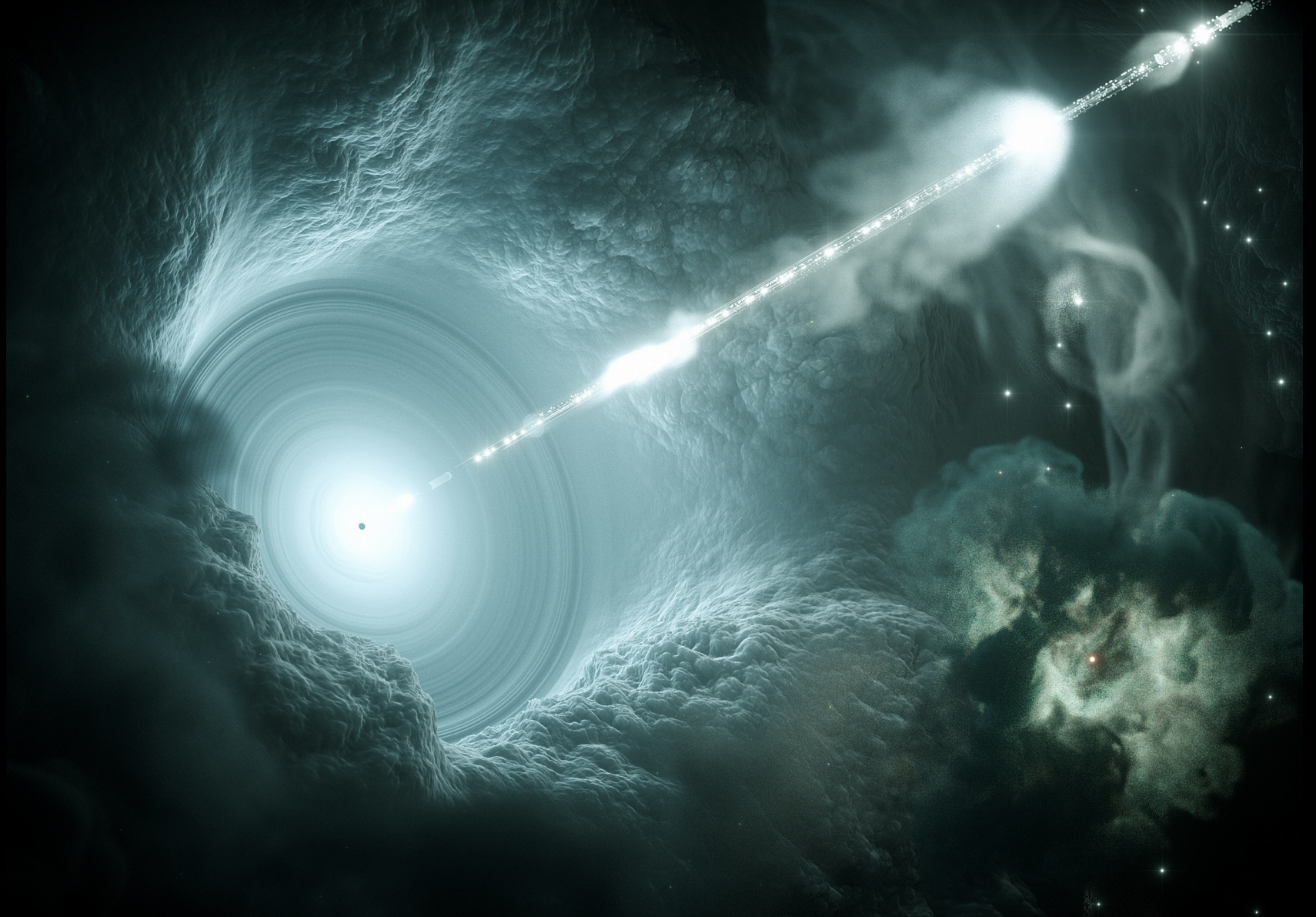
The present and future of flavor in high-energy cosmic neutrinos

Mauricio Bustamante
Niels Bohr Institute, University of Copenhagen

UNIVERSITY OF COPENHAGEN

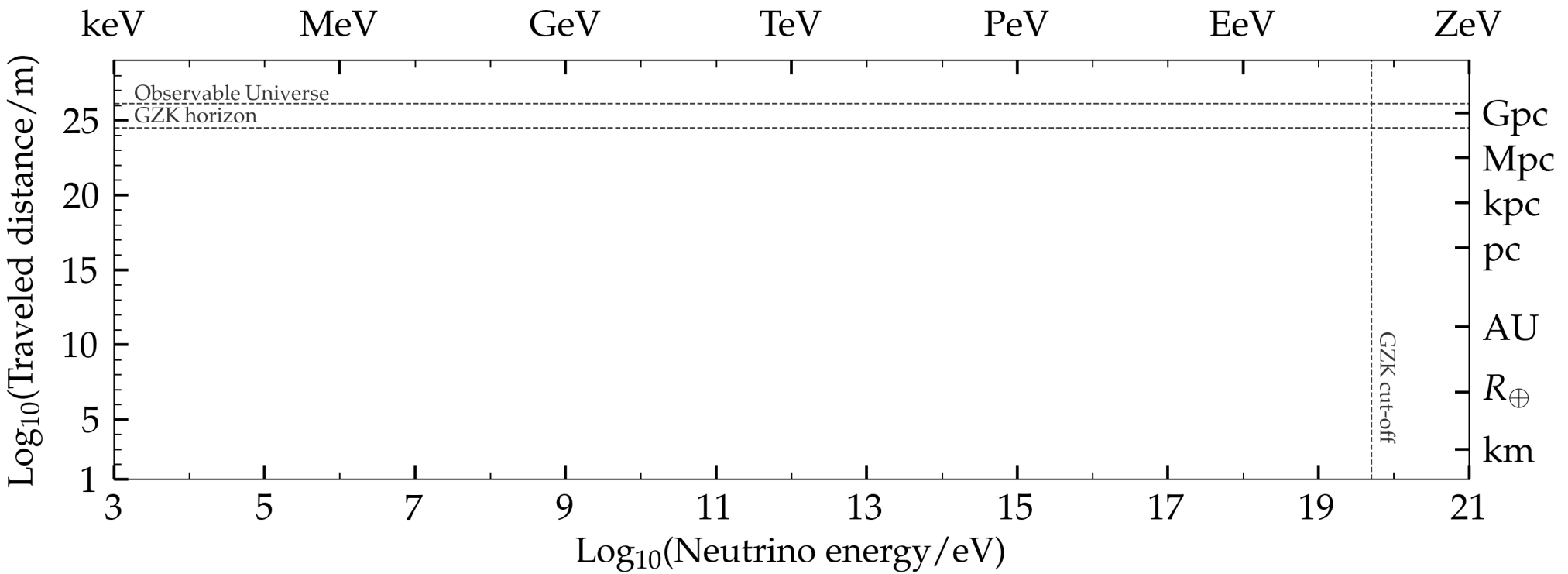
VILLUM FONDEN

N3AS Seminar
March 26, 2024

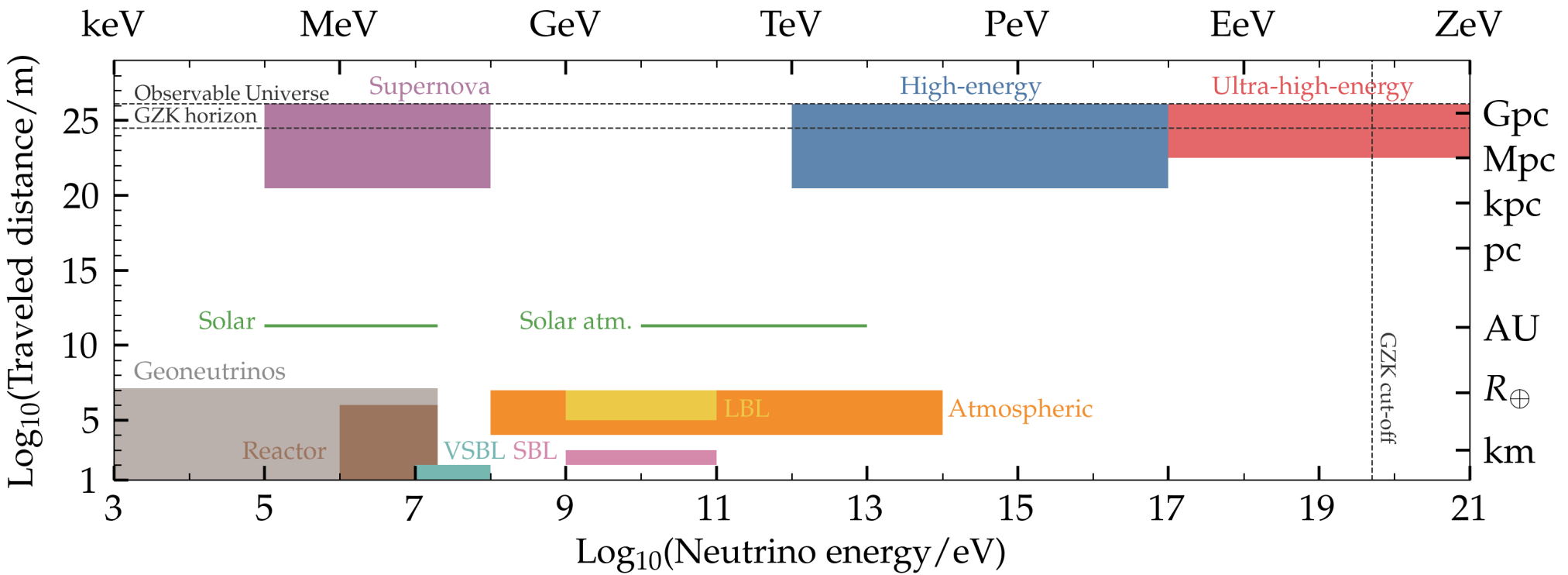


DESY

DESY

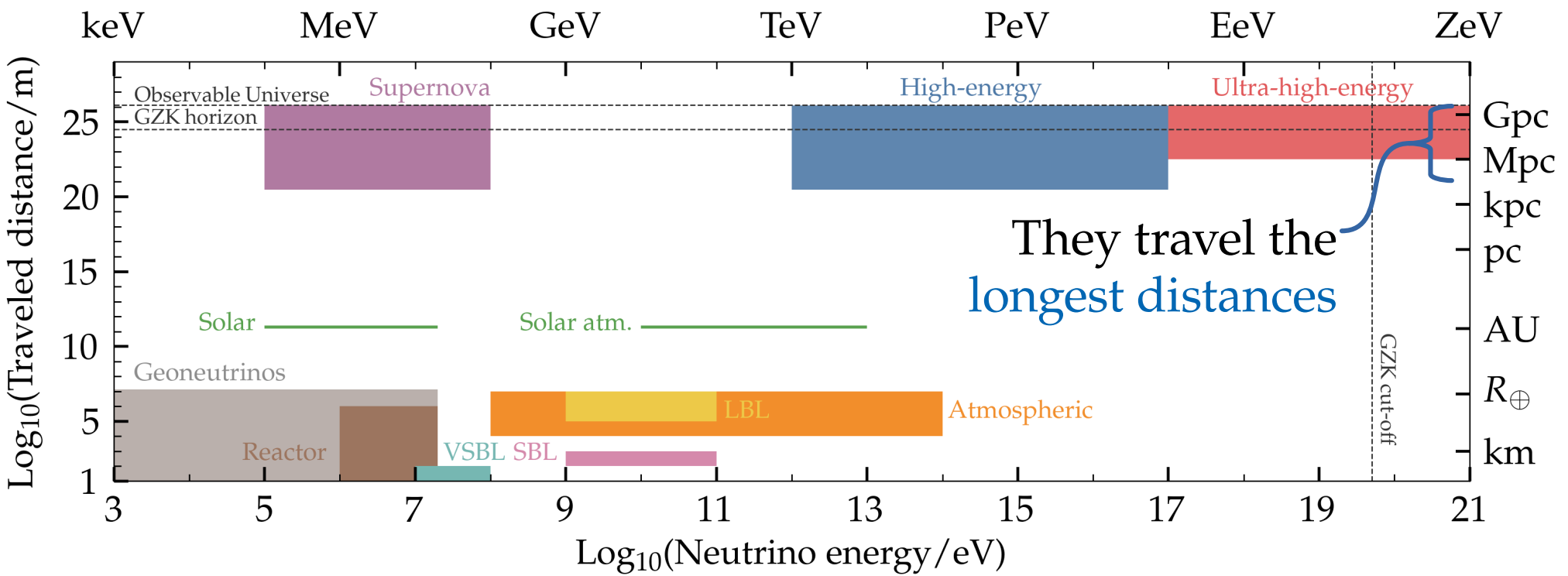


Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333), adapted



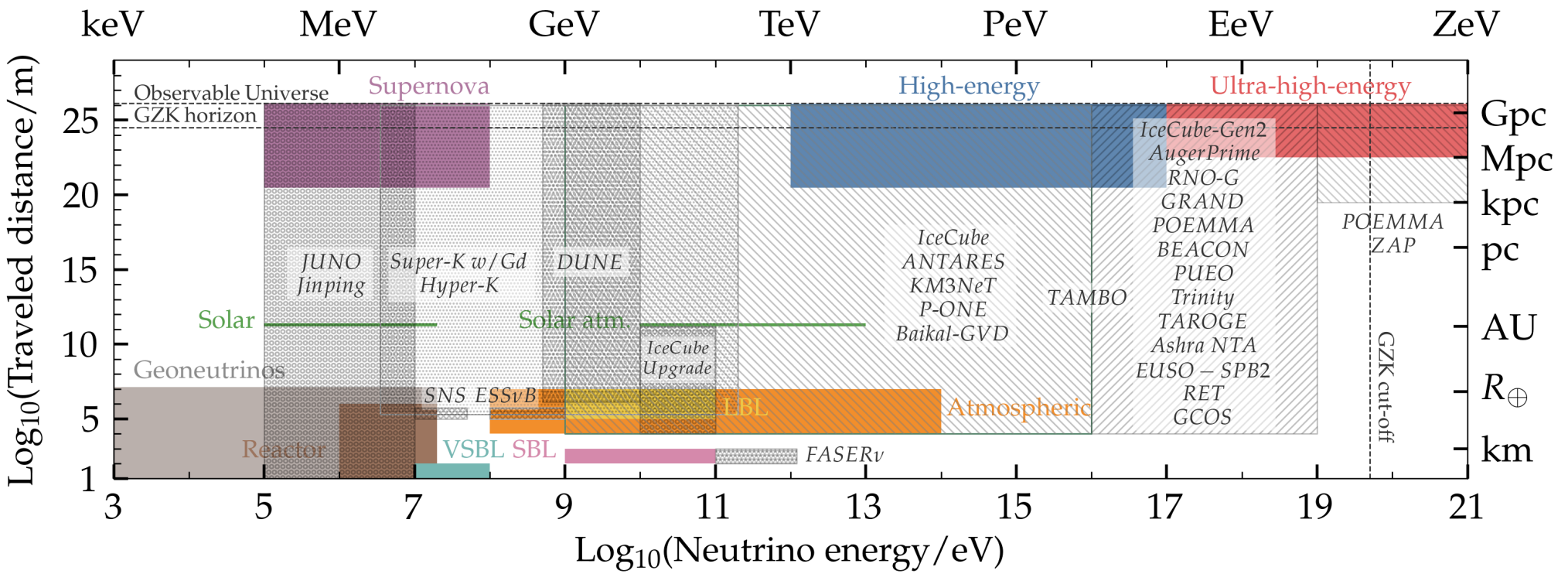
Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333), adapted

They have the highest energies

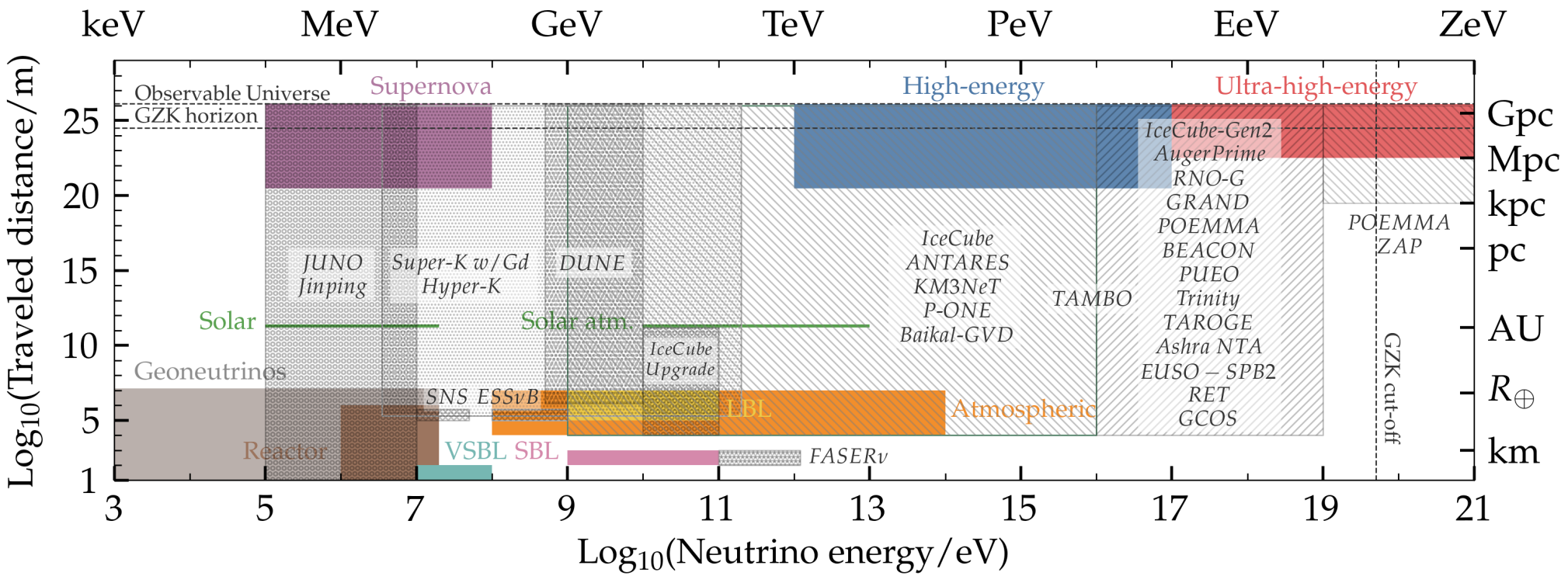


They travel the longest distances

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



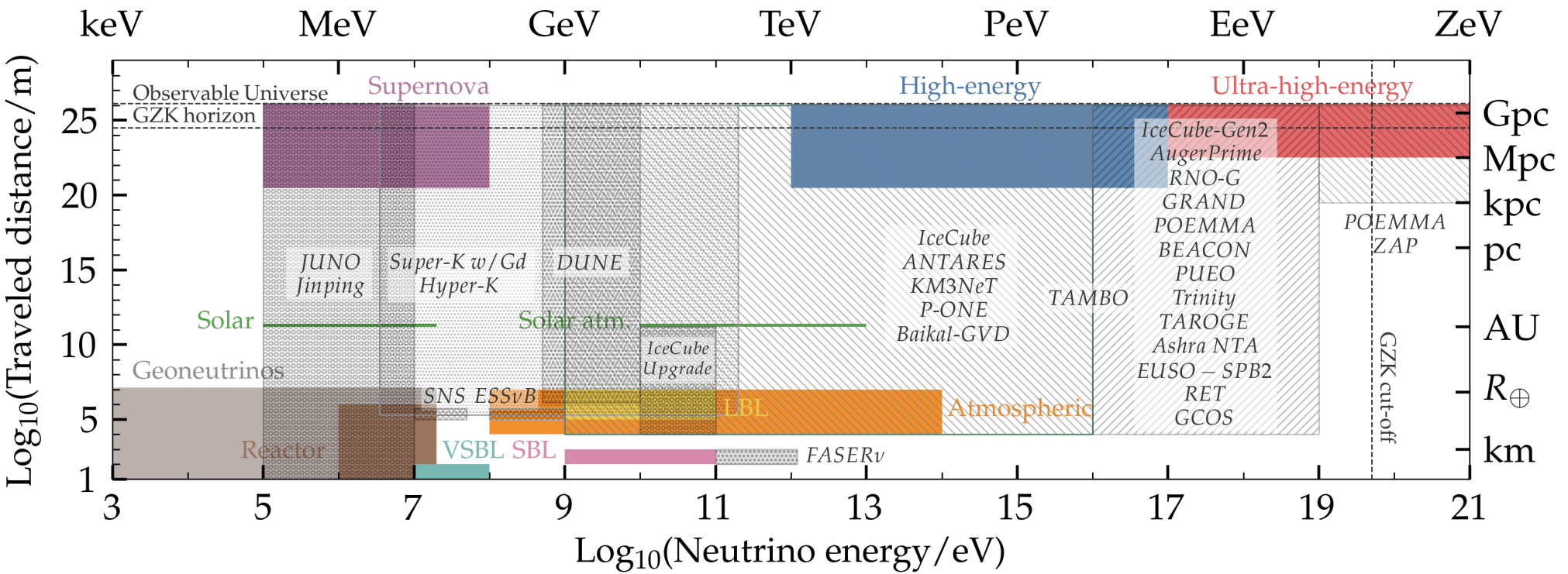
Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333), adapted



Synergies with lower energies

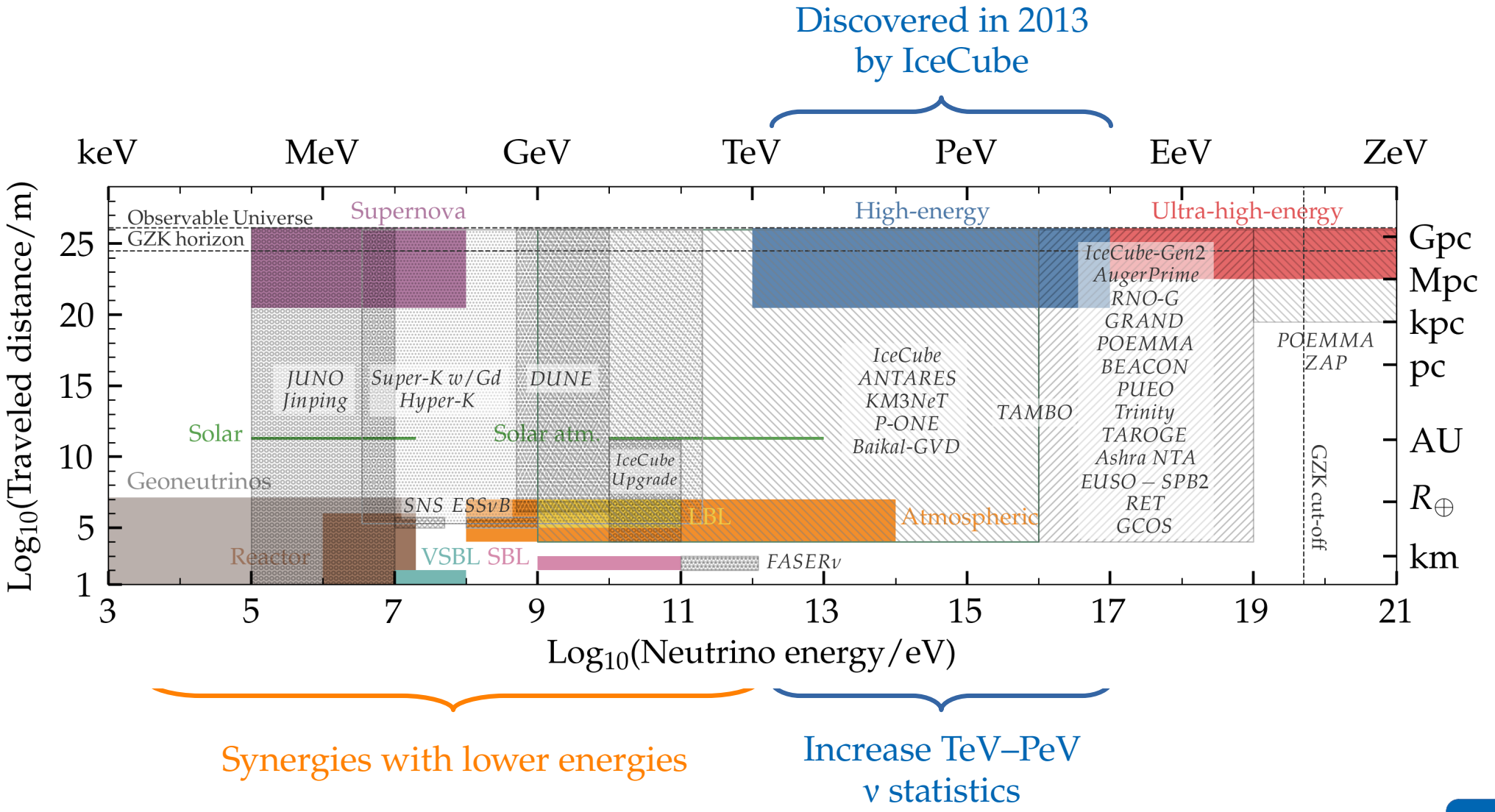
Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333), adapted

Discovered in 2013
by IceCube

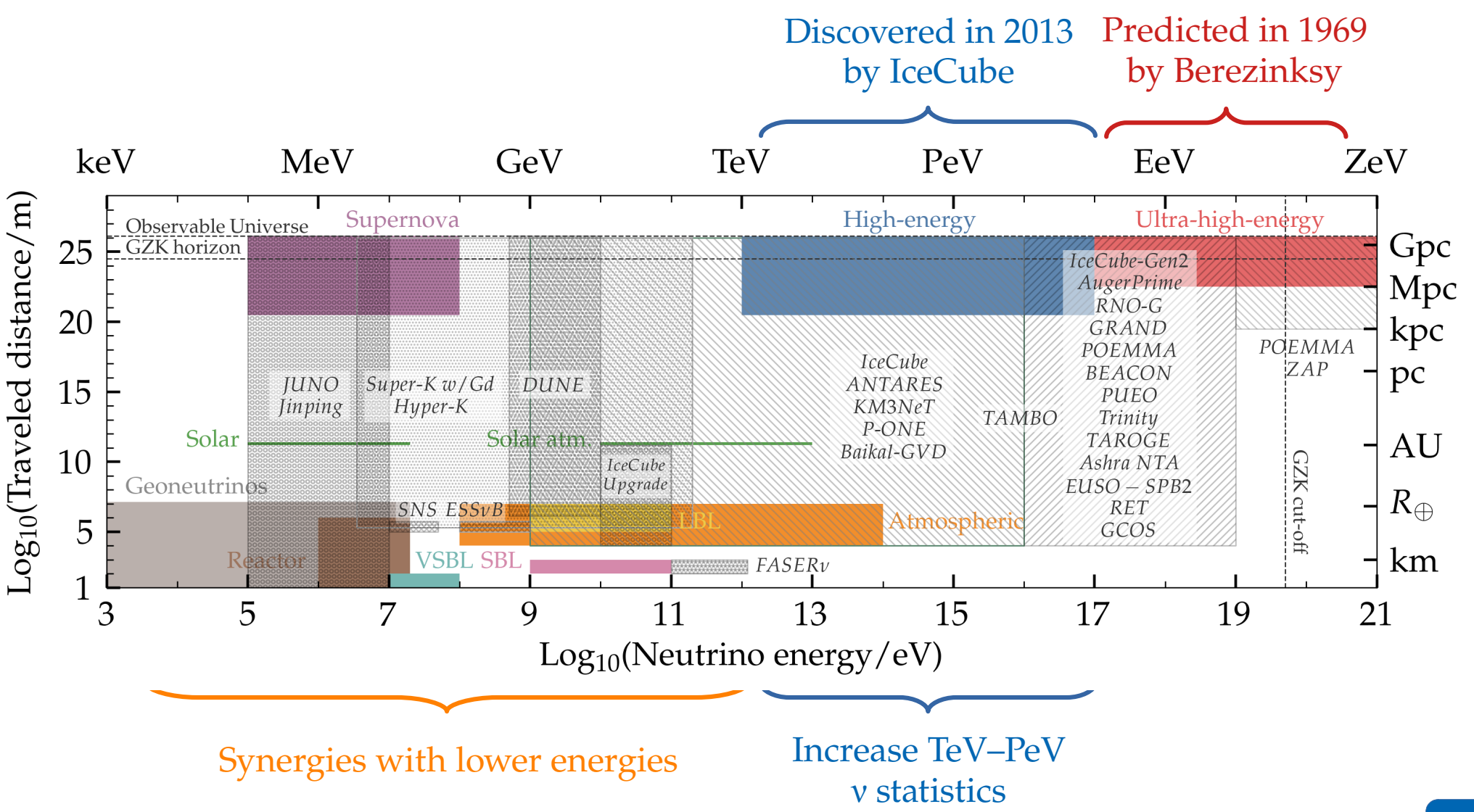


Synergies with lower energies

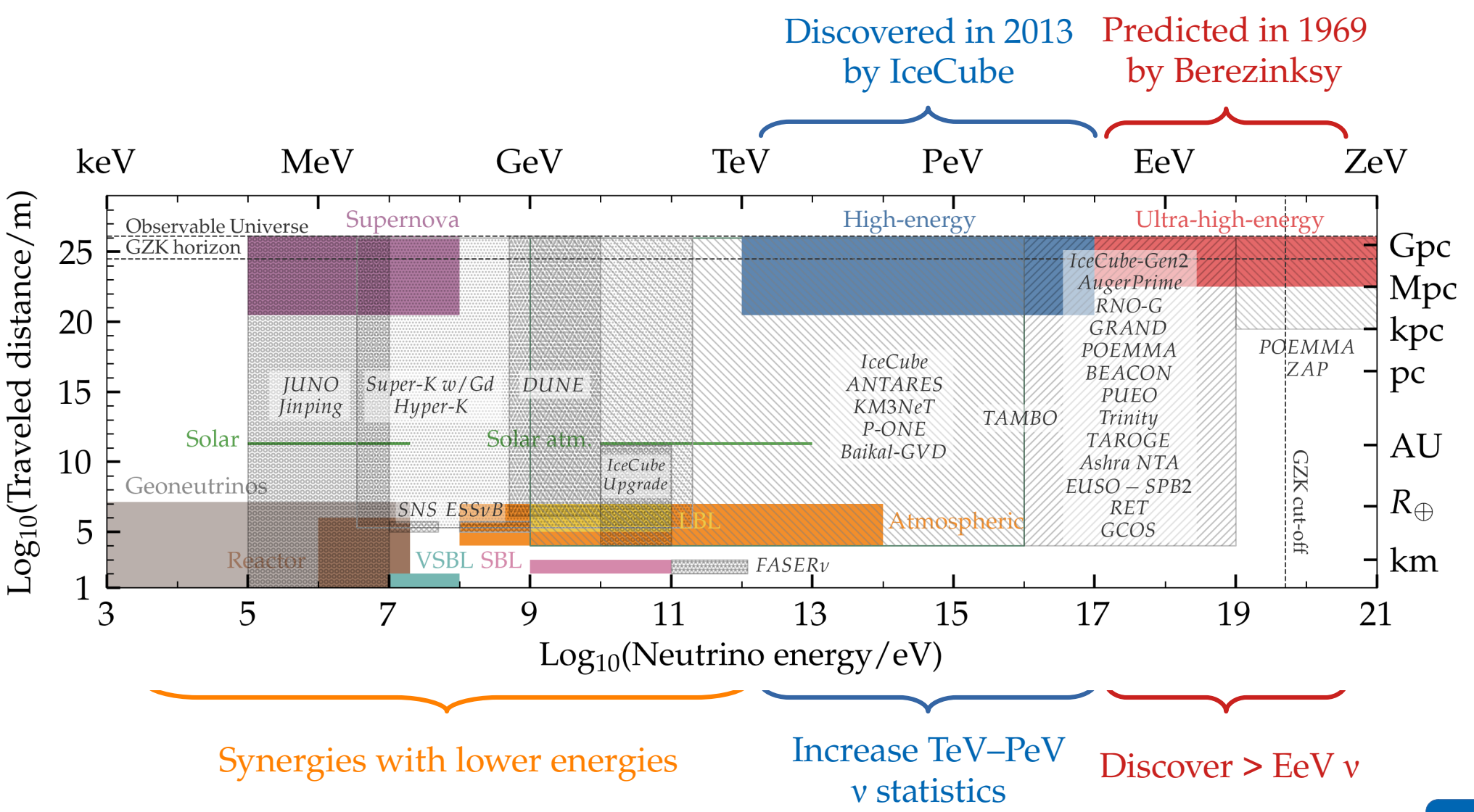
Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333), adapted



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



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



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

Making high-energy astrophysical neutrinos: a toy model

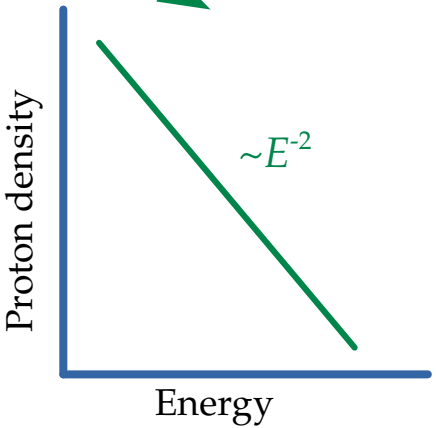
(or $p + p$)

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

Making high-energy astrophysical neutrinos: a toy model

(or $p + p$)

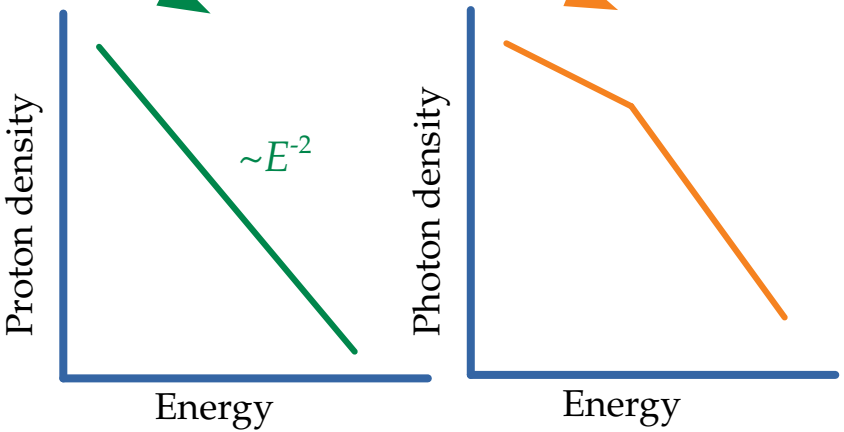
$$p + \gamma_{\text{target}} \rightarrow \Delta^{+} \rightarrow \begin{cases} p + \pi^{0}, & \text{Br} = 2/3 \\ n + \pi^{+}, & \text{Br} = 1/3 \end{cases}$$



Making high-energy astrophysical neutrinos: a toy model

(or $p + p$)

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



Making high-energy astrophysical neutrinos: a toy model

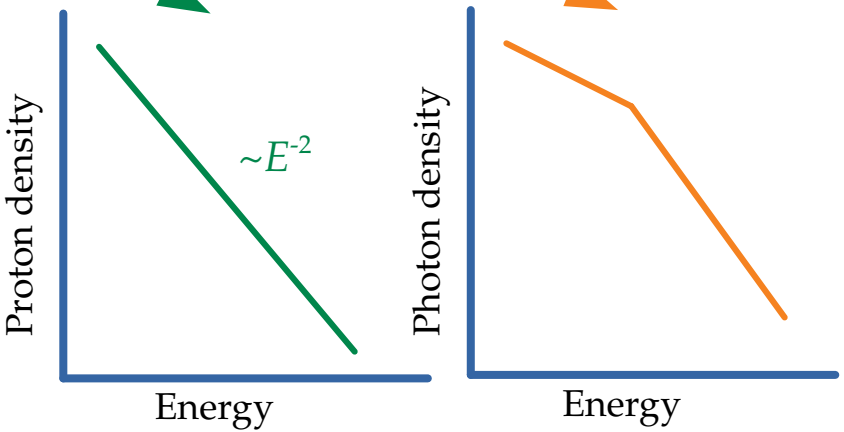
(or $p + p$)

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

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

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

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



Making high-energy astrophysical neutrinos: a toy model

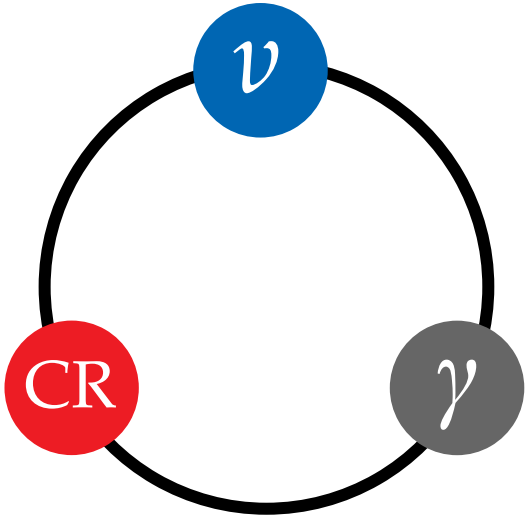
(or $p + p$)

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

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

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

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

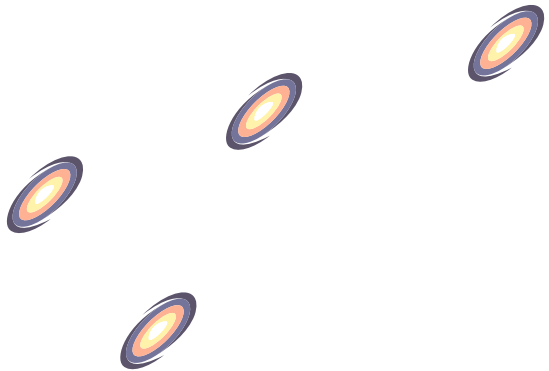


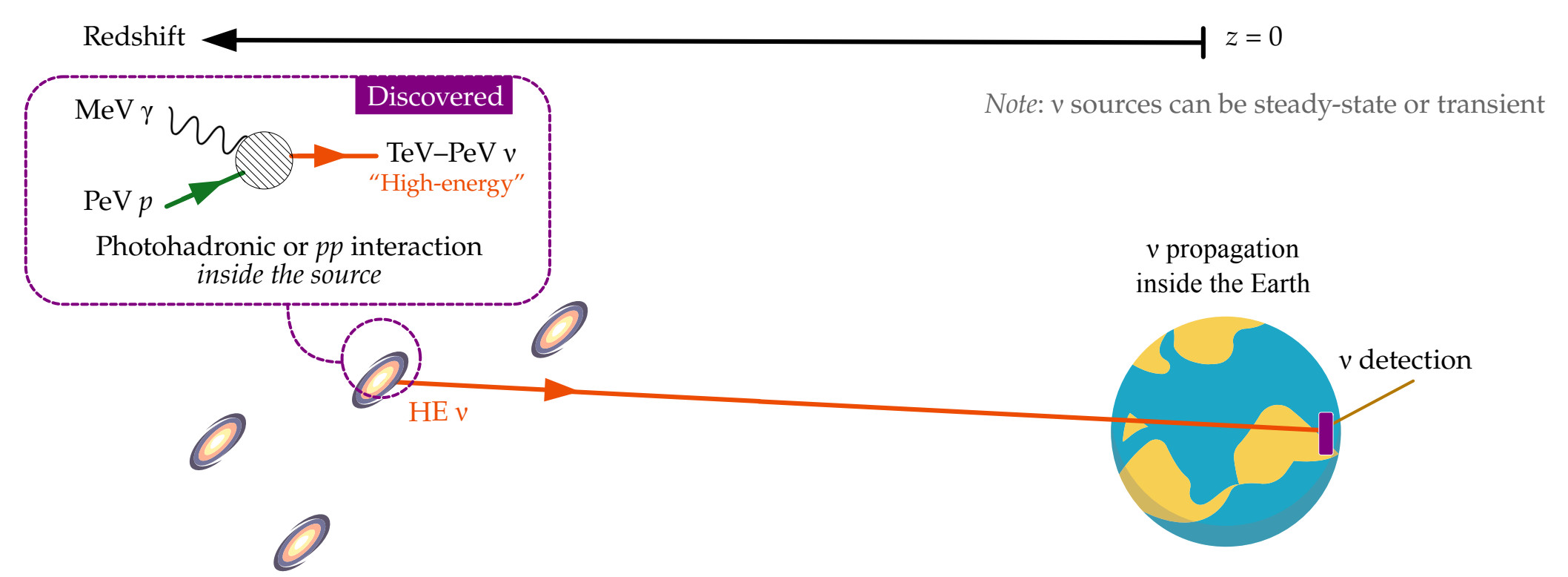
Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 10

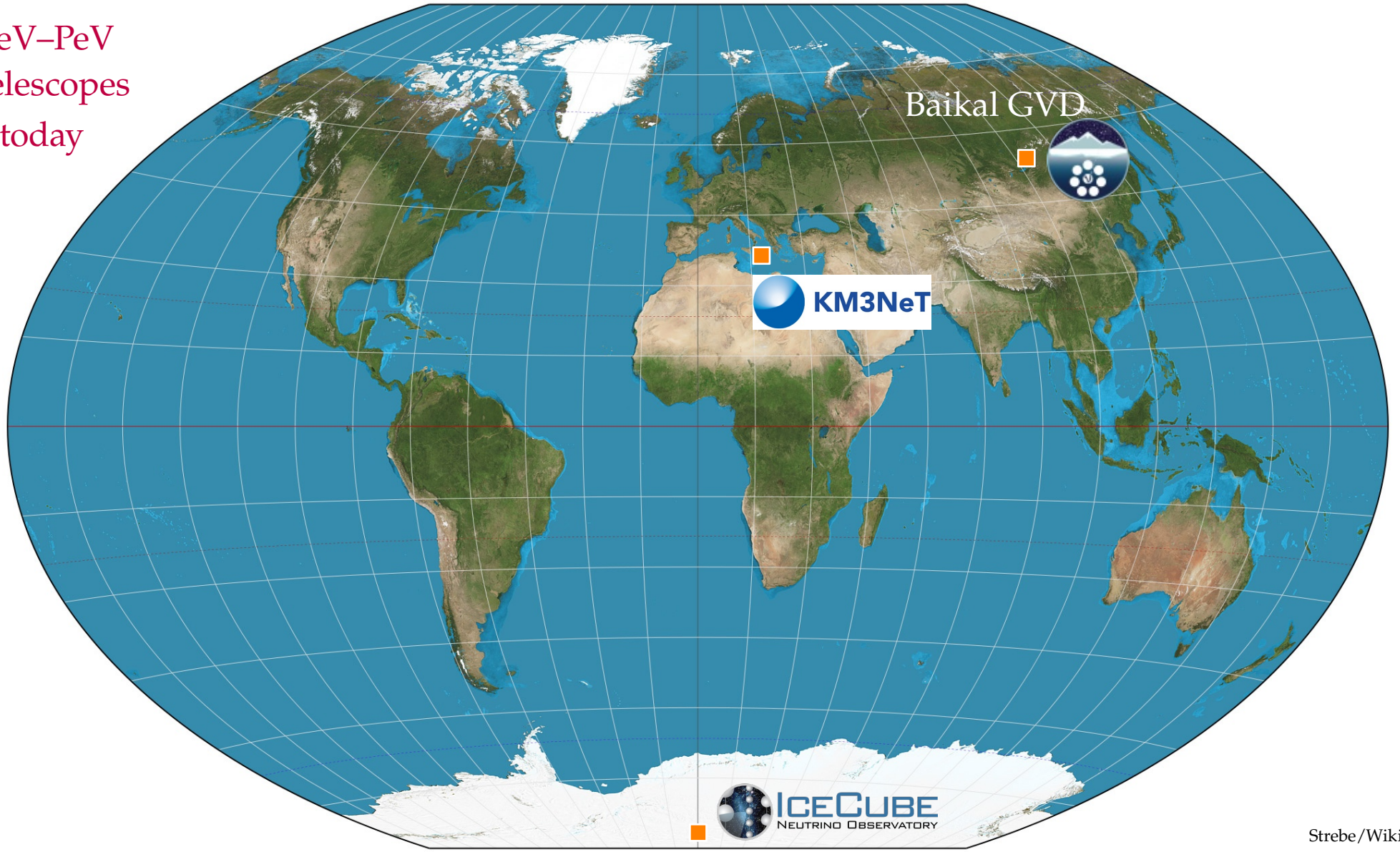
Redshift $z = 0$

Note: ν sources can be steady-state or transient



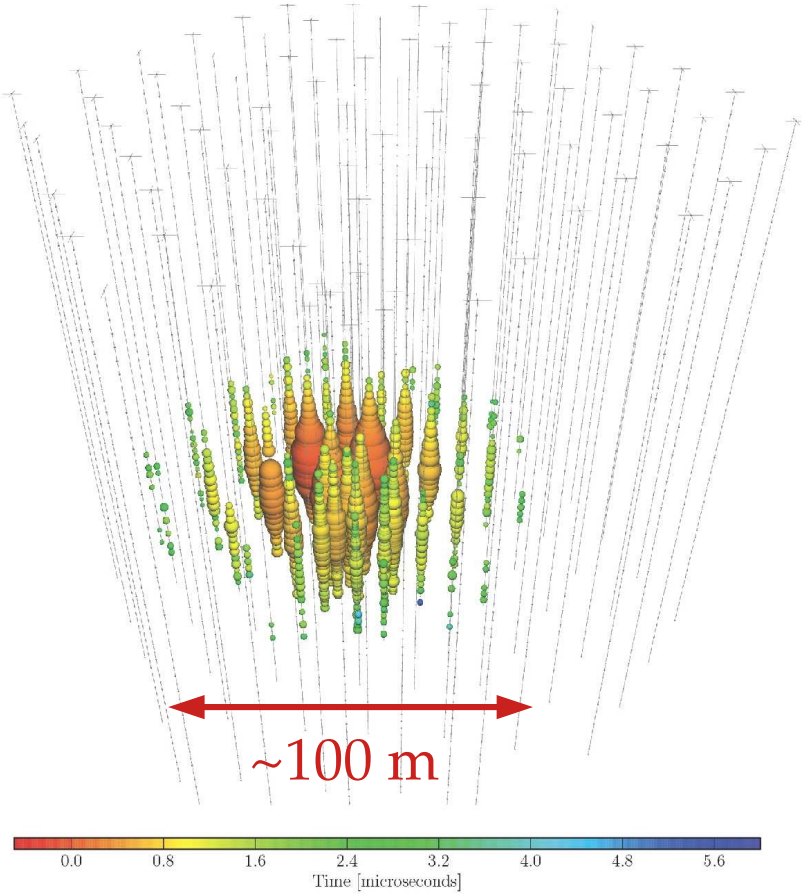

Redshift
z = 0
Discovered
MeV γ
TeV–PeV ν
"High-energy"
PeV p
Photohadronic or pp interaction
inside the source
Note: ν sources can be steady-state or transient
ν propagation
inside the Earth
ν detection
HE ν

TeV–PeV ν telescopes today



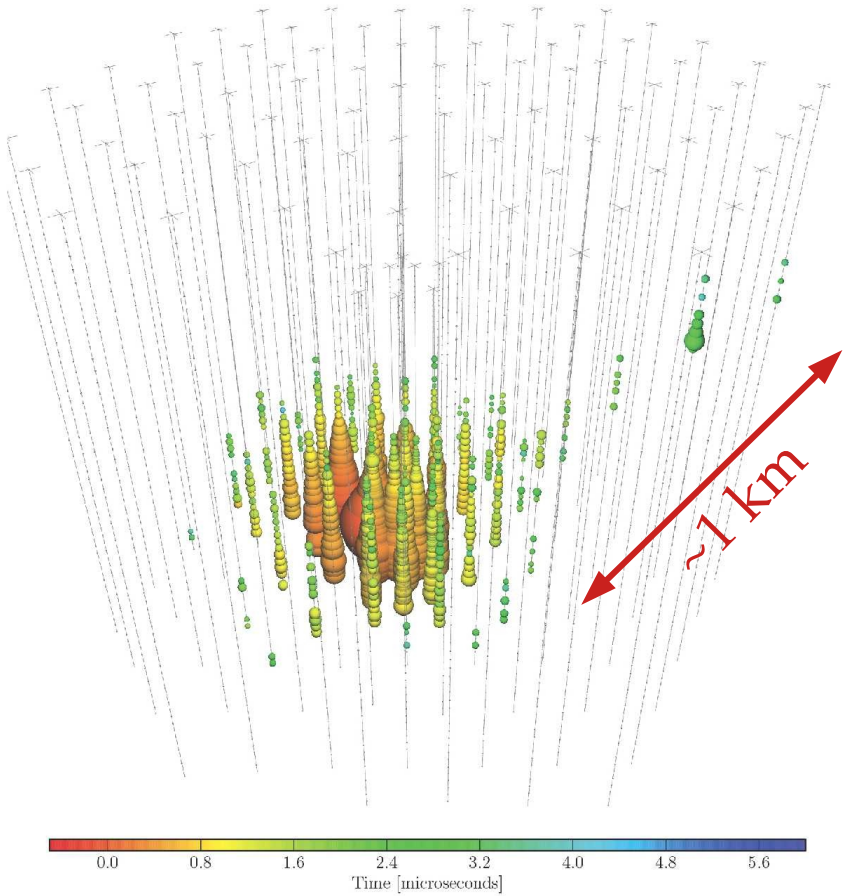
Strebe/Wikipedia

Shower
(mainly from ν_e and ν_τ)

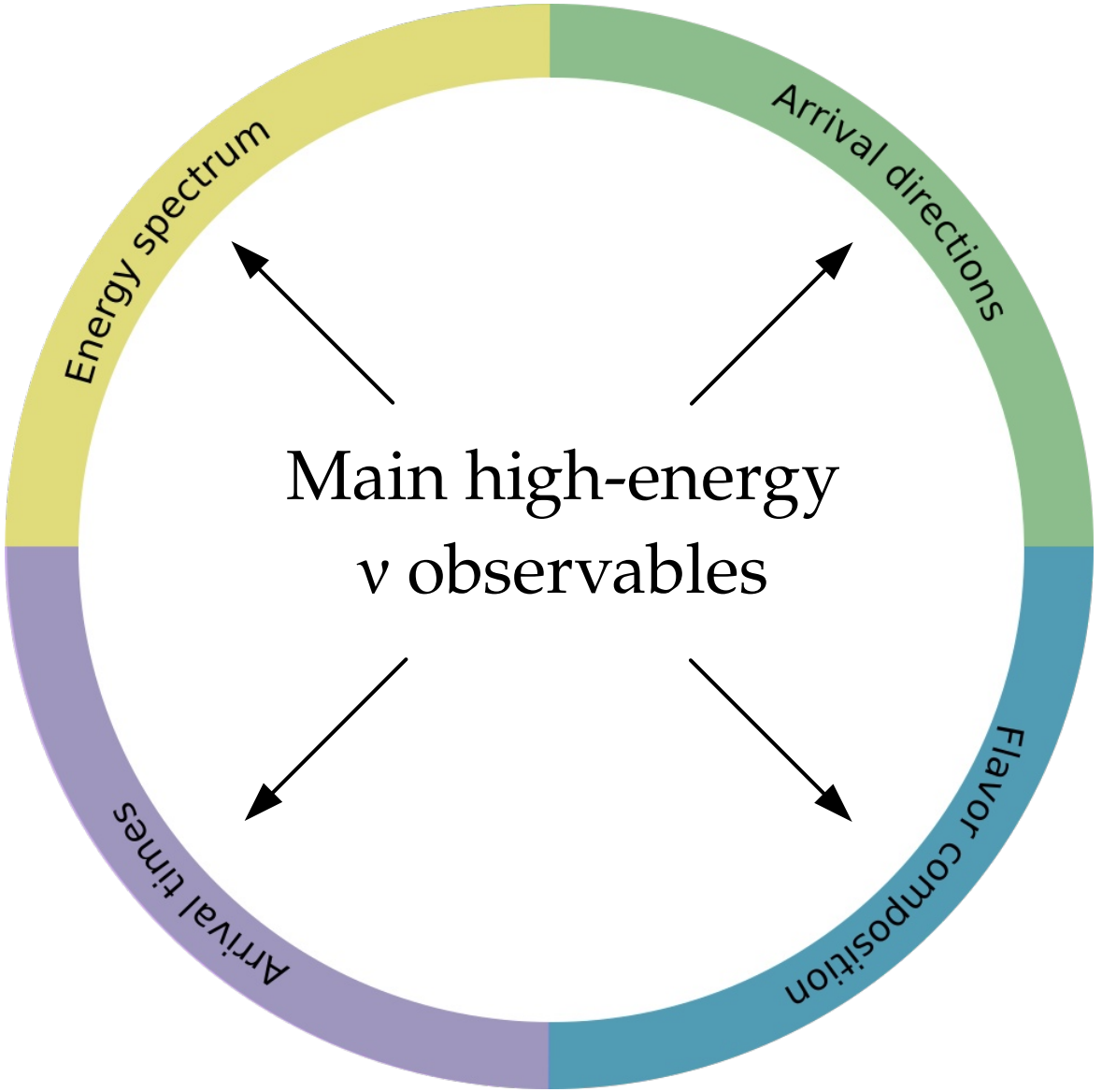


Poor angular resolution: ~10°

Track
(mainly from ν_μ)

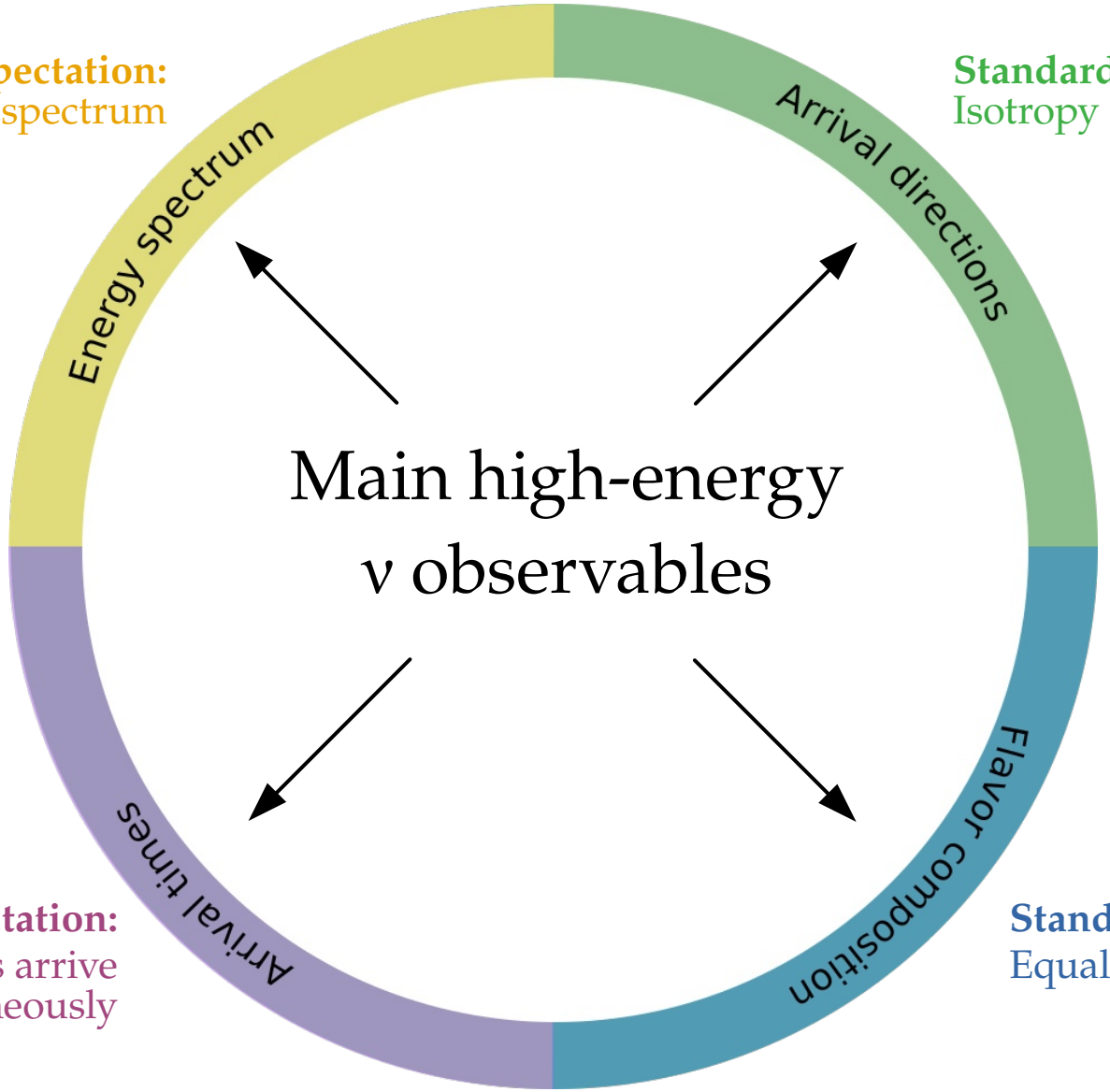


Angular resolution: < 1°


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

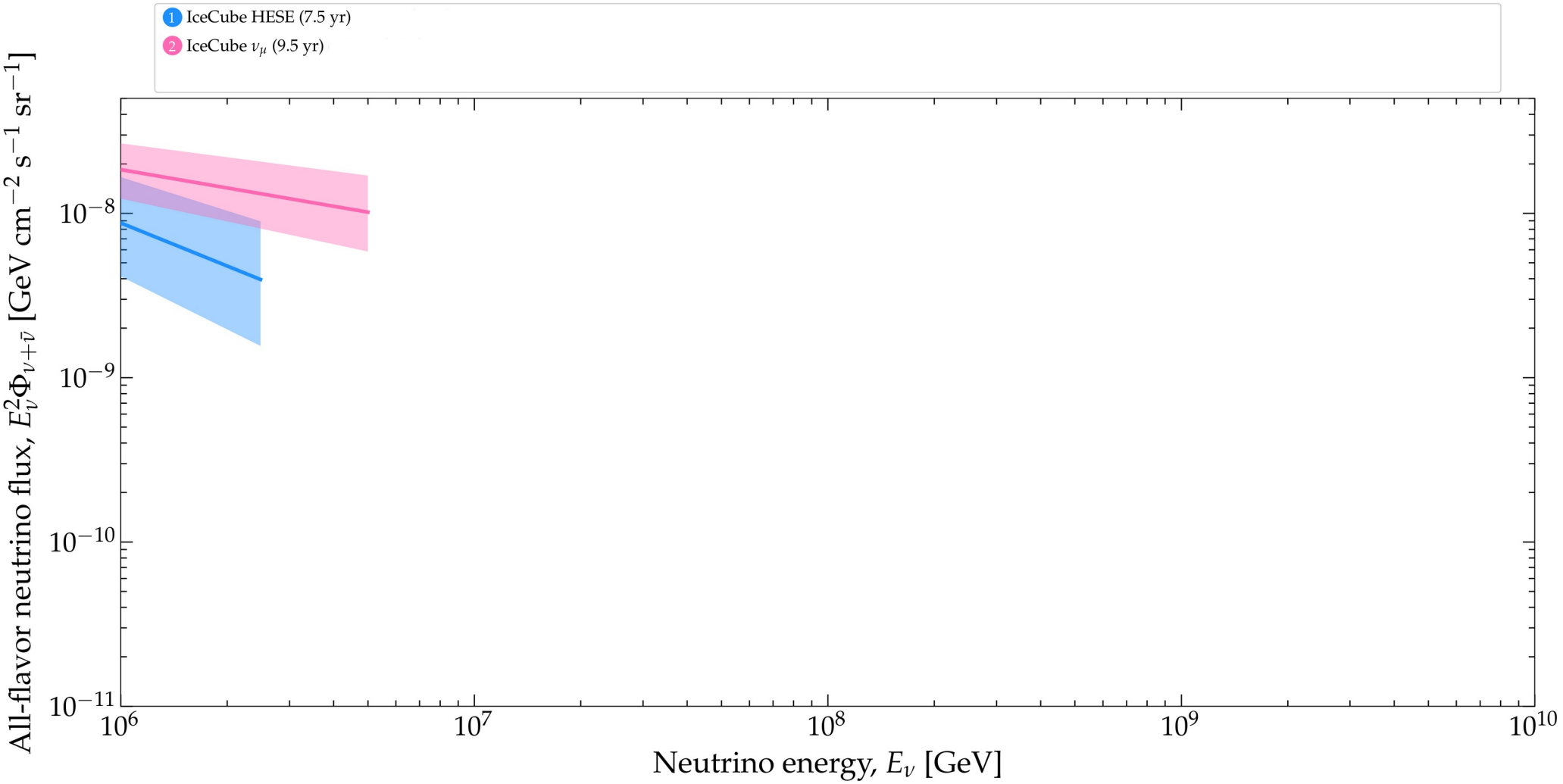
Standard expectation:
Power-law energy spectrum

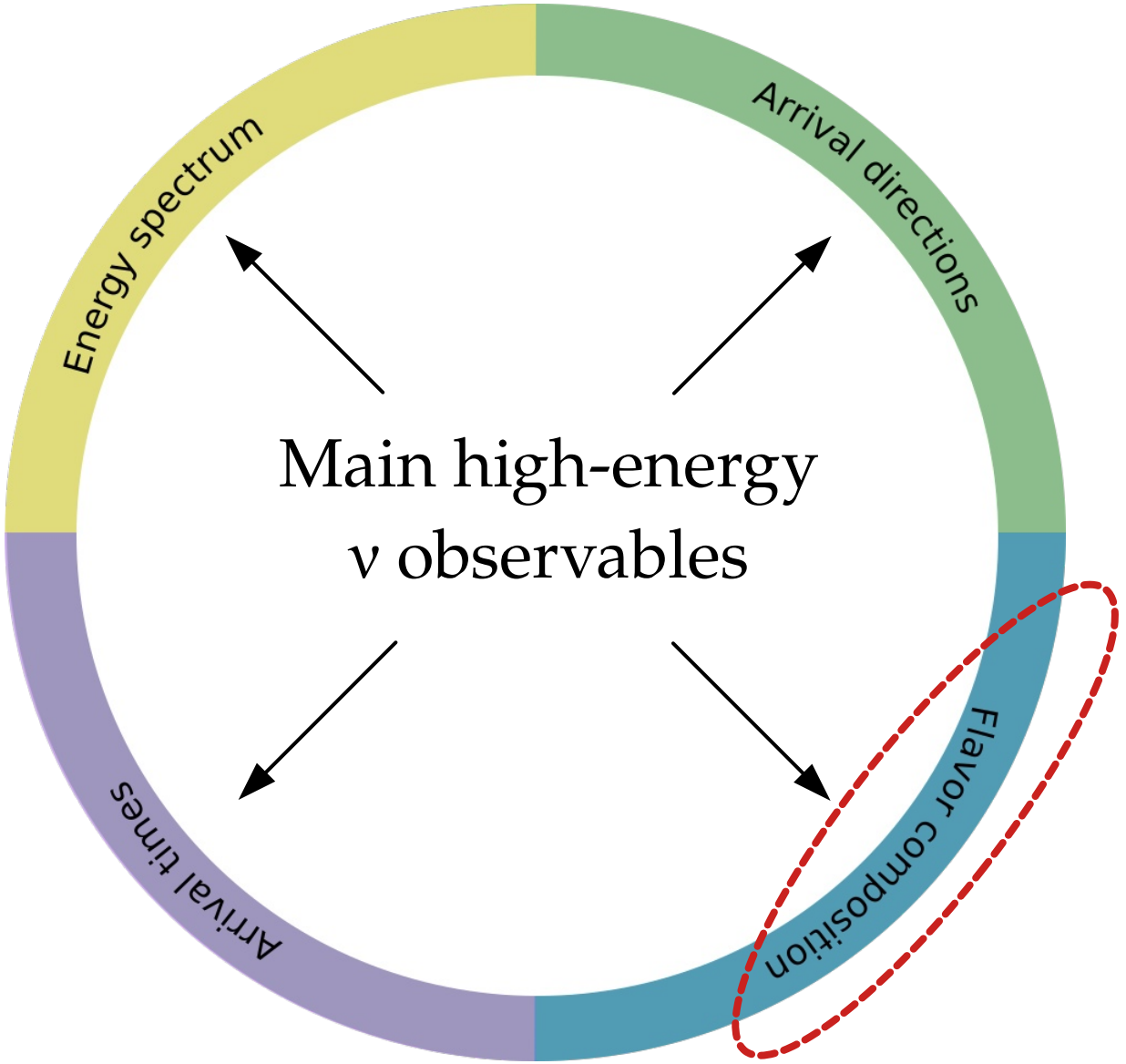
Standard expectation:
Isotropy (for diffuse flux)



Standard expectation:
ν and γ from transients arrive simultaneously

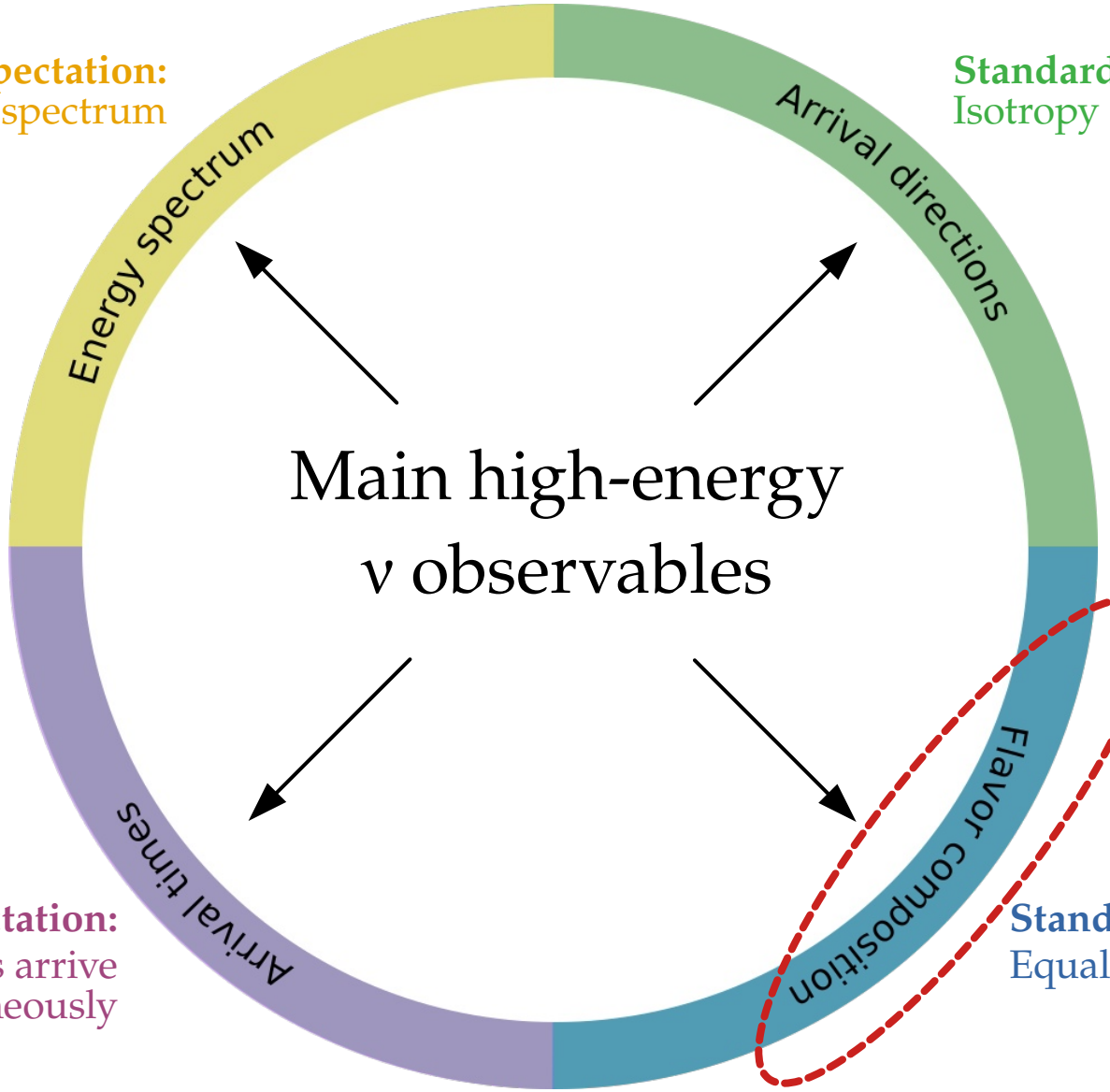
Standard expectation:
Equal number of ν_e, ν_μ, ν_τ


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]


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

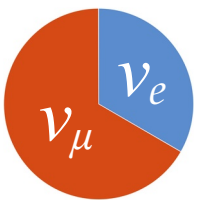
Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Astrophysical sources

Earth

Up to a few Gpc

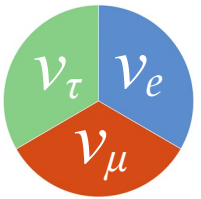
E.g.,



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):

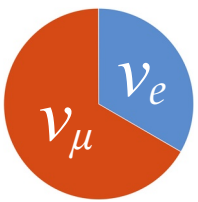
$$f_{\alpha,\oplus} = \sum_{\beta=e,\mu,\tau} P_{\nu_\beta \to \nu_\alpha} f_{\beta,S}$$

Astrophysical sources

Earth

Up to a few Gpc

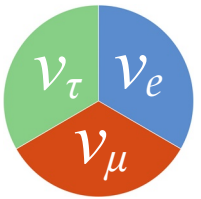
E.g.,



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 ($\alpha = e, \mu, \tau$):

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

Standard oscillations
or
new physics

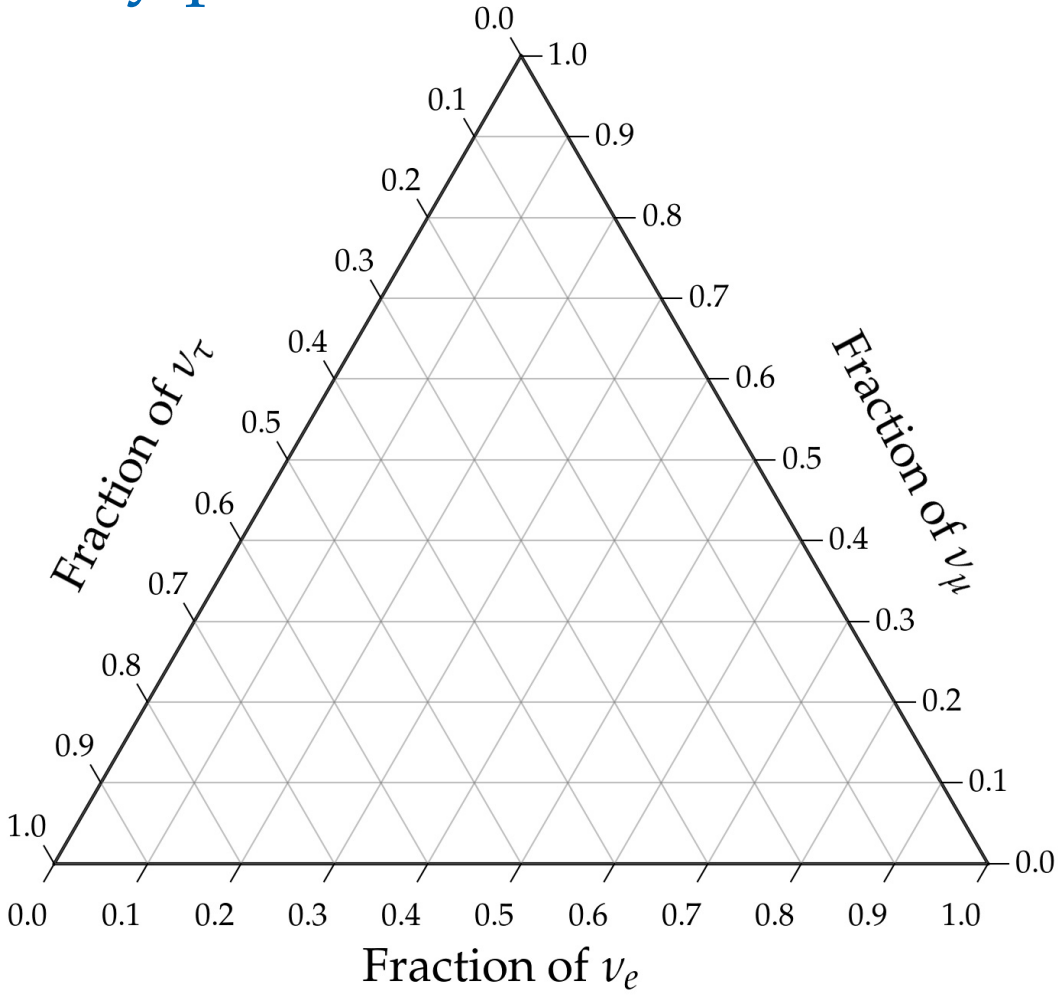
Quick aside: how to read a ternary plot

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)



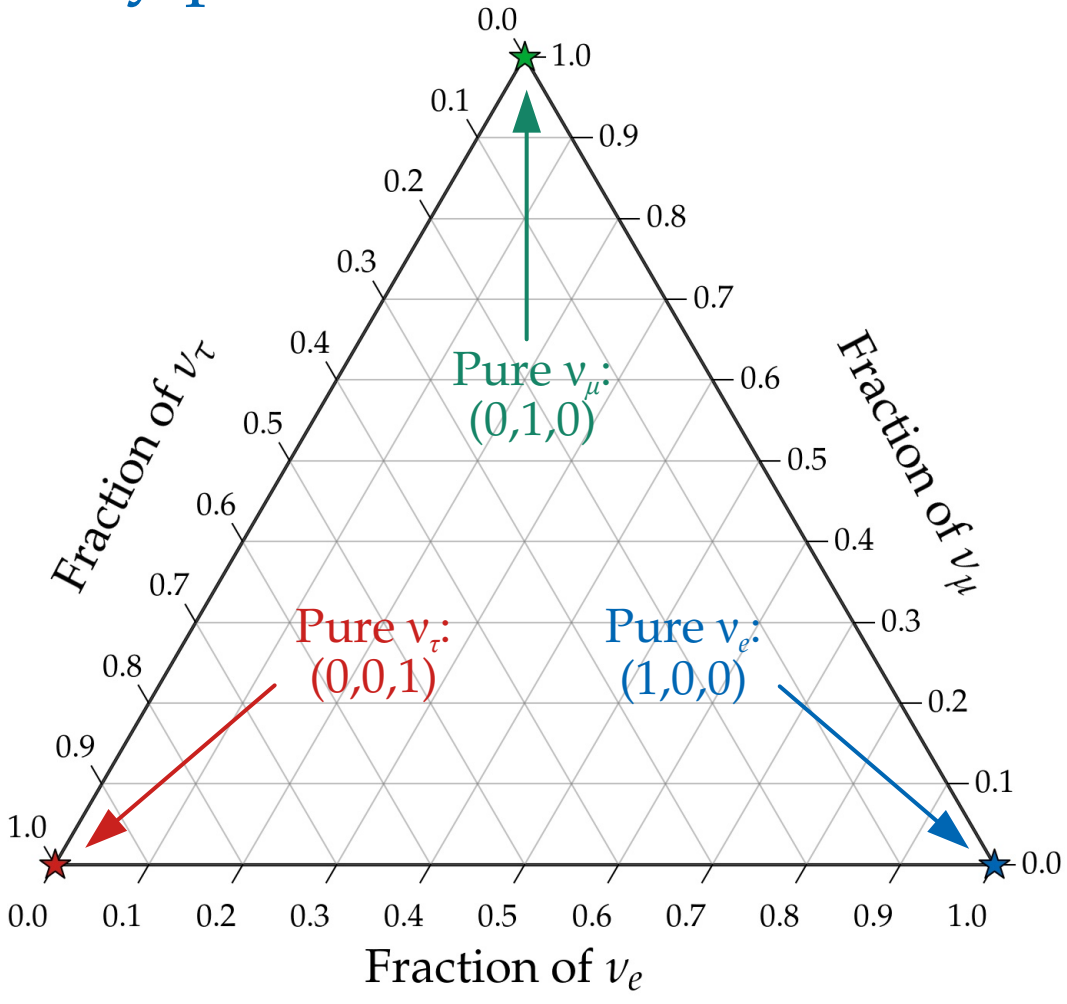
Quick aside: how to read a ternary plot

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)



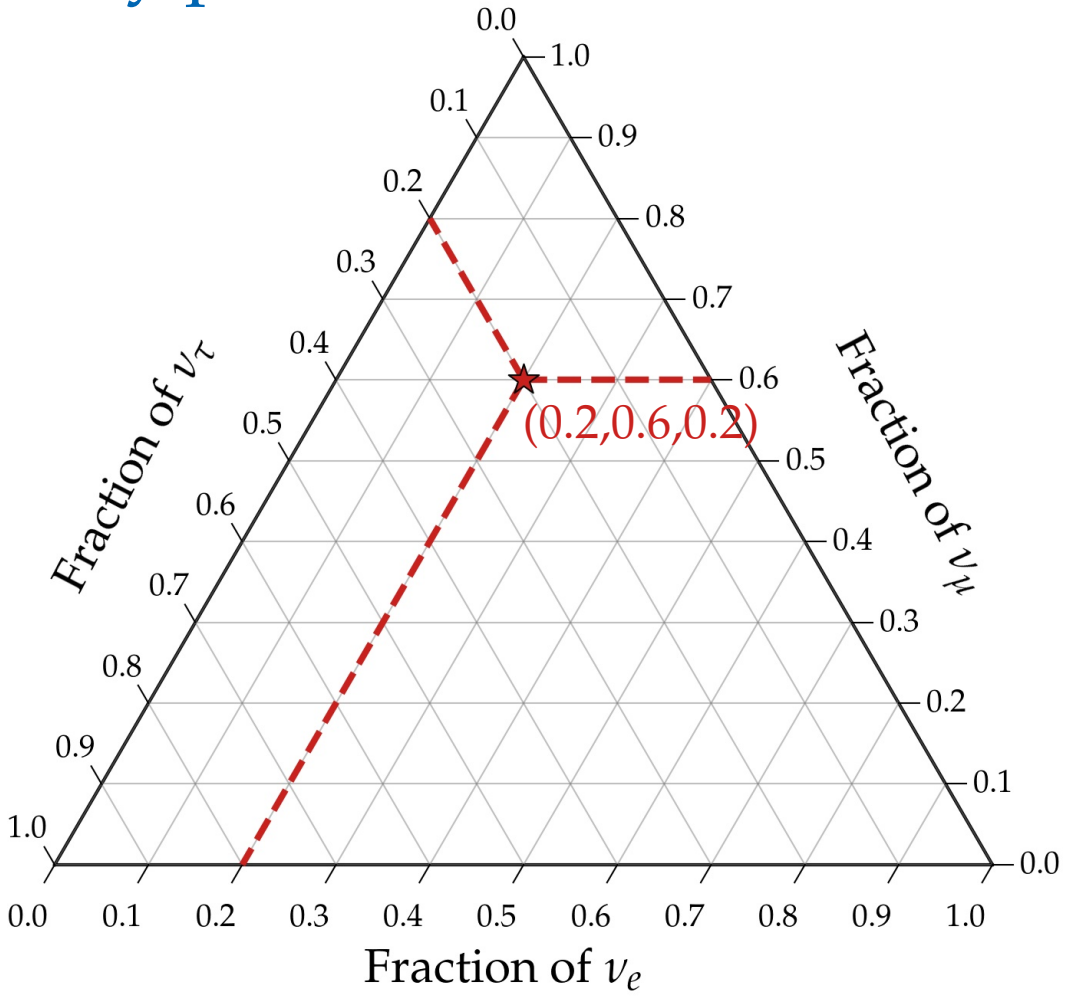
Quick aside: how to read a ternary plot

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)



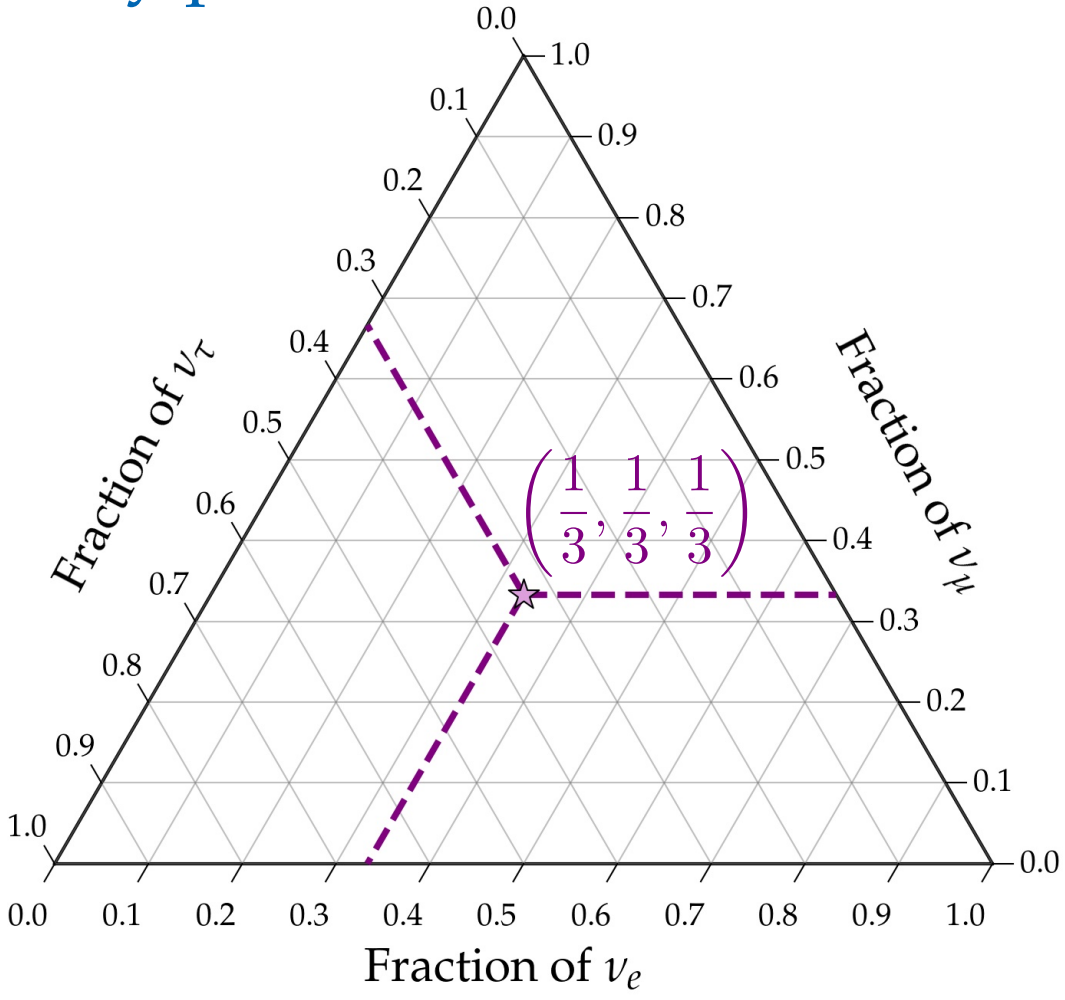
Quick aside: how to read a ternary plot

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

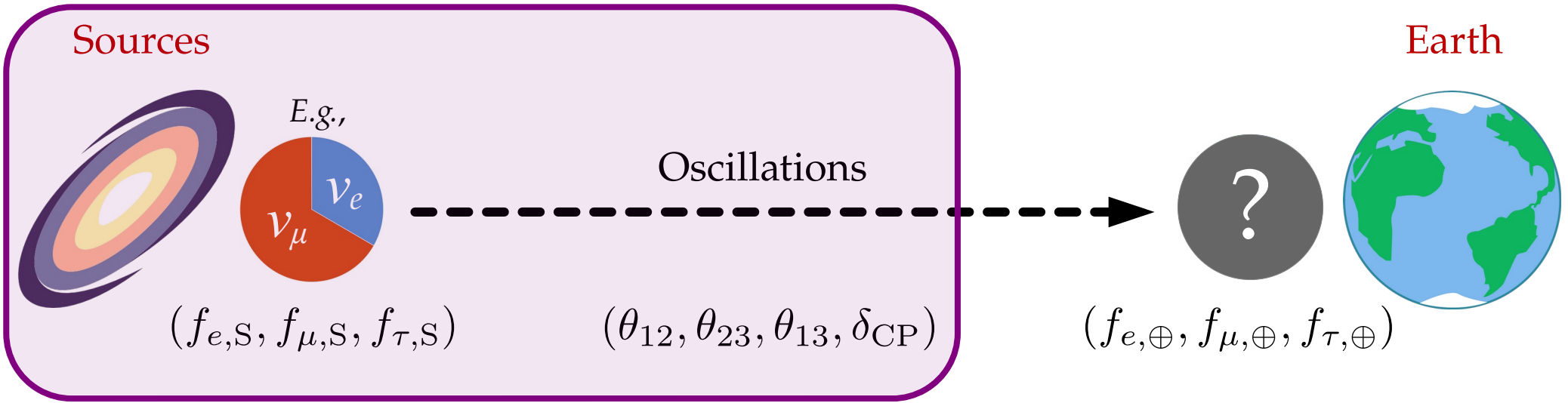
How to read it:

Follow the tilt of the tick marks

Always in this order: (f_e, f_μ, f_τ)



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

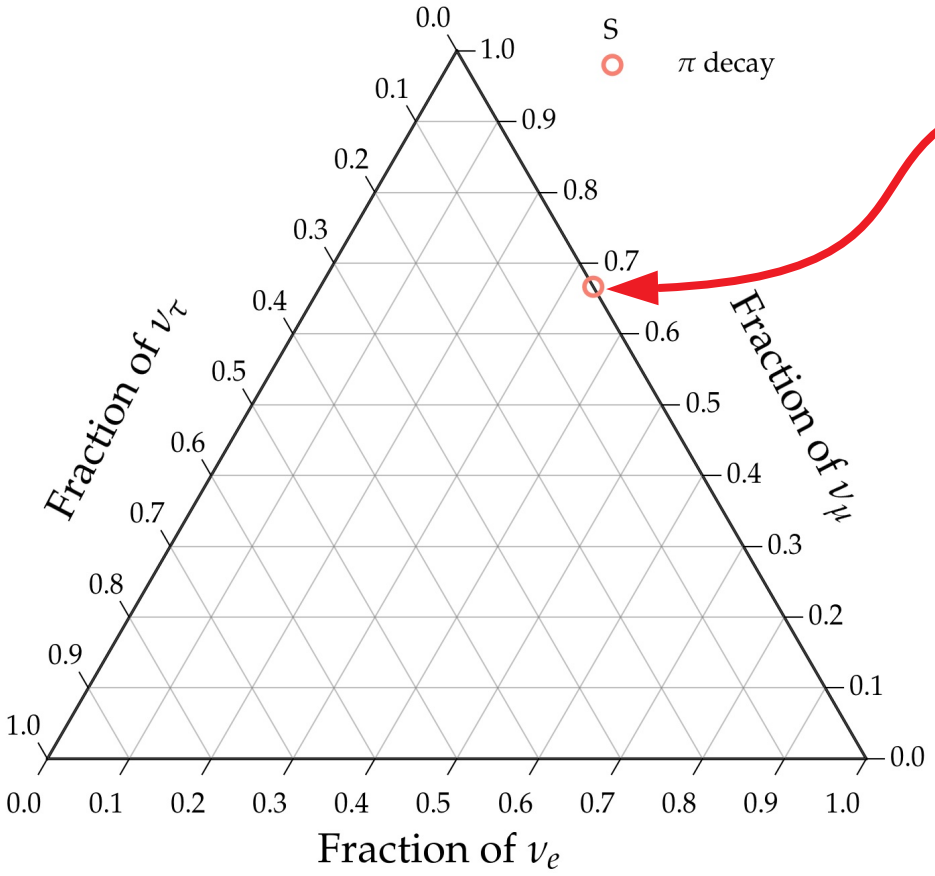
Full π decay chain

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

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

One likely TeV–PeV ν production scenario:

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



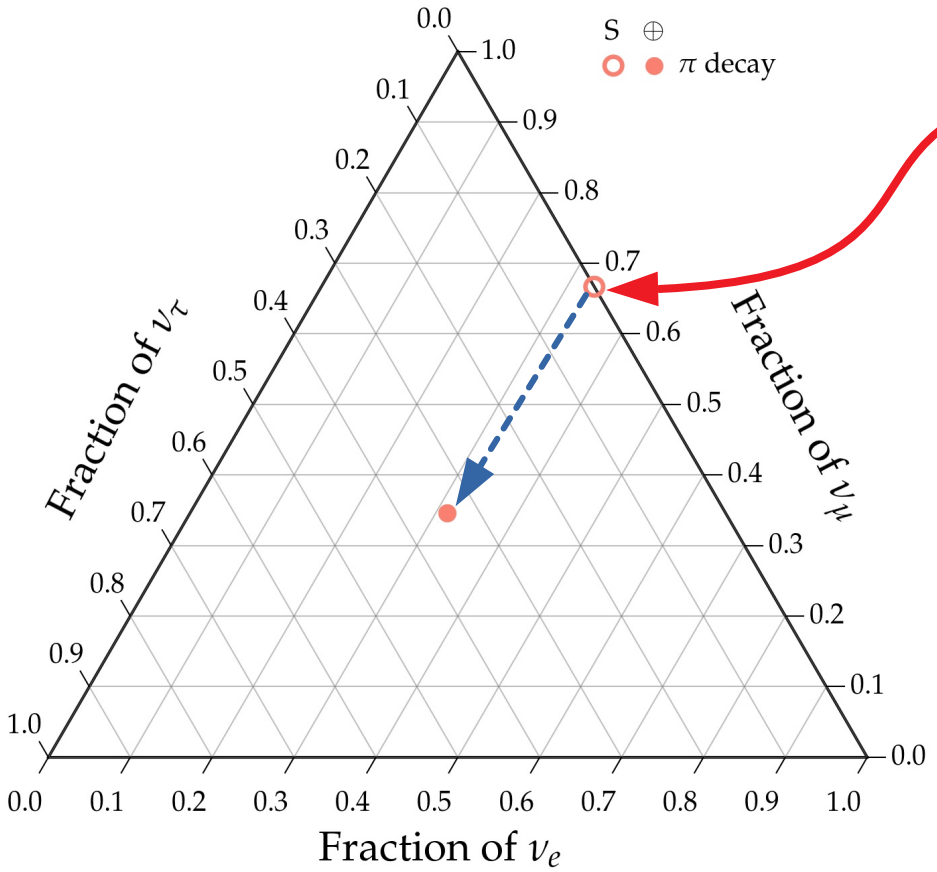
Full π decay chain

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

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

One likely TeV–PeV ν production scenario:

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



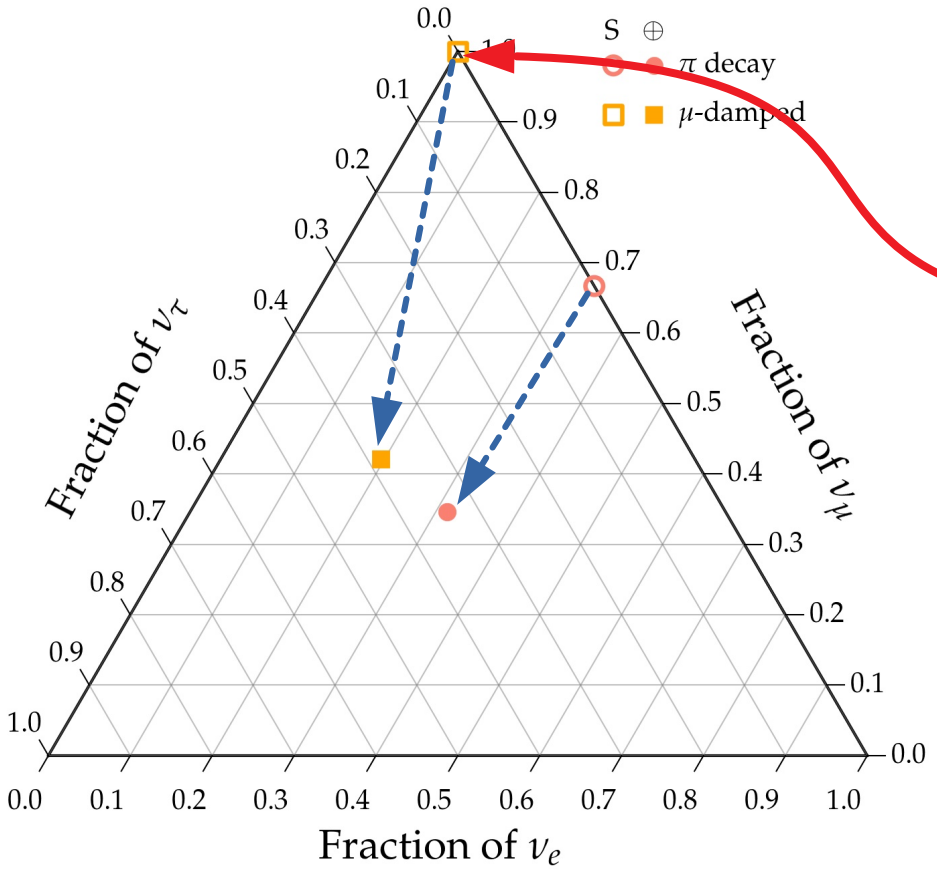
Full π decay chain

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

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

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

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

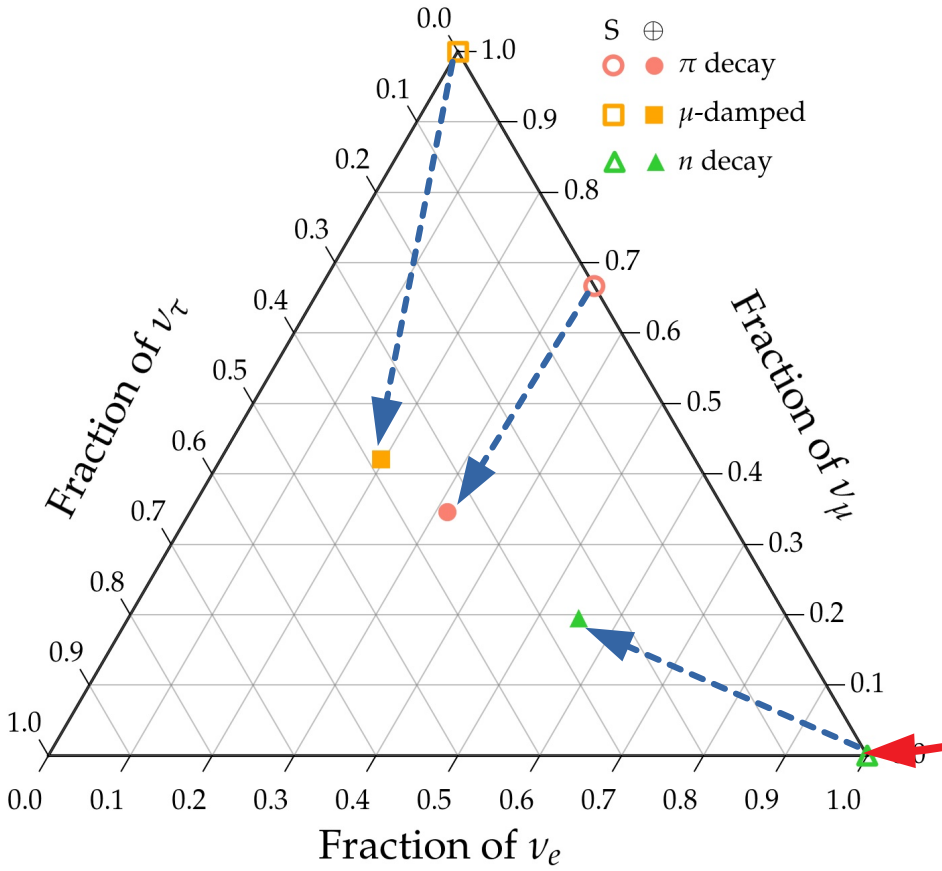
Muon damped

$(0:1:0)_S$

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

One likely TeV–PeV ν production scenario:

