A Universe's Worth of Electrons to Probe Long-Range Neutrino Interactions

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In collaboration with Sanjib Agarwalla, 1808.02042

TeVPA

Berlin, August 29, 2018

UNIVERSITY OF COPENHAGEN

Infinite-range (Coulomb) interactions

$$V \sim \frac{1}{r}$$

Massless mediator

- Electromagnetism
- Gravity

vs

Limited-range (Yukawa) interactions

$$V \sim \frac{1}{r} e^{-mr}$$

Massive mediator

- Weak interaction
- Strong interaction
- ?

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vs

Limited-range (Yukawa) interactions

Range of the interaction: $1/m$

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Massive mediator

- Weak interaction
- Strong interaction
- ?

Ultra-long-range flavorful interactions

- The SM *must* be extended
- Simple extension: promote global symmetries of the SM to local symmetries
- Economical option: anomaly-free lepton-number symmetries L_μ-L_τ, L_e-L_μ, L_e-L_τ
- Gauging any of them introduces a new neutral vector boson (Z')
- L_μ-L_τ: studied for ability to generate maximal $\mu\tau$ mixing
- L_e-L_μ, L_e-L_τ: introduce new interaction between electrons and ν_e and ν_μ or ν_τ

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

Ultra-long-range flavorful interactions

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- Simple ext… …metries
- Economic… …L_e-L_μ, L_e-L_τ
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Ok, but *why* is this interesting?

- Detectable through effects on neutrino oscillations
- If the Z' is *very* light, *many* electrons can contribute

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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 ~$(1/m')$

Electron-neutrino interactions can kill oscillations

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

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

$$\mathrm{H}_{\mathrm{tot}} = \mathrm{H}_{\mathrm{vac}} + \underbrace{\mathrm{V}_{e\beta}}_{\substack{\textbf{New neutrino-electron interaction:} \\ \text{This is diagonal}}} = \mathrm{diag}(V_{e\mu}, -V_{e\mu}, 0)$$

Electron-neutrino interactions can kill oscillations

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New neutrino-electron interaction:

This is diagonal

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

Electron-neutrino interactions can kill oscillations

$$\mathrm{H}_{\mathrm{tot}} = \mathrm{H}_{\mathrm{vac}} + \underbrace{\mathrm{V}_{e\beta}}_{\text{New neutrino-electron interaction: This is diagonal}}$$

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

New neutrino-electron interaction:

This is diagonal

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

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

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

$\sim 1/E$

Energy-independent

Electron-neutrino interactions can kill oscillations

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

~$1/E$

Energy-independent

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

Electrons in the local and distant Universe

Potential:

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

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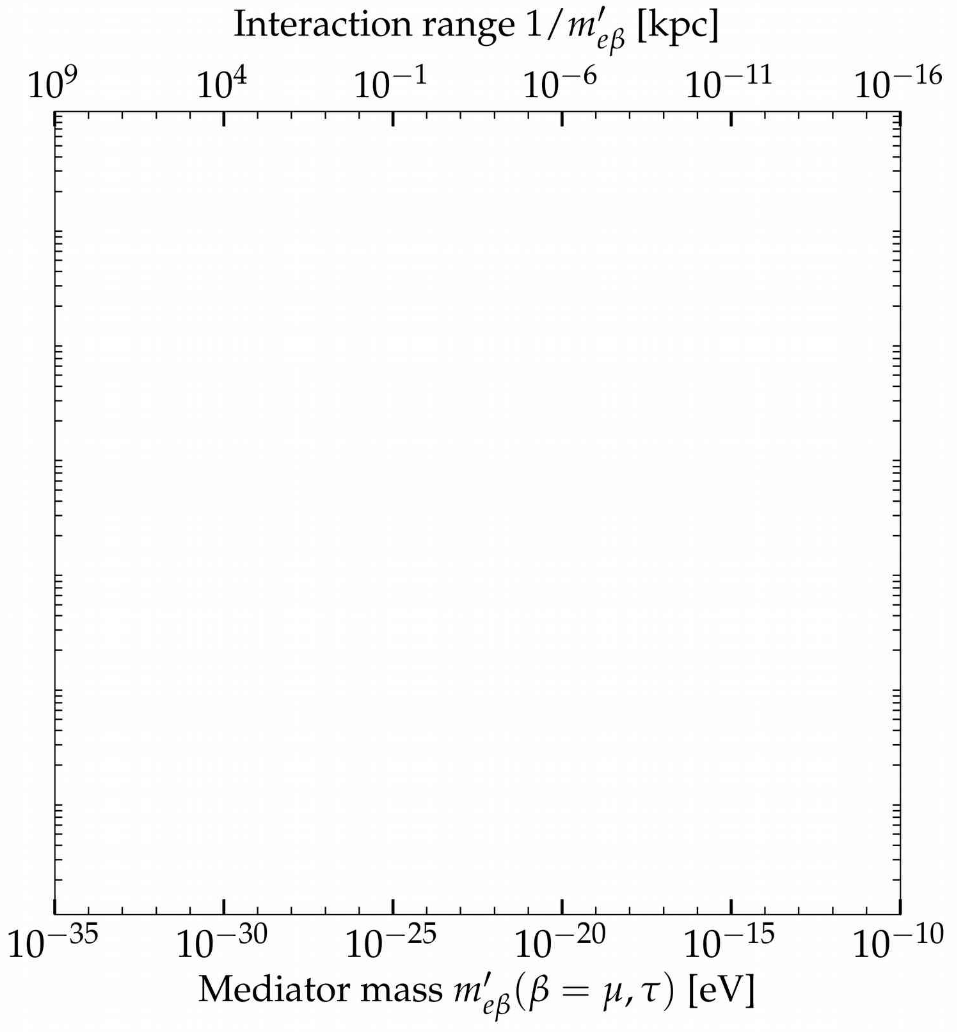
Interaction range: $\dfrac{1}{m'_{e\beta}}$

Electrons in the local and distant Universe



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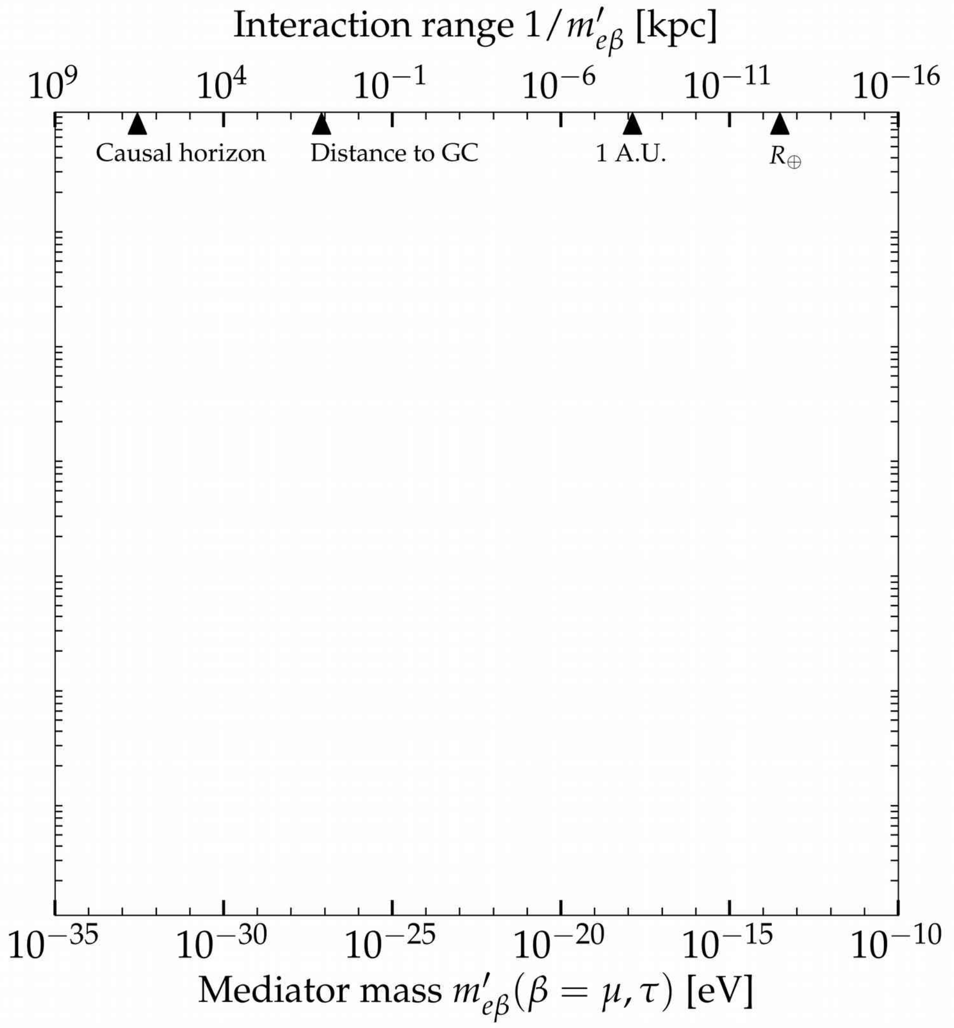

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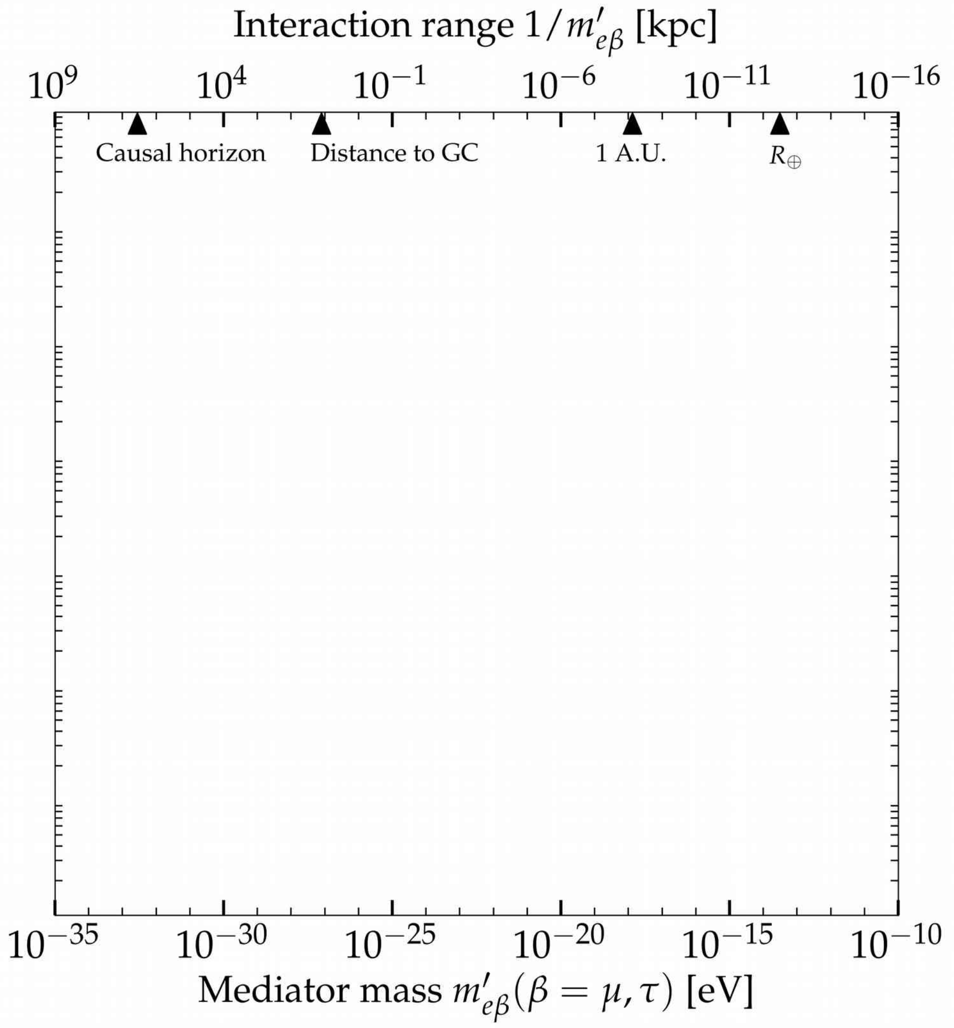

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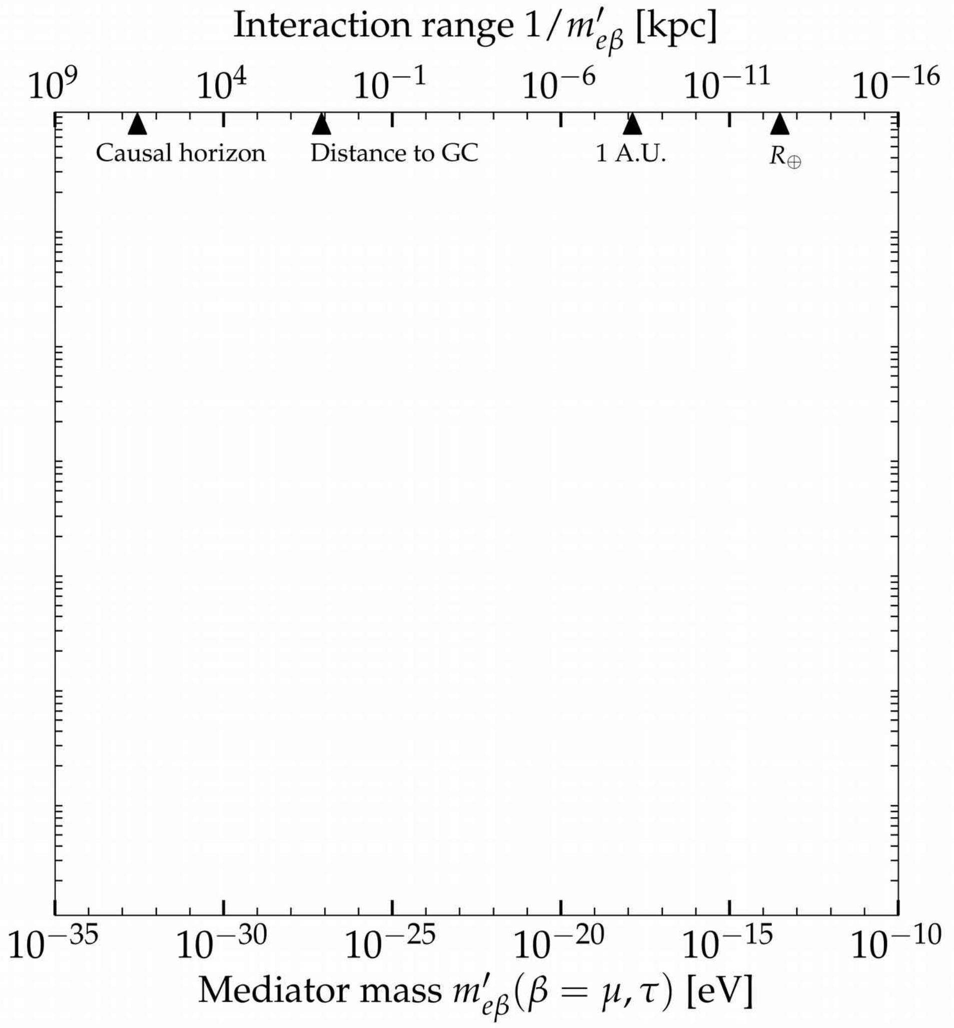
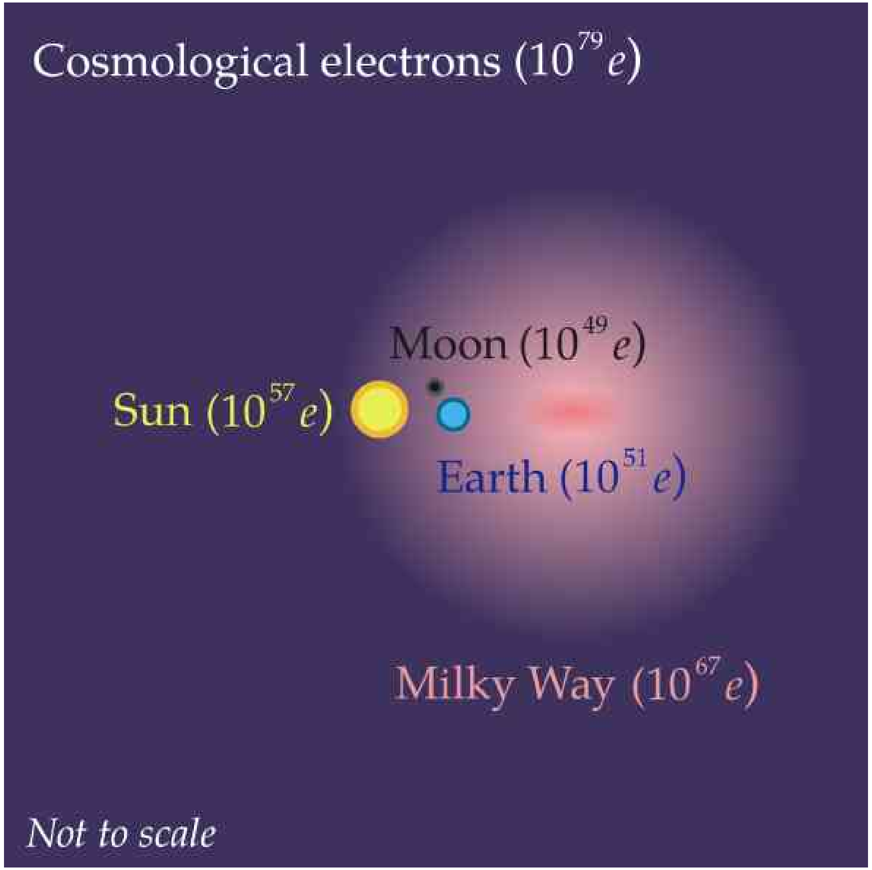
Interaction range: $\frac{1}{m'_{e\beta}}$

Light mediators
$\Rightarrow$ Long interaction ranges

Electrons in the local and distant Universe





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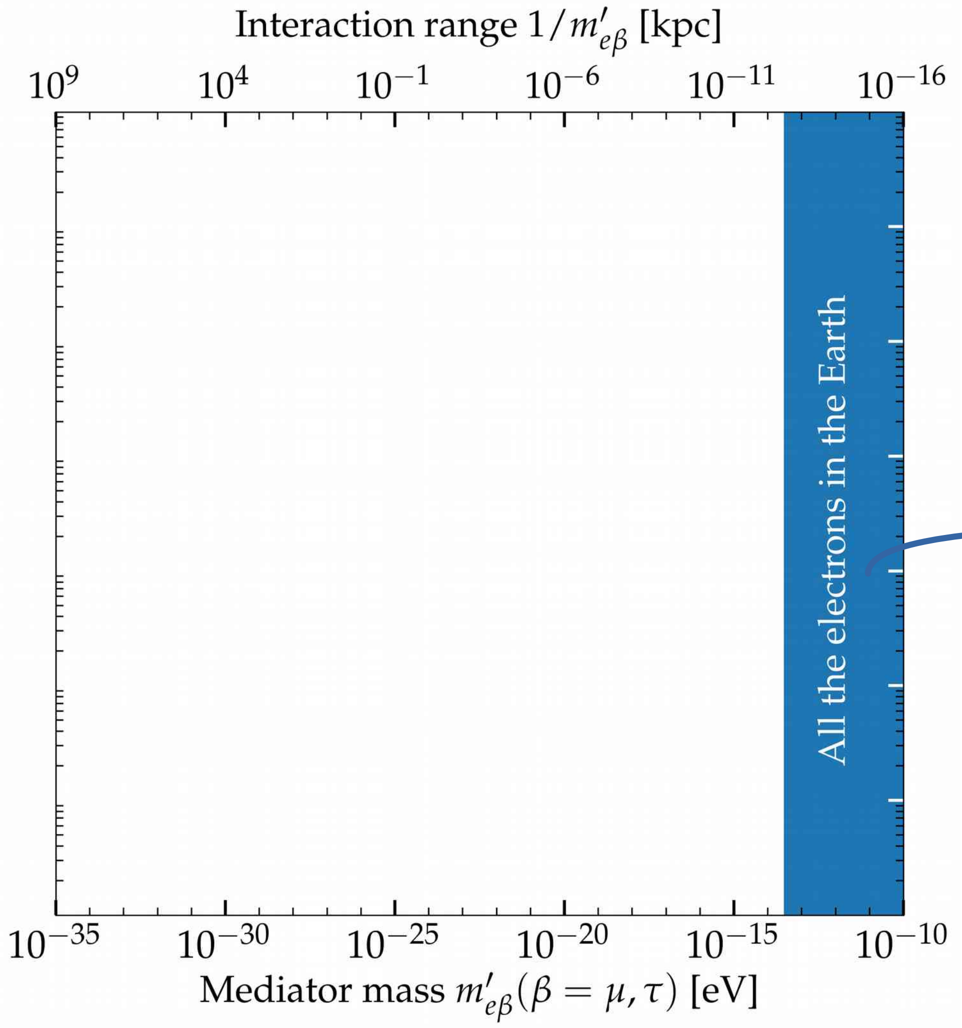

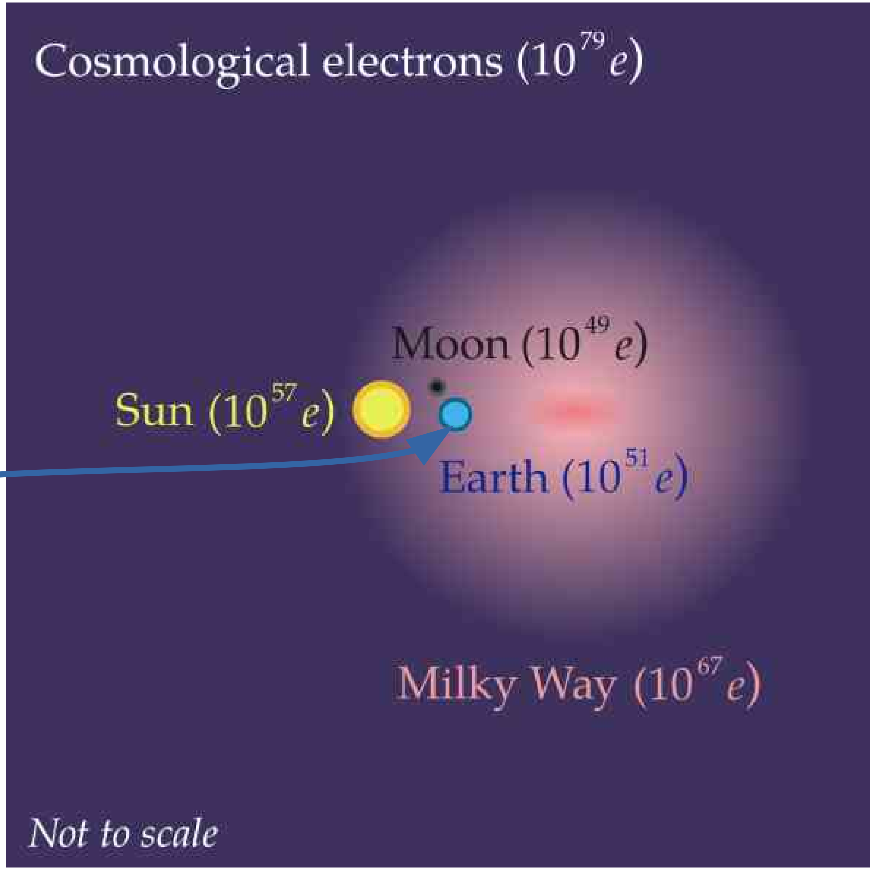

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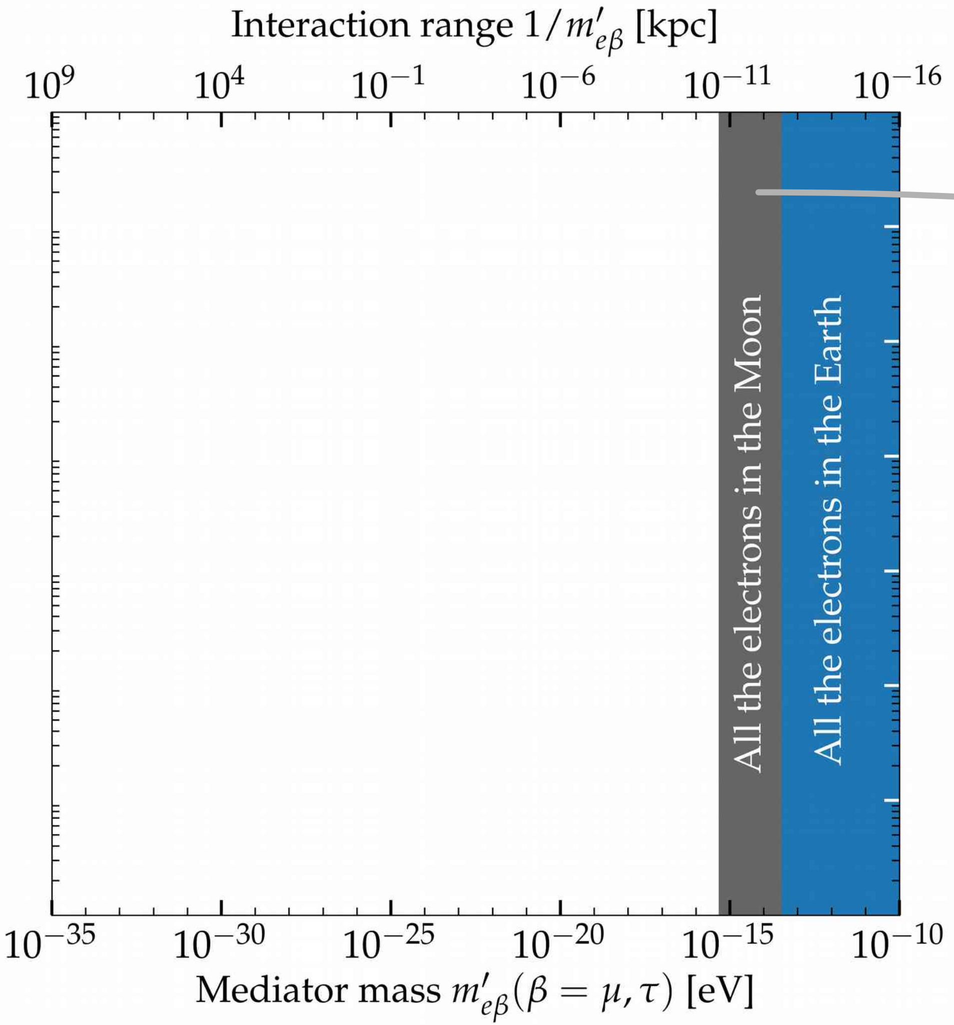

