The future of high-energy astrophysical neutrino flavor measurements

Mauricio Bustamante

Niels Bohr Institute, University of Copenhagen

Based on:
Ningqiang Song, Shirley Li, Carlos Argüelles, **MB**, Aaron Vincent
JCAP 04, 054 (2021) [2012.12893]

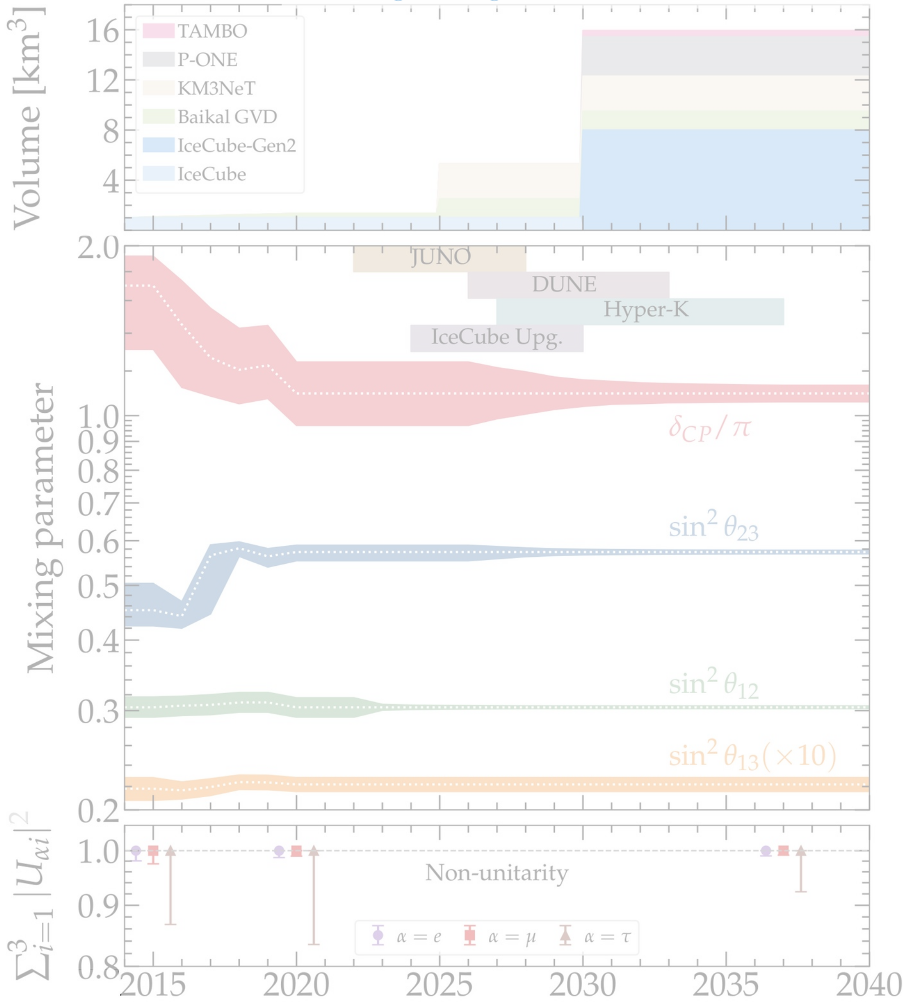
EPS-HEP
July 29, 2021

UNIVERSITY OF COPENHAGEN

VILLUM FONDEN

Three reasons to be excited

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



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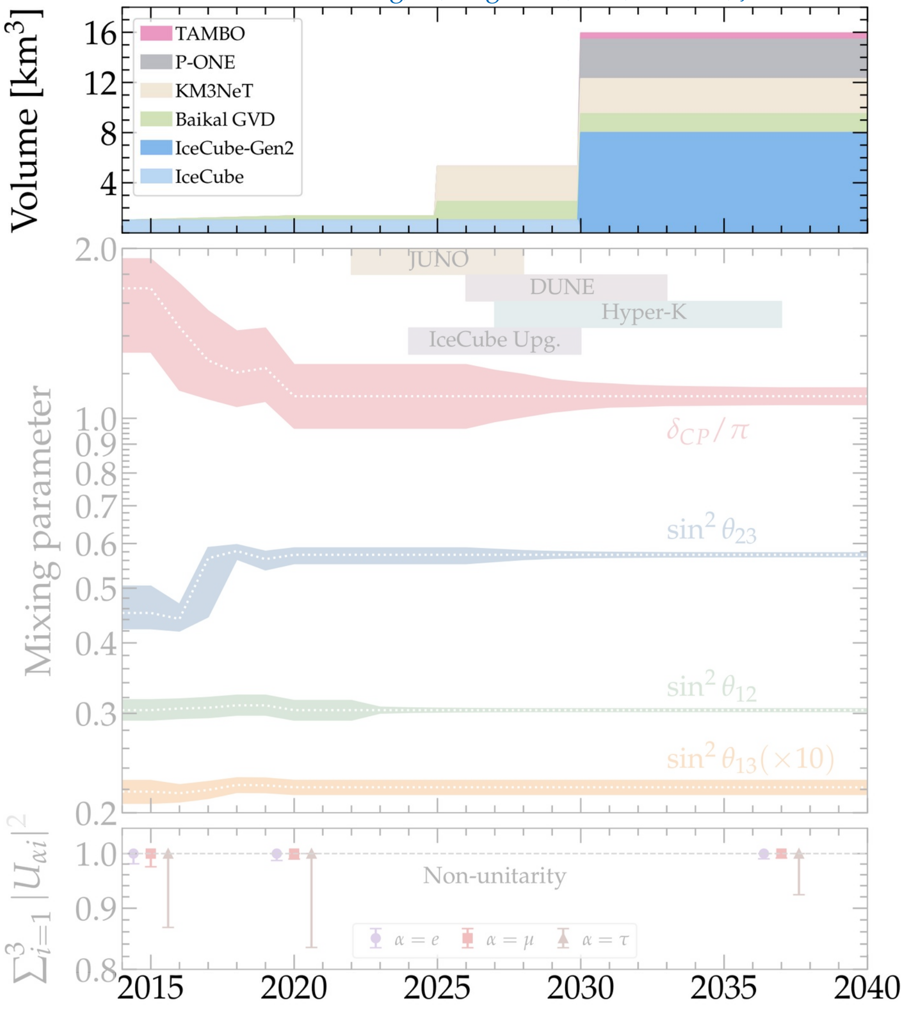

Flavor measurements:

New neutrino telescopes = more events, better flavor measurement

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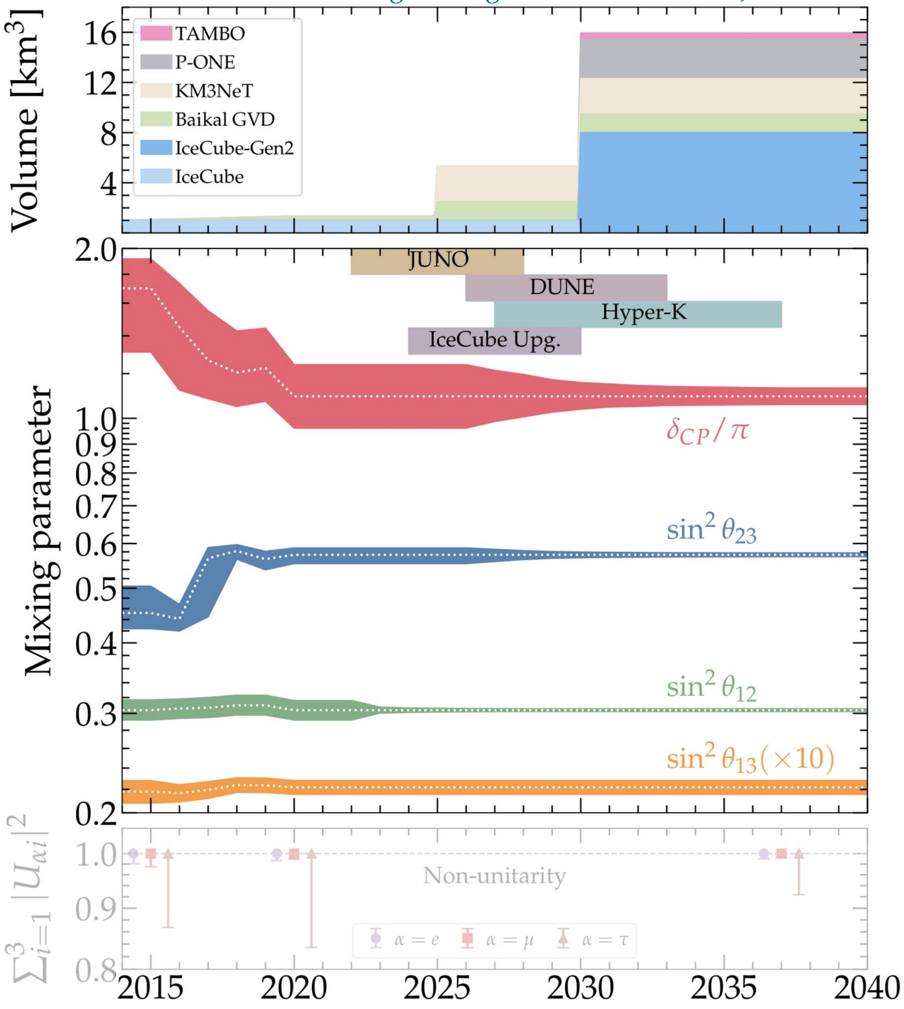

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Oscillation physics:

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

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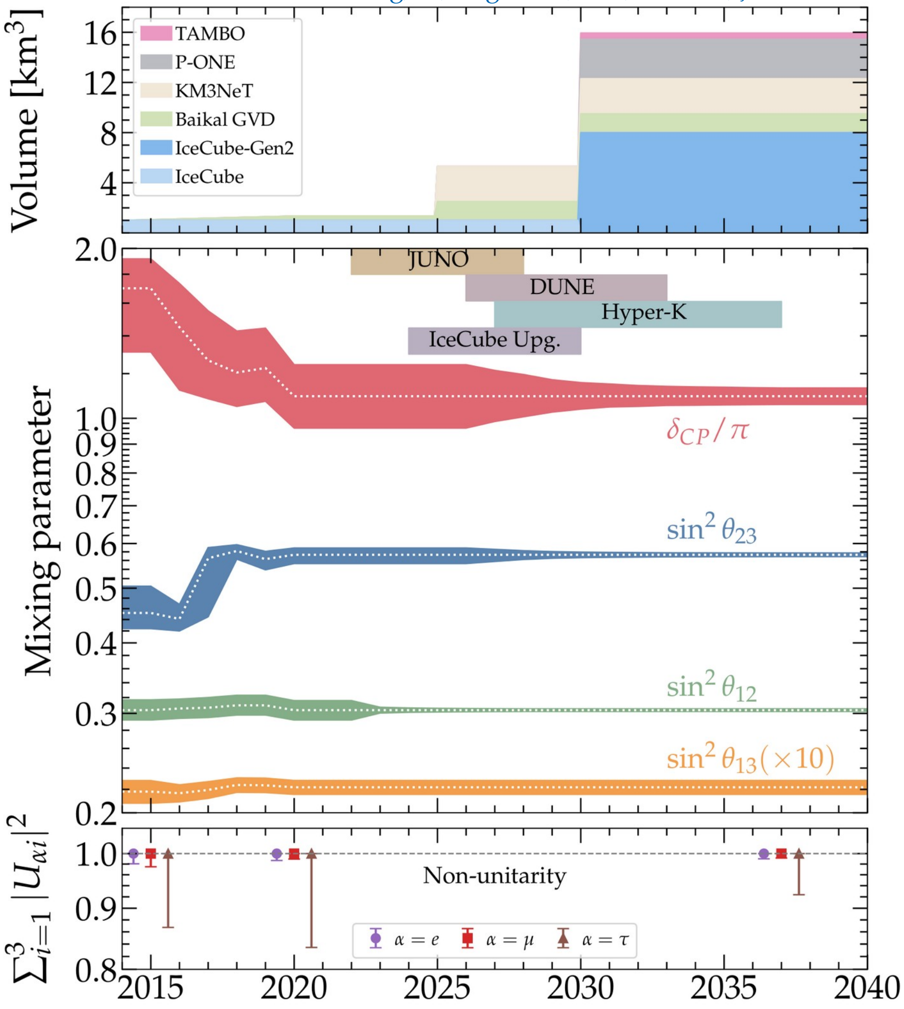
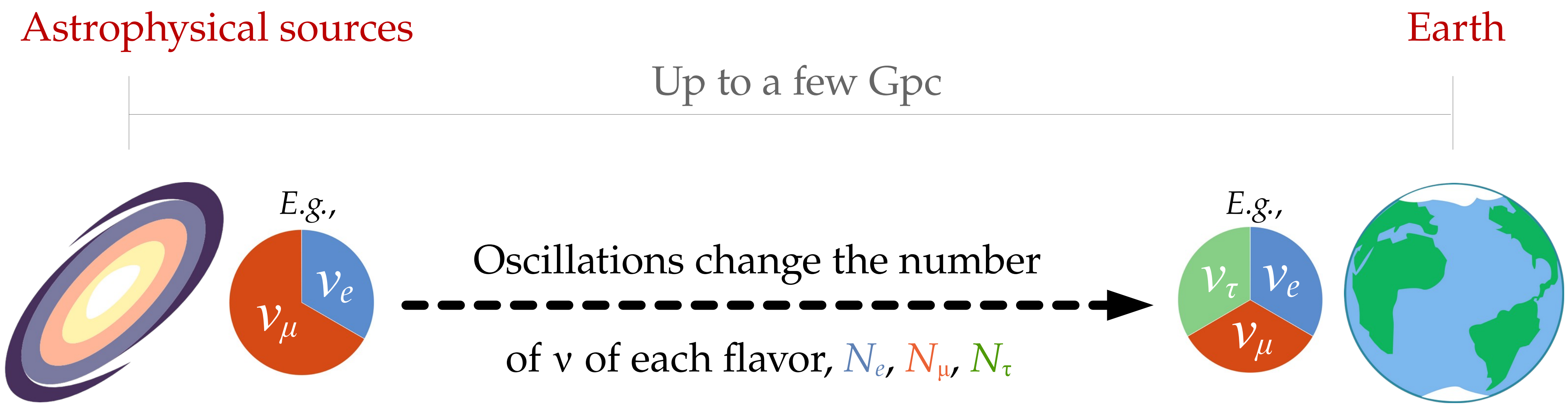


Flavor measurements:
New neutrino telescopes = more events, better flavor measurement

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

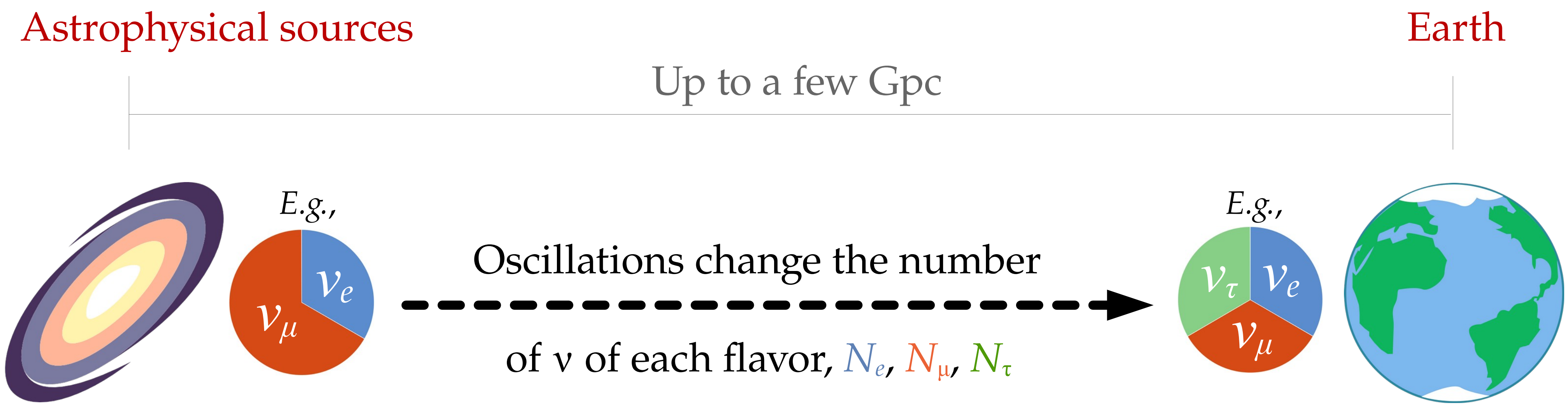


Different production mechanisms yield different flavor ratios:

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

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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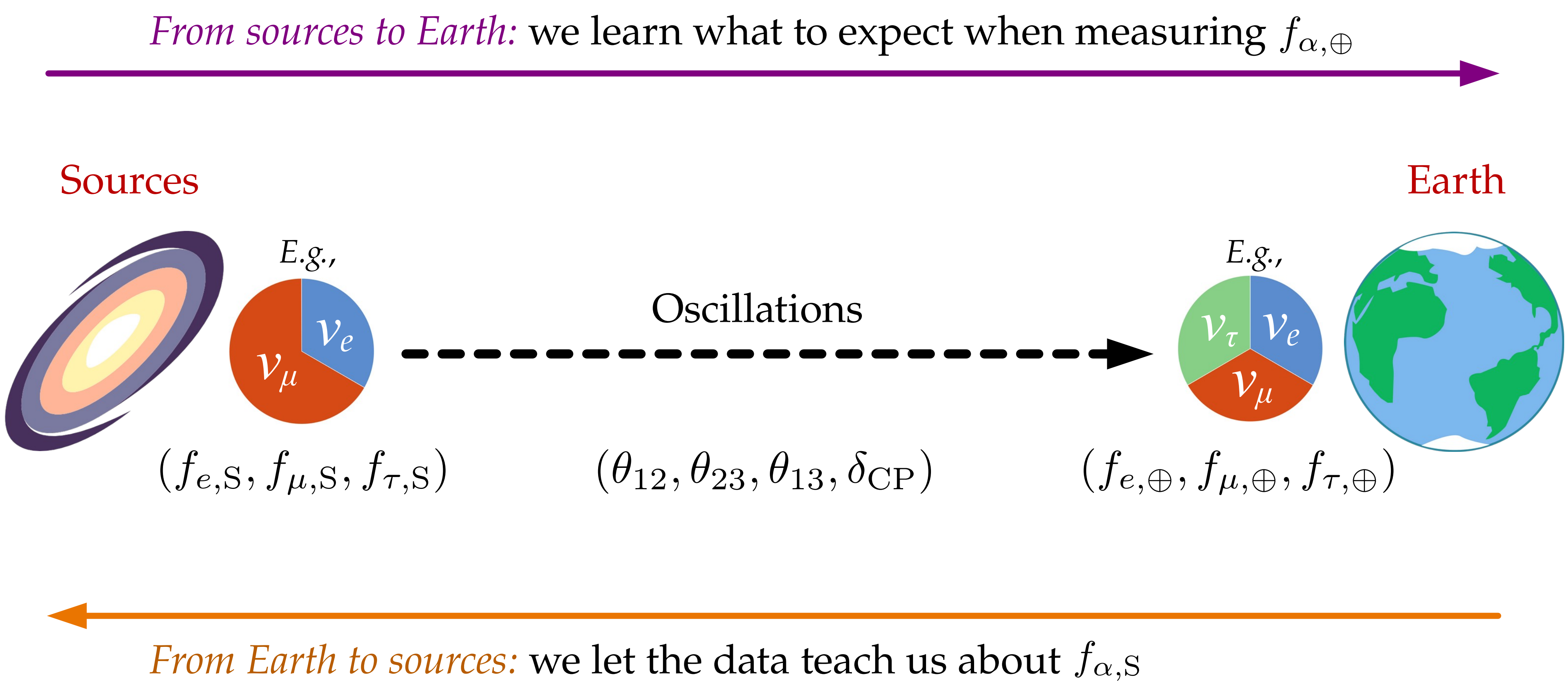
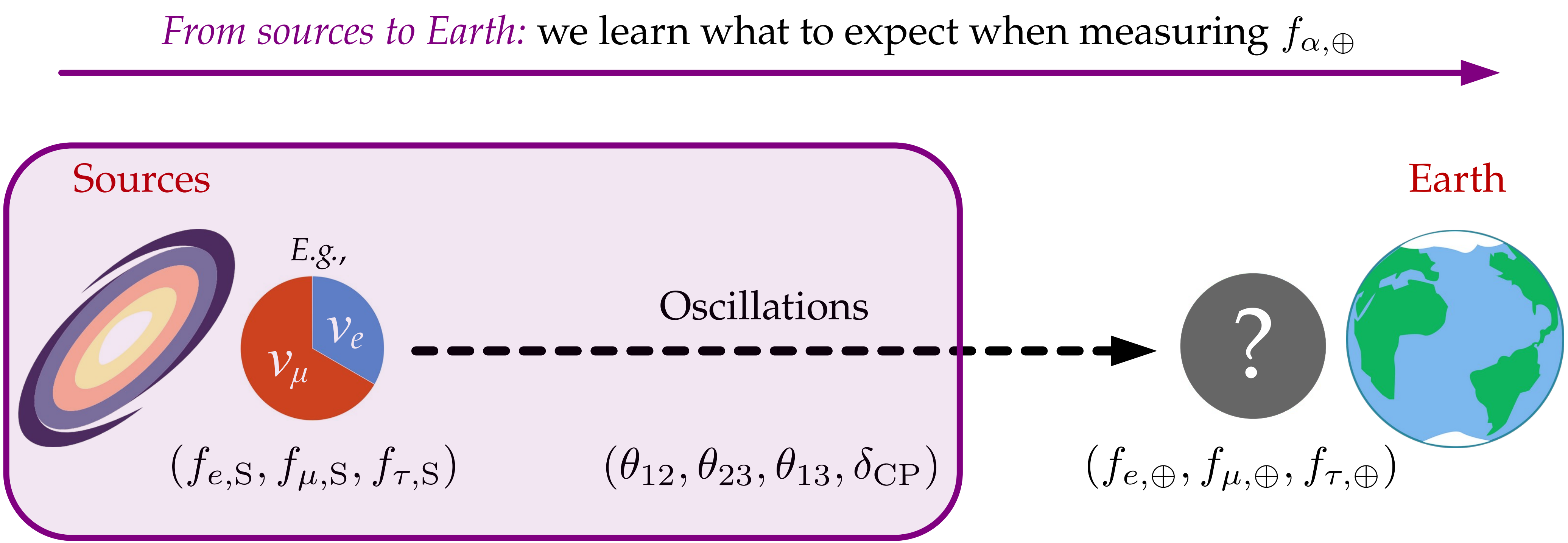
Standard oscillations
or
new physics


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 $f_{\alpha,\mathrm{S}}$



From sources to Earth: we learn what to expect when measuring $f_{\alpha,\oplus}$
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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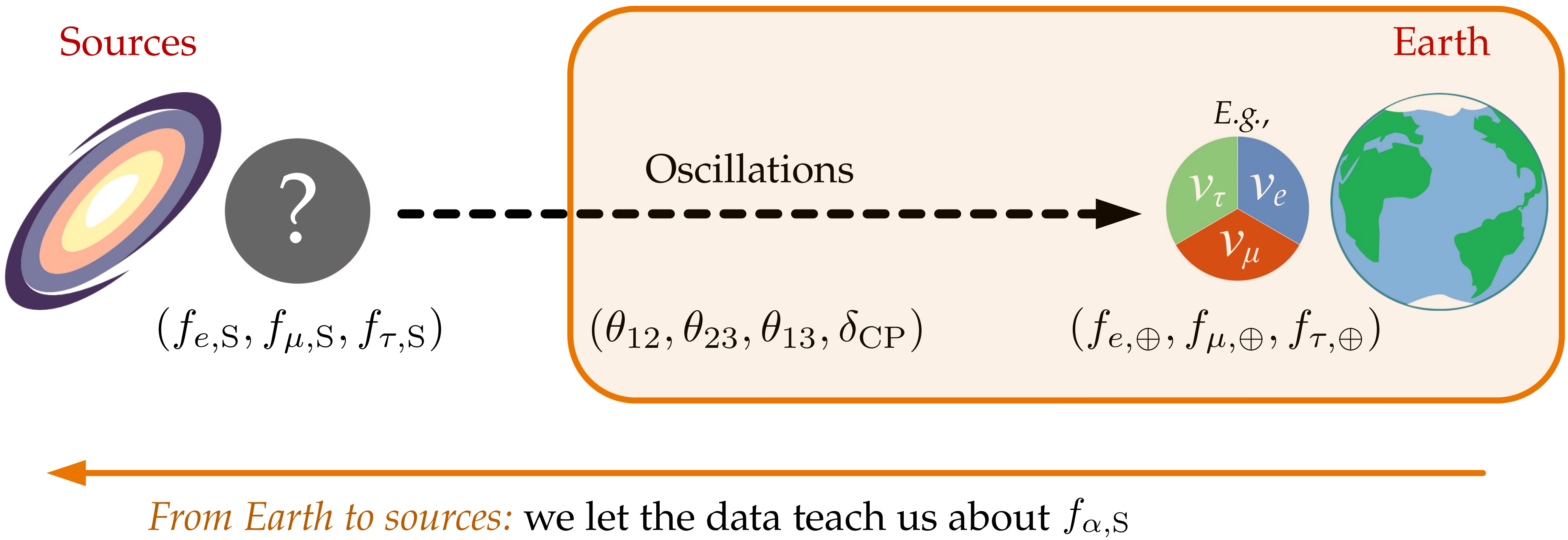
Sources
?
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E.g.,
ν_τ
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From Earth to sources: we let the data teach us about $f_{\alpha,\rm S}$

One likely TeV–PeV ν production scenario:

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

Full π decay chain

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

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

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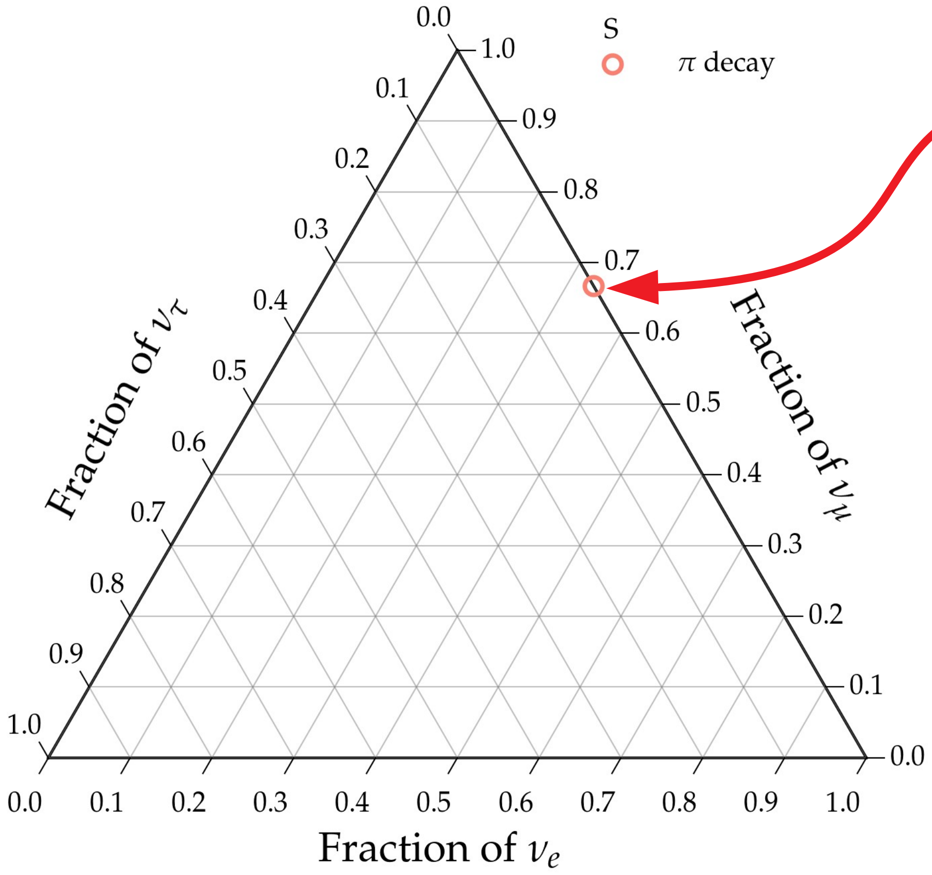

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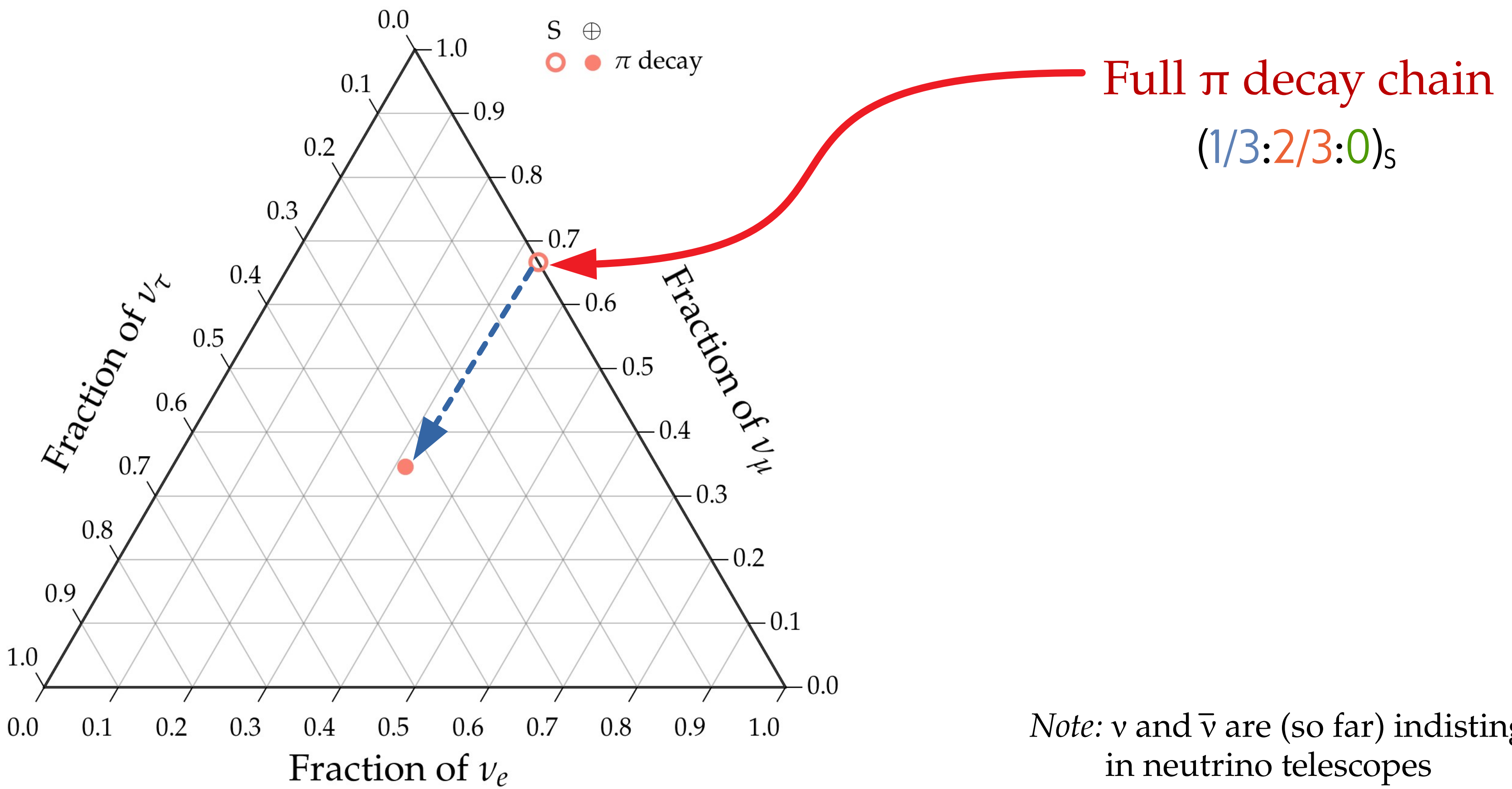

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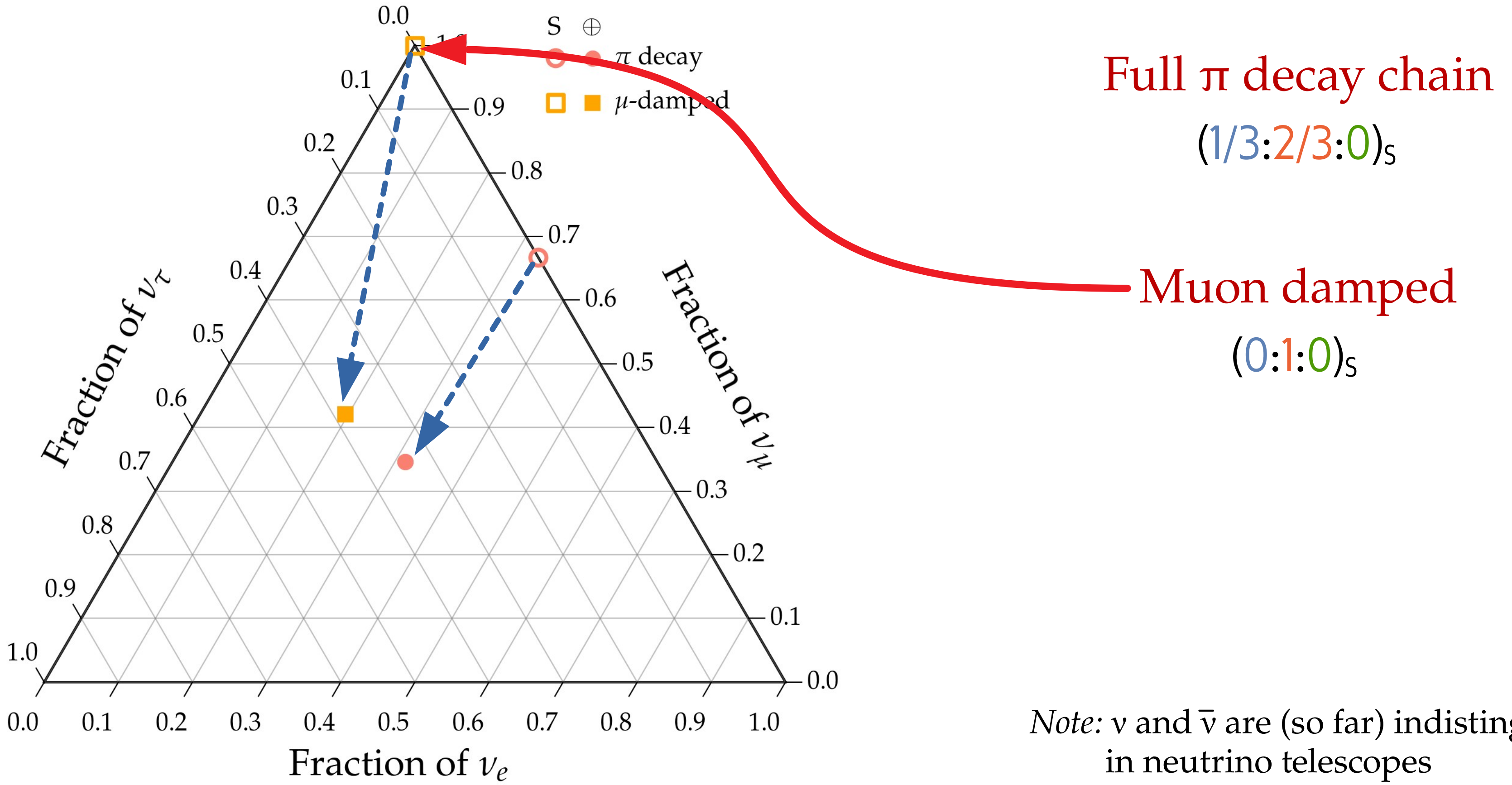

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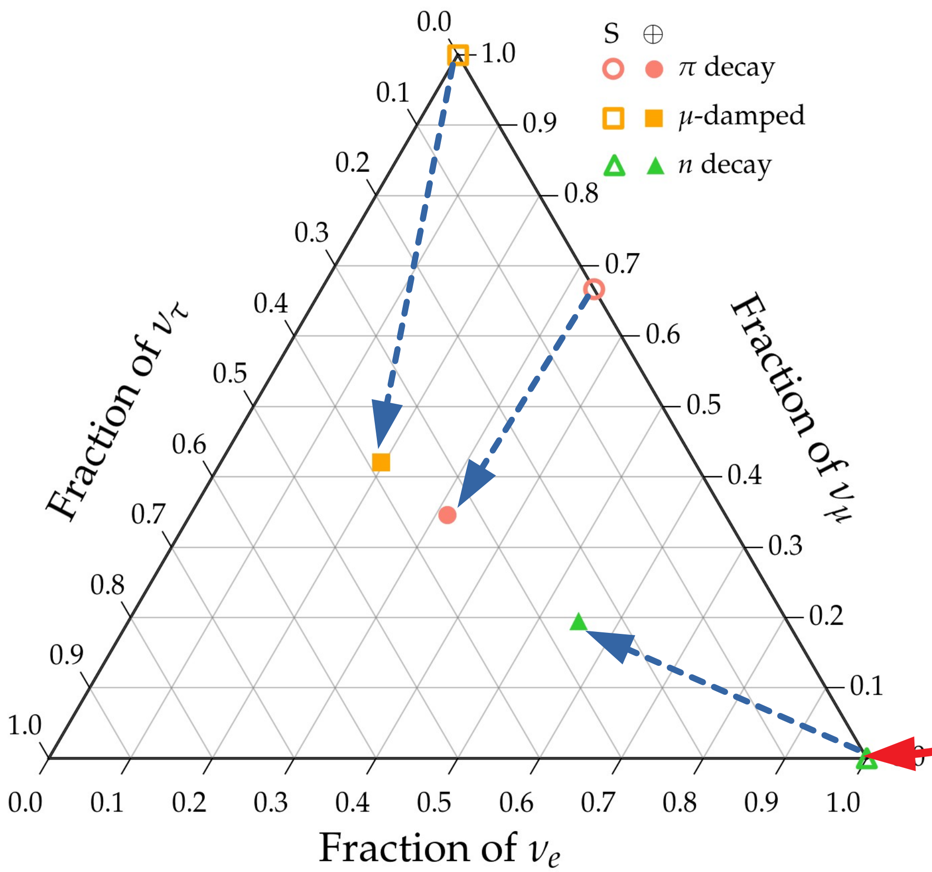

Full π decay chain

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

Muon damped

$(0:1:0)_S$

Neutron decay

$(1:0:0)_S$

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

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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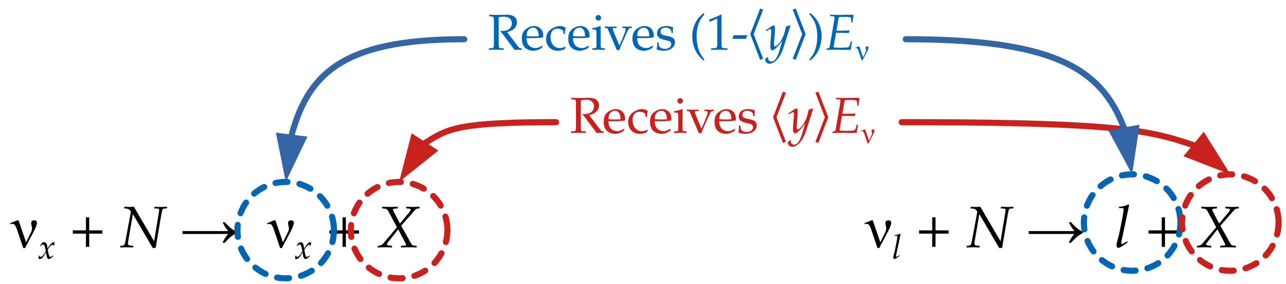
Neutral current (NC) Charged current (CC)



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

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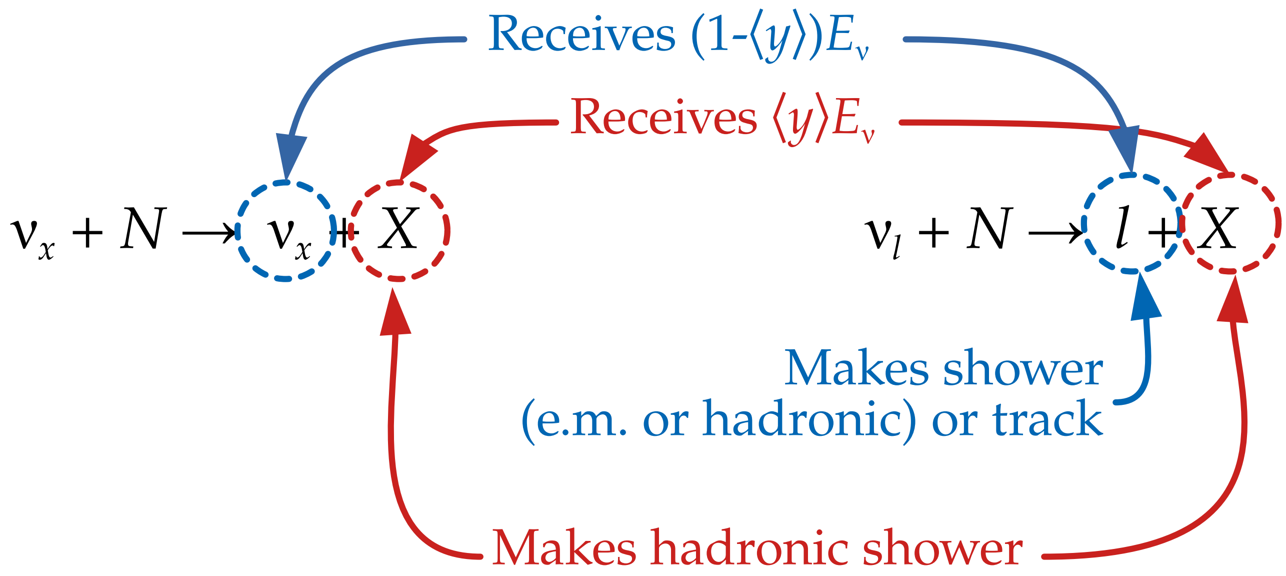

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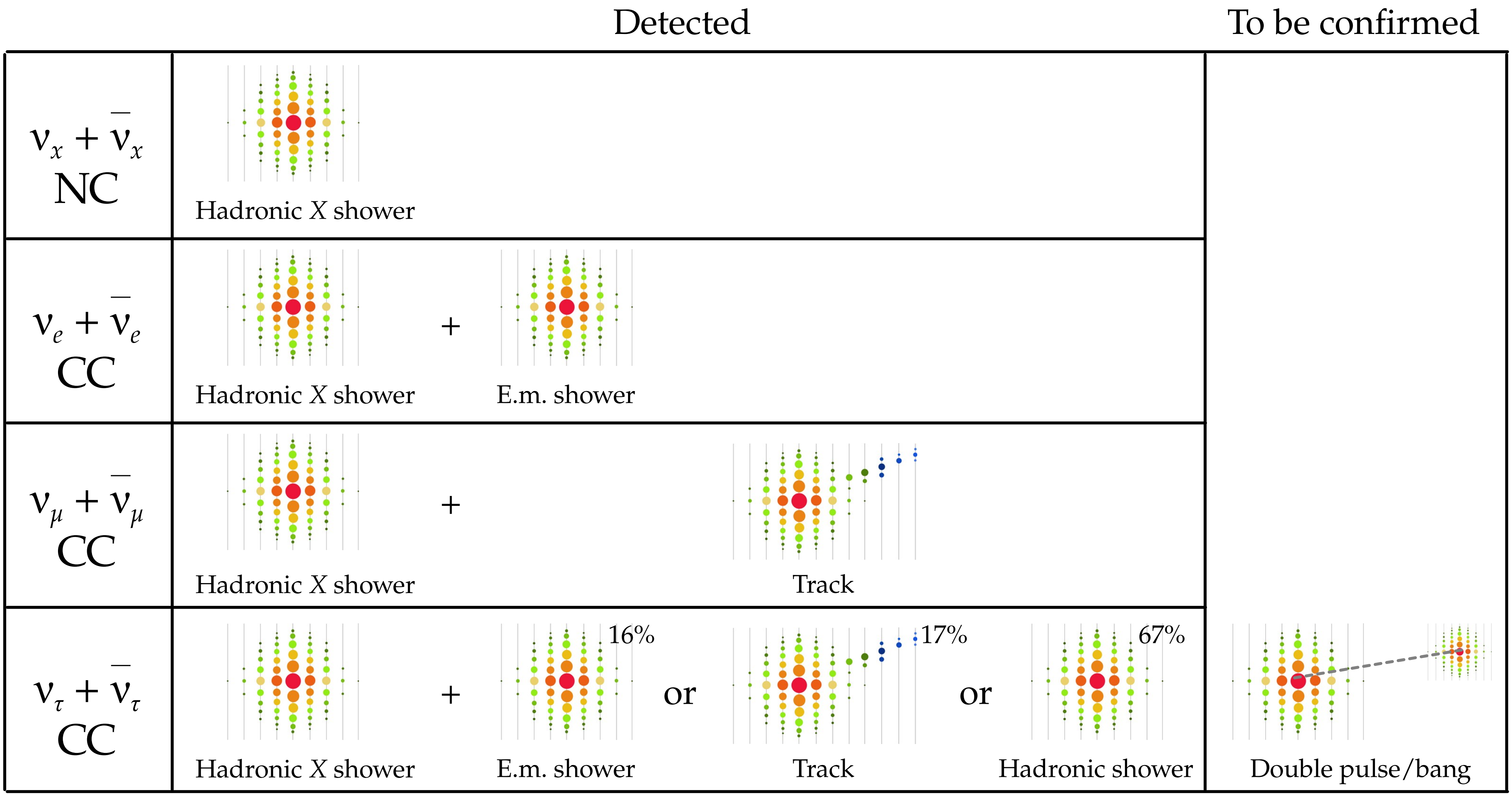
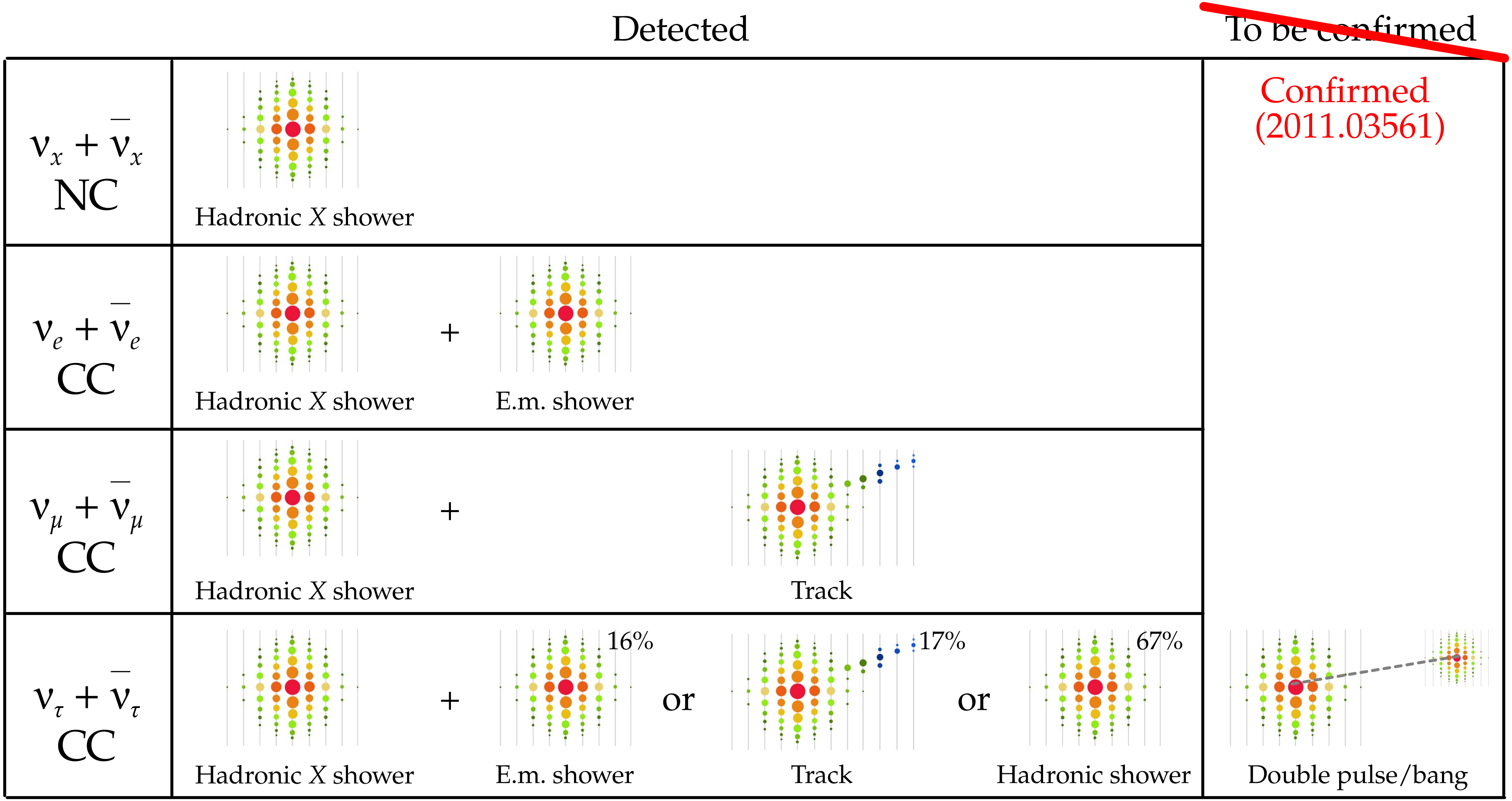


Detected
To be confirmed
$\nu_x + \bar{\nu}_x$ NC
Hadronic X shower
$\nu_e + \bar{\nu}_e$ CC
Hadronic X shower
+
E.m. shower
$\nu_\mu + \bar{\nu}_\mu$ CC
Hadronic X shower
+
Track
$\nu_\tau + \bar{\nu}_\tau$ CC
Hadronic X shower
+
16%
E.m. shower
or
17%
Track
or
67%
Hadronic shower
Double pulse/bang


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
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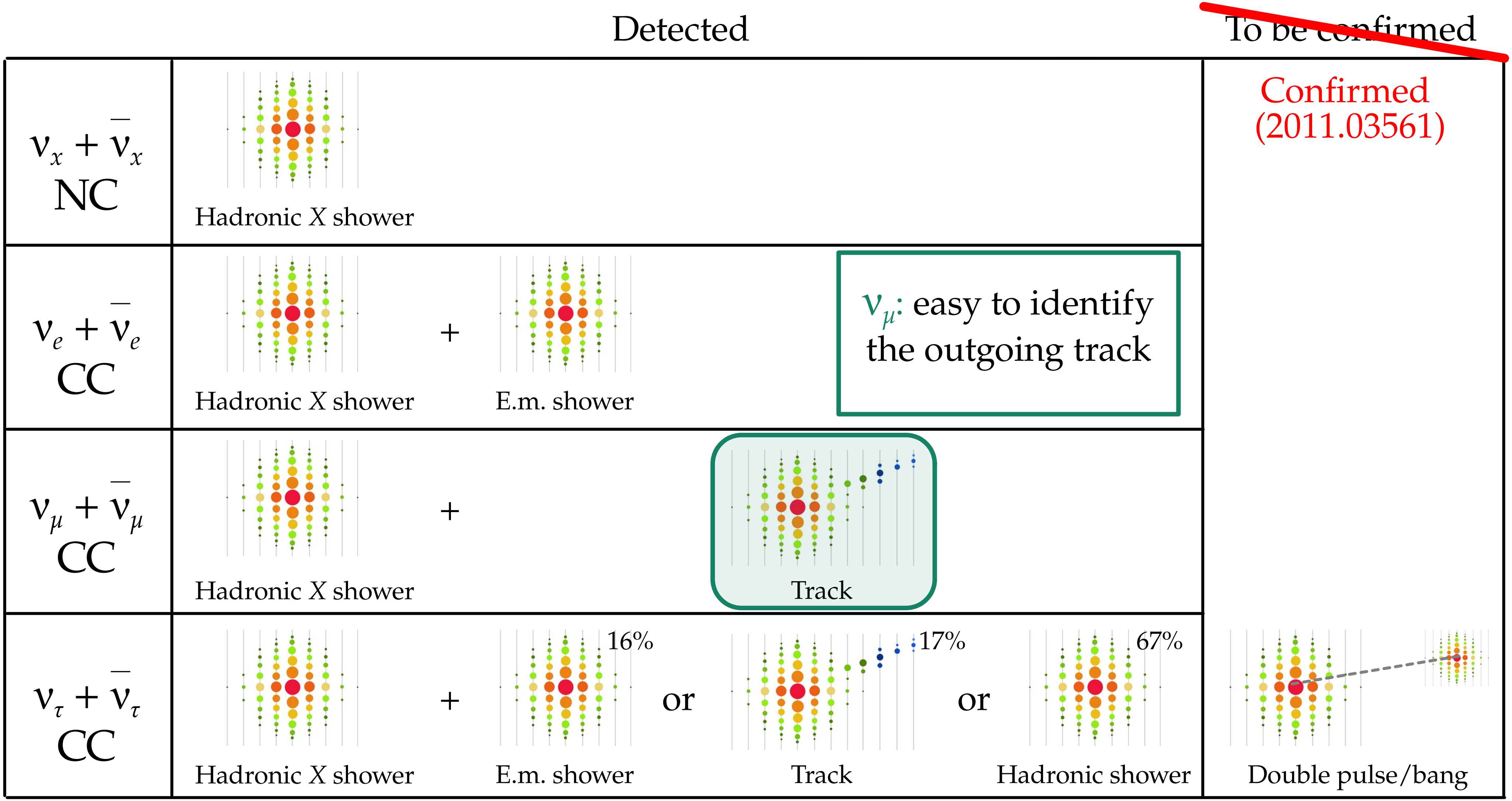
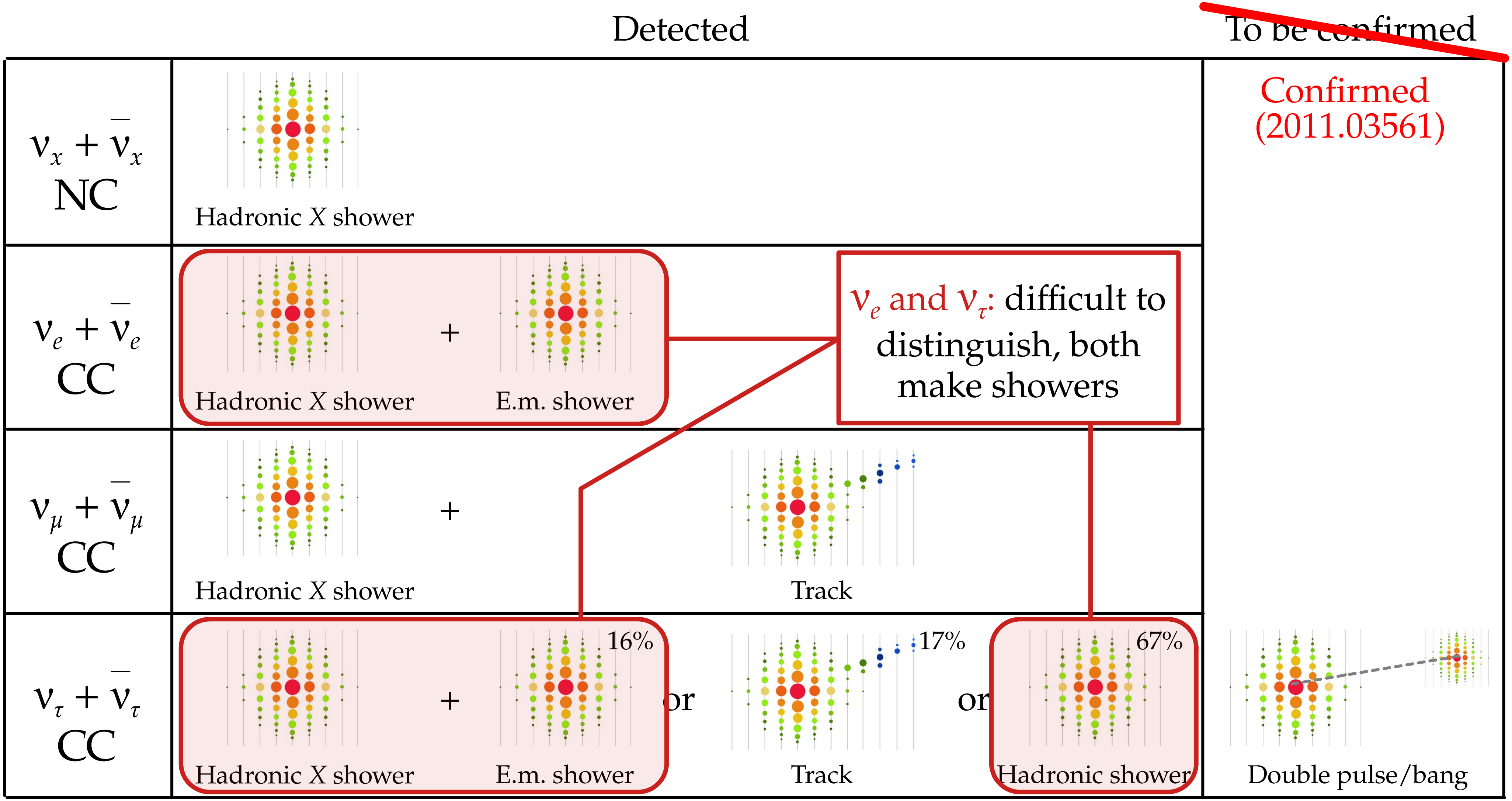
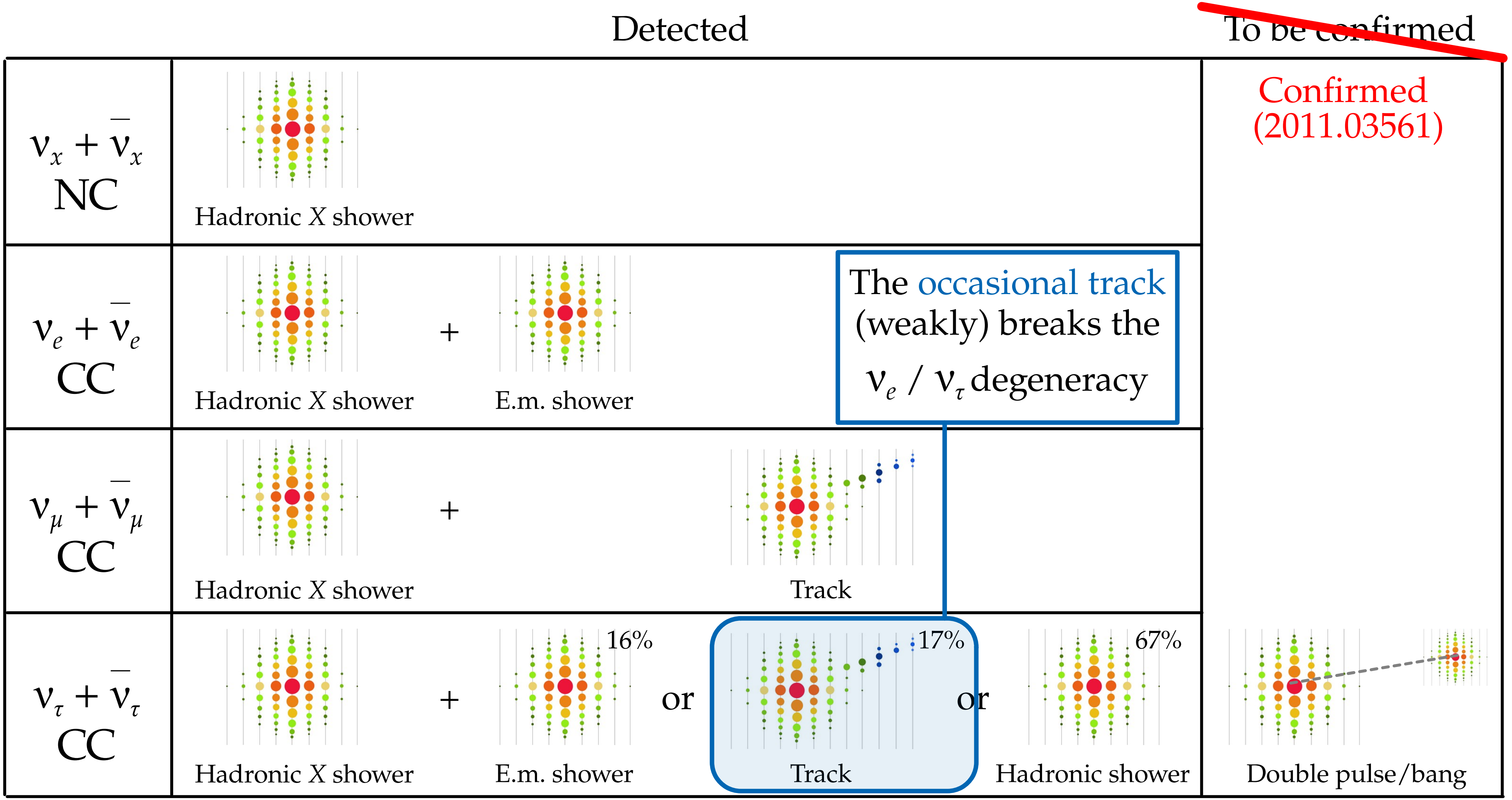
67%
Hadronic shower
Double pulse/bang



