The flavor of high-energy cosmic neutrinos as a tool for particle physics and astrophysics: *current status, future prospects*

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Niels Bohr Institute, University of Copenhagen

PPNT19

Uppsala, October 08, 2019

UNIVERSITY OF COPENHAGEN

VILLUM FONDEN

The multi-messenger connection: a simple picture

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

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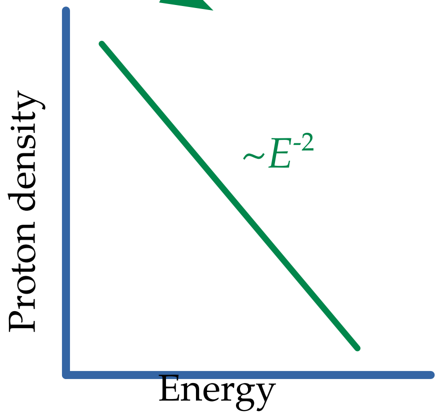

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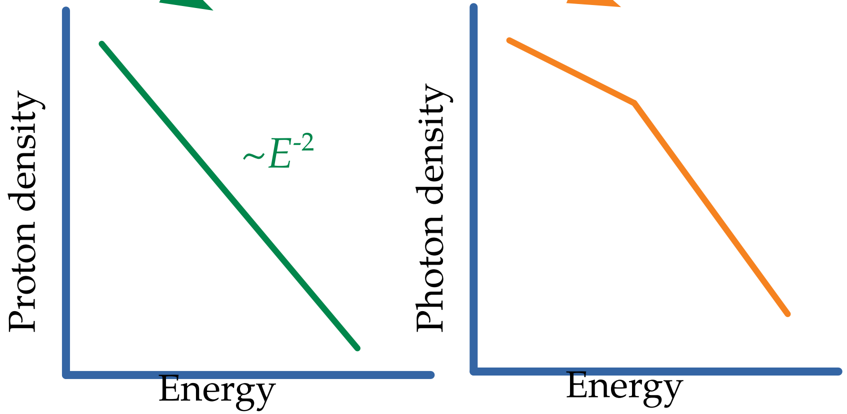

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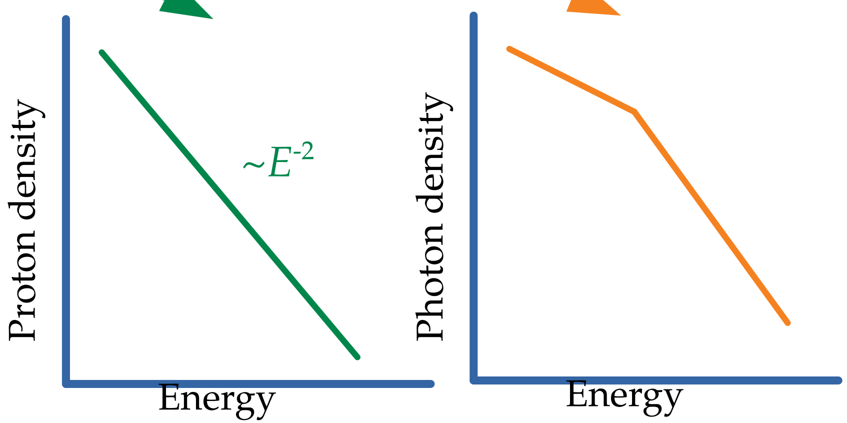
$$\pi^+ \to \mu^+ + \nu_\mu \to \bar{\nu}_\mu + e^+ + \nu_e + \nu_\mu$$

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



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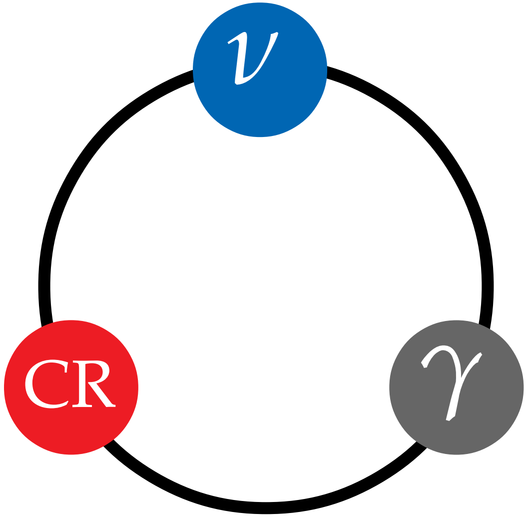

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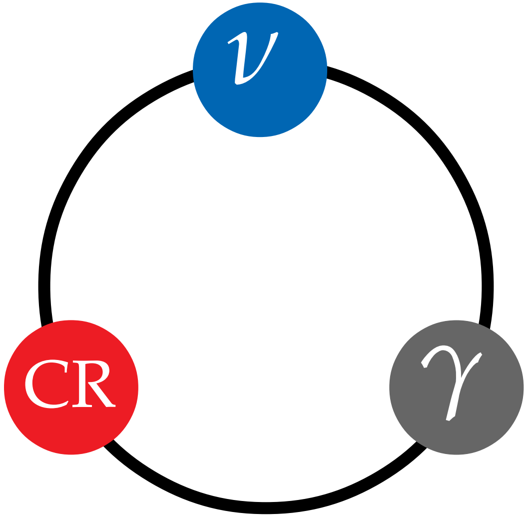
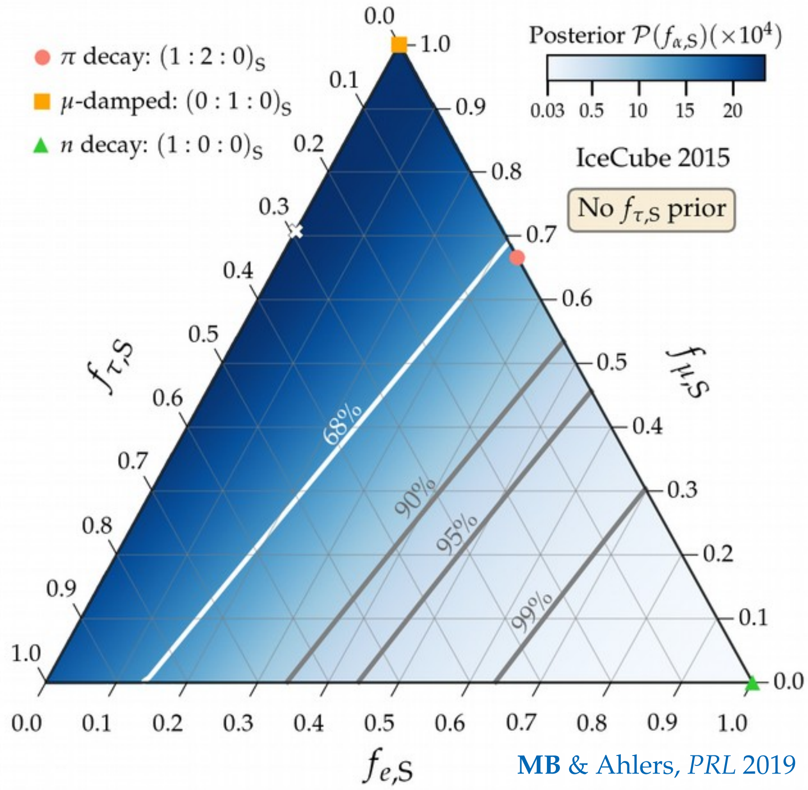


Flavor is an observable that is unique to neutrinos

… *and a versatile one at that*

Flavor is a two-edged sword (one that's increasingly sharper)

Trusting particle physics
and learning about astrophysics



MB & Ahlers, *PRL* 2019

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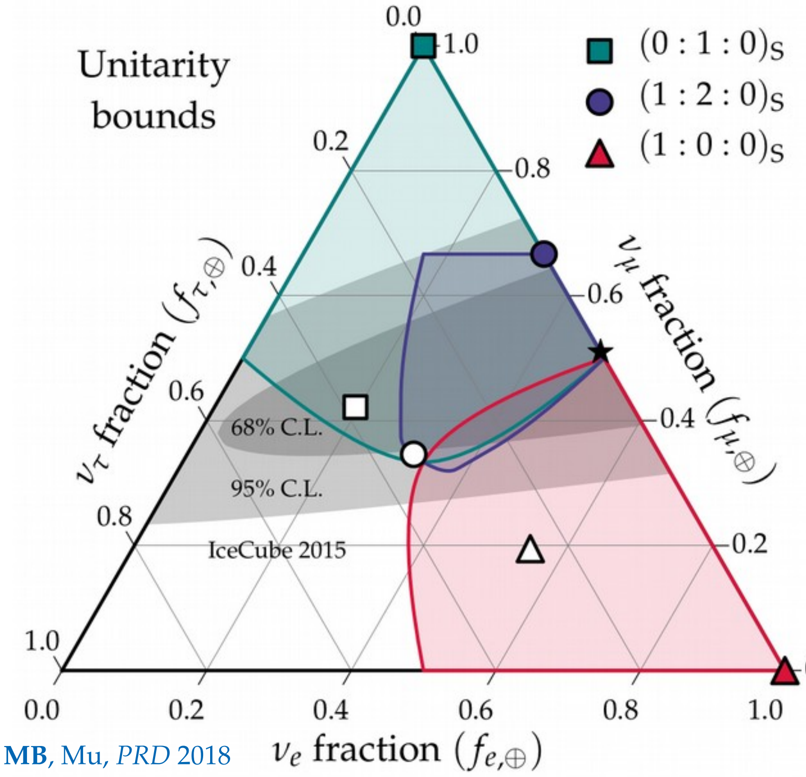
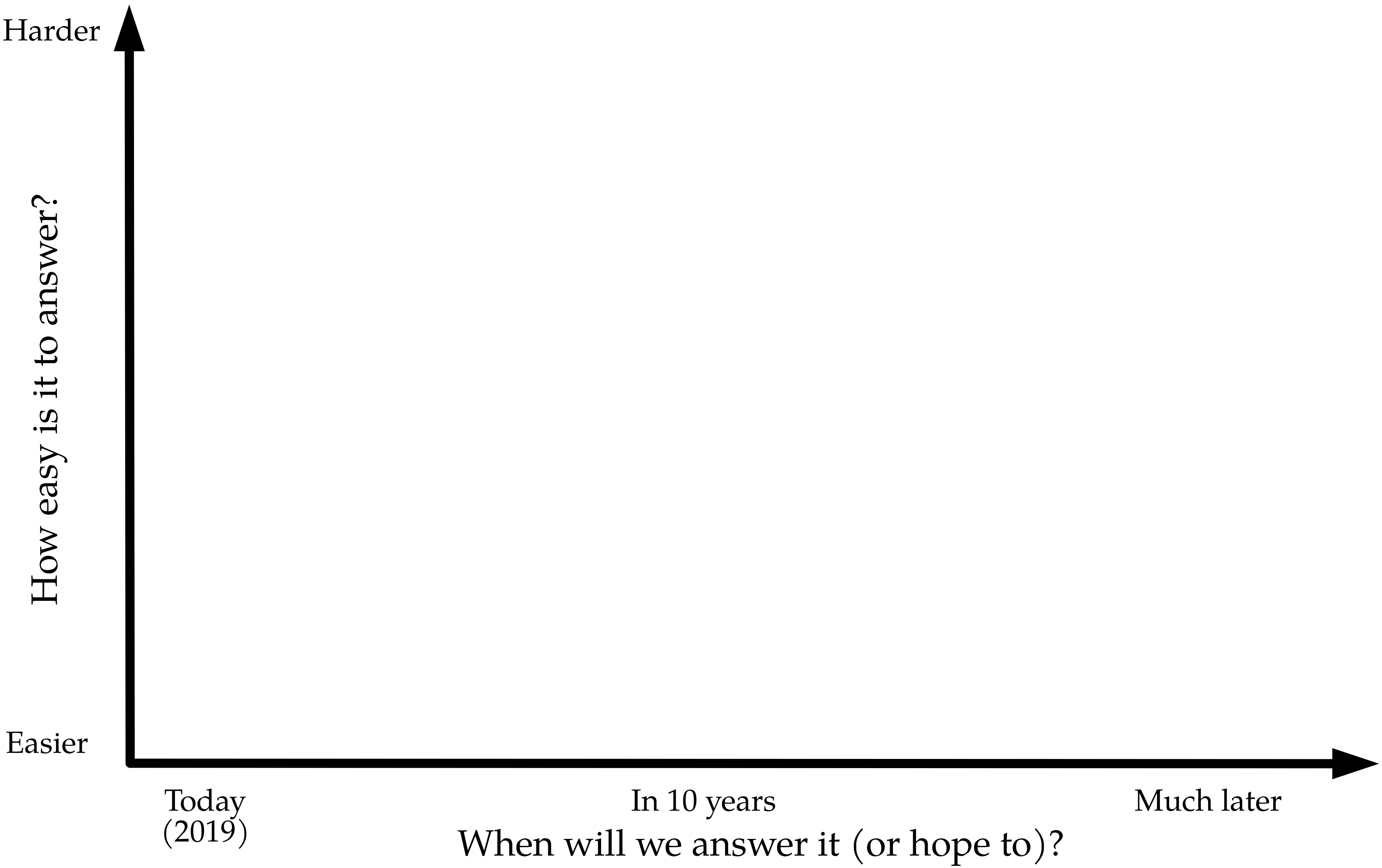
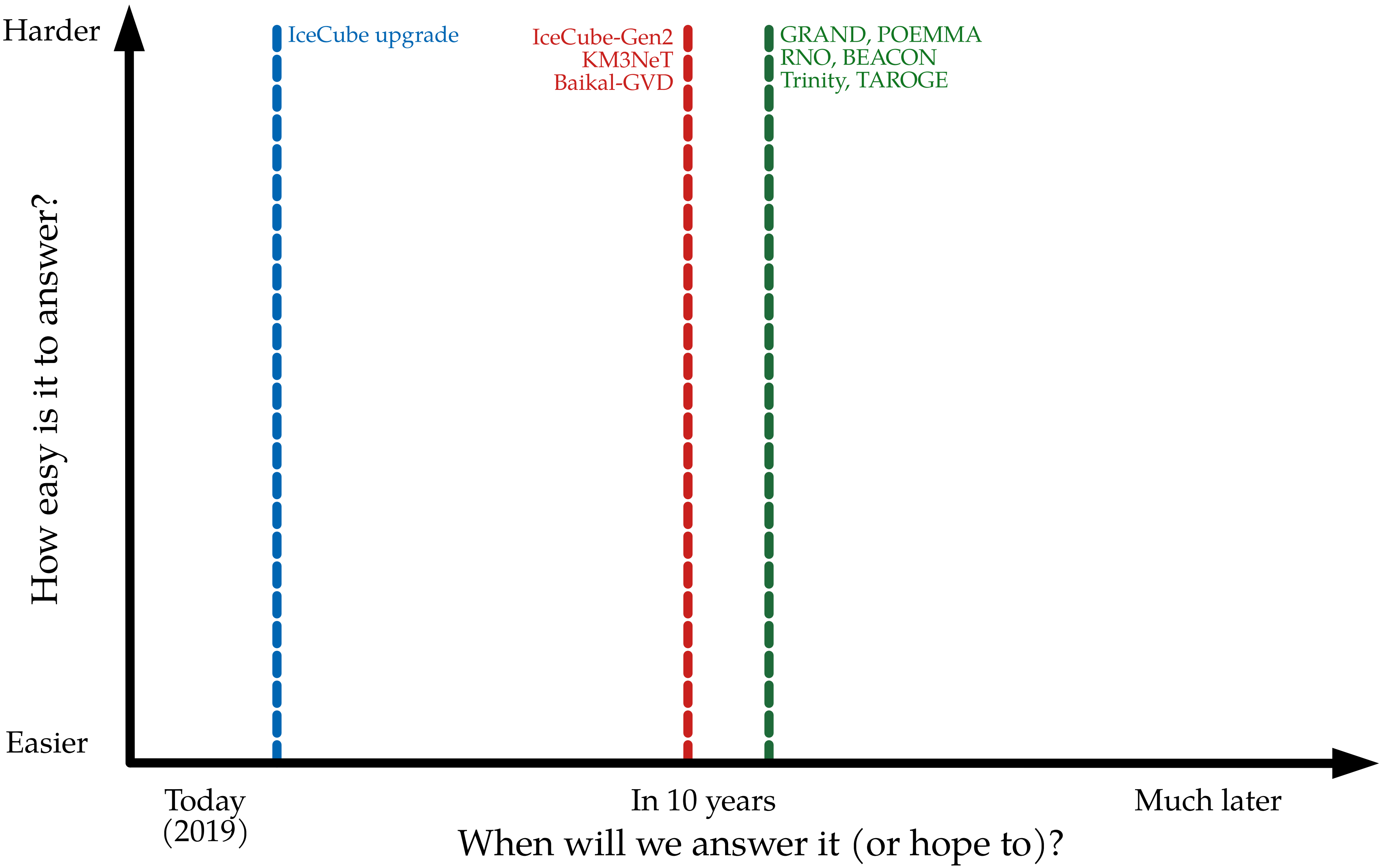


Ahlers, **MB**, Mu, *PRD* 2018


Harder
How easy is it to answer?
Easier
Today
(2019)
In 10 years
Much later
When will we answer it (or hope to)?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IceCube-Gen2
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Baikal-GVD
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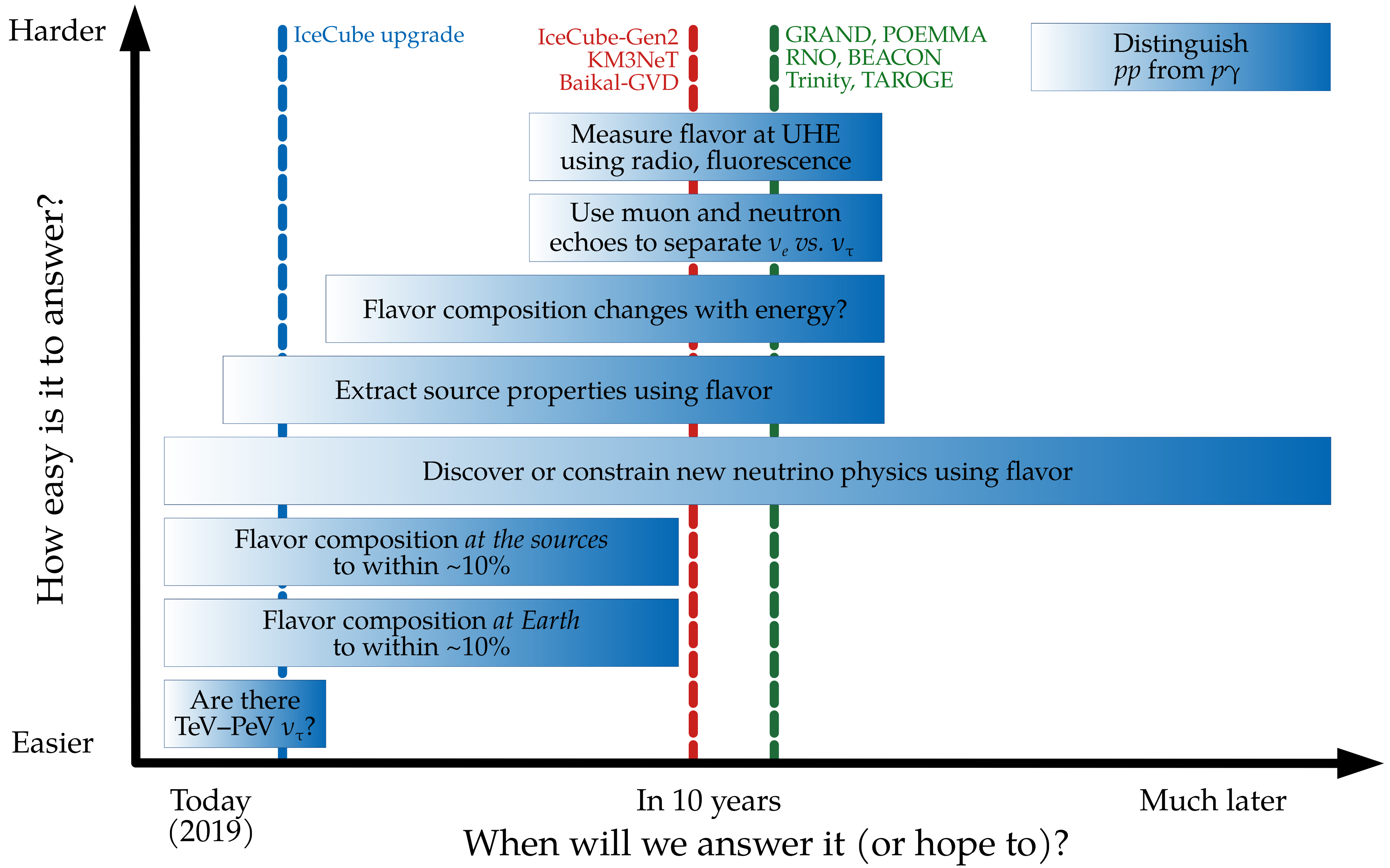

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Distinguish
pp from $p\gamma$
Measure flavor at UHE
using radio, fluorescence
Use muon and neutron
echoes to separate ν_e *vs.* ν_τ
Flavor composition changes with energy?
Extract source properties using flavor
Discover or constrain new neutrino physics using flavor
Flavor composition *at the sources*
to within ~10%
Flavor composition *at Earth*
to within ~10%
Are there
TeV–PeV ν_τ?
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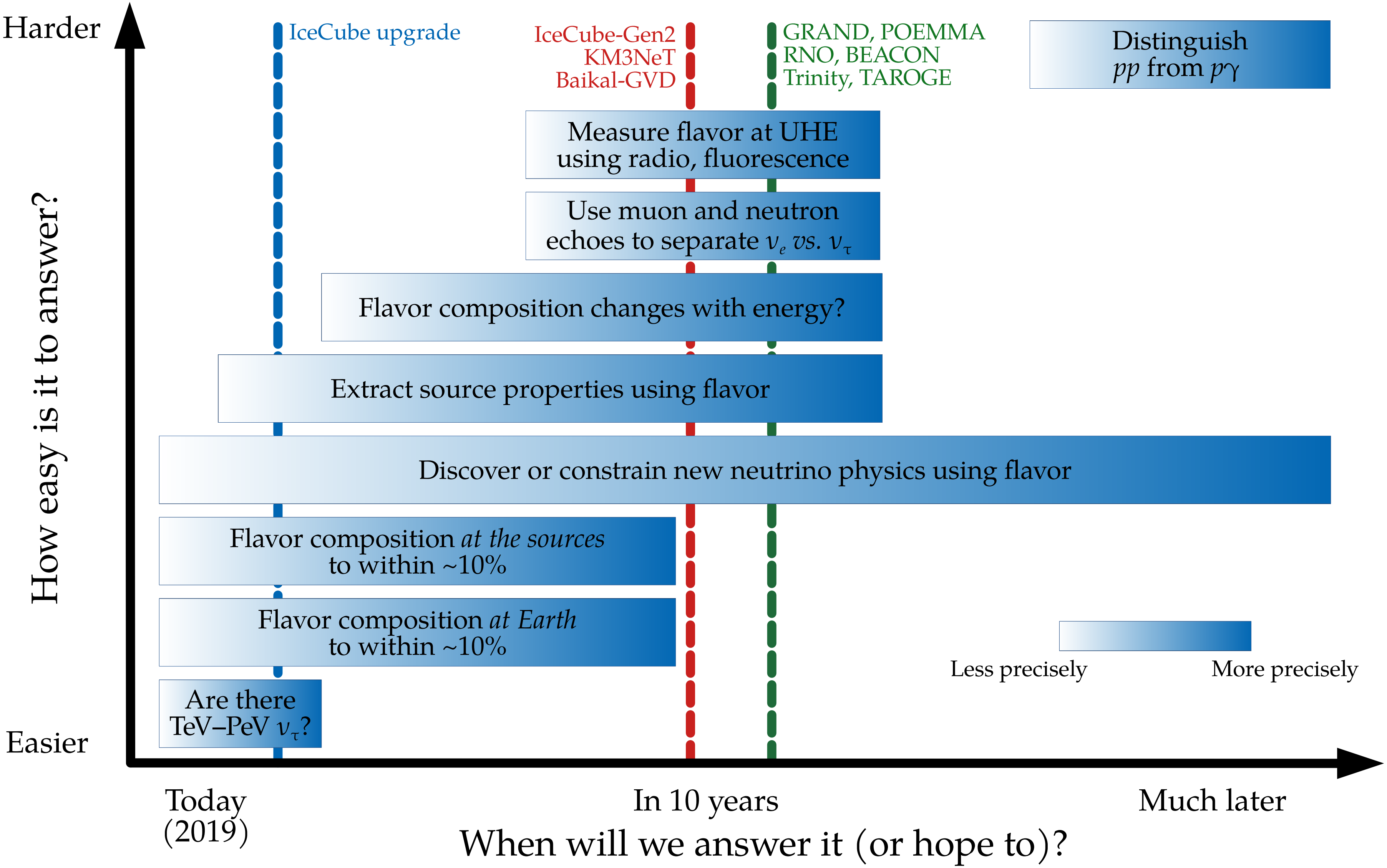

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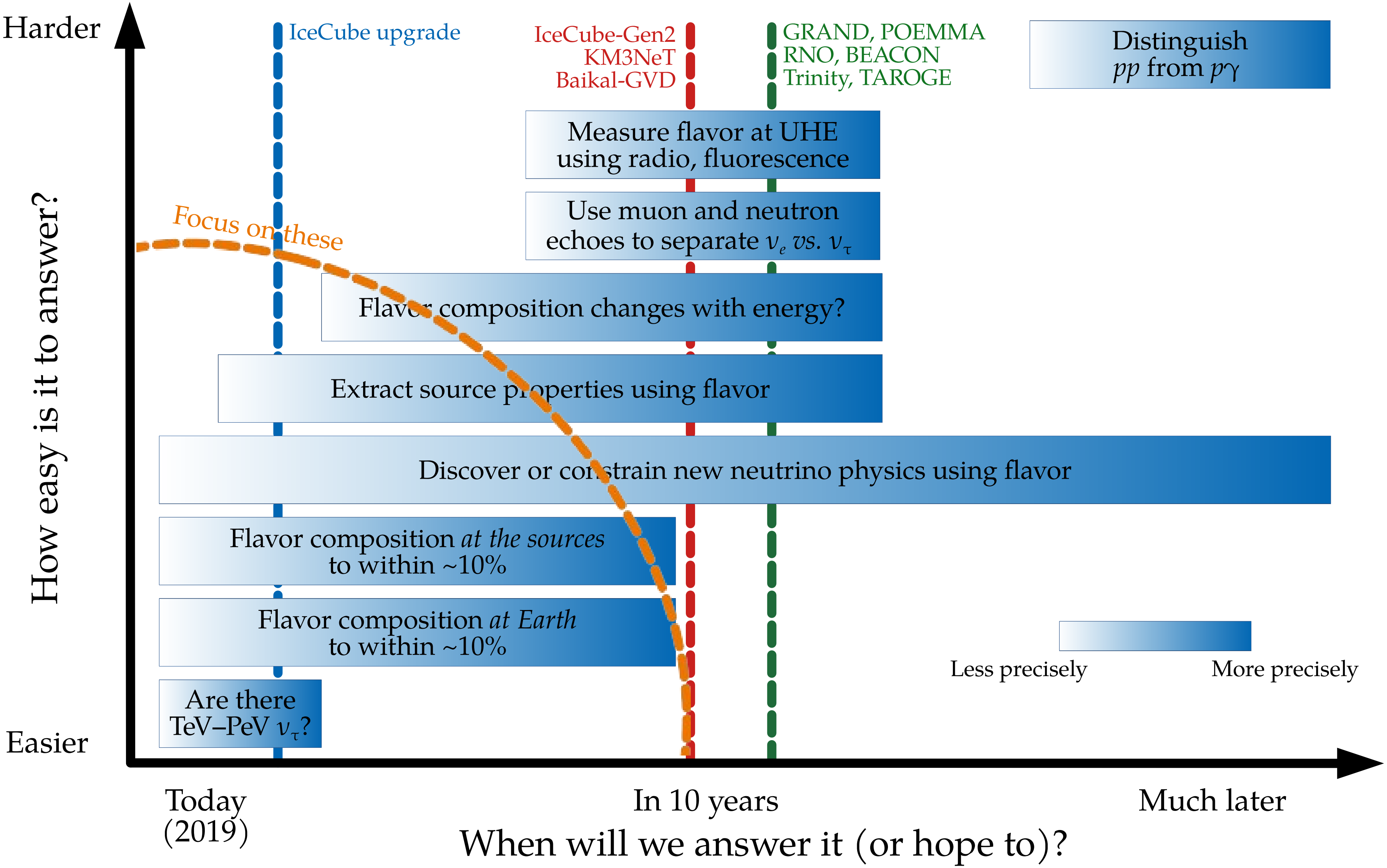

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Measure flavor at UHE
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Focus on these
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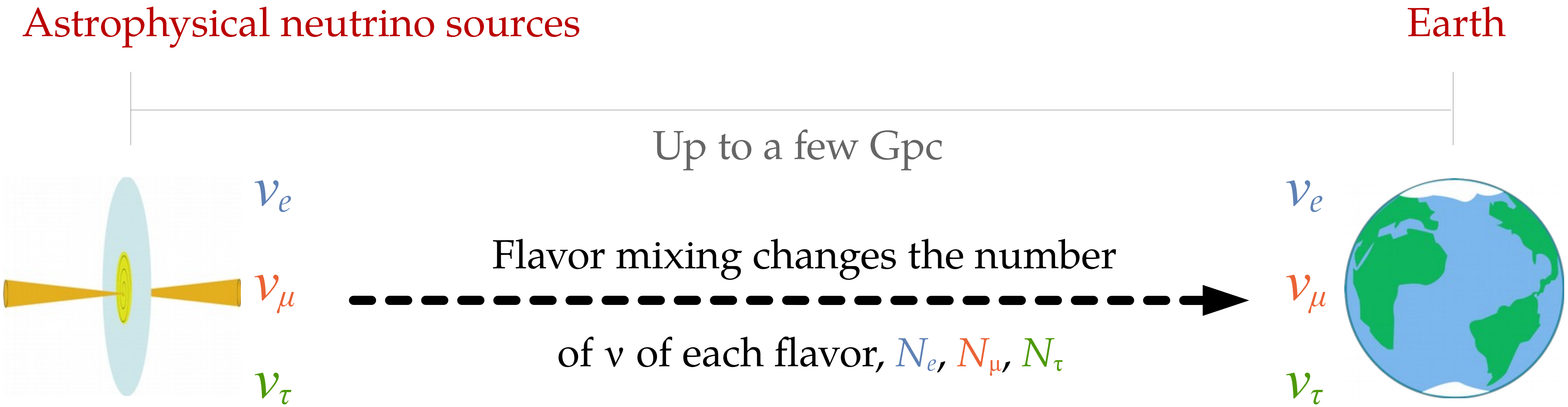
Flavor composition basics



- Different processes yield different ratios of neutrinos of each flavor:

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

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

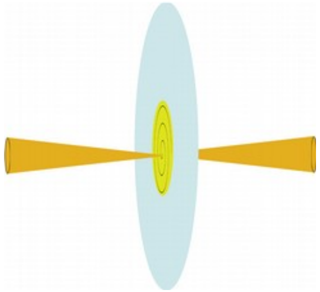
$$f_{\alpha,\oplus} = \sum_{\beta=e,\mu,\tau} P_{\nu_\beta \to \nu_\alpha} f_{\beta,\mathrm{S}}$$

Flavor composition basics

Astrophysical neutrino sources

Earth

Up to a few Gpc



ν_e

ν_μ

ν_τ

Flavor mixing changes the number

of ν of each flavor, N_e, N_μ, N_τ

ν_e

ν_μ

ν_τ

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Standard oscillations
or
new physics

One likely TeV–PeV ν production scenario:

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

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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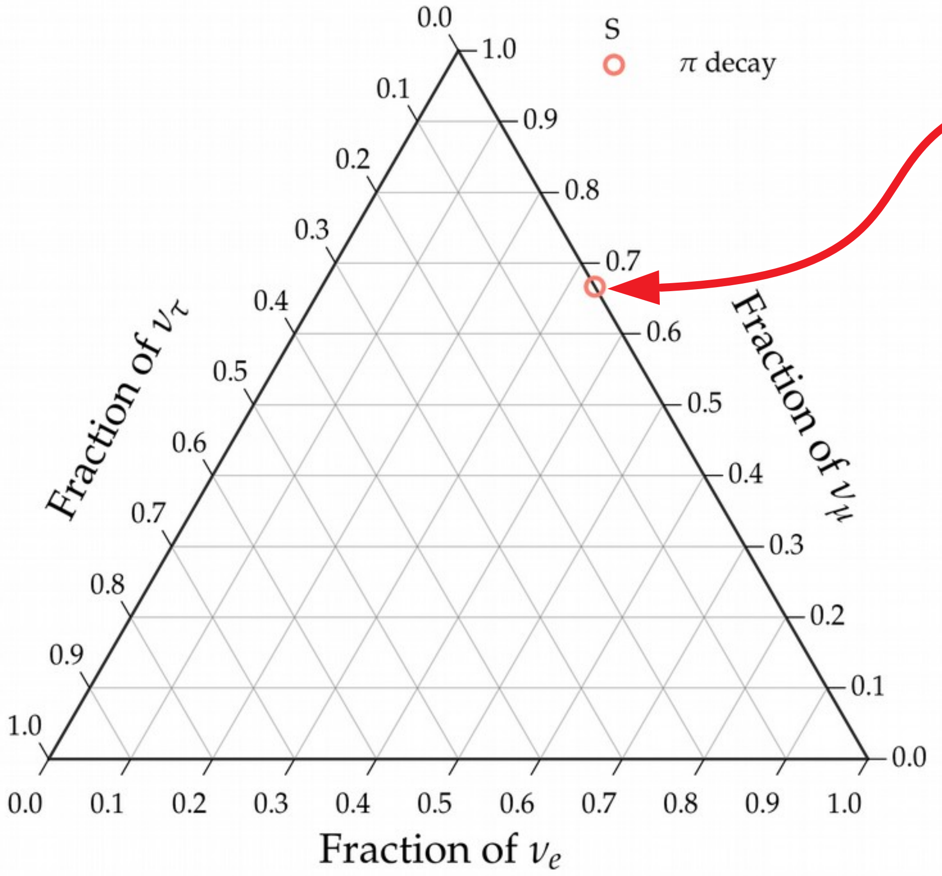

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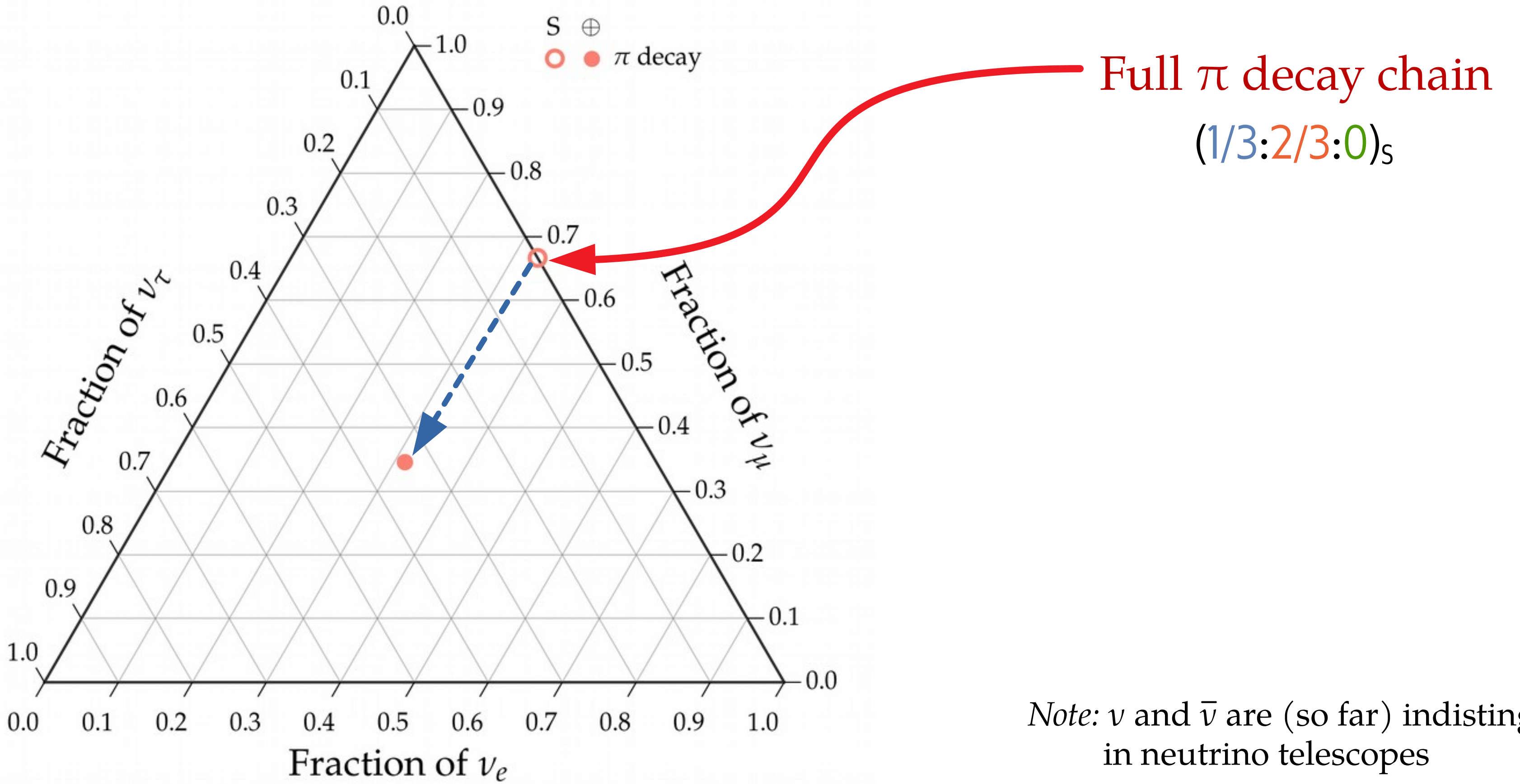

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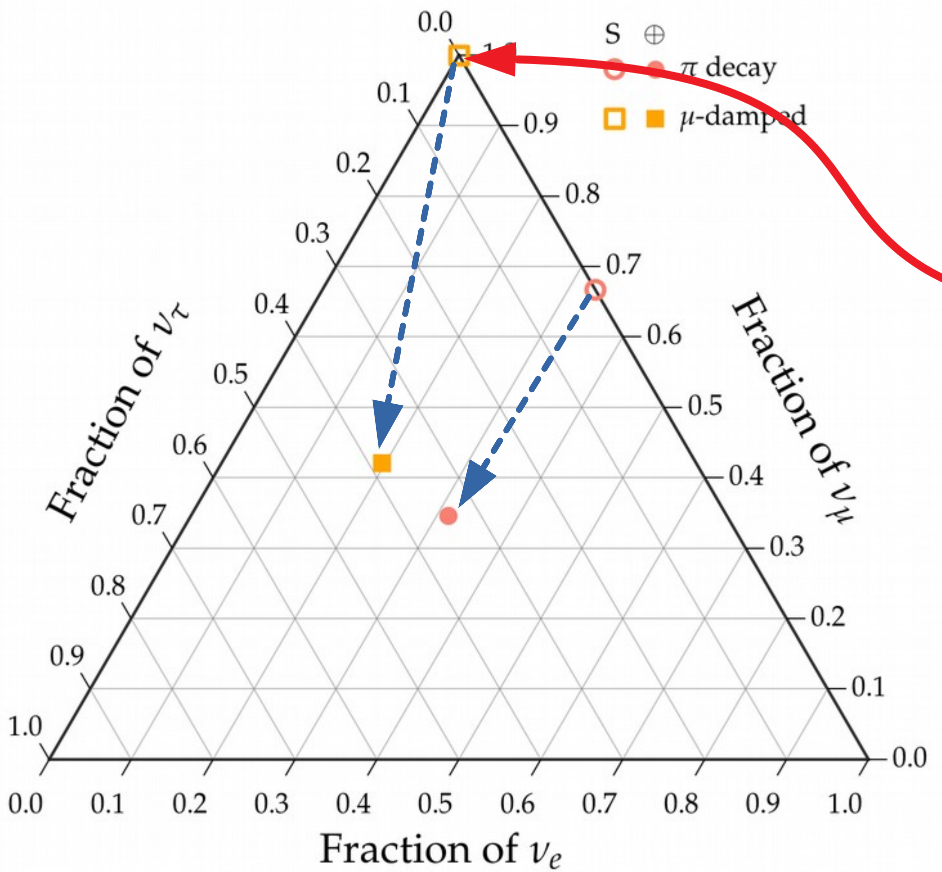

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Muon damped

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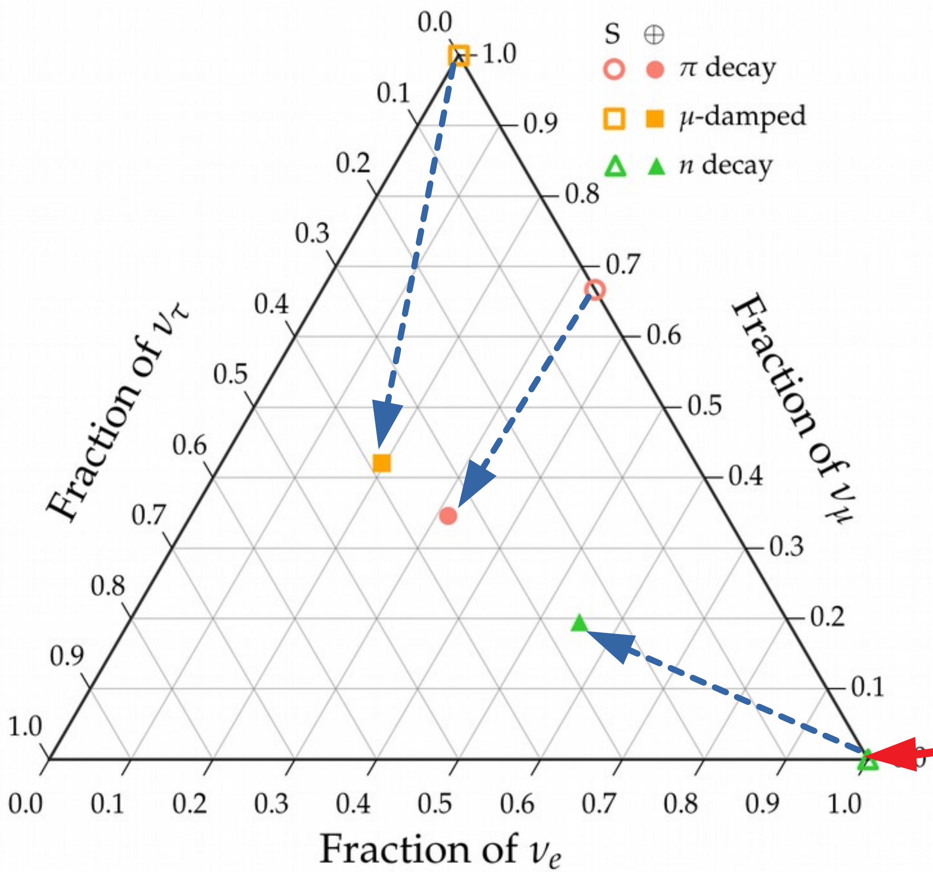

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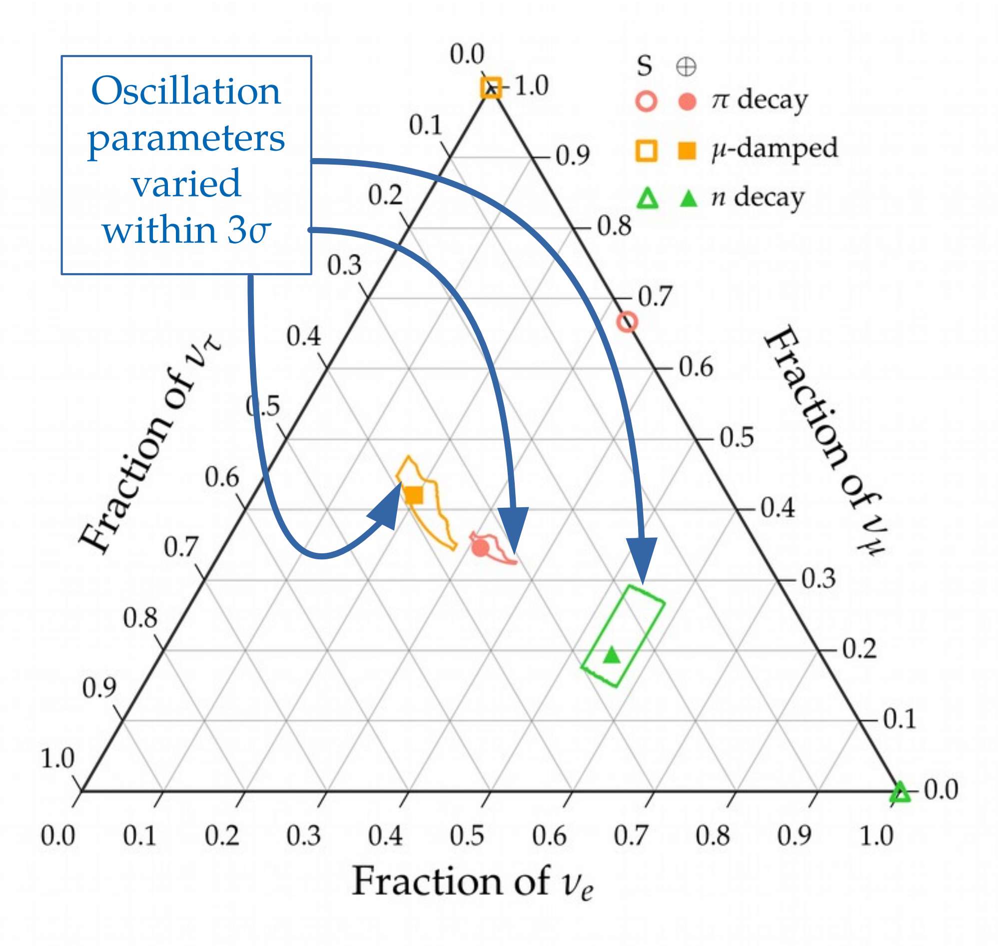

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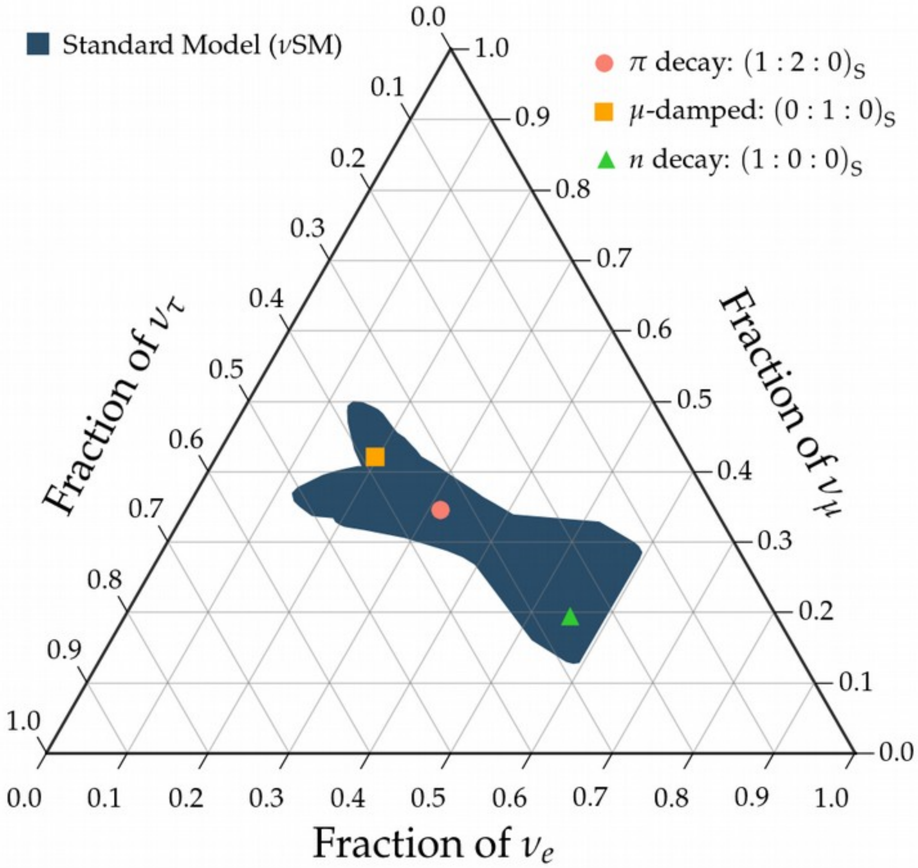

