The future of high-energy astrophysical neutrino flavor measurements

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EPS-HEP
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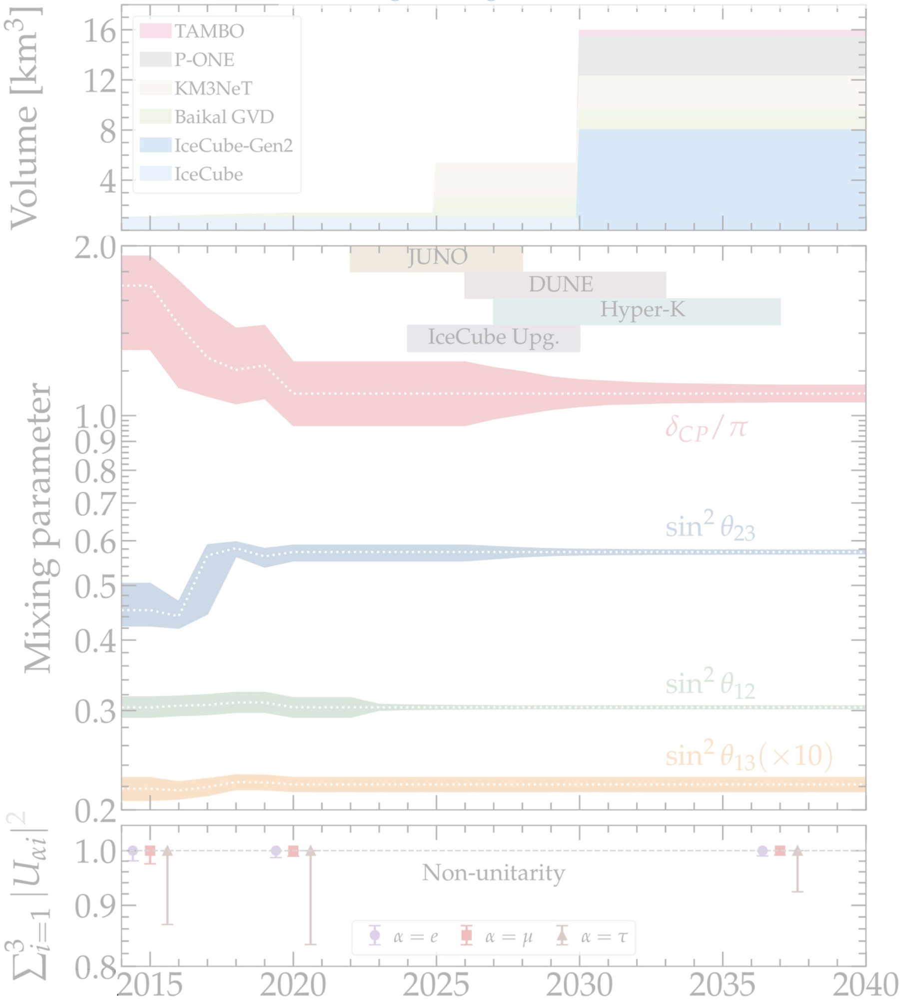
UNIVERSITY OF COPENHAGEN

VILLUM FONDEN

Three reasons to be excited

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



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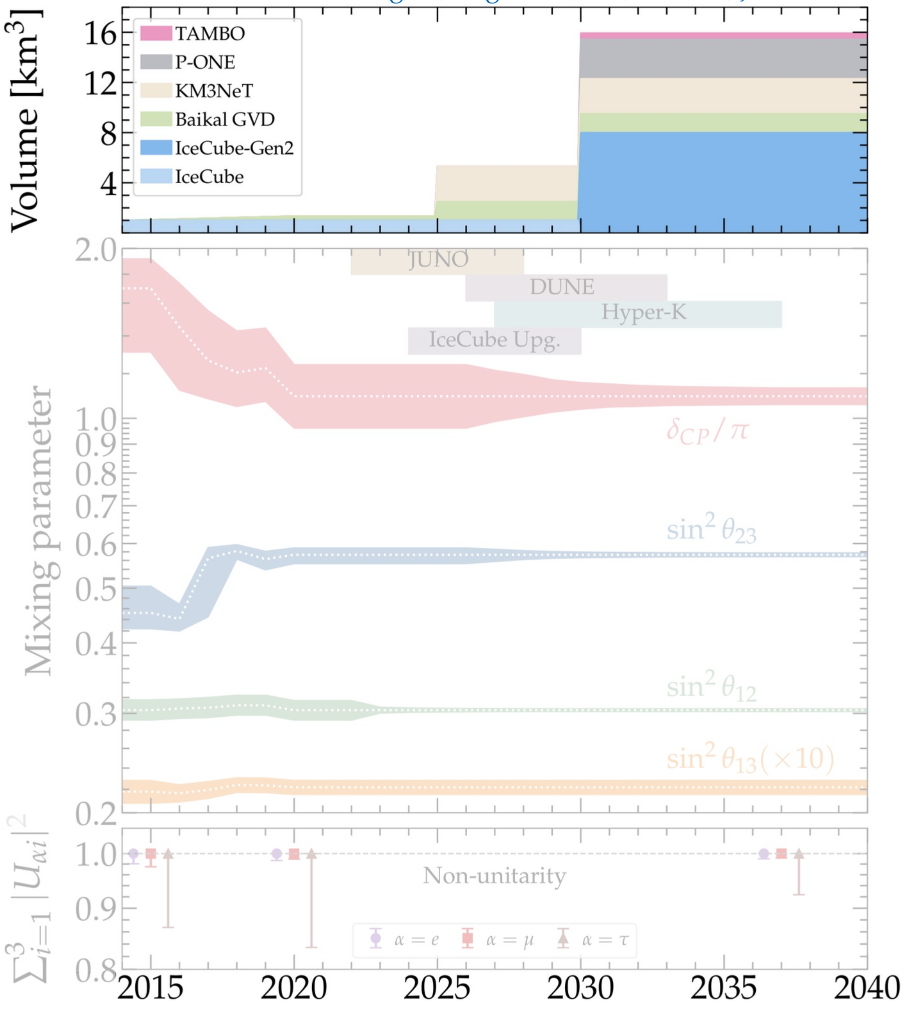
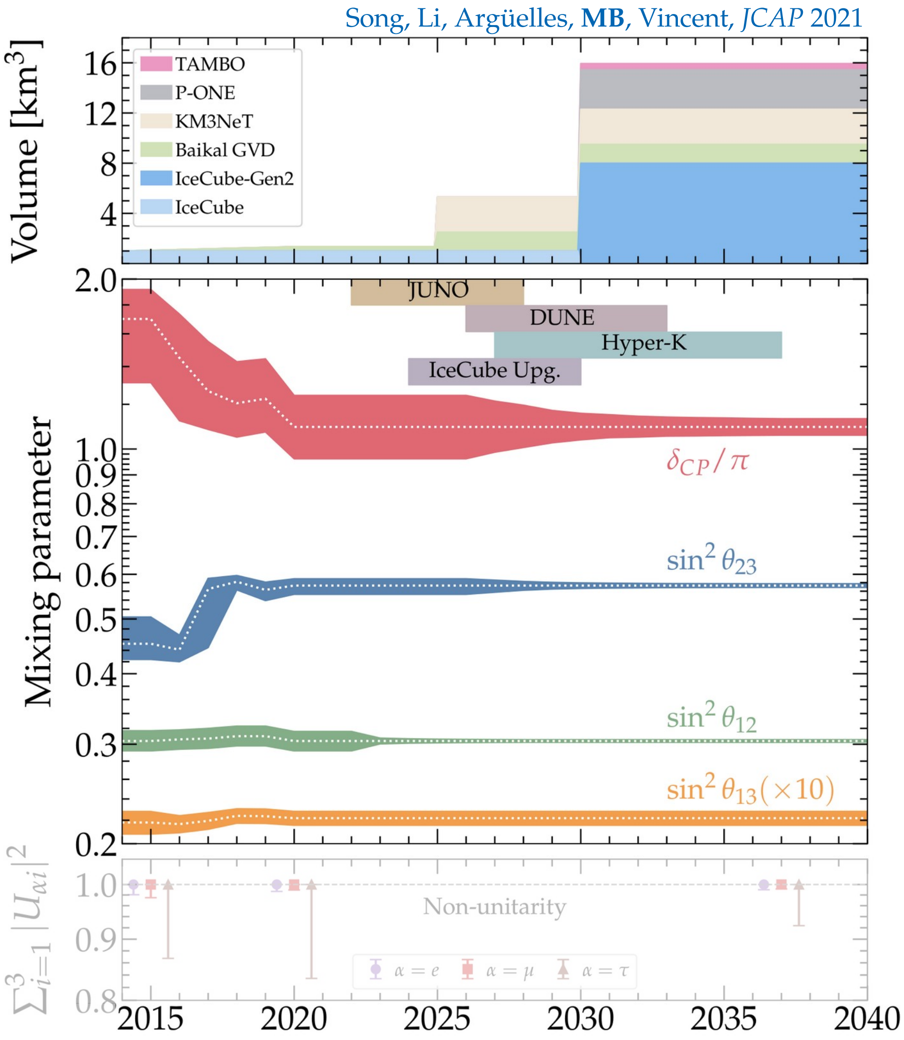


Flavor measurements:

New neutrino telescopes = more events, better flavor measurement

Three reasons to be excited



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New neutrino telescopes = more events, better flavor measurement

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

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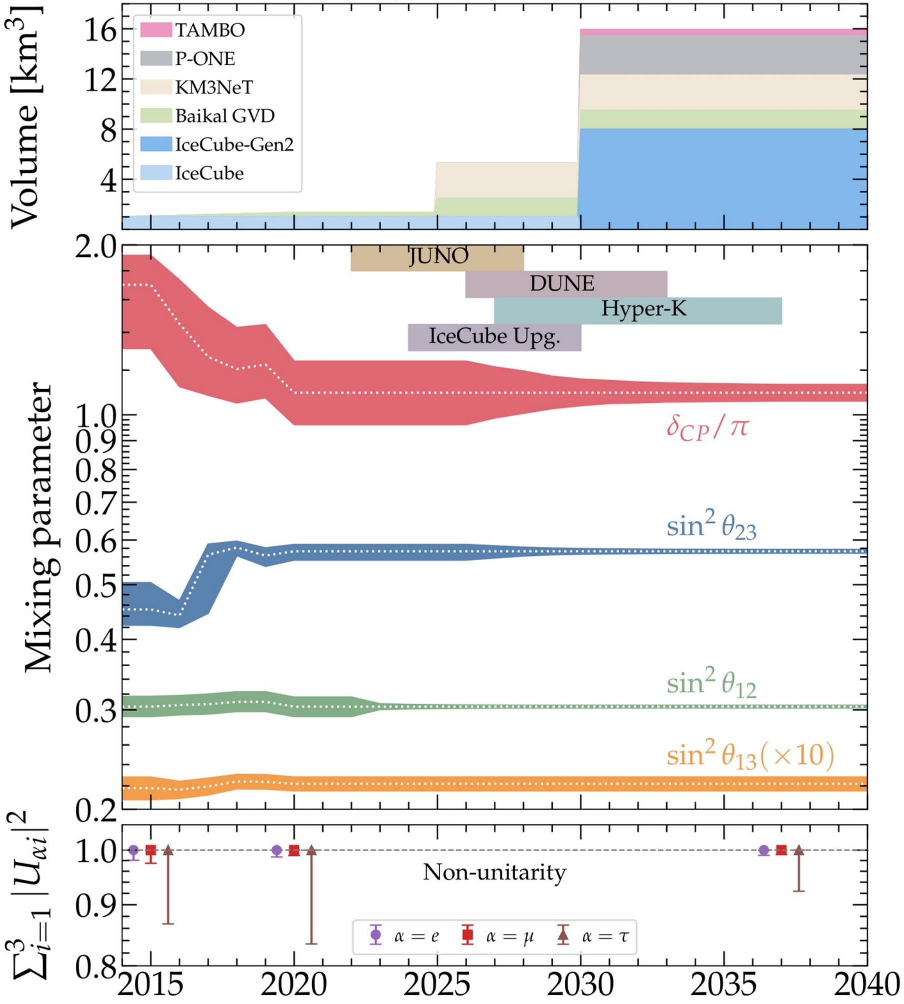
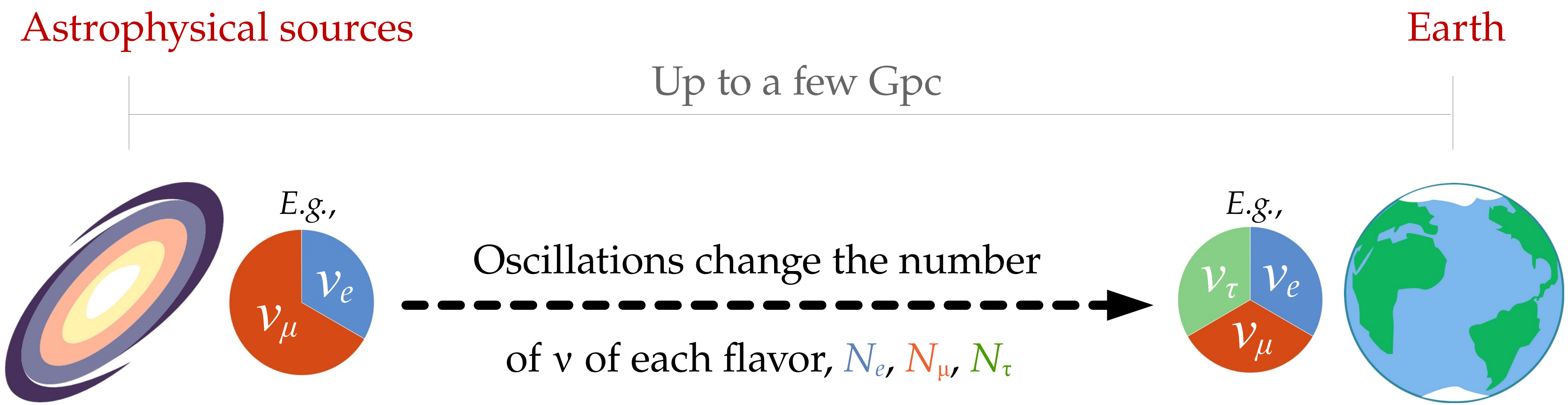


Flavor measurements:
New neutrino telescopes = more events, better flavor measurement

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

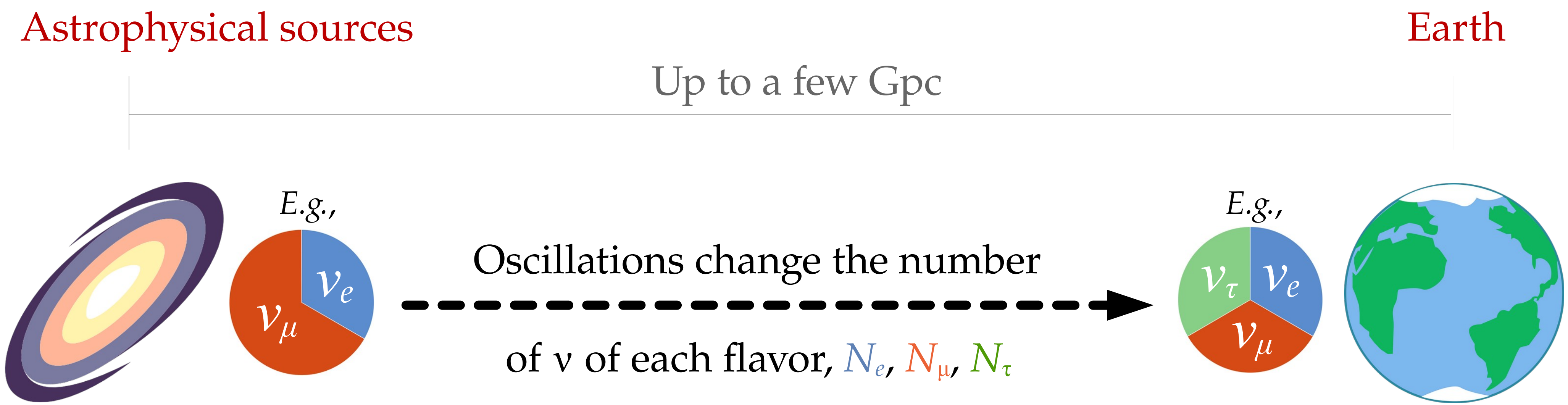


Different production mechanisms yield different flavor ratios:

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

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

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



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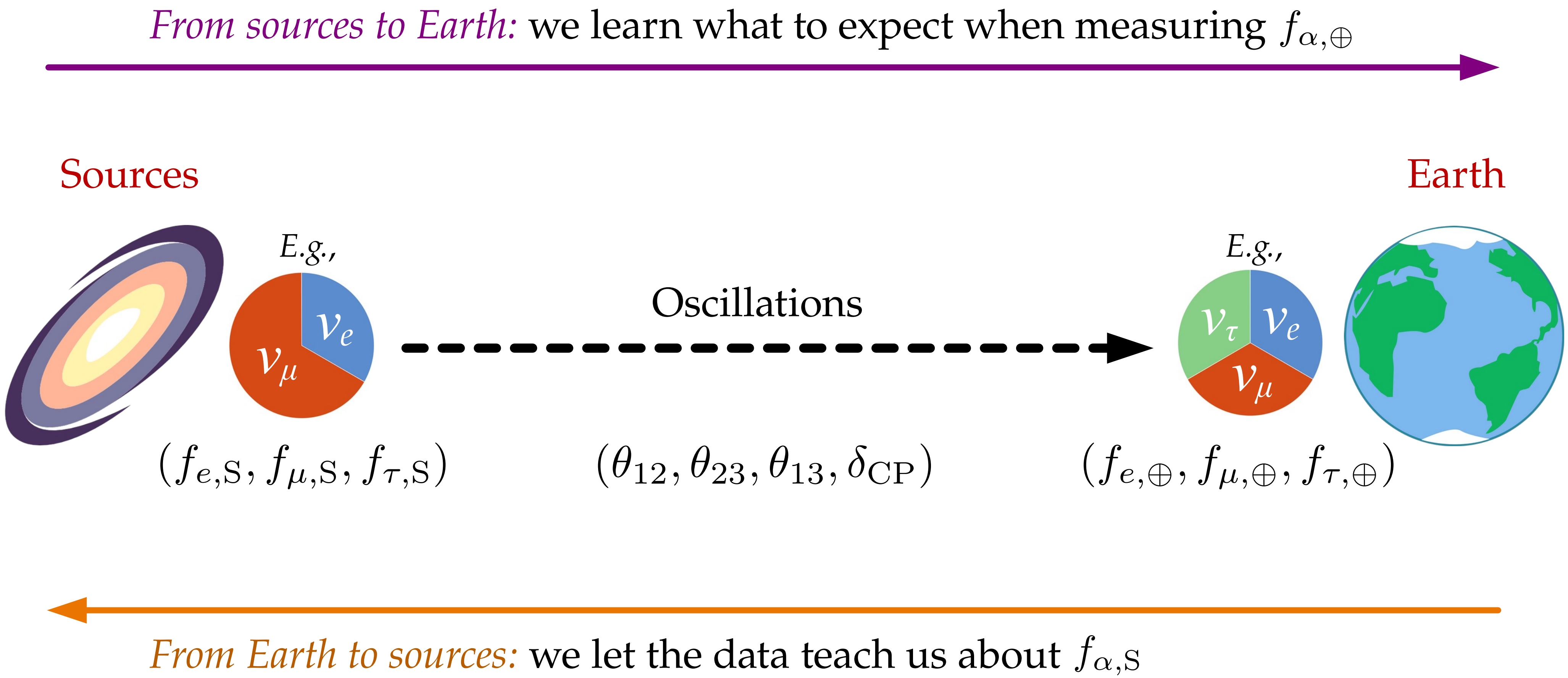
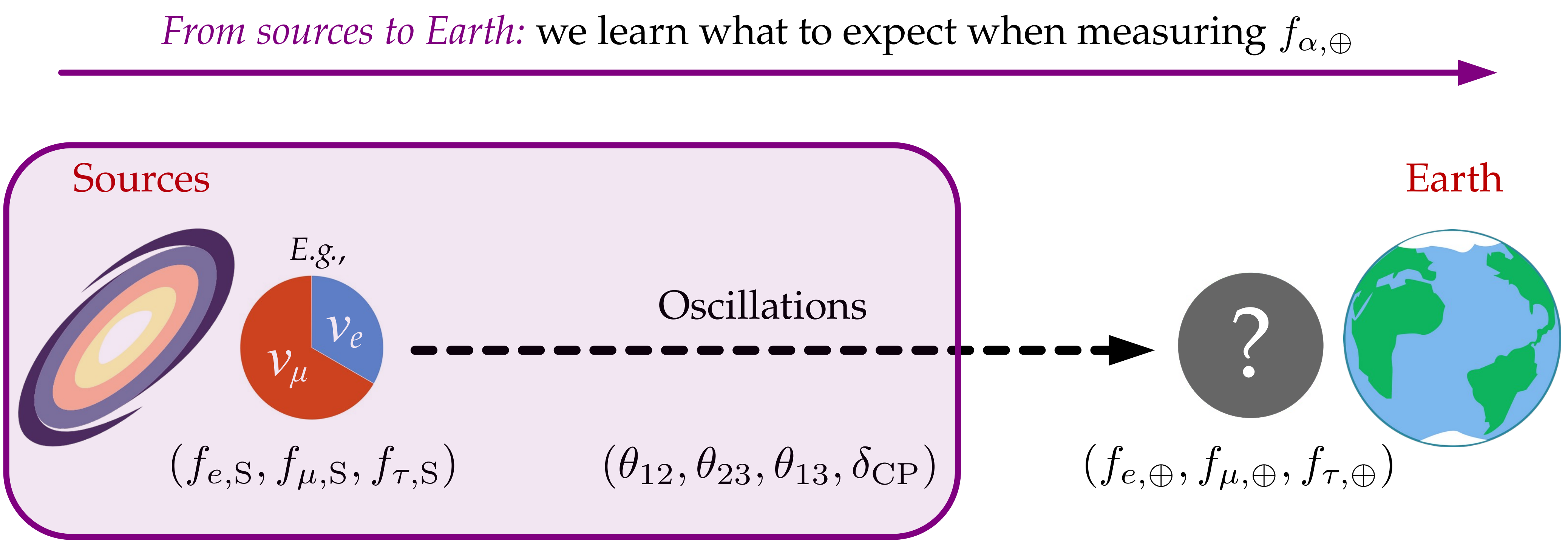
Standard oscillations
or
new physics


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



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Sources
Earth
E.g.,
ν_e
ν_μ
Oscillations
?
$(f_{e,\mathrm{S}}, f_{\mu,\mathrm{S}}, f_{\tau,\mathrm{S}})$
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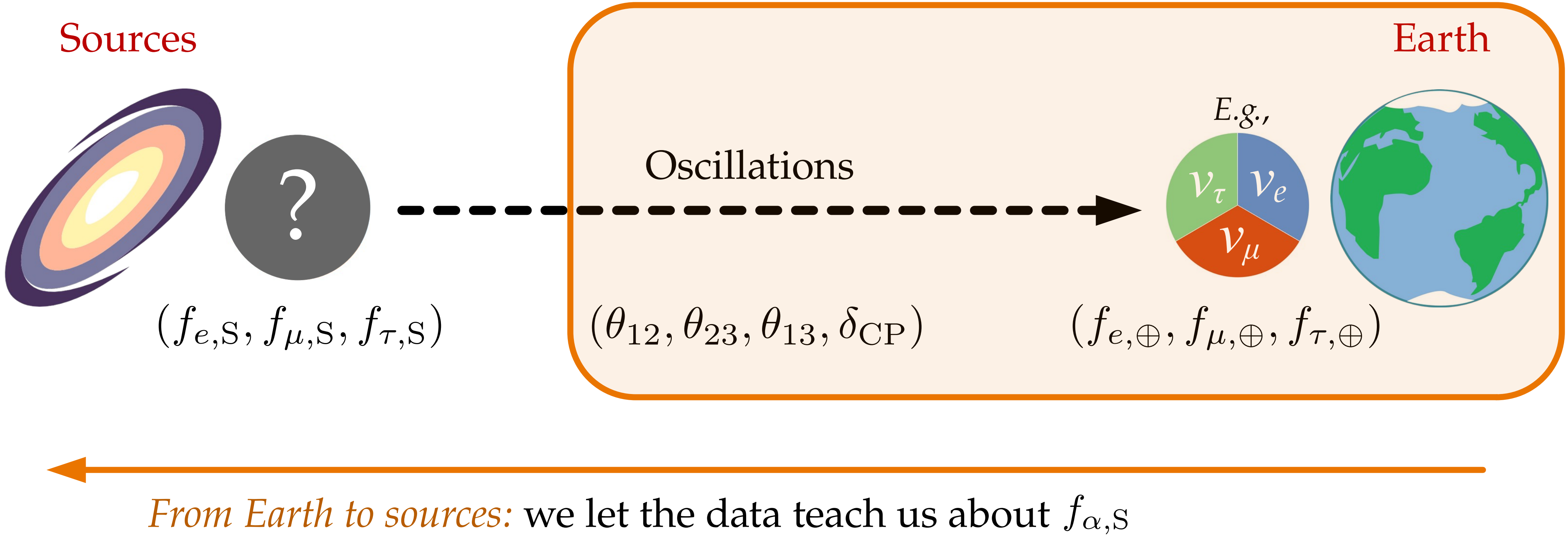
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ν_τ
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From Earth to sources: we let the data teach us about $f_{\alpha,\mathrm{S}}$

One likely TeV–PeV ν production scenario:

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

Full π decay chain

$(1/3:2/3:0)_\mathrm{S}$

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

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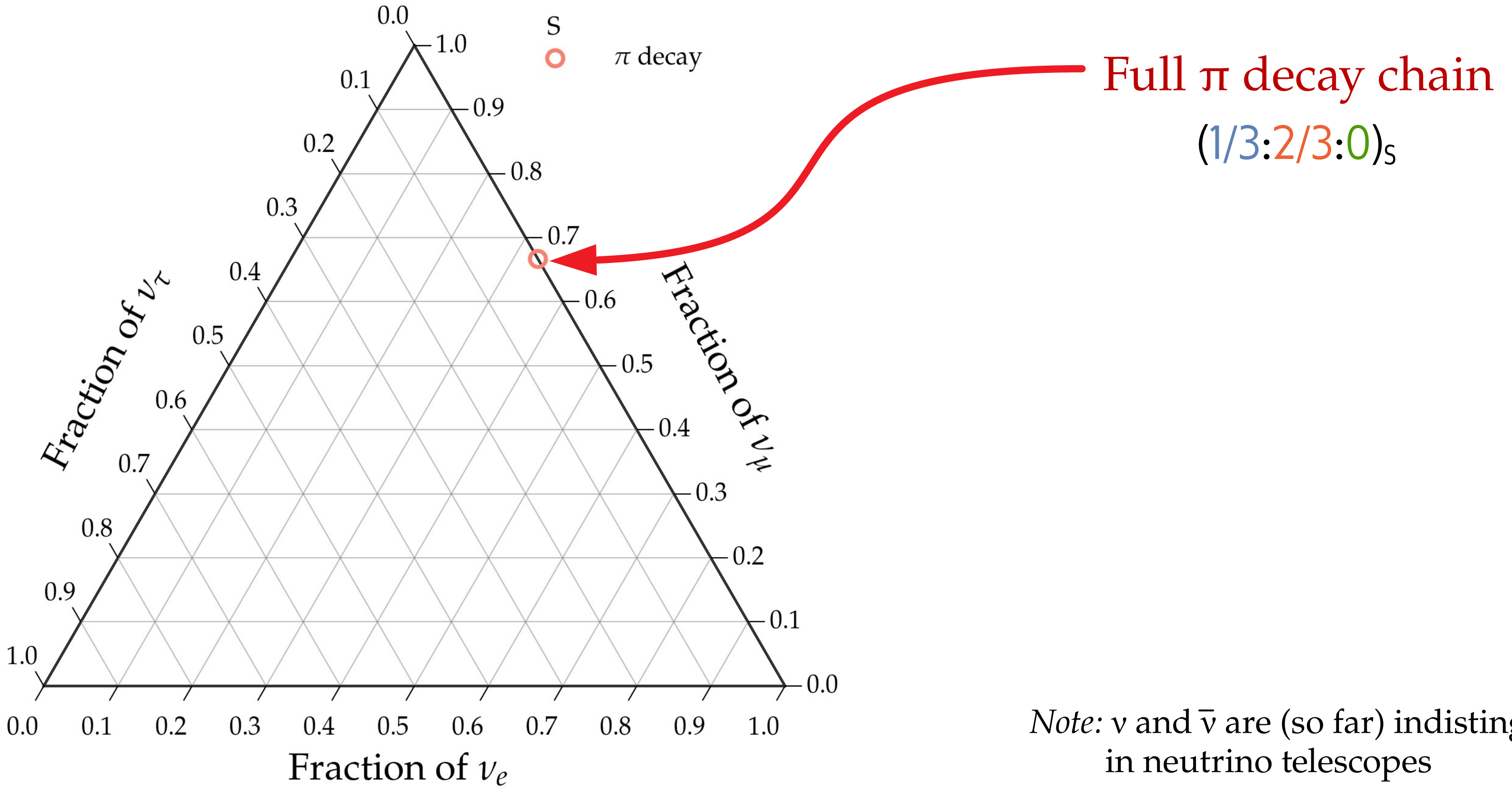

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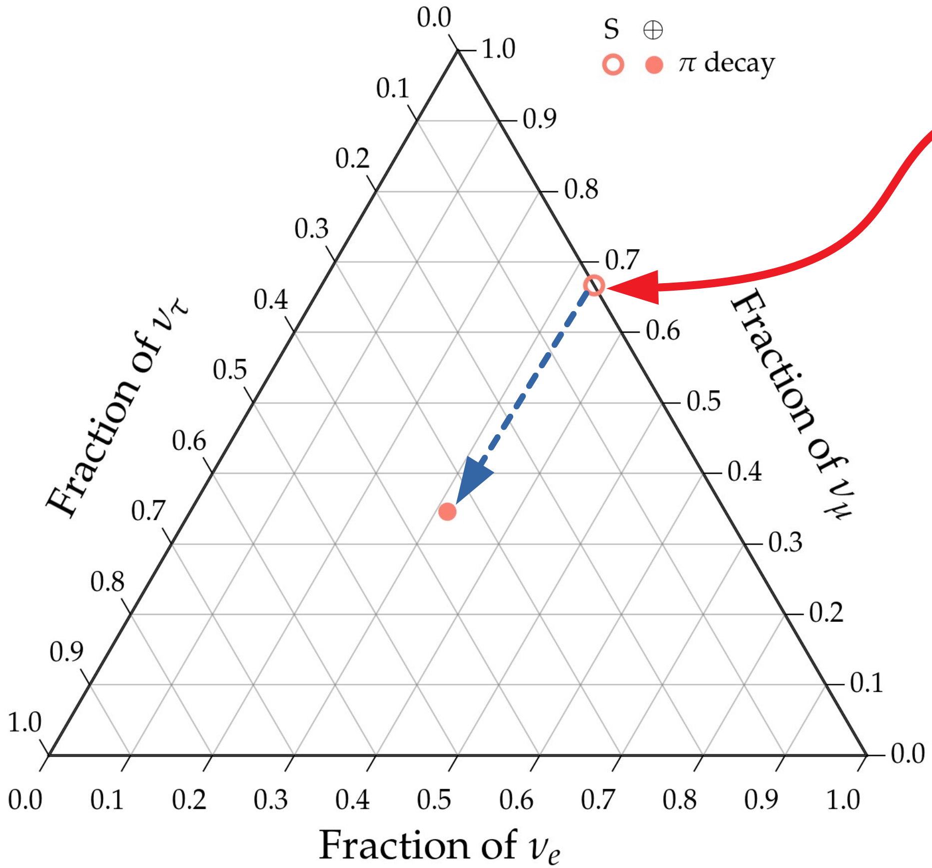

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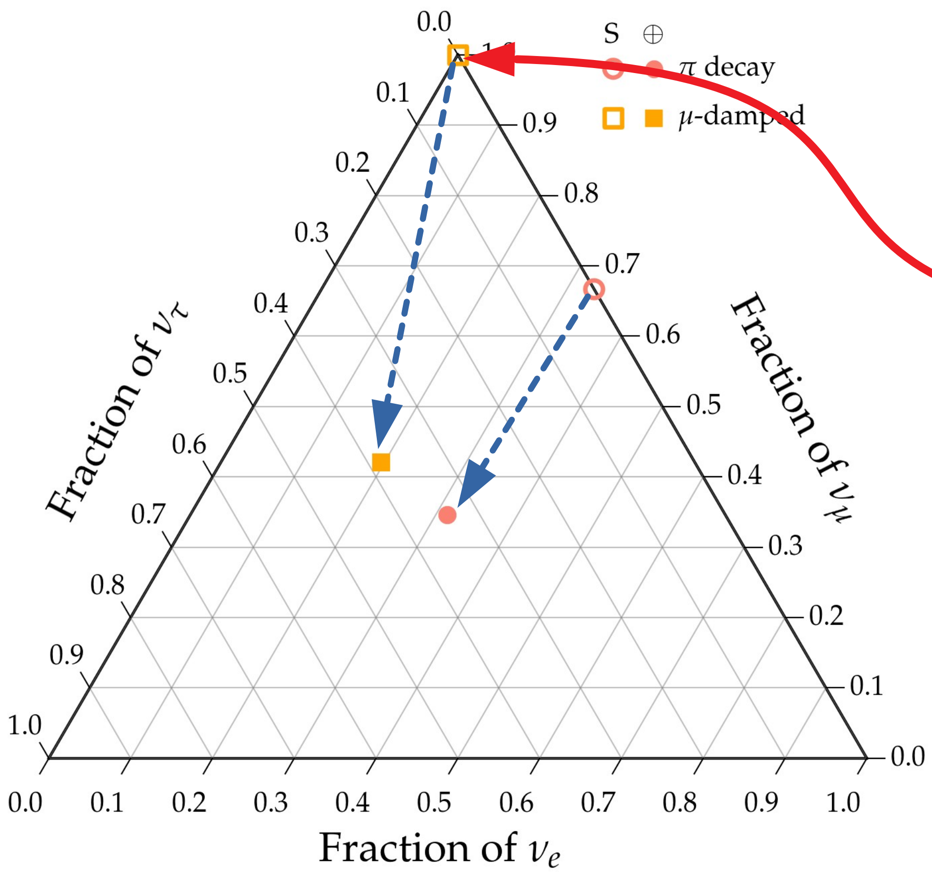

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Muon damped

$(0:1:0)_S$

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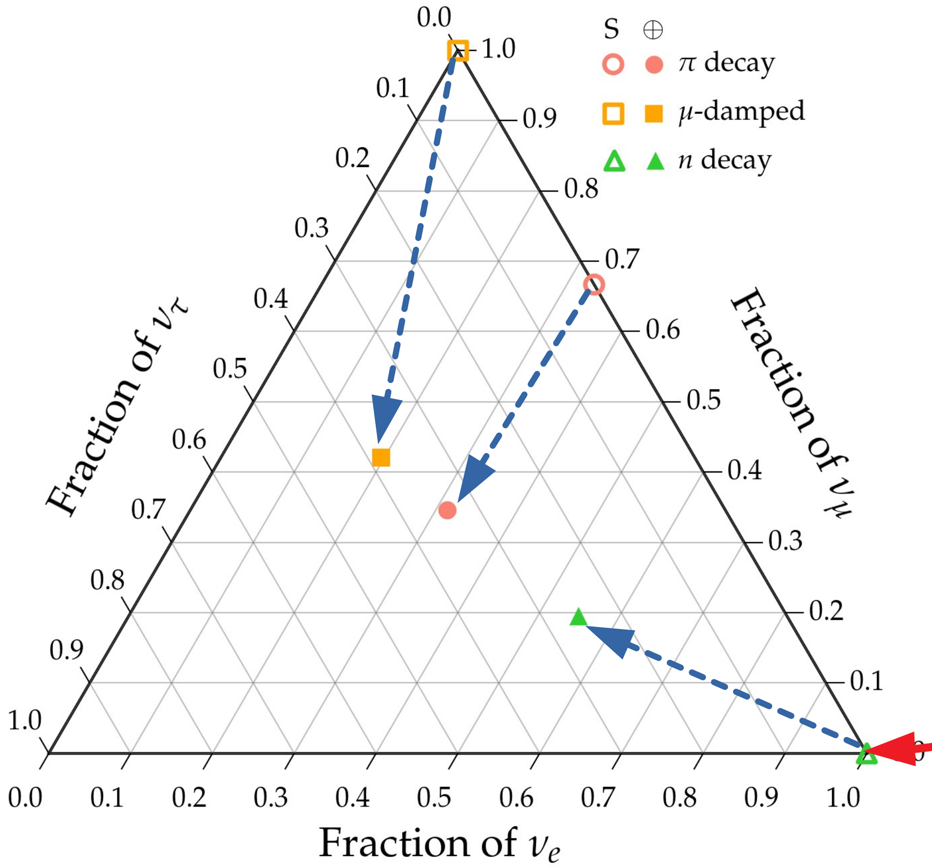

Full π decay chain

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

Muon damped

$(0:1:0)_S$

Neutron decay

$(1:0:0)_S$

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How does IceCube see TeV–PeV neutrinos?

Deep inelastic neutrino-nucleon scattering

Neutral current (NC)

$$\nu_x + N \longrightarrow \nu_x + X$$

Charged current (CC)

$$\nu_l + N \longrightarrow l + X$$

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Charged current (CC)

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

Receives $\langle y \rangle E_\nu$

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

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

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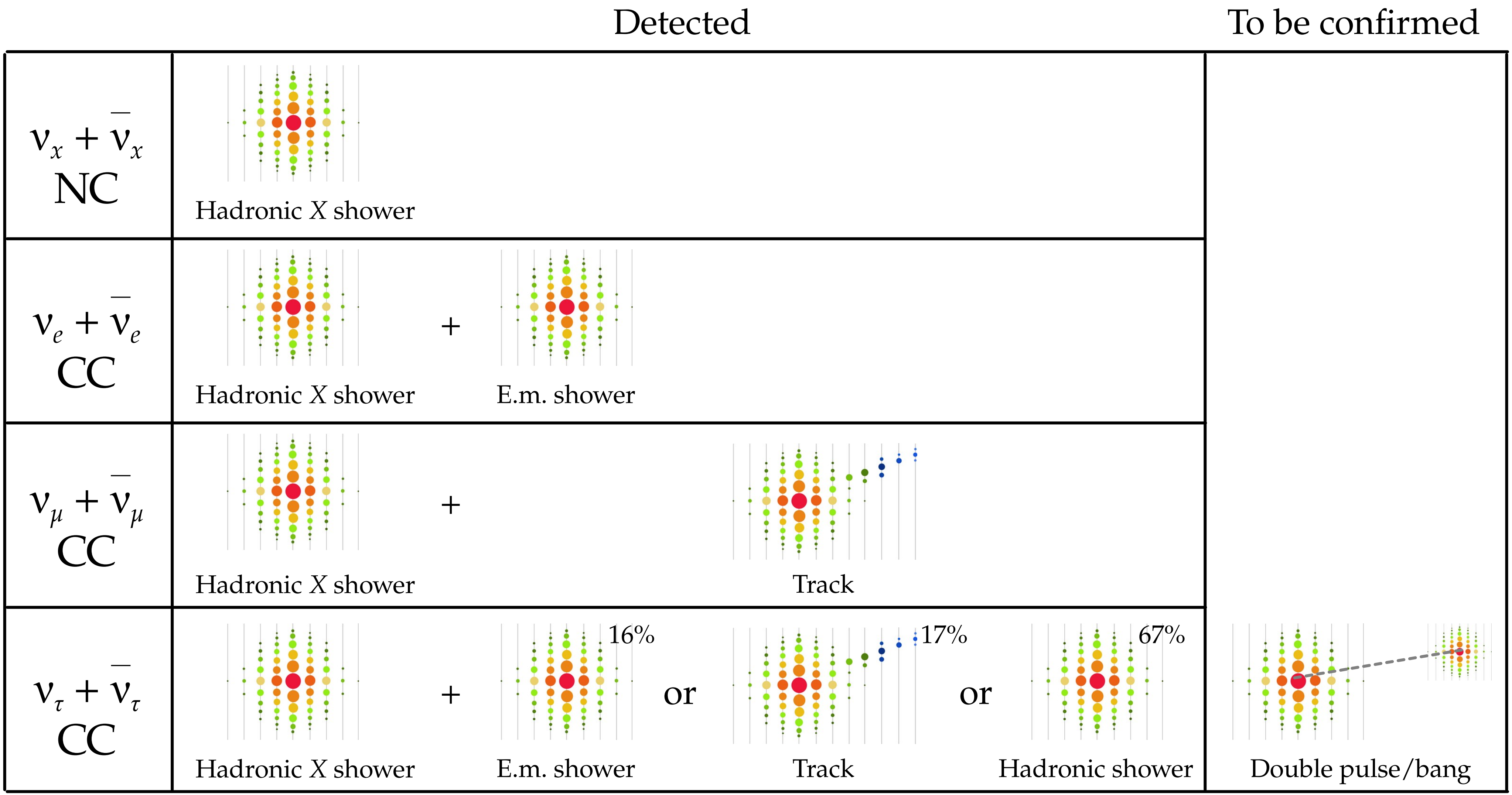
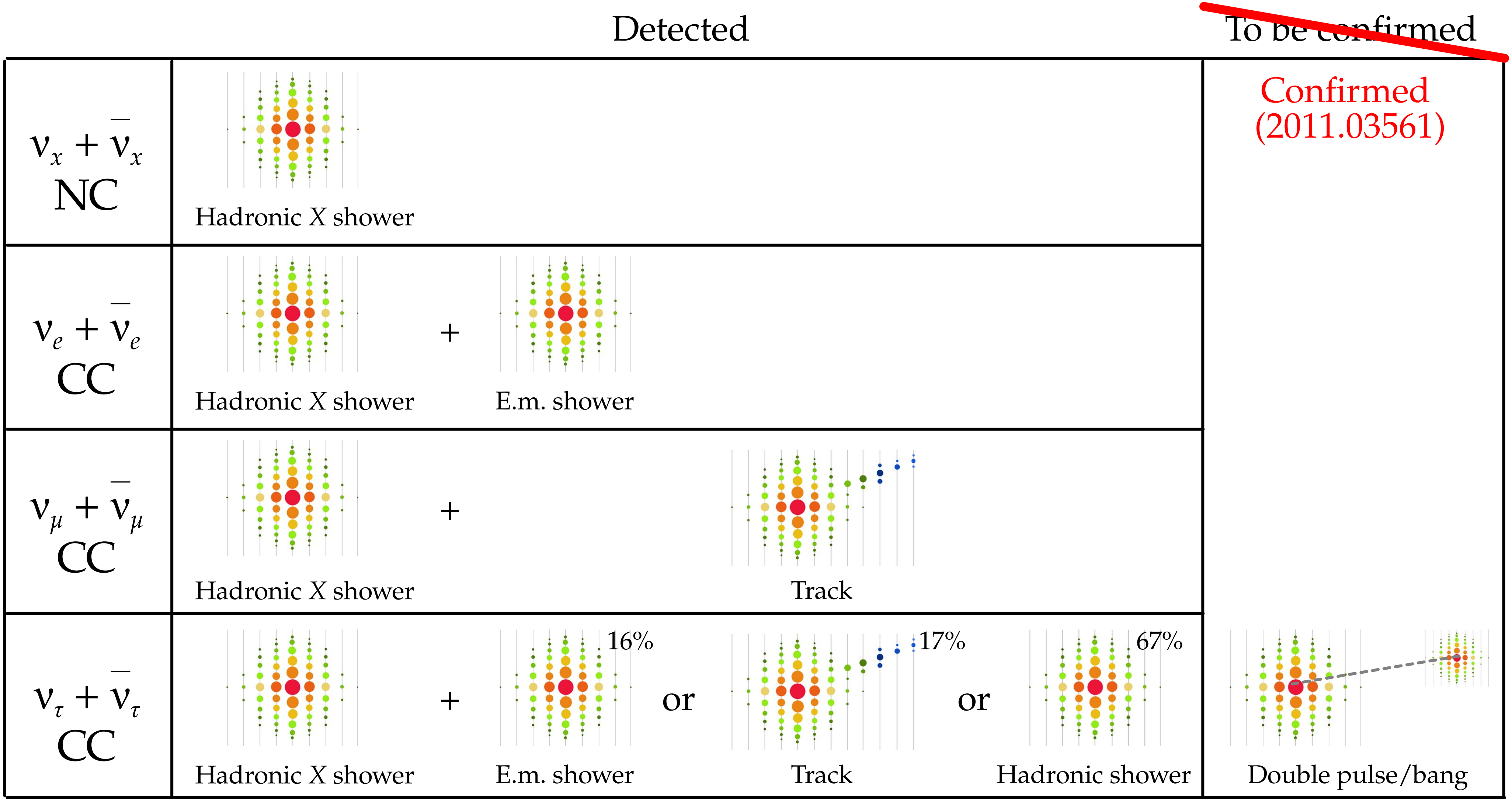
Makes shower
(e.m. or hadronic) or track

Makes hadronic shower

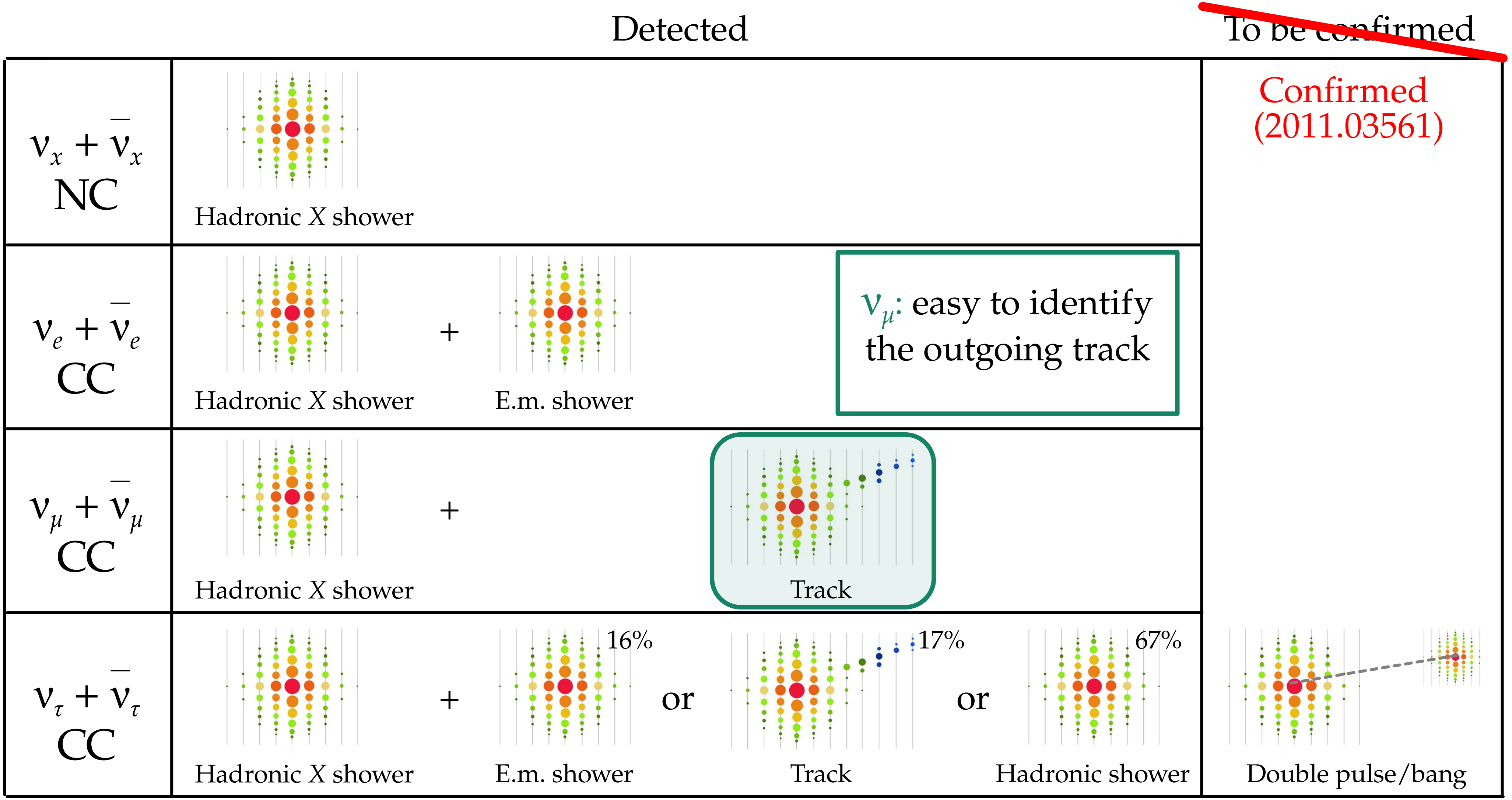
At TeV–PeV, the average inelasticity $\langle y \rangle$ = 0.25–0.30



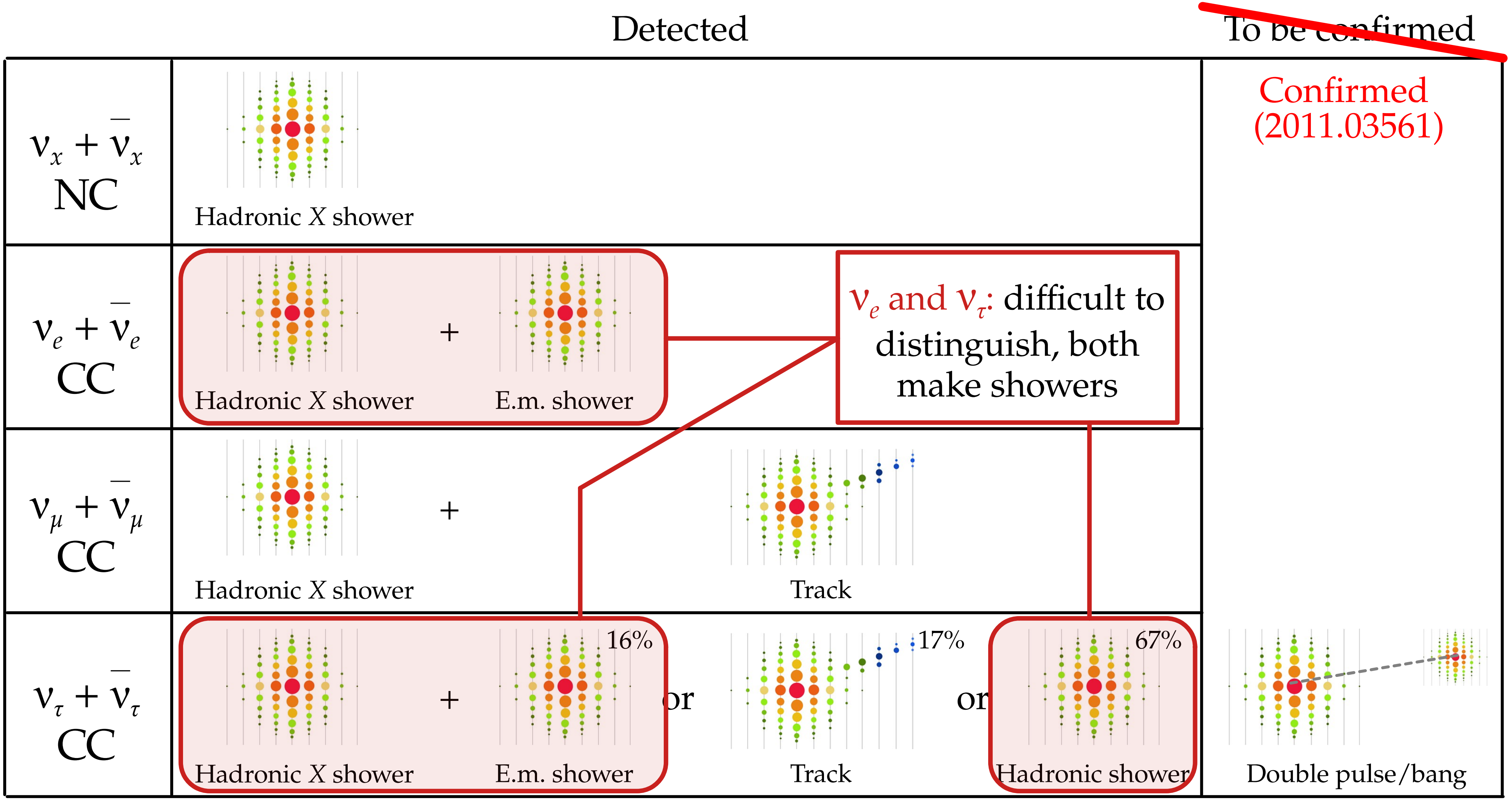
Detected
To be confirmed
$\nu_x + \bar{\nu}_x$ NC
Hadronic X shower
$\nu_e + \bar{\nu}_e$ CC
Hadronic X shower
+
E.m. shower
$\nu_\mu + \bar{\nu}_\mu$ CC
Hadronic X shower
+
Track
$\nu_\tau + \bar{\nu}_\tau$ CC
Hadronic X shower
+
16%
E.m. shower
or
17%
Track
or
67%
Hadronic shower
Double pulse/bang

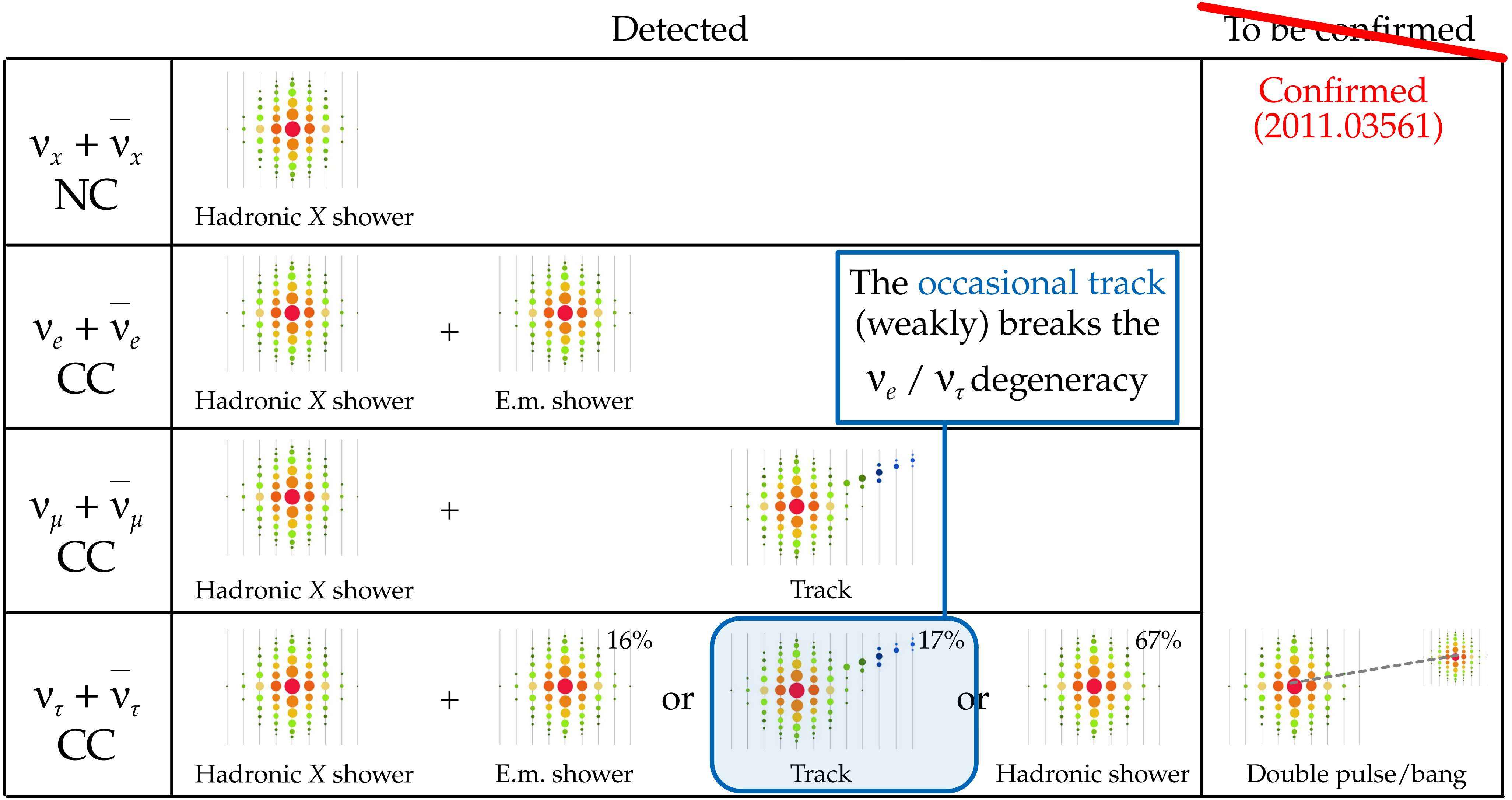


Detected
~~To be confirmed~~
Confirmed
(2011.03561)
$\nu_x + \bar{\nu}_x$ NC
Hadronic X shower
$\nu_e + \bar{\nu}_e$ CC
Hadronic X shower
+
E.m. shower
$\nu_\mu + \bar{\nu}_\mu$ CC
Hadronic X shower
+
Track
$\nu_\tau + \bar{\nu}_\tau$ CC
Hadronic X shower
+
16%
E.m. shower
or
17%
Track
or
67%
Hadronic shower
Double pulse/bang



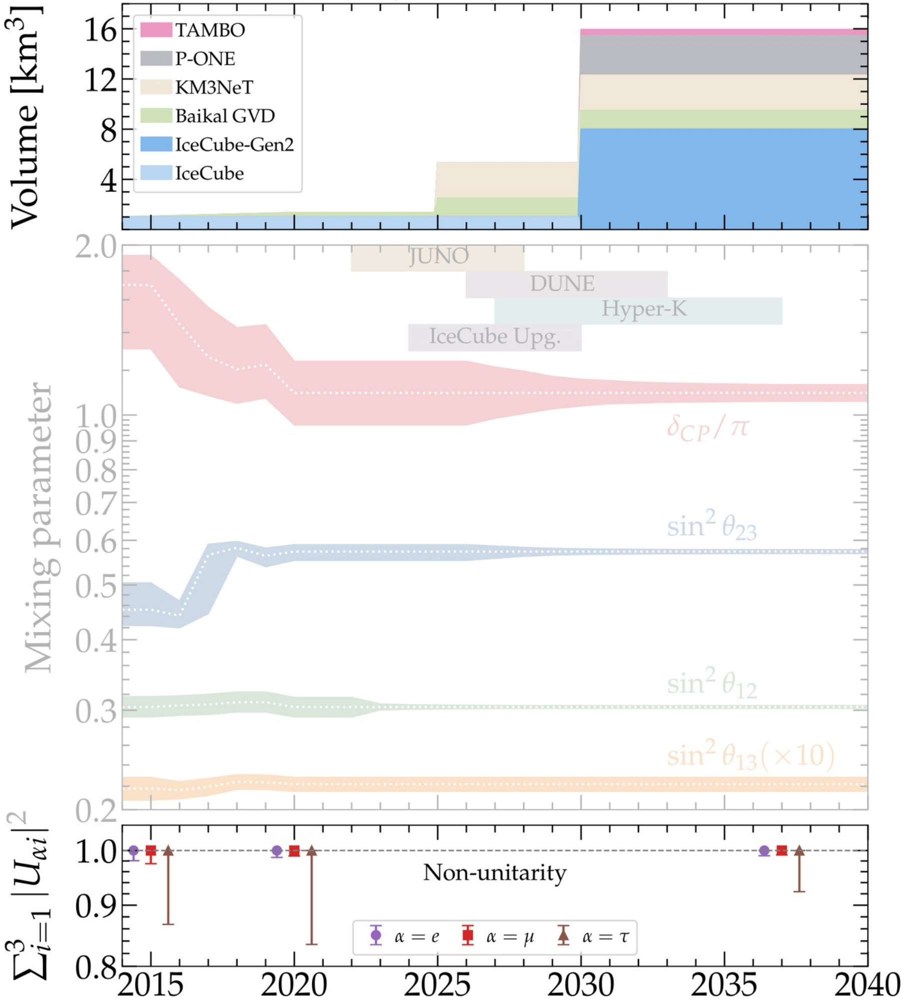
Detected
~~To be confirmed~~
Confirmed
(2011.03561)
$\nu_x + \bar{\nu}_x$
NC
Hadronic X shower
$\nu_e + \bar{\nu}_e$
CC
Hadronic X shower
+
E.m. shower
ν_μ: easy to identify the outgoing track
$\nu_\mu + \bar{\nu}_\mu$
CC
Hadronic X shower
+
Track
$\nu_\tau + \bar{\nu}_\tau$
CC
Hadronic X shower
+
16%
E.m. shower
or
17%
Track
or
67%
Hadronic shower
Double pulse/bang


Detected
To be confirmed
Confirmed
(2011.03561)
$\nu_x + \bar{\nu}_x$
NC
Hadronic X shower
$\nu_e + \bar{\nu}_e$
CC
Hadronic X shower
+
E.m. shower
ν_e and ν_τ: difficult to distinguish, both make showers
$\nu_\mu + \bar{\nu}_\mu$
CC
Hadronic X shower
+
Track
$\nu_\tau + \bar{\nu}_\tau$
CC
Hadronic X shower
+
E.m. shower
16%
or
Track
17%
or
Hadronic shower
67%
Double pulse/bang


Detected
To be confirmed
Confirmed
(2011.03561)
$\nu_x + \bar{\nu}_x$
NC
Hadronic X shower
$\nu_e + \bar{\nu}_e$
CC
Hadronic X shower
+
E.m. shower
The occasional track (weakly) breaks the ν_e / ν_τ degeneracy
$\nu_\mu + \bar{\nu}_\mu$
CC
Hadronic X shower
+
Track
$\nu_\tau + \bar{\nu}_\tau$
CC
Hadronic X shower
+
16%
E.m. shower
or
17%
Track
or
67%
Hadronic shower
Double pulse/bang