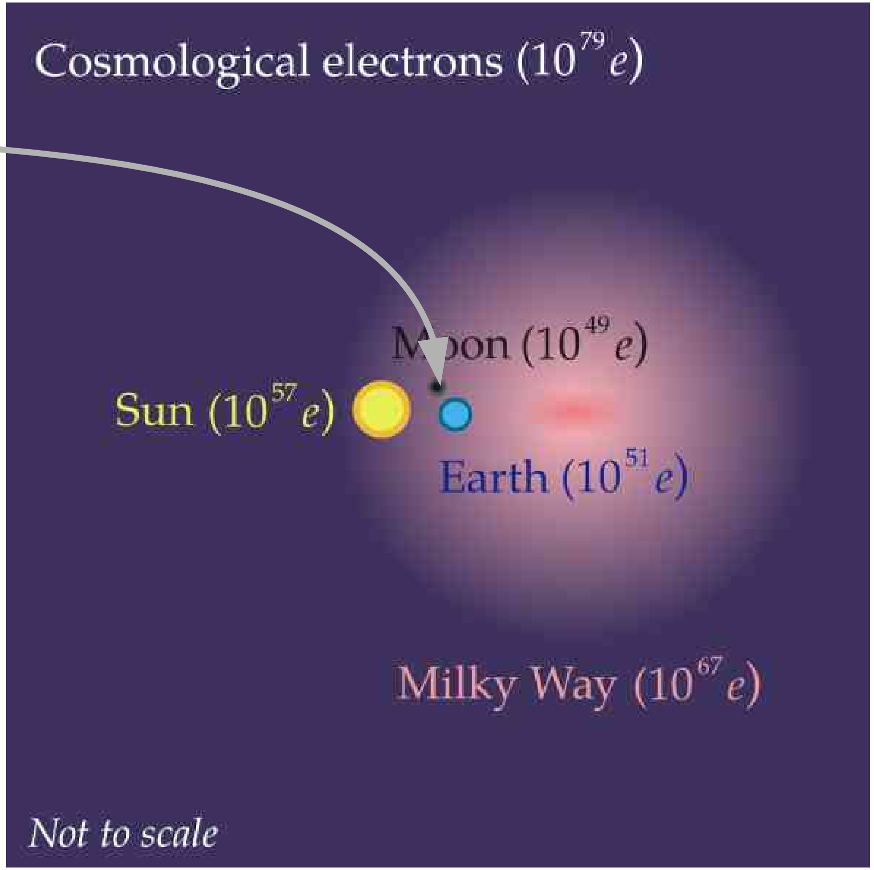

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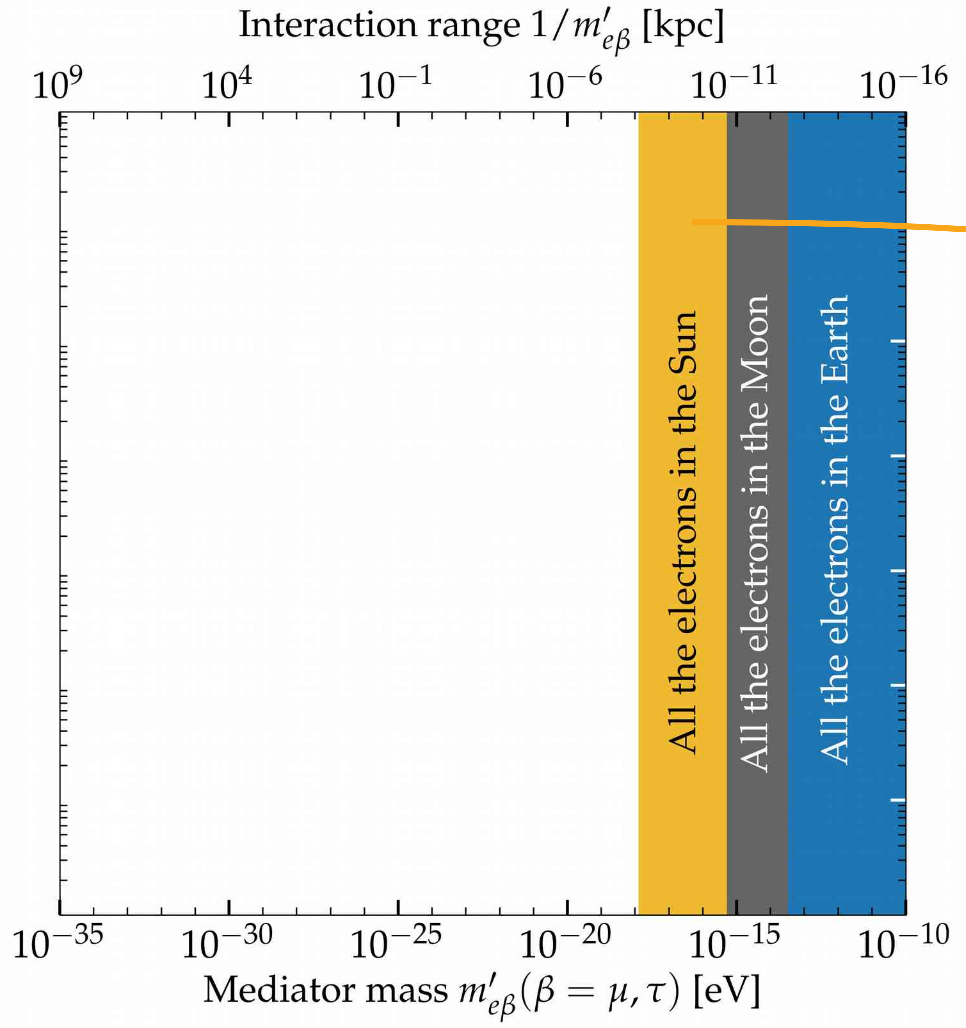
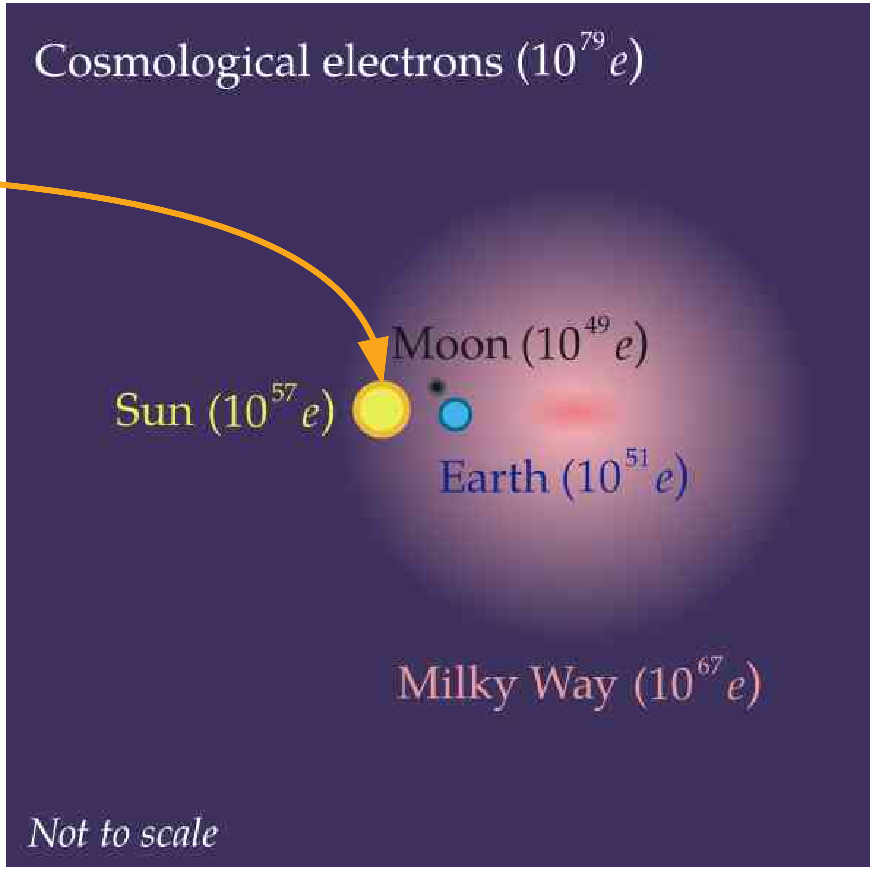
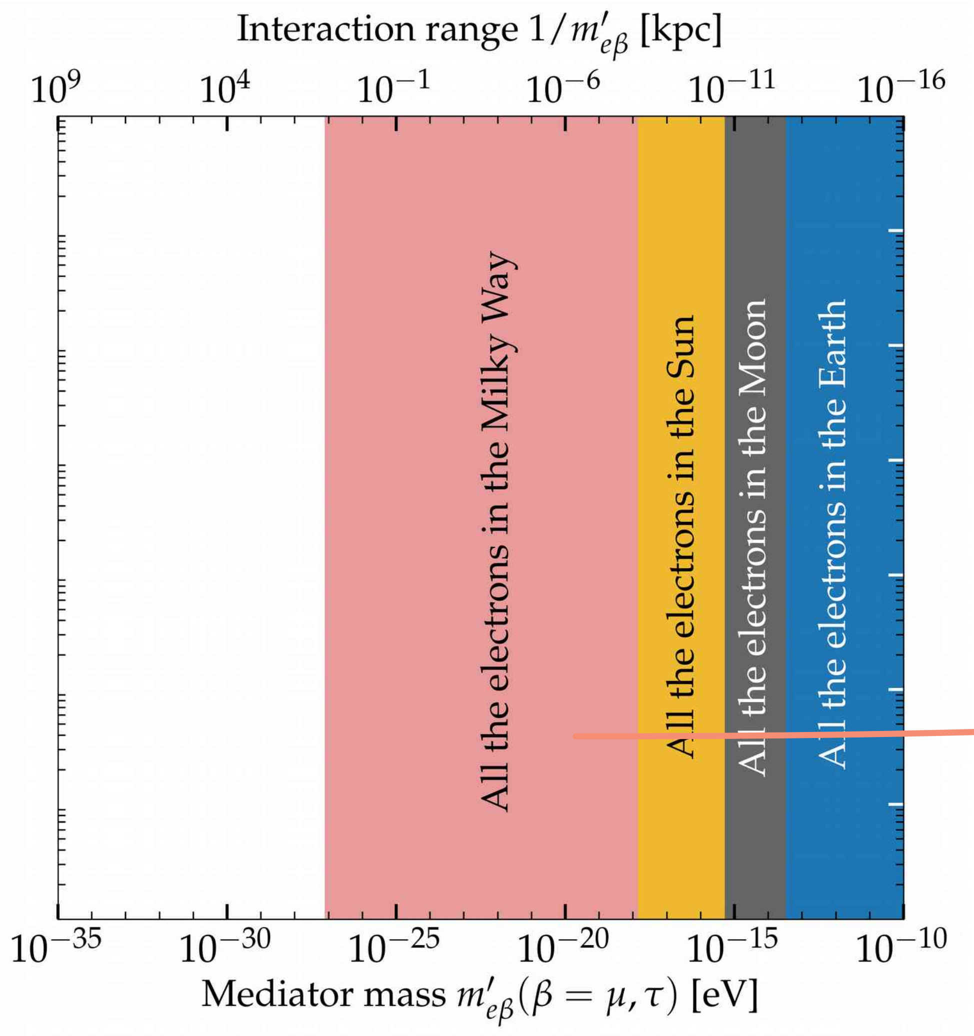
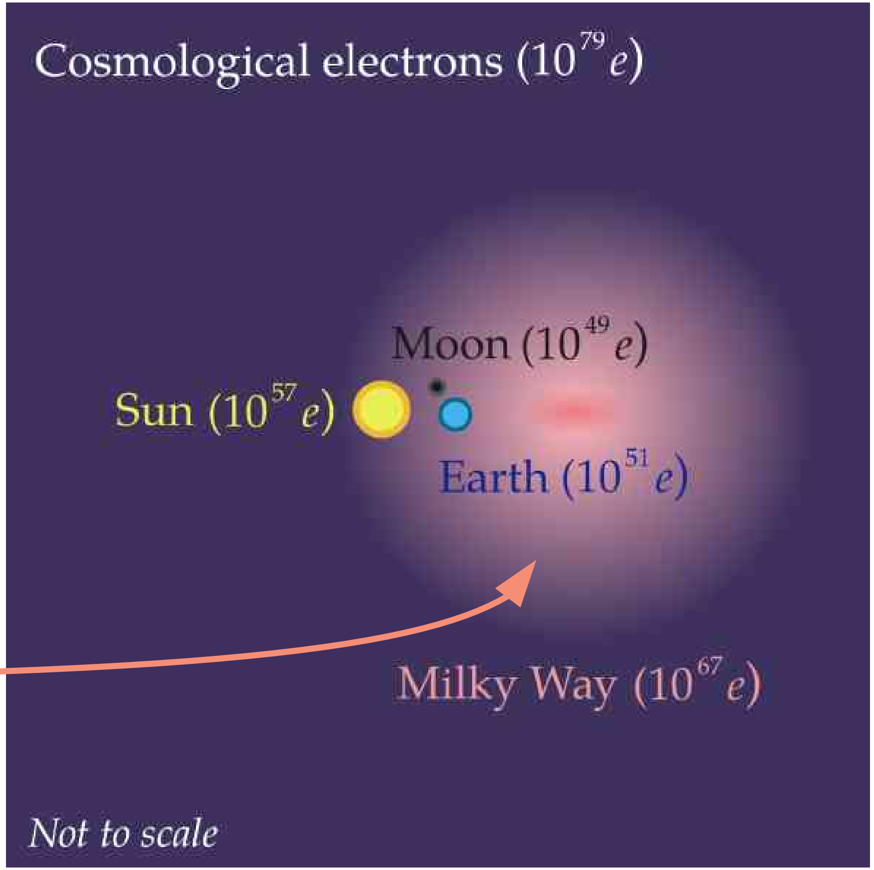




Electrons in the local and distant Universe





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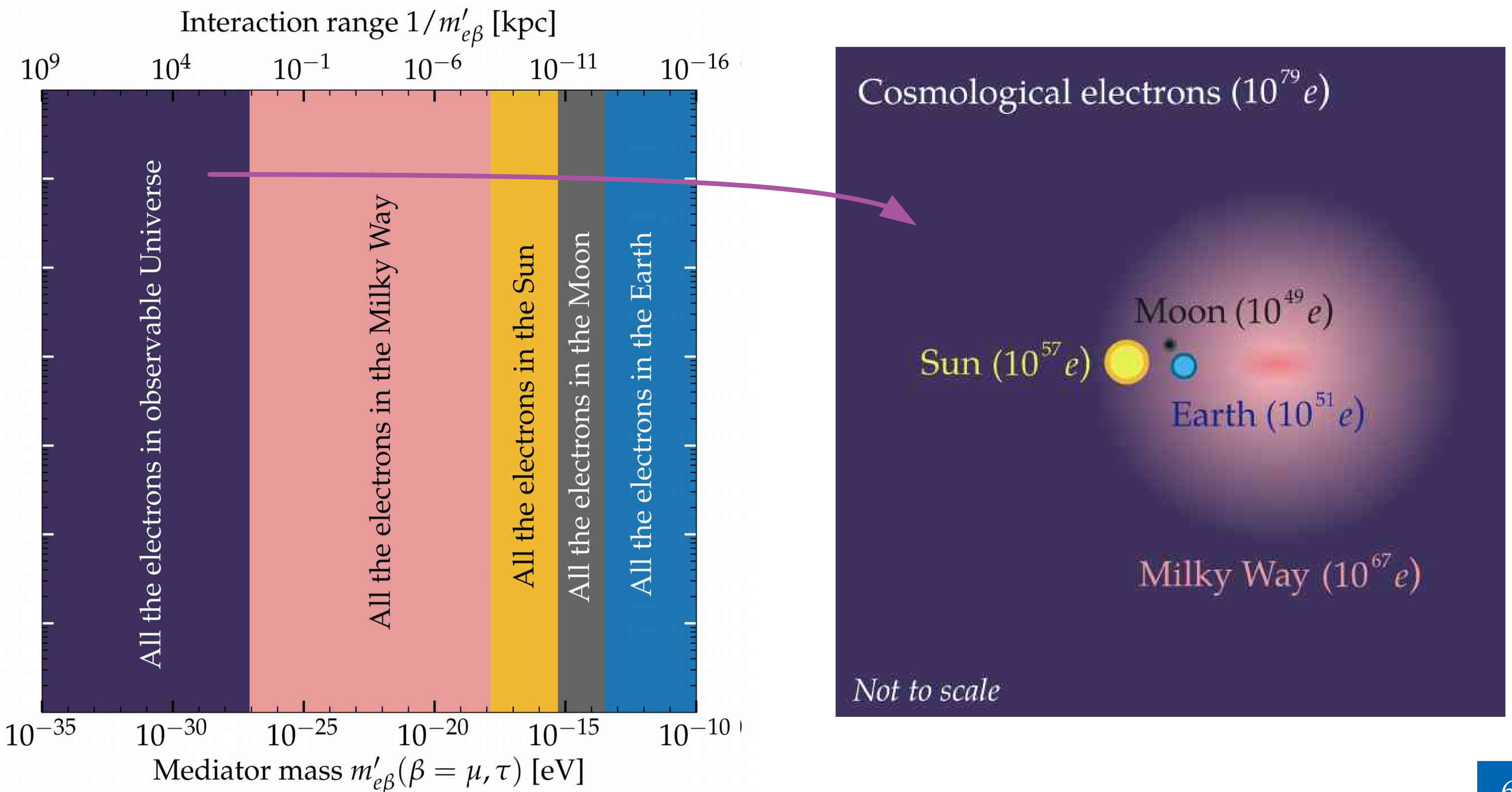
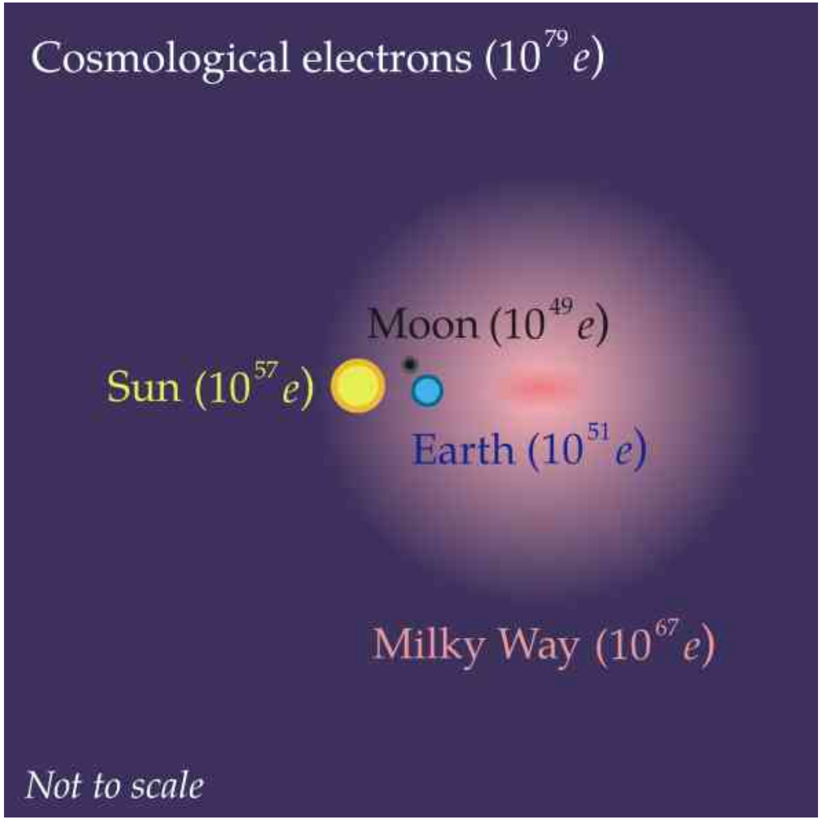


The total potential



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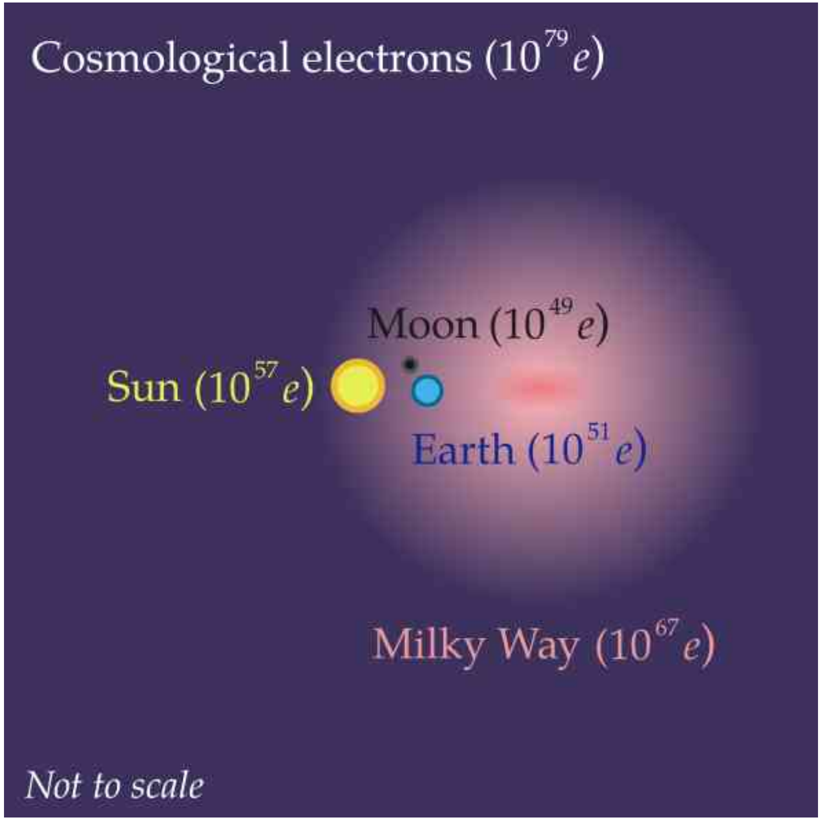
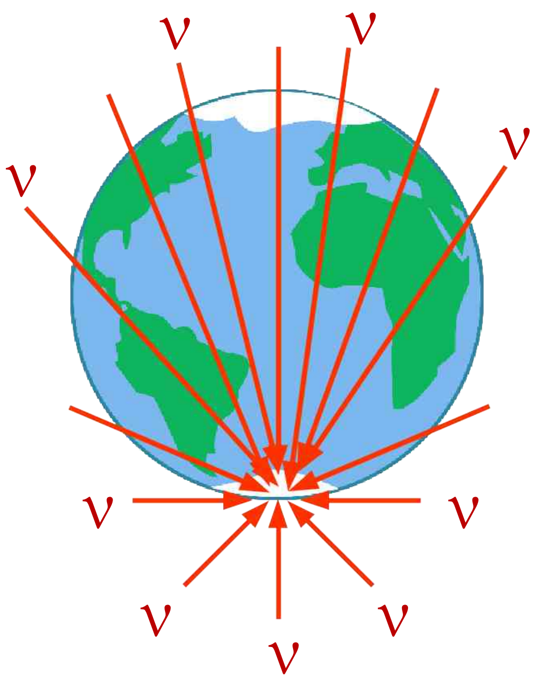


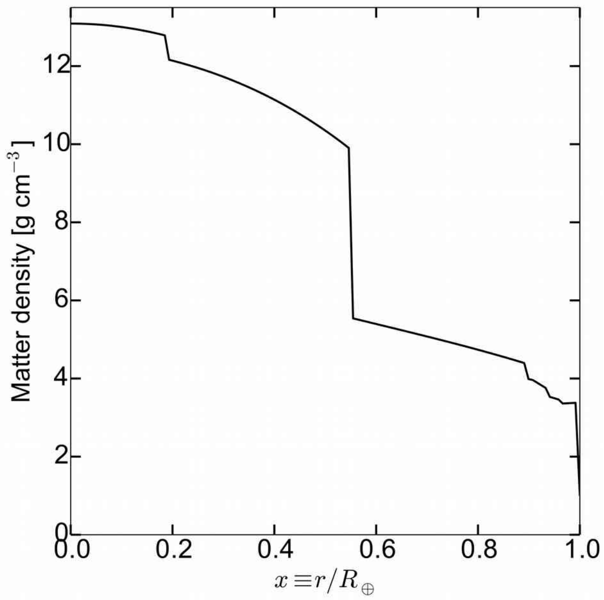
$$V_{e\beta} = V_{e\beta}^{\oplus}$$

Earth:



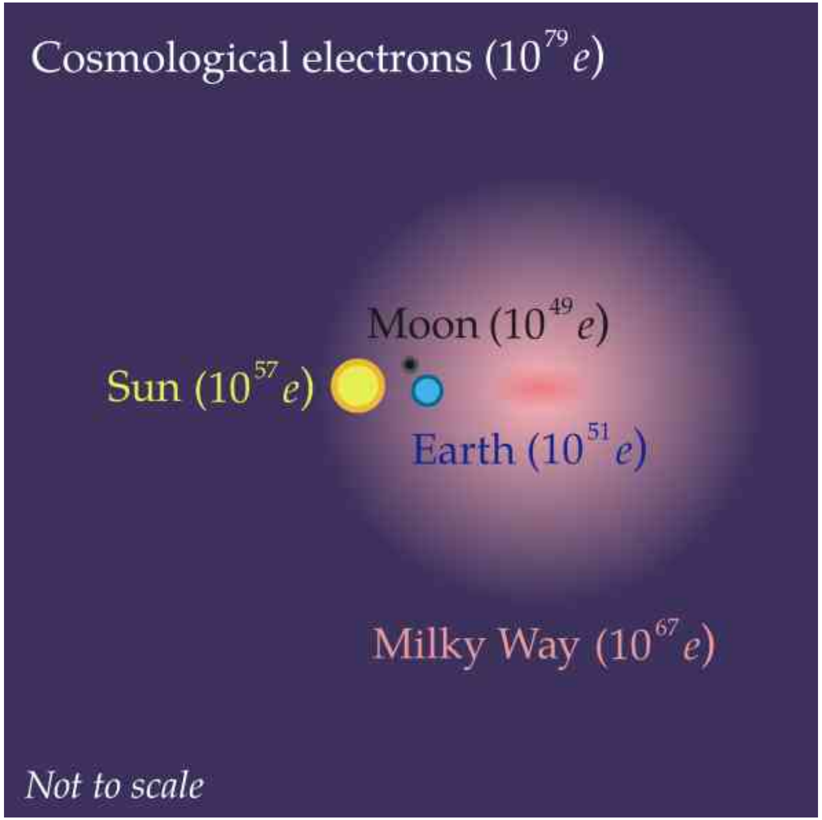
Preliminary Reference Earth Model

Dziewonski & Anderson 1981

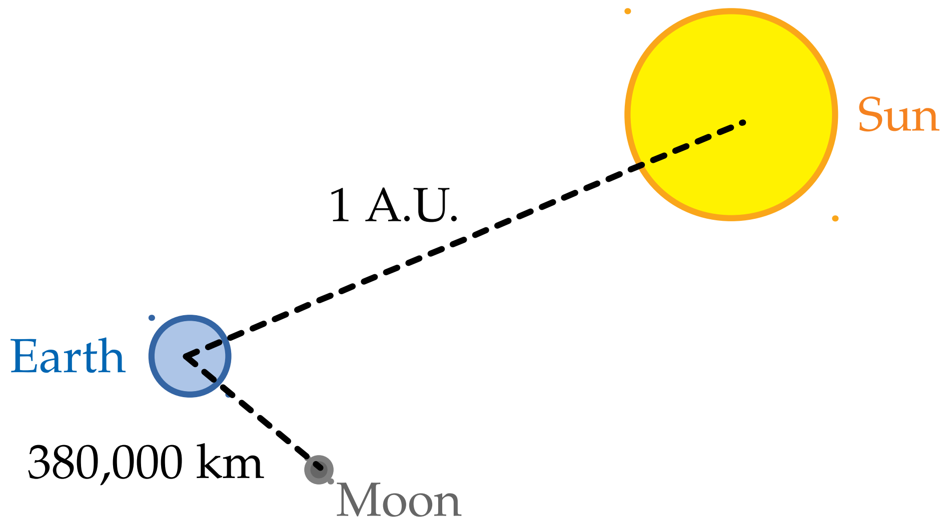


Neutrinos traverse different electron column depths

The total potential



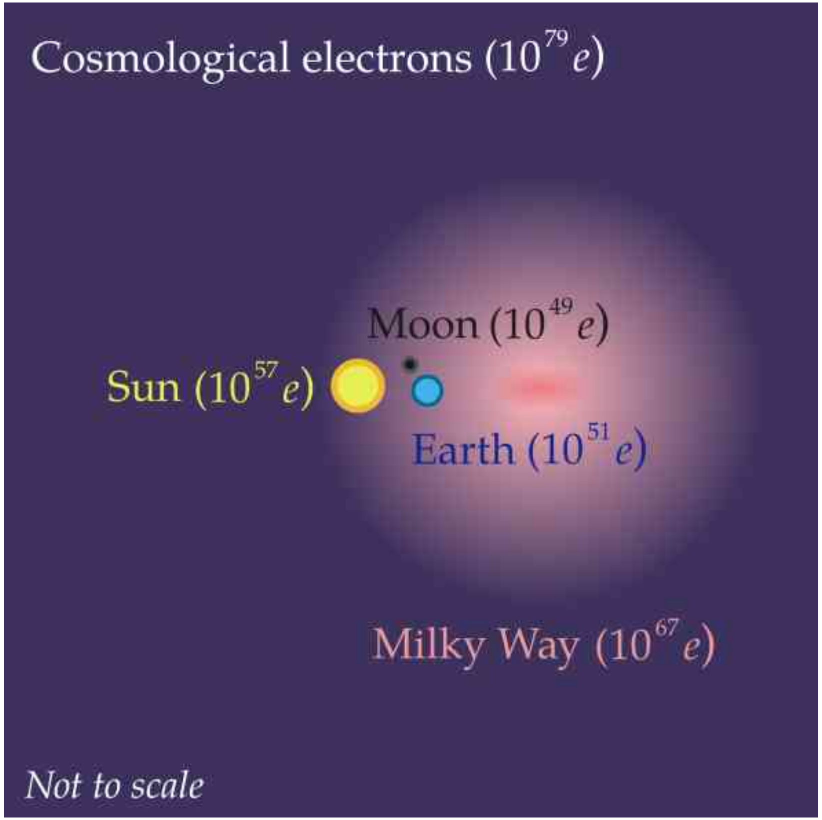
Moon and Sun:



Treated as point sources of electrons

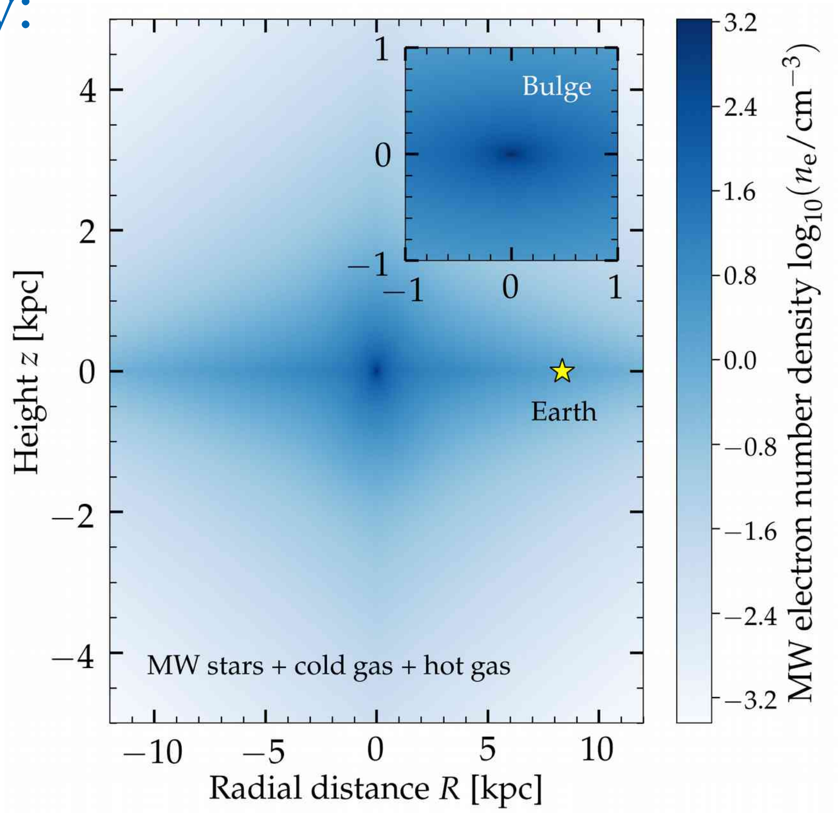
$$V_{e\beta} = V_{e\beta}^{\oplus} + V_{e\beta}^{\text{Moon}} + V_{e\beta}^{\odot}$$

The total potential



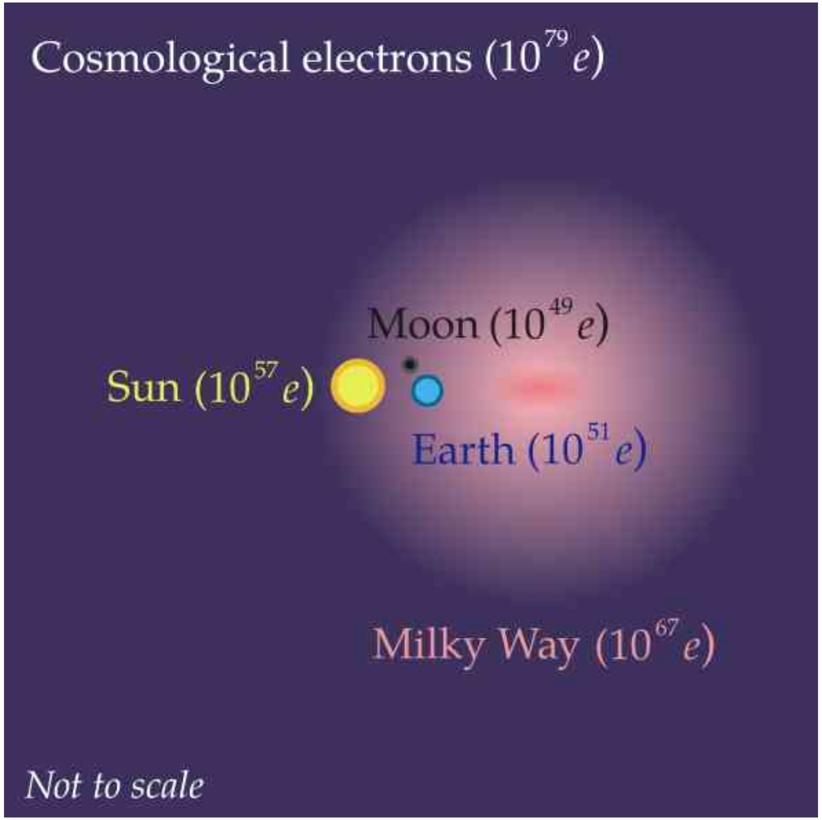
Milky Way:

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



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

The total potential



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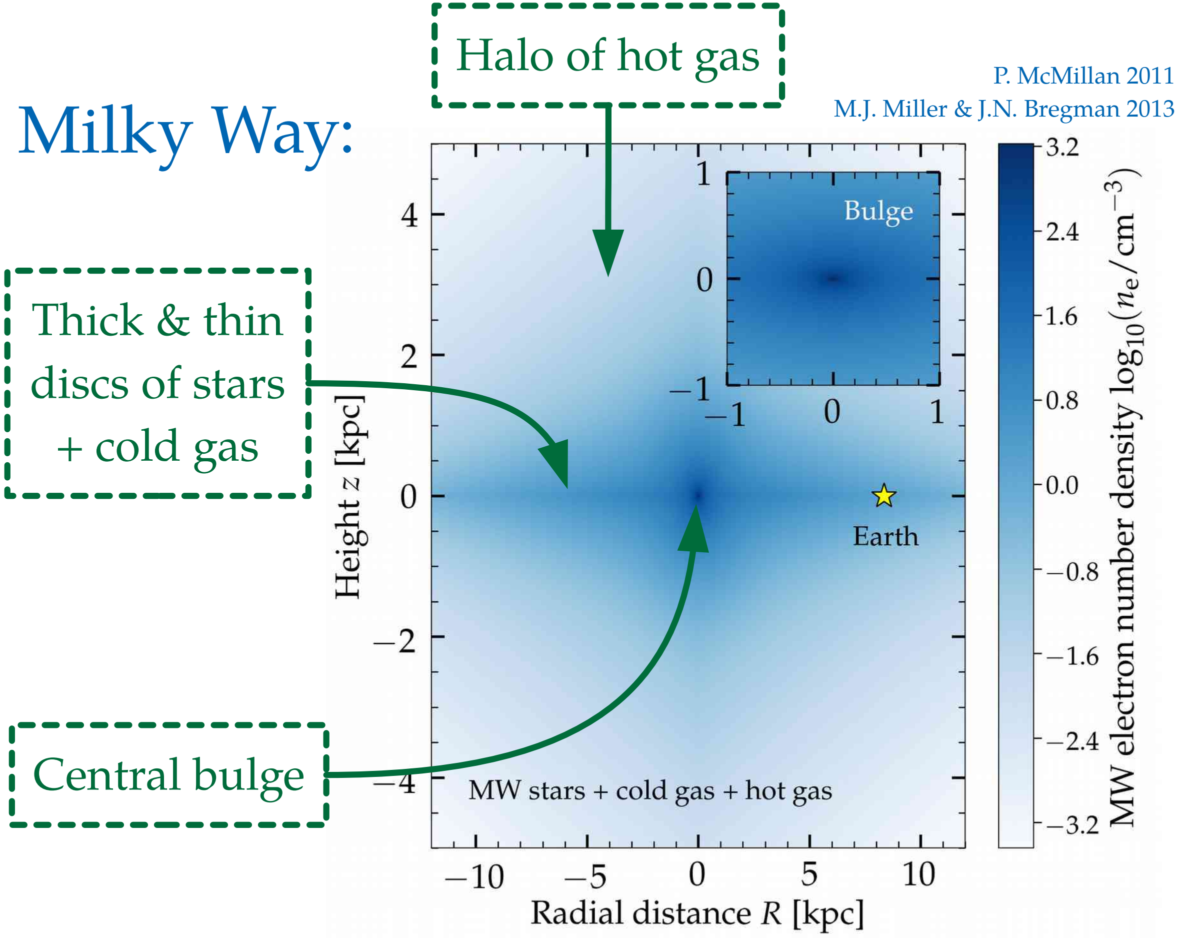

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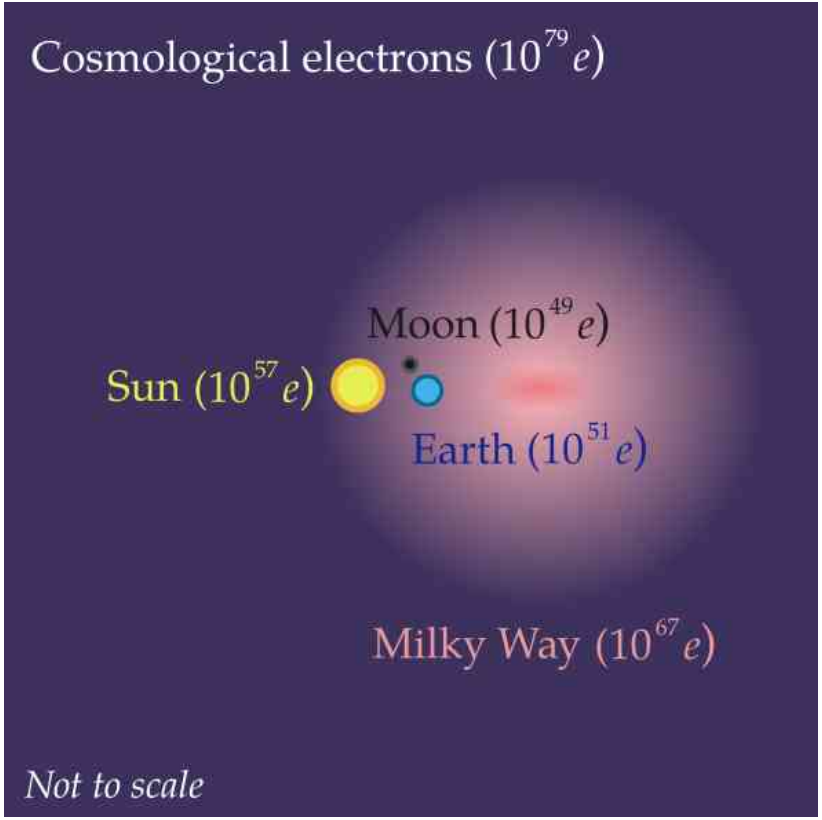
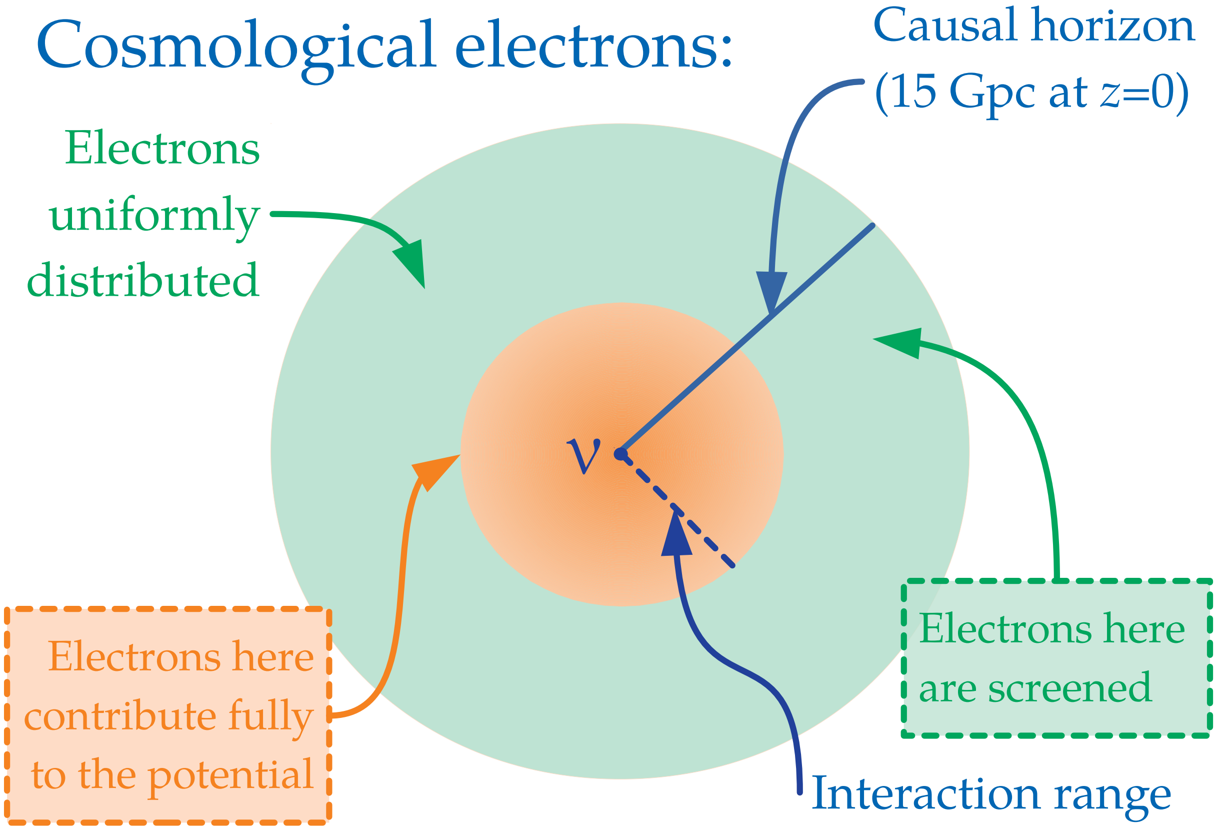
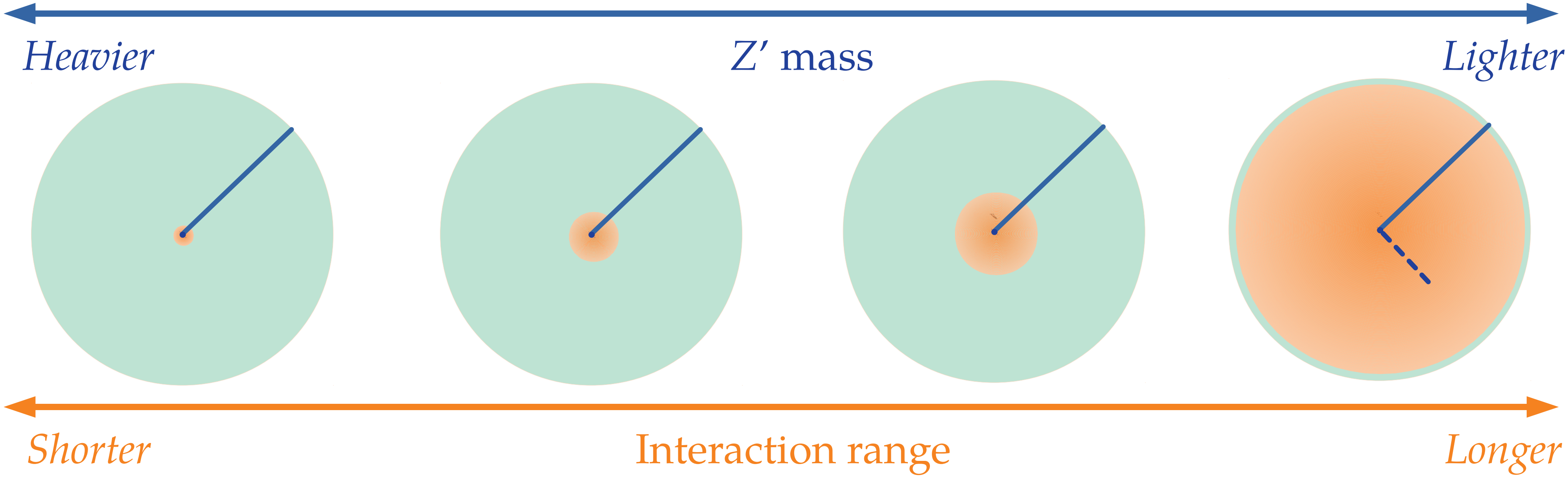


Cosmological electrons:



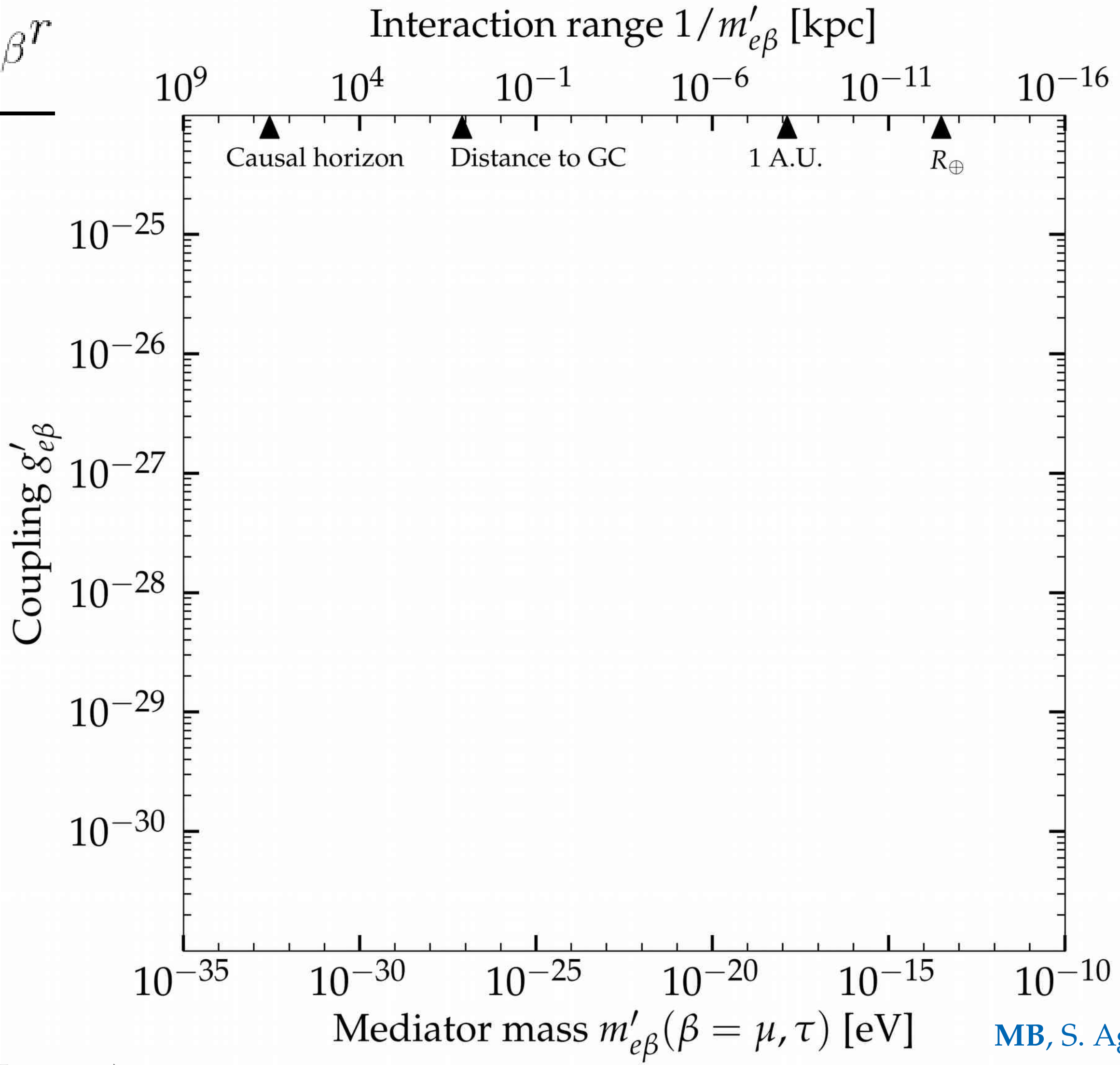
$$V_{e\beta} = V_{e\beta}^{\oplus} + V_{e\beta}^{\rm Moon} + V_{e\beta}^{\odot} + V_{e\beta}^{\rm MW} + V_{e\beta}^{\rm cos}$$

The total potential



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

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



MB, S. Agarwalla, 1808.02042

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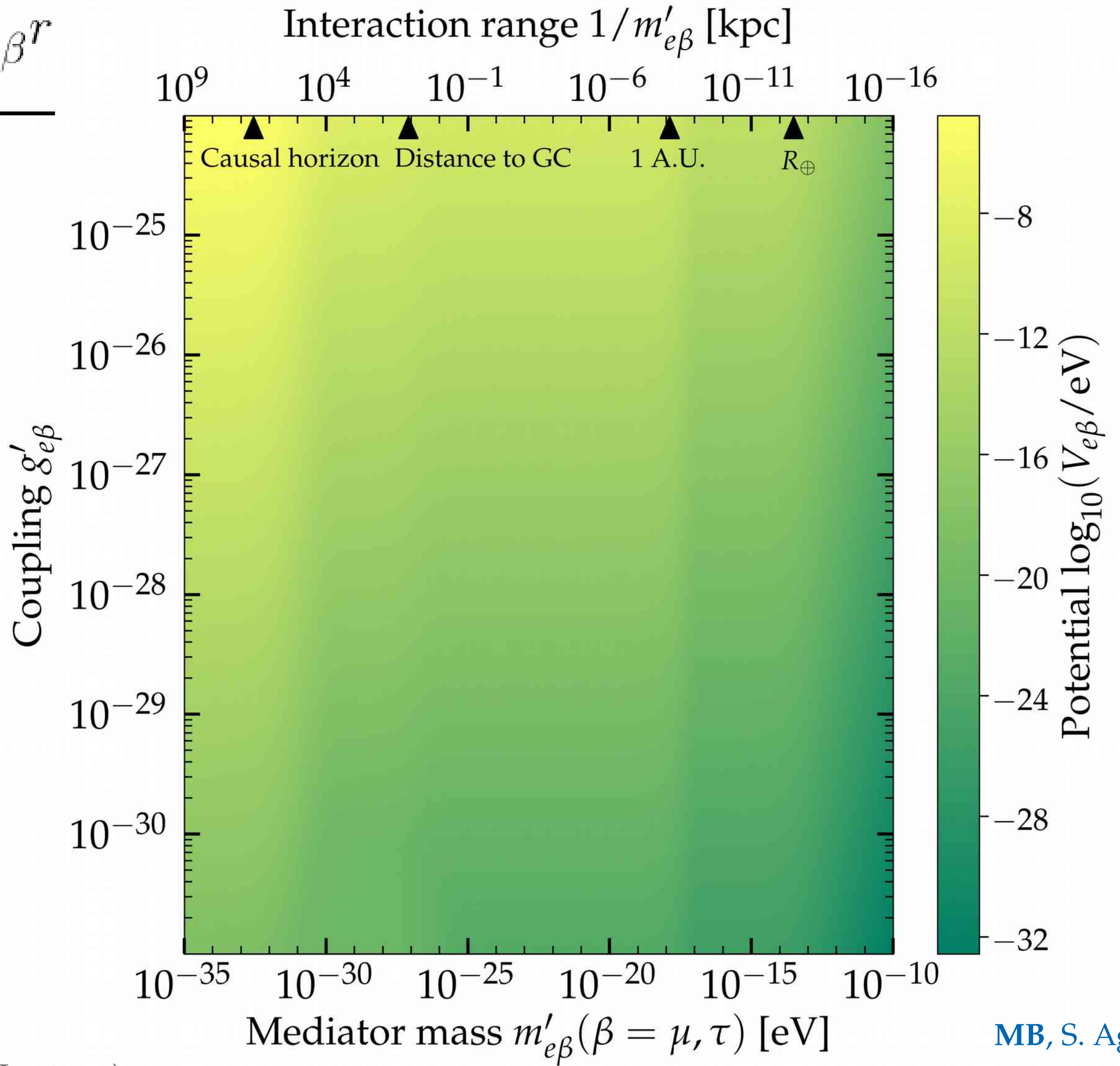
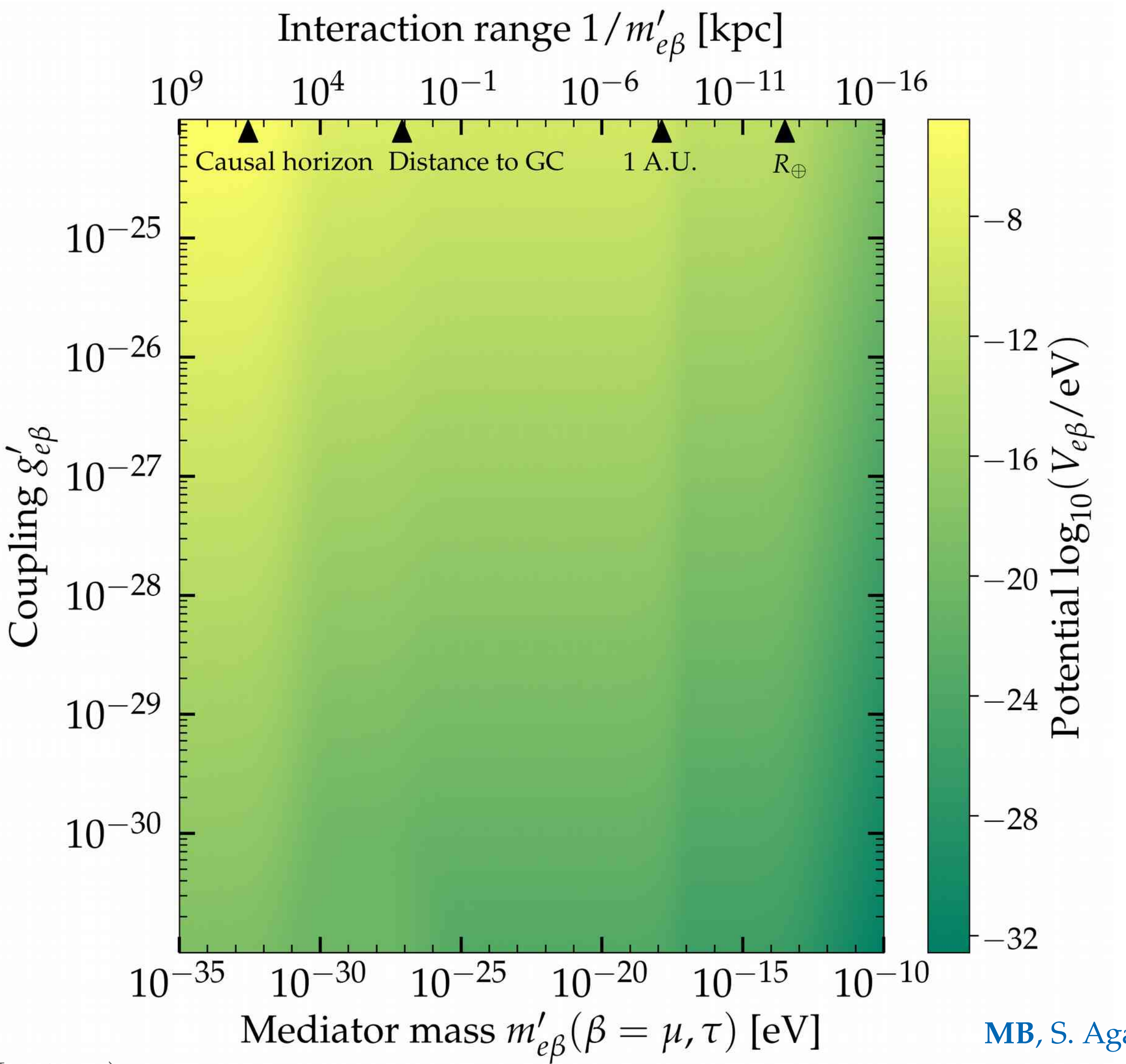


