# Flavor in high-energy cosmic neutrinos: Interpretation and new challenges

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PAHEN
Berlin, September 27, 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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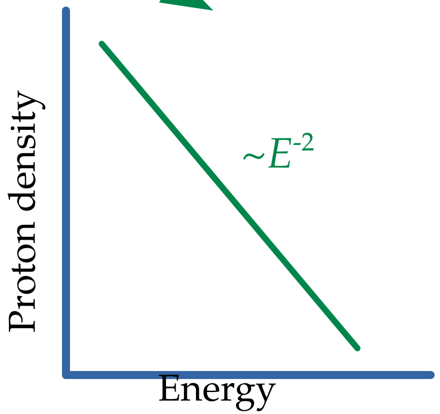

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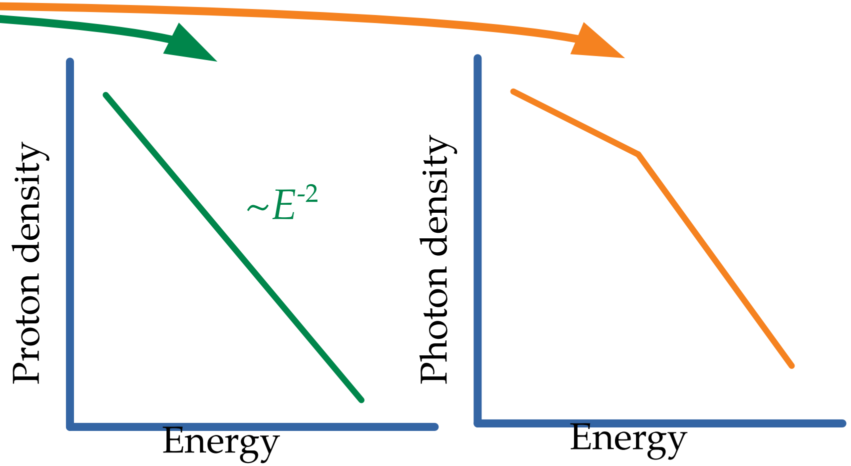

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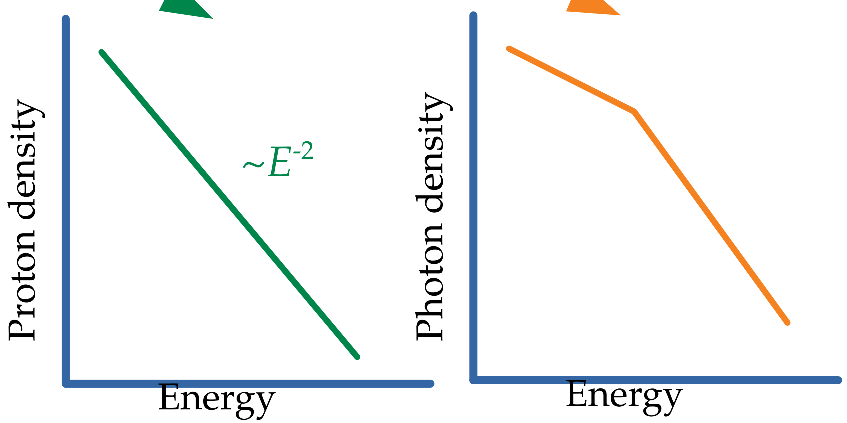
$$\pi^0 \rightarrow \gamma + \gamma$$

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

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



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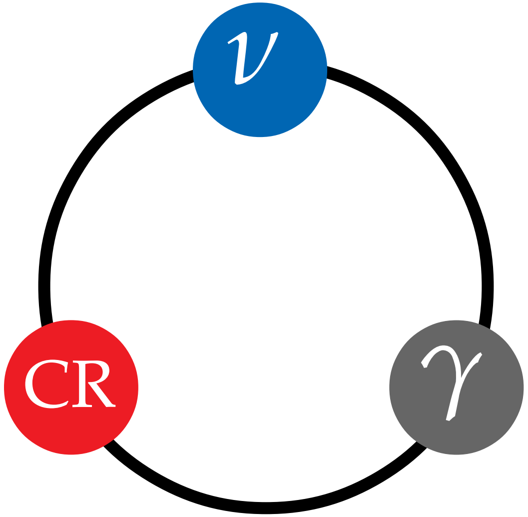


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Gamma-ray energy = Proton energy / 10

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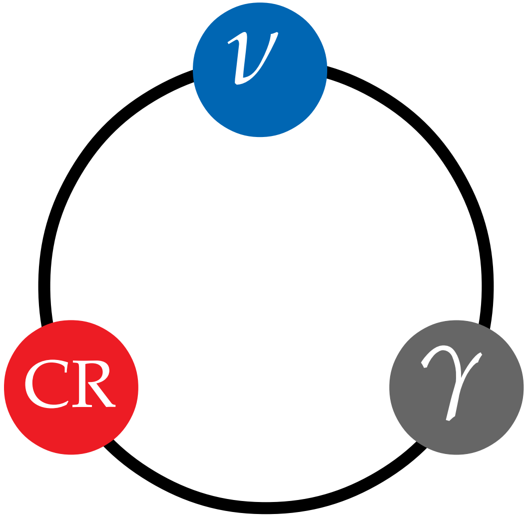


1 PeV 20 PeV

Neutrino energy = Proton energy / 20

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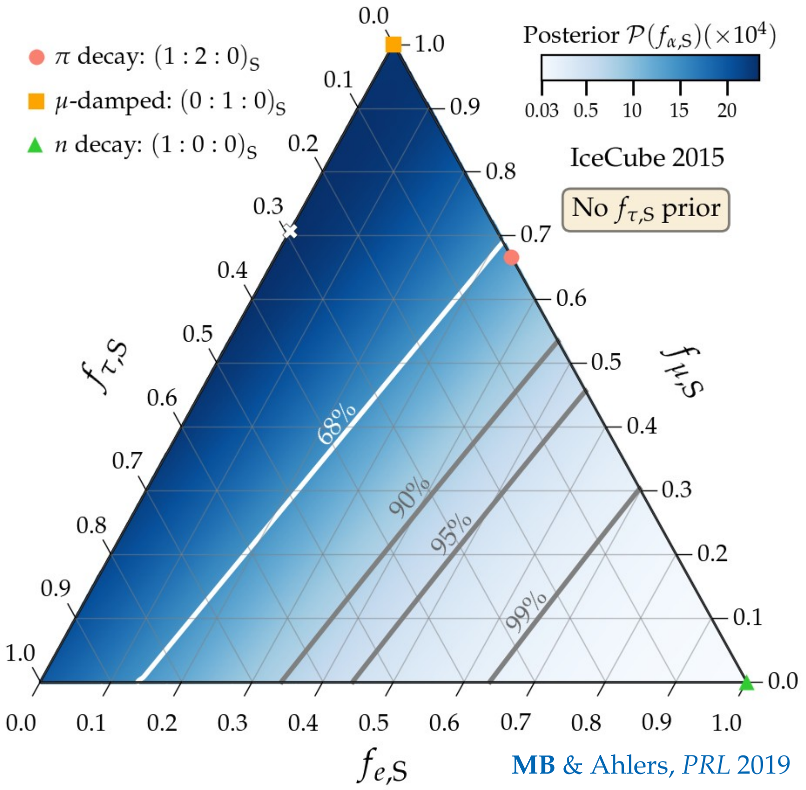
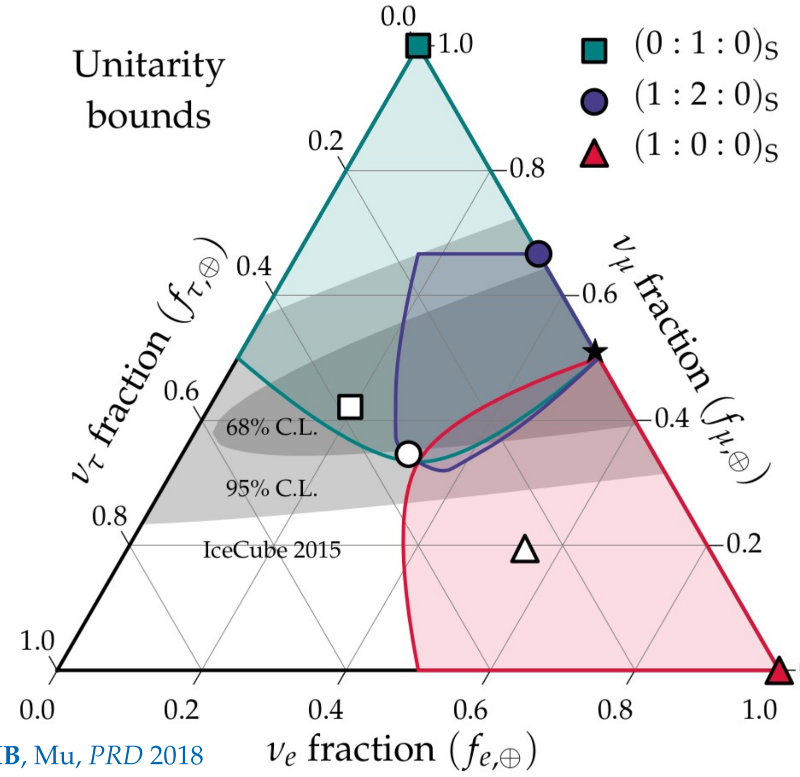
# Flavor is a two-edged sword (one that's increasingly sharper)

## Trusting particle physics and learning about astrophysics

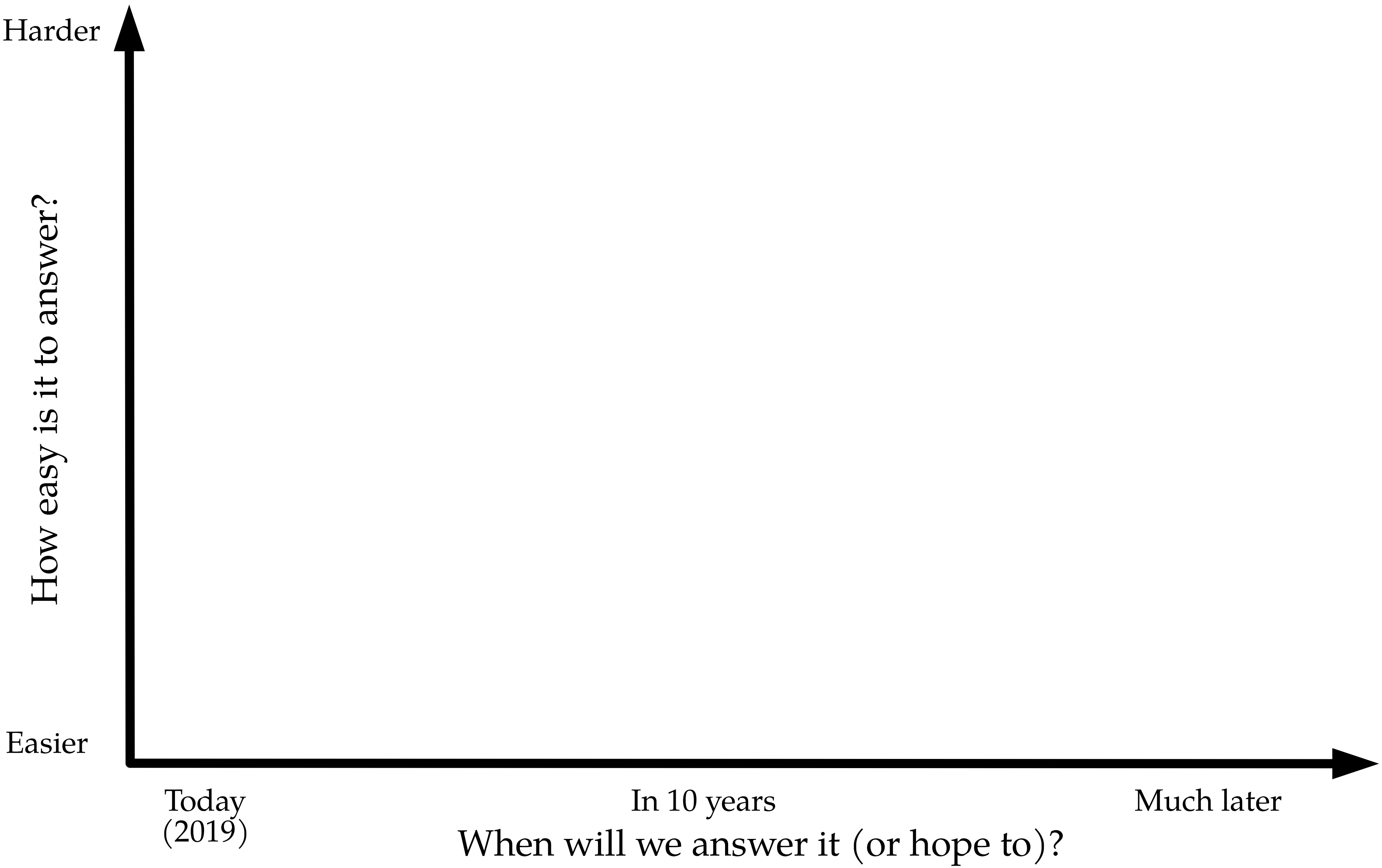


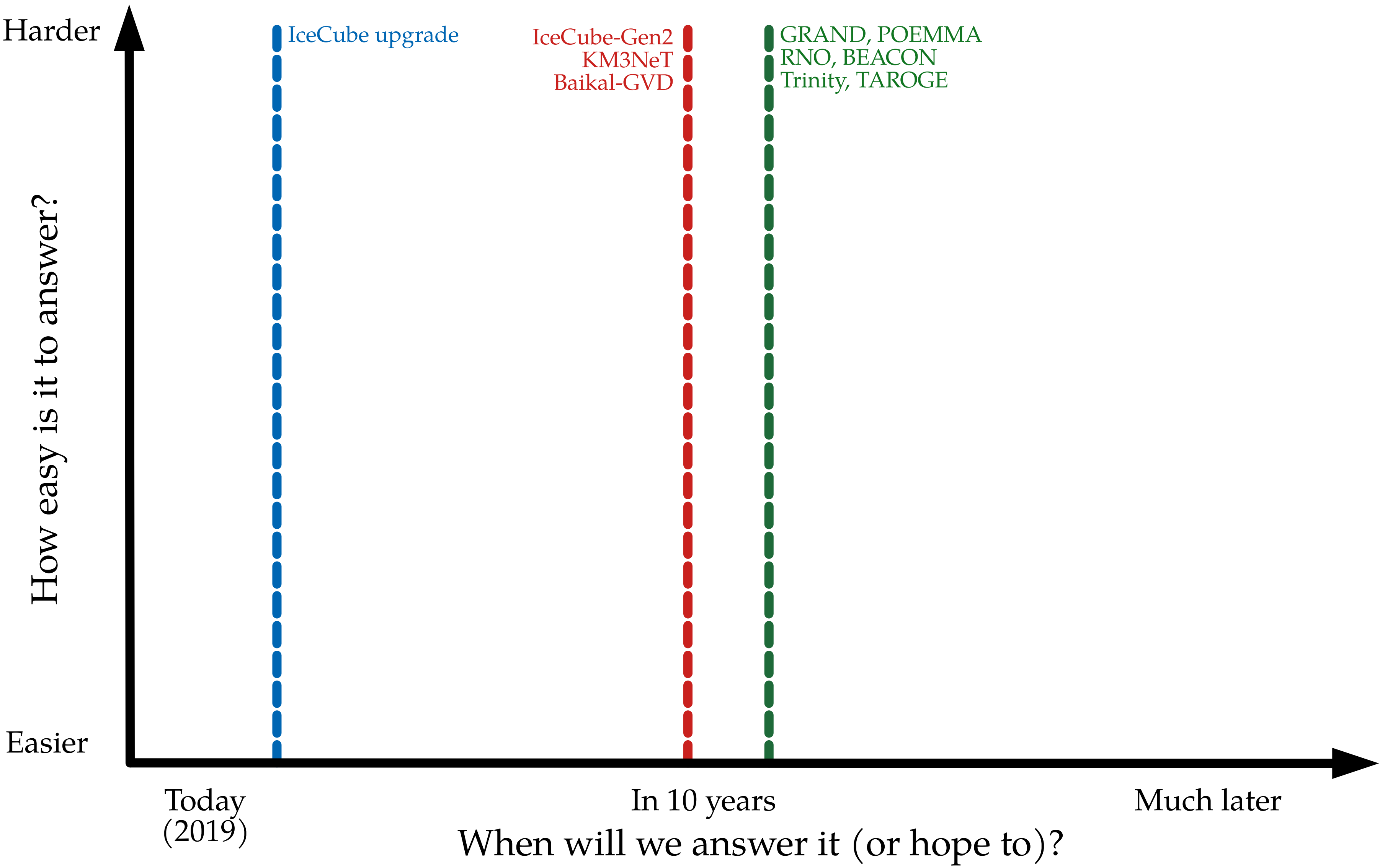

**MB** & Ahlers, *PRL* 2019

## Trusting astrophysics and learning about particle physics




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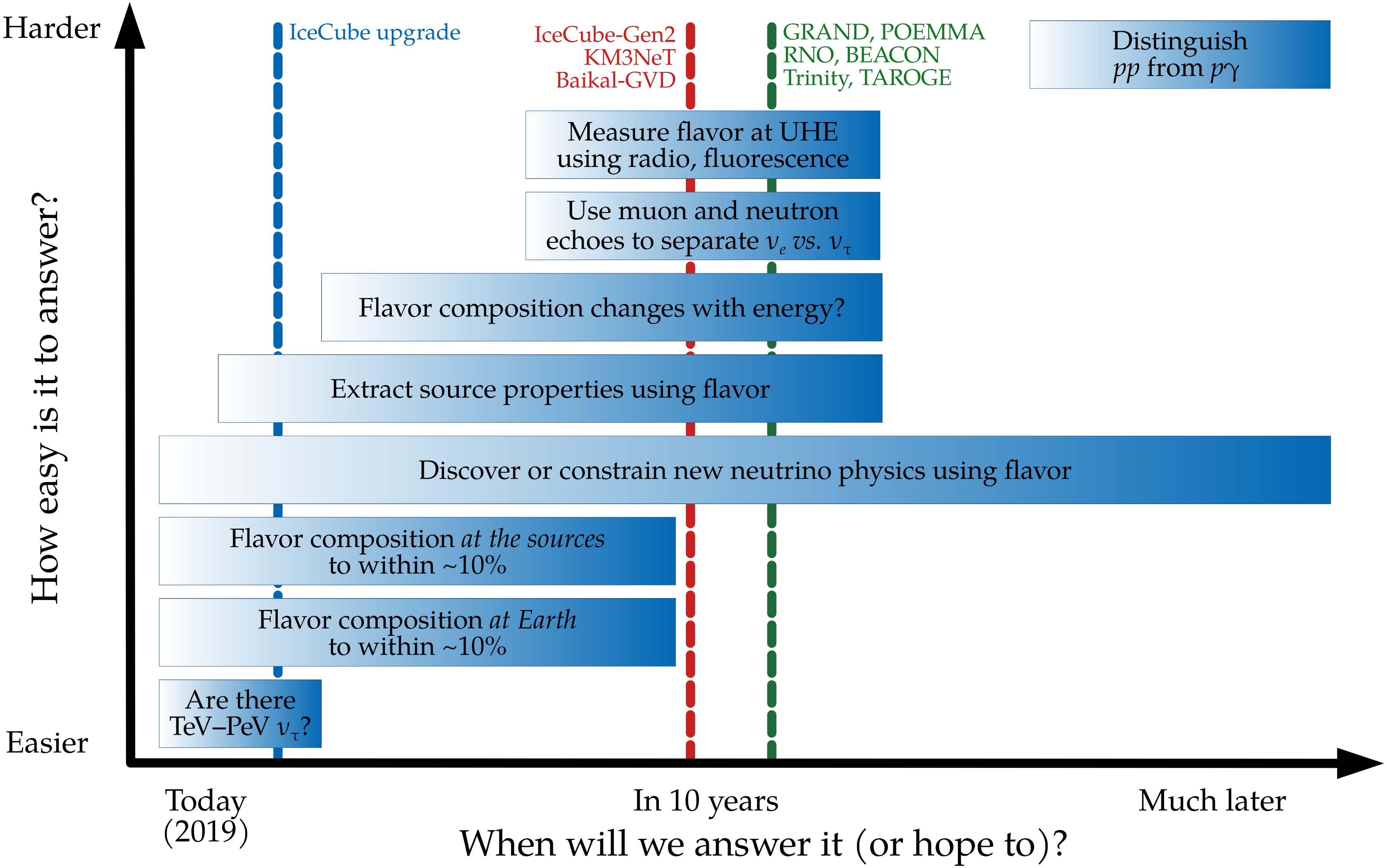
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Distinguish
$pp$ from $p\gamma$
Measure flavor at UHE
using radio, fluorescence
Use muon and neutron
echoes to separate $\nu_e$ *vs.* $\nu_\tau$
Flavor composition changes with energy?
Extract source properties using flavor
Discover or constrain new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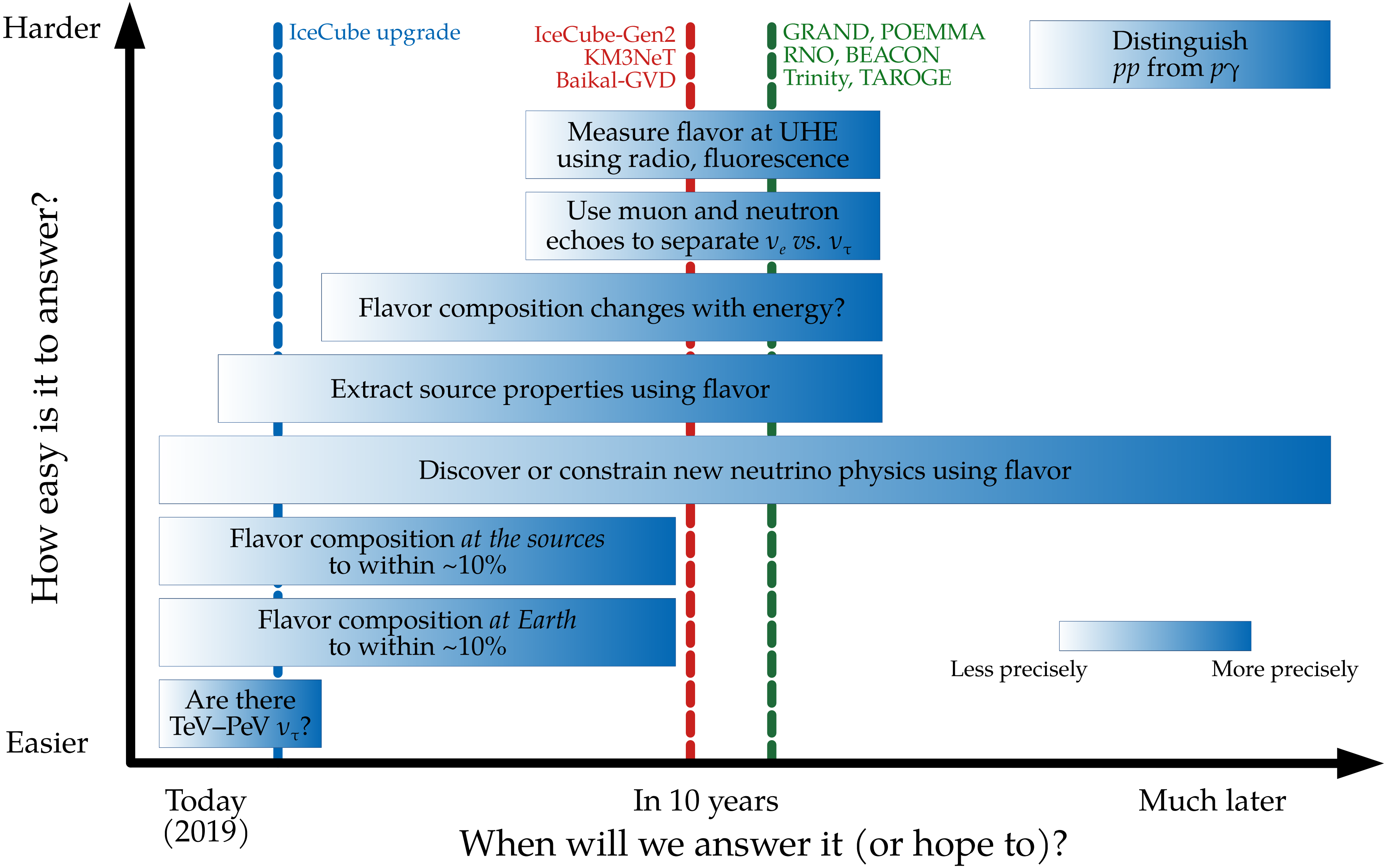

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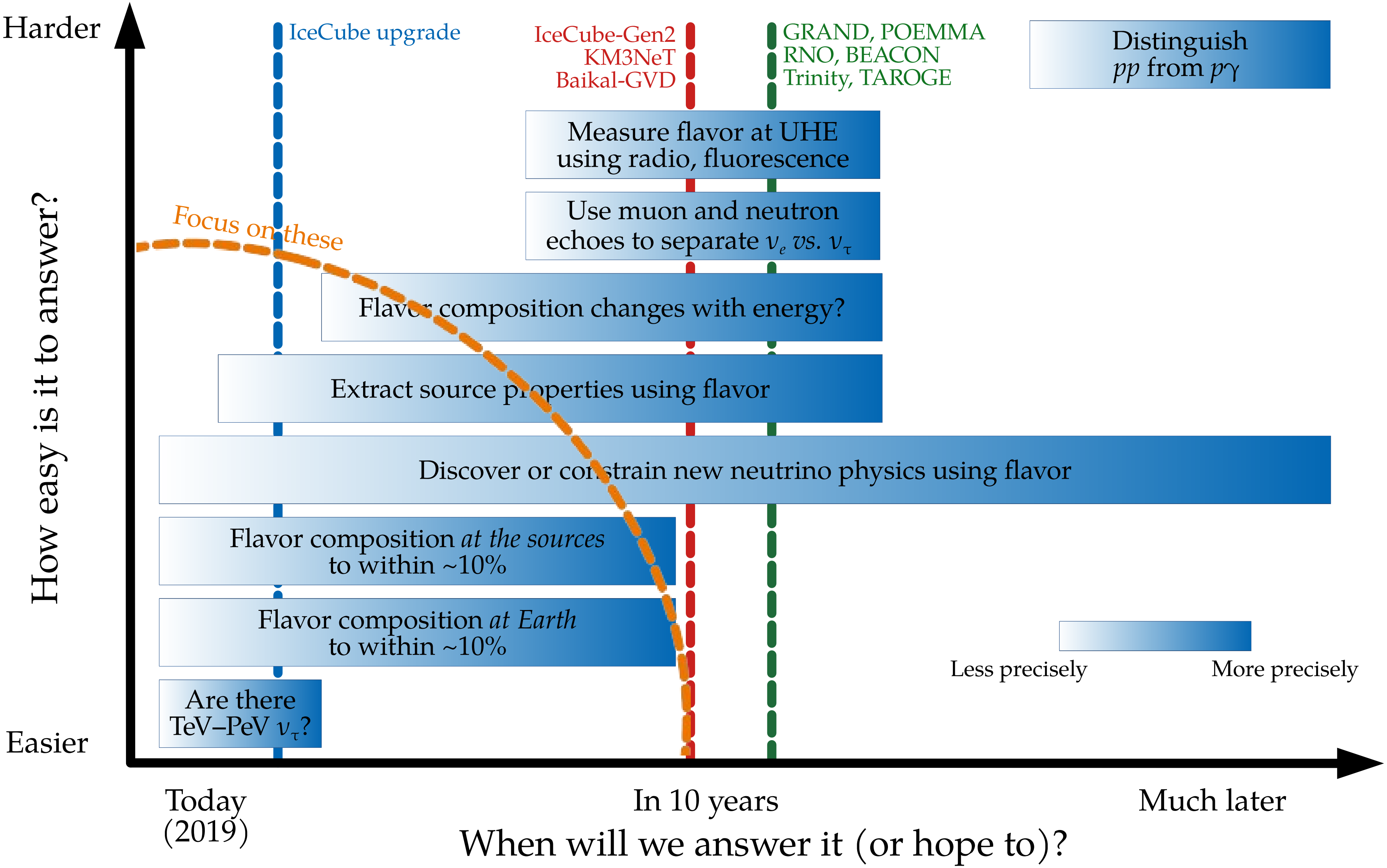

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Measure flavor at UHE using radio, fluorescence
Use muon and neutron echoes to separate $\nu_e$ *vs.* $\nu_\tau$
Focus on these
Flavor composition changes with energy?
Extract source properties using flavor
Discover or constrain new neutrino physics using flavor
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Less precisely
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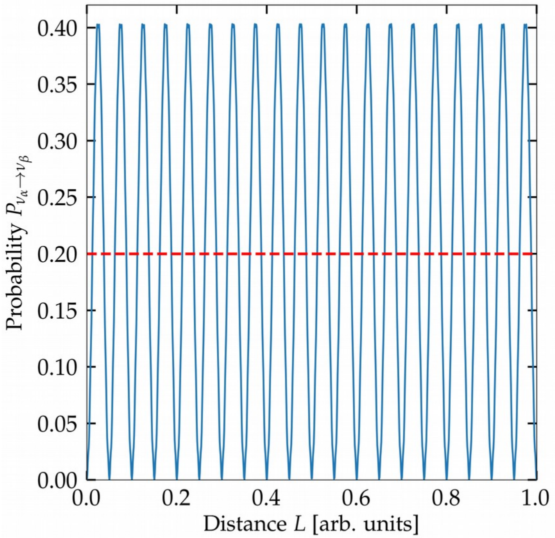
When will we answer it (or hope to)?

# High-energy neutrinos oscillate *fast*




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

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

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

# High-energy neutrinos oscillate *fast*

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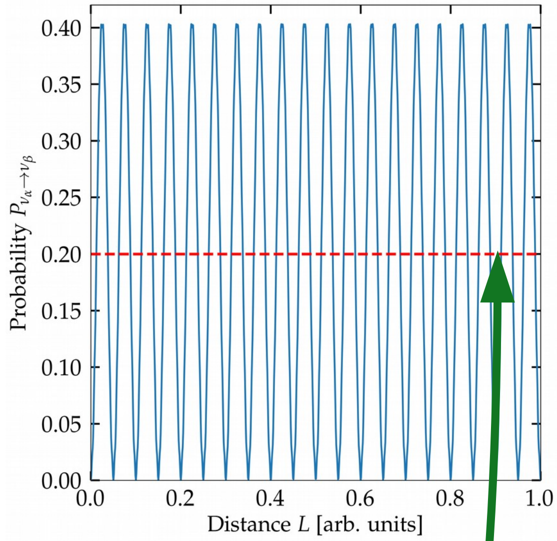


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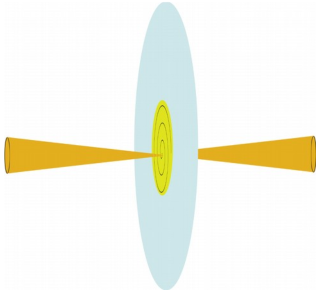
# Flavor composition basics

Astrophysical neutrino sources | Earth

Up to a few Gpc



$\nu_e$

$\nu_\mu$

$\nu_\tau$

Flavor mixing changes the number of ν of each flavor, $N_e$, $N_\mu$, $N_\tau$

$\nu_e$

$\nu_\mu$

$\nu_\tau$

- 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 ($\alpha = e, \mu, \tau$):

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

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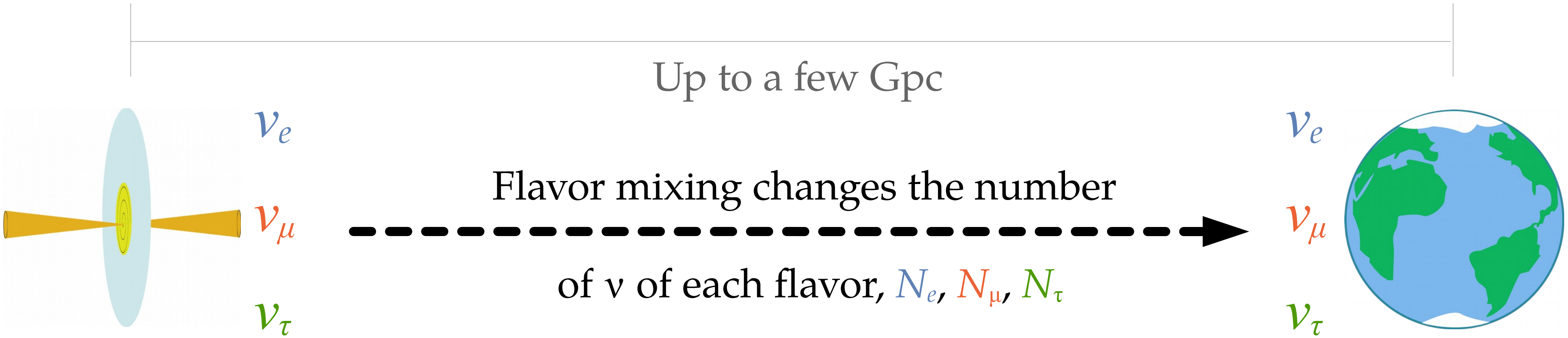


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Standard oscillations *or* new physics

# 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

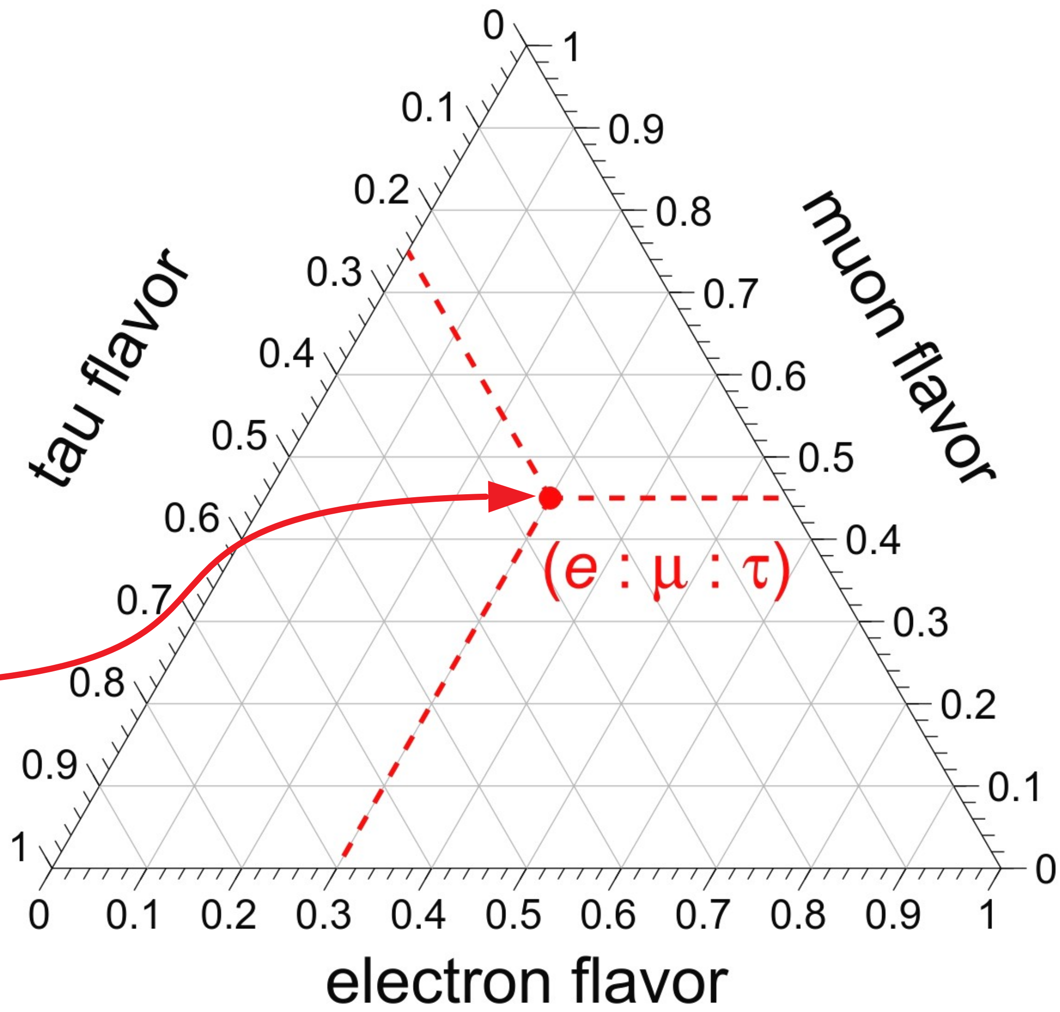
*Note: Ratios are for $\nu + \bar{\nu}$, since neutrino telescopes cannot tell them apart*