All possible flavor ratios at the sources

+

Vary oscillation parameters within 3σ

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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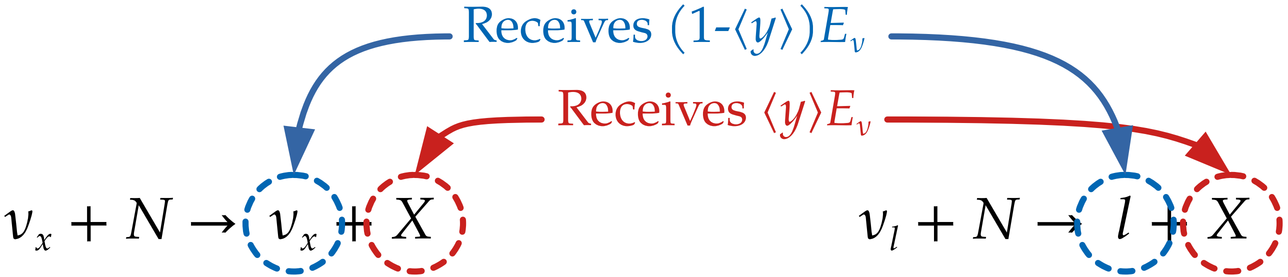
Deep inelastic neutrino-nucleon scattering

Neutral current (NC) — Charged current (CC)



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

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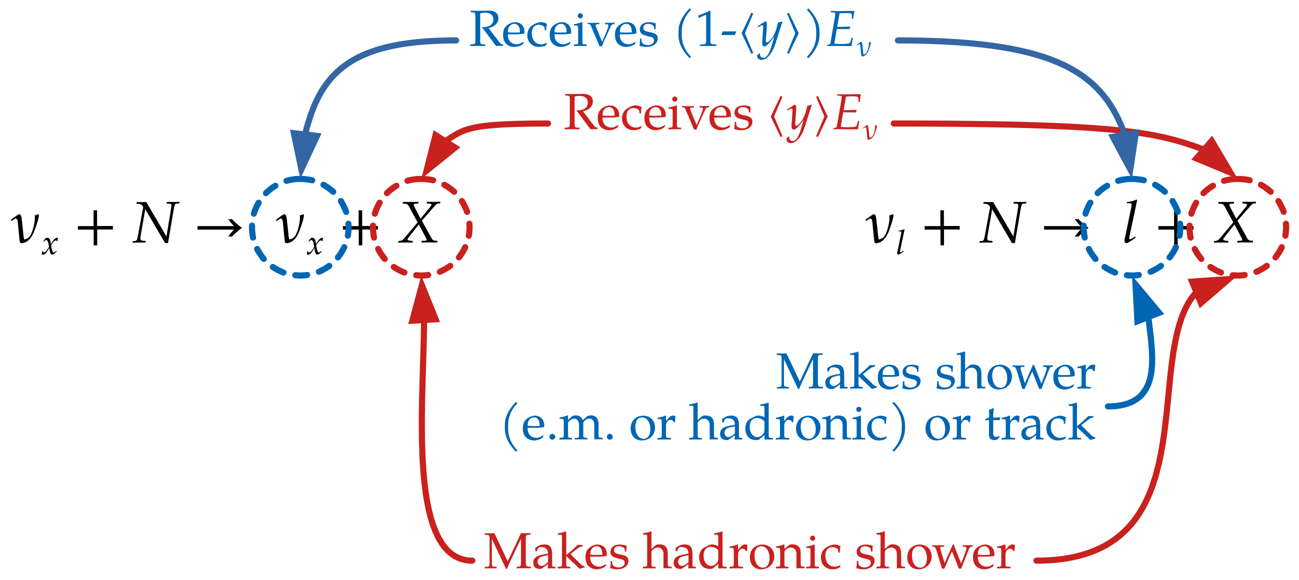

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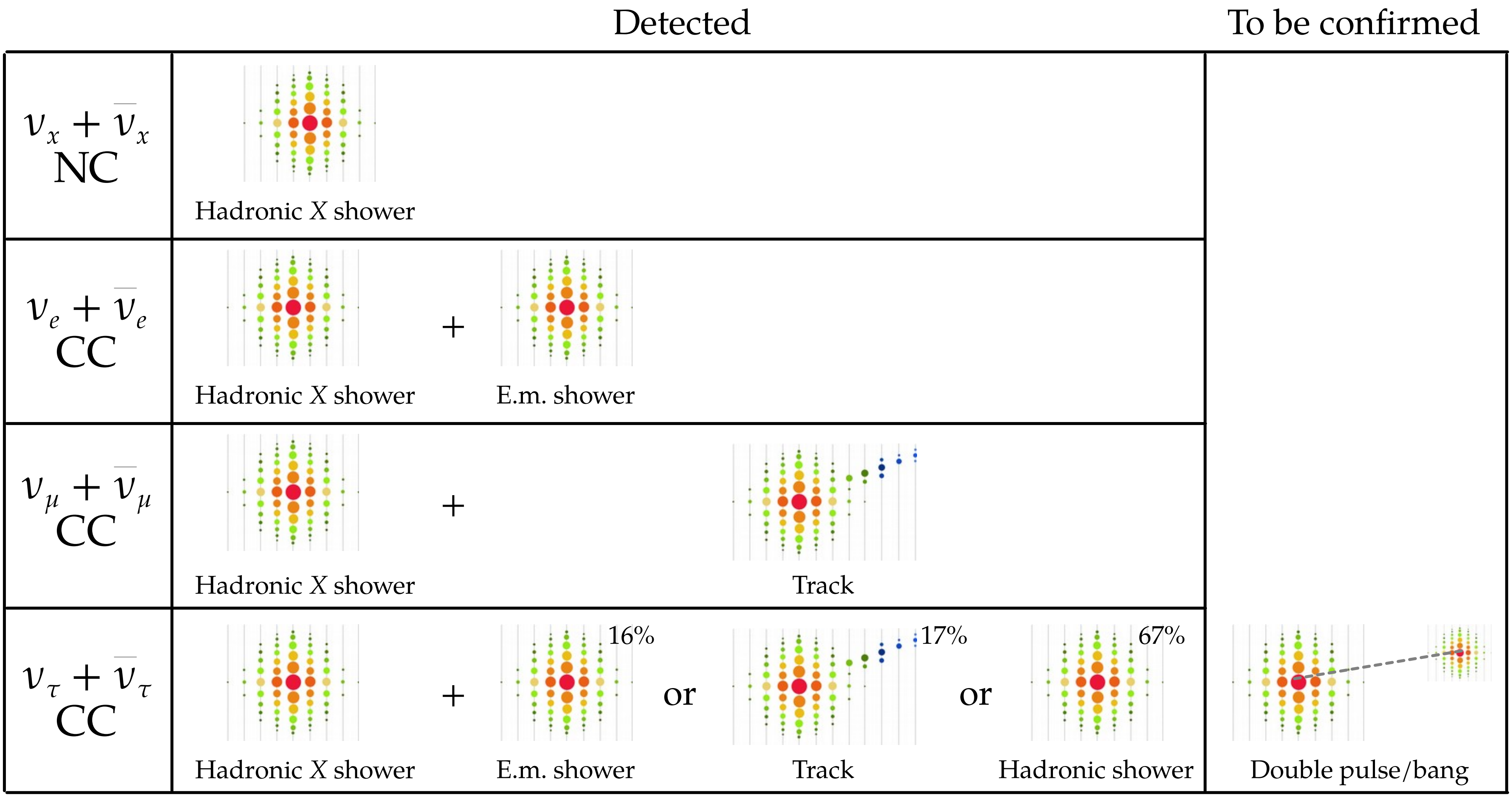
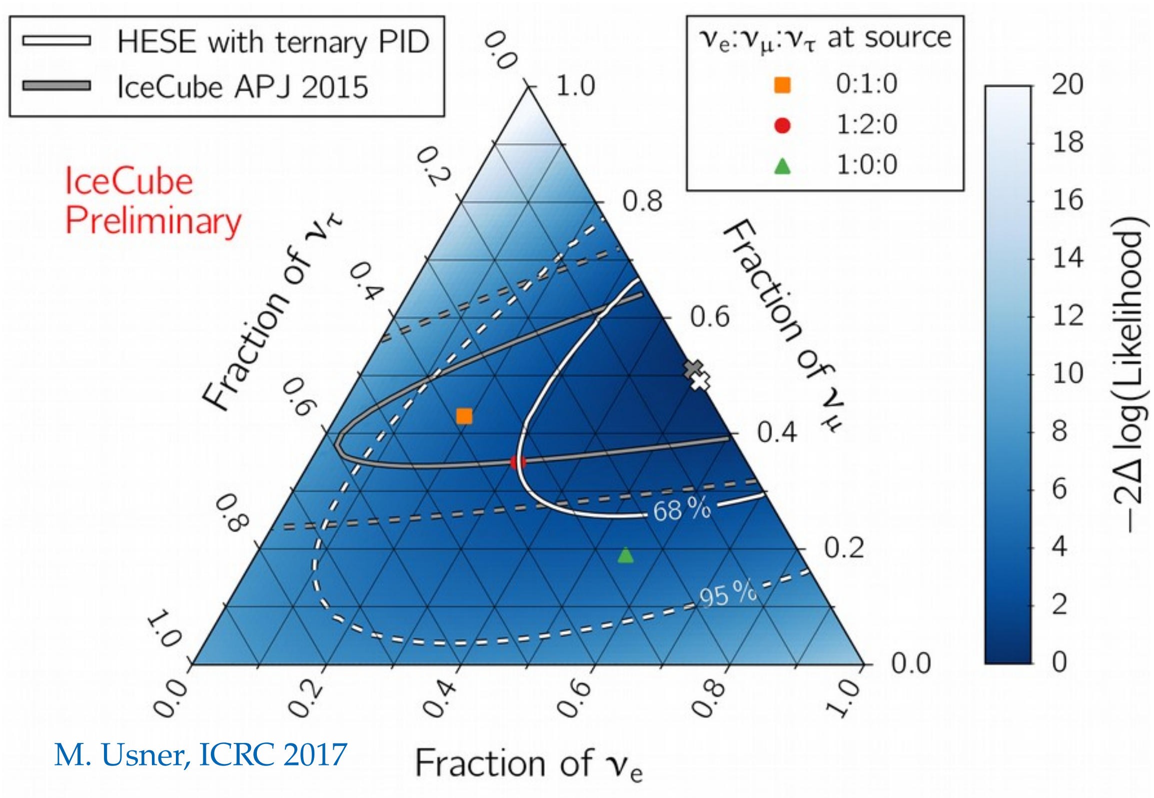


Detected
To be confirmed
$\nu_x + \bar{\nu}_x$ NC
Hadronic X shower
$\nu_e + \bar{\nu}_e$ CC
Hadronic X shower
+
E.m. shower
$\nu_\mu + \bar{\nu}_\mu$ CC
Hadronic X shower
+
Track
$\nu_\tau + \bar{\nu}_\tau$ CC
Hadronic X shower
+
16%
E.m. shower
or
17%
Track
or
67%
Hadronic shower
Double pulse/bang

IceCube results: Flavor composition



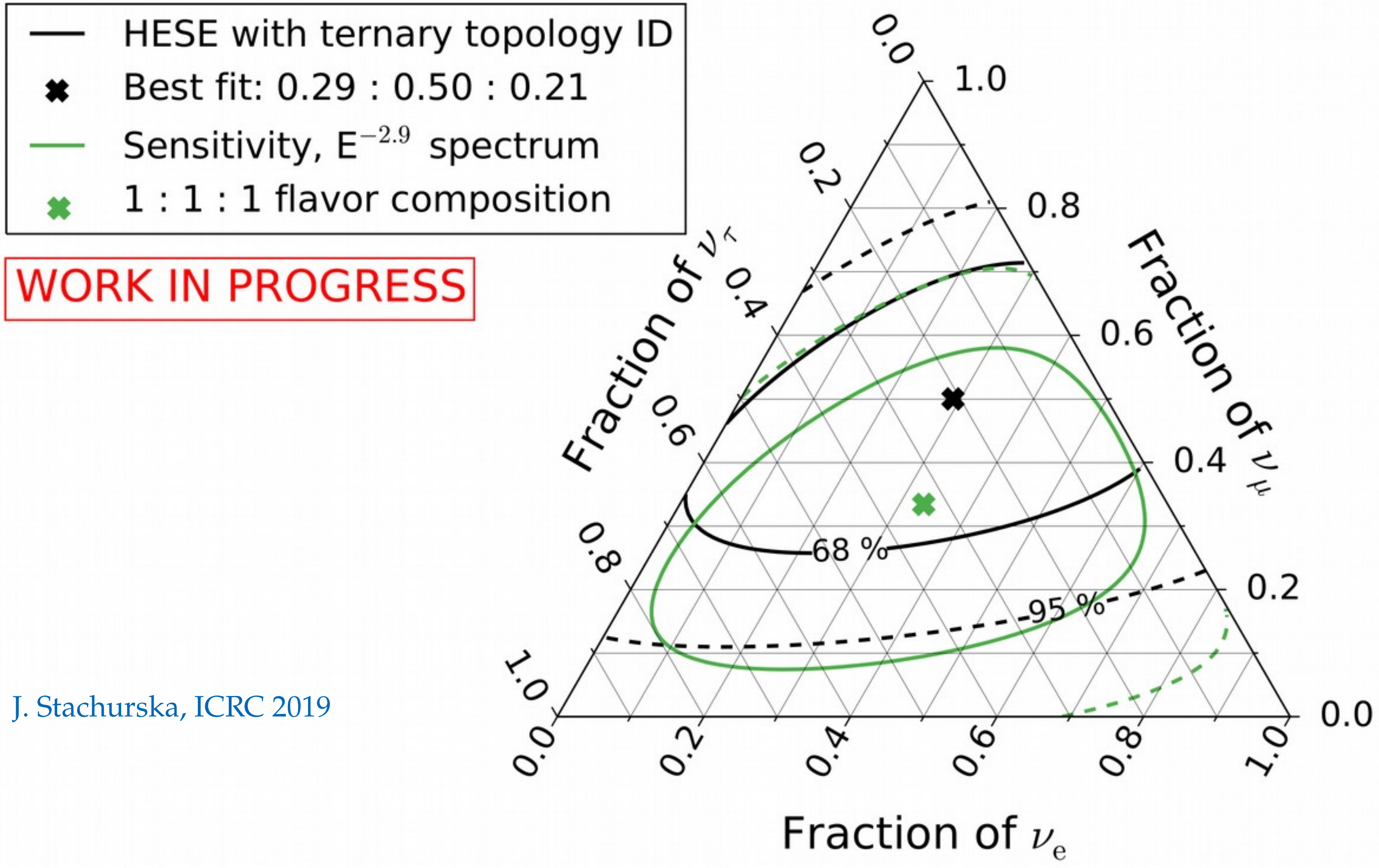
M. Usner, ICRC 2017

- Compare number of tracks (ν_μ) *vs.* showers (all flavors)
- Best fit: $(f_e : f_\mu : f_\tau)_\oplus = (0.5 : 0.5 : 0)_\oplus$
- Compatible with standard source compositions
- Lots of room for improvement: more statistics, better flavor-tagging

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

IceCube results: Flavor composition

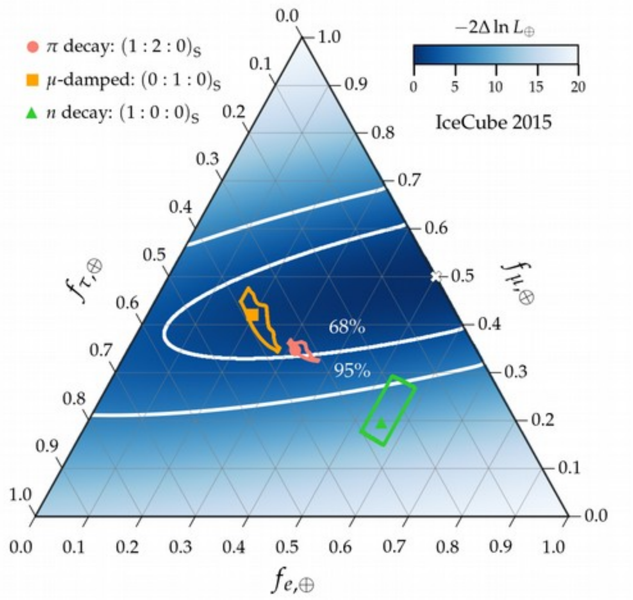
There are 2 ν_τ candidate events which change the flavor composition:



J. Stachurska, ICRC 2019

Flavor composition: now and in the future

Today
IceCube



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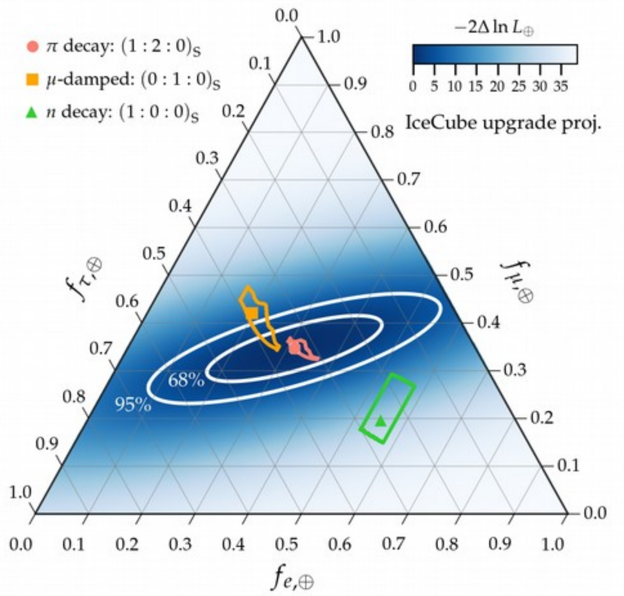
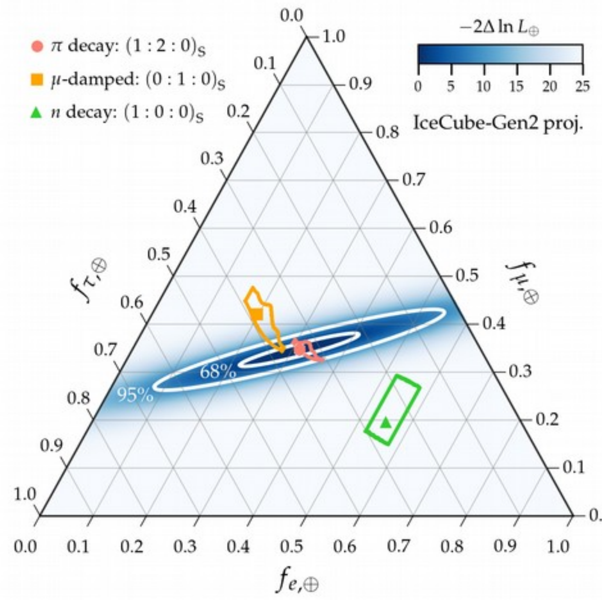
- Hints of one ν_τ (not shown)

Near future (2022)
IceCube upgrade



In 10 years (2030s)
IceCube-Gen2



Assuming production by the full pion decay chain

Plus possibly better flavor-tagging, *e.g.*, muon and neutron echoes
[Li, **MB**, Beacom *PRL* 2019]

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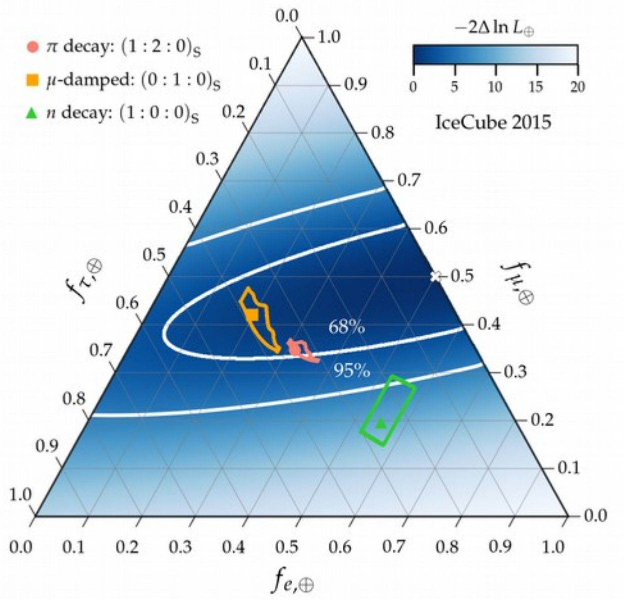

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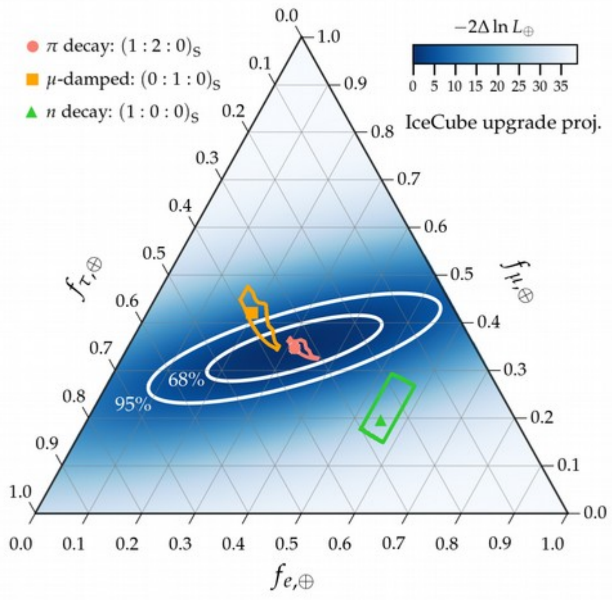

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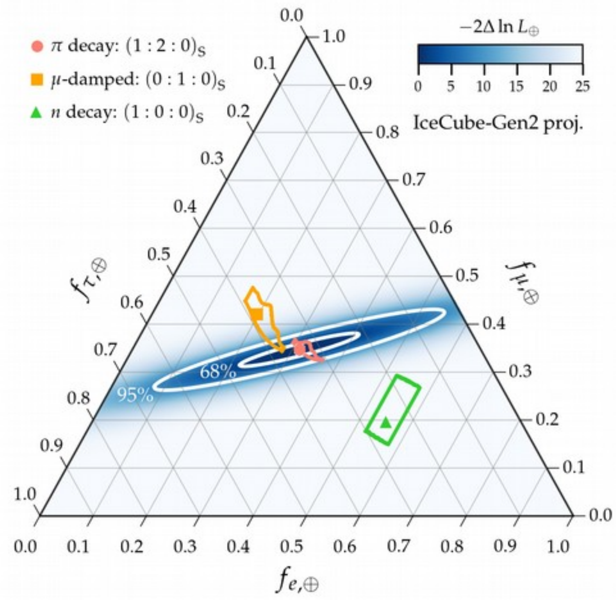

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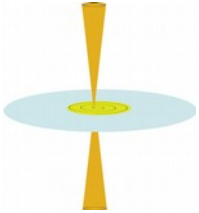
See talk by Lutz Köpke

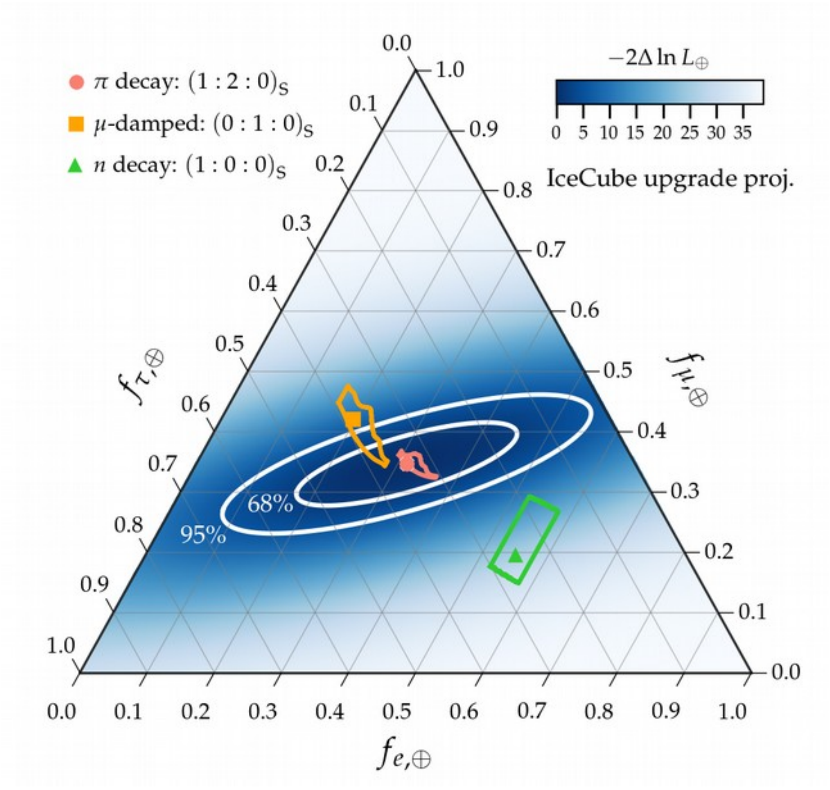
Inferring the flavor composition at the sources

Measured:
Flavor ratios at Earth

Invert flavor oscillations



Inferred:
Flavor ratios at astrophysical sources



MB & Ahlers, *PRL* 2019

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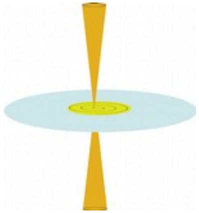

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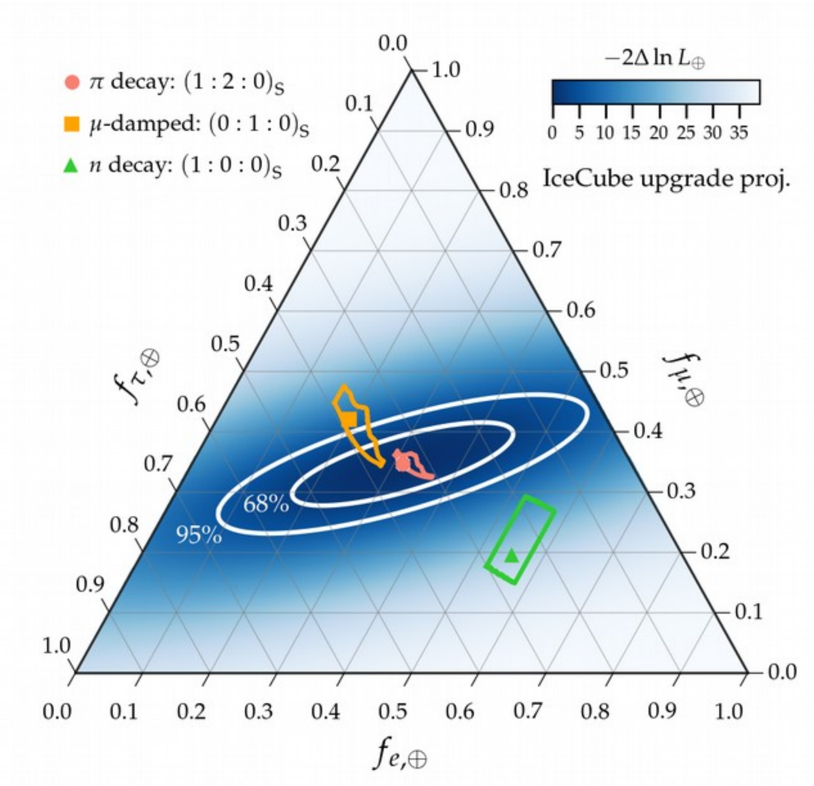

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MB & Ahlers, *PRL* 2019

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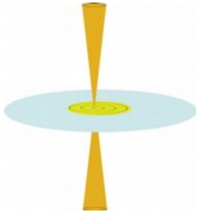

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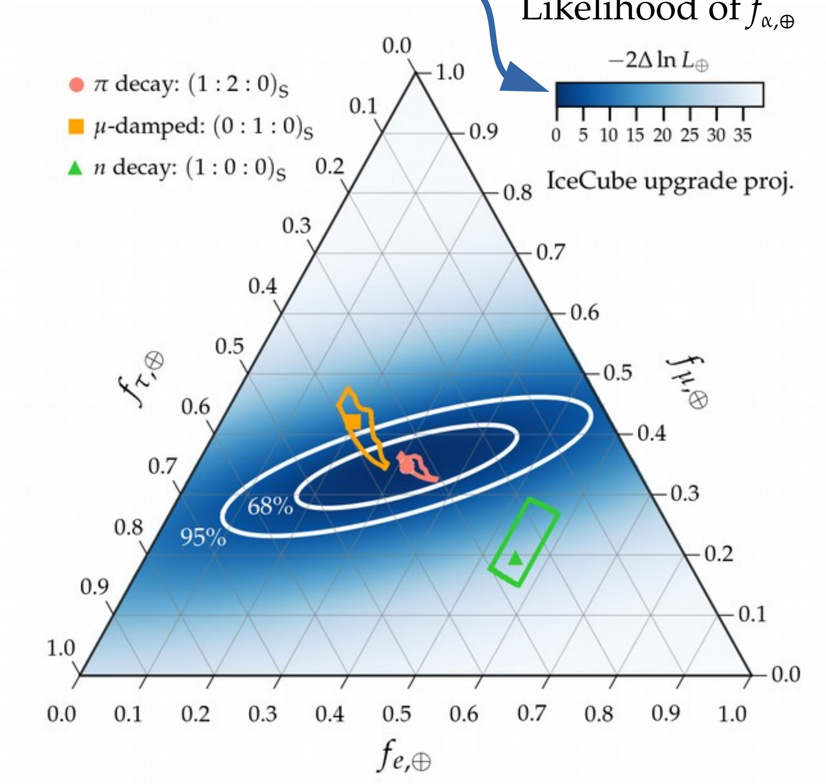
More likely

Likelihood of $f_{\alpha,\oplus}$



MB & Ahlers, *PRL* 2019

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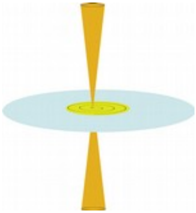

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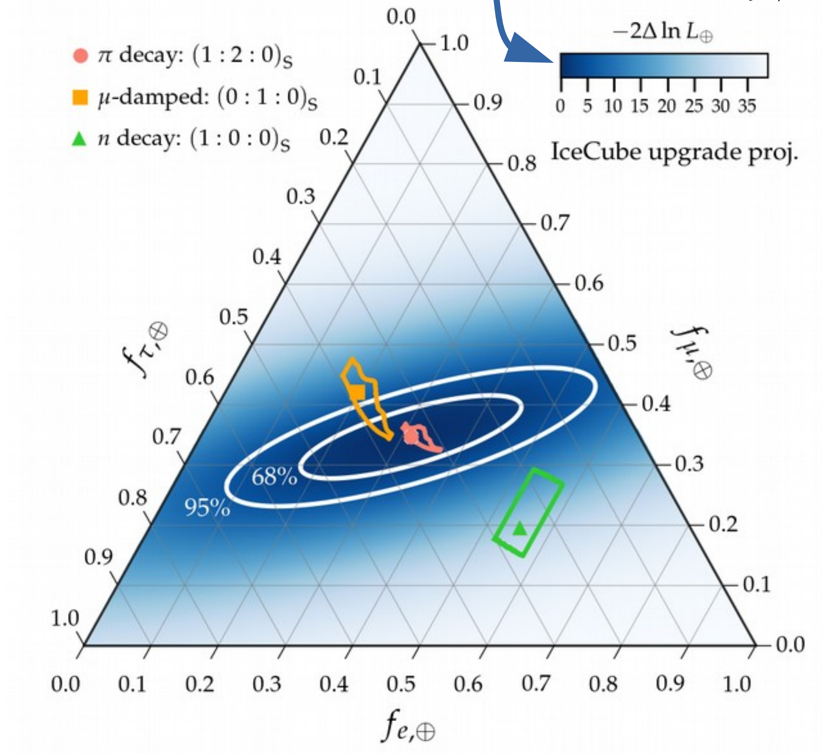
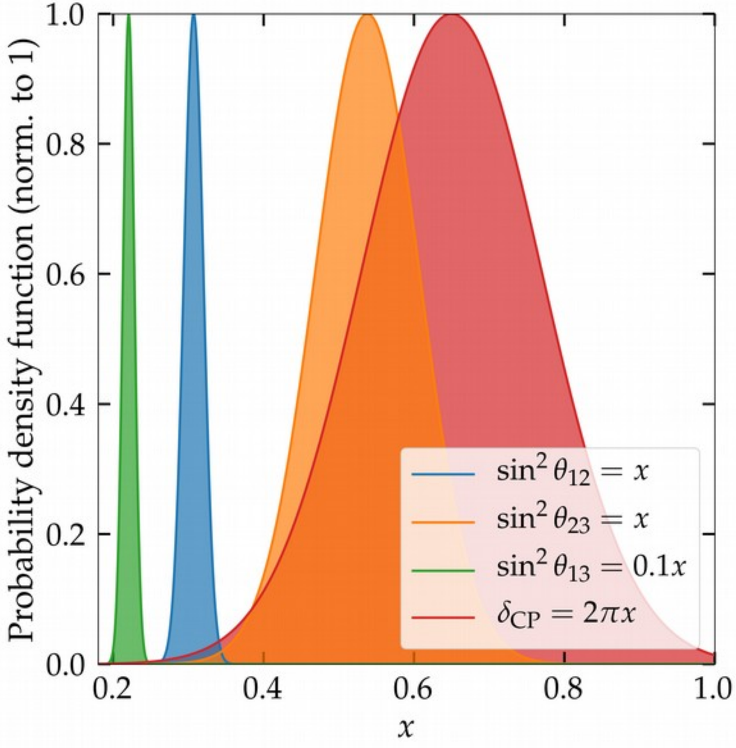


PDFs of mixing parameters



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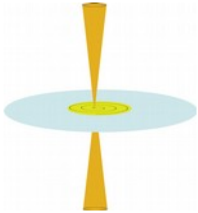

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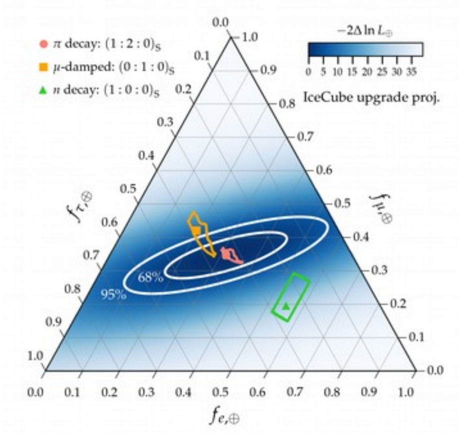
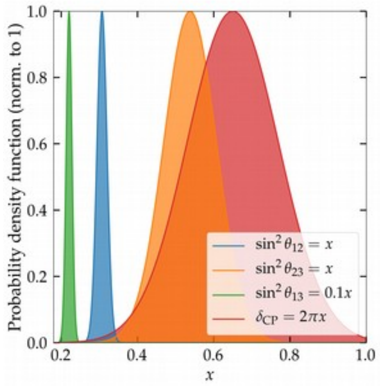




Posterior probability density of $f_{\alpha,\mathrm{S}}$ being the flavor ratios at the sources:

$$\mathcal{P}\left(f_{\alpha,\mathrm{S}}\right) \equiv \int \mathrm{d}\boldsymbol{\theta} \frac{\mathcal{P}(\boldsymbol{\theta})}{\mathcal{N}(\boldsymbol{\theta})} \mathcal{L}_\oplus \left[f_{e,\oplus}(f_{\alpha,\mathrm{S}}, \boldsymbol{\theta}), f_{\mu,\oplus}(f_{\alpha,\mathrm{S}}, \boldsymbol{\theta})\right]$$

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

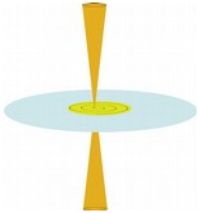
Normalization: $\mathcal{N}(\boldsymbol{\theta}) \equiv \int_0^1 \mathrm{d}f_{e,\mathrm{S}} \int_0^{1-f_{e,\mathrm{S}}} \mathrm{d}f_{\mu,\mathrm{S}} \; \mathcal{L}_\oplus \left[f_{e,\oplus}(f_{\alpha,\mathrm{S}}, \boldsymbol{\theta}), f_{\mu,\oplus}(f_{\alpha,\mathrm{S}}, \boldsymbol{\theta})\right]$

MB & Ahlers, *PRL* 2019

Inferring the flavor composition at the sources

Measured:
Flavor ratios at Earth

Invert flavor oscillations



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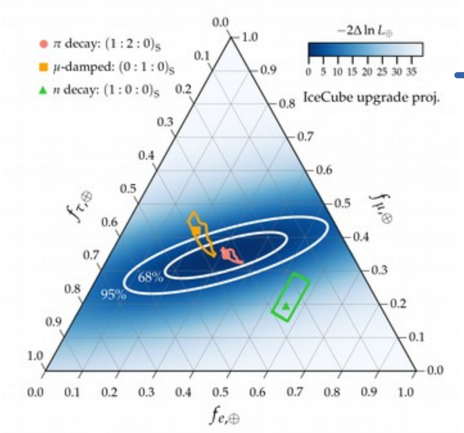

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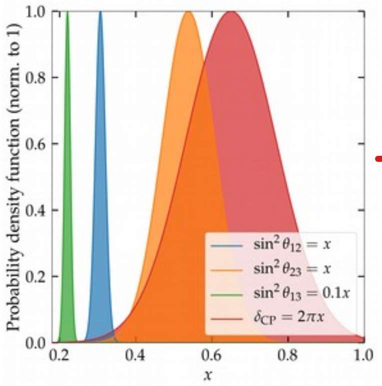

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MB & Ahlers, *PRL* 2019

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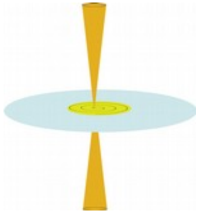

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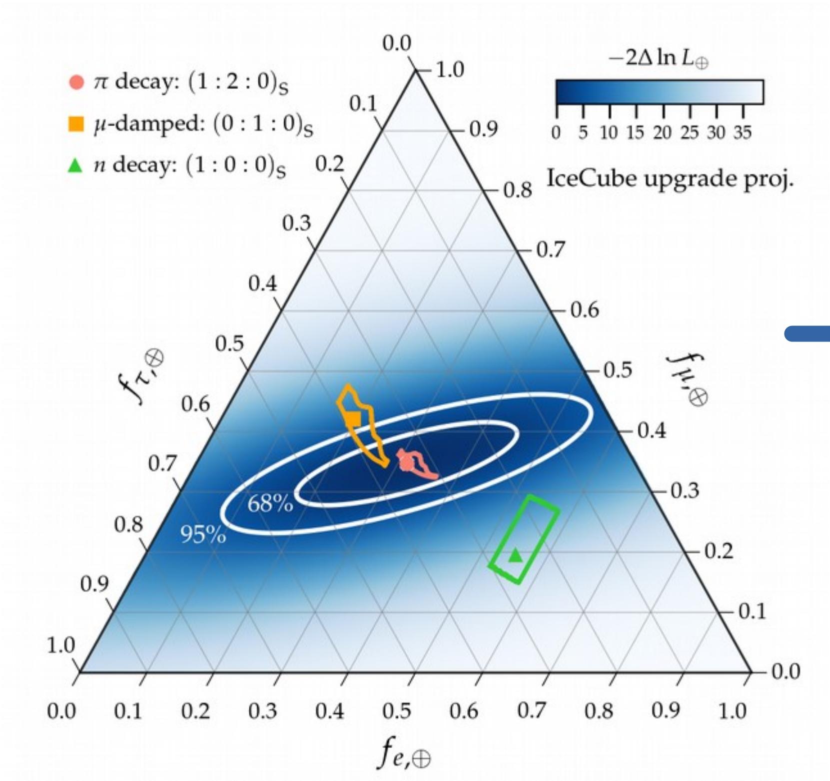

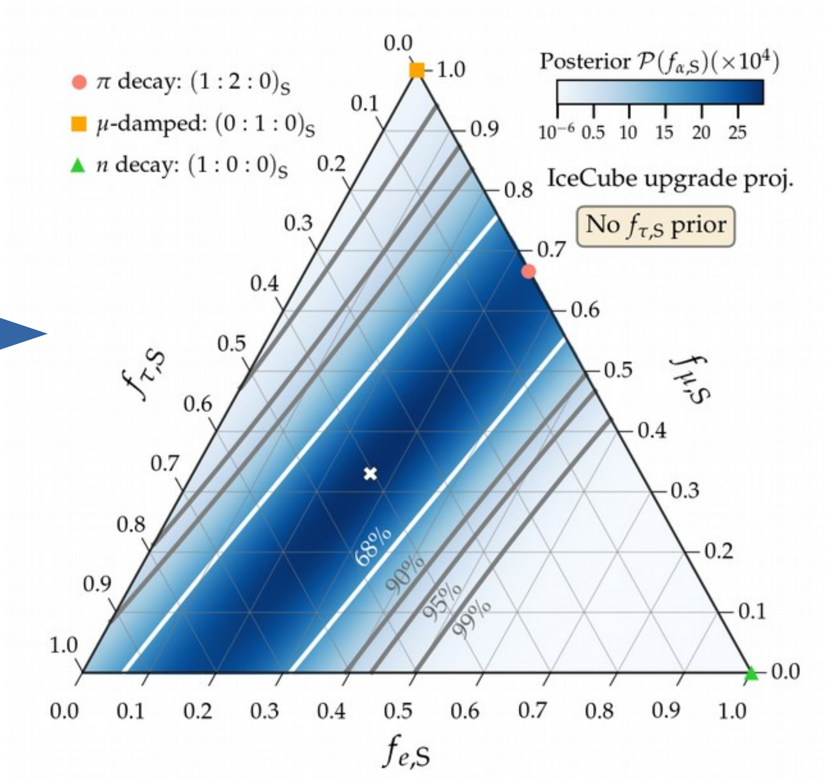

MB & Ahlers, *PRL* 2019

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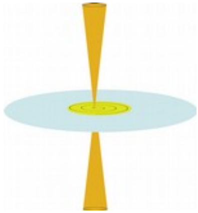