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



Full π decay chain

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

Muon damped

$(0:1:0)_S$

Neutron decay

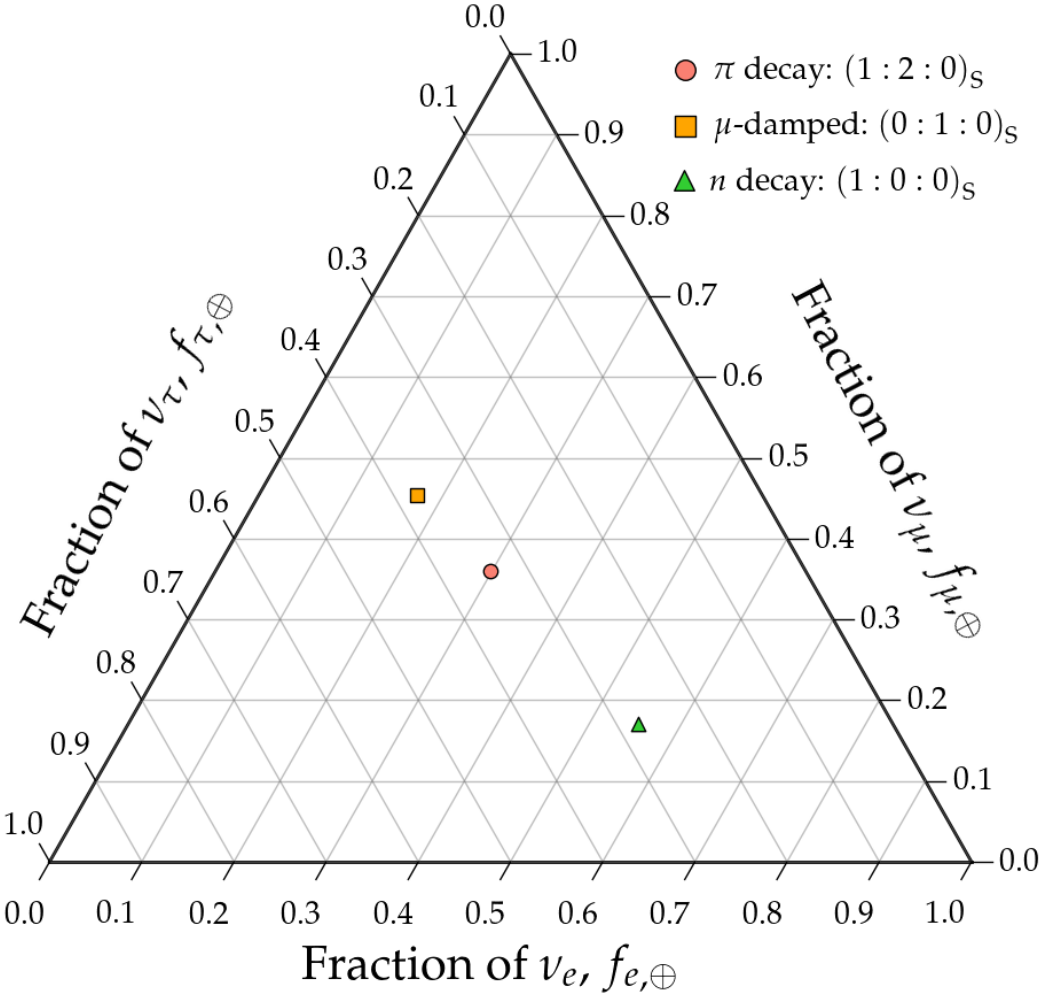
$(1:0:0)_S$

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

Measuring flavor composition: 2015–2020

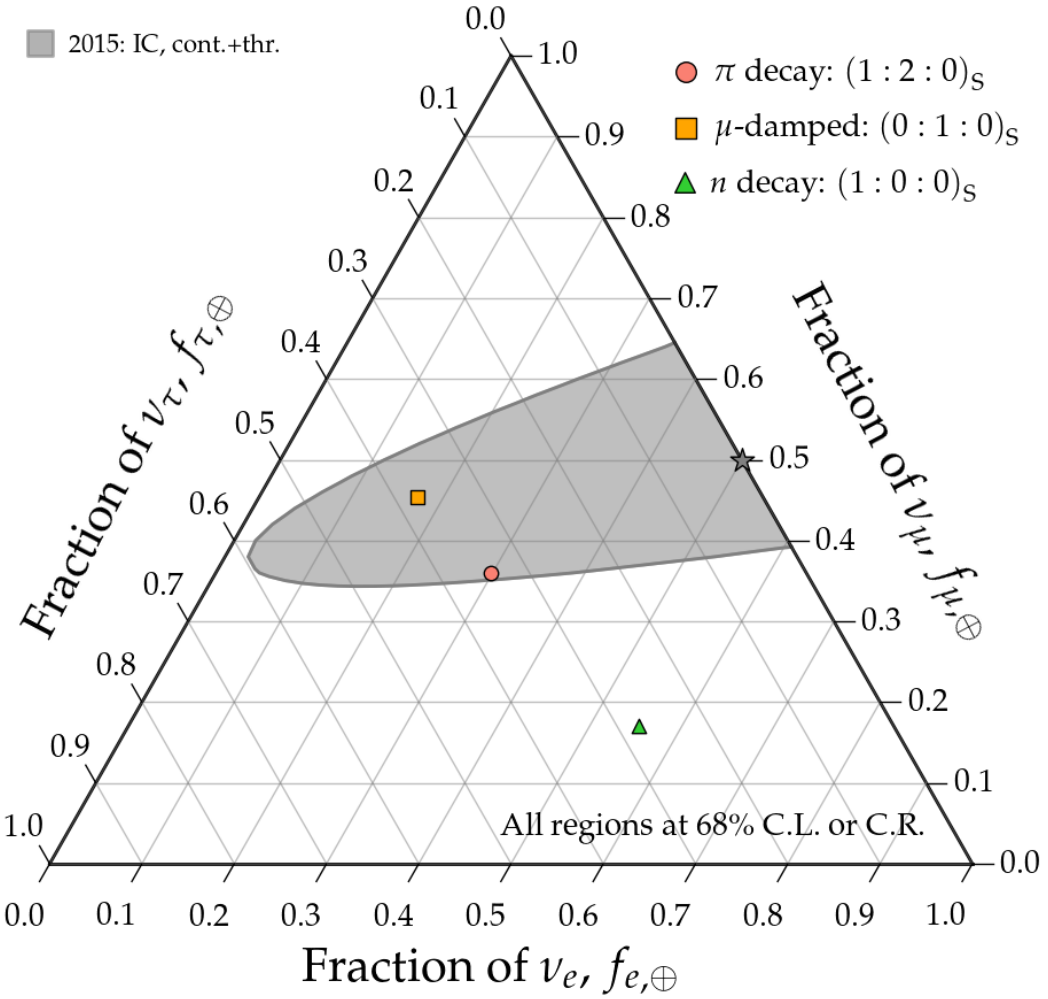
IceCube Collab., *EPJC* 2022
IceCube Collab., *PRD* 2019
IceCube Collab., *ApJ* 2015

Measuring flavor composition: 2015–2020



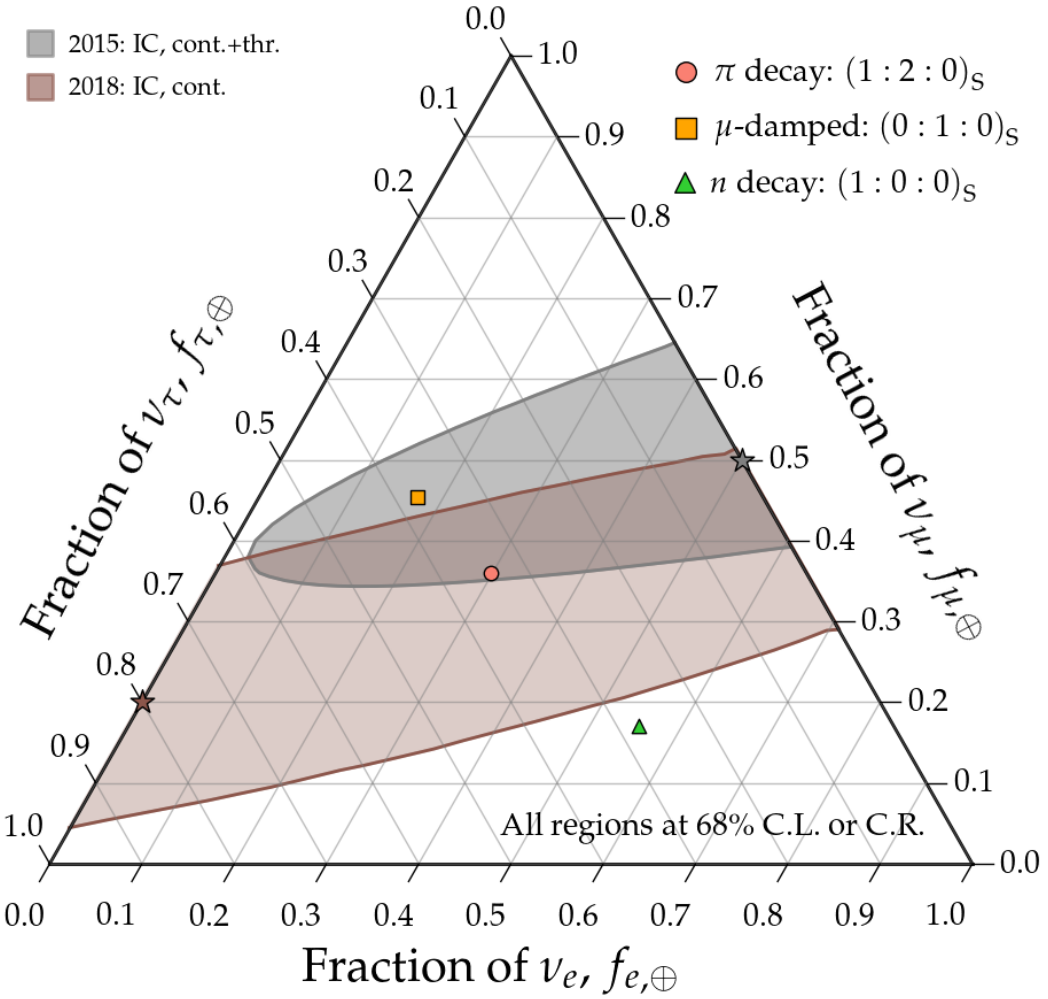
IceCube Collab., *EPJC* 2022
IceCube Collab., *PRD* 2019
IceCube Collab., *ApJ* 2015

Measuring flavor composition: 2015–2020



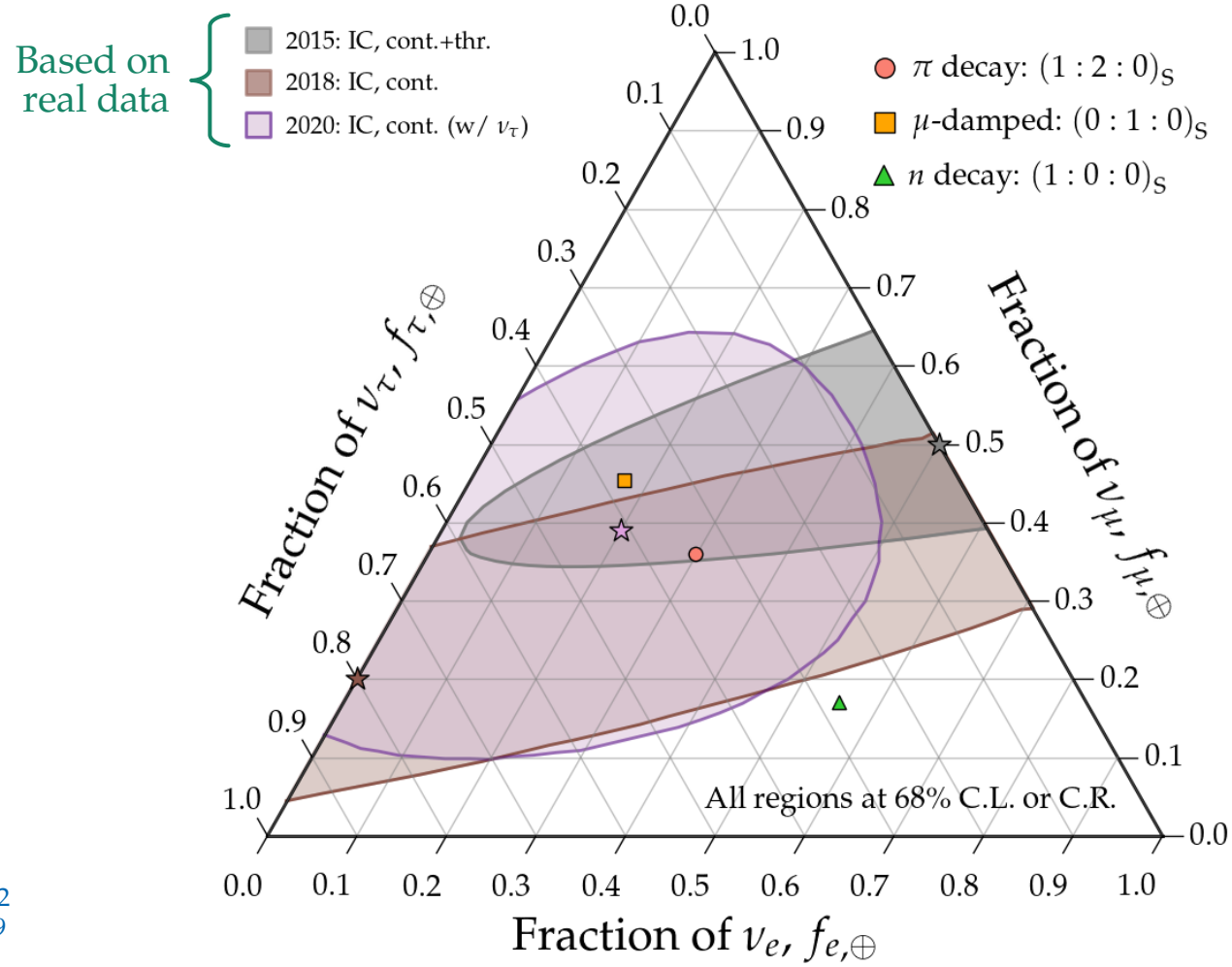
IceCube Collab., *EPJC* 2022
IceCube Collab., *PRD* 2019
IceCube Collab., *ApJ* 2015

Measuring flavor composition: 2015–2020



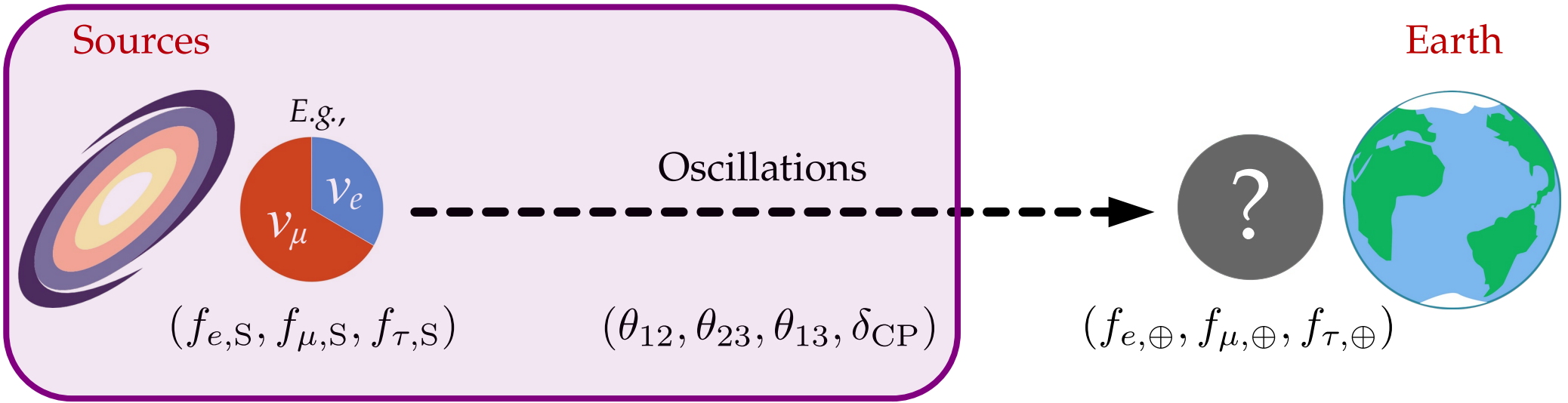
IceCube Collab., *EPJC* 2022
IceCube Collab., *PRD* 2019
IceCube Collab., *ApJ* 2015

Measuring flavor composition: 2015–2020



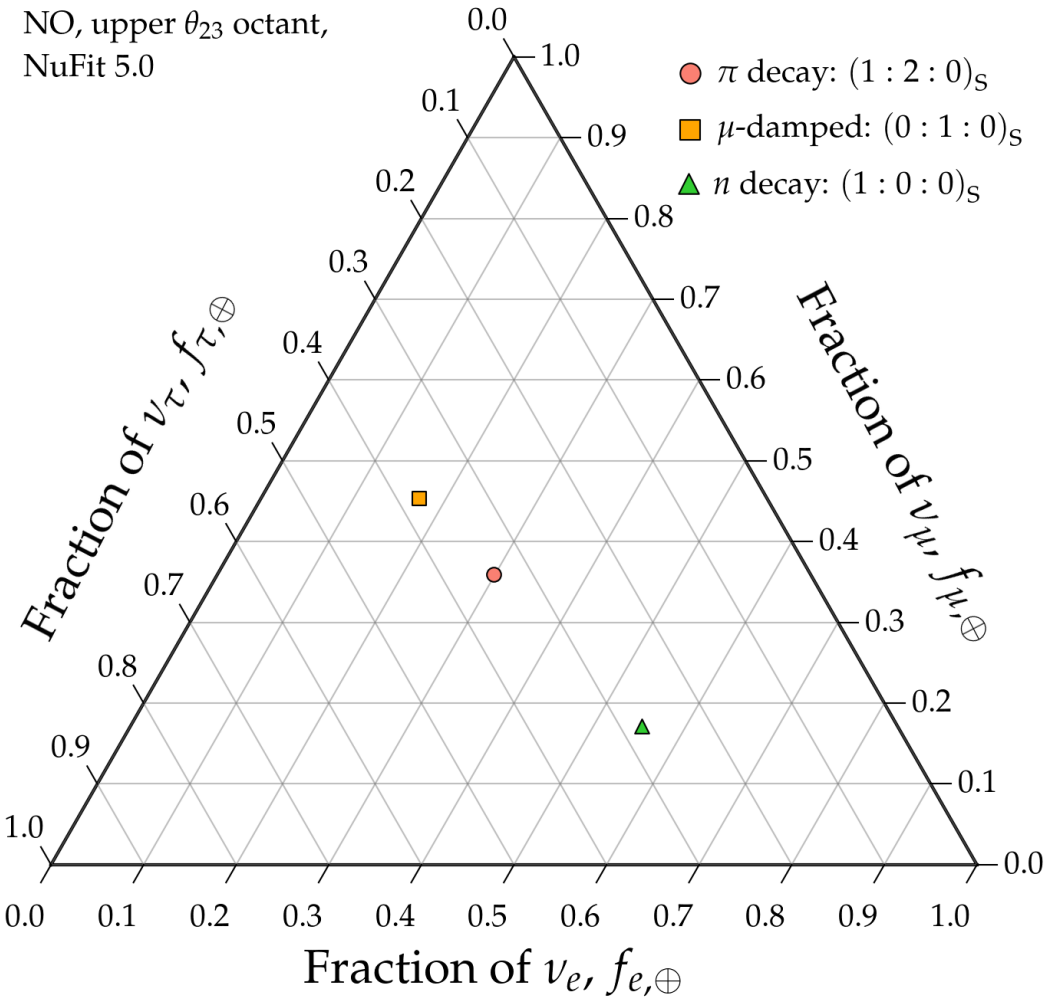
IceCube Collab., *EPJC* 2022
IceCube Collab., *PRD* 2019
IceCube Collab., *ApJ* 2015

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



Known from oscillation experiments, to different levels of precision

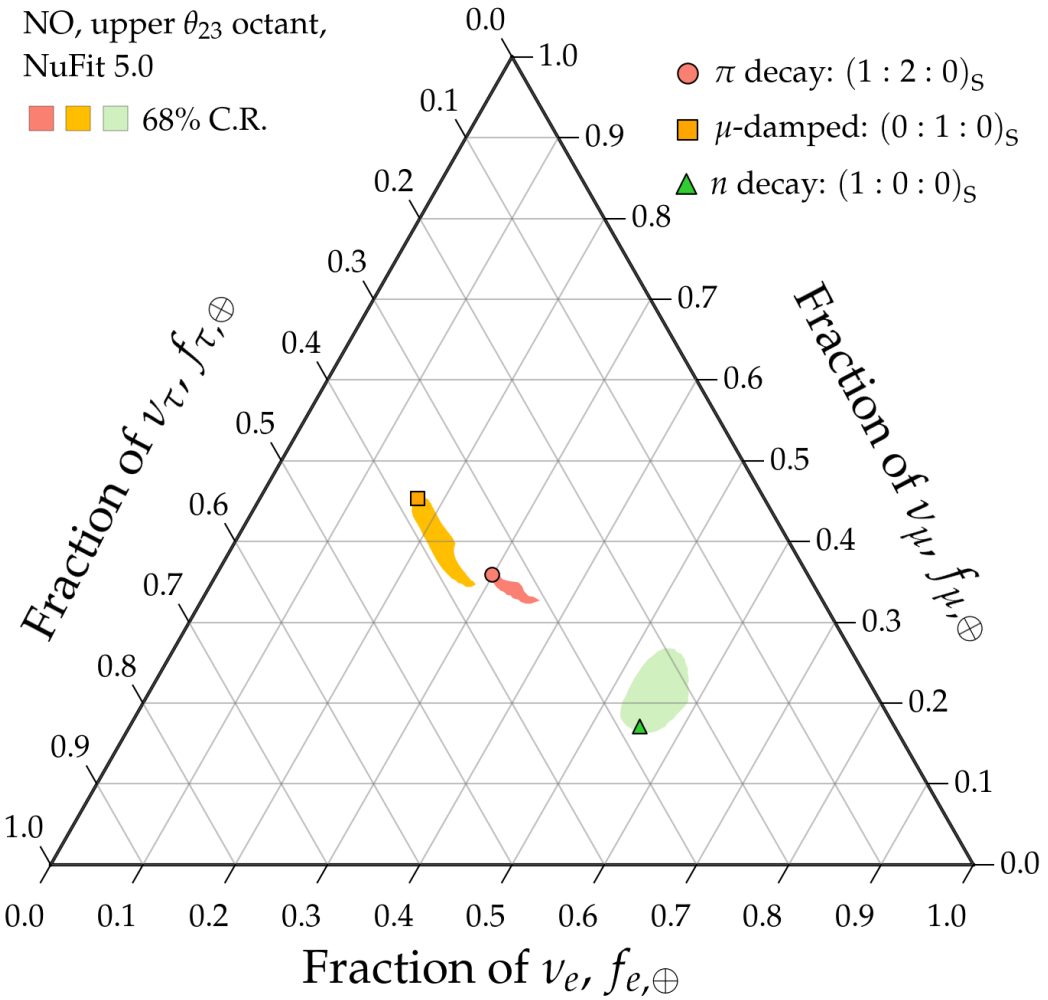
Theoretically palatable regions: today



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

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

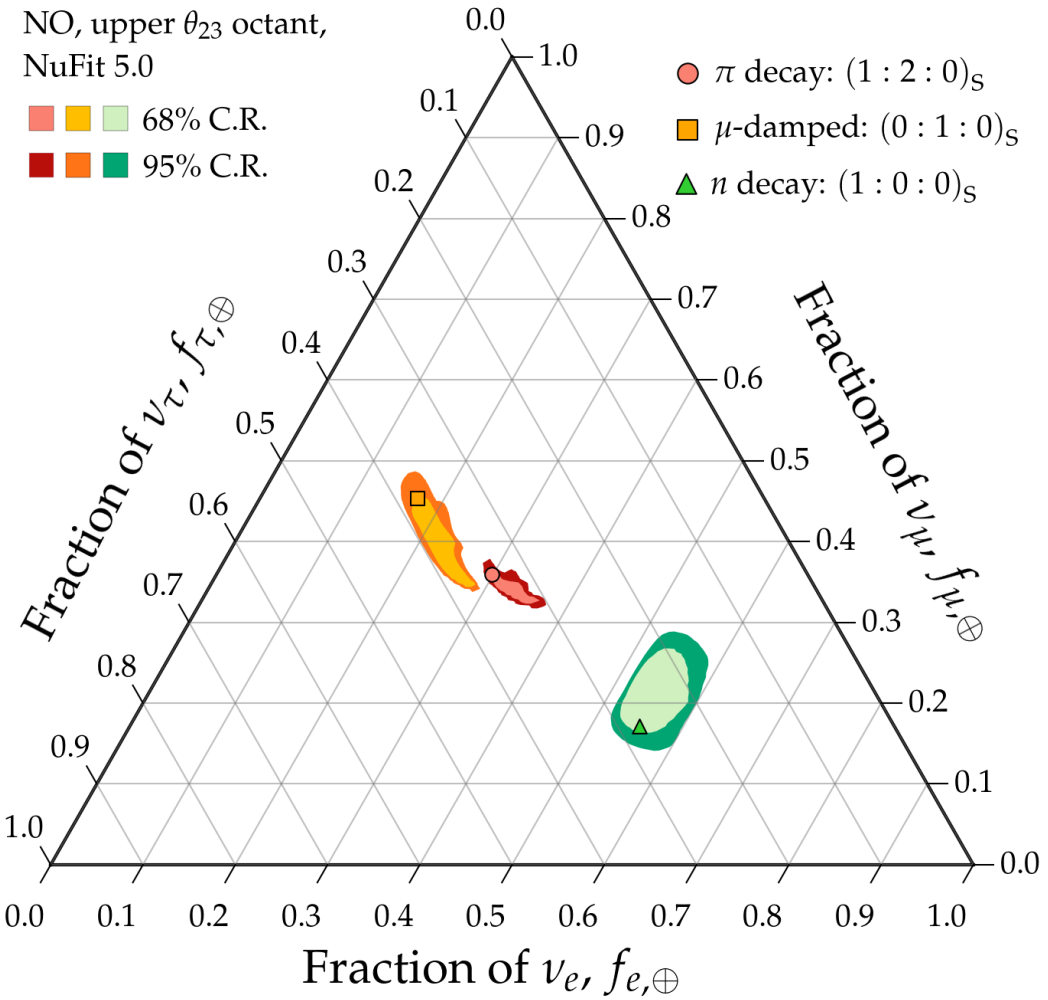
Theoretically palatable regions: today



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

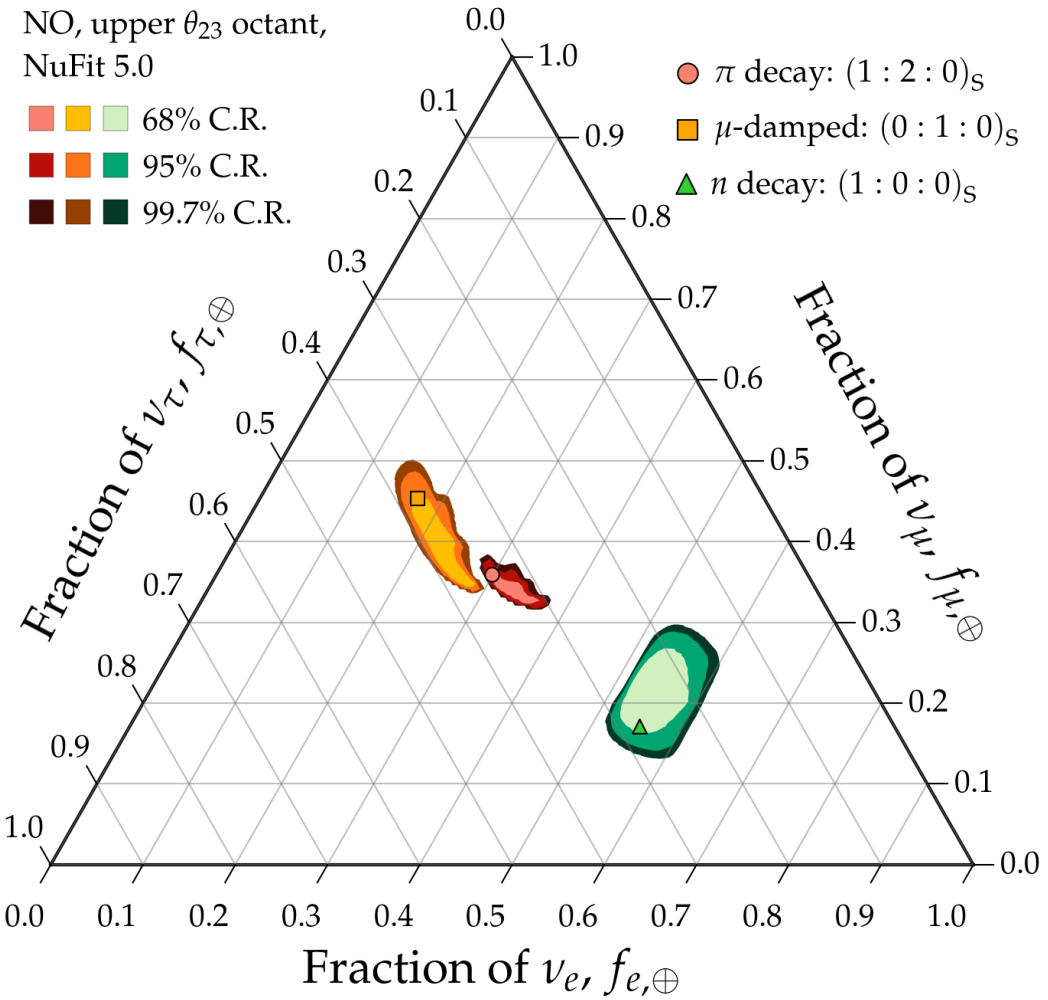
Theoretically palatable regions: today



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

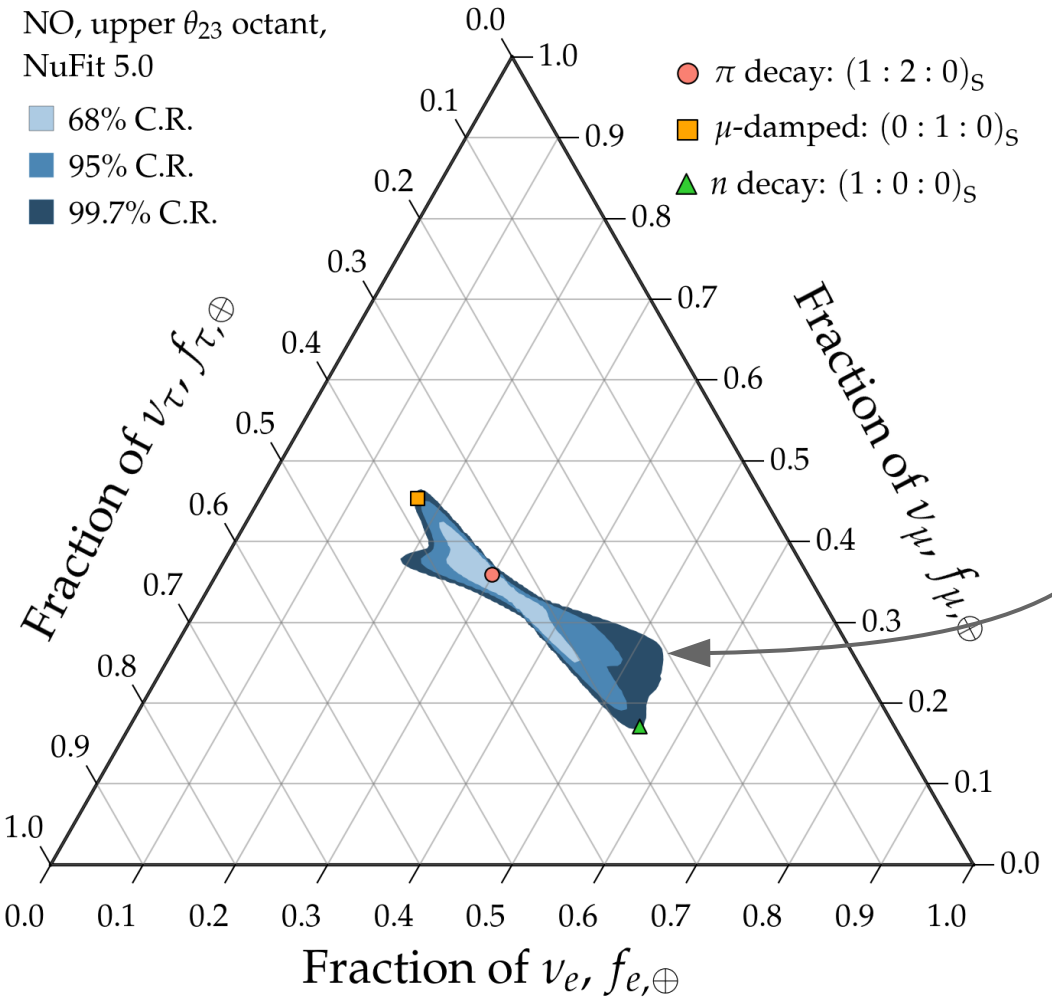
Theoretically palatable regions: today



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

Theoretically palatable regions: today



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

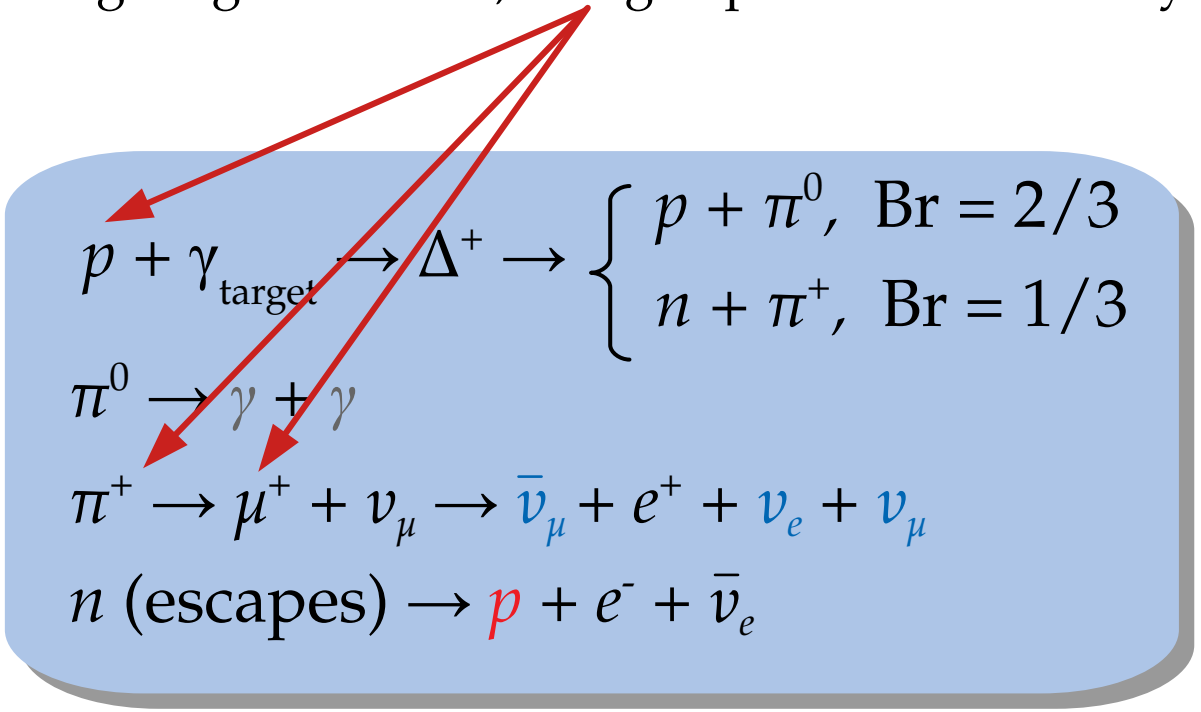
Theoretically palatable regions: today

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

Using high-energy neutrinos as magnetometers

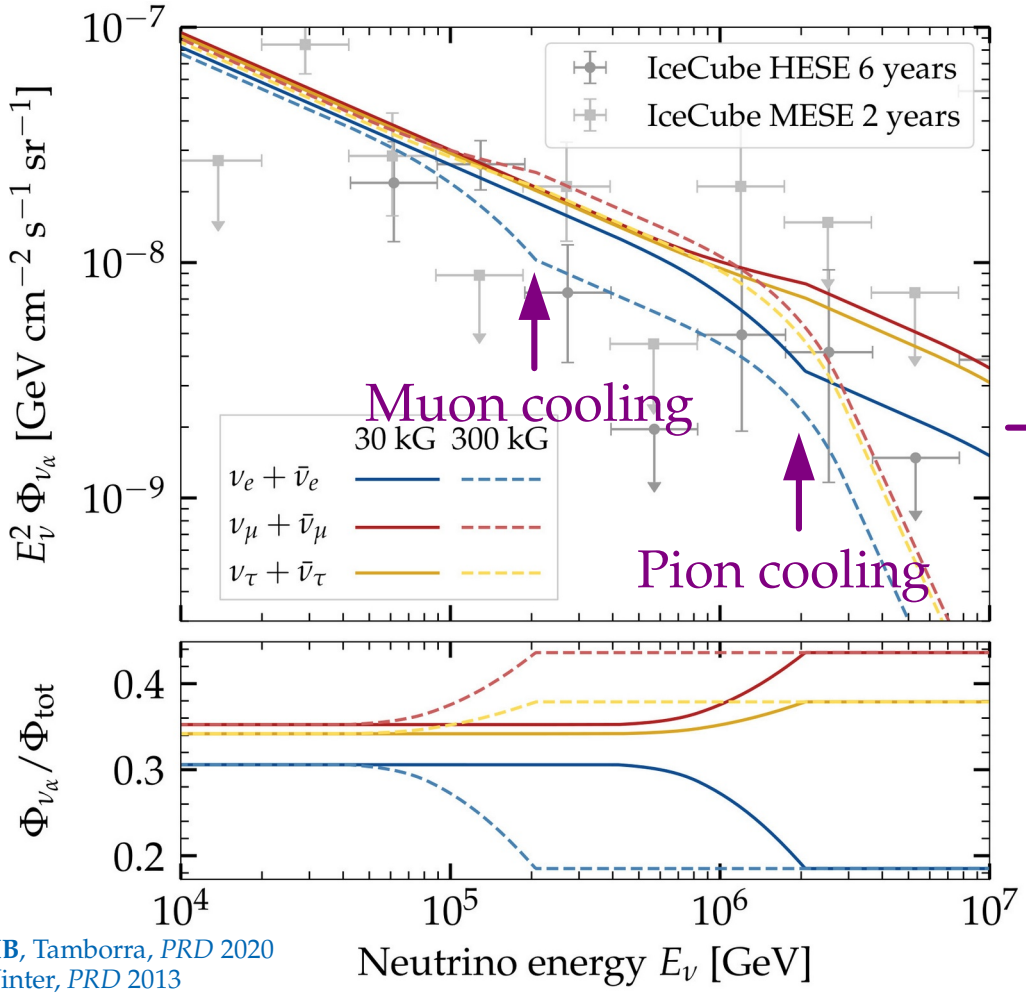
If sources have strong magnetic fields, charged particles cool via synchrotron:



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

Using high-energy neutrinos as magnetometers

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

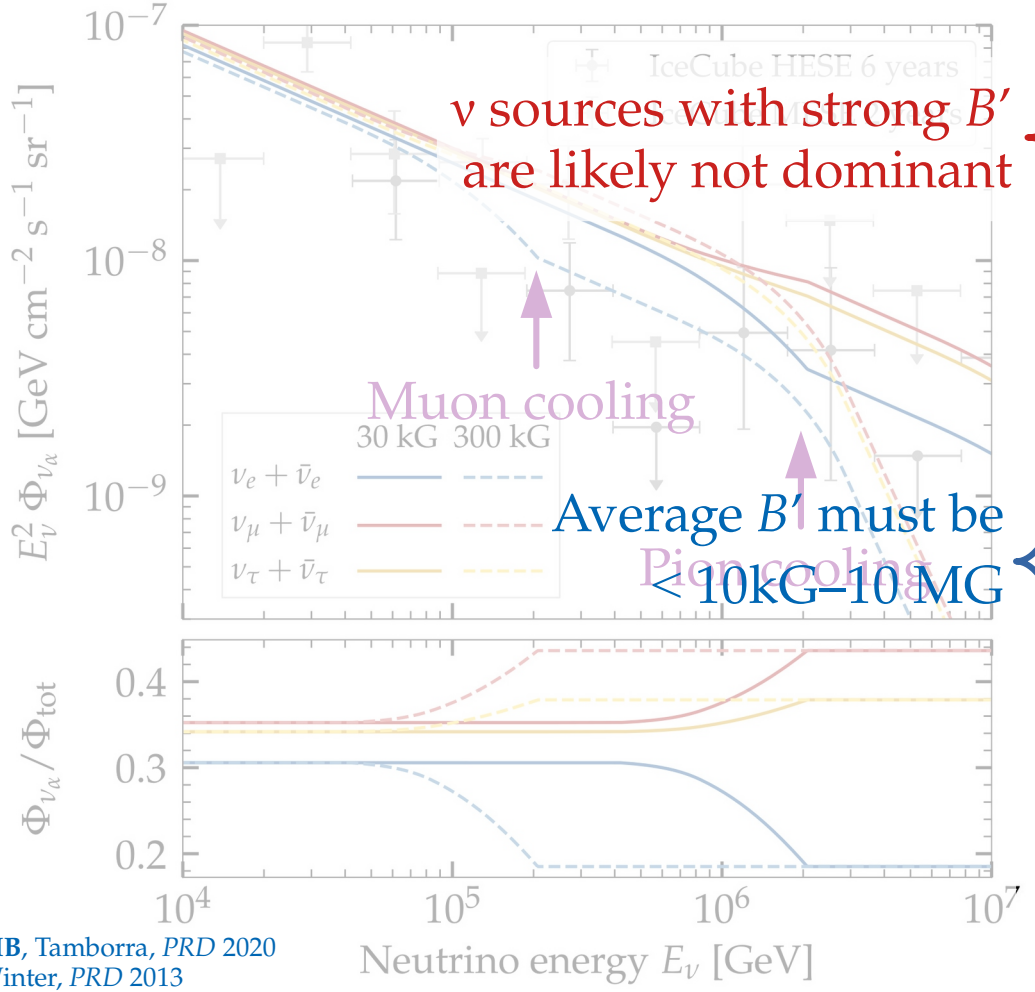


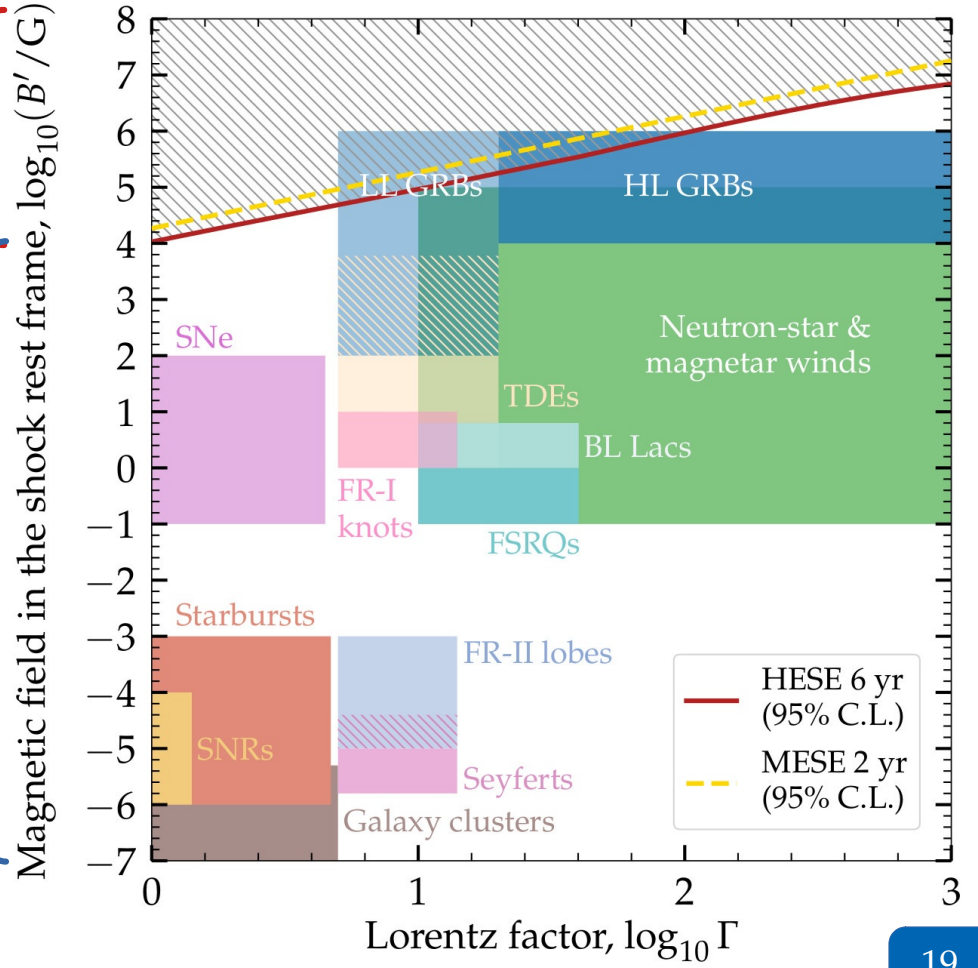
→ Proton cooling

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

Using high-energy neutrinos as magnetometers

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

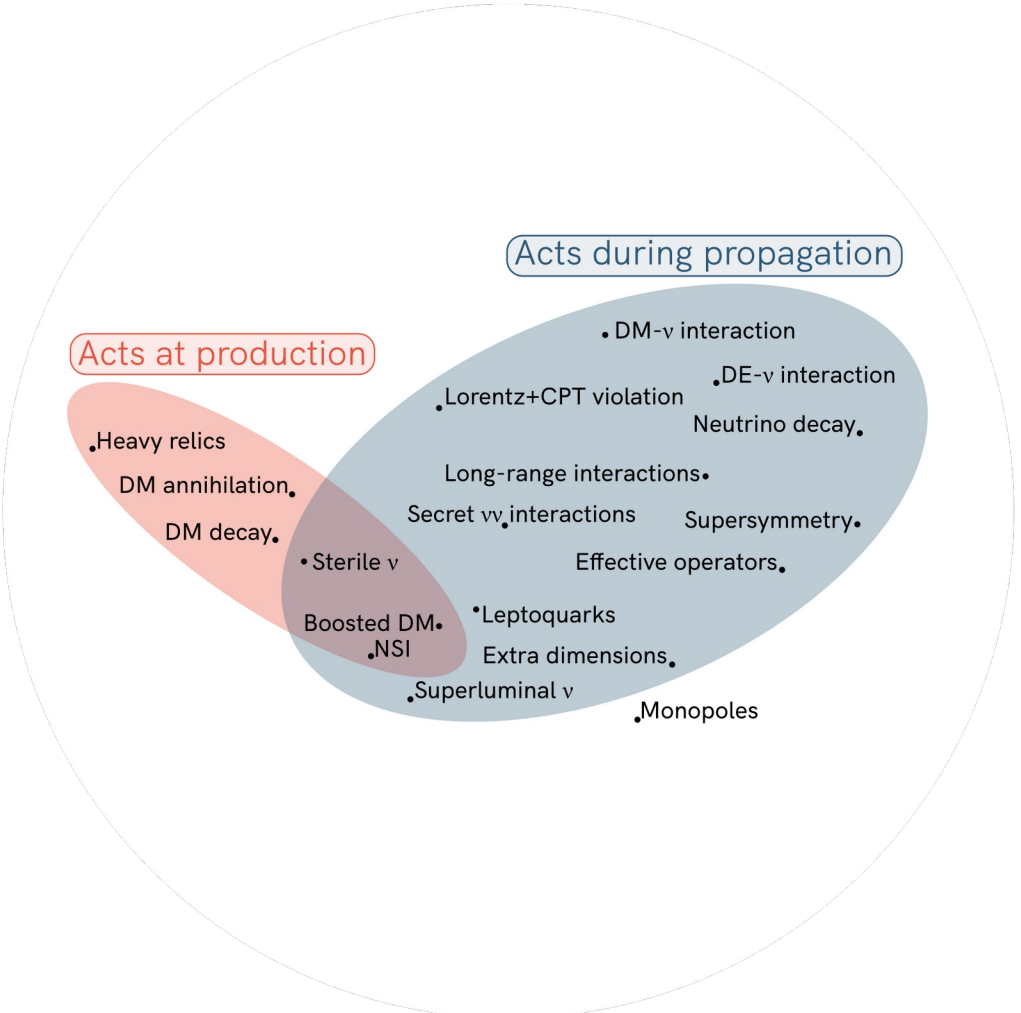




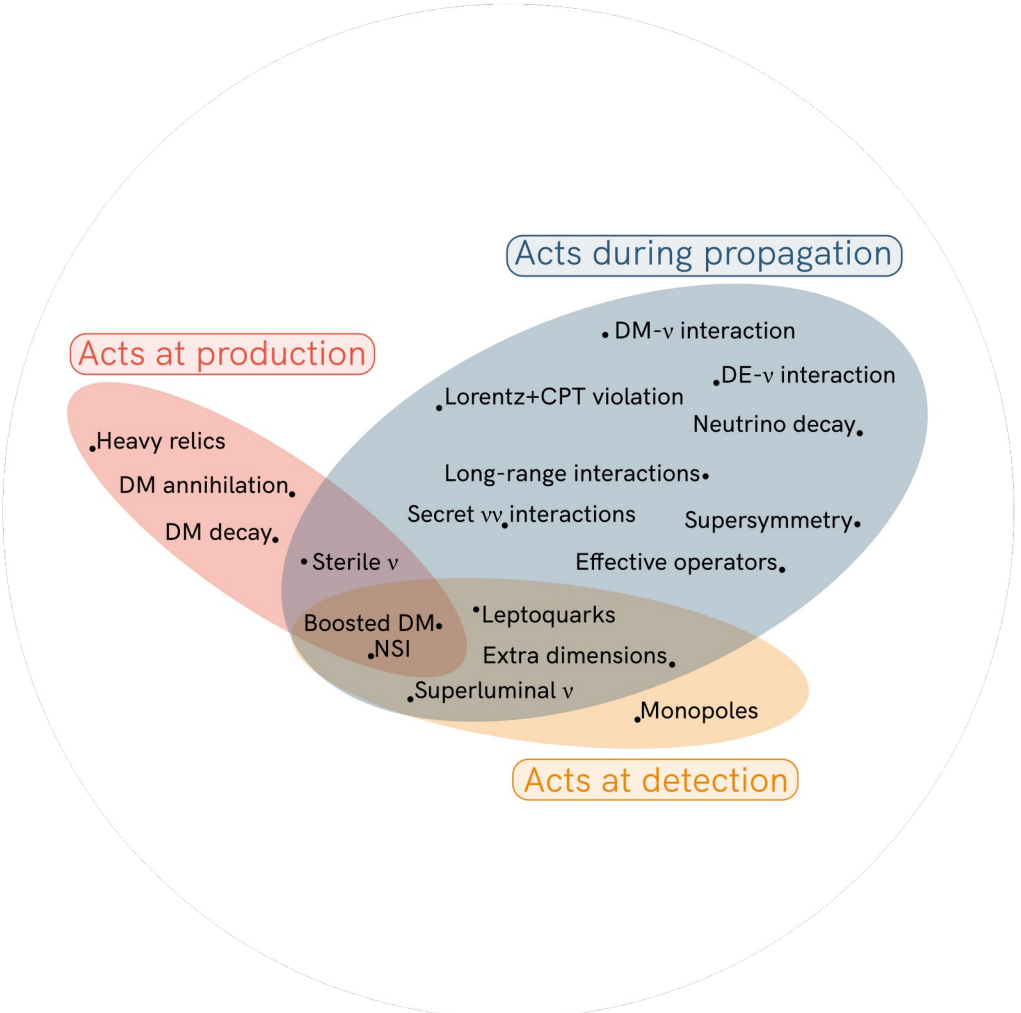
MB, Tamborra, *PRD* 2020
Winter, *PRD* 2013

Note: Not an exhaustive list

Note: Not an exhaustive list



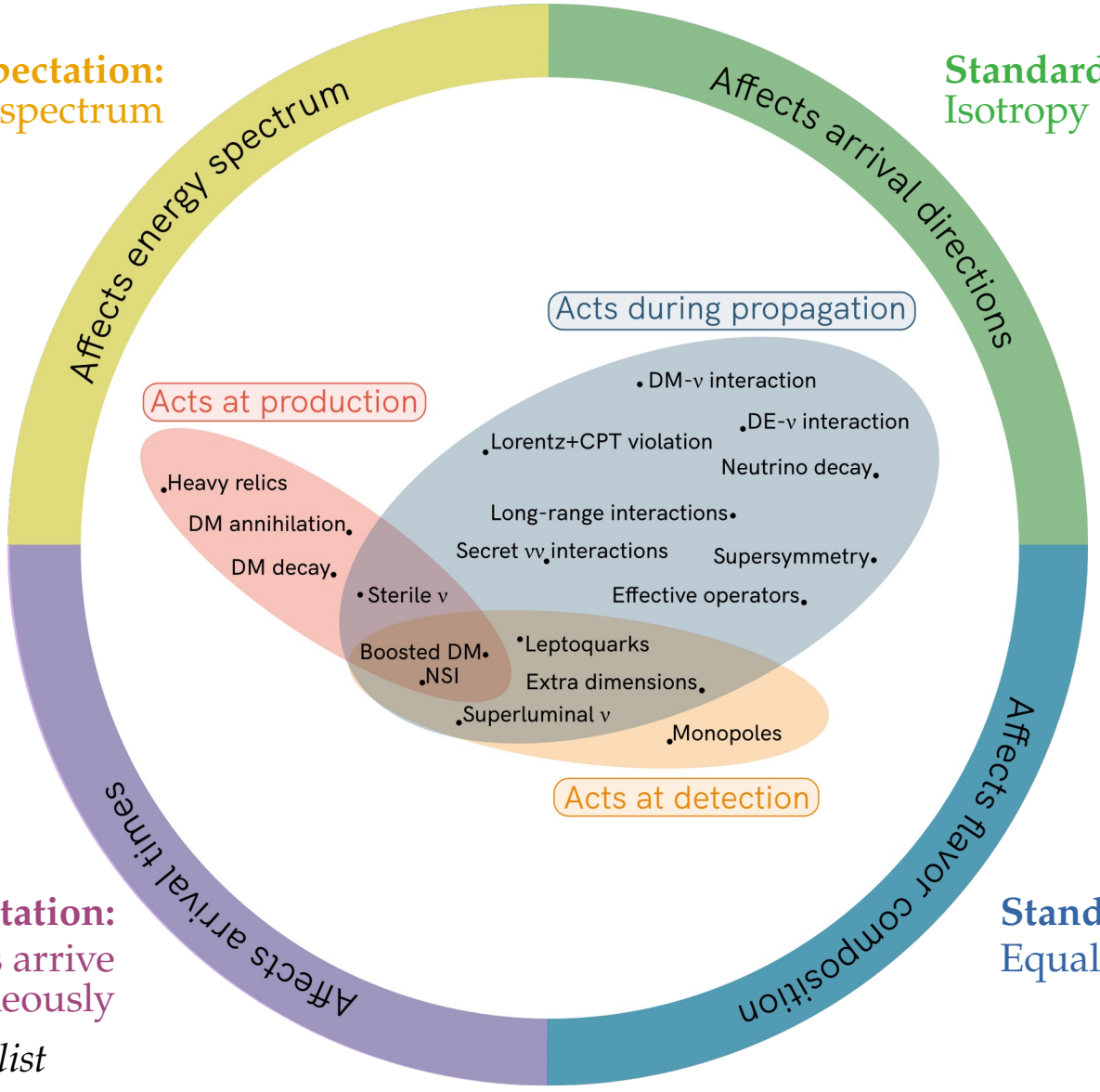
Note: Not an exhaustive list



Note: Not an exhaustive list

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



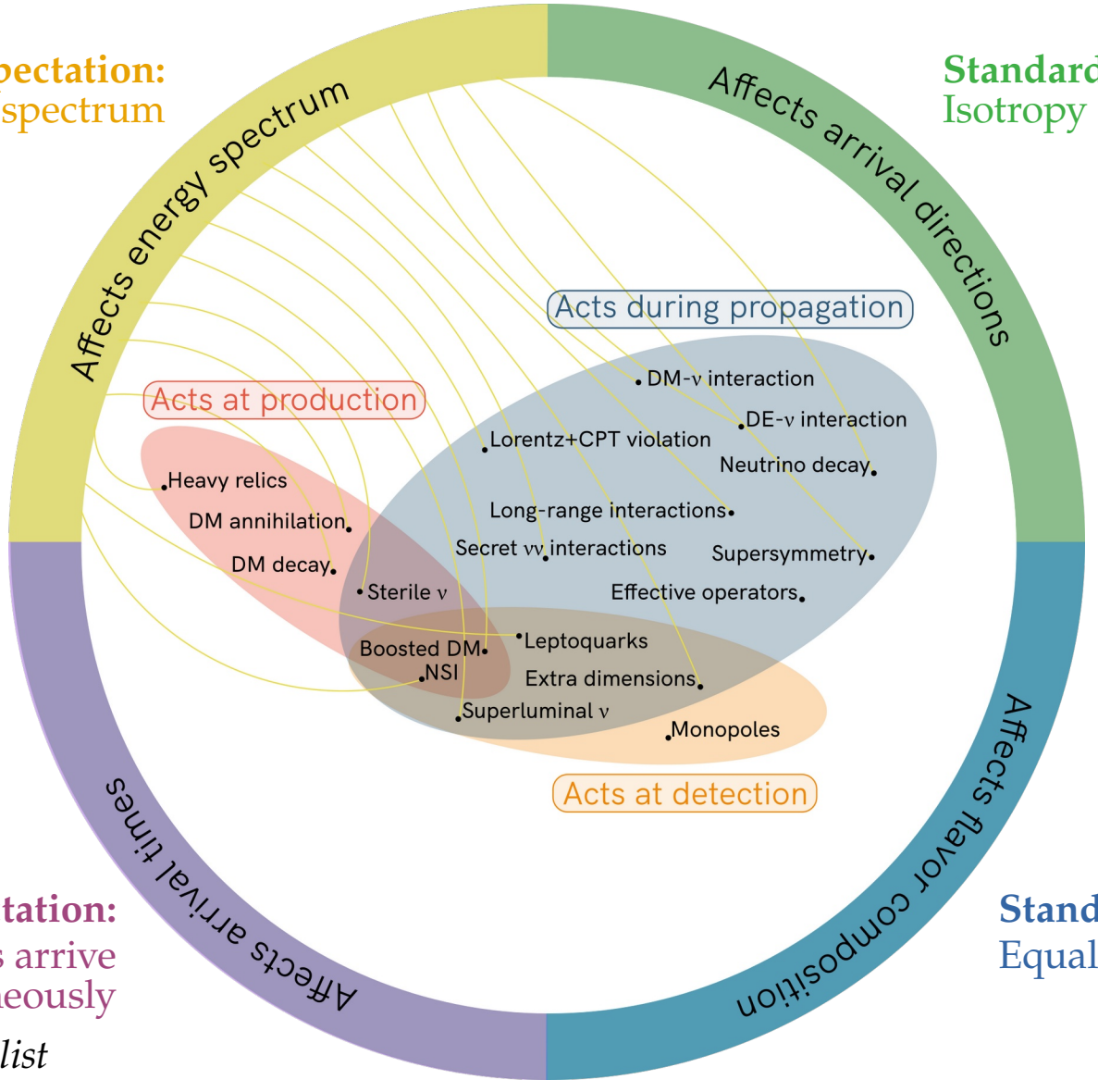
Standard expectation:
ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Note: Not an exhaustive list

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



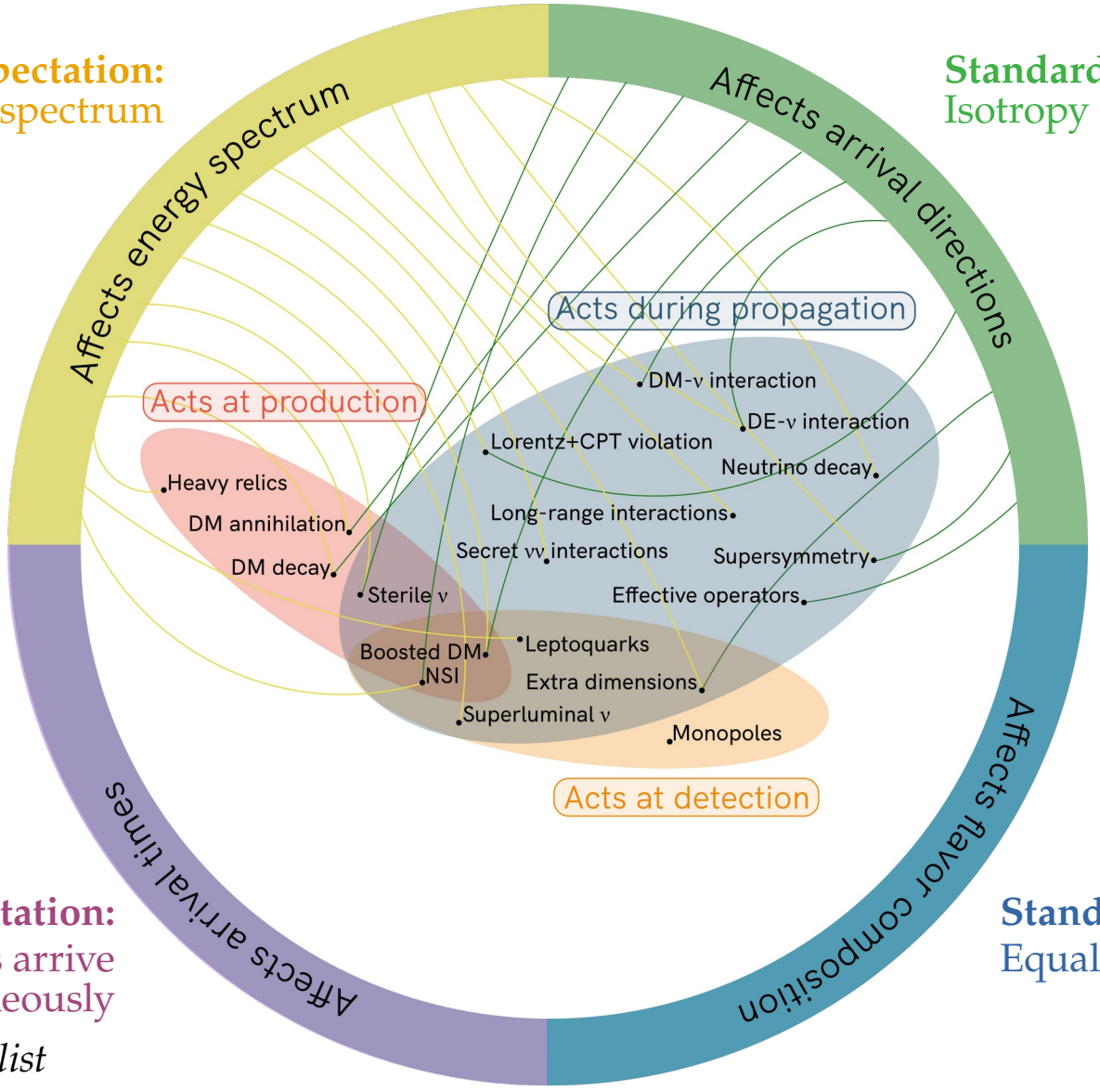
Standard expectation:
ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Note: Not an exhaustive list

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



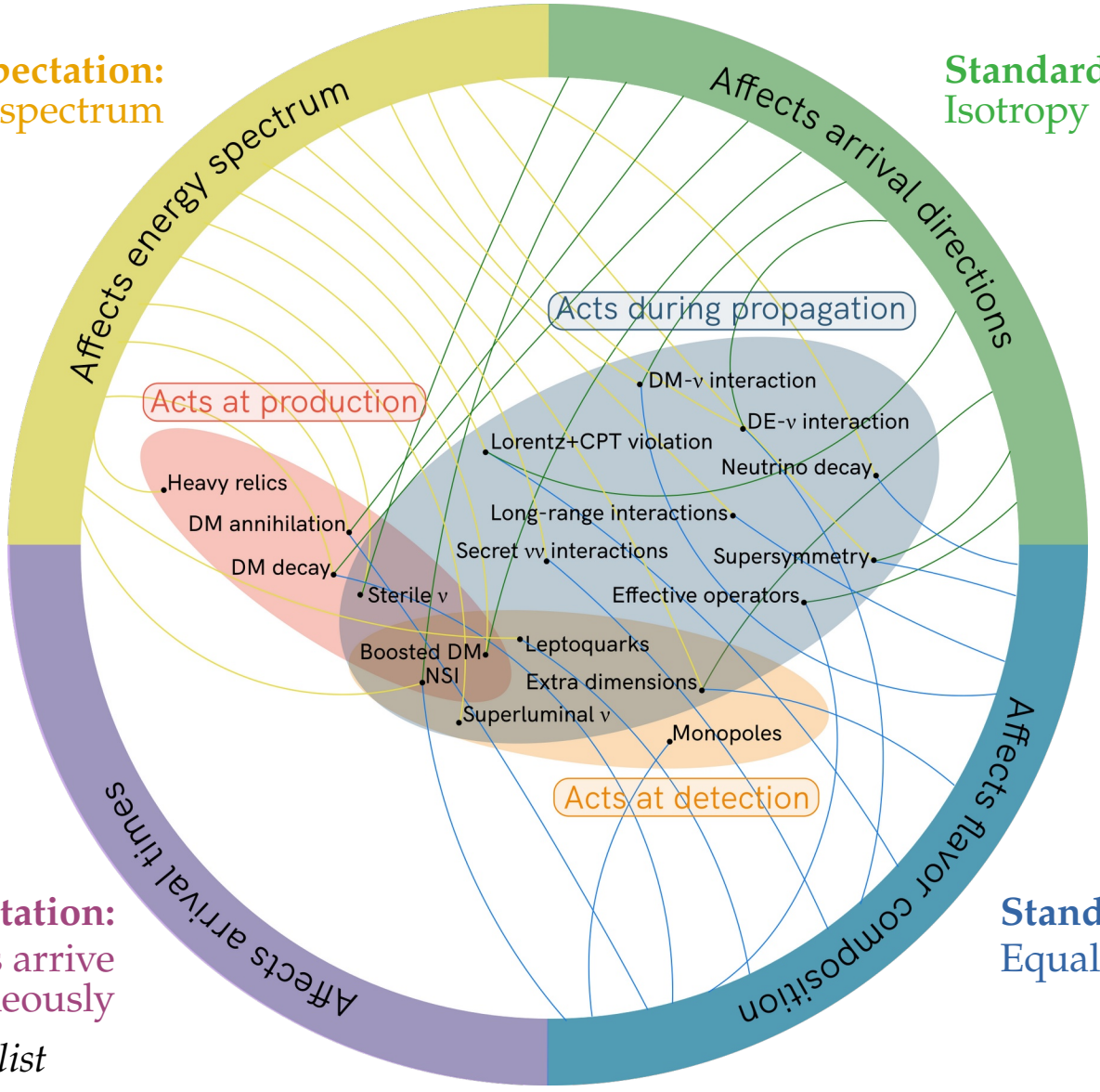
Standard expectation:
ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Note: Not an exhaustive list

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



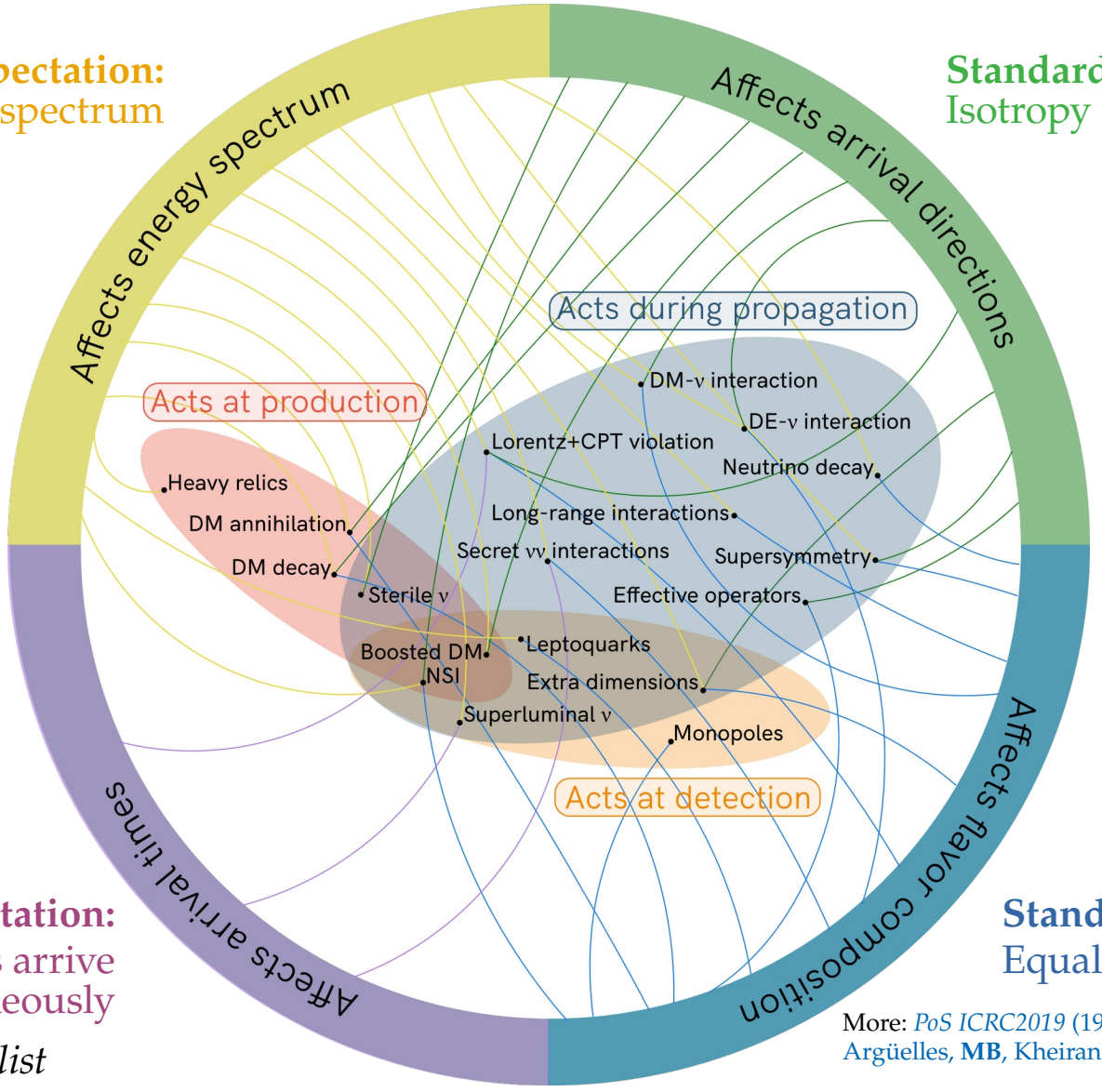
Standard expectation:
ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Note: Not an exhaustive list

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



Standard expectation:
ν and γ from transients arrive simultaneously

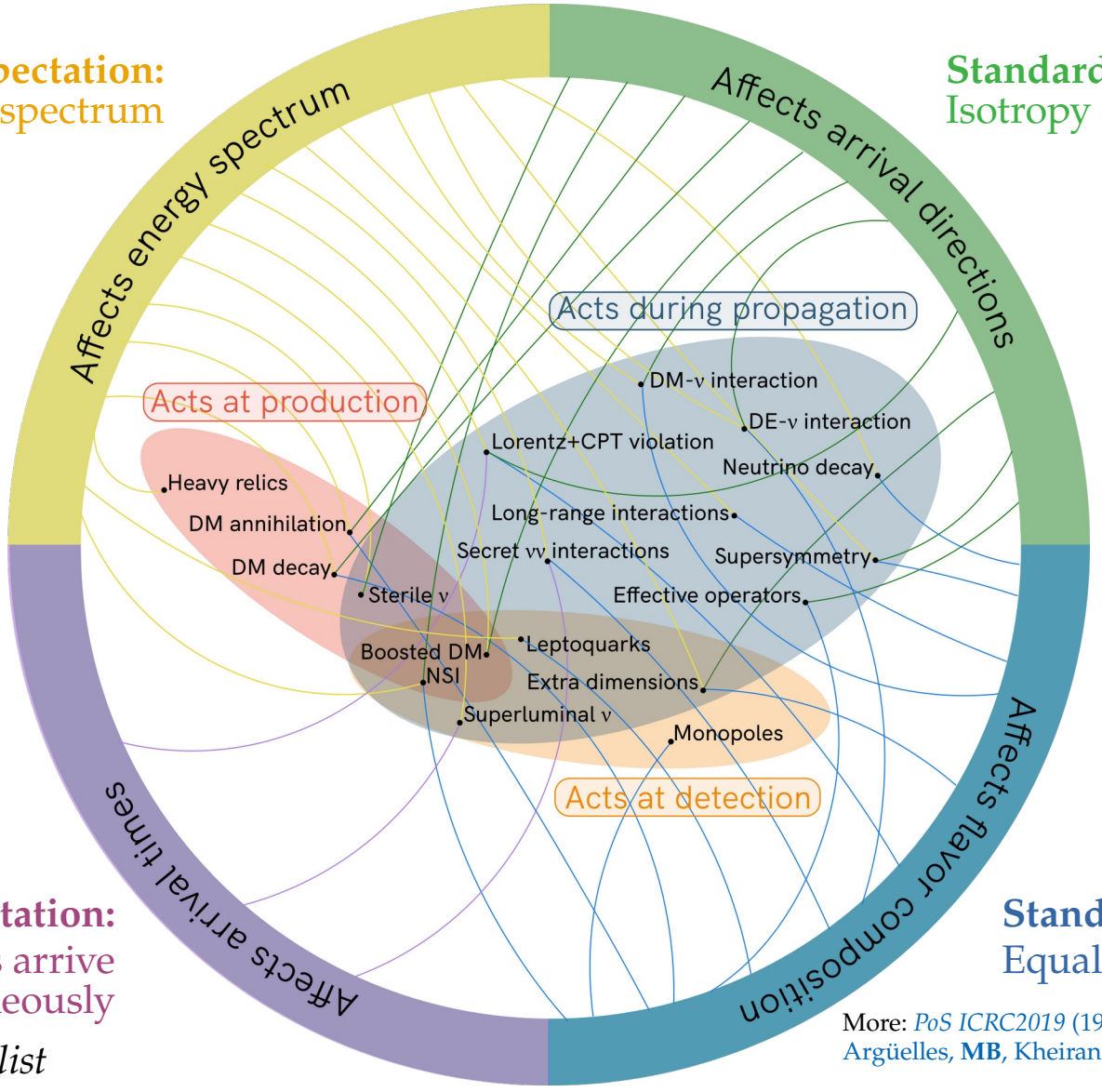
Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Note: Not an exhaustive list

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

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



Standard expectation:
ν and γ from transients arrive simultaneously

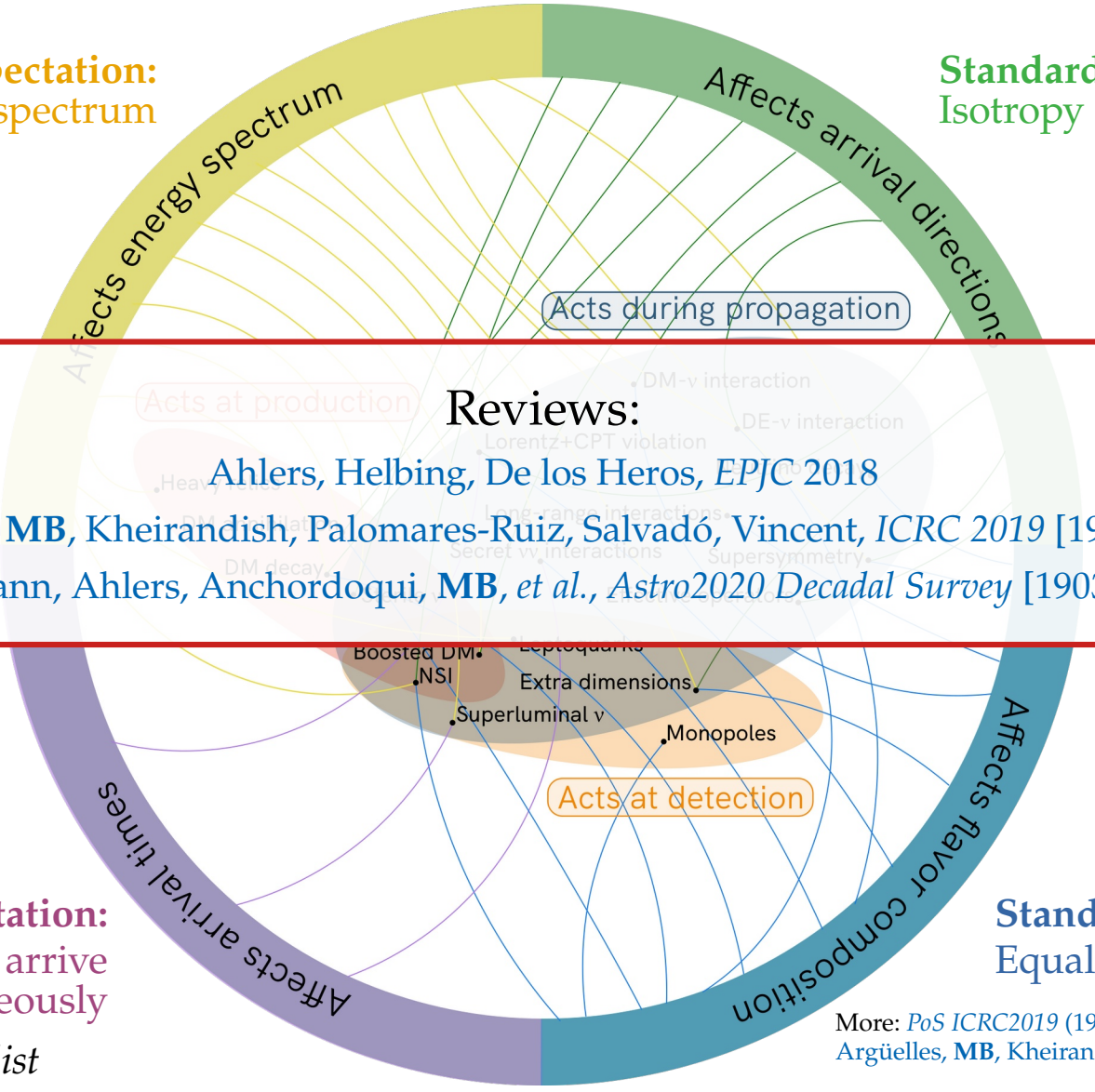
Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Note: Not an exhaustive list

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

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



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]

Standard expectation:
ν and γ from transients arrive simultaneously

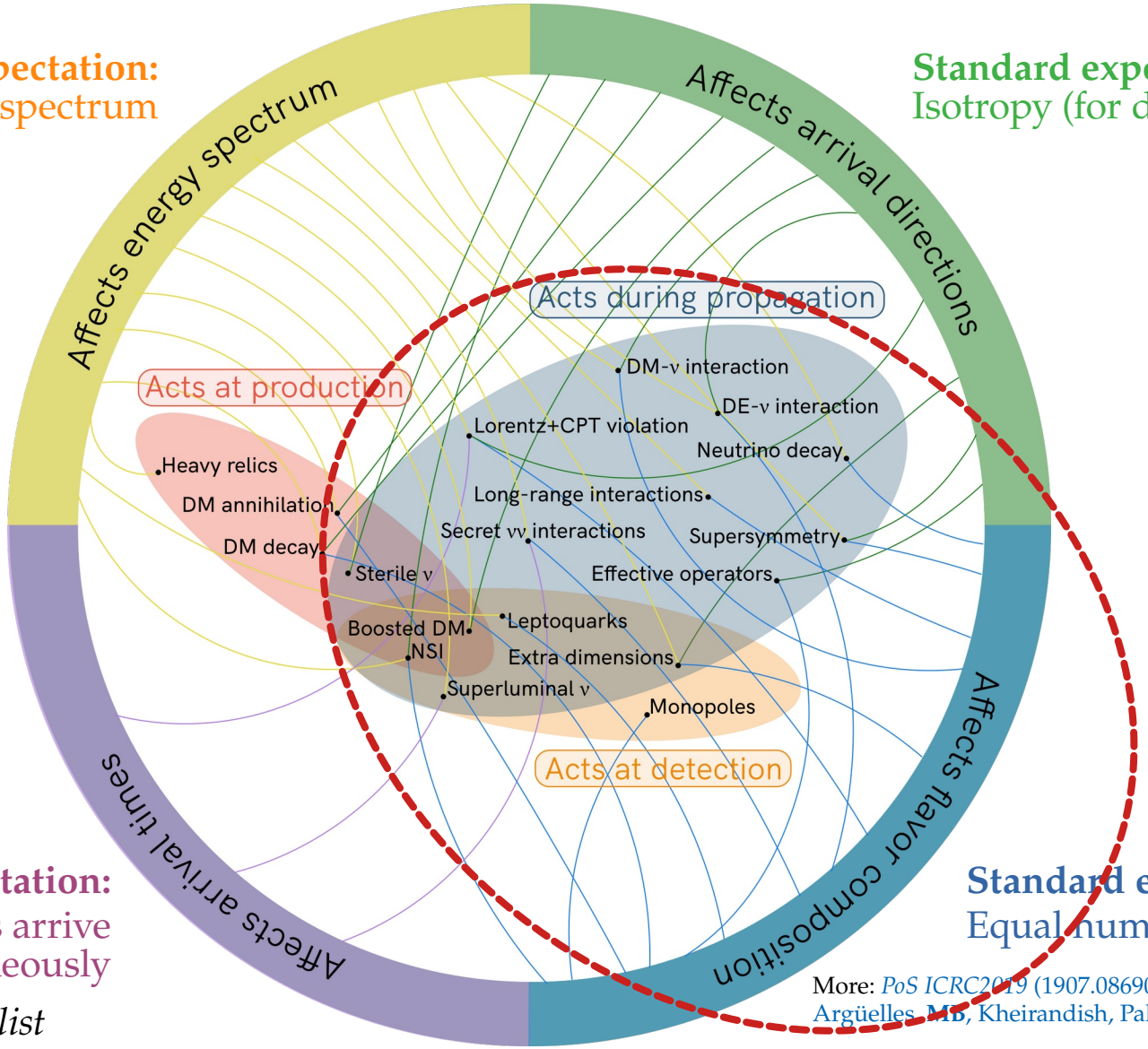
Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Note: Not an exhaustive list

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

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



Standard expectation:
ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Note: Not an exhaustive list

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

New physics in flavor composition

Use the flavor sensitivity to test new physics:

New physics in flavor composition

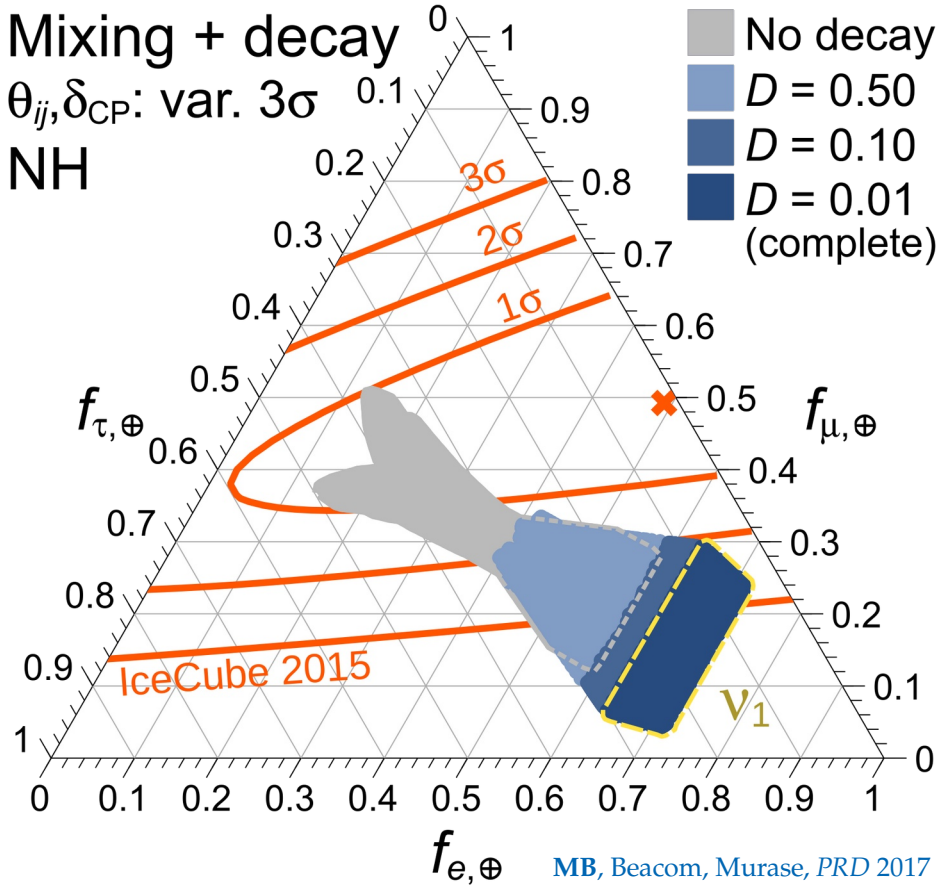
Use the flavor sensitivity to test new physics:

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

New physics in flavor composition

Use the flavor sensitivity to test new physics:

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



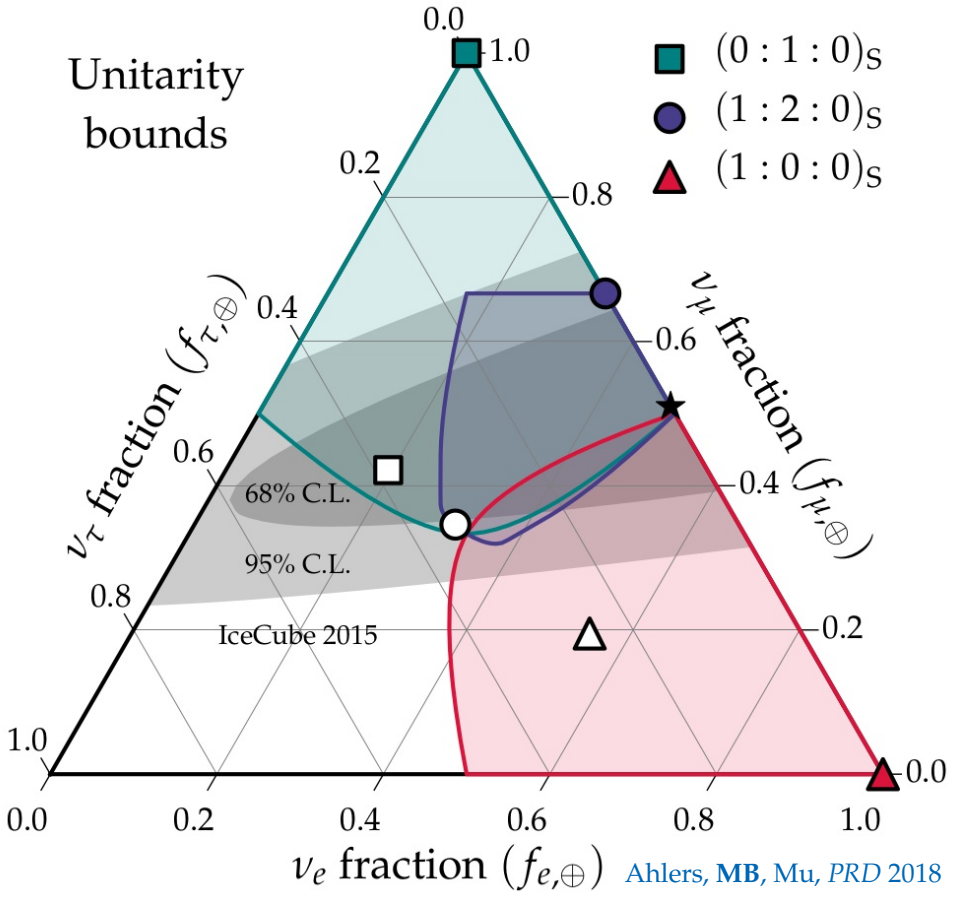
Reviews:
Argüelles *et al.* (inc. **MB**), *EPJC* 2023; Mehta & Winter, *JCAP* 2011; Rasmussen *et al.*, *PRD* 2017

MB, Beacom, Murase, *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]
- Tests of unitarity at high energy
  [Xu, He, Rodejohann, *JCAP* 2014; Ahlers, **MB**, Mu, *PRD* 2018; Ahlers, **MB**, Nortvig, *JCAP* 2021]



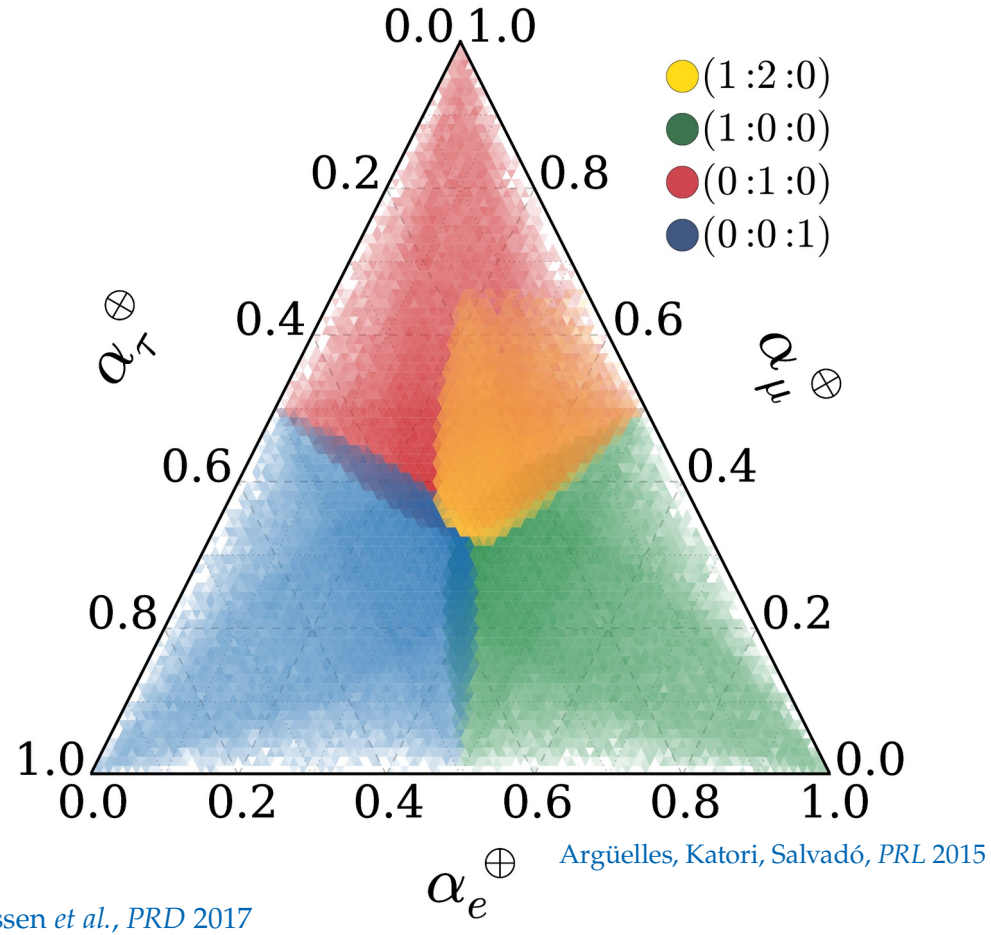
Ahlers, **MB**, Mu, *PRD* 2018

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]
- Tests of unitarity at high energy
  [Xu, He, Rodejohann, *JCAP* 2014; Ahlers, **MB**, Mu, *PRD* 2018; Ahlers, **MB**, Nortvig, *JCAP* 2021]
- Lorentz- and CPT-invariance violation
  [Barenboim & Quigg, *PRD* 2003; **MB**, Gago, Peña-Garay, *JHEP* 2010; Kostelecky & Mewes 2004; Argüelles, Katori, Salvadó, *PRL* 2015]



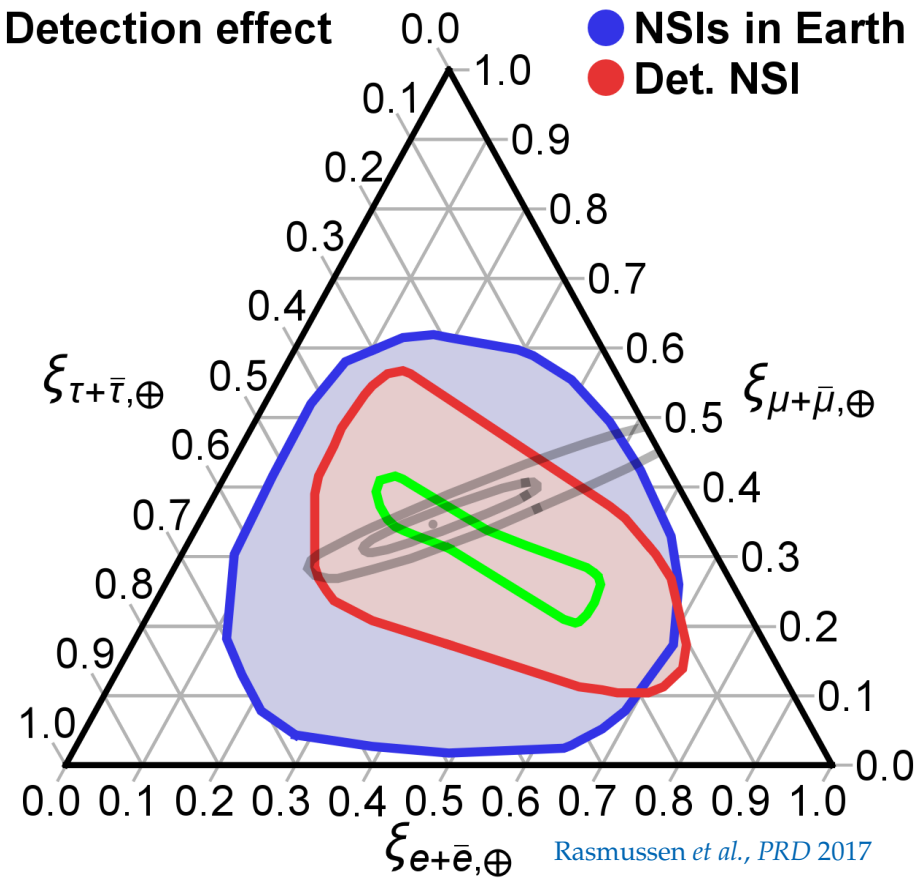
Argüelles, Katori, Salvadó, *PRL* 2015

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]
- Tests of unitarity at high energy
  [Xu, He, Rodejohann, *JCAP* 2014; Ahlers, **MB**, Mu, *PRD* 2018; Ahlers, **MB**, Nortvig, *JCAP* 2021]
- Lorentz- and CPT-invariance violation
  [Barenboim & Quigg, *PRD* 2003; **MB**, Gago, Peña-Garay, *JHEP* 2010; Kostelecky & Mewes 2004; Argüelles, Katori, Salvadó, *PRL* 2015]
- Non-standard interactions
  [González-García *et al.*, *Astropart. Phys.* 2016; Rasmussen *et al.*, *PRD* 2017]