# 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 content of neutrino mass eigenstates

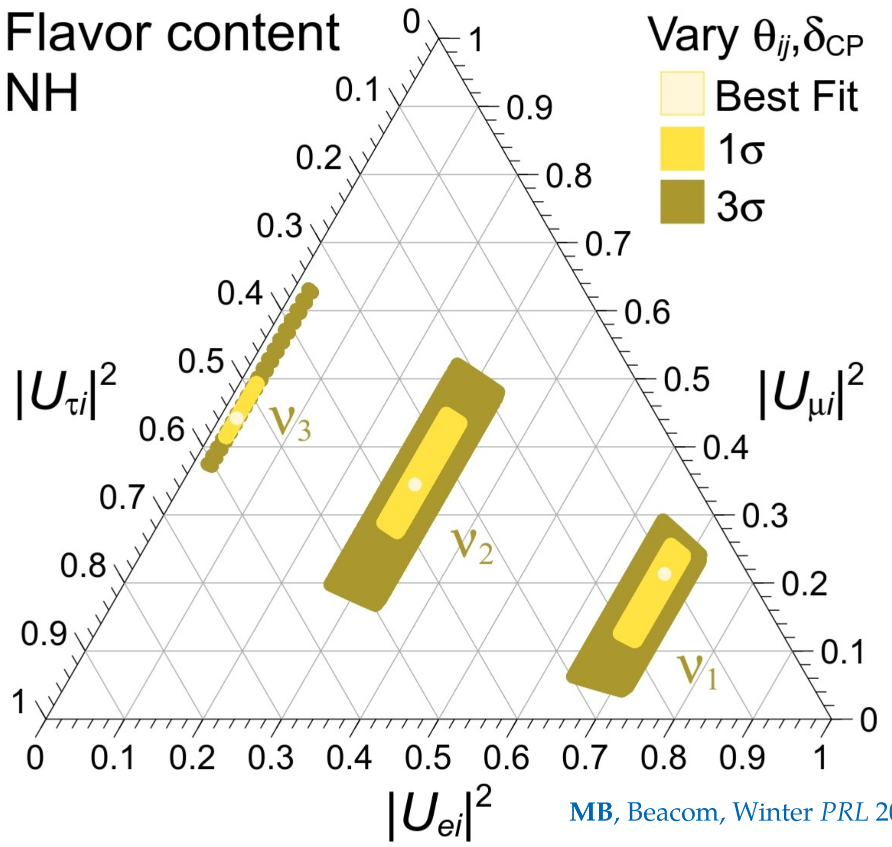
Flavor content for every allowed combination of mixing parameters –

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

One likely TeV–PeV $\nu$ production scenario:

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

Full $\pi$ decay chain

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

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

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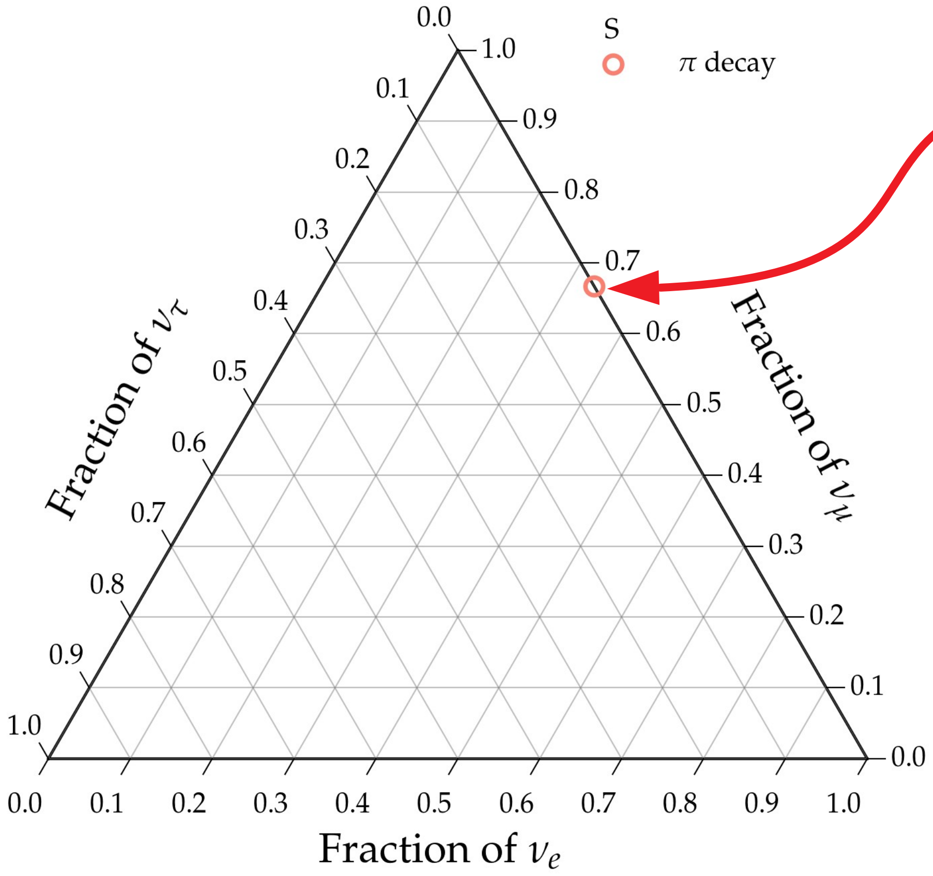


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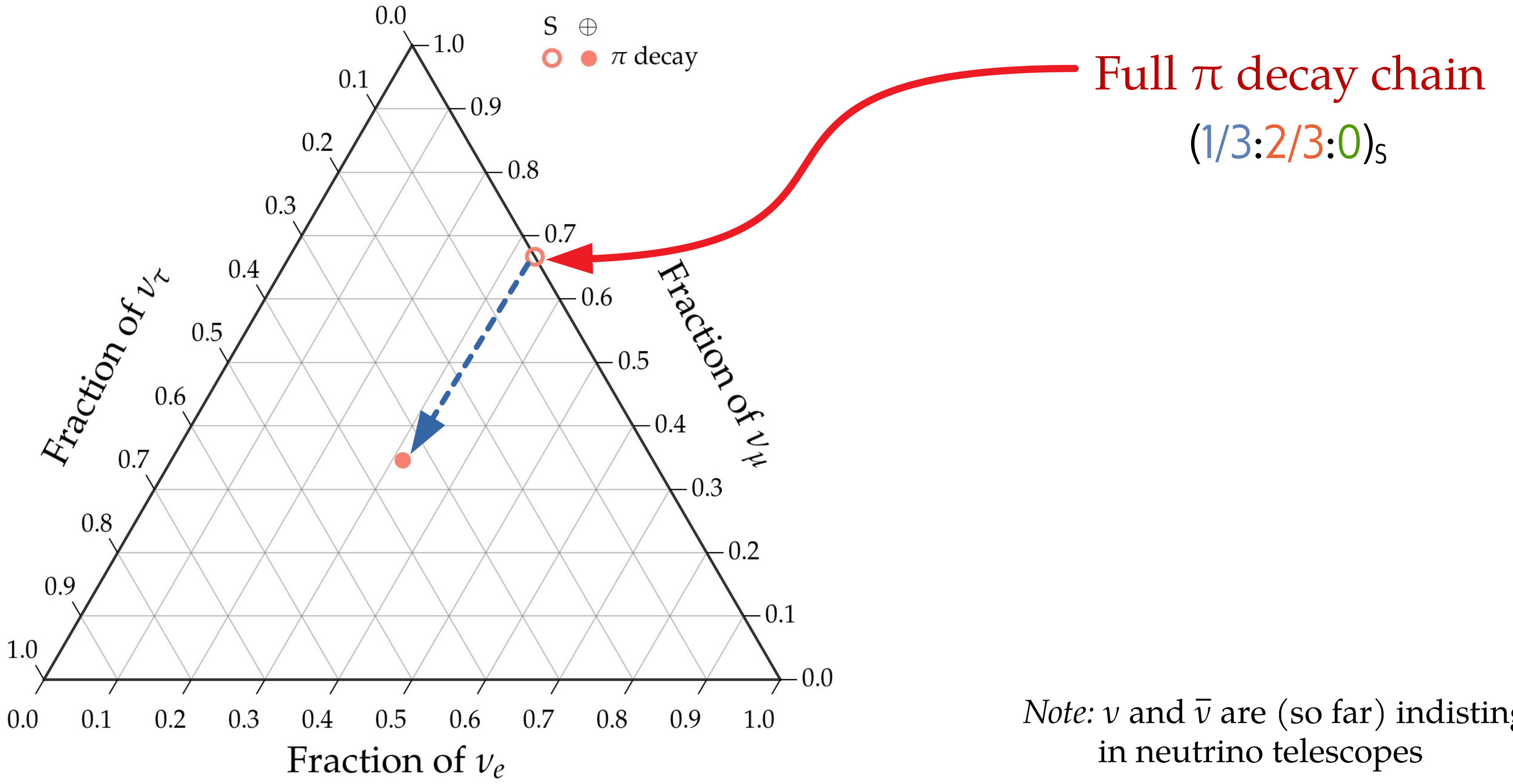


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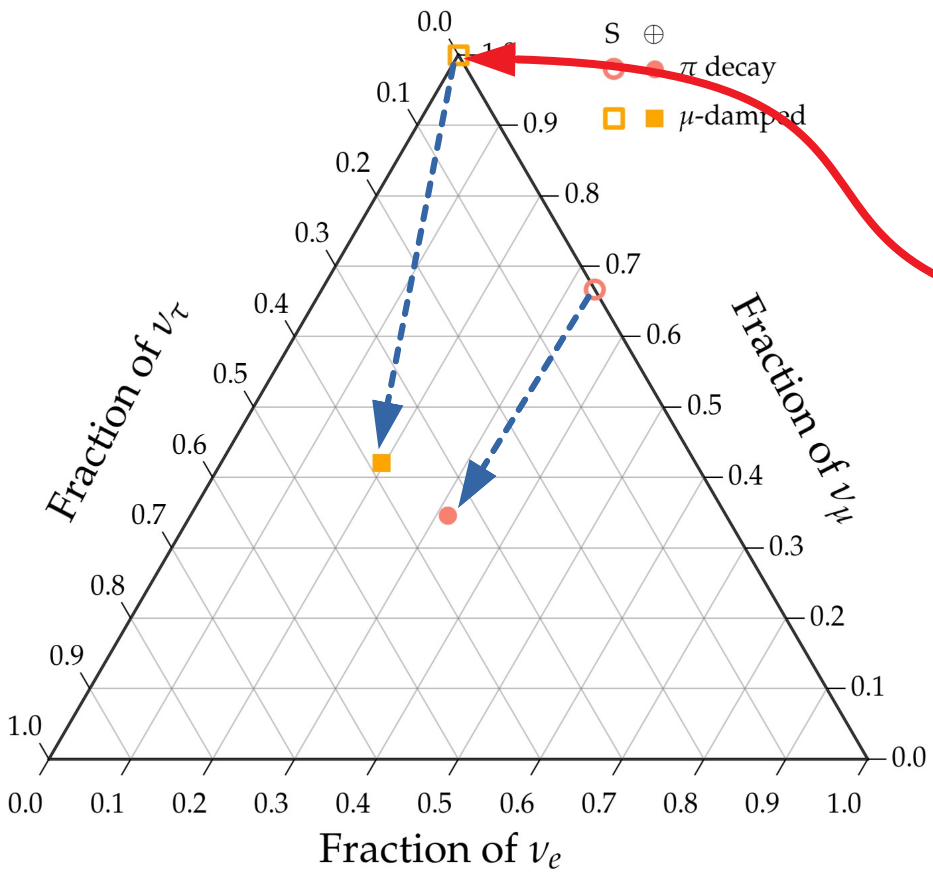


Full $\pi$ decay chain

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

Muon damped

$(0:1:0)_S$

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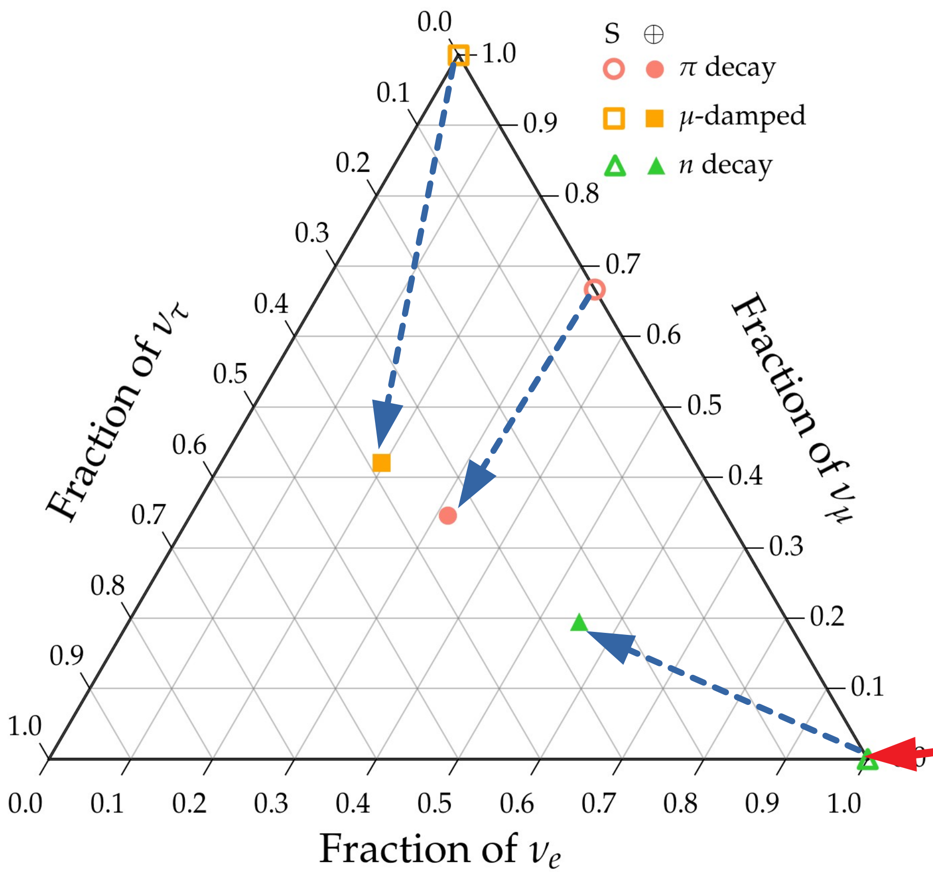


**Full π decay chain**

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

**Muon damped**

$(0:1:0)_S$

**Neutron decay**

$(1:0:0)_S$

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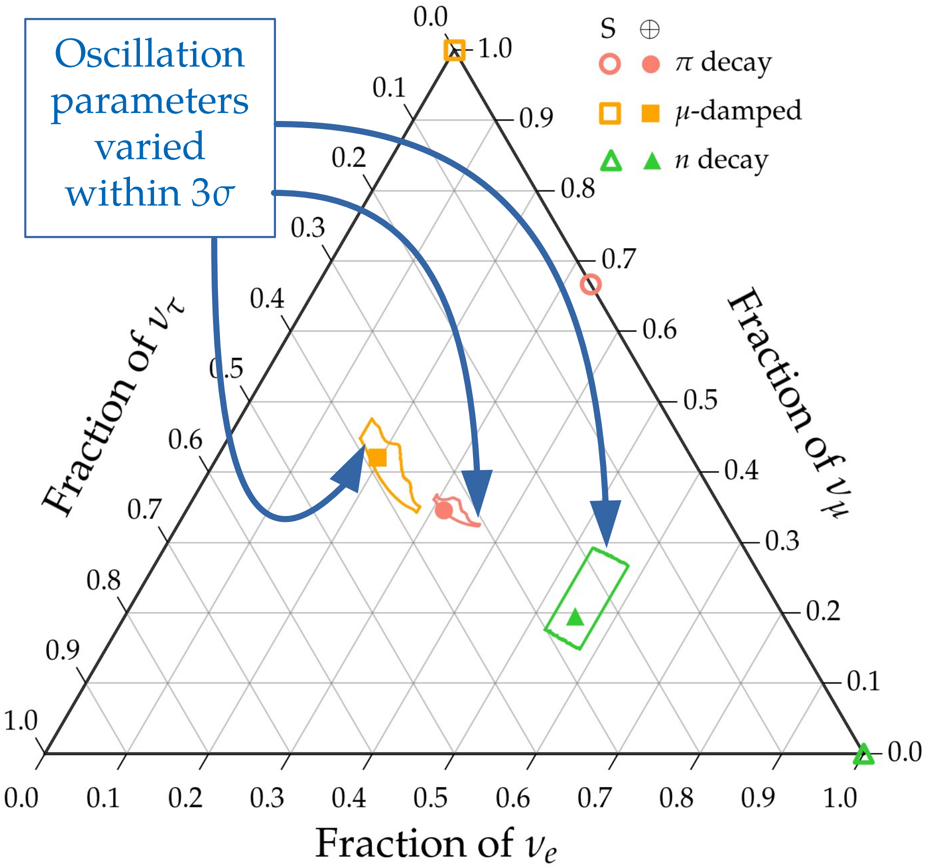


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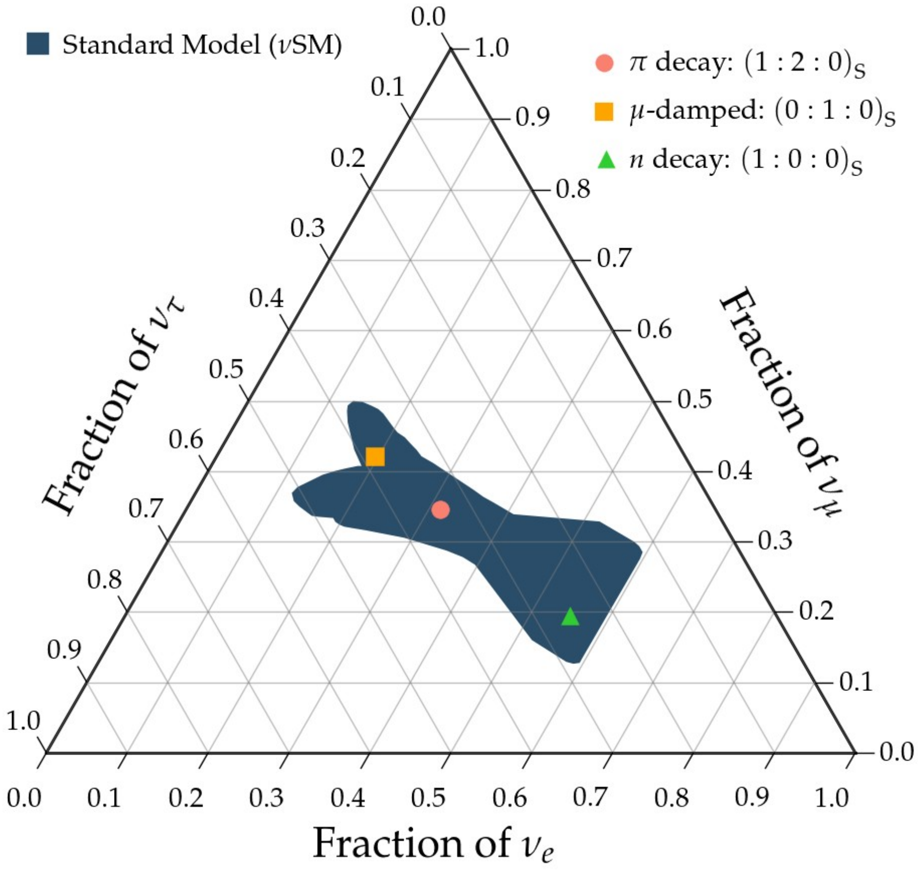


All possible flavor ratios at the sources

+

Vary oscillation parameters within $3\sigma$

*Note:* $\nu$ 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)

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

# How does IceCube see TeV–PeV neutrinos?

**Deep inelastic neutrino-nucleon scattering**

Neutral current (NC)

Charged current (CC)

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

Receives $\langle y \rangle E_\nu$

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

$\nu_l + N \rightarrow l + X$

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

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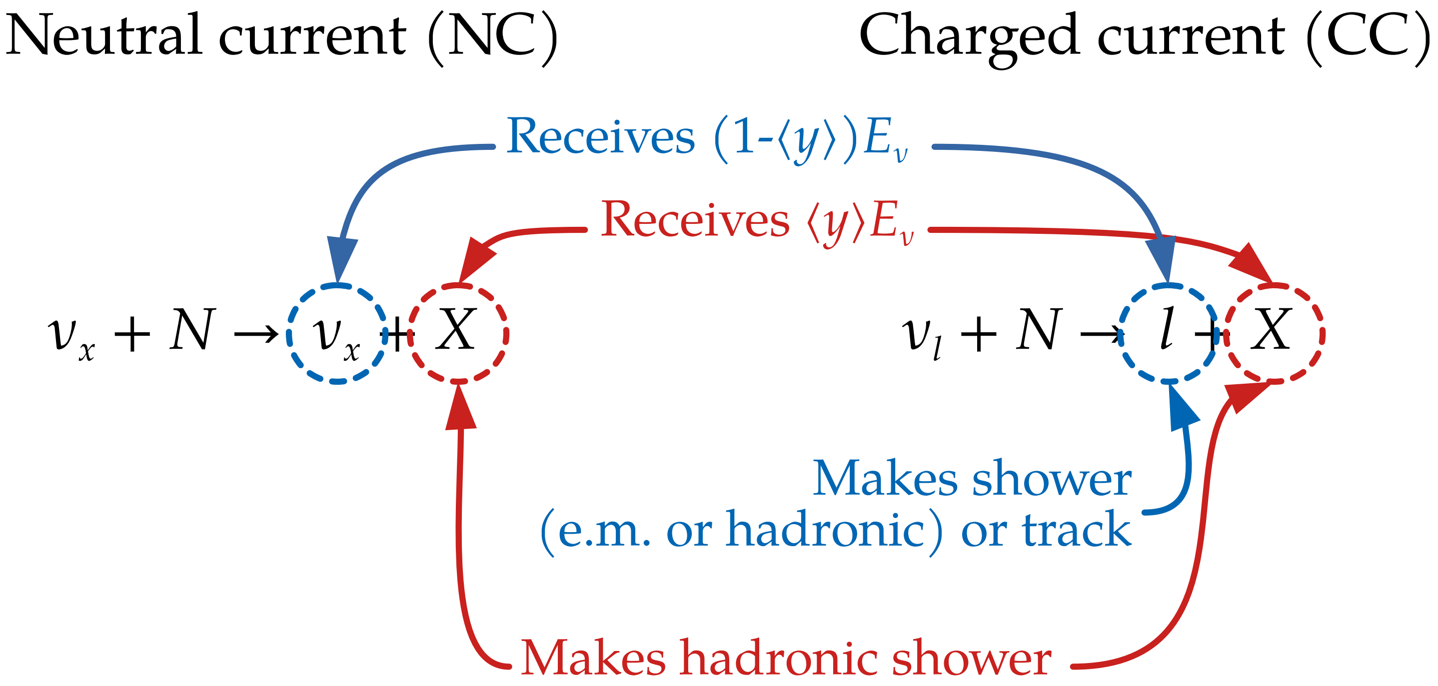


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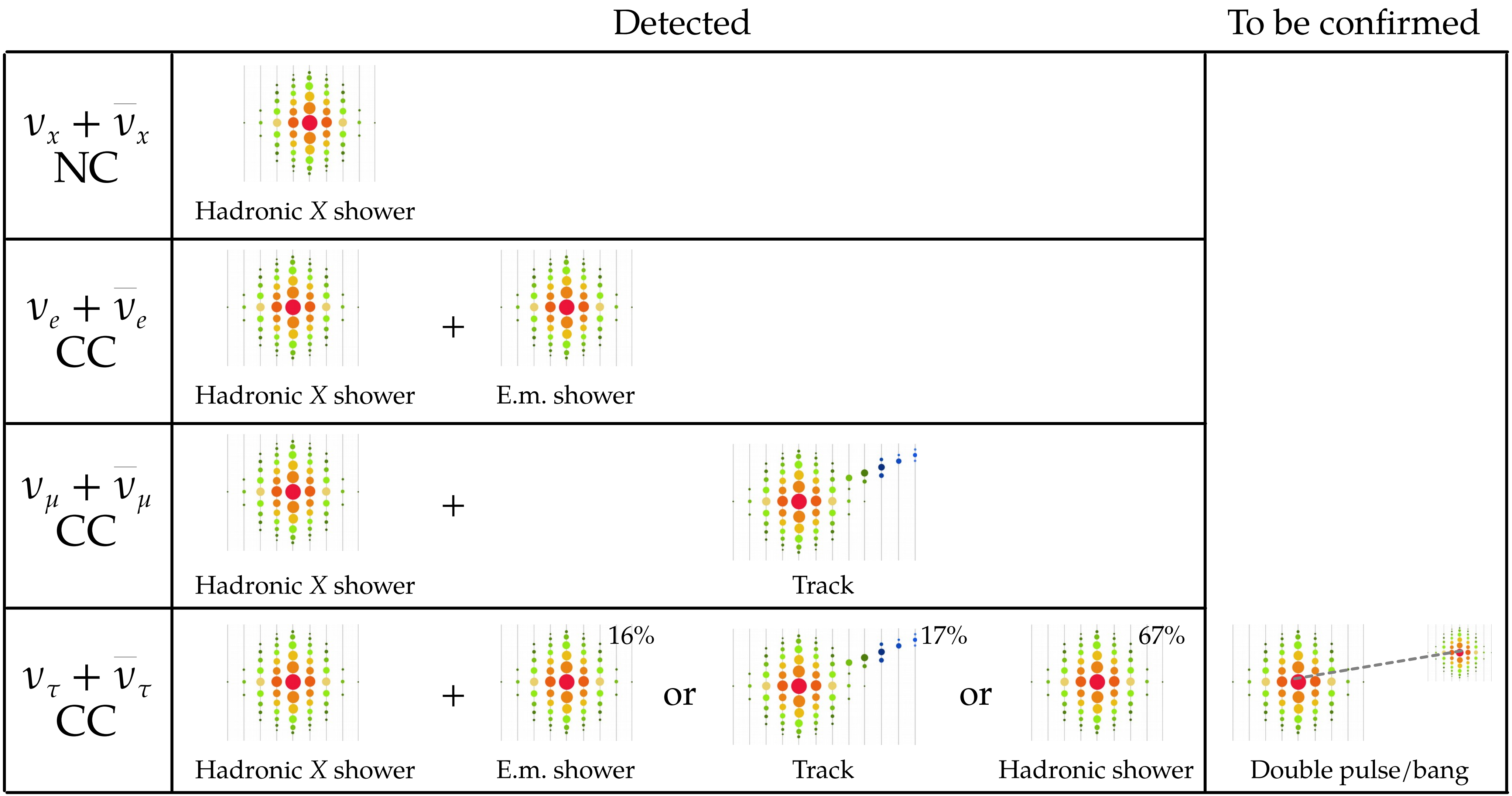
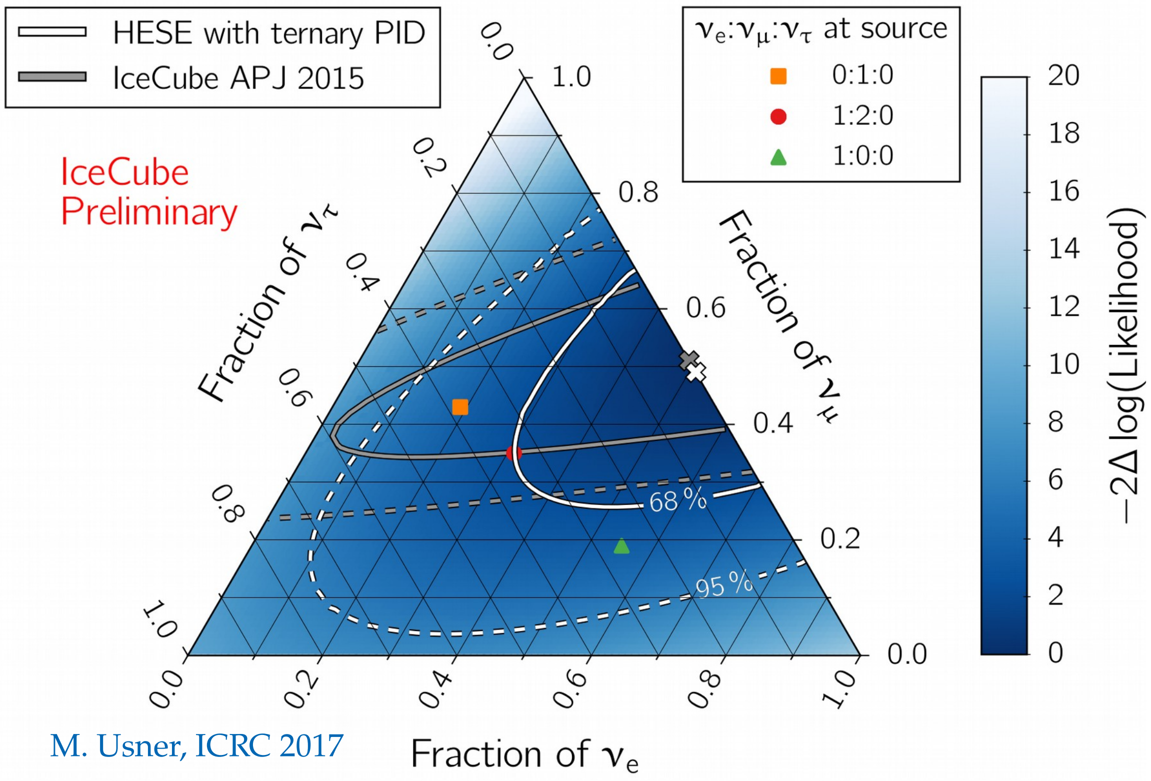

Detected
To be confirmed
$\nu_x + \bar{\nu}_x$ NC
Hadronic $X$ shower
$\nu_e + \bar{\nu}_e$ CC
Hadronic $X$ shower
+
E.m. shower
$\nu_\mu + \bar{\nu}_\mu$ CC
Hadronic $X$ shower
+
Track
$\nu_\tau + \bar{\nu}_\tau$ CC
Hadronic $X$ shower
+
16%
E.m. shower
or
17%
Track
or
67%
Hadronic shower
Double pulse/bang

# IceCube results: Flavor composition



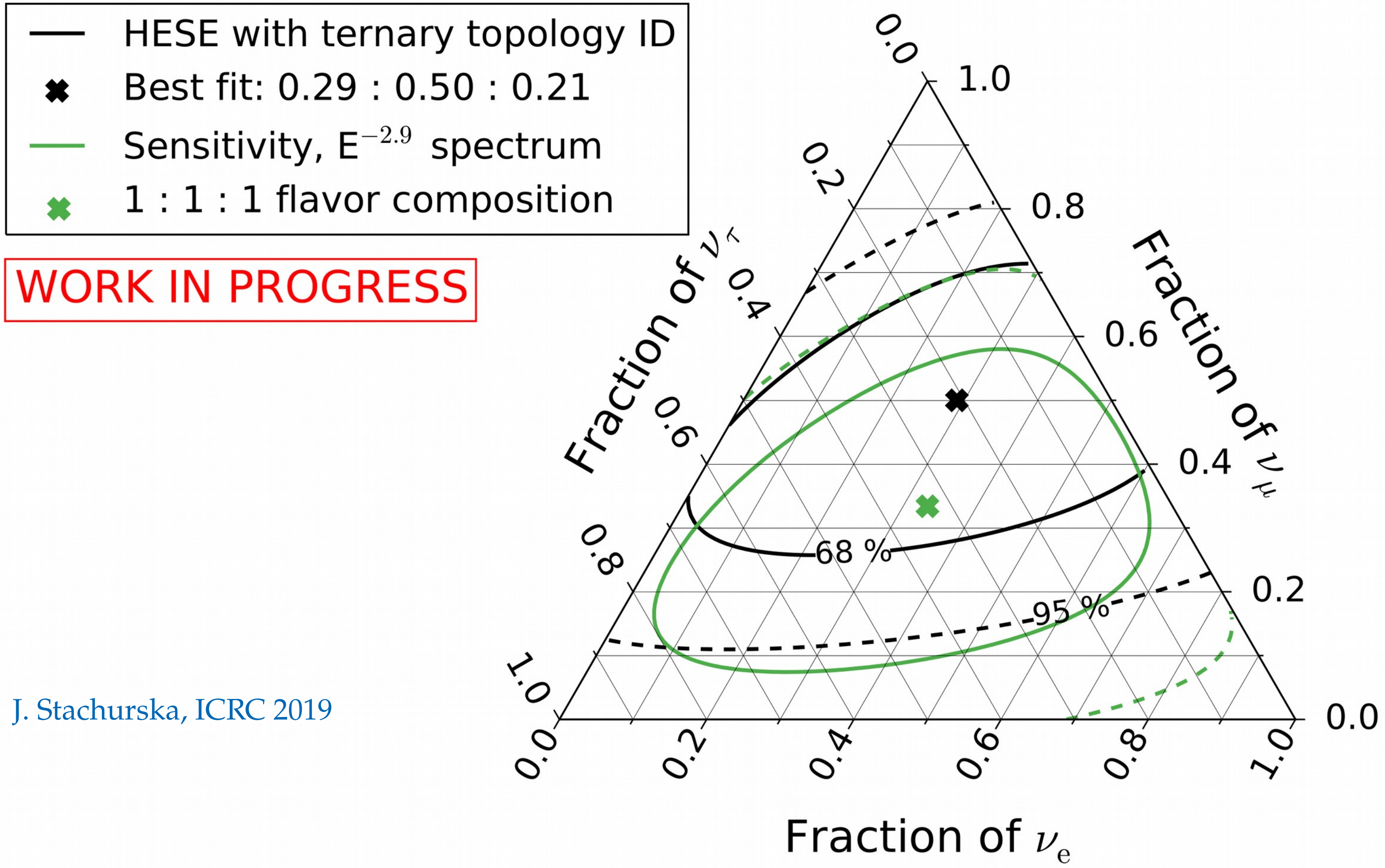

M. Usner, ICRC 2017

- Compare number of tracks ($\nu_\mu$) *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

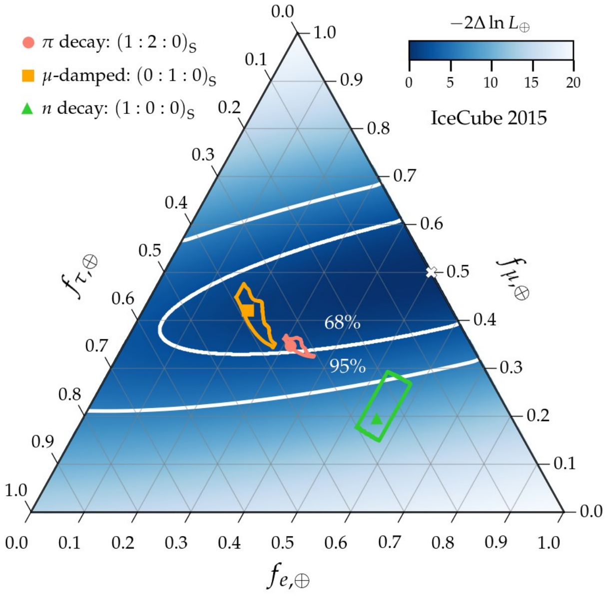
There are 2 $\nu_\tau$ candidate events which change the flavor composition:



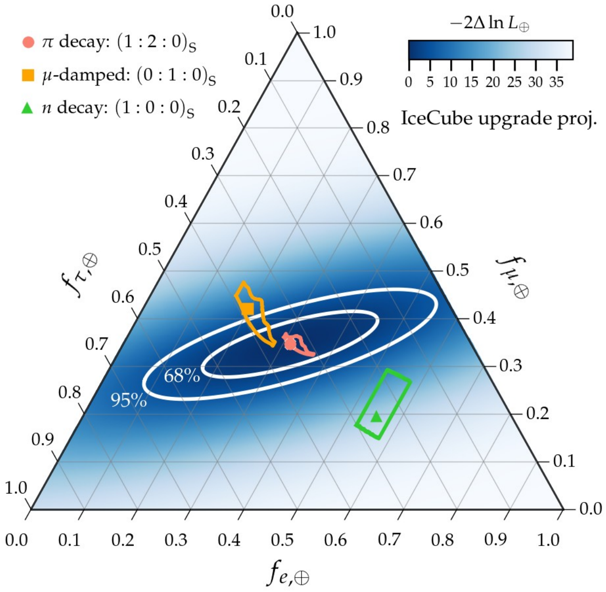

J. Stachurska, ICRC 2019

# Flavor composition: now and in the future

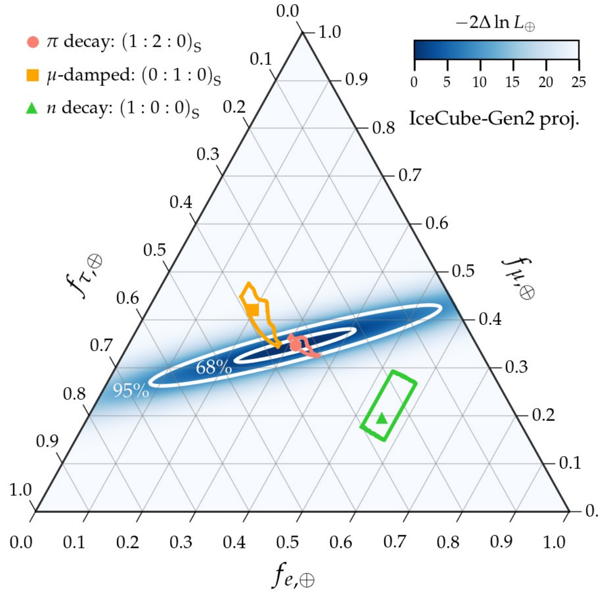
## Today
IceCube




## Near future (2022)
IceCube upgrade




## In 10 years (2030s)
IceCube-Gen2




- Best fit: $(f_e : f_\mu : f_\tau)_\oplus = (0.5 : 0.5 : 0)_\oplus$
- Compatible with standard source compositions
- Hints of one $\nu_\tau$ (not shown)

Assuming production by the full pion decay chain

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

# High-energy cosmic neutrinos made in neutron decays?

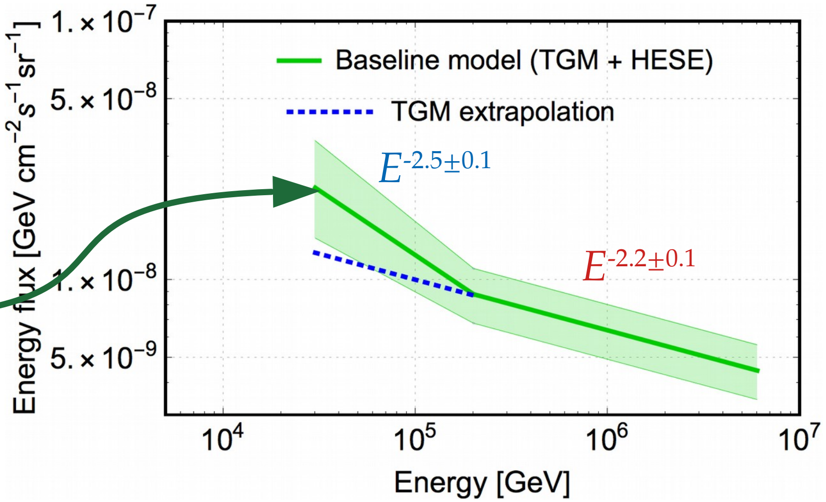
- Palladino, *EPJC* 2019
- Join the two IceCube spectrum fits:

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

  Use it between 30 and 200 TeV

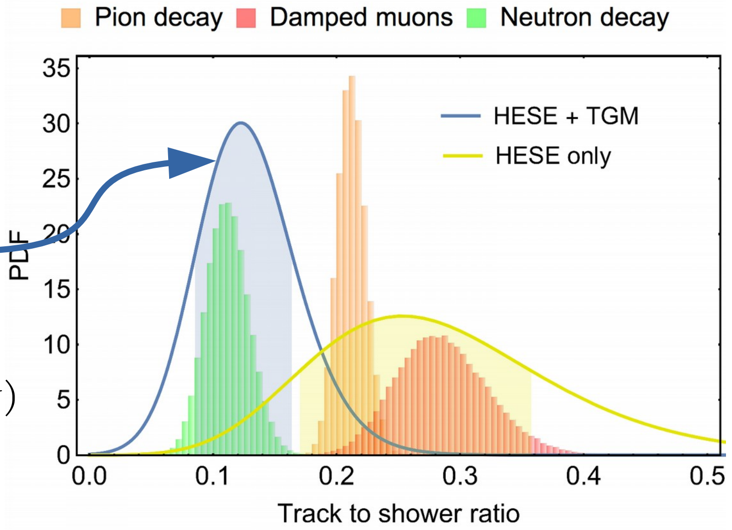
  From only through-going muons: $\Phi \propto E^{-2.2\pm0.1}$

  Use it above 200 TeV




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

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



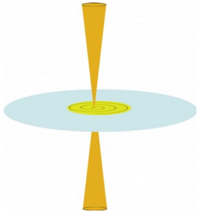

- Main problem with this interpretation: the energy budget

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

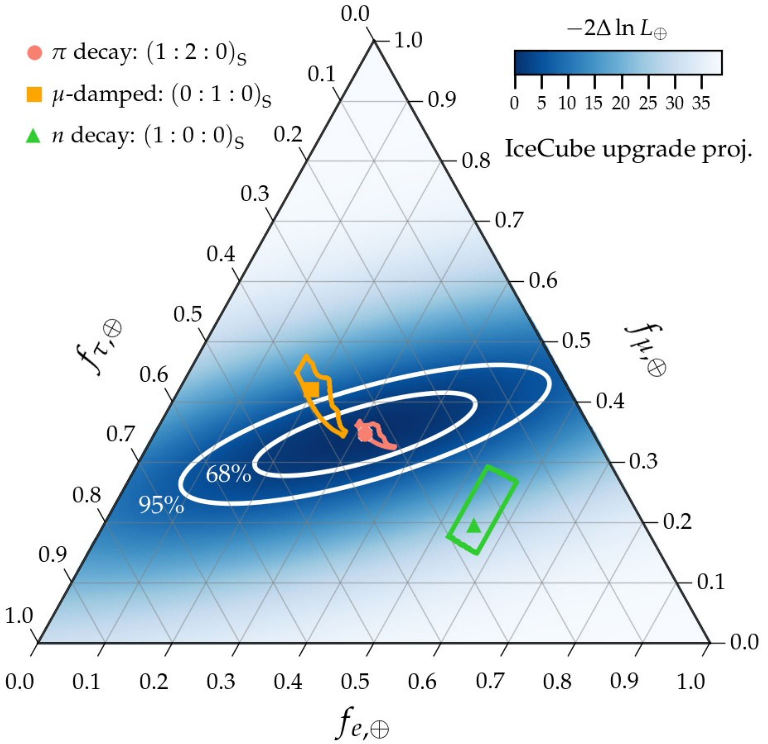
# Inferring the flavor composition at the sources

**Measured:**
Flavor ratios at Earth

Invert flavor oscillations



**Inferred:**
Flavor ratios at astrophysical sources




**MB** & Ahlers, *PRL* 2019

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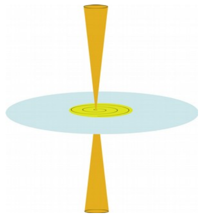

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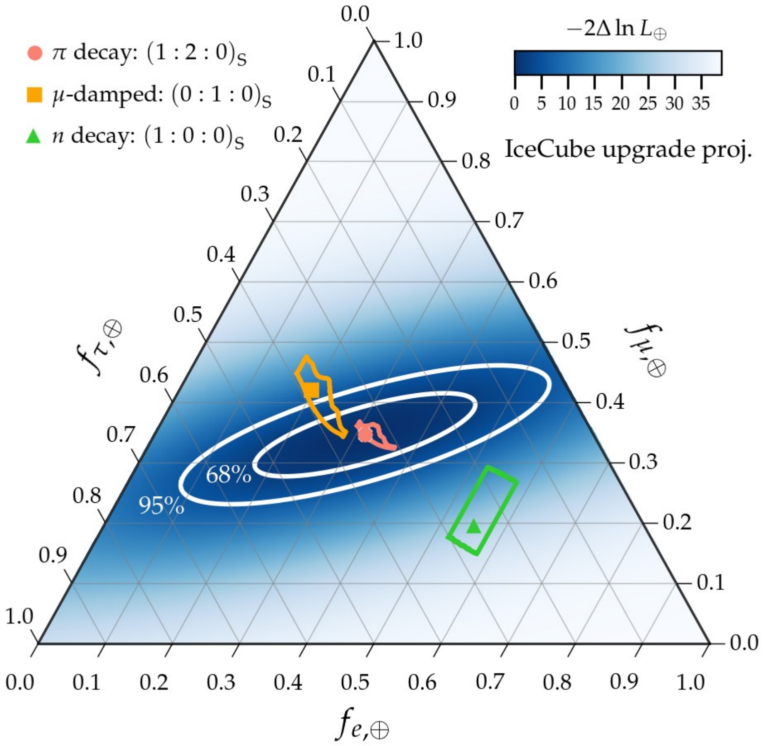


?

**MB** & Ahlers, *PRL* 2019

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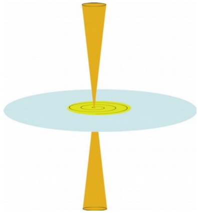
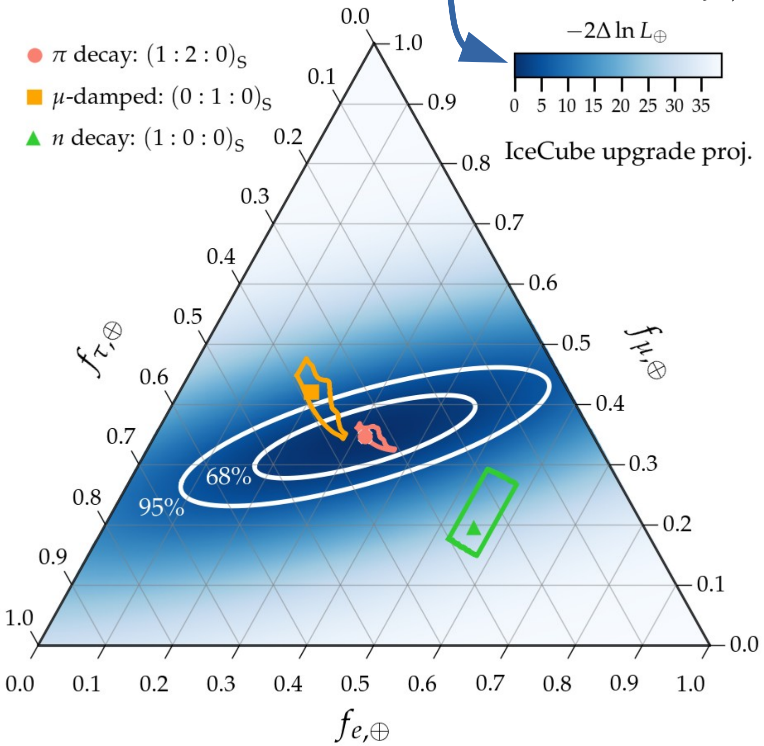


**Inferred:**
Flavor ratios at astrophysical sources

More likely

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




**MB** & Ahlers, *PRL* 2019

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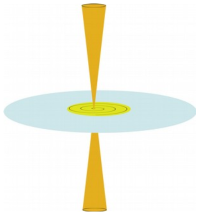

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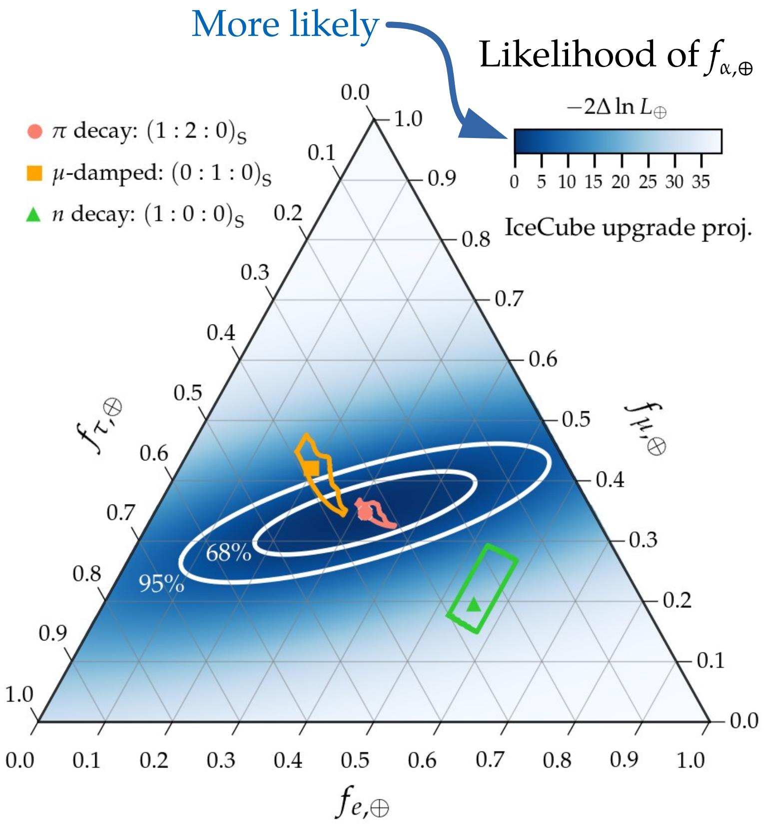
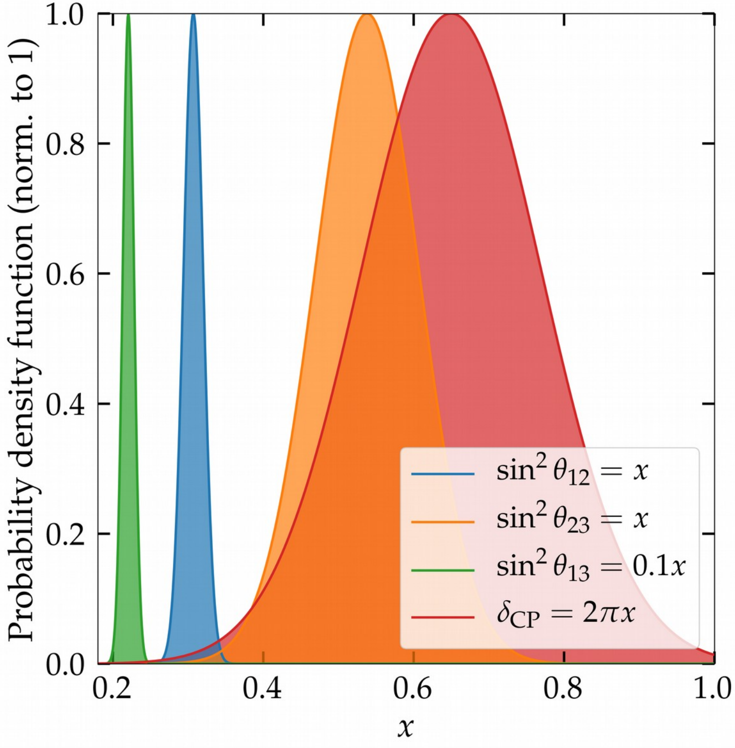



PDFs of mixing parameters




**MB** & Ahlers, *PRL* 2019

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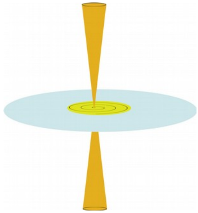

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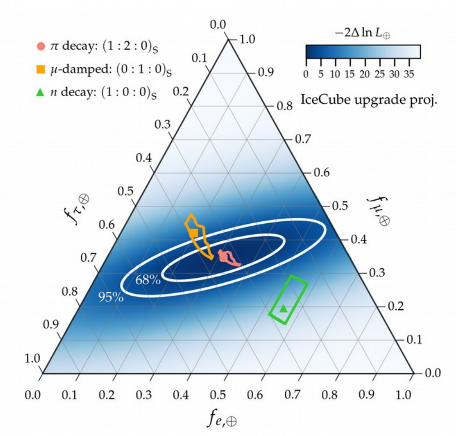
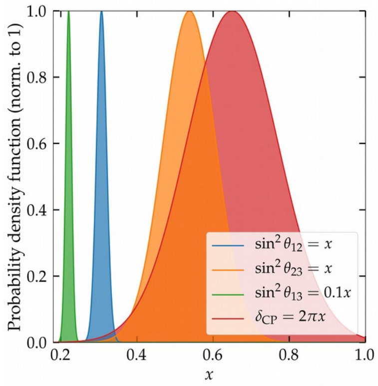



Posterior probability density of $f_{\alpha,S}$ being the flavor ratios at the sources:

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

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




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

**MB** & Ahlers, *PRL* 2019

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**Measured:**
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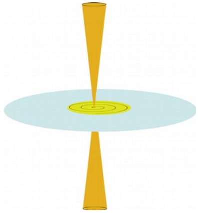
Invert flavor oscillations



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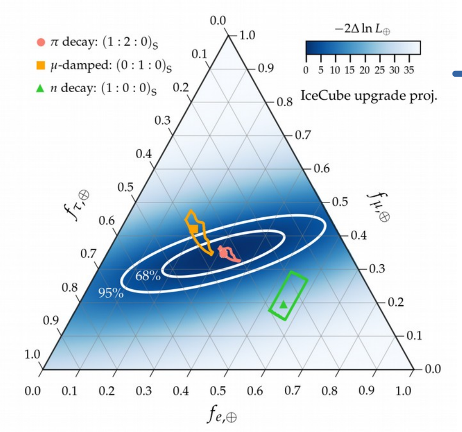


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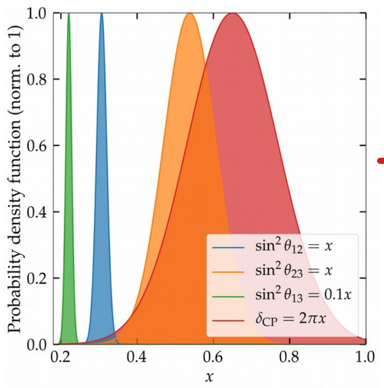


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**MB** & Ahlers, *PRL* 2019

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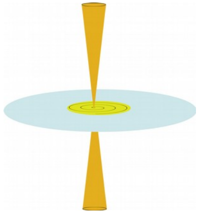

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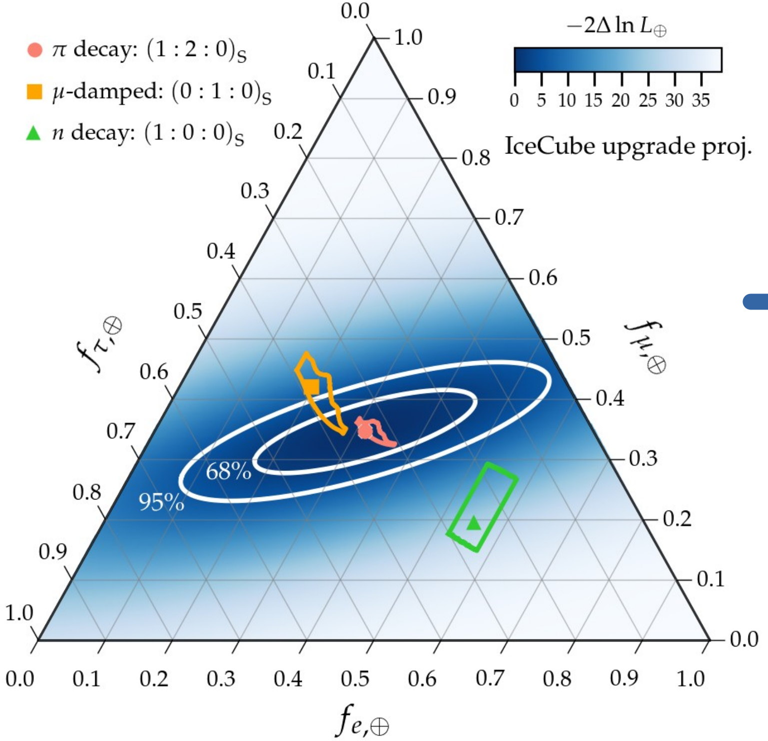


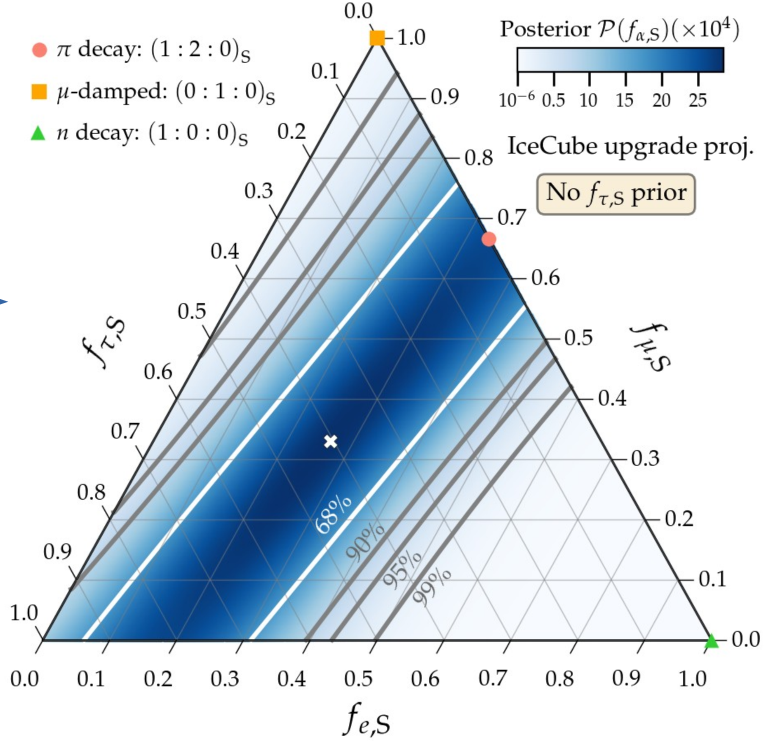


**MB** & Ahlers, *PRL* 2019

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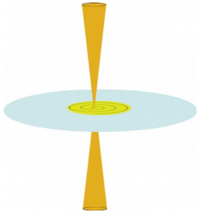

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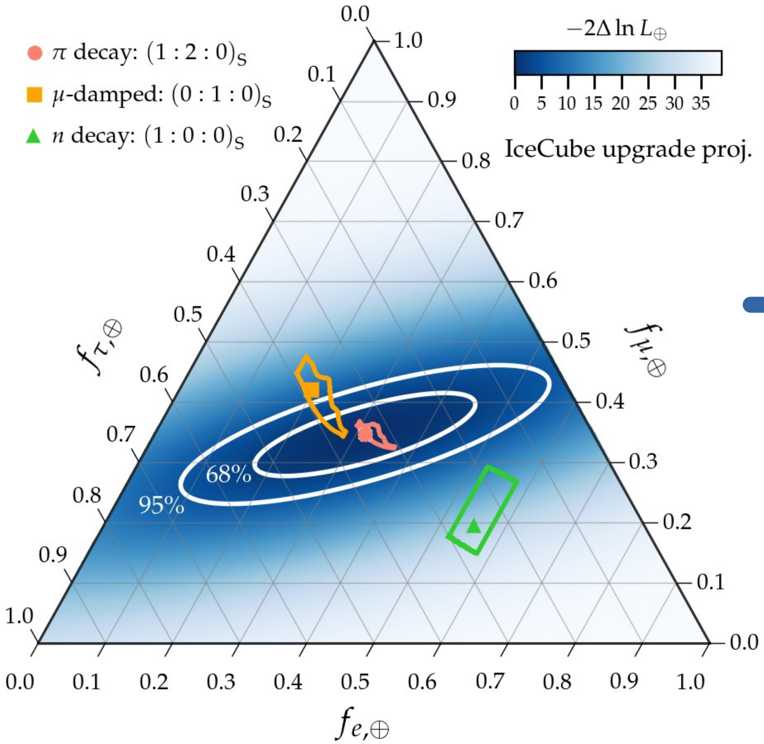
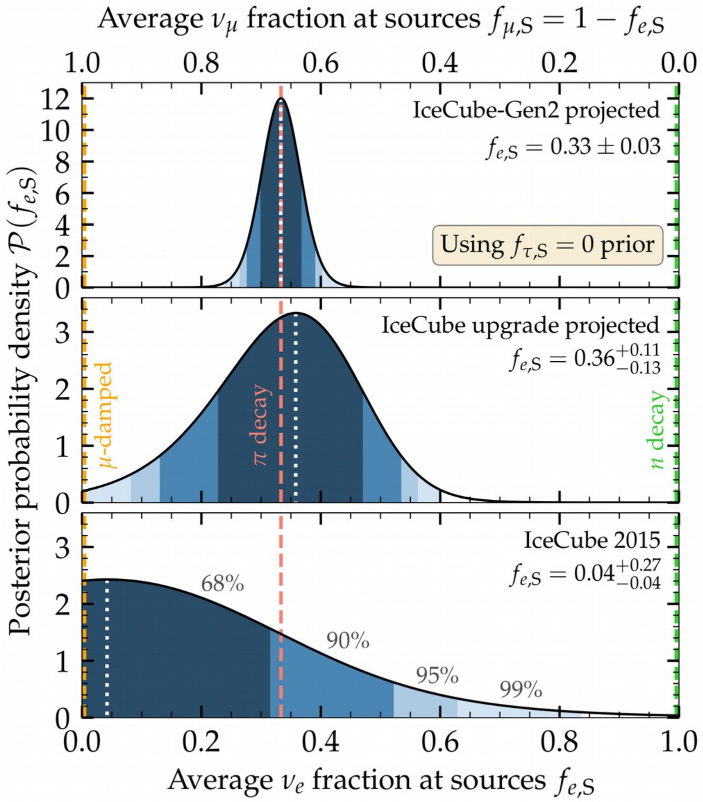
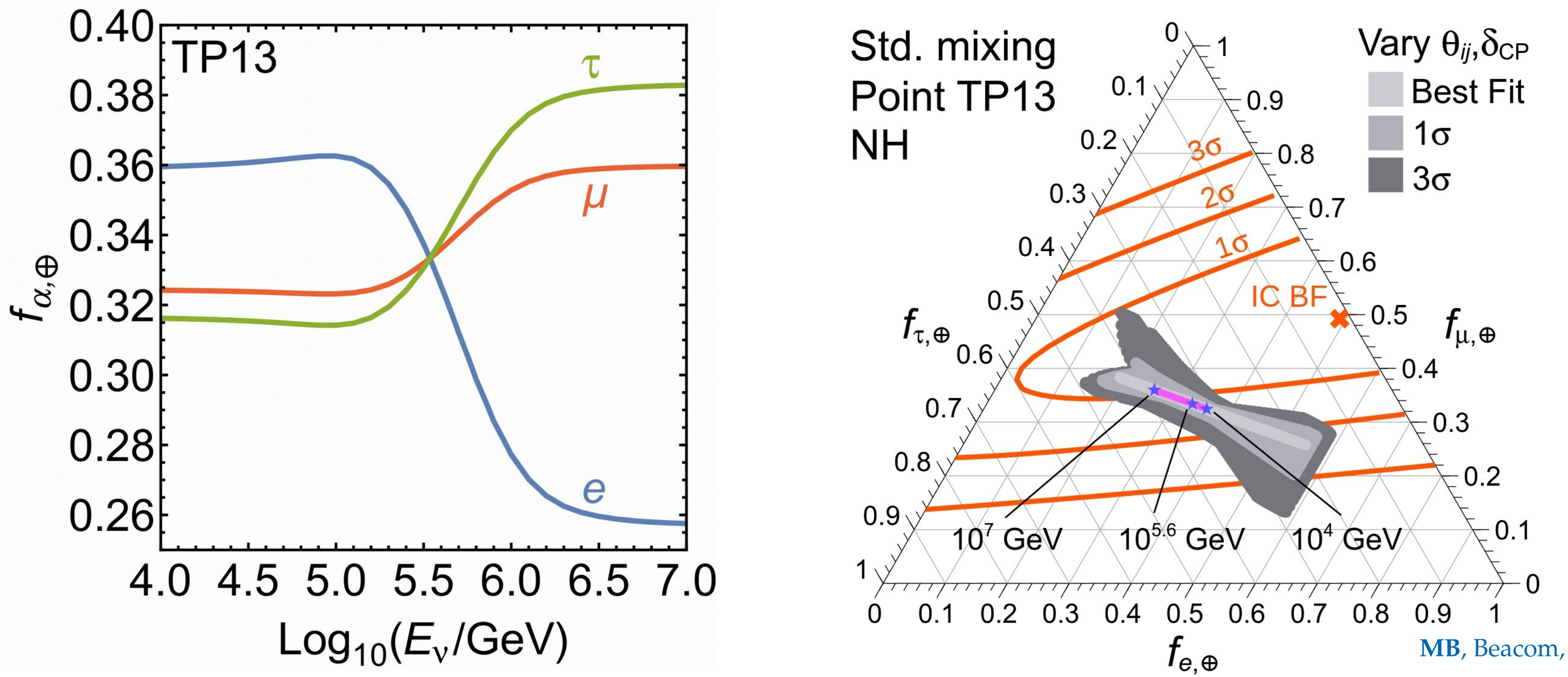



**MB** & Ahlers, *PRL* 2019

# Energy dependence of the flavor composition?

Different neutrino production channels accessible at different energies –



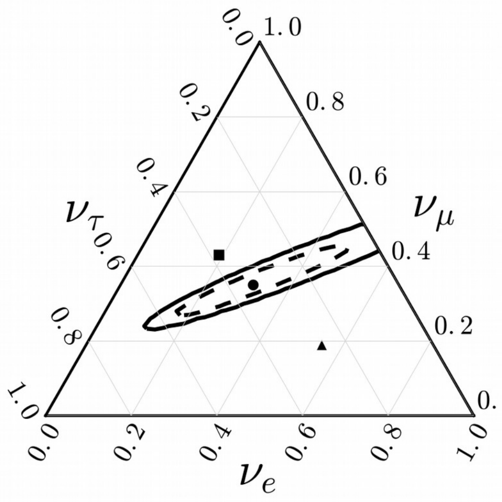

**MB**, Beacom, Winter *PRL* 2015

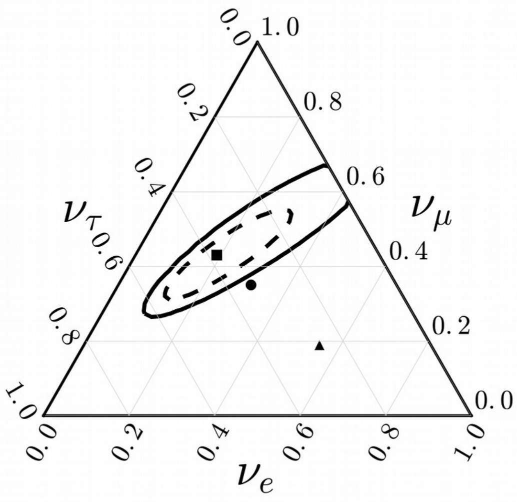
- TP13: $p\gamma$ model, target photons from electron-positron annihilation [Hümmer *et al.*, *Astropart. Phys.* 2010]
- Will be difficult to resolve [Kashti, Waxman, *PRL* 2005; Lipari, Lusignoli, Meloni, *PRD* 2007]

# … Observable in IceCube-Gen2?

**< PeV:**
Full pion decay chain

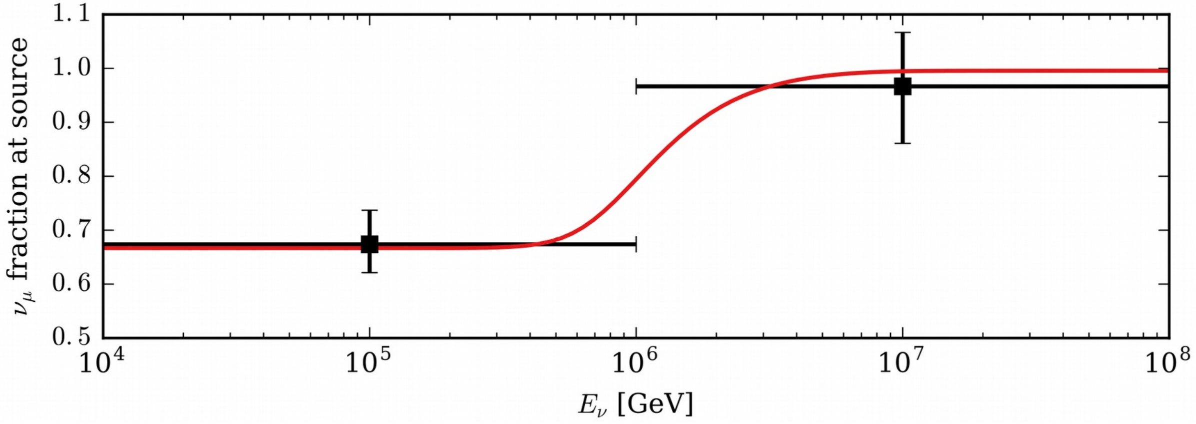
$(f_e : f_\mu : f_\tau)_\oplus$
$\approx$
$(1/3 : 1/3 : 1/3)$




**> PeV:**
Muon damping

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

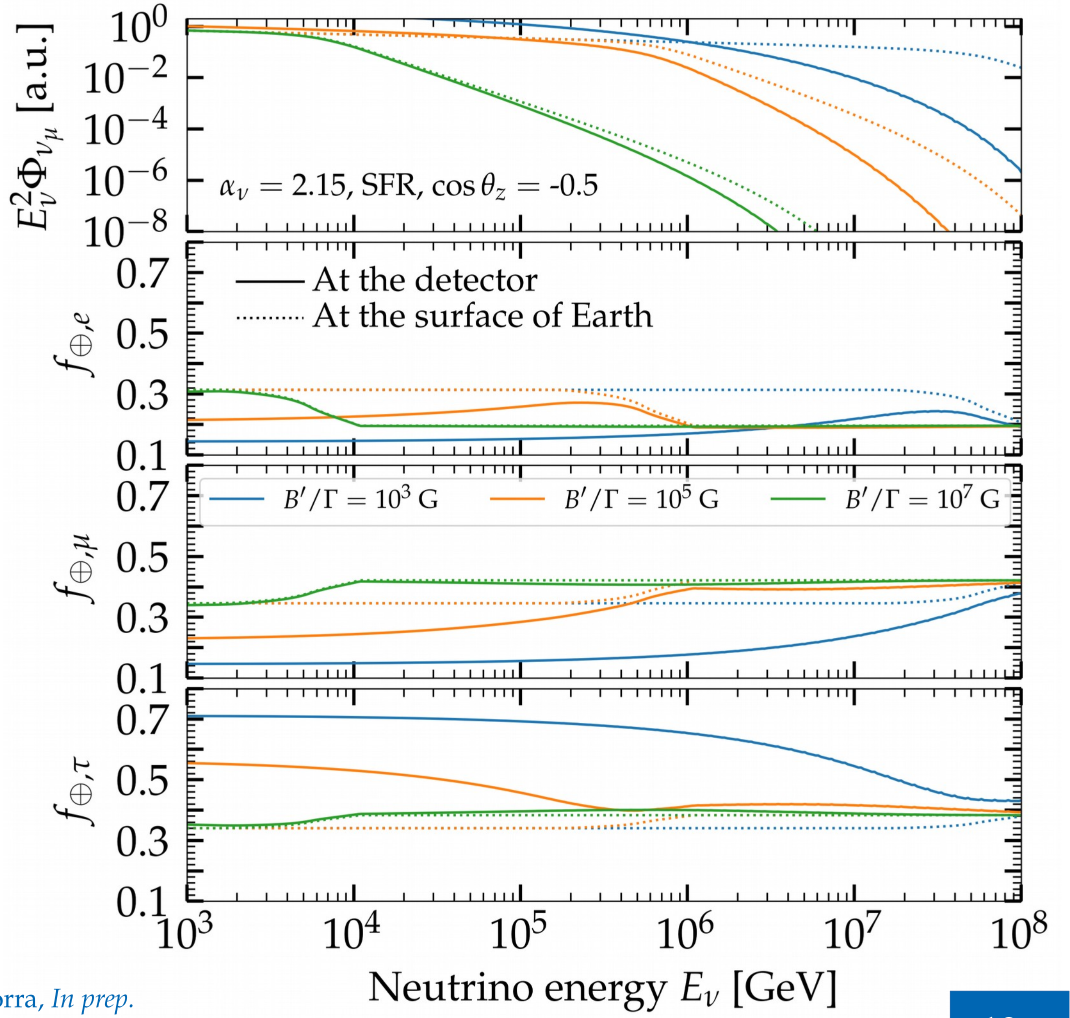



More detailed studies are required

Borrowed from J. van Santen & M. Kowalski

# Extracting source properties using flavor

- Goal: Use the flavor composition (and spectrum) of the diffuse $\nu$ 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 $\nu N$ interactions deplete the flux
  - Neutral-current $\nu N$ interactions pile-up low energy $\nu$
  - $\nu_\tau$ regeneration computed
- The arrival direction matters!