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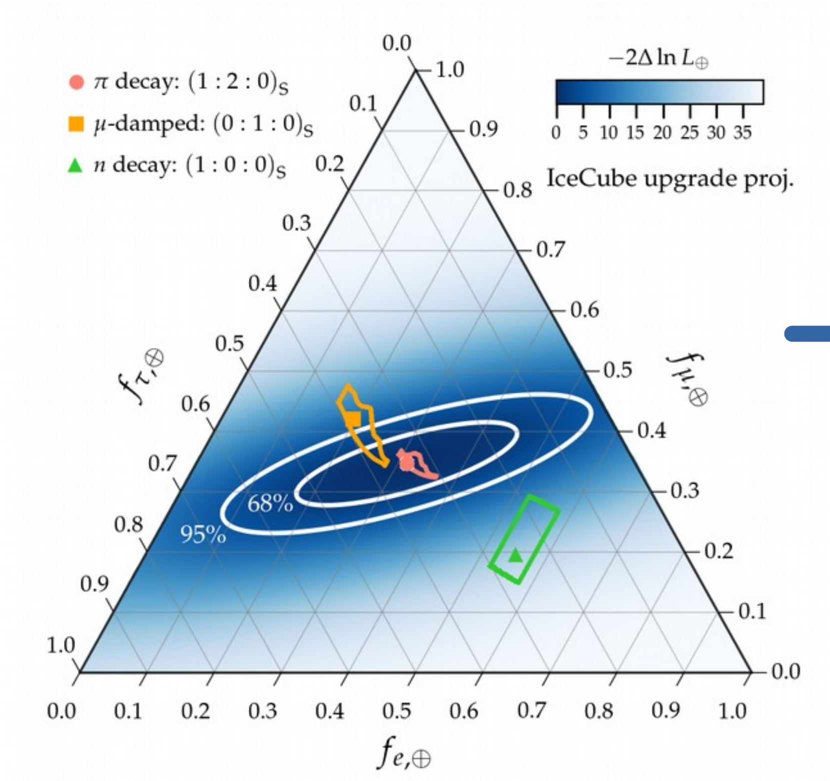
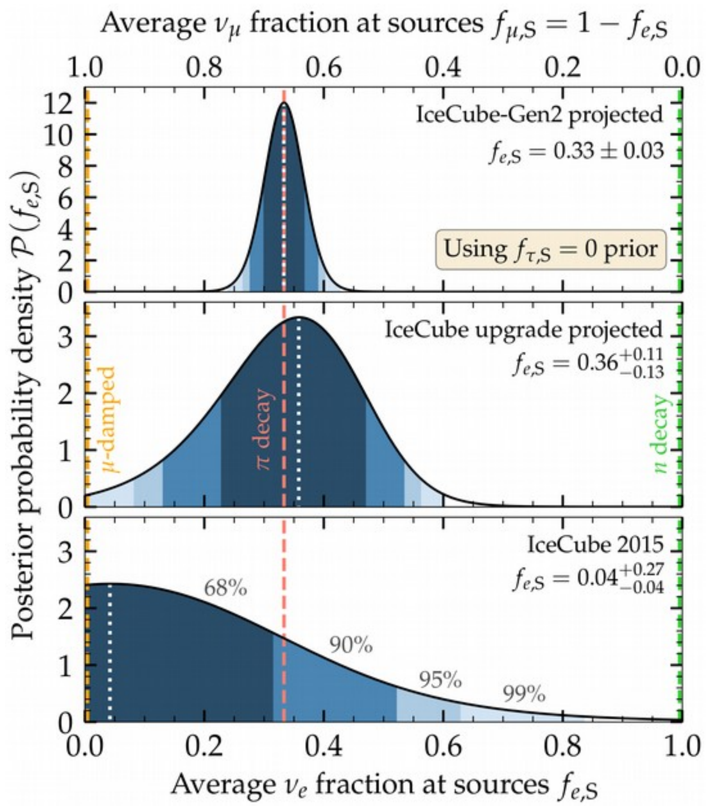
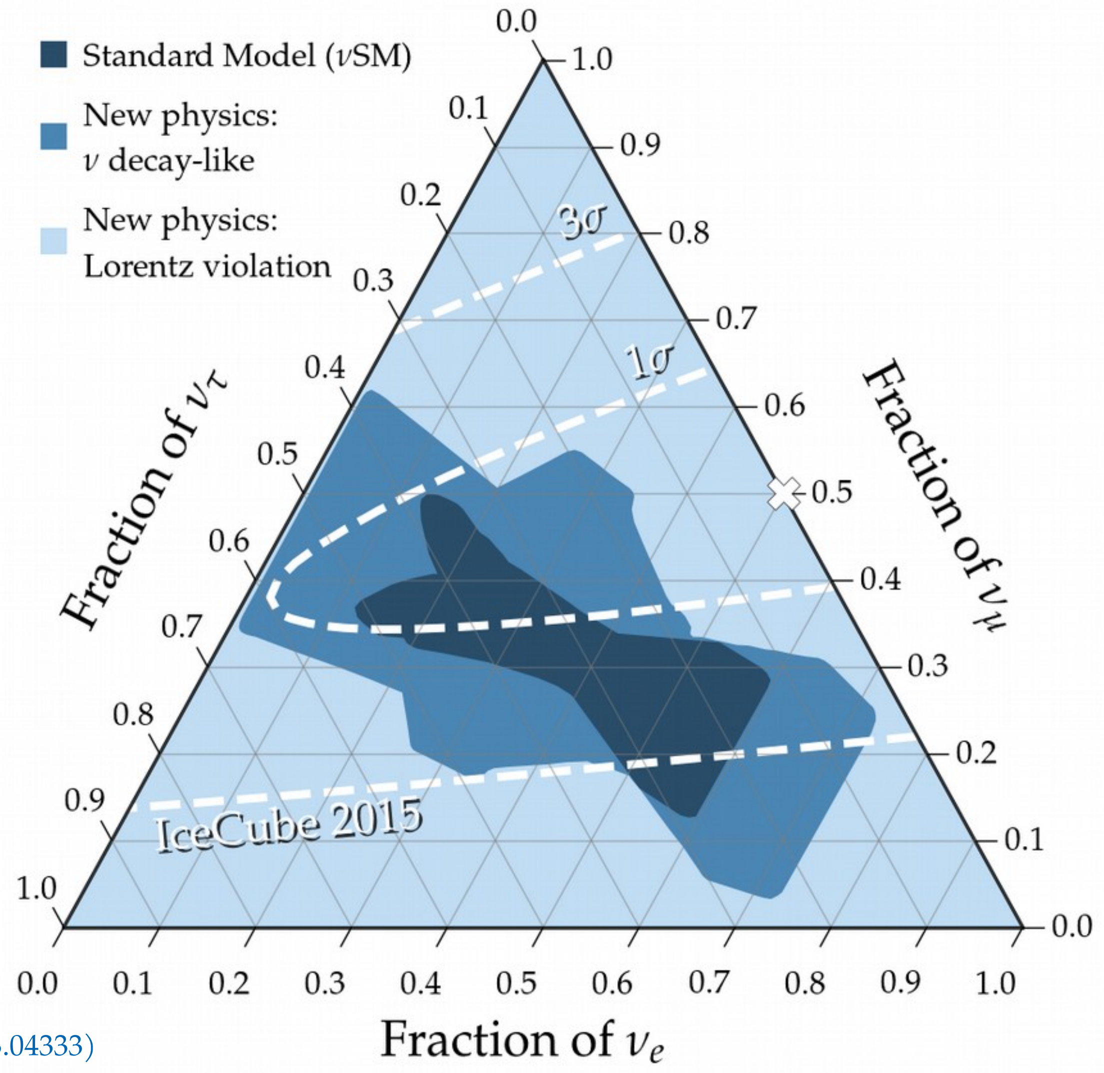
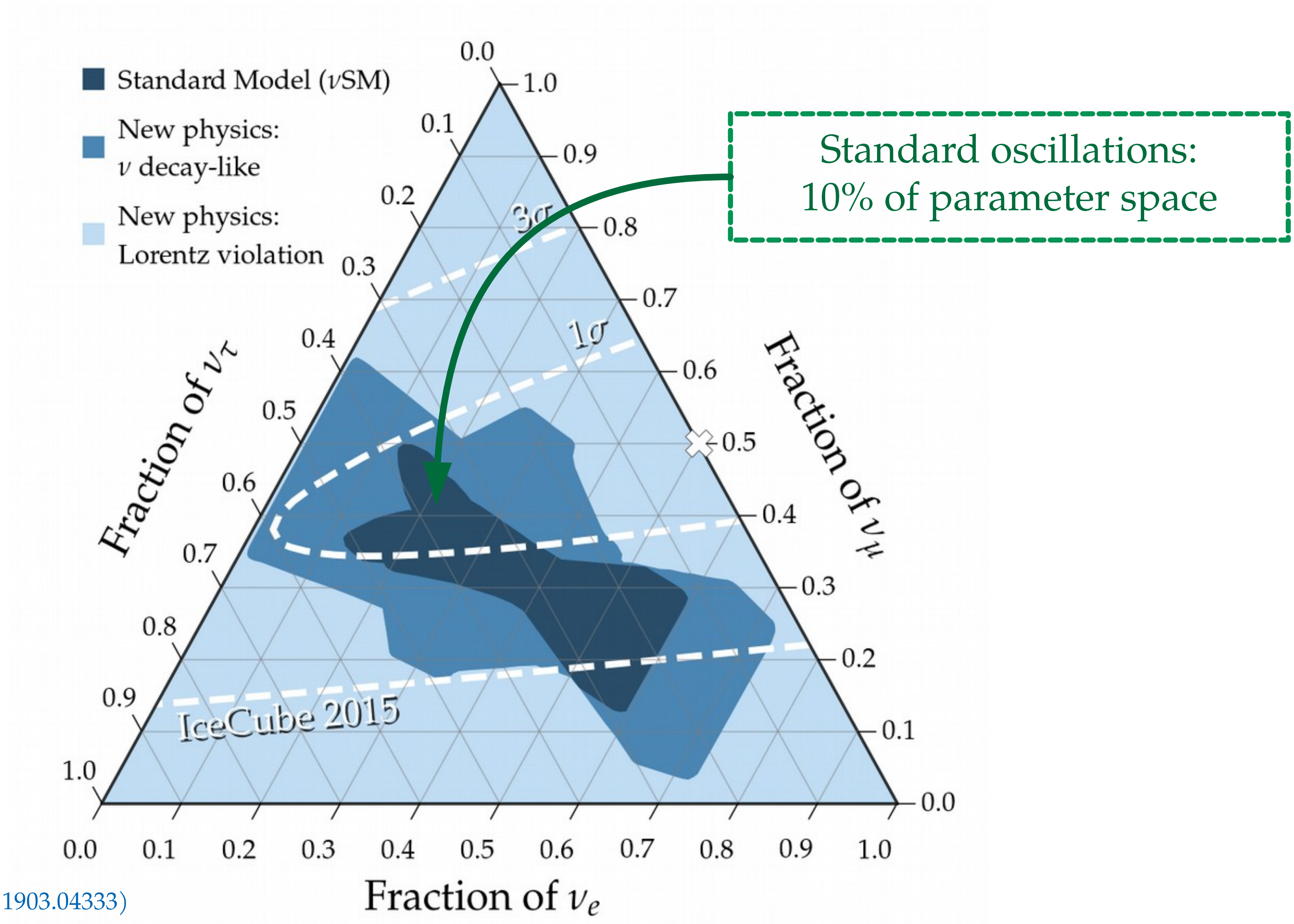




MB & Ahlers, *PRL* 2019



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



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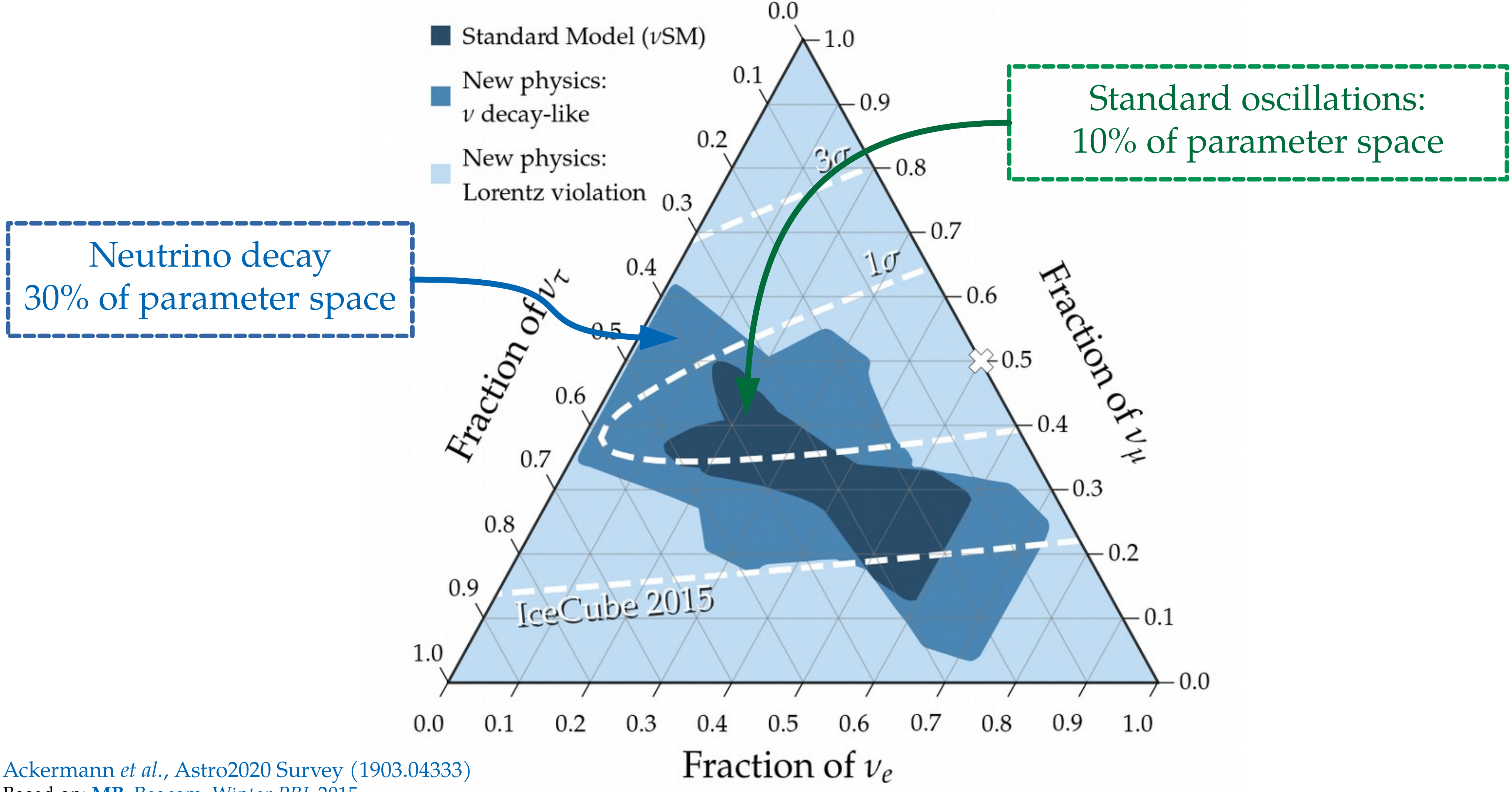

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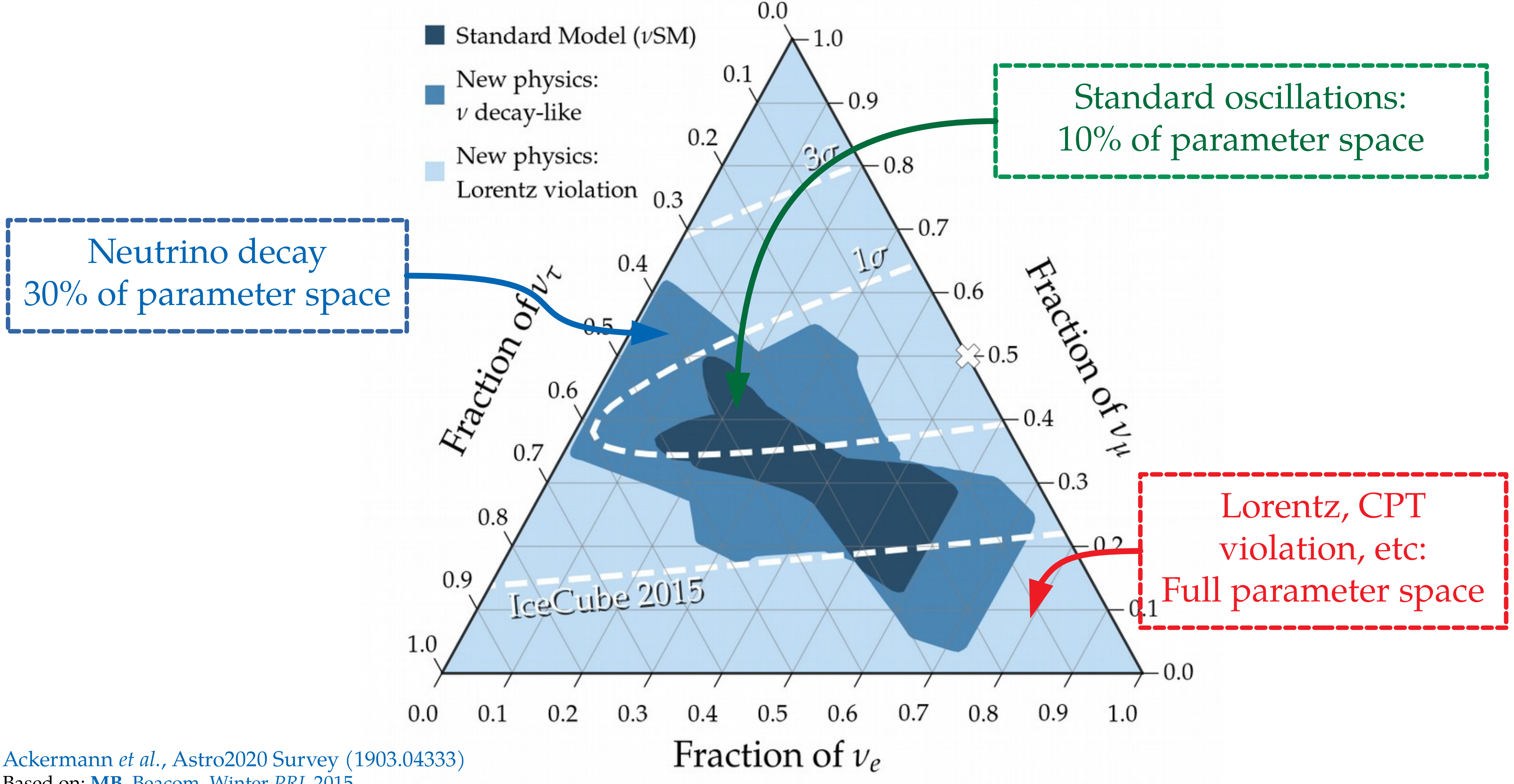
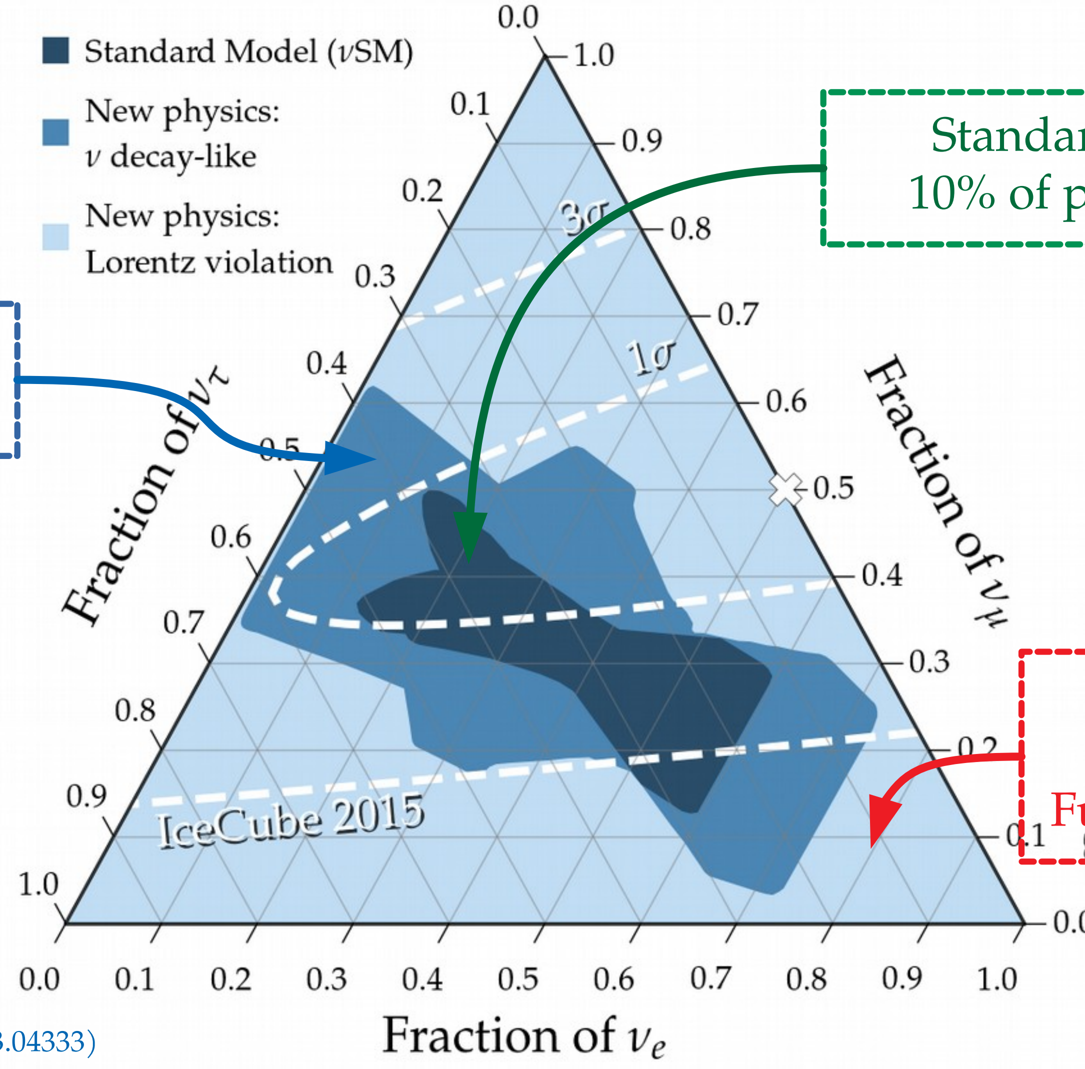


Ackermann *et al.*, Astro2020 Survey (1903.04333)
Based on: **MB**, Beacom, Winter *PRL* 2015

Neutrino decay
30% of parameter space

Standard oscillations:
10% of parameter space

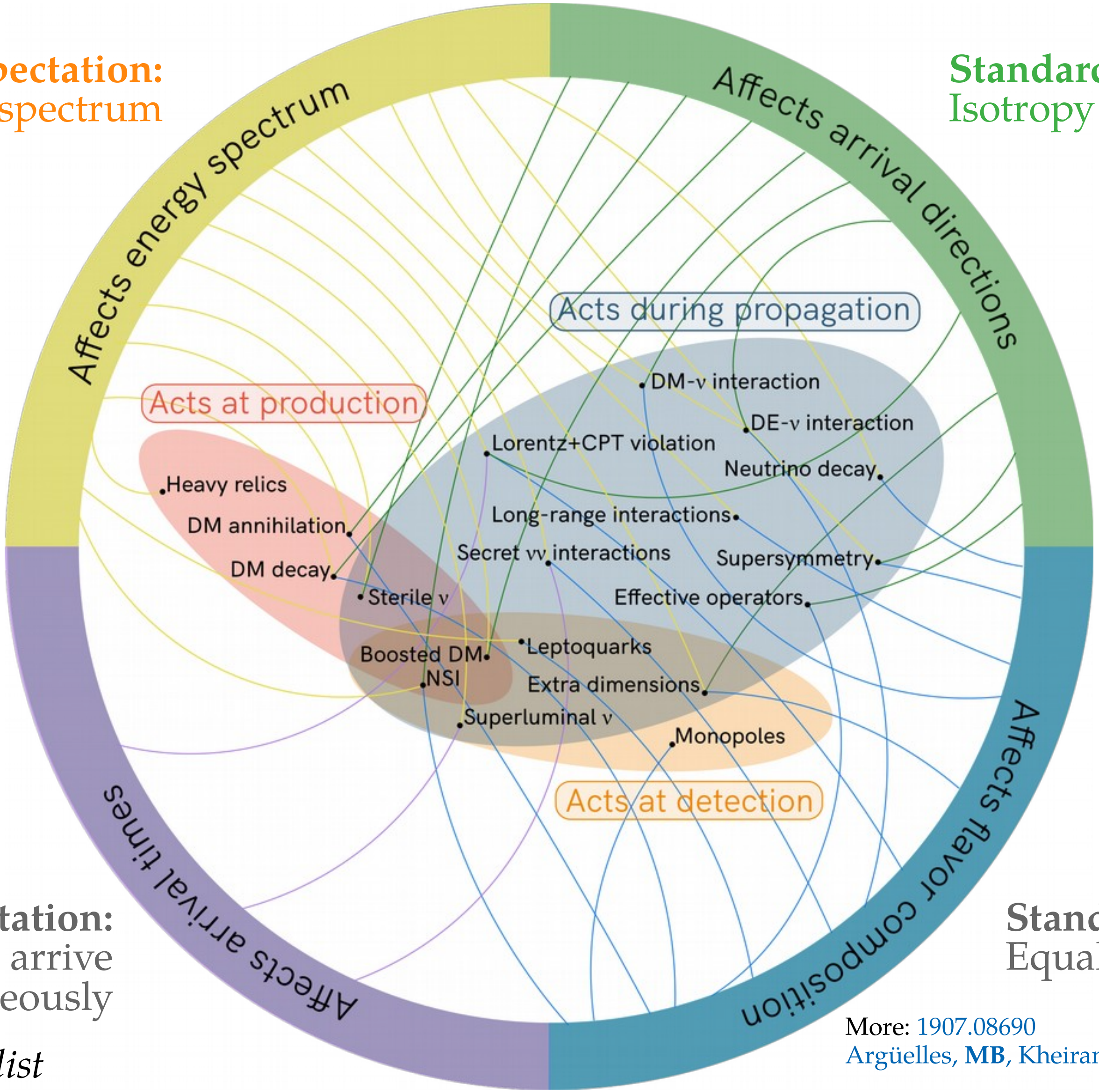


Lorentz, CPT violation, etc:
Full parameter space

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

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



See talk by Jordi Salvadó

Standard expectation:
ν and γ from transients arrive simultaneously

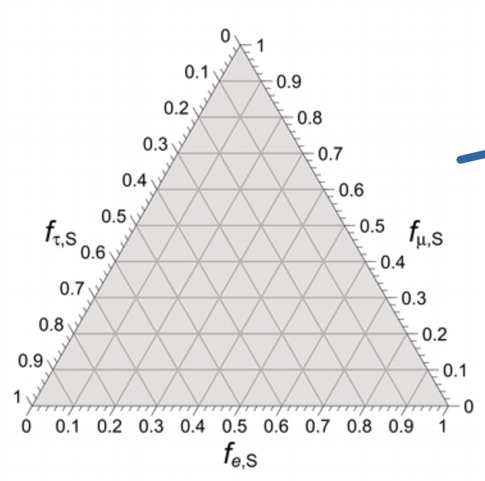
Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Note: Not an exhaustive list

More: 1907.08690
Argüelles, **MB**, Kheirandish, Palomares-Ruiz, Salvadó, Vincent

Measuring the neutrino lifetime

Sources



$\nu_2, \nu_3 \to \nu_1$

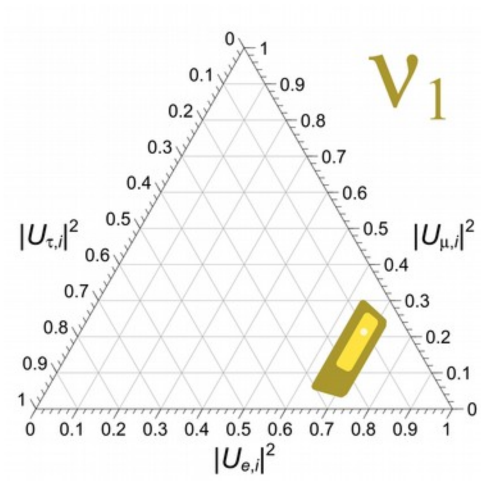
ν_1 lightest and stable

If all unstable neutrinos decay

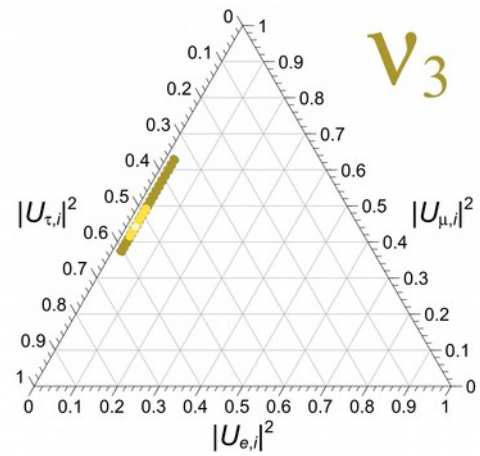
$\nu_1, \nu_2 \to \nu_3$

ν_3 lightest and stable

Earth



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



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

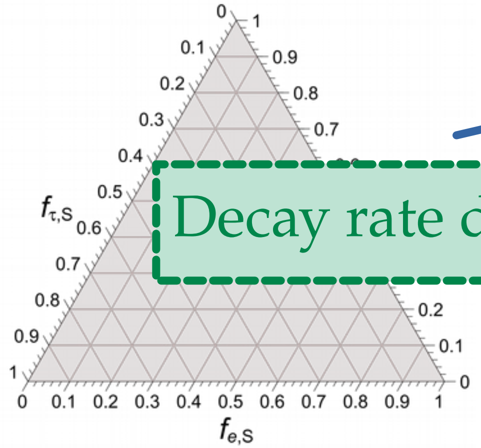
Measuring the neutrino lifetime

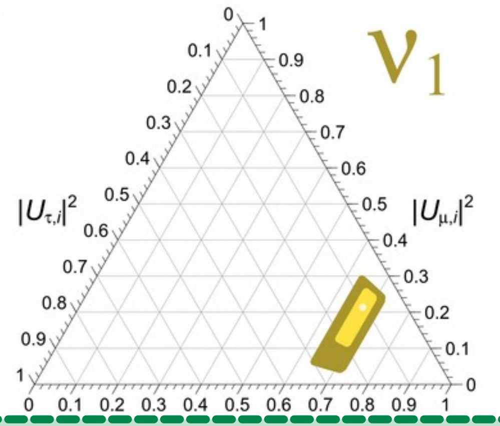
Earth

$\nu_2, \nu_3 \rightarrow \nu_1$

ν_1 lightest and stable

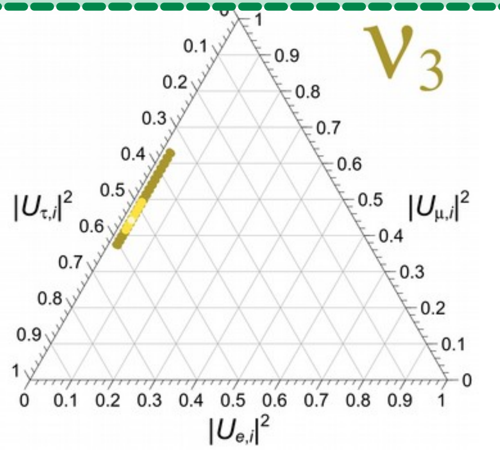
Sources





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

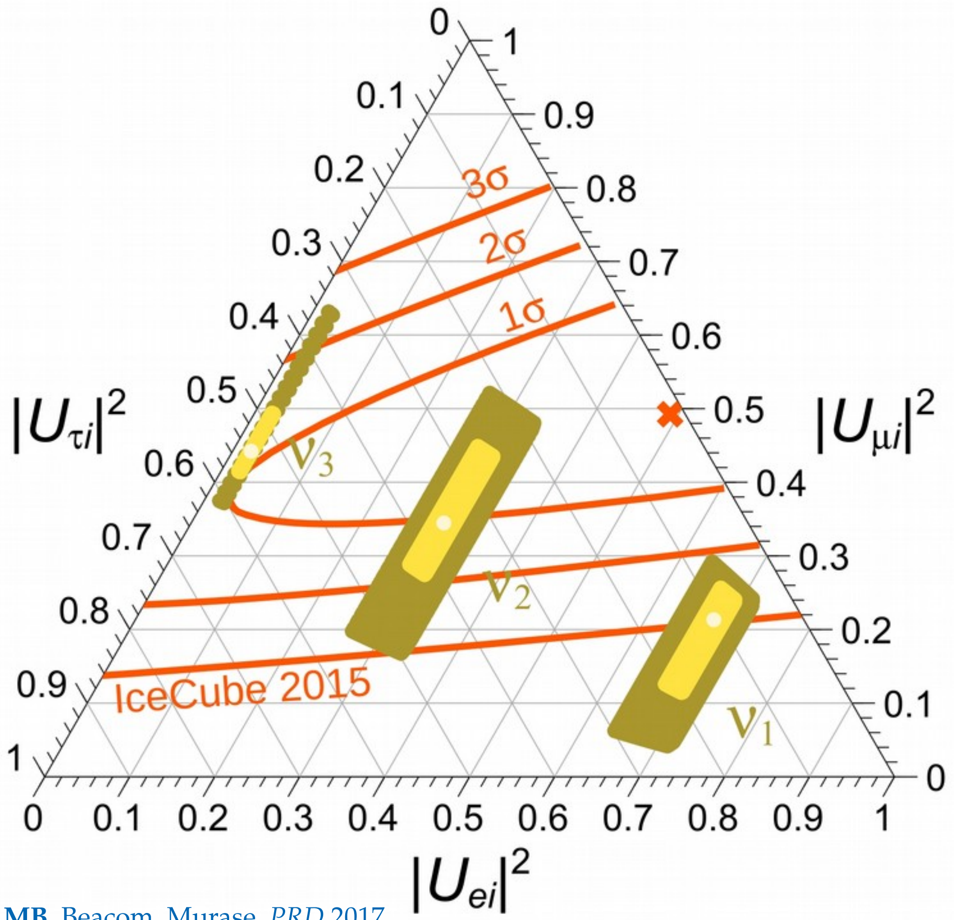
Decay rate depends on $\exp[- t \,/\, (\gamma\tau_i)] = \exp[- (L/E) \cdot (m_i/\tau_i)]$



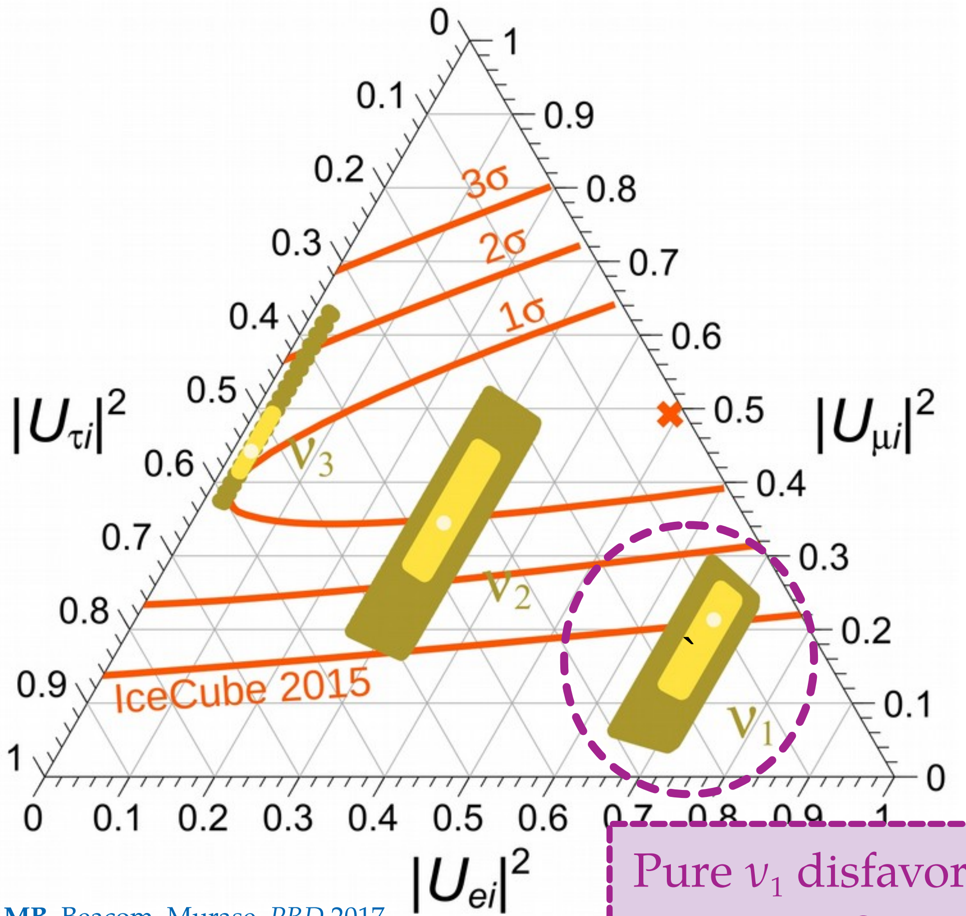
$f_{\alpha,\oplus} = |U_{\alpha 3}|^2$

$\nu_1, \nu_2 \rightarrow \nu_3$

ν_3 lightest and stable



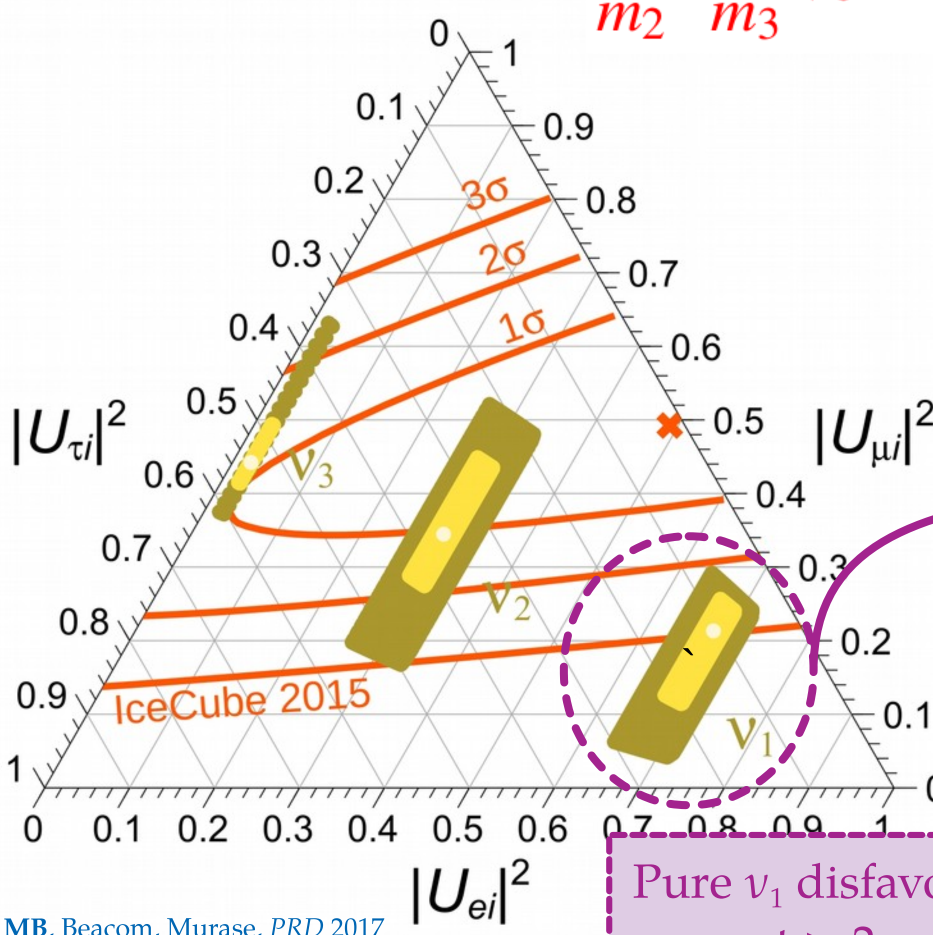
MB, Beacom, Murase, *PRD* 2017

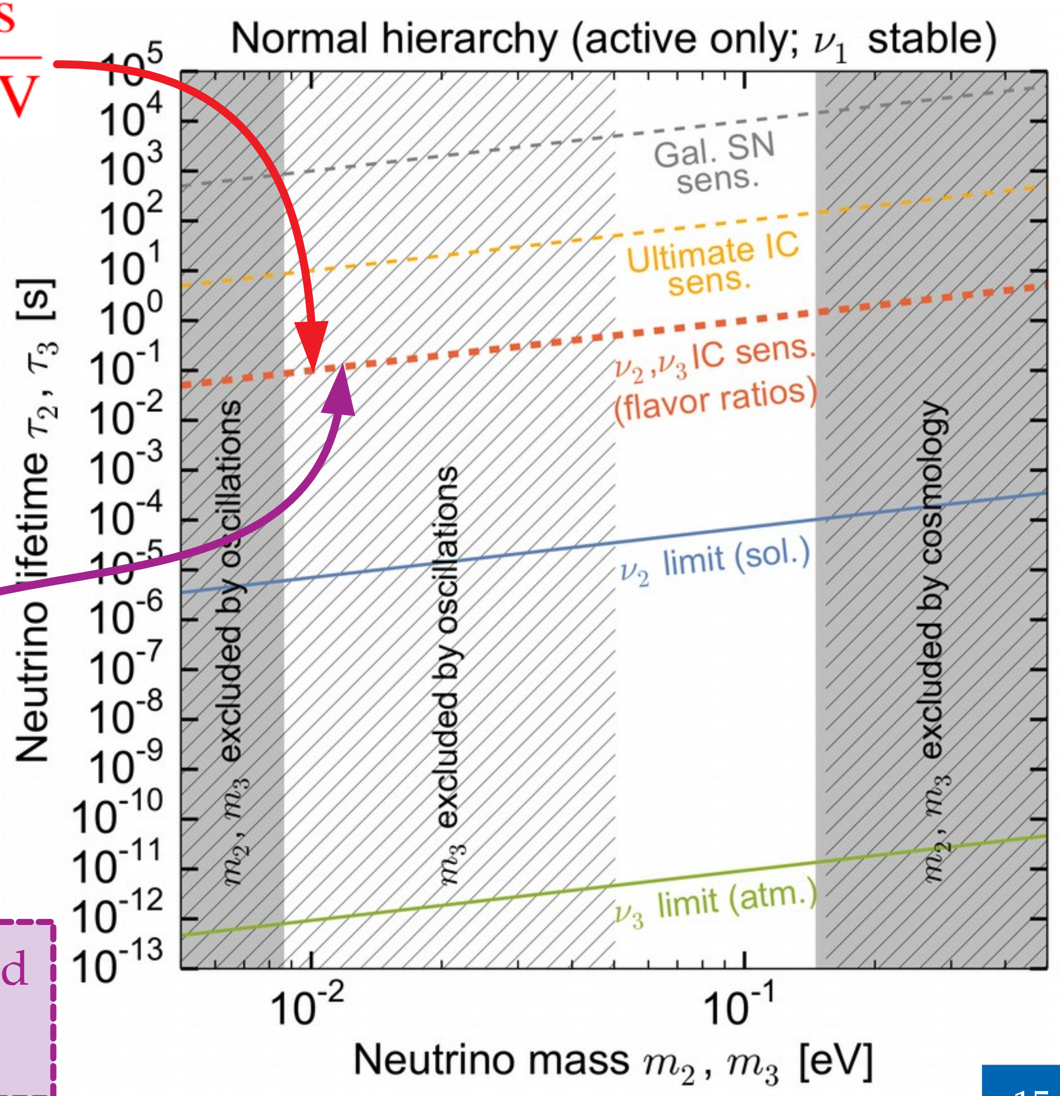


MB, Beacom, Murase, *PRD* 2017

Pure ν_1 disfavored at $> 2\sigma$

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





Pure ν_1 disfavored at > 2σ

MB, Beacom, Murase, *PRD* 2017

How to access all of the flavor triangle? *Pick your monster*

- High-energy effective field theories
  - Violation of Lorentz and CPT invariance
    [Barenboim & Quigg, *PRD* 2003; Kostelecky & Mewes 2004; **MB**, Gago, Peña-Garay, *JHEP* 2010]
  - Violation of equivalence principle
    [Gasperini, *PRD* 1989; Glashow *et al.*, *PRD* 1997]
  - Coupling to a gravitational torsion field
    [De Sabbata & Gasperini, *Nuovo Cim.* 1981]
  - Renormalization-group-running of mixing parameters
    [**MB**, Gago, Jones, *JHEP* 2011]
  - General non-unitary propagation
    [Ahlers, **MB**, Mu, *PRD* 2018]

- Active-sterile mixing
  [Aeikens *et al.*, *JCAP* 2015; Brdar, *JCAP* 2017; Argüelles *et al.*, 1909.05341]

- Flavor-violating physics
  - New neutrino-electron interactions
    [**MB** & Agarwalla, *PRL* 2019]
  - New $\nu\nu$ interactions
    [Ng & Beacom, *PRD* 2014; Cherry, Friedland, Shoemaker, 1411.1071; Blum, Hook, Murase, 1408.3799]

- …

Toho Company Ltd.

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 $\sim(1/m')$

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 —

Z′ coupling

Z′ mass

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

Distance to neutrino

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

Electron-neutrino interactions can kill oscillations

Electron-neutrino interactions can kill oscillations

$$\mathrm{H}_{\mathrm{tot}} = \underbrace{\mathrm{H}_{\mathrm{vac}}}$$

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

Electron-neutrino interactions can kill oscillations

$$\mathrm{H}_{\mathrm{tot}} = \mathrm{H}_{\mathrm{vac}}$$

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

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

Electron-neutrino interactions can kill oscillations

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

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

New neutrino-electron interaction:
This is diagonal

Electron-neutrino interactions can kill oscillations

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

New neutrino-electron interaction:
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Z' parameters

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

Electron-neutrino interactions can kill oscillations

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

New neutrino-electron interaction:
This is diagonal

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 $\mathrm{V}_{e\beta}$ 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

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

$\sim 1/E$

Energy-independent

Electron-neutrino interactions can kill oscillations

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

$\sim 1/E$

Energy-independent

$\therefore$ We can use high-energy astrophysical neutrinos

Electrons in the local and distant Universe

Potential:

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

Electrons in the local and distant Universe

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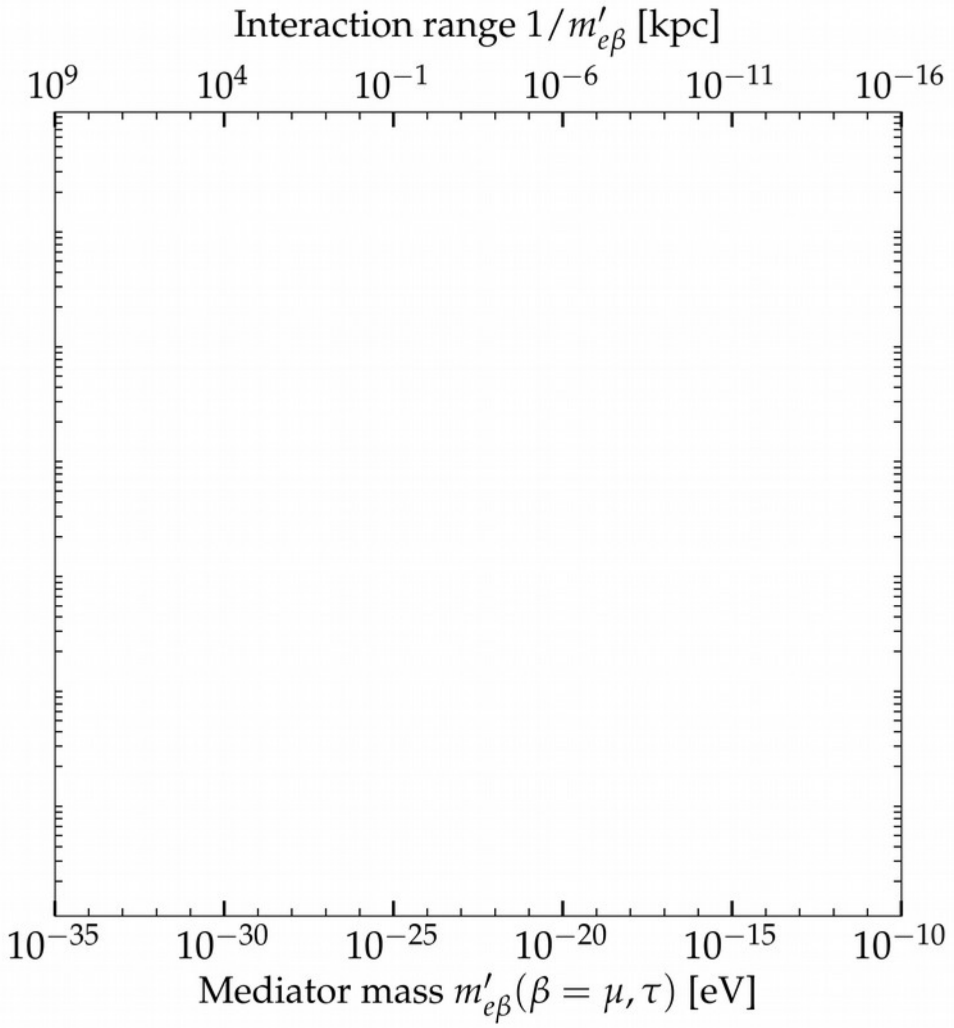
Interaction range: $\frac{1}{m'_{e\beta}}$

Electrons in the local and distant Universe



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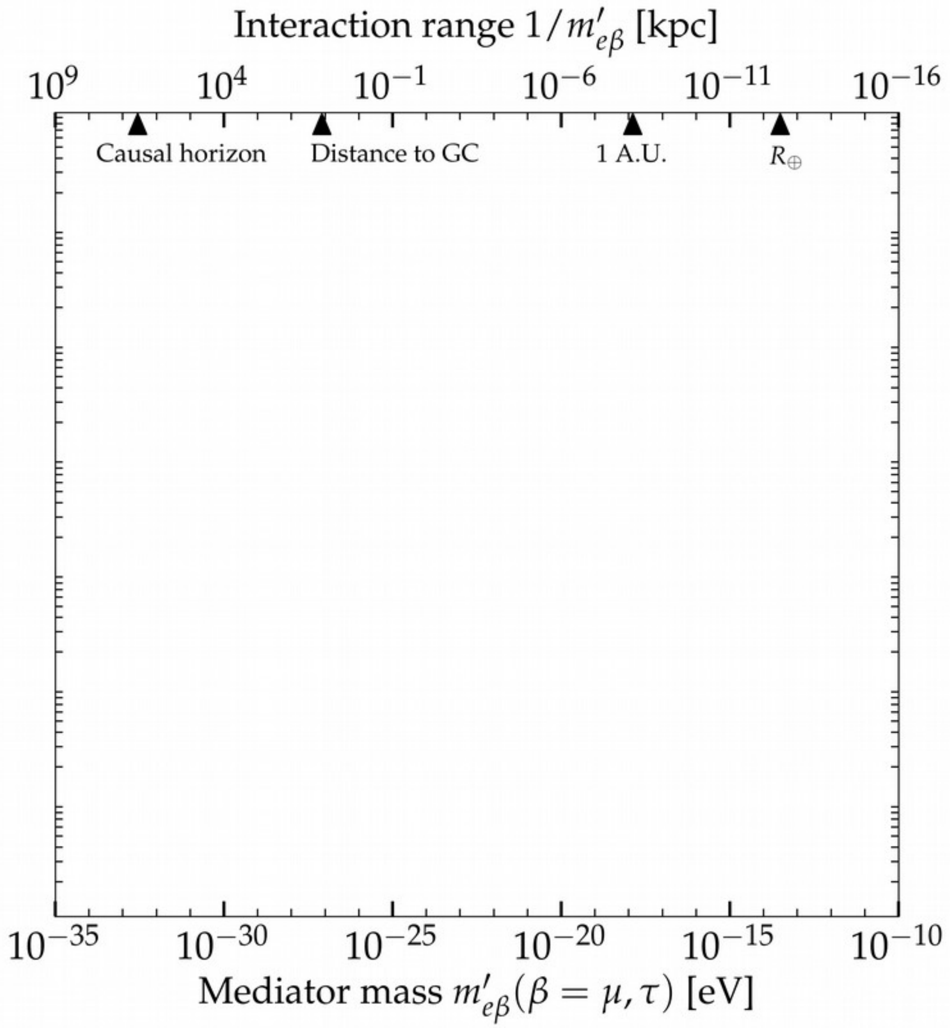