Measuring flavor composition: 2015–2040

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



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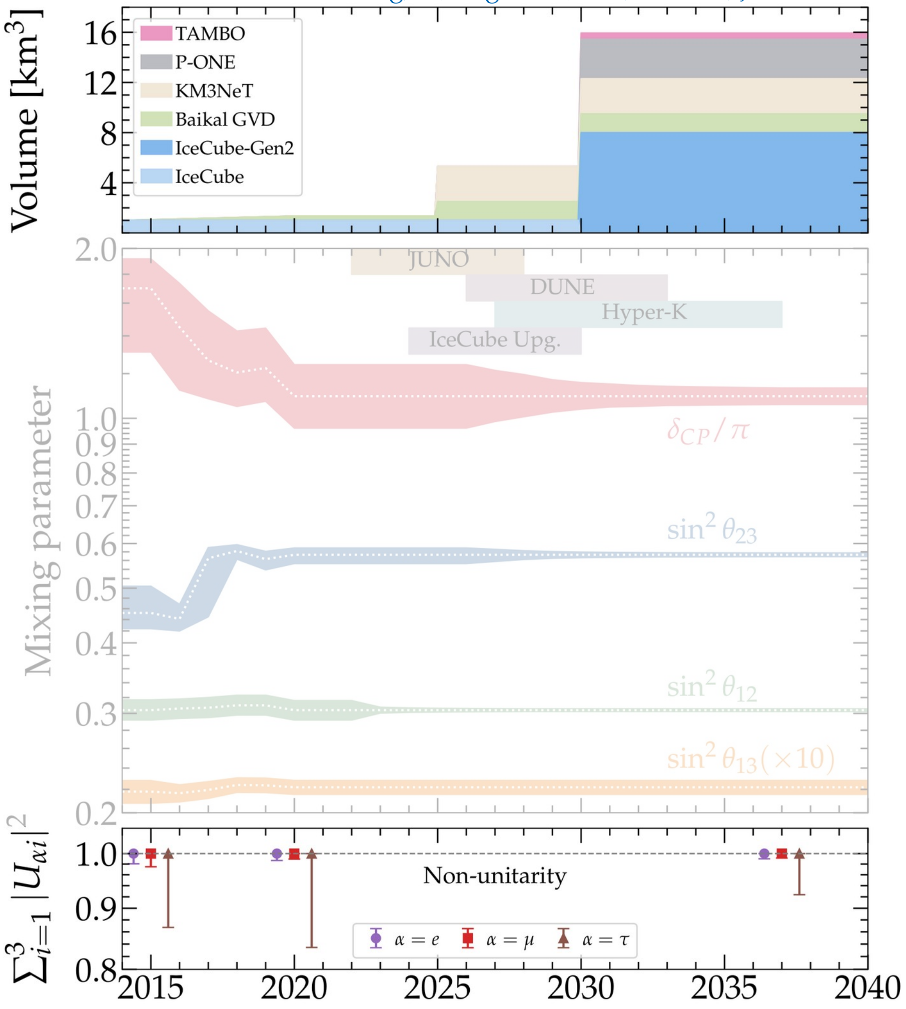

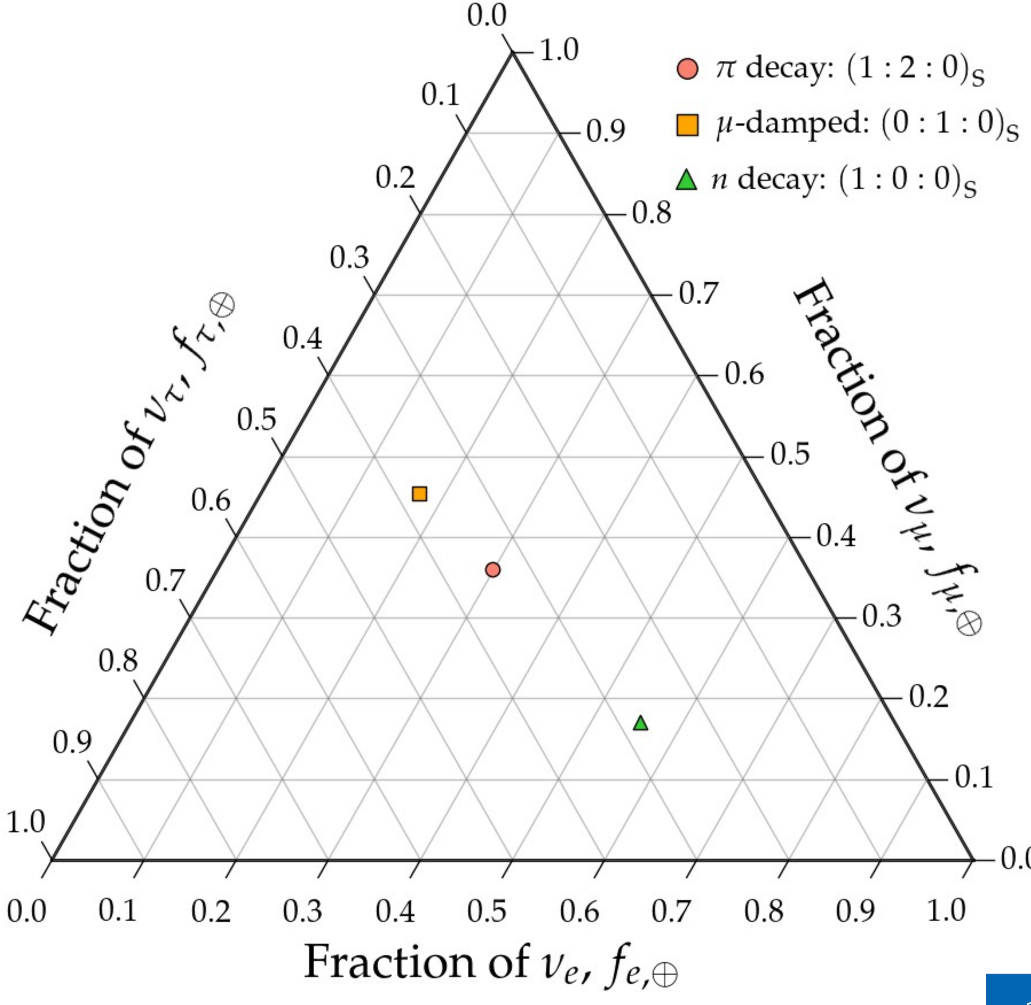

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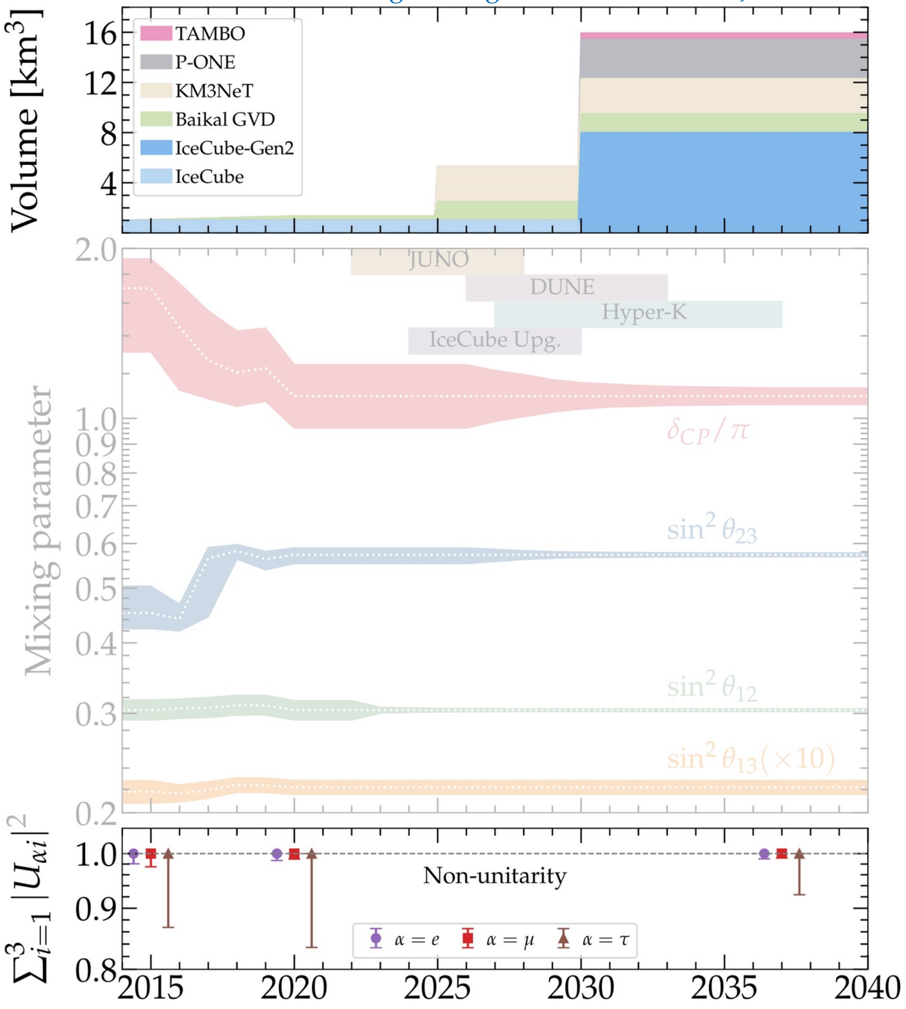

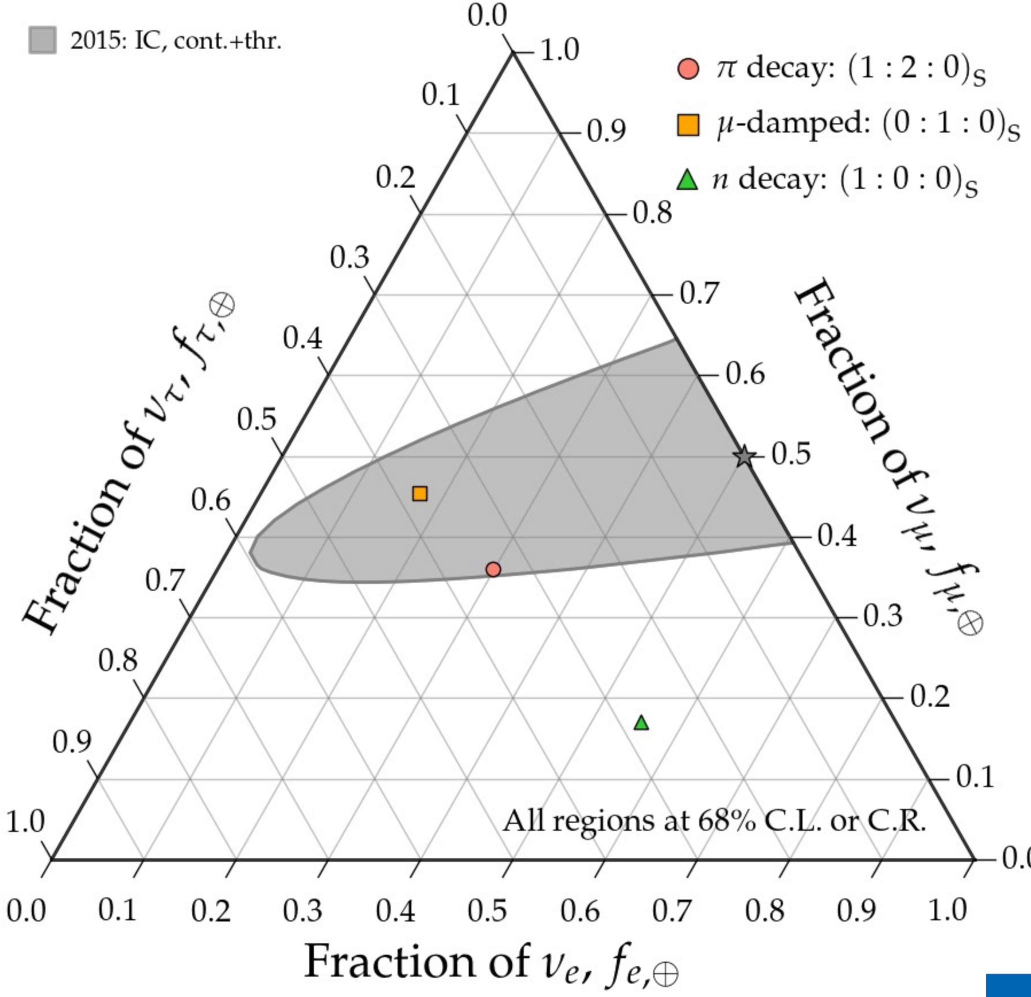

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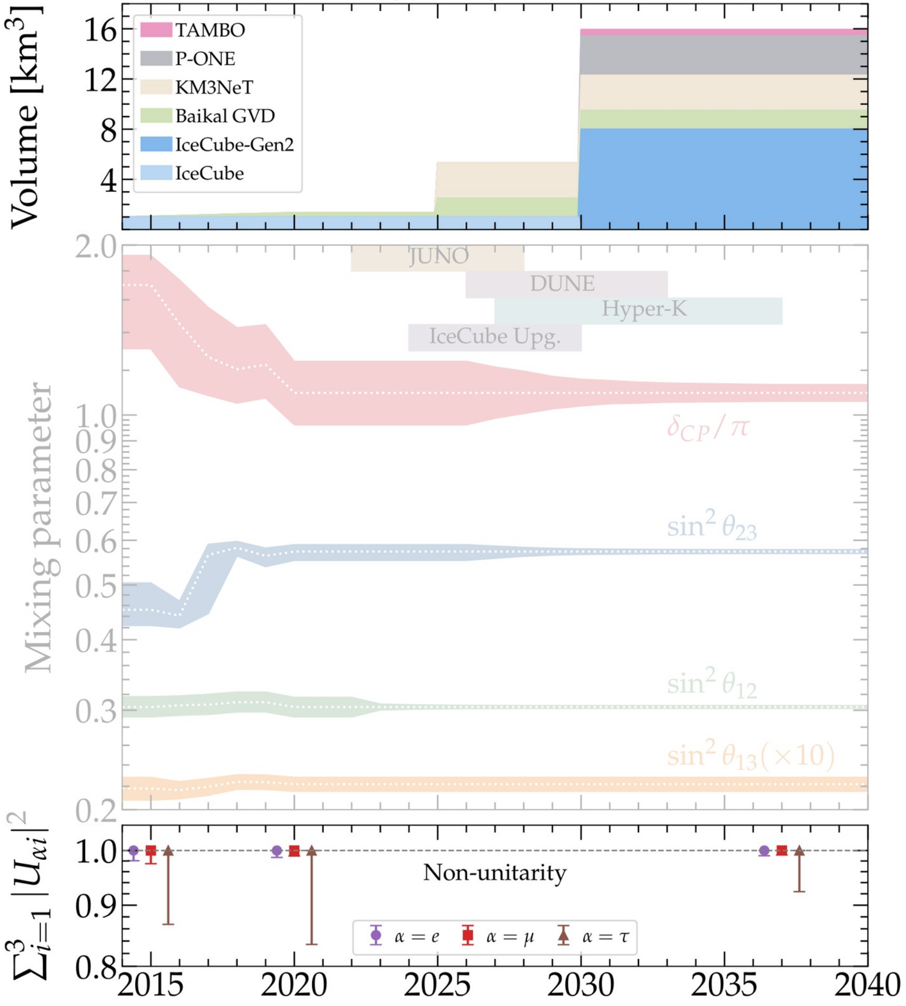

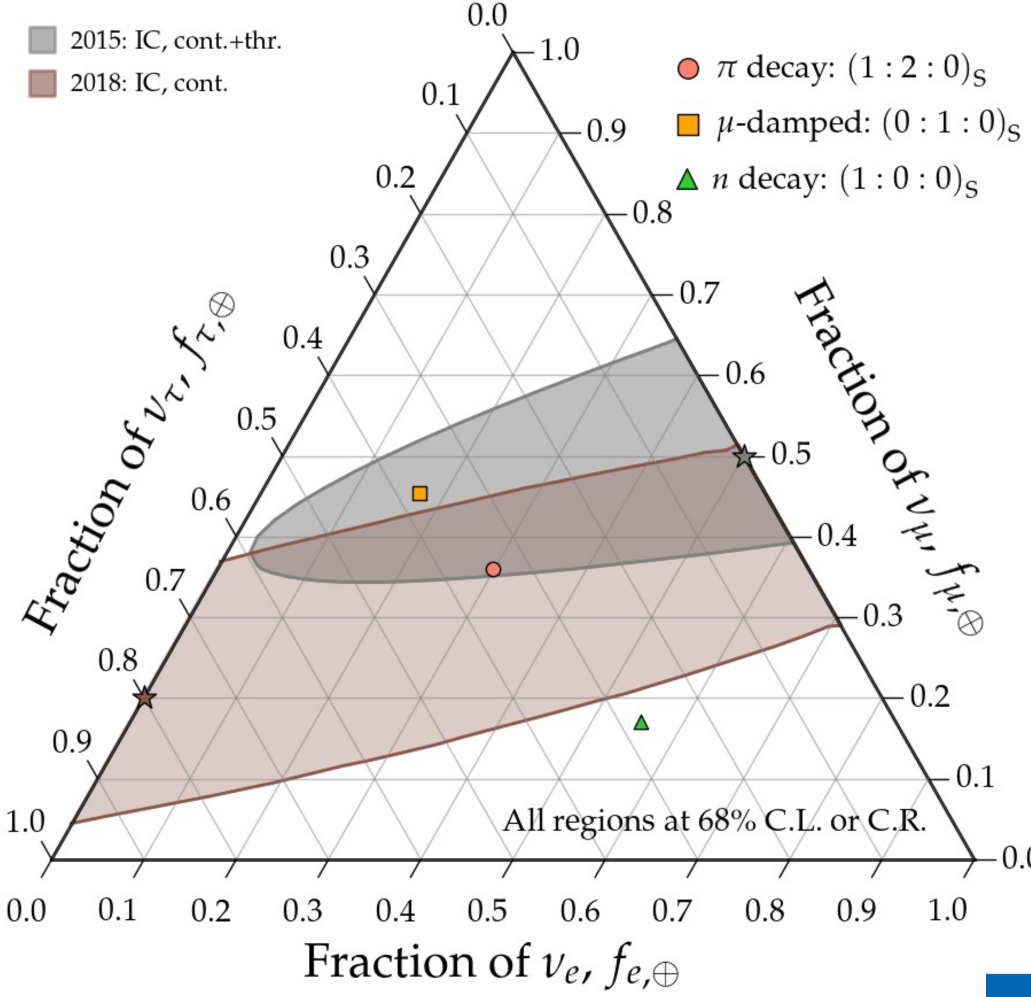

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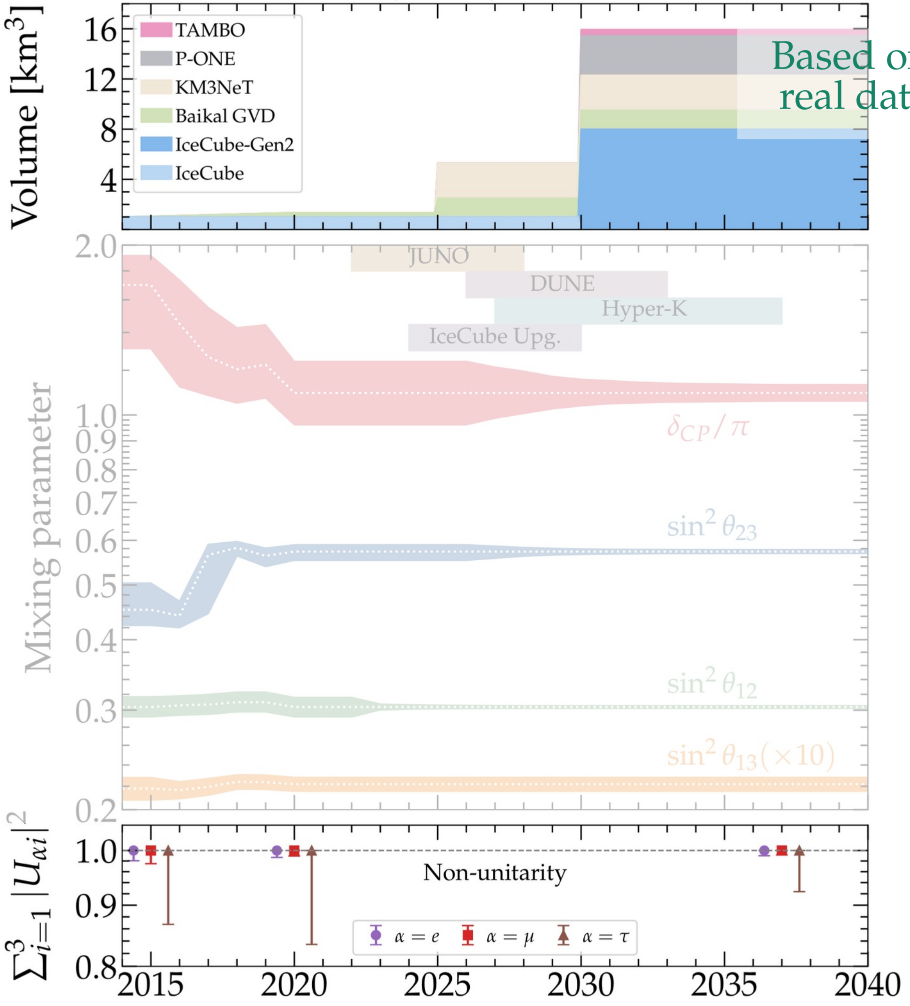
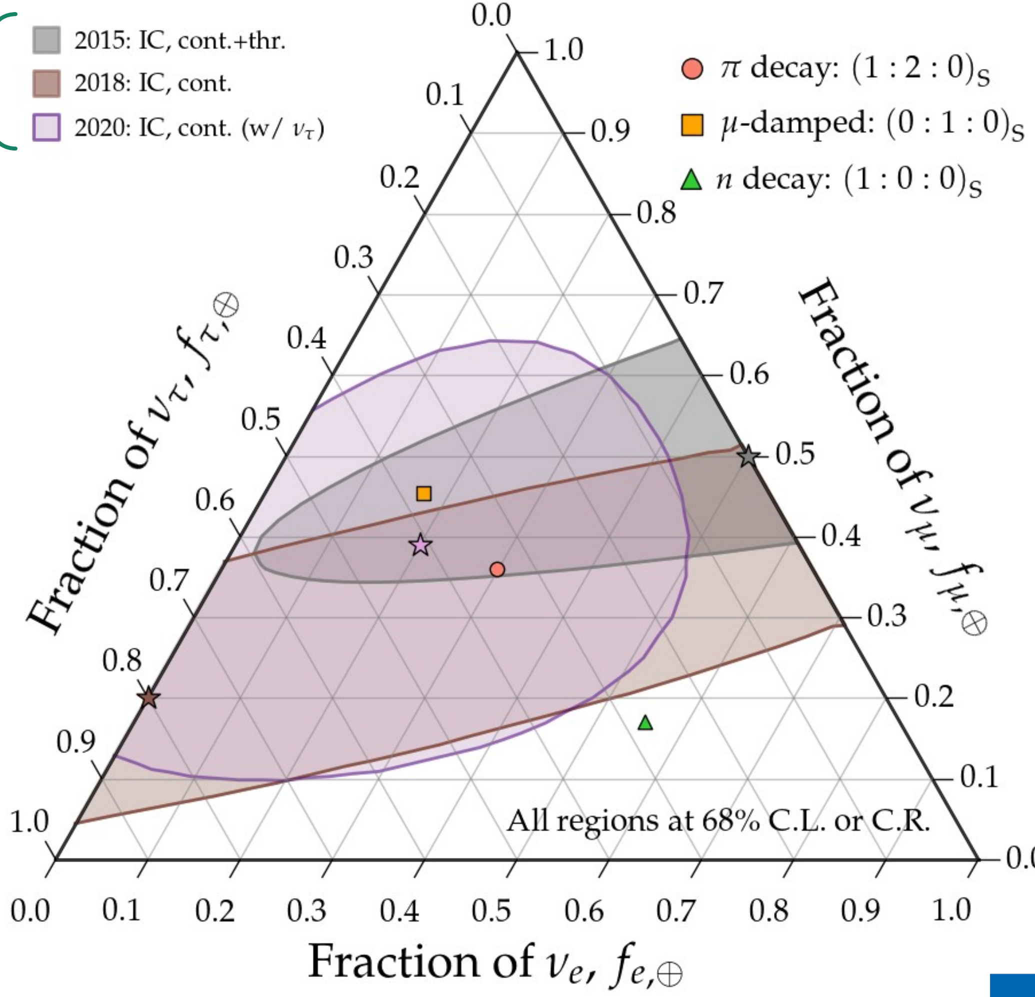


Based on real data



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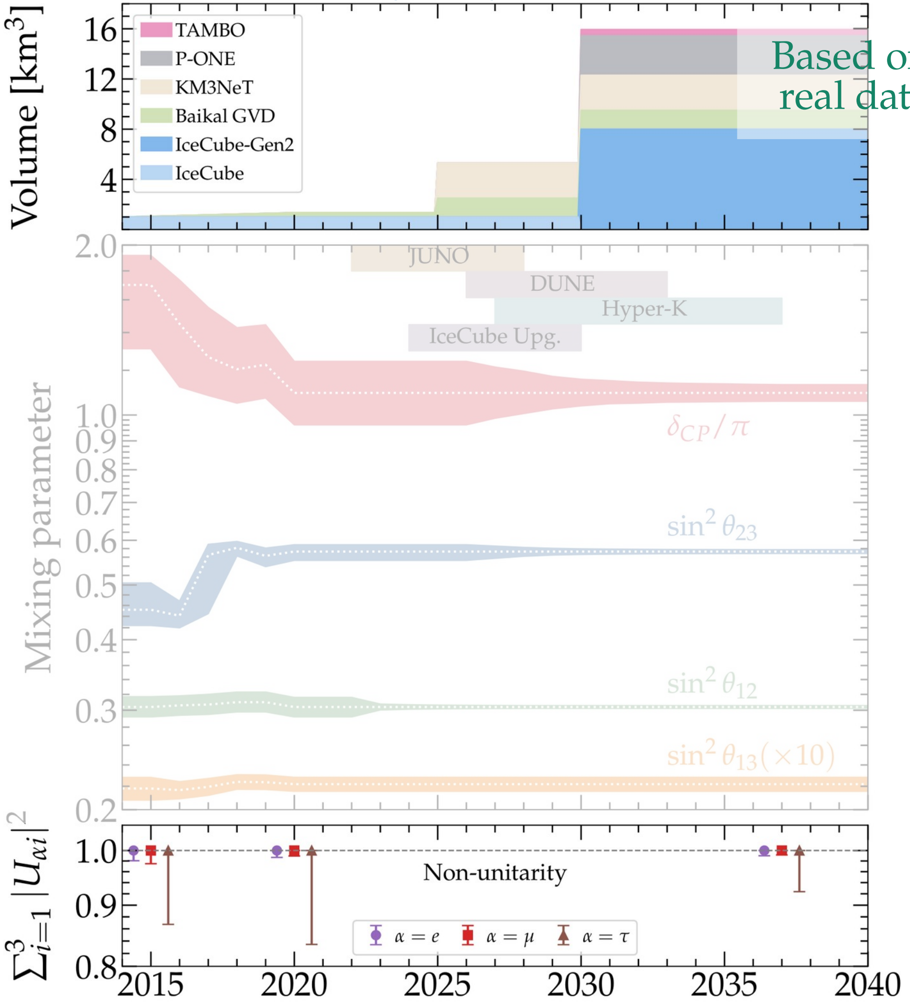

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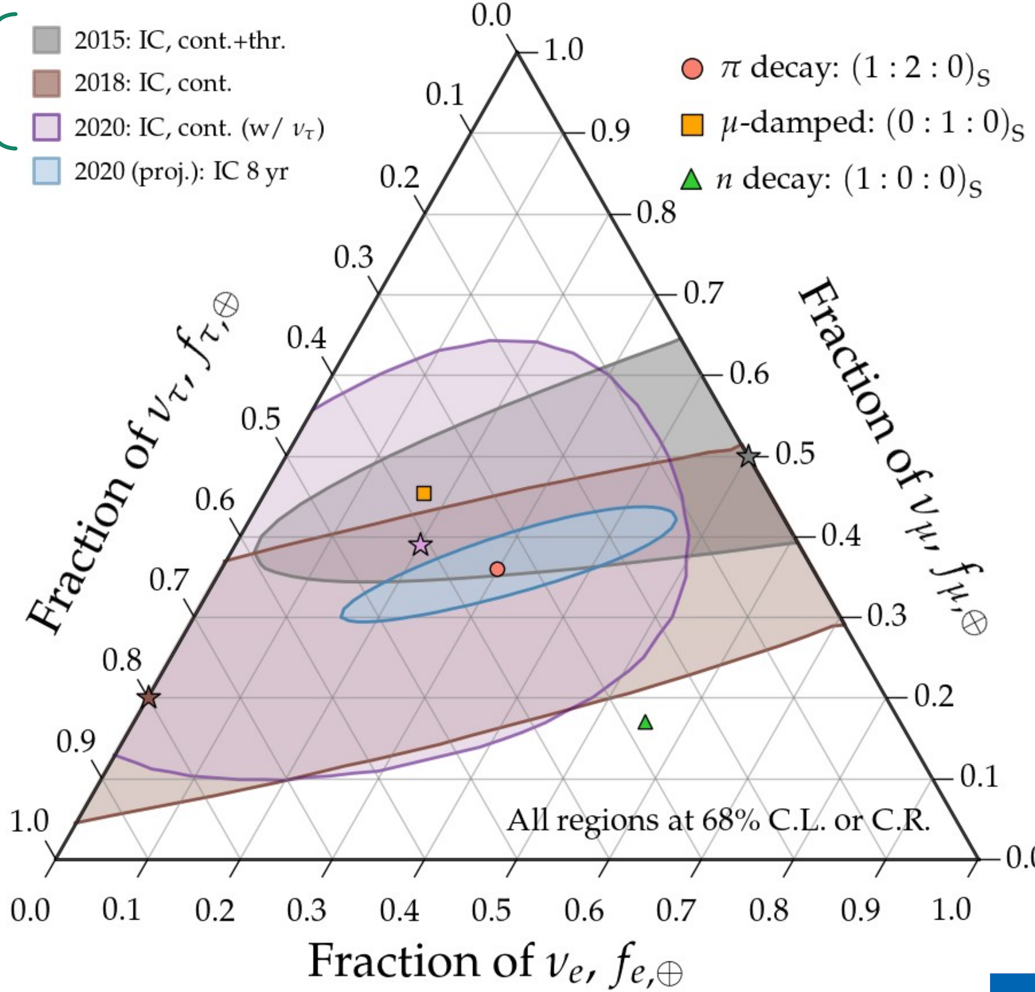

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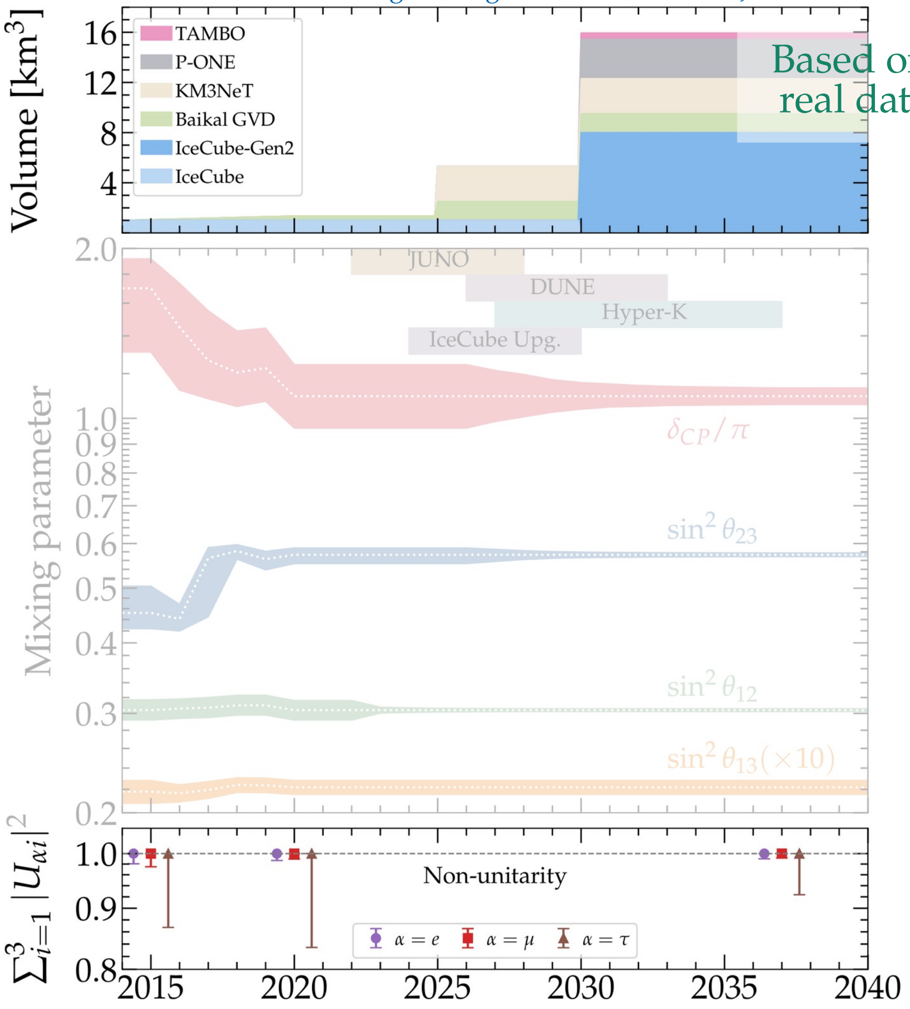

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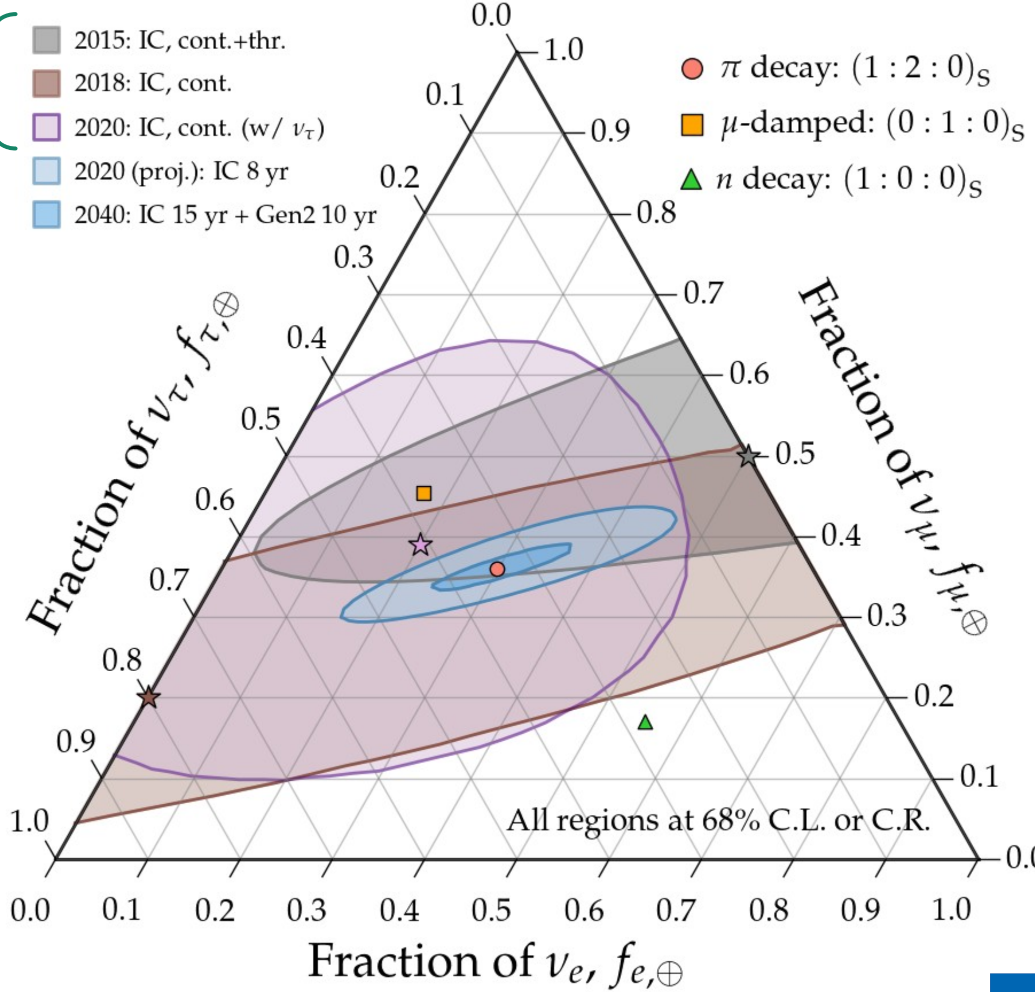

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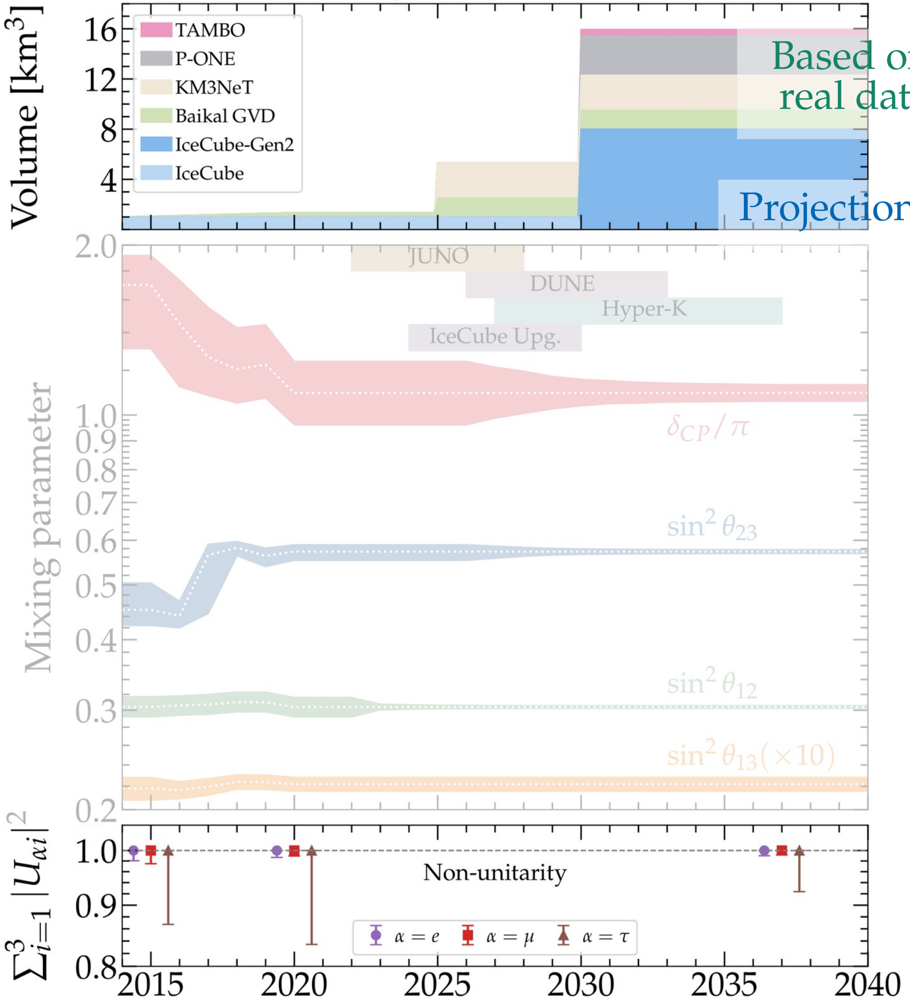

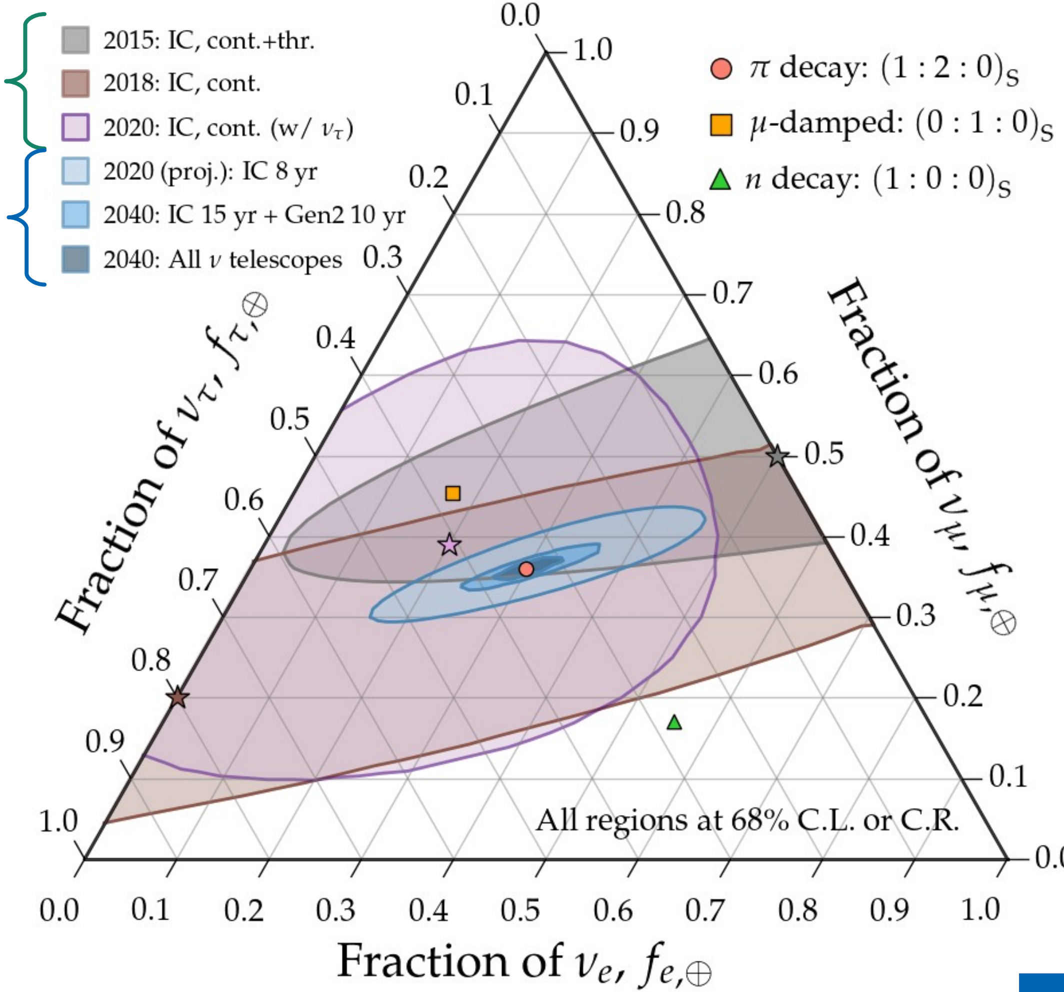

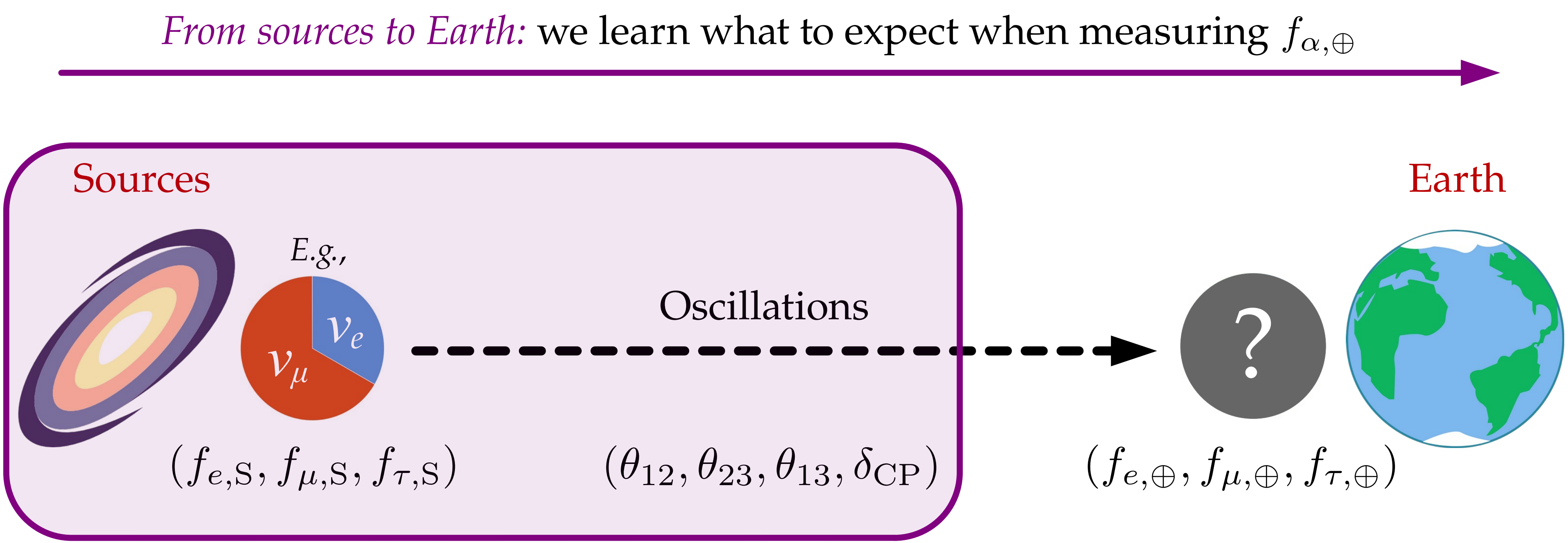

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Earth
E.g.,
ν_e
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Oscillations
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Flavor at the Earth: *theoretically palatable regions*

Theoretically palatable flavor regions

$\equiv$

MB, Beacom, Winter, *PRL* 2015

Allowed regions of flavor ratios at Earth derived from oscillations

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

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Ingredient #1:

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(pion decay, muon-damped, neutron decay)

or

Explore all possible combinations

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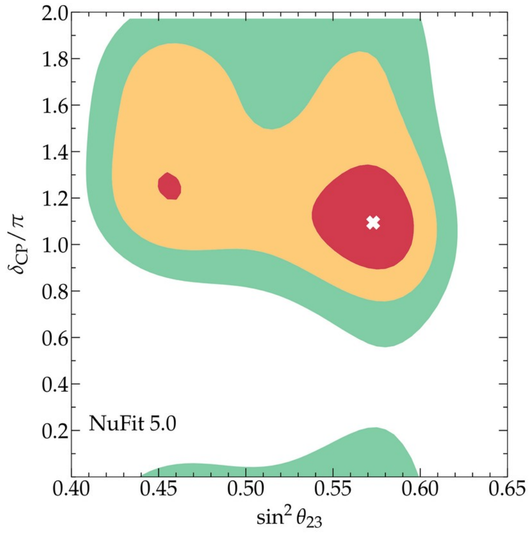
2020: Use χ^2 profiles from the NuFit 5.0 global fit (solar + atmospheric + reactor + accelerator)

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



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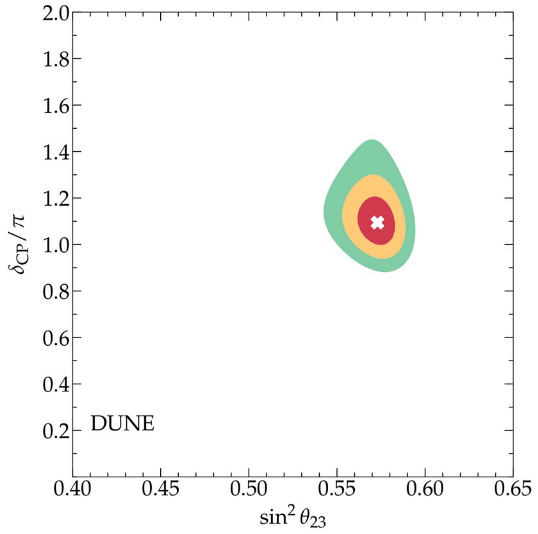
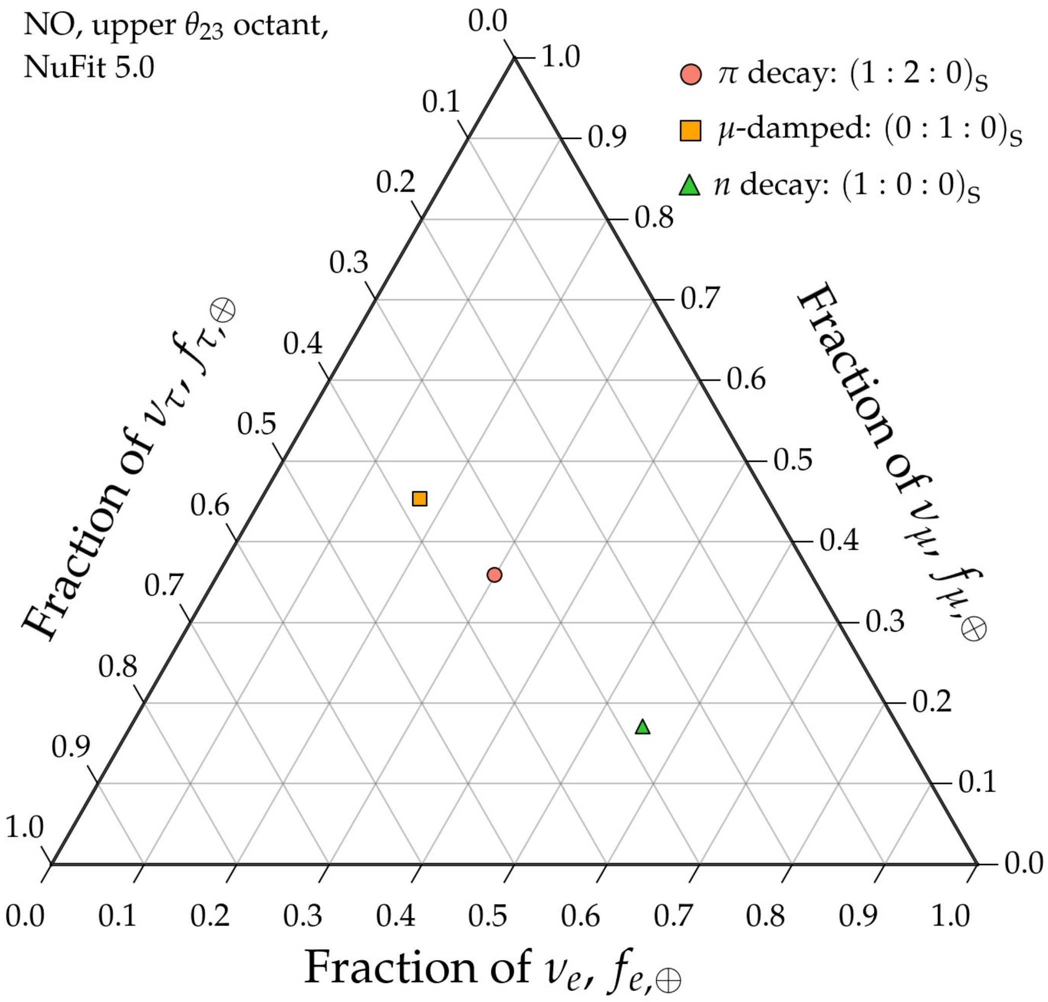
Post-2020: Build our own profiles using simulations of JUNO, DUNE, Hyper-K

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



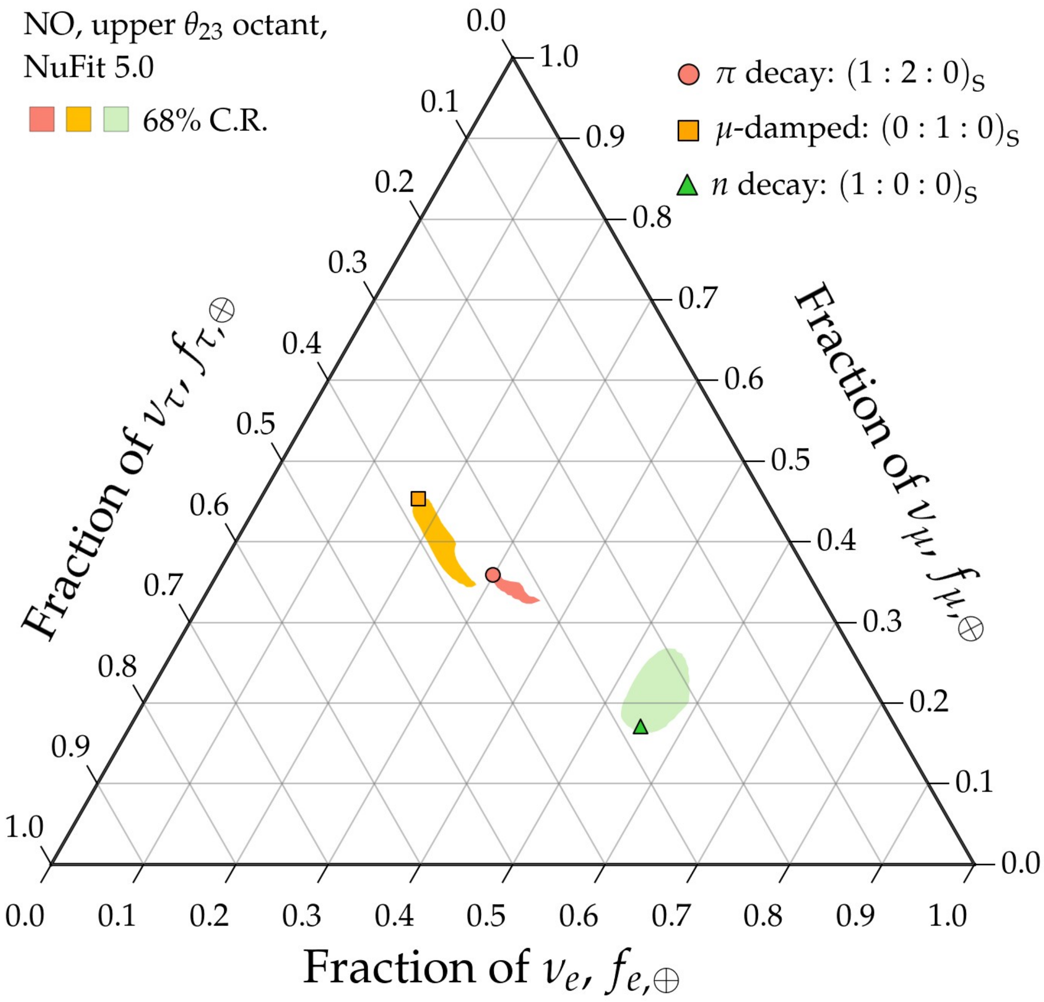
Theoretically palatable regions: today (2021)



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

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

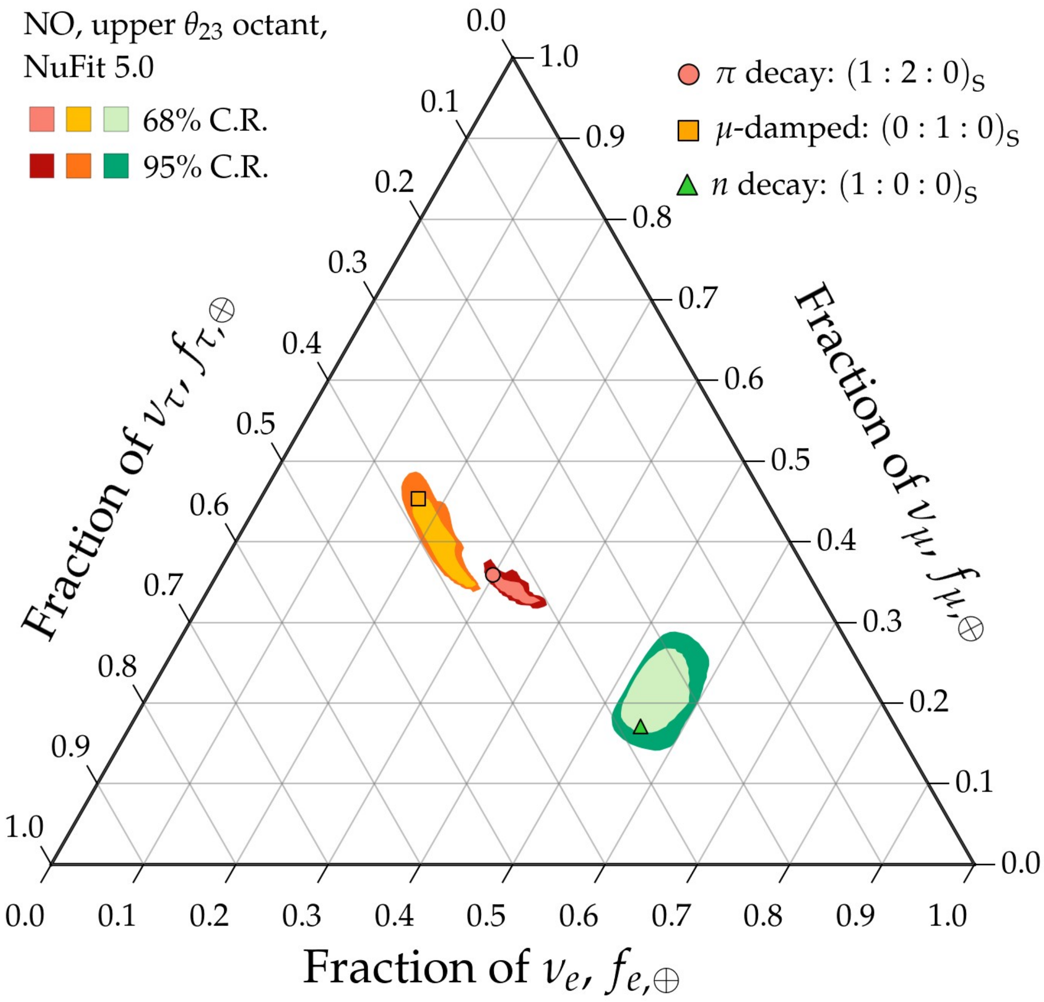
Theoretically palatable regions: today (2021)



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

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

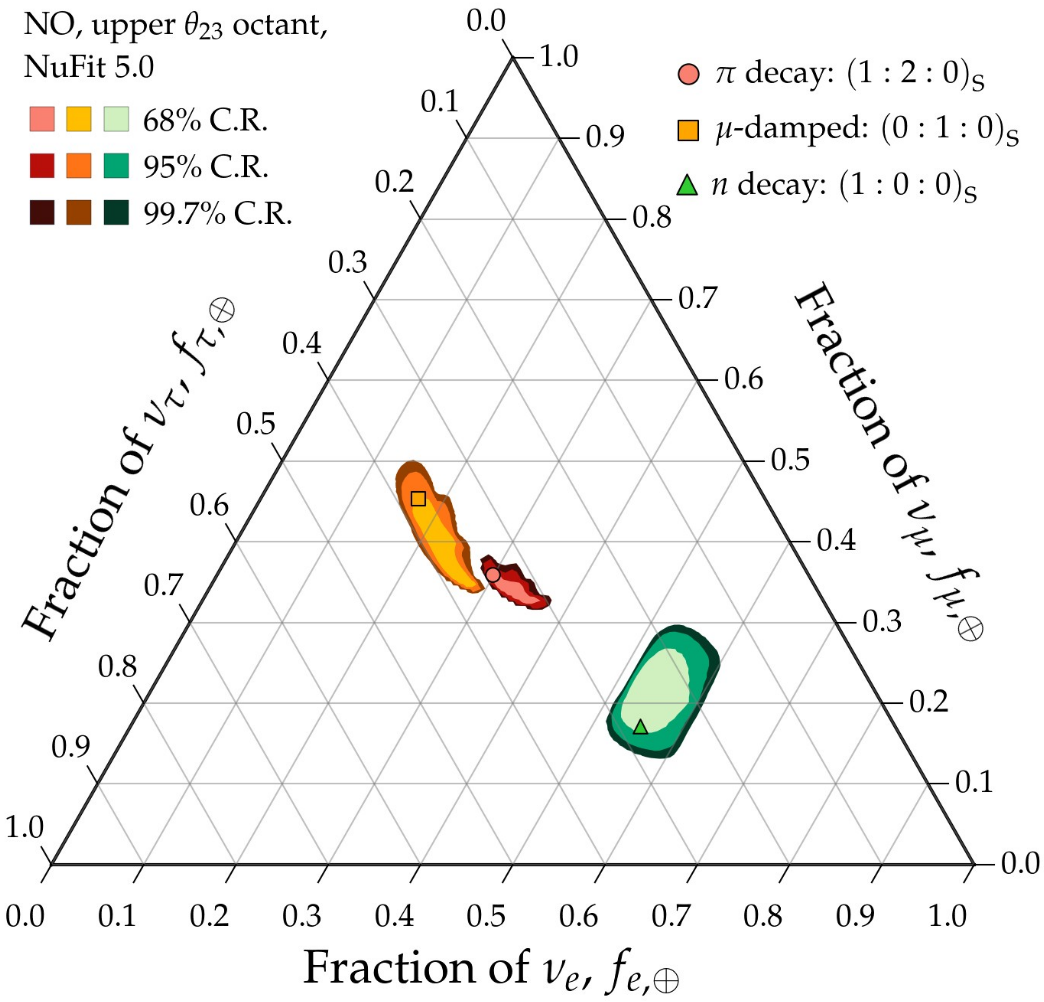
Theoretically palatable regions: today (2021)



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

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

Theoretically palatable regions: today (2021)



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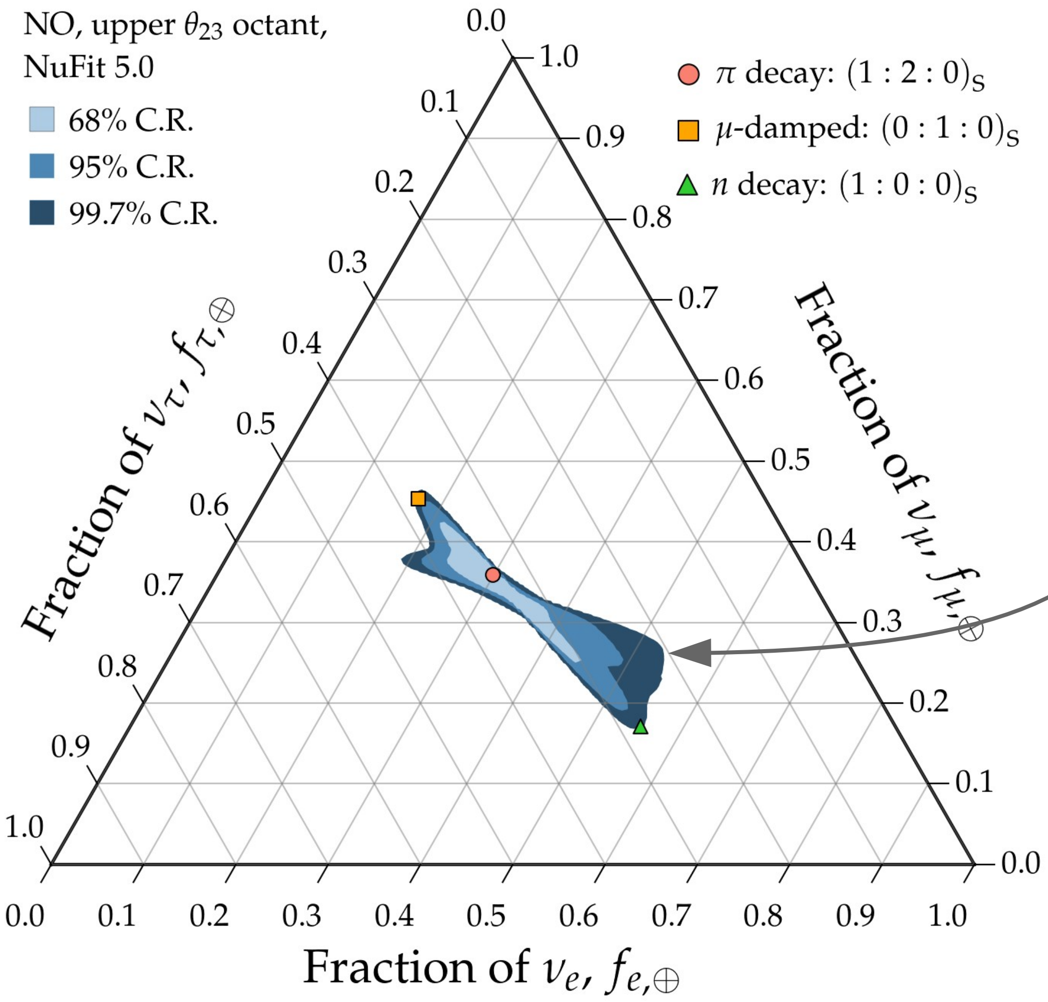
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Theoretically palatable regions: today (2021)

