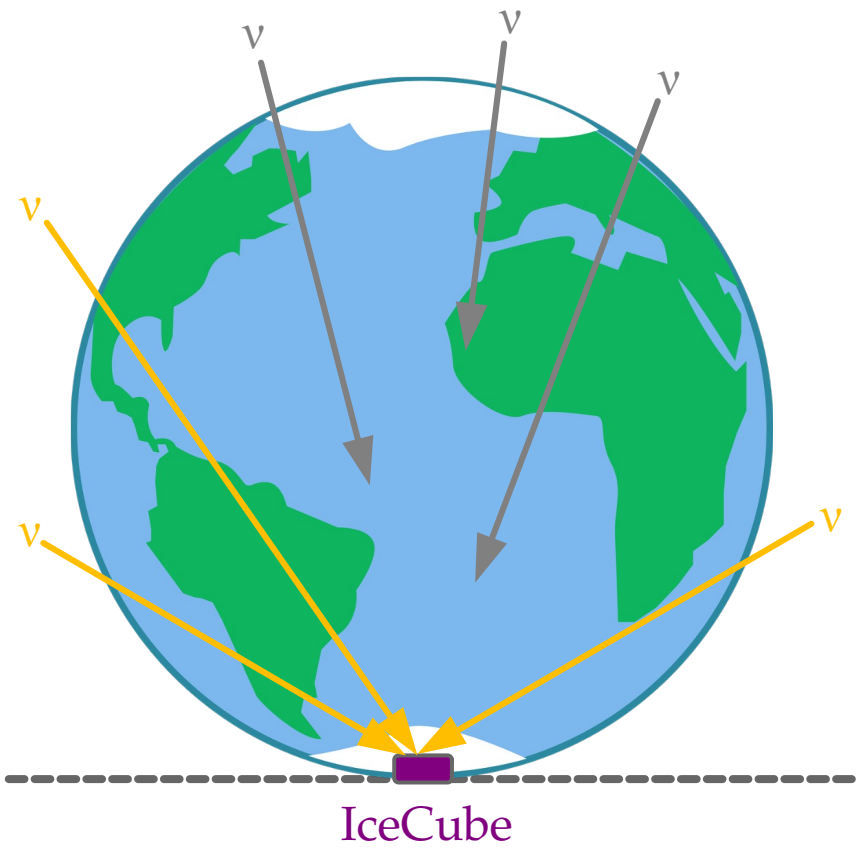
2

The **flavor composition** of high-energy cosmic neutrinos reflects the physical conditions inside cosmic accelerators

3

At **ultra-high energies** ($> 10^{18}$ EeV), ν_τ provide unique detection opportunities (ν_τ regeneration, Earth-skimming ν_τ)

TeV–PeV:



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

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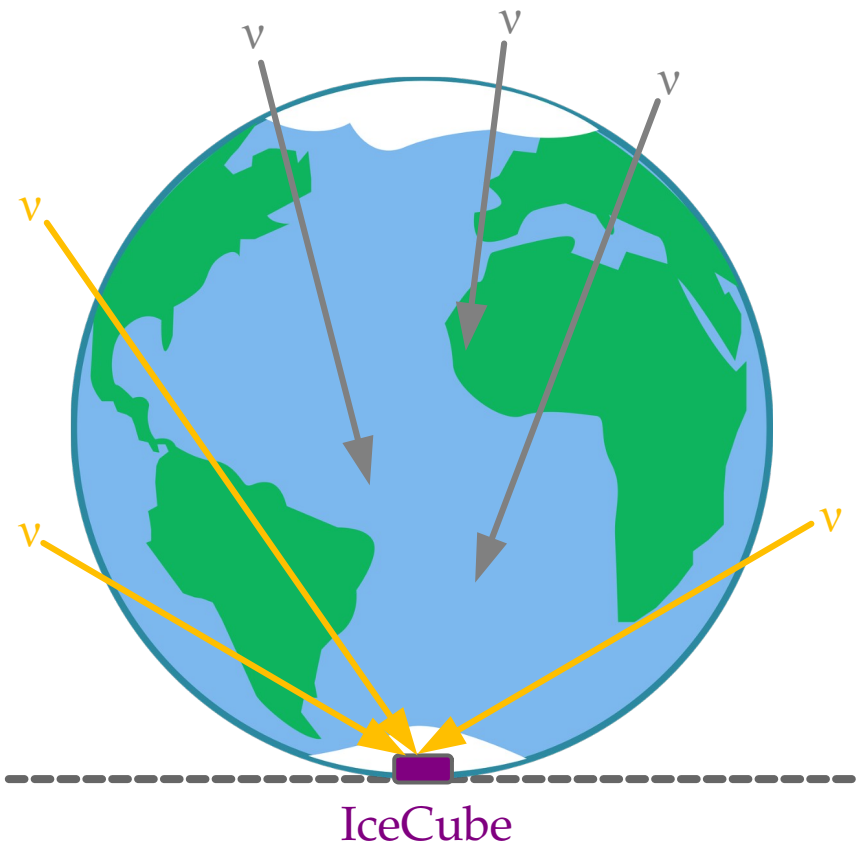

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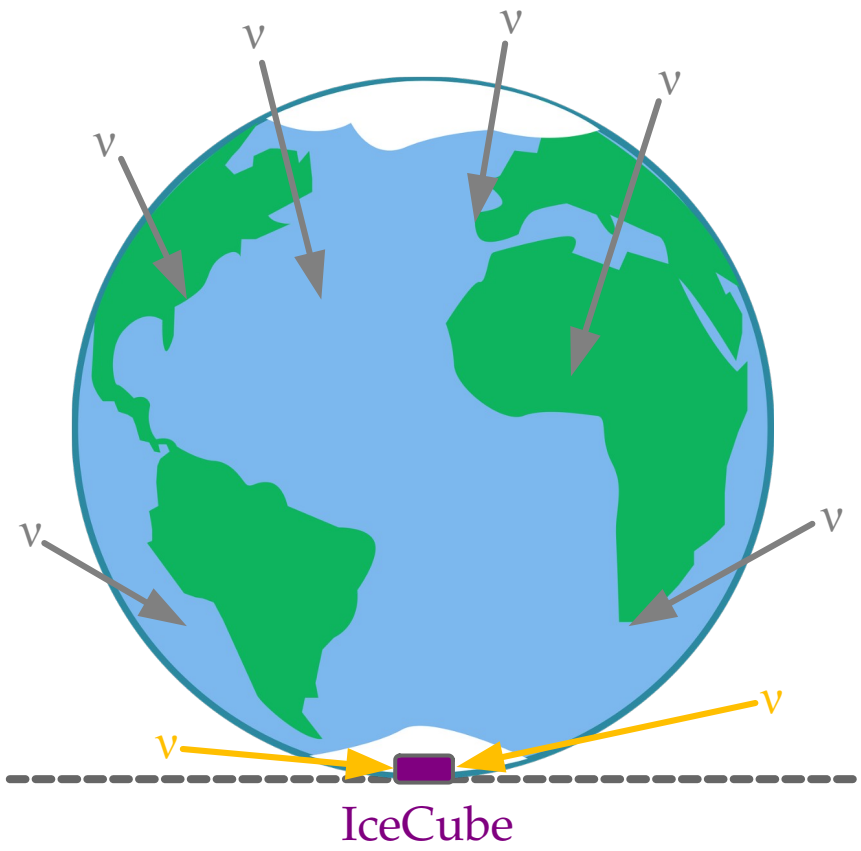
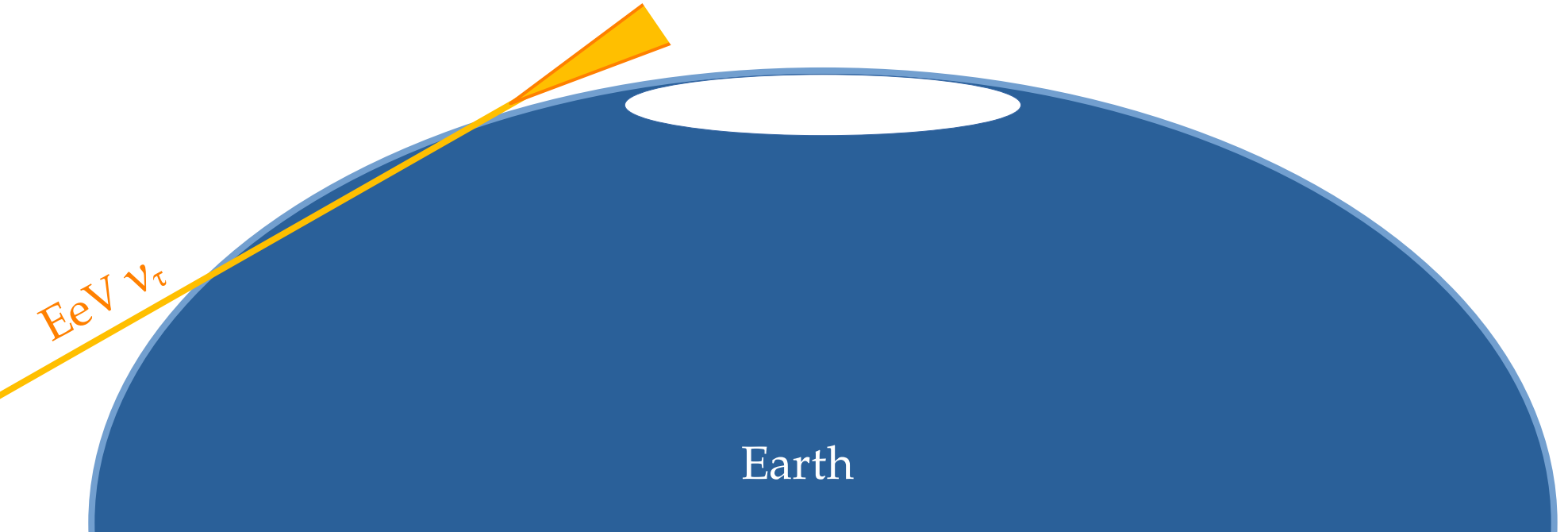
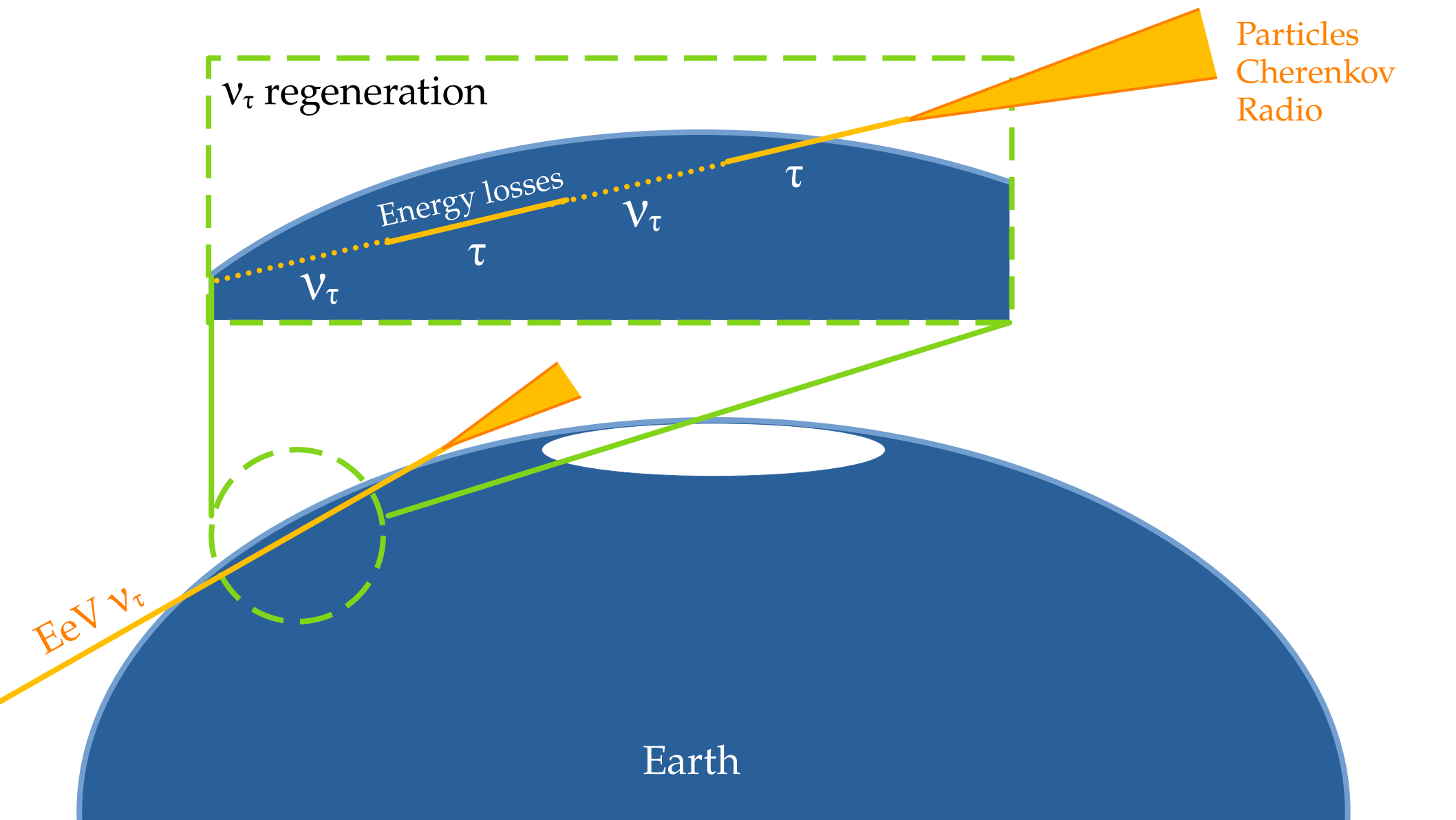
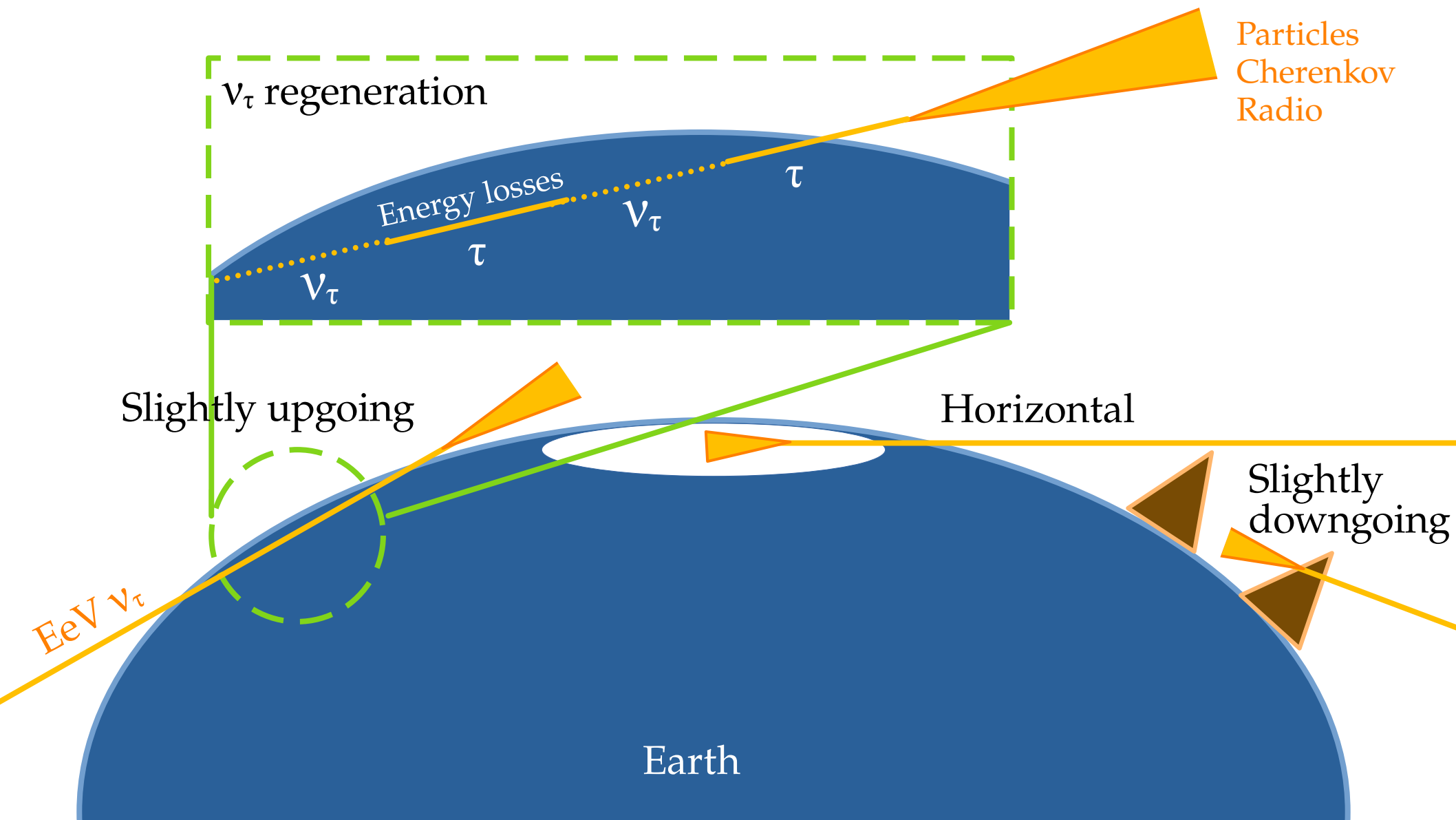
> 100 PeV:

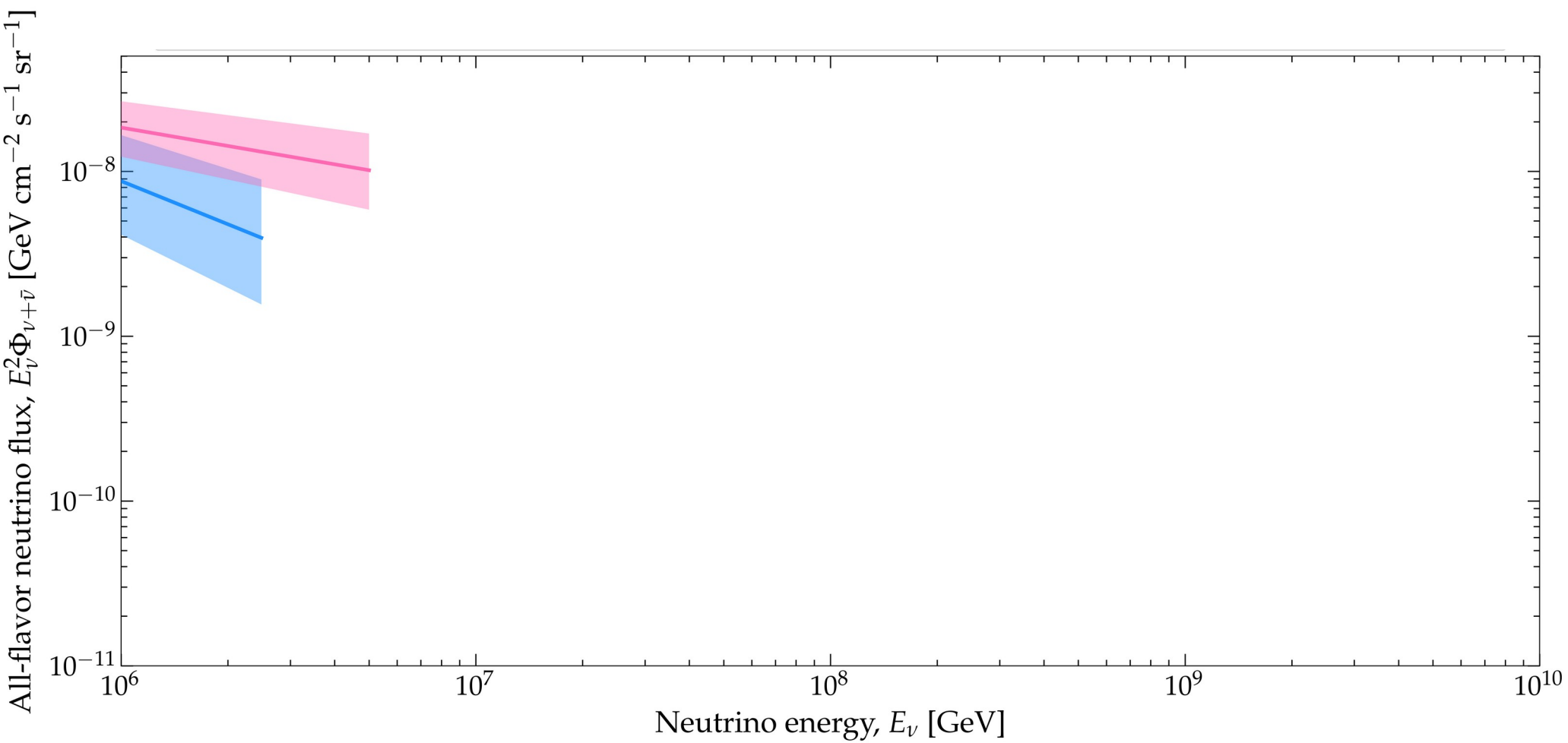


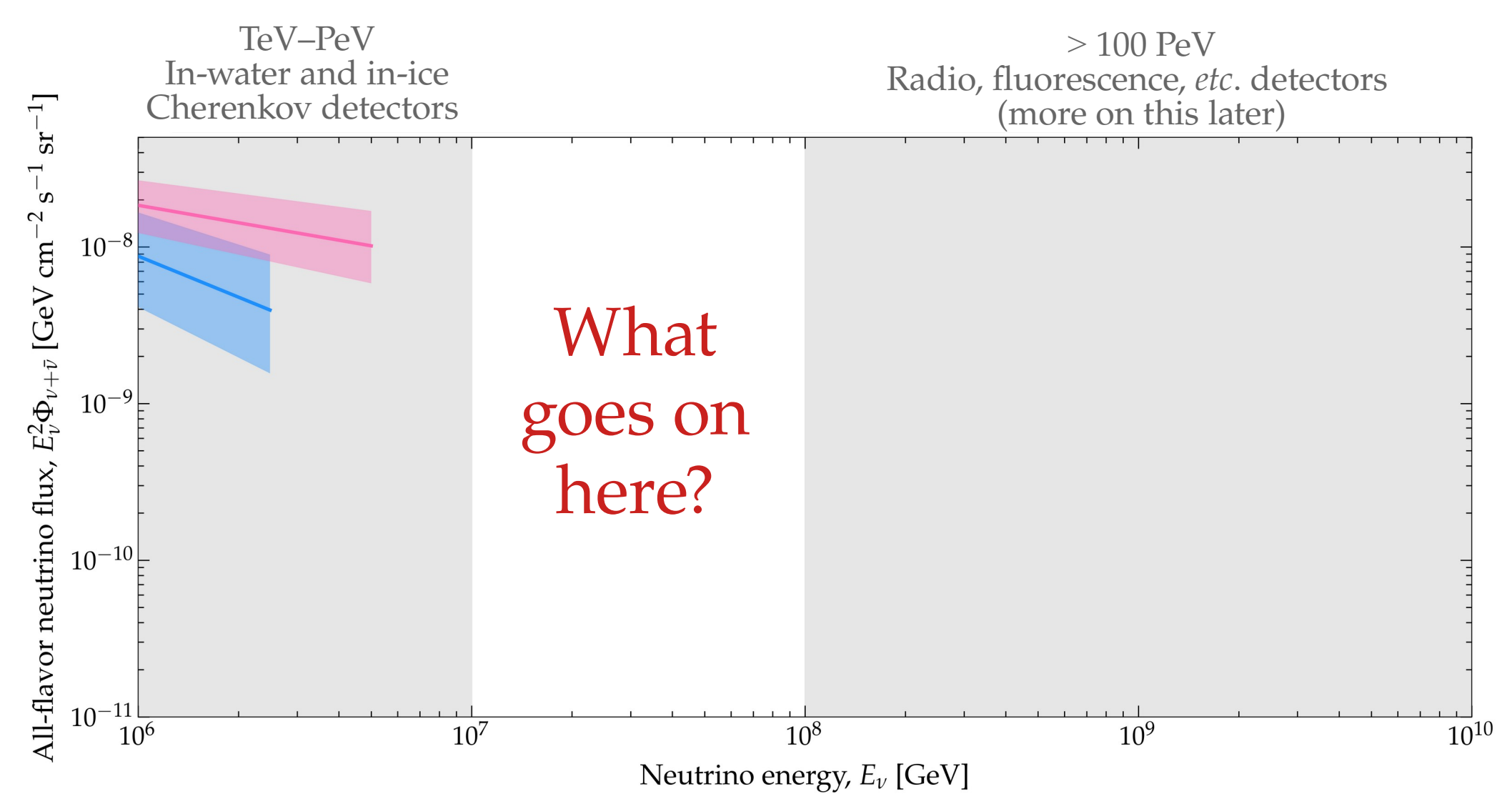
Earth is *completely* opaque,
but horizontal ν still make it through