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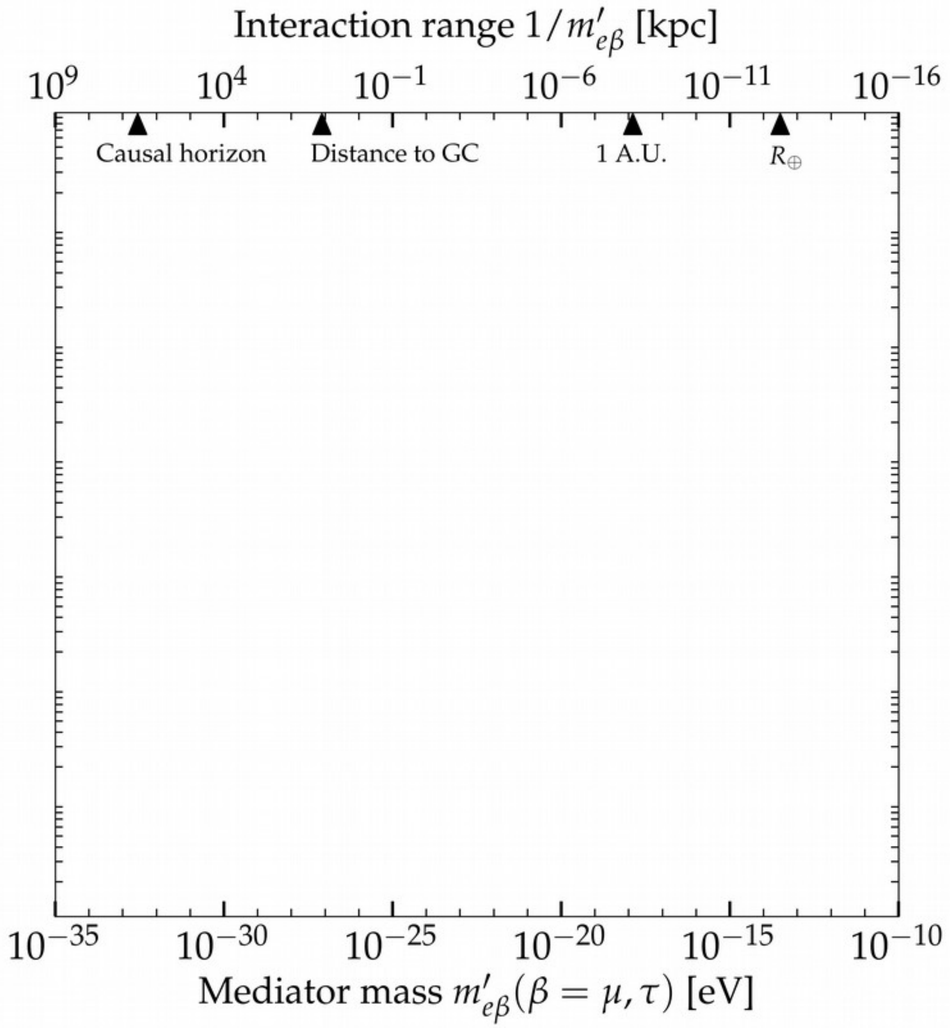

Potential:

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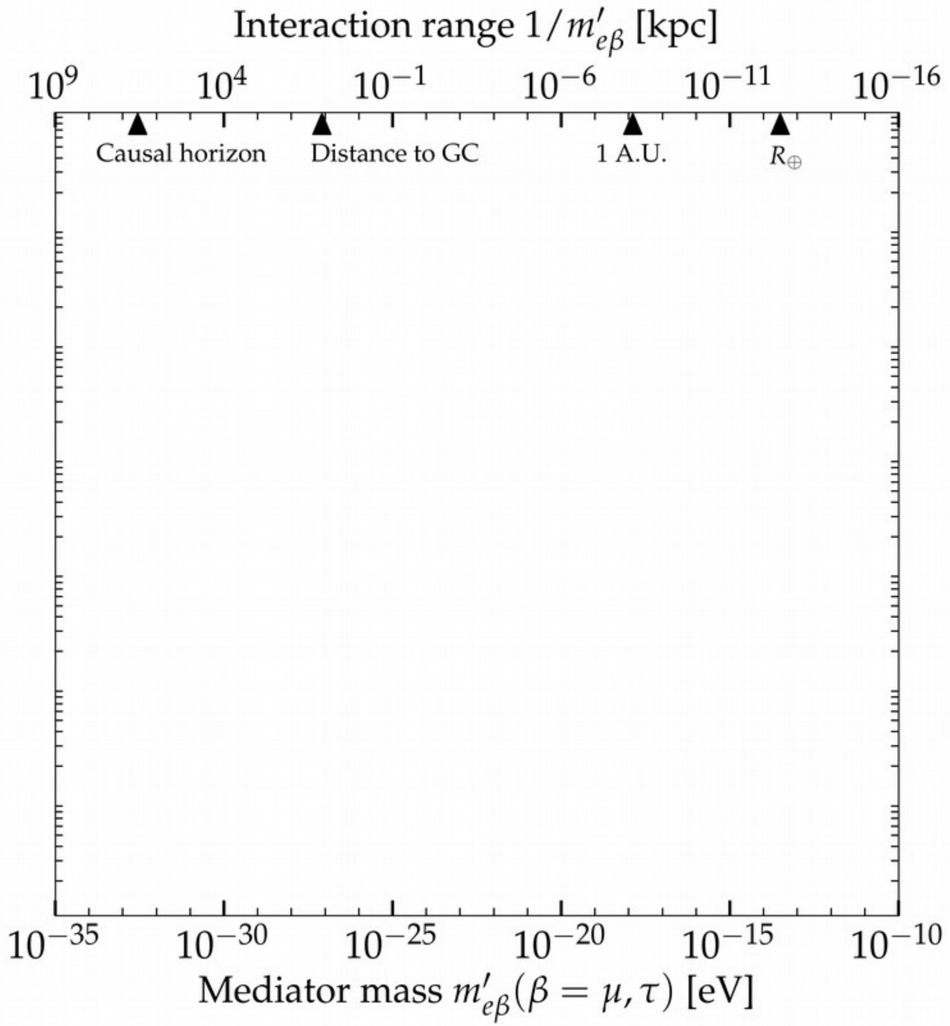
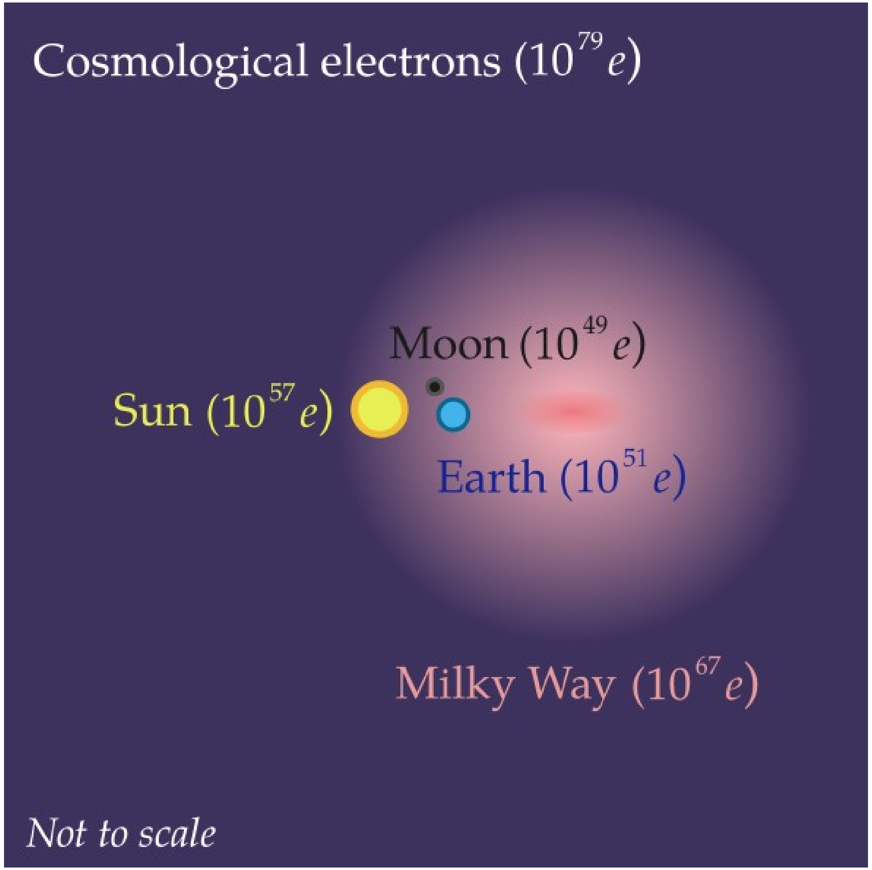
Interaction range: $\frac{1}{m'_{e\beta}}$

Light mediators
⇒ Long interaction ranges

Electrons in the local and distant Universe





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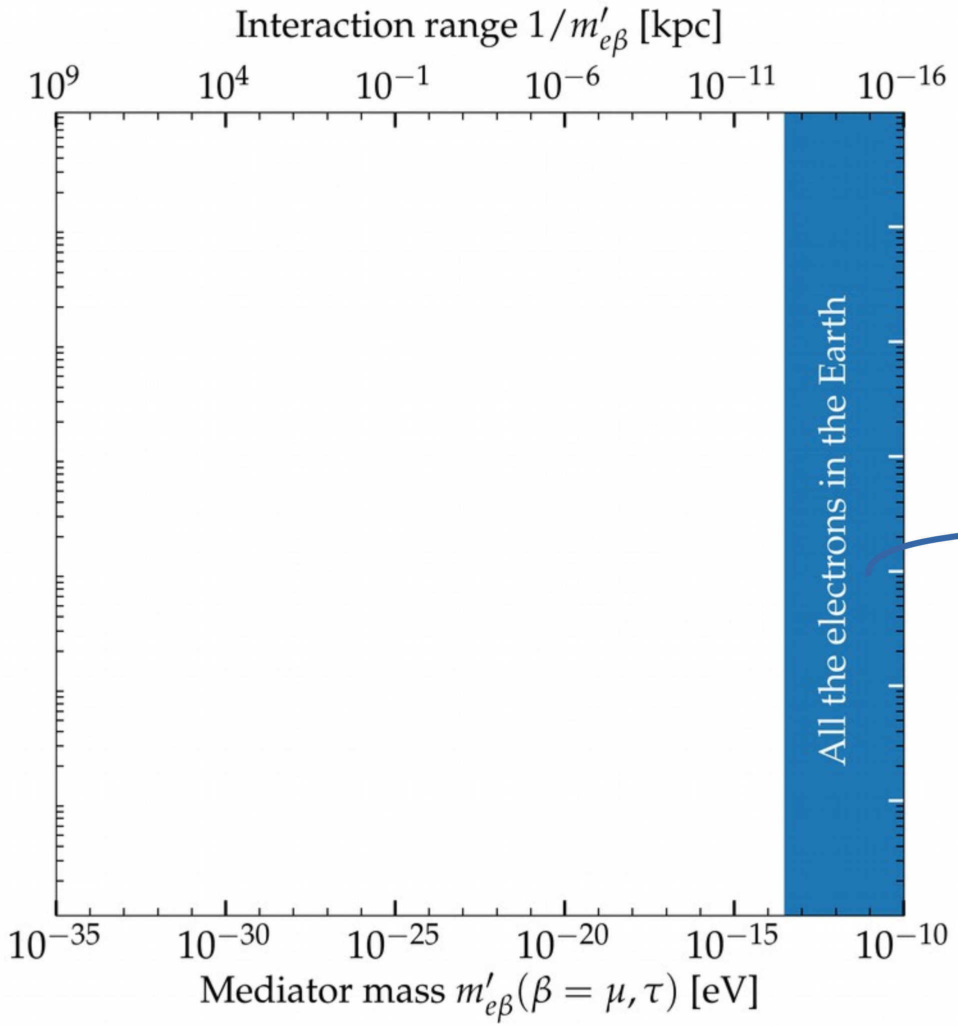

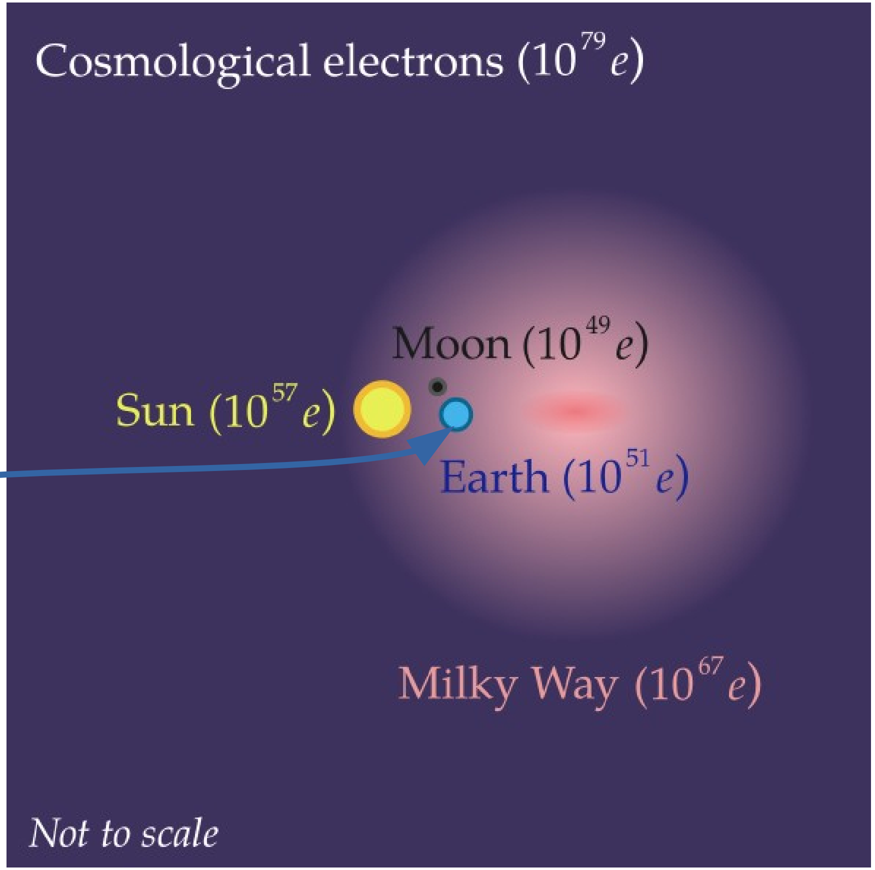

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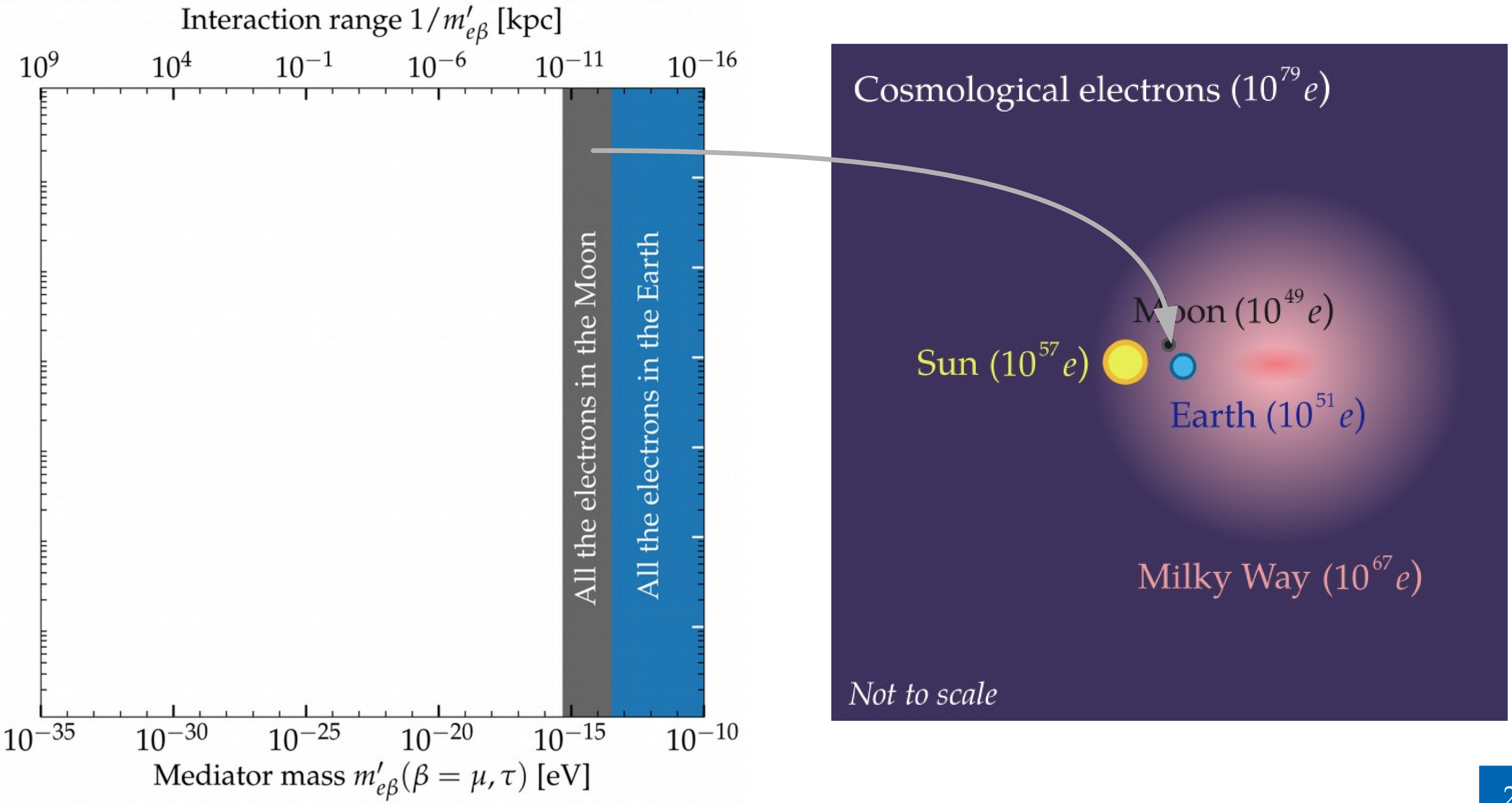

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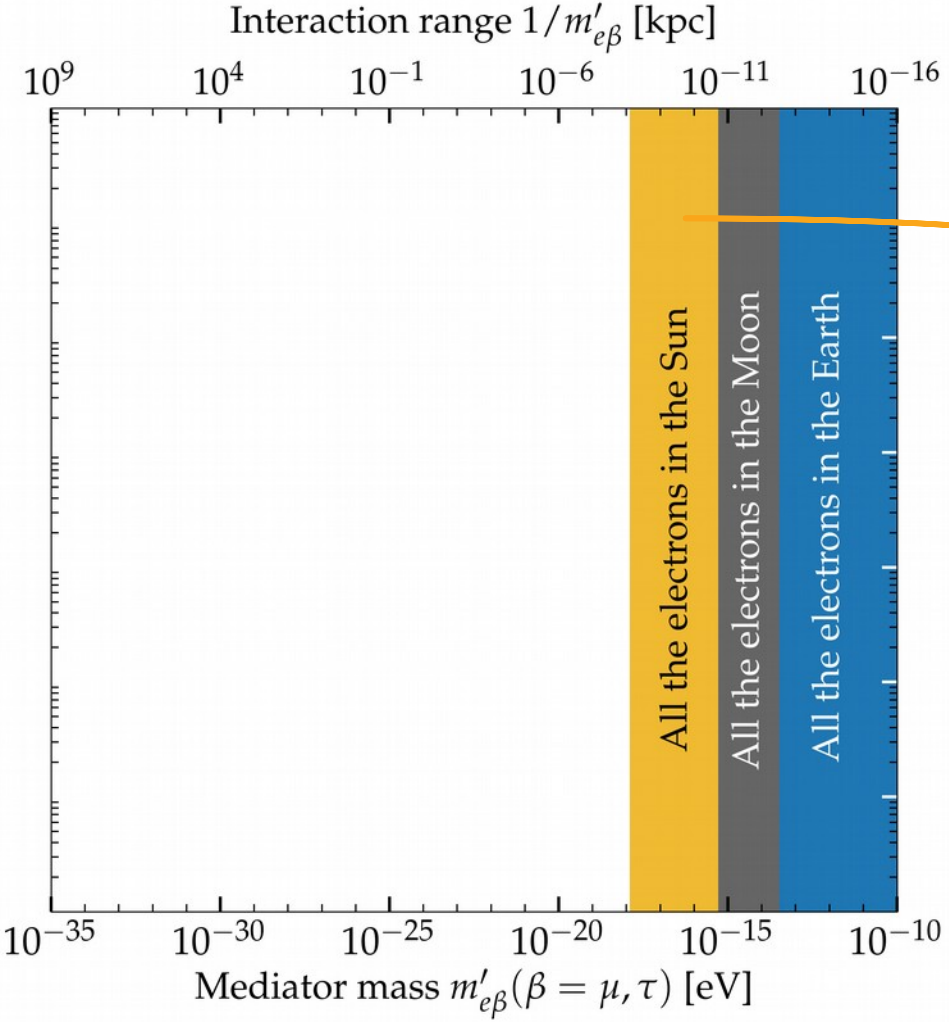

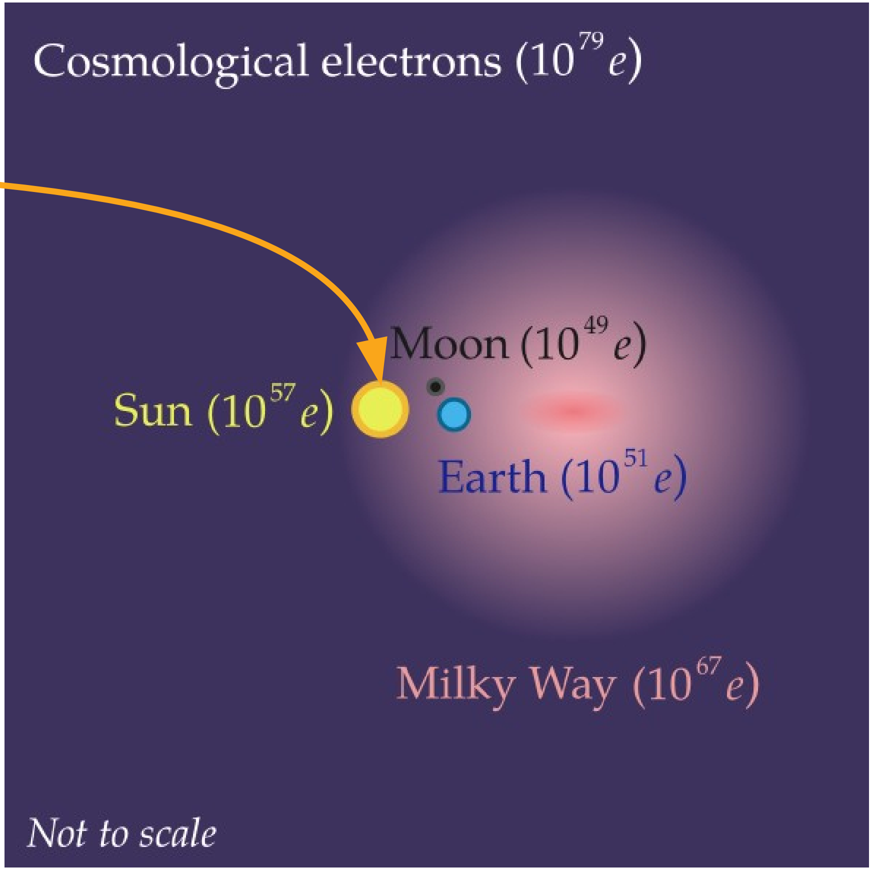

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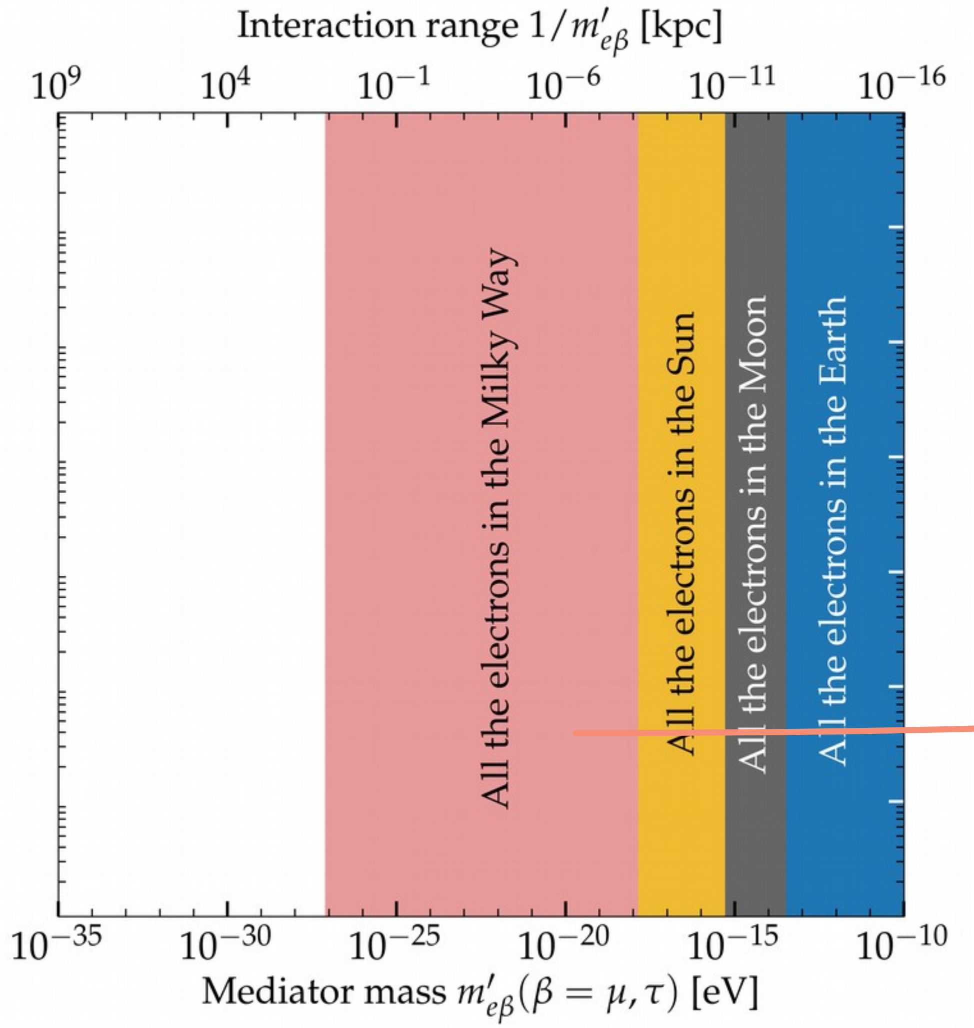
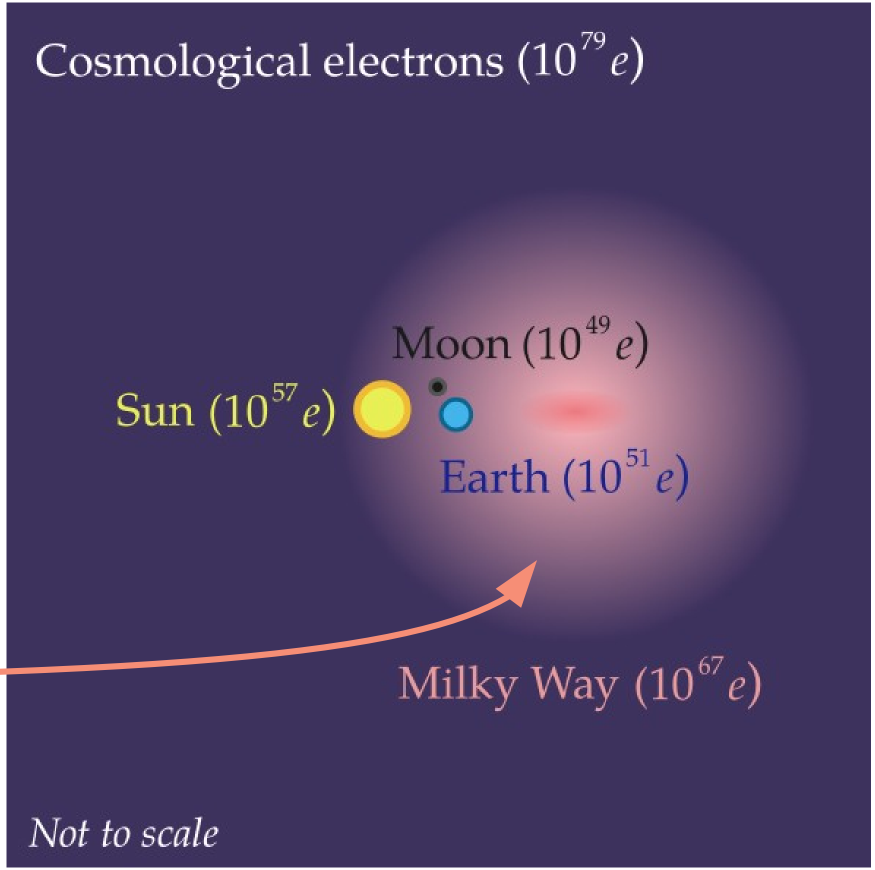
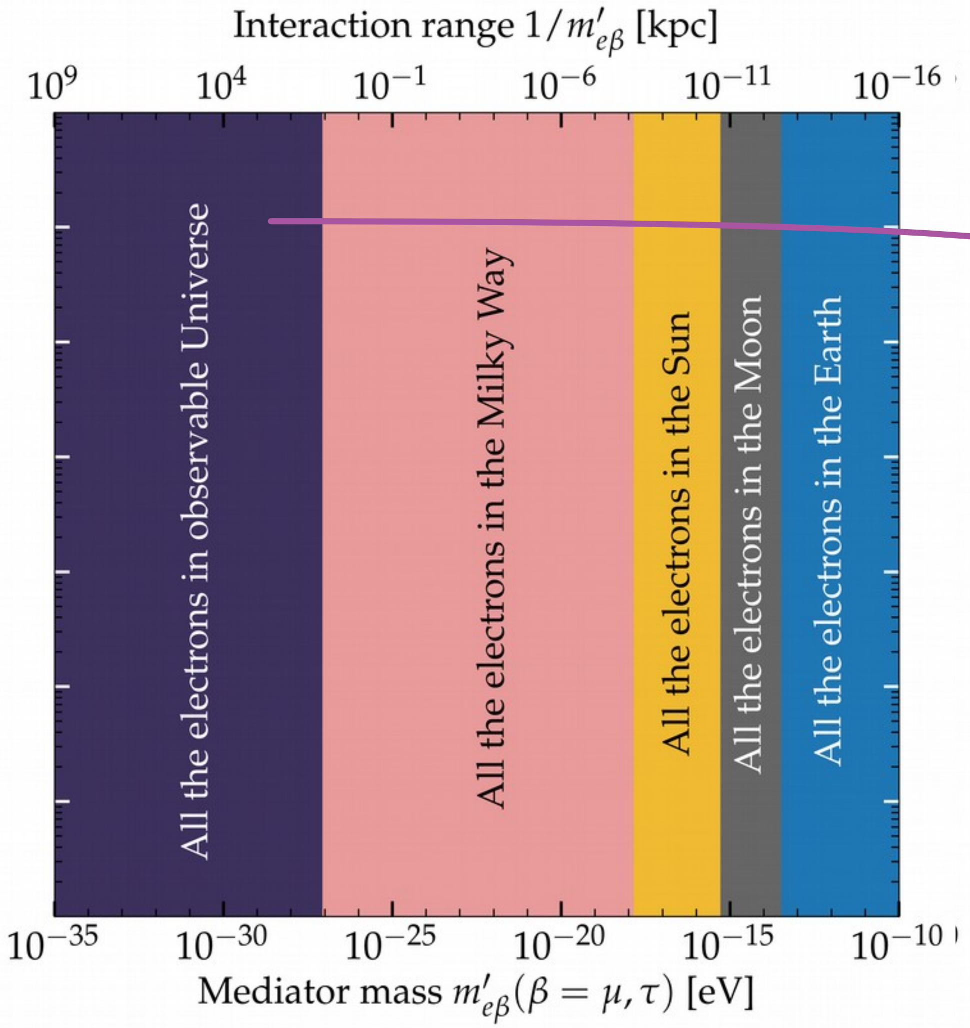
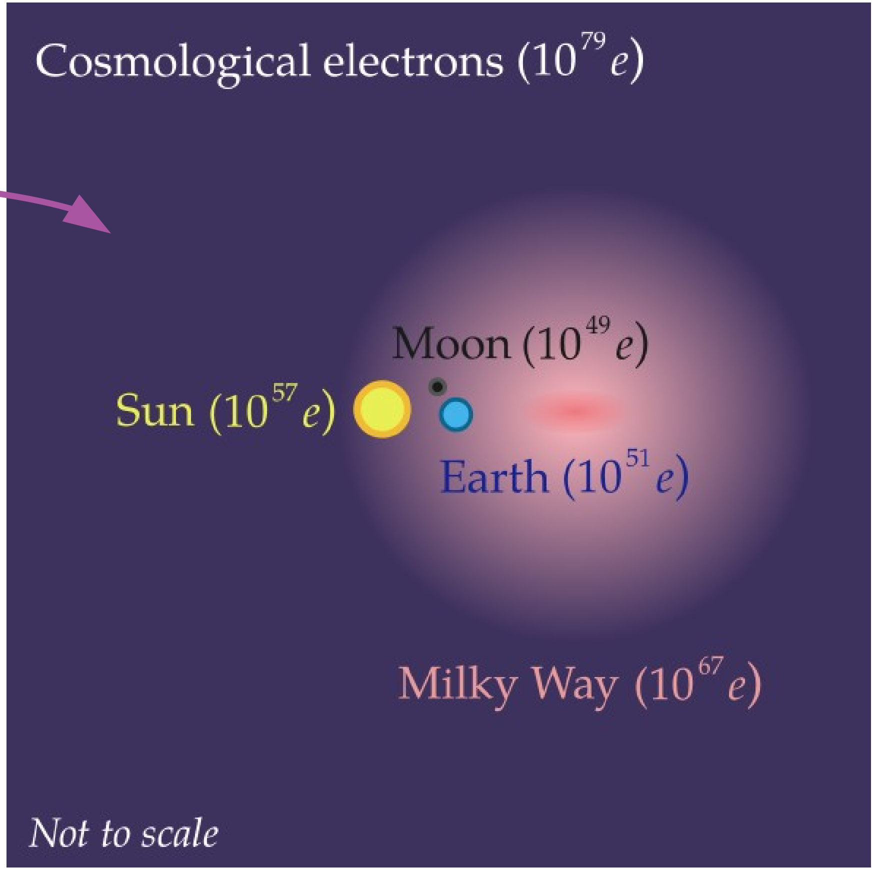




Electrons in the local and distant Universe





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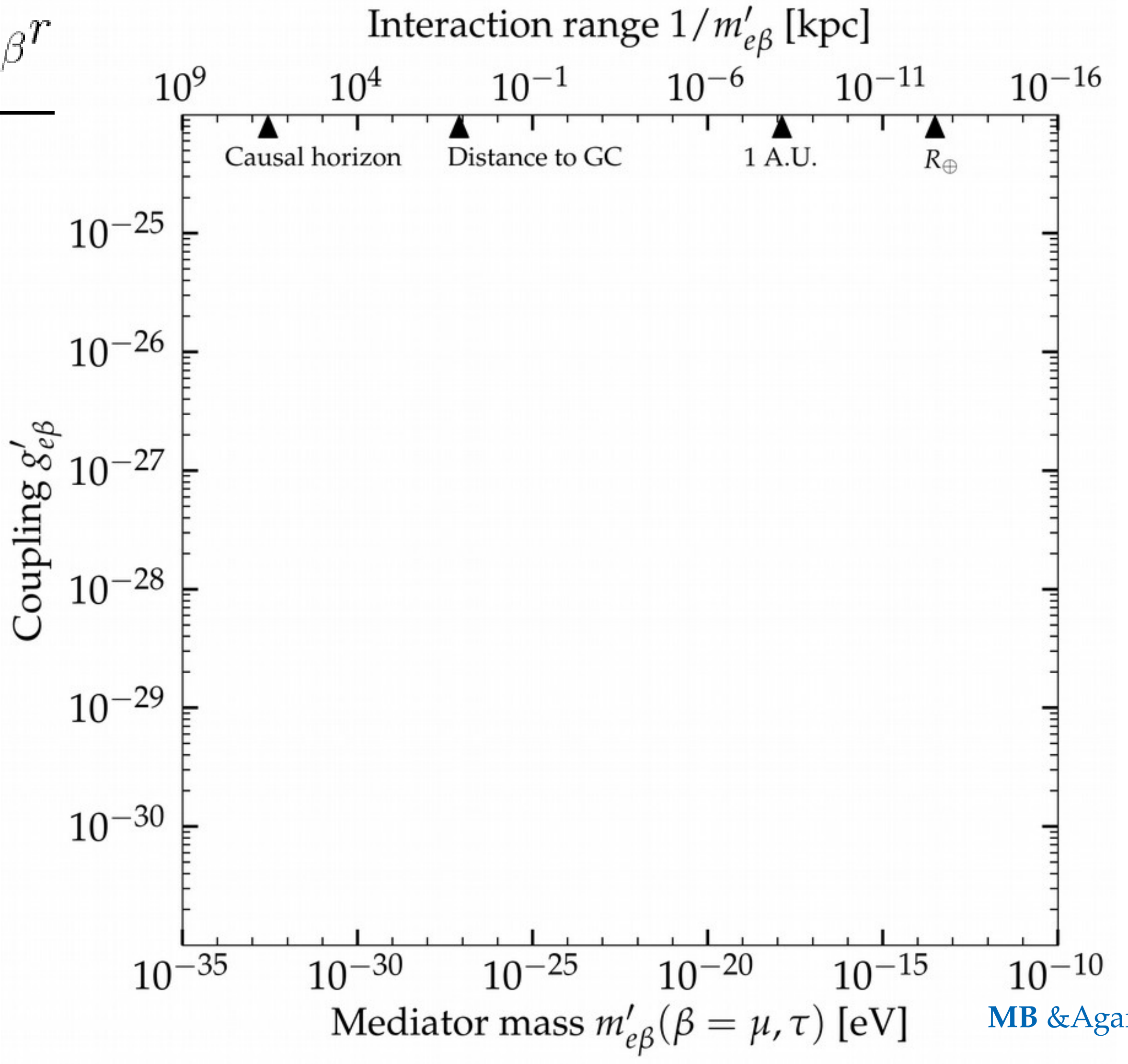

MB &Agarwalla, *PRL* 2019

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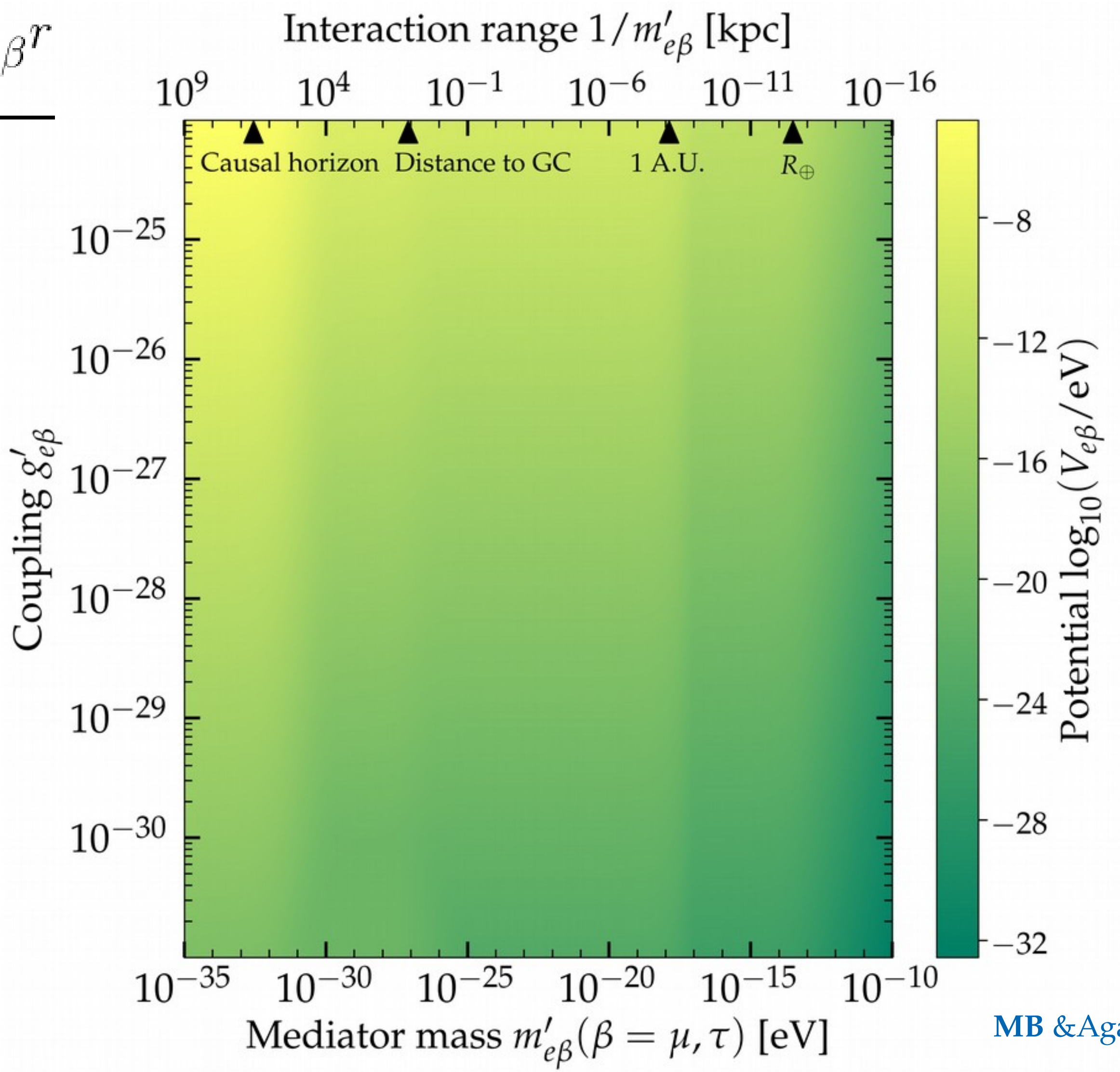
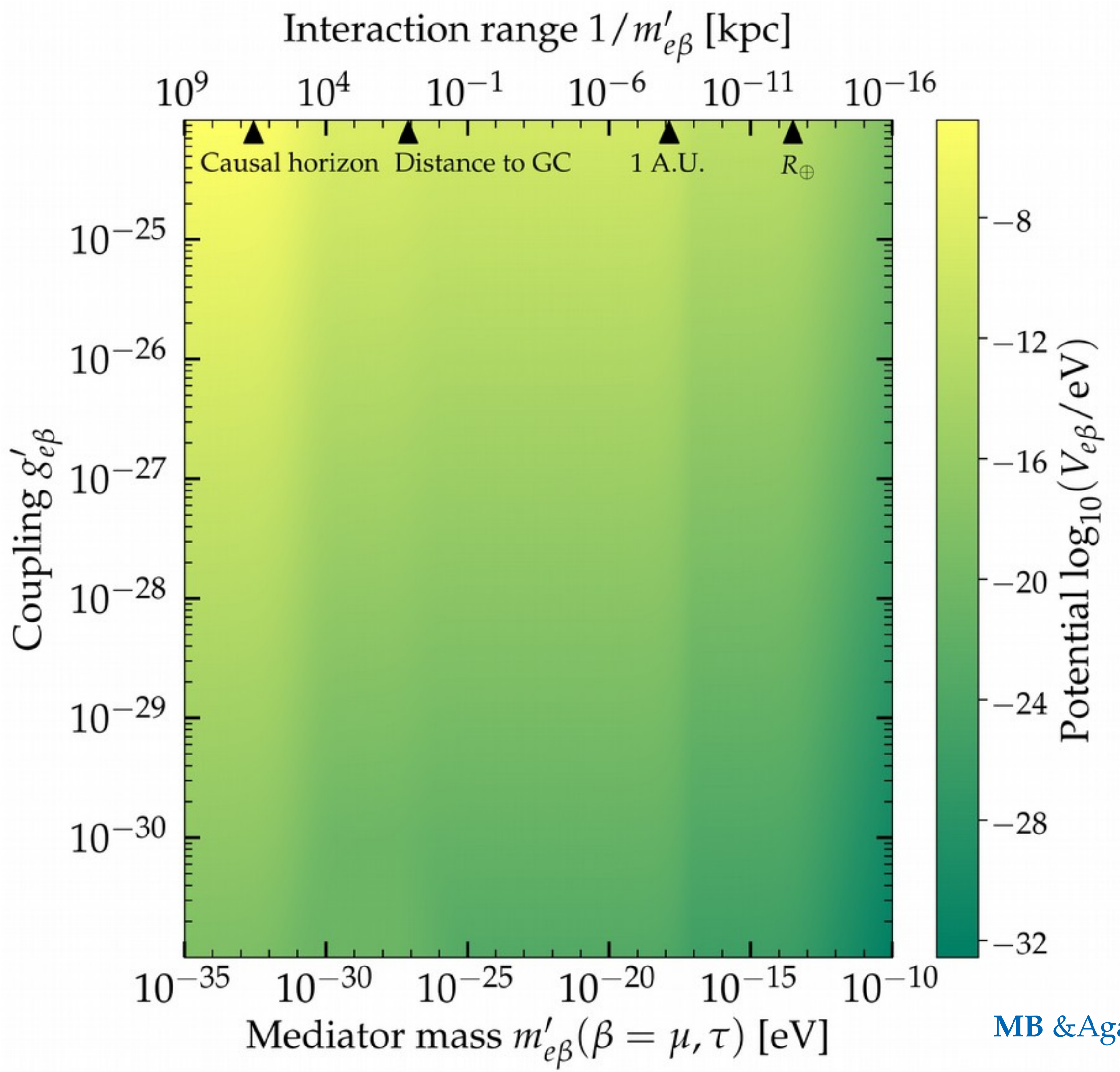


