Flavor composition of high-energy astrophysical neutrinos: *Why you should be excited*

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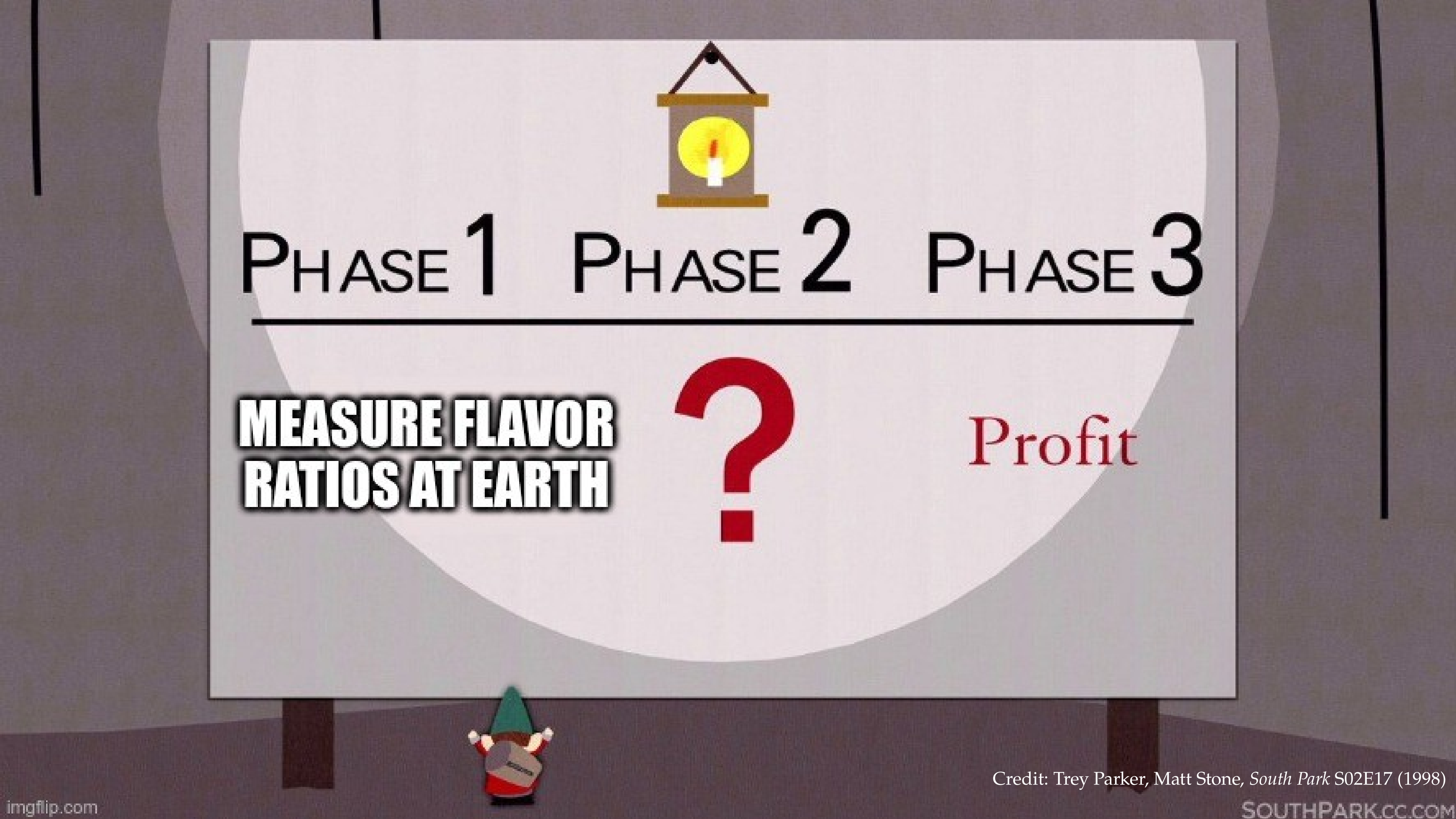
Niels Bohr Institute, University of Copenhagen

UNIVERSITY OF COPENHAGEN

VILLUM FONDEN

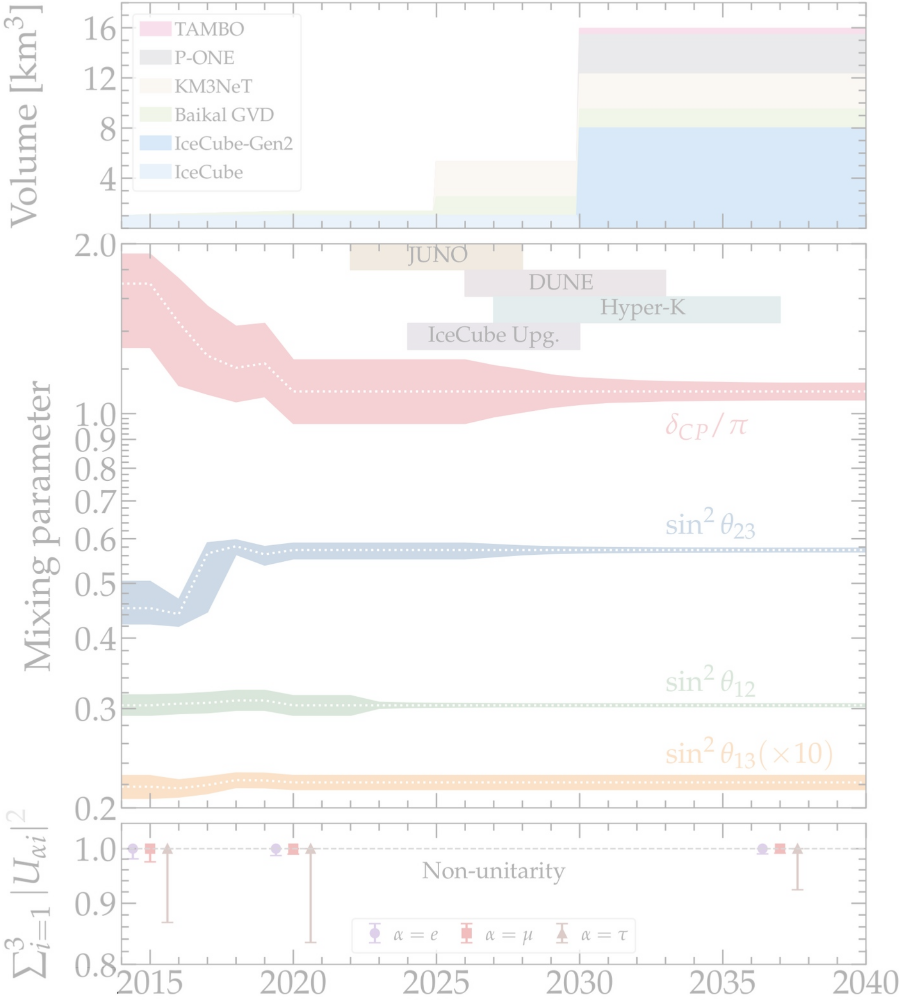
Cosmic Rays and Neutrinos in the Multi-Messenger Era
December 11, 2020



Credit: Trey Parker, Matt Stone, *South Park* S02E17 (1998)

Three reasons to be excited

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX



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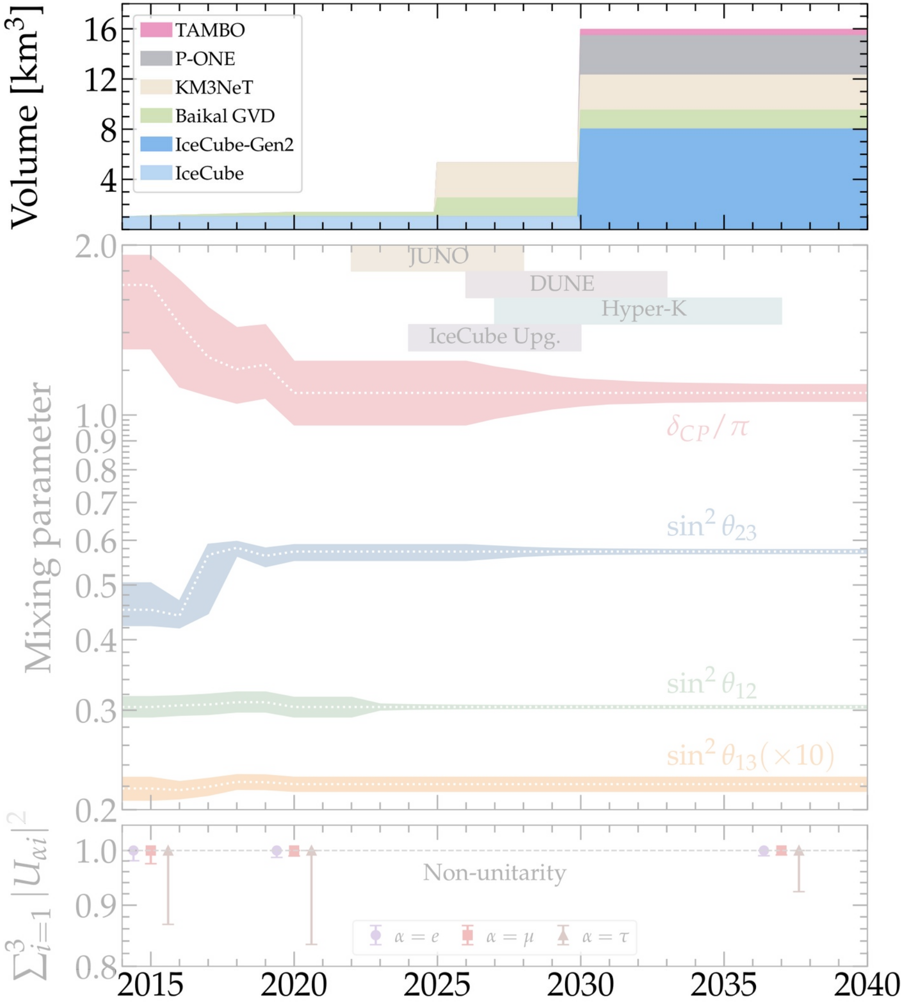

Flavor measurements:

New neutrino telescopes = more events, better flavor measurement

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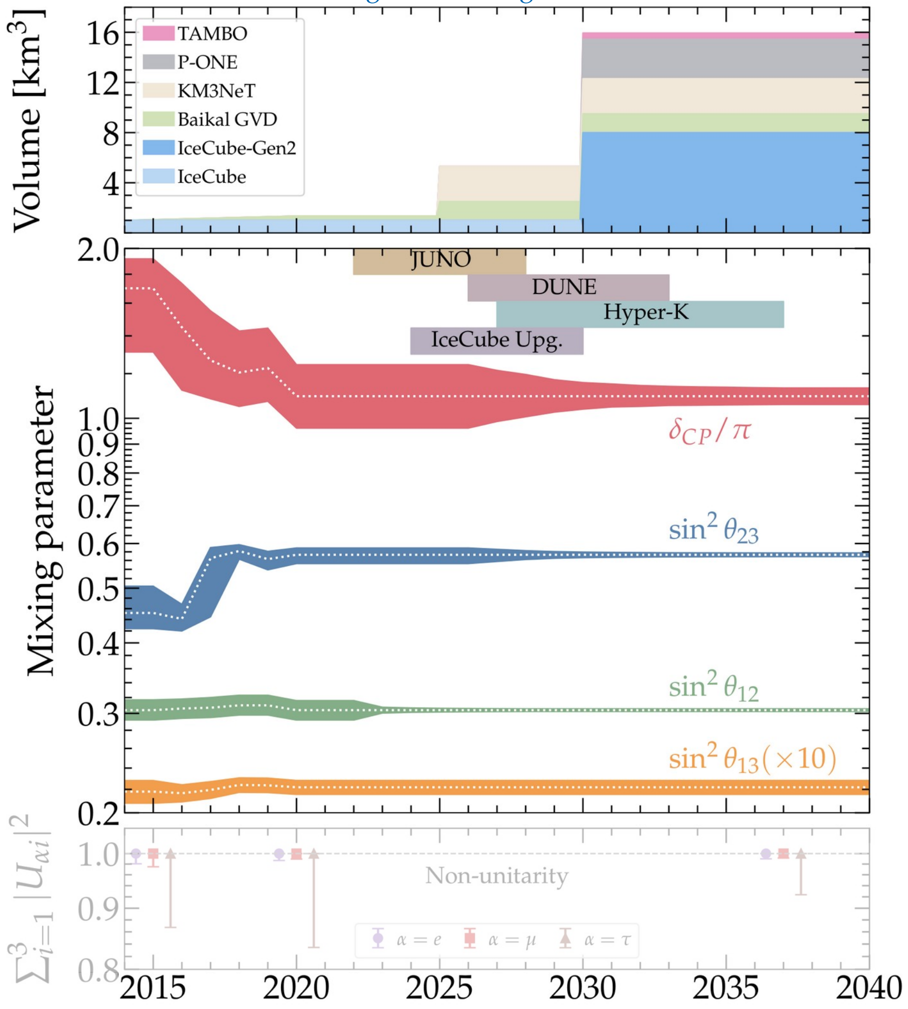

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Oscillation physics:
We will know the mixing parameters better (JUNO, DUNE, Hyper-K, IceCube Upgrade)

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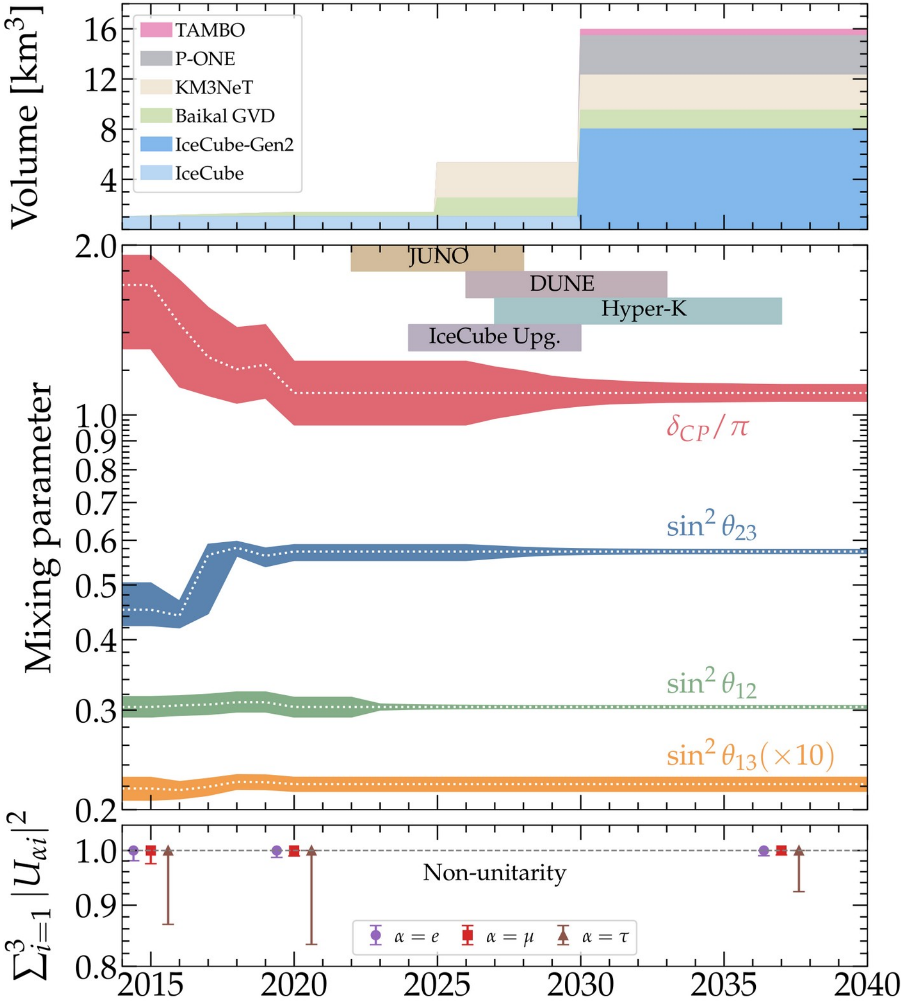

Flavor measurements:
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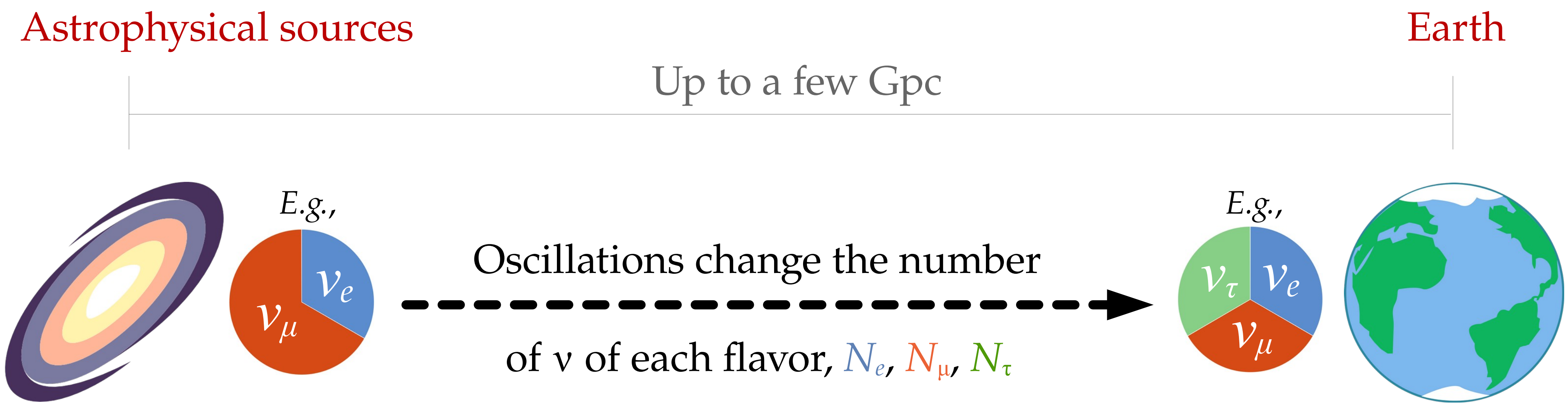
Test of the oscillation framework:
We will be able to do what we want even if oscillations are non-unitary

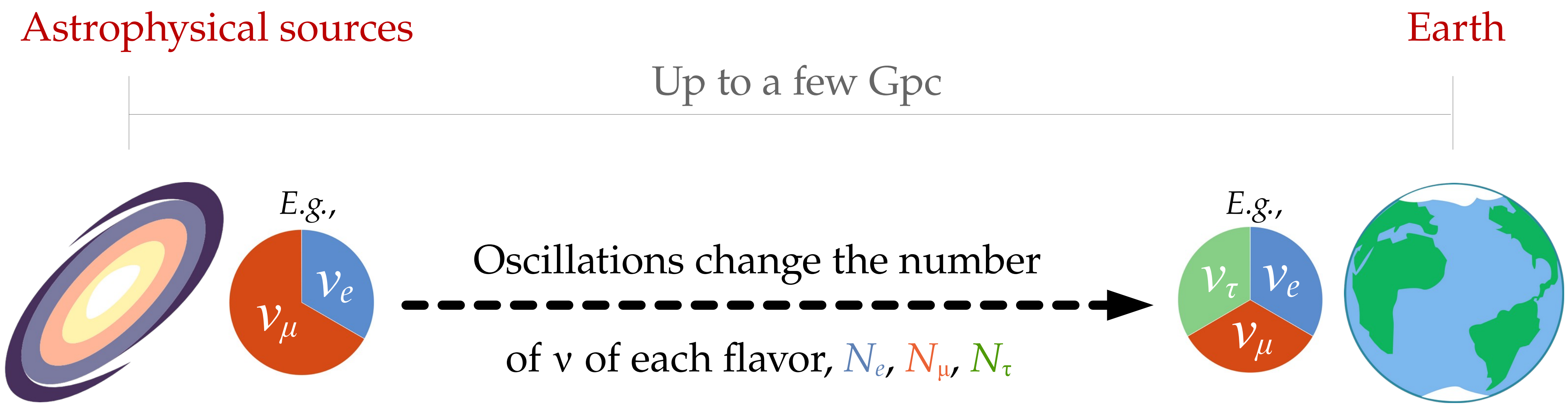


Different production mechanisms yield different flavor ratios:

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

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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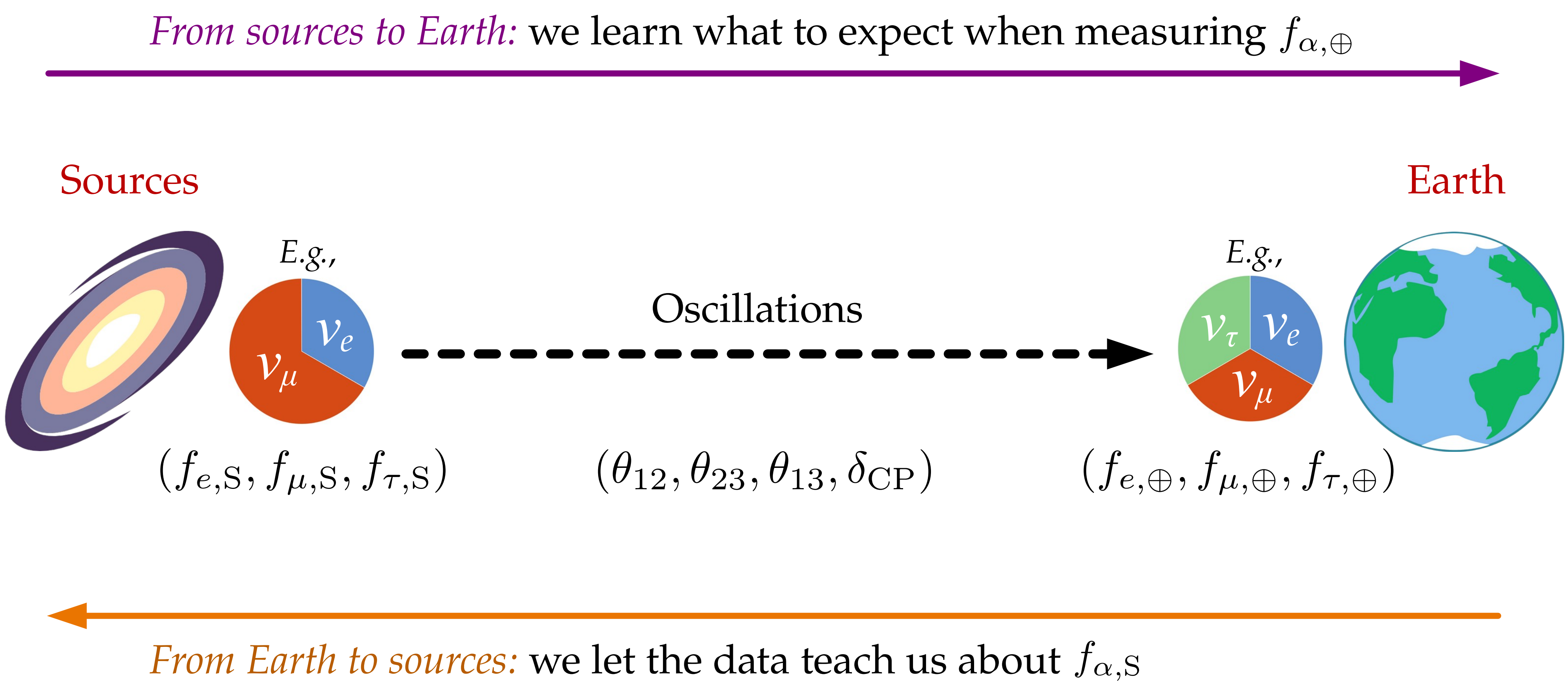
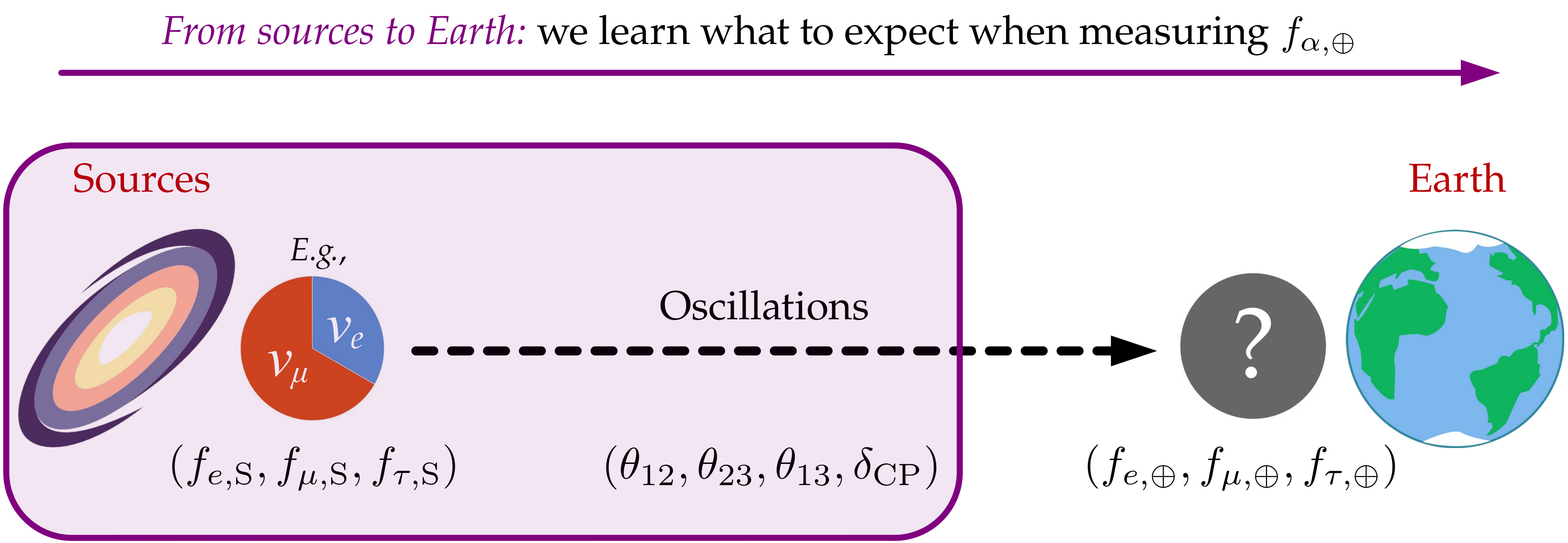
Standard oscillations
or
new physics



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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E.g.,
ν_e
ν_μ
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?
Earth
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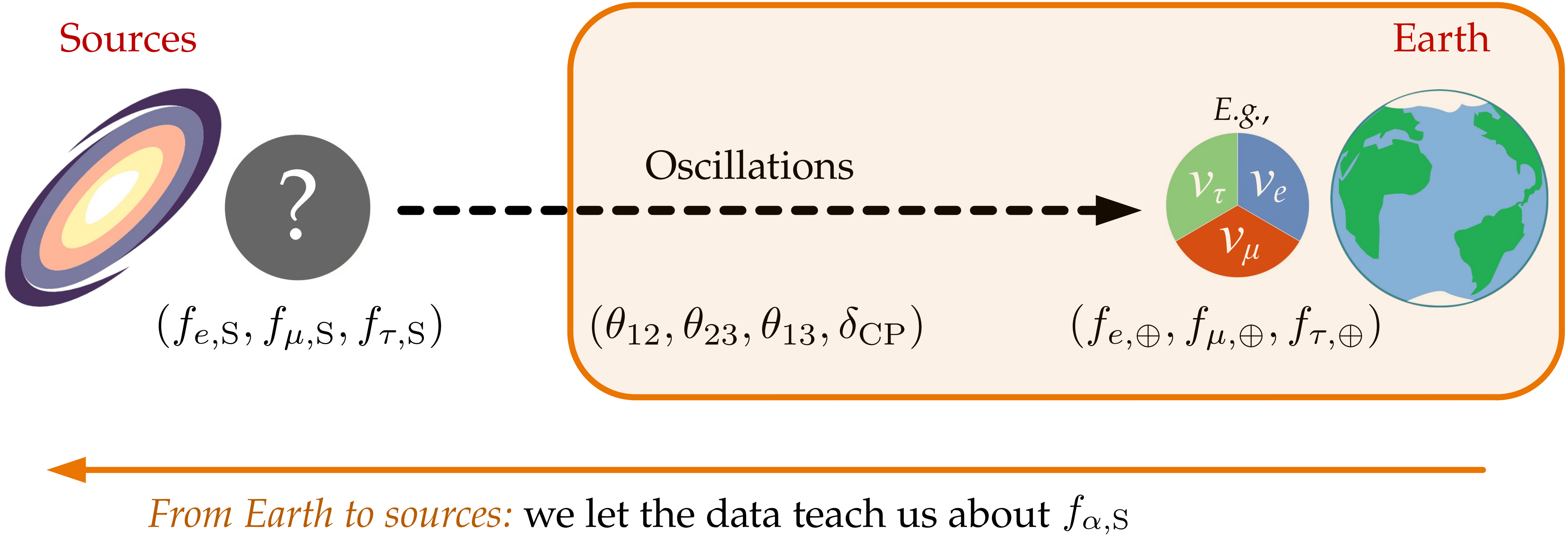
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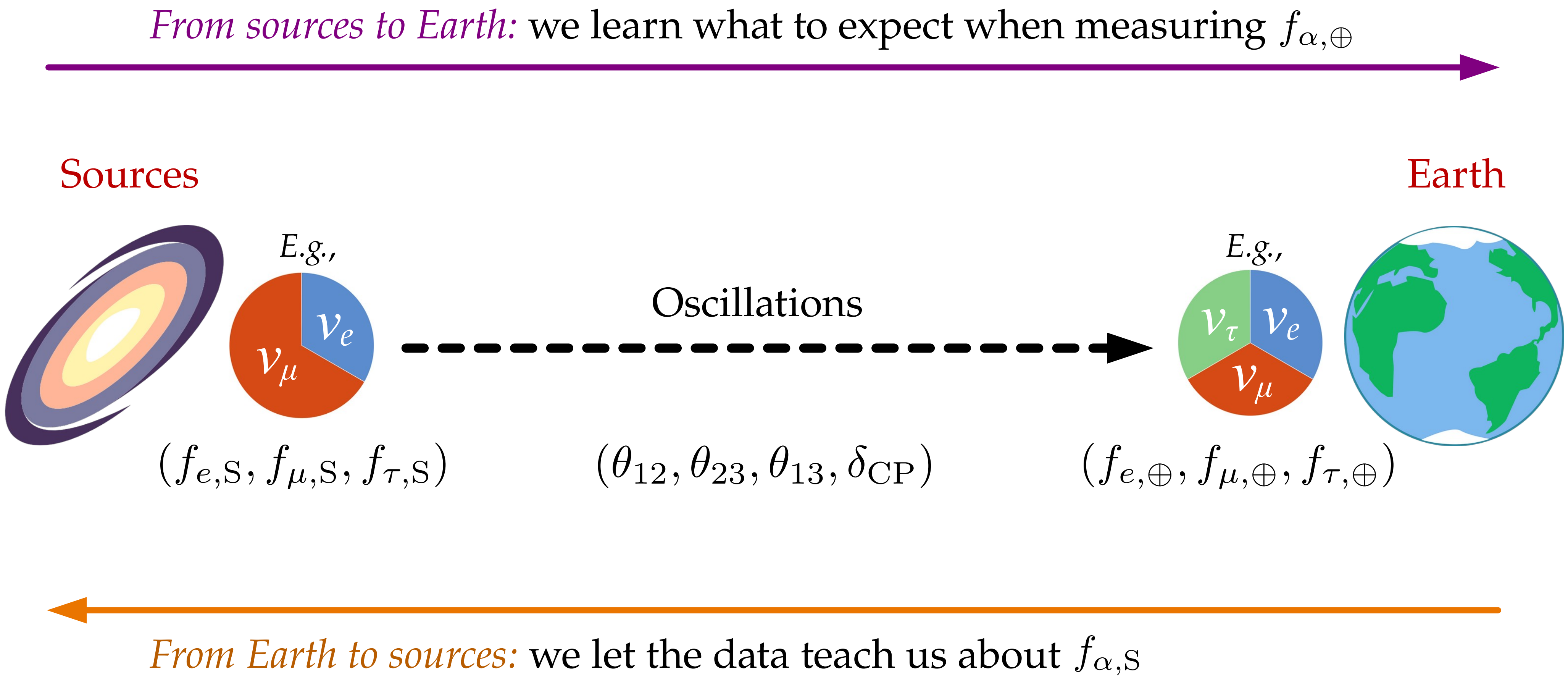

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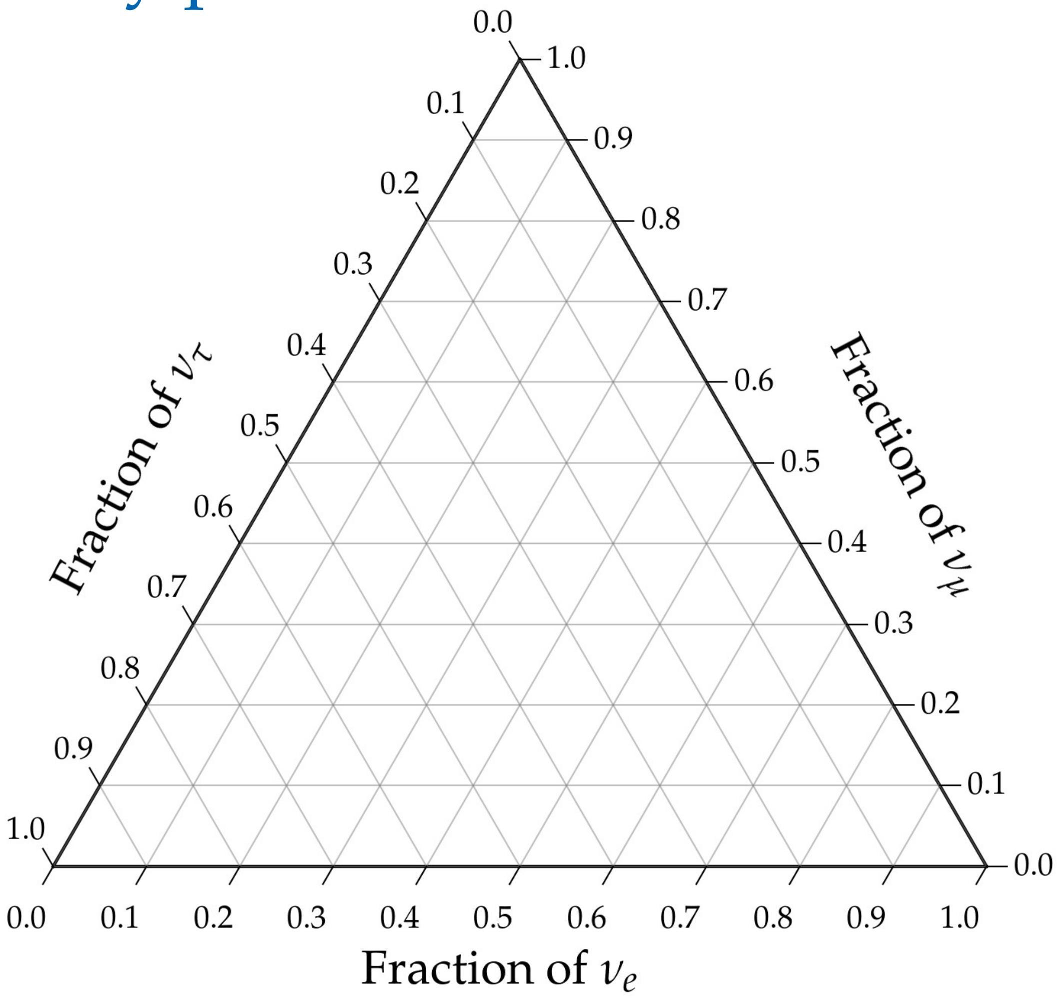
Quick aside: how to read a ternary plot

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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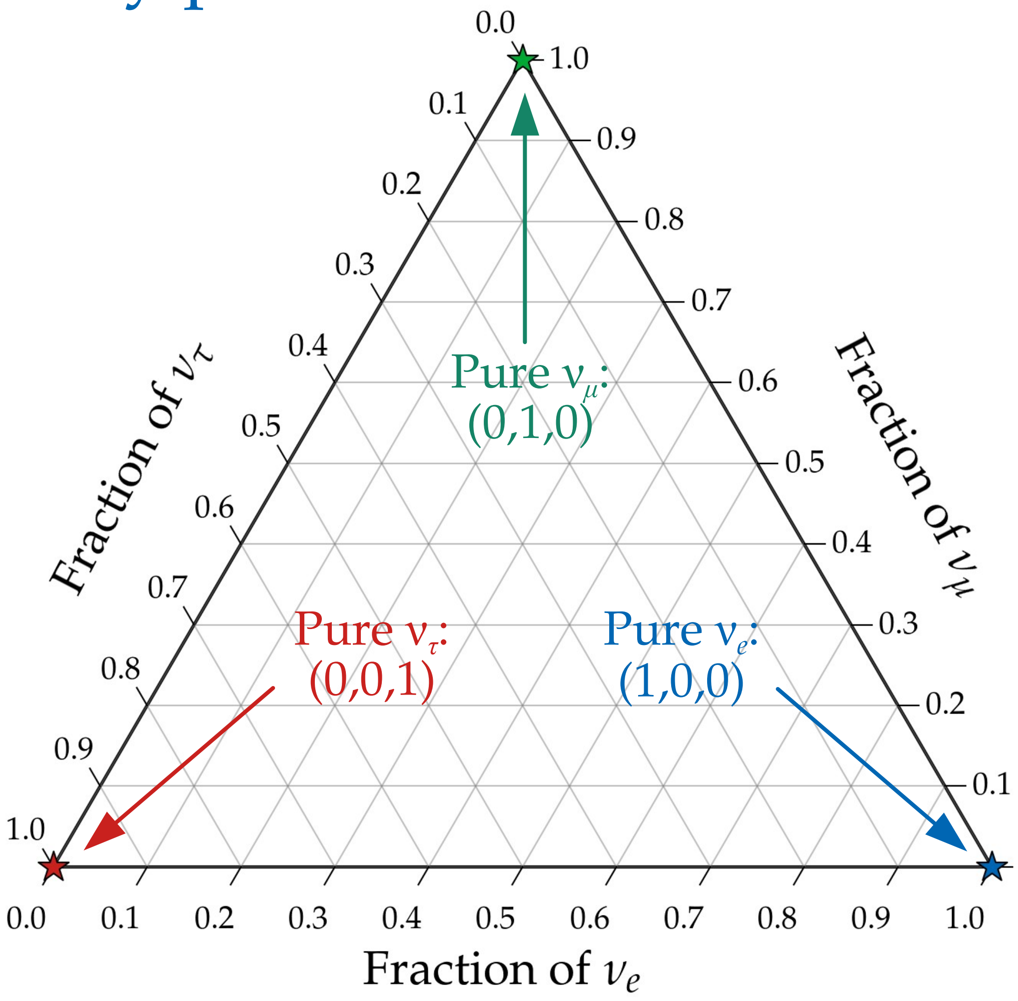

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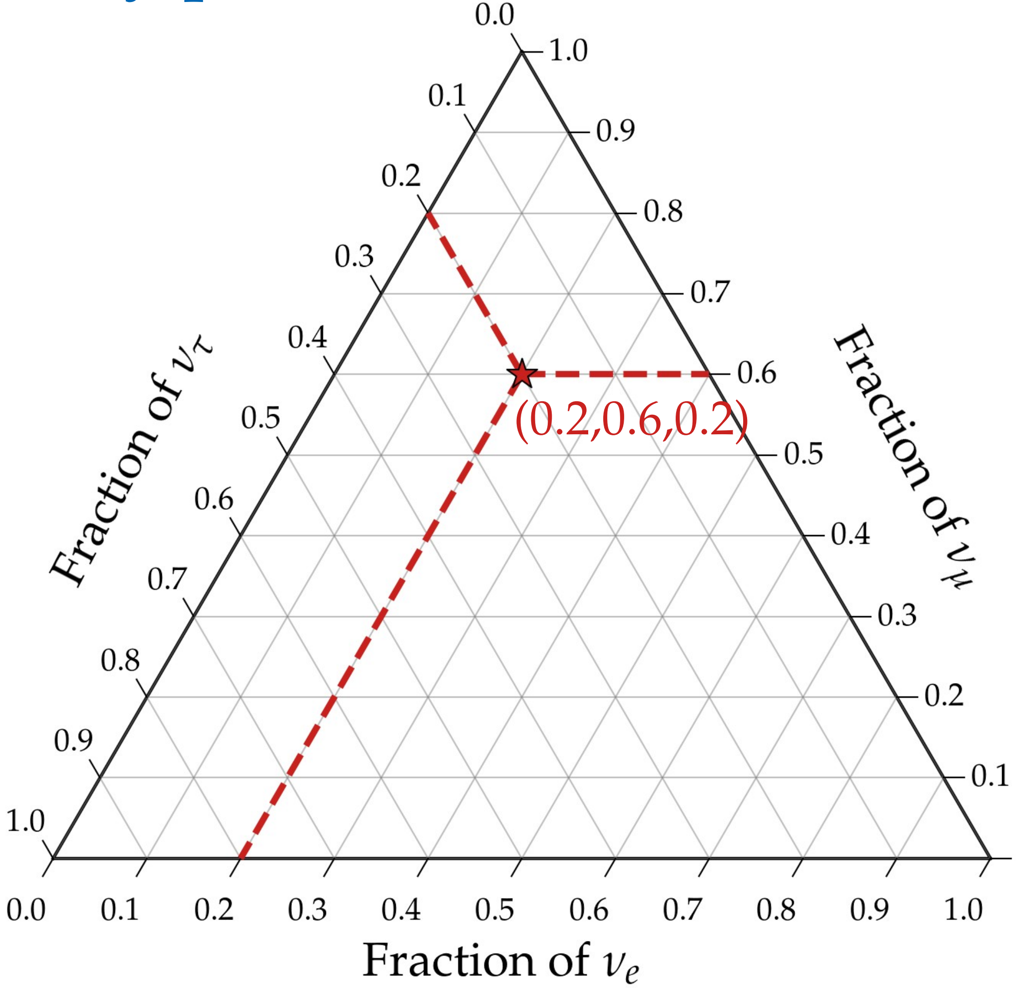

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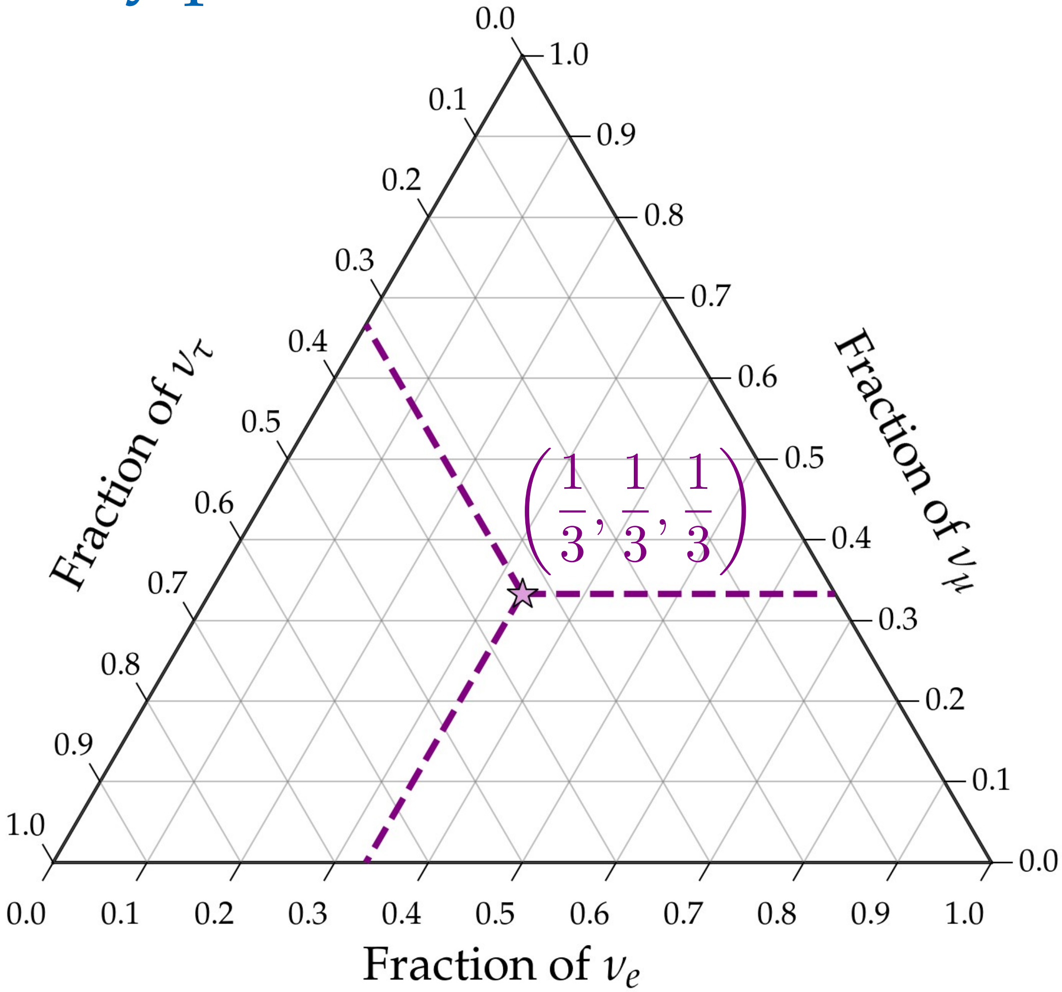

One likely TeV–PeV ν production scenario:

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

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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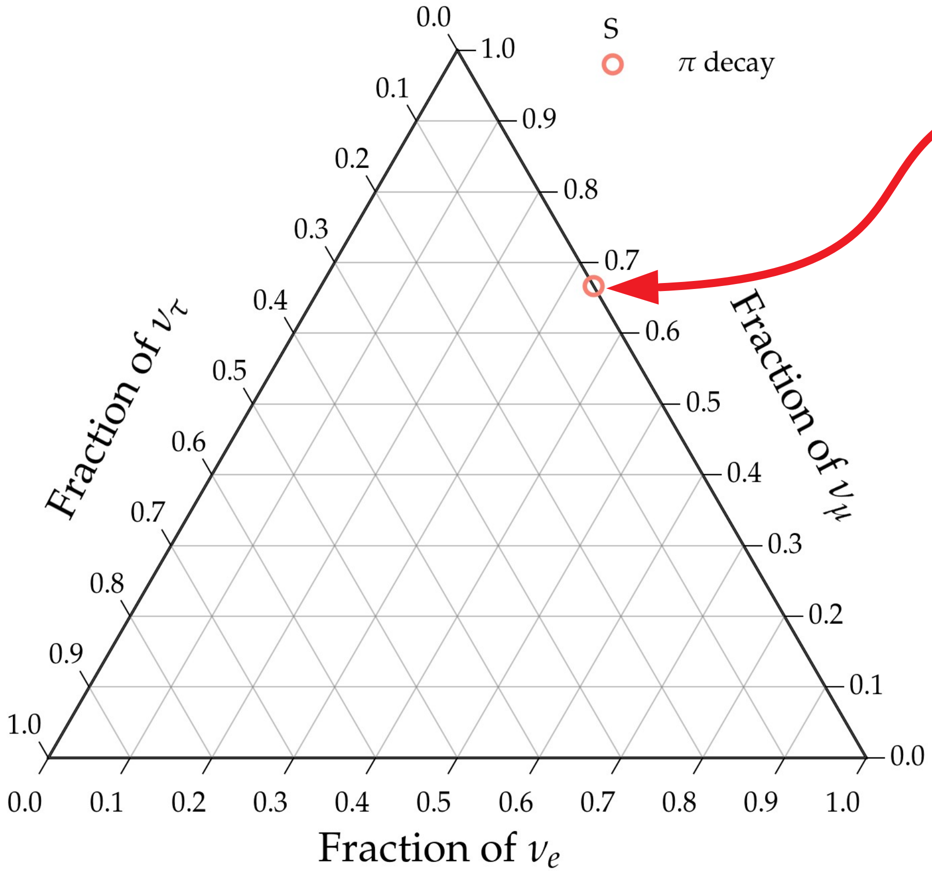

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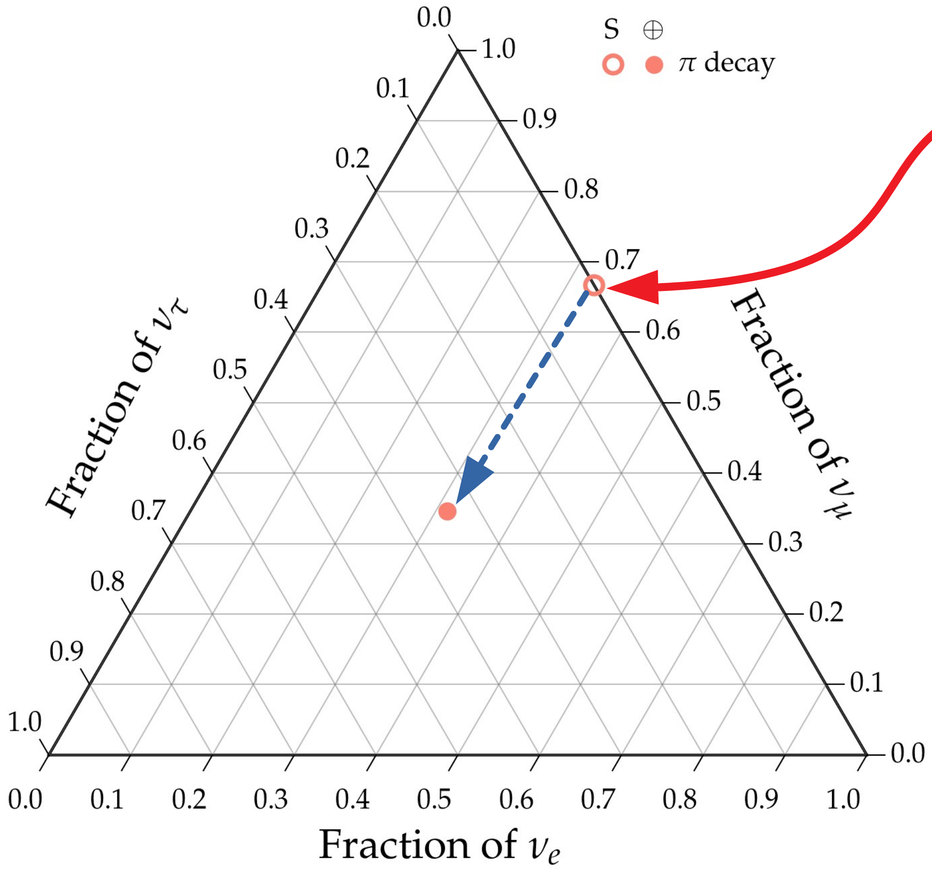

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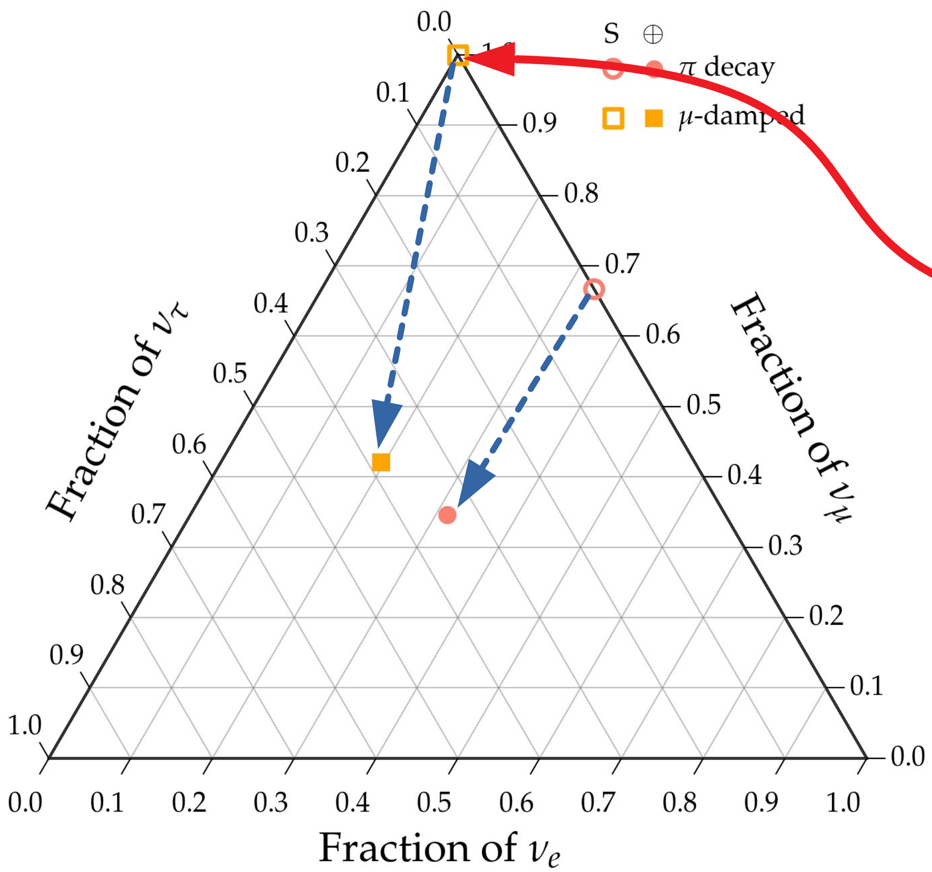

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Muon damped

$(0:1:0)_S$

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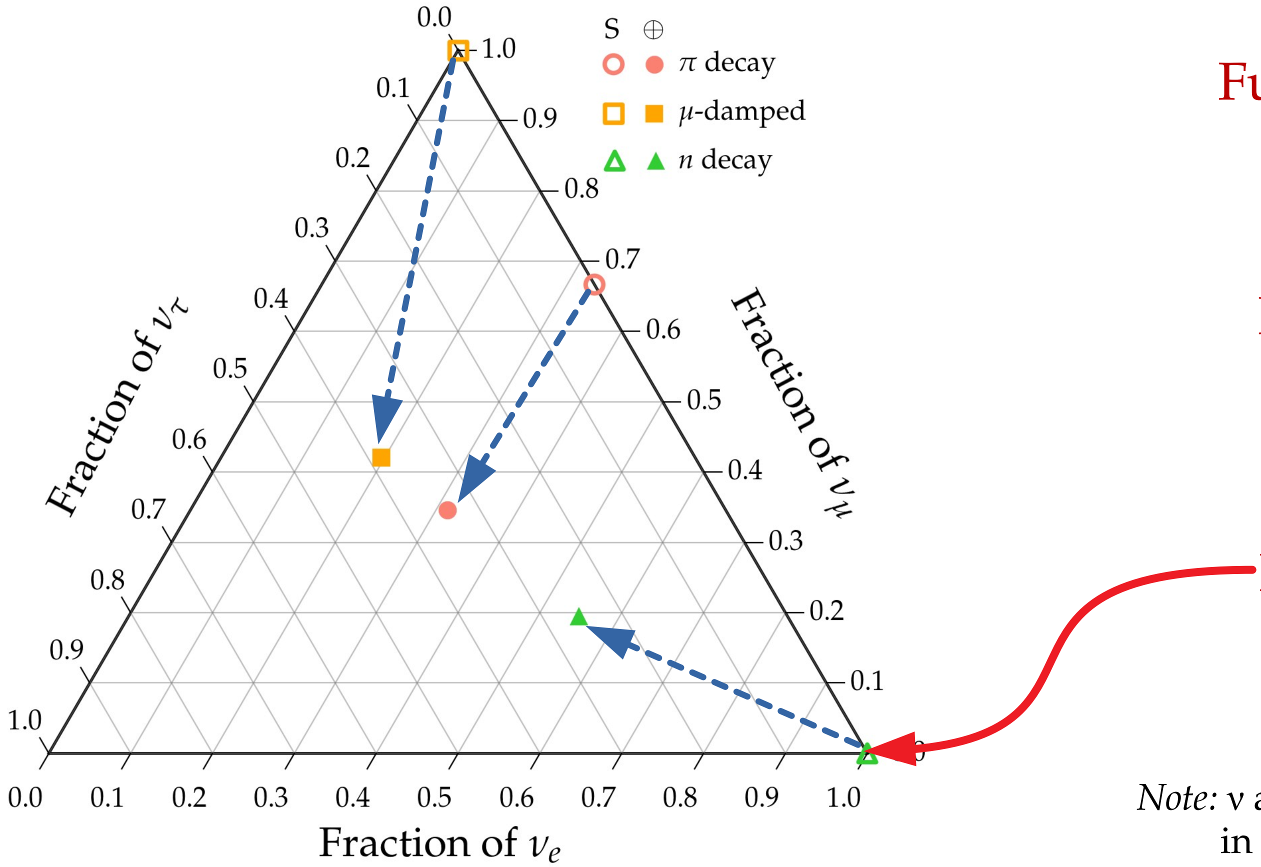

Full π decay chain

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

Muon damped

$(0:1:0)_S$

Neutron decay

$(1:0:0)_S$

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

How does IceCube see TeV–PeV neutrinos?

Deep inelastic neutrino-nucleon scattering

Neutral current (NC)

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

Charged current (CC)

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

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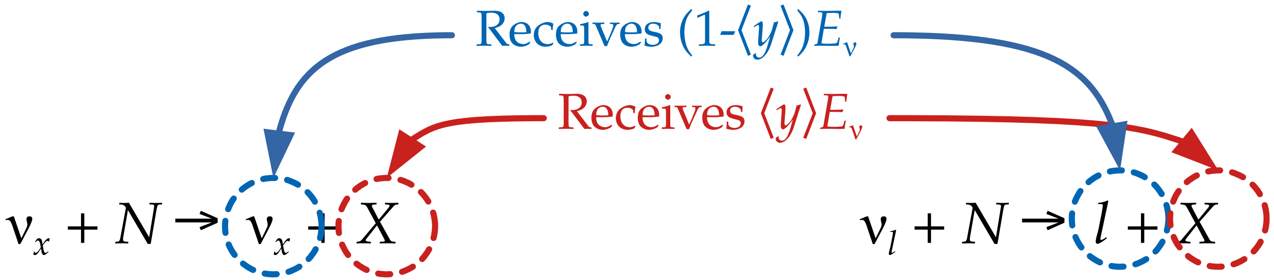

At TeV–PeV, the average inelasticity $\langle y \rangle = 0.25$–0.30

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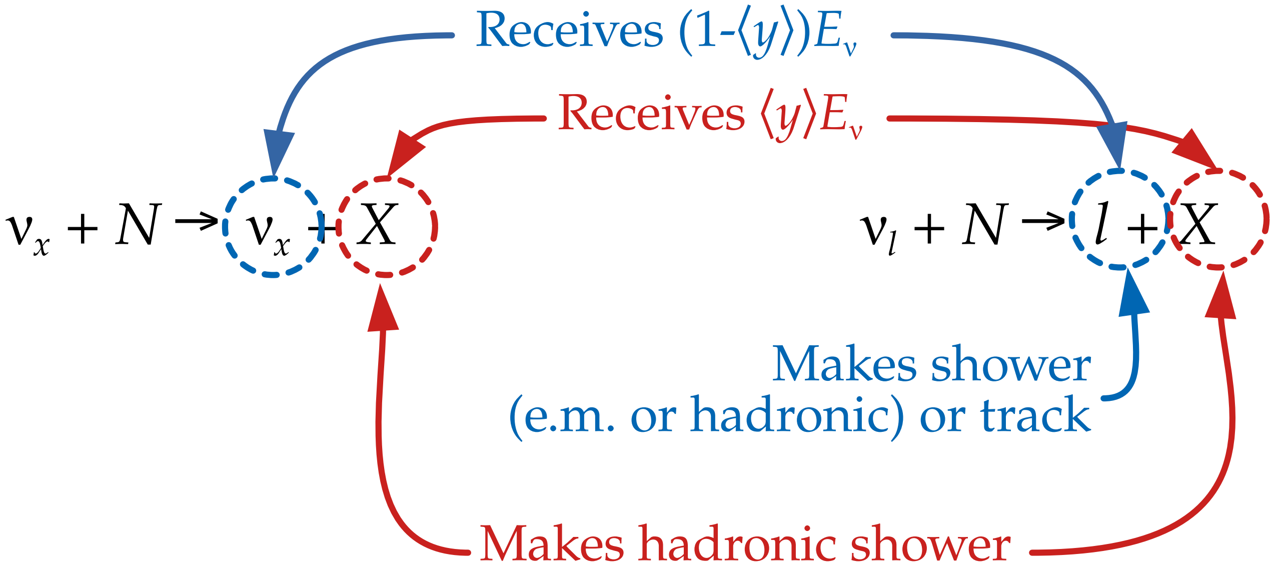

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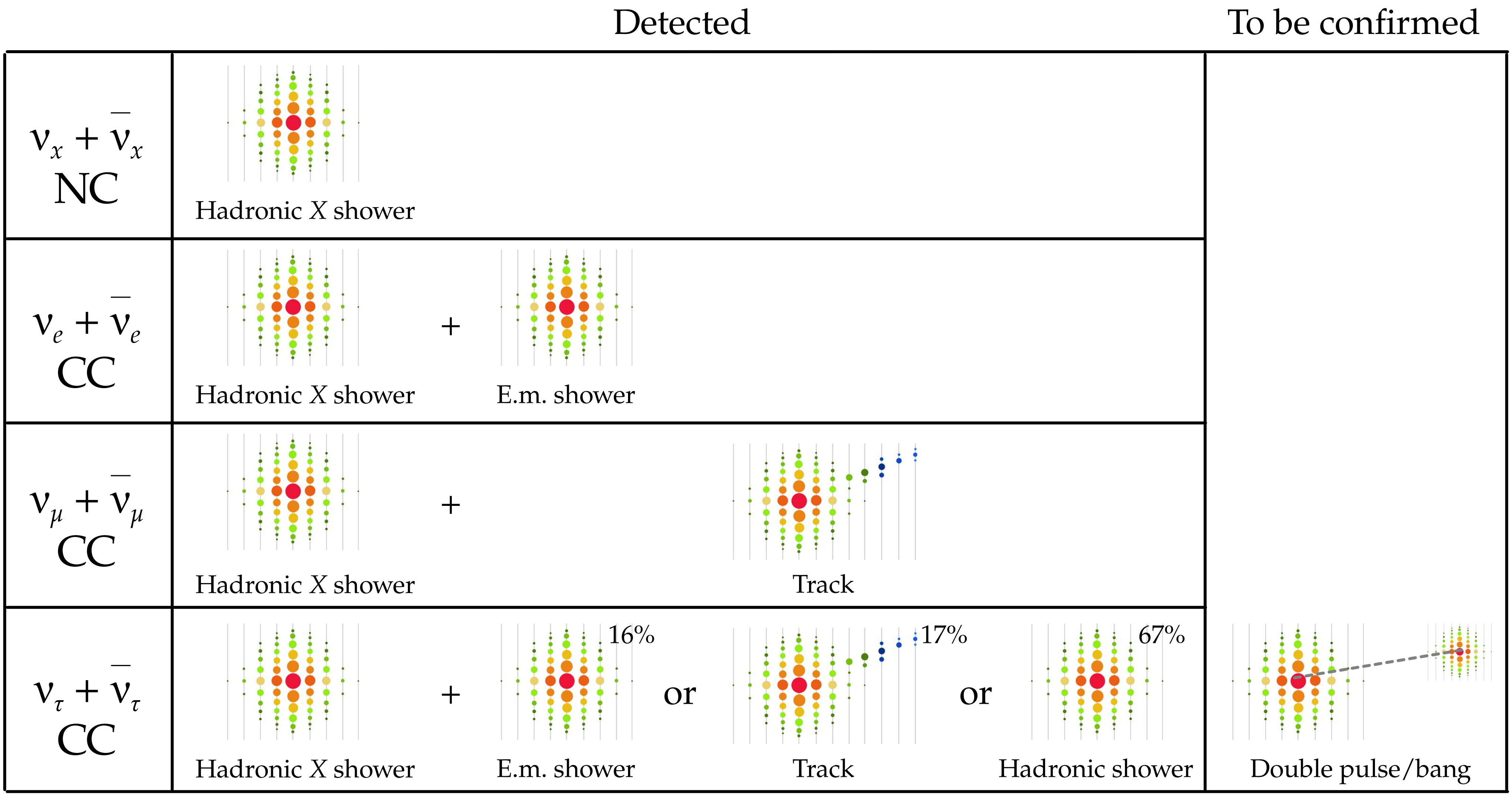
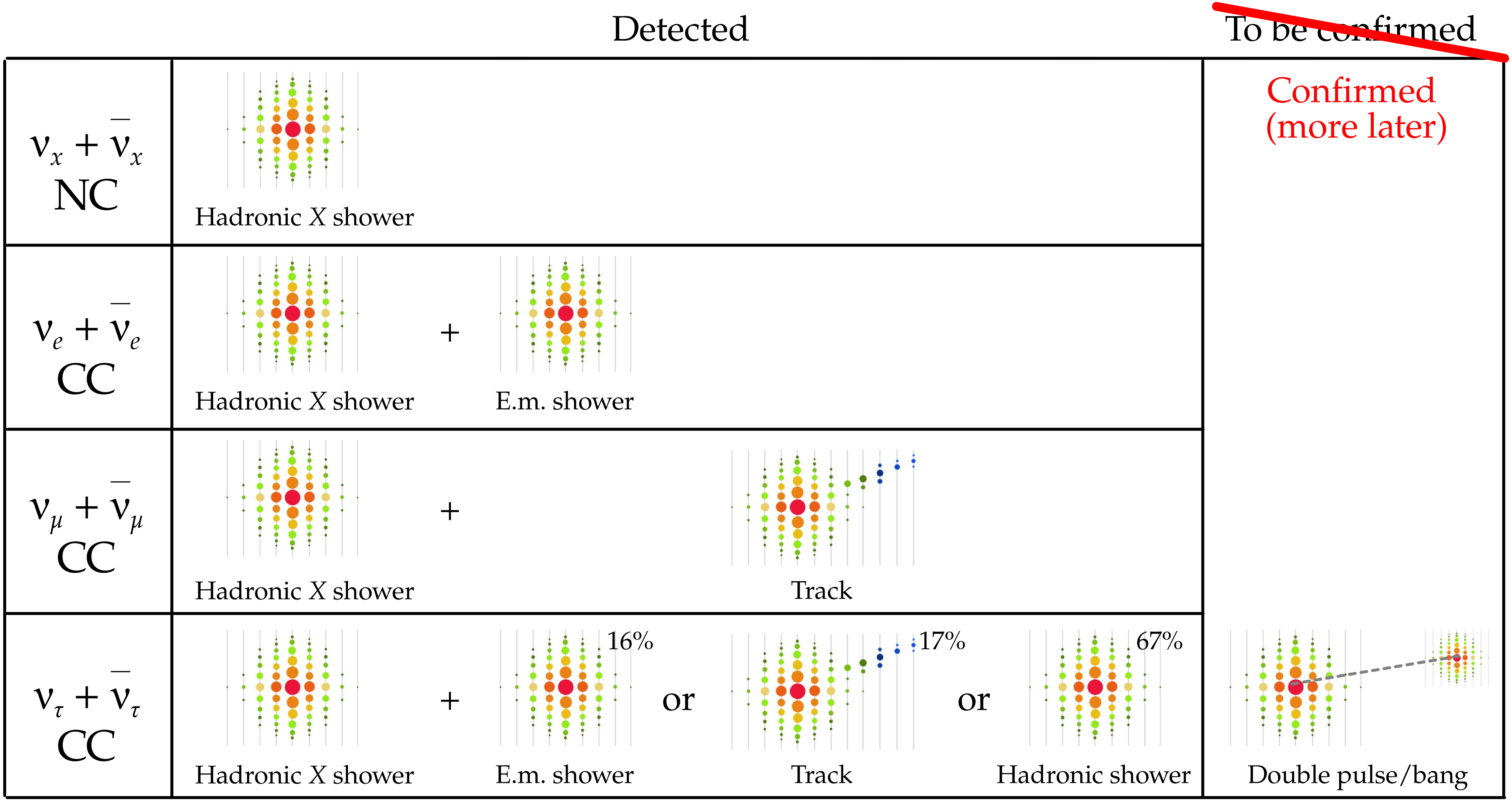

Detected
To be confirmed
$\nu_x + \bar{\nu}_x$ NC
Hadronic X shower
$\nu_e + \bar{\nu}_e$ CC
Hadronic X shower
+
E.m. shower
$\nu_\mu + \bar{\nu}_\mu$ CC
Hadronic X shower
+
Track
$\nu_\tau + \bar{\nu}_\tau$ CC
Hadronic X shower
+
16%
E.m. shower
or
17%
Track
or
67%
Hadronic shower
Double pulse/bang



Detected
To be confirmed
Confirmed
(more later)
$\nu_x + \bar{\nu}_x$ NC
Hadronic X shower
$\nu_e + \bar{\nu}_e$ CC
Hadronic X shower
+
E.m. shower
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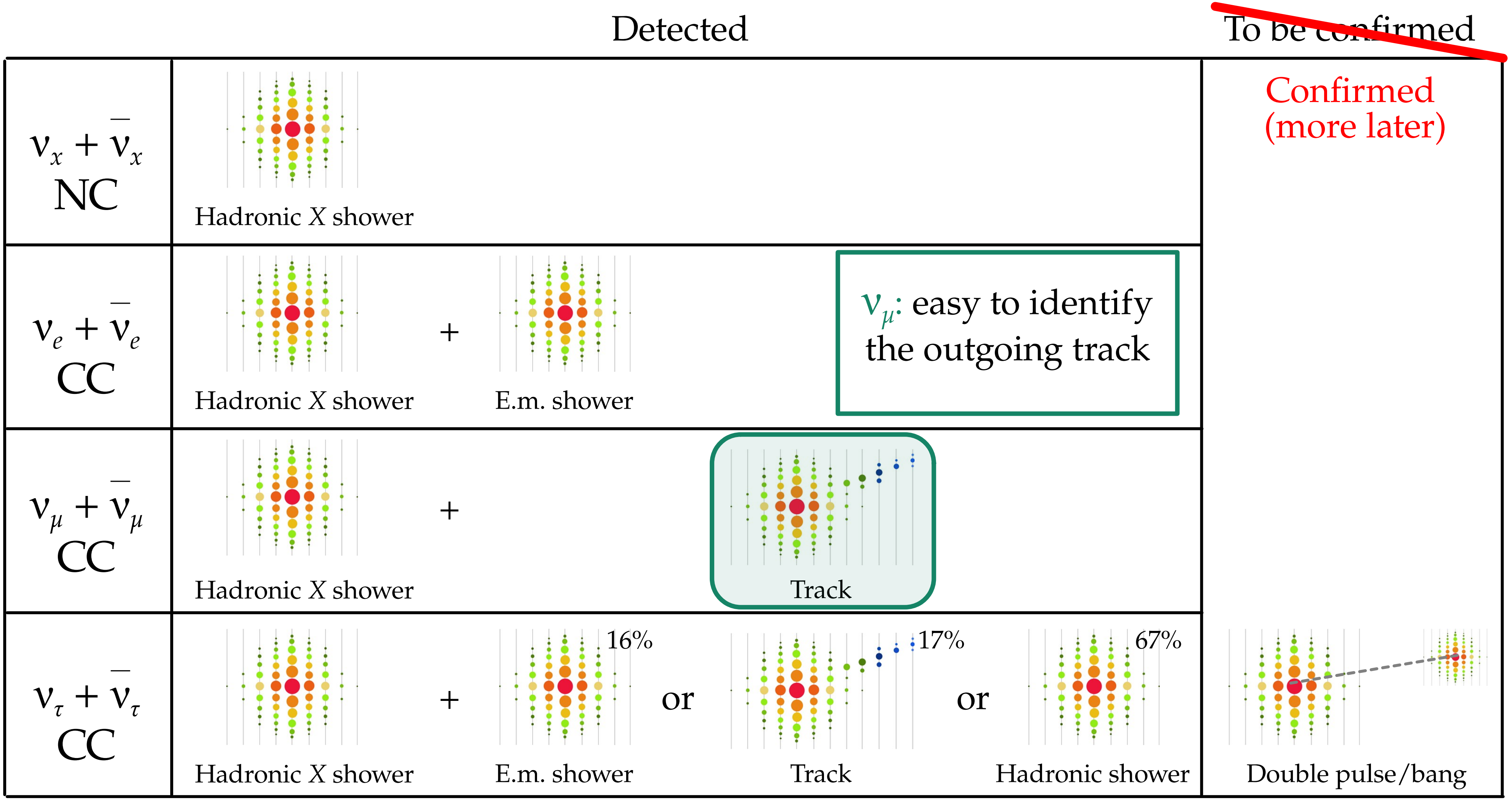
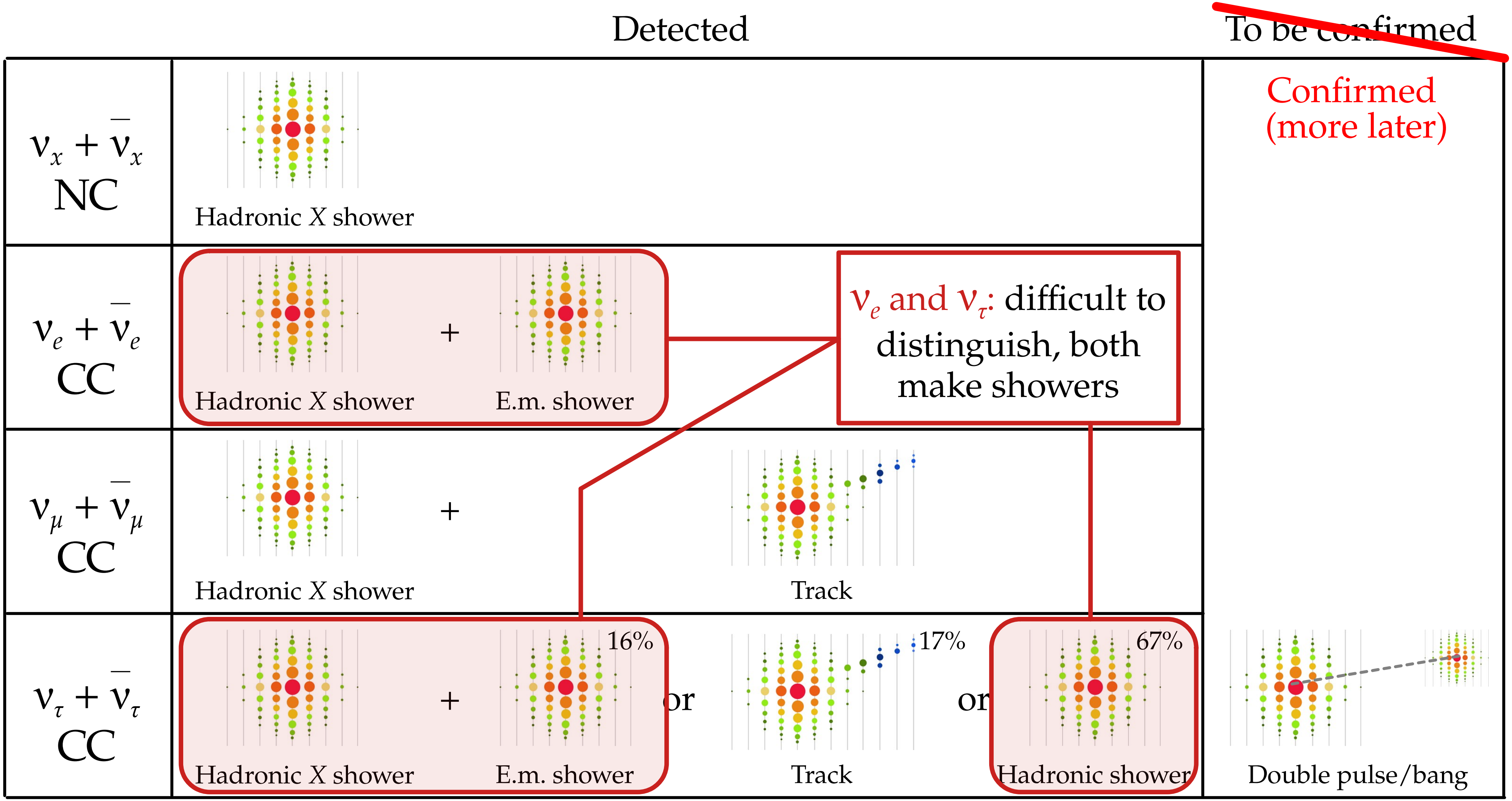
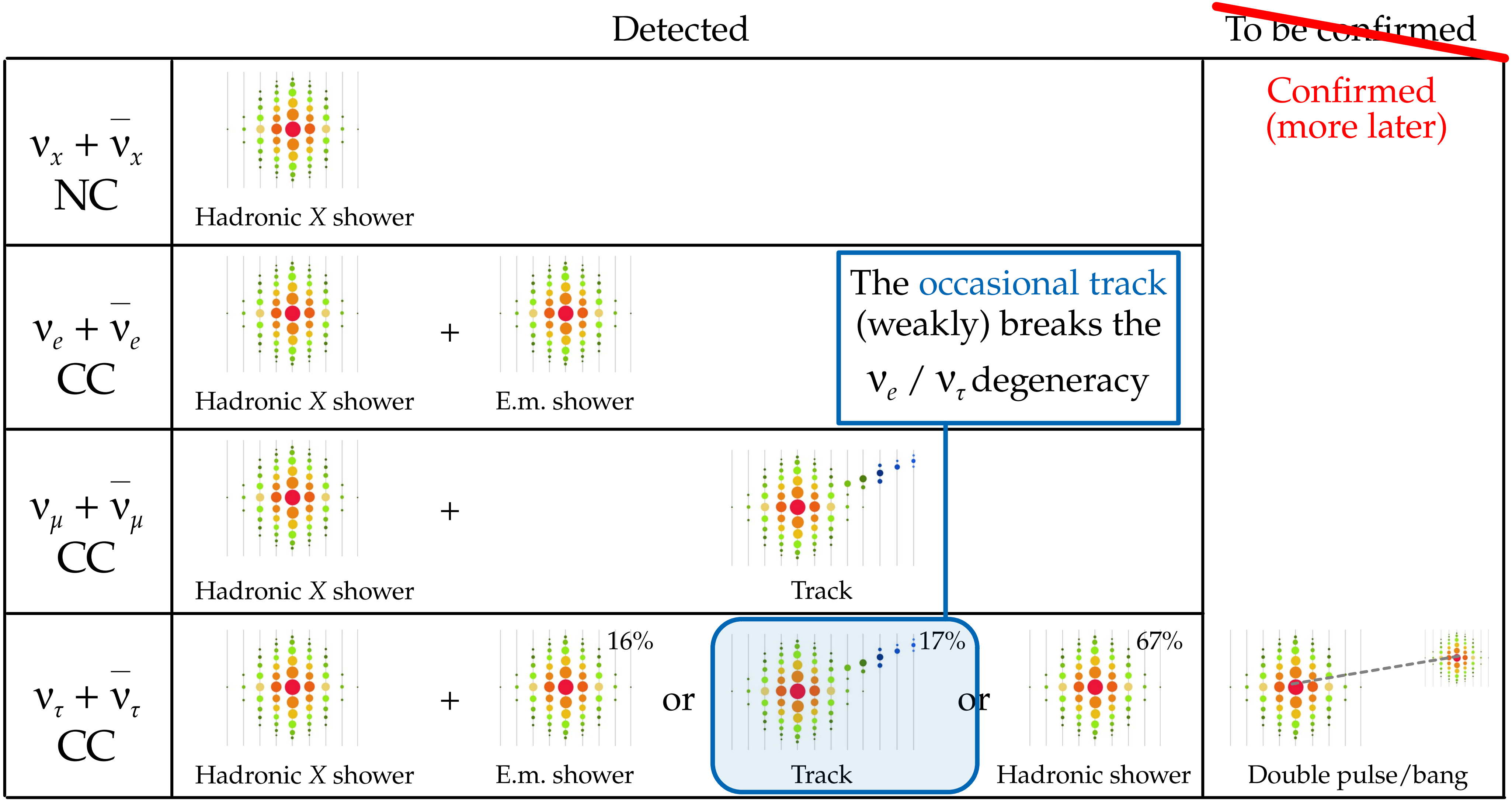