**MB** & Tamborra, *In prep.*

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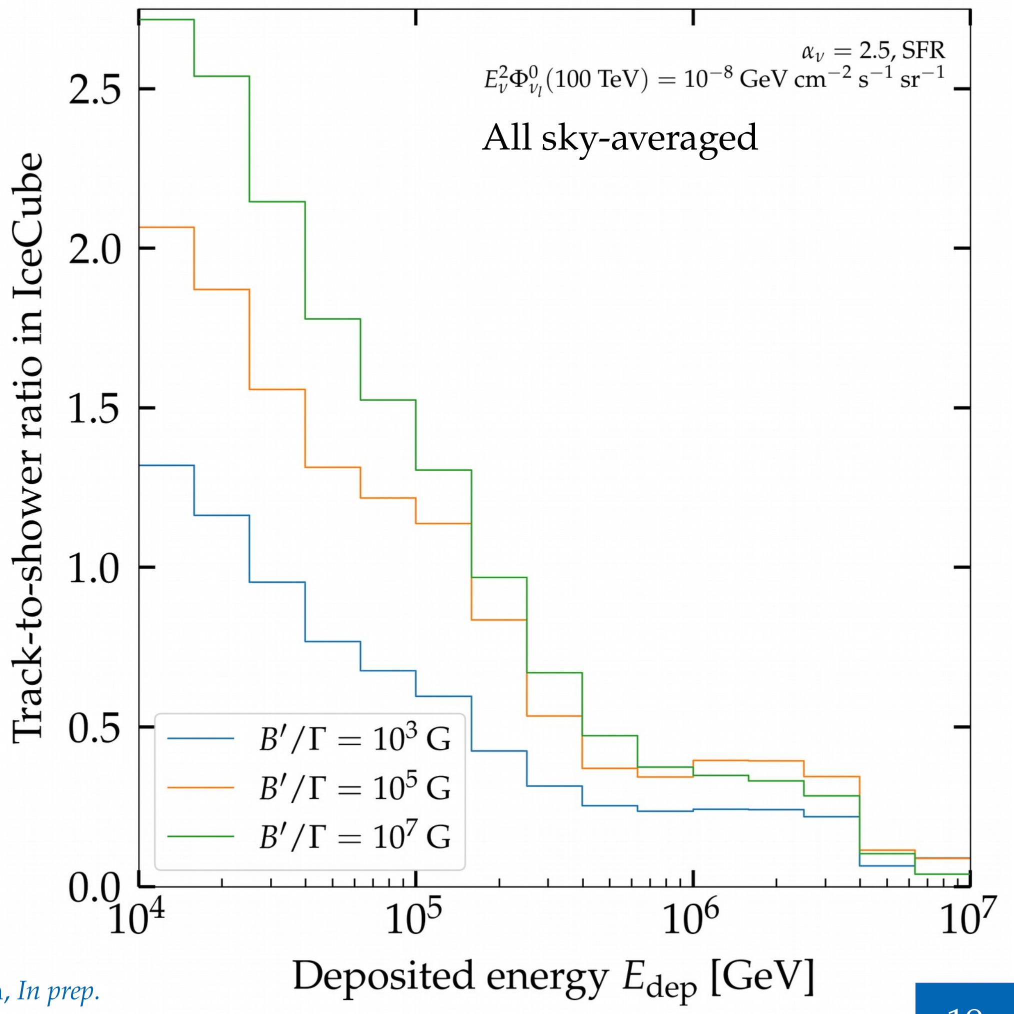
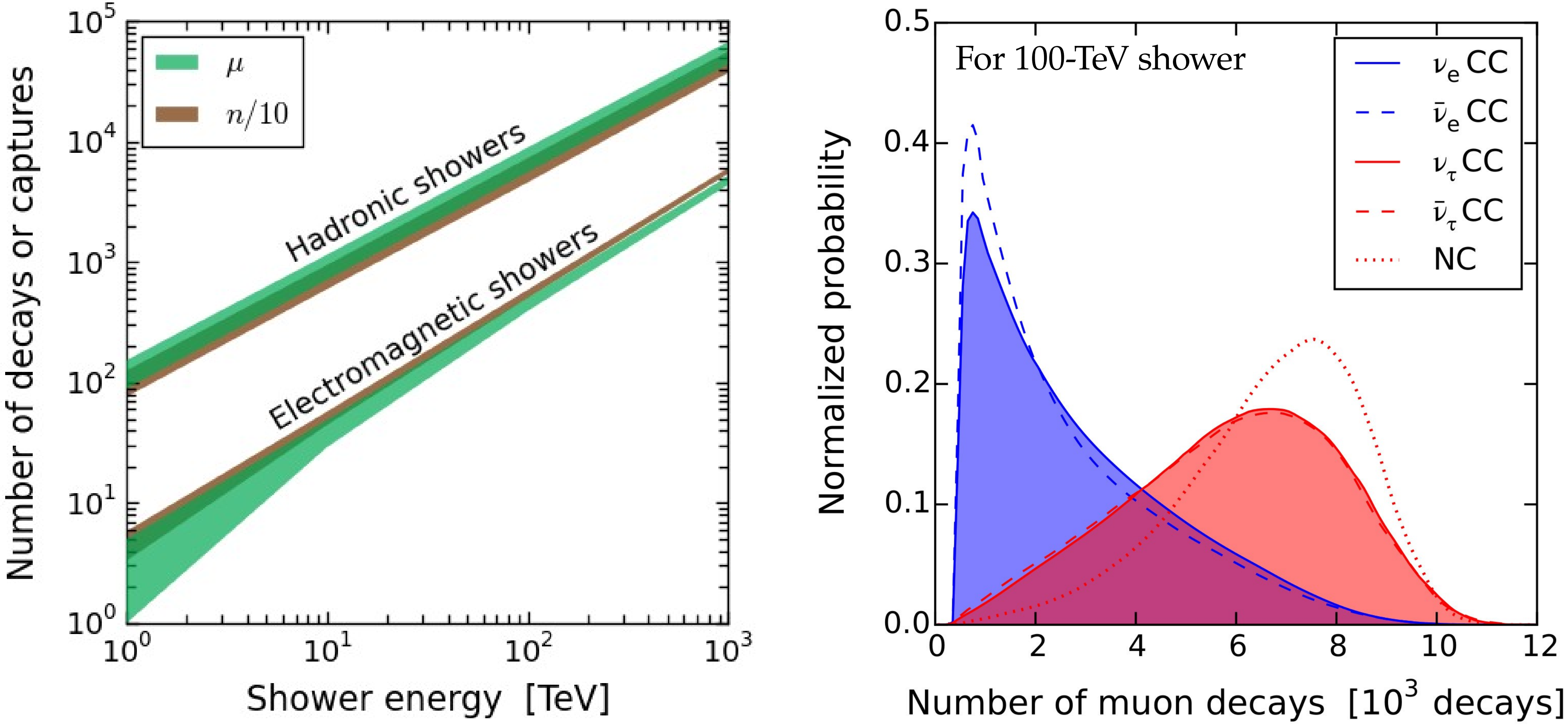



**MB** & Tamborra, *In prep.*

# The low-energy behavior of high-energy showers

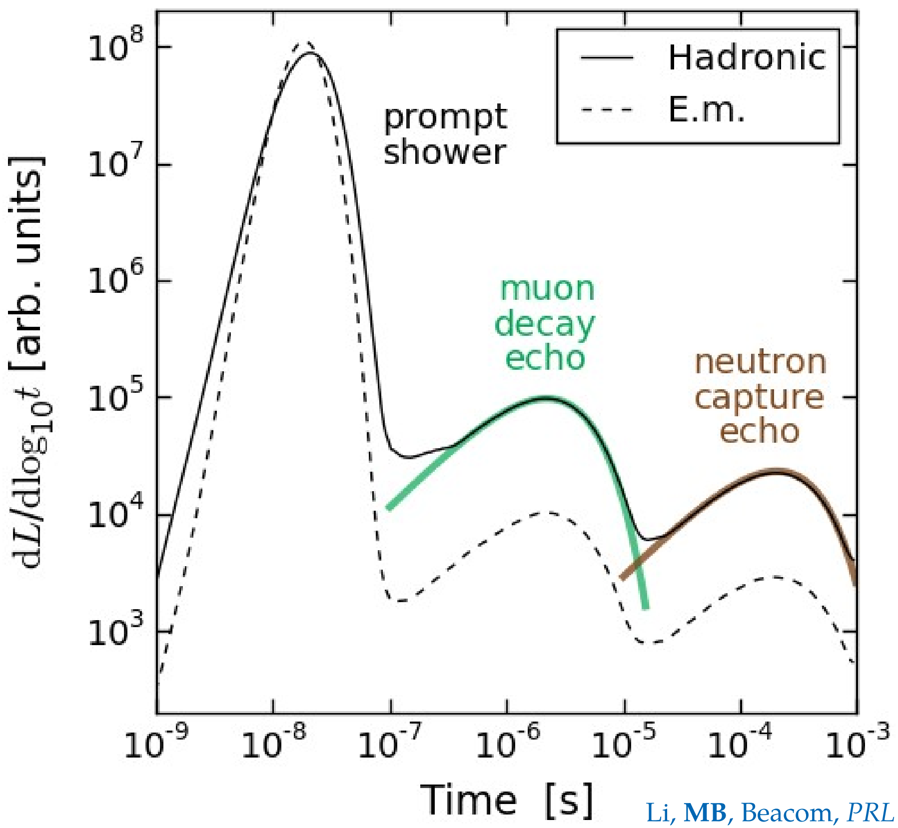


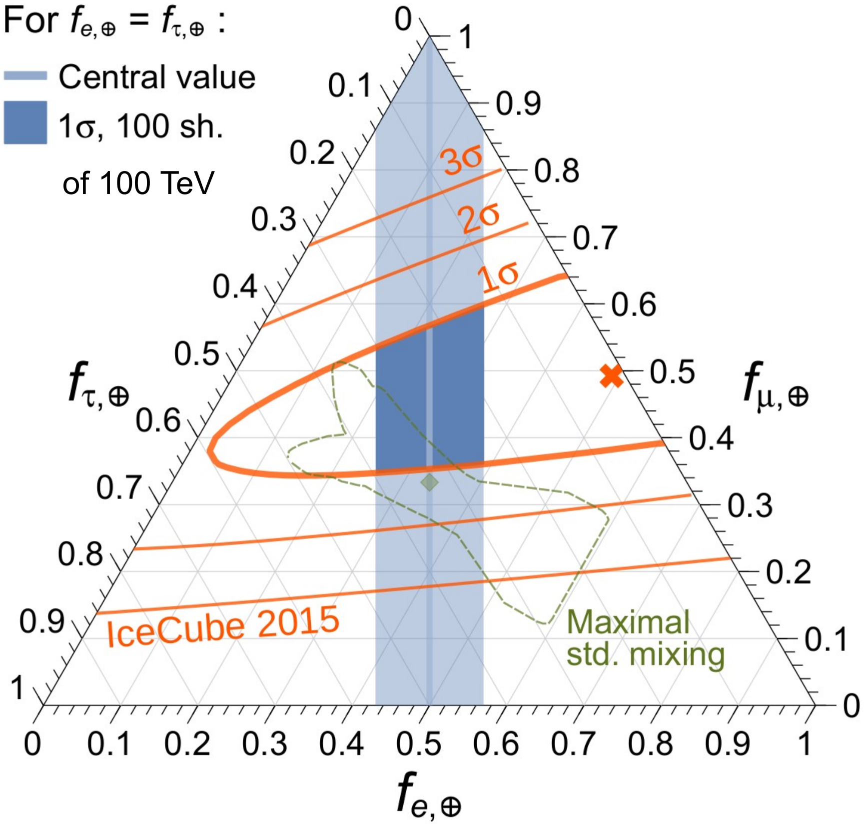

Li, **MB**, Beacom, *PRL* 2019

(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 $\nu_e$ and $\nu_\tau$ —




Li, **MB**, Beacom, *PRL* 2019
Preliminary IceCube results: A. Steuer & L. Köpke, ICRC 2017

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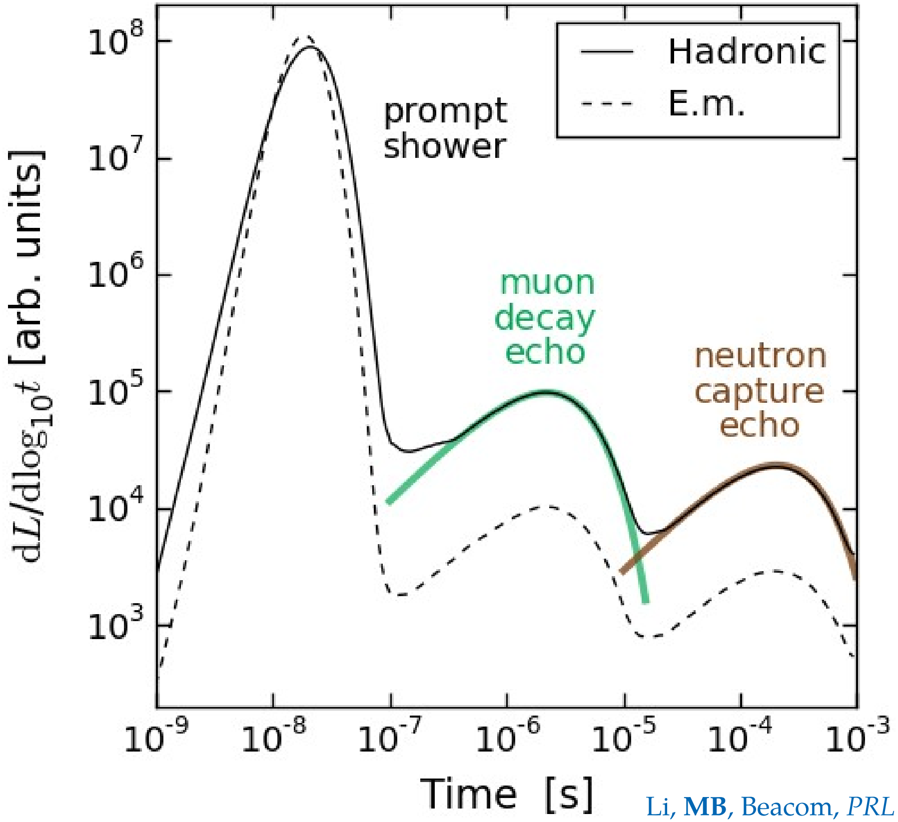


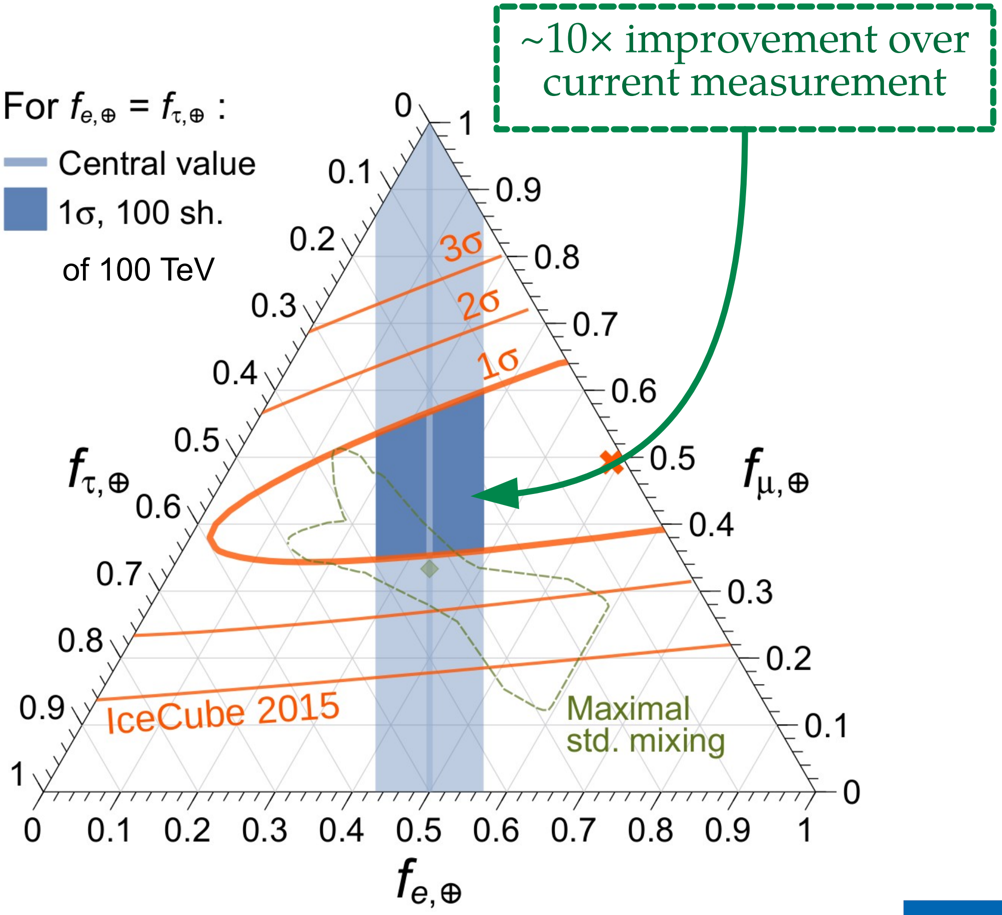


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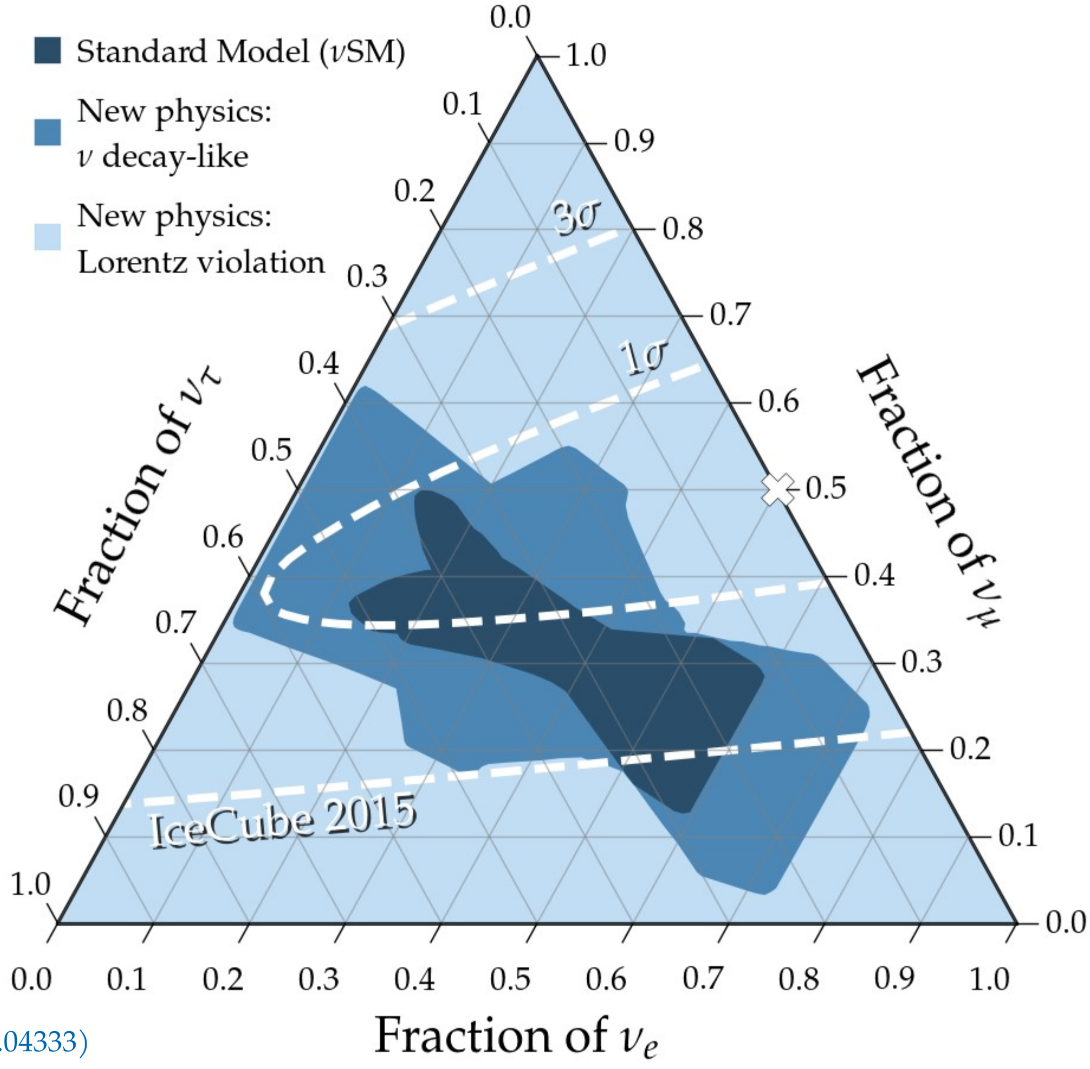
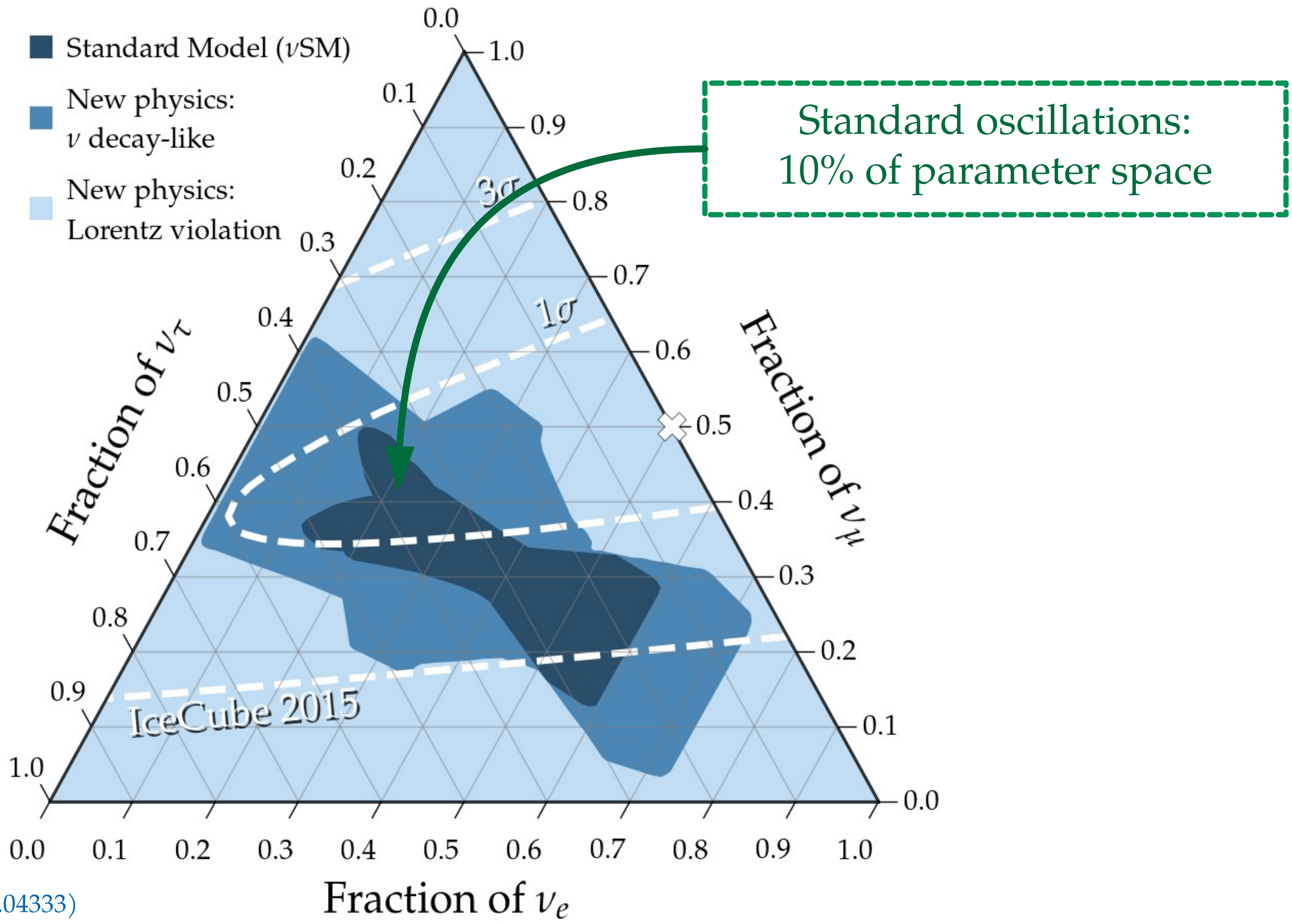



Ackermann *et al.*, Astro2020 Survey (1903.04333)
Based on: **MB**, Beacom, Winter *PRL* 2015

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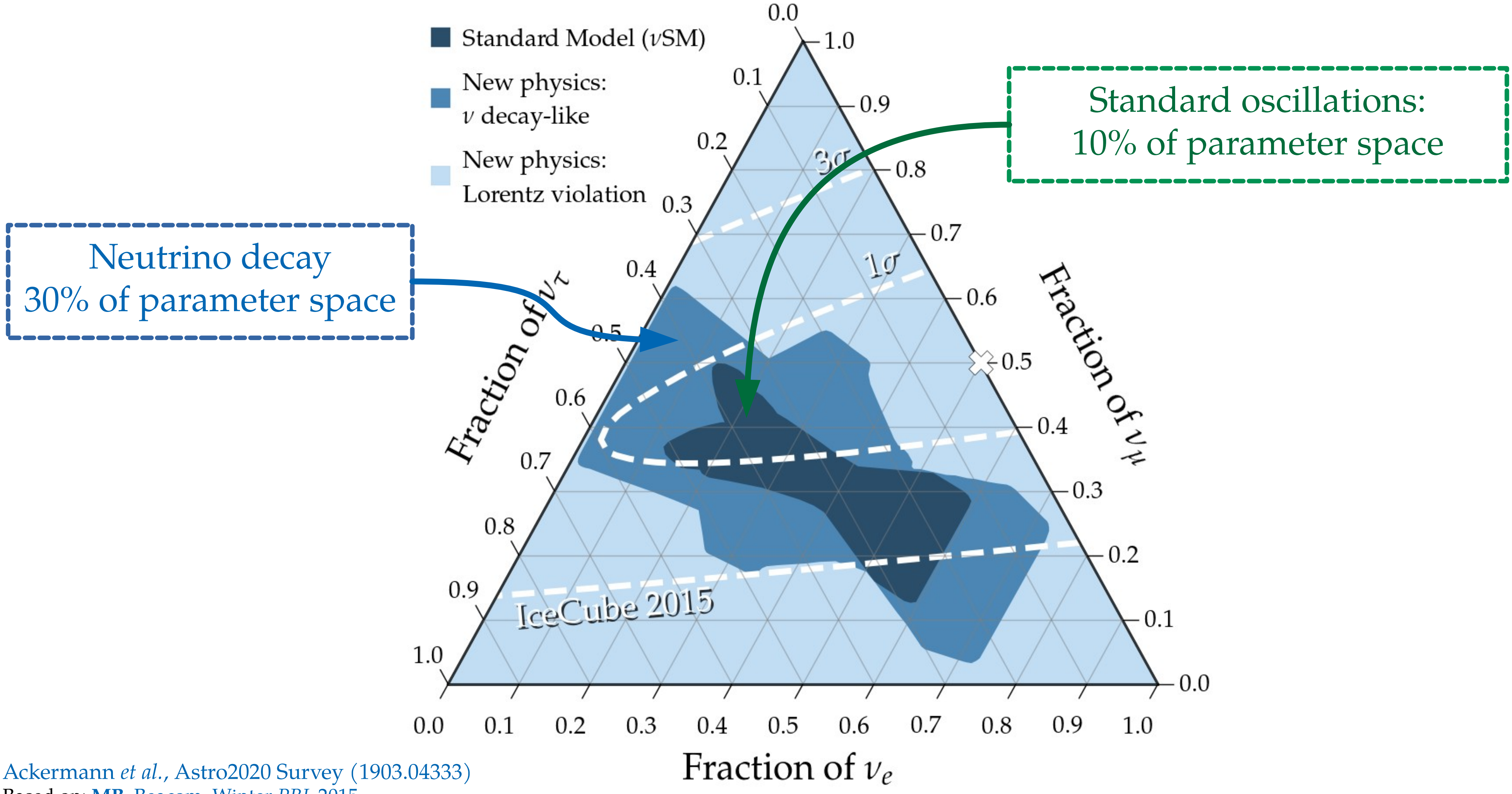


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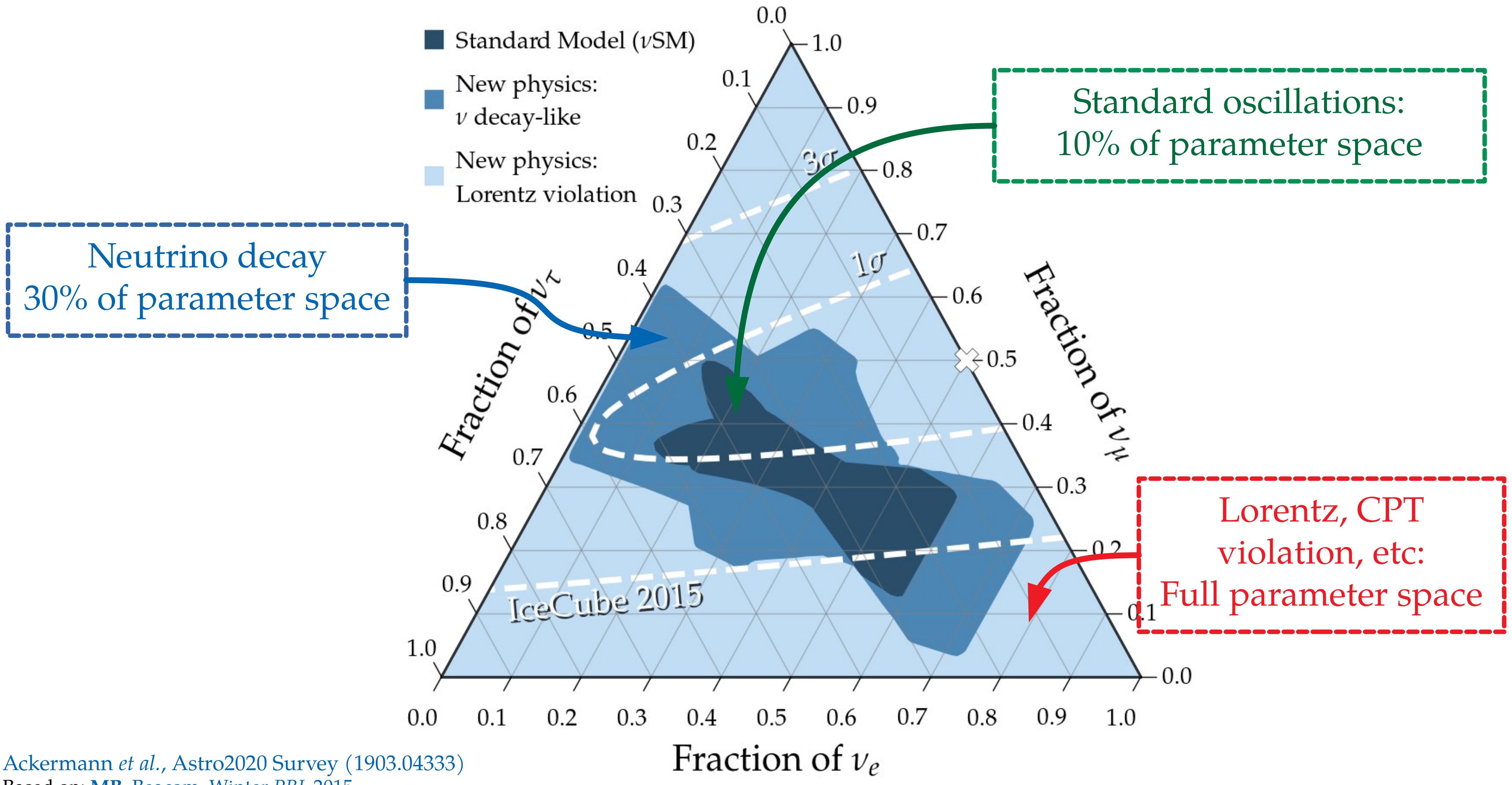
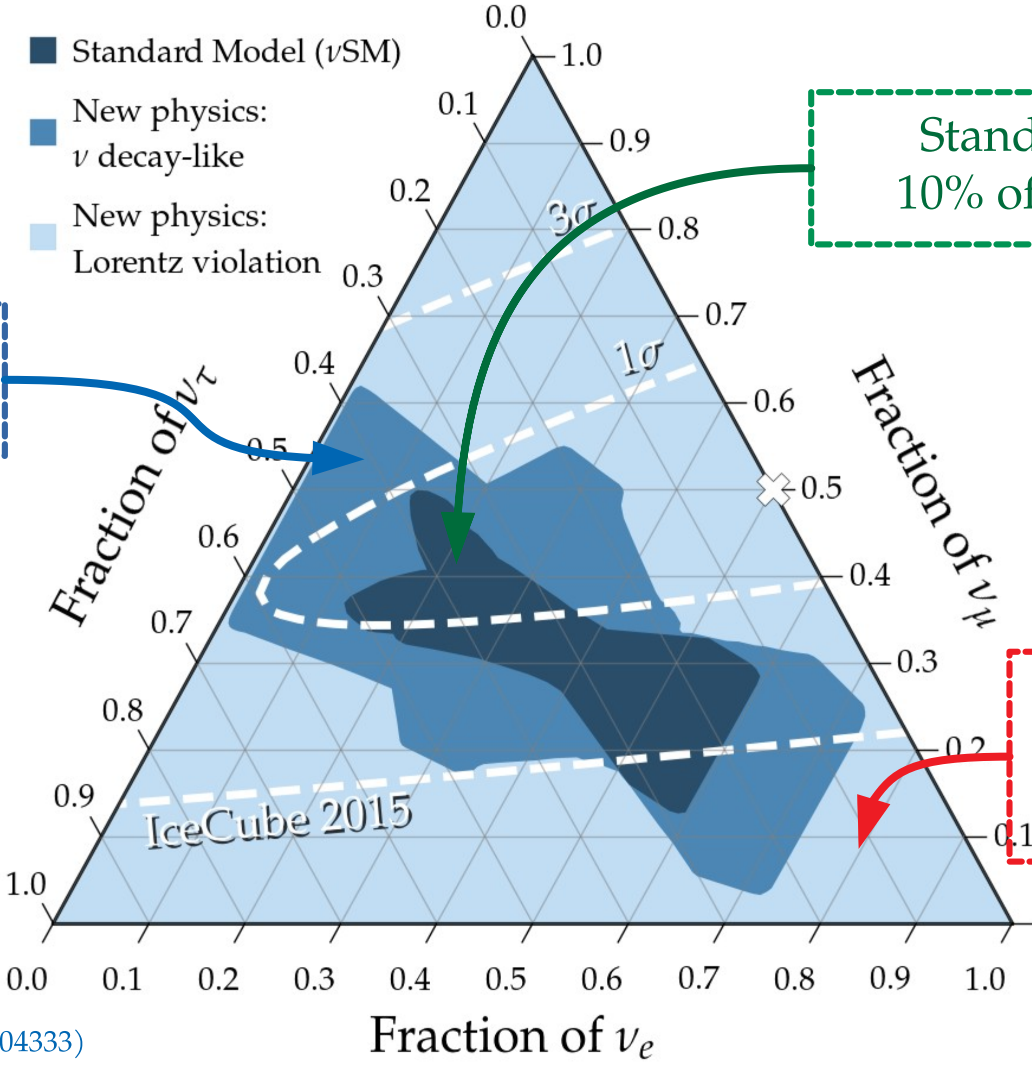



Ackermann *et al.*, Astro2020 Survey (1903.04333)