EeV ν_τ
Earth


ν_τ regeneration
Particles
Cherenkov
Radio
Energy losses
τ
ν_τ
ν_τ
τ
EeV ν_τ
Earth


ν_τ regeneration
Particles
Cherenkov
Radio
Energy losses
τ
ν_τ
τ
ν_τ
Slightly upgoing
Horizontal
Slightly
downgoing
EeV ν_τ
Earth


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]


TeV–PeV
In-water and in-ice
Cherenkov detectors
> 100 PeV
Radio, fluorescence, *etc*. detectors
(more on this later)
What
goes on
here?
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
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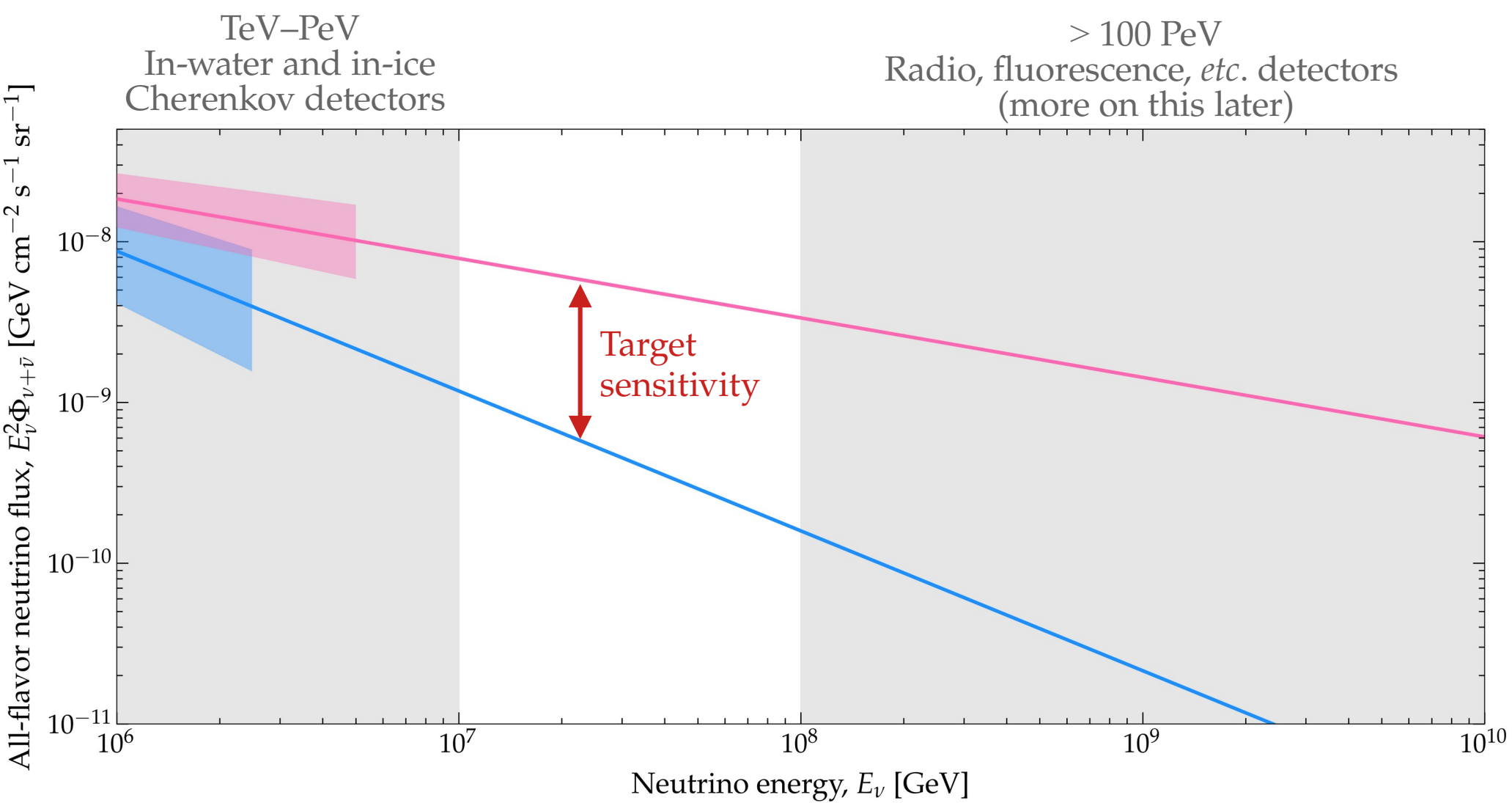
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]


TeV–PeV
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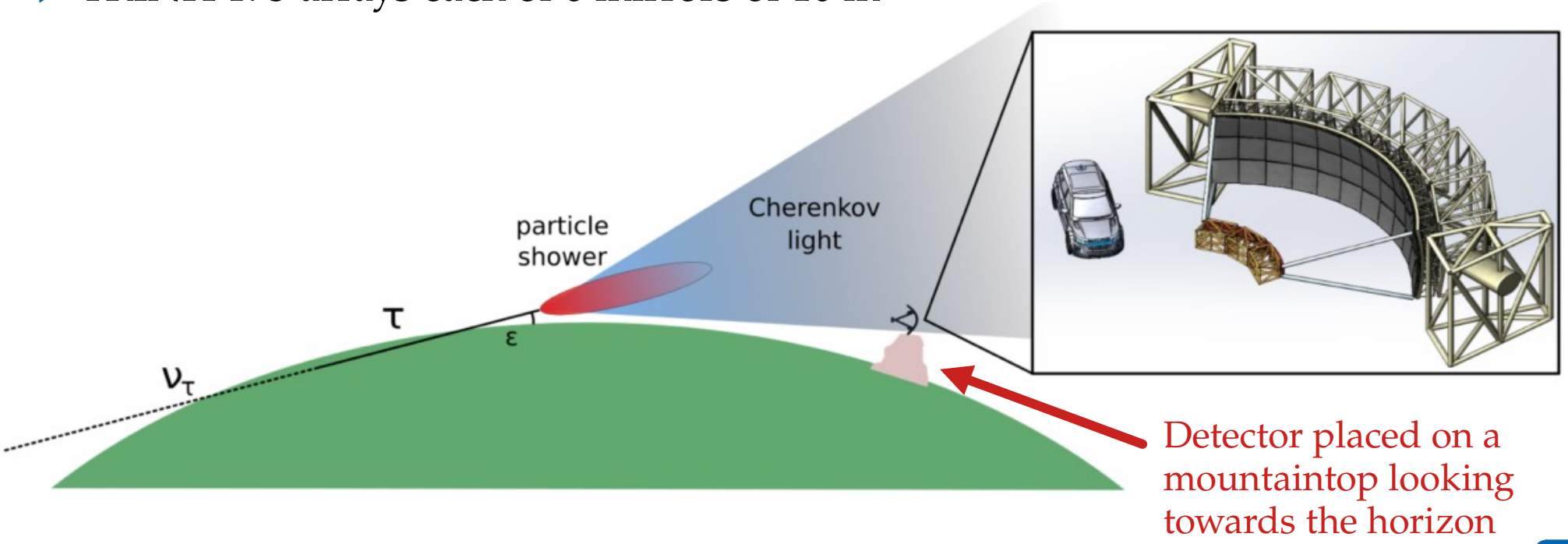
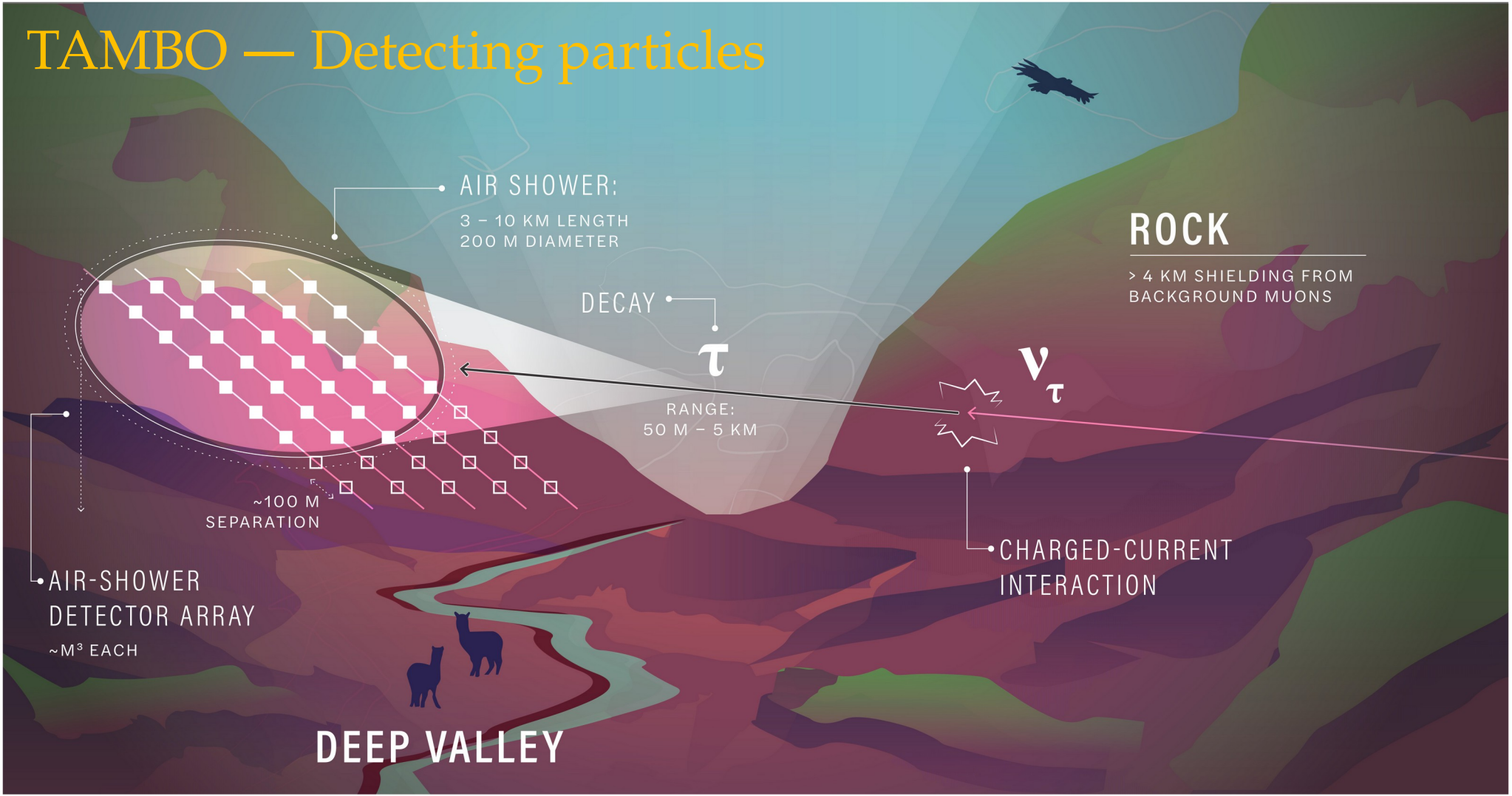
Target
sensitivity
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]

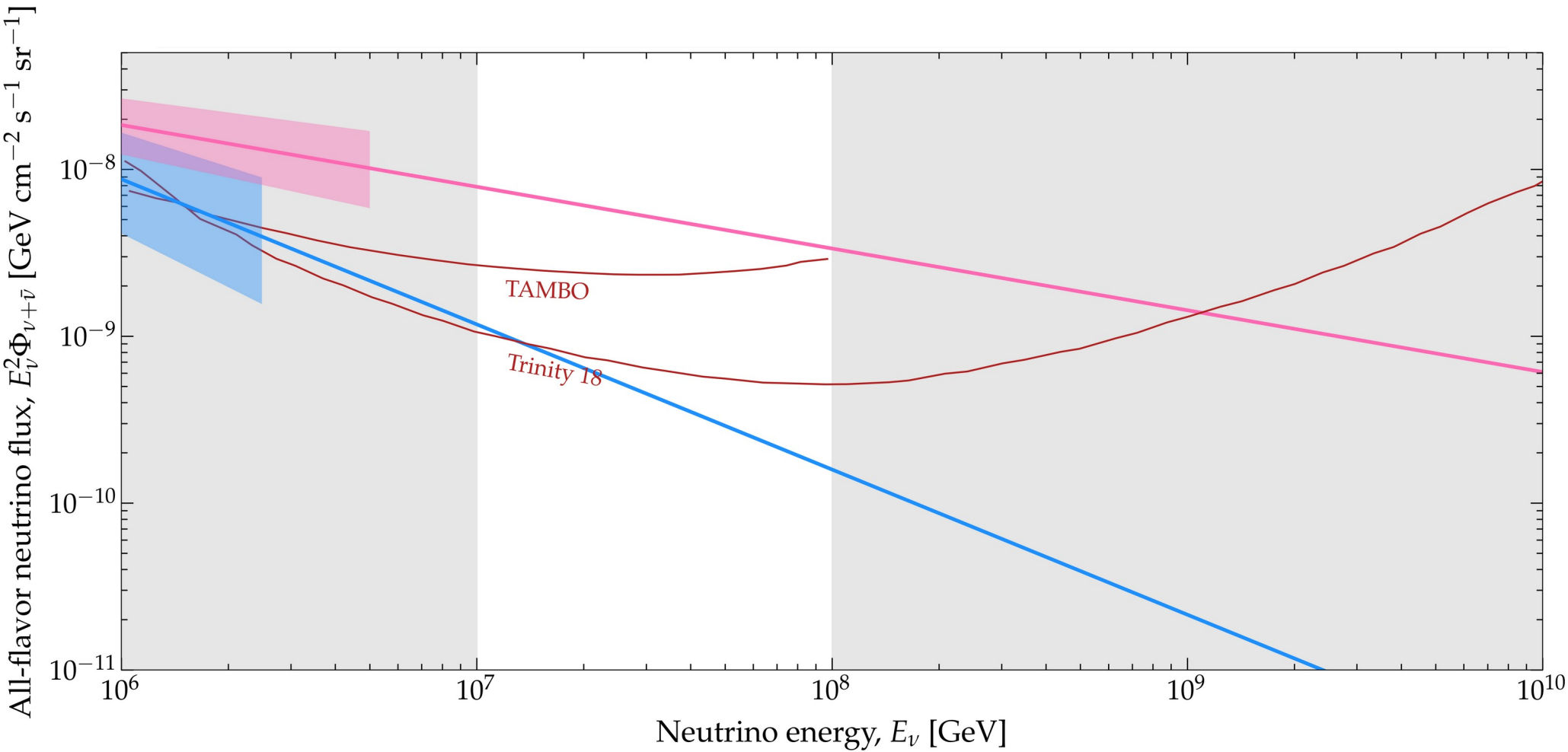
TRINITY — Detecting Cherenkov light

- Atmospheric Cherenkov imaging applied to PeV neutrinos
- Pioneered by MAGIC (pointing at Atlantic), ASHRA, and NTA (Mauna Kea)
- TRINITY: 3 arrays each of 6 mirrors of 10 m^2





TAU AIR-SHOWER MOUNTAIN-BASED OBSERVATORY (TAMBO) · COLCA VALLEY, PERU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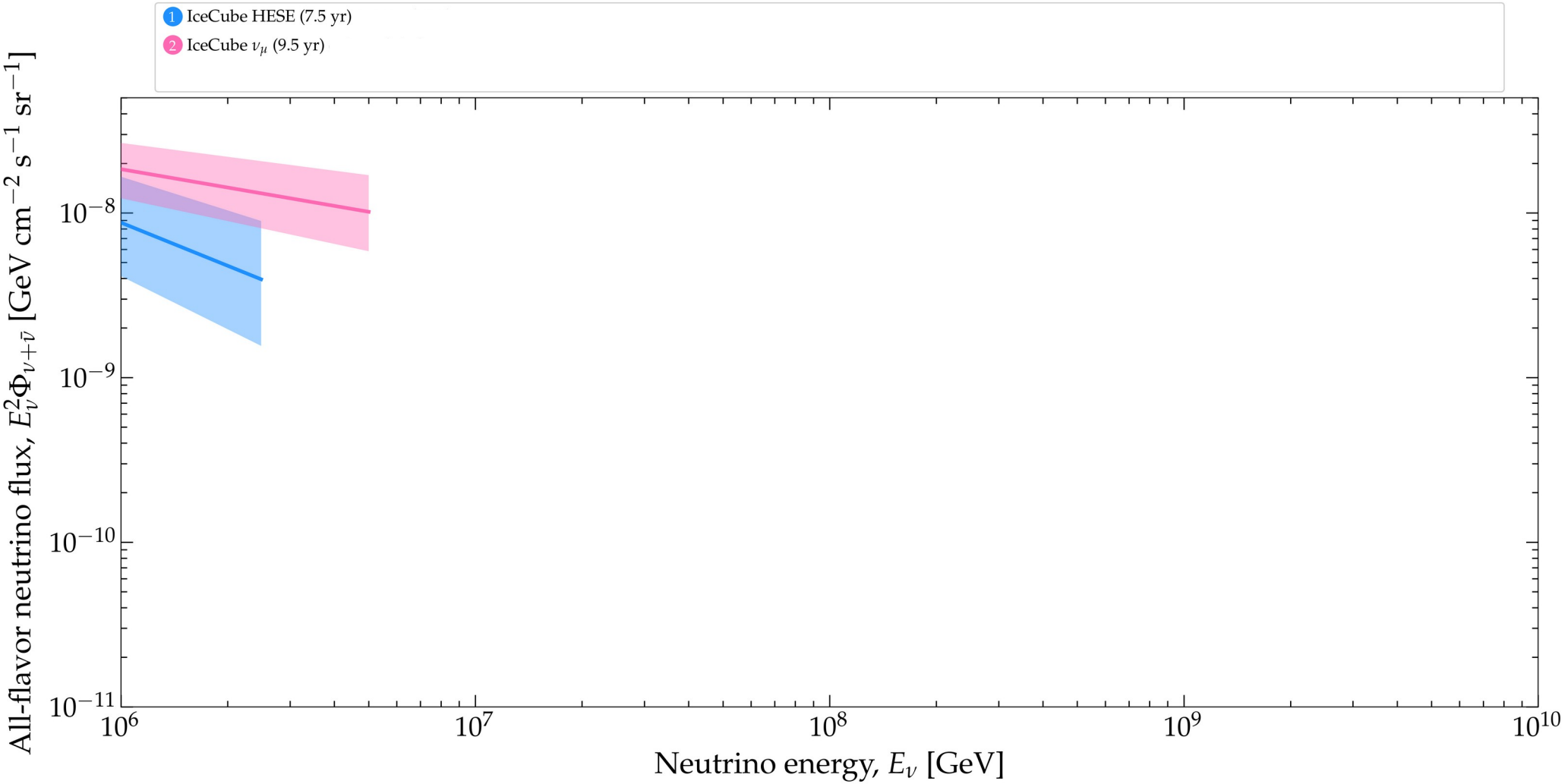
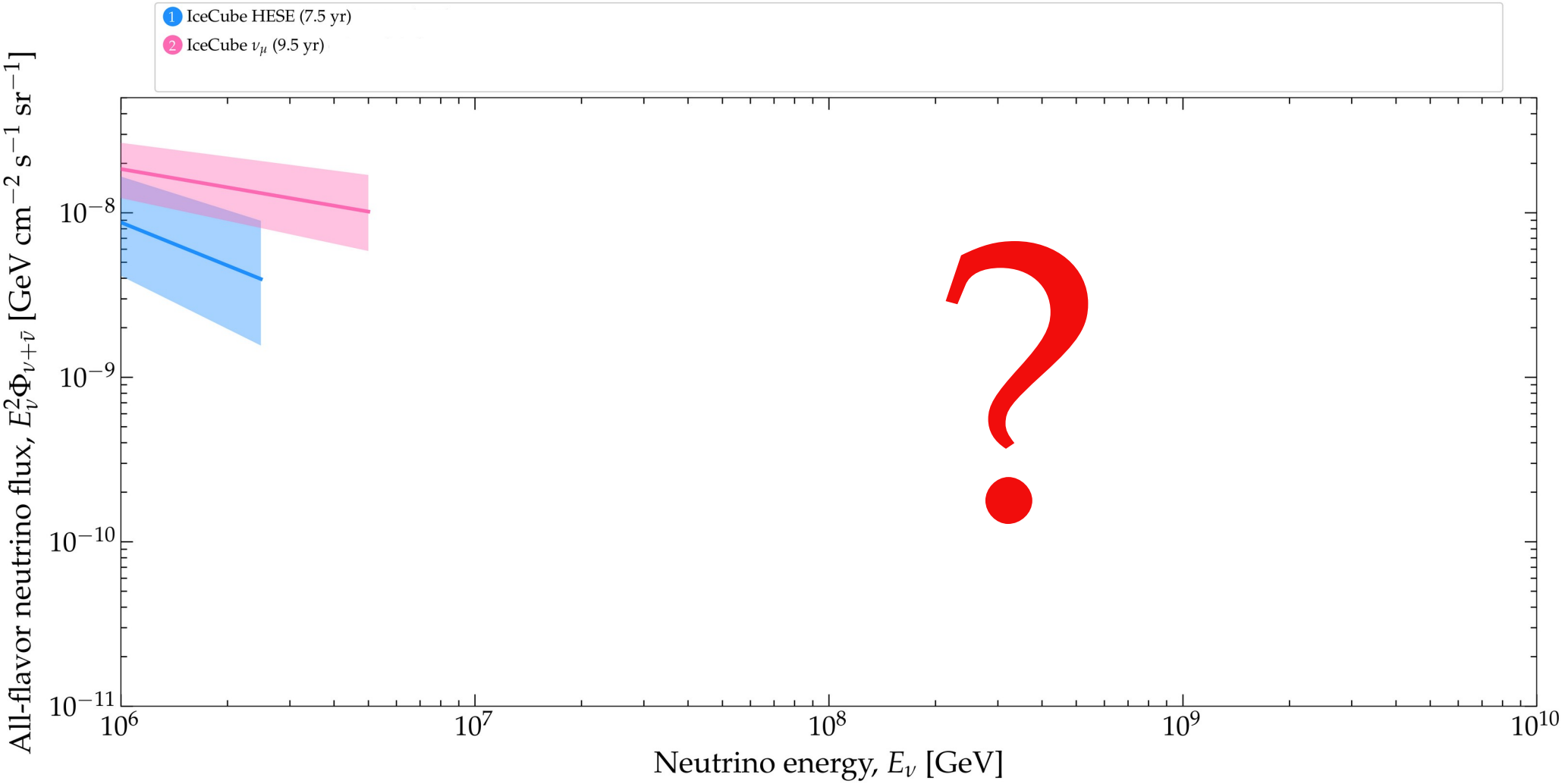
10^{-8}
10^{-9}
10^{-10}
10^{-11}
TAMBO
Trinity 18
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]