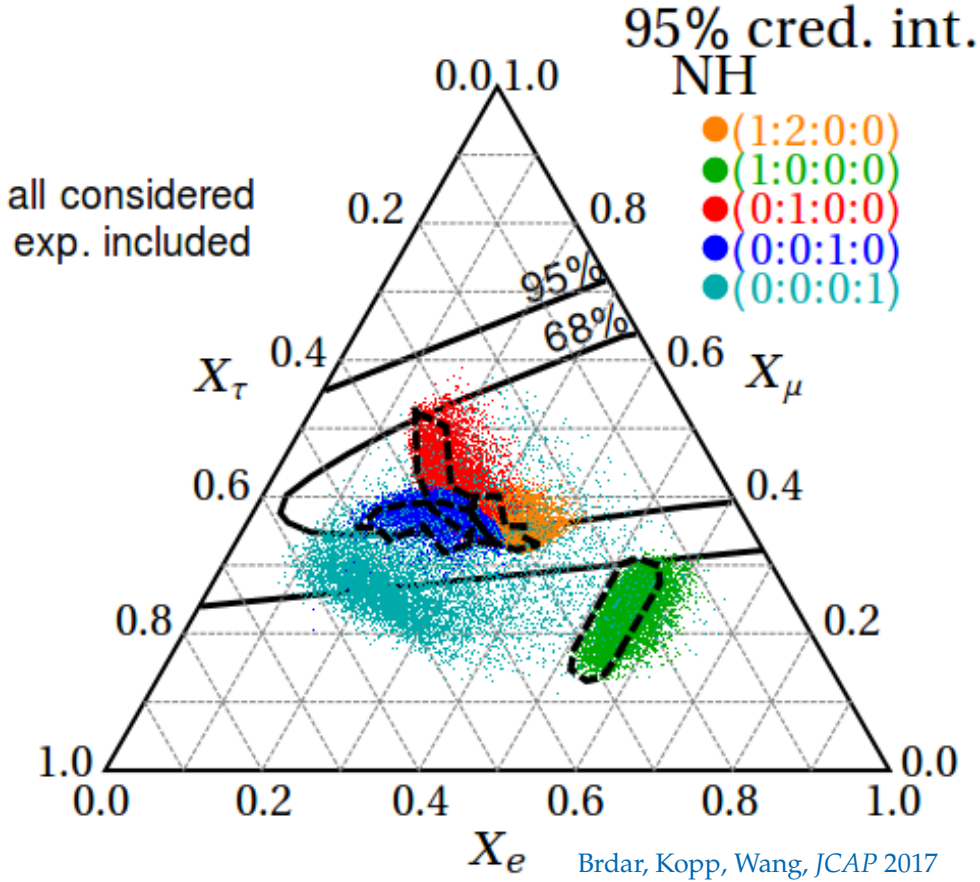
Rasmussen *et al.*, *PRD* 2017

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

New physics in flavor composition

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]
- Tests of unitarity at high energy
  [Xu, He, Rodejohann, *JCAP* 2014; Ahlers, **MB**, Mu, *PRD* 2018; Ahlers, **MB**, Nortvig, *JCAP* 2021]
- Lorentz- and CPT-invariance violation
  [Barenboim & Quigg, *PRD* 2003; **MB**, Gago, Peña-Garay, *JHEP* 2010; Kostelecky & Mewes 2004; Argüelles, Katori, Salvadó, *PRL* 2015]
- Non-standard interactions
  [González-García *et al.*, *Astropart. Phys.* 2016; Rasmussen *et al.*, *PRD* 2017]
- Active-sterile ν mixing
  [Aeikens *et al.*, *JCAP* 2015; Brdar, Kopp, Wang, *JCAP* 2017; Argüelles *et al.*, *JCAP* 2020; Ahlers, **MB**, *JCAP* 2021]



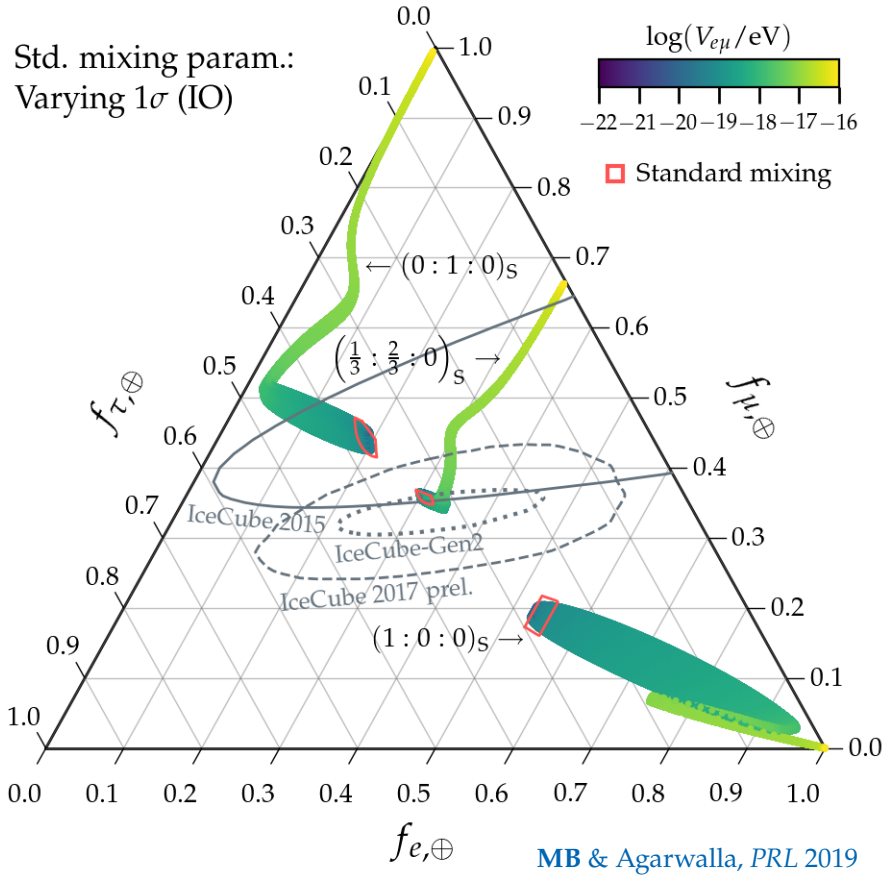
Brdar, Kopp, Wang, *JCAP* 2017

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:

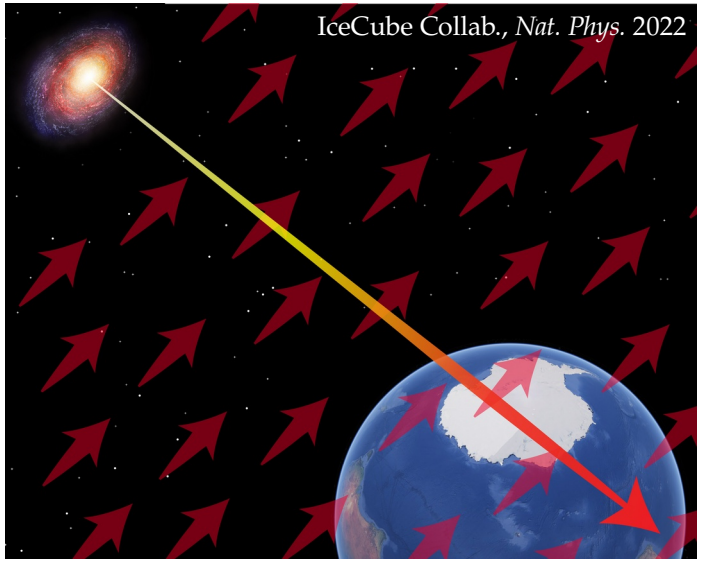
- Neutrino decay
  [Beacom *et al.*, *PRL* 2003; Baerwald, **MB**, Winter, JCAP 2010; **MB**, Beacom, Winter, *PRL* 2015; **MB**, Beacom, Murase, *PRD* 2017]
- Tests of unitarity at high energy
  [Xu, He, Rodejohann, *JCAP* 2014; Ahlers, **MB**, Mu, *PRD* 2018; Ahlers, **MB**, Nortvig, *JCAP* 2021]
- Lorentz- and CPT-invariance violation
  [Barenboim & Quigg, *PRD* 2003; **MB**, Gago, Peña-Garay, *JHEP* 2010; Kostelecky & Mewes 2004; Argüelles, Katori, Salvadó, *PRL* 2015]
- Non-standard interactions
  [González-García *et al.*, *Astropart. Phys.* 2016; Rasmussen *et al.*, *PRD* 2017]
- Active-sterile ν mixing
  [Aeikens *et al.*, *JCAP* 2015; Brdar, Kopp, Wang, *JCAP* 2017; Argüelles *et al.*, *JCAP* 2020; Ahlers, **MB**, *JCAP* 2021]
- Long-range *eν* interactions
  [**MB** & Agarwalla, *PRL* 2019]



MB & Agarwalla, *PRL* 2019

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

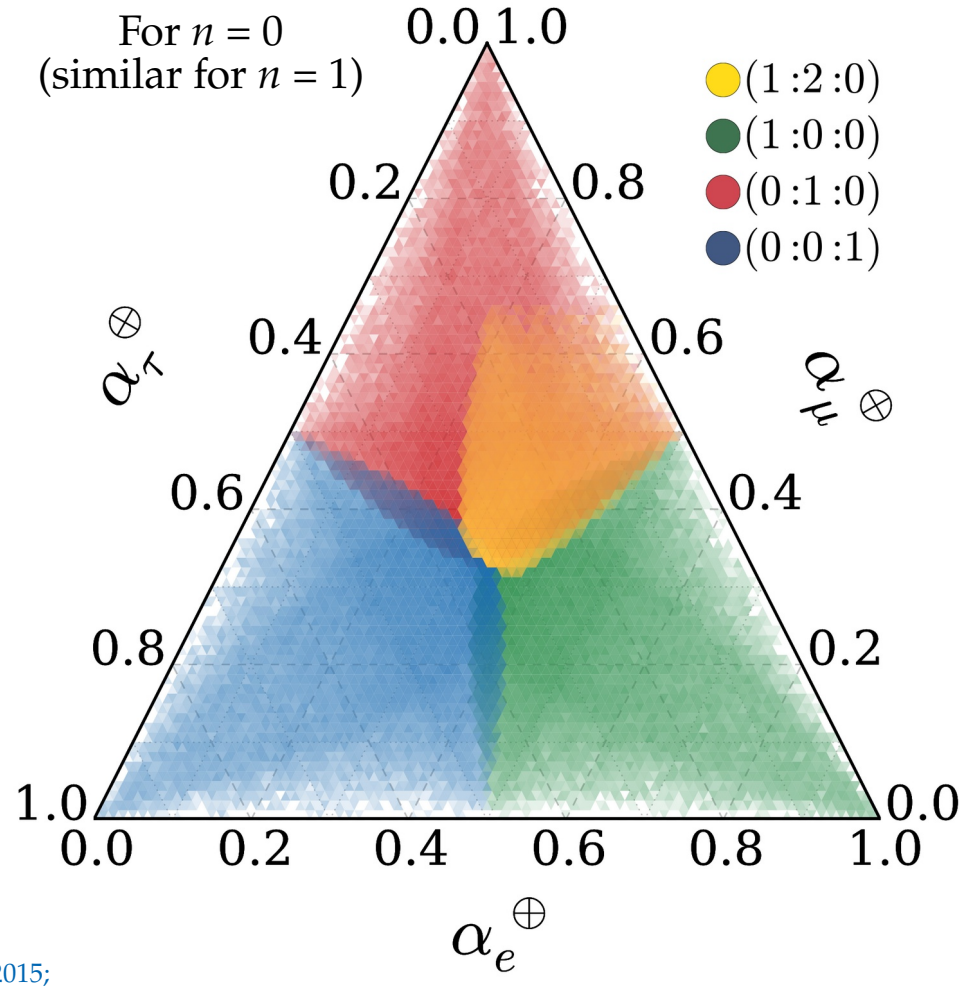
Lorentz-invariance violation can fill up the flavor triangle



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

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

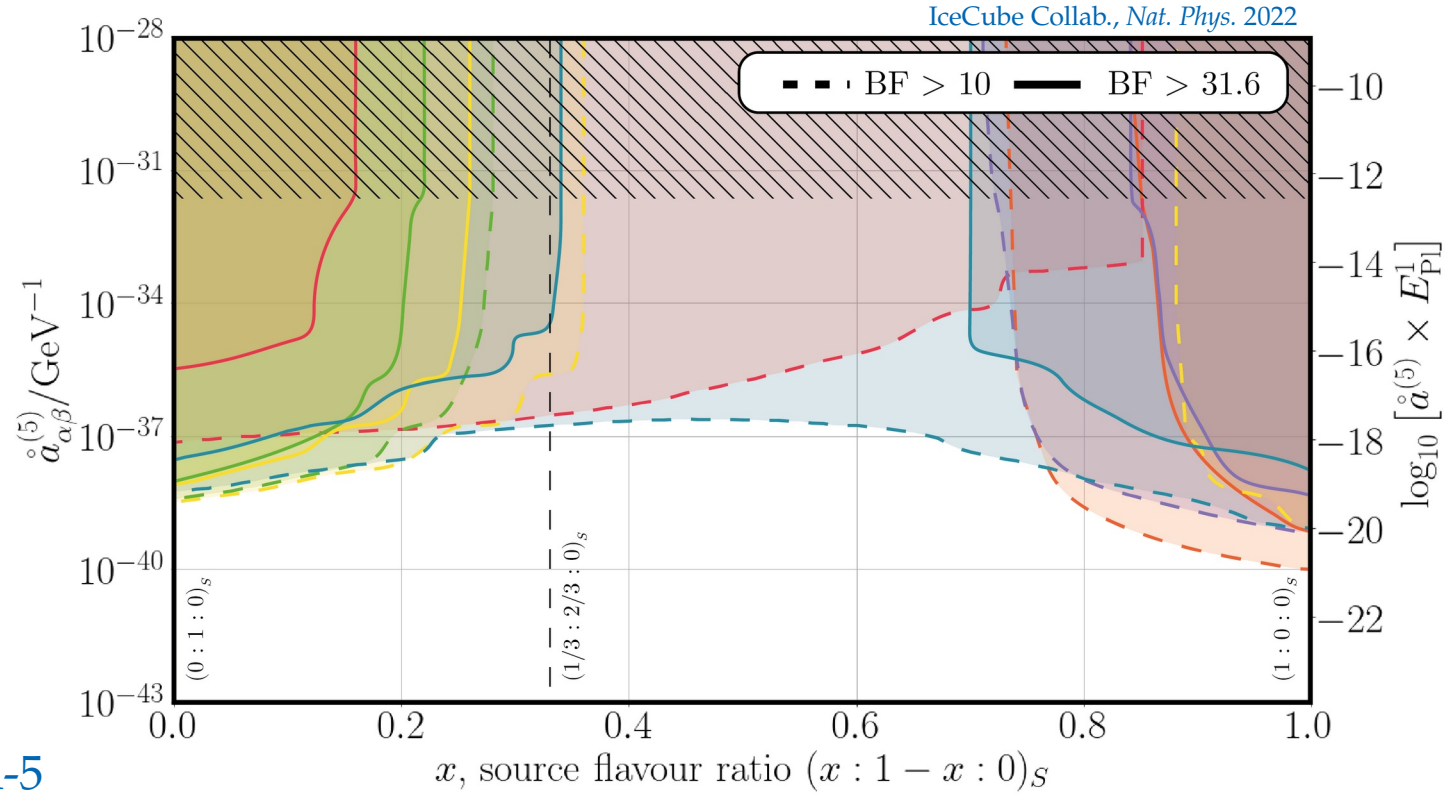
$$H_{\text{NP}} = \sum_n \left(\frac{E}{\Lambda_n}\right)^n U_n^{\dagger}\, \text{diag}\left(O_{n,1}, O_{n,2}, O_{n,3}\right) U_n$$



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

Argüelles, Katori, Salvadó, *PRL* 2015

IceCube Collab., *Nat. Phys.* 2022



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

Astrophysical sources

Earth

L ~ up to a few Gpc

E.g.,

Decay changes the number

of each ν mass eigenstate, N_1, N_2, N_3

?

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

Mass of ν_i Lifetime of ν_i

Astrophysical sources

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

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

?

Lower-E ν are longer-lived…

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

… but ν that travel longer L are more attenuated!

Astrophysical sources

Earth

L ~ up to a few Gpc

E.g.,

Astrophysical sources

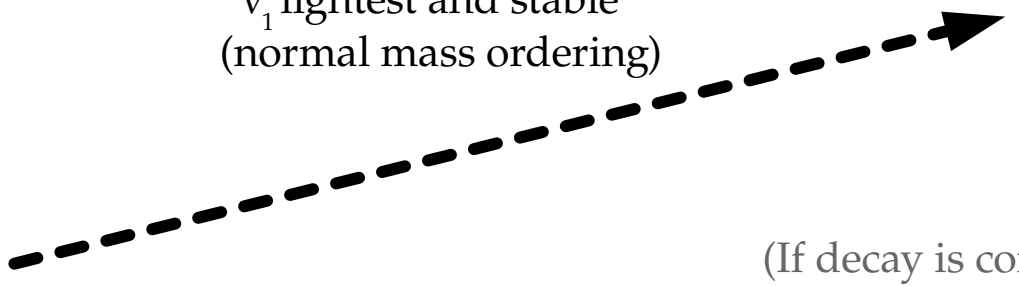
Earth

L ~ up to a few Gpc

$\nu_2, \nu_3 \rightarrow \nu_1$

ν_1 lightest and stable
(normal mass ordering)

E.g.,



(If decay is complete)

Astrophysical sources

Earth

L ~ up to a few Gpc

$\nu_2, \nu_3 \rightarrow \nu_1$

ν_1 lightest and stable
(normal mass ordering)

E.g.,

(If decay is complete)

$\nu_1, \nu_2 \rightarrow \nu_3$

ν_3 lightest and stable
(inverted mass ordering)

Astrophysical sources

Earth

L ~ up to a few Gpc

$\nu_2, \nu_3 \to \nu_1$

ν_1 lightest and stable
(normal mass ordering)

E.g.,

(If decay is complete)

$\nu_1, \nu_2 \to \nu_3$

ν_3 lightest and stable
(inverted mass ordering)

Fine print:

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

Astrophysical sources

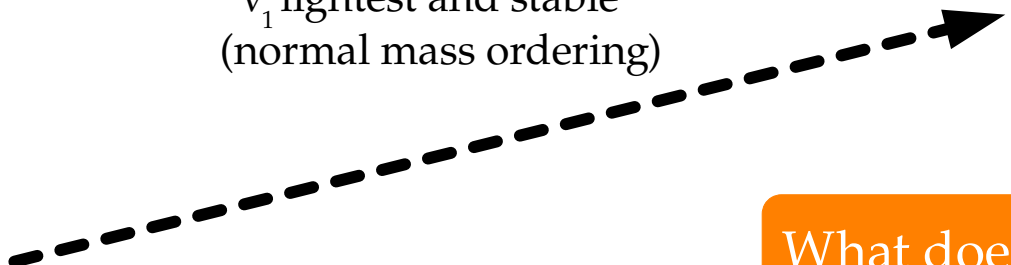
Earth

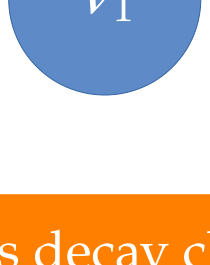
L ~ up to a few Gpc

$\nu_2, \nu_3 \rightarrow \nu_1$

ν_1 lightest and stable
(normal mass ordering)

E.g.,





What does decay change?

$\nu_1, \nu_2 \rightarrow \nu_3$

ν_3 lightest and stable
(inverted mass ordering)

Fine print:

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

What does neutrino decay change?

Flavor composition ⟺ Spectrum shape ⟺ Event rate

What does neutrino decay change?

Flavor composition ⟺ Spectrum shape ⟺ Event rate

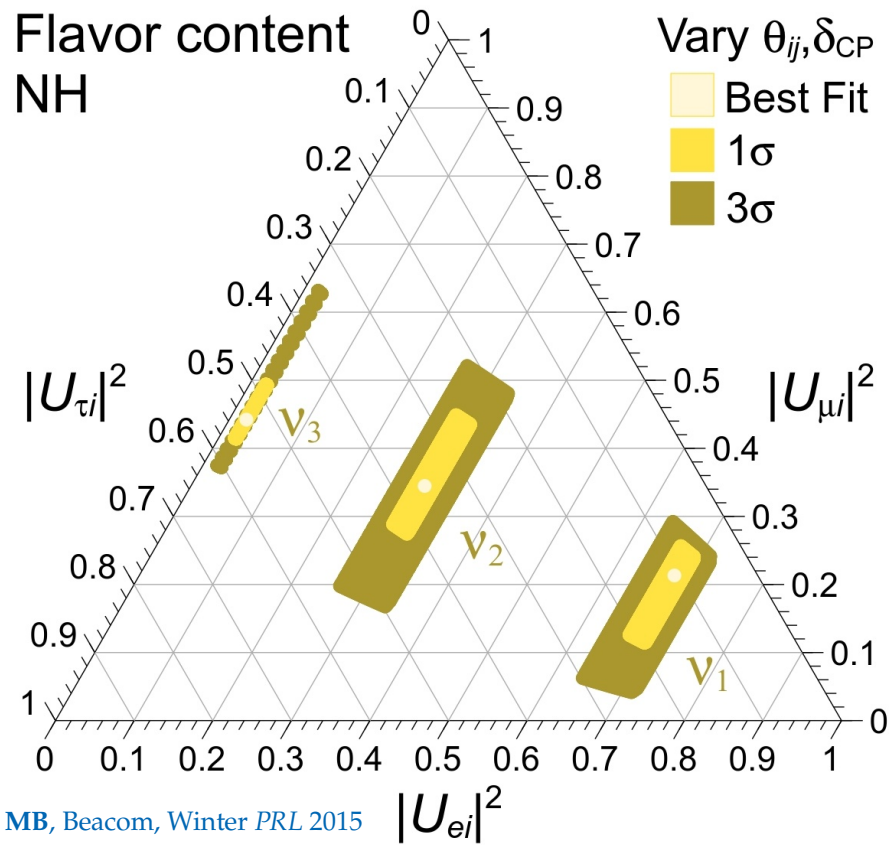
Flavor content of mass eigenstates:

Known to within 2%

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

Known to within 8%

Known to within 20% (or worse)



MB, Beacom, Winter *PRL* 2015

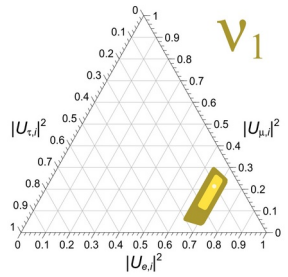
What does neutrino decay change?

Flavor composition ⟺ Spectrum shape ⟺ Event rate

$\nu_2, \nu_3 \to \nu_1$

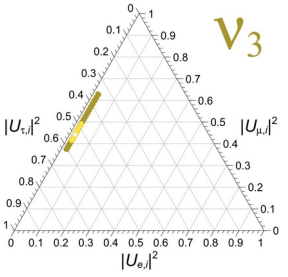
ν_1 lightest and stable
(normal mass ordering)

E.g.,



$\nu_1, \nu_2 \to \nu_3$

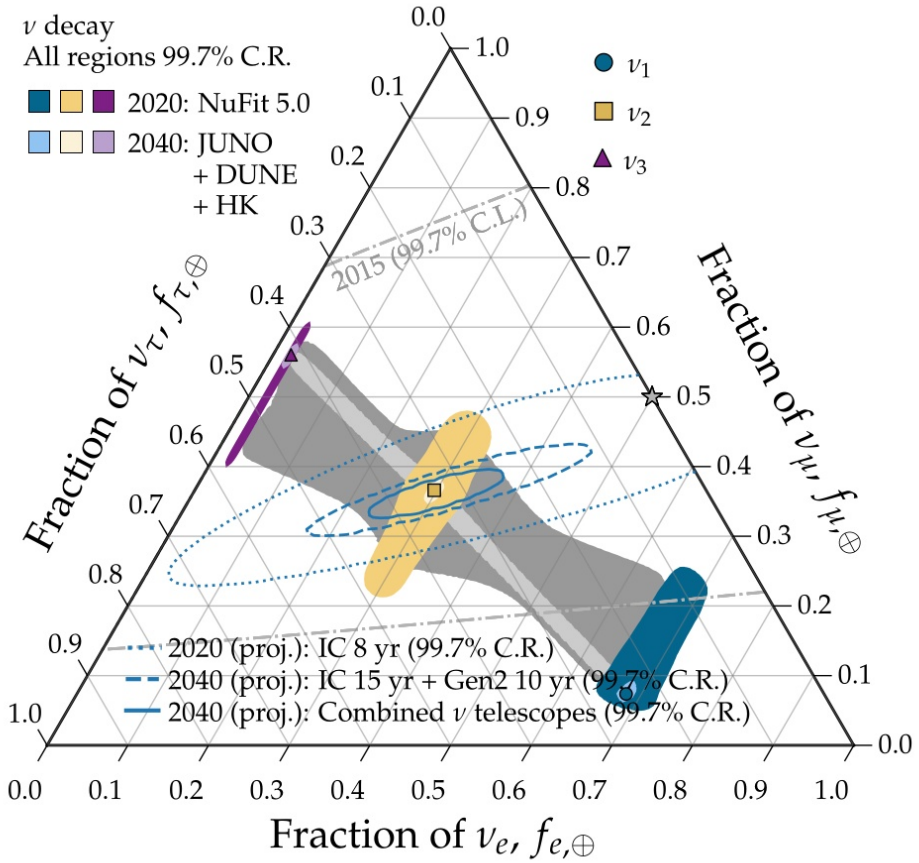
ν_3 lightest and stable
(inverted mass ordering)



What does neutrino decay change?

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

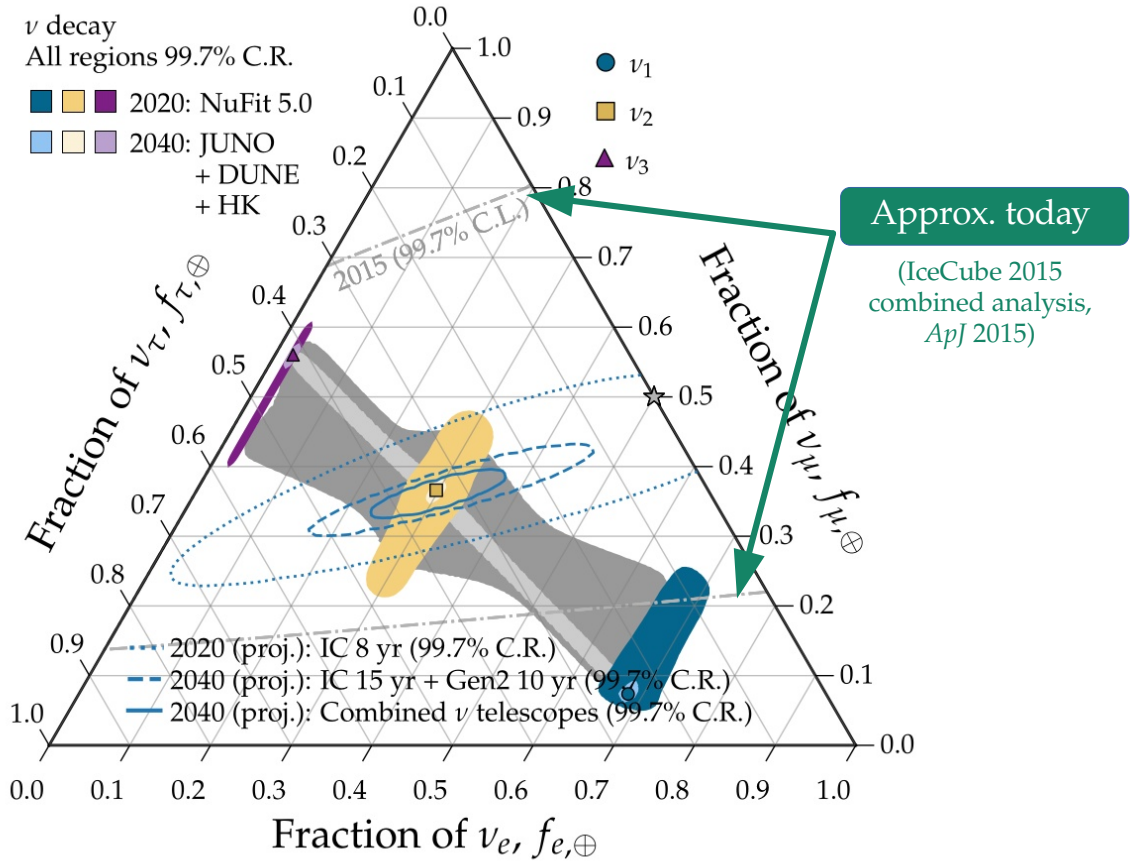
Flavor composition ⟺ Spectrum shape ⟺ Event rate



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

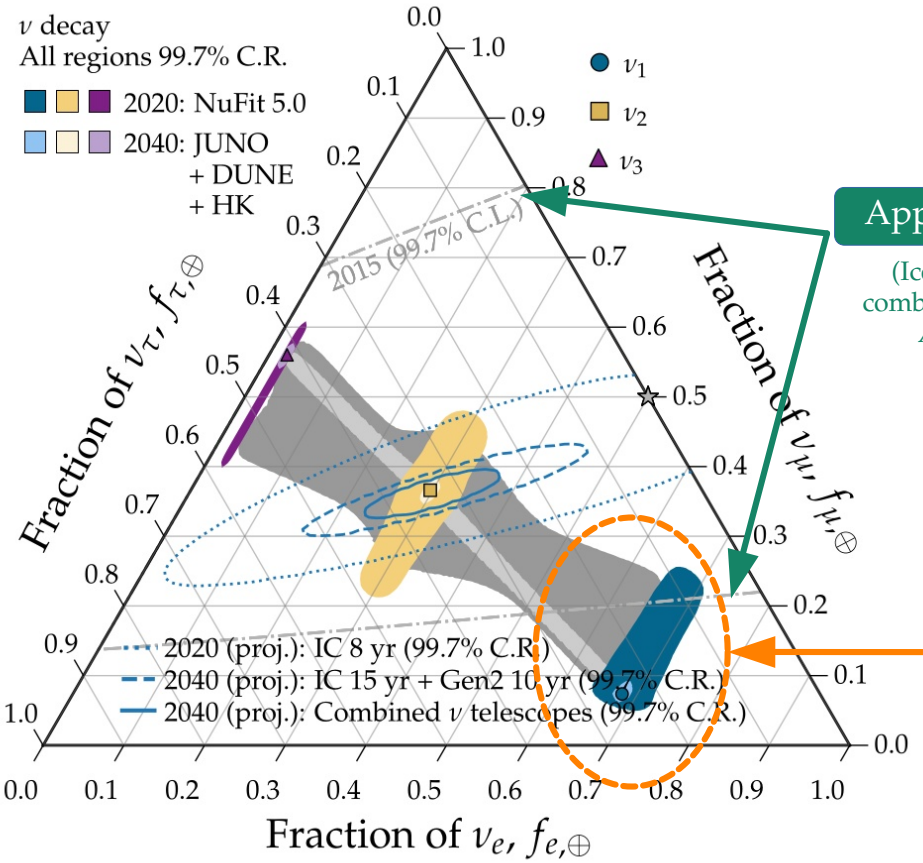
Flavor composition ⟺ Spectrum shape ⟺ Event rate



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



Approx. today

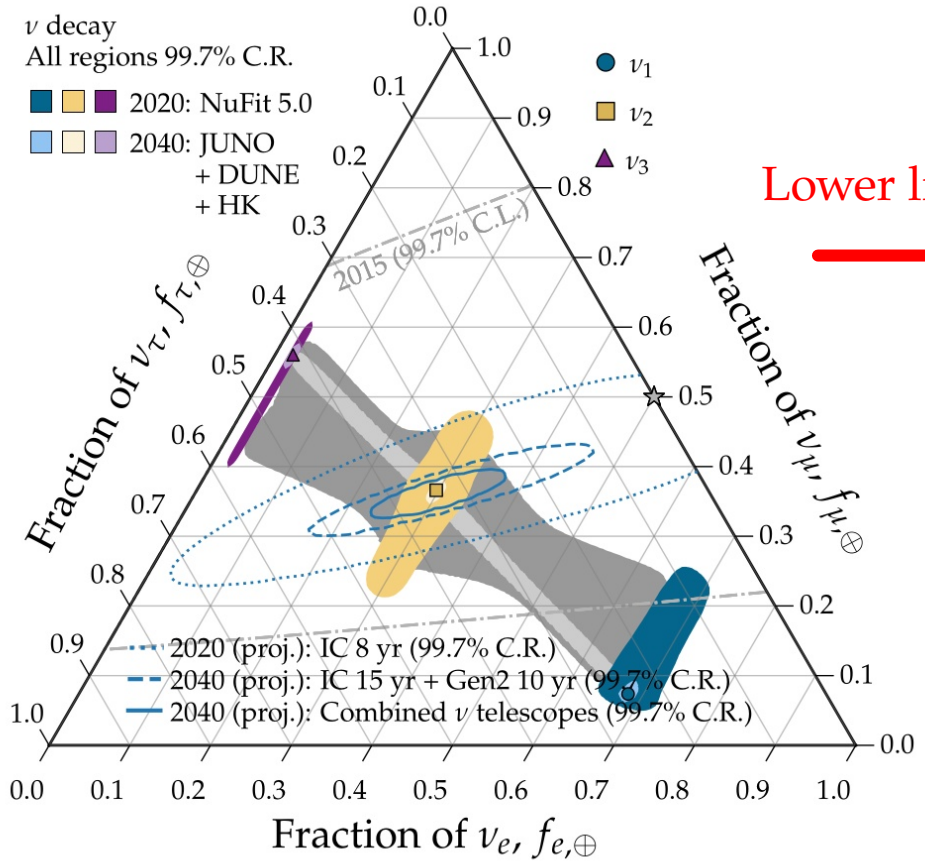
(IceCube 2015 combined analysis, *ApJ* 2015)

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

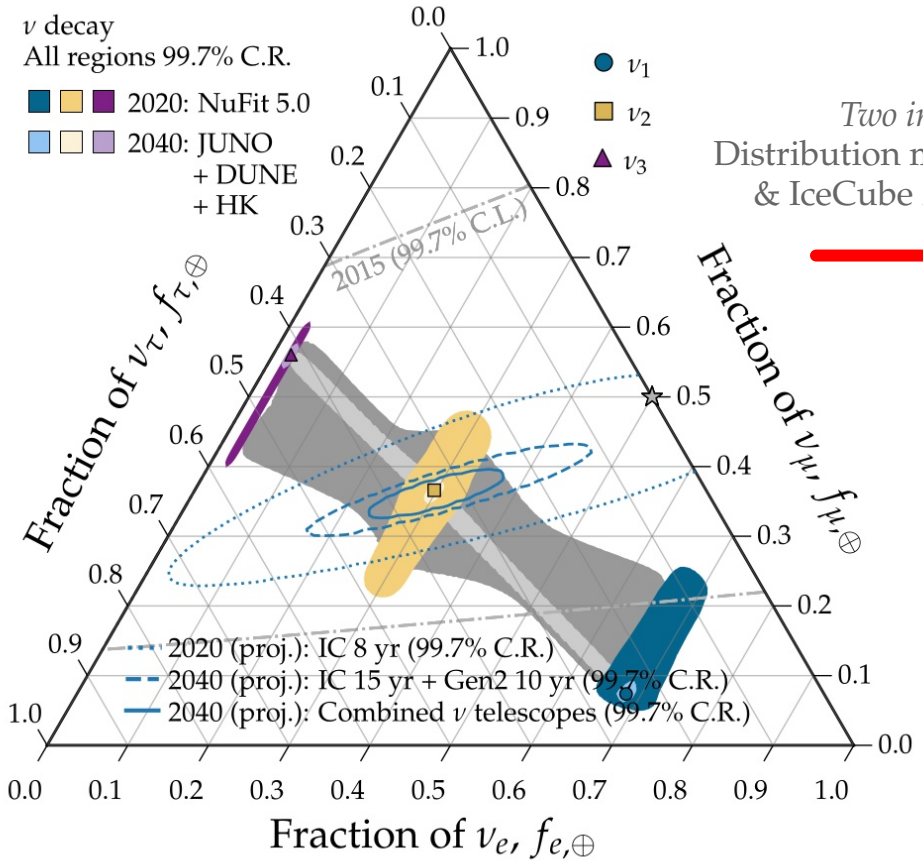


Lower limit on τ/m →

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

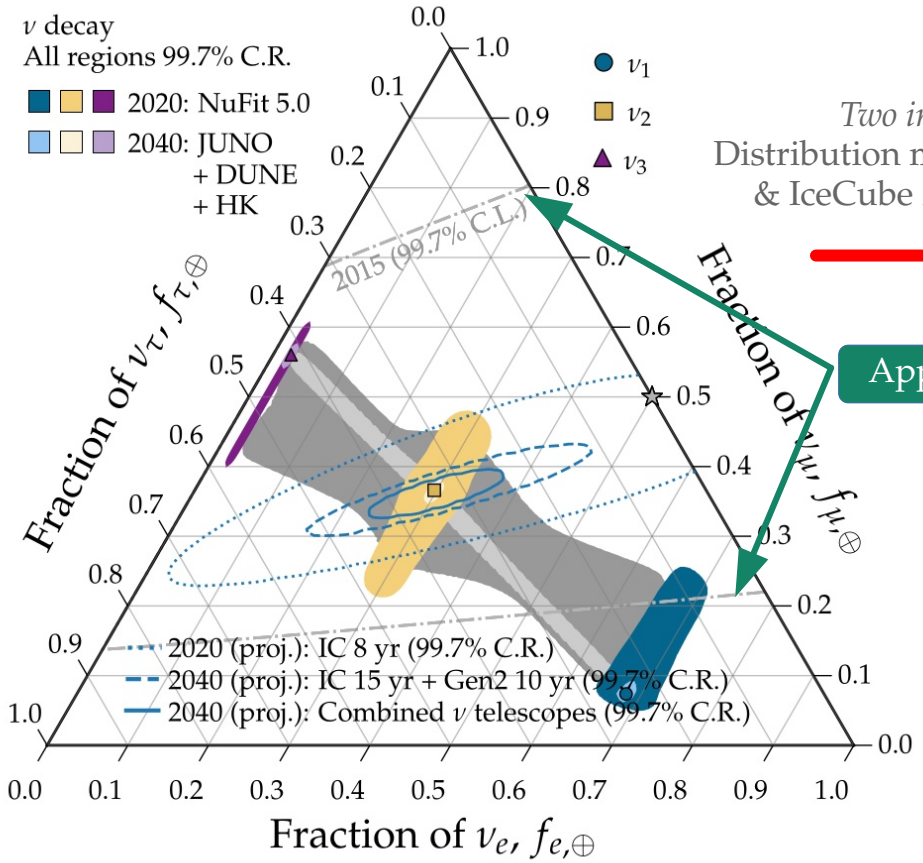


Two ingredients:
Distribution mixing parameters
& IceCube flavor posterior

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



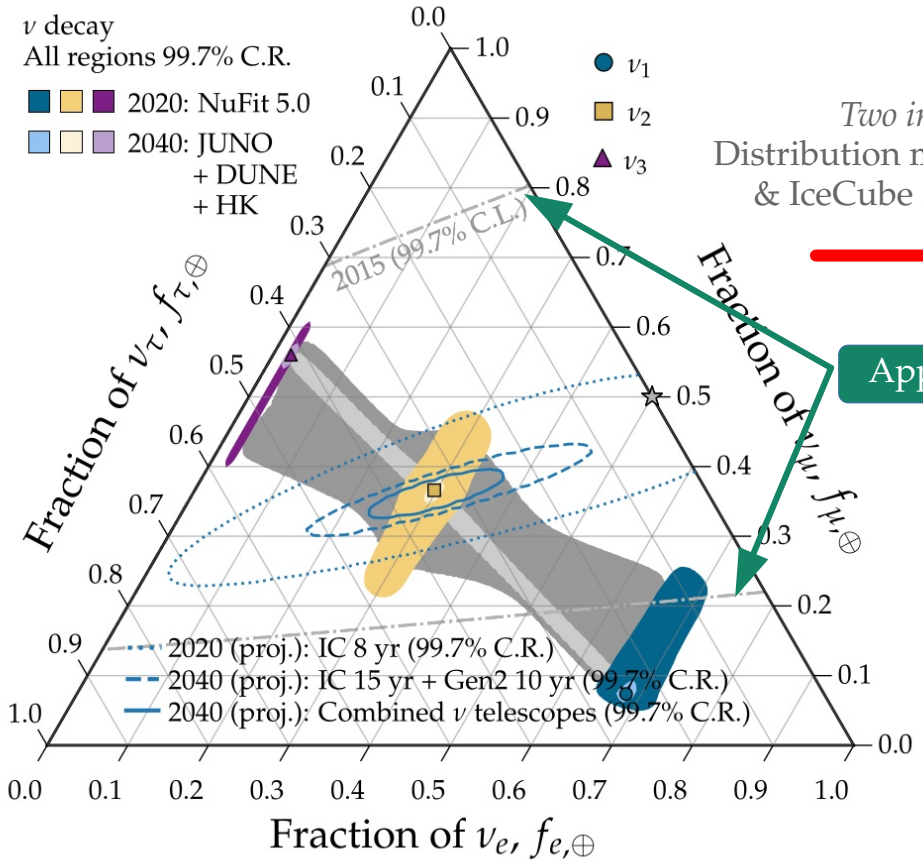
Two ingredients:
Distribution mixing parameters
& IceCube flavor posterior

Approx. today

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

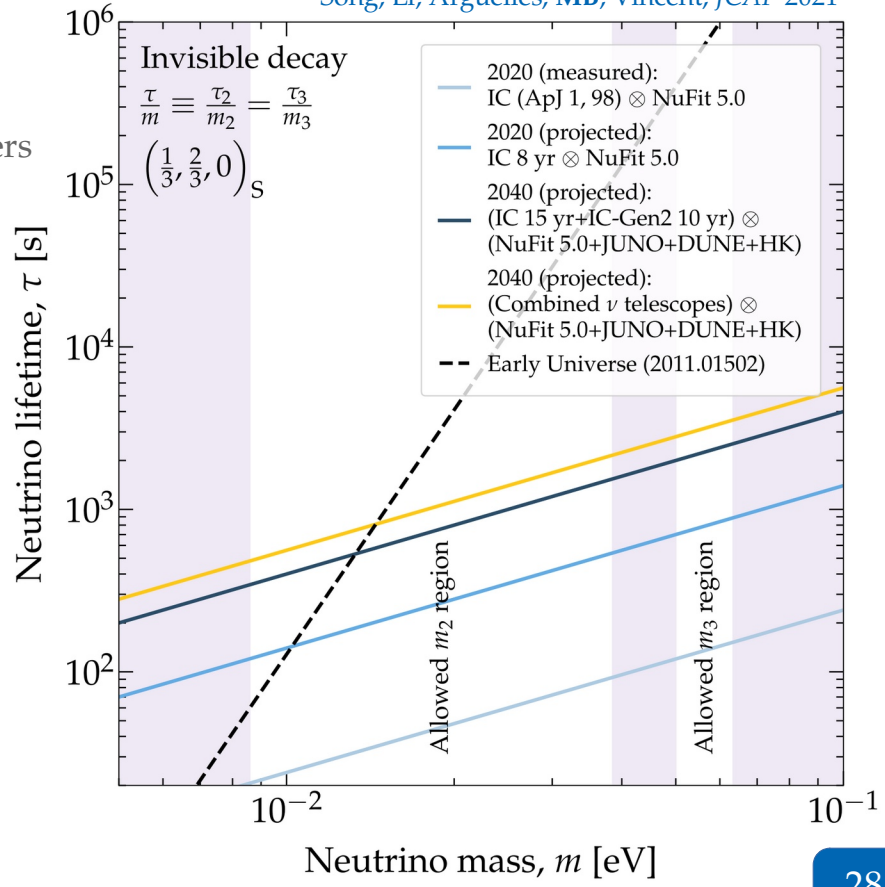
Flavor composition ⟺ Spectrum shape ⟺ Event rate



Two ingredients:
Distribution mixing parameters
& IceCube flavor posterior

Approx. today

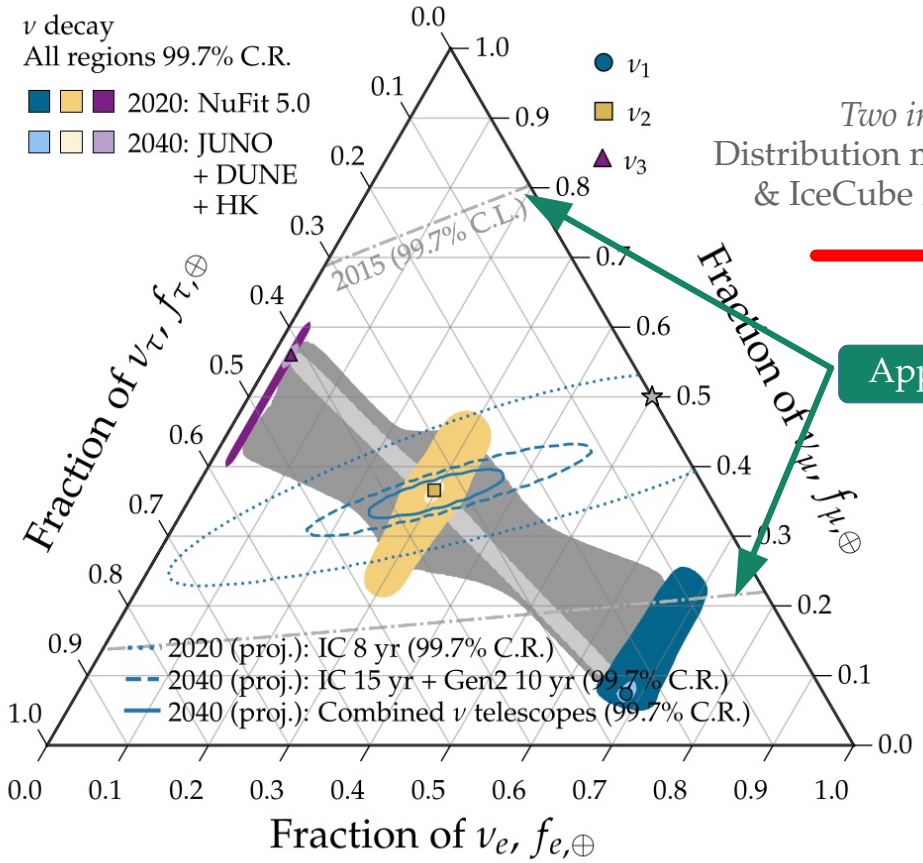
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



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

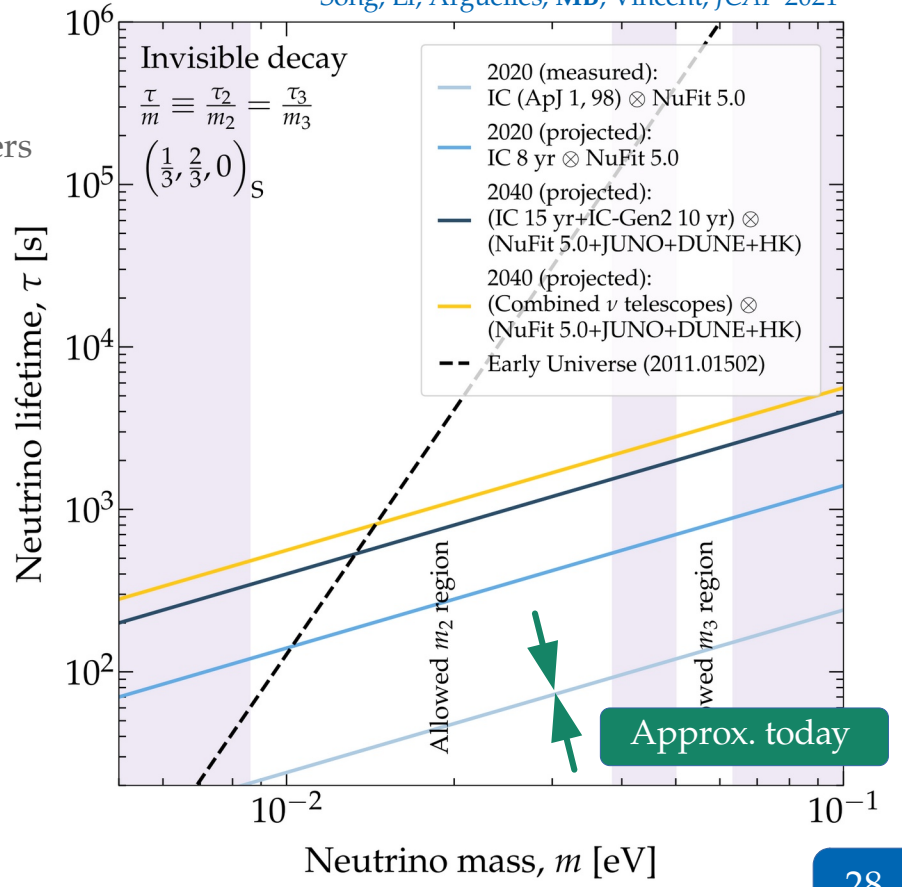
Flavor composition ⟺ Spectrum shape ⟺ Event rate



Two ingredients:
Distribution mixing parameters
& IceCube flavor posterior

Approx. today

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

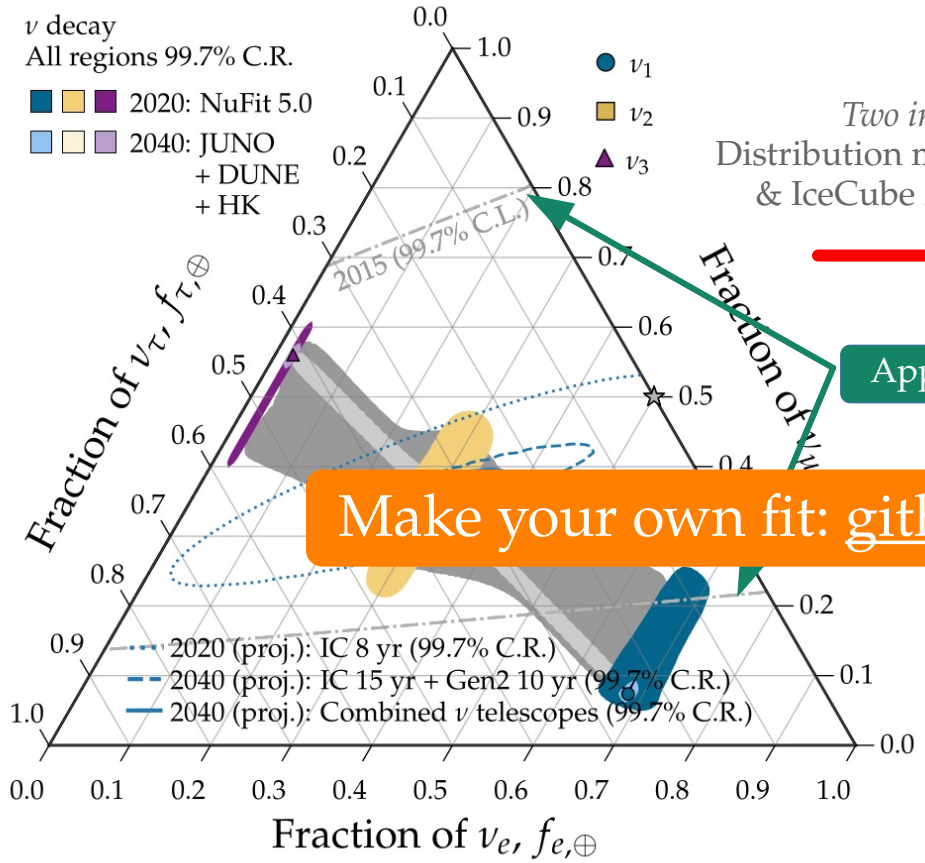


Approx. today

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

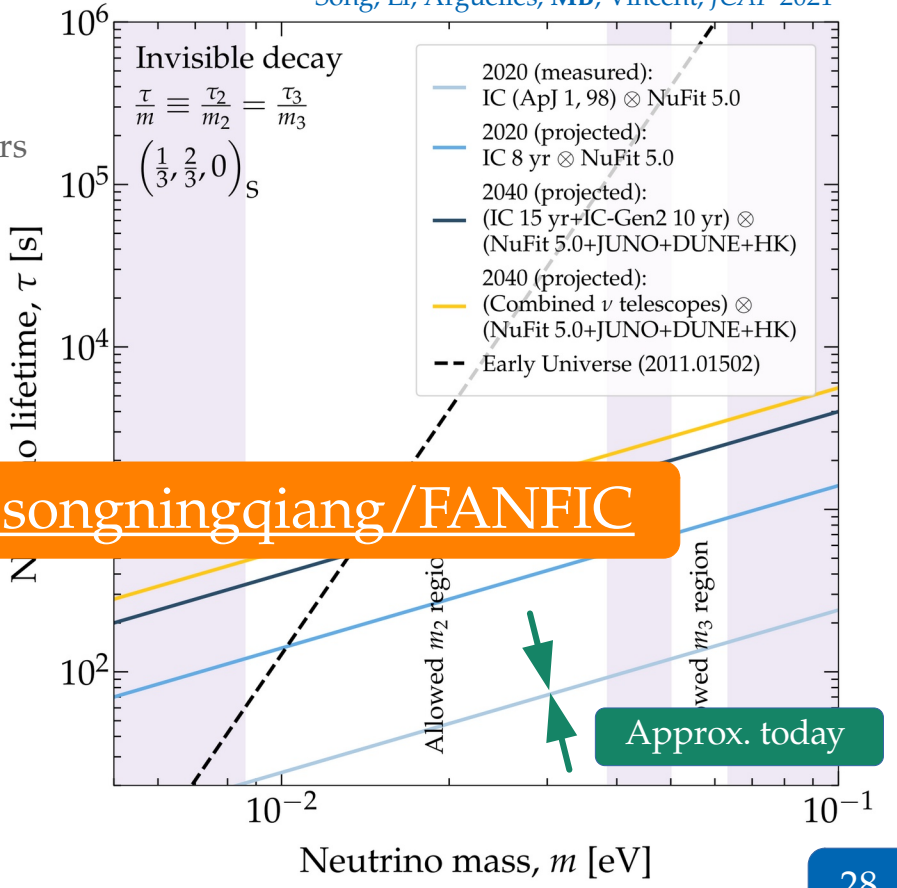
Flavor composition ⟺ Spectrum shape ⟺ Event rate



Two ingredients:
Distribution mixing parameters
& IceCube flavor posterior

Approx. today

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



Approx. today

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

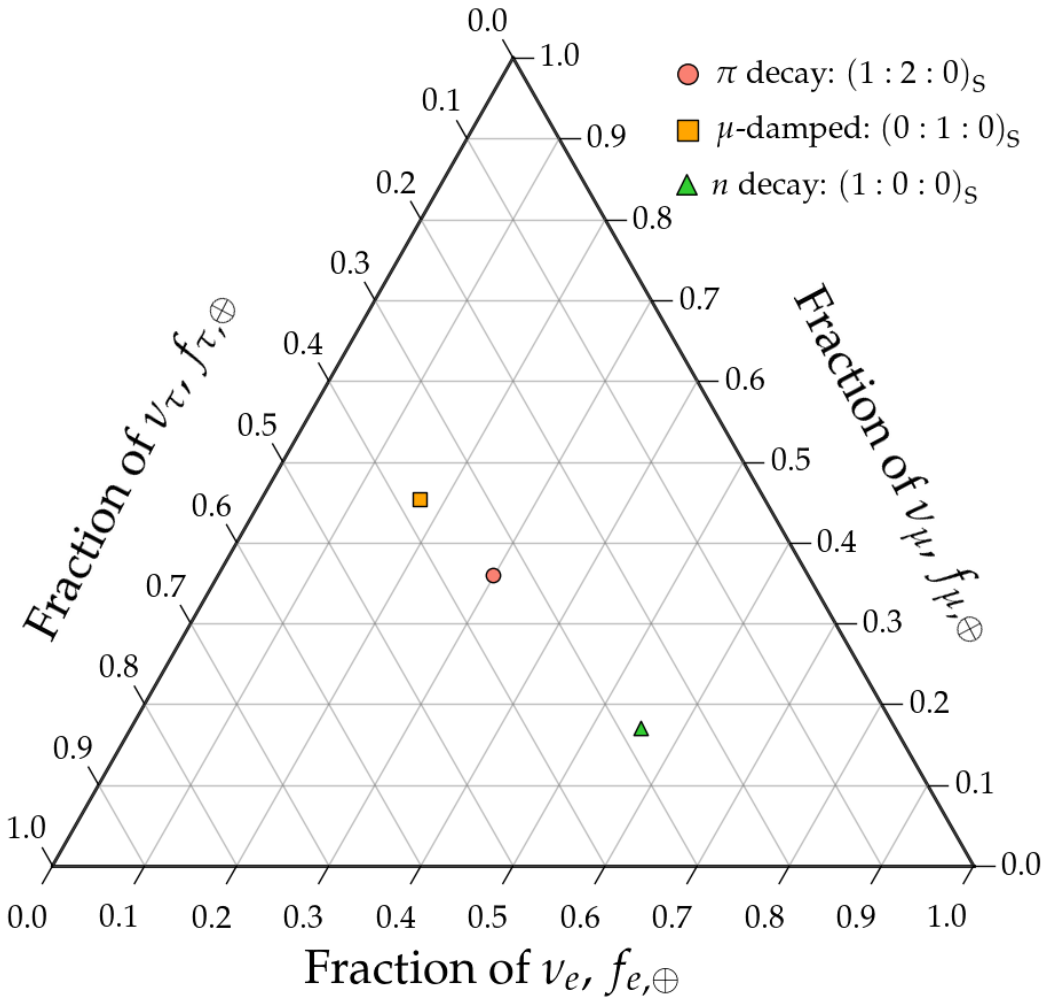
Towards high statistics

Strebe/Wikipedia

Measuring flavor composition: 2015–2040

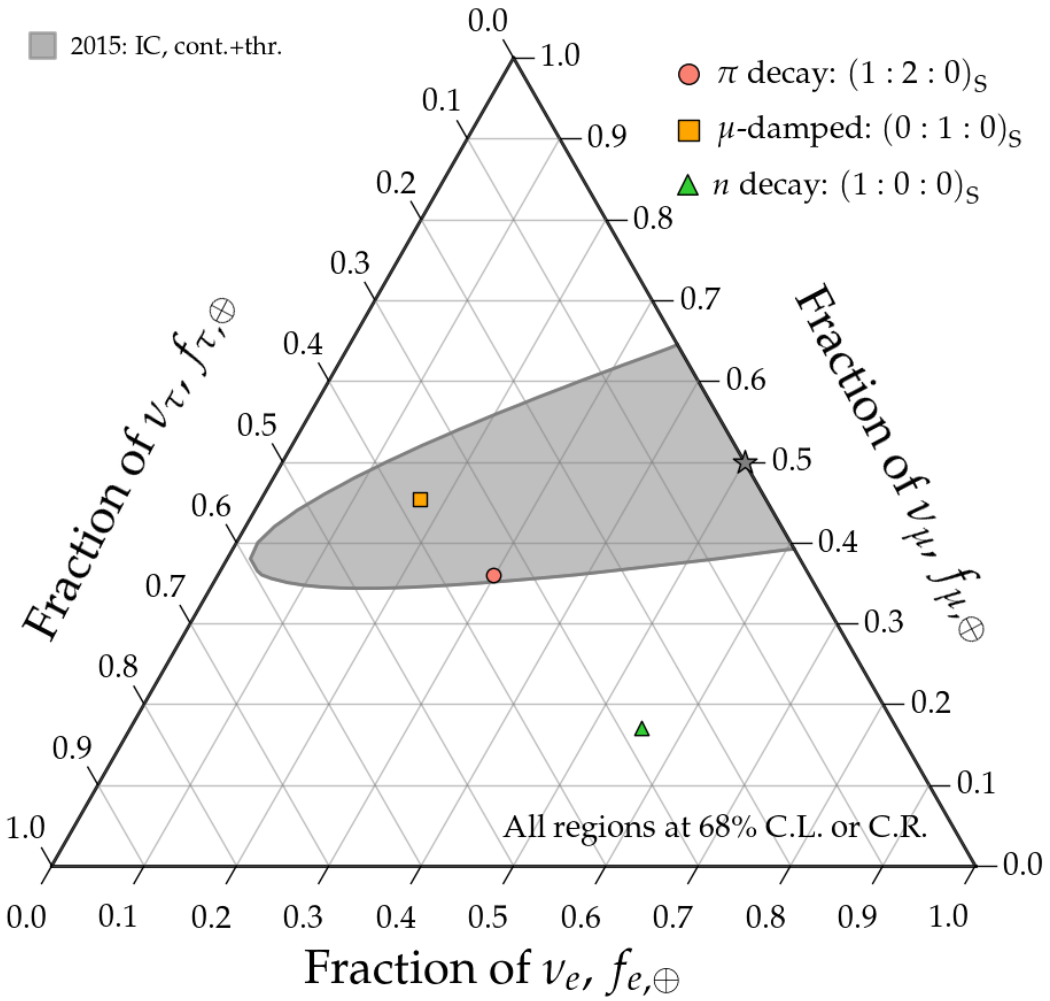
IceCube Collab., *EPJC* 2022
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
IceCube Collab., *PRD* 2019
IceCube Collab., *ApJ* 2015

Measuring flavor composition: 2015–2040



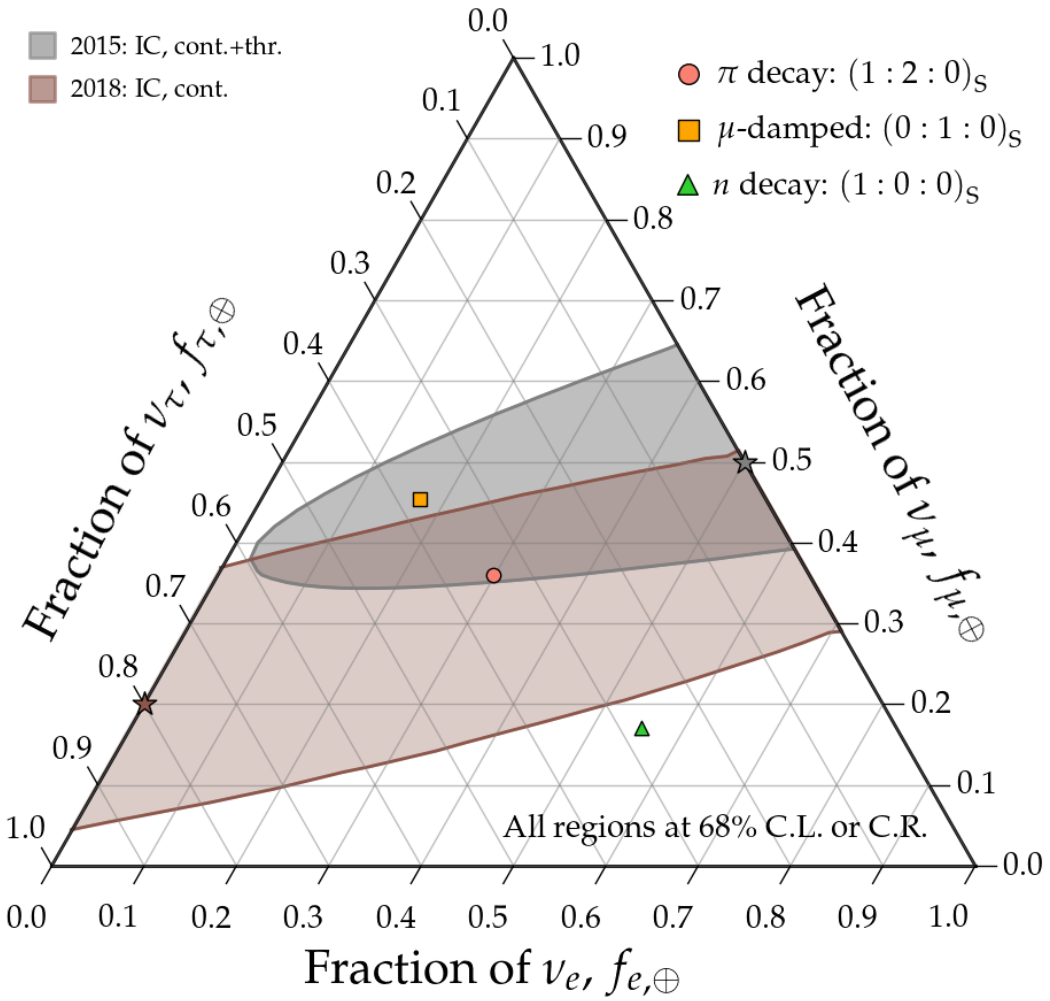
IceCube Collab., *EPJC* 2022
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
IceCube Collab., *PRD* 2019
IceCube Collab., *ApJ* 2015

Measuring flavor composition: 2015–2040



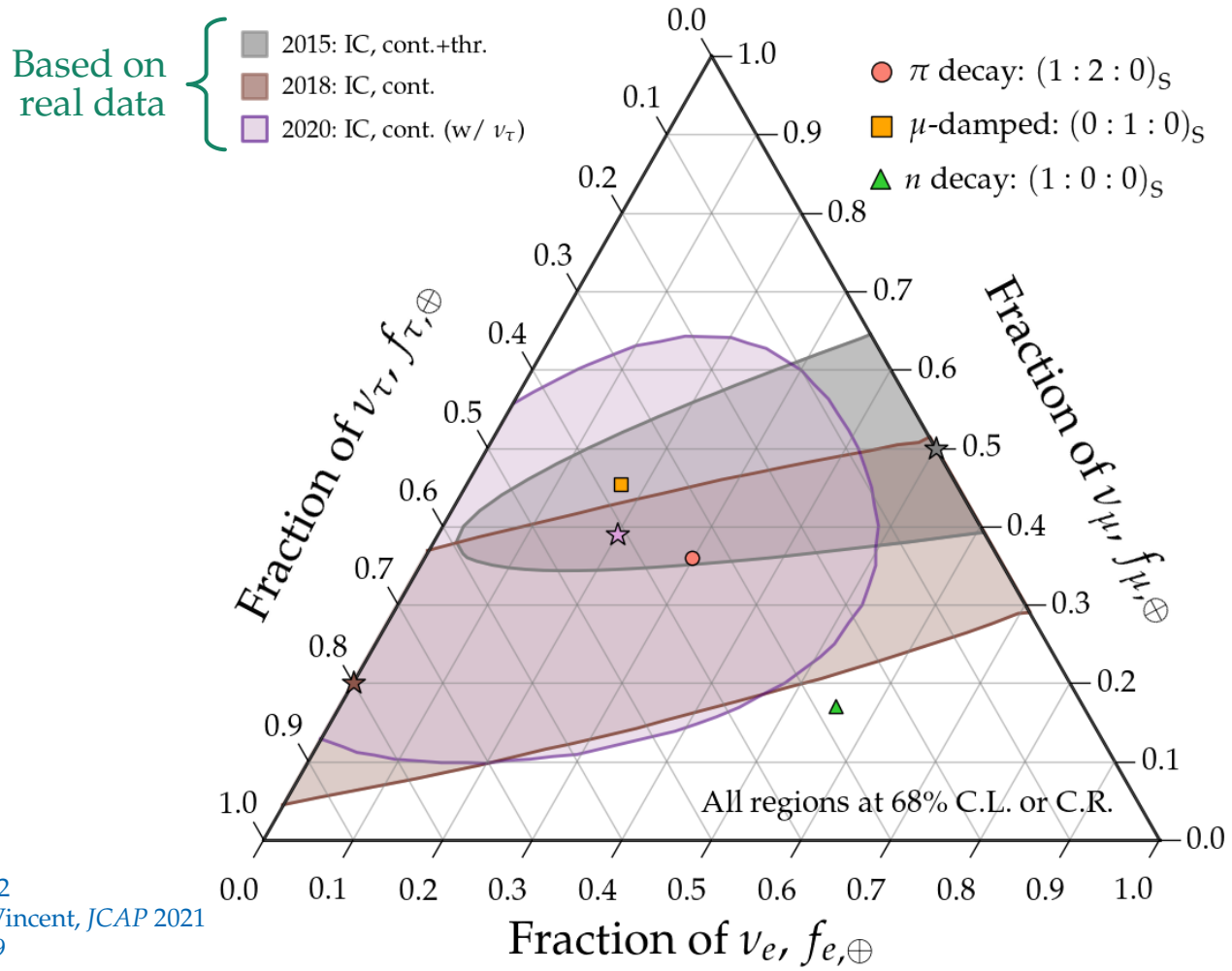
IceCube Collab., *EPJC* 2022
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
IceCube Collab., *PRD* 2019
IceCube Collab., *ApJ* 2015

Measuring flavor composition: 2015–2040



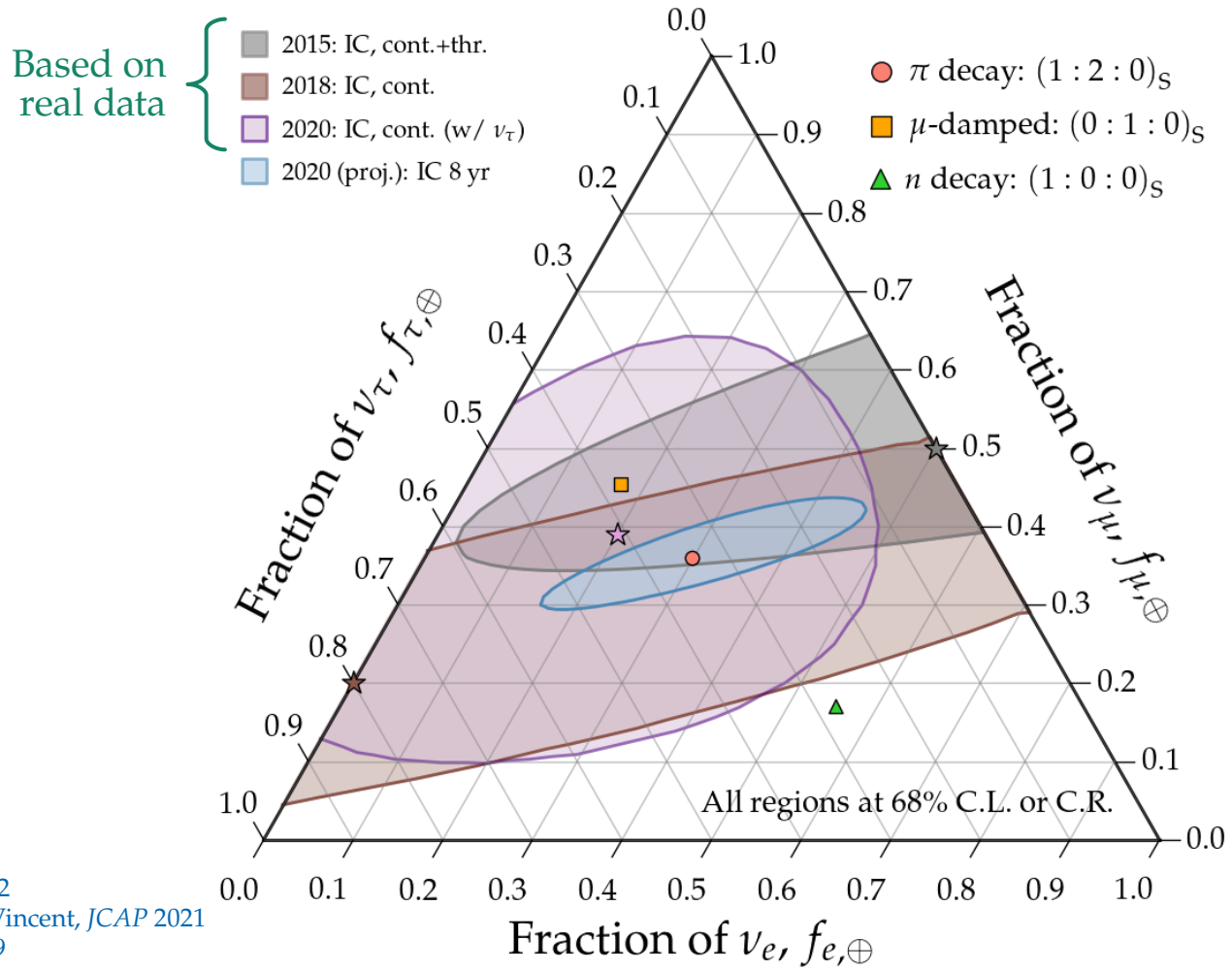
IceCube Collab., *EPJC* 2022
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
IceCube Collab., *PRD* 2019
IceCube Collab., *ApJ* 2015

Measuring flavor composition: 2015–2040



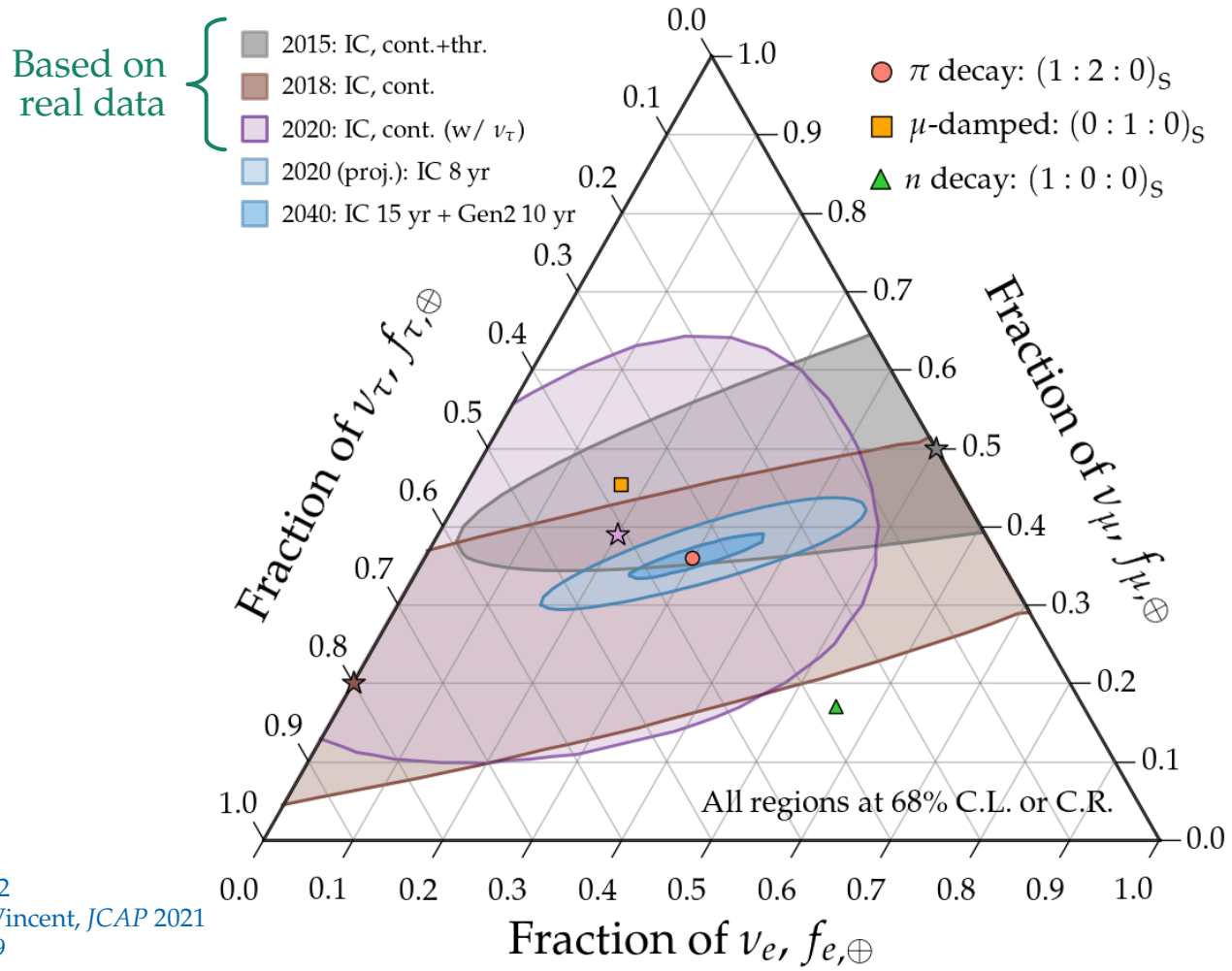
IceCube Collab., *EPJC* 2022
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
IceCube Collab., *PRD* 2019
IceCube Collab., *ApJ* 2015

Measuring flavor composition: 2015–2040



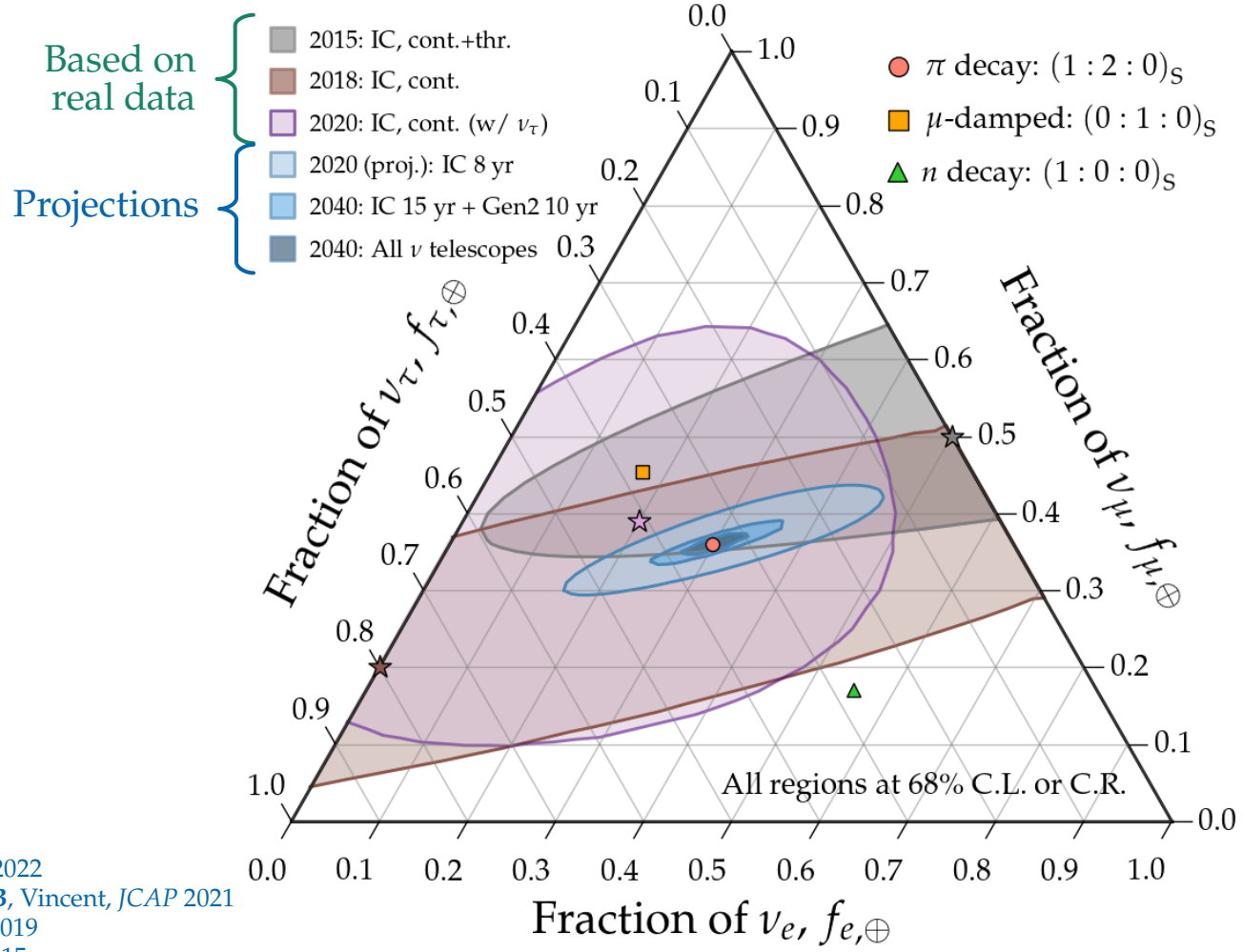
IceCube Collab., *EPJC* 2022
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
IceCube Collab., *PRD* 2019
IceCube Collab., *ApJ* 2015

Measuring flavor composition: 2015–2040



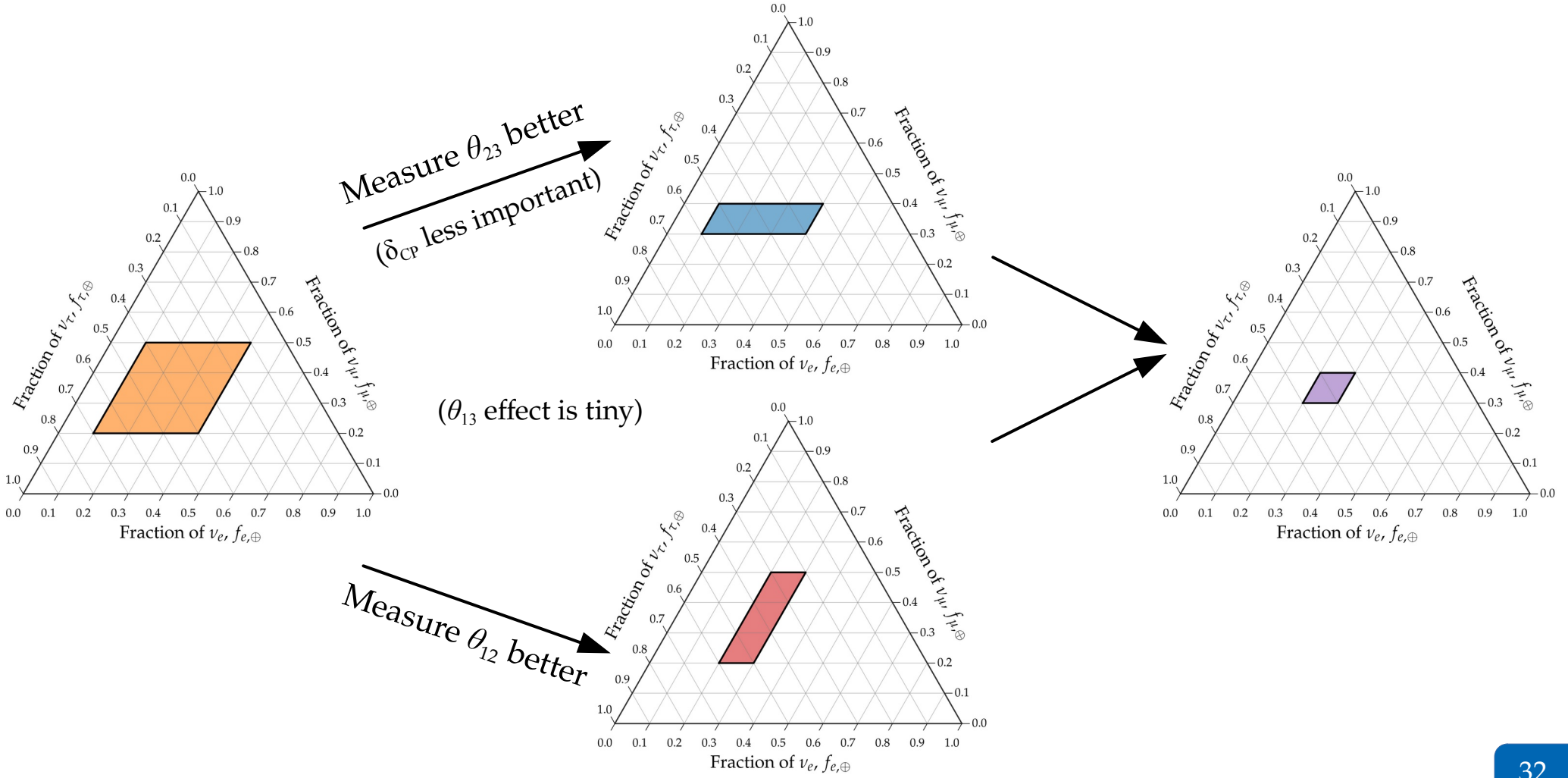
IceCube Collab., *EPJC* 2022
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
IceCube Collab., *PRD* 2019
IceCube Collab., *ApJ* 2015

Measuring flavor composition: 2015–2040



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

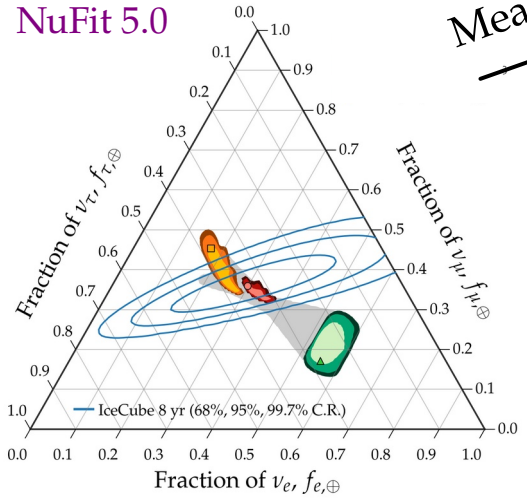
How knowing the mixing parameters better helps



How knowing the mixing parameters better helps

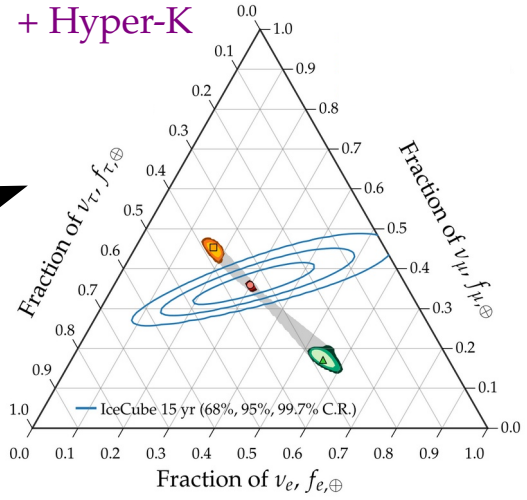
2020

NuFit 5.0

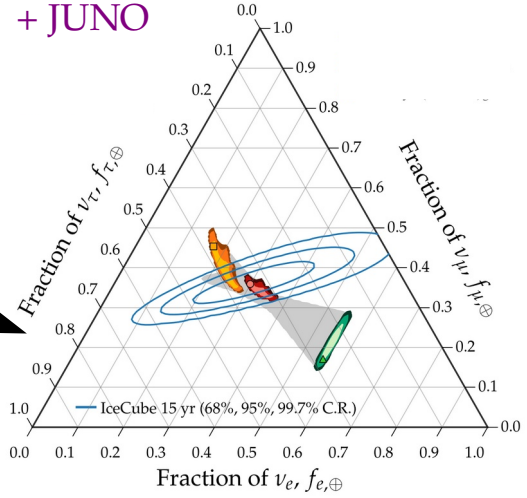


Measure θ_{23} better

+ Hyper-K



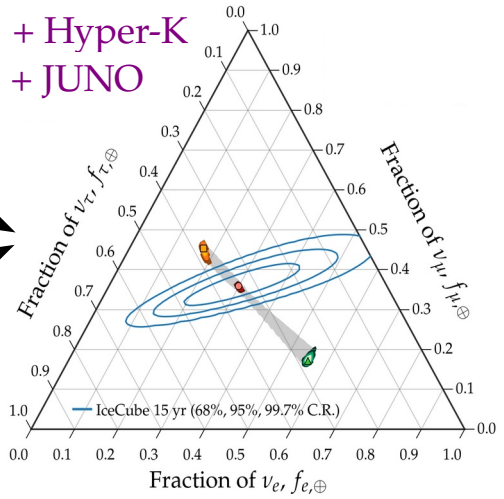
+ JUNO



Measure θ_{12} better

~2030

+ Hyper-K
+ JUNO



In our results:
JUNO + Hyper-K + DUNE

Marginal improvement til 2040

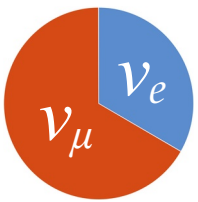
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Back to the sources

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

Sources

E.g.,



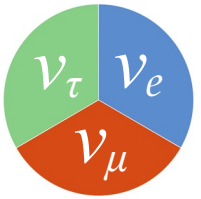
Oscillations

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

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

Earth

E.g.,



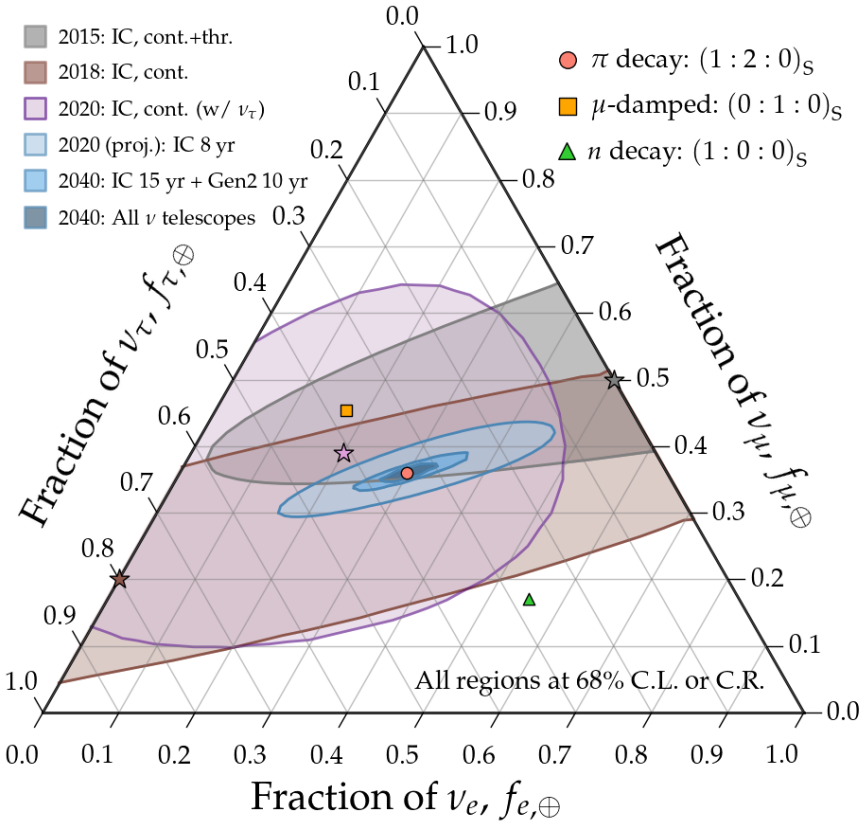
$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$

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

Inferring the flavor composition at the sources

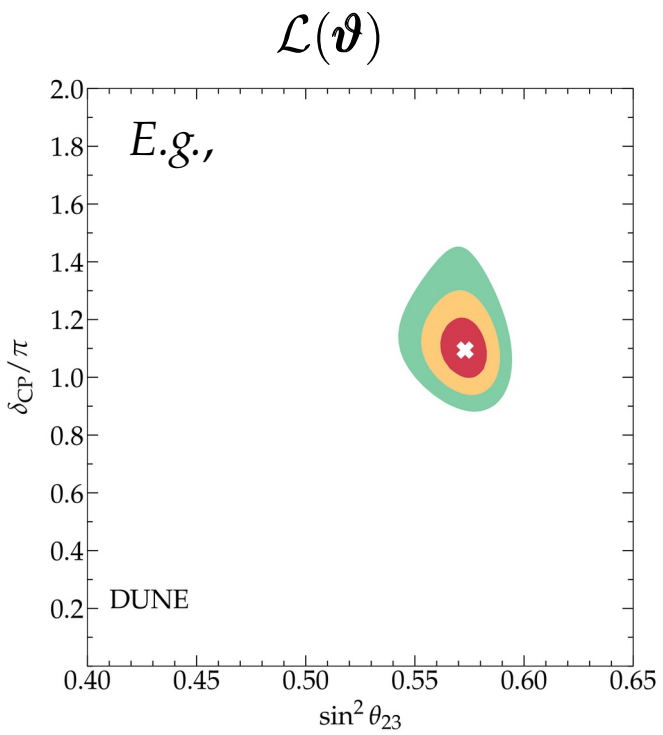
Ingredient #1:

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



Ingredient #2:

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

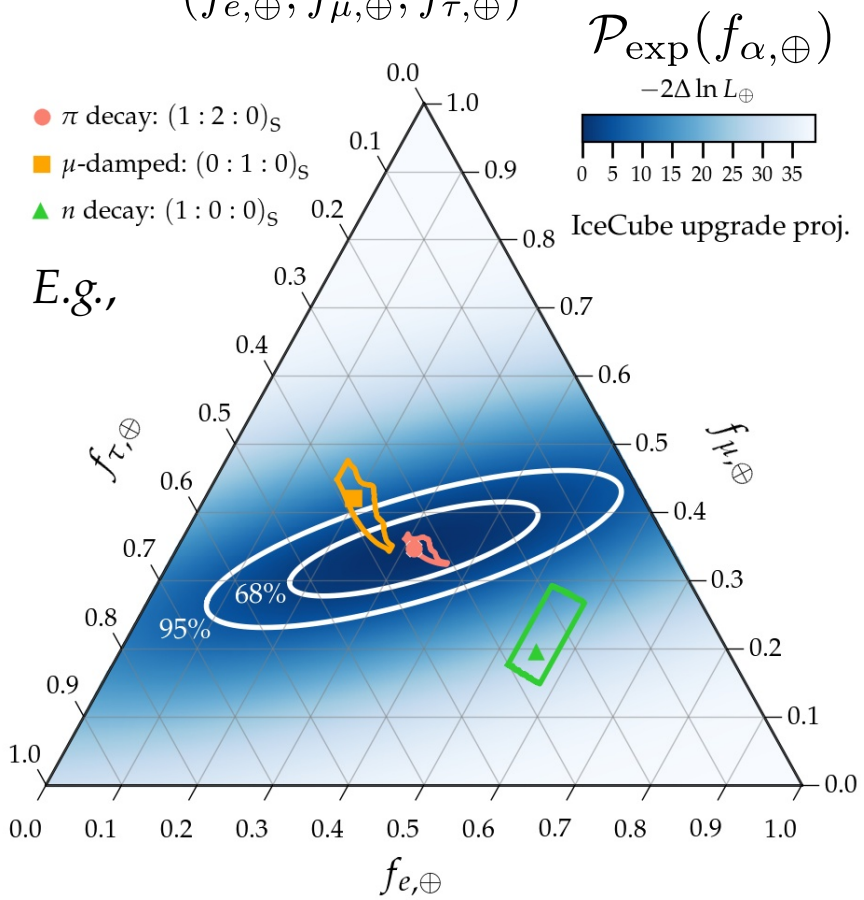


Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
MB & Ahlers, *PRL* 2019

Inferring the flavor composition at the sources

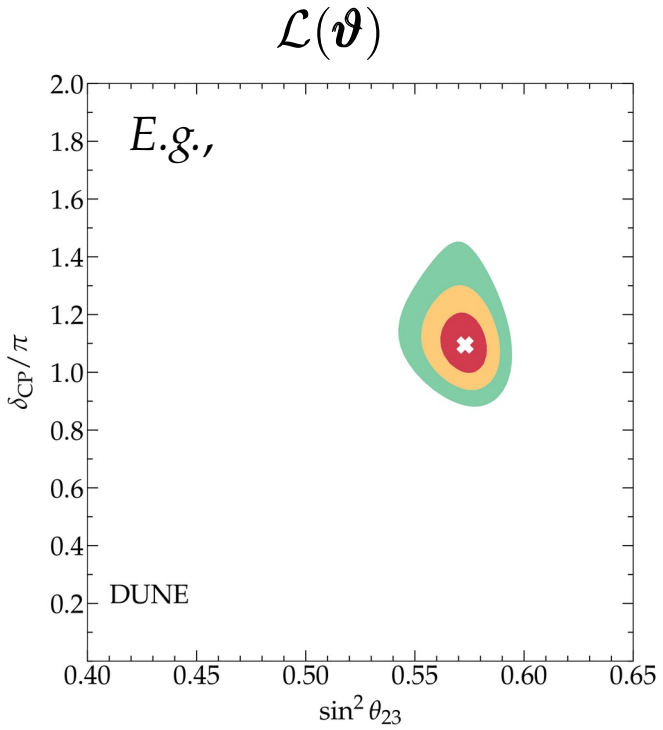
Ingredient #1:

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



Ingredient #2:

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

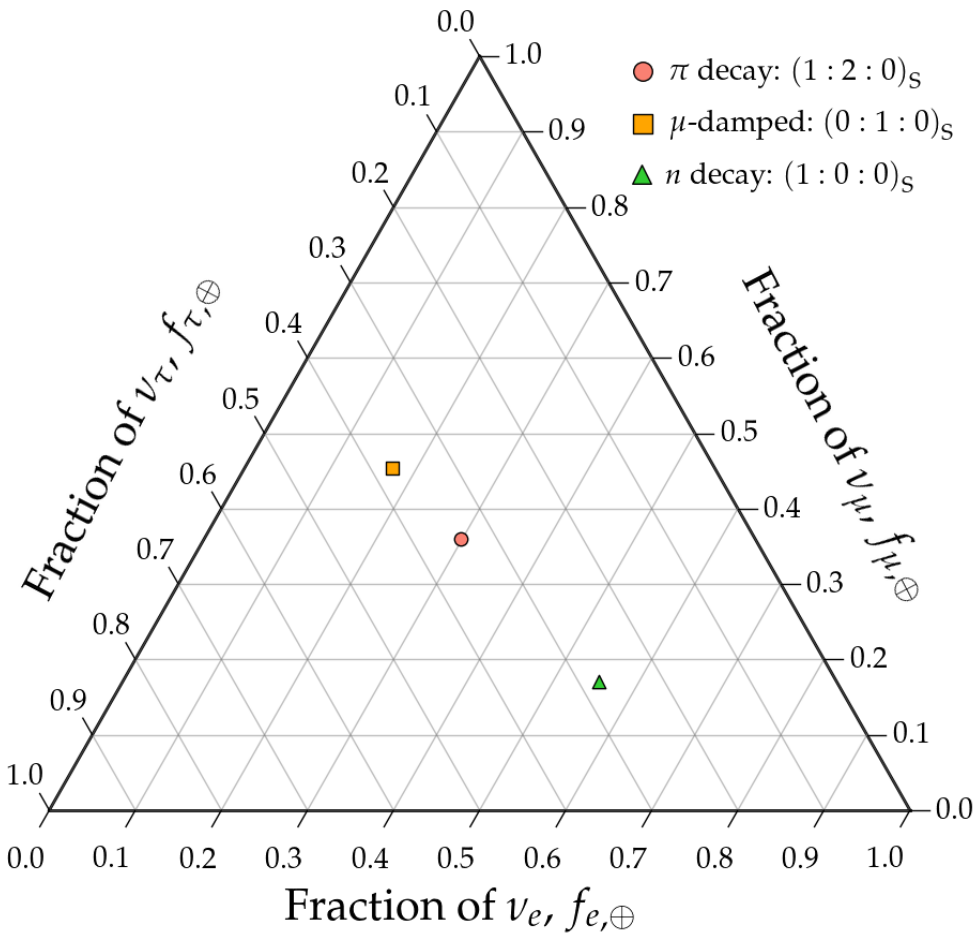


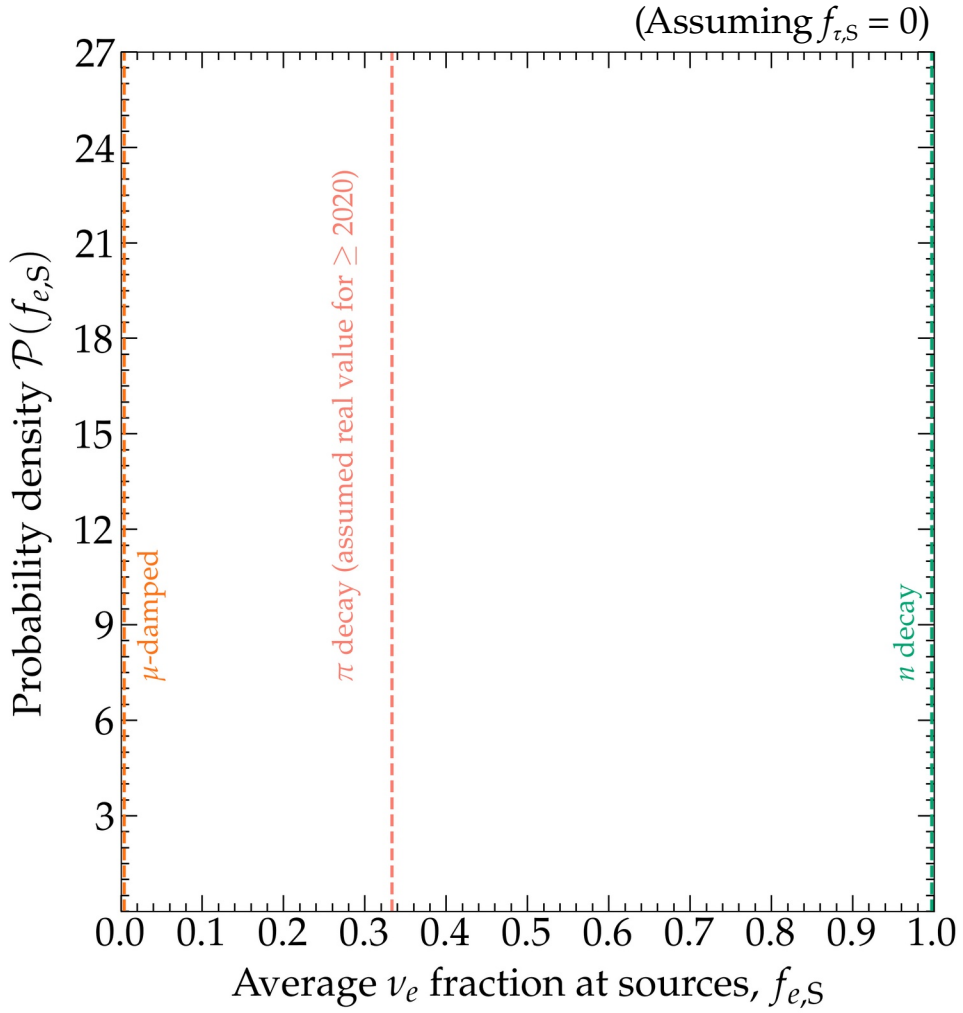
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
MB & Ahlers, *PRL* 2019

Inferring the flavor composition at the sources

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

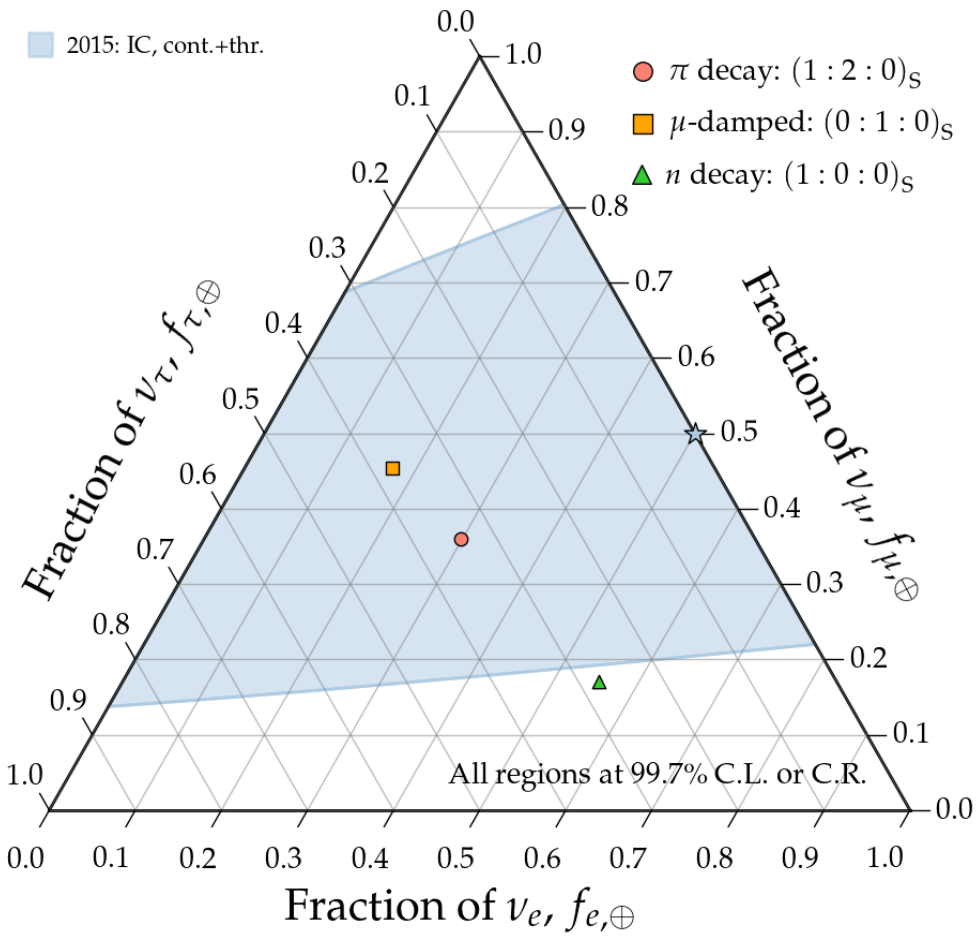
Inferring the flavor composition at the sources

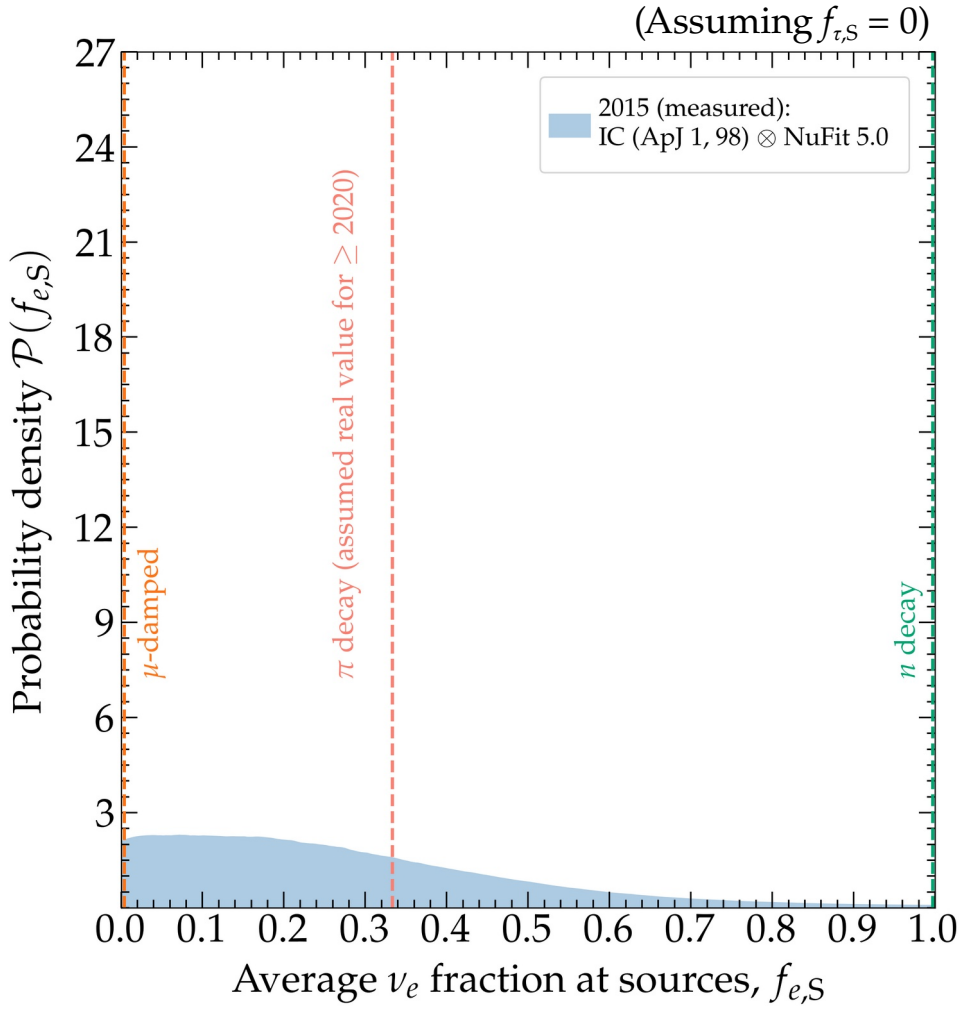




Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
MB & Ahlers, *PRL* 2019

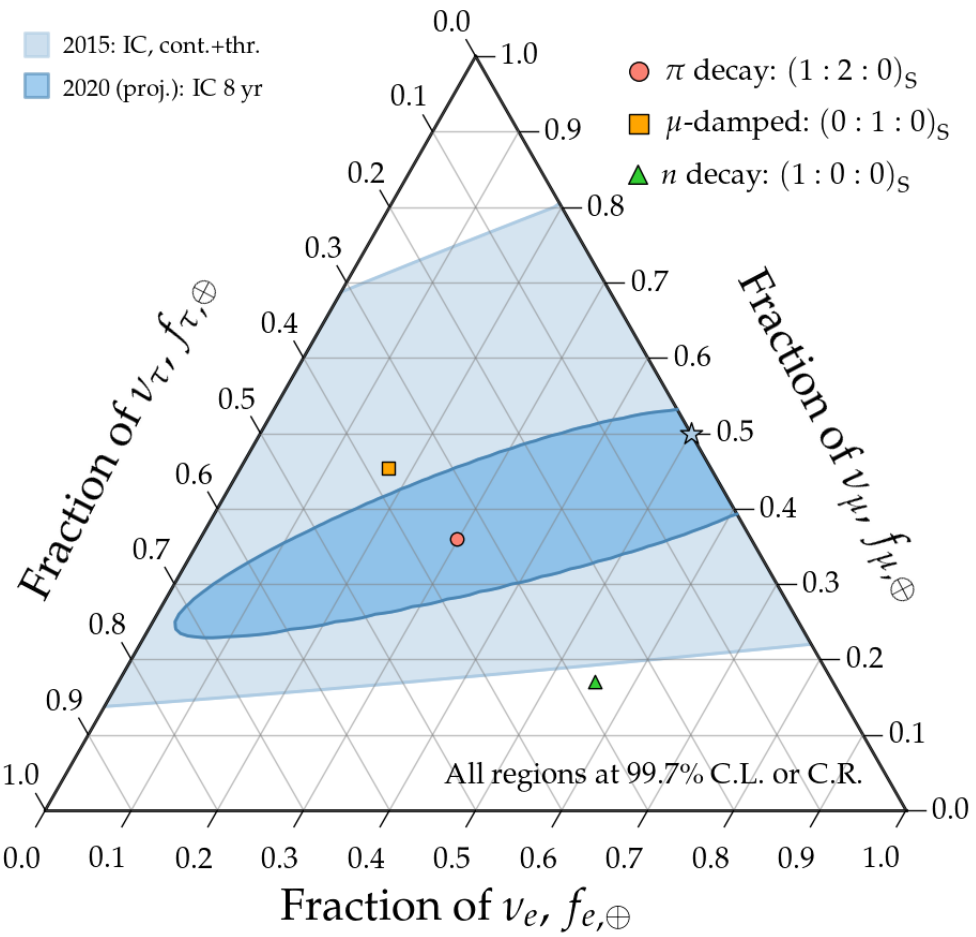
Inferring the flavor composition at the sources

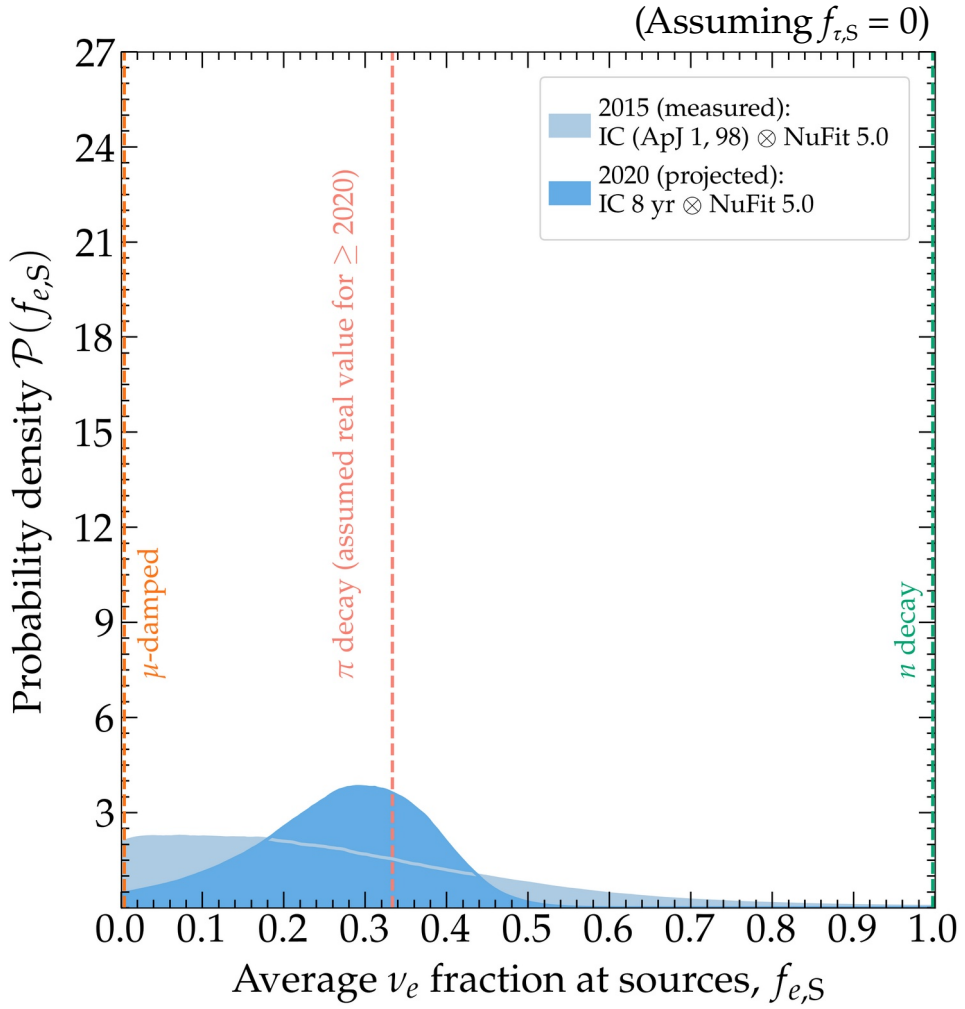




Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
MB & Ahlers, *PRL* 2019

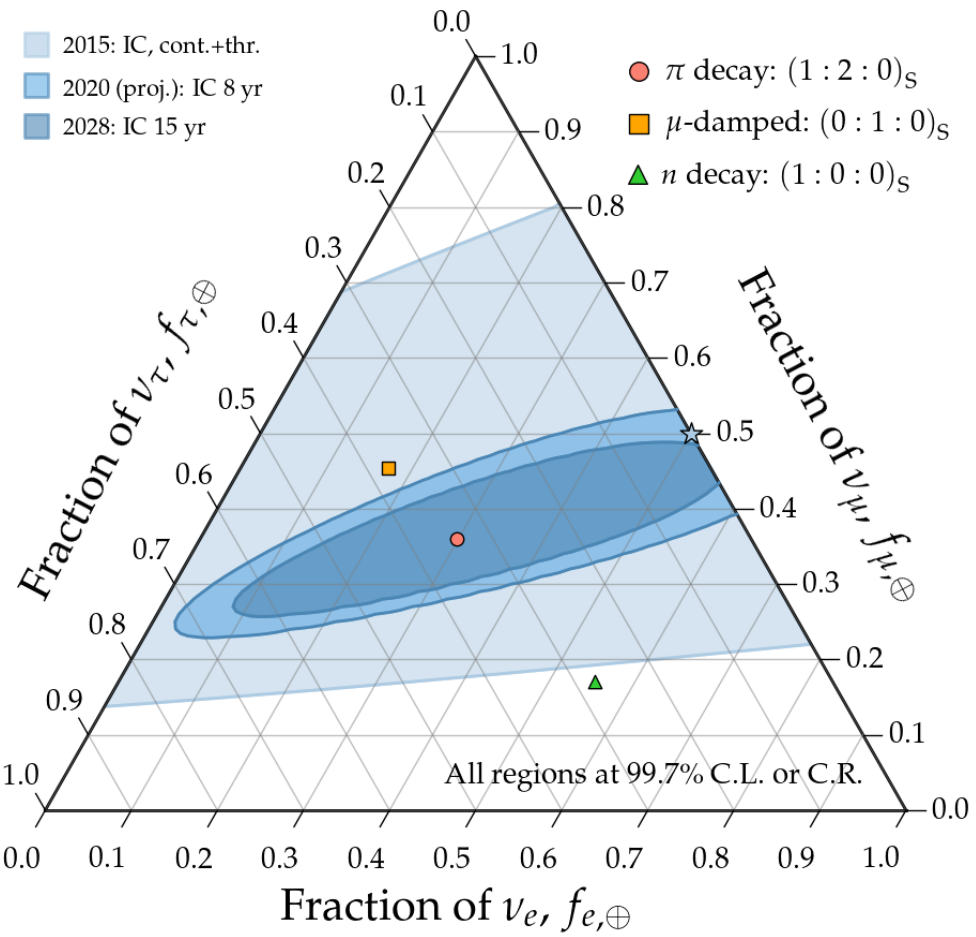
Inferring the flavor composition at the sources

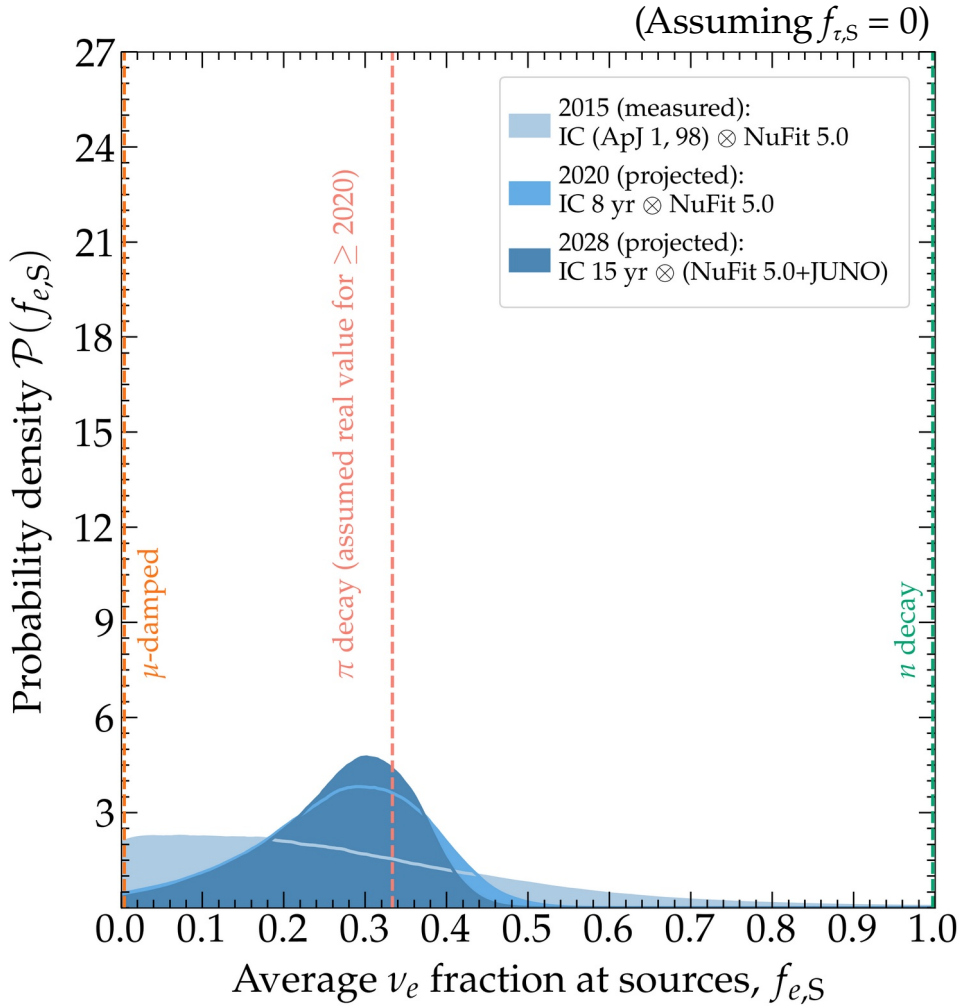




Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
MB & Ahlers, *PRL* 2019

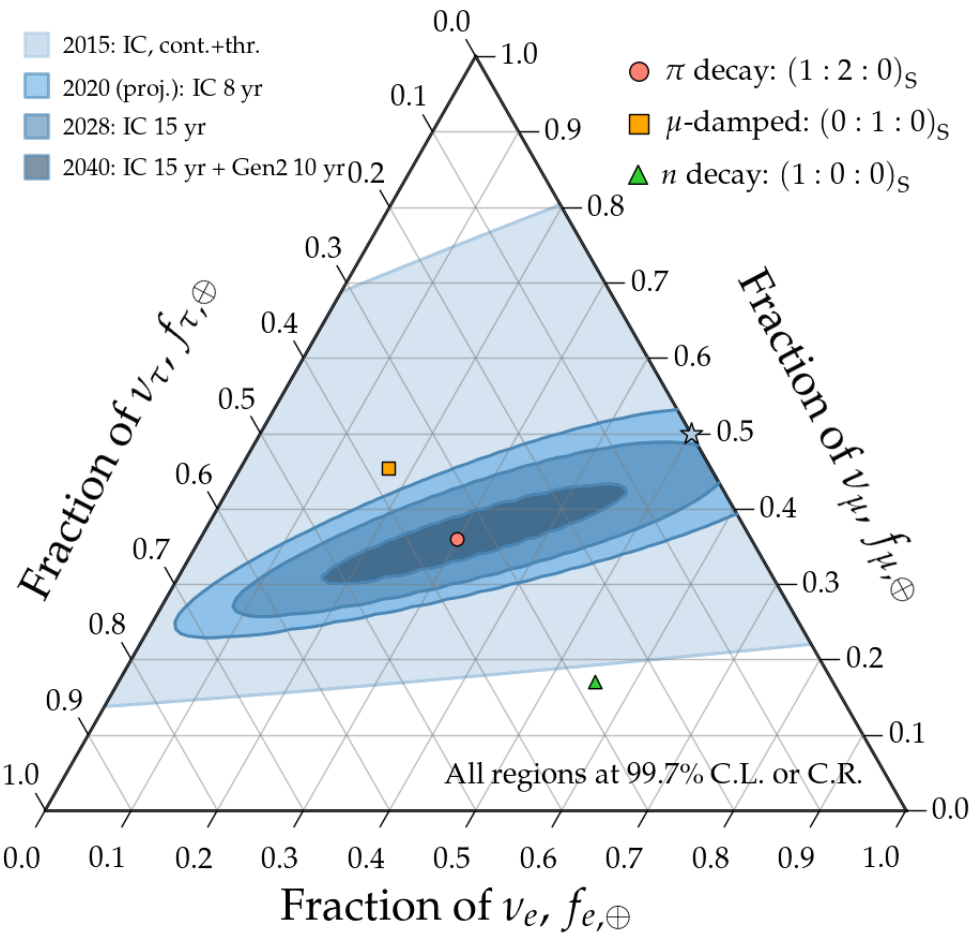
Inferring the flavor composition at the sources

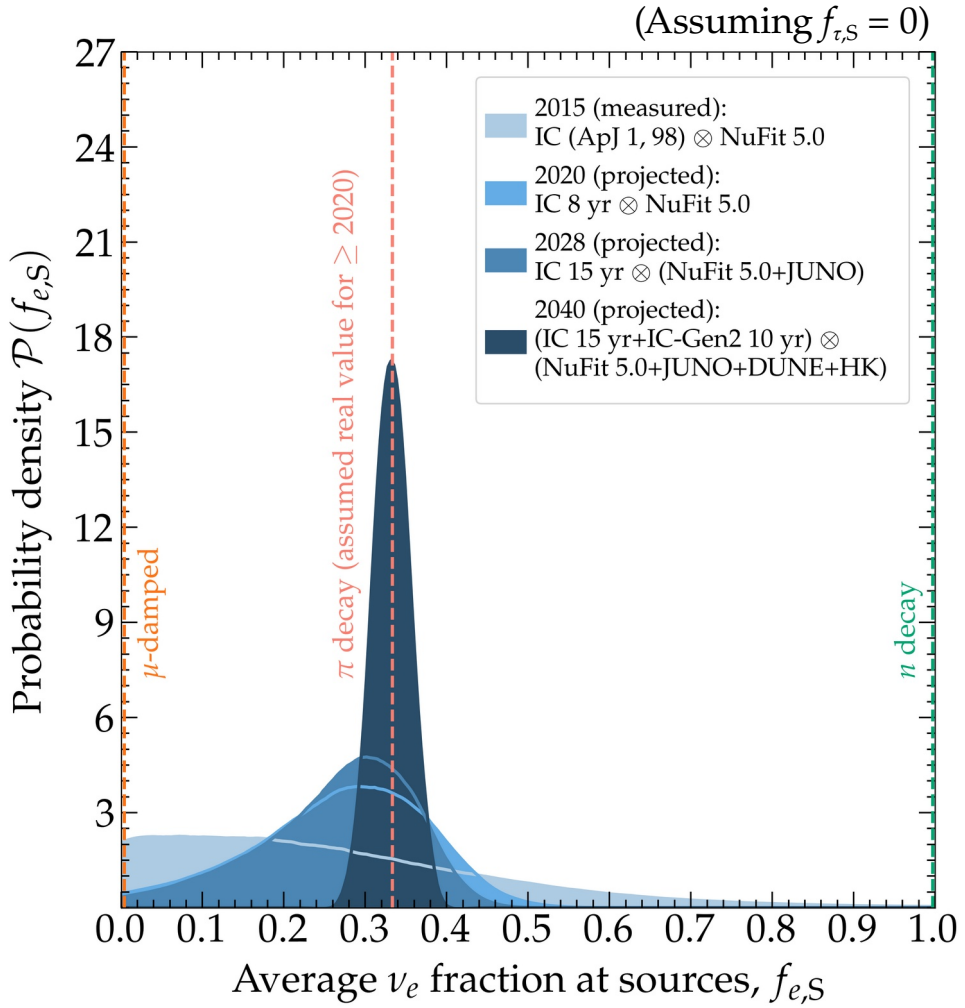




Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
MB & Ahlers, *PRL* 2019

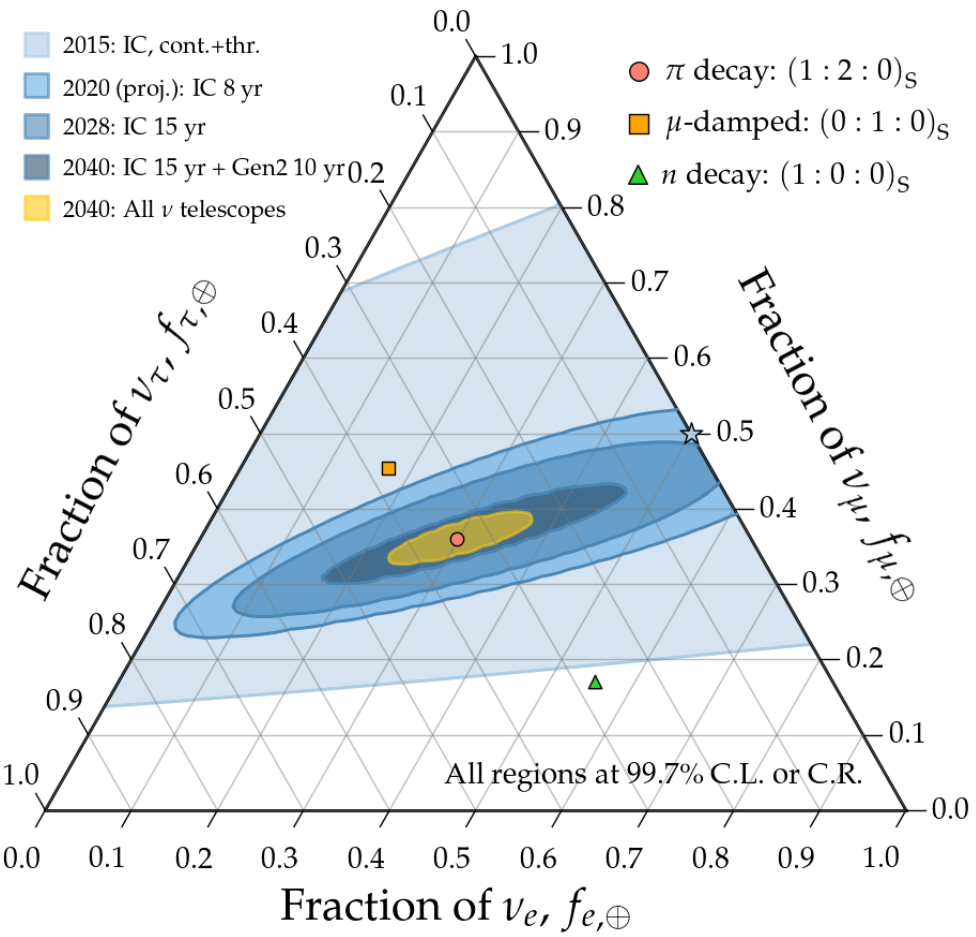
Inferring the flavor composition at the sources

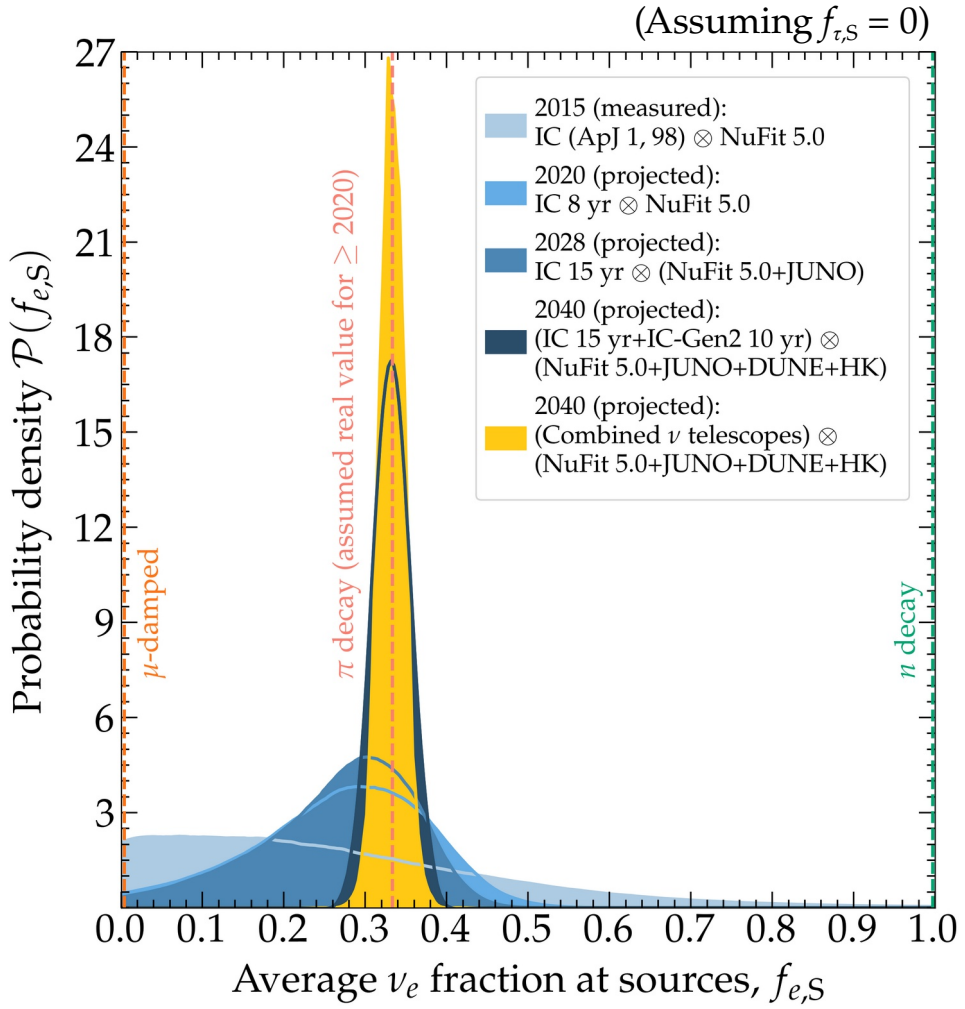




Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
MB & Ahlers, *PRL* 2019

Inferring the flavor composition at the sources

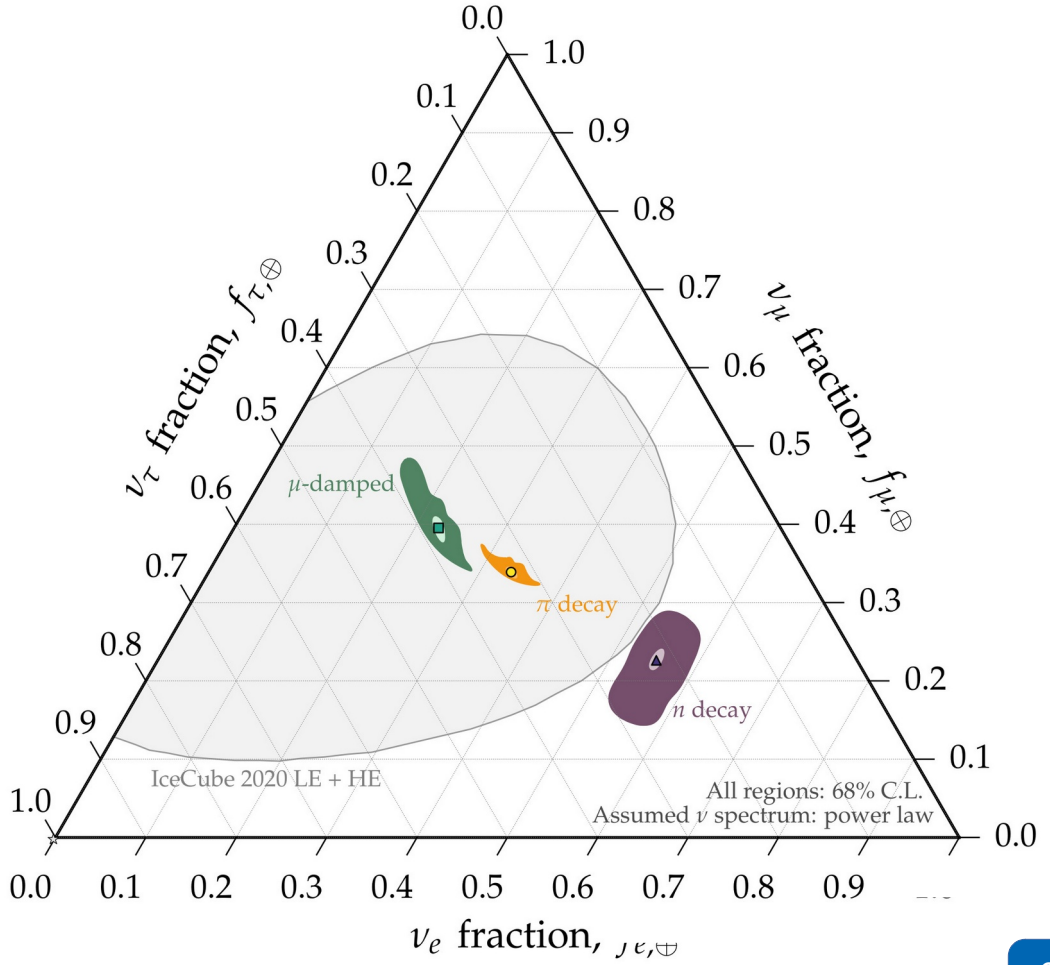




Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
MB & Ahlers, *PRL* 2019

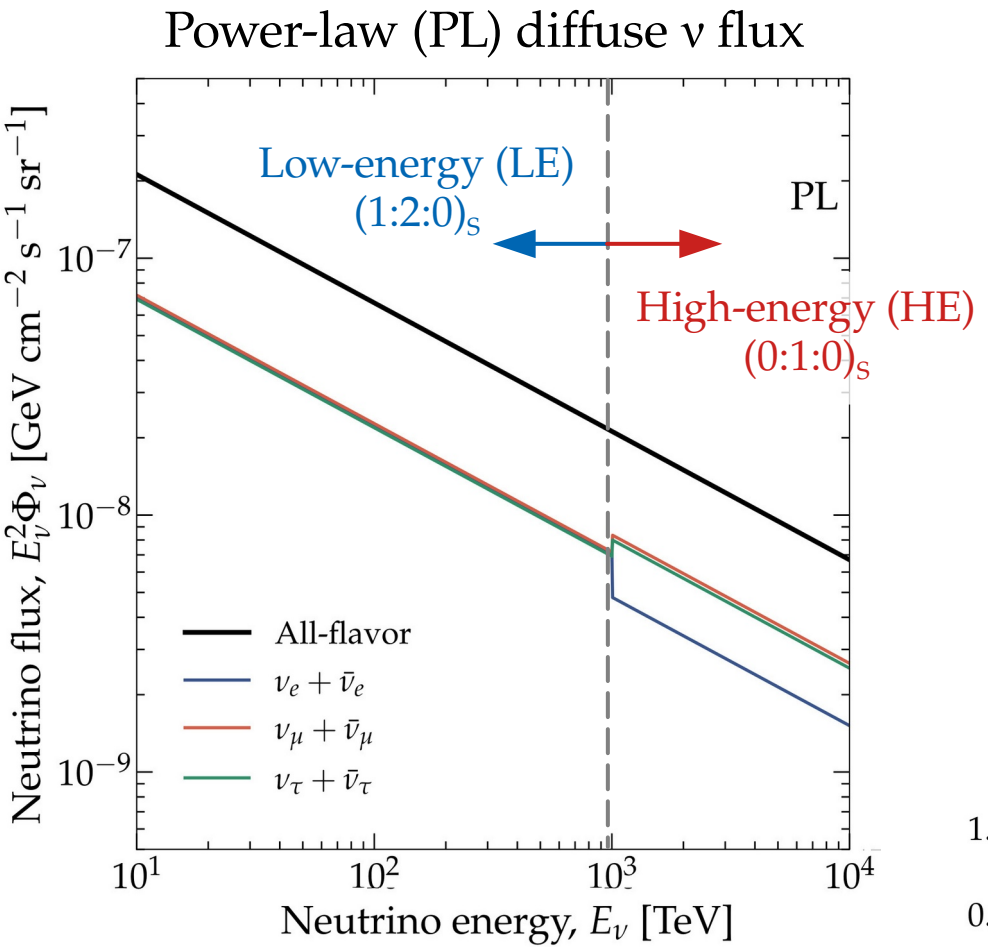
Measuring energy-dependent flavor composition

Flavor composition: measuring the energy dependence

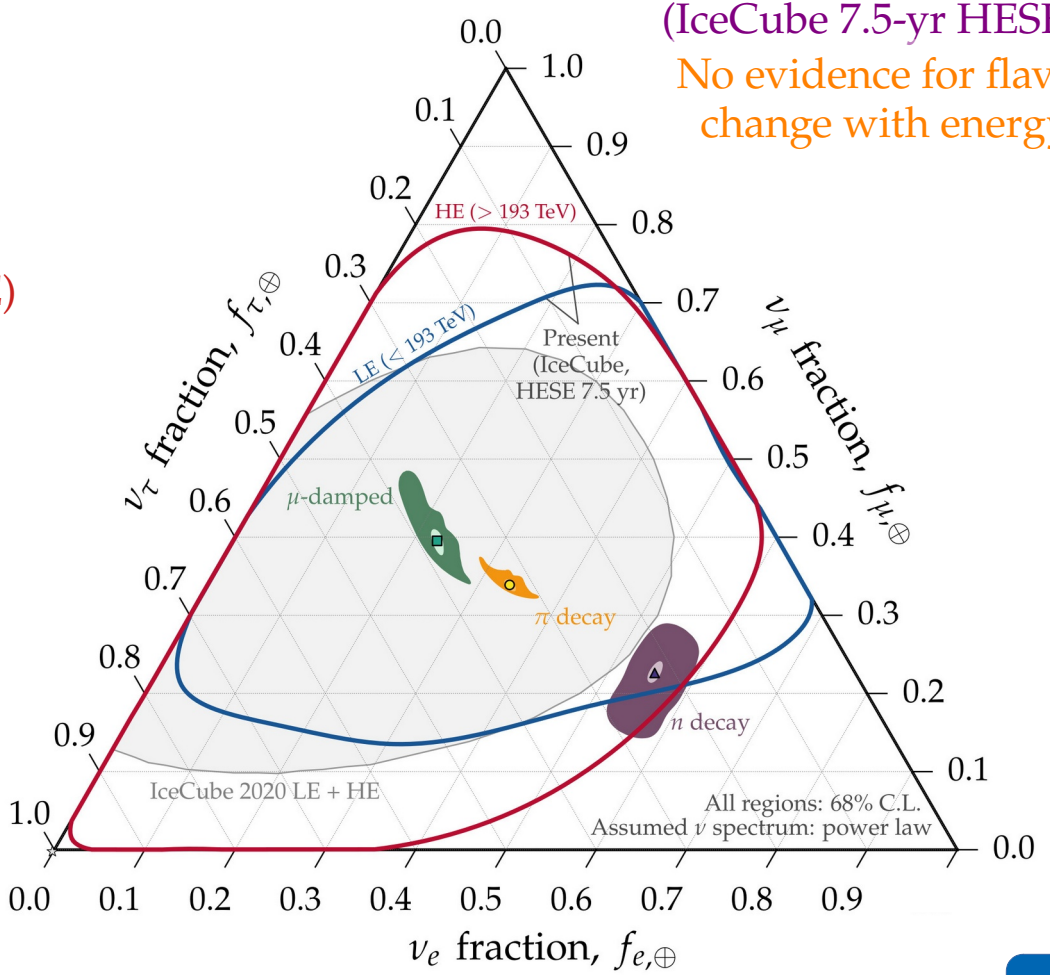


Liu, Fiorillo, Argüelles, **MB**, Song, Vincent, 2312.07649

Flavor composition: measuring the energy dependence

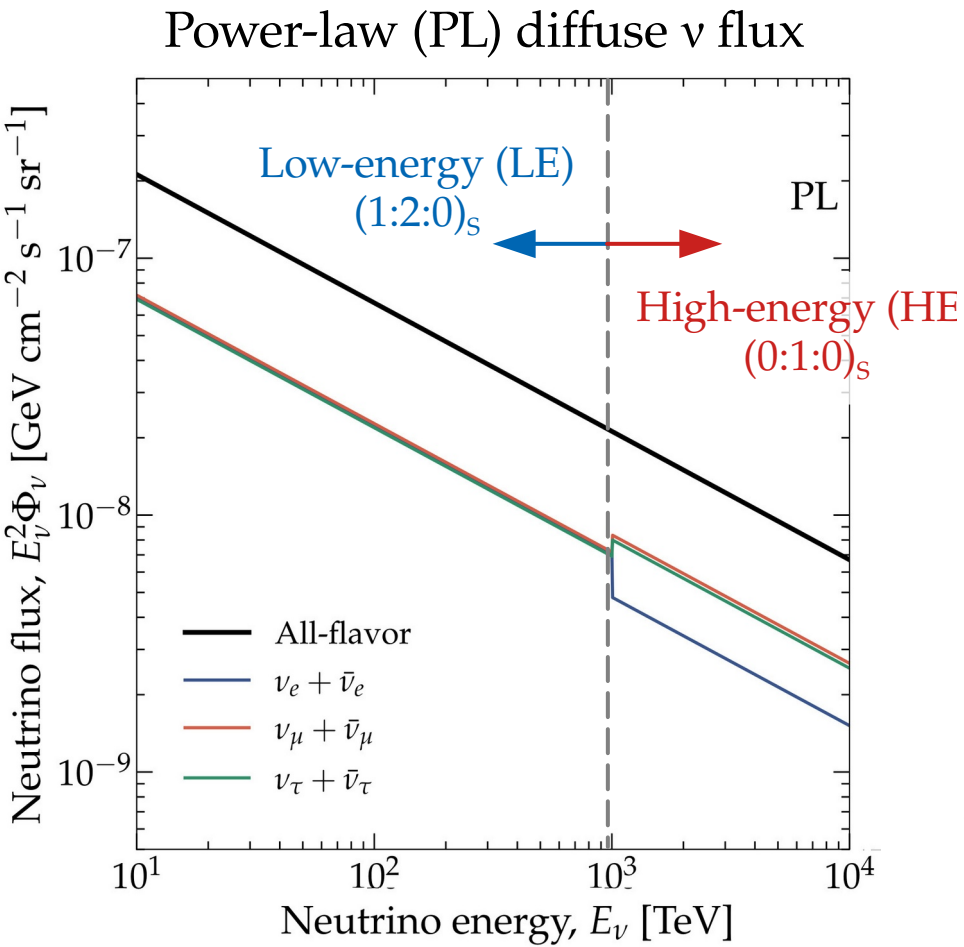


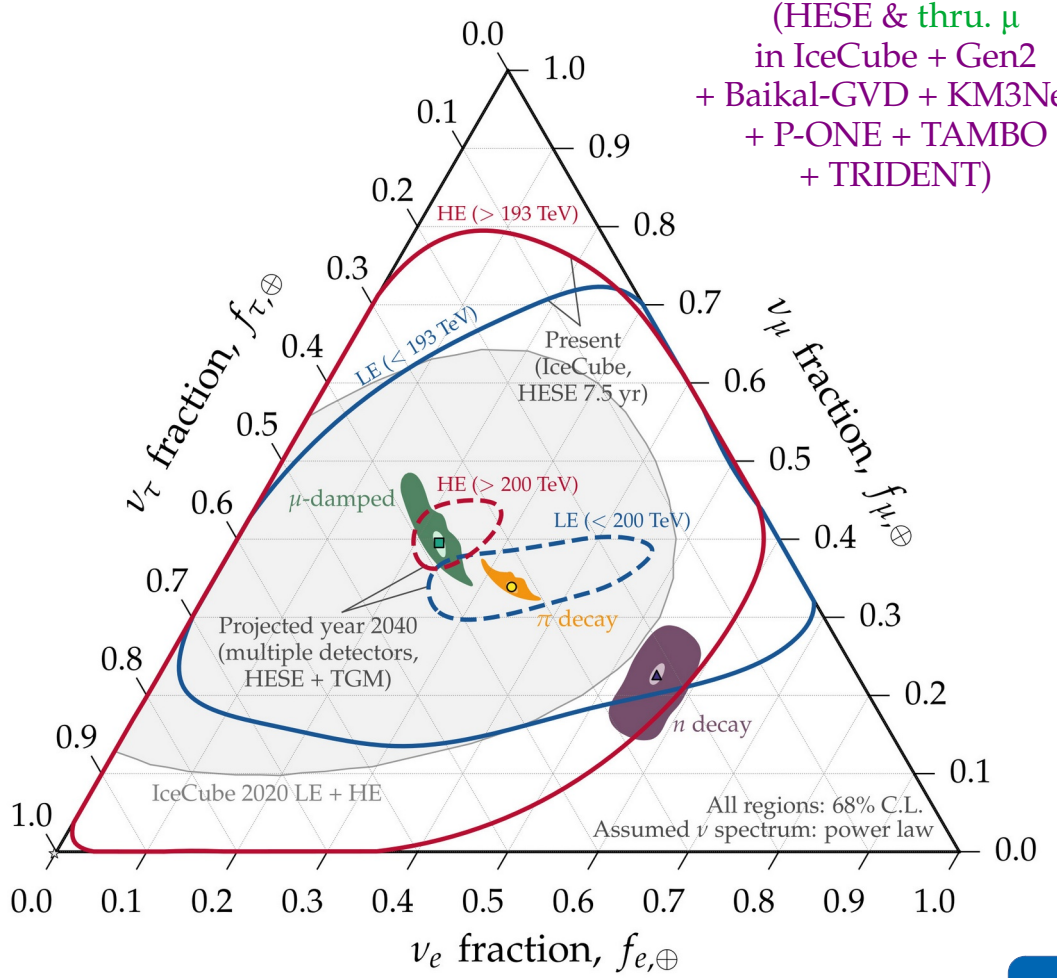
Today
(IceCube 7.5-yr HESE):
No evidence for flavor change with energy



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

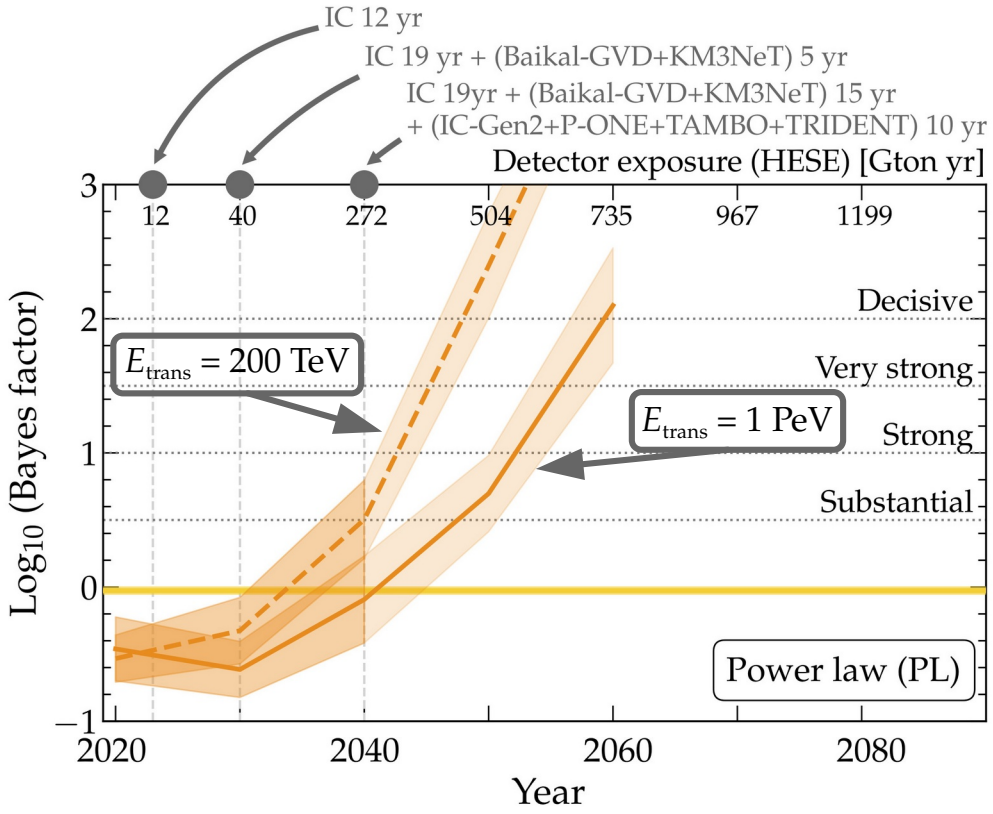
Flavor composition: measuring the energy dependence

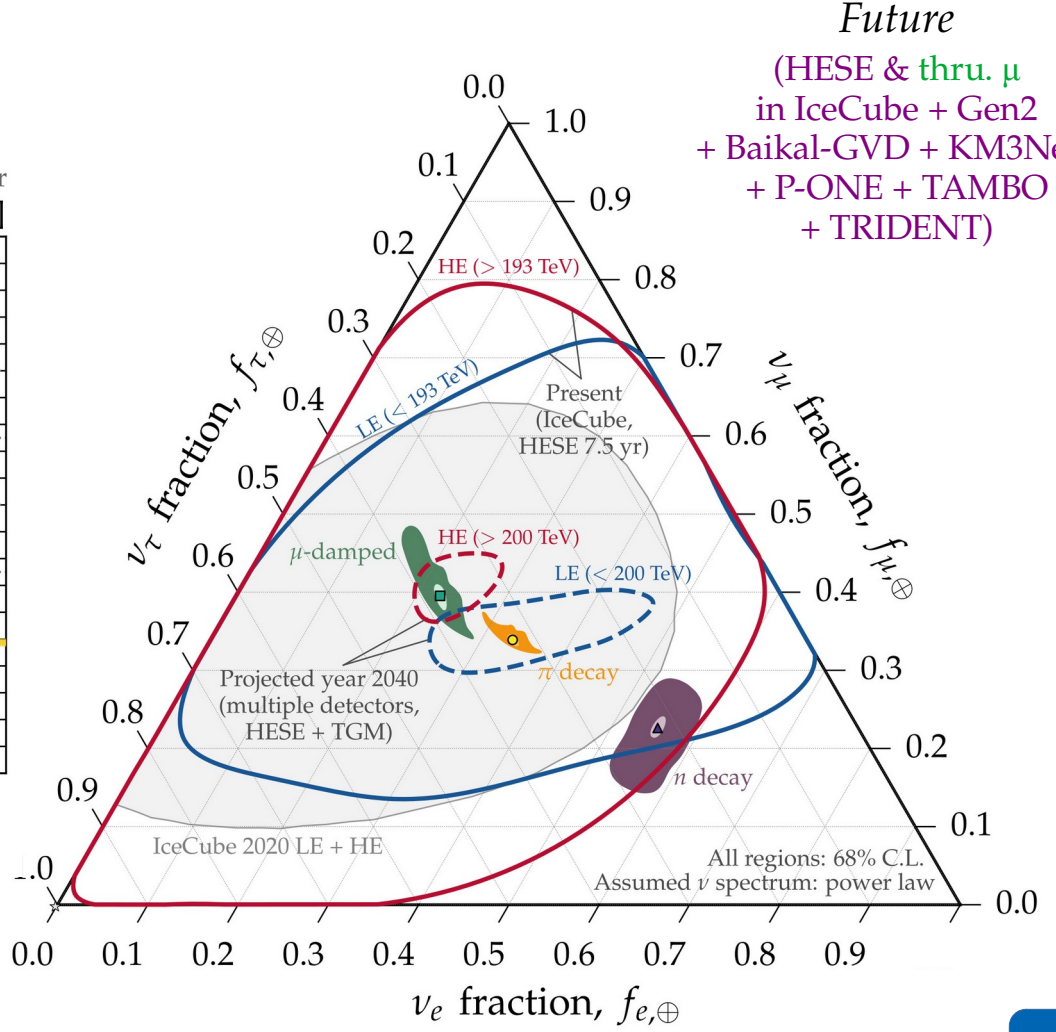




Liu, Fiorillo, Argüelles, **MB**, Song, Vincent, 2312.07649

Flavor composition: measuring the energy dependence

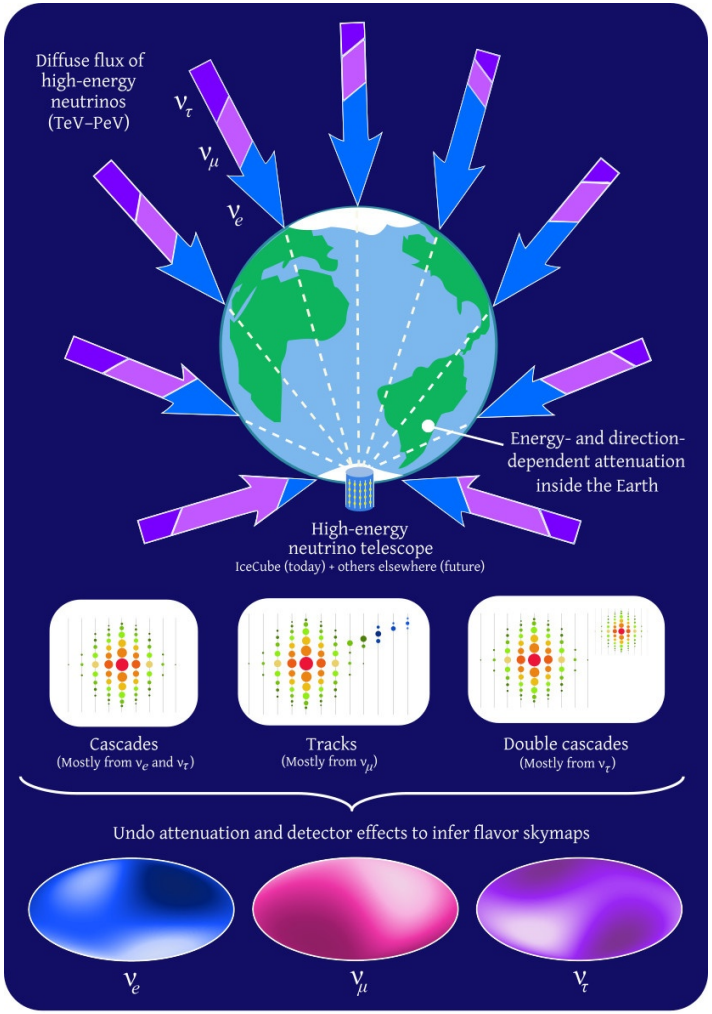




Liu, Fiorillo, Argüelles, **MB**, Song, Vincent, 2312.07649

Measuring flavor anisotropy

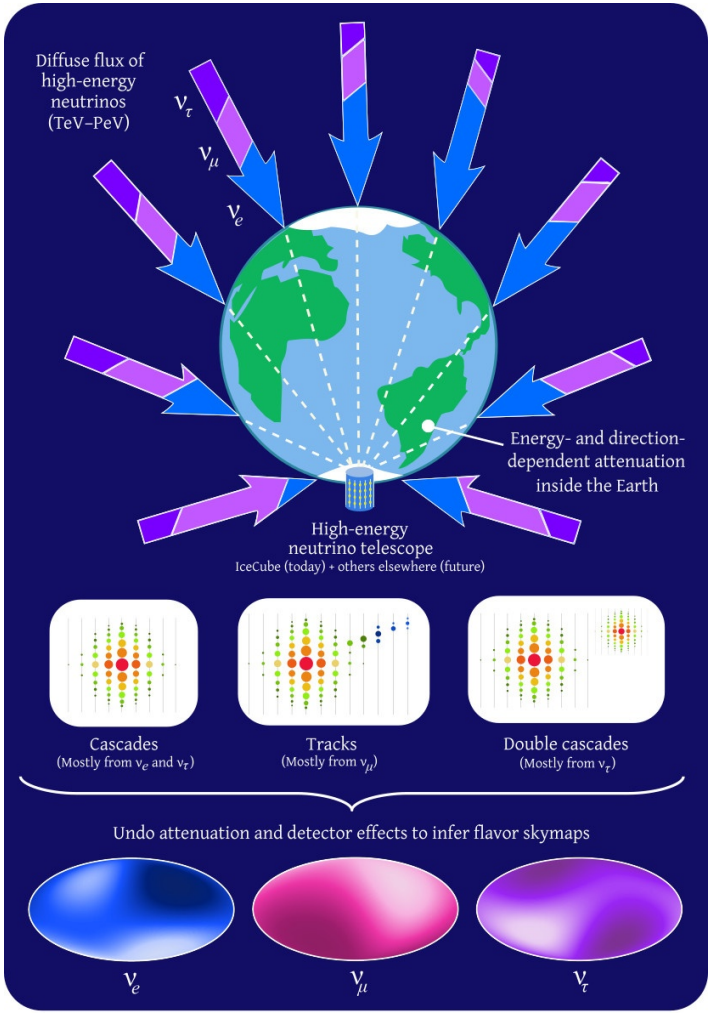
Flavor anisotropy in the high-energy neutrino sky



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

Telalovic, **MB**, 2310.15224

Flavor anisotropy in the high-energy neutrino sky

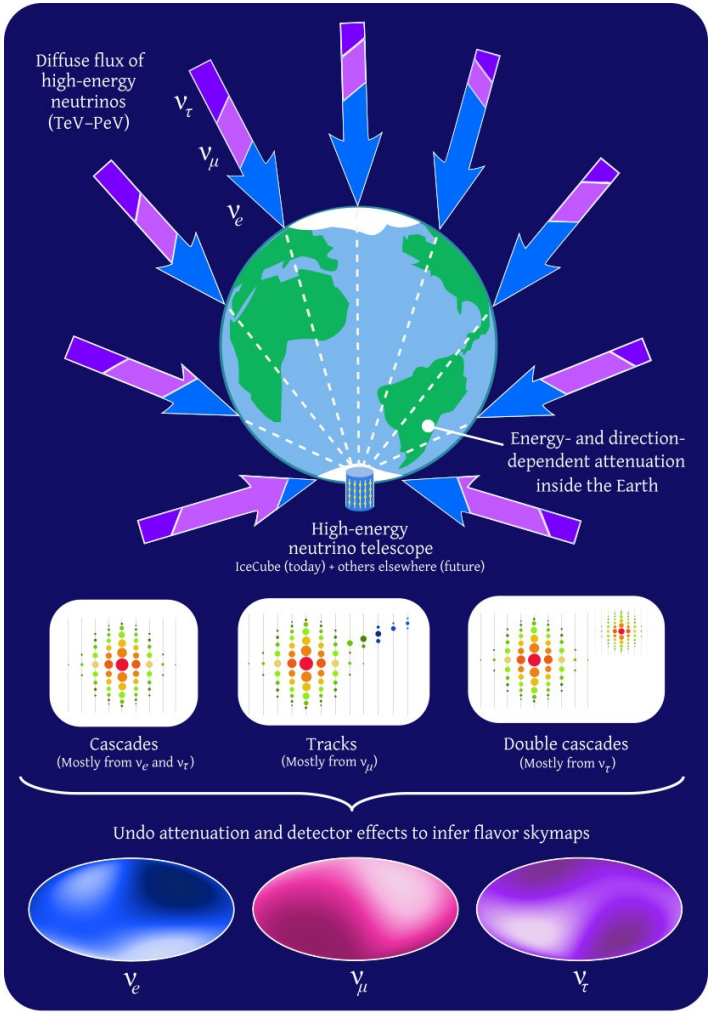


Does the high-energy sky shine equally brightly
In neutrinos of all flavors?

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

Telalovic, **MB**, 2310.15224

Flavor anisotropy in the high-energy neutrino sky



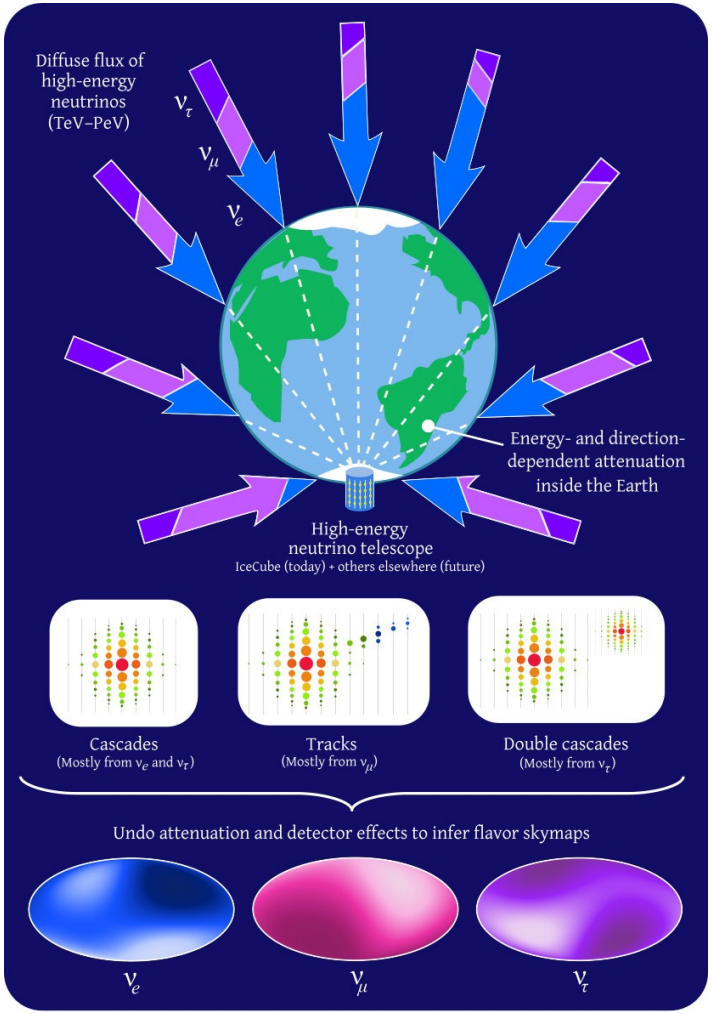
Does the high-energy sky shine equally brightly
In neutrinos of all flavors?

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

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

Telalovic, **MB**, 2310.15224

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)

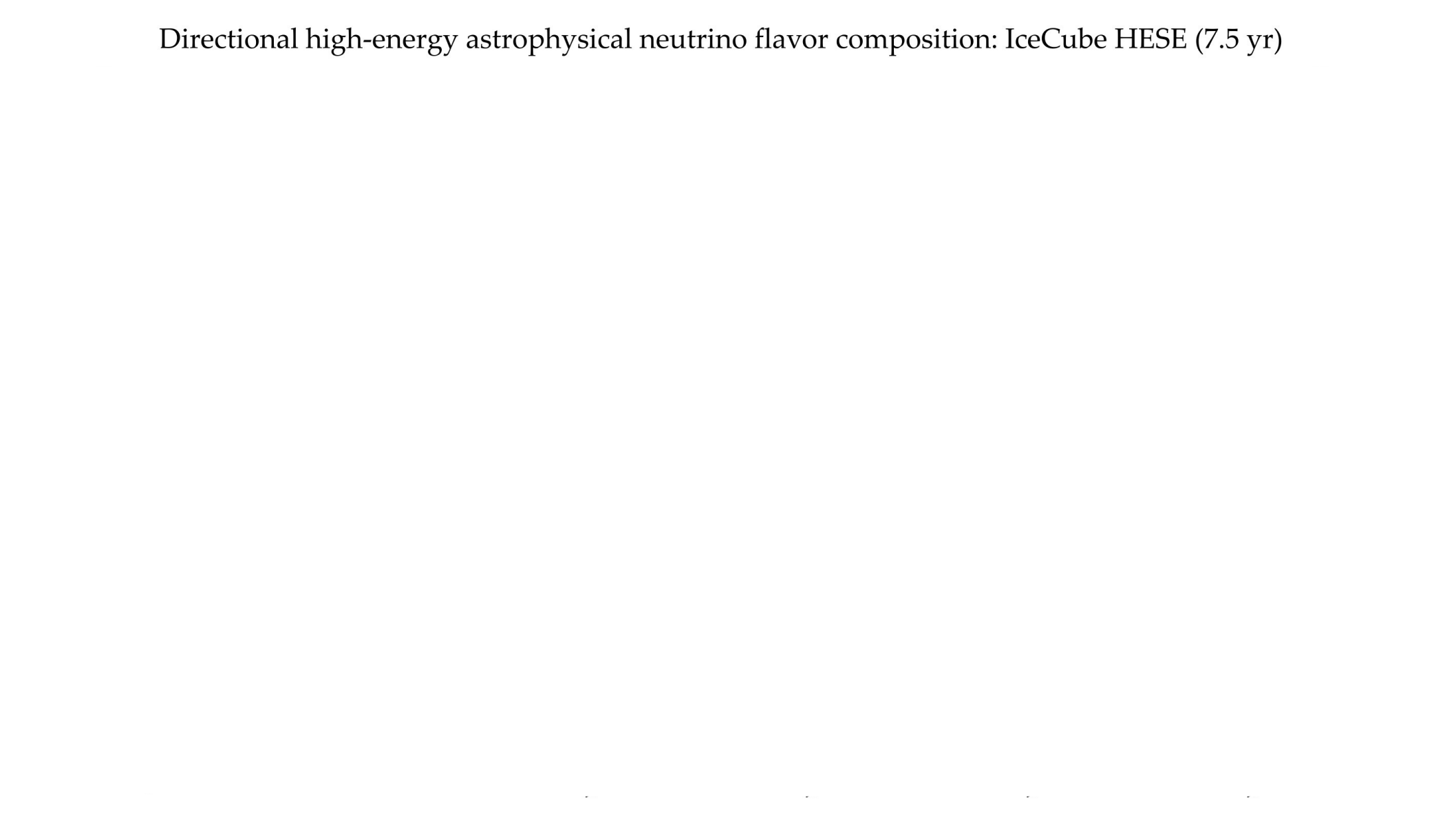
… we infer the directional dependence of the diffuse fluxes of ν_e, ν_μ, ν_τ

Telalovic, **MB**, 2310.15224

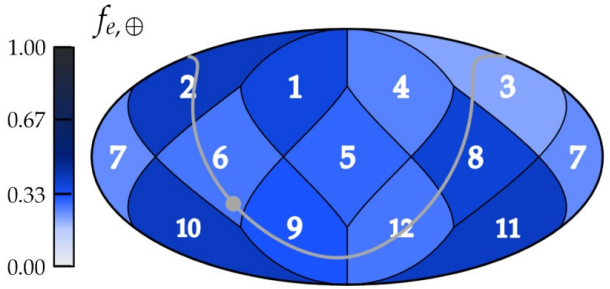
Directional high-energy astrophysical neutrino flavor composition: IceCube HESE (7.5 yr)

Real, public data

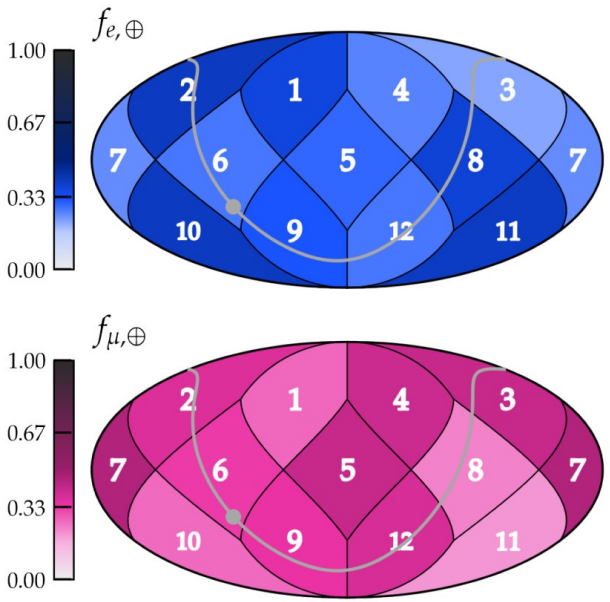
Directional high-energy astrophysical neutrino flavor composition: IceCube HESE (7.5 yr)



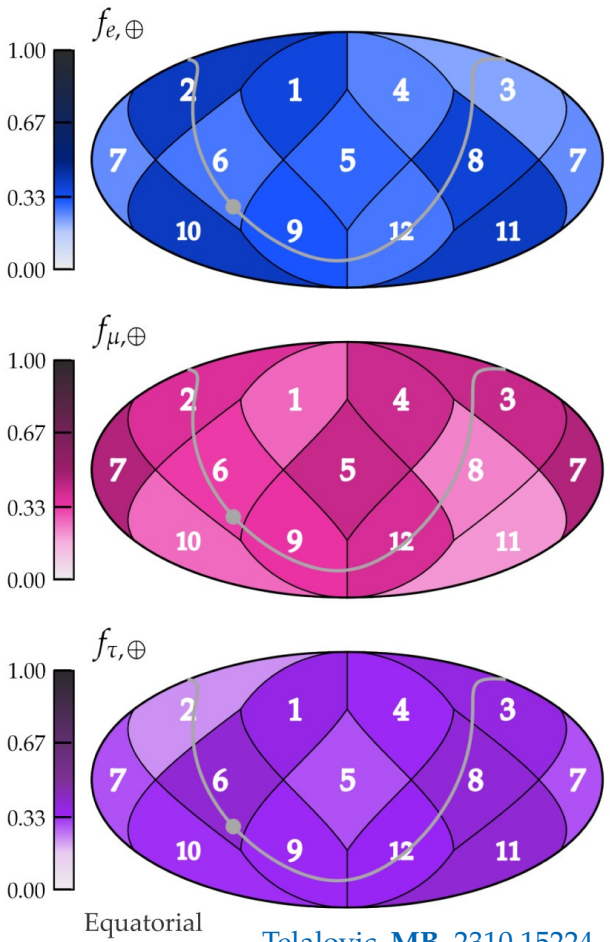
Directional high-energy astrophysical neutrino flavor composition: IceCube HESE (7.5 yr)



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

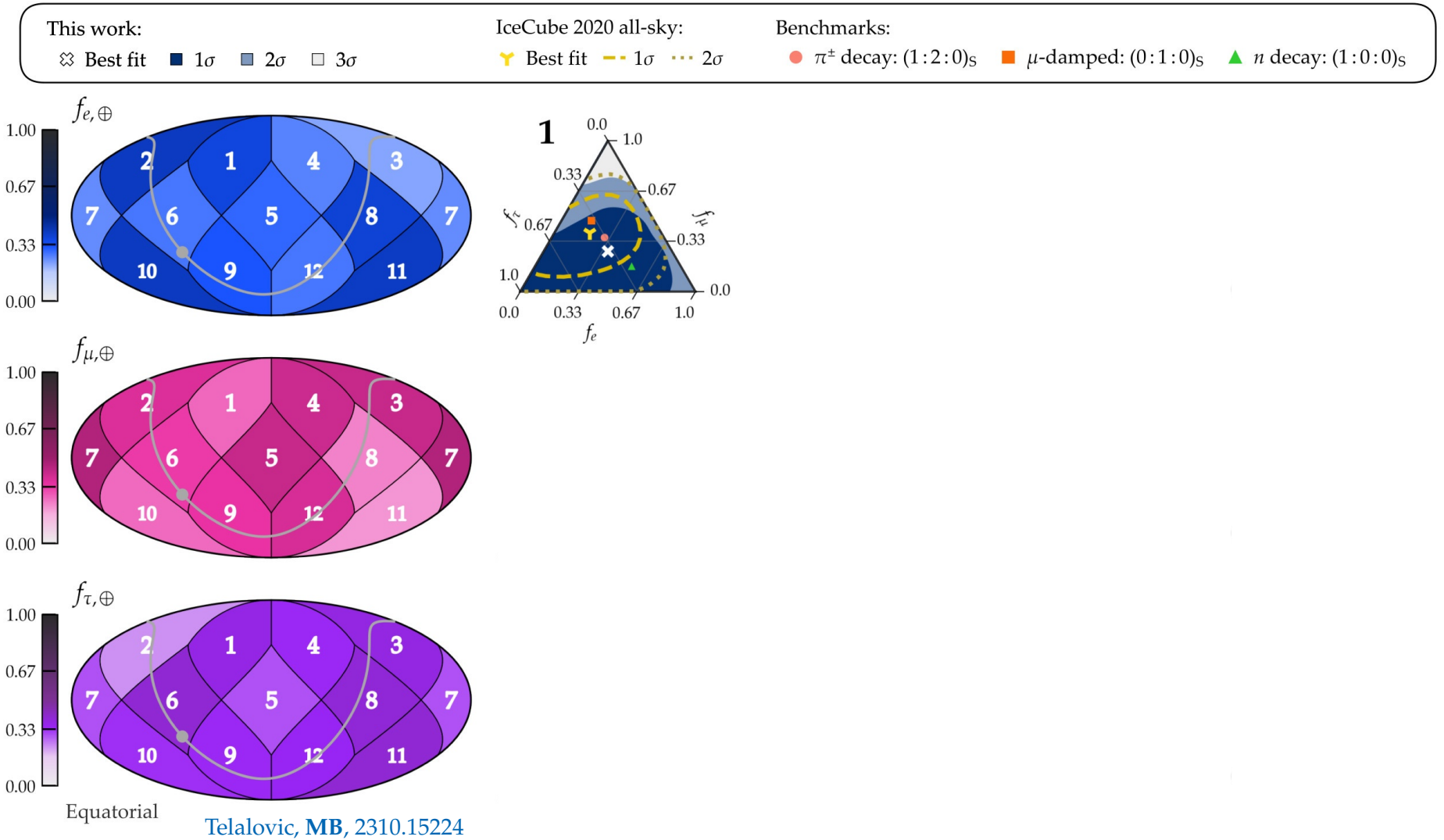


Directional high-energy astrophysical neutrino flavor composition: IceCube HESE (7.5 yr)