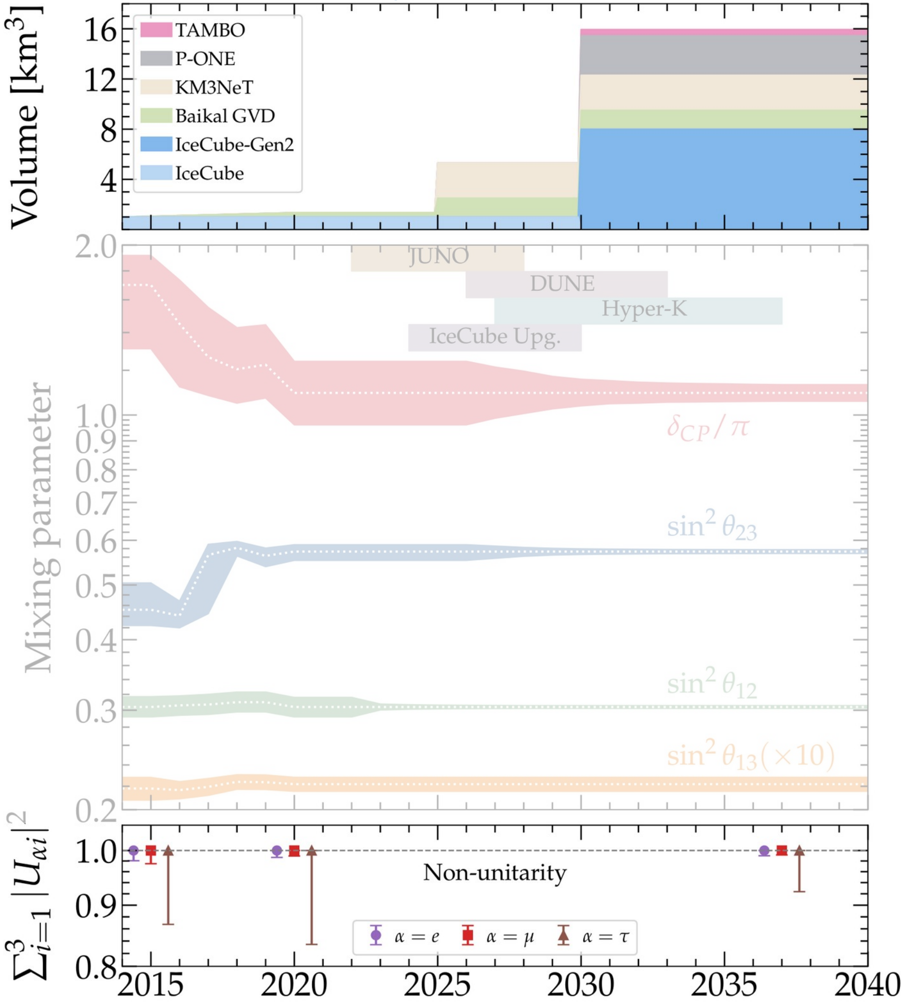
Detected
To be confirmed
Confirmed
(2011.03561)
$\nu_x + \bar{\nu}_x$ NC
Hadronic X shower
$\nu_e + \bar{\nu}_e$ CC
Hadronic X shower
+
E.m. shower
ν_μ: easy to identify the outgoing track
$\nu_\mu + \bar{\nu}_\mu$ CC
Hadronic X shower
+
Track
$\nu_\tau + \bar{\nu}_\tau$ CC
Hadronic X shower
+
16%
E.m.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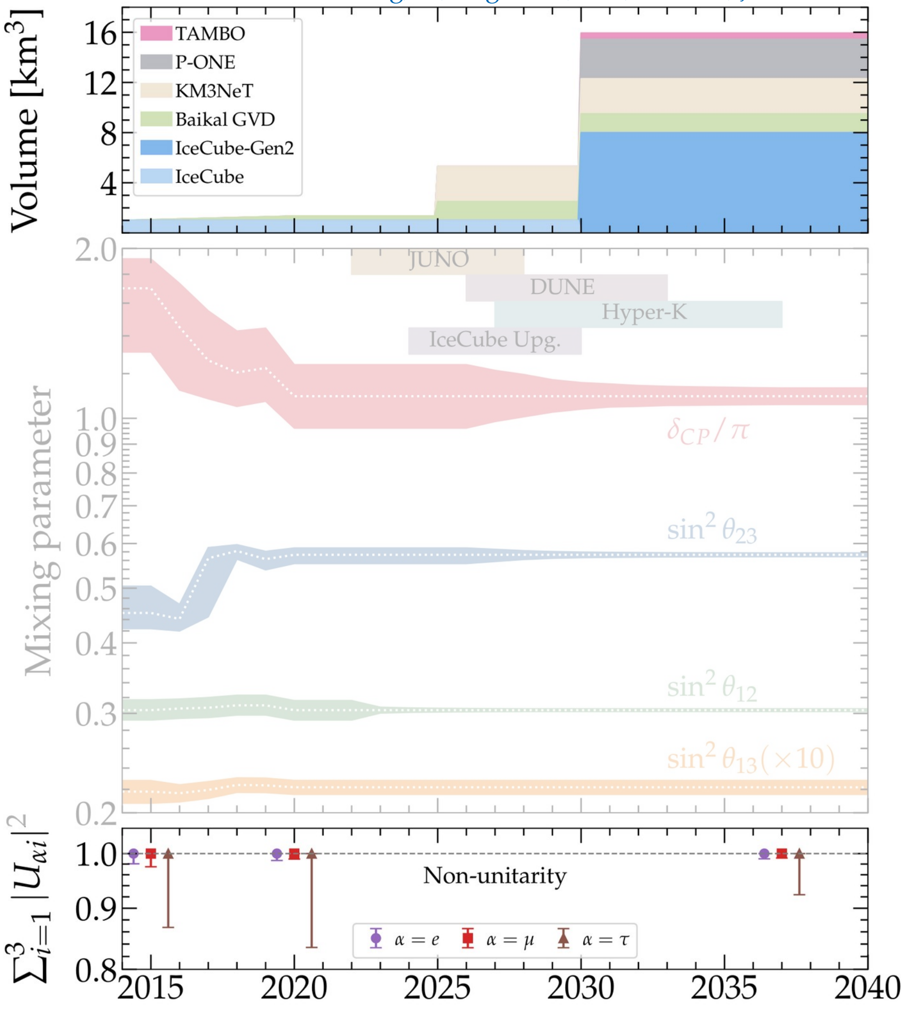

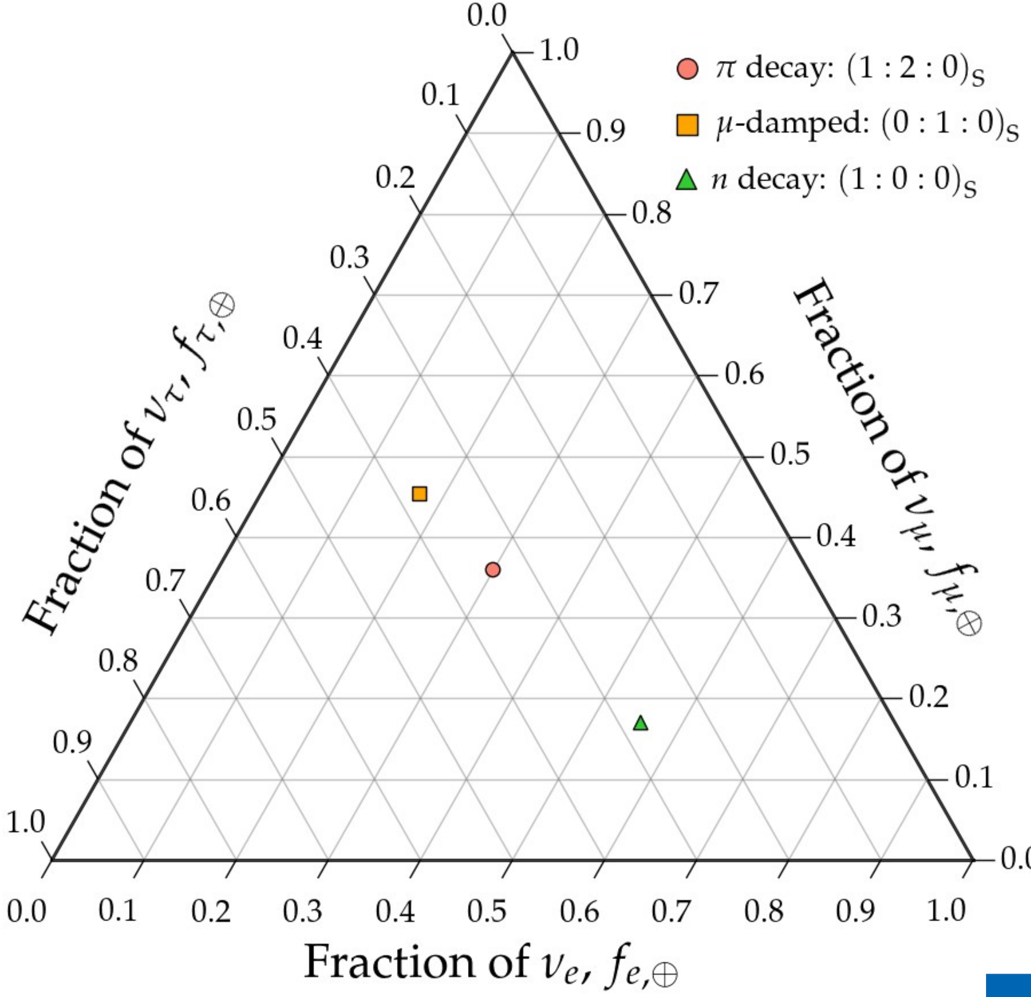

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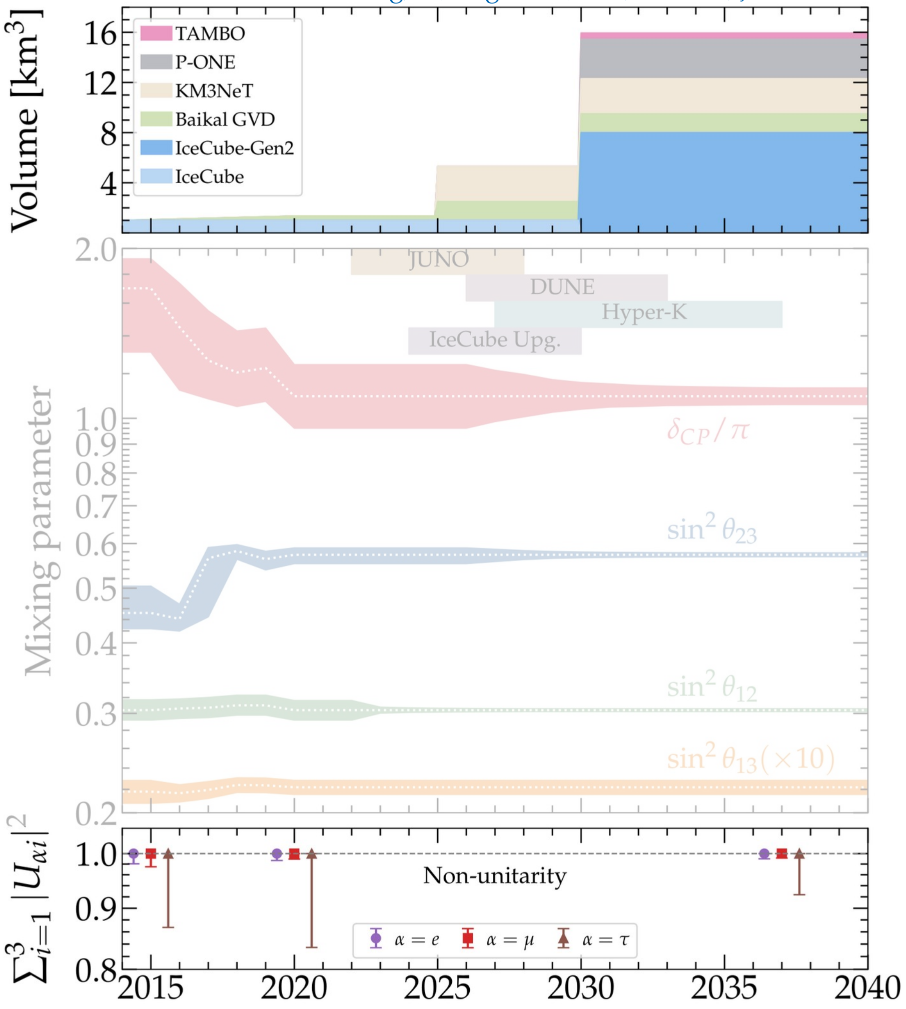

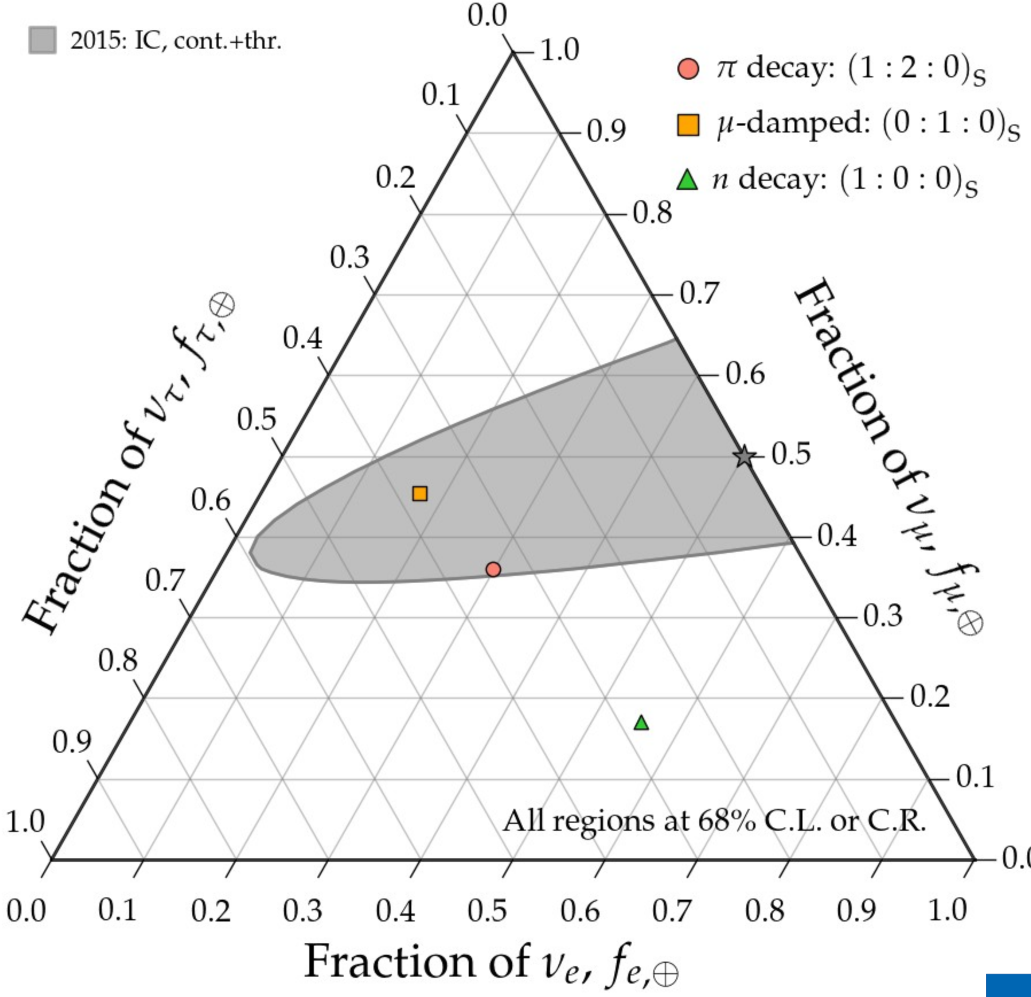

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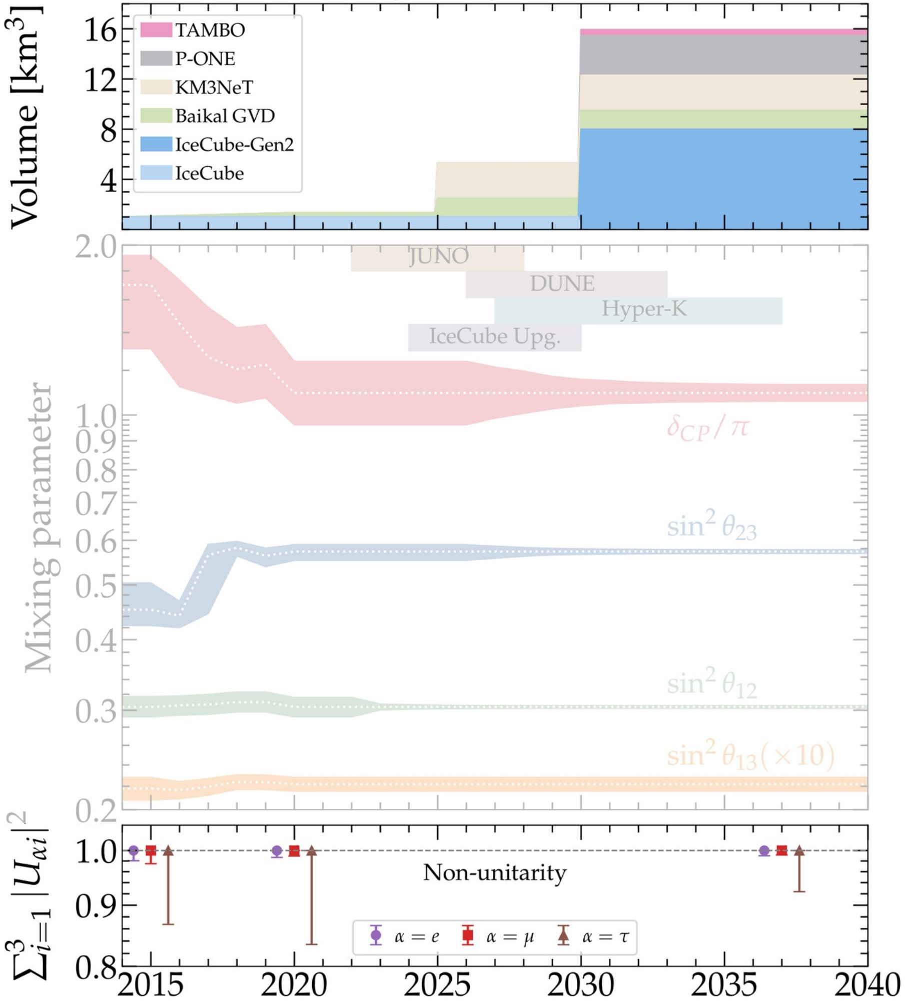

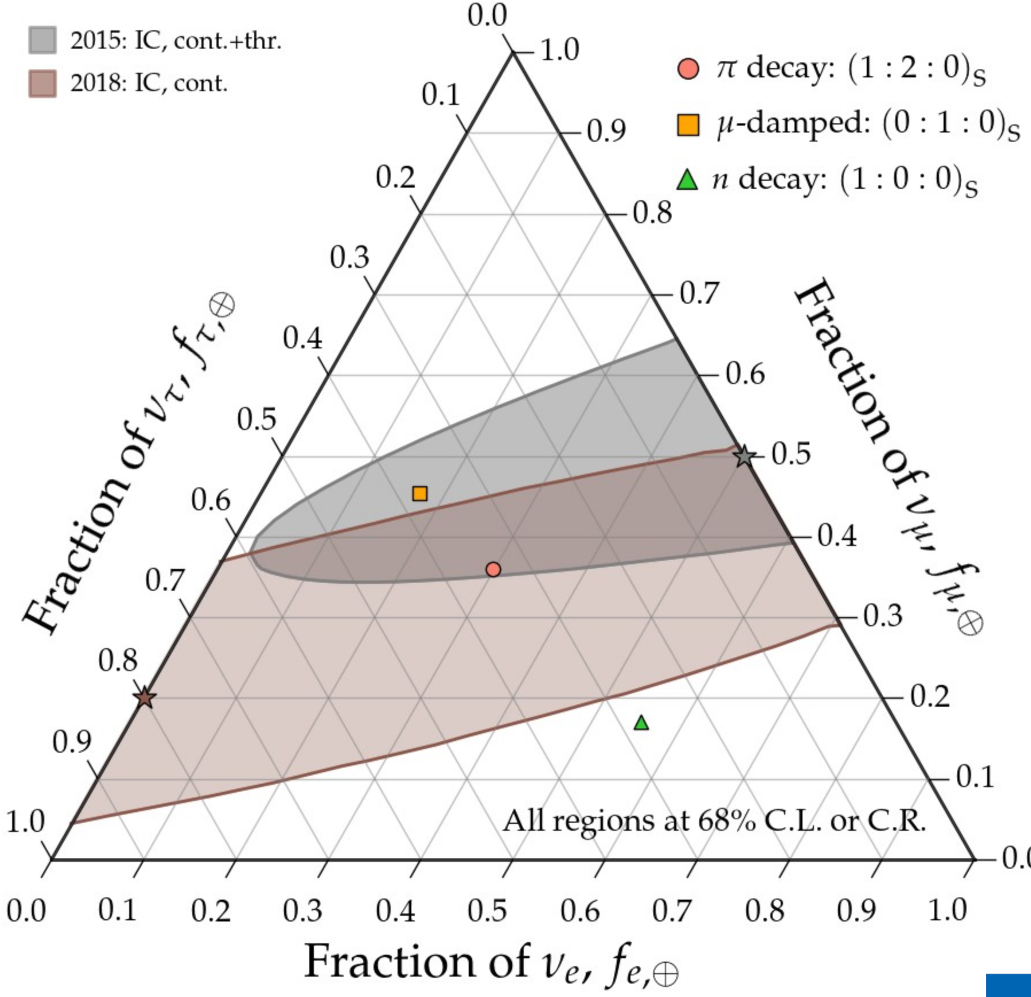

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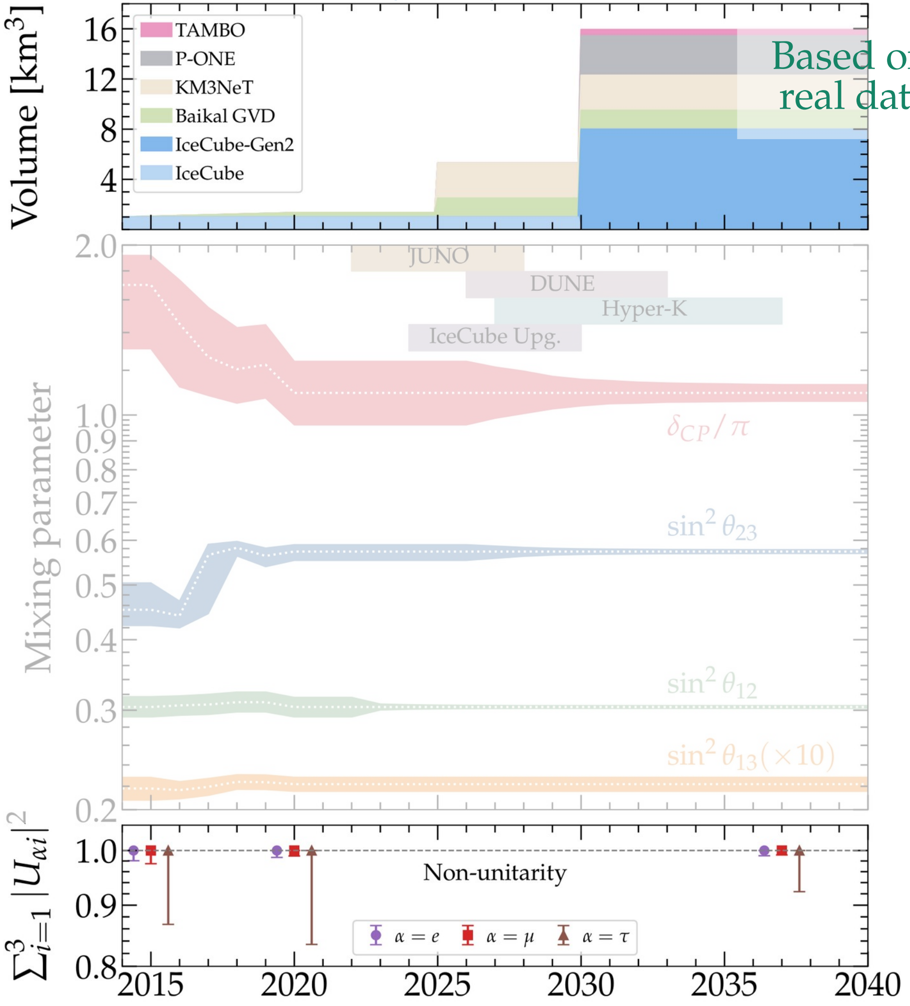
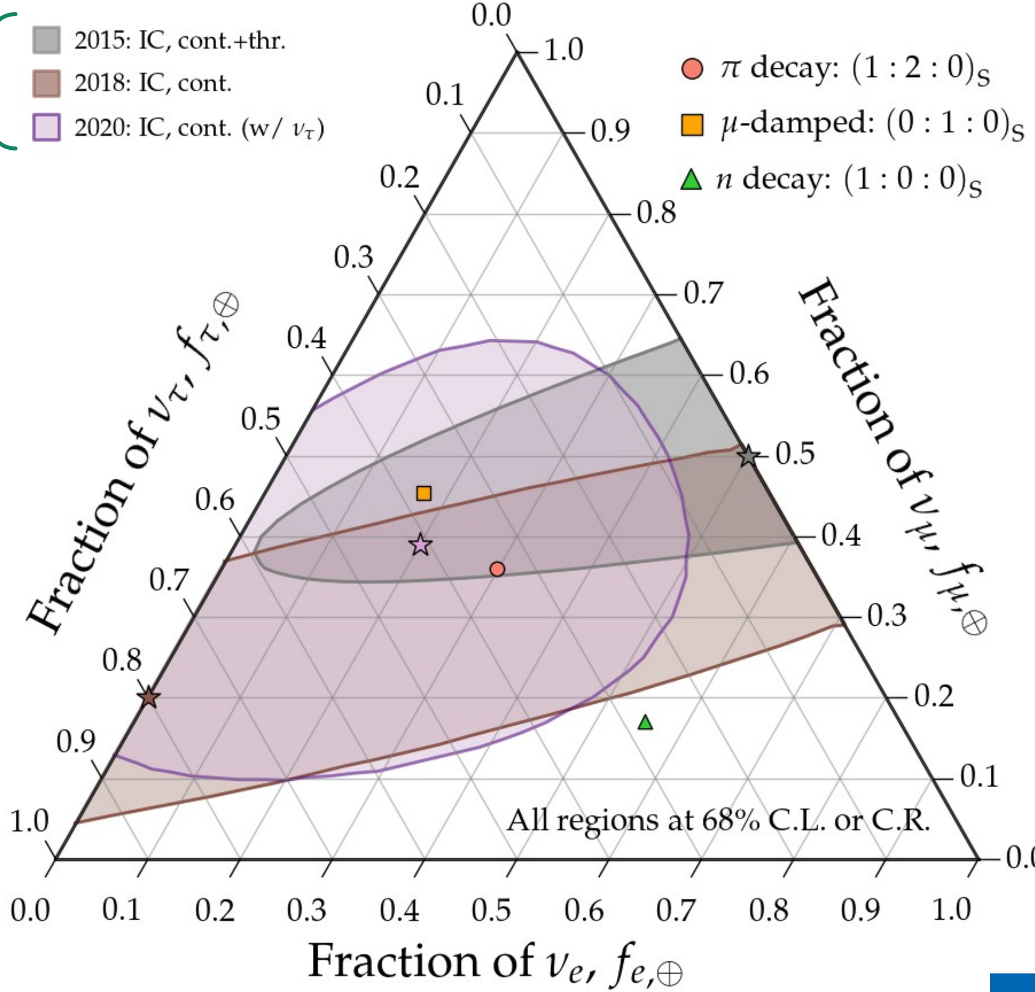


Based on real data



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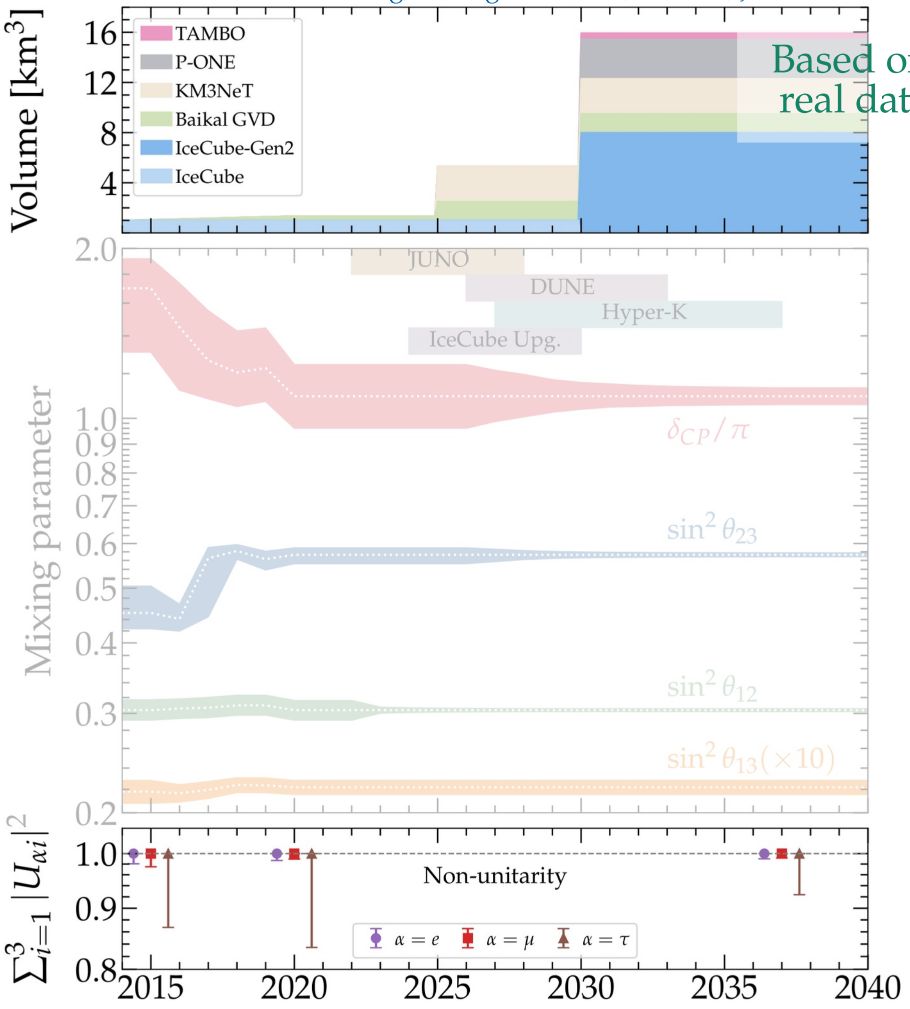

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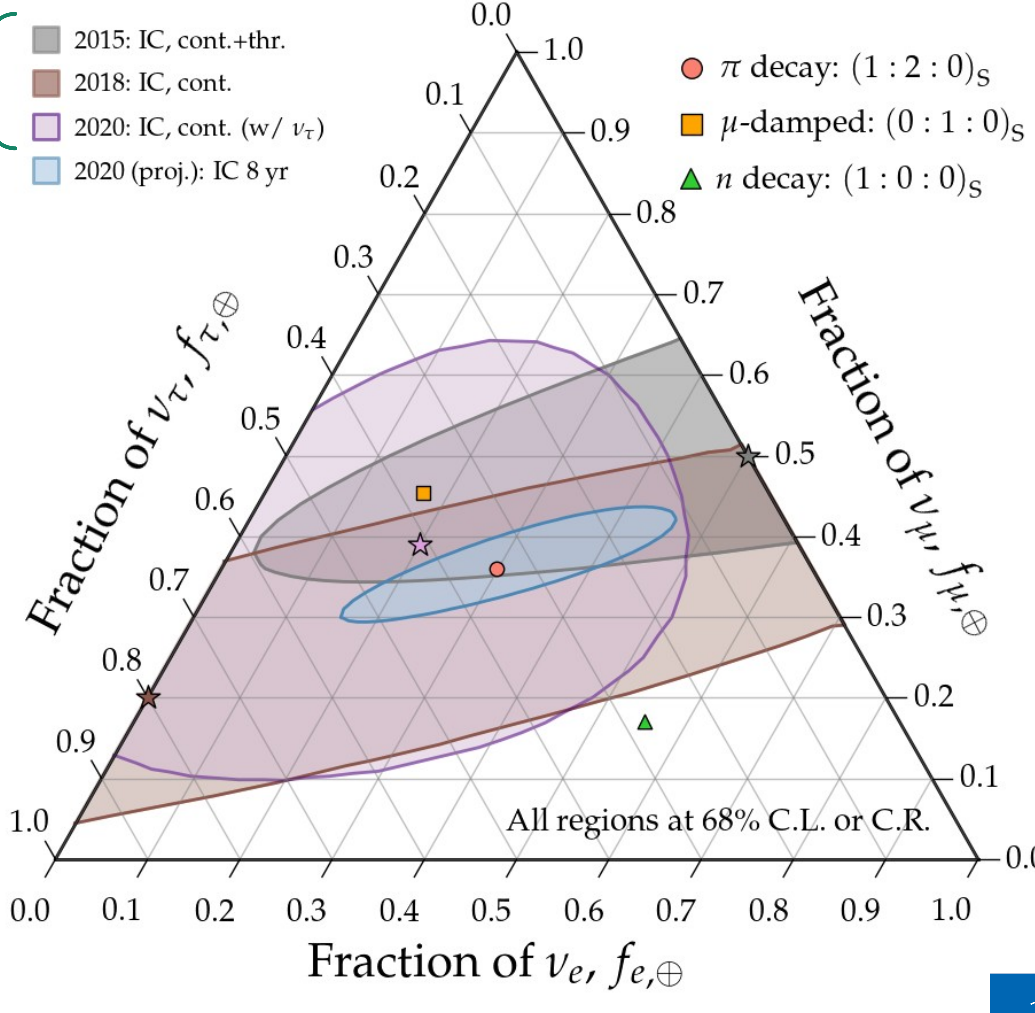

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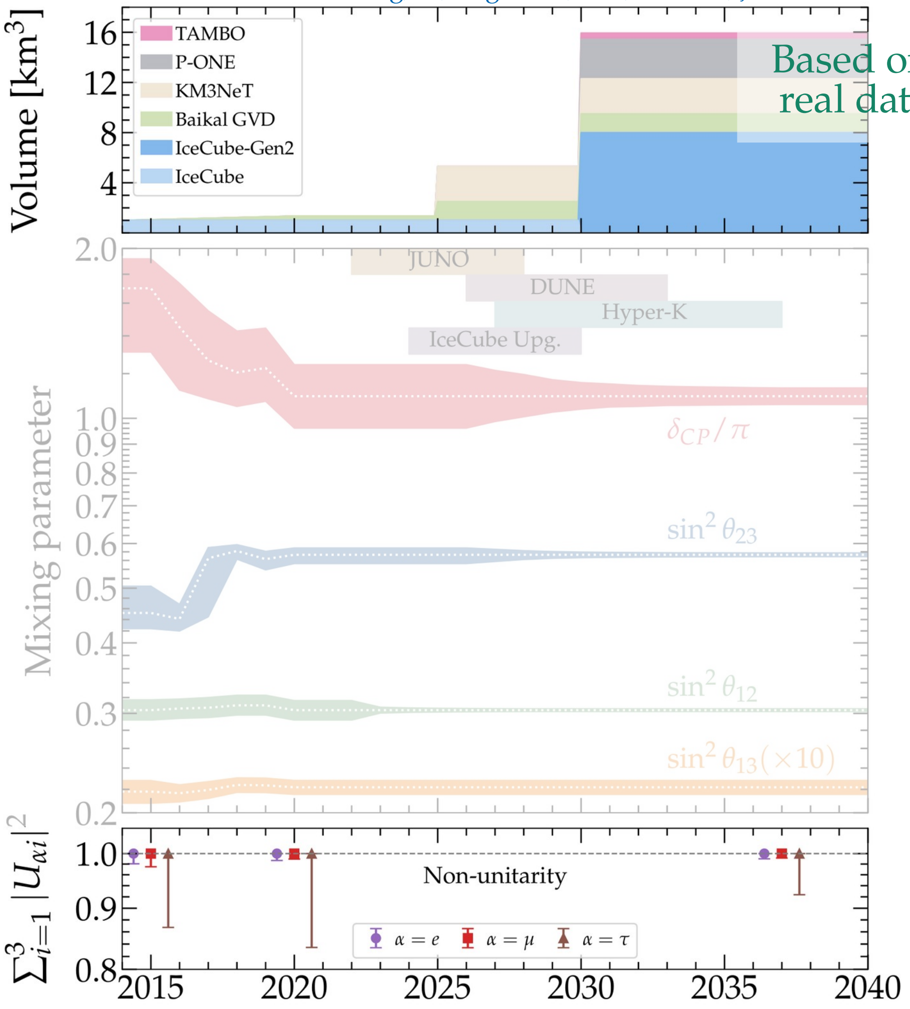

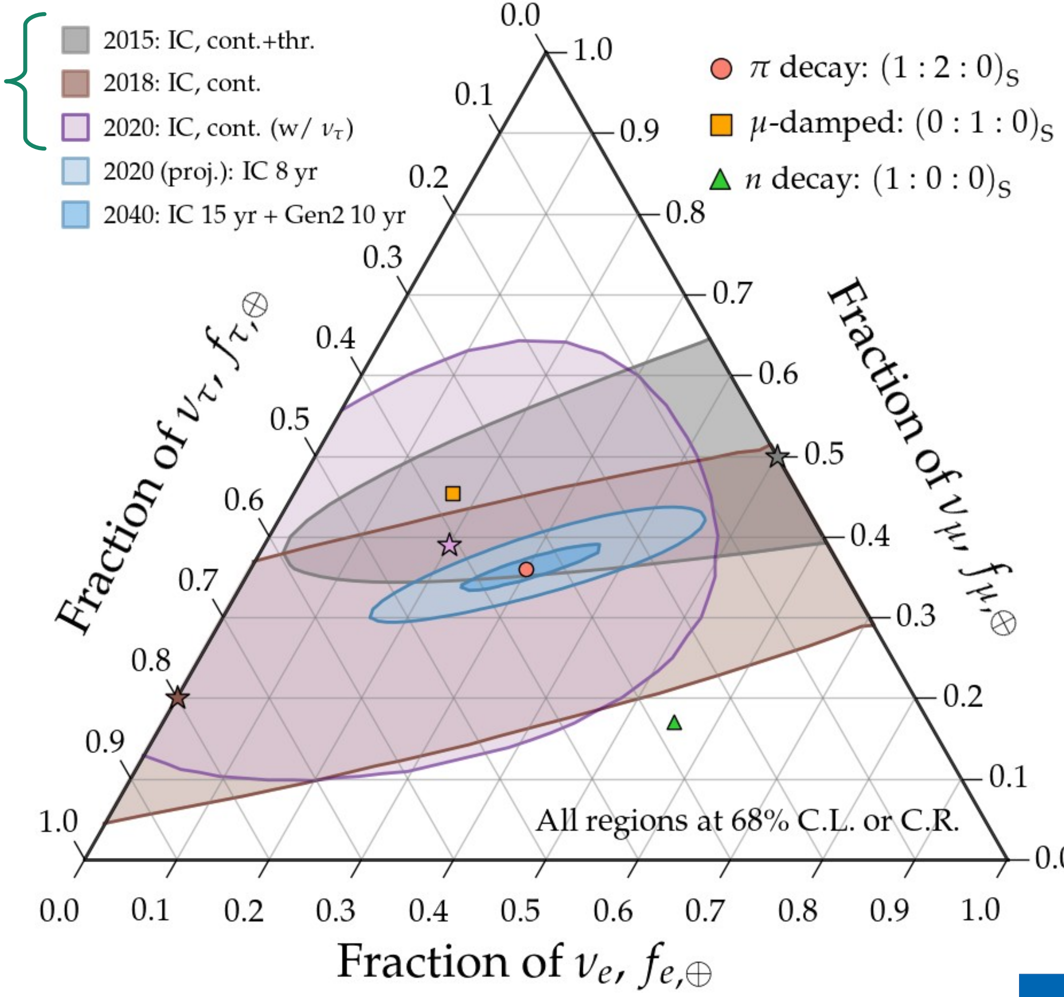

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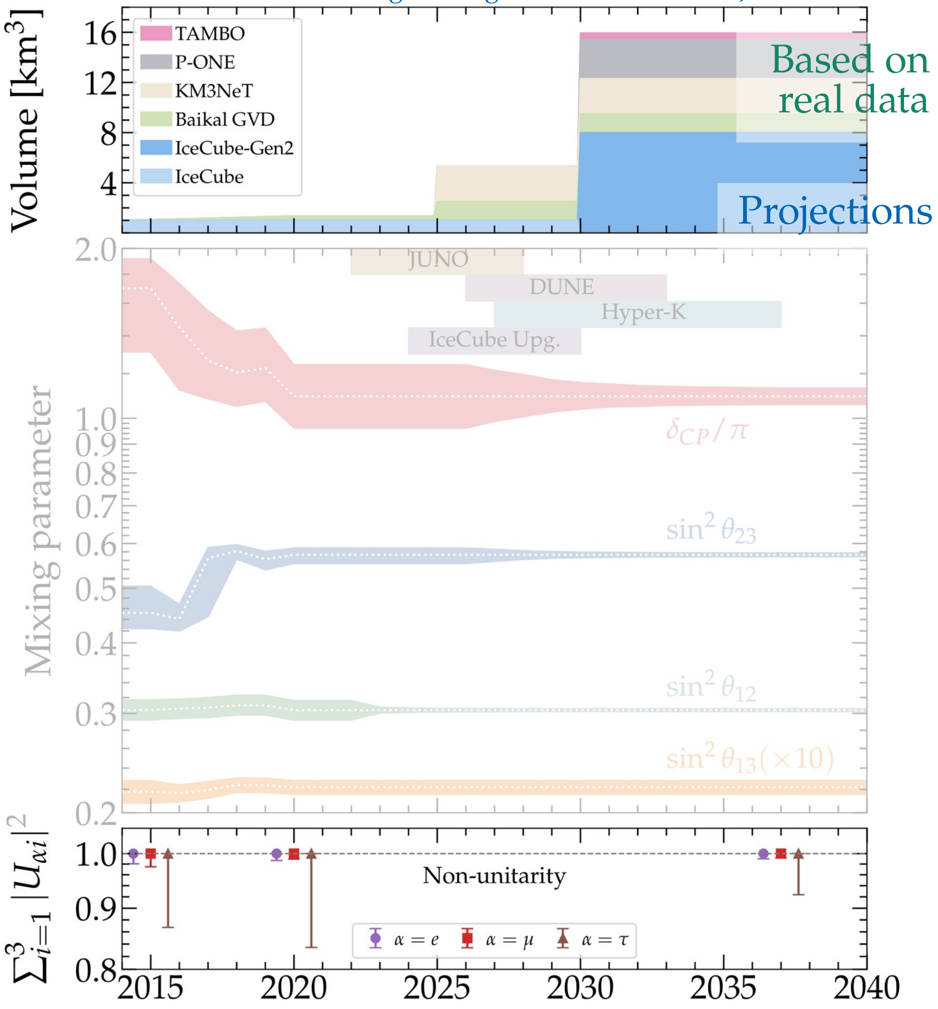

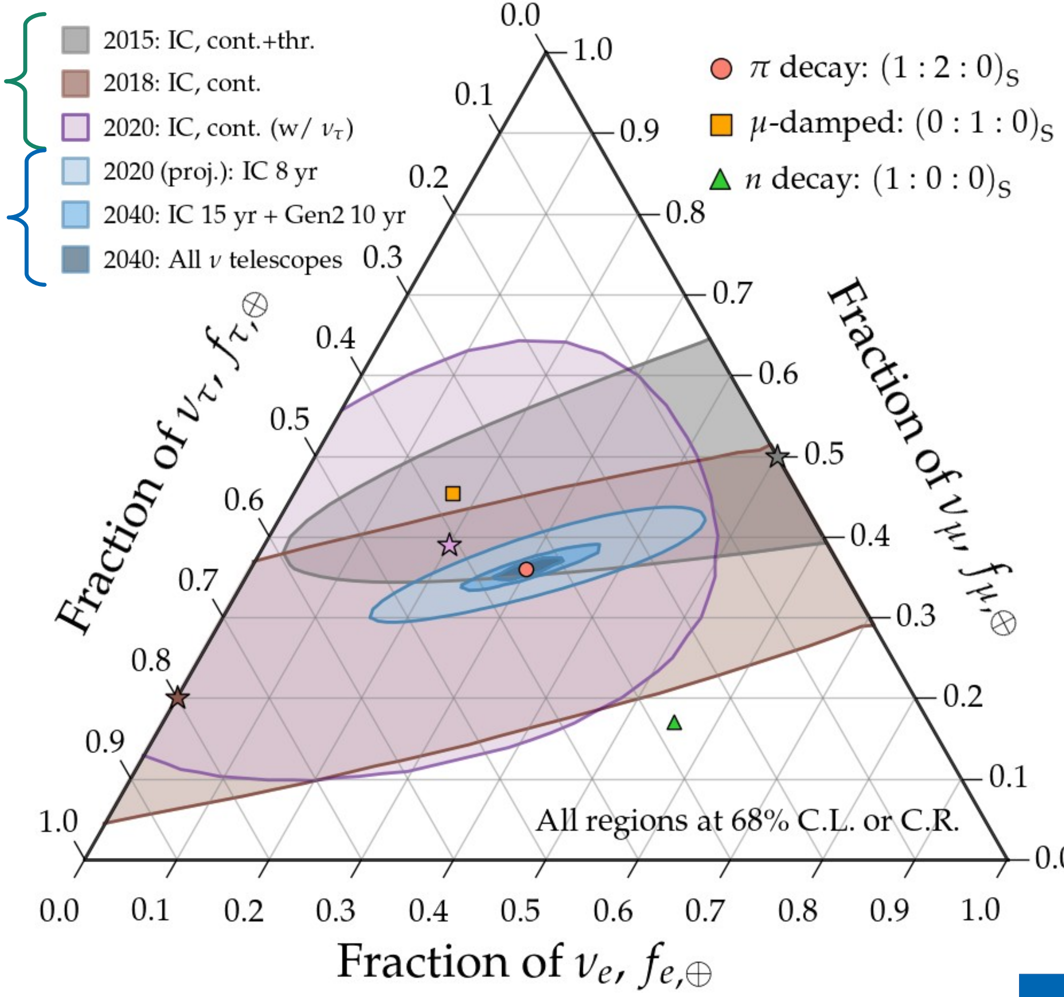

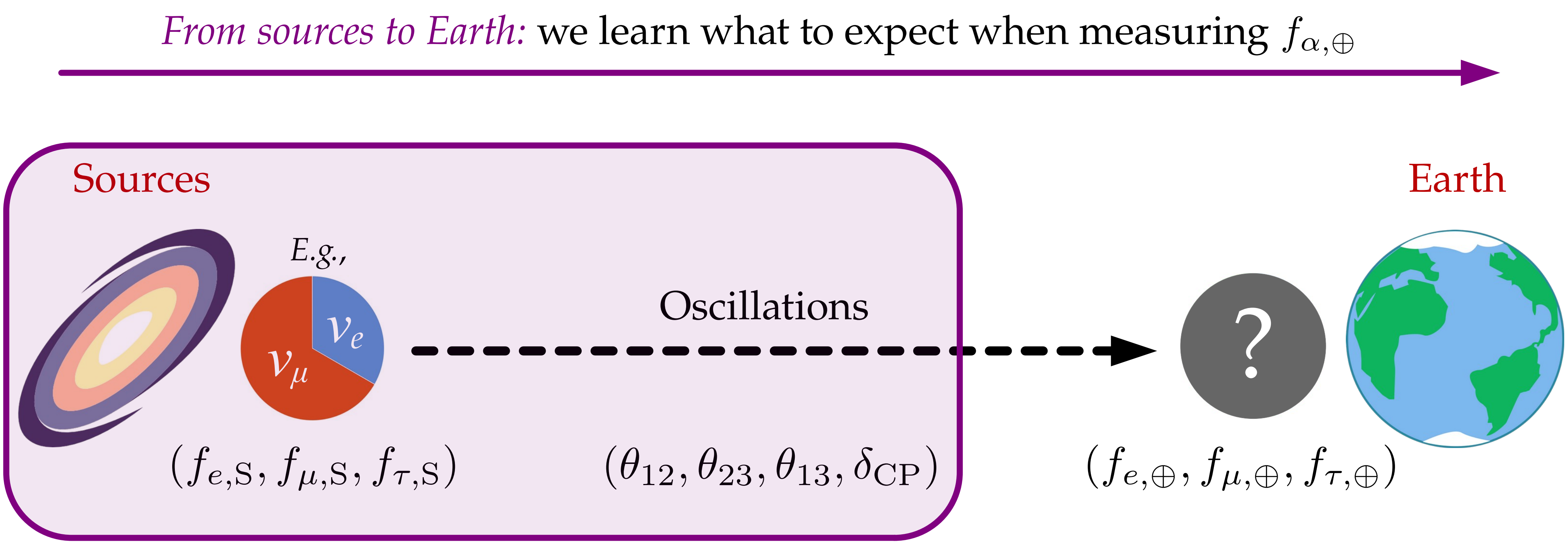
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Oscillations
$(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\mathrm{CP}})$
?
Earth
$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$

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:

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

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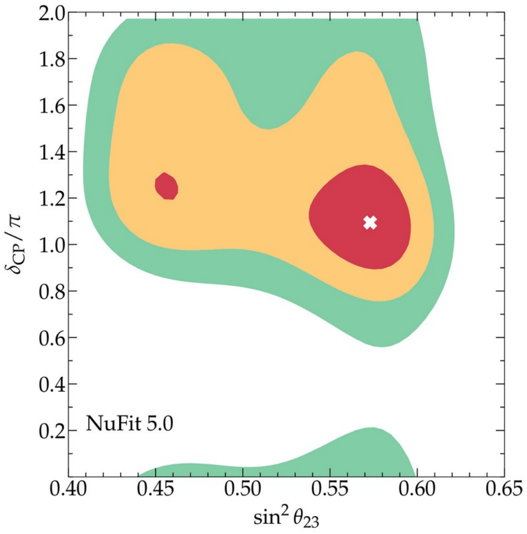
2020: Use χ^2 profiles from the NuFit 5.0 global fit (solar + atmospheric + reactor + accelerator)

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



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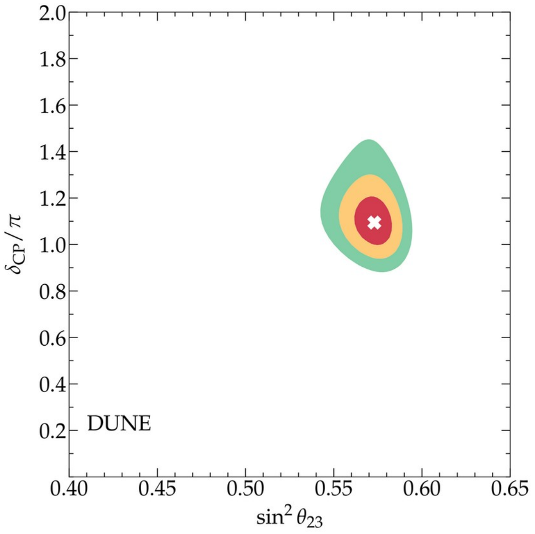
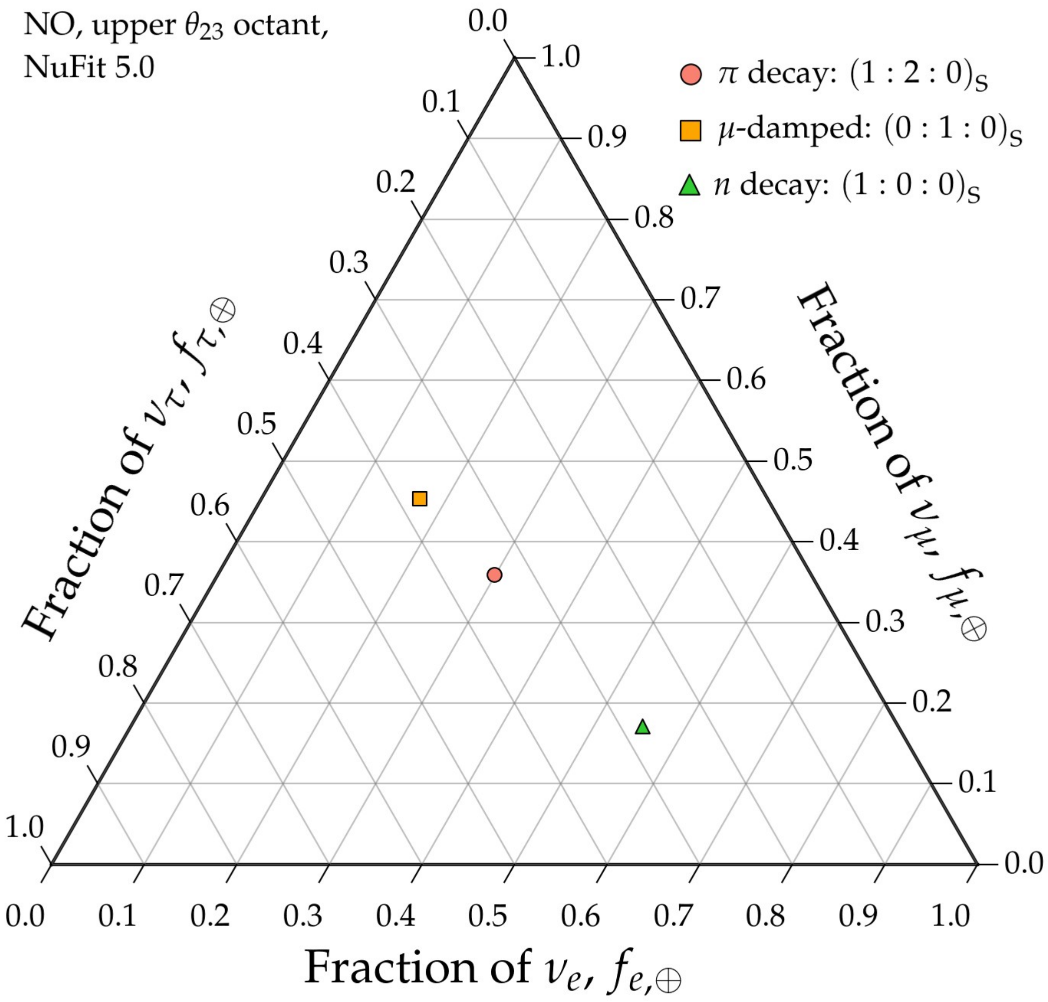
Post-2020: Build our own profiles using simulations of JUNO, DUNE, Hyper-K

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



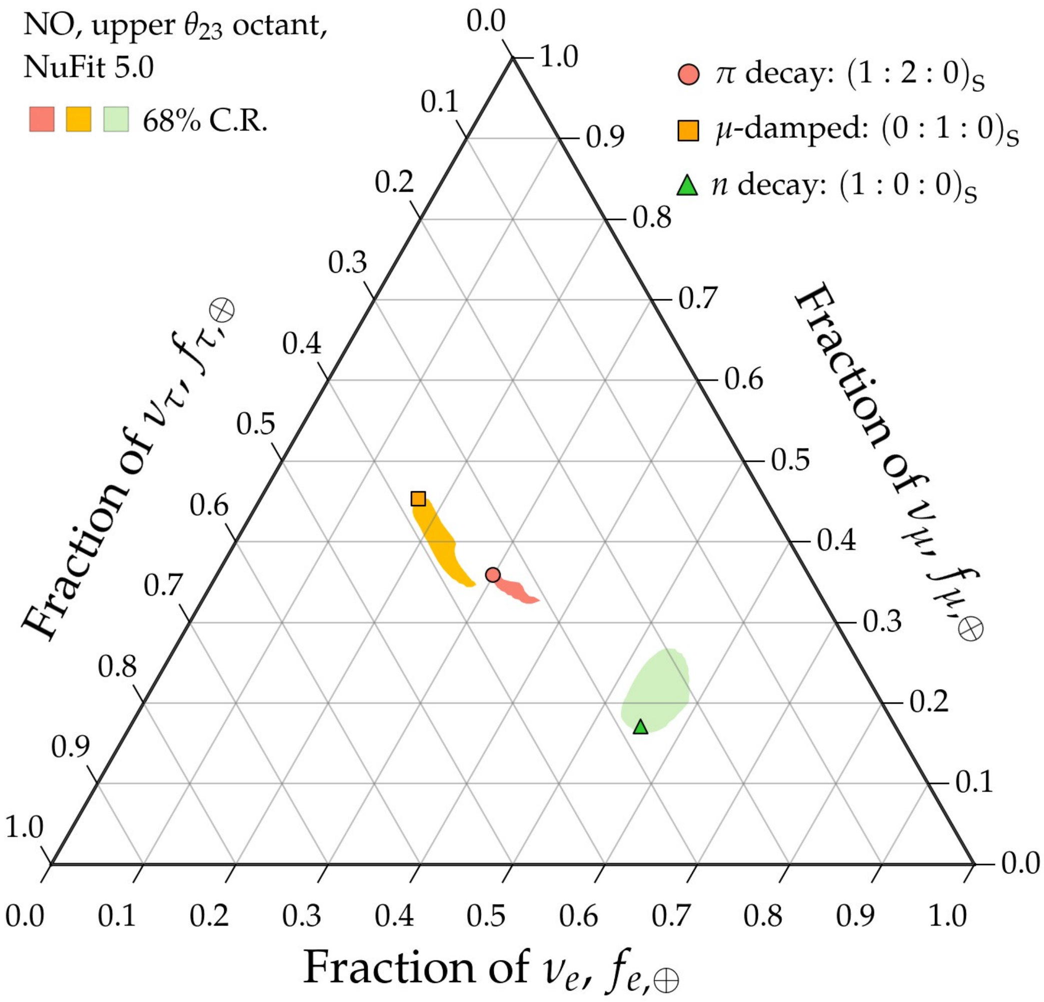
Theoretically palatable regions: today (2021)



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

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

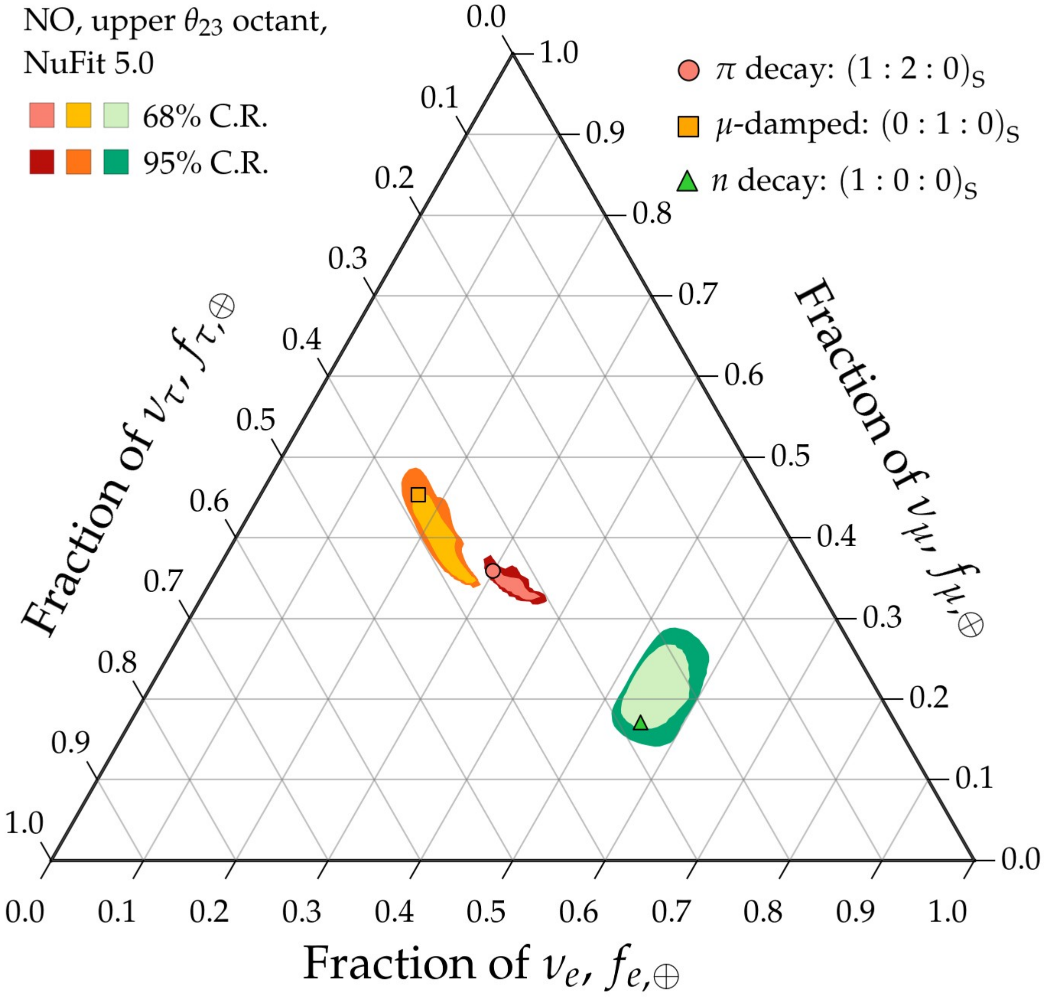
Theoretically palatable regions: today (2021)



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

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

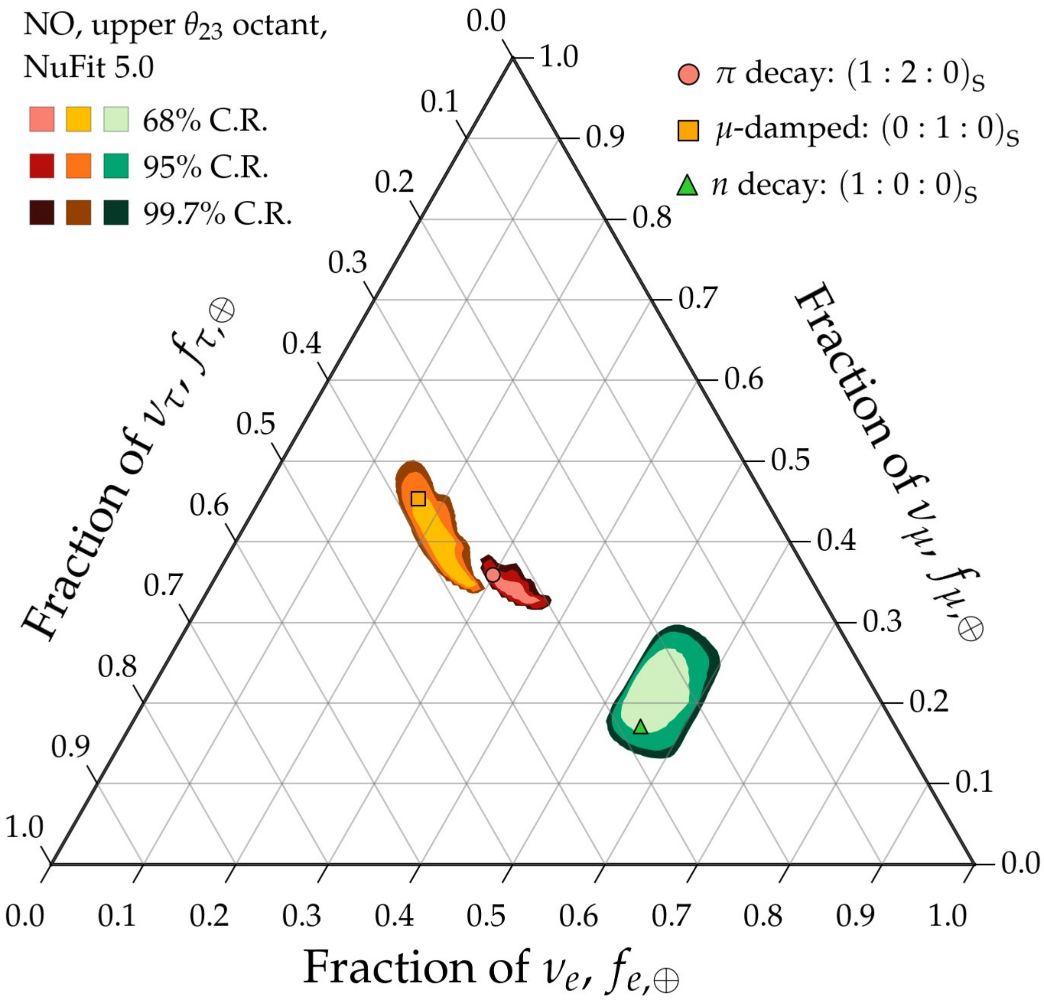
Theoretically palatable regions: today (2021)