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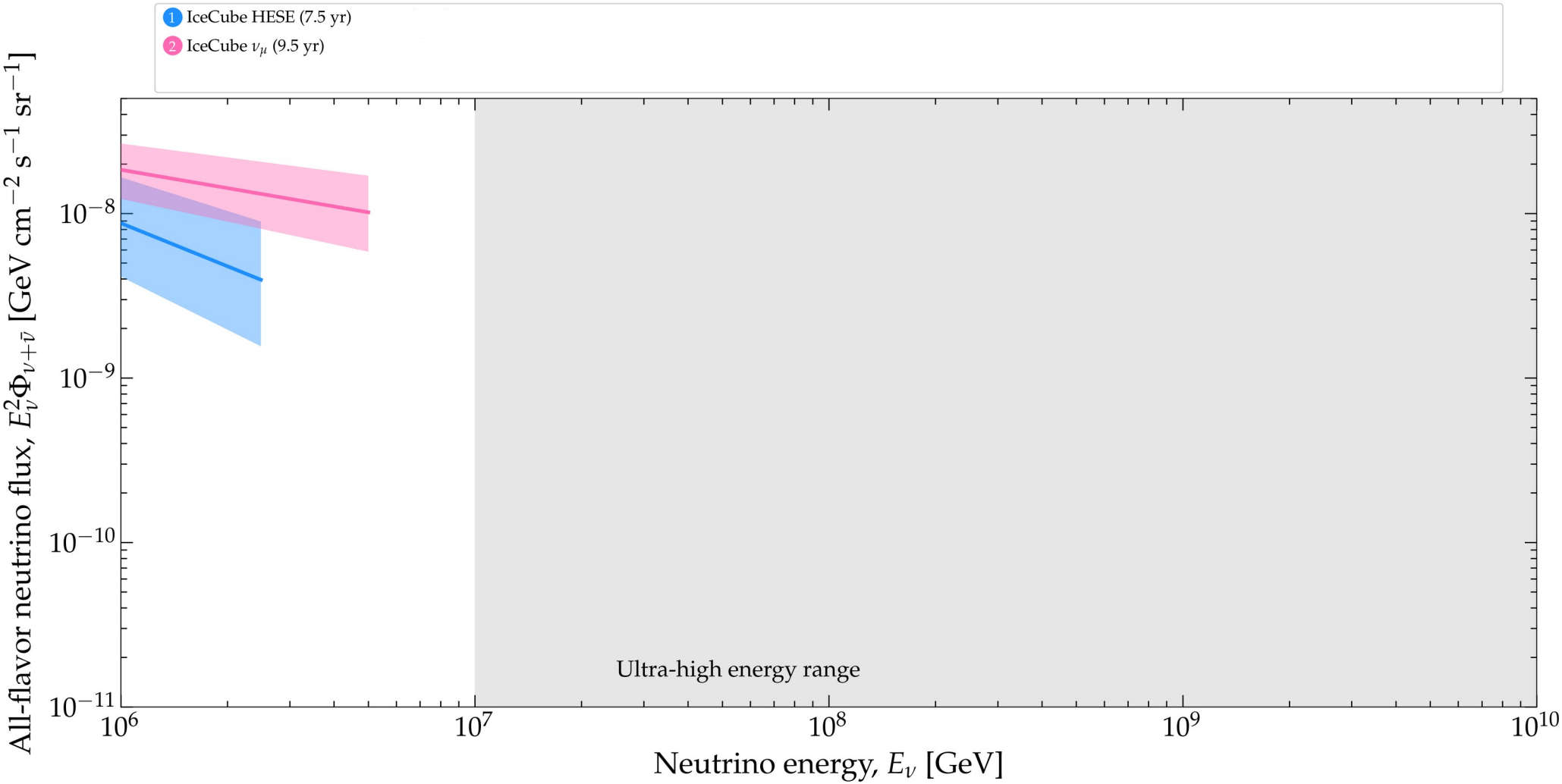
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]
?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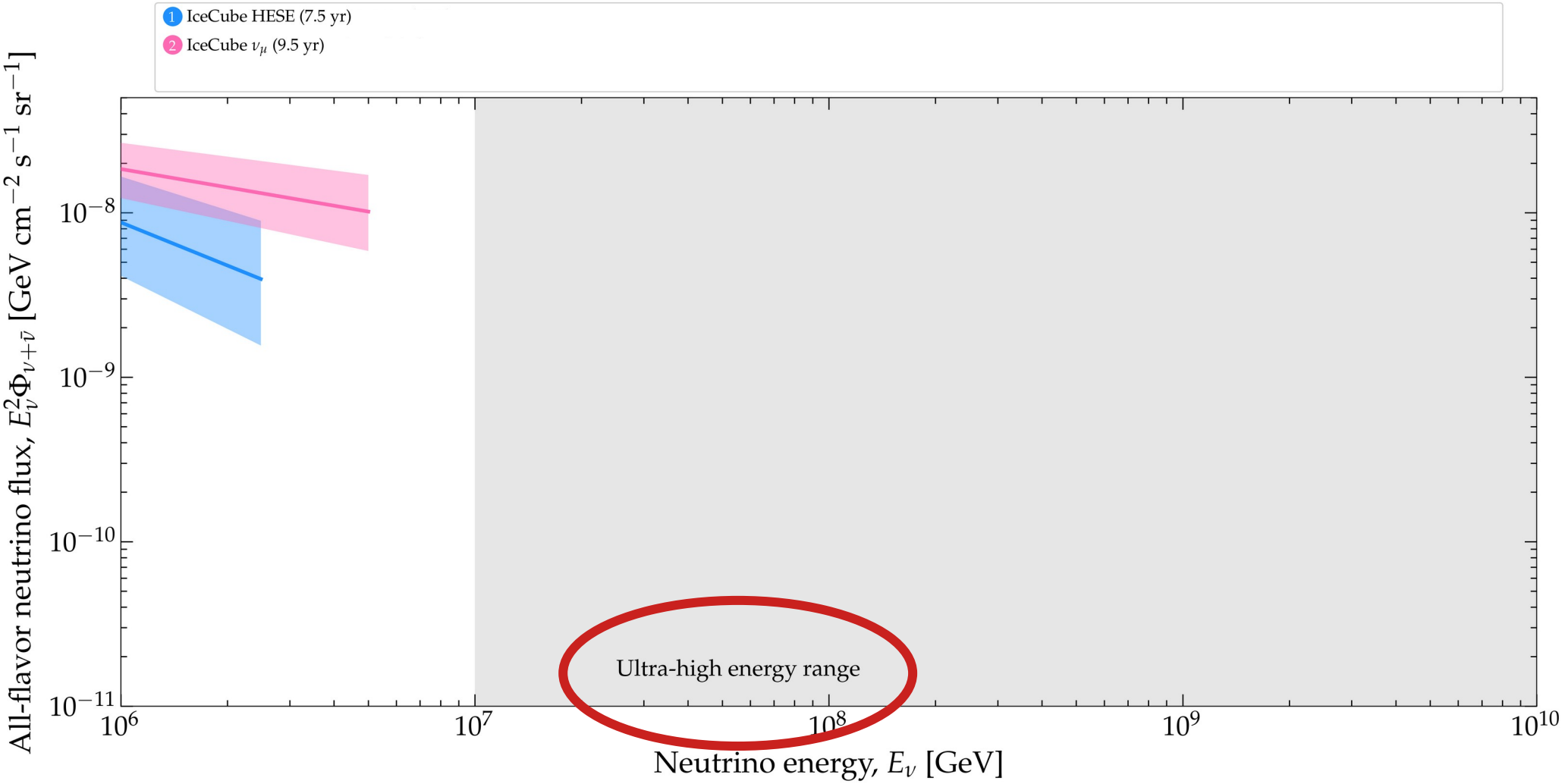
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
Ultra-high energy range
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]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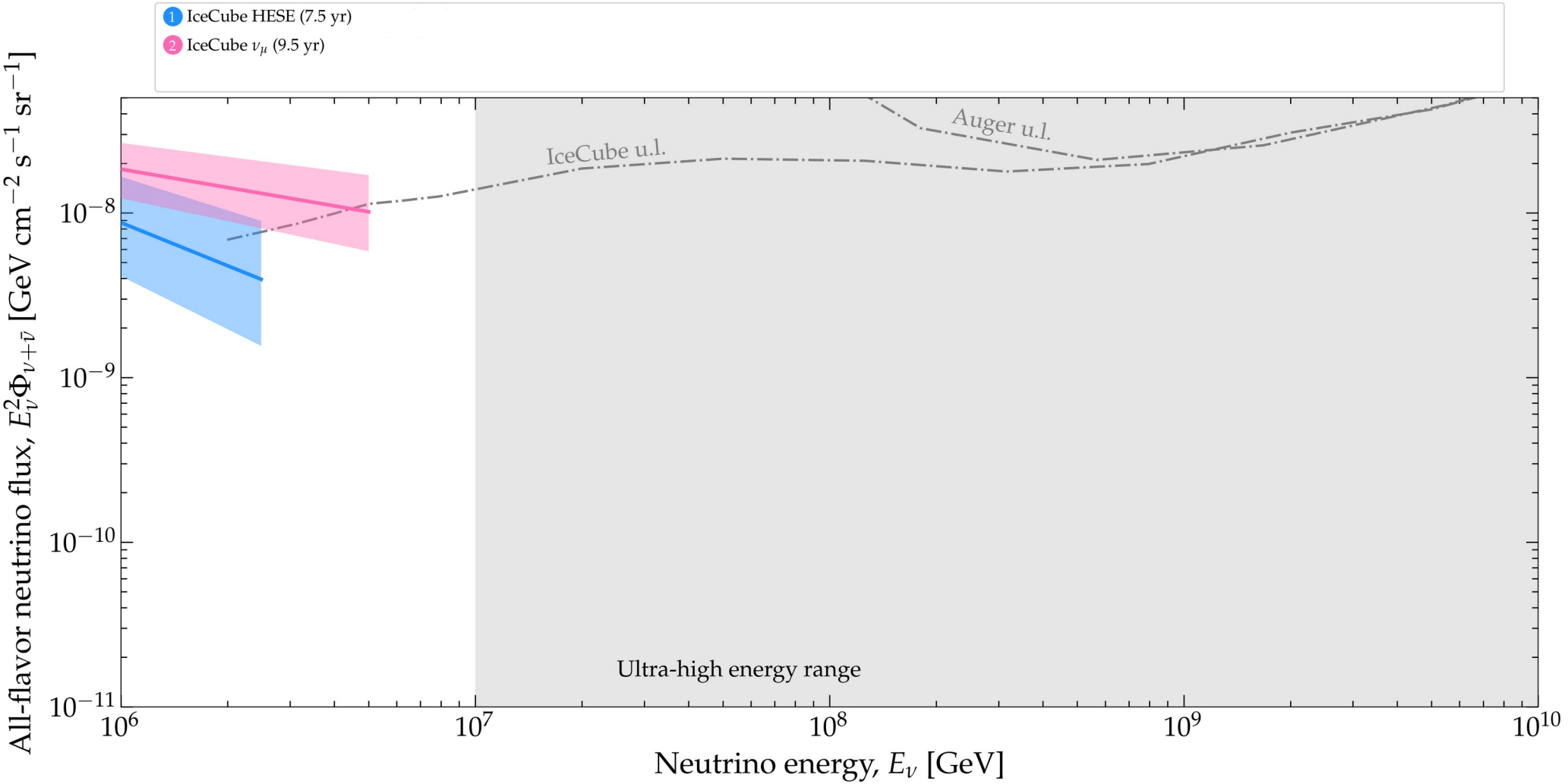
2 IceCube ν_μ (9.5 yr)
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
Ultra-high energy range
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]


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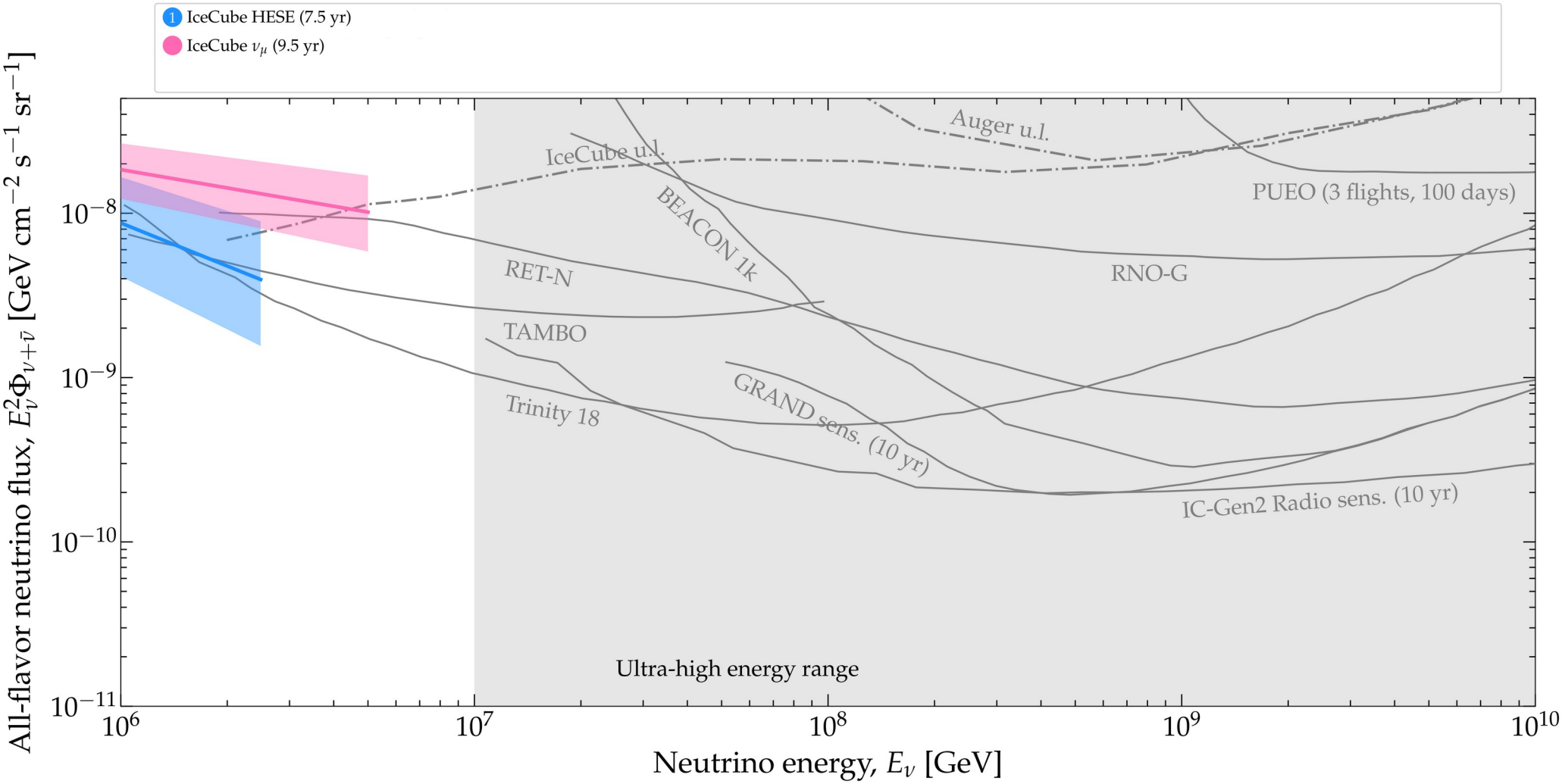
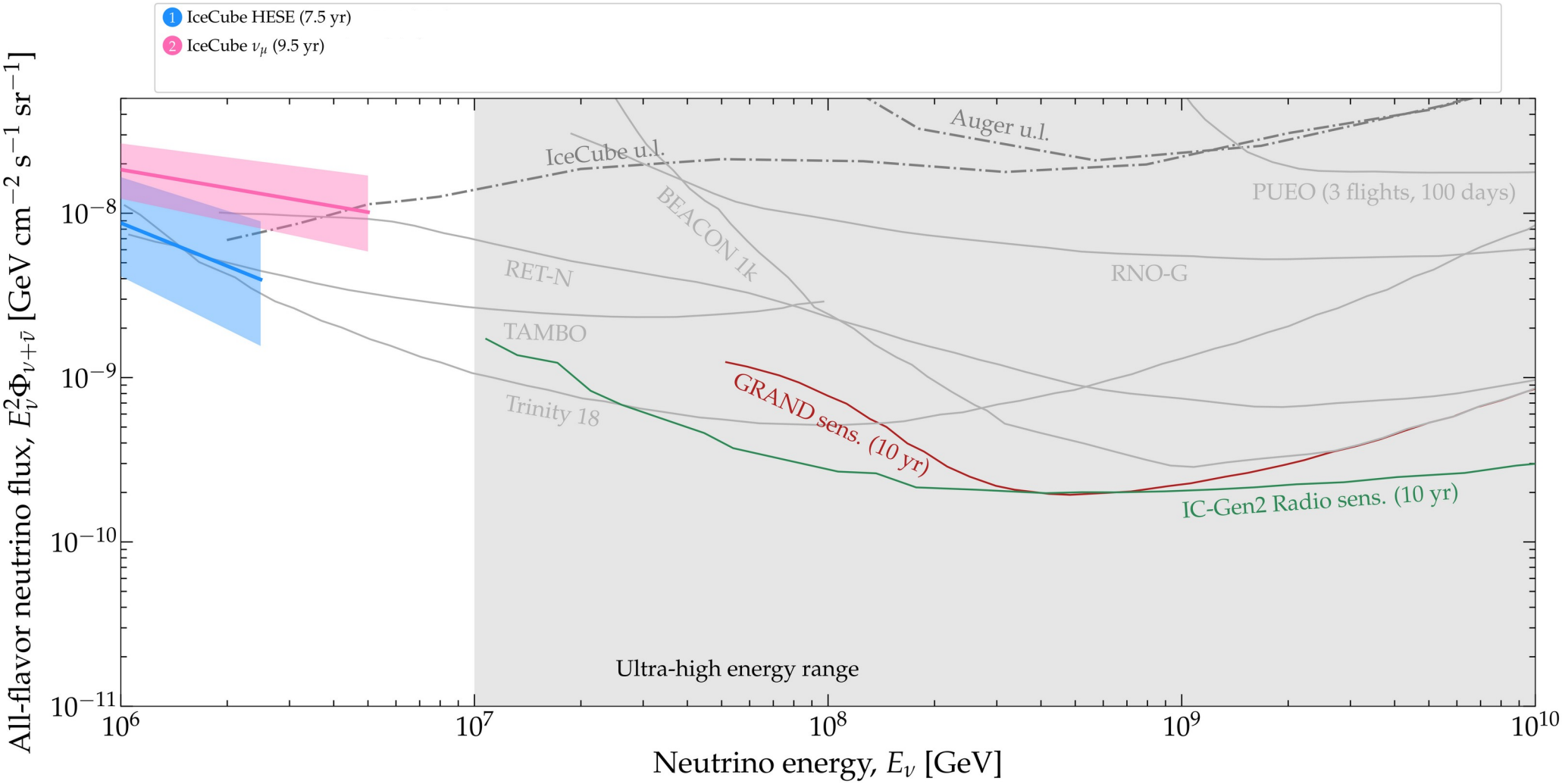
10^9
10^{10}