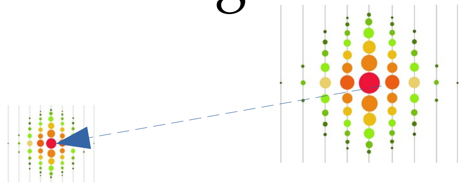
Detected
To be confirmed
Confirmed
(more later)
$\nu_x + \bar{\nu}_x$ NC
Hadronic X shower
$\nu_e + \bar{\nu}_e$ CC
Hadronic X shower
+
E.m. shower
ν_μ: easy to identify the outgoing track
$\nu_\mu + \bar{\nu}_\mu$ CC
Hadronic X shower
+
Track
$\nu_\tau + \bar{\nu}_\tau$ CC
Hadronic X shower
+
16%
E.m.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


Detected
To be confirmed
Confirmed
(more later)
$\nu_x + \bar{\nu}_x$ 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
(more later)
$\nu_x + \bar{\nu}_x$ 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

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

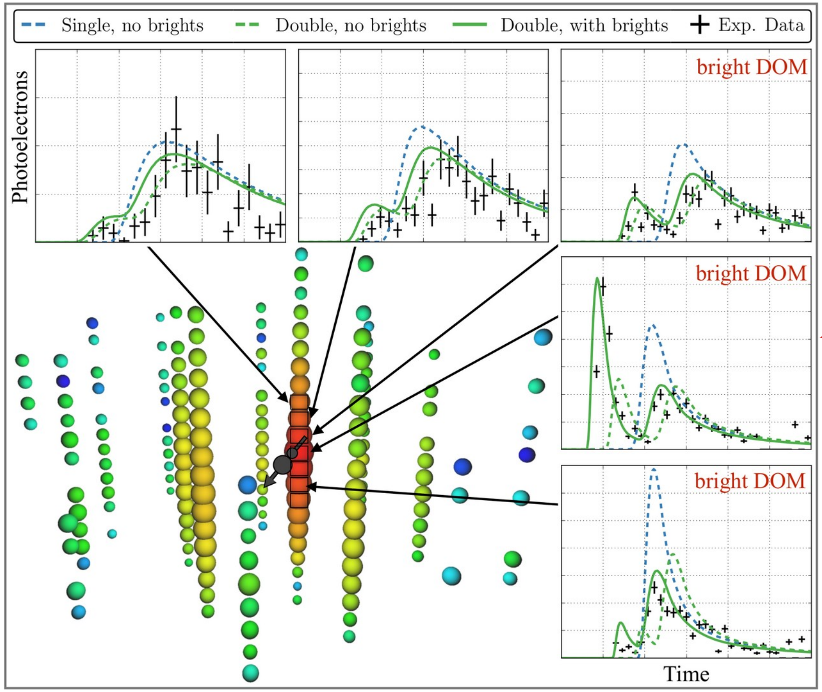
Double bang:

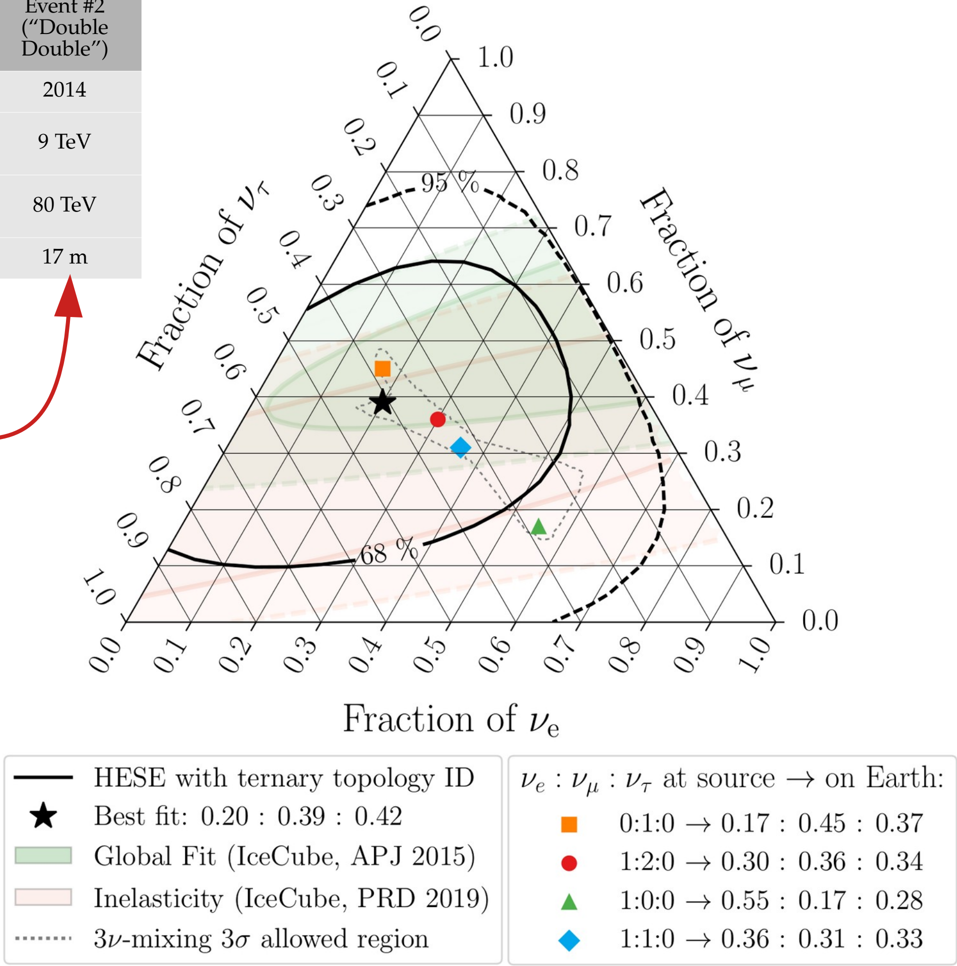


τ decay $\nu_\tau N$ scattering

	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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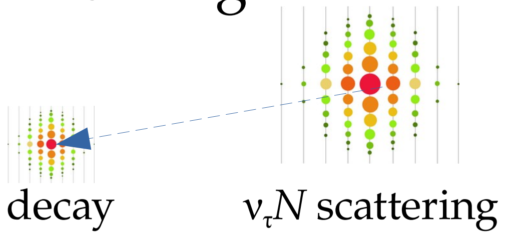

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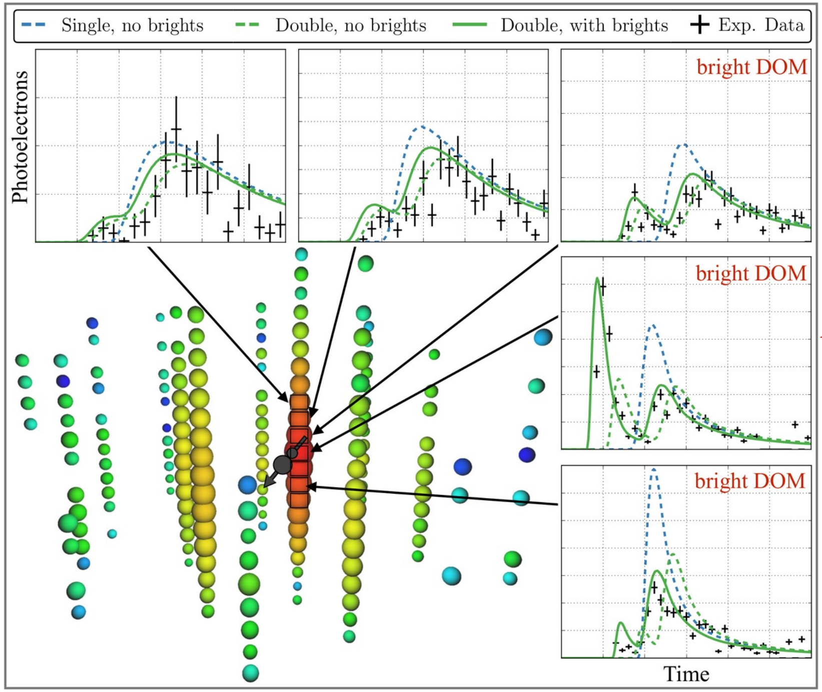

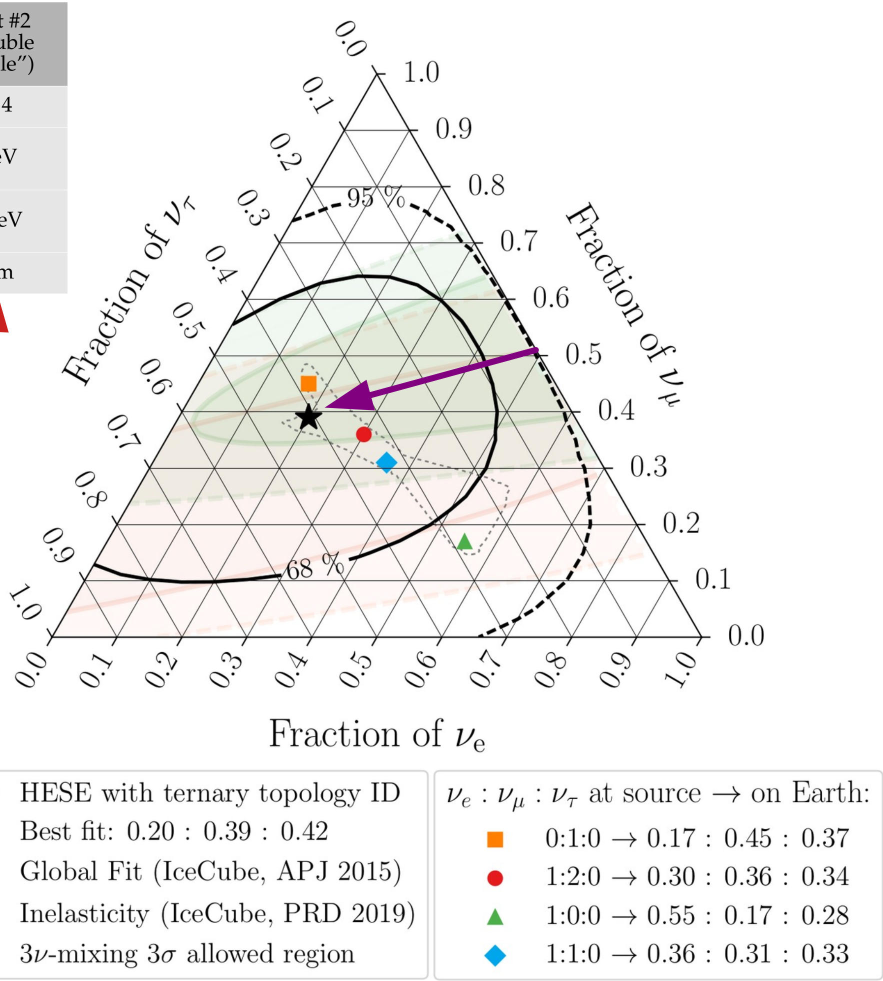

IceCube, 2011.03561

Measuring flavor composition: 2015–2040

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX
IceCube, *PRL* 2015, *ApJ* 2015, *PRD* 2019, 2008.04323, 2011.03561

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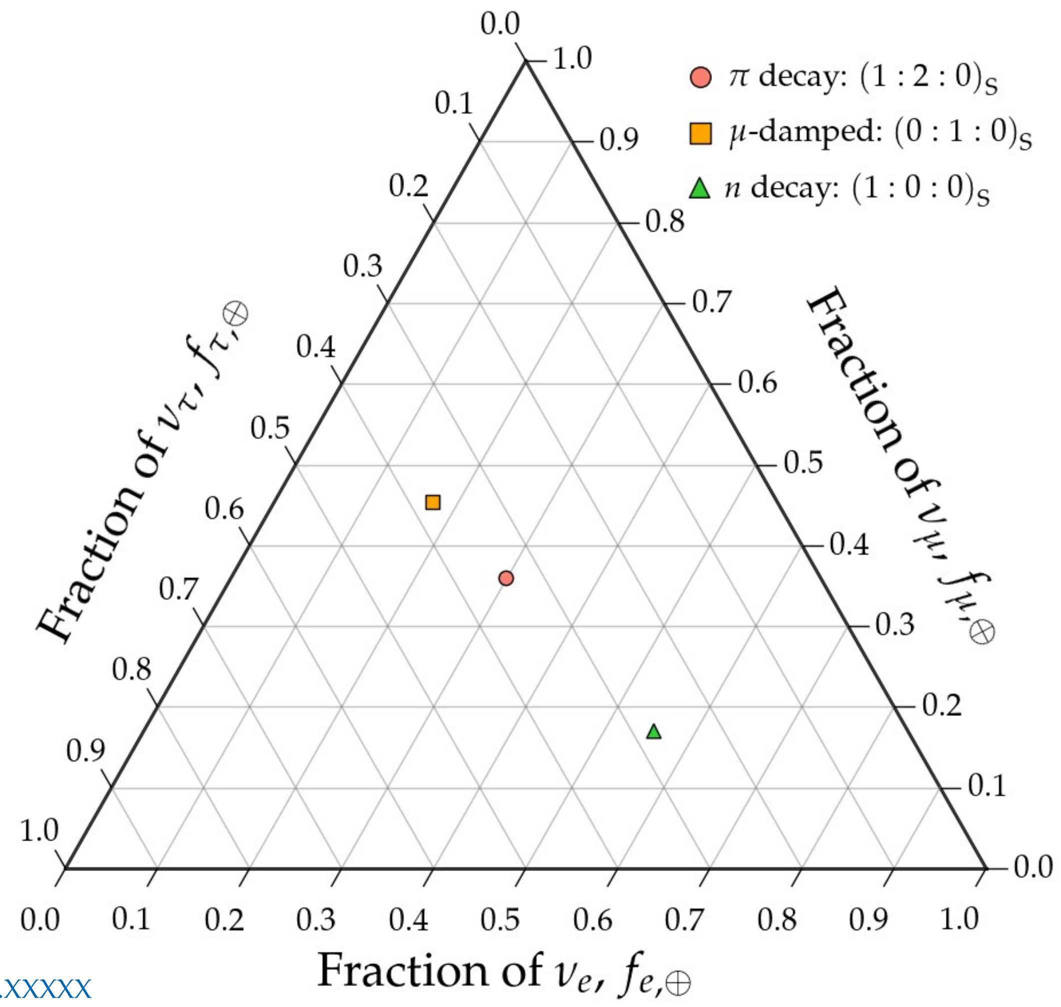

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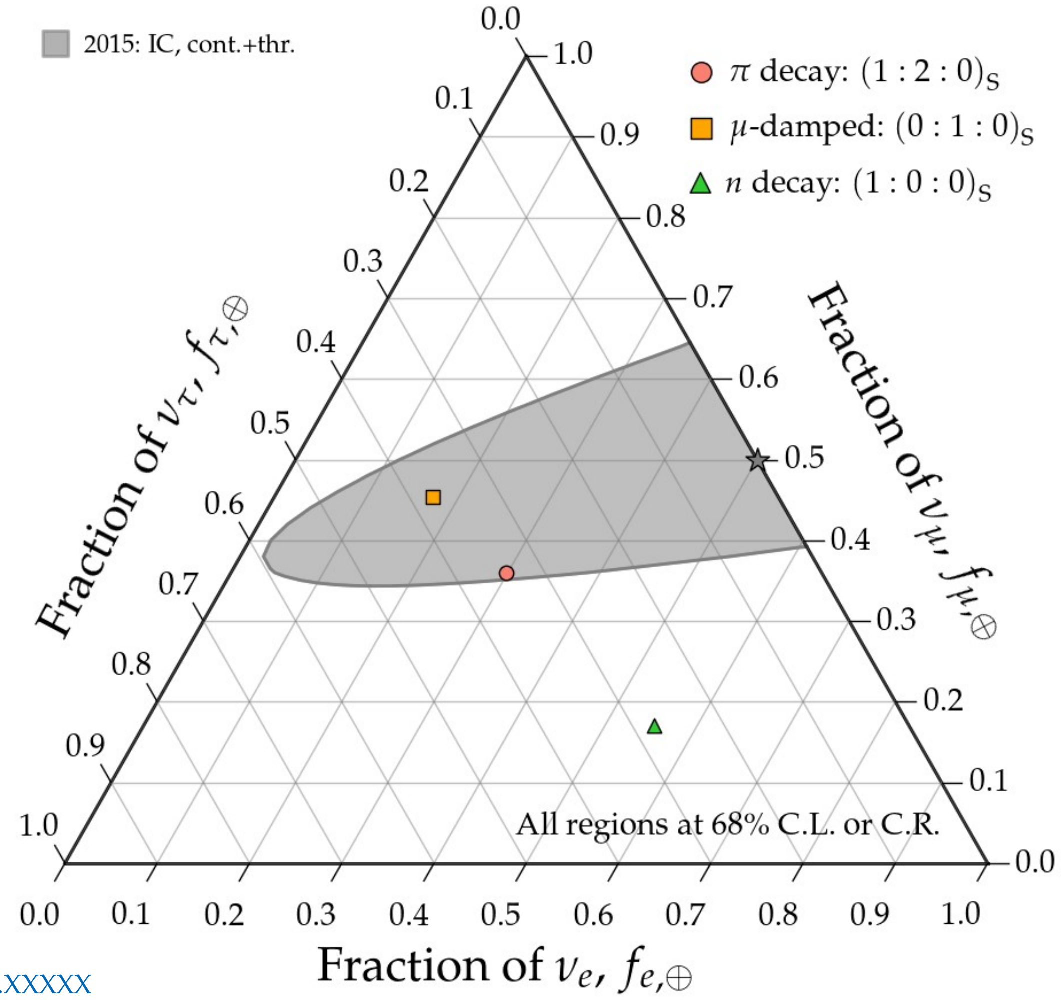

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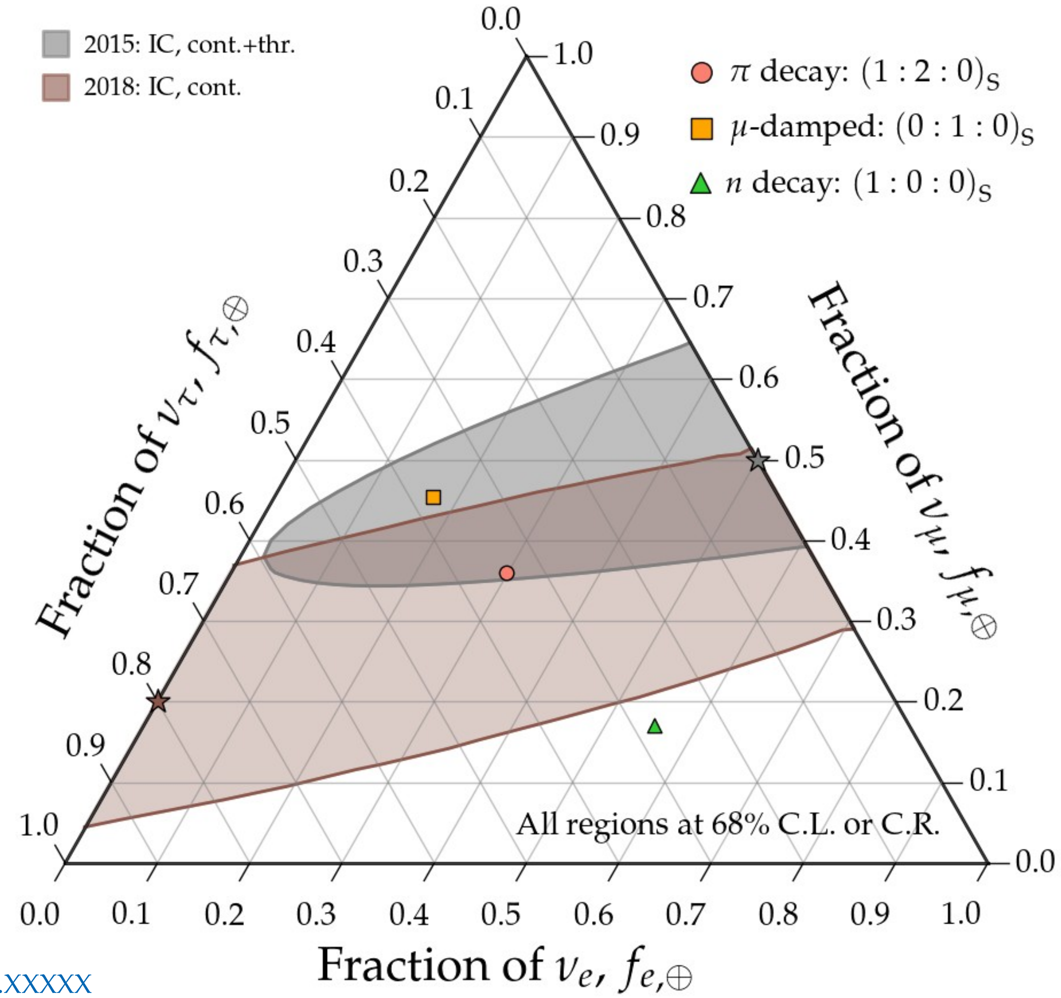

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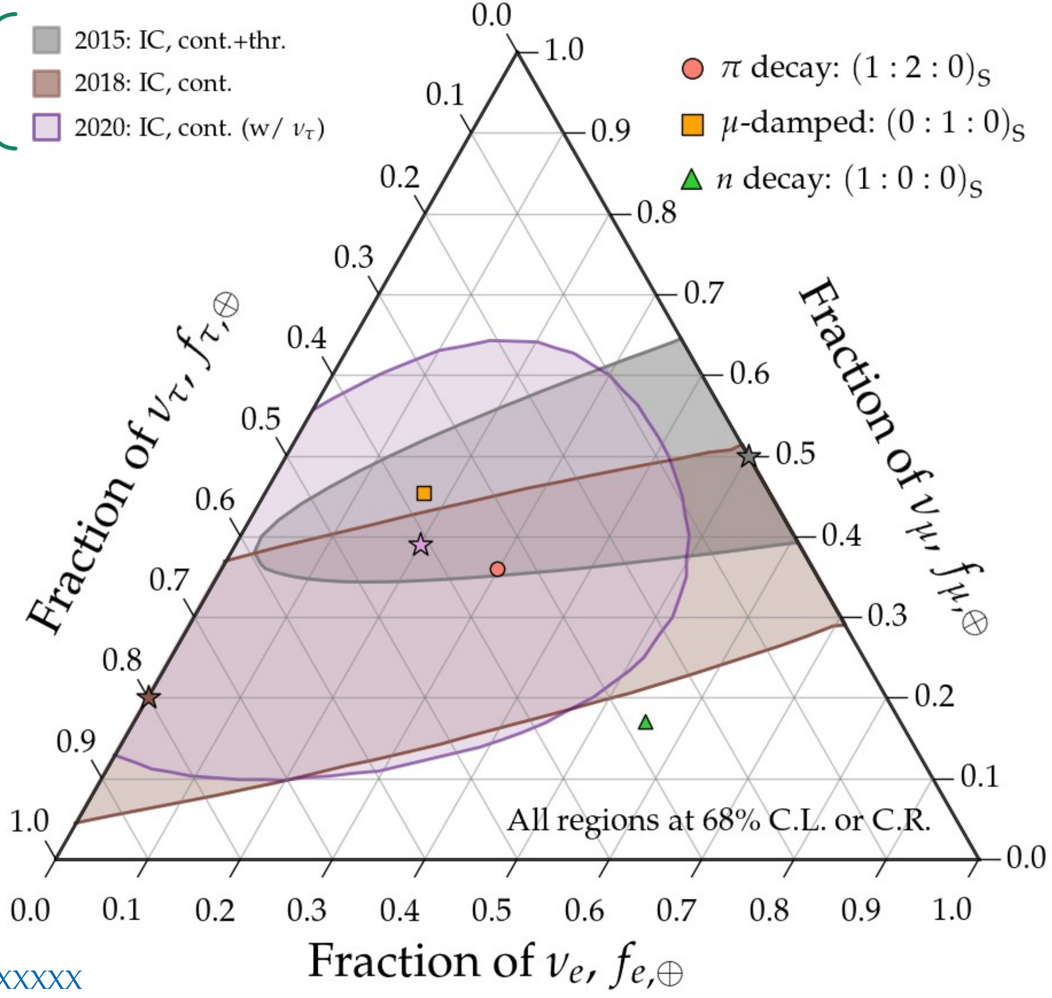
Measuring flavor composition: 2015–2040

Based on real data



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

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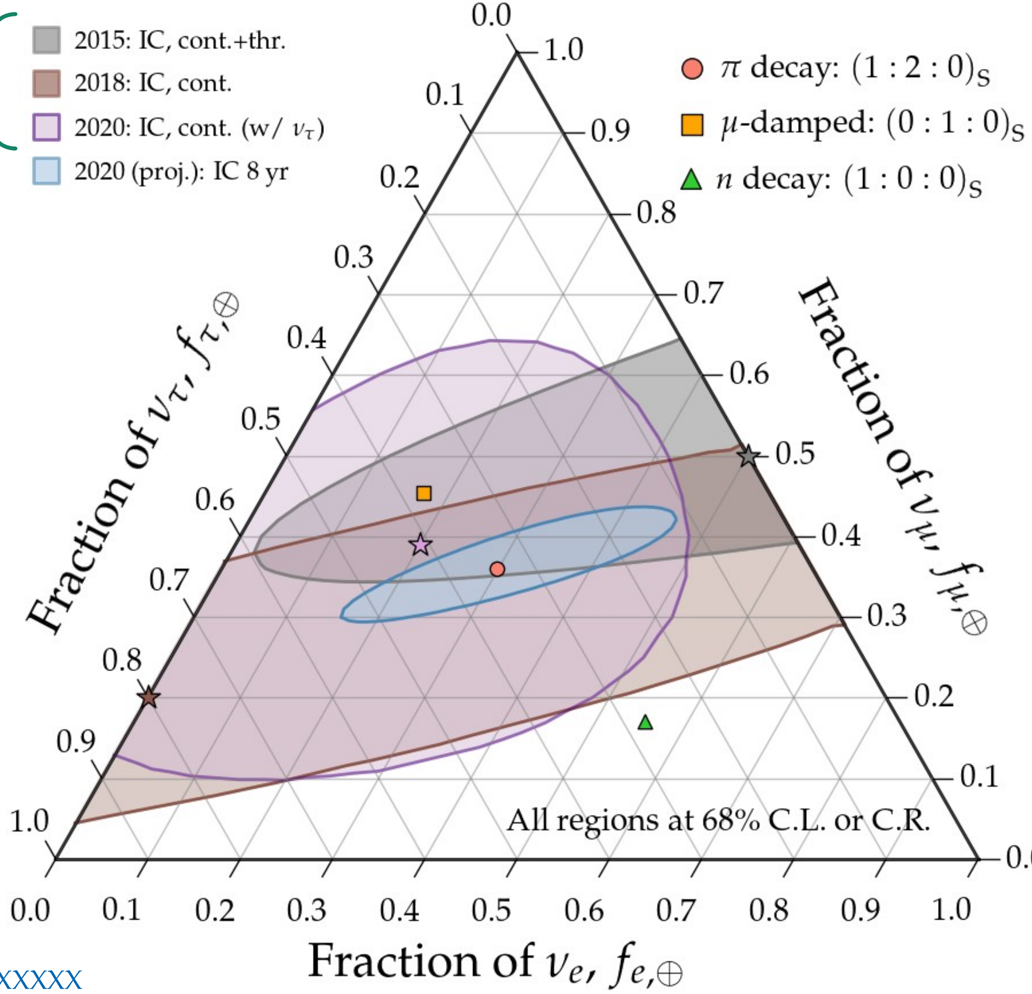

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Near future (~2020):
× 5 reduction using 8 yr of IC contained + thru.

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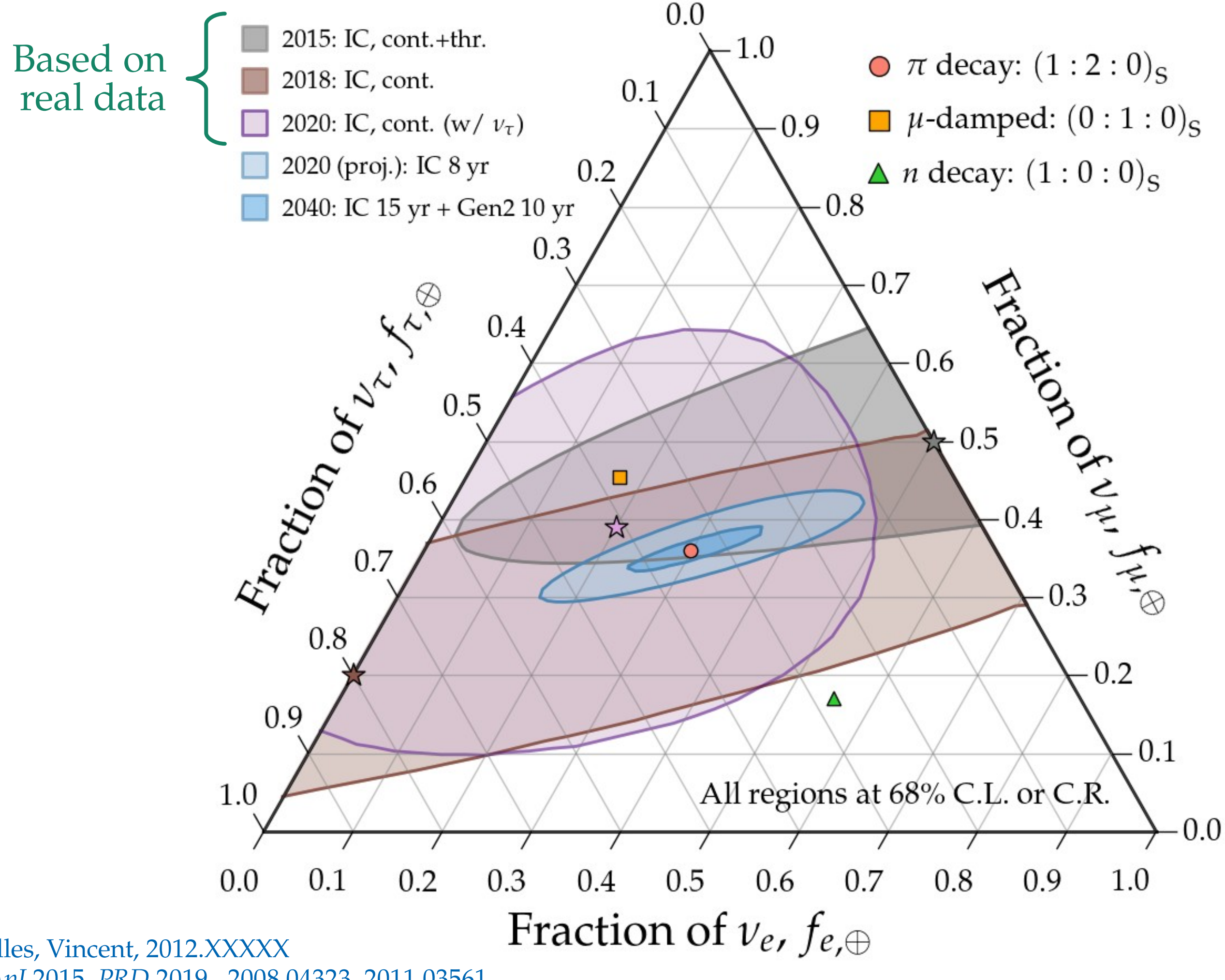

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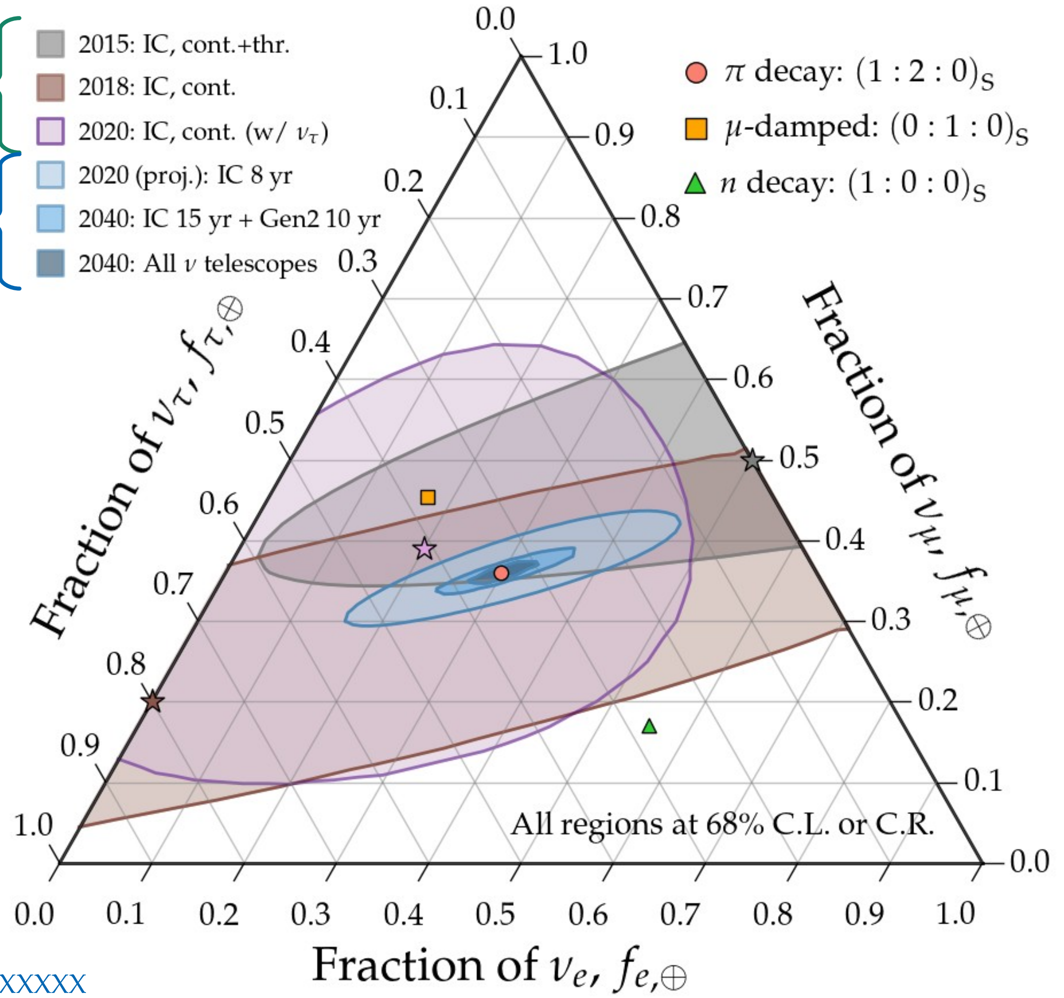

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Coming up (~2040):
× 10 reduction using Gen2 and all ν telescopes

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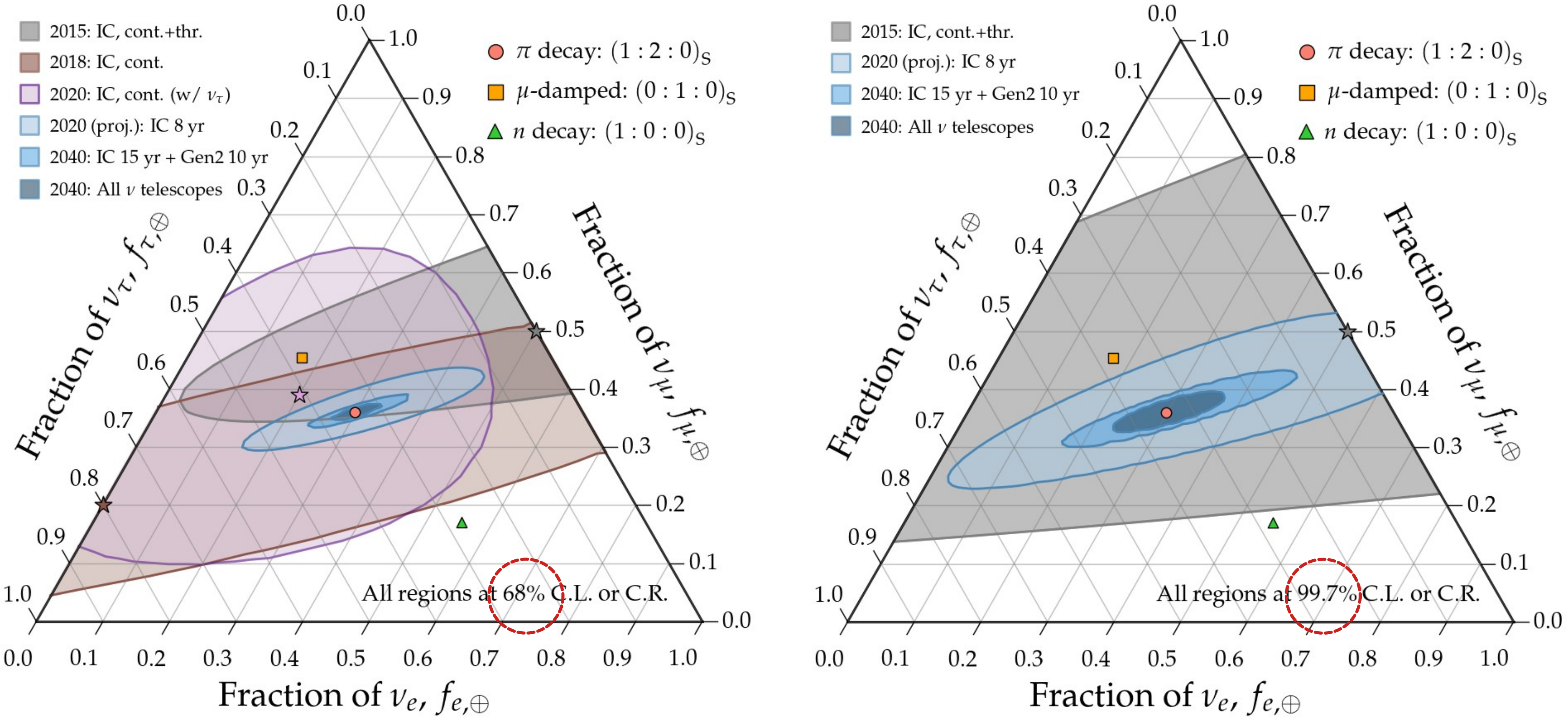
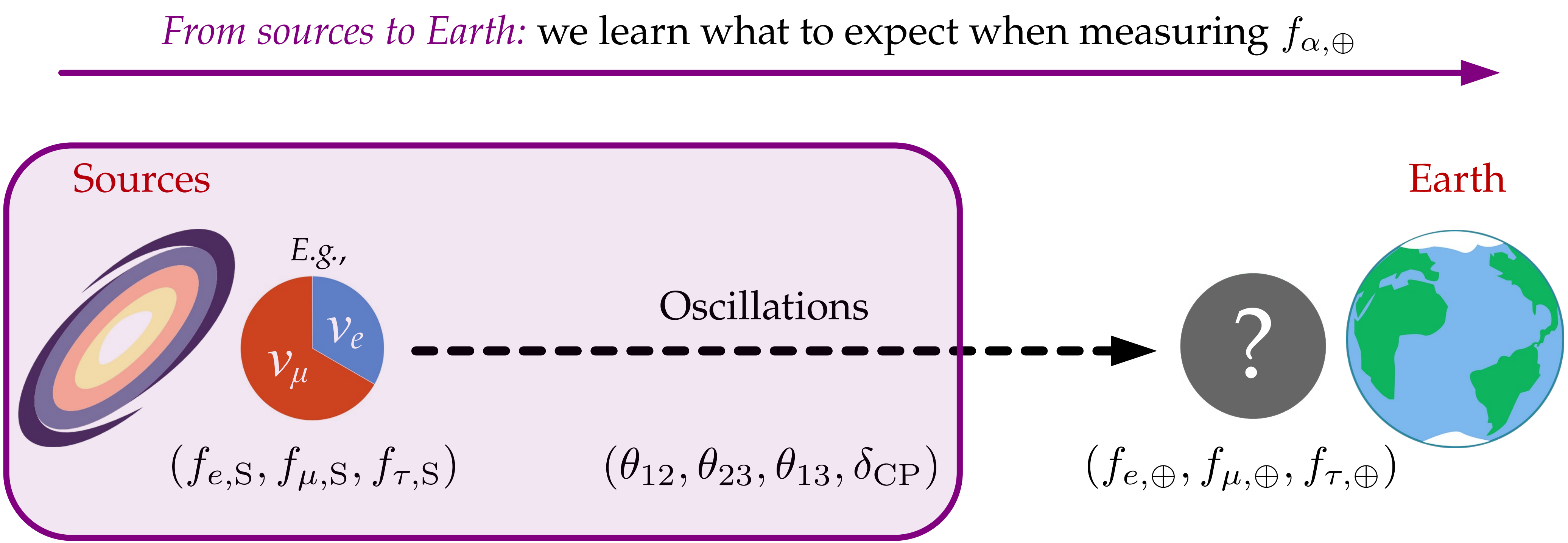


Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX
IceCube, *PRL* 2015, *ApJ* 2015, *PRD* 2019, 2008.04323, 2011.03561



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

Flavor at the Earth: *theoretically palatable regions*

Theoretically palatable flavor regions

≡

MB, Beacom, Winter, *PRL* 2015

Allowed regions of flavor ratios at Earth derived from oscillations

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

Flavor at the Earth: *theoretically palatable regions*

Theoretically palatable flavor regions

≡

MB, Beacom, Winter, *PRL* 2015

Allowed regions of flavor ratios at Earth derived from oscillations

Ingredient #1:

Flavor ratios at the source,

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

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

or

Explore all possible combinations

Note:
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Flavor at the Earth: *theoretically palatable regions*

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

Note:
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Flavor at the Earth: *theoretically palatable regions*

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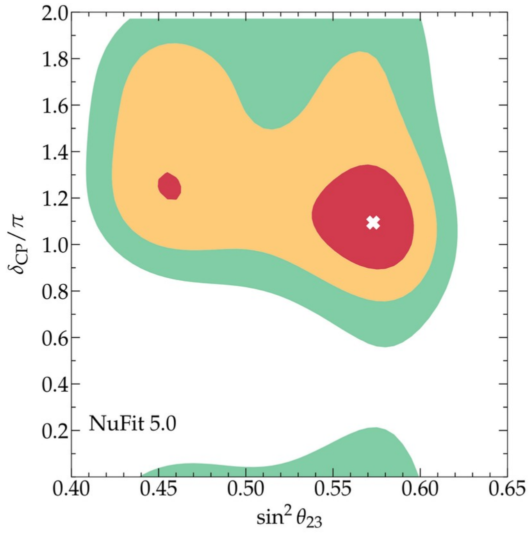
2020: Use χ^2 profiles from the NuFit 5.0 global fit (solar + atmospheric + reactor + accelerator)

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



Note:
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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

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Explore all possible combinations

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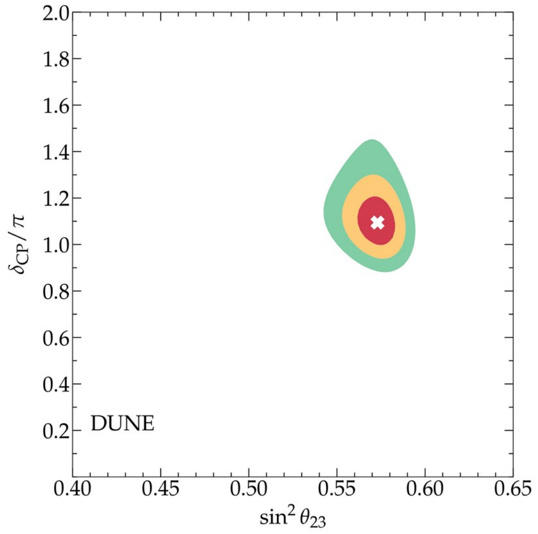
Probability density of mixing parameters $(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{CP})$

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

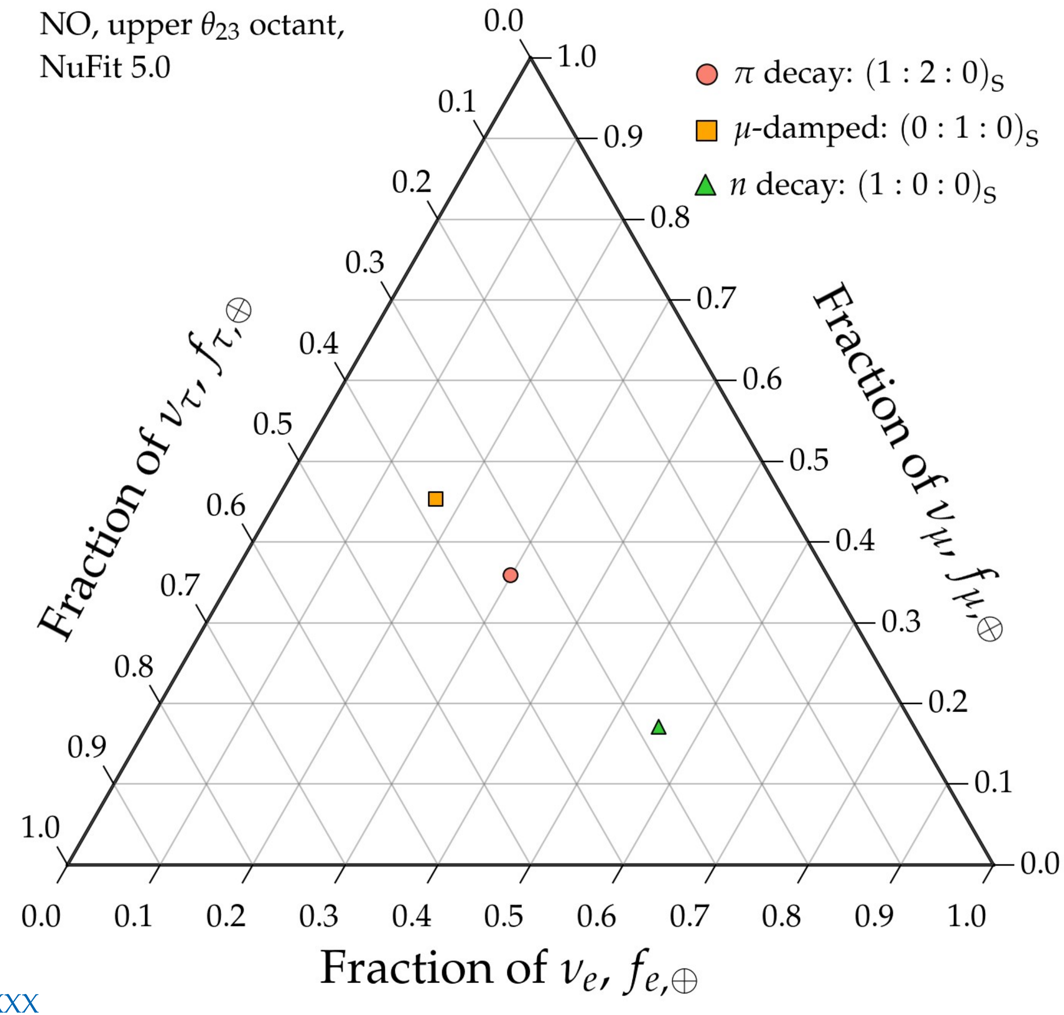
Esteban *et al.*, *JHEP* 2020
www.nu-fit.org

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

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



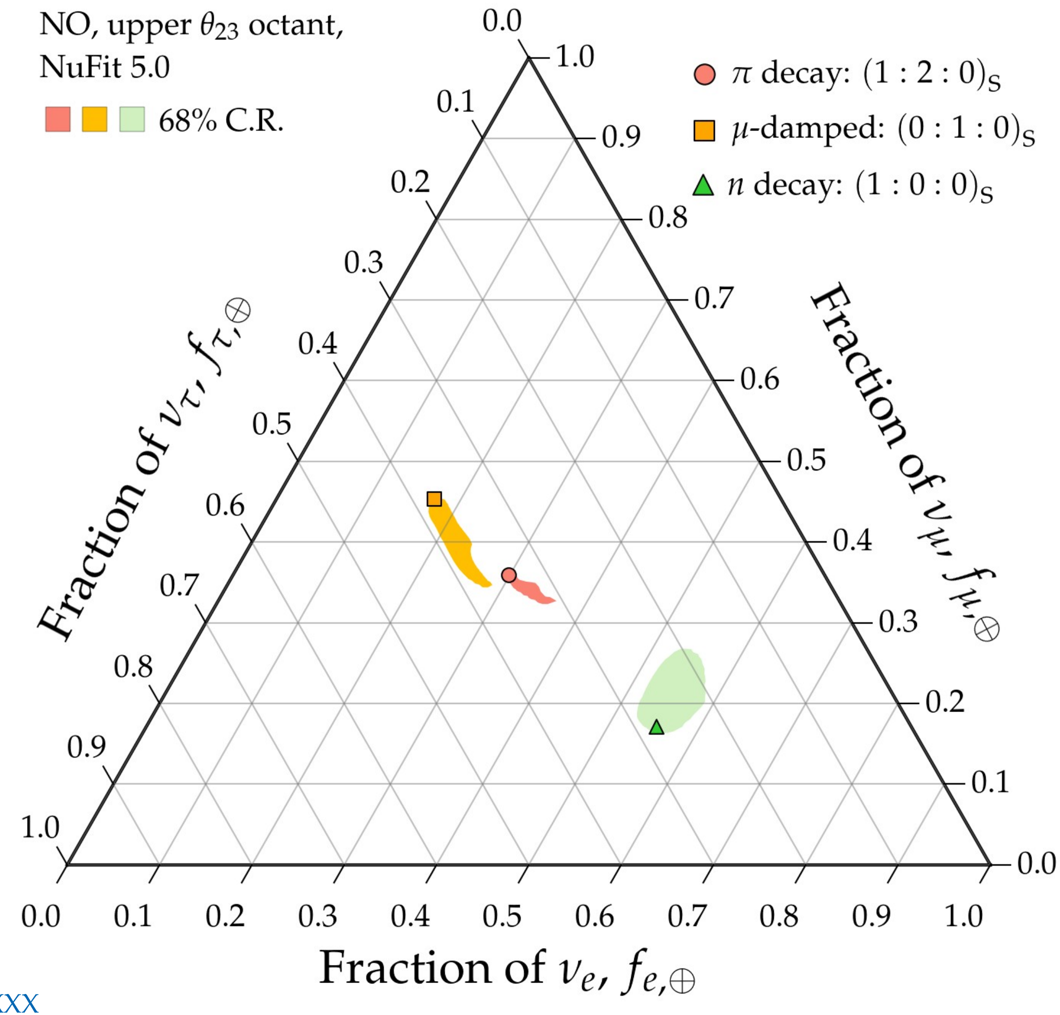
Theoretically palatable regions: today (2020)



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

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

Theoretically palatable regions: today (2020)



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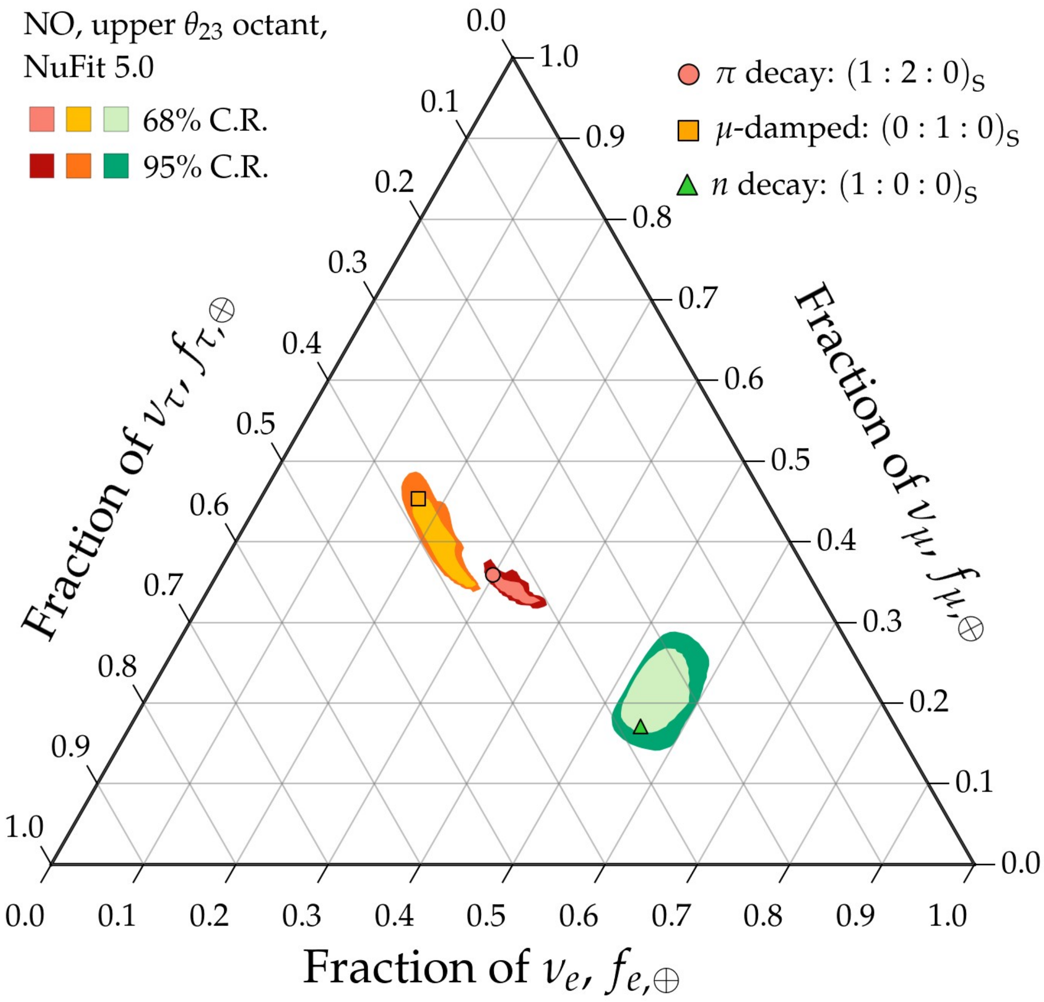

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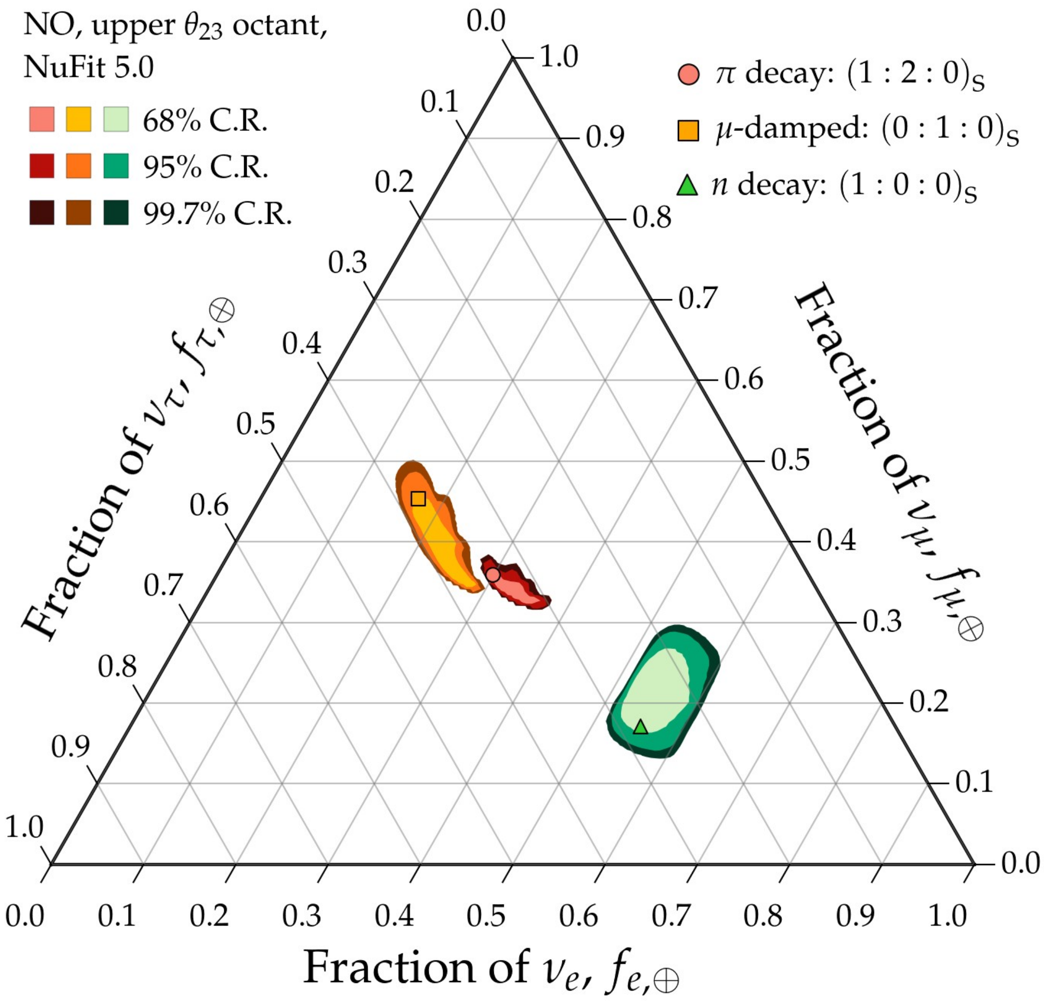

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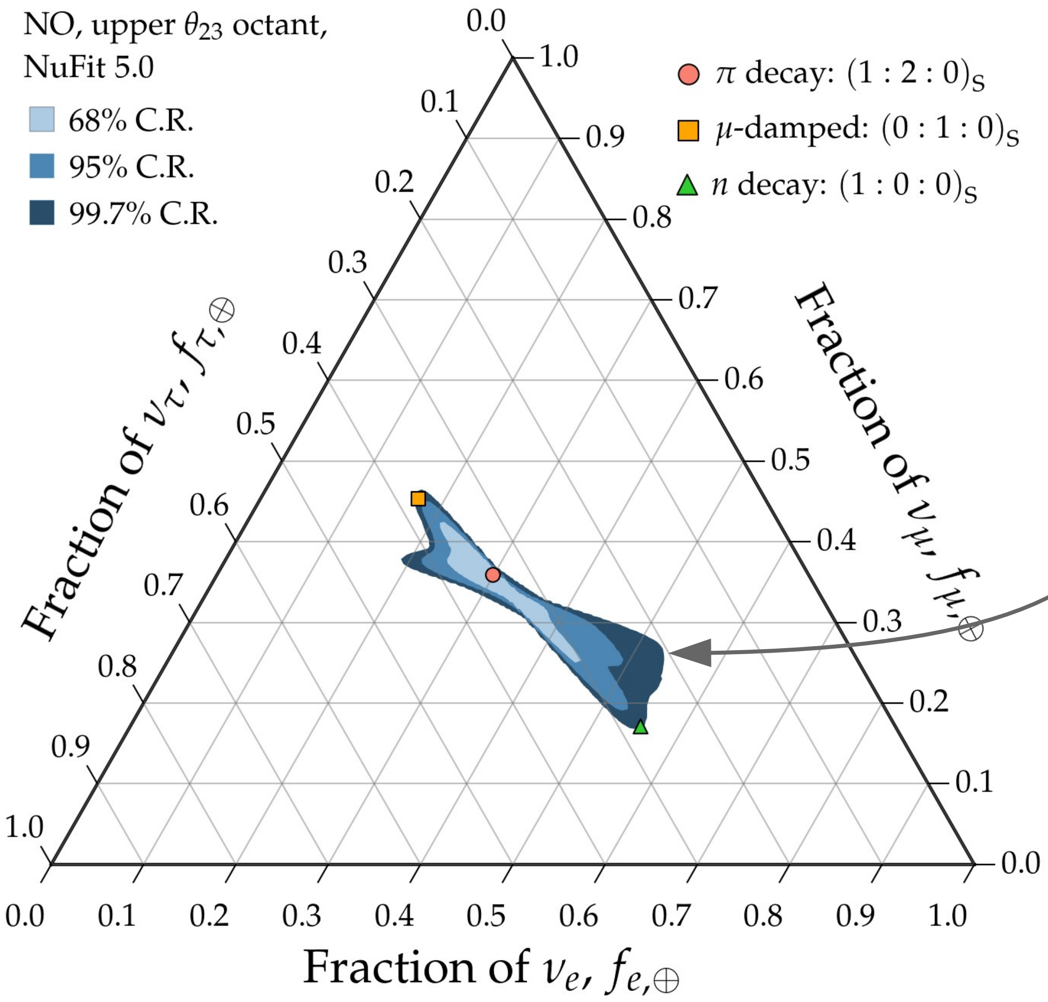
Theoretically palatable regions: today (2020)

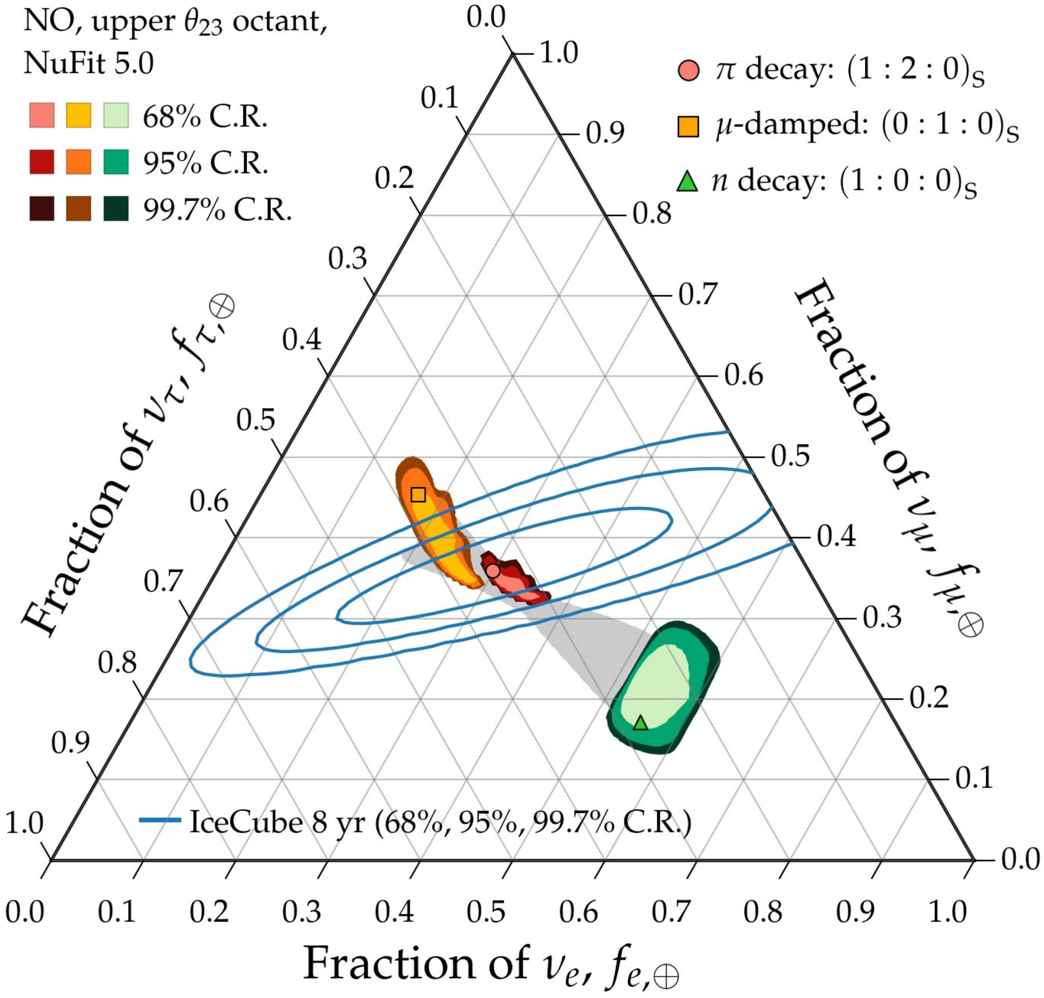


Varying over all possible flavor ratios at the source

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

Song, Li, **MB**, Argüelles, Vincent, 2012.X

Theoretically palatable regions: today (2020)



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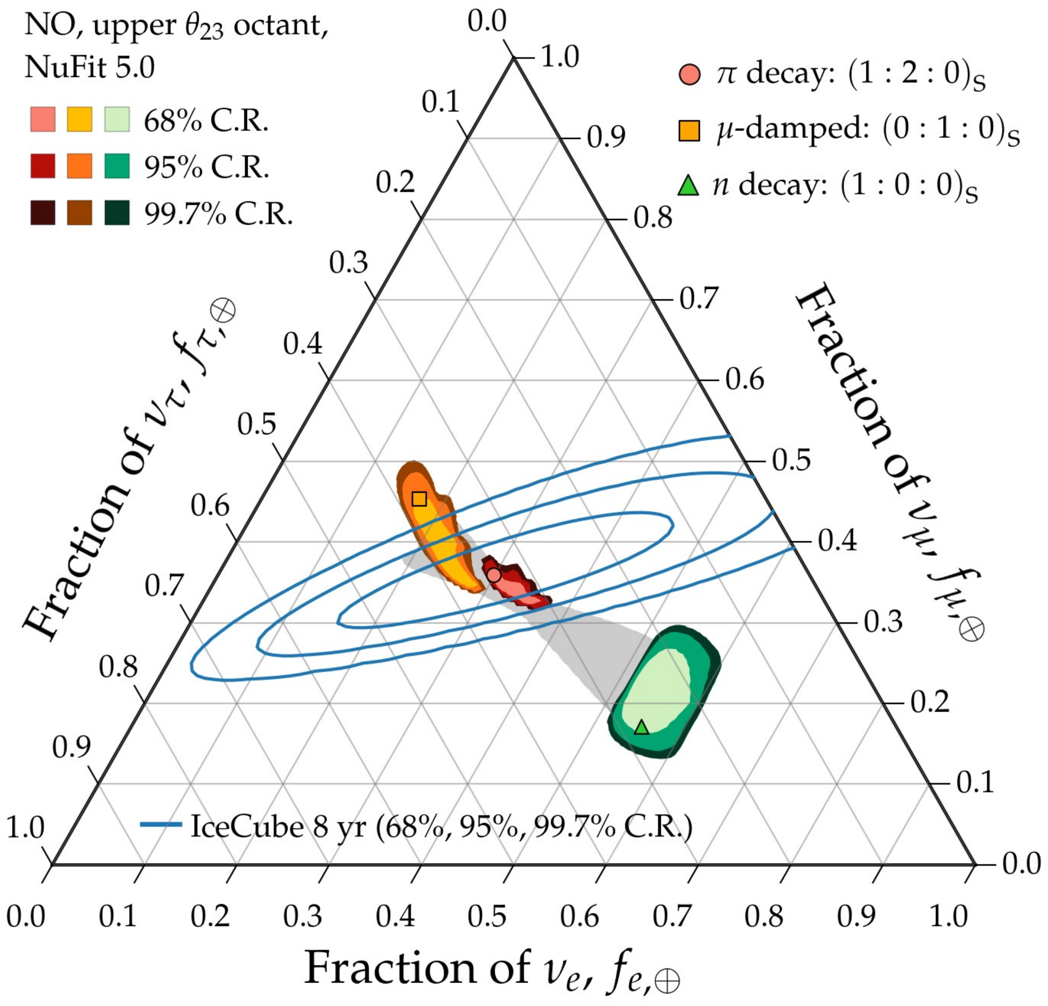
Song, Li, **MB**, Argüelles, Vincent, 2012.X

Theoretically palatable regions: today (2020)



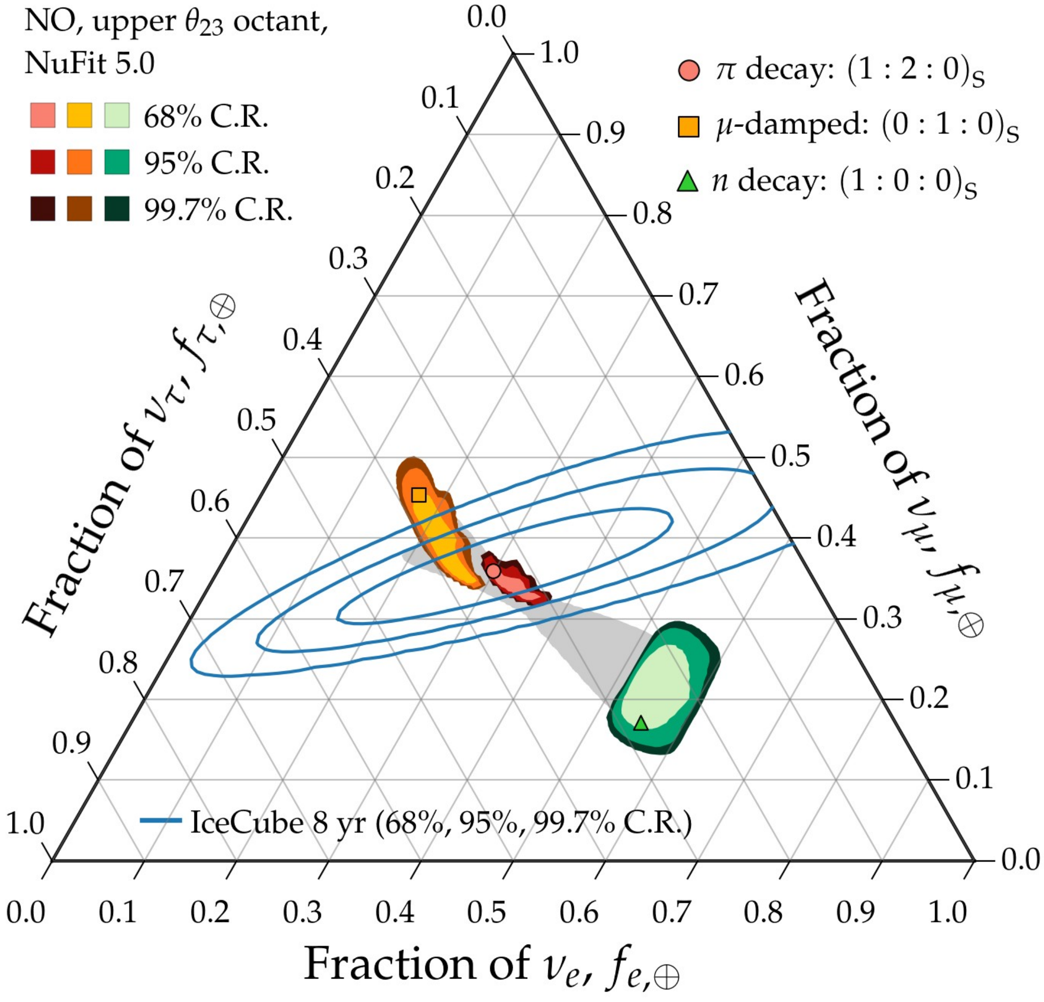
Two limitations:

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, **MB**, Argüelles, Vincent, 2012.XXXXX

Theoretically palatable regions: today (2020)



Two limitations:

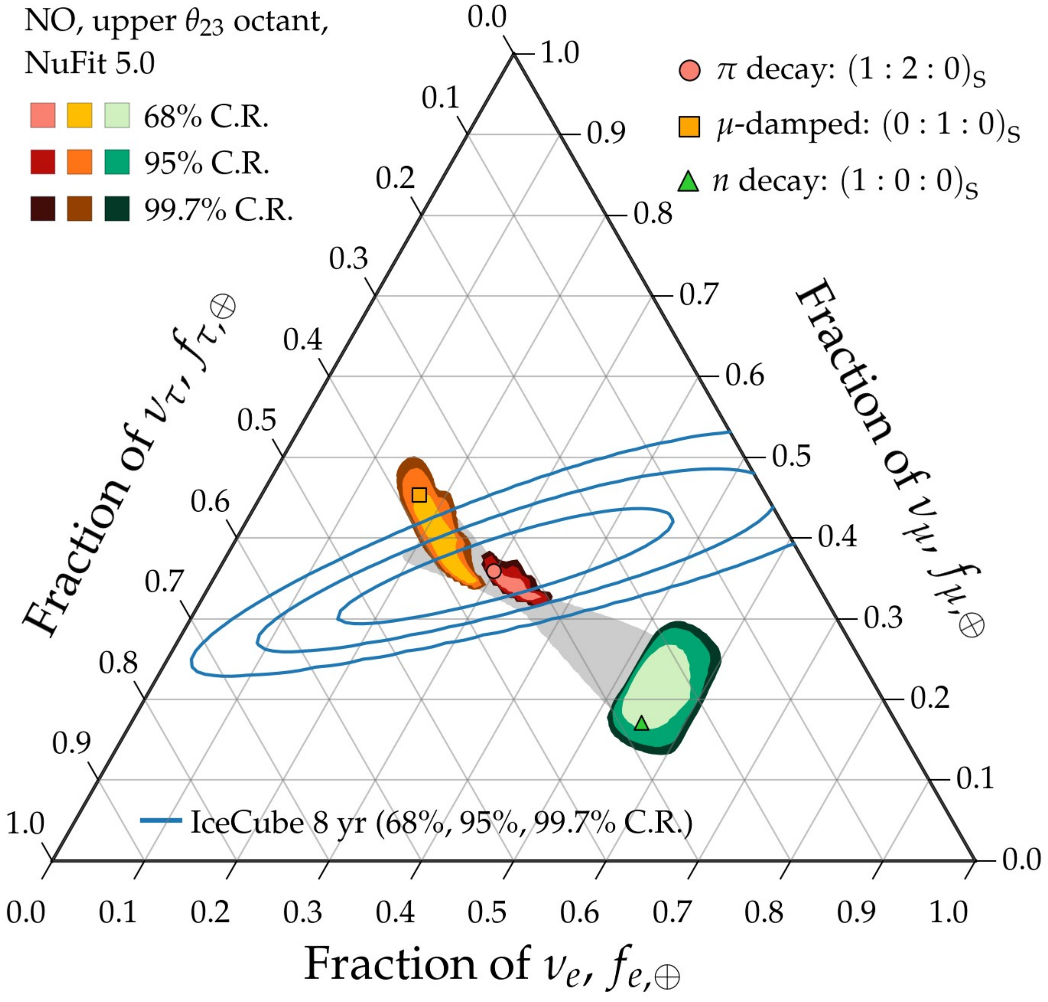
Allowed flavor regions overlap –
Insufficient precision in the mixing parameters

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, **MB**, Argüelles, Vincent, 2012.XXXXX

Theoretically palatable regions: today (2020)



Two limitations:

Allowed flavor regions overlap –
Insufficient precision in the mixing parameters

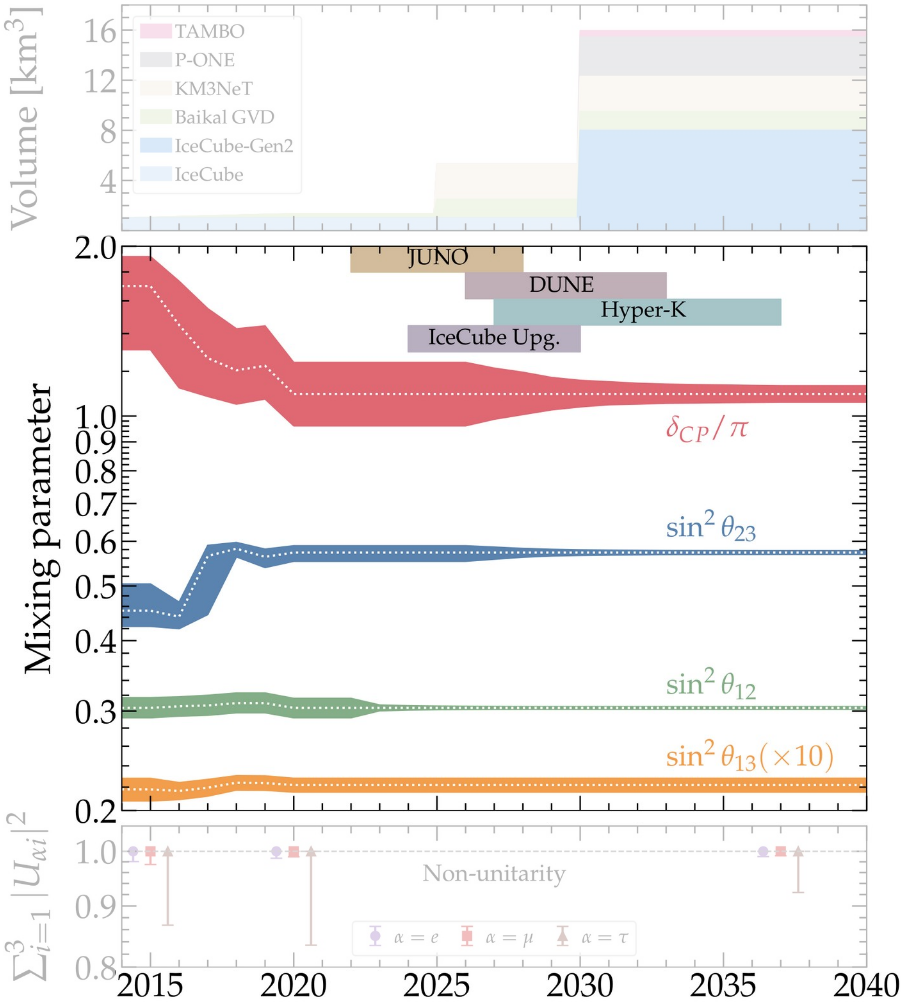
Will be overcome by 2030

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, **MB**, Argüelles, Vincent, 2012.XXXXX