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


*Note: Not an exhaustive list*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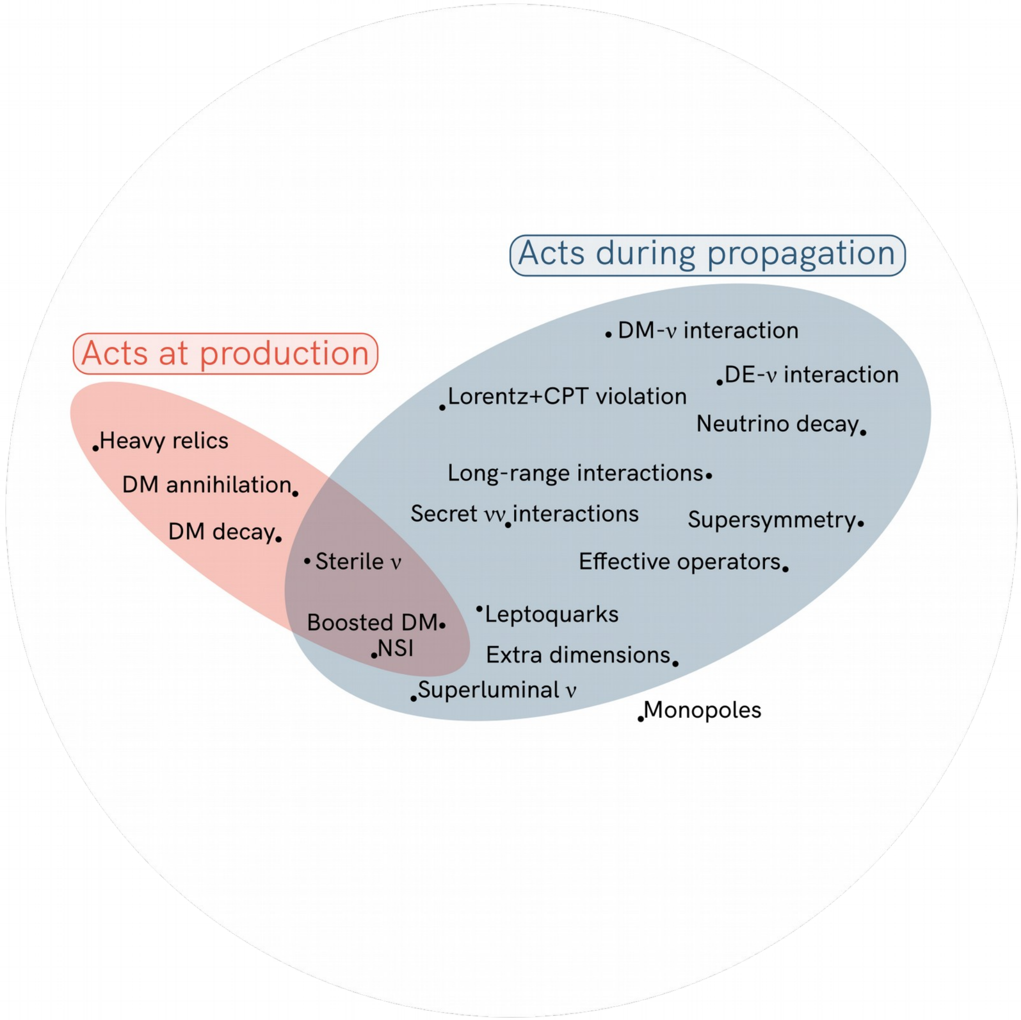


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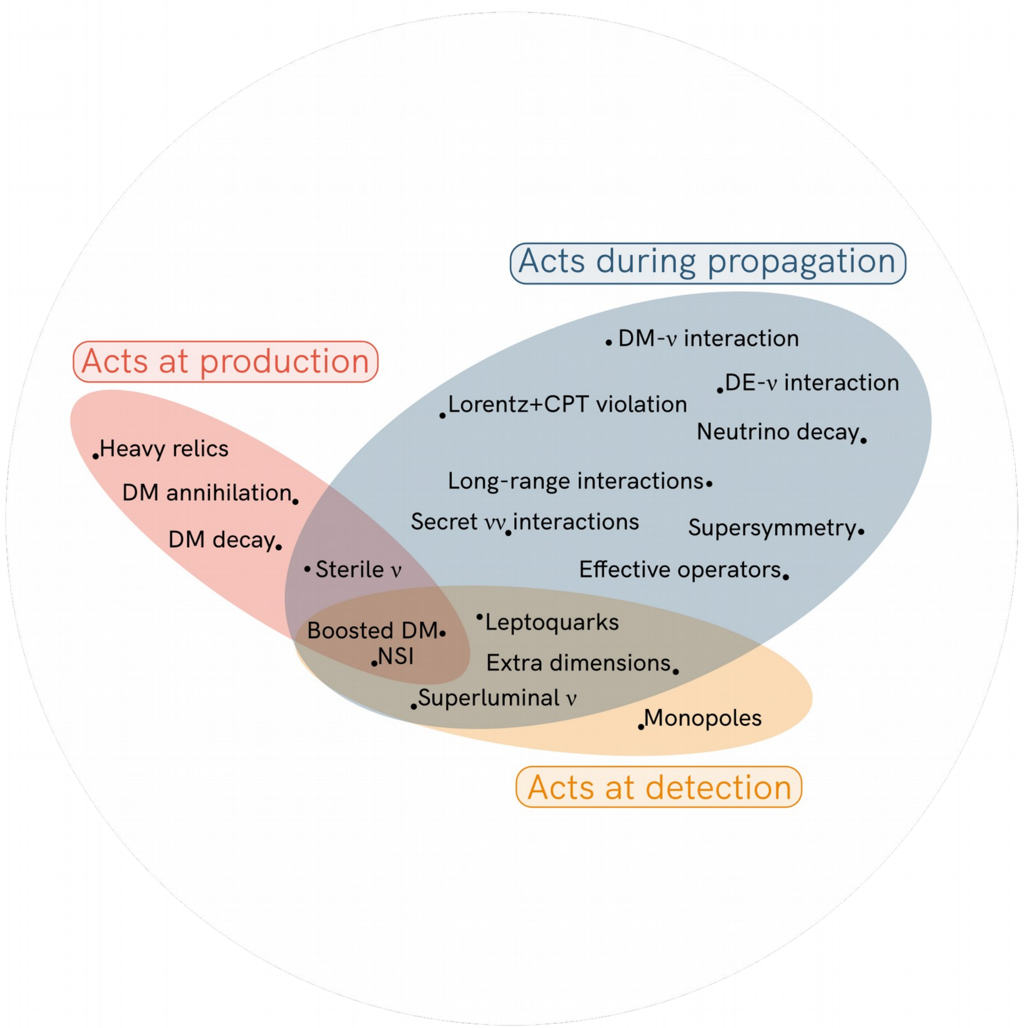


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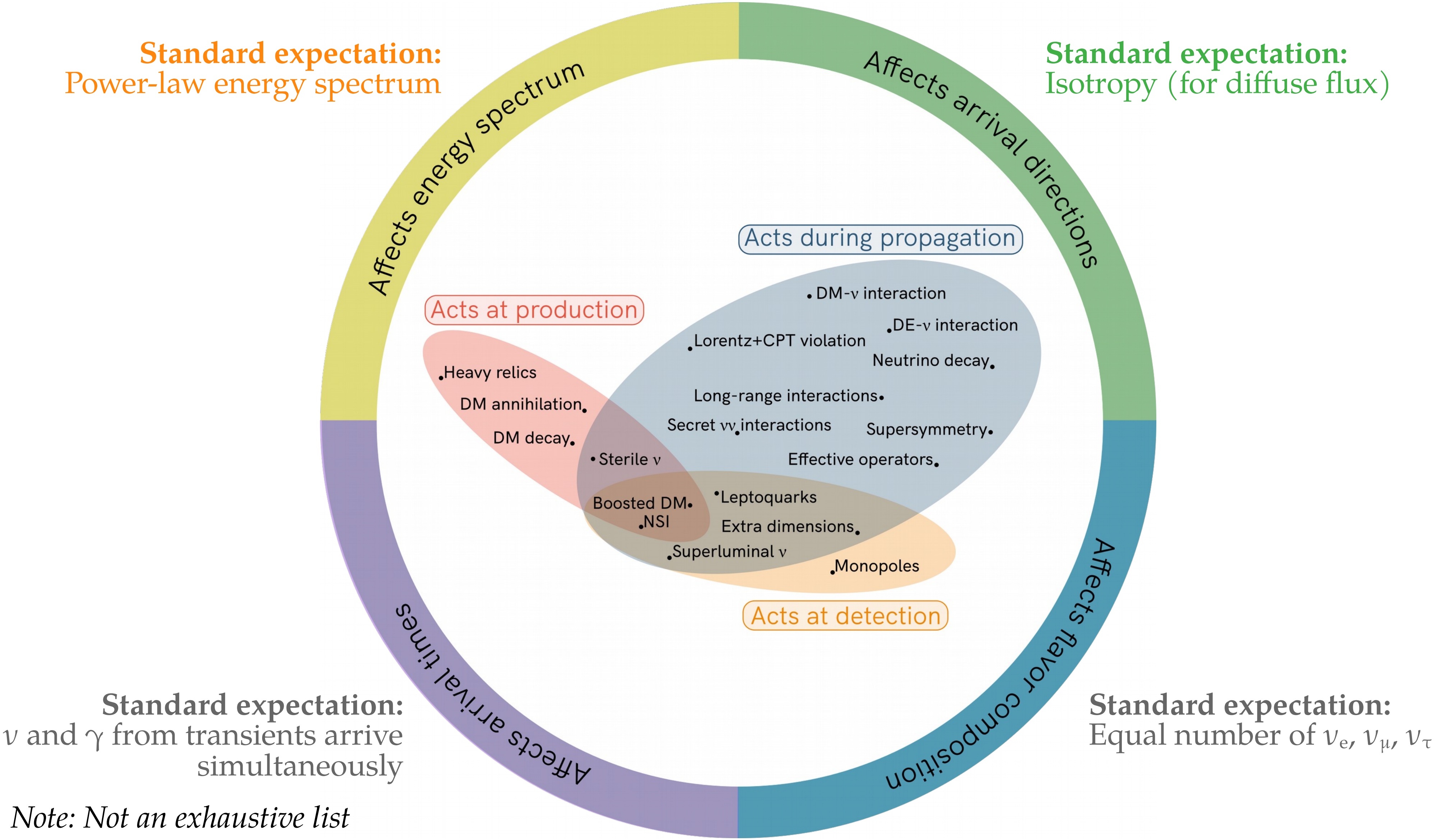


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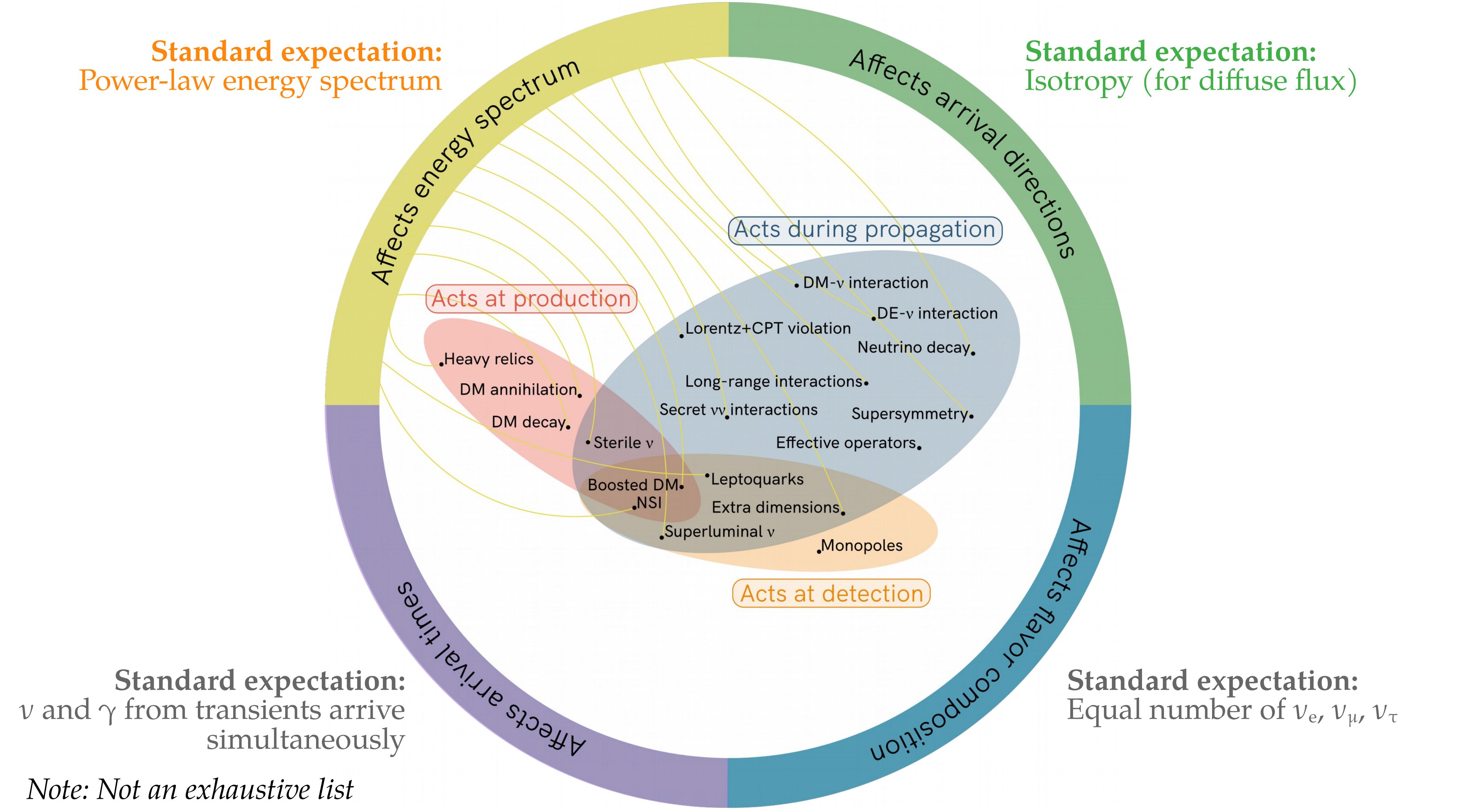


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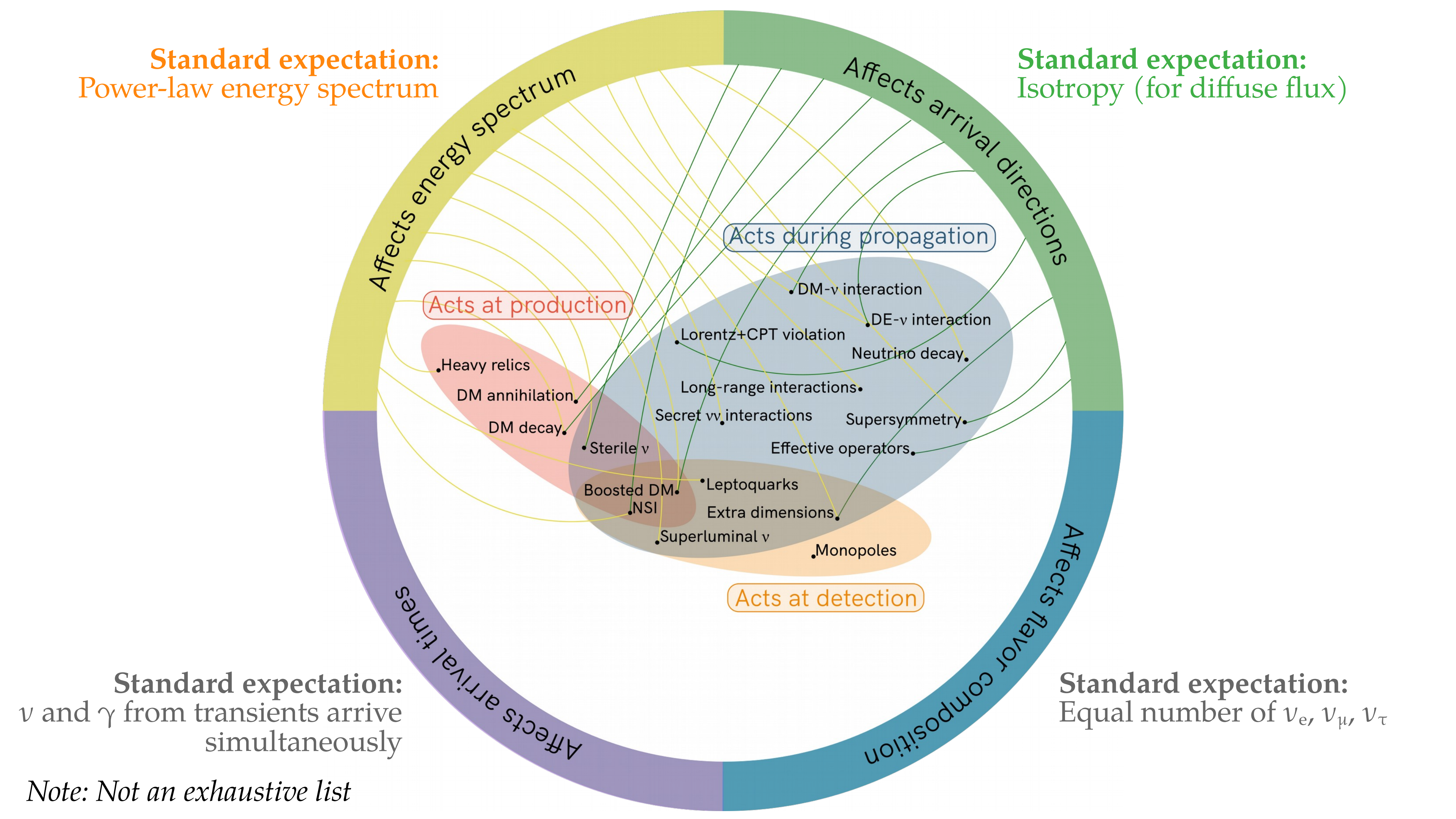

Standard expectation:
Power-law energy spectrum
Standard expectation:
Isotropy (for diffuse flux)
Standard expectation:
ν and γ from transients arrive simultaneously
Standard expectation:
Equal number of $\nu_e$, $\nu_\mu$, $\nu_\tau$
Affects energy spectrum
Affects arrival directions
Affects flavor composition
Affects arrival times
Acts at production
Acts during propagation
Acts at detection
Heavy relics
DM annihilation
DM decay
Sterile ν
Boosted DM
NSI
DM-ν interaction
DE-ν interaction
Lorentz+CPT violation
Neutrino decay
Long-range interactions
Secret νν interactions
Supersymmetry
Effective operators
Leptoquarks
Extra dimensions
Superluminal ν
Monopoles
Note: Not an exhaustive list

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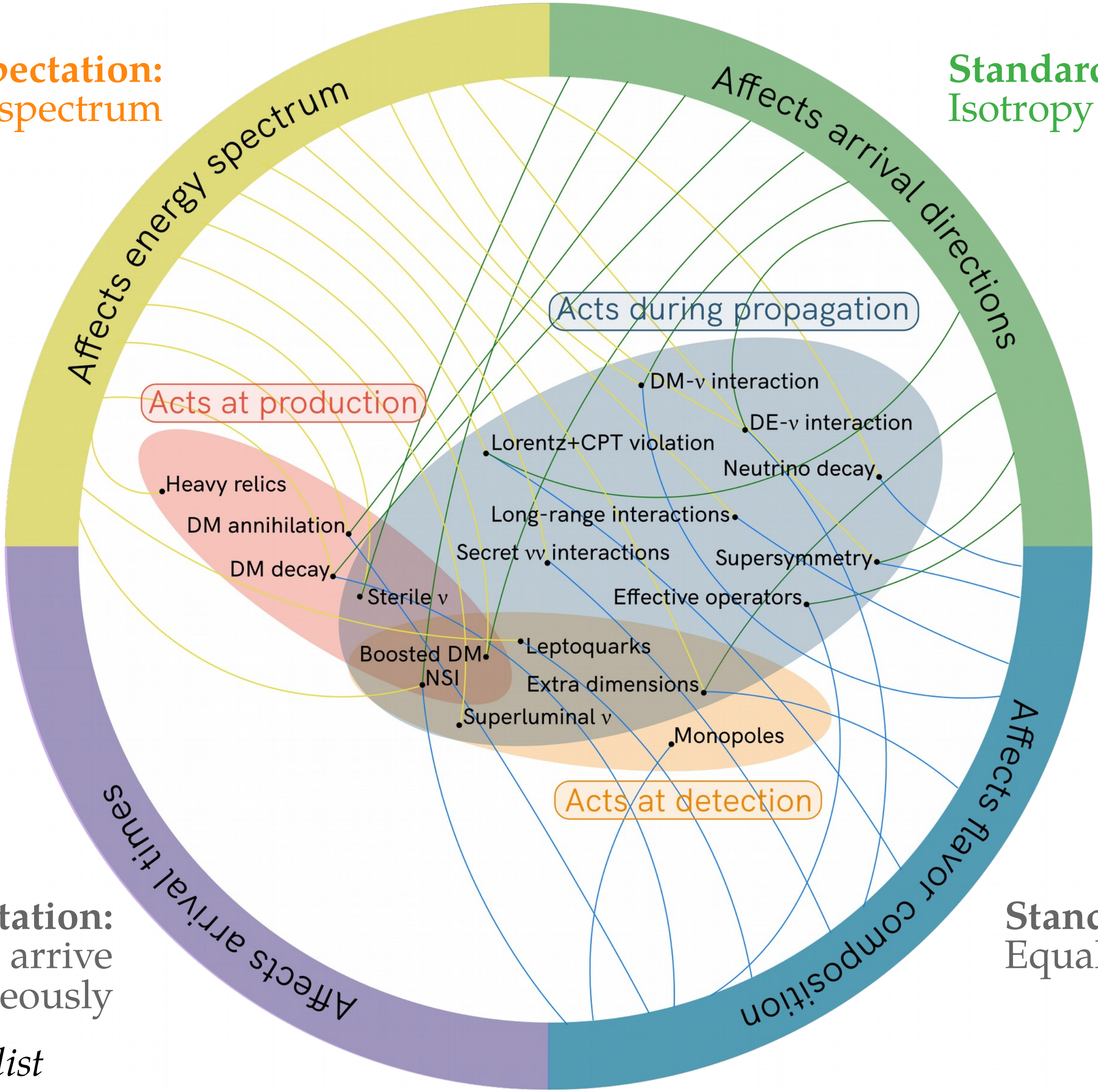


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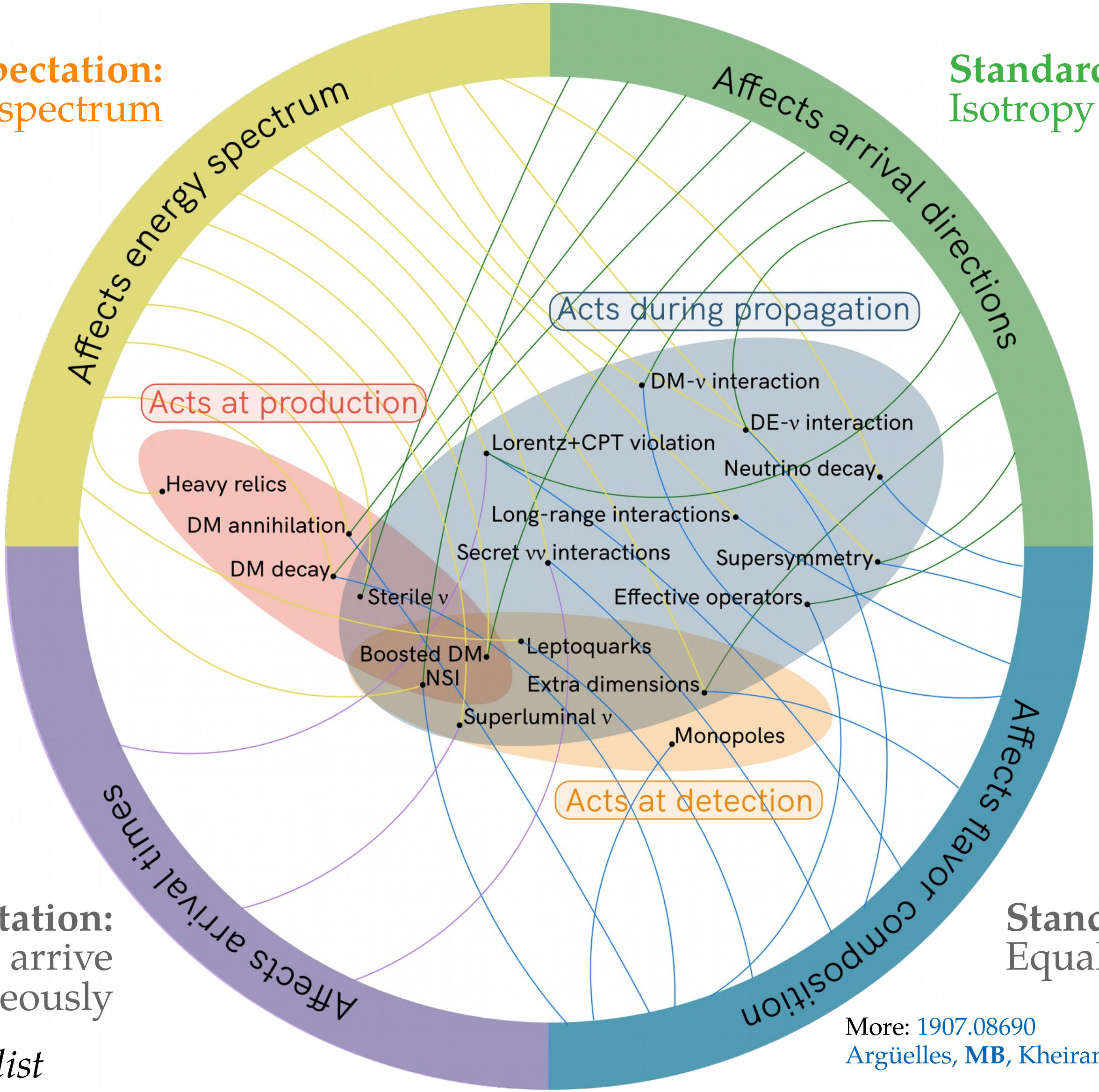


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More: 1907.08690
Argüelles, **MB**, Kheirandish, Palomares-Ruiz, Salvadó, Vincent

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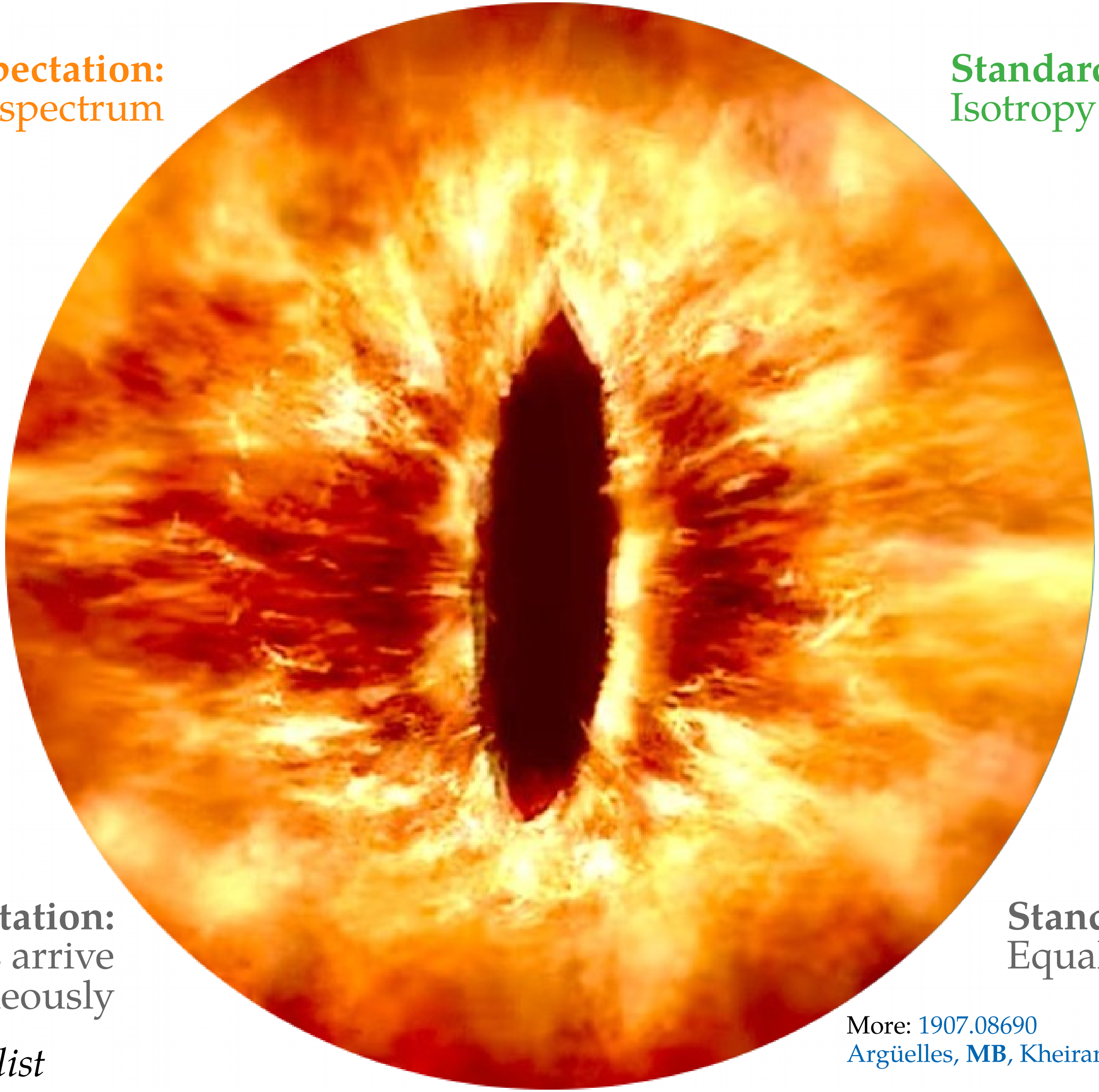

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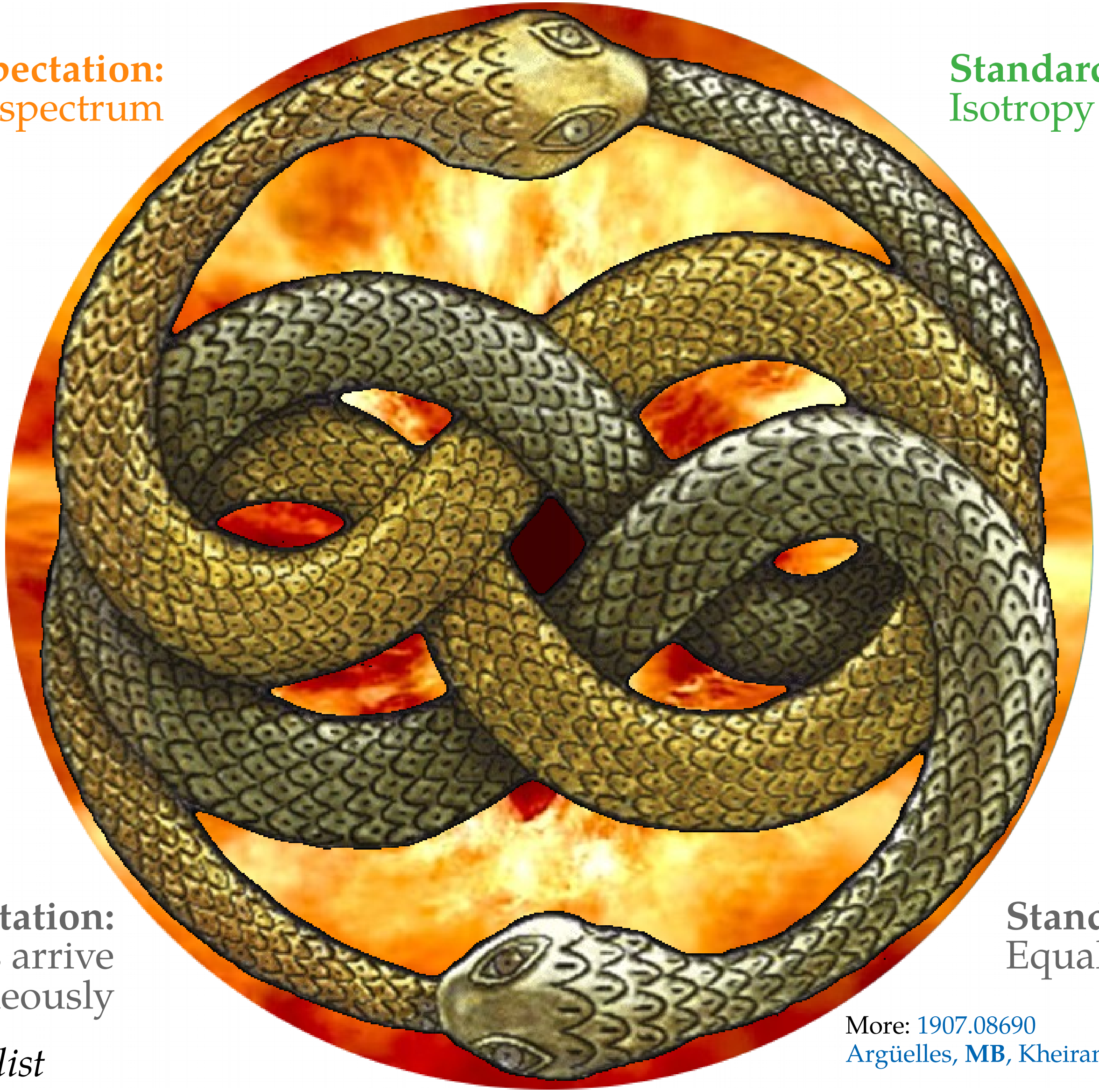

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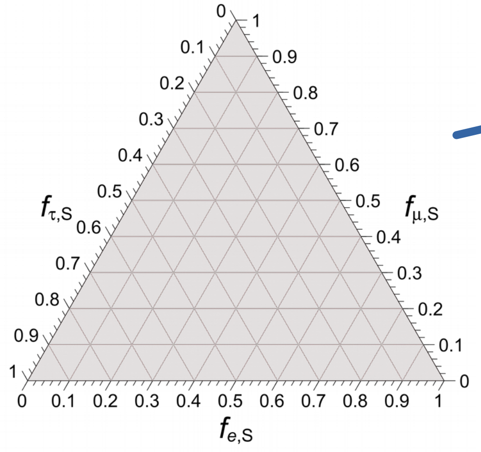
# Measuring the neutrino lifetime

## Sources




$\nu_2, \nu_3 \to \nu_1$

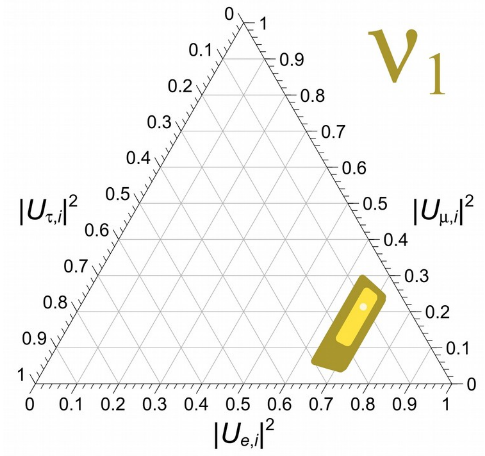
$\nu_1$ lightest and stable

If all unstable neutrinos decay

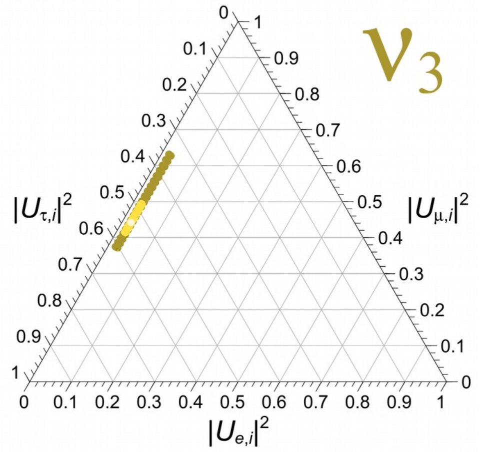
$\nu_1, \nu_2 \to \nu_3$

$\nu_3$ lightest and stable

## Earth




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

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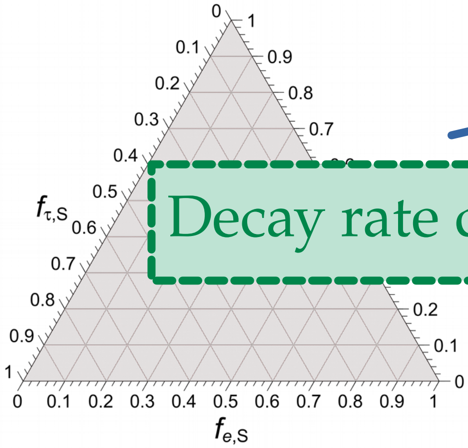
# Measuring the neutrino lifetime