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

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

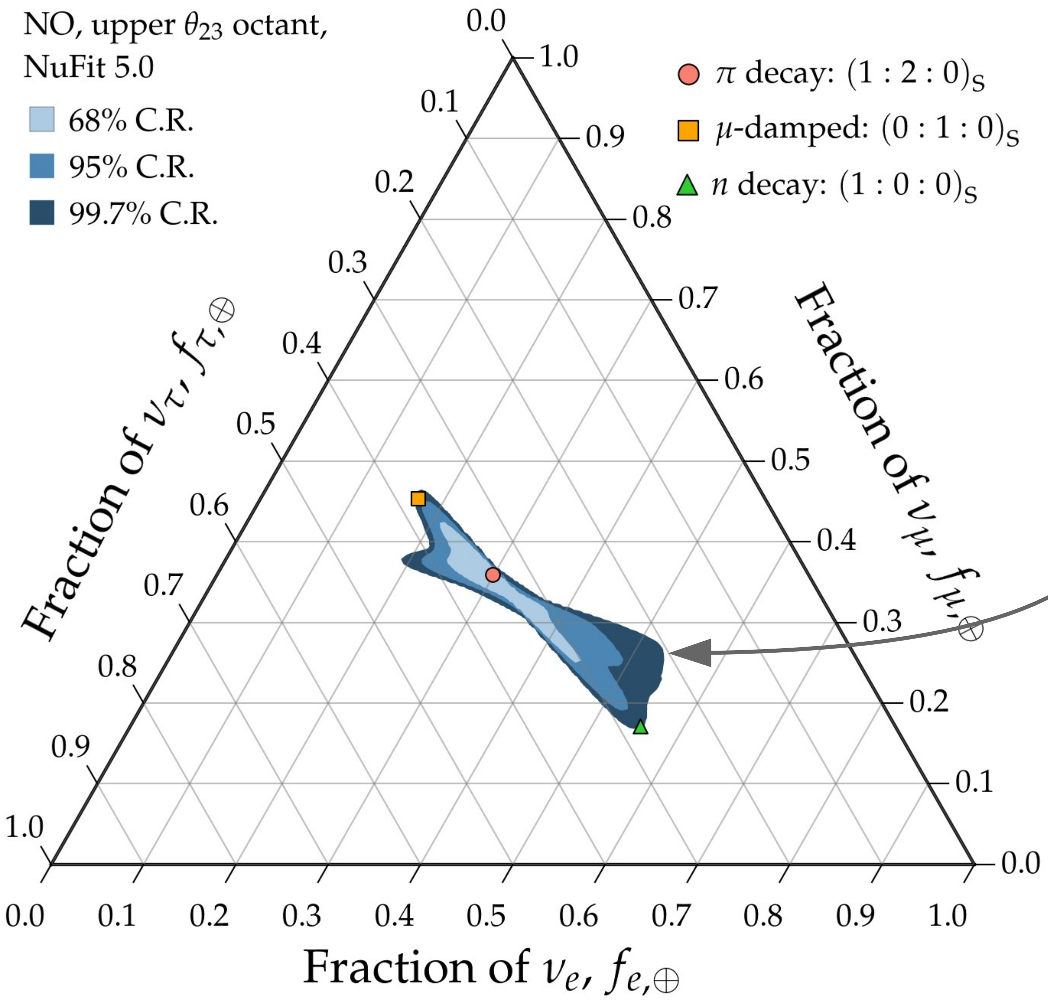
Theoretically palatable regions: today (2021)



Note:
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)

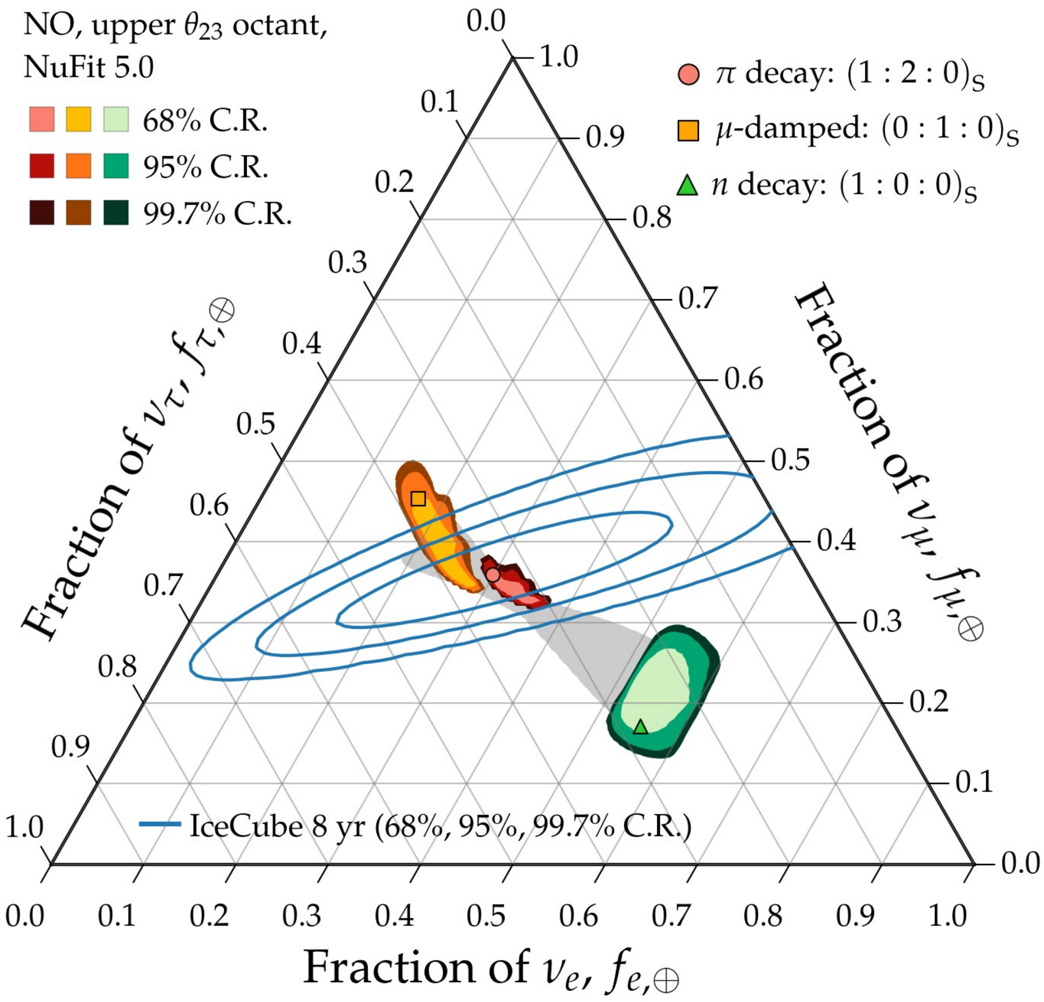


Varying over all possible flavor ratios at the source

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

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

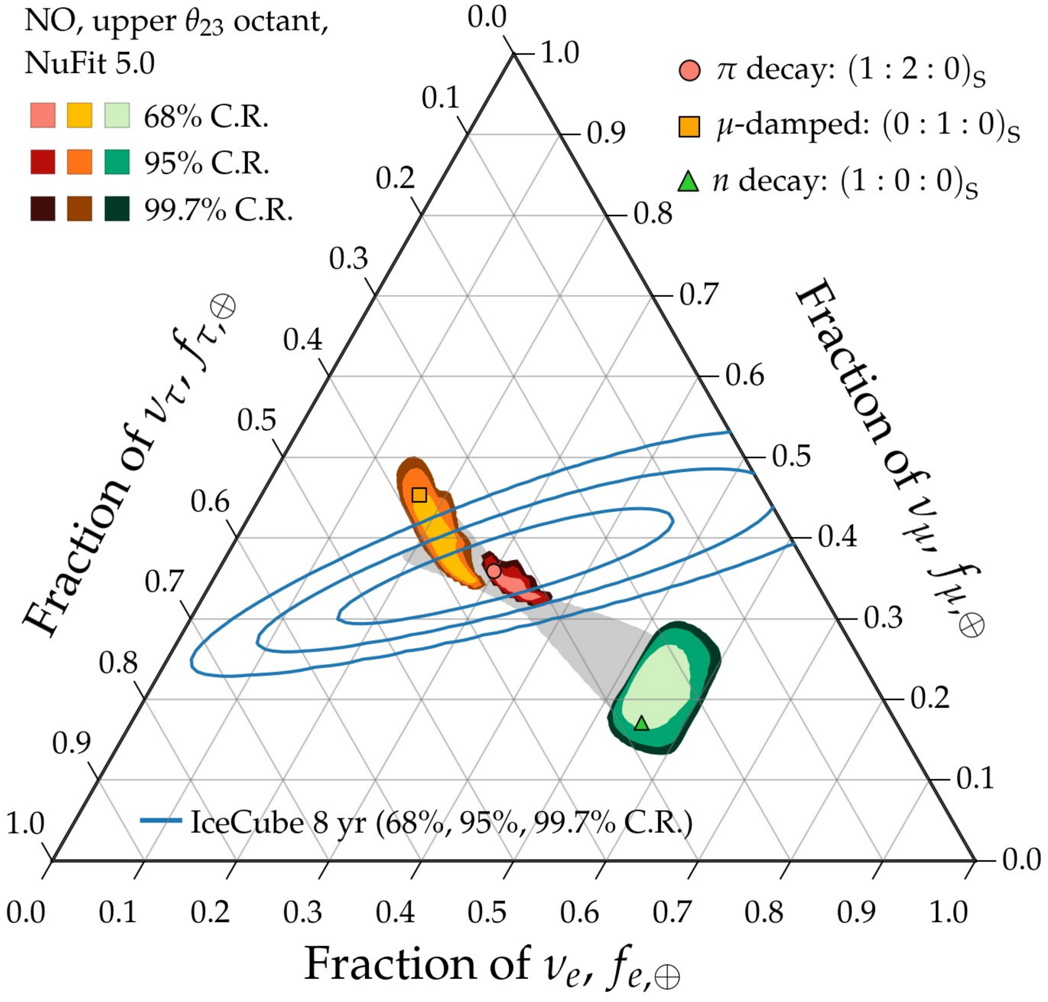
Theoretically palatable regions: today (2021)



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)



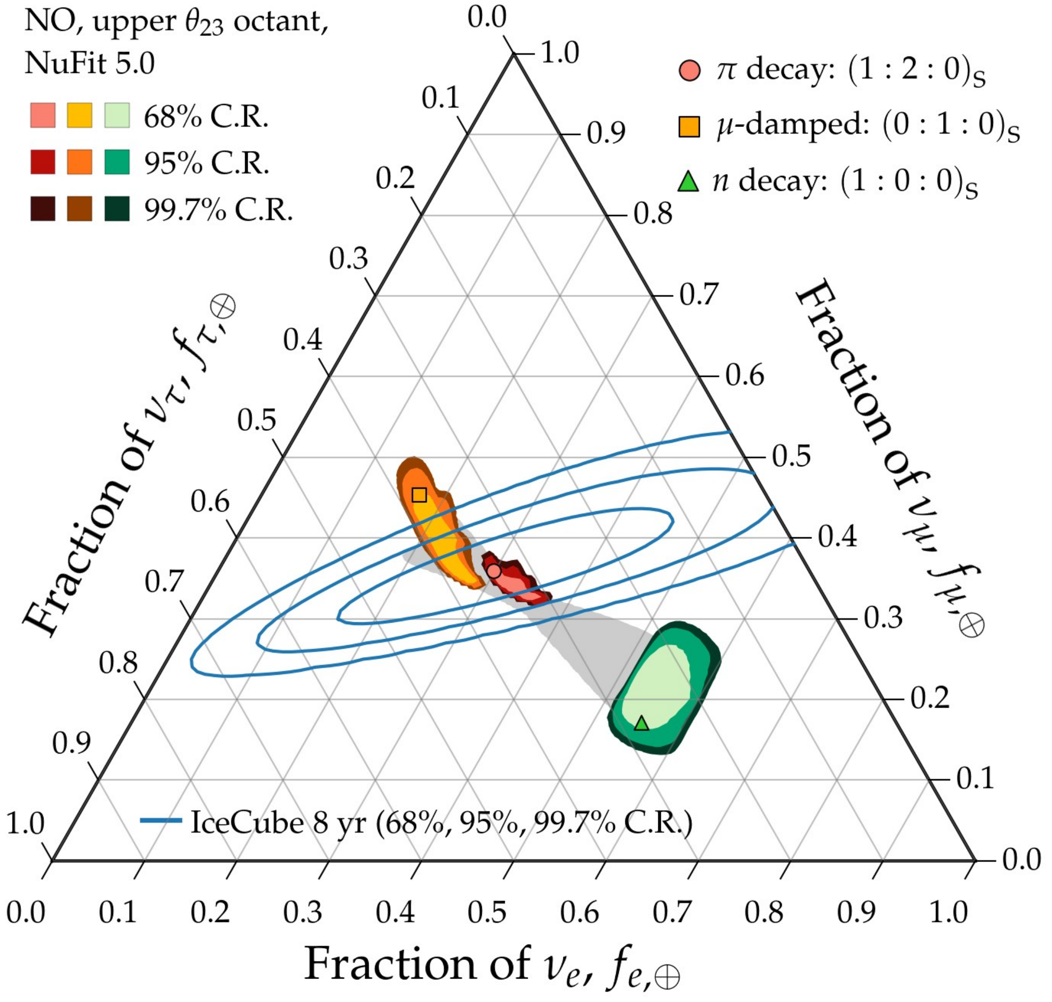
Two limitations:

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:

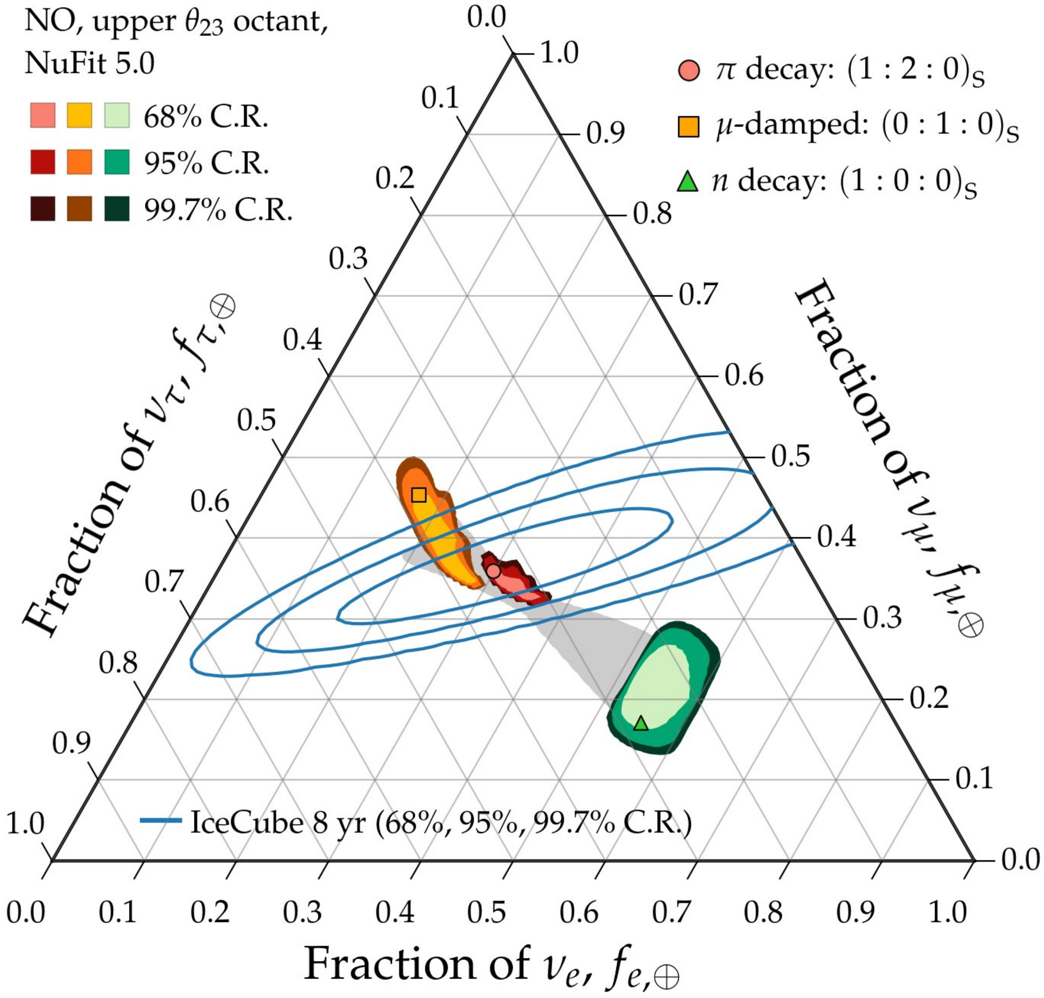
Allowed flavor regions overlap –
Insufficient precision in the mixing parameters

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

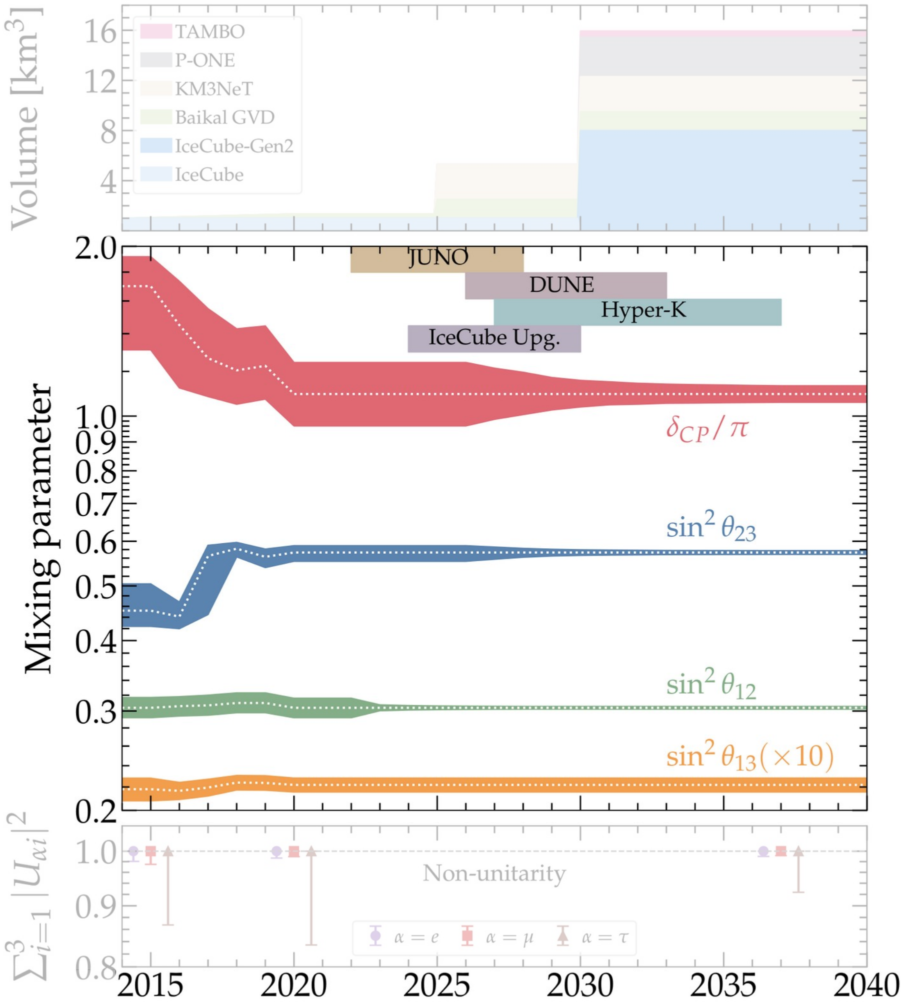
Will be overcome by 2030

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

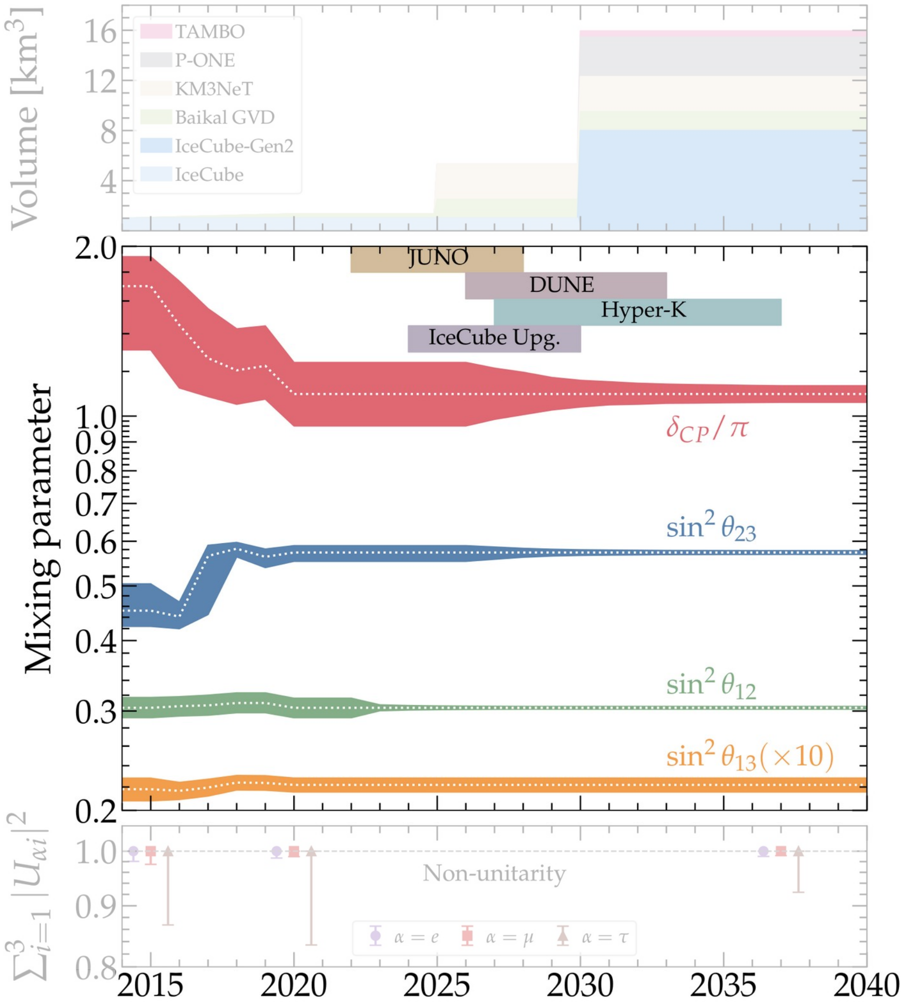


We can compute the oscillation probability more precisely:

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

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

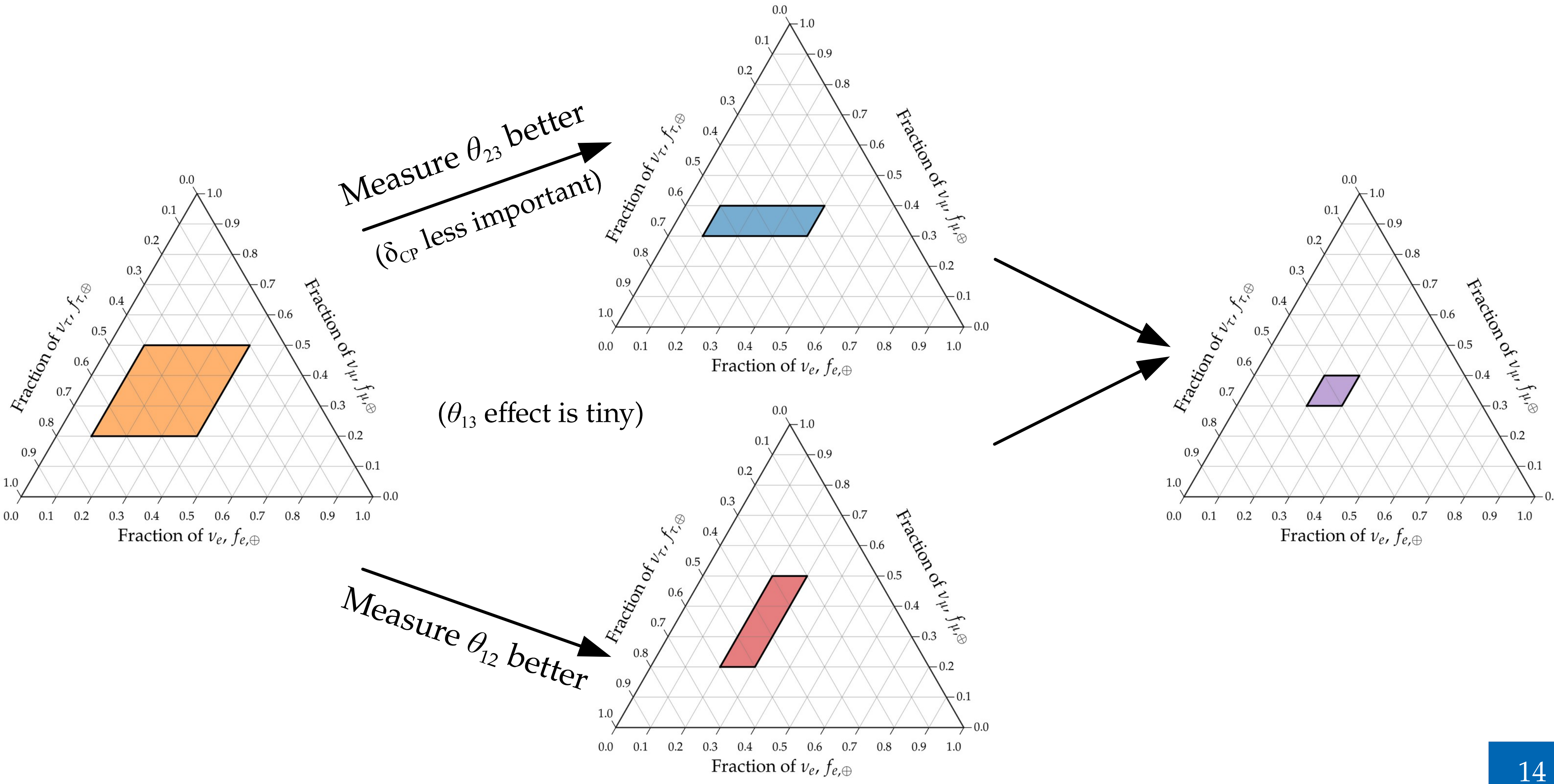
$$\chi^2_\varepsilon(\boldsymbol{\vartheta}) = \sum_i \frac{(\vartheta_i - \bar{\vartheta}_i)^2}{\sigma^2_{i,\varepsilon}}$$

From our simulations

We combine experiments in a likelihood:

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

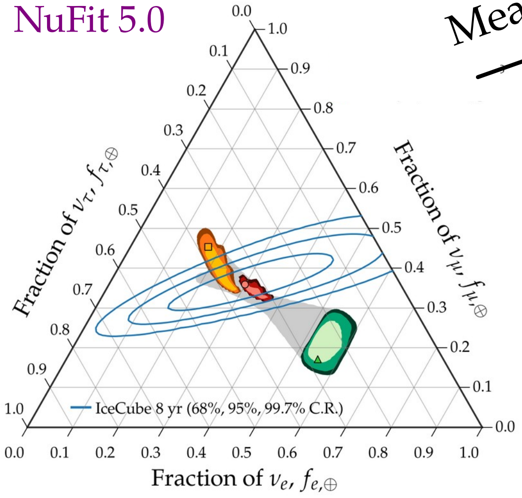
How knowing the mixing parameters better helps



How knowing the mixing parameters better helps

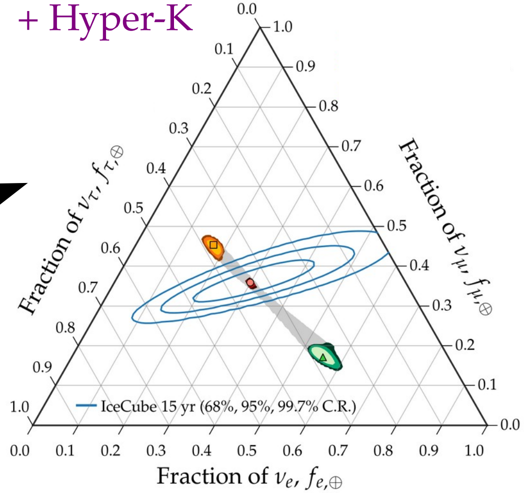
2020

NuFit 5.0



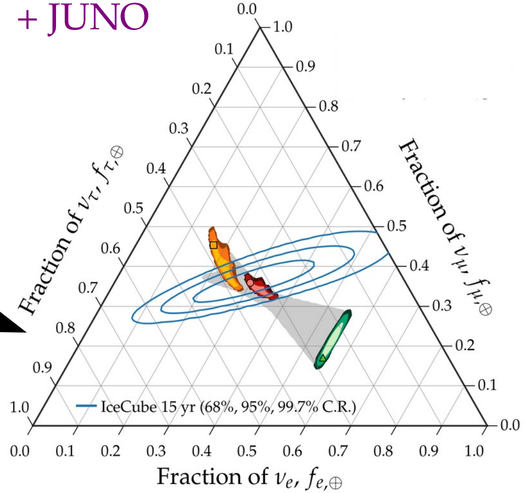
Measure θ_{23} better

+ Hyper-K



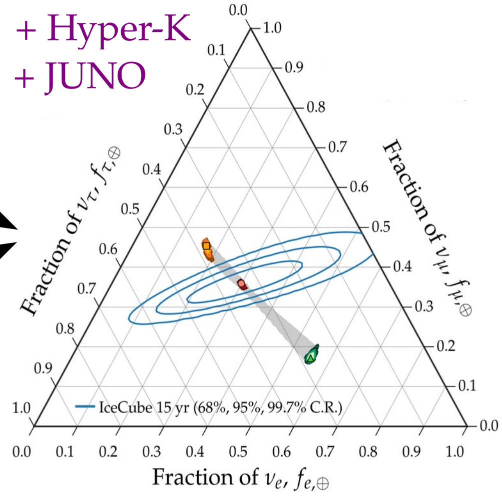
Measure θ_{12} better

+ JUNO



~2030

+ Hyper-K
+ JUNO



In our results:
JUNO + Hyper-K + DUNE

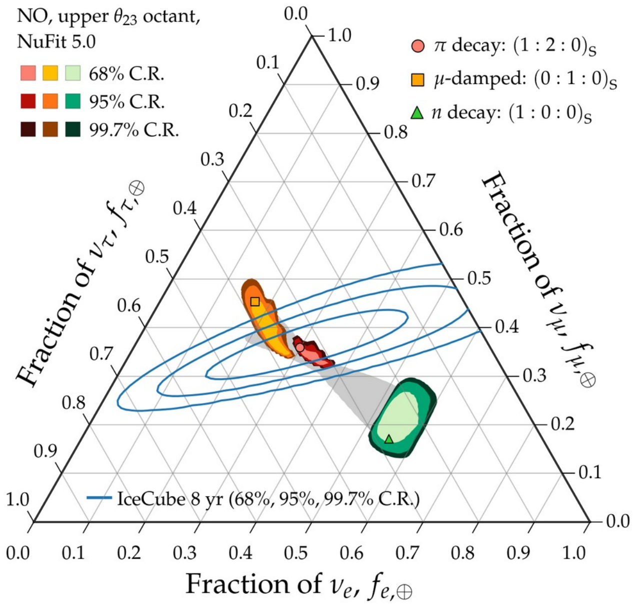
Marginal improvement til 2040

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

Theoretically palatable regions: 2020 → 2030 → 2040

Theoretically palatable regions: 2020 → 2030 → 2040

2020



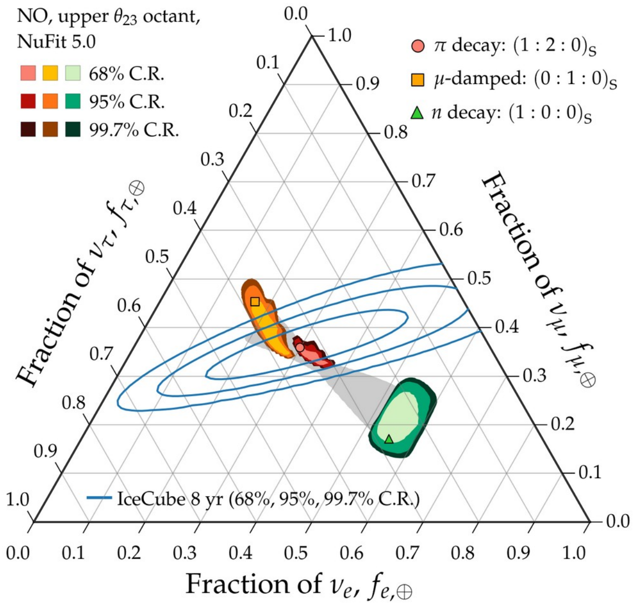
Allowed regions: overlapping

Measurement: imprecise

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

Theoretically palatable regions: 2020 → 2030 → 2040

2020



Allowed regions: overlapping

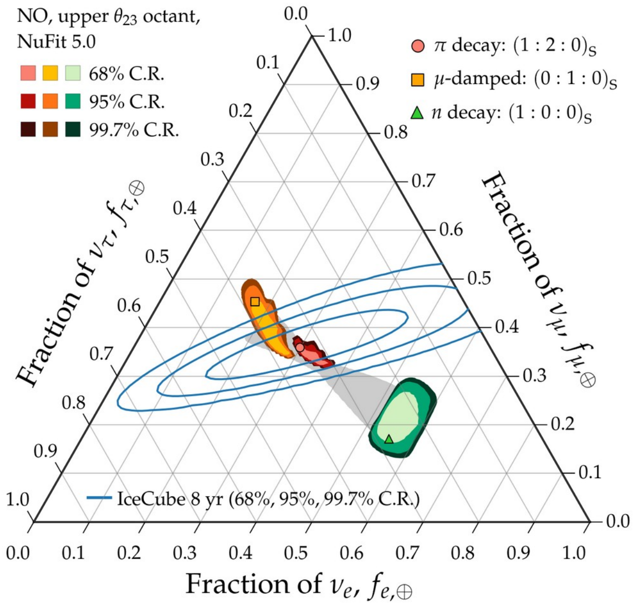
Measurement: imprecise

Not ideal

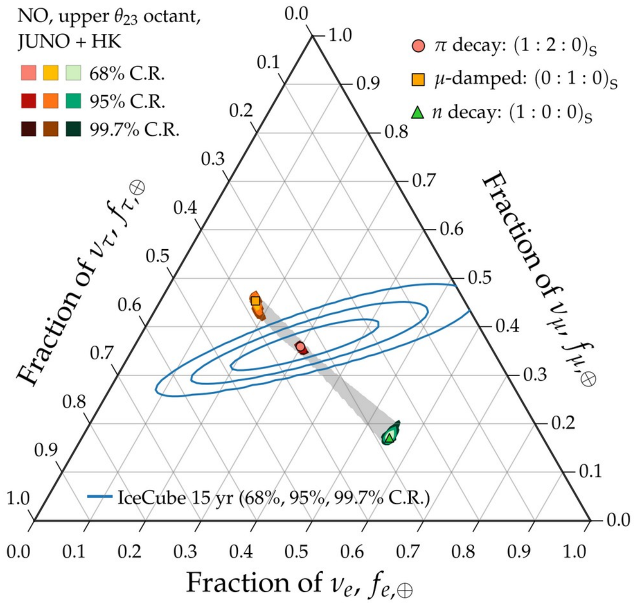
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Theoretically palatable regions: 2020 → 2030 → 2040

2020



2030



Allowed regions: overlapping
Measurement: imprecise

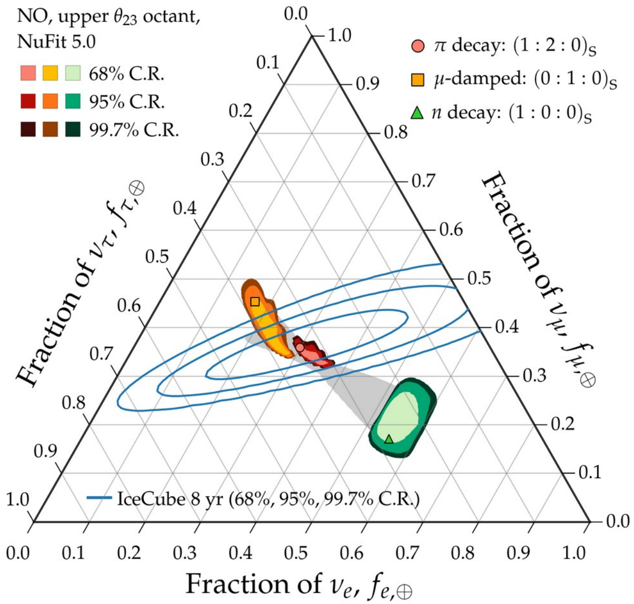
Not ideal

Allowed regions: well separated
Measurement: improving

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

Theoretically palatable regions: 2020 → 2030 → 2040

2020

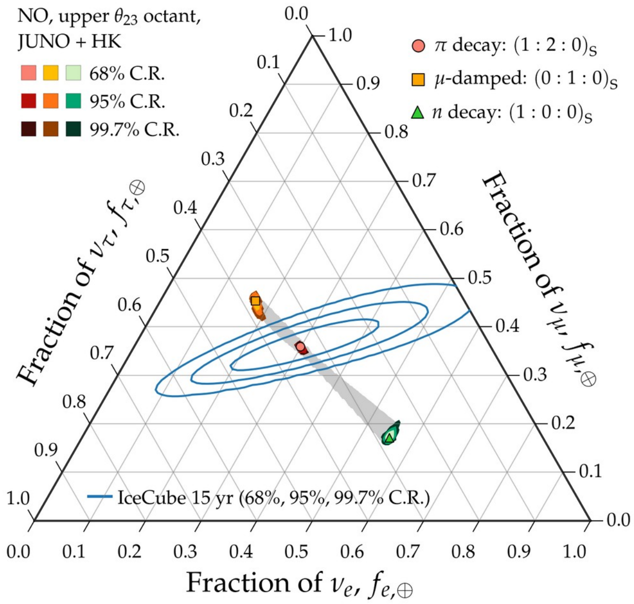


Allowed regions: overlapping

Measurement: imprecise

Not ideal

2030



Allowed regions: well separated

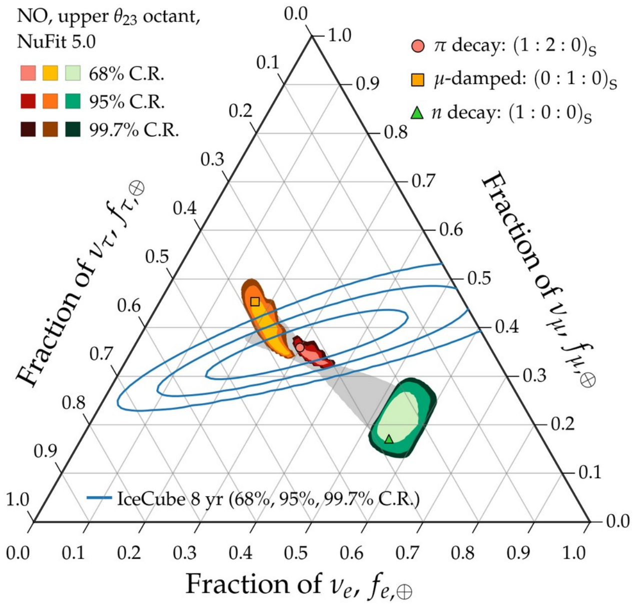
Measurement: improving

Nice

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

Theoretically palatable regions: 2020 → 2030 → 2040

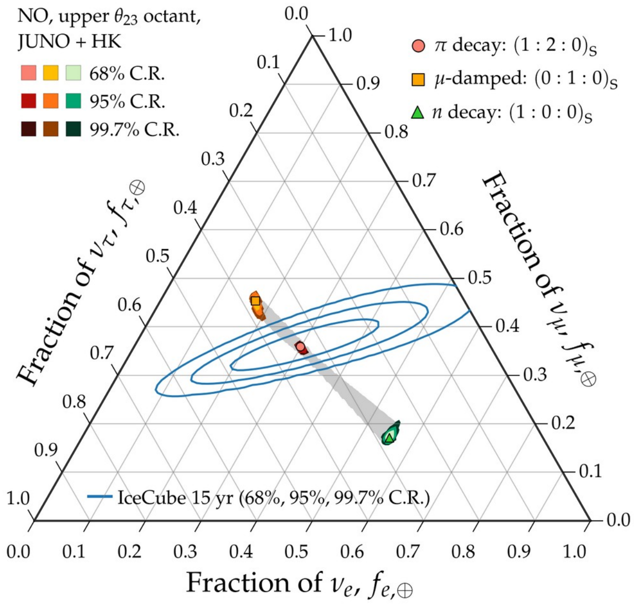
2020



Allowed regions: overlapping
Measurement: imprecise

Not ideal

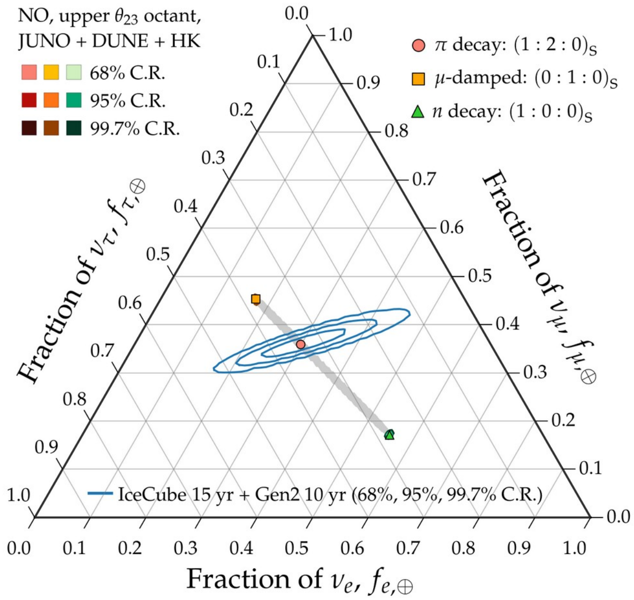
2030



Allowed regions: well separated
Measurement: improving

Nice

2040

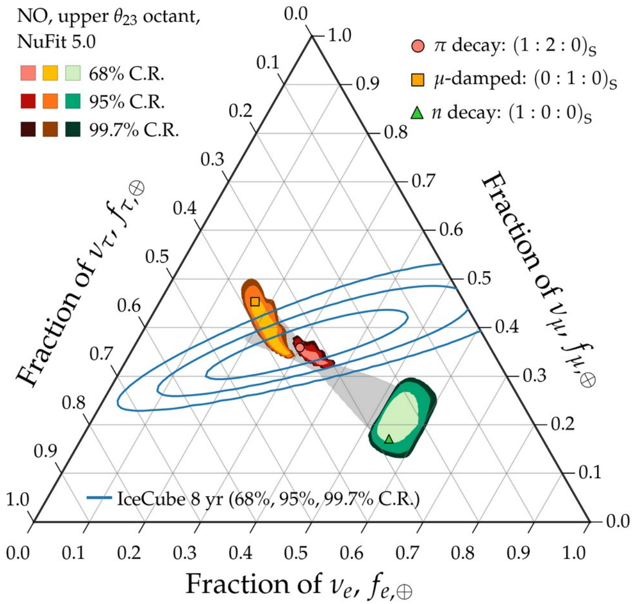


Allowed regions: well separated
Measurement: precise

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

Theoretically palatable regions: 2020 → 2030 → 2040

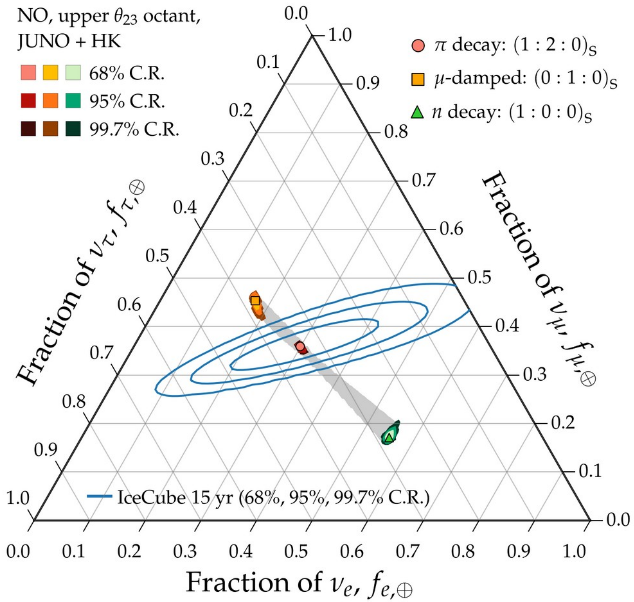
2020



Allowed regions: overlapping
Measurement: imprecise

Not ideal

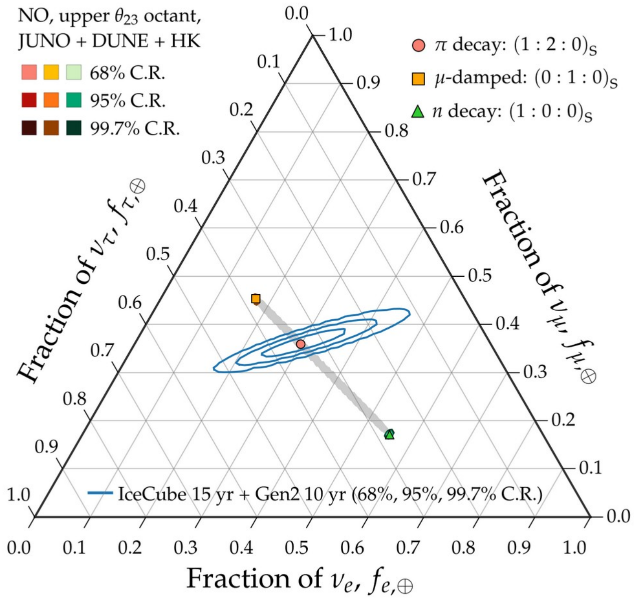
2030



Allowed regions: well separated
Measurement: improving

Nice

2040

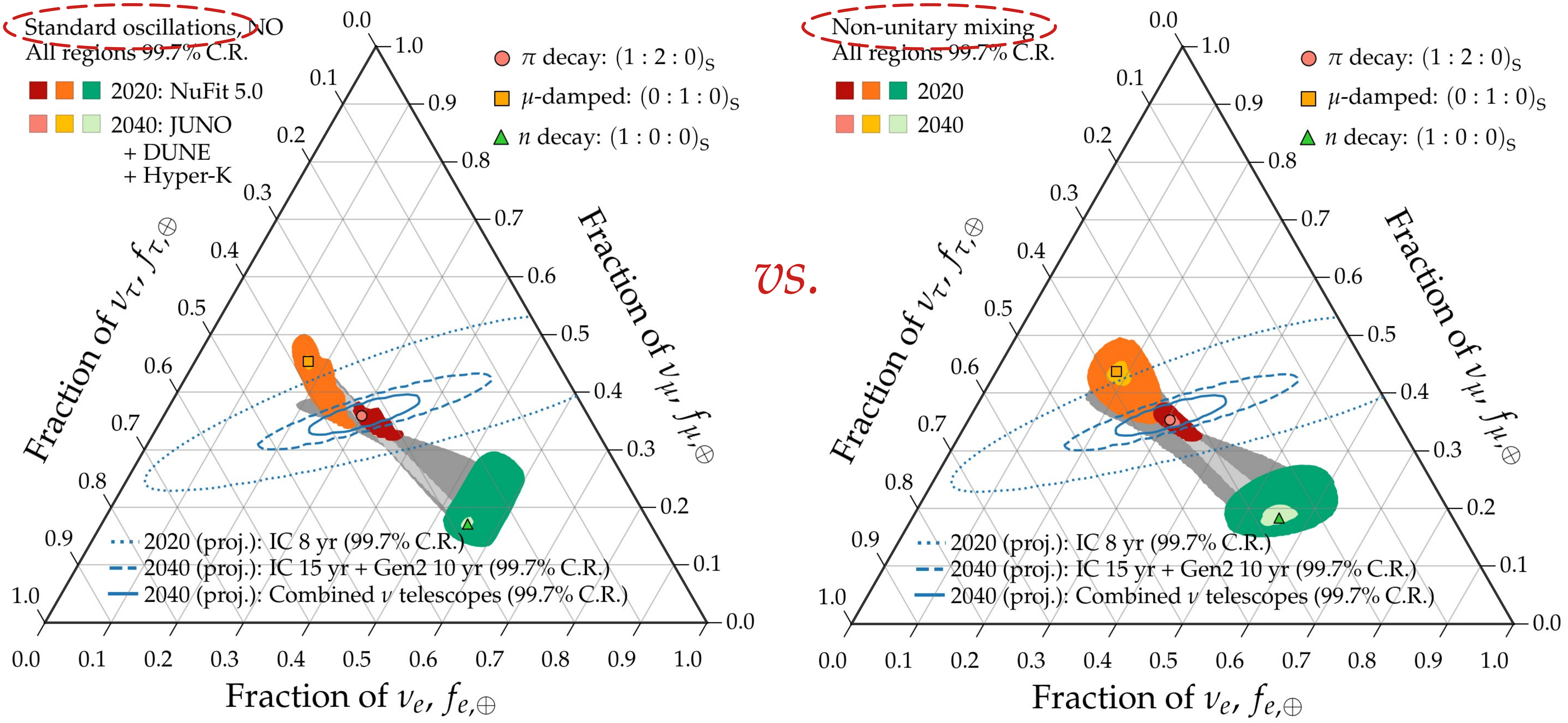


Allowed regions: well separated
Measurement: precise

Success

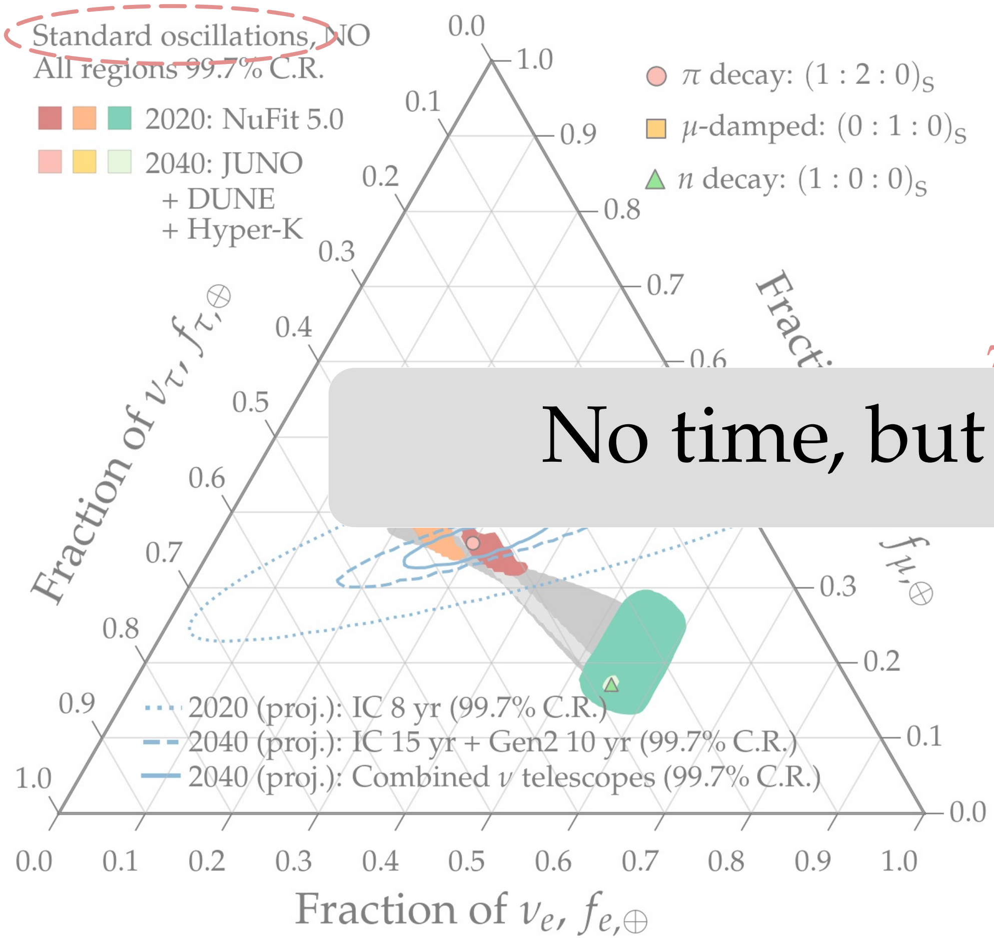
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

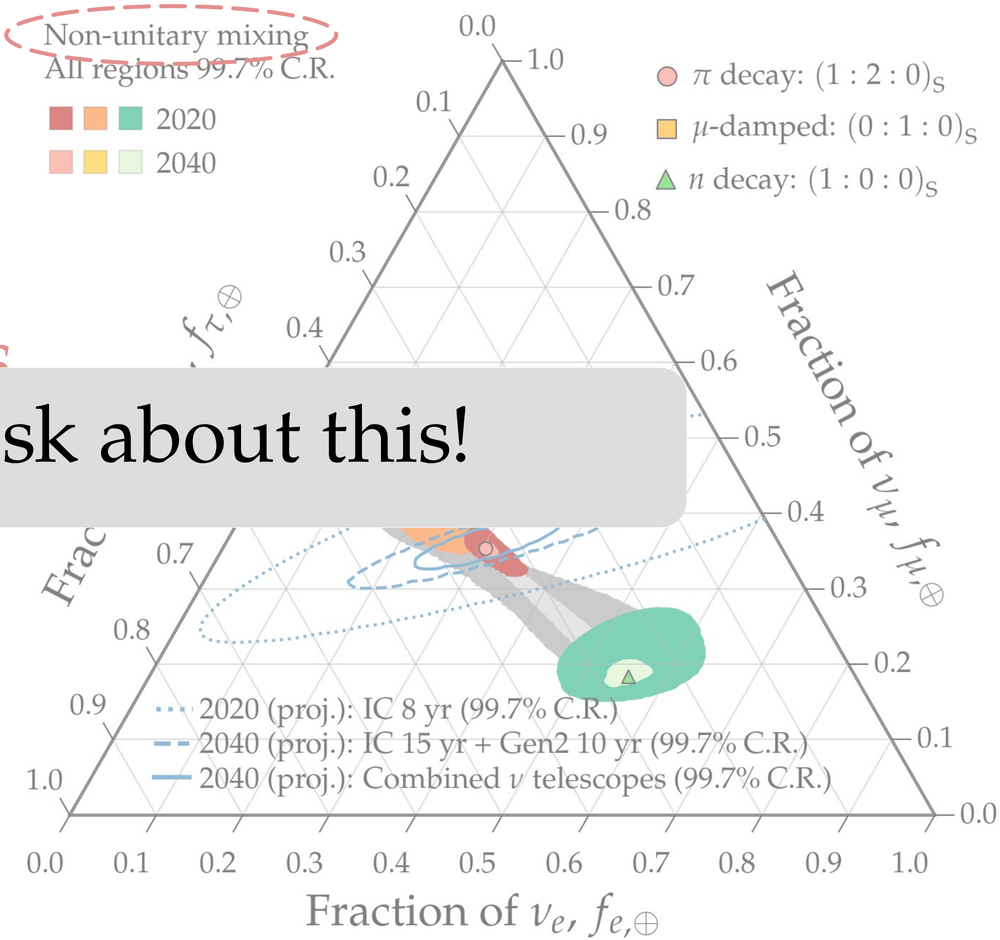
No unitarity? *No problem*



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

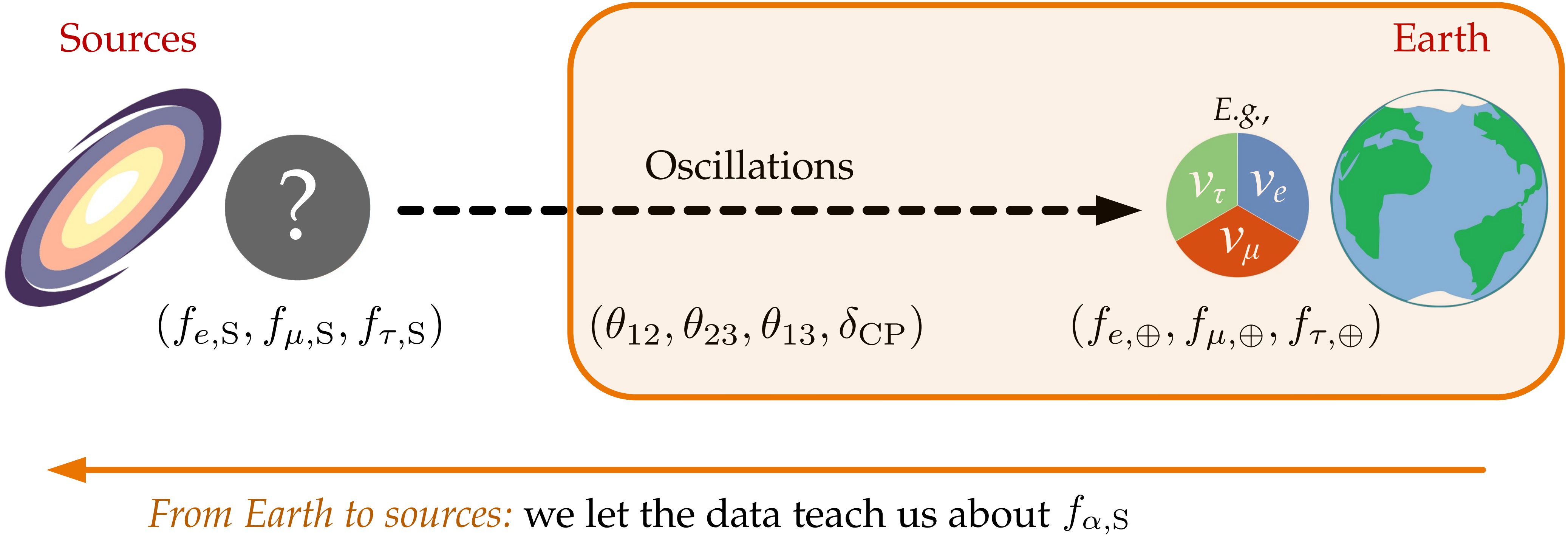
No unitarity? *No problem*





No time, but ask about this!