How knowing the mixing parameters better helps

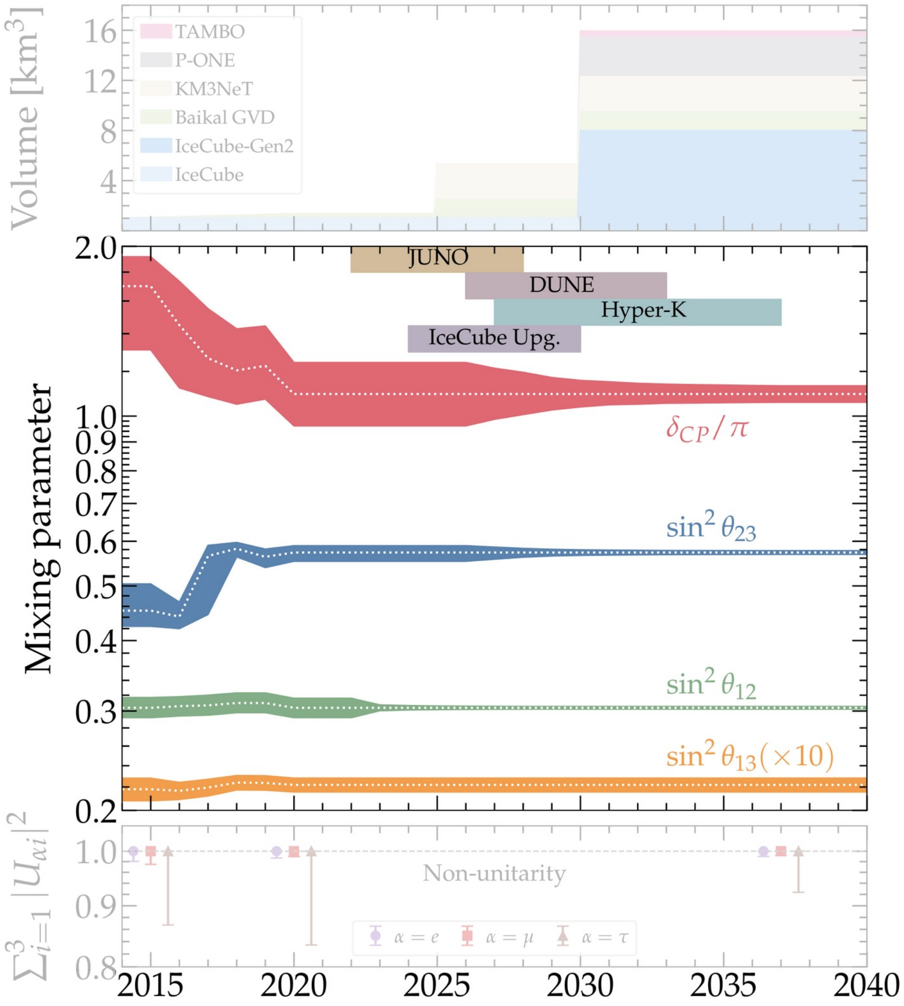


We can compute the oscillation probability more precisely:

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

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

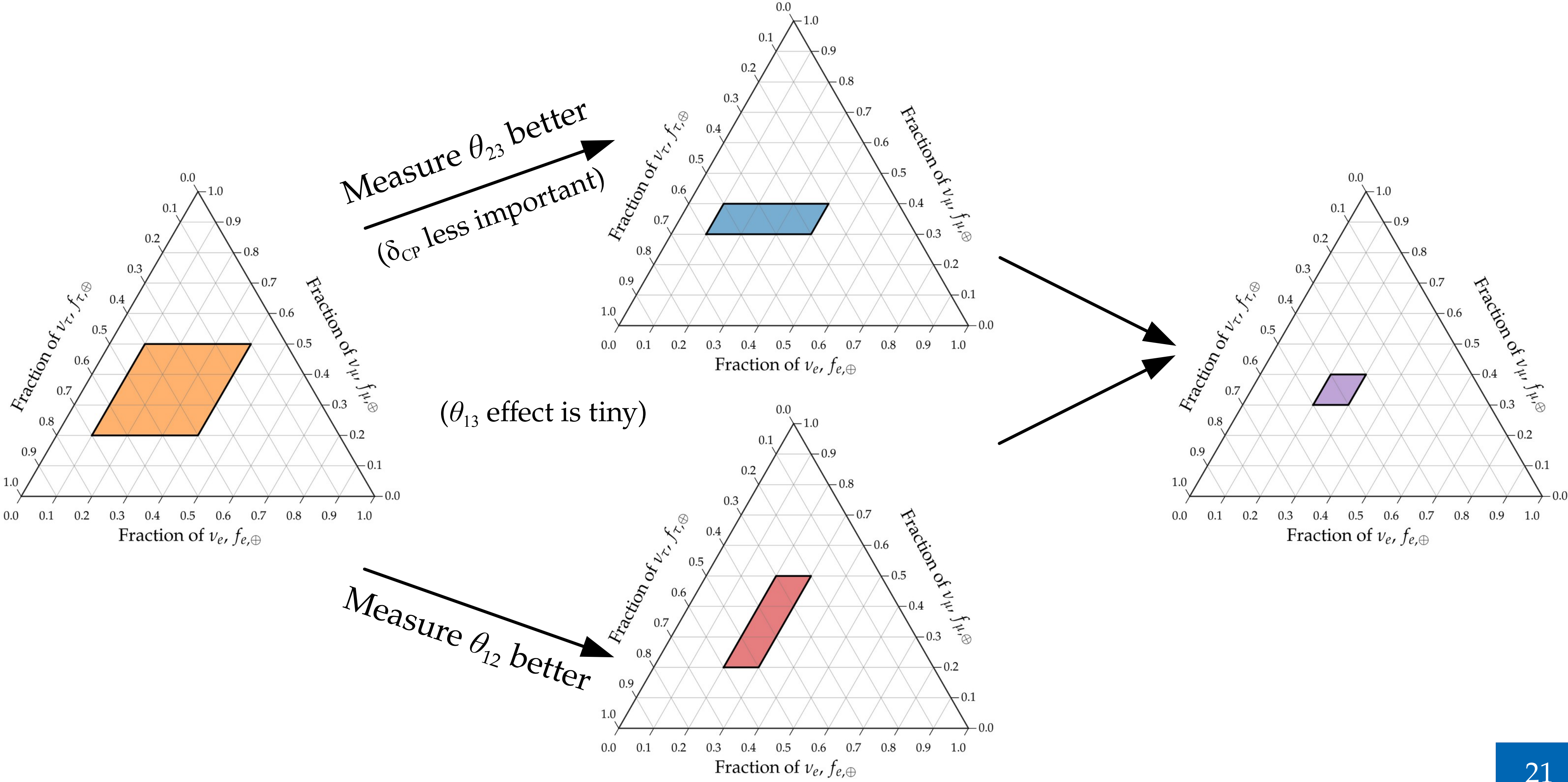
$$\chi^2_\varepsilon(\boldsymbol{\vartheta}) = \sum_i \frac{(\vartheta_i - \bar{\vartheta}_i)^2}{\sigma^2_{i,\varepsilon}}$$

From our simulations

We combine experiments in a likelihood:

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

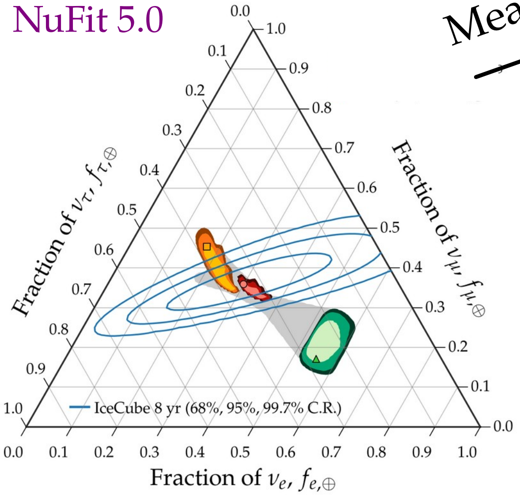
How knowing the mixing parameters better helps



How knowing the mixing parameters better helps

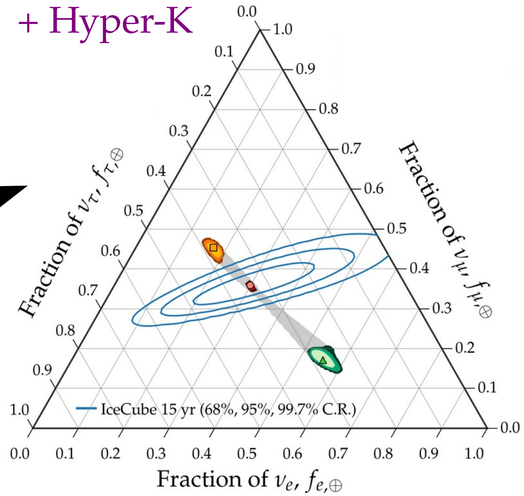
2020

NuFit 5.0



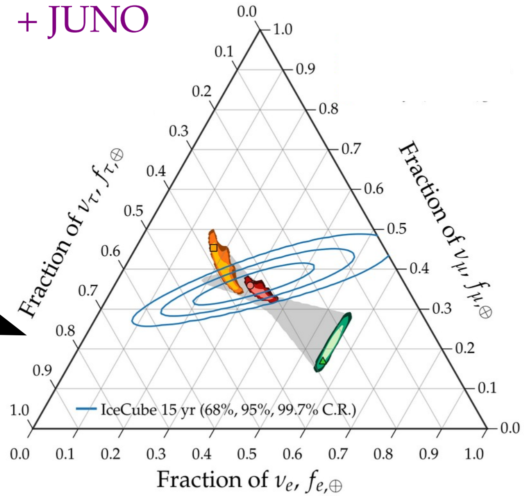
Measure θ_{23} better

+ Hyper-K



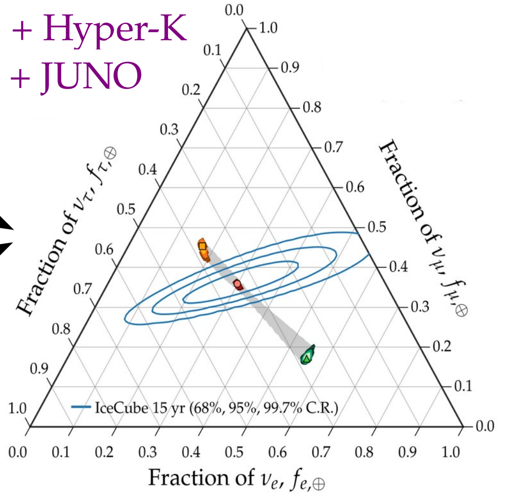
Measure θ_{12} better

+ JUNO



~2030

+ Hyper-K
+ JUNO



In our results:
JUNO + Hyper-K + DUNE

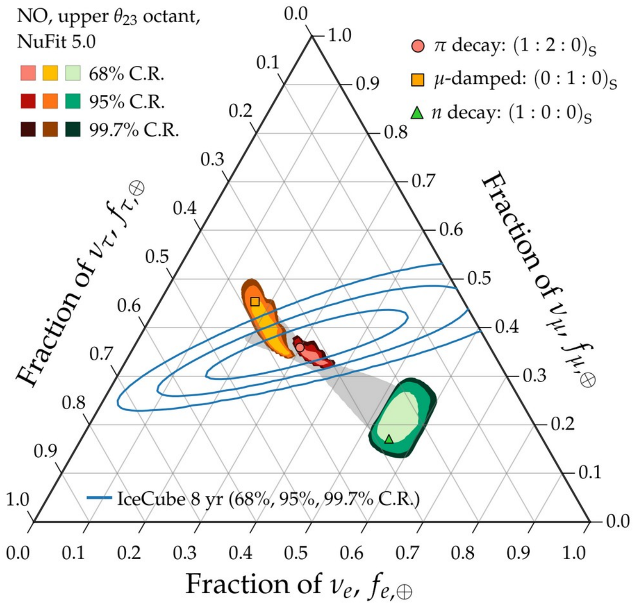
Marginal improvement til 2040

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

Theoretically palatable regions: 2020 $\rightarrow$ 2030 $\rightarrow$ 2040

Theoretically palatable regions: 2020 → 2030 → 2040

2020



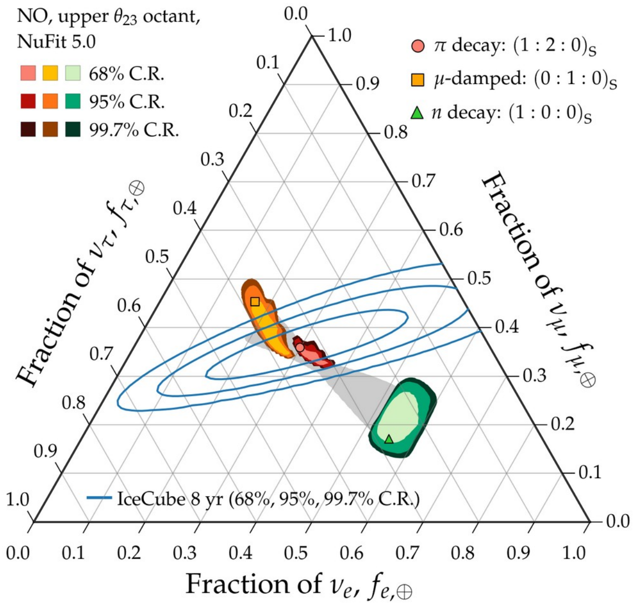
Allowed regions: overlapping

Measurement: imprecise

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

Theoretically palatable regions: 2020 → 2030 → 2040

2020



Allowed regions: overlapping

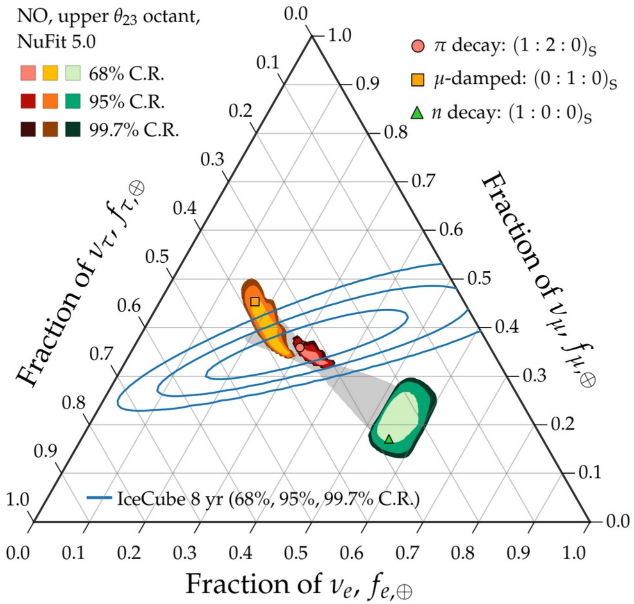
Measurement: imprecise

Not ideal

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

Theoretically palatable regions: 2020 → 2030 → 2040

2020

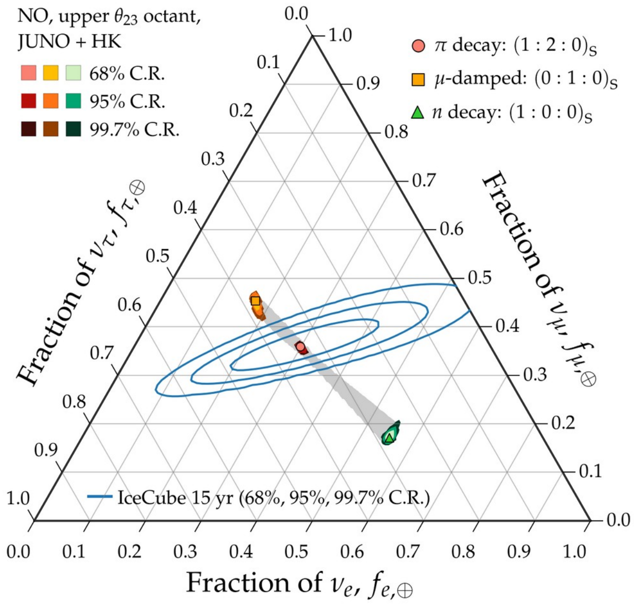


Allowed regions: overlapping

Measurement: imprecise

Not ideal

2030



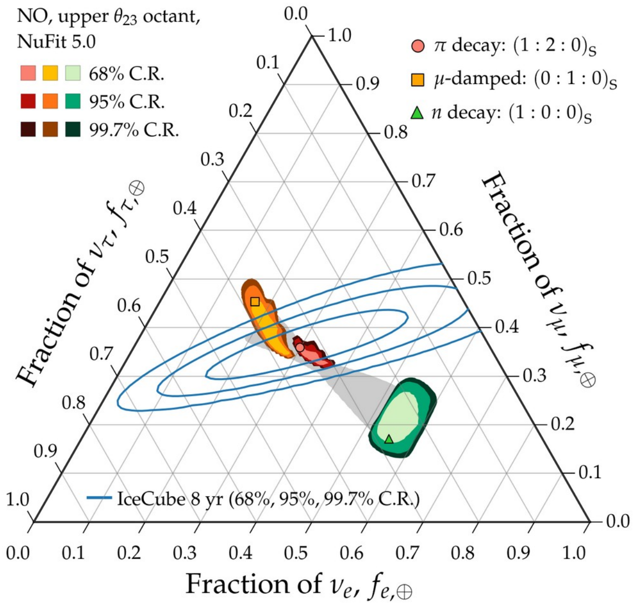
Allowed regions: well separated

Measurement: improving

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

Theoretically palatable regions: 2020 → 2030 → 2040

2020

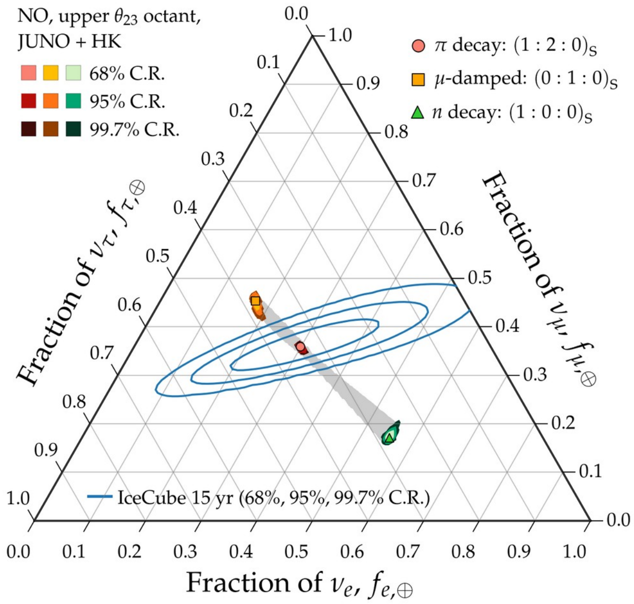


Allowed regions: overlapping

Measurement: imprecise

Not ideal

2030



Allowed regions: well separated

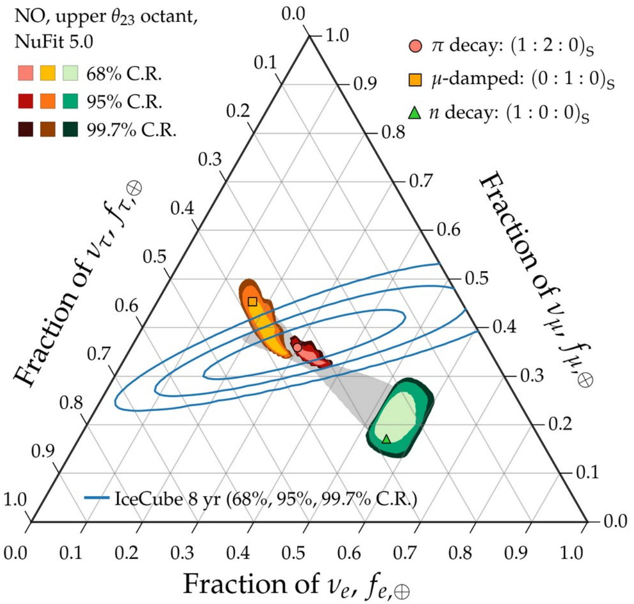
Measurement: improving

Nice

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

Theoretically palatable regions: 2020 → 2030 → 2040

2020

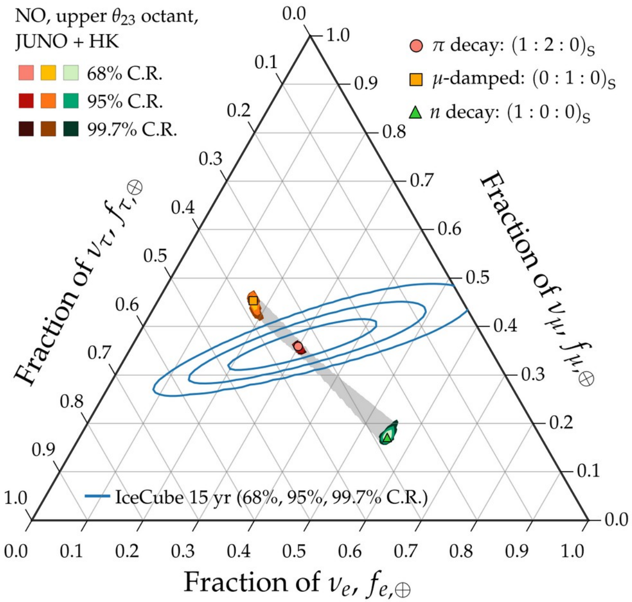


Allowed regions: overlapping

Measurement: imprecise

Not ideal

2030

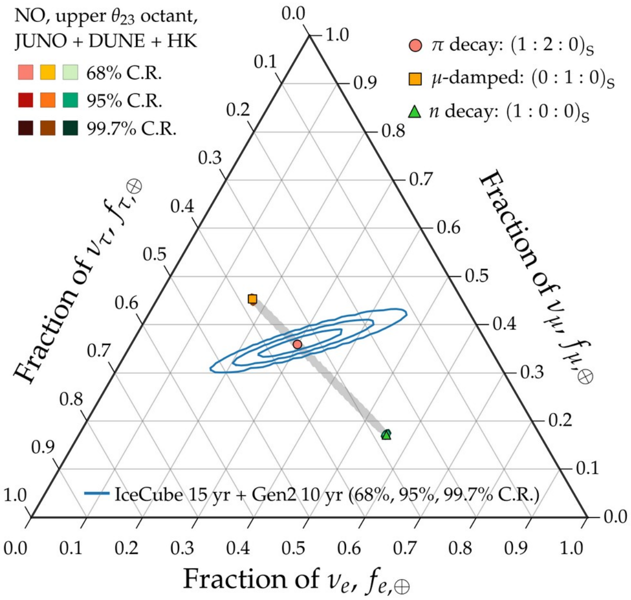


Allowed regions: well separated

Measurement: improving

Nice

2040



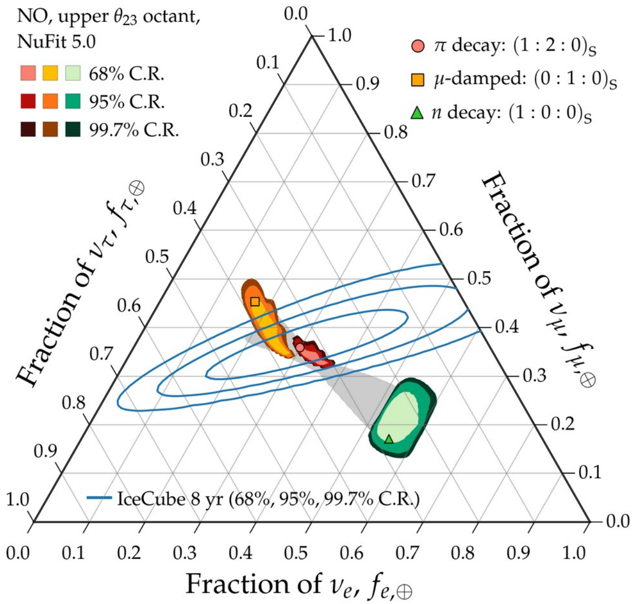
Allowed regions: well separated

Measurement: precise

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

Theoretically palatable regions: 2020 → 2030 → 2040

2020

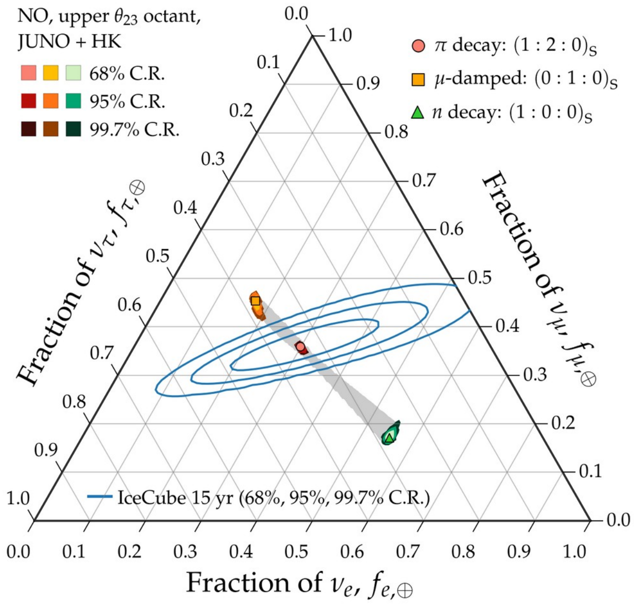


Allowed regions: overlapping

Measurement: imprecise

Not ideal

2030

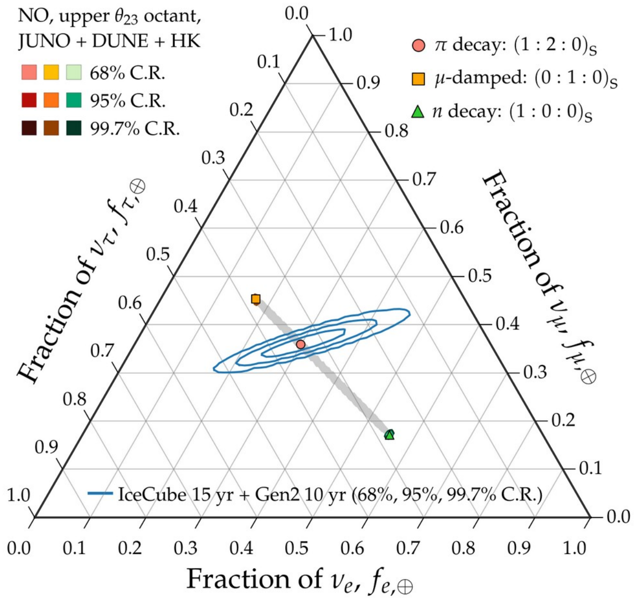


Allowed regions: well separated

Measurement: improving

Nice

2040



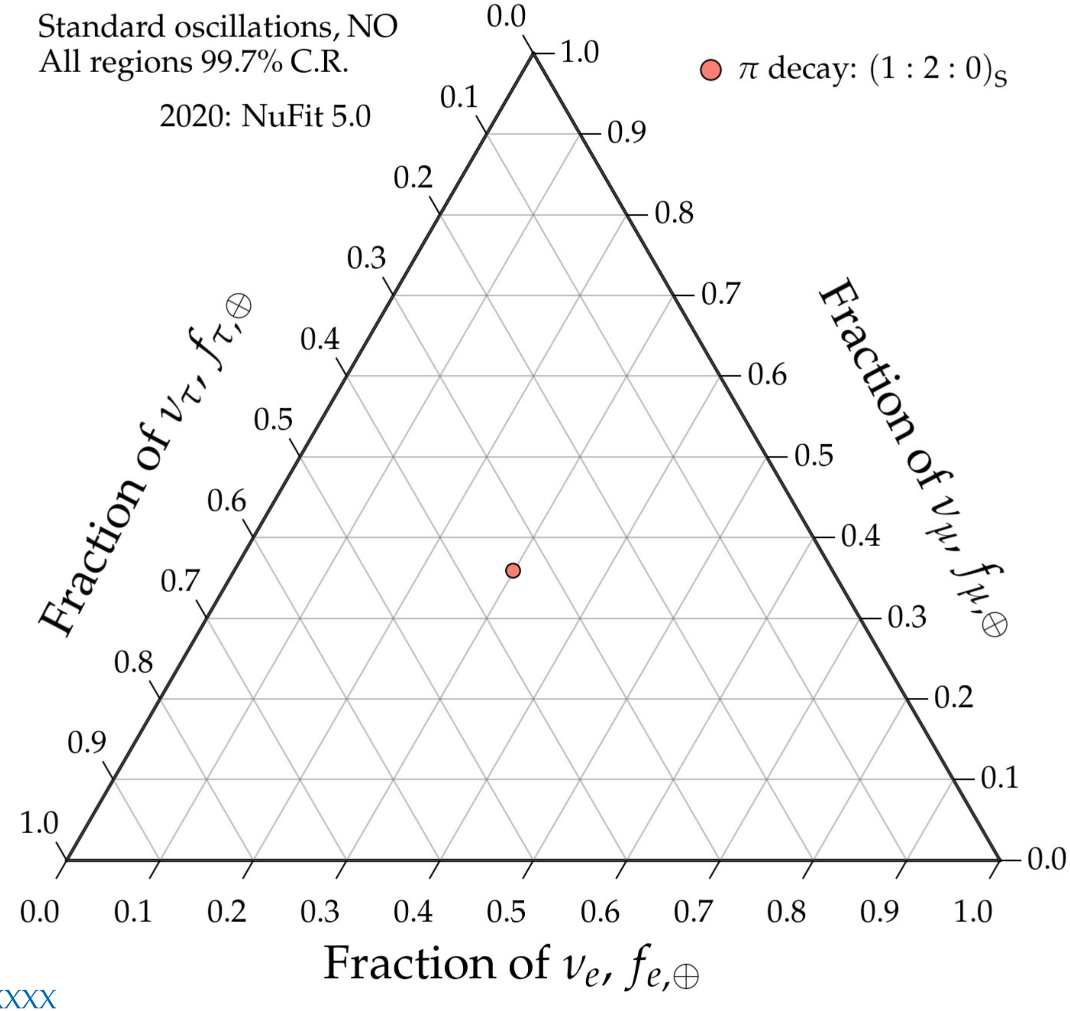
Allowed regions: well separated

Measurement: precise

Success

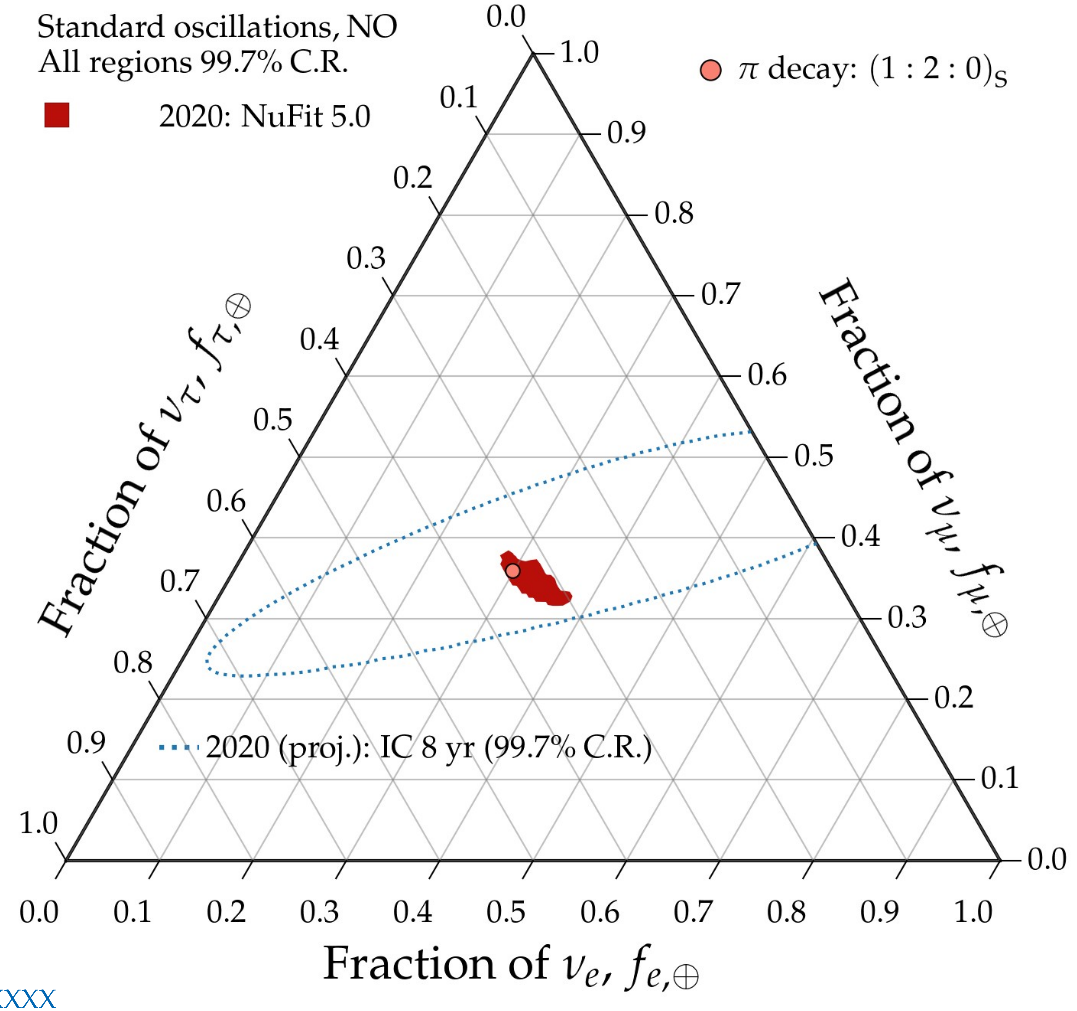
Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

Theoretically palatable regions: 2020 *vs.* 2040



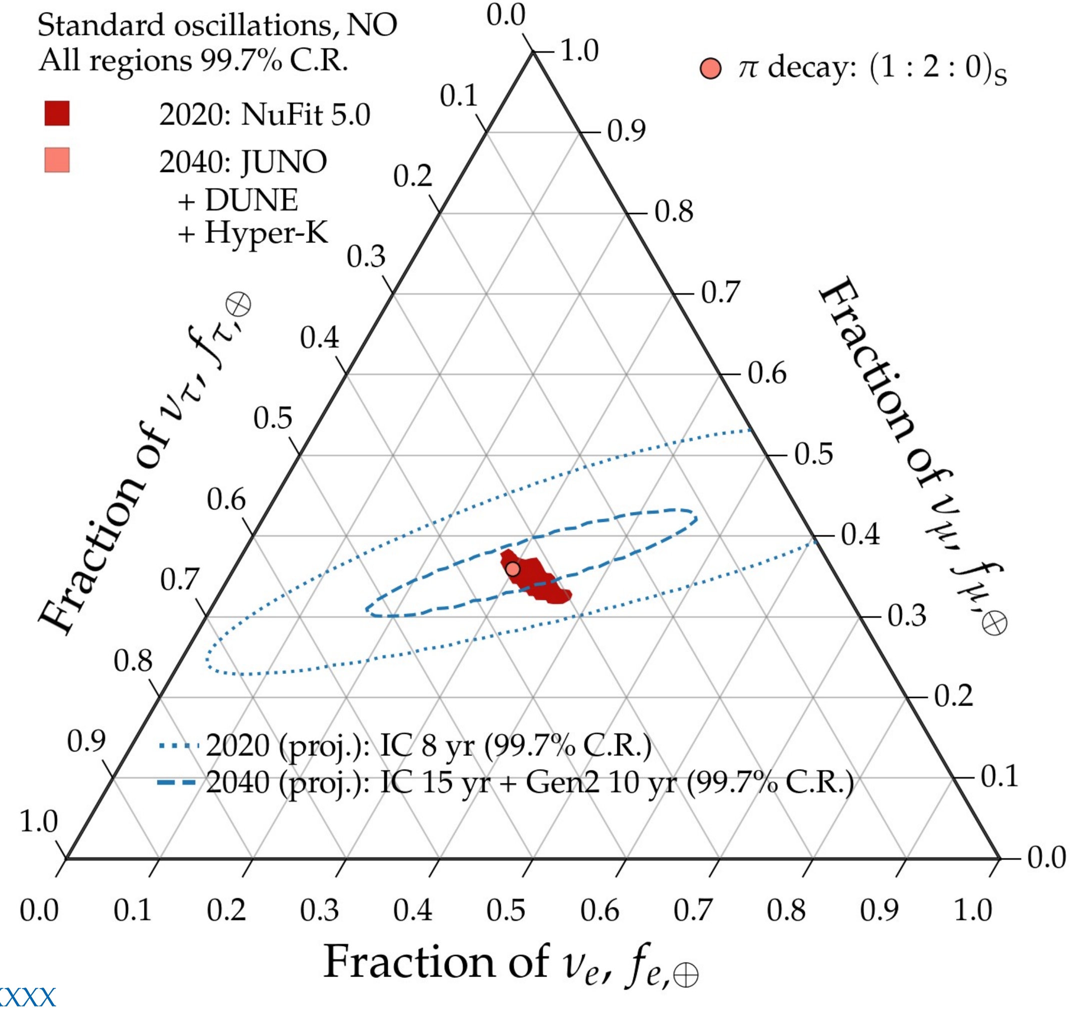
Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

Theoretically palatable regions: 2020 *vs.* 2040



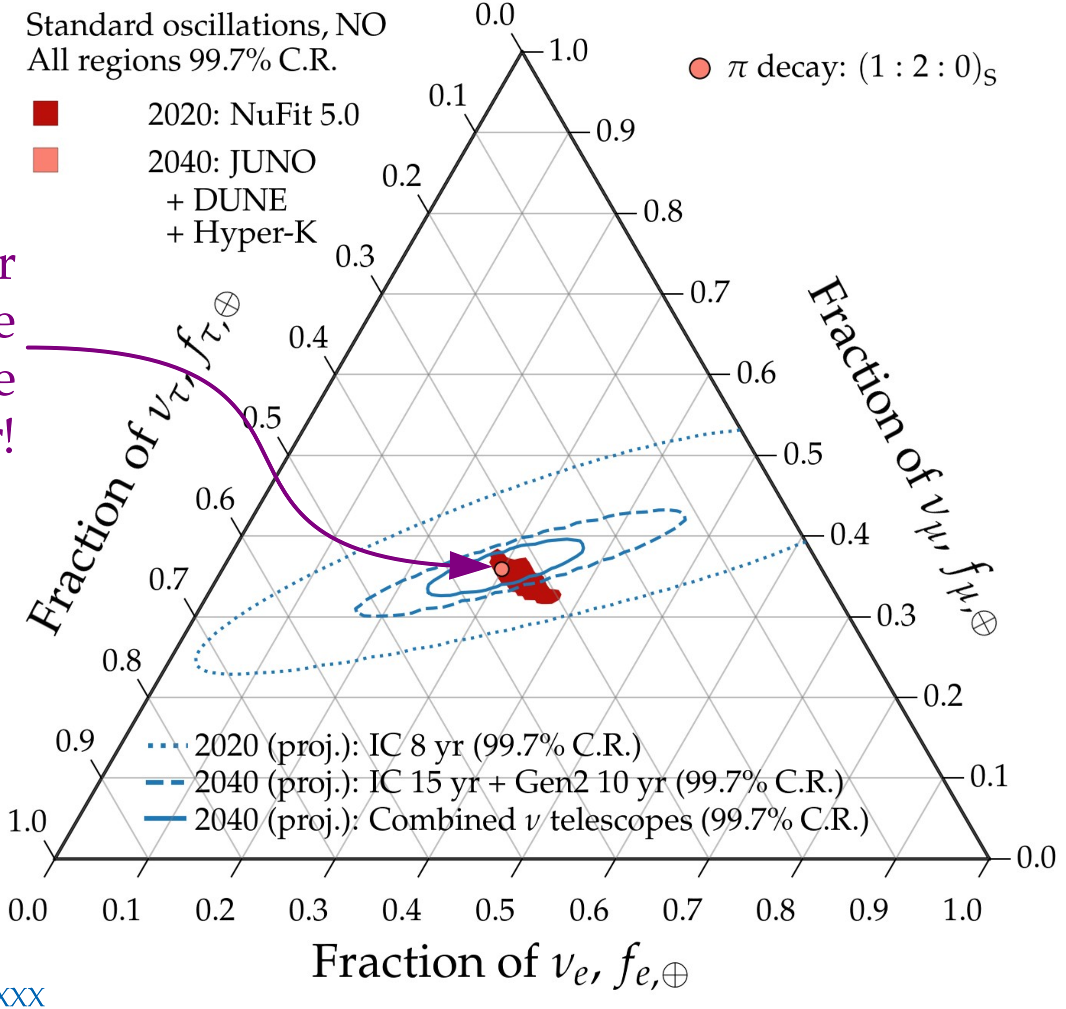
Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

Theoretically palatable regions: 2020 *vs.* 2040



Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

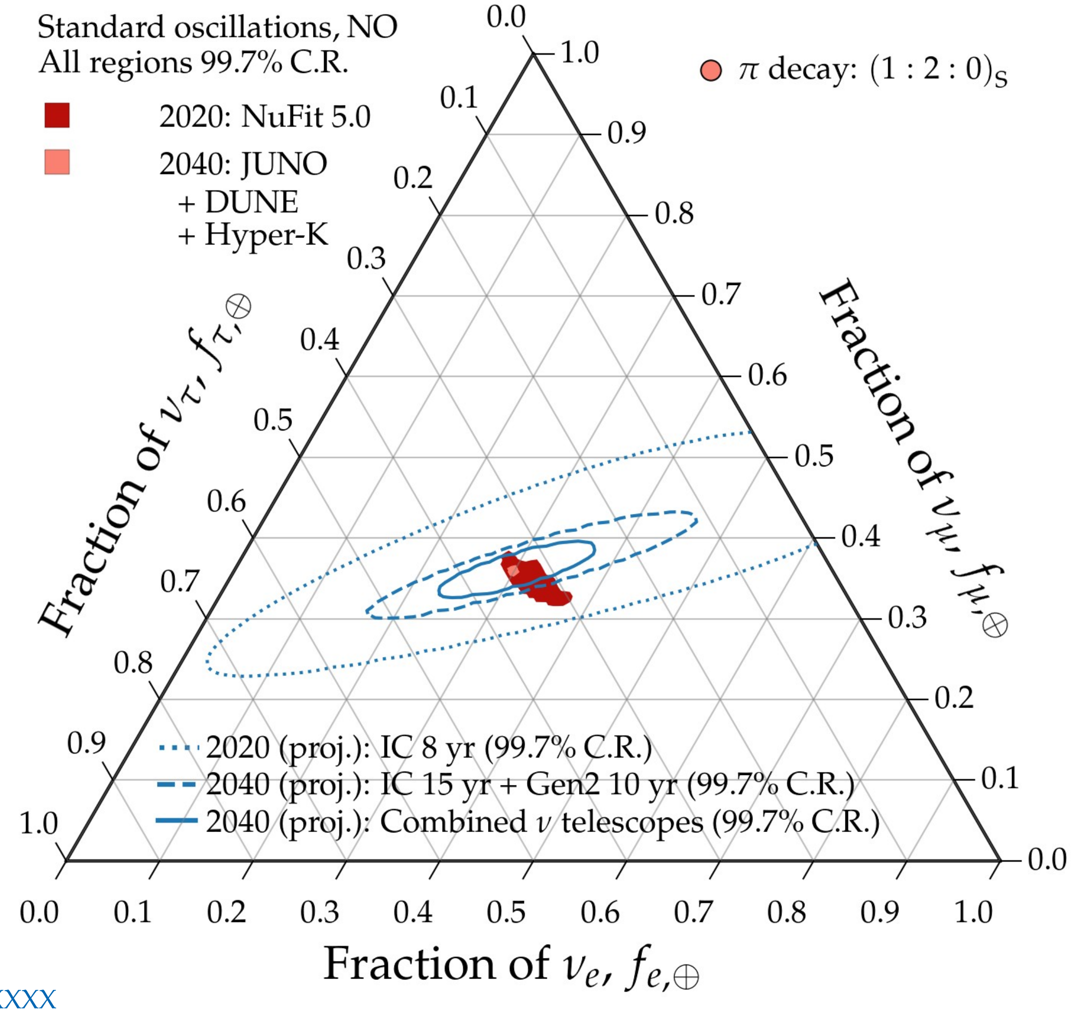
Theoretically palatable regions: 2020 *vs.* 2040



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

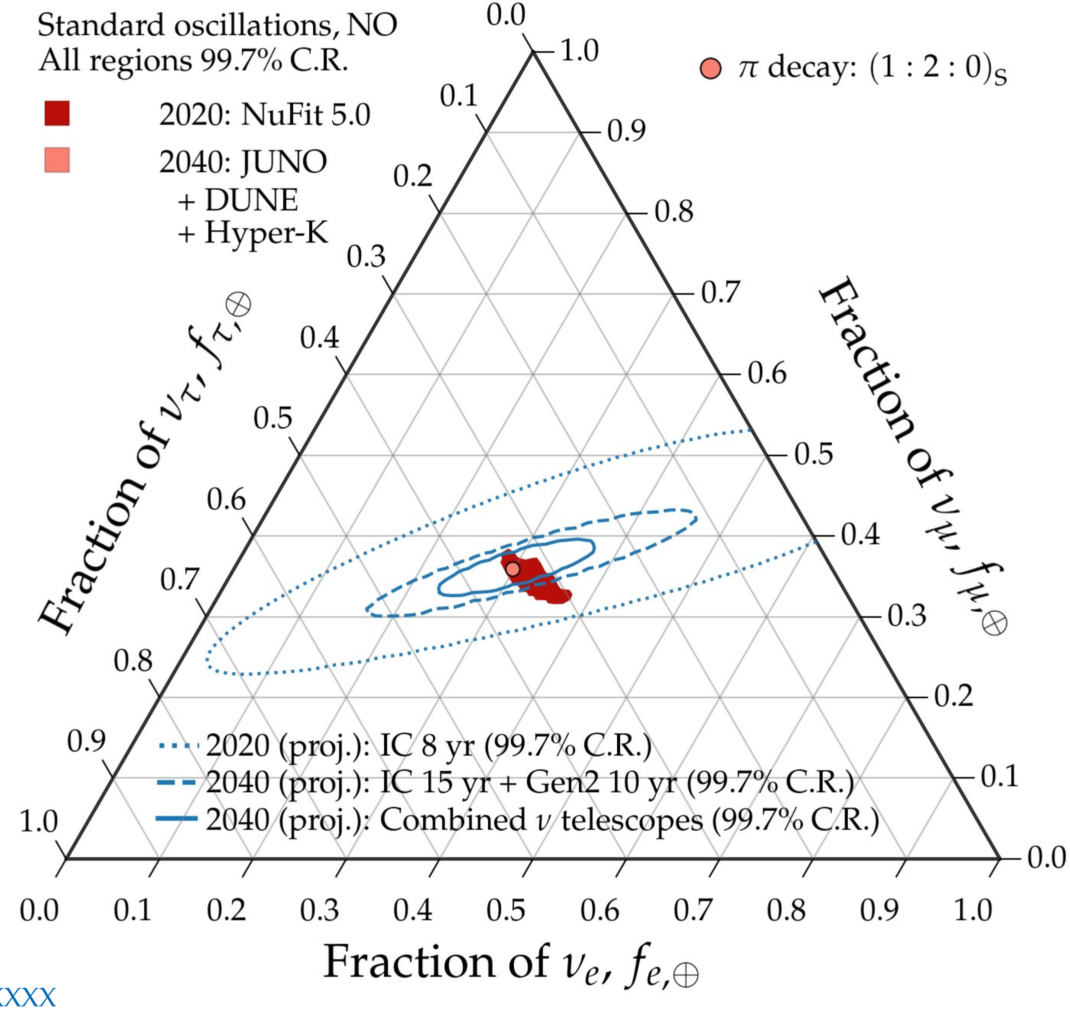
Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

Theoretically palatable regions: 2020 *vs.* 2040



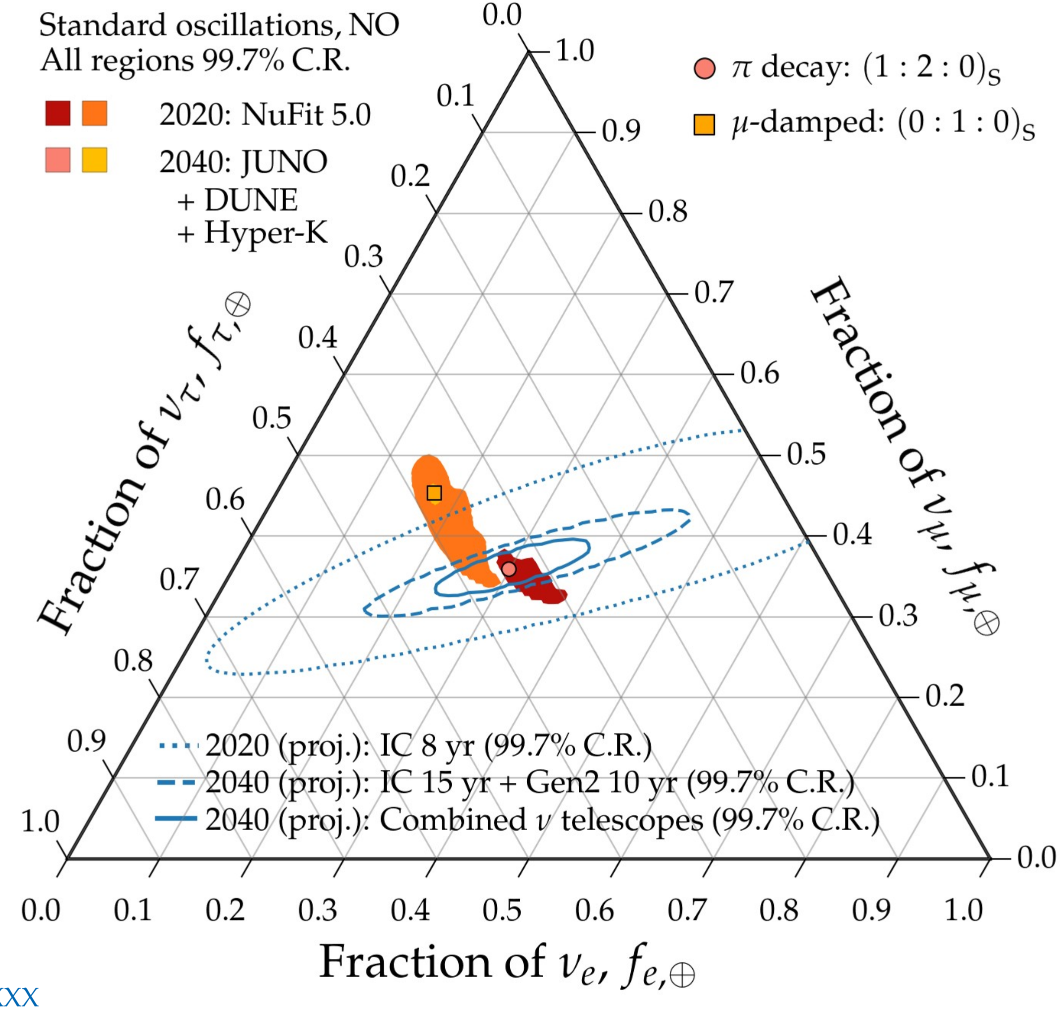
Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

Theoretically palatable regions: 2020 *vs.* 2040



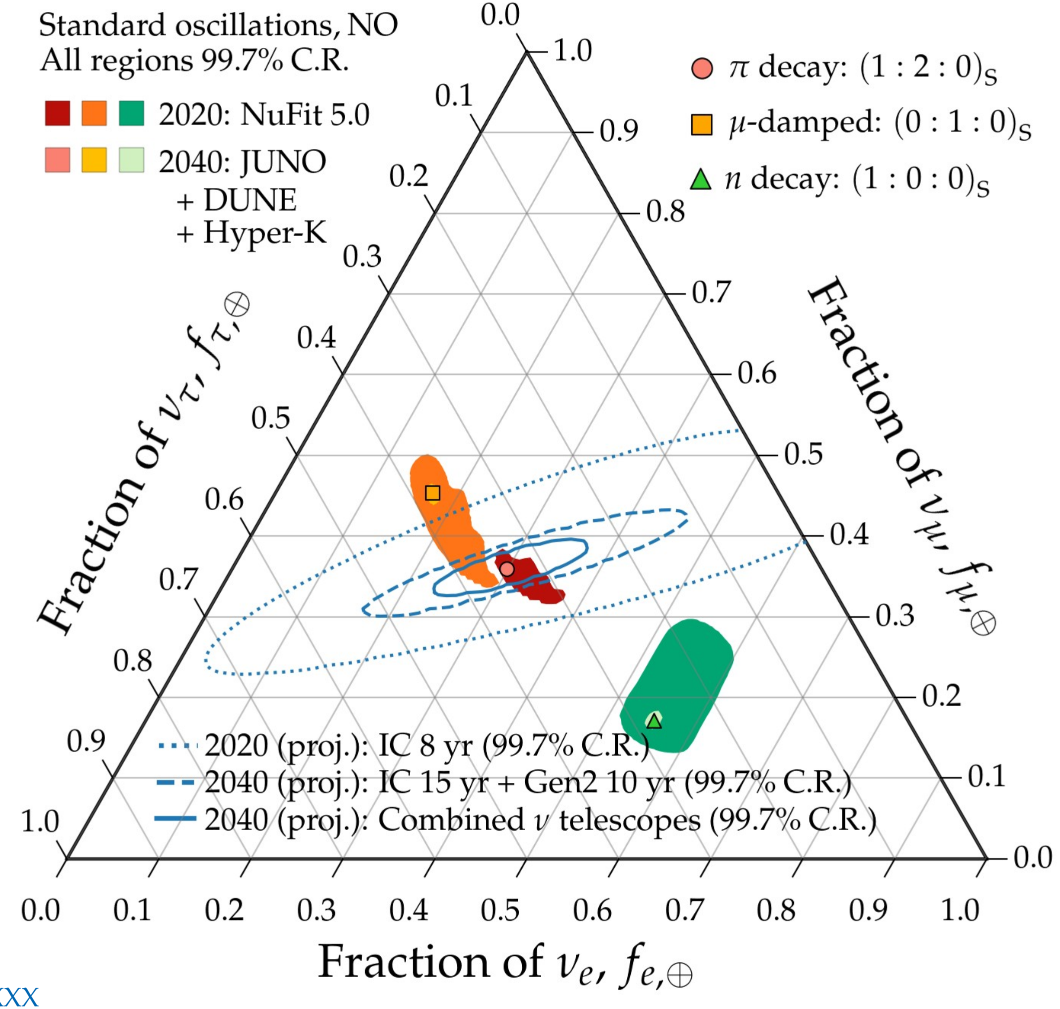
Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

Theoretically palatable regions: 2020 *vs.* 2040



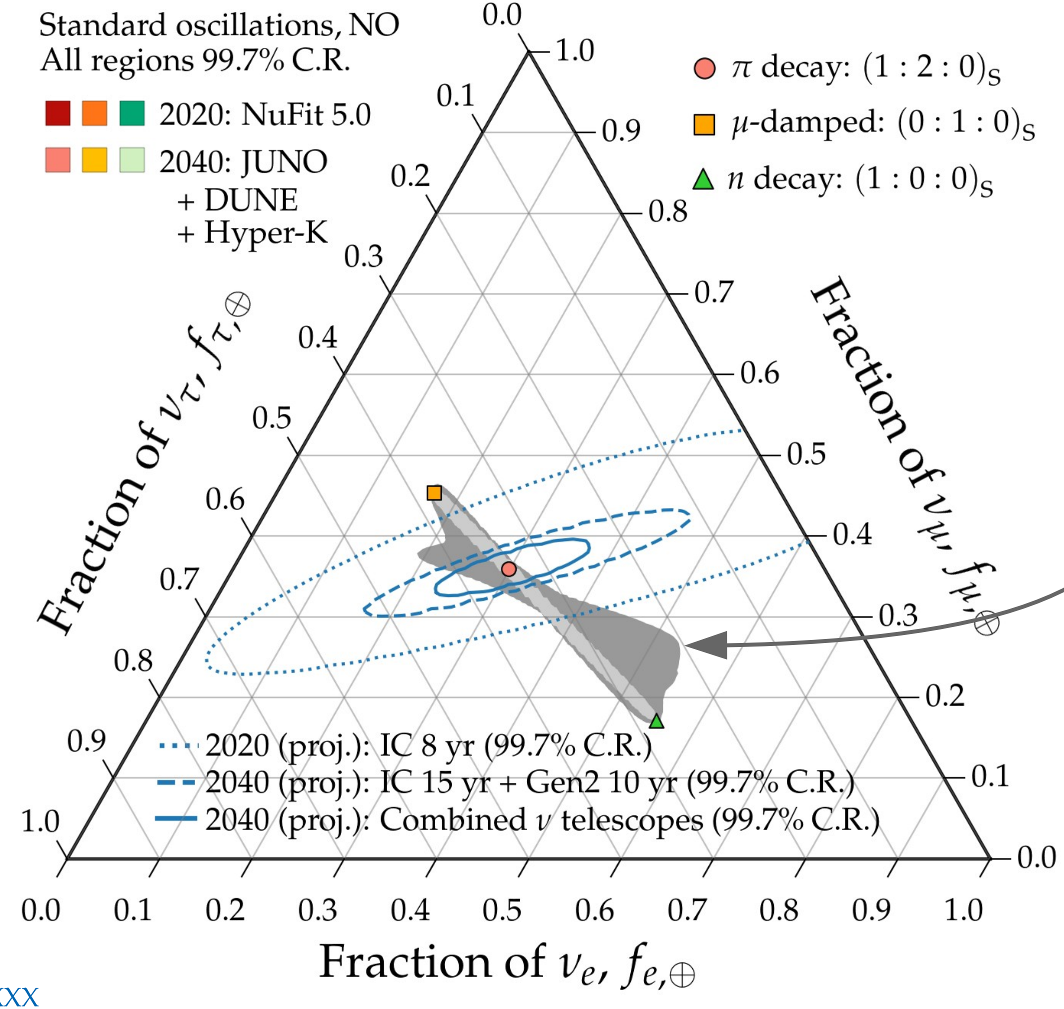
Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

Theoretically palatable regions: 2020 *vs.* 2040



Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

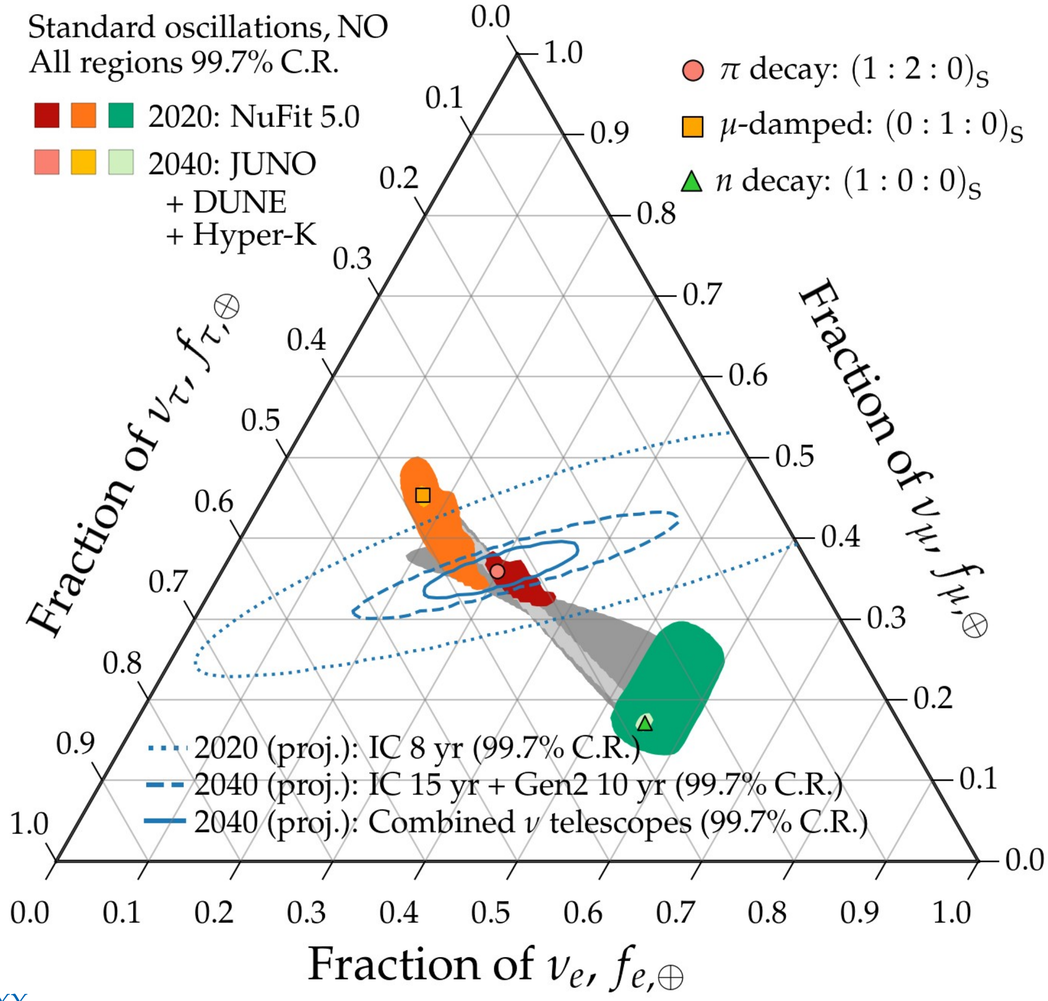
Theoretically palatable regions: 2020 *vs.* 2040



Varying over all possible flavor ratios at the source

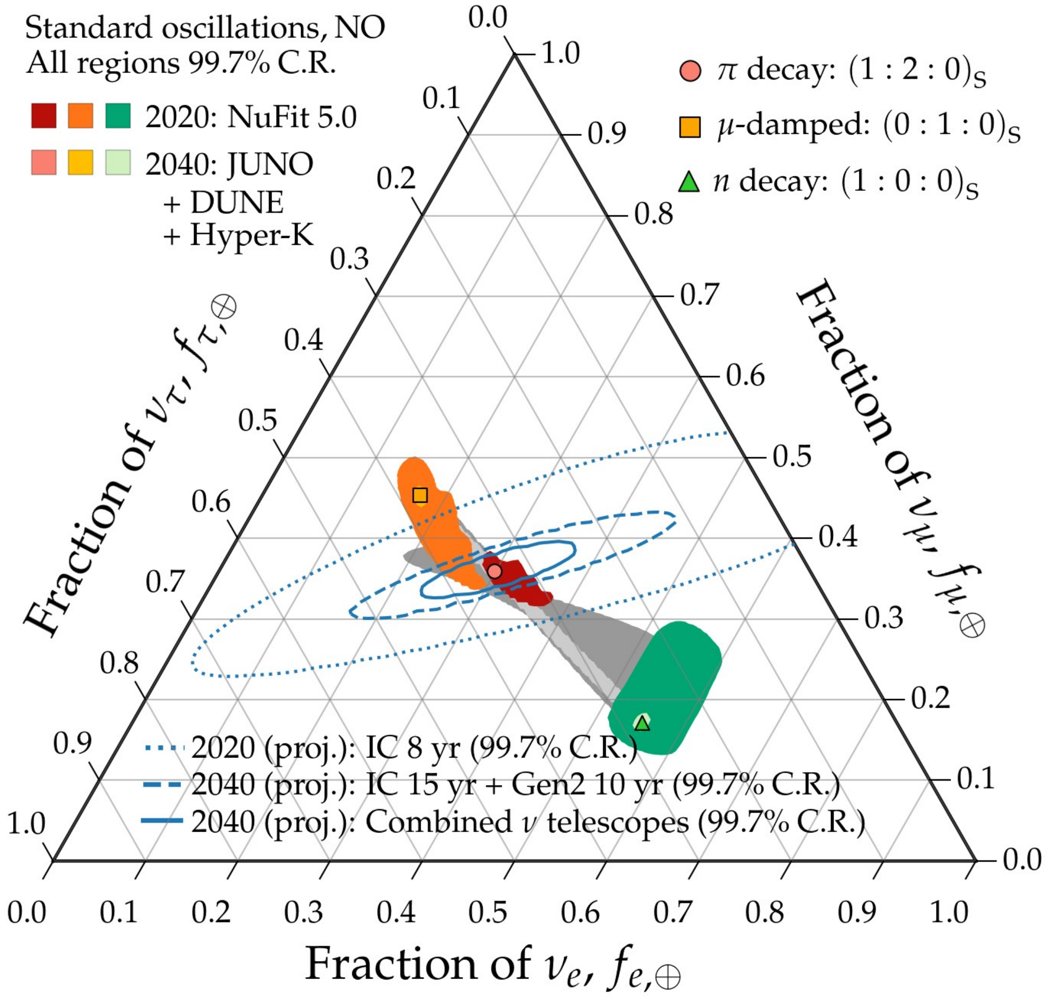
Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

Theoretically palatable regions: 2020 *vs.* 2040



Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

Theoretically palatable regions: 2020 *vs.* 2040



By 2040:

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

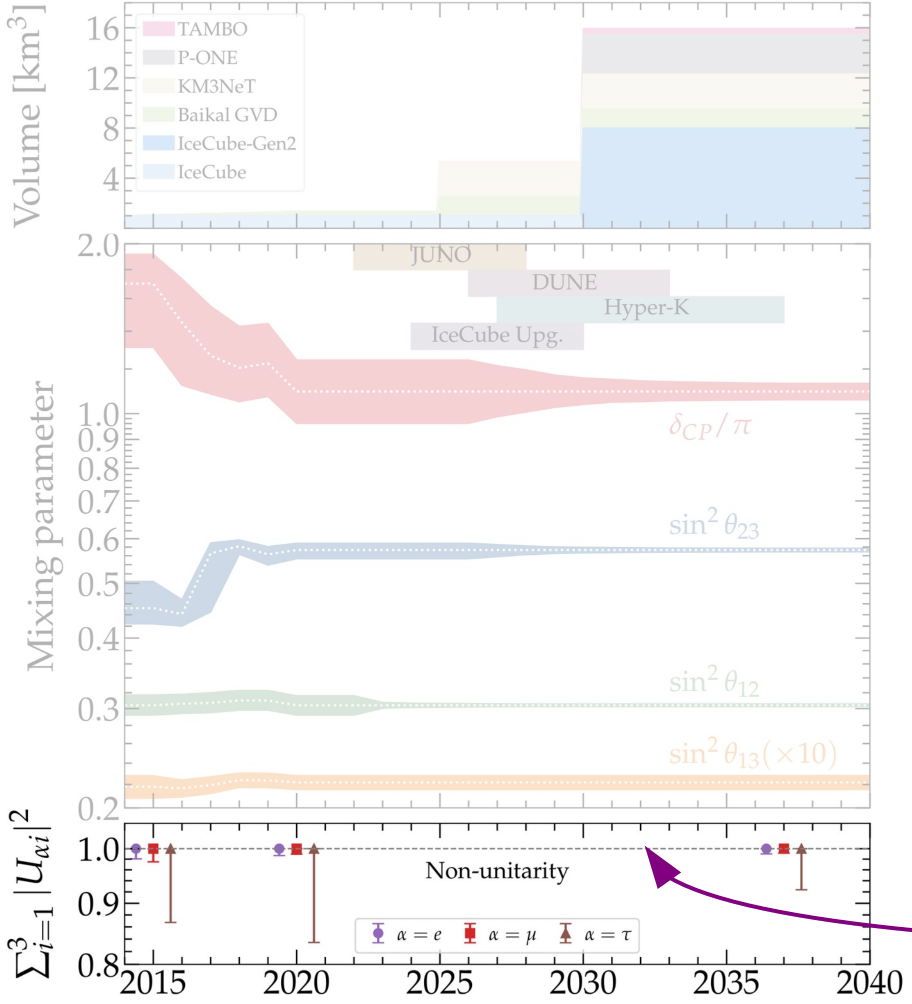
Measurement of flavor ratios –
Can distinguish between similar predictions at 99.7% C.R. (3σ)

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

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

No unitarity? *No problem*

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX



The 3×3 active mixing matrix is a non-unitary sub-matrix of a bigger one:

Active flavors

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

Additional sterile flavors

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

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

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

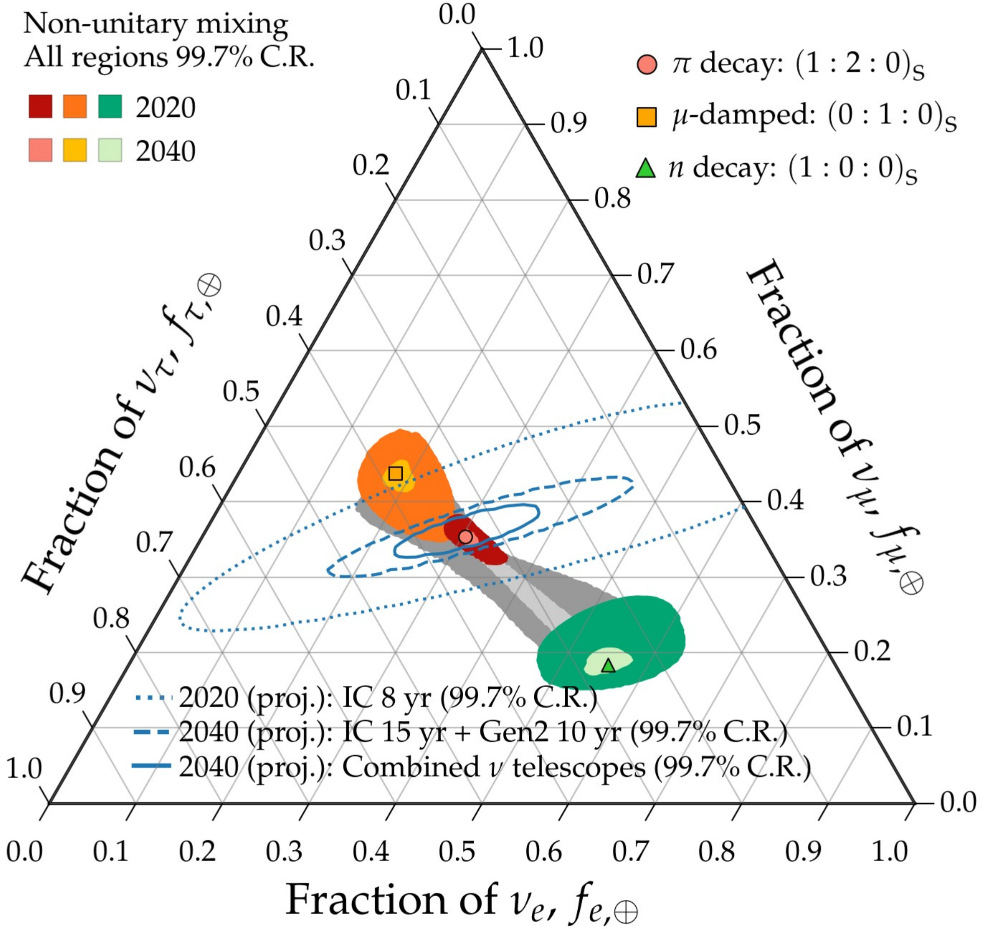
No unitarity? *No problem*

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)



Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

No unitarity? *No problem*

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

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

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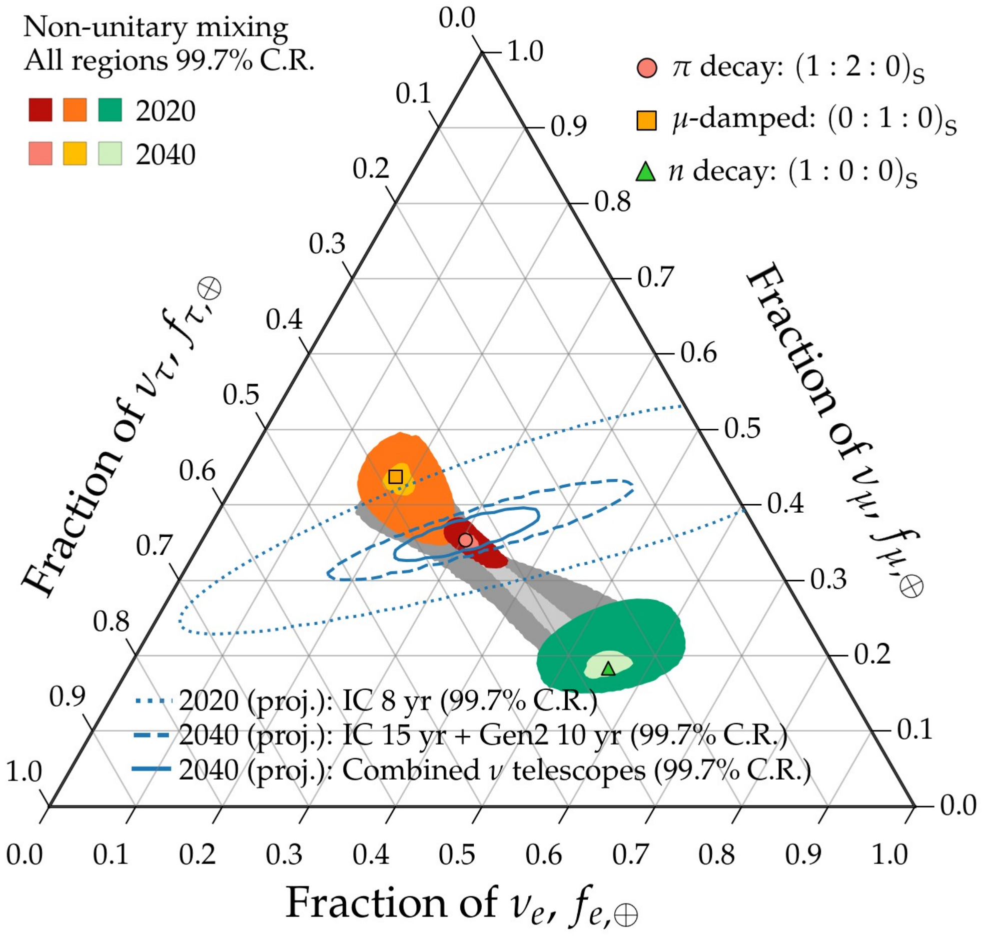

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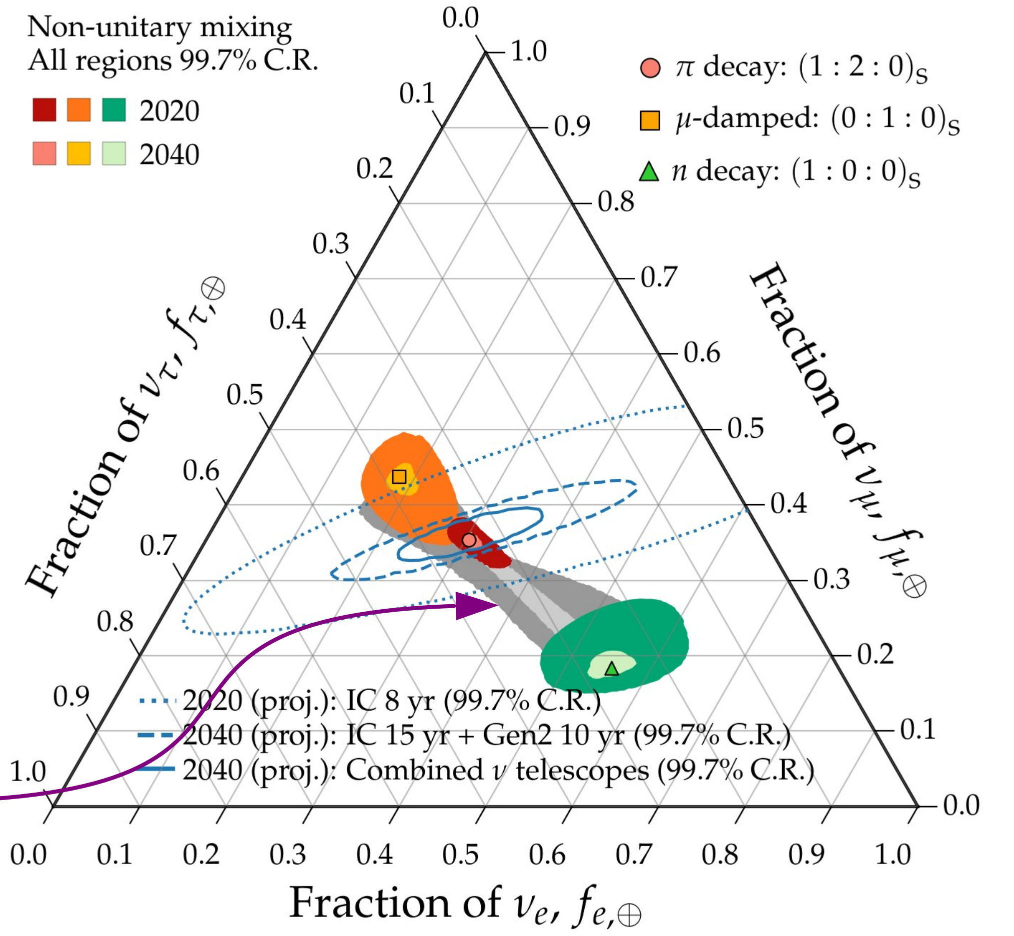

The allowed flavor regions are bigger, but *not much bigger*!

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

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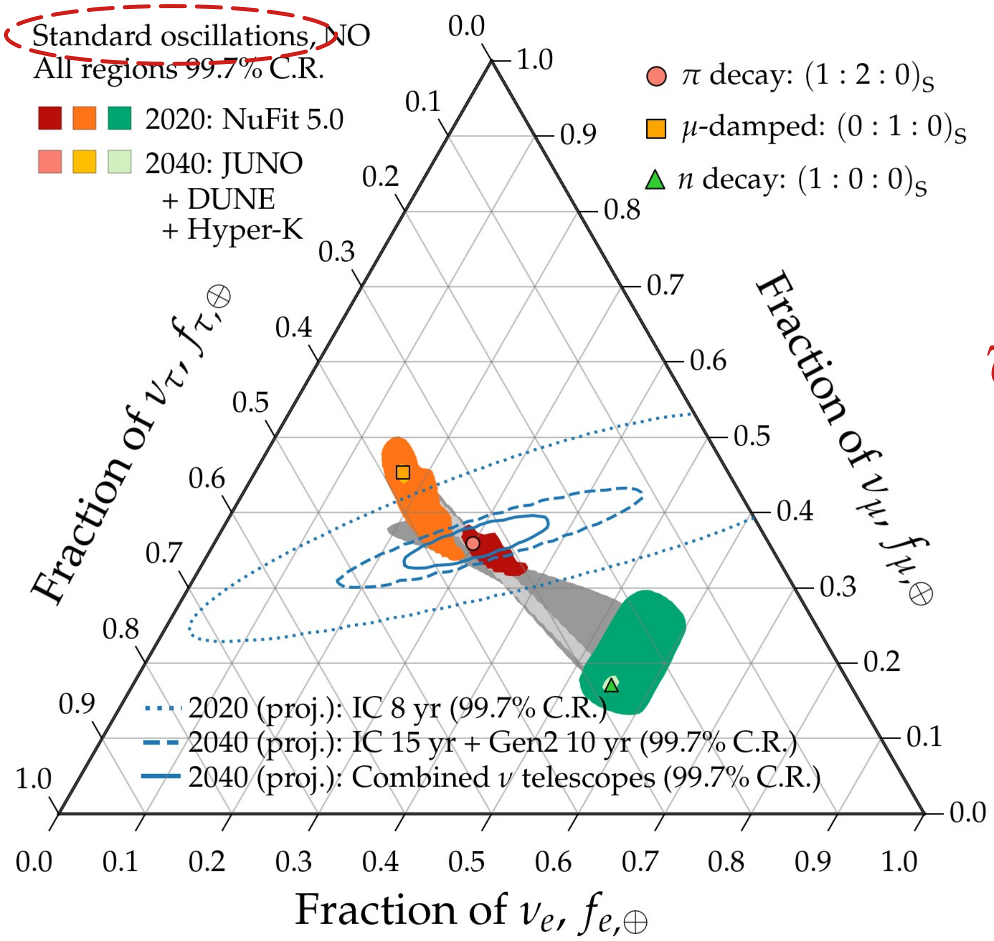
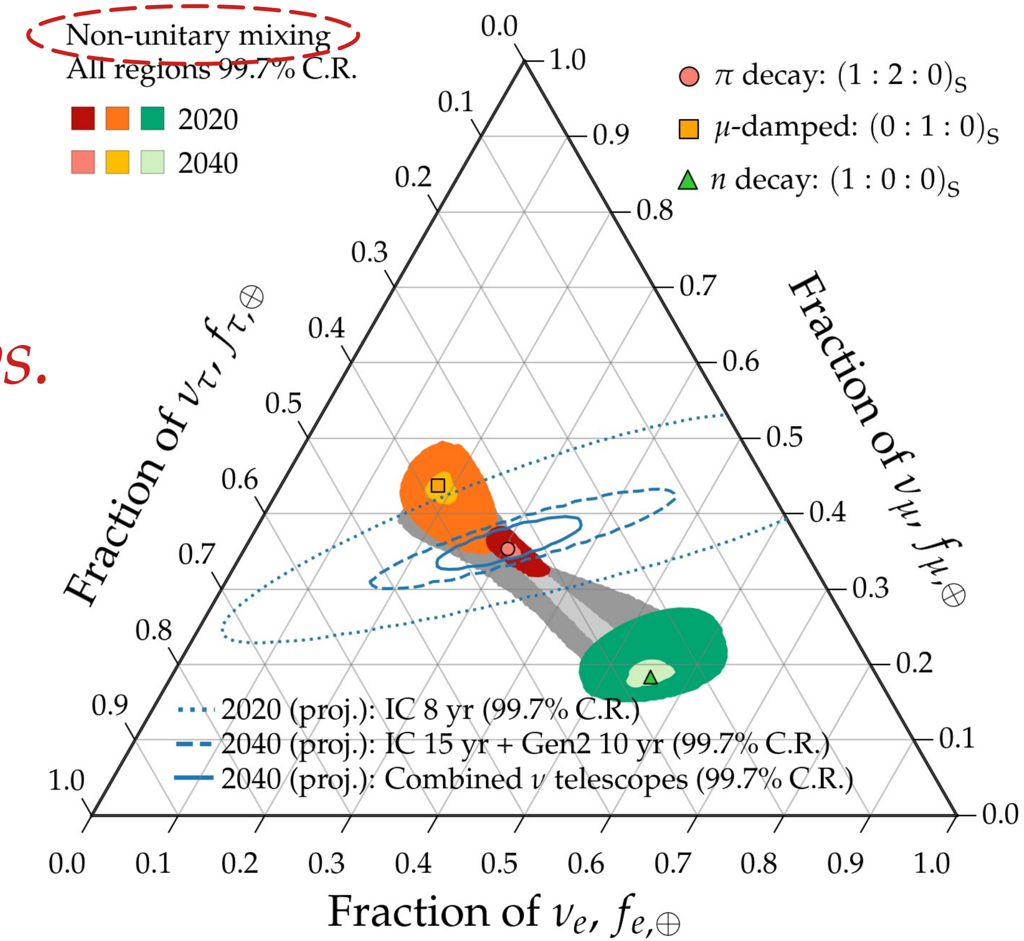


vs.