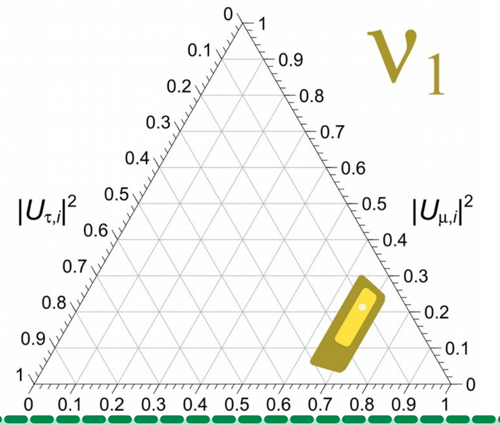
## Sources




$\nu_2, \nu_3 \rightarrow \nu_1$

$\nu_1$ lightest and stable

## Earth

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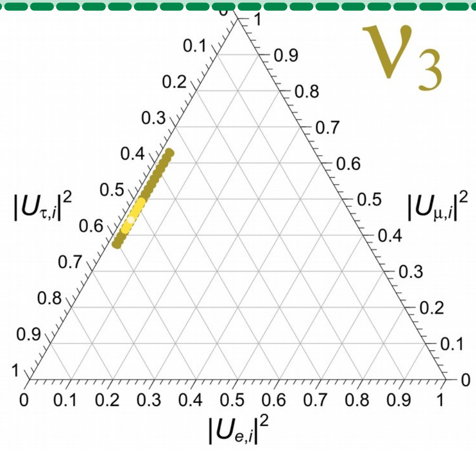
**Decay rate depends on $\exp[-\,t\,/\,(\gamma\tau_i)] = \exp[-\,(L/E)\cdot(m_i/\tau_i)]$**

$\nu_1, \nu_2 \rightarrow \nu_3$

$\nu_3$ lightest and stable

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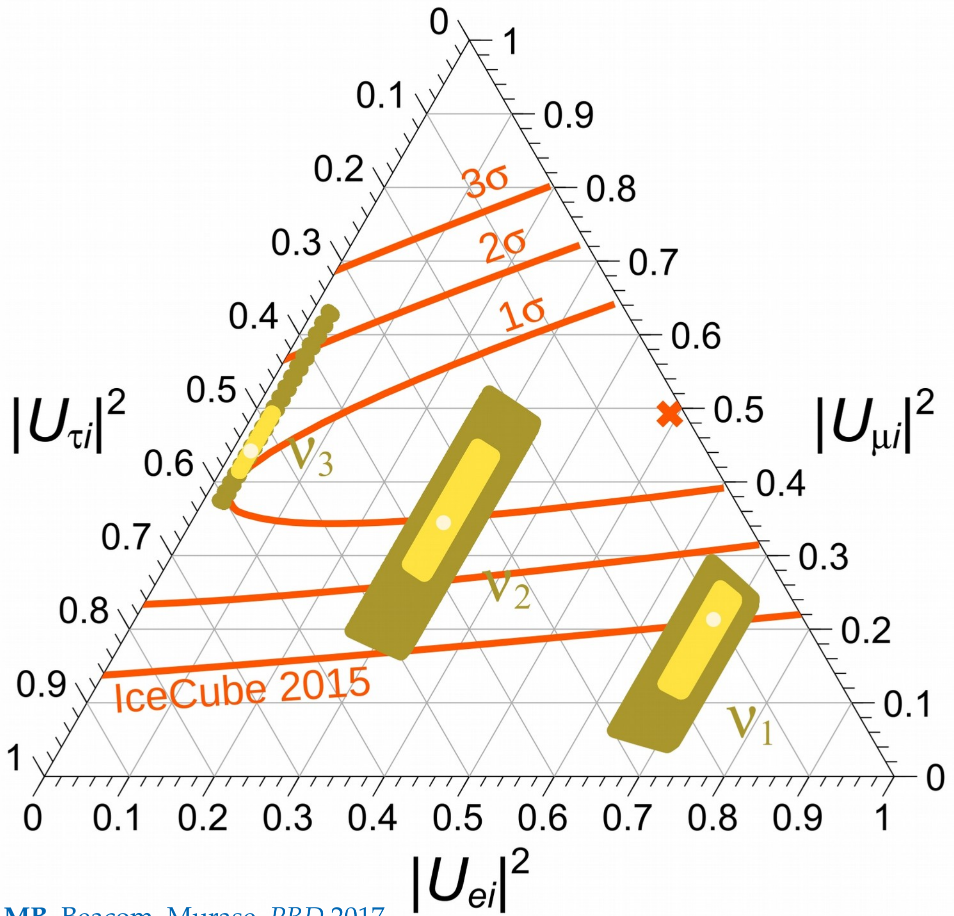
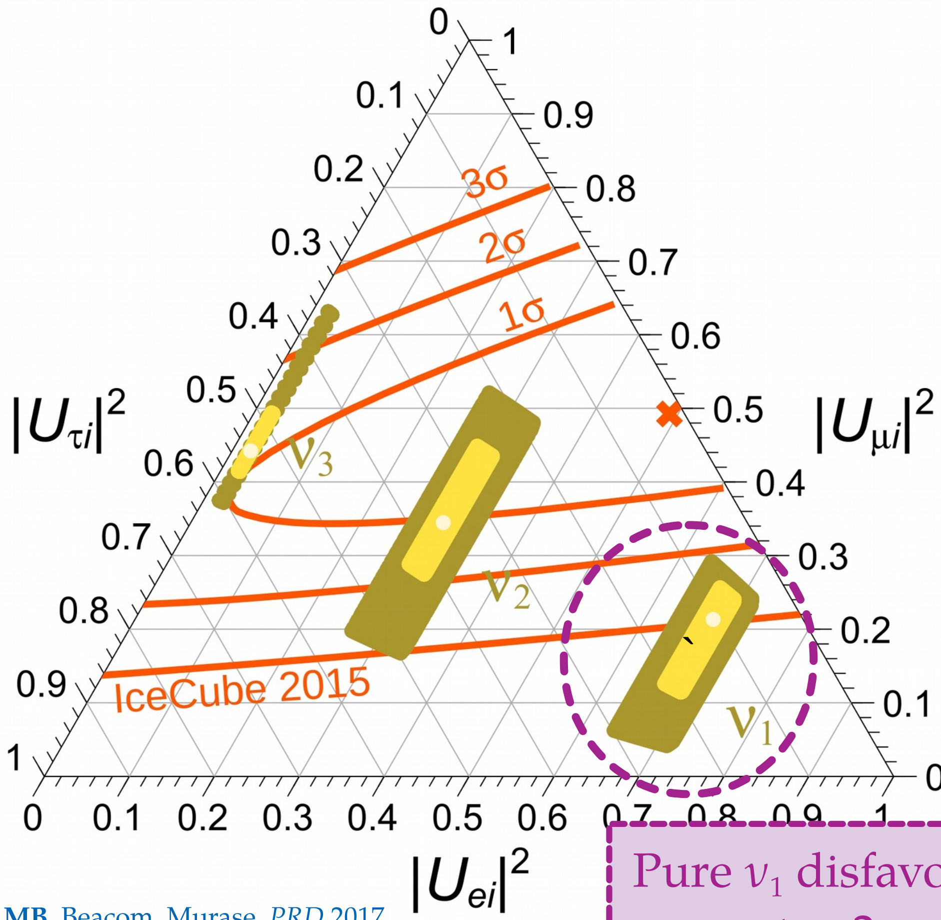


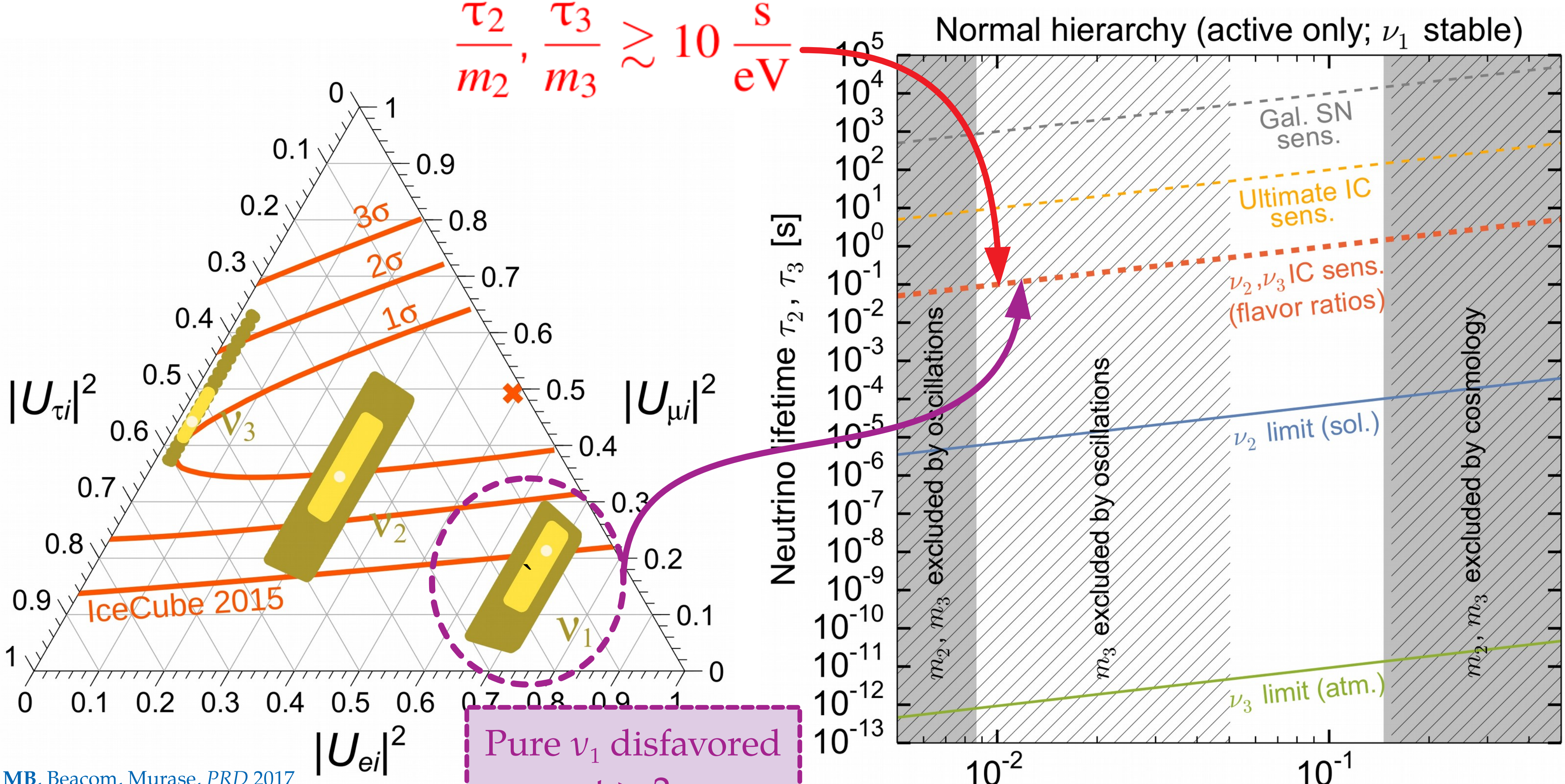

**MB**, Beacom, Murase, *PRD* 2017




**MB**, Beacom, Murase, *PRD* 2017

Pure $\nu_1$ disfavored at > 2σ

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

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**MB**, Beacom, Murase, *PRD* 2017

# What lies beyond? *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]

- …

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# New physics – High-energy effects

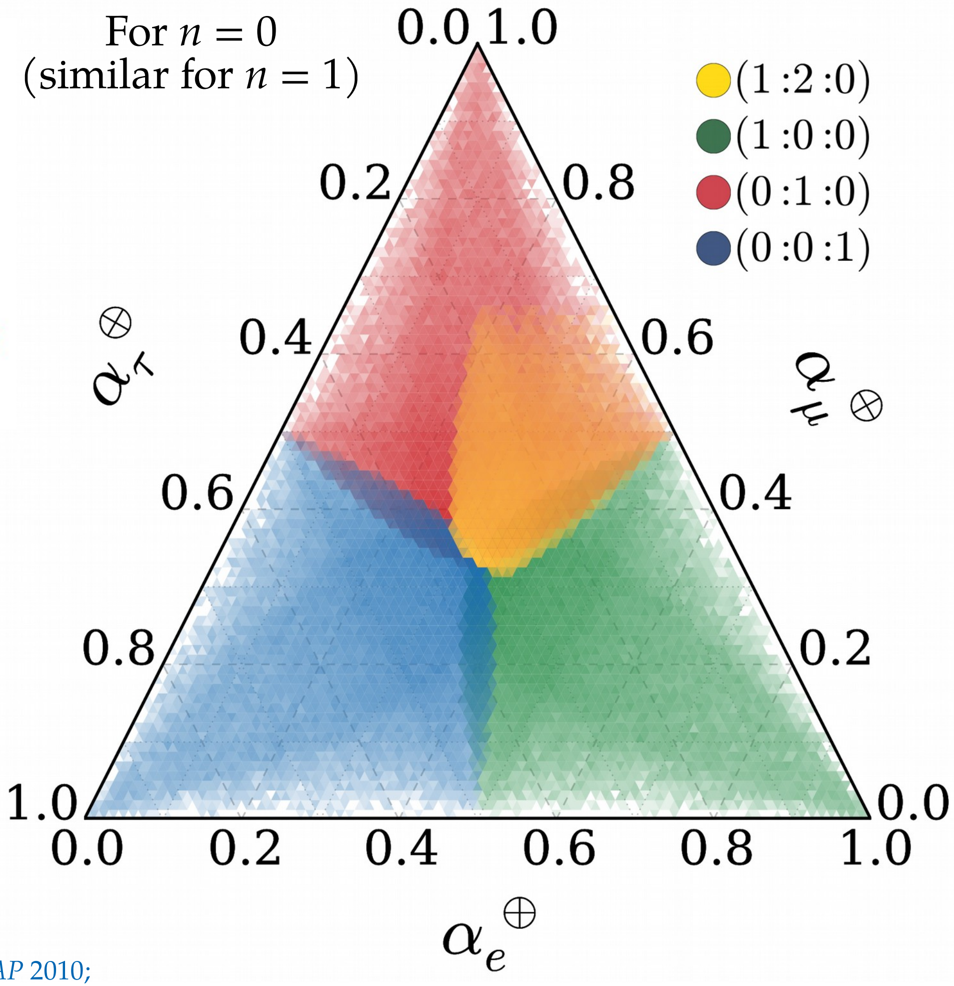
$$H_{\text{tot}} = H_{\text{std}} + H_{\text{NP}}$$

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

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

This can populate *all* of the triangle –

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




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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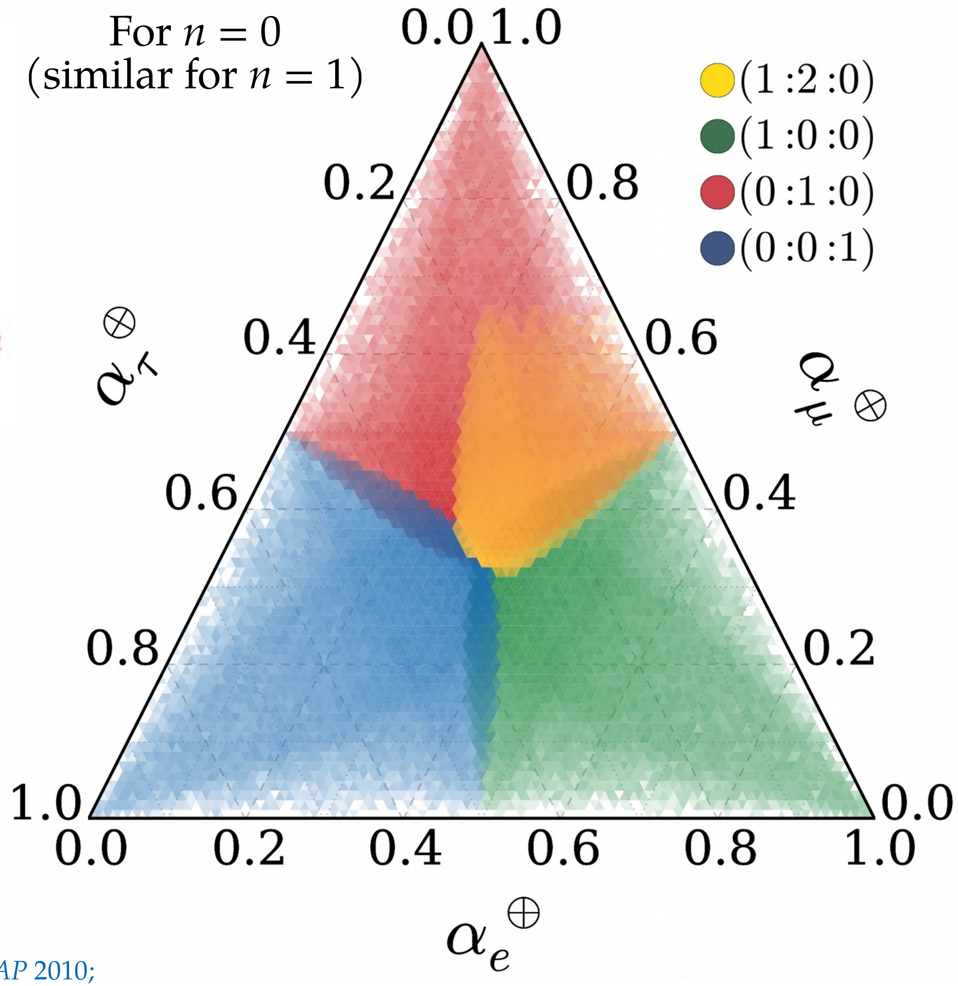


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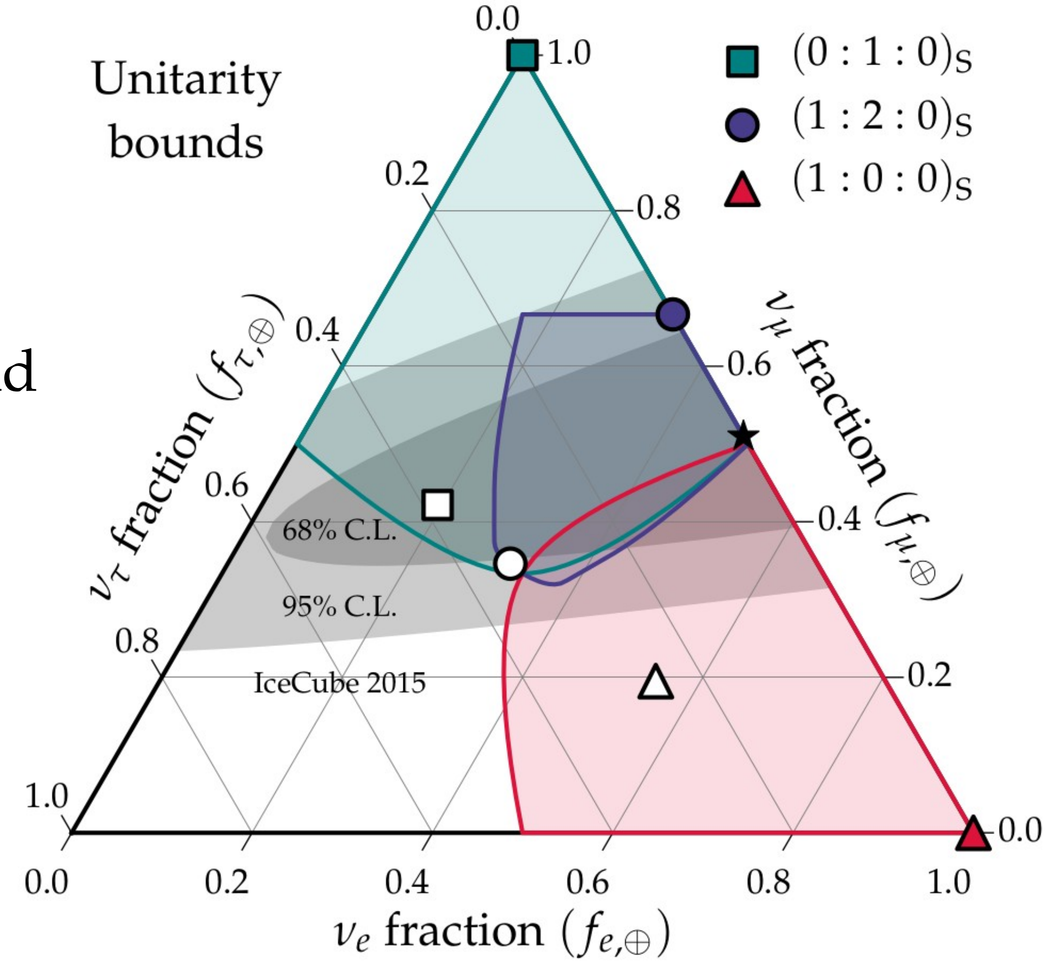
# Using unitarity to constrain new physics

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

- New mixing angles unconstrained
- Use unitarity ($U_{\text{NP}} U_{\text{NP}}^\dagger = 1$) 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 *before* deployment
  - Put serious thought into flavor measurements in non-optical Cherenkov detectors
- Exciting prospects: larger statistics, better reconstruction, higher energies

# Backup slides

# Flavor-transition probability: the quick and dirty of it

- In matrix form: $$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}U^*_{e1} & U^*_{e2} & U^*_{e3}\\ U^*_{\mu 1} & U^*_{\mu 2} & U^*_{\mu 3}\\ U^*_{\tau 1} & U^*_{\tau 2} & U^*_{\tau 3}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$
- 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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Atmospheric — Cross mixing — Solar — Majorana CP phases

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# Flavor composition – a few source choices

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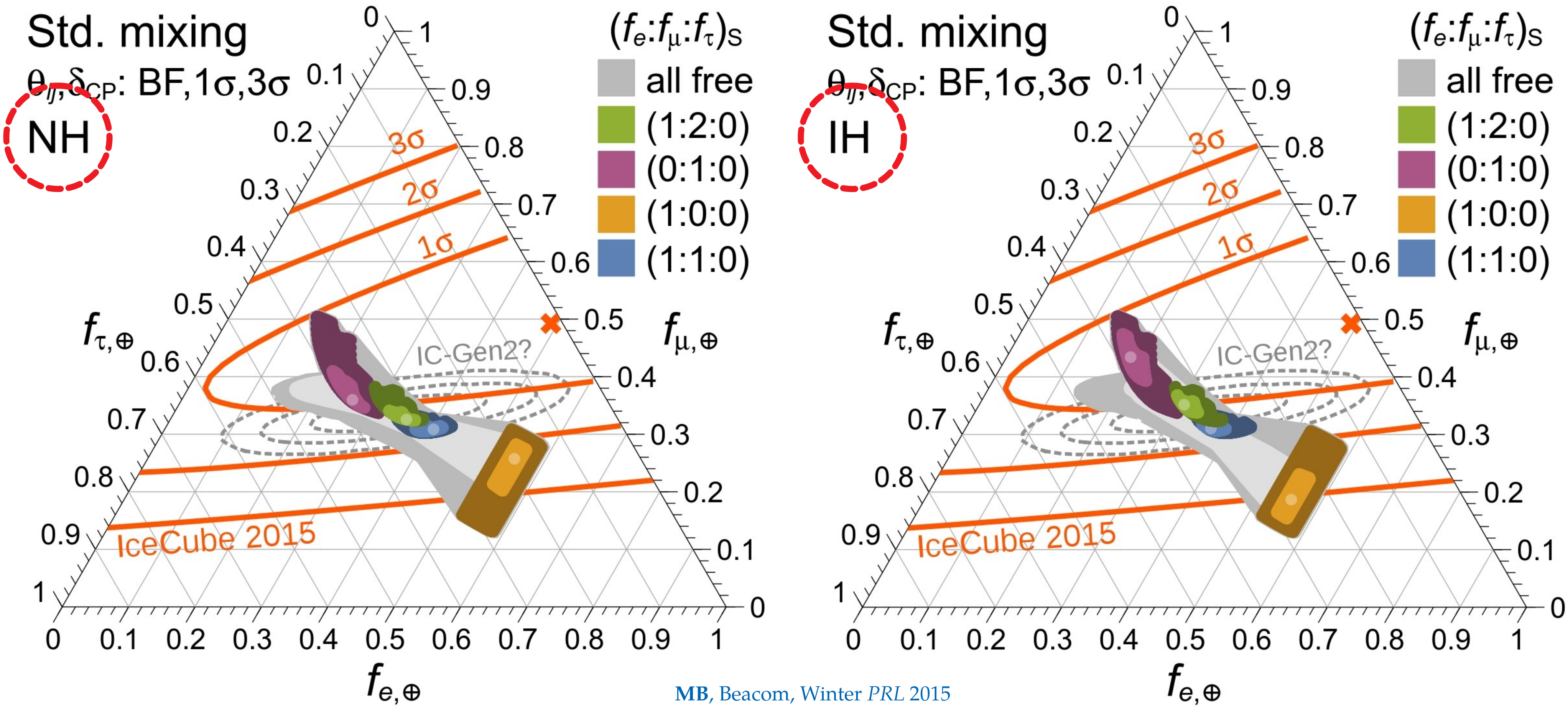


MB, Beacom, Winter *PRL* 2015

# 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

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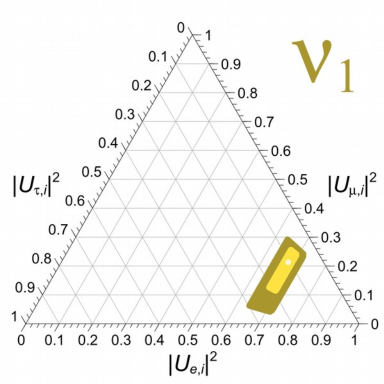
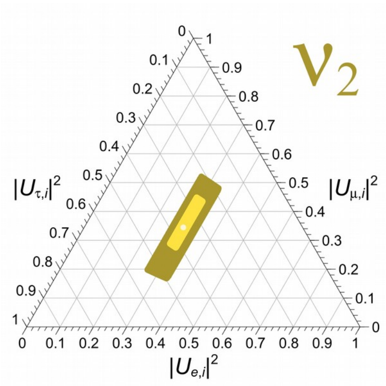
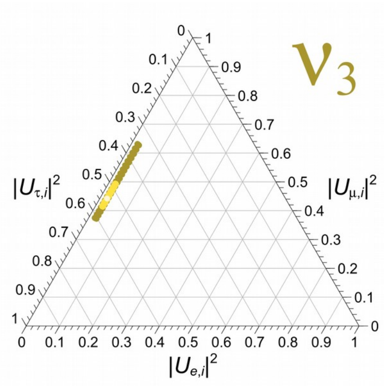
  *In spite of*
  poor energy, angular, flavor reconstruction
  & astrophysical unknowns

# Two classes of new physics

- Neutrinos propagate as an incoherent mix of $\nu_1$, $\nu_2$, $\nu_3$
- Each one has a different flavor content:




- Flavor ratios at Earth are the result of their combination
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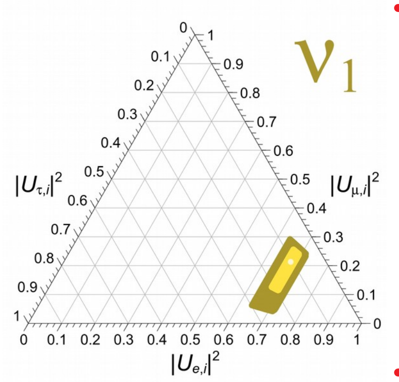
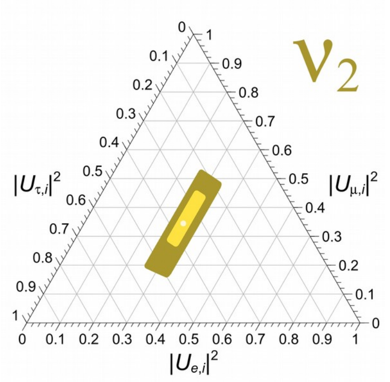
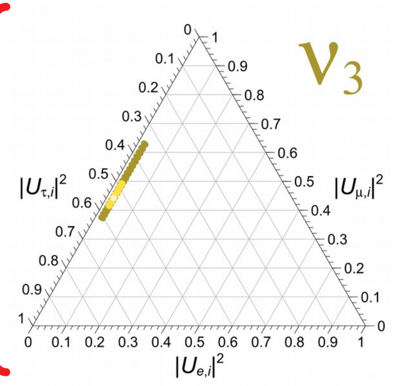
$w_1$ [ 

] $+ w_2$ [ 

] $+ w_3$ [ 

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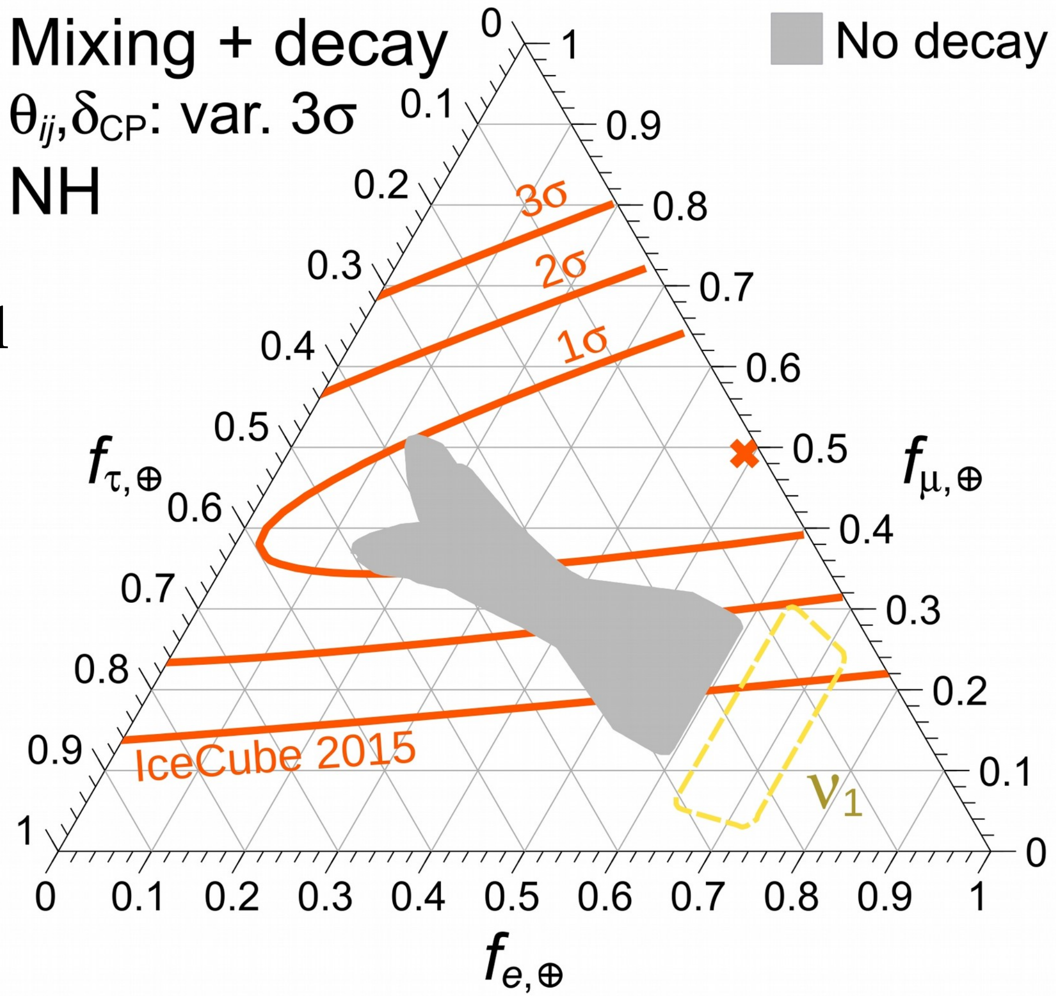
# Measuring the neutrino lifetime

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 $\nu_2$, $\nu_3$)




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

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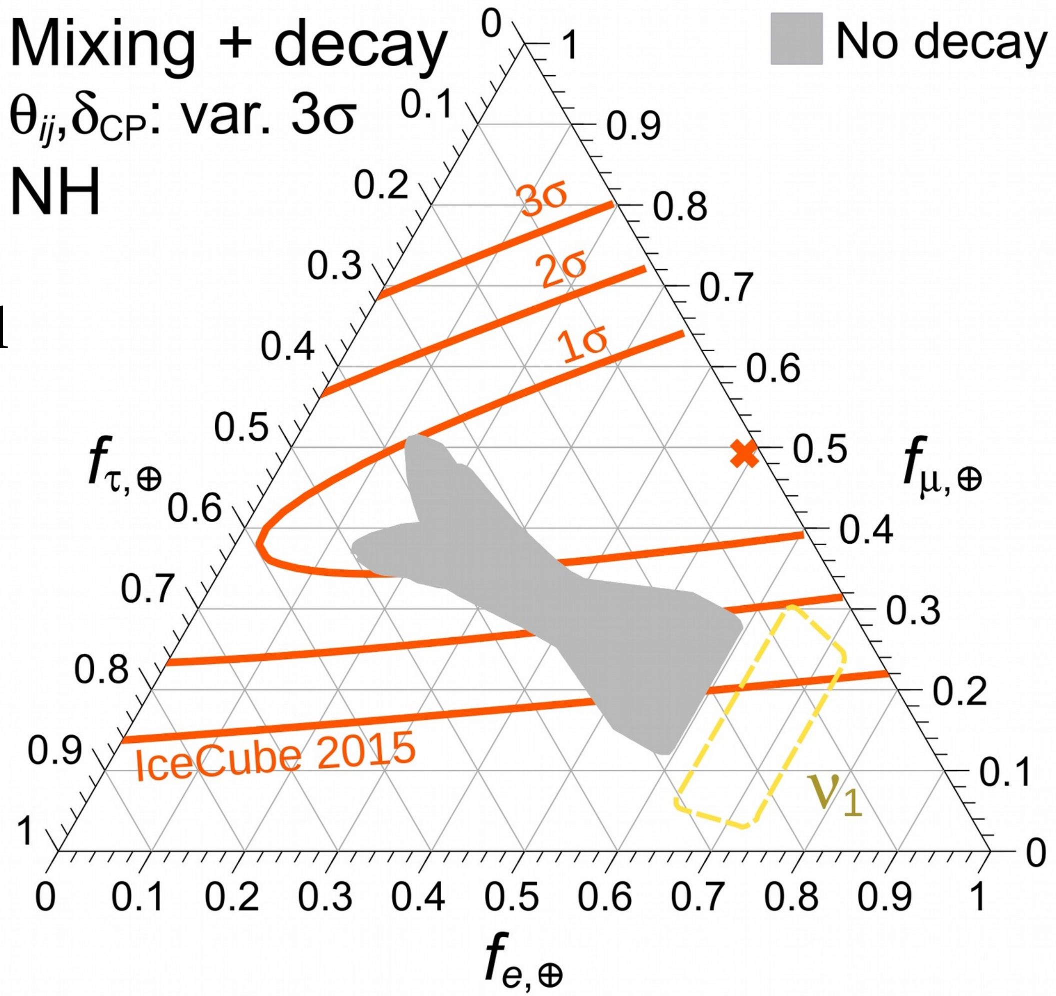