MB &Agarwalla, *PRL* 2019

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



MB &Agarwalla, *PRL* 2019

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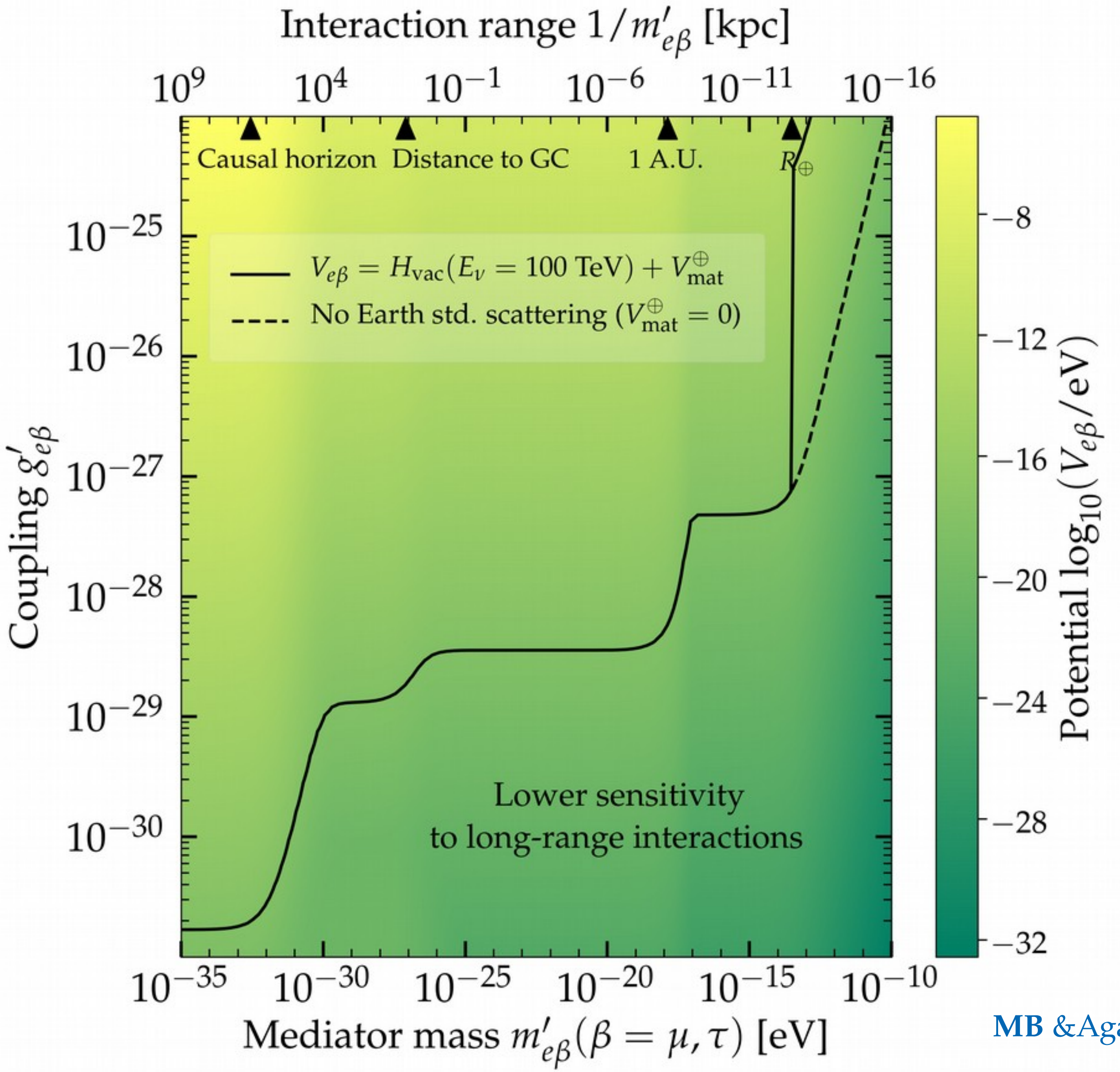
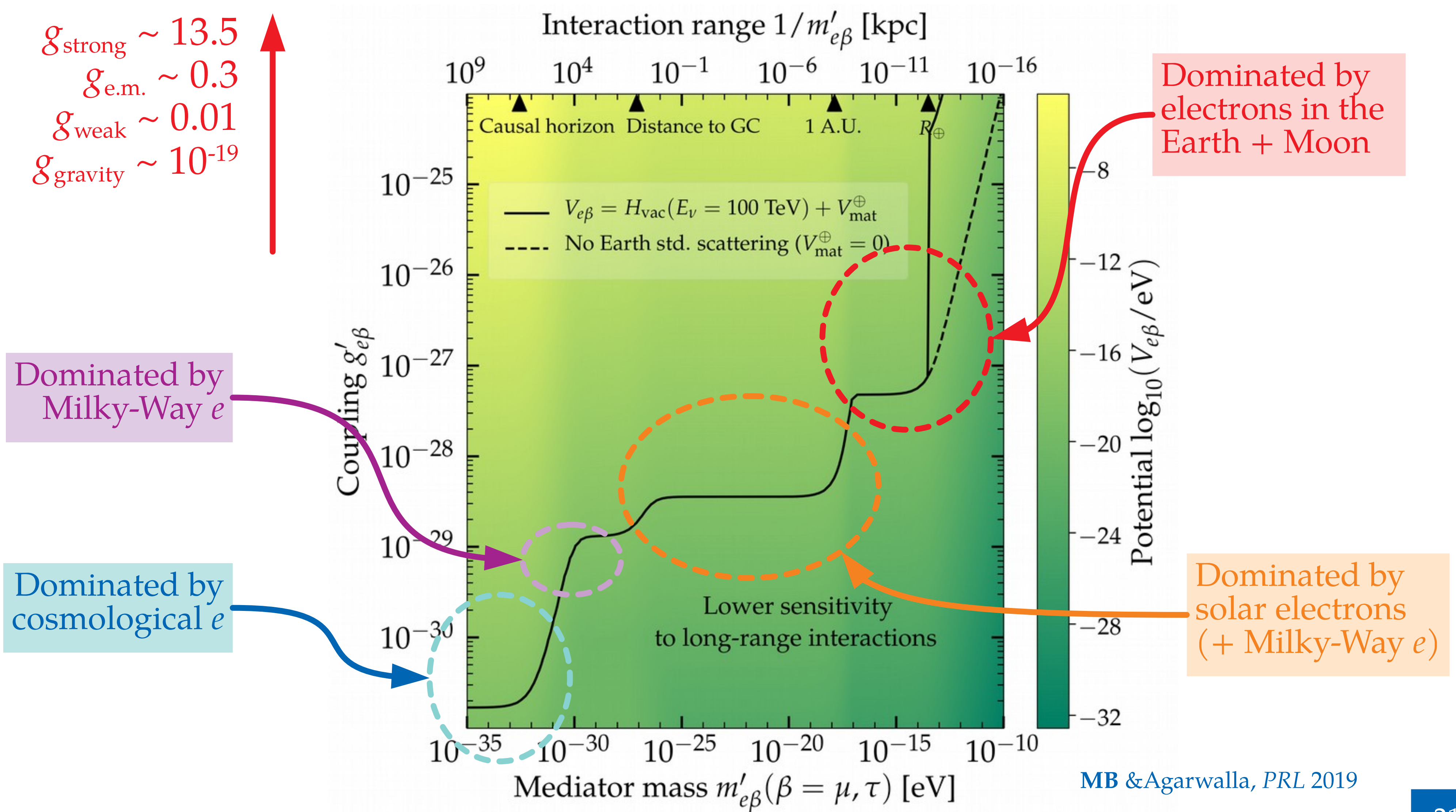
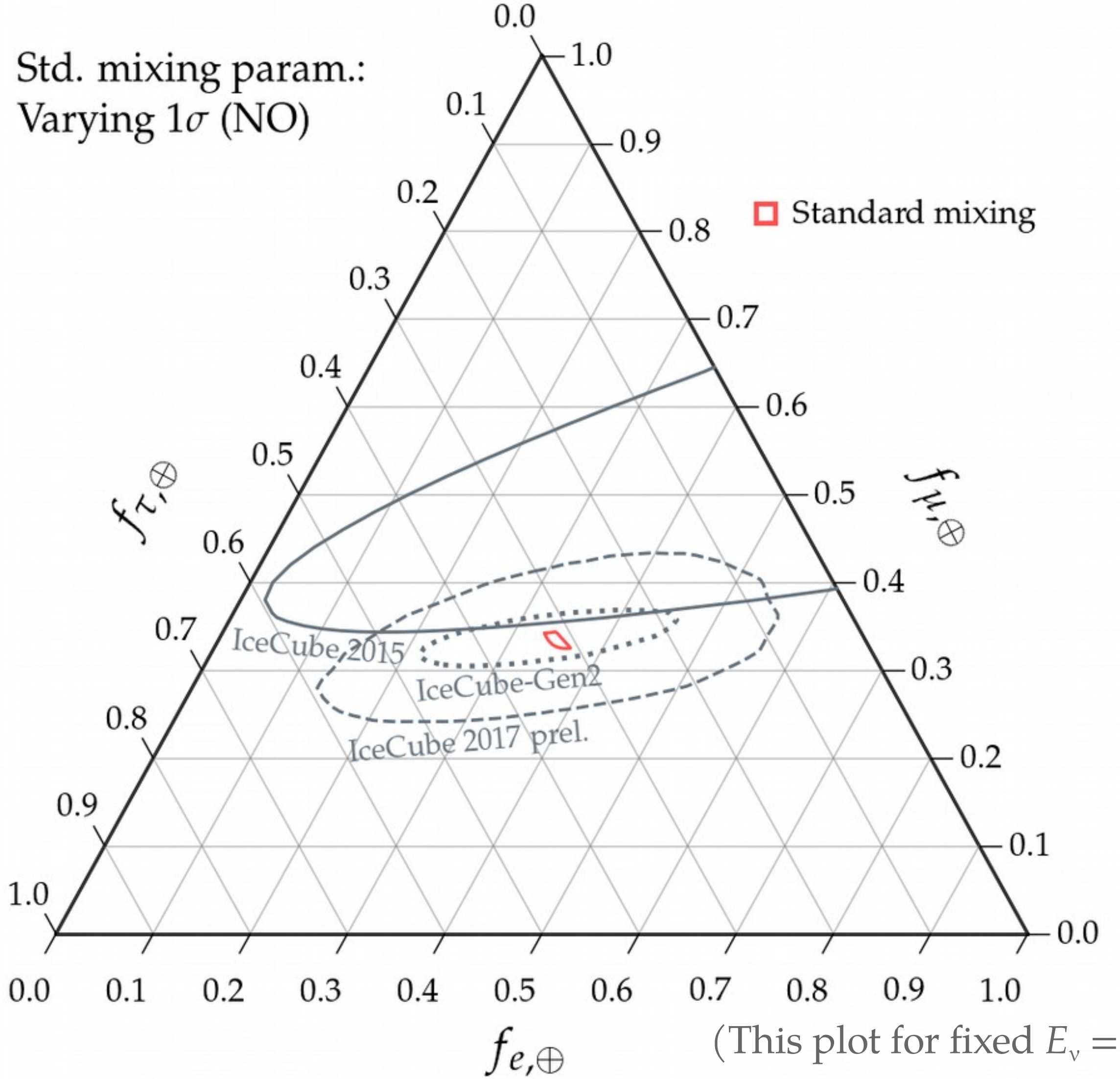


MB &Agarwalla, *PRL* 2019

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

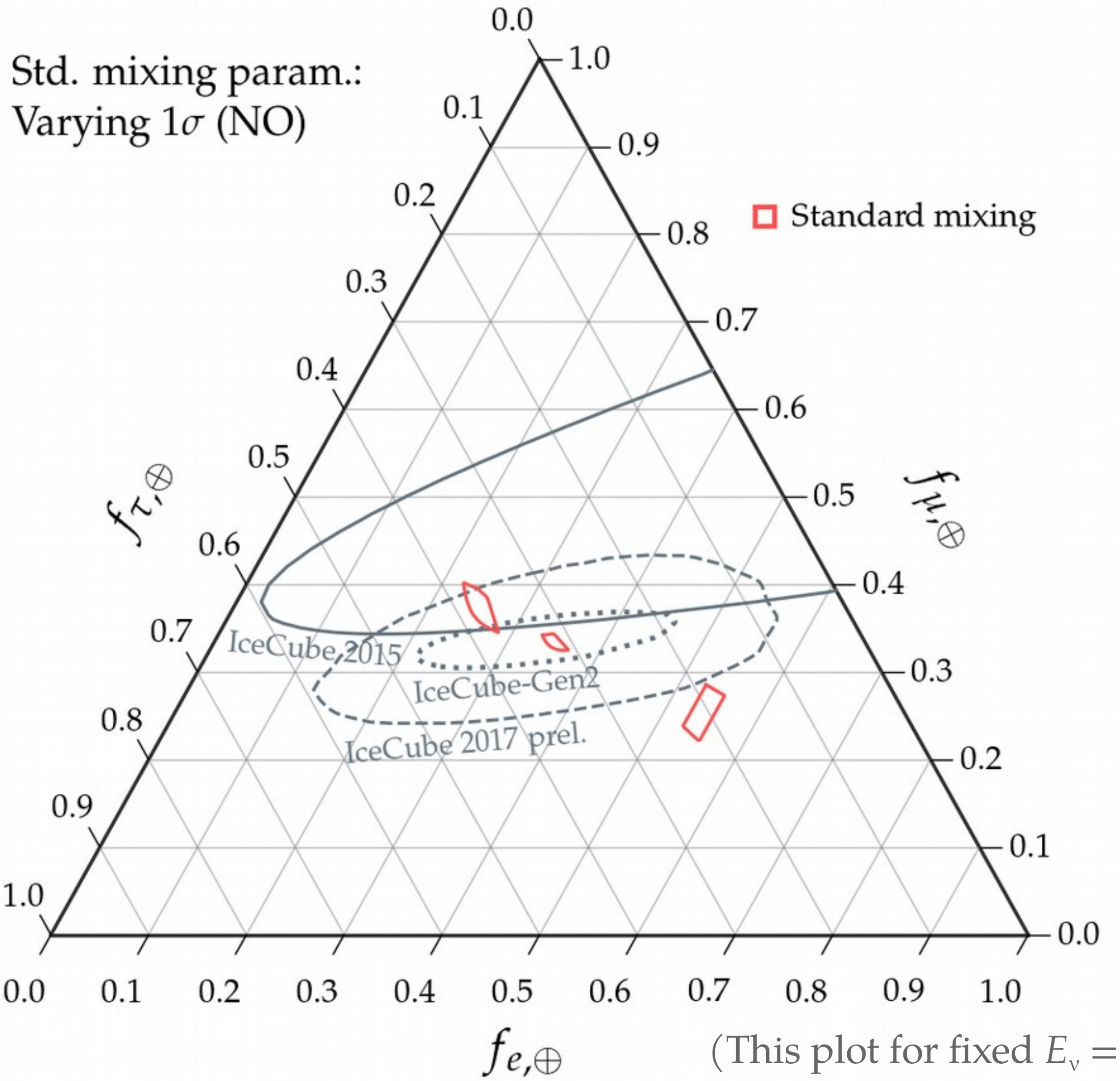


MB &Agarwalla, *PRL* 2019



MB & Agarwalla, *PRL* 2019

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



MB & Agarwalla, *PRL* 2019

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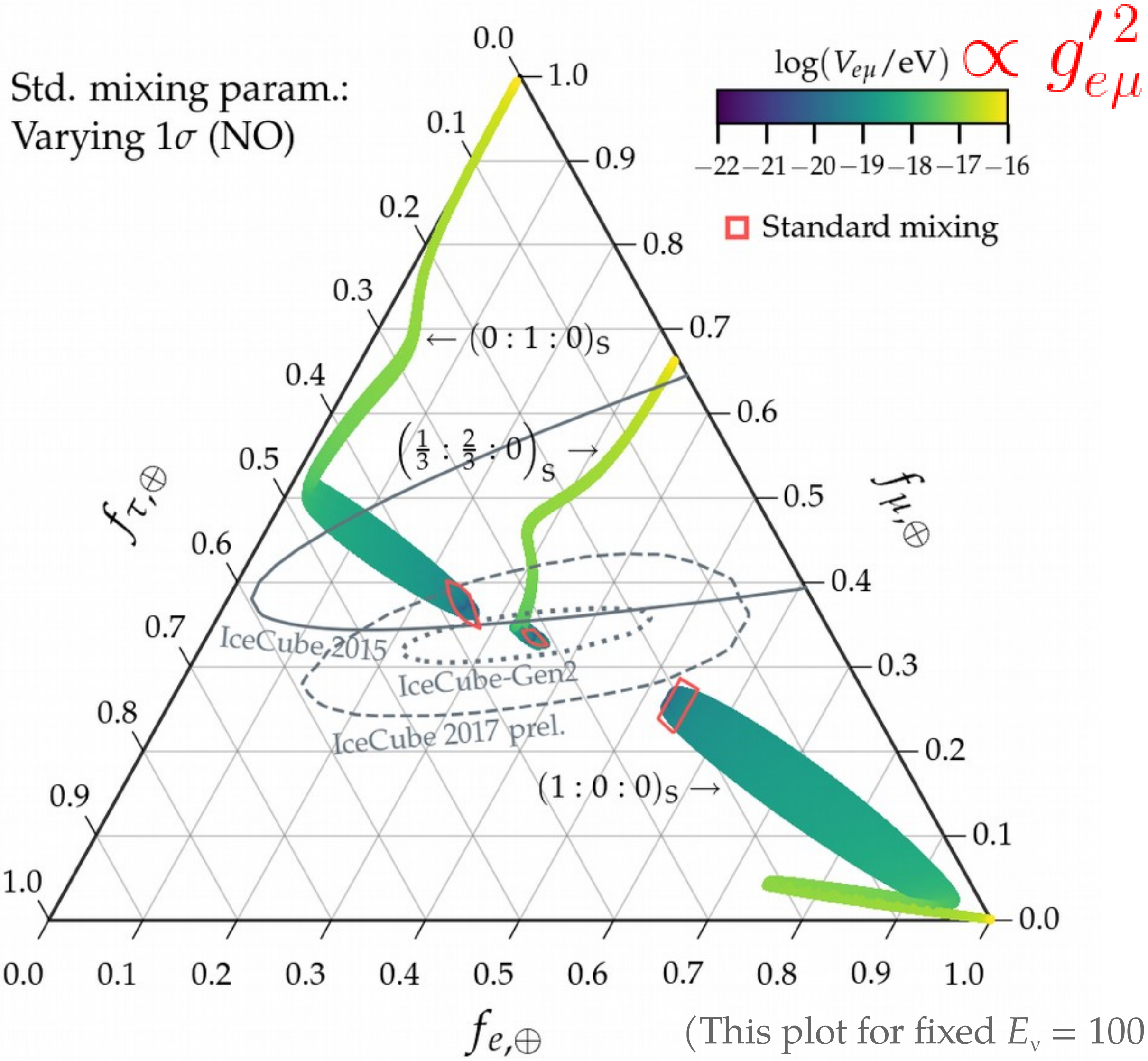

MB & Agarwalla, *PRL* 2019

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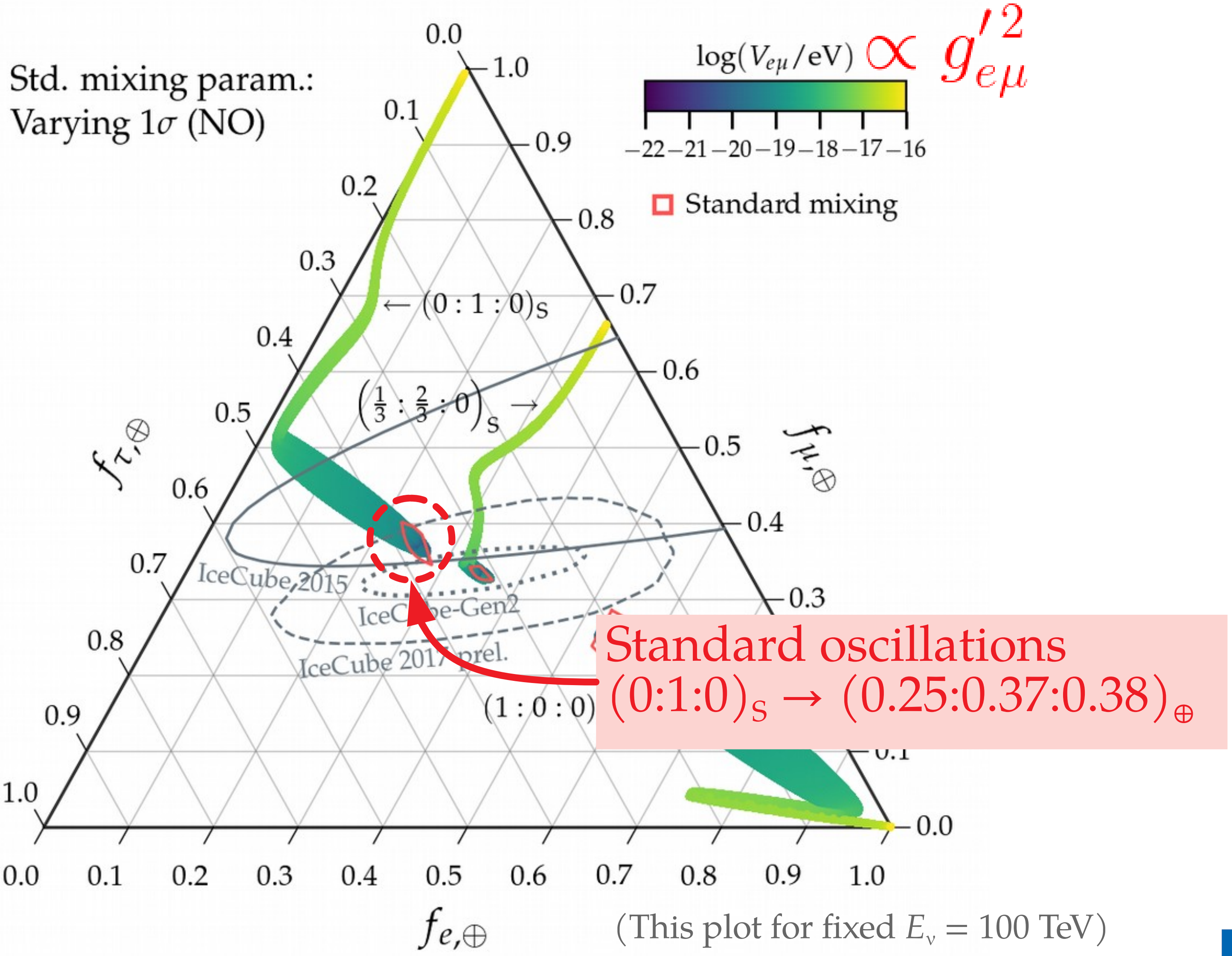
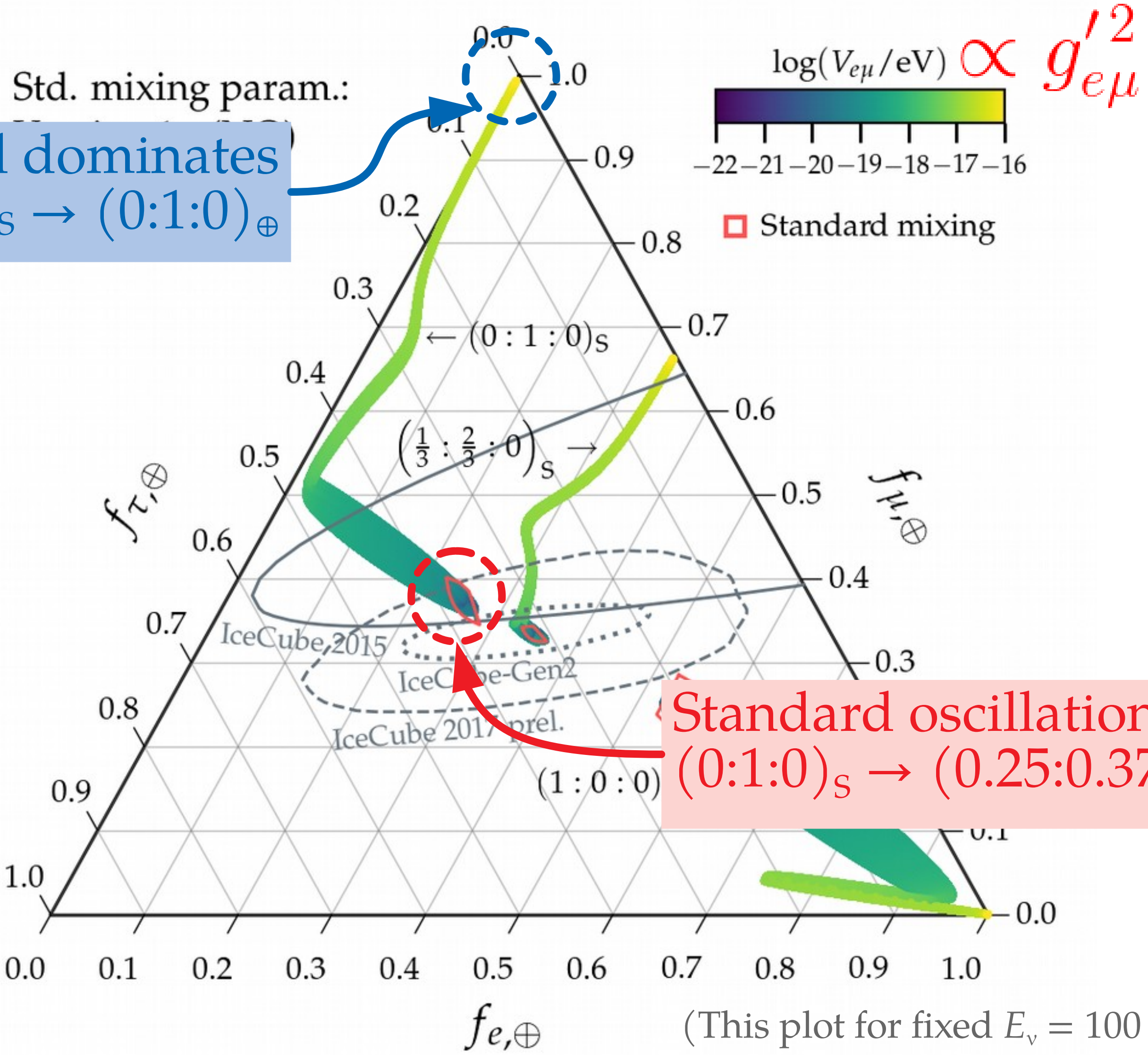


MB & Agarwalla, *PRL* 2019

(This plot for fixed E_ν = 100 TeV)

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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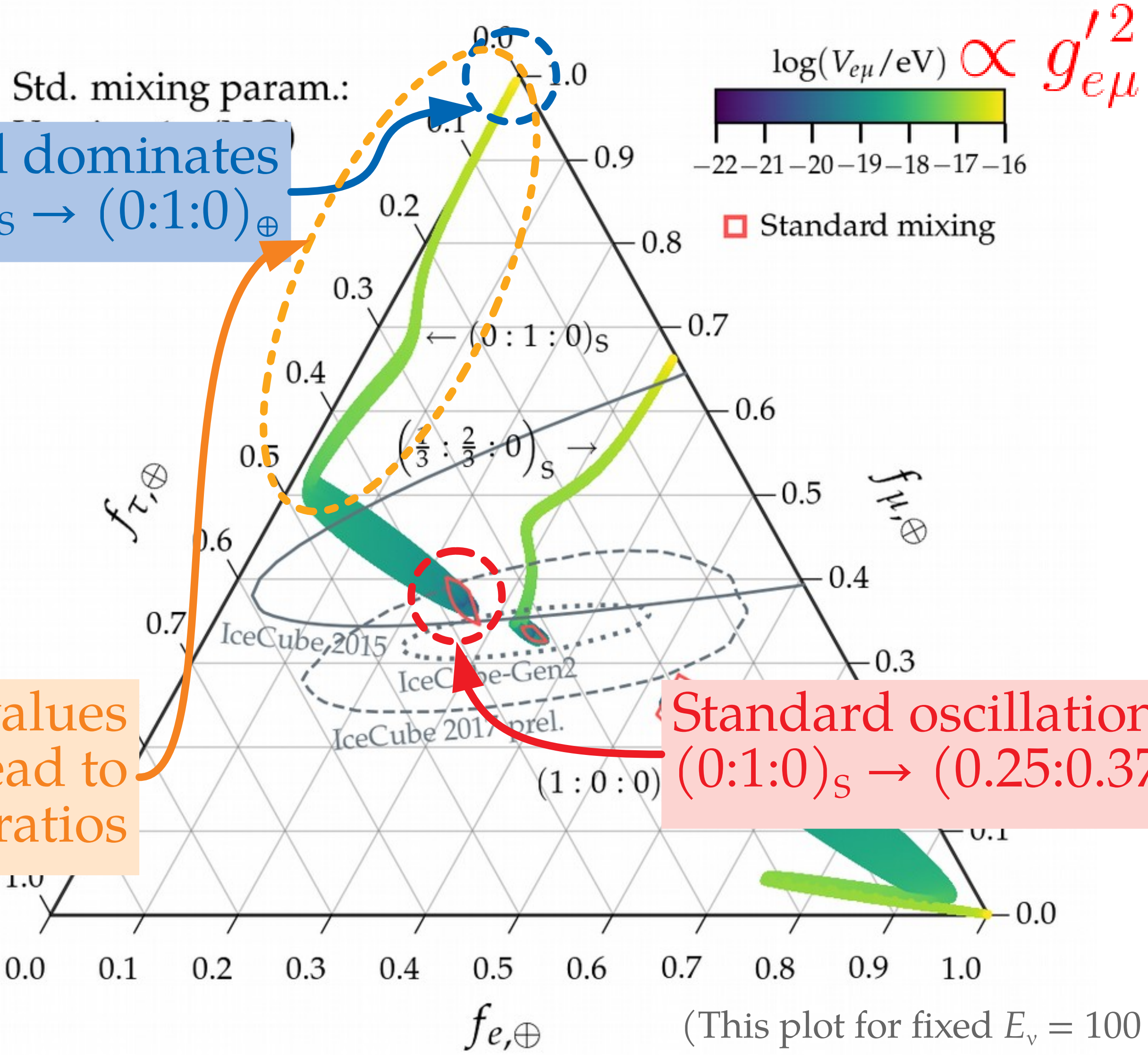

New potential dominates
$(0{:}1{:}0)_S \rightarrow (0{:}1{:}0)_\oplus$

We can disfavor all values of m' and g' that lead to these flavor ratios

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

MB & Agarwalla, *PRL* 2019

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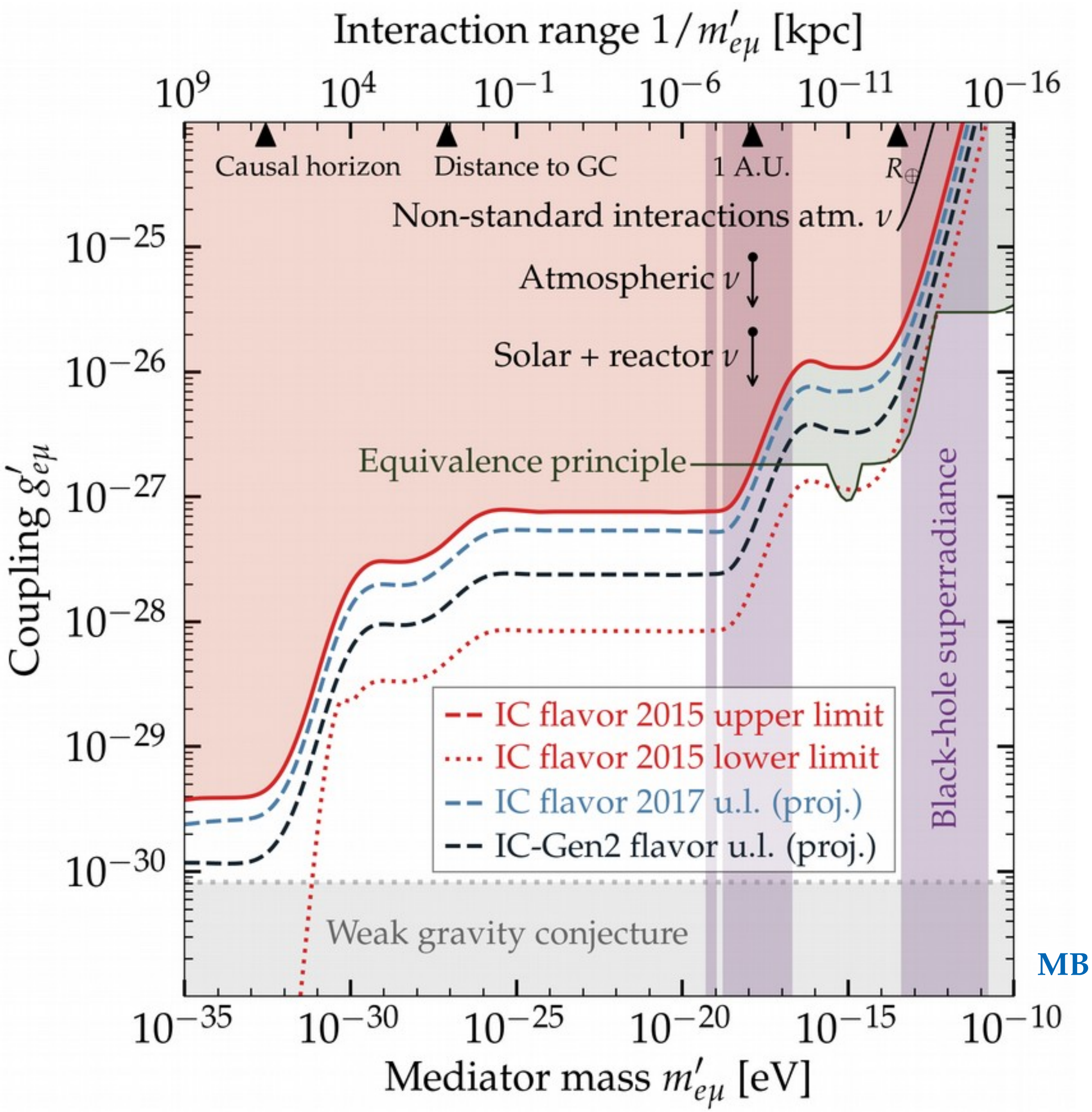


MB &Agarwalla, *PRL* 2019

New physics – High-energy effects

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

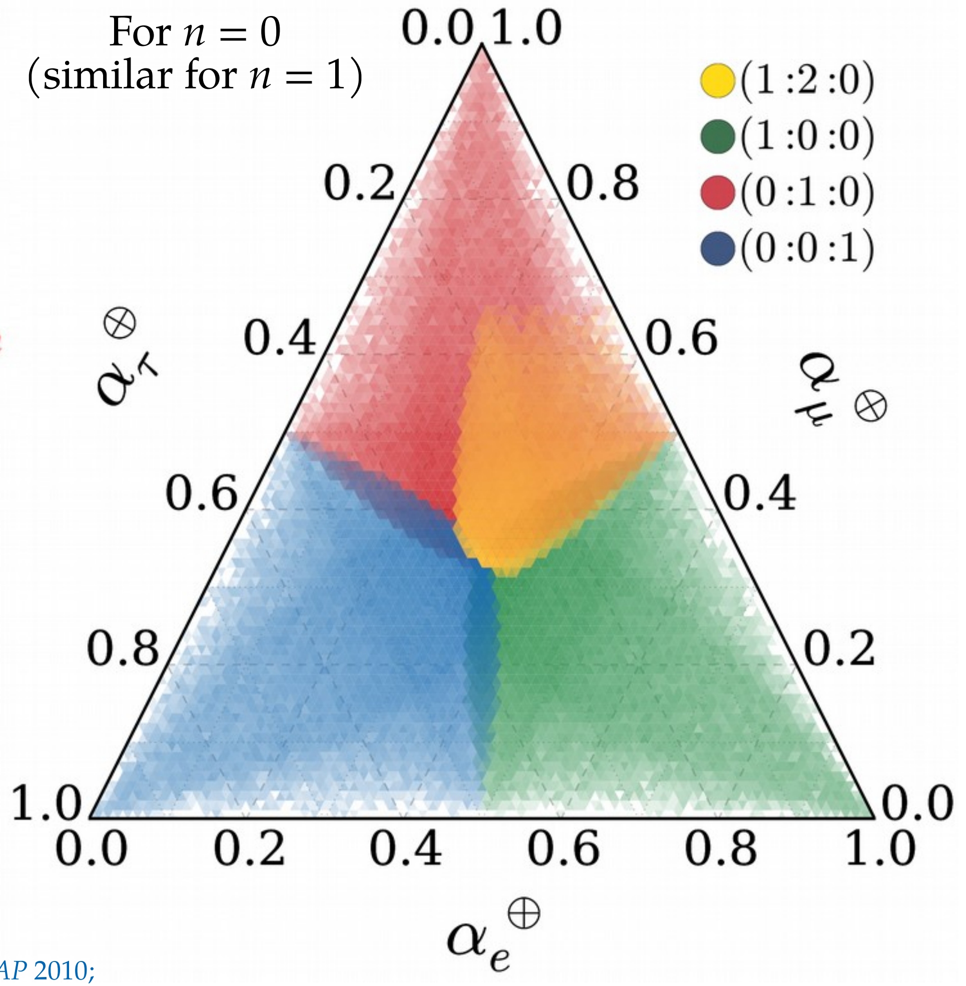
$$H_{\text{std}} = \frac{1}{2E} U^\dagger_{\text{PMNS}} \, \text{diag}\left(0, \Delta m^2_{21}, \Delta m^2_{31}\right) U_{\text{PMNS}}$$

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

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

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



Argüelles, Katori, Salvadó, *PRL* 2015

See also: 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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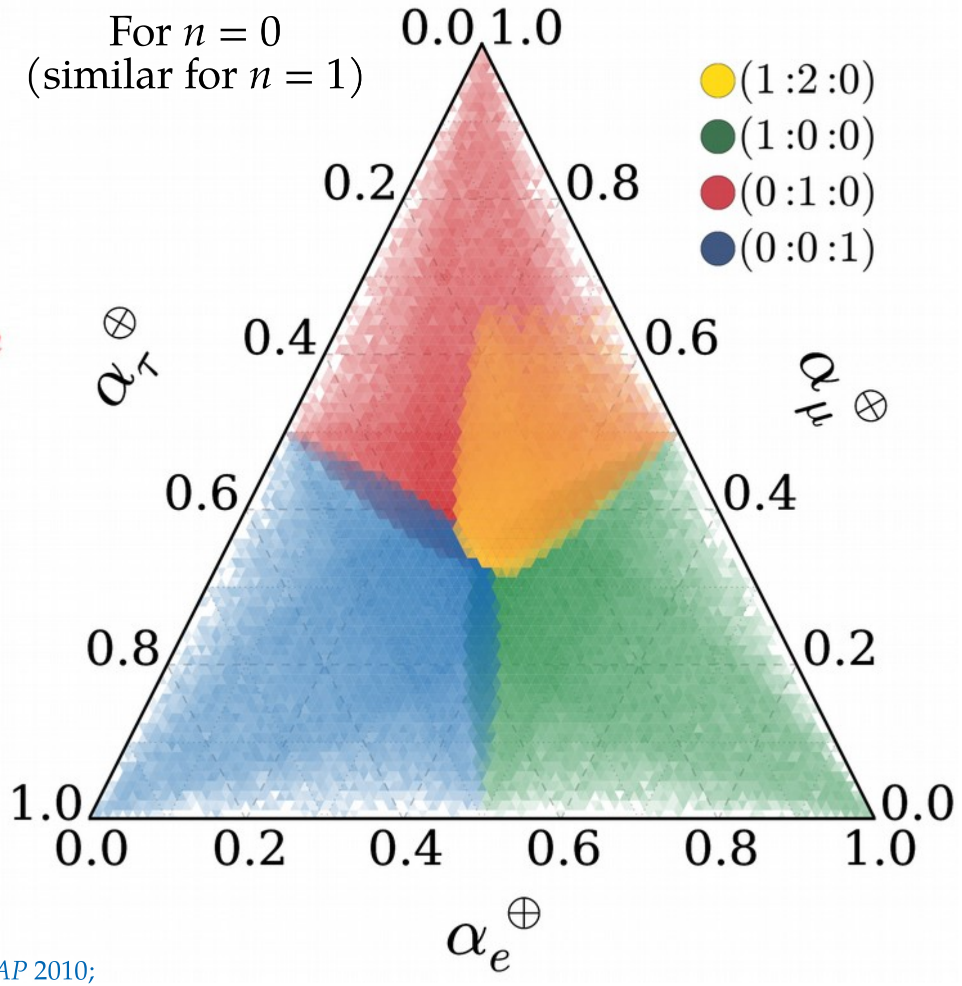

Argüelles, Katori, Salvadó, *PRL* 2015

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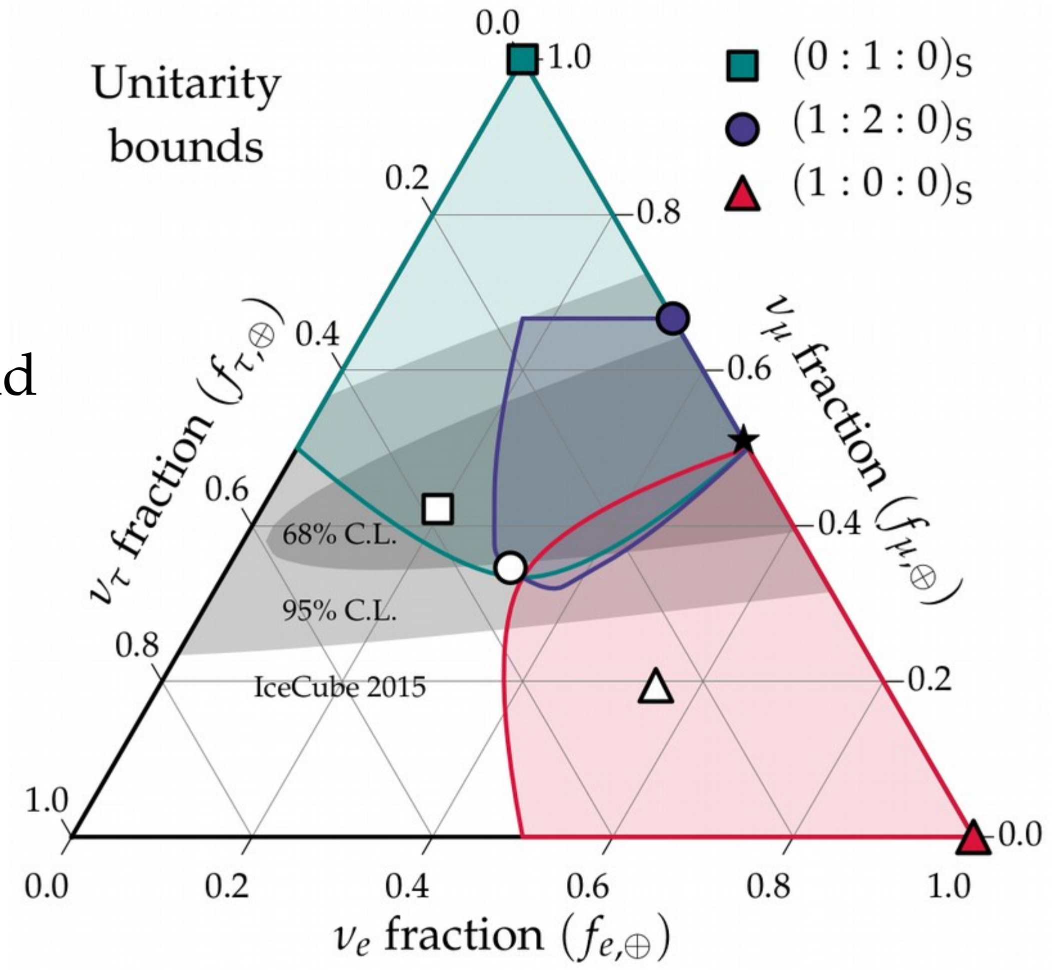
Bazo, **MB**, Gago, Miranda *IJMPA* 2009; + many others

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

Final thoughts

- Flavor has a vast potential to test astrophysics and particle physics
- We can tap into this potential *already today*
- Where should we go as a community?
  - Move beyond the simplest flavor-ratio fits (*i.e.*, include flavor ID, $\bar{\nu}/\nu$)
  - Include the uncertainties in mixing parameters in analyses – they matter
  - Experimental collaborations could provide the likelihood or posterior of $f_{\alpha,\oplus}$
  - Muon and neutron echoes in IC-Gen2: characterize afterpulsing in PMTs
  - Put serious thought into flavor measurements in non-optical Cherenkov detectors

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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High-energy neutrinos oscillate *fast*

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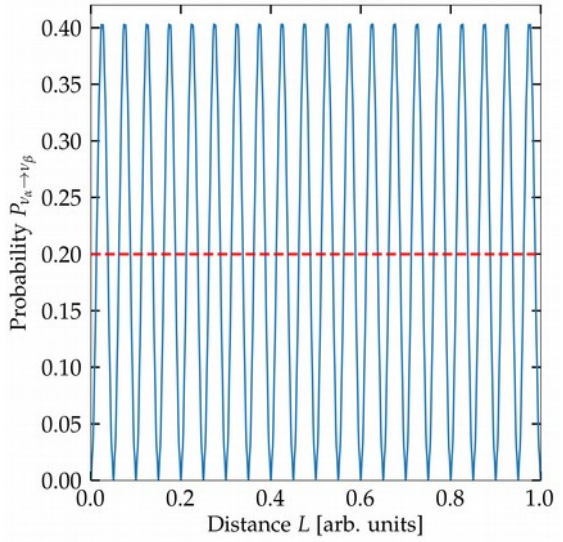

Oscillation length for 1-TeV ν: $2\pi \times 2E/\Delta m^2 \sim 0.1$ pc

$\sim$ 8% of the way to Proxima Centauri
$\ll$ Distance to Galactic Center (8 kpc)
$\ll$ Distance to Andromeda (1 Mpc)
$\ll$ Cosmological distances (few Gpc)

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

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

Mixing parameters
(NuFit 4.1, normal mass ordering):
$\theta_{23} \approx 48°$, $\theta_{13} \approx 9°$, $\theta_{12} \approx 34°$, $\delta \approx 222°$

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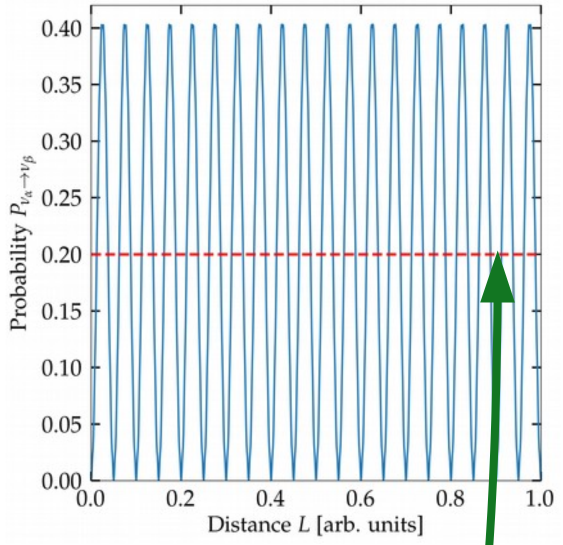

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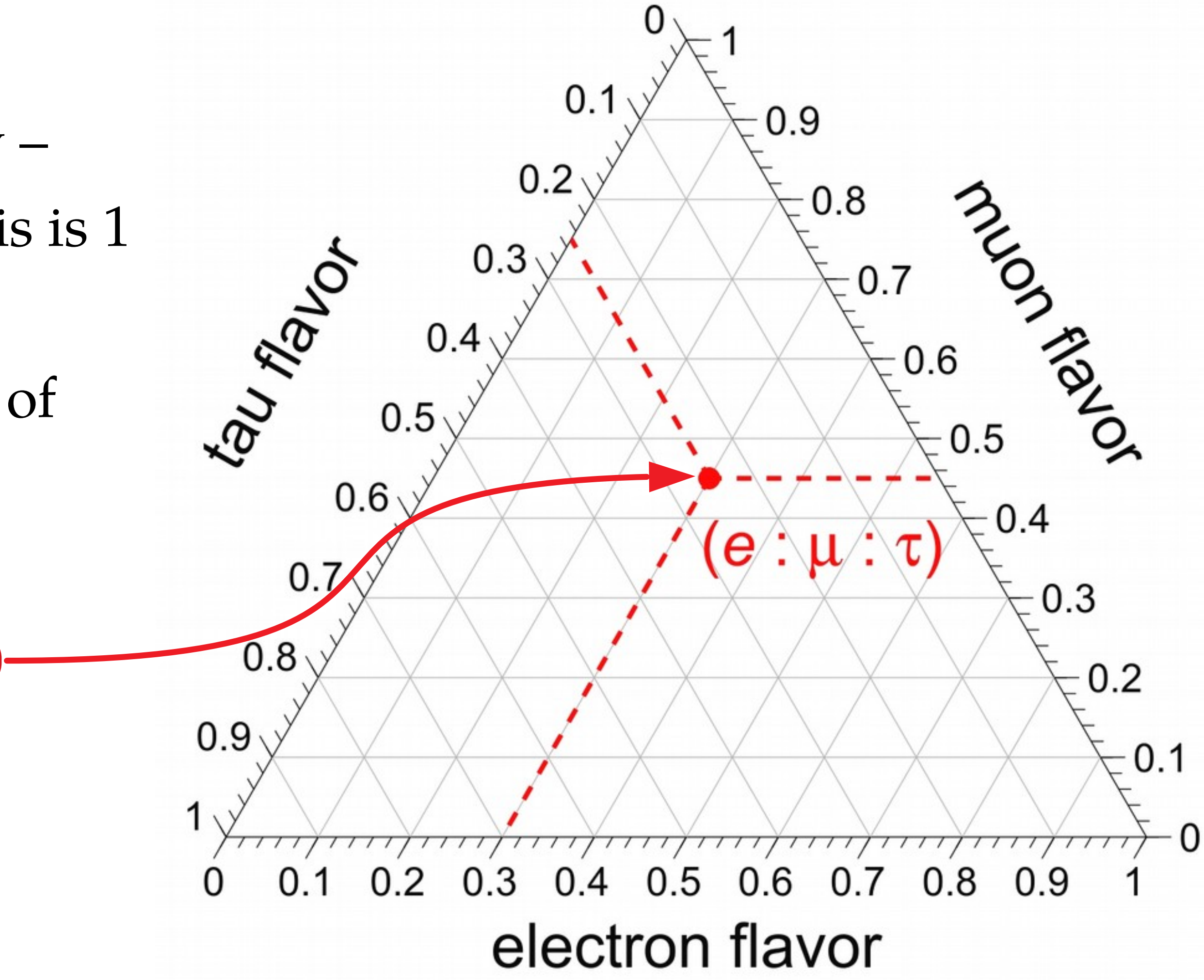
$\theta_{23} \approx 48°$, $\theta_{13} \approx 9°$, $\theta_{12} \approx 34°$, $\delta \approx 222°$

Reading 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, *e.g.*,

$(e{:}\mu{:}\tau) = (0.30{:}0.45{:}0.25)$



Flavor content of neutrino mass eigenstates

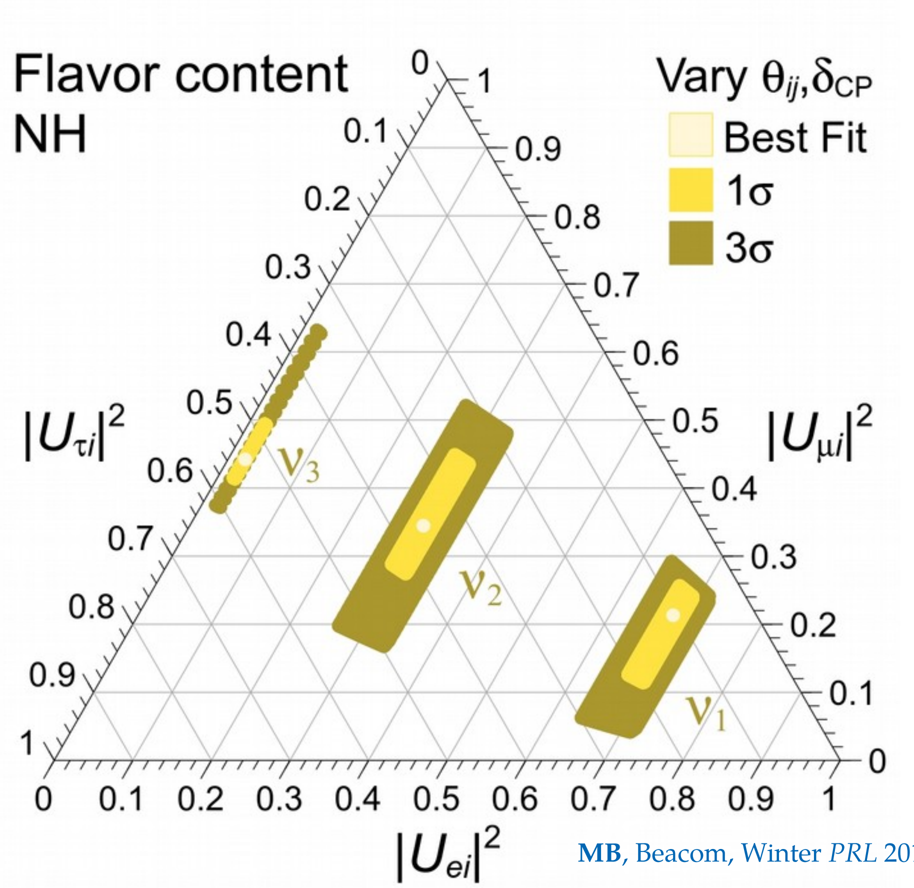
Flavor content for every allowed combination of mixing parameters –

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

Why are flavor ratios useful?