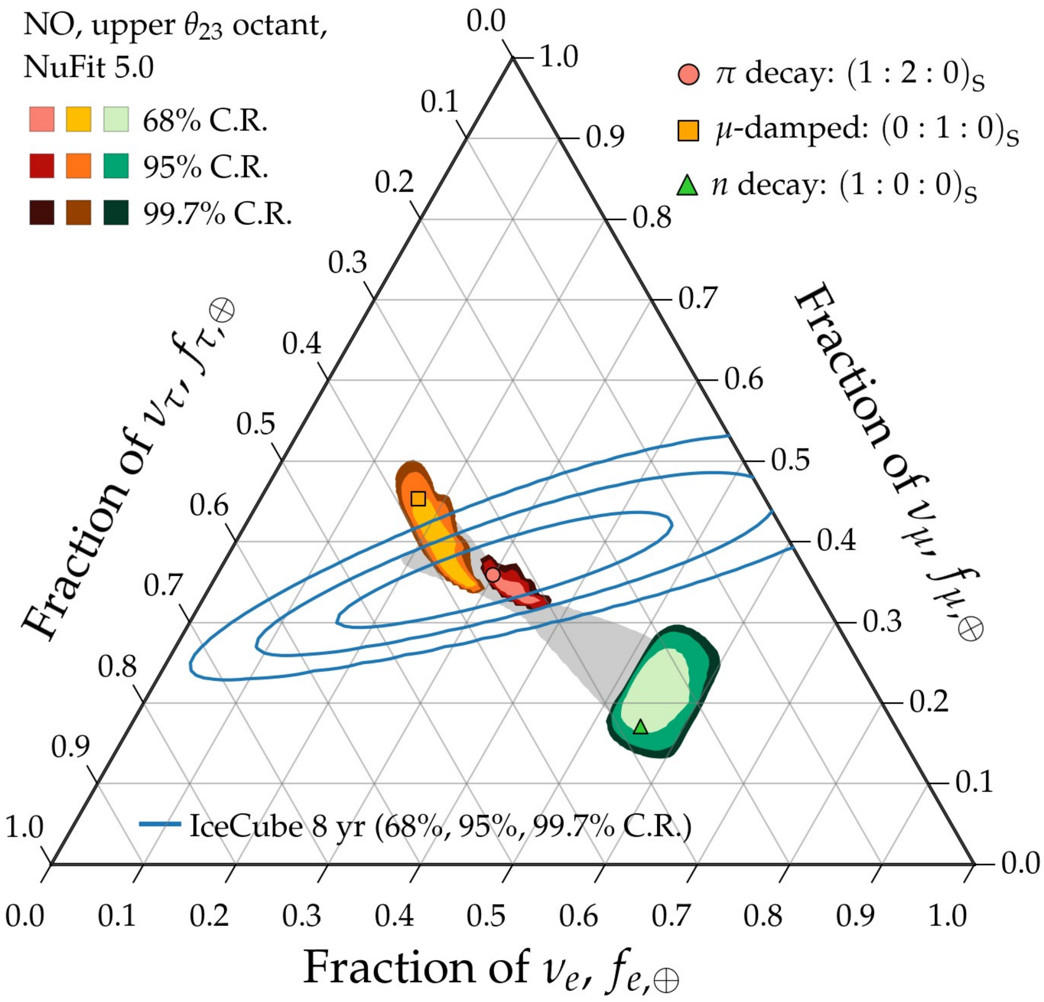


Varying over all possible flavor ratios at the source

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

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

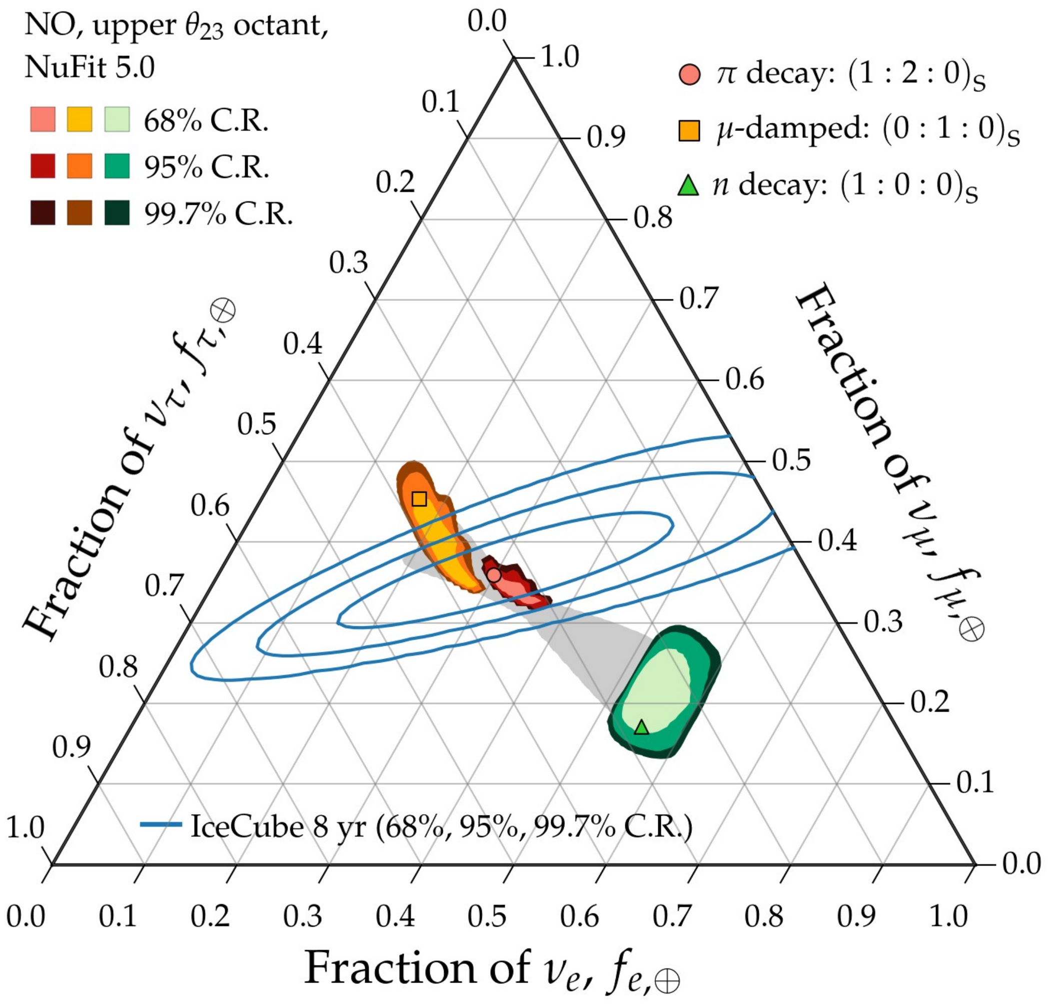
Theoretically palatable regions: today (2021)



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

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

Theoretically palatable regions: today (2021)



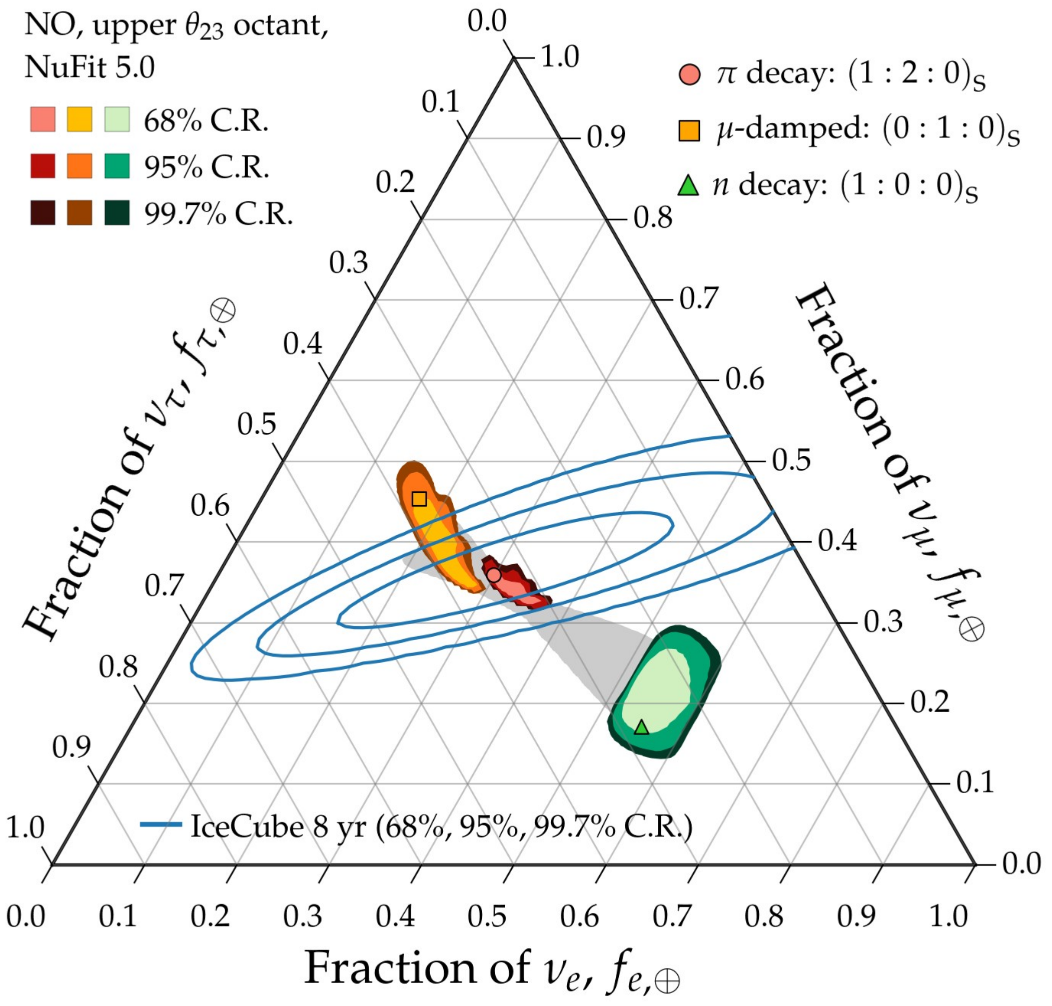
Two limitations:

Allowed flavor regions overlap –
Insufficient precision in the mixing parameters

Measurement of flavor ratios –
Cannot distinguish between pion-decay and muon-damped benchmarks even at 68% C.R. (1σ)

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

Theoretically palatable regions: today (2021)



Two limitations:

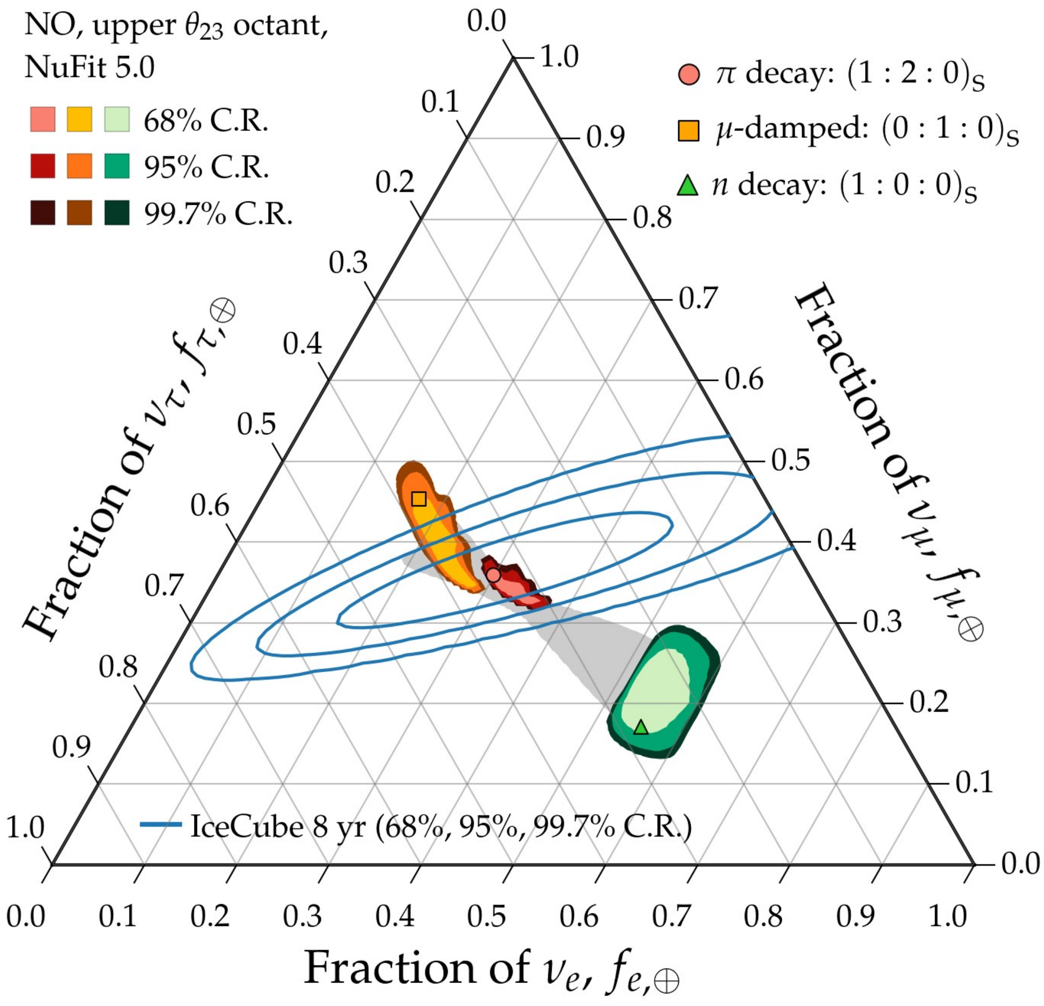
Allowed flavor regions overlap –
Insufficient precision in the mixing parameters

Will be overcome by 2030

Measurement of flavor ratios –
Cannot distinguish between pion-decay and muon-damped benchmarks even at 68% C.R. (1σ)

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

Theoretically palatable regions: today (2021)



Two limitations:

Allowed flavor regions overlap –
Insufficient precision in the mixing parameters

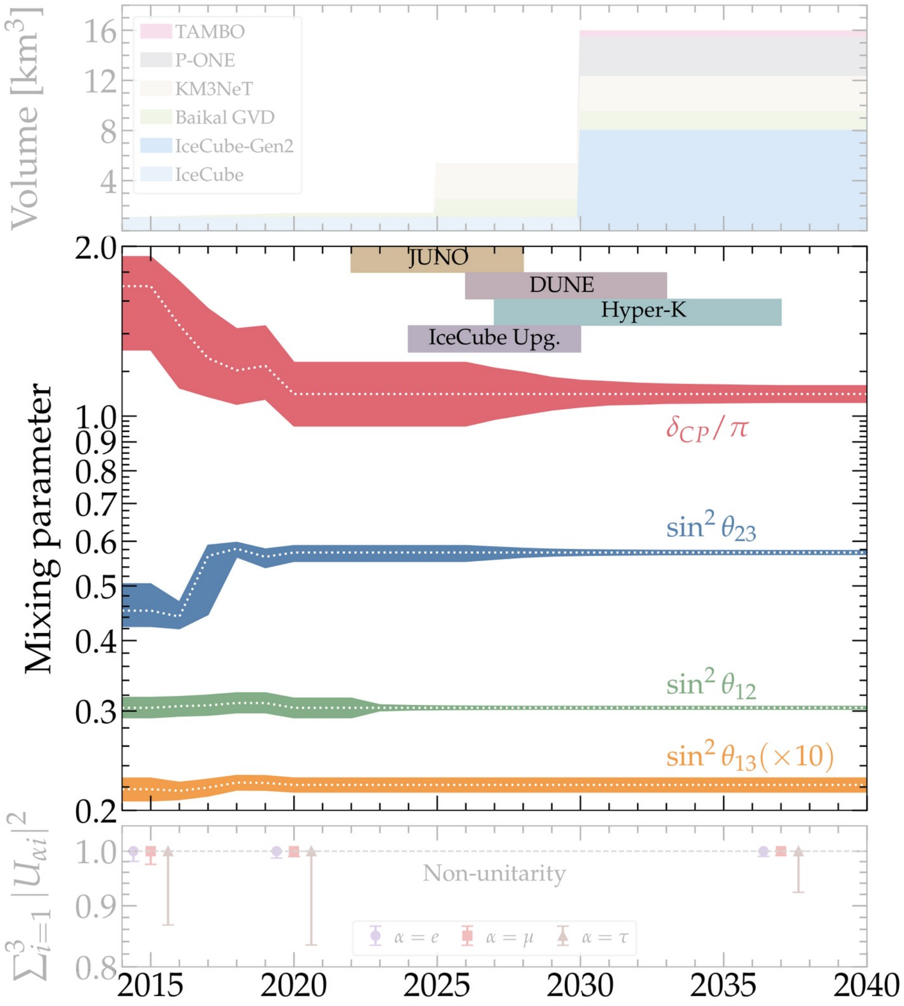
Will be overcome by 2030

Measurement of flavor ratios –
Cannot distinguish between pion-decay and muon-damped benchmarks even at 68% C.R. (1σ)

Will be overcome by 2040

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

How knowing the mixing parameters better helps

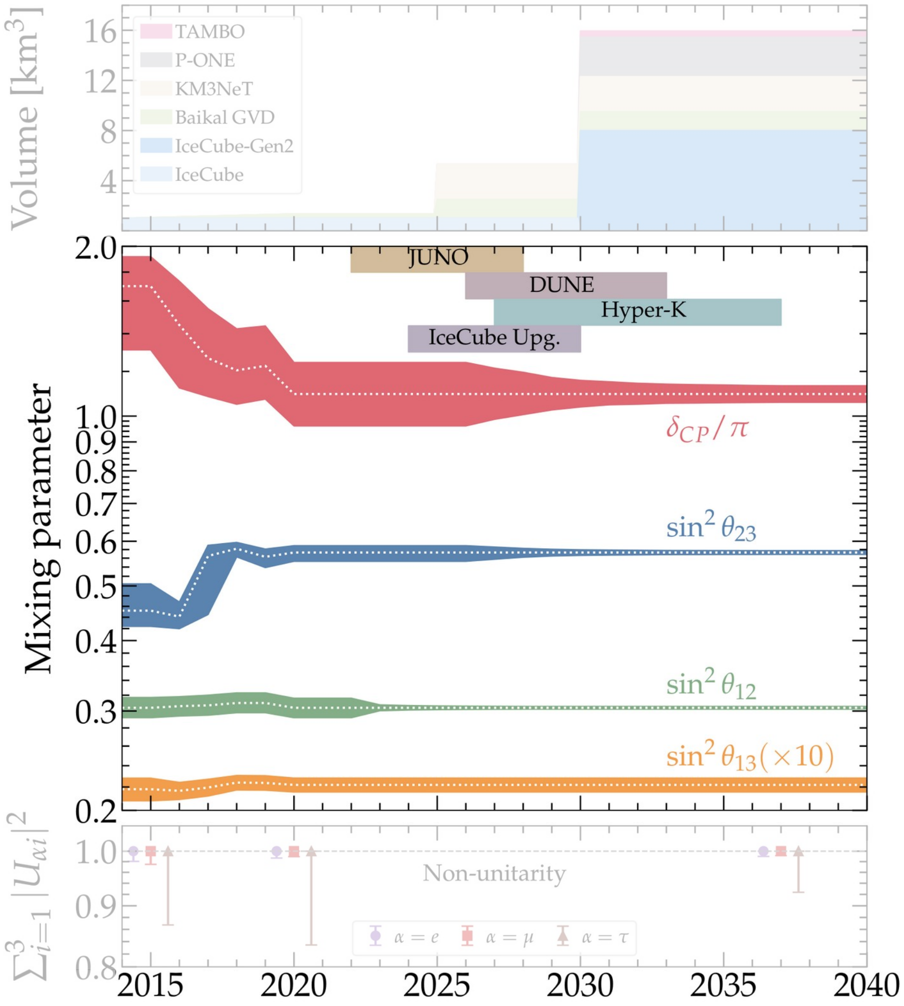


We can compute the oscillation probability more precisely:

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

So we can convert back and forth between source and Earth more precisely

How knowing the mixing parameters better helps



For a future experiment
ε = JUNO, DUNE, Hyper-K:

Best fit from NuFit 5.0

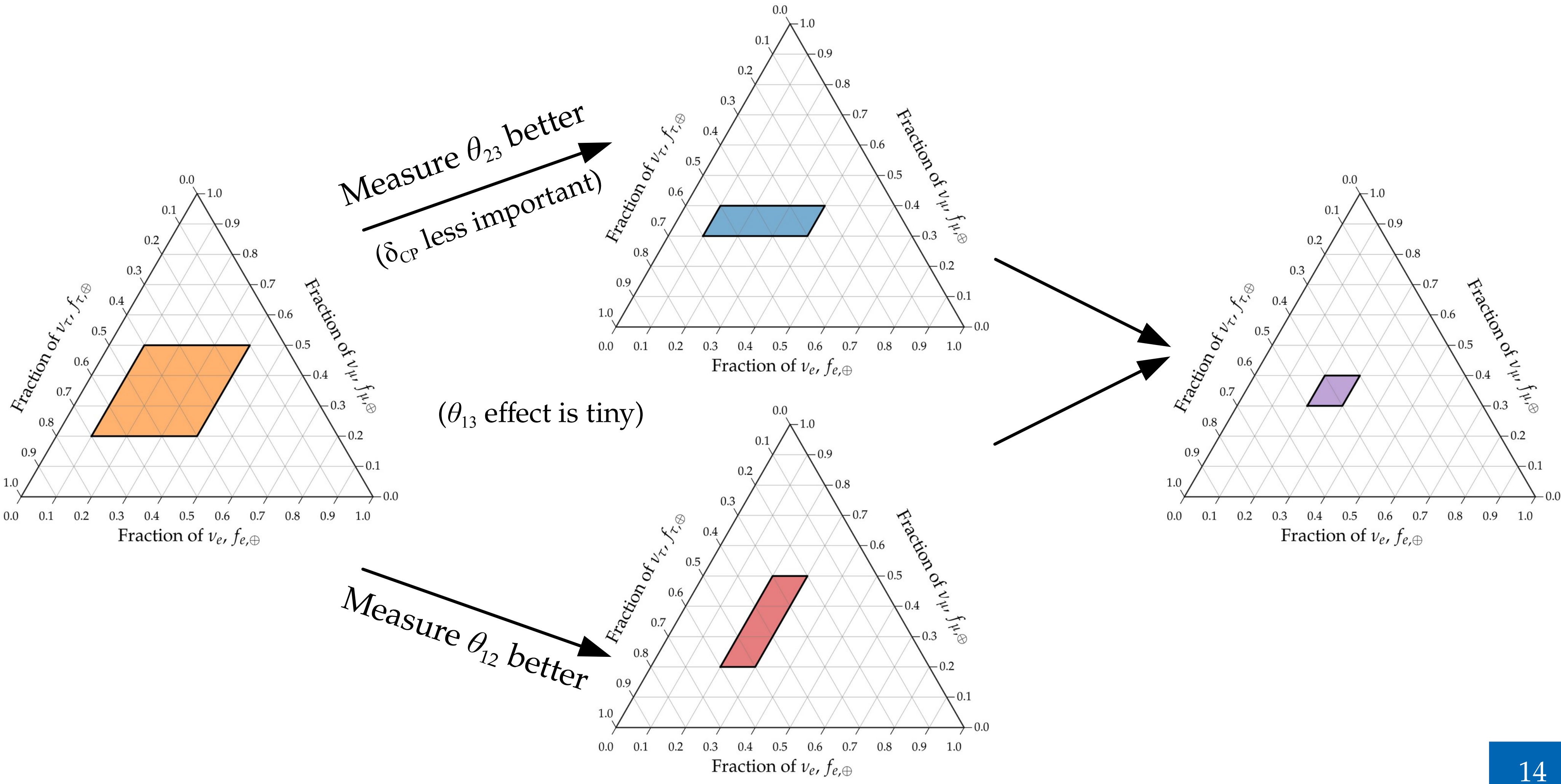
$$\chi^2_\varepsilon(\boldsymbol{\vartheta}) = \sum_i \frac{(\vartheta_i - \bar{\vartheta}_i)^2}{\sigma^2_{i,\varepsilon}}$$

From our simulations

We combine experiments in a likelihood:

$$-2\log\mathcal{L}(\boldsymbol{\theta}) = \sum_\varepsilon \chi^2_\varepsilon(\boldsymbol{\vartheta})$$

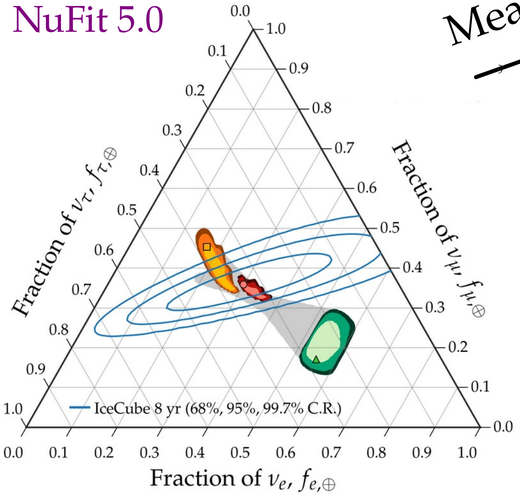
How knowing the mixing parameters better helps



How knowing the mixing parameters better helps

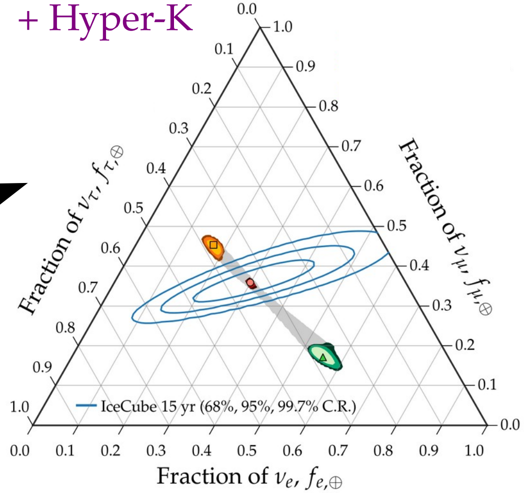
2020

NuFit 5.0



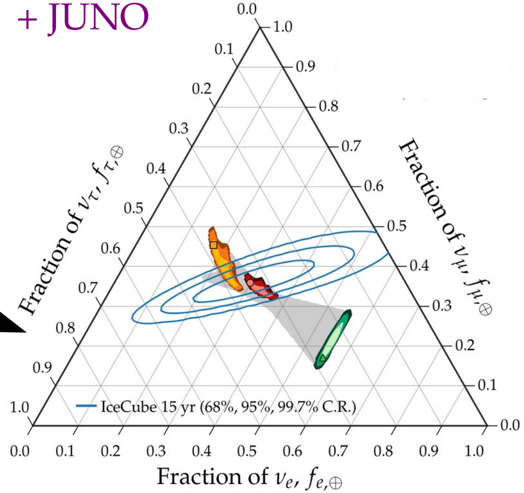
Measure θ_{23} better

+ Hyper-K



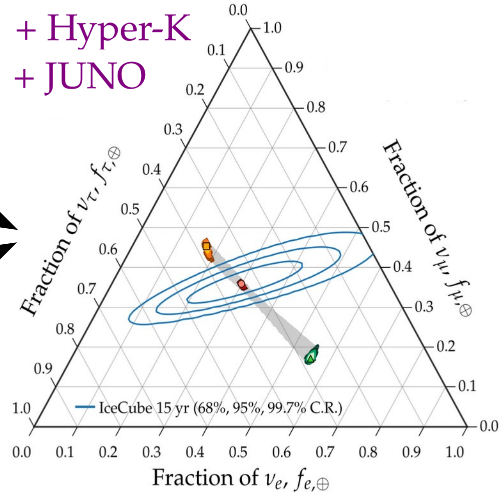
Measure θ_{12} better

+ JUNO



~2030

+ Hyper-K
+ JUNO



In our results:
JUNO + Hyper-K + DUNE

Marginal improvement til 2040

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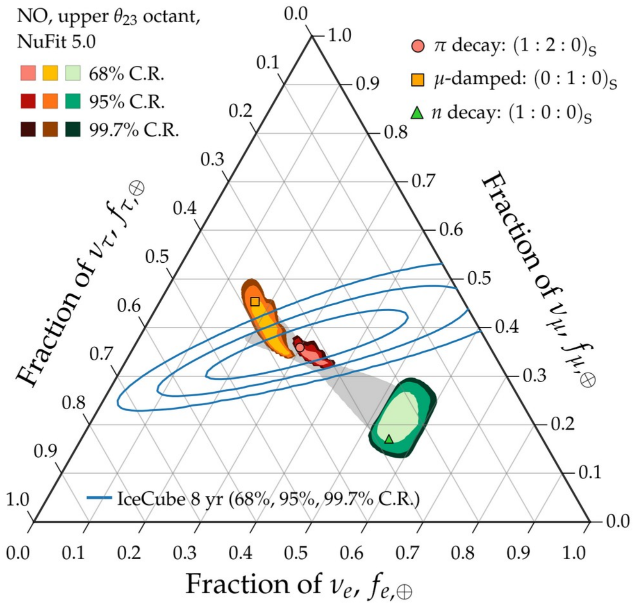
Theoretically palatable regions: 2020 → 2030 → 2040

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

Theoretically palatable regions: 2020 → 2030 → 2040

2020



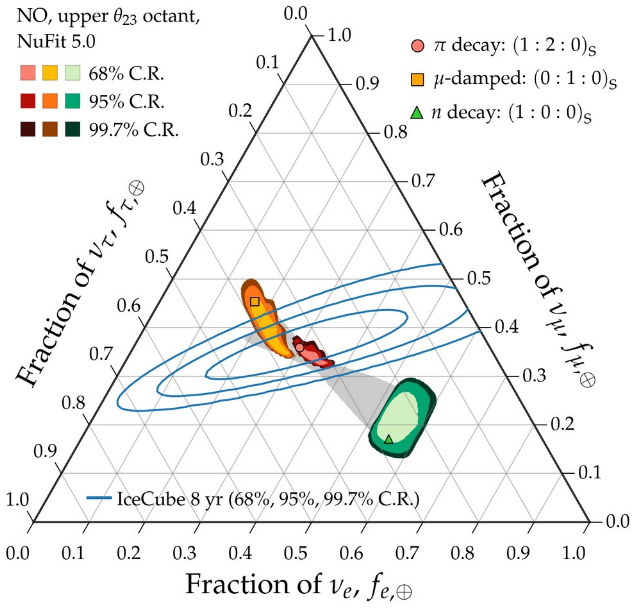
Allowed regions: overlapping

Measurement: imprecise

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

Theoretically palatable regions: 2020 → 2030 → 2040

2020



Allowed regions: overlapping

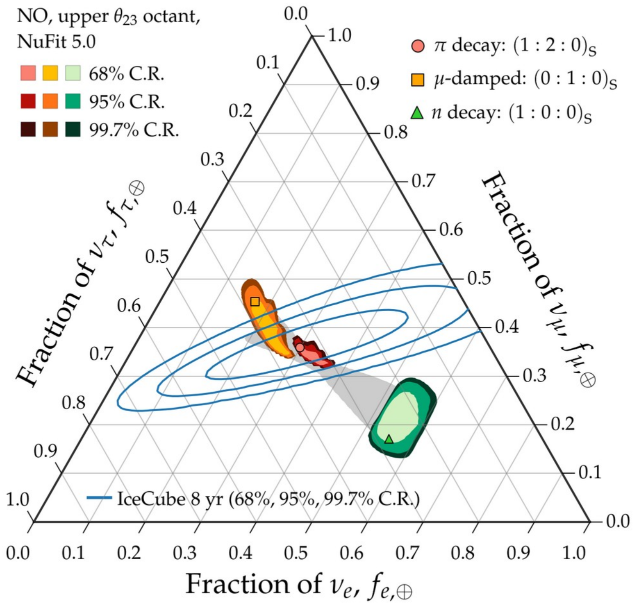
Measurement: imprecise

Not ideal

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

Theoretically palatable regions: 2020 → 2030 → 2040

2020

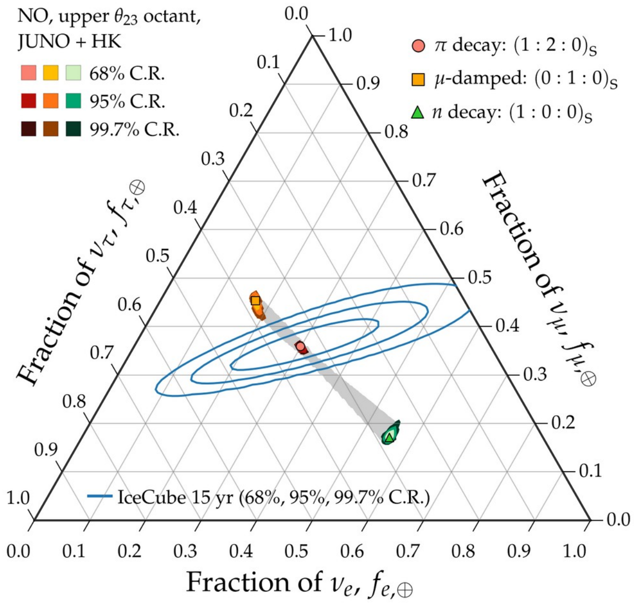


Allowed regions: overlapping

Measurement: imprecise

Not ideal

2030



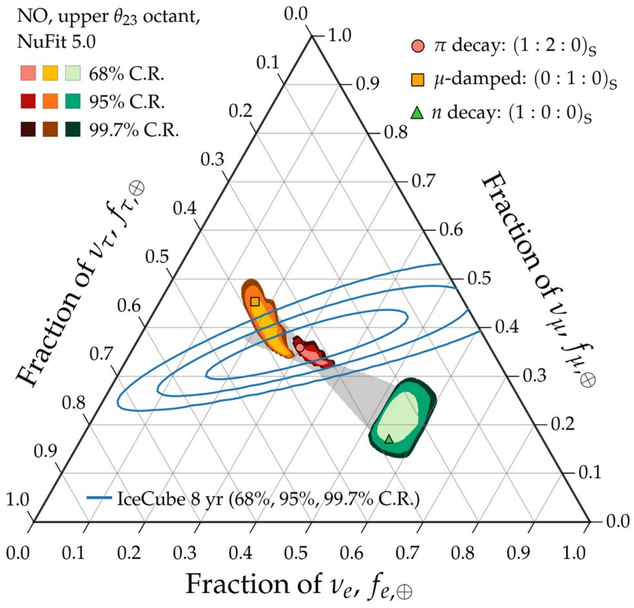
Allowed regions: well separated

Measurement: improving

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

Theoretically palatable regions: 2020 → 2030 → 2040

2020

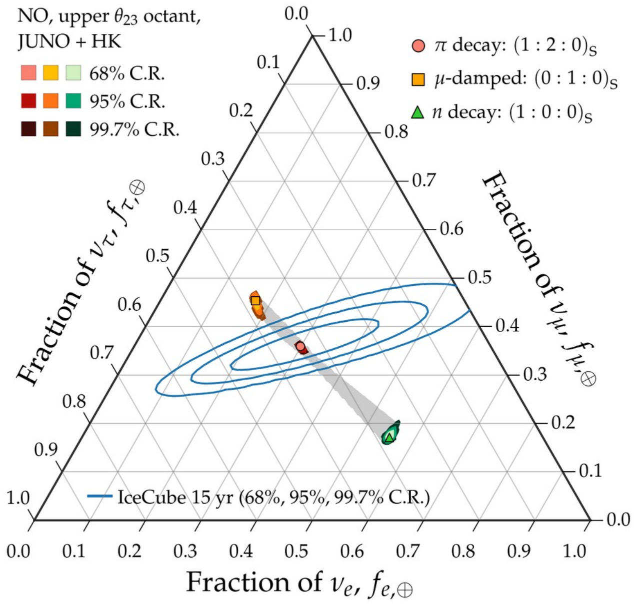


Allowed regions: overlapping

Measurement: imprecise

Not ideal

2030



Allowed regions: well separated

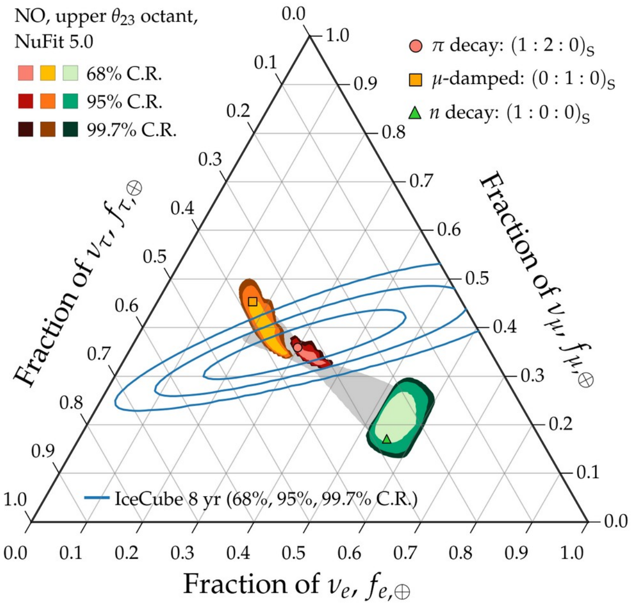
Measurement: improving

Nice

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

Theoretically palatable regions: 2020 → 2030 → 2040

2020

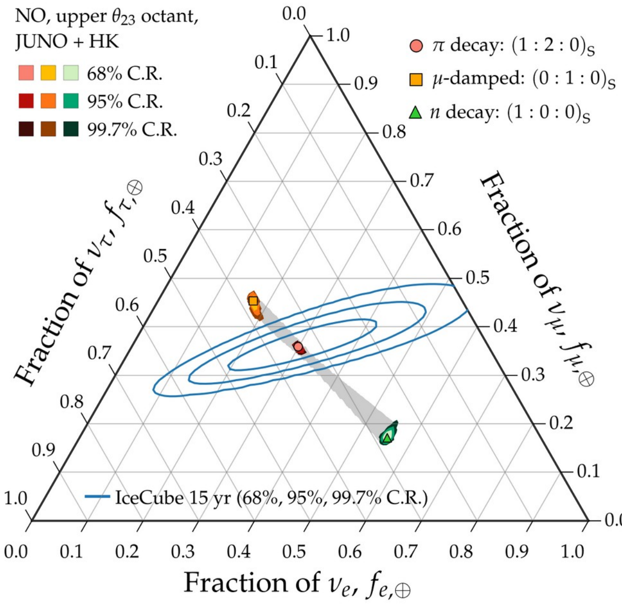


Allowed regions: overlapping

Measurement: imprecise

Not ideal

2030

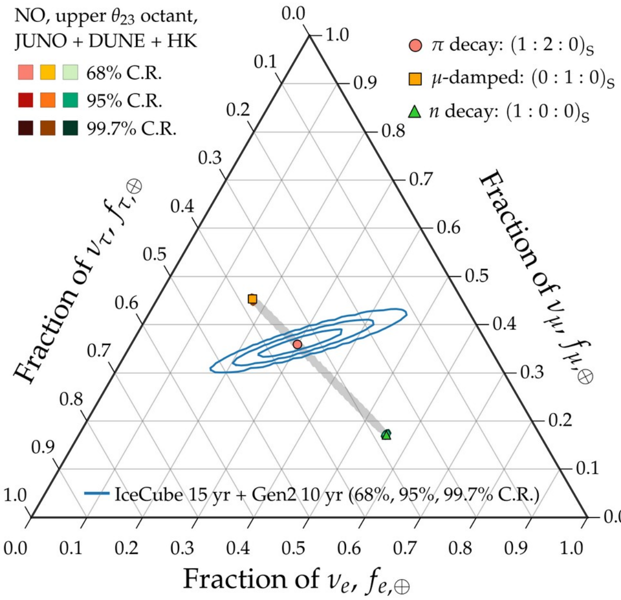


Allowed regions: well separated

Measurement: improving

Nice

2040



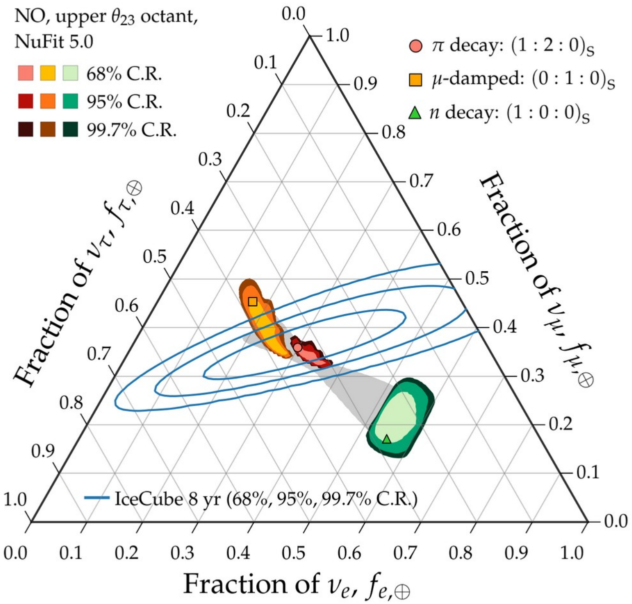
Allowed regions: well separated

Measurement: precise

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

Theoretically palatable regions: 2020 → 2030 → 2040

2020

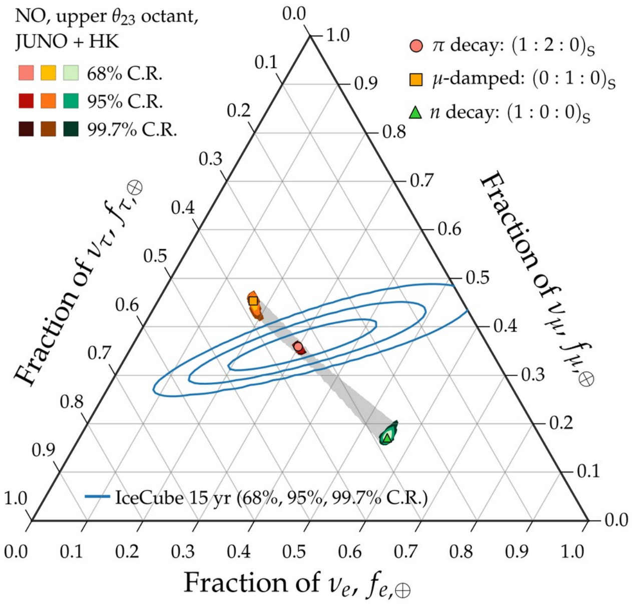


Allowed regions: overlapping

Measurement: imprecise

Not ideal

2030

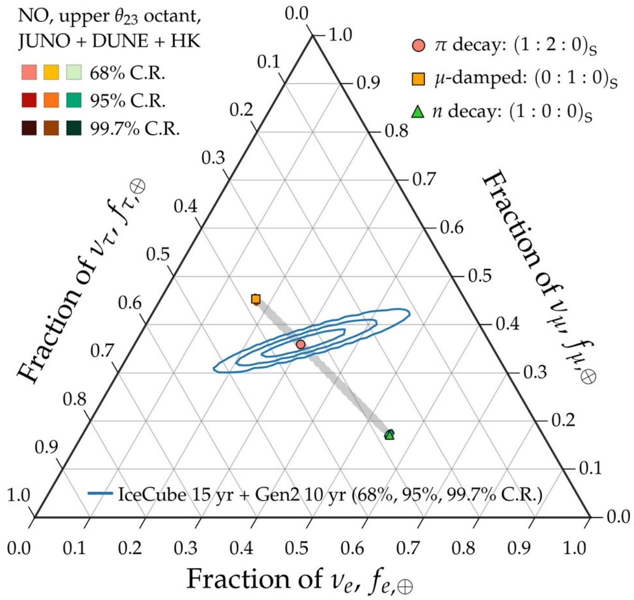


Allowed regions: well separated

Measurement: improving

Nice

2040



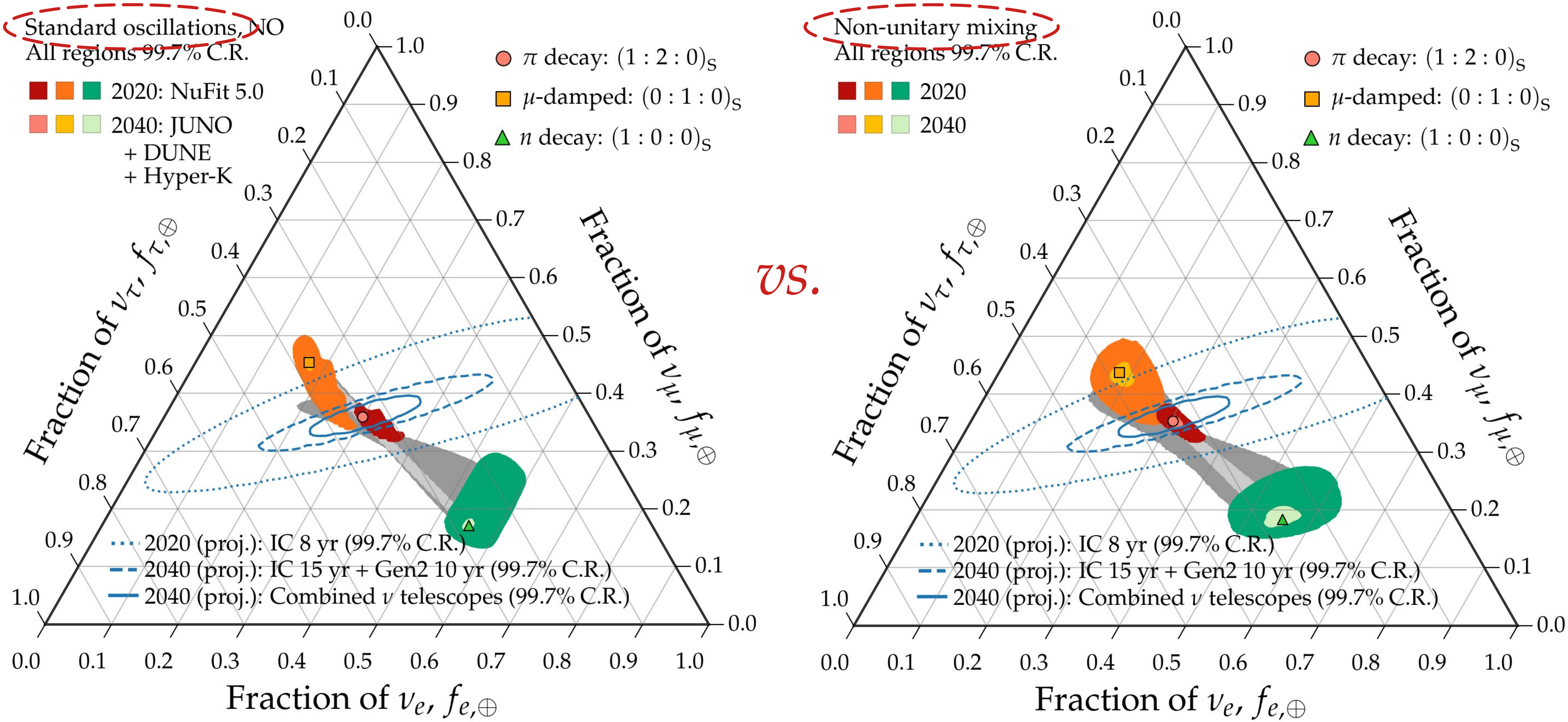
Allowed regions: well separated

Measurement: precise

Success

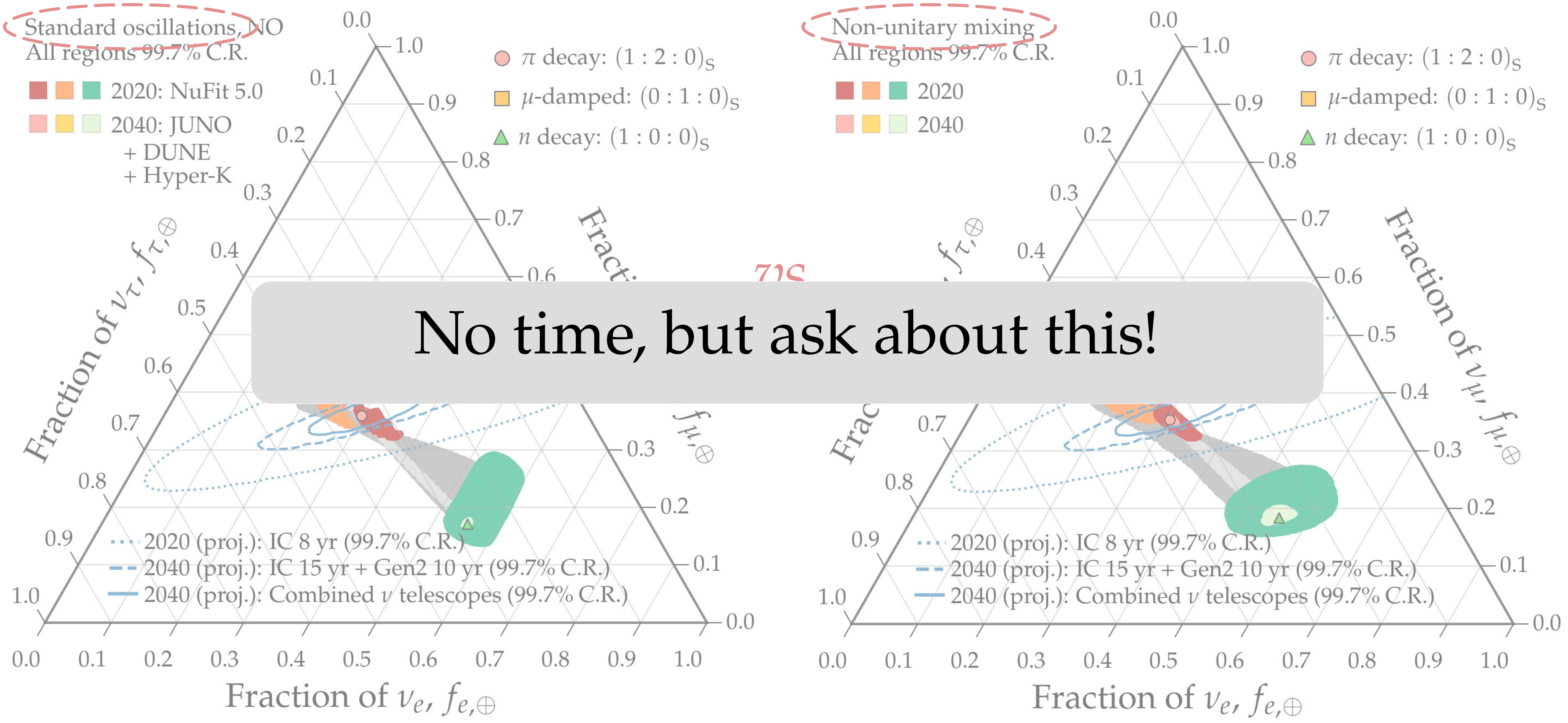
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

No unitarity? *No problem*



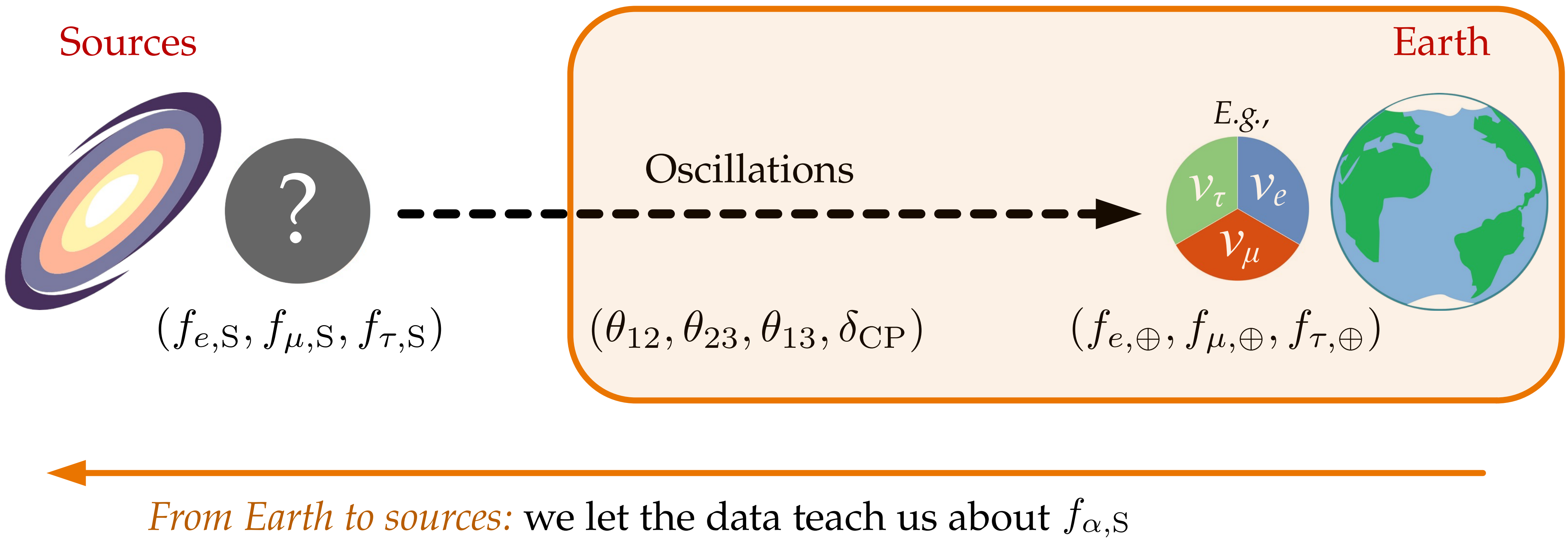
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

No unitarity? *No problem*



No time, but ask about this!

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



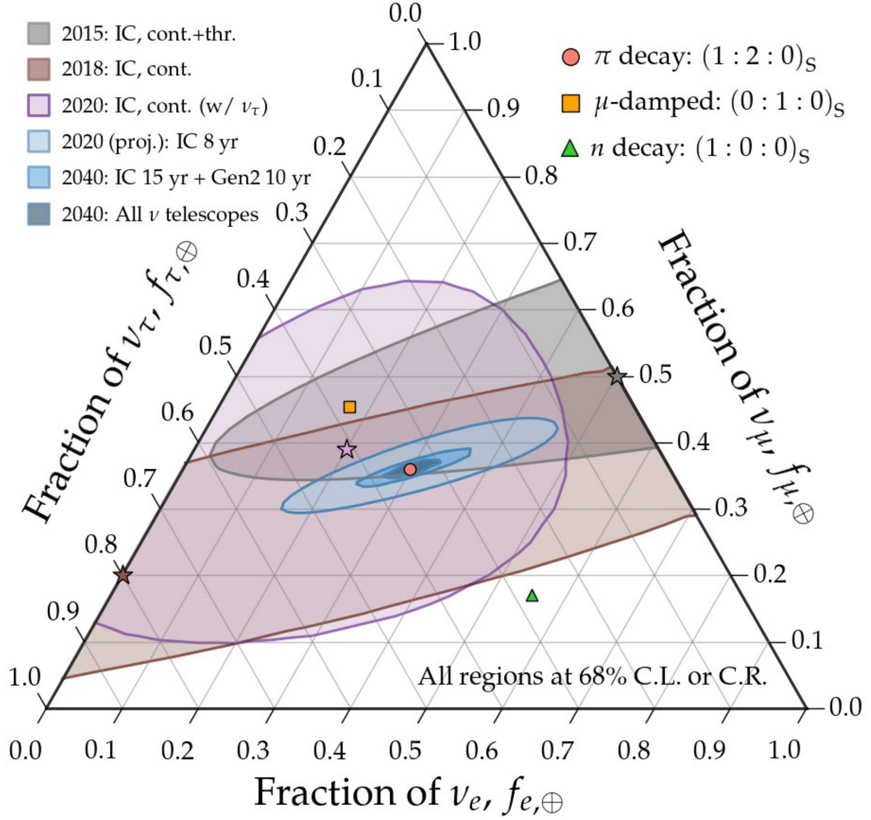
Sources
?
$(f_{e,\mathrm{S}}, f_{\mu,\mathrm{S}}, f_{\tau,\mathrm{S}})$
Oscillations
$(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\mathrm{CP}})$
Earth
E.g.,
ν_τ
ν_e
ν_μ
$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$
From Earth to sources: we let the data teach us about $f_{\alpha,\mathrm{S}}$

Inferring the flavor composition at the sources

Ingredient #1:

Flavor ratios measured at Earth,

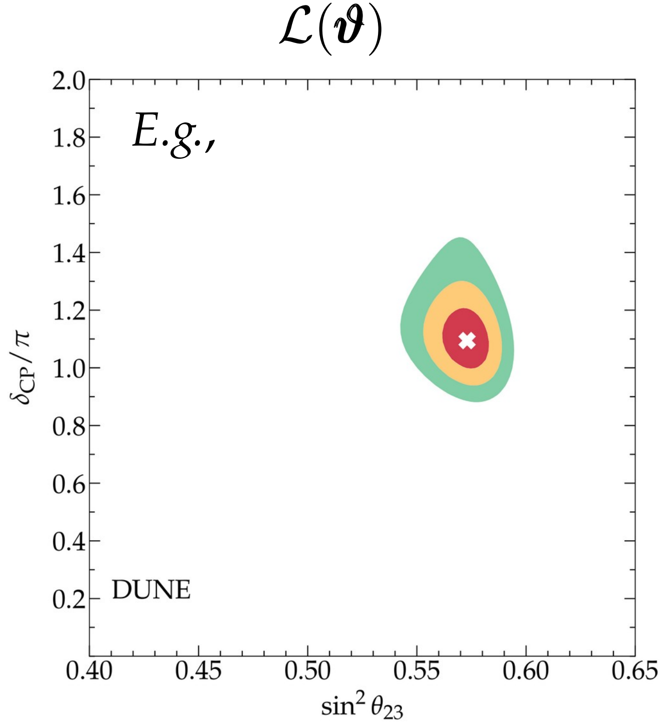
$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$



Ingredient #2:

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

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



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

Inferring the flavor composition at the sources

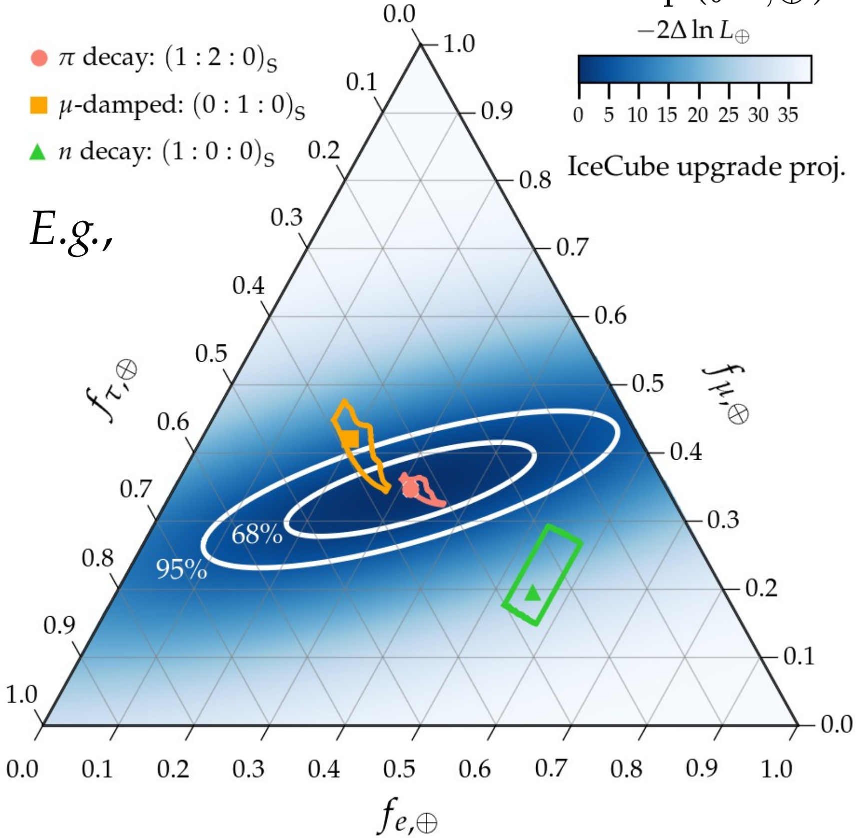
Ingredient #1:

Flavor ratios measured at Earth,

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

E.g.,

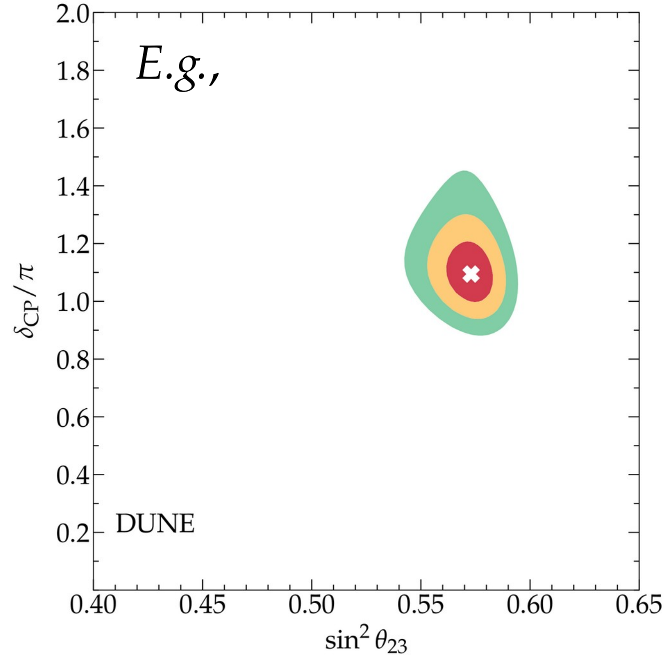
$\mathcal{P}_{\rm exp}(f_{\alpha,\oplus})$



Ingredient #2:

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

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



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

Inferring the flavor composition at the sources

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

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

Posterior probability of $f_{\alpha,\rm S}$ [**MB** & Ahlers, *PRL* 2019]:

$$\mathcal{P}(\boldsymbol{f}_s) = \int d\boldsymbol{\vartheta} \mathcal{L}(\boldsymbol{\vartheta}) \mathcal{P}_{\rm exp}(\boldsymbol{f}_\oplus(\boldsymbol{f}_{\rm S}, \boldsymbol{\vartheta}))$$

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

Inferring the flavor composition at the sources

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

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Posterior probability of $f_{\alpha,\rm S}$ [**MB** & Ahlers, *PRL* 2019]:

$$\mathcal{P}(\boldsymbol{f}_s) = \int d\boldsymbol{\vartheta} \underbrace{\mathcal{L}(\boldsymbol{\vartheta})}_{\text{Oscillation experiments}} \underbrace{\mathcal{P}_{\rm exp}(\boldsymbol{f}_\oplus(\boldsymbol{f}_{\rm S}, \boldsymbol{\vartheta}))}_{\text{Neutrino telescopes}}$$

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,
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Posterior probability of $f_{\alpha,\rm S}$ [**MB** & Ahlers, *PRL* 2019]:

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

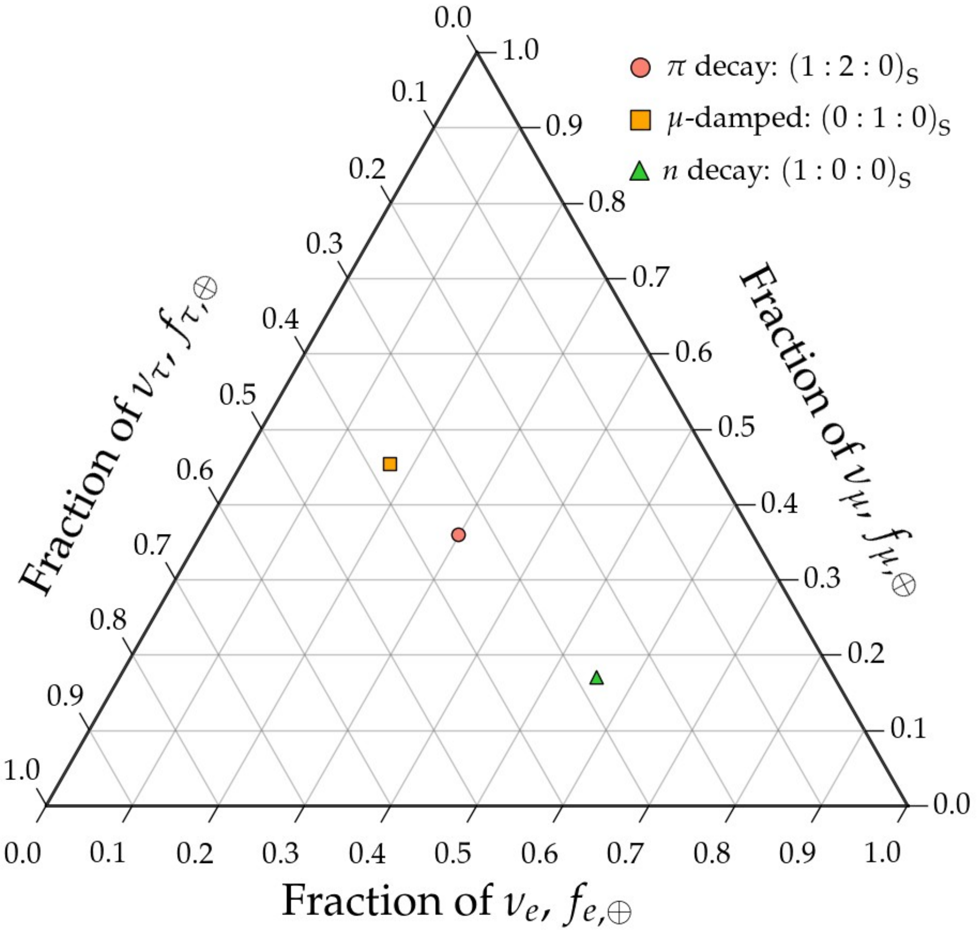
$$\mathcal{P}(\boldsymbol{f}_s) = \int d\boldsymbol{\vartheta} \underbrace{\mathcal{L}(\boldsymbol{\vartheta})}_{\text{Oscillation experiments}} \underbrace{\mathcal{P}_{\rm exp}(\boldsymbol{f}_\oplus(\overbrace{\boldsymbol{f}_{\rm S},\boldsymbol{\vartheta}}))}_{\text{Neutrino telescopes}}$$

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

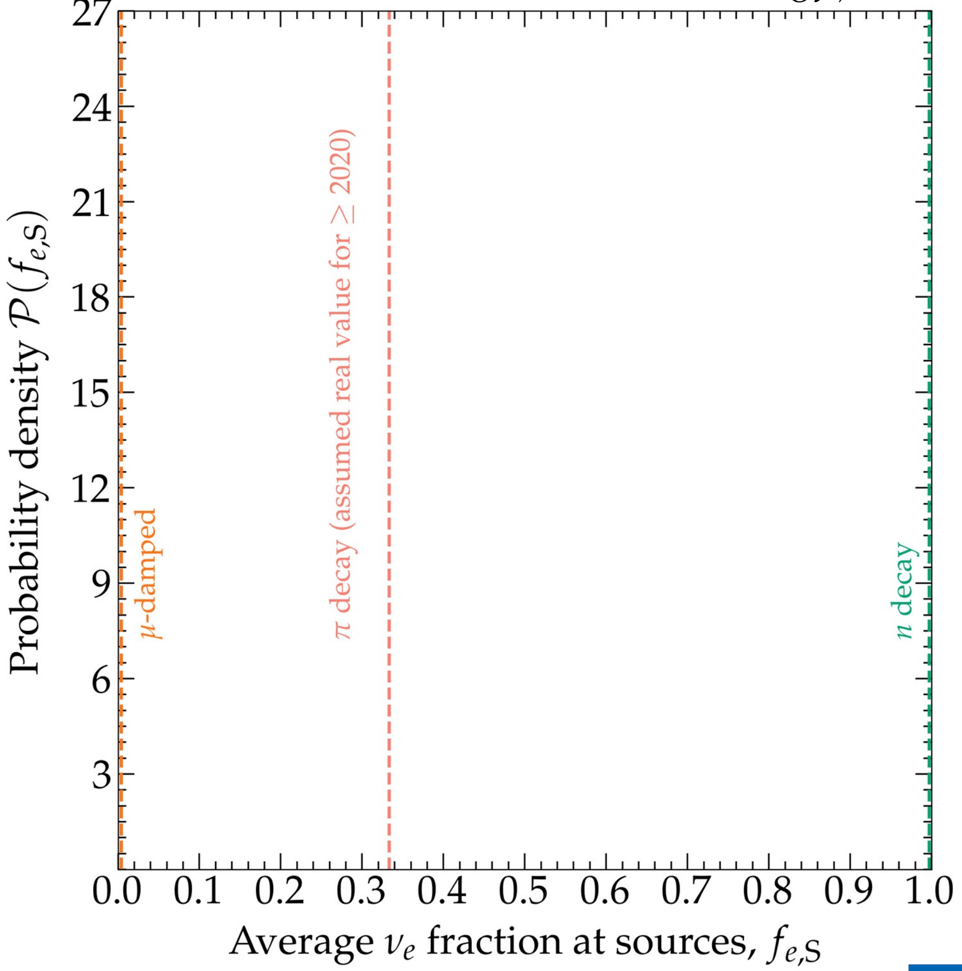
Inferring the flavor composition at the sources

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

Inferring the flavor composition at the sources

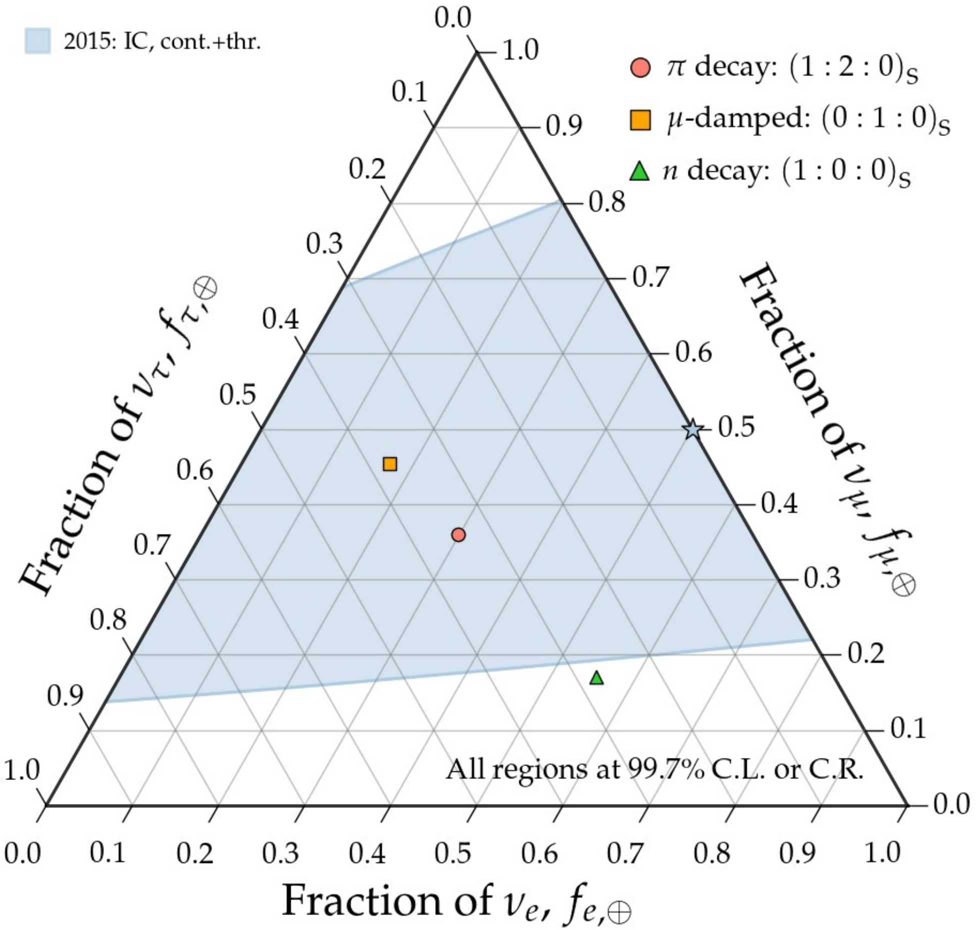


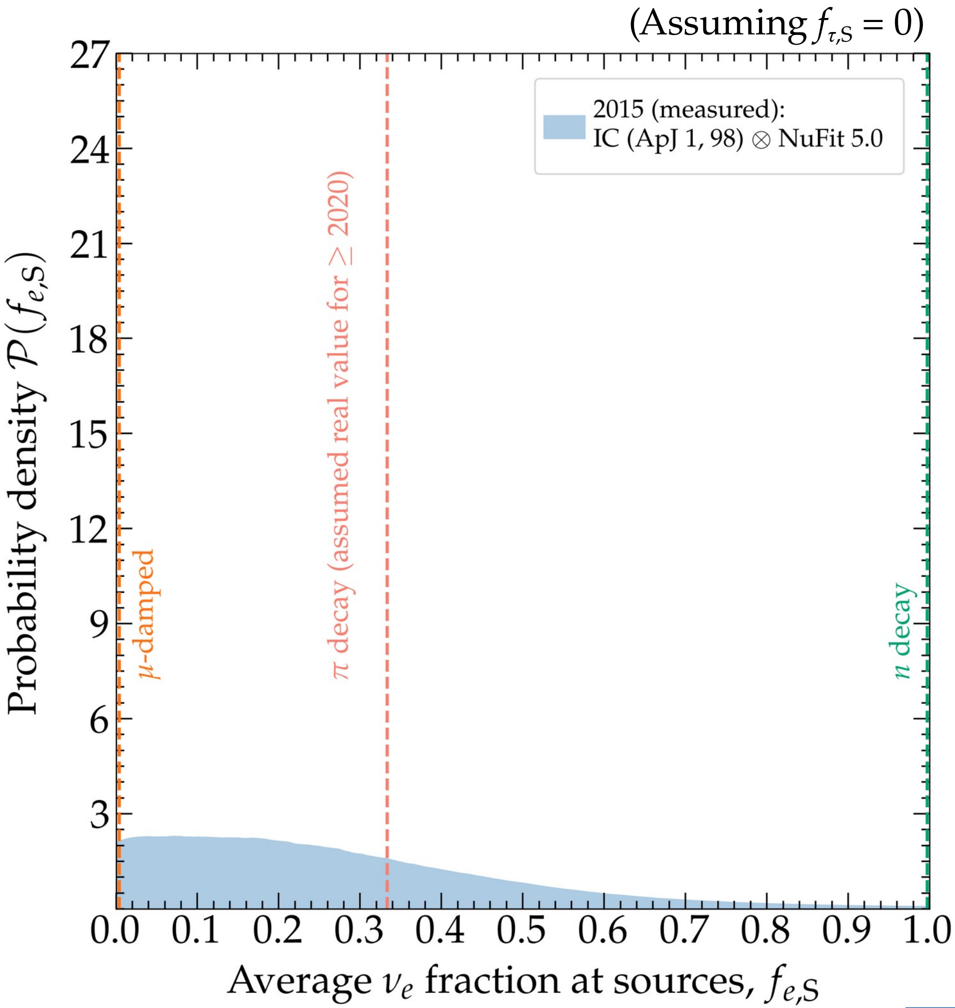
(Assuming $f_{\tau,\rm S} = 0$)



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

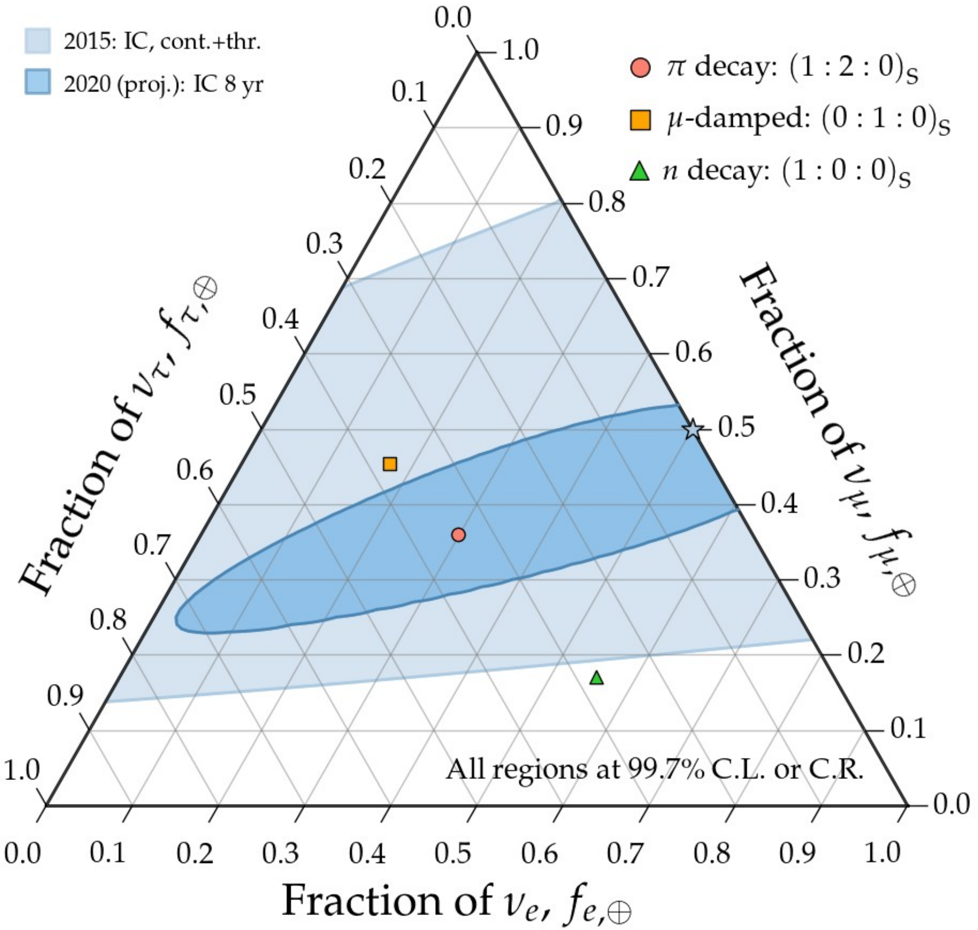
Inferring the flavor composition at the sources



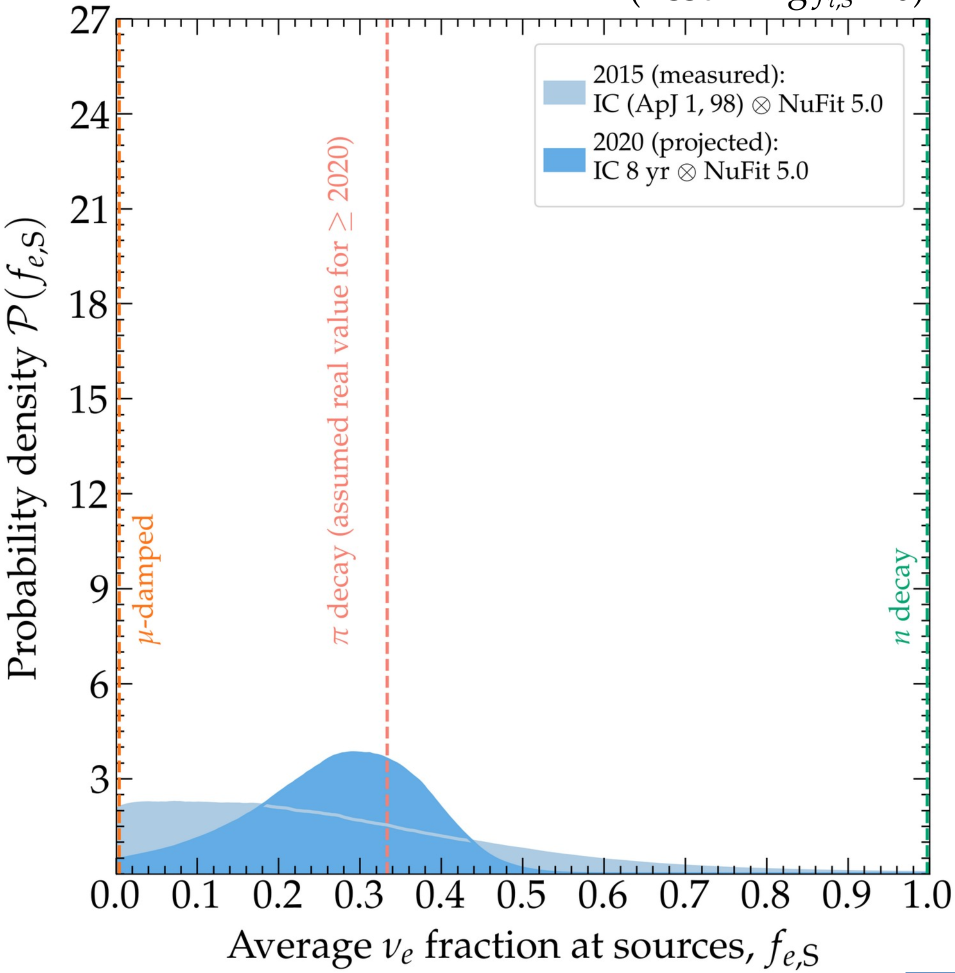


Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
MB & Ahlers, *PRL* 2019

Inferring the flavor composition at the sources

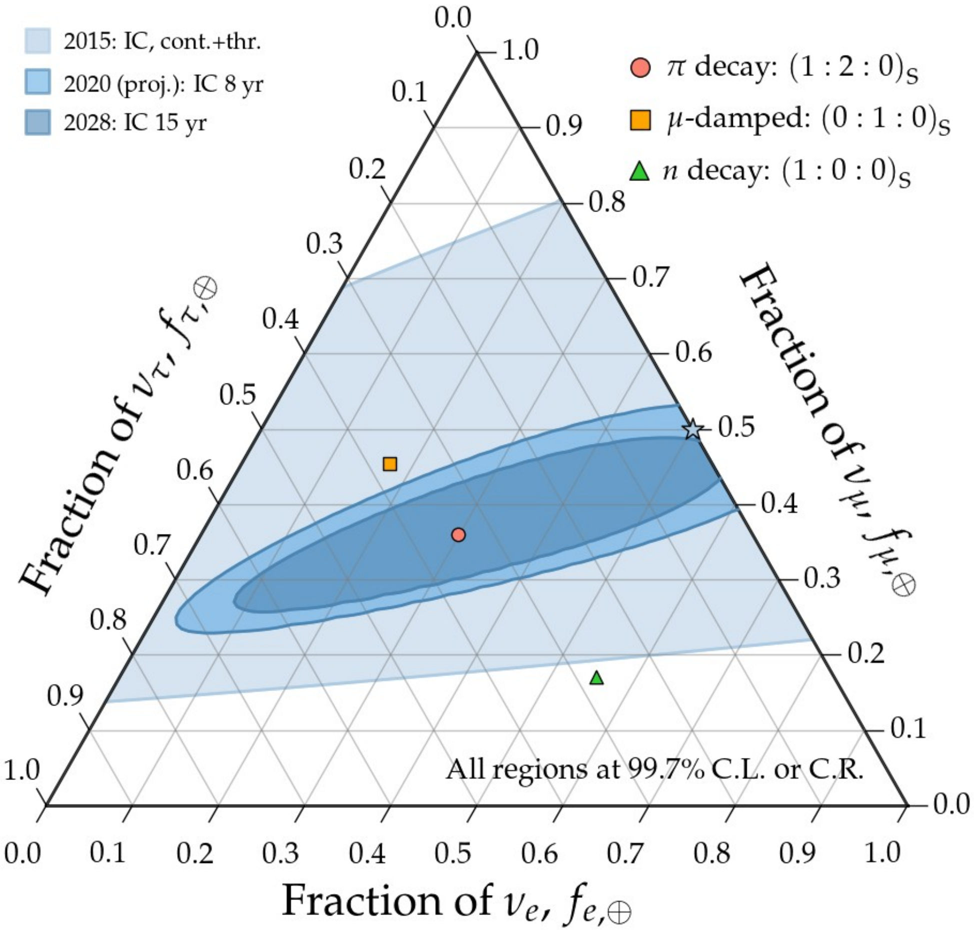


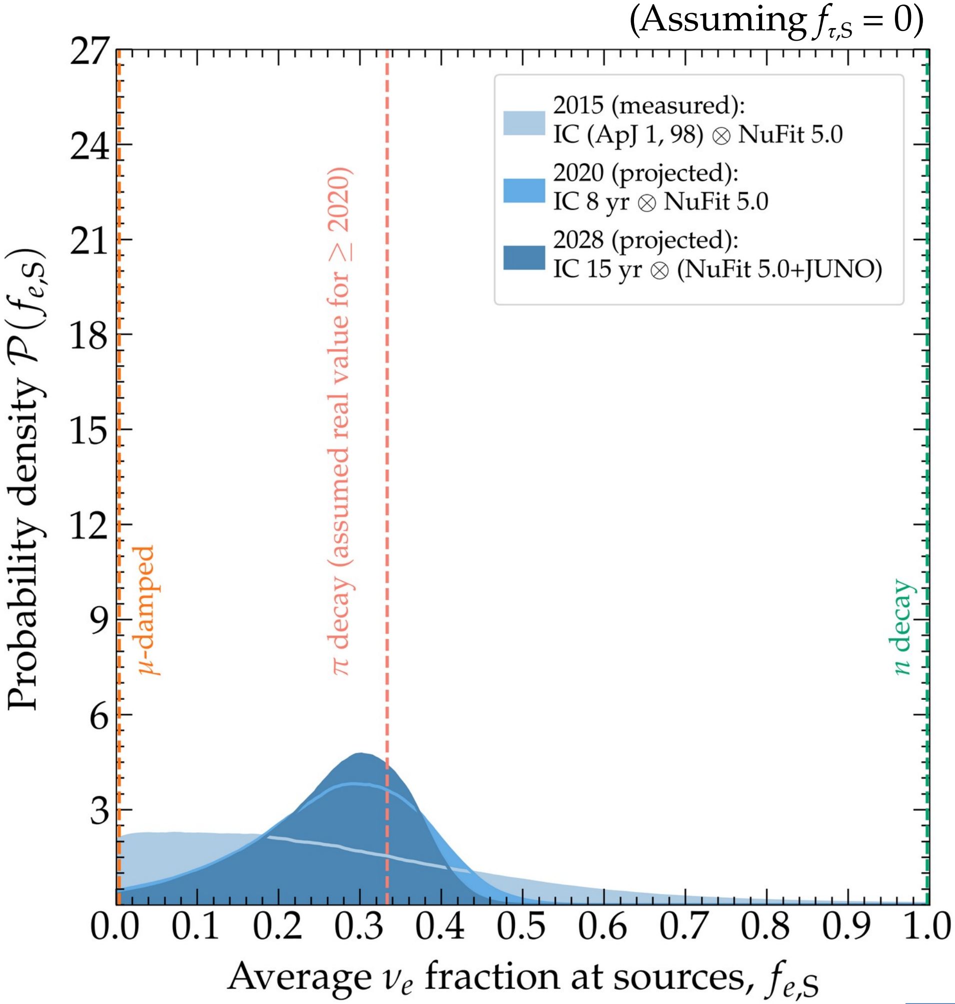
(Assuming $f_{\tau,S} = 0$)



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

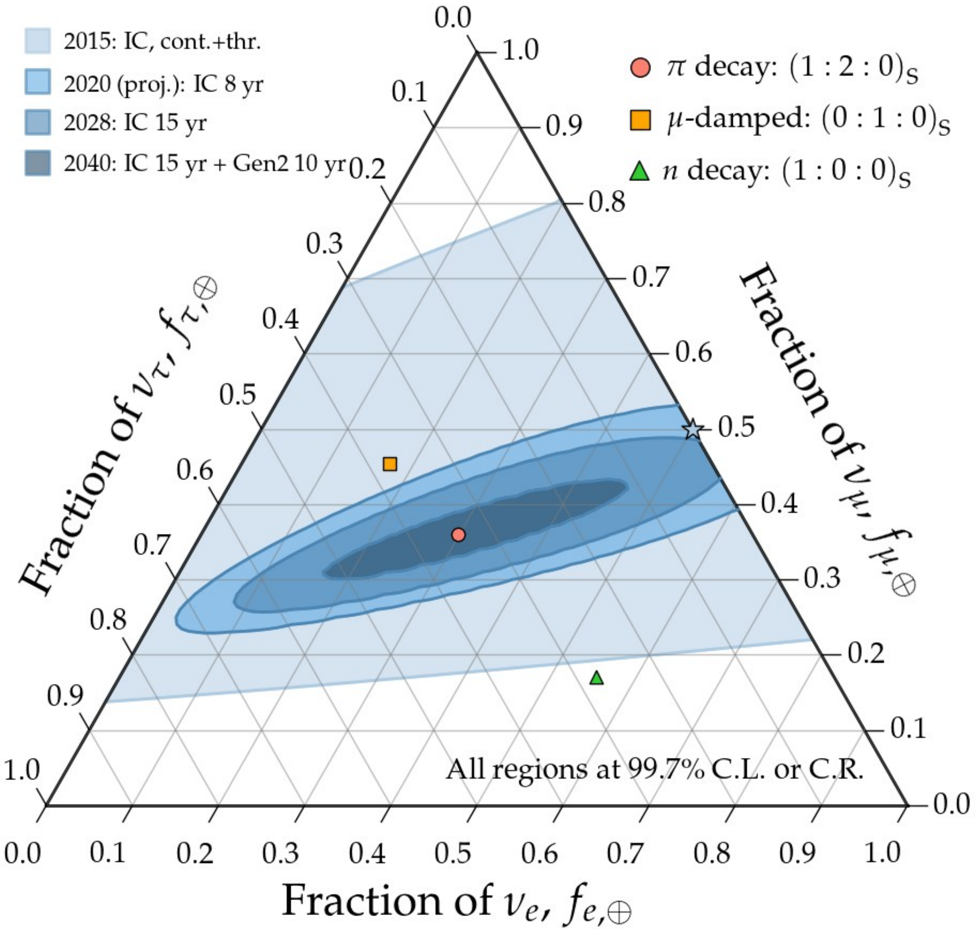
Inferring the flavor composition at the sources

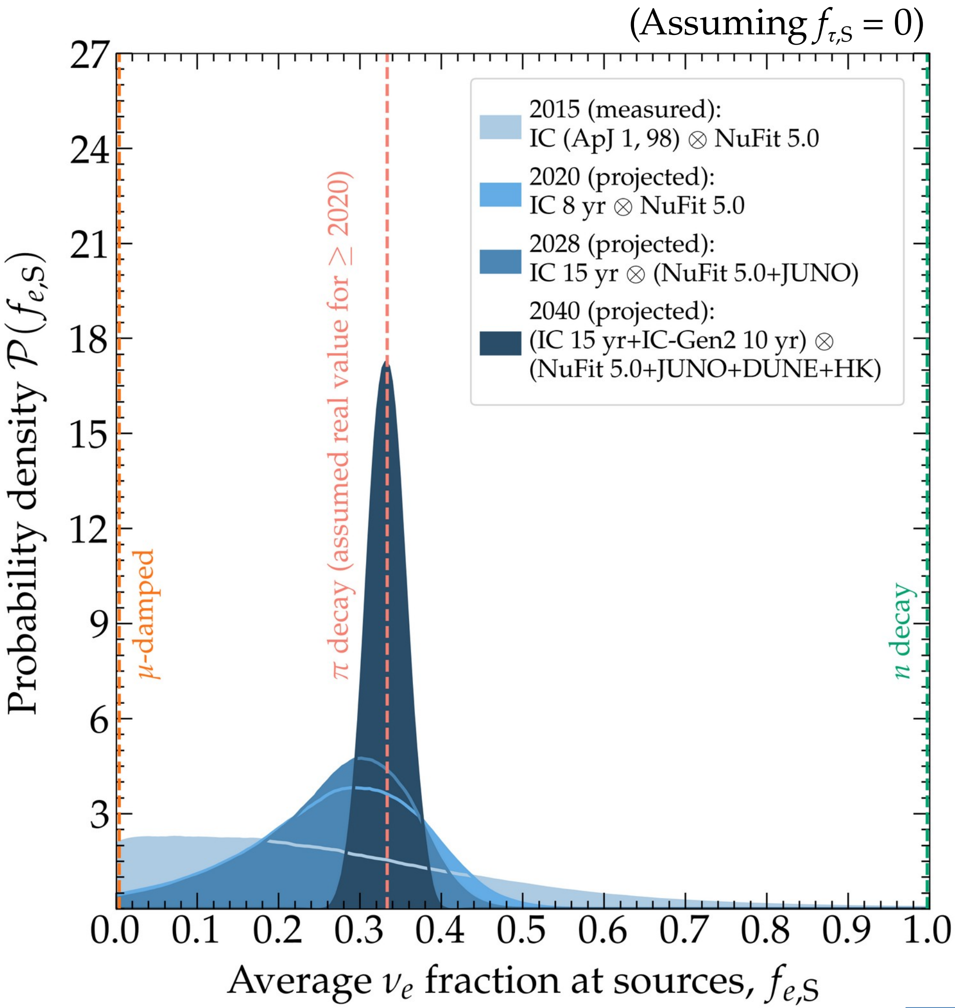




Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
MB & Ahlers, *PRL* 2019

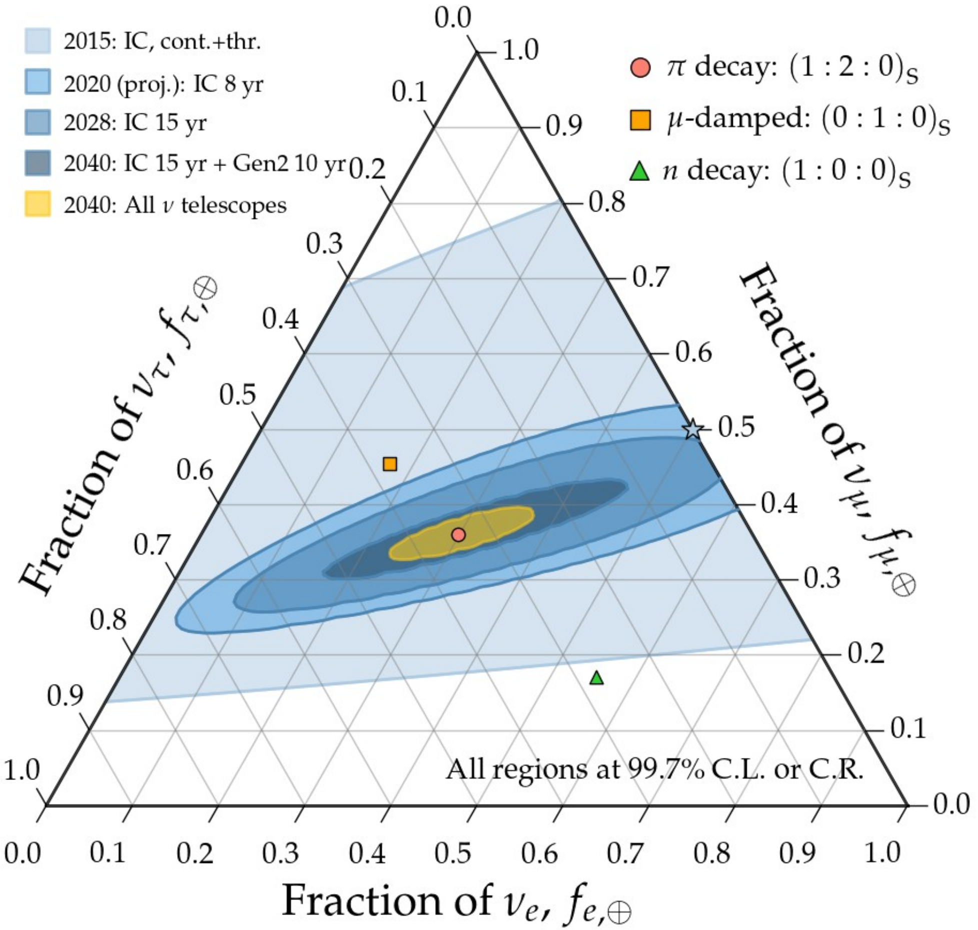
Inferring the flavor composition at the sources

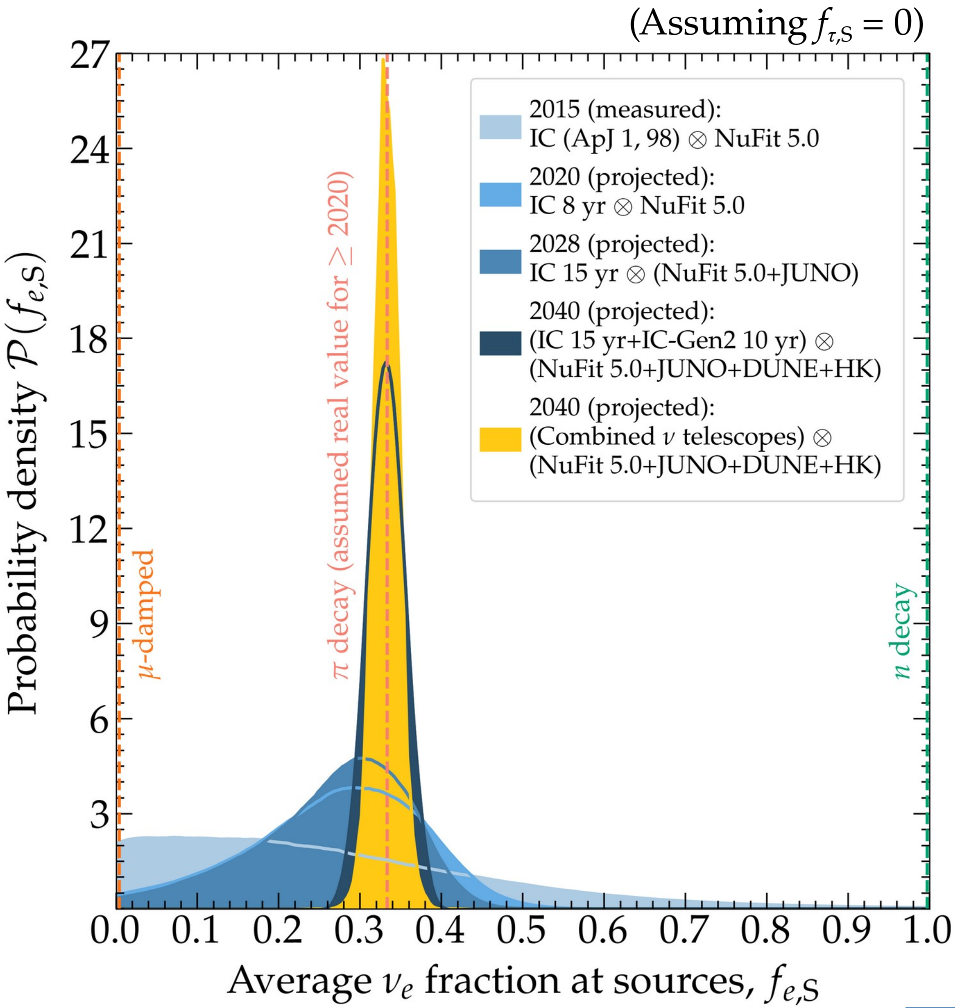




Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
MB & Ahlers, *PRL* 2019

Inferring the flavor composition at the sources





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

New physics in flavor composition

Repurpose the flavor sensitivity to test new physics:

New physics in flavor composition

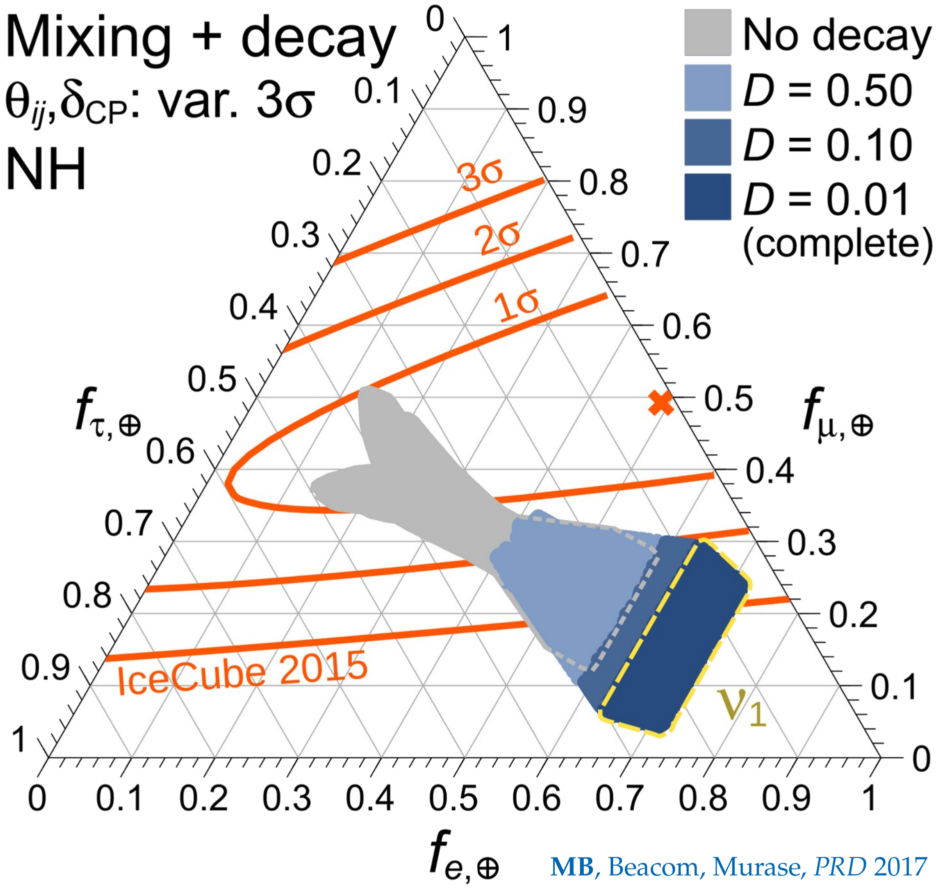
Repurpose the flavor sensitivity to test new physics:

Reviews:
Mehta & Winter, *JCAP* 2011; Rasmussen *et al.*, *PRD* 2017

New physics in flavor composition

Repurpose 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]



MB, Beacom, Murase, *PRD* 2017

Reviews:
Mehta & Winter, *JCAP* 2011; Rasmussen *et al.*, *PRD* 2017

New physics in flavor composition

Repurpose the flavor sensitivity to test new physics:

- Neutrino decay
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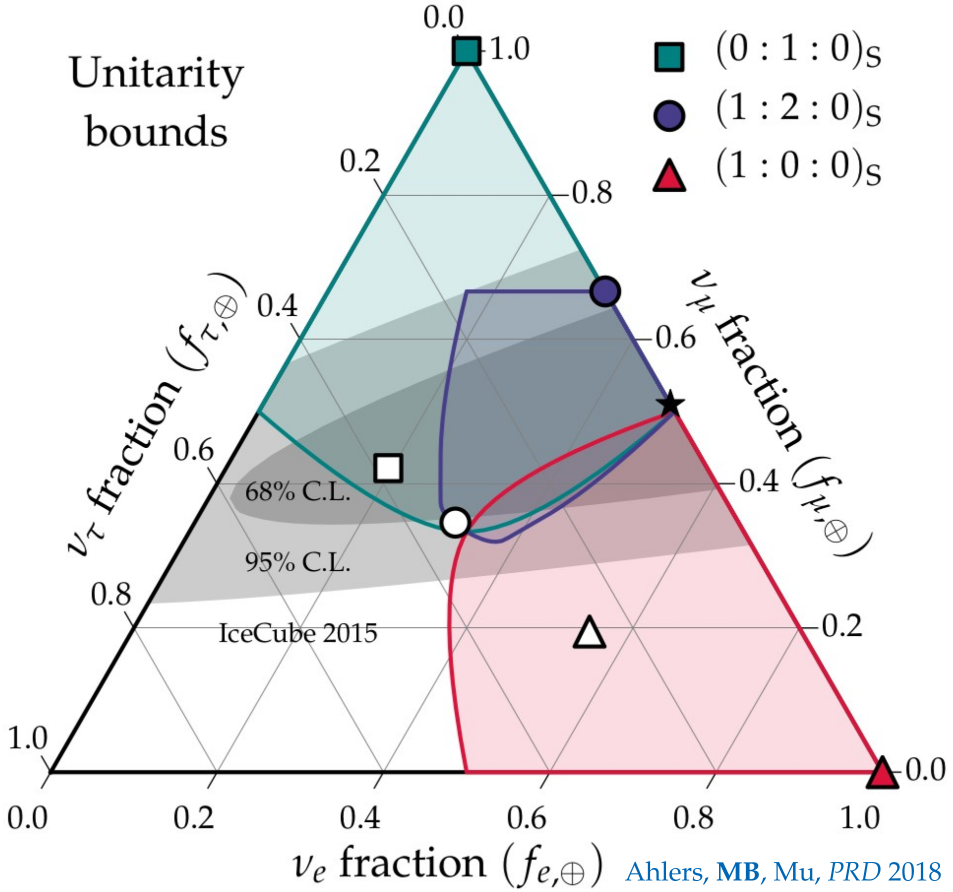

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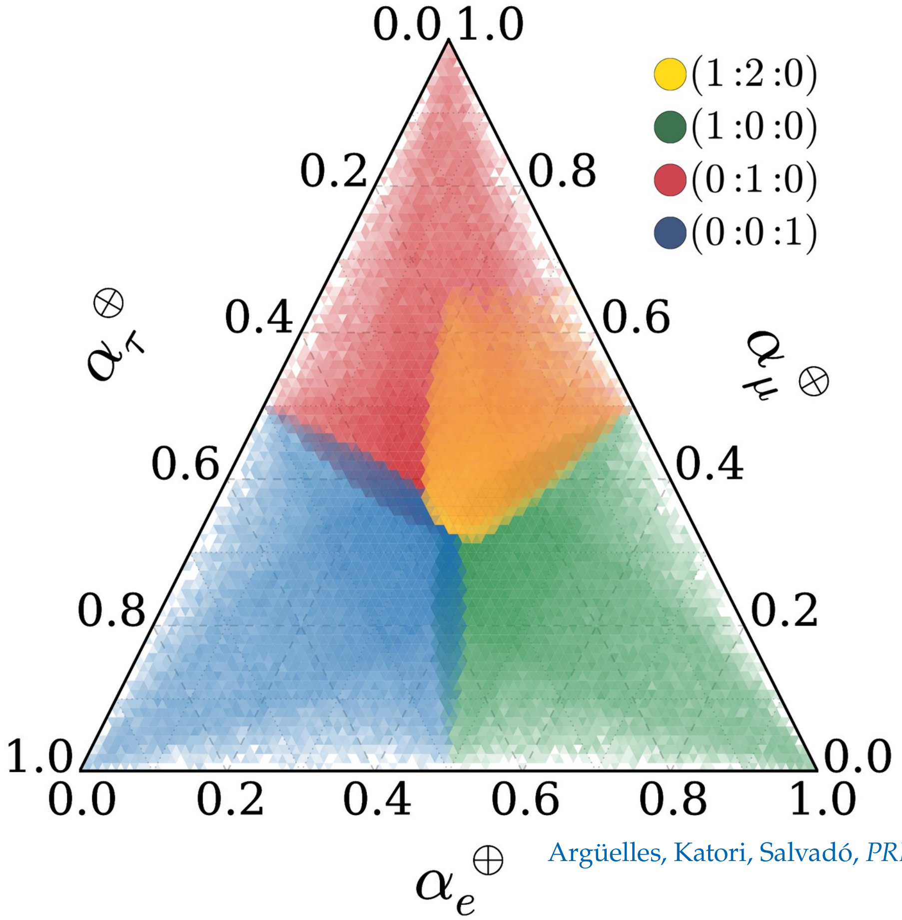

Argüelles, Katori, Salvadó, *PRL* 2015

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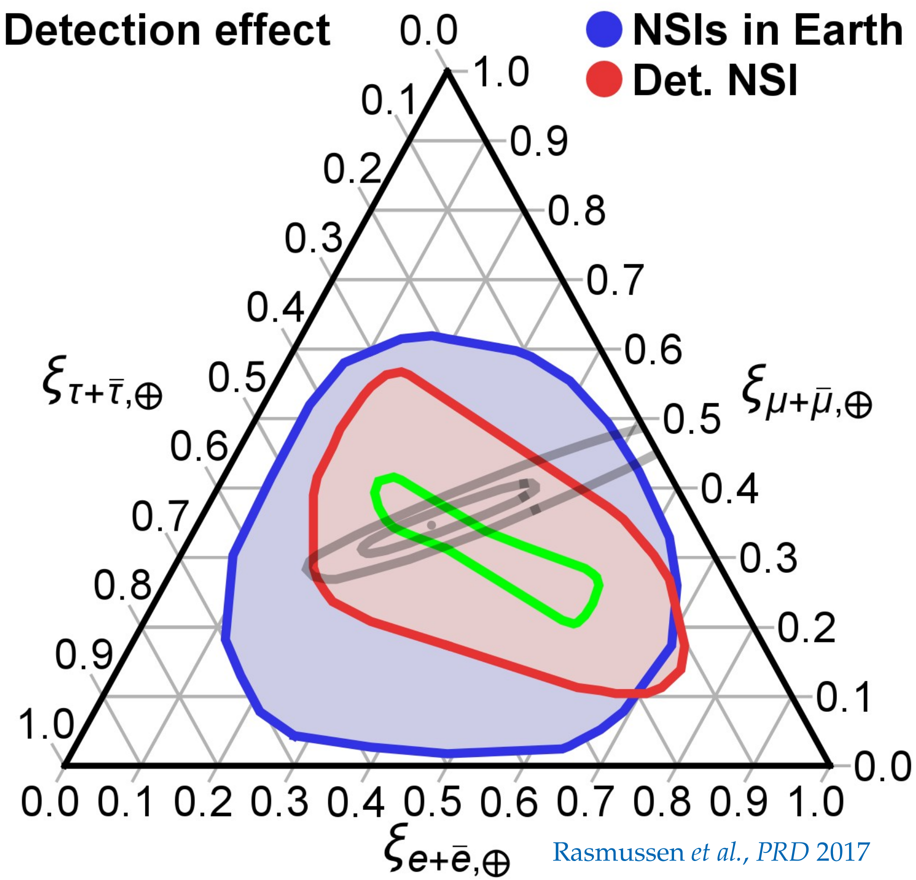

Rasmussen *et al.*, *PRD* 2017

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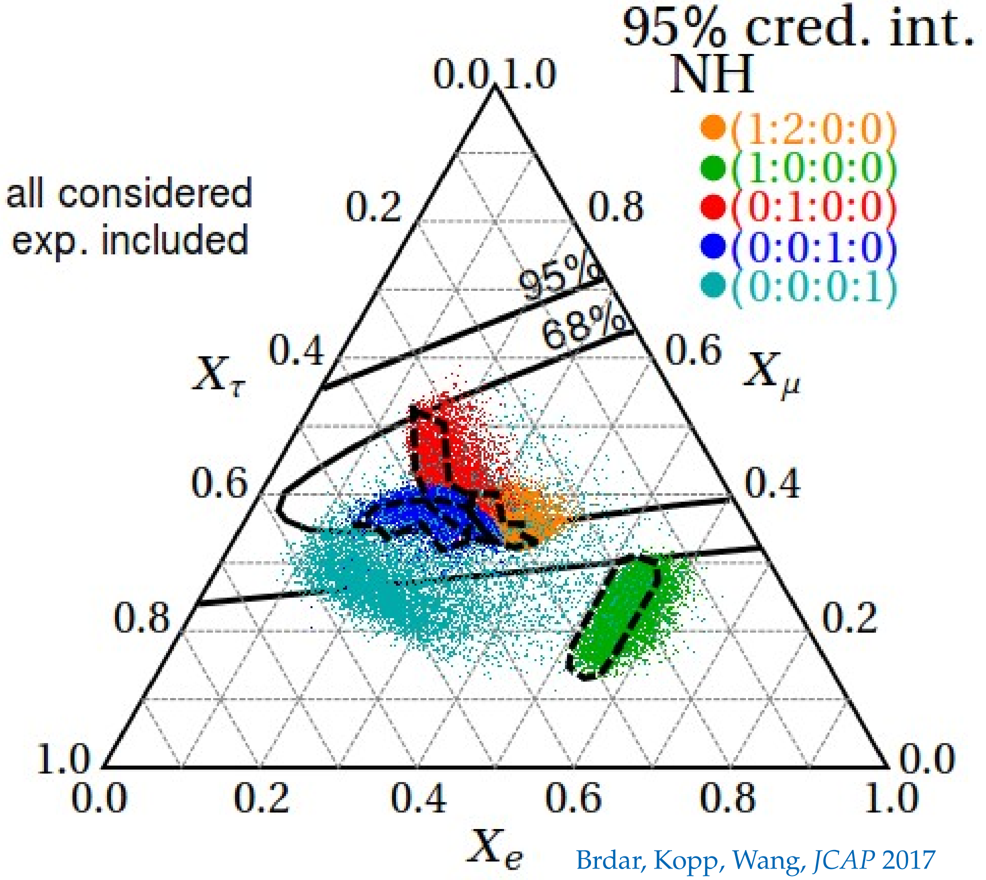

Brdar, Kopp, Wang, *JCAP* 2017

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Mehta & Winter, *JCAP* 2011; Rasmussen *et al.*, *PRD* 2017

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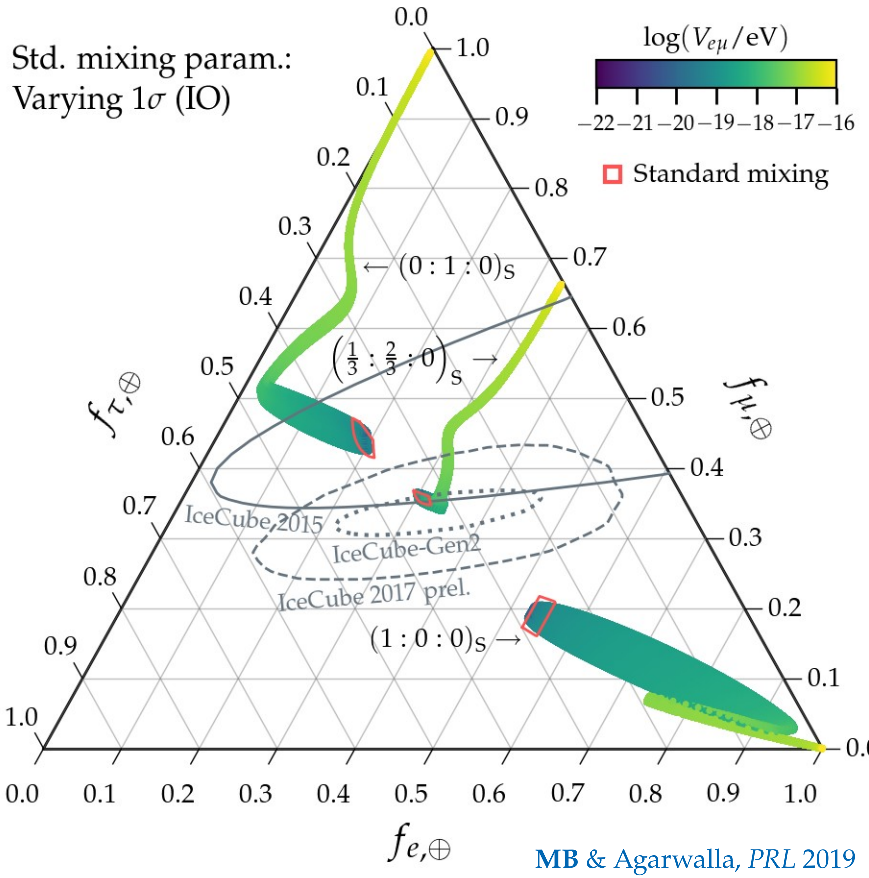
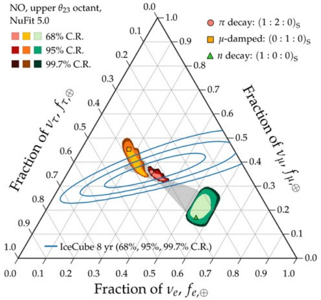
- **Long-range *e*ν interactions**
  [**MB** & Agarwalla, *PRL* 2019]

Reviews:
Mehta & Winter, *JCAP* 2011; Rasmussen *et al.*, *PRD* 2017

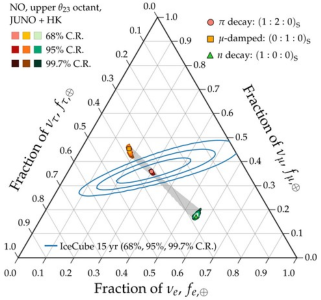


MB & Agarwalla, *PRL* 2019

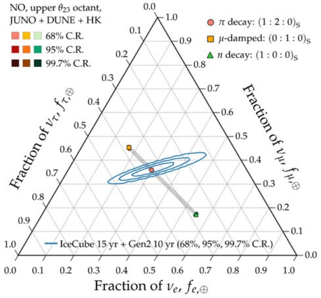
The high-energy flavor charter



Today: Allowed flavor regions at Earth large, imprecise flavor measurements



2030: Allowed flavor regions shrunk, thanks to JUNO + Hyper-K + DUNE



2040: Allowed flavor regions shrunk + precise flavor measurements

Opportunities for astrophysics and particle physics exist throughout!

Backup slides

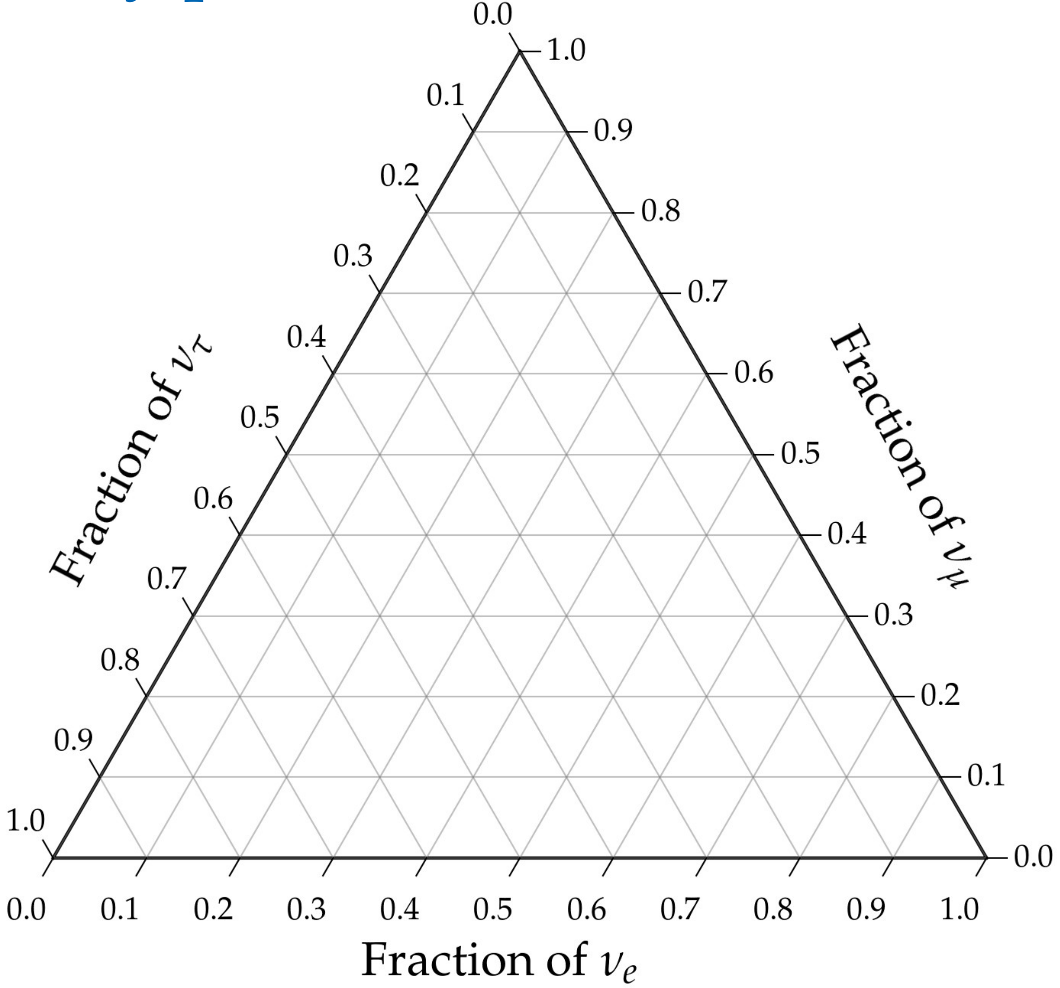
Quick aside: how to read a ternary plot

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

How to read it:

Follow the tilt of the tick marks

Always in this order: (f_e, f_μ, f_τ)



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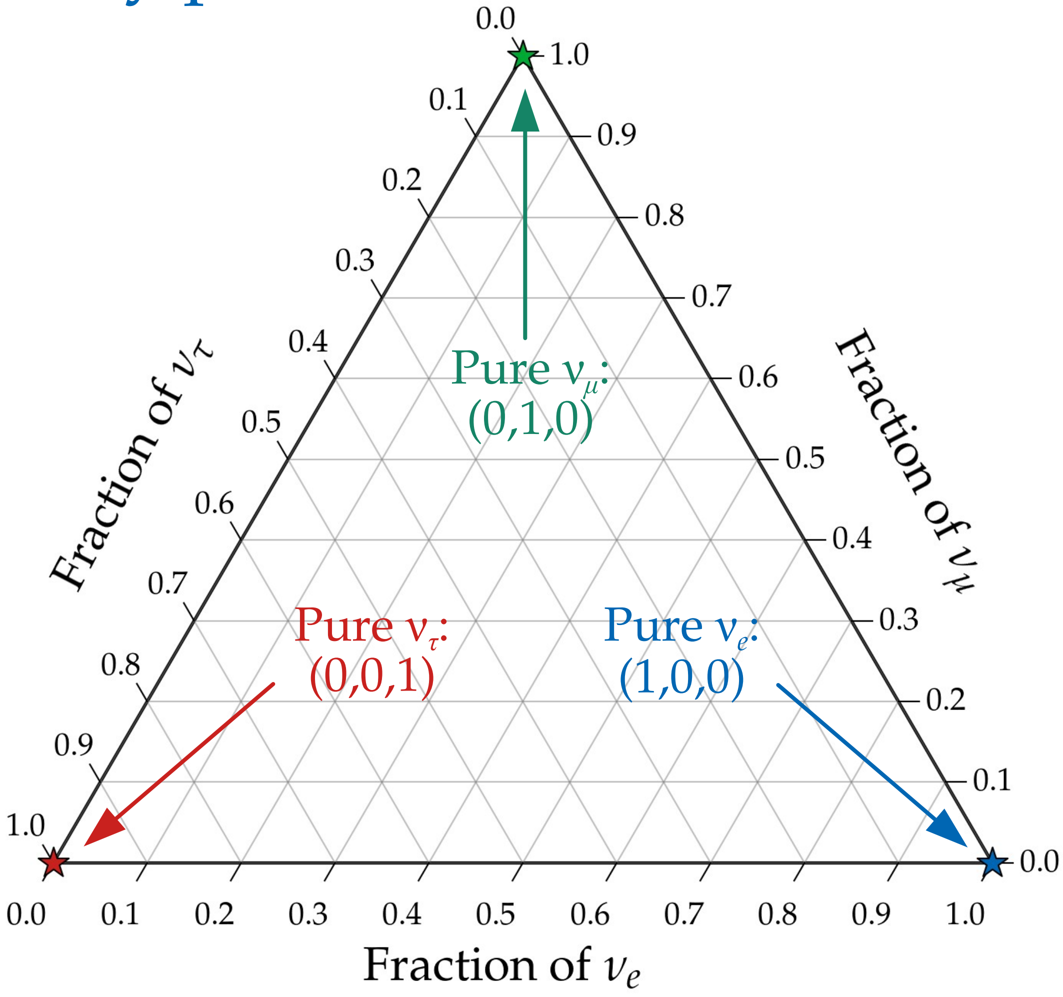

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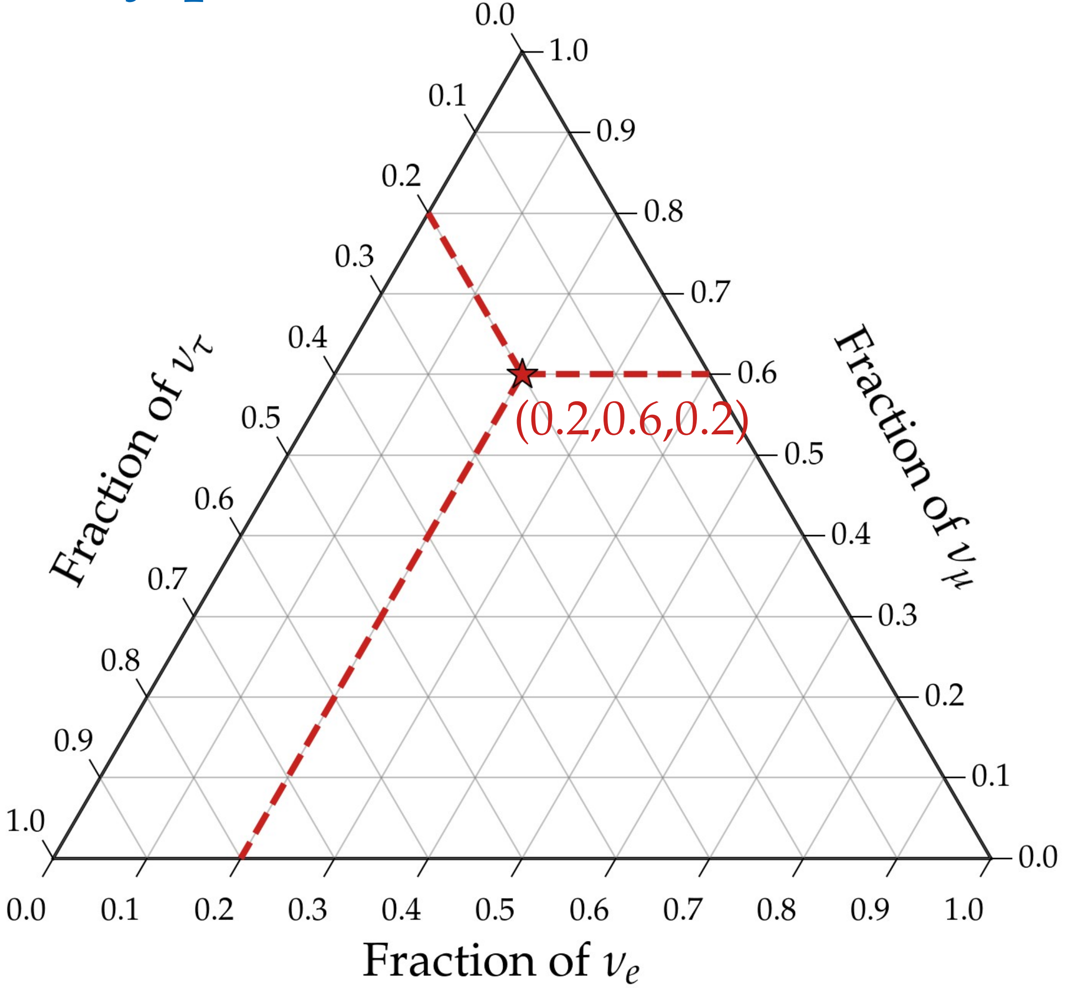