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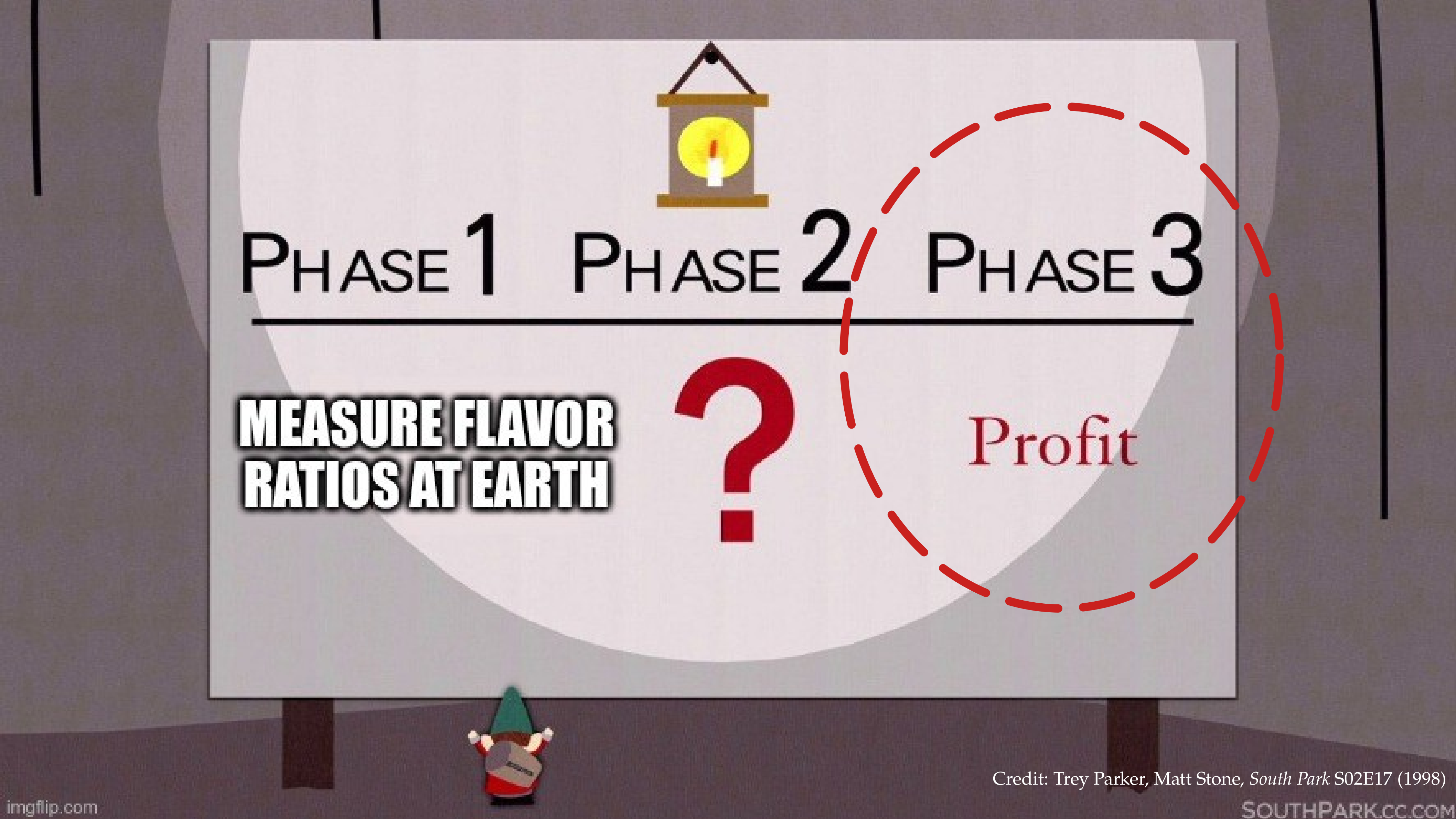
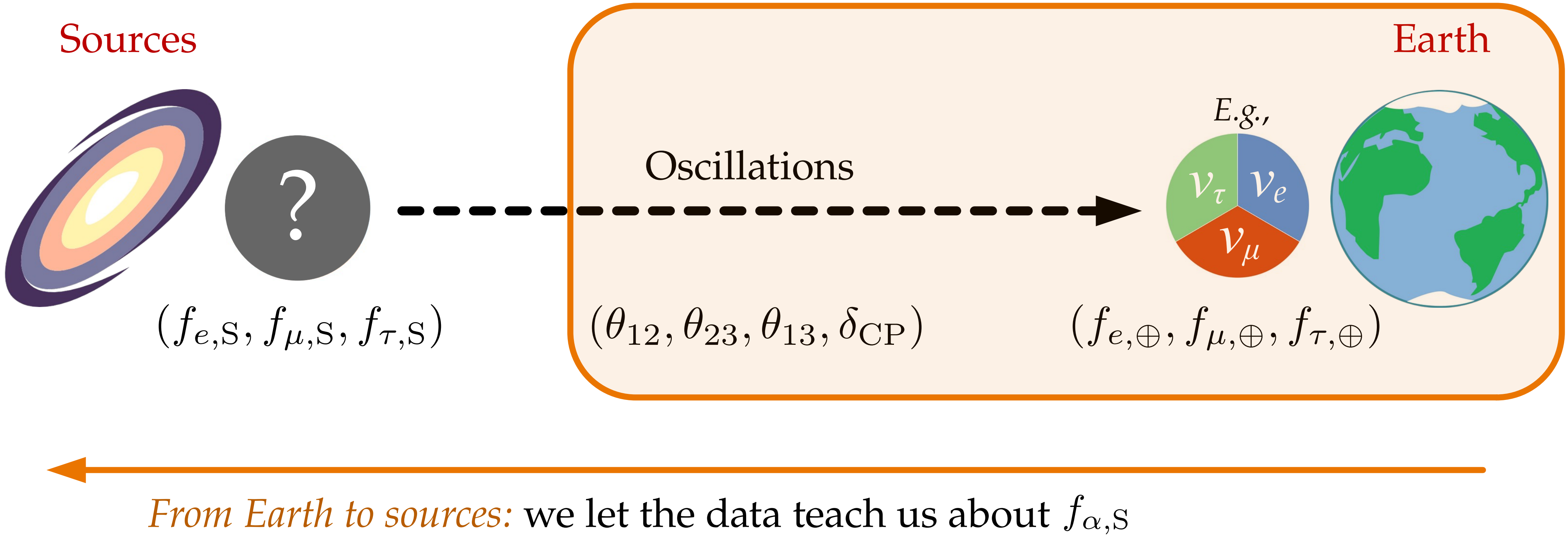


Credit: Trey Parker, Matt Stone, *South Park* S02E17 (1998)



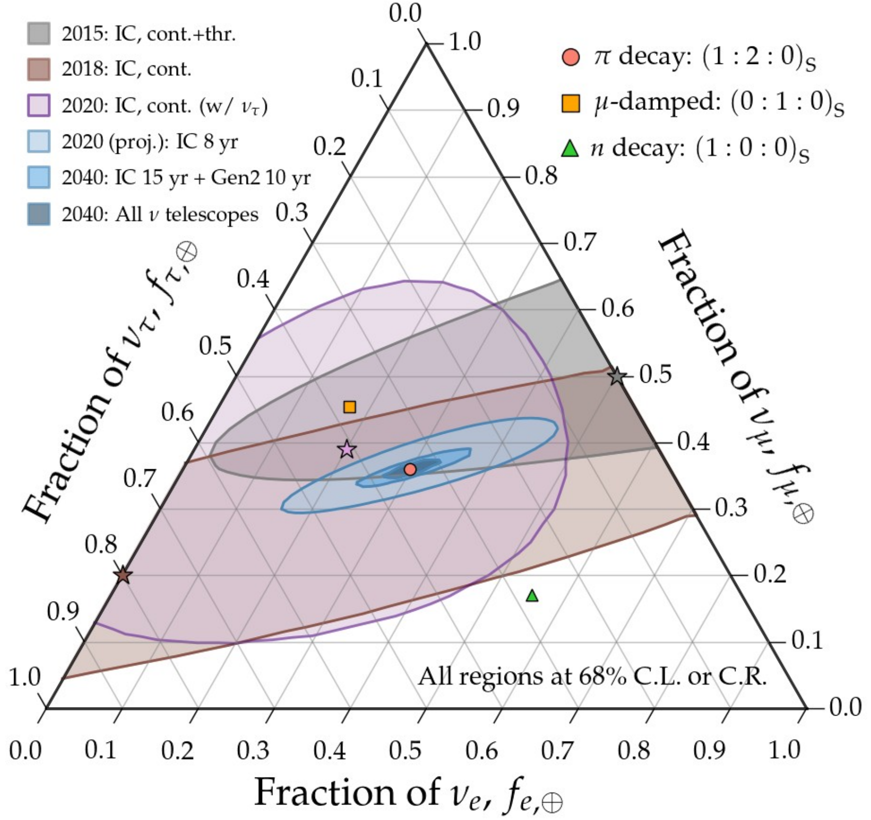
Sources
?
$(f_{e,\mathrm{S}}, f_{\mu,\mathrm{S}}, f_{\tau,\mathrm{S}})$
Oscillations
Earth
E.g.,
ν_τ
ν_e
ν_μ
$(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\mathrm{CP}})$
$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$
From Earth to sources: we let the data teach us about $f_{\alpha,\mathrm{S}}$

Inferring the flavor composition at the sources

Ingredient #1:

Flavor ratios measured at Earth,

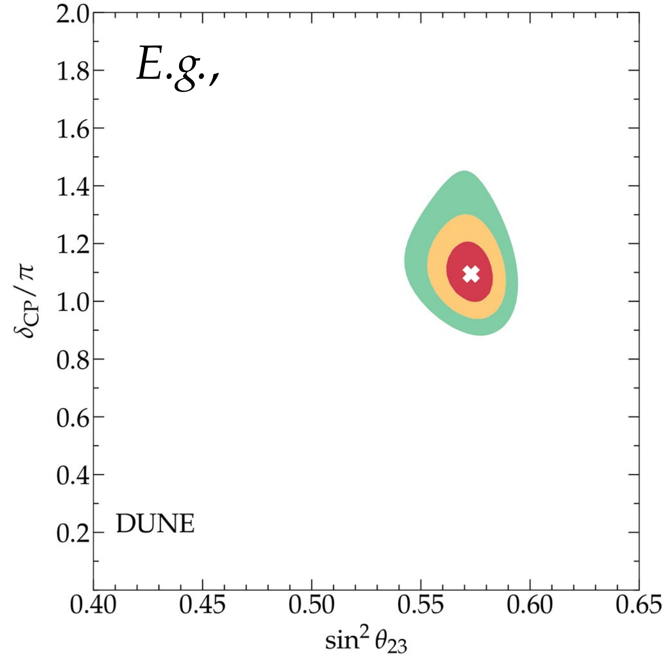
$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$



Ingredient #2:

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

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

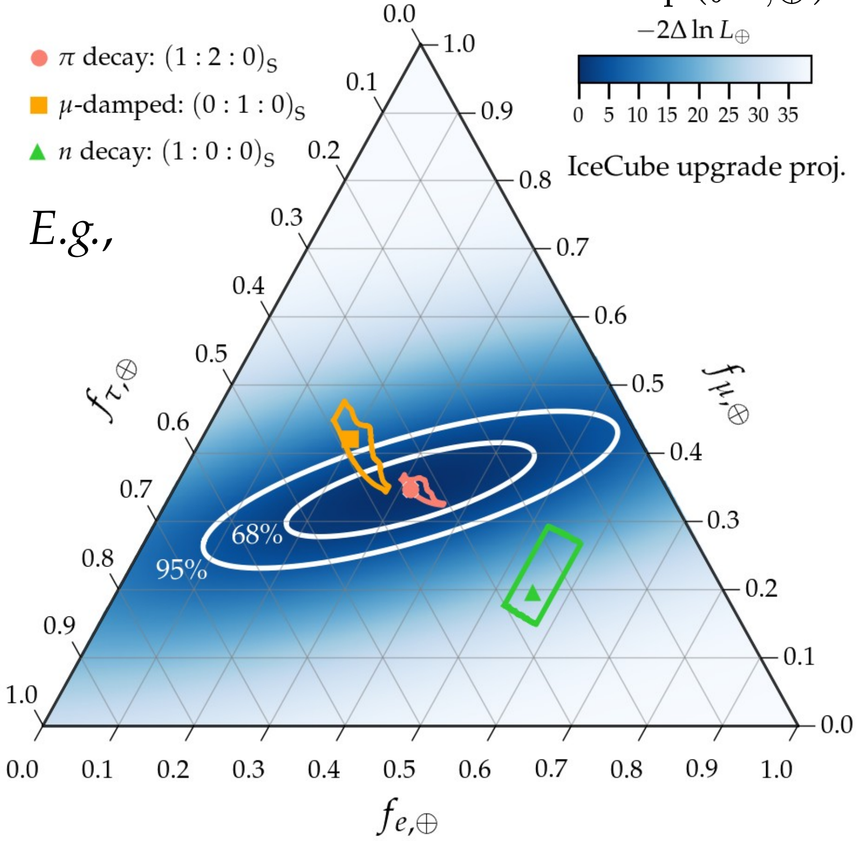


Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX
MB & Ahlers, *PRL* 2019

Inferring the flavor composition at the sources

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

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



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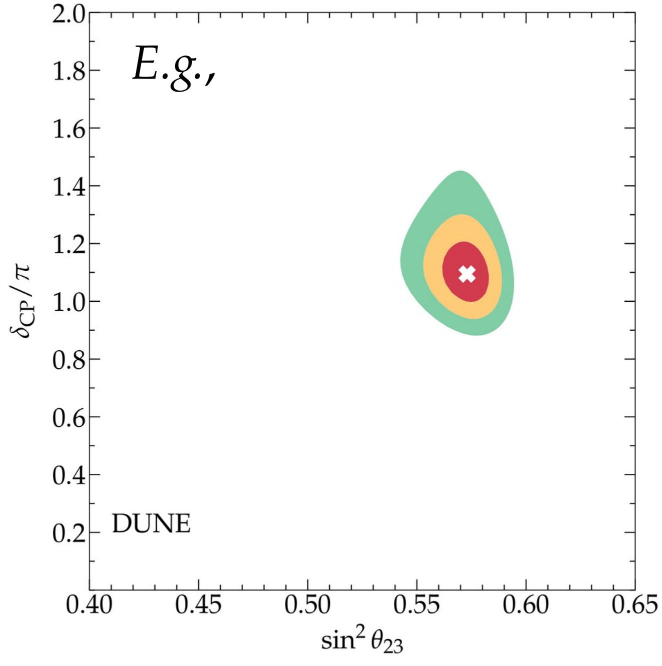

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX
MB & Ahlers, *PRL* 2019

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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, **MB**, Argüelles, Vincent, 2012.XXXXX
MB & Ahlers, *PRL* 2019

Inferring the flavor composition at the sources

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

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX
MB & Ahlers, *PRL* 2019

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Oscillation experiments Neutrino telescopes

Inferring the flavor composition at the sources

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX
MB & Ahlers, *PRL* 2019

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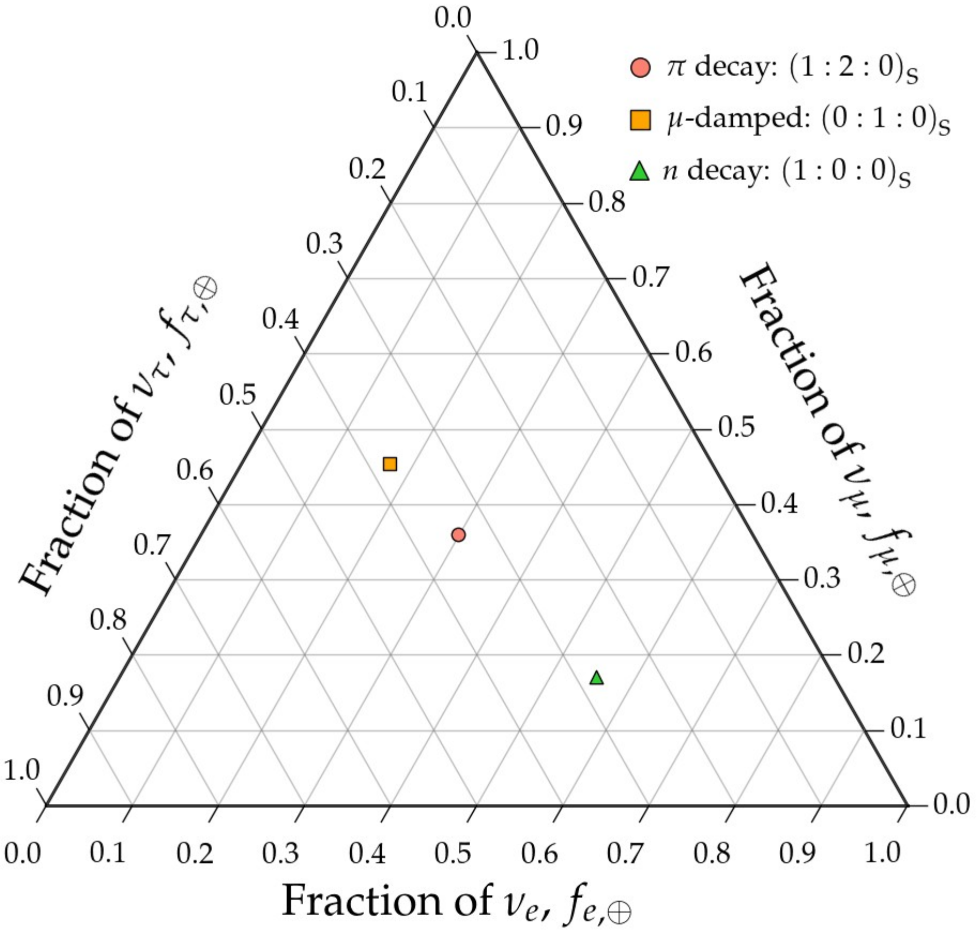

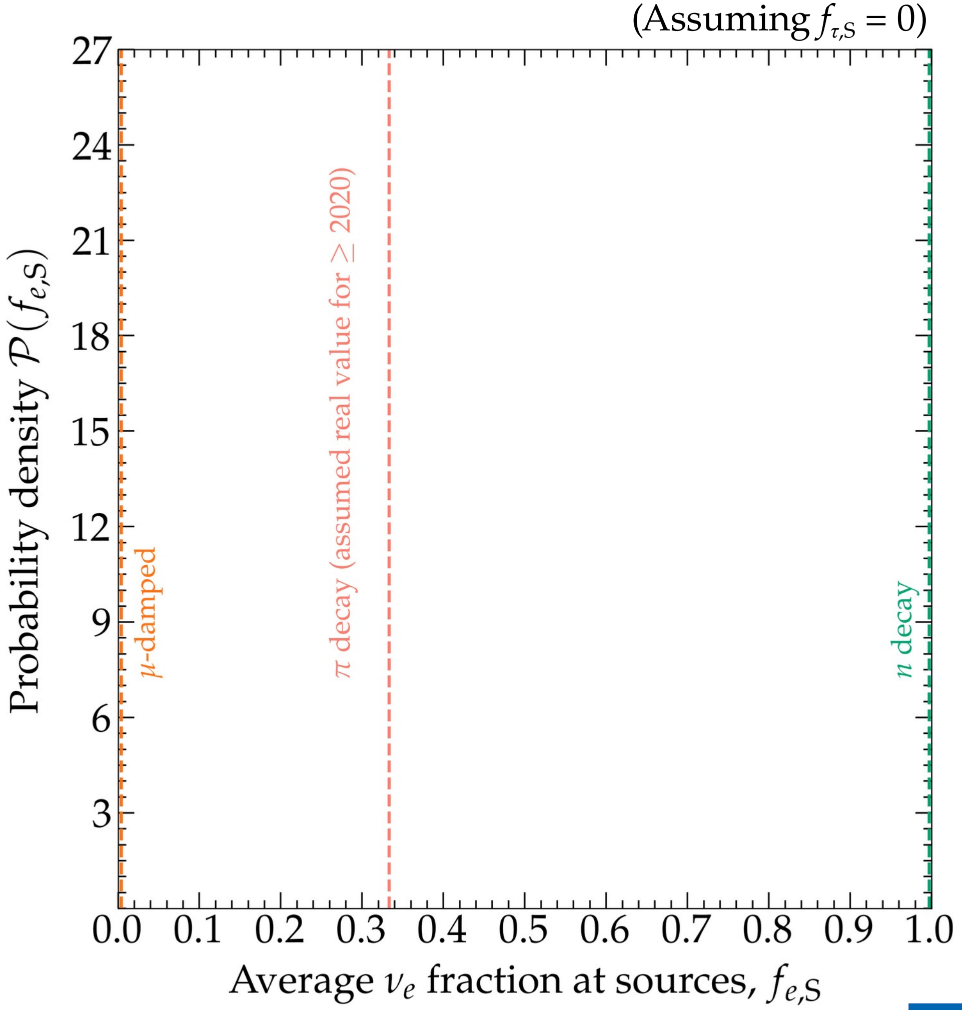

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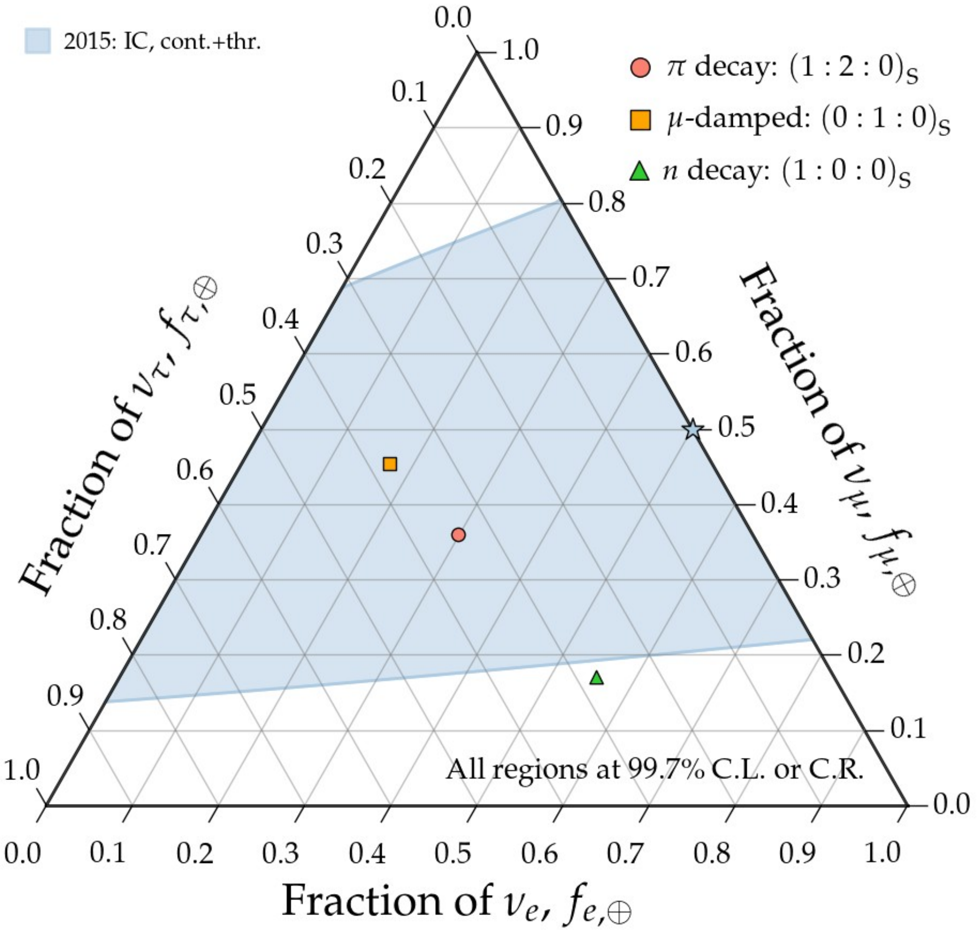
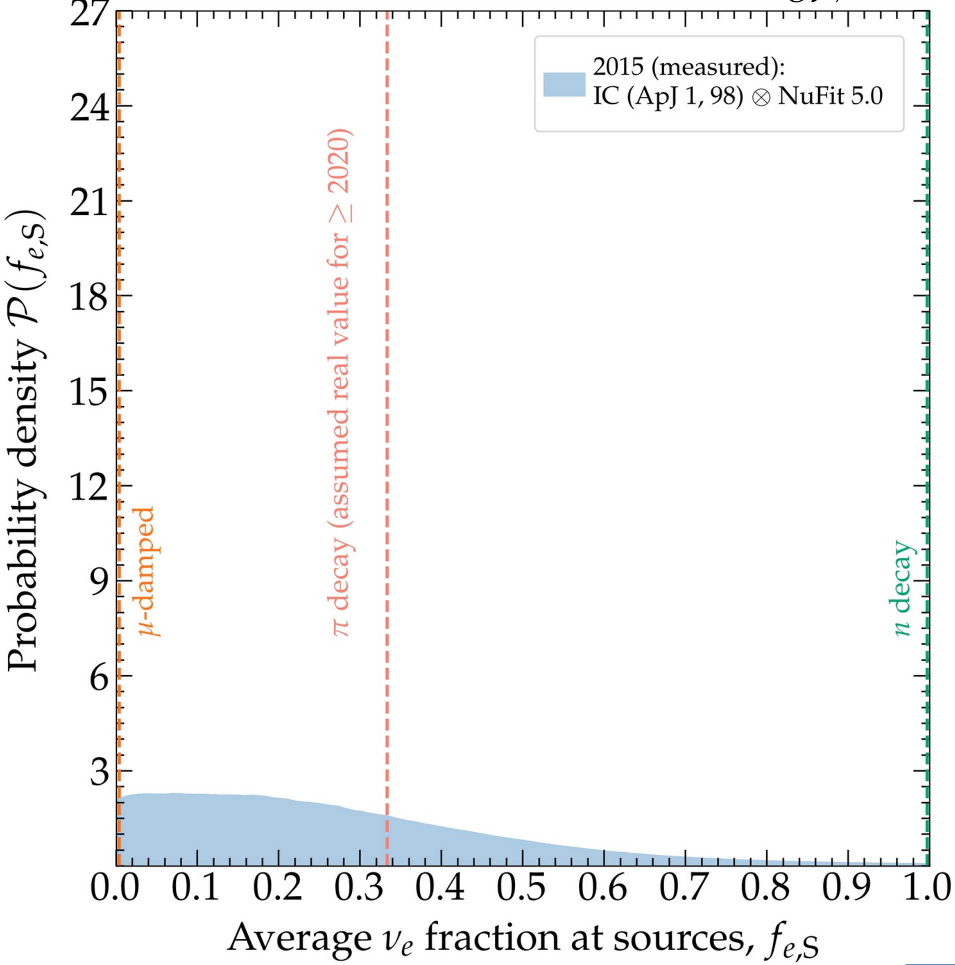


(Assuming $f_{\tau,S} = 0$)



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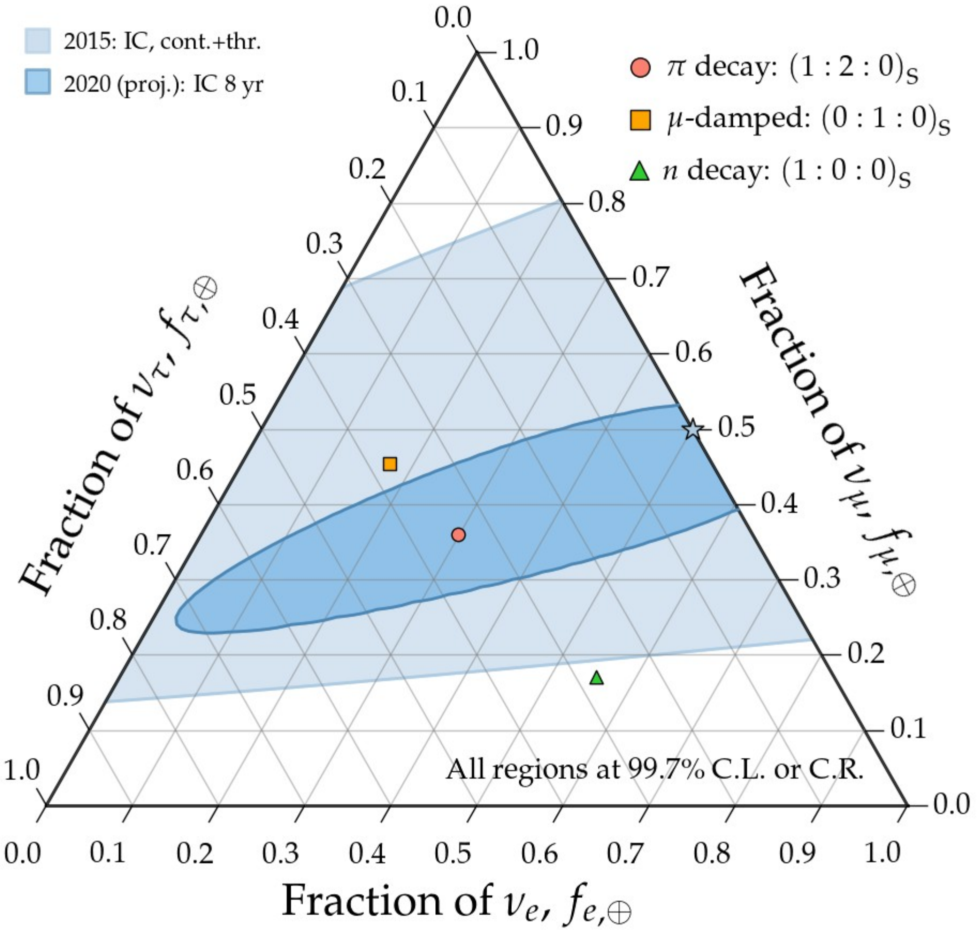

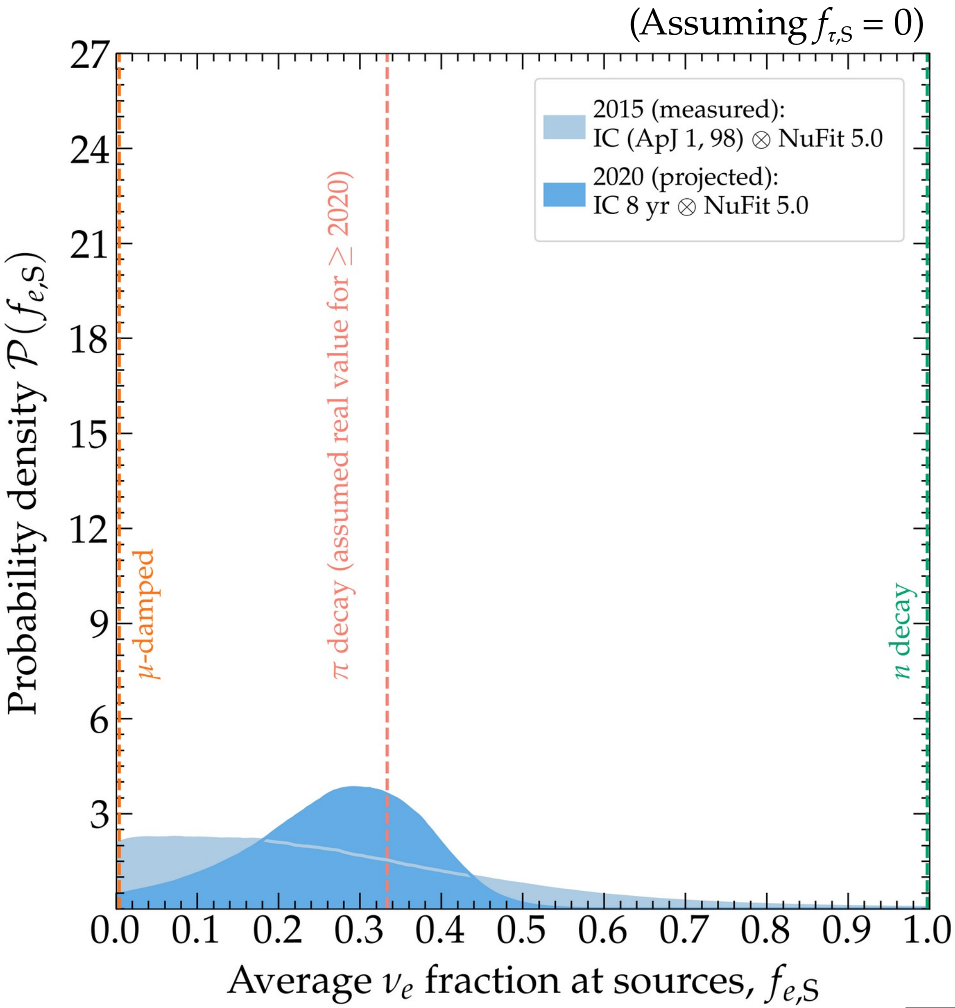

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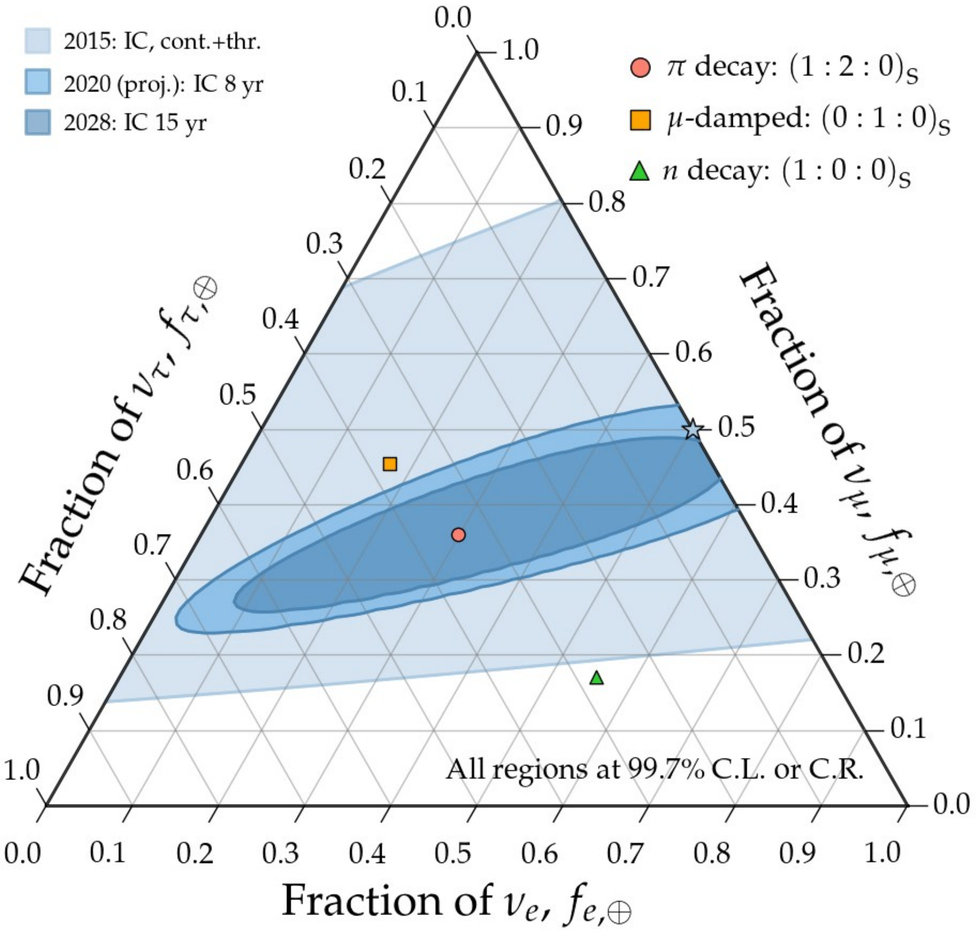

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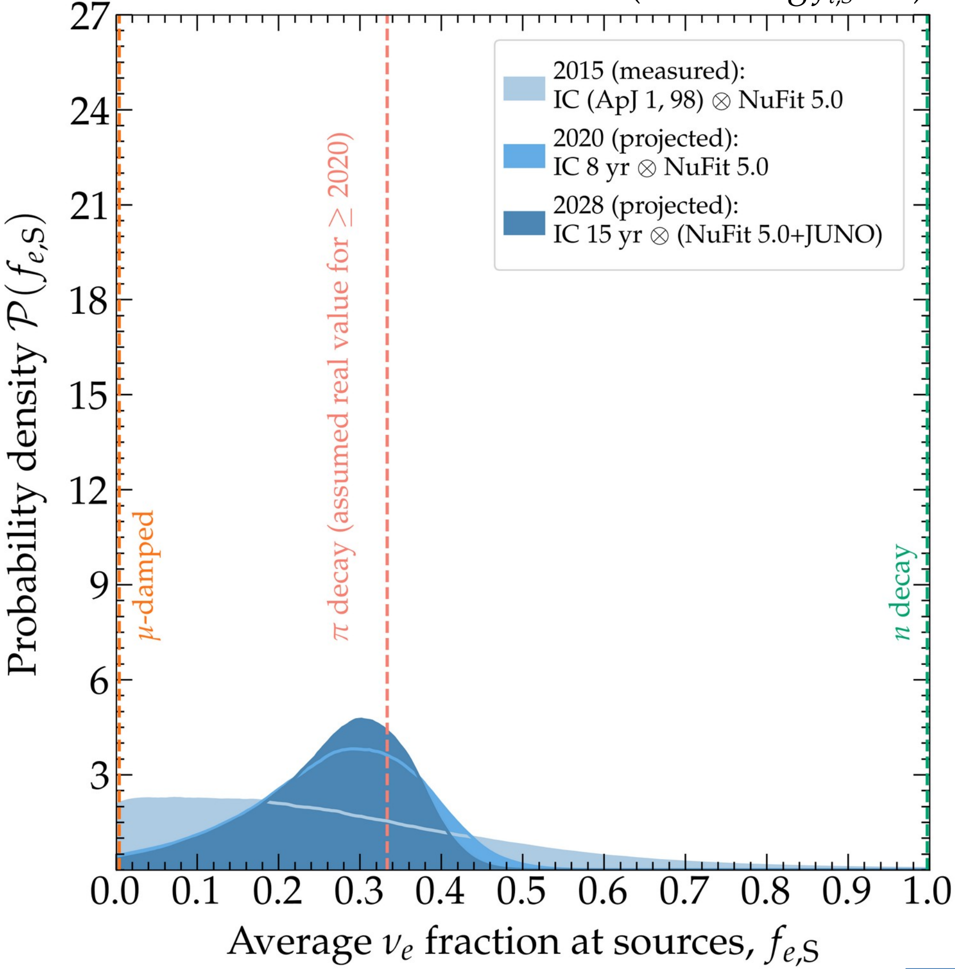

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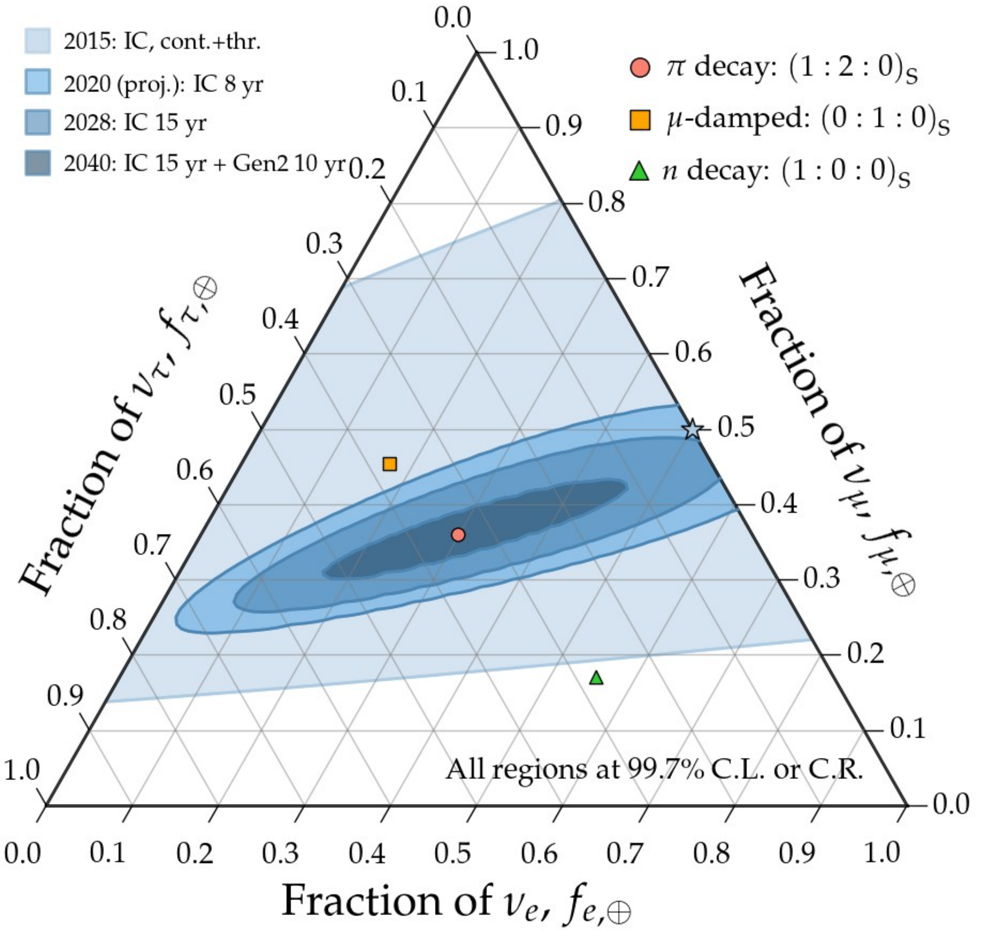

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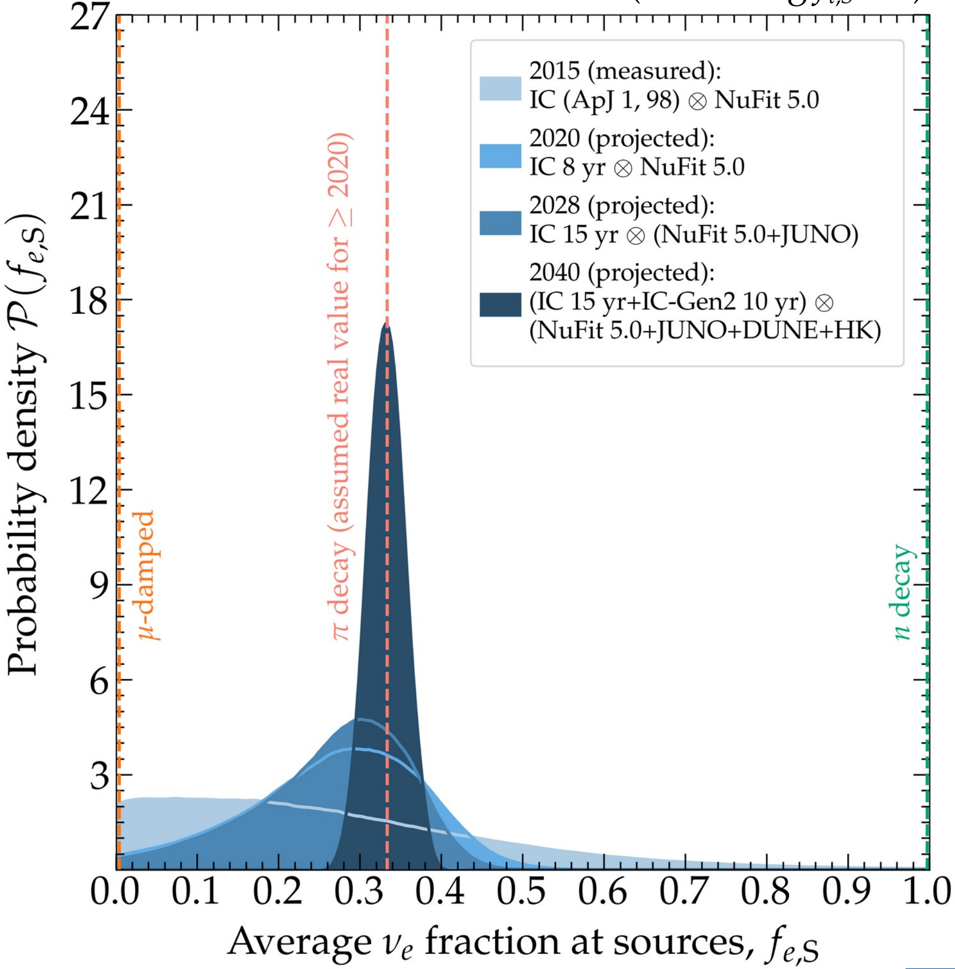

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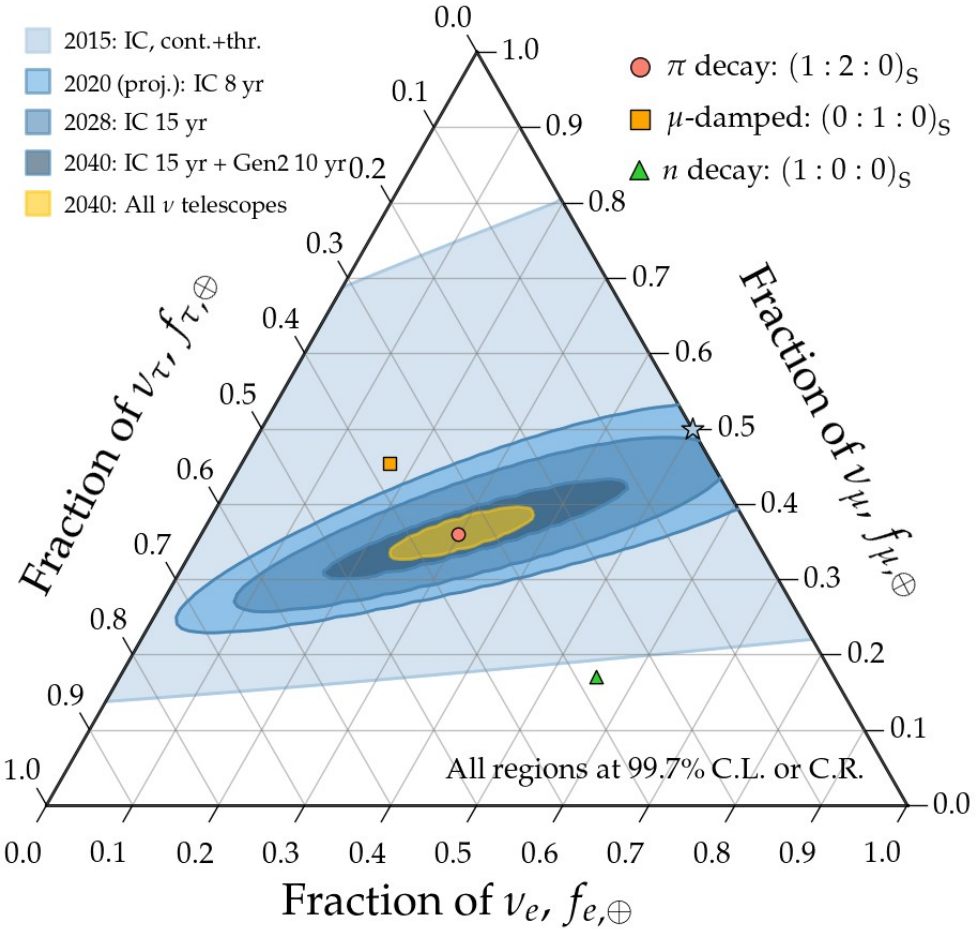

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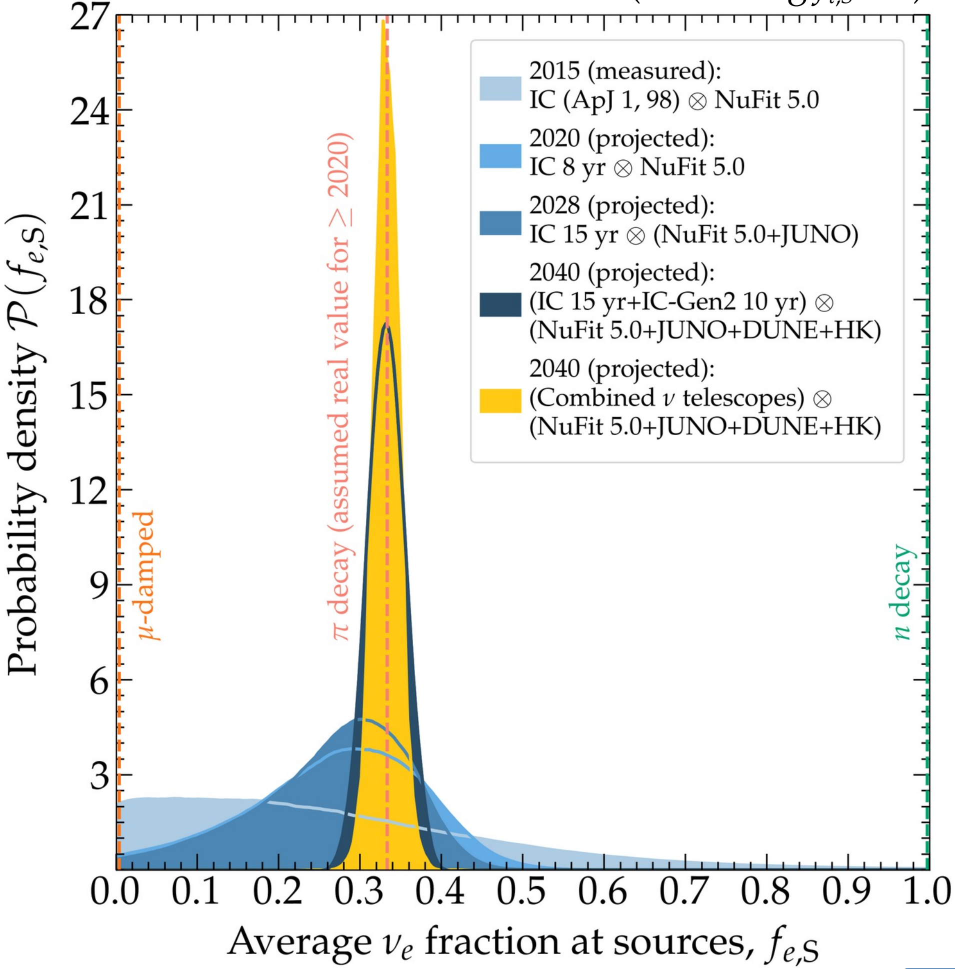


Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX
MB & Ahlers, *PRL* 2019

More than one production mechanism?

Can we detect the contribution of multiple ν production mechanisms?

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

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

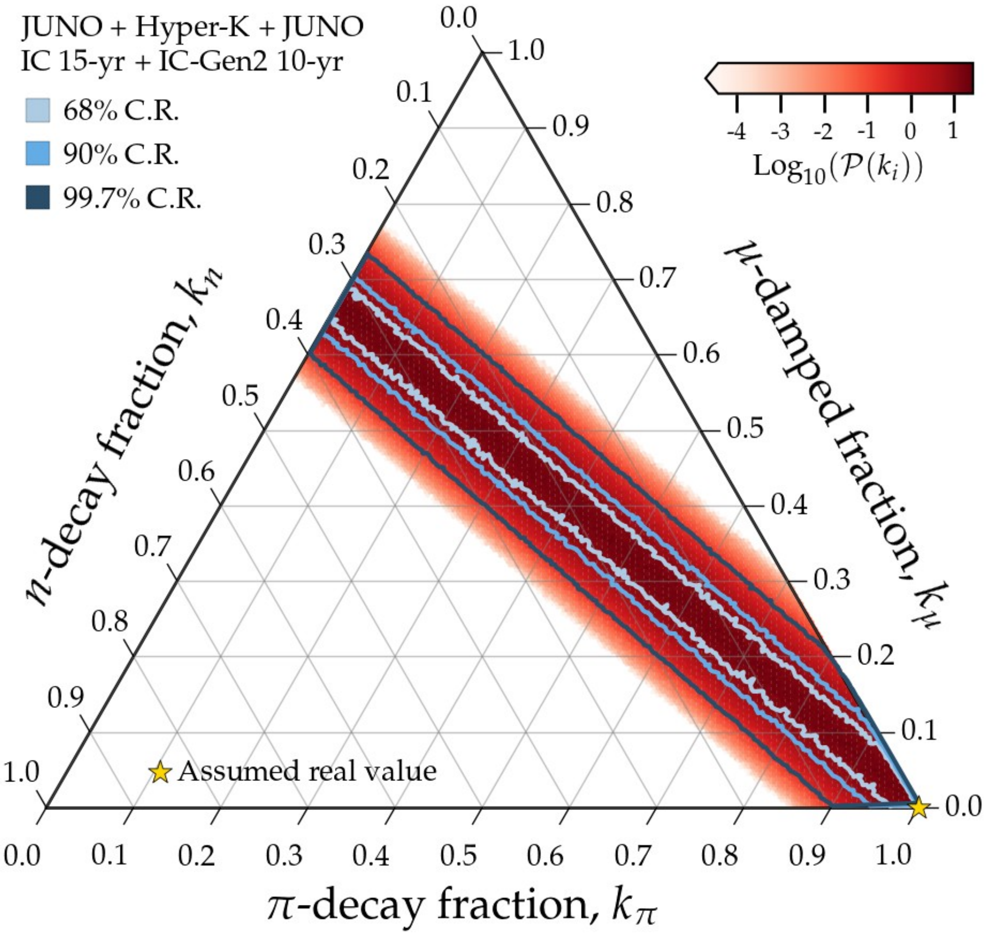
Propagate to Earth ↓

$\boldsymbol{f}_\oplus$

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

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

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



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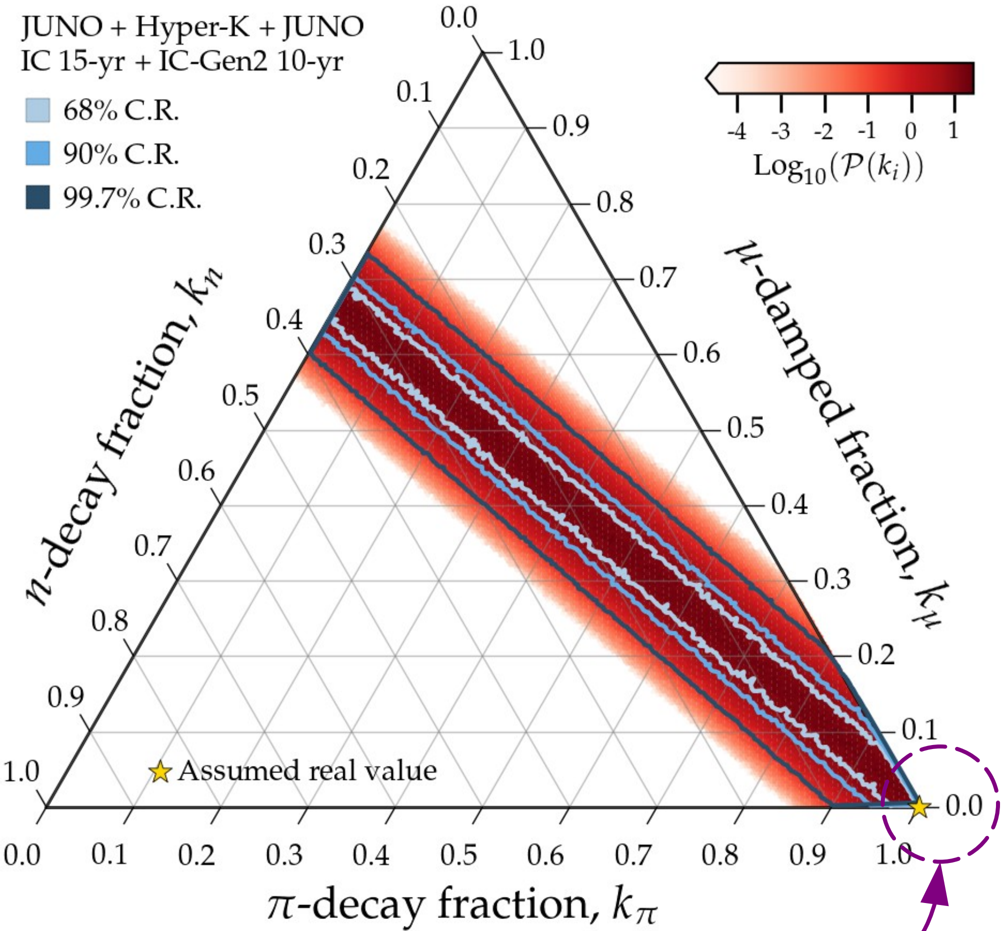

We do recover the real value

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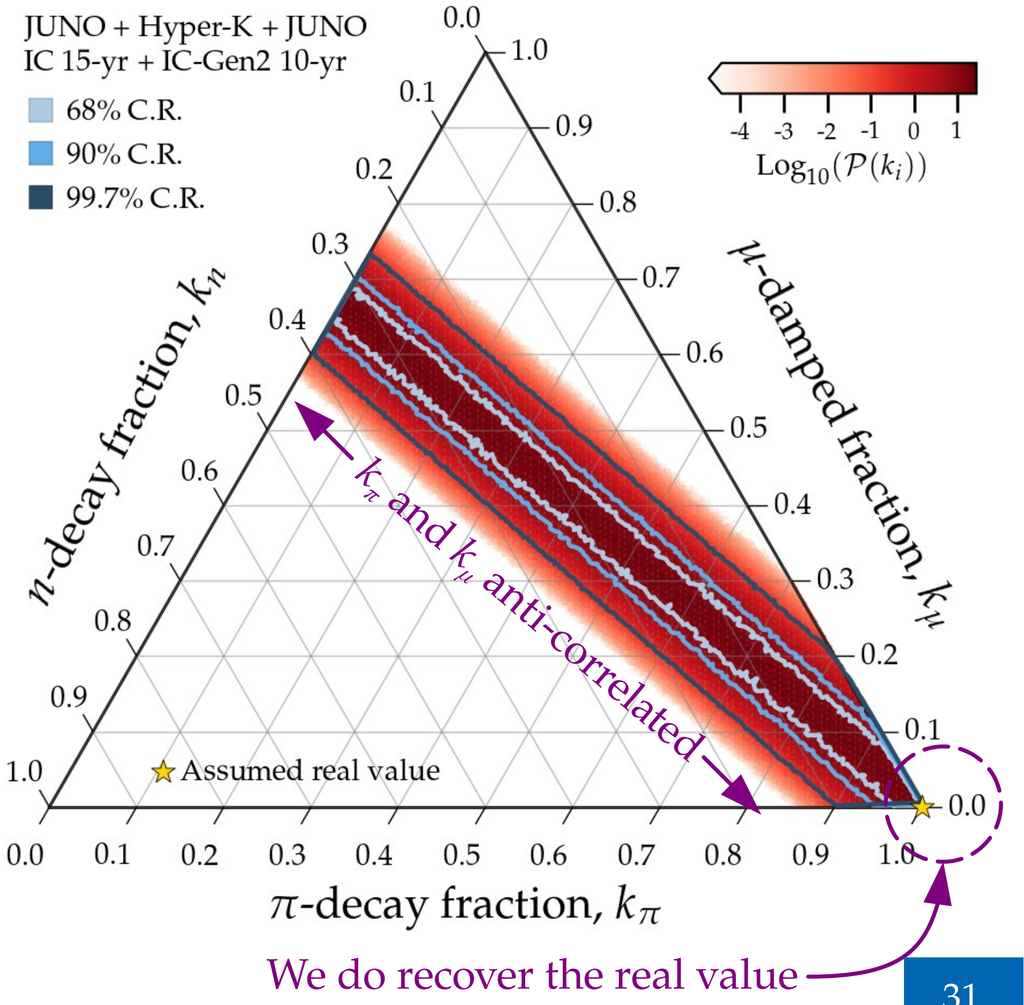

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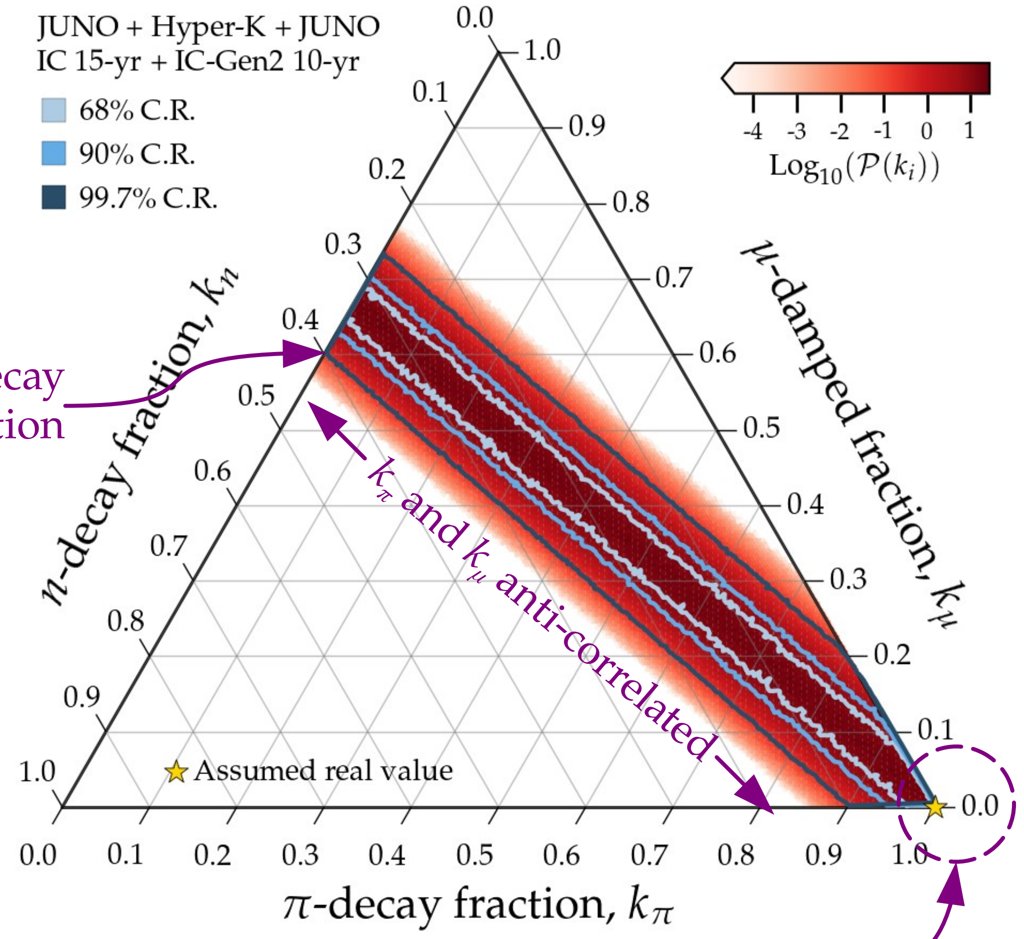

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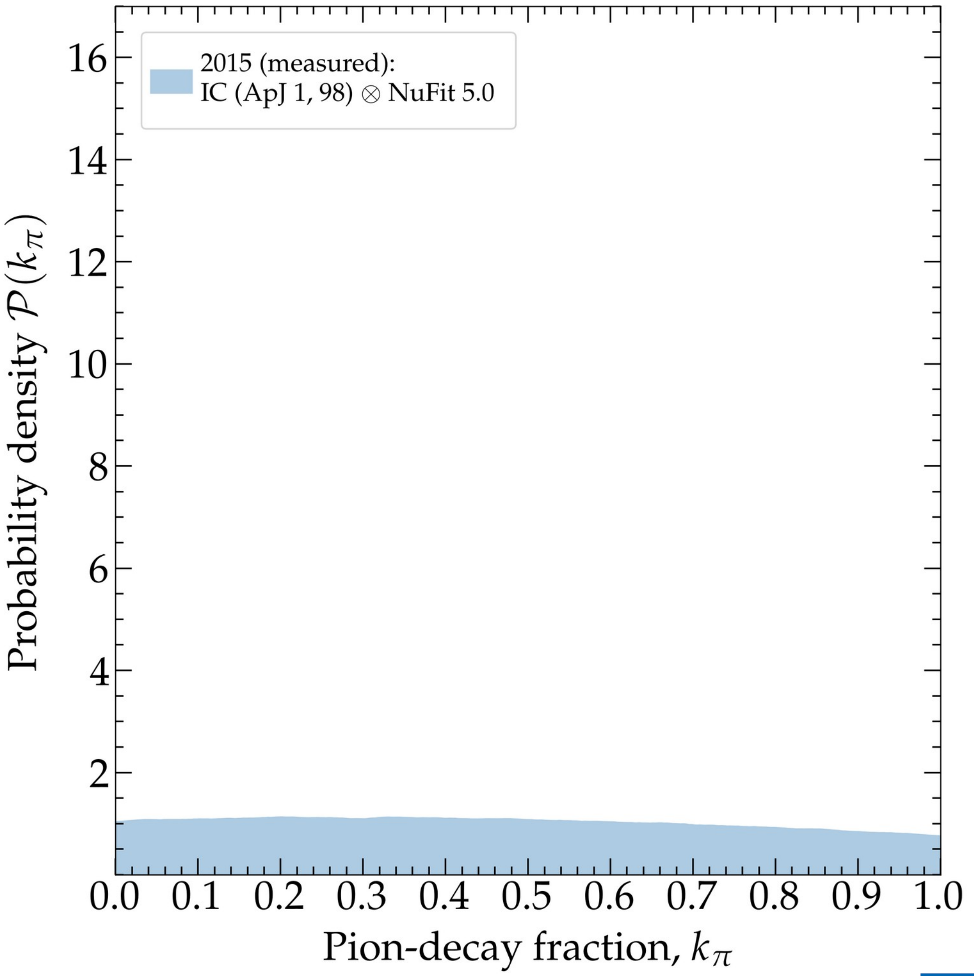

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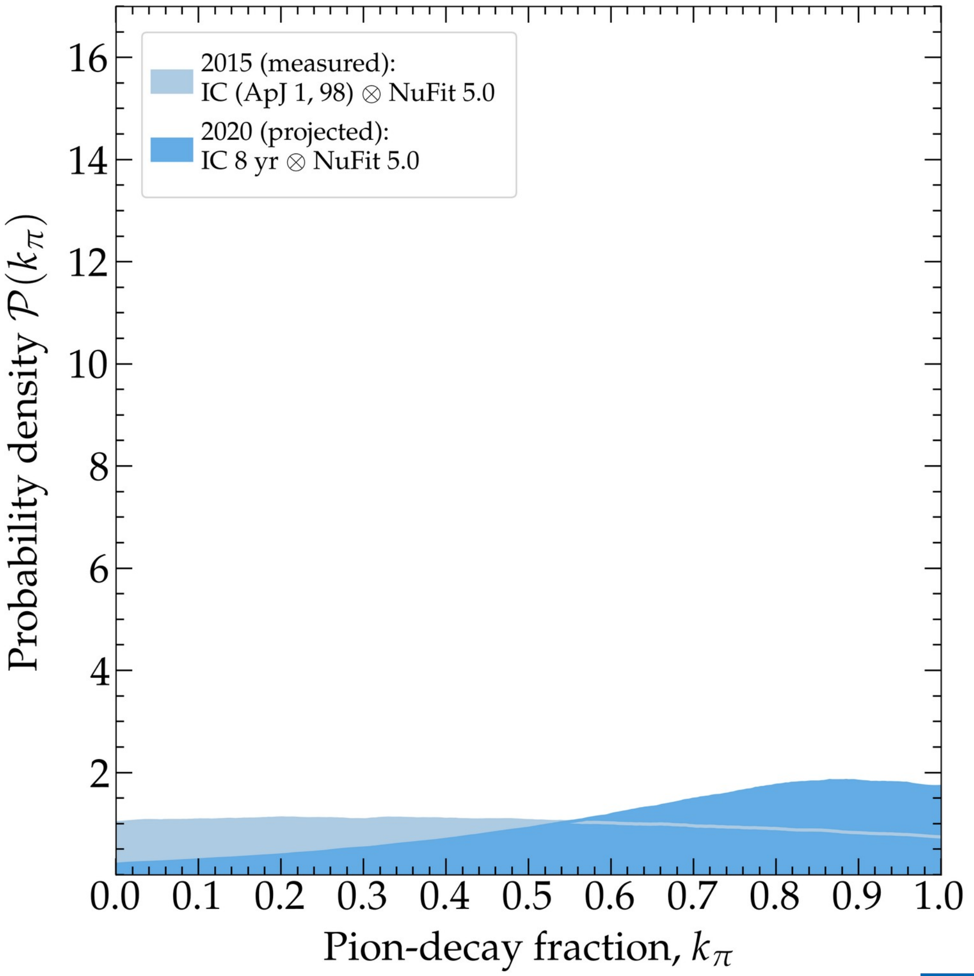

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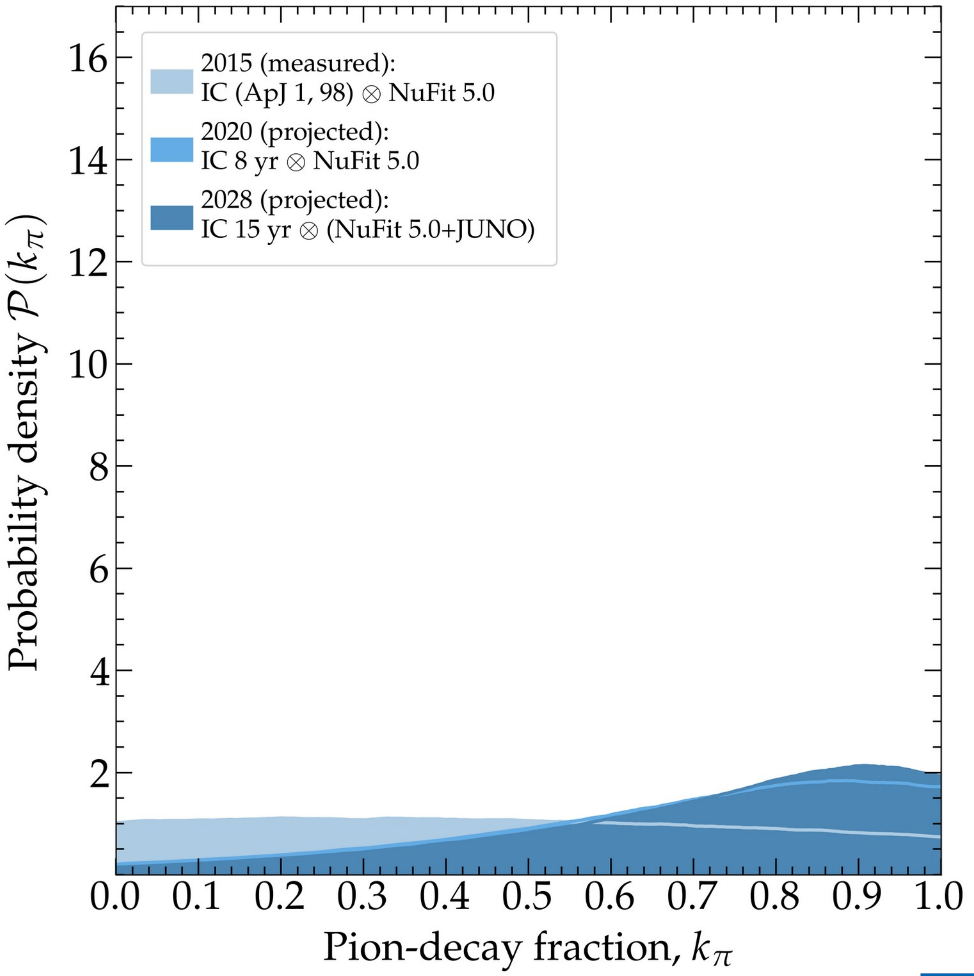

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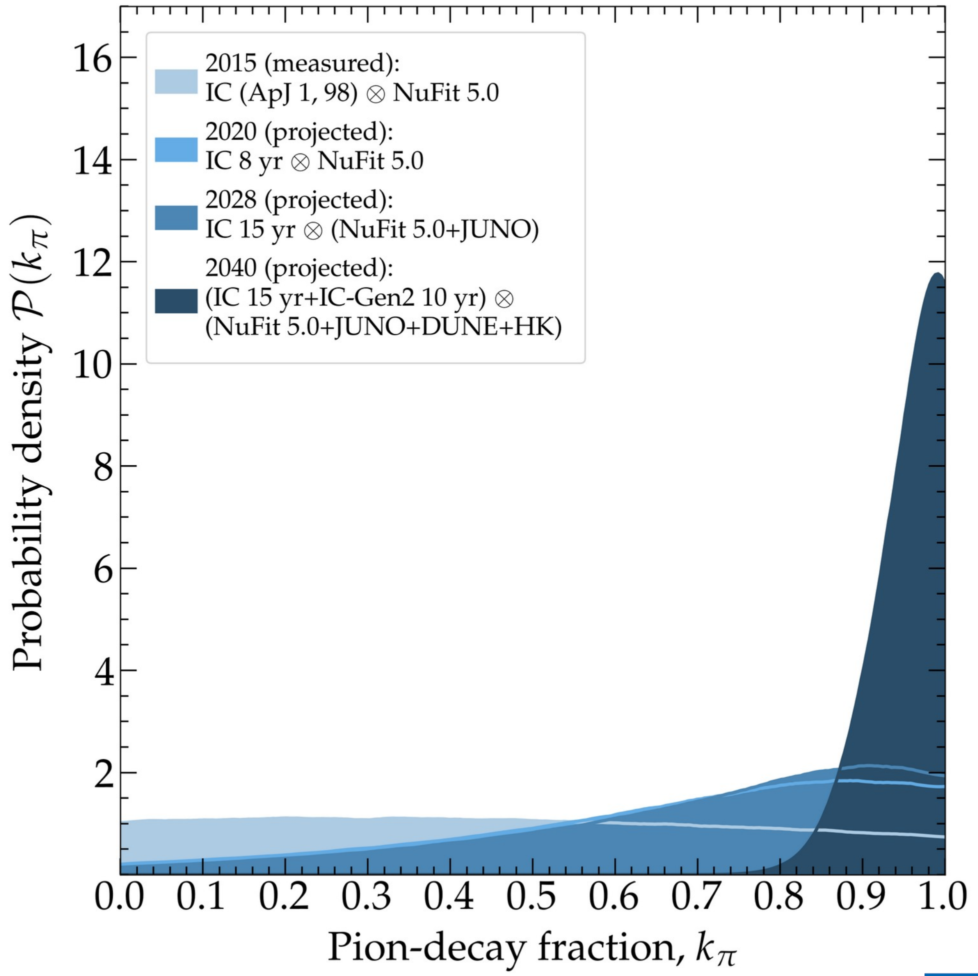

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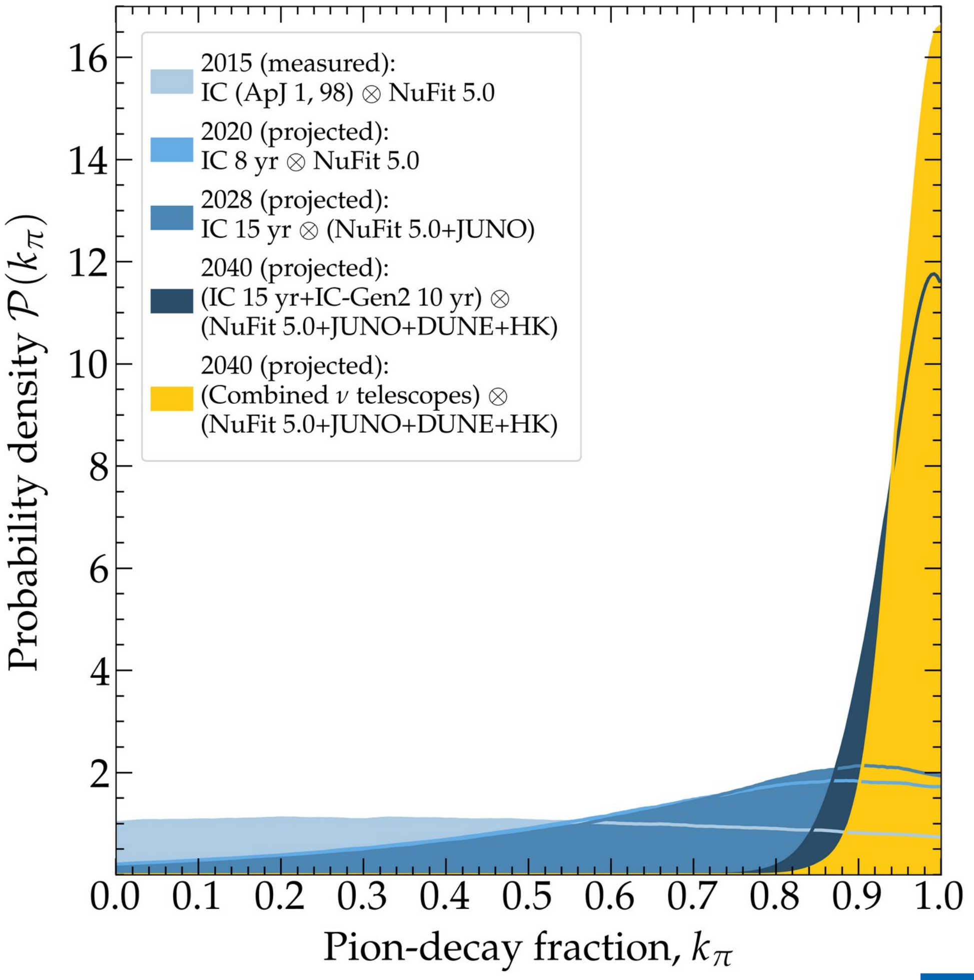