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

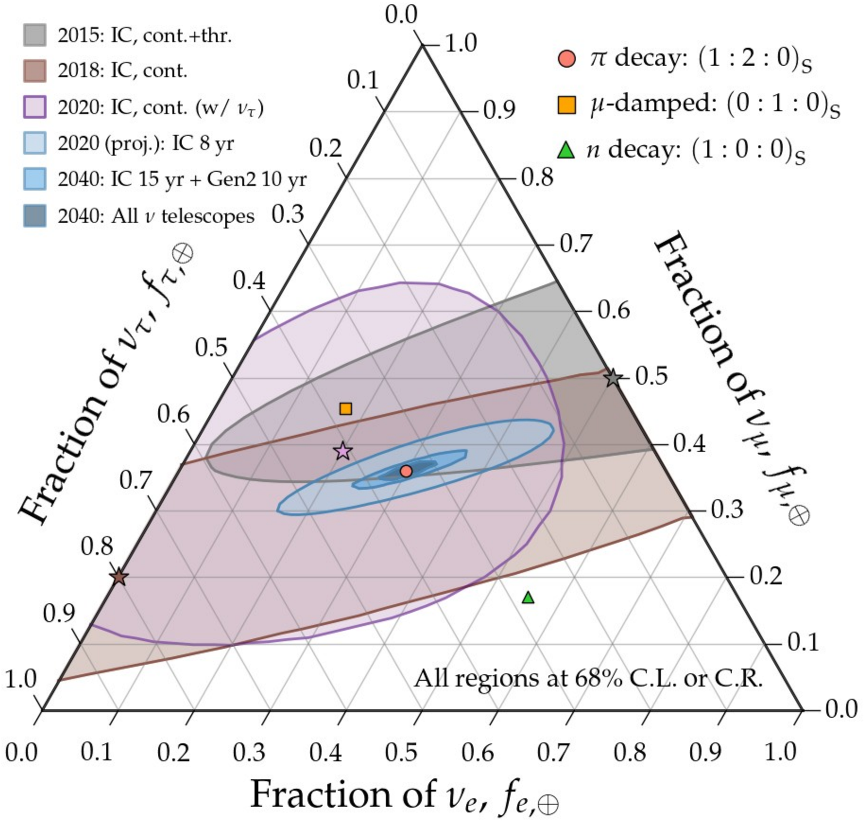

Sources
?
$(f_{e,\mathrm{S}}, f_{\mu,\mathrm{S}}, f_{\tau,\mathrm{S}})$
Oscillations
$(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\mathrm{CP}})$
Earth
E.g.,
ν_τ
ν_e
ν_μ
$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$
From Earth to sources: we let the data teach us about $f_{\alpha,\mathrm{S}}$

Inferring the flavor composition at the sources

Ingredient #1:

Flavor ratios measured at Earth,

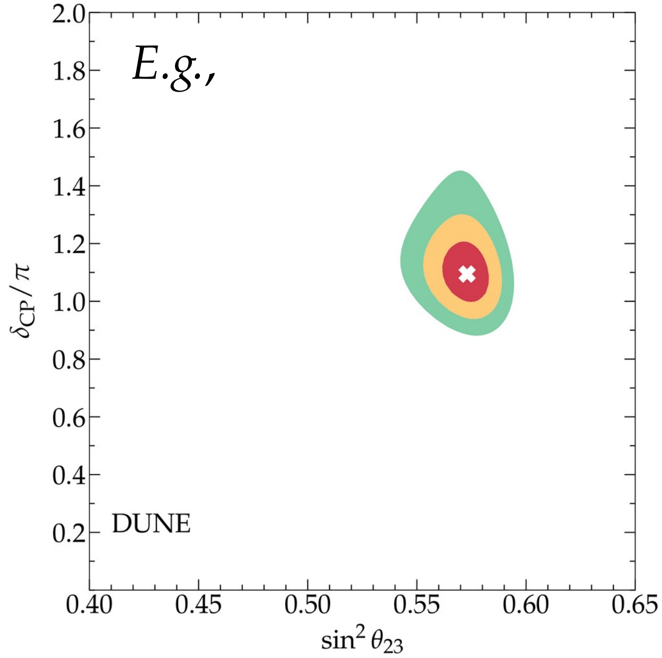
$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$



Ingredient #2:

Probability density of mixing parameters (θ_{12}, θ_{23}, θ_{13}, δ_{CP})

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



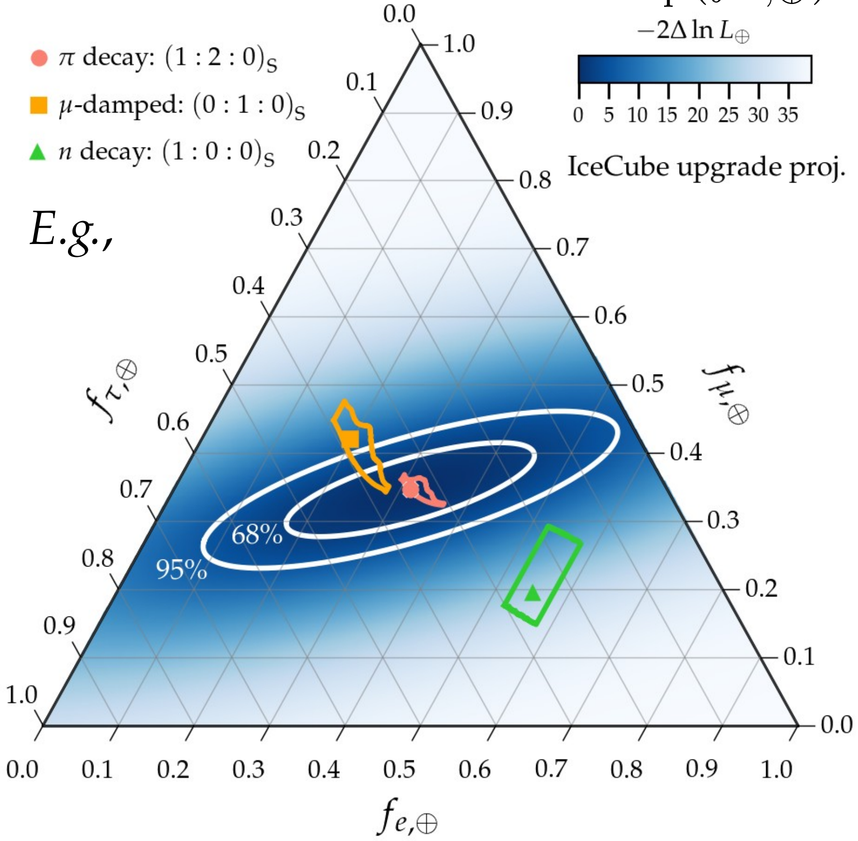
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
MB & Ahlers, *PRL* 2019

Inferring the flavor composition at the sources

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

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

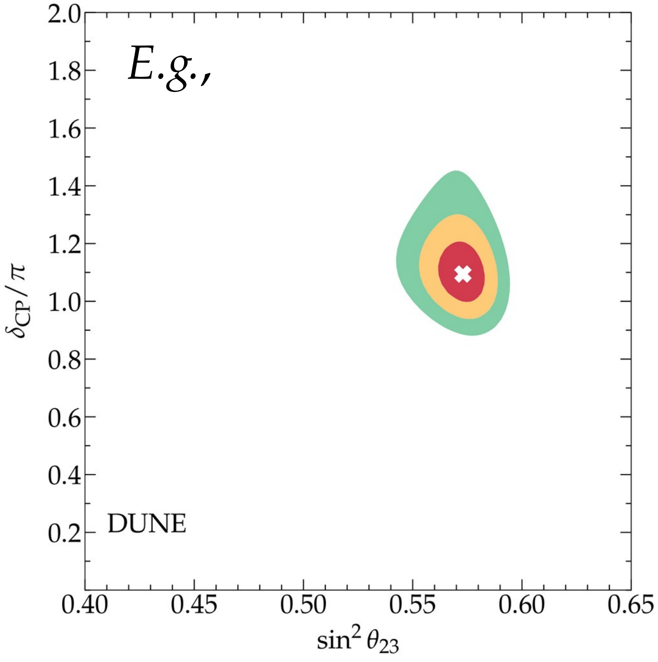
E.g.,



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

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

E.g.,



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

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

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

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

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

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

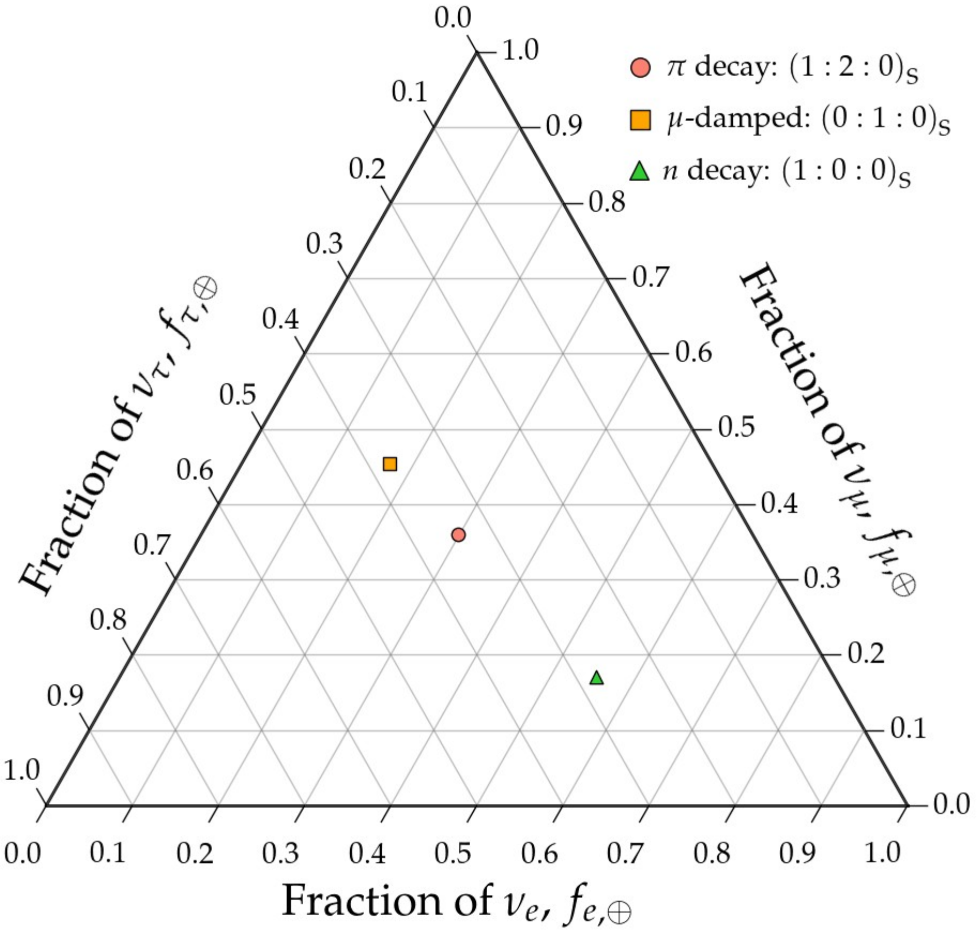
$$\mathcal{P}(\boldsymbol{f}_s) = \int d\boldsymbol{\vartheta} \underbrace{\mathcal{L}(\boldsymbol{\vartheta})}_{\text{Oscillation experiments}} \underbrace{\mathcal{P}_{\rm exp}(\boldsymbol{f}_\oplus(\boldsymbol{f}_{\rm S}, \boldsymbol{\vartheta}))}_{\text{Neutrino telescopes}}$$

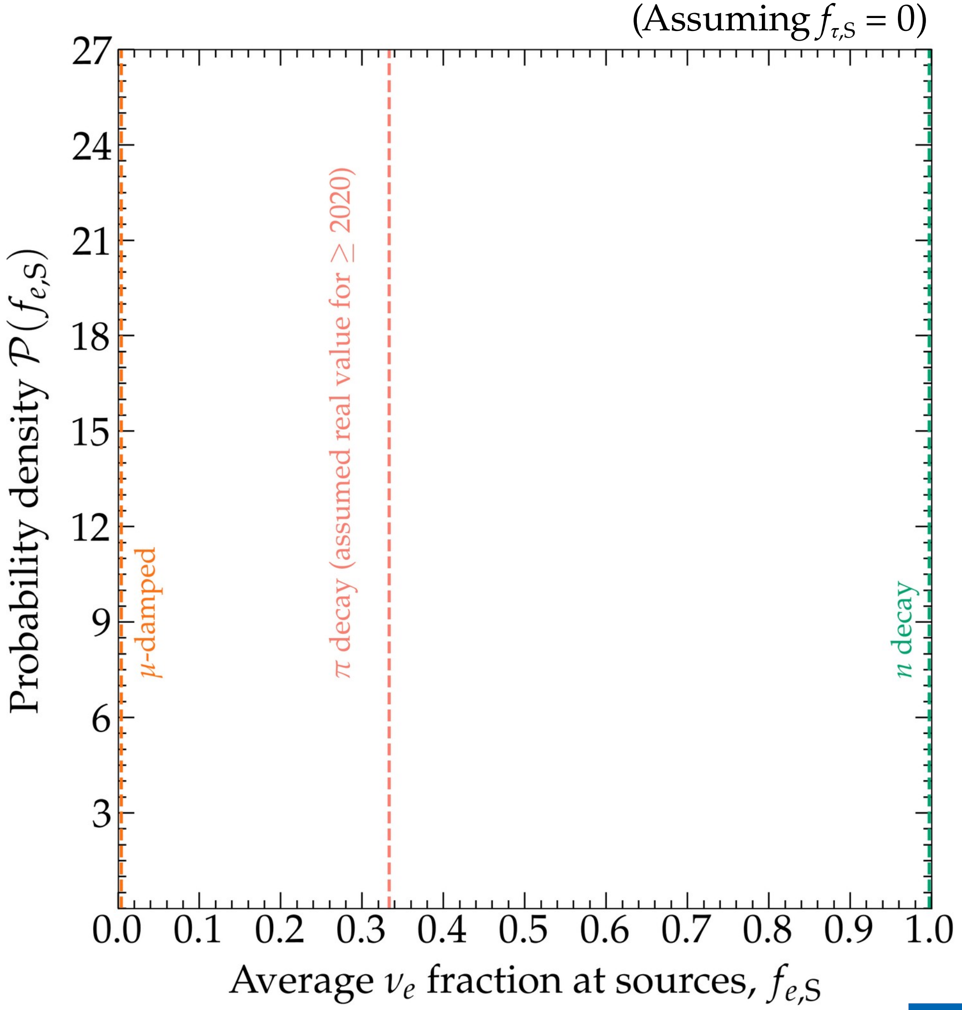
Oscillation experiments Neutrino telescopes

Inferring the flavor composition at the sources

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

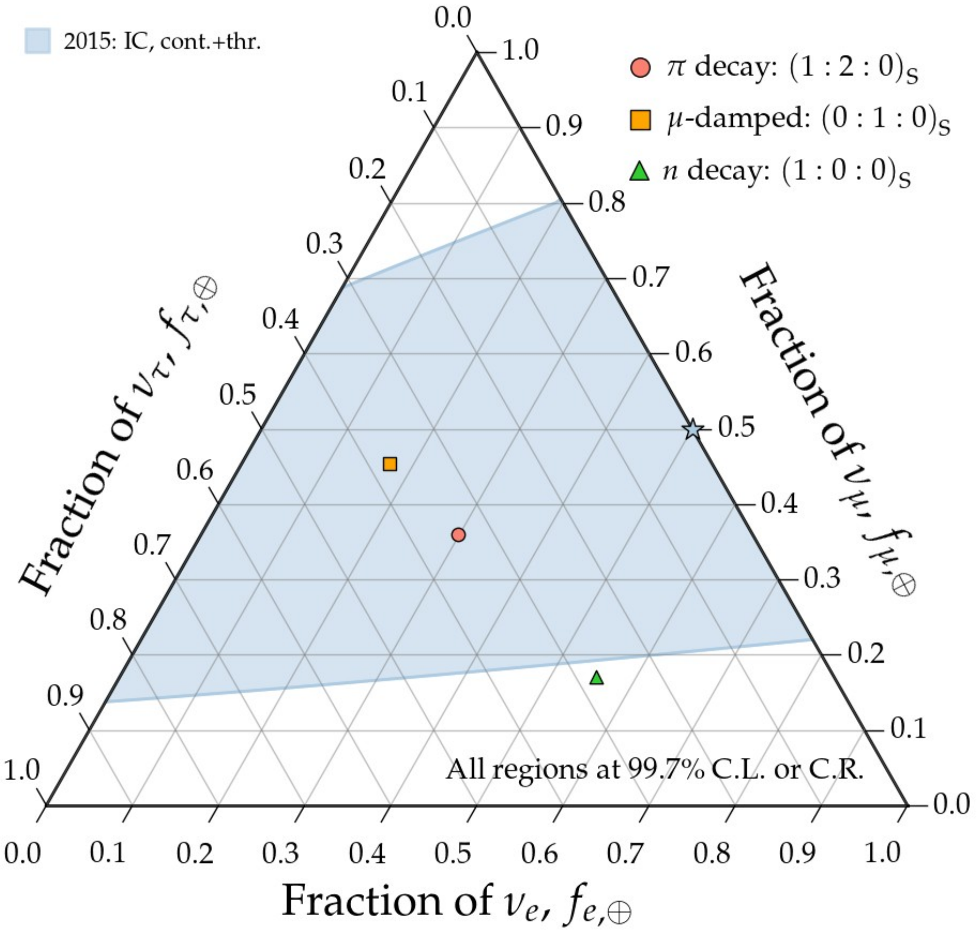
Inferring the flavor composition at the sources

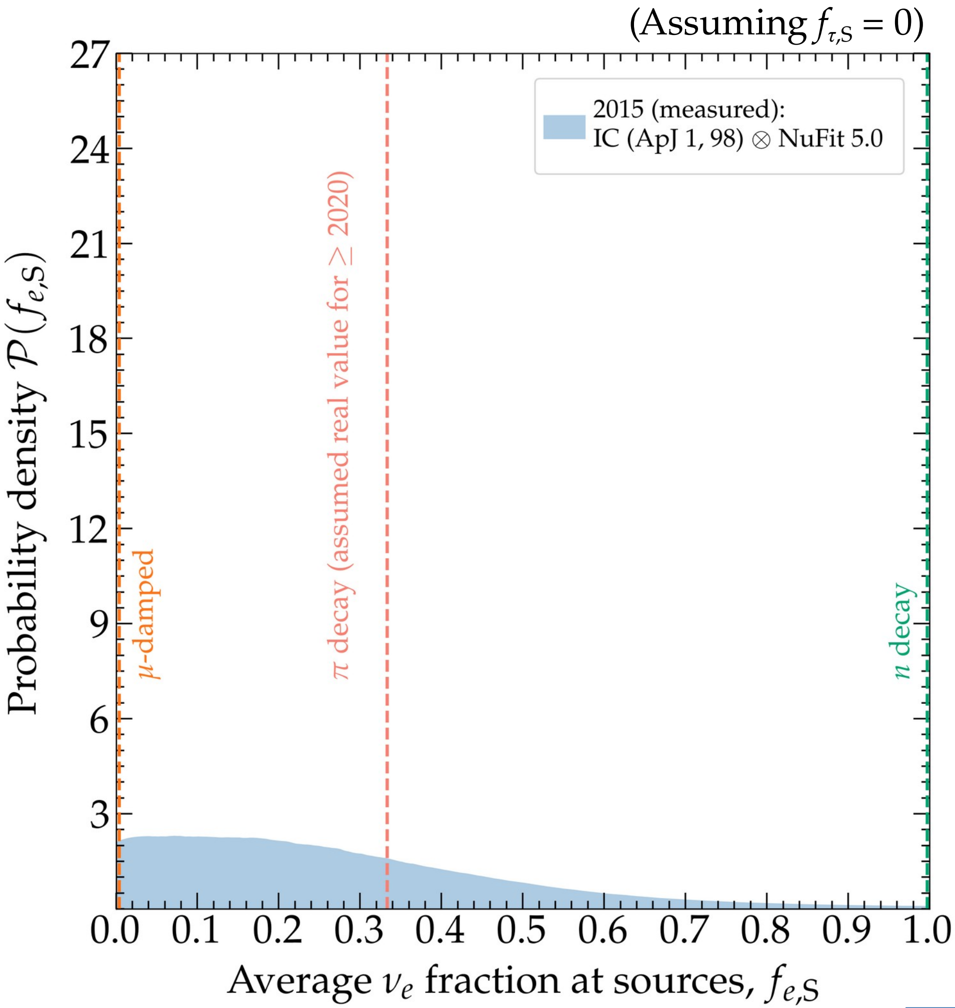




Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
MB & Ahlers, *PRL* 2019

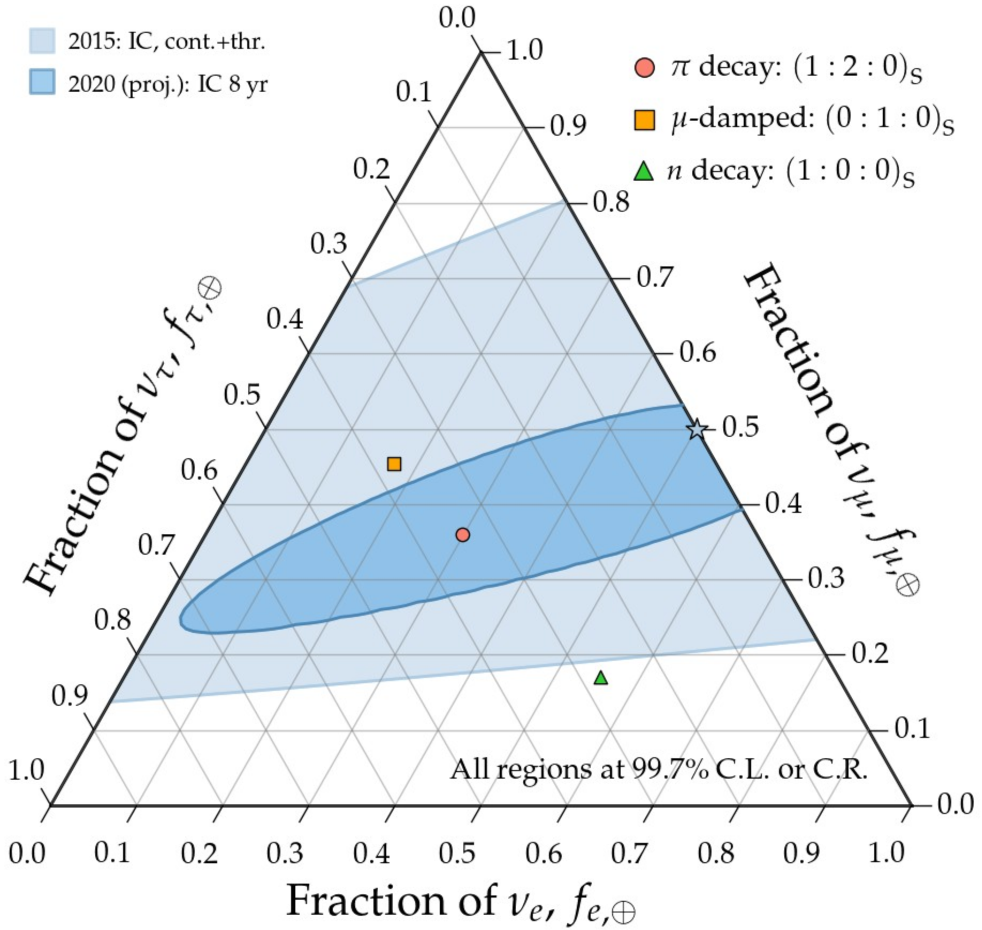
Inferring the flavor composition at the sources

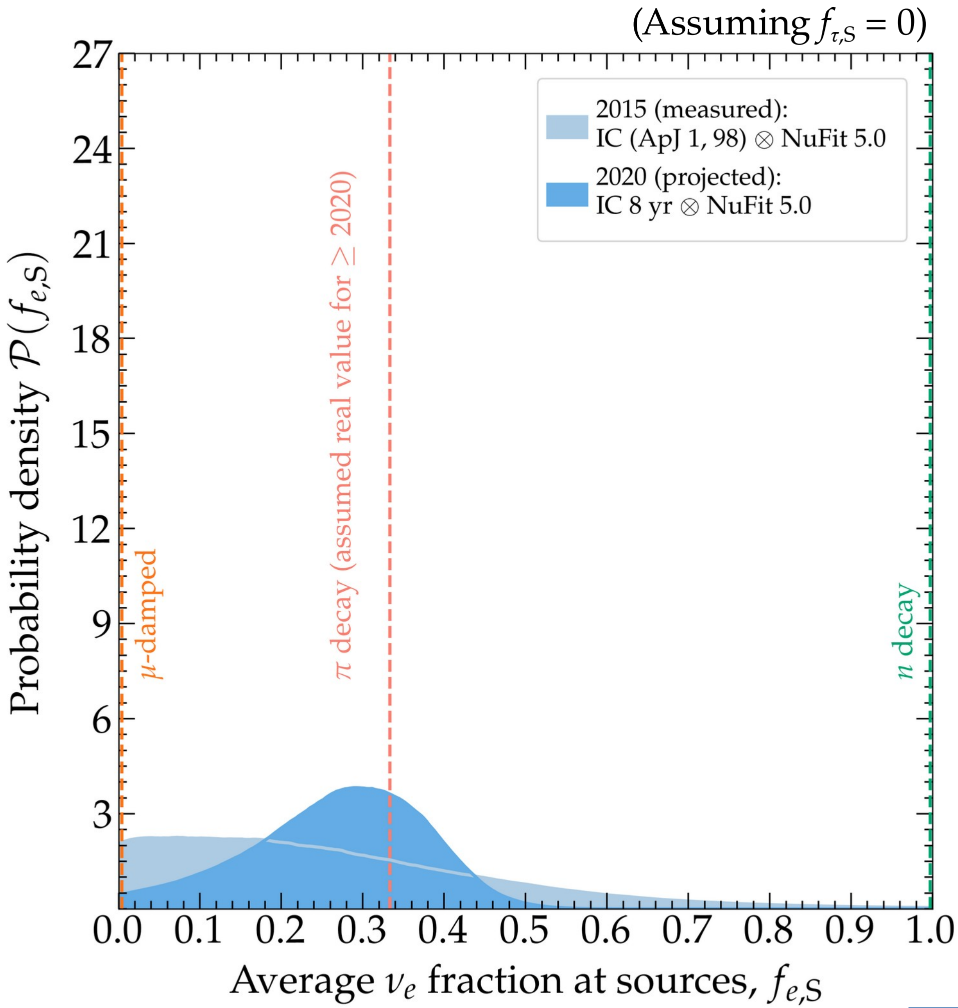




Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
MB & Ahlers, *PRL* 2019

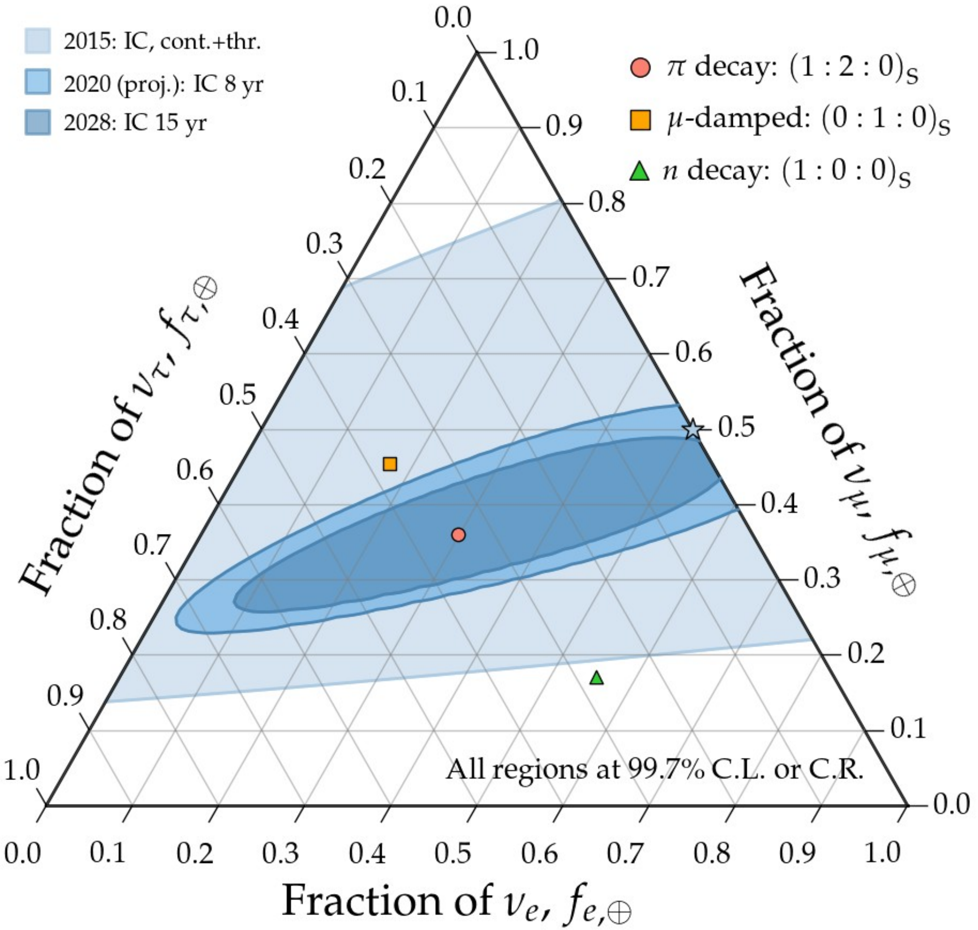
Inferring the flavor composition at the sources



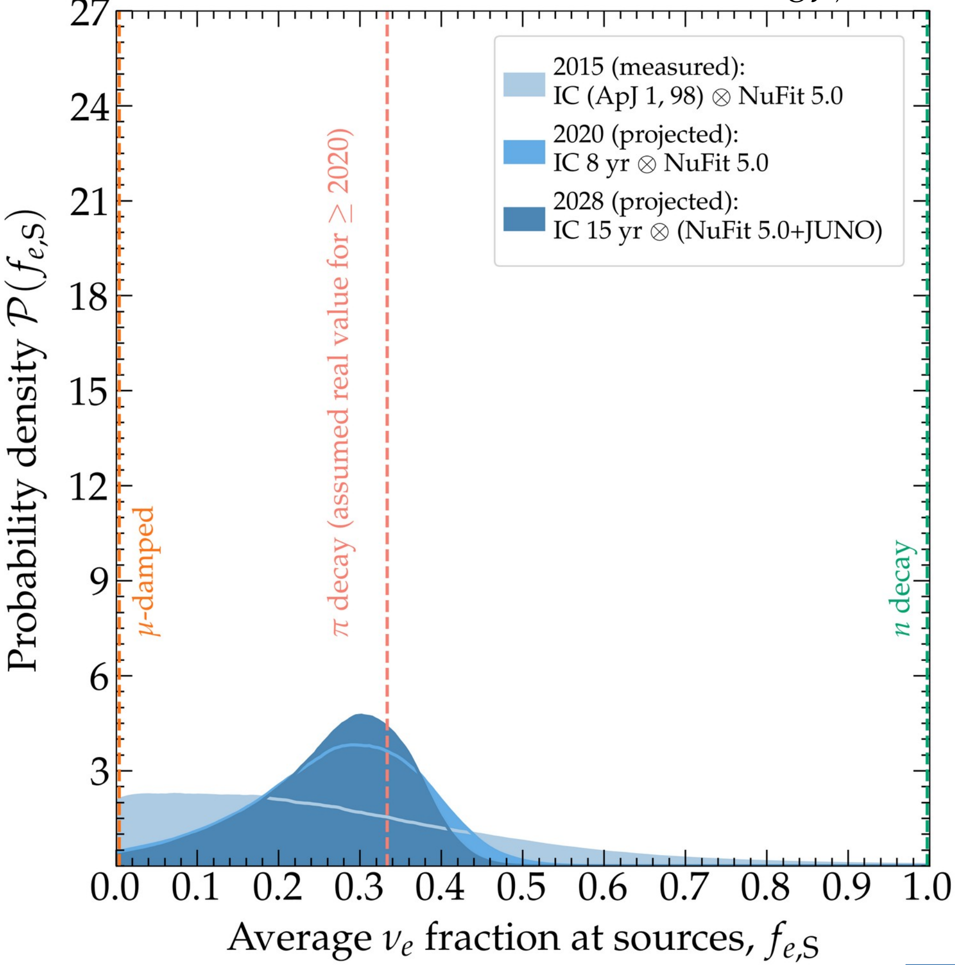


Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
MB & Ahlers, *PRL* 2019

Inferring the flavor composition at the sources

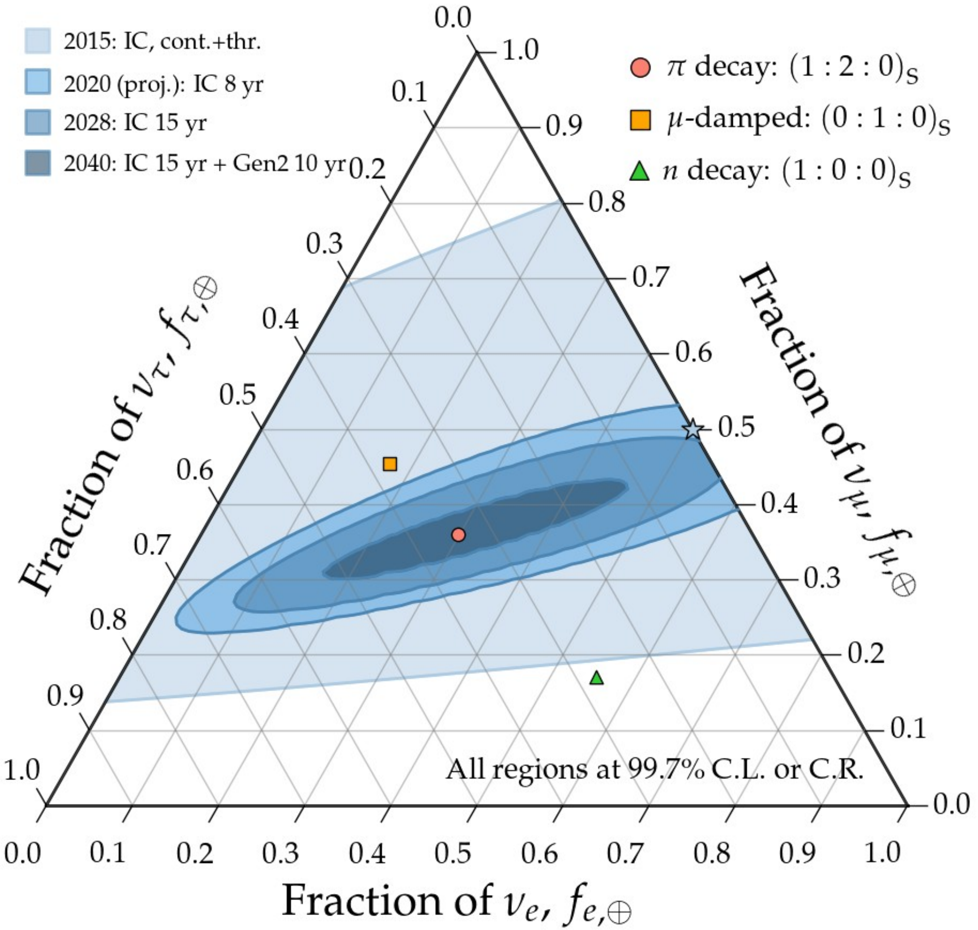


(Assuming $f_{\tau,S} = 0$)

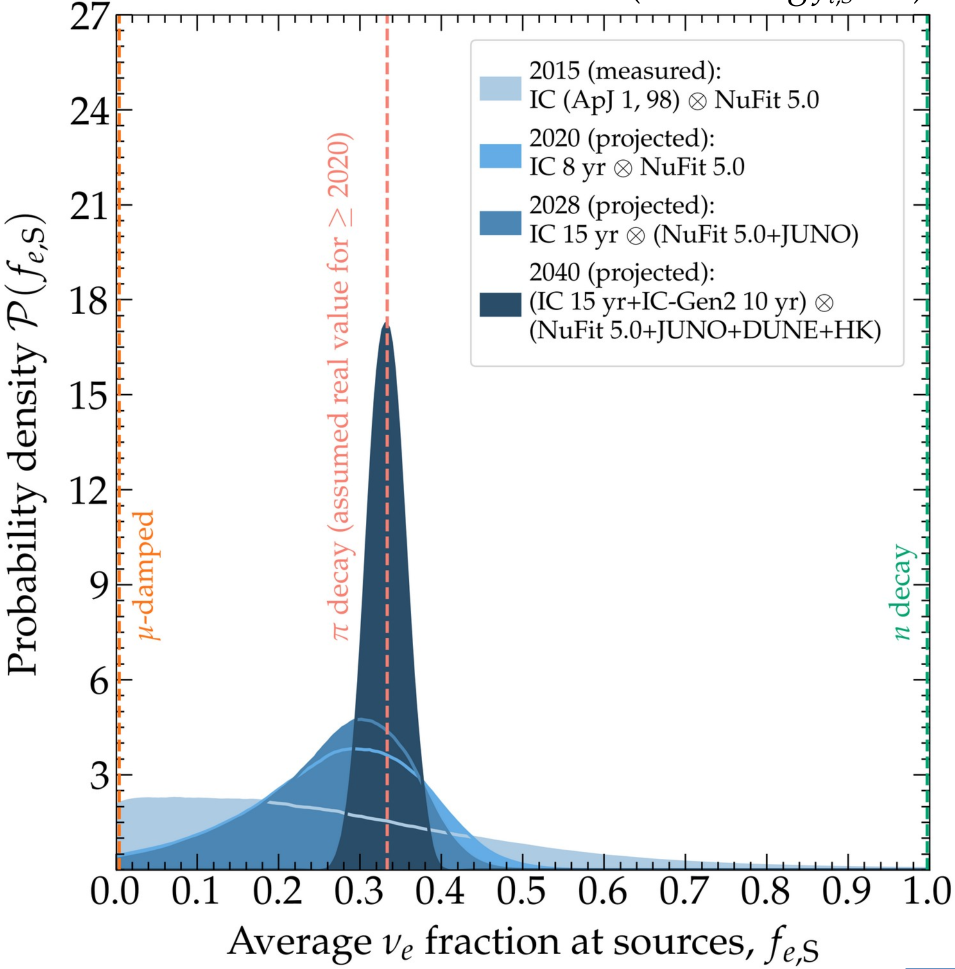


Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
MB & Ahlers, *PRL* 2019

Inferring the flavor composition at the sources

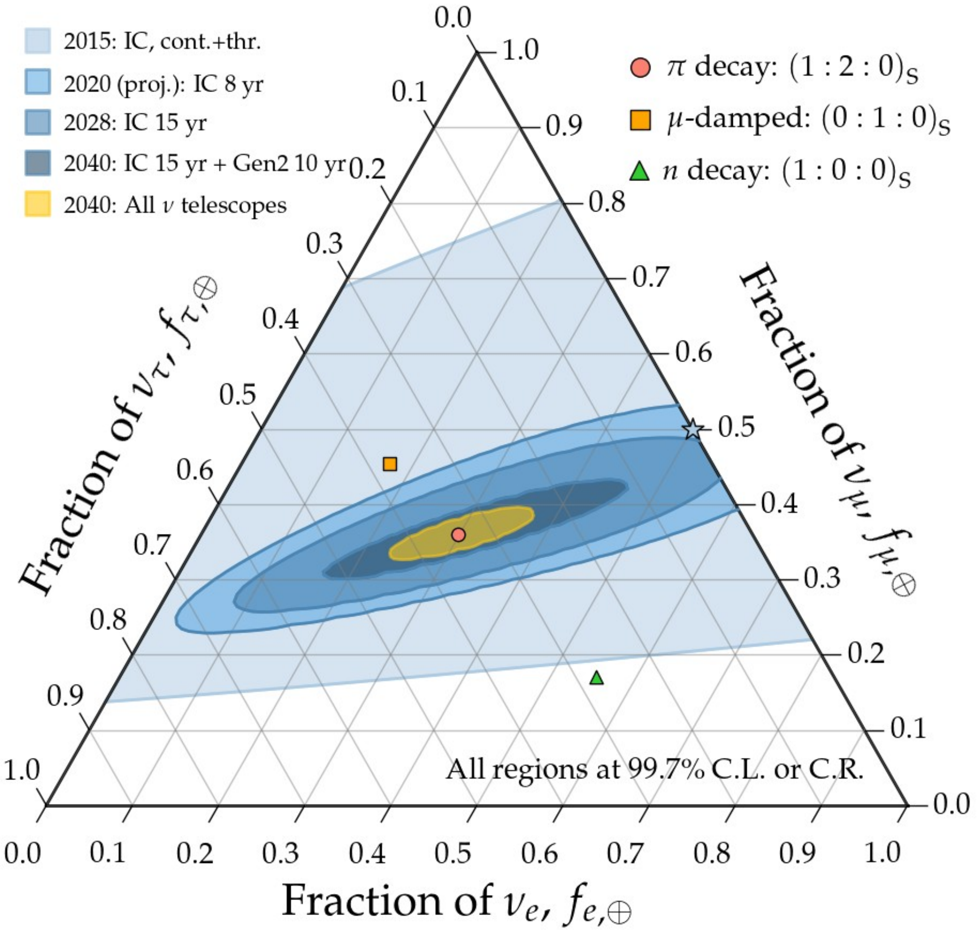


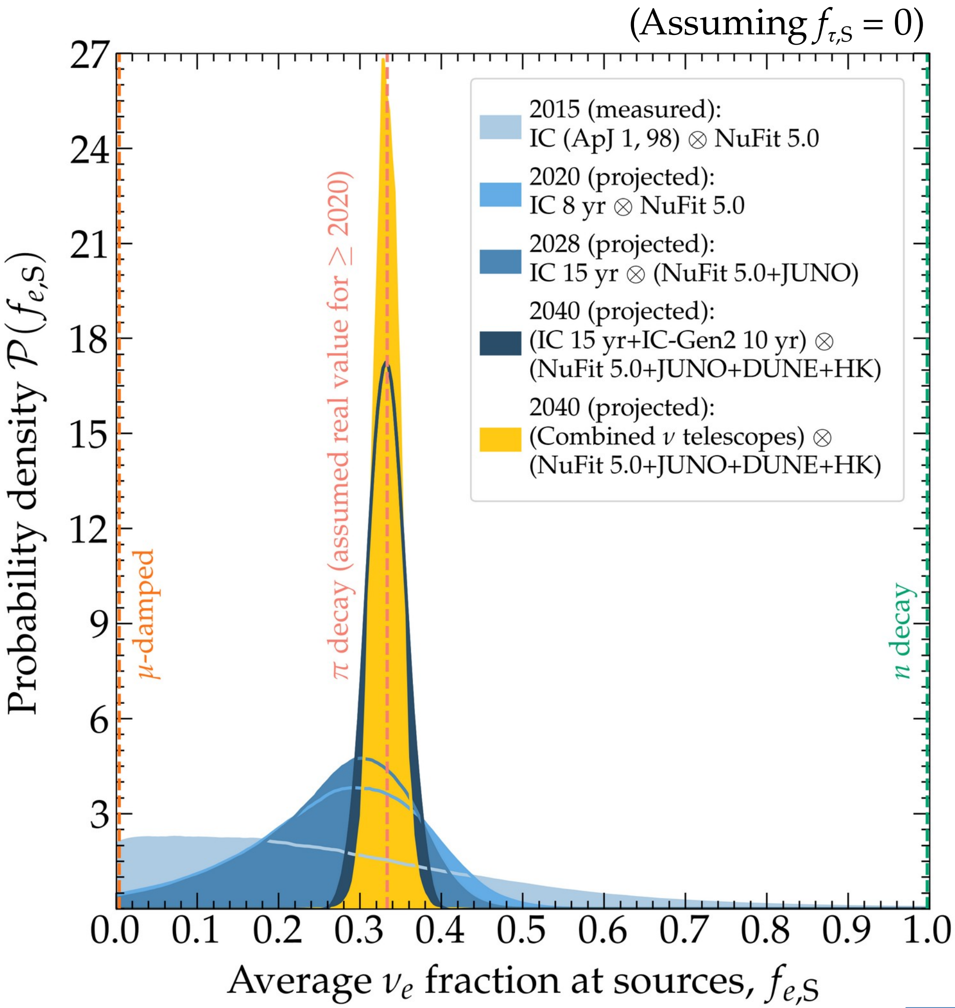
(Assuming $f_{\tau,S} = 0$)



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

New physics in flavor composition

Repurpose the flavor sensitivity to test new physics:

New physics in flavor composition

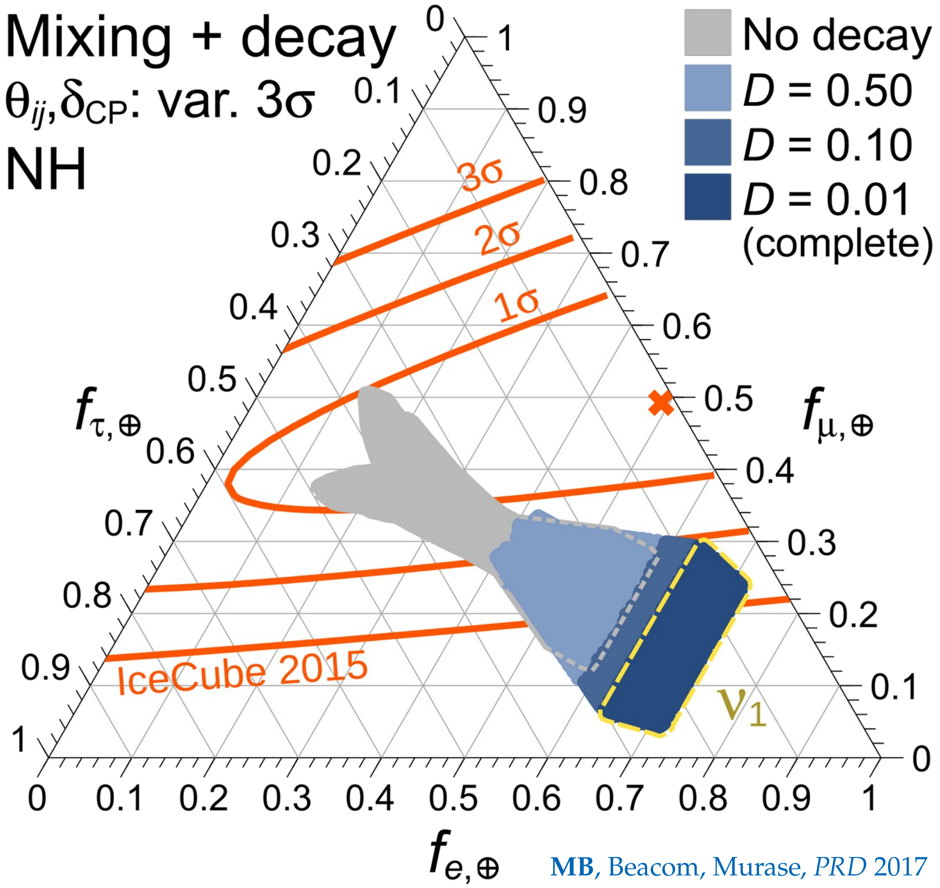
Repurpose the flavor sensitivity to test new physics:

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:

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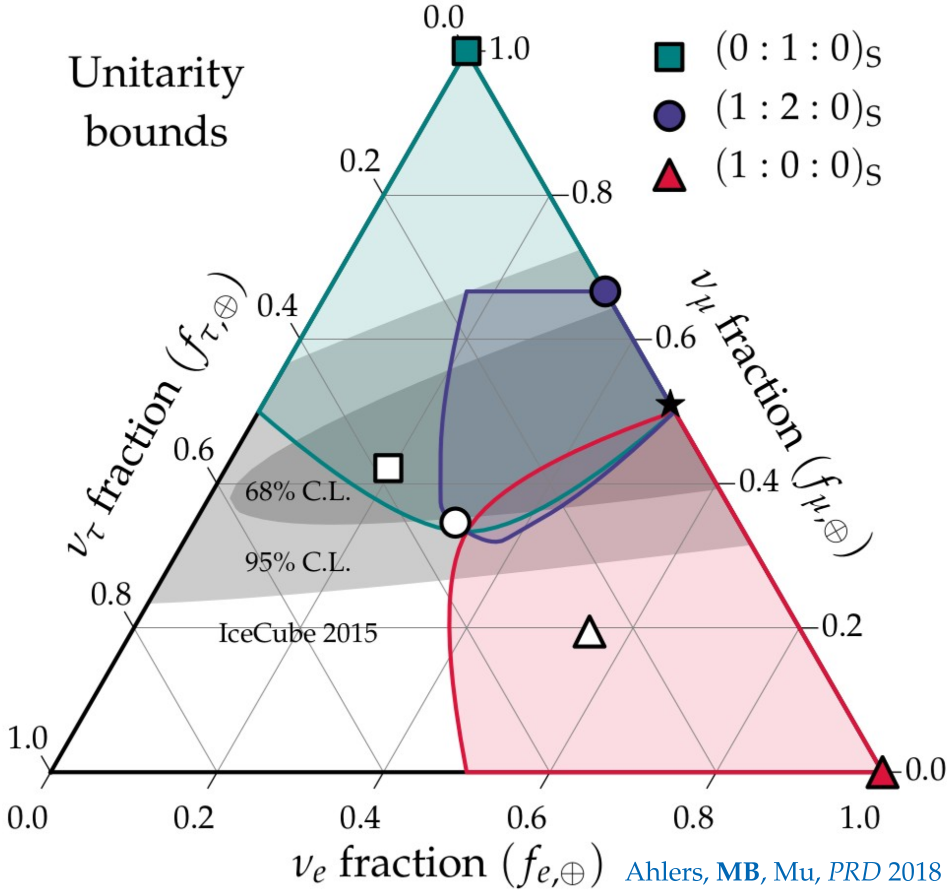

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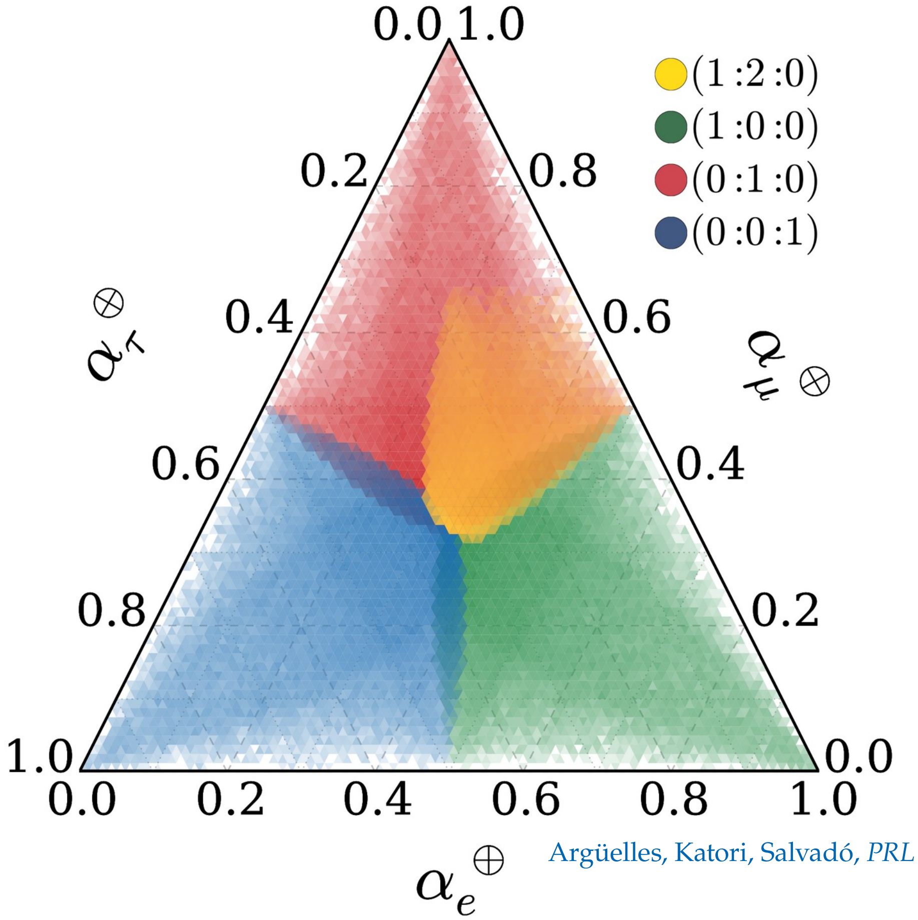

Argüelles, Katori, Salvadó, *PRL* 2015

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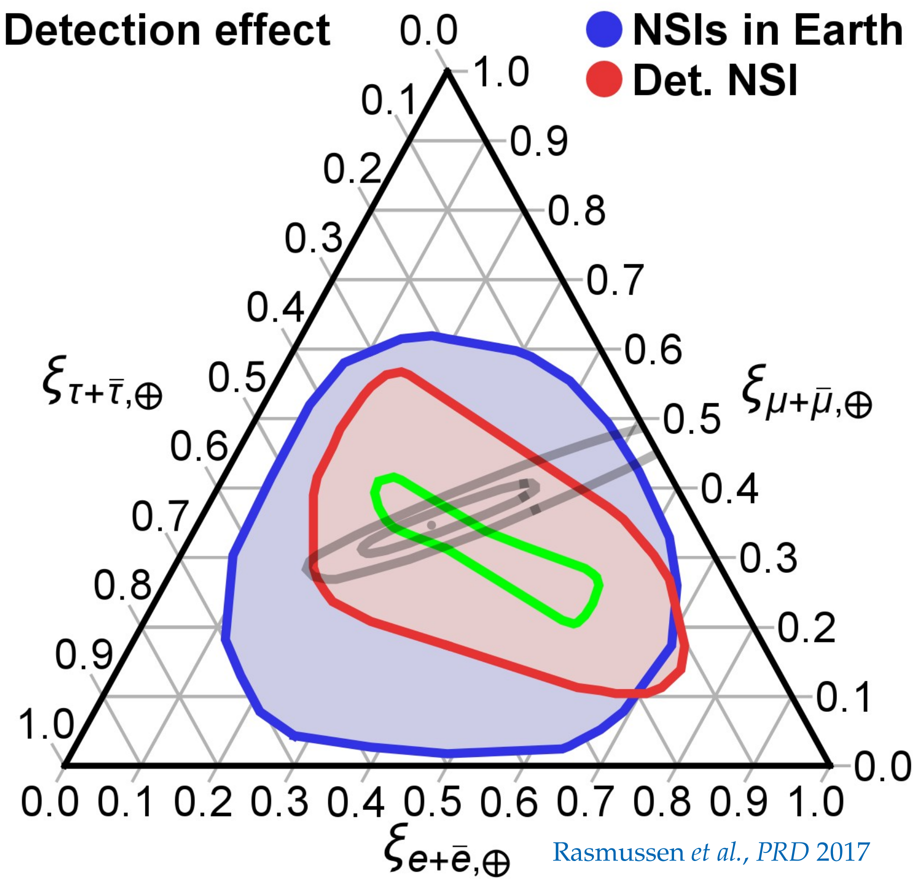

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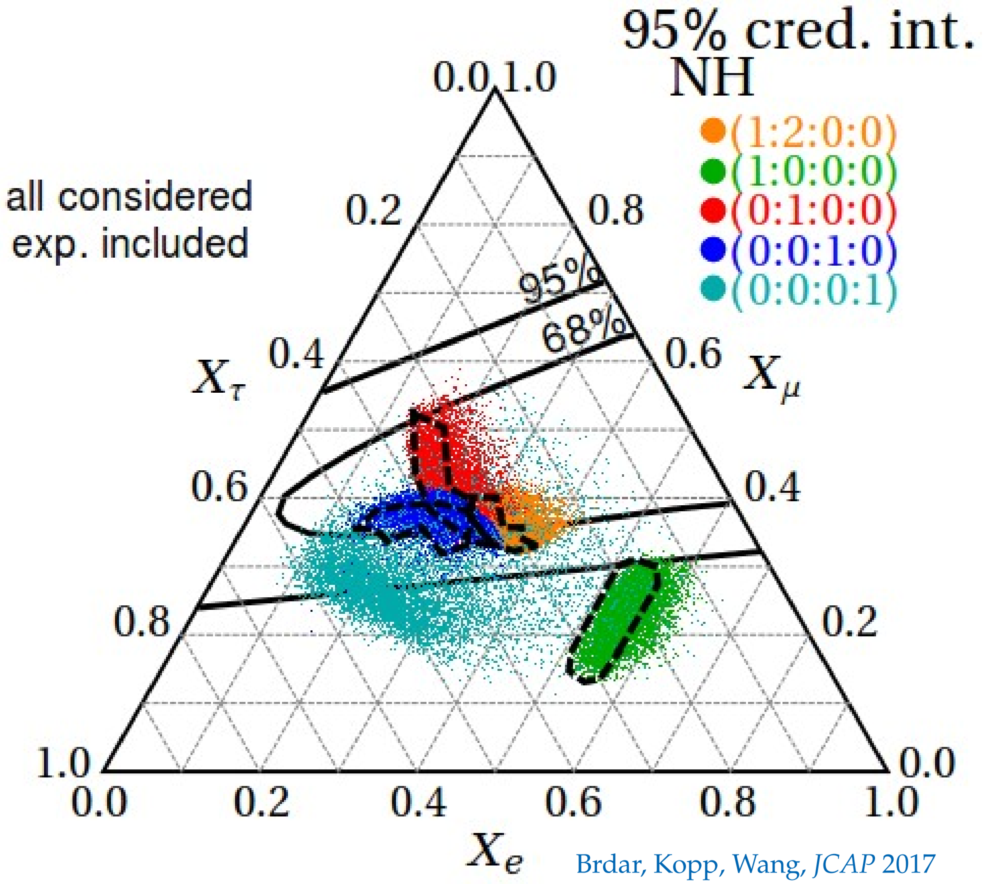

Brdar, Kopp, Wang, *JCAP* 2017

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

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

Reviews:
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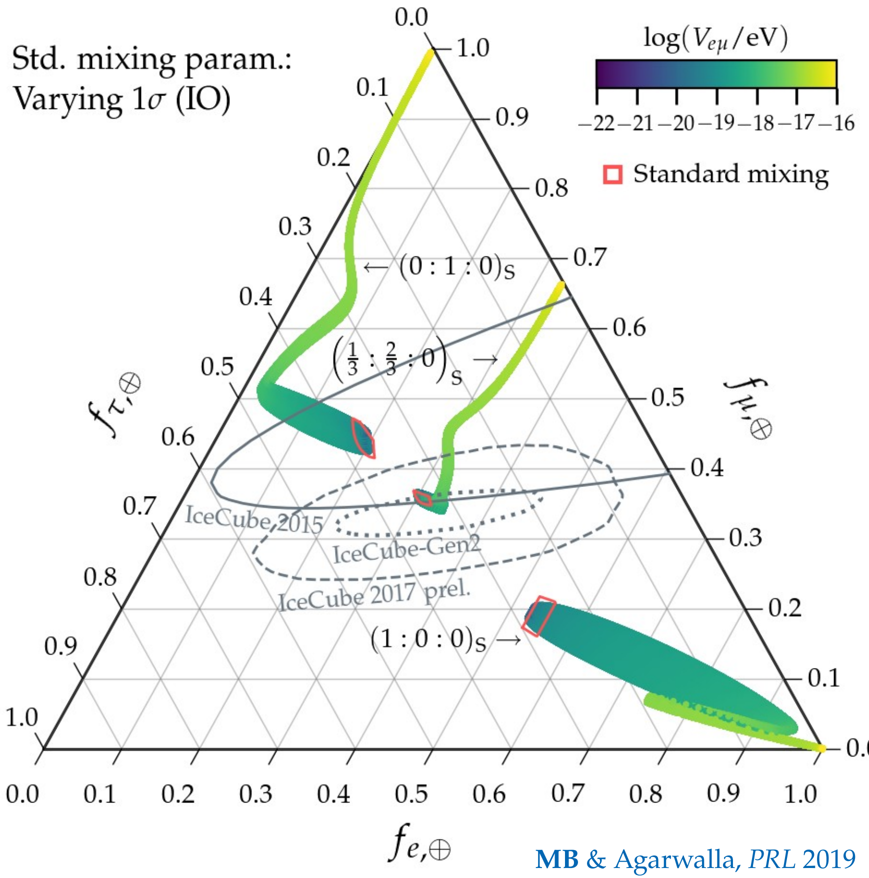
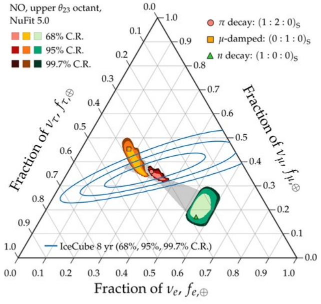
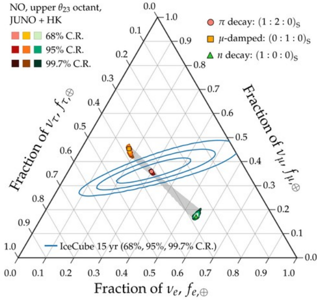


MB & Agarwalla, *PRL* 2019

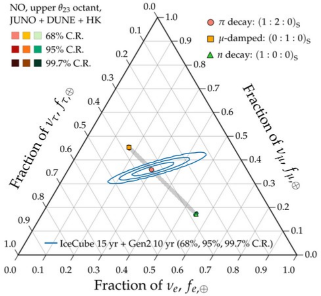
The high-energy flavor charter



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



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

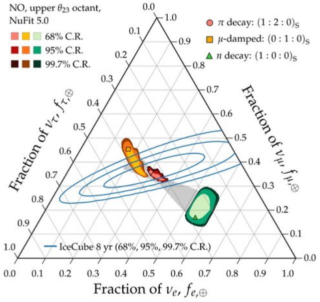


2040: Allowed flavor regions shrunk + precise flavor measurements

Opportunities for astrophysics and particle physics exist throughout!