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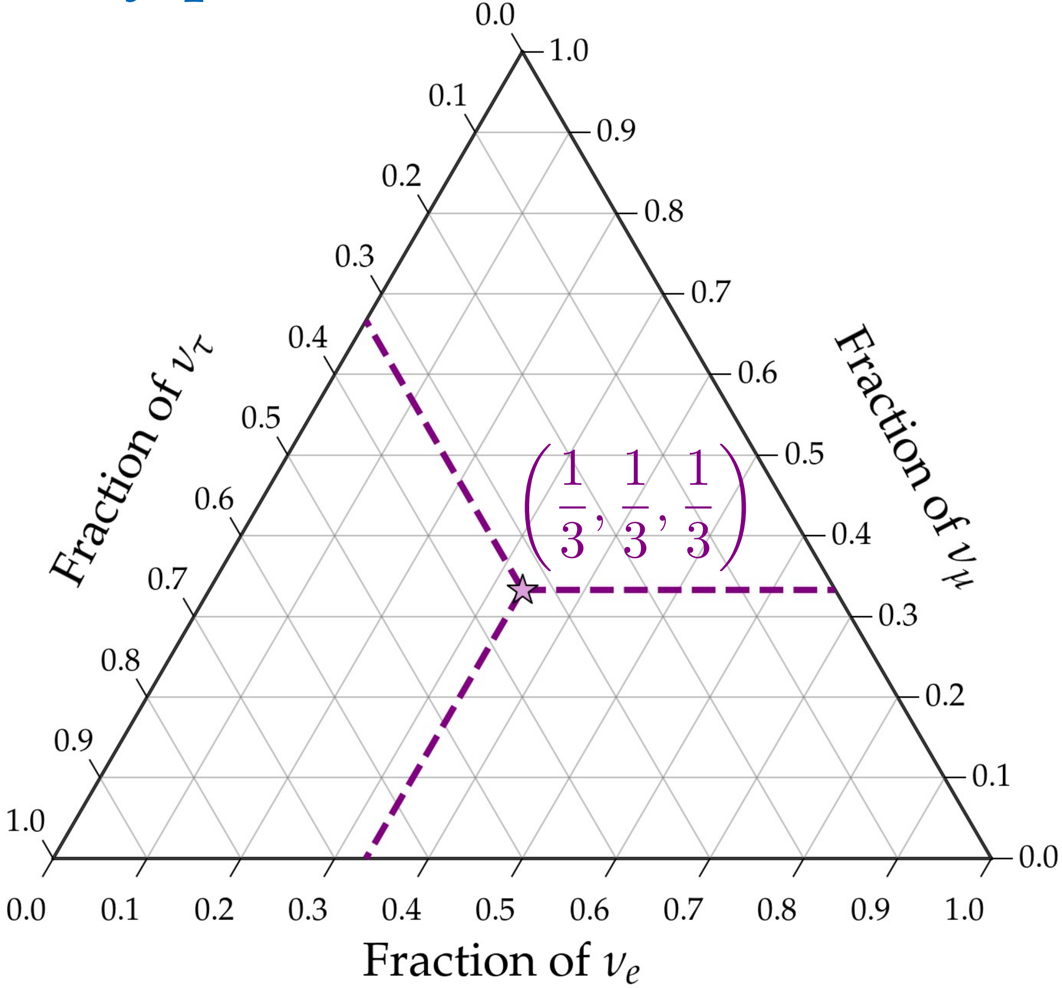
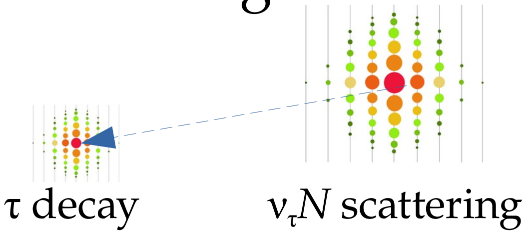


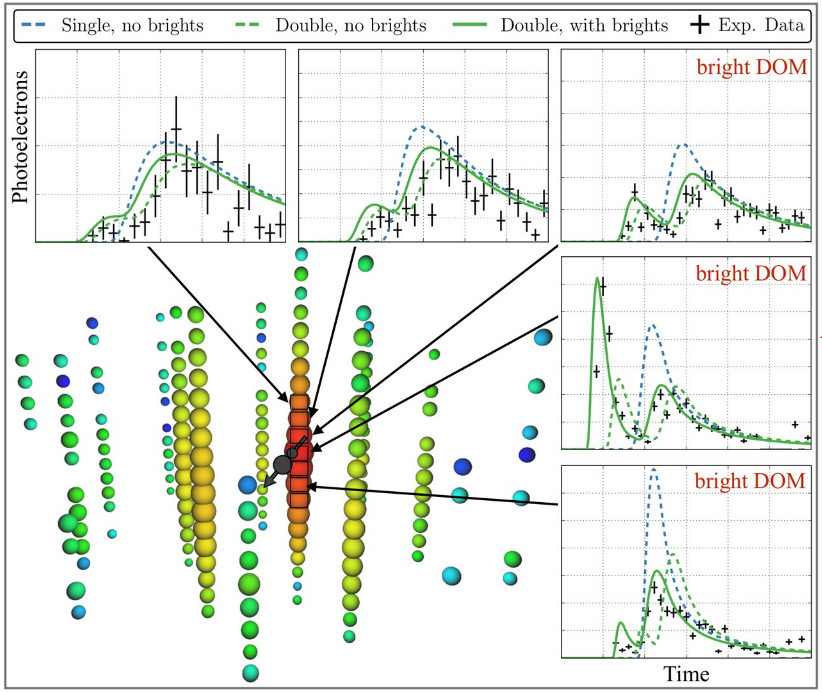
New (IC 7.5 yr): First identified high-energy astrophysical ν_τ

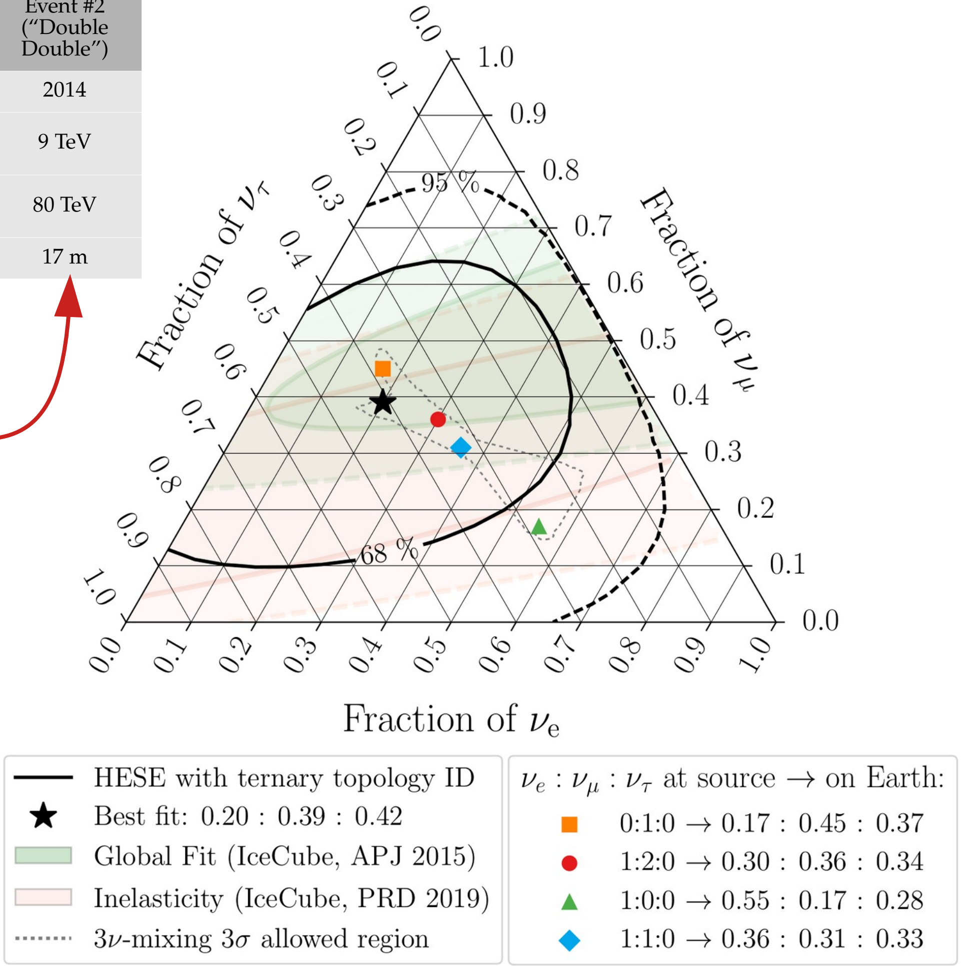
Double bang:



	Event #1 ("Big Bird")	Event #2 ("Double Double")
Year	2012	2014
Energy 1st cascade	1.2 PeV	9 TeV
Energy 2nd cascade	0.6 PeV	80 TeV
Length	16 m	17 m

Most likely to be a ν_τ





IceCube, 2011.03561

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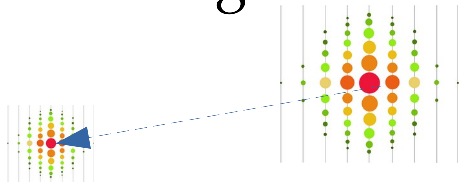

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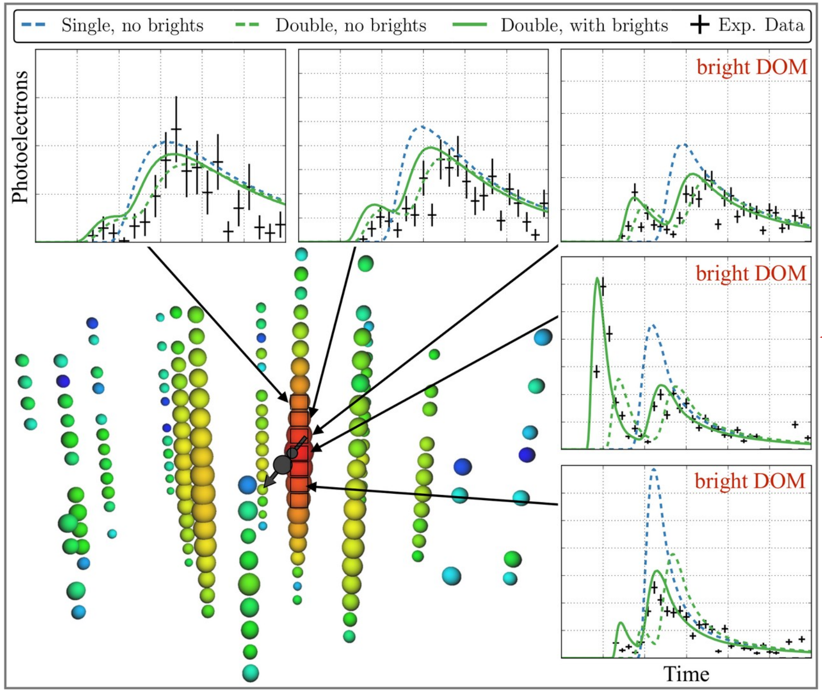

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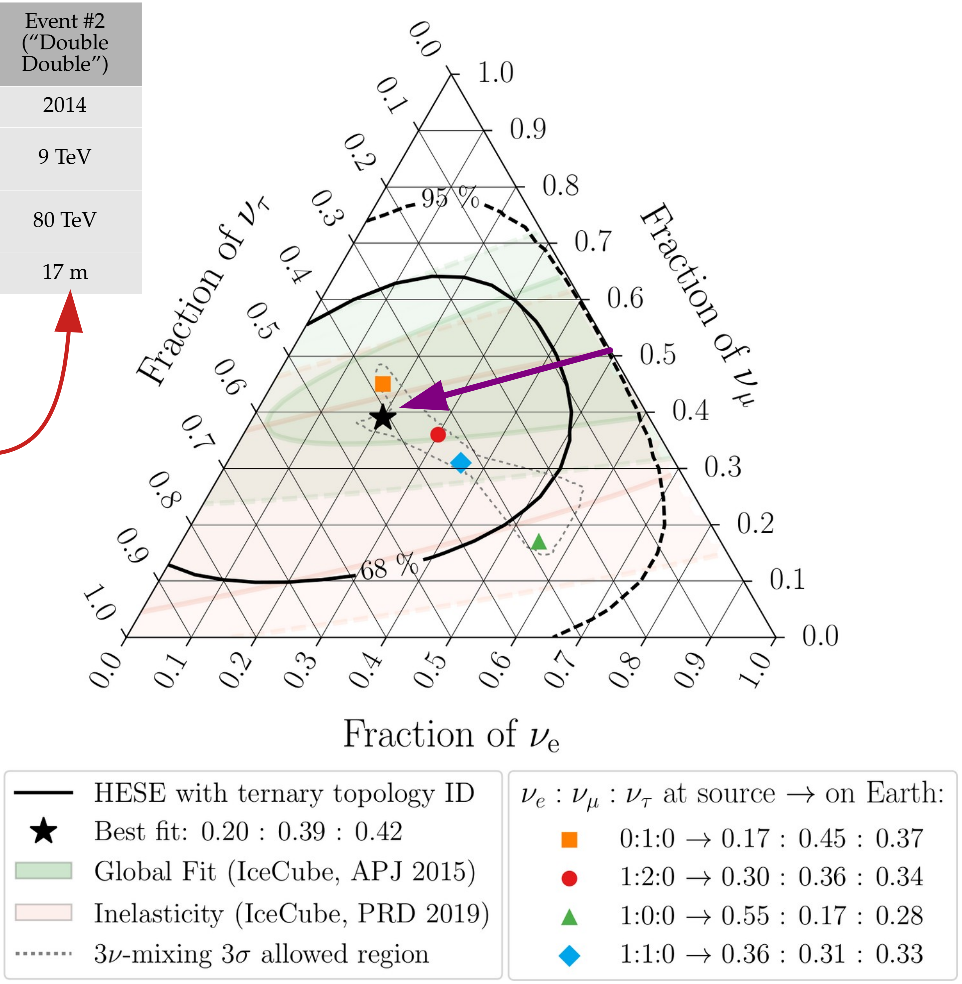
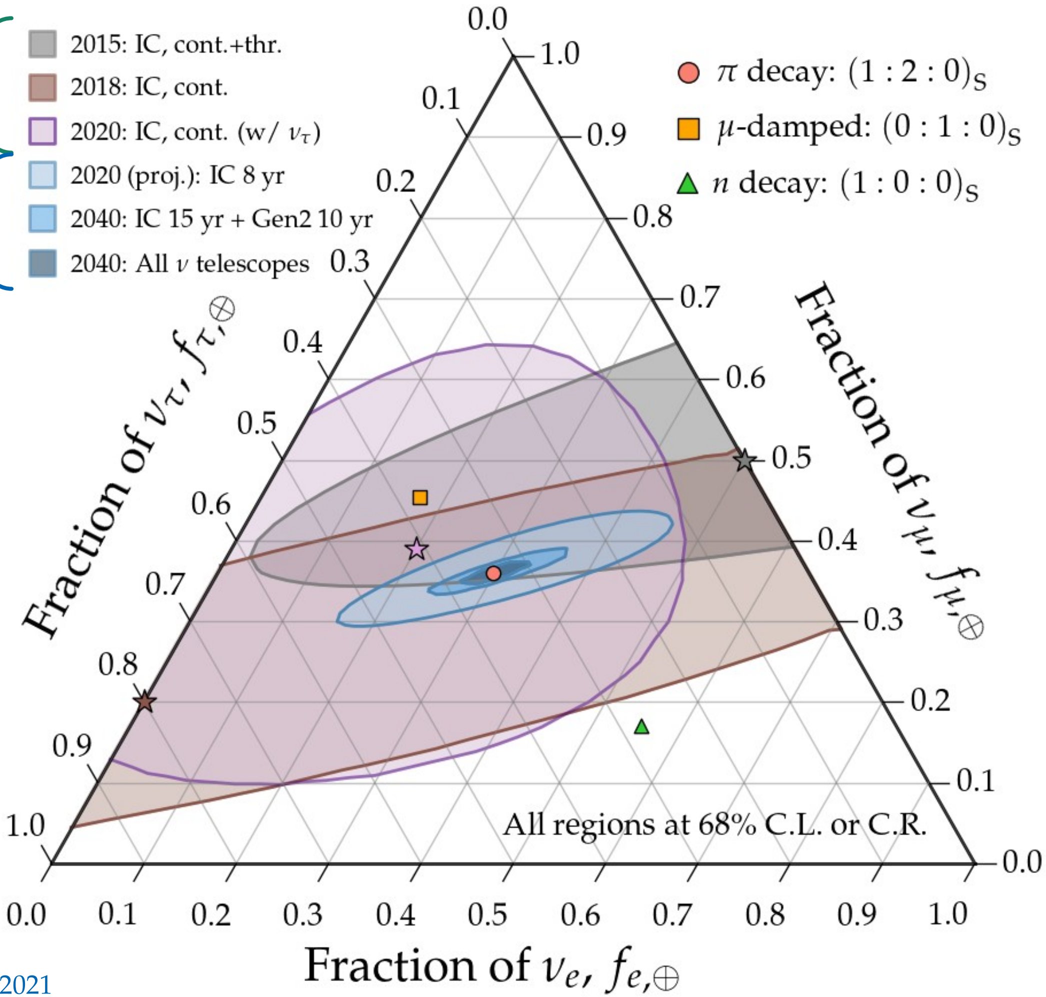


IceCube, 2011.03561

Measuring flavor composition: 2015–2040

Based on real data

Projections



Status today:
Measurements are compatible with standard expectations (but errors are large!)

Projections:

Near future (~2020):
× 5 reduction using 8 yr of IC contained + thru.

Coming up (~2040):
× 10 reduction using Gen2 and all ν telescopes

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
IceCube, *PRL* 2015, *ApJ* 2015, *PRD* 2019, *J. Phys. G* 2021, 2011.03561

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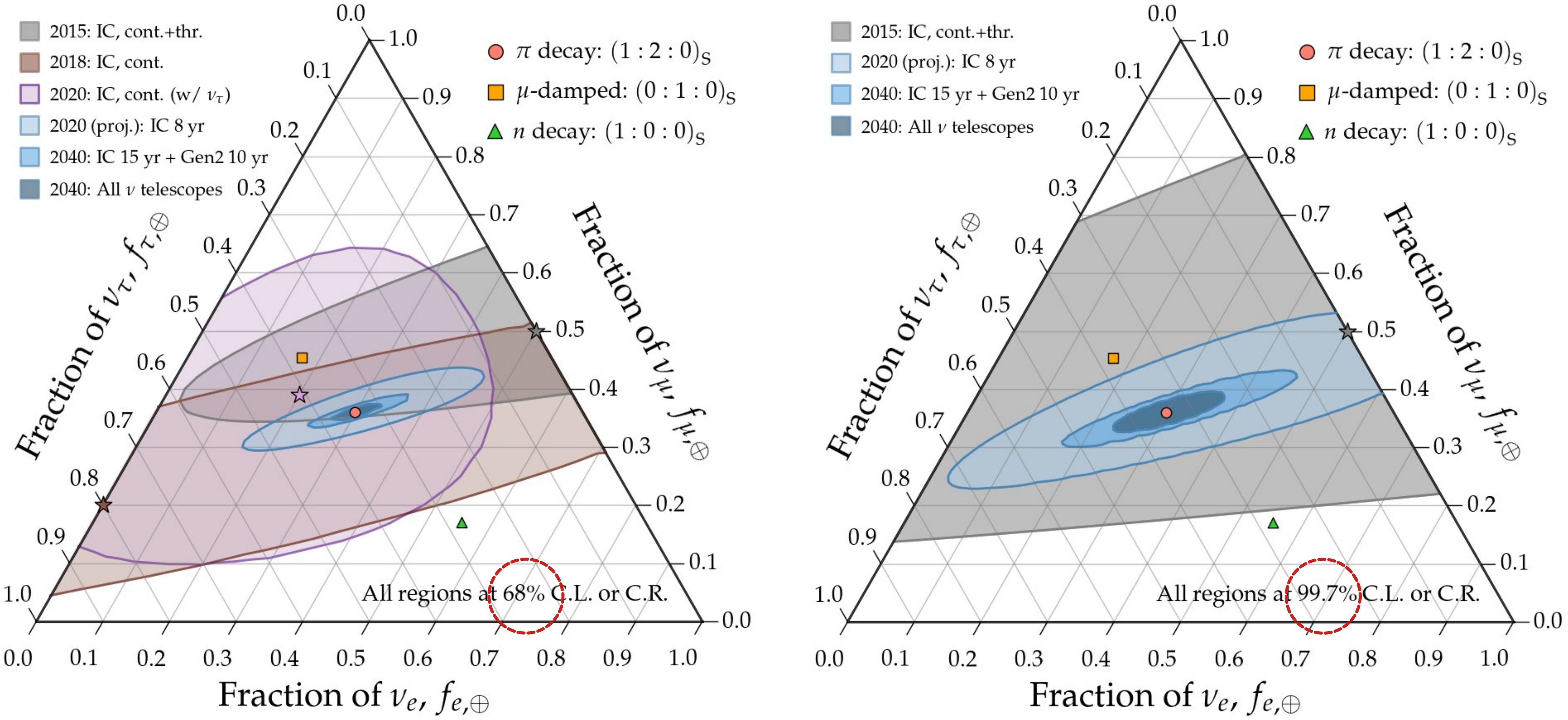

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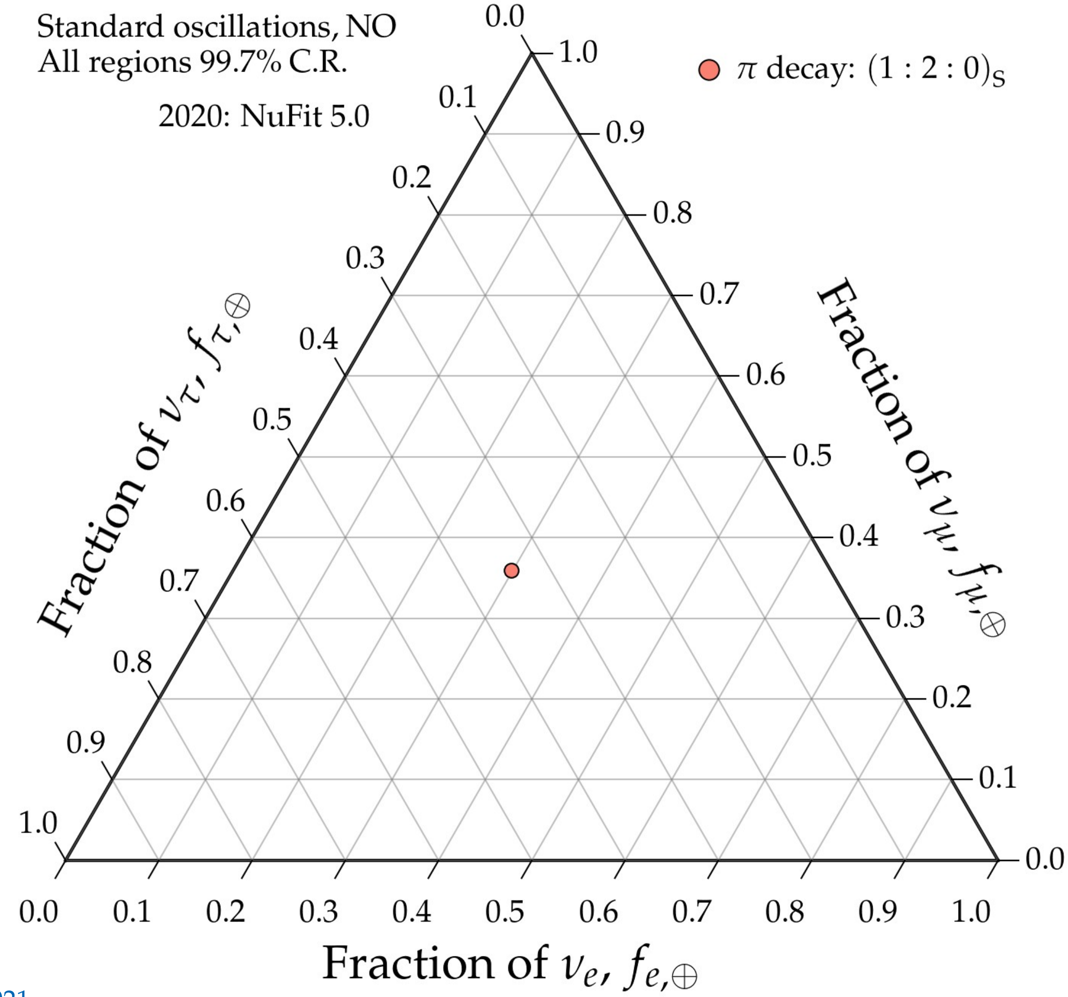
Theoretically palatable regions: 2020 *vs.* 2040



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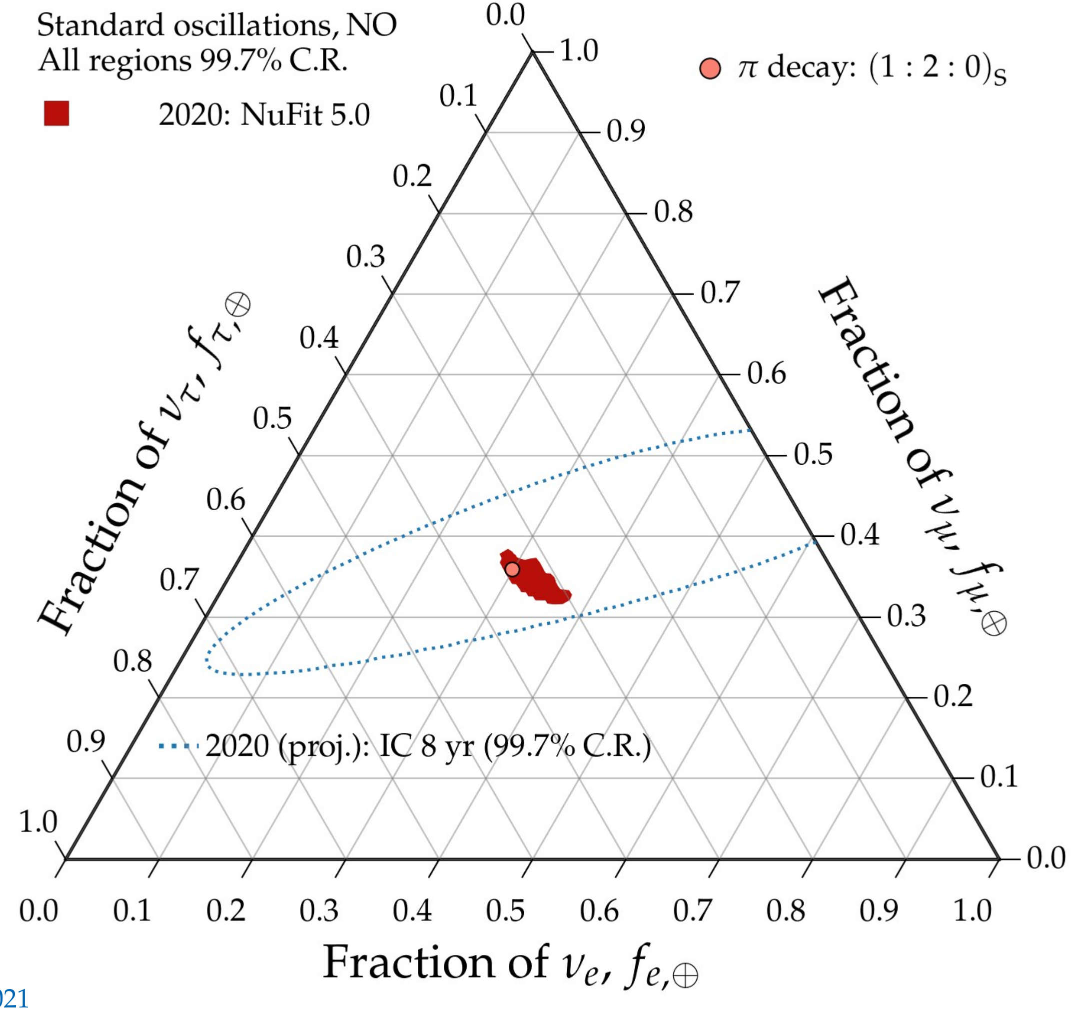

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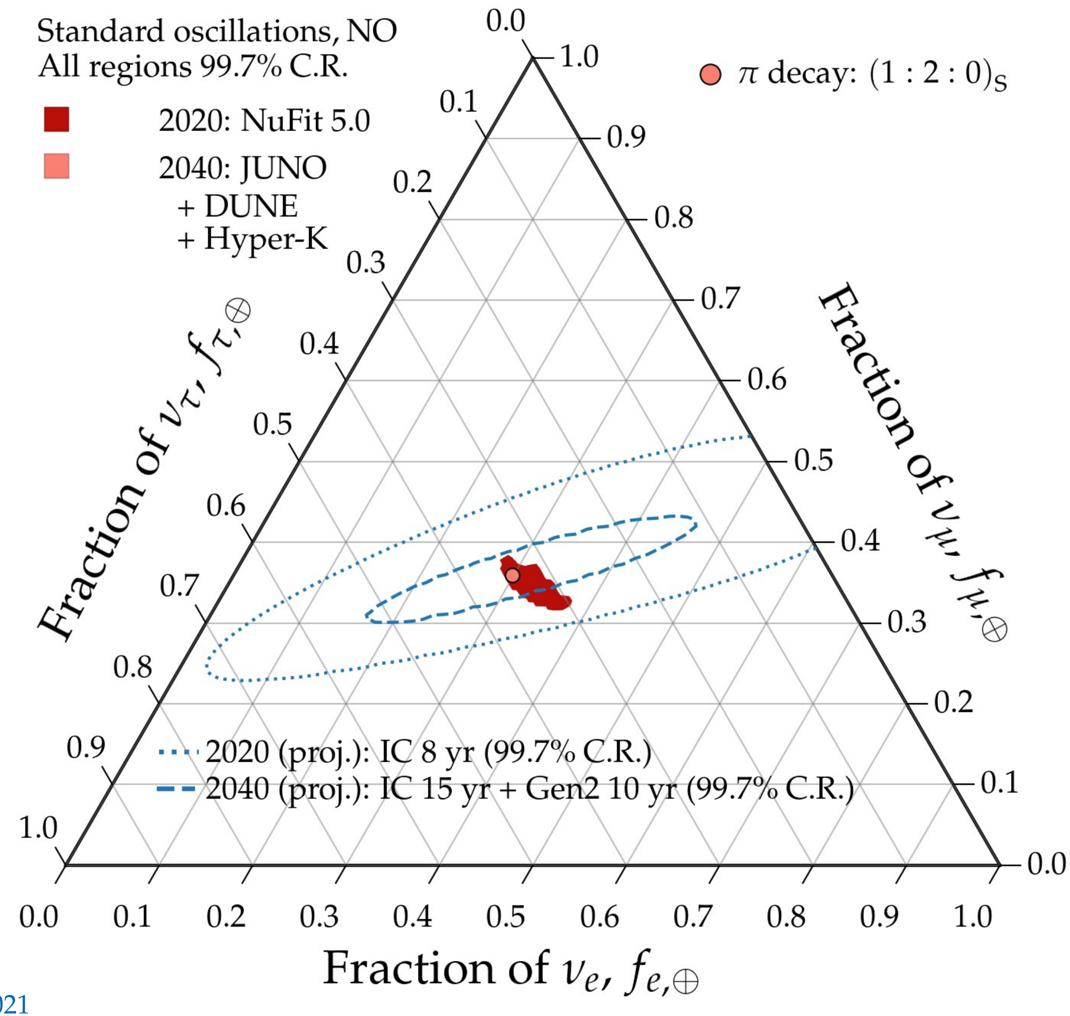
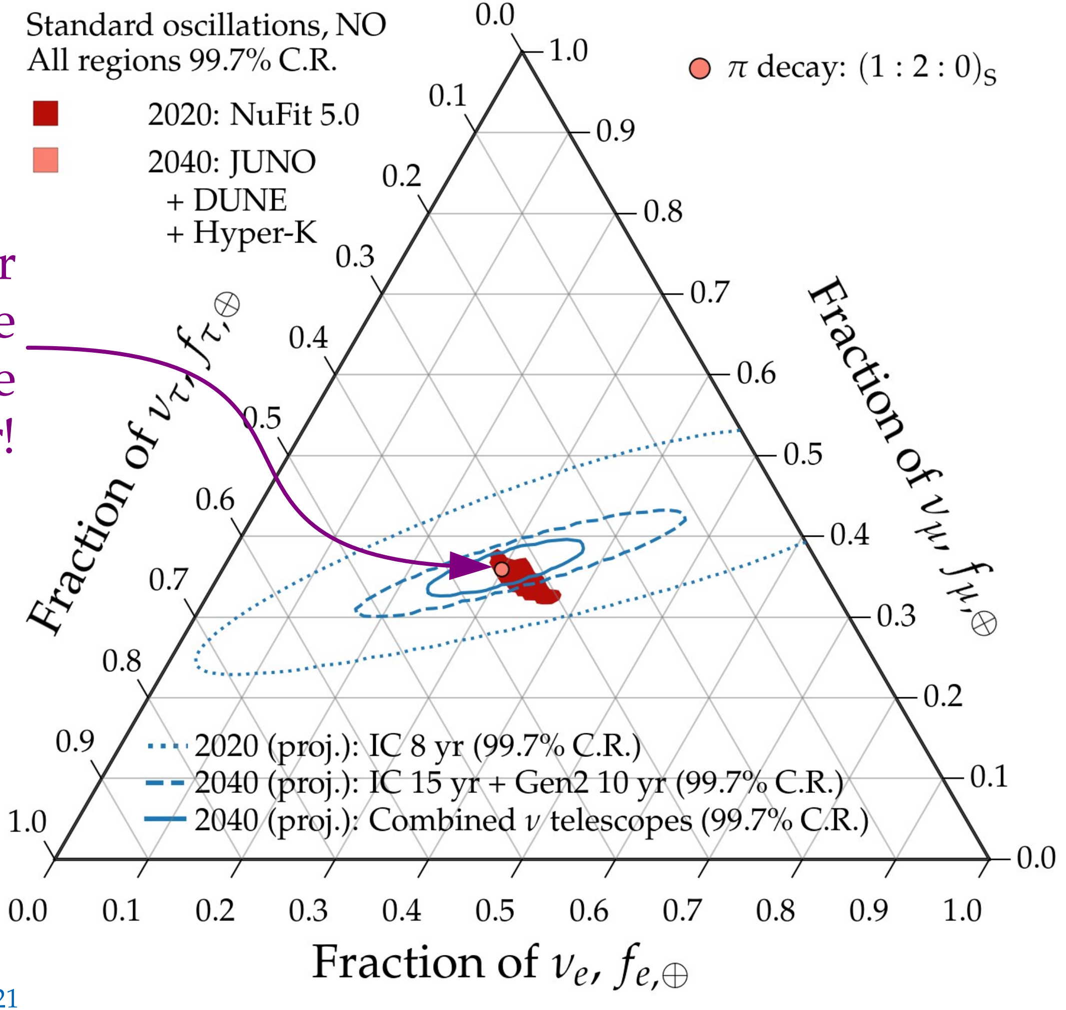


Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Theoretically palatable regions: 2020 *vs.* 2040

The allowed flavor region in 2040 is the same size as the best-fit point marker!



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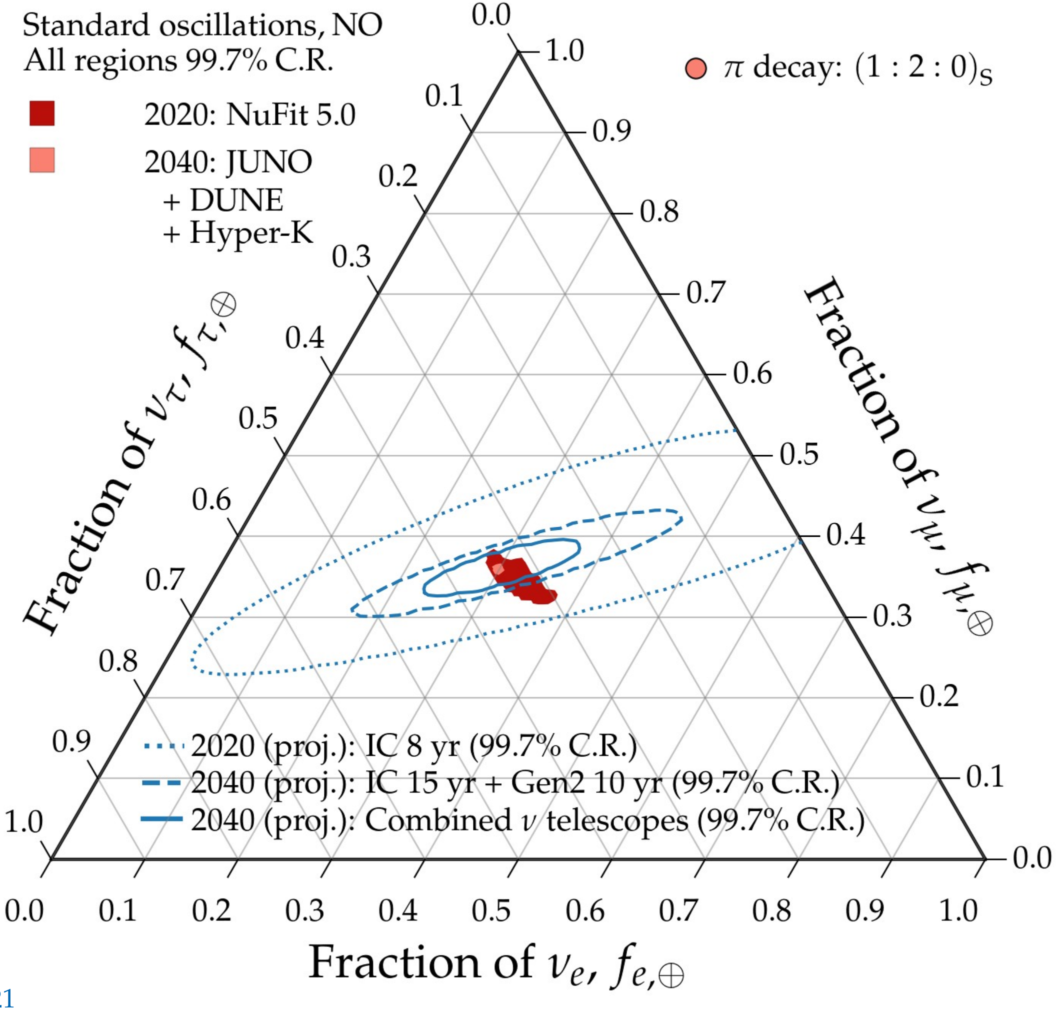

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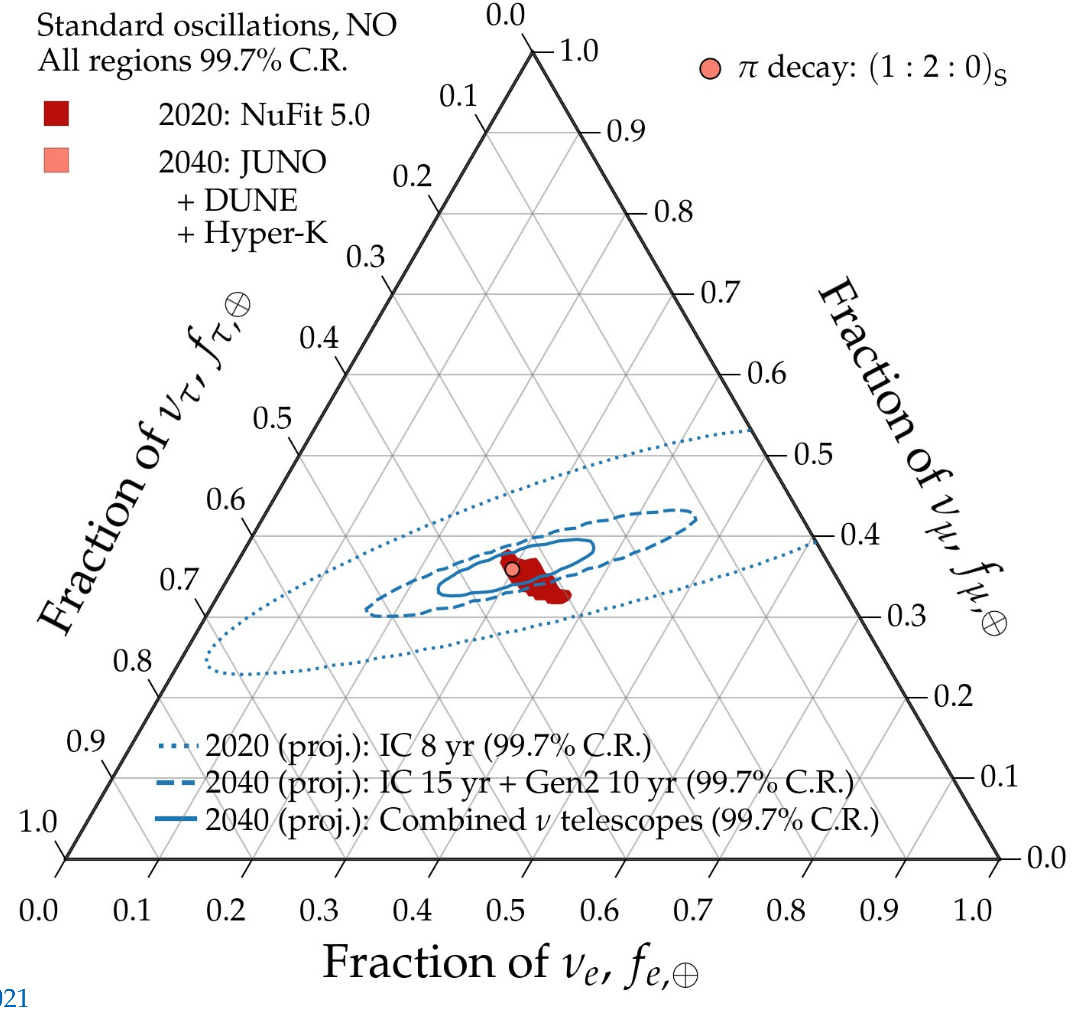

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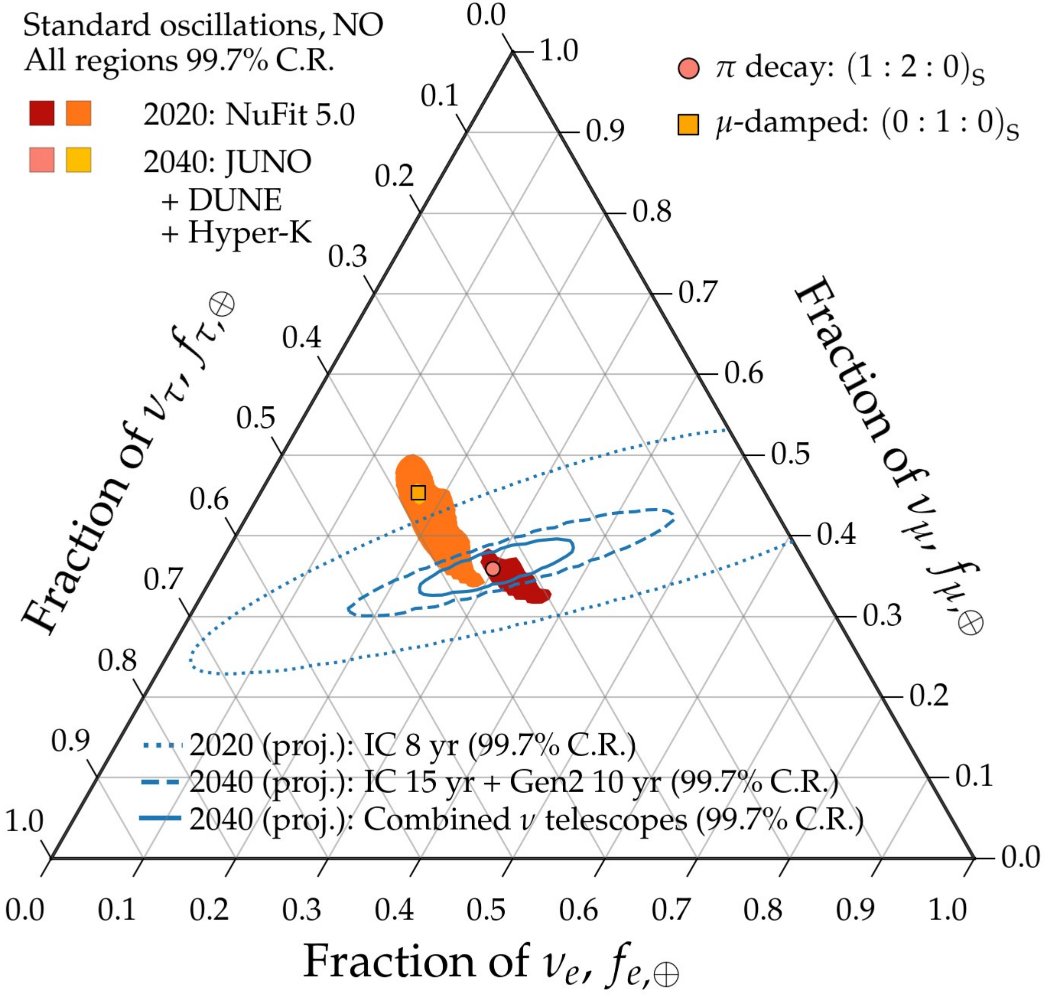

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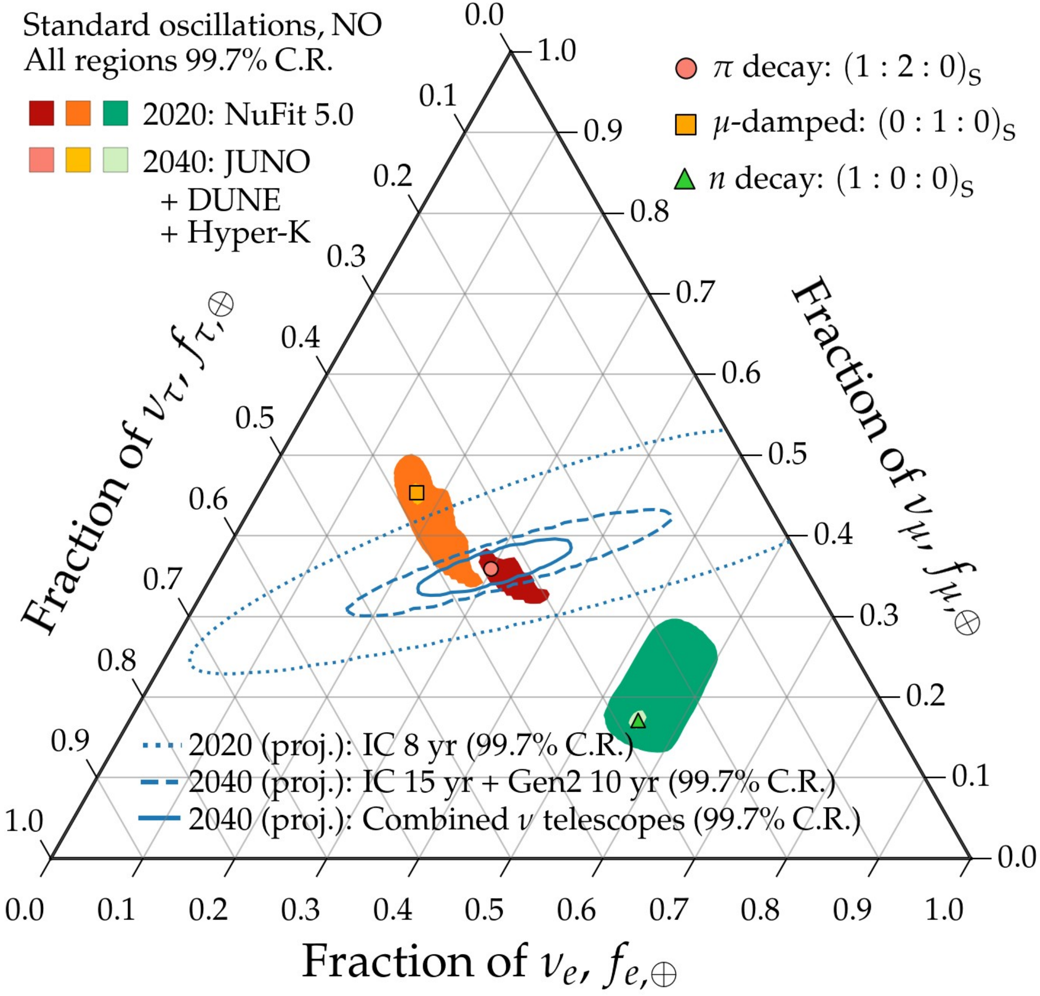

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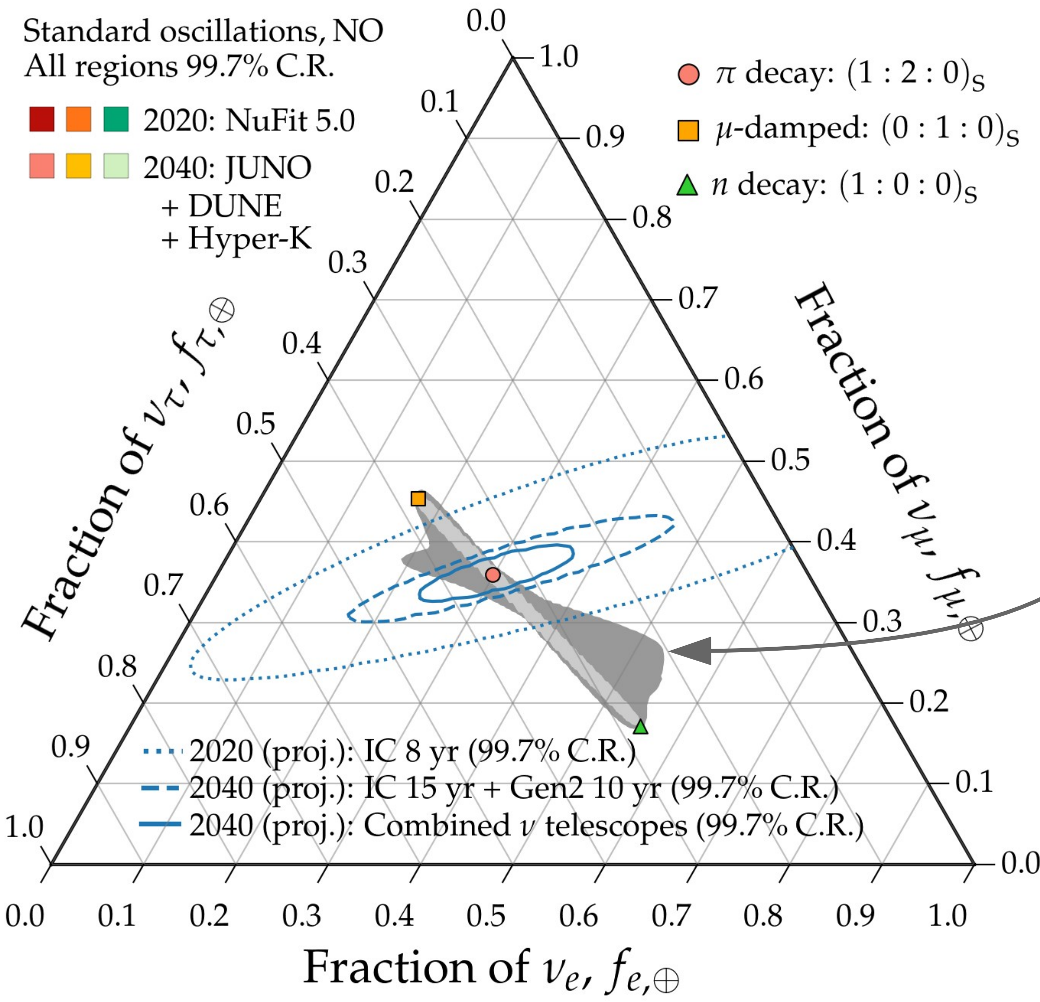

Varying over all possible flavor ratios at the source

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

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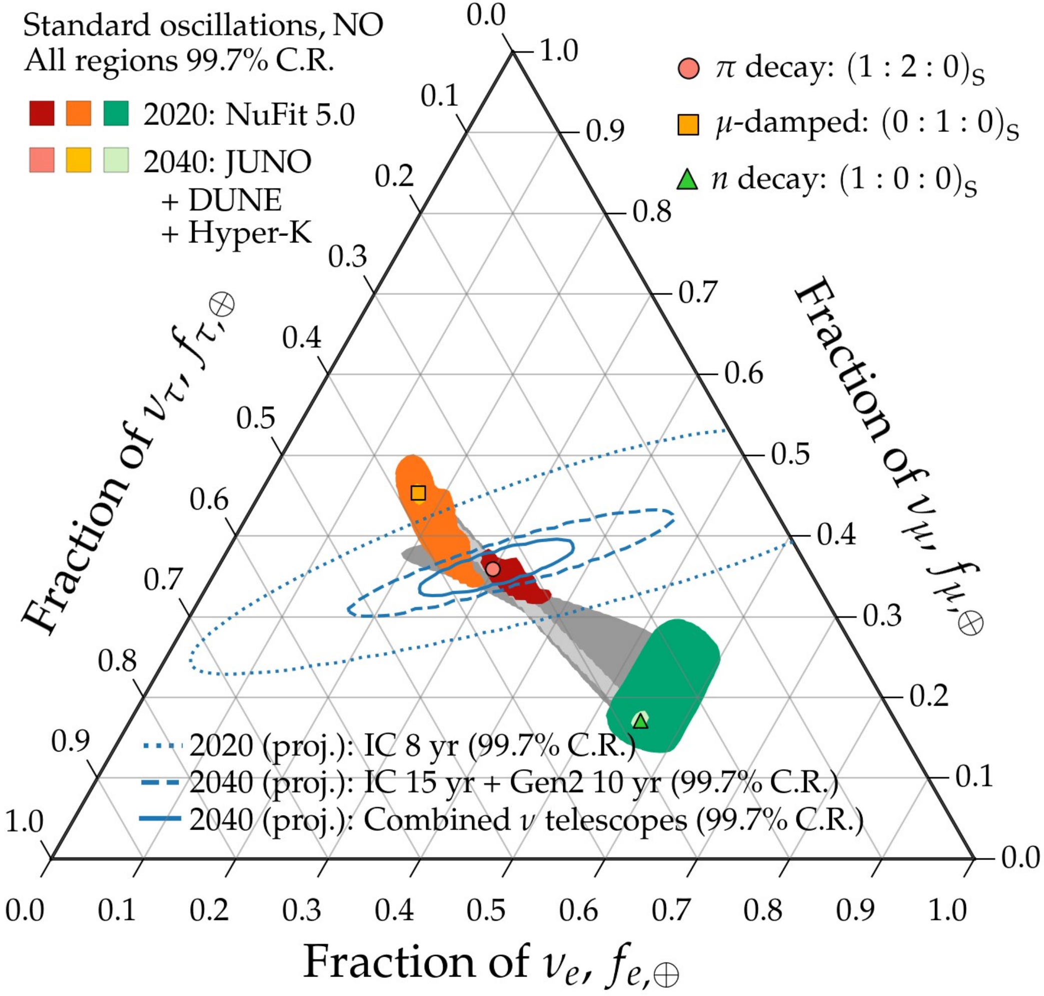

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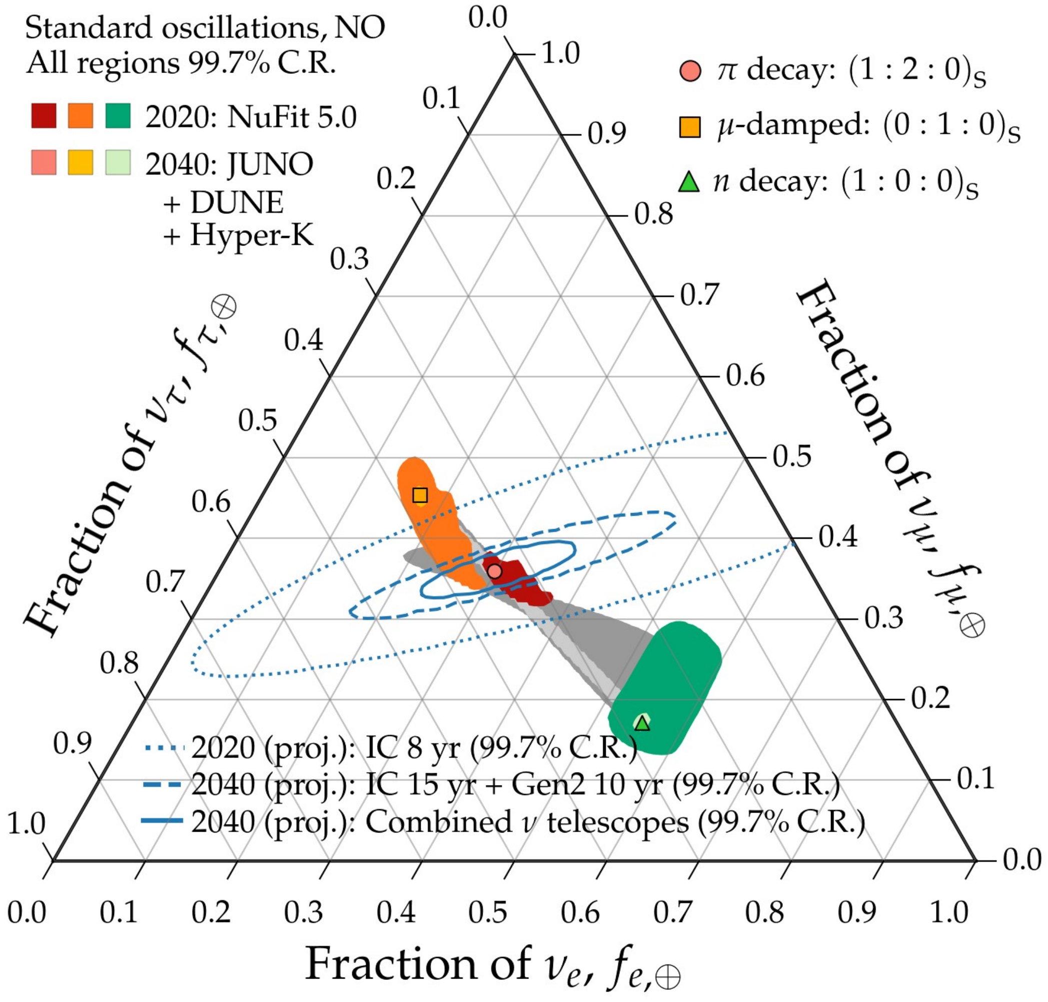


By 2040:

Theory –
Mixing parameters known precisely: allowed flavor regions are *almost* points (already by 2030)

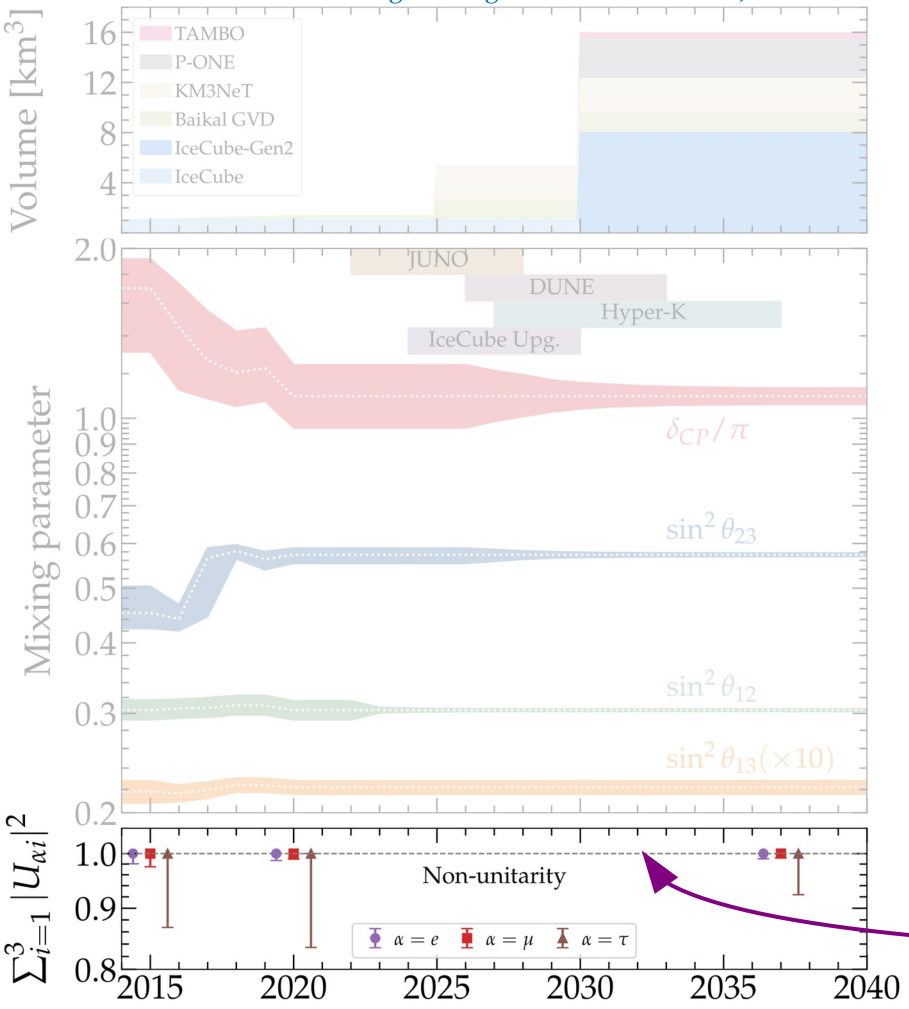
Measurement of flavor ratios –
Can distinguish between similar predictions at 99.7% C.R. (3σ)

Can finally use the full power of flavor composition for astrophysics and neutrino physics

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

No unitarity? *No problem*

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



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, *JHEP* 2020
Parke & Ross-Lonergan, *PRD* 2016

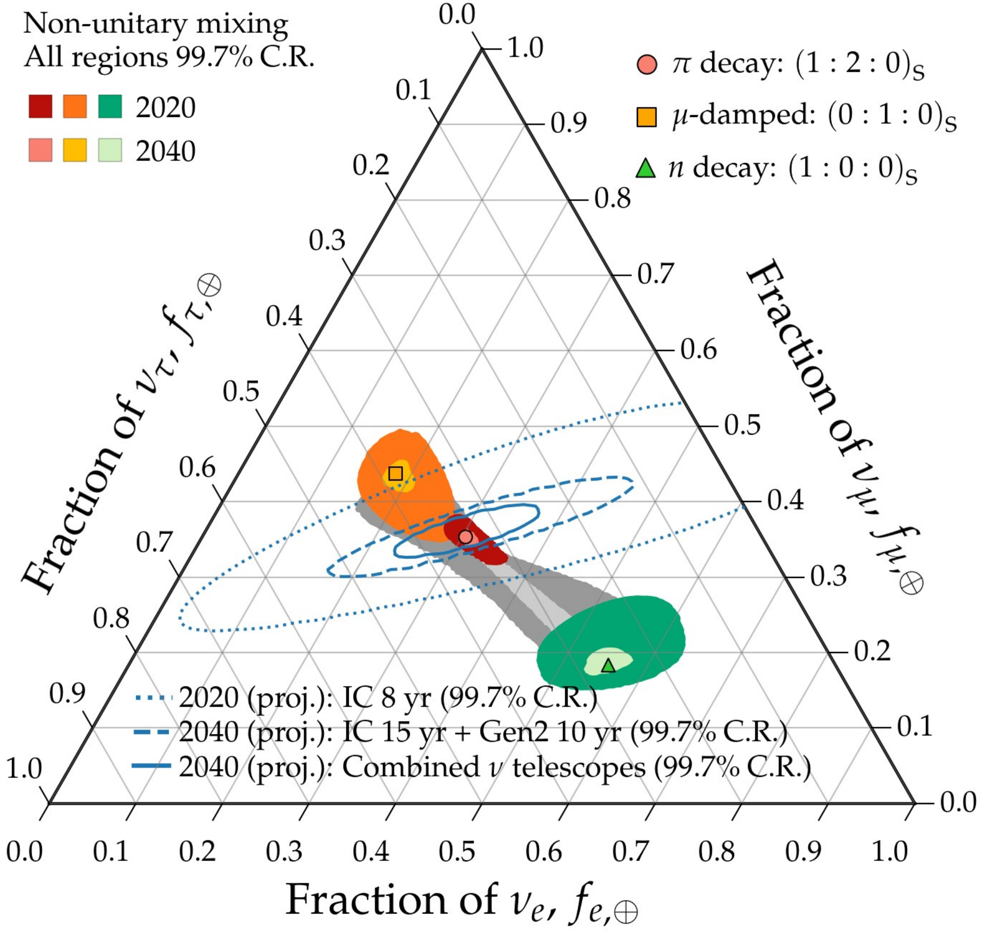
No unitarity? *No problem*

Flavor ratios at Earth:

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

Same as for standard oscillations…

… but the probability is computed directly using the values of the $|U_{\alpha i}|^2$ (instead of the mixing angles)



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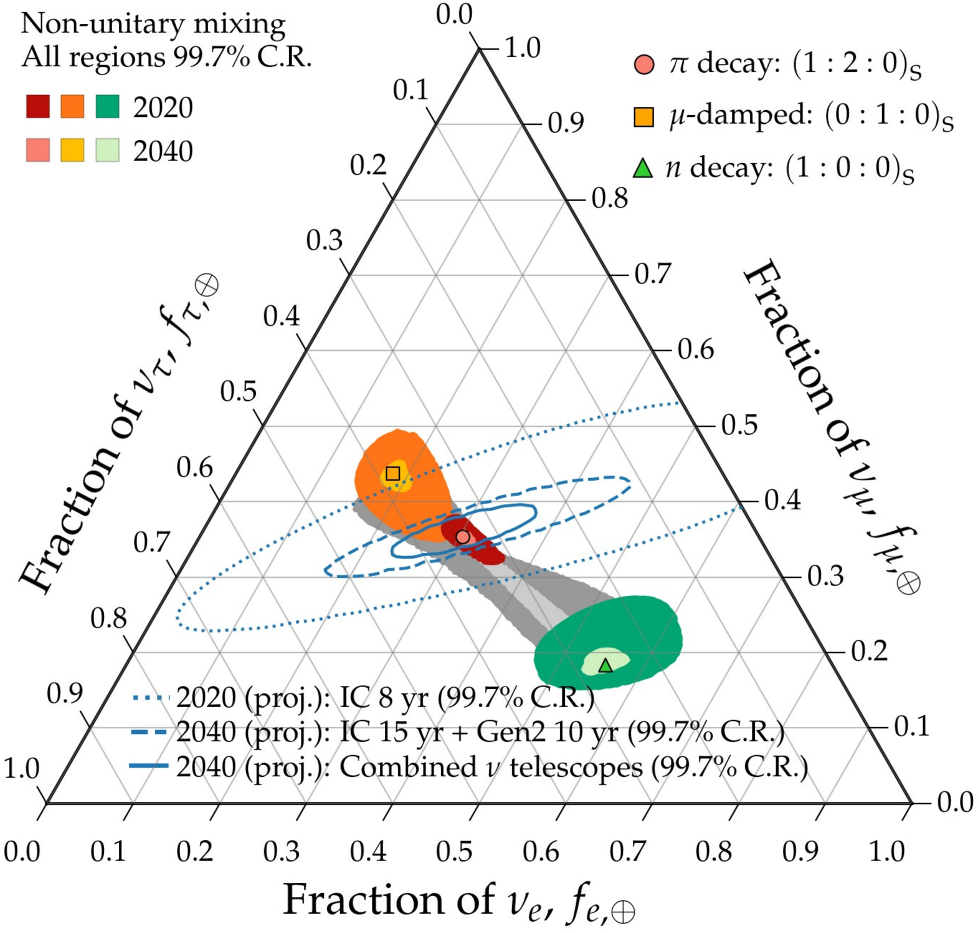

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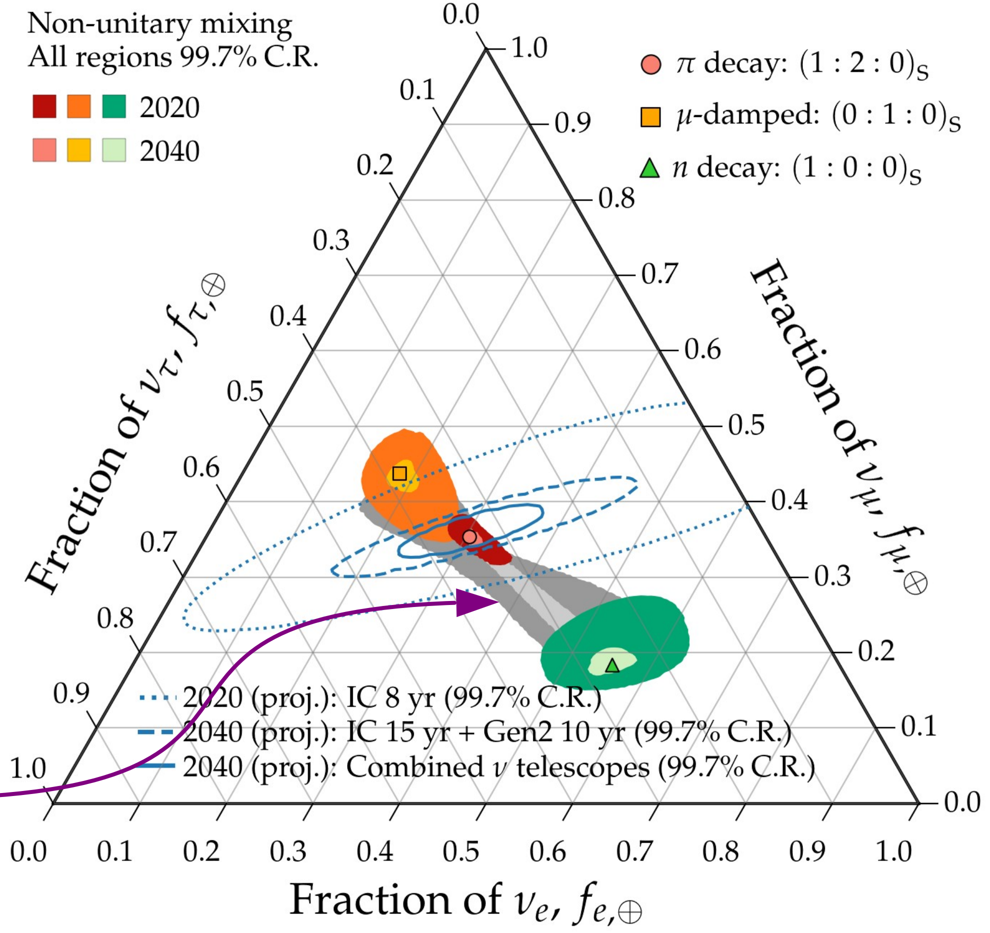

The allowed flavor regions are bigger, but *not much bigger*!