MB, S. Agarwalla, 1808.02042

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



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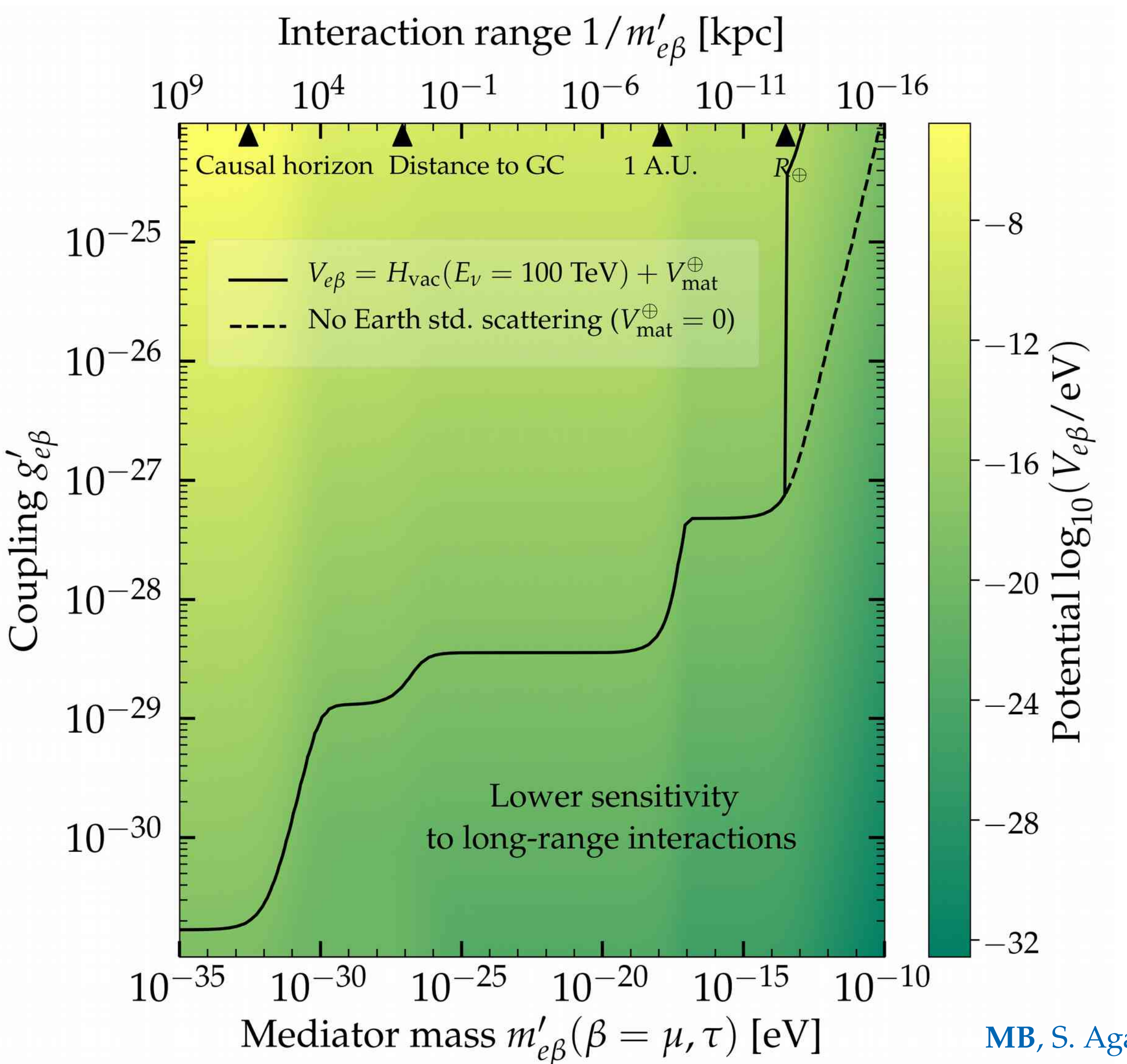

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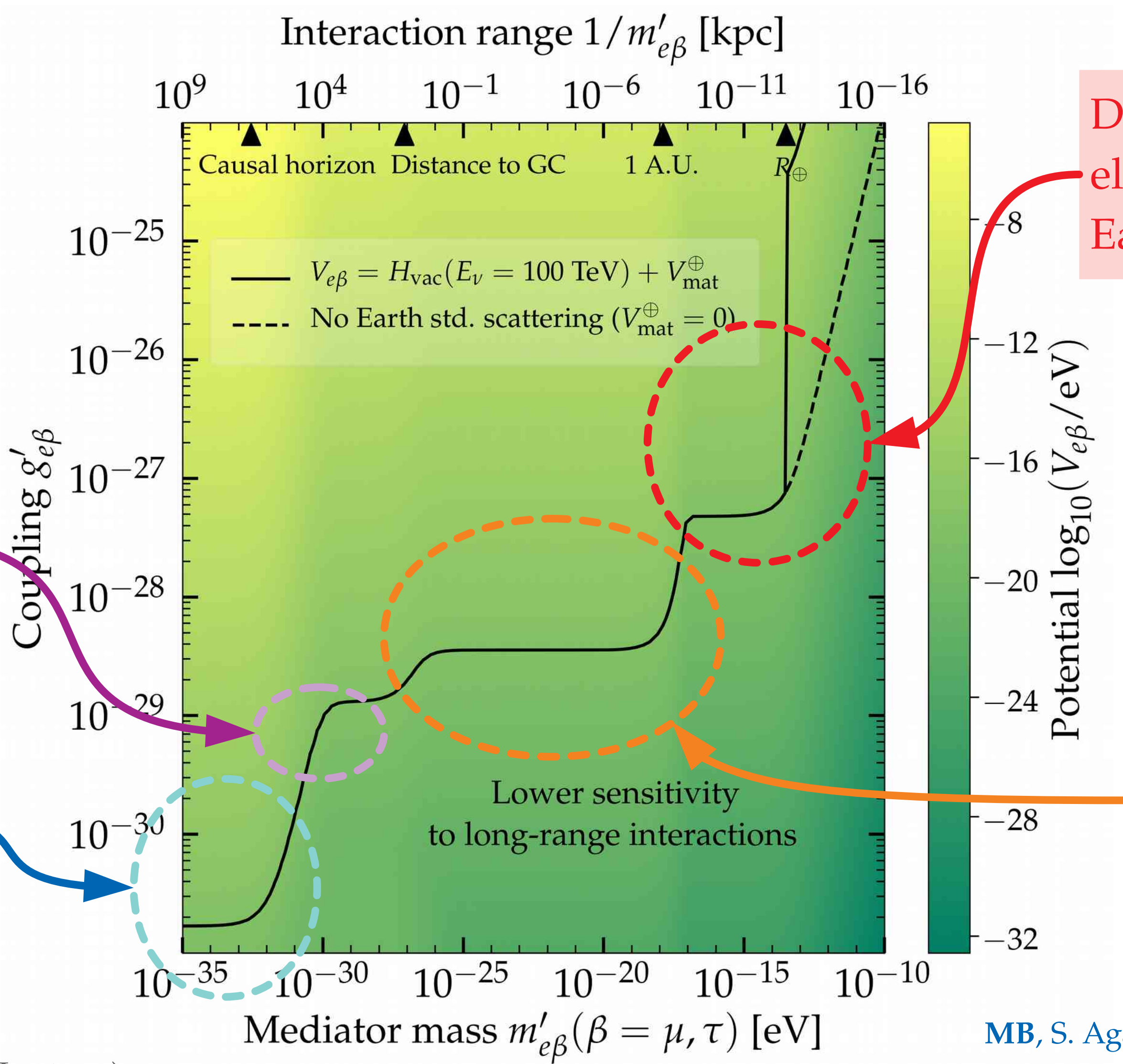
Dominated by Milky-Way *e*

Dominated by cosmological *e*

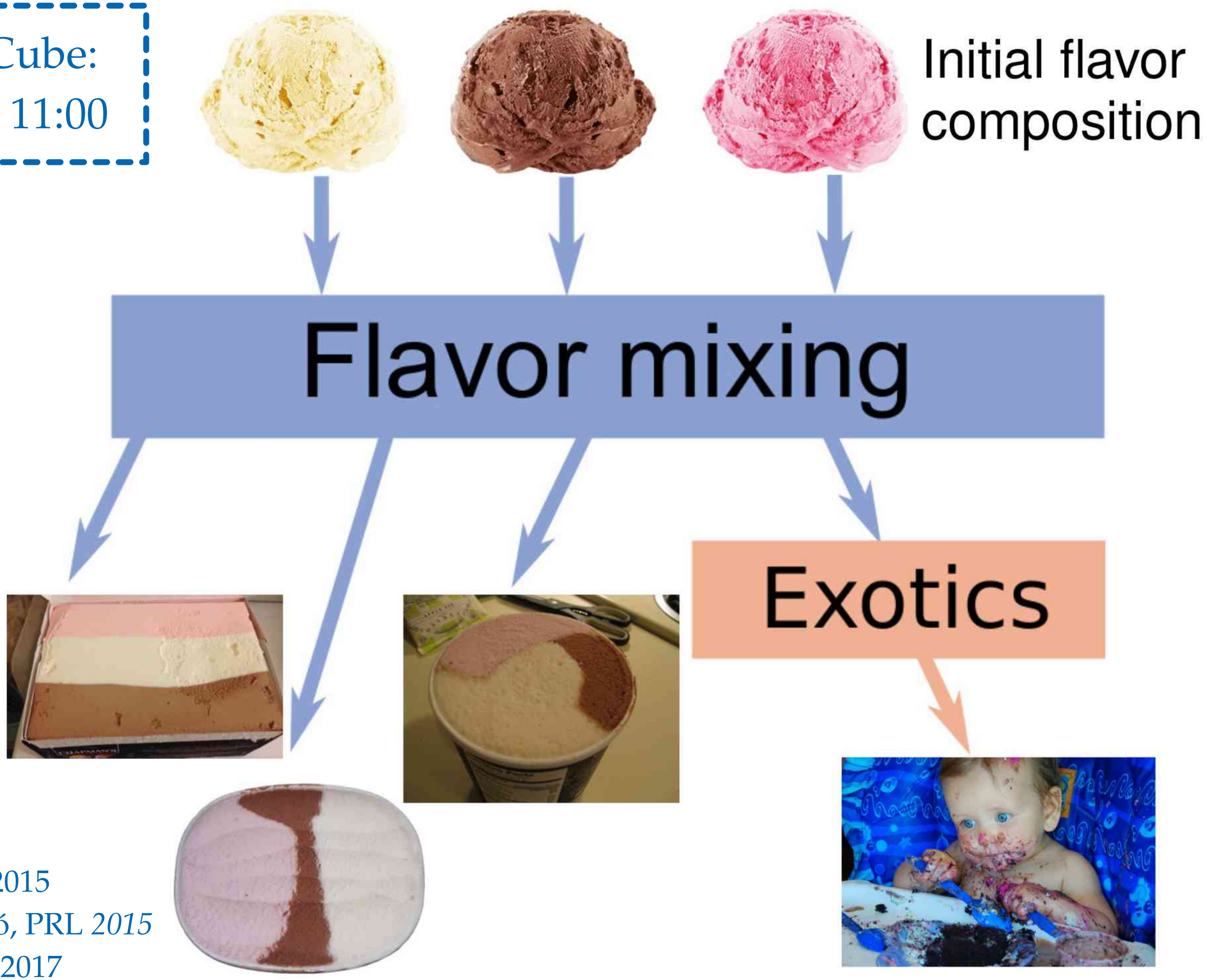


Dominated by electrons in the Earth + Moon

Dominated by solar electrons (+ Milky-Way *e*)

MB, S. Agarwalla, 1808.02042

New physics in IceCube:
Carlos Argüelles Fri 11:00

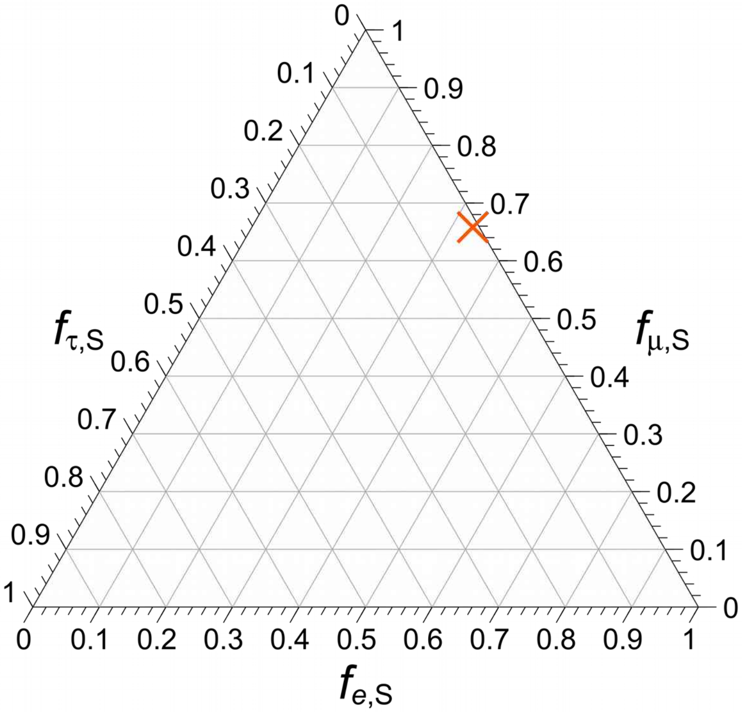


MB, J. Beacom, W. Winter, *PRL* 2015
C. Argüelles, T. Katori, J. Salvadó, PRL *2015*
MB, J. Beacom, K. Murase, *PRD* 2017
R. Rasmussen *et al.*, *PRD* 2017

Flavor – there and here

At the sources

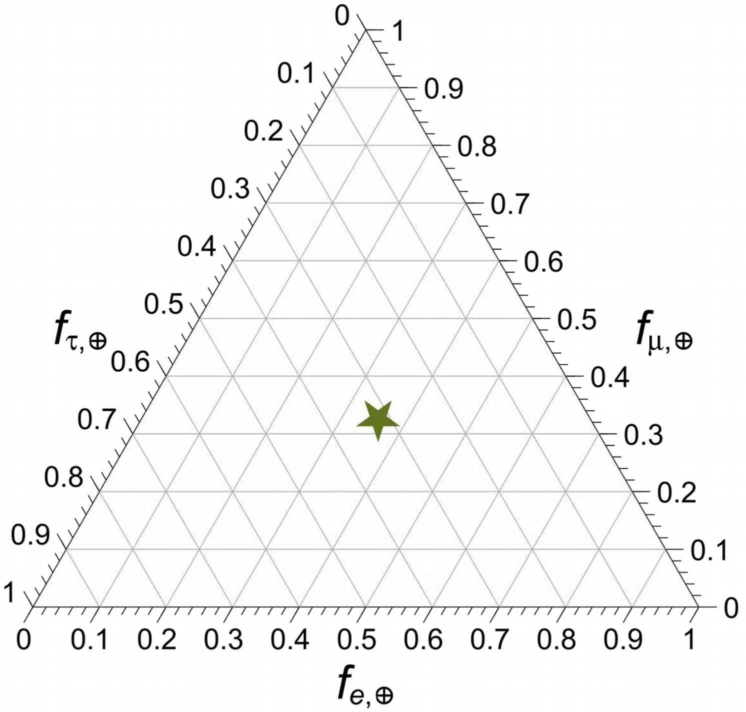
$$(f_e{:}f_\mu{:}f_\tau)_S = (1/3 : 2/3 : 0)_S$$



Neutrino oscillations

At Earth

$$(0.36 : 0.32 : 0.32)_\oplus$$



Flavor – there and here

$$p + \gamma \rightarrow \bar{\nu}_\mu + \nu_\mu + \nu_e$$

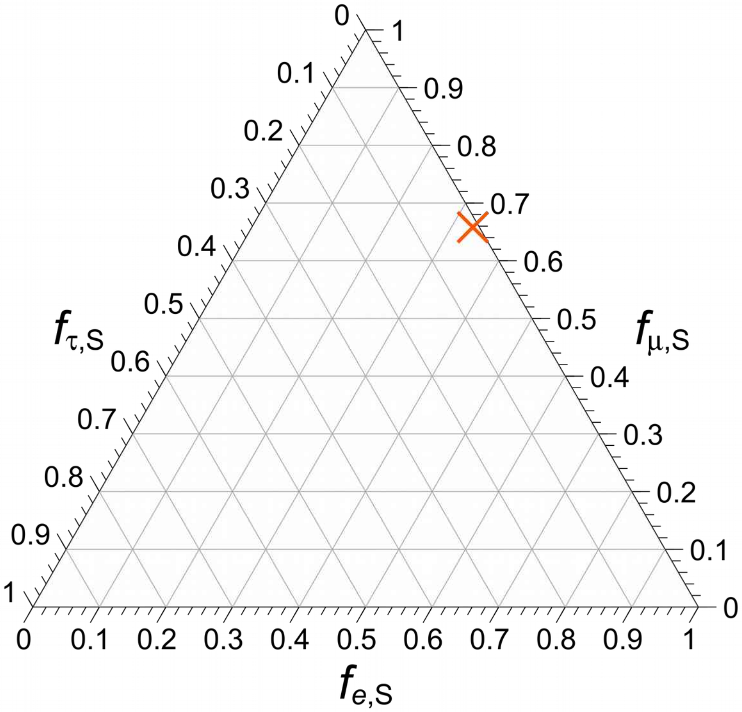
At the sources

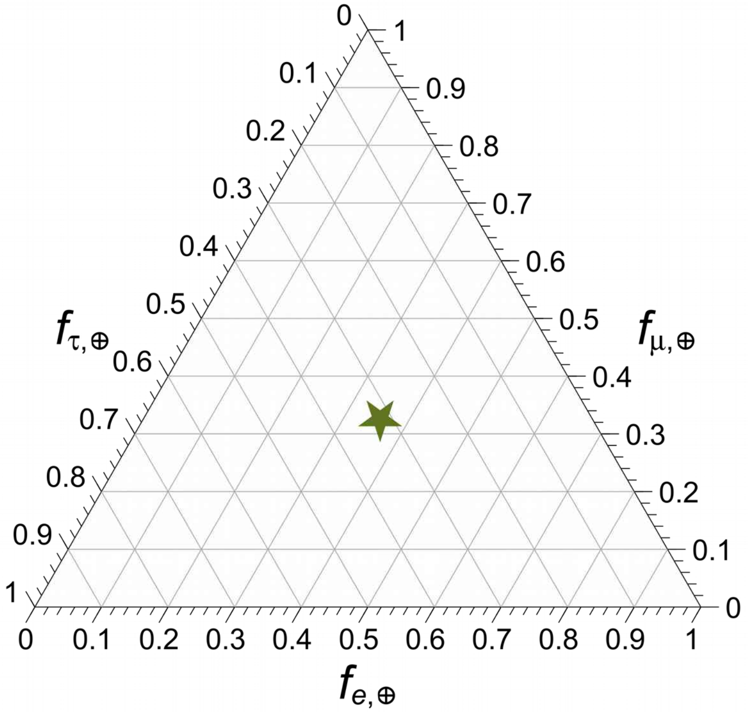
Neutrino oscillations

At Earth

$$(f_e{:}f_\mu{:}f_\tau)_S = (1/3 : 2/3 : 0)_S$$

$$(0.36 : 0.32 : 0.32)_\oplus$$





Flavor – there and here

$p + \gamma \rightarrow \bar{\nu}_\mu + \nu_\mu + \nu_e$

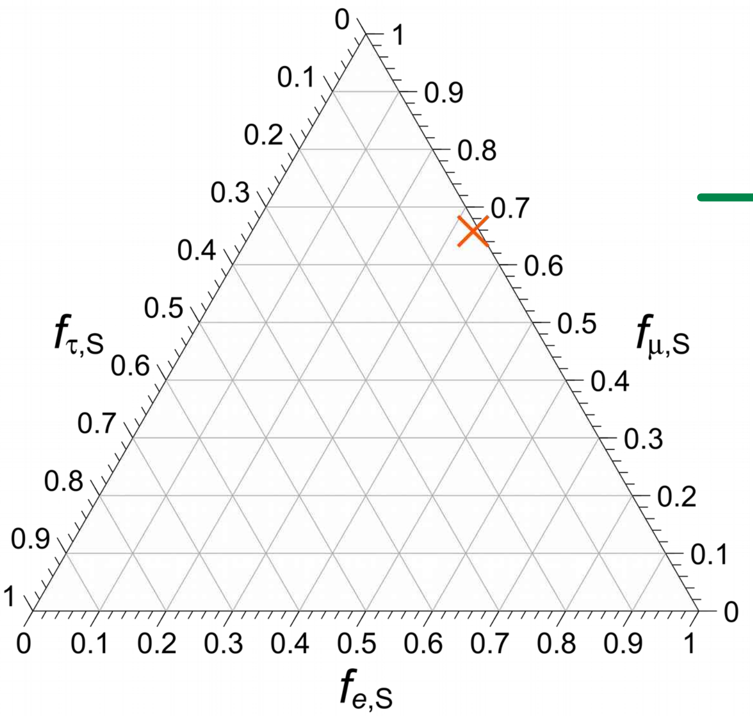
At the sources

$(f_e:f_\mu:f_\tau)_S = (1/3 : 2/3 : 0)_S$

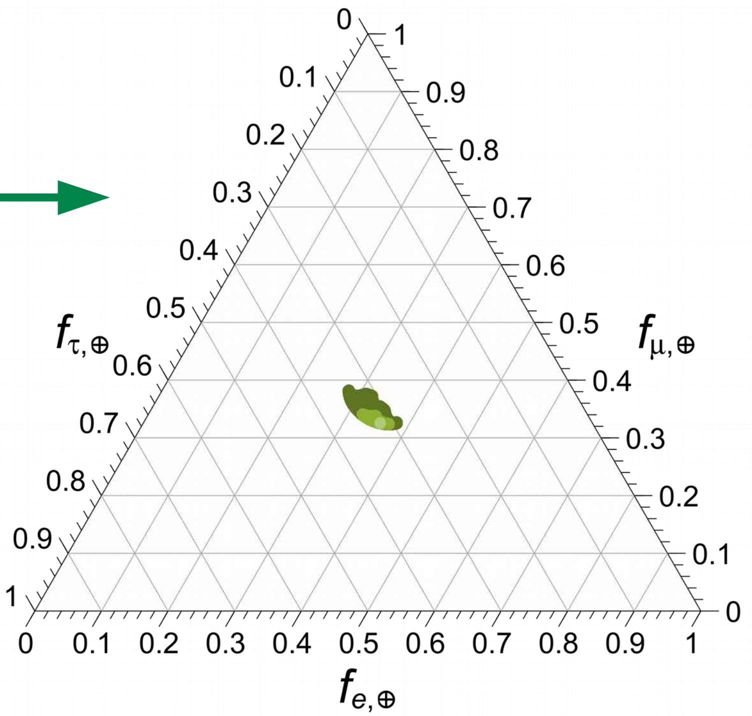
Neutrino oscillations

At Earth

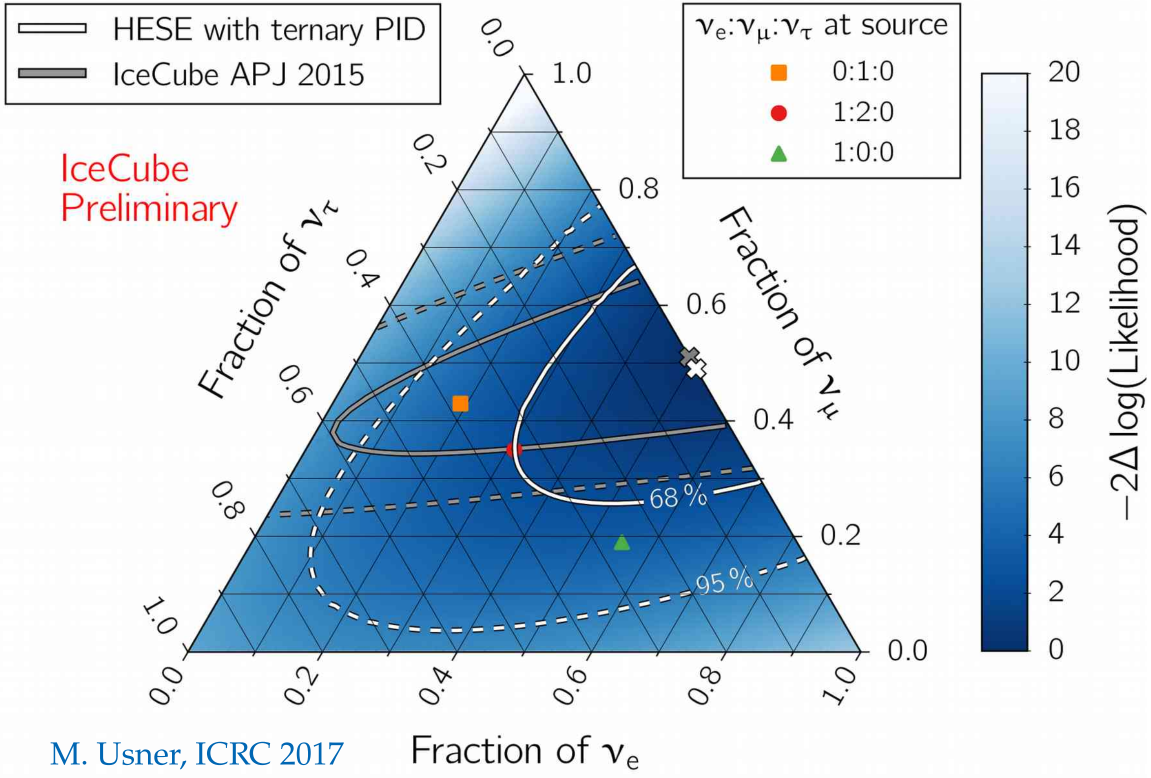
$(0.36 : 0.32 : 0.32)_\oplus$



Uncertainties in values of mixing parameter (1σ, 3σ)



IceCube analysis of flavor composition (pre-Neutrino 2018)