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

Using high-energy neutrinos as magnetometers

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

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

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

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

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Proton cooling

Induce a high-energy cut-off
in the emitted ν spectrum:

$$E_\nu'^2 \frac{dN_\nu}{dE_\nu'} \propto E_\nu'^{2-\alpha_\nu} e^{-E_\nu'/E_\nu'^{\max}}$$

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

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MB, Tamborra, *PRD* 2020
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$$E'^2_\nu \frac{dN_\nu}{dE'_\nu} \propto E'^{2-\alpha_\nu}_\nu e^{-E'_\nu / E'^{\max}_\nu}$$

$$E^{\max}_\nu \approx \frac{10^{10}\Gamma \text{ GeV}}{\sqrt{B'/\text{G}}}$$

Muon cooling

Change flavor composition:

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

$$E^{\text{sync}}_{\nu,\mu} \approx 10^9 \Gamma \frac{\text{G}}{B'} \text{ GeV}$$

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

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MB, Tamborra, *PRD* 2020
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$$E_{\nu,\mu}^{\text{sync}} \approx 10^9 \Gamma \frac{\text{G}}{B'} \text{ GeV}$$

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

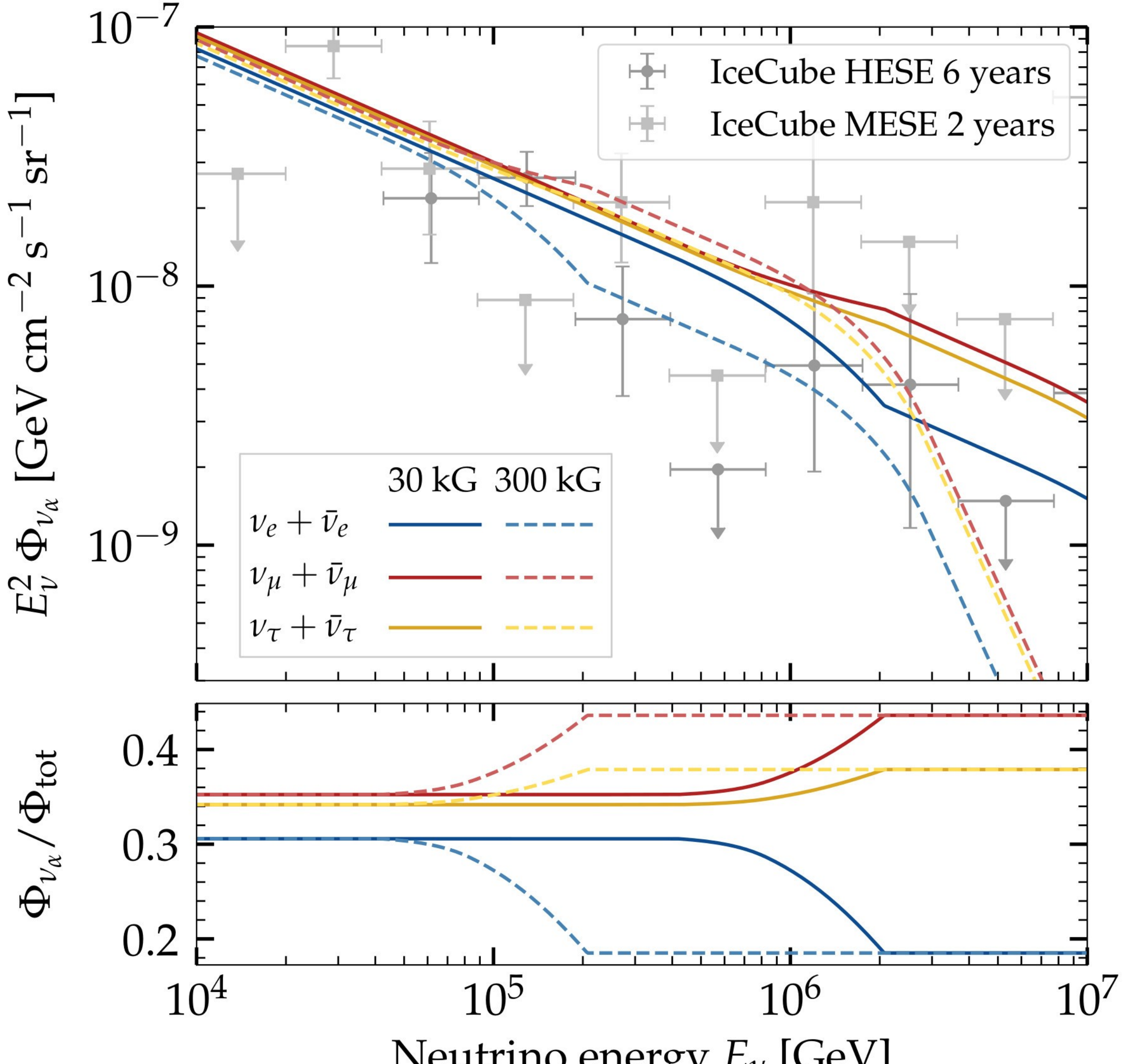
$$\mu^+ \rightarrow \bar{\nu}_\mu + e^+ + \nu_e$$

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



MB, Tamborra, *PRD* 2020
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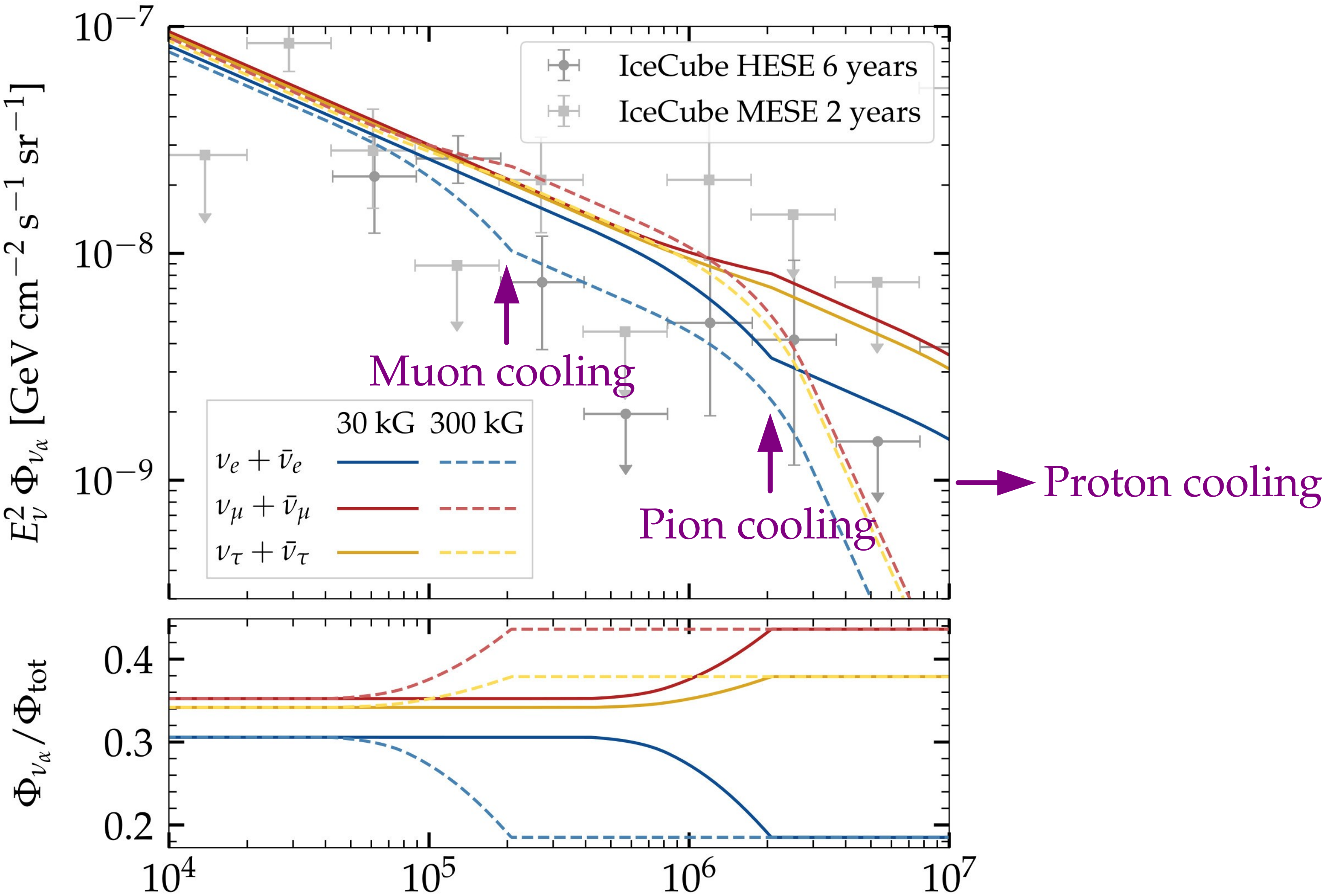
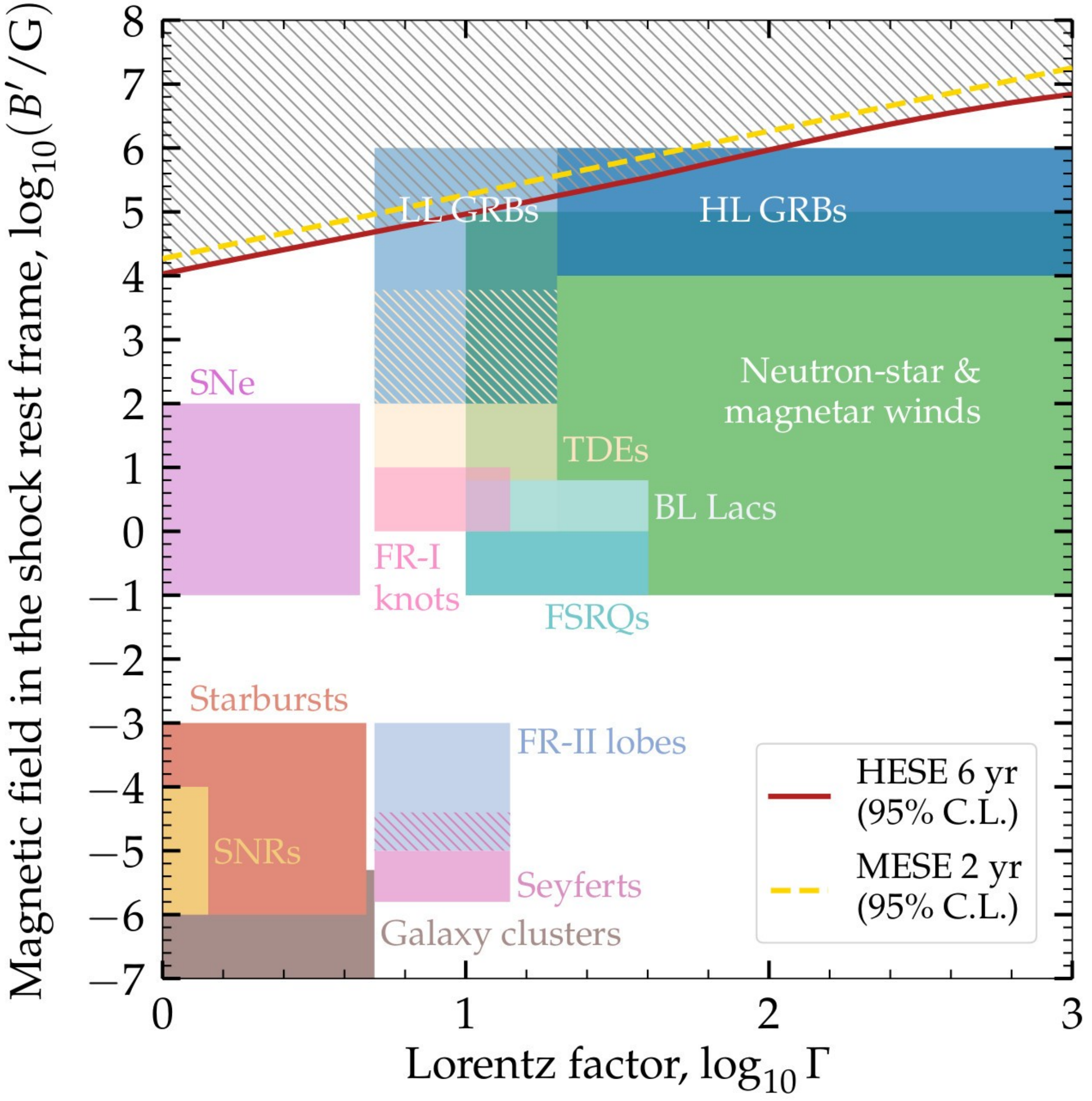


MB, Tamborra, *PRD* 2020
See also: Winter, *PRD* 2013

ν sources with strong B' are likely not dominant

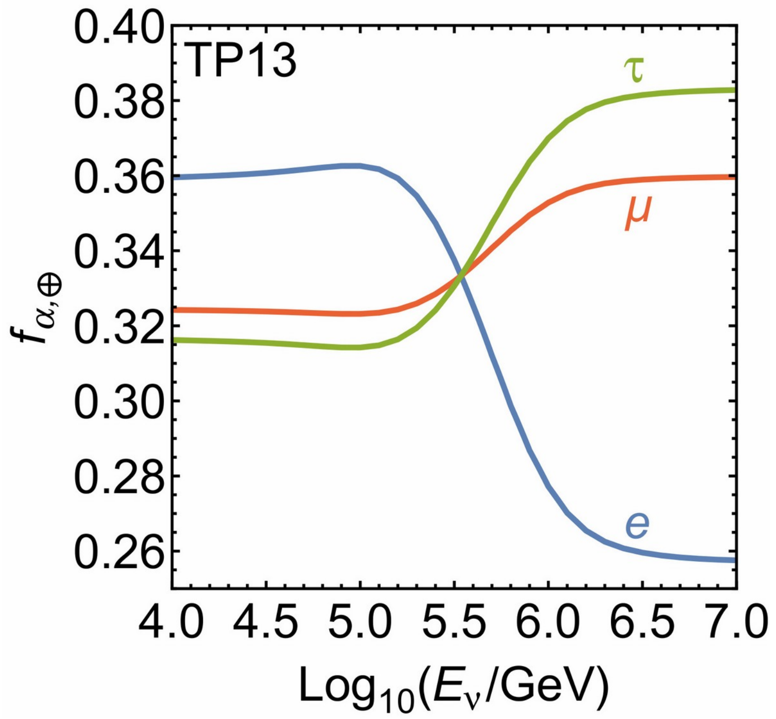
Average B' must be $<$ 10kG–10 MG

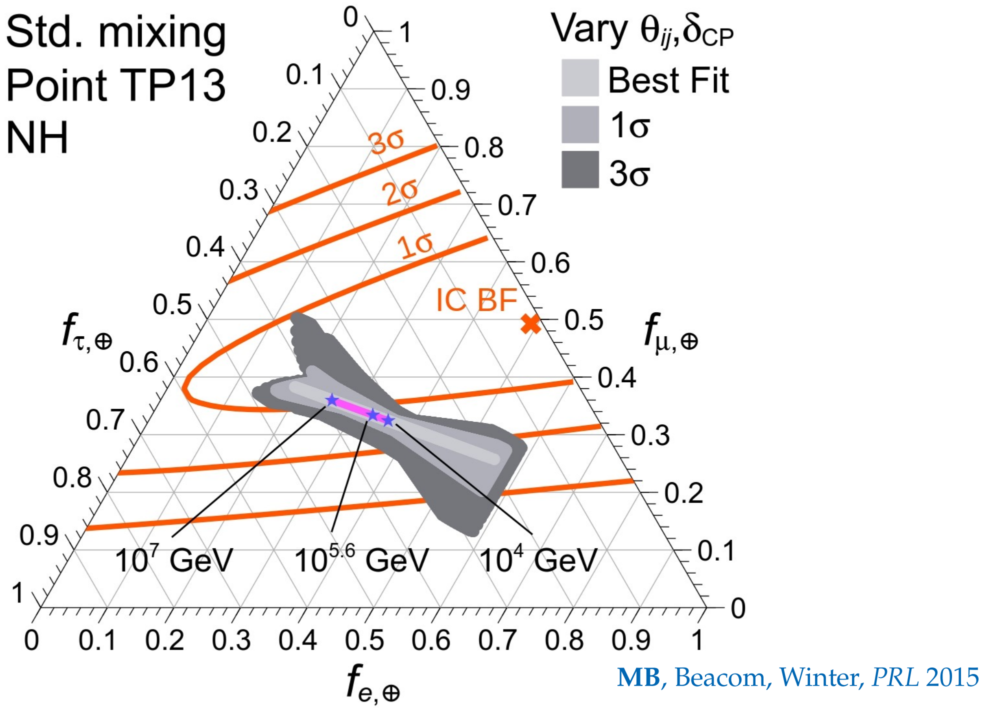


MB, Tamborra, *PRD* 2020
See also: Winter, *PRD* 2013

Energy dependence of the flavor composition?

Different neutrino production channels accessible at different energies –



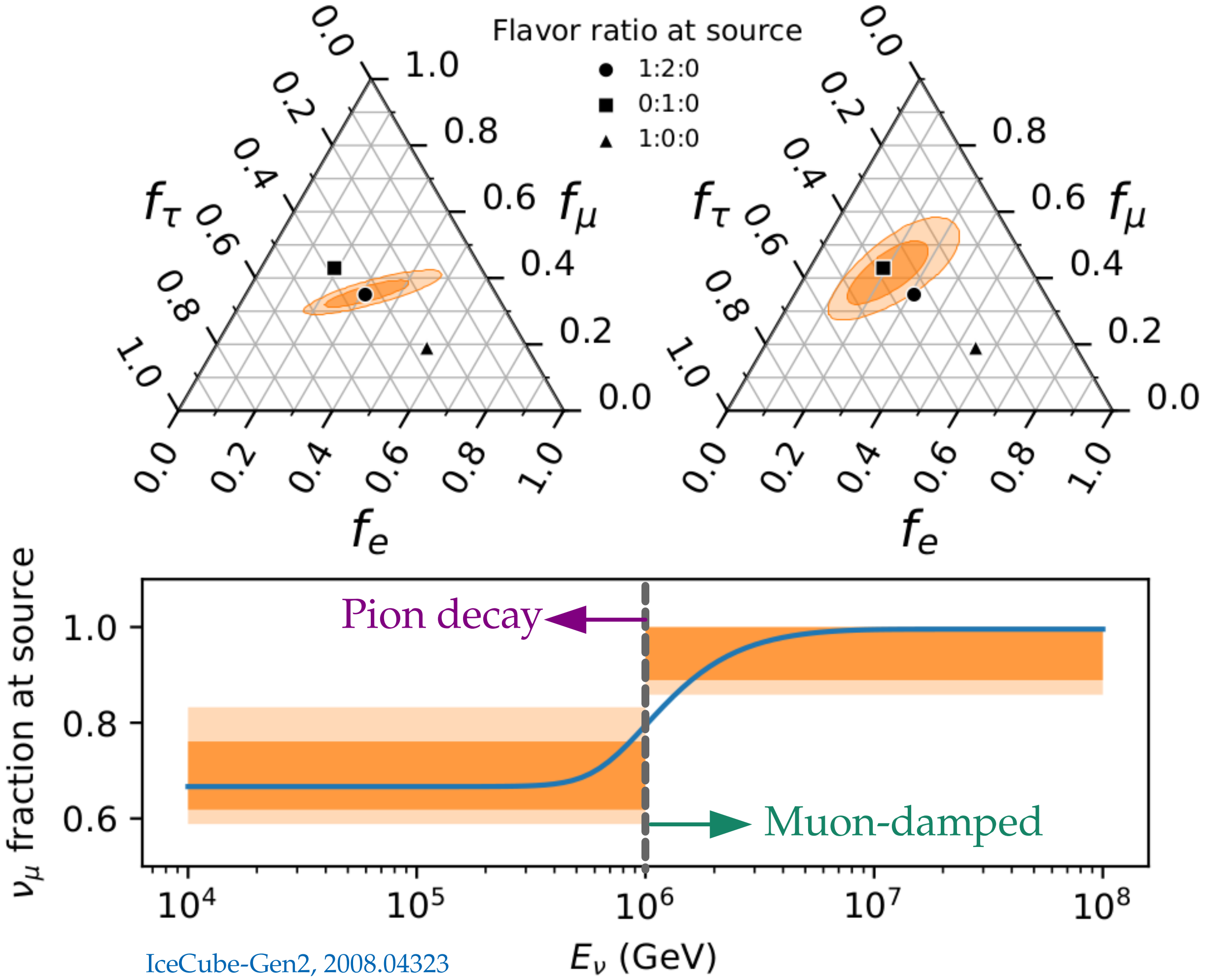


MB, Beacom, Winter, *PRL* 2015

- 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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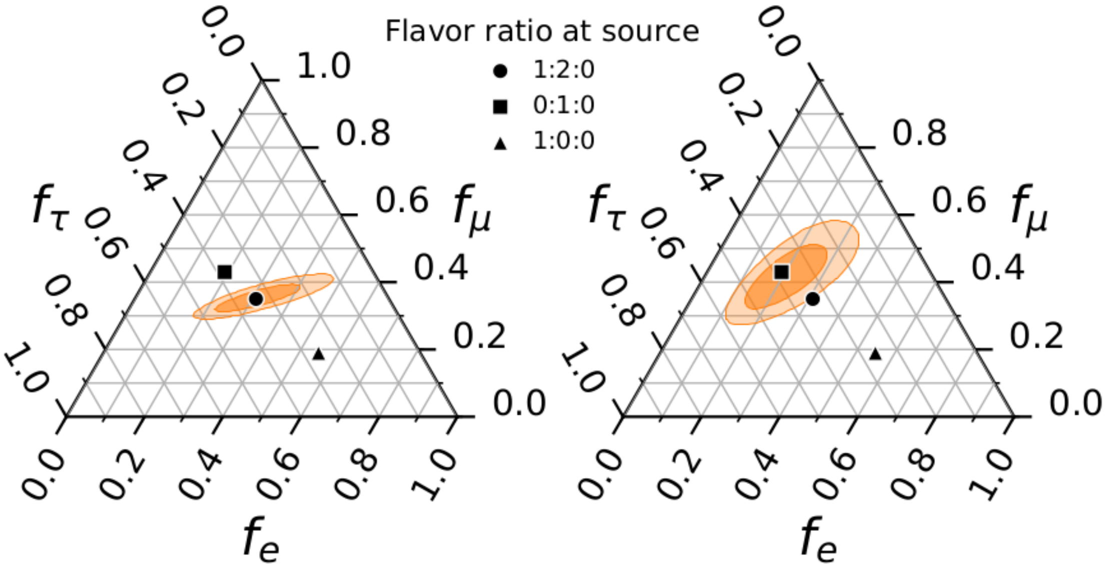
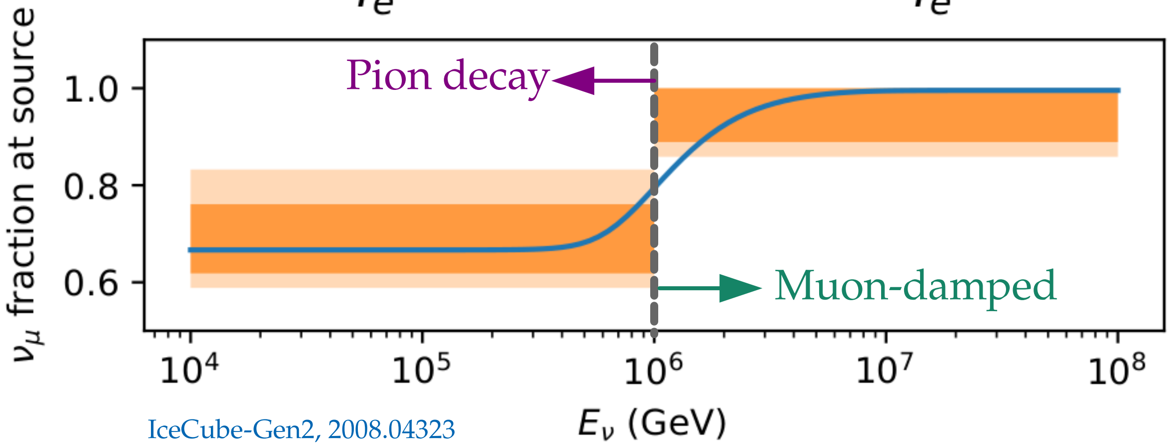
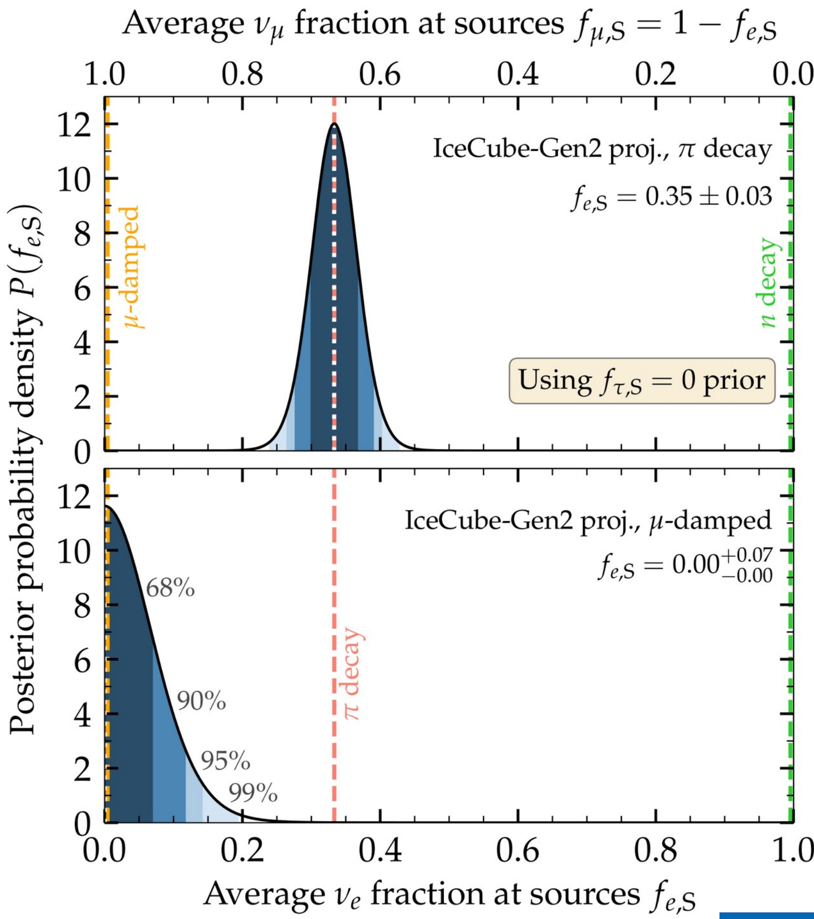




IceCube-Gen2, 2008.04323

Inferred (at sources):



MB & Ahlers, *PRL* 2019

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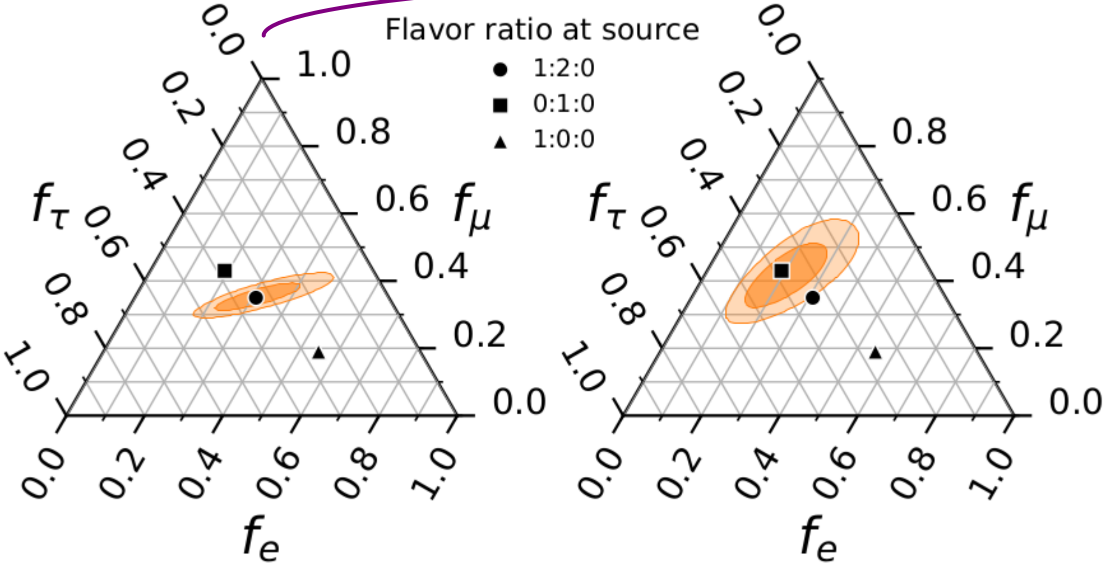

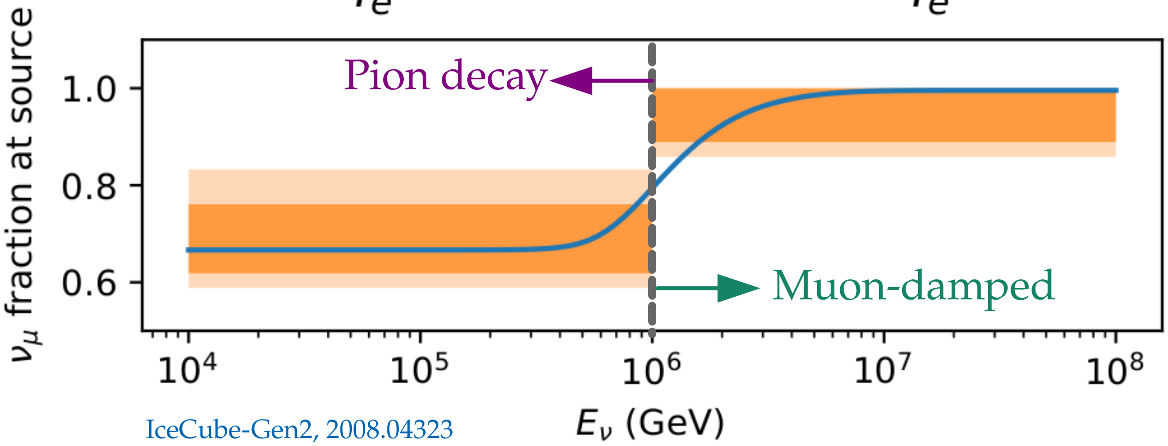

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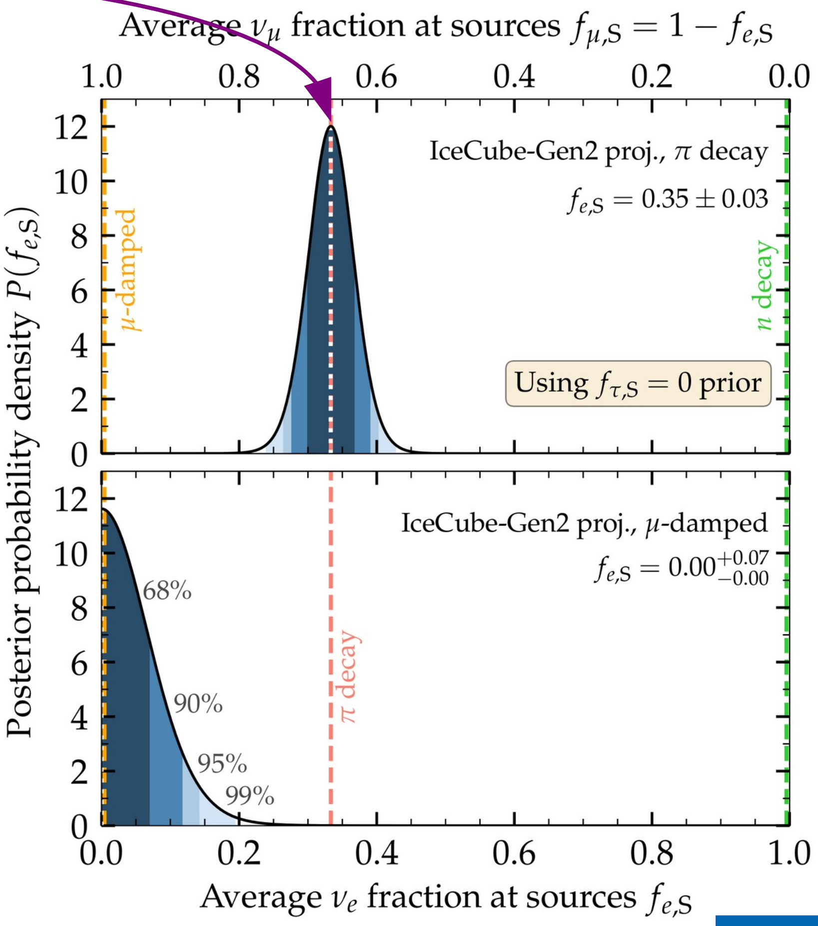

MB & Ahlers, *PRL* 2019

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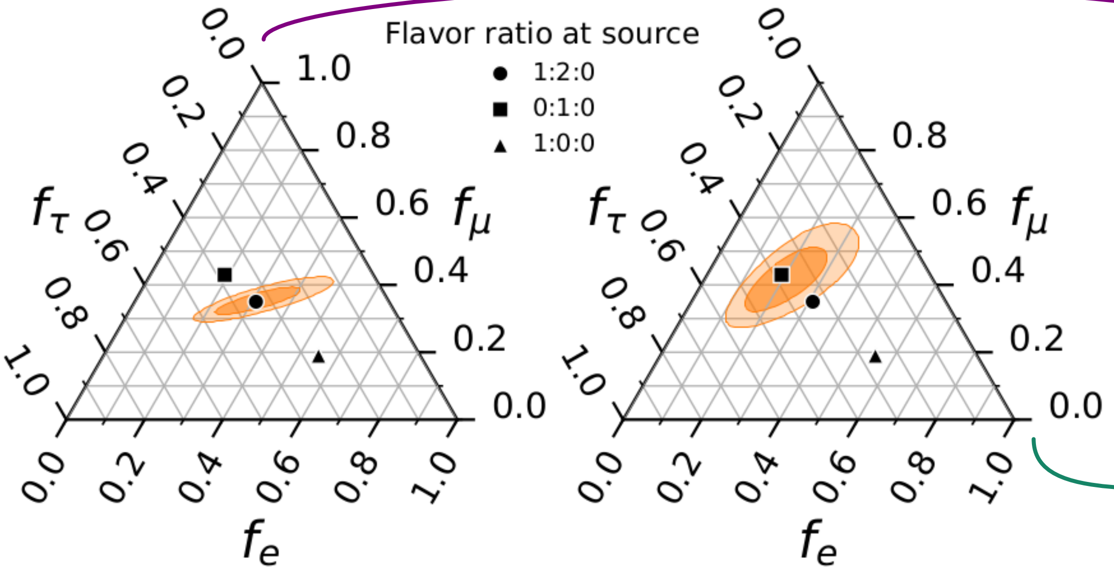

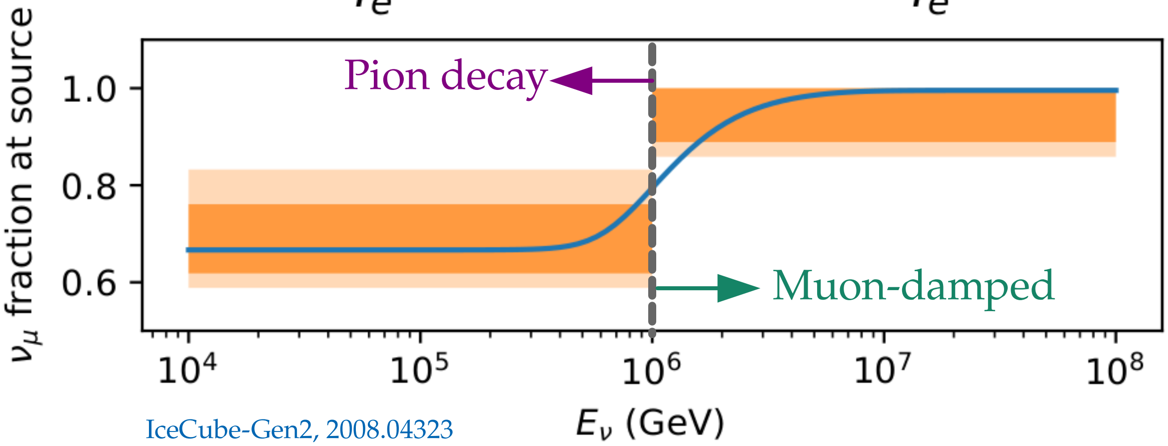

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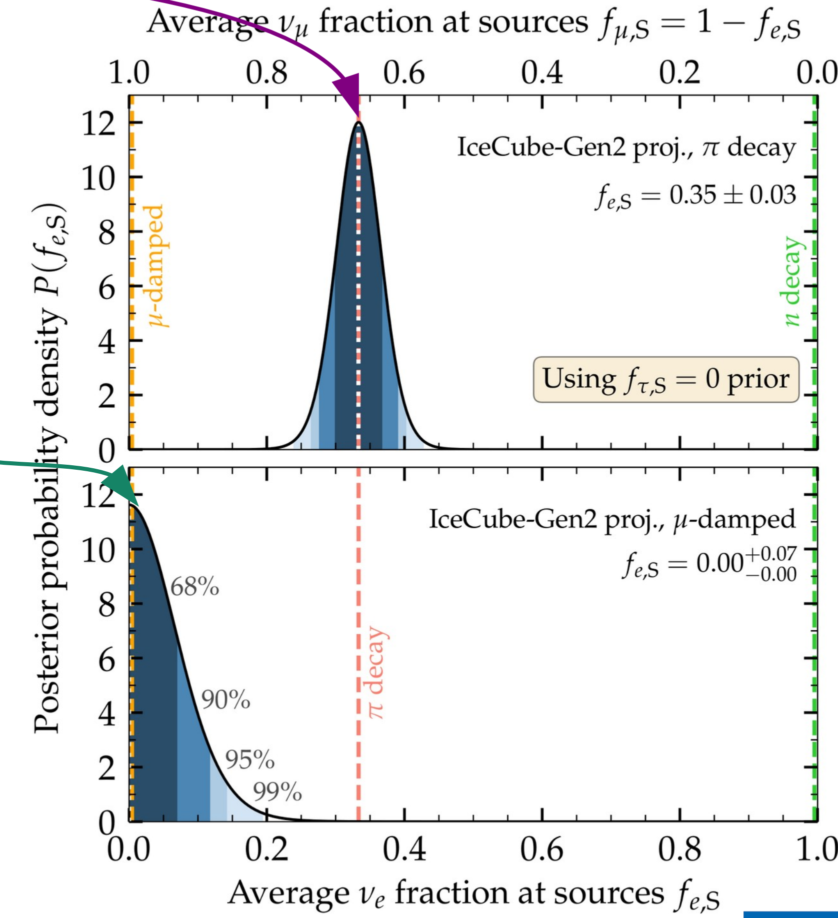


IceCube-Gen2, 2008.04323

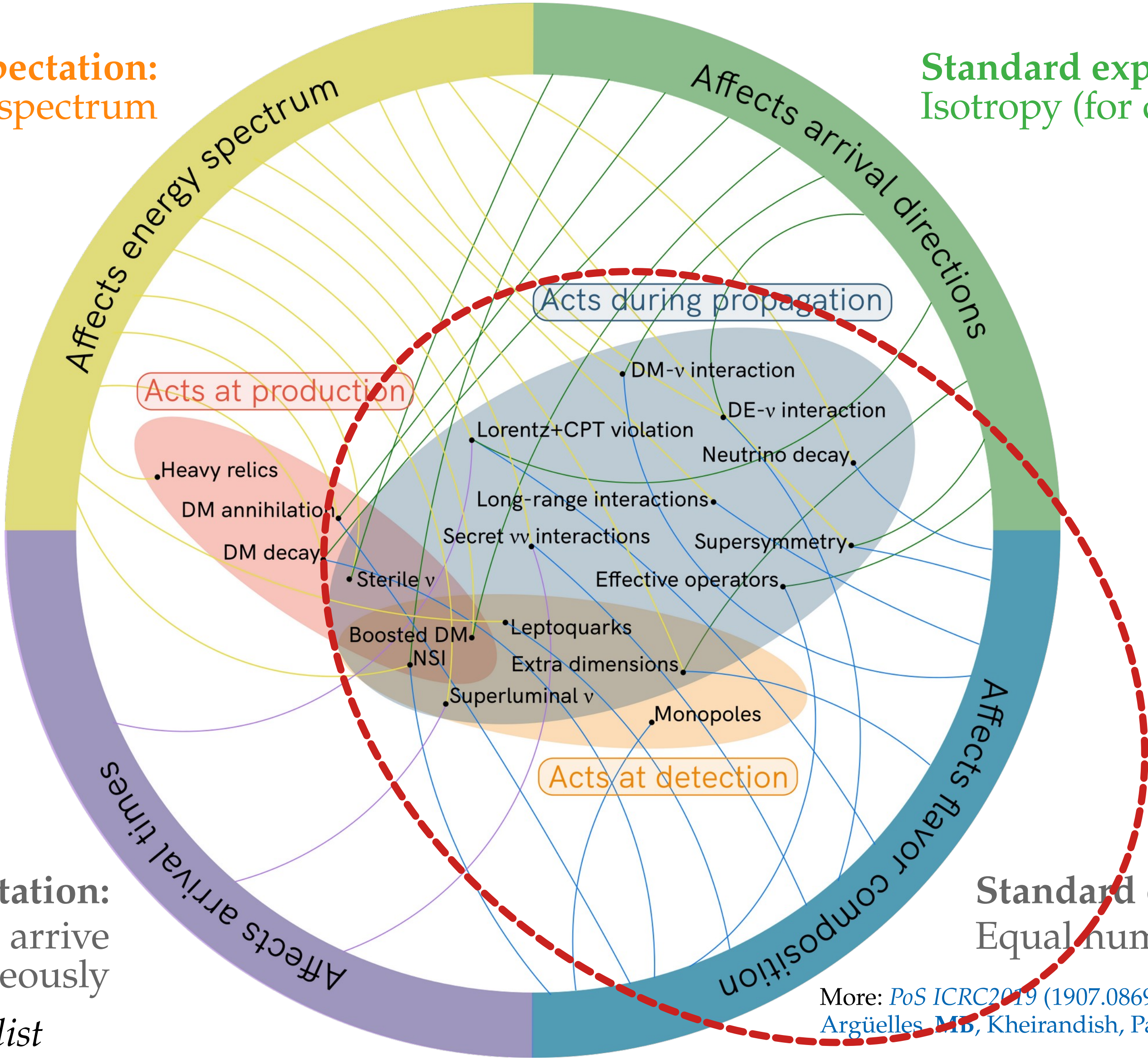
MB & Ahlers, *PRL* 2019

New physics in flavor composition

Repurpose the flavor sensitivity to test new physics:

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



Standard expectation:
ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Note: Not an exhaustive list

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

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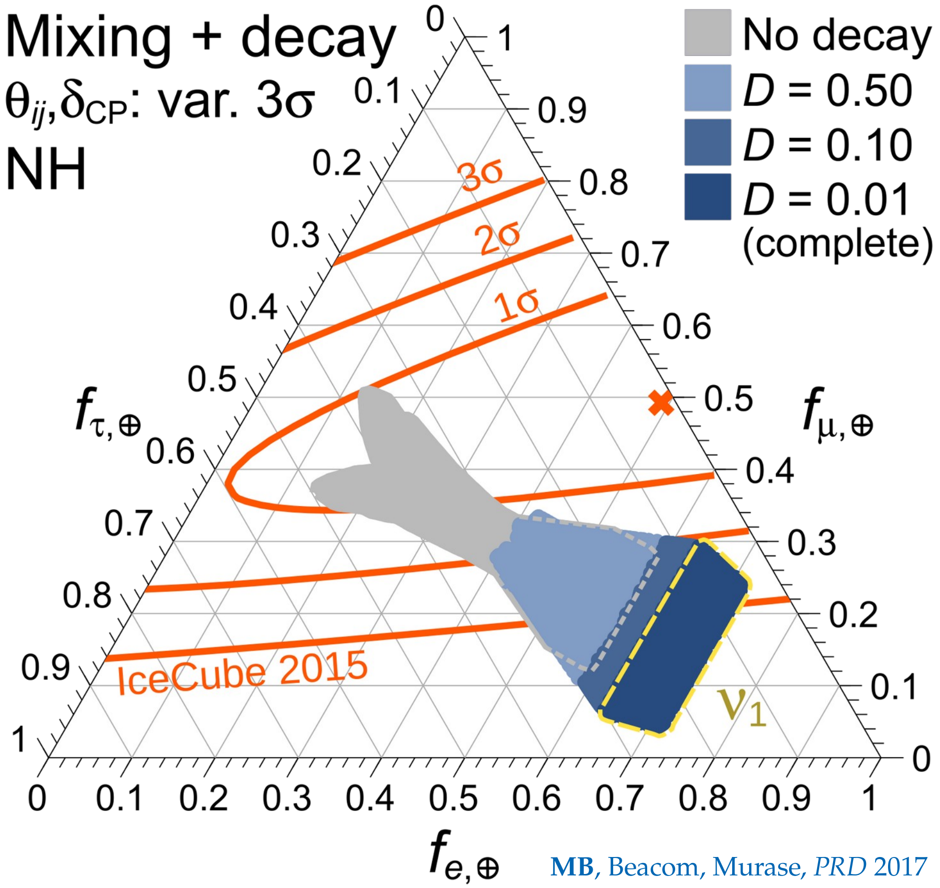
Repurpose the flavor sensitivity to test new physics:

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

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

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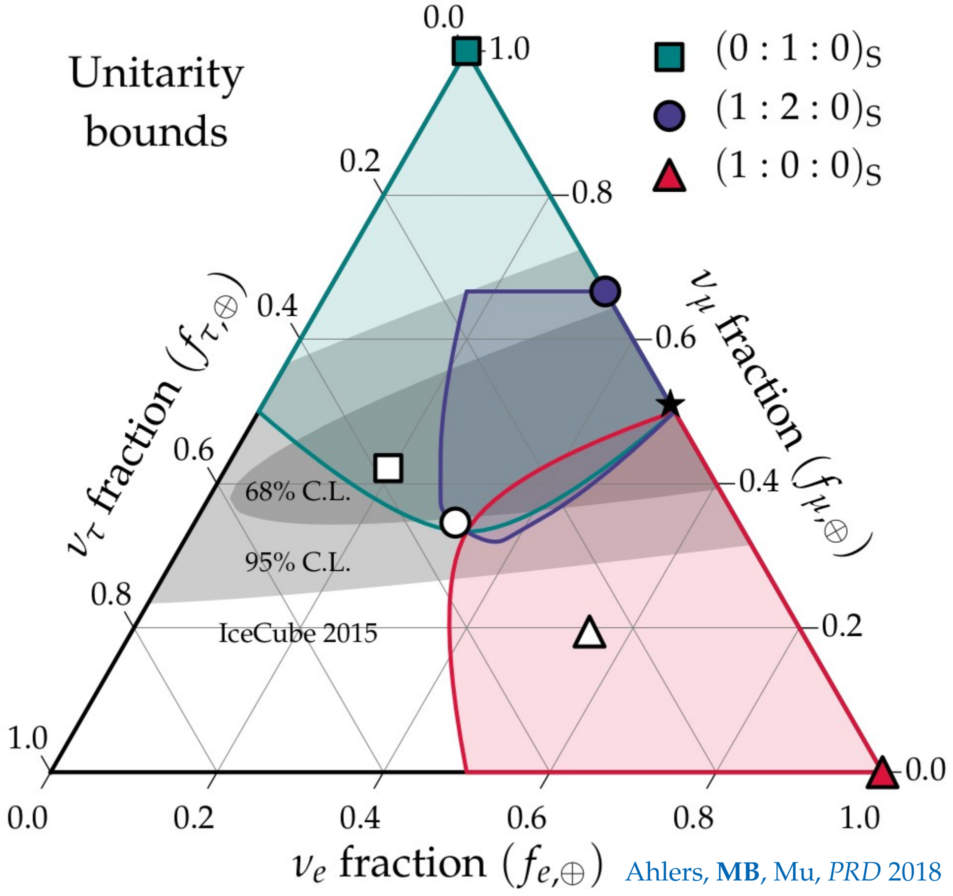
  [Xu, He, Rodejohann, *JCAP* 2014; Ahlers, **MB**, Mu, *PRD* 2018; Ahlers, **MB**, Nortvig, 2009.01253]



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

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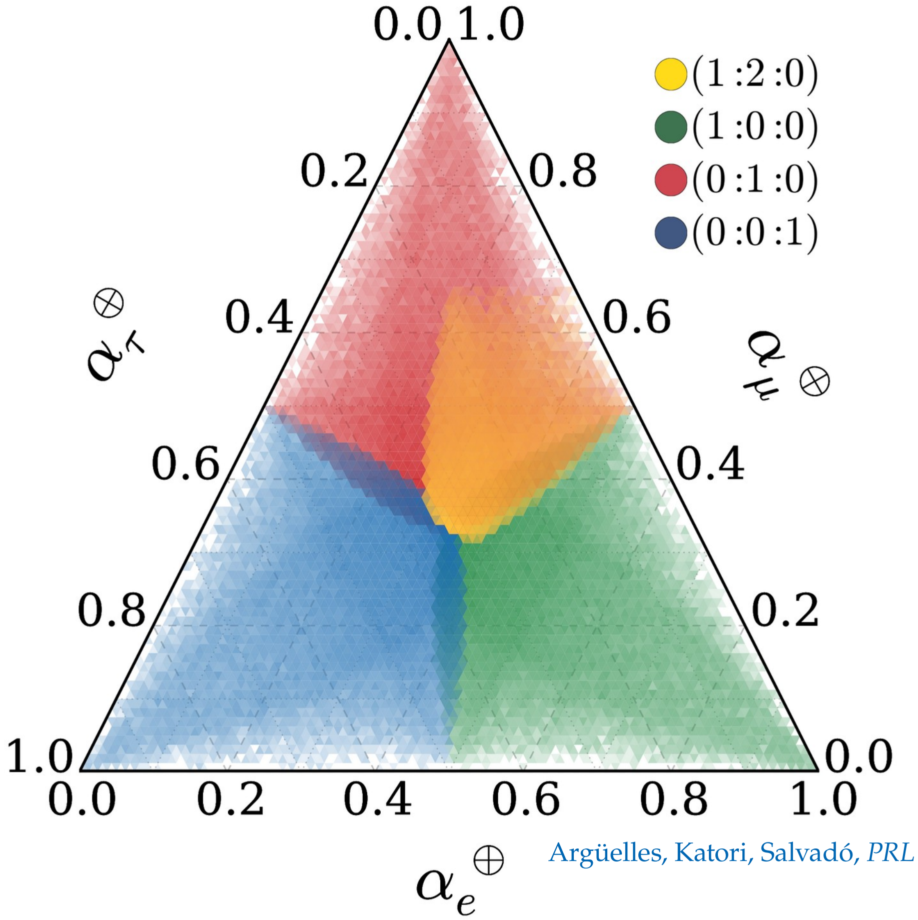

Argüelles, Katori, Salvadó, *PRL* 2015

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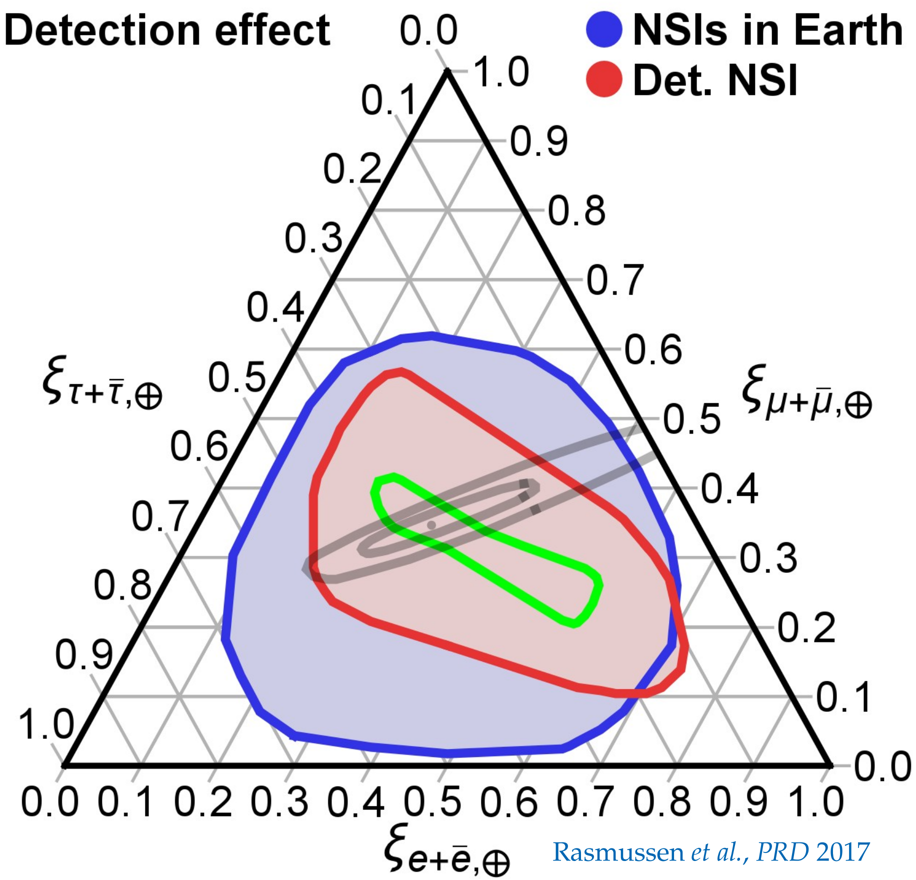

Rasmussen *et al.*, *PRD* 2017

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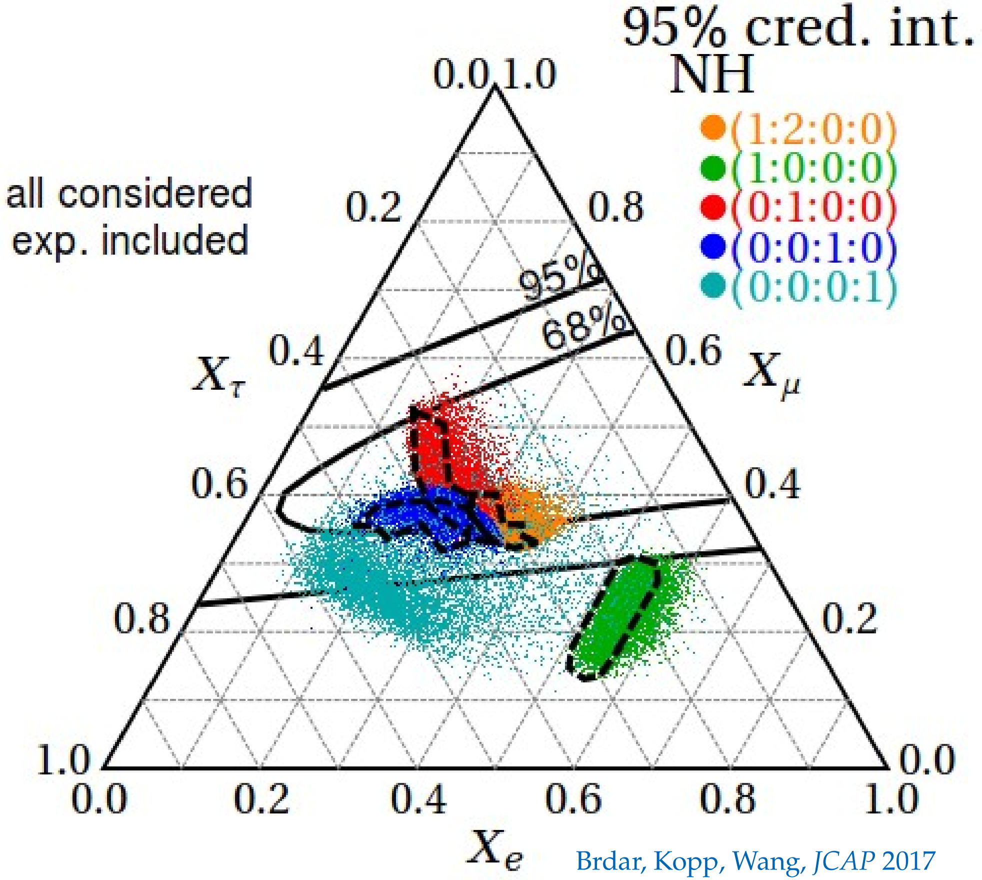

Brdar, Kopp, Wang, *JCAP* 2017

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

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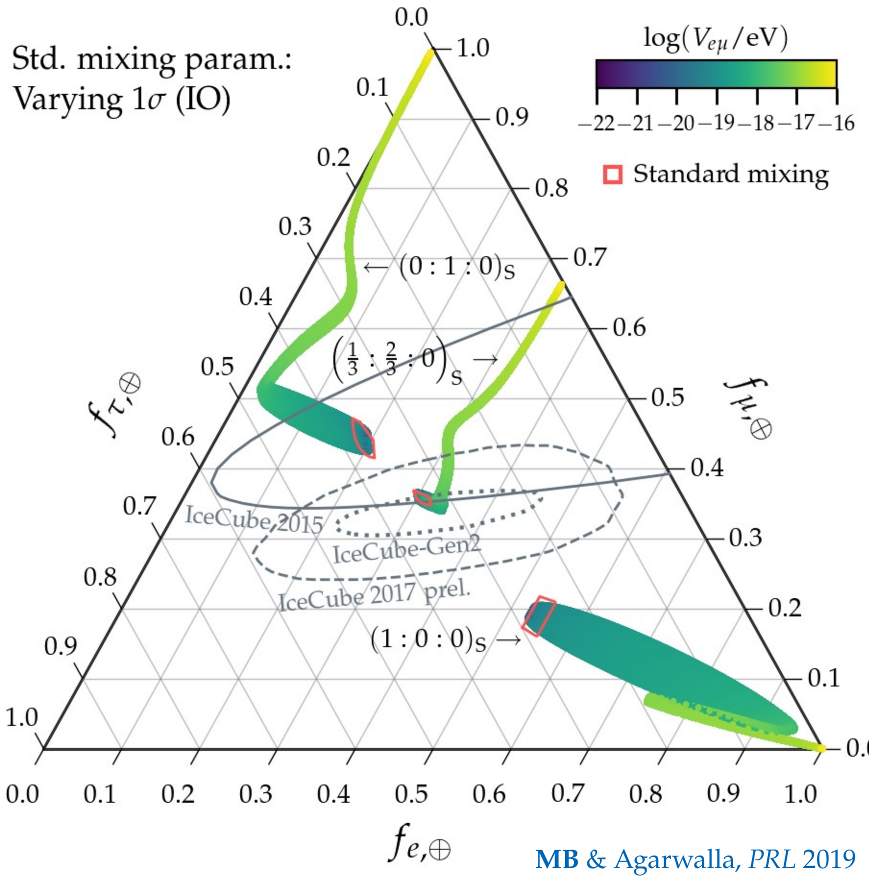
- ▸ Long-range *e*ν interactions
  [**MB** & Agarwalla, *PRL* 2019]



MB & Agarwalla, *PRL* 2019

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

Assorted answerable questions

Measure flavor ratios better in water-based Cherenkov ν telescopes?

Neutron and muon echoes separate better showers from ν_e and ν_τ [Li, **MB**, Beacom, *PRL* 2019]

Might also help distinguish e.m. *vs.* hadronic showers

Flavor ratios from point sources?

Need enough events, probably only doable with IceCube-Gen2 or a global ν observatory (PLEνUM)

Trigger with tracks, then look for cascades in the same direction

Flavor ratios of ν vs. $\bar{\nu}$?

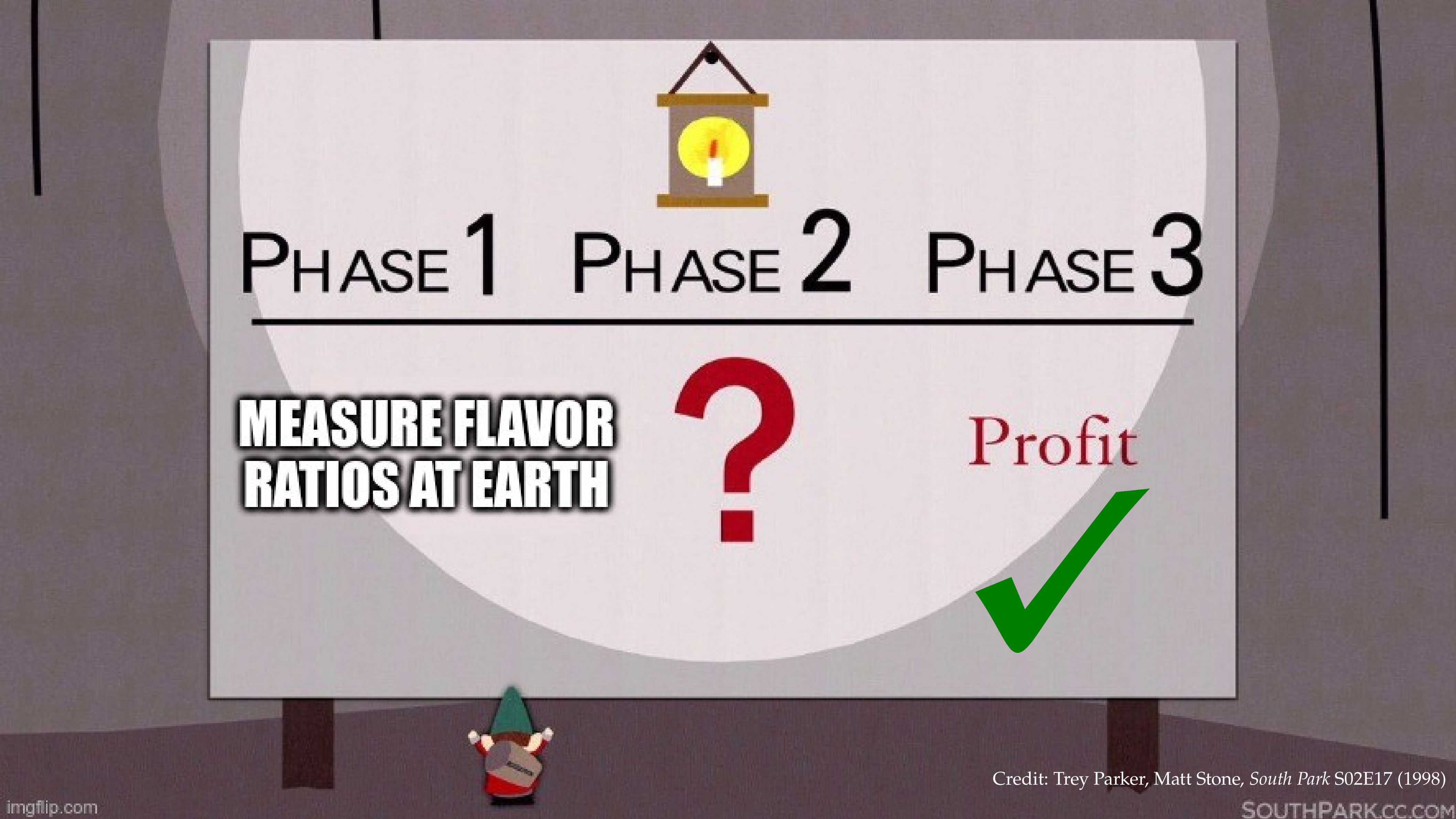
Hard: cross sections and inelasticity distributions are very similar

Glashow resonance helps – from 1 candidate: $\bar{\nu}_e/\nu_e = 1$ [Lu, UHECR 2018], $\bar{\nu}/\nu = 0.64 \pm 0.23$ [**MB**, 2004.06844]

Can we measure the flavor composition of ultra-high-energy neutrinos?

Using in-ice radio (RNO-G, IceCube-Gen2): promising! [García-Fernández, Nelles, Glaser, *PRD* 2020]

Other techniques (atmospheric radio, fluorescence, *etc.*): remains to be seen



Credit: Trey Parker, Matt Stone, *South Park* S02E17 (1998)

Backup slides

Flavor-transition probability: the quick and dirty of it

- In matrix form: $$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}U^*_{e1} & U^*_{e2} & U^*_{e3}\\ U^*_{\mu1} & U^*_{\mu2} & U^*_{\mu3}\\ U^*_{\tau1} & U^*_{\tau2} & U^*_{\tau3}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

- Pontecorvo-Maki-Nakagawa-Sakata matrix ($c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$):

$$U = \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}}_{\text{Atmospheric}} \underbrace{\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}}_{\text{Cross mixing}} \underbrace{\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\text{Solar}} \underbrace{\begin{pmatrix}e^{i\alpha_1/2} & 0 & 0\\ 0 & e^{i\alpha_2/2} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\text{Majorana CP phases}}$$

- Probability for $\nu_\alpha \to \nu_\beta$: $$P_{\nu_\alpha\to\nu_\beta} = \delta_{\alpha\beta} - 4\sum_{i>j}\mathrm{Re}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2\left(\Delta m^2_{ij}\frac{L}{4E}\right) + 2\sum_{i>j}\mathrm{Im}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin\left(\Delta m^2_{ij}\frac{L}{2E}\right)$$

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$\theta_{23} \approx 48°$
$\theta_{13} \approx 9°$
$\theta_{12} \approx 34°$
$\delta \approx 222°$

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Atmospheri
c

Cross
mixing

Solar

Majorana CP phases

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… But high-energy neutrinos oscillate *fast*

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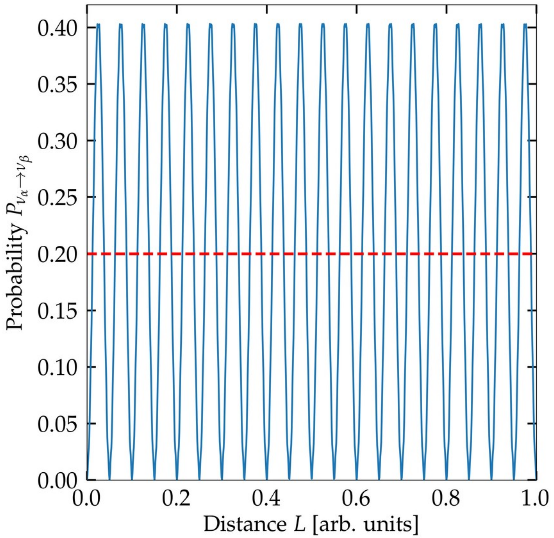

Oscillation length for 1-TeV ν: $2\pi \times 2E/\Delta m^2 \sim 0.1$ pc

~ 8% of the way to Proxima Centauri
≪ Distance to Galactic Center (8 kpc)
≪ Distance to Andromeda (1 Mpc)
≪ Cosmological distances (few Gpc)

We cannot resolve oscillations, so we use instead the average probability:

$$\langle P_{\nu_\alpha \to \nu_\beta} \rangle = \sum_{i=1}^{3} |U_{\alpha i}|^2 |U_{\beta i}|^2$$

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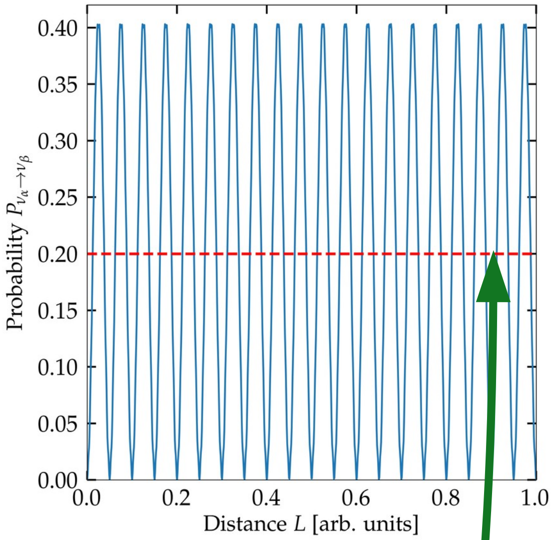

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Flavor composition – a few source choices

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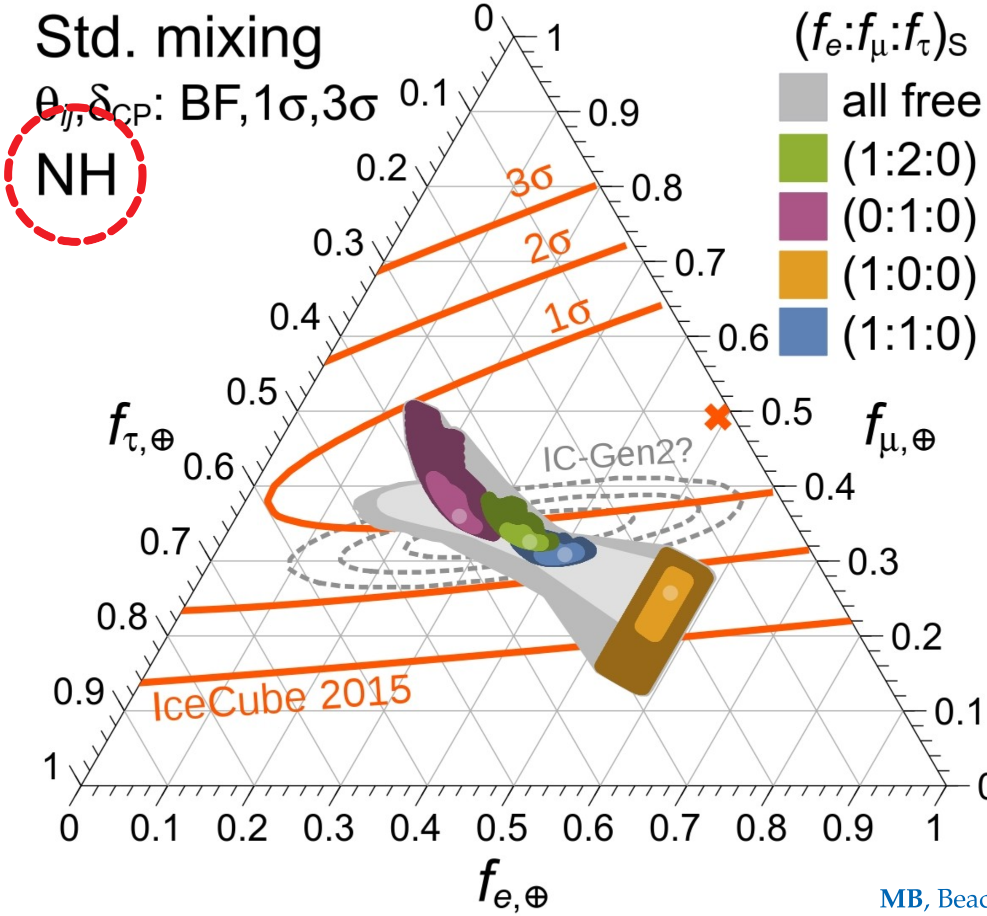
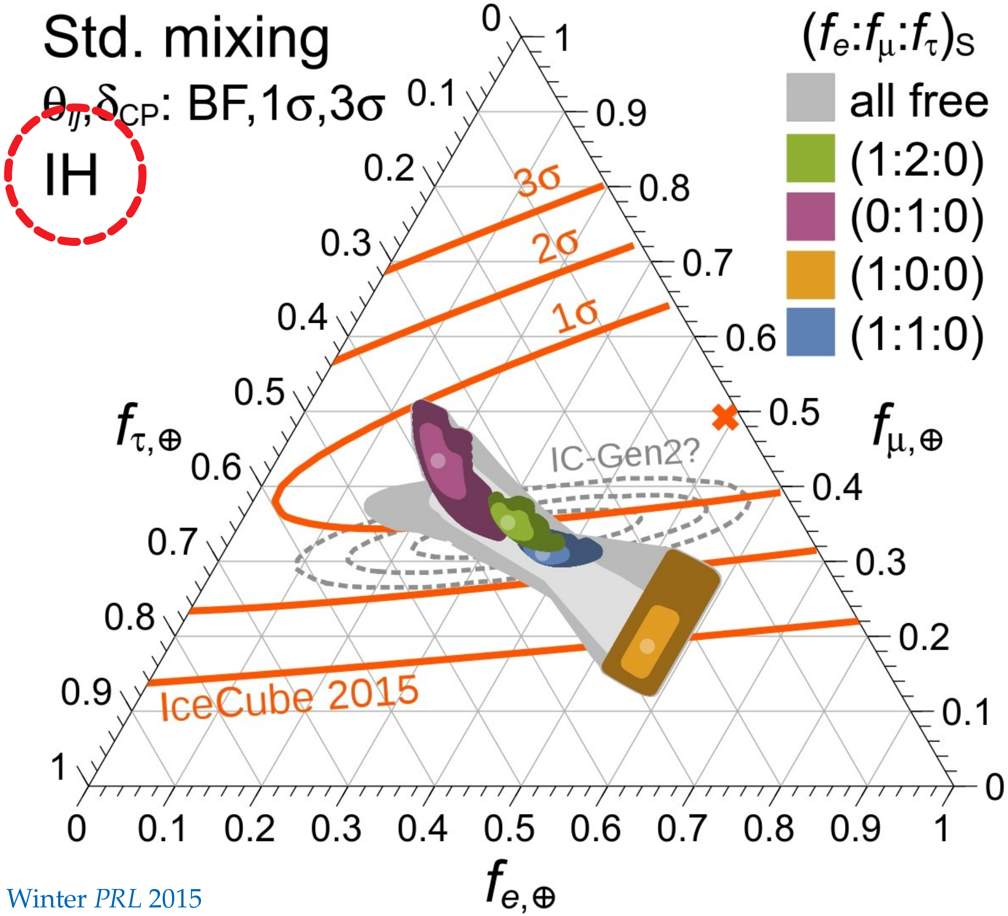
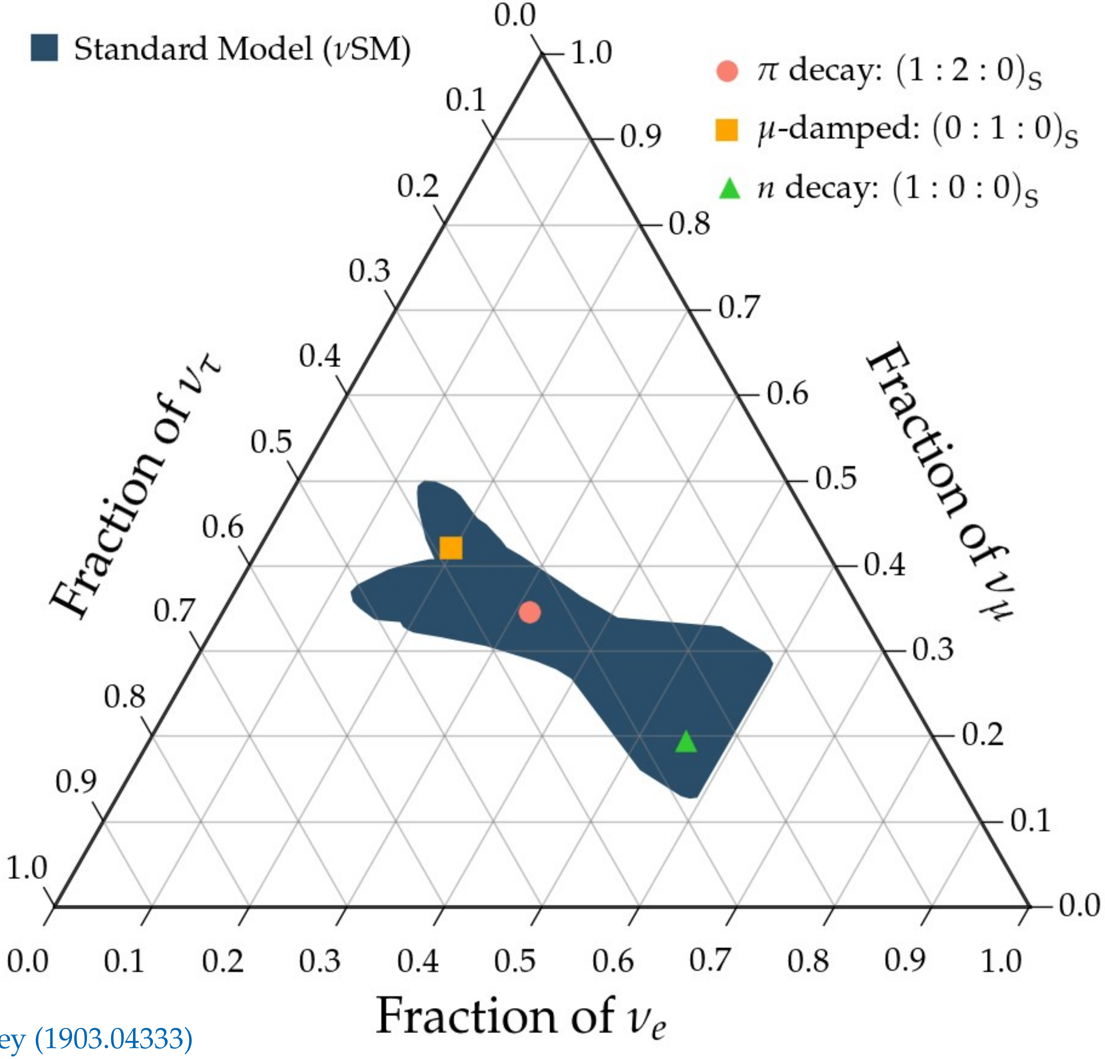
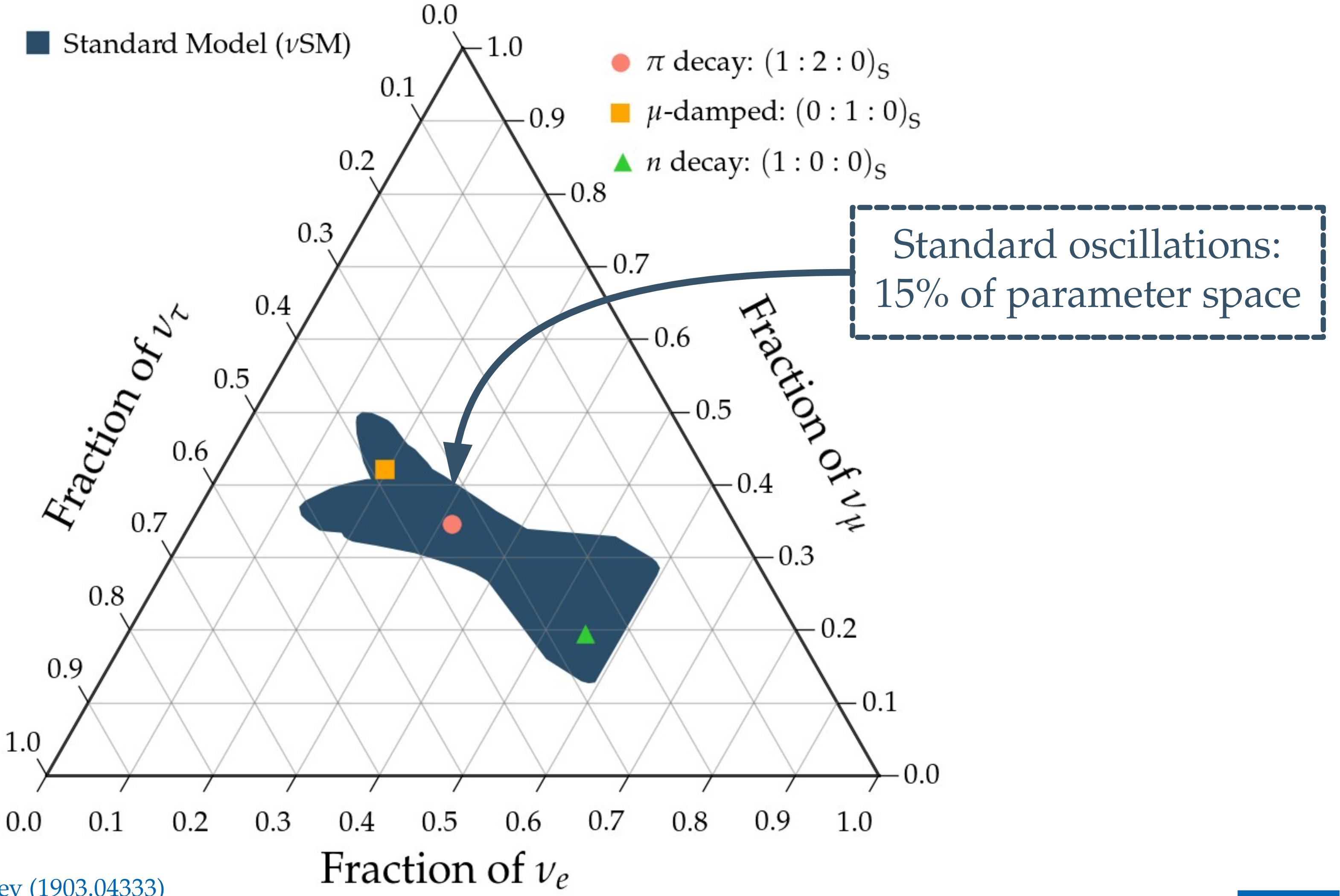