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

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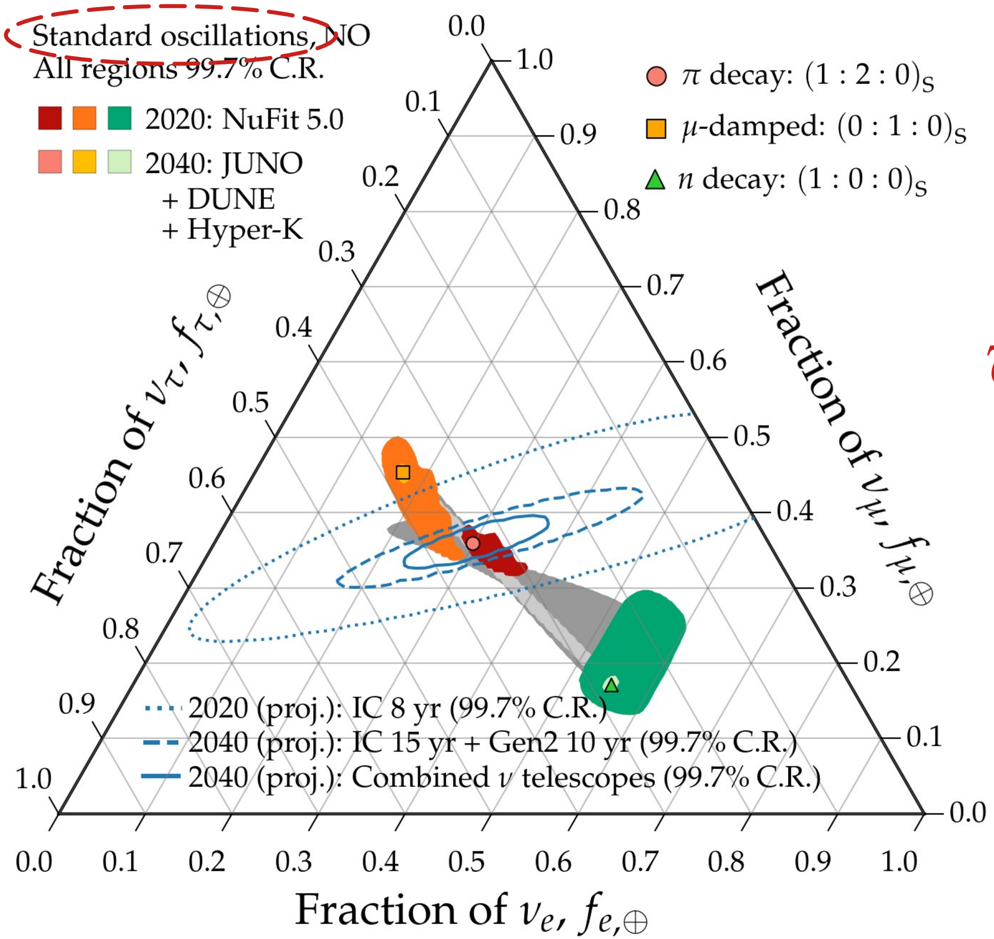
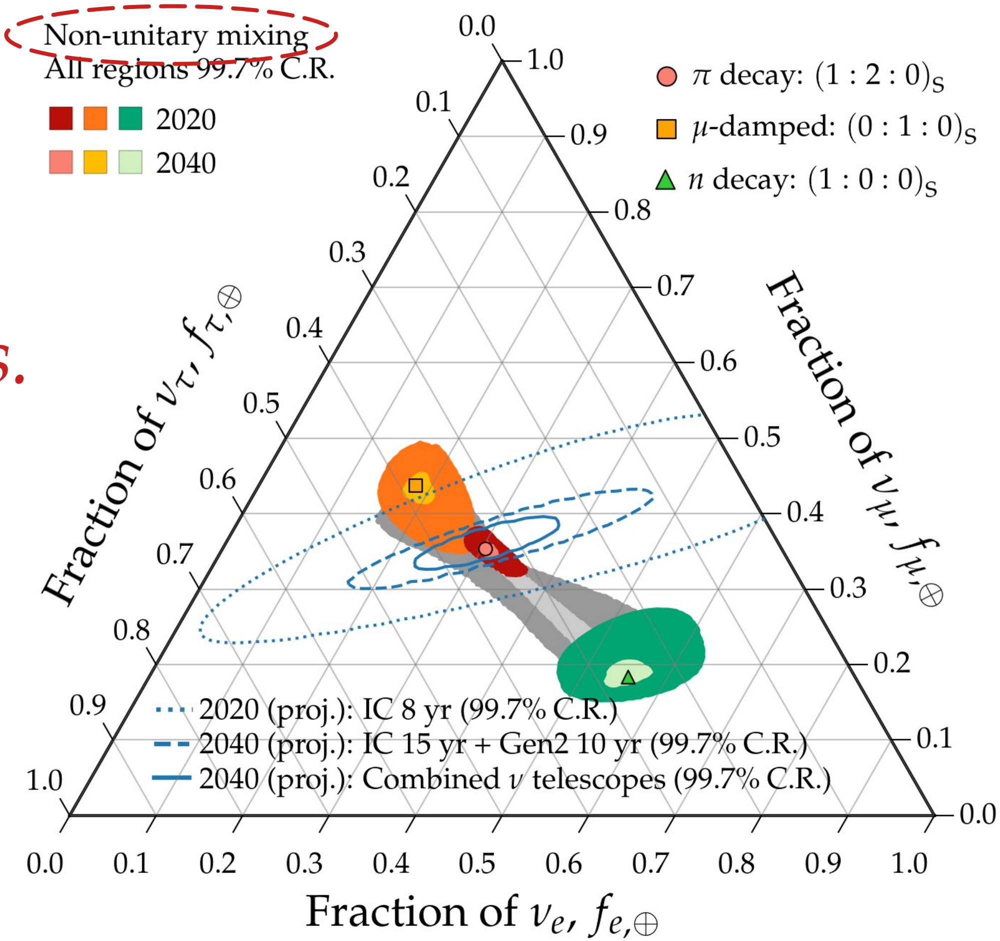


vs.



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

More than one production mechanism?

Can we detect the contribution of multiple ν production mechanisms?

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

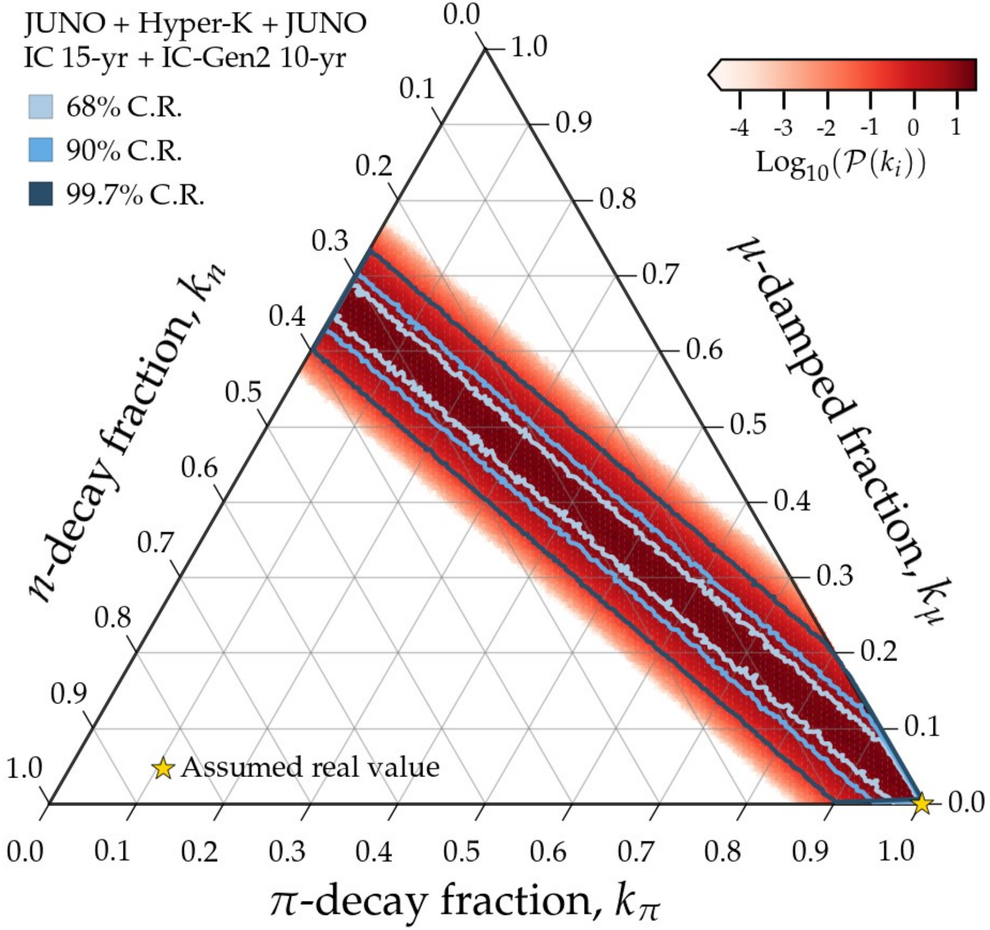
$$\downarrow \text{Propagate to Earth}$$

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

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

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

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



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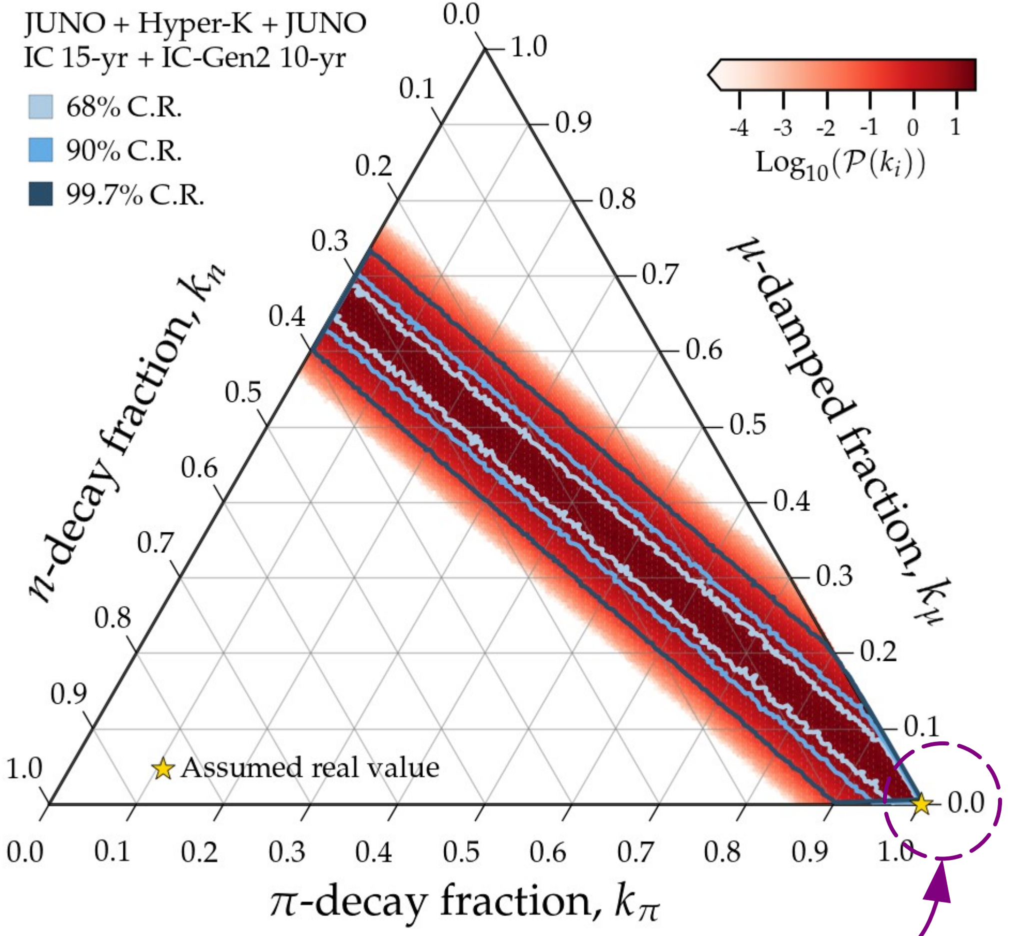

We do recover the real value

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

More than one production mechanism?

Can we detect the contribution of multiple ν production mechanisms?

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Propagate to Earth

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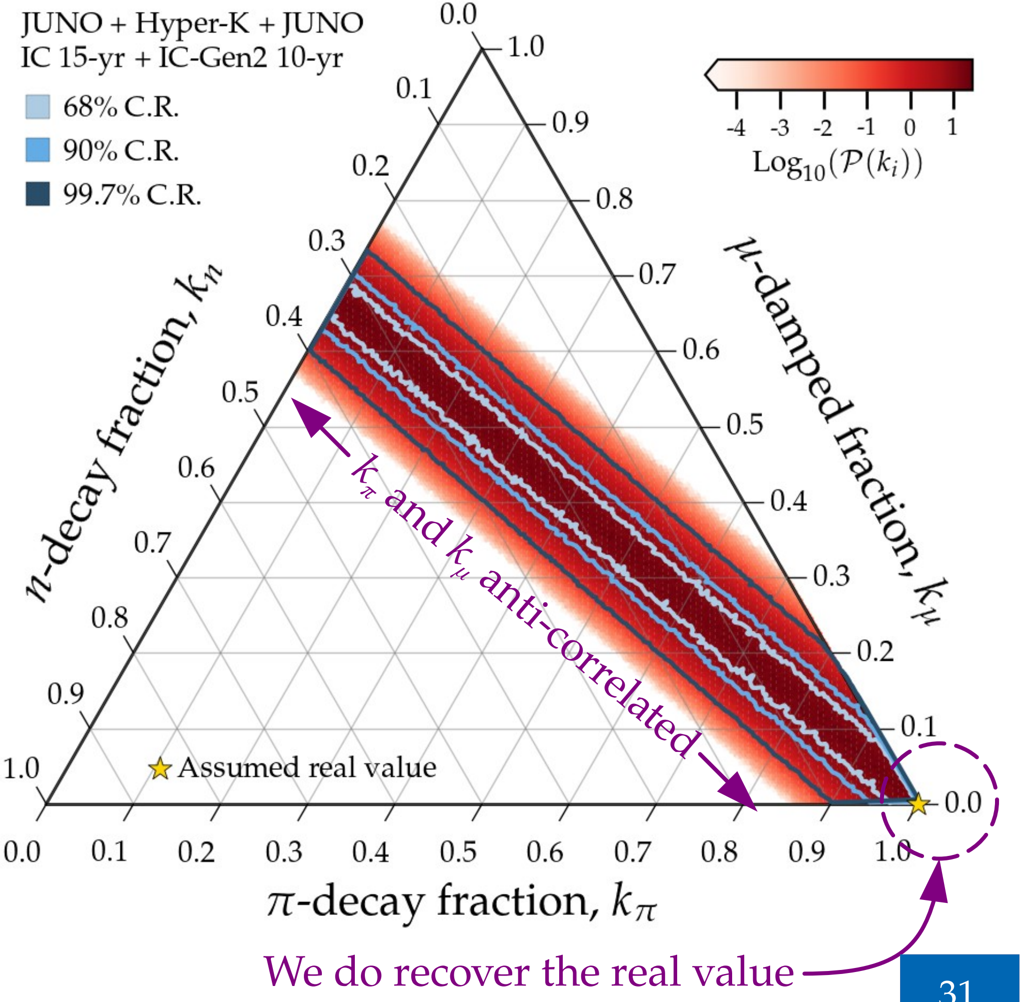

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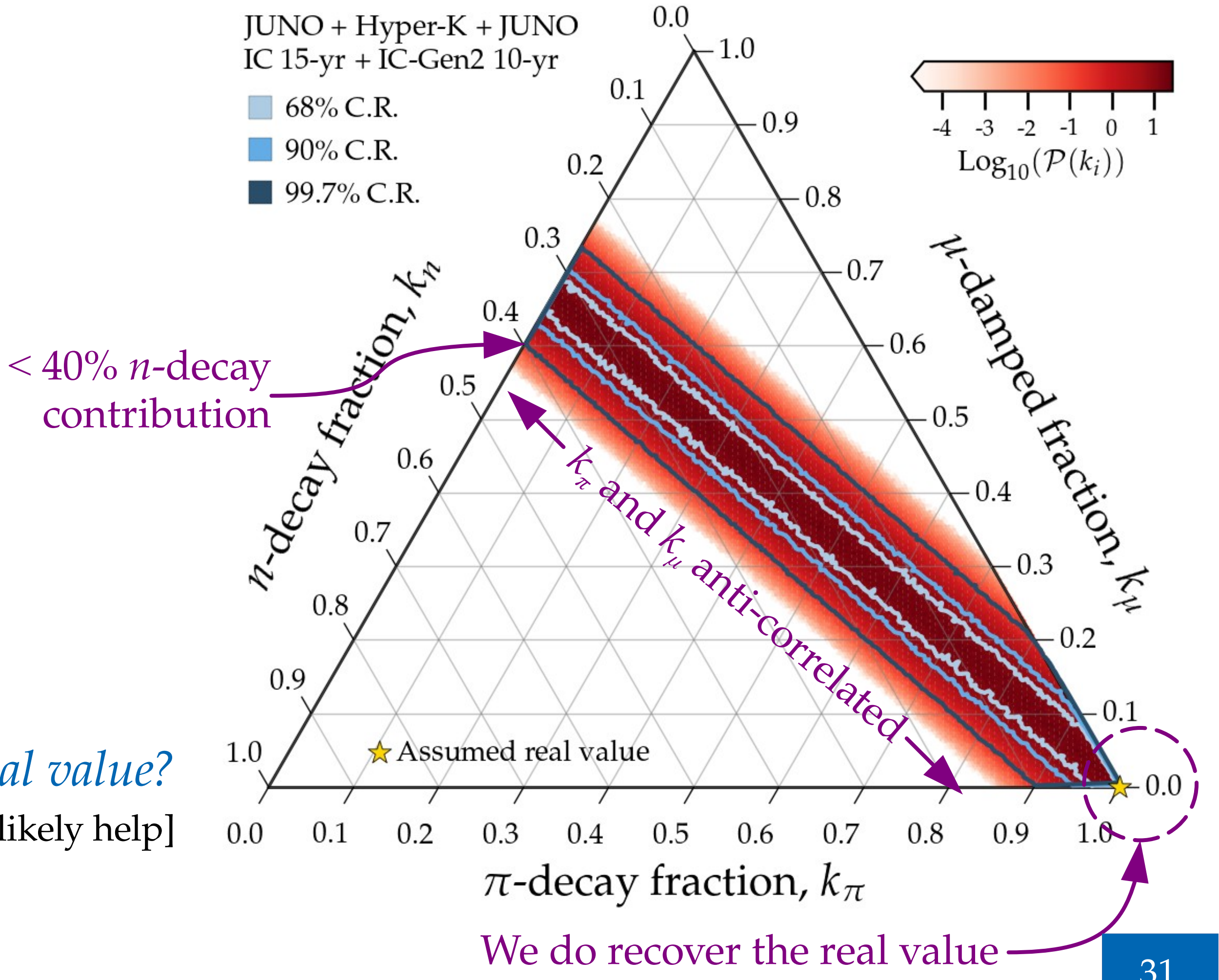

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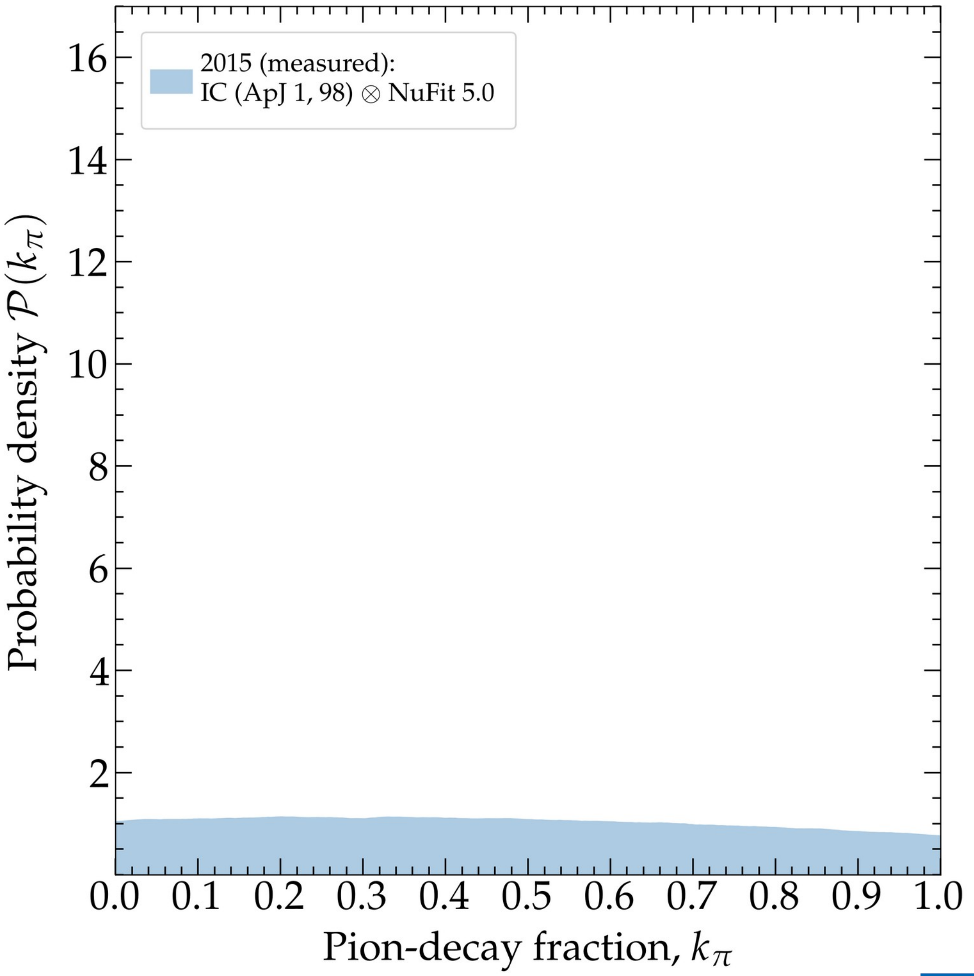

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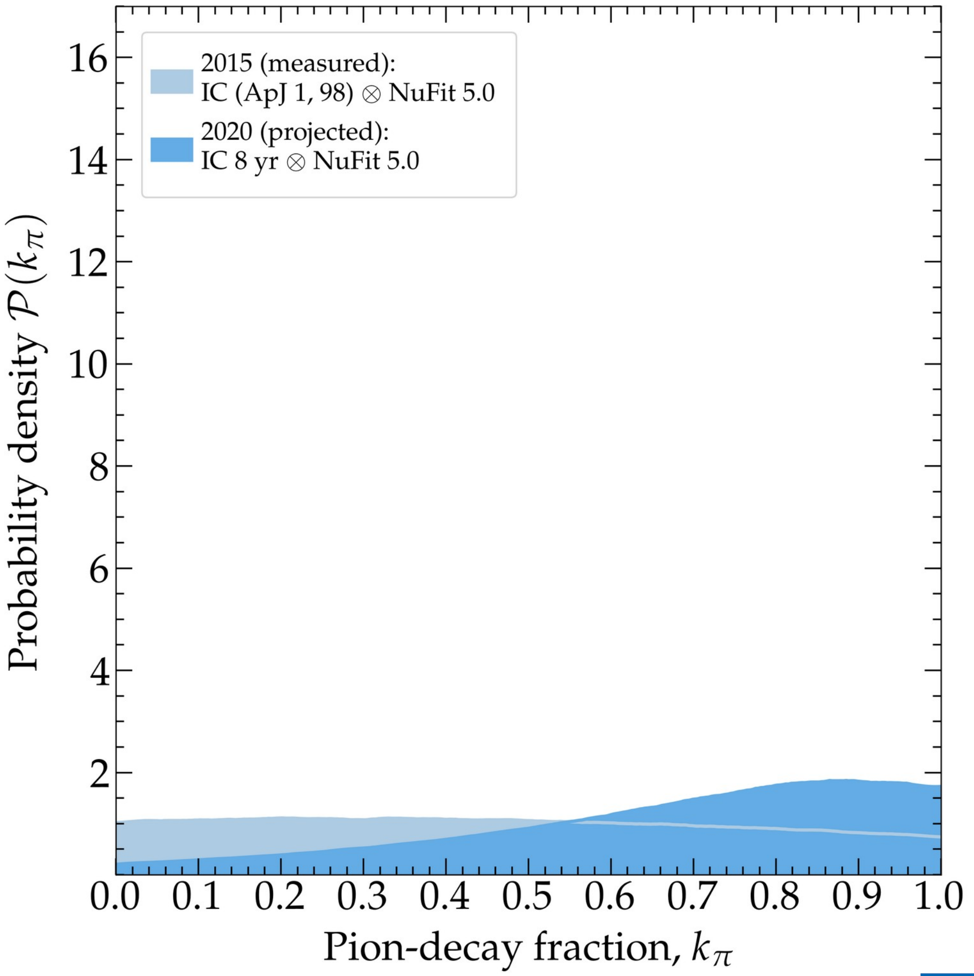

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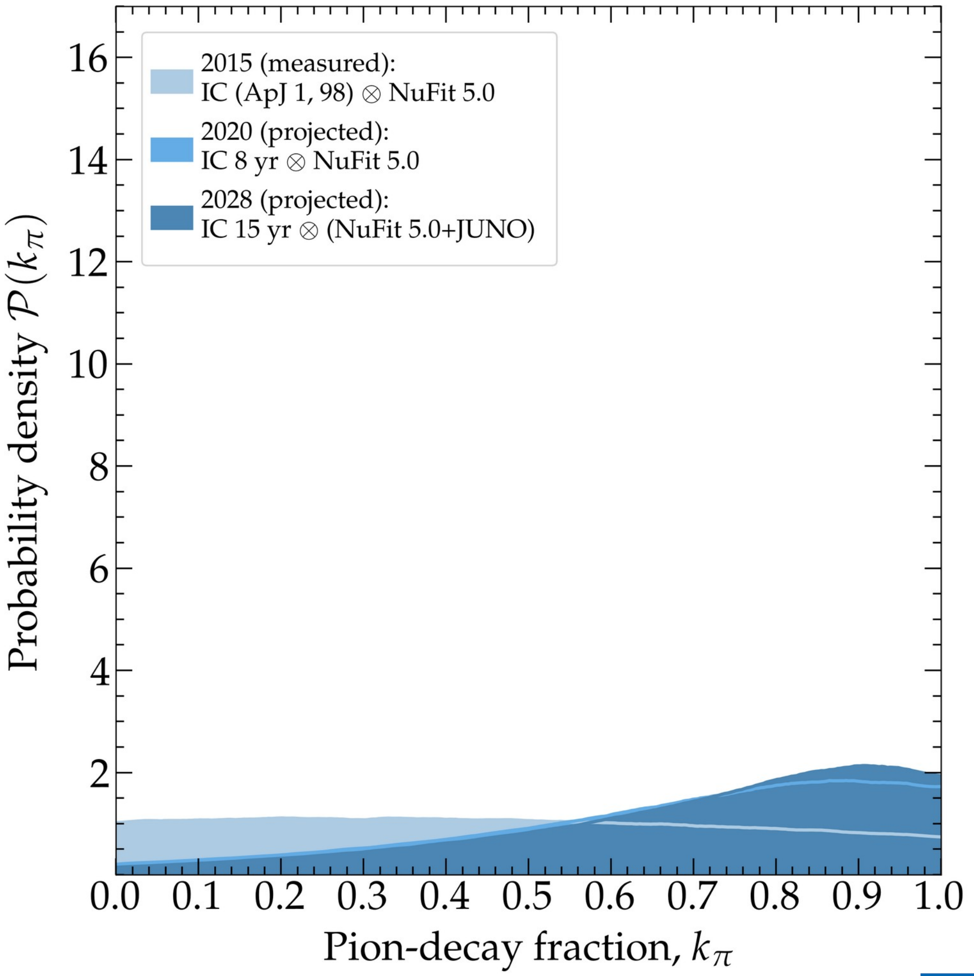

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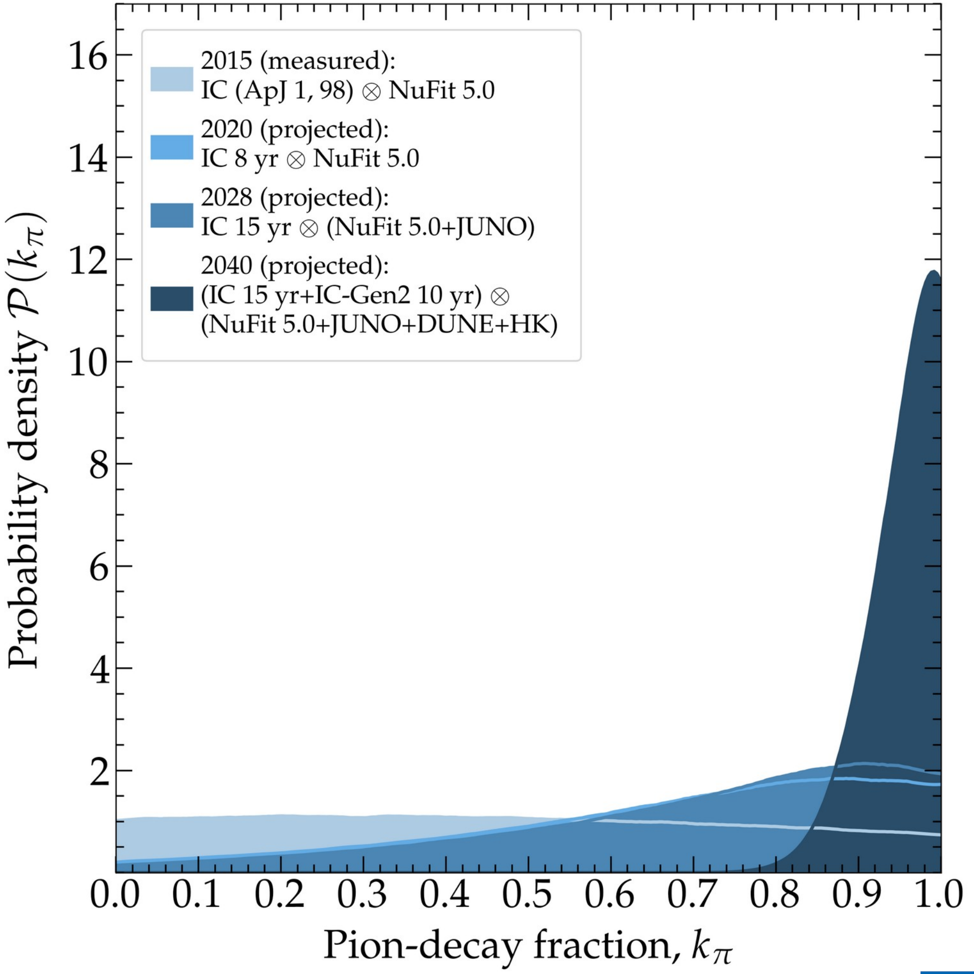

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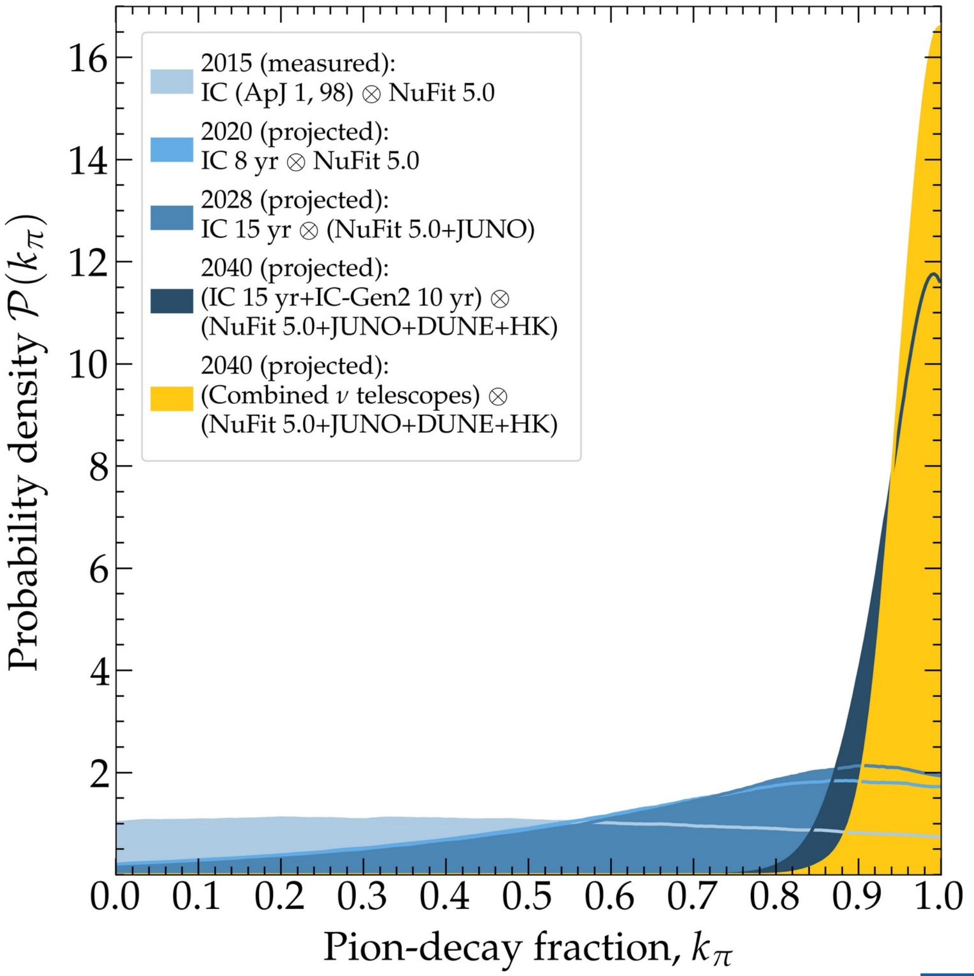

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Using high-energy neutrinos as magnetometers

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

$$p + \gamma(p) \to \pi^+ \to \mu^+ + \nu_\mu$$

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

MB, Tamborra, *PRD* 2020
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Proton cooling

Induce a high-energy cut-off
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$$E_\nu'^2 \frac{dN_\nu}{dE_\nu'} \propto E_\nu'^{2-\alpha_\nu} e^{-E_\nu'/E_\nu'^{\max}}$$

$$E_\nu^{\max} \approx \frac{10^{10}\Gamma\ \mathrm{GeV}}{\sqrt{B'/\mathrm{G}}}$$

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Muon cooling

Change flavor composition:

$$(f_{e,\text{S}}, f_{\mu,\text{S}}, f_{\tau,\text{S}}) = \begin{cases} (\frac{1}{3}, \frac{2}{3}, 0), & \text{if } E_\nu < E_{\nu,\mu}^{\text{sync}} \\ (0, 1, 0), & \text{if } E_\nu \geq E_{\nu,\mu}^{\text{sync}} \end{cases}$$

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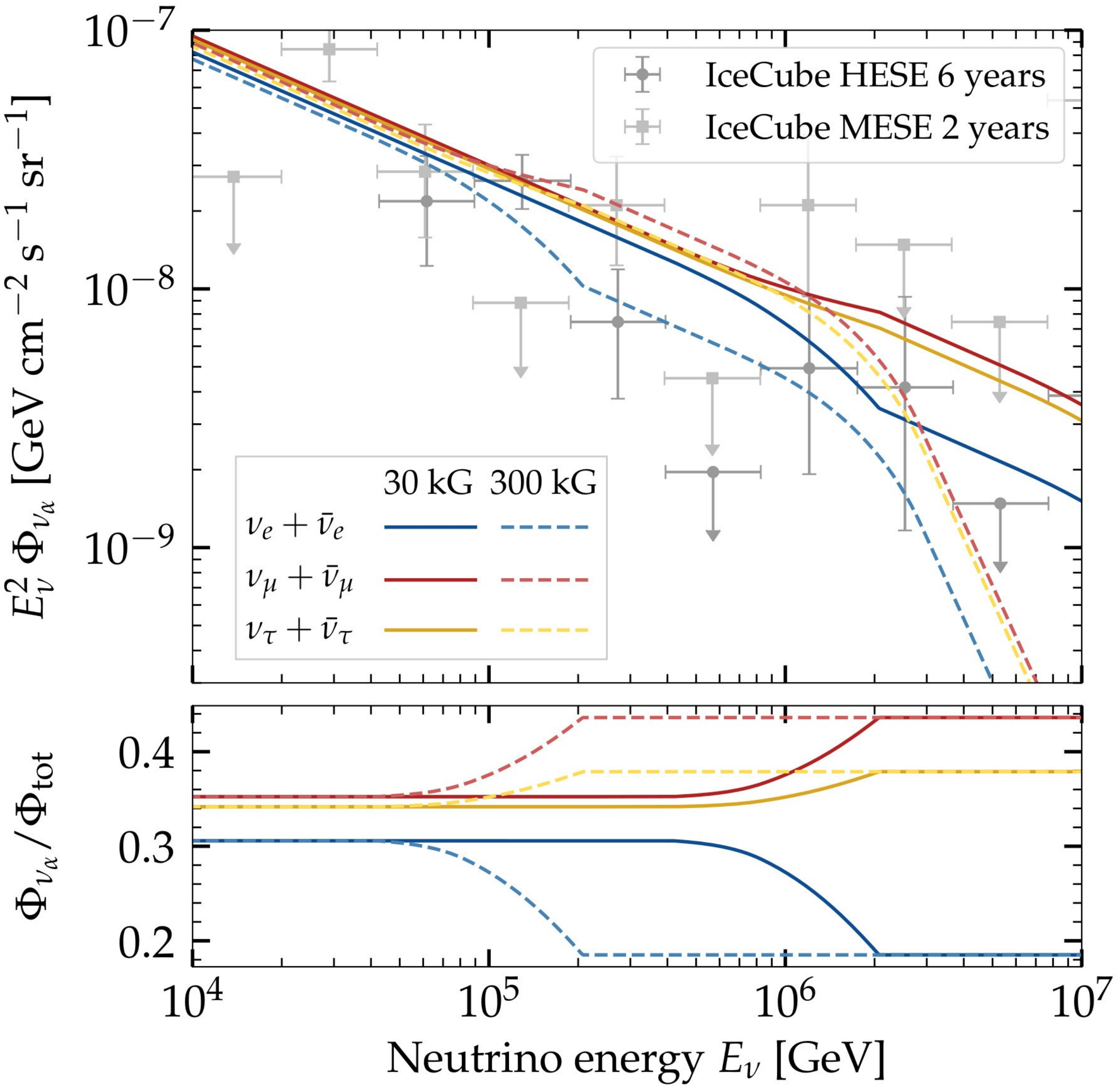
Pion cooling

Steepen the ν spectrum: $\alpha_\nu = \begin{cases} \gamma, & \text{if } E_\nu < E_{\nu,\pi}^{\mathrm{sync}} \\ \gamma + 2, & \text{if } E_\nu \geq E_{\nu,\pi}^{\mathrm{sync}} \end{cases}$

$$E_{\nu,\pi}^{\mathrm{sync}} \approx 10^{10} \Gamma \frac{\mathrm{G}}{B'} \ \mathrm{GeV}$$

MB, Tamborra, *PRD* 2020
See also: Winter, *PRD* 2013



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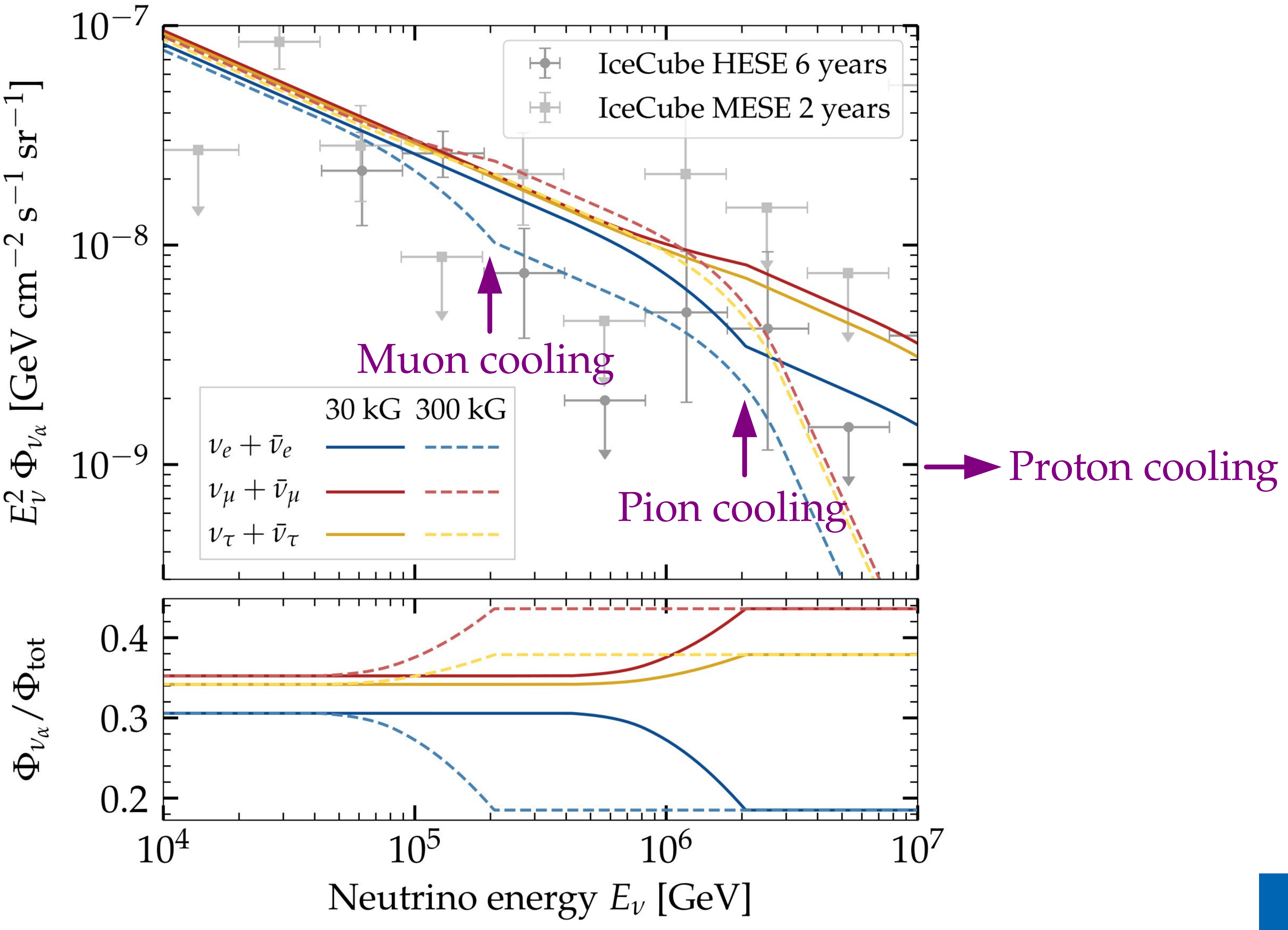
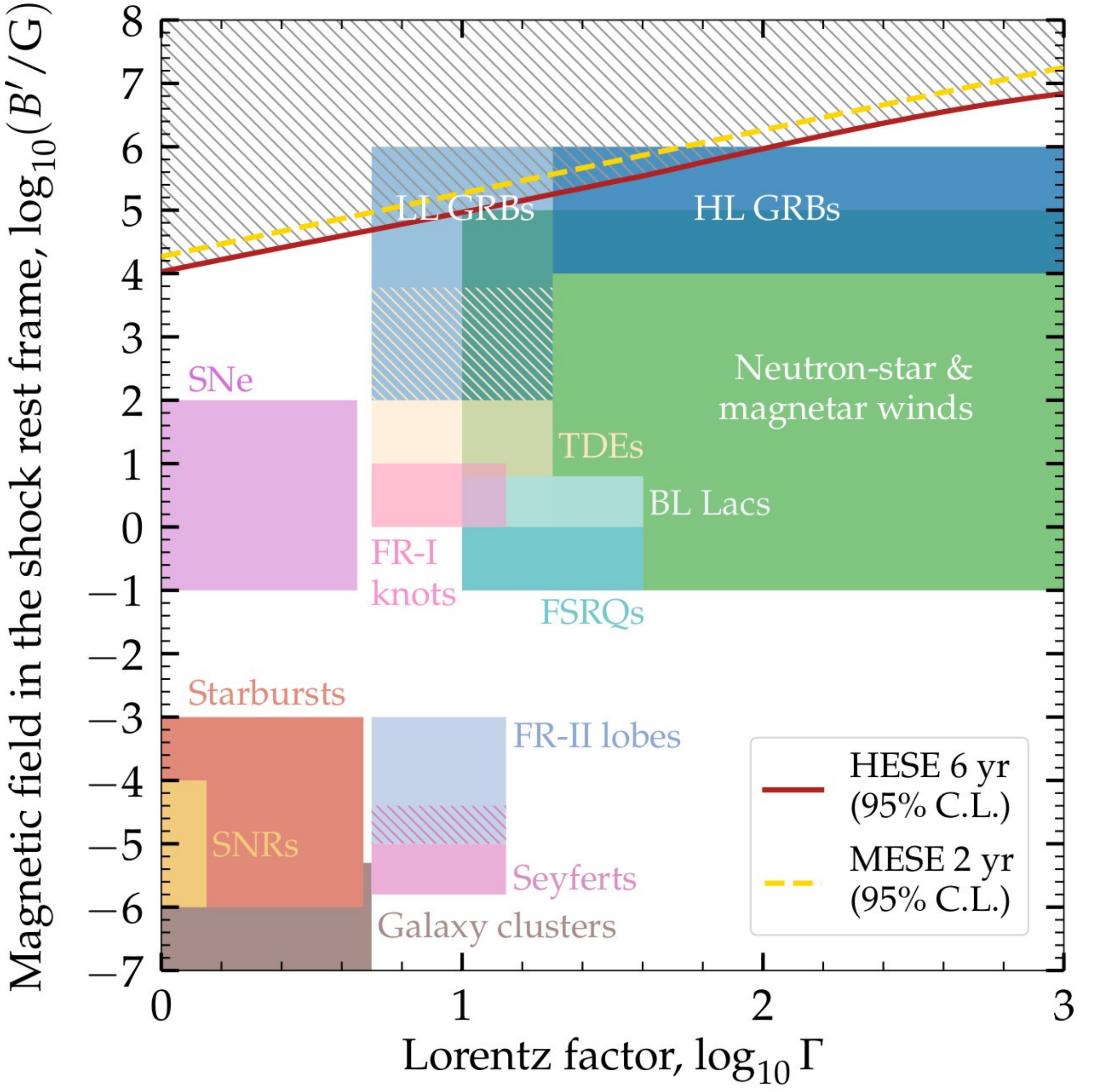


MB, Tamborra, *PRD* 2020
See also: Winter, *PRD* 2013

ν sources with strong B' are likely not dominant

Average B' must be < 10kG–10 MG



MB, Tamborra, *PRD* 2020
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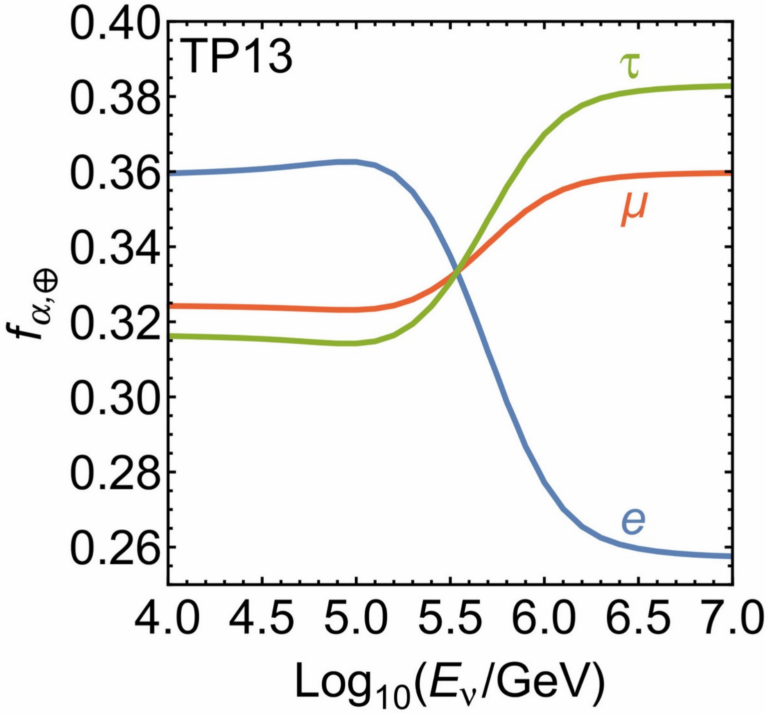
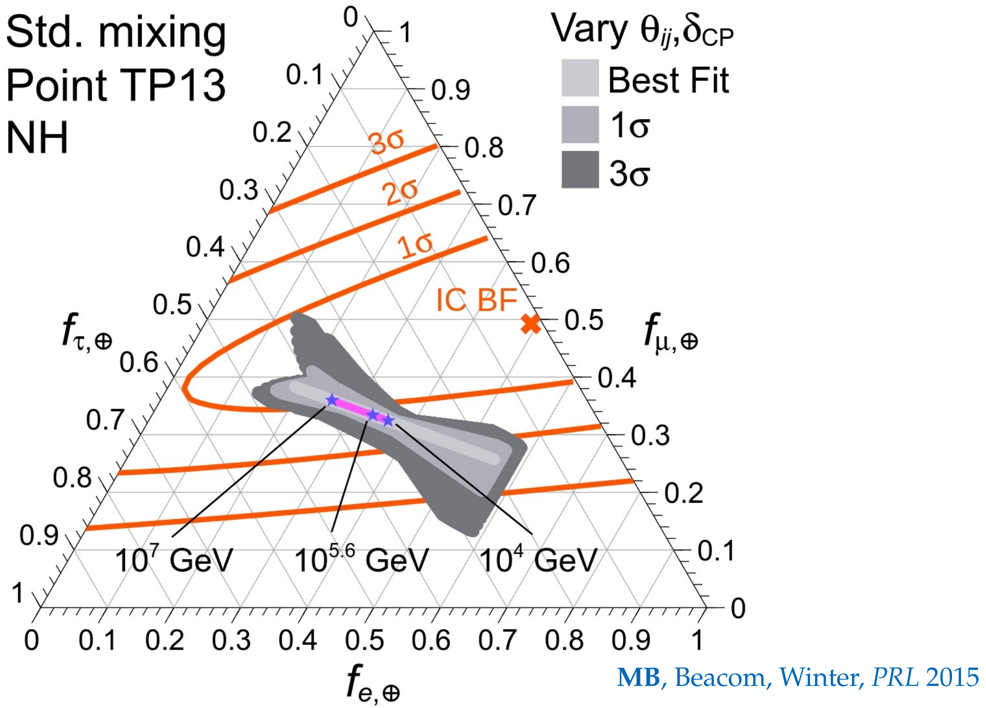
Energy dependence of the flavor composition?