1 IceCube HESE (7.5 yr)
IceCube ν_μ (9.5 yr)
Auger u.l.
IceCube u.l.
BEACON 1k
PUEO (3 flights, 100 days)
RET-N
RNO-G
TAMBO
Trinity 18
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy, E_ν [GeV]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}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Auger u.l.
IceCube u.l.
BEACON 1k
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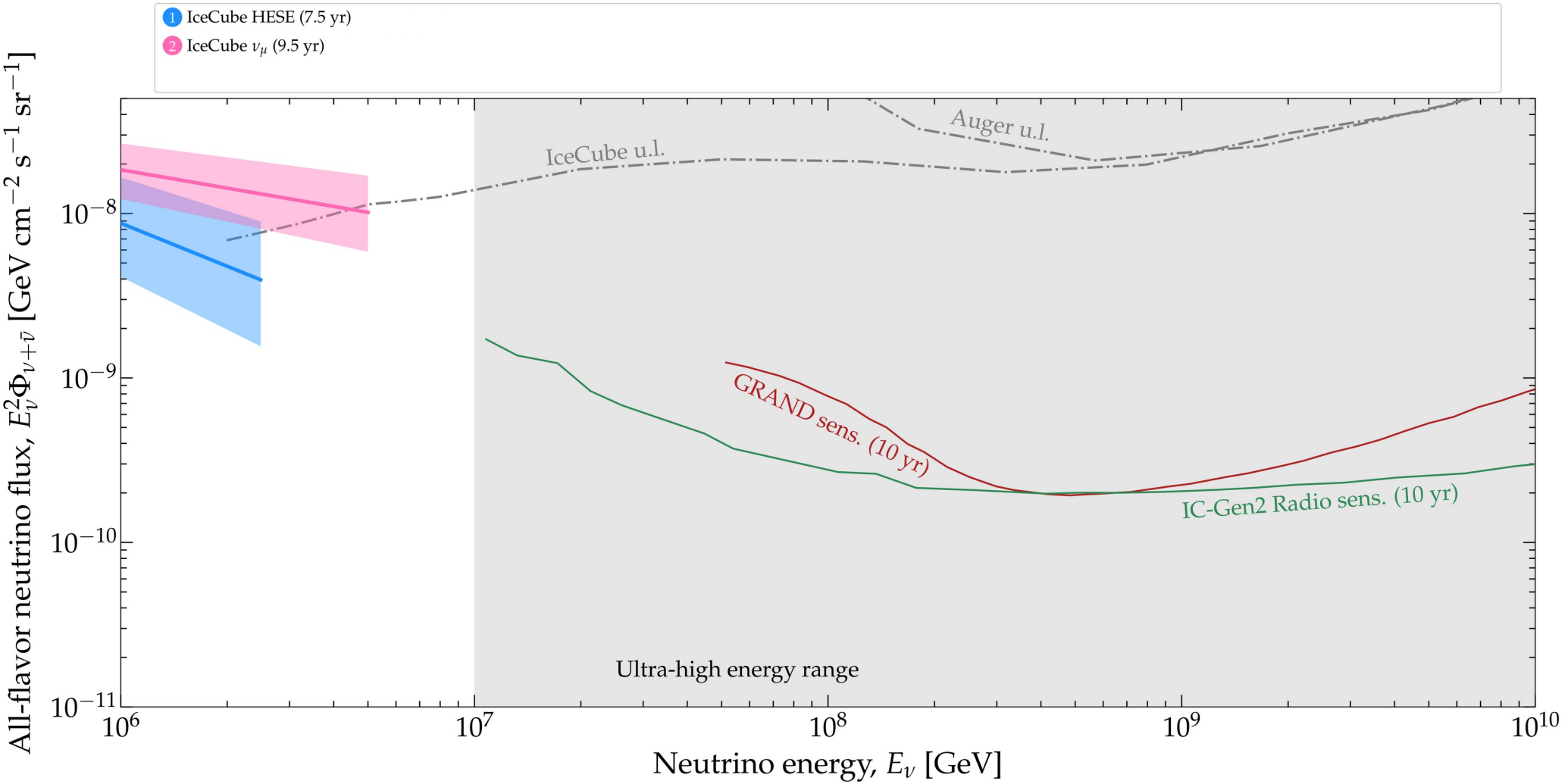
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}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Auger u.l.
IceCube u.l.
GRAND sens. (10 yr)
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10^{-8}
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10^6
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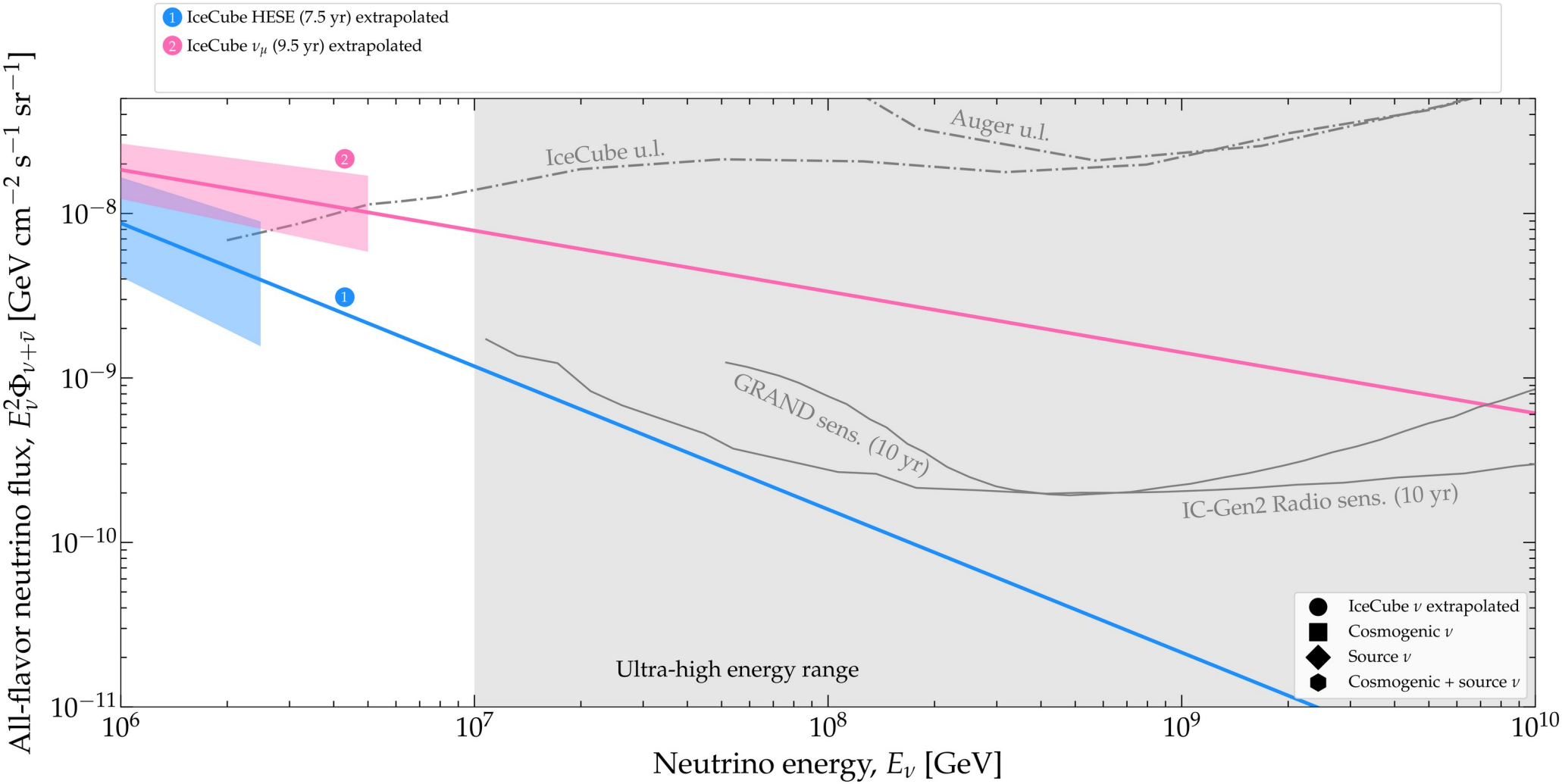
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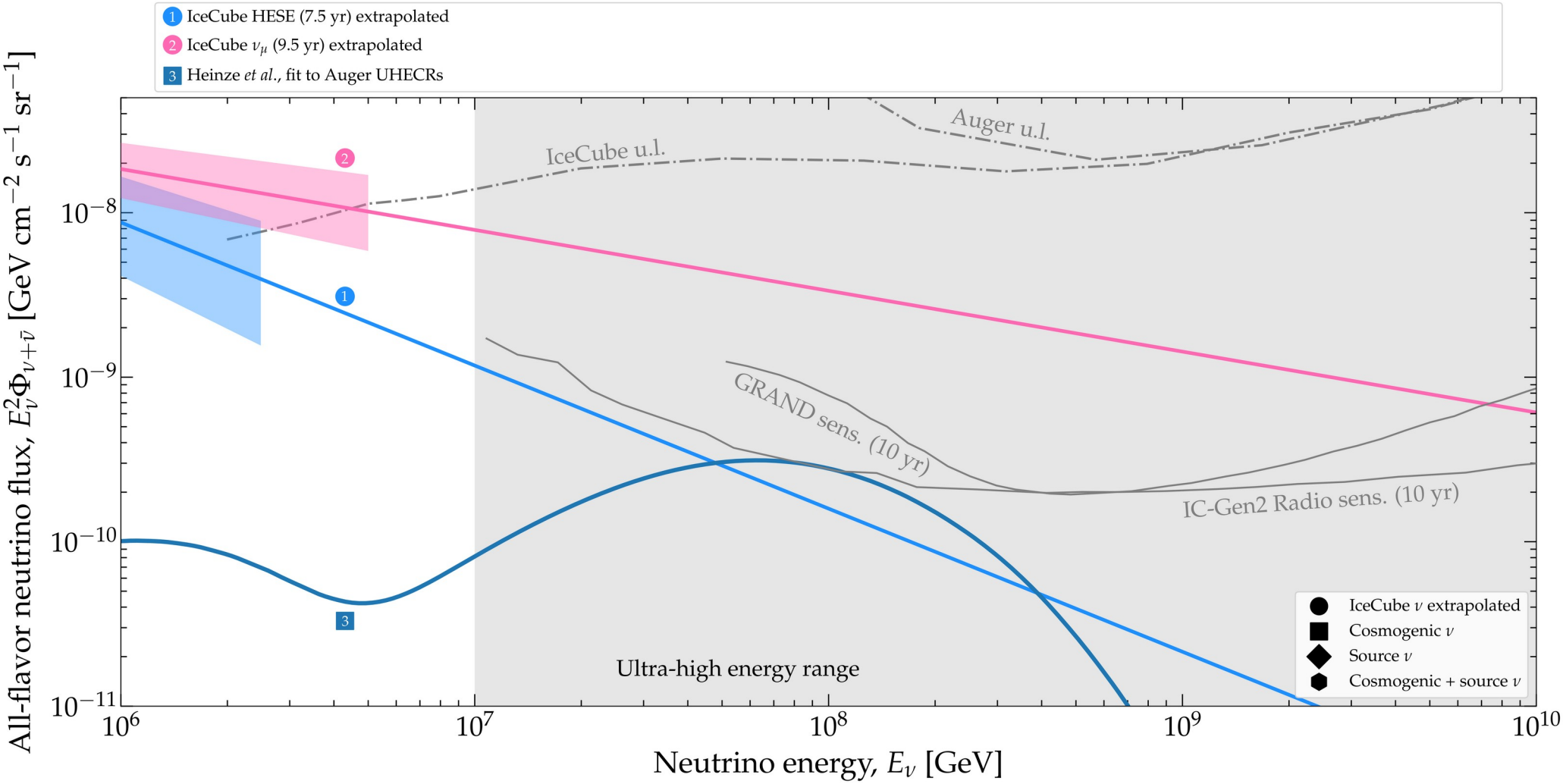
2 IceCube ν_μ (9.5 yr) extrapolated
Auger u.l.
IceCube u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
IceCube ν extrapolated
Cosmogenic ν
Source ν
Cosmogenic + source ν
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy, 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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3 Heinze *et al.*, fit to Auger UHECRs
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
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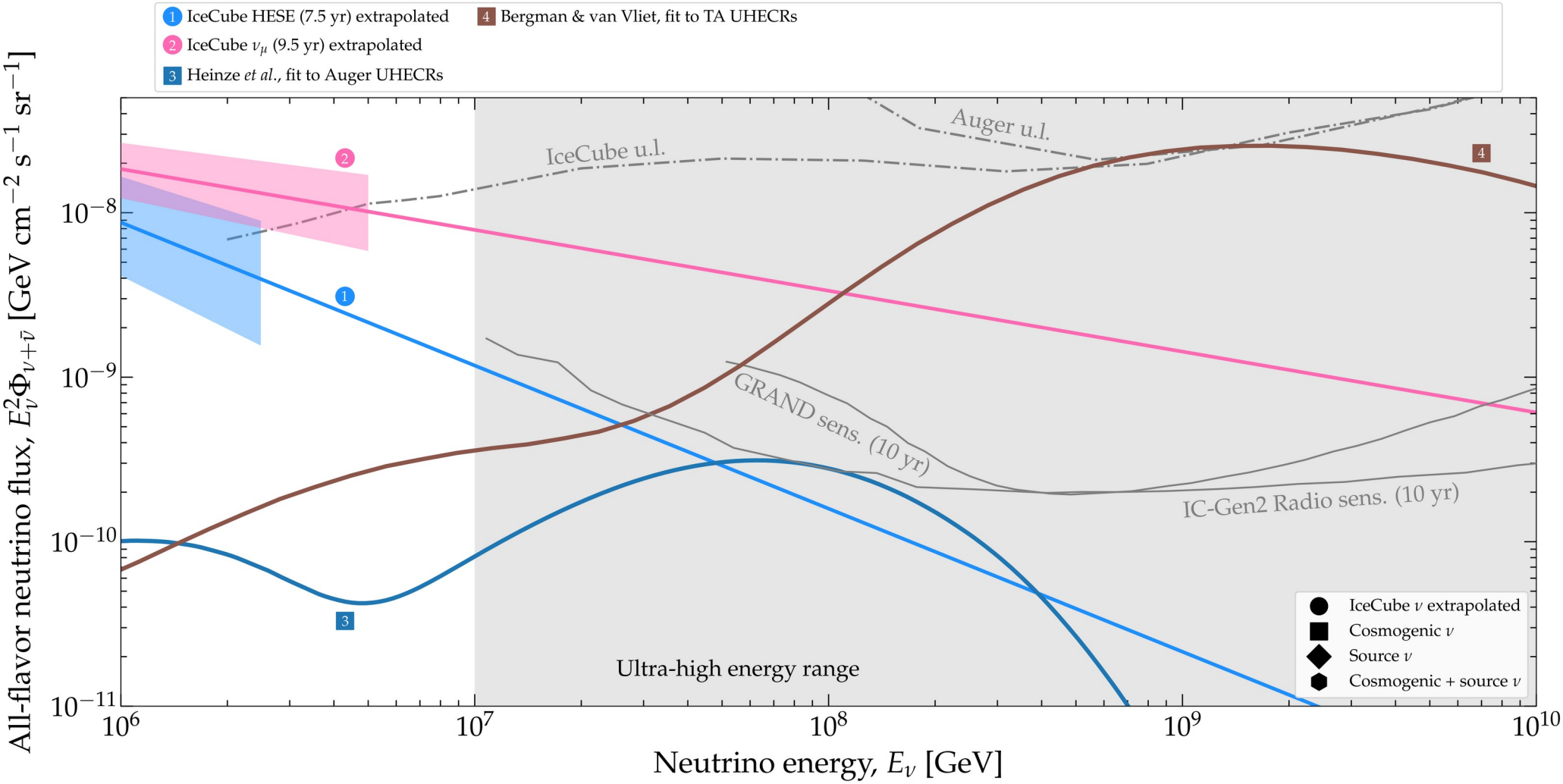
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]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IceCube u.l.
Auger u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
IceCube ν extrapolated
Cosmogenic ν
Source ν
Cosmogenic + source ν
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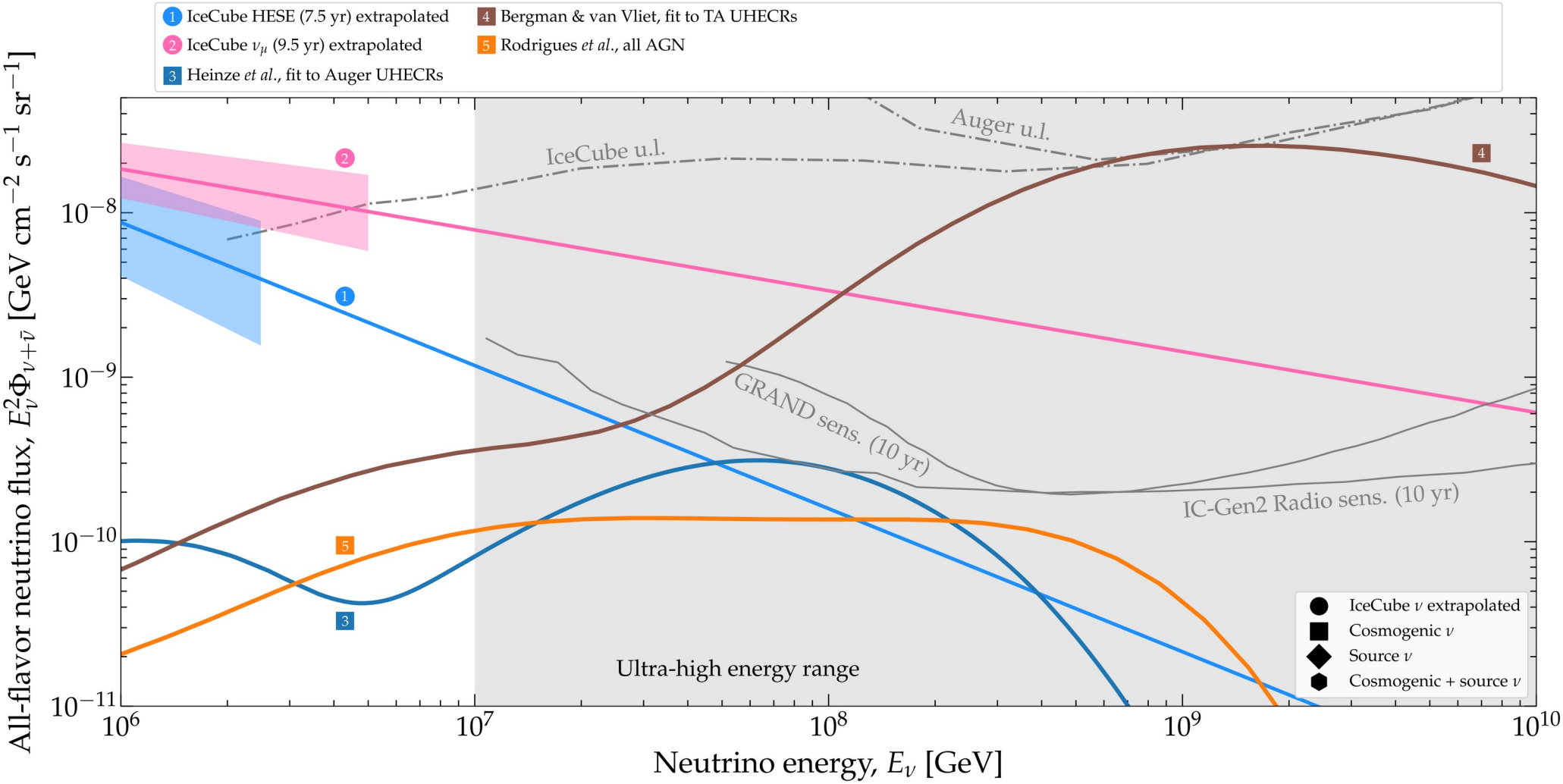
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}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IceCube u.l.
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GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
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IceCube ν extrapolated
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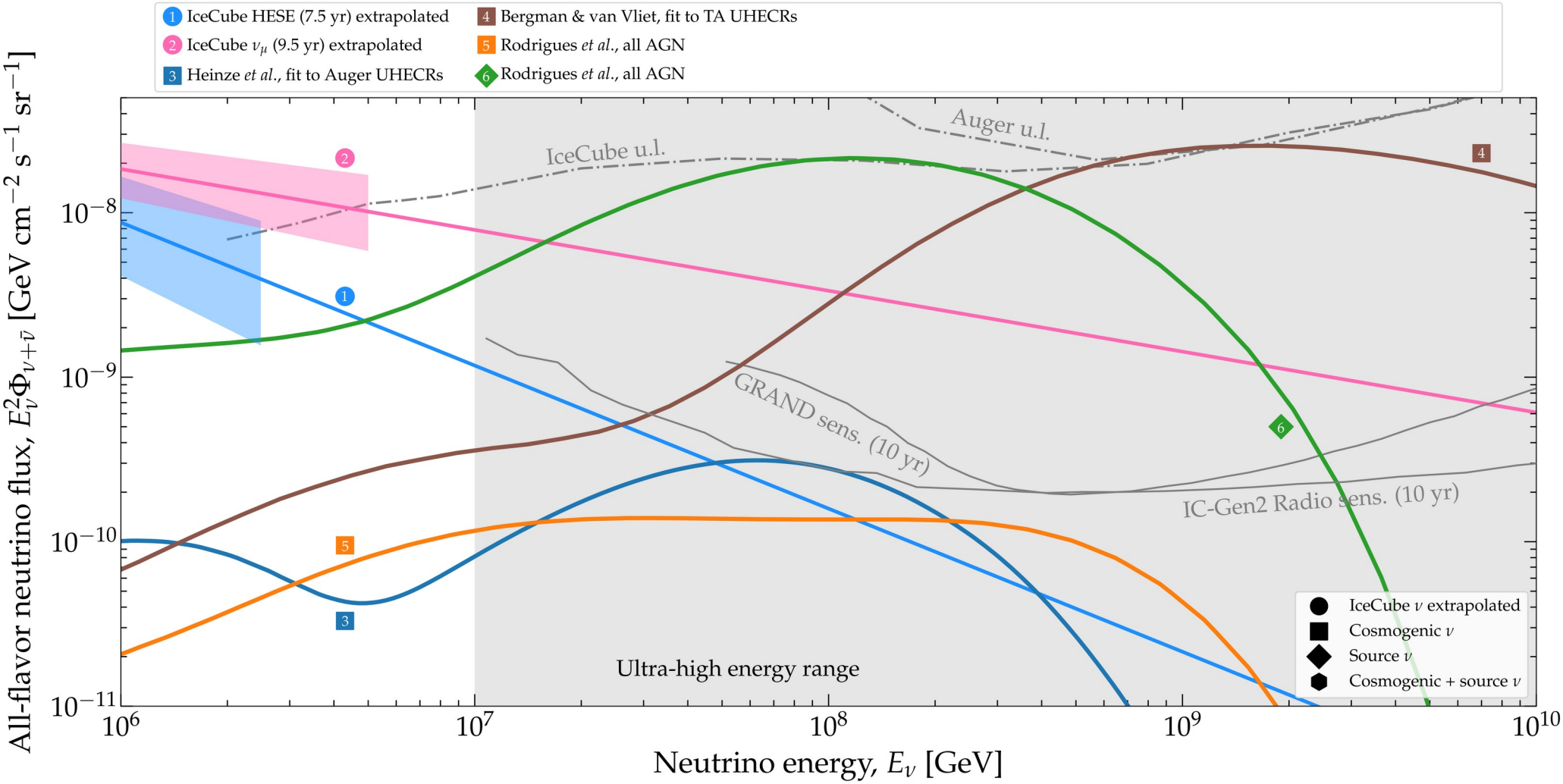
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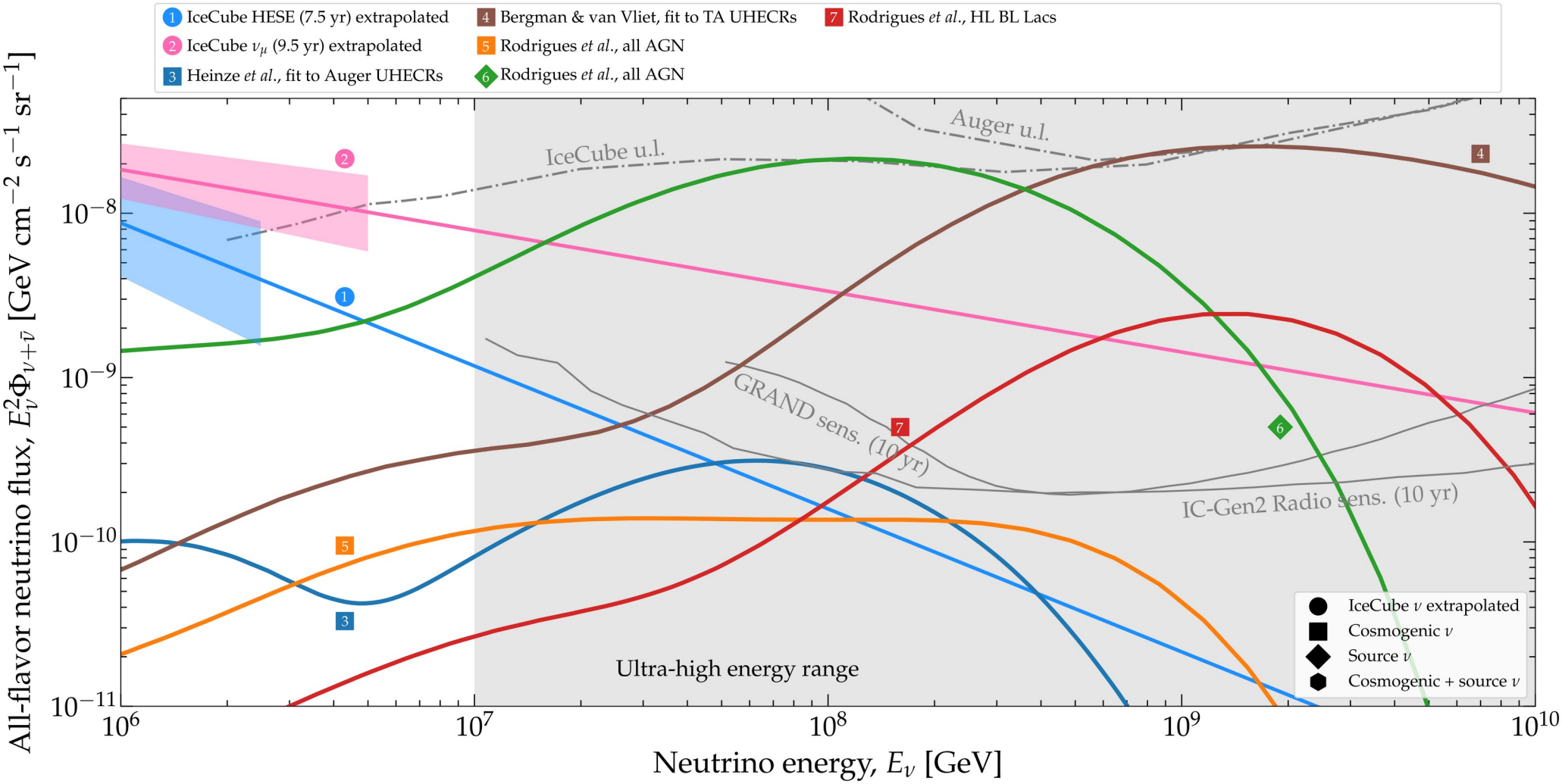
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IceCube u.l.