The high-energy flavor charter

See PLEνM for what we can do for other observables by combining future detectors: 2107.13534



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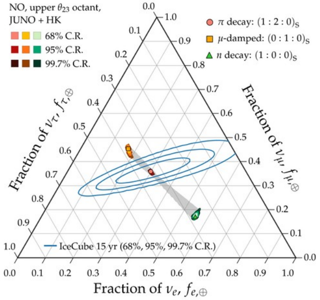

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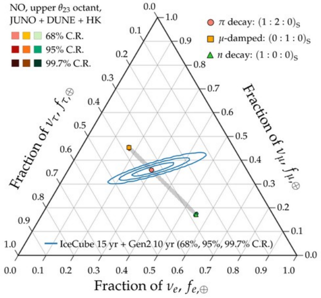

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Backup slides

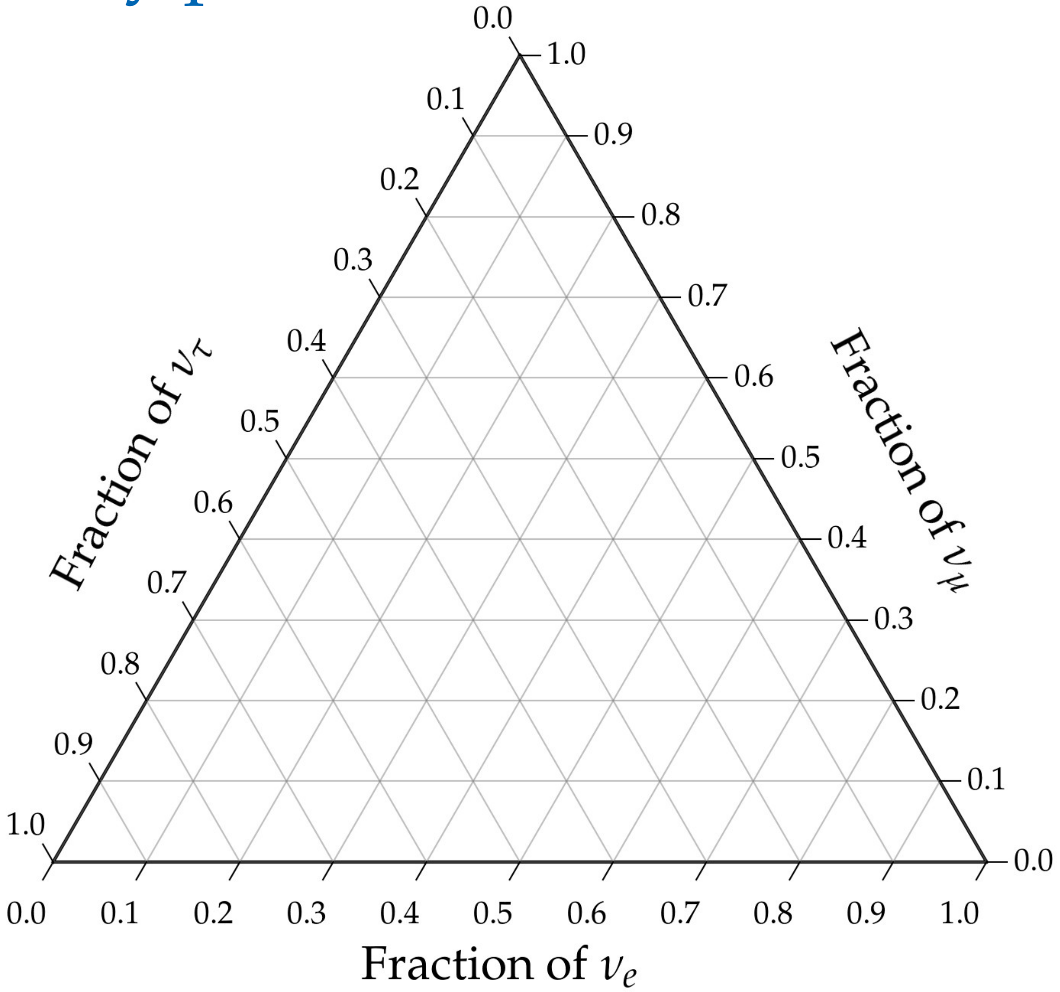
Quick aside: how to read a ternary plot

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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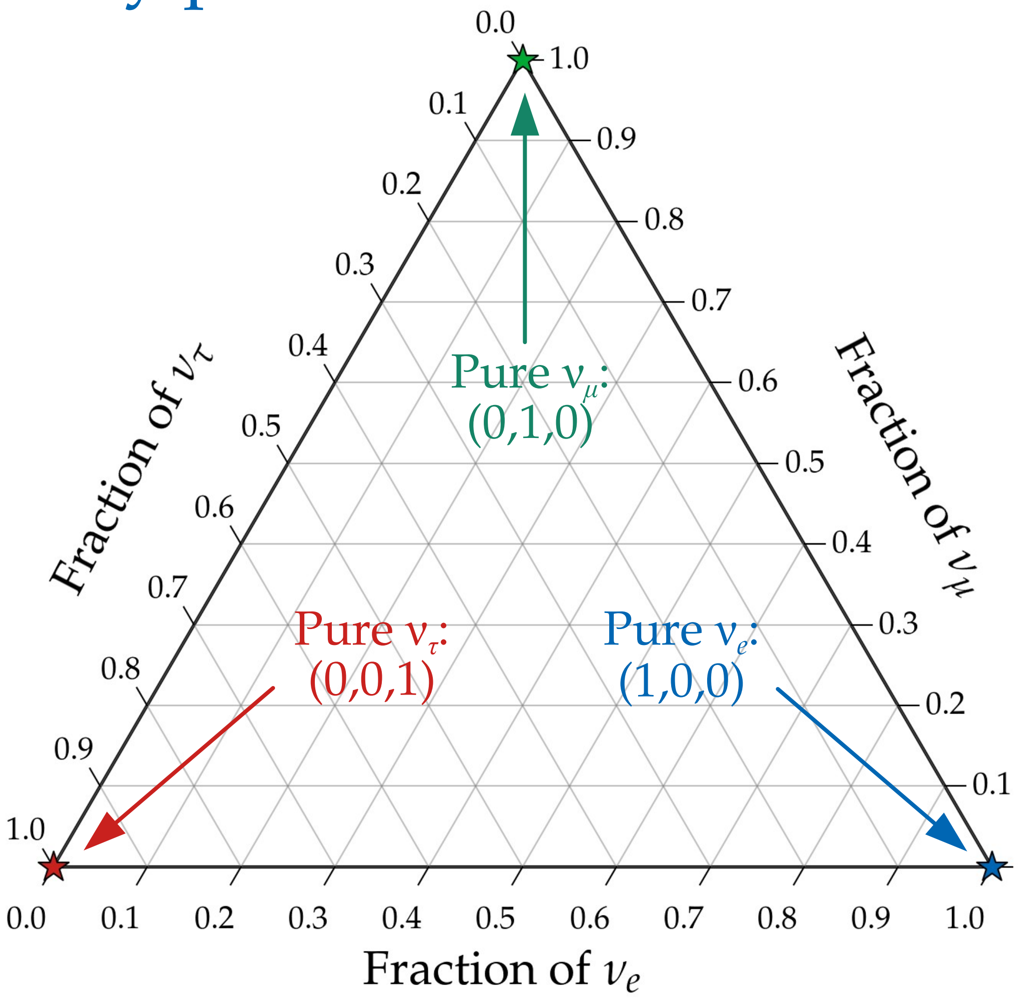

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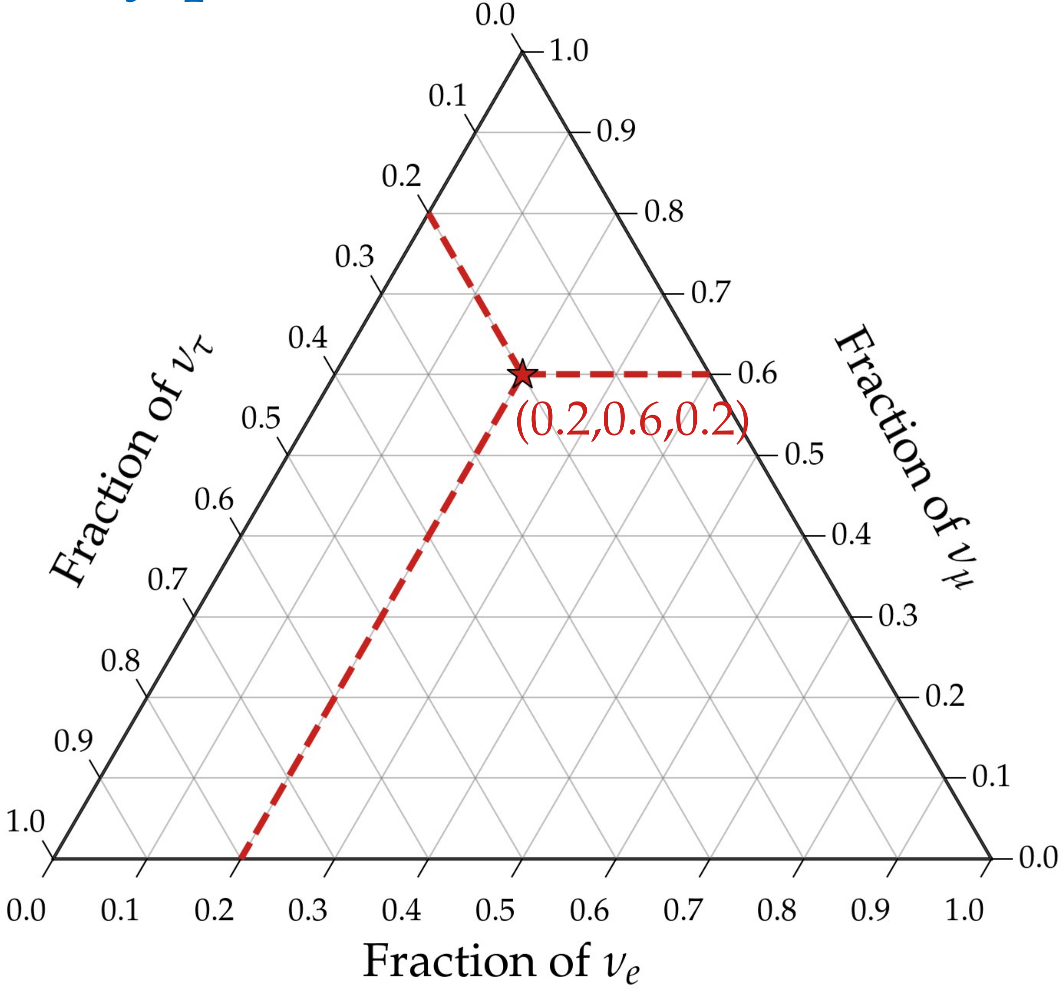

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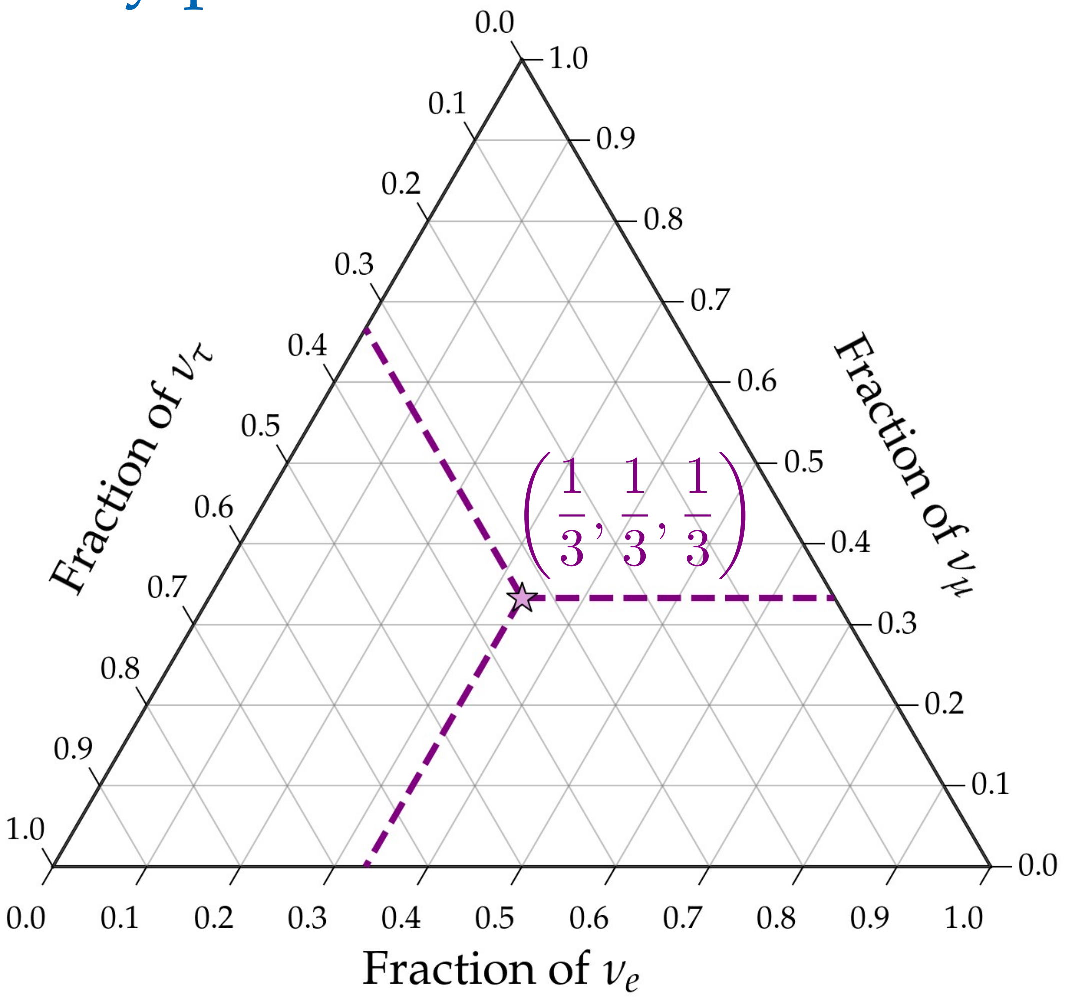
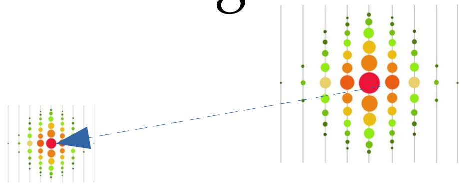


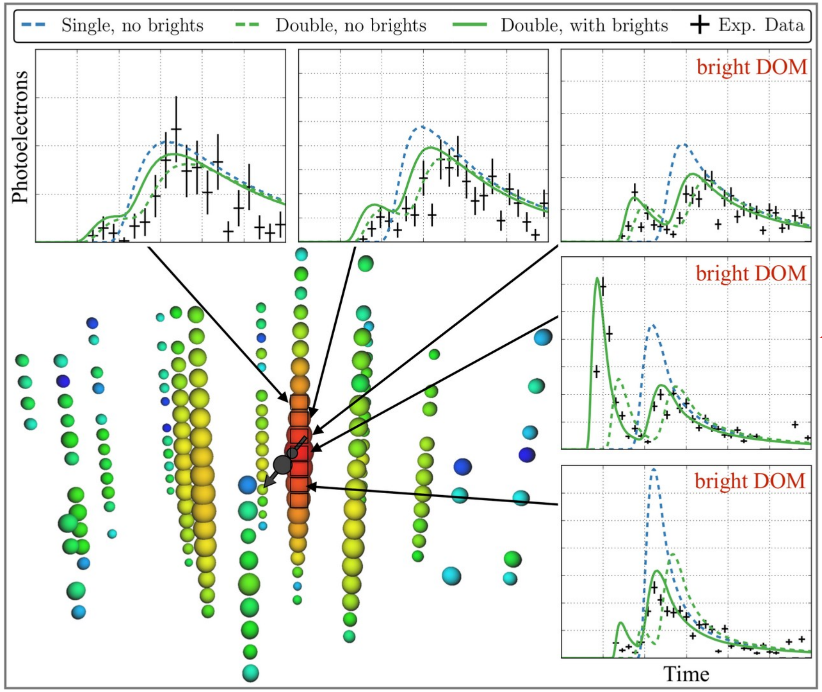
New (IC 7.5 yr): First identified high-energy astrophysical ν_τ

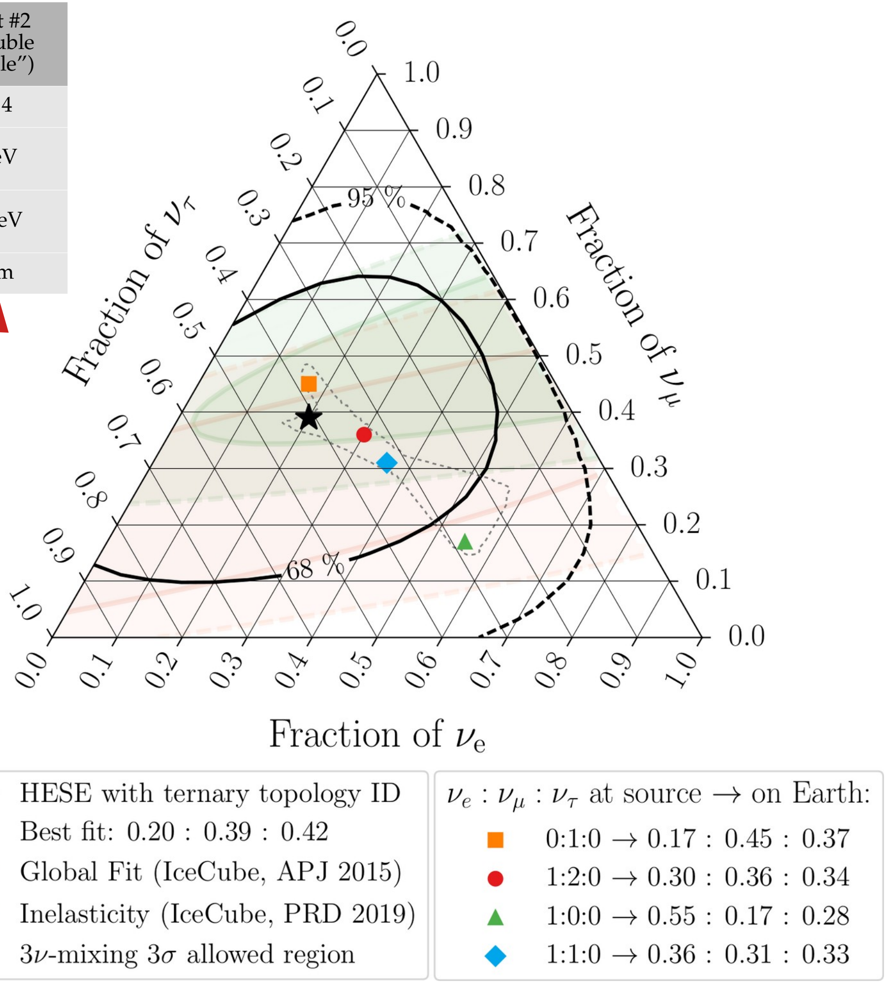
Double bang:



	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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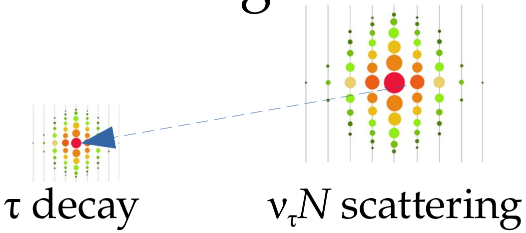

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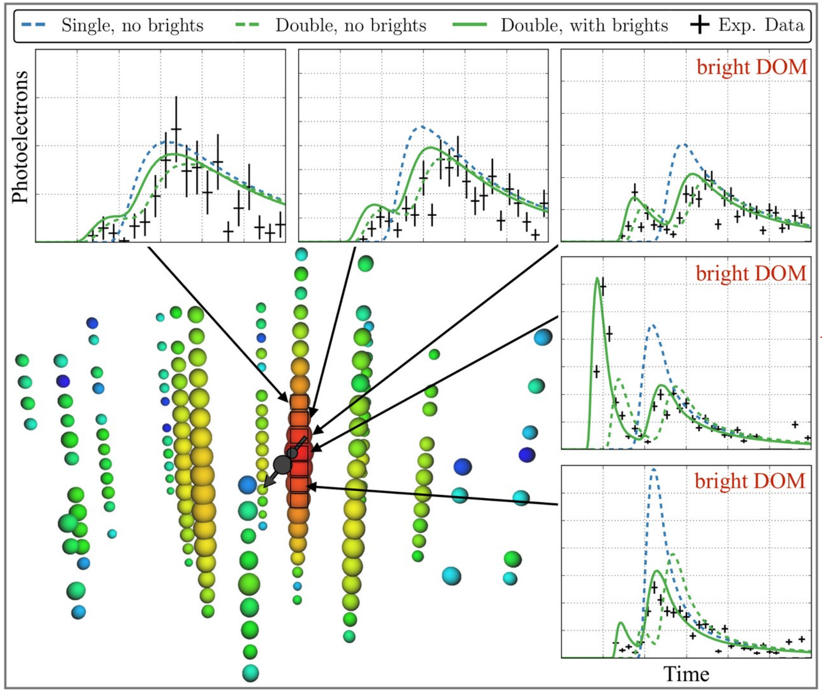

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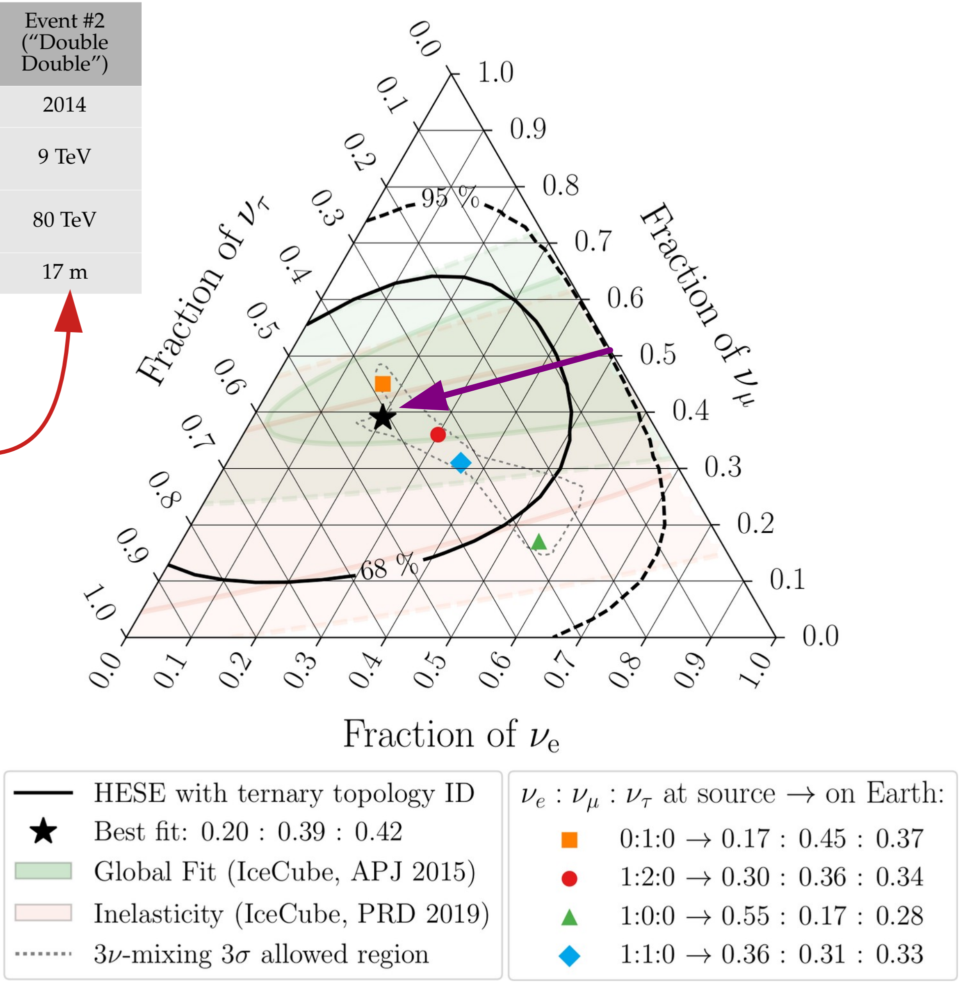

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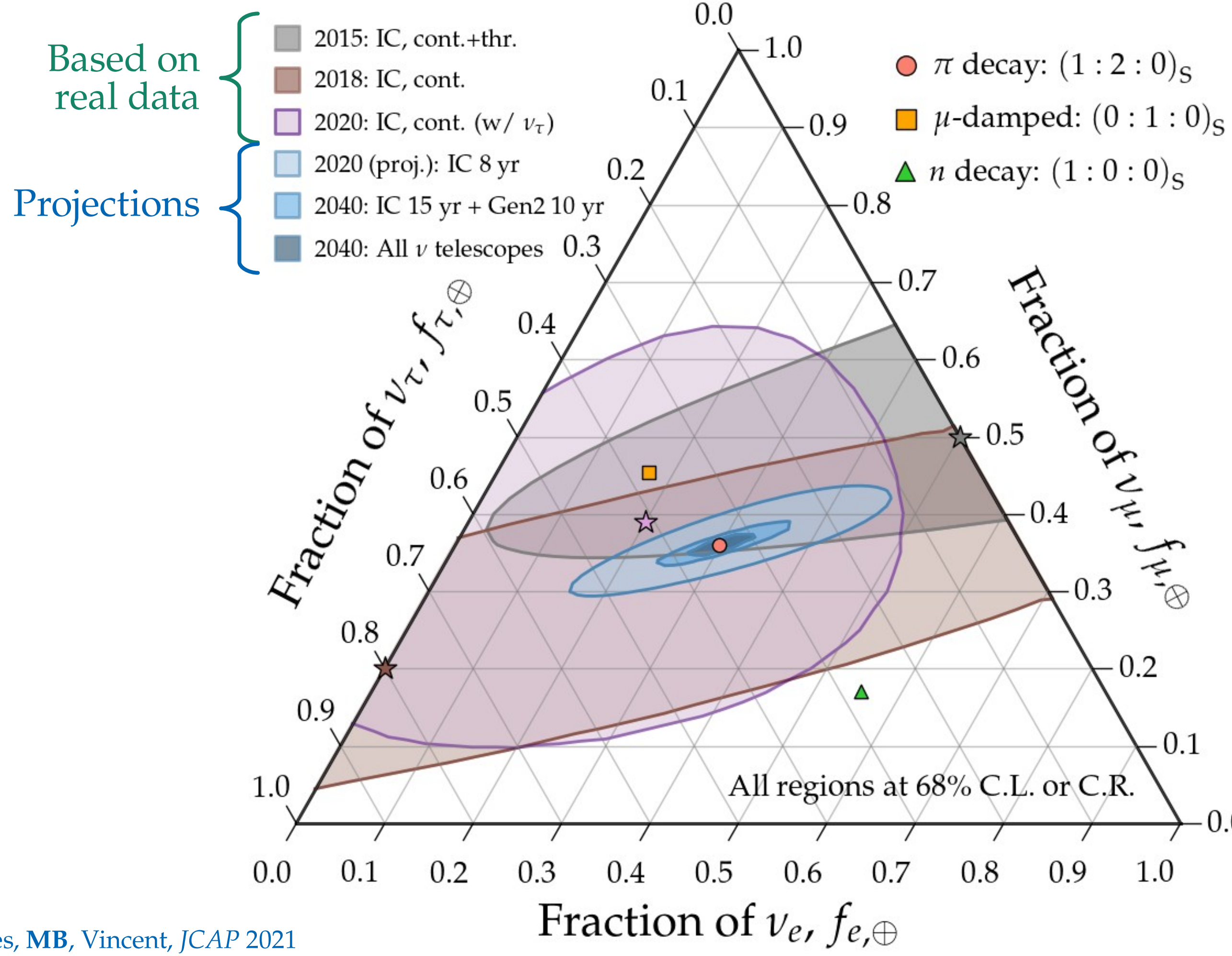
Measuring flavor composition: 2015–2040



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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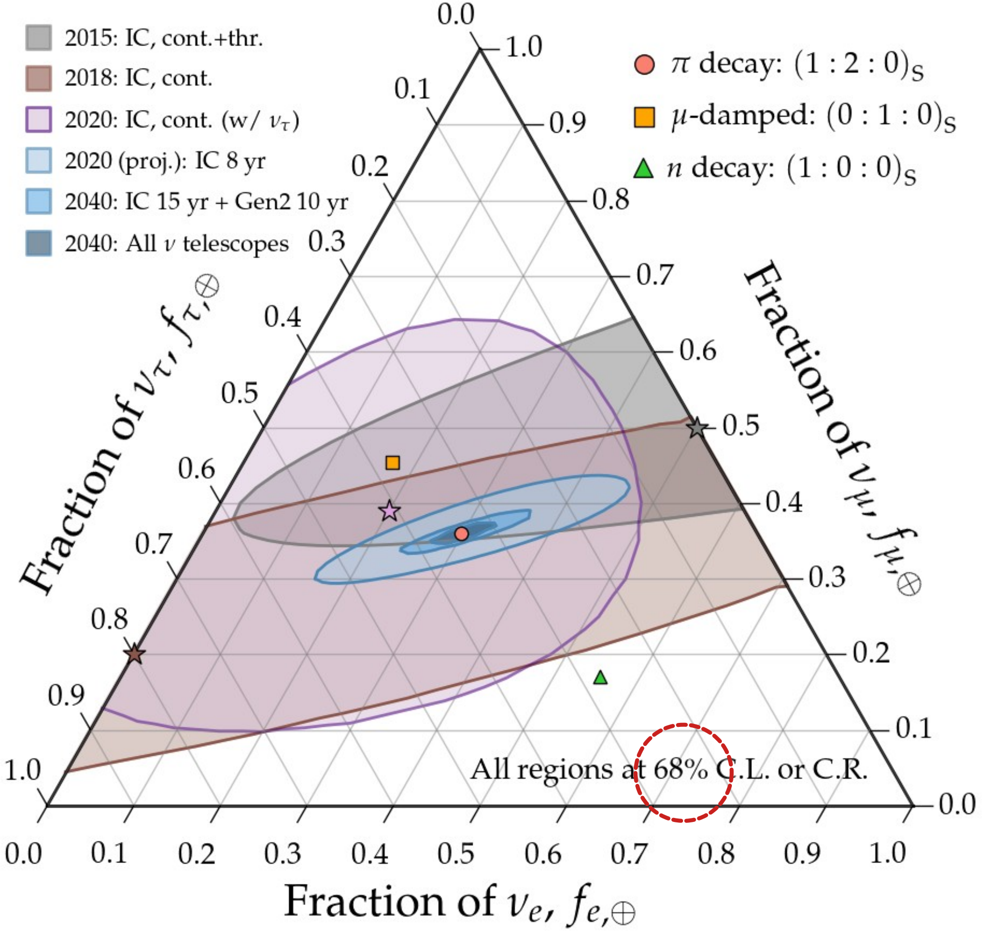
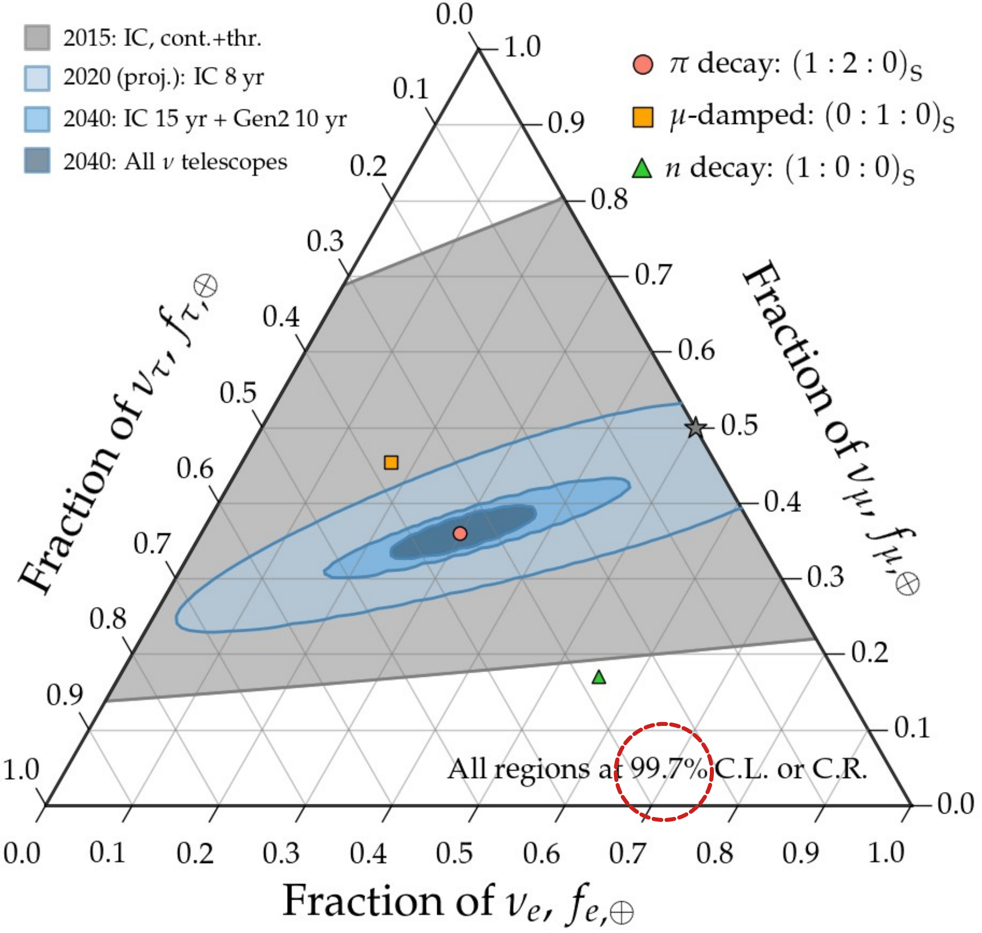
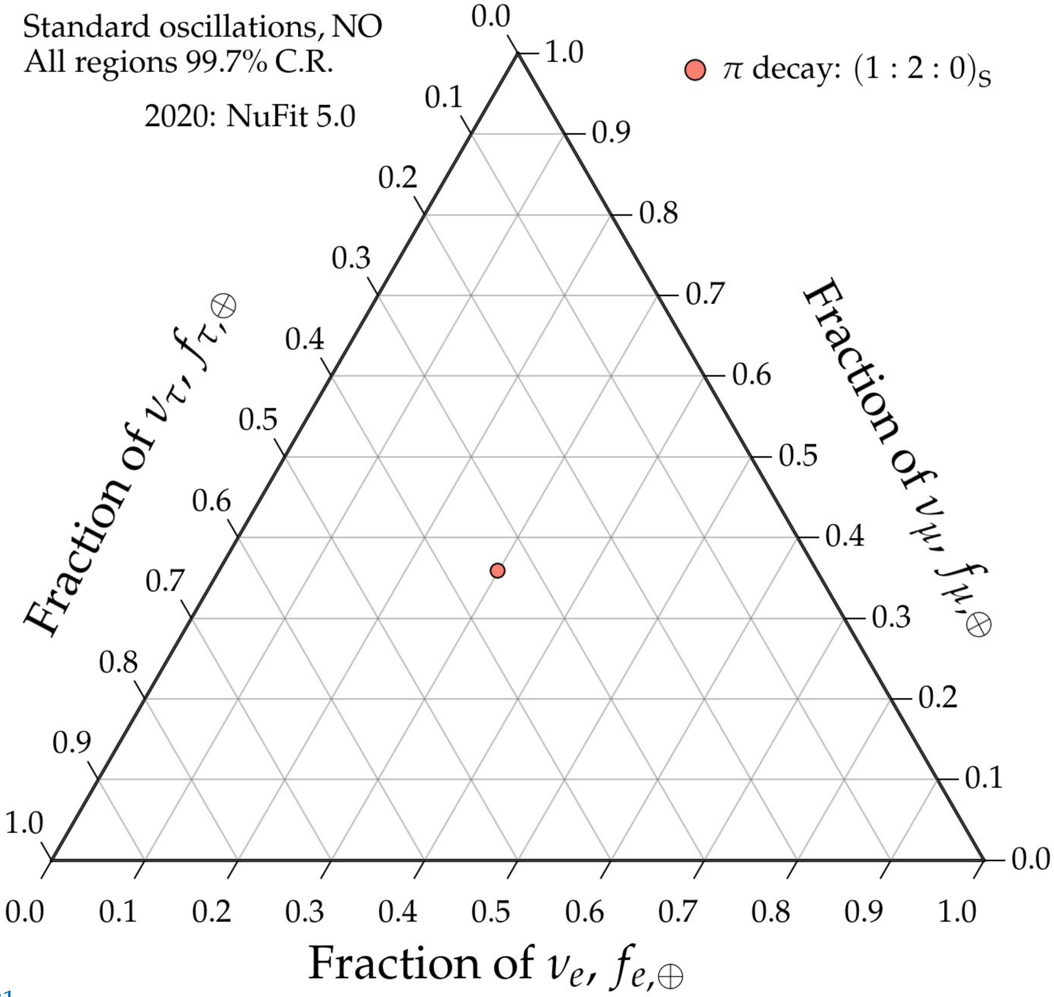




Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
IceCube, *PRL* 2015, *ApJ* 2015, *PRD* 2019, *J. Phys. G* 2021, 2011.03561

Theoretically palatable regions: 2020 *vs.* 2040



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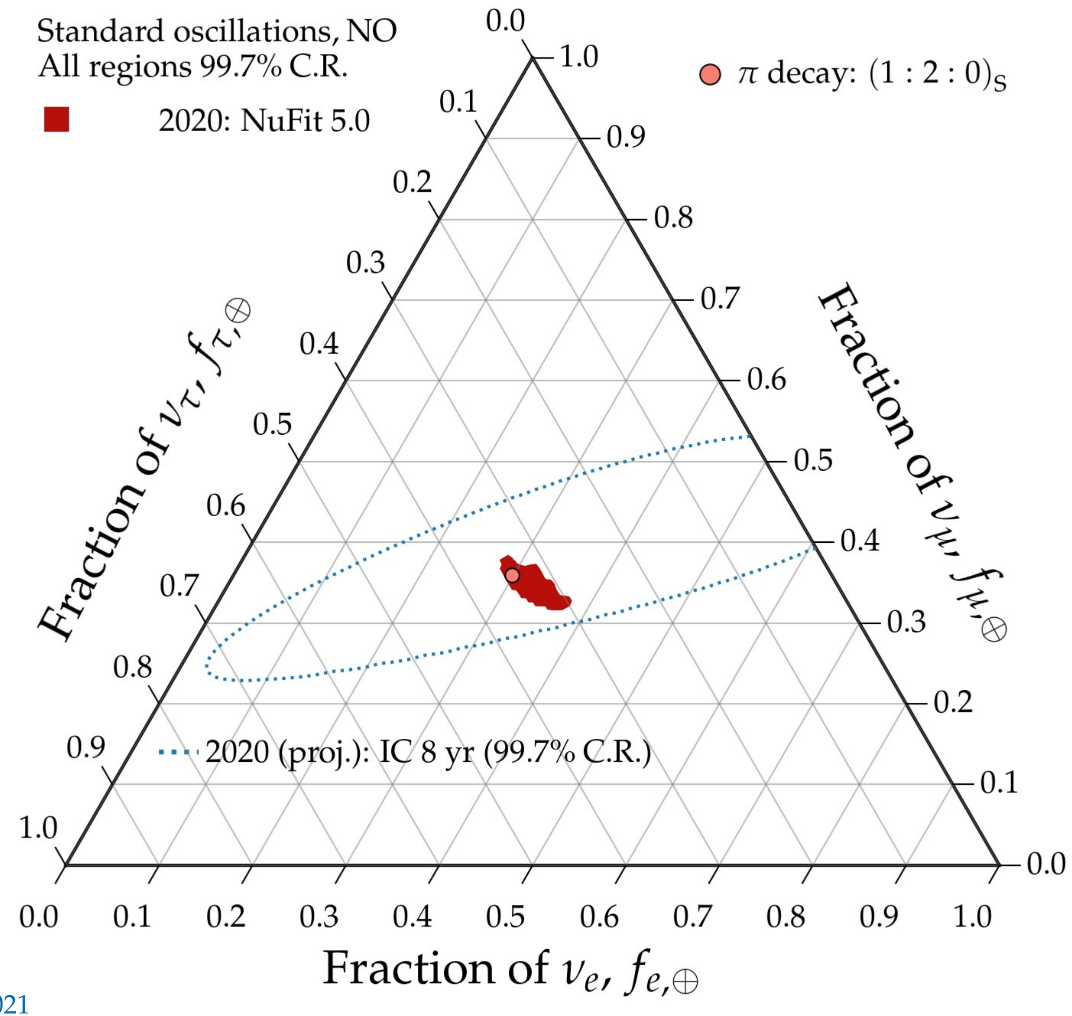

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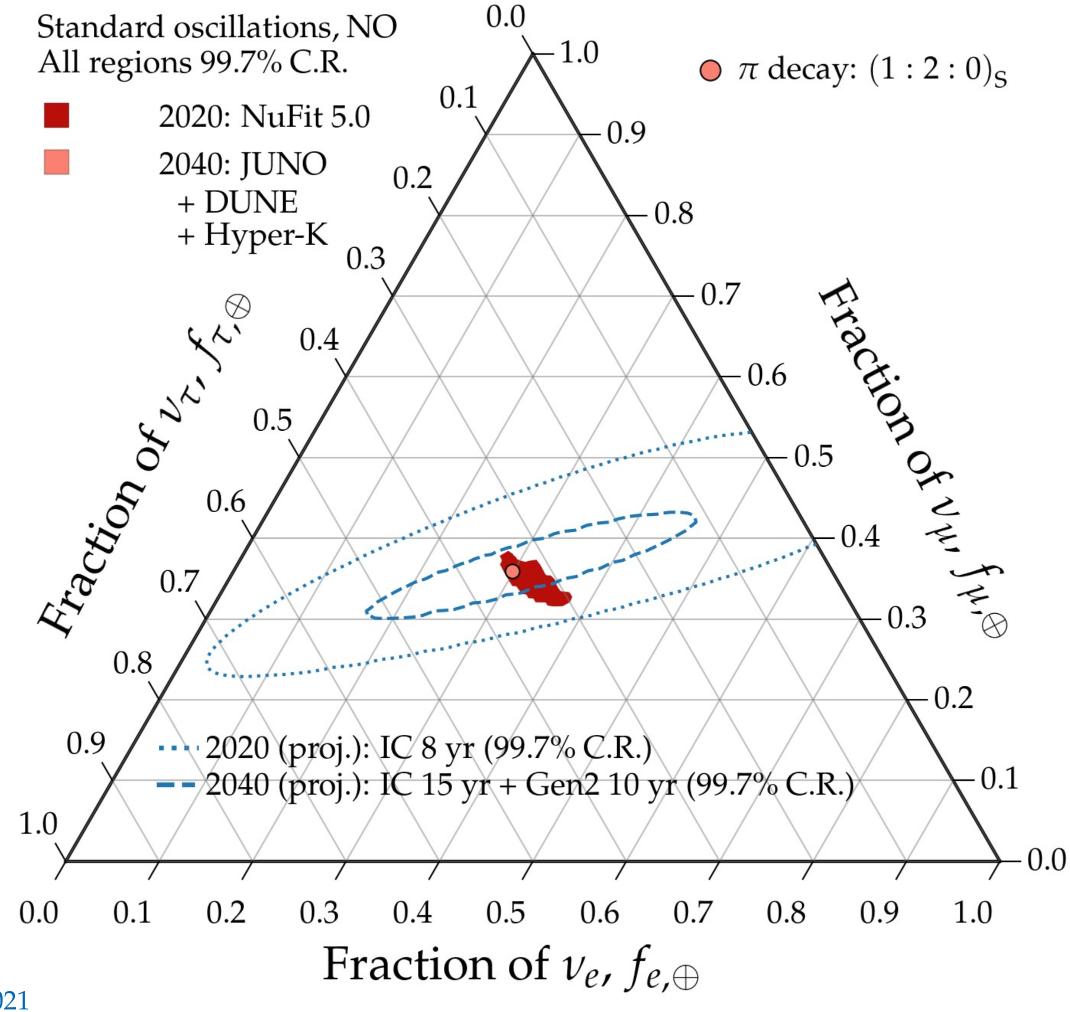
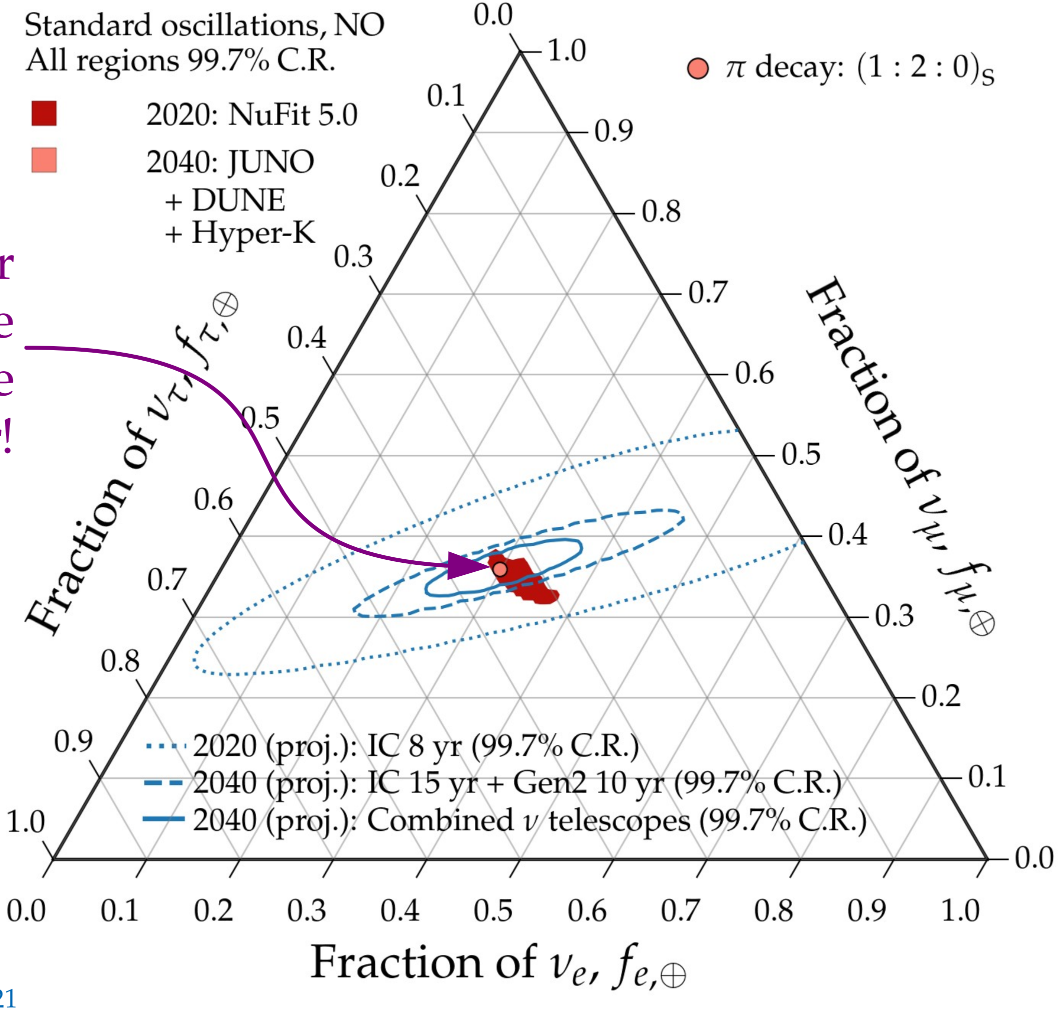


Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

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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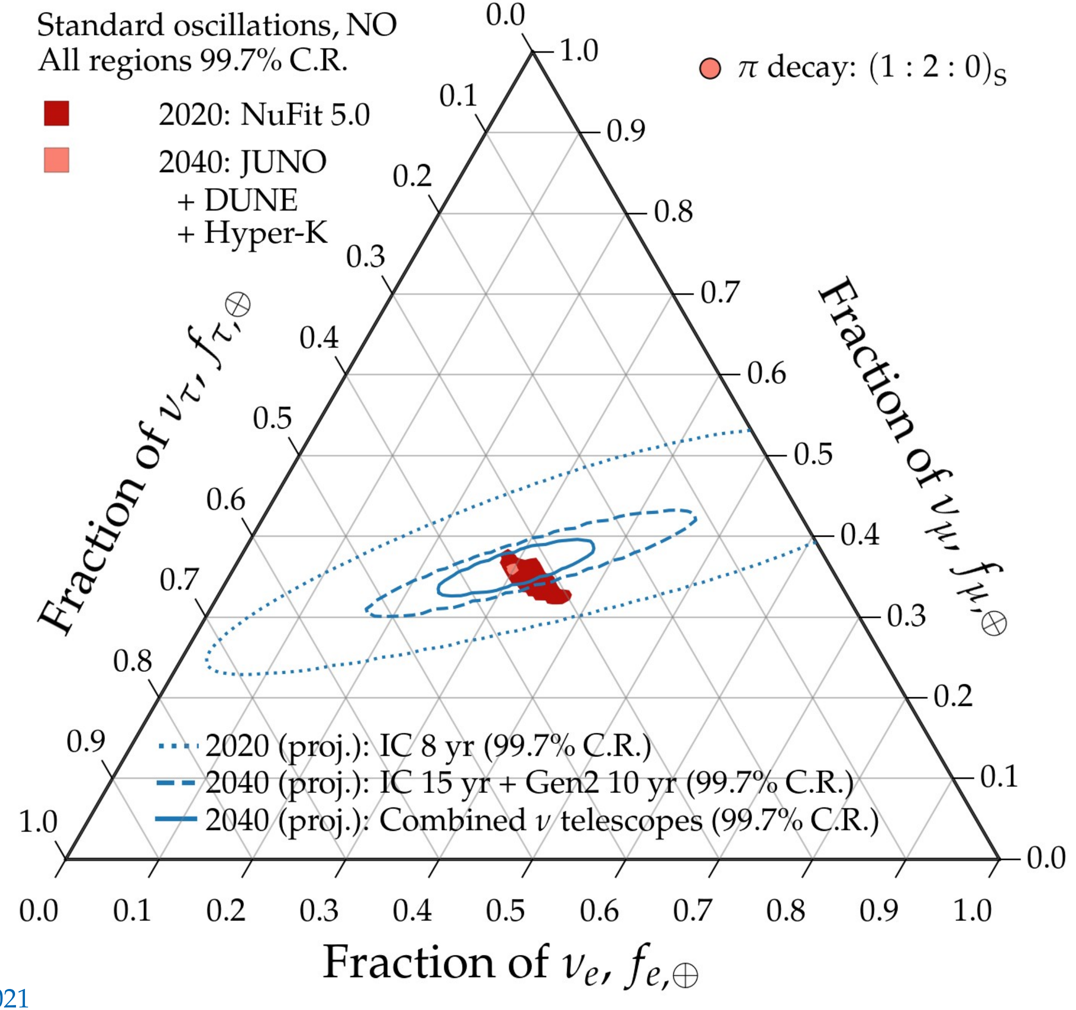

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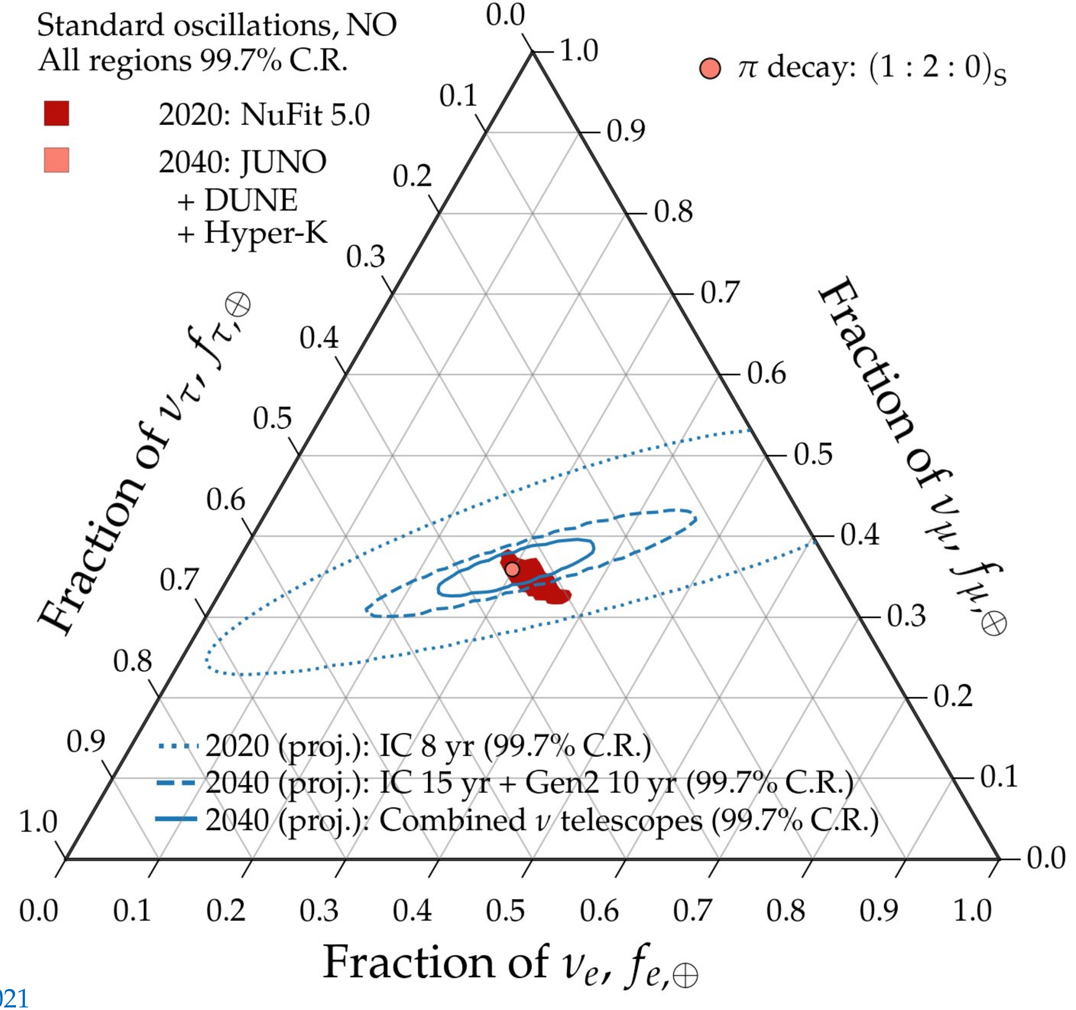

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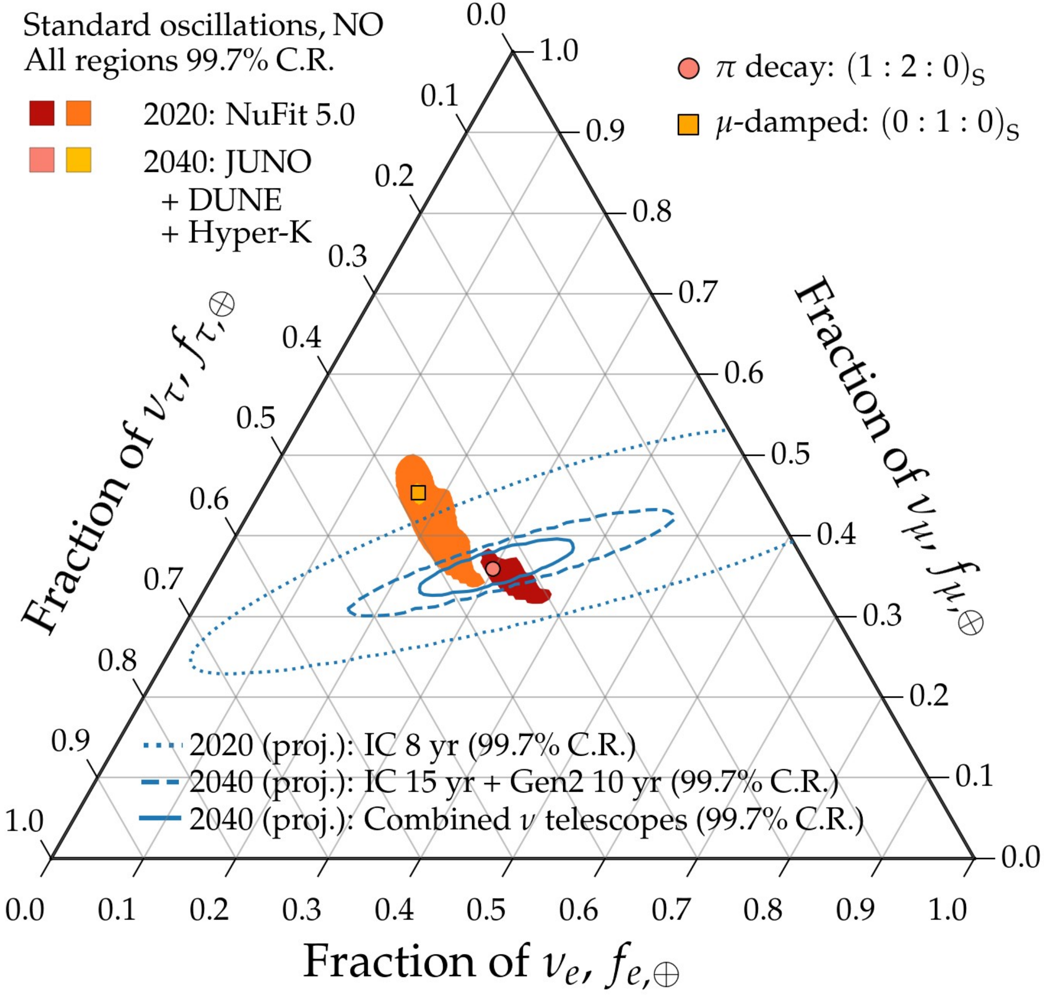

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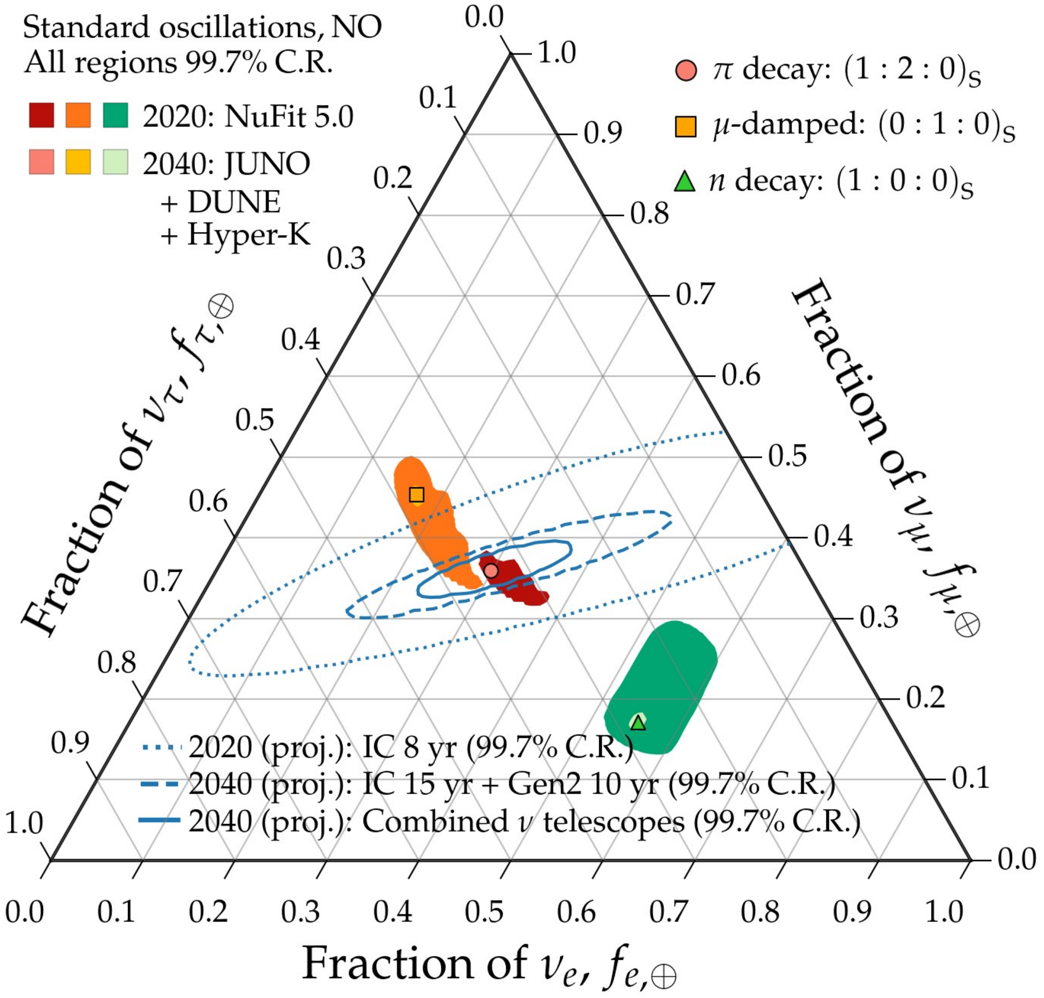

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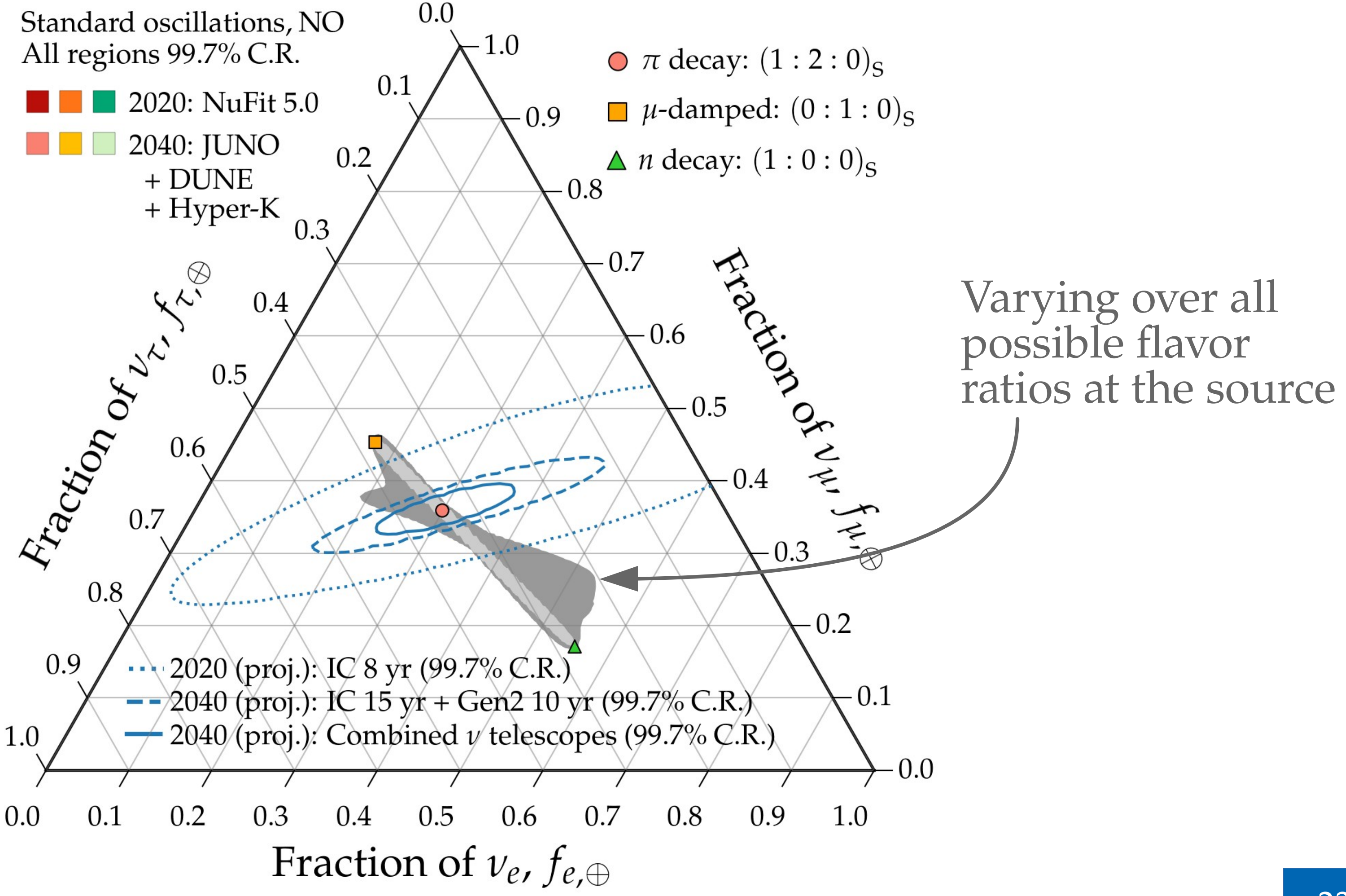

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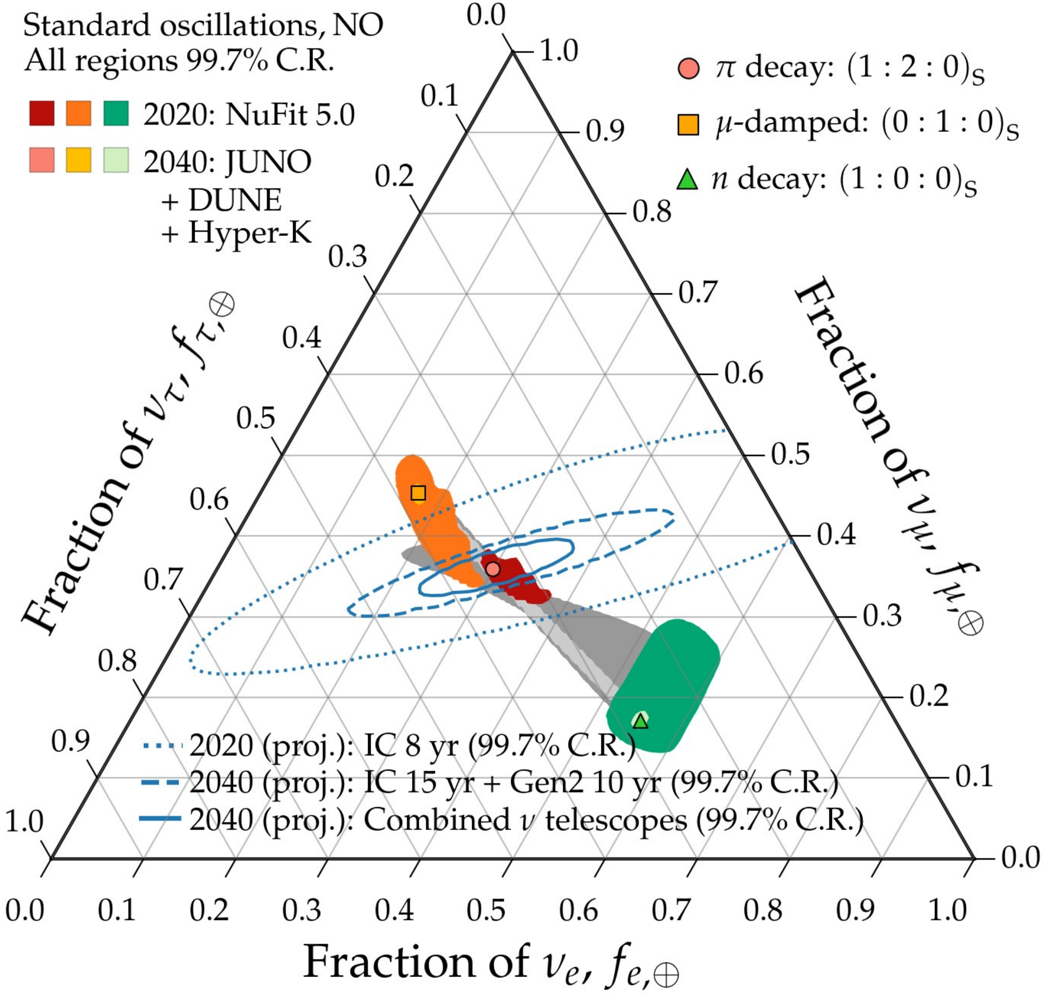

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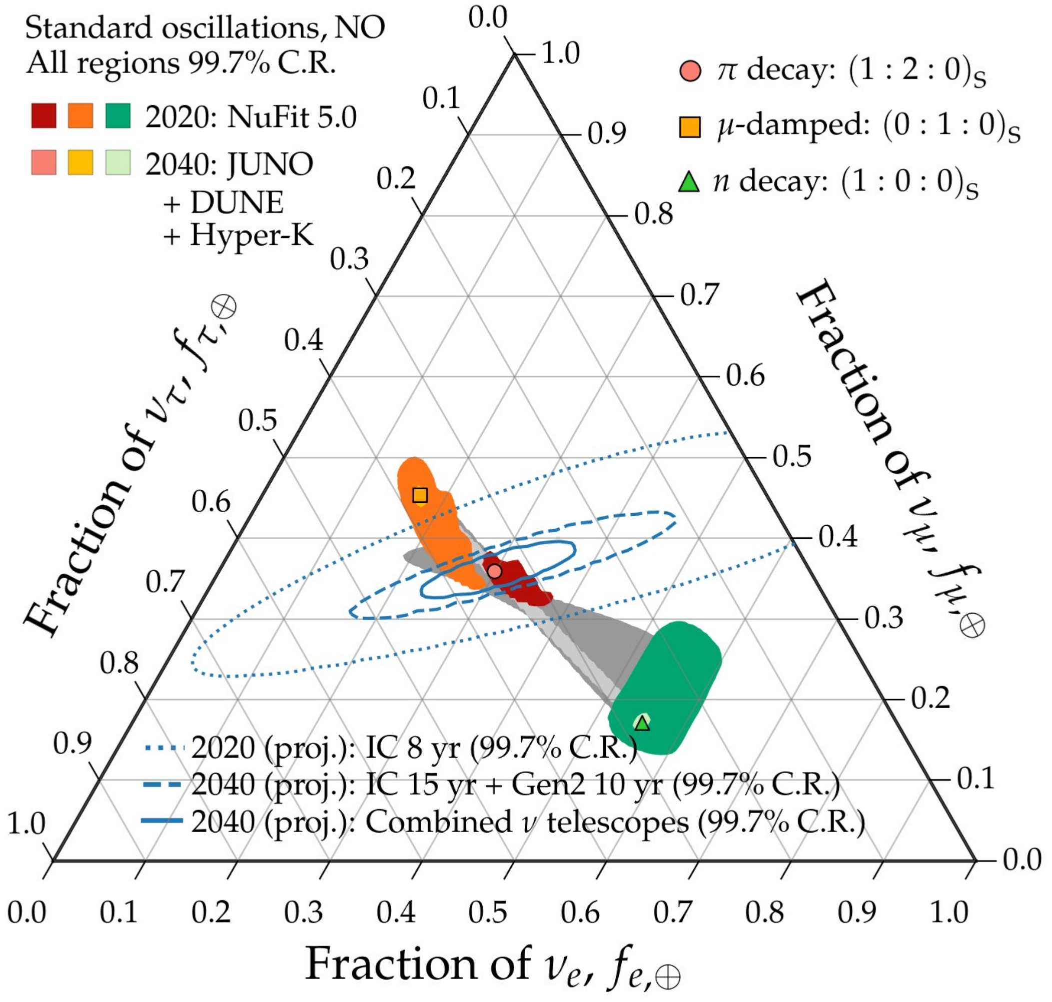