Different neutrino production channels accessible at different energies –



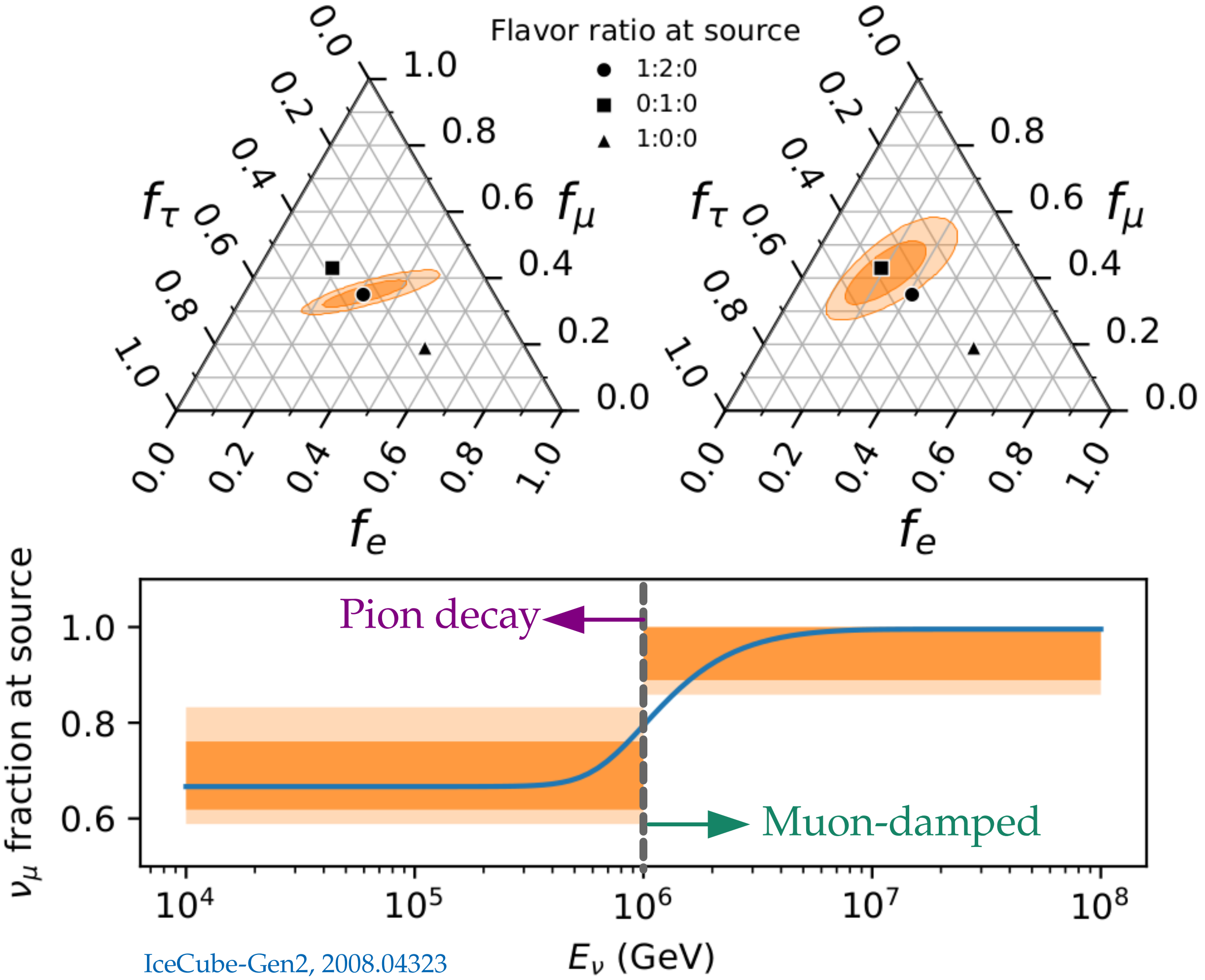


MB, Beacom, Winter, *PRL* 2015

- TP13: $p\gamma$ model, target photons from e^-e^+ annihilation [Hümmer+, *Astropart. Phys.* 2010]
- Will be difficult to resolve [Kashti, Waxman, *PRL* 2005; Lipari, Lusignoli, Meloni, *PRD* 2007]

Energy dependence of flavor ratios – in IceCube-Gen2

Measured:



IceCube-Gen2, 2008.04323

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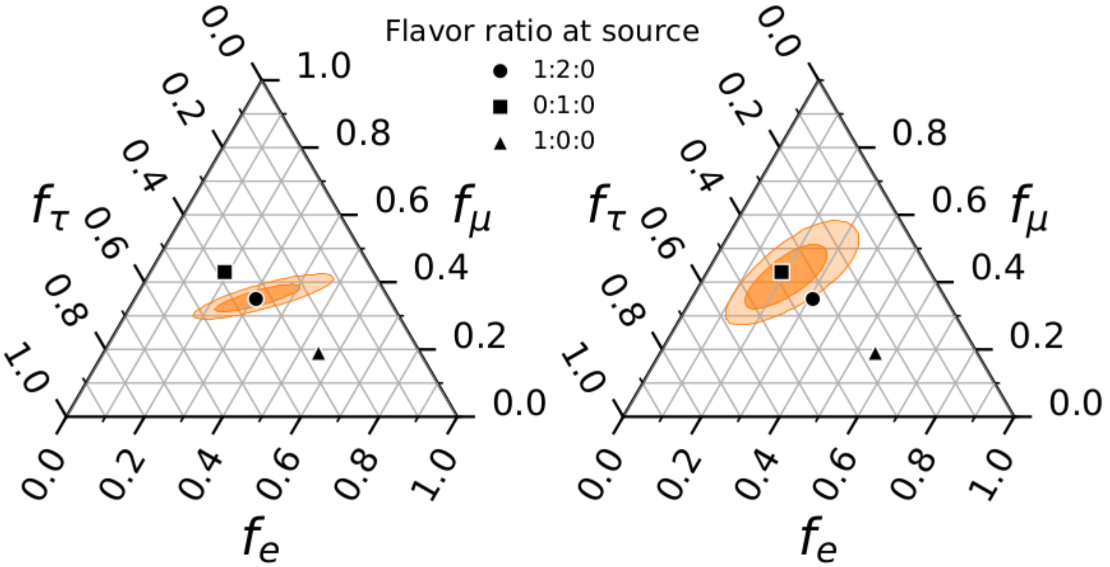

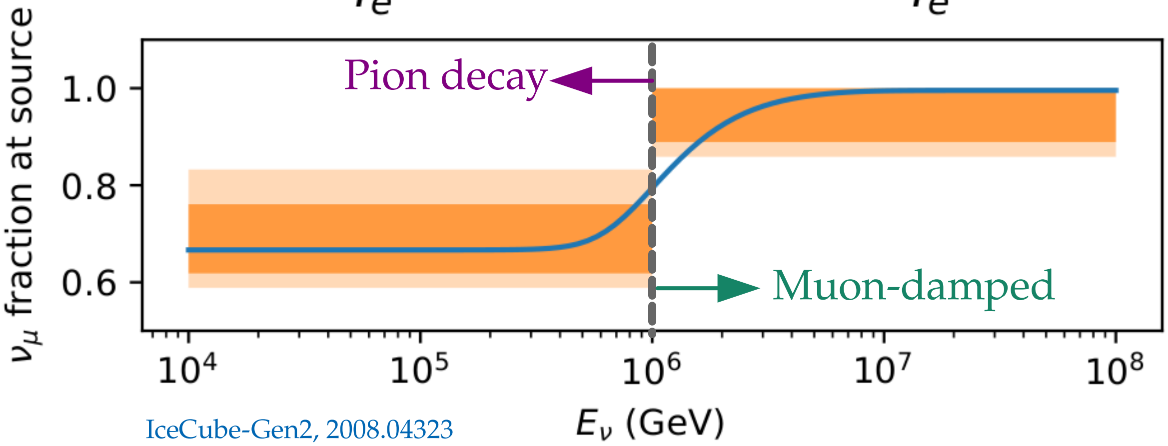

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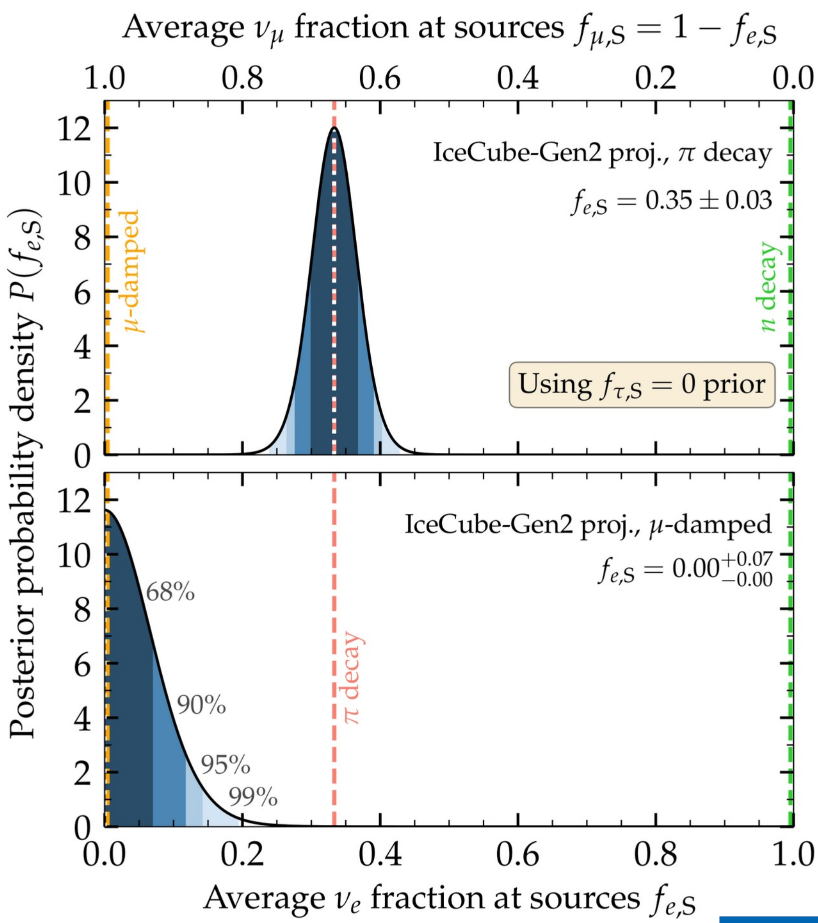

MB & Ahlers, *PRL* 2019

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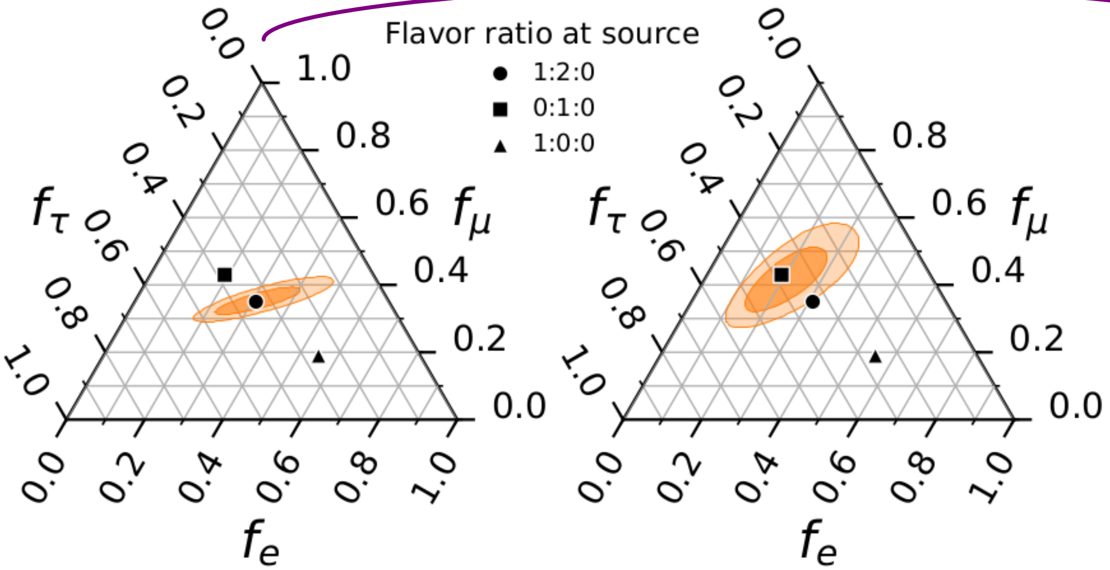

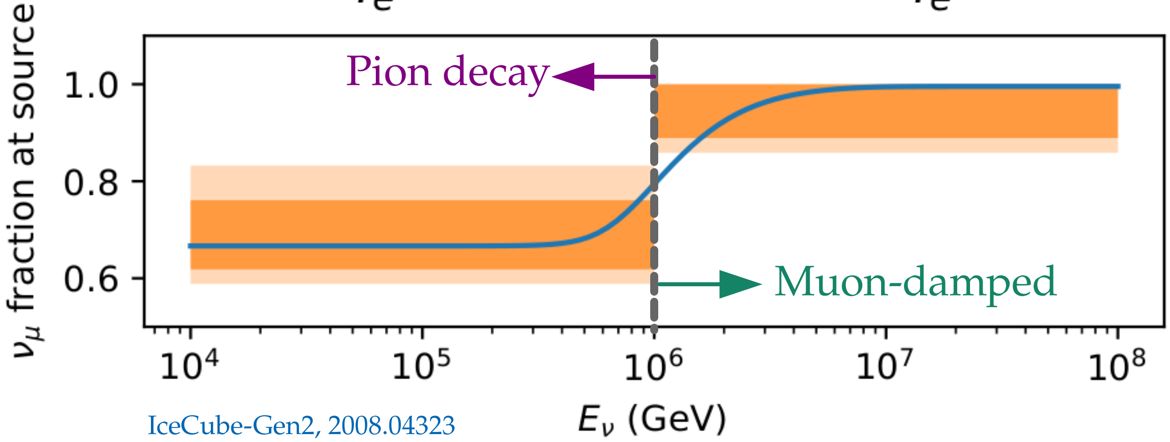

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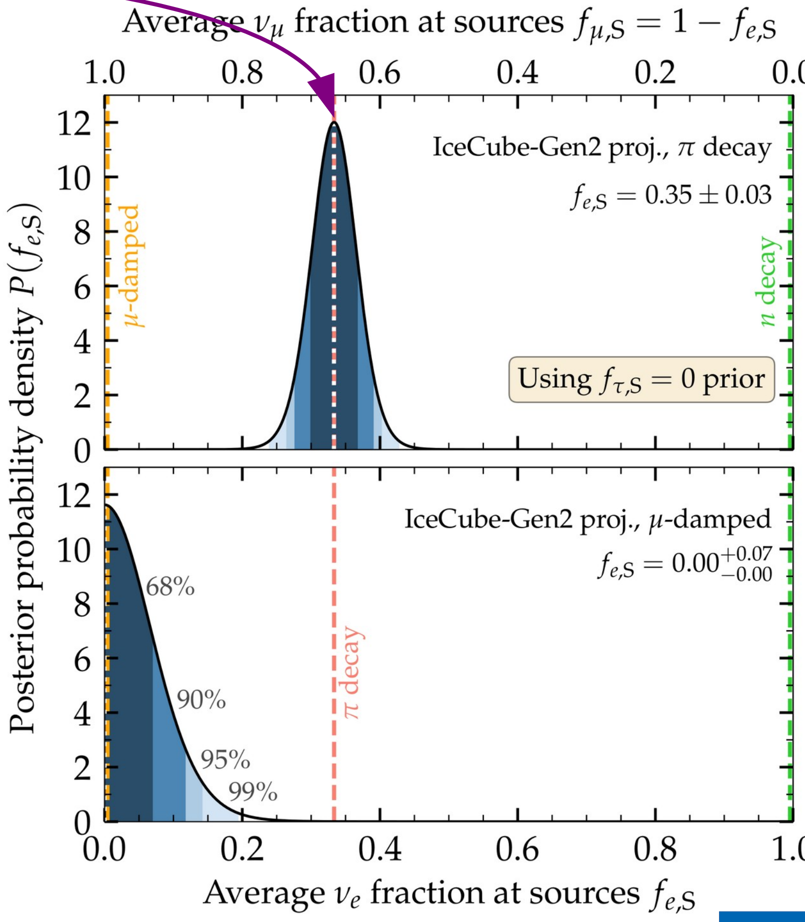

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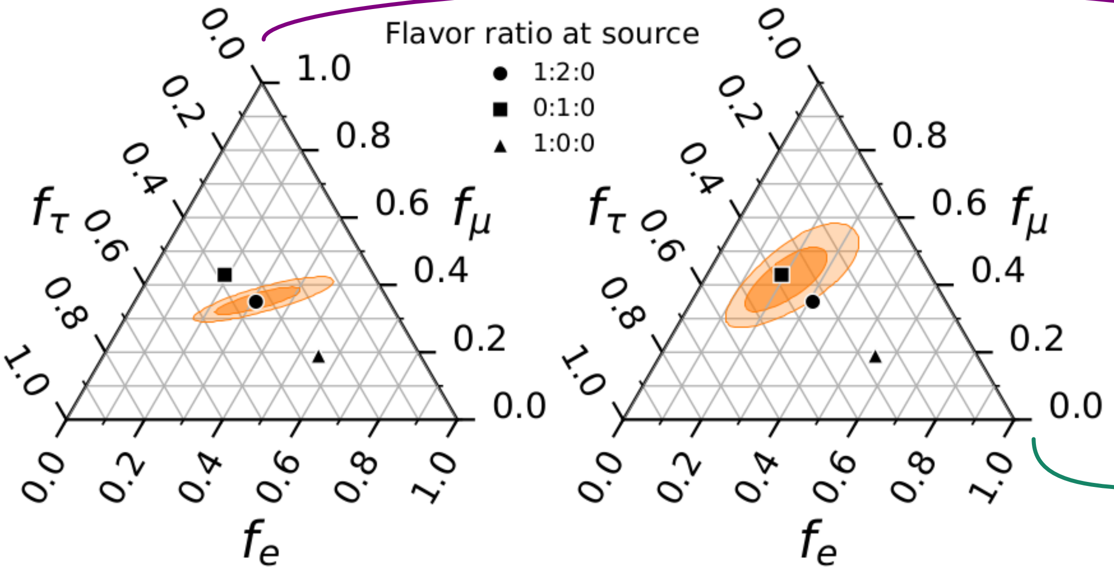

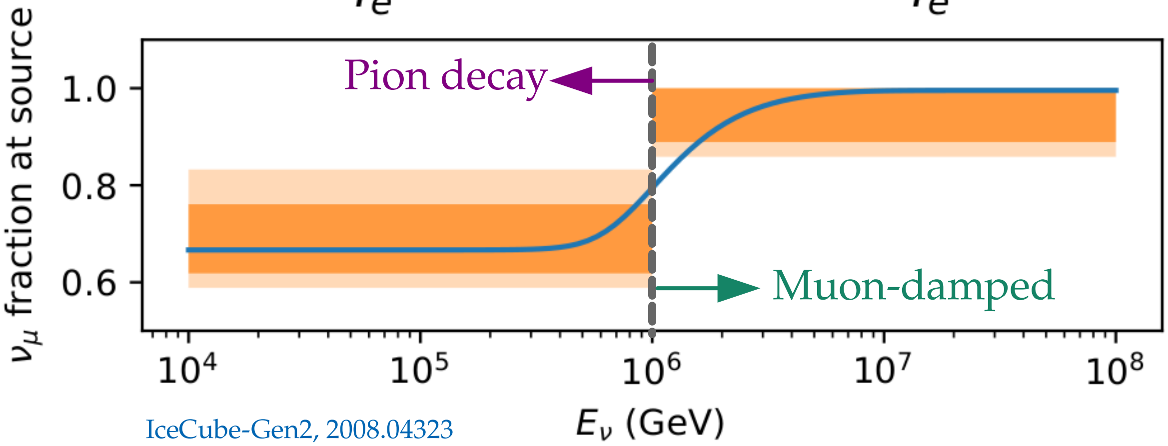

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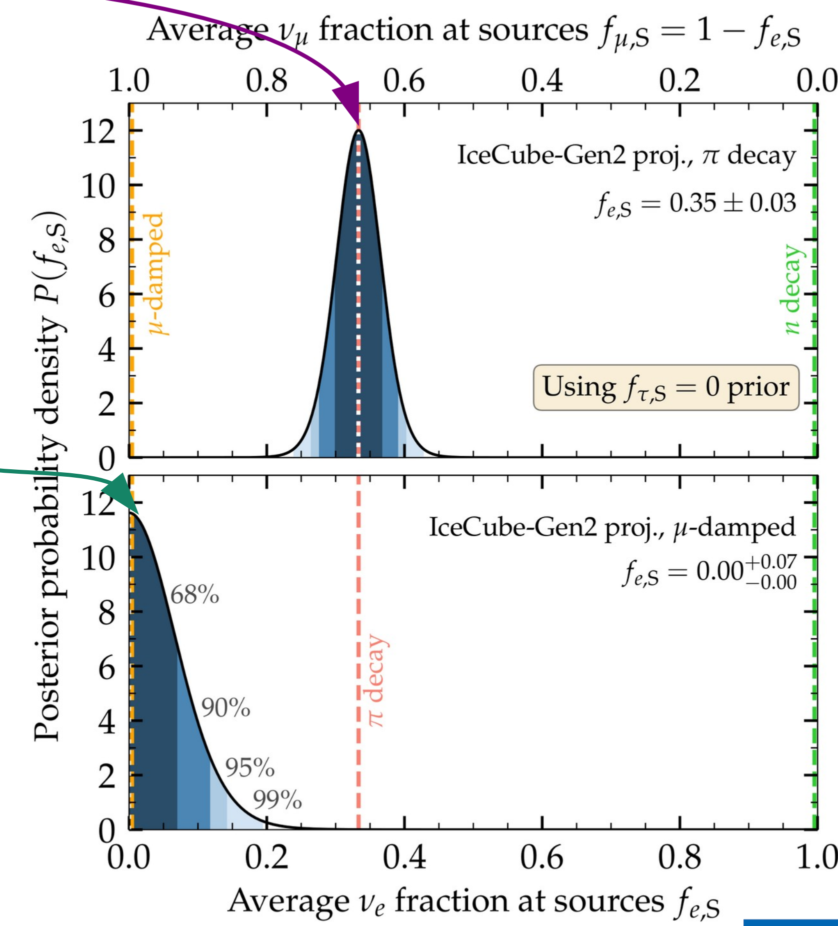

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Flavor composition – a few source choices

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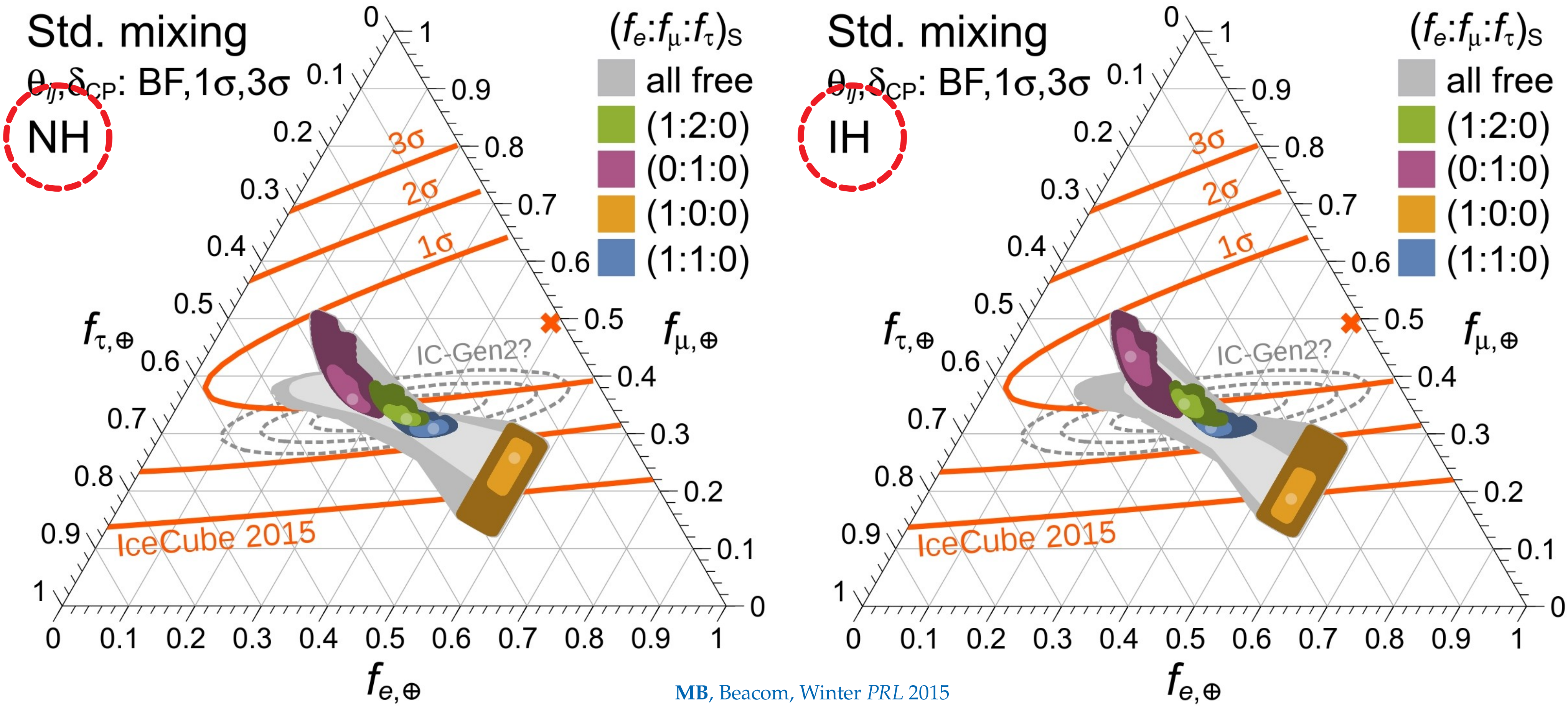
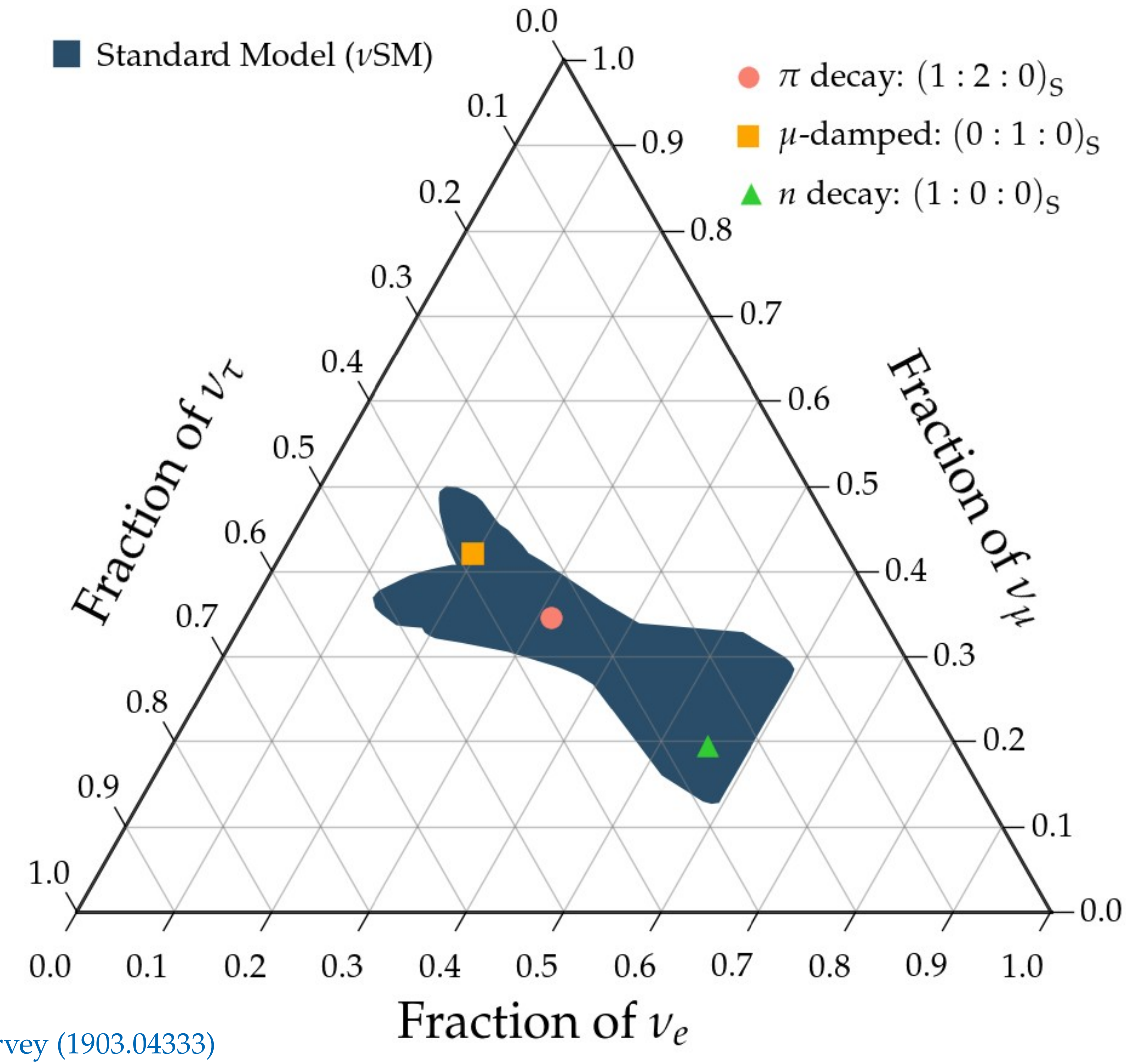
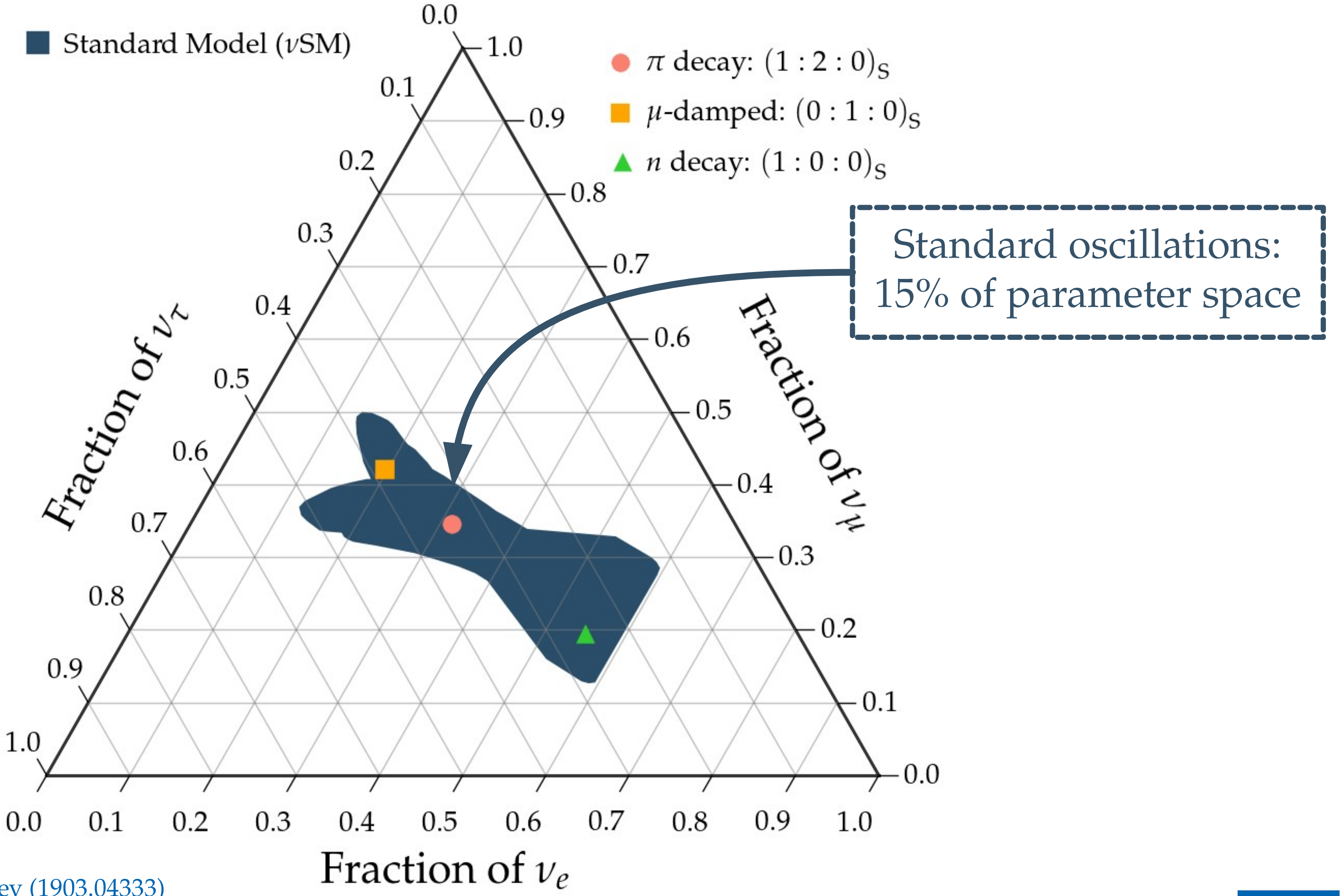


MB, Beacom, Winter *PRL* 2015



Ackermann, **MB**, *et al.*, Astro2020 Survey (1903.04333)
Based on: **MB**, Beacom, Winter *PRL* 2015



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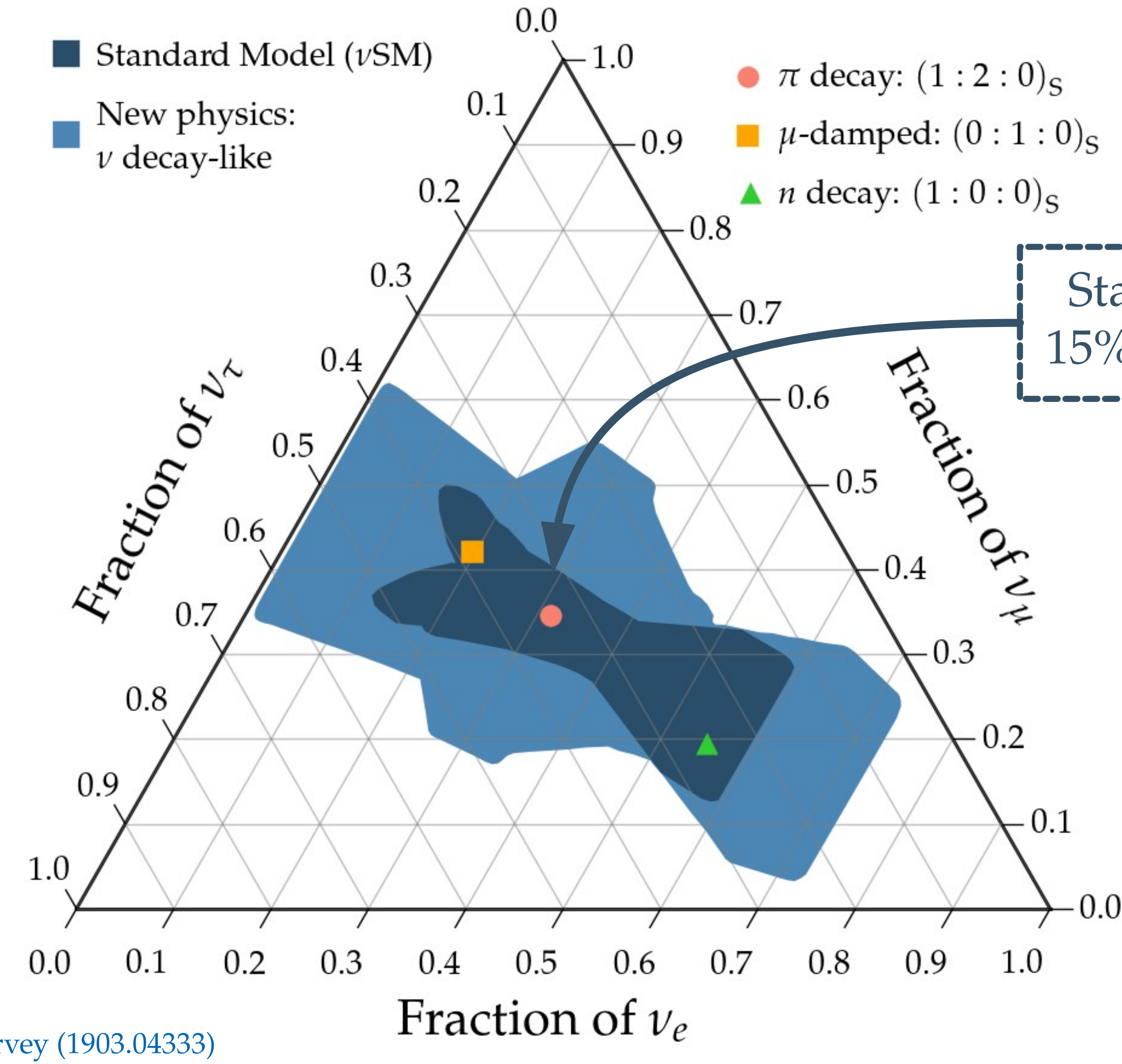

Standard oscillations: 15% of parameter space

Ackermann, **MB**, *et al.*, Astro2020 Survey (1903.04333)
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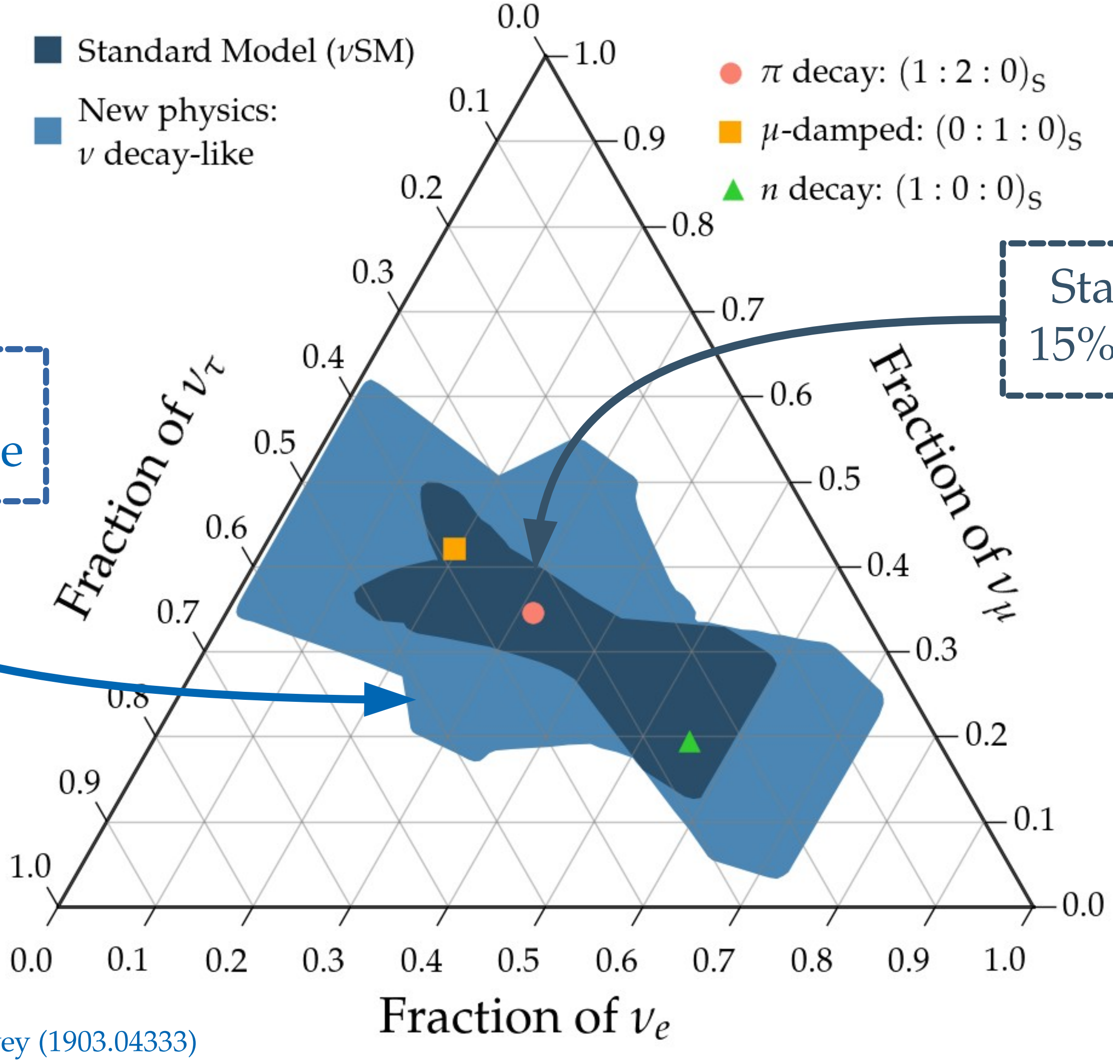
Neutrino decay
30% of parameter space



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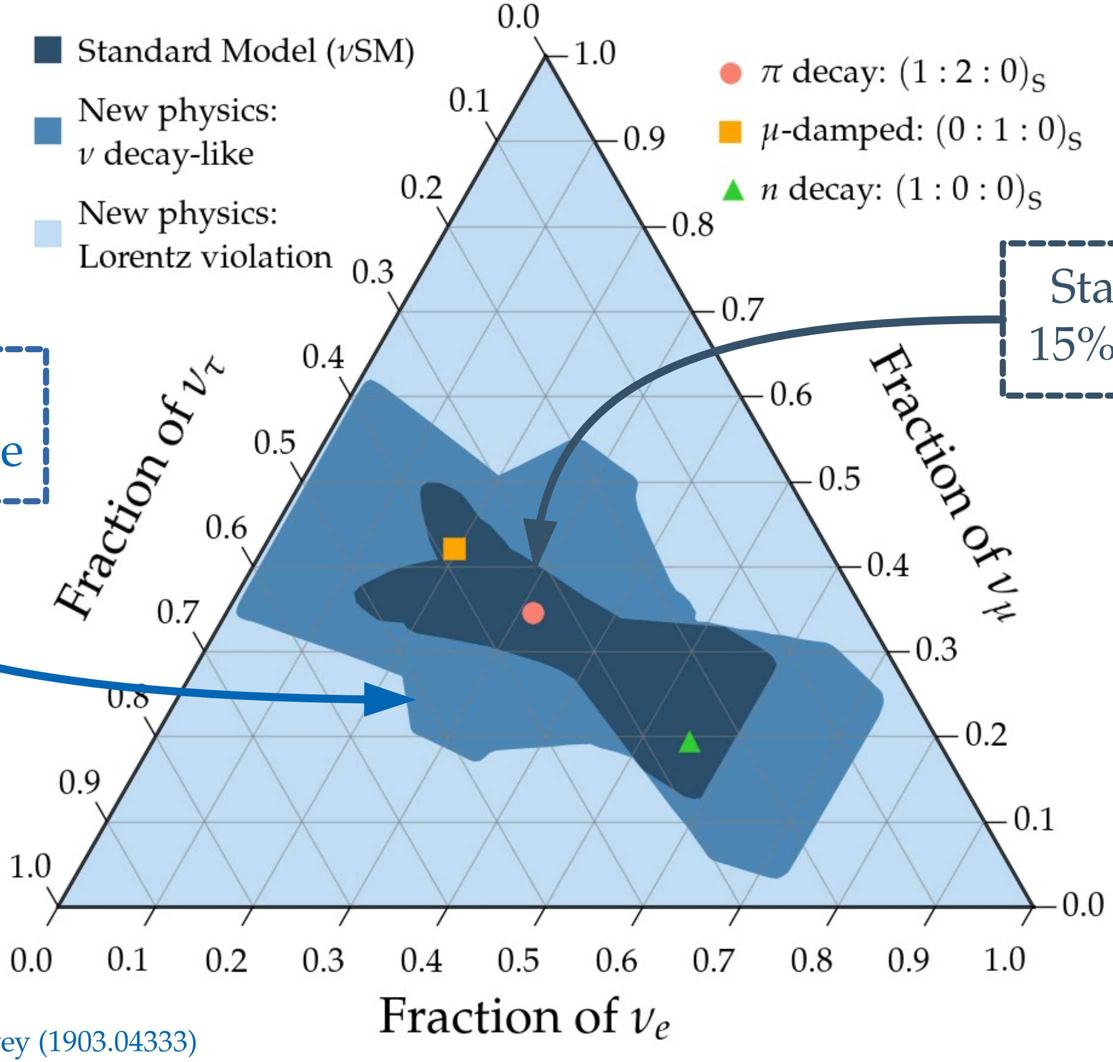

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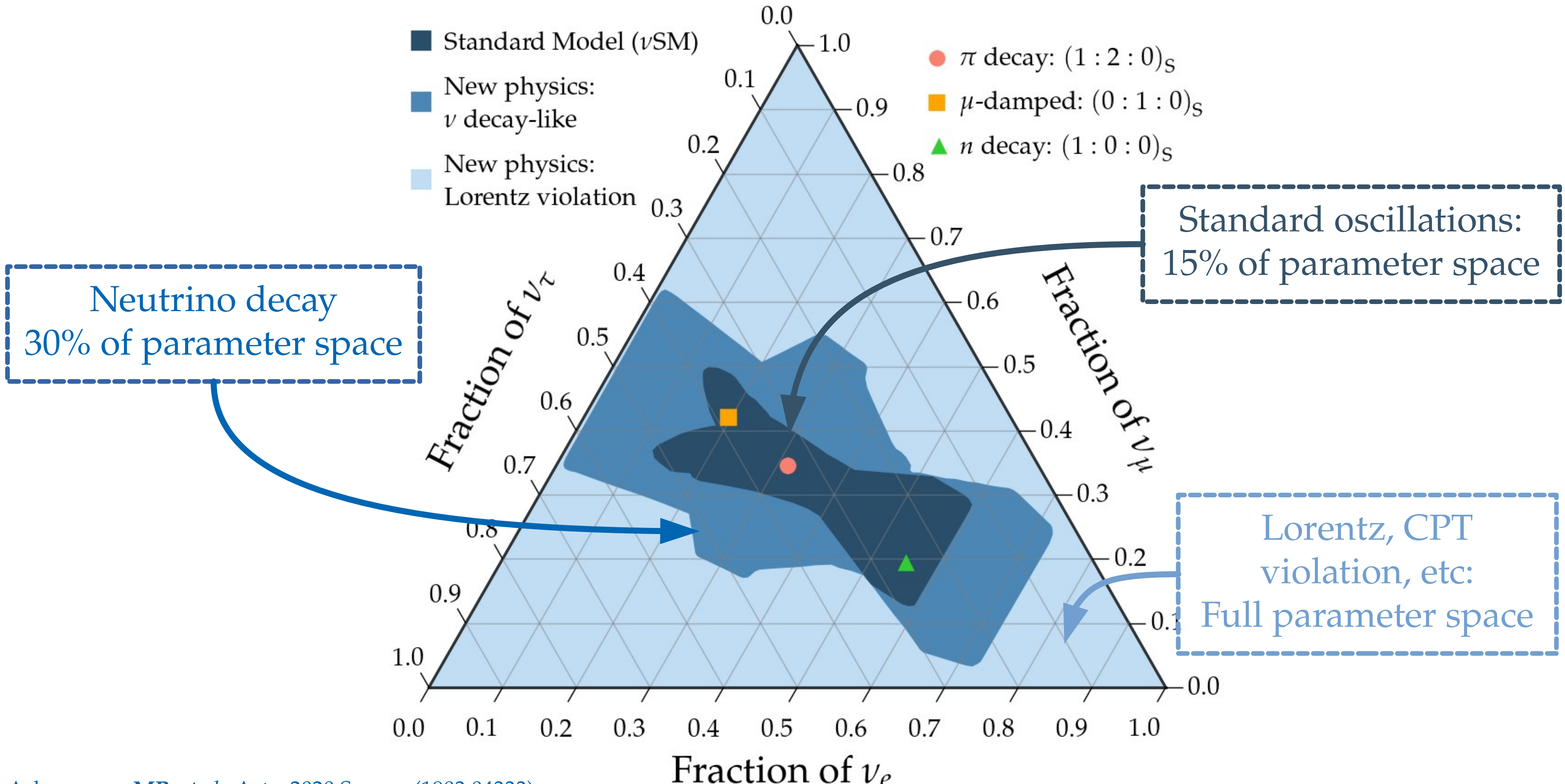

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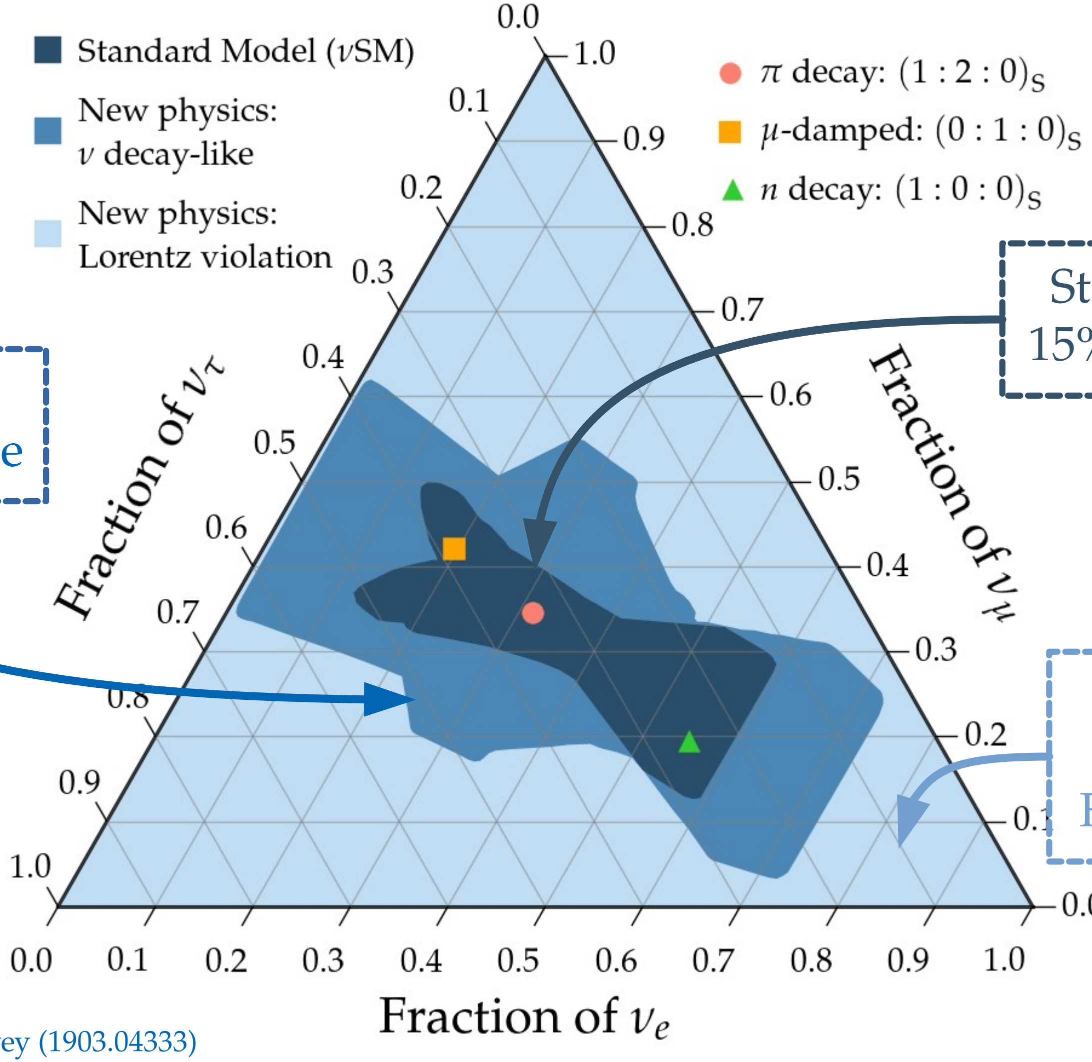

Lorentz, CPT violation, etc:
Full parameter space

Ackermann, **MB**, *et al.*, Astro2020 Survey (1903.04333)
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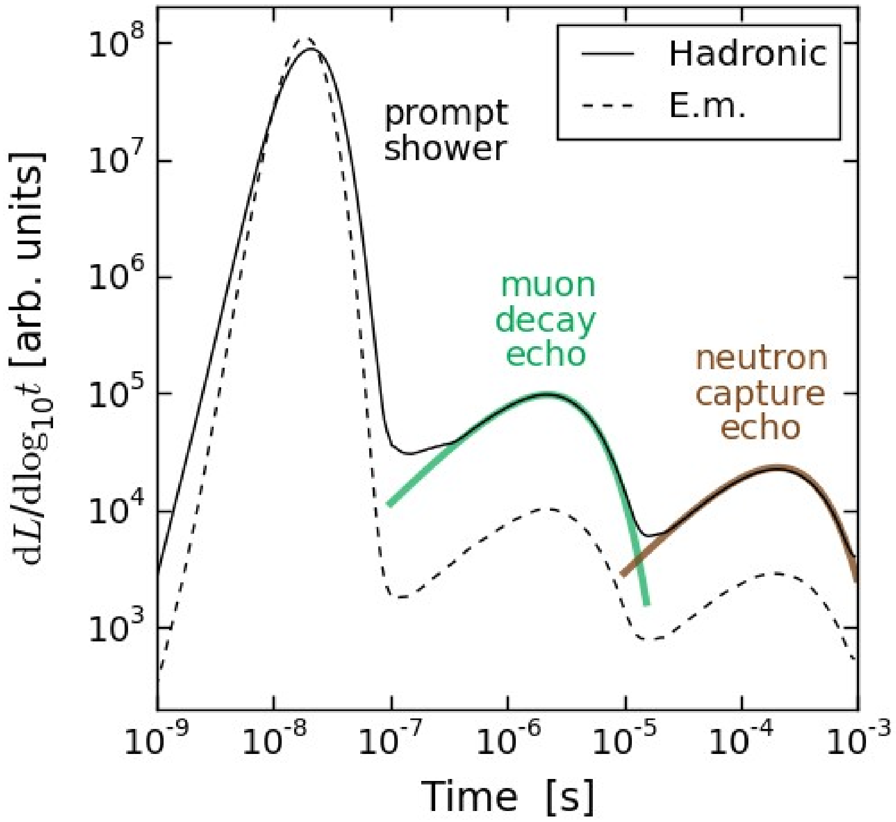
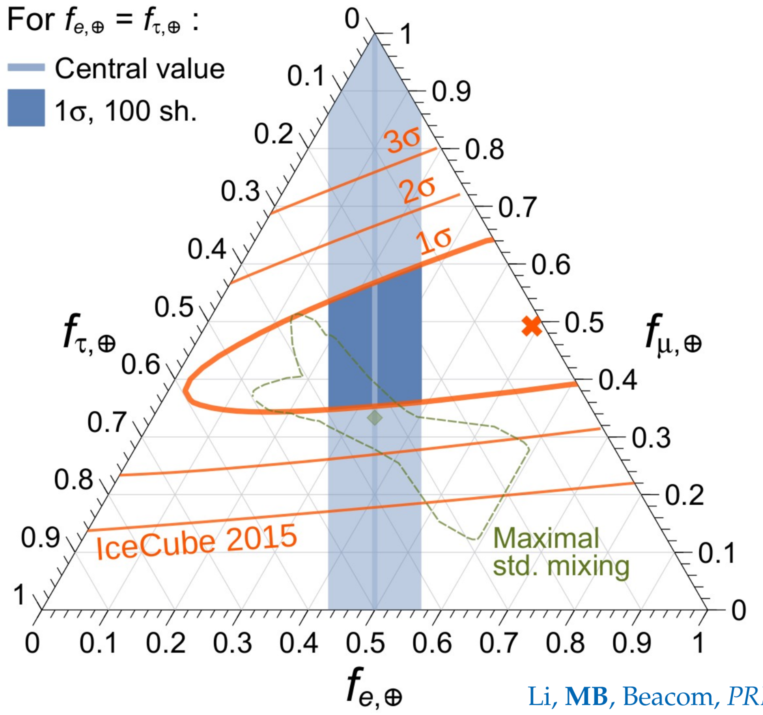
Side note: Improving flavor-tagging using *echoes*

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





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

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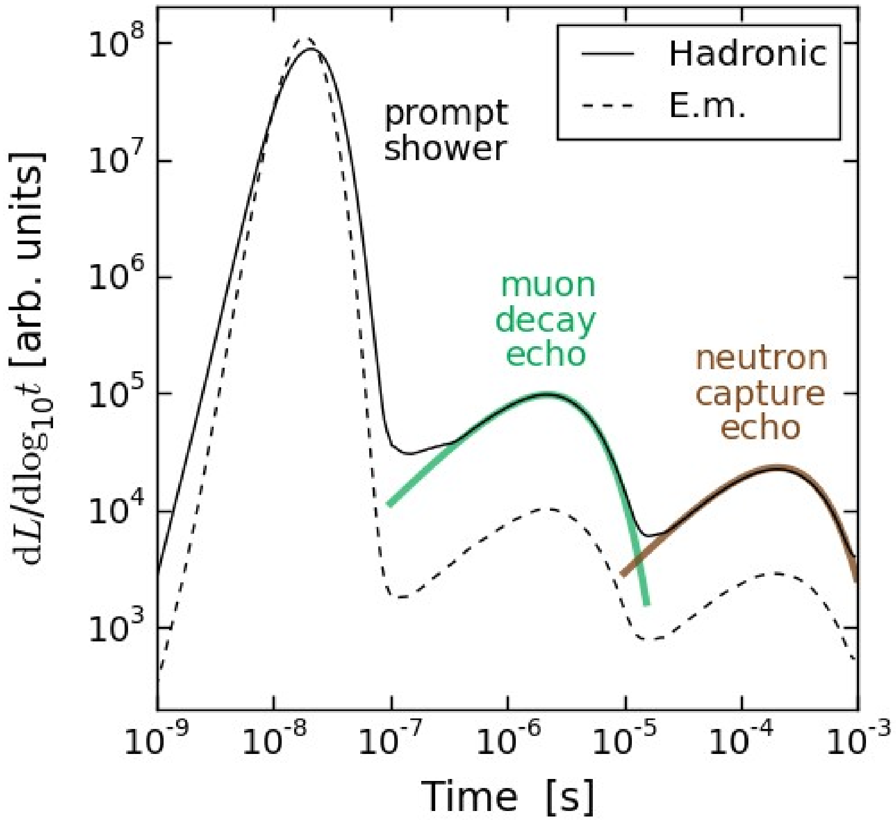
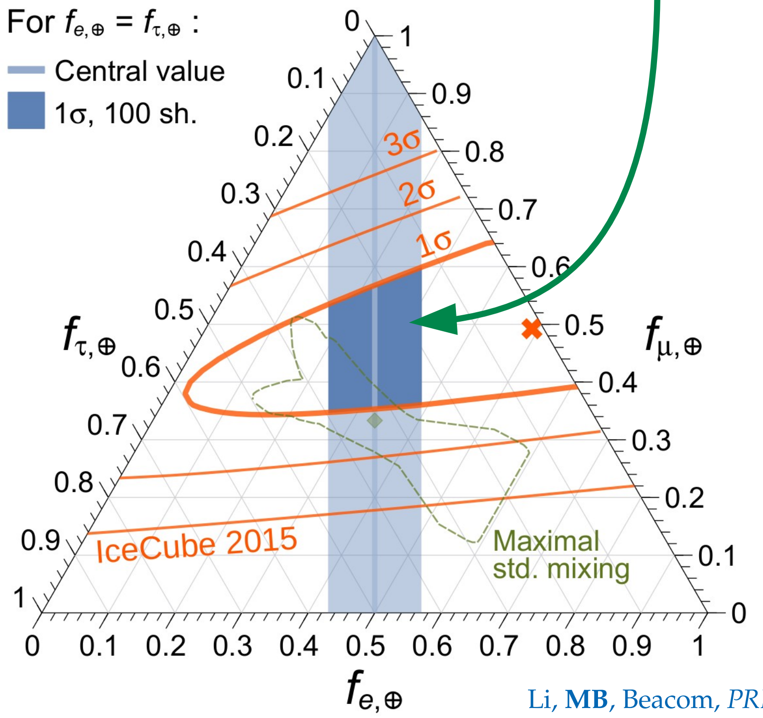


~10 × improvement over current measurement



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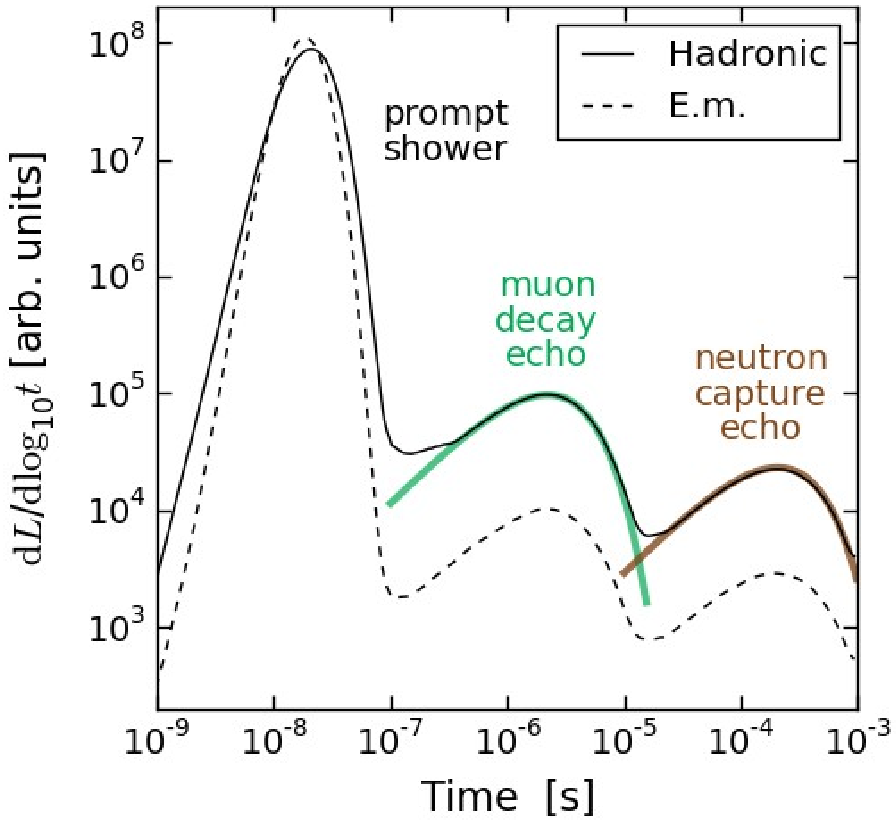

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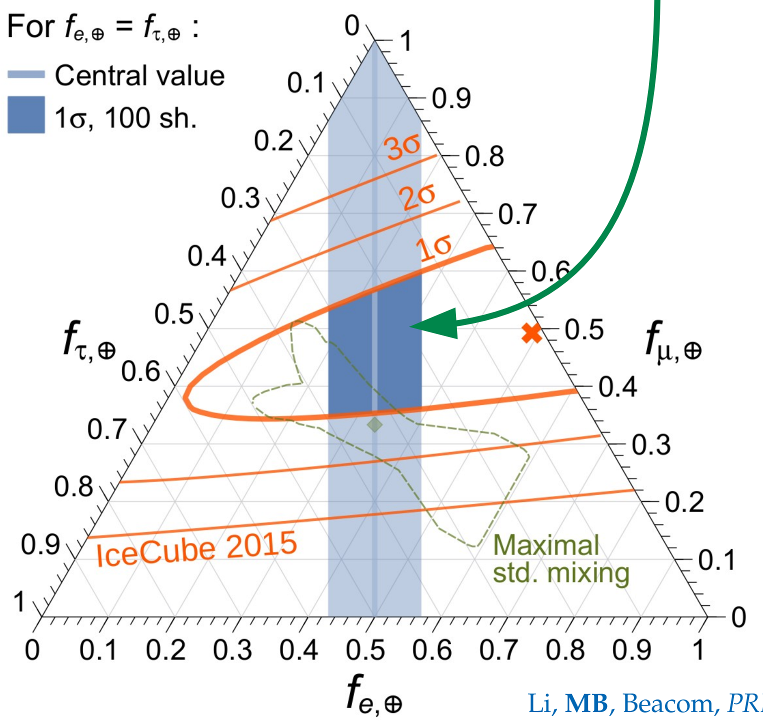
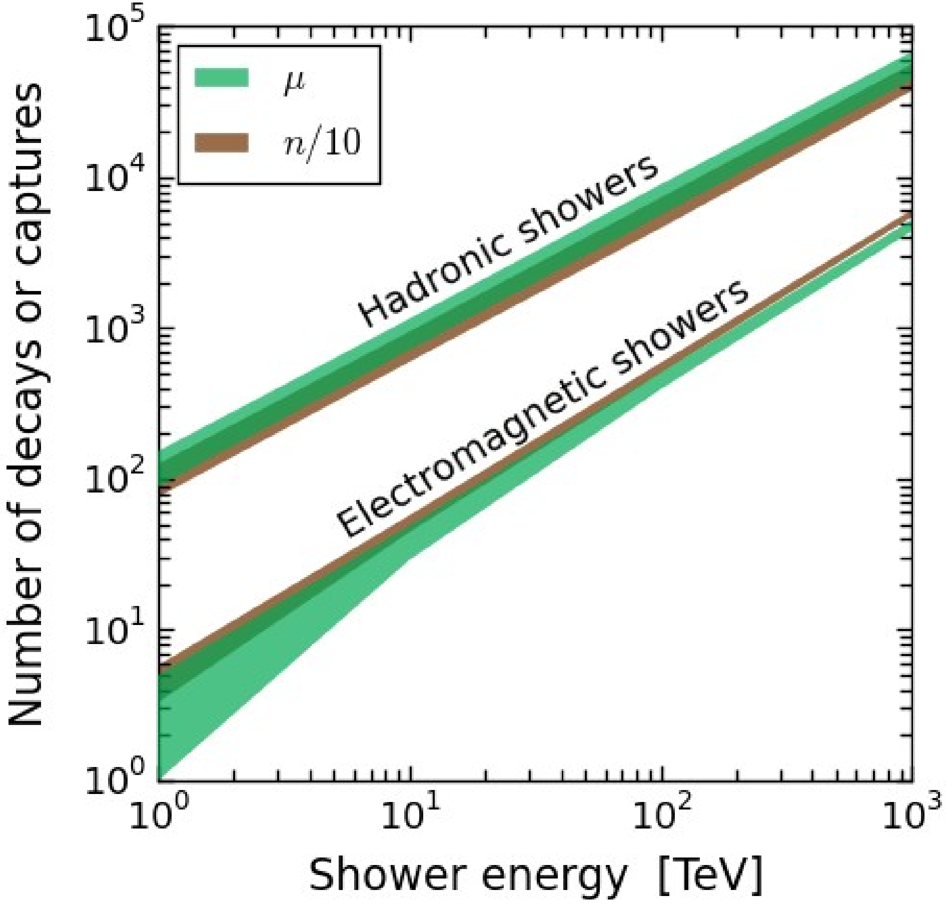
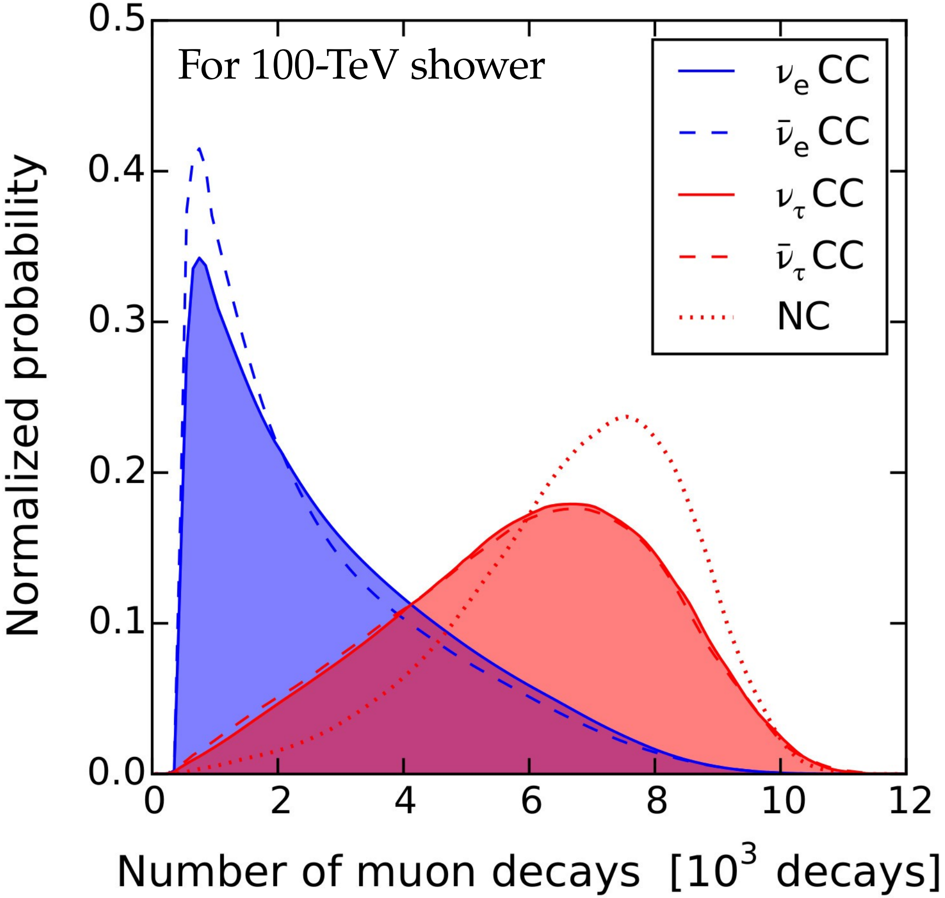