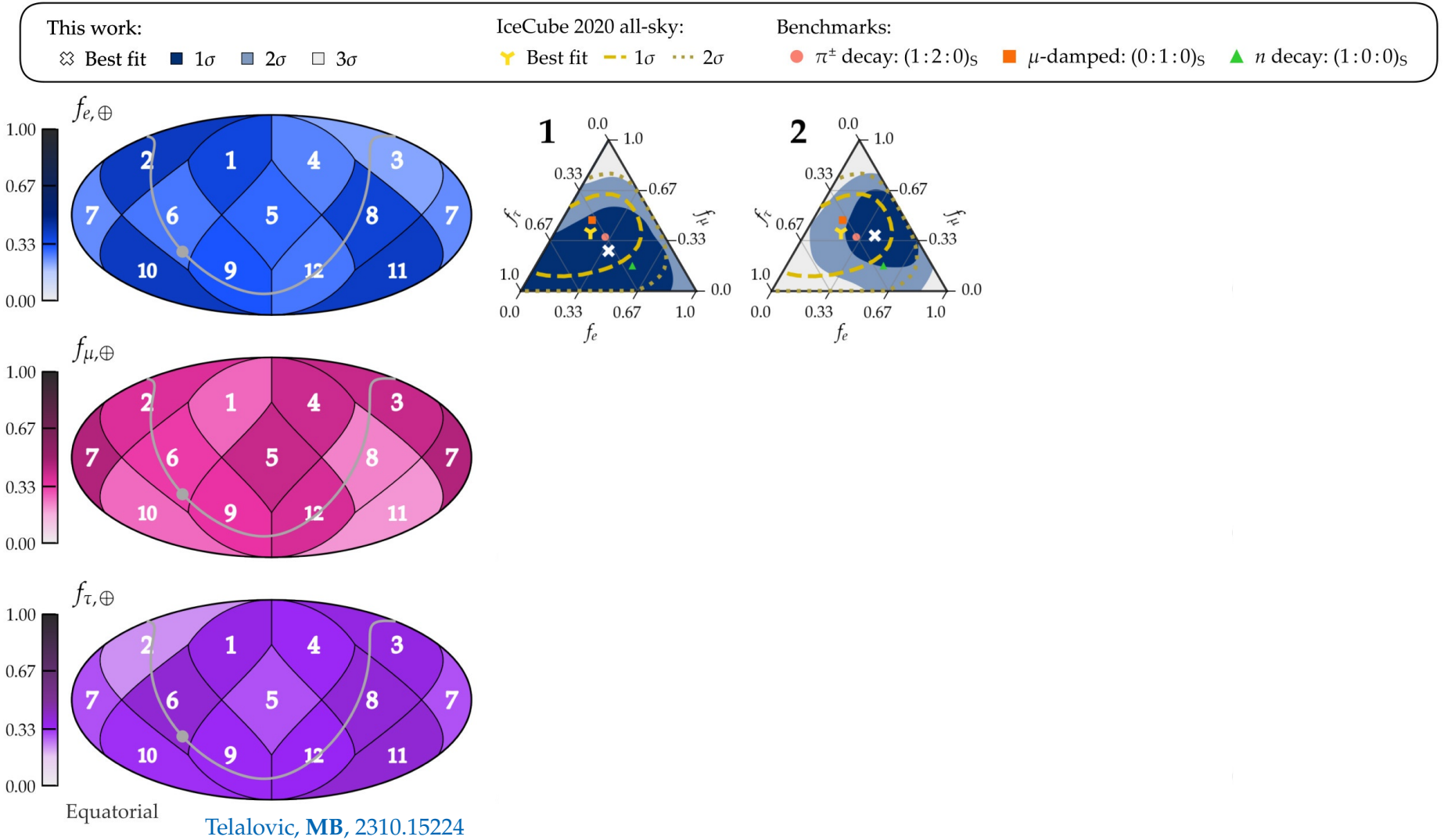
Telalovic, **MB**, 2310.15224

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



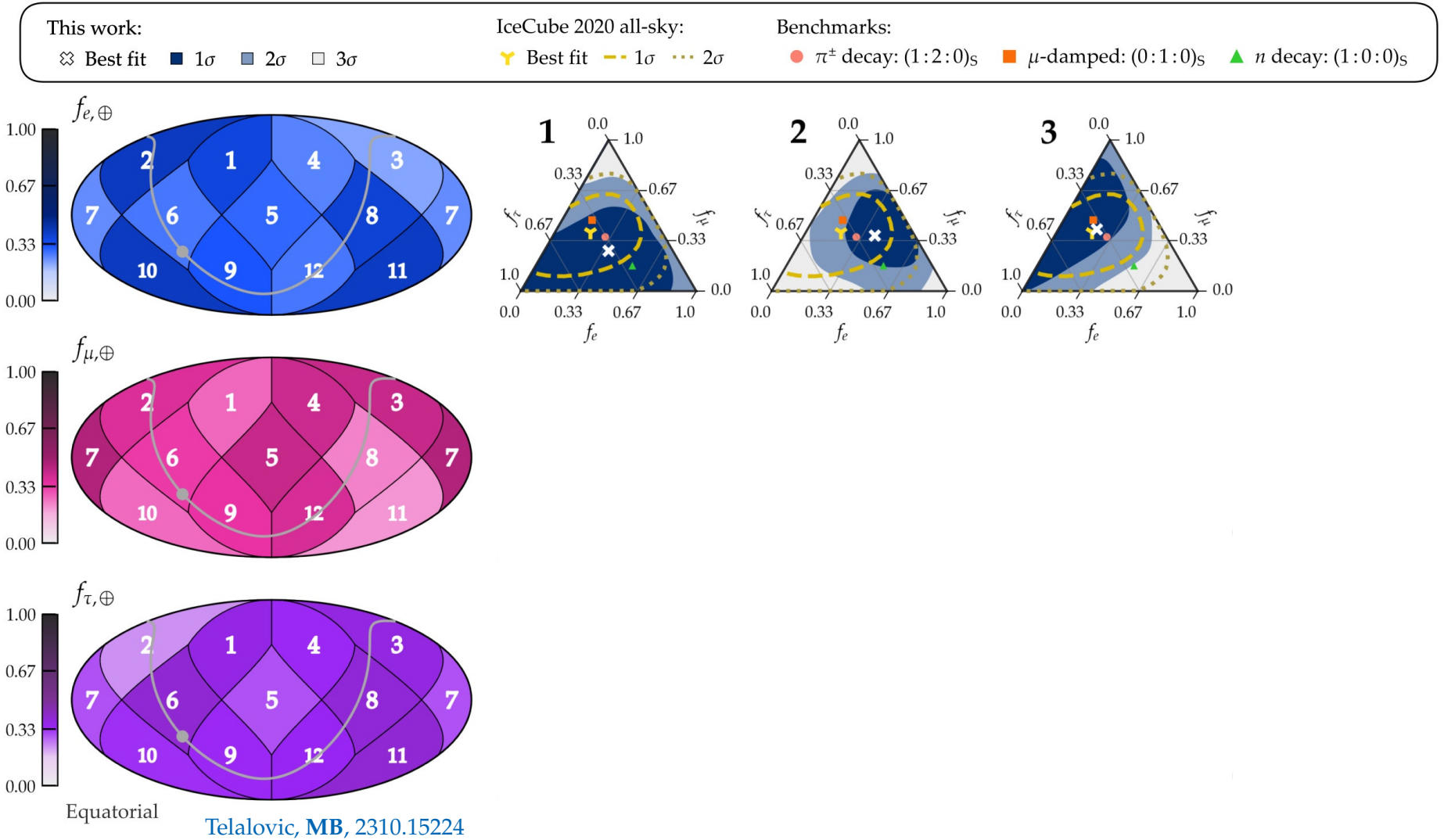
Telalovic, **MB**, 2310.15224

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



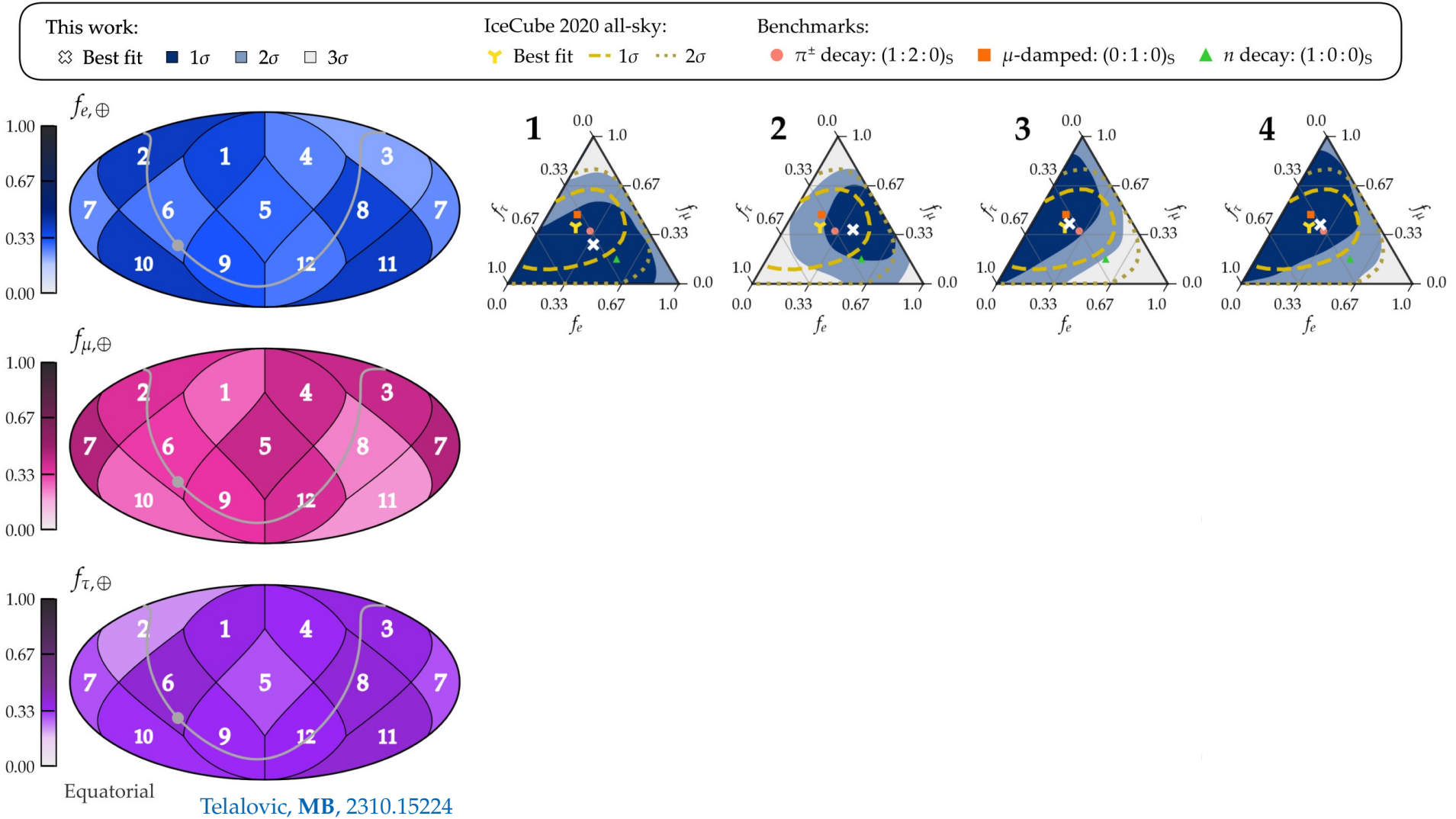
Telalovic, **MB**, 2310.15224

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



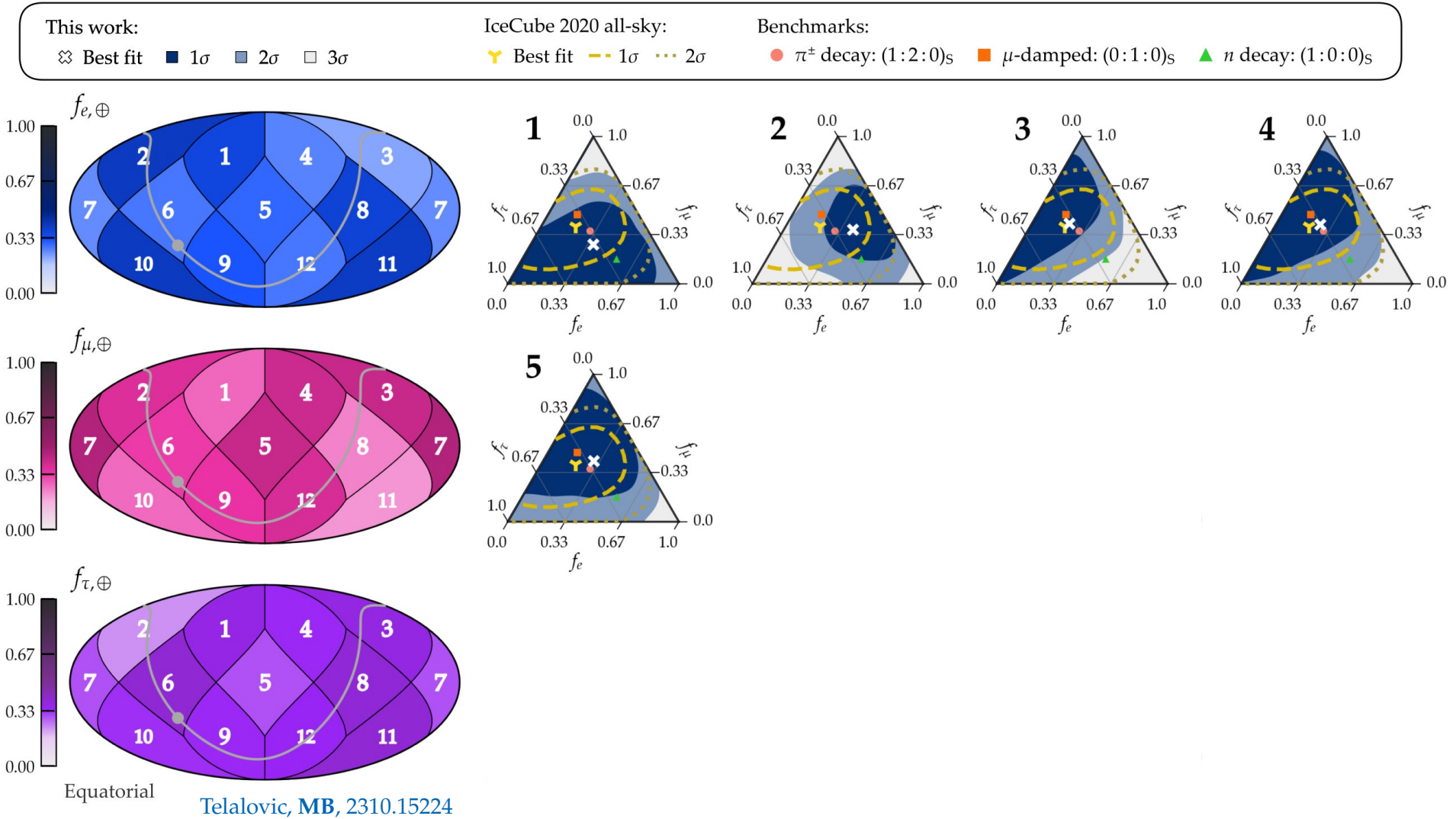
Telalovic, **MB**, 2310.15224

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



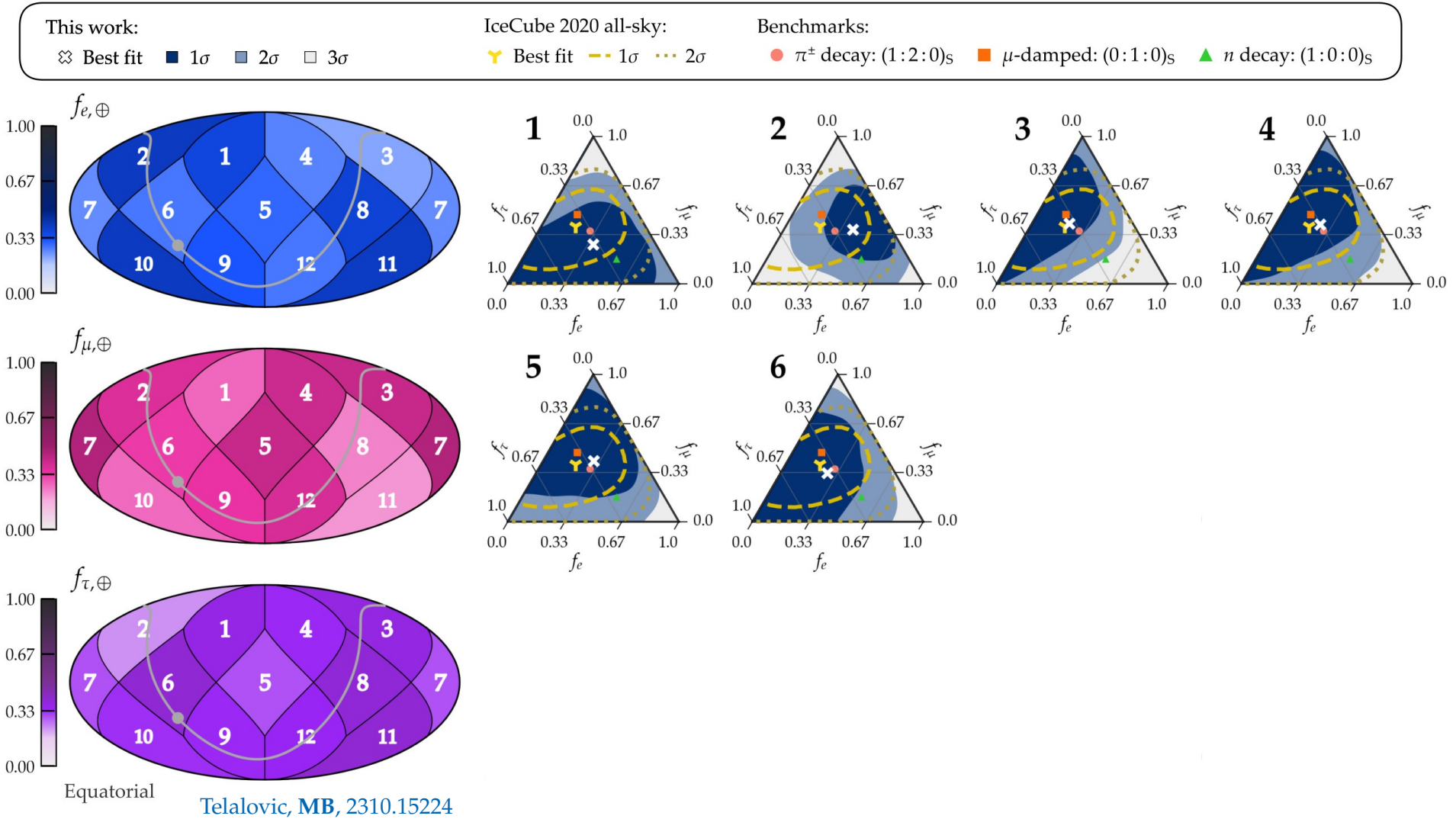
Telalovic, **MB**, 2310.15224

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



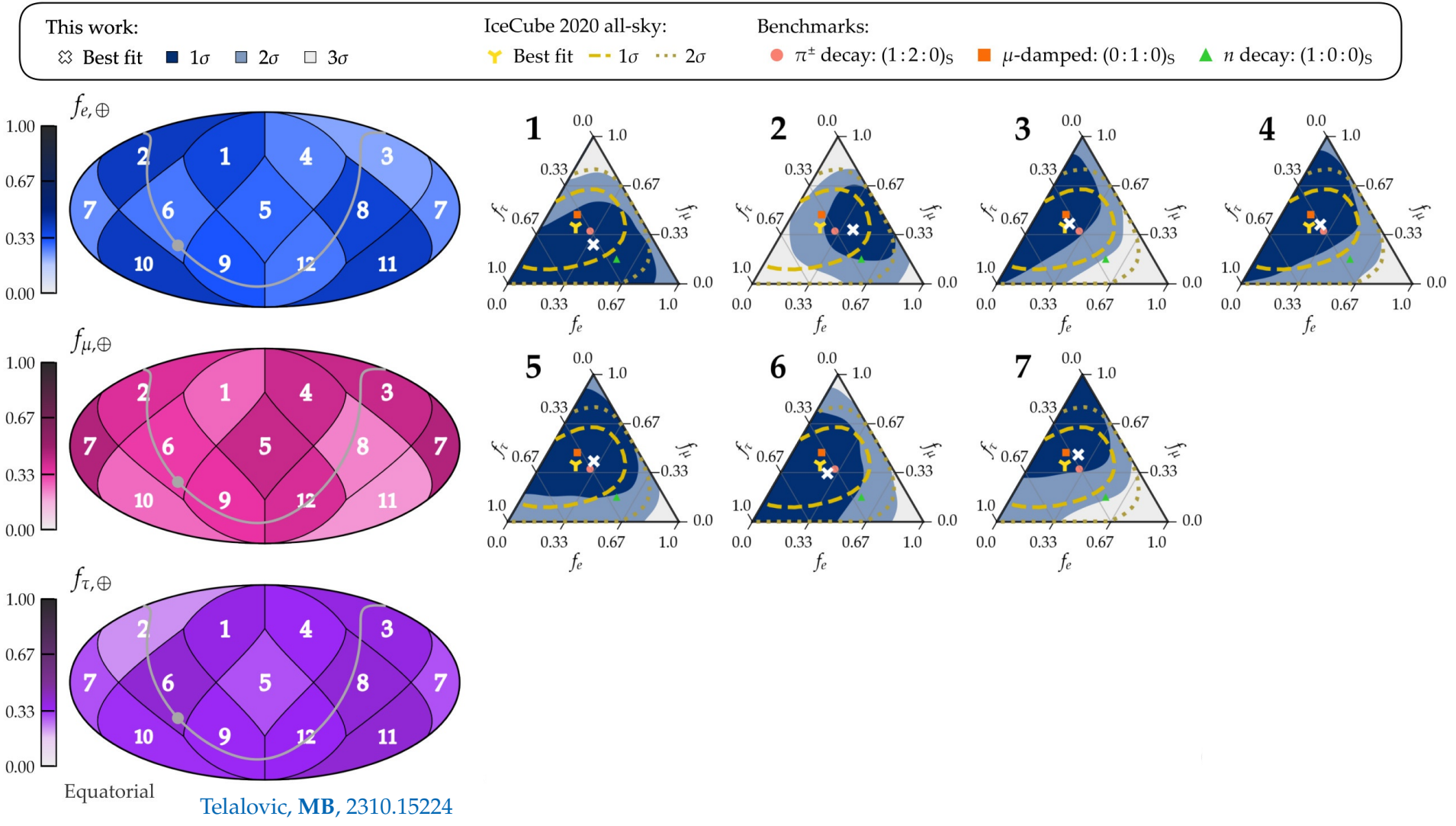
Telalovic, **MB**, 2310.15224

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



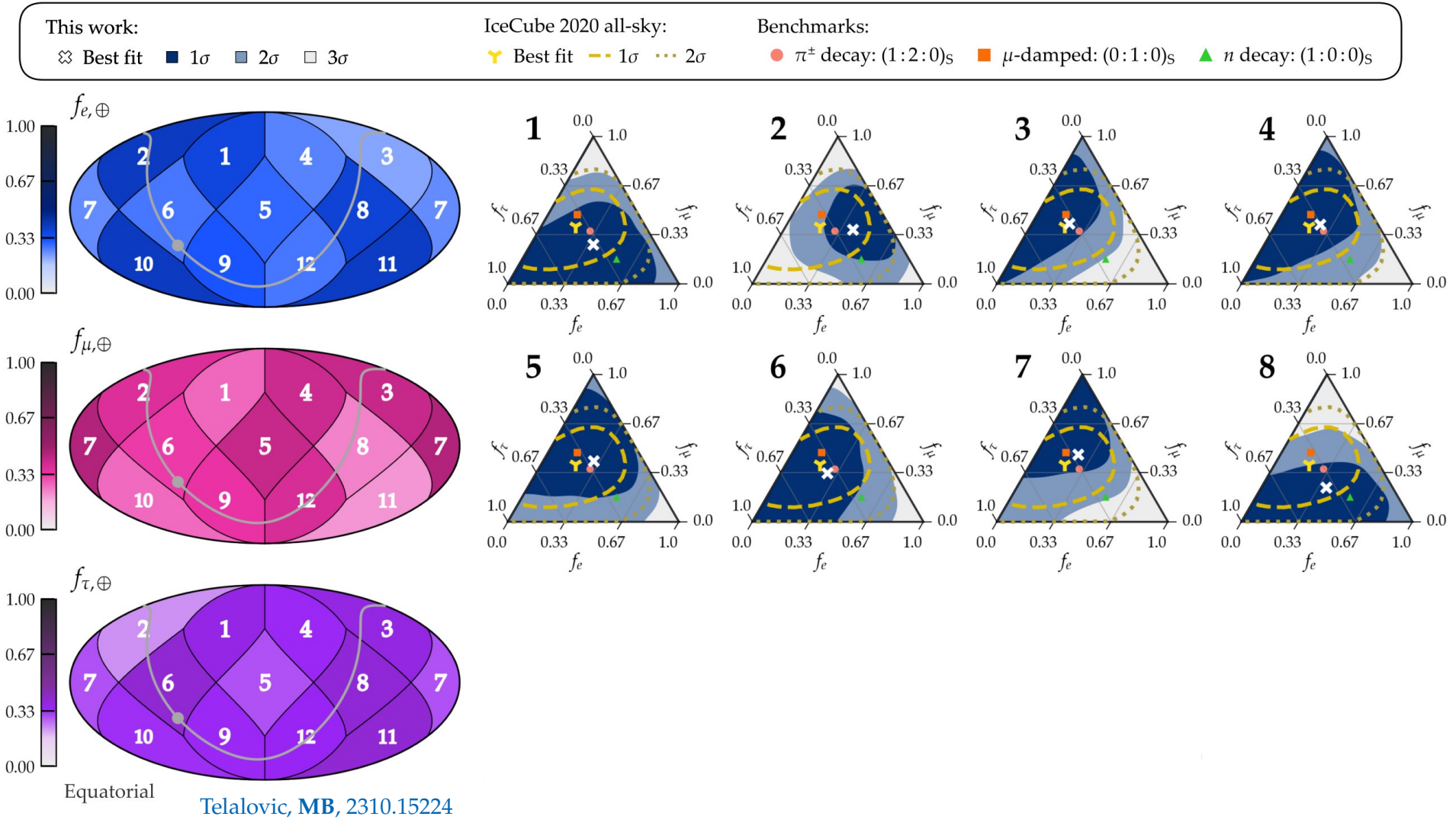
Telalovic, **MB**, 2310.15224

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



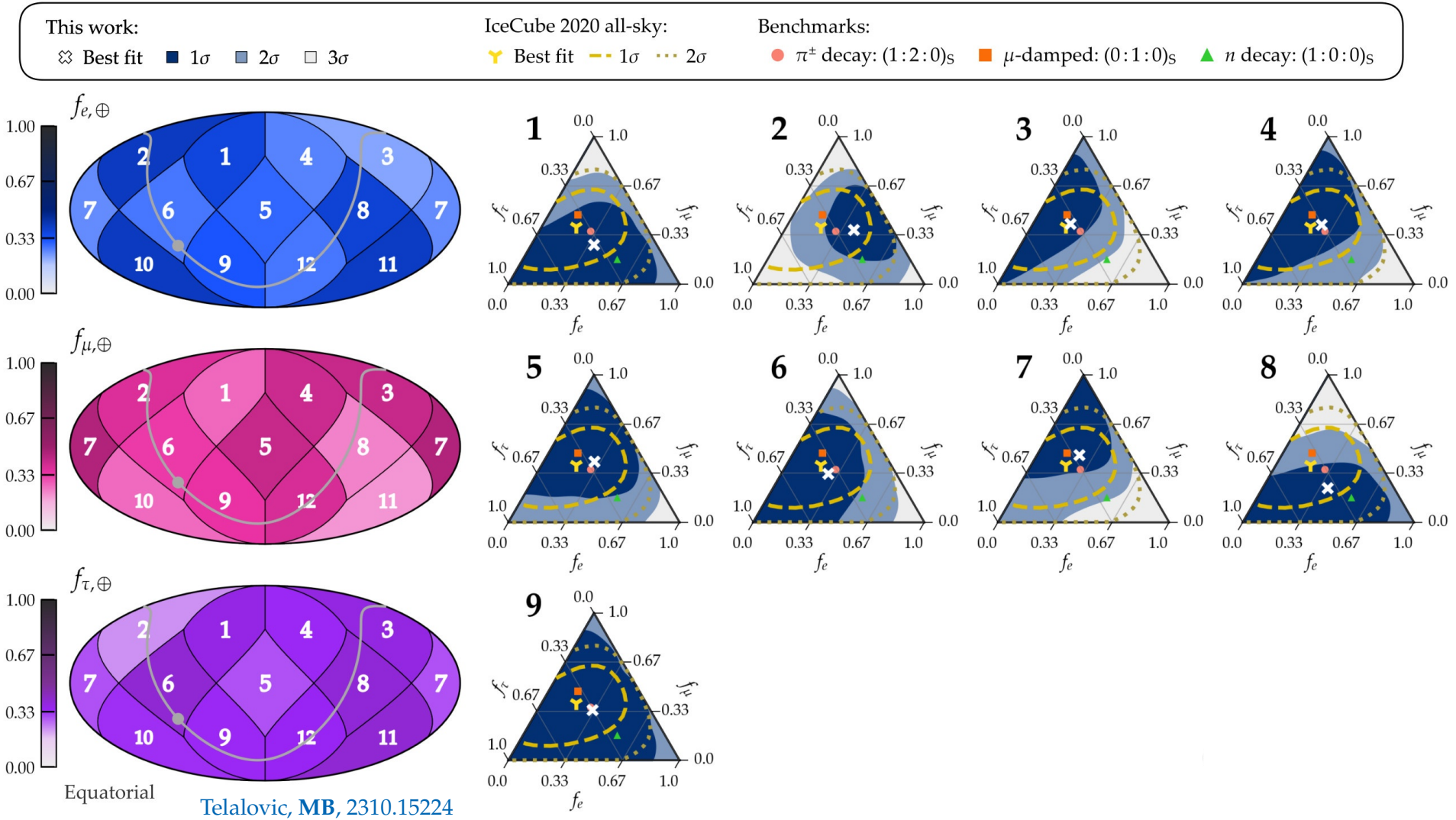
Telalovic, **MB**, 2310.15224

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



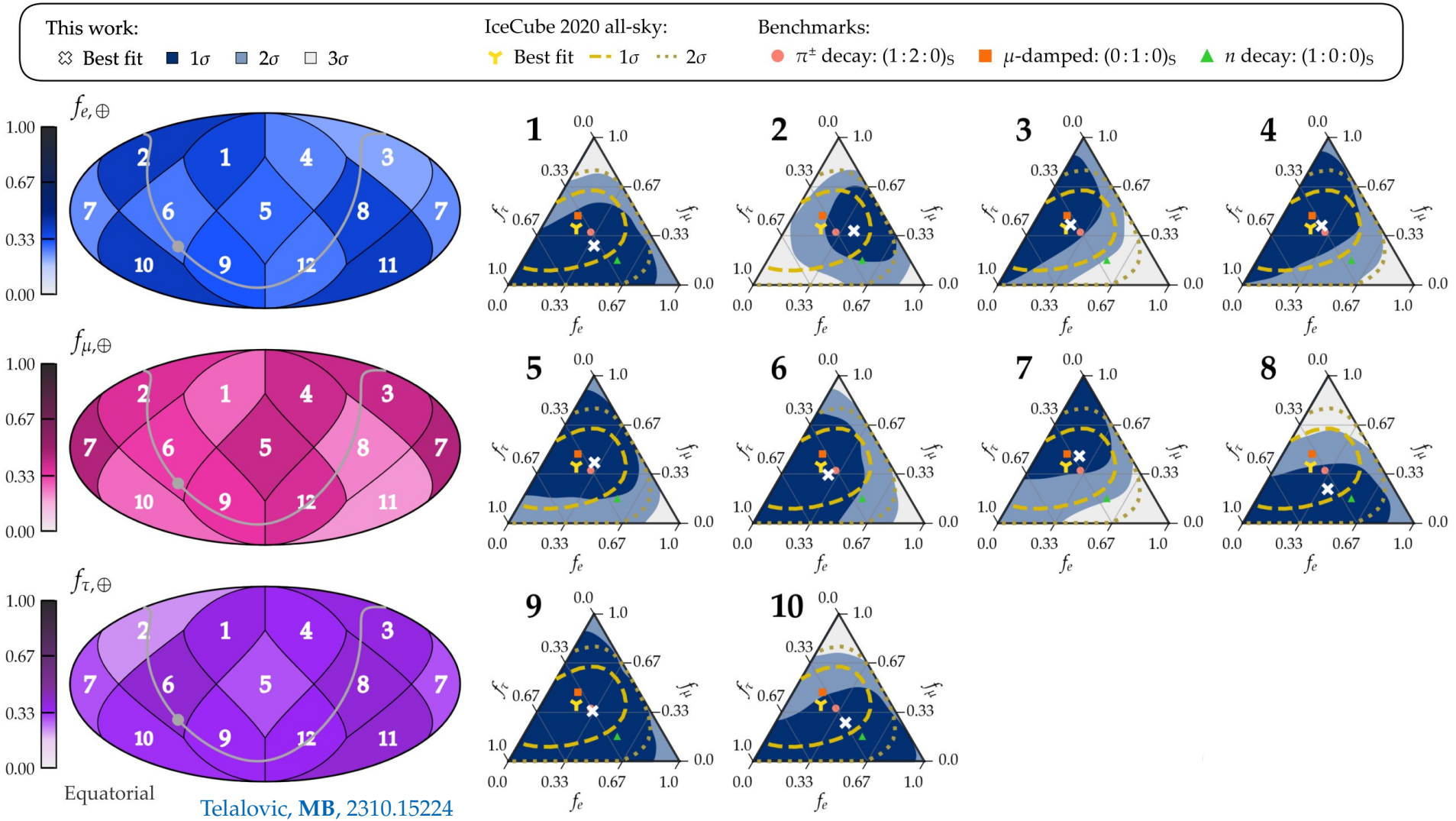
Telalovic, **MB**, 2310.15224

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



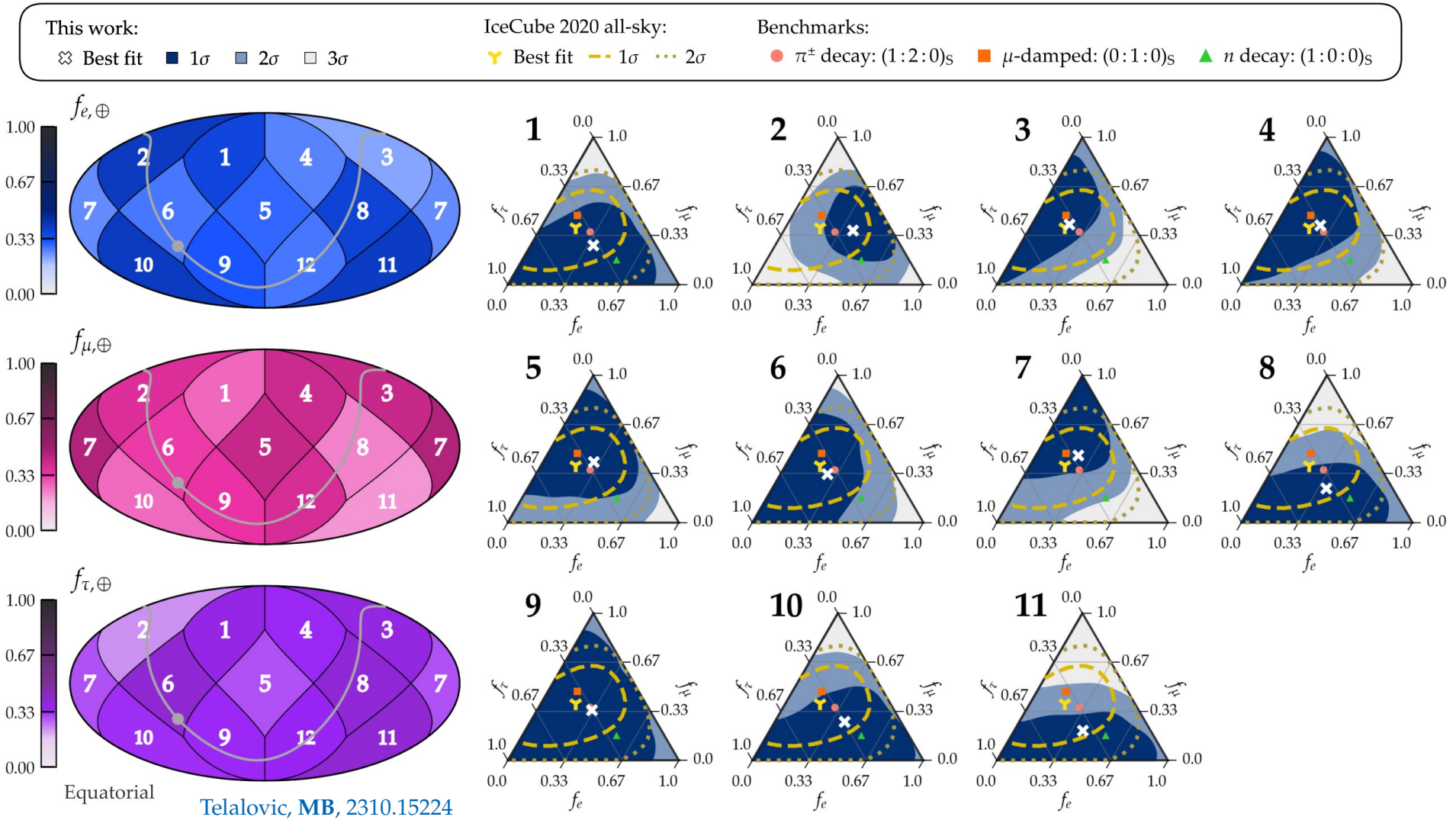
Telalovic, **MB**, 2310.15224

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



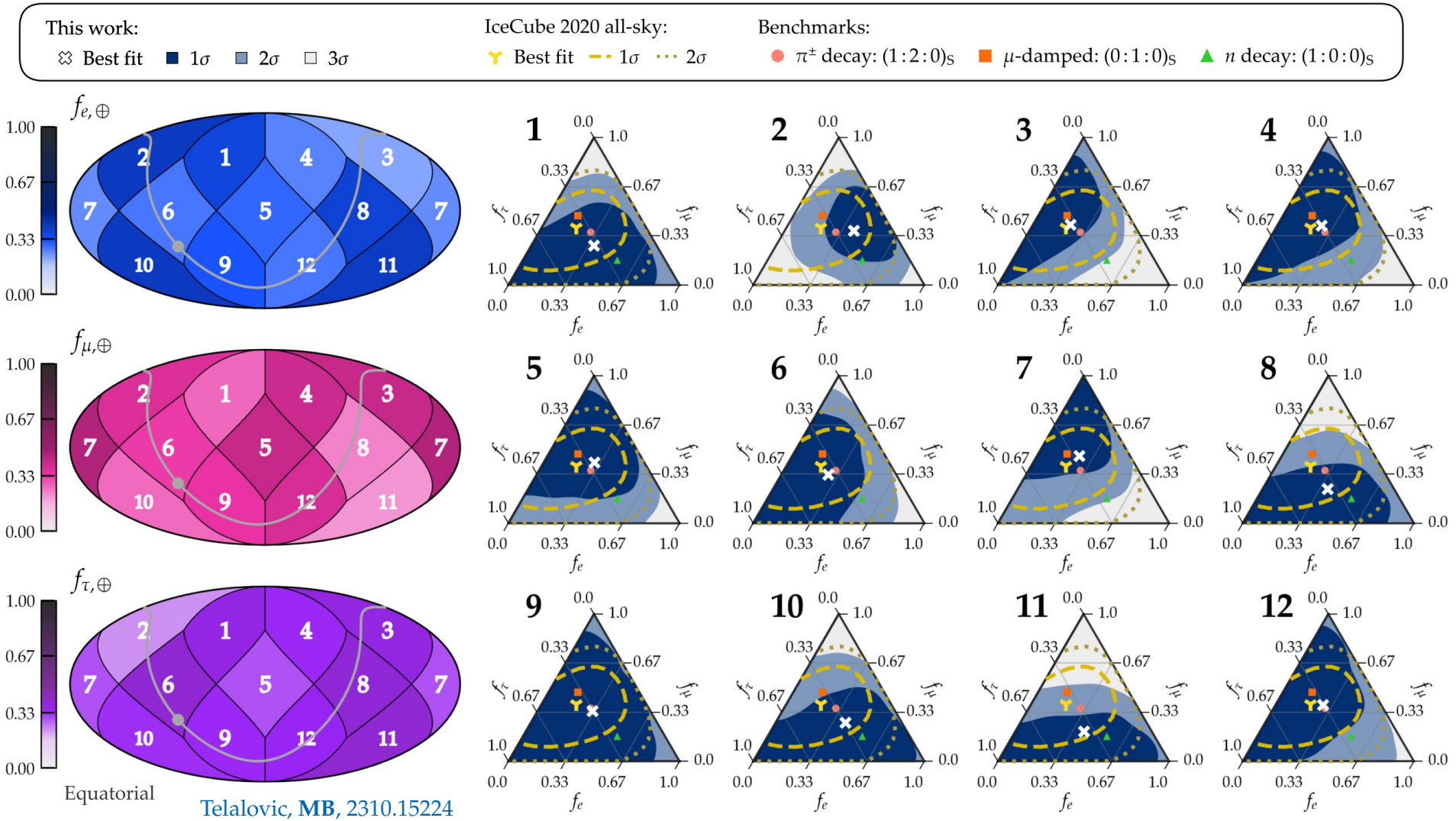
Telalovic, **MB**, 2310.15224

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



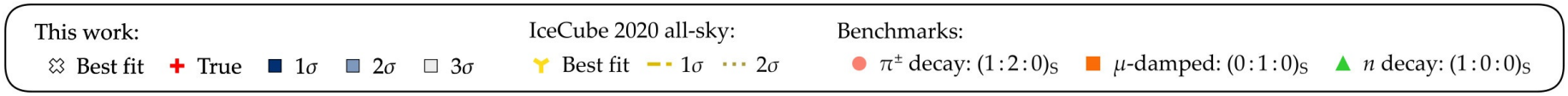
Telalovic, **MB**, 2310.15224

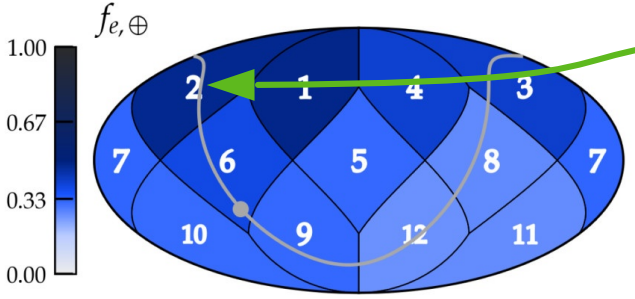
Directional high-energy astrophysical neutrino flavor composition: IceCube HESE (7.5 yr)

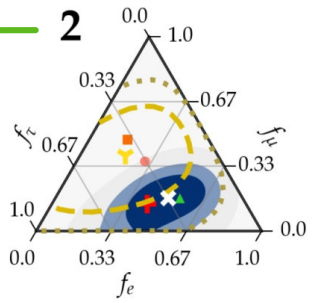


Telalovic, **MB**, 2310.15224

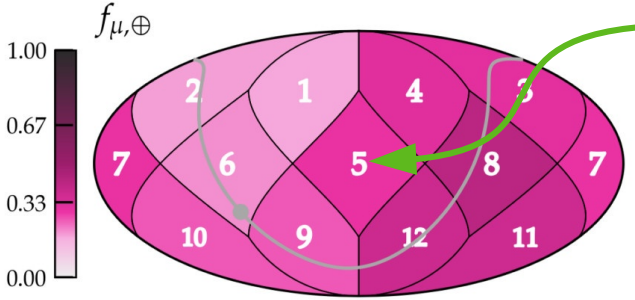
Directional high-energy astrophysical neutrino flavor composition: Anisotropic (2040, all detectors)

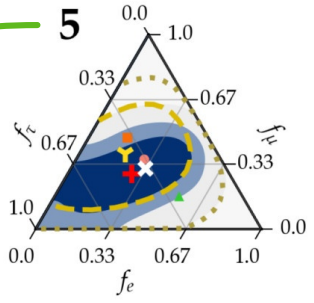




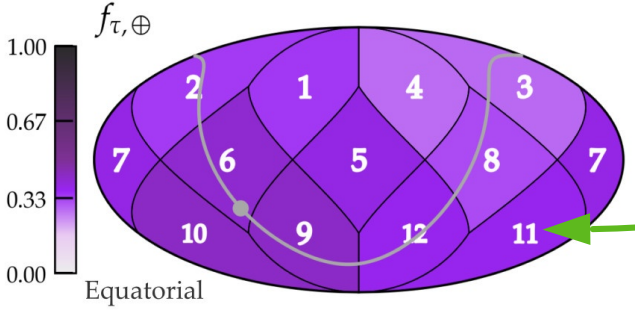


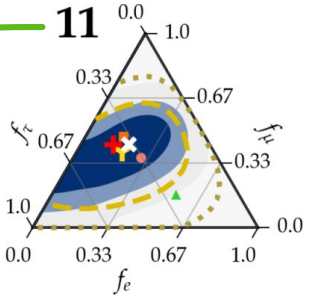
High ν_e content:
Production by neutron decay





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





High ν_μ content:
Muon-damped

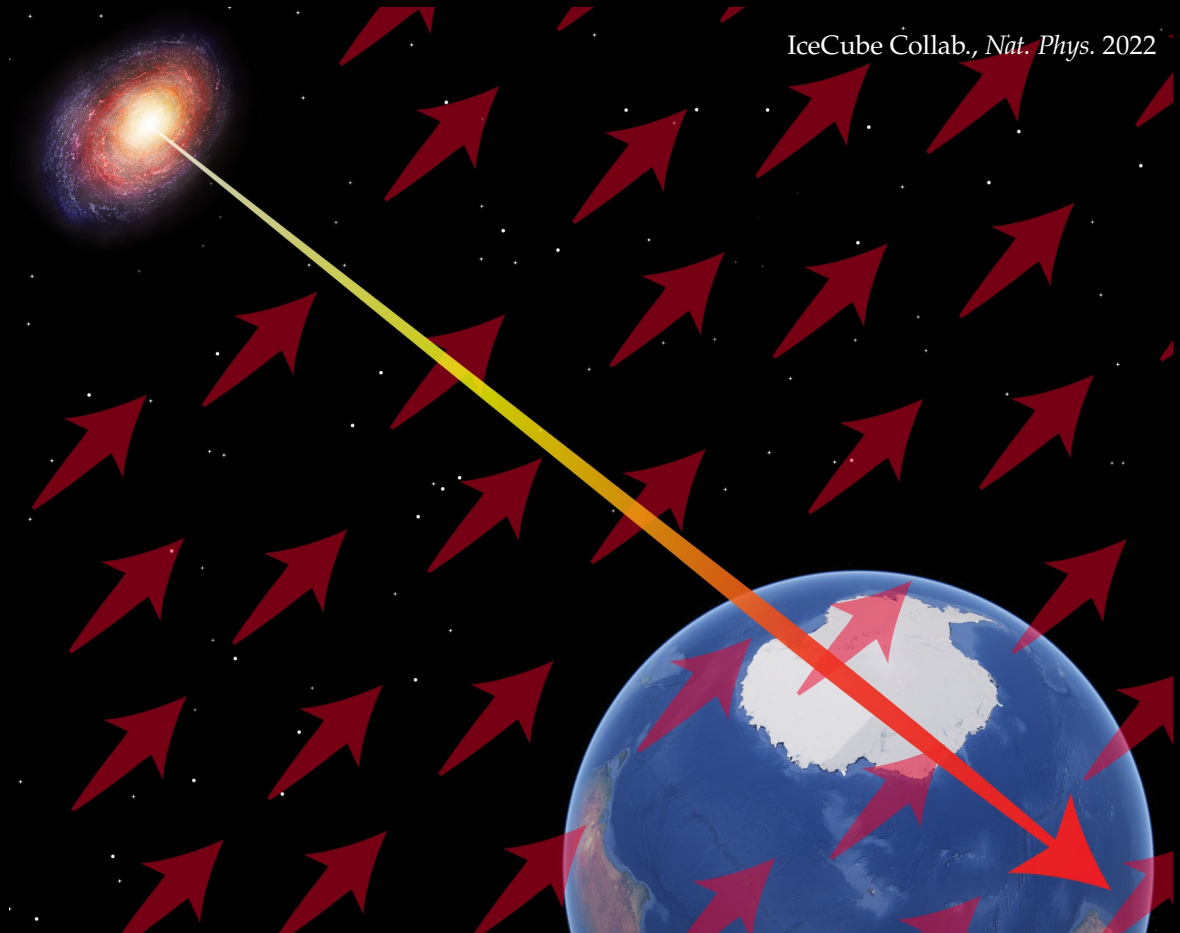
There is no sign of flavor anisotropy in present-day IceCube data (Bayes factor is ~1)

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

Work led by Bernanda Telalovic

Why is this interesting for neutrino physics?

Because new physics can introduce preferred directions for different flavors



Why is this interesting for neutrino physics?

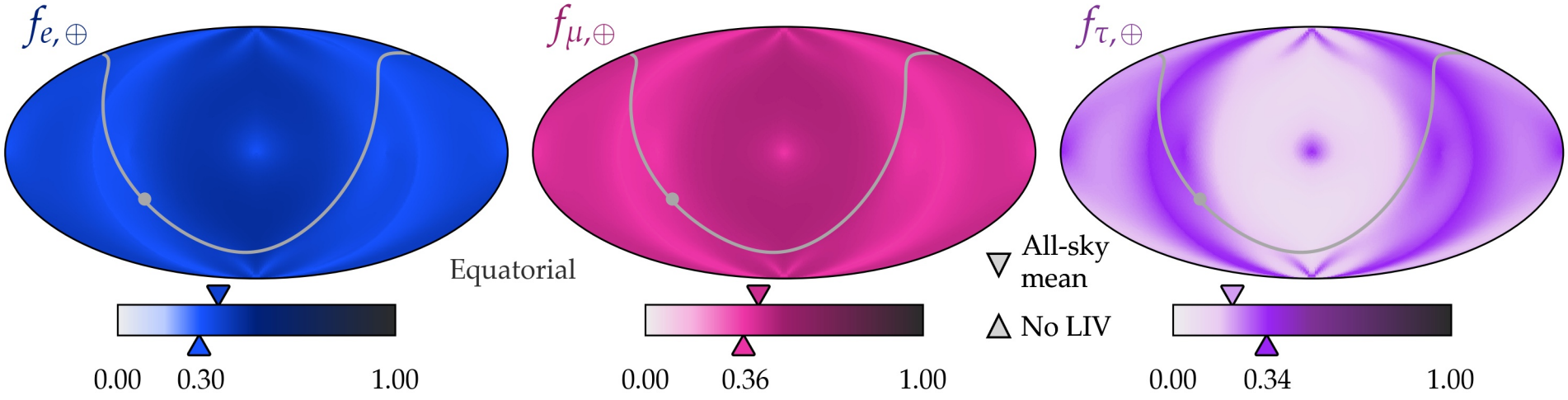
Because new physics can introduce preferred directions for different flavors

Telalovic, **MB**, 2310.15224

Why is this interesting for neutrino physics?

Because new physics can introduce preferred directions for different flavors

E.g., compass asymmetries from Lorentz-invariance violation

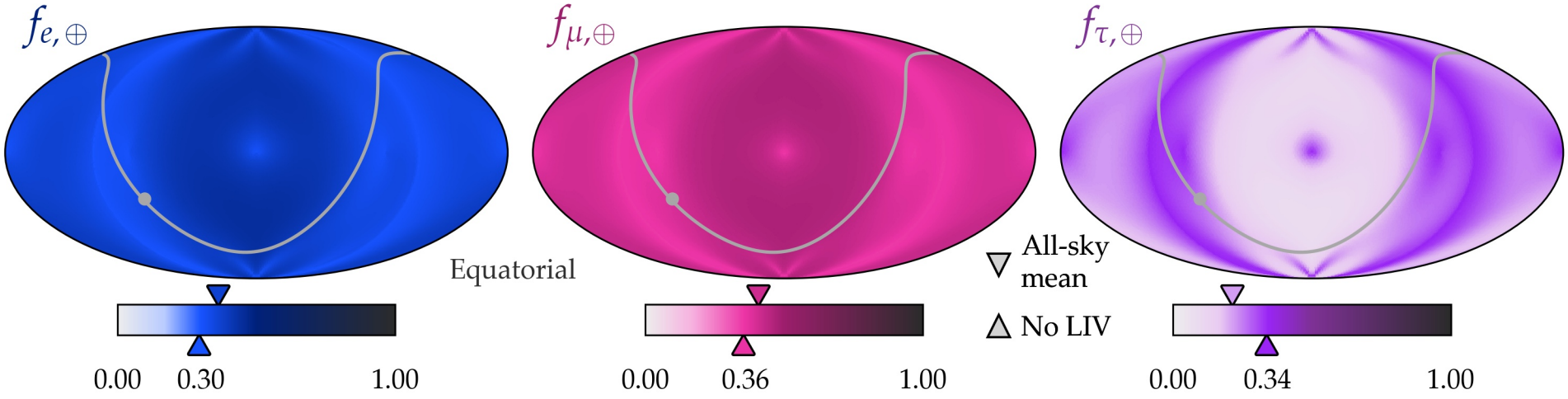


Telalovic, **MB**, 2310.15224

Why is this interesting for neutrino physics?

Because new physics can introduce preferred directions for different flavors

E.g., compass asymmetries from Lorentz-invariance violation



For dimension-5 CPT-odd LIV coefficient

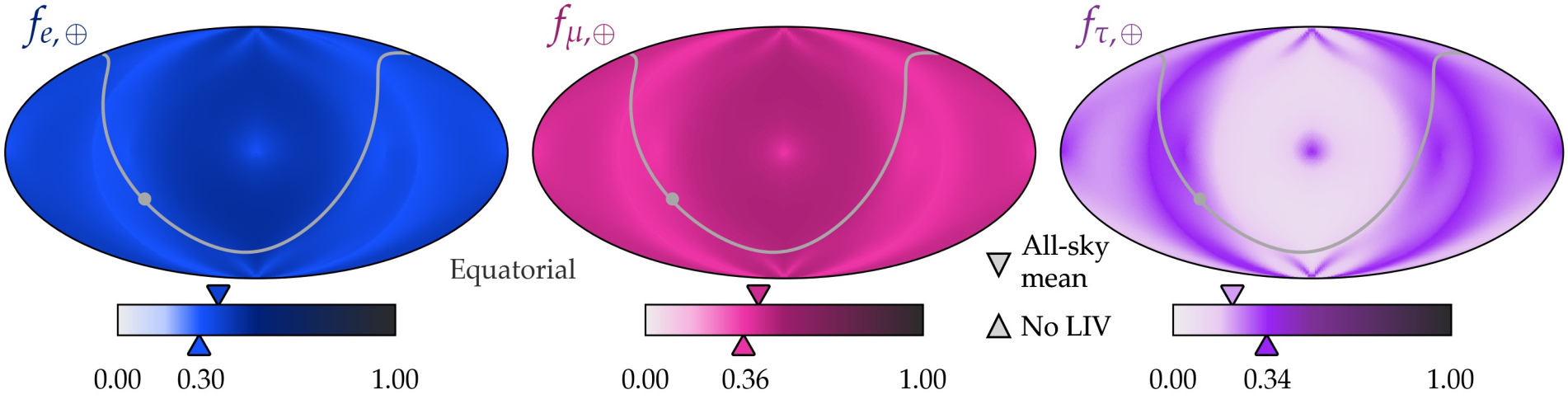
Upper limits from accelerator ν (MINOS): $< 10^{-20}$–10^{-15} GeV^{-1}

Telalovic, **MB**, 2310.15224

Why is this interesting for neutrino physics?

Because new physics can introduce preferred directions for different flavors

E.g., compass asymmetries from Lorentz-invariance violation



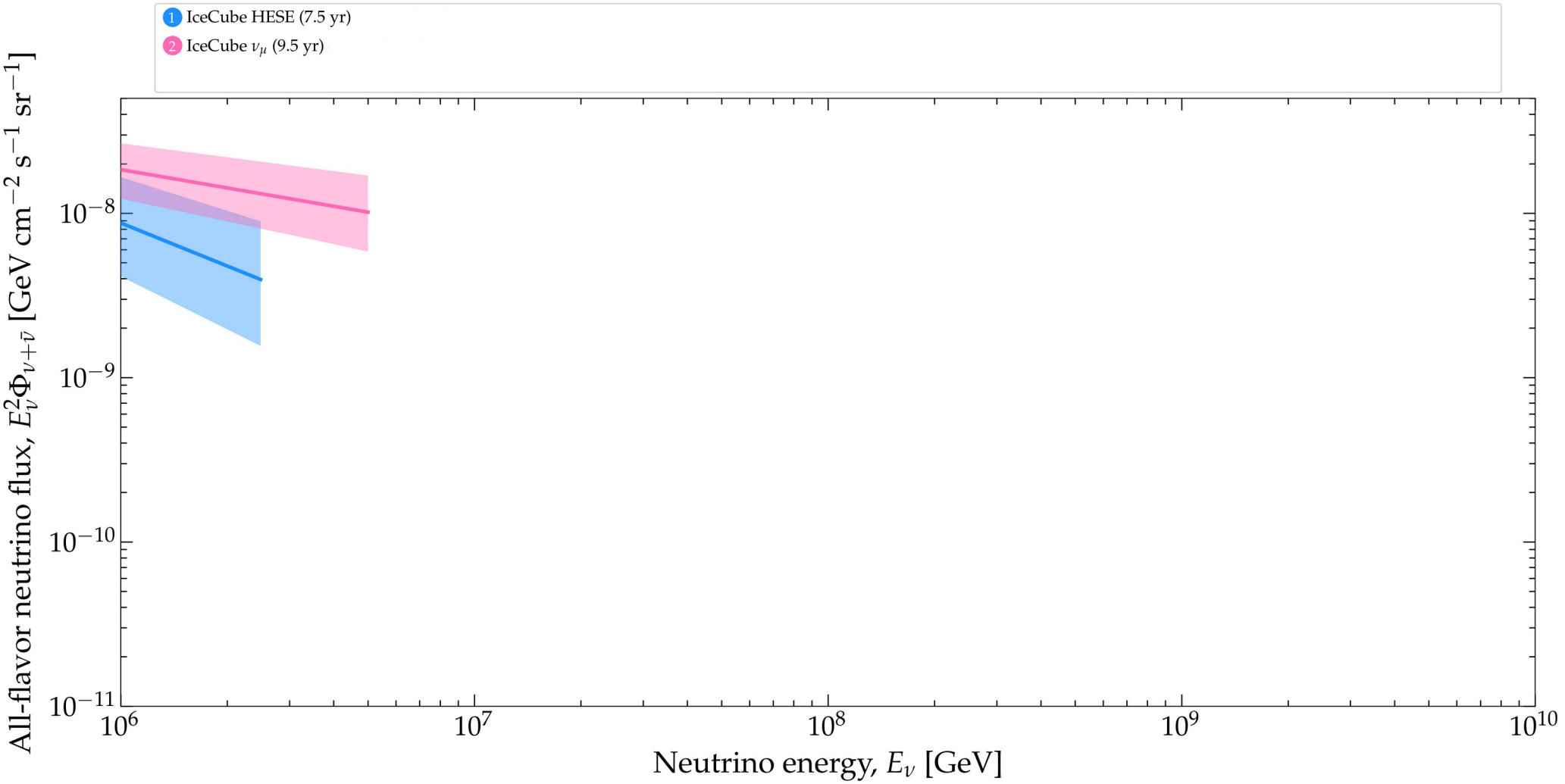
For dimension-5 CPT-odd LIV coefficient

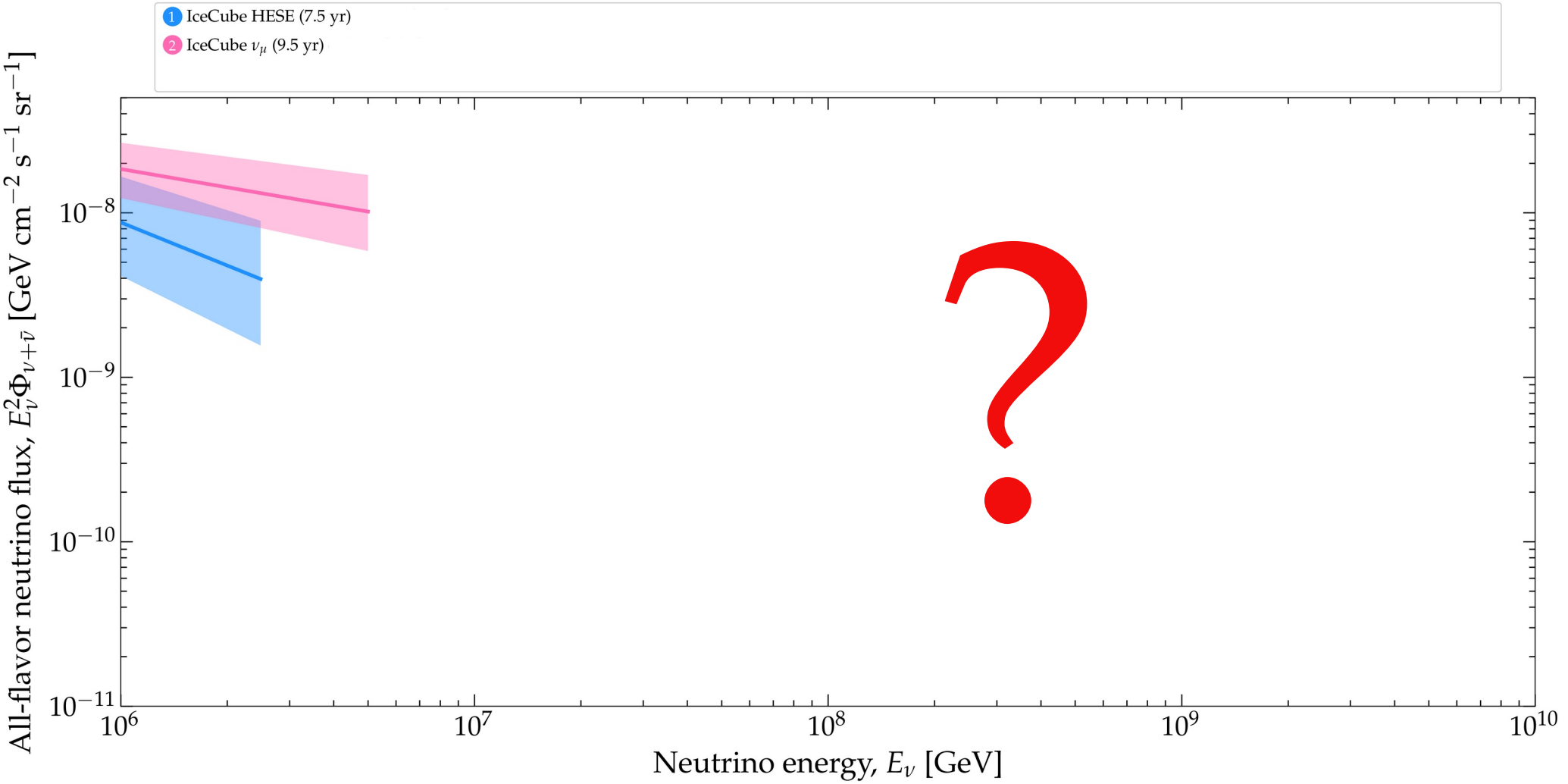
Upper limits from accelerator ν (MINOS): $< 10^{-20}$–10^{-15} GeV^{-1}

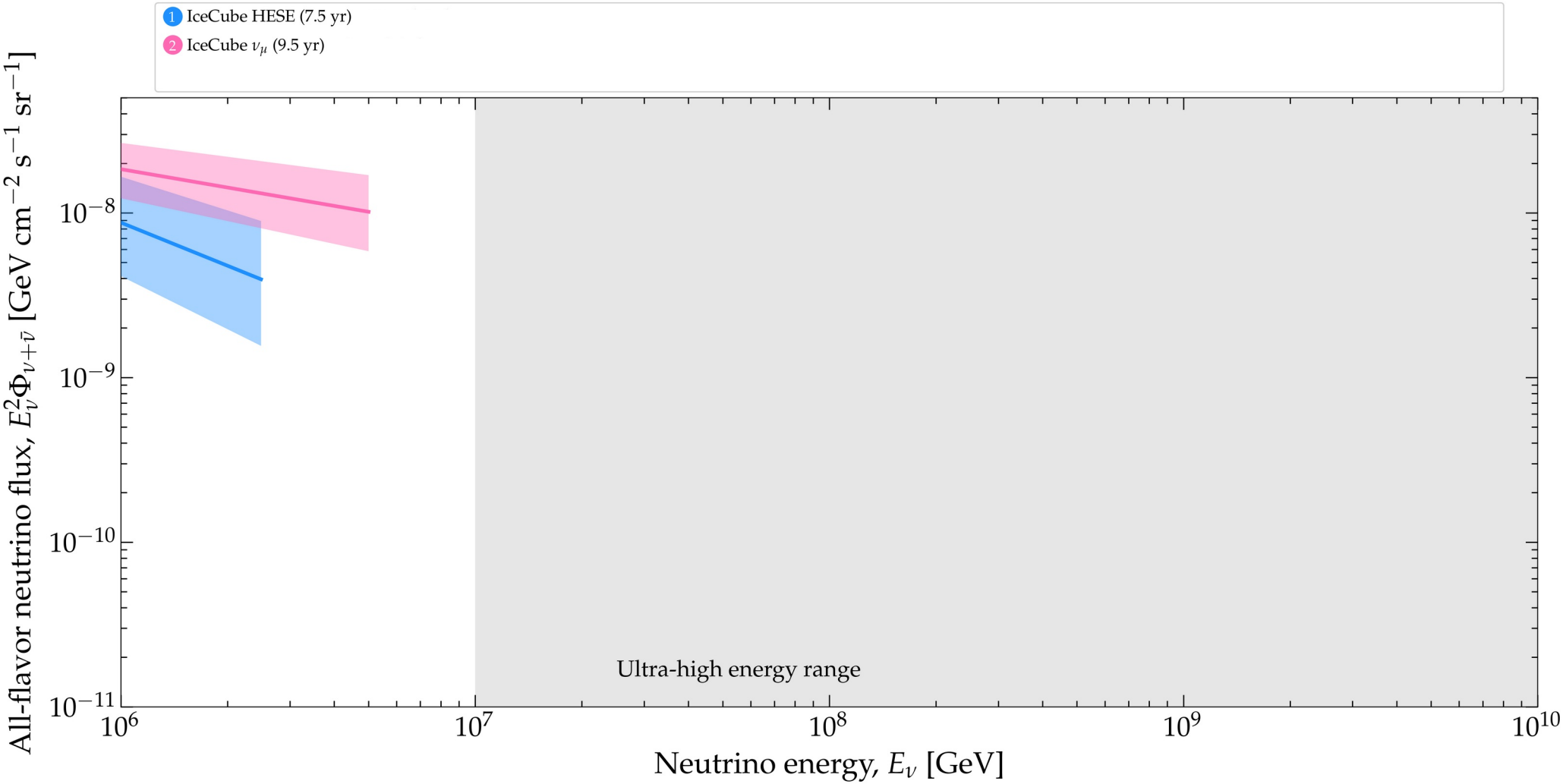
Upper limits from 7.5-year HESE: $< 10^{-34}$ GeV^{-1}

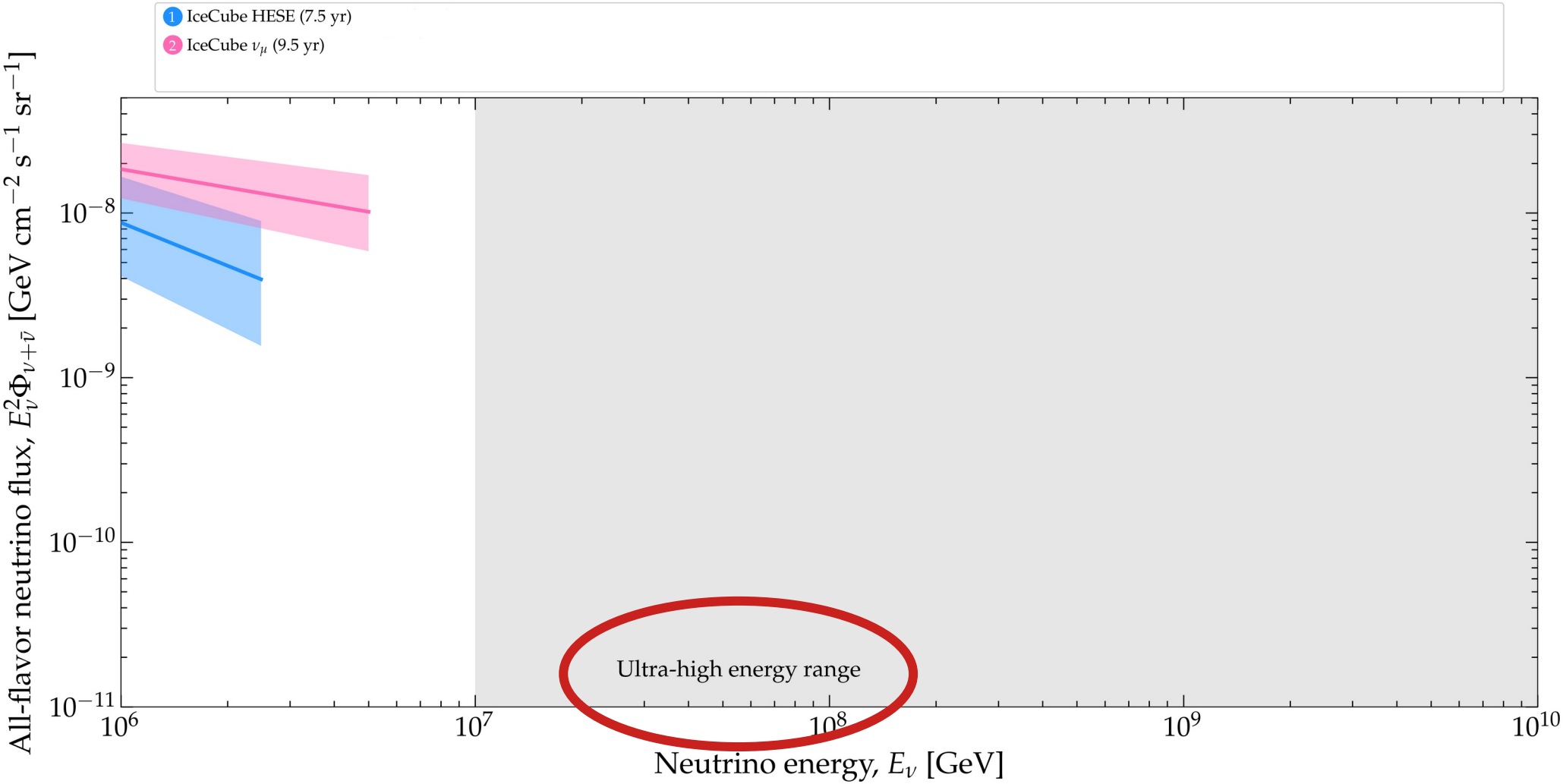
Telalovic, **MB**, 2310.15224

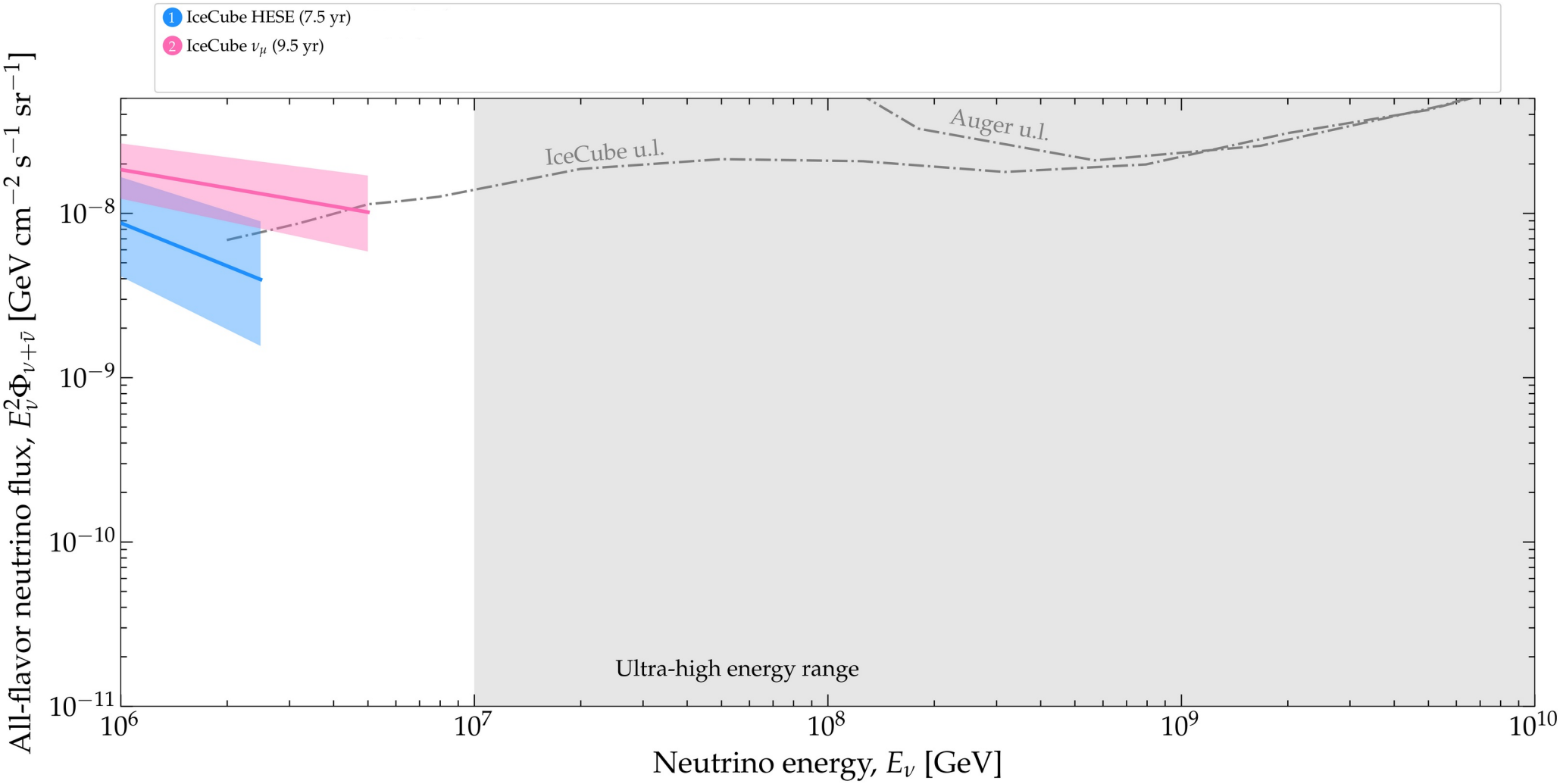
Towards ultra-high energies

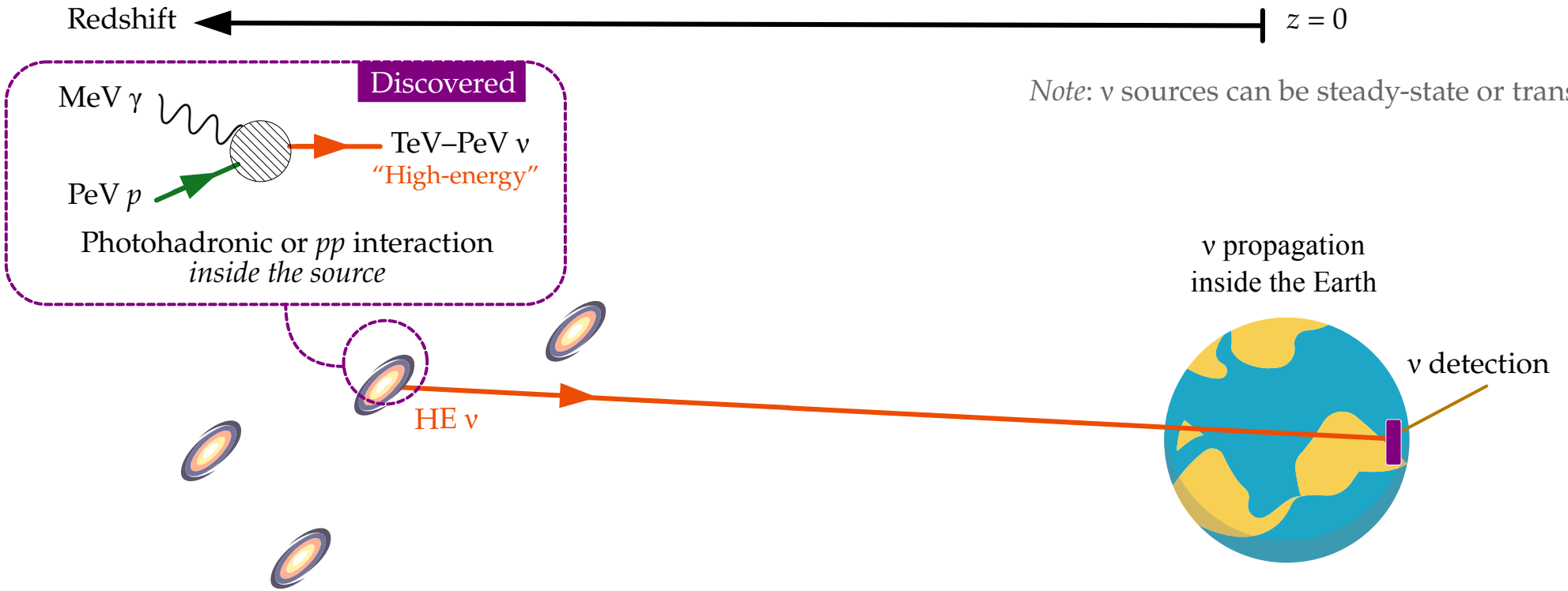

1 IceCube HESE (7.5 yr)
2 IceCube ν_μ (9.5 yr)
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]


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]
?

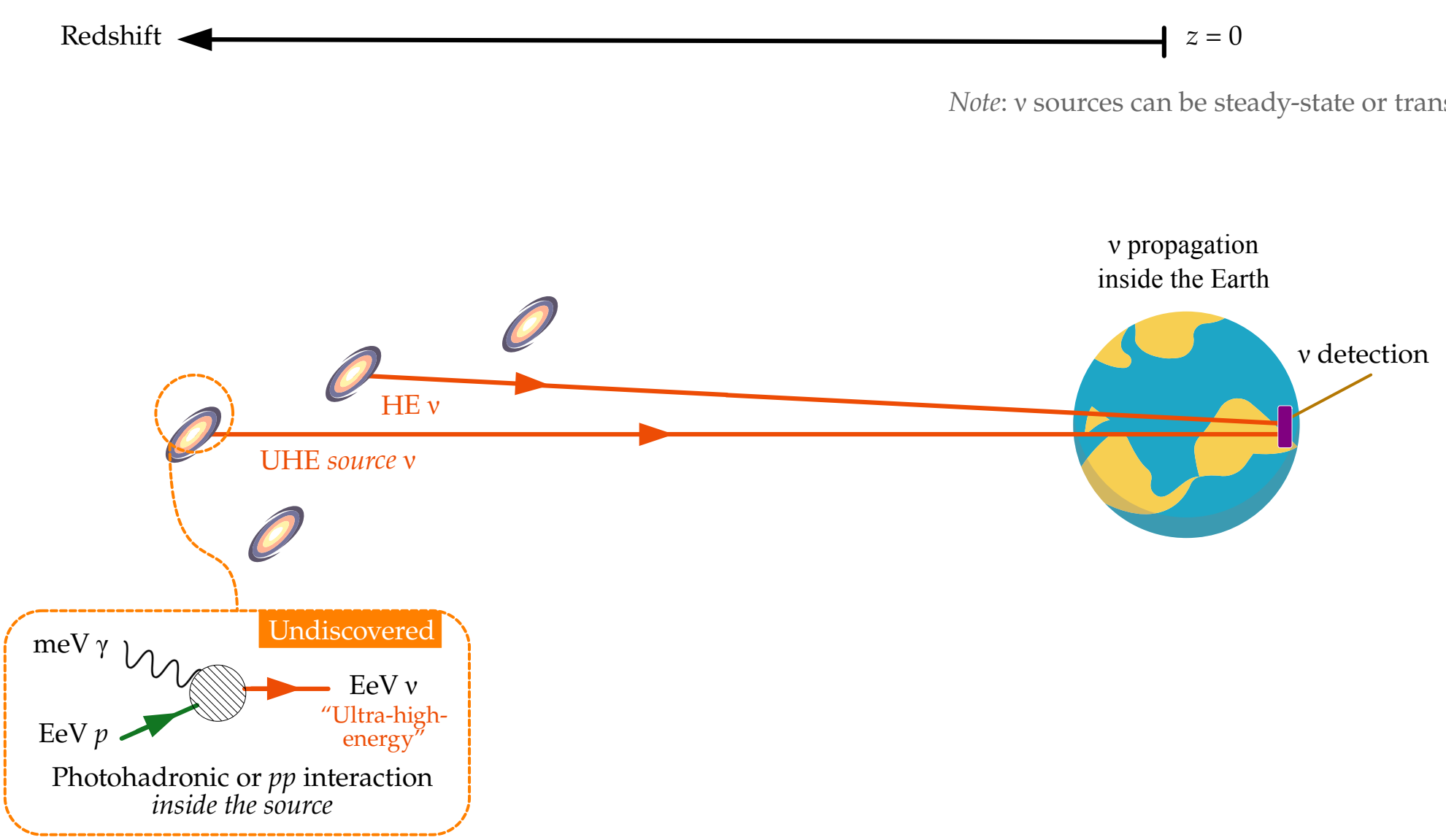

1 IceCube HESE (7.5 yr)
2 IceCube ν_μ (9.5 yr)
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
Ultra-high energy range
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]

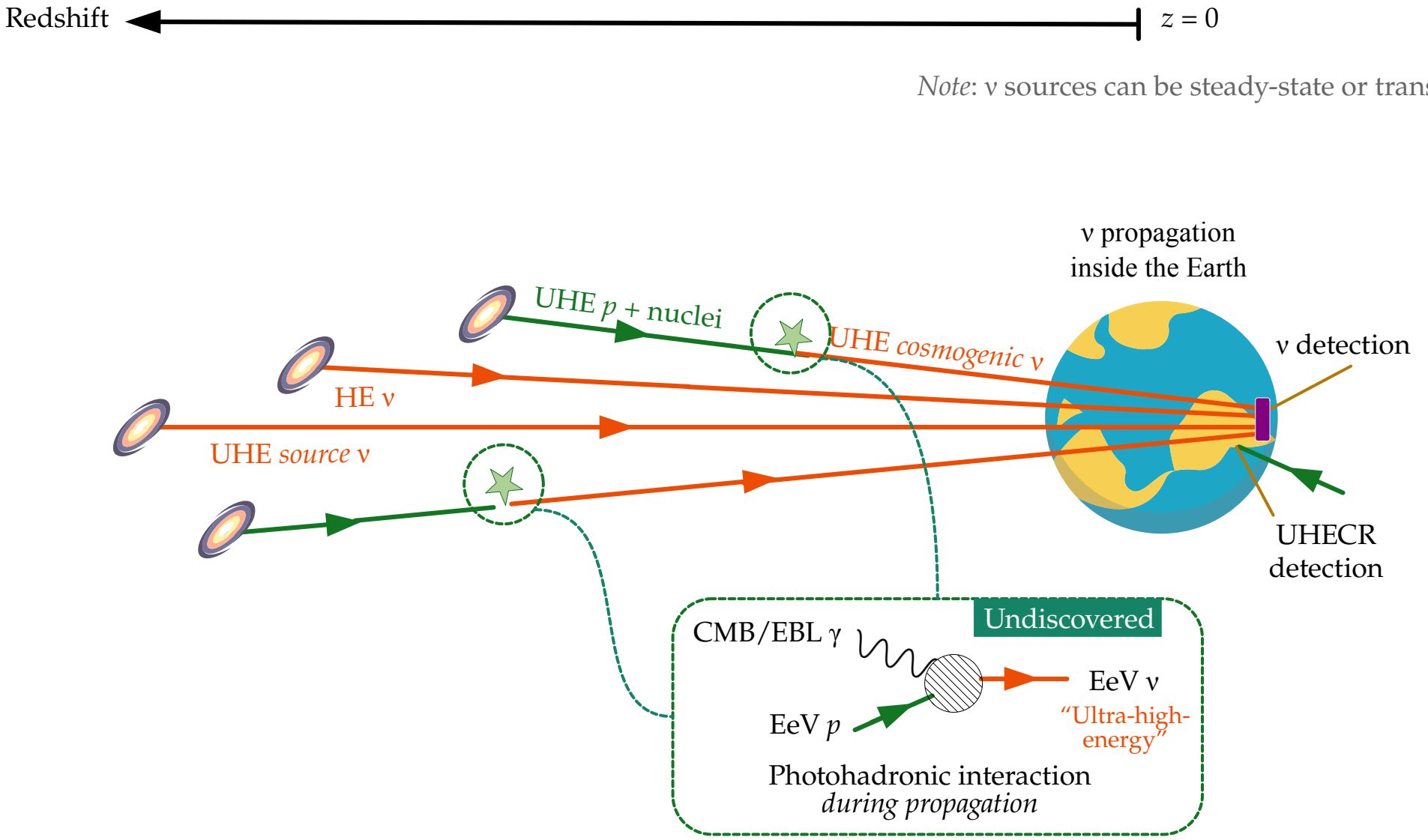

1 IceCube HESE (7.5 yr)
2 IceCube ν_μ (9.5 yr)
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
Ultra-high energy range
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]

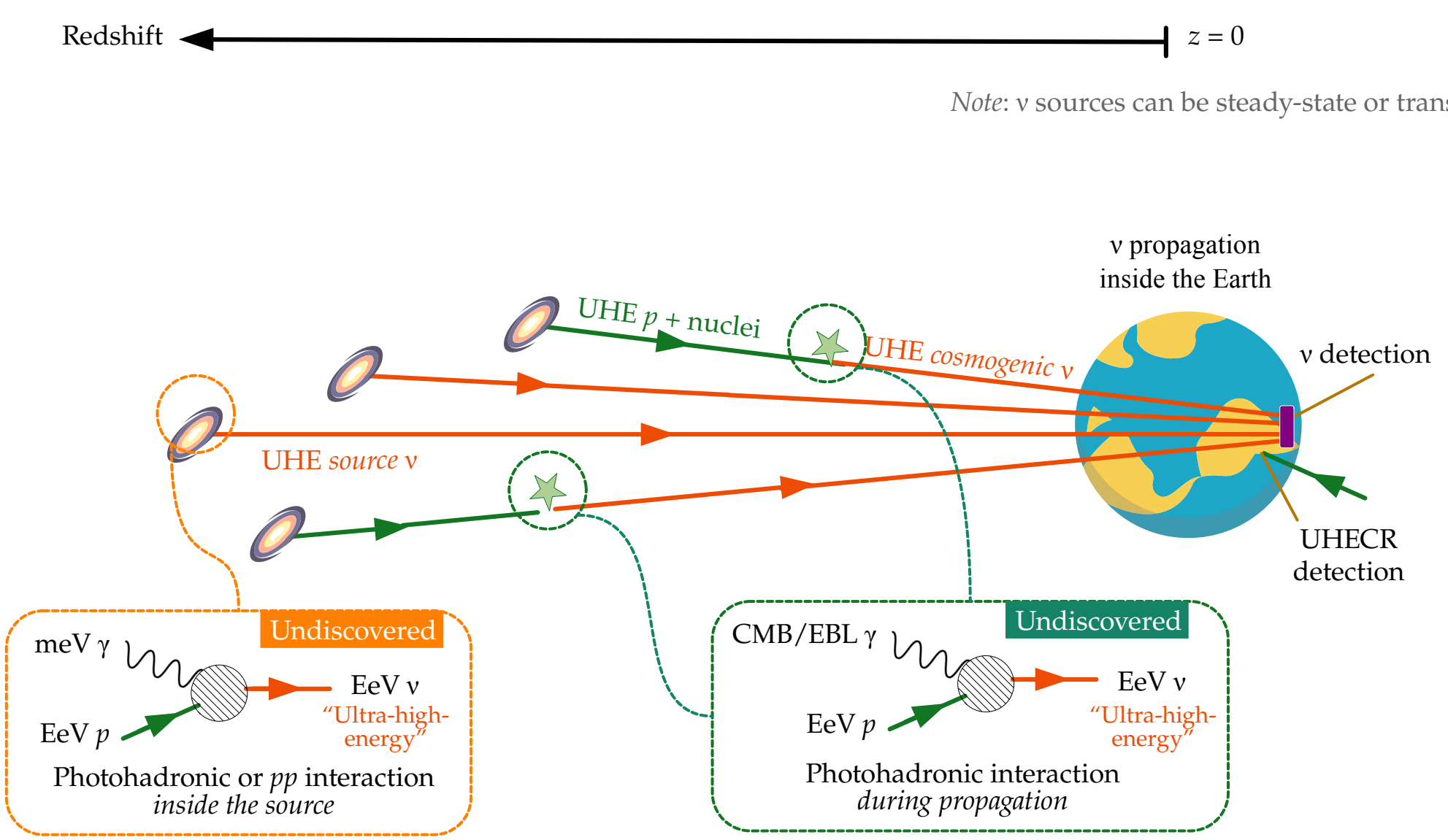

1 IceCube HESE (7.5 yr)
2 IceCube ν_μ (9.5 yr)
IceCube u.l.
Auger u.l.
Ultra-high energy range
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy, E_ν [GeV]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}

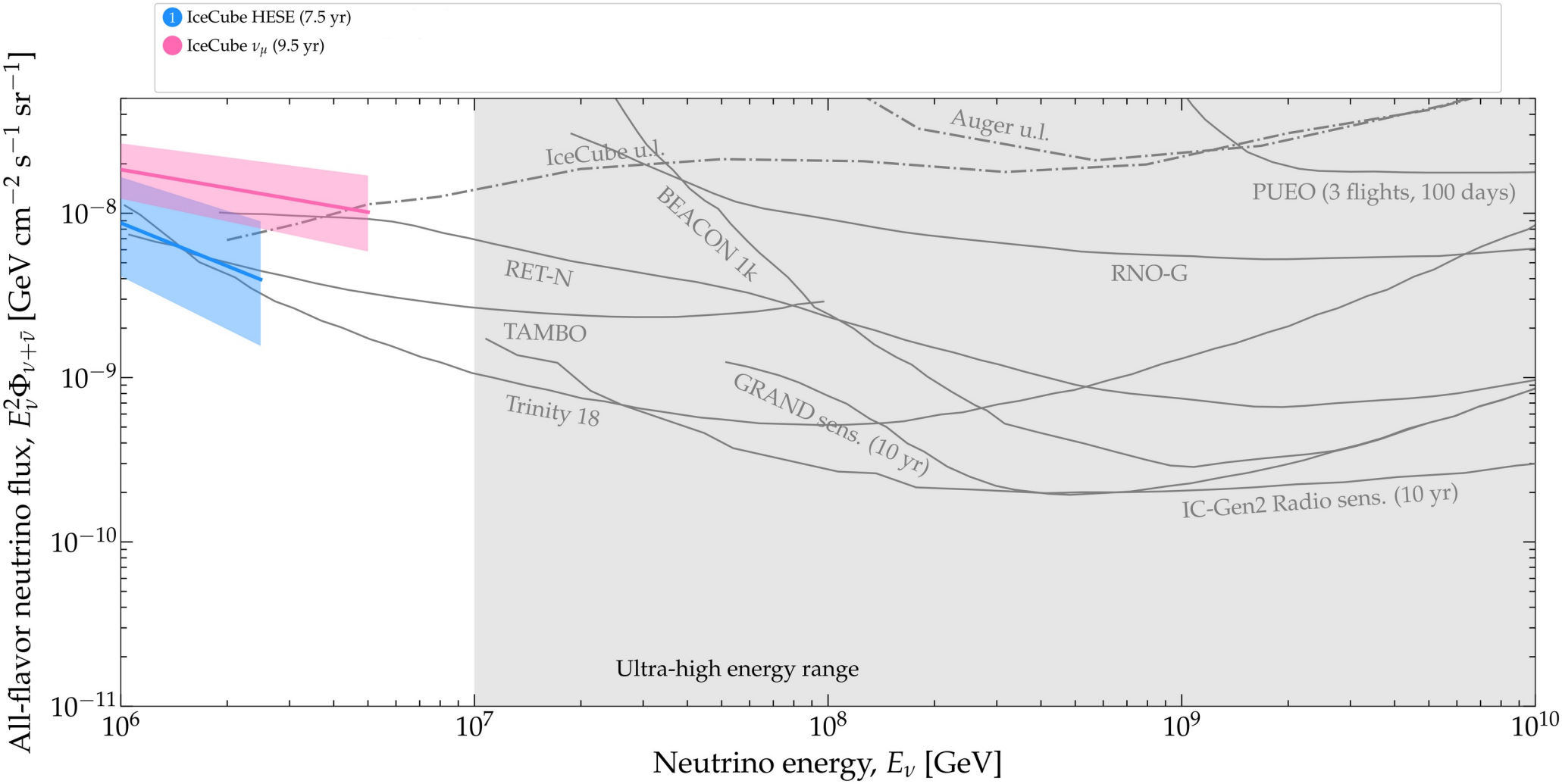


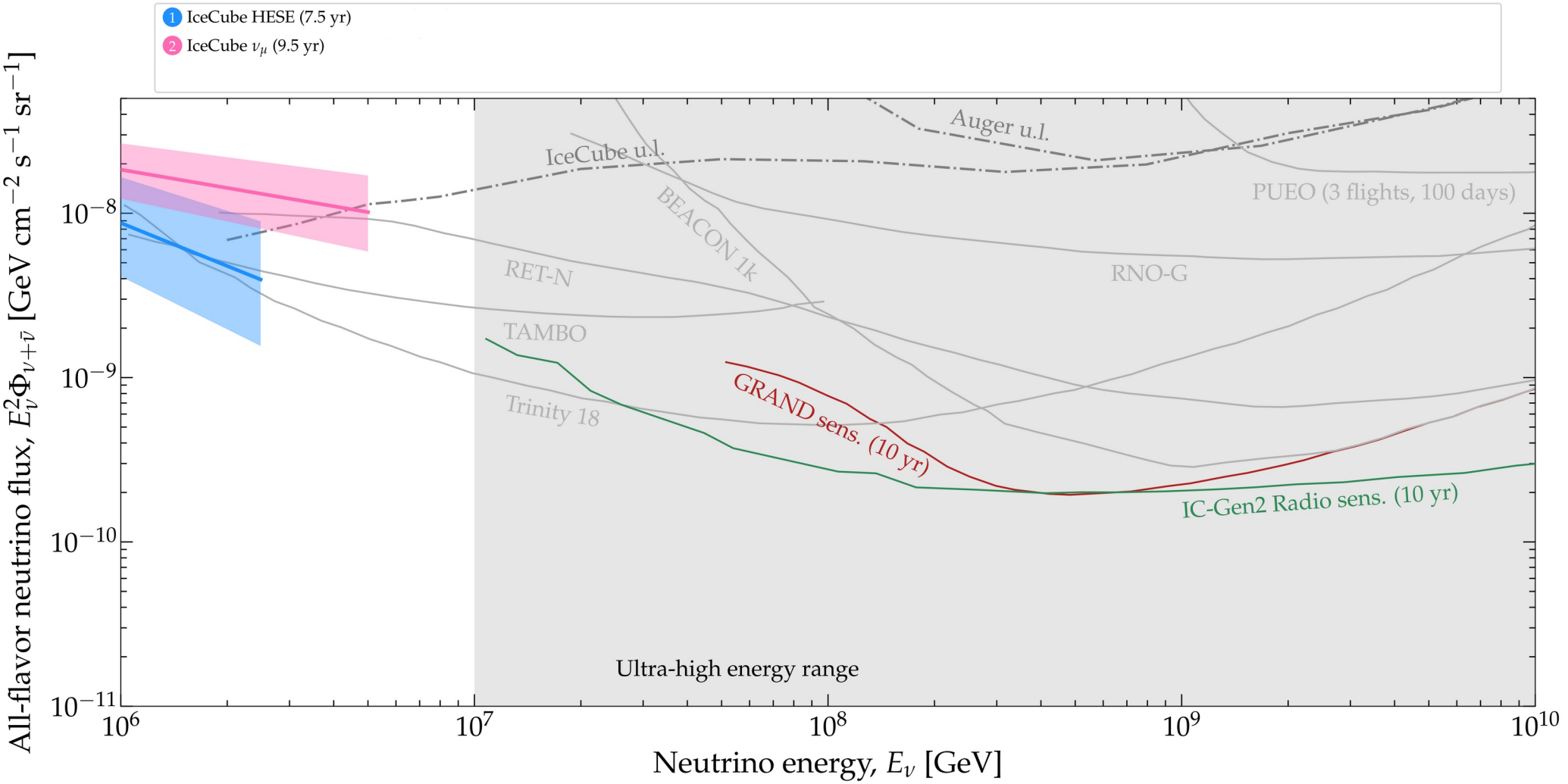
Note: ν sources can be steady-state or transient

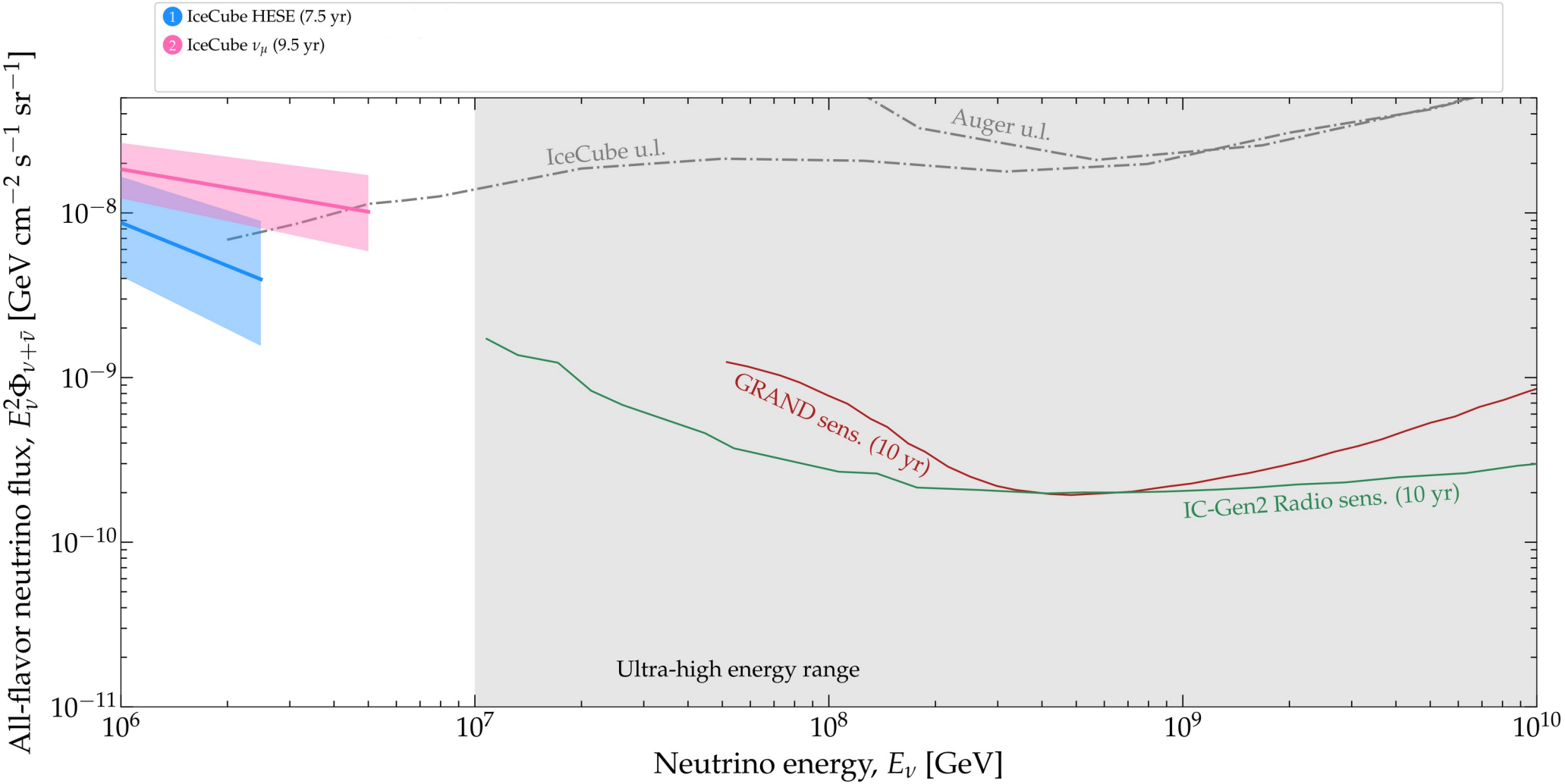

Redshift
z = 0
Note: ν sources can be steady-state or transient
ν propagation
inside the Earth
ν detection
HE ν
UHE source ν
Undiscovered
meV γ
EeV ν
"Ultra-high-
energy"
EeV p
Photohadronic or pp interaction
inside the source

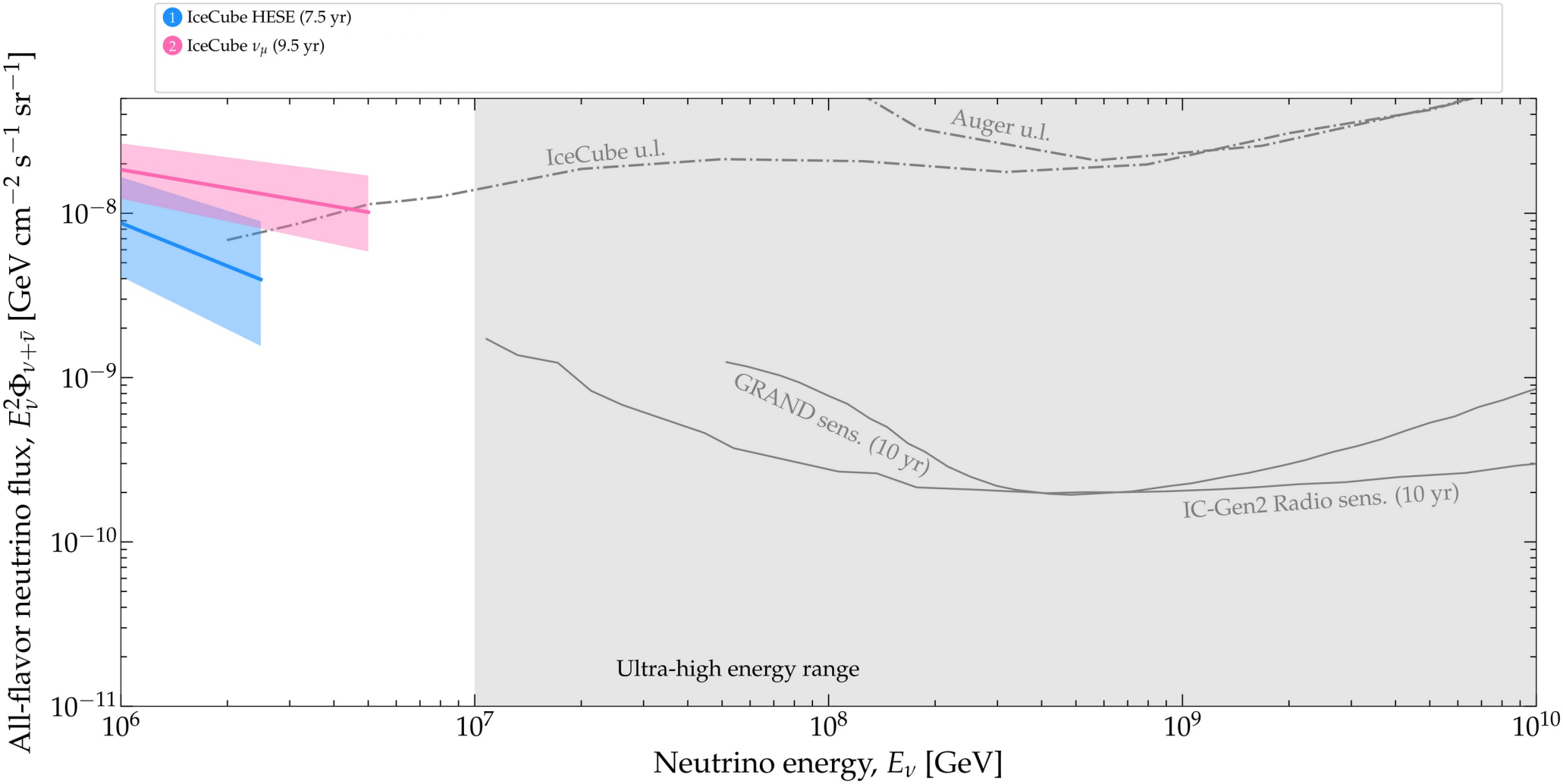

Redshift
z = 0
Note: ν sources can be steady-state or transient
ν propagation
inside the Earth
UHE p + nuclei
UHE cosmogenic ν
ν detection
HE ν
UHE source ν
UHECR
detection
Undiscovered
CMB/EBL γ
EeV ν
"Ultra-high-
energy"
EeV p
Photohadronic interaction
during propagation


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

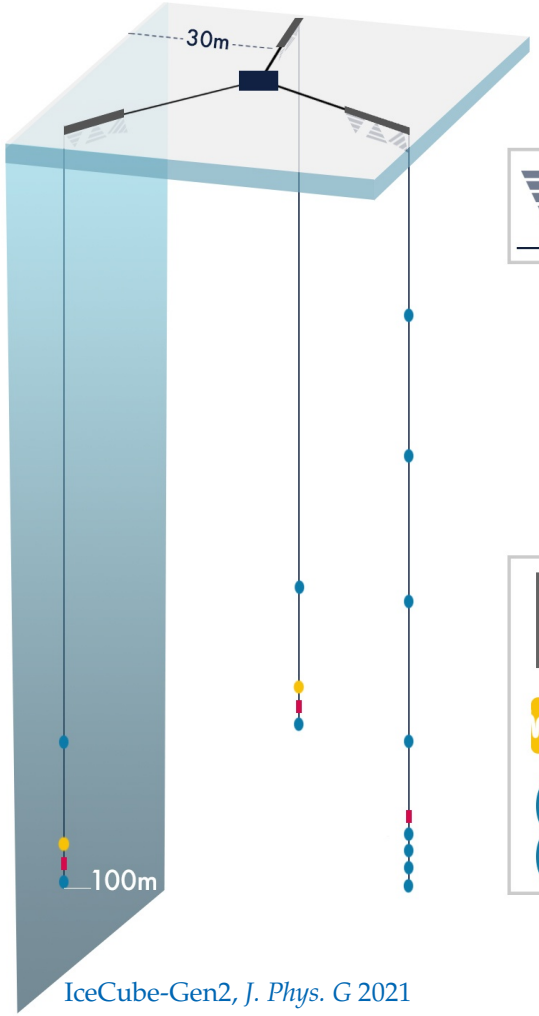

1 IceCube HESE (7.5 yr)
IceCube ν_μ (9.5 yr)
Auger u.l.
IceCube u.l.
BEACON 1k
PUEO (3 flights, 100 days)
RET-N
RNO-G
TAMBO
Trinity 18
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino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

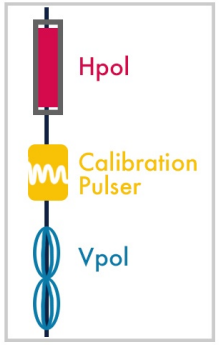

1 IceCube HESE (7.5 yr)
2 IceCube ν_μ (9.5 yr)
Auger u.l.
IceCube u.l.
BEACON 1k
PUEO (3 flights, 100 days)
RET-N
RNO-G
TAMBO
Trinity 18
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino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

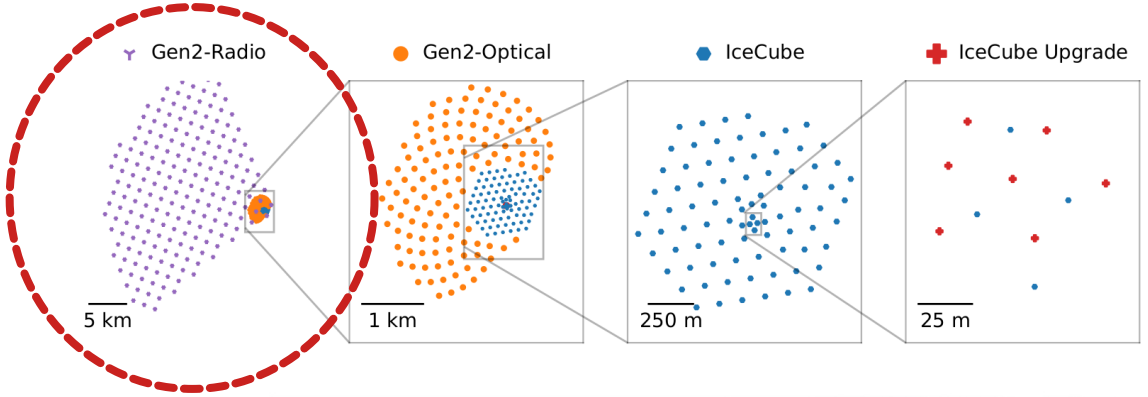

1 IceCube HESE (7.5 yr)
2 IceCube ν_μ (9.5 yr)
Auger u.l.
IceCube u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy, E_ν [GeV]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8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