MB, Beacom, Winter *PRL* 2015



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



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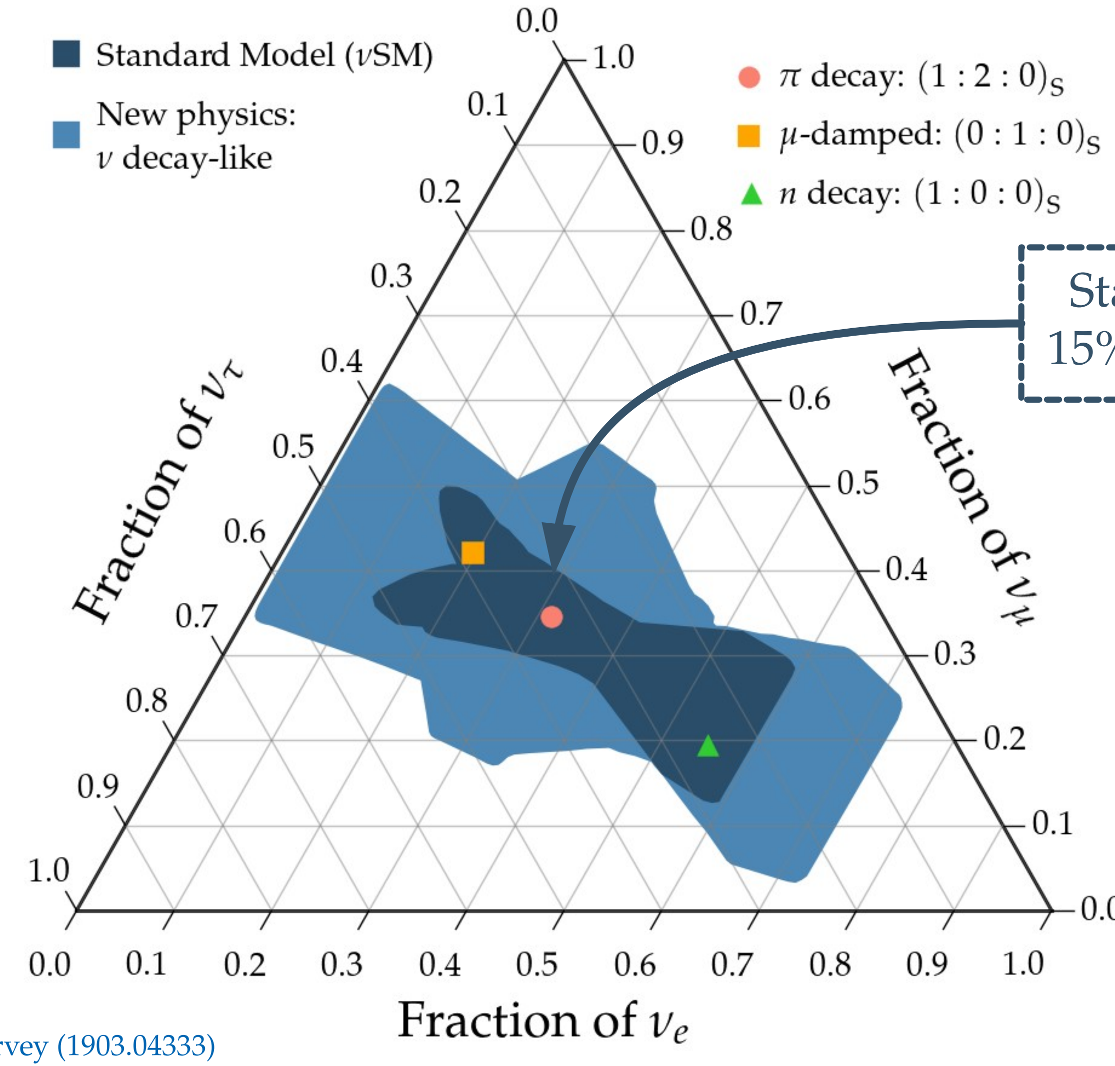
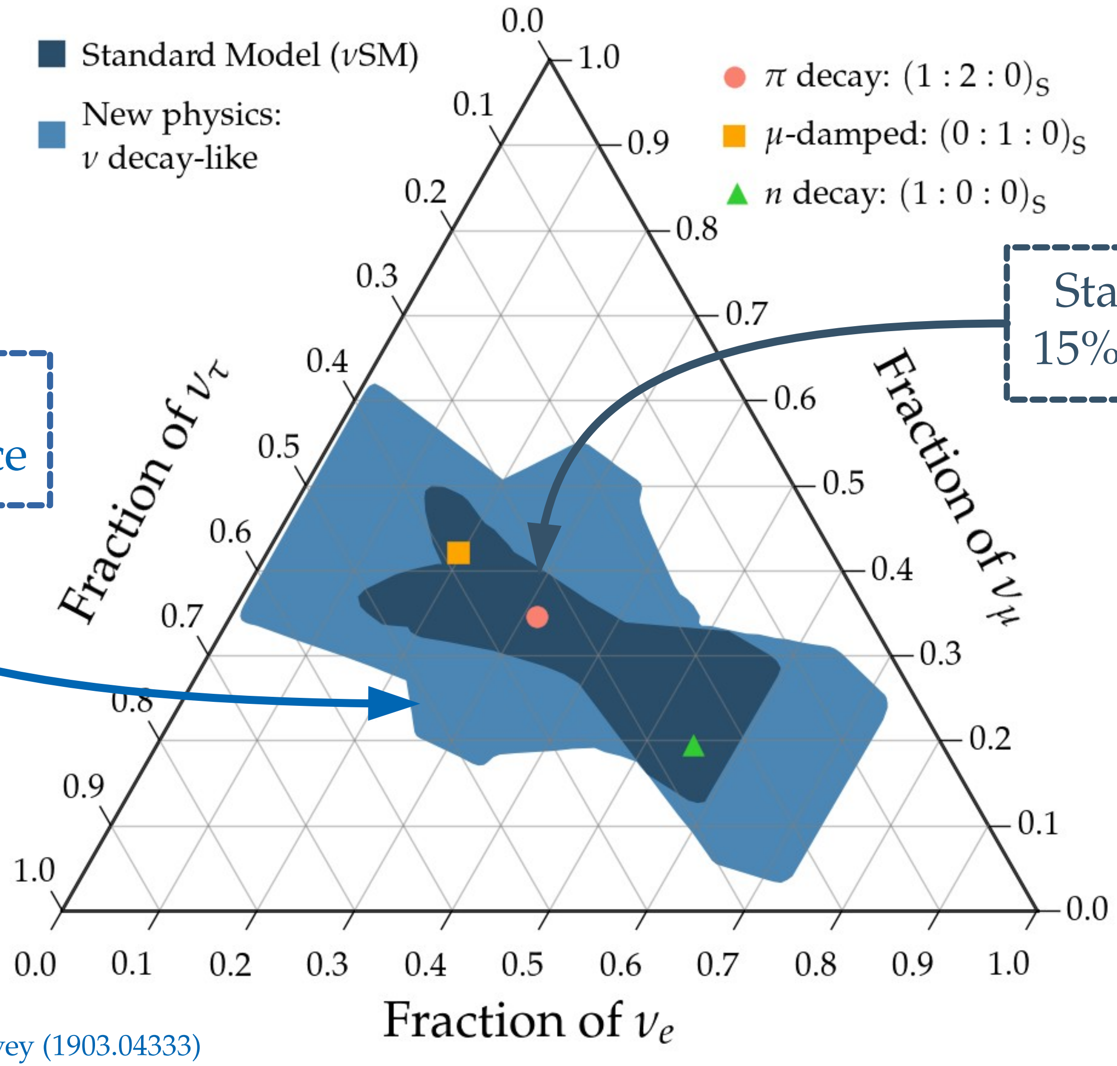


Standard oscillations:
15% of parameter space

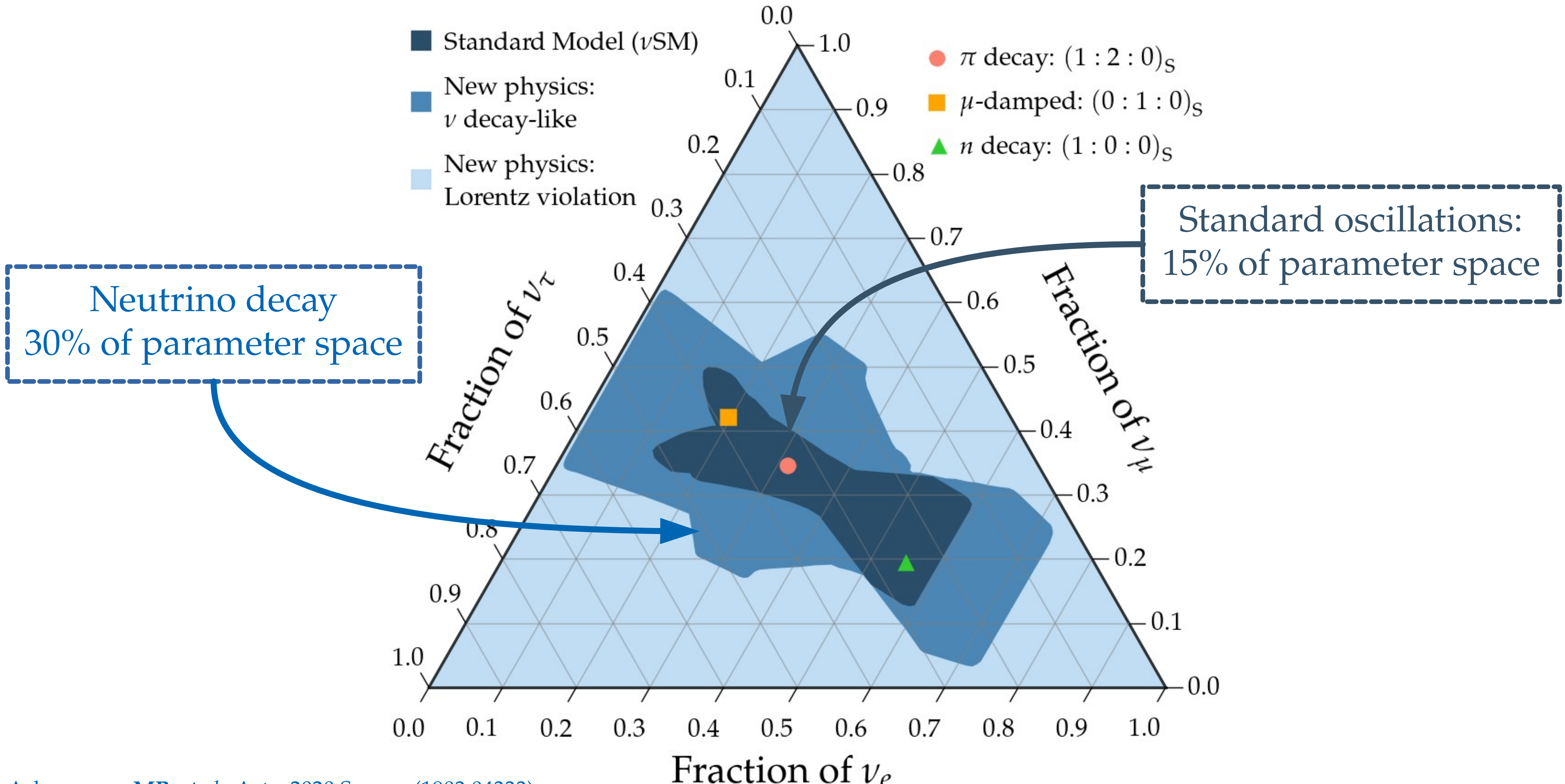
Ackermann, **MB**, *et al.*, Astro2020 Survey (1903.04333)
Based on: **MB**, Beacom, Winter *PRL* 2015



Standard oscillations:
15% of parameter space

Neutrino decay
30% of parameter space

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



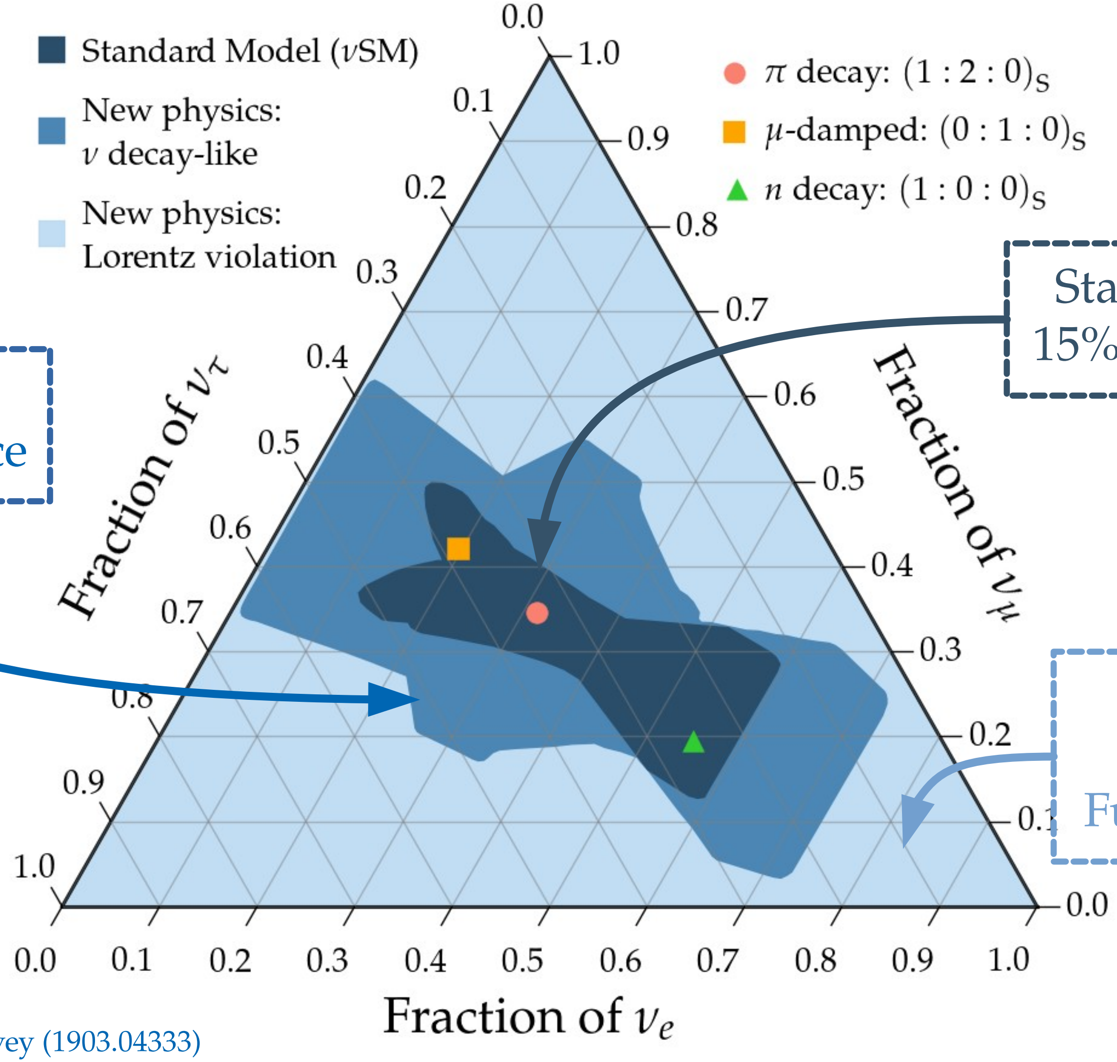
Ackermann, **MB**, *et al.*, Astro2020 Survey (1903.04333)

Based on: **MB**, Beacom, Winter *PRL* 2015

Neutrino decay
30% of parameter space

Standard oscillations:
15% of parameter space

Lorentz, CPT
violation, etc:
Full parameter space



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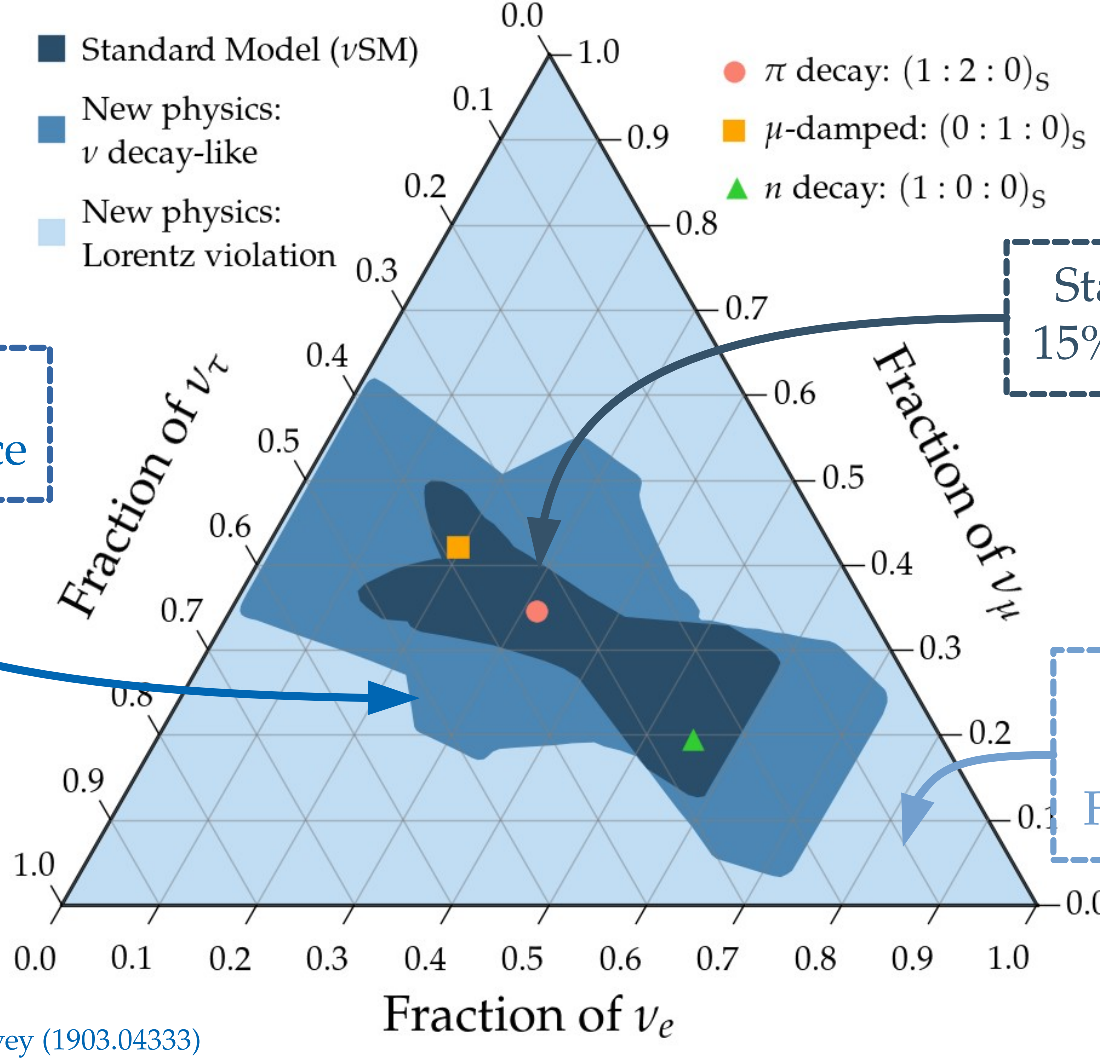
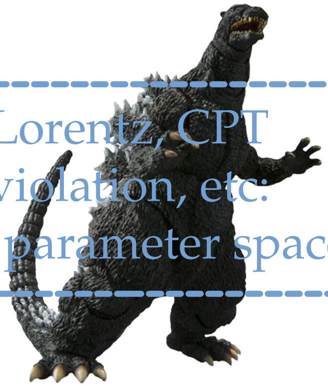


Standard oscillations:
15% of parameter space



Lorentz, CPT violation, etc:
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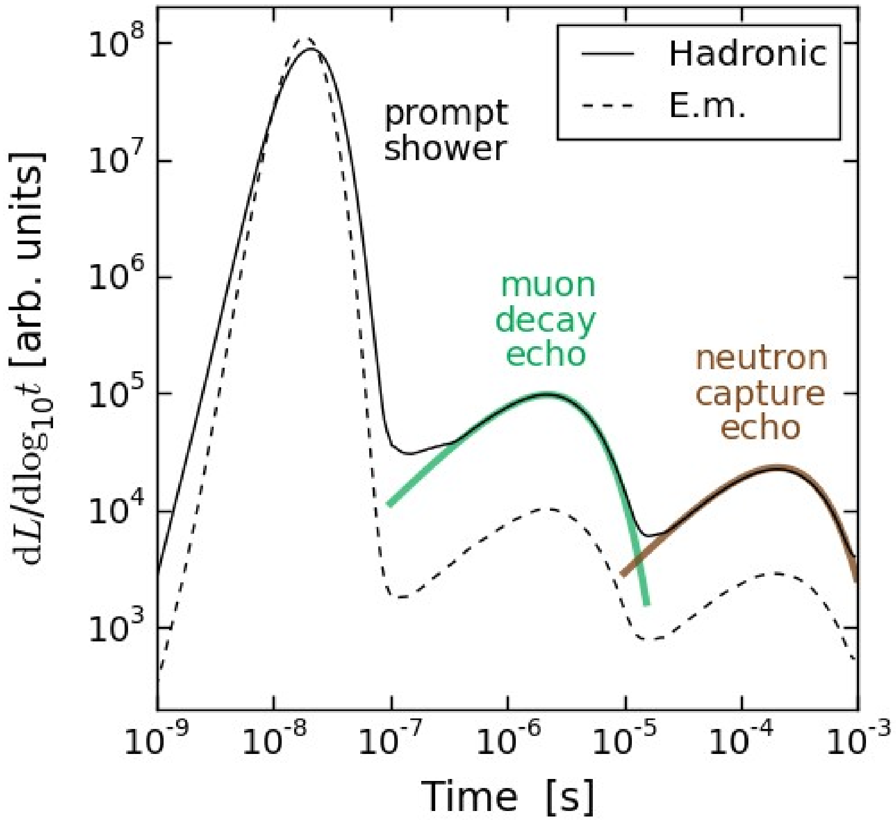
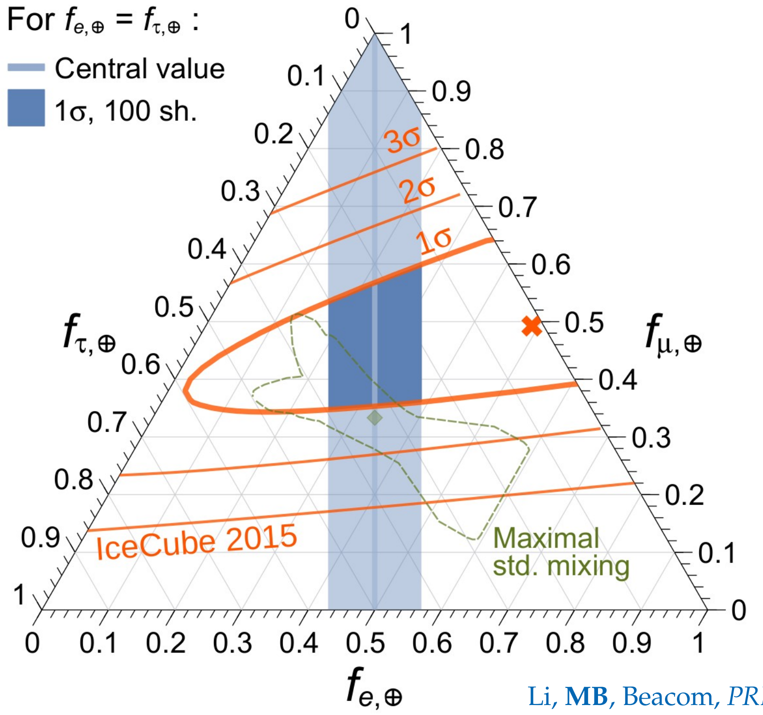
Side note: Improving flavor-tagging using *echoes*

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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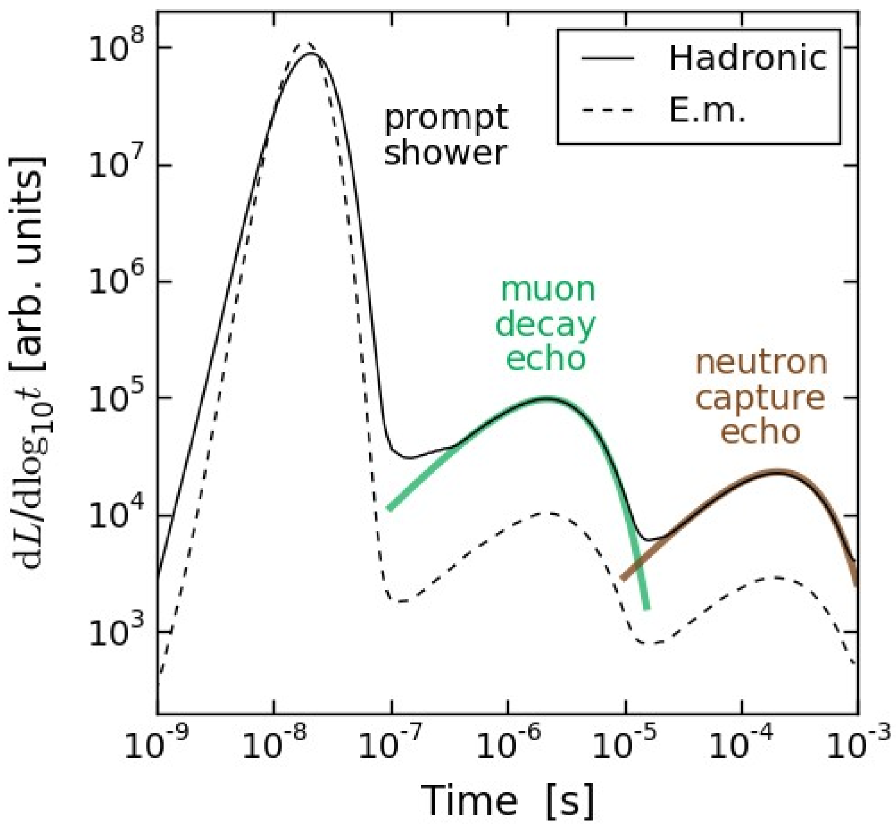
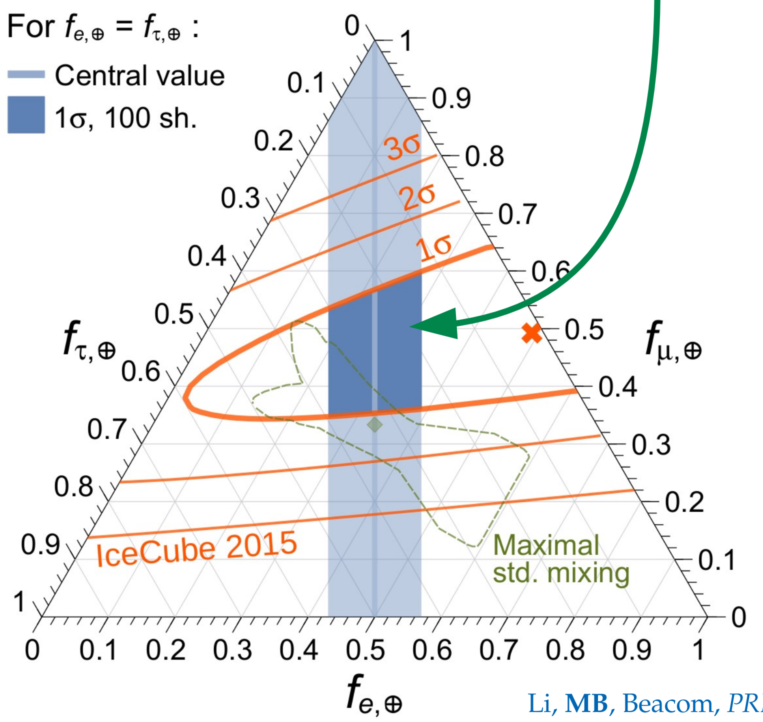


~10 × improvement over current measurement



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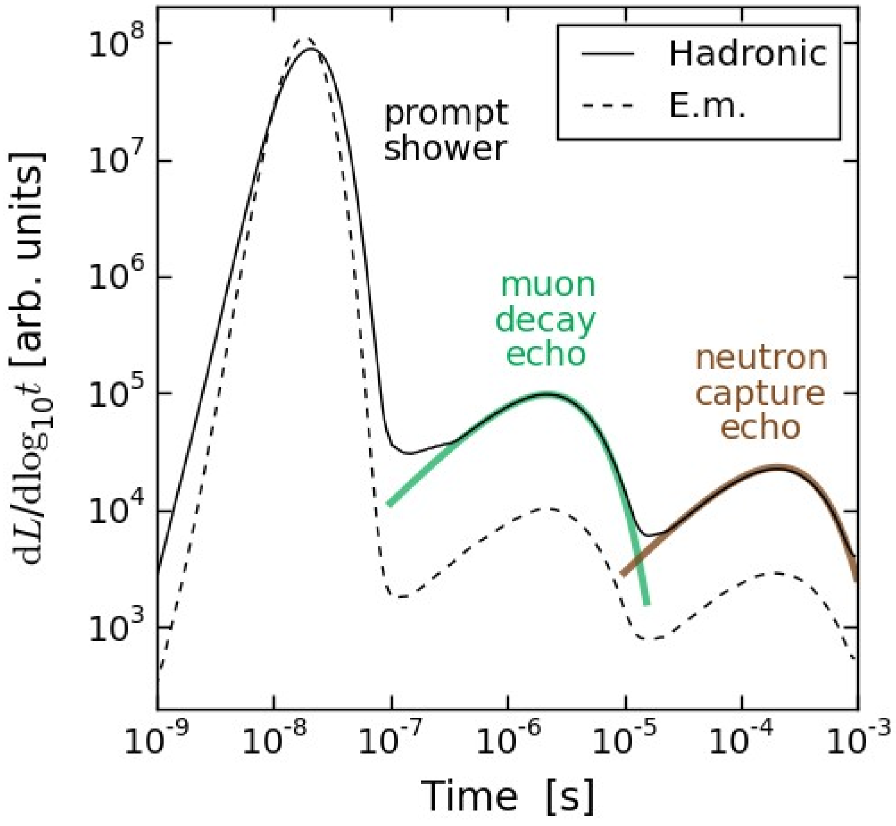

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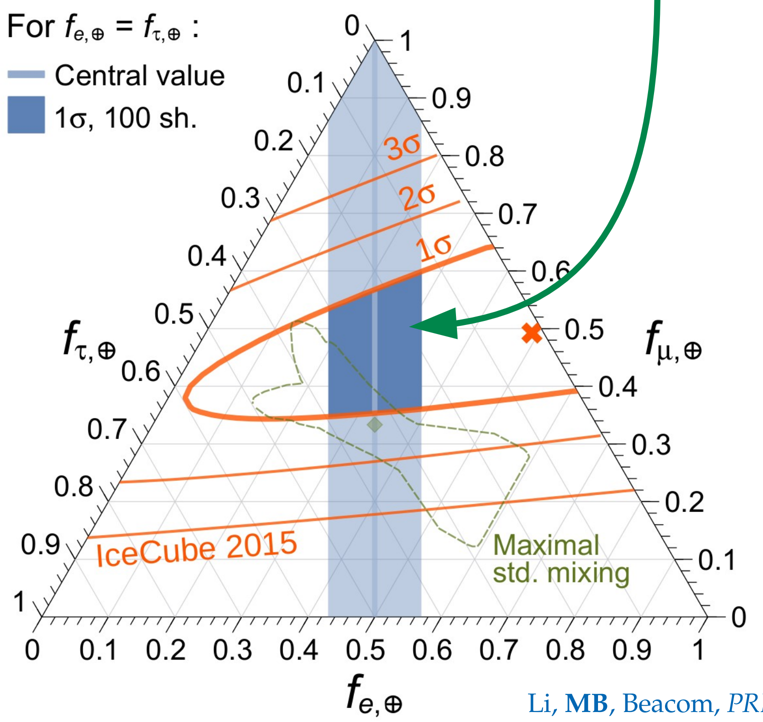
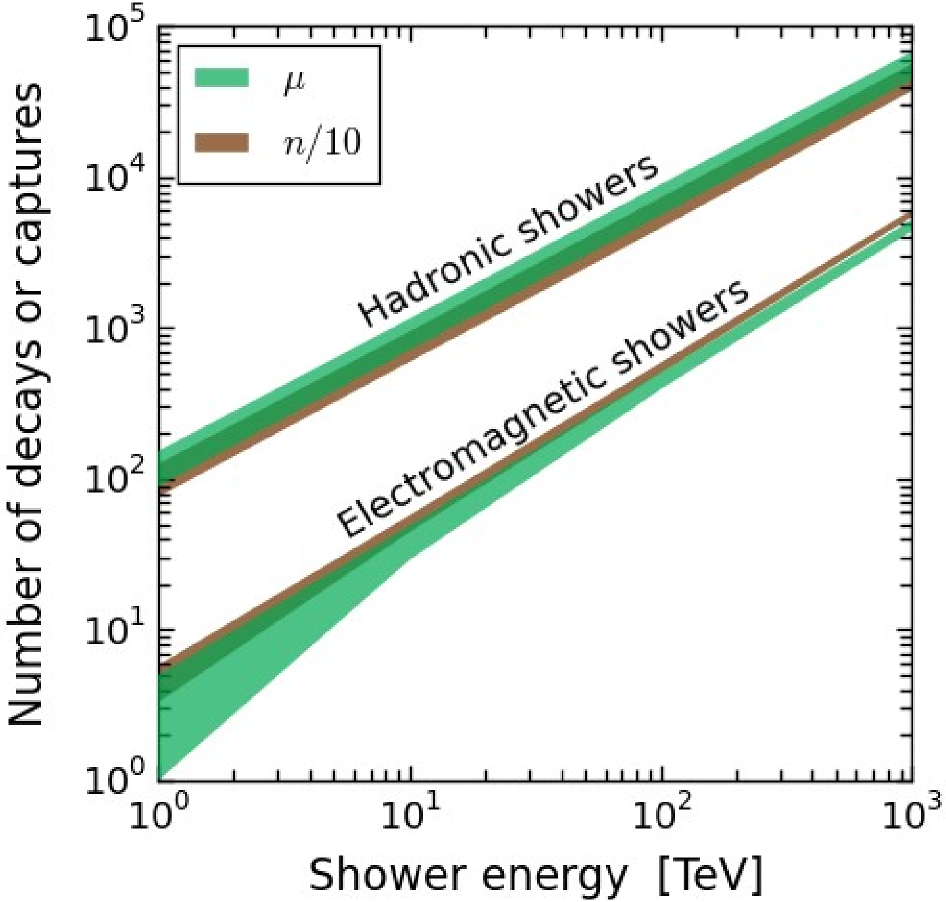
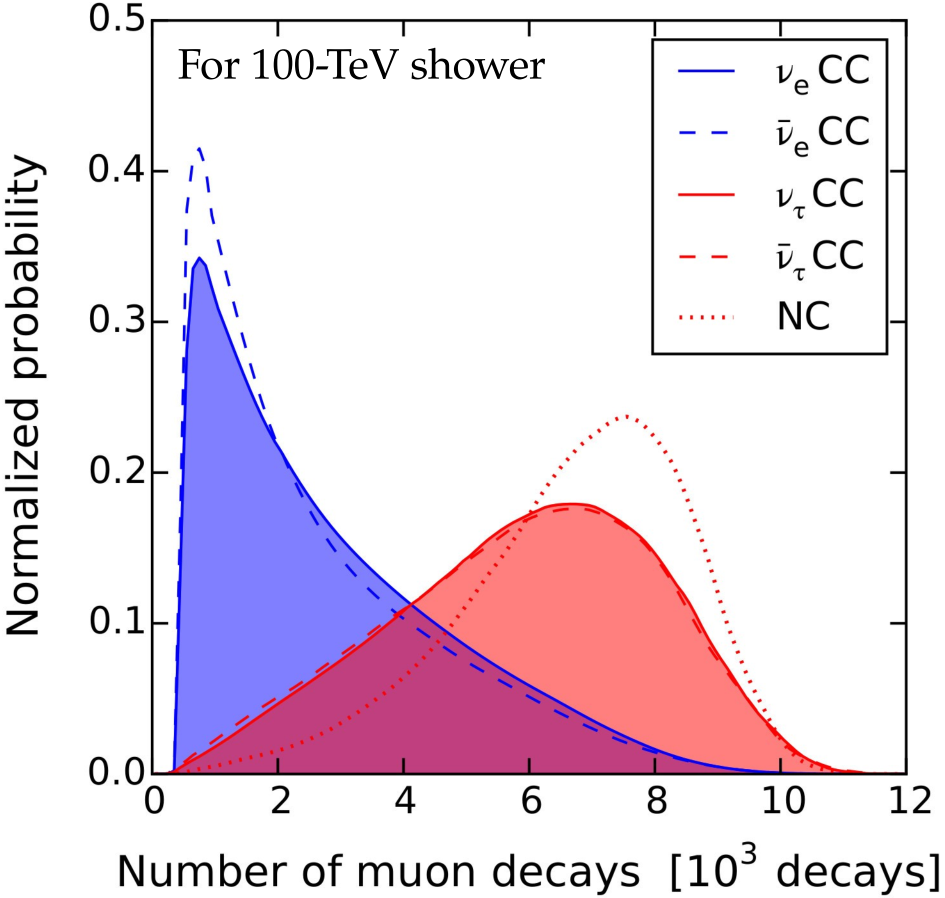


Li, **MB**, Beacom, *PRL* 2019

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 ($\nu_i \rightarrow \nu_j + \gamma$): $\tau > 10^{36}\,(m_i/\text{eV})^{-5}$ yr
  - Two-photon decay ($\nu_i \rightarrow \nu_j + \gamma + \gamma$): $\tau > 10^{57}\,(m_i/\text{eV})^{-9}$ yr
  - Three-neutrino decay ($\nu_i \rightarrow \nu_j + \nu_k + \bar{\nu}_k$): $\tau > 10^{55}\,(m_i/\text{eV})^{-5}$ yr

  } » Age of Universe (~ 14.5 Gyr)

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

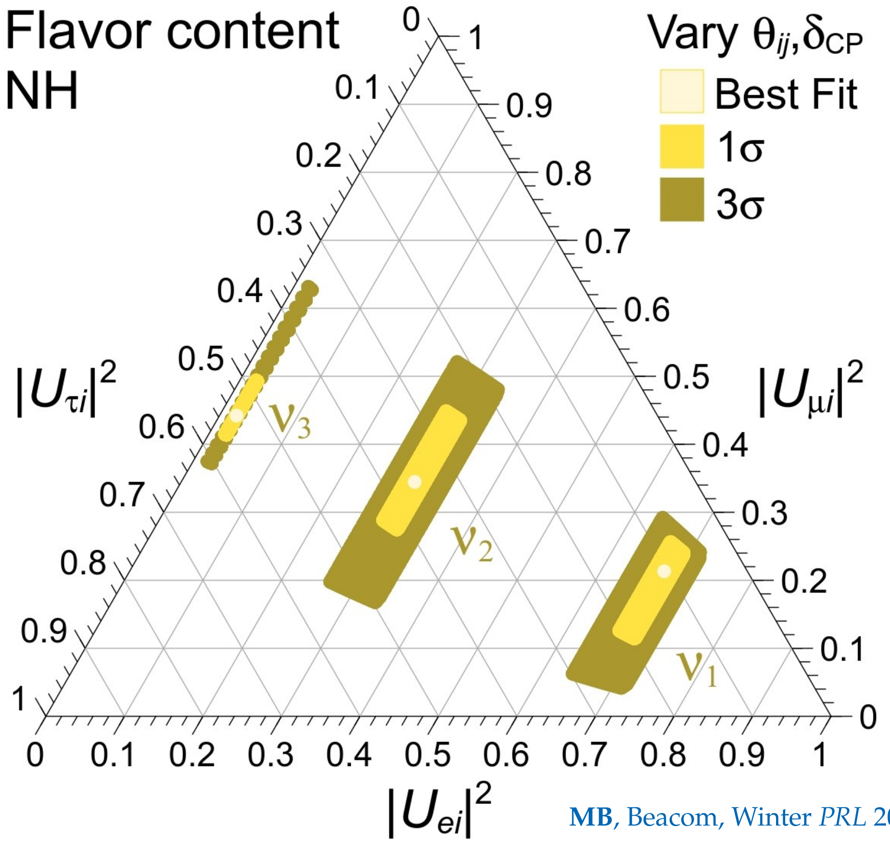
Flavor content of neutrino mass eigenstates

Known to within 2%

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

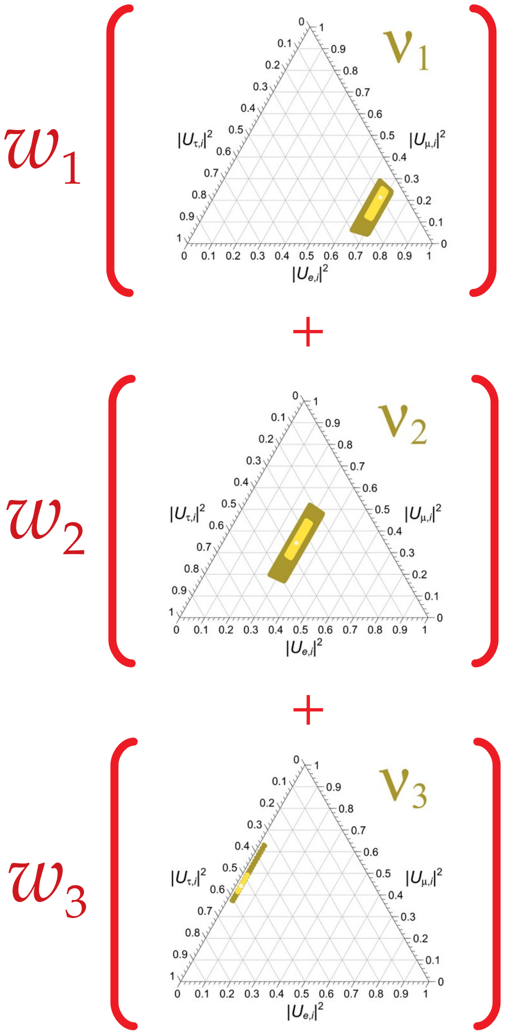
Known to within 8%

Known to within 20% (or worse)

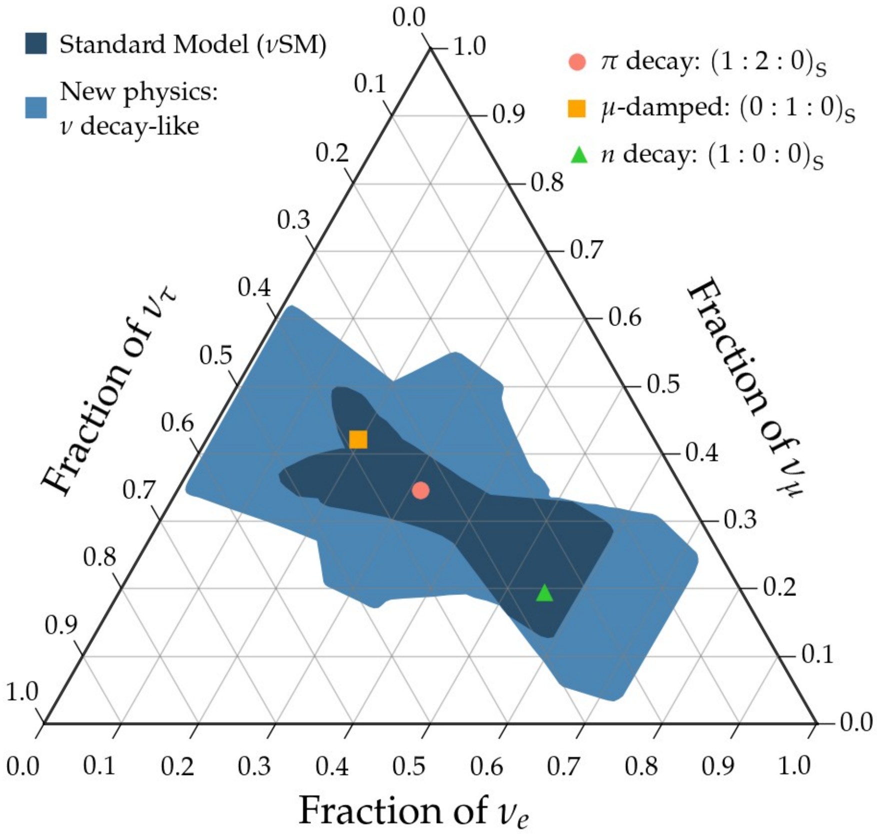


MB, Beacom, Winter *PRL* 2015

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



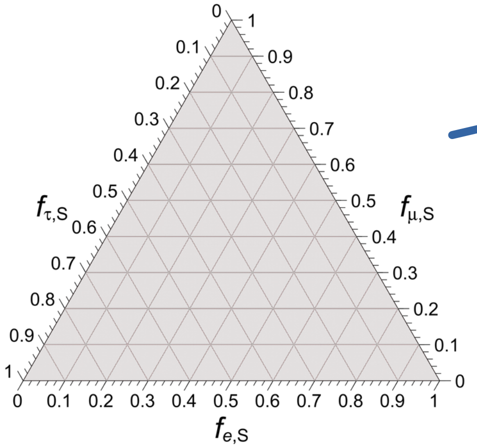
Varying all possible combinations of weights w_i and mixing parameters



Complete decay selects particular weights with striking consequences for flavor ▸

Measuring the neutrino lifetime

Sources



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

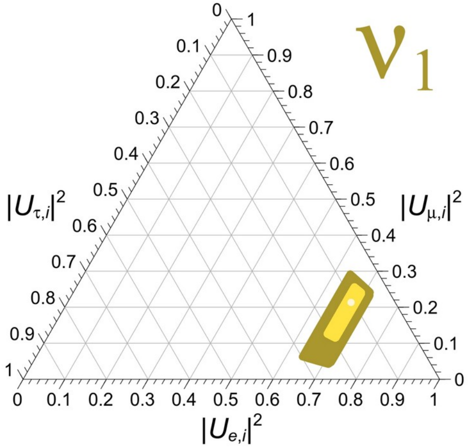
ν_1 lightest and stable
(normal mass ordering)

If all unstable neutrinos decay

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

ν_3 lightest and stable
(inverted mass ordering)

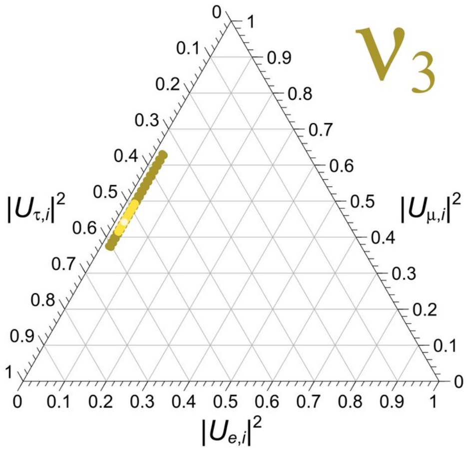
Earth



ν_1

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

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



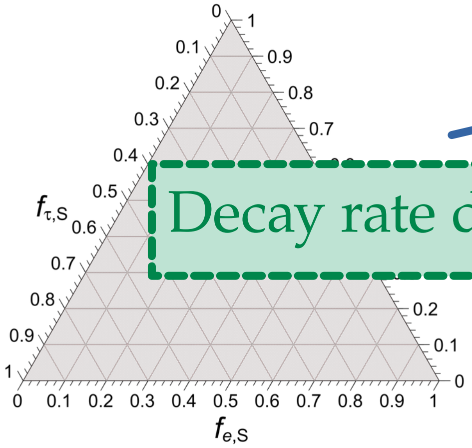
ν_3

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

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

Measuring the neutrino lifetime

Sources



$\nu_2, \nu_3 \to \nu_1$

ν_1 lightest and stable
(normal mass ordering)

$\nu_1, \nu_2 \to \nu_3$

ν_3 lightest and stable
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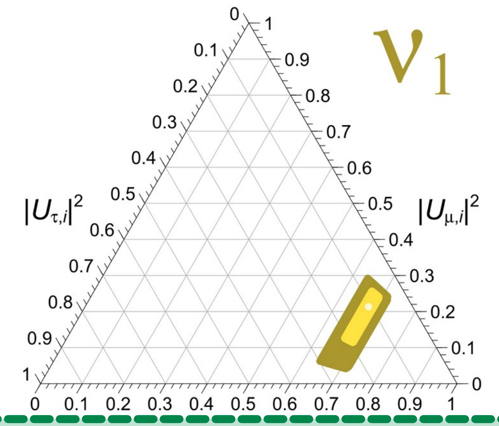
Decay rate depends on $\exp[-\, t \,/\, (\gamma\, \tau_i)] = \exp[-\, (L/E) \cdot (m_i/\tau_i)]$

Earth



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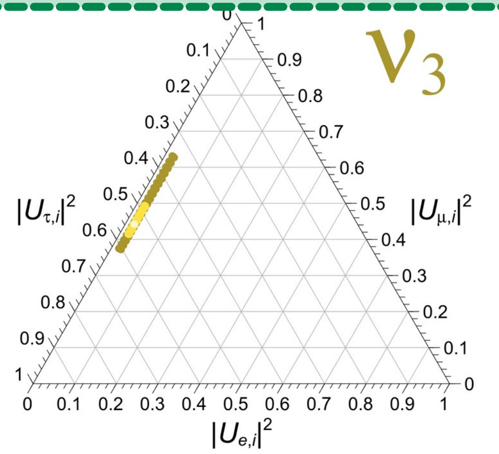

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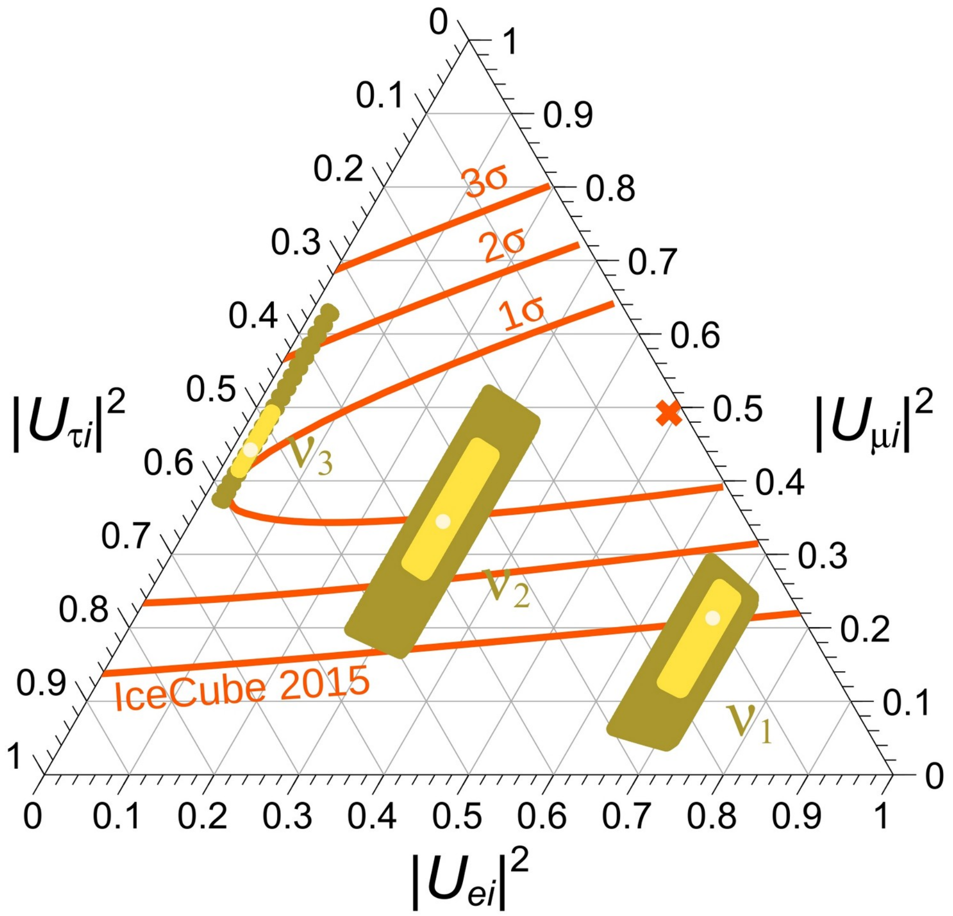
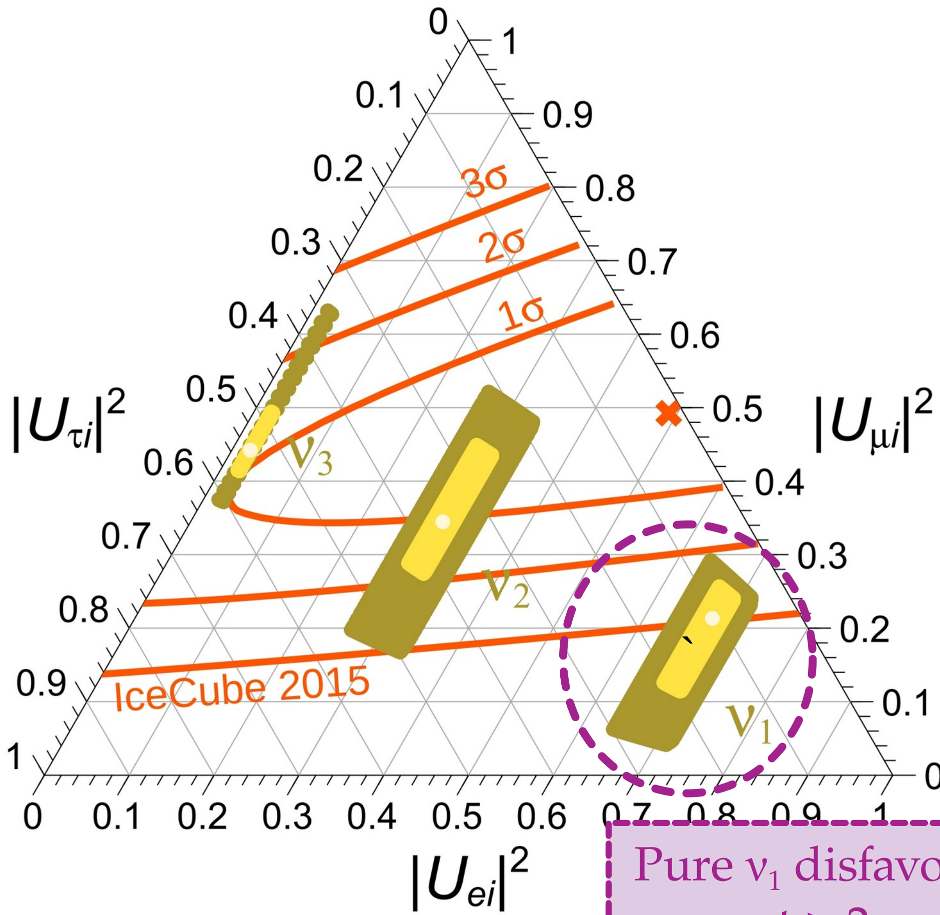


MB, Beacom, Murase, *PRD* 2017

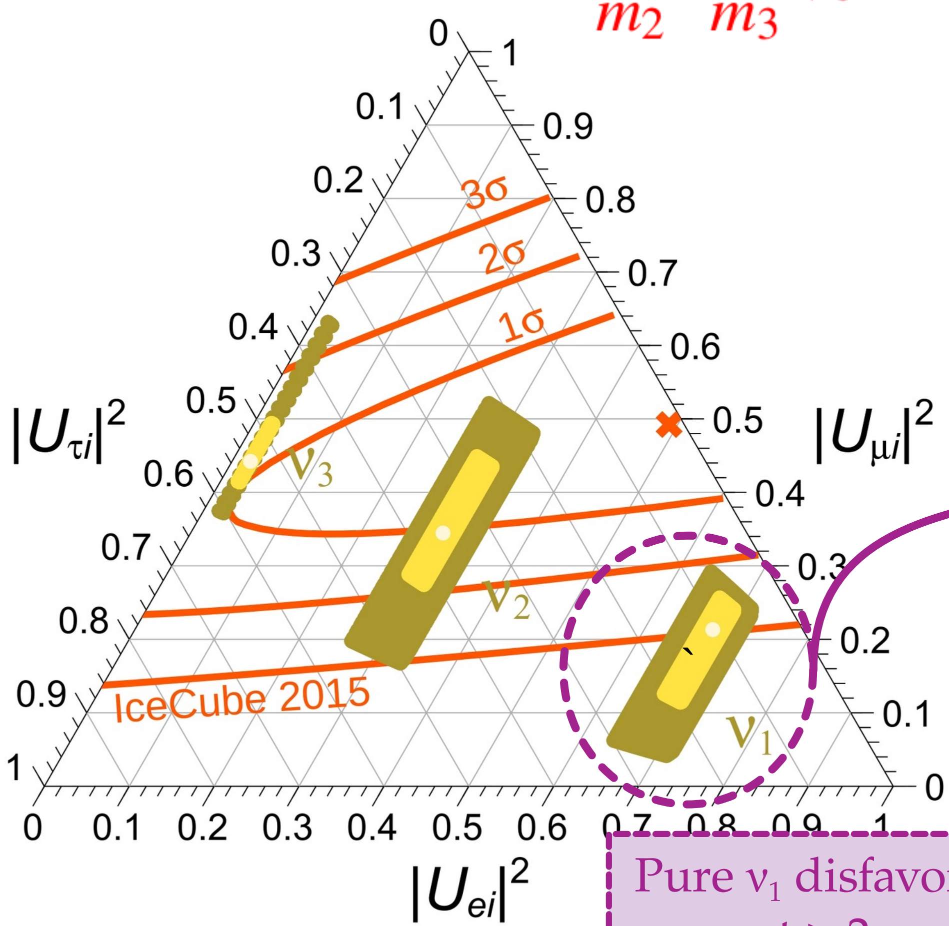
Baerwald, **MB**, Winter, *JCAP* 2012



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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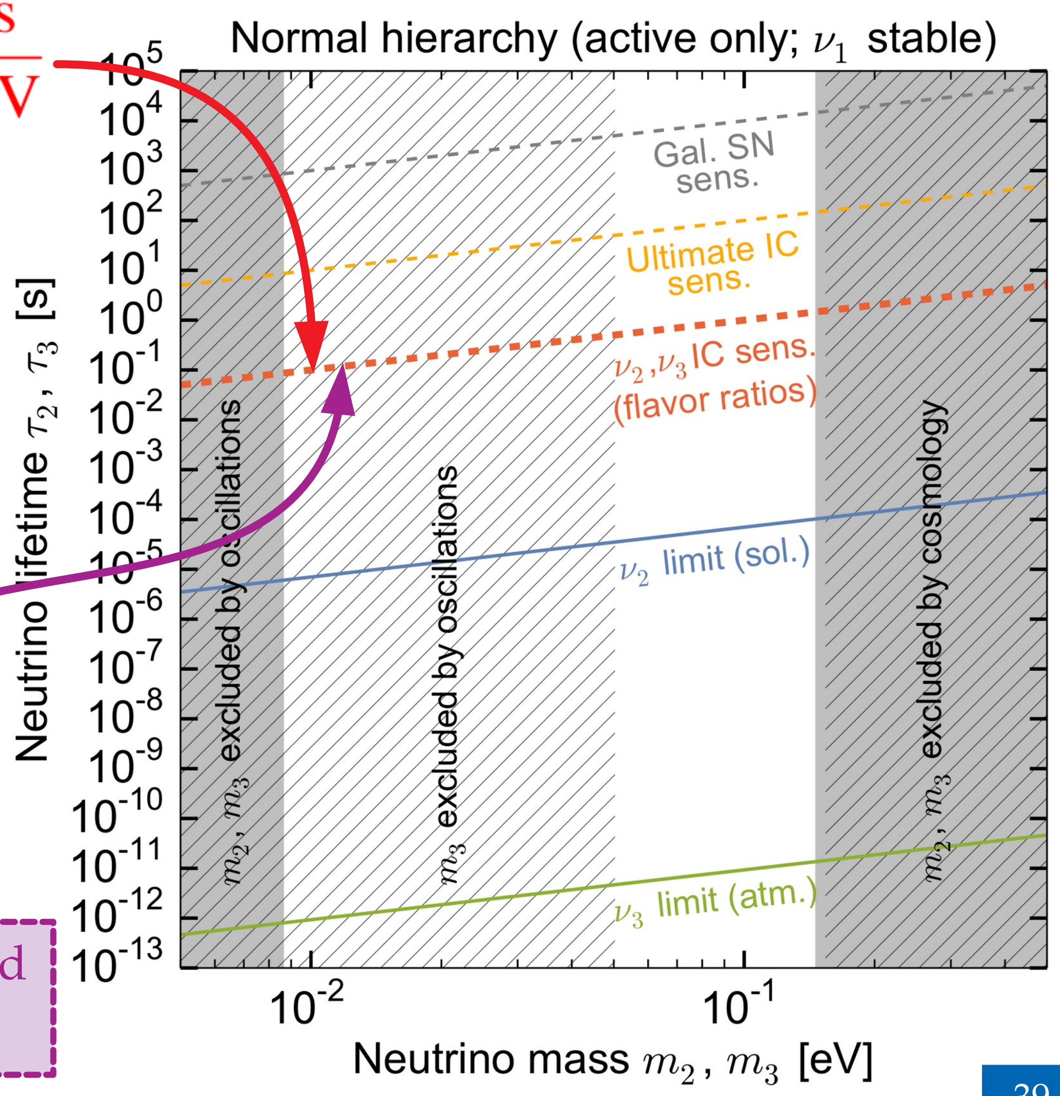
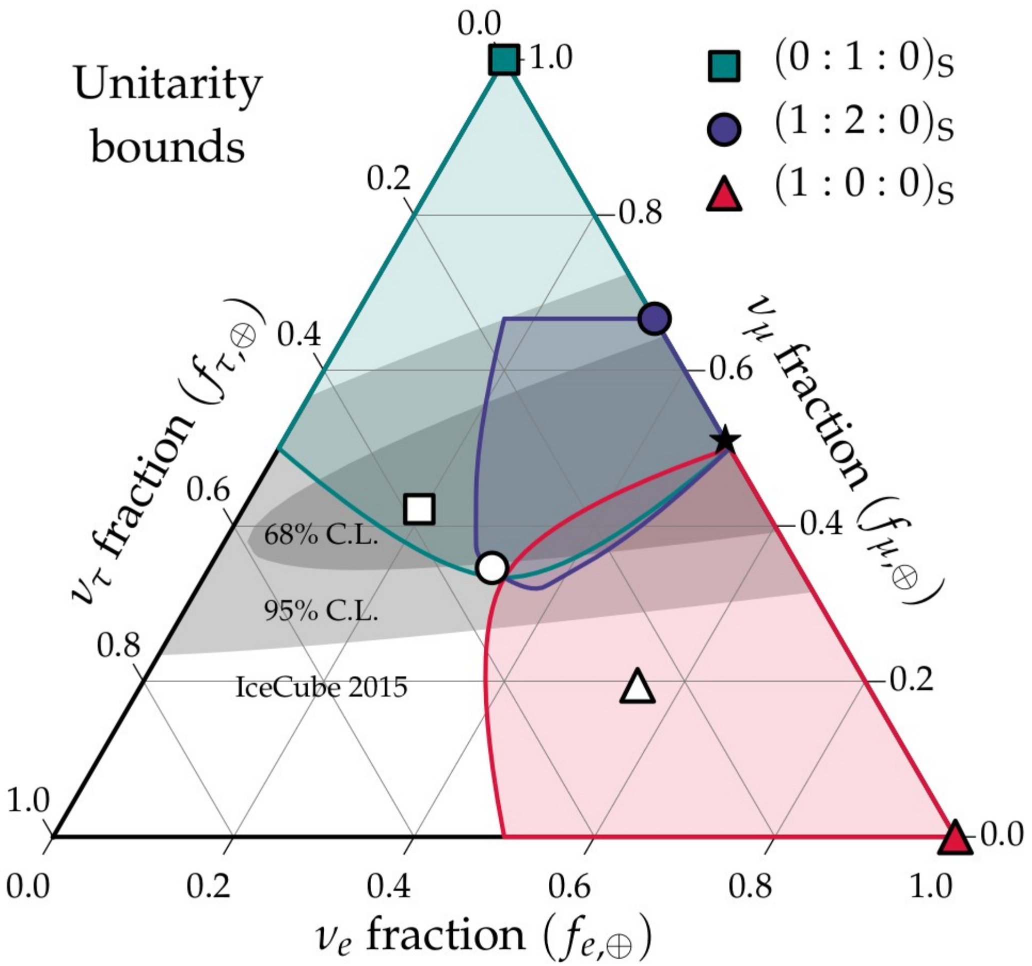


MB, Beacom, Murase, *PRD* 2017
Baerwald, **MB**, Winter, *JCAP* 2012

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?

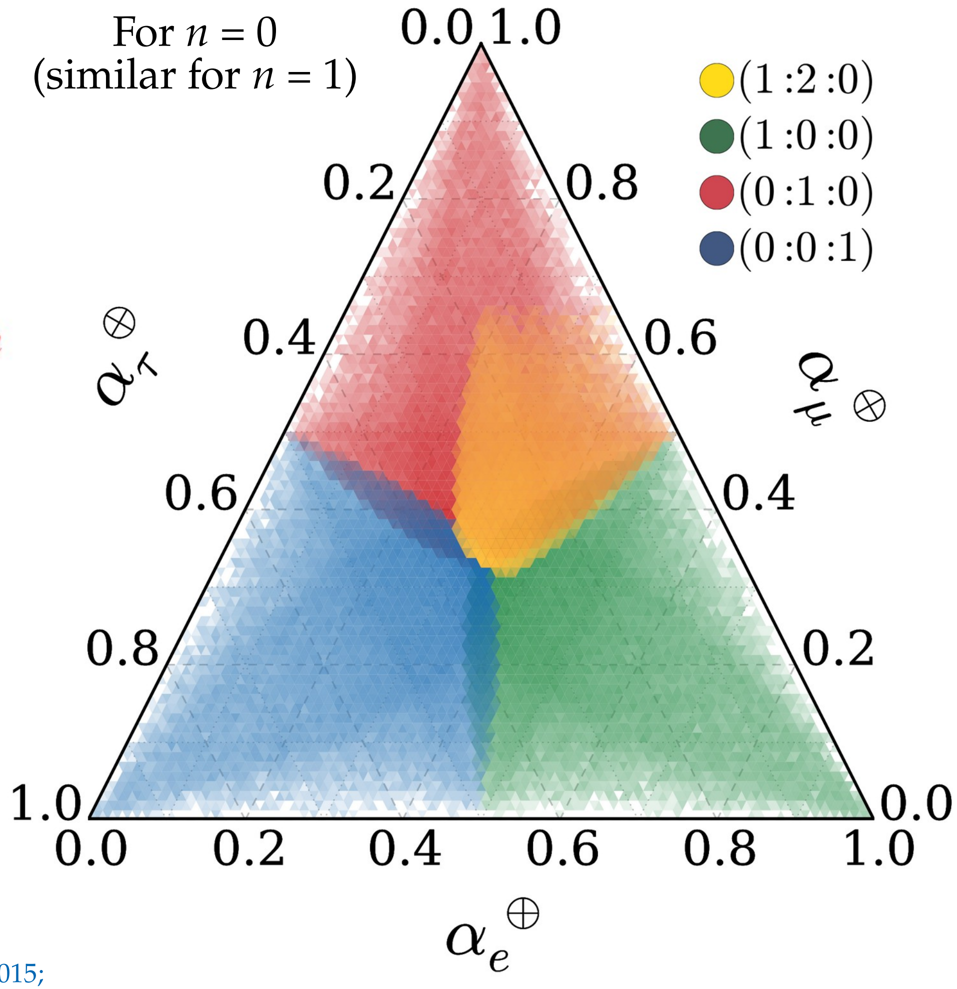
$$H_{\rm tot} = H_{\rm std} + H_{\rm NP}$$

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

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

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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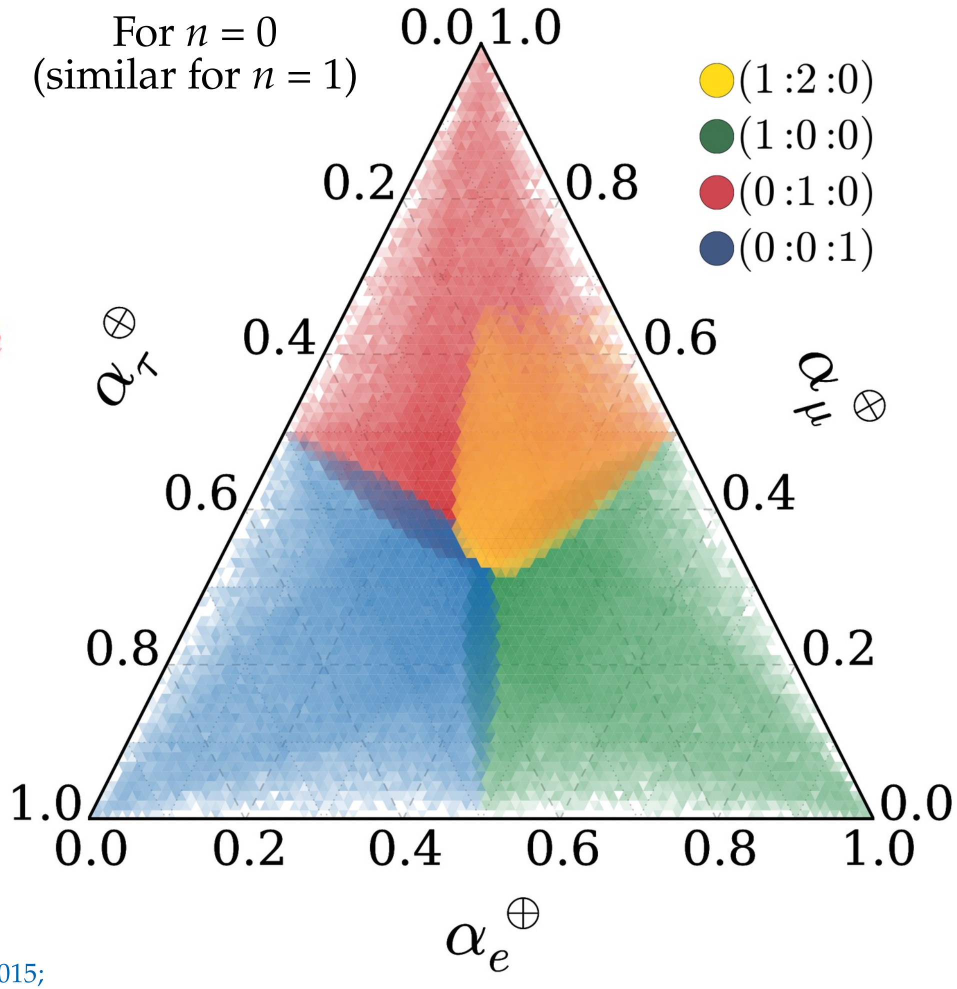

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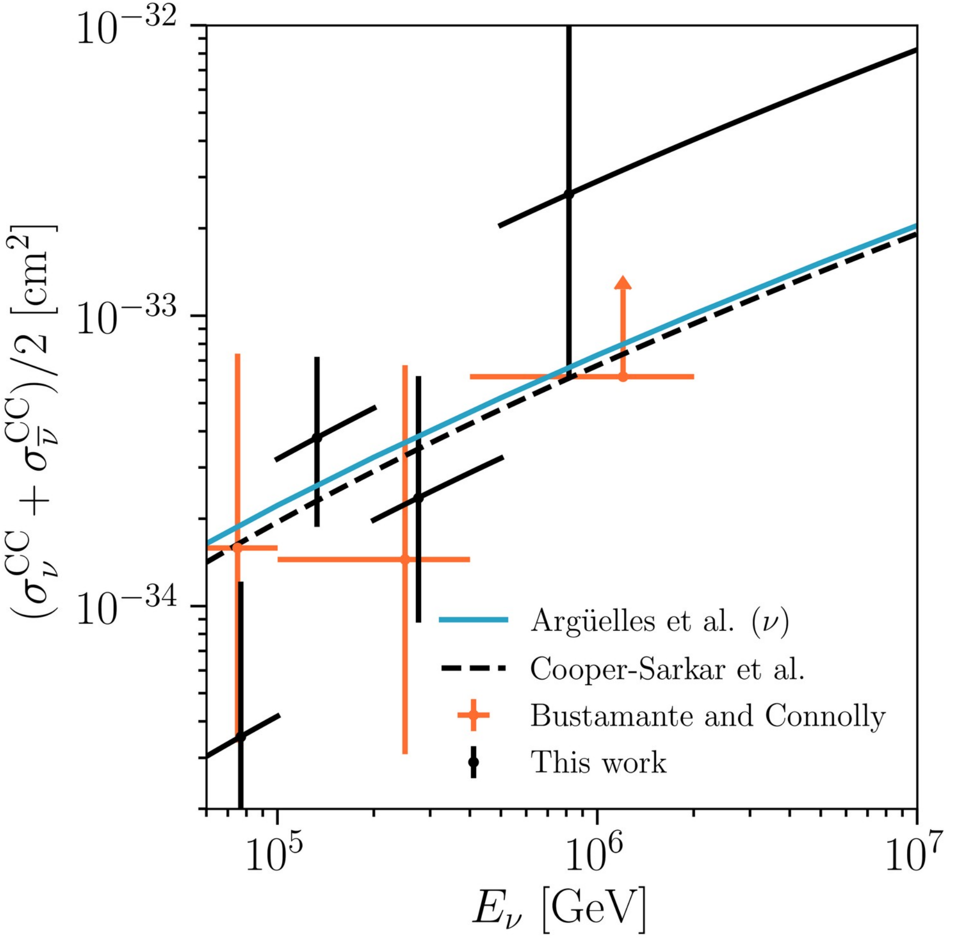
New (IC 7.5 yr): Updated cross section measurement

- Uses 7.5 years of IceCube data
- Uses starting showers + tracks
  - *Vs.* starting showers only in Bustamante & Connolly 2017
  - *Vs.* throughgoing muons in IceCube 2017
- Extends measurement to 10 PeV
- Still compatible with Standard Model predictions
- Higher energies? Work in progress by Valera & Bustamante



IceCube, 2011.03560

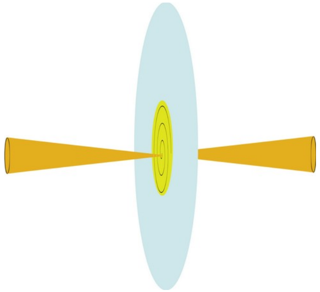
Astrophysical neutrino sources

Earth

Galactic (kpc) or extragalactic (Mpc – Gpc) distance

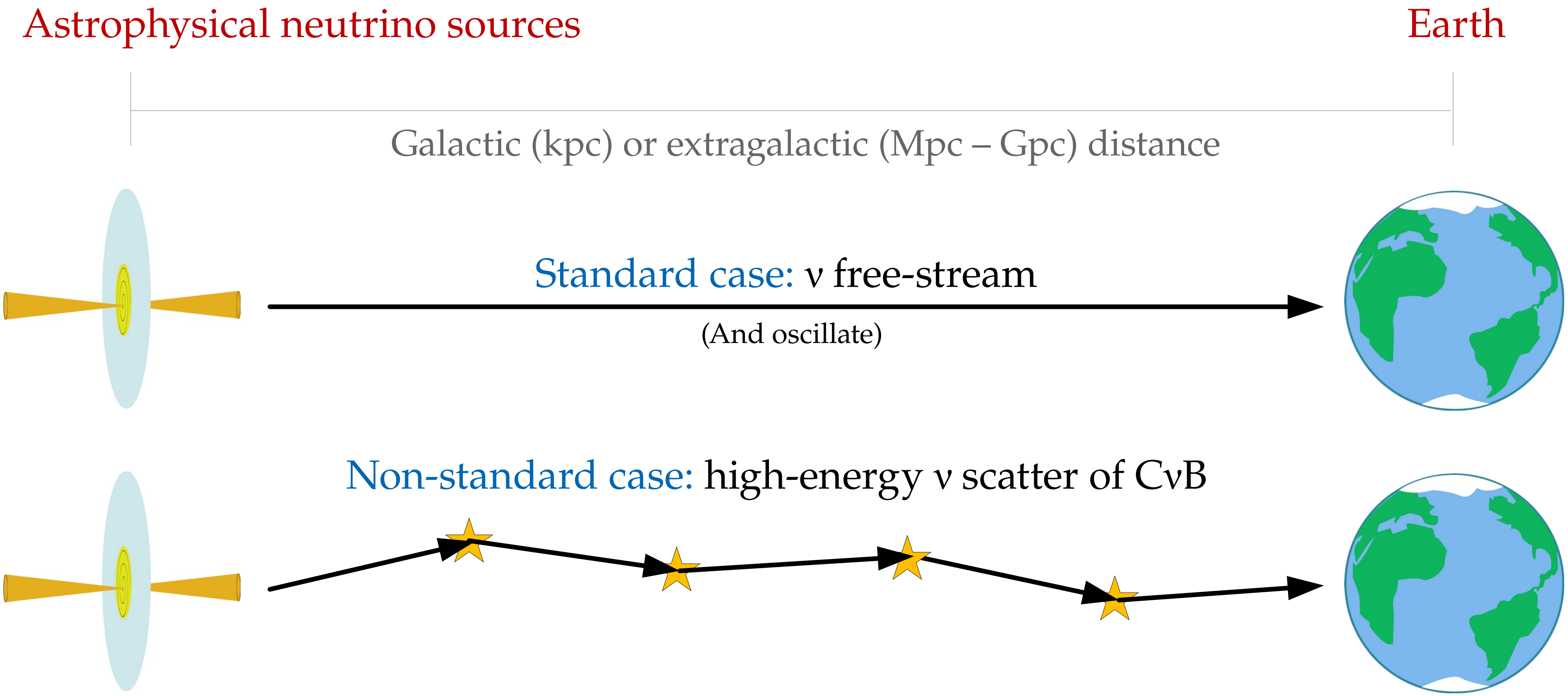
Astrophysical neutrino sources | Earth

Galactic (kpc) or extragalactic (Mpc – Gpc) distance



Standard case: ν free-stream

(And oscillate)