By 2040:

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

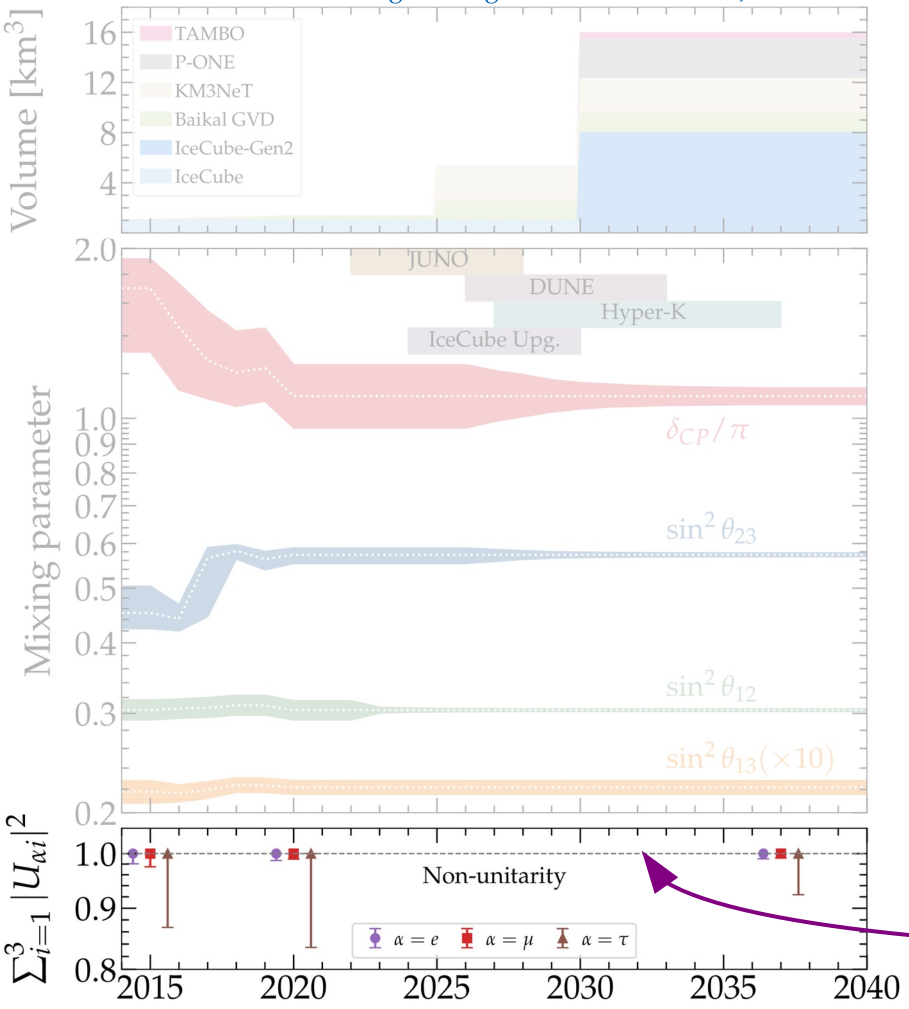
Measurement of flavor ratios –
Can distinguish between similar predictions at 99.7% C.R. (3σ)

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

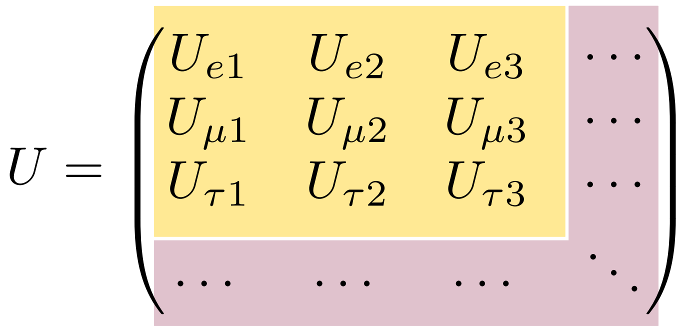
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

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:



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

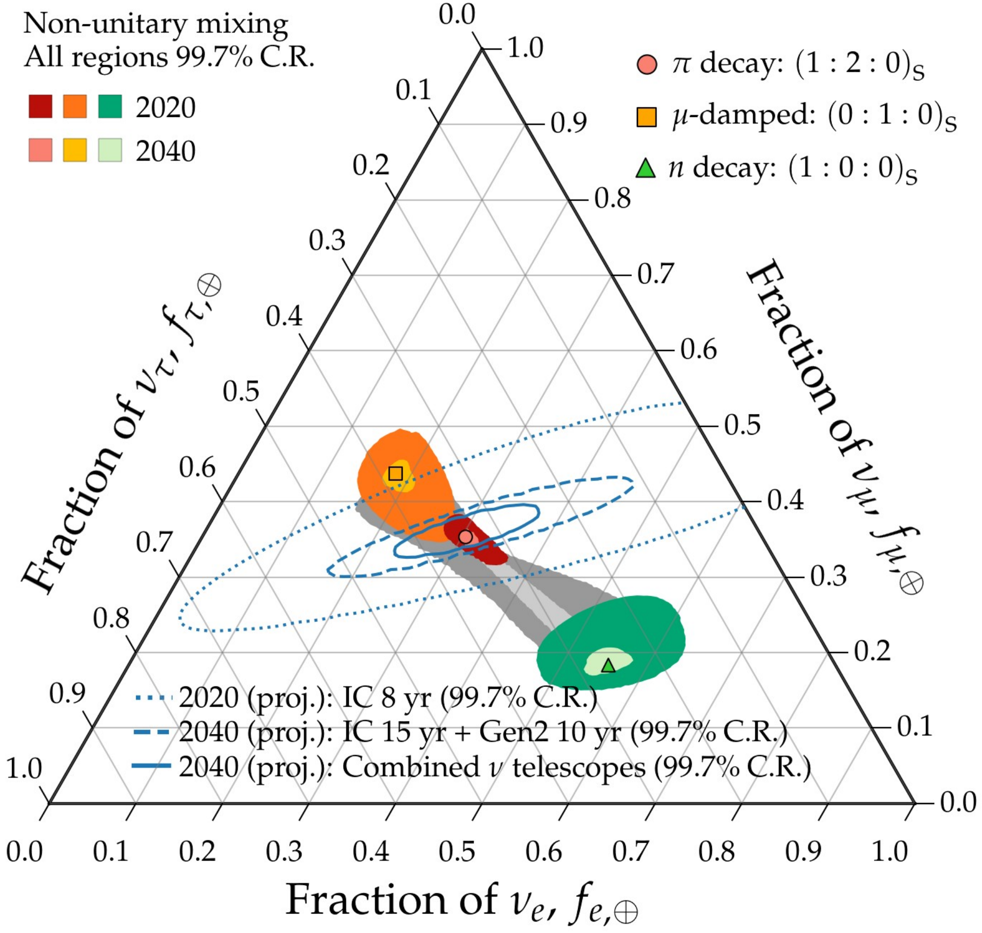
No unitarity? *No problem*

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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No unitarity? *No problem*

Flavor ratios at Earth: $P_{\beta\alpha} = \sum_{i=1,2,3} |U_{\alpha i}|^2 |U_{\beta i}|^2$

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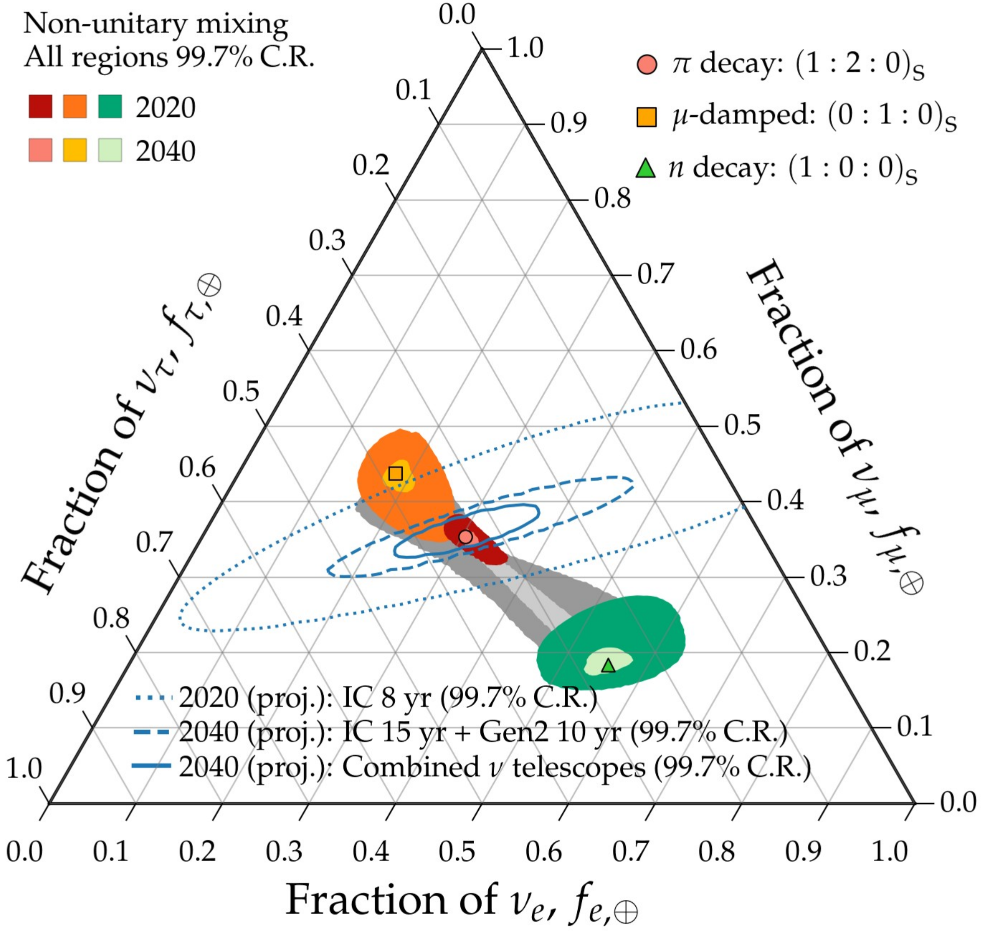

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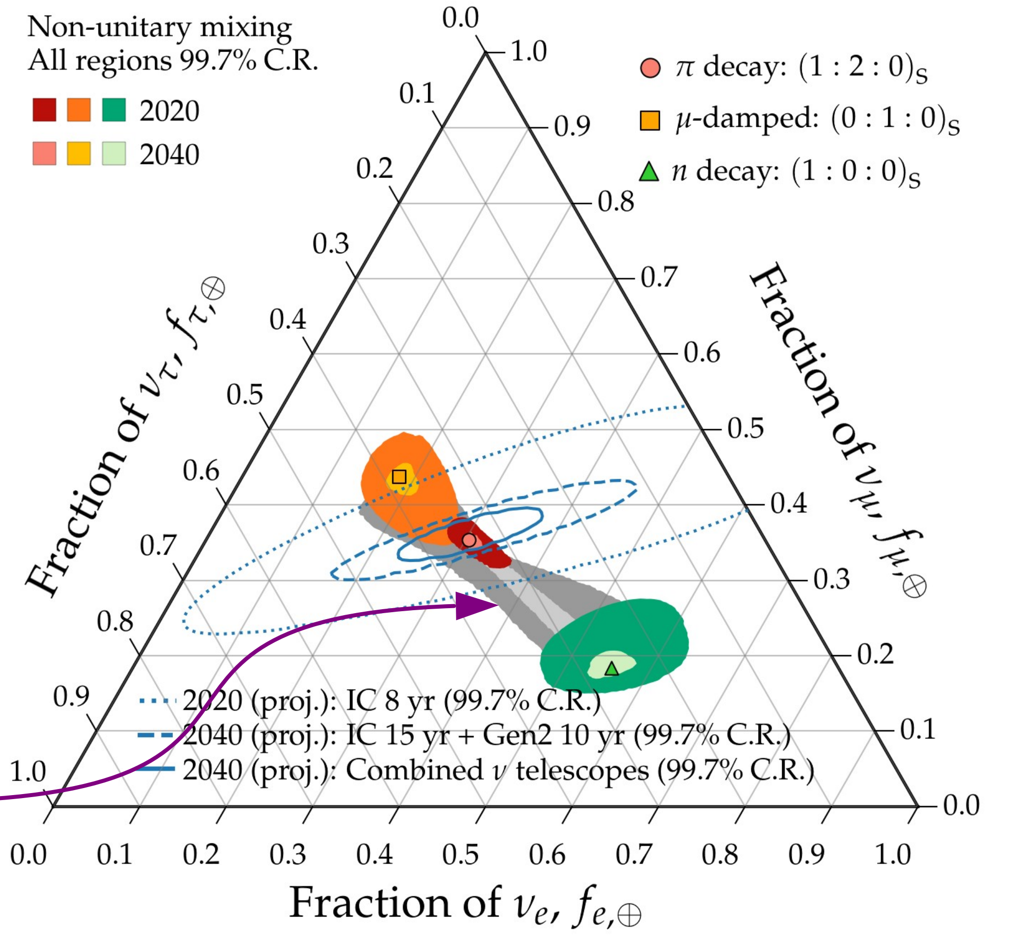

The allowed flavor regions are bigger, but *not much bigger*!

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

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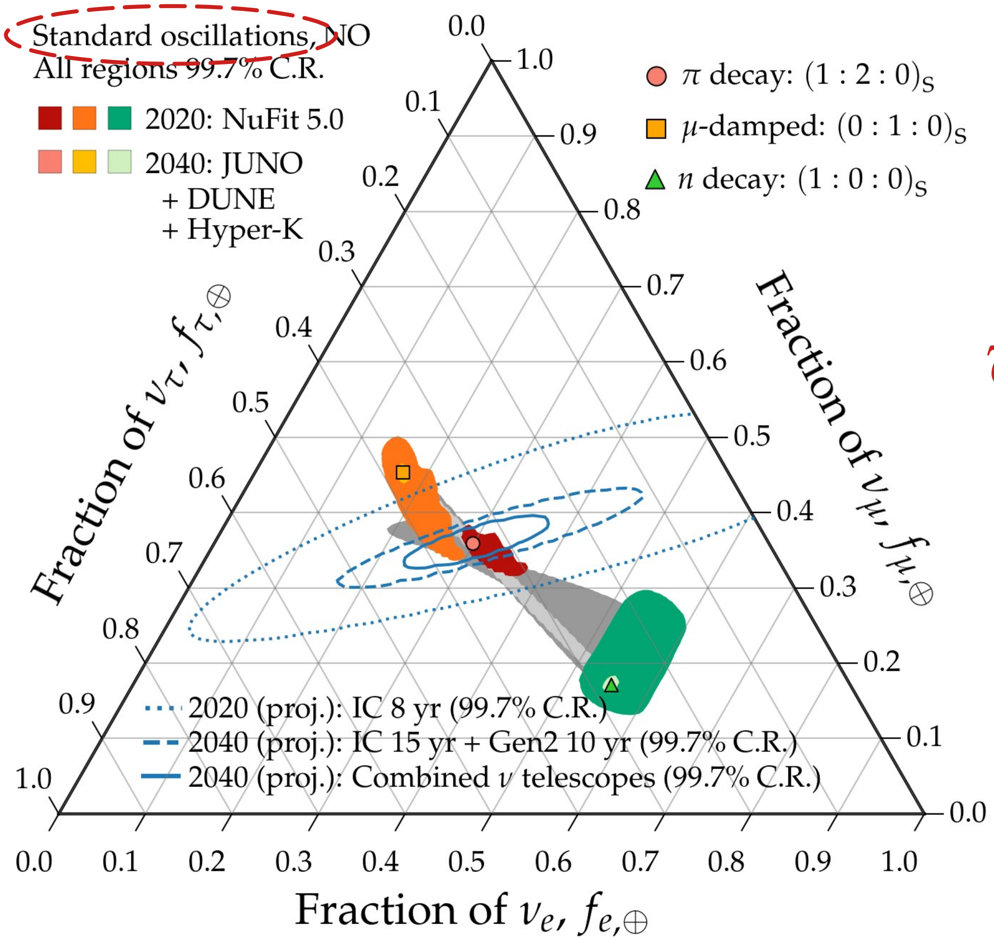
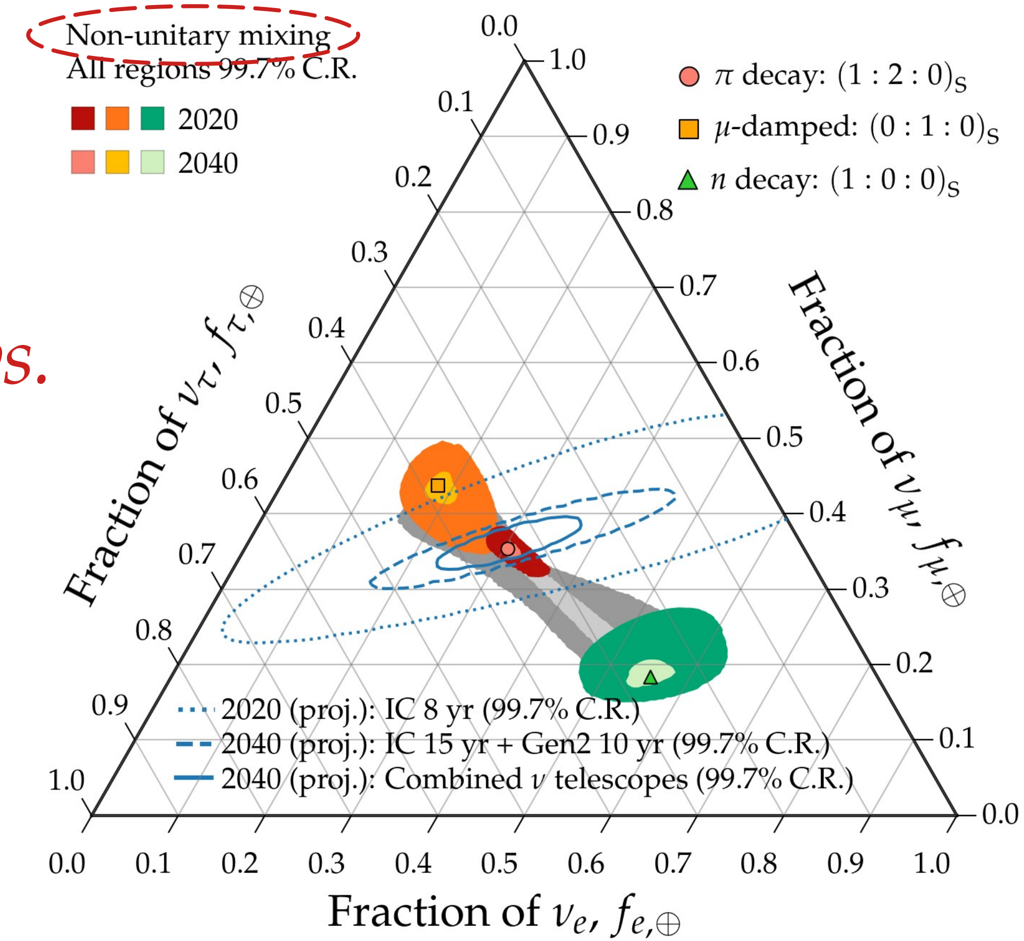


vs.



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

More than one production mechanism?

Can we detect the contribution of multiple ν production mechanisms?

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

π decay: (1/3, 2/3, 0)

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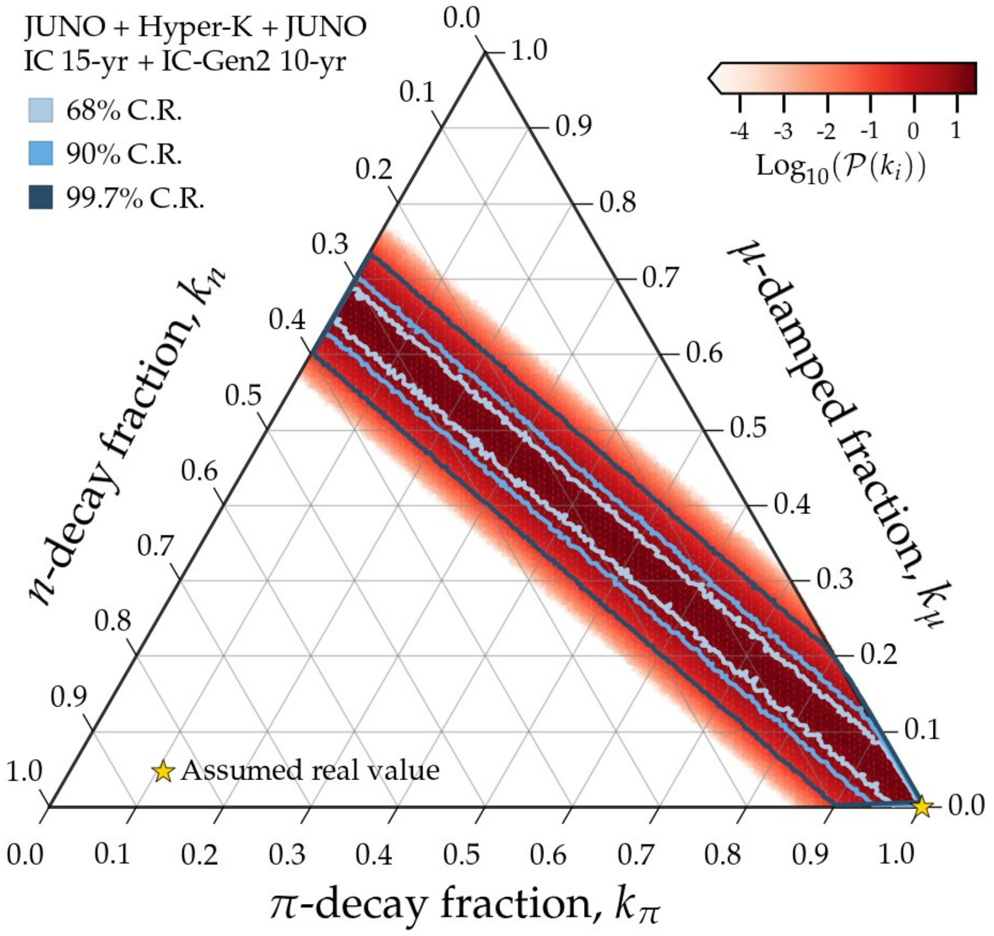
[Adding spectrum information (not shown) will likely help]



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

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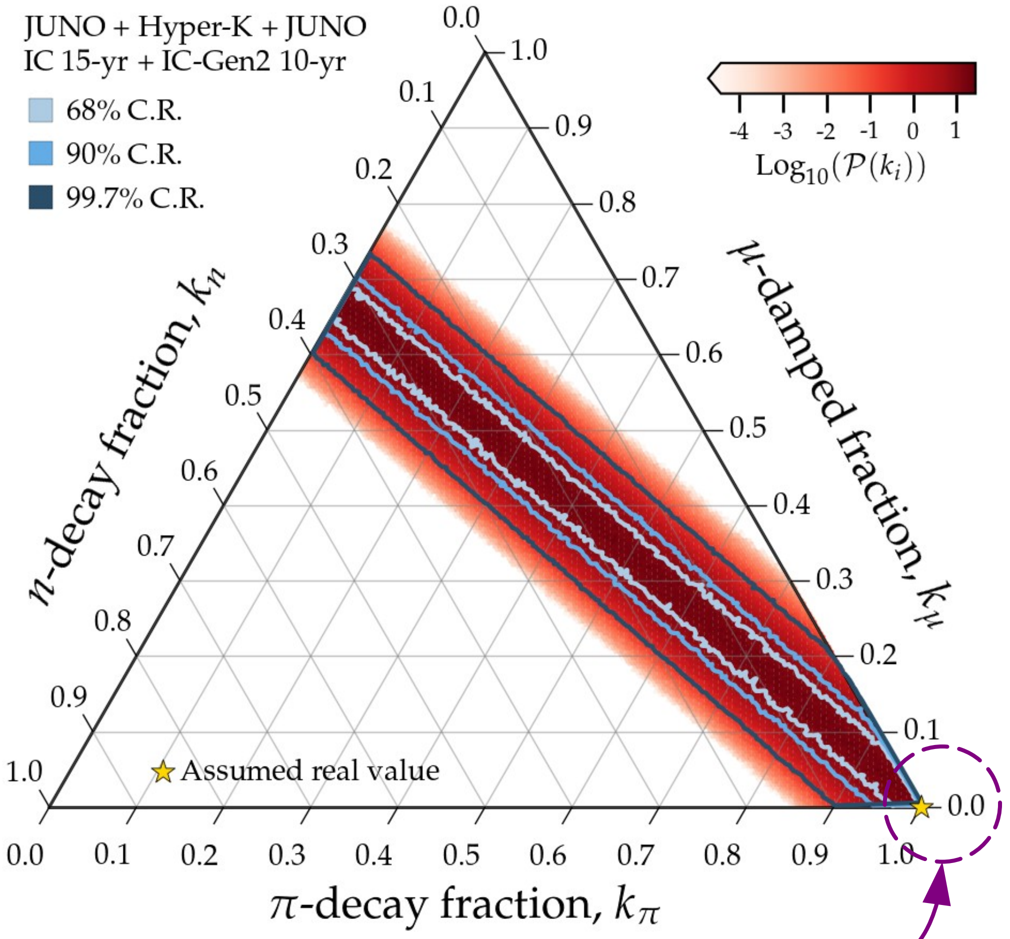

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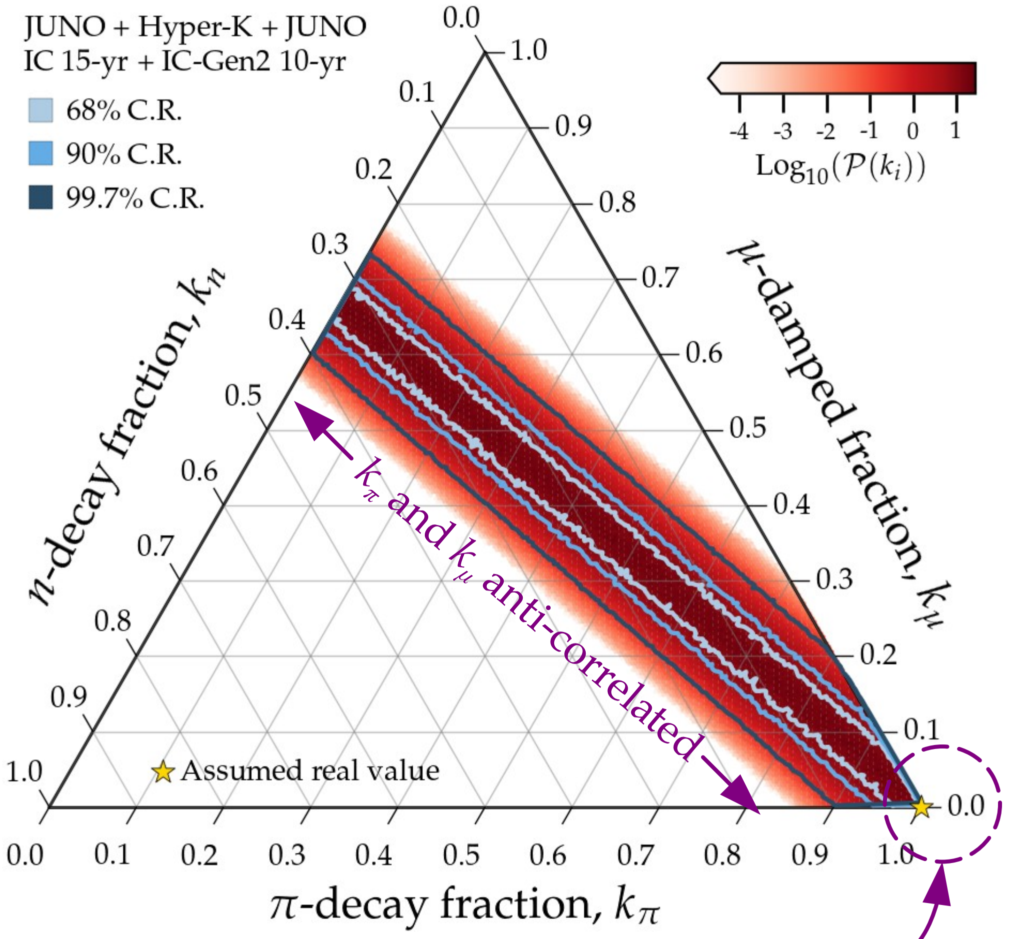

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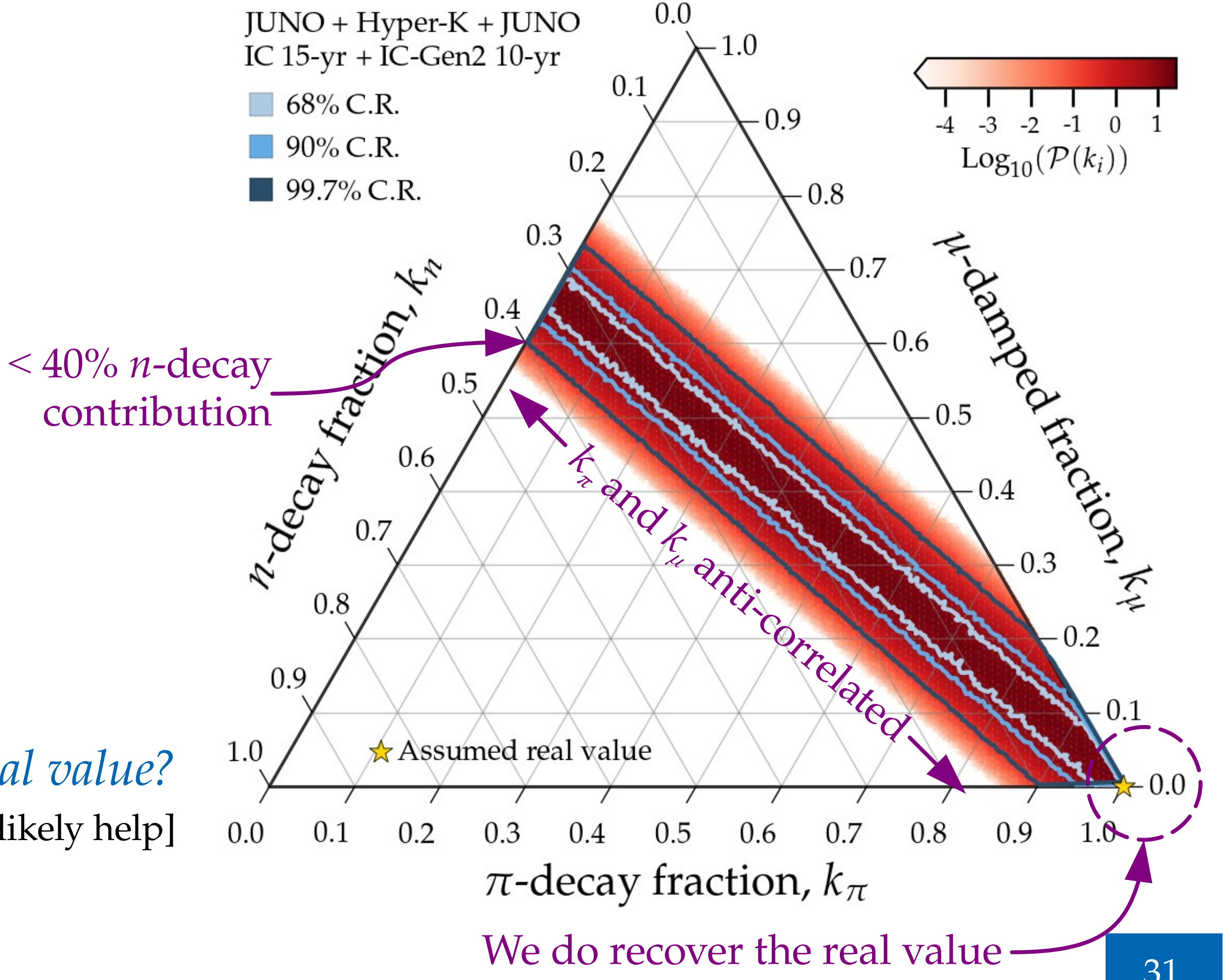

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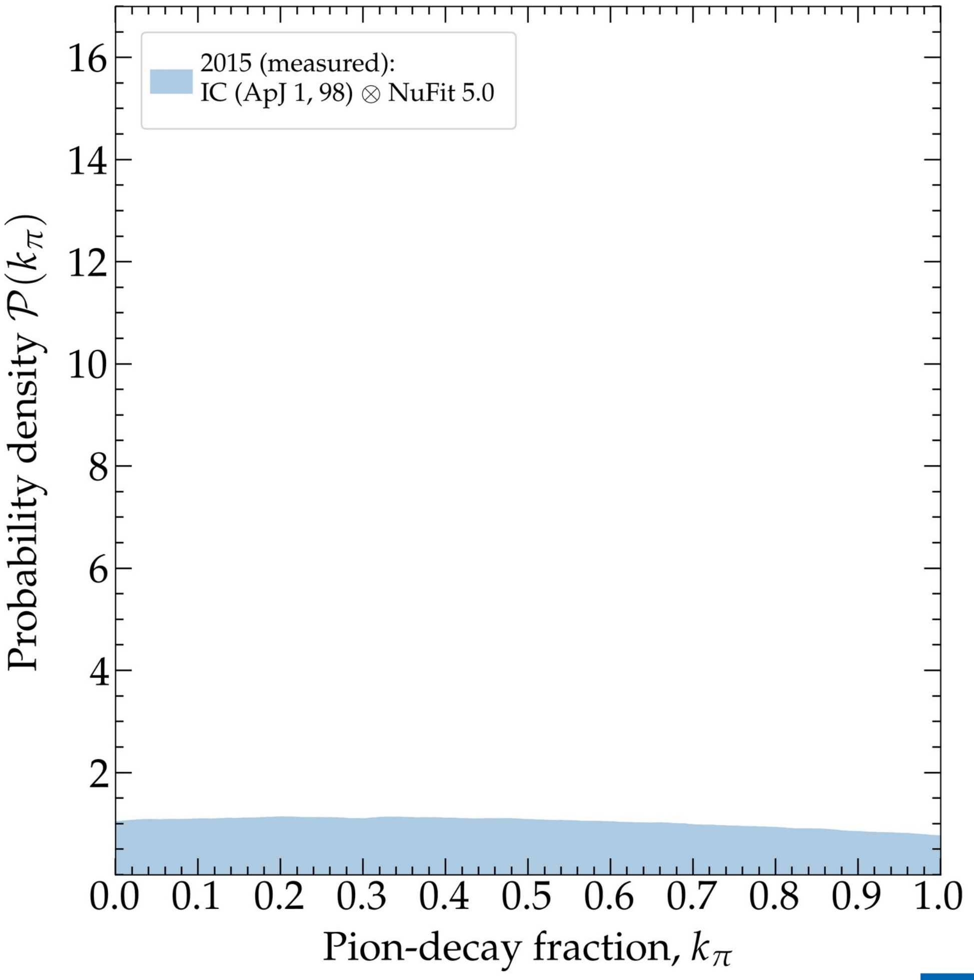

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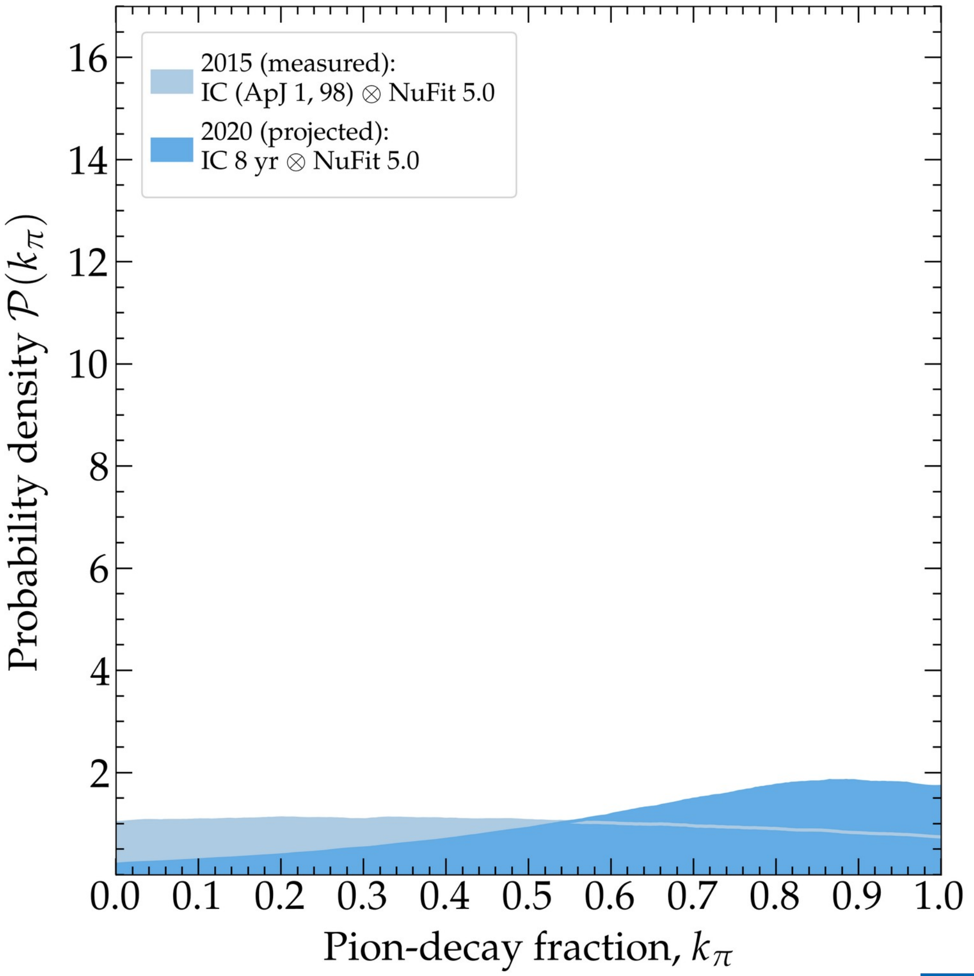

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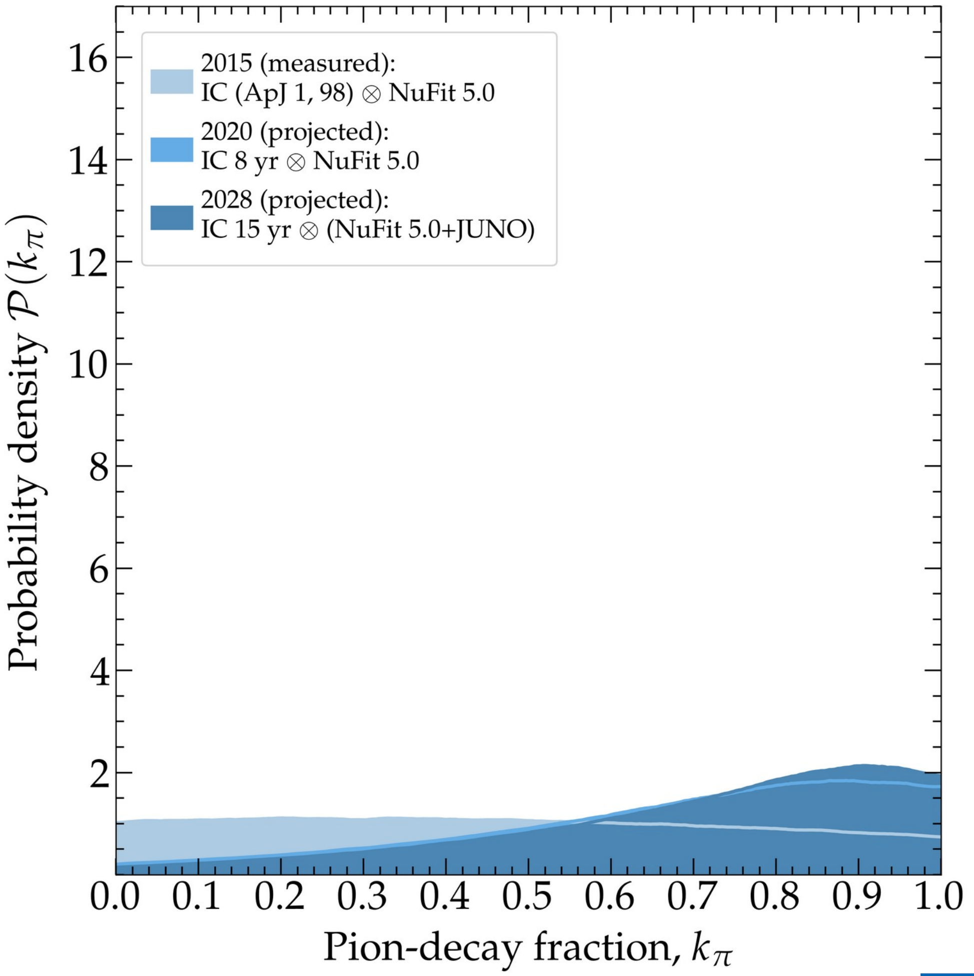

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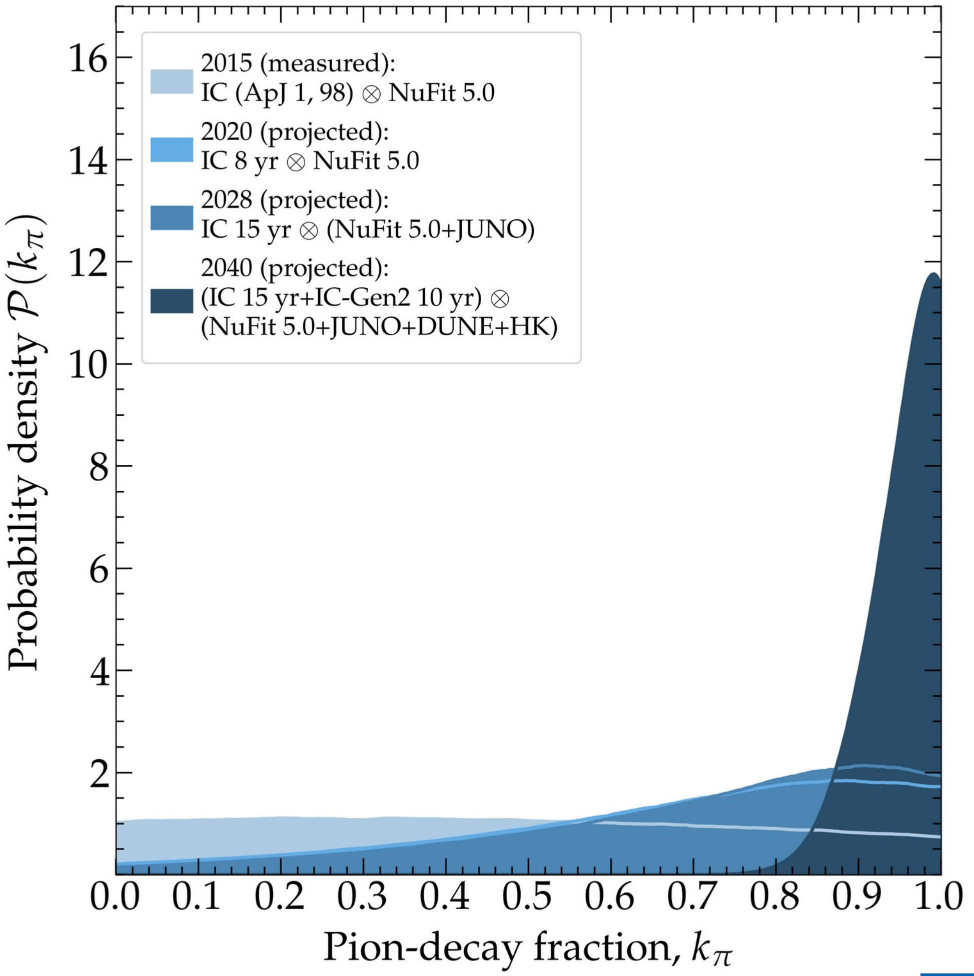

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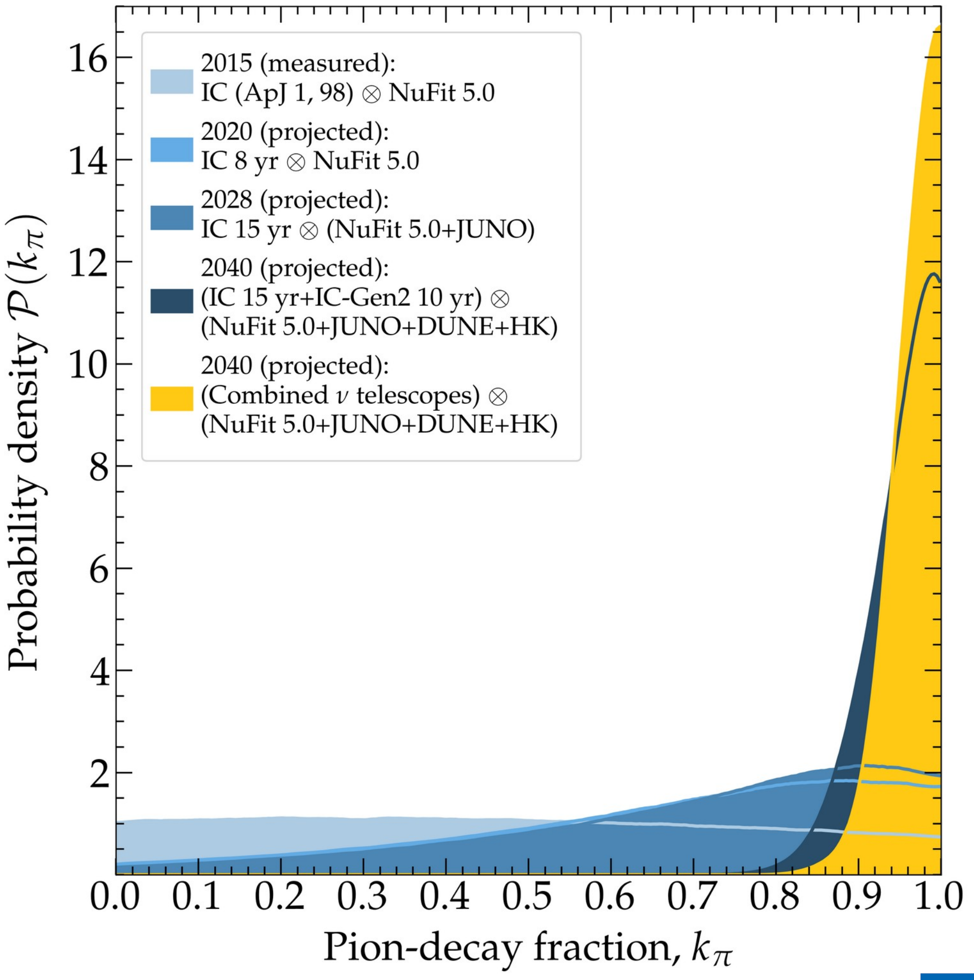

Using high-energy neutrinos as magnetometers

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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Muon cooling

Change flavor composition:

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

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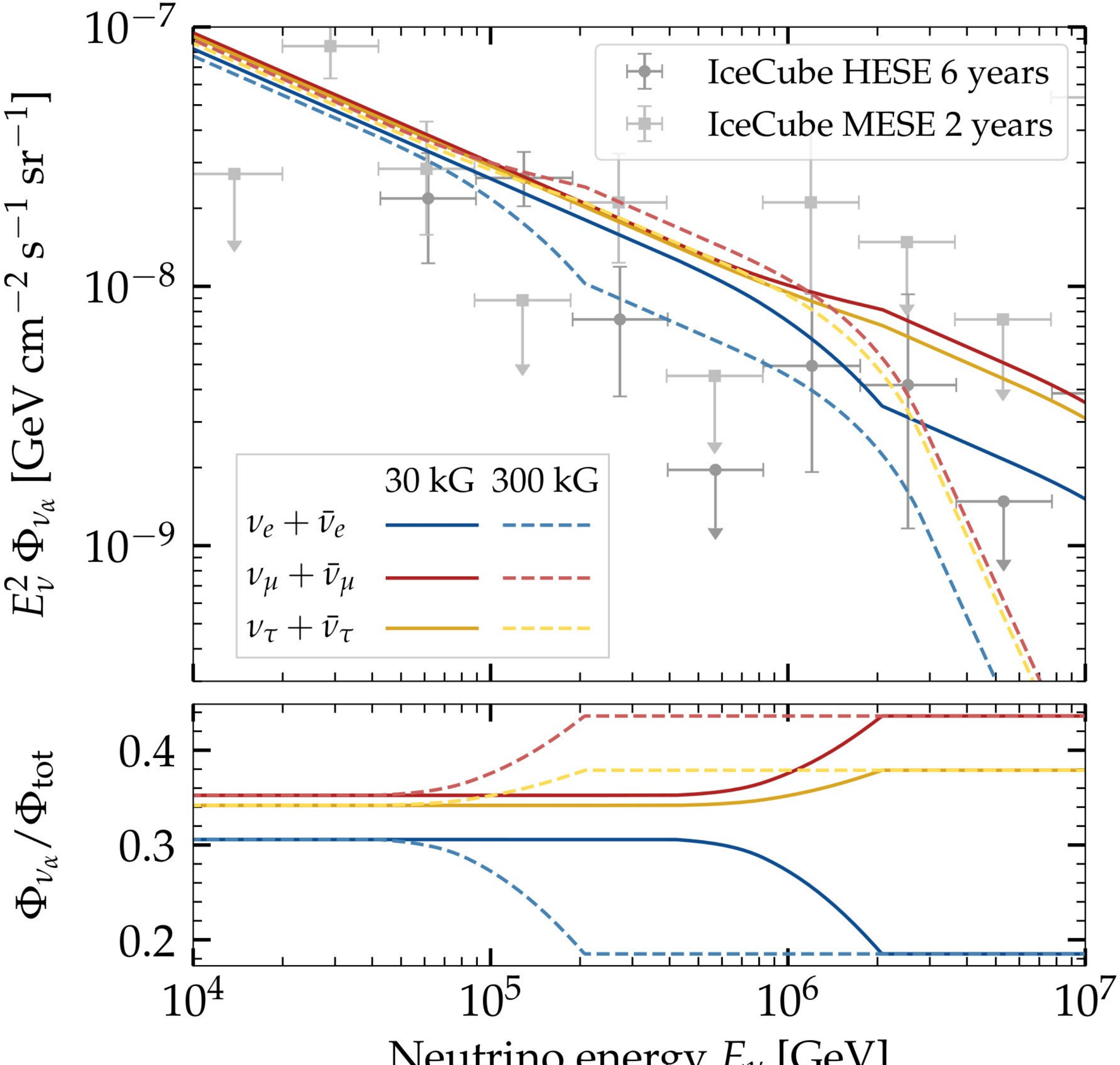
Pion cooling

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

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

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



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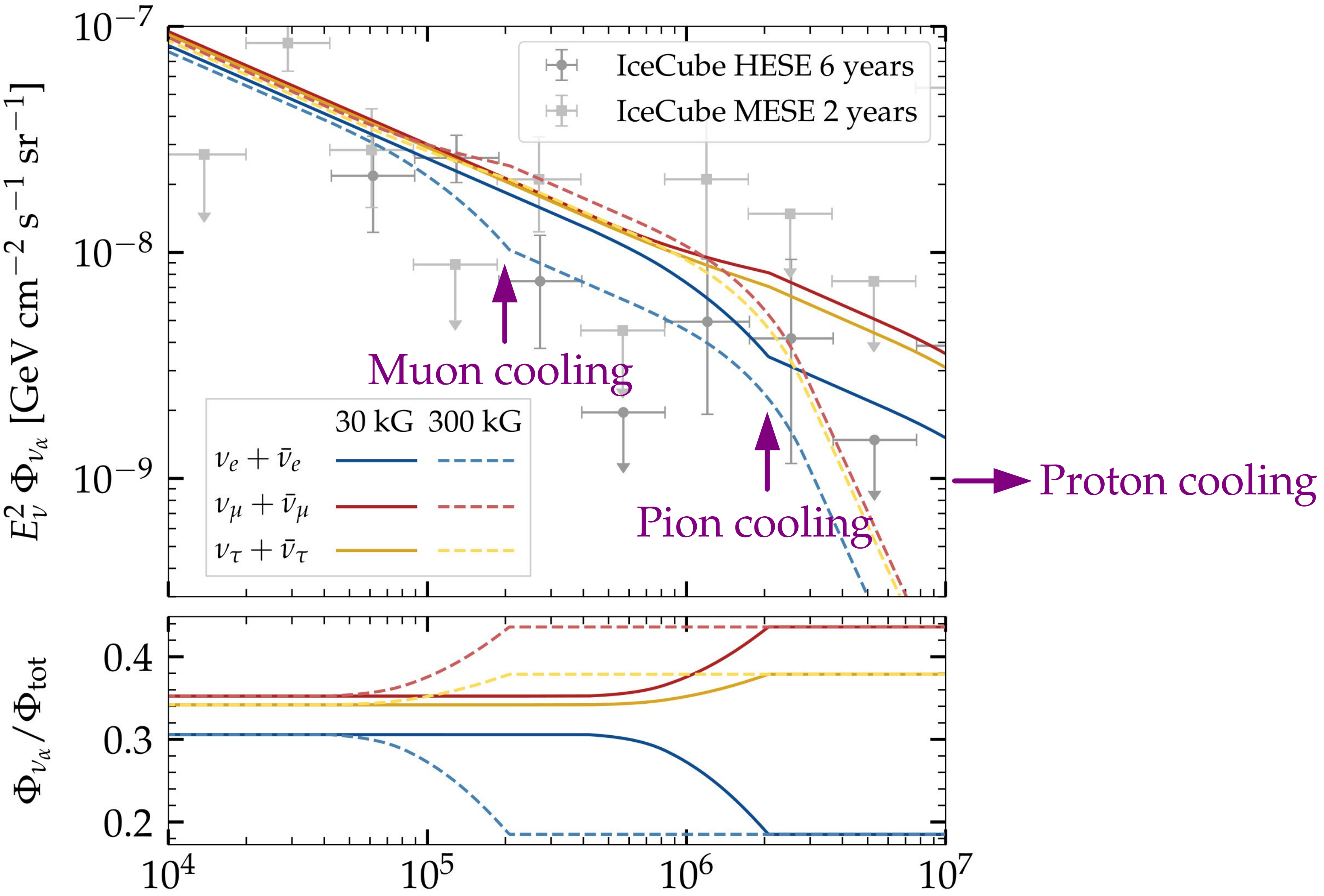

MB, Tamborra, *PRD* 2020
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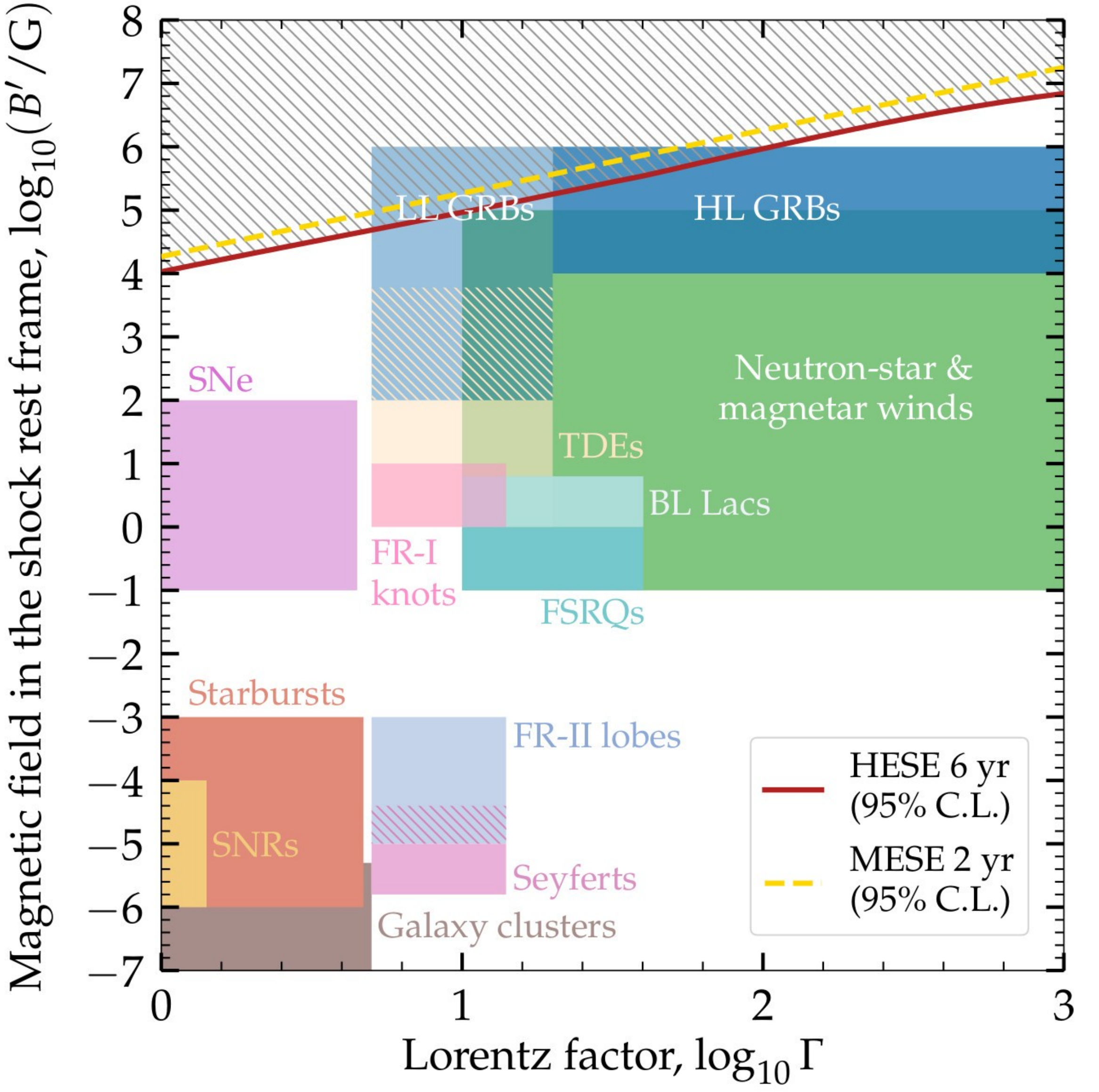
ν sources with strong B' are likely not dominant

Average B' must be < 10kG–10 MG



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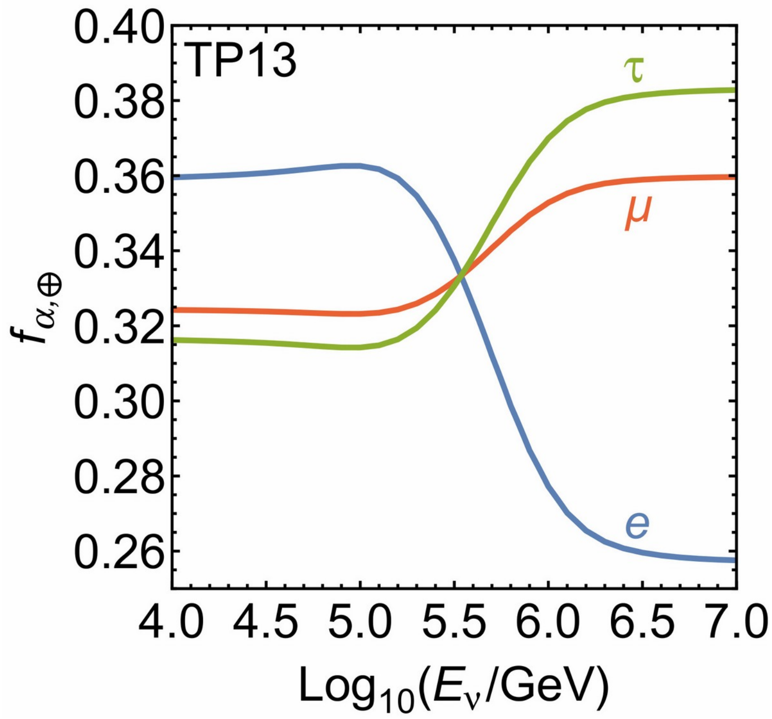
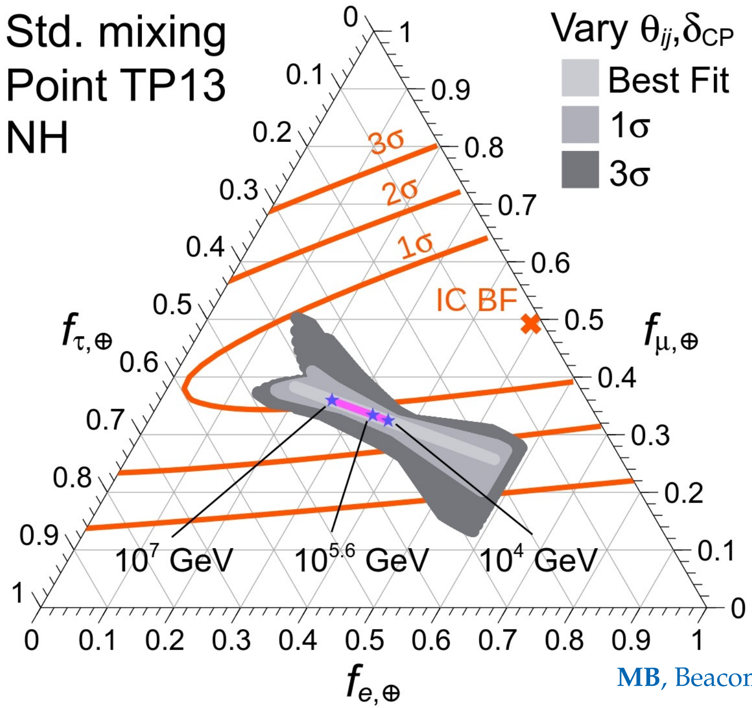
Energy dependence of the flavor composition?