M. Usner, ICRC 2017

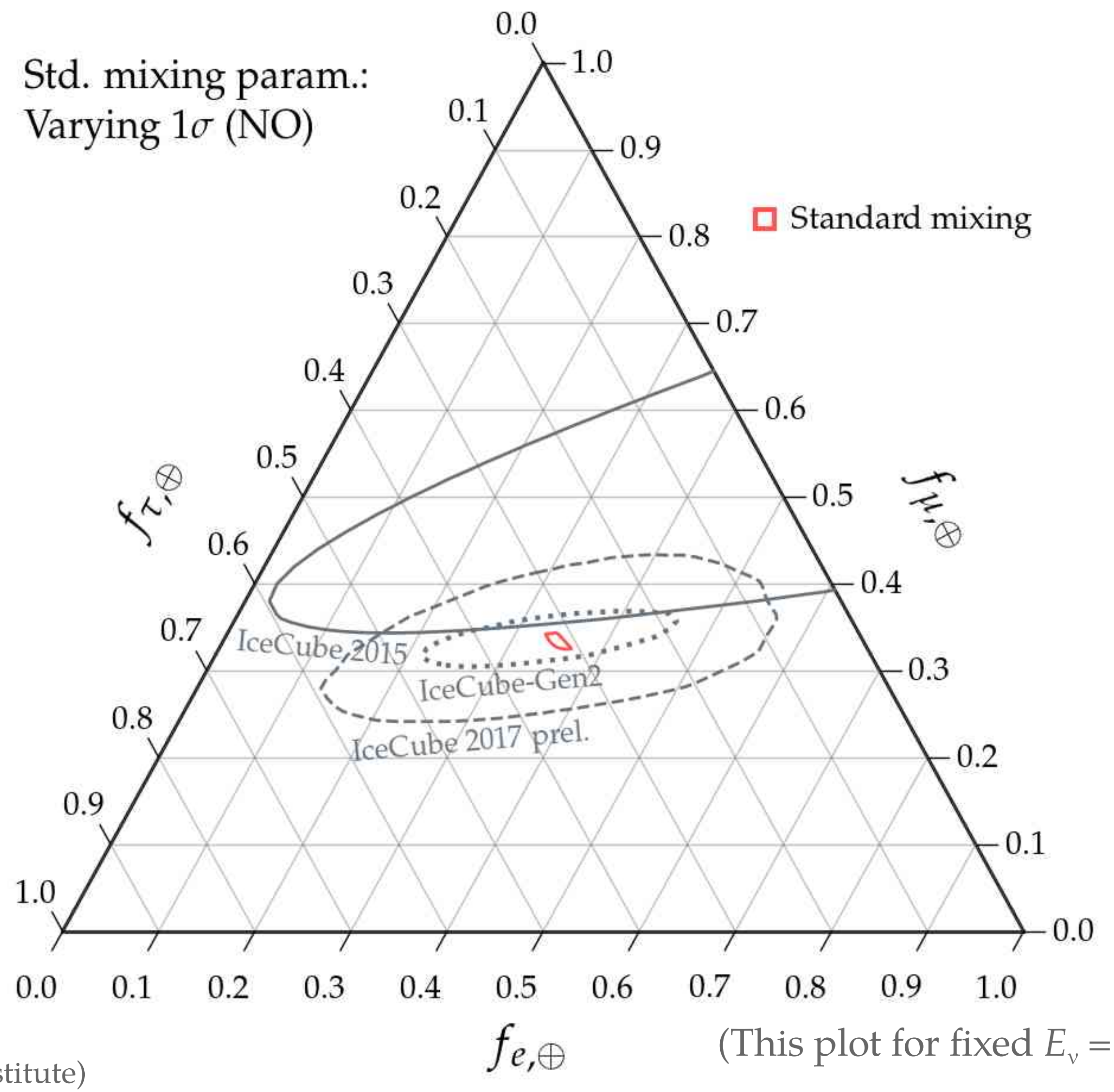
- Best (published) fit:

$$(f_e : f_\mu : f_\tau)_\oplus = (0.49 : 0.51 : 0)_\oplus$$

- Compatible with standard source compositions

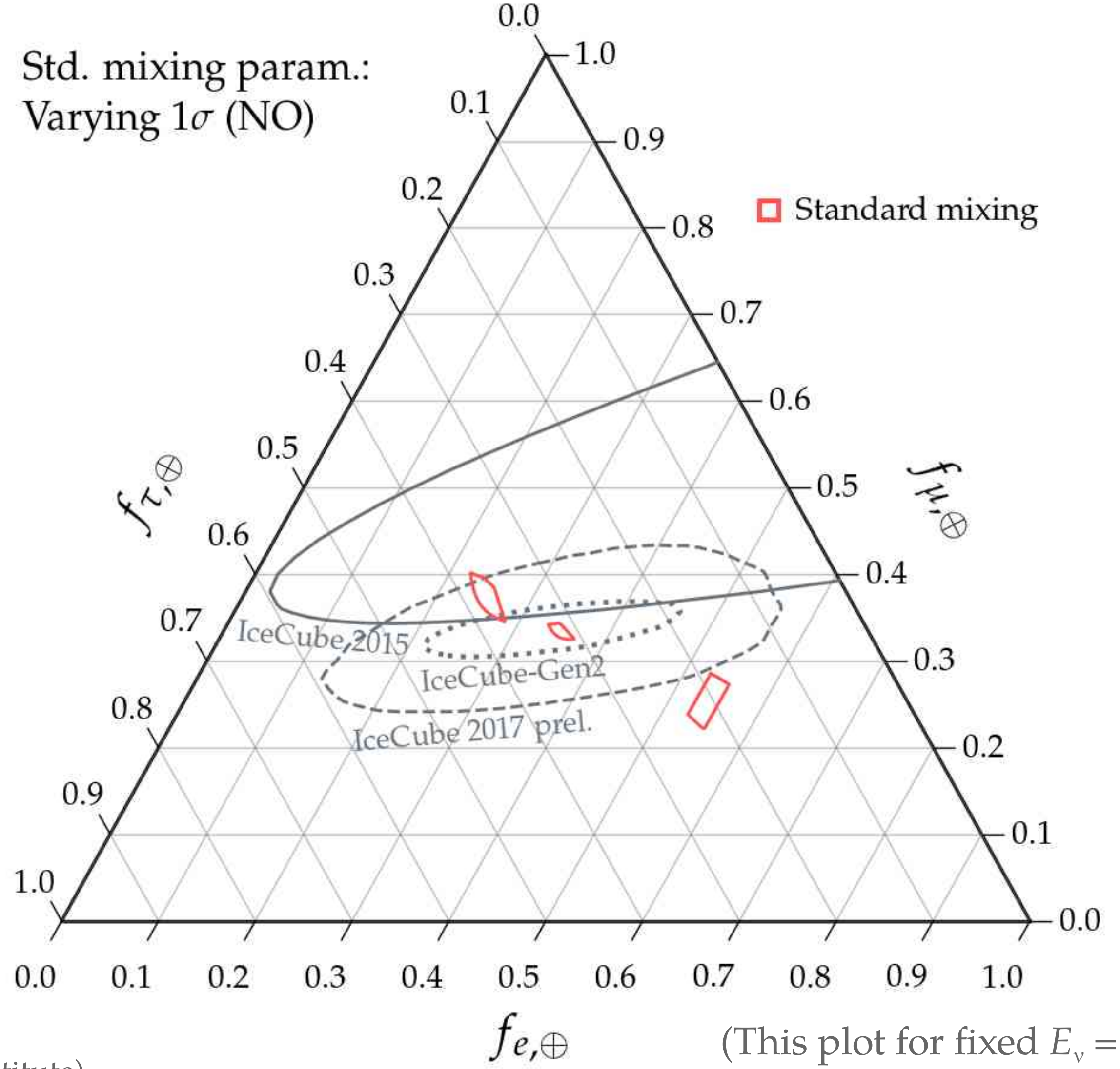
- Lots of room for improvement: more statistics, better flavor-tagging

See talk by Juliana Stachurska
Mon 16:50



MB, S. Agarwalla, 1808.02042

(This plot for fixed E_ν = 100 TeV)



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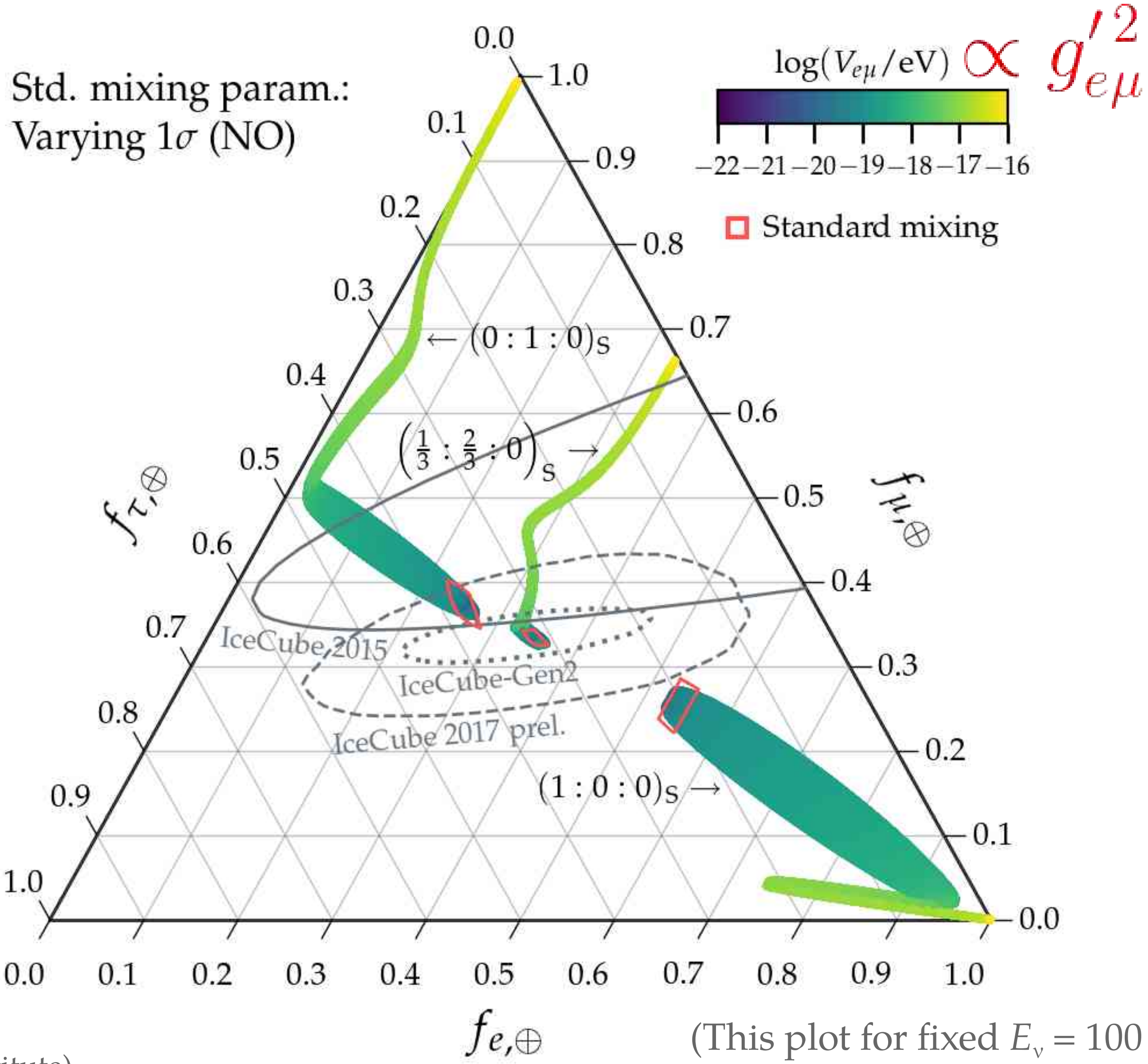
(This plot for fixed E_ν = 100 TeV)

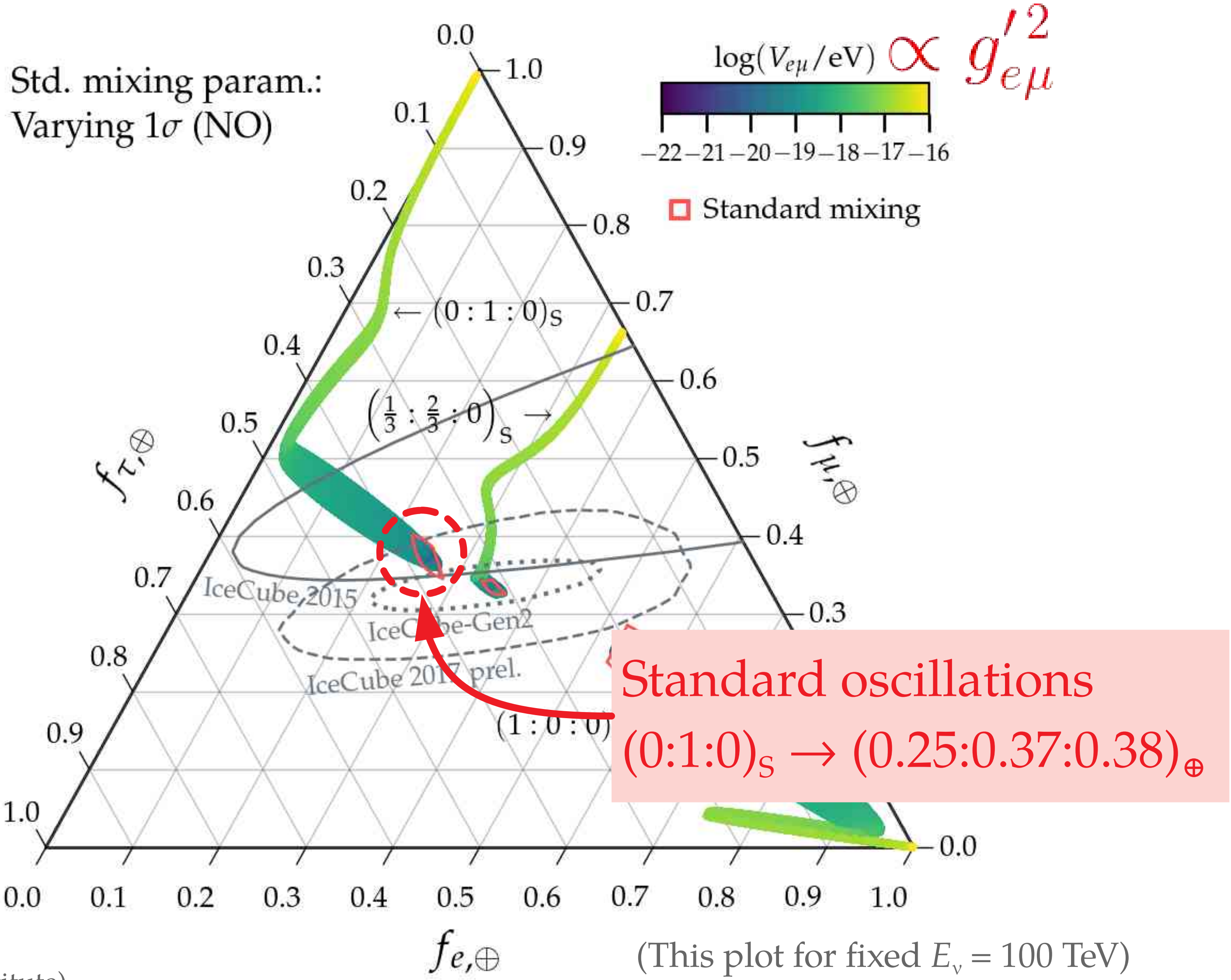
We assume equal proportions of ν and ν̄ (*e.g.*, production via *pp*)



MB, S. Agarwalla, 1808.02042

(This plot for fixed E_ν = 100 TeV)

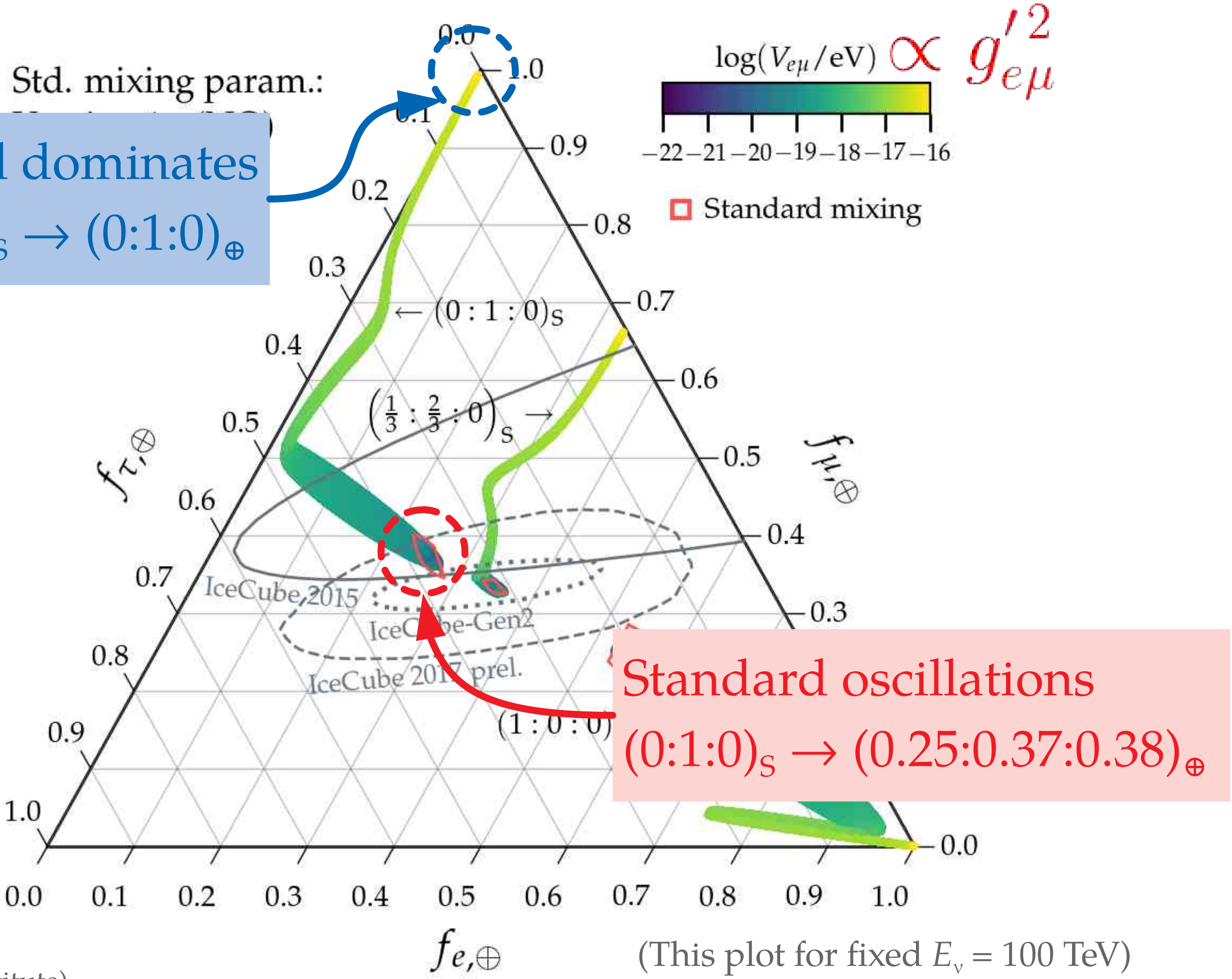
We assume equal proportions of ν and ν̄ (*e.g.*, production via *pp*)



MB, S. Agarwalla, 1808.02042

(This plot for fixed E_ν = 100 TeV)

We assume equal proportions of ν and ν̄ (e.g., pr

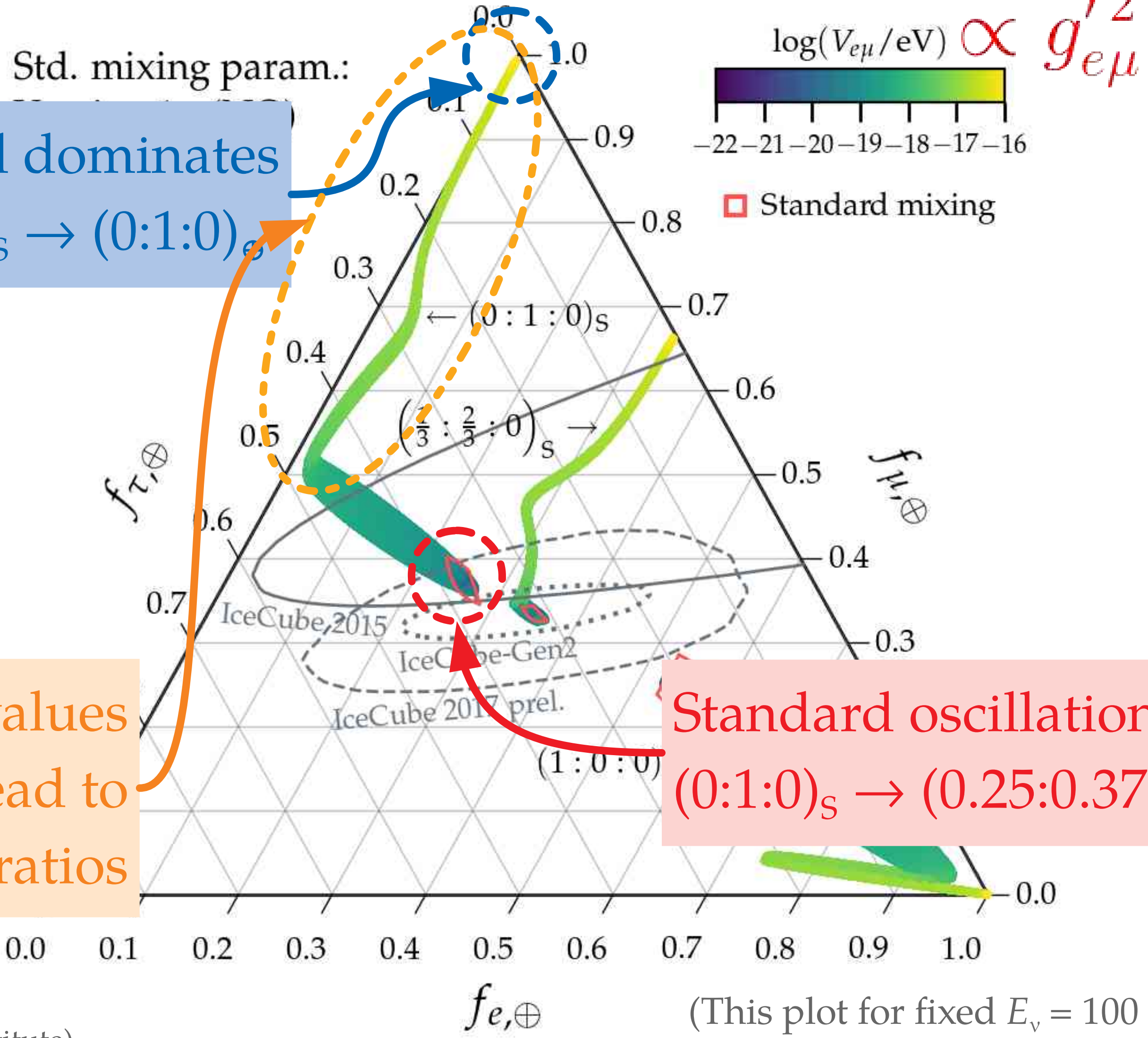


(This plot for fixed E_ν = 100 TeV)

MB, S. Agarwalla, 1808.02042

We assume equal proportions of ν and ν̄ (e.g., pr

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



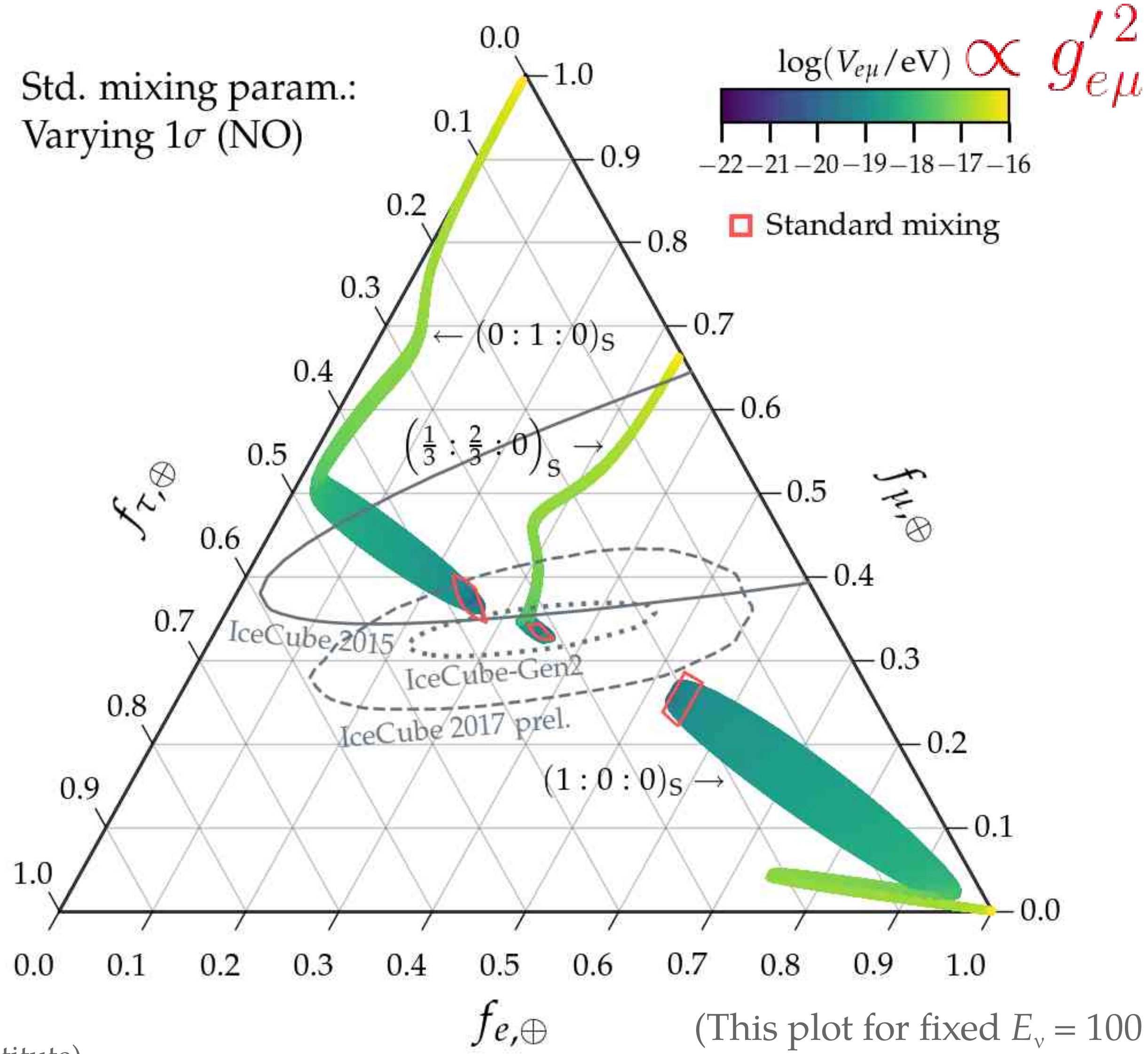
We can disfavor all values of m' and g' that lead to these flavor ratios

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

MB, S. Agarwalla, 1808.02042

(This plot for fixed E_ν = 100 TeV)

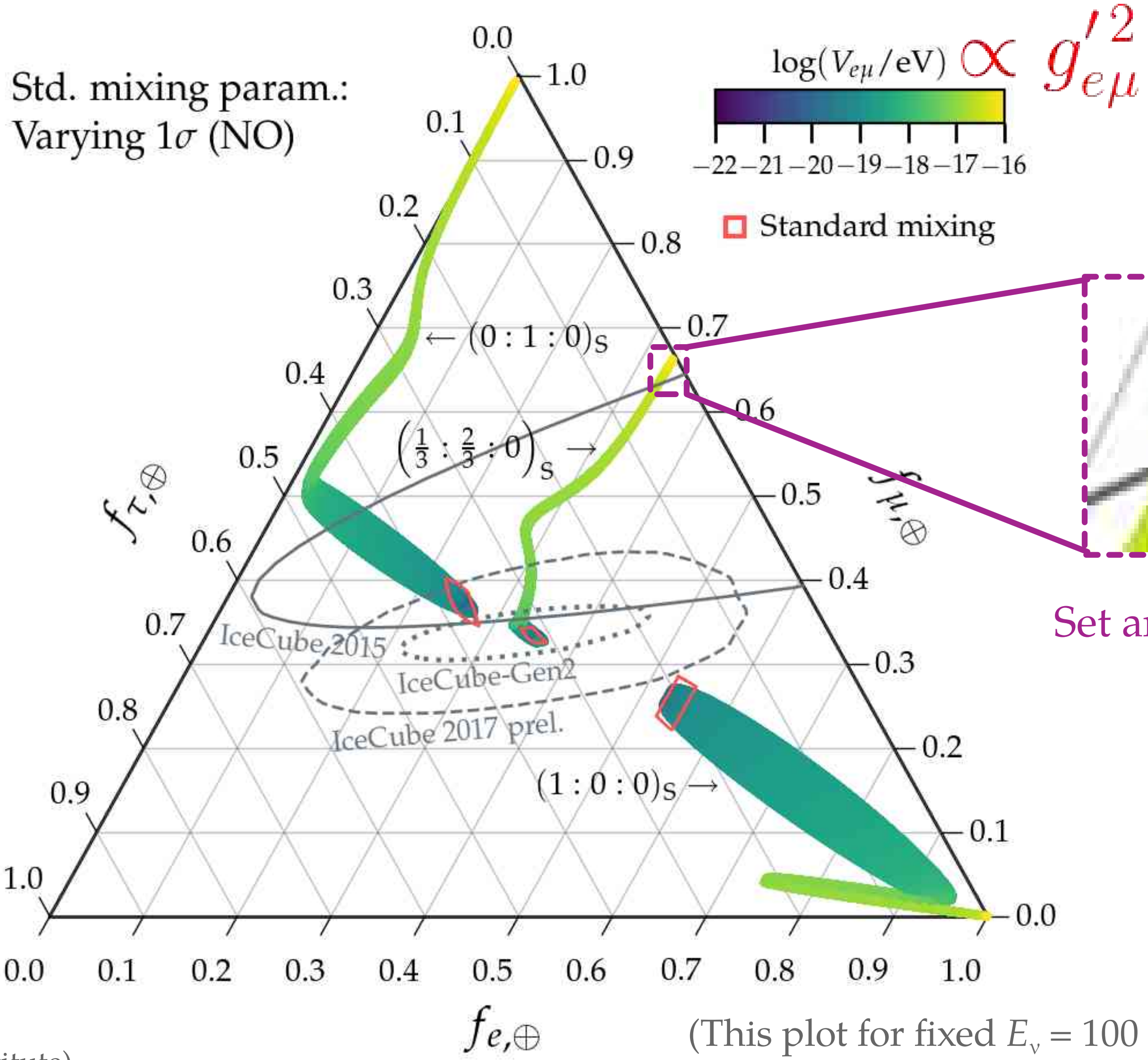
We assume equal proportions of ν and ν̄ (*e.g.*, production via *pp*)