Astrophysical neutrino sources
Earth
Galactic (kpc) or extragalactic (Mpc – Gpc) distance
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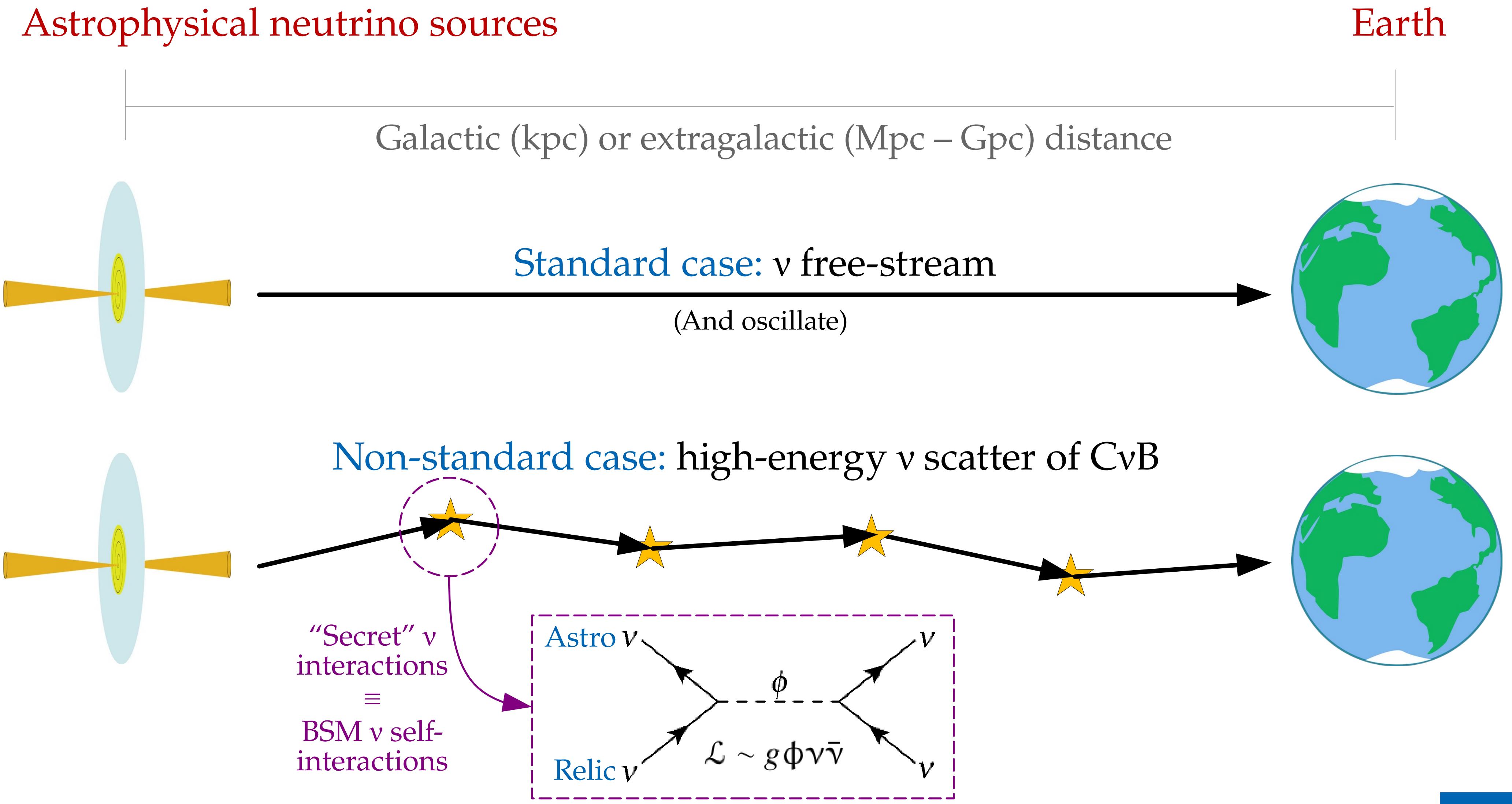
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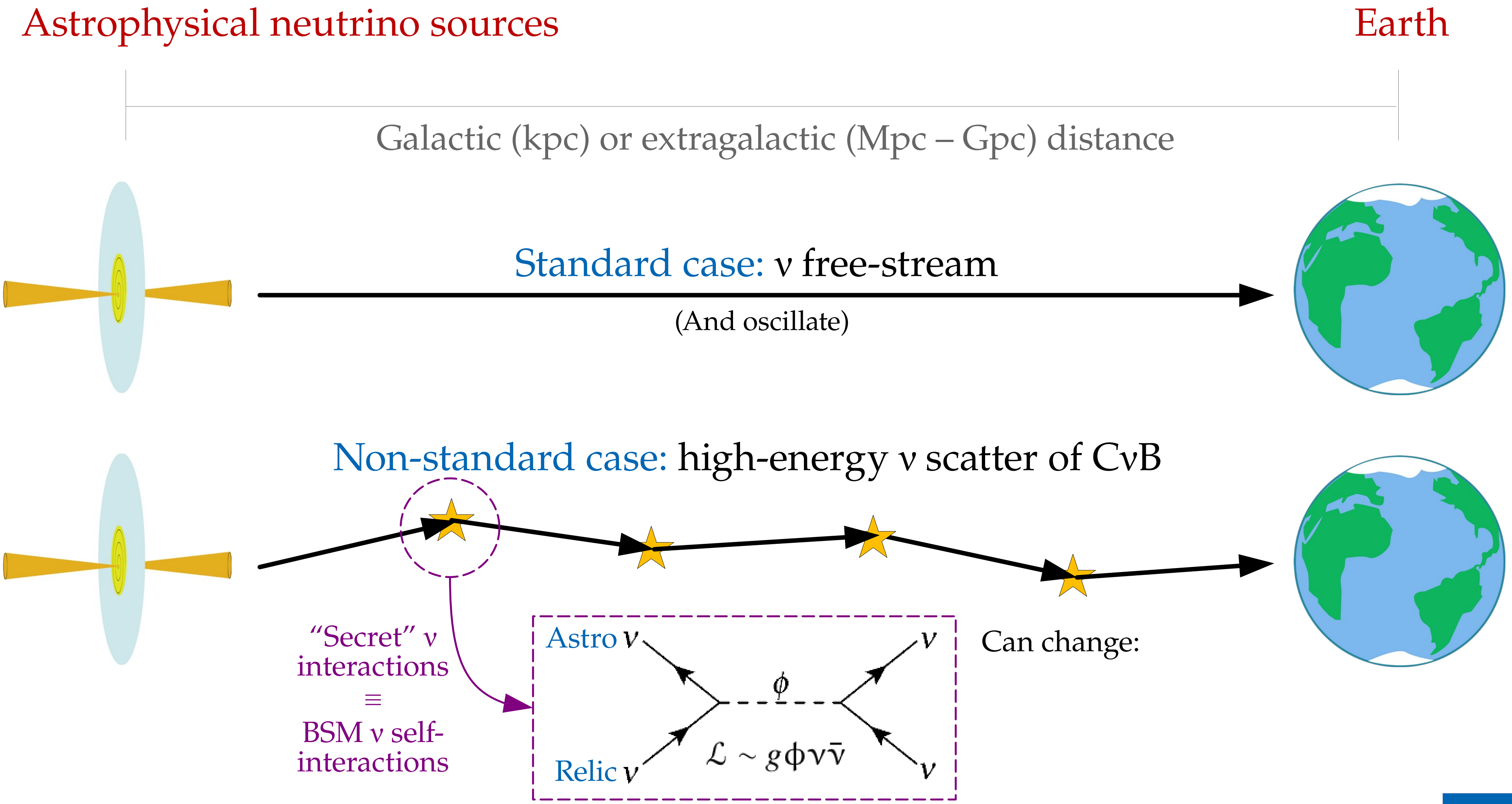
"Secret" ν interactions ≡ BSM ν self-interactions
Astro ν
ν
ϕ
Relic ν
ν
$\mathcal{L} \sim g\phi\nu\bar{\nu}$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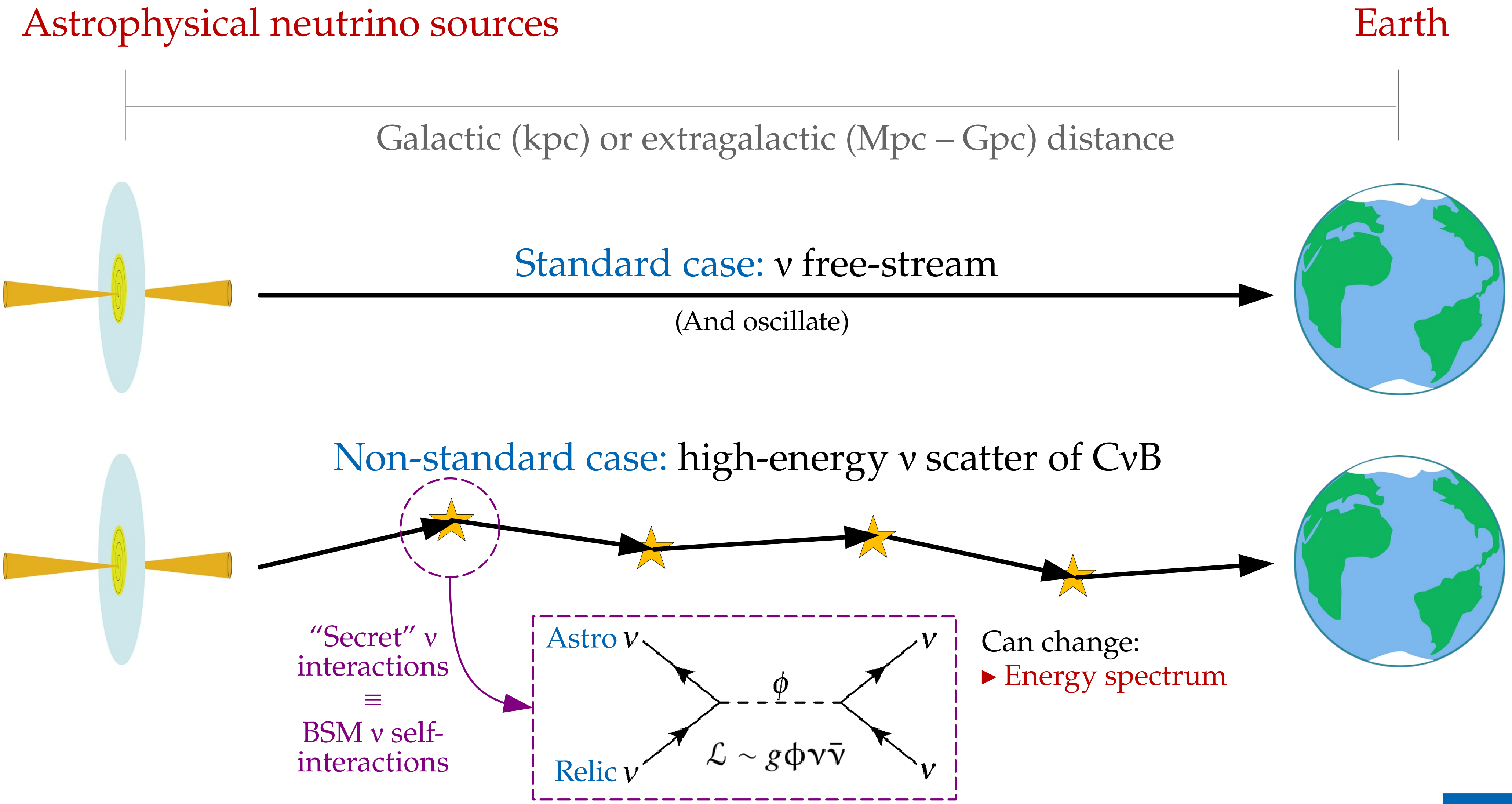
Can change: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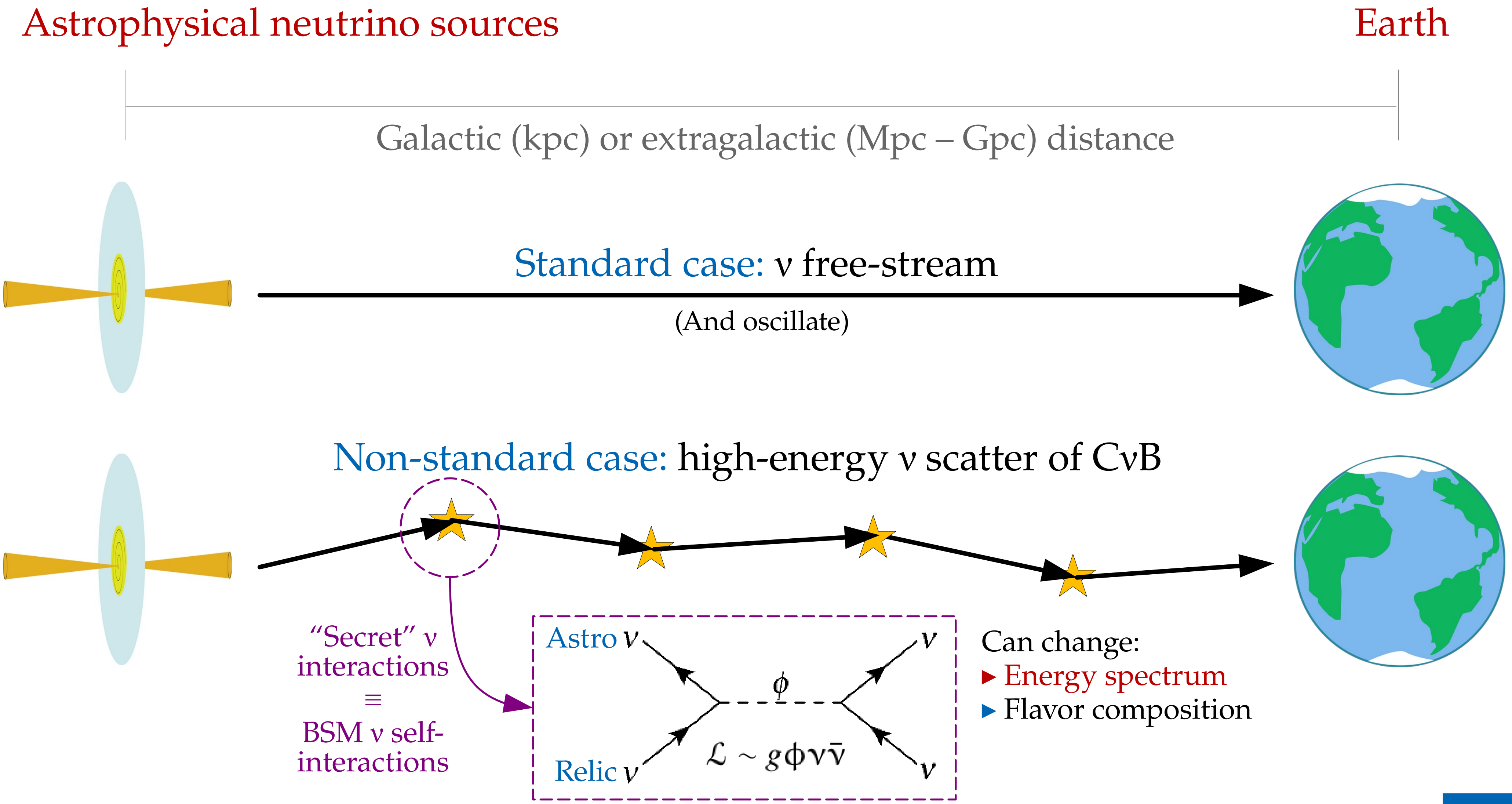
Can change:
▸ Energy spectrum



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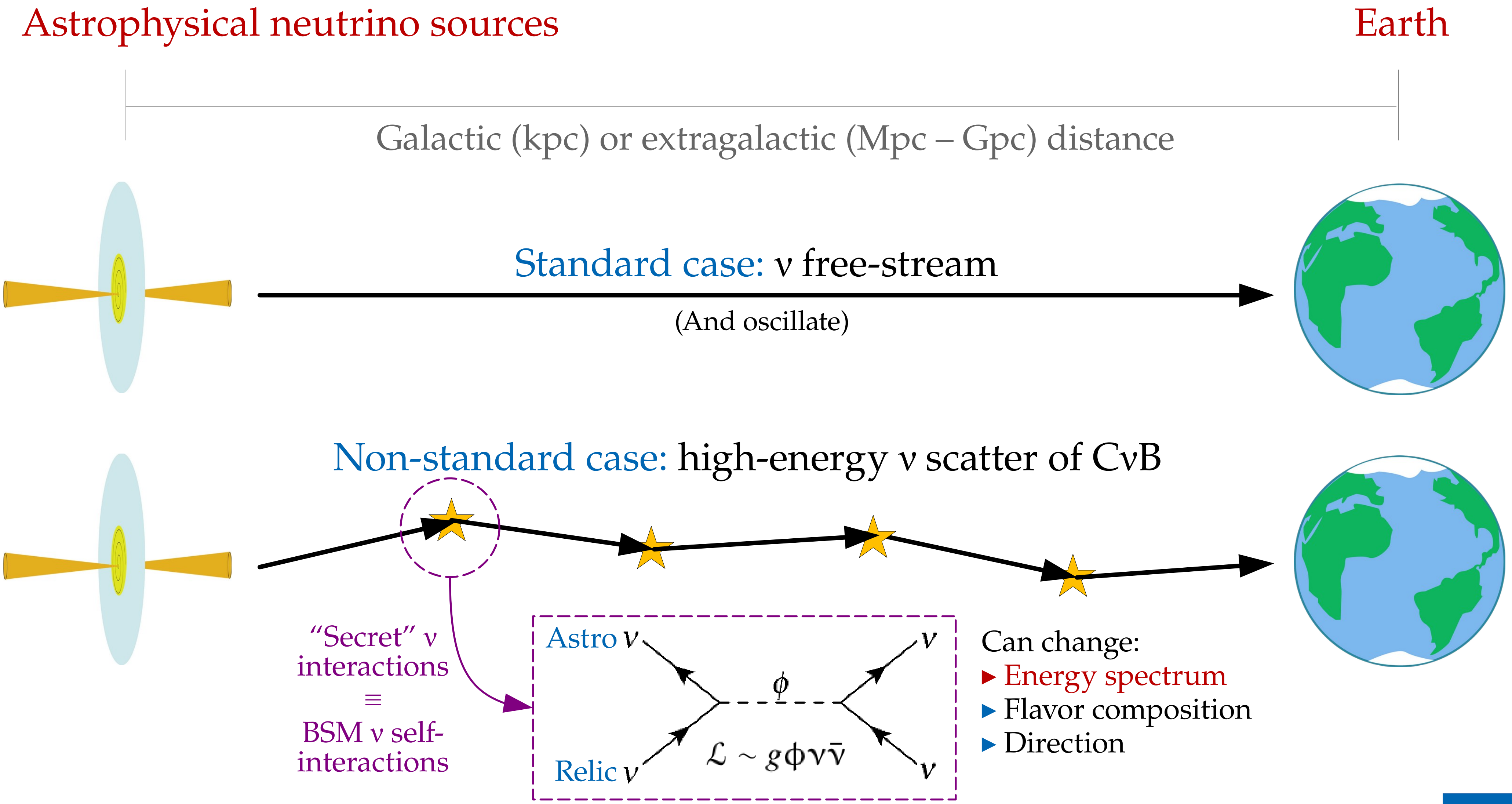
Can change:
▸ Energy spectrum
▸ Flavor composition



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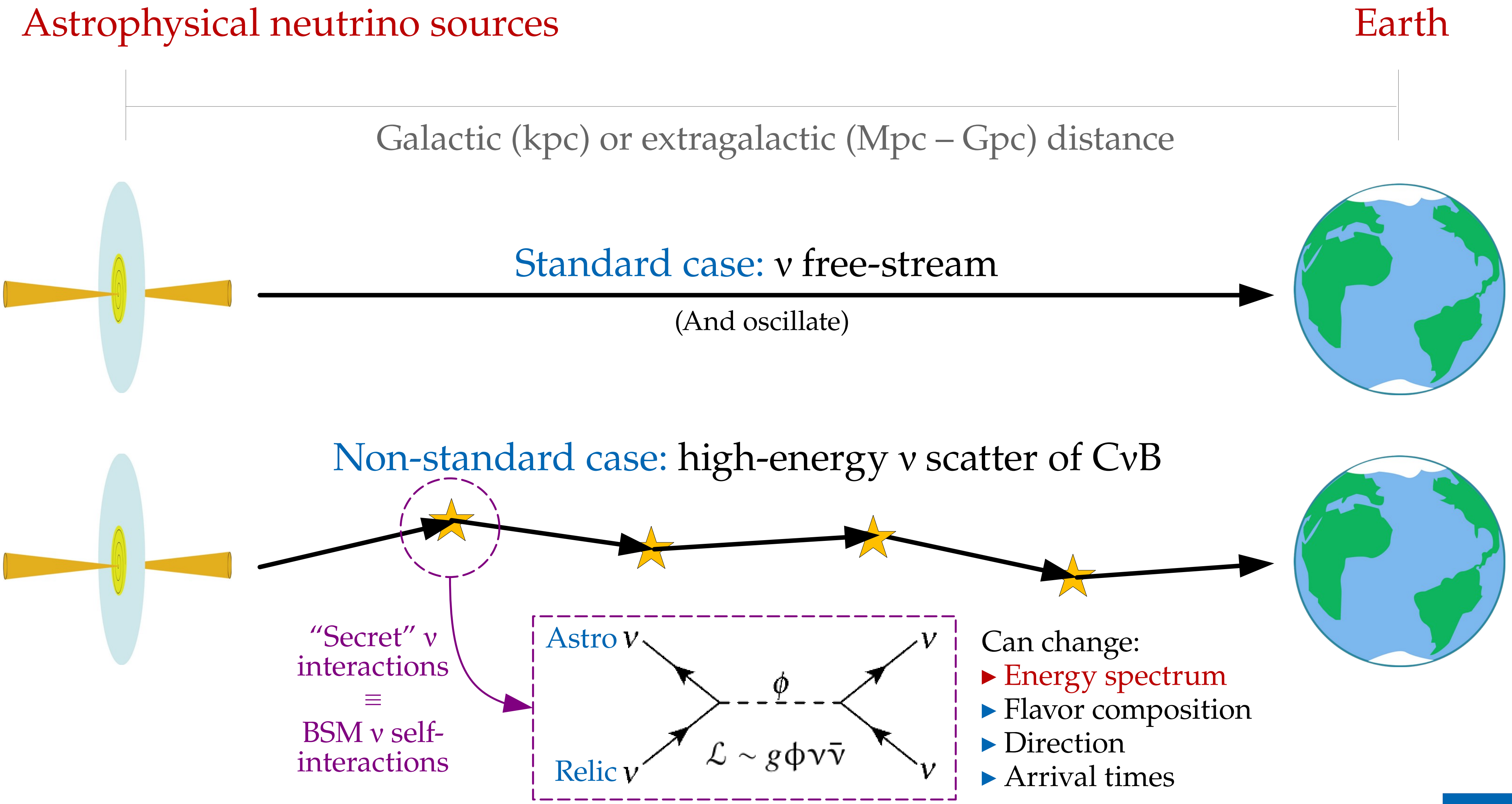
▸ Direction



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Can change:
▸ Energy spectrum
▸ Flavor composition
▸ Direction
▸ Arrival times

Fundamental physics with HE cosmic neutrinos

- Numerous new-physics effects grow as $\sim \kappa_n \cdot E^n \cdot L$

- So we can probe $\kappa_n \sim 4 \cdot 10^{-47} (E/\mathrm{PeV})^{-n} (L/\mathrm{Gpc})^{-1}\,\mathrm{PeV}^{1-n}$

- Improvement over limits using atmospheric ν: $\kappa_0 < 10^{-29}$ PeV, $\kappa_1 < 10^{-33}$

- Fundamental physics can be extracted from four neutrino observables:
  - Spectral shape
  - Angular distribution
  - Flavor composition
  - Timing

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- Fundamental physics can be extracted from four neutrino observables:
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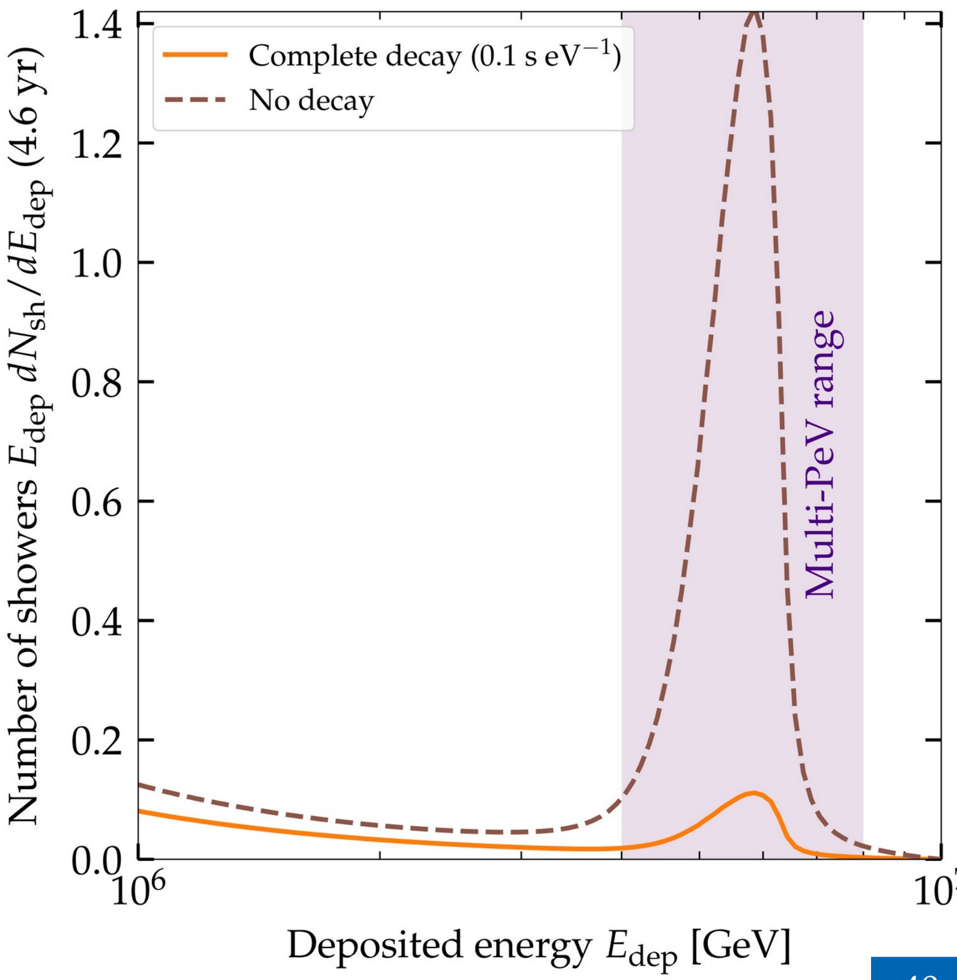
  In spite of
  poor energy, angular, flavor reconstruction
  & astrophysical unknowns

Using the Glashow resonance to test decay

- At 6.3 PeV, the Glashow resonance ($\bar{\nu}_e + e \to W$) should trigger showers in IceCube
- … unless ν_1, ν_2 decay to ν_3 en route to Earth (the surviving ν_3 have little electron content)
- IceCube has seen 1 shower in the 4–8 PeV range, so ν_1, ν_2 *must* make it to Earth
- So we set *lower* limits on their lifetimes (in the inverted mass ordering)
- Translated into *upper* limits on coupling



MB, 2004.06844
See also: **MB**, Beacom, Murase, *PRD* 2017

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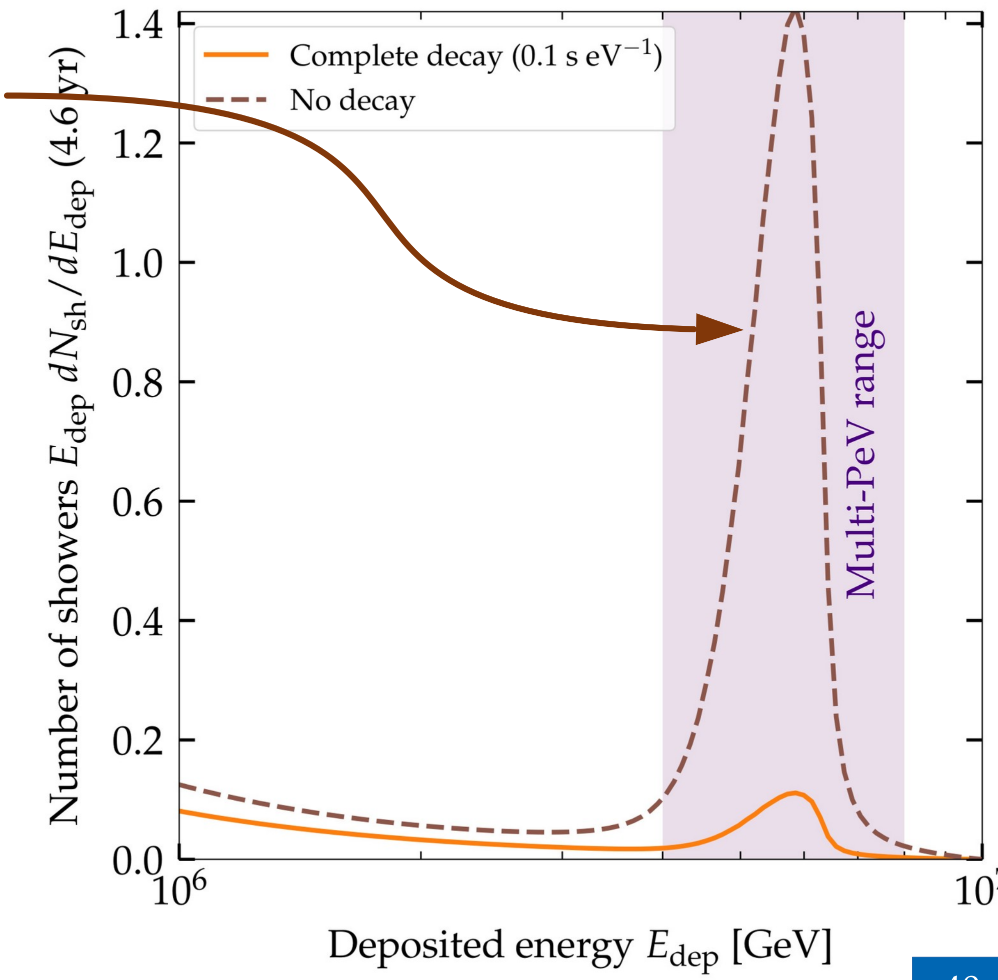

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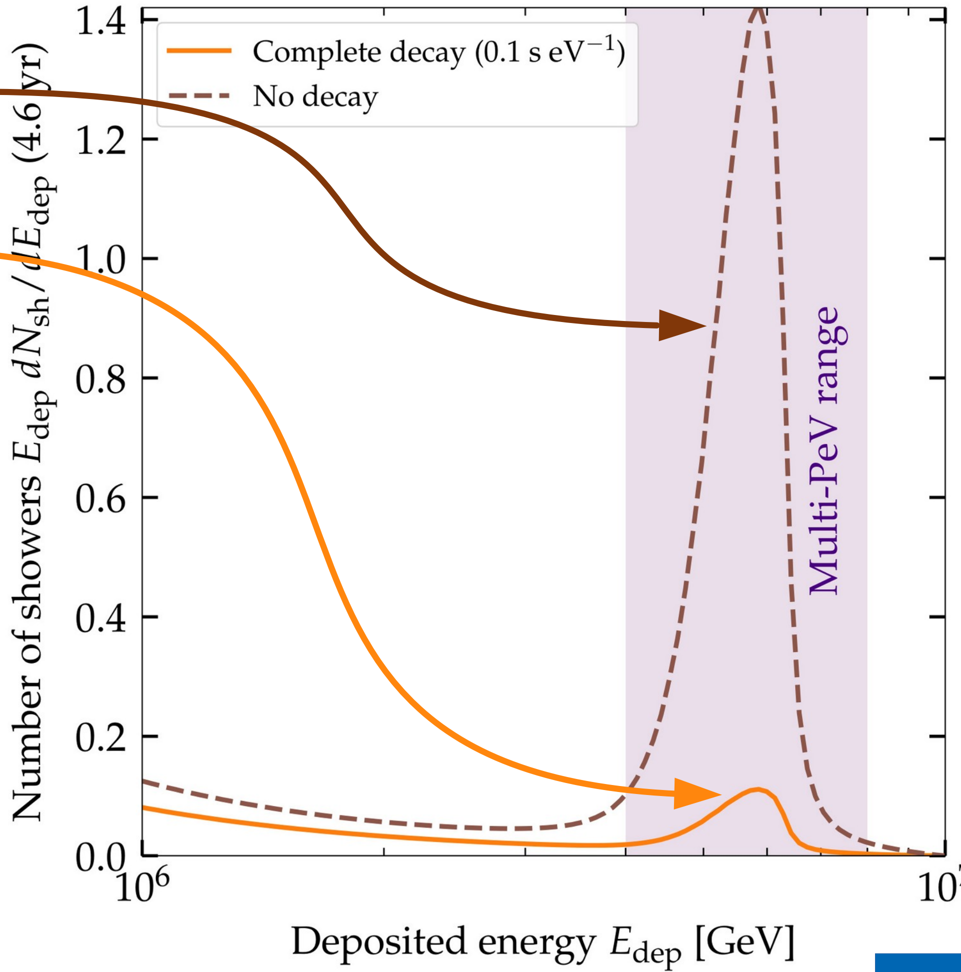
Using the Glashow resonance to test decay

- At 6.3 PeV, the Glashow resonance ($\bar{\nu}_e + e \to W$) should trigger showers in IceCube
- … unless ν_1, ν_2 decay to ν_3 en route to Earth (the surviving ν_3 have little electron content)
- IceCube has seen 1 shower in the 4–8 PeV range, so ν_1, ν_2 *must* make it to Earth
- So we set *lower* limits on their lifetimes (in the inverted mass ordering)
- Translated into *upper* limits on coupling



MB, 2004.06844
See also: **MB**, Beacom, Murase, *PRD* 2017

Using the Glashow resonance to test decay

$\tau_1/m_1 > 2.91 \times 10^{-3}$ s eV^{-1} (90% C.L.)
$\tau_2/m_2 > 1.26 \times 10^{-3}$ s eV^{-1} (90% C.L.)

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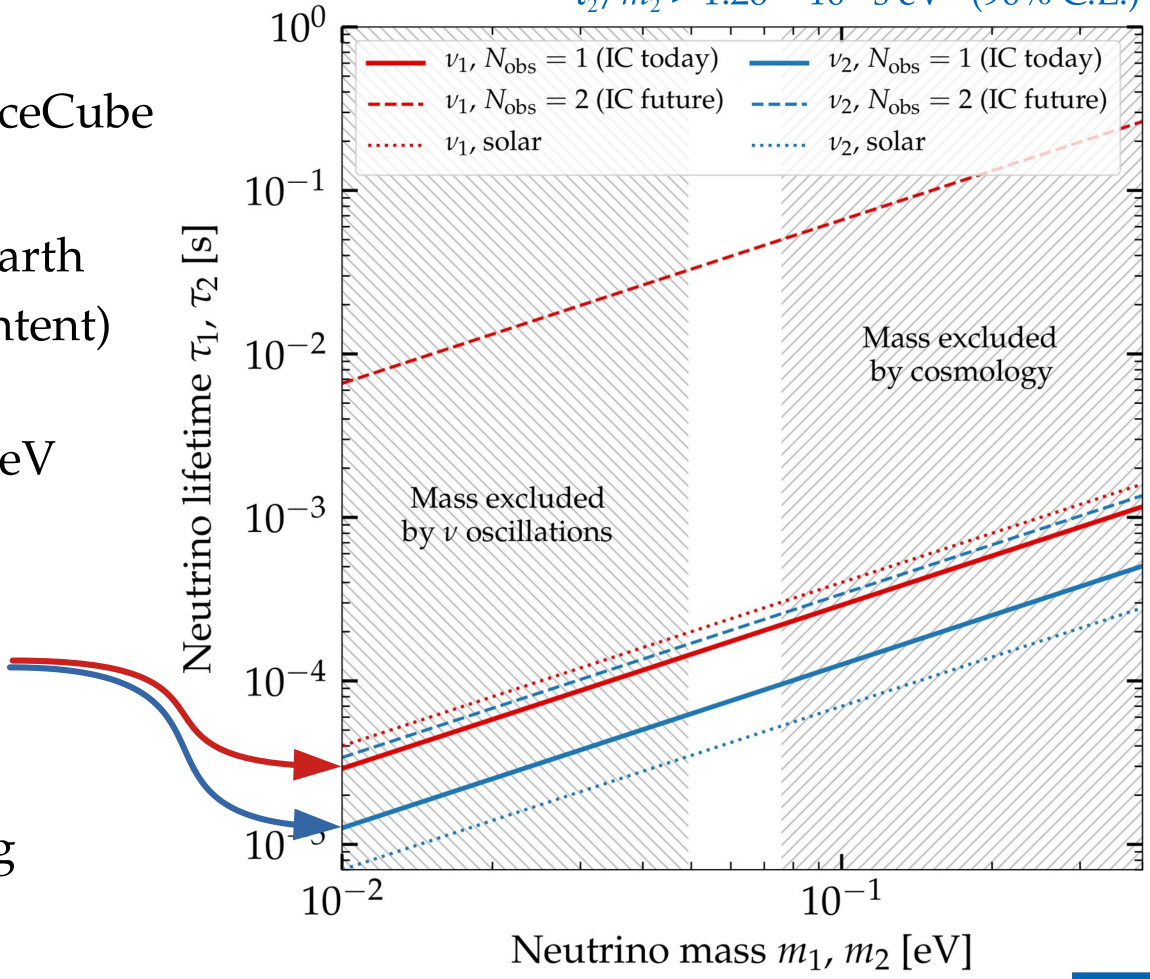

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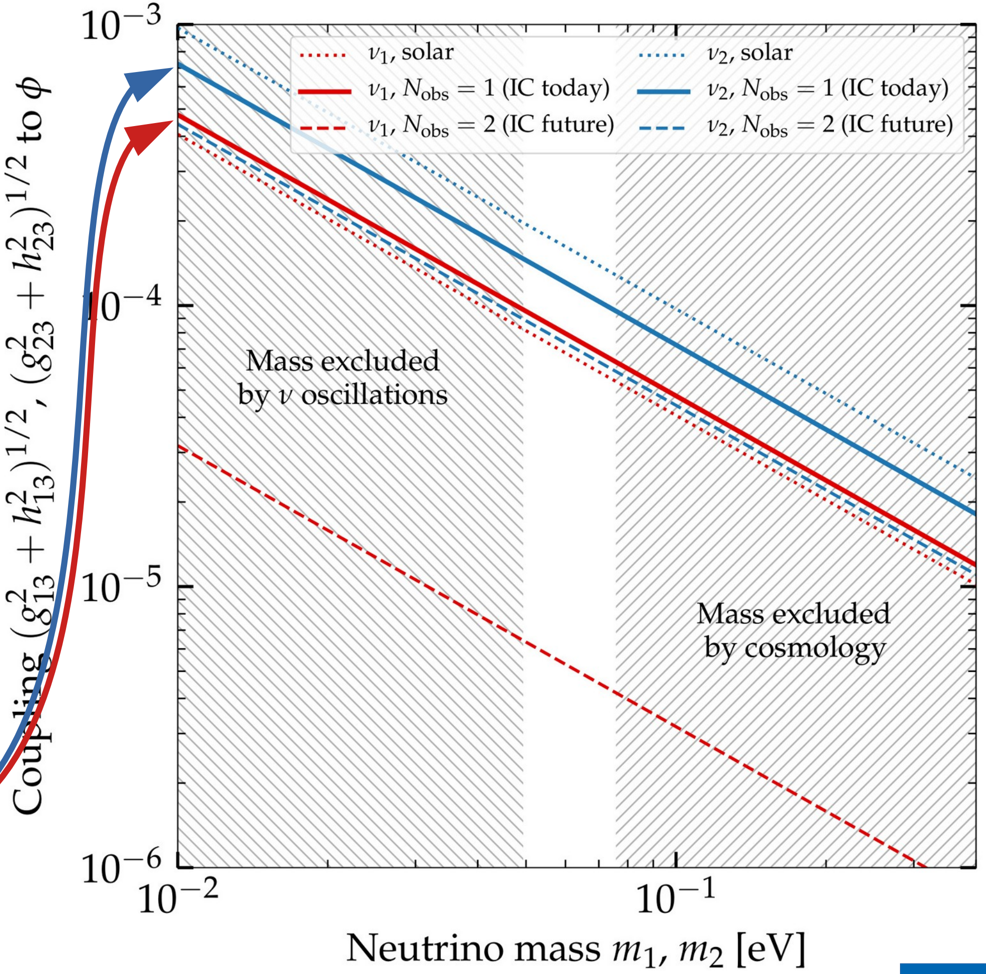
$$\mathcal{L} = g_{ij}\bar{\nu}_i\nu_j\phi + h_{ij}\bar{\nu}_i\gamma_5\nu_j\phi + \text{h.c.}$$



MB, 2004.06844
See also: **MB**, Beacom, Murase, *PRD* 2017

Ultra-long-range flavorful interactions

- Simple extension of the SM: Promote the global lepton-number symmetries L_e-L_μ, L_e-L_τ to local symmetries

- They introduce new interaction between electrons and ν_e and ν_μ or ν_τ mediated by a new neutral vector boson (Z'):
  - Affects oscillations
  - If the Z' is *very* light, *many* electrons can contribute

X.-G. He, G.C. Joshi, H. Lew, R. R. Volkas, *PRD* 1991 / R. Foot, X.-G. He, H. Lew, R. R. Volkas, *PRD* 1994
A. Joshipura, S. Mohanty, *PLB* 2004 / J. Grifols & E. Massó, PLB 2004 / A. Bandyopadhyay, A. Dighe, A. Joshipura, *PRD* 2007
M.C. González-García, P..C. de Holanda, E. Massó, R. Zukanovich Funchal, *JCAP* 2007 / A. Samanta, *JCAP* 2011
S.-S. Chatterjee, A. Dasgupta, S. Agarwalla, *JHEP* 2015

The new potential sourced by an electron

Under the L_e-L_μ or L_e-L_τ symmetry, an electron sources a Yukawa potential —

$$V \sim \frac{g'^2_{e\beta}}{r} e^{-m'_{e\beta} r}$$

A neutrino "feels" all the electrons within the interaction range ~$(1/m')$

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Under the L_e-L_μ or L_e-L_τ symmetry, an electron sources a Yukawa potential —

Z' coupling

Z' mass

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Distance to neutrino

A neutrino "feels" all the electrons within the interaction range ~$(1/m')$

Electron-neutrino interactions can kill oscillations

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$$H_{\text{tot}} = \underbrace{H_{\text{vac}}}$$

Standard oscillations:
Neutrinos change flavor
because this is non-diagonal

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↓

$$P_{\nu_\alpha \to \nu_\beta}\left(\theta_{ij}, \delta_{\mathrm{CP}}\right)$$

Electron-neutrino interactions can kill oscillations

$$= \mathrm{diag}(V_{e\mu}, -V_{e\mu}, 0)$$

$$\mathrm{H}_{\mathrm{tot}} = \mathrm{H}_{\mathrm{vac}} + \underbrace{\mathrm{V}_{e\beta}}$$

New neutrino-electron interaction:
This is diagonal

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New neutrino-electron interaction:
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Z' parameters

$$P_{\nu_\alpha \to \nu_\beta}\left(\theta_{ij}, \delta_{\text{CP}}, \Delta m^2_{ij}, E_\nu, g'_{e\mu}, m'_{e\mu}\right)$$

Electron-neutrino interactions can kill oscillations

$$\mathrm{H}_{\mathrm{tot}} = \mathrm{H}_{\mathrm{vac}} + \mathrm{V}_{e\beta} \qquad = \mathrm{diag}(V_{e\mu}, -V_{e\mu}, 0)$$

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Z′ parameters

$$P_{\nu_\alpha \to \nu_\beta}\left(\theta_{ij}, \delta_{\mathrm{CP}}, \Delta m^2_{ij}, E_\nu, g'_{e\mu}, m'_{e\mu}\right)$$

If $V_{e\beta}$ dominates ($g' \gg 1$, $m' \ll 1$), oscillations turn off

Electron-neutrino interactions can kill oscillations

$$\mathrm{H}_{\mathrm{tot}} = \mathrm{H}_{\mathrm{vac}} + \mathrm{V}_{e\beta}$$

Electron-neutrino interactions can kill oscillations

$$\mathrm{H}_{\mathrm{tot}} = \mathrm{H}_{\mathrm{vac}} + \mathrm{V}_{e\beta}$$

$\sim 1/E$

Energy-independent

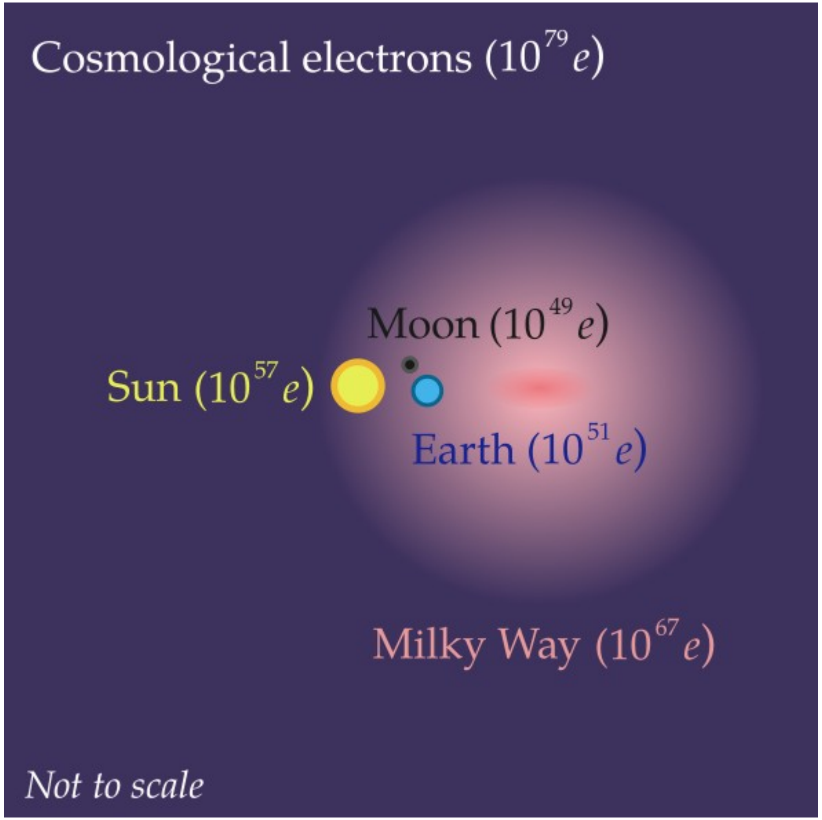
Electron-neutrino interactions can kill oscillations

$$H_{tot} = H_{vac} + V_{e\beta}$$

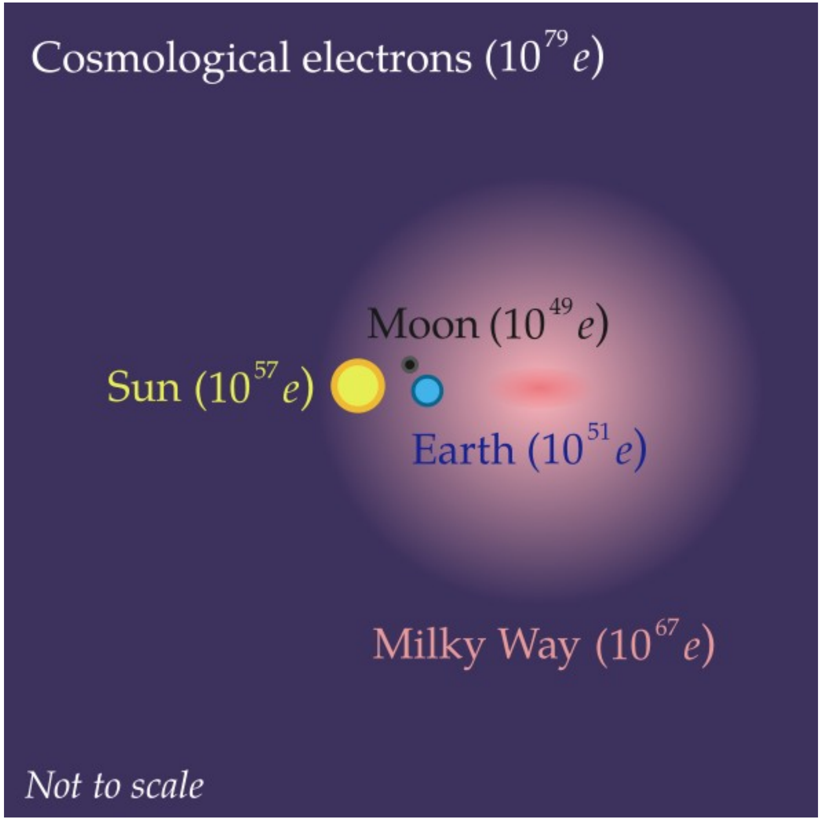
$\sim 1/E$ | Energy-independent

∴ We can use high-energy astrophysical neutrinos

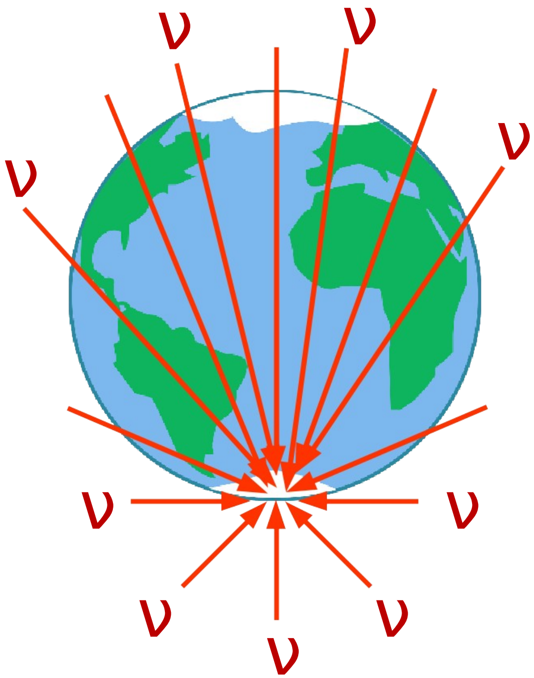
The total potential

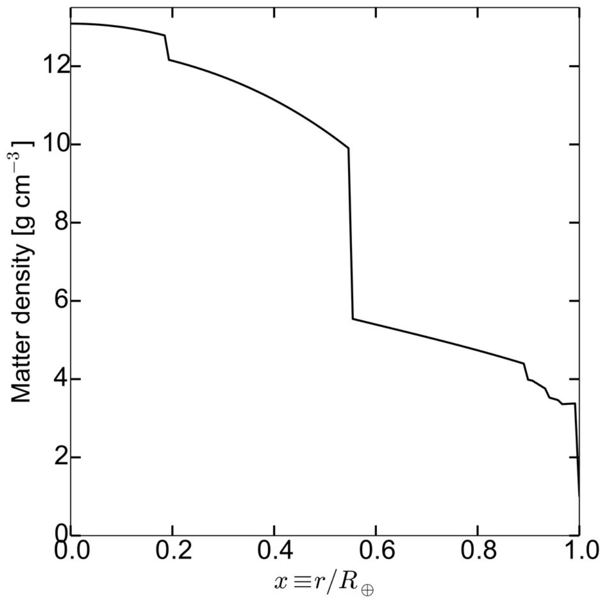


The total potential



Earth:

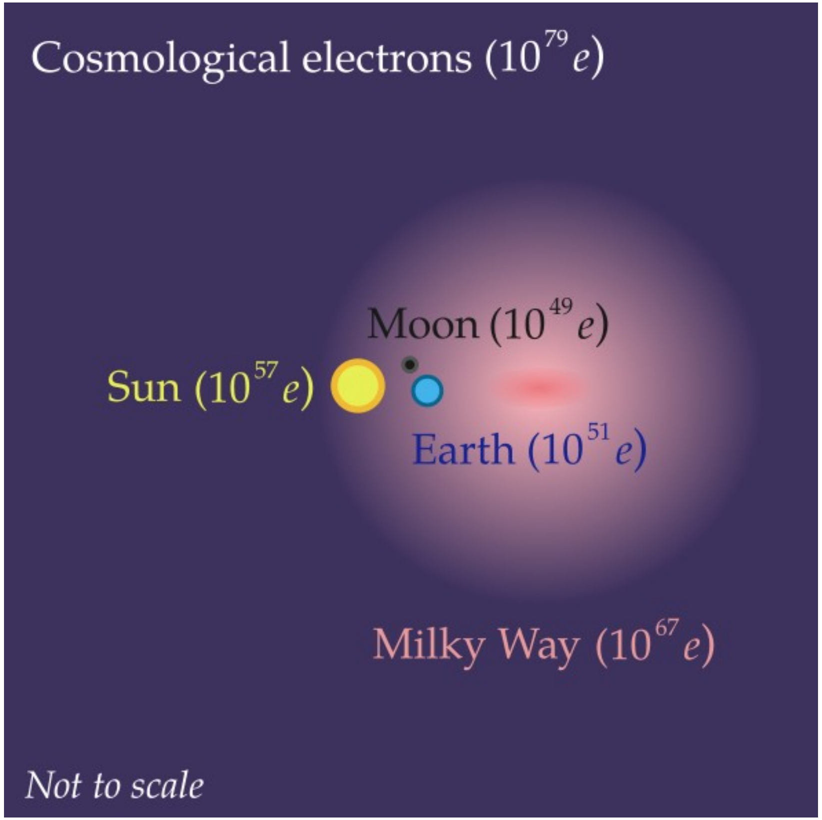




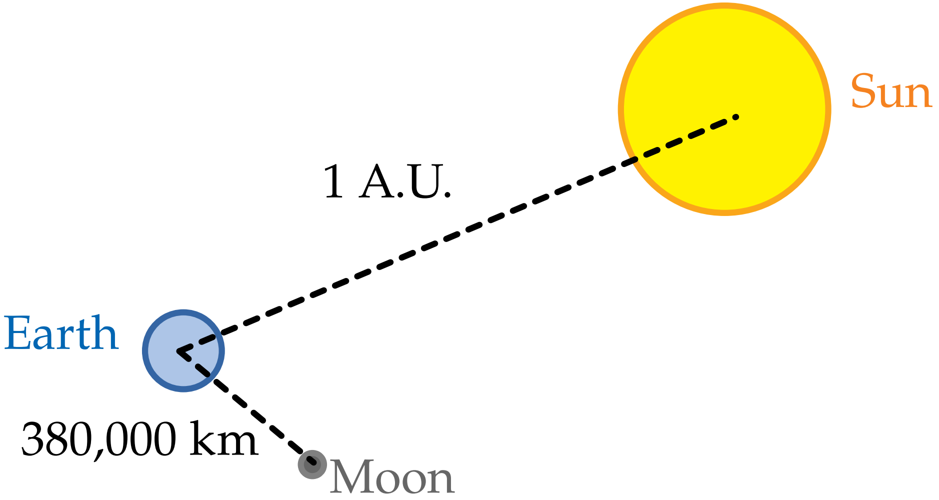
Neutrinos traverse different electron column depths

$$V_{e\beta} = V_{e\beta}^{\oplus}$$

The total potential



Moon and Sun:

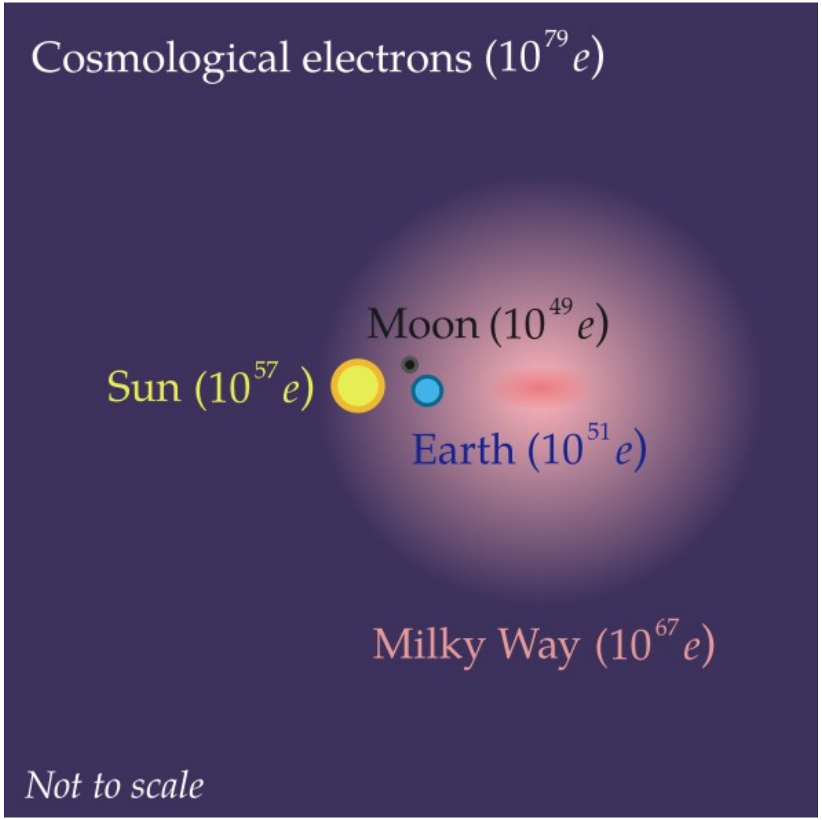


Treated as point sources of electrons

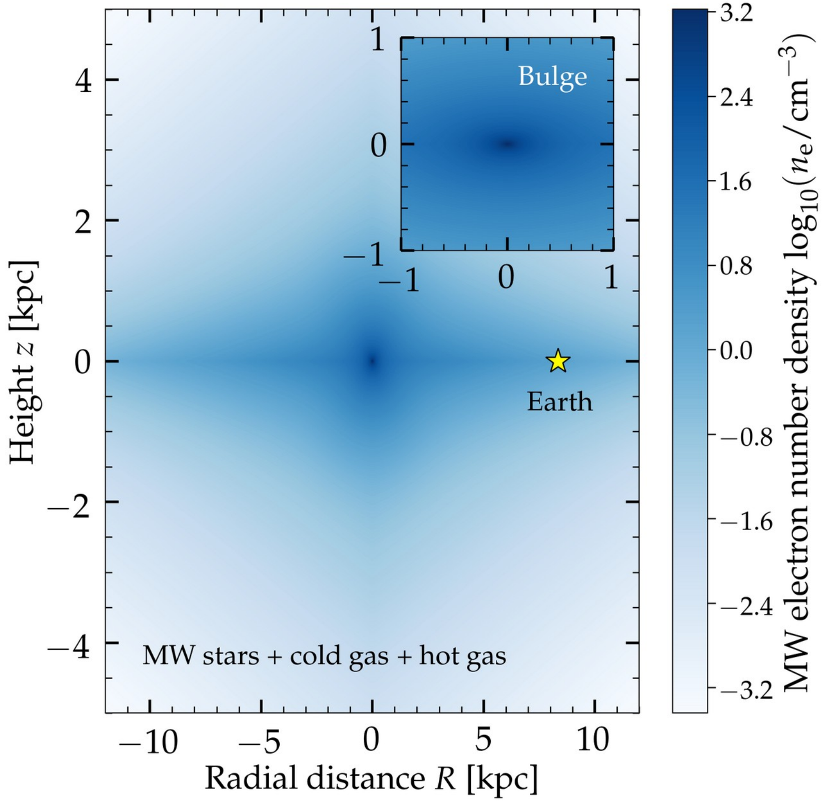
$$V_{e\beta} = V_{e\beta}^{\oplus} + V_{e\beta}^{\mathrm{Moon}} + V_{e\beta}^{\odot}$$

The total potential

P. McMillan 2011
M.J. Miller & J.N. Bregman 2013

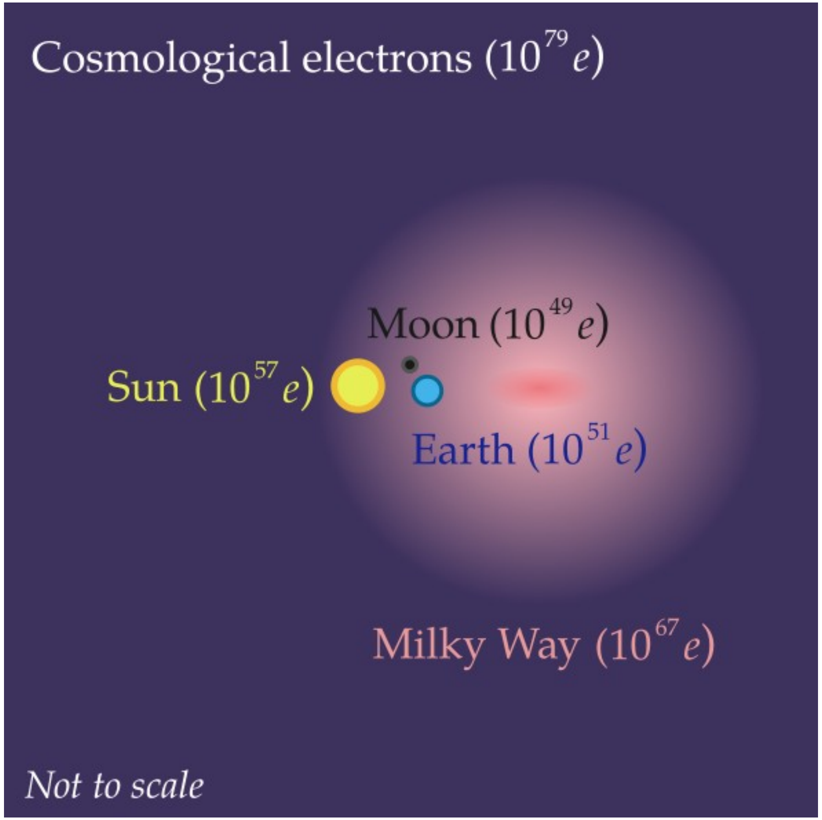


Milky Way:



$$V_{e\beta} = V_{e\beta}^{\oplus} + V_{e\beta}^{\text{Moon}} + V_{e\beta}^{\odot} + V_{e\beta}^{\text{MW}}$$

The total potential



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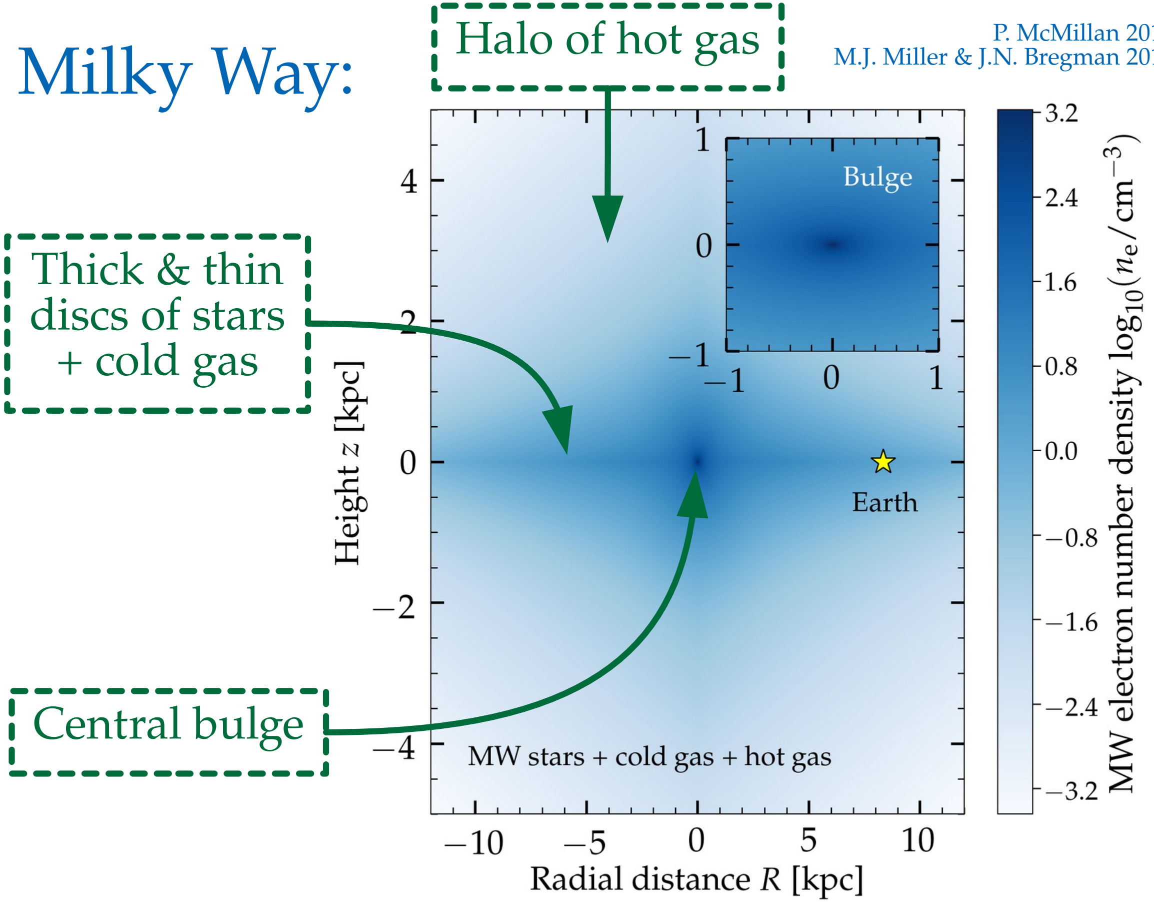

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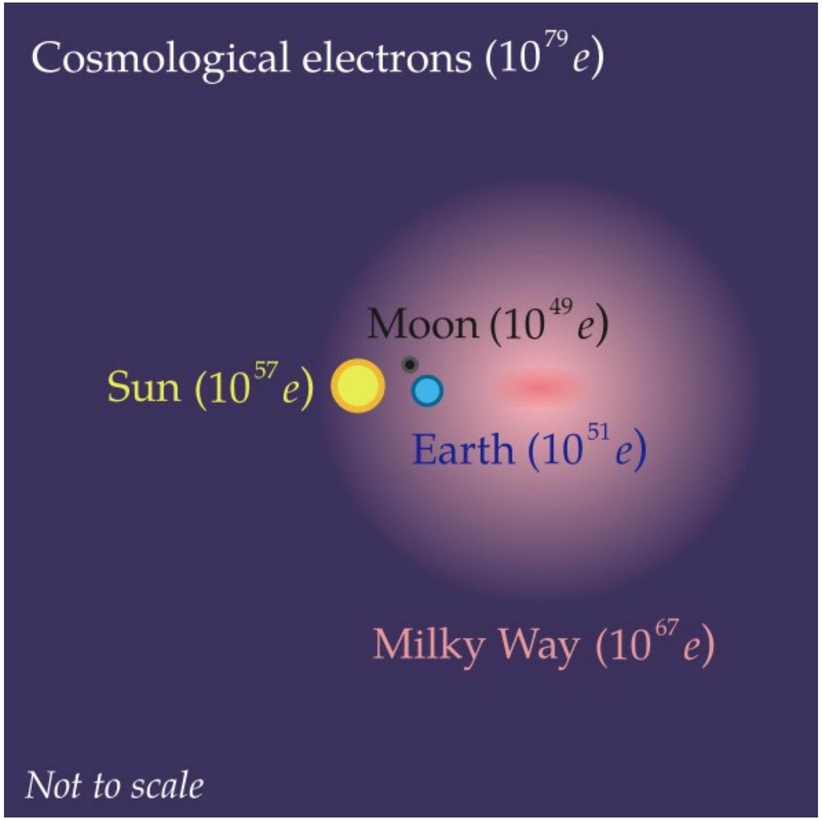
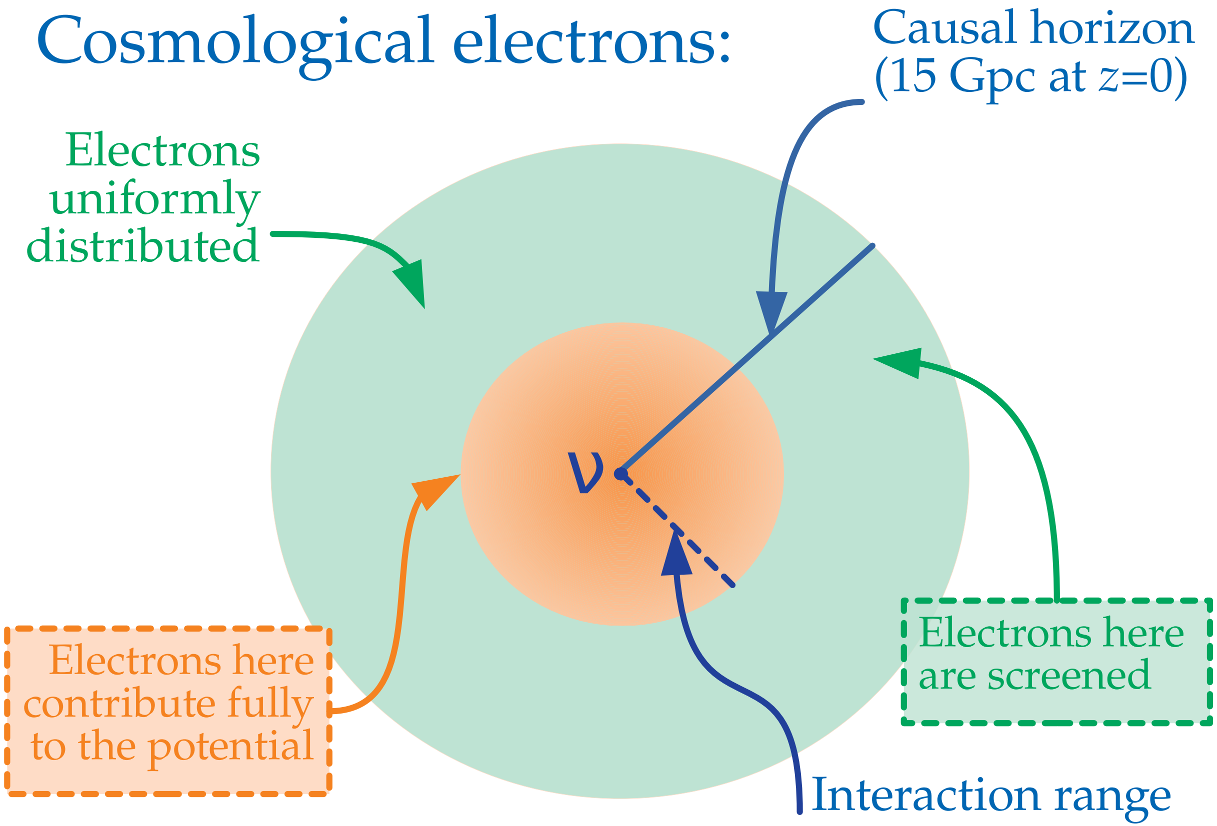
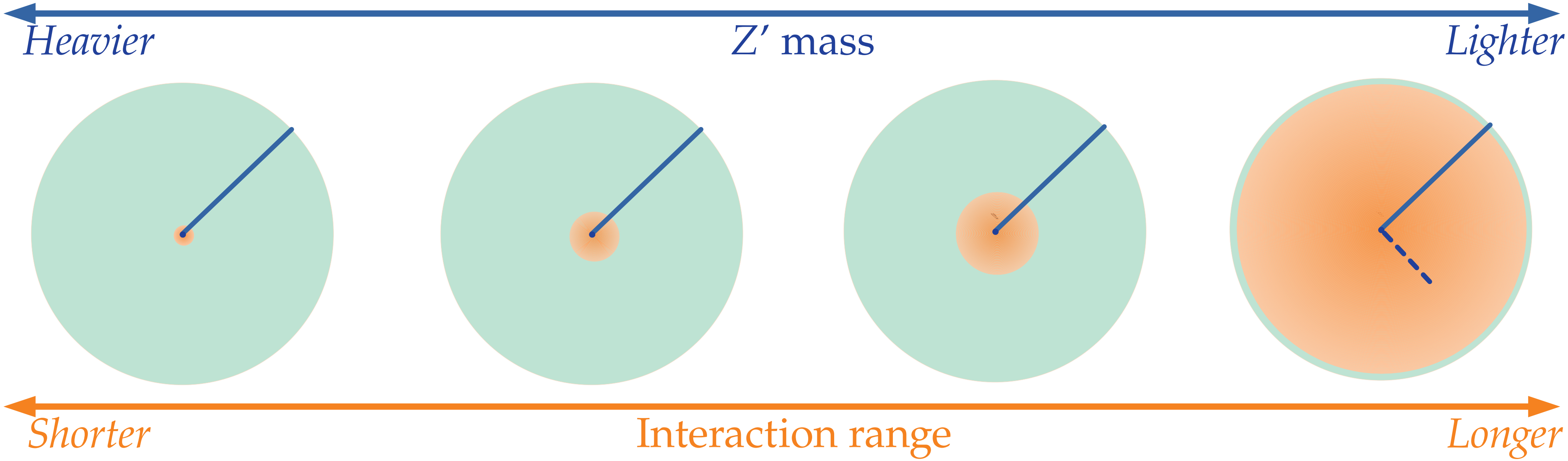


Cosmological electrons:



$$V_{e\beta} = V_{e\beta}^{\oplus} + V_{e\beta}^{\mathrm{Moon}} + V_{e\beta}^{\odot} + V_{e\beta}^{\mathrm{MW}} + V_{e\beta}^{\cos}$$

The total potential



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Electrons in the local and distant Universe

Potential:

$$V_{e\beta} \propto \frac{1}{r} e^{-m'_{e\beta} r}$$

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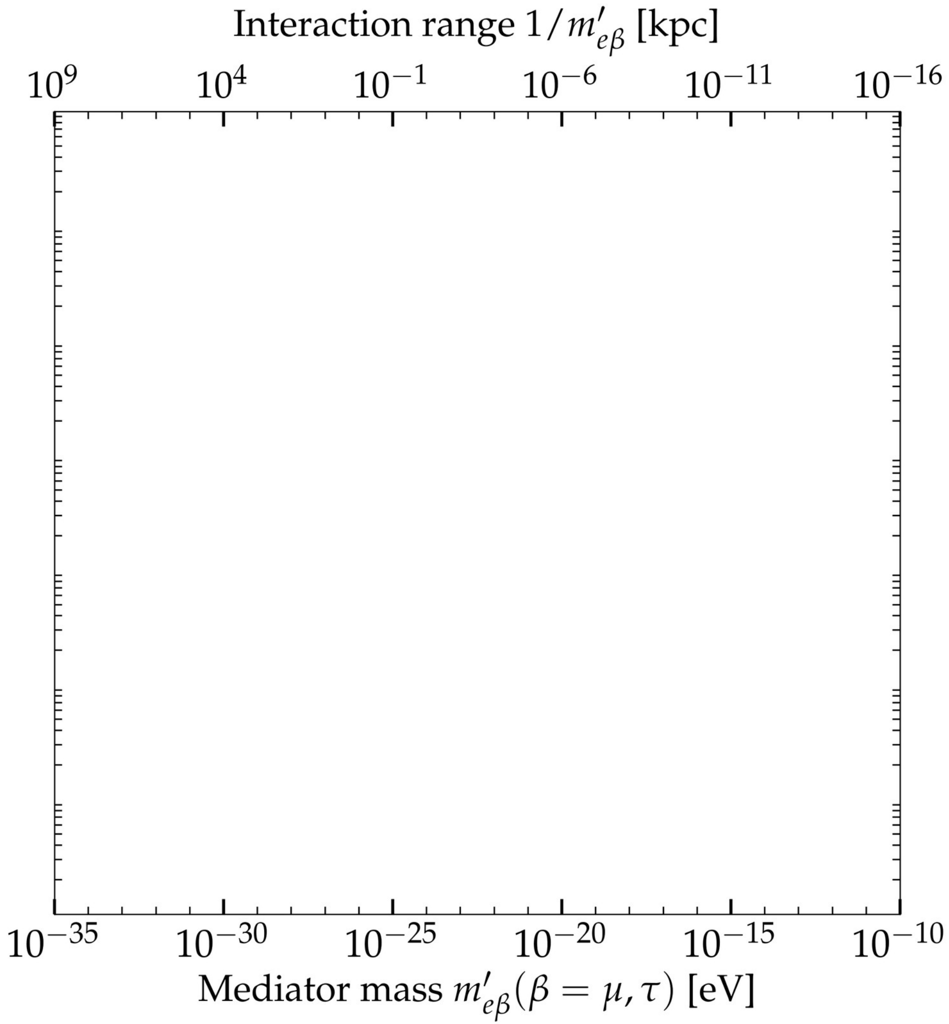

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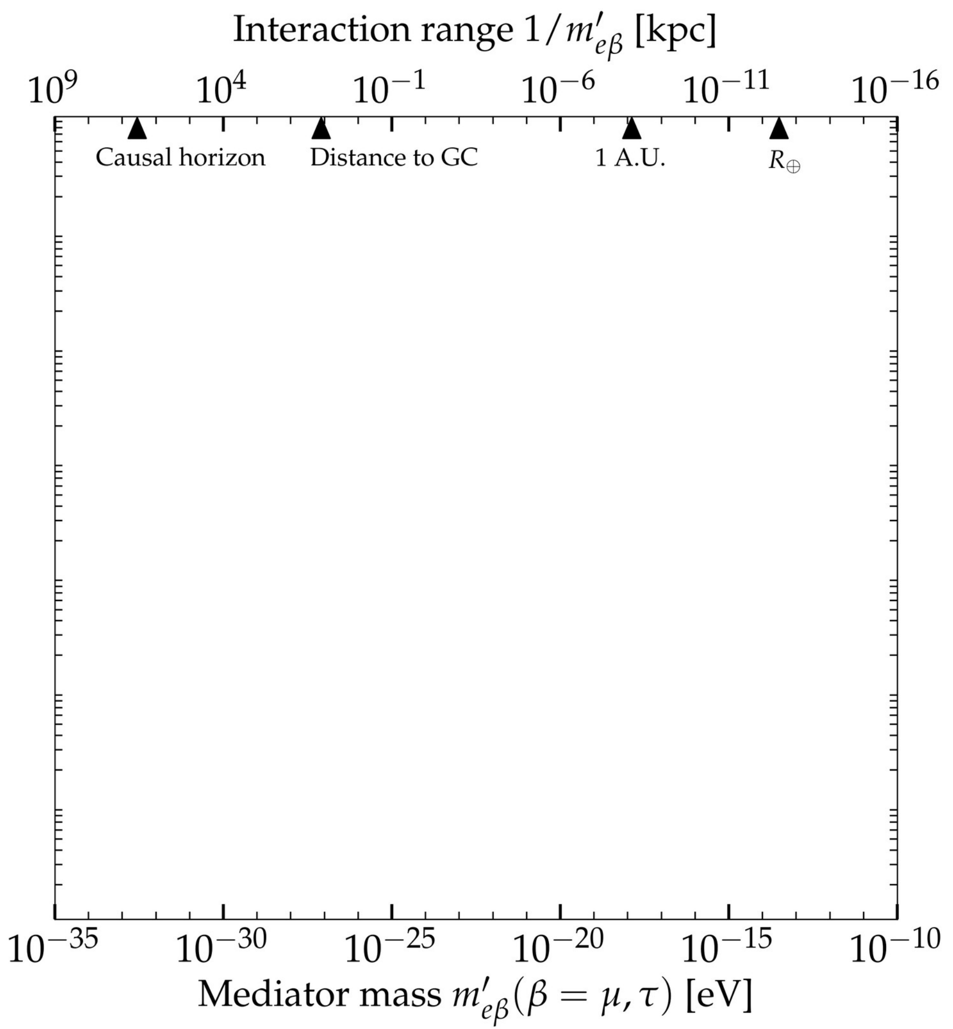