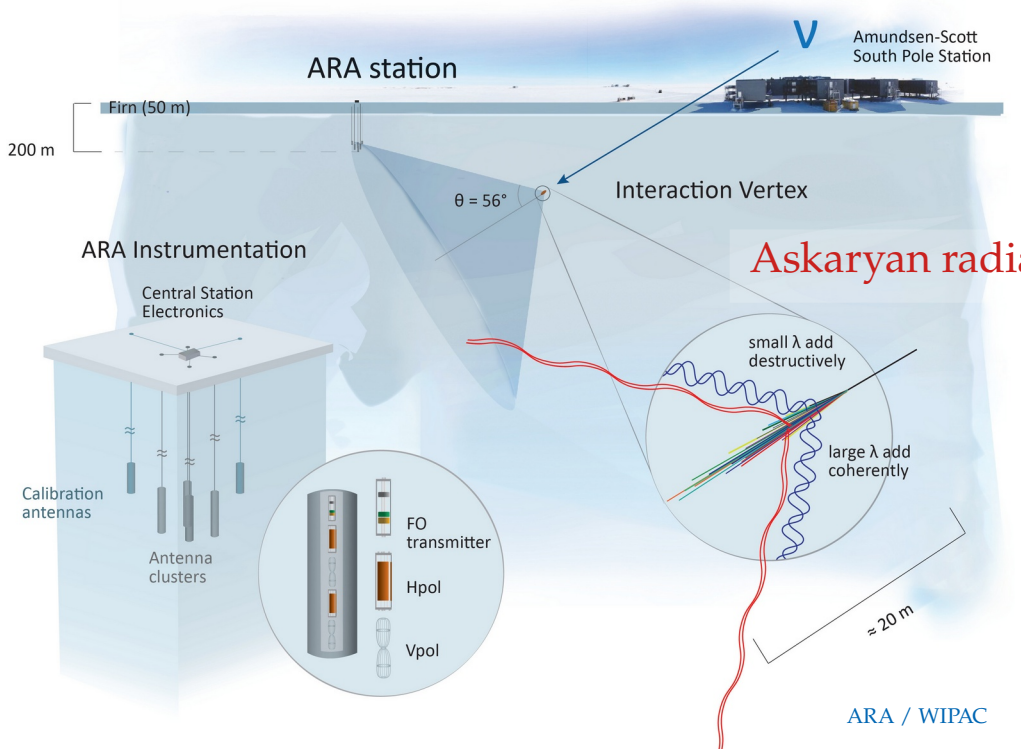

1 IceCube HESE (7.5 yr)
2 IceCube ν_μ (9.5 yr)
Auger u.l.
IceCube u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy, E_ν [GeV]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8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

IceCube-Gen2 Radio



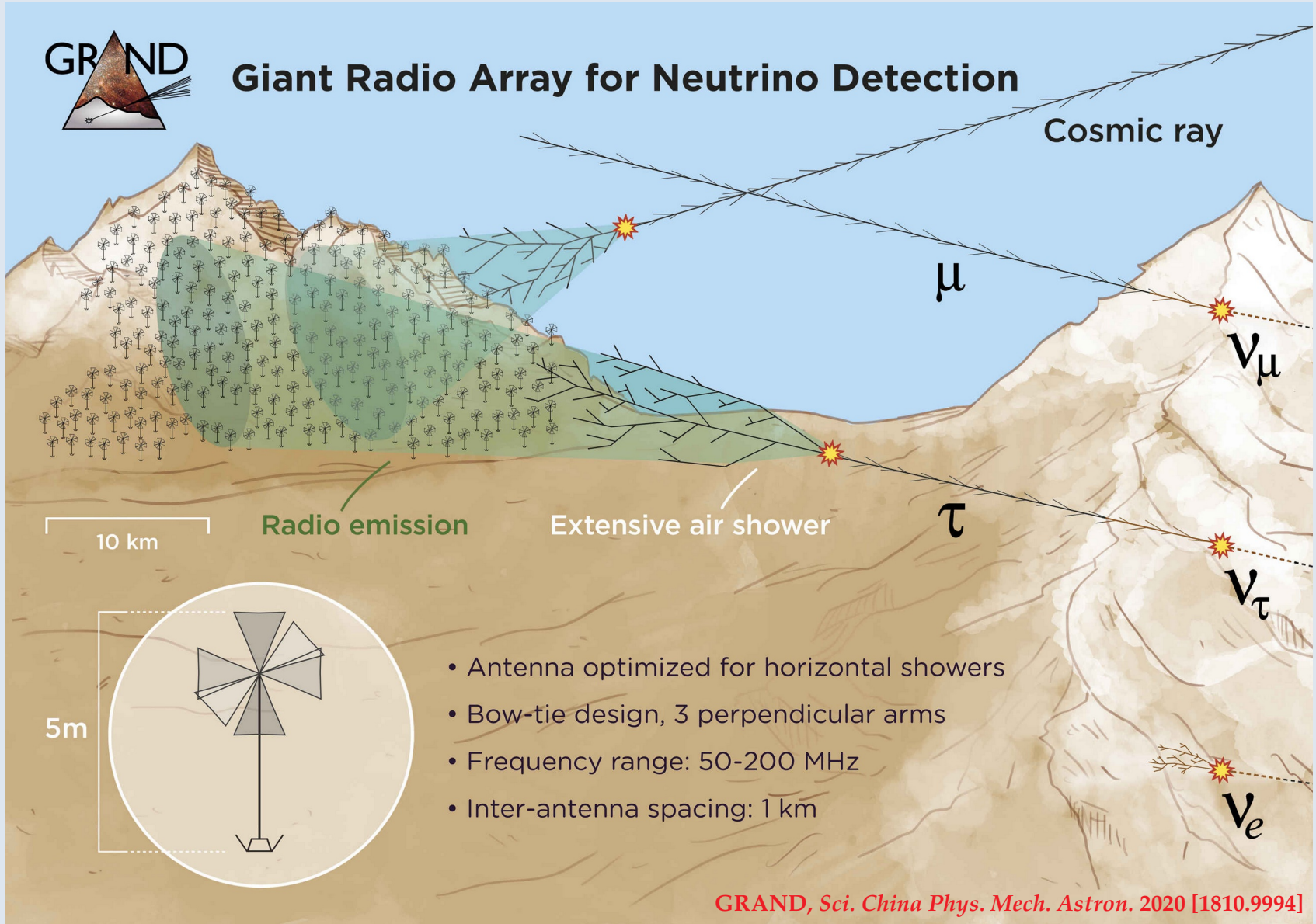






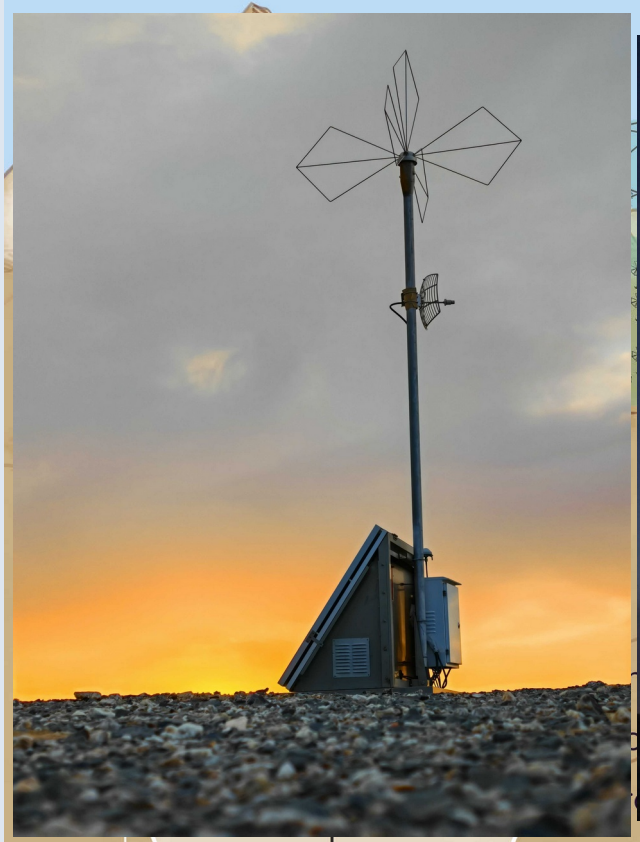
IceCube-Gen2, *J. Phys. G* 2021

ARA / WIPAC


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

Giant Radio Array for Neutrino Detection

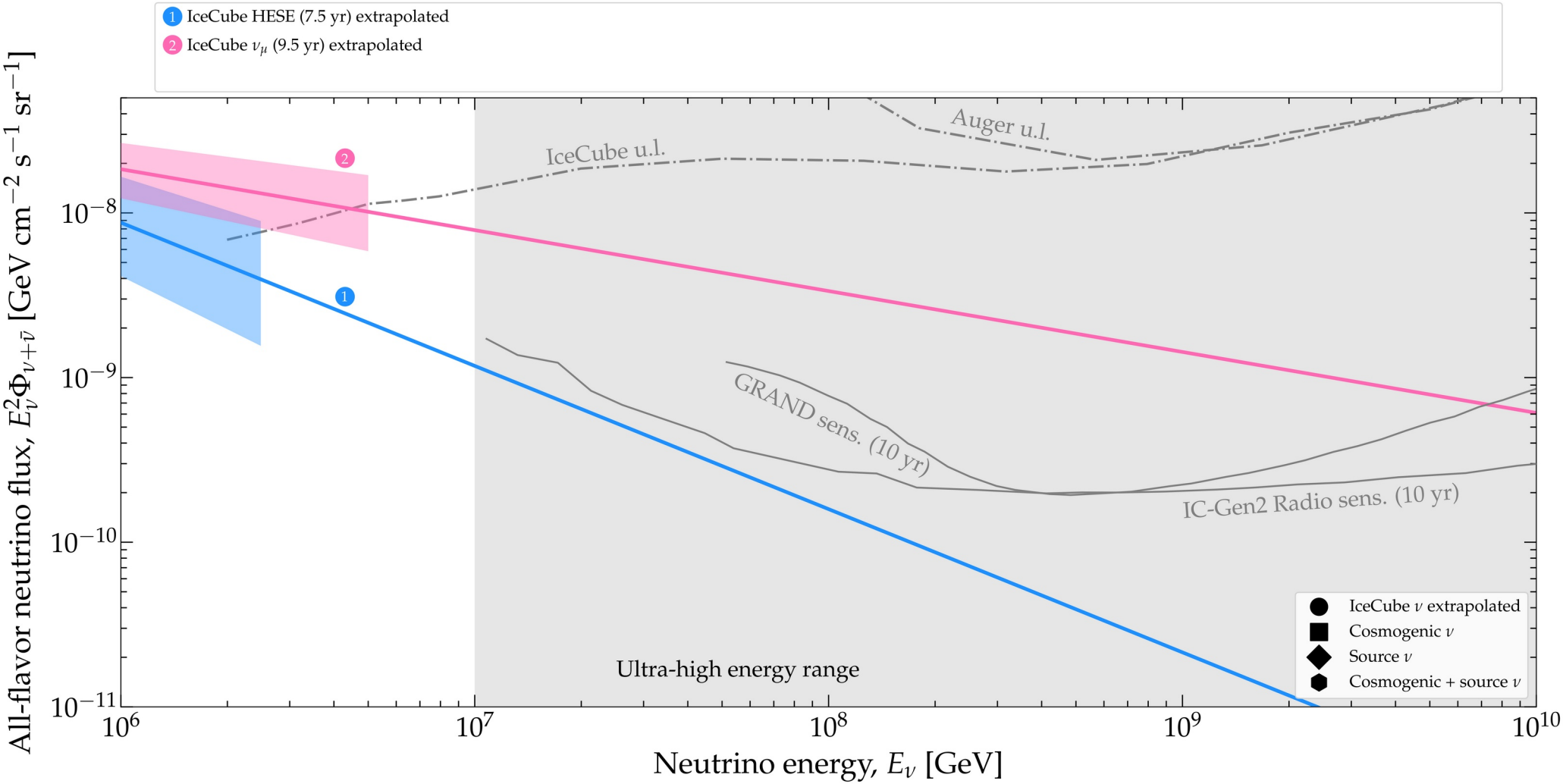
Cosmic ray

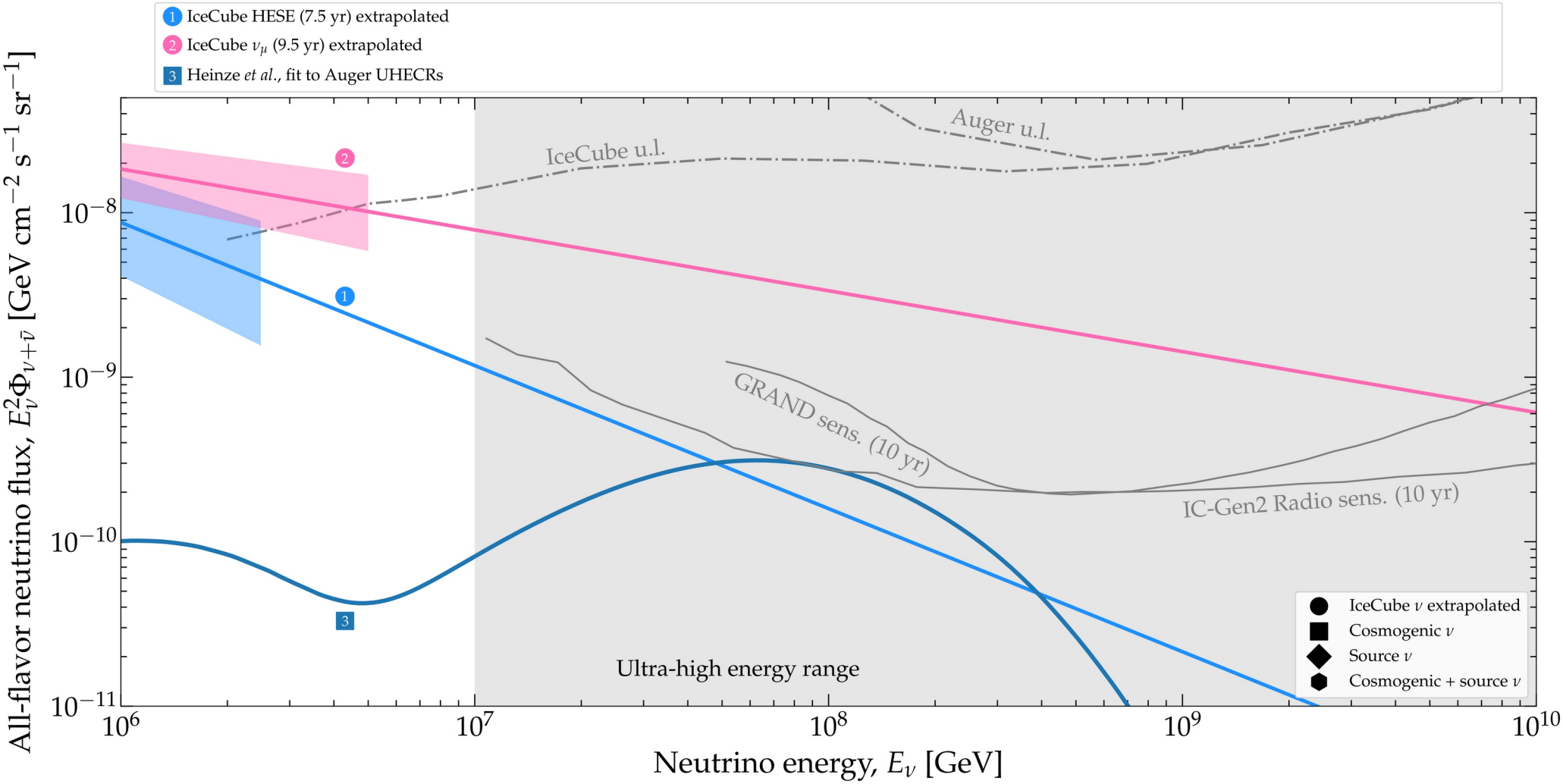


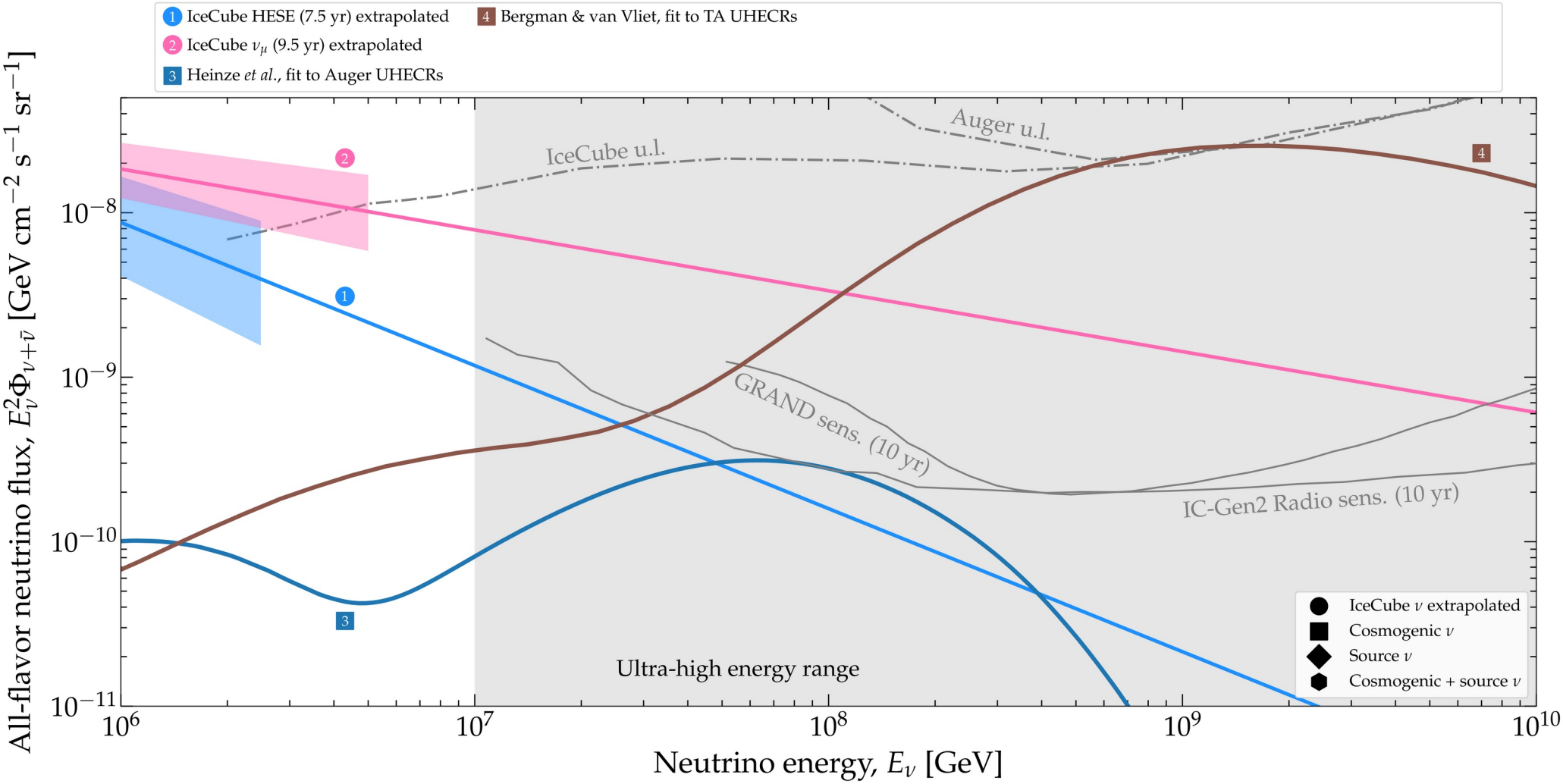
- Inter-antenna spacing: 1 km

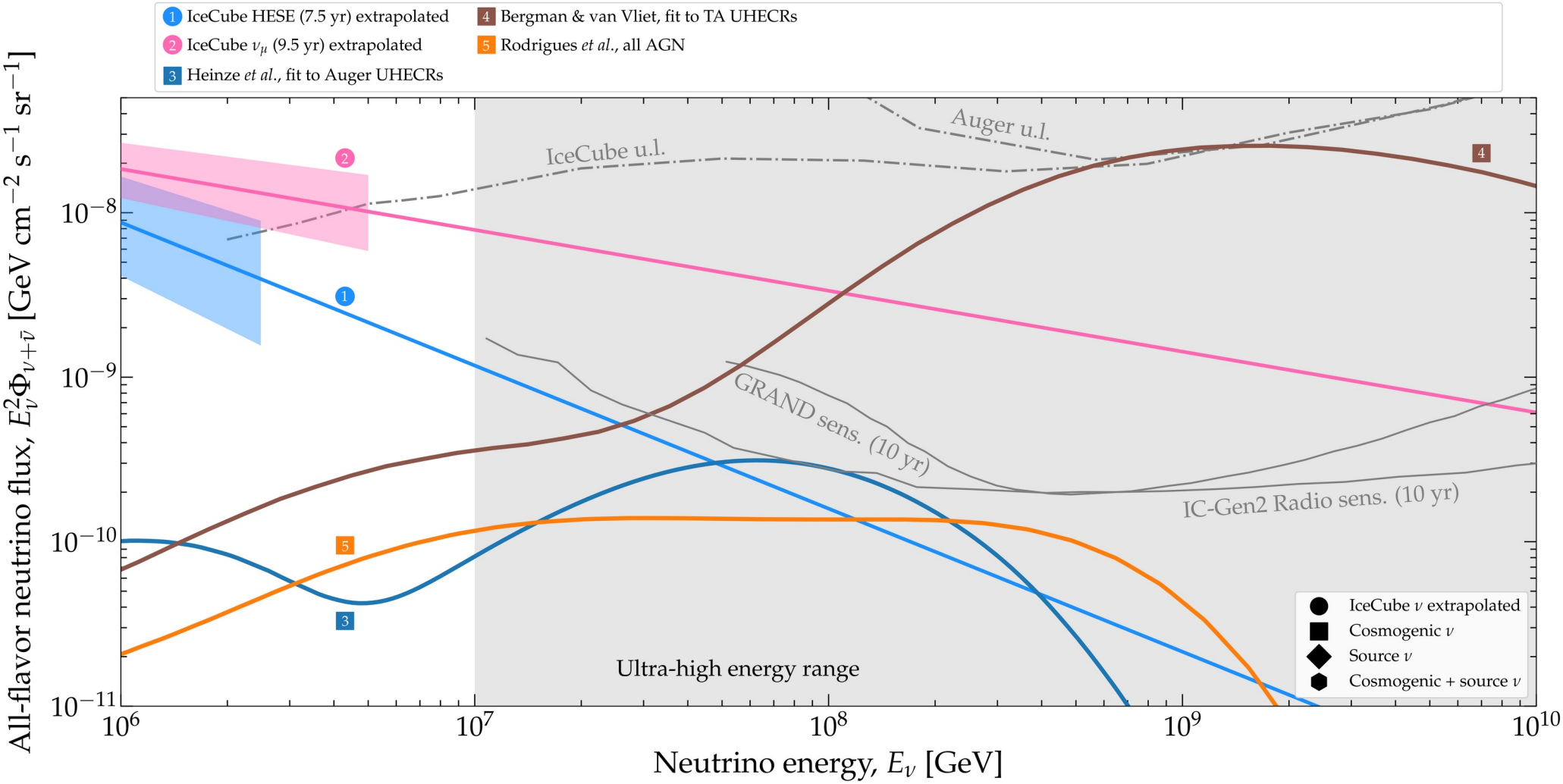
ν_e

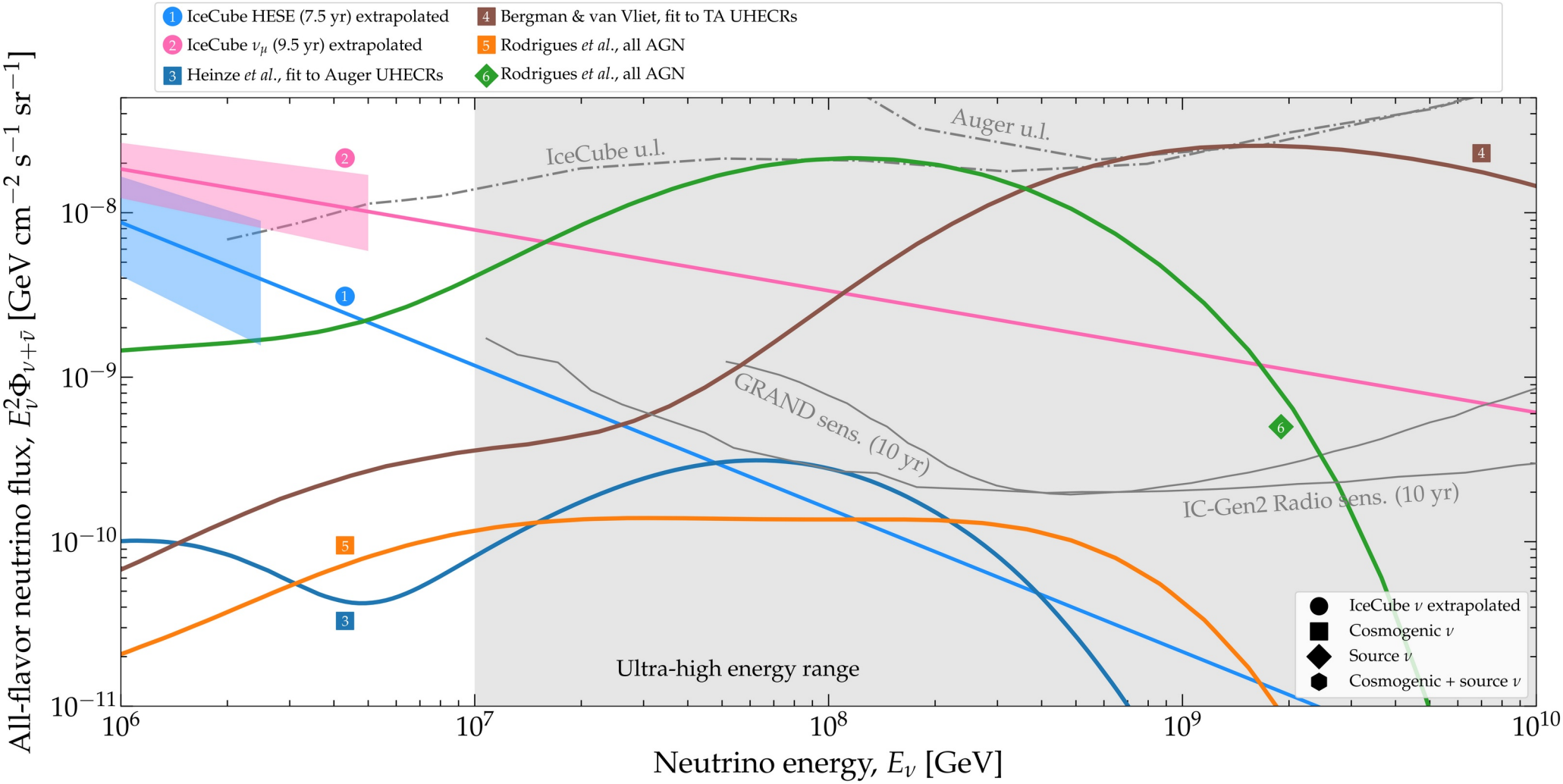
GRAND, *Sci. China Phys. Mech. Astron.* 2020 [1810.9994]

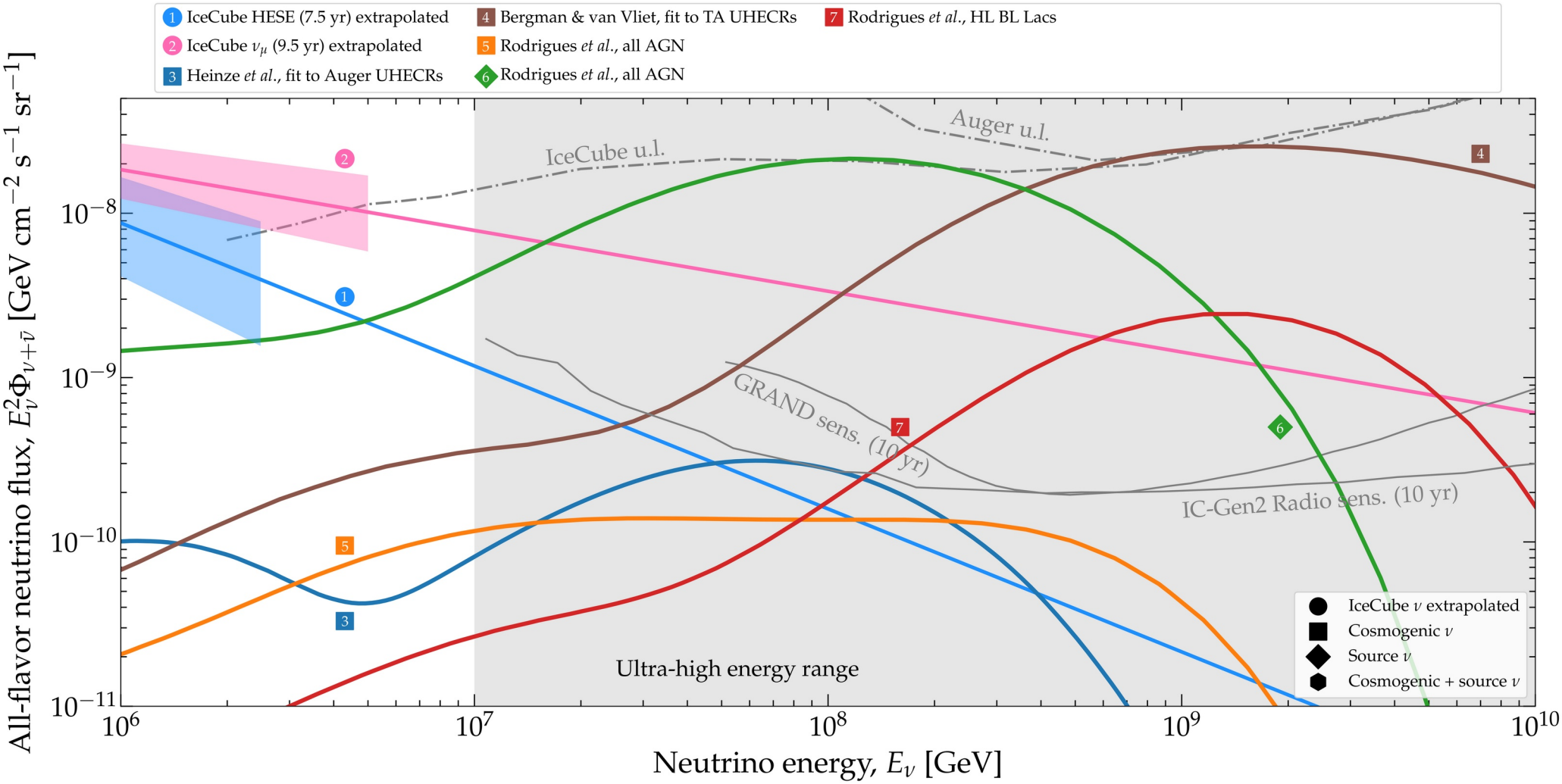

1 IceCube HESE (7.5 yr) extrapolated
2 IceCube ν_μ (9.5 yr) extrapolated
Auger u.l.
IceCube u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
IceCube ν extrapolated
Cosmogenic ν
Source ν
Cosmogenic + source ν
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2}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

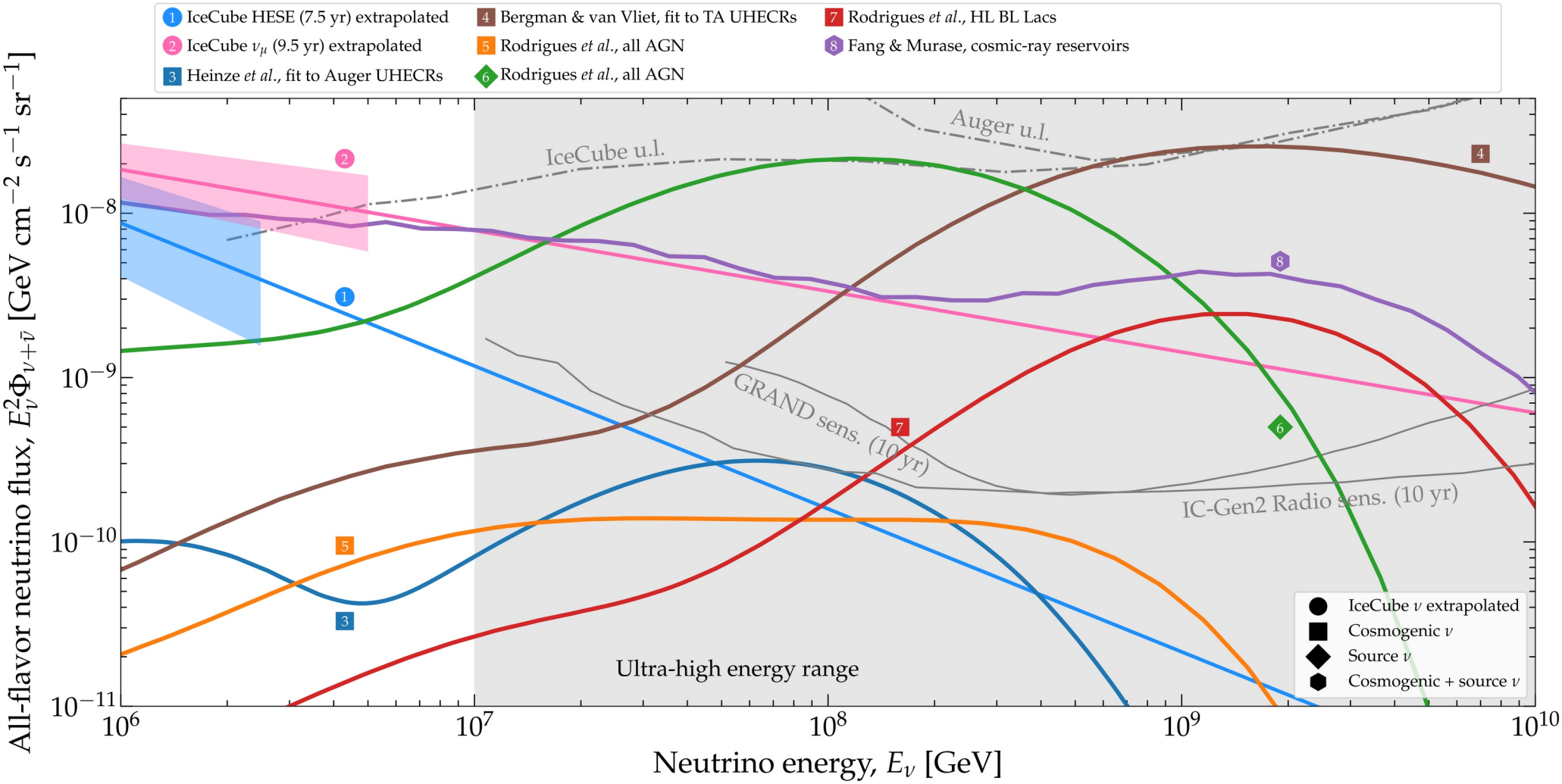

1 IceCube HESE (7.5 yr) extrapolated
2 IceCube ν_μ (9.5 yr) extrapolated
3 Heinze *et al.*, fit to Auger UHECRs
Auger u.l.
IceCube u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
IceCube ν extrapolated
Cosmogenic ν
Source ν
Cosmogenic + source ν
All-flavor neutrino flux,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

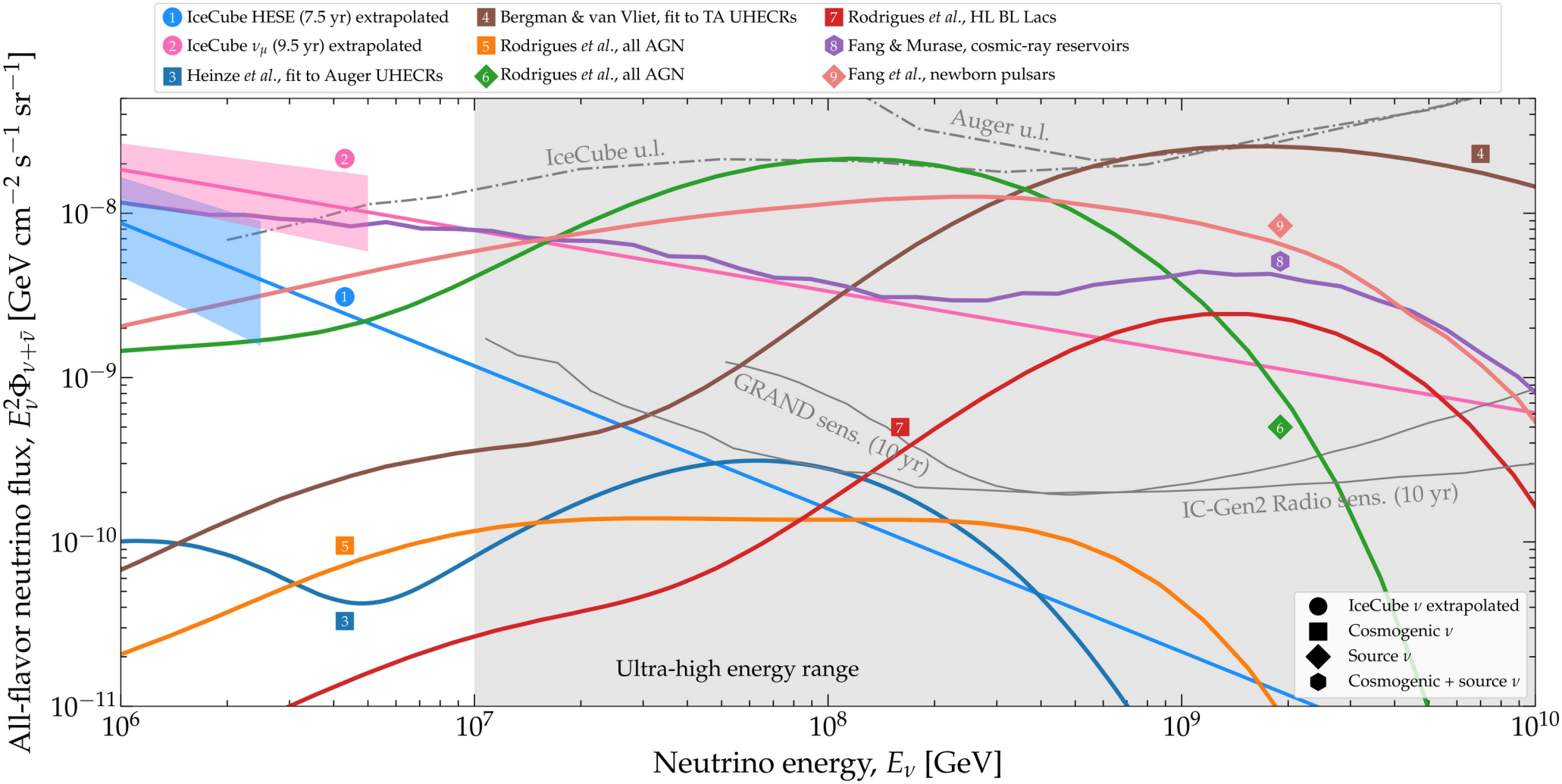

1 IceCube HESE (7.5 yr) extrapolated
2 IceCube ν_μ (9.5 yr) extrapolated
3 Heinze *et al.*, fit to Auger UHECRs
4 Bergman & van Vliet, fit to TA UHECRs
IceCube u.l.
Auger u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
IceCube ν extrapolated
Cosmogenic ν
Source ν
Cosmogenic + 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}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}

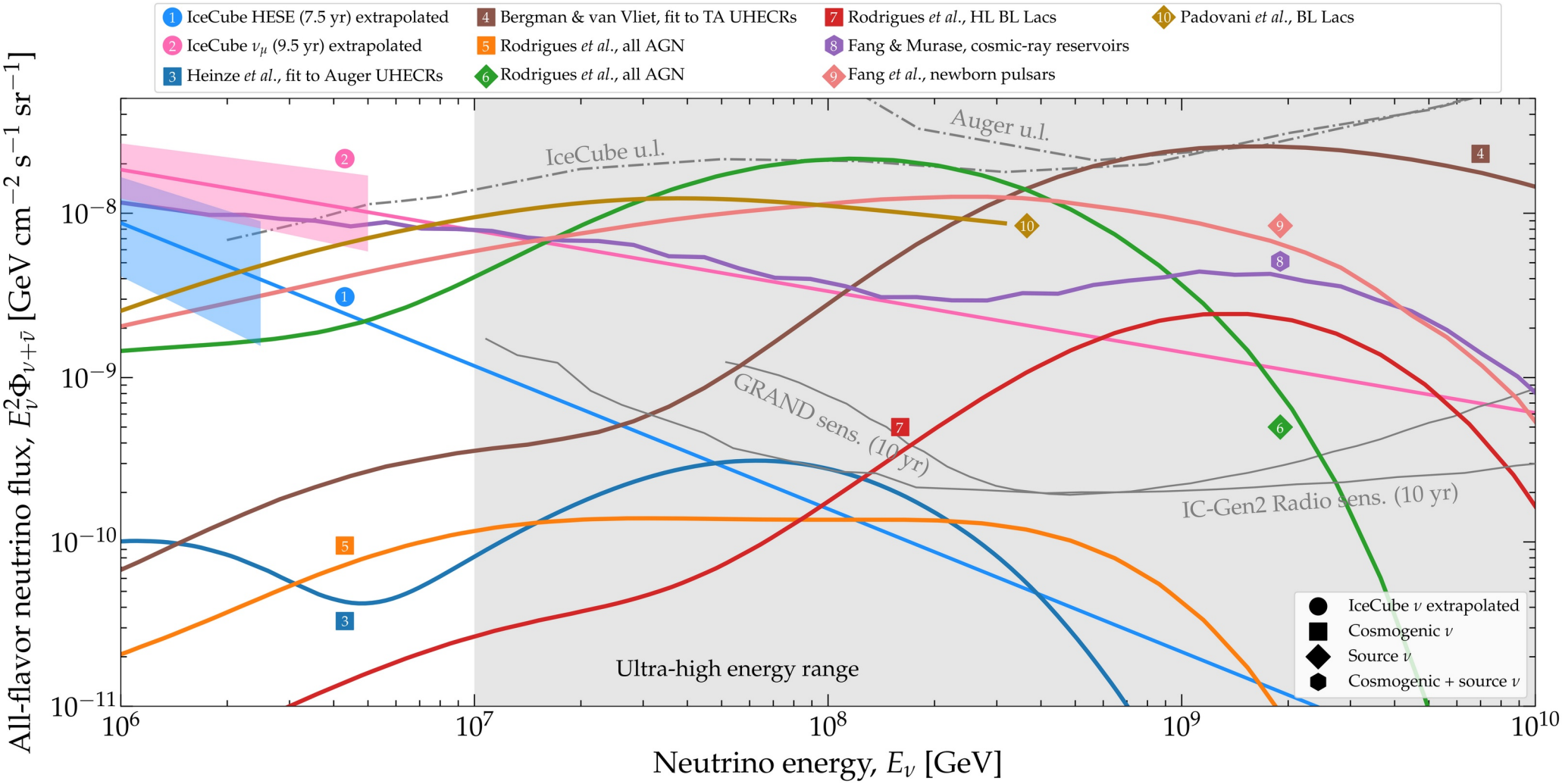

1 IceCube HESE (7.5 yr) extrapolated
2 IceCube ν_μ (9.5 yr) extrapolated
3 Heinze *et al.*, fit to Auger UHECRs
4 Bergman & van Vliet, fit to TA UHECRs
5 Rodrigues *et al.*, all AGN
Auger u.l.
IceCube u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
IceCube ν extrapolated
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}

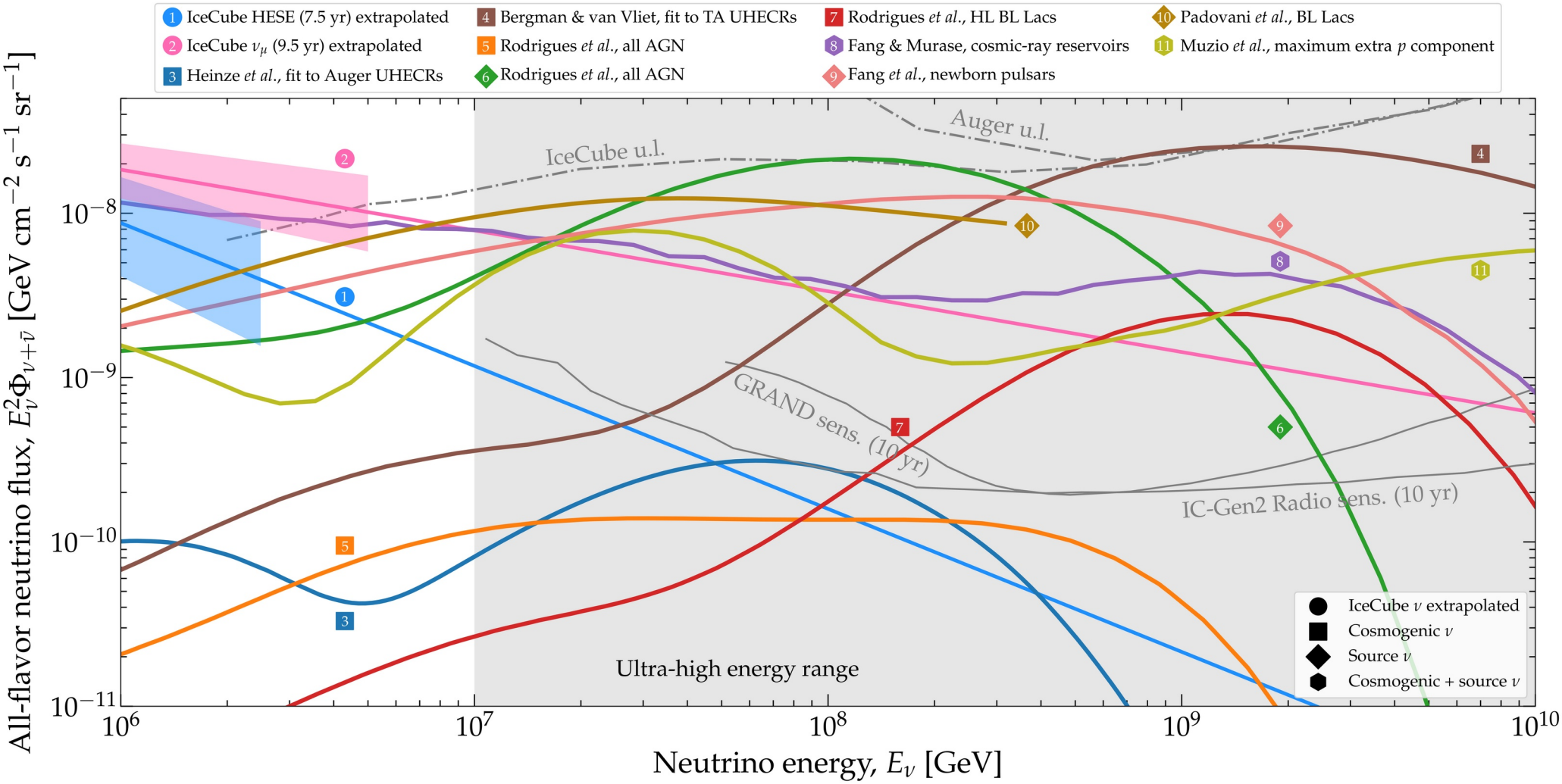

1 IceCube HESE (7.5 yr) extrapolated
2 IceCube ν_μ (9.5 yr) extrapolated
3 Heinze et al., fit to Auger UHECRs
4 Bergman & van Vliet, fit to TA UHECRs
5 Rodrigues et al., all AGN
6 Rodrigues et al., all AGN
IceCube u.l.
Auger u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
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}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}

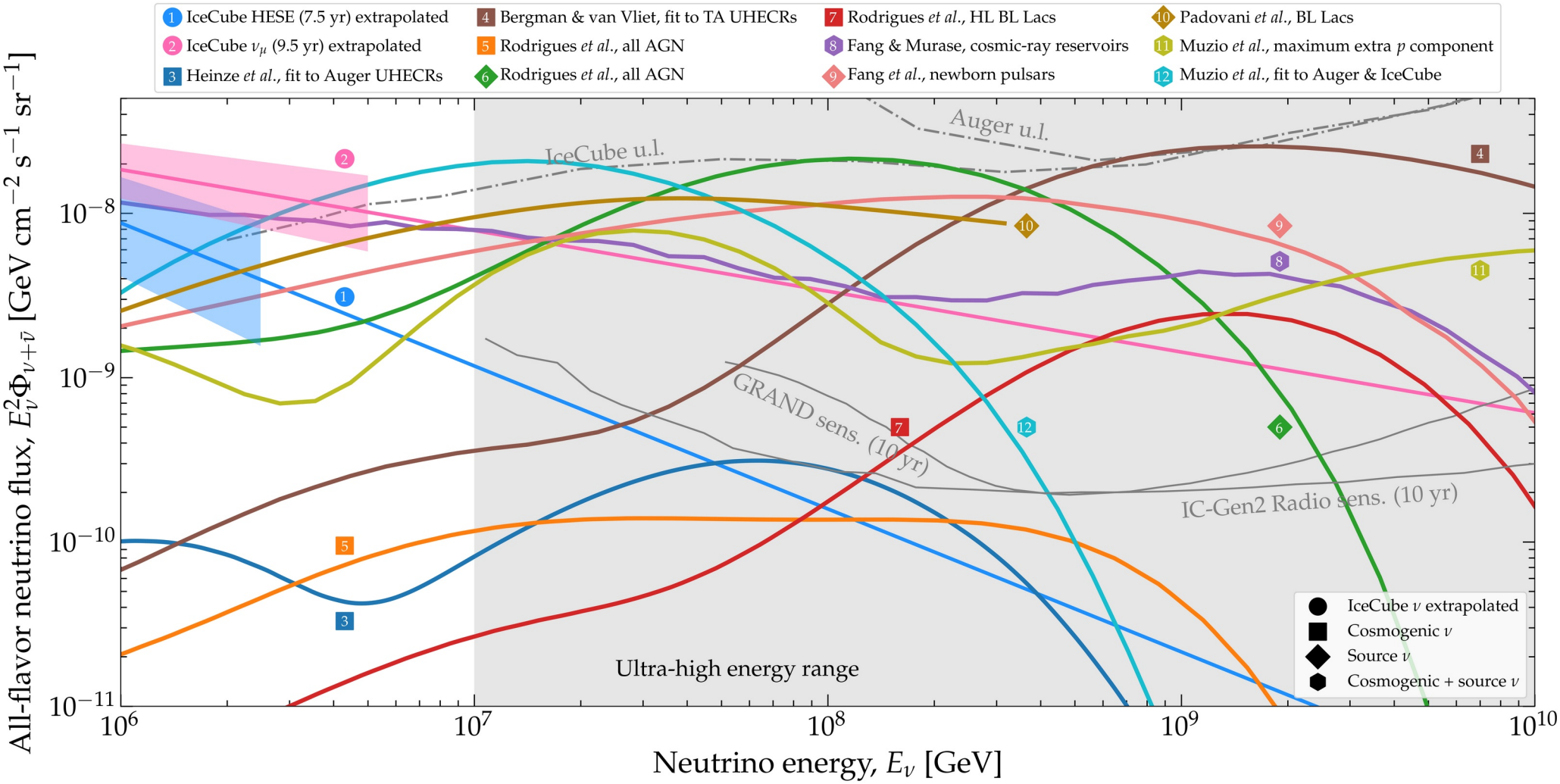

1 IceCube HESE (7.5 yr) extrapolated
2 IceCube ν_μ (9.5 yr) extrapolated
3 Heinze et al., fit to Auger UHECRs
4 Bergman & van Vliet, fit to TA UHECRs
5 Rodrigues et al., all AGN
6 Rodrigues et al., all AGN
7 Rodrigues et al., HL BL Lacs
IceCube u.l.
Auger u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (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}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}

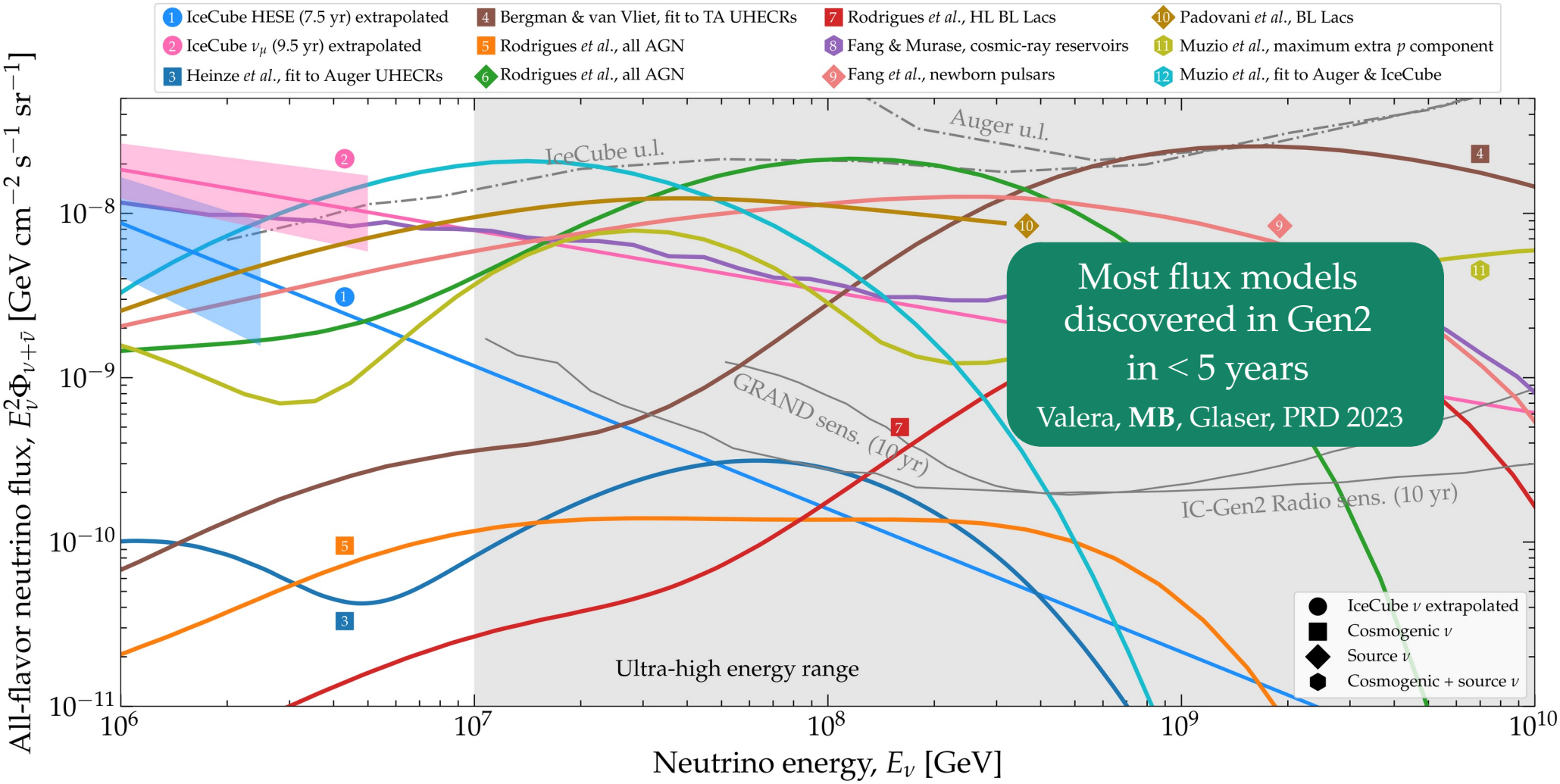

1 IceCube HESE (7.5 yr) extrapolated
2 IceCube ν_μ (9.5 yr) extrapolated
3 Heinze et al., fit to Auger UHECRs
4 Bergman & van Vliet, fit to TA UHECRs
5 Rodrigues et al., all AGN
6 Rodrigues et al., all AGN
7 Rodrigues et al., HL BL Lacs
8 Fang & Murase, cosmic-ray reservoirs
IceCube u.l.
Auger u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
IceCube ν extrapolated
Cosmogenic ν
Source ν
Cosmogenic + source ν
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}


1 IceCube HESE (7.5 yr) extrapolated
2 IceCube ν_μ (9.5 yr) extrapolated
3 Heinze et al., fit to Auger UHECRs
4 Bergman & van Vliet, fit to TA UHECRs
5 Rodrigues et al., all AGN
6 Rodrigues et al., all AGN
7 Rodrigues et al., HL BL Lacs
8 Fang & Murase, cosmic-ray reservoirs
9 Fang et al., newborn pulsars
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}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}


1 IceCube HESE (7.5 yr) extrapolated
2 IceCube ν_μ (9.5 yr) extrapolated
3 Heinze et al., fit to Auger UHECRs
4 Bergman & van Vliet, fit to TA UHECRs
5 Rodrigues et al., all AGN
6 Rodrigues et al., all AGN
7 Rodrigues et al., HL BL Lacs
8 Fang & Murase, cosmic-ray reservoirs
9 Fang et al., newborn pulsars
10 Padovani et al., BL Lacs
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}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}


1 IceCube HESE (7.5 yr) extrapolated
2 IceCube ν_μ (9.5 yr) extrapolated
3 Heinze et al., fit to Auger UHECRs
4 Bergman & van Vliet, fit to TA UHECRs
5 Rodrigues et al., all AGN
6 Rodrigues et al., all AGN
7 Rodrigues et al., HL BL Lacs
8 Fang & Murase, cosmic-ray reservoirs
9 Fang et al., newborn pulsars
10 Padovani et al., BL Lacs
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}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}

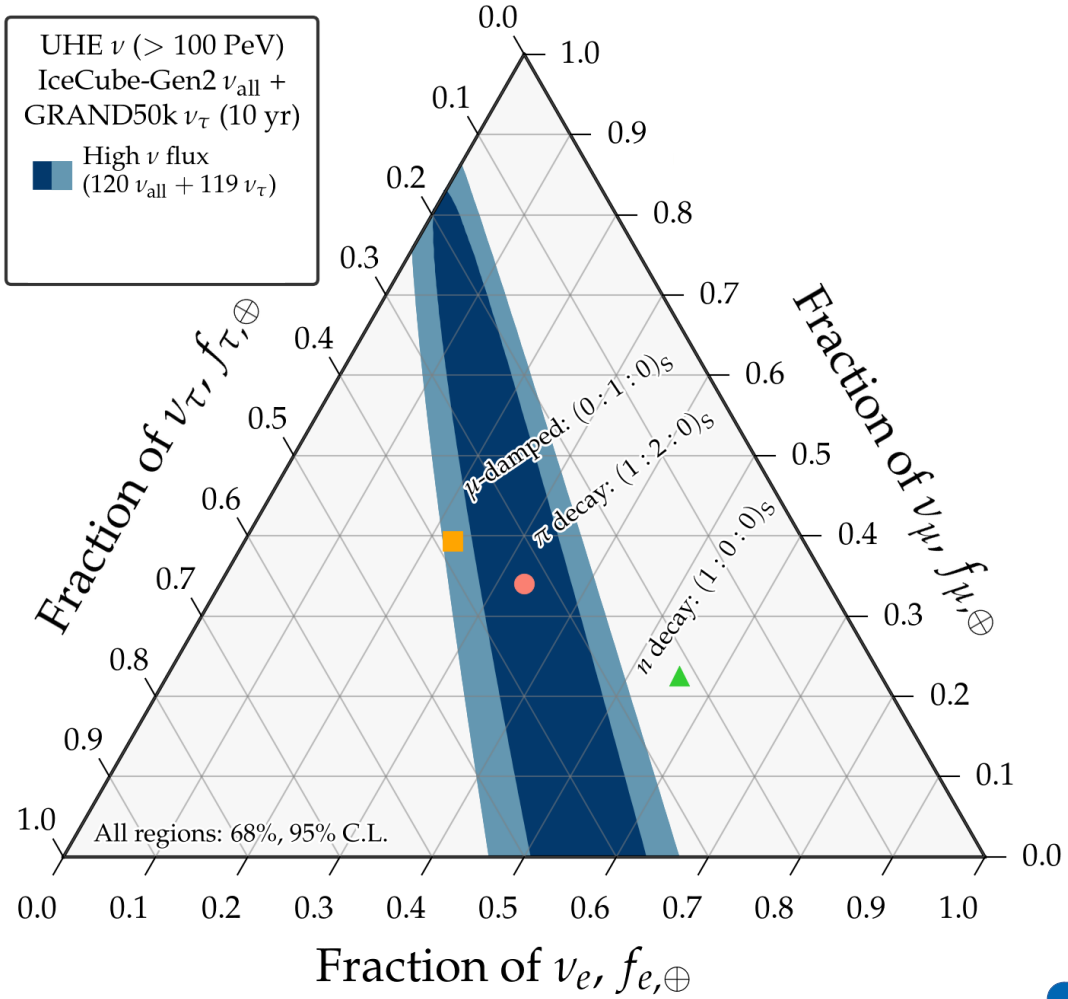

1 IceCube HESE (7.5 yr) extrapolated
2 IceCube ν_μ (9.5 yr) extrapolated
3 Heinze et al., fit to Auger UHECRs
4 Bergman & van Vliet, fit to TA UHECRs
5 Rodrigues et al., all AGN
6 Rodrigues et al., all AGN
7 Rodrigues et al., HL BL Lacs
8 Fang & Murase, cosmic-ray reservoirs
9 Fang et al., newborn pulsars
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]


1 IceCube HESE (7.5 yr) extrapolated
2 IceCube ν_μ (9.5 yr) extrapolated
3 Heinze et al., fit to Auger UHECRs
4 Bergman & van Vliet, fit to TA UHECRs
5 Rodrigues et al., all AGN
6 Rodrigues et al., all AGN
7 Rodrigues et al., HL BL Lacs
8 Fang & Murase, cosmic-ray reservoirs
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
Most flux models discovered in Gen2 in < 5 years
Valera, MB, Glaser, PRD 2023
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}

Manufacturing UHE flavor sensitivity with two detectors

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

Then we combine two detectors:



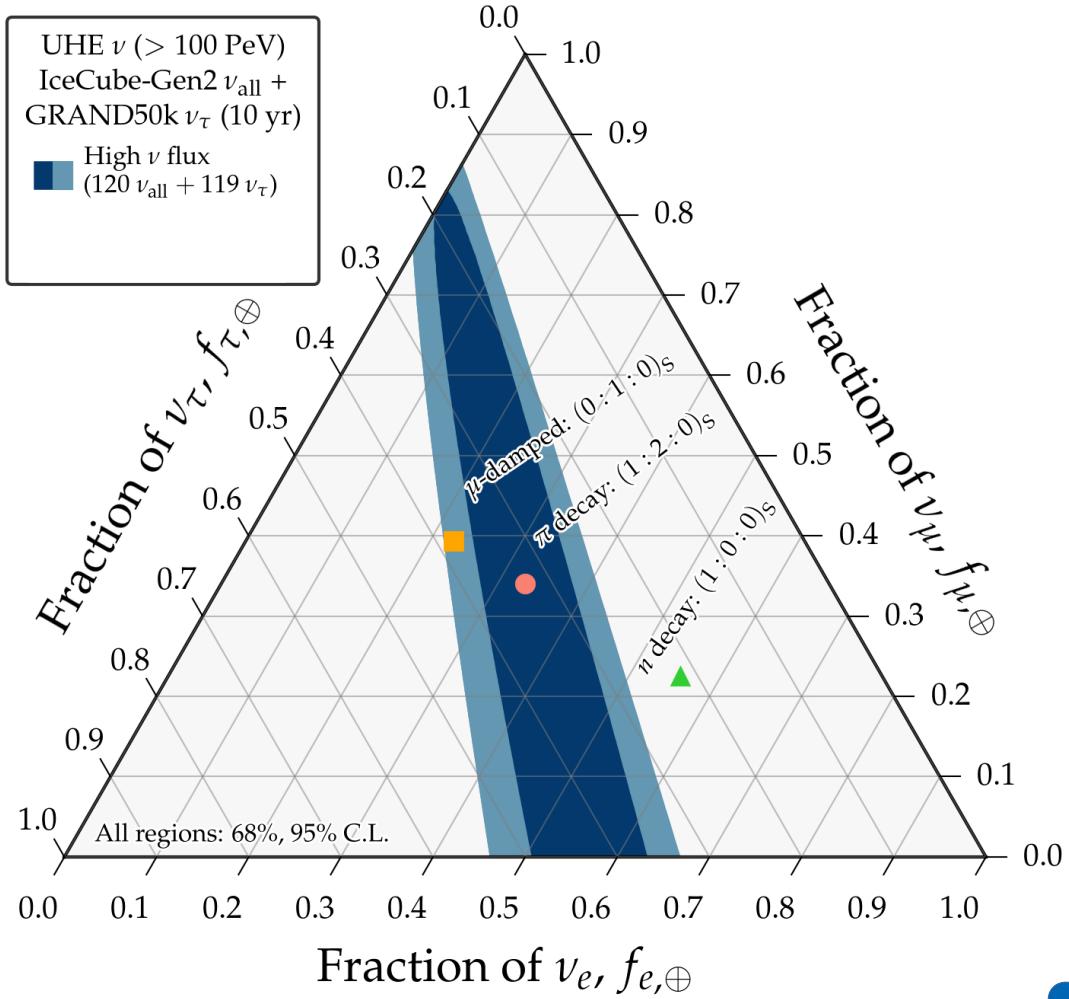
Testagrossa, Fiorillo, **MB**, 2310.12215

Manufacturing UHE flavor sensitivity with two detectors

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

Then we combine two detectors:

indistinct detection of all flavors by IceCube-Gen2 (radio)



Testagrossa, Fiorillo, **MB**, 2310.12215

Manufacturing UHE flavor sensitivity with two detectors

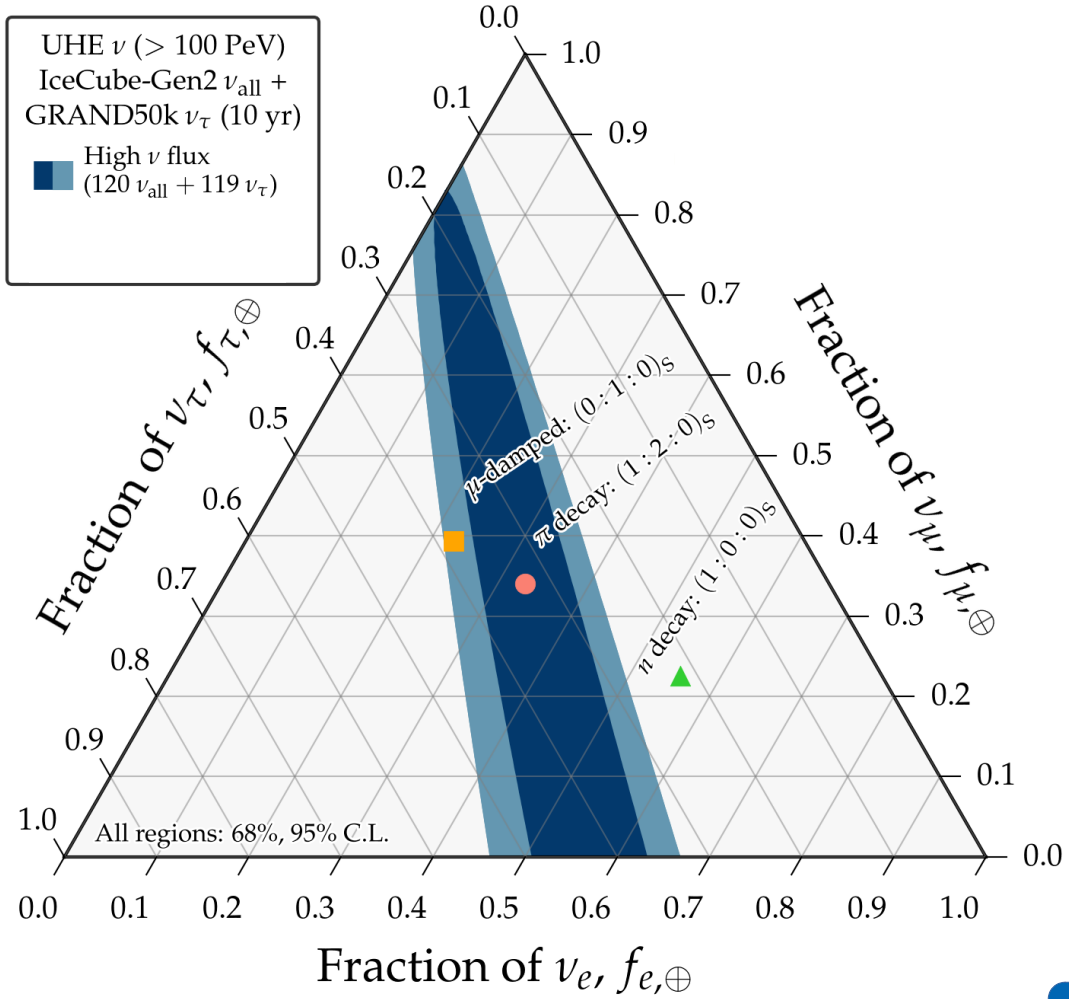
What if future UHE radio-detection neutrino telescopes cannot see flavor?

Then we combine two detectors:

indistinct detection of all flavors by IceCube-Gen2 (radio)

+

predominant detection of ν_τ by GRAND



Testagrossa, Fiorillo, **MB**, 2310.12215

Manufacturing UHE flavor sensitivity with two detectors

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

Then we combine two detectors:

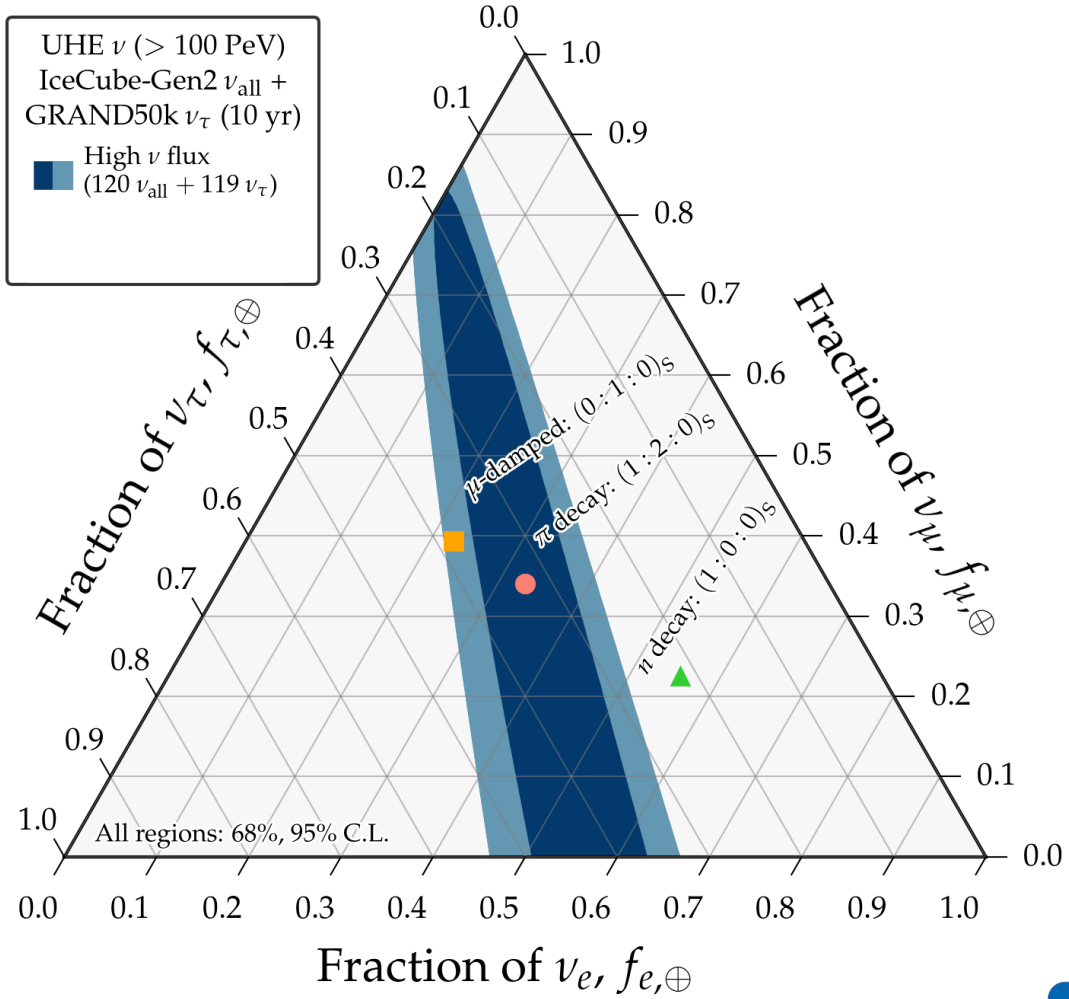
indistinct detection of all flavors by IceCube-Gen2 (radio)

+

predominant detection of ν_τ by GRAND

=

sensitivity to the fraction of UHE ν_τ



Testagrossa, Fiorillo, **MB**, 2310.12215

Manufacturing UHE flavor sensitivity with two detectors

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

Then we combine two of detectors:

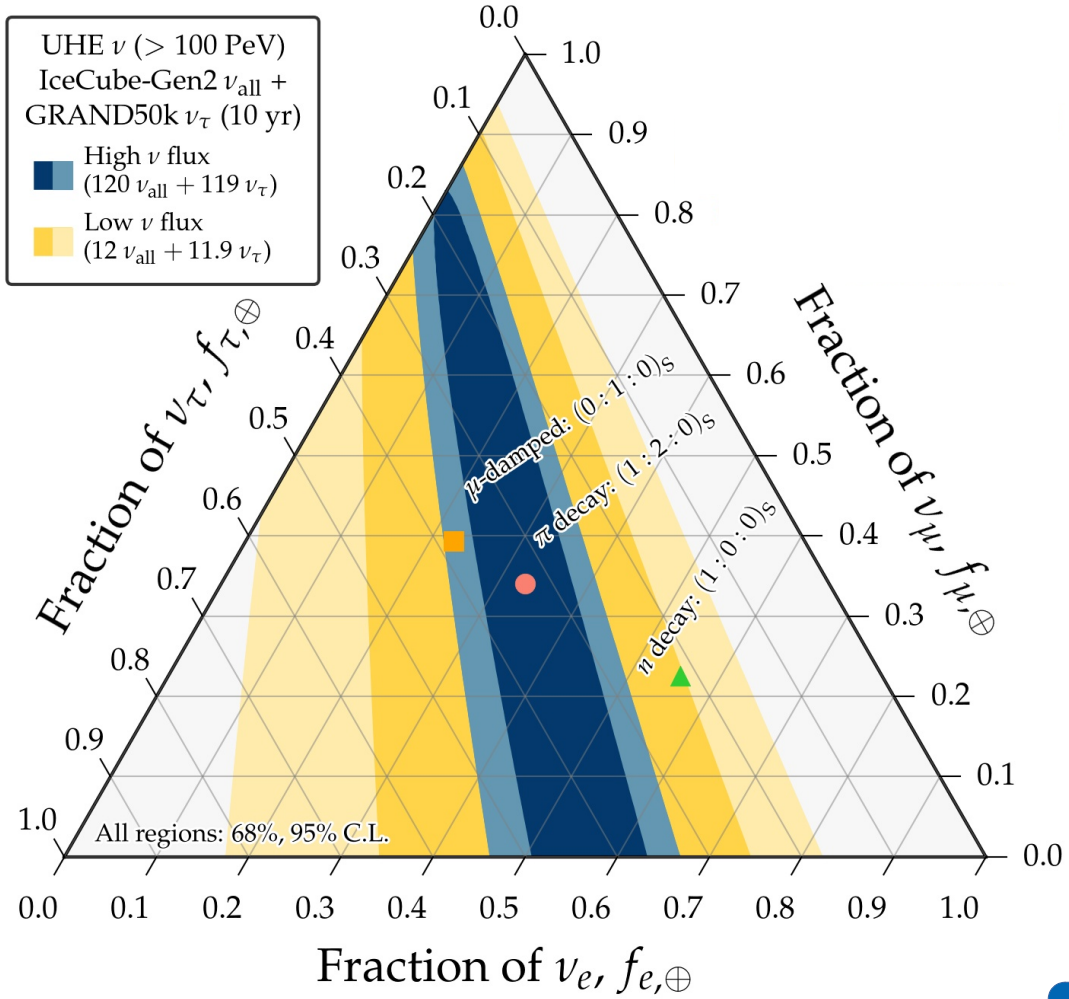
indistinct detection of all flavors by IceCube-Gen2 (radio)

+

predominant detection of ν_τ by GRAND

=

sensitivity to the fraction of UHE ν_τ



Testagrossa, Fiorillo, **MB**, 2310.12215

Manufacturing UHE flavor sensitivity with two detectors

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

Then we combine two of detectors:

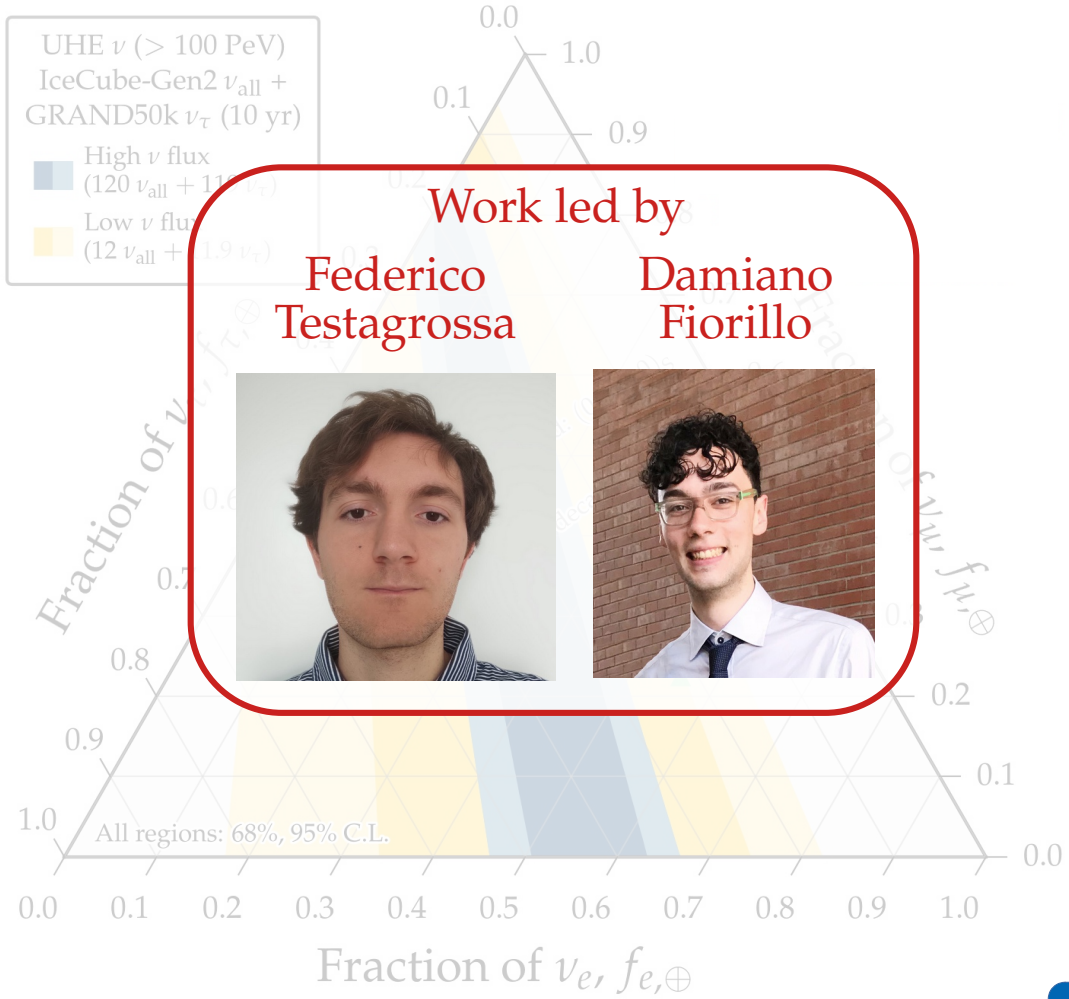
indistinct detection of all flavors
by IceCube-Gen2 (radio)

+

predominant detection of ν_τ
by GRAND

=

sensitivity to the fraction of UHE ν_τ



Testagrossa, Fiorillo, **MB**, 2310.12215

Manufacturing UHE flavor sensitivity with two detectors

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

Then we combine two of detectors:

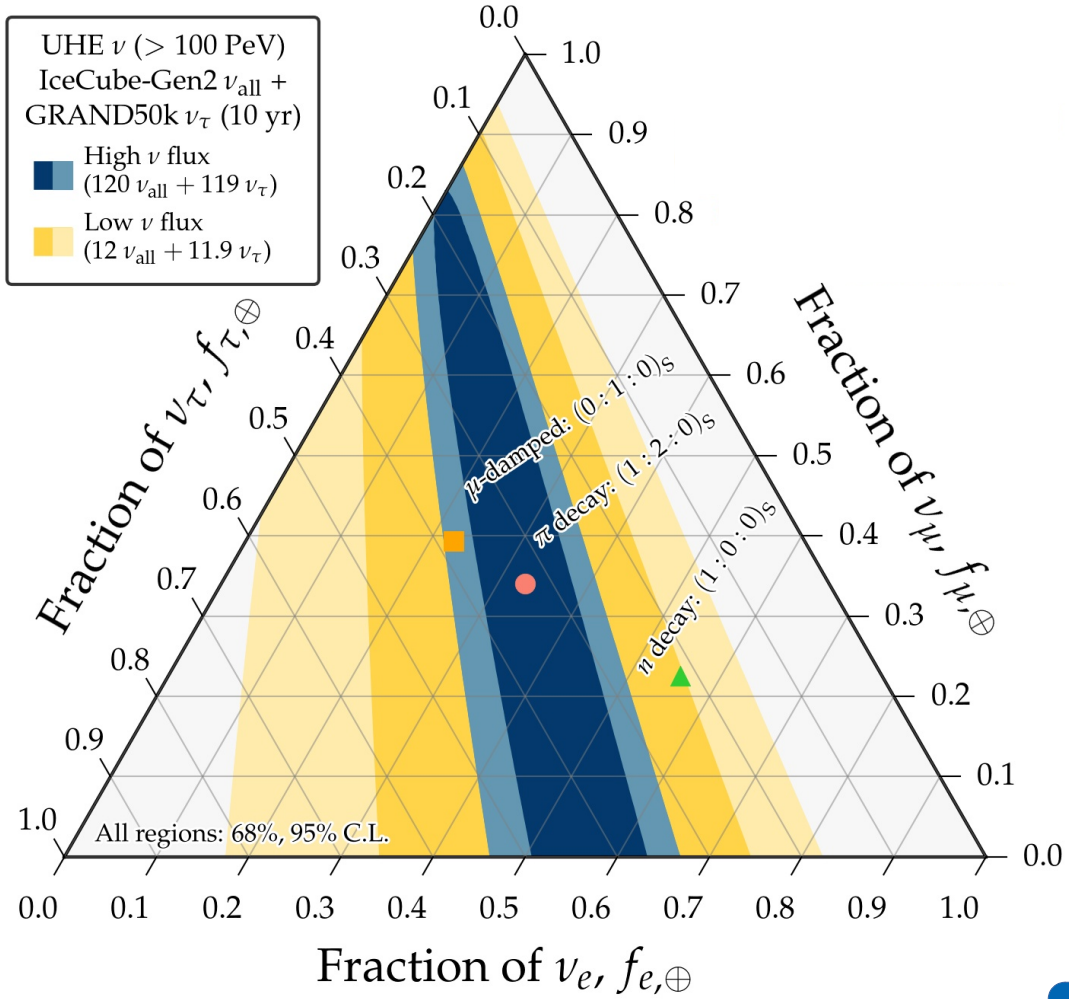
indistinct detection of all flavors by IceCube-Gen2 (radio)

+

predominant detection of ν_τ by GRAND

=

sensitivity to the fraction of UHE ν_τ



Testagrossa, Fiorillo, **MB**, 2310.12215

Manufacturing UHE flavor sensitivity with two detectors

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

Then we combine two of detectors:

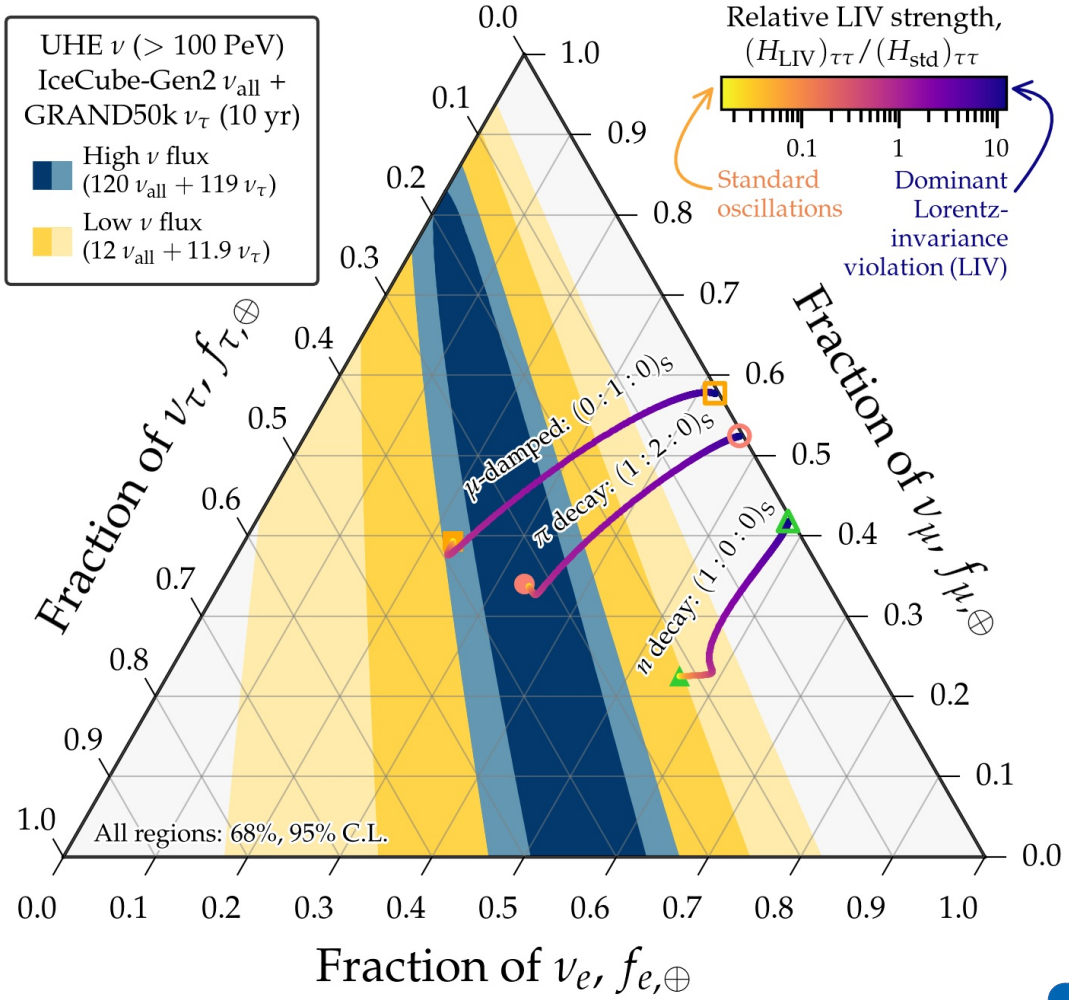
indistinct detection of all flavors by IceCube-Gen2 (radio)

+

predominant detection of ν_τ by GRAND

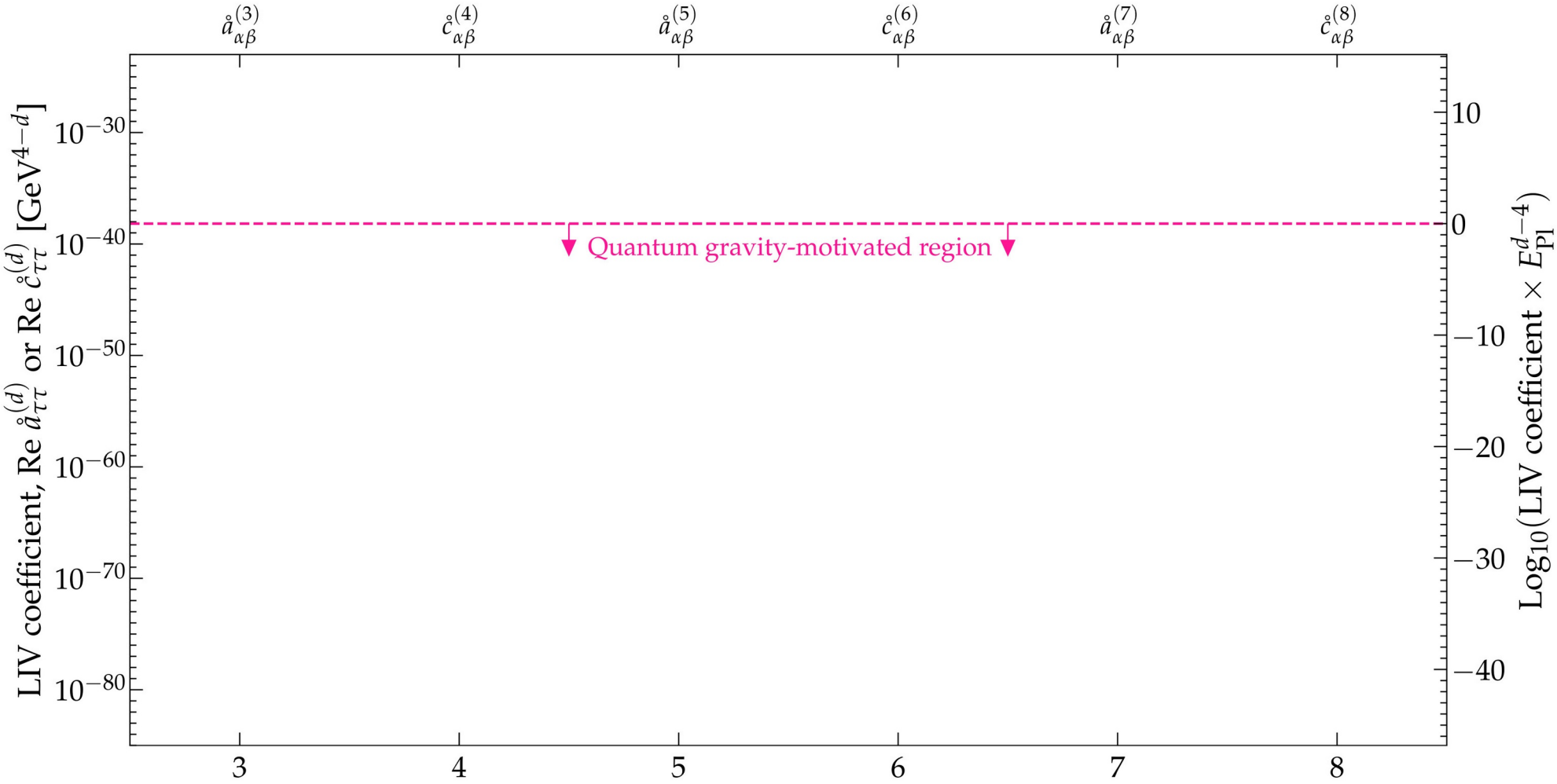
=

sensitivity to the fraction of UHE ν_τ



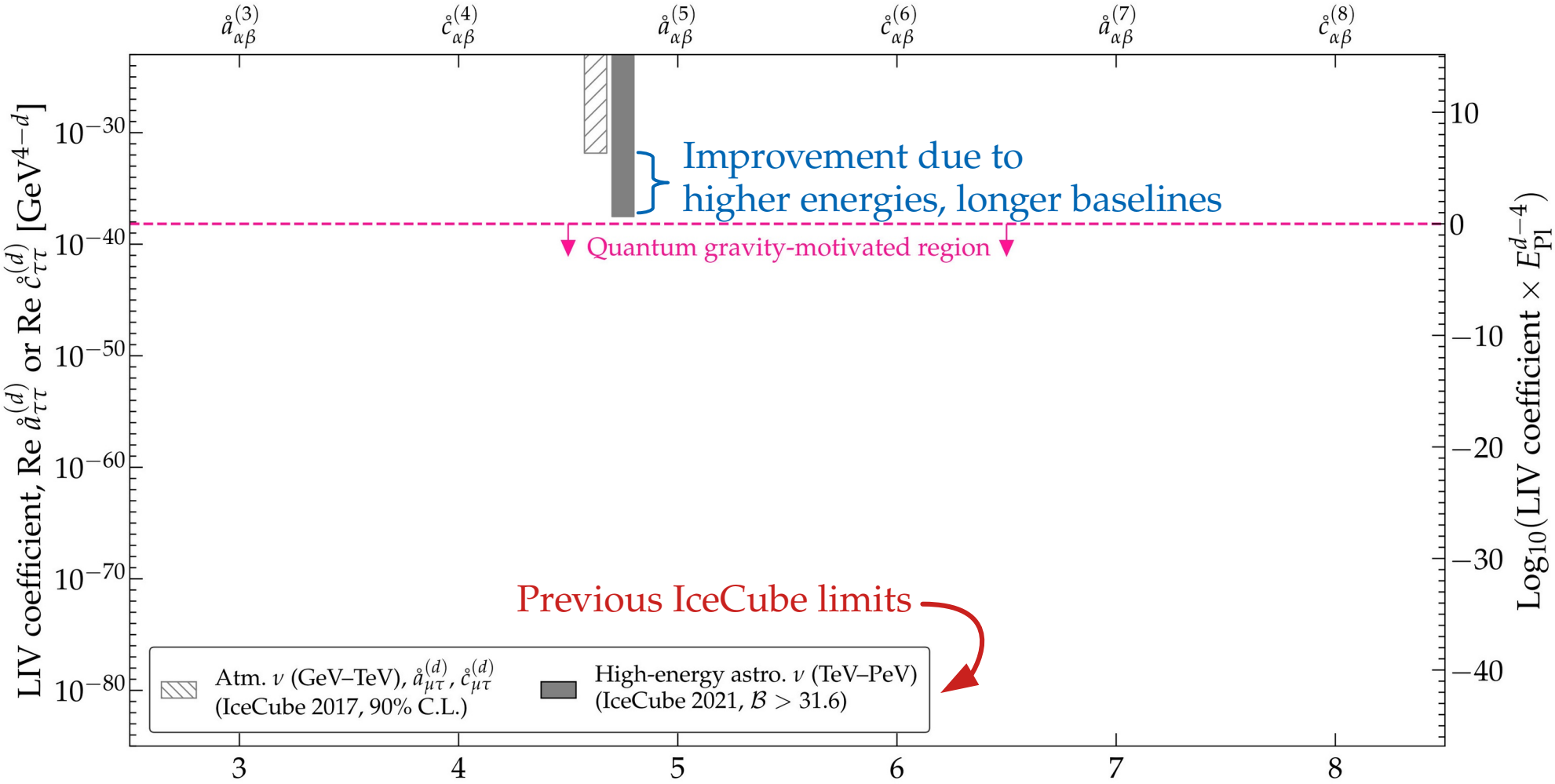
Testagrossa, Fiorillo, **MB**, 2310.12215