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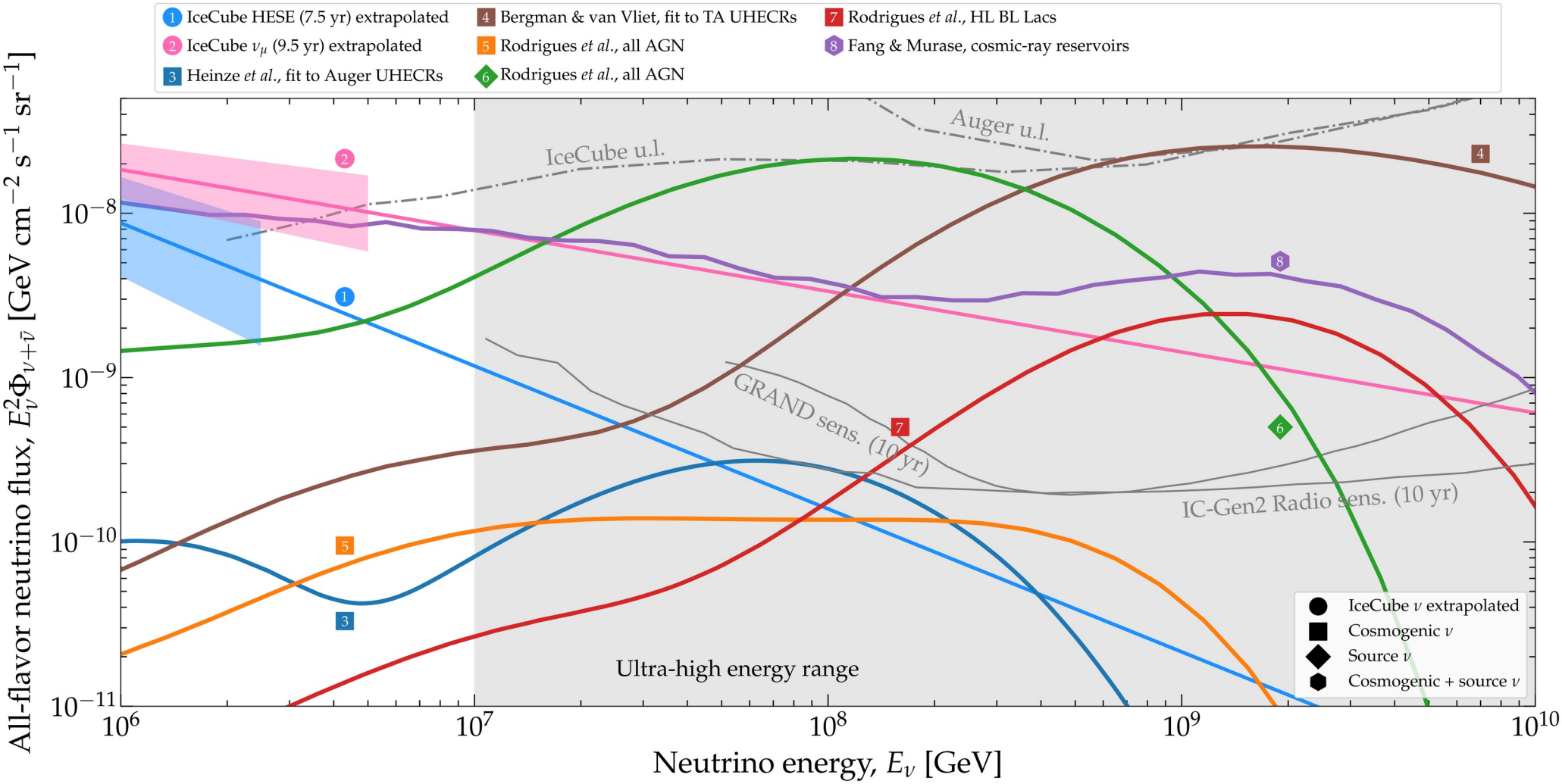
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IceCube u.l.
Auger u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
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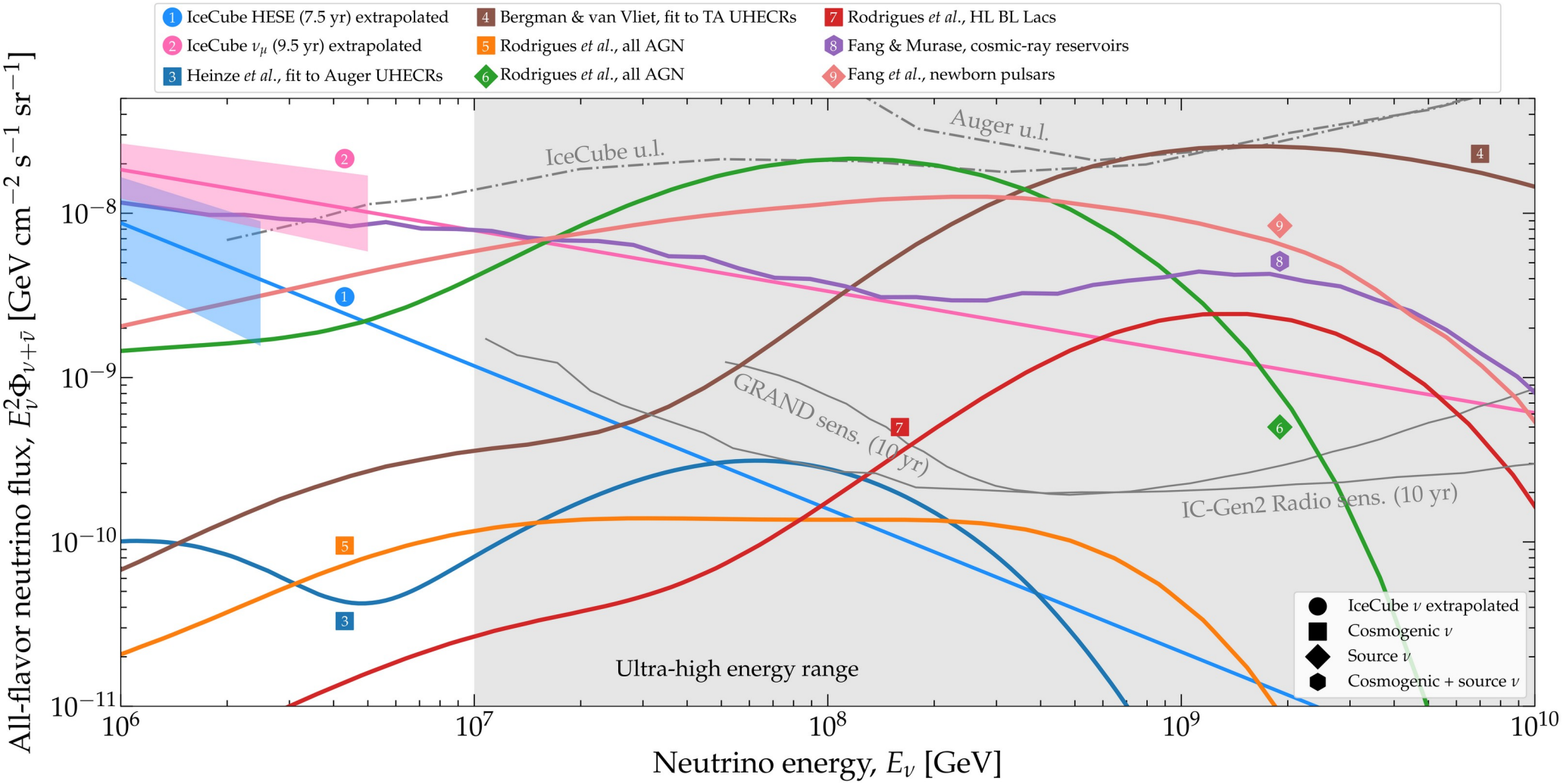
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IceCube u.l.
Auger u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
IceCube ν extrapolated
Cosmogenic ν
Source ν
Cosmogenic + source ν
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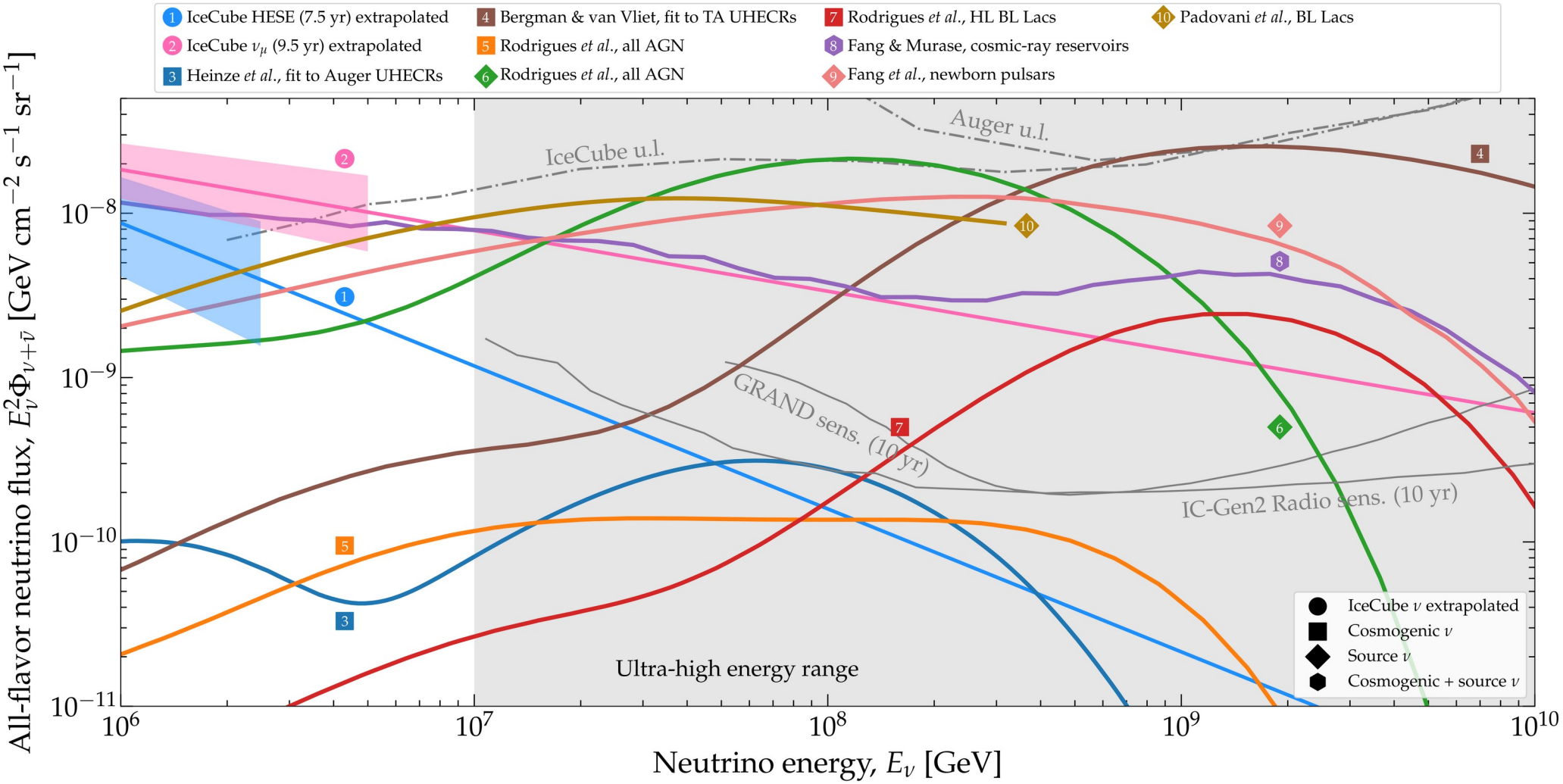
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IceCube u.l.
Auger u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
IceCube ν extrapolated
Cosmogenic ν
Source ν
Cosmogenic + source ν
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
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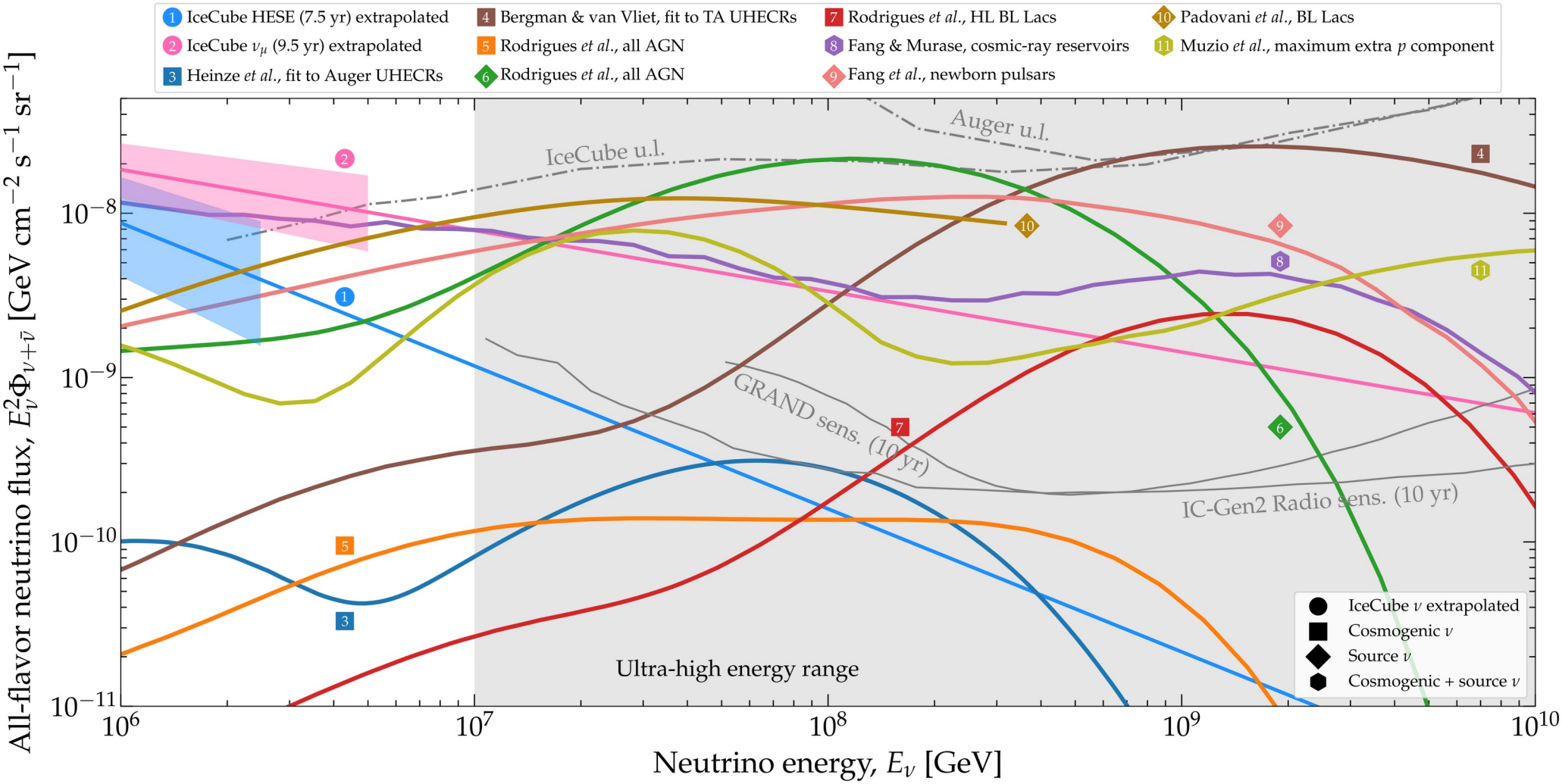
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11 Muzio et al., maximum extra p component
IceCube u.l.
Auger u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
IceCube ν extrapolated
Cosmogenic ν
Source ν
Cosmogenic + source ν
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy, E_ν [GeV]
10^{-8}
10^{-9}
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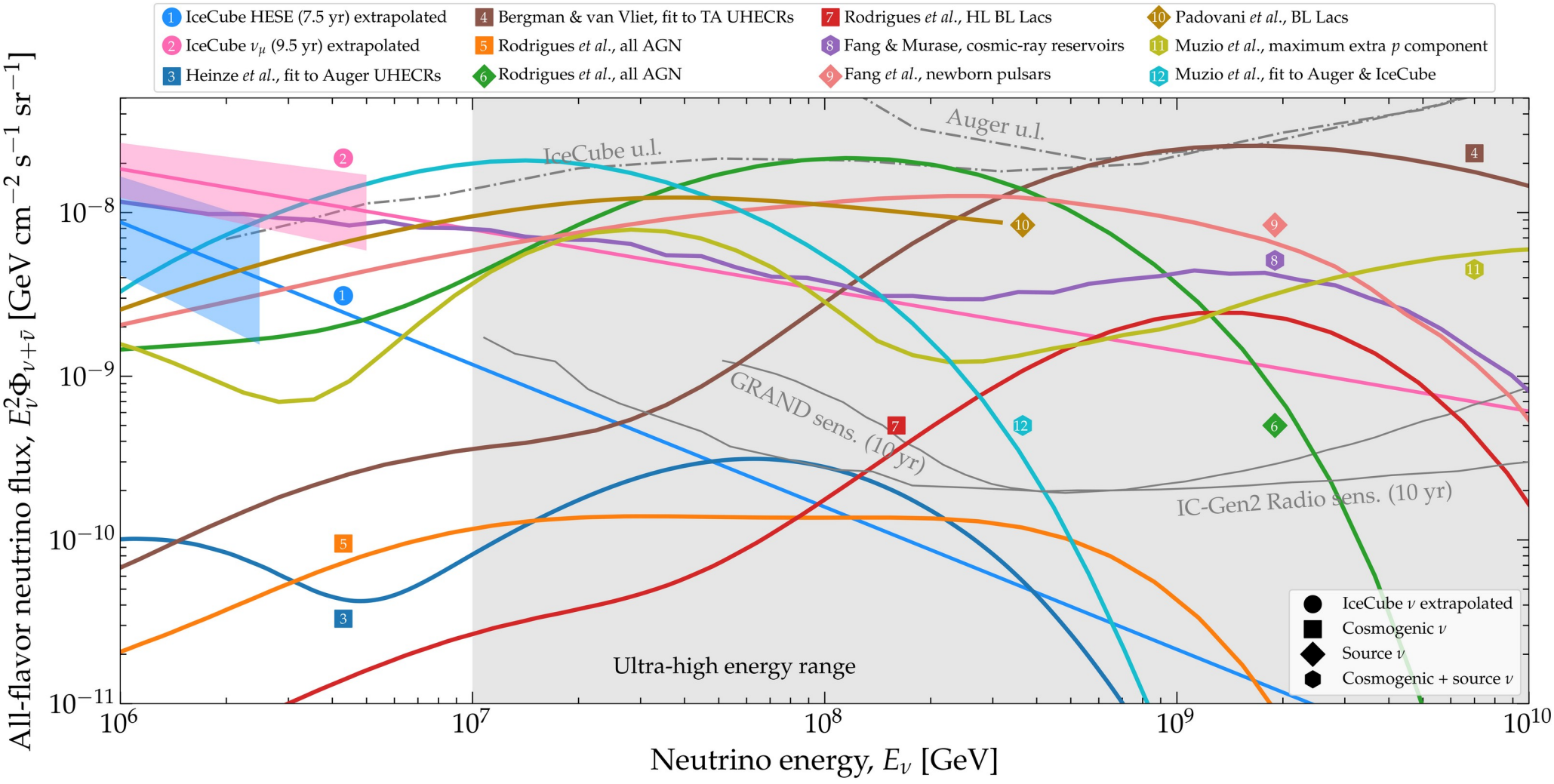
1 IceCube HESE (7.5 yr) extrapolated
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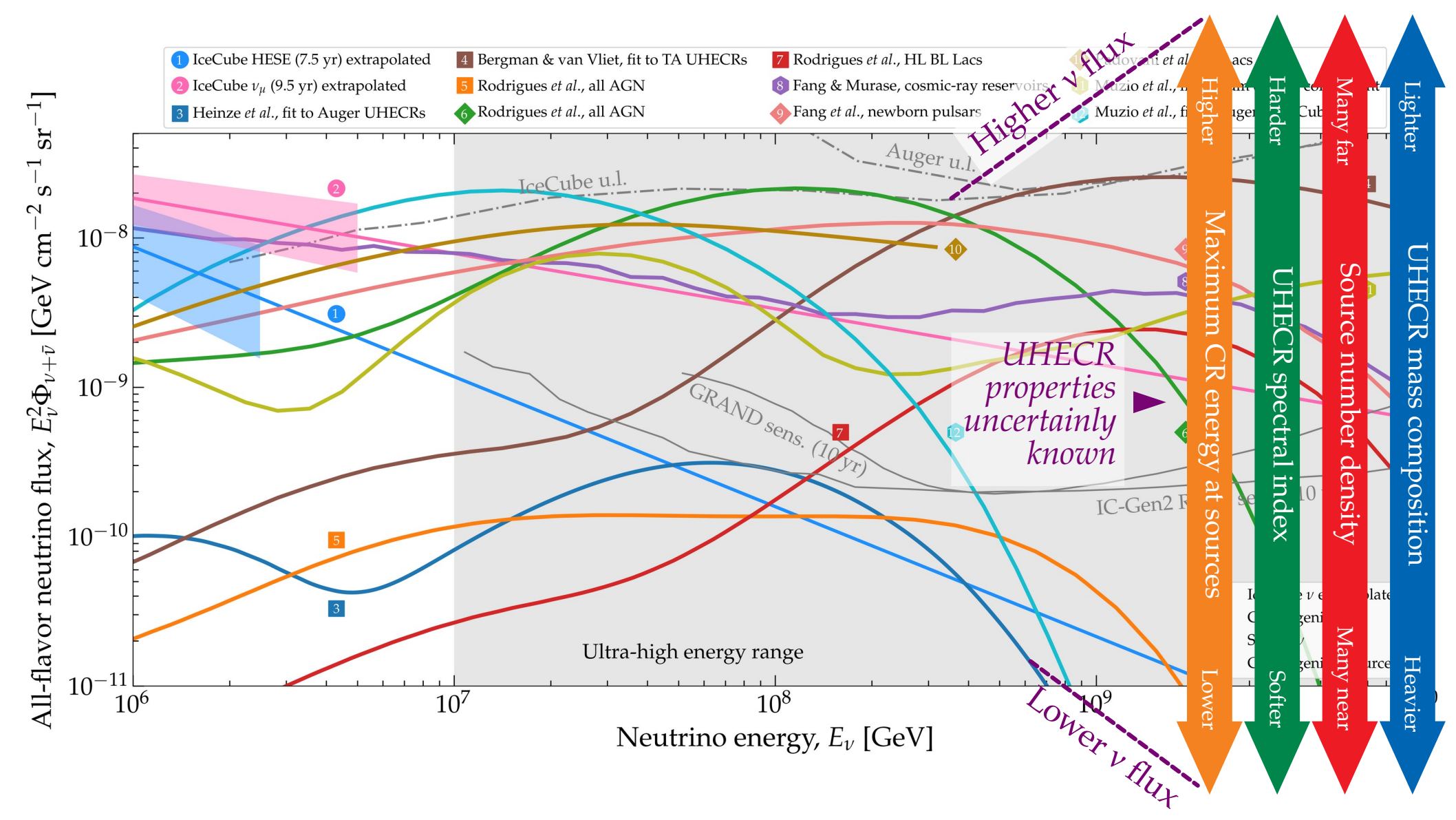
9 Fang et al., newborn pulsars
10 Padovani et al., BL Lacs
11 Muzio et al., maximum extra p component
12 Muzio et al., fit to Auger & IceCube
IceCube u.l.
Auger u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
IceCube ν extrapolated
Cosmogenic ν
Source ν
Cosmogenic + source ν
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]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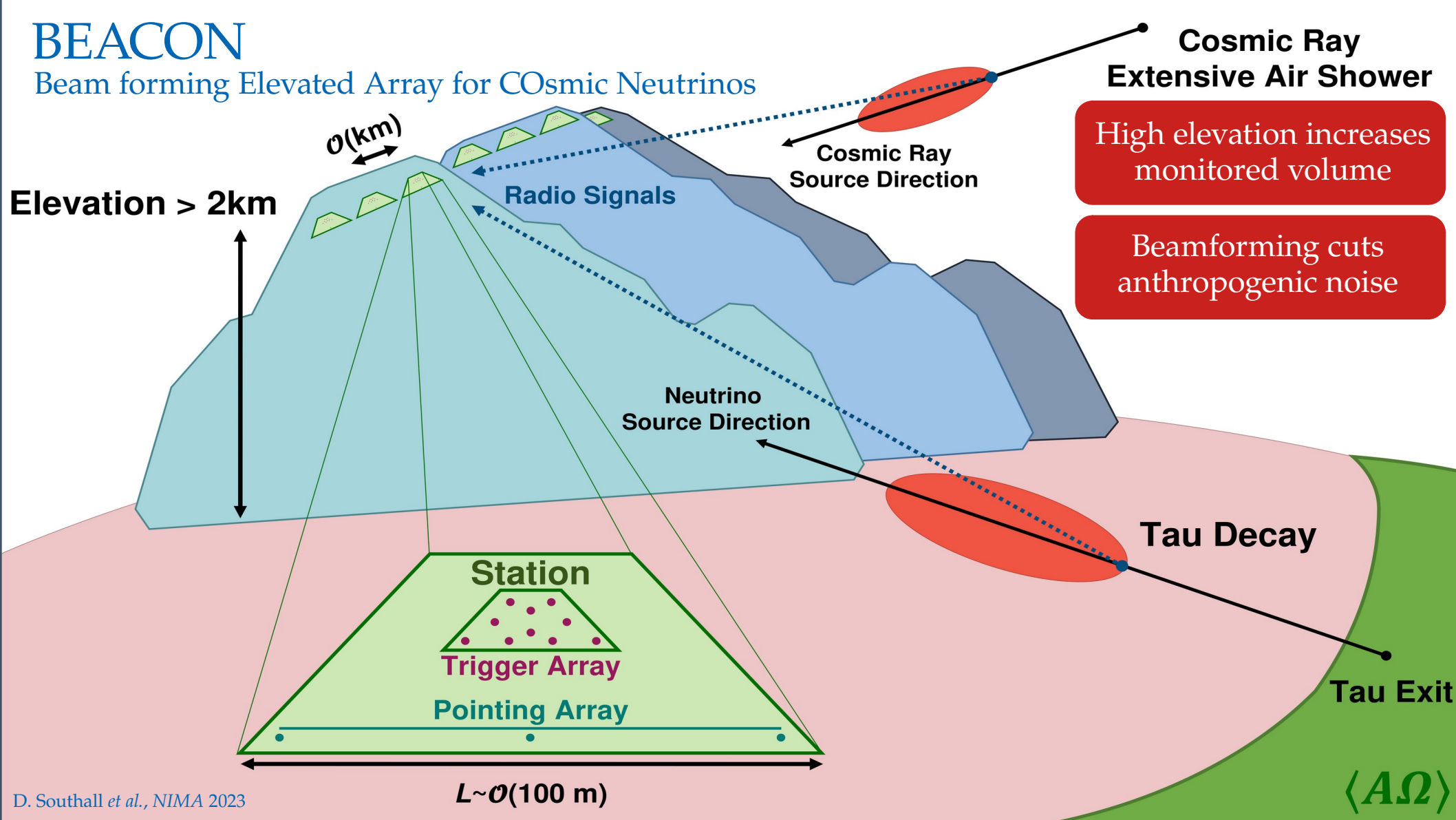
9 Fang et al., newborn pulsars
Higher ν flux
Auger u.l.
IceCube u.l.
GRAND sens. (10 yr)
IC-Gen2 R
UHECR properties uncertainly known
Ultra-high energy range
Lower ν flux
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy, E_ν [GeV]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
Higher
Maximum CR energy at sources
Lower
Harder
UHECR spectral index
Softer
Many far
Source number density
Many near
Lighter
UHECR mass composition
Heavier