Different neutrino production channels accessible at different energies –



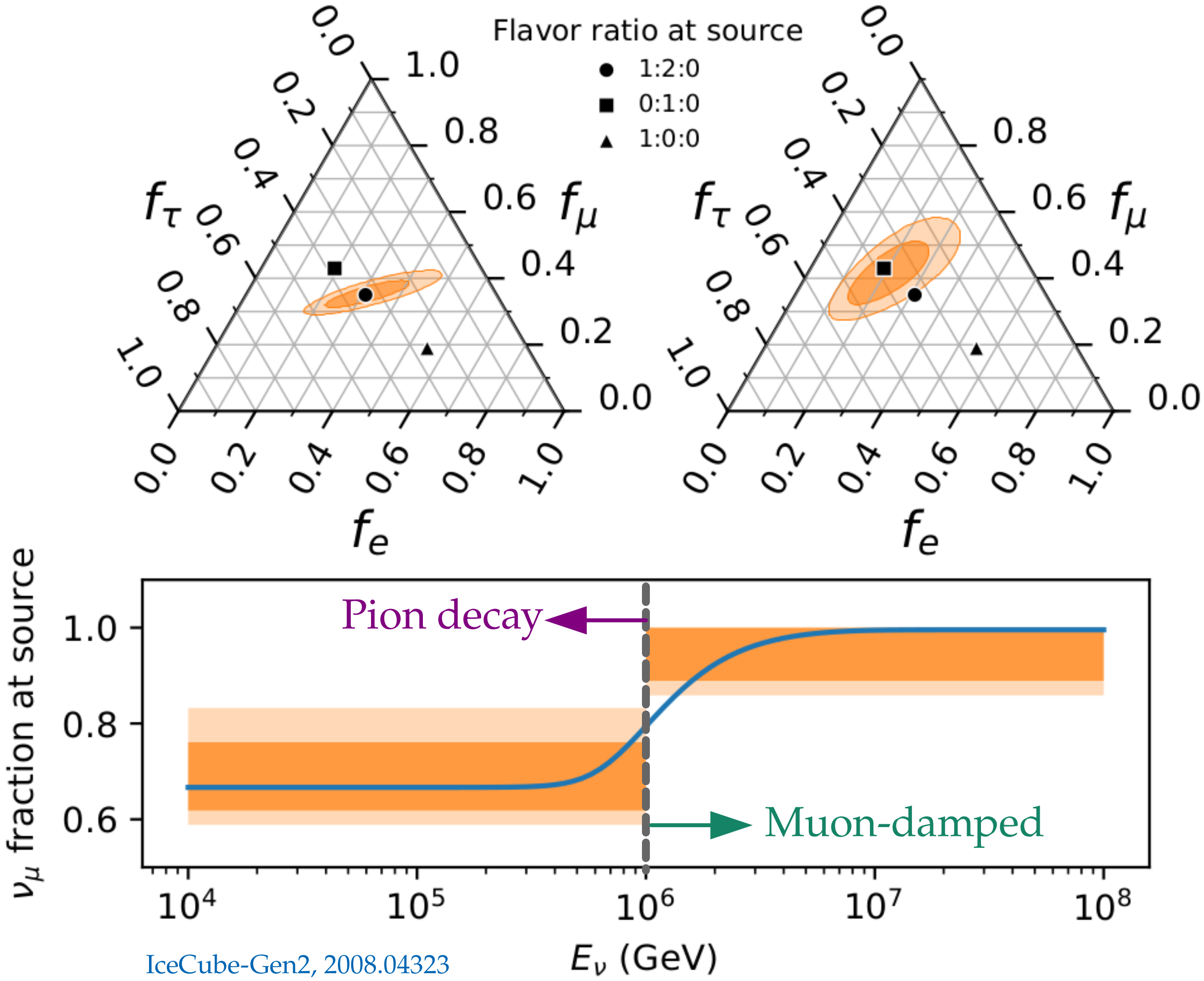


MB, Beacom, Winter, *PRL* 2015

- ▸ 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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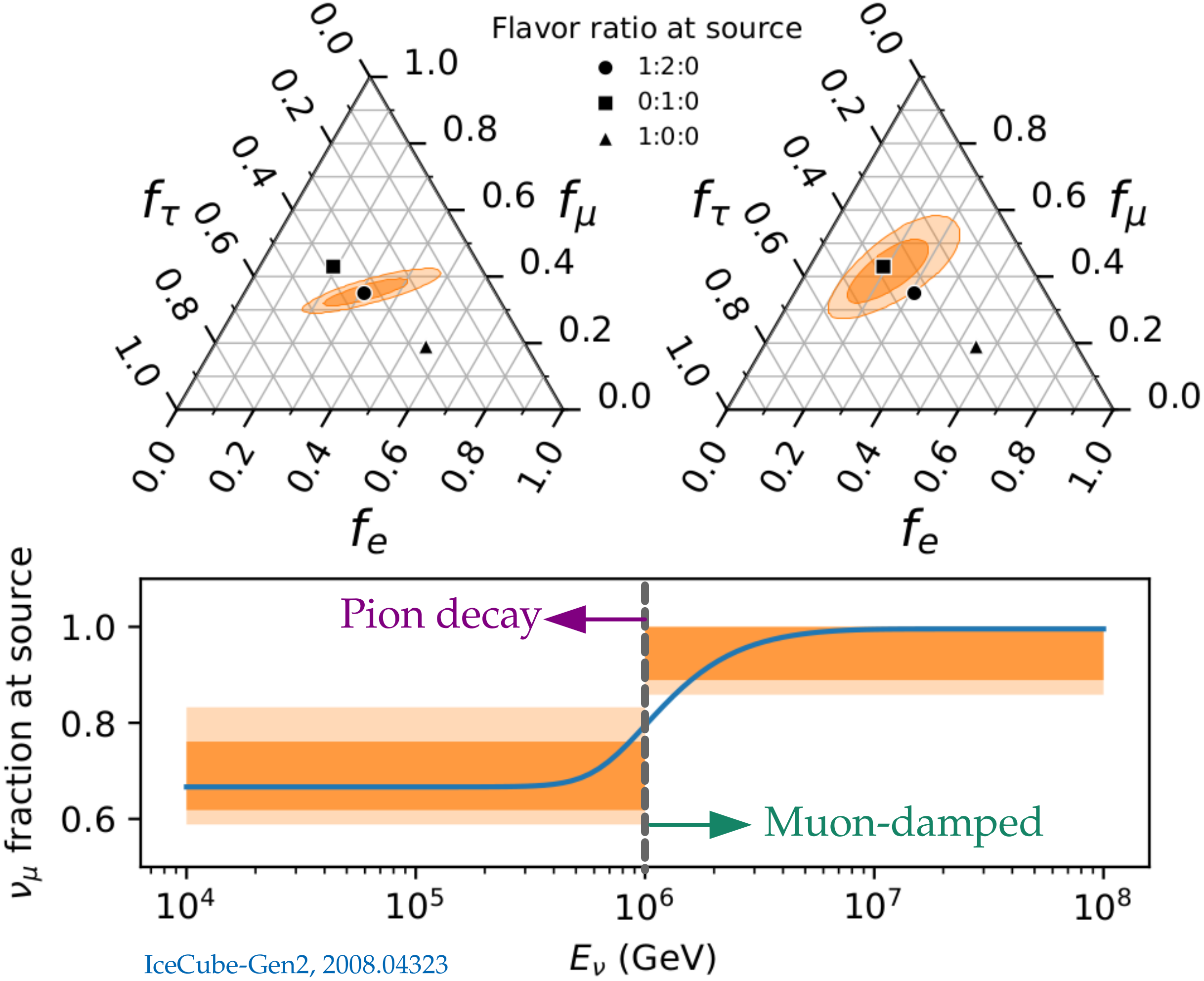

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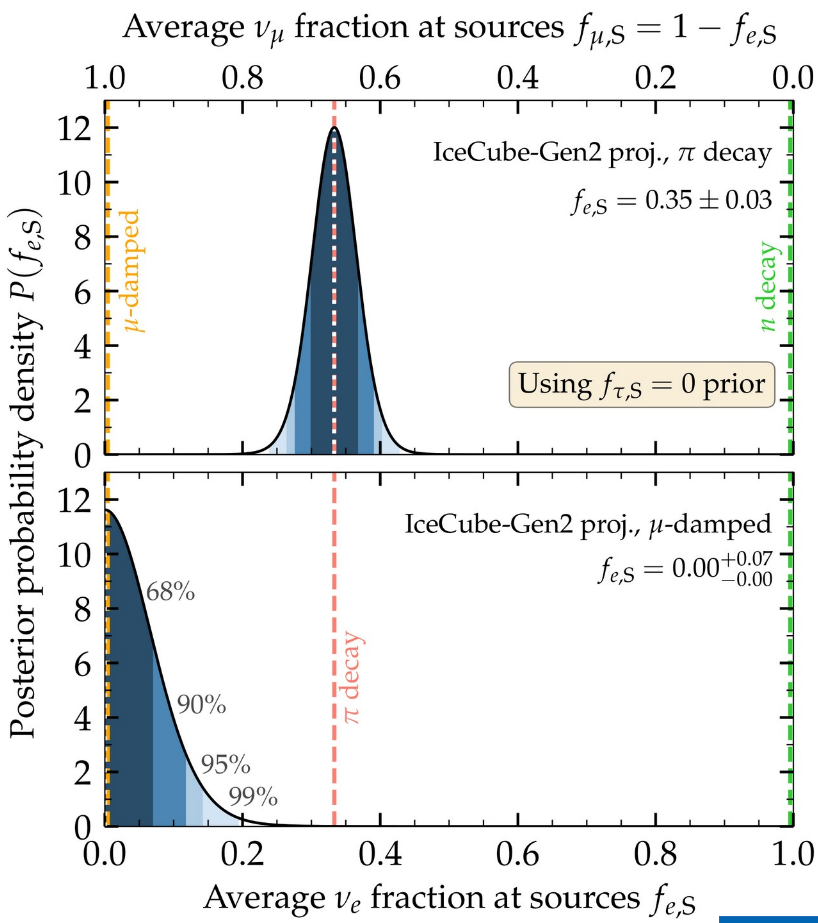
Inferred (at sources):



MB & Ahlers, *PRL* 2019

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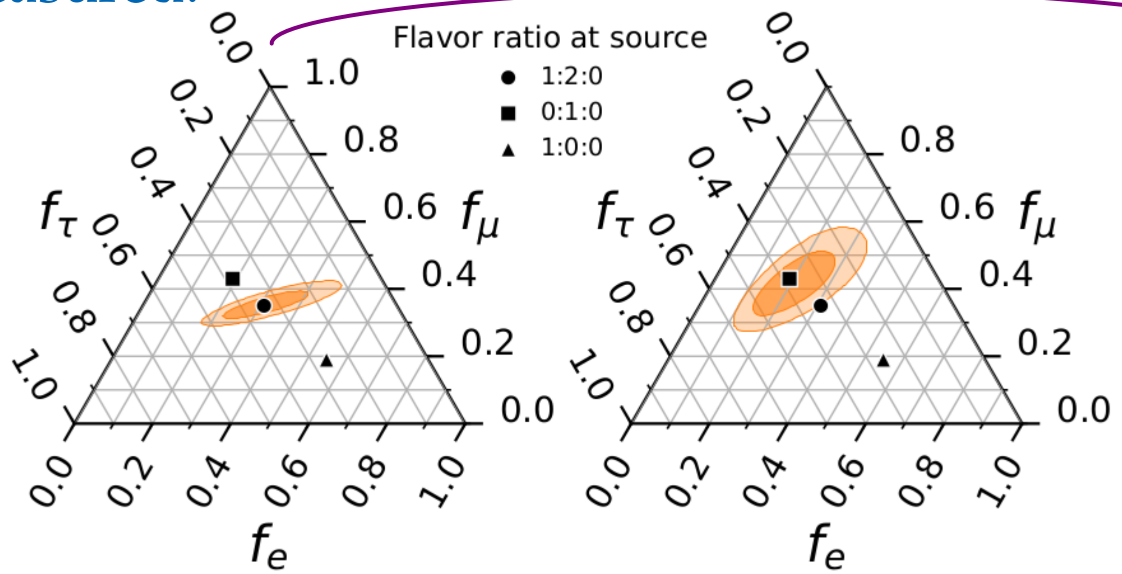

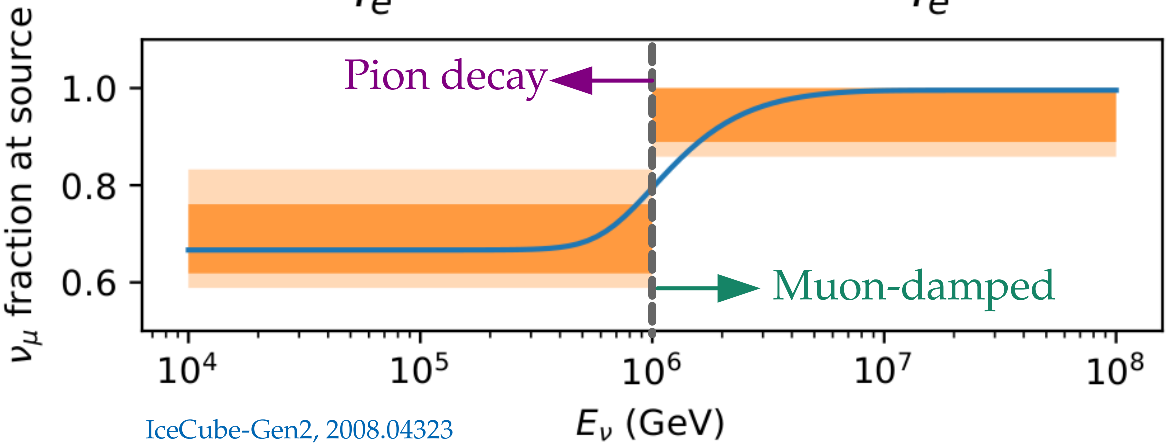

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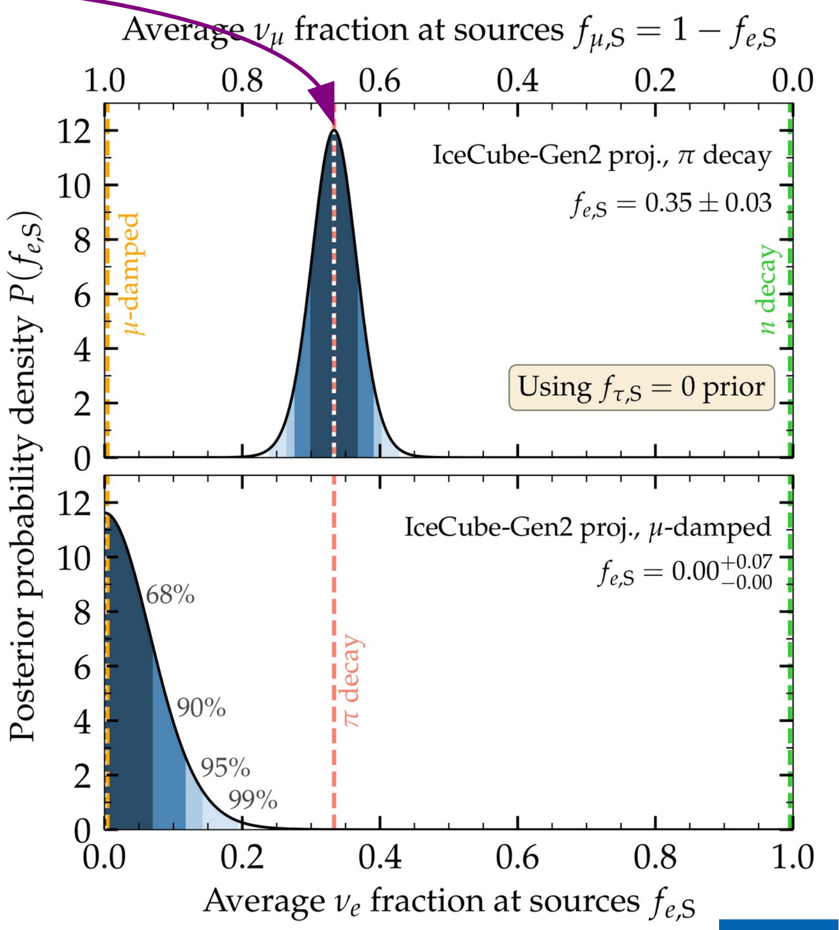

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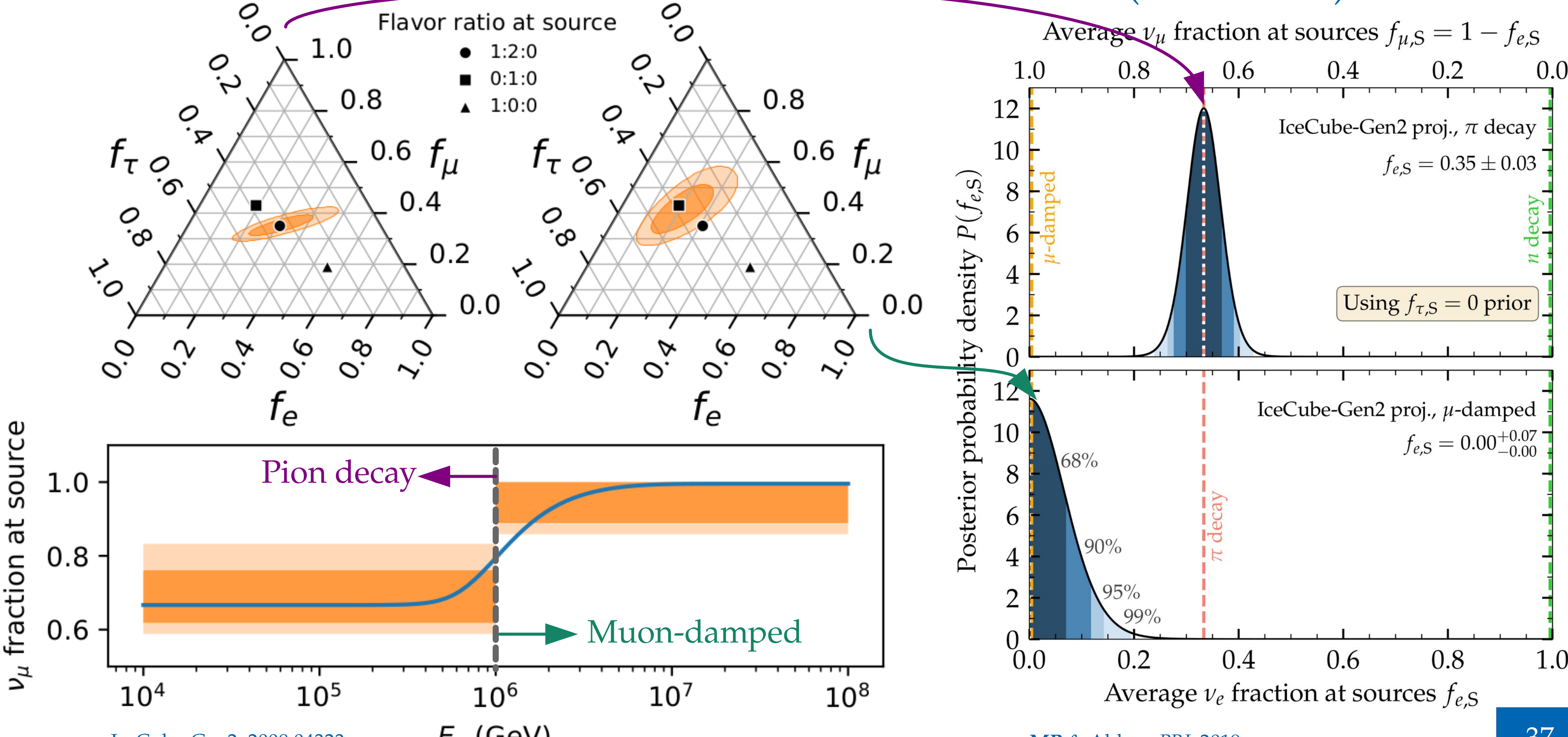

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Flavor composition – a few source choices

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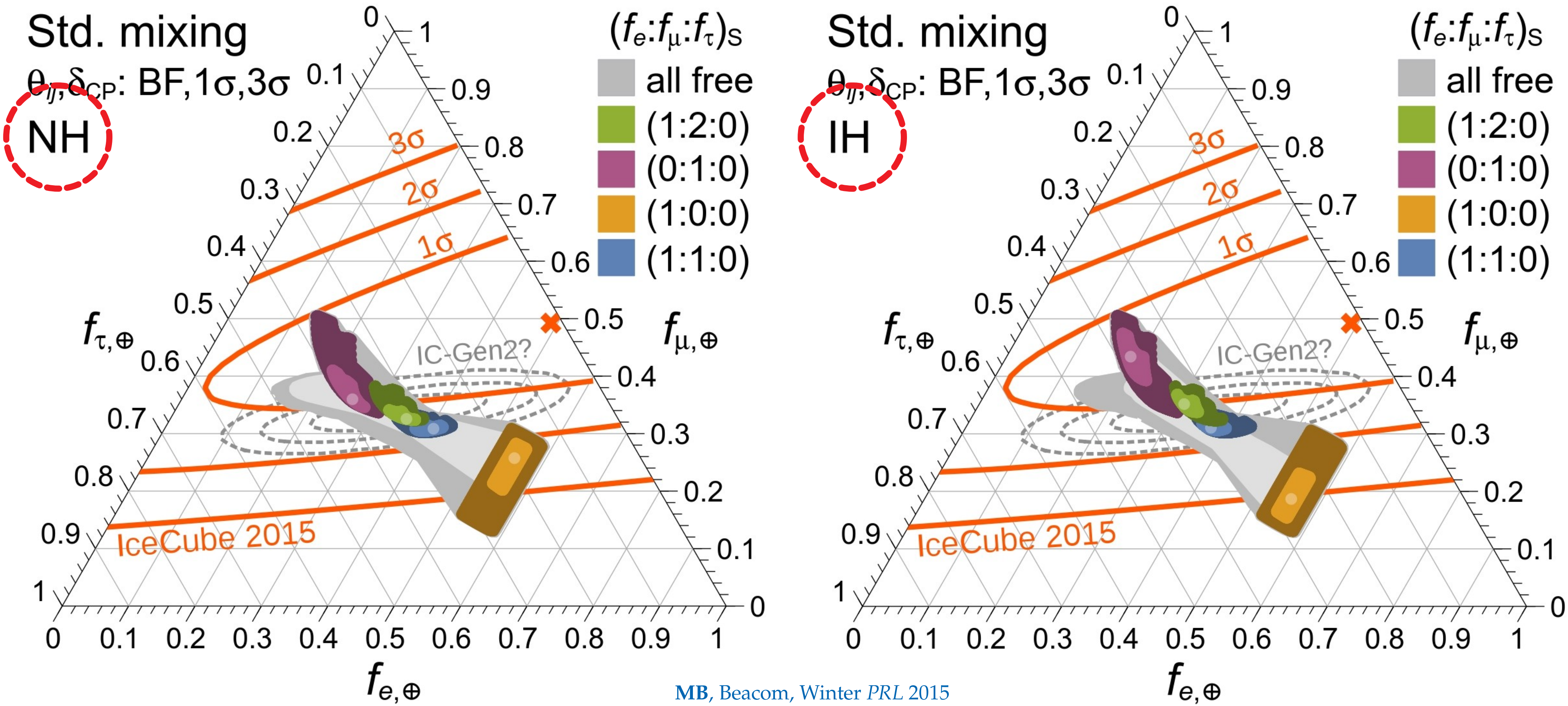
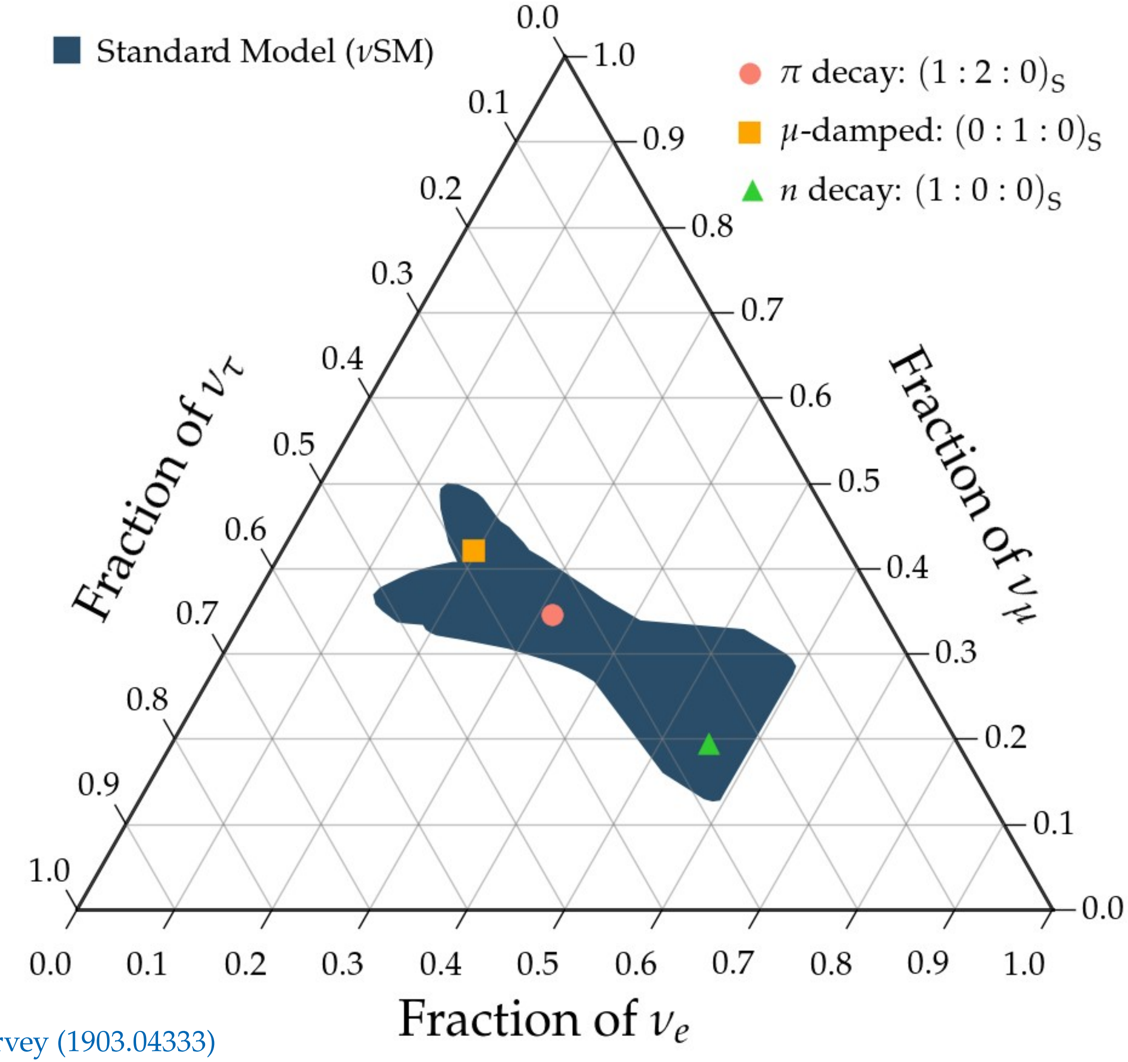
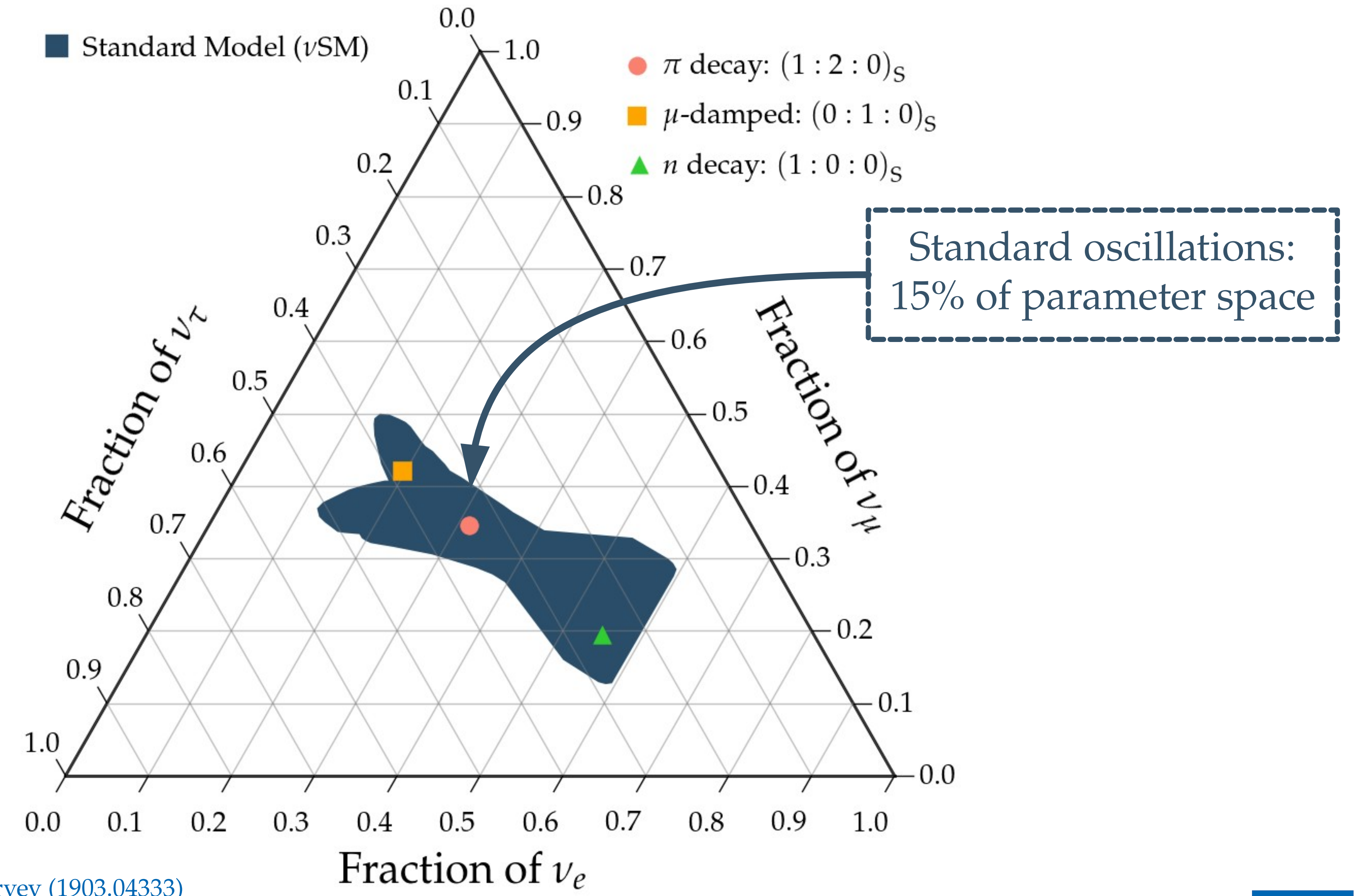


MB, Beacom, Winter *PRL* 2015



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



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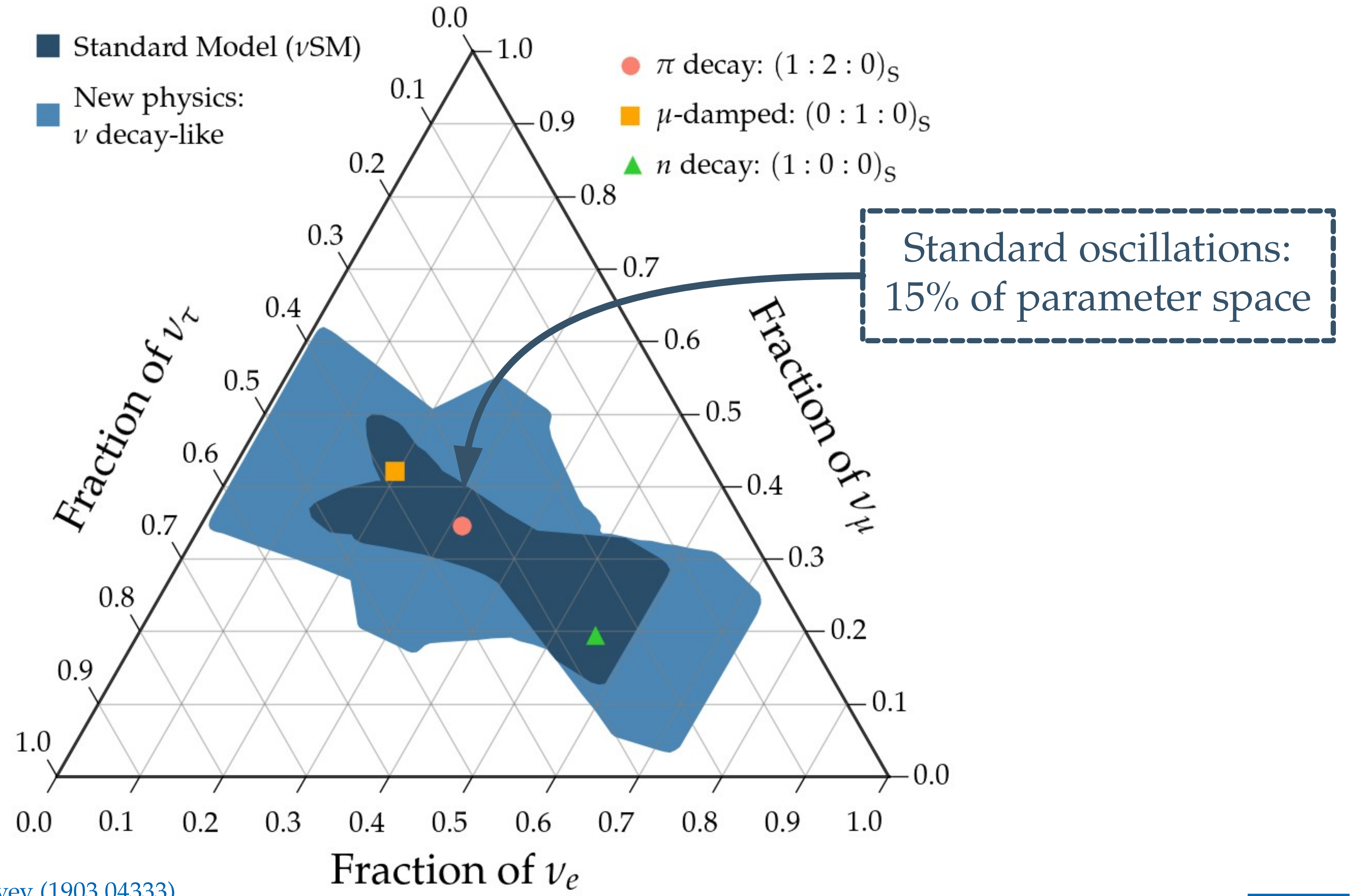

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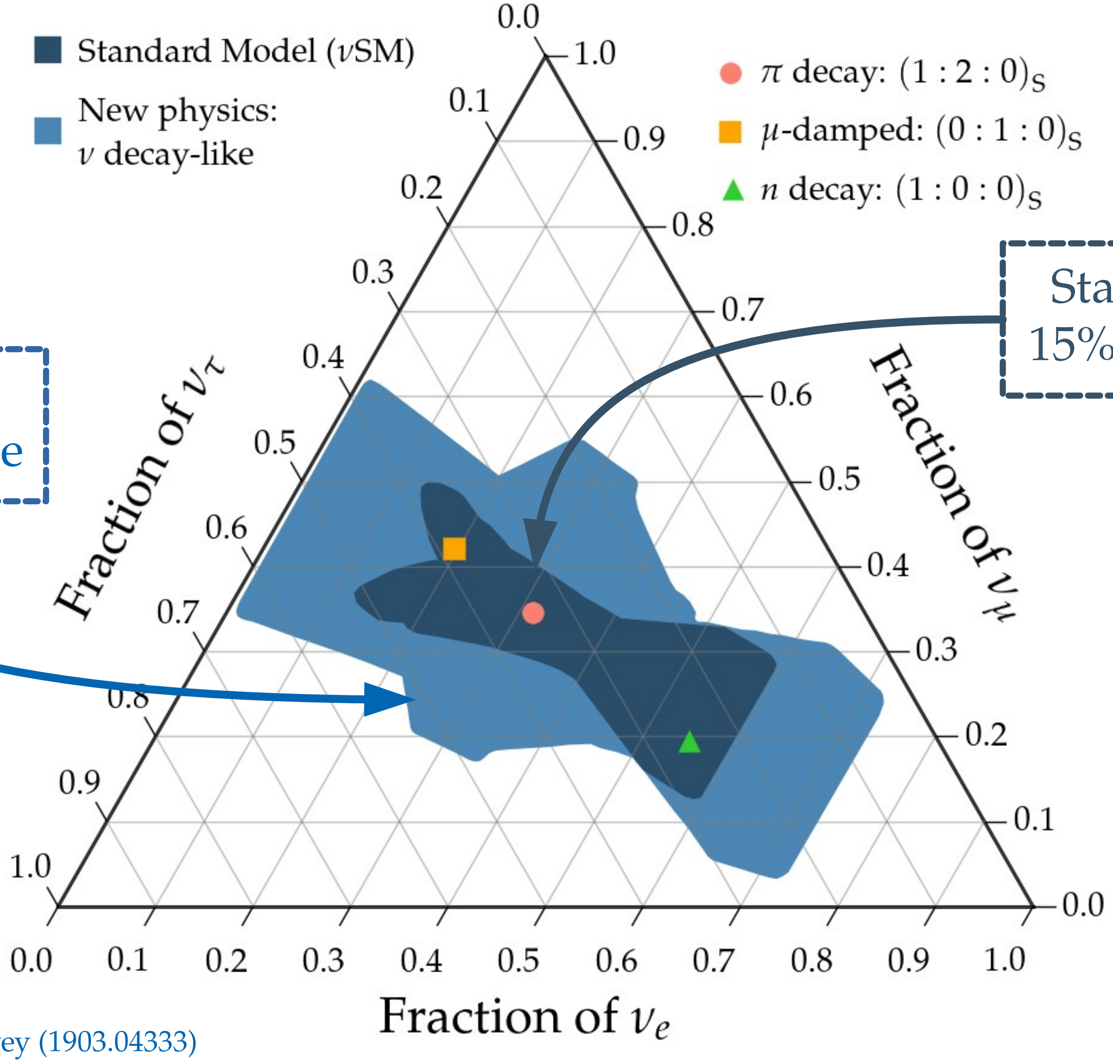
Neutrino decay
30% of parameter space



Standard oscillations:
15% of parameter space

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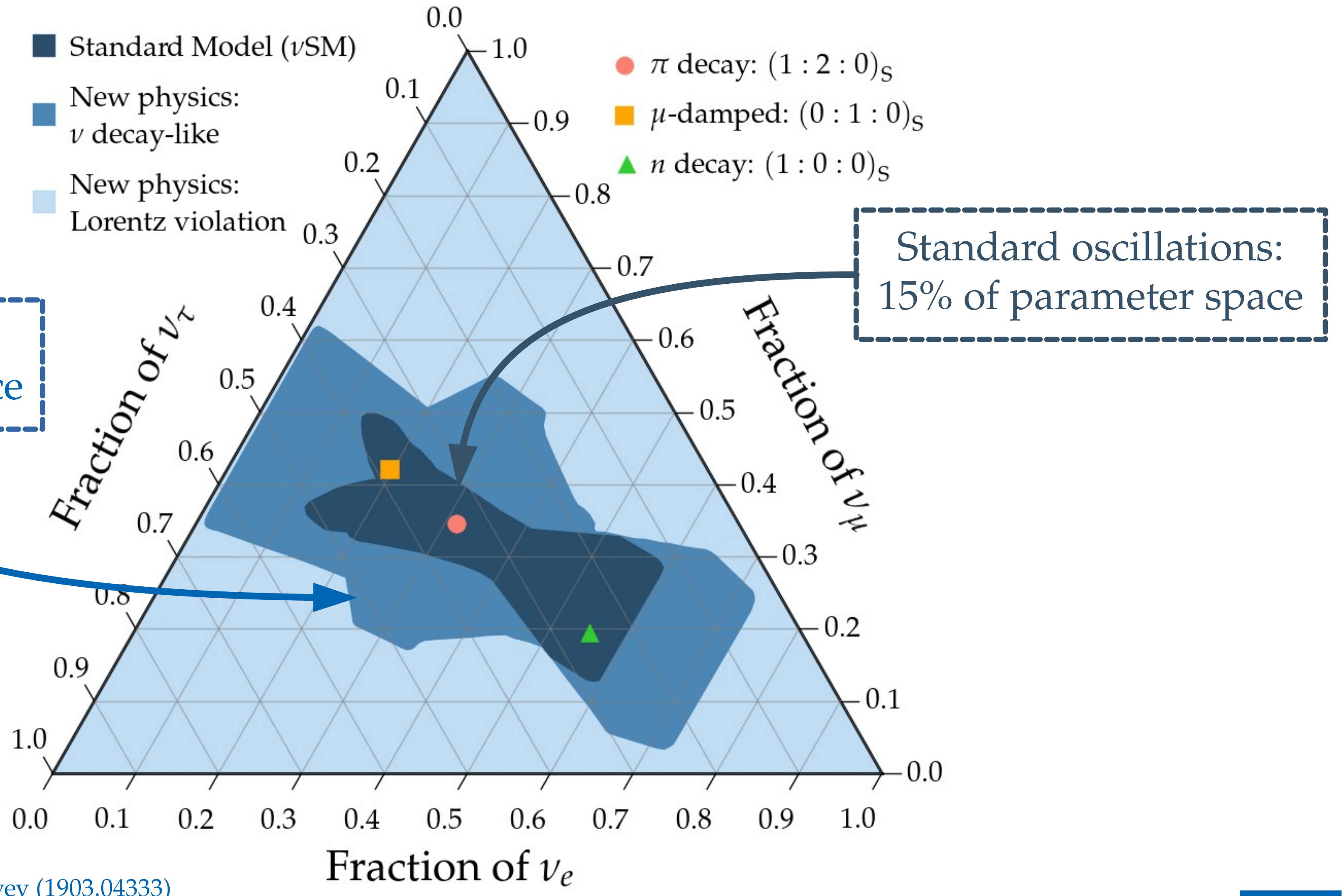

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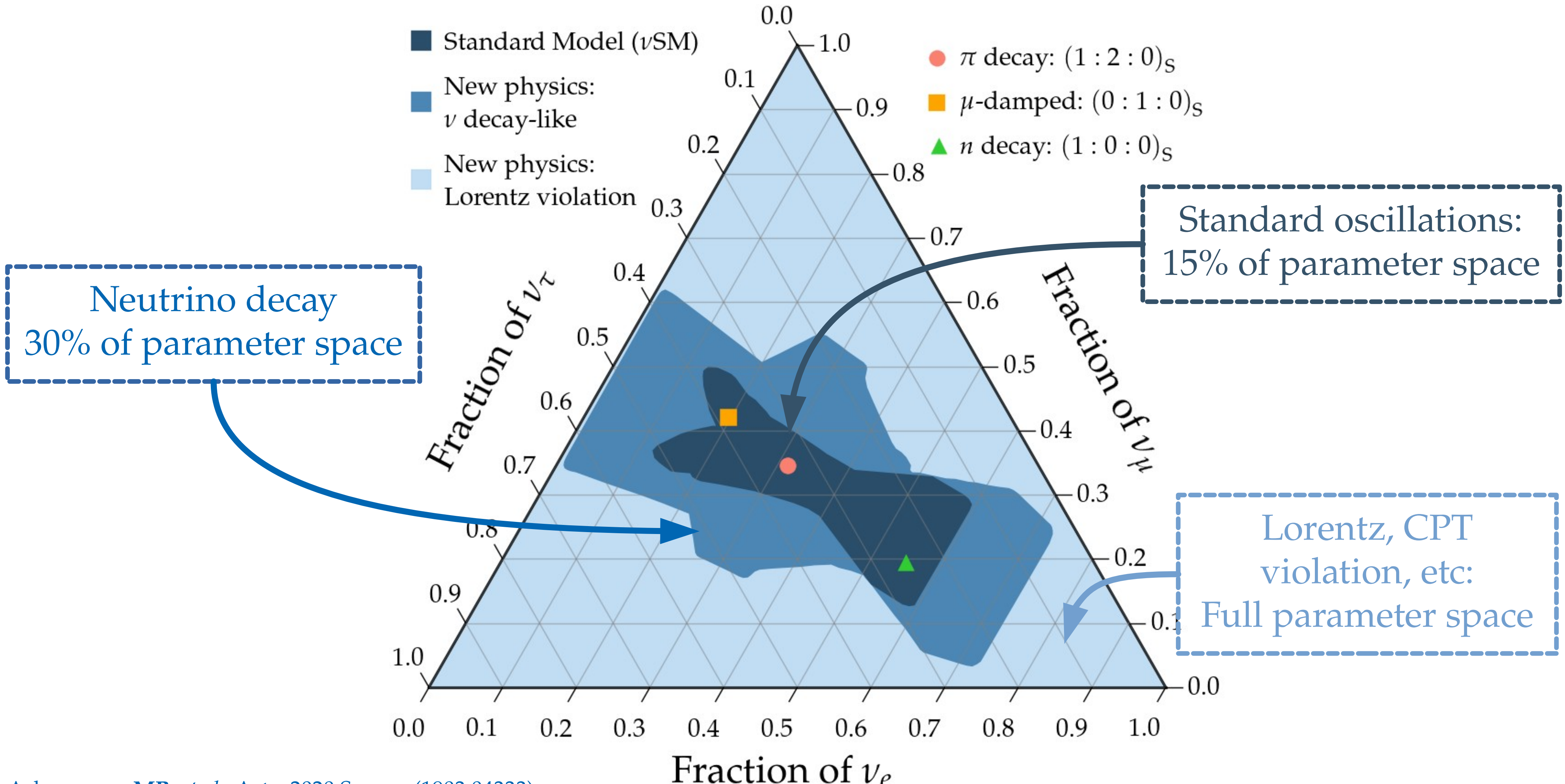

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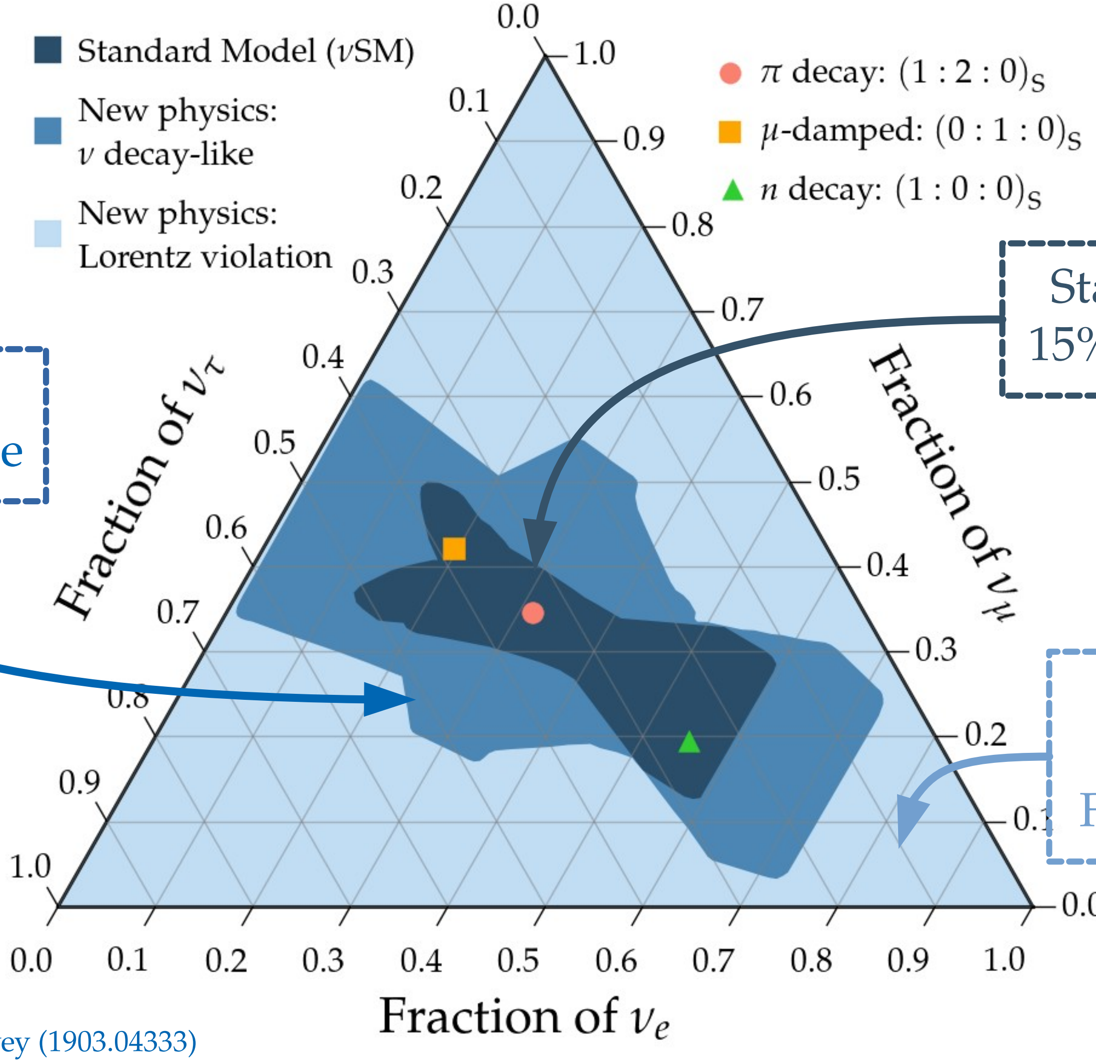

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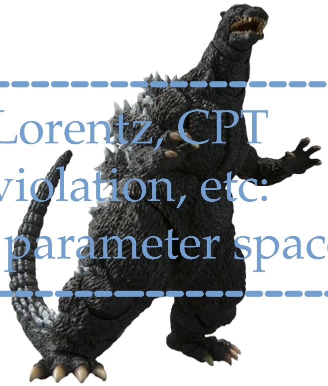

Lorentz, CPT violation, etc:
Full parameter space

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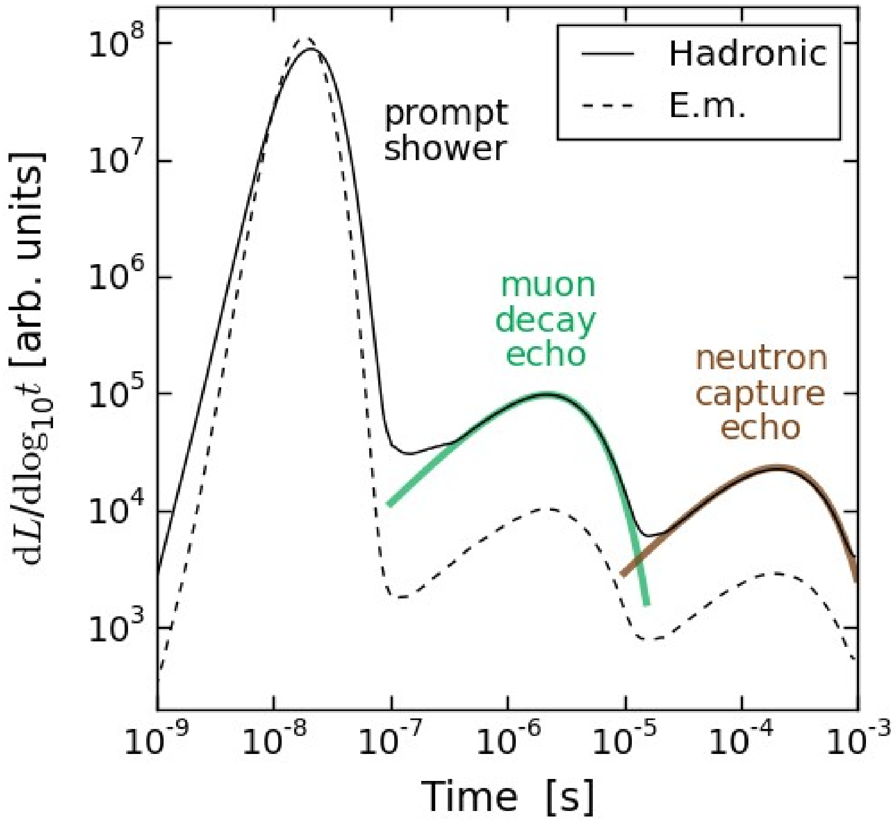
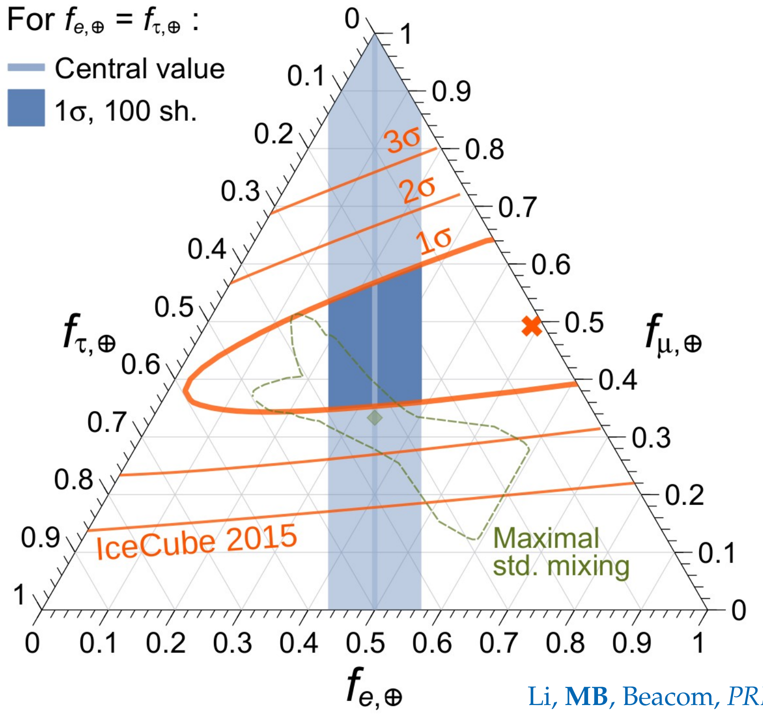
Side note: Improving flavor-tagging using *echoes*

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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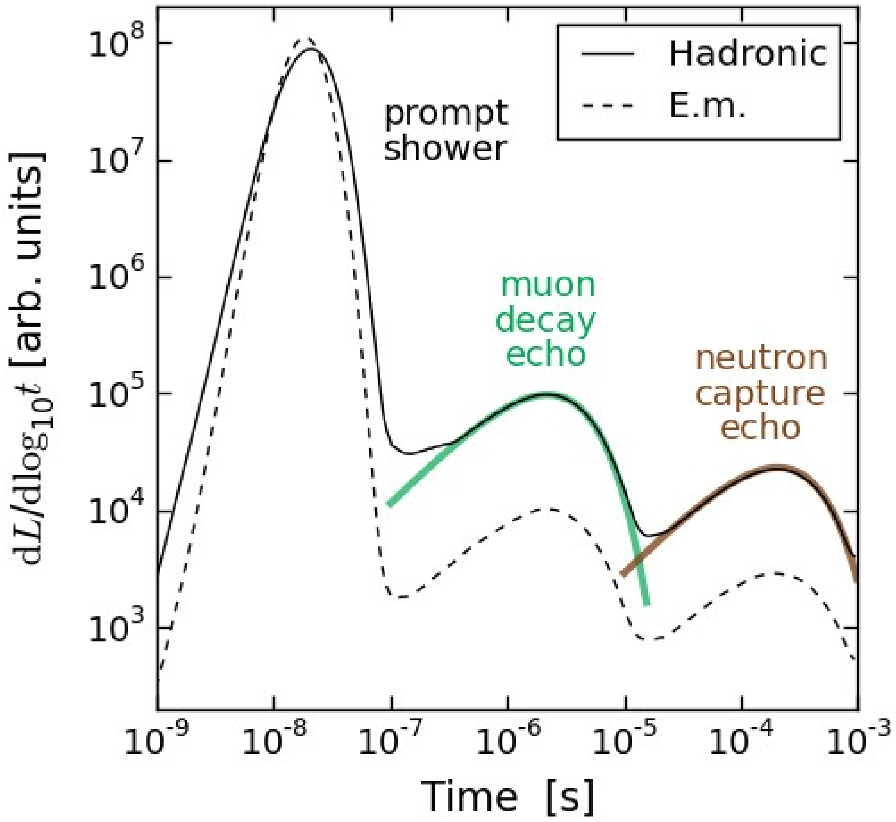
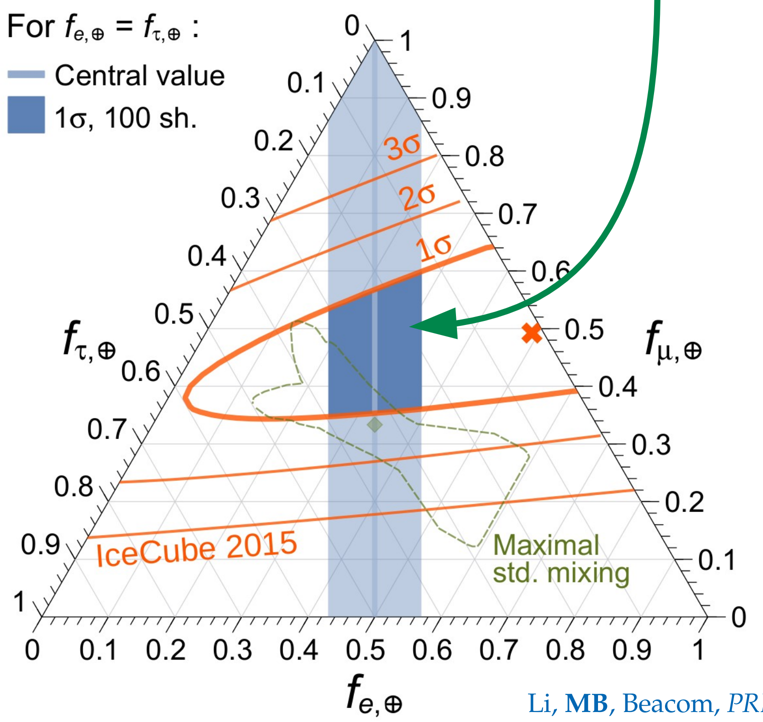


~10 × improvement over current measurement



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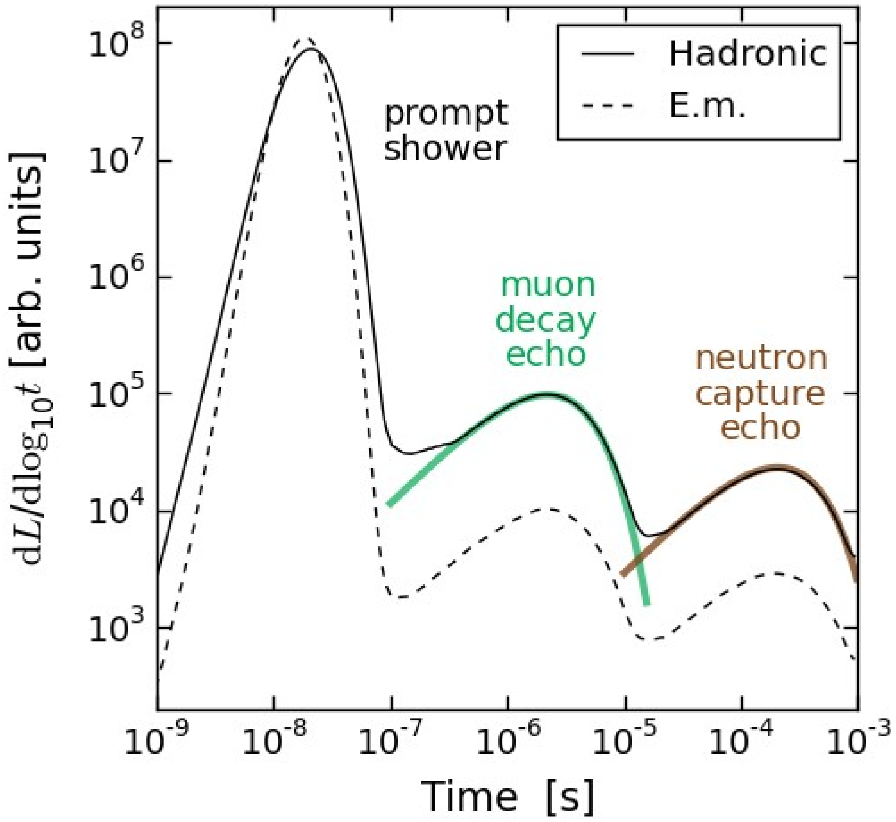
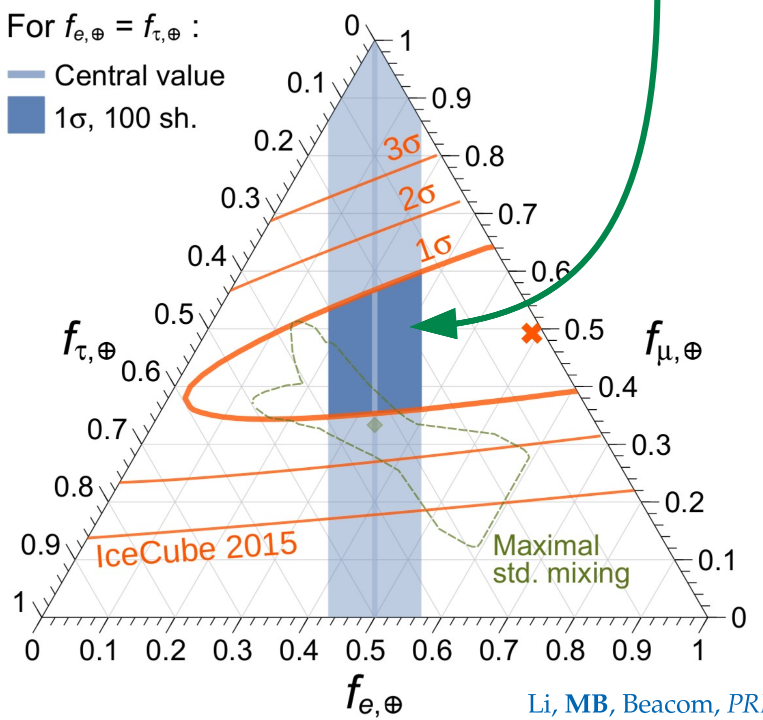
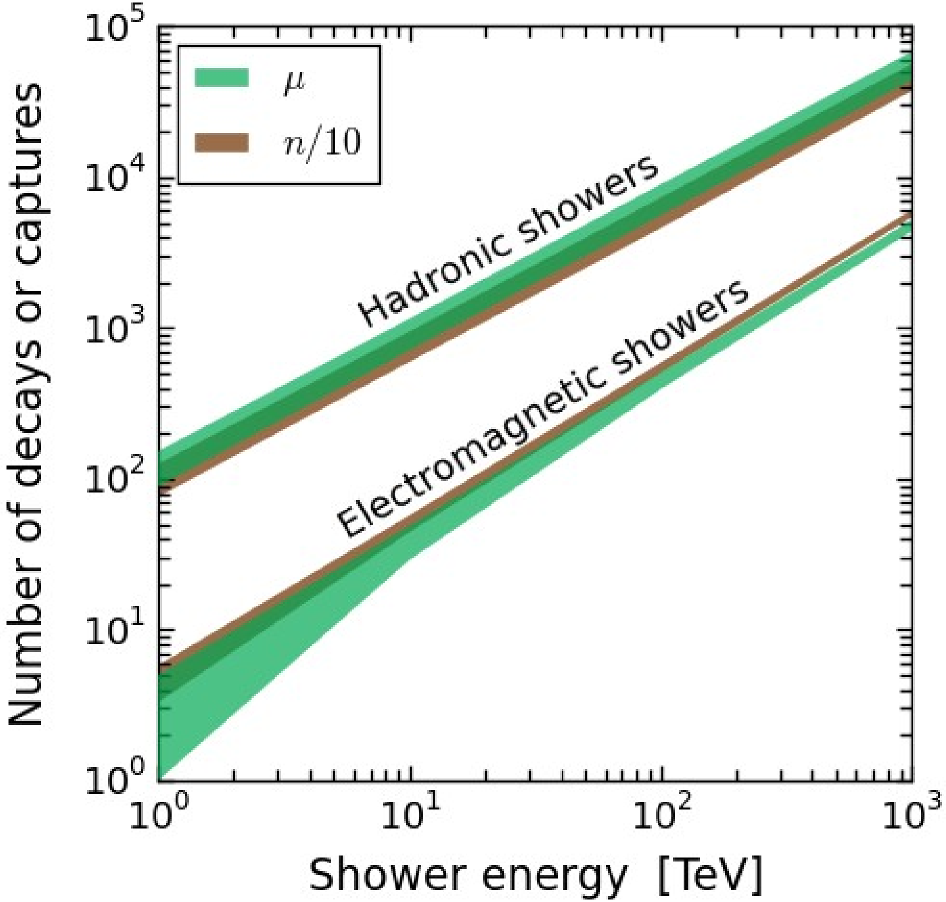
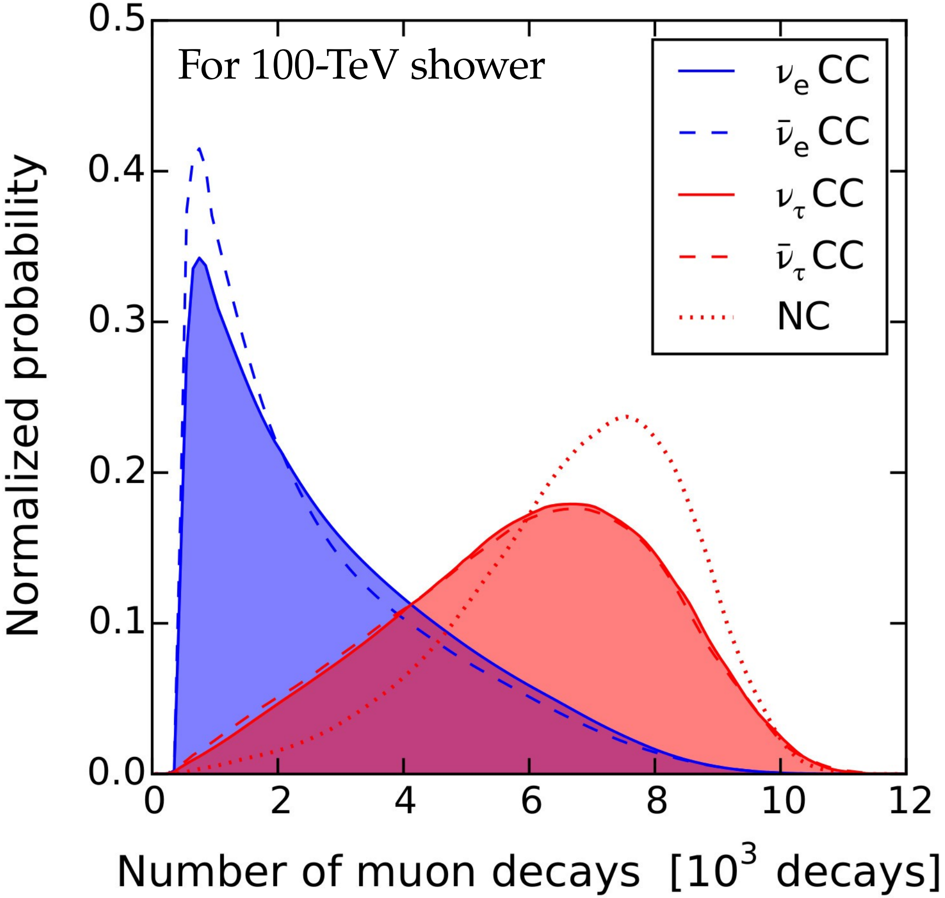