Lorentz-invariance violation at ultra-high energies



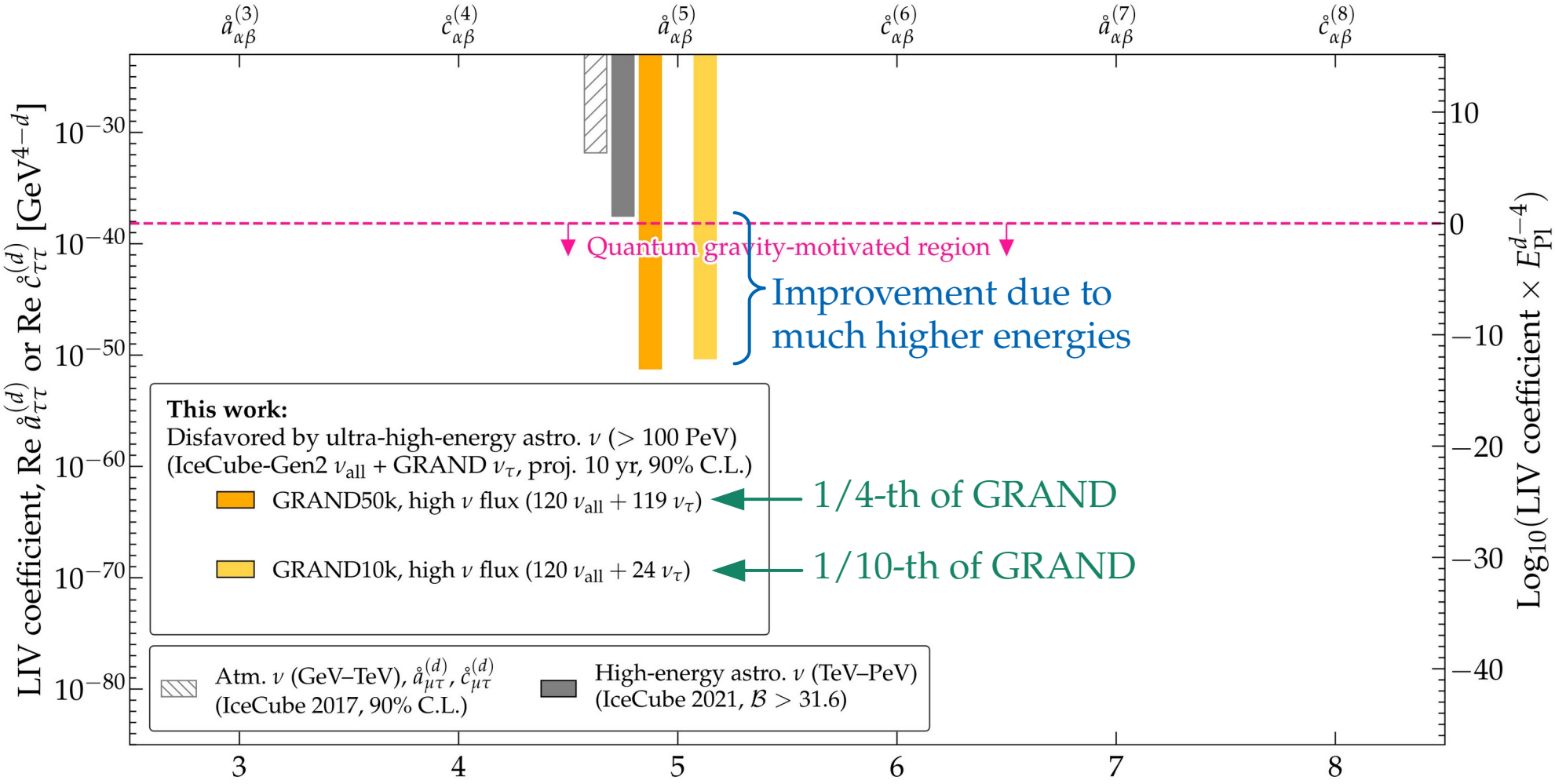
Testagrossa, Fiorillo, **MB**, 2310.12215

Lorentz-invariance violation at ultra-high energies



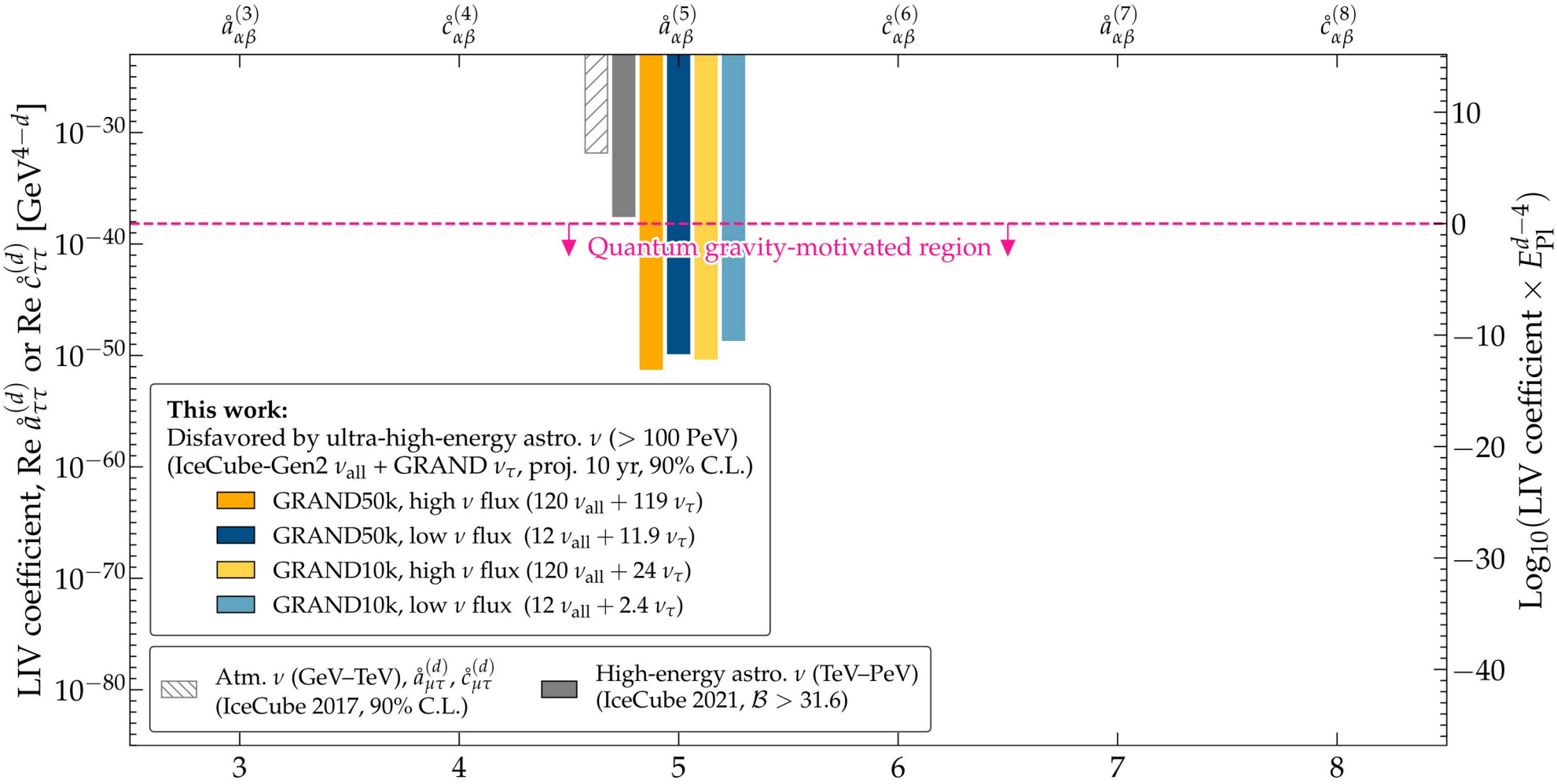
Testagrossa, Fiorillo, **MB**, 2310.12215

Lorentz-invariance violation at ultra-high energies



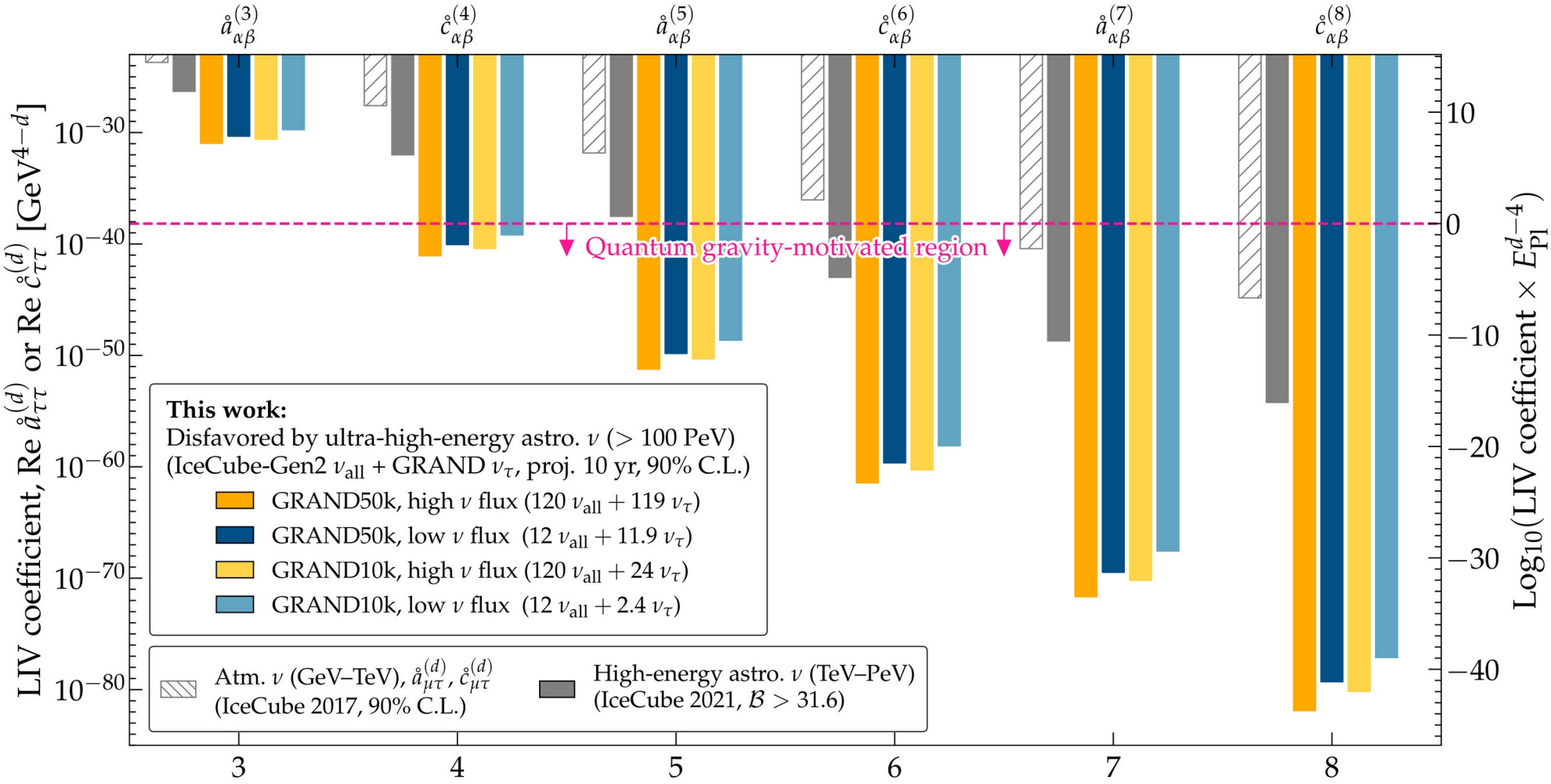
Testagrossa, Fiorillo, **MB**, 2310.12215

Lorentz-invariance violation at ultra-high energies



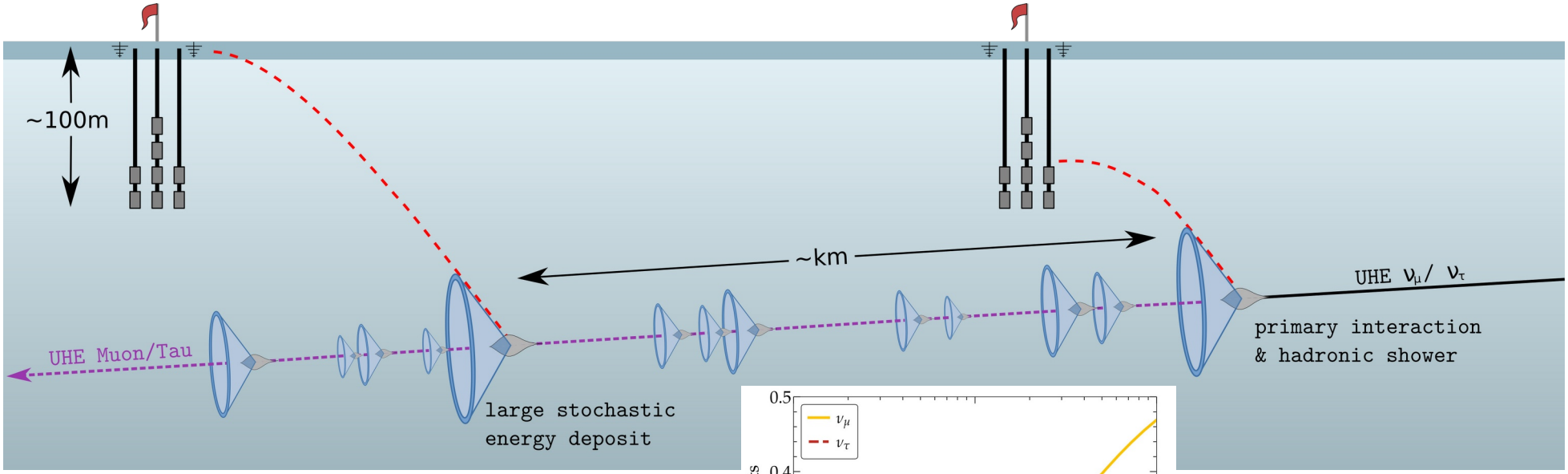
Testagrossa, Fiorillo, **MB**, 2310.12215

Lorentz-invariance violation at ultra-high energies

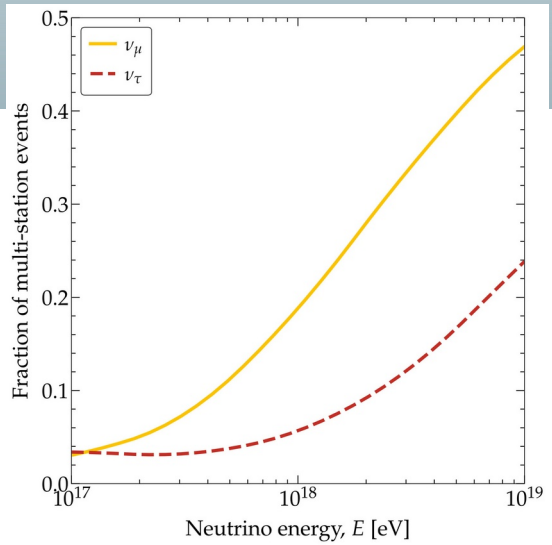


Testagrossa, Fiorillo, **MB**, 2310.12215

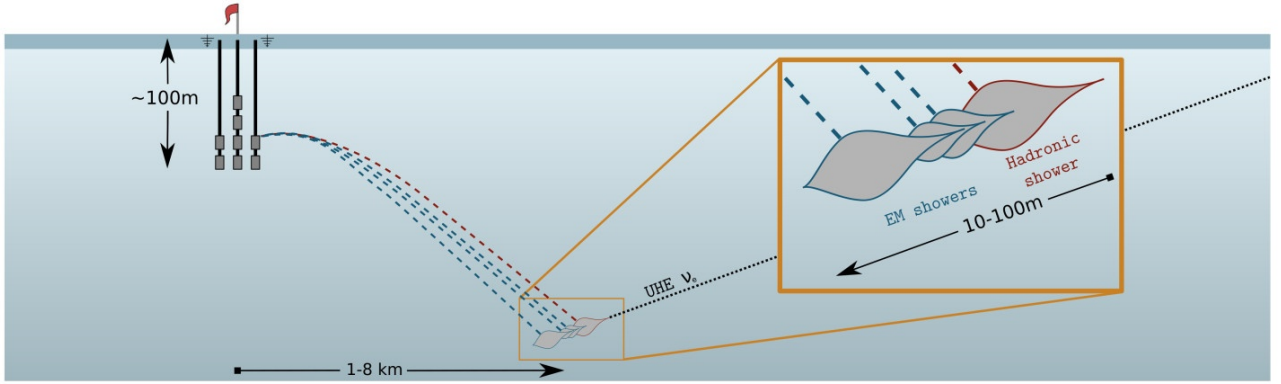
Multi-shower events from $\nu_\mu + \nu_\tau$ in IceCube-Gen2 (radio)

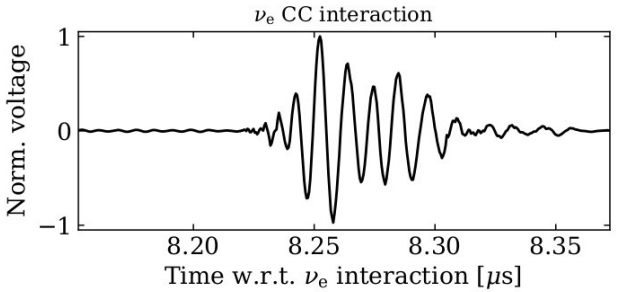


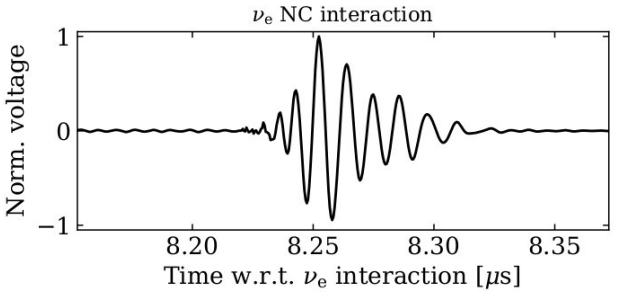
Coleman, Ericsson, **MB**, Glaser, 2402.02432

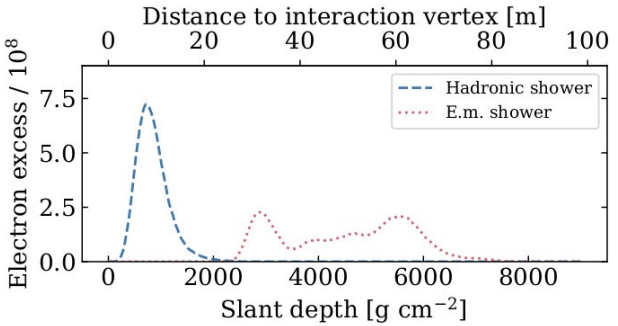


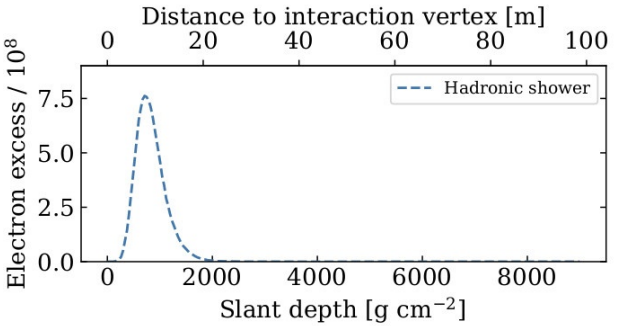
Multi-shower ν_e CC interactions in IceCube-Gen2 (radio)





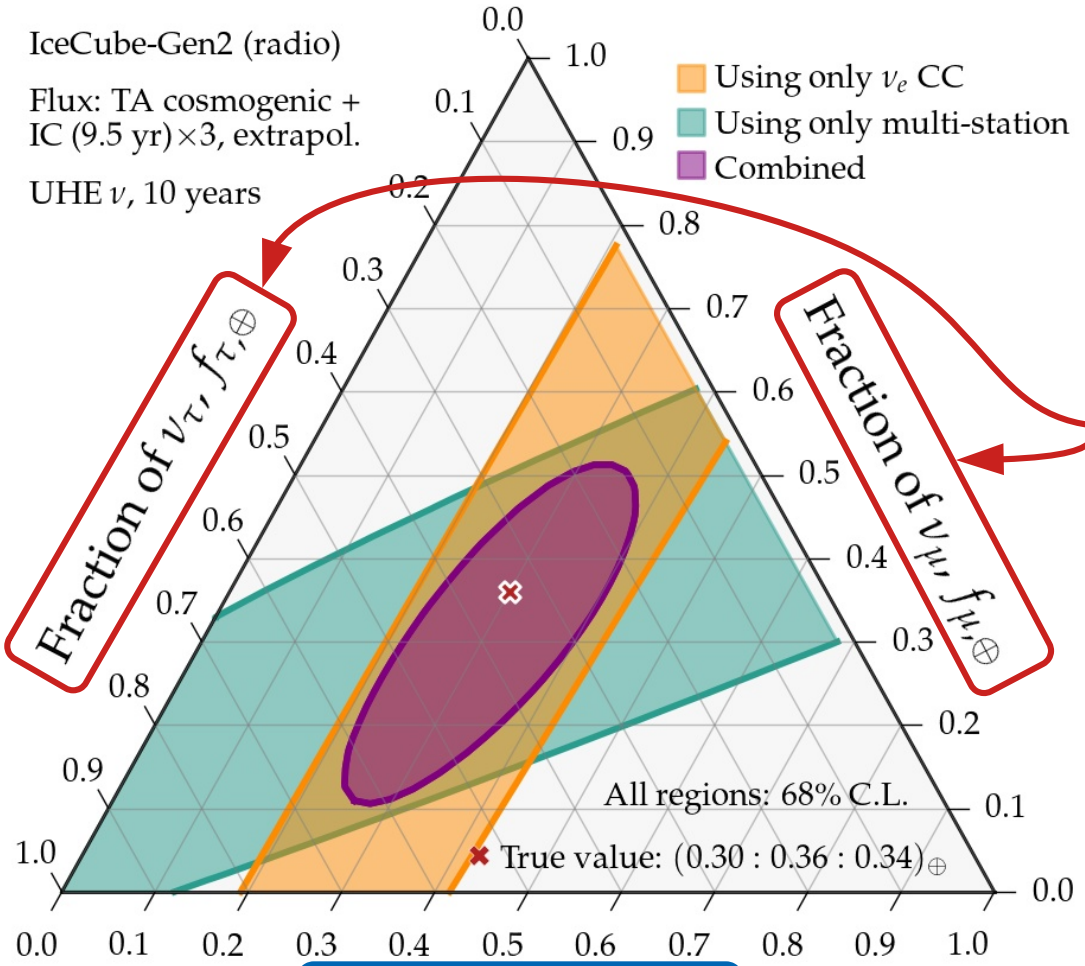






Coleman, Ericsson, **MB**, Glaser, 2402.02432

IceCube-Gen2 (radio) alone might measure flavor



Fraction of ν_e

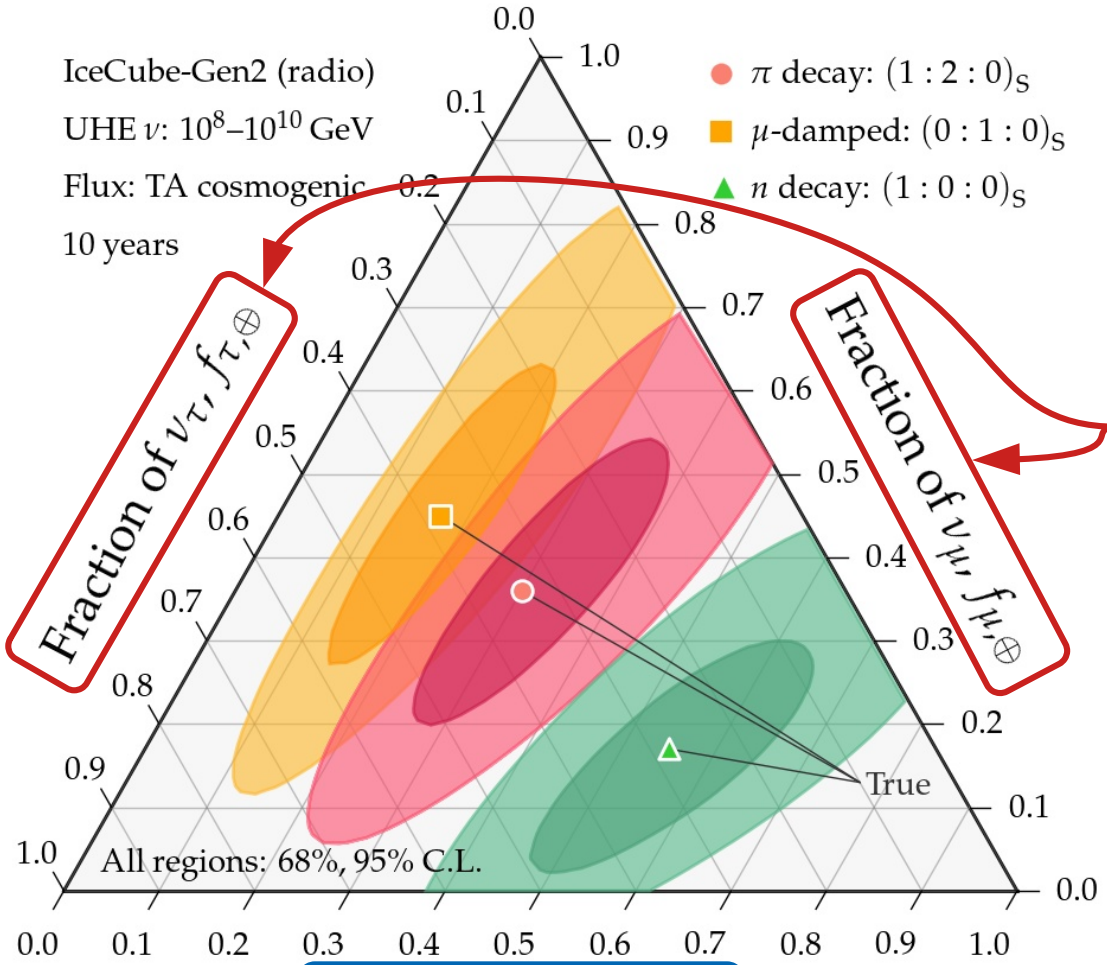
Showers are elongated due to the LPM effect

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

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

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

IceCube-Gen2 (radio) alone might measure flavor



Fraction of ν_e

Showers are elongated due to the LPM effect

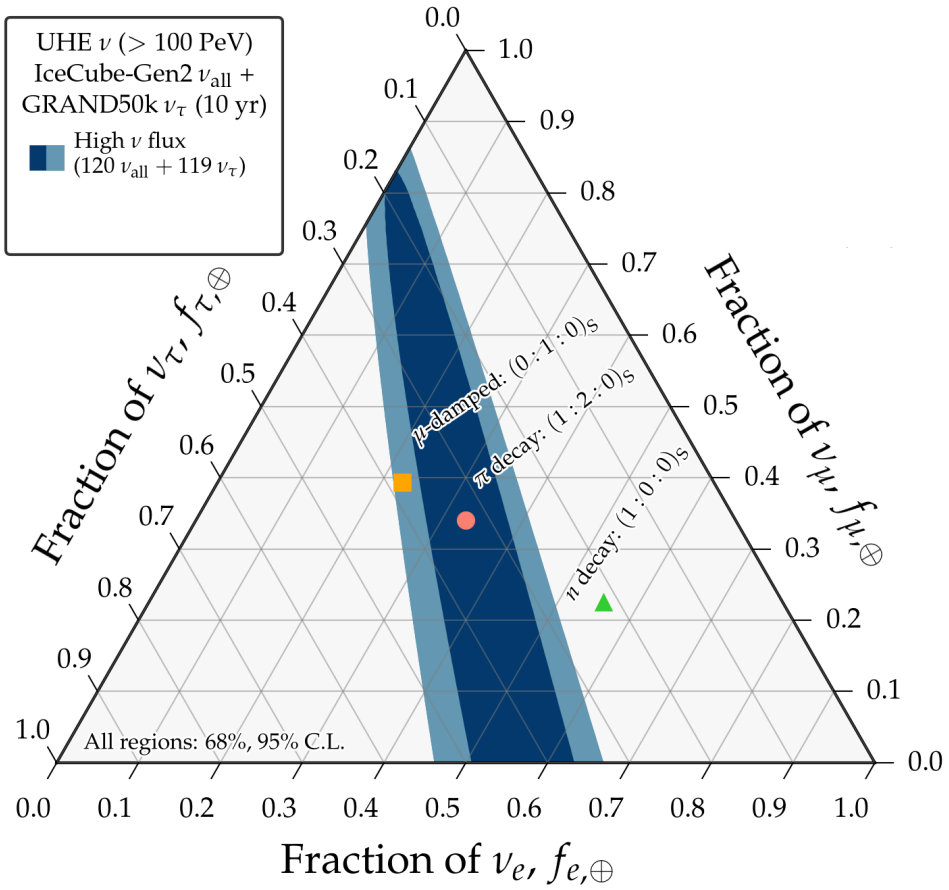
Fraction of $\nu_\mu + \nu_\tau$

Secondary muons and tauons create showers that hit >1 radio station

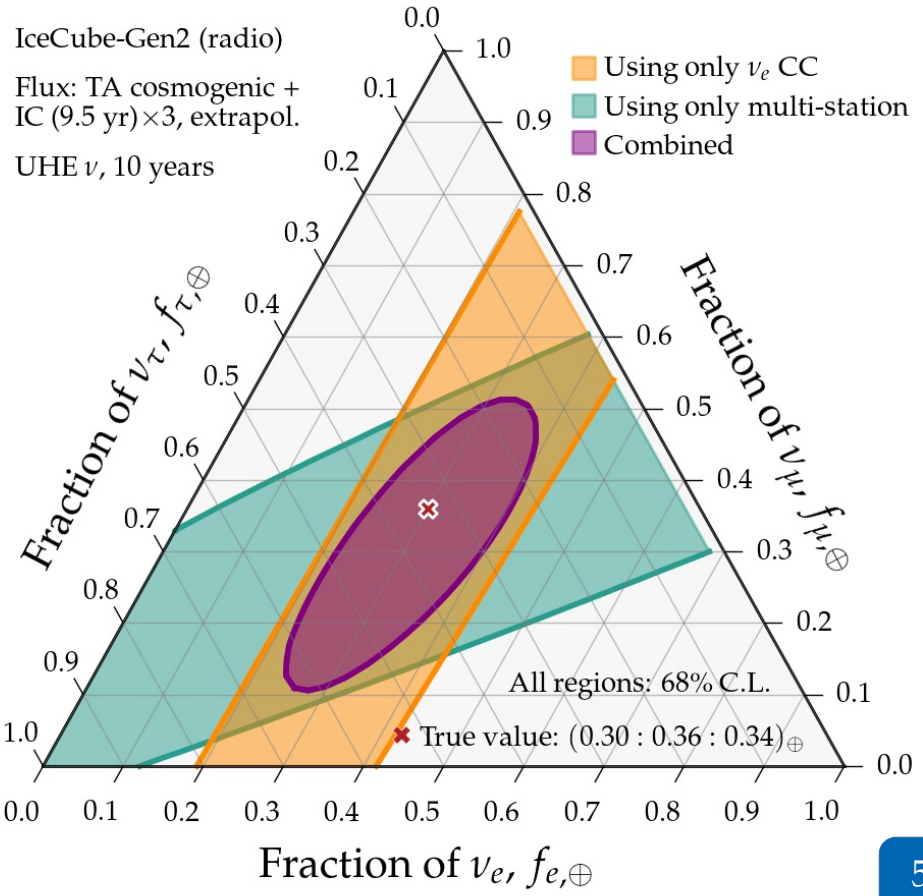
Coleman, Ericsson, **MB**, Glaser, 2402.02432

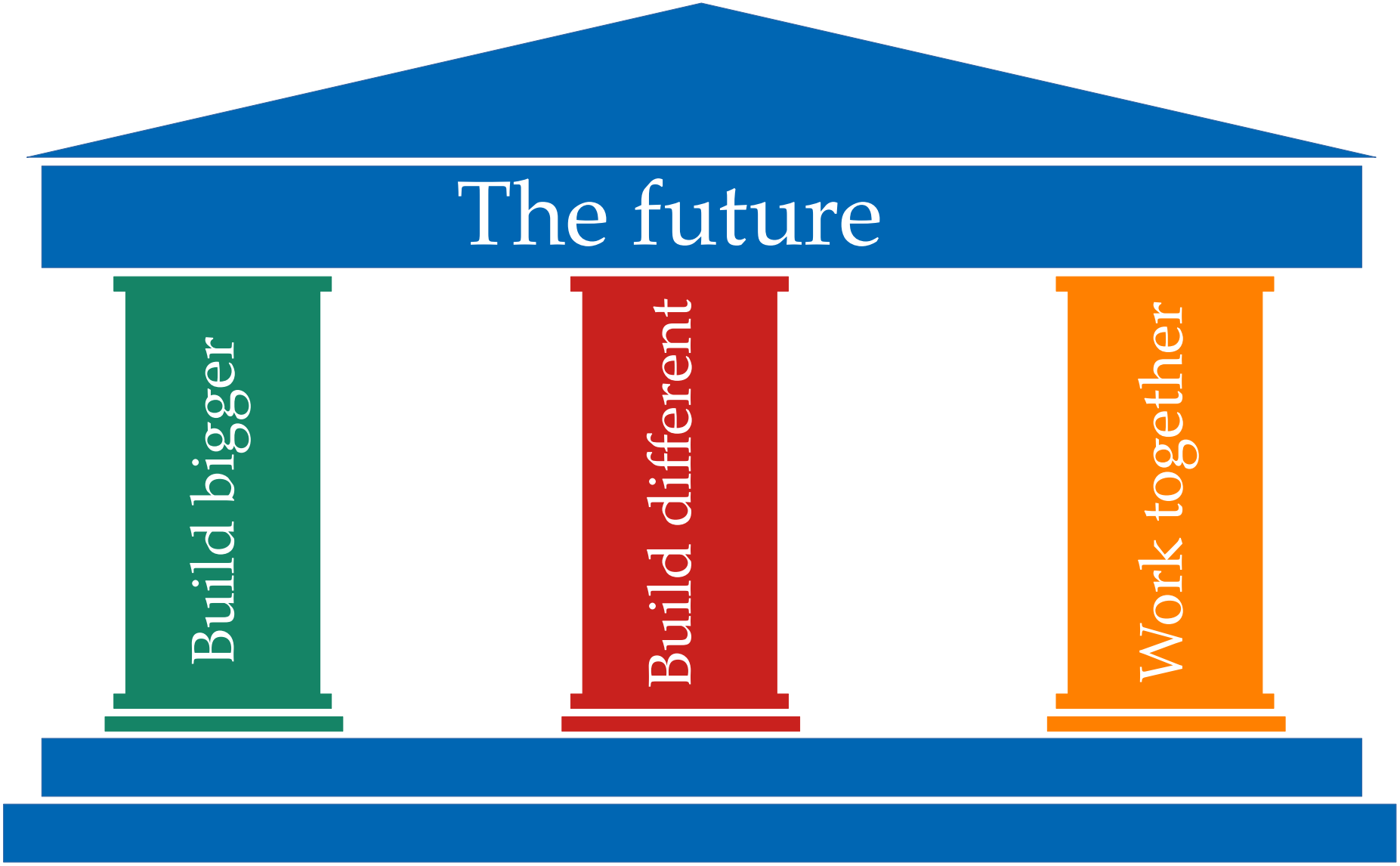
Accessing the full UHE flavor information

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)

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

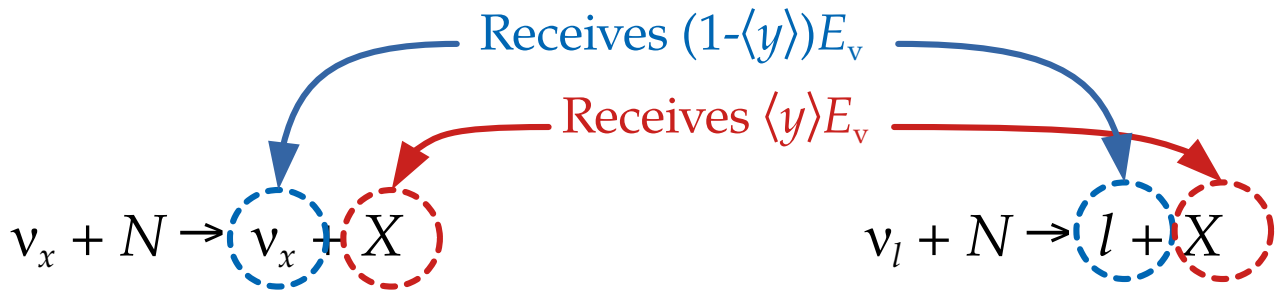
Charged current (CC)

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

How does IceCube see TeV–PeV neutrinos?

Deep inelastic neutrino-nucleon scattering

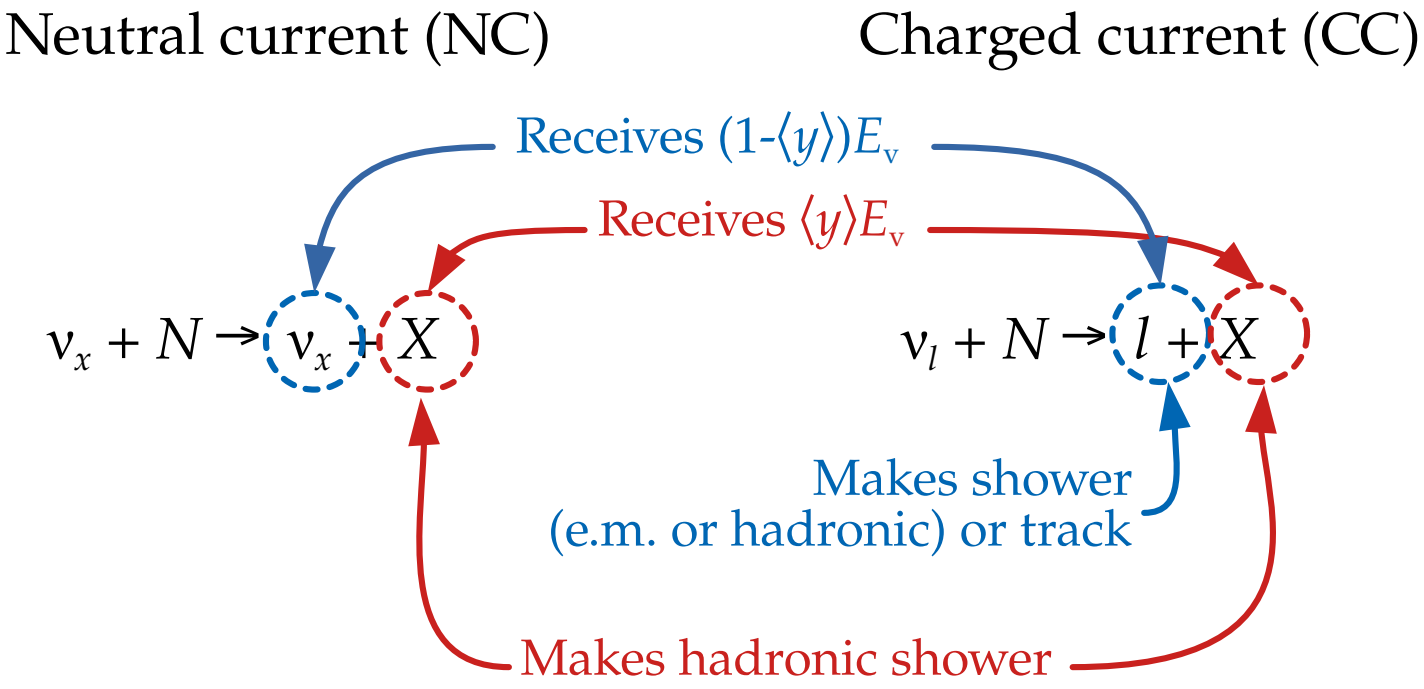
Neutral current (NC) Charged current (CC)



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

How does IceCube see TeV–PeV neutrinos?

Deep inelastic neutrino-nucleon scattering



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

Flavor at the Earth: *theoretically palatable regions*

Theoretically palatable flavor regions

≡

Allowed regions of flavor ratios at Earth derived from oscillations

MB, Beacom, Winter, *PRL* 2015

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

Flavor at the Earth: *theoretically palatable regions*

Theoretically palatable flavor regions

≡

Allowed regions of flavor ratios at Earth derived from oscillations

MB, Beacom, Winter, *PRL* 2015

Ingredient #1:

Flavor ratios at the source,

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

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

or

Explore all possible combinations

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

≡

Allowed regions of flavor ratios at Earth derived from oscillations

MB, Beacom, Winter, *PRL* 2015

Ingredient #1:

Flavor ratios at the source,

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

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

or

Explore all possible combinations

Ingredient #2:

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

≡

Allowed regions of flavor ratios at Earth derived from oscillations

MB, Beacom, Winter, *PRL* 2015

Ingredient #1:
Flavor ratios at the source,
$(f_{e,S}, f_{\mu,S}, f_{\tau,S})$

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

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

≡

Allowed regions of flavor ratios at Earth derived from oscillations

MB, Beacom, Winter, *PRL* 2015

Ingredient #1:

Flavor ratios at the source,

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

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

or

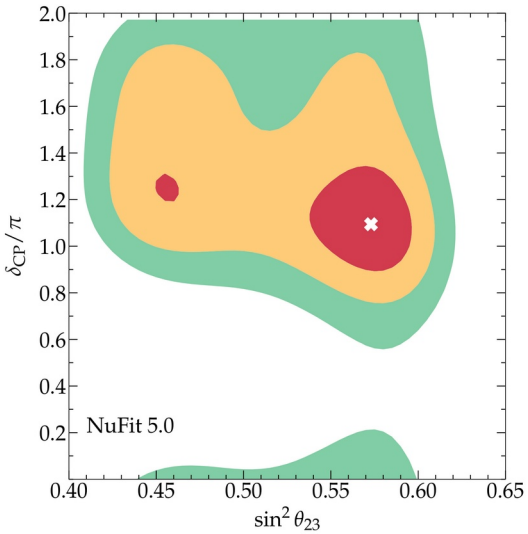
Explore all possible combinations

Ingredient #2:

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

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

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



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

≡

Allowed regions of flavor ratios at Earth derived from oscillations

MB, Beacom, Winter, *PRL* 2015

Ingredient #1:

Flavor ratios at the source,

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

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

or

Explore all possible combinations

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

Ingredient #2:

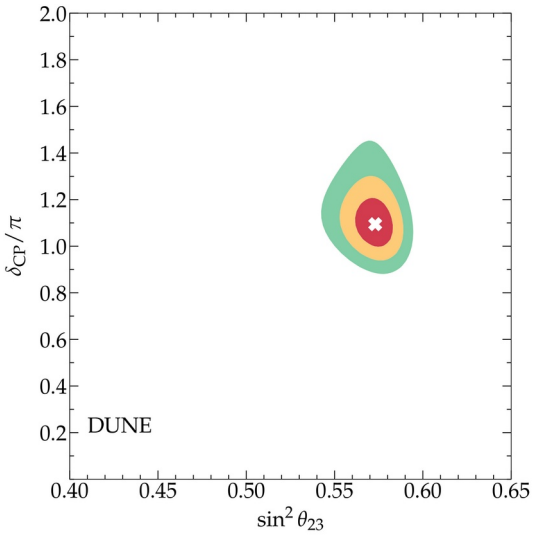
Probability density of mixing parameters $(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{CP})$

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

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

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

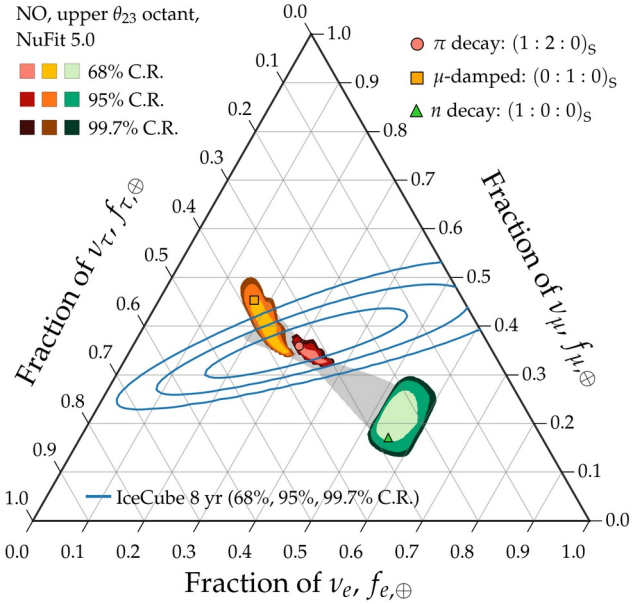


Theoretically palatable regions: 2020 → 2030 → 2040

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

Theoretically palatable regions: 2020 → 2030 → 2040

2020



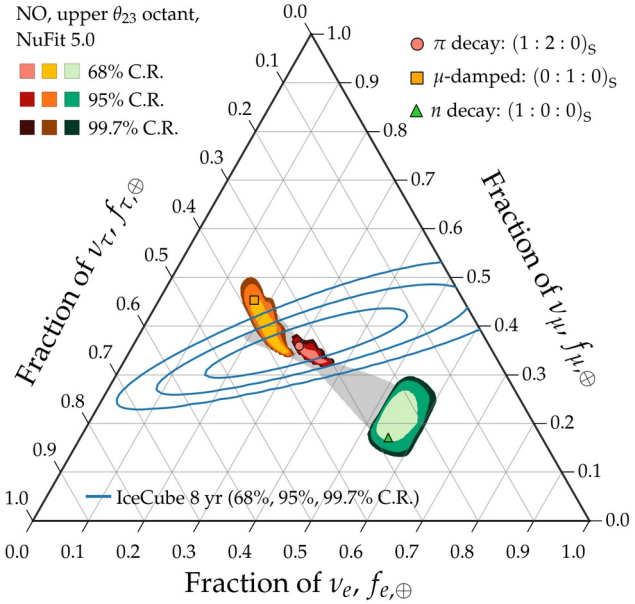
Allowed regions: overlapping

Measurement: imprecise

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

Theoretically palatable regions: 2020 → 2030 → 2040

2020



Allowed regions: overlapping

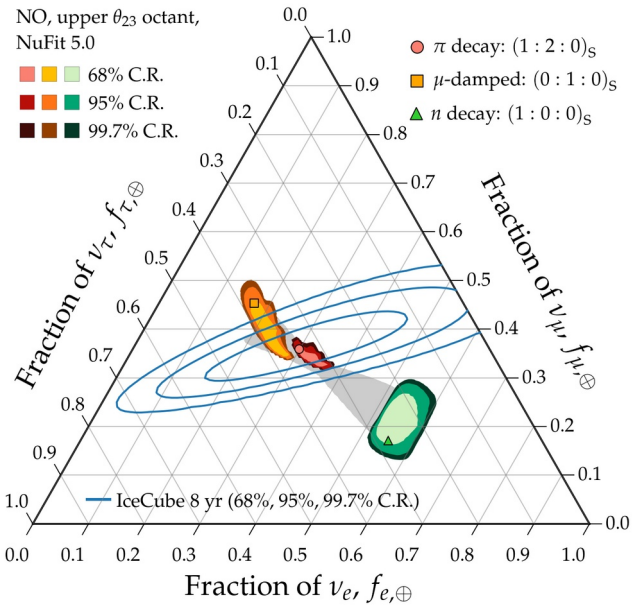
Measurement: imprecise

Not ideal

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

Theoretically palatable regions: 2020 → 2030 → 2040

2020

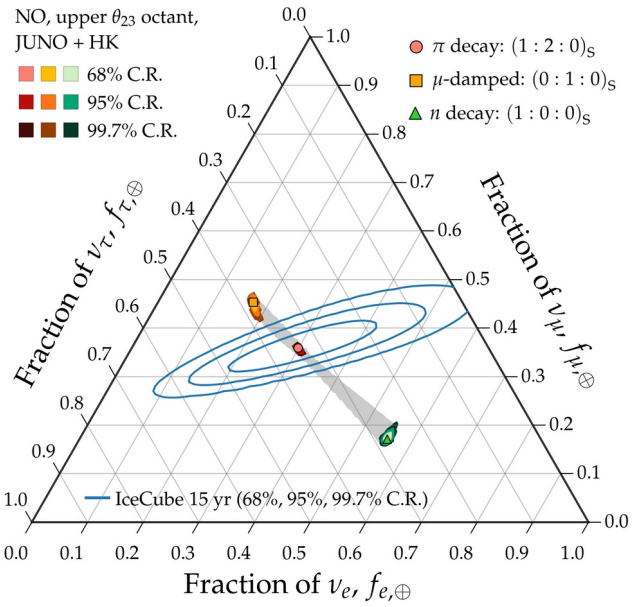


Allowed regions: overlapping

Measurement: imprecise

Not ideal

2030



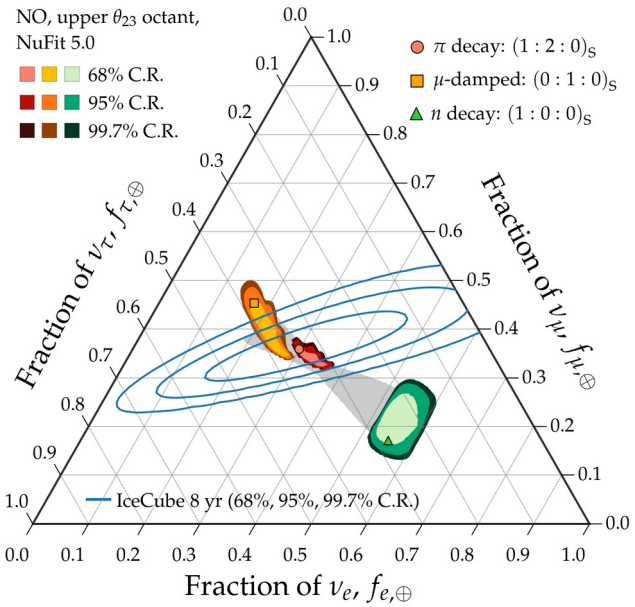
Allowed regions: well separated

Measurement: improving

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

Theoretically palatable regions: 2020 → 2030 → 2040

2020

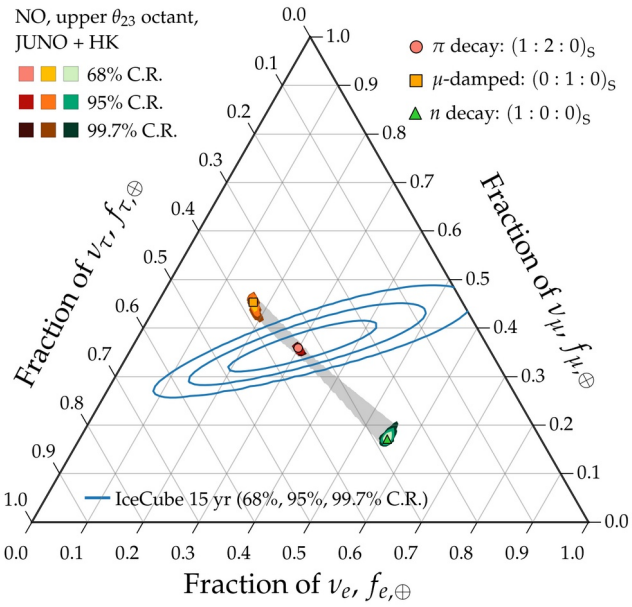


Allowed regions: overlapping

Measurement: imprecise

Not ideal

2030



Allowed regions: well separated

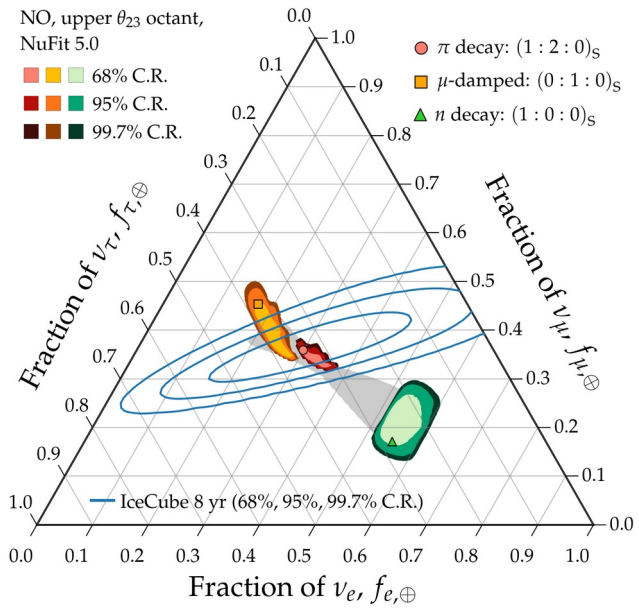
Measurement: improving

Nice

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

Theoretically palatable regions: 2020 → 2030 → 2040

2020

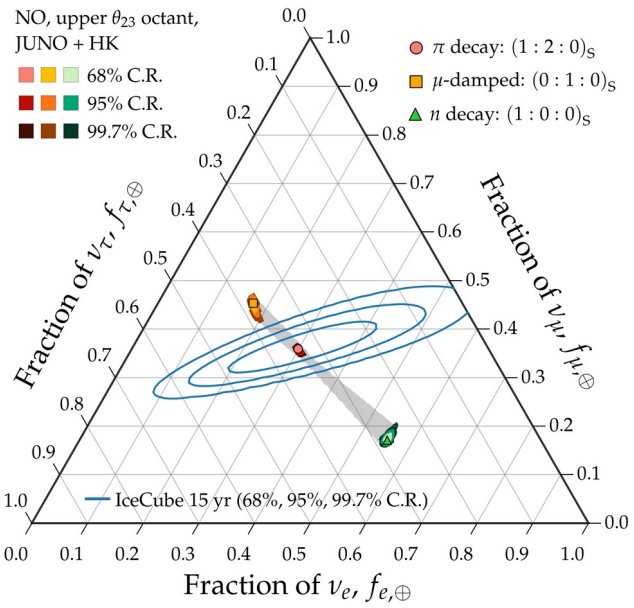


Allowed regions: overlapping

Measurement: imprecise

Not ideal

2030

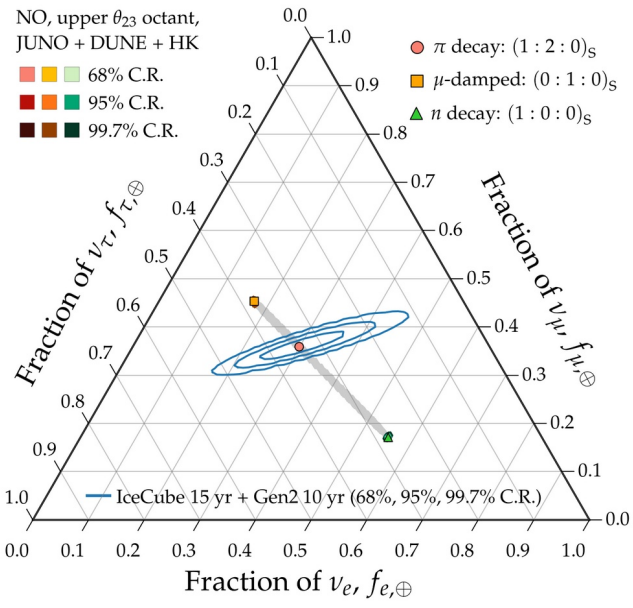


Allowed regions: well separated

Measurement: improving

Nice

2040



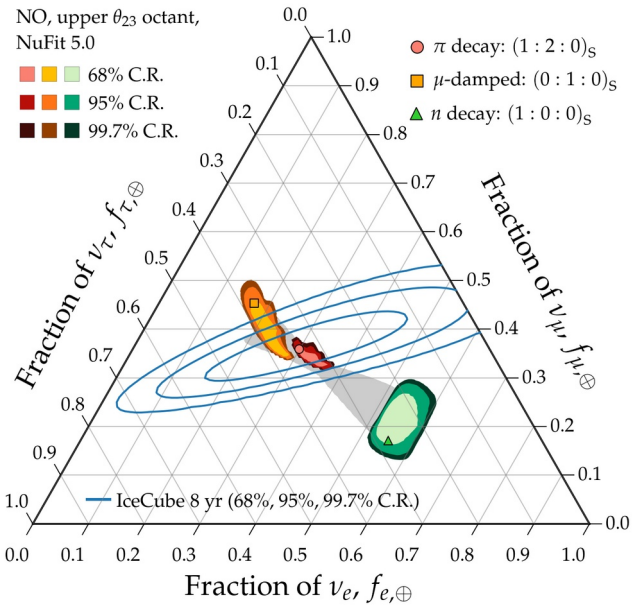
Allowed regions: well separated

Measurement: precise

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

Theoretically palatable regions: 2020 → 2030 → 2040

2020

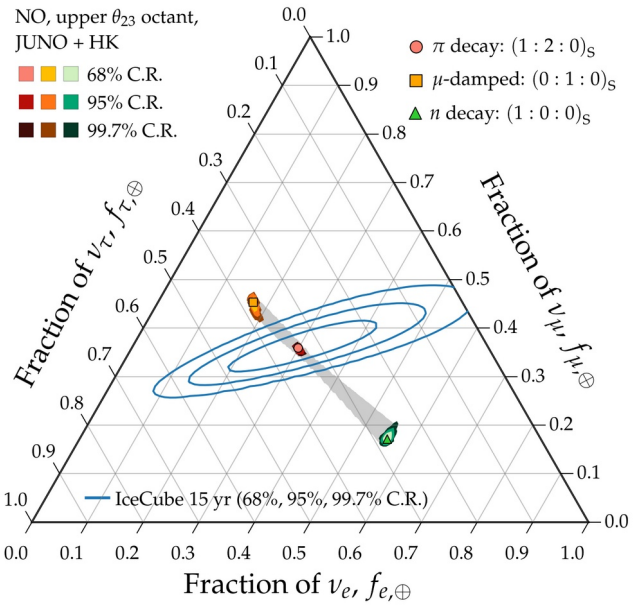


Allowed regions: overlapping

Measurement: imprecise

Not ideal

2030

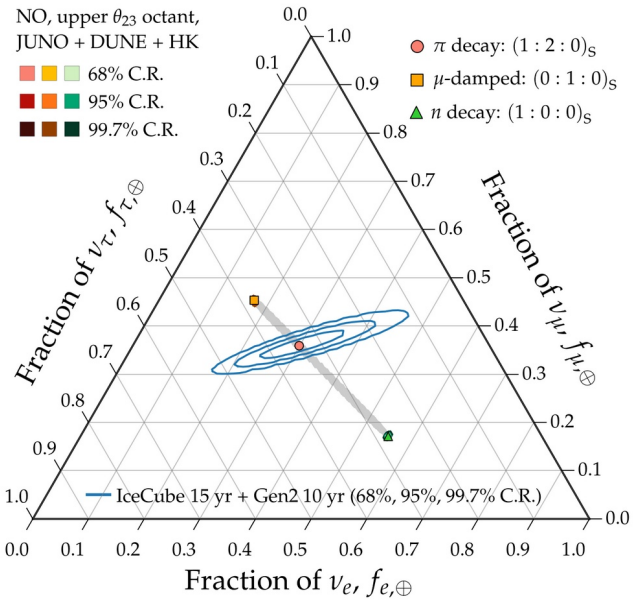


Allowed regions: well separated

Measurement: improving

Nice

2040

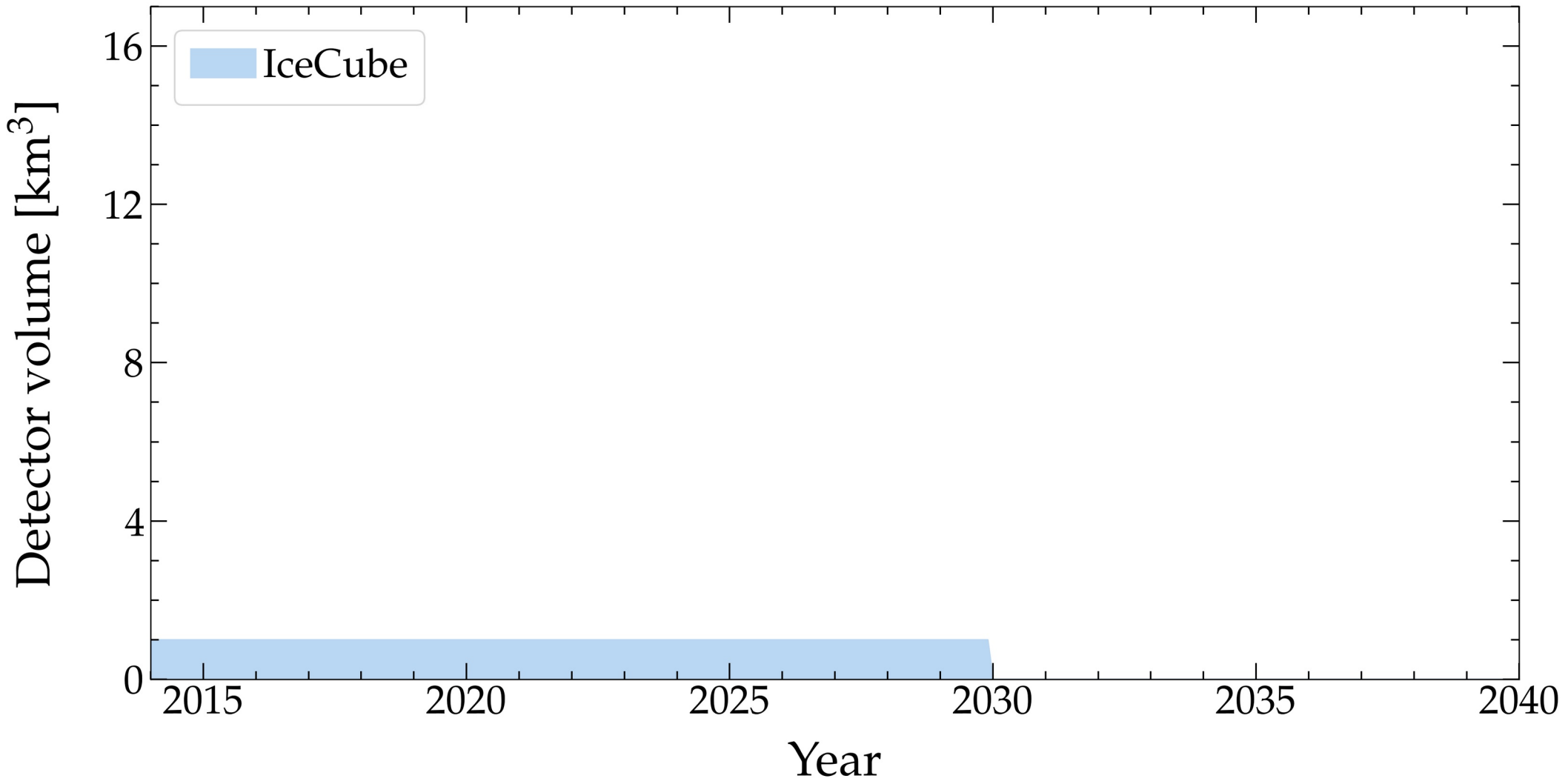


Allowed regions: well separated

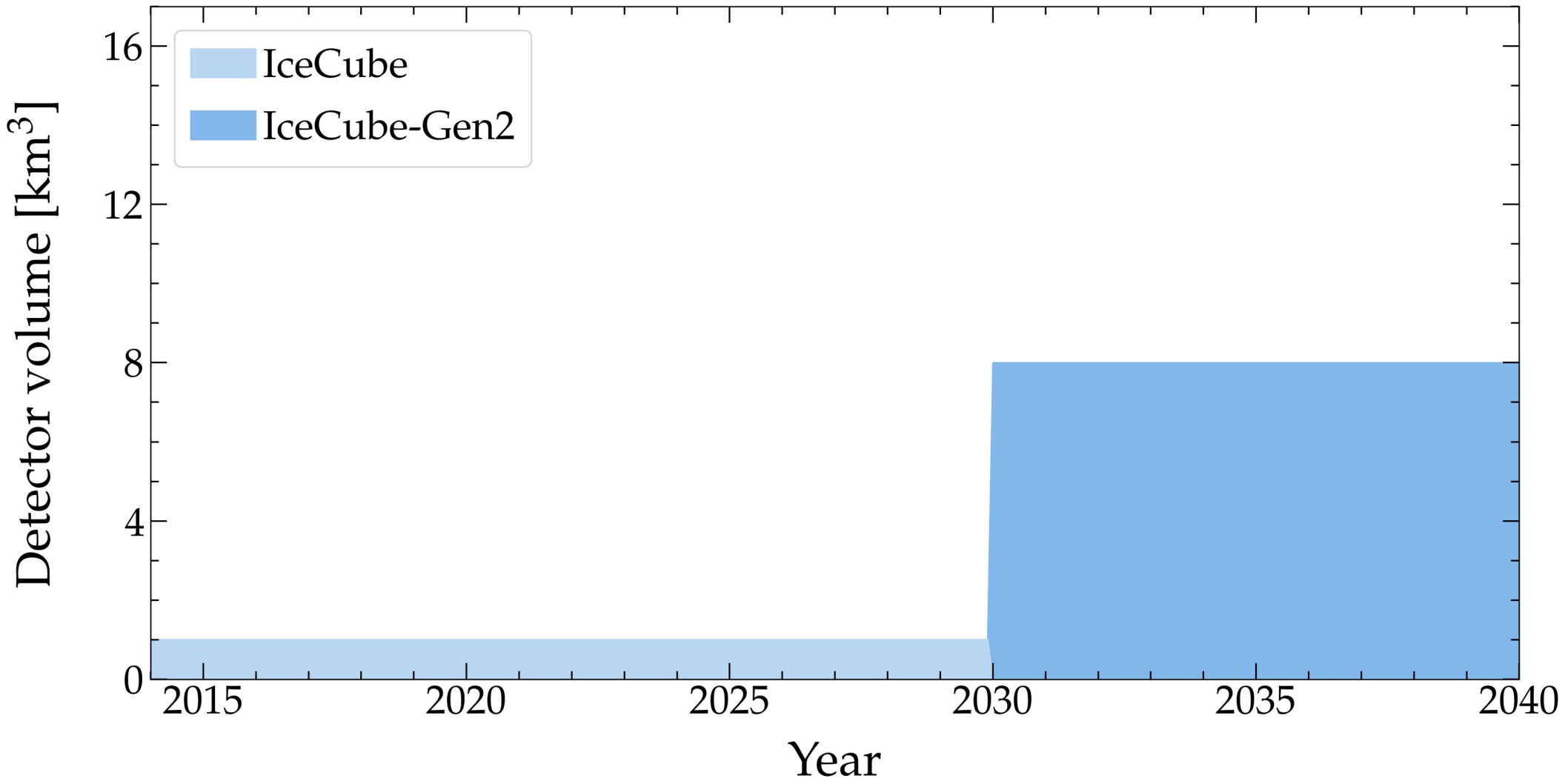
Measurement: precise

Success

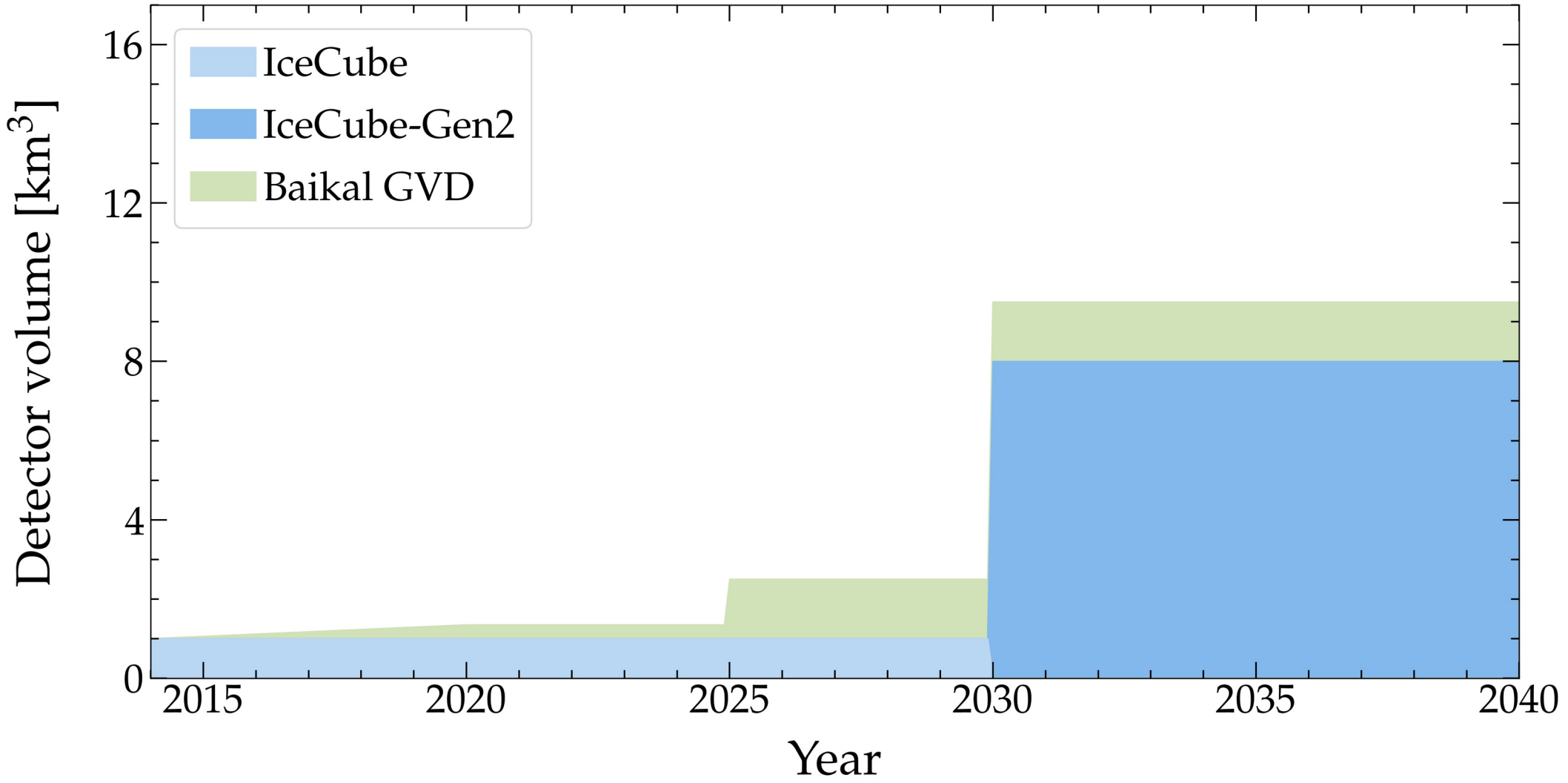
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



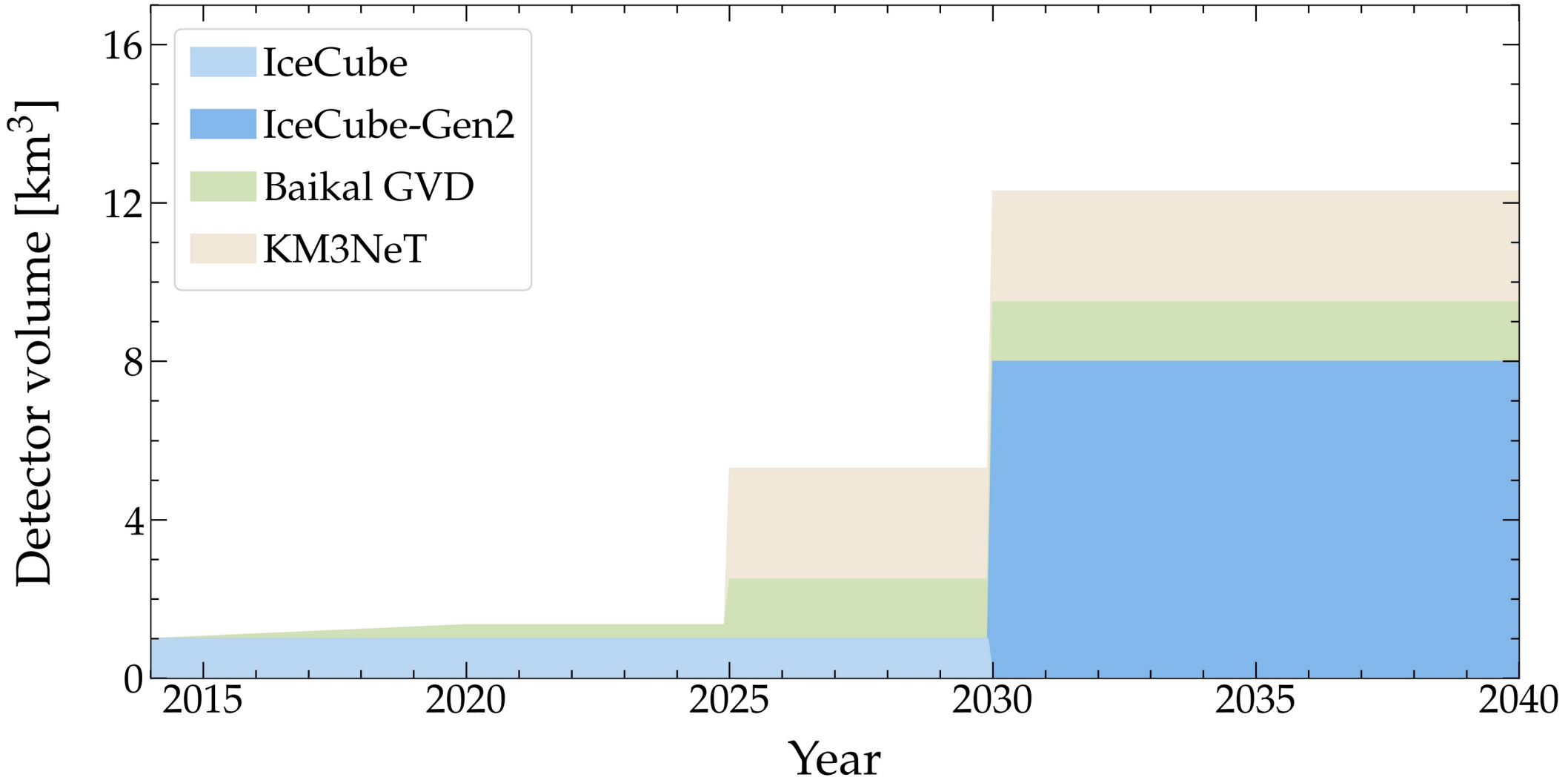
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



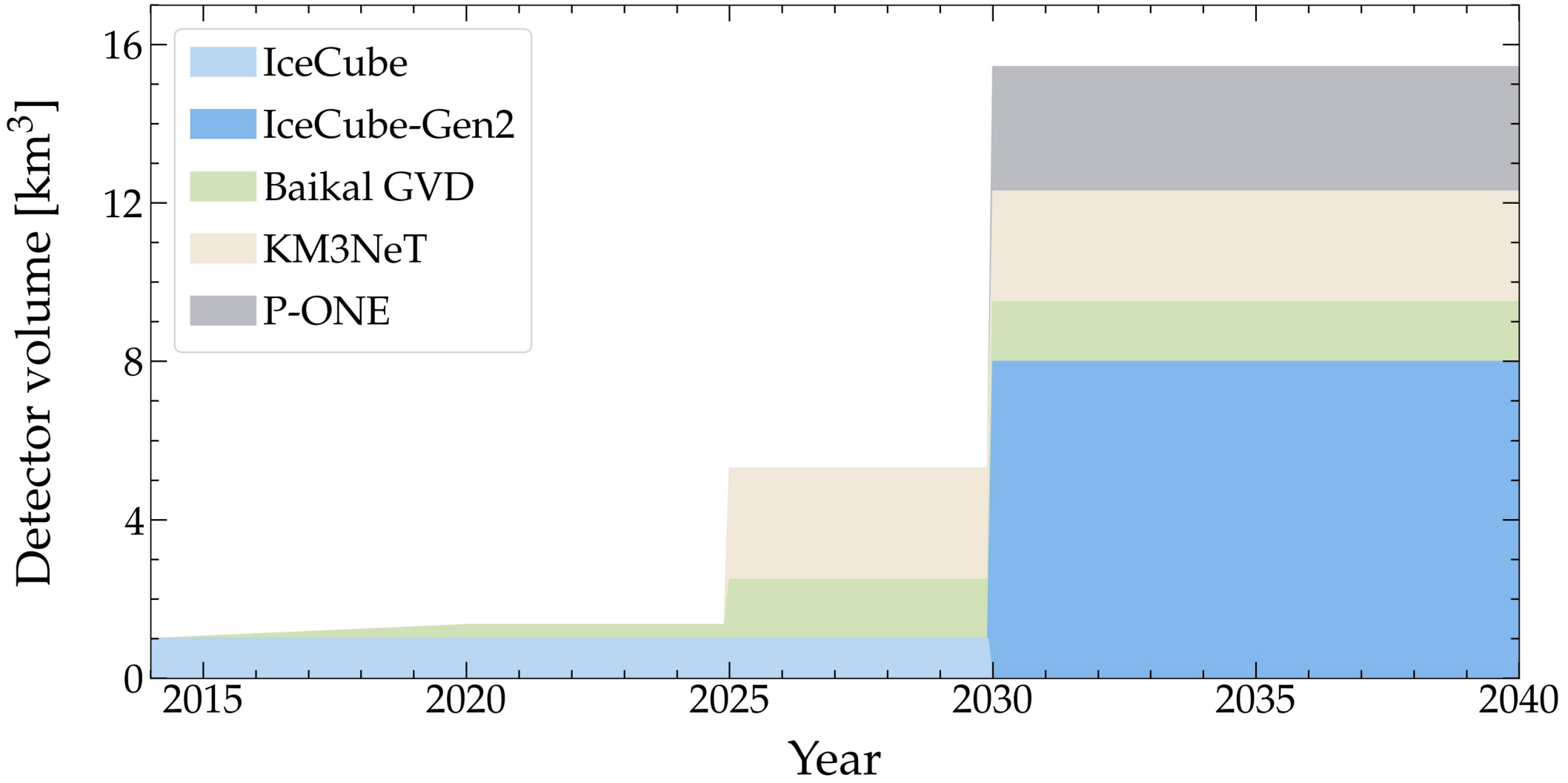
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



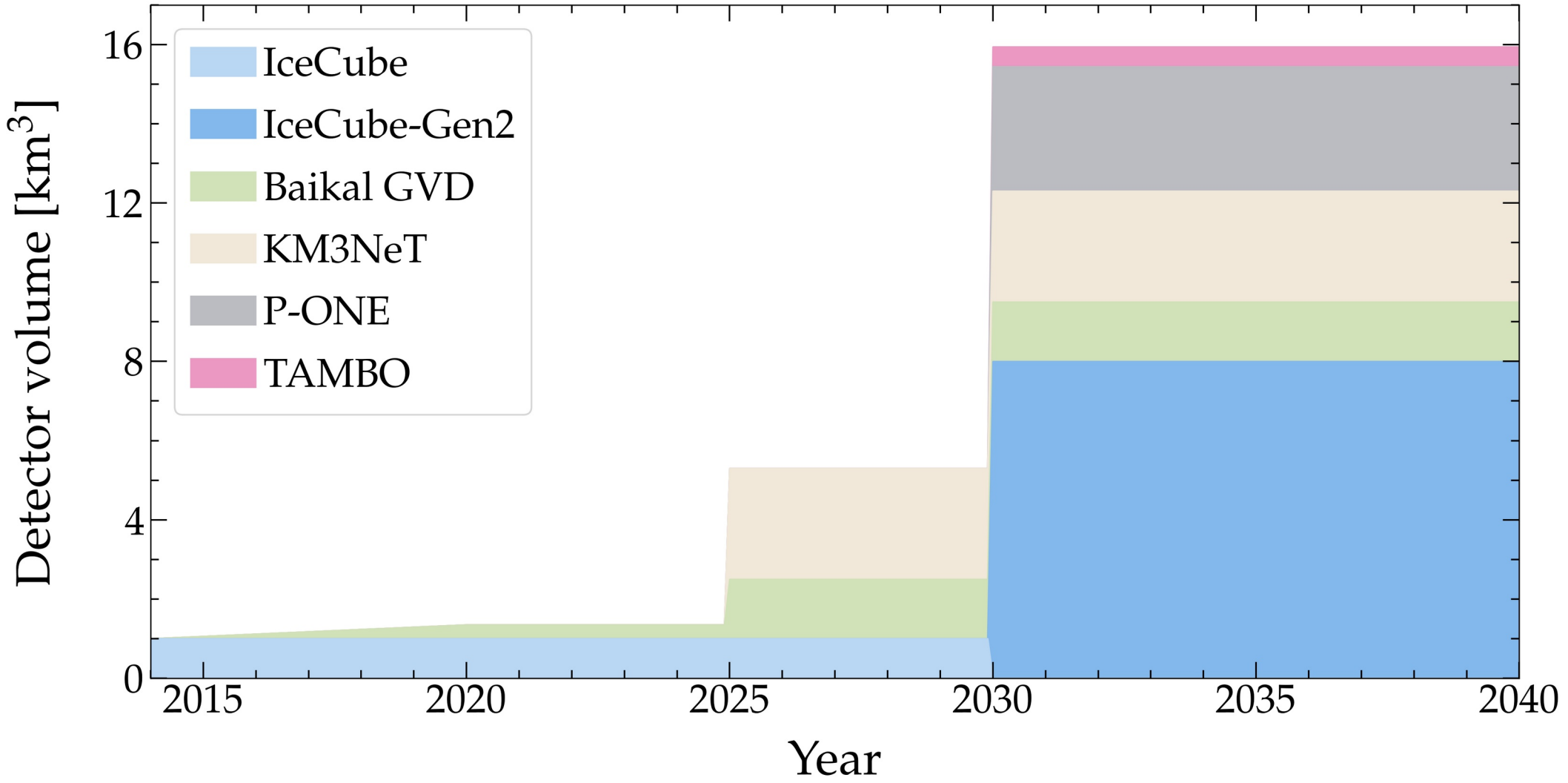
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



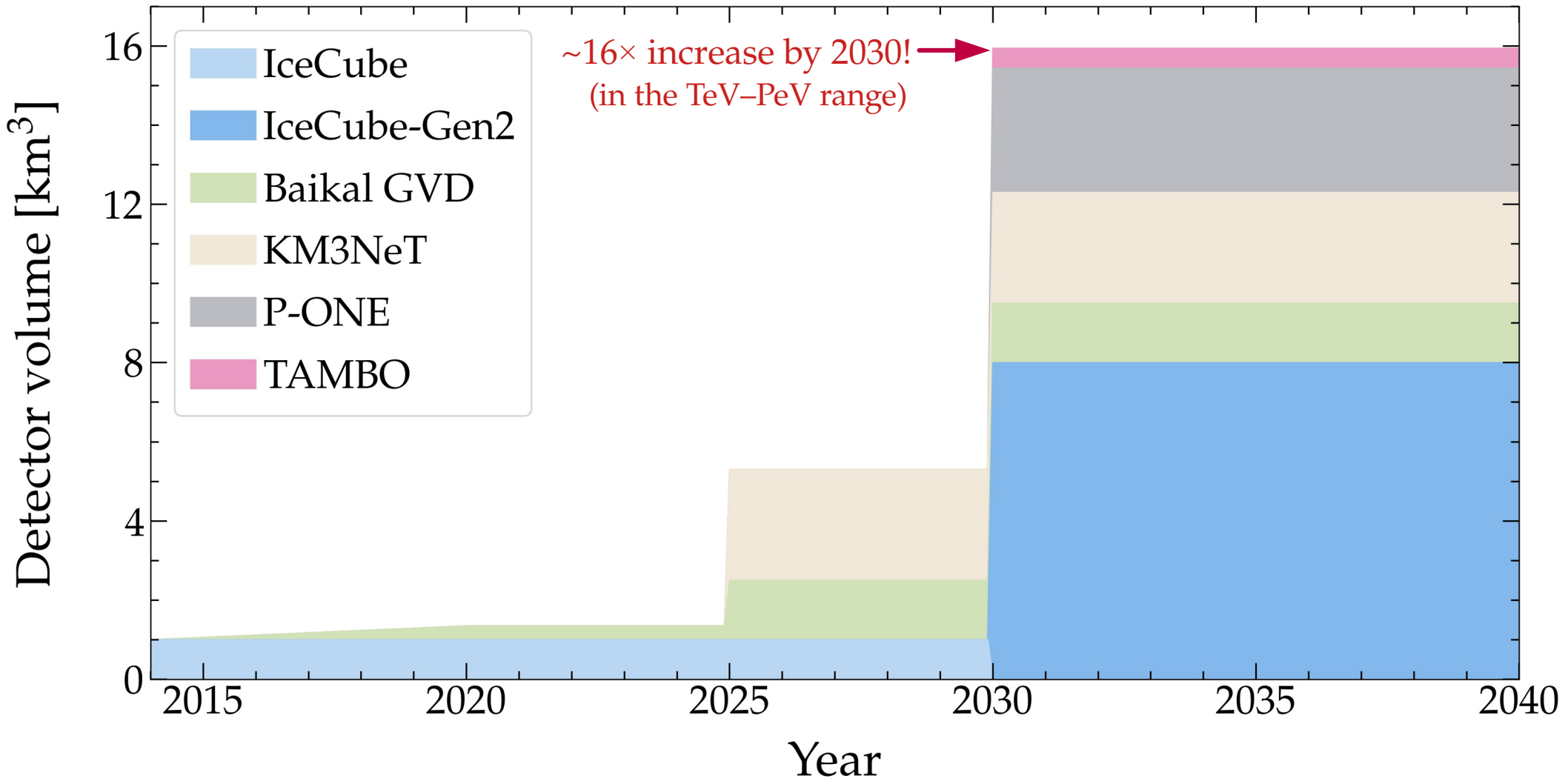
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



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



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



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

Fundamental physics with high-energy cosmic neutrinos

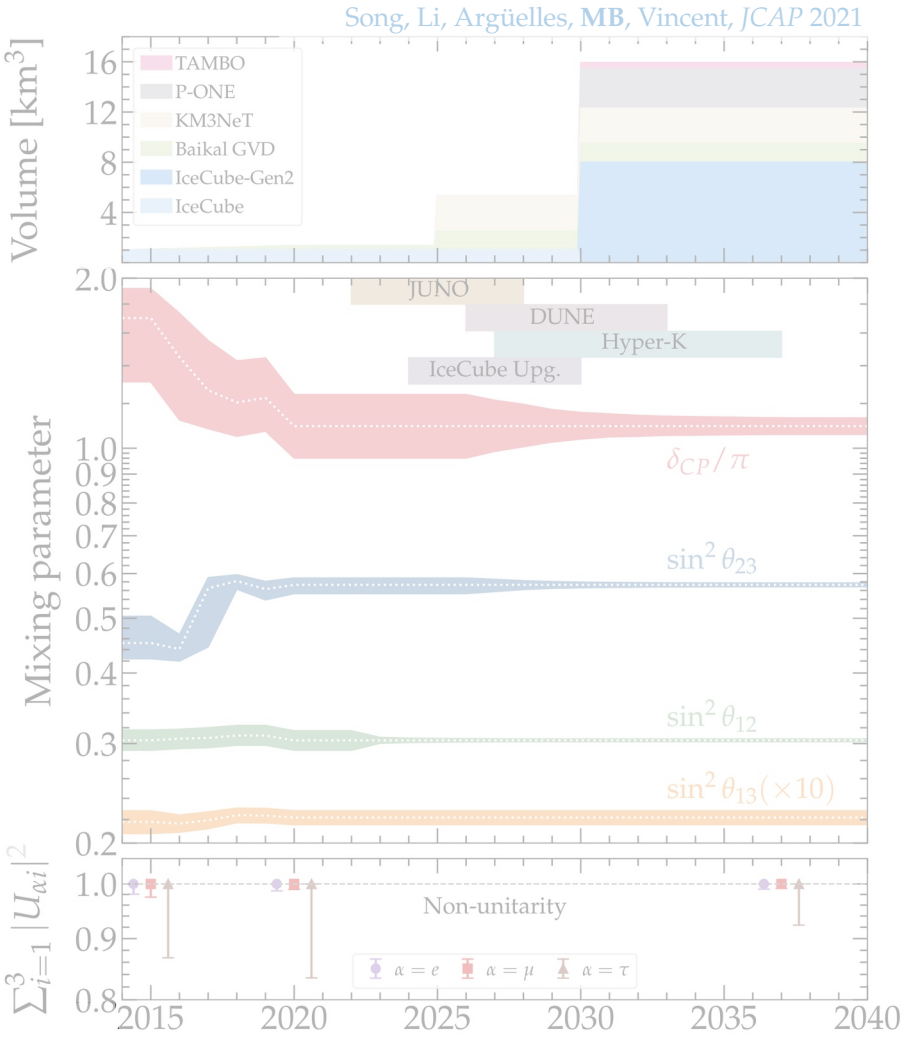
- Numerous new ν physics effects grow as $\sim \kappa_n \cdot E^n \cdot L$
- So we can probe $\kappa_n \sim 4 \cdot 10^{-47}\ (E/\mathrm{PeV})^{-n}\ (L/\mathrm{Gpc})^{-1}\ \mathrm{PeV}^{1-n}$
- Improvement over limits using atmospheric ν: $\kappa_0 < 10^{-29}$ PeV, $\kappa_1 < 10^{-33}$

Fundamental physics with high-energy cosmic neutrinos

- Numerous new ν physics effects grow as $\sim \kappa_n \cdot E^n \cdot L$ } *E.g.*,
  n = -1: neutrino decay
  n = 0: CPT-odd Lorentz violation
  n = +1: CPT-even Lorentz violation
- 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, $\kappa_1 < 10^{-33}$

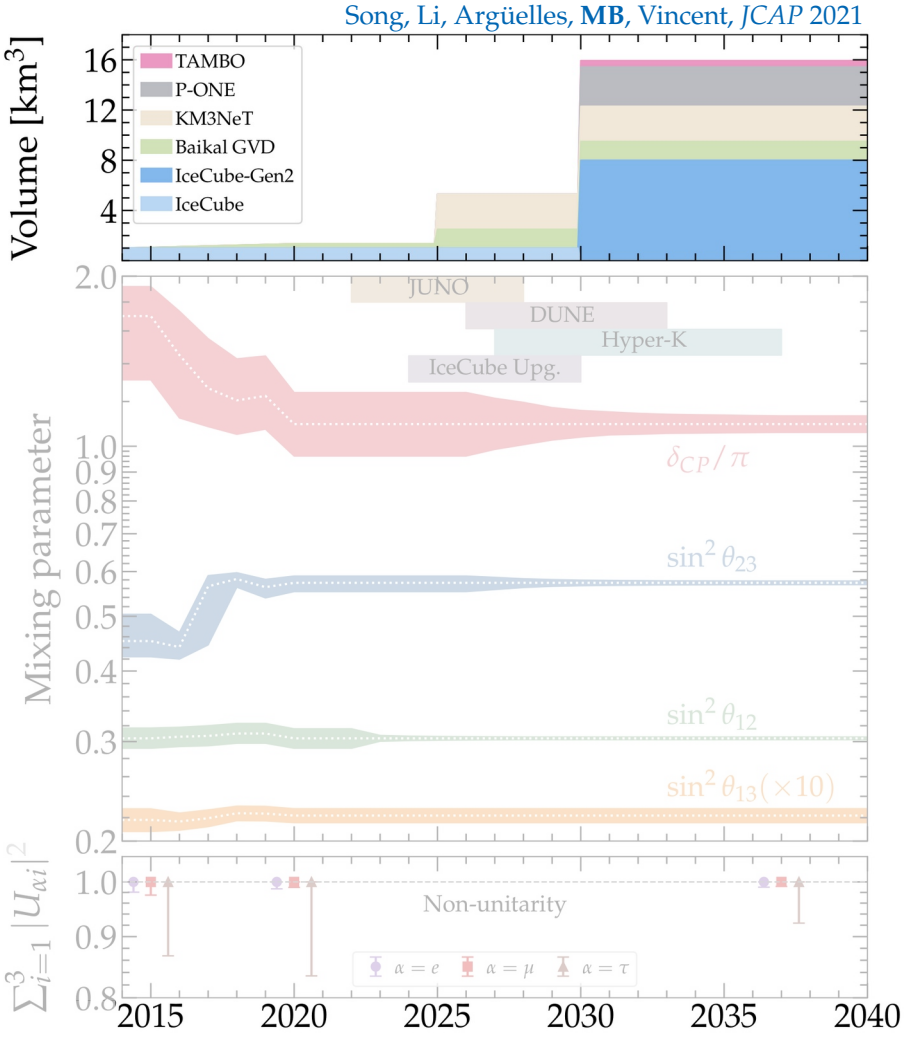
Three reasons to be excited

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



Three reasons to be excited

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

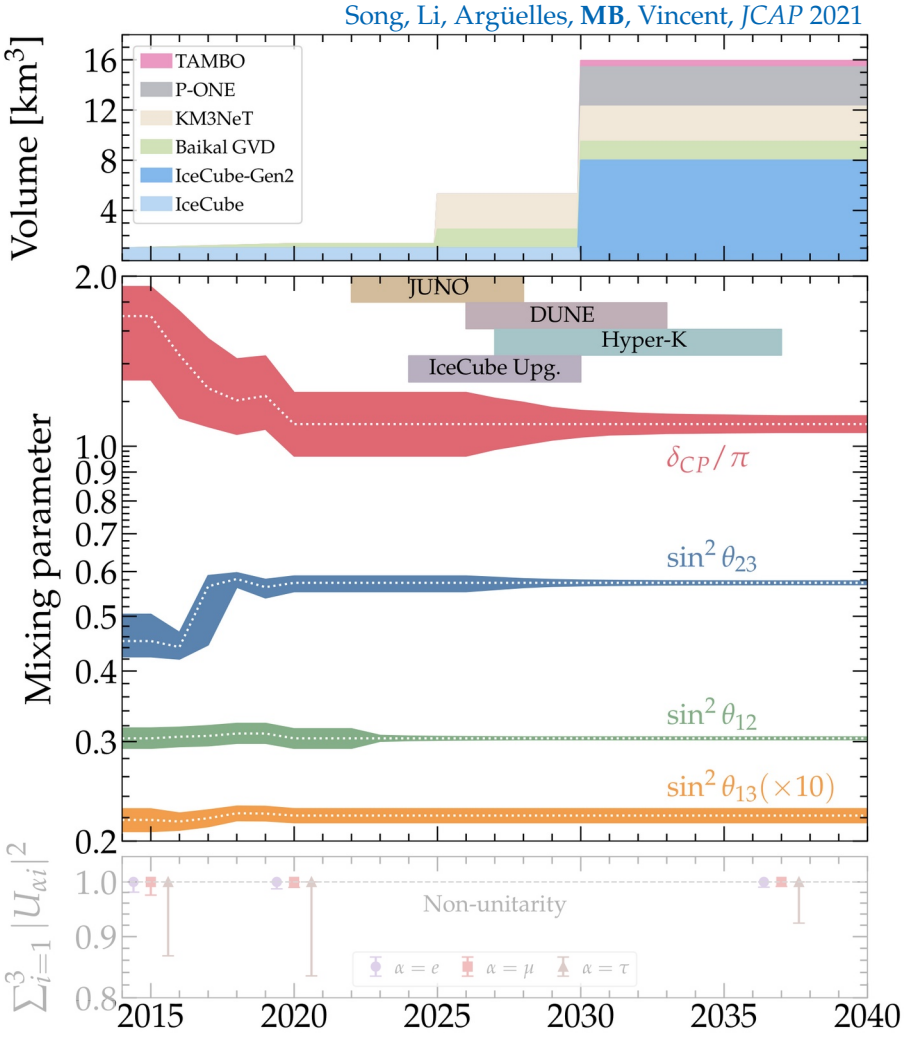


Flavor measurements:

New neutrino telescopes = more events, better flavor measurement

Three reasons to be excited

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



Flavor measurements:

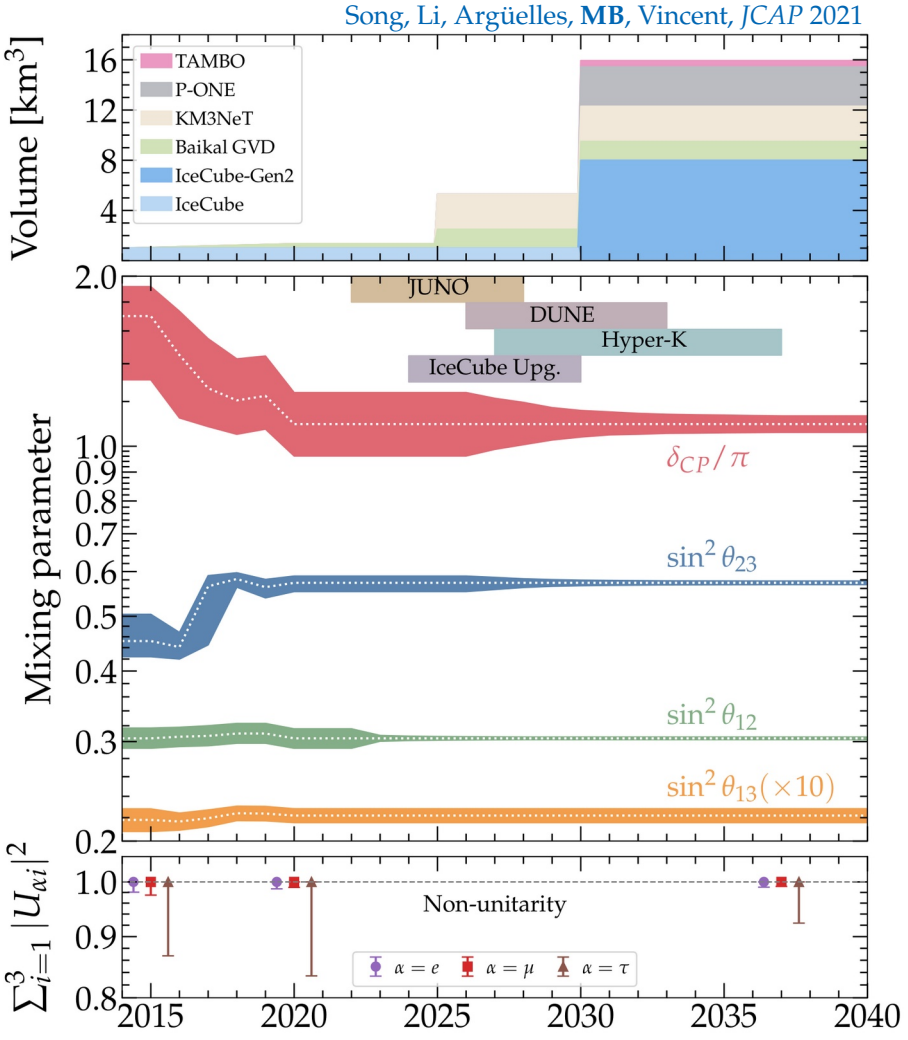
New neutrino telescopes = more events, better flavor measurement

Oscillation physics:

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

Three reasons to be excited

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



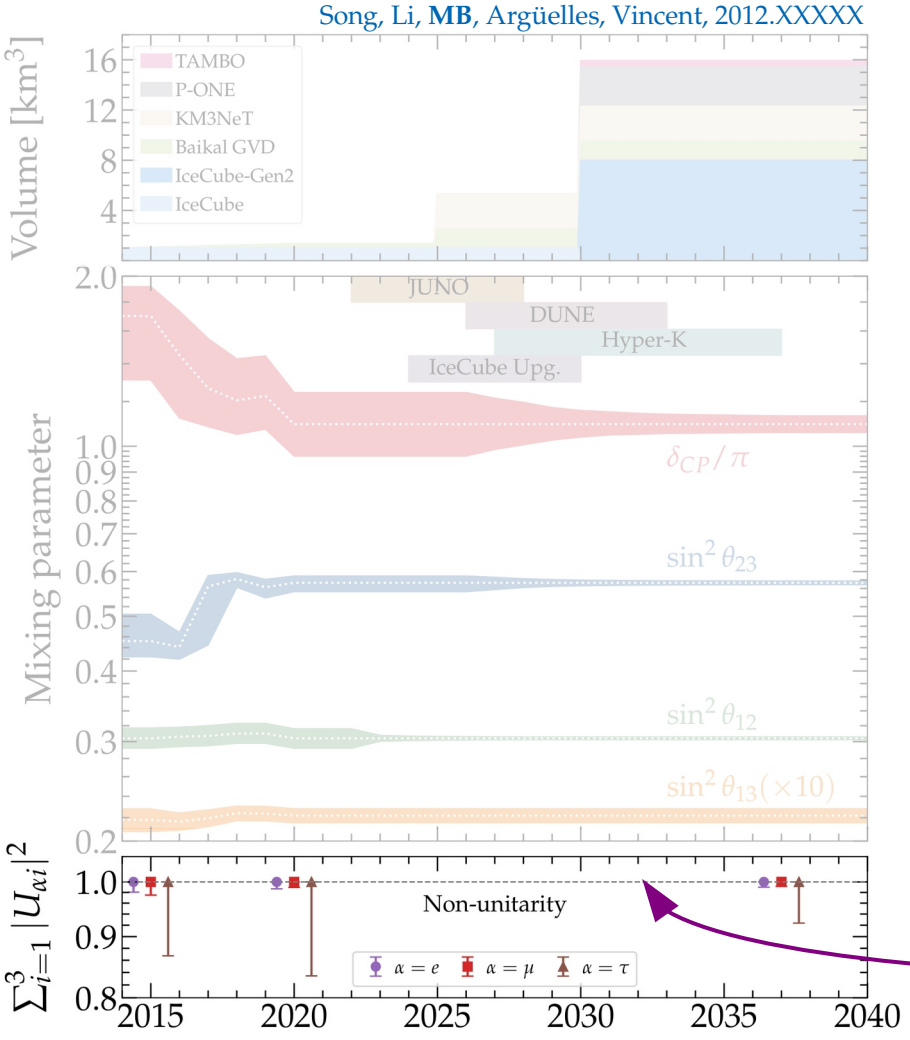
Flavor measurements:
New neutrino telescopes = more events, better flavor measurement

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

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

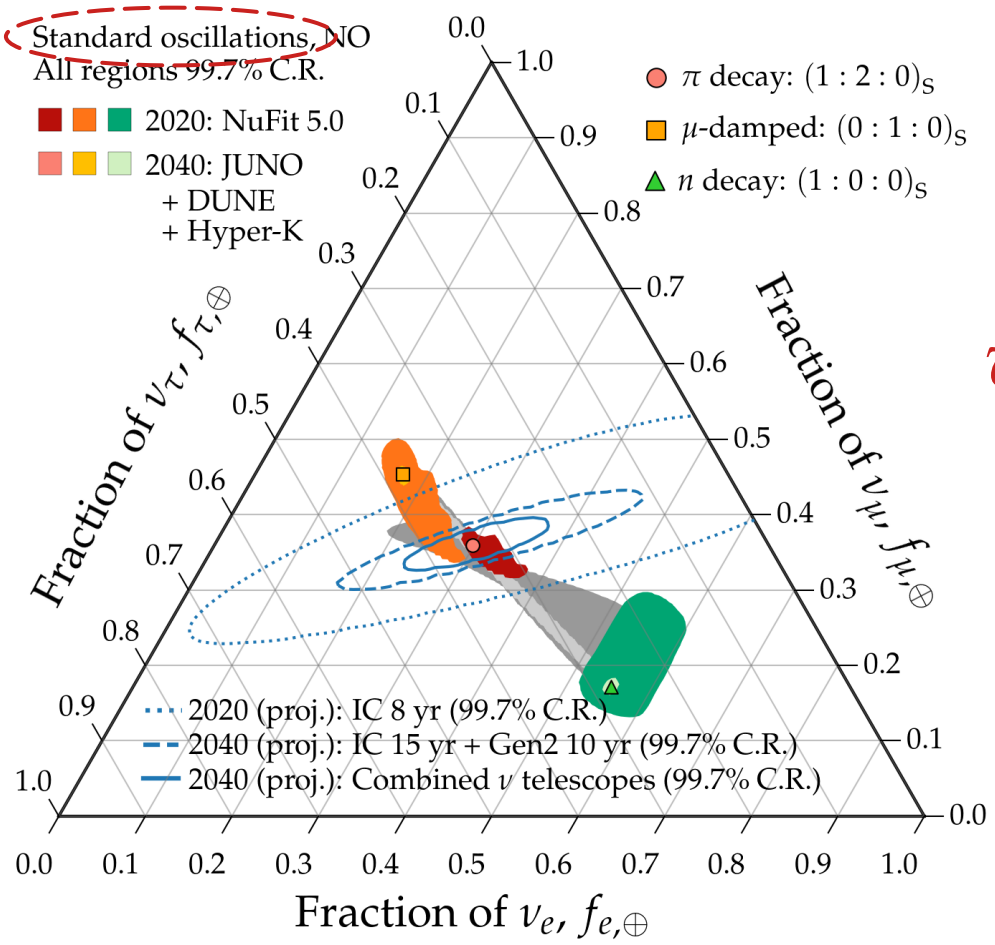
Additional sterile flavors

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

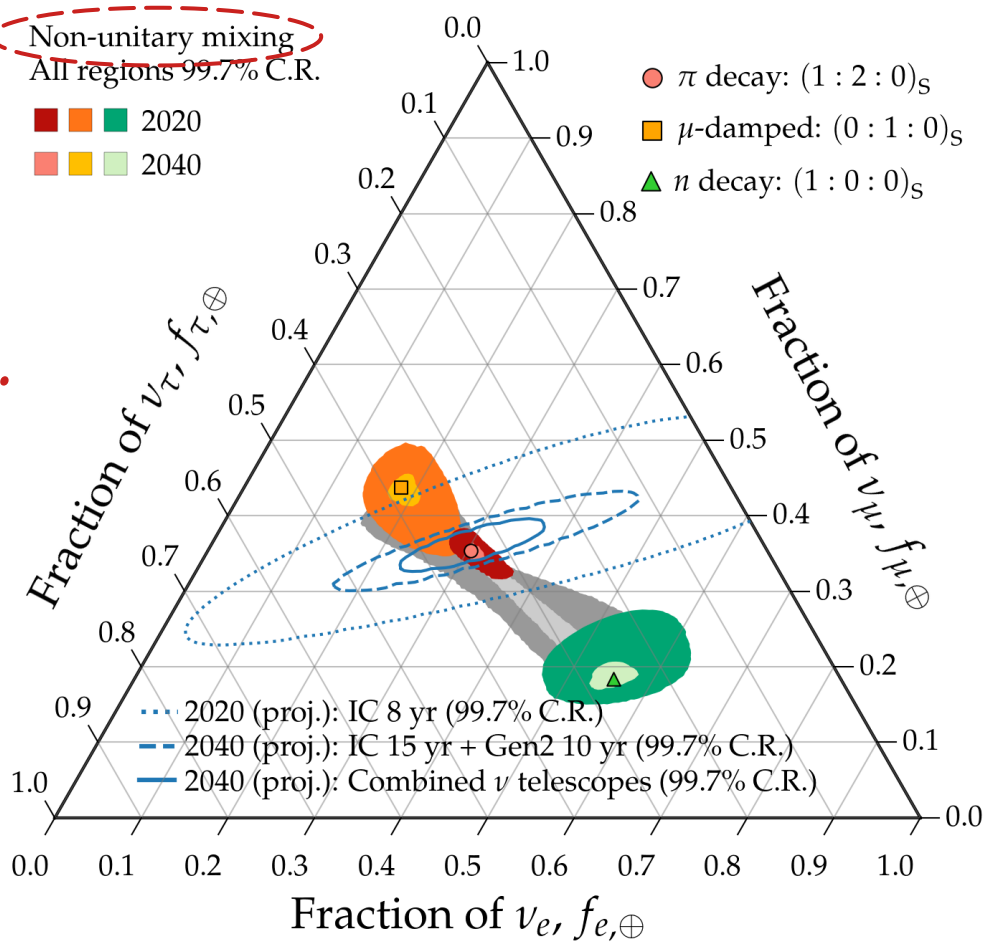
Because the sub-matrix is not-unitary ($U_{3\nu}^{\dagger} U_{3\nu} \neq 1$), the "row sum" may be < 1

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

No unitarity? *No problem*



vs.