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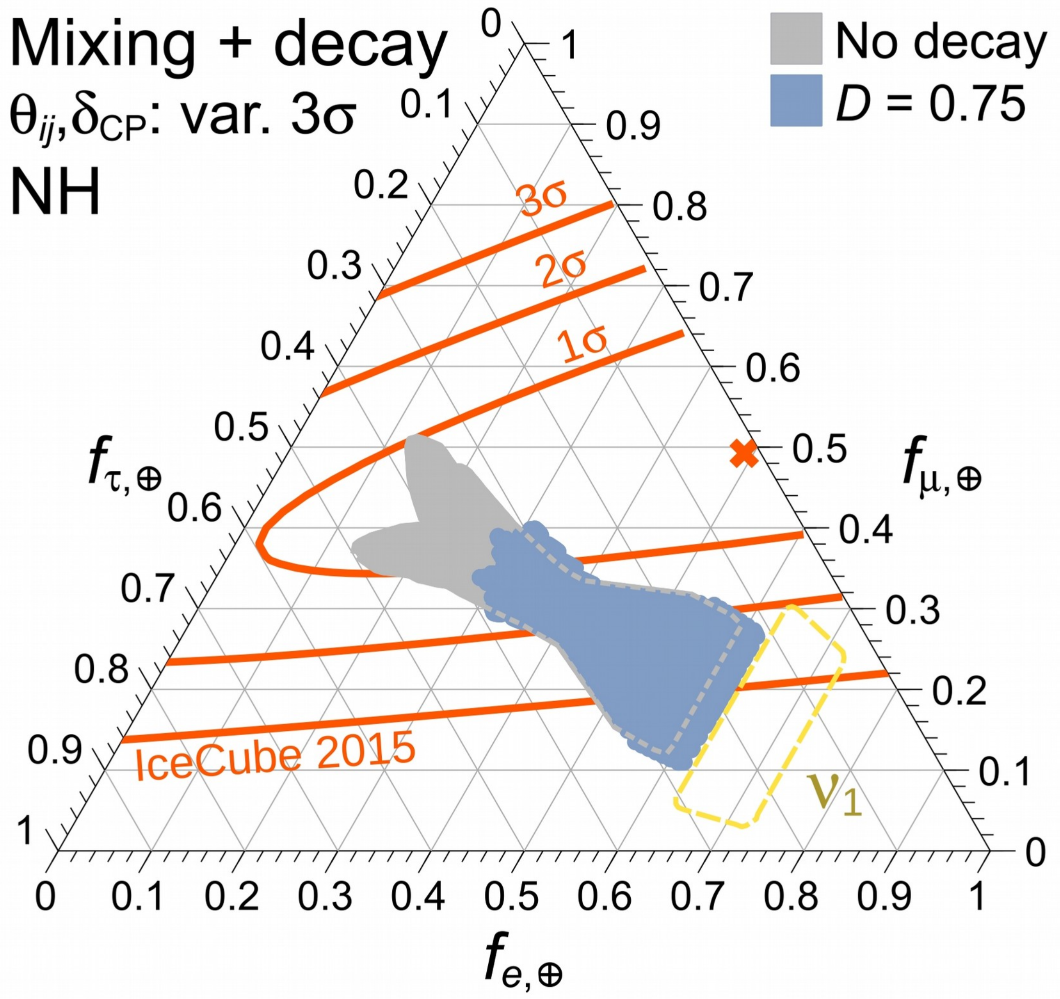

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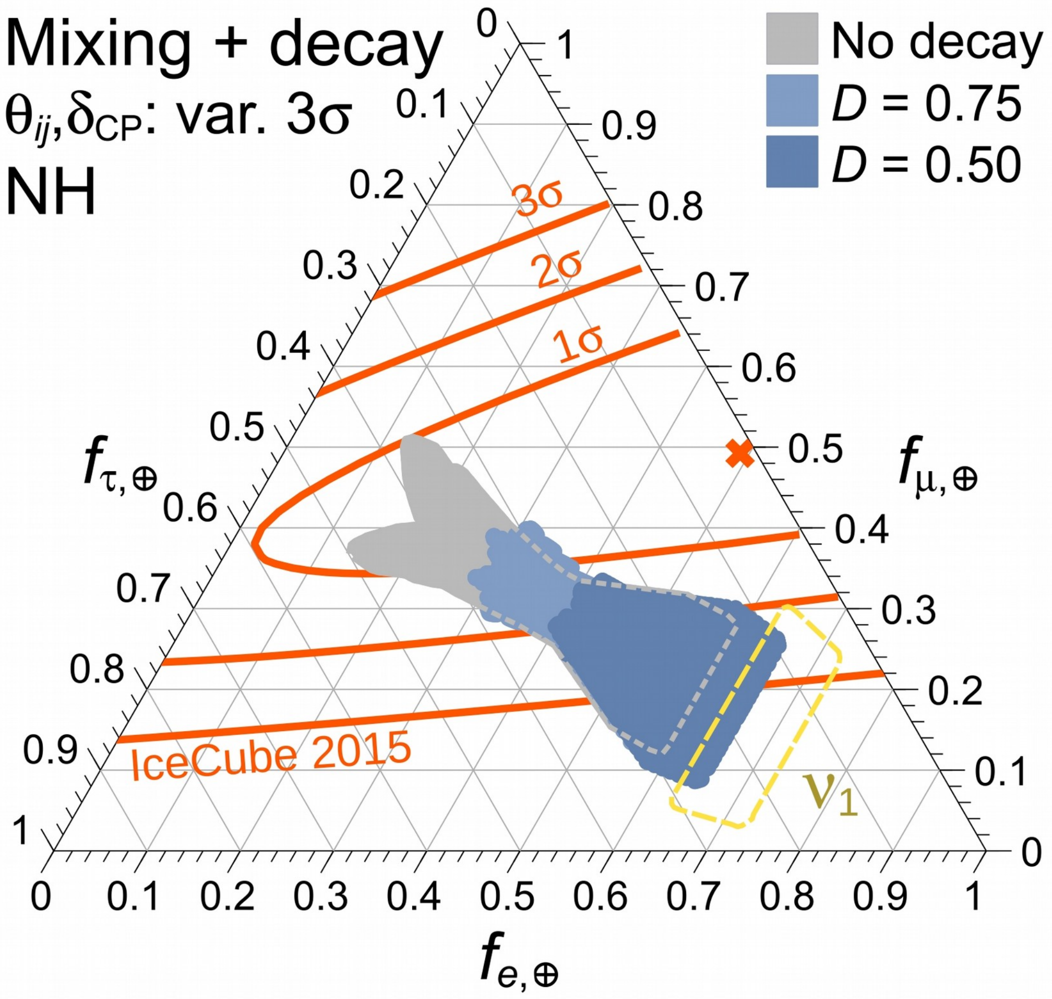


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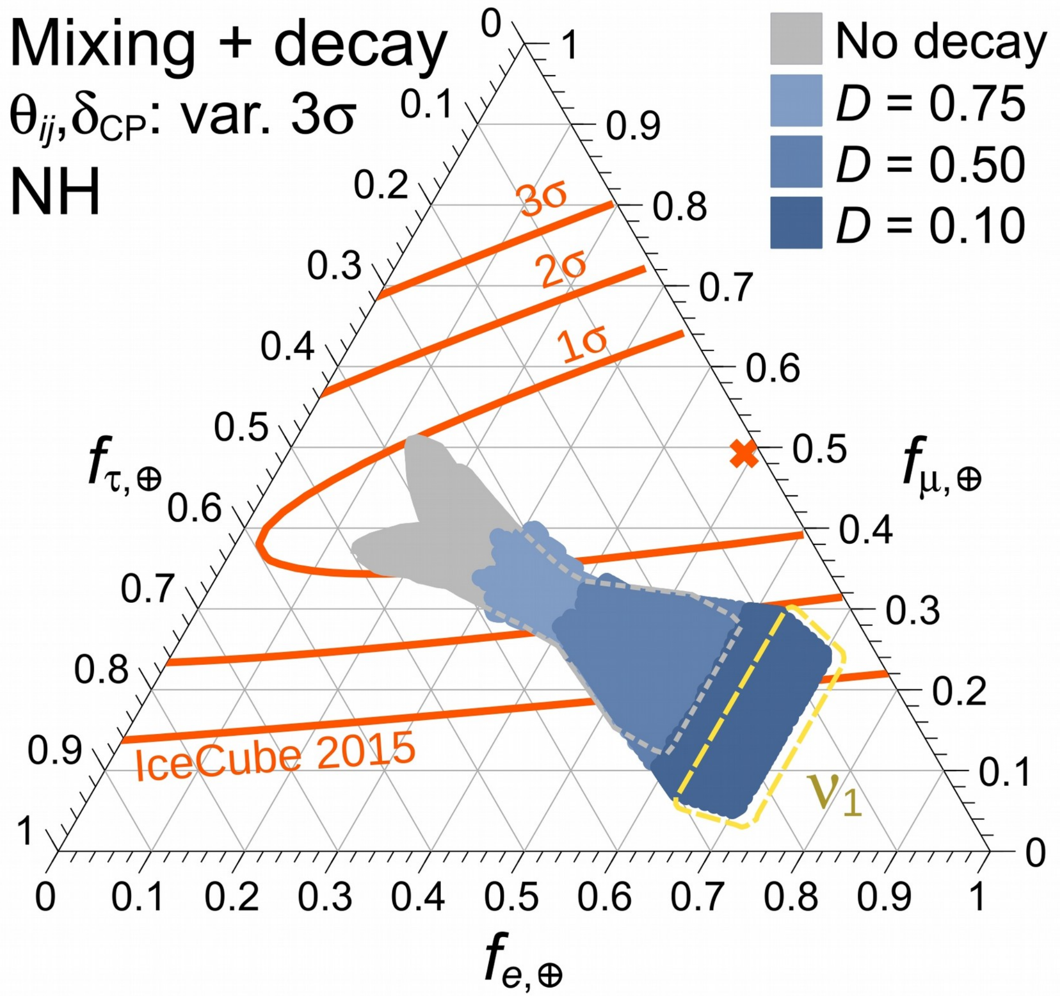


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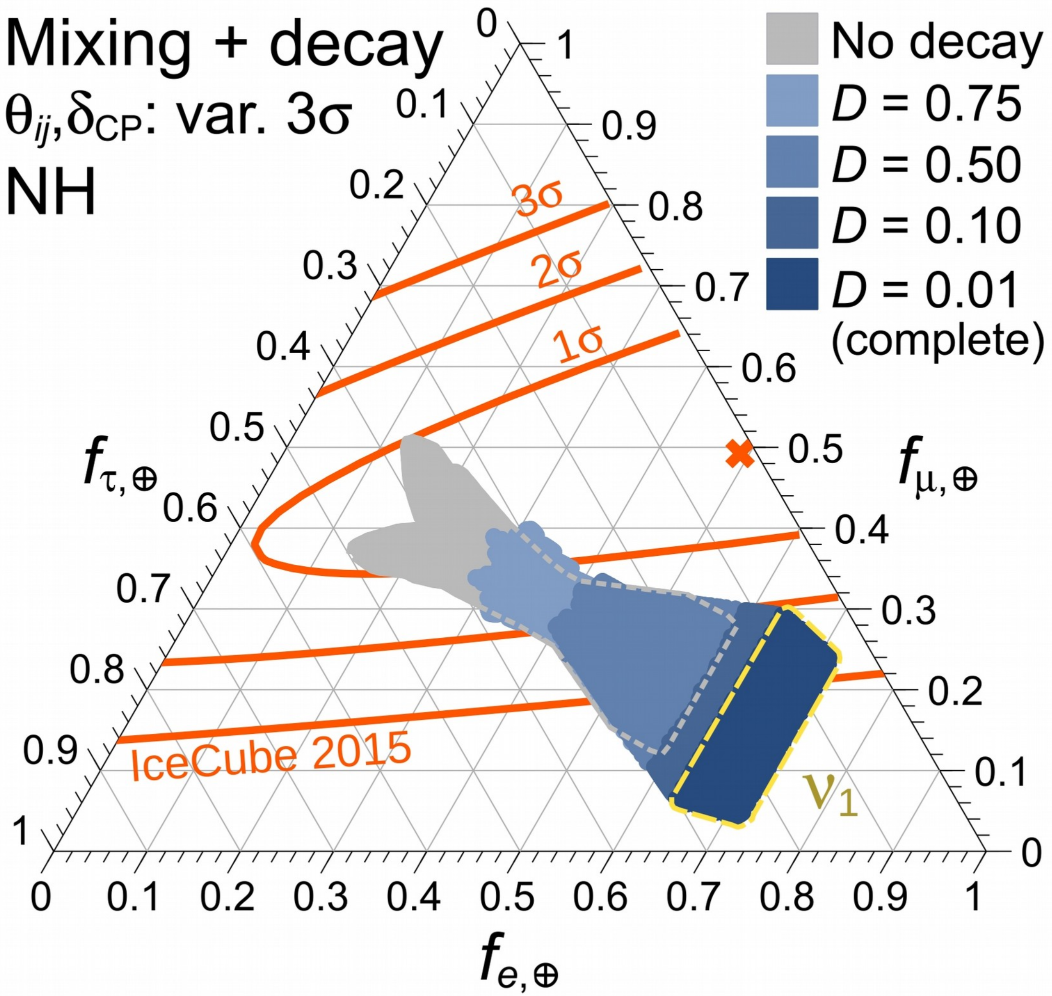


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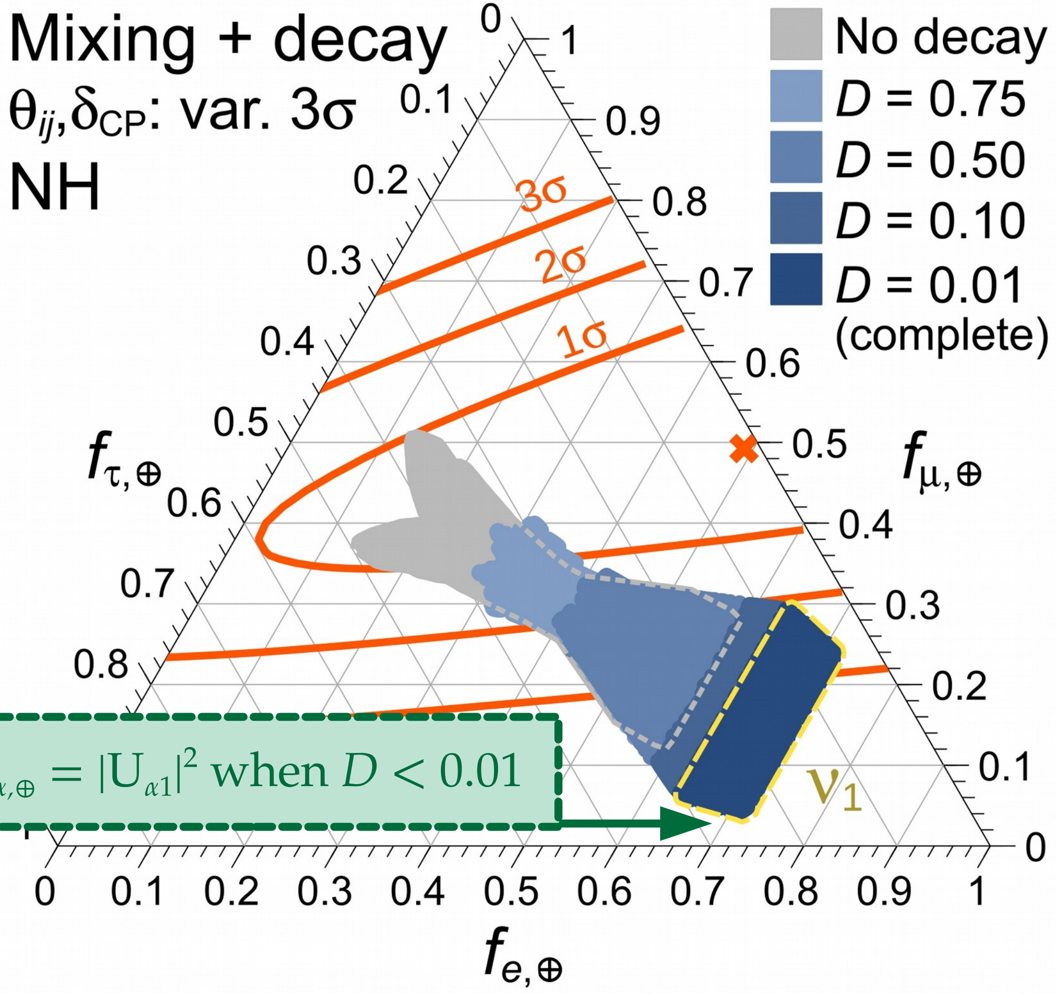


$f_{\alpha,\oplus} = |U_{\alpha 1}|^2$ when $D < 0.01$

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

# Ultra-long-range flavorful interactions

- Simple extension of the SM: Promote the global lepton-number symmetries $L_e$-$L_\mu$, $L_e$-$L_\tau$ to local symmetries

- They introduce new interaction between electrons and $\nu_e$ and $\nu_\mu$ or $\nu_\tau$ 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 $L_e$-$L_\mu$ or $L_e$-$L_\tau$ symmetry, an electron sources a Yukawa potential —

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

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

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

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

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

**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

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

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

**New neutrino-electron interaction:**
This is diagonal

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$Z'$ parameters

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$Z'$ parameters

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

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

# Electron-neutrino interactions can kill oscillations

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

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

$\sim 1/E$

Energy-independent

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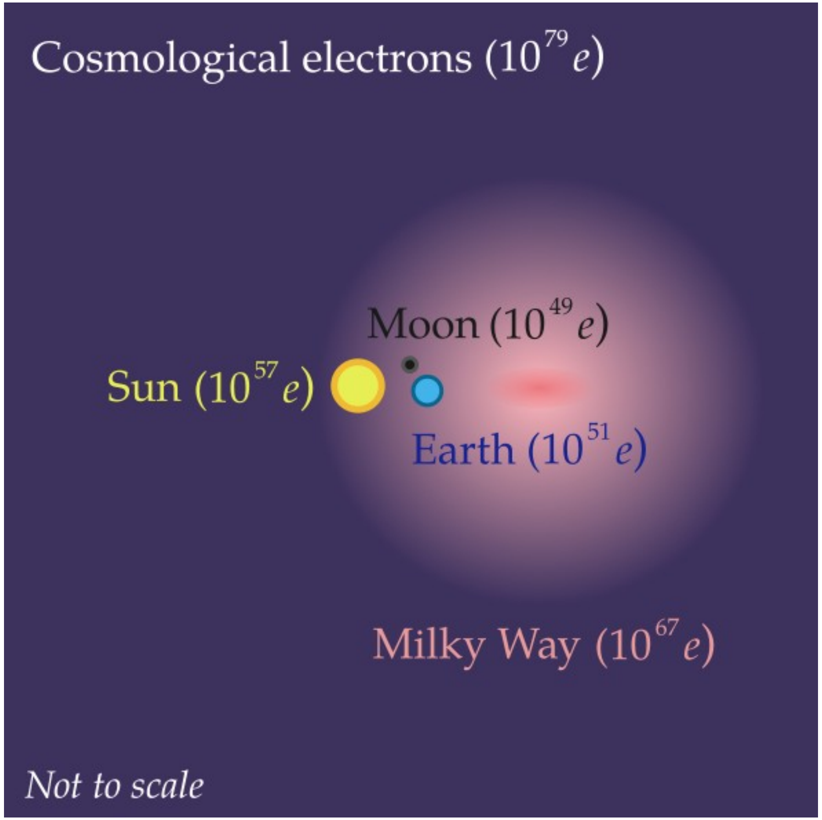
$$\mathrm{H}_{\mathrm{tot}} = \mathrm{H}_{\mathrm{vac}} + \mathrm{V}_{e\beta}$$

~$1/E$

Energy-independent

∴ We can use high-energy astrophysical neutrinos

# The total potential



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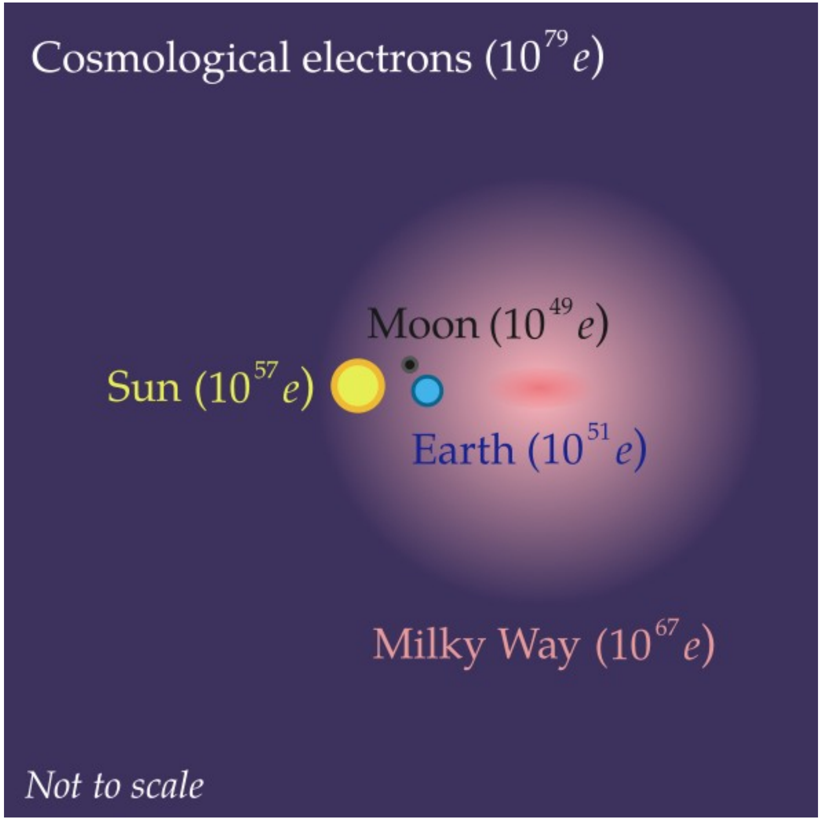
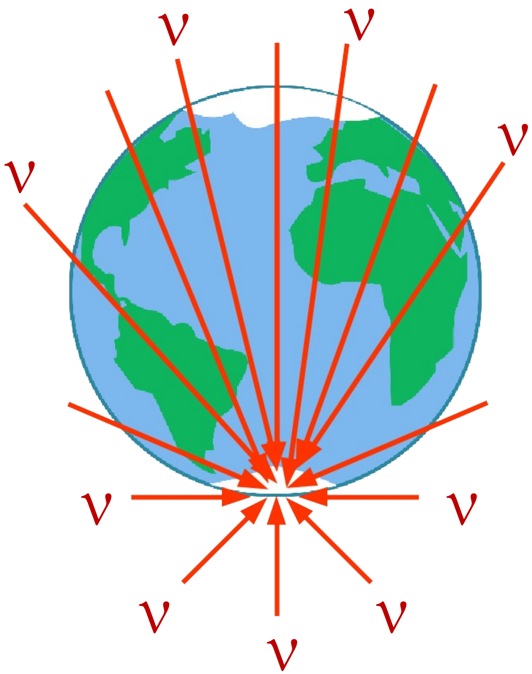
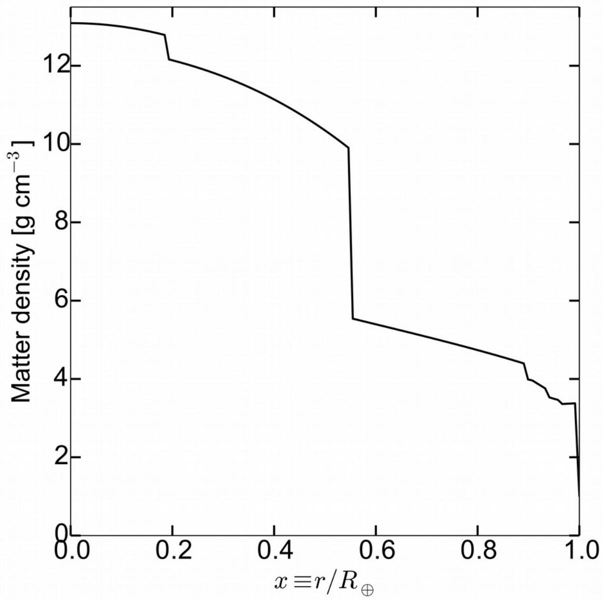



$$V_{e\beta} = V_{e\beta}^{\oplus}$$

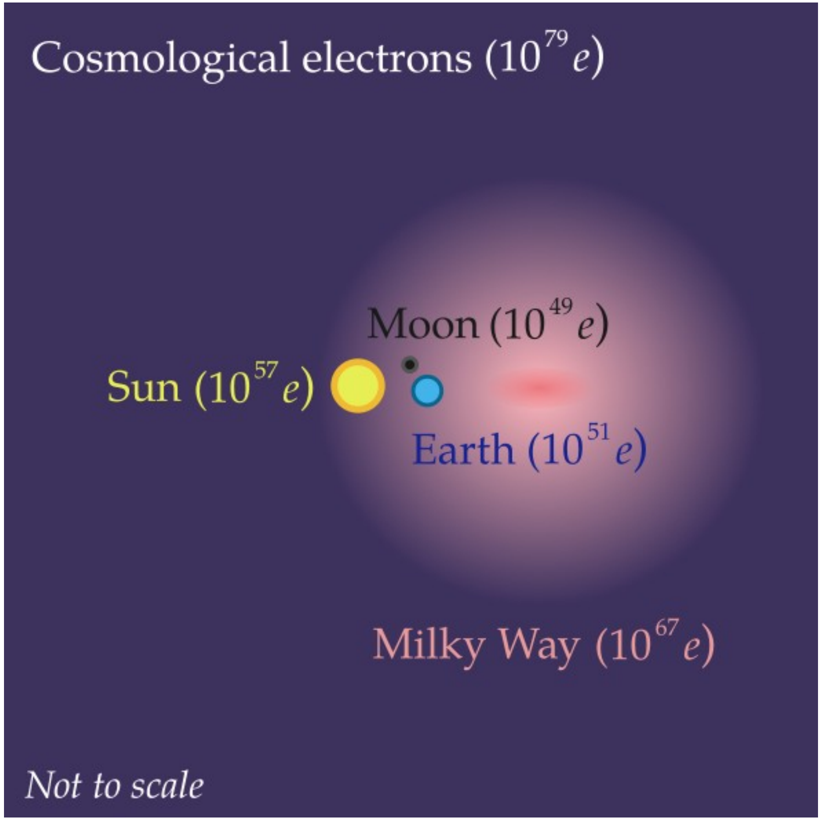
## Earth:



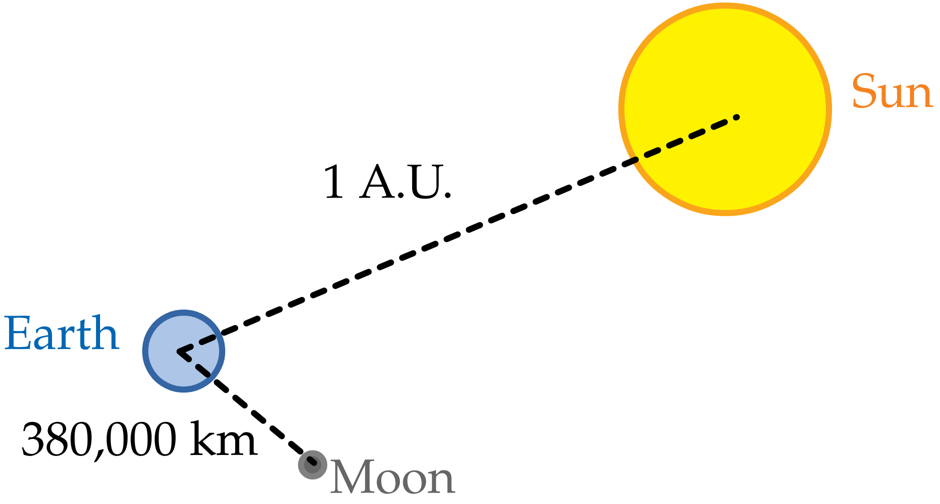




Neutrinos traverse different electron column depths

# The total potential



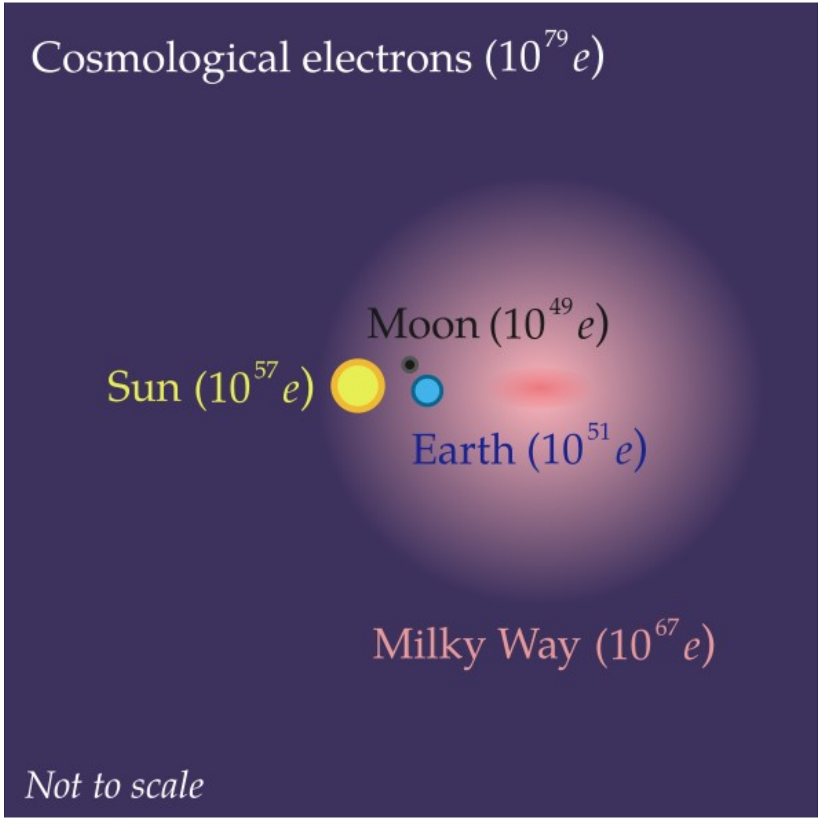

## Moon and Sun:




Treated as point sources of electrons

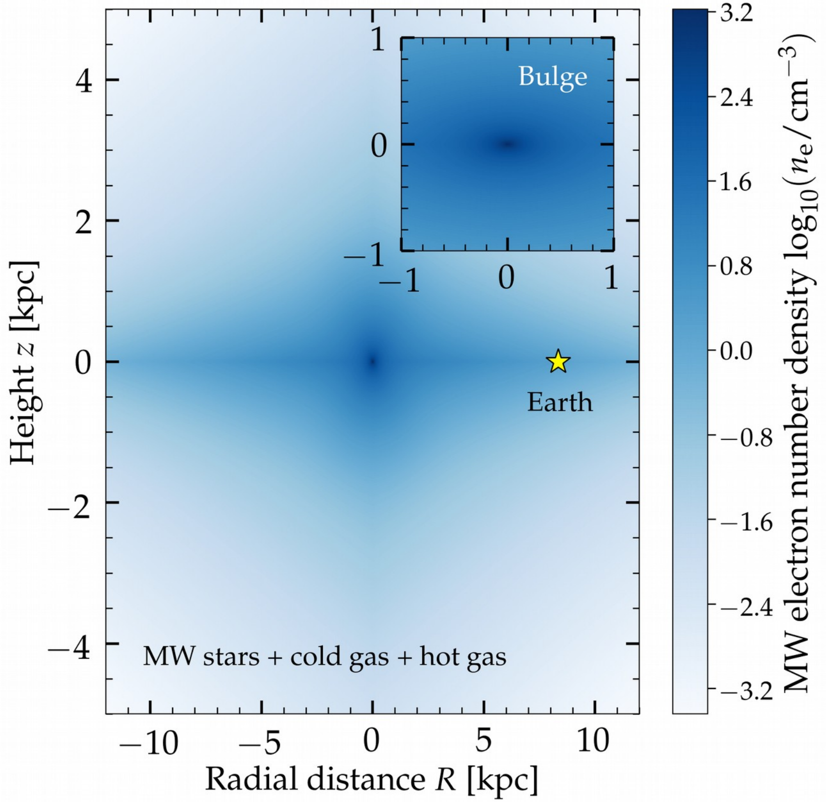
$$V_{e\beta} = V_{e\beta}^{\oplus} + V_{e\beta}^{\text{Moon}} + V_{e\beta}^{\odot}$$

# The total potential



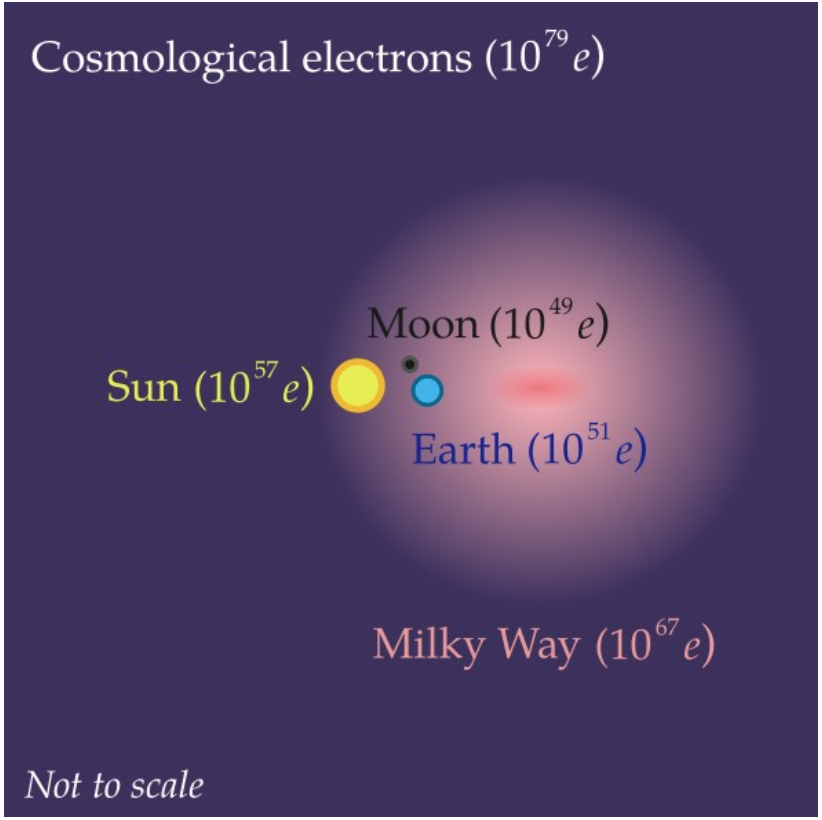

## Milky Way:

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

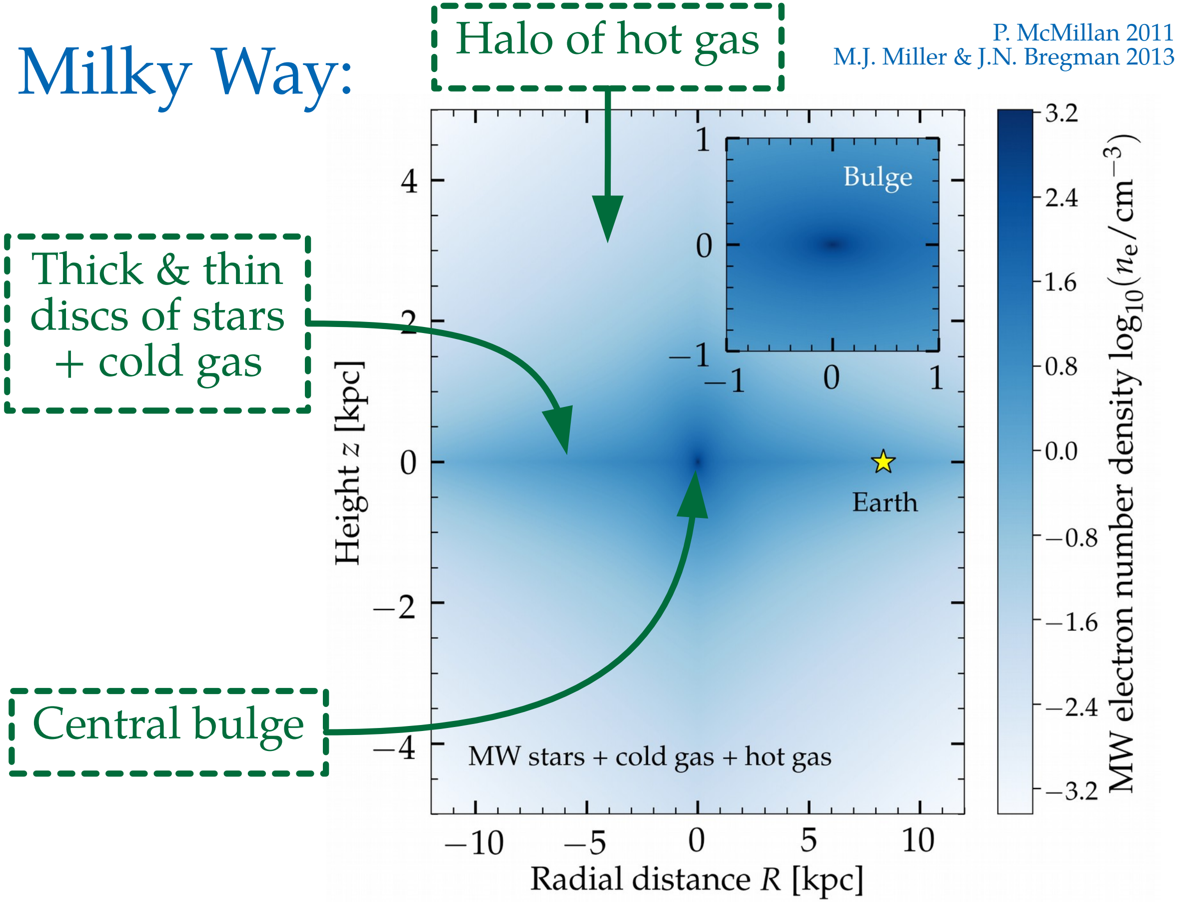



$$V_{e\beta} = V_{e\beta}^{\oplus} + V_{e\beta}^{\text{Moon}} + V_{e\beta}^{\odot} + V_{e\beta}^{\text{MW}}$$