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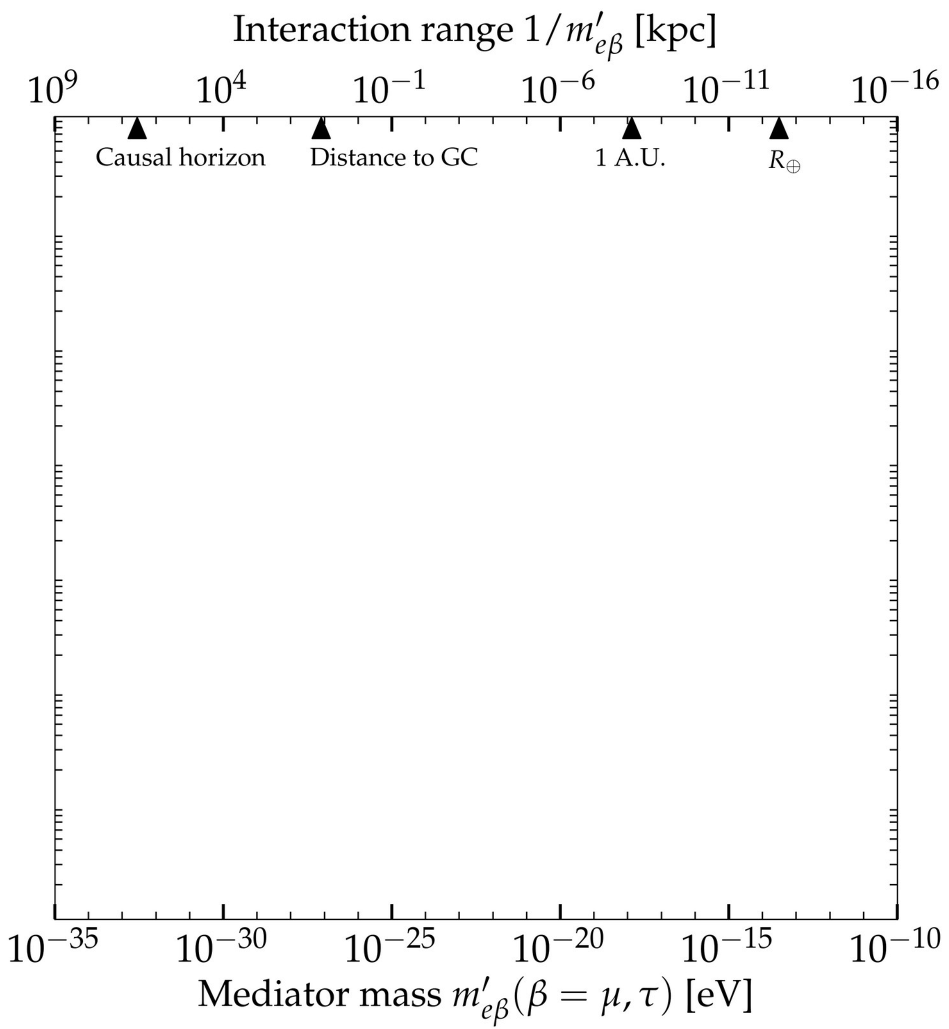

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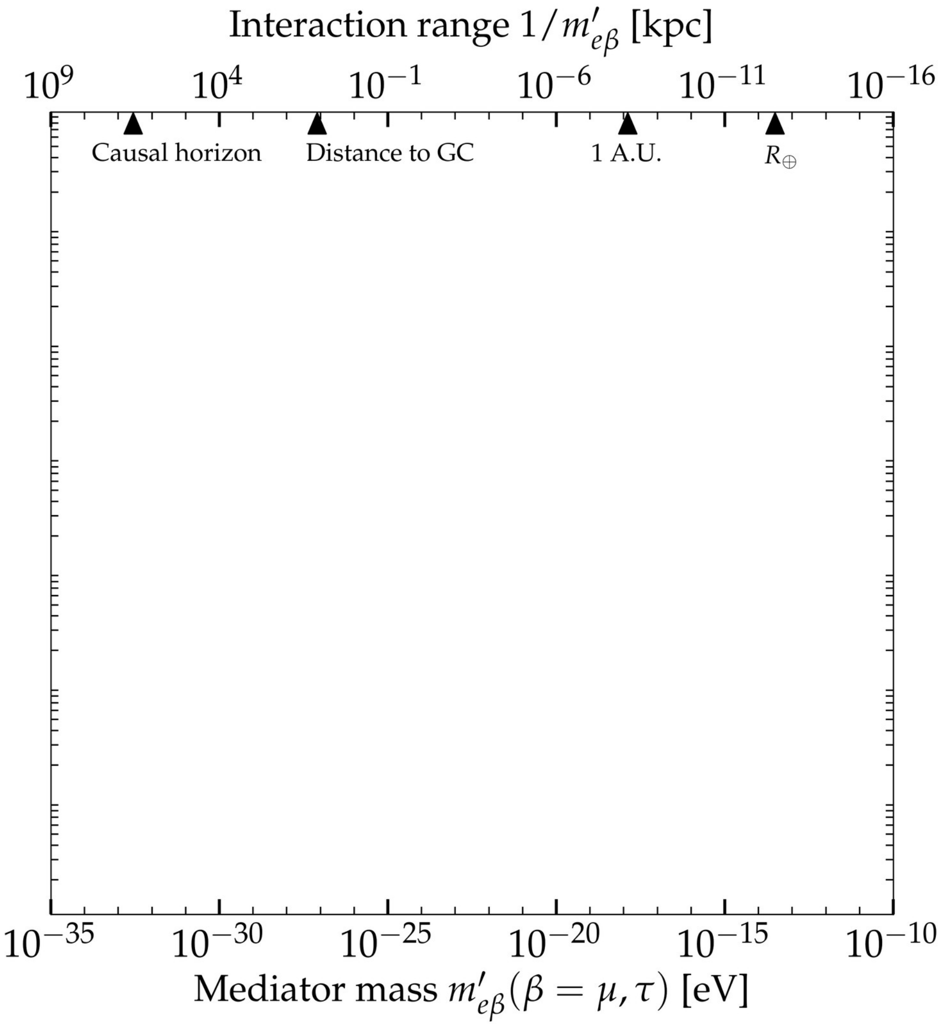
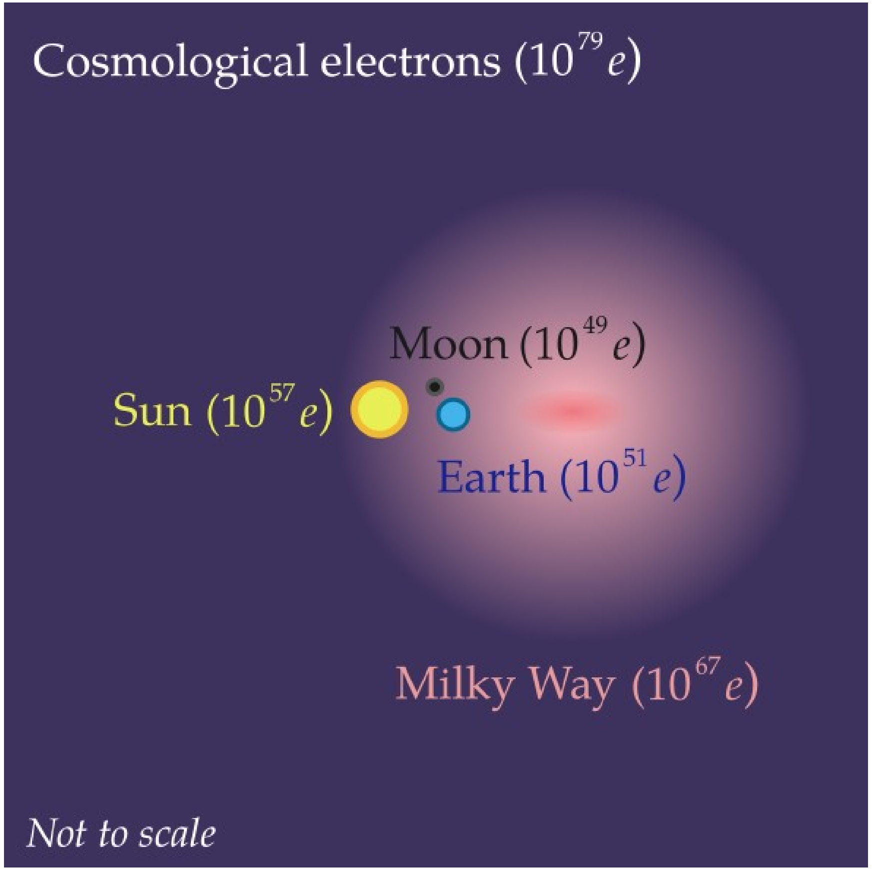
Light mediators
⇒ Long interaction ranges

Electrons in the local and distant Universe





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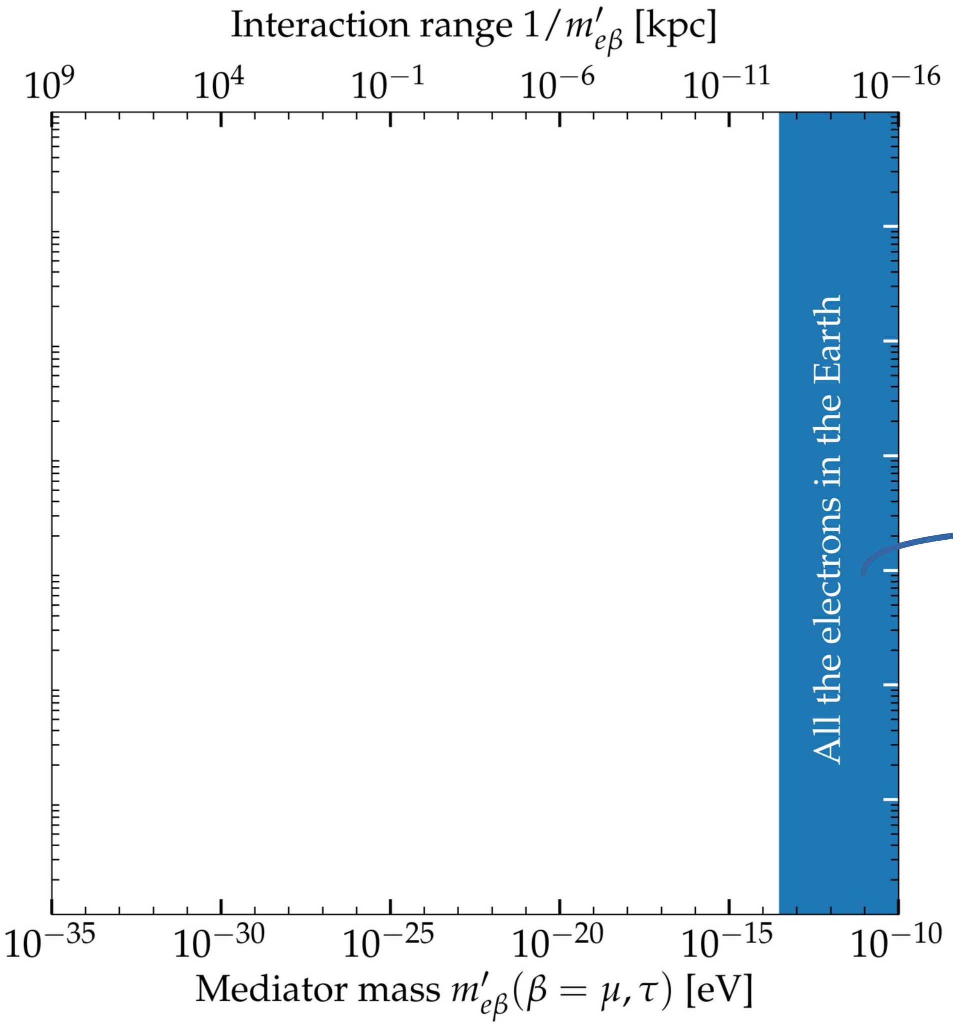

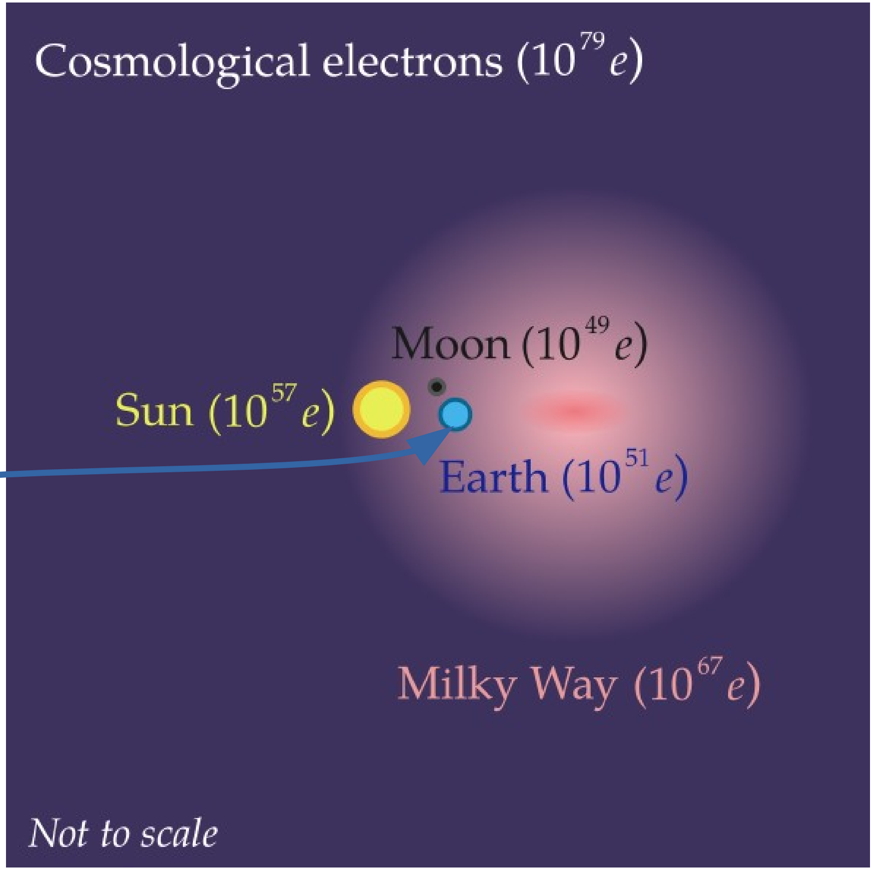

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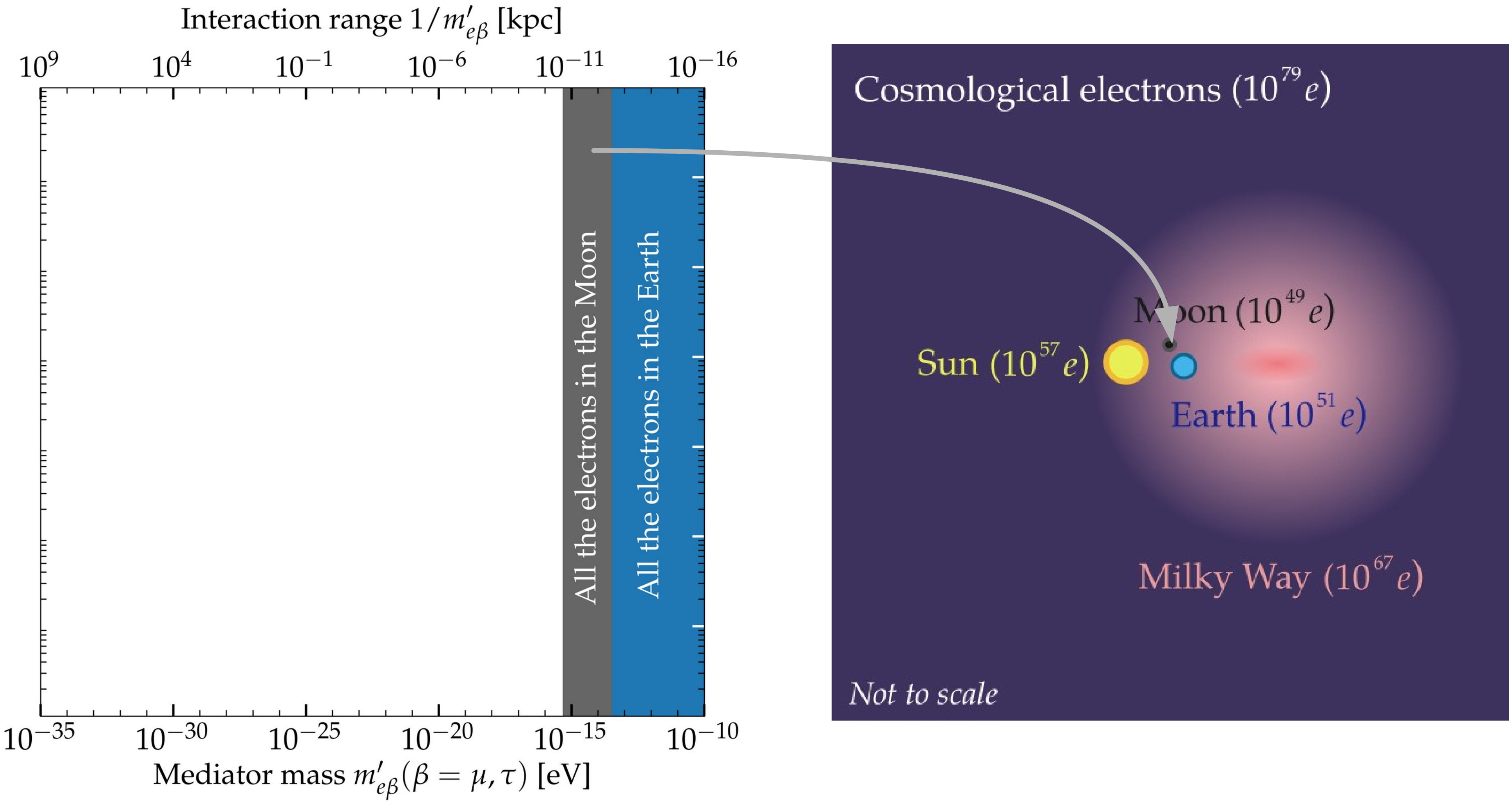

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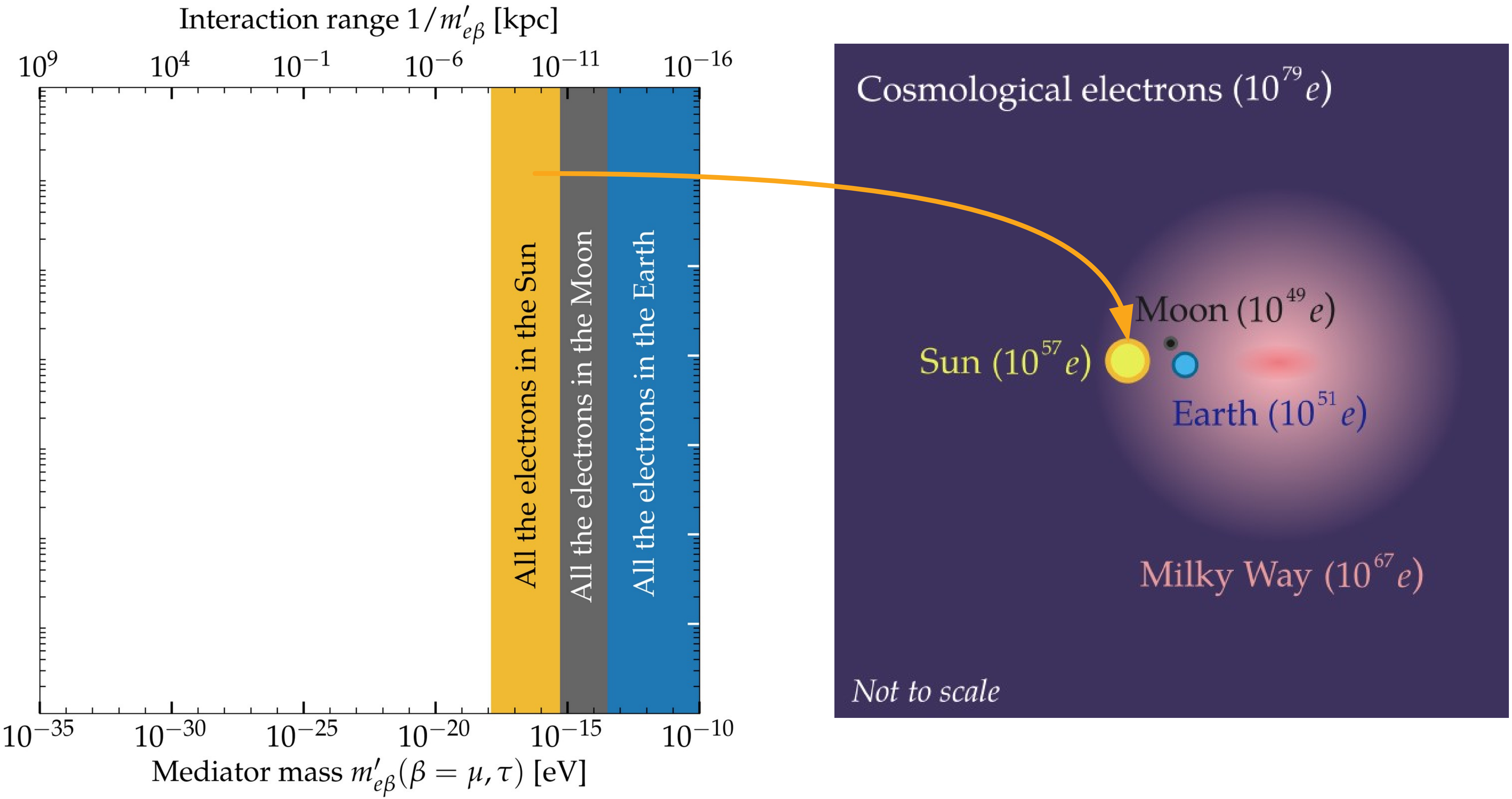

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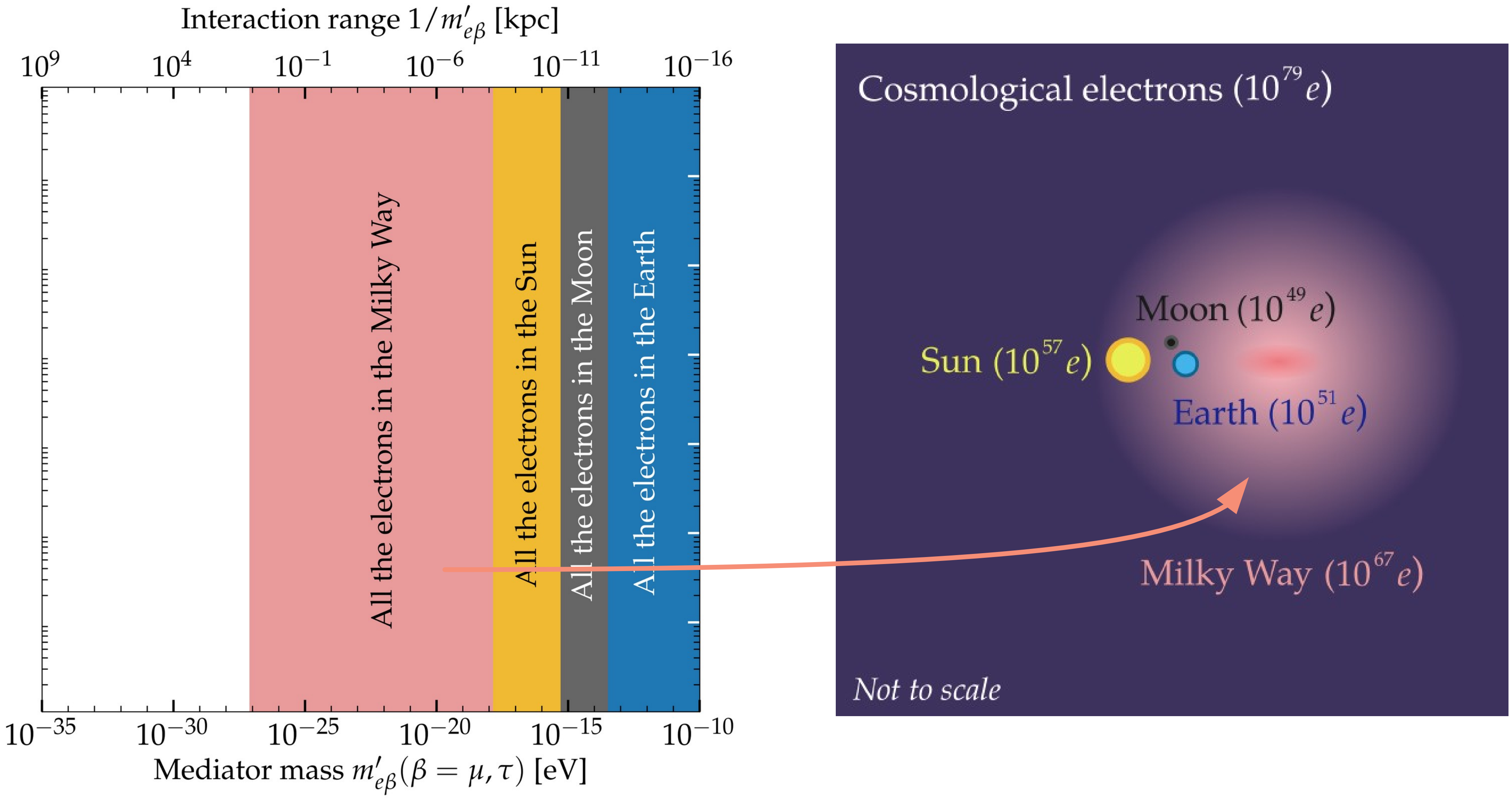
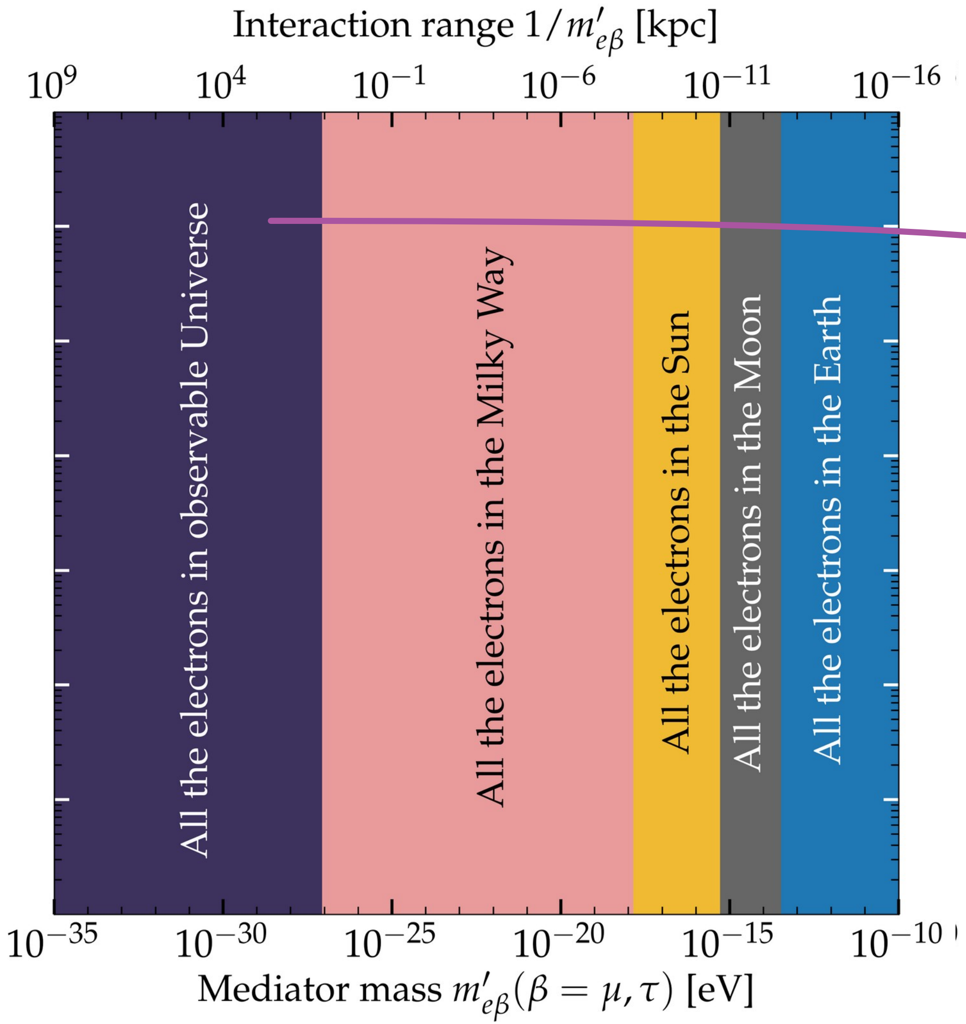
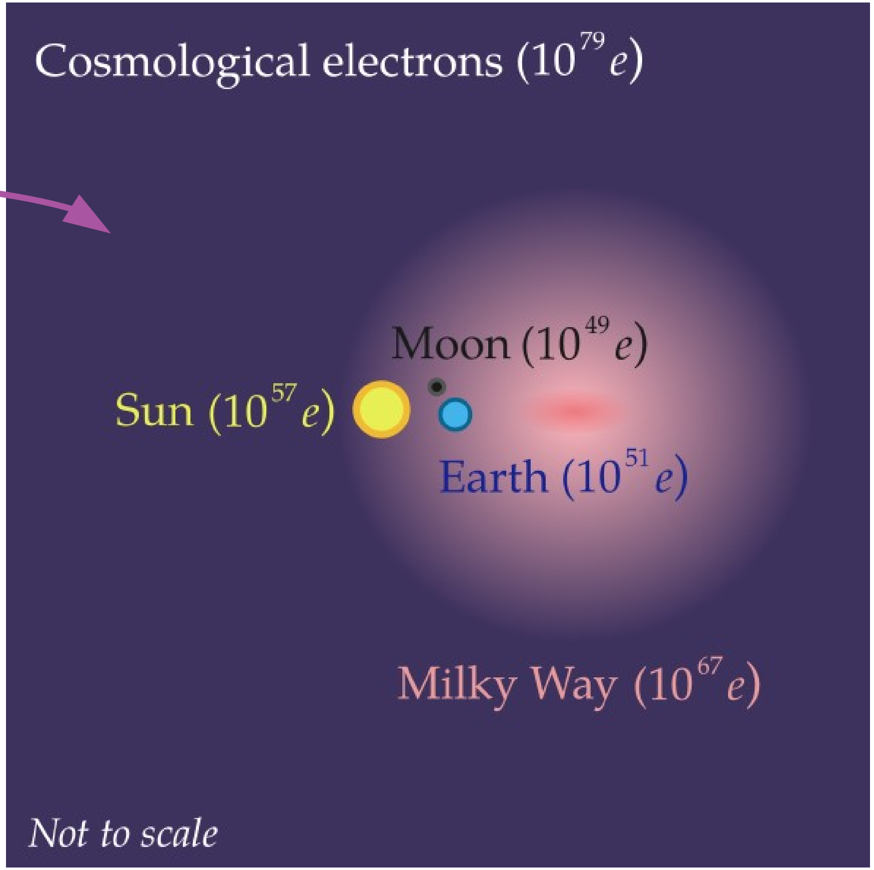
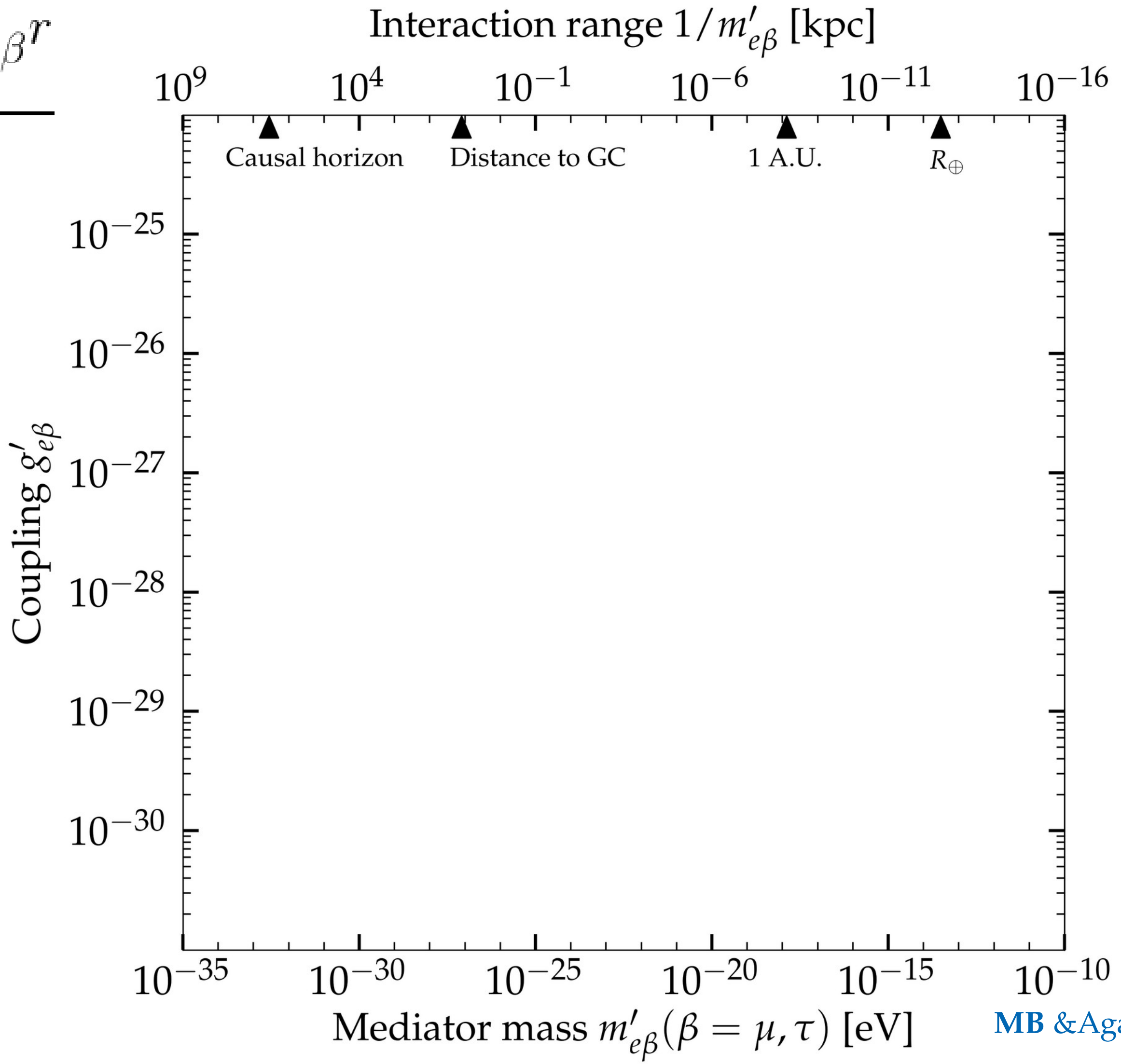


Electrons in the local and distant Universe





$$V_{e\beta} = \frac{g'^2_{e\beta}}{4\pi} \frac{e^{-m'_{e\beta} r}}{r}$$



MB &Agarwalla, *PRL* 2019

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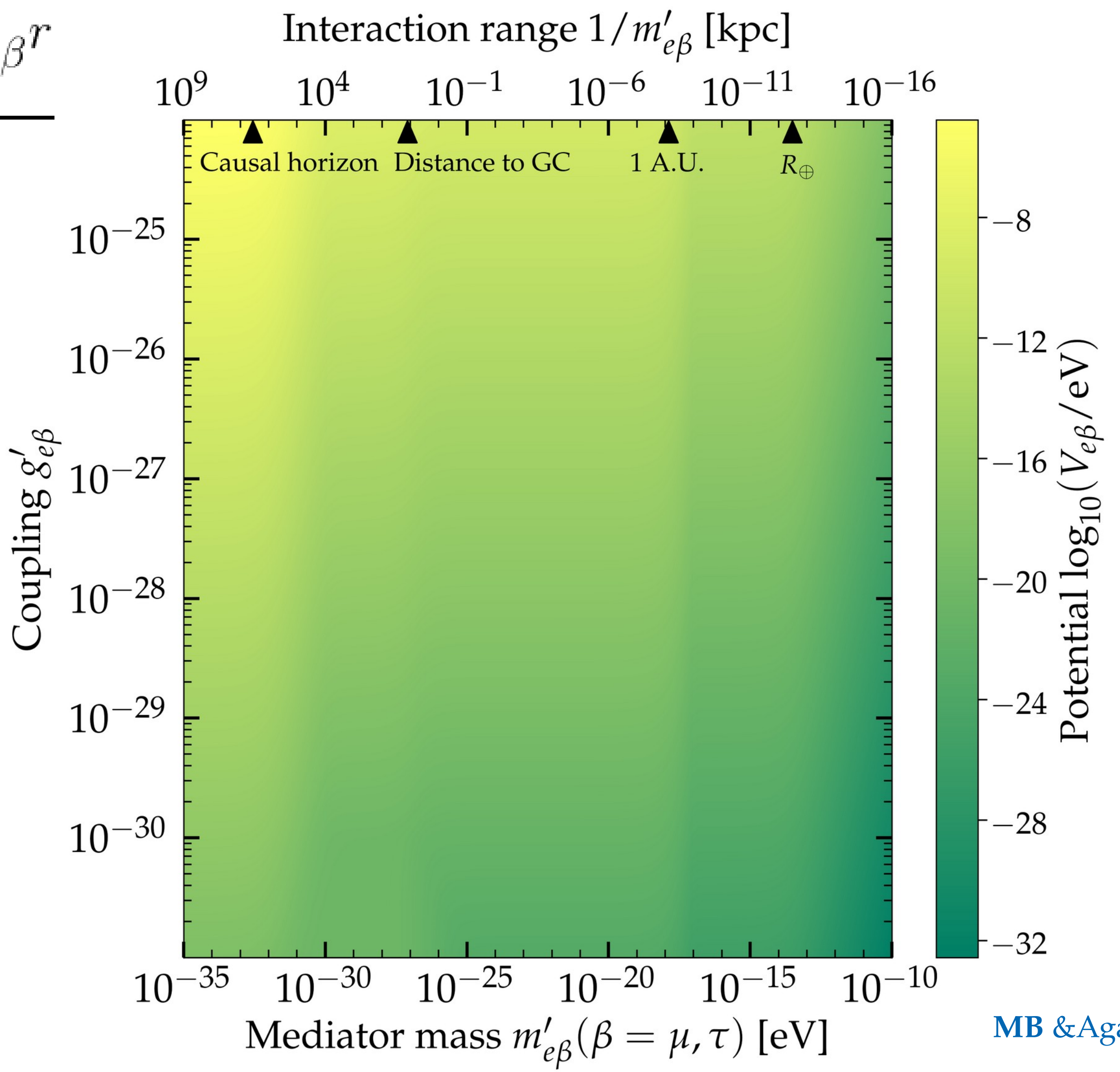
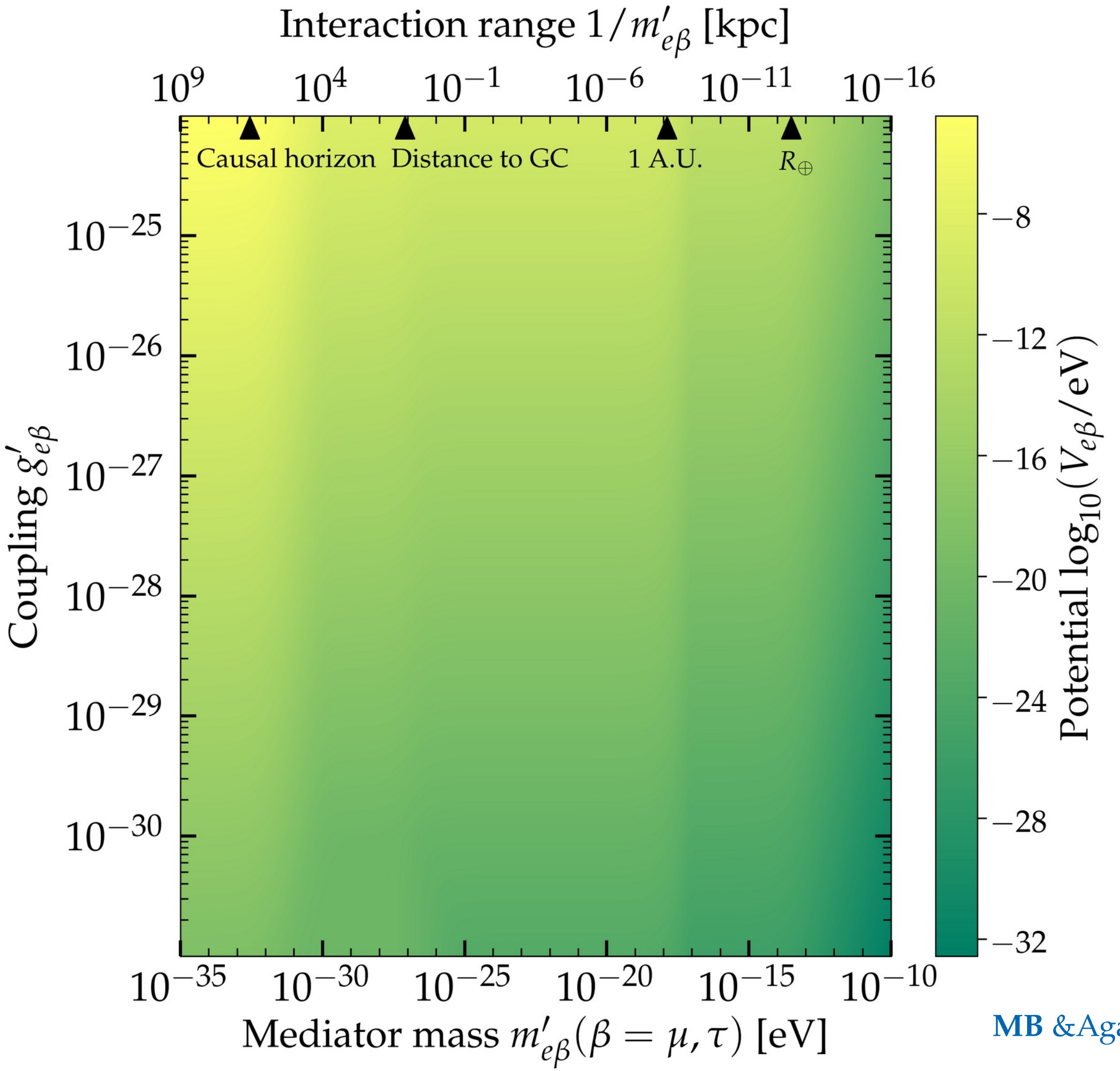


MB &Agarwalla, *PRL* 2019

$g_{\text{strong}} \sim 13.5$
$g_{\text{e.m.}} \sim 0.3$
$g_{\text{weak}} \sim 0.01$
$g_{\text{gravity}} \sim 10^{-19}$



MB &Agarwalla, *PRL* 2019

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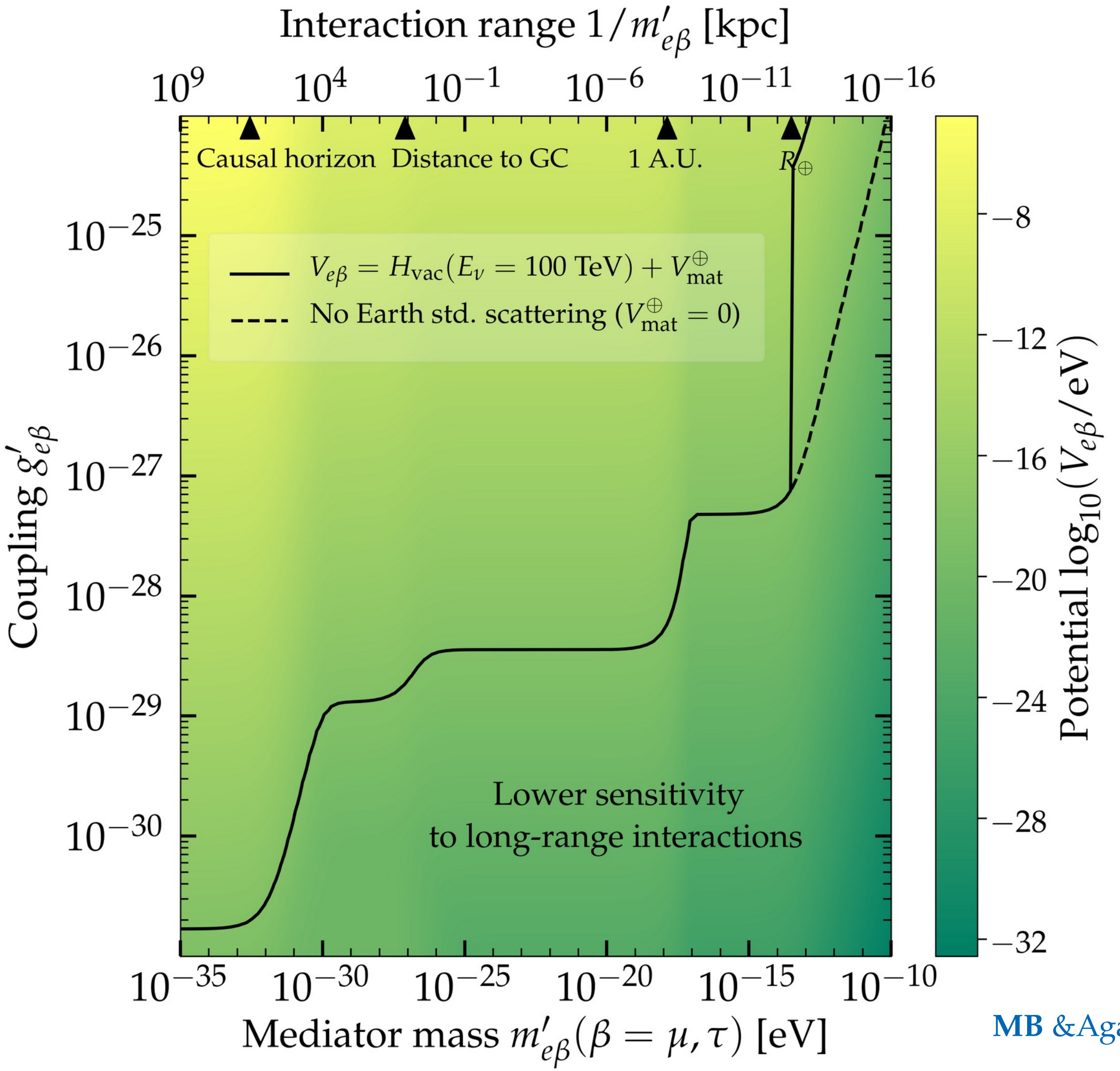

MB &Agarwalla, *PRL* 2019

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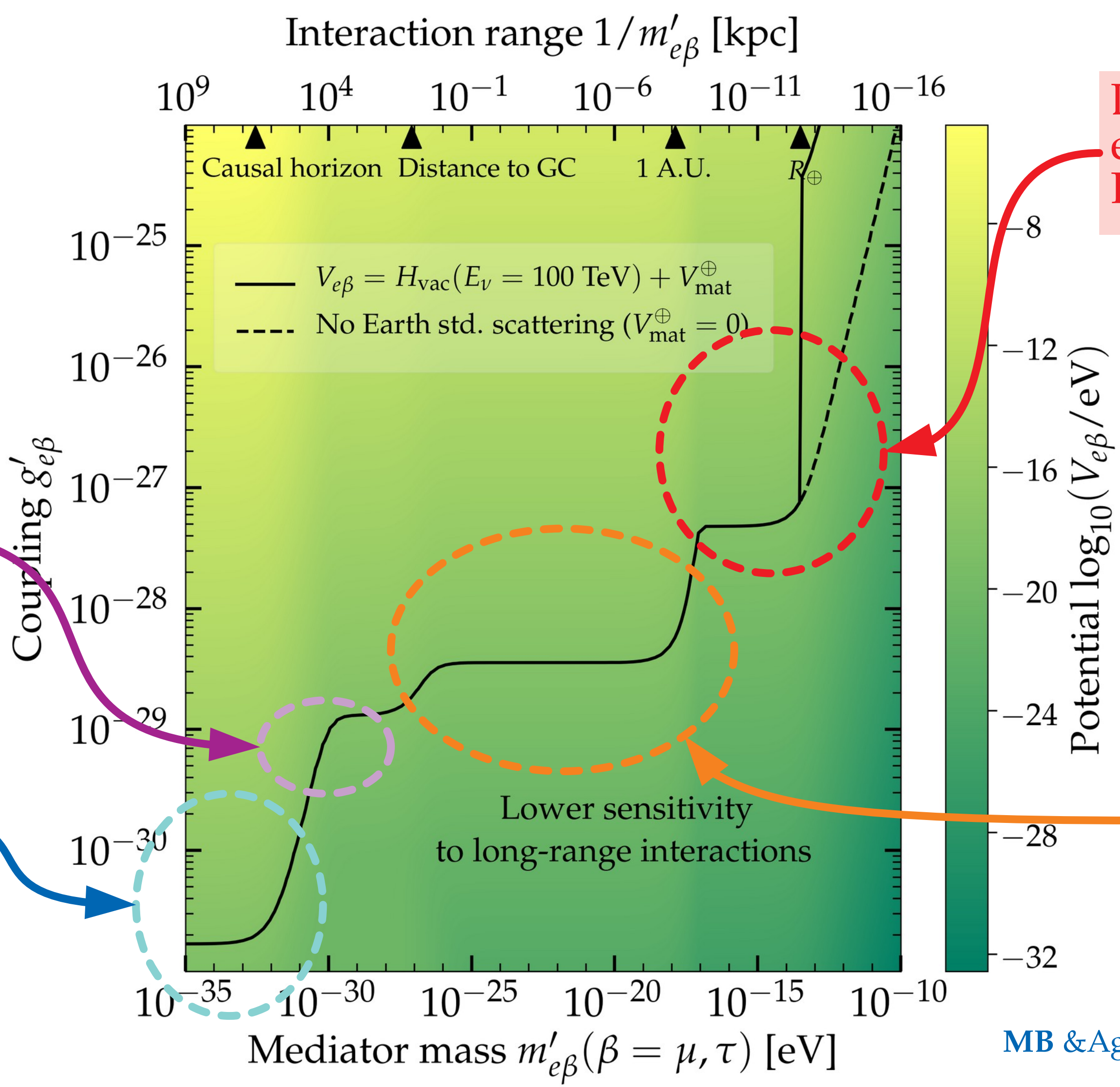


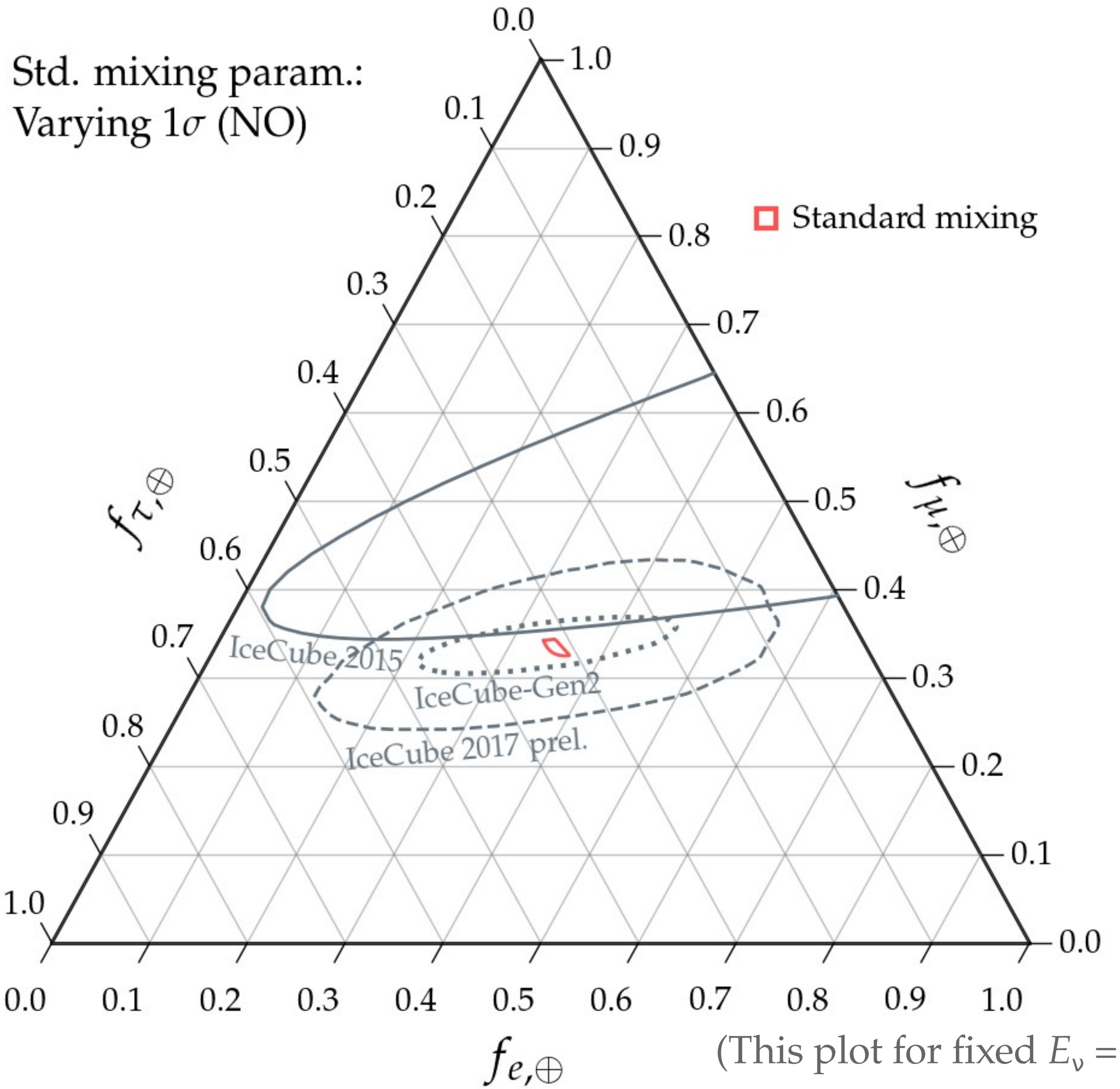
Dominated by electrons in the Earth + Moon

Dominated by Milky-Way e

Dominated by solar electrons (+ Milky-Way e)

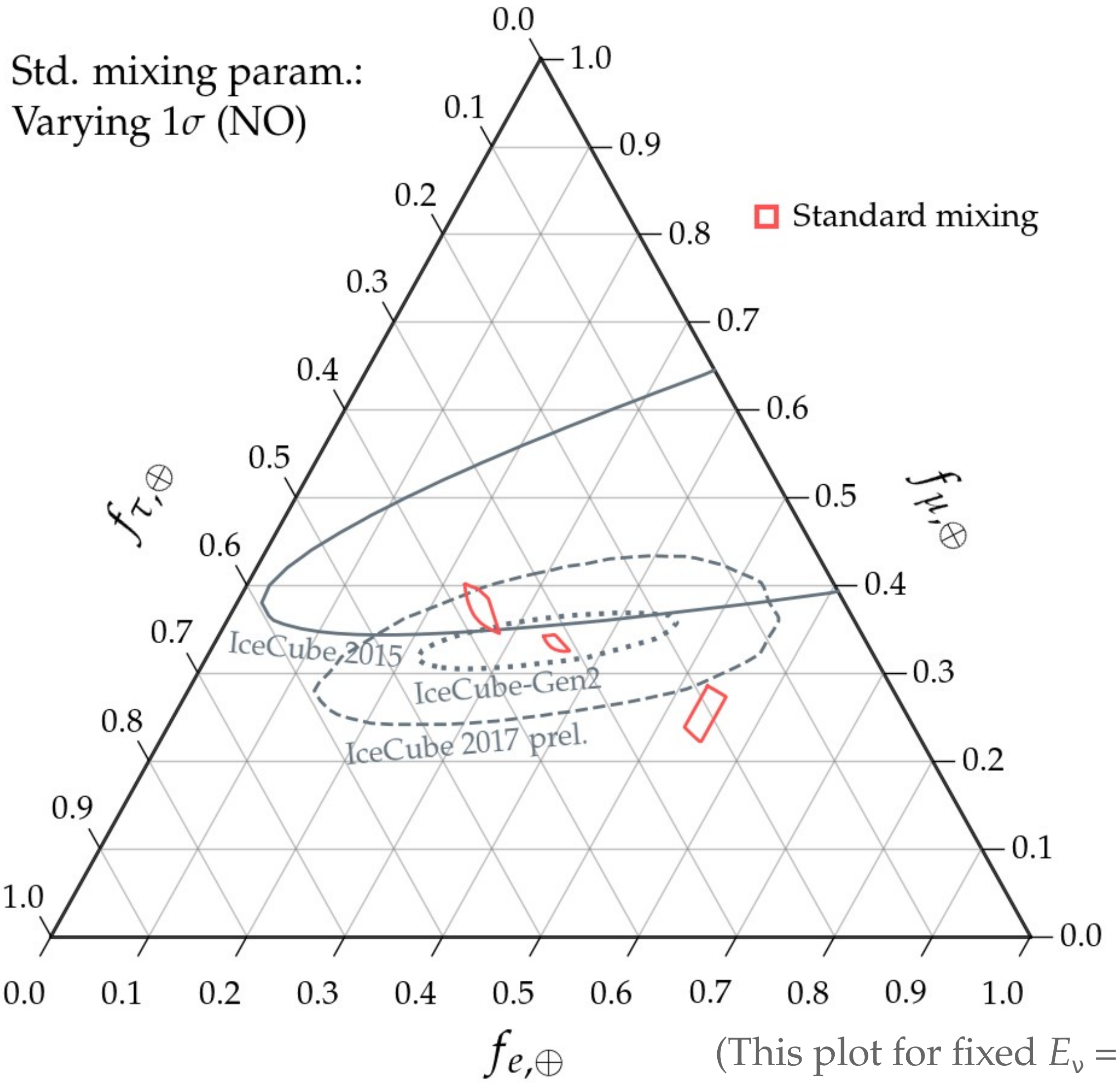
Dominated by cosmological e

MB &Agarwalla, *PRL* 2019



MB & Agarwalla, *PRL* 2019

(This plot for fixed E_ν = 100 TeV)



MB & Agarwalla, *PRL* 2019

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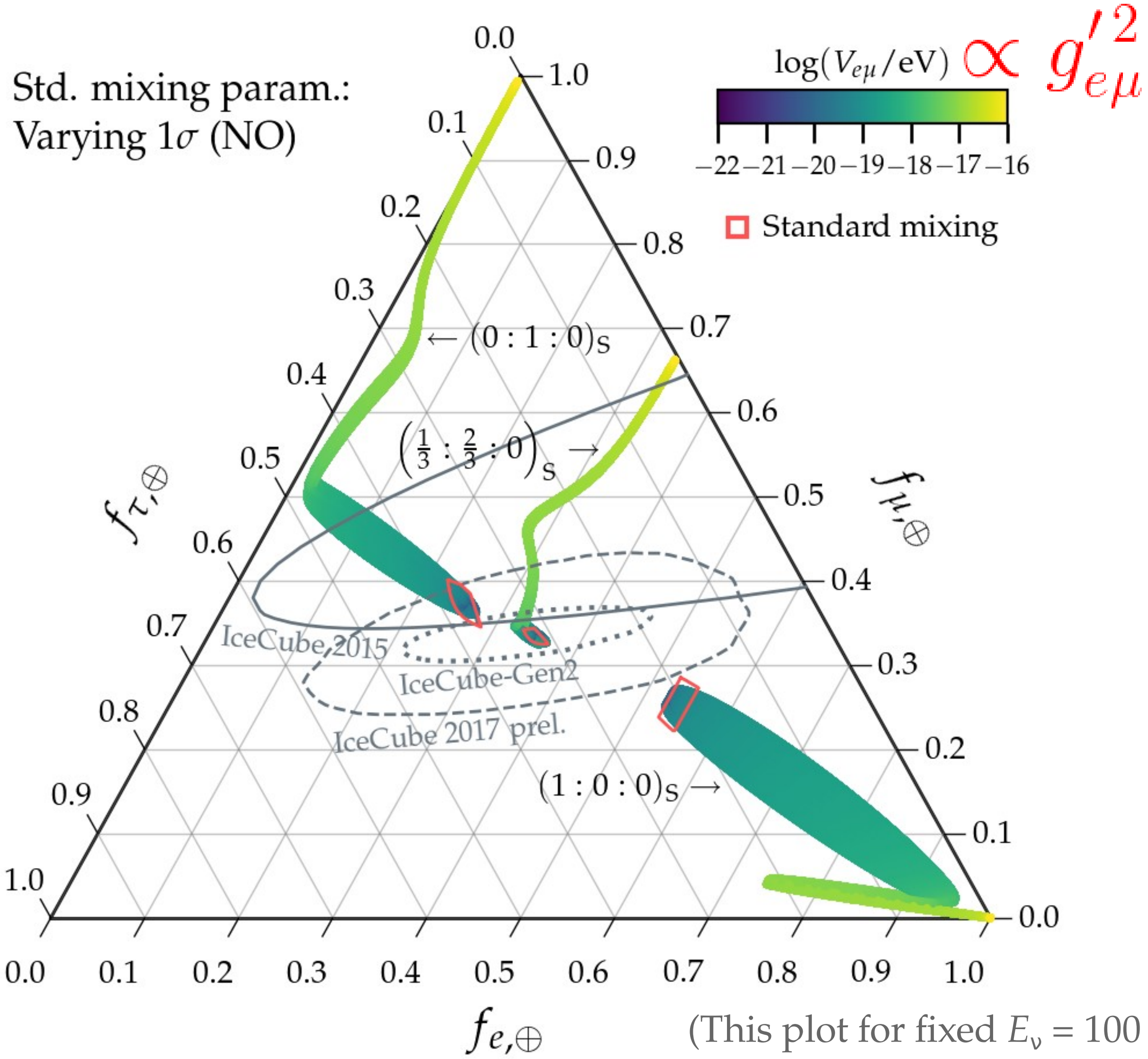

MB & Agarwalla, *PRL* 2019

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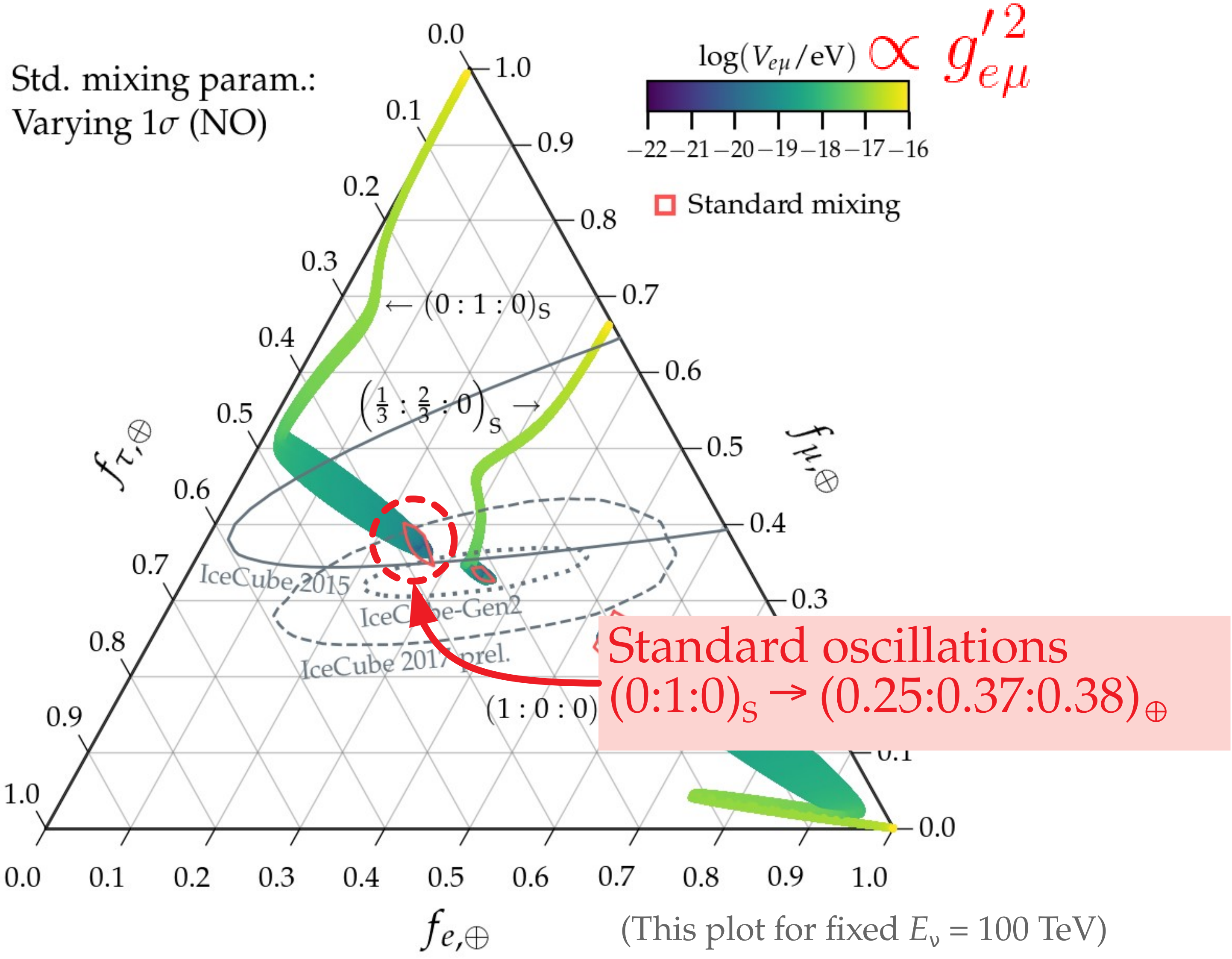

MB & Agarwalla, *PRL* 2019

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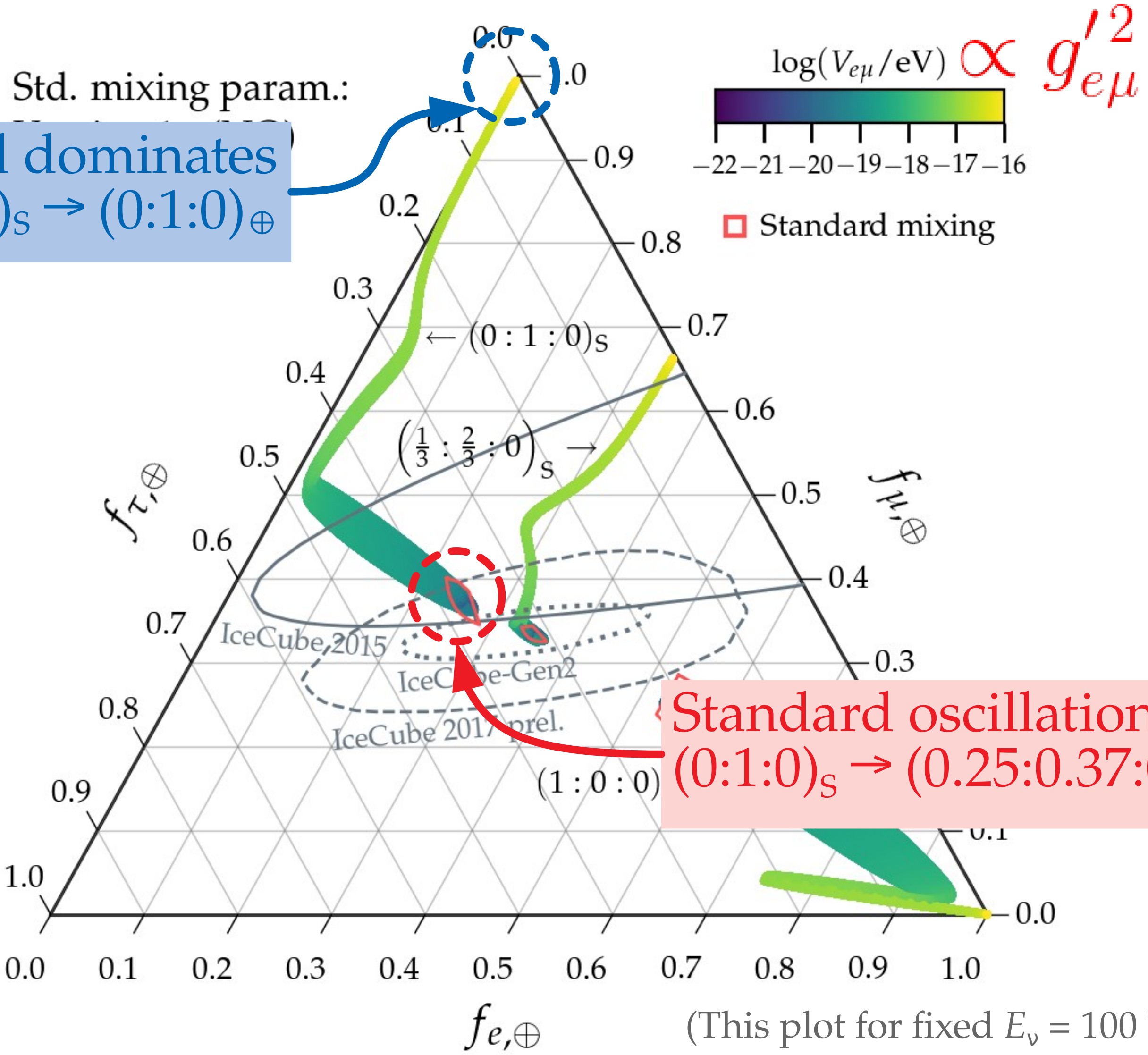

New potential dominates
$(0:1:0)_S \rightarrow (0:1:0)_\oplus$

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

MB & Agarwalla, *PRL* 2019

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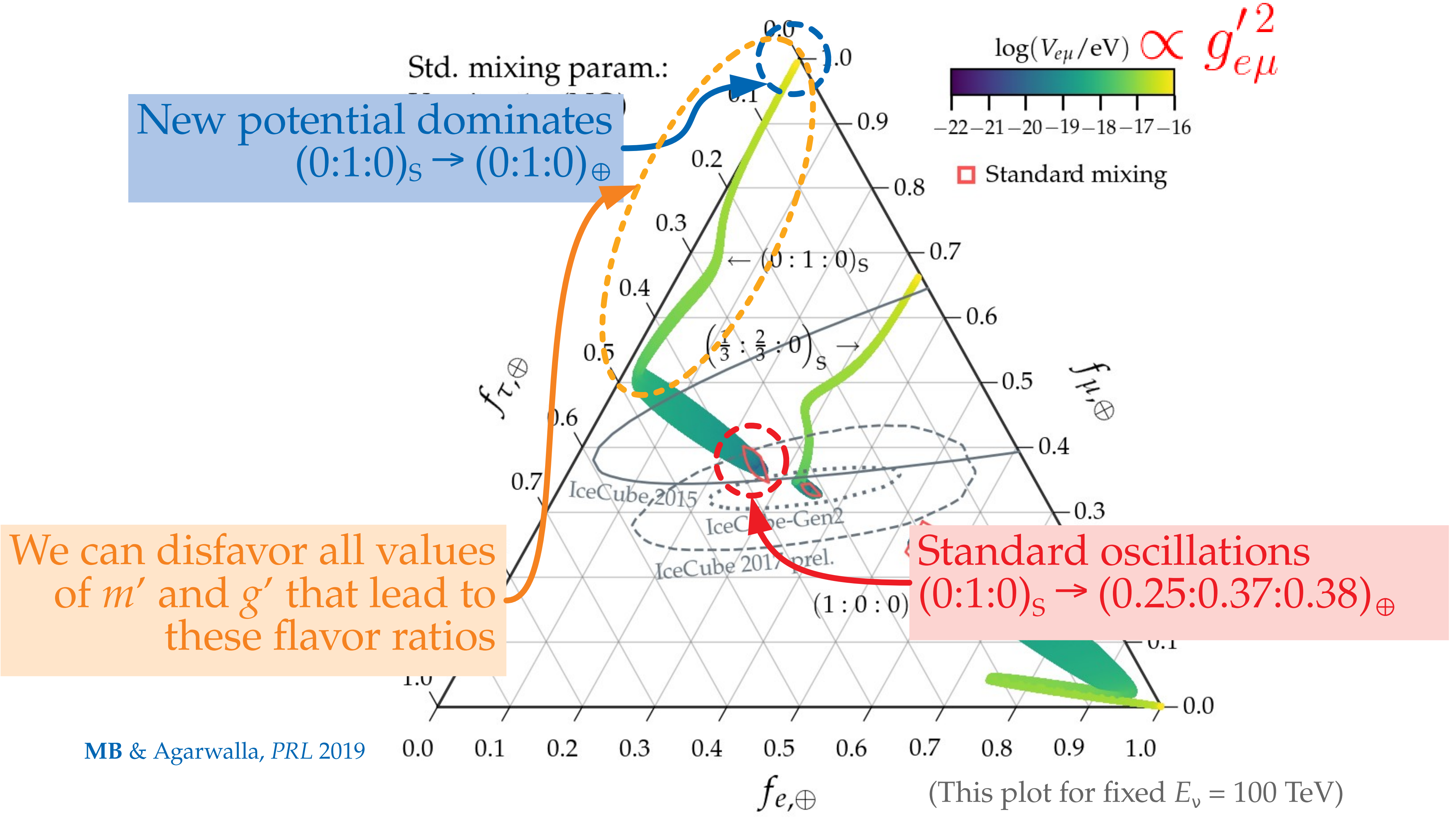
New potential dominates
$(0:1:0)_S \to (0:1:0)_\oplus$
Std. mixing param.:
$\log(V_{e\mu}/\text{eV}) \propto g'^2_{e\mu}$
−22 −21 −20 −19 −18 −17 −16
Standard mixing
$\leftarrow (0:1:0)_S$
$\left(\frac{1}{3}:\frac{2}{3}:0\right)_S \to$
$(1:0:0)_S$
IceCube 2015
IceCube-Gen2
IceCube 2017 prel.
$f_{\tau,\oplus}$
$f_{\mu,\oplus}$
$f_{e,\oplus}$
We can disfavor all values of m' and g' that lead to these flavor ratios
Standard oscillations
$(0:1:0)_S \to (0.25:0.37:0.38)_\oplus$
MB & Agarwalla, *PRL* 2019
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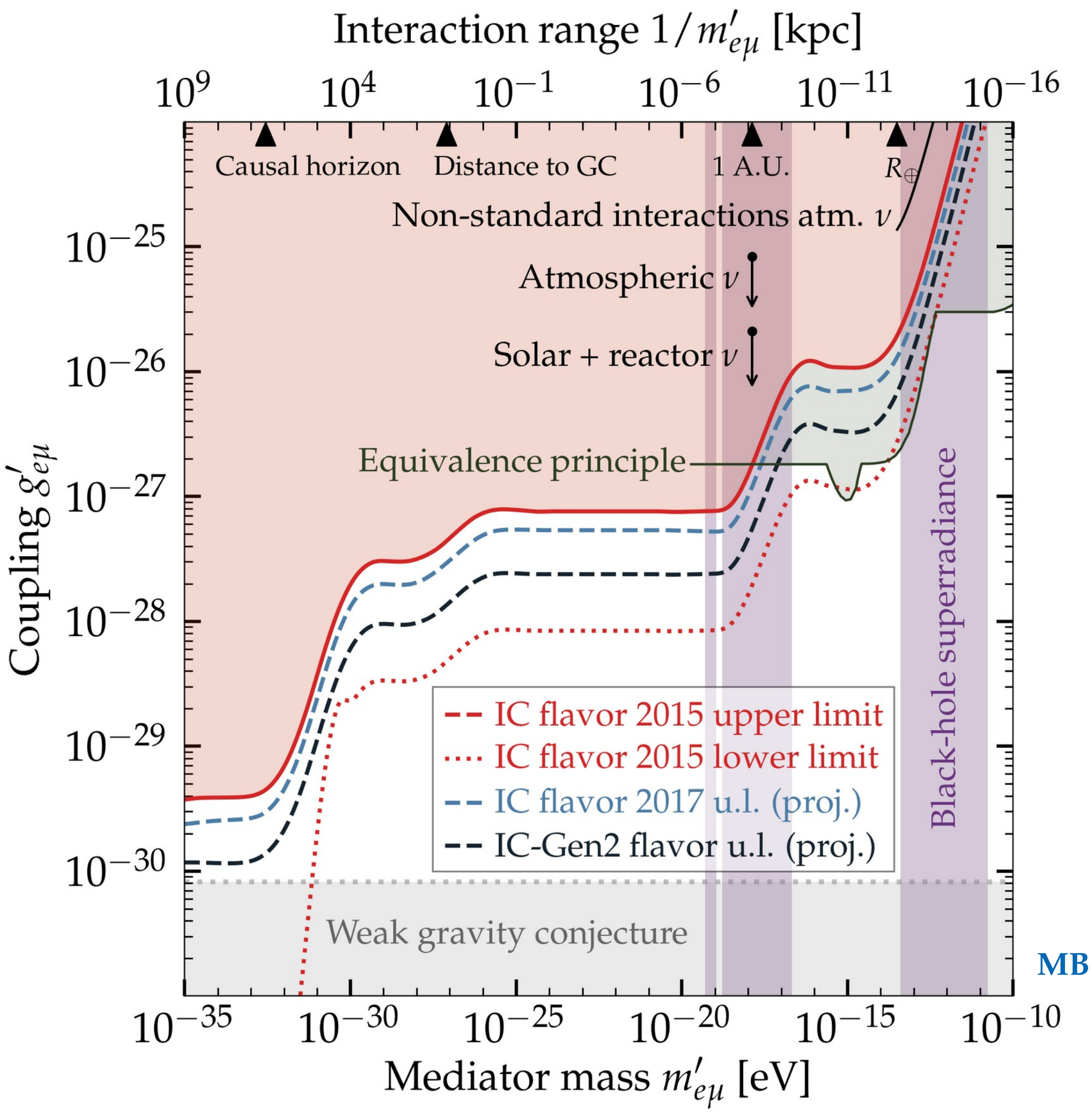

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