- The normalization of the flux is uncertain – but it cancels out in flavor ratios:

$$\alpha\text{-flavor ratio at Earth } (f_{\alpha,\oplus}) = \frac{\text{Flux at Earth of } \nu_\alpha \ (\alpha = e, \mu, \tau)}{\text{Sum of fluxes of all flavors}}$$

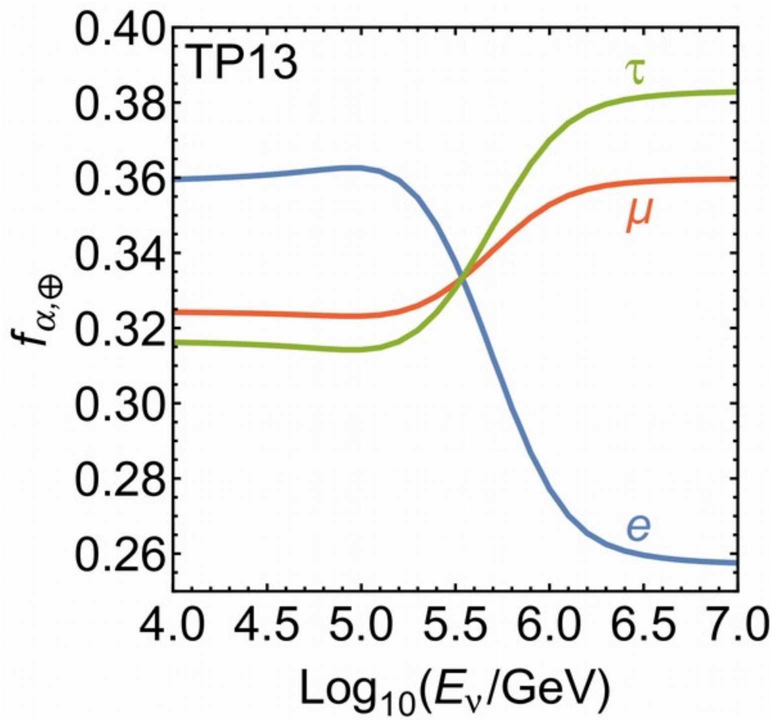
- Ratios remove systematic uncertainties common to all flavors

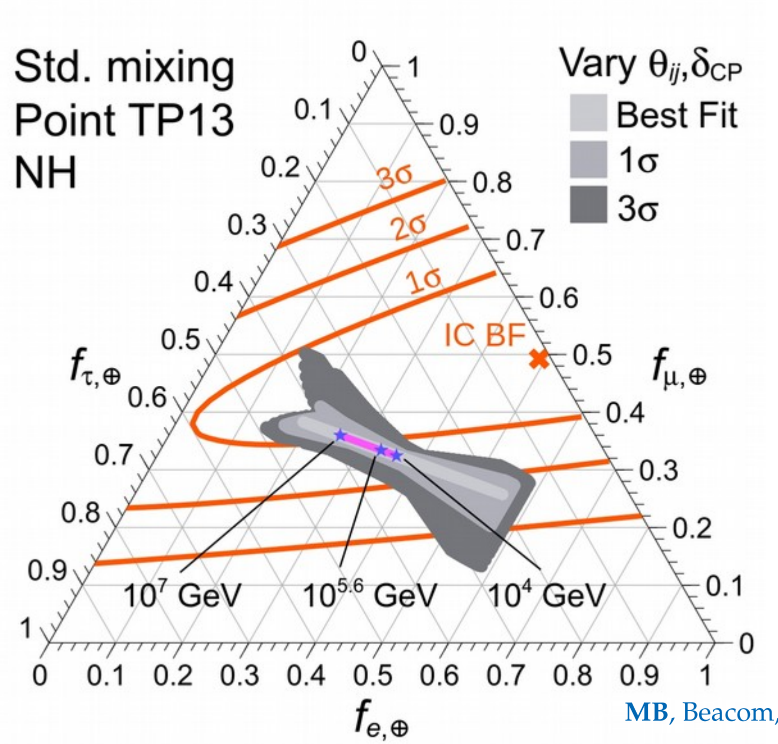
- Flavor ratios are useful in astrophysics and particle physics

Note: Ratios are for $\nu + \bar{\nu}$, since neutrino telescopes cannot tell them apart

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 electron-positron annihilation [Hümmer *et al.*, *Astropart. Phys.* 2010]
- Will be difficult to resolve [Kashti, Waxman, *PRL* 2005; Lipari, Lusignoli, Meloni, *PRD* 2007]

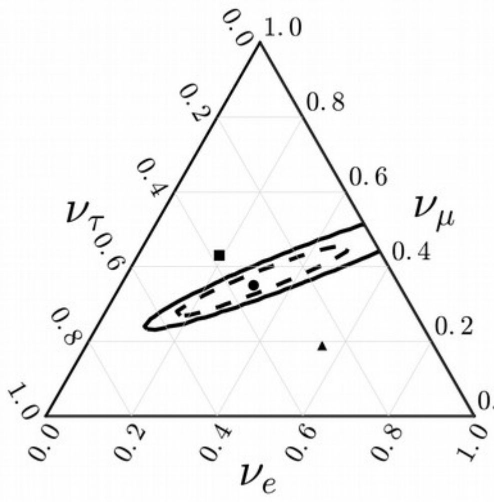
... Observable in IceCube-Gen2?

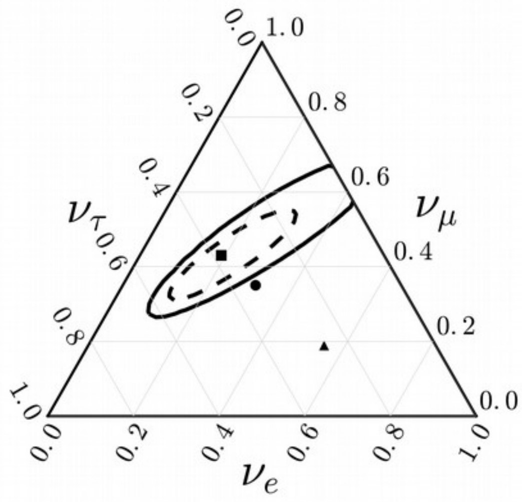
< PeV:
Full pion decay chain

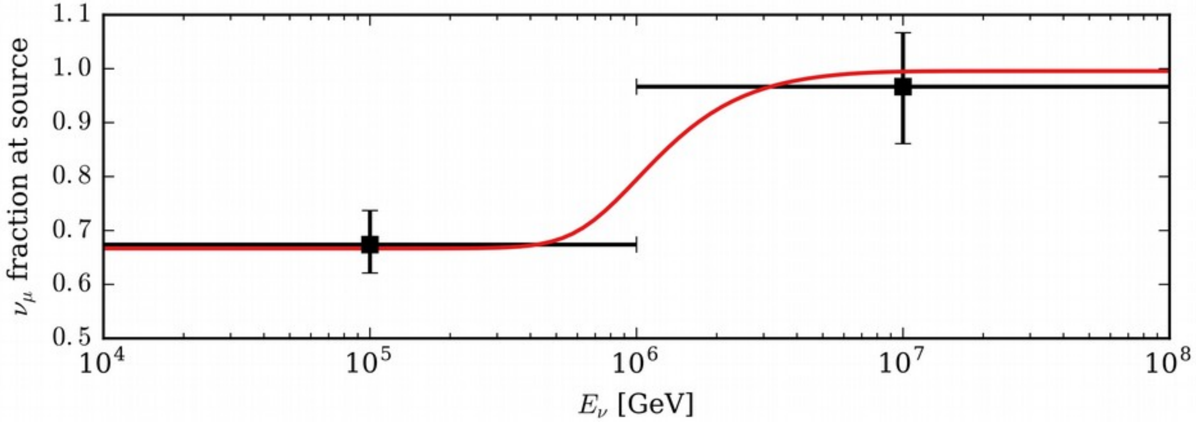
$(f_e : f_\mu : f_\tau)_\oplus \approx (1/3 : 1/3 : 1/3)$

> PeV:
Muon damping

$(f_e : f_\mu : f_\tau)_\oplus \approx (0.2 : 0.4 : 0.4)$







More detailed studies are required

Borrowed from J. van Santen & M. Kowalski

High-energy cosmic neutrinos made in neutron decays?

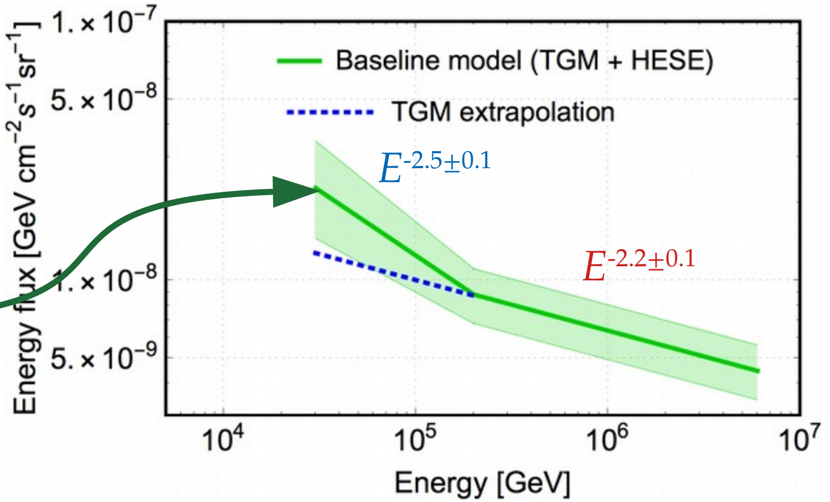
- Palladino, *EPJC* 2019
- Join the two IceCube spectrum fits:

  From HESE + through-going muons: $\Phi \propto E^{-2.5\pm0.1}$

  Use it between 30 and 200 TeV

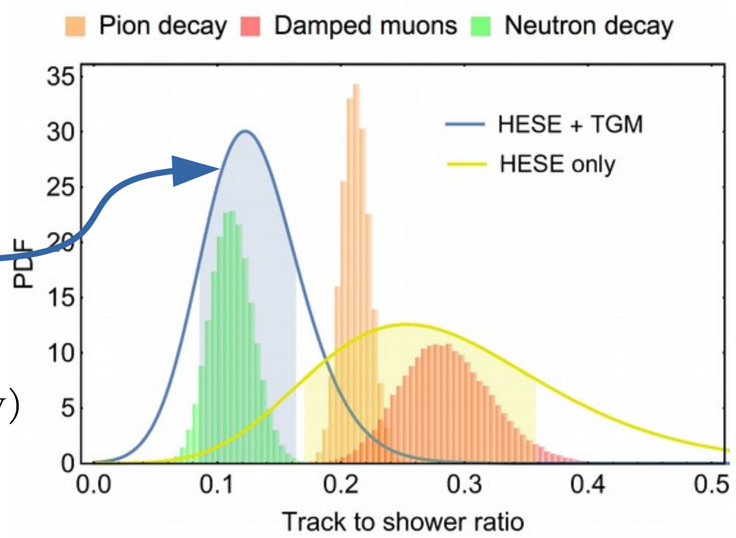
  From only through-going muons: $\Phi \propto E^{-2.2\pm0.1}$

  Use it above 200 TeV



- Pro: Through-going-muon spectrum has low atmospheric ν contamination
- Using the broken power law, compute track-to-shower ratio r ($\sim f_{\mu,\oplus}/f_{e,\oplus}$) of astrophysical ν in 7.5 yr of HESE

  Fit to HESE data favors high content of $\nu_e+\bar{\nu}_e$, like from neutron decay



- Main problem with this interpretation: the energy budget

  $\bar{\nu}_e$ from n decay gets 0.1% of the n energy (*vs.* 5% of the p energy in π decay)

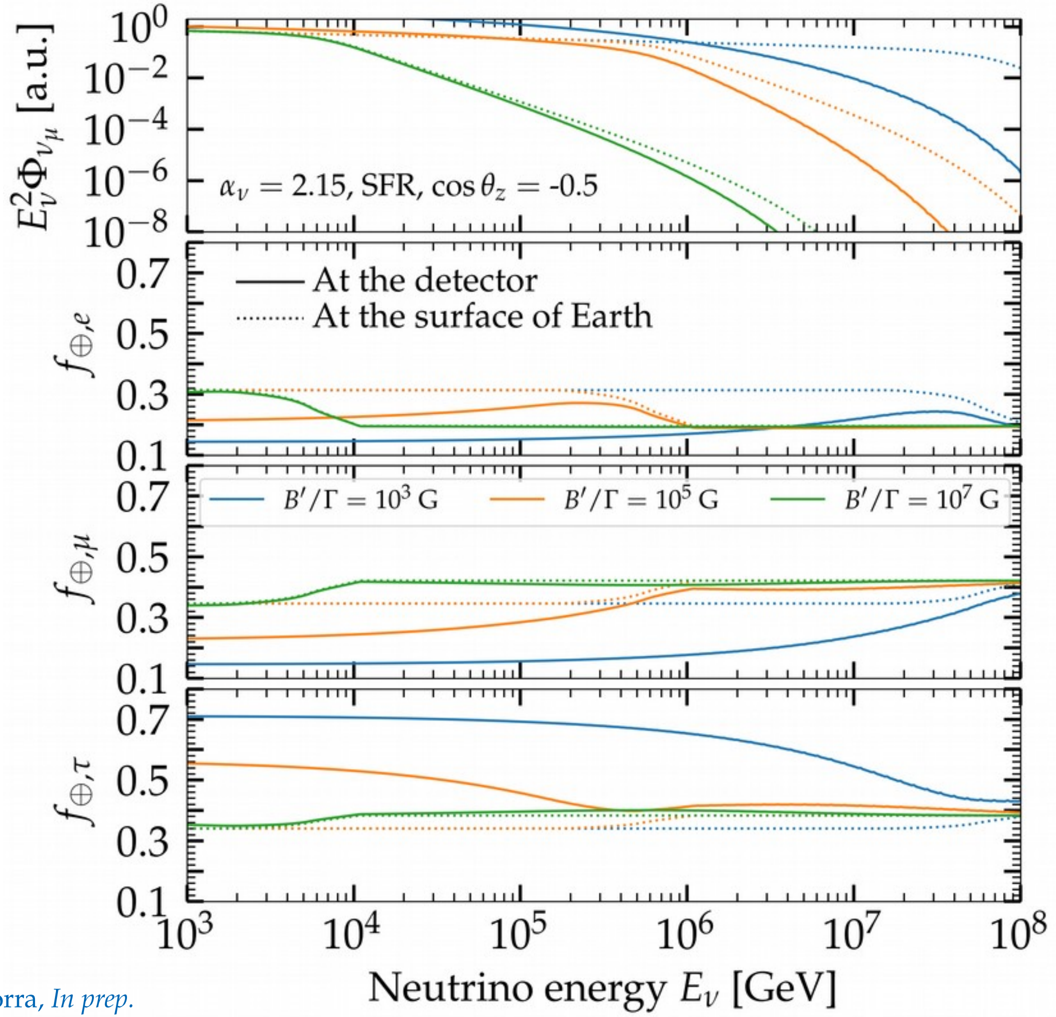
Extracting source properties using flavor

- Goal: Use the flavor composition (and spectrum) of the diffuse ν flux to extract the *average* magnetic strength B of the sources

- After synchrotron cooling sets in (at an energy ~$1/B$):
  - The spectrum steepens by E^{-2}
  - The flavor ratios change to $(0:1:0)_S$

- We propagate the fluxes coming from each direction inside the Earth to the detector (with NuSQuIDS):
  - Charged-current νN interactions deplete the flux
  - Neutral-current νN interactions pile-up low energy ν
  - ν_τ regeneration computed

- The arrival direction matters!



MB & Tamborra, *In prep.*

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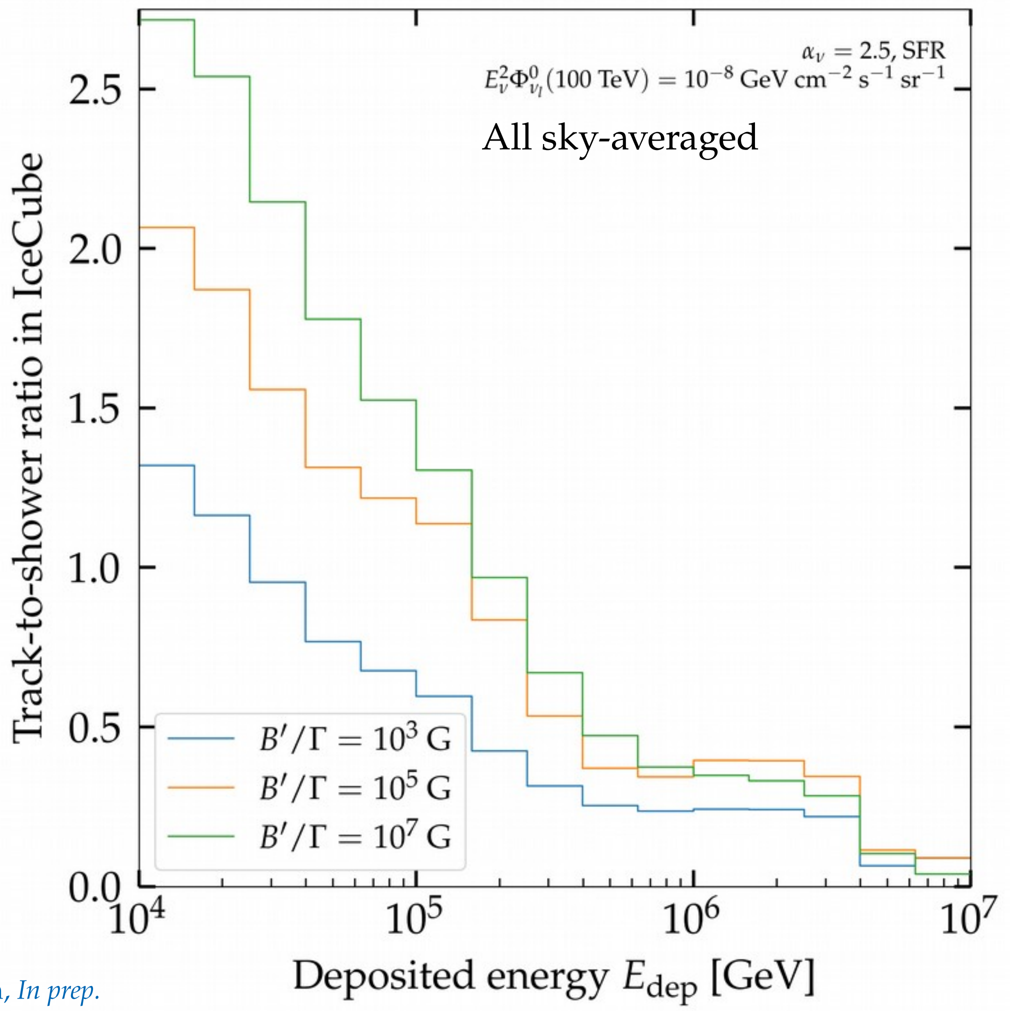
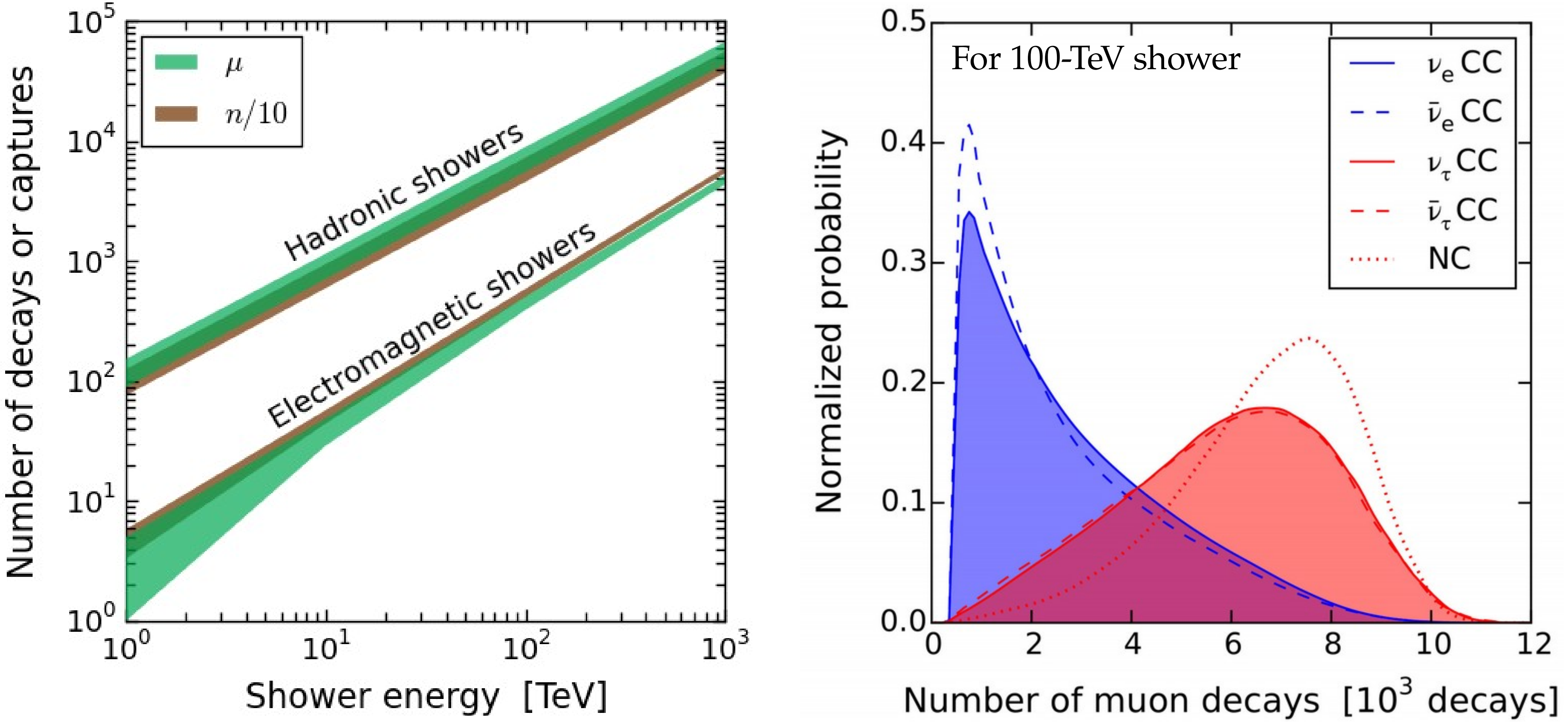


MB & Tamborra, *In prep.*

The low-energy behavior of high-energy showers

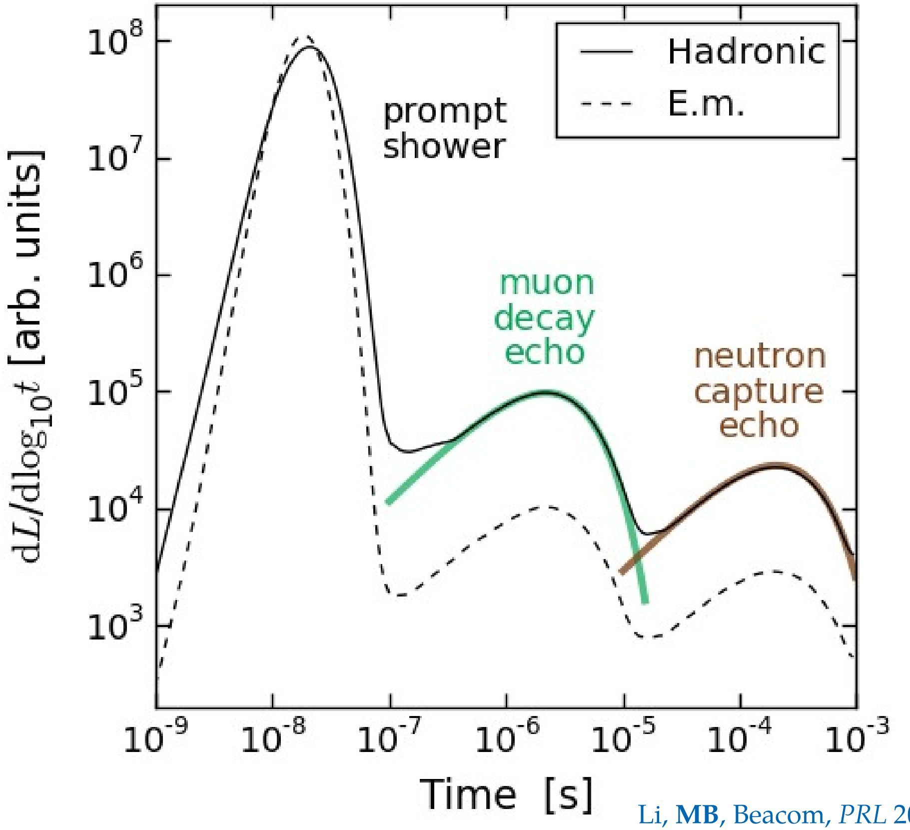


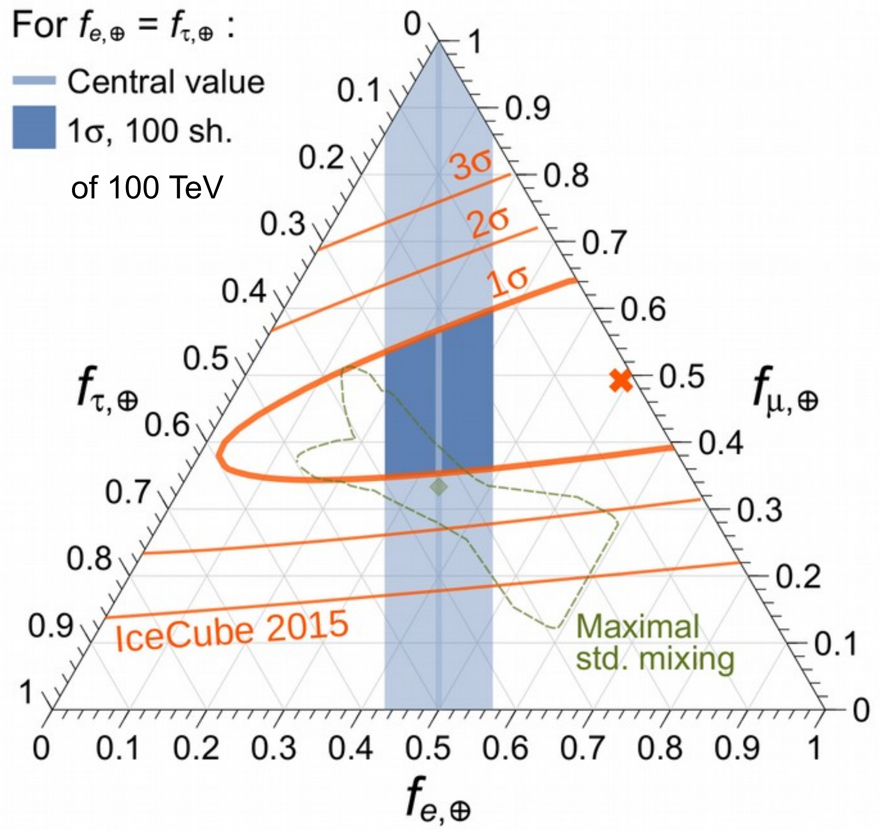
Li, **MB**, Beacom, *PRL* 2019

(Results based on FLUKA simulations)

Improving flavor-tagging using light 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
Preliminary IceCube results: A. Steuer & L. Köpke, ICRC 2017

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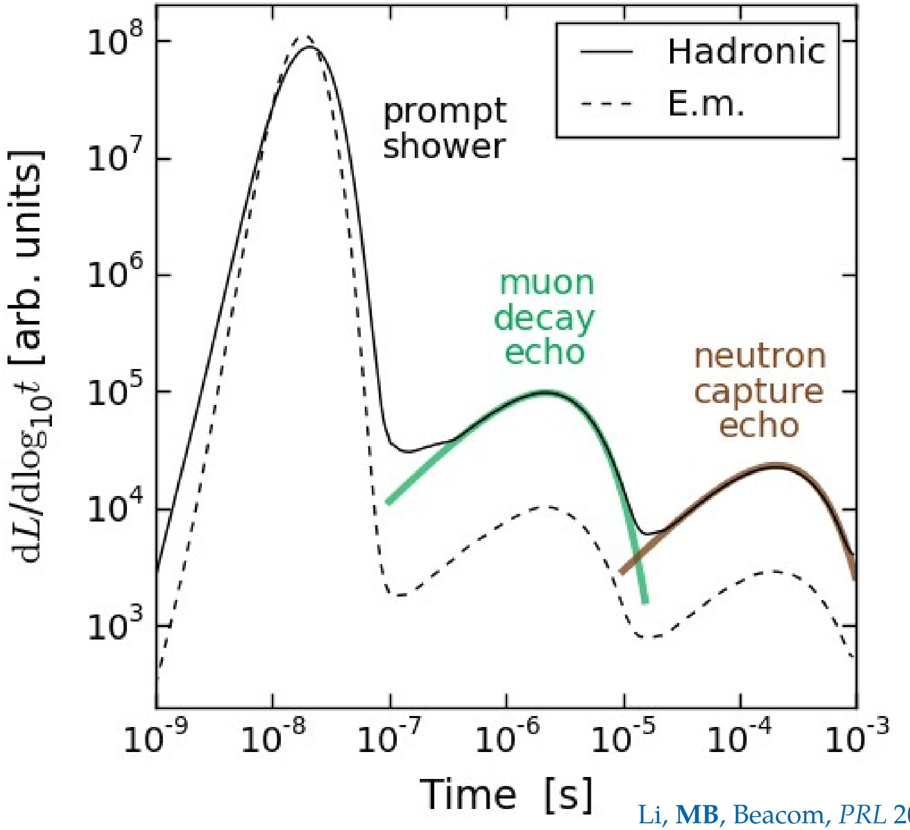

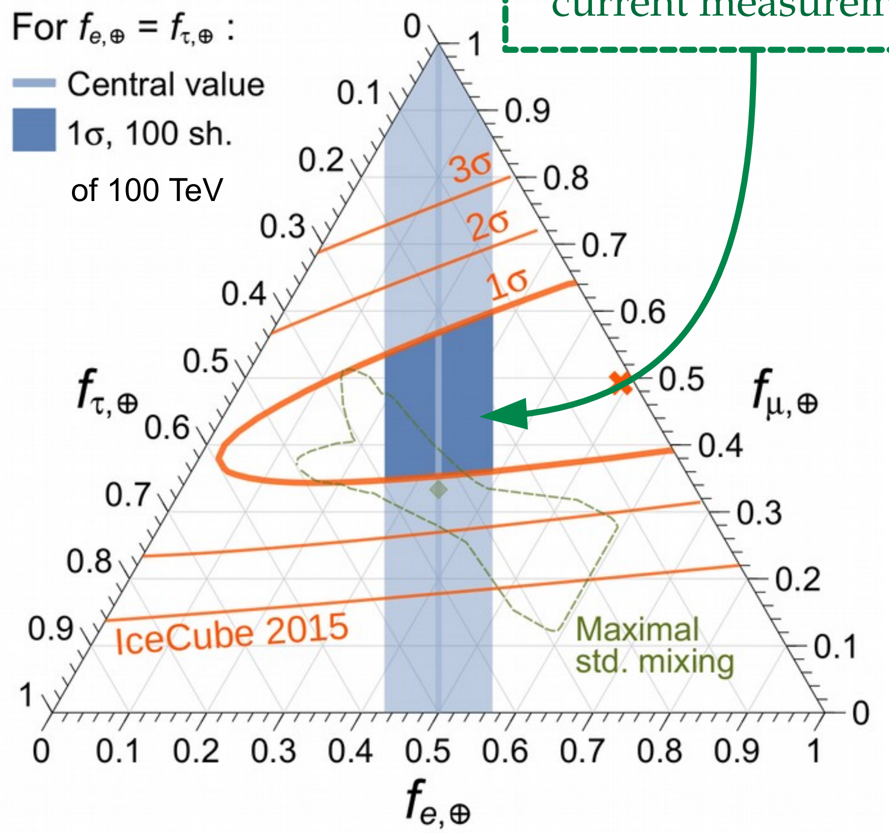

~10× improvement over current measurement

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

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Flavor composition – a few source choices

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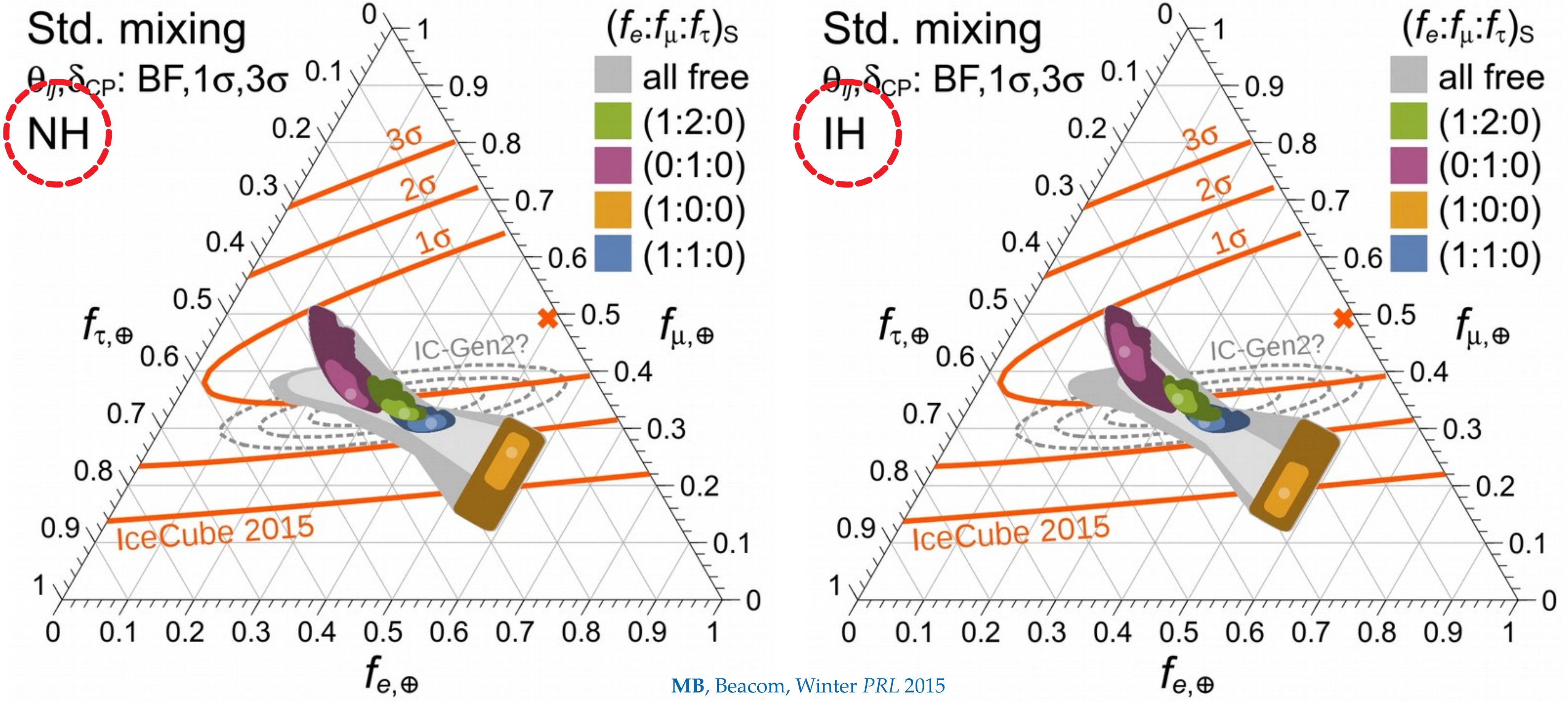

MB, Beacom, Winter *PRL* 2015

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 current limits: $\kappa_0 < 10^{-29}$ PeV, $\kappa_1 < 10^{-33}$

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

Argüelles, **MB**, Kheirandish, Palomares-Ruiz, Salvadó, Vincent, 1907.08690

Fundamental physics with HE cosmic neutrinos

- Numerous new-physics effects grow as $\sim \kappa_n \cdot E^n \cdot L$
  - n = -1: neutrino decay
  - n = 0: CPT-odd Lorentz violation
  - n = +1: CPT-even Lorentz violation

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

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  - Timing

Argüelles, **MB**, Kheirandish, Palomares-Ruiz, Salvadó, Vincent, 1907.08690

Fundamental physics with HE cosmic neutrinos

- Numerous new-physics effects grow as $\sim \kappa_n \cdot E^n \cdot L$
  - n = -1: neutrino decay
  - n = 0: CPT-odd Lorentz violation
  - n = +1: CPT-even Lorentz violation

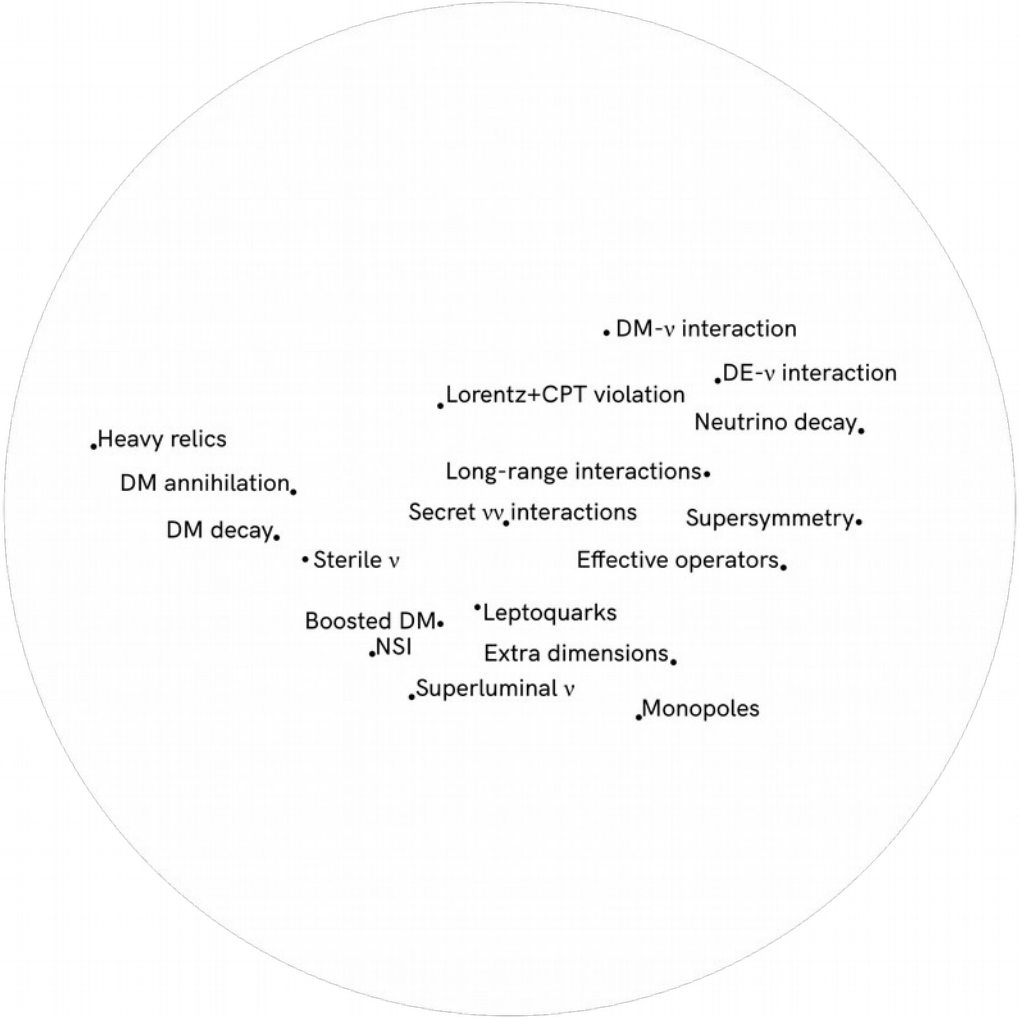
- So we can probe $\kappa_n \sim 4 \cdot 10^{-47}\,(E/\mathrm{PeV})^{-n}\,(L/\mathrm{Gpc})^{-1}\,\mathrm{PeV}^{1-n}$

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

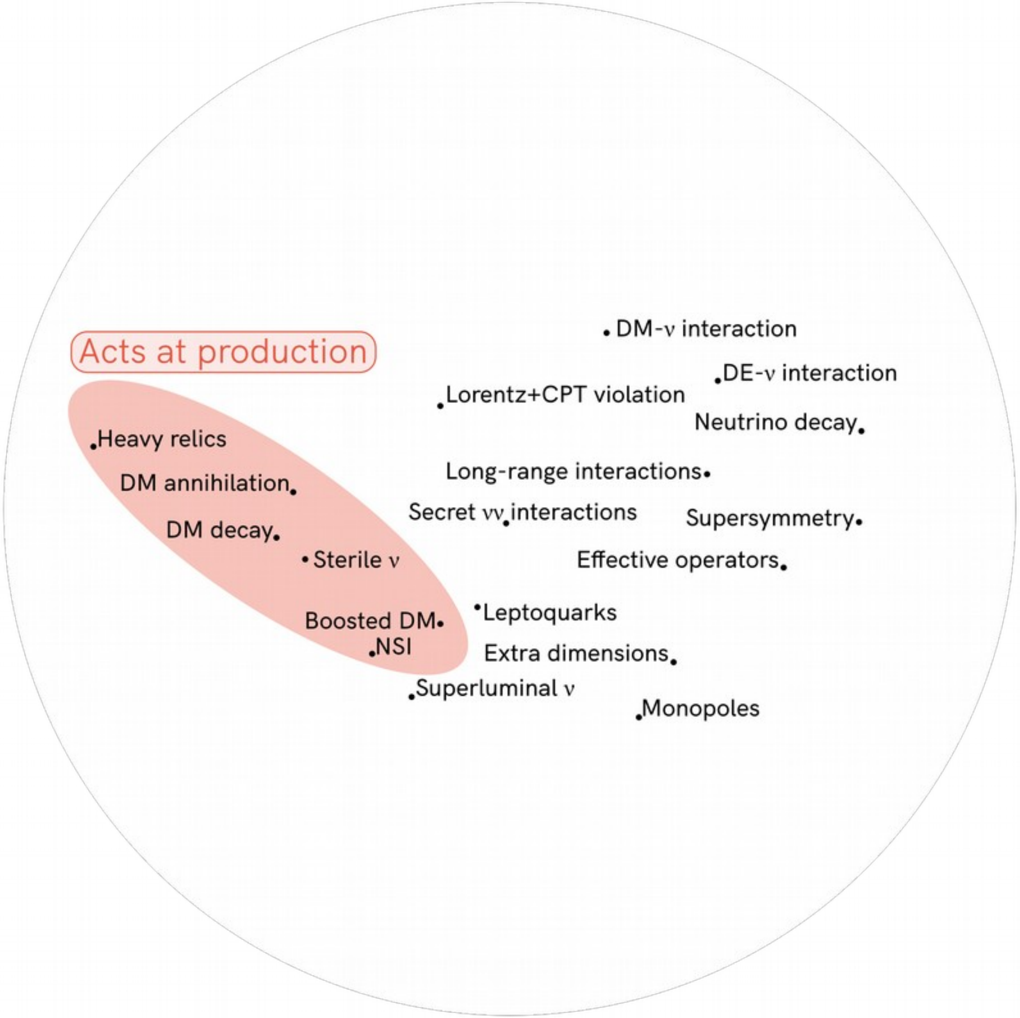
- Fundamental physics can be extracted from four neutrino observables:
  - Spectral shape
  - Angular distribution
  - Flavor composition
  - Timing