# The total potential

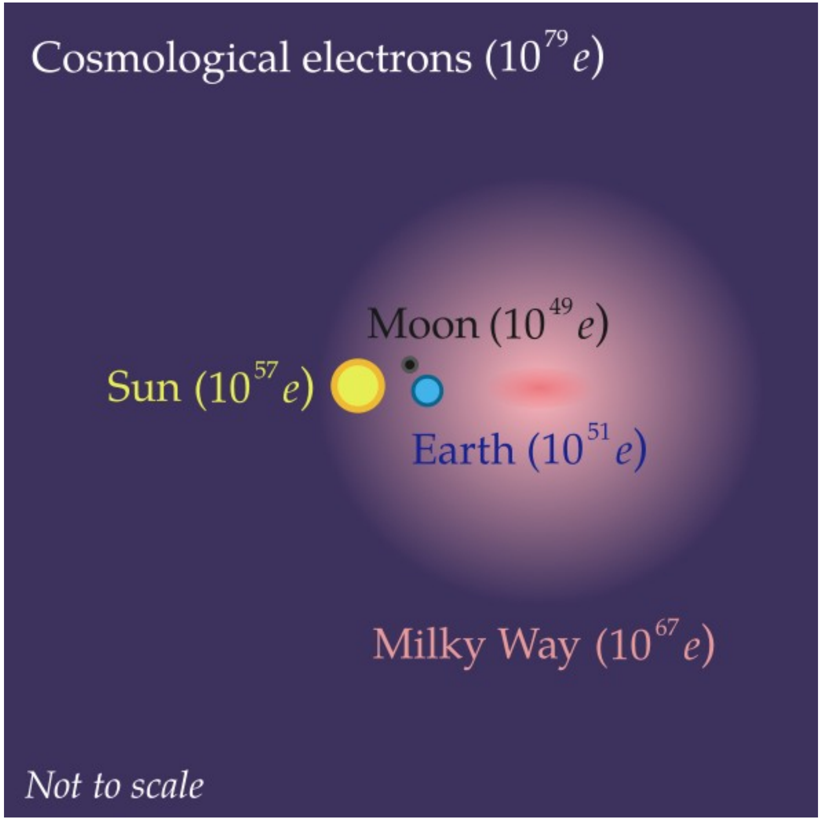



Milky Way:

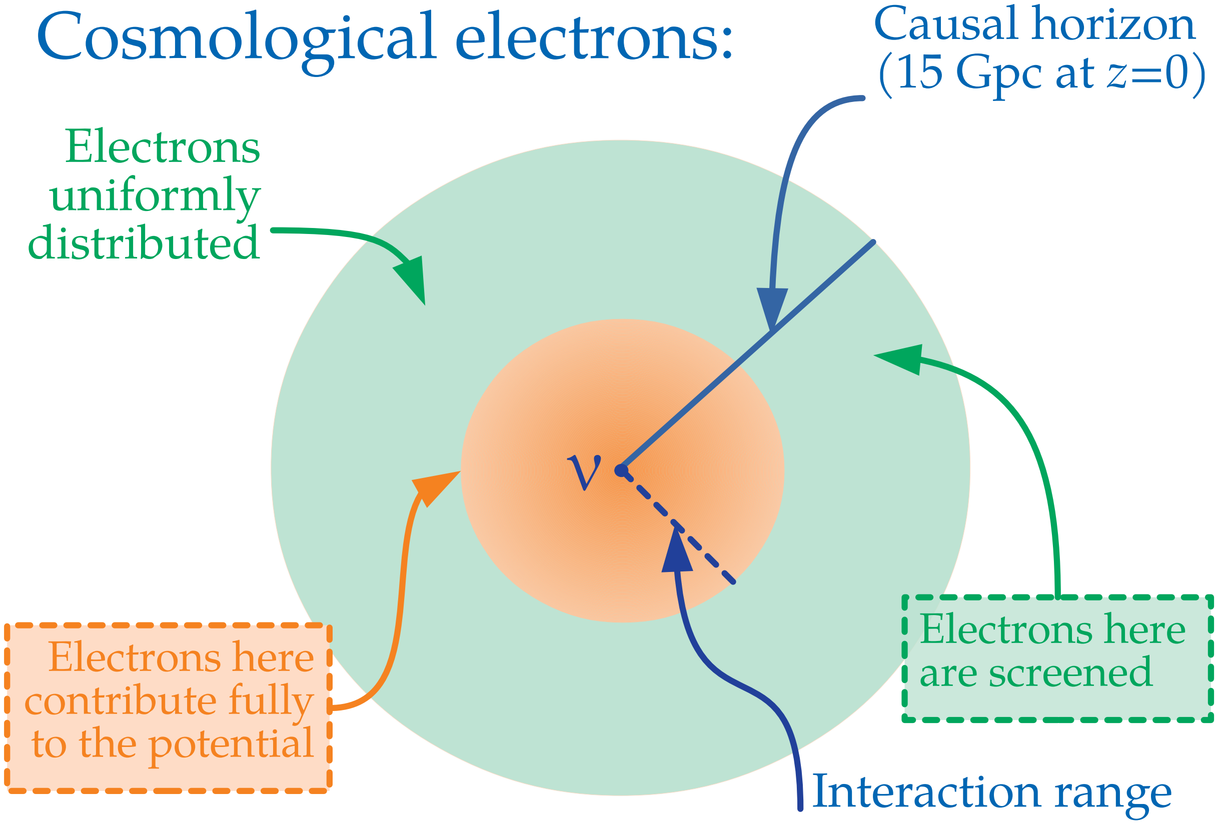



$$V_{e\beta} = V_{e\beta}^{\oplus} + V_{e\beta}^{\text{Moon}} + V_{e\beta}^{\odot} + V_{e\beta}^{\text{MW}}$$

# The total potential

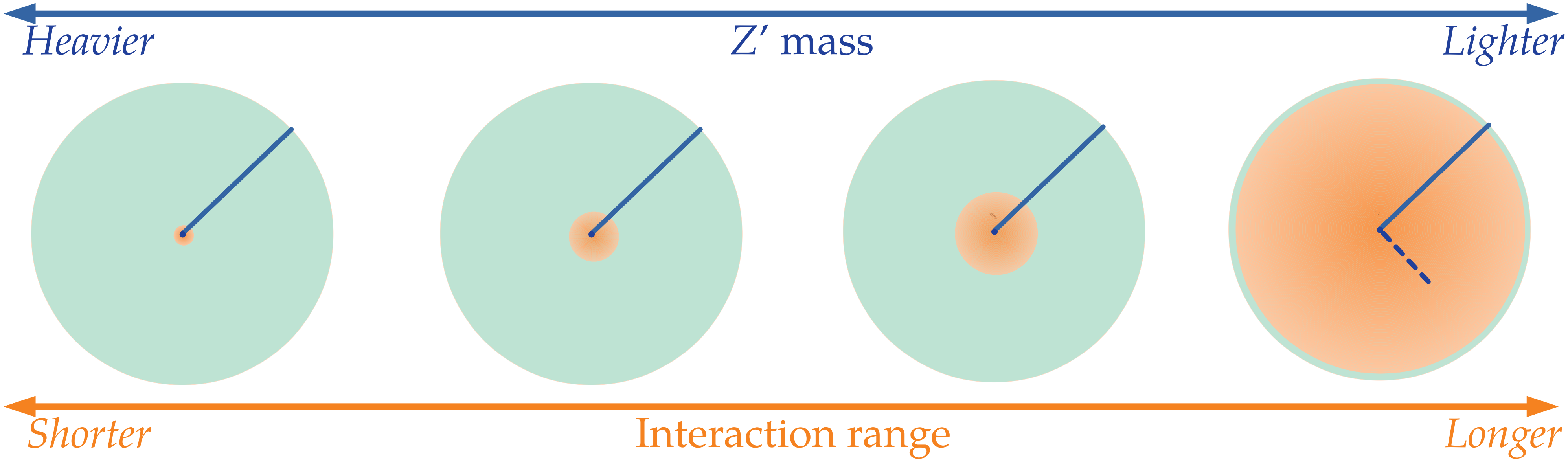



## Cosmological electrons:




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

# The total potential




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

# Electrons in the local and distant Universe

Potential:

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

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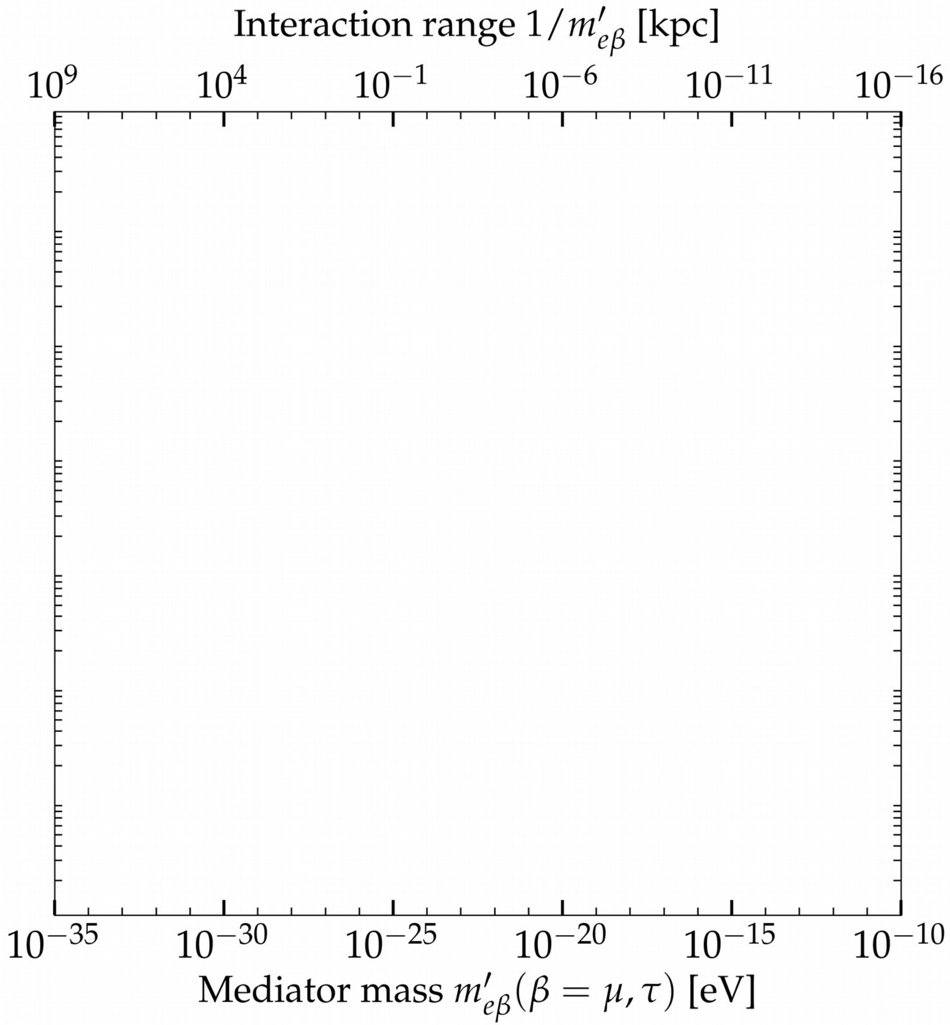


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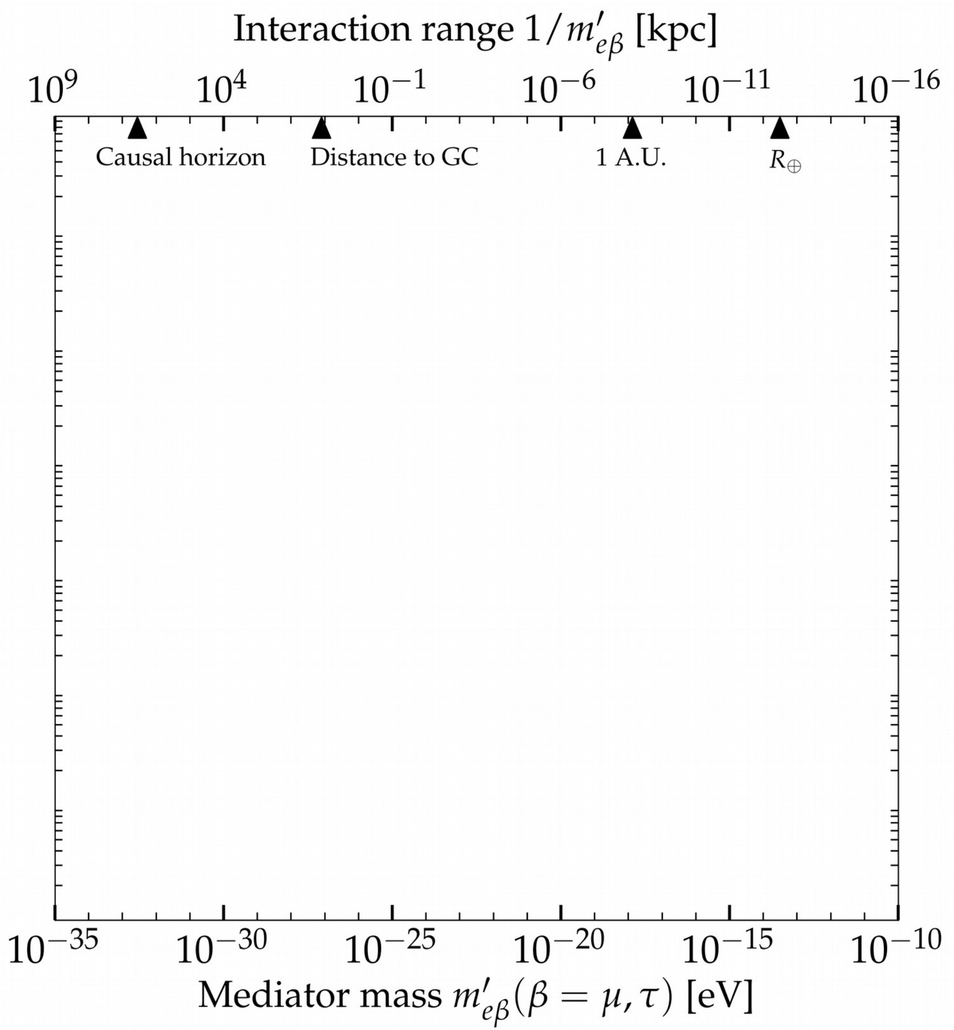


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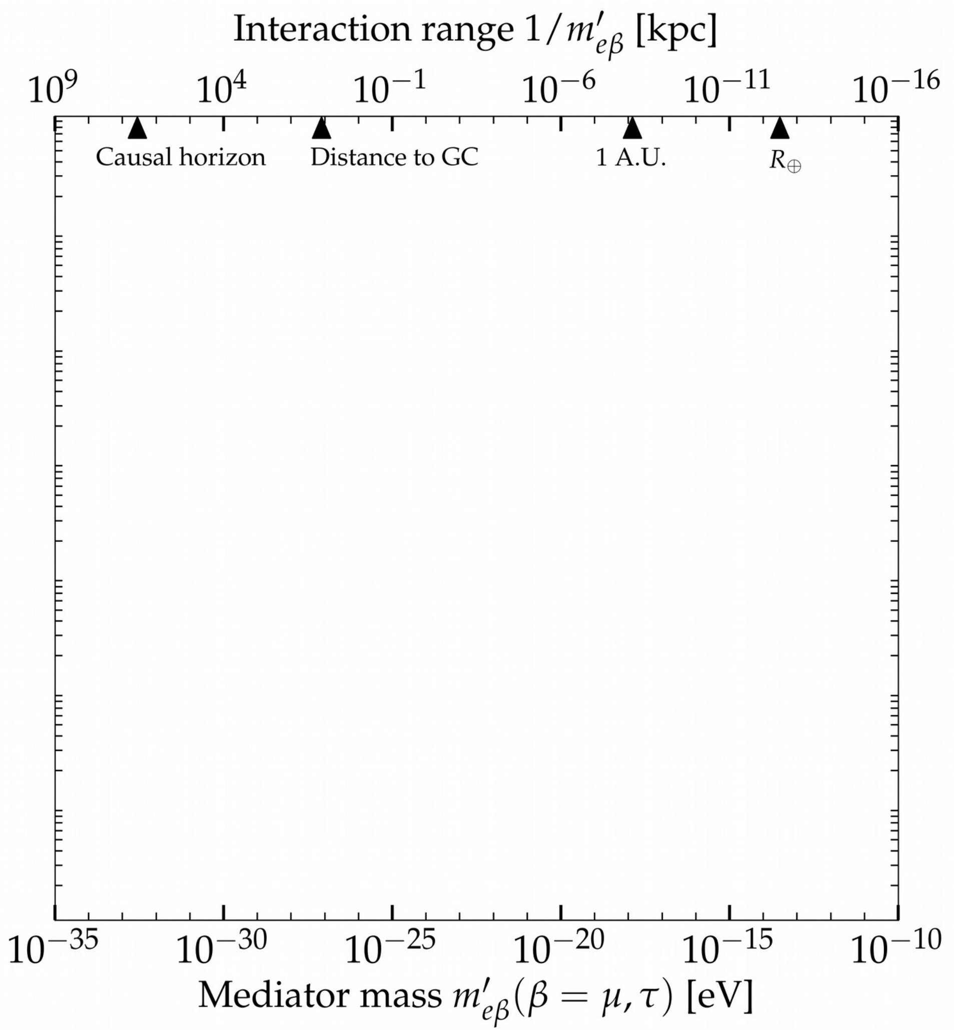


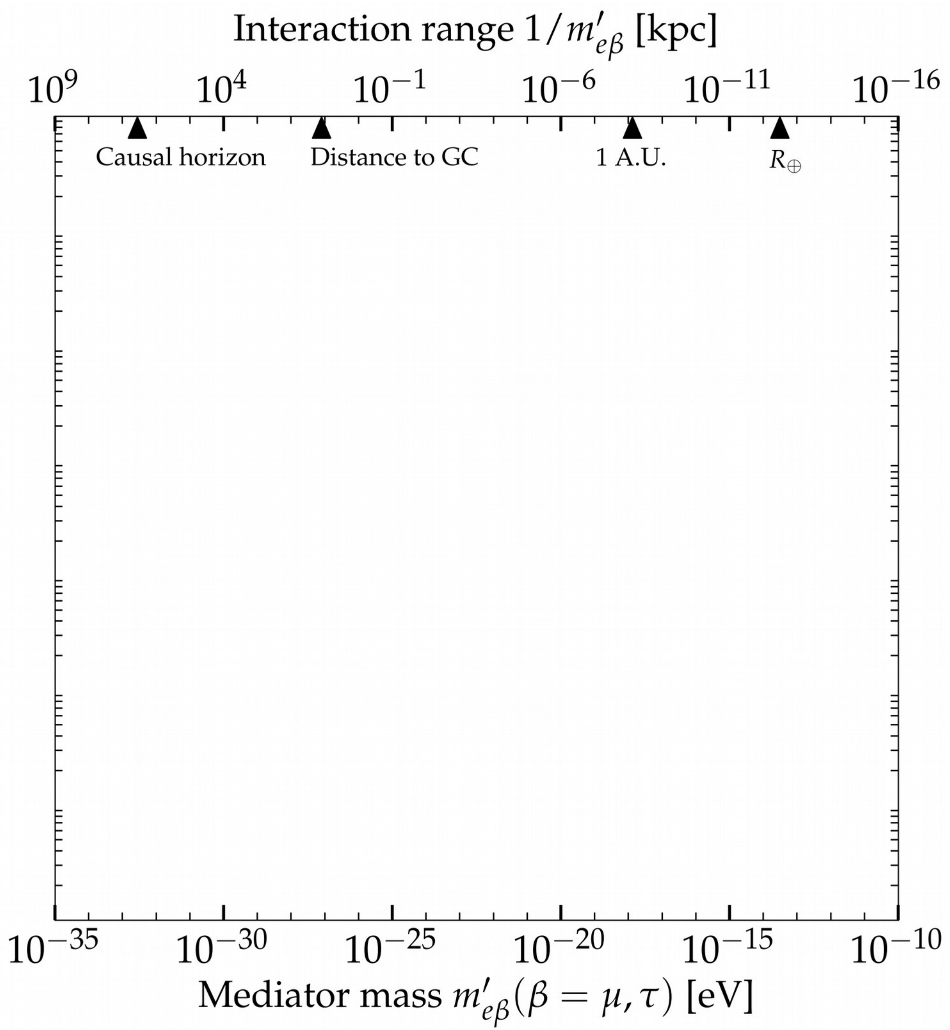

Potential:

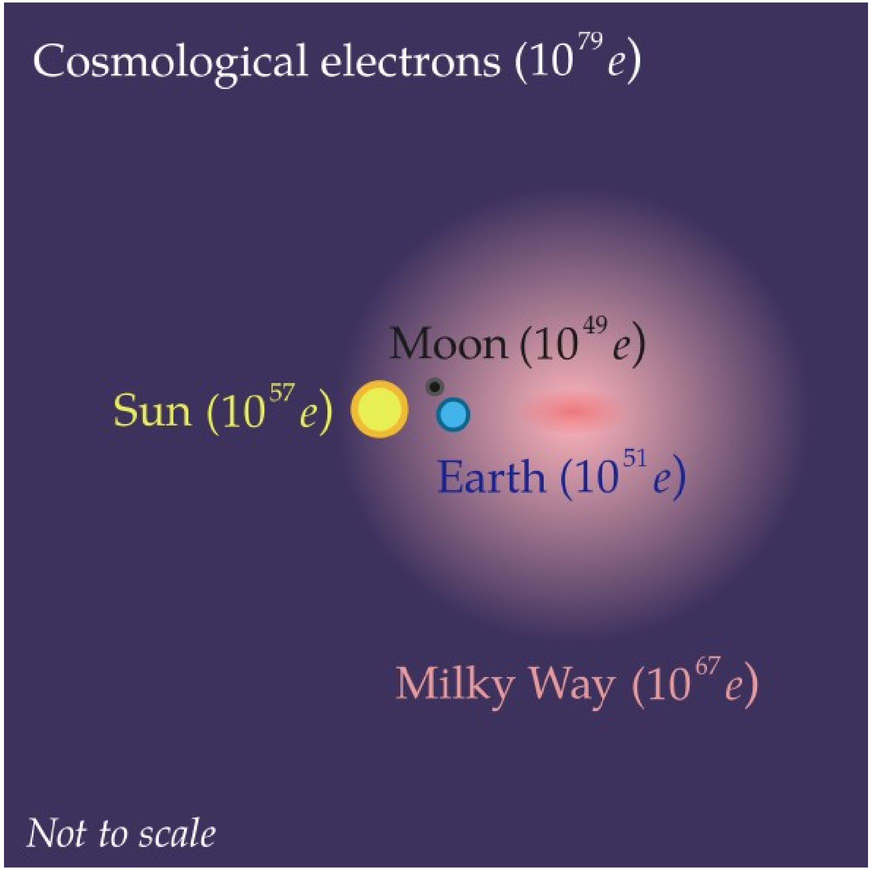
$$V_{e\beta} \propto \frac{1}{r} e^{-m'_{e\beta} r}$$

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

Light mediators
$\Rightarrow$ Long interaction ranges

# Electrons in the local and distant Universe



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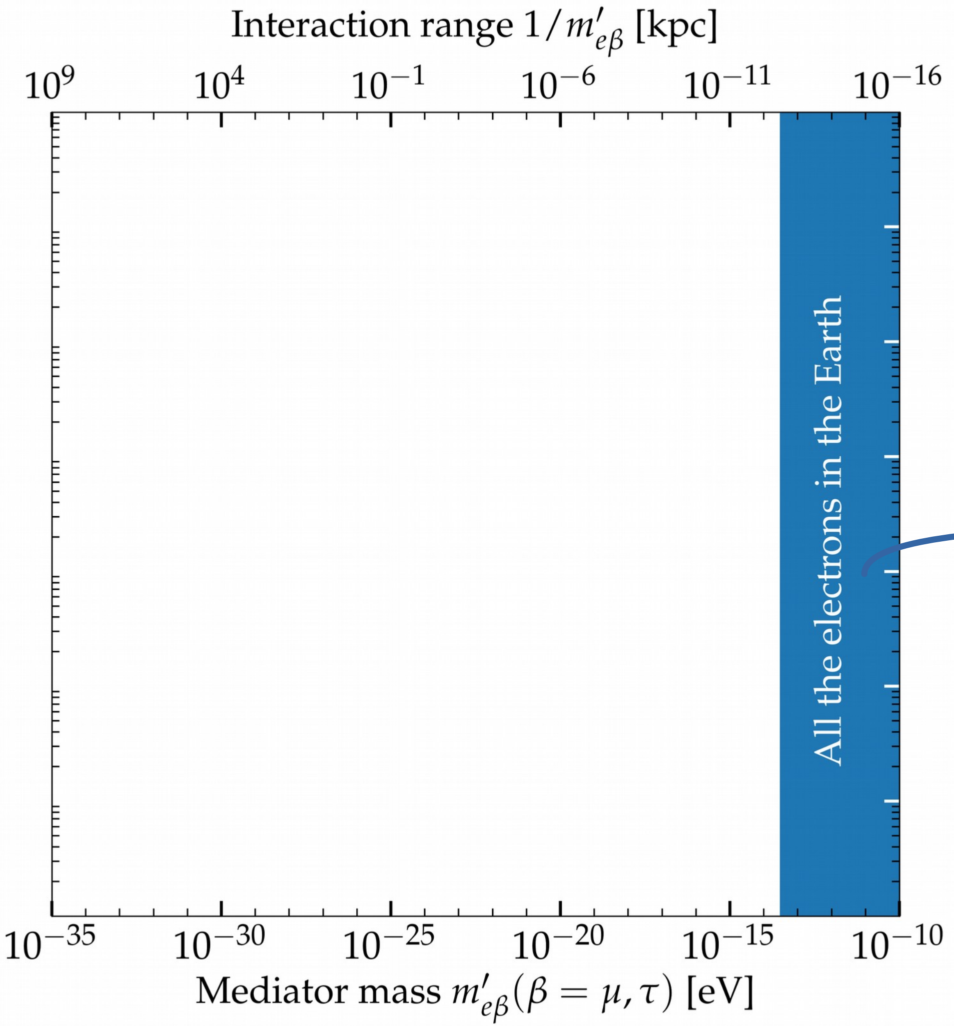
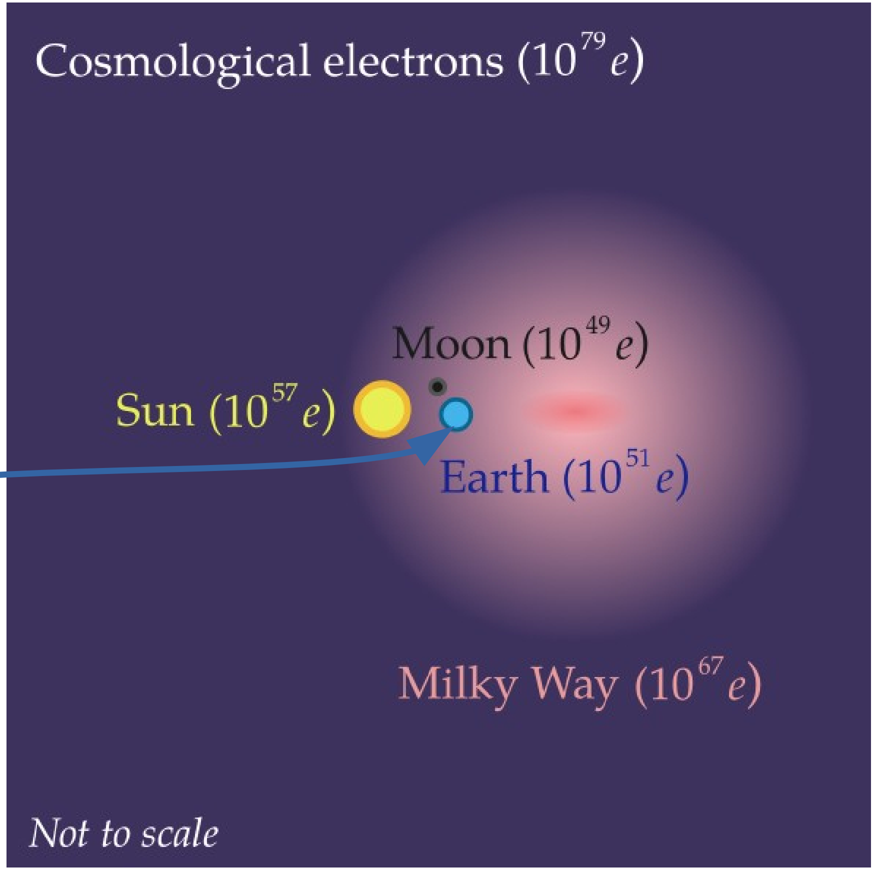
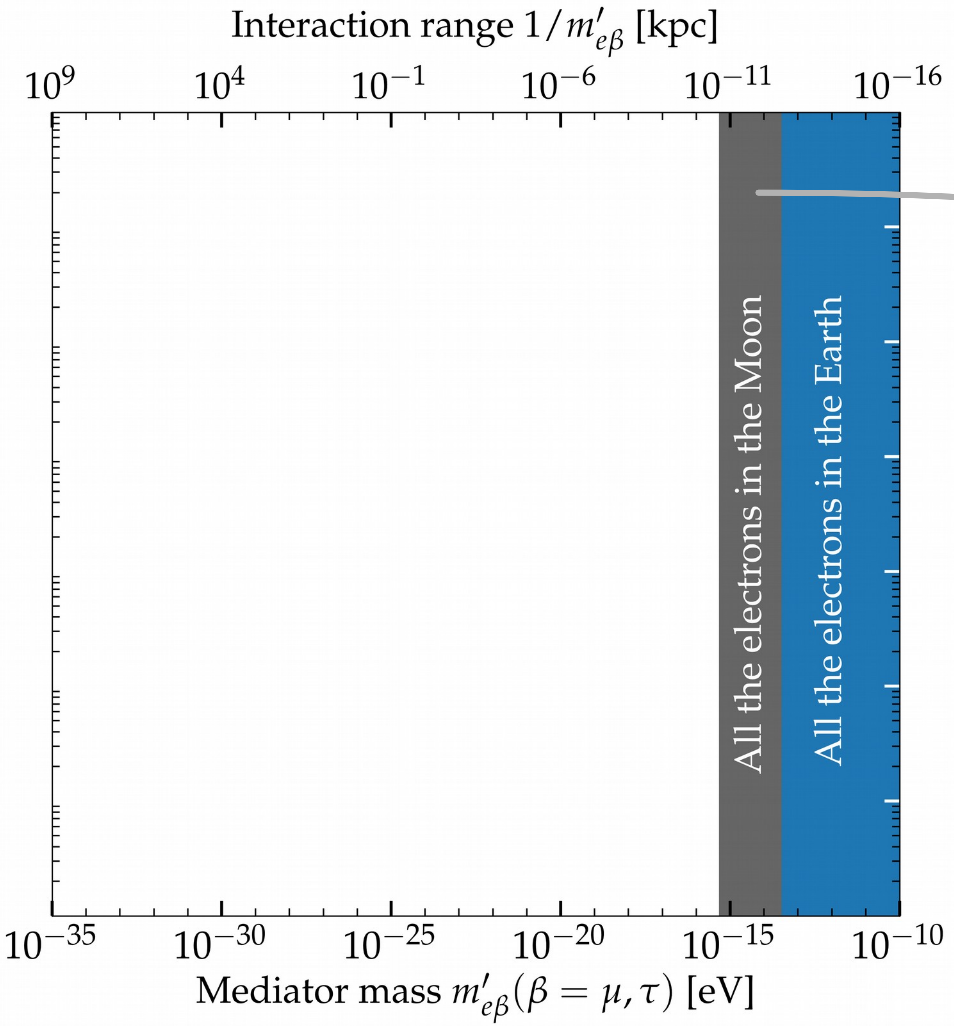
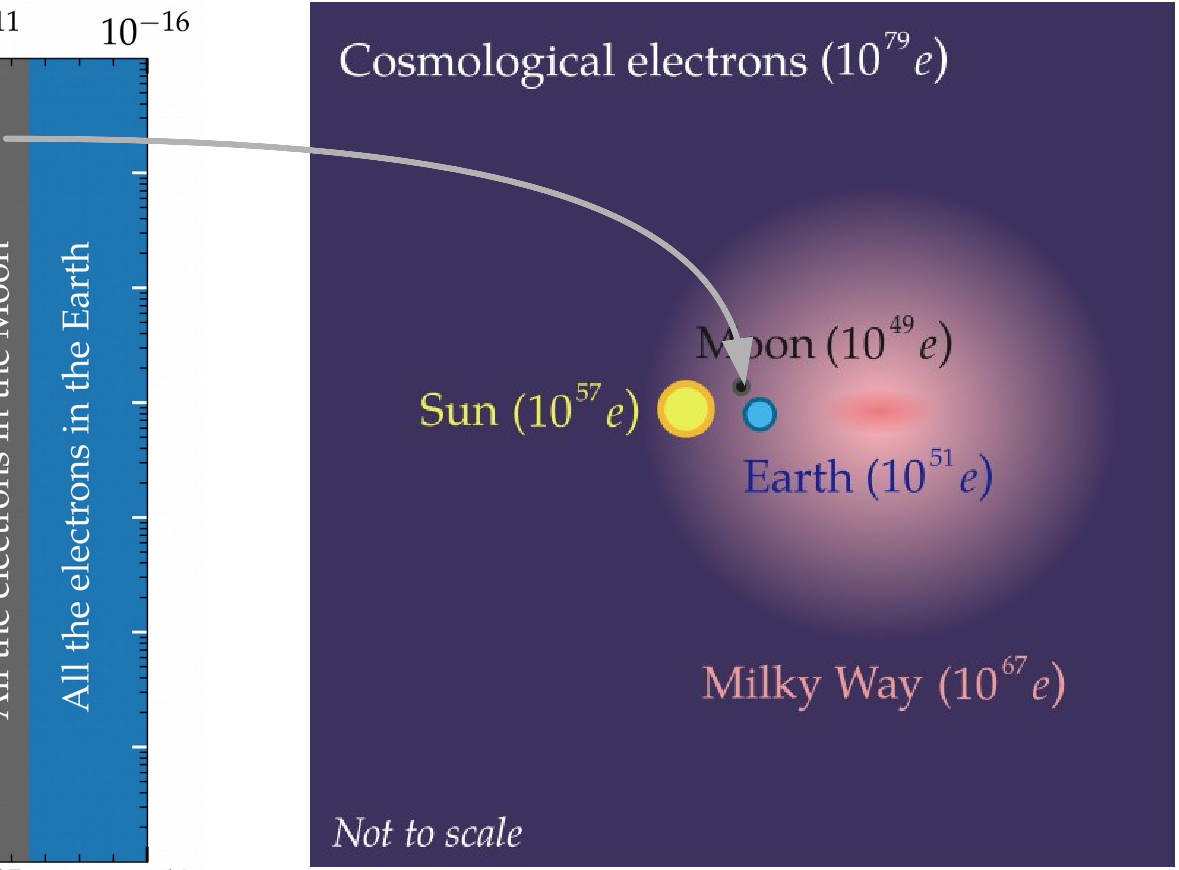