BEACON

Beam forming Elevated Array for COsmic Neutrinos



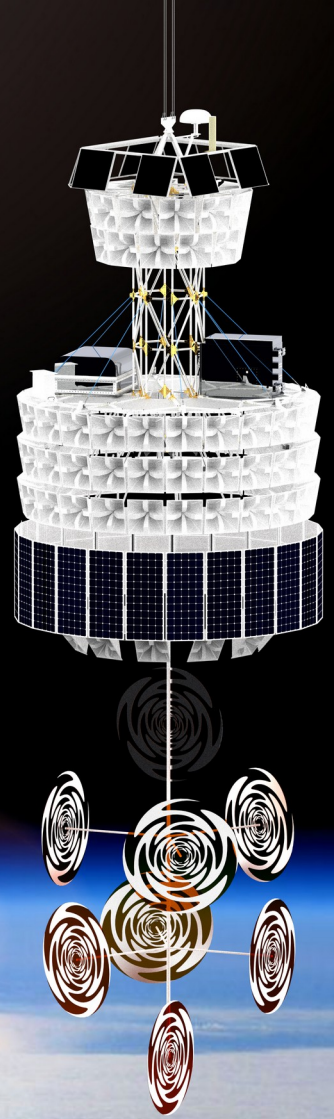
D. Southall *et al.*, *NIMA* 2023

PUEO

Payload for Ultrahigh Energy Observations

30-day flight above Antarctica

Builds on earlier ANITA I–IV flights



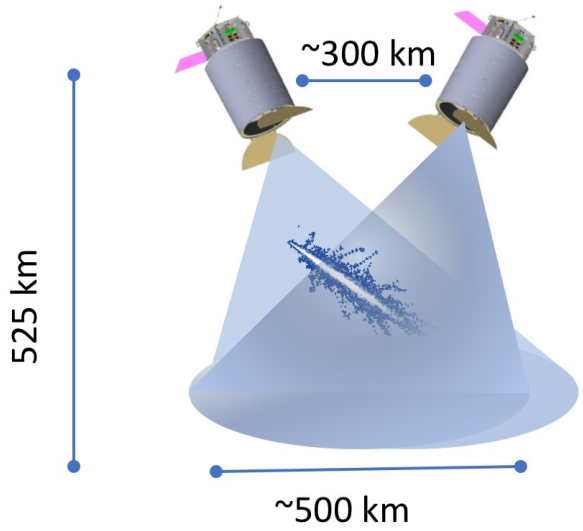
PUEO Collaboration

POEMMA: Probe of Extreme Multi-Messenger Astrophysics

Observing fluorescence and Cherenkov radiation from space using twin satellites

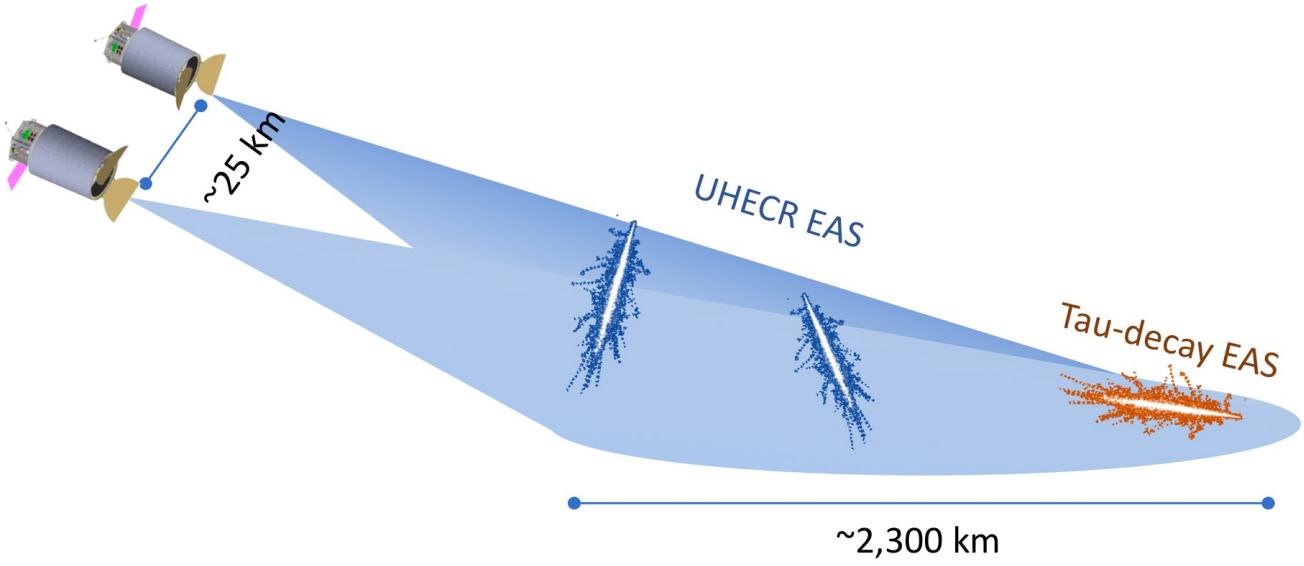
Fluorescence

POEMMA-Stereo



Cherenkov radiation

POEMMA-Limb



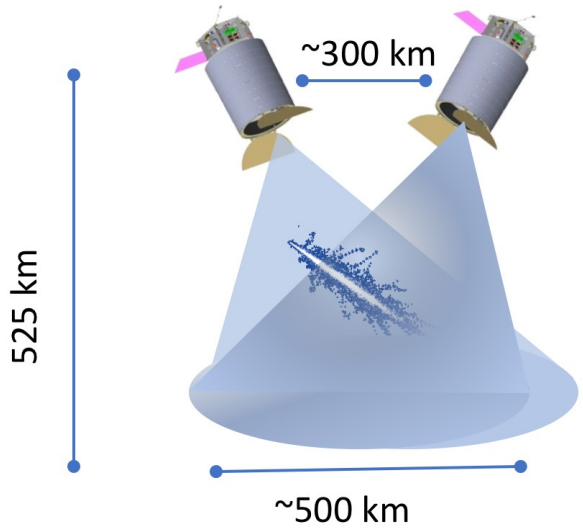
POEMMA, *JCAP* 2021 (2012.07945)

POEMMA: Probe of Extreme Multi-Messenger Astrophysics

Observing fluorescence and Cherenkov radiation from space using twin satellites

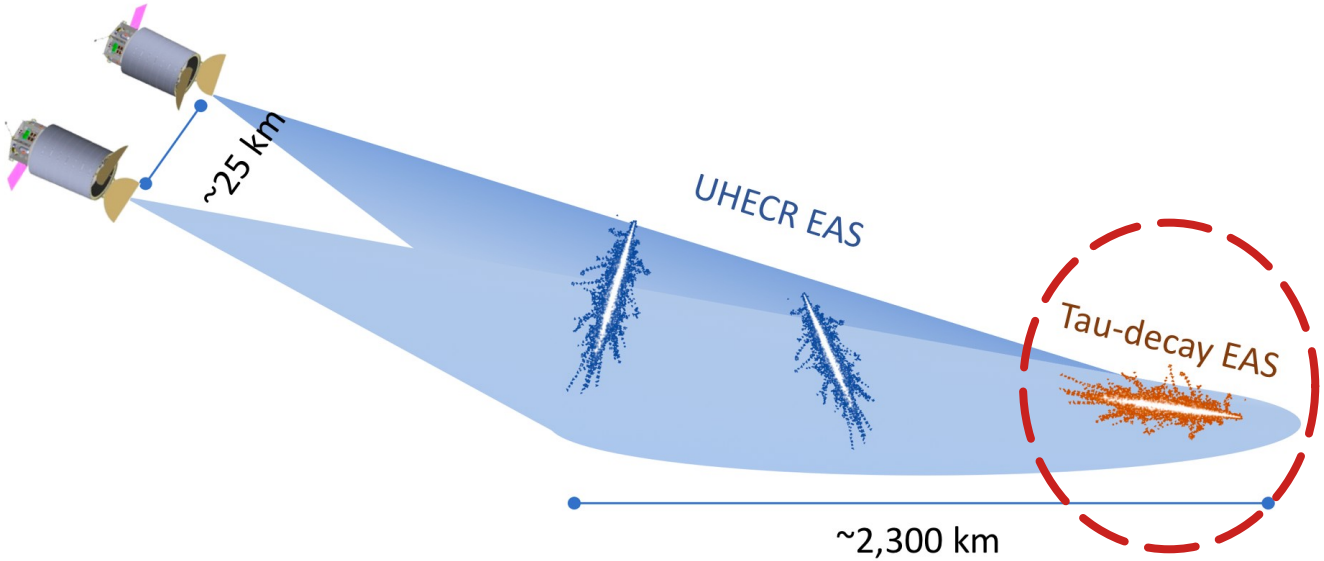
Fluorescence

POEMMA-Stereo



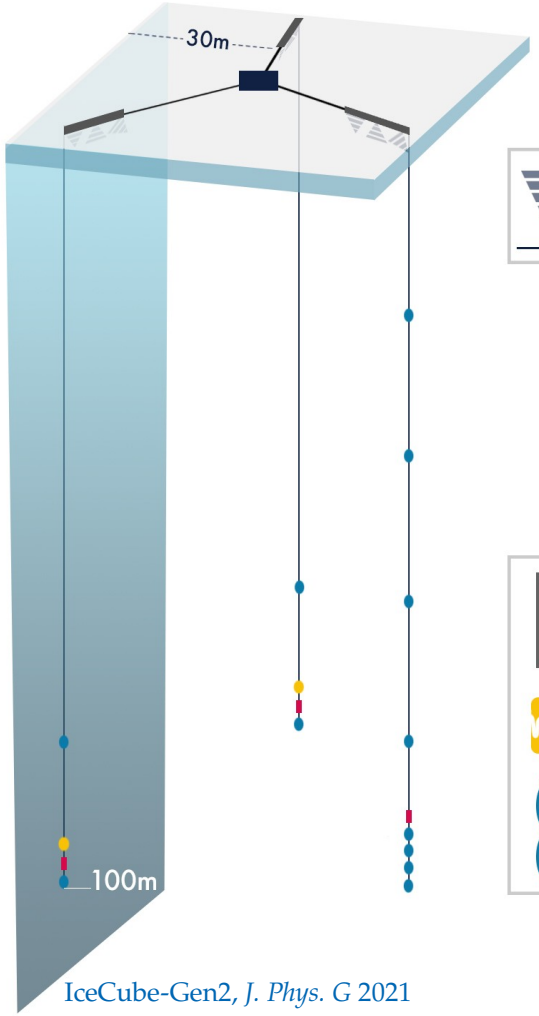
Cherenkov radiation

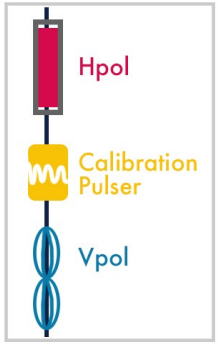
POEMMA-Limb

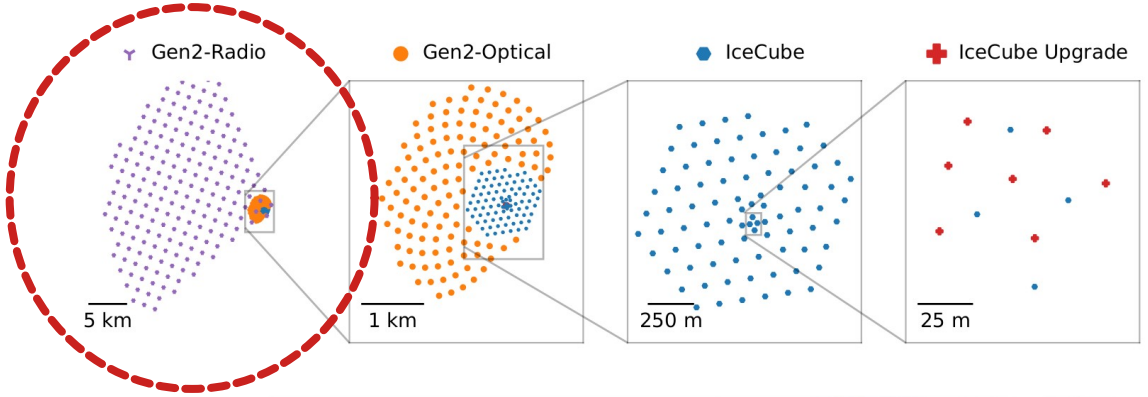


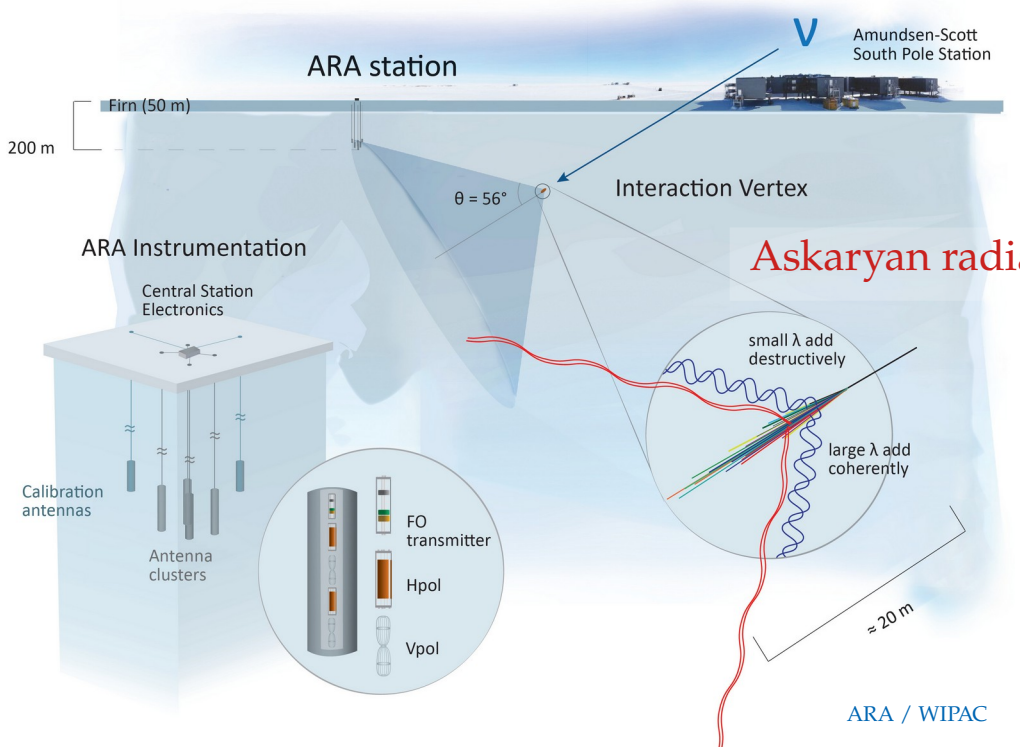
POEMMA, *JCAP* 2021 (2012.07945)