MB, S. Agarwalla, 1808.02042

(This plot for fixed E_ν = 100 TeV)

We assume equal proportions of ν and $\bar{\nu}$ (*e.g.*, production via *pp*)

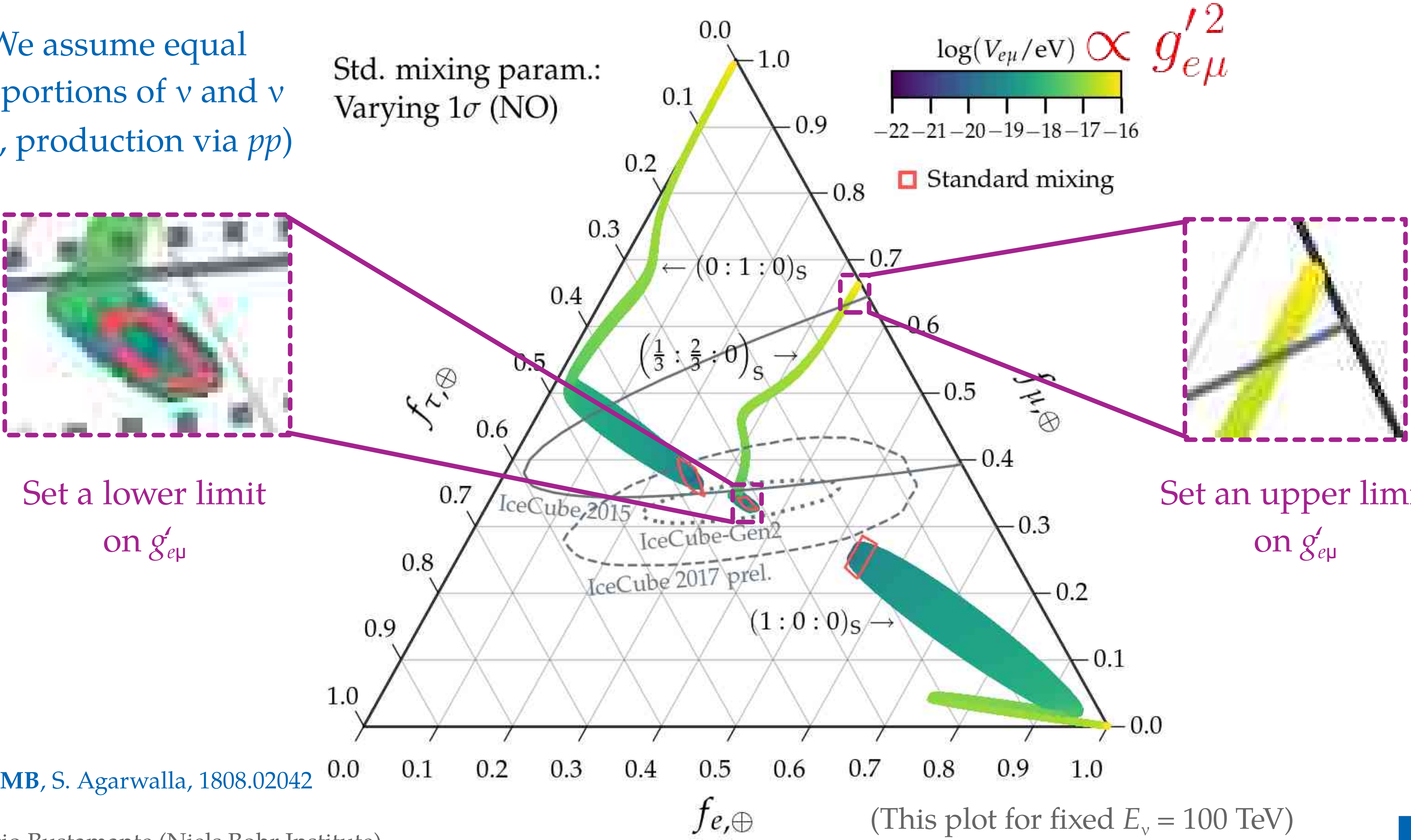


Set an upper limit on $g'_{e\mu}$

MB, S. Agarwalla, 1808.02042

(This plot for fixed E_ν = 100 TeV)

We assume equal proportions of ν and ν̄ (*e.g.*, production via *pp*)



Set a lower limit on $g'_{e\mu}$

Set an upper limit on $g'_{e\mu}$

MB, S. Agarwalla, 1808.02042

(This plot for fixed E_ν = 100 TeV)

Connecting flavor-ratio predictions to experiment

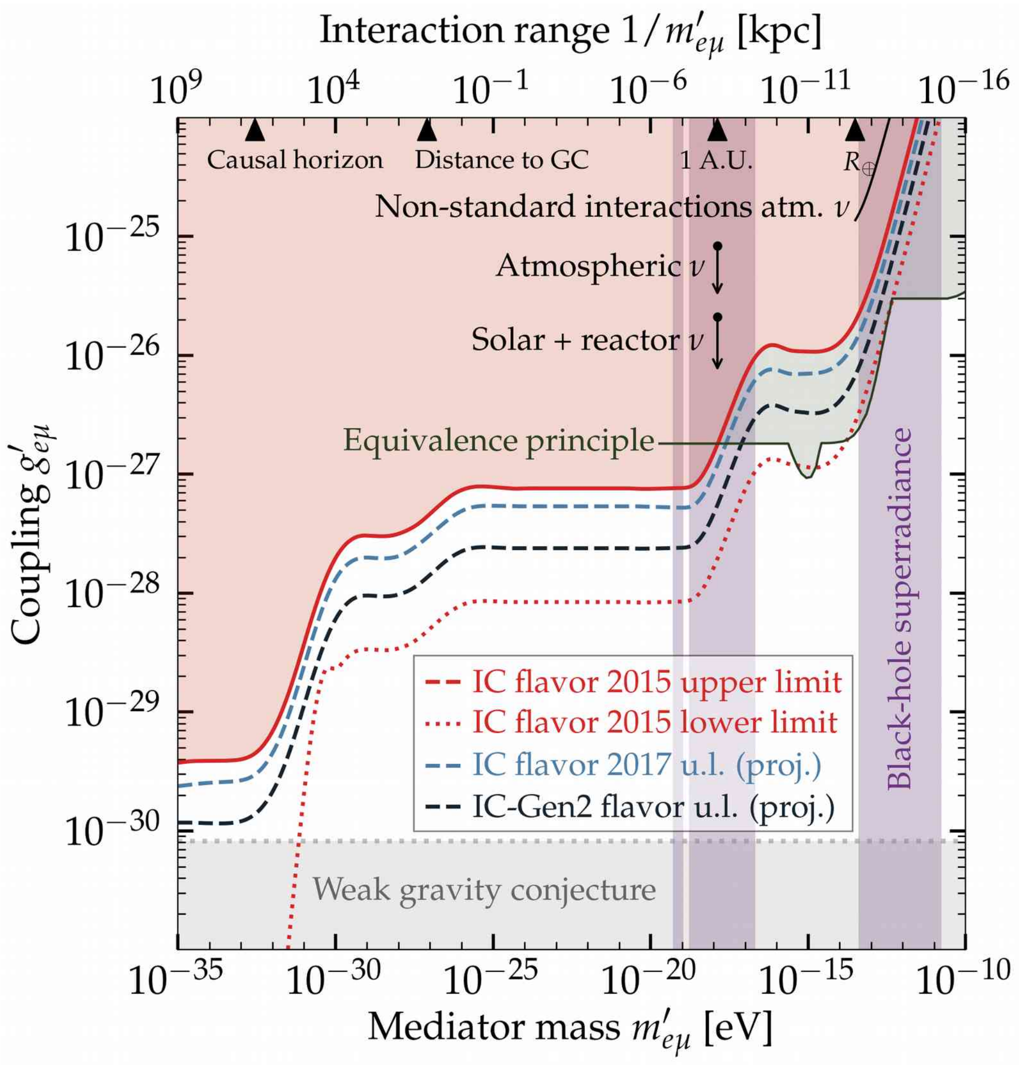
1. Integrate potential in redshift, weighed by source number density
   ↦ Assume star formation rate

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

Density of cosmological *e* grows with *z*

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

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



The result

- Best sensitivity at low Z' masses
- But significance is low (1σ) because of difficulty in measuring flavor
- Results are robust against:
  - Uncertainty in mixing parameters
  - Uncertainty in ν spectral index
  - Choice of neutrino mass ordering
- Similar results for L_e-L_τ

← For this plot, mass ordering is normal and flavor at sources is $(1/3 : 2/3 : 0)_S$

MB, S. Agarwalla, 1808.02042

What are you taking home?

- No significant evidence of long-range flavored neutrino interactions

- The best sensitivity to long-range flavored neutrino interactions comes from:
  - Using *all* of the electrons; and
  - Using high-energy astrophysical neutrinos

- Sensitivity is robust

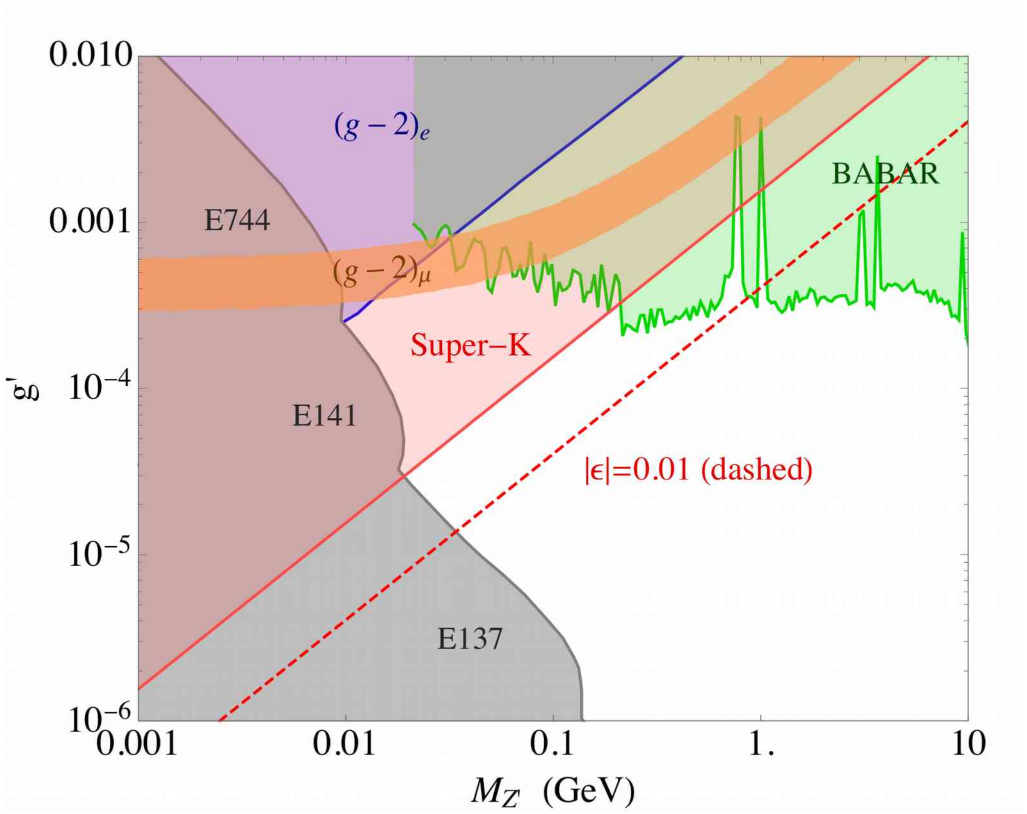
- Yet, for now, statistical significance is low

- Forthcoming improvements: statistics, better reconstruction, higher energies

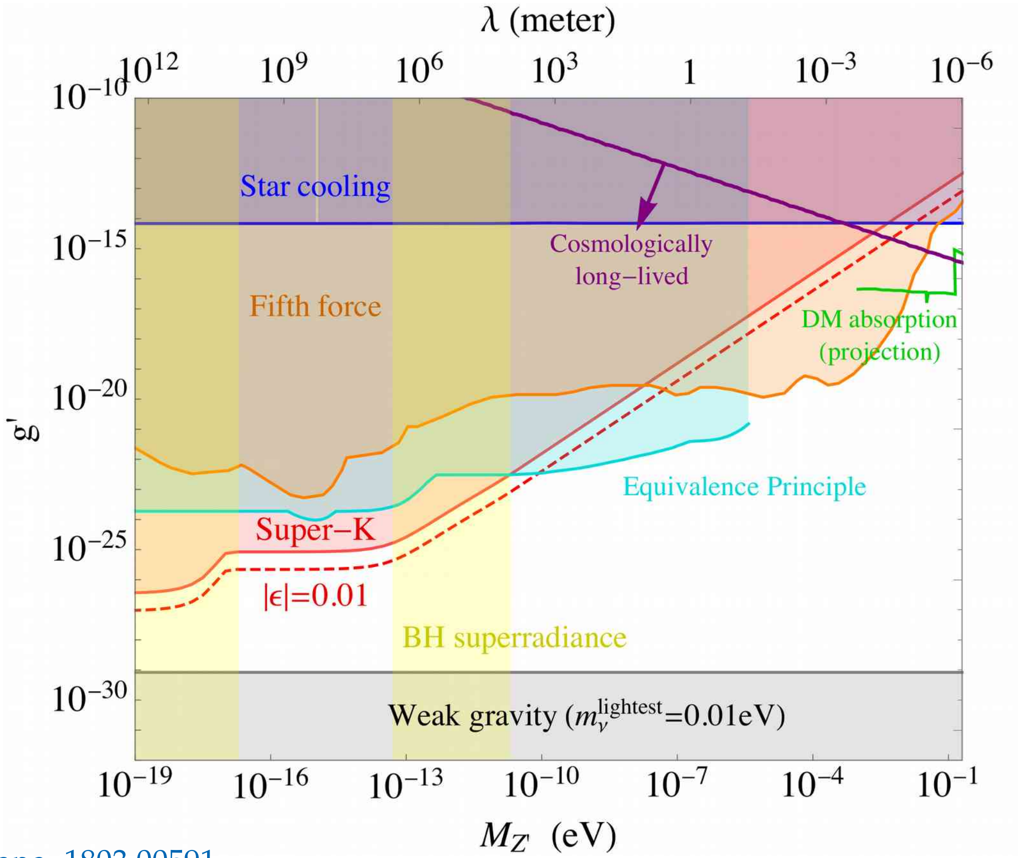
Backup slides

Current limits on the Z'

MeV–GeV masses

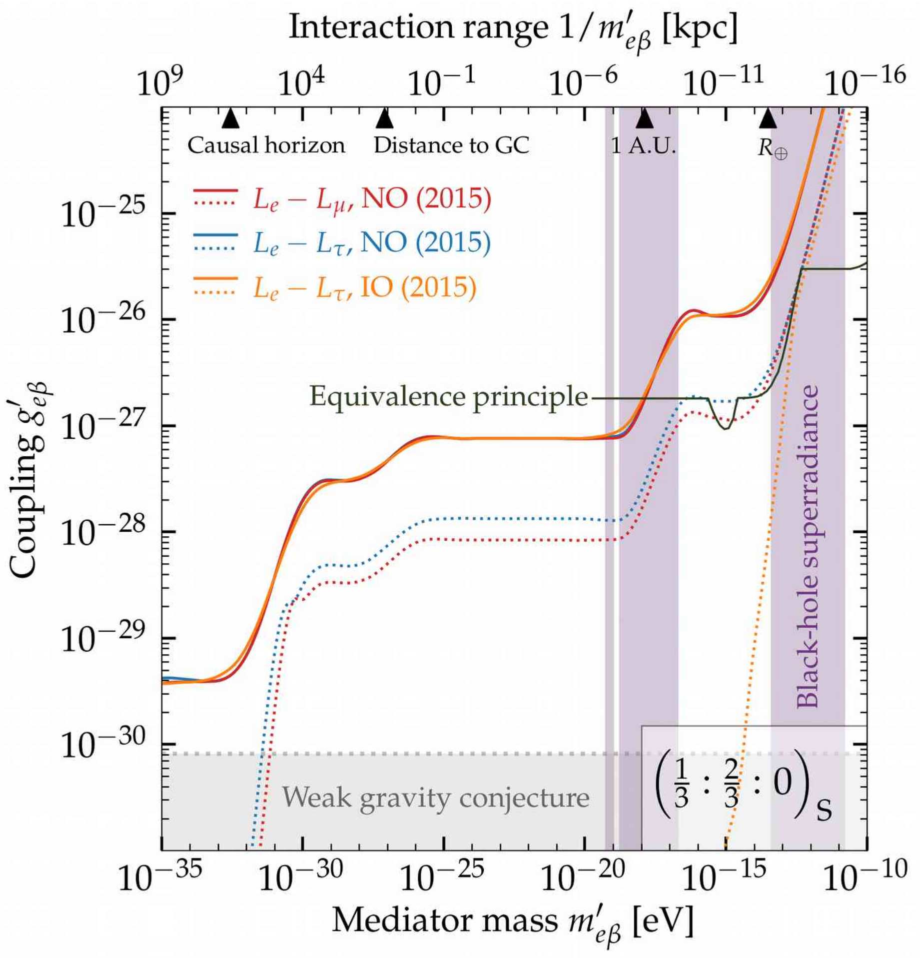


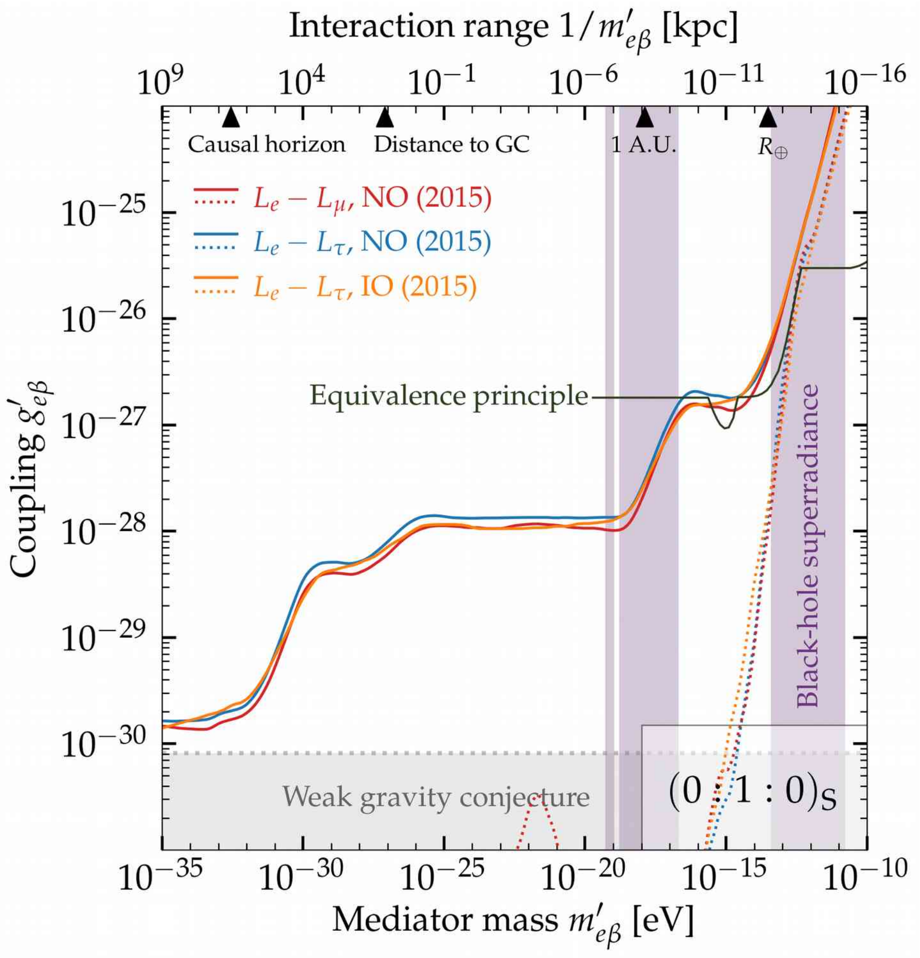
Sub-eV masses



M. Wise & Y. Zhang, 1803.00591

Effect of initial flavor ratios and mass ordering





The multi-messenger connection

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

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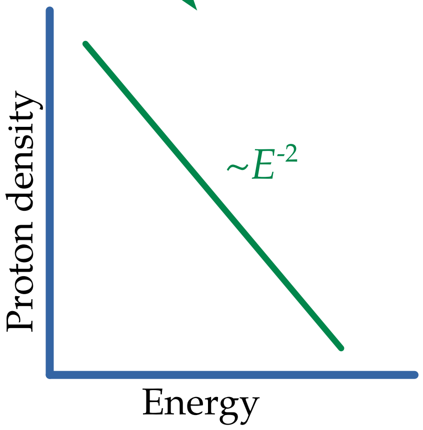

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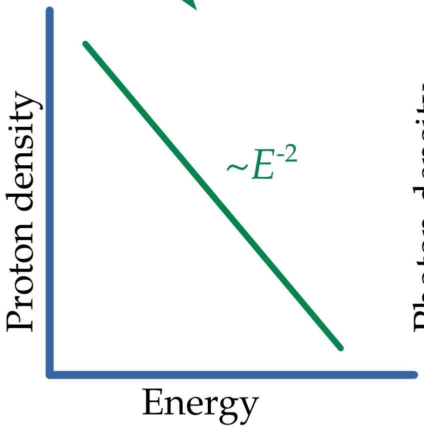

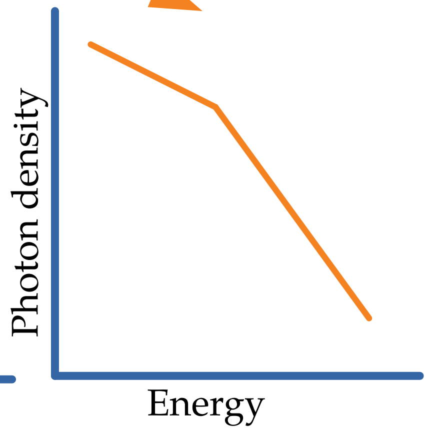

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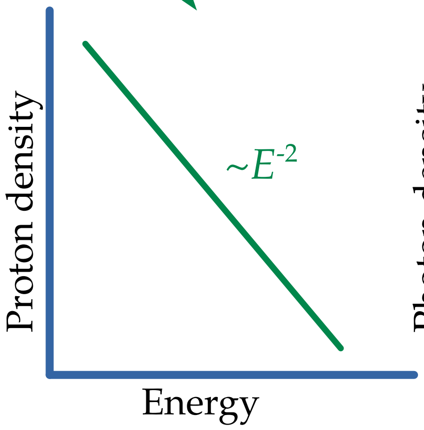
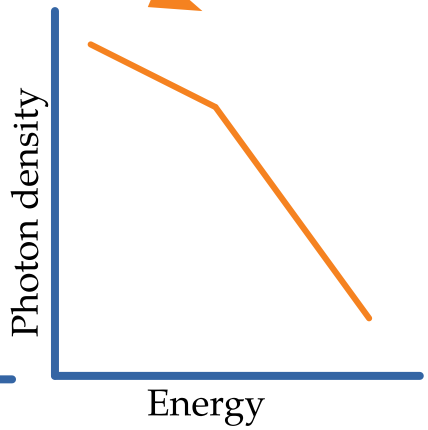
$$\pi^0 \rightarrow \gamma + \gamma$$

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

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





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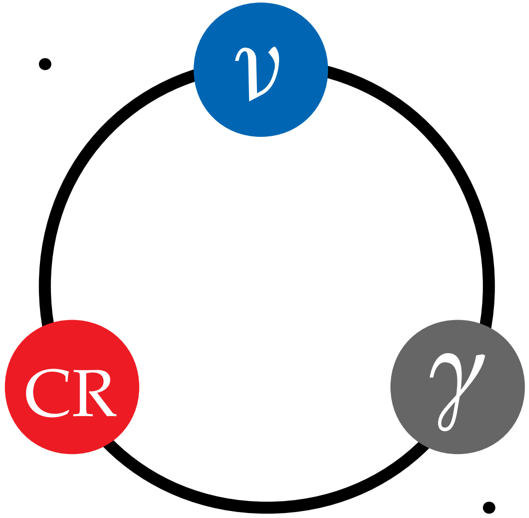

Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 20

The multi-messenger connection

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

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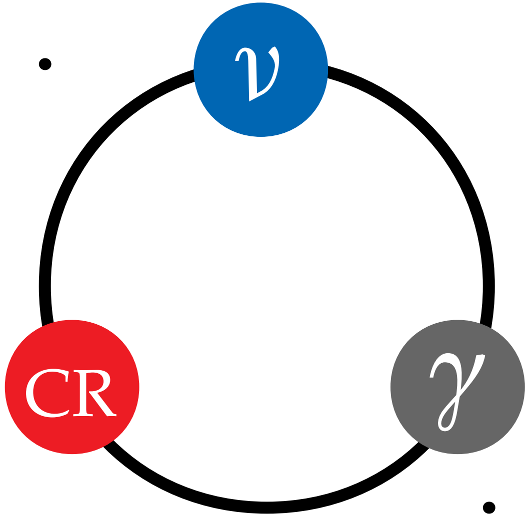

1 PeV 20 PeV

Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 20

The multi-messenger connection

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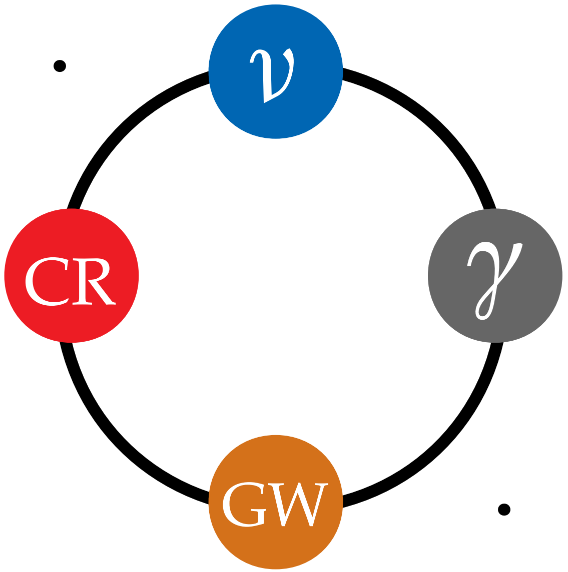