In spite of
poor energy, angular, flavor reconstruction
& astrophysical unknowns

Argüelles, **MB**, Kheirandish, Palomares-Ruiz, Salvadó, Vincent, 1907.08690



Note: Not an exhaustive list



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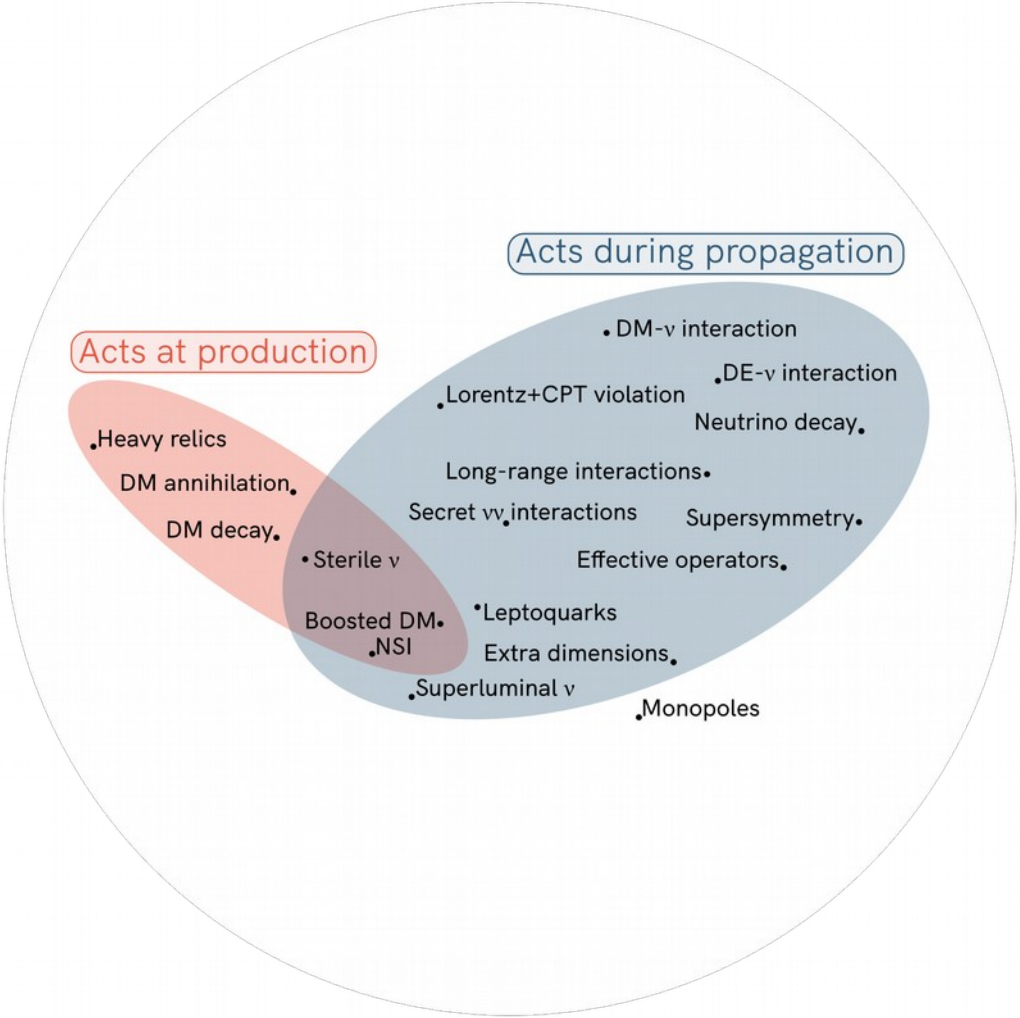

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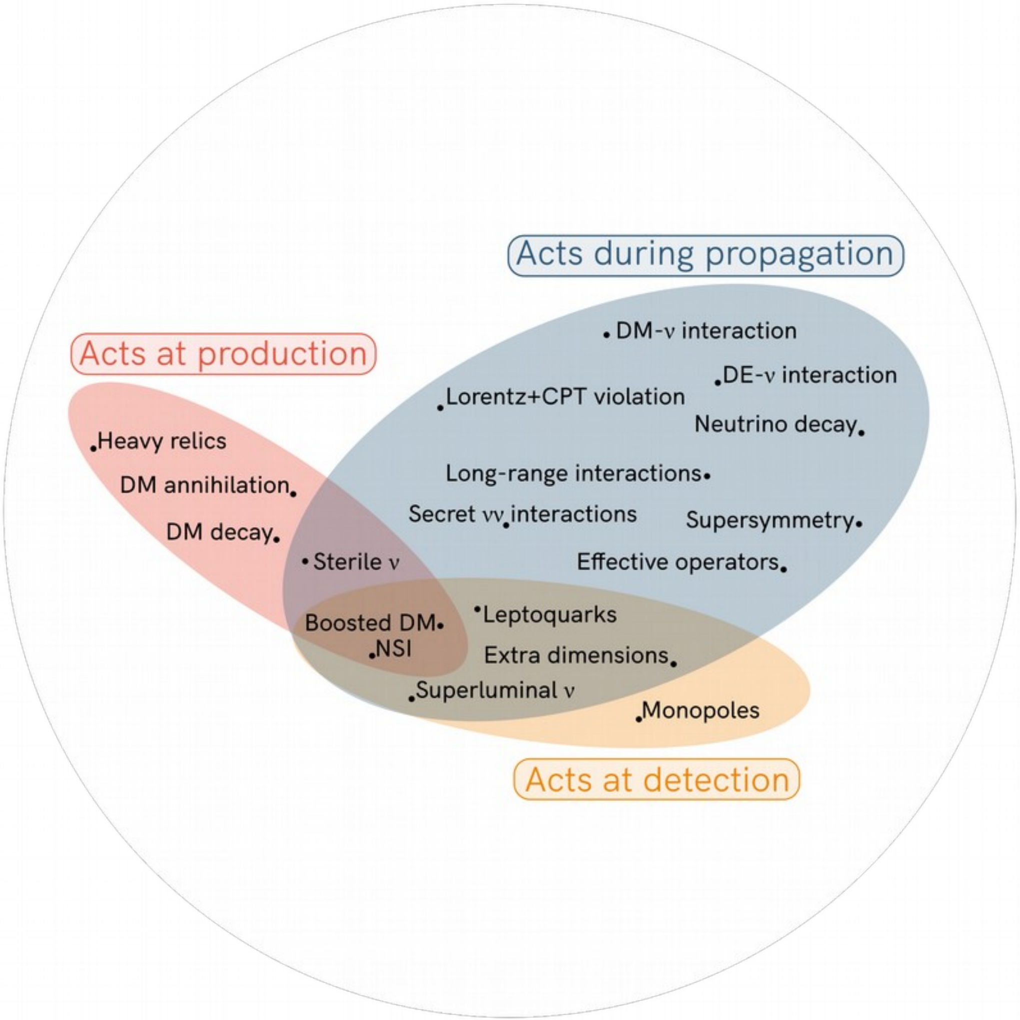

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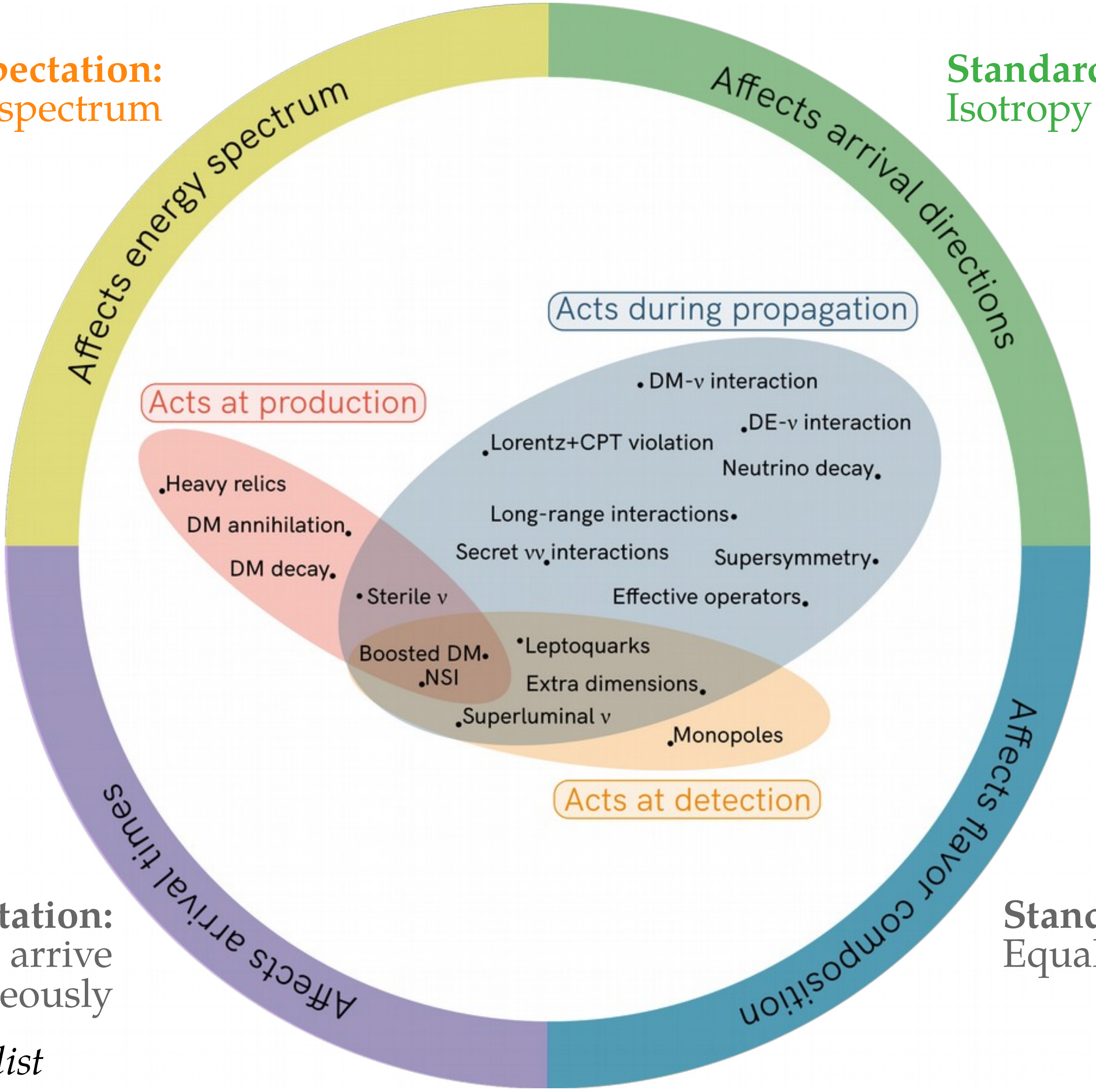
Standard expectation:
Power-law energy spectrum

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

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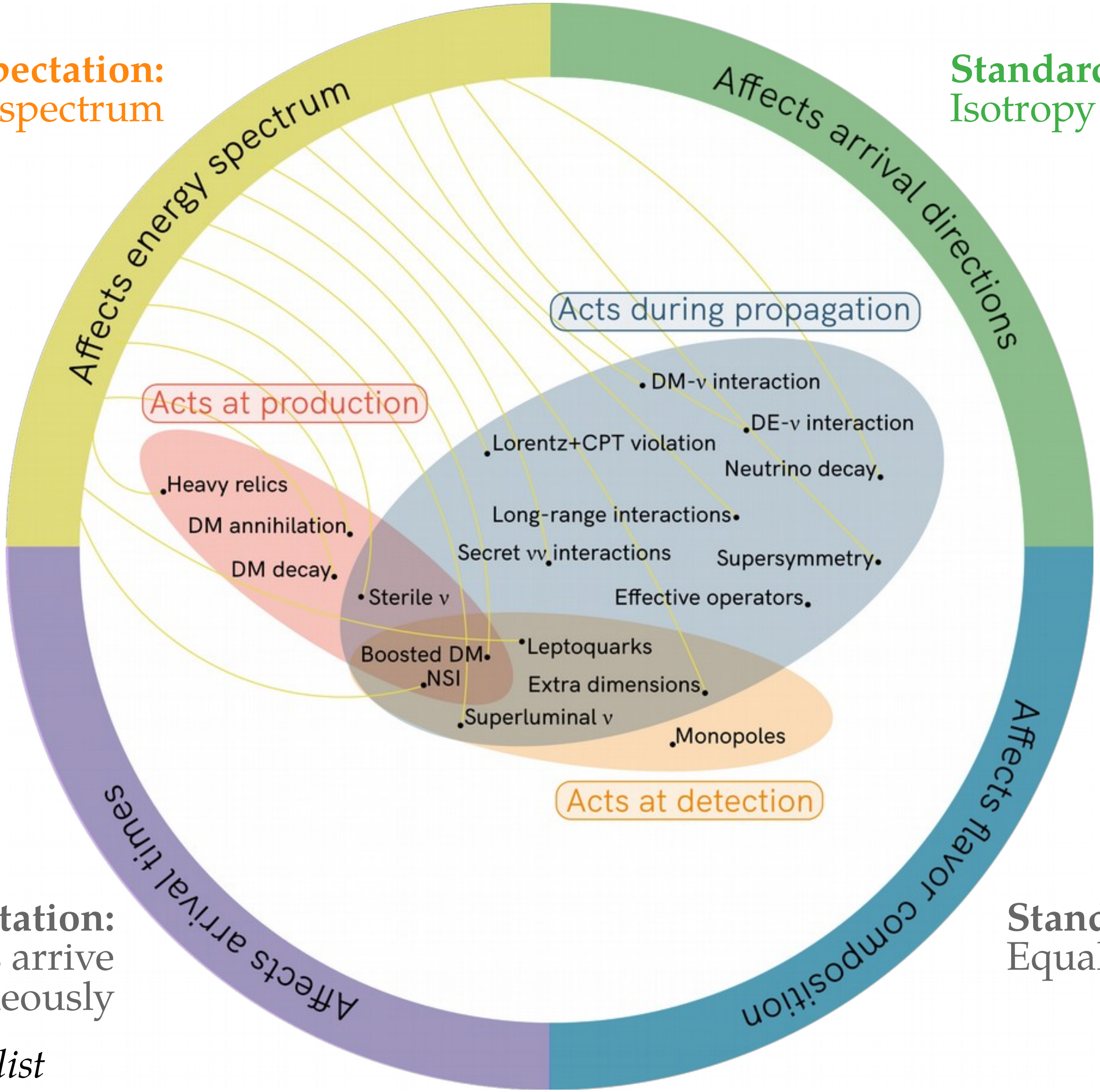

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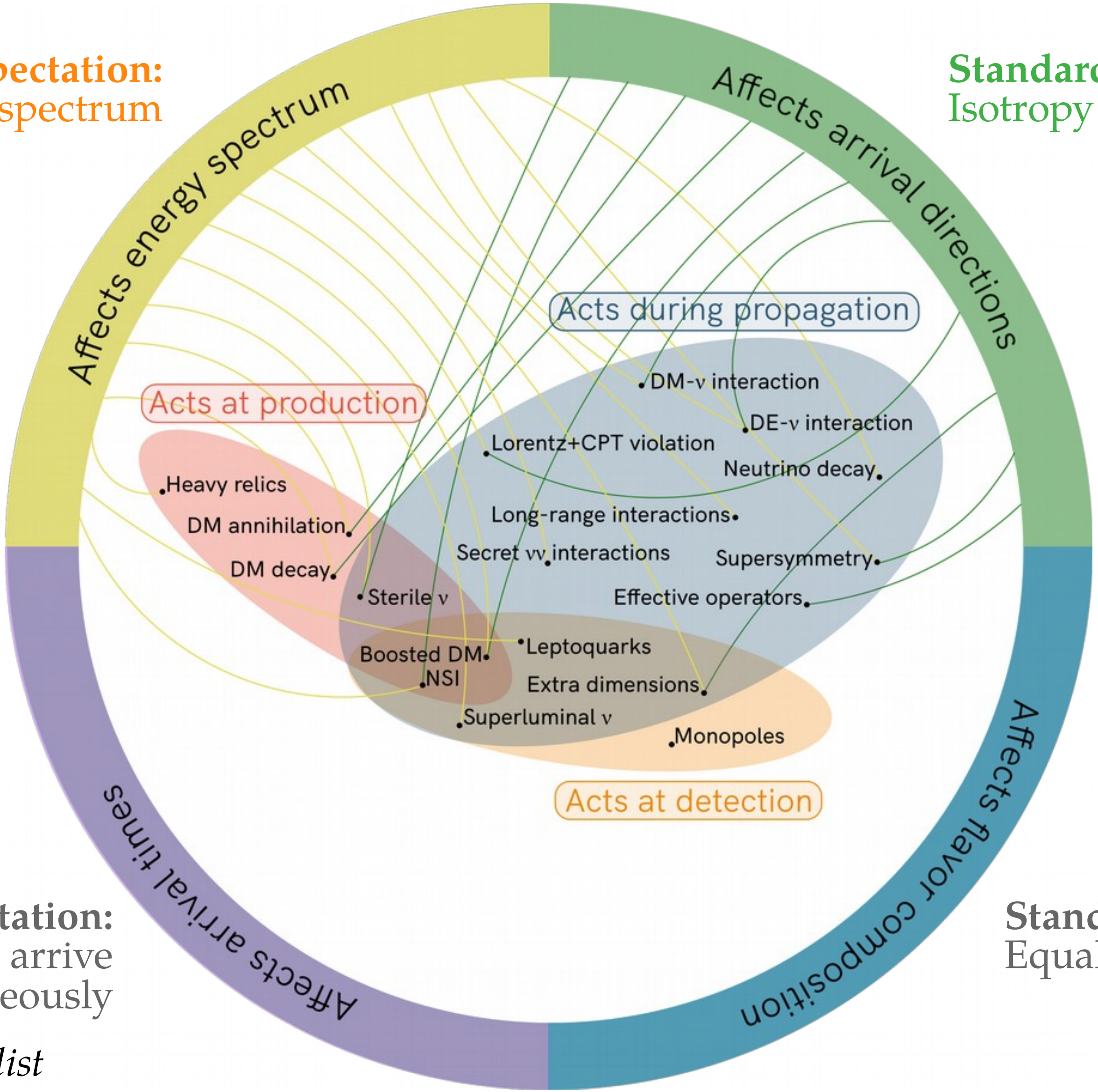

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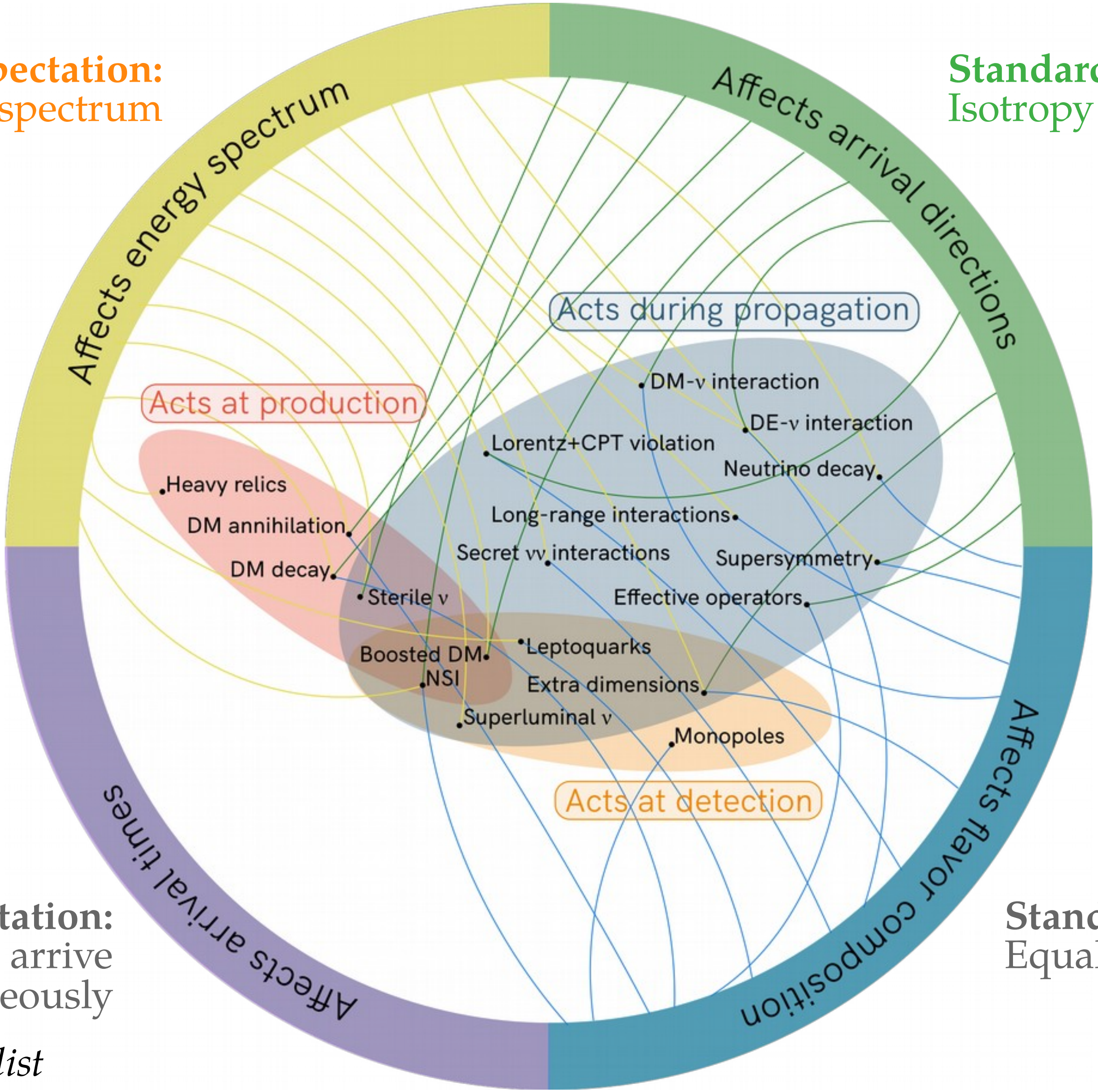

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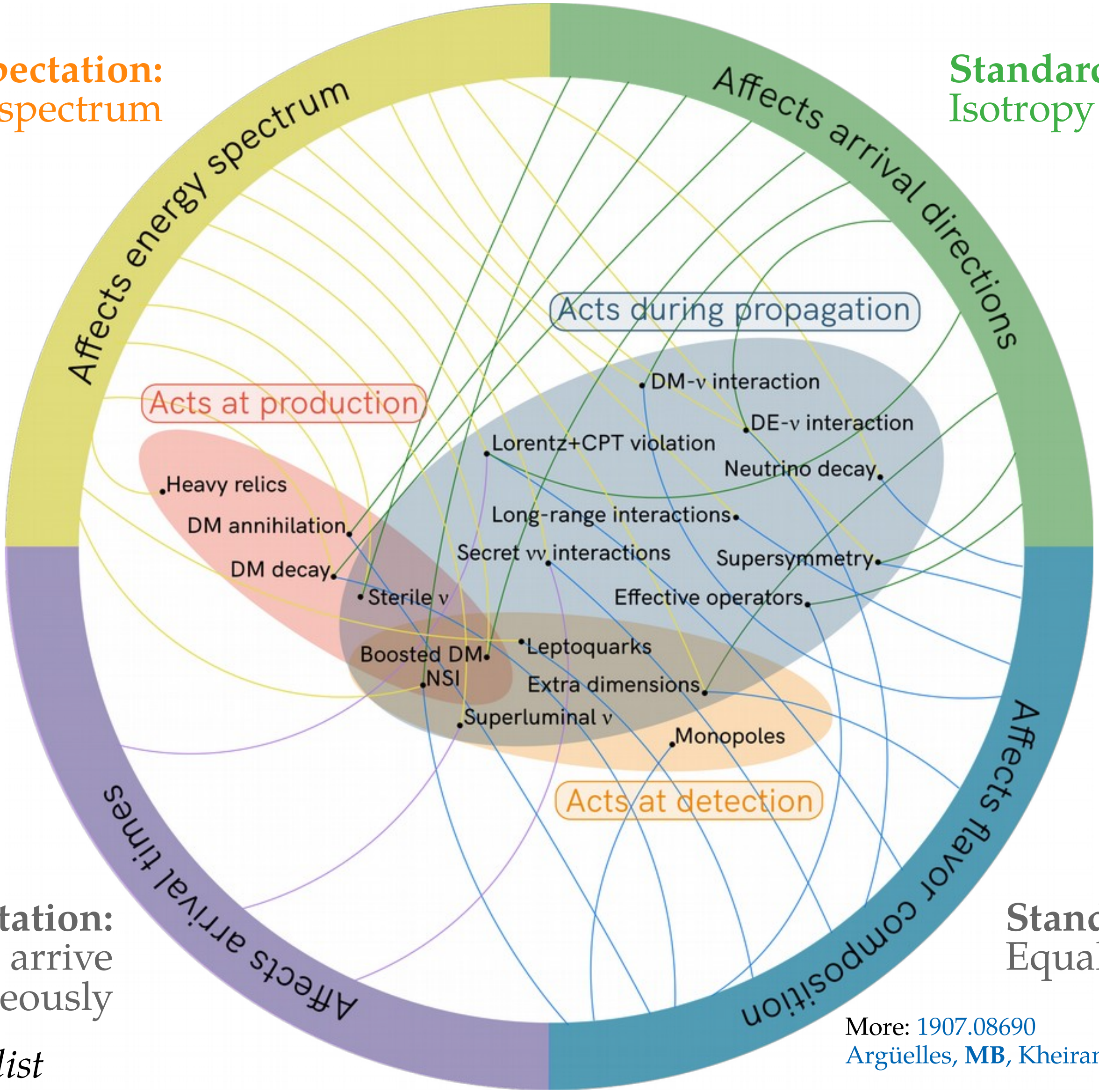

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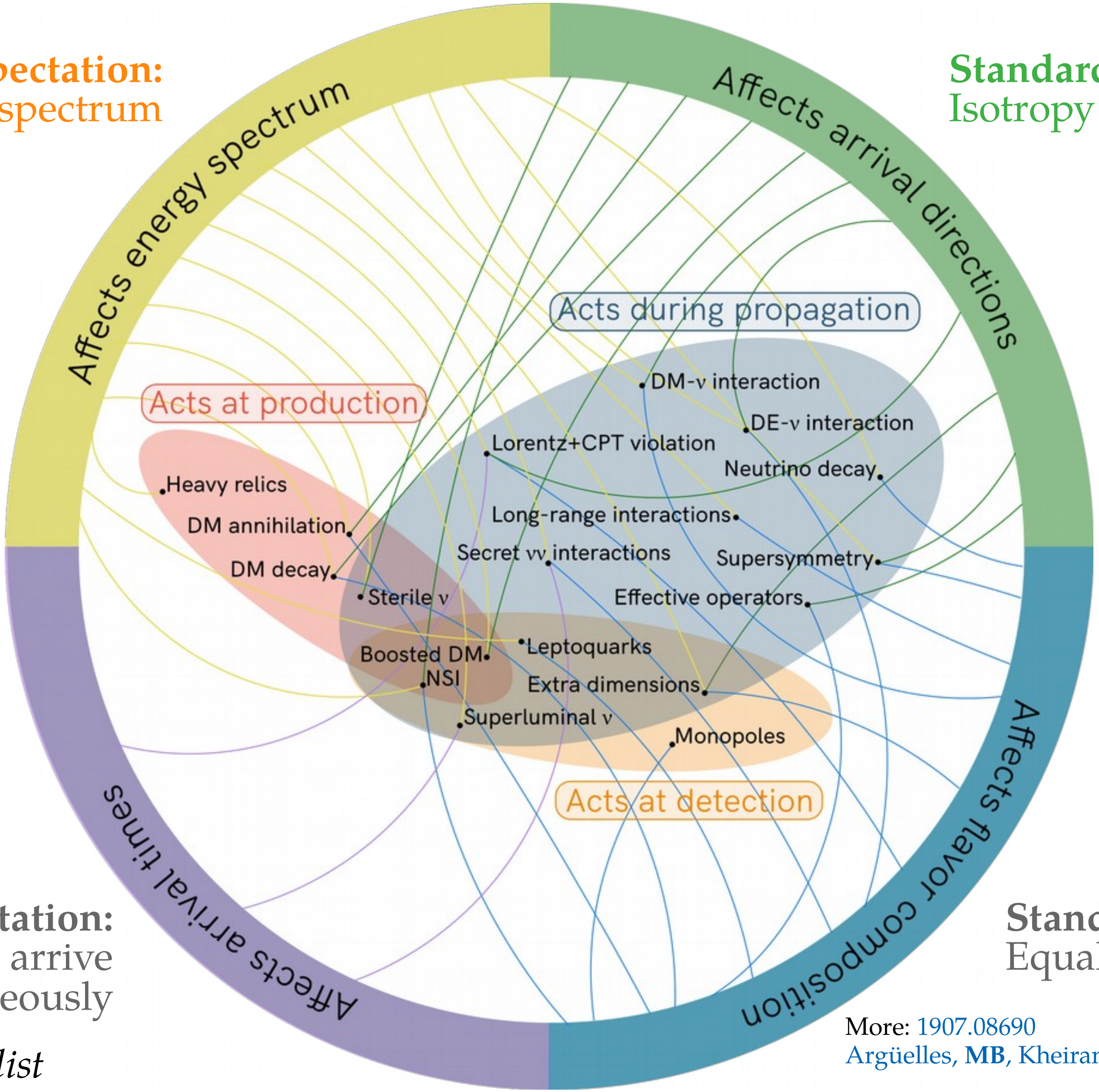

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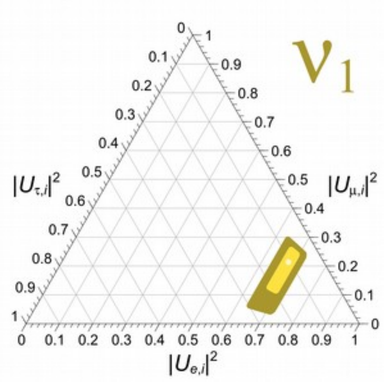
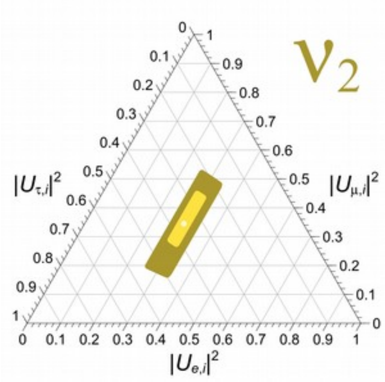
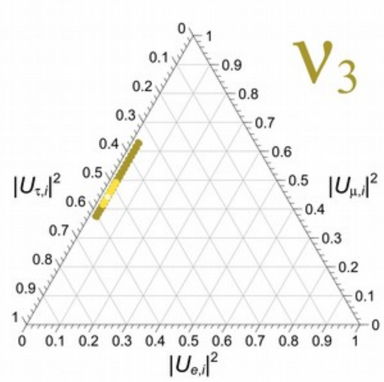
Two classes of new physics

- Neutrinos propagate as an incoherent mix of ν_1, ν_2, ν_3
- Each one has a different flavor content:







- Flavor ratios at Earth are the result of their combination
- New physics may:
  - Only reweigh the proportion of each ν_i reaching Earth (*e.g.*, ν decay)
  - Redefine the propagation states (*e.g.*, Lorentz-invariance violation)

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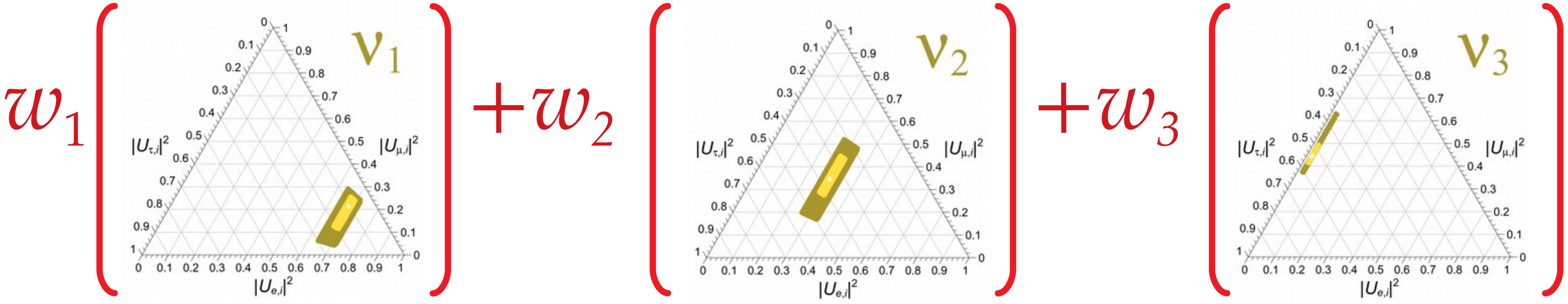

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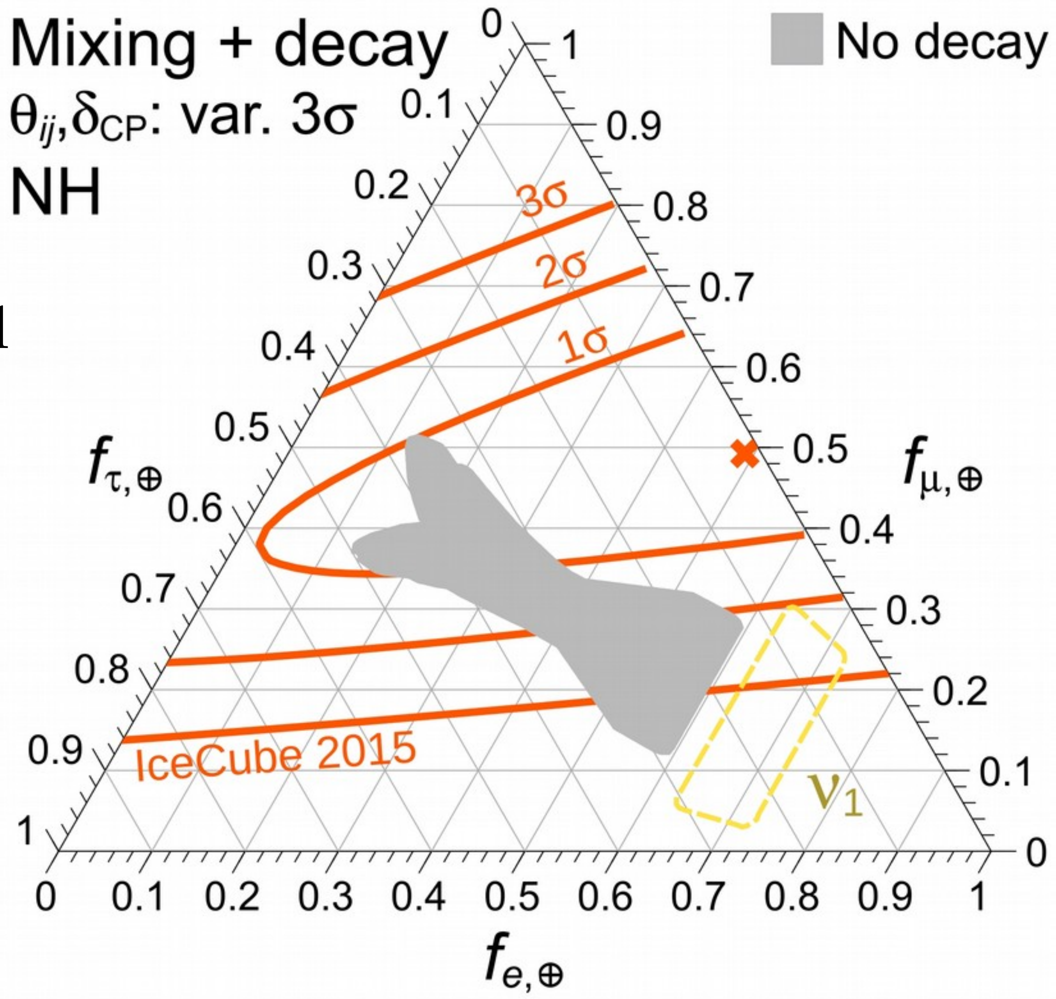
Measuring the neutrino lifetime

Find the value of D so that decay is complete, *i.e.*, $f_{\alpha,\oplus} = |U_{\alpha 1}|^2$, for

- Any value of mixing parameters; and
- Any flavor ratios at the sources

(Assume equal lifetimes of ν_2, ν_3)



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

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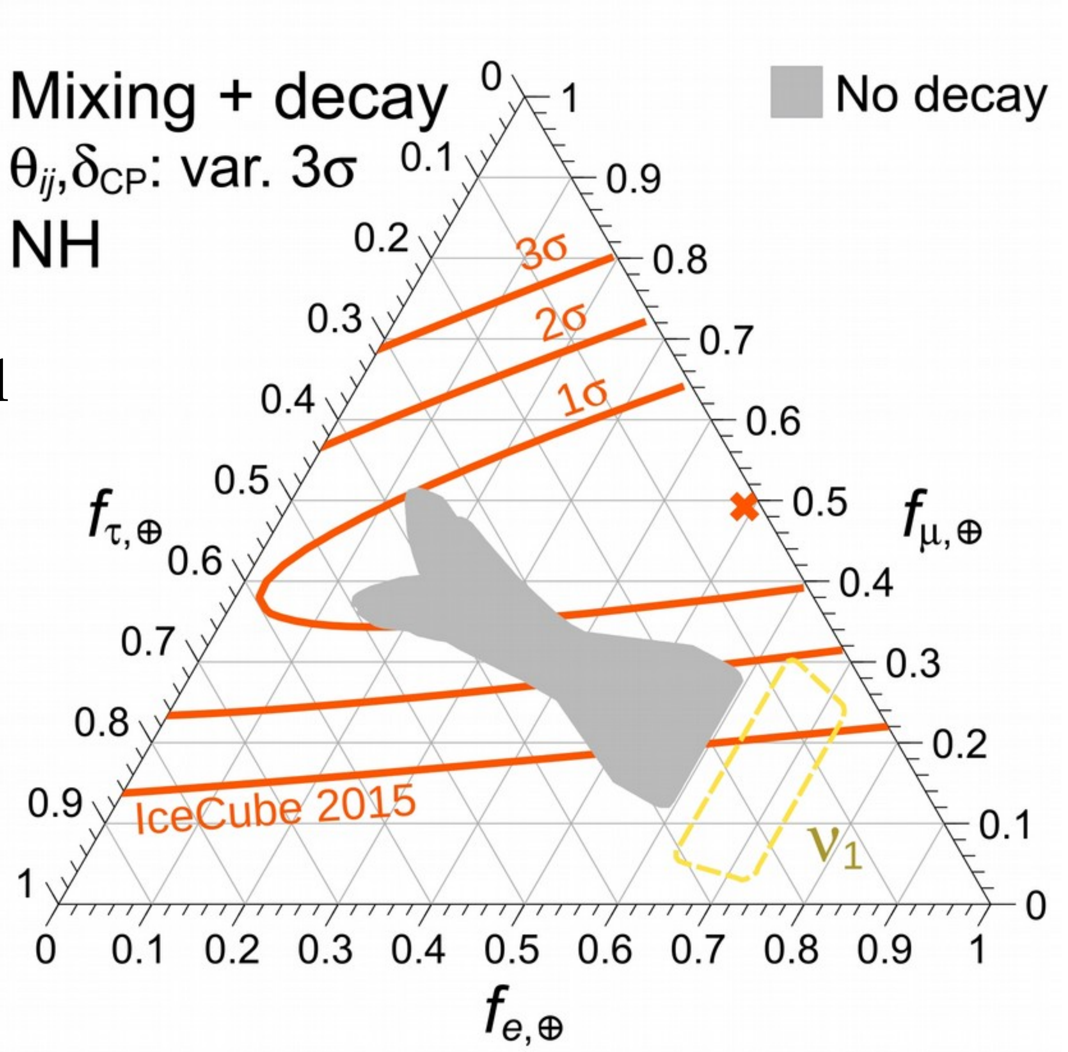

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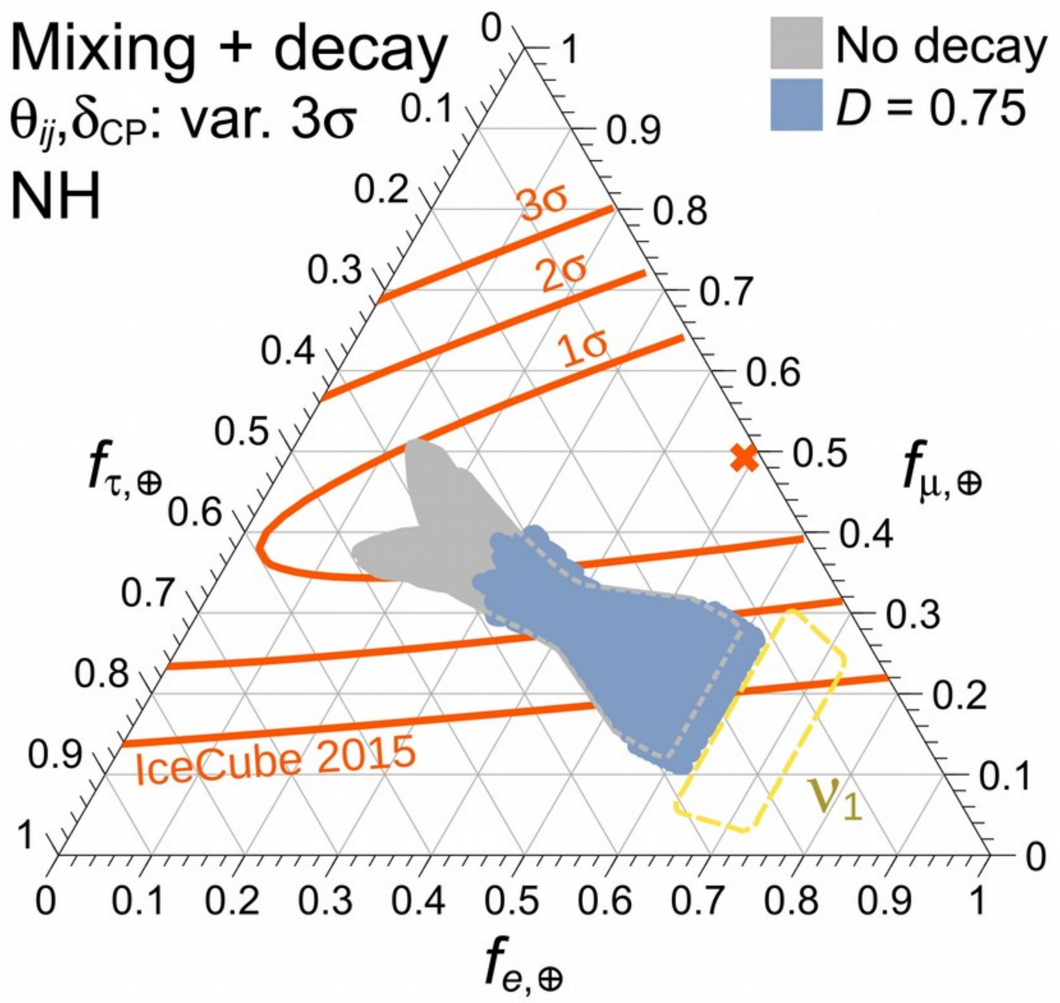

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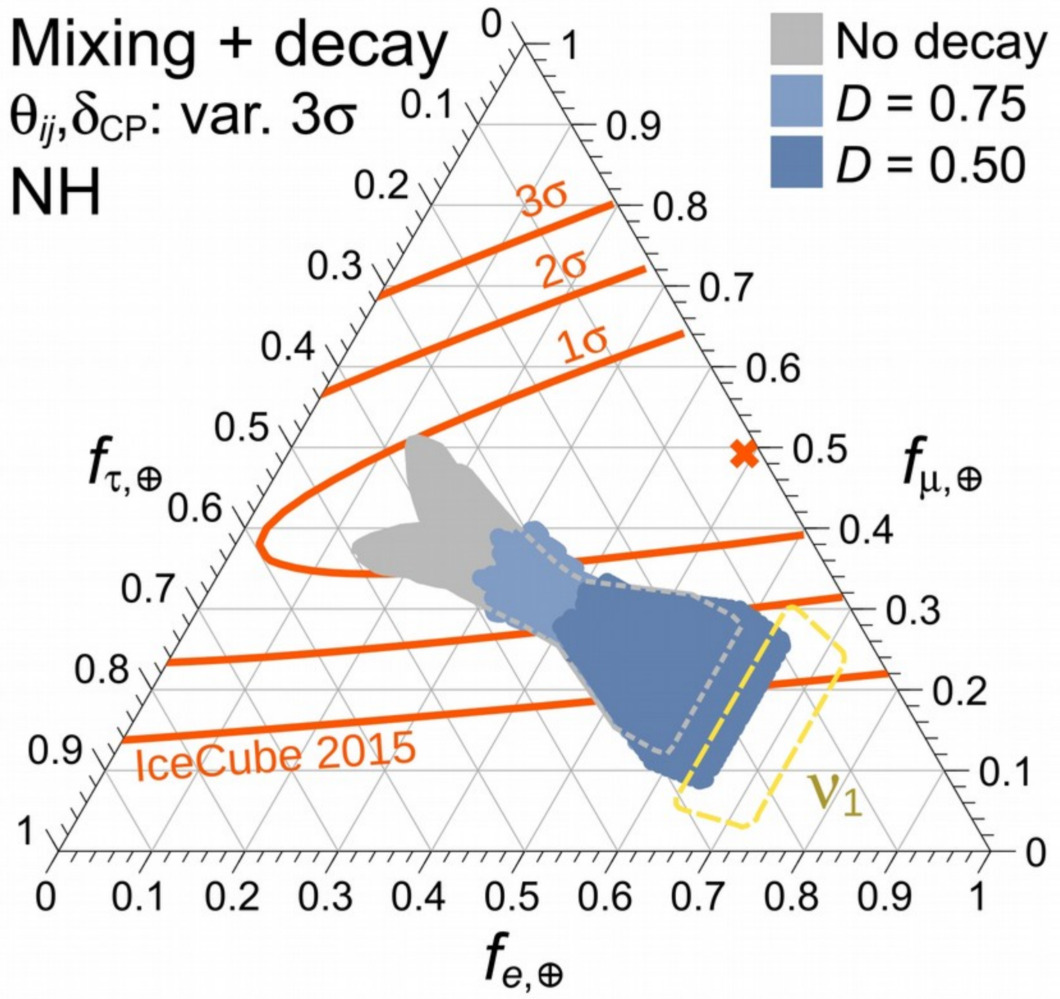