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

Are neutrinos forever?

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

  } » Age of Universe (~ 14.5 Gyr)

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

- We work in a model-independent way:
  the nature of φ is unimportant if it is invisible to neutrino detectors

Are neutrinos forever?

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

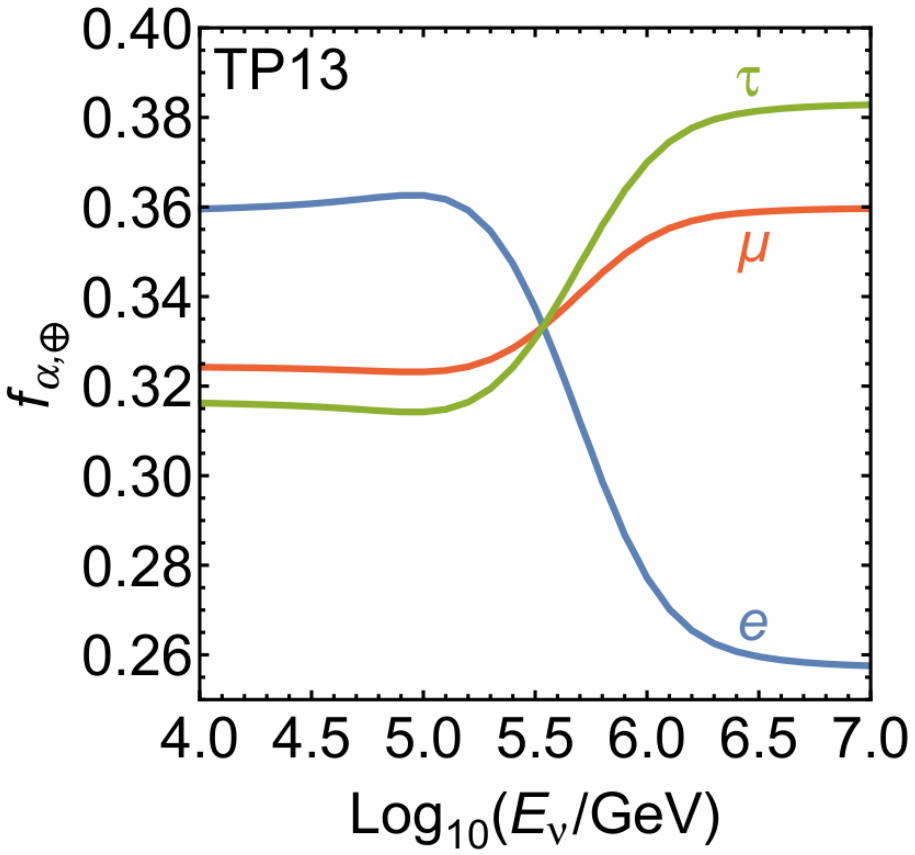
  } » Age of Universe (~ 14.5 Gyr)

- BSM decays may have significantly higher rates: $\nu_i \to \nu_j + \varphi$ — φ: Nambu-Goldstone boson of a broken symmetry

- We work in a model-independent way:
  the nature of φ is unimportant if it is invisible to neutrino detectors

Flavor composition: measuring the energy dependence

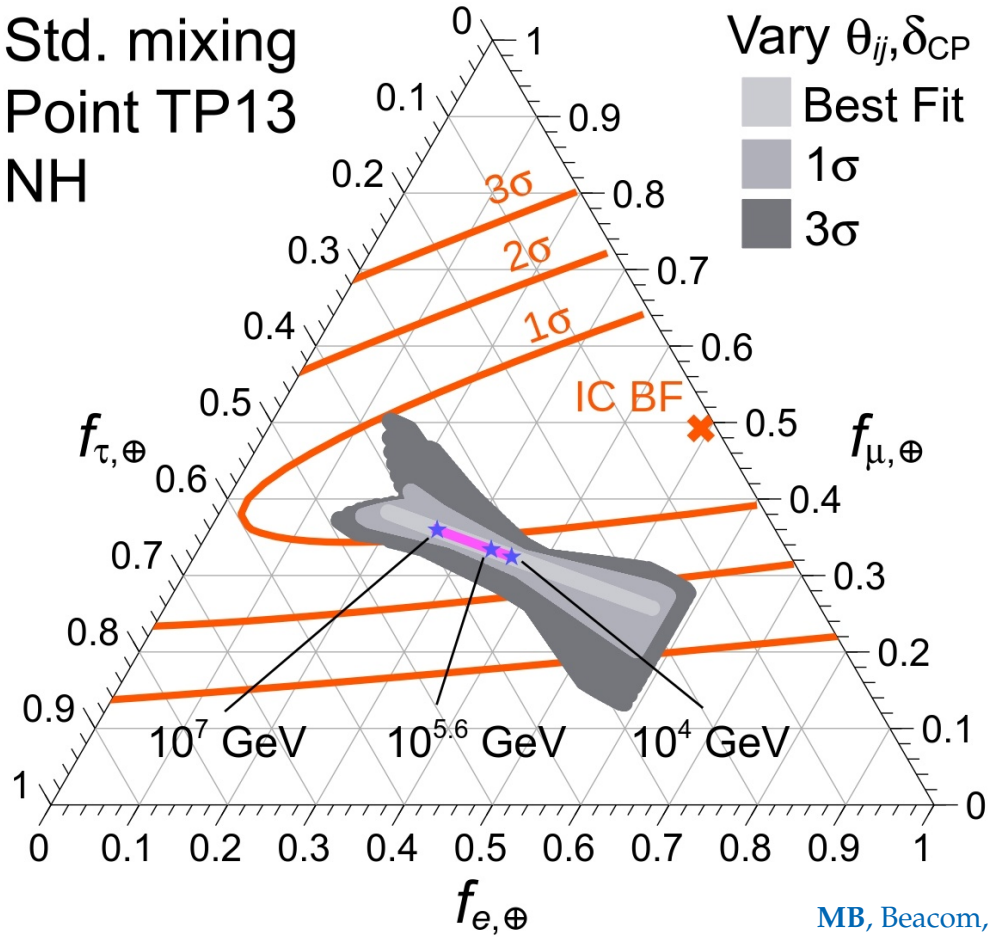
Expected from astrophysical processes



MB, Beacom, Winter *PRL* 2015

Flavor composition: measuring the energy dependence

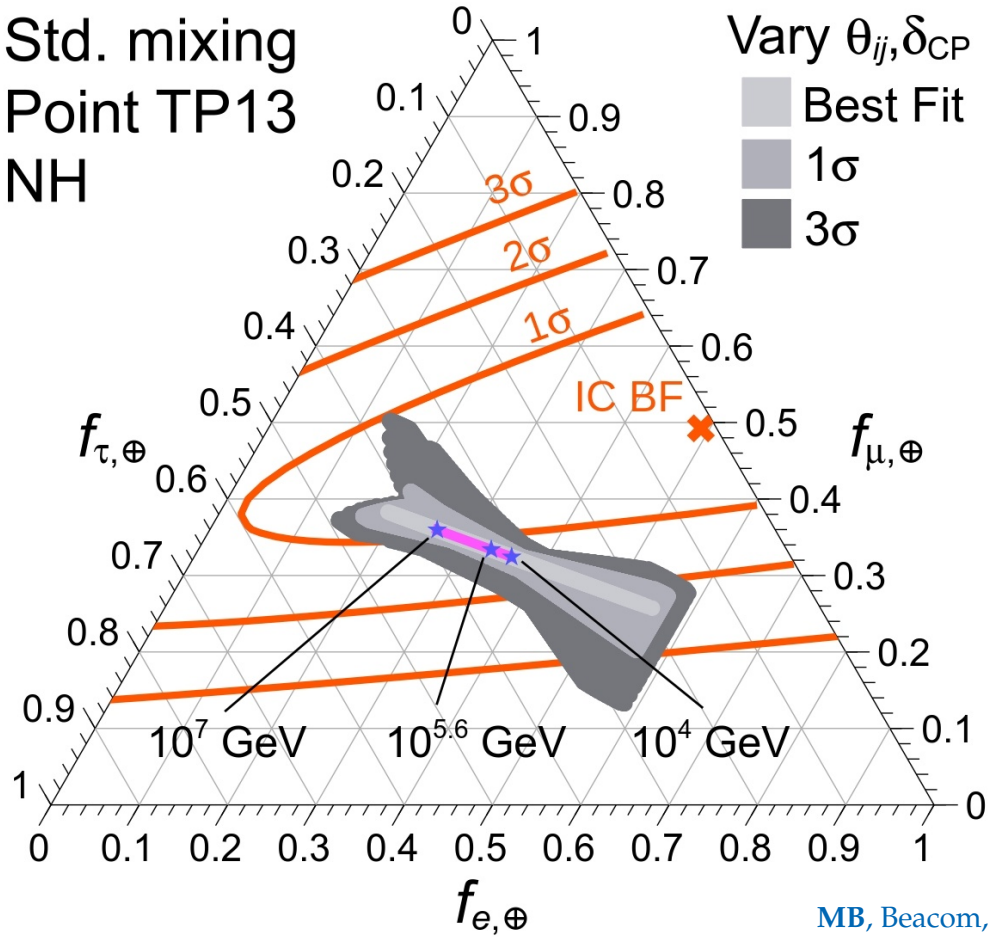
Expected from astrophysical processes



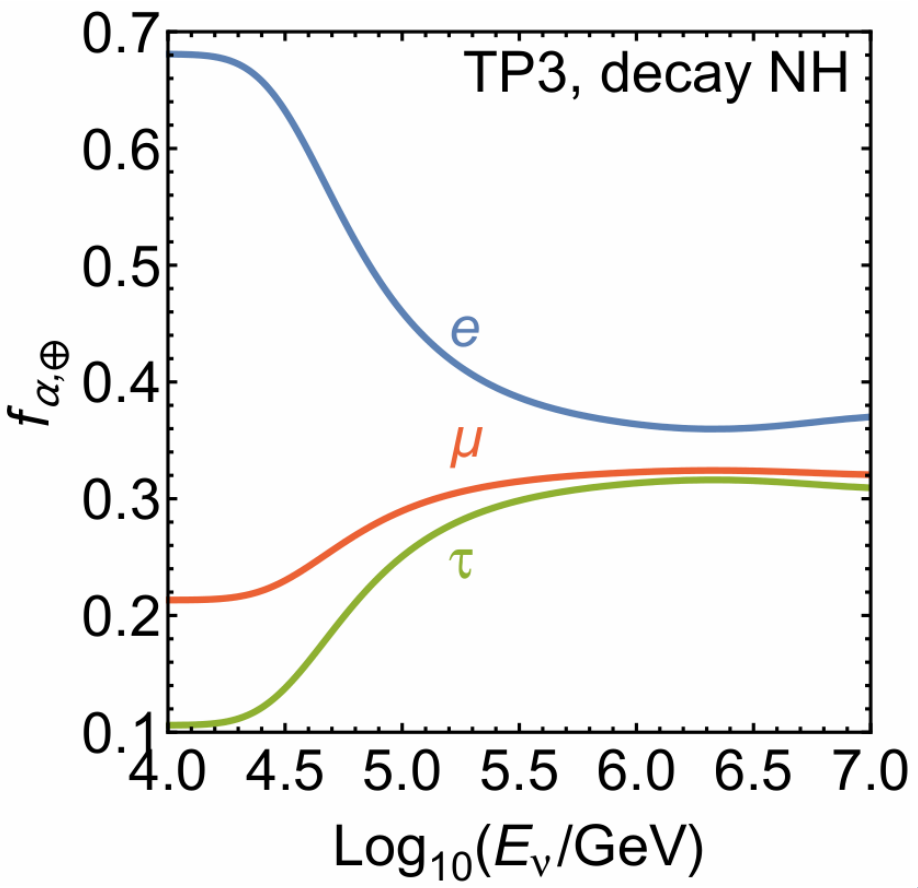
MB, Beacom, Winter *PRL* 2015

Flavor composition: measuring the energy dependence

Expected from astrophysical processes



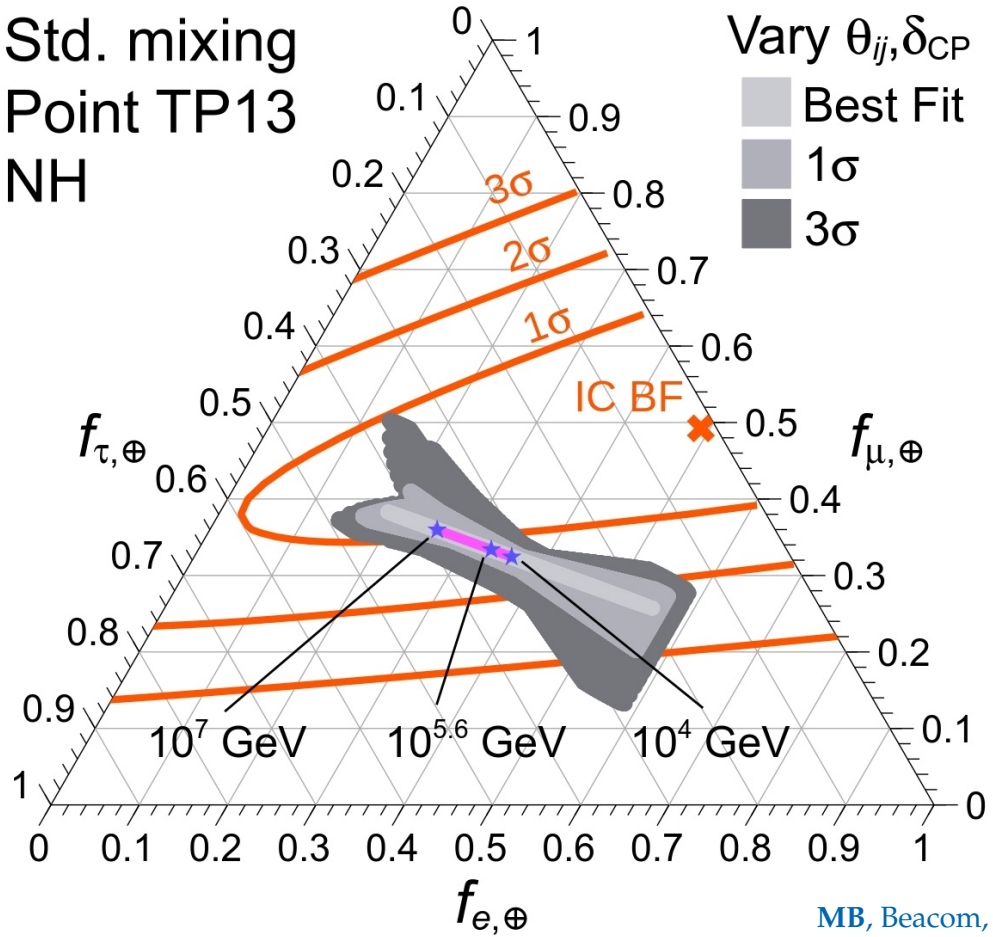
Expected from new physics (*e.g.*, ν decay)



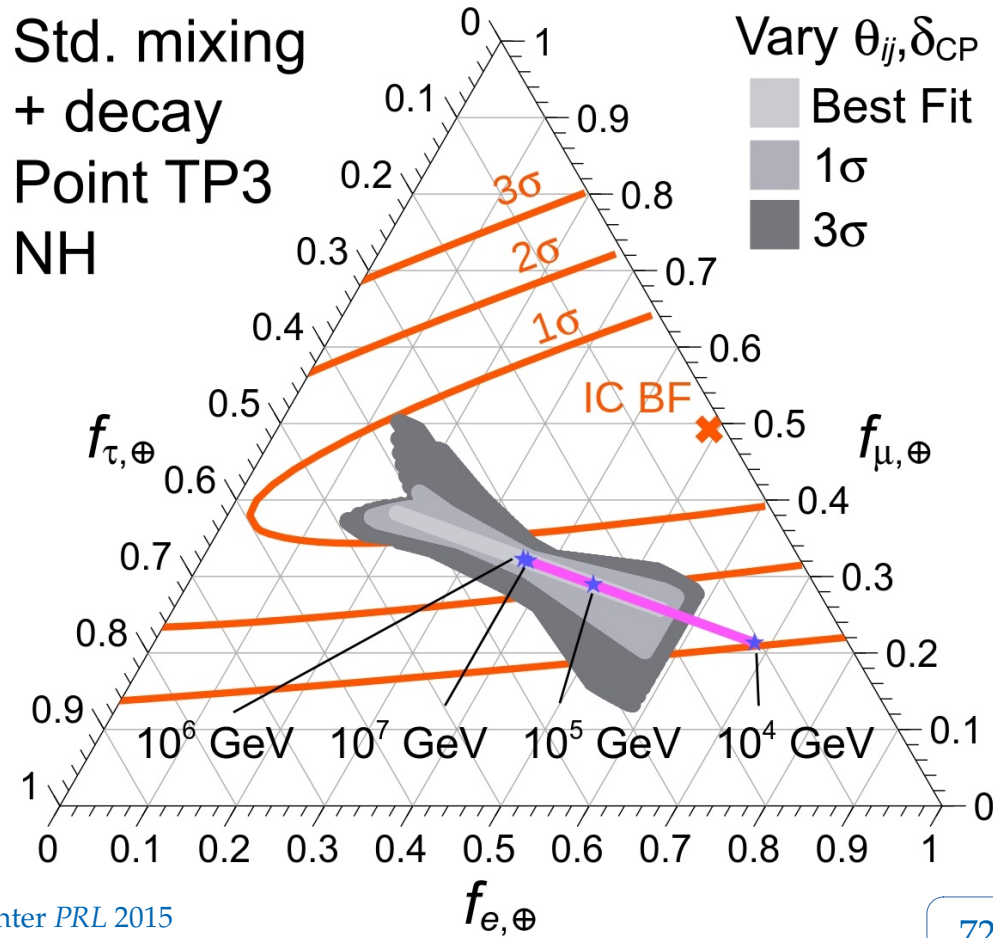
MB, Beacom, Winter *PRL* 2015

Flavor composition: measuring the energy dependence

Expected from astrophysical processes



Expected from new physics (*e.g.*, ν decay)



MB, Beacom, Winter *PRL* 2015

More than one production mechanism?

Can we detect the contribution of multiple ν production mechanisms?

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

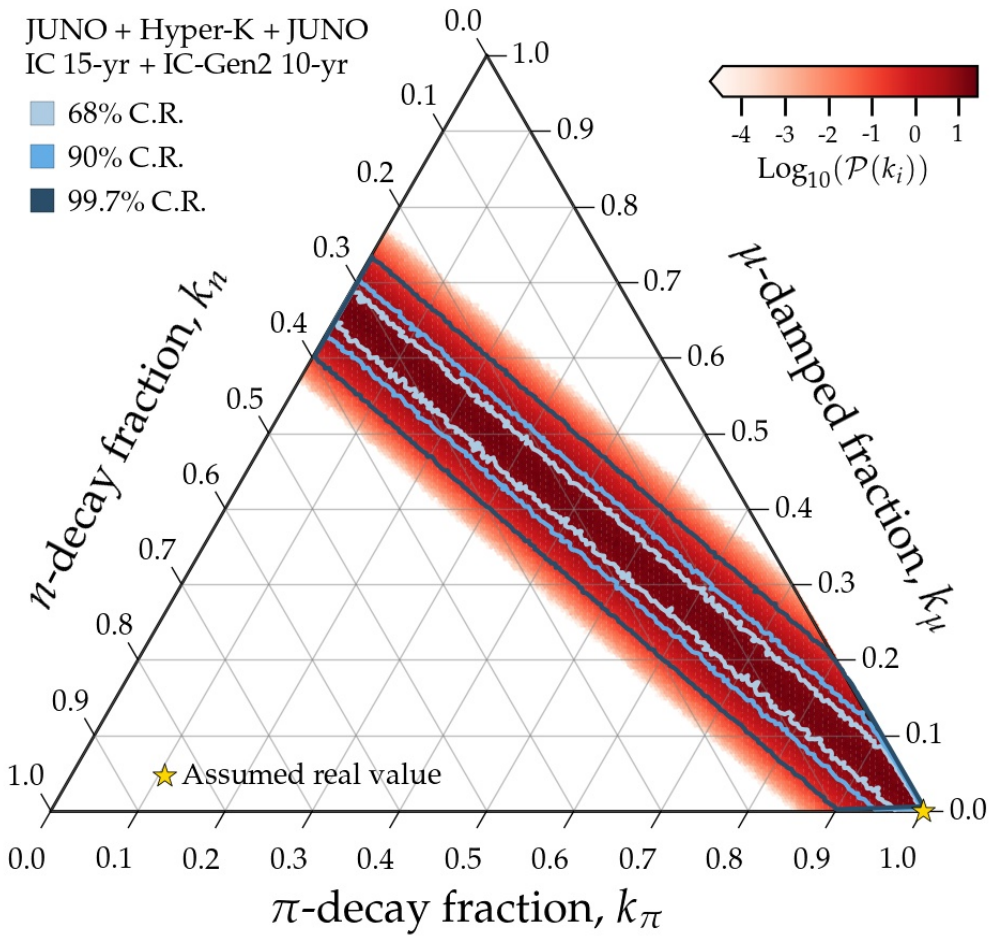
Propagate to Earth ↓

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

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

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

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



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

More than one production mechanism?

Can we detect the contribution of multiple ν production mechanisms?

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

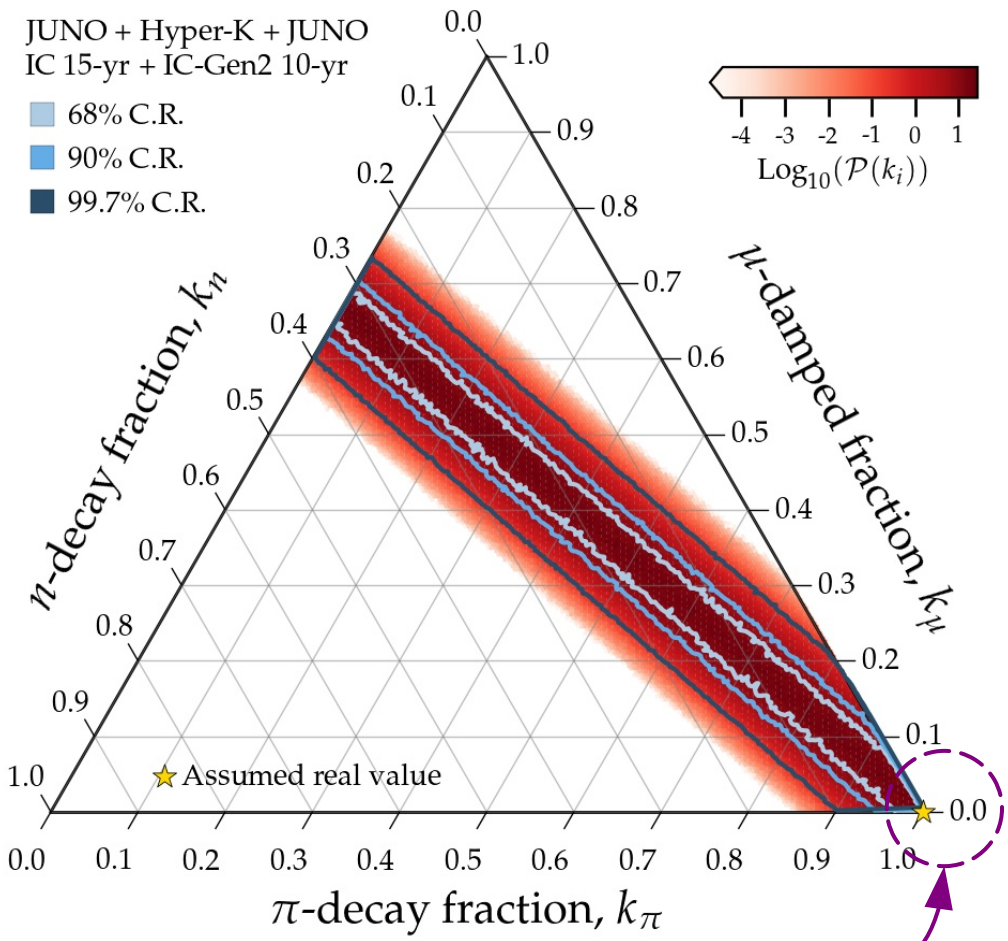
Propagate to Earth ↓

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

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

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

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



We do recover the real value

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

More than one production mechanism?

Can we detect the contribution of multiple ν production mechanisms?

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

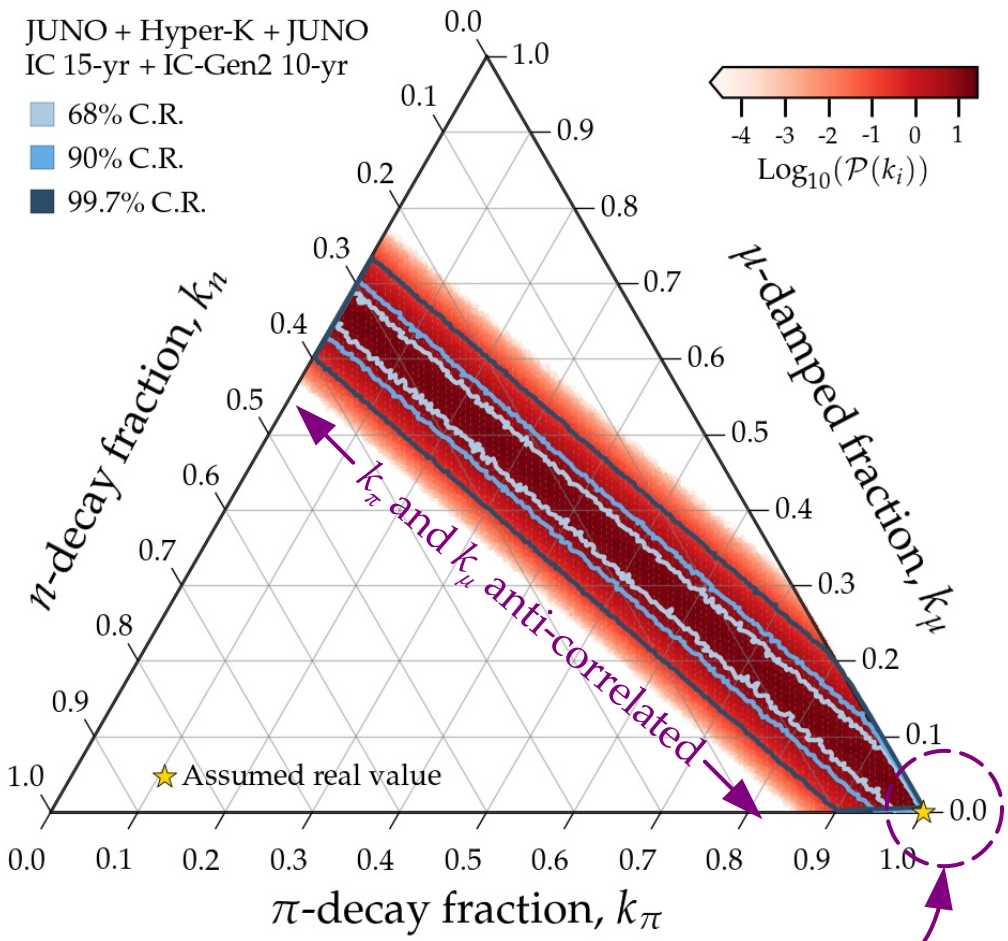
Propagate to Earth ↓

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

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

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

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



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

More than one production mechanism?

Can we detect the contribution of multiple ν production mechanisms?

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

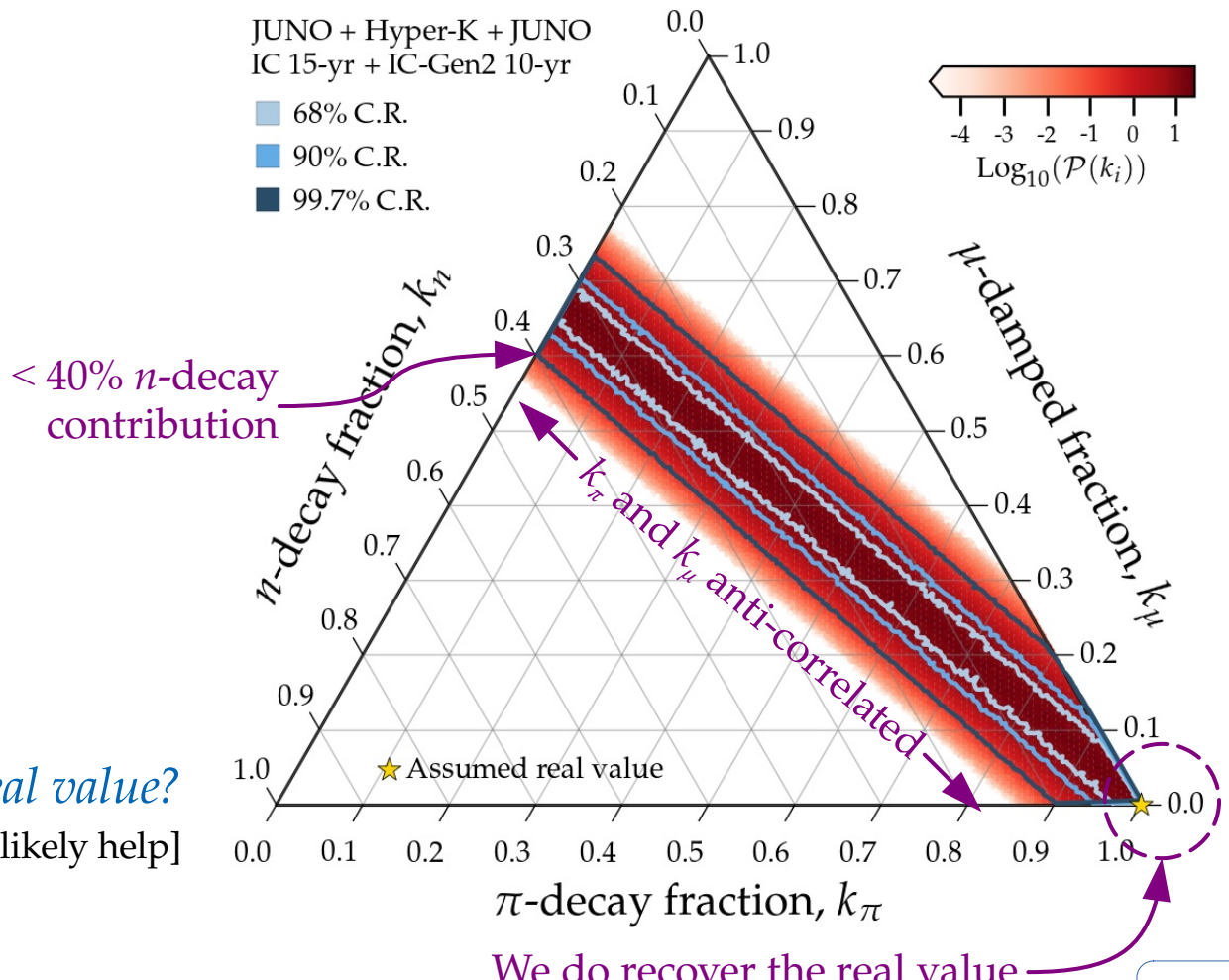
Propagate to Earth ↓

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

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

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

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



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

More than one production mechanism?

Can we detect the contribution of multiple ν production mechanisms?

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

Propagate to Earth ↓

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

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

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

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

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

More than one production mechanism?

Can we detect the contribution of multiple ν production mechanisms?

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

π decay: (1/3, 2/3, 0)

μ damped: (0, 1, 0)

n decay: (1, 0, 0)

Propagate to Earth

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

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

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

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

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

More than one production mechanism?

Can we detect the contribution of multiple ν production mechanisms?

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

π decay: (1/3, 2/3, 0)

μ damped: (0, 1, 0)

n decay: (1, 0, 0)

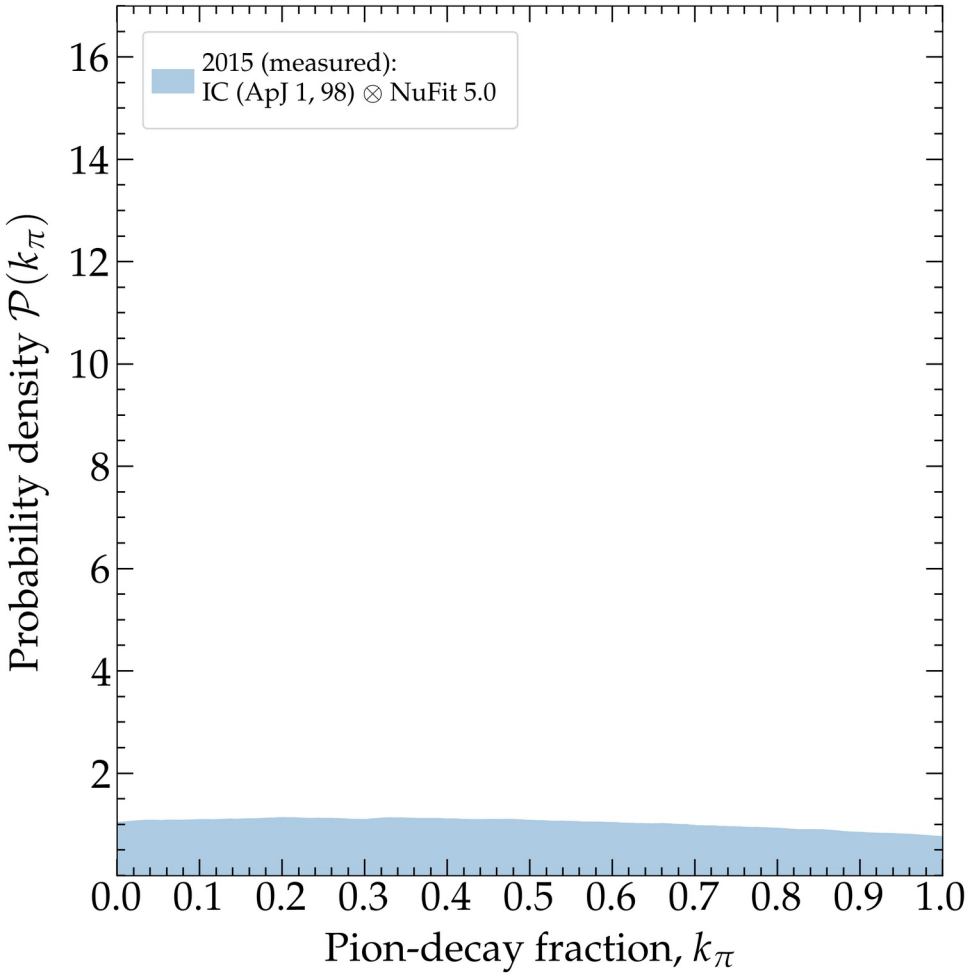
Propagate to Earth

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

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]



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

More than one production mechanism?

Can we detect the contribution of multiple ν production mechanisms?

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

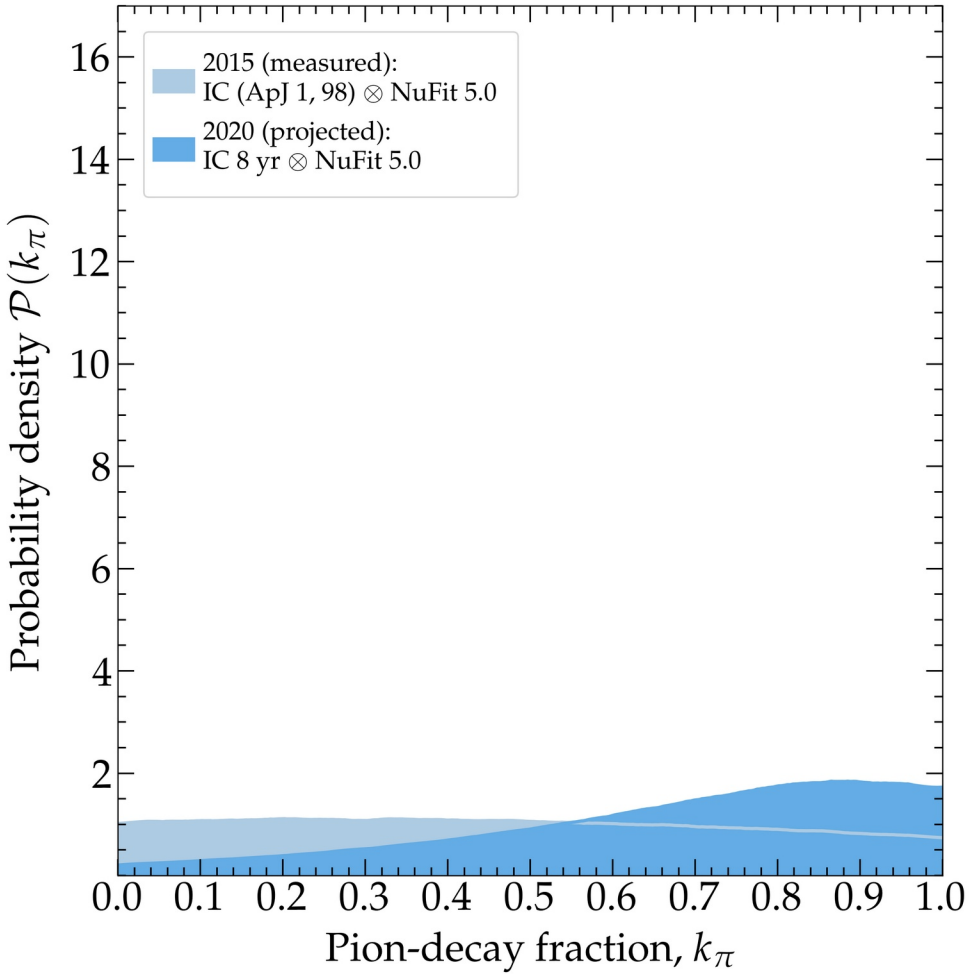
Propagate to Earth

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

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

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

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



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

More than one production mechanism?

Can we detect the contribution of multiple ν production mechanisms?

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

π decay: (1/3, 2/3, 0)

μ damped: (0, 1, 0)

n decay: (1, 0, 0)

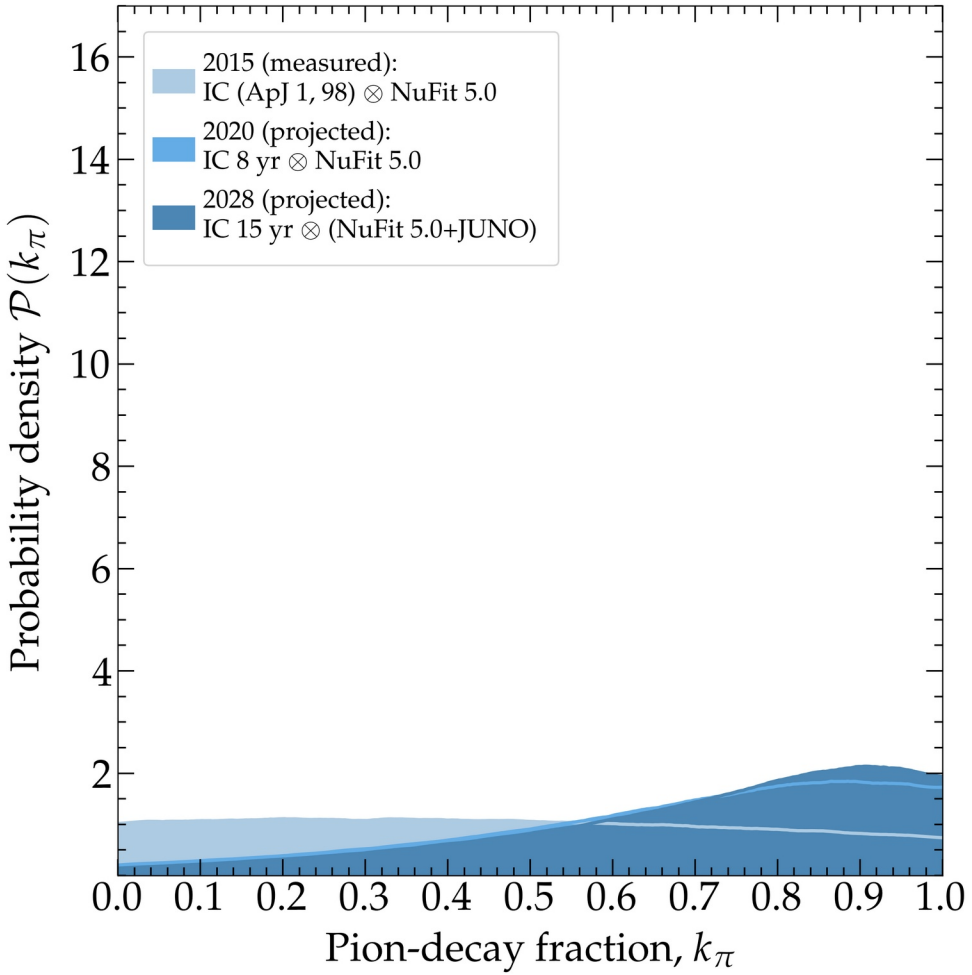
Propagate to Earth

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

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

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

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



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

More than one production mechanism?

Can we detect the contribution of multiple ν production mechanisms?

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

π decay: (1/3, 2/3, 0)

μ damped: (0, 1, 0)

n decay: (1, 0, 0)

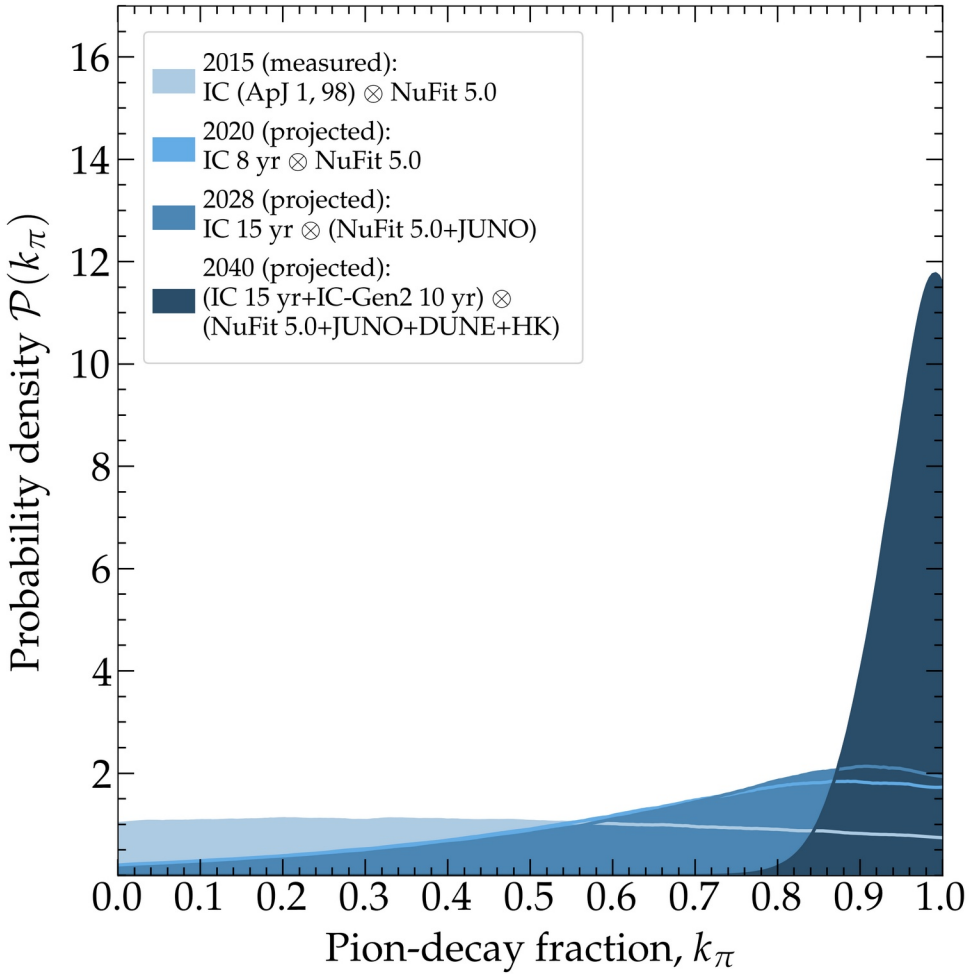
Propagate to Earth

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

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

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

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



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

More than one production mechanism?

Can we detect the contribution of multiple ν production mechanisms?

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

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

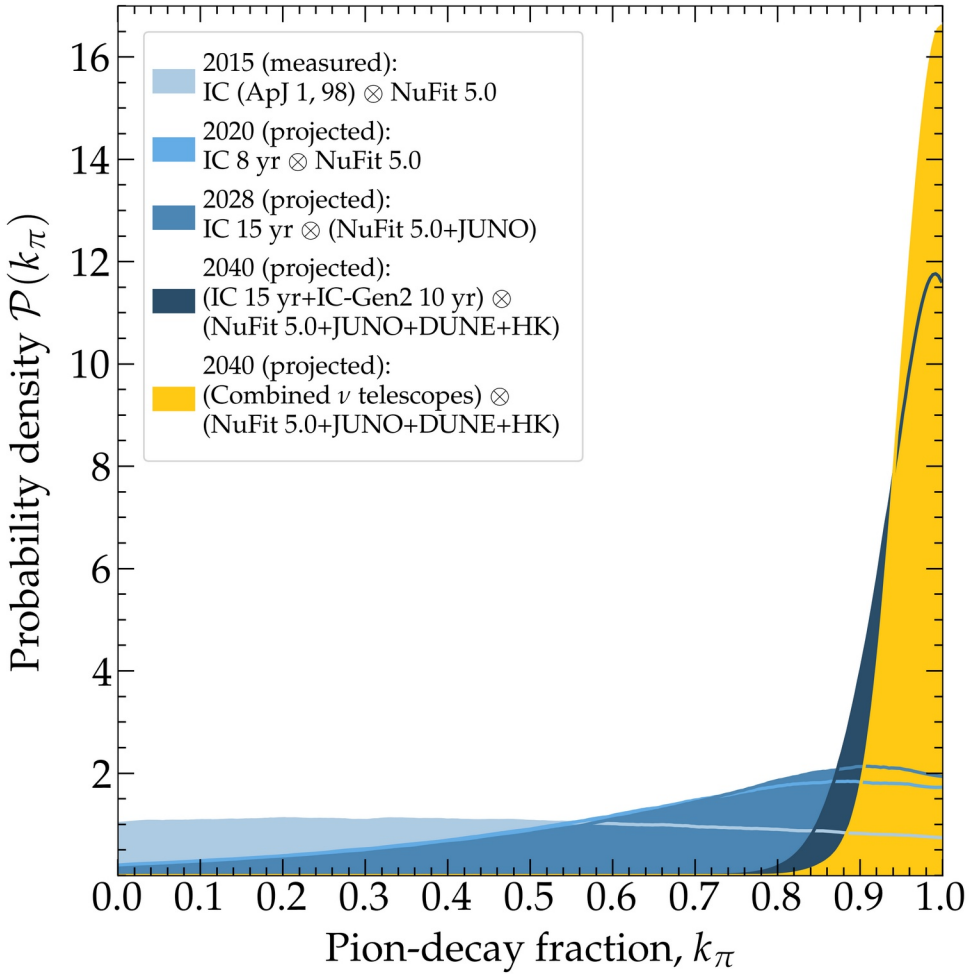
Propagate to Earth

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

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

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

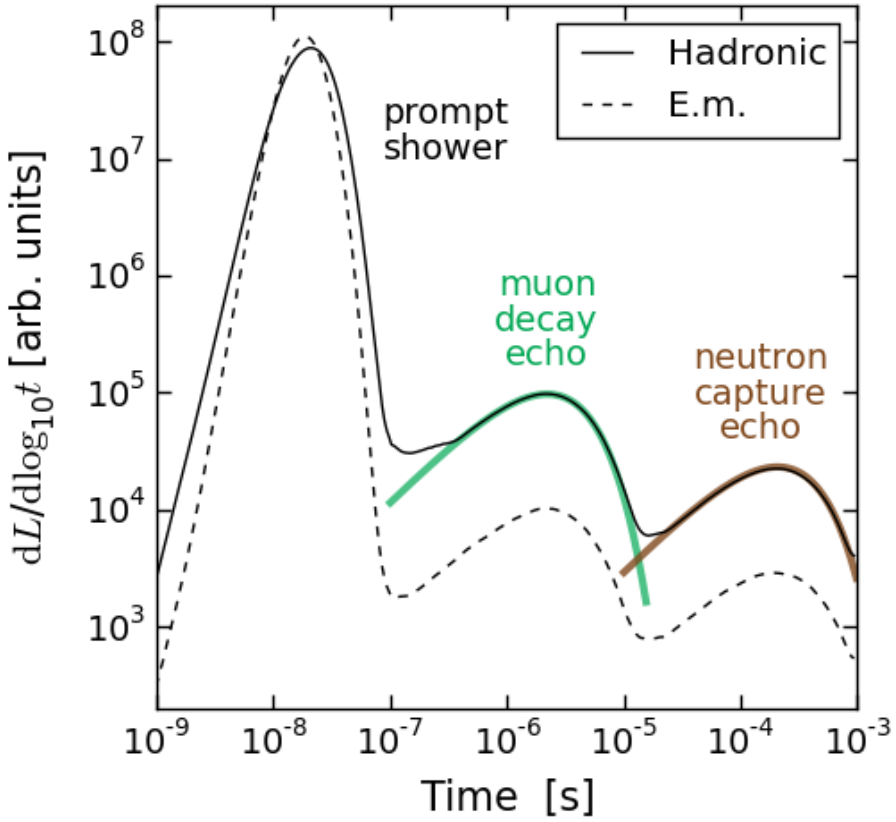
[Adding spectrum information (not shown) will likely help]

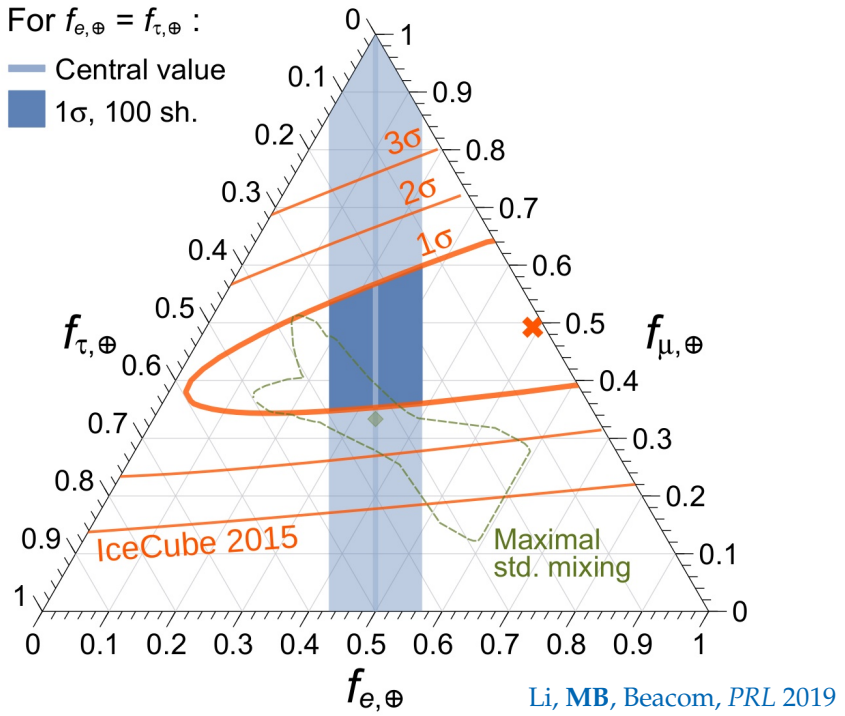


Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

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 –

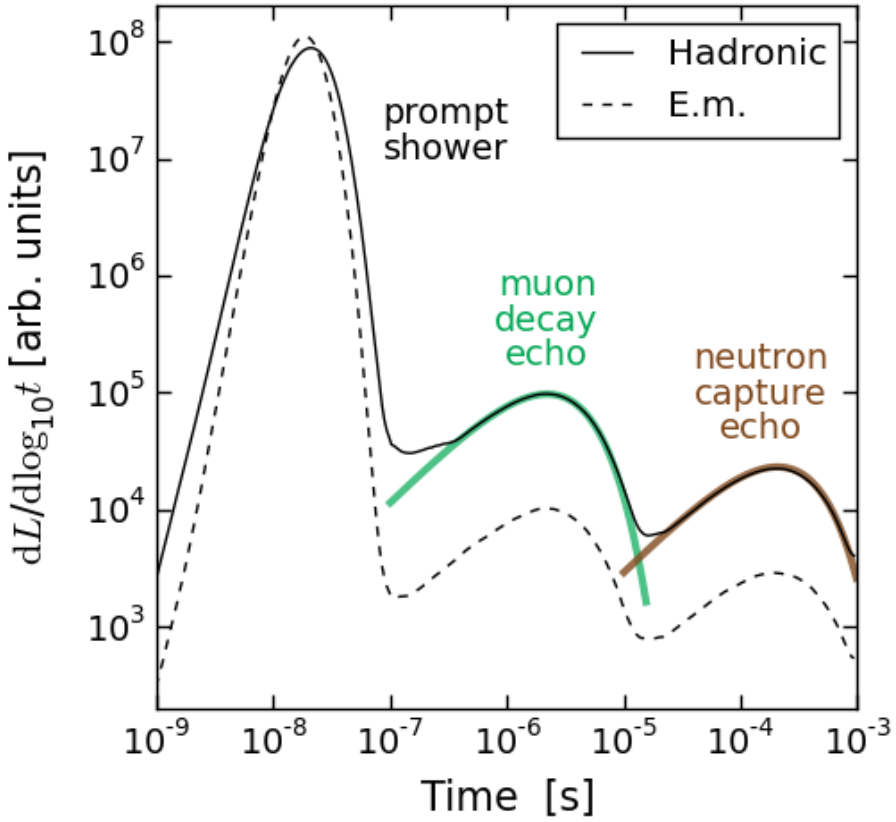


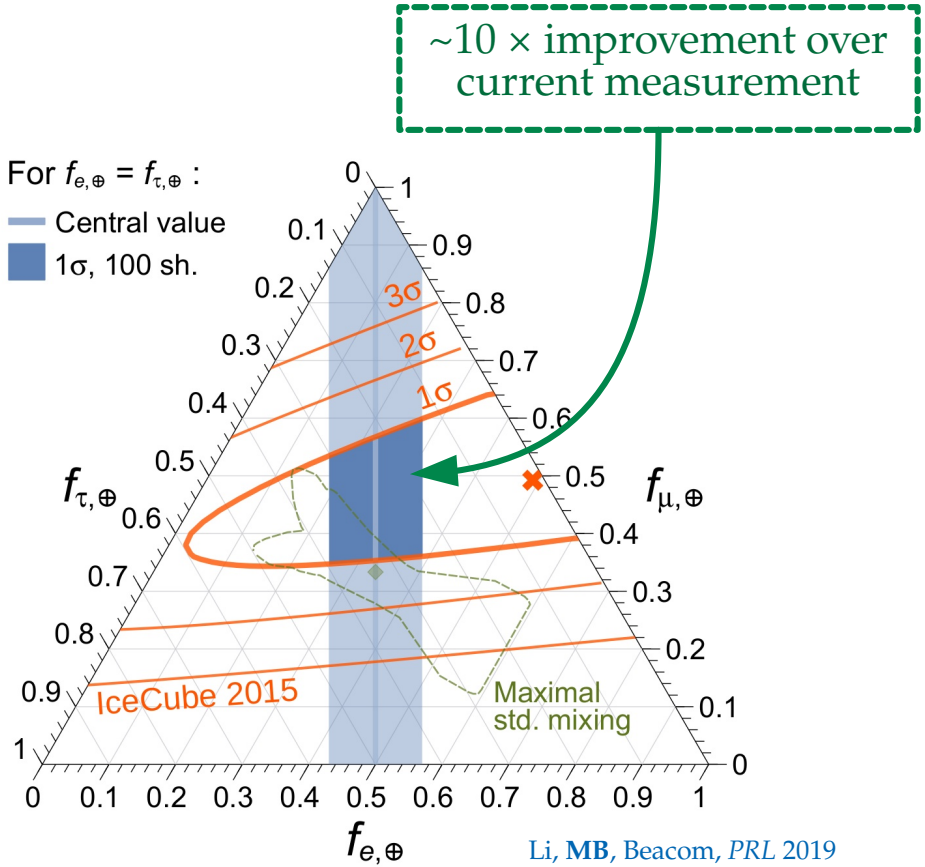


Li, **MB**, Beacom, *PRL* 2019

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 –

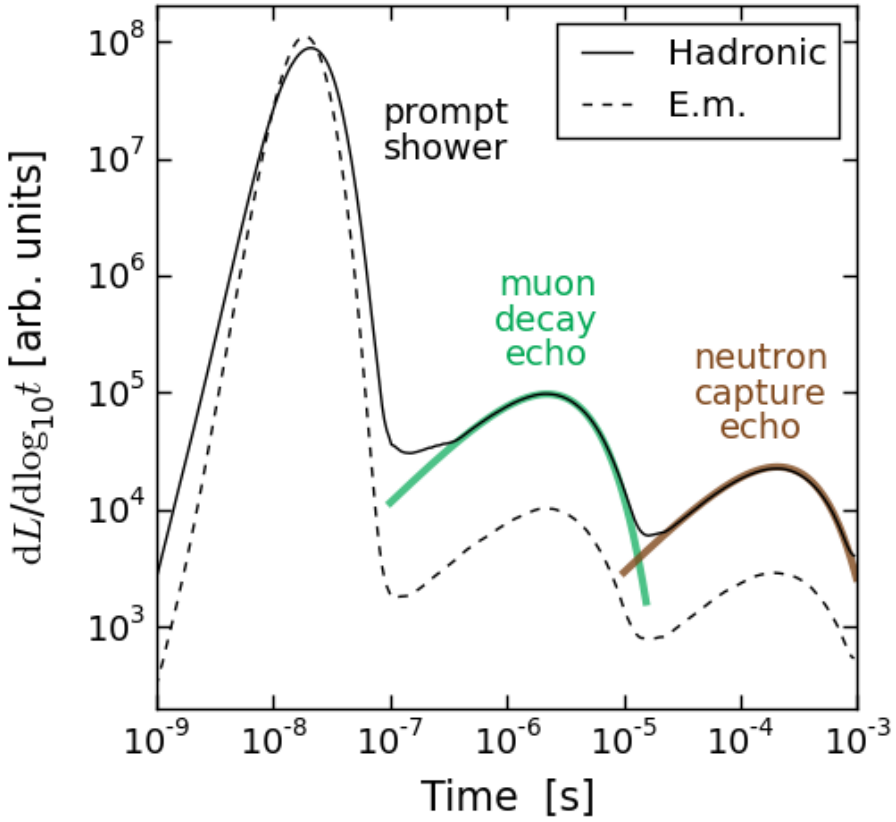


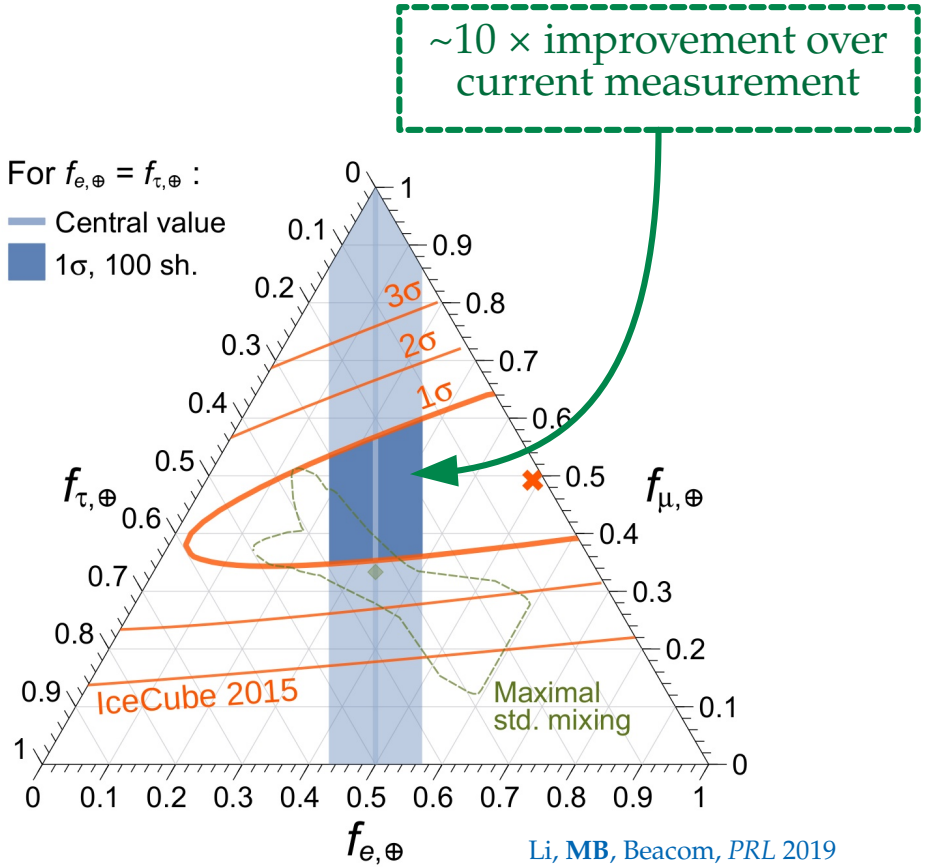


Li, **MB**, Beacom, *PRL* 2019

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 –

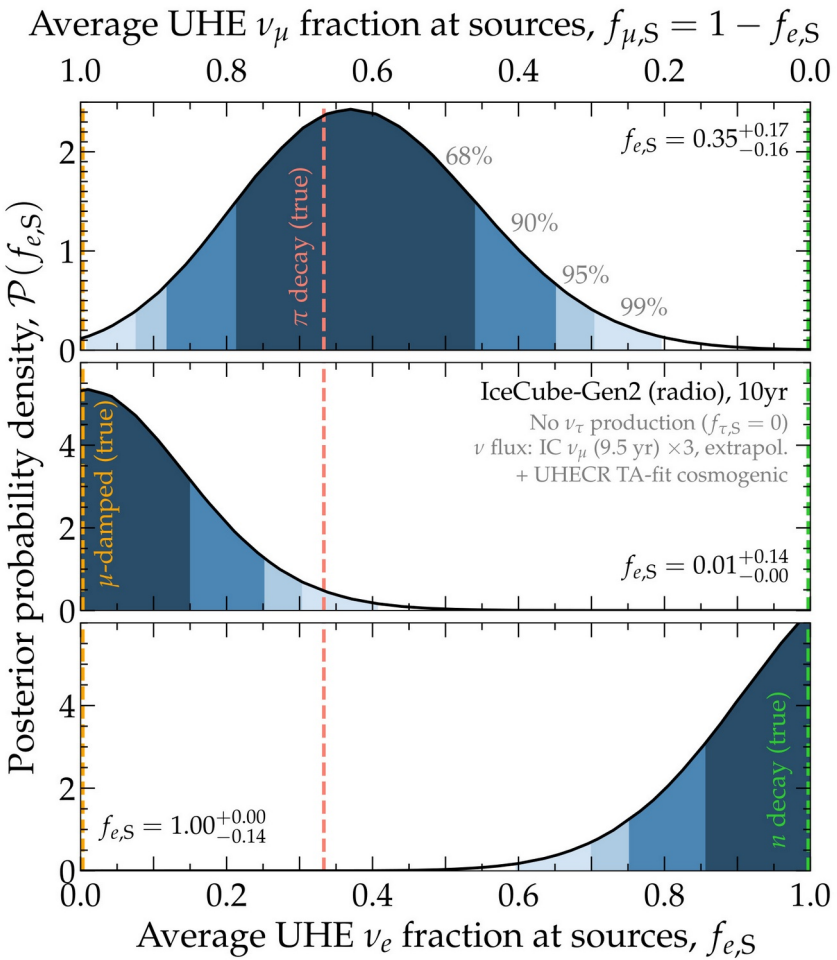




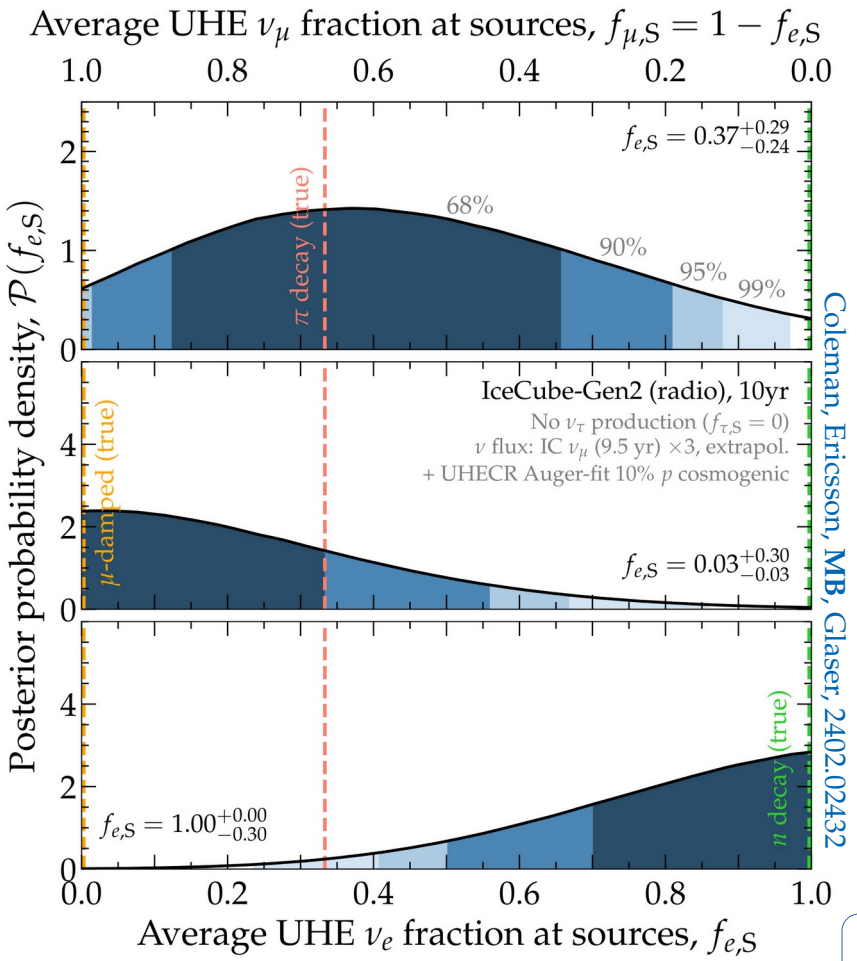
Li, **MB**, Beacom, *PRL* 2019

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

Assuming a high UHE flux



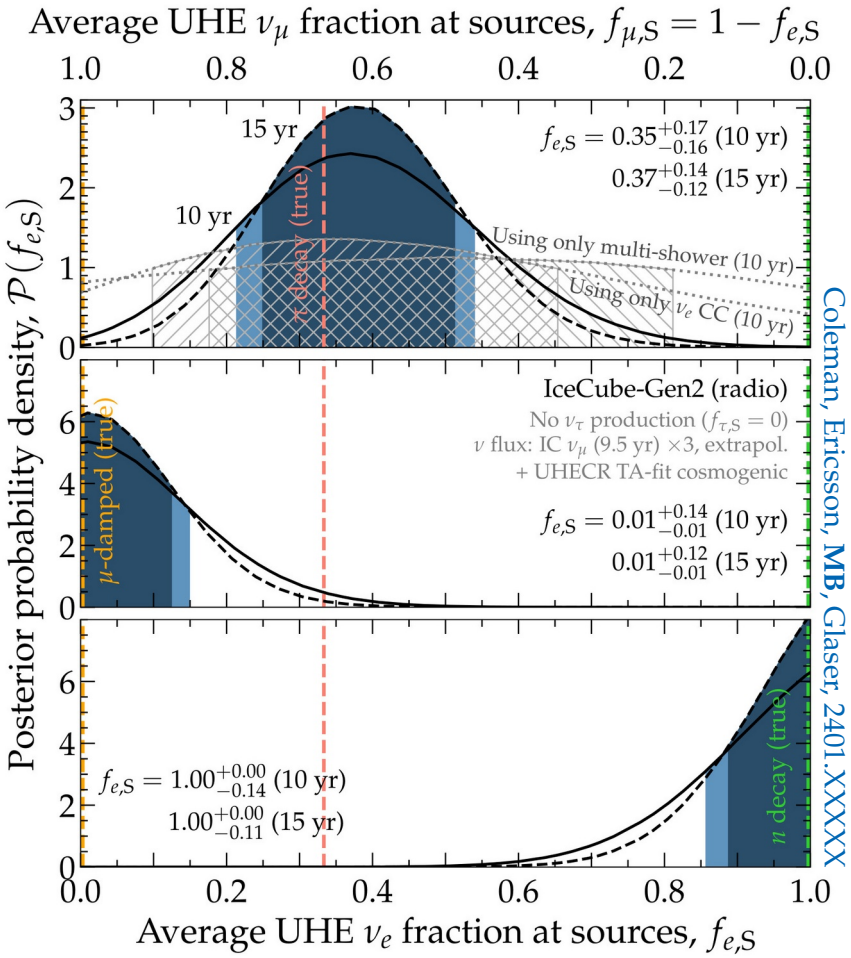
Assuming a low UHE flux



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

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

10 yr *vs.* 15 yr, individual channels



Flavor composition: measuring the energy dependence

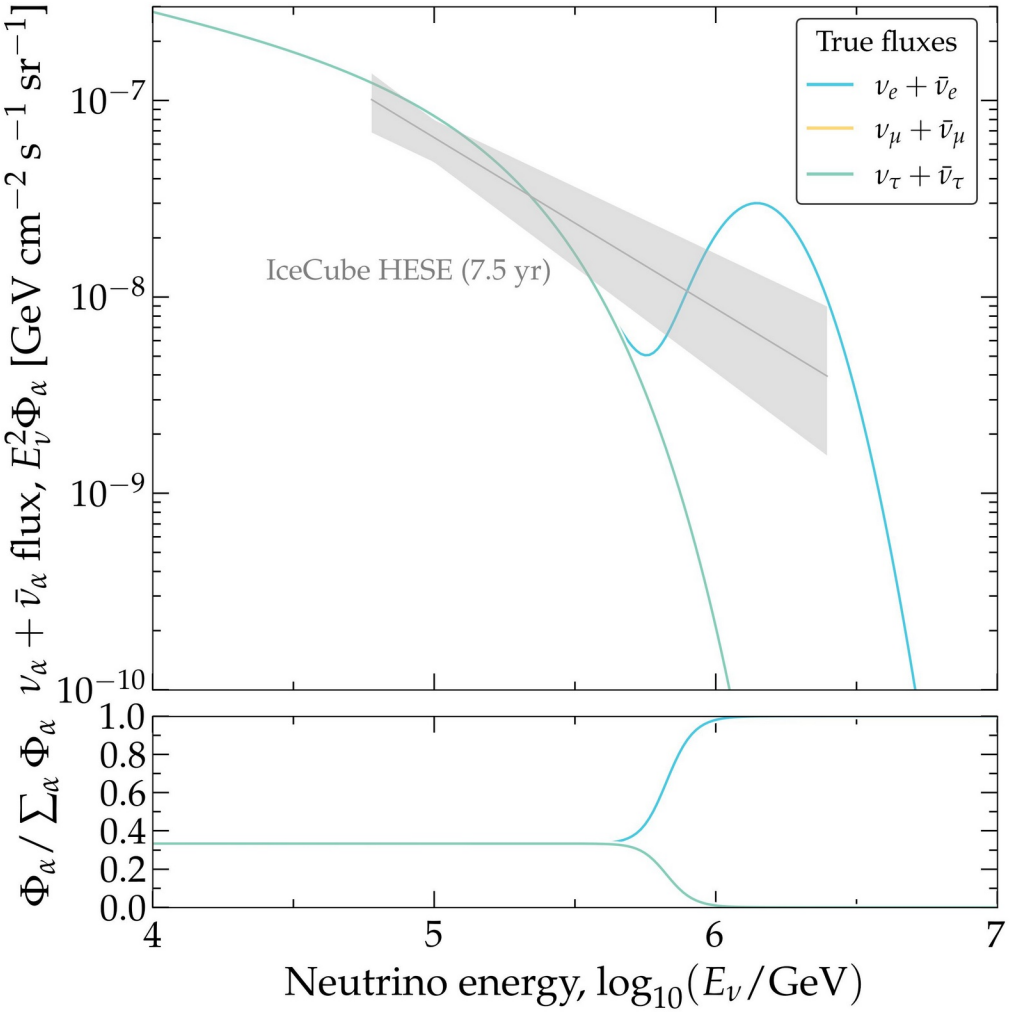
Can we do better?

Maybe

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

How?

—Infer the spectrum of ν_e, ν_μ, ν_τ separately



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

Flavor composition: measuring the energy dependence

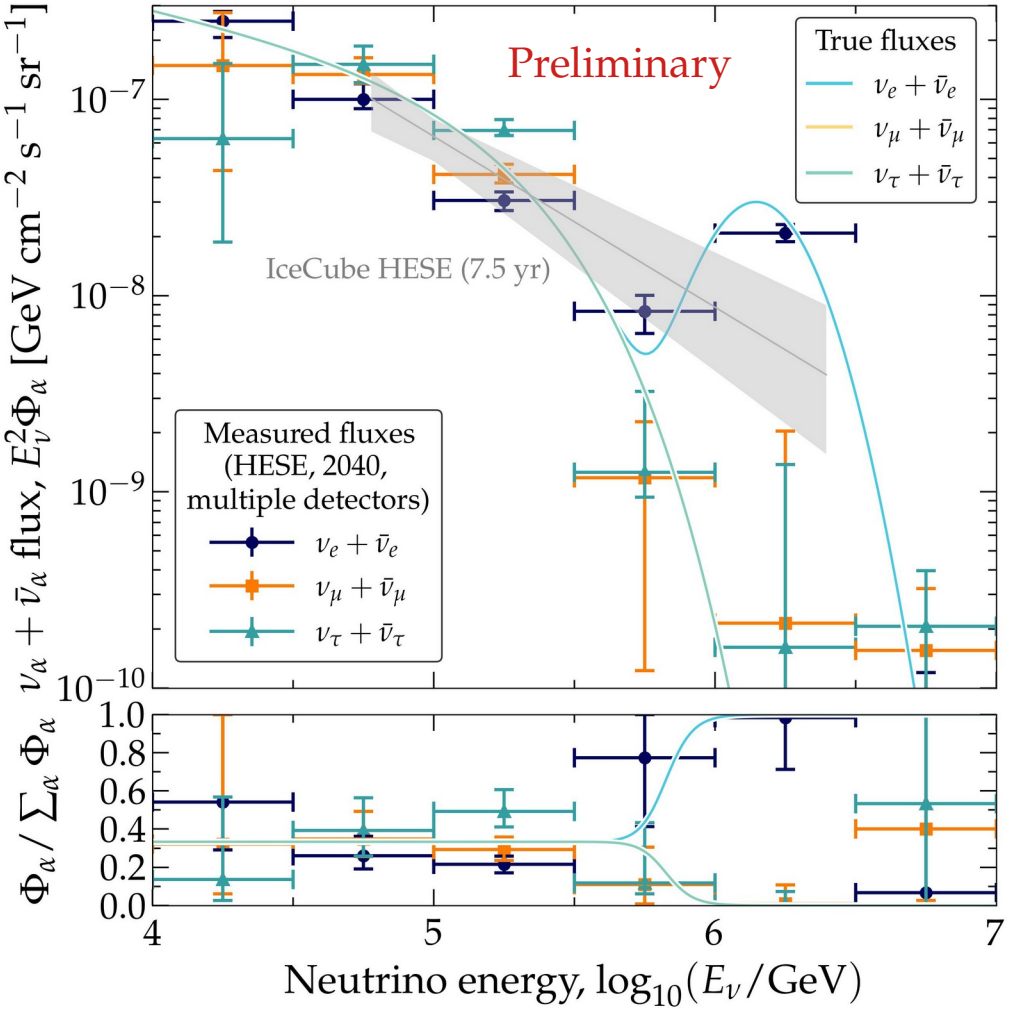
Can we do better?

Maybe

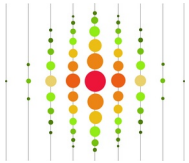
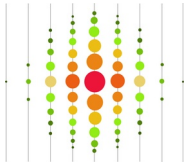
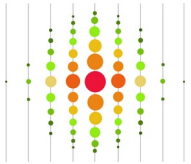
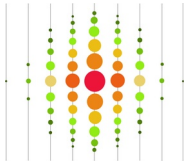
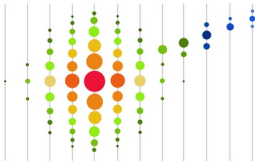
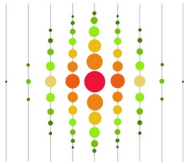
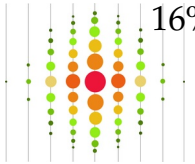
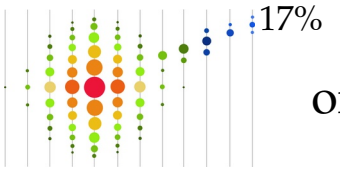
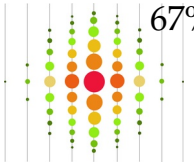
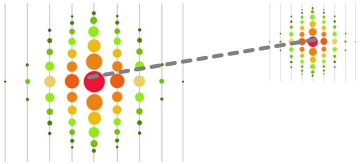
—If we do not try to pinpoint the energy of flavor transition

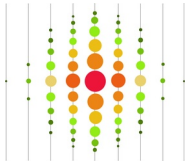
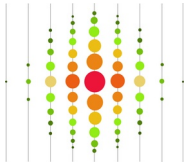
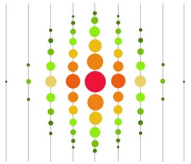
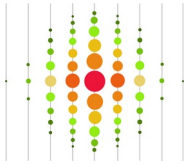
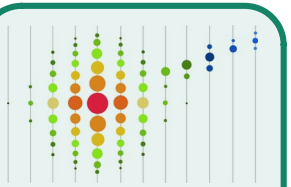
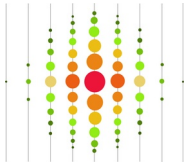
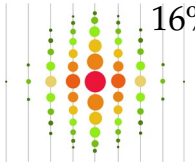
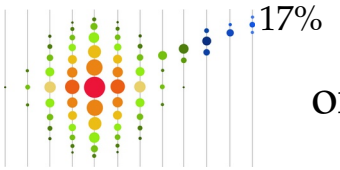
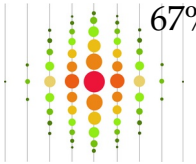
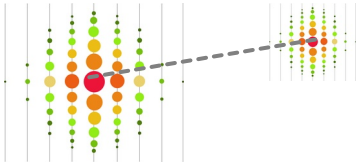
How?

—Infer the spectrum of ν_e, ν_μ, ν_τ separately

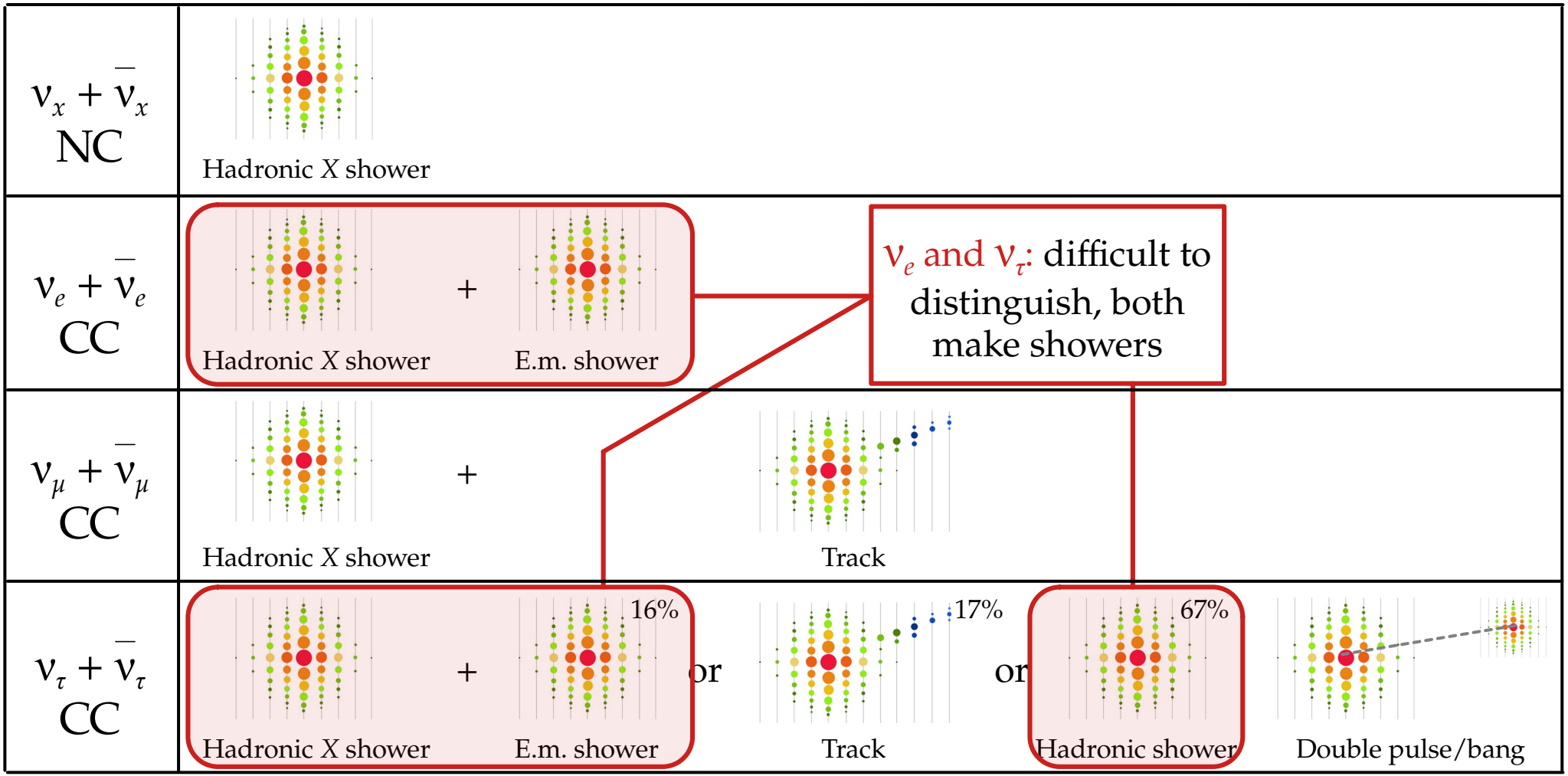


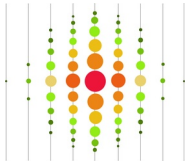
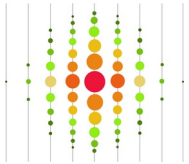
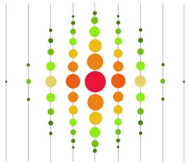
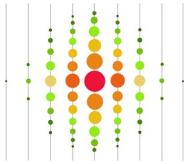
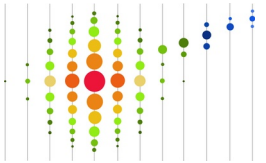
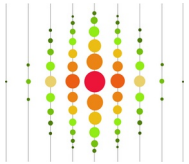
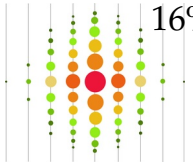
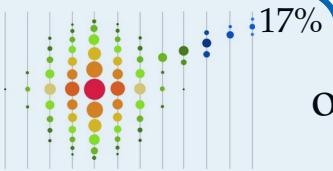
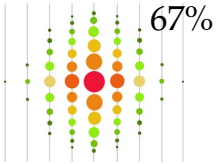
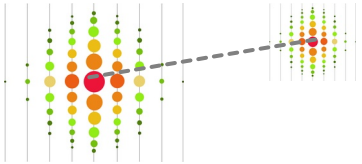
Liu, **MB**, *In prep.*

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

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

ν_μ: easy to identify the outgoing track


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

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

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