1 PeV 20 PeV

Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 20

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

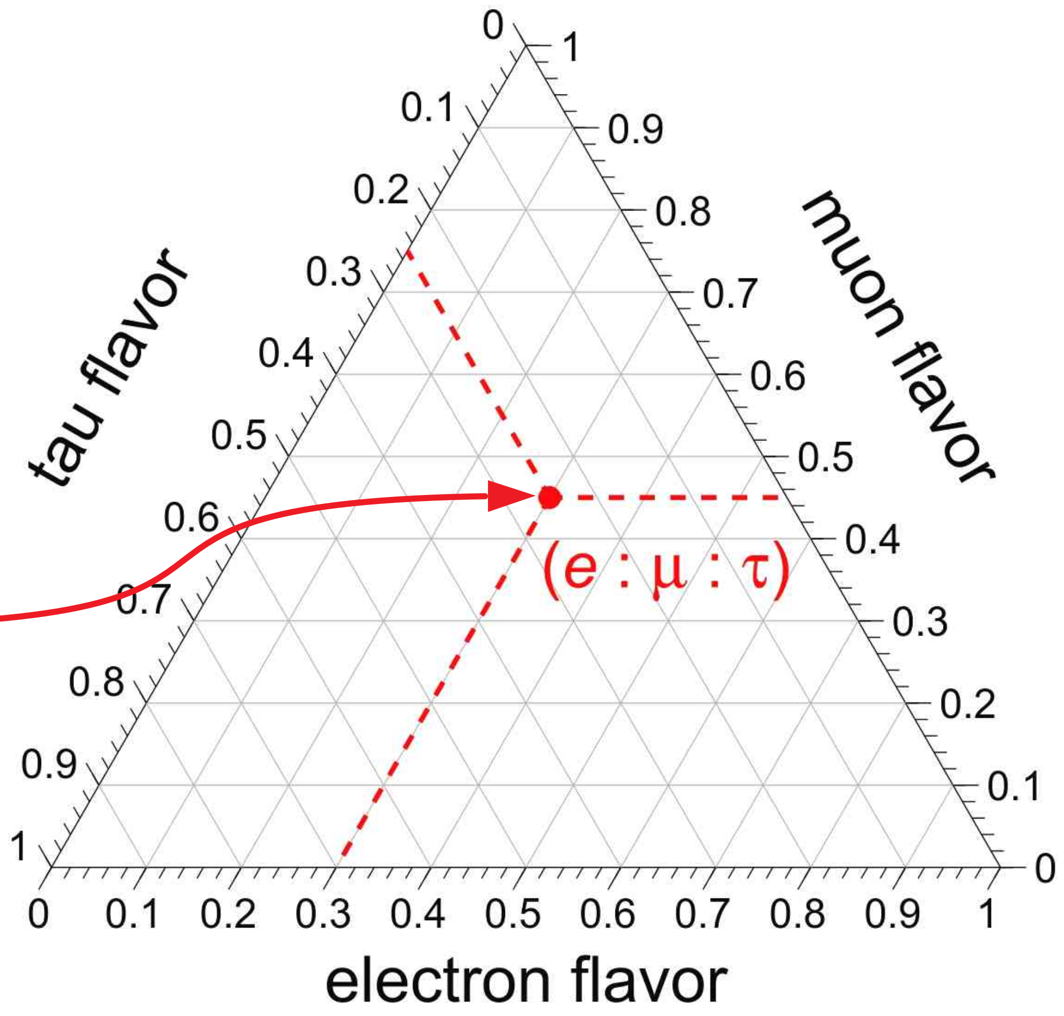
Note: Ratios are for $\nu + \bar{\nu}$, since neutrino telescopes cannot tell them apart

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.*,

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

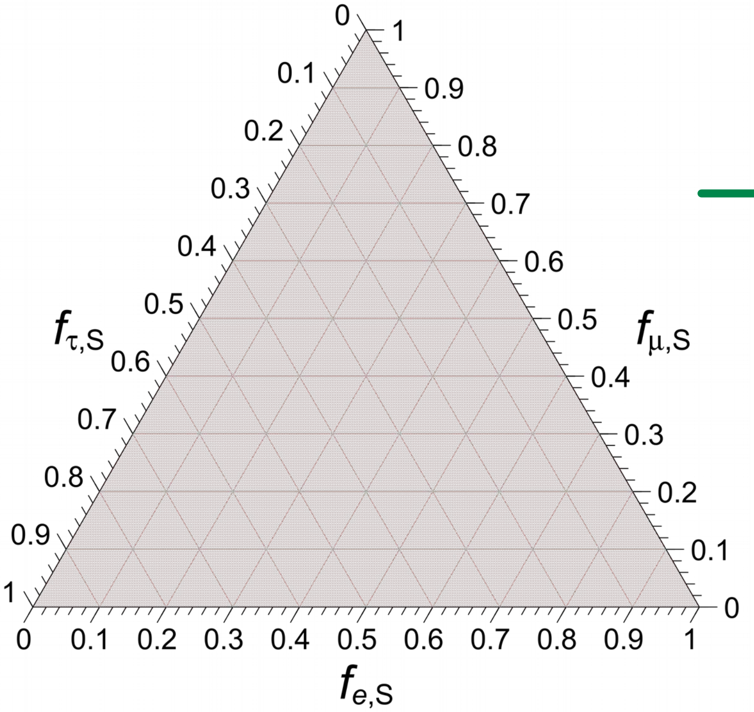


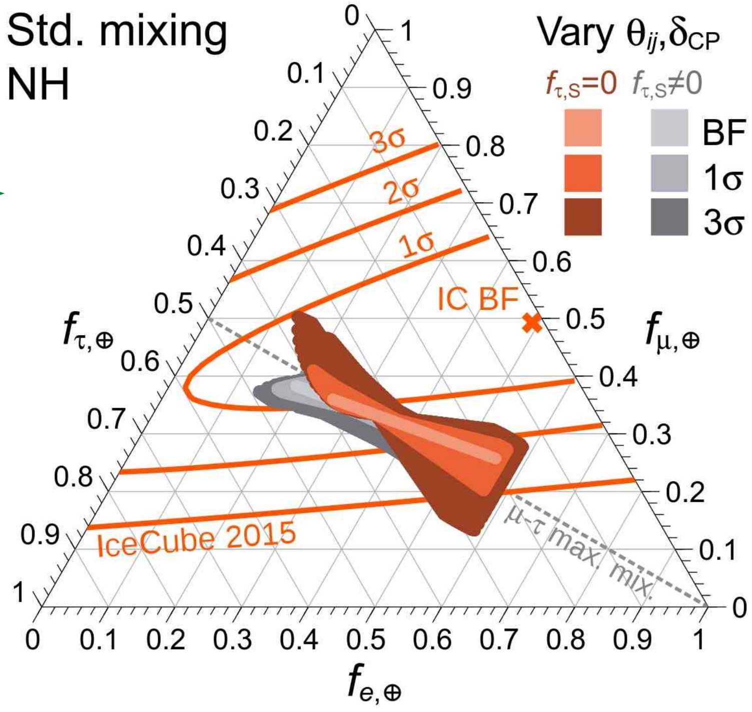
Flavor composition – Standard allowed region

At the sources

At Earth

All possible flavor ratios





MB, Beacom, Winter *PRL* 2015

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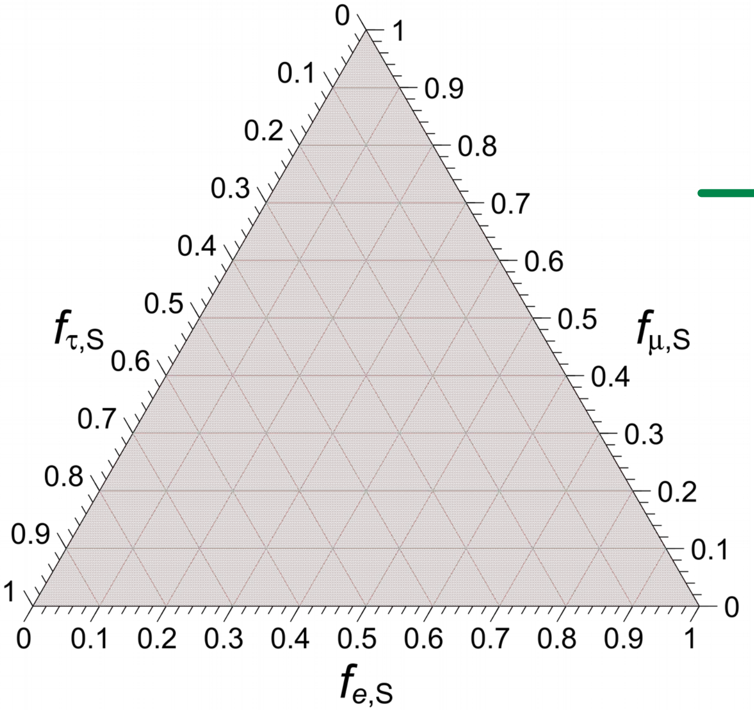
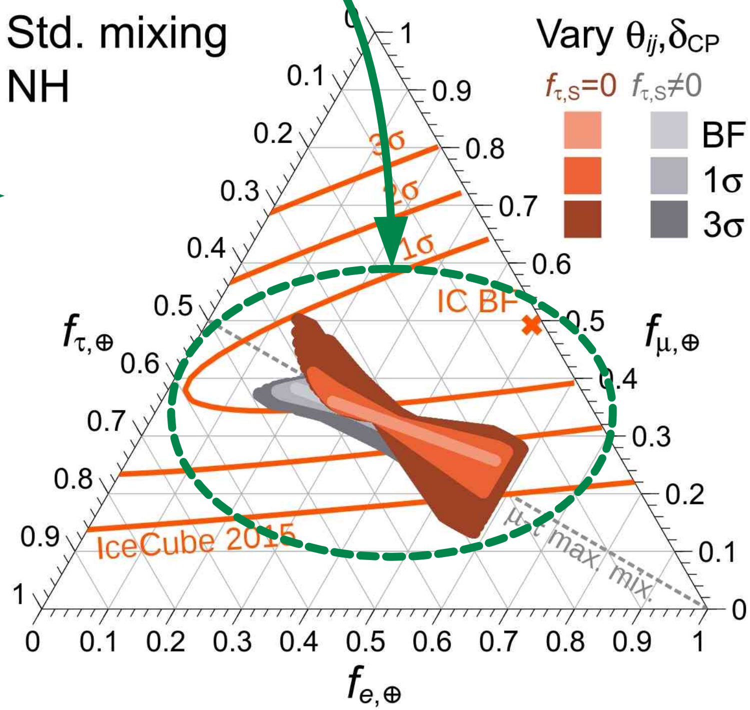


Only 10% of parameter space

At Earth



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How does IceCube see neutrinos?

Two types of fundamental interactions ...

Charged-current (CC)

$$\nu_l + N \rightarrow \boxed{l} + \boxed{\text{hadrons}}$$

Neutral-current (NC)

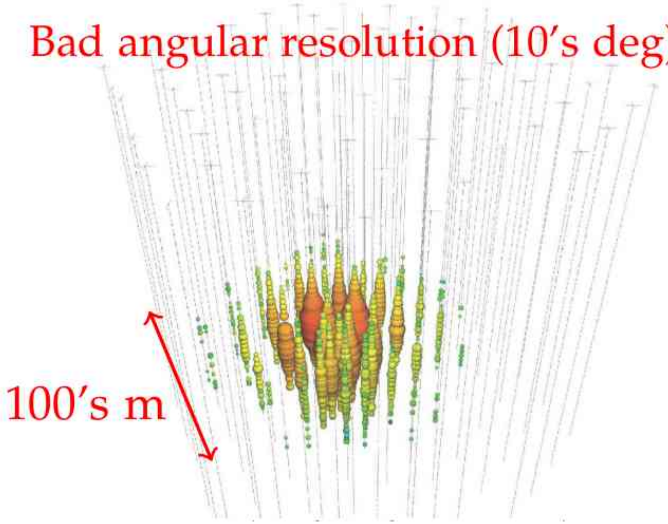
$$\nu_l + N \rightarrow \nu_l + \boxed{\text{hadrons}}$$

These shower and make light

... create two event topologies ...

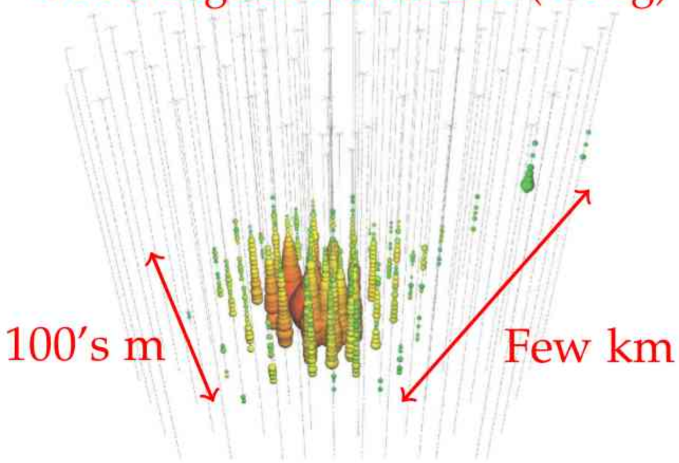
Showers — From CC ν_e or ν_τ, or NC ν_x

Bad angular resolution (10's deg)

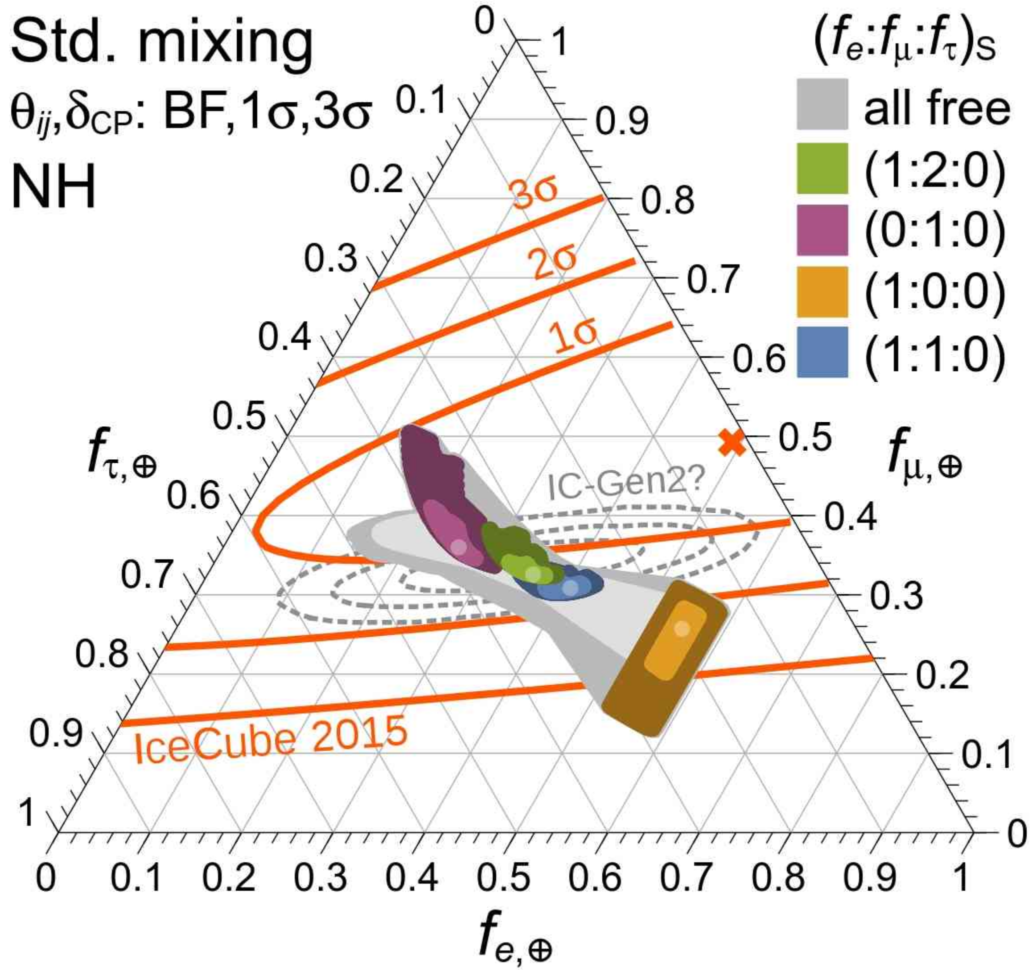


Tracks — From CC ν_μ mainly

Good angular resolution (< deg)



Flavor composition – A few source choices



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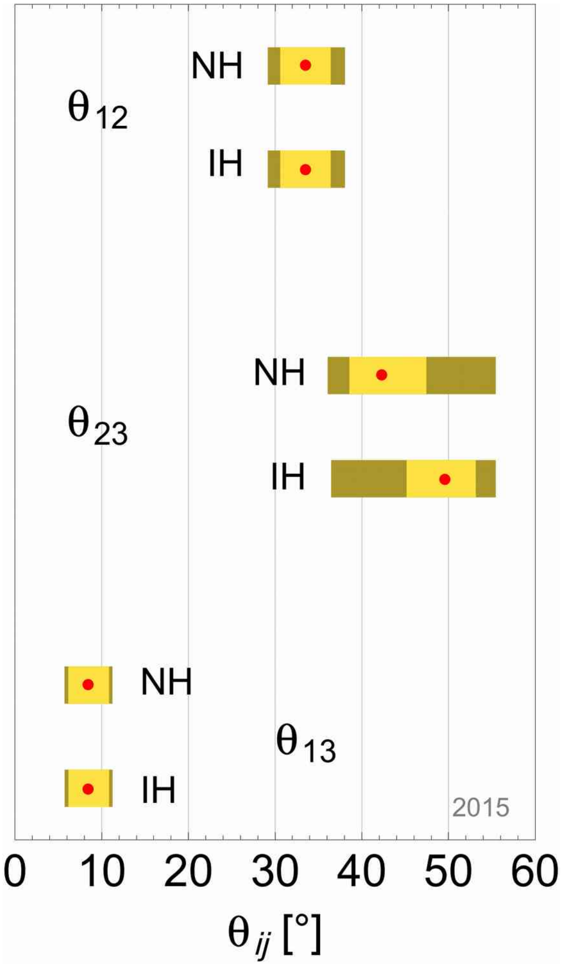
Uncertainties in lepton mixing angles

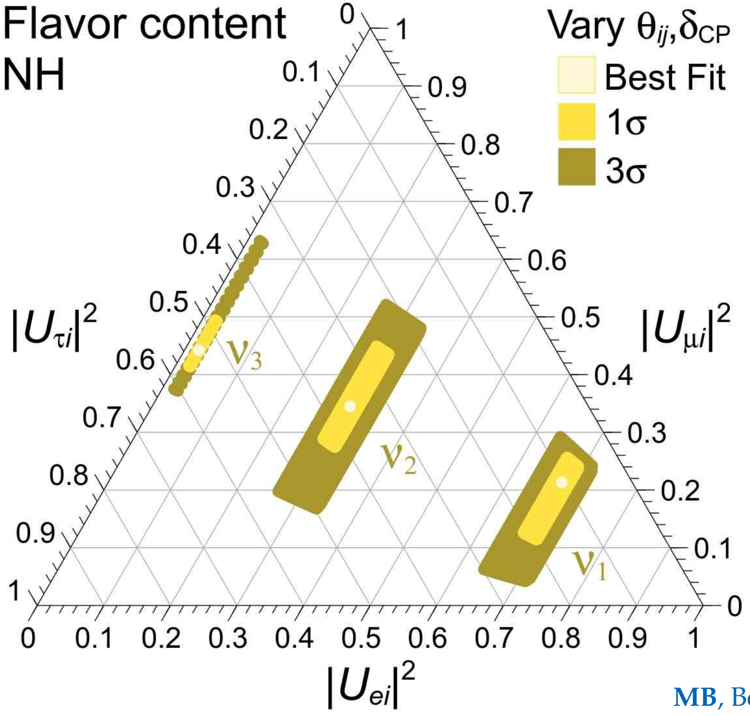
As of 2015 –

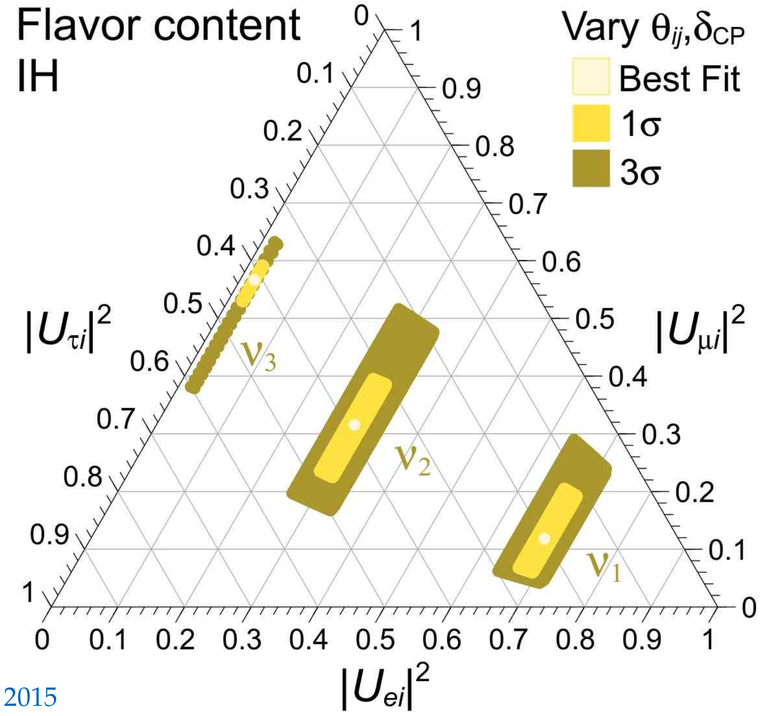


Flavor content of neutrino mass eigenstates

Flavor content for every allowed combination of mixing parameters –

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





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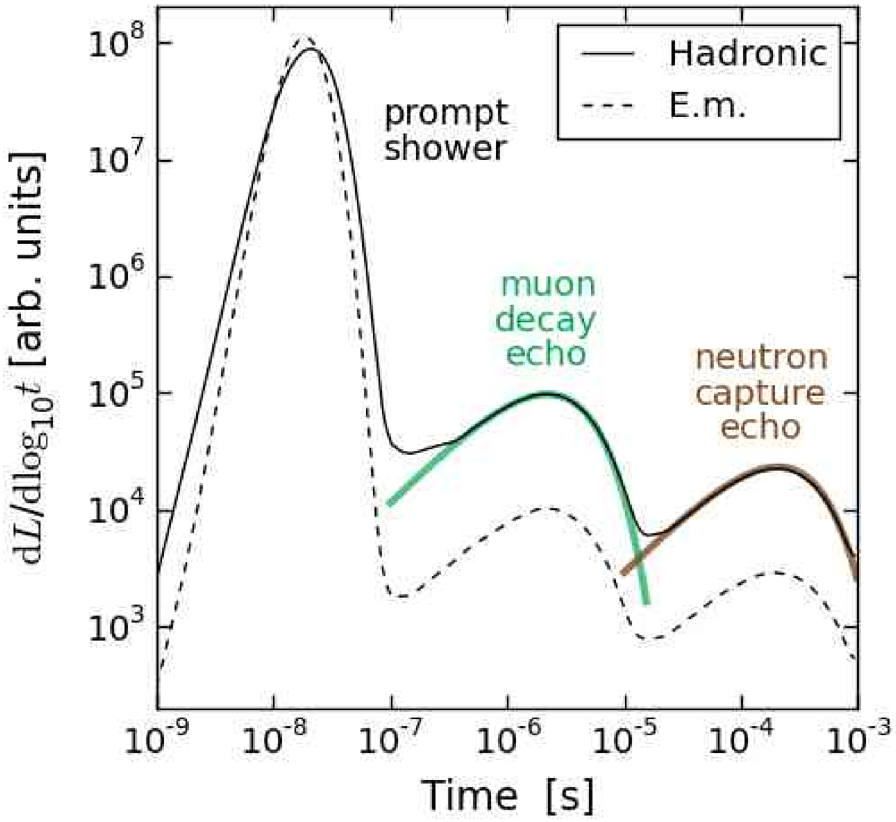
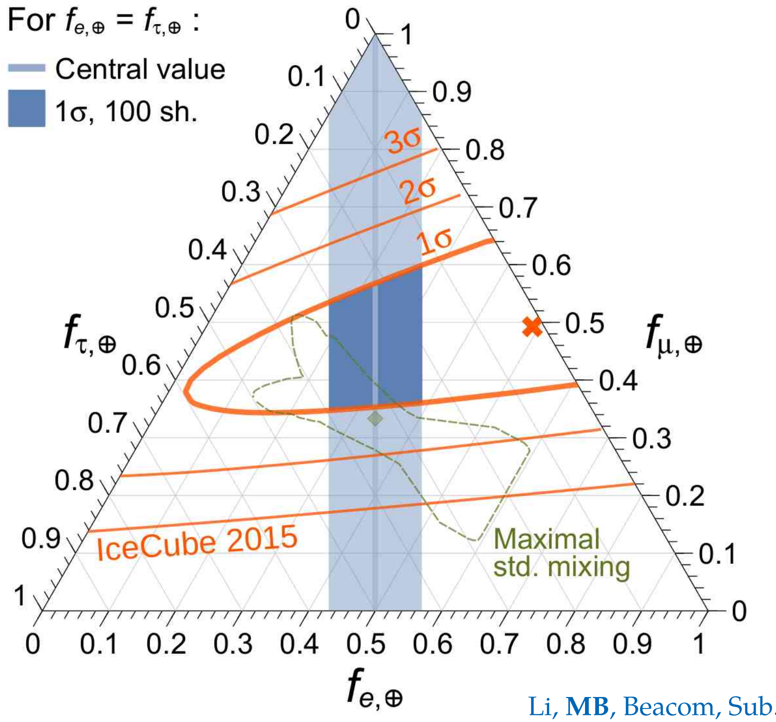
Side note: Improving flavor-tagging using *echoes*

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





Li, **MB**, Beacom, Sub. to *PRL*

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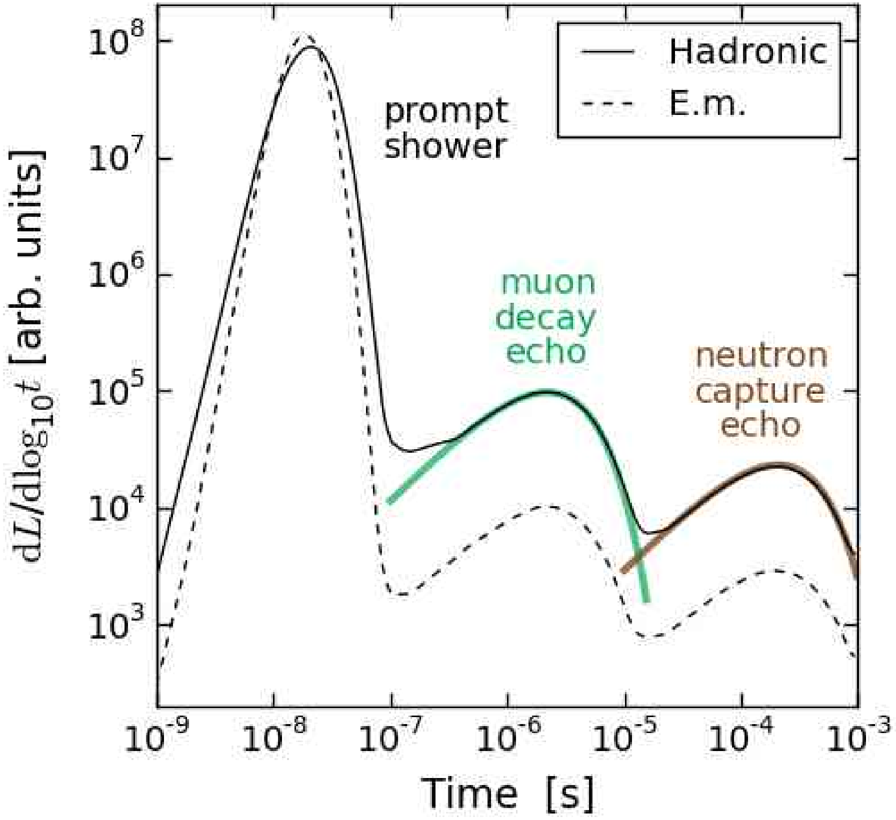
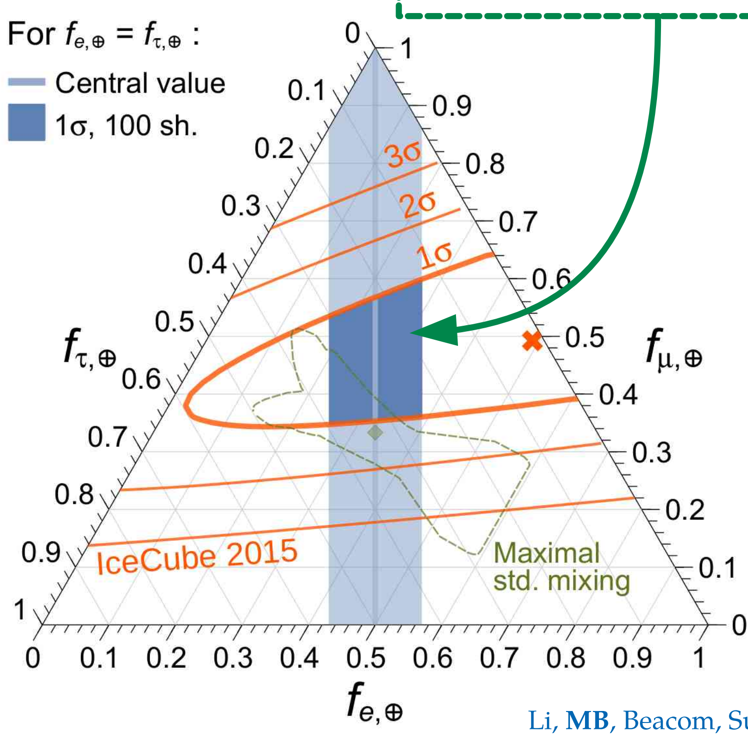
~10 × improvement over current measurement