Li, **MB**, Beacom, *PRL* 2019

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

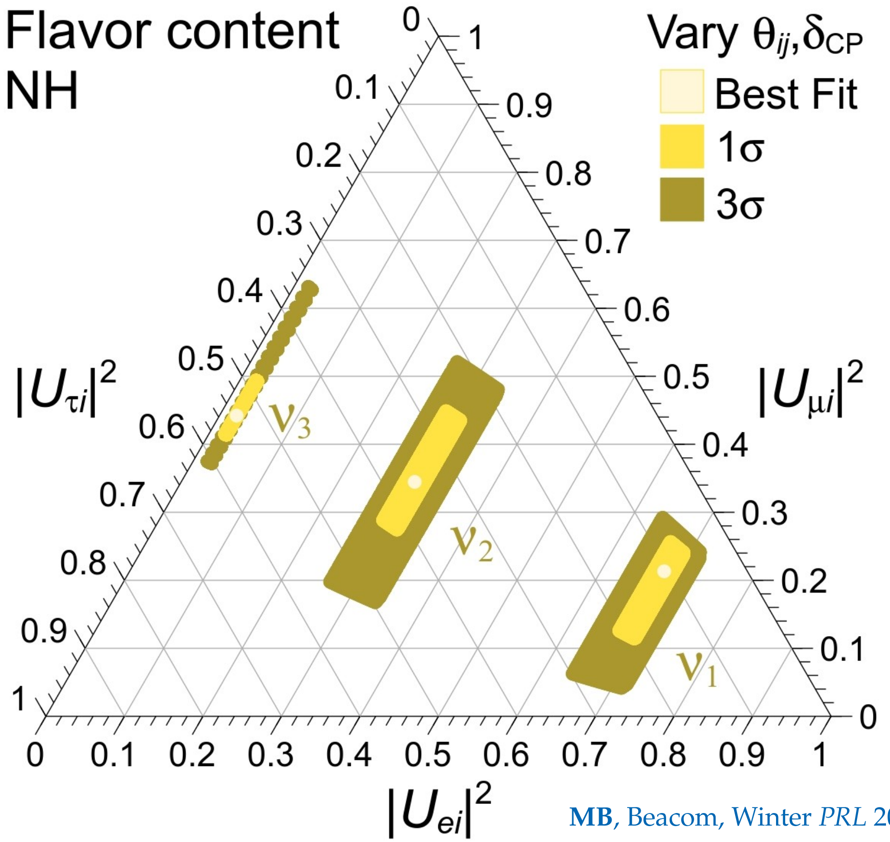
Flavor content of neutrino mass eigenstates

Known to within 2%

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

Known to within 8%

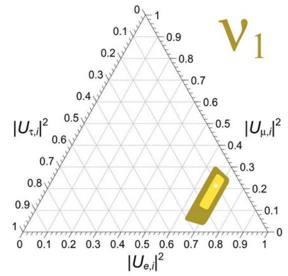
Known to within 20%
(or worse)



MB, Beacom, Winter *PRL* 2015

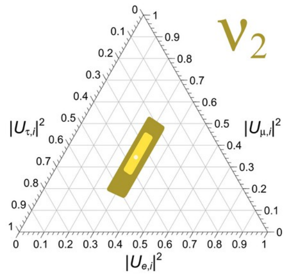
Neutrinos propagate as an incoherent mix of ν_1, ν_2, ν_3 —

w_1



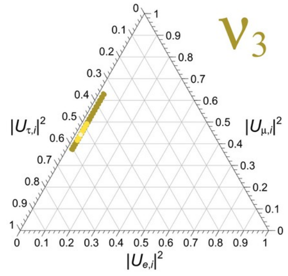
+

w_2

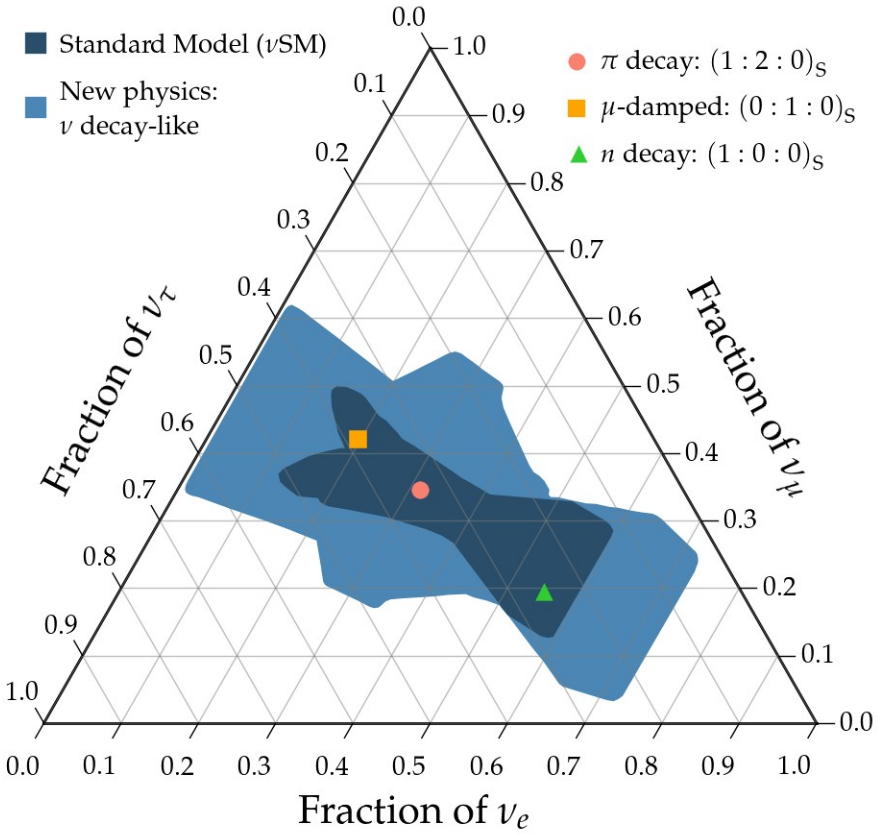


+

w_3



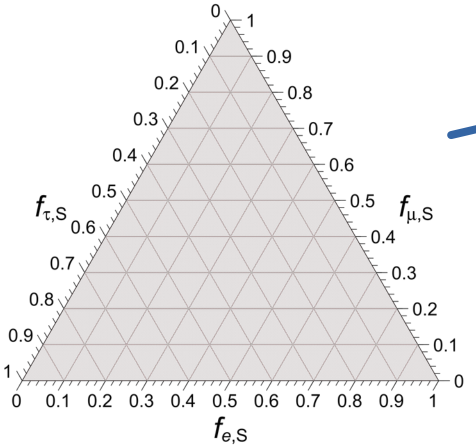
Varying all possible combinations of weights w_i and mixing parameters



Complete decay selects particular weights ▸ with striking consequences for flavor

Measuring the neutrino lifetime

Sources



$\nu_2, \nu_3 \rightarrow \nu_1$

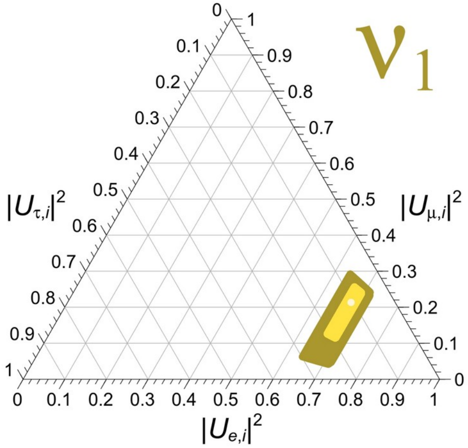
ν_1 lightest and stable
(normal mass ordering)

If all unstable
neutrinos decay

$\nu_1, \nu_2 \rightarrow \nu_3$

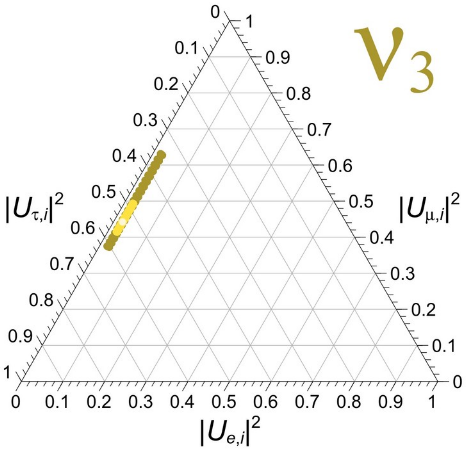
ν_3 lightest and stable
(inverted mass ordering)

Earth



$f_{\alpha,\oplus} = |U_{\alpha 1}|^2$

$(w_1 \sim 1; w_2, w_3 \sim 0)$

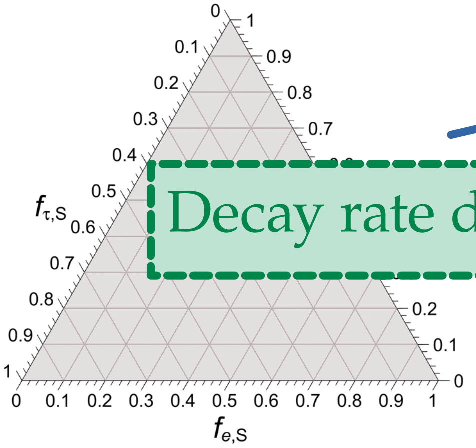


$f_{\alpha,\oplus} = |U_{\alpha 3}|^2$

$(w_3 \sim 1; w_1, w_2 \sim 0)$

Measuring the neutrino lifetime

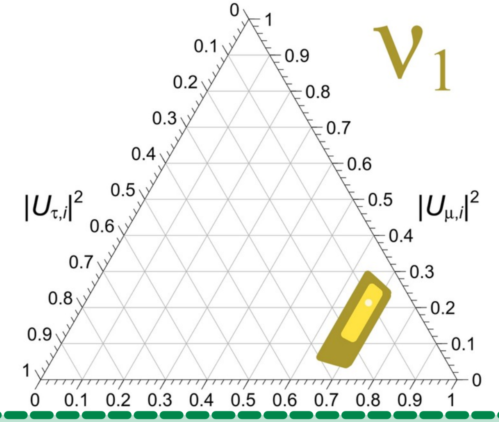
Sources



$\nu_2, \nu_3 \to \nu_1$

ν_1 lightest and stable
(normal mass ordering)

Earth



ν_1

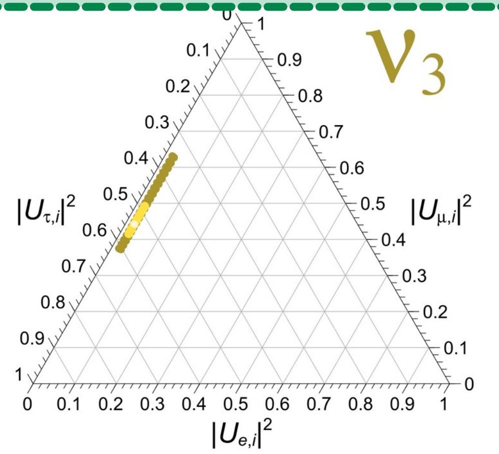
$f_{\alpha,\oplus} = |U_{\alpha 1}|^2$

$(w_1 \sim 1; w_2, w_3 \sim 0)$

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

$\nu_1, \nu_2 \to \nu_3$

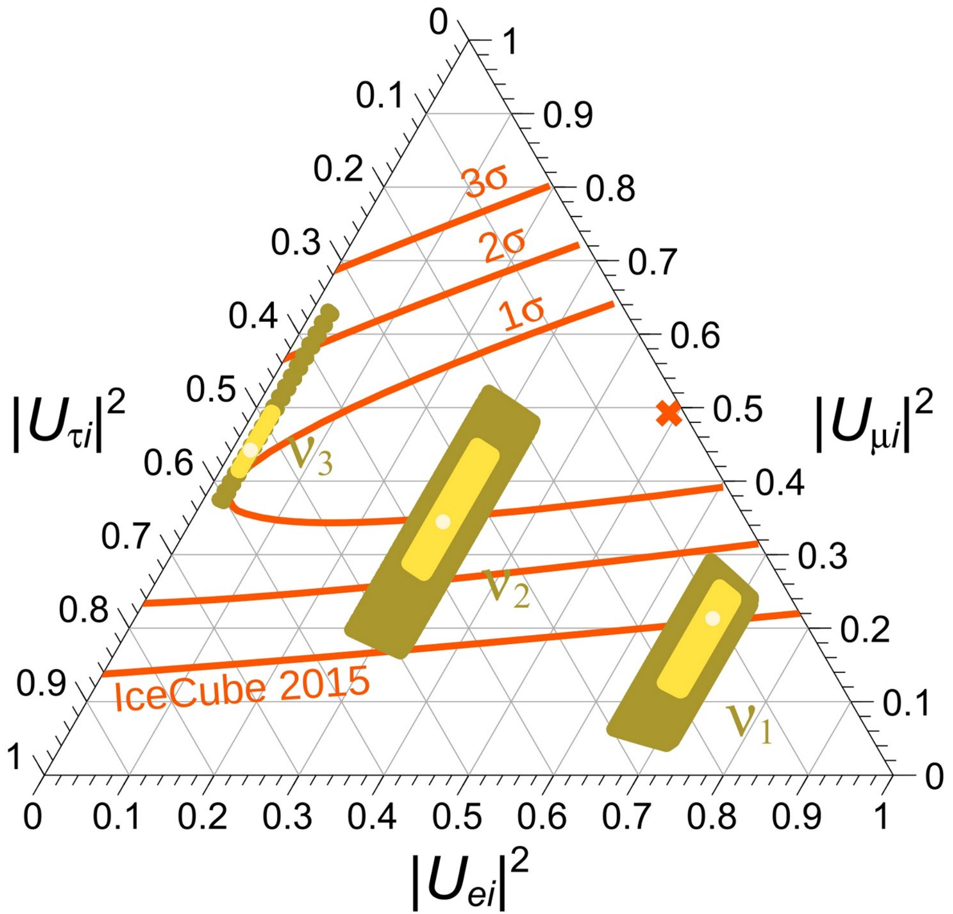
ν_3 lightest and stable
(inverted mass ordering)



ν_3

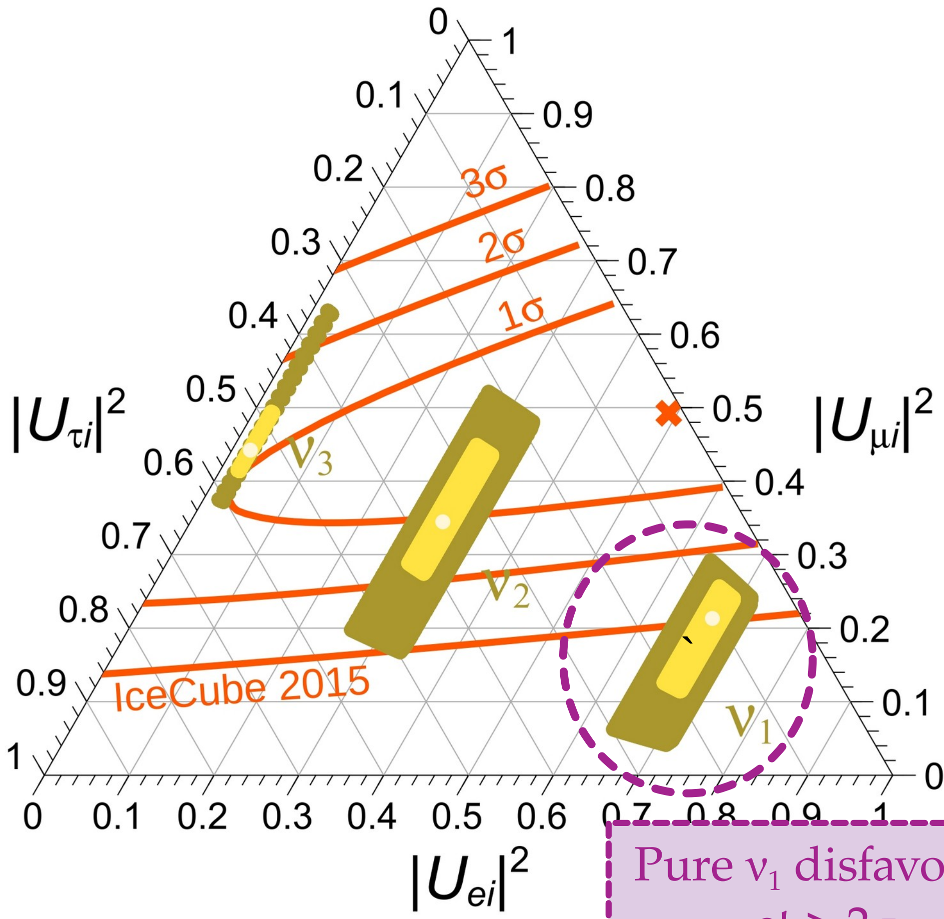
$f_{\alpha,\oplus} = |U_{\alpha 3}|^2$

$(w_3 \sim 1; w_1, w_2 \sim 0)$



MB, Beacom, Murase, *PRD* 2017

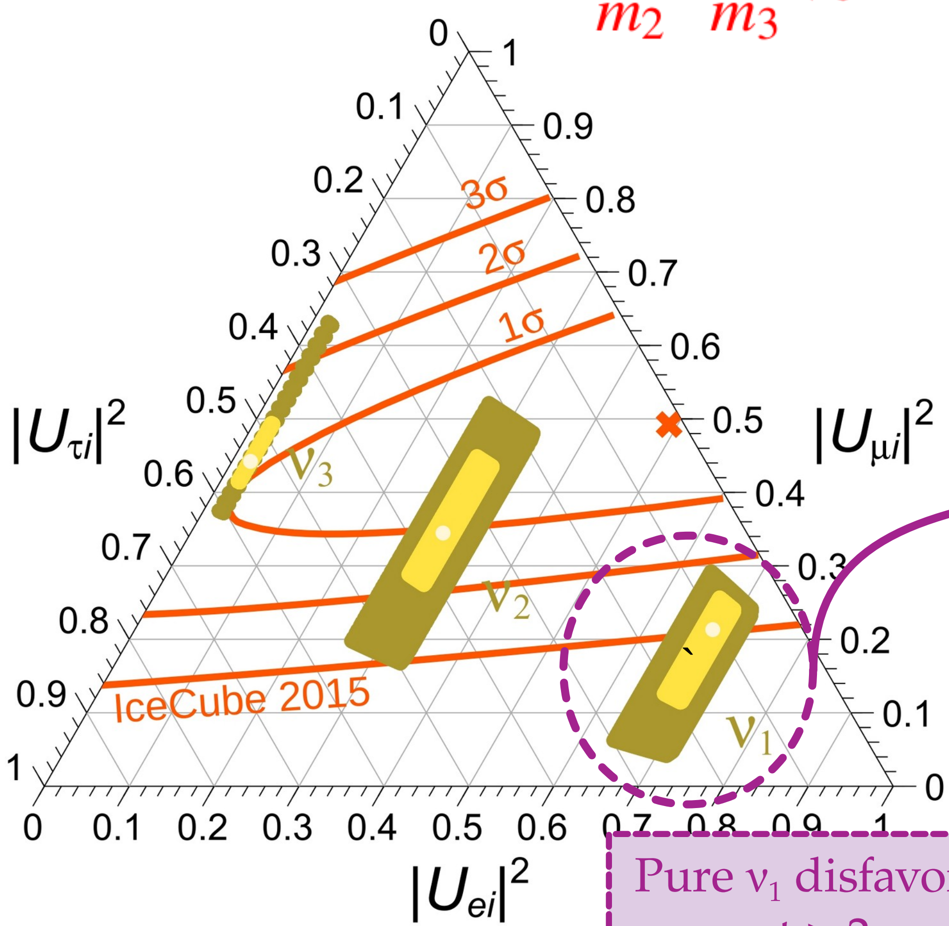
Baerwald, **MB**, Winter, *JCAP* 2012



Pure ν_1 disfavored at > 2σ

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

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



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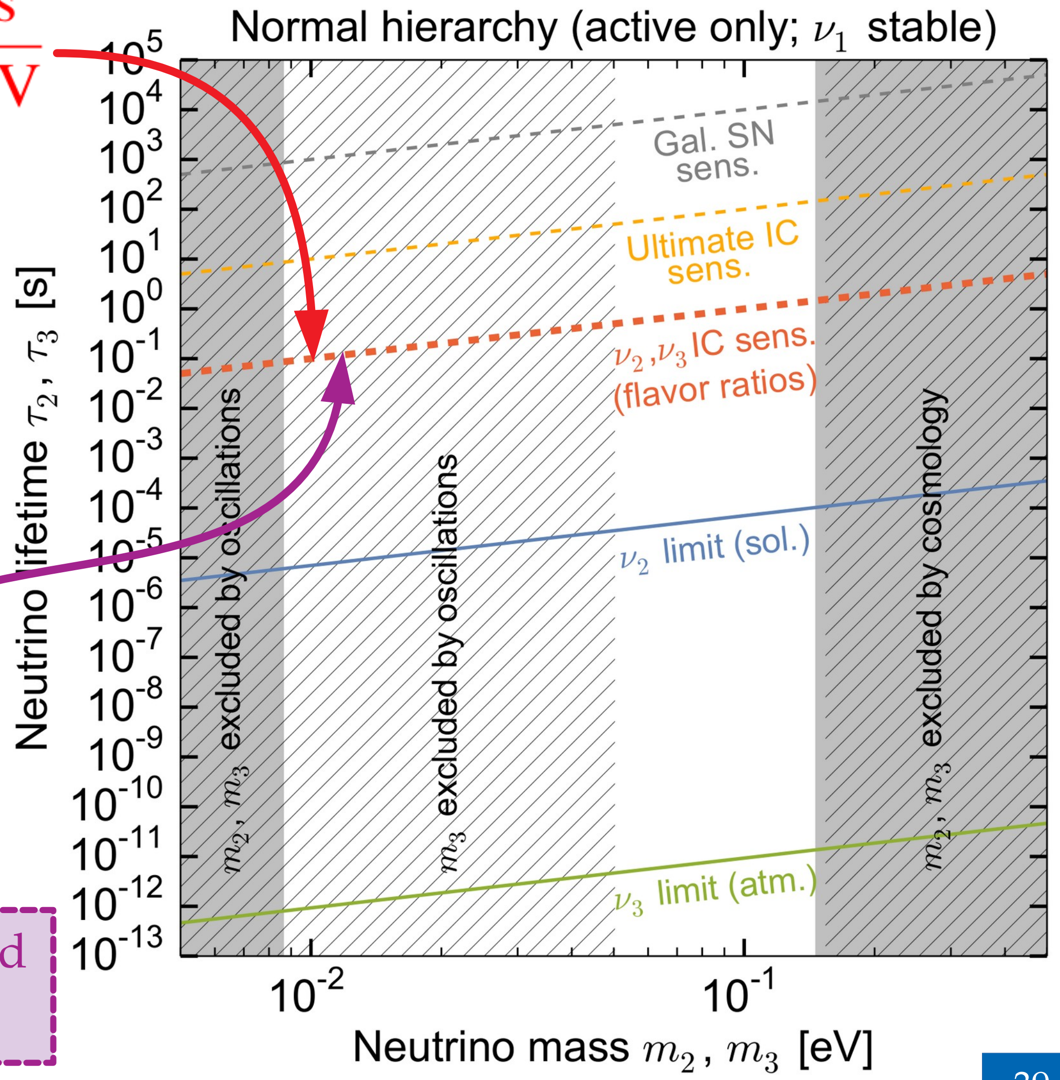
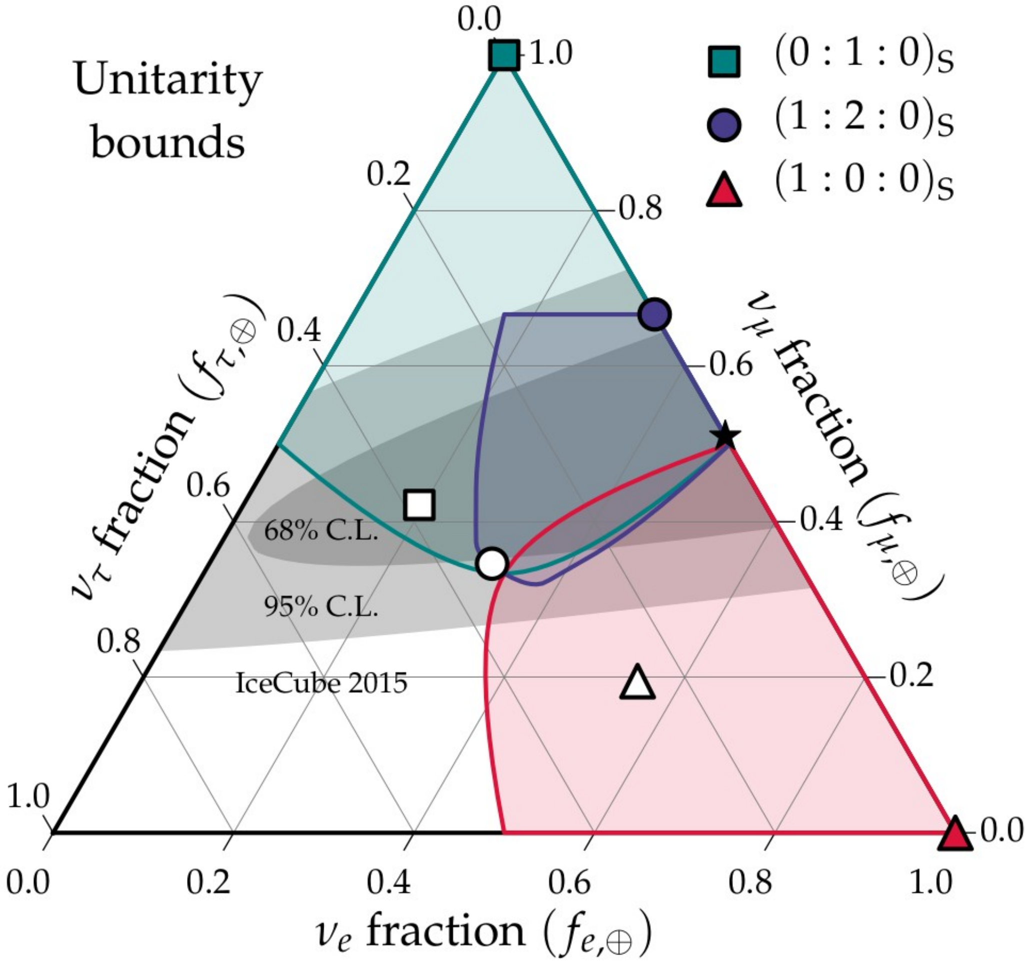


MB, Beacom, Murase, *PRD* 2017
Baerwald, **MB**, Winter, *JCAP* 2012

Using unitarity to constrain new physics

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

- New mixing angles unconstrained
- Use unitarity ($U_{NP}U_{NP}^{\dagger} = 1$) 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?

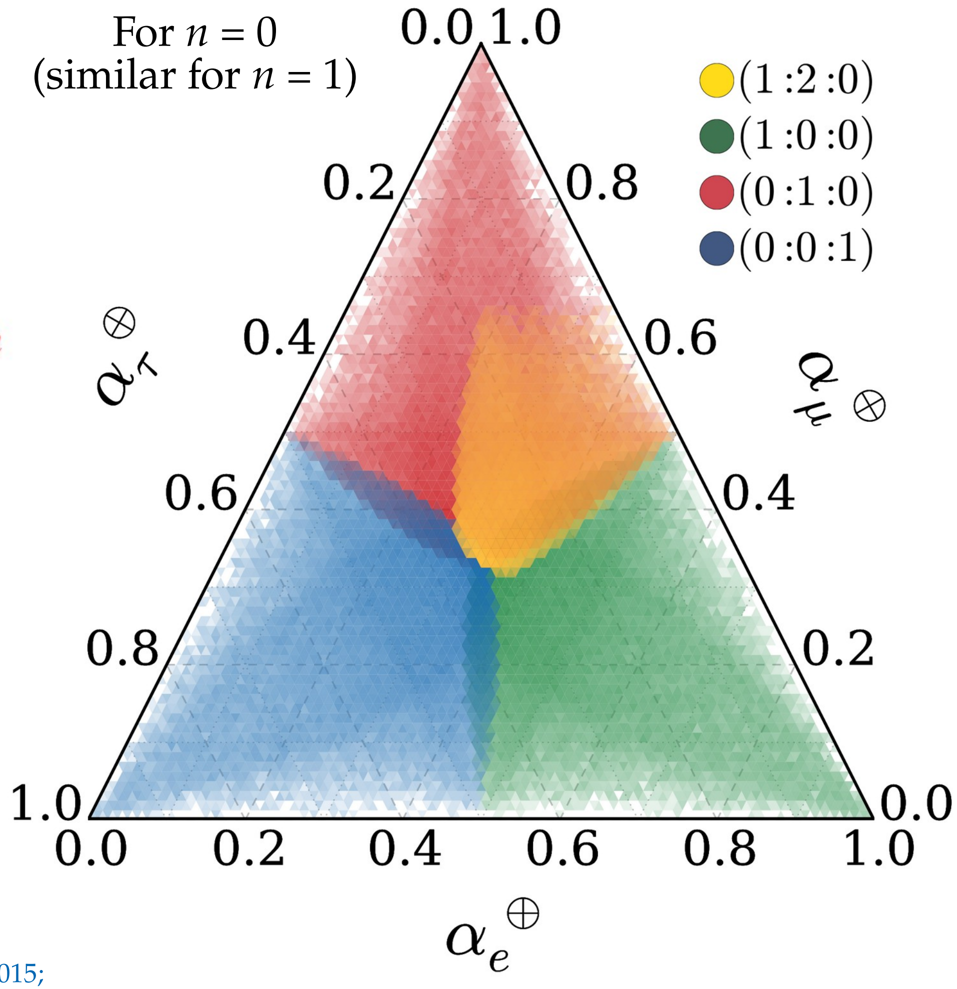
$$H_{\text{tot}} = H_{\text{std}} + H_{\text{NP}}$$

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

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

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



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

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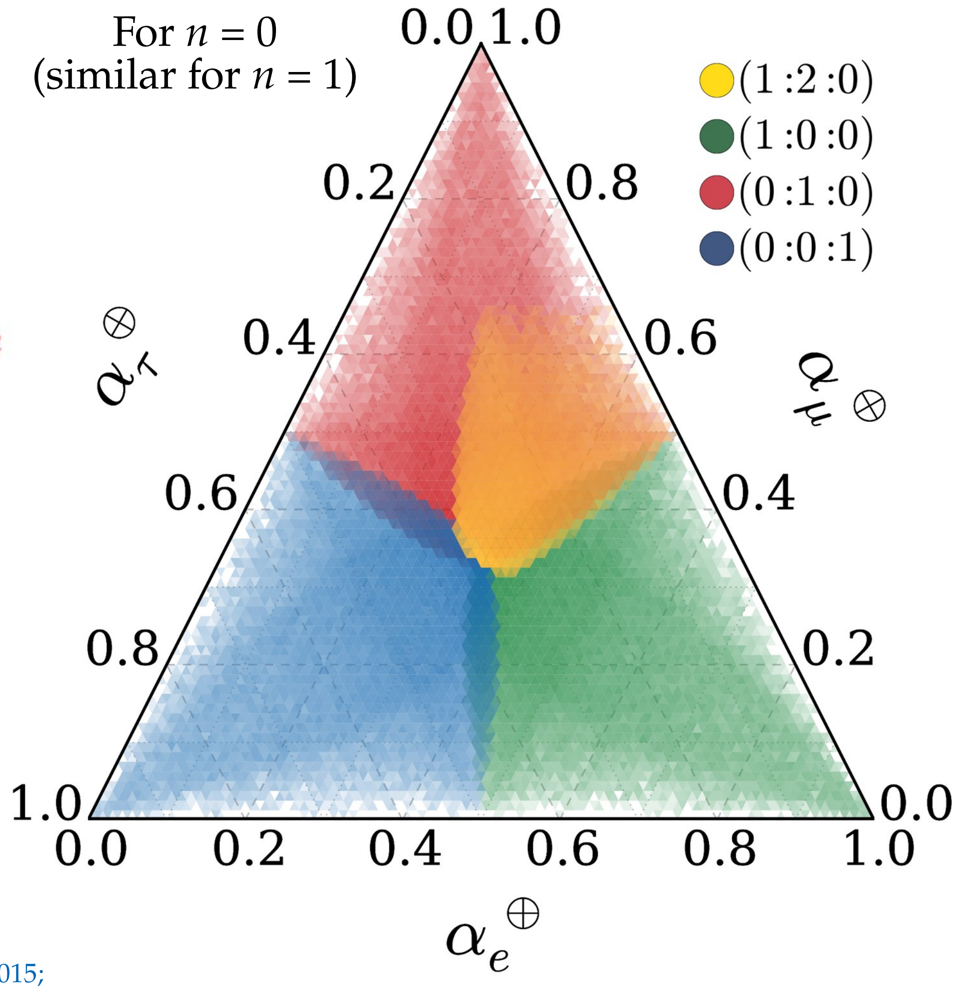
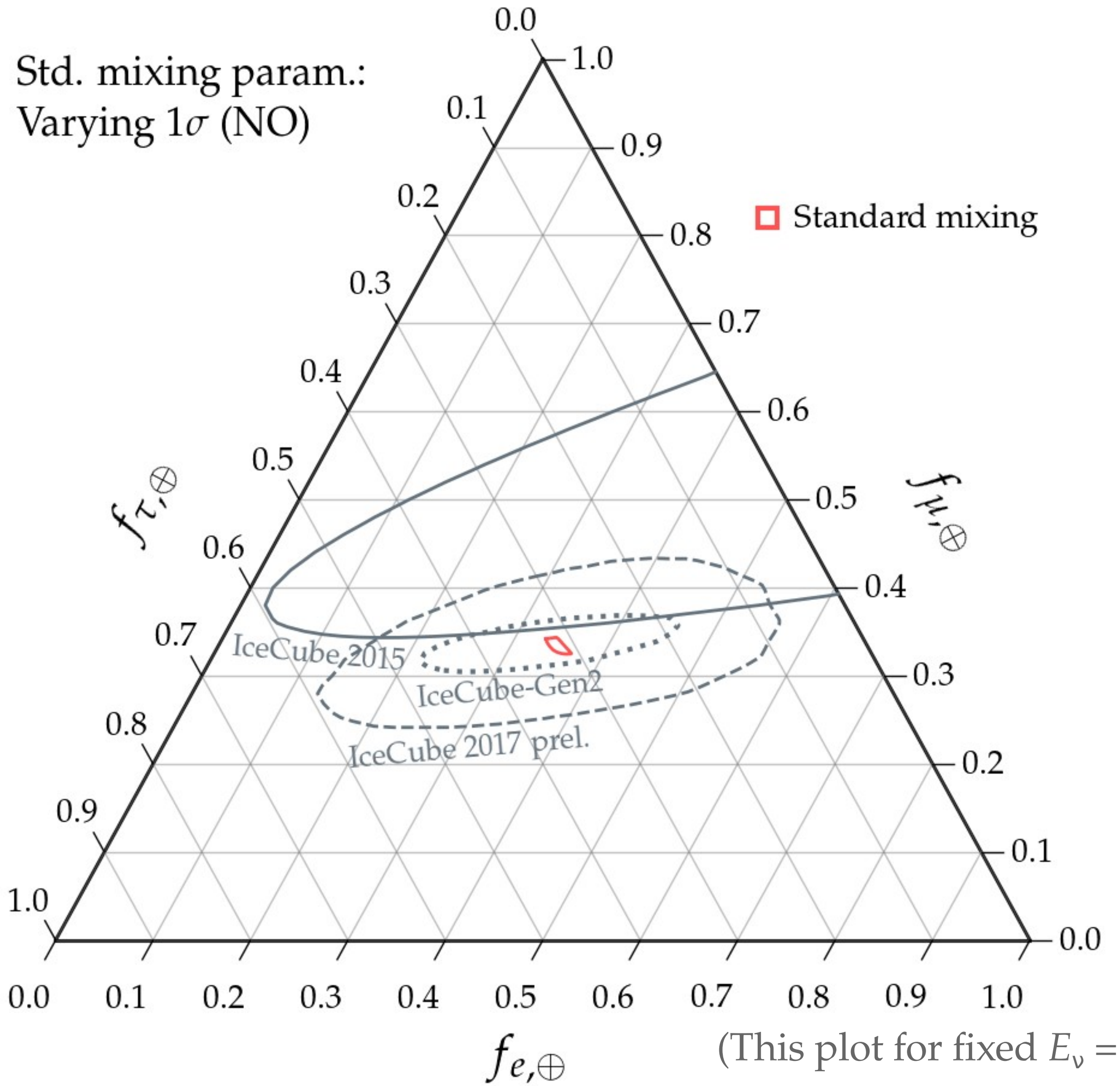


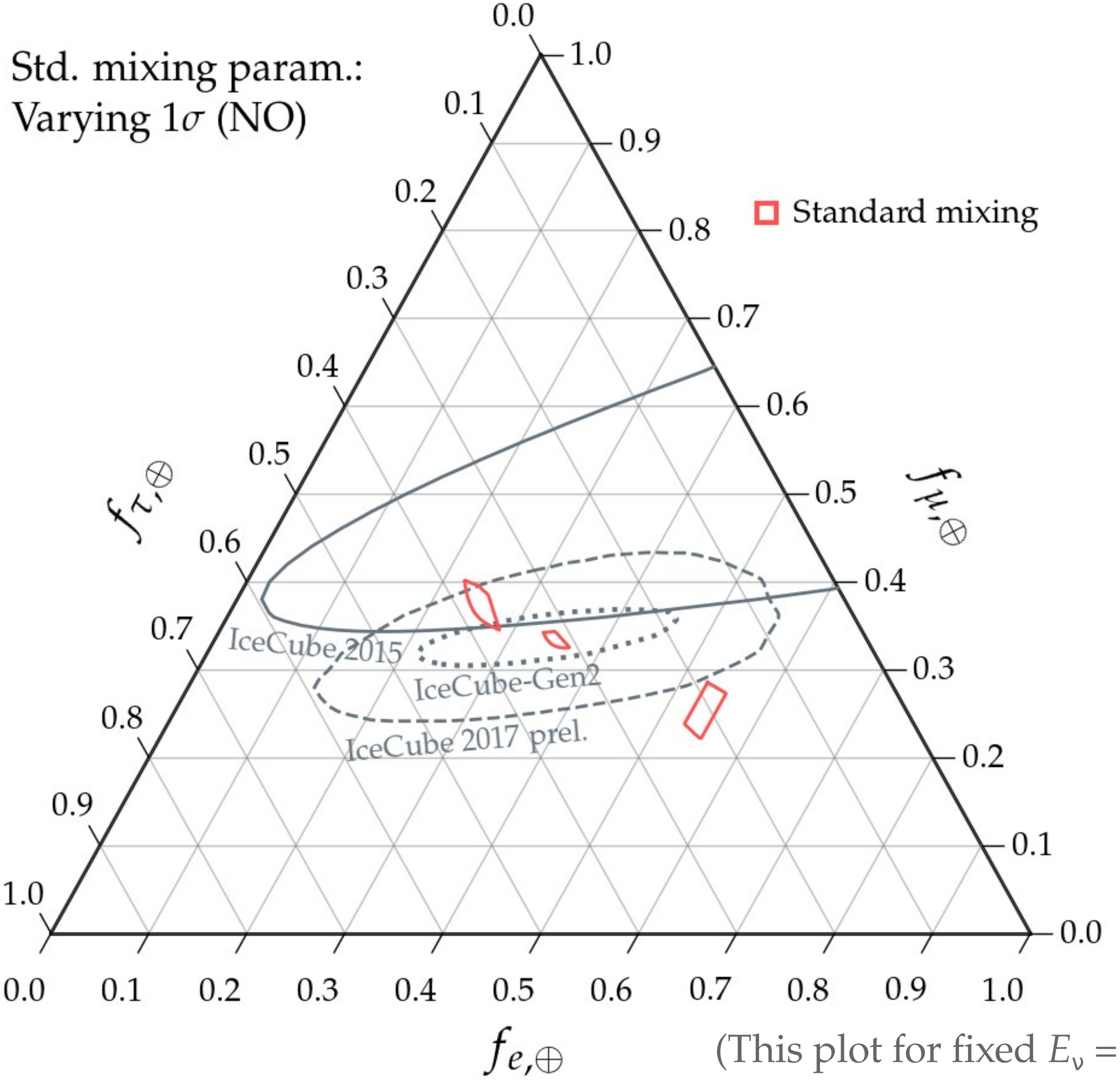
Argüelles, Katori, Salvadó, *PRL* 2015

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

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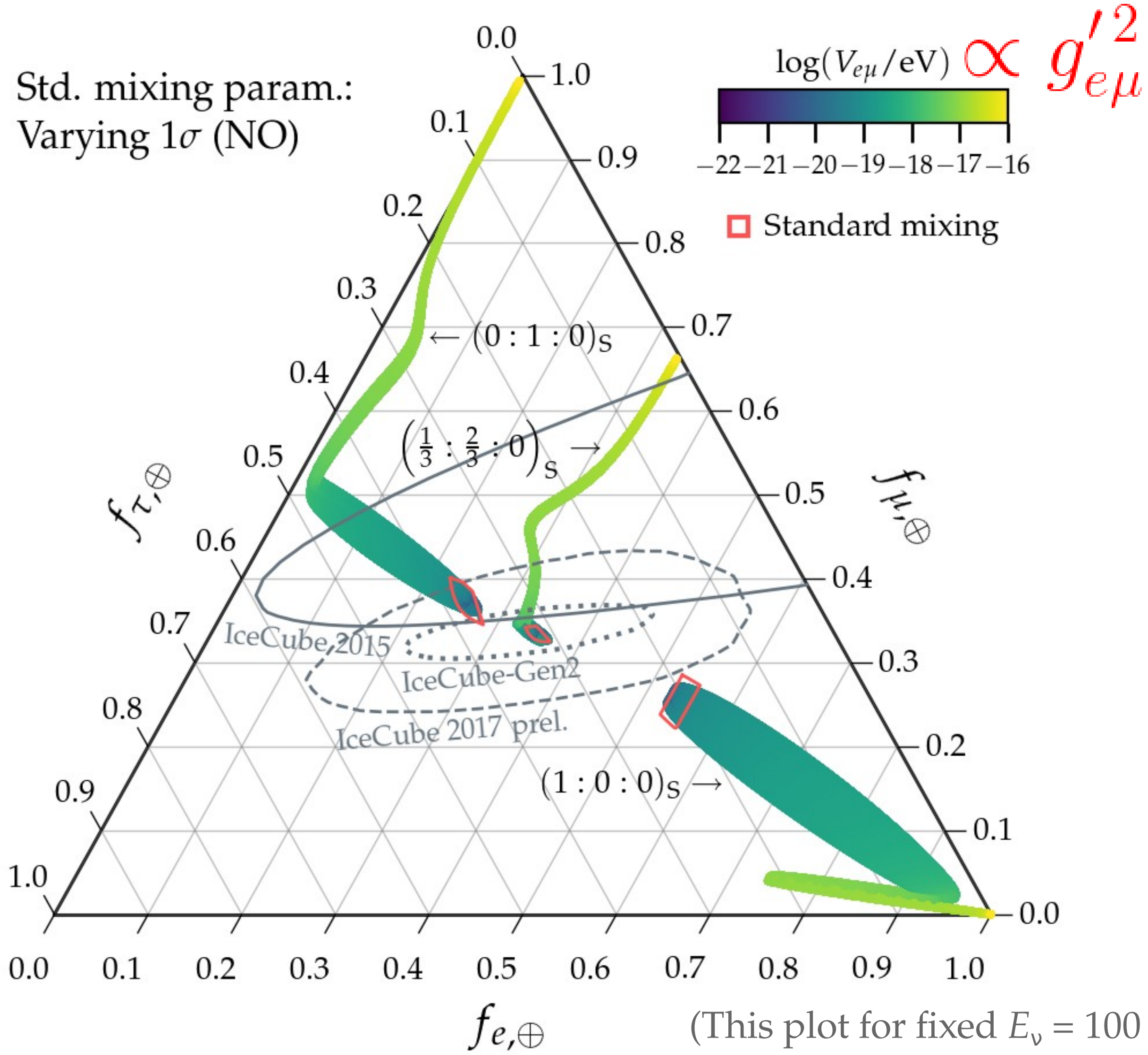

MB & Agarwalla, *PRL* 2019

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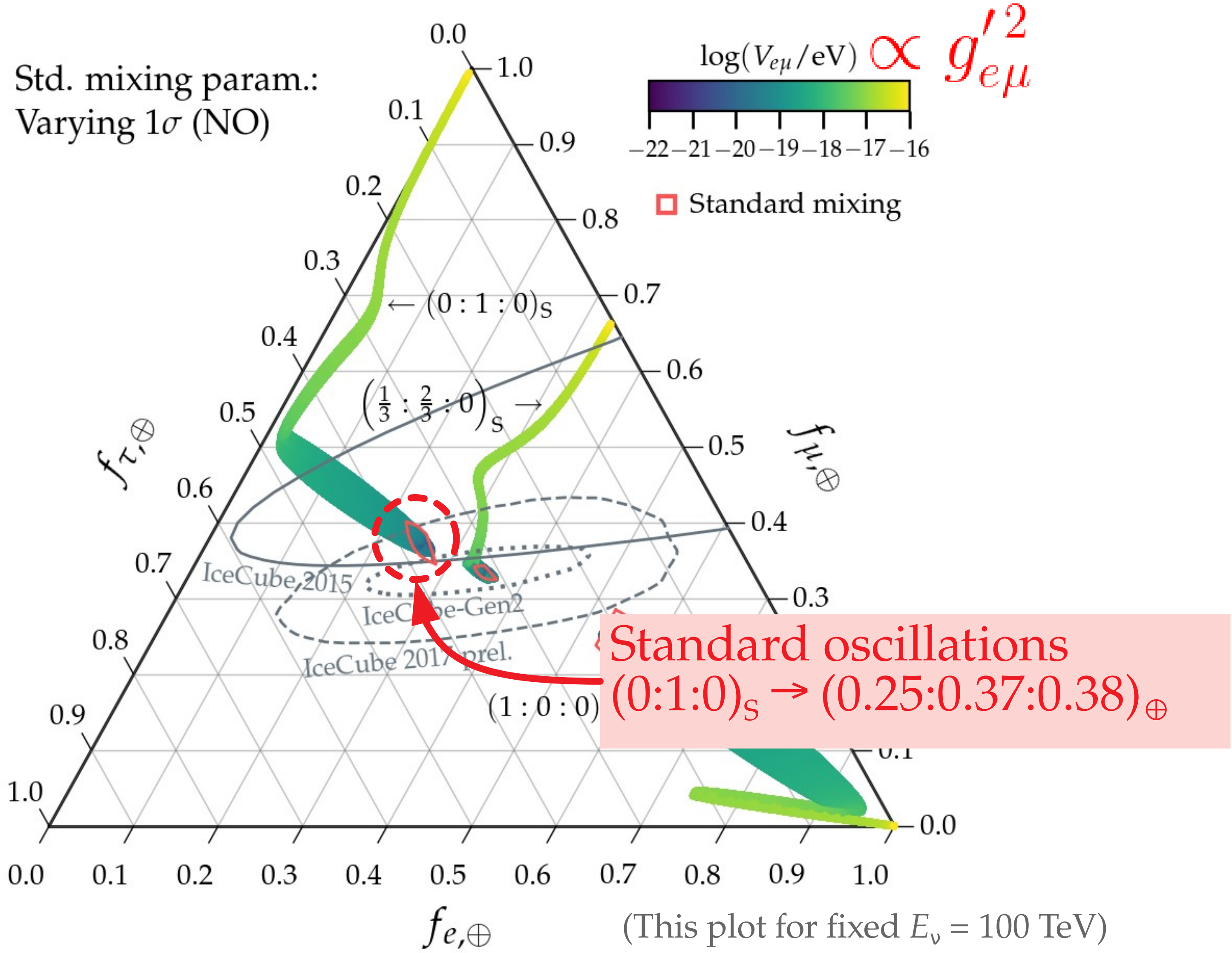

MB & Agarwalla, *PRL* 2019

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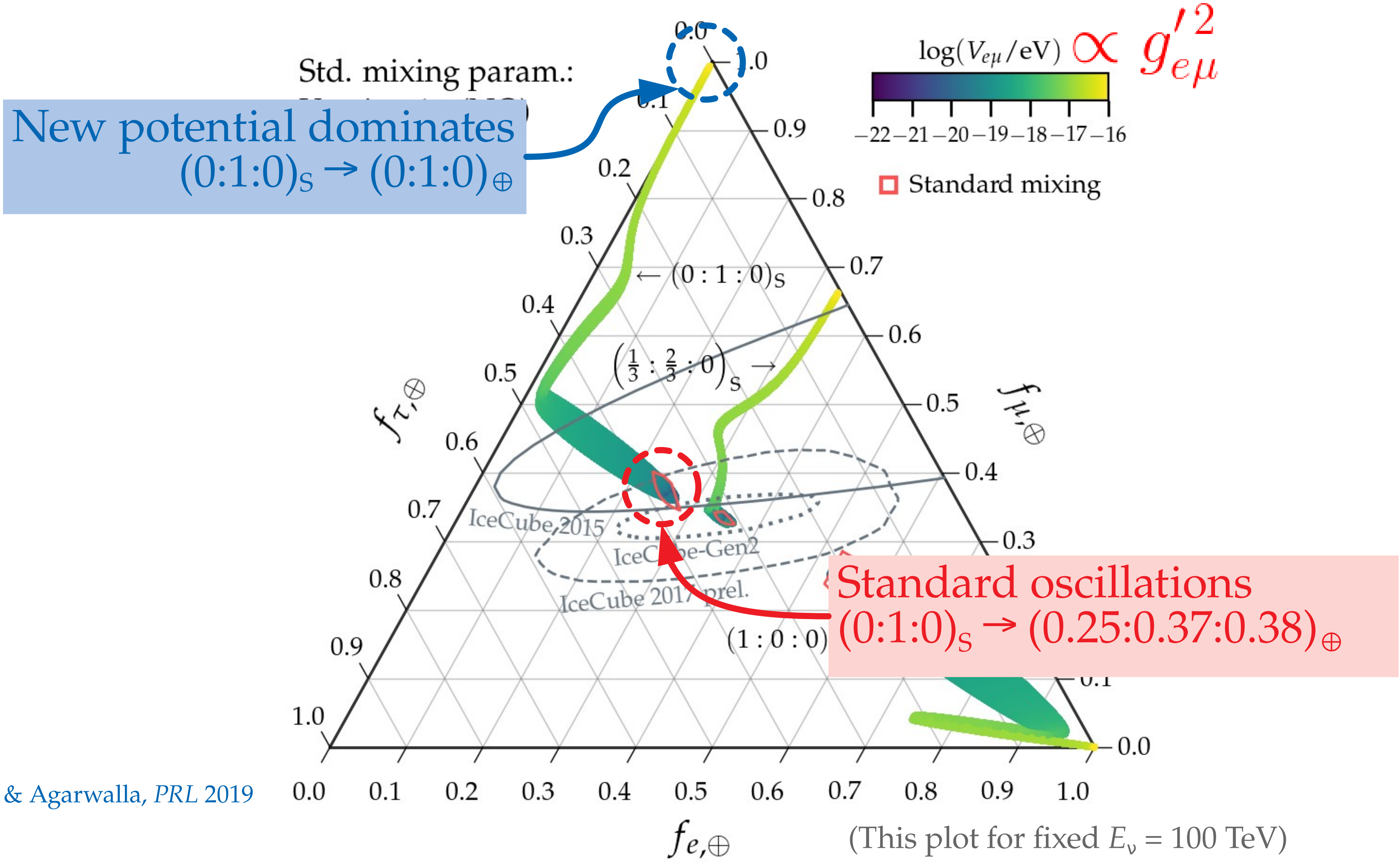
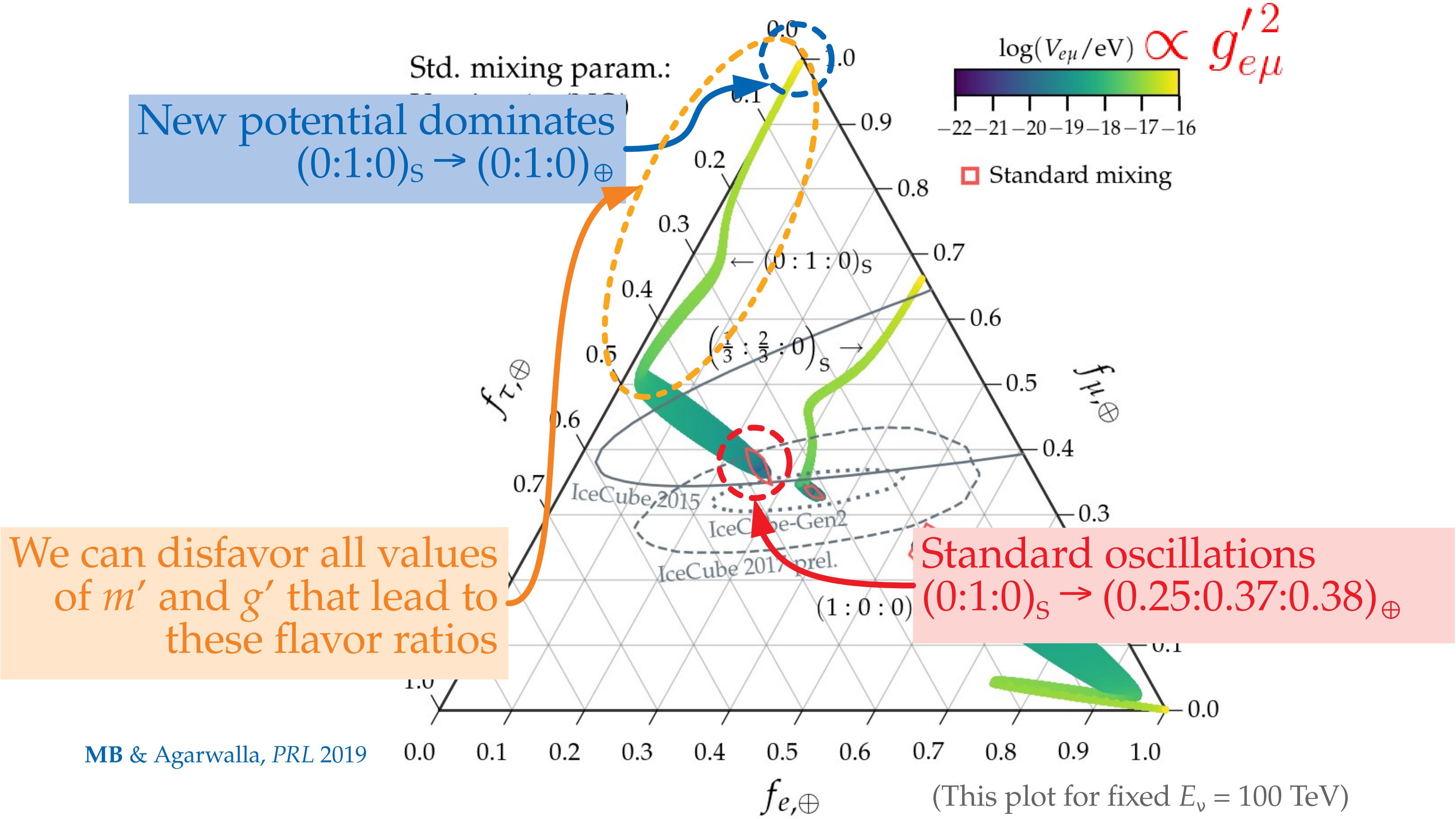
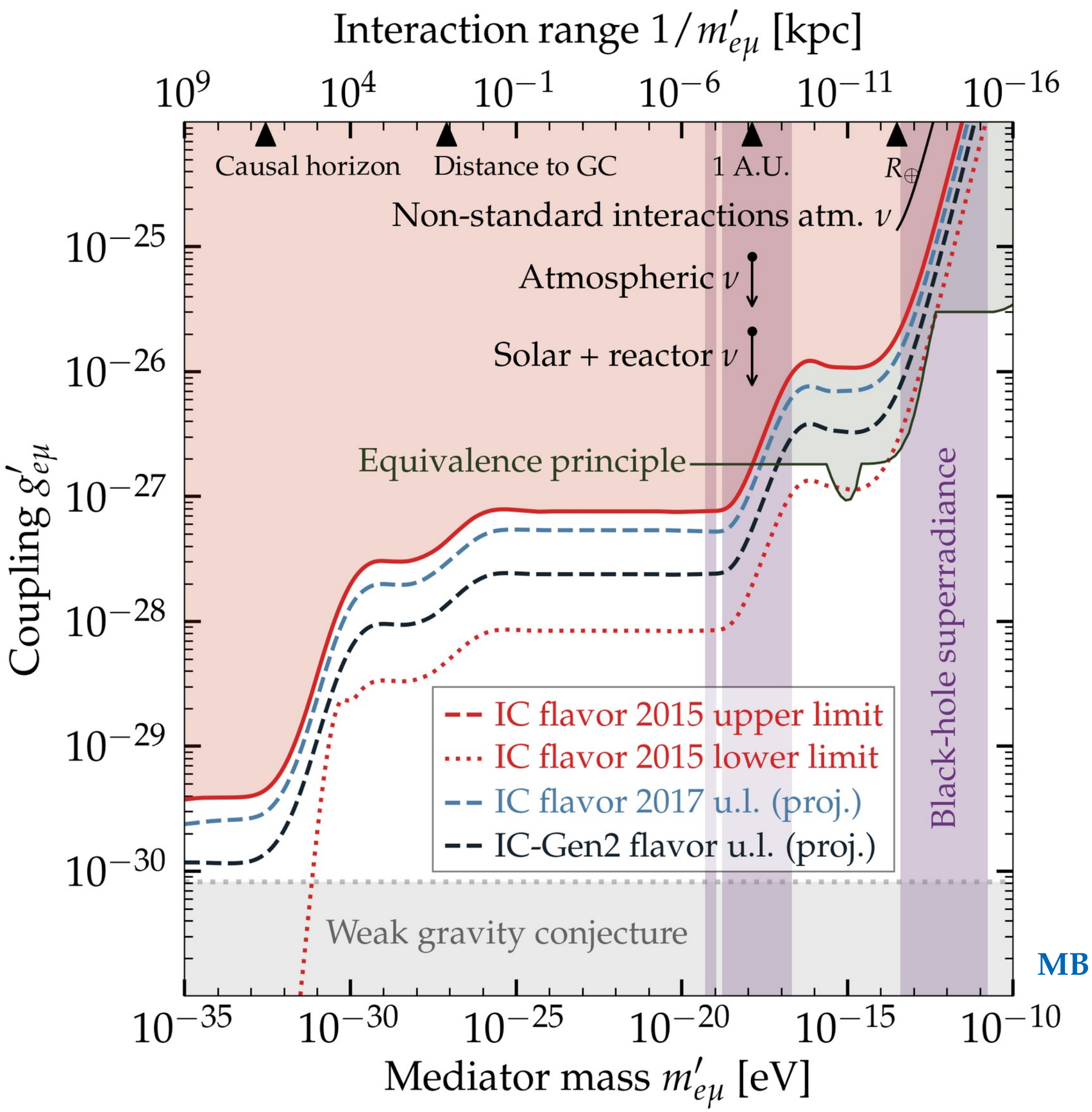


MB & Agarwalla, *PRL* 2019



MB & Agarwalla, *PRL* 2019



MB &Agarwalla, *PRL* 2019