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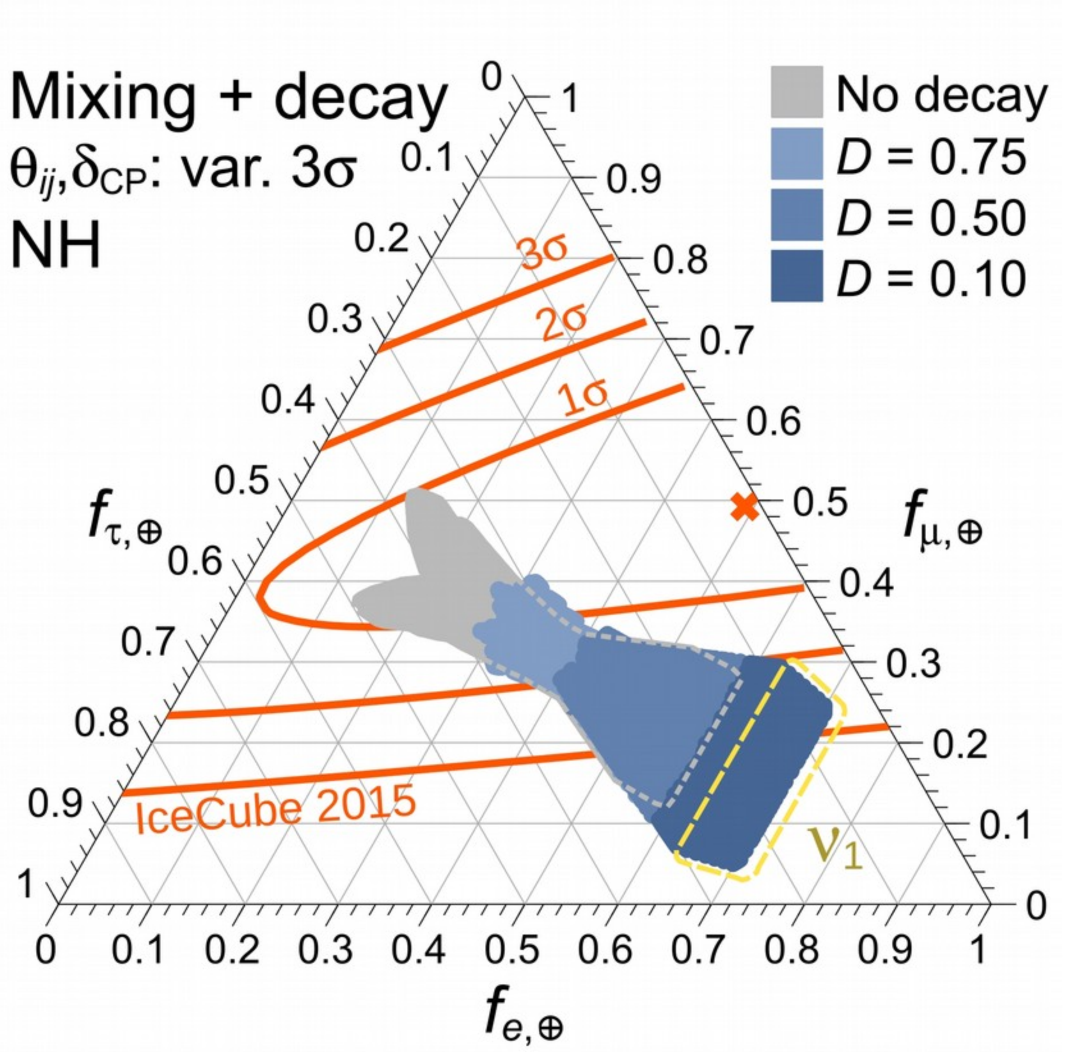

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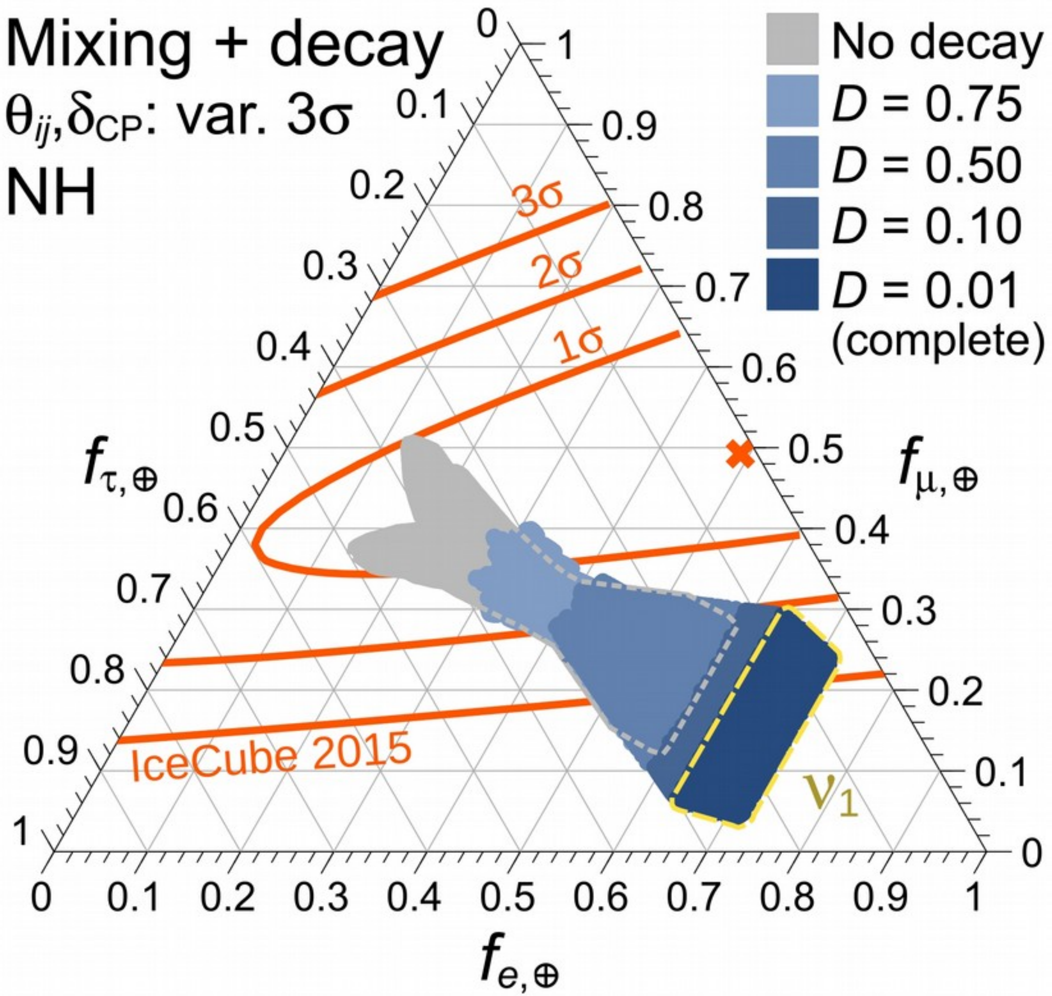

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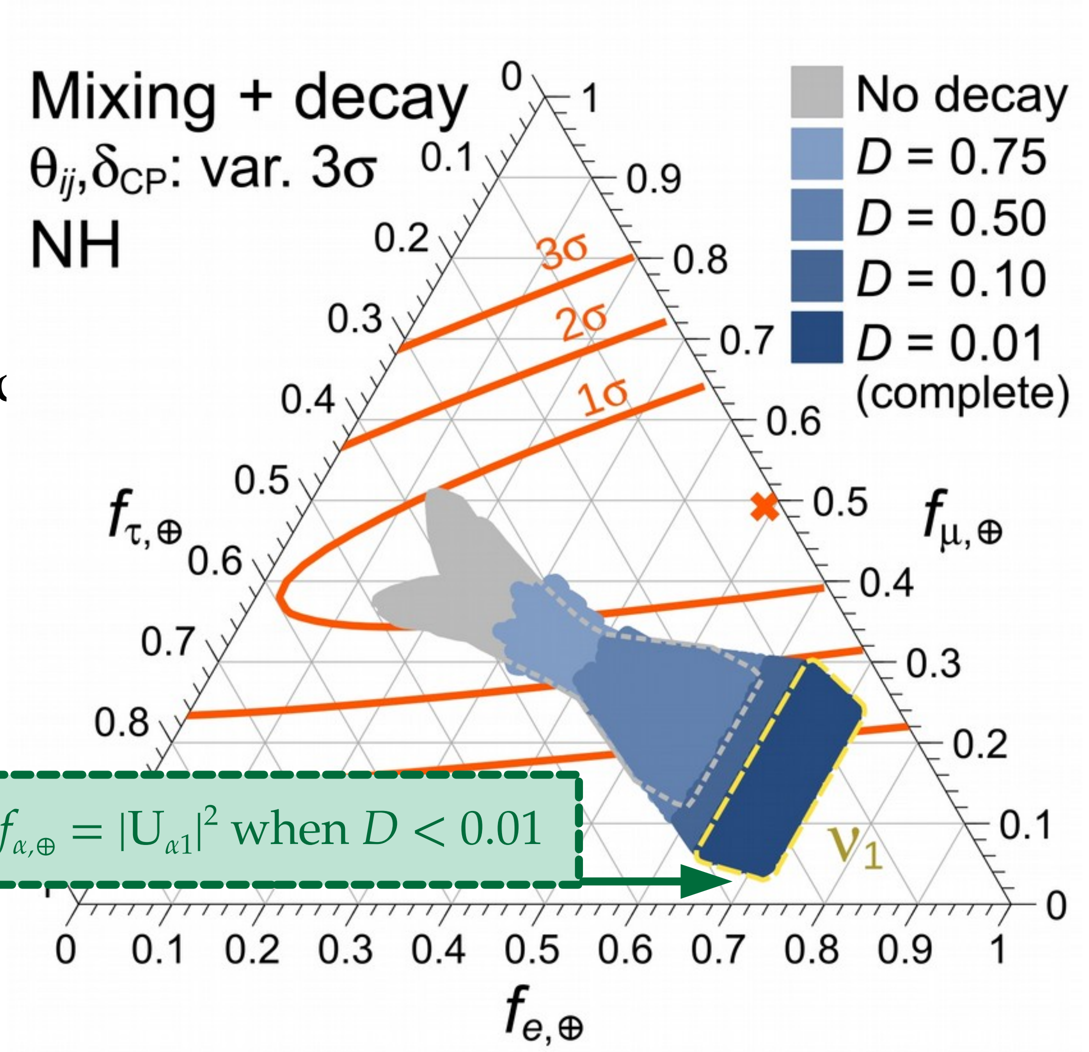
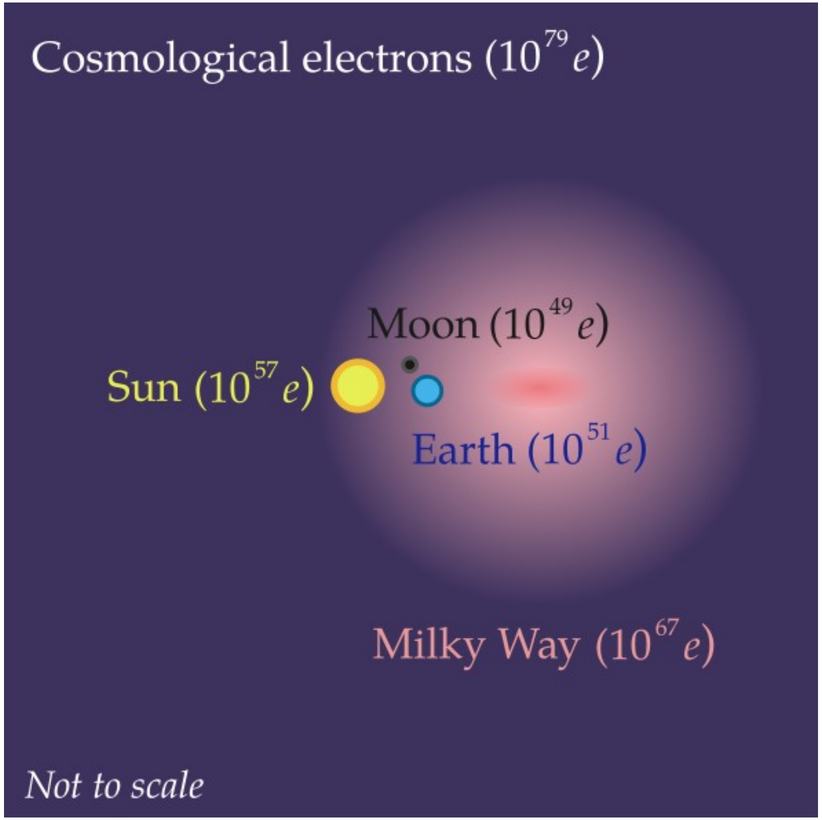


$f_{\alpha,\oplus} = |U_{\alpha 1}|^2$ when $D < 0.01$

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

The total potential



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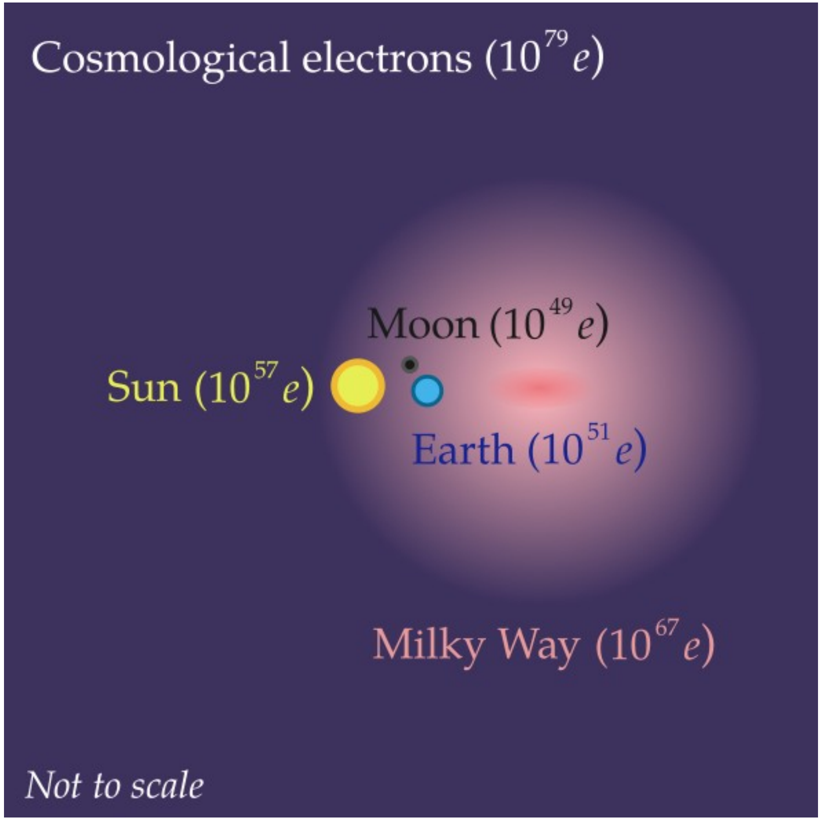
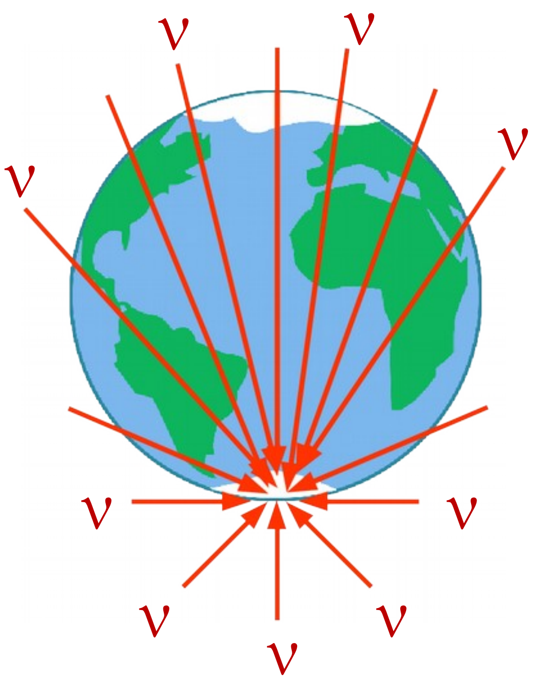
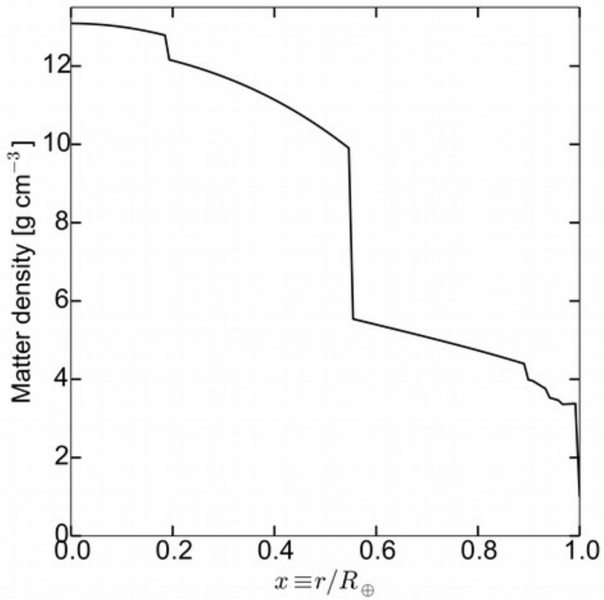


$$V_{e\beta} = V_{e\beta}^{\oplus}$$

Earth:

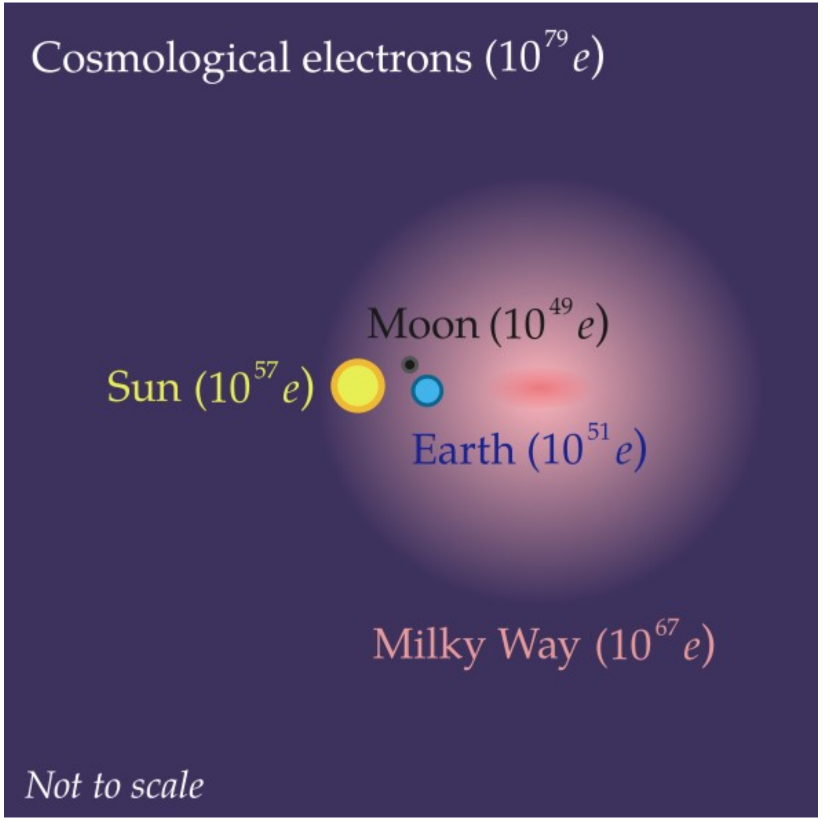


Preliminary Reference Earth Model
Dziewonski & Anderson 1981

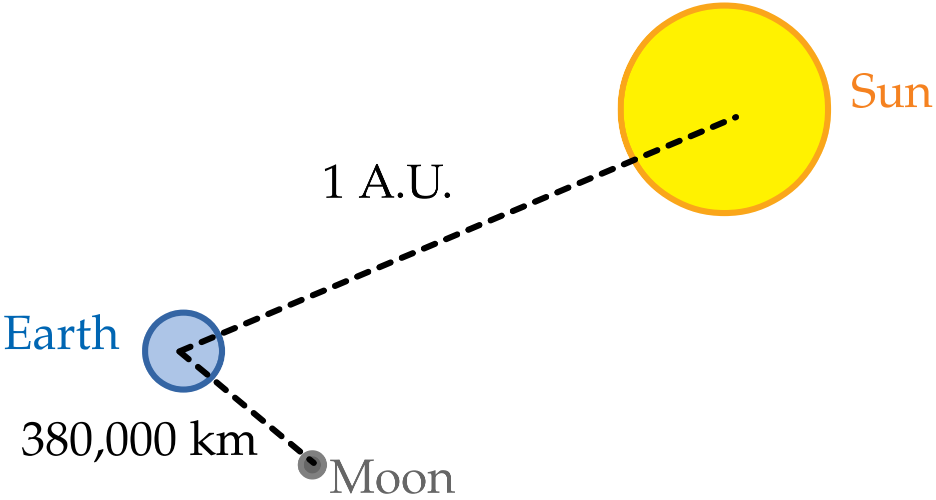


Neutrinos traverse different electron column depths

The total potential



Moon and Sun:

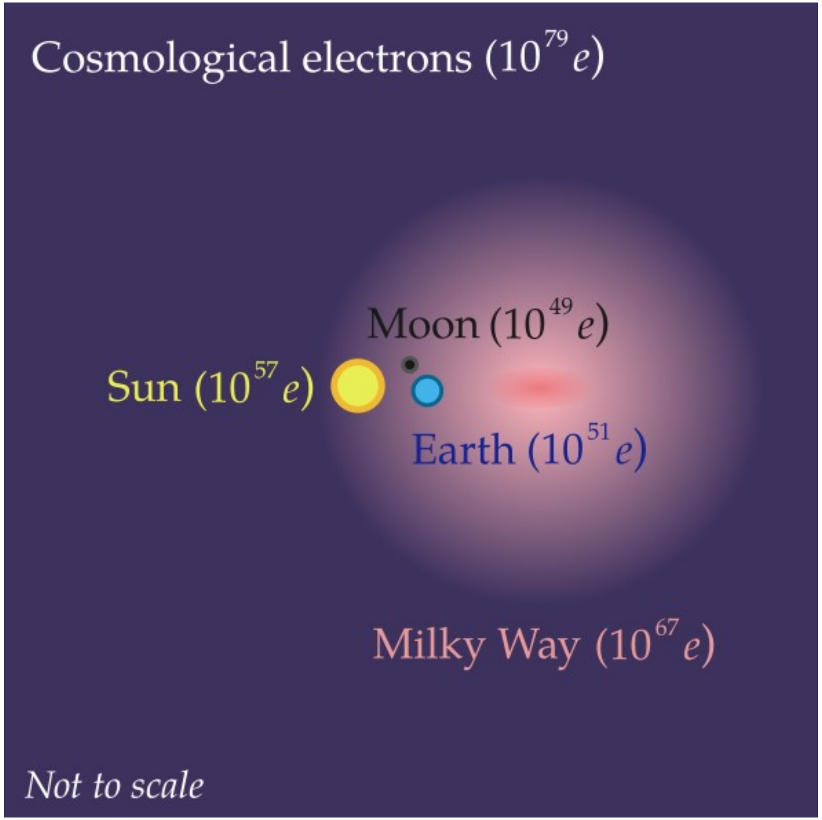


Treated as point sources of electrons

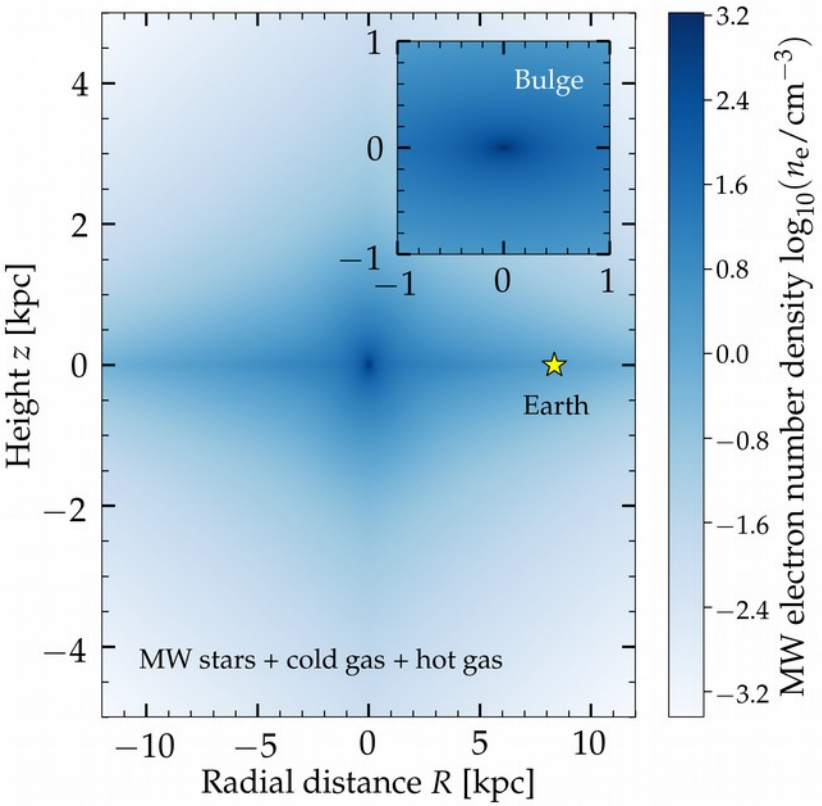
$$V_{e\beta} = V_{e\beta}^{\oplus} + V_{e\beta}^{\mathrm{Moon}} + V_{e\beta}^{\odot}$$

The total potential

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

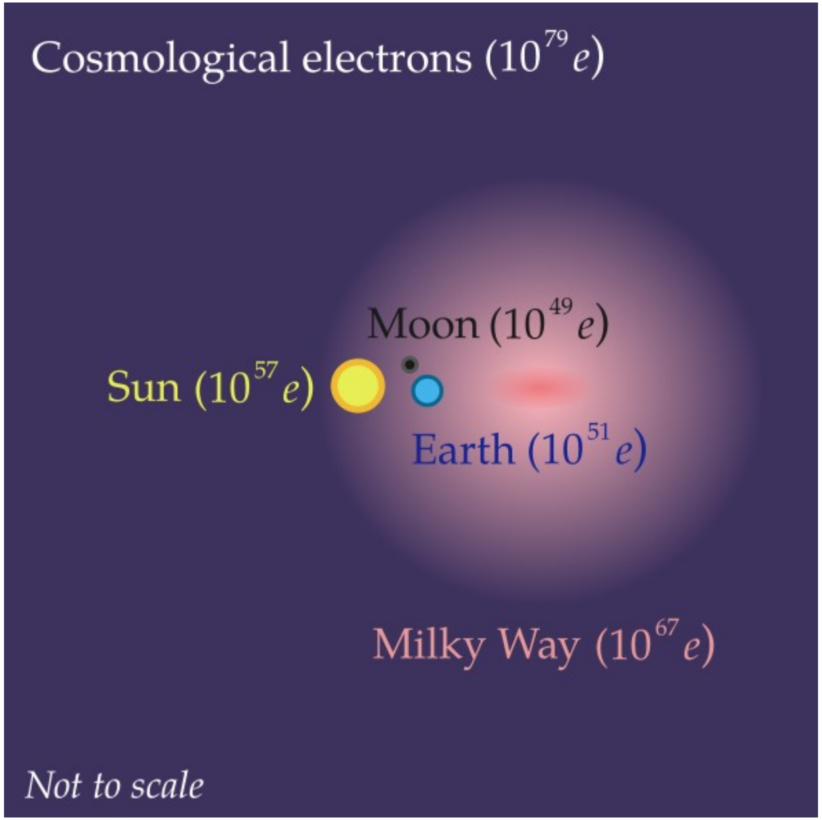


Milky Way:



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

The total potential



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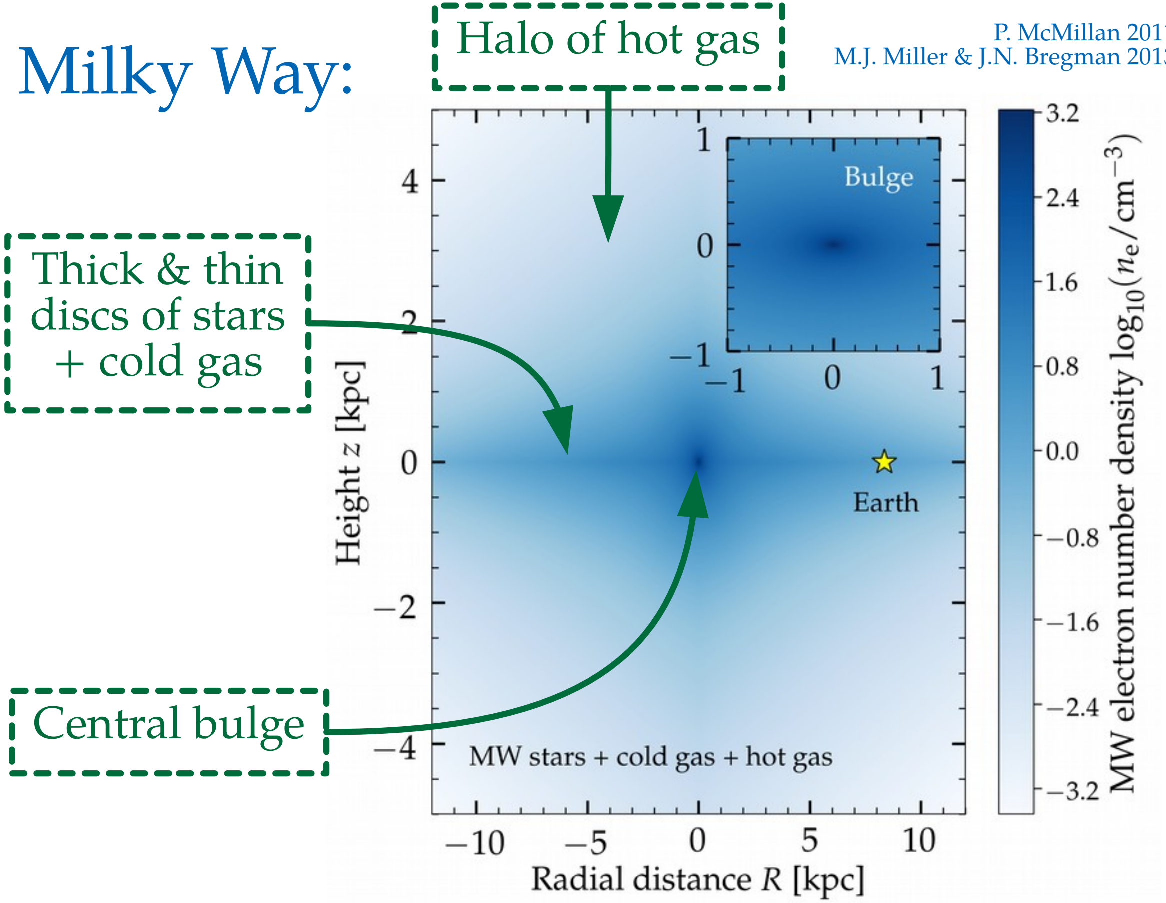

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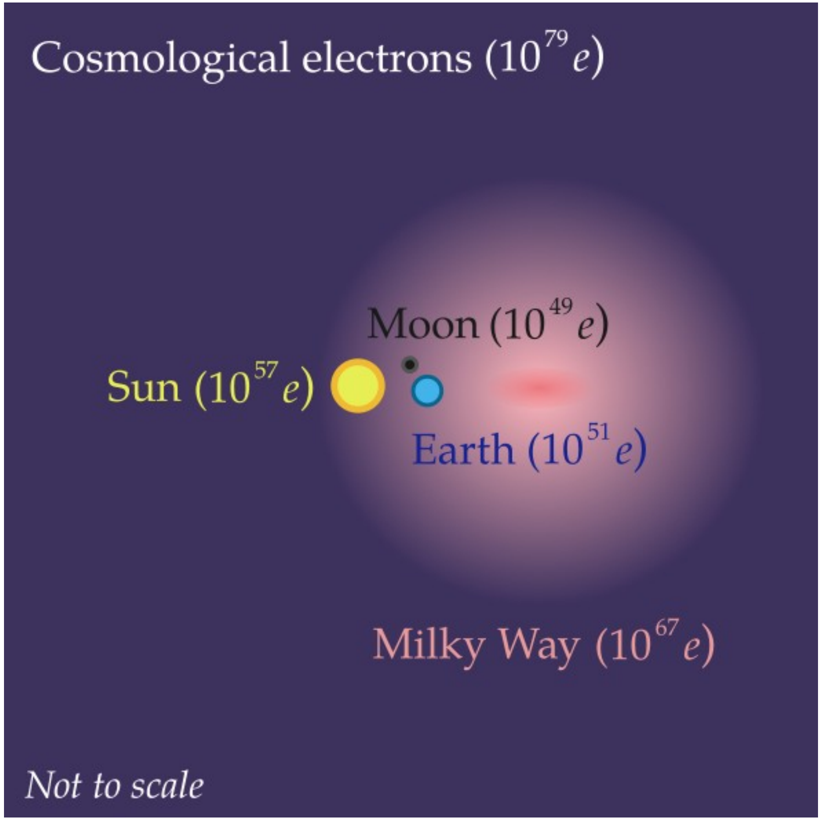
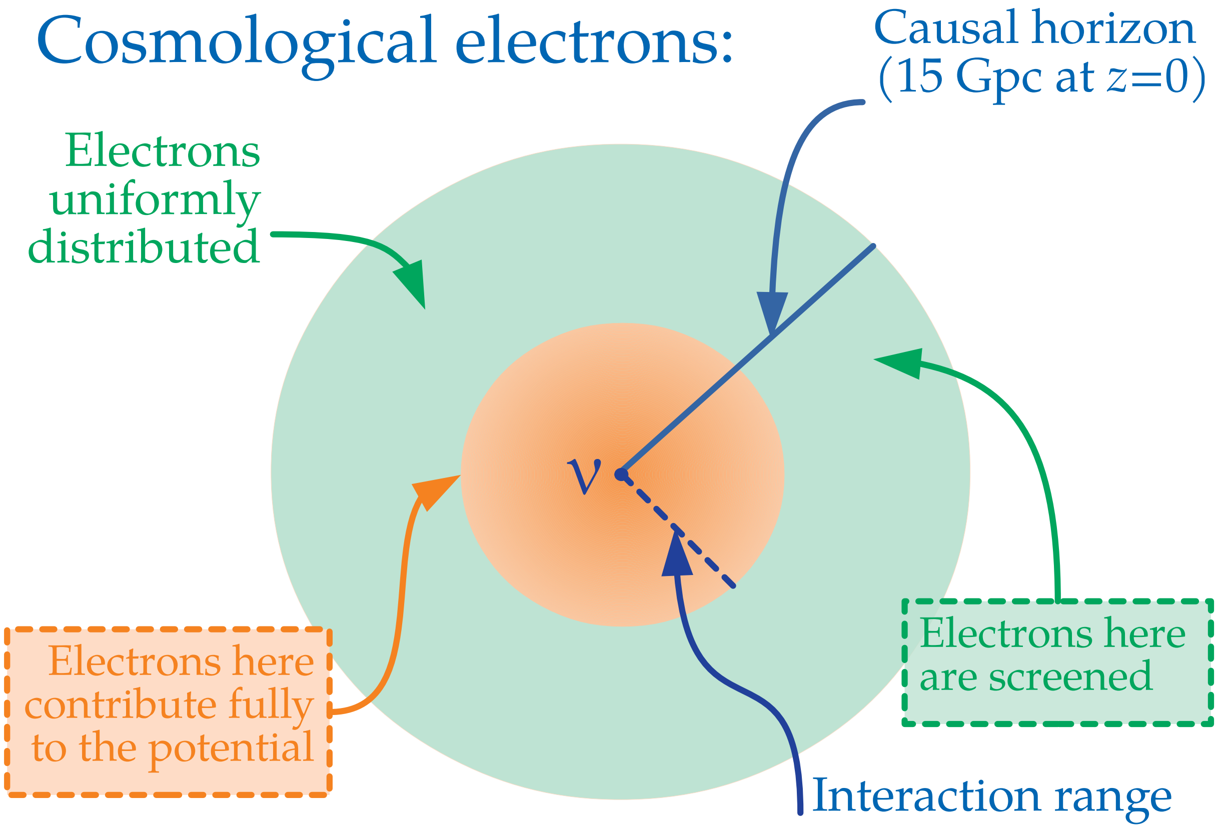


Cosmological electrons:



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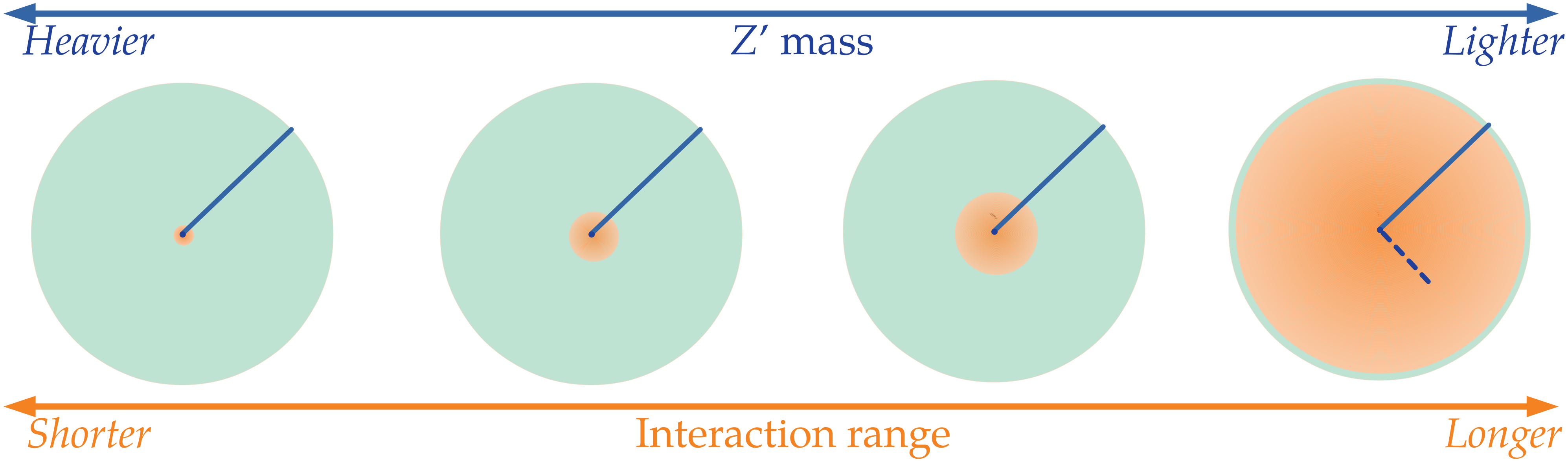

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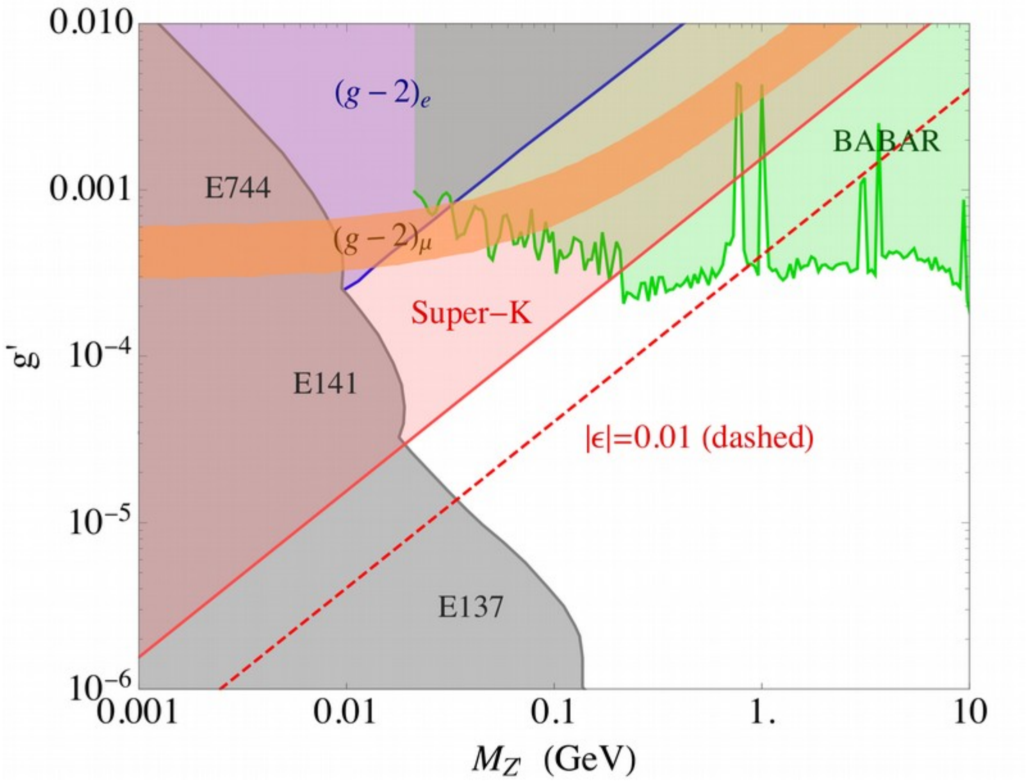
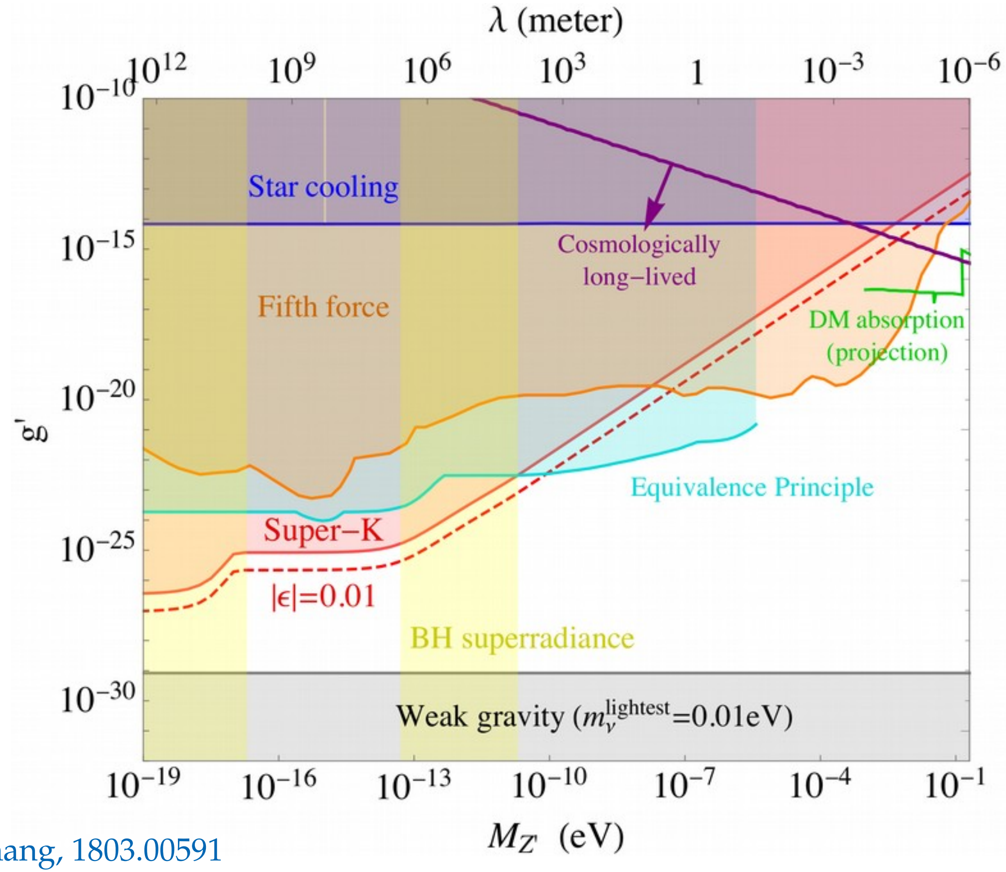
Current limits on the Z'

MeV–GeV masses



Sub-eV masses



M. Wise & Y. Zhang, 1803.00591

Connecting flavor-ratio predictions to experiment

1. Integrate potential in redshift, weighed by source number density
$\mapsto$ Assume star formation rate

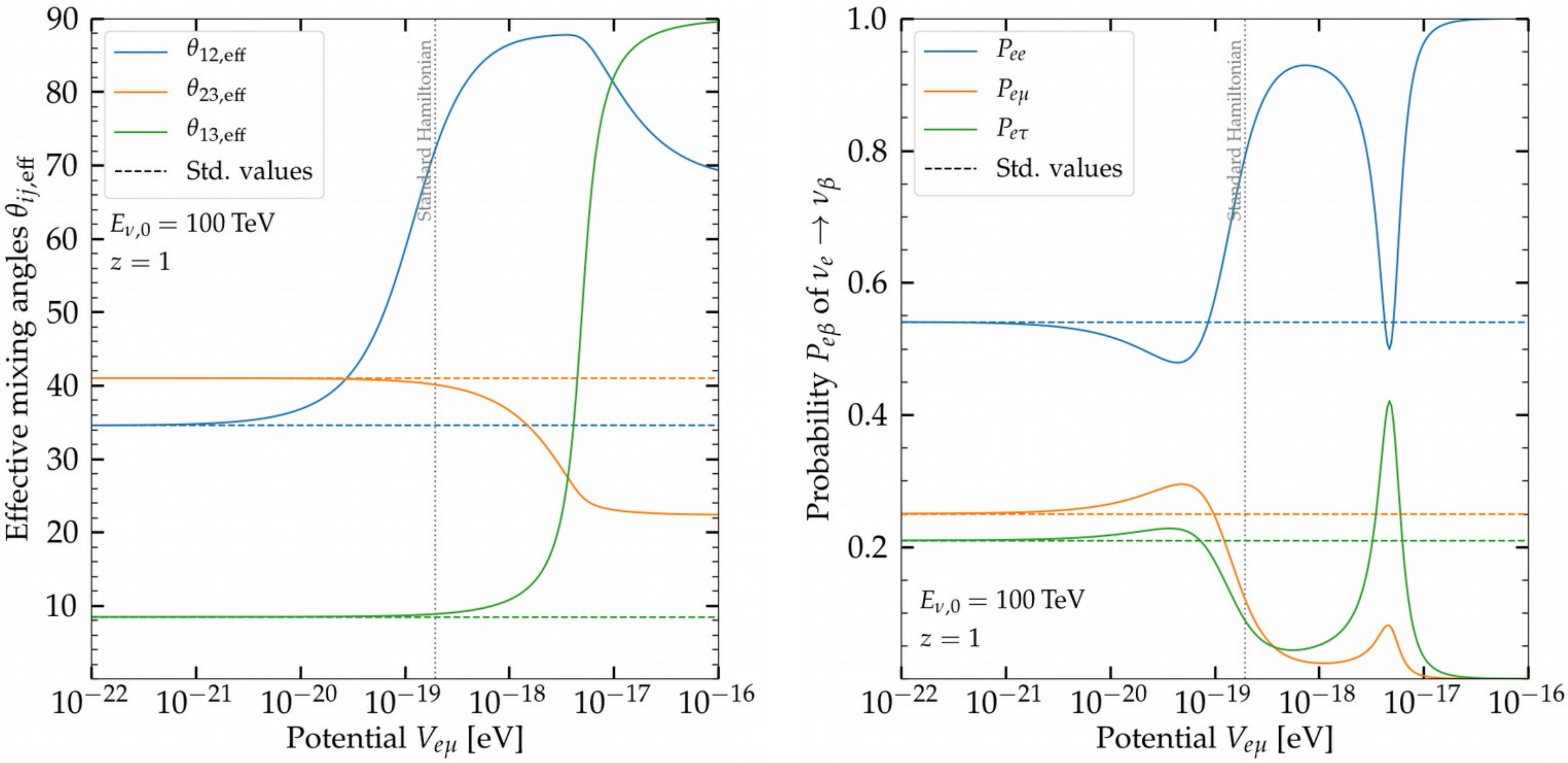
$$\langle V_{e\beta}^{\cos} \rangle \propto \int dz \; \rho_{\rm SFR}(z) \cdot \frac{dV_{\rm c}}{dz} \cdot V_{e\beta}^{\cos}(z)$$

Density of cosmological e grows with z

2. Convolve flavor ratios with observed neutrino energy spectrum
$\mapsto$ Either $E^{-2.50}$ (combined analysis) or $E^{-2.13}$ (through-going muons)

$$\underbrace{\langle \Phi_\alpha \rangle \propto \int dE_\nu \; f_{\alpha,\oplus}(E_\nu) \; E_\nu^{-\gamma}}_{\text{Energy-averaged flux}} \Rightarrow \underbrace{\langle f_{\alpha,\oplus} \rangle \equiv \frac{\langle \Phi_\alpha \rangle}{\sum_{\beta=e,\mu,\tau} \langle \Phi_\beta \rangle}}_{\text{Energy-averaged flavor ratios}}$$

Resonance due to the L_e-L_μ symmetry



Resonance due to the L_e-L_μ symmetry (*cont.*)