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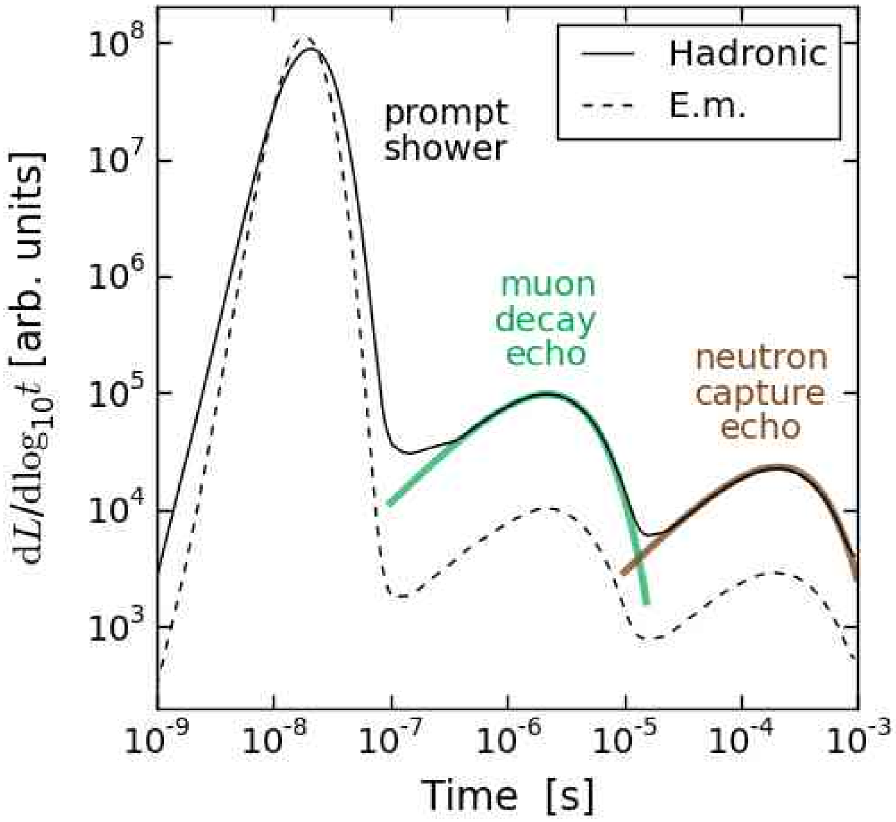
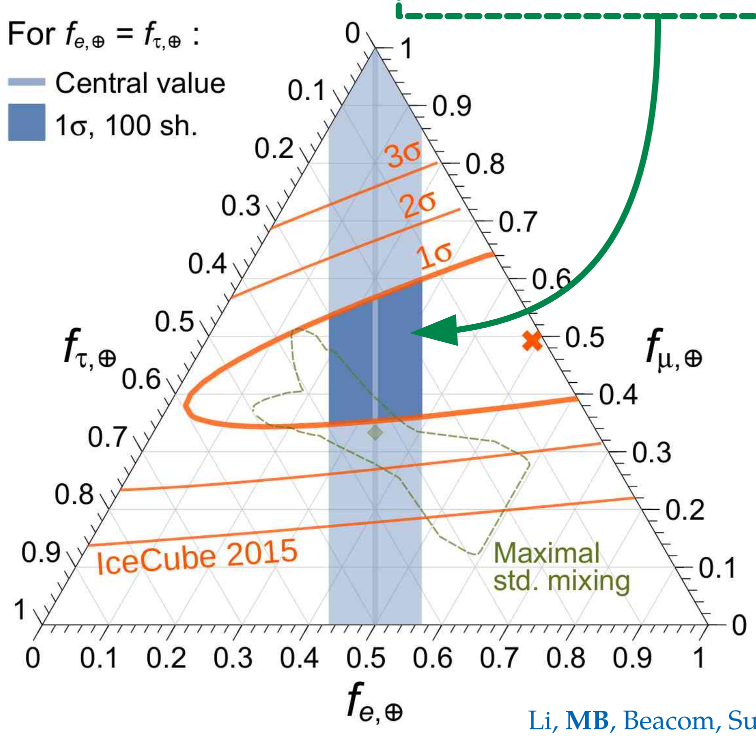
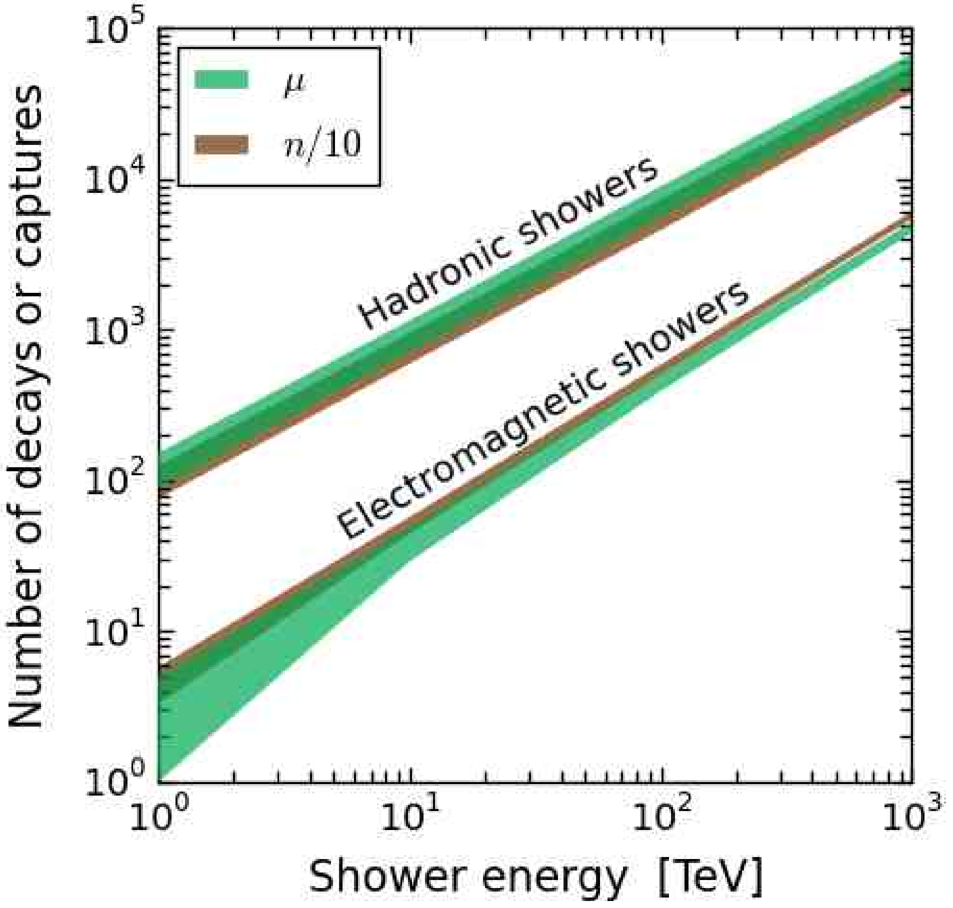
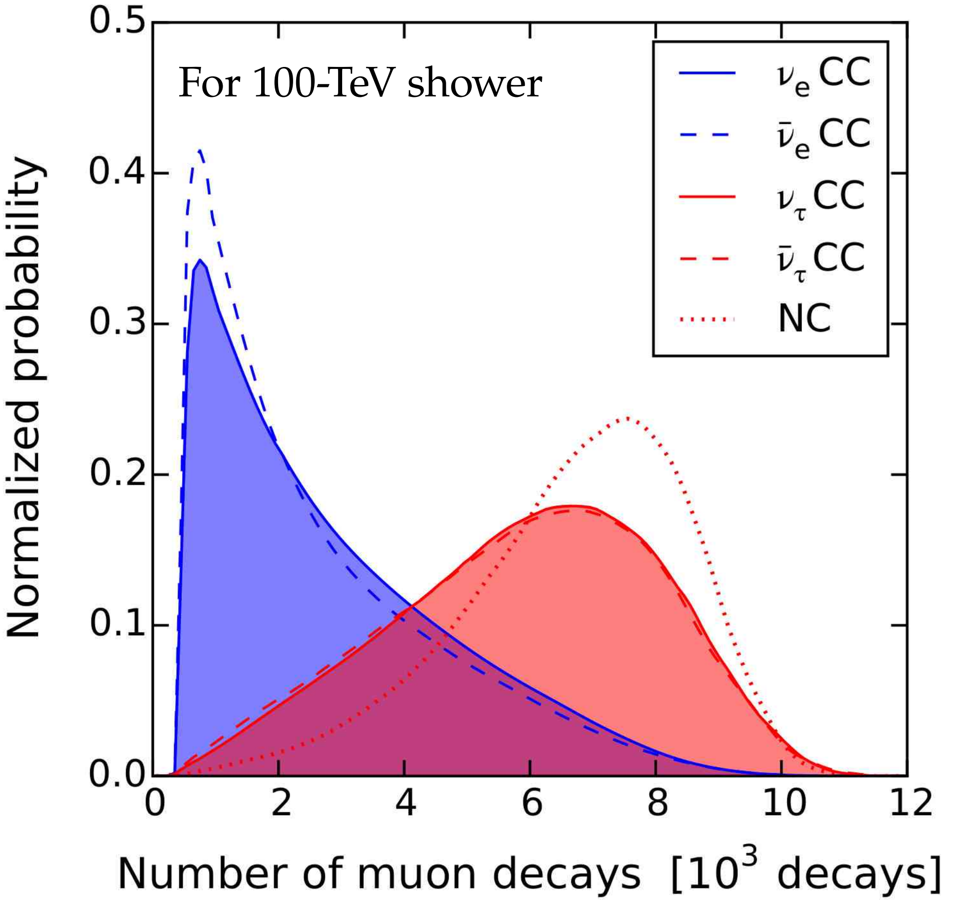




Li, **MB**, Beacom, Sub. to *PRL*

Hadronic *vs.* electromagnetic showers





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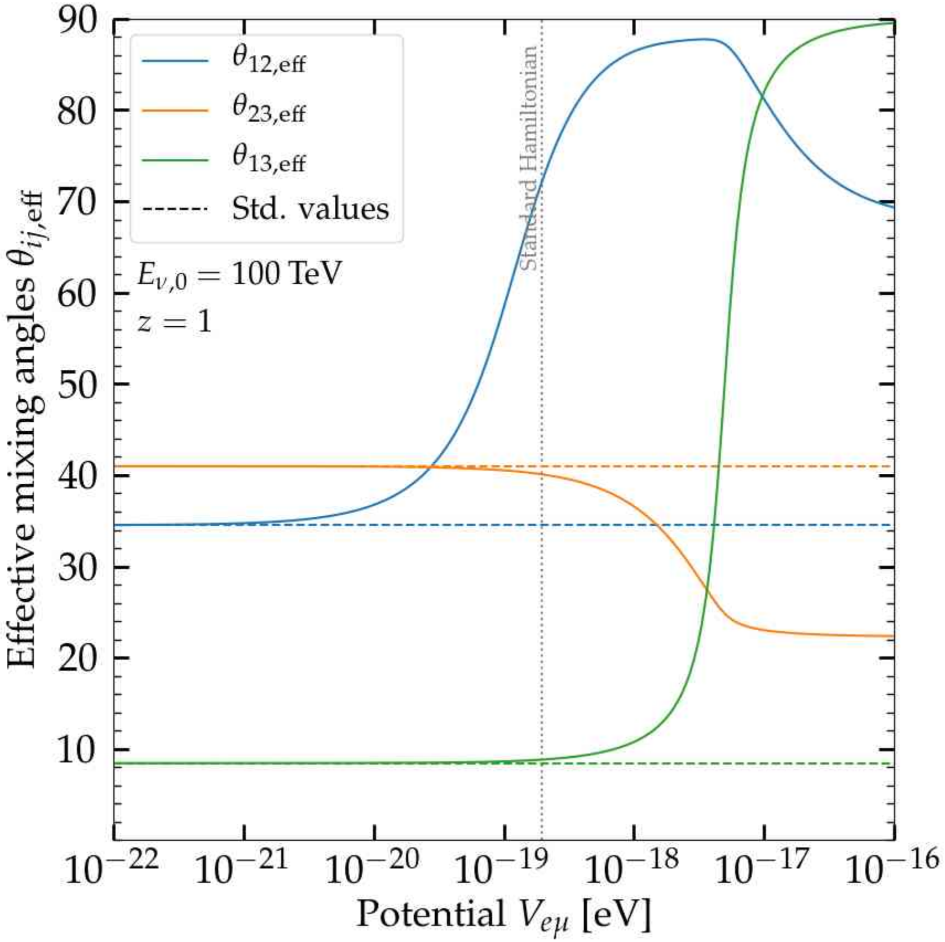
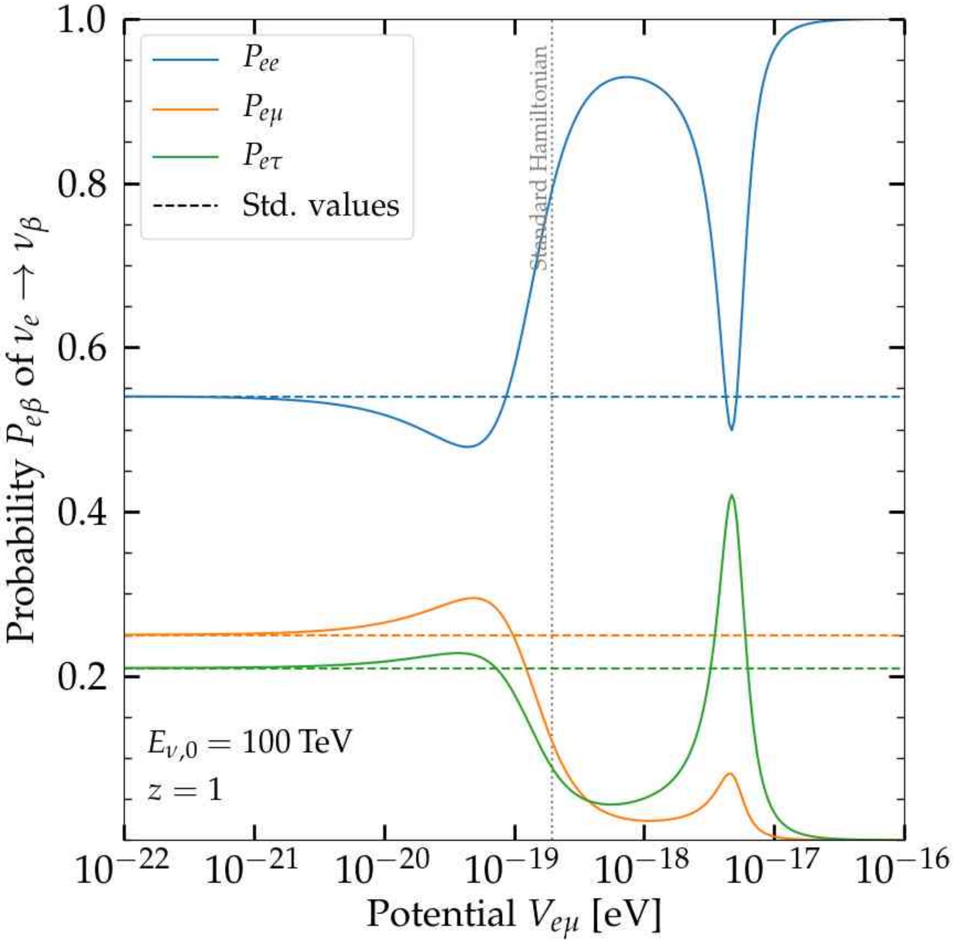
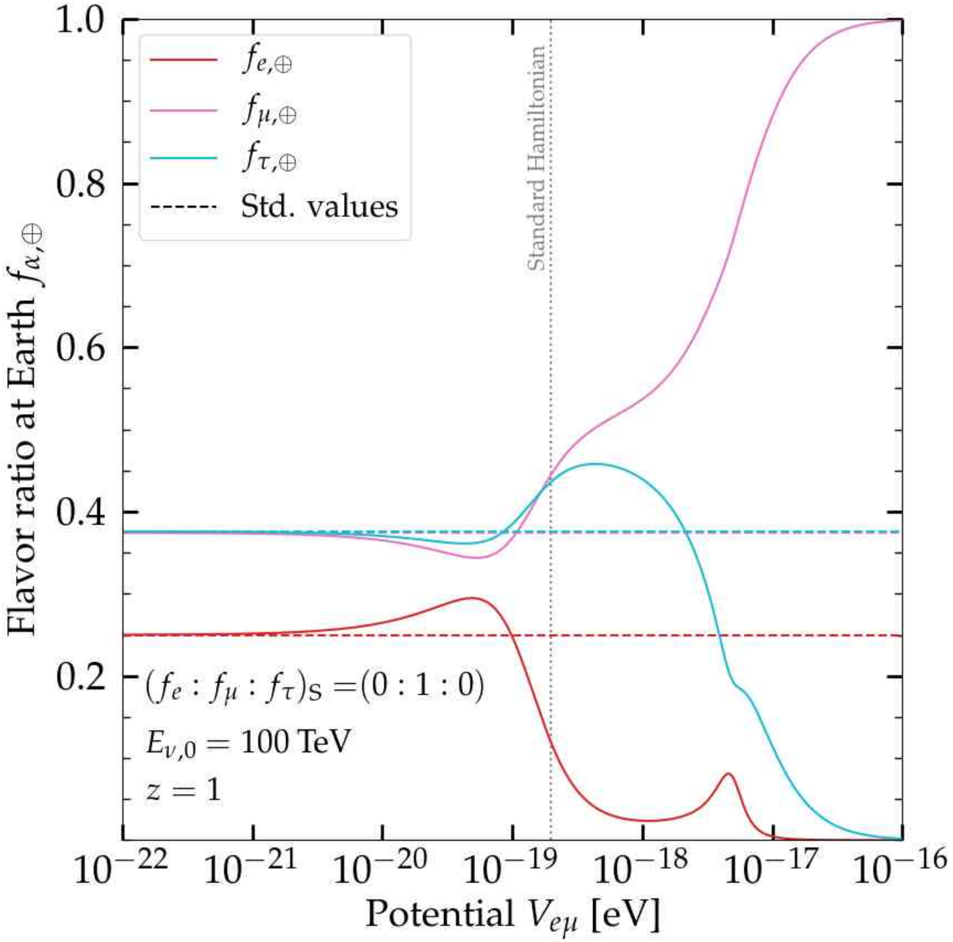
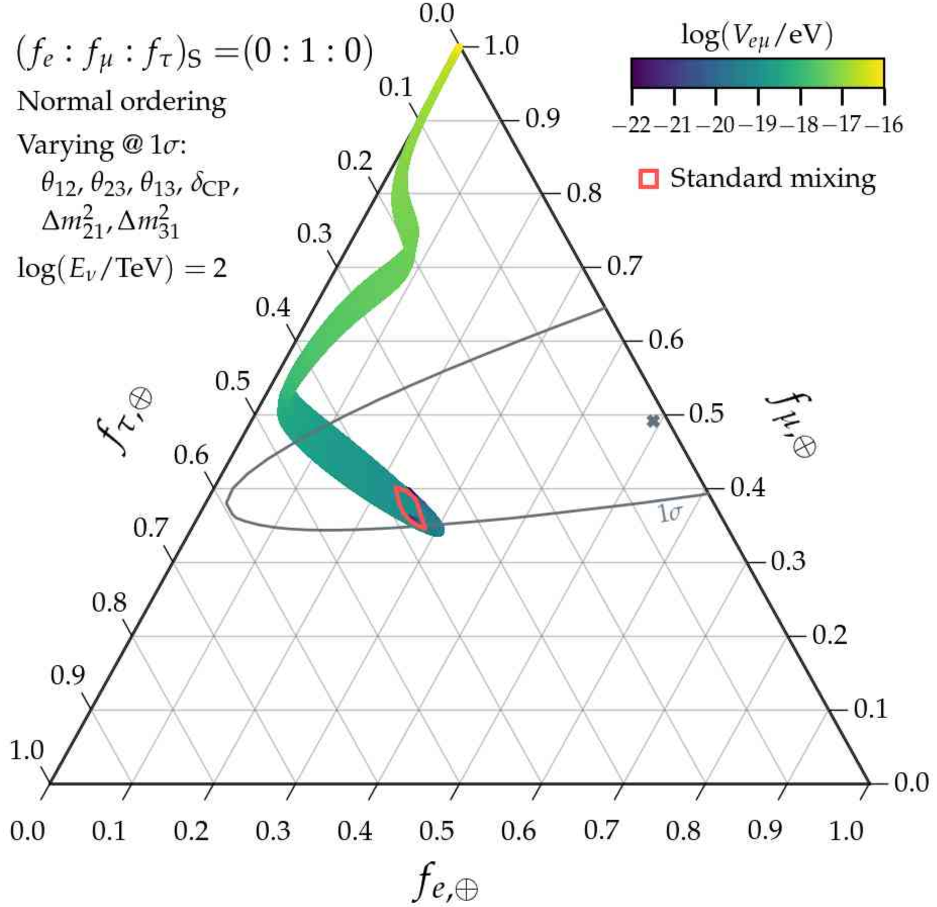
Resonance due to the L_e-L_μ symmetry



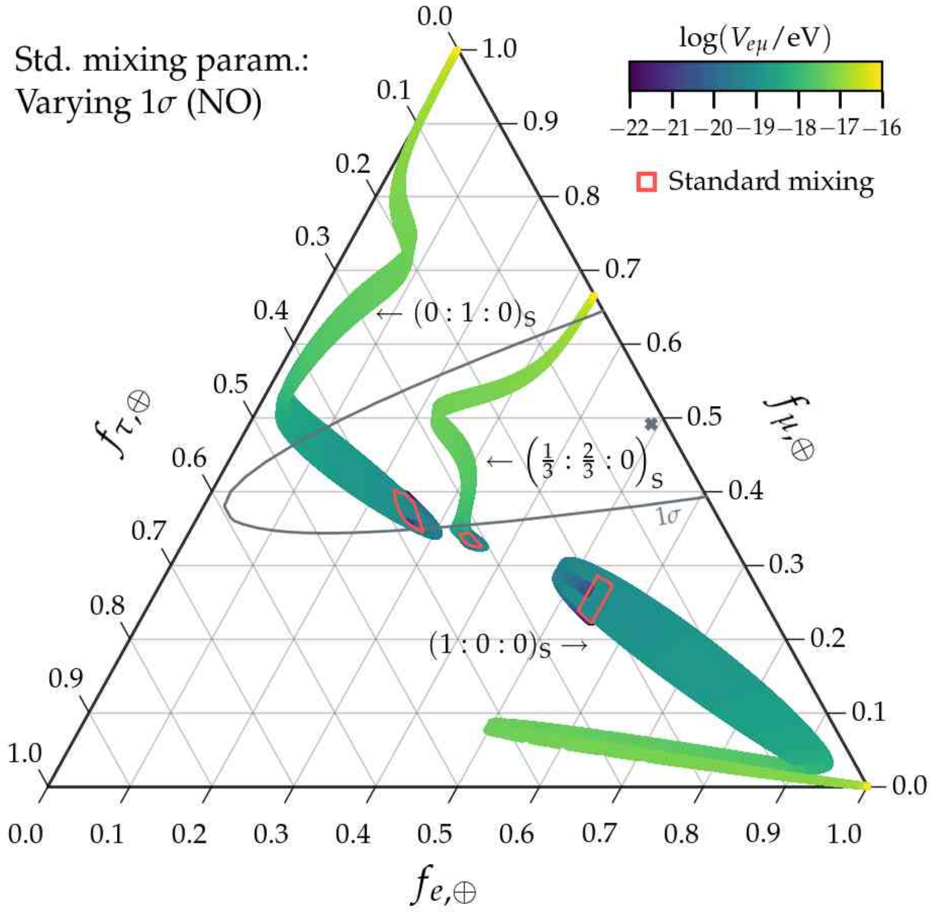


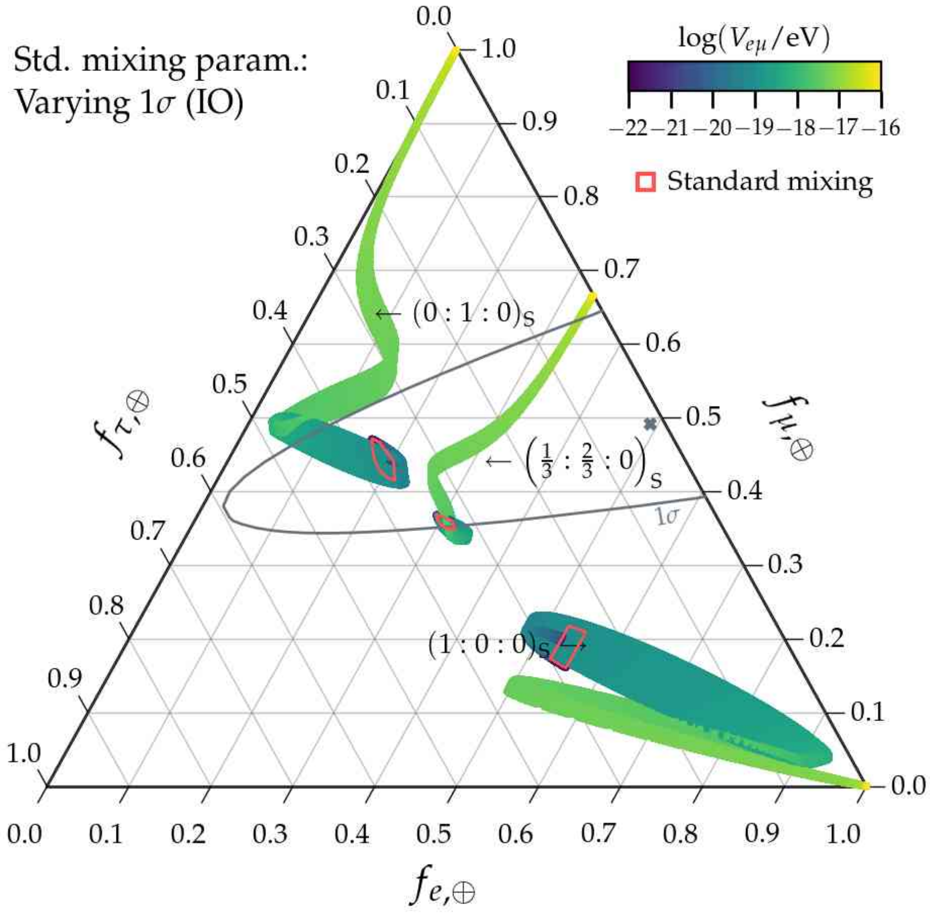
Resonance due to the L_e-L_μ symmetry (*cont.*)





Flavor ratios for the L_e-L_μ symmetry: NO *vs.* IO





Flavor ratios for the L_e-L_τ symmetry: NO *vs.* IO