Li, **MB**, Beacom, *PRL* 2019

Hadronic *vs.* electromagnetic showers





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

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 (*e.g.*, Majoron)

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

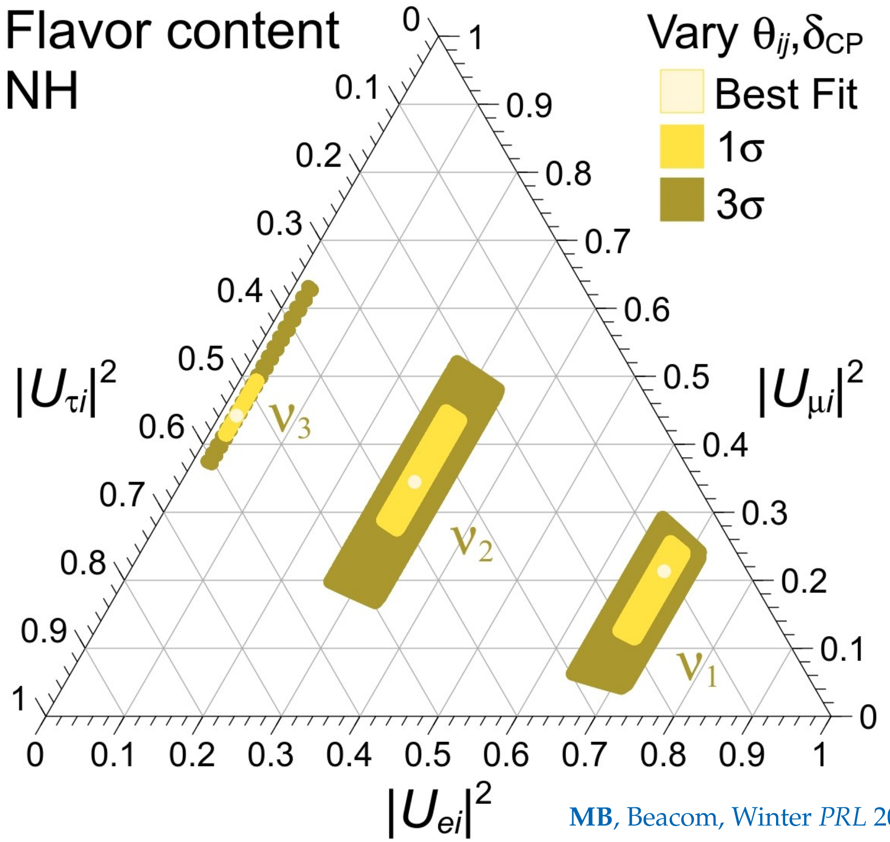
Flavor content of neutrino mass eigenstates

Known to within 2%

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

Known to within 8%

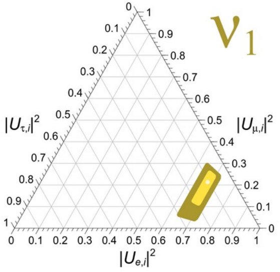
Known to within 20% (or worse)



MB, Beacom, Winter *PRL* 2015

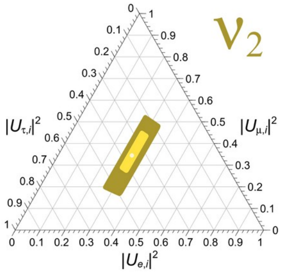
Neutrinos propagate as an incoherent mix of ν_1, ν_2, ν_3 —

w_1



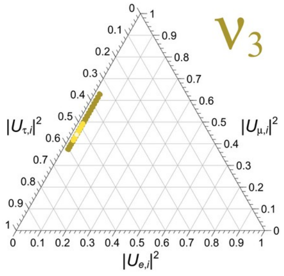
+

w_2

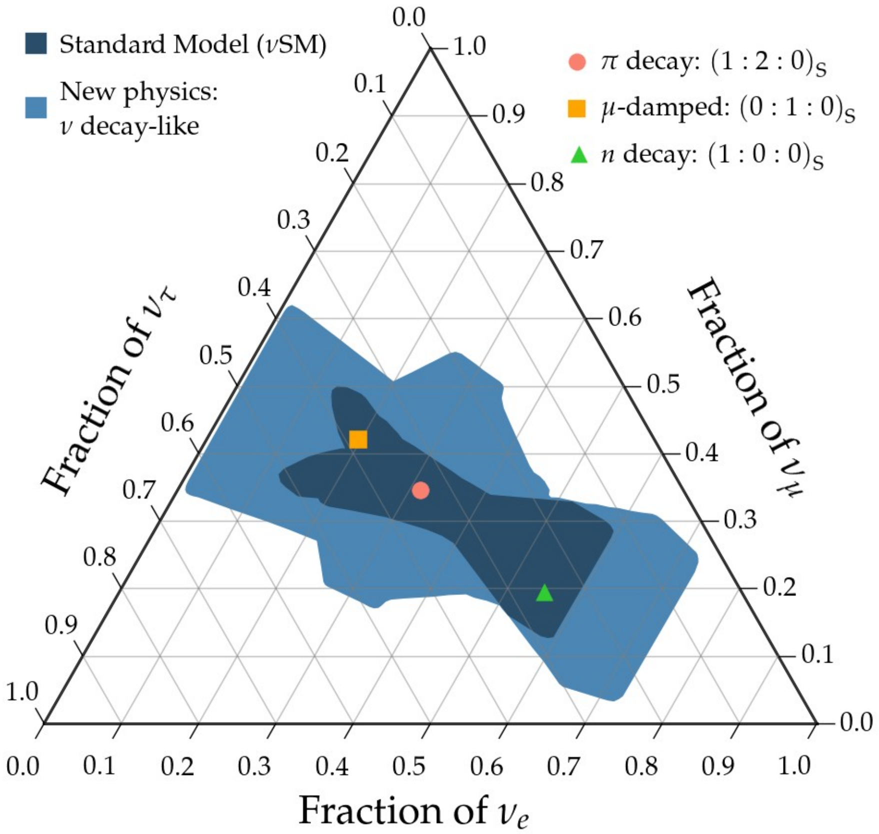


+

w_3



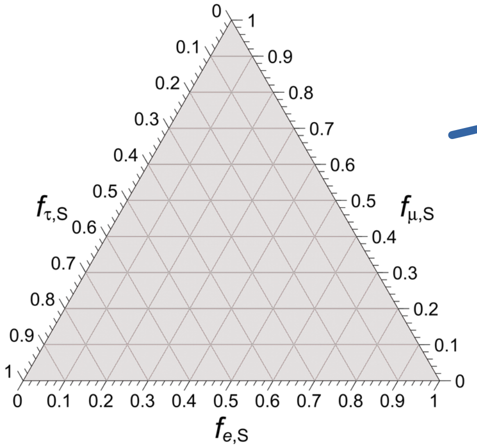
Varying all possible combinations of weights w_i and mixing parameters



Complete decay selects particular weights ▸
with striking consequences for flavor

Measuring the neutrino lifetime

Sources



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

ν_1 lightest and stable
(normal mass ordering)

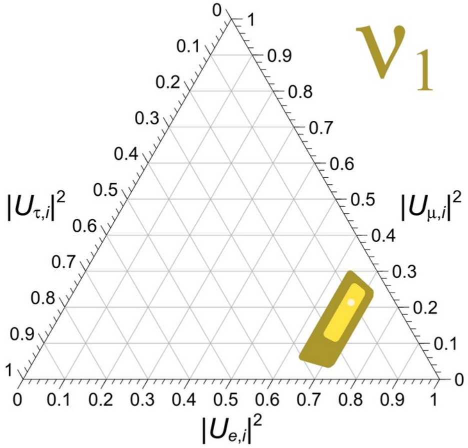
If all unstable
neutrinos decay

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

ν_3 lightest and stable
(inverted mass ordering)

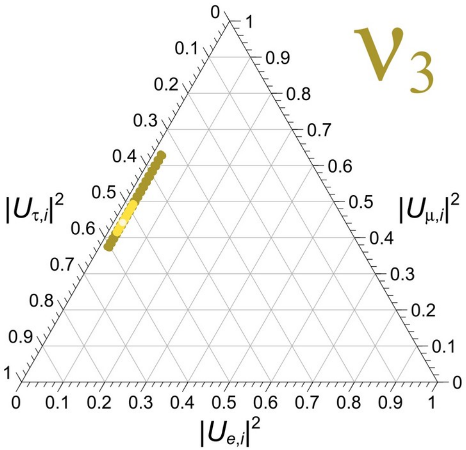
Earth

ν_1



$$f_{\alpha,\oplus} = |U_{\alpha 1}|^2$$
$(w_1 \sim 1; w_2, w_3 \sim 0)$

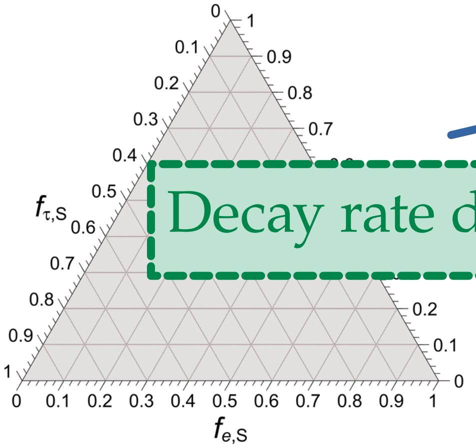
ν_3



$$f_{\alpha,\oplus} = |U_{\alpha 3}|^2$$
$(w_3 \sim 1; w_1, w_2 \sim 0)$

Measuring the neutrino lifetime

Sources



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

ν_1 lightest and stable
(normal mass ordering)

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

ν_3 lightest and stable
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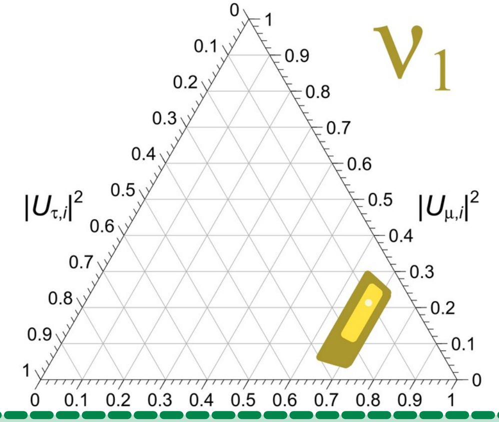
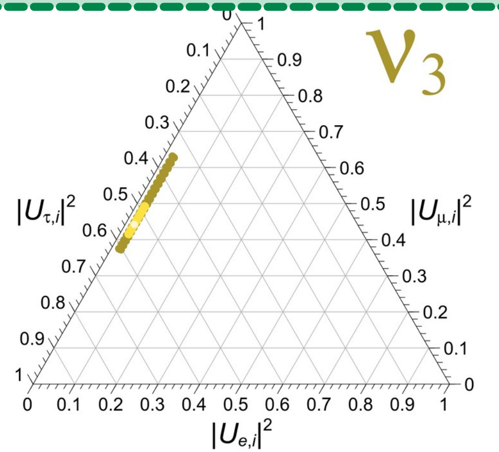
Earth



ν_1

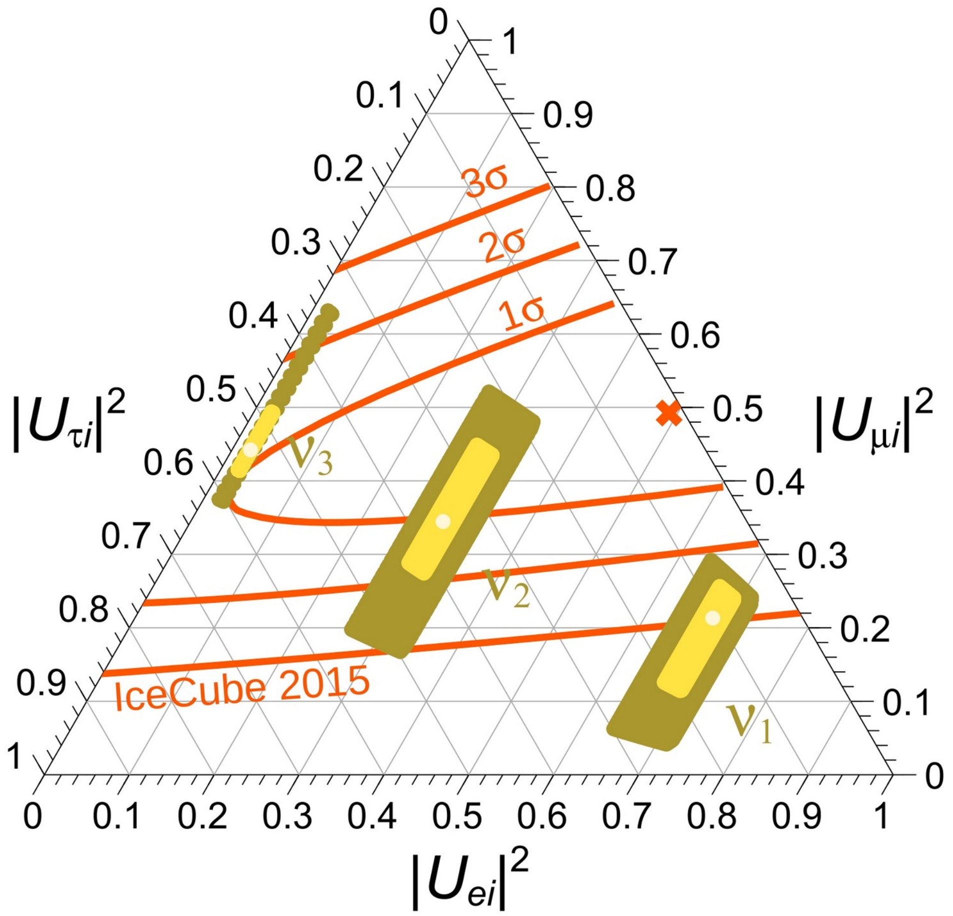
$$f_{\alpha,\oplus} = |U_{\alpha 1}|^2$$
$(w_1 \sim 1; w_2, w_3 \sim 0)$



ν_3

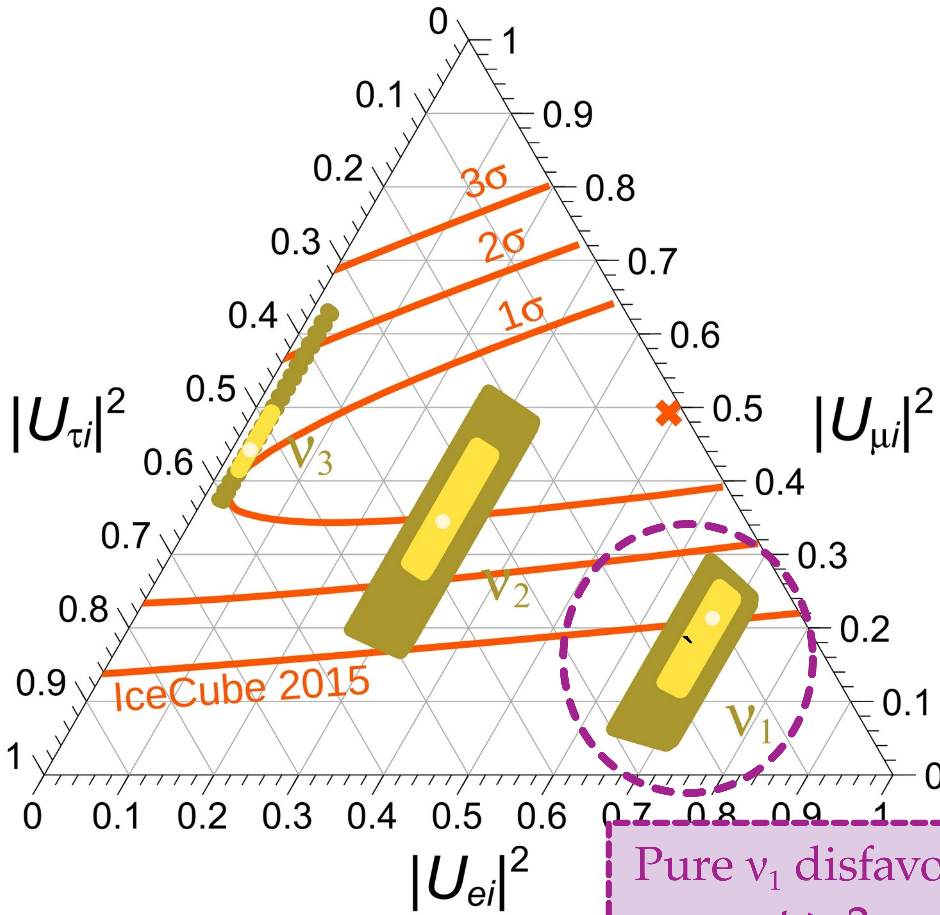
$$f_{\alpha,\oplus} = |U_{\alpha 3}|^2$$
$(w_3 \sim 1; w_1, w_2 \sim 0)$

$$\boxed{\text{Decay rate depends on } \exp[-\,t\,/\,(\gamma\,\tau_i)] = \exp[-\,(L/E)\cdot(m_i/\tau_i)]}$$



MB, Beacom, Murase, *PRD* 2017

Baerwald, **MB**, Winter, *JCAP* 2012

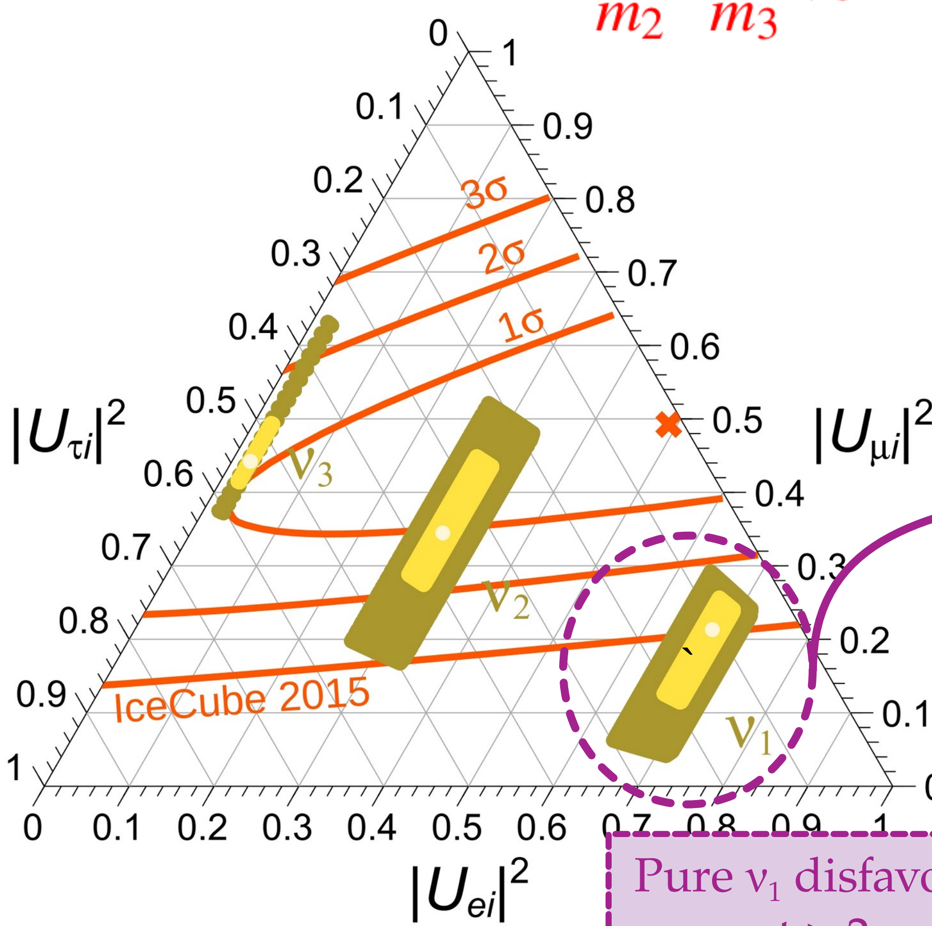


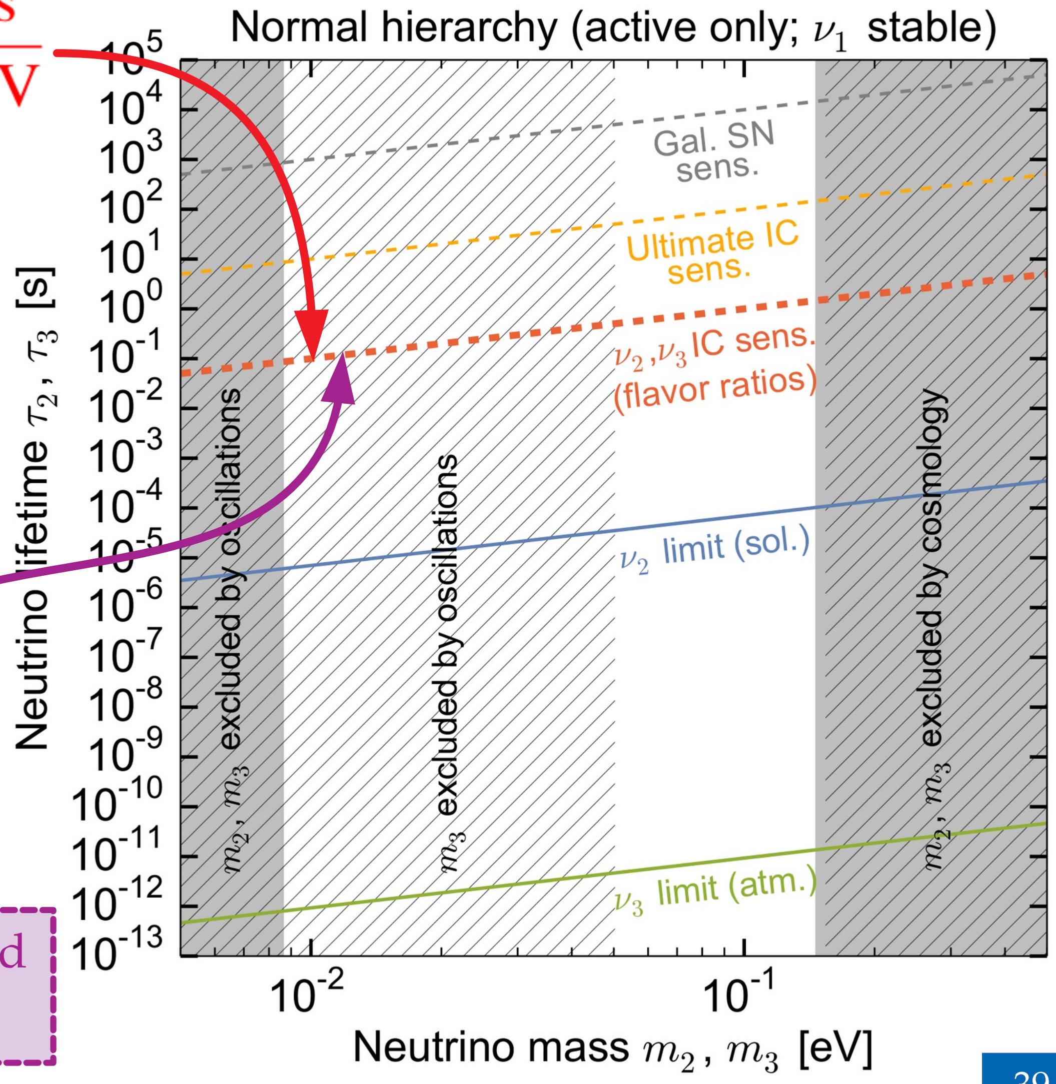
Pure ν_1 disfavored at > 2σ

MB, Beacom, Murase, *PRD* 2017

Baerwald, **MB**, Winter, *JCAP* 2012

$$\frac{\tau_2}{m_2}, \frac{\tau_3}{m_3} \gtrsim 10 \frac{\mathrm{s}}{\mathrm{eV}}$$





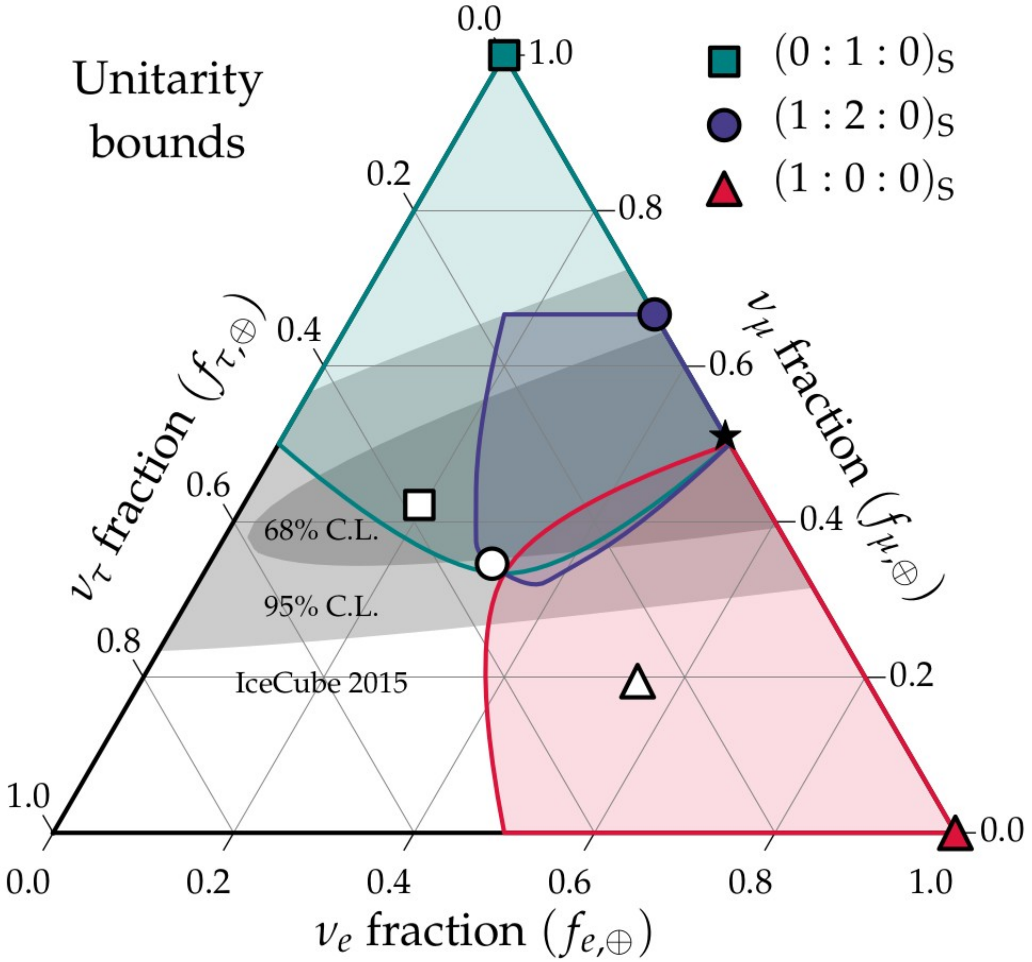
Pure ν_1 disfavored at > 2σ

MB, Beacom, Murase, *PRD* 2017
Baerwald, **MB**, Winter, *JCAP* 2012

Using unitarity to constrain new physics

$$\mathrm{H}_{\mathrm{tot}} = \mathrm{H}_{\mathrm{std}} + \mathrm{H}_{\mathrm{NP}}$$

- New mixing angles unconstrained
- Use unitarity ($\mathrm{U}_{\mathrm{NP}}\mathrm{U}_{\mathrm{NP}}^{\dagger} = 1$) to bound all possible flavor ratios at Earth
- Can be used as prior in new-physics searches in IceCube



Ahlers, **MB**, Mu, *PRD* 2018
See also: Xu, He, Rodejohann, *JCAP* 2014

How to fill out the flavor triangle?

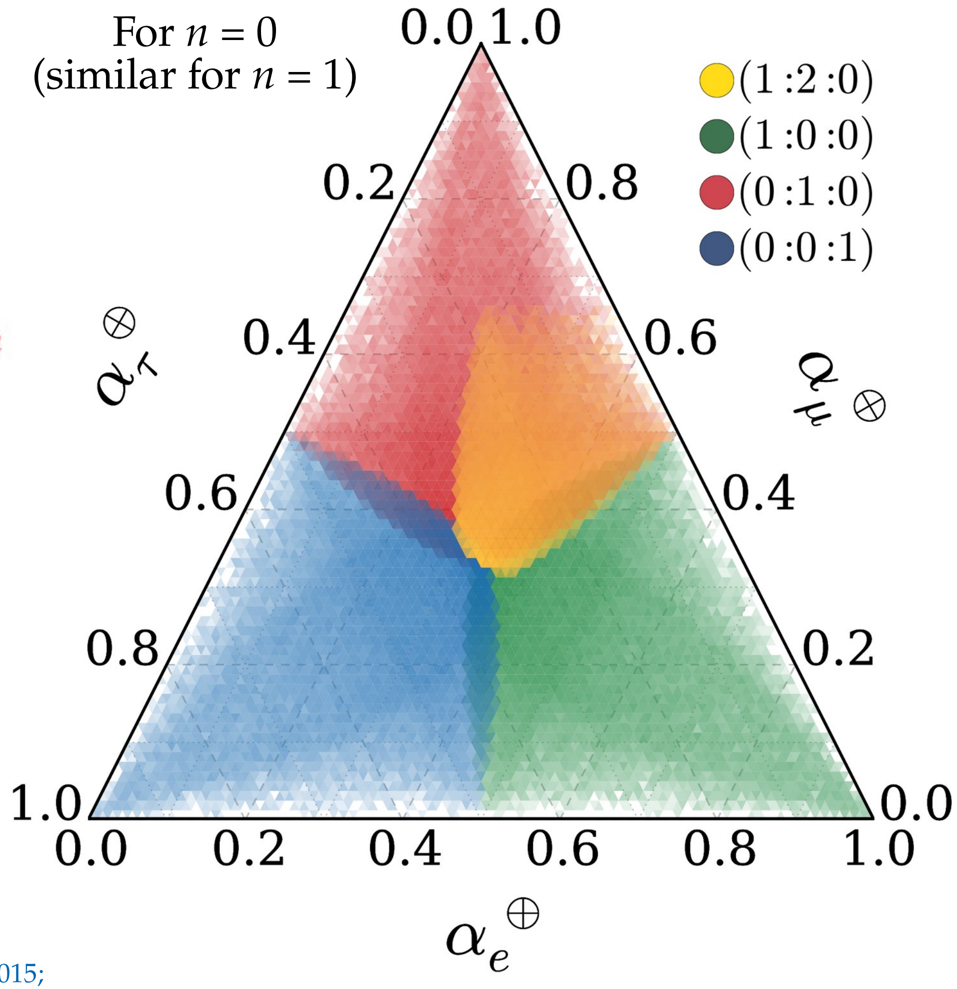
$$H_{\text{tot}} = H_{\text{std}} + H_{\text{NP}}$$

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

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

This can populate *all* of the triangle –

- Use current atmospheric bounds on $O_{n,i}$:
  $O_0 < 10^{-23}$ GeV, $O_1/\Lambda_1 < 10^{-27}$ GeV
- Sample the unknown new mixing angles



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

How to fill out the flavor triangle?

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

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

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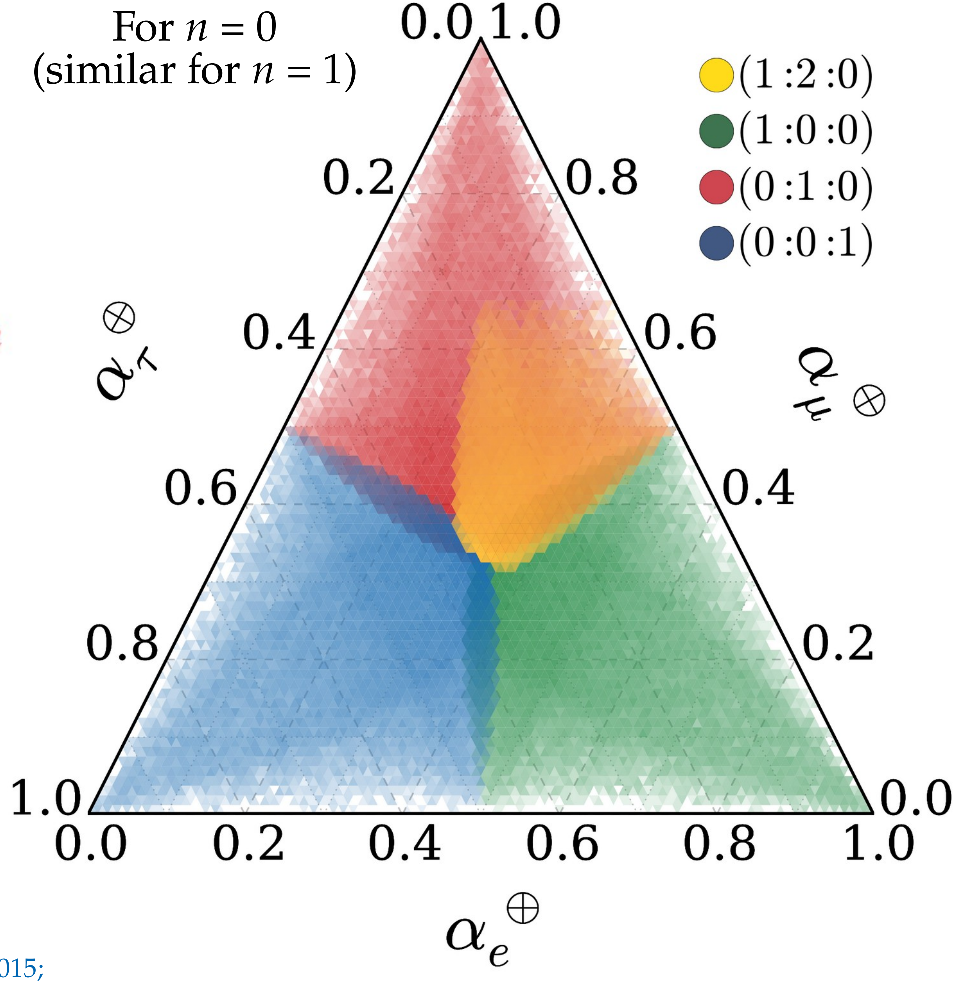
This can populate *all* of the triangle –

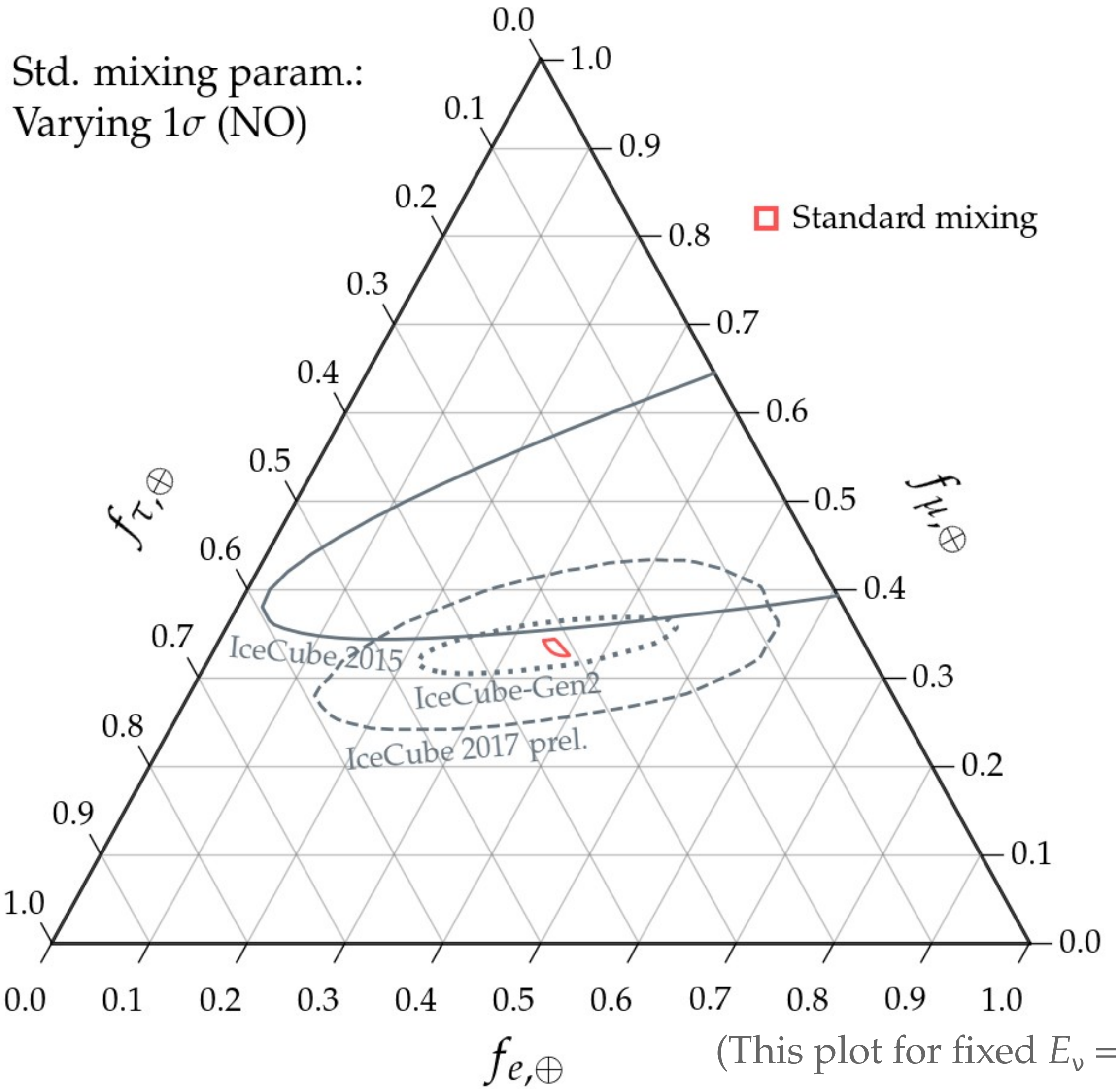
- Use current atmospheric bounds on $O_{n,i}$:
  $O_0 < 10^{-23}$ GeV, $O_1/\Lambda_1 < 10^{-27}$ GeV
- Sample the unknown new mixing angles

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



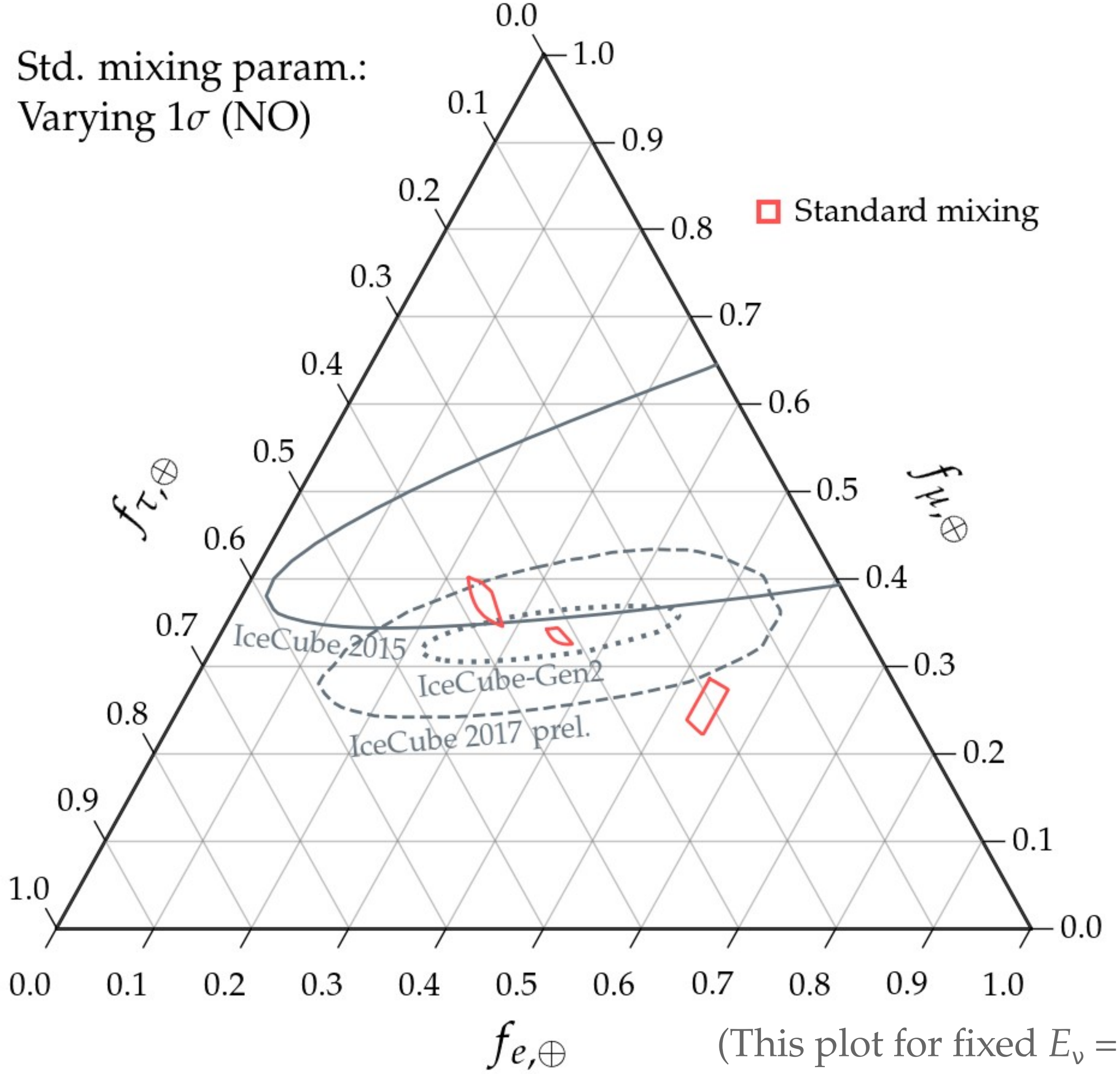
Argüelles, Katori, Salvadó, *PRL* 2015

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



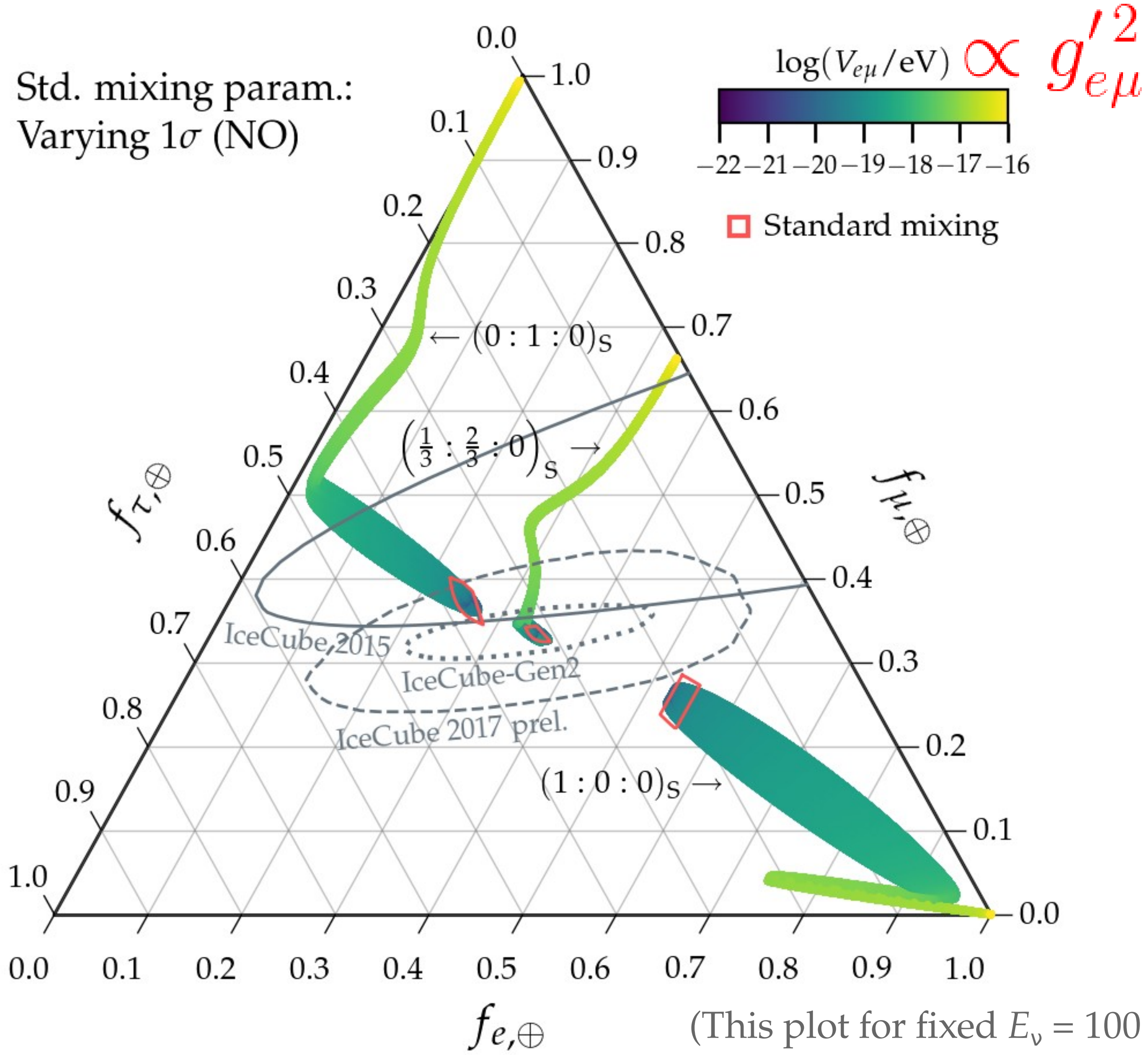
MB & Agarwalla, *PRL* 2019

(This plot for fixed E_ν = 100 TeV)



MB & Agarwalla, *PRL* 2019

(This plot for fixed $E_\nu = 100$ TeV)



MB & Agarwalla, *PRL* 2019

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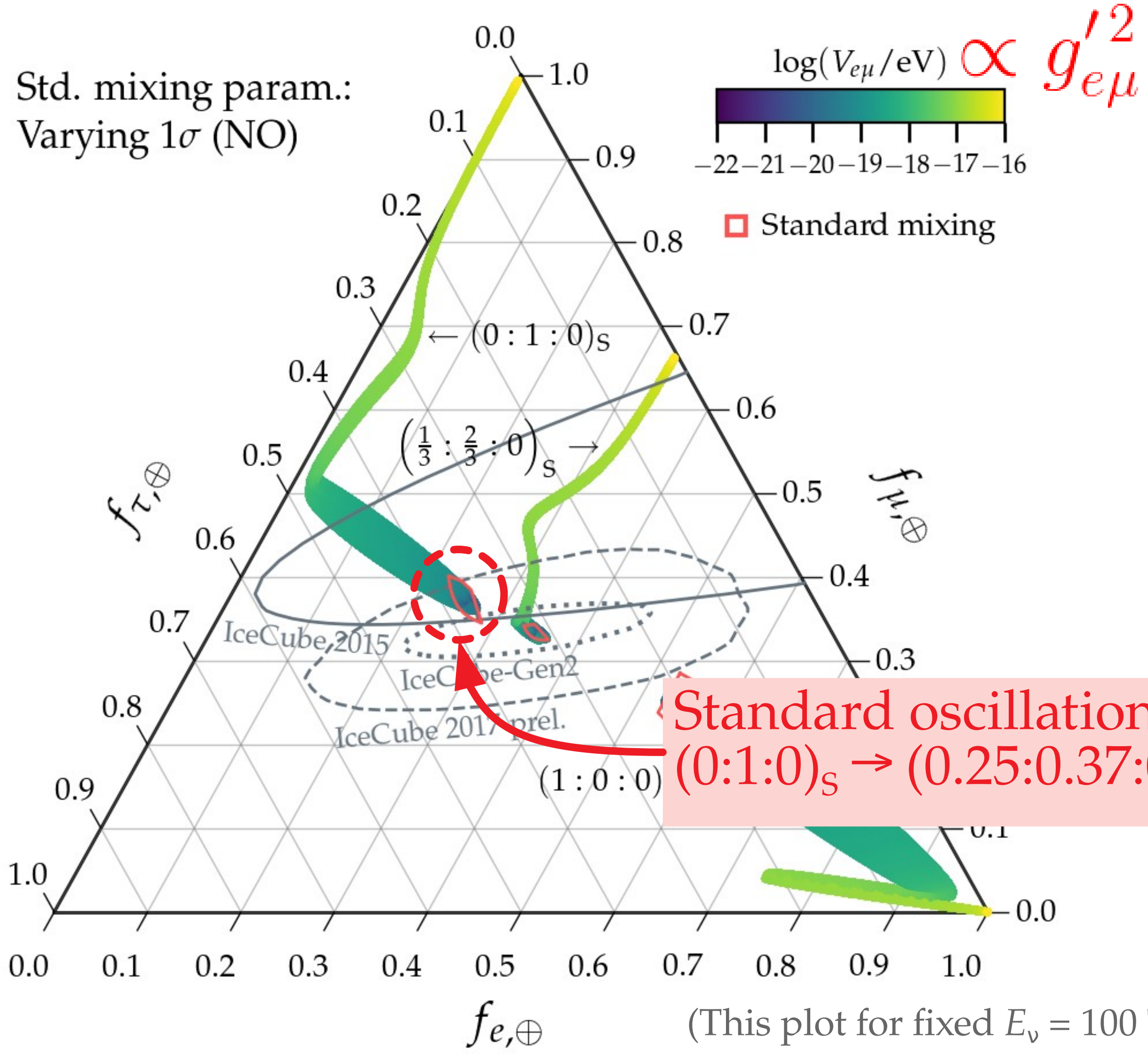
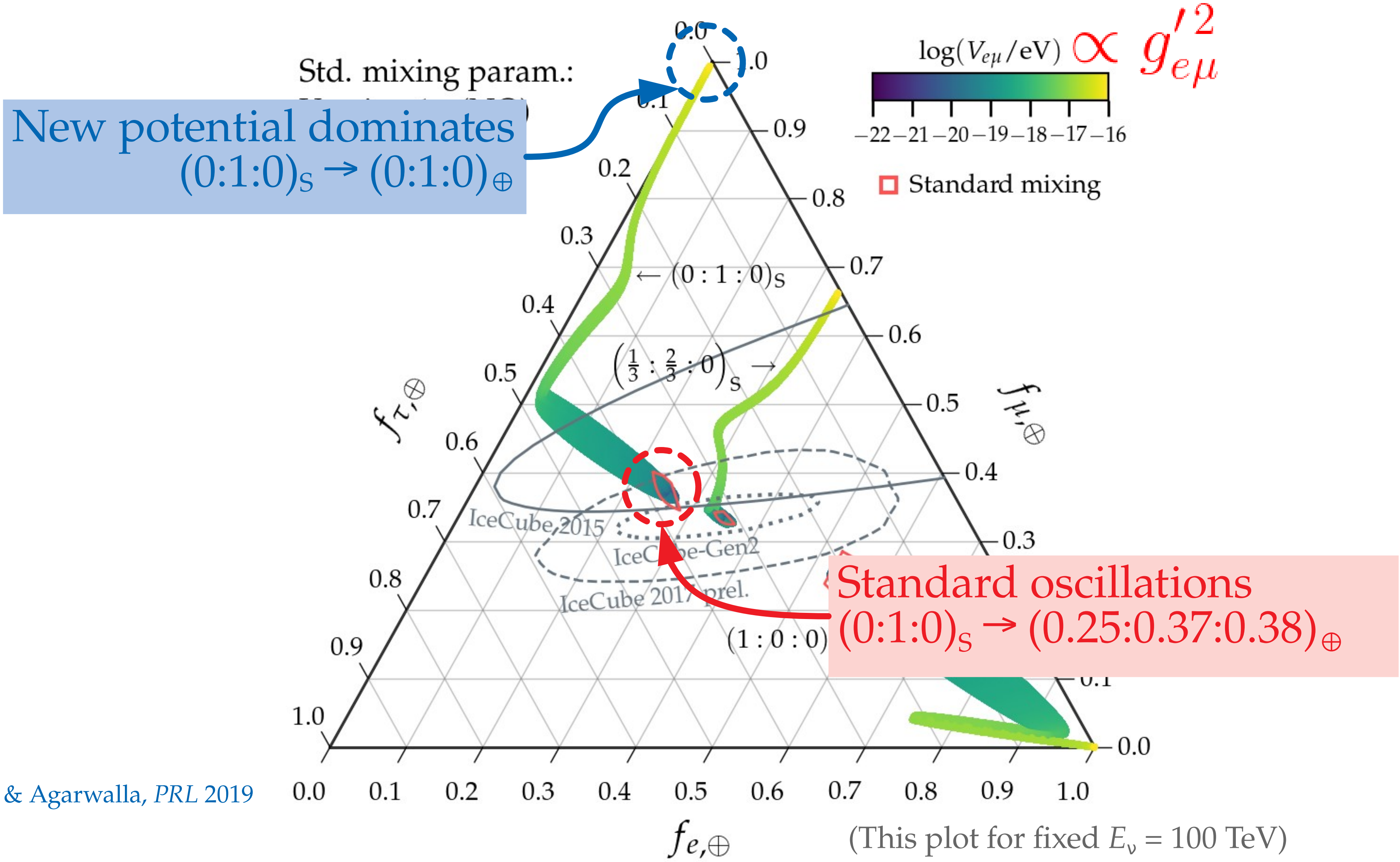


Standard oscillations
$(0:1:0)_S \rightarrow (0.25:0.37:0.38)_\oplus$

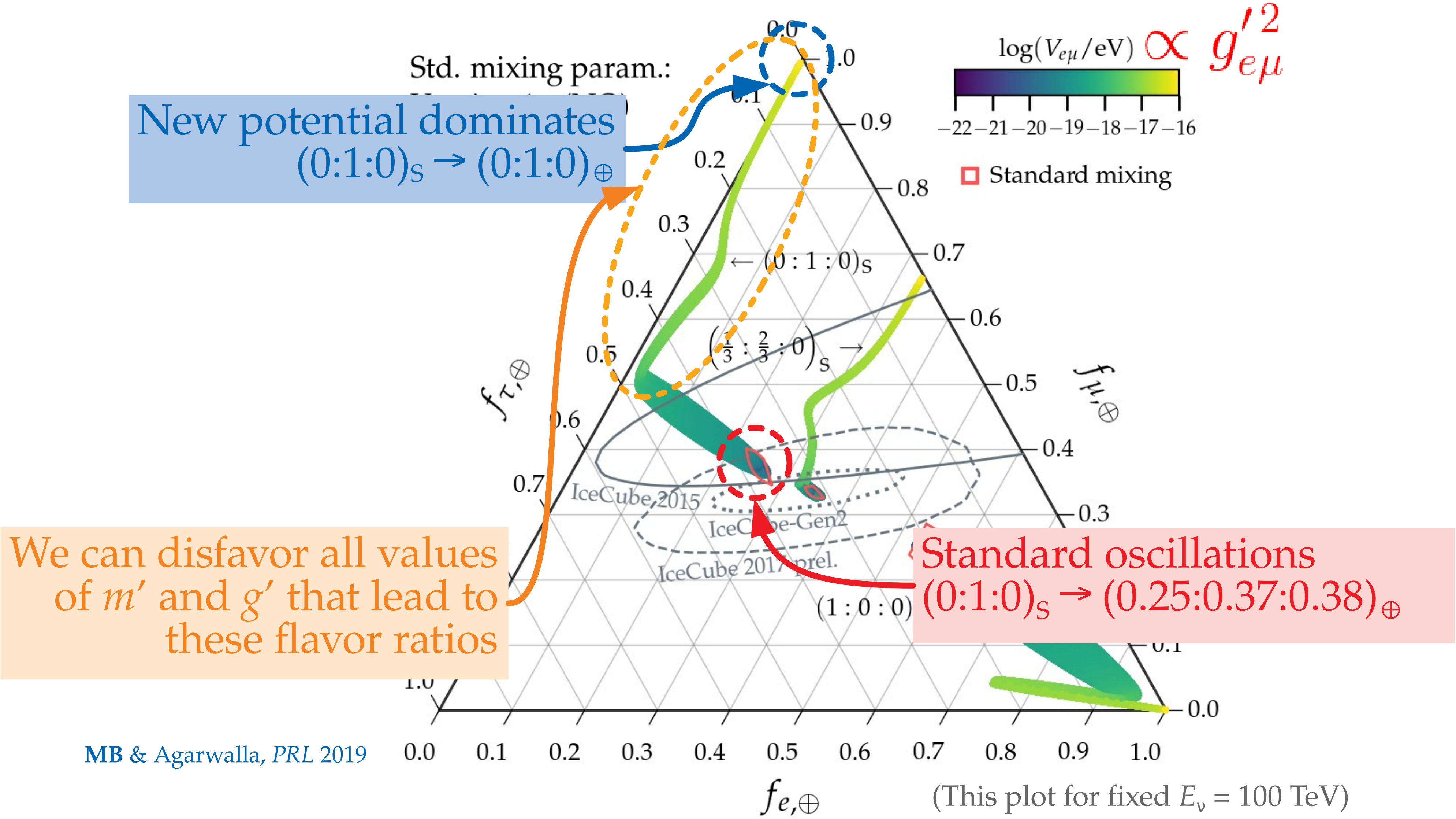
MB & Agarwalla, *PRL* 2019

(This plot for fixed E_ν = 100 TeV)



MB & Agarwalla, *PRL* 2019

(This plot for fixed E_ν = 100 TeV)



MB & Agarwalla, *PRL* 2019

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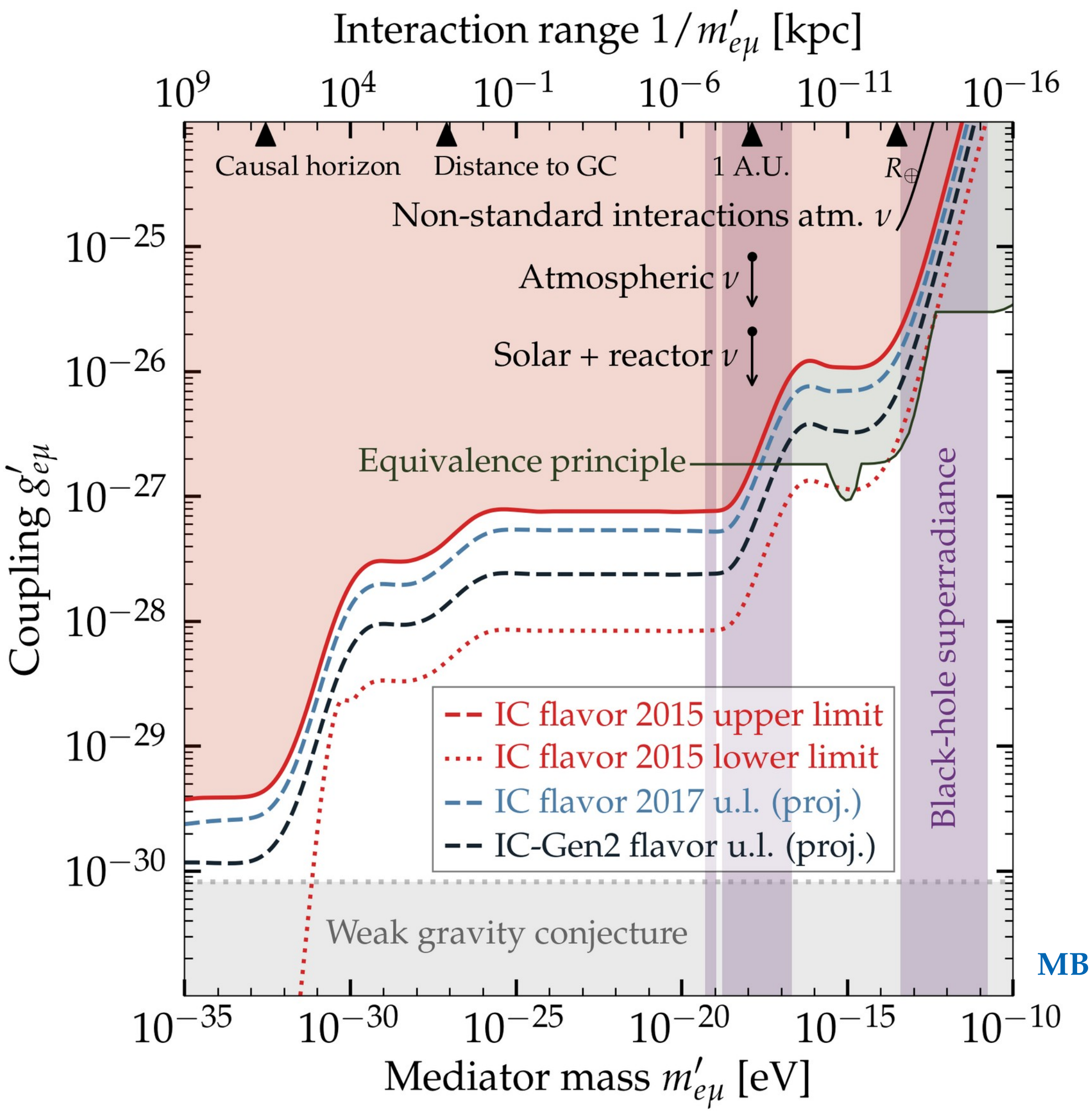

MB &Agarwalla, *PRL* 2019