IceCube-Gen2 Radio





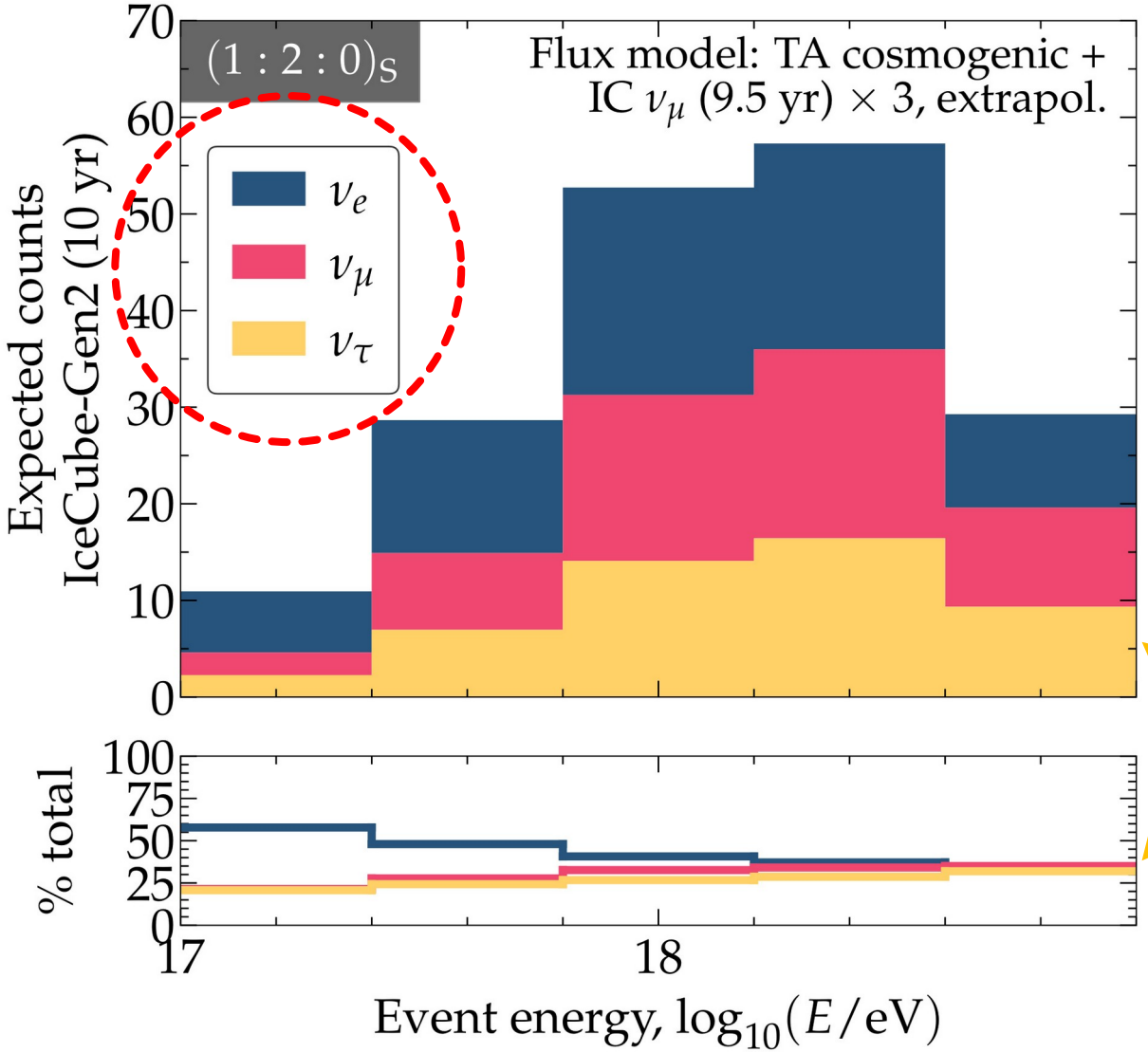




IceCube-Gen2, *J. Phys. G* 2021

ARA / WIPAC

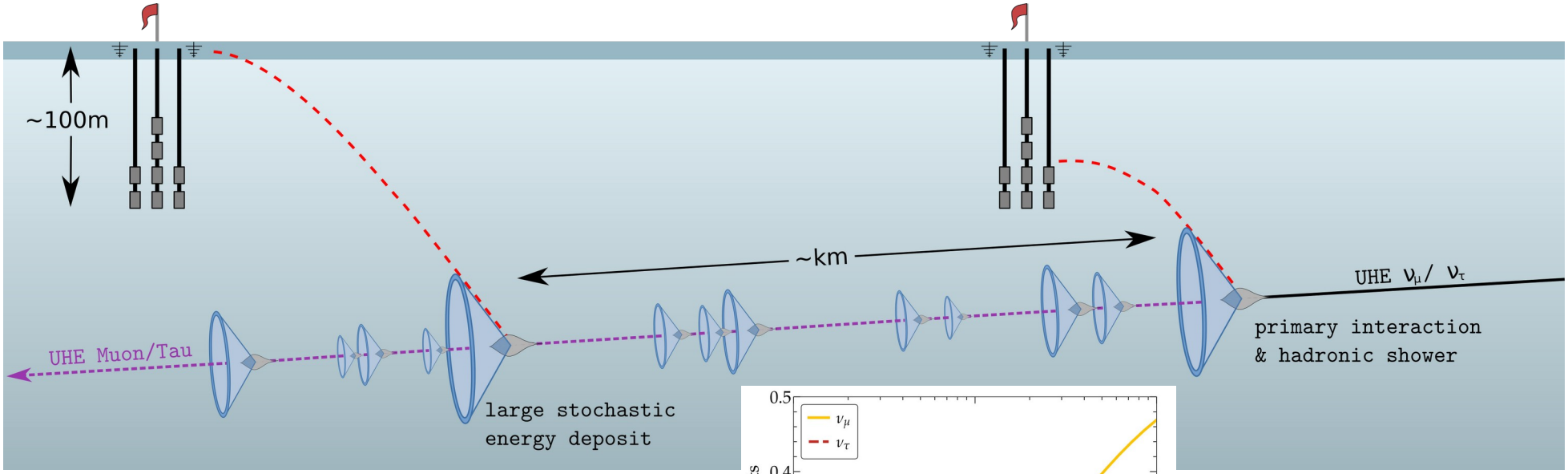
The radio array of Gen2 is sensitive to all flavors



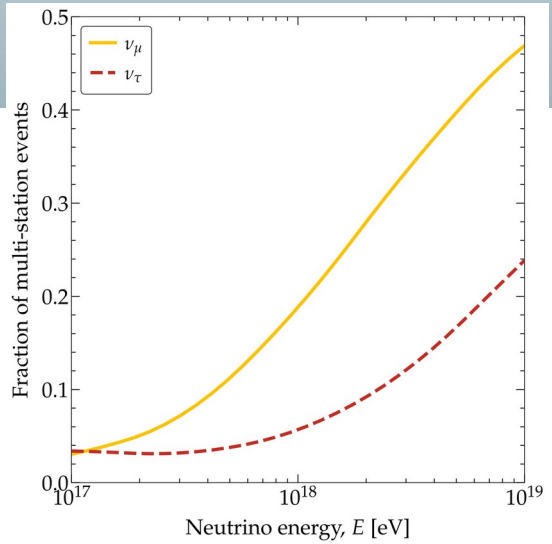
20–40% of events are due to ν_τ

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

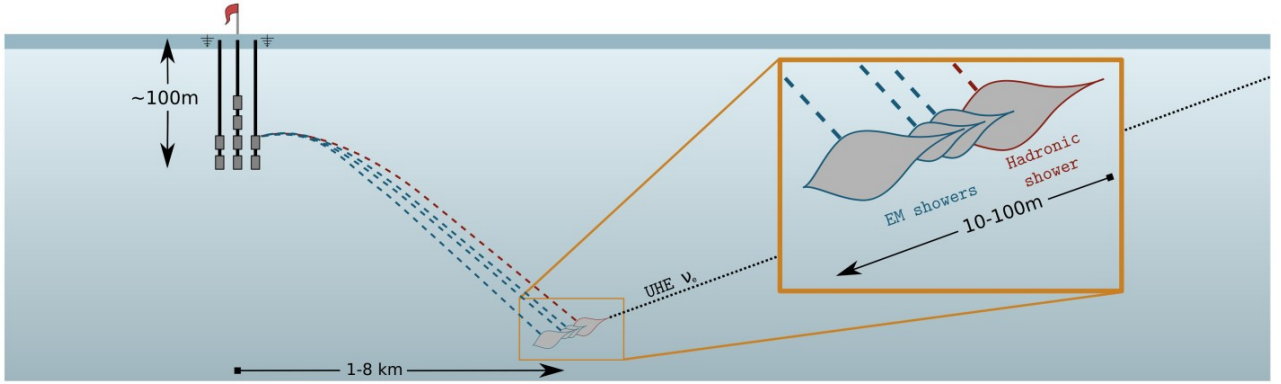
Multi-shower events from $\nu_\mu + \nu_\tau$ in IceCube-Gen2 (radio)

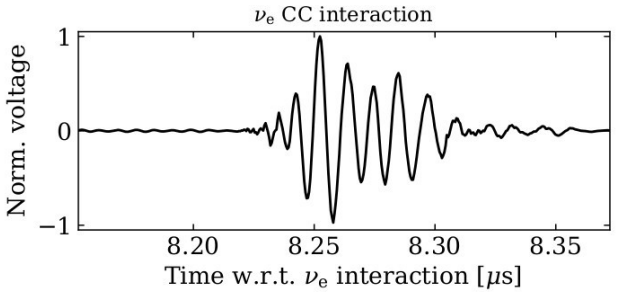


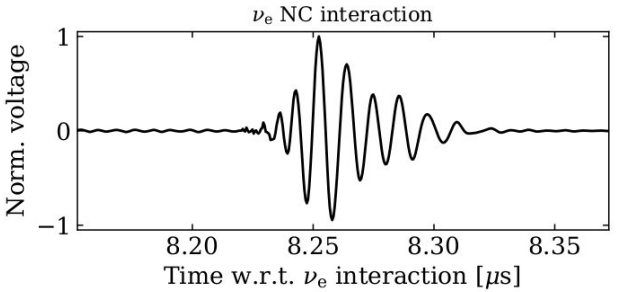
Coleman, Ericsson, **MB**, Glaser, 2402.02432

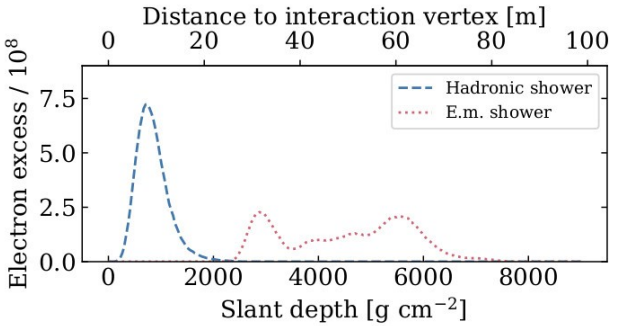


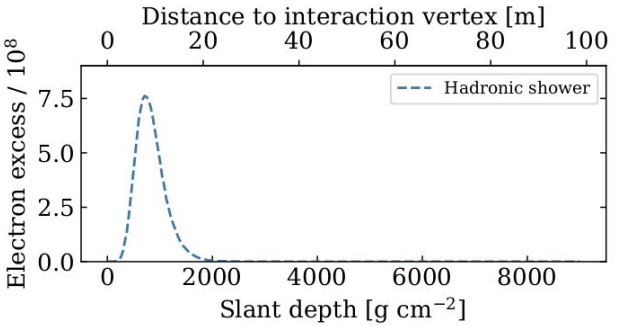
Multi-shower ν_e CC interactions in IceCube-Gen2 (radio)











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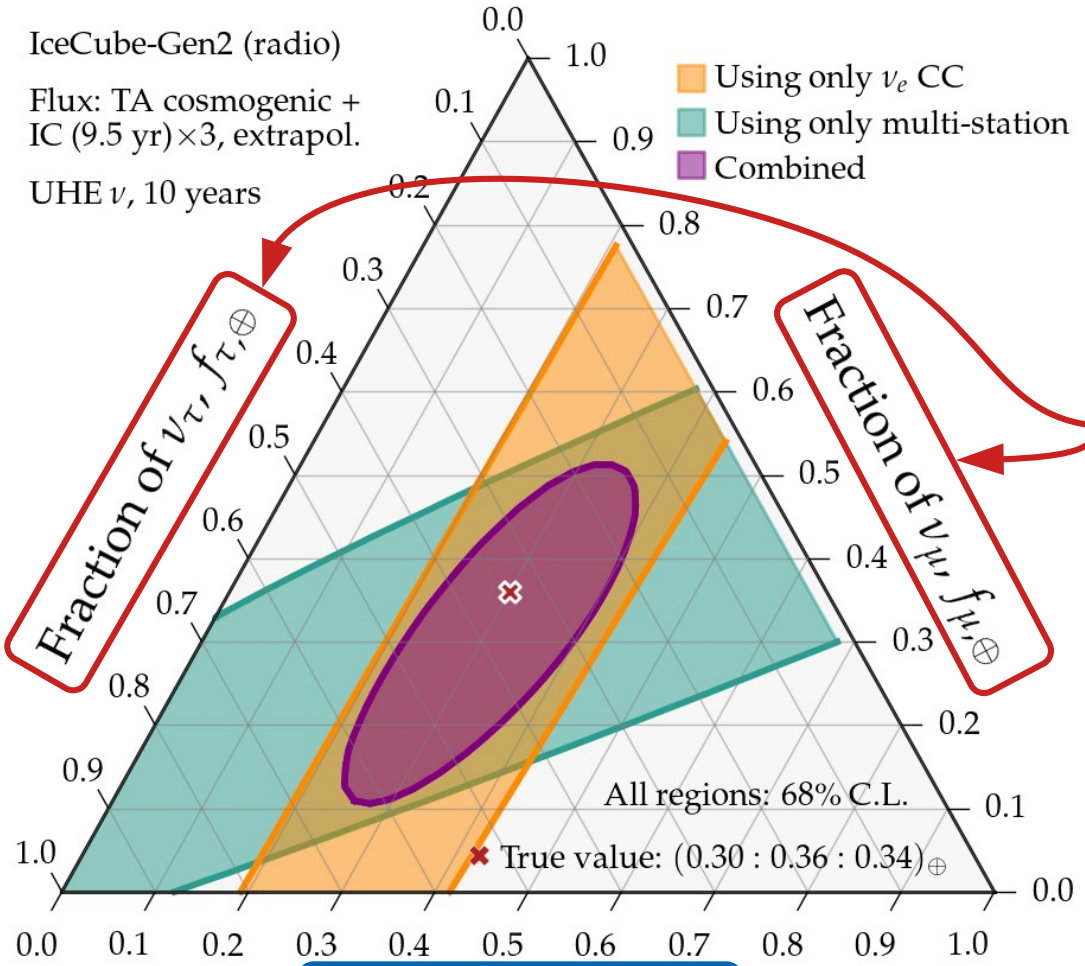
IceCube-Gen2 (radio) alone might measure flavor



Fraction of ν_e

Showers are elongated due to the LPM effect

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

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

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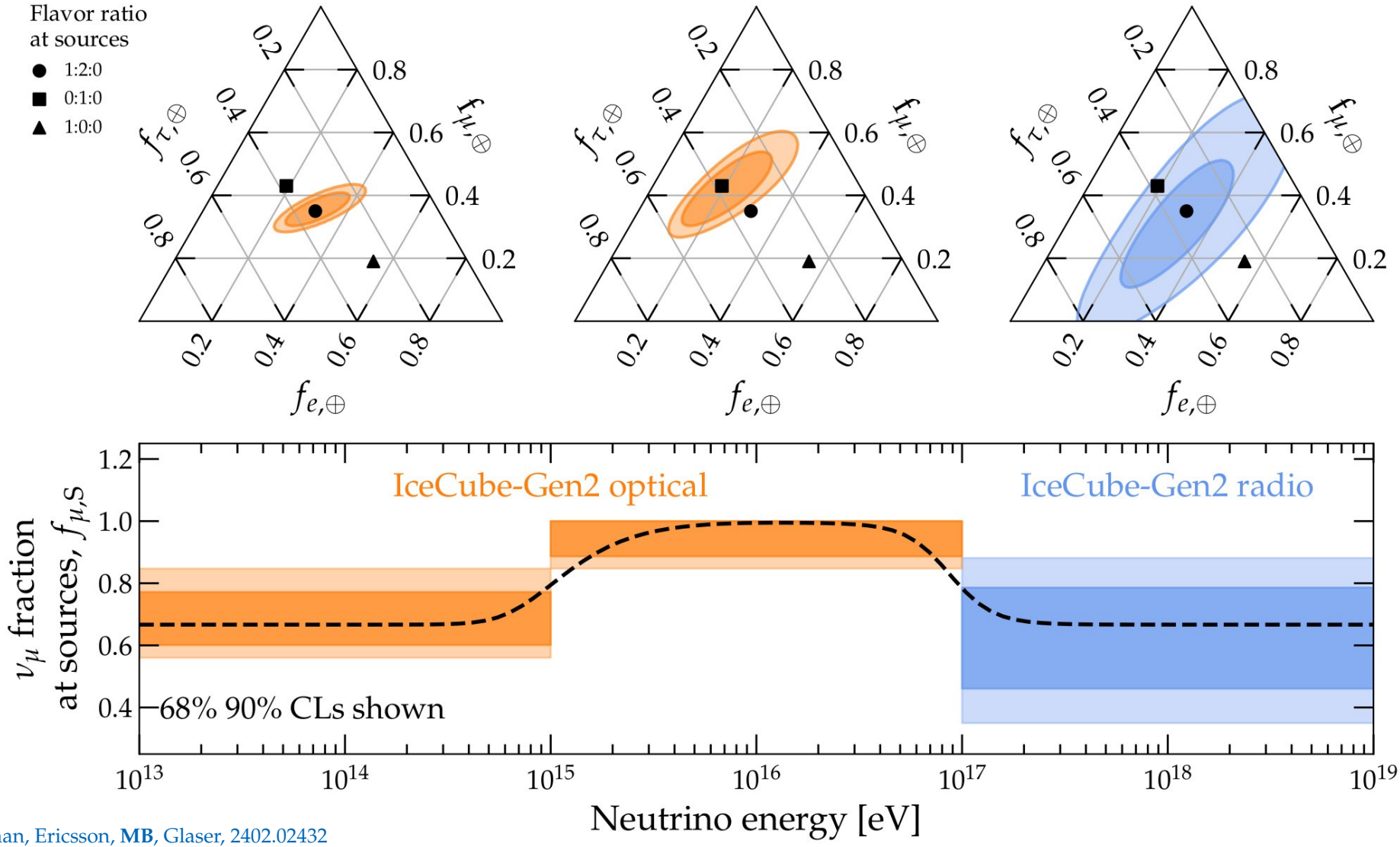

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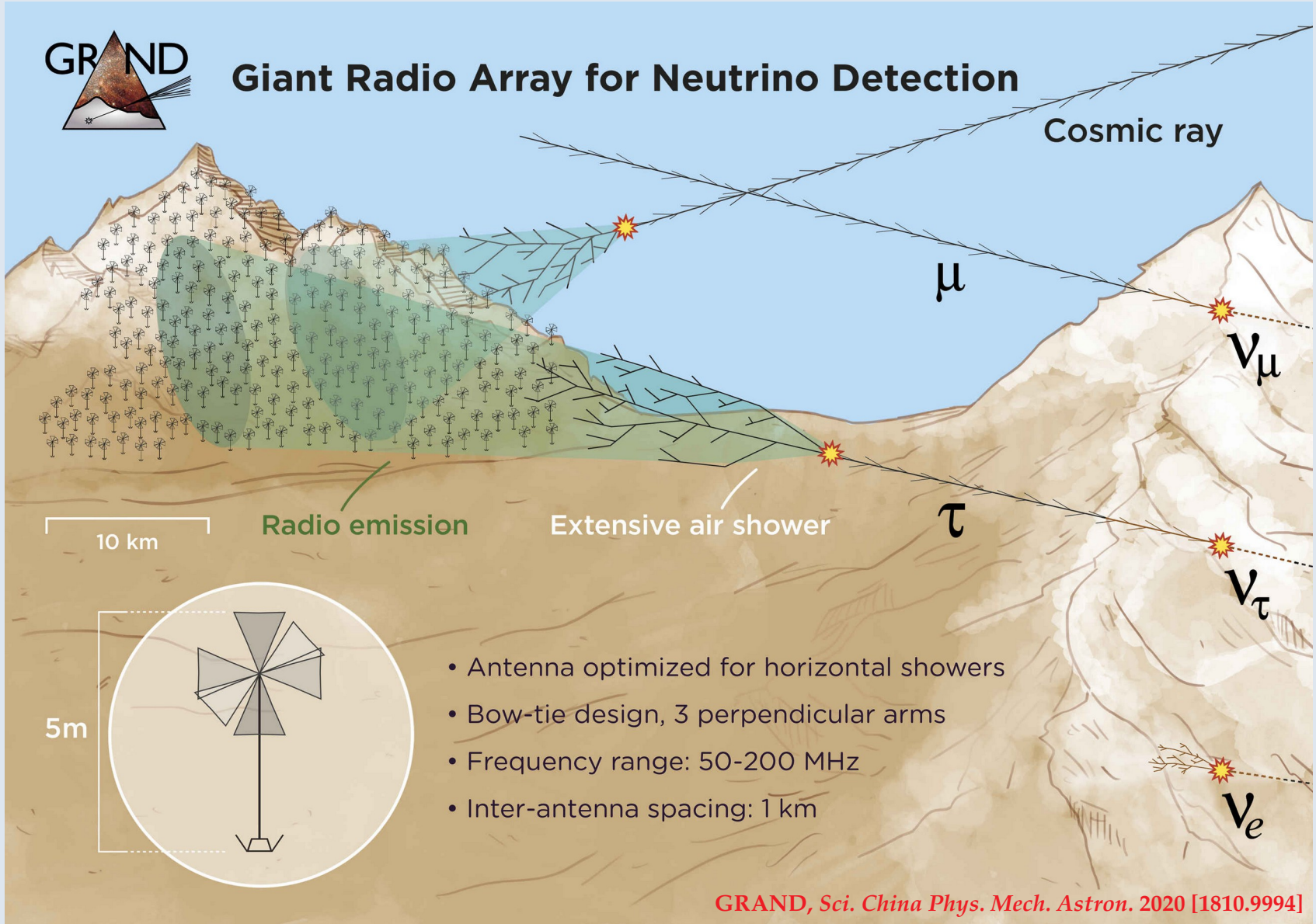

GRAND
Giant Radio Array for Neutrino Detection
Cosmic ray
μ
τ
ν_μ
ν_τ
ν_e
10 km
Radio emission
Extensive air shower
5m
• Antenna optimized for horizontal showers
• Bow-tie design, 3 perpendicular arms
• Frequency range: 50-200 MHz
• Inter-antenna spacing: 1 km
GRAND, *Sci. China Phys. Mech. Astron.*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

GRANDProto300@China

GRAND@Nançay

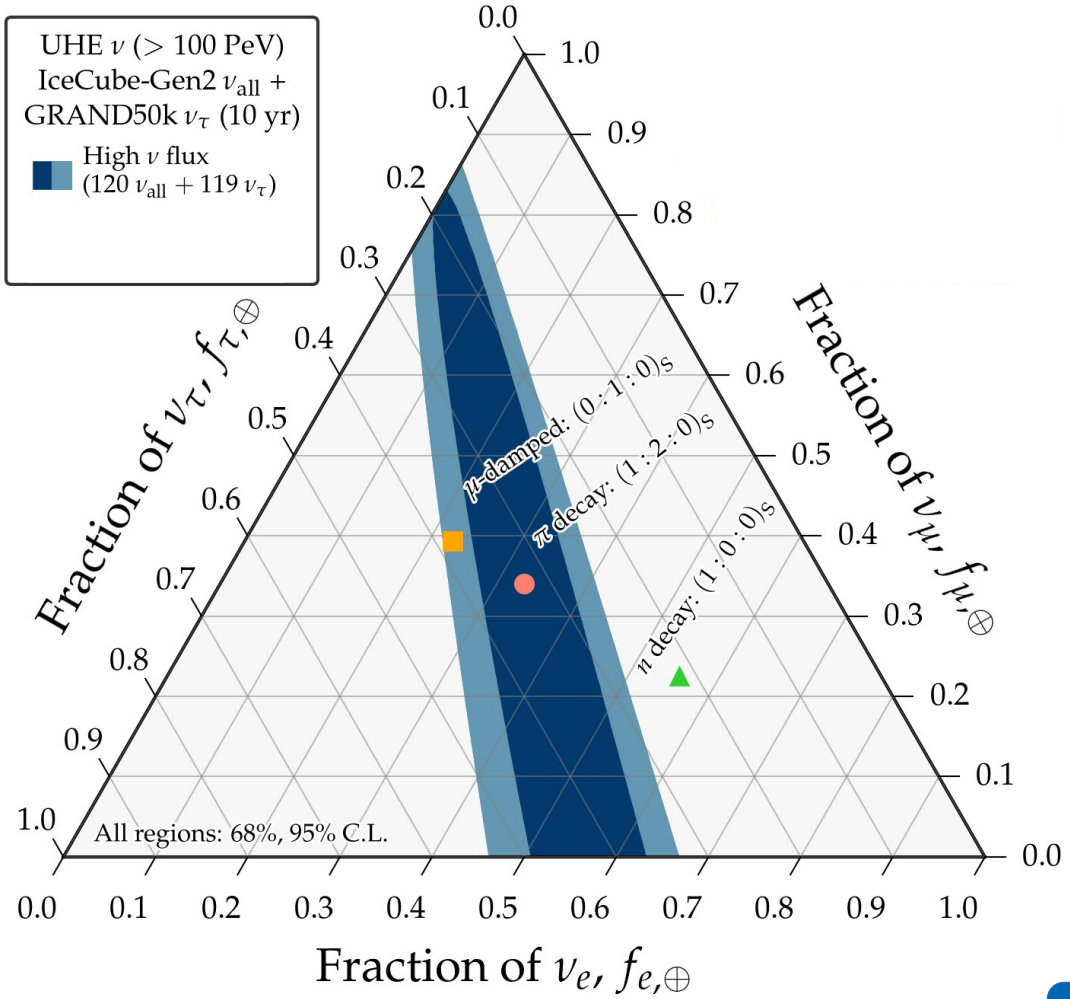
GRAND@Auger

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

Manufacturing UHE flavor sensitivity with two detectors

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

Then we combine two of detectors:



Testagrossa, Fiorillo, **MB**, 2310.12215

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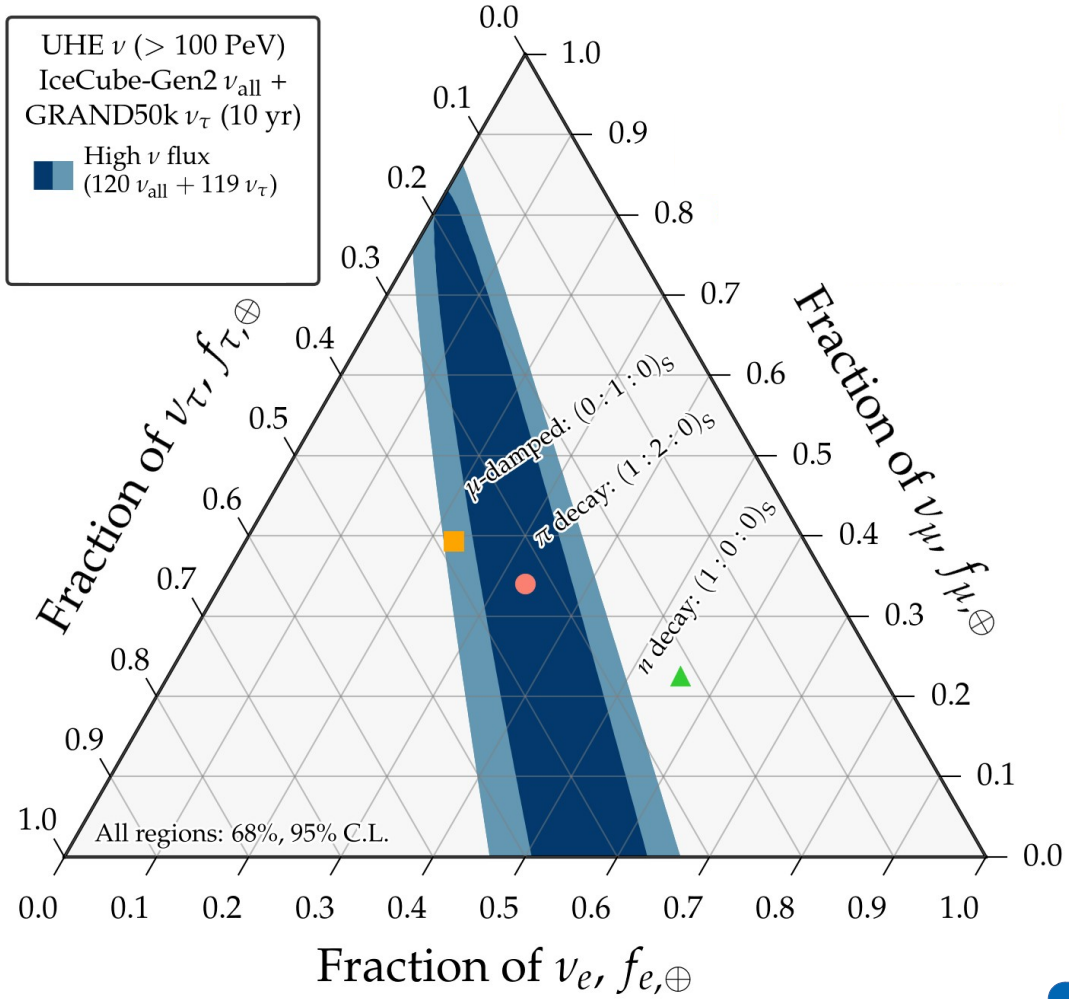

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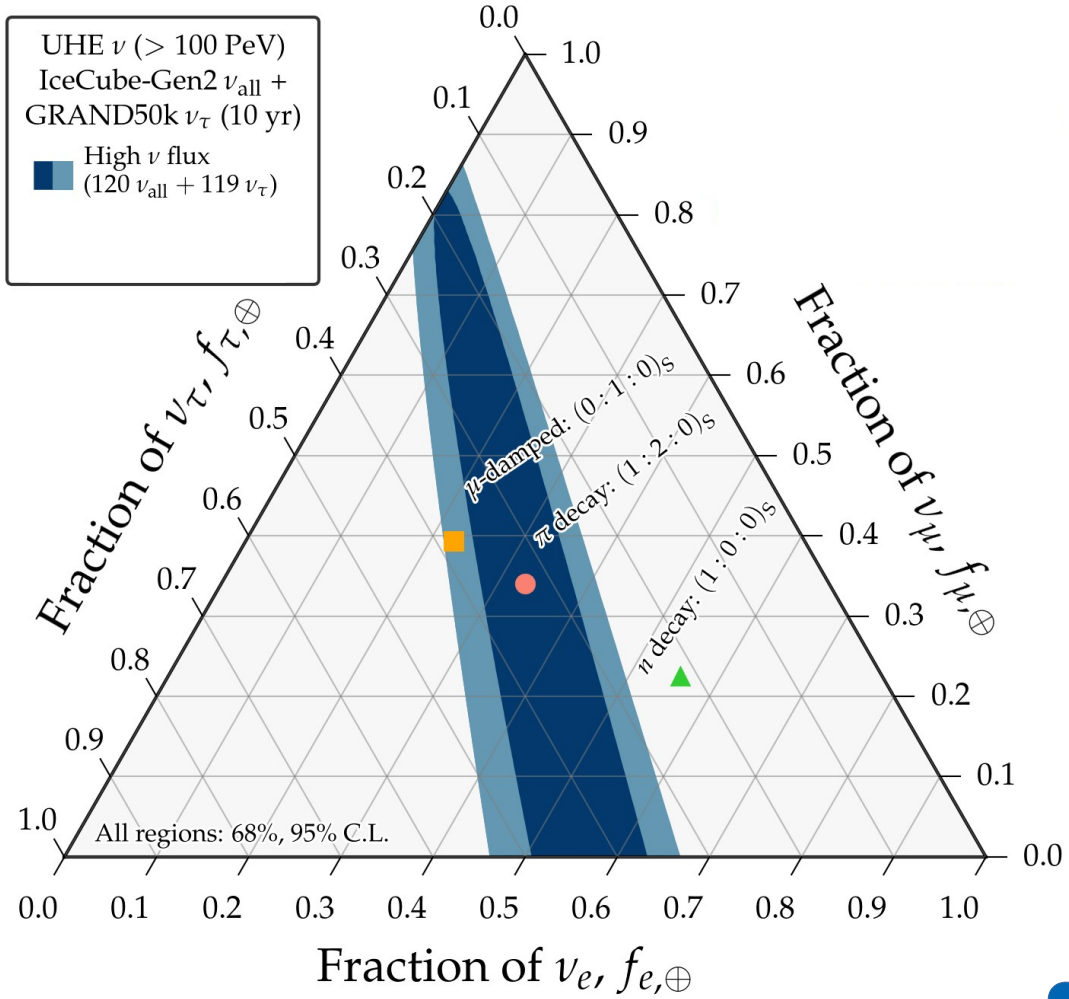

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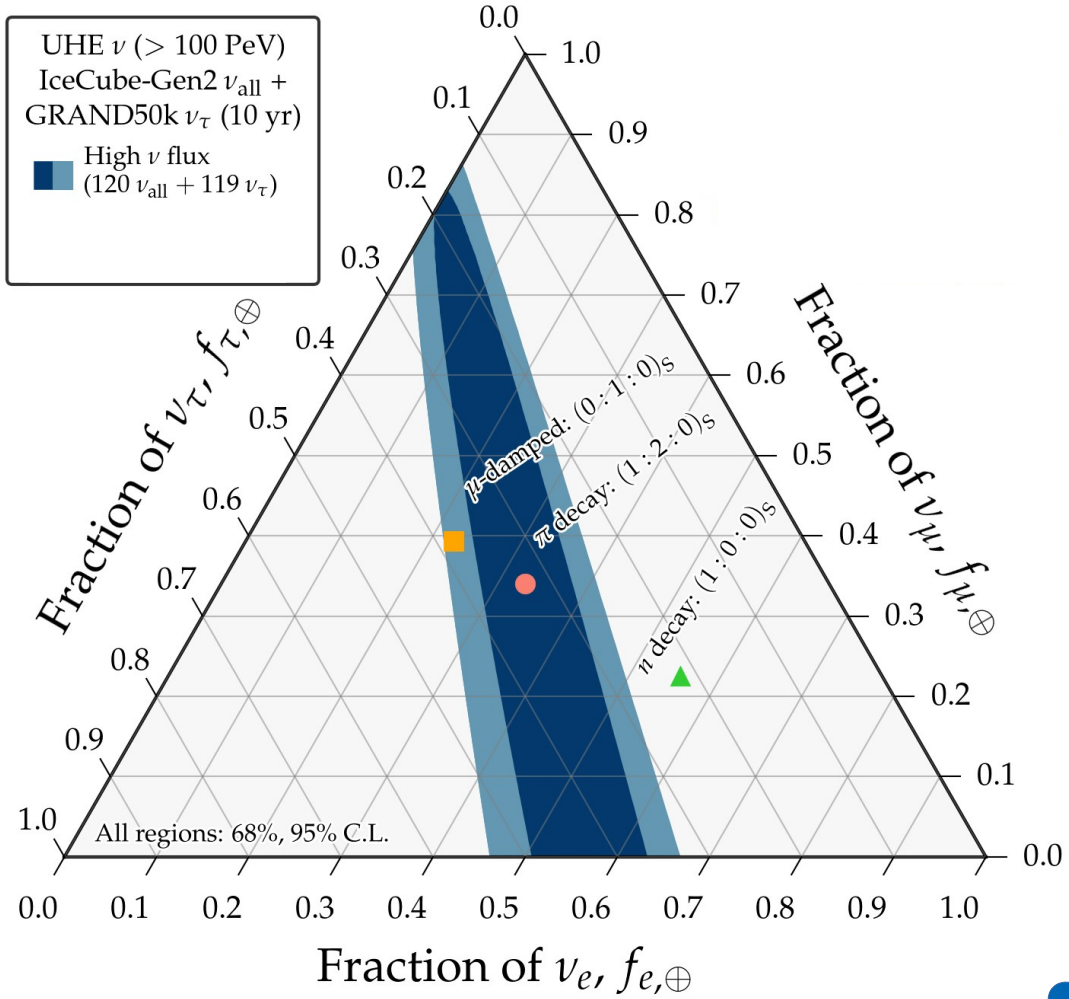

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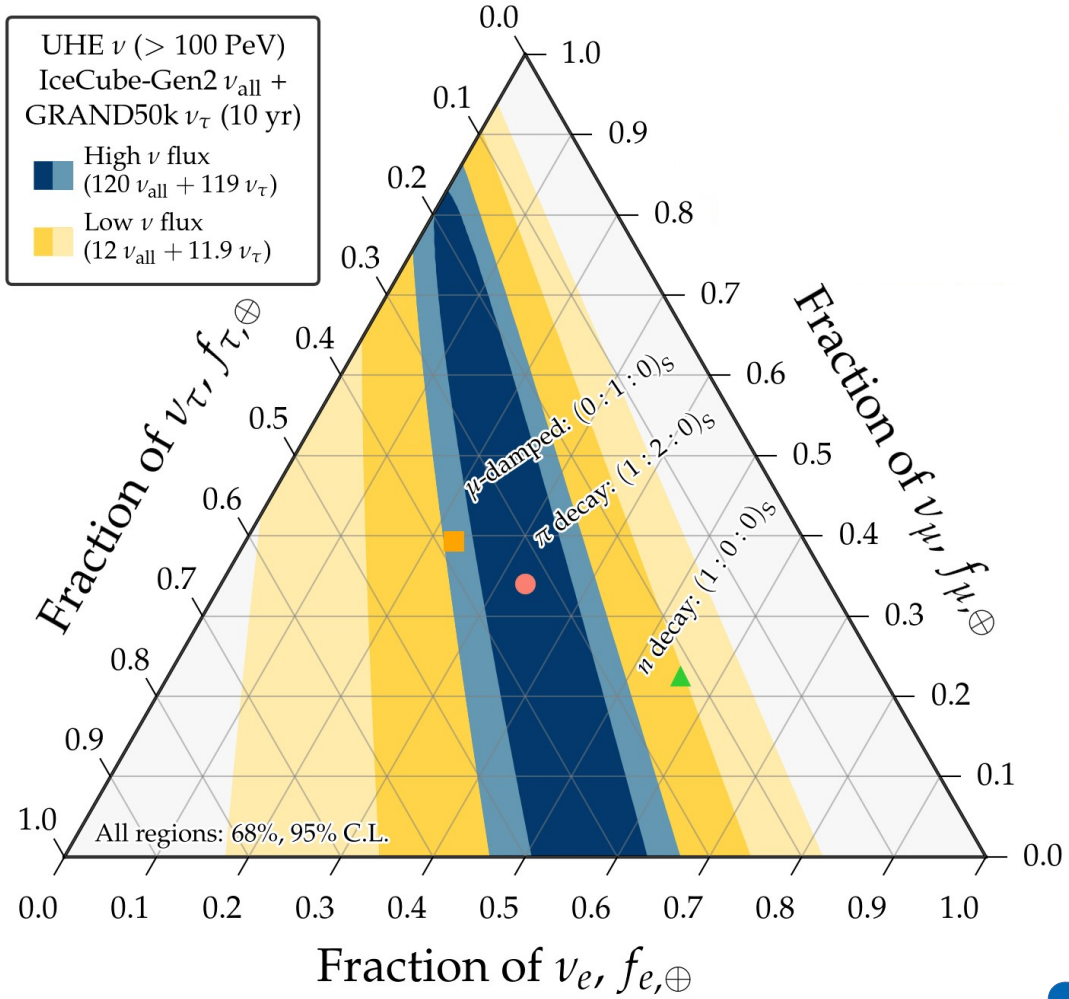

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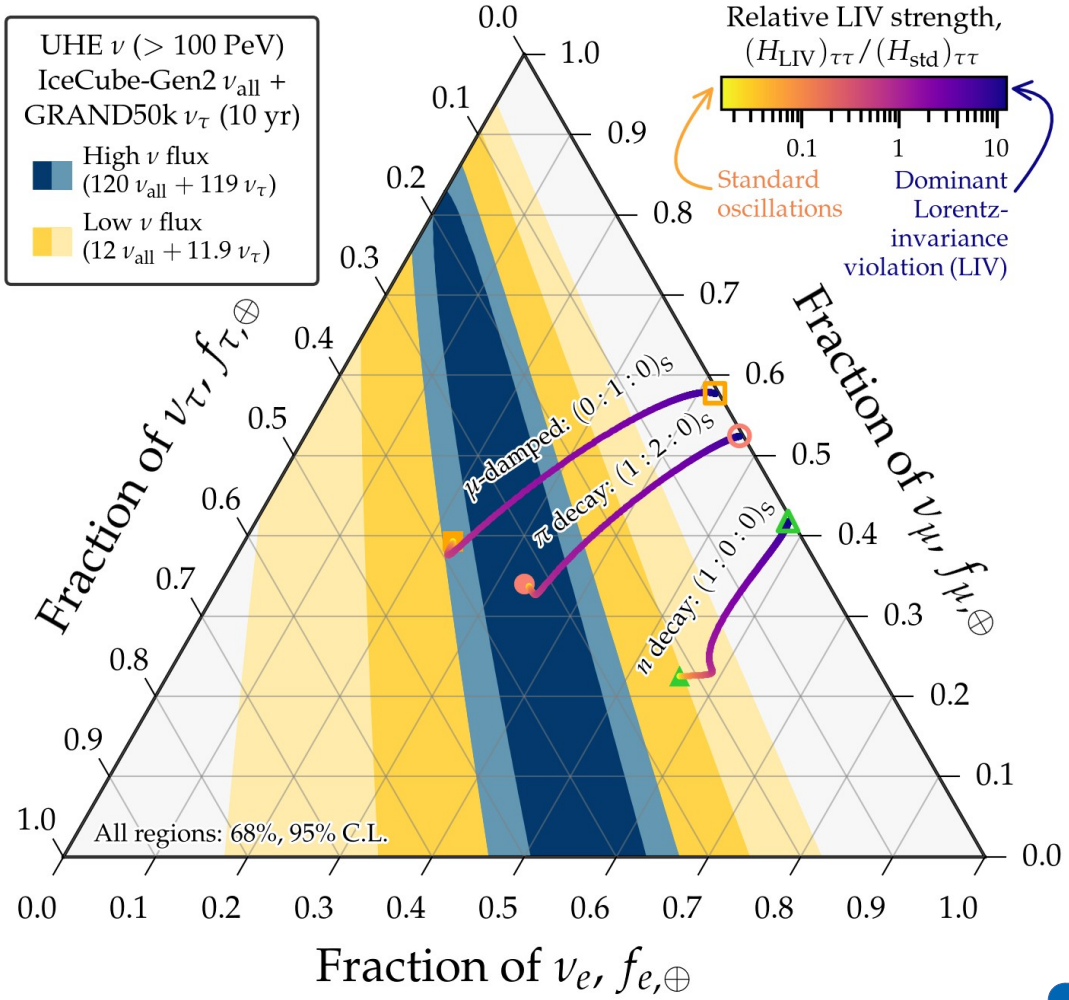

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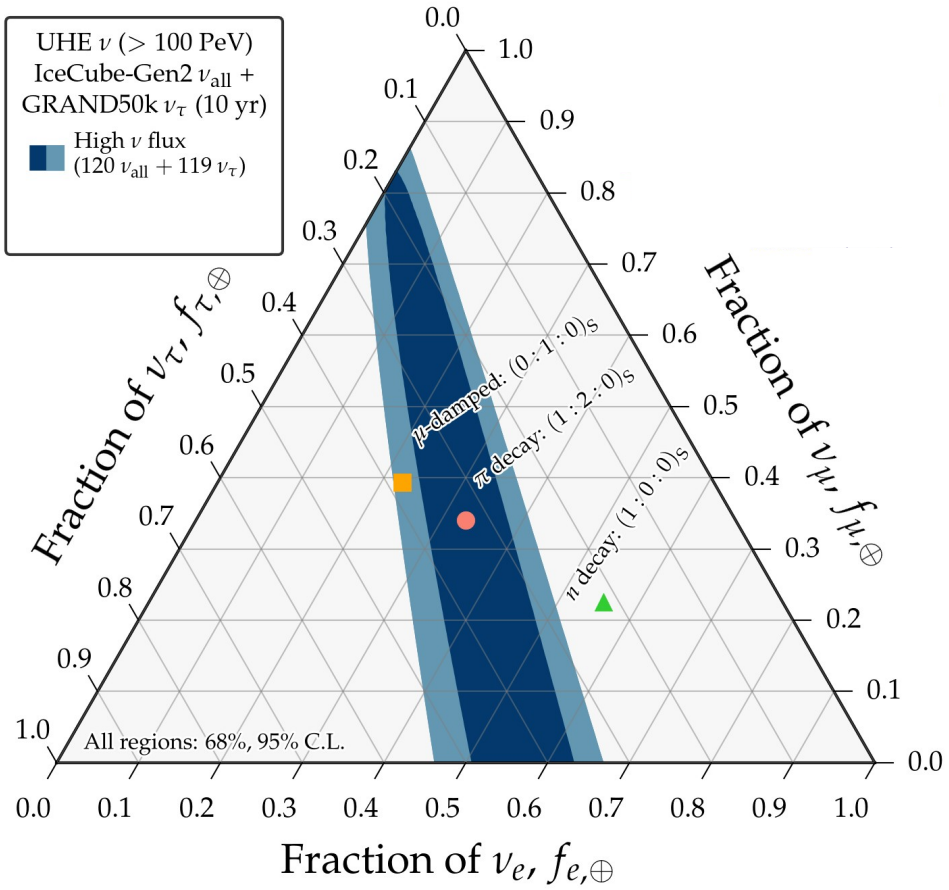
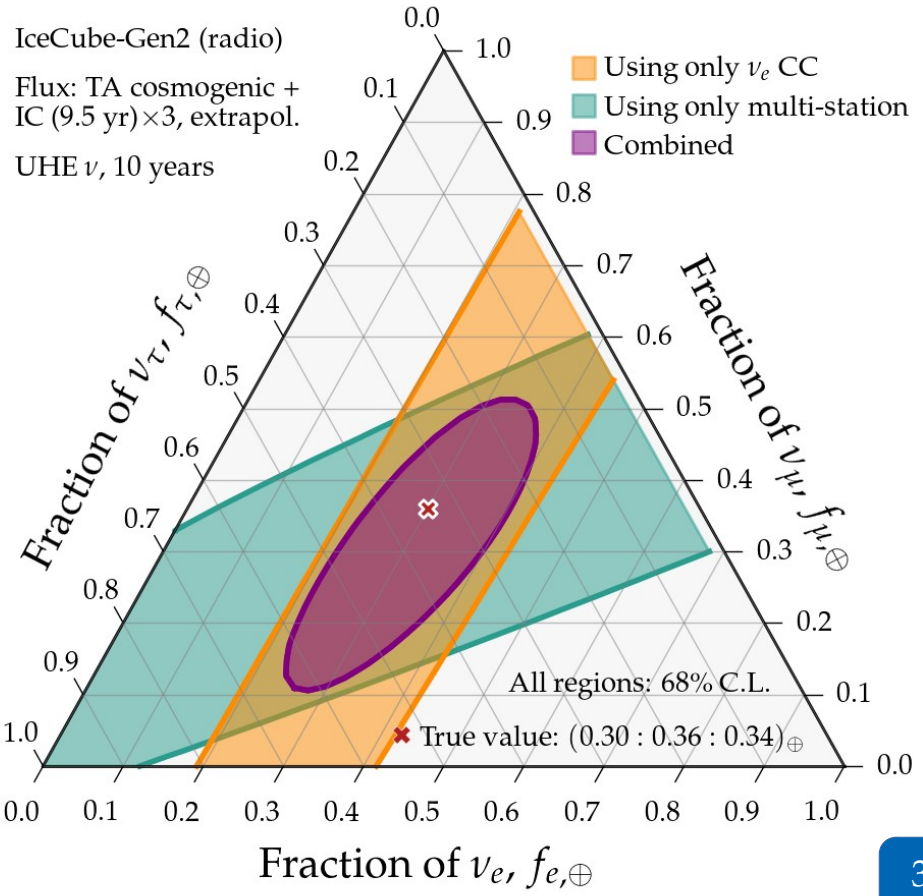
Accessing the full UHE flavor information

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



1

Neutrino oscillations is a three-state system (ν_e, ν_μ, ν_τ), but we study them using mainly two (ν_e and ν_μ)

2

The **flavor composition** of high-energy cosmic neutrinos reflects the physical conditions inside cosmic accelerators

3

At **ultra-high energies** ($> 10^{18}$ EeV), ν_τ provide unique detection opportunities (ν_τ regeneration, Earth-skimming ν_τ)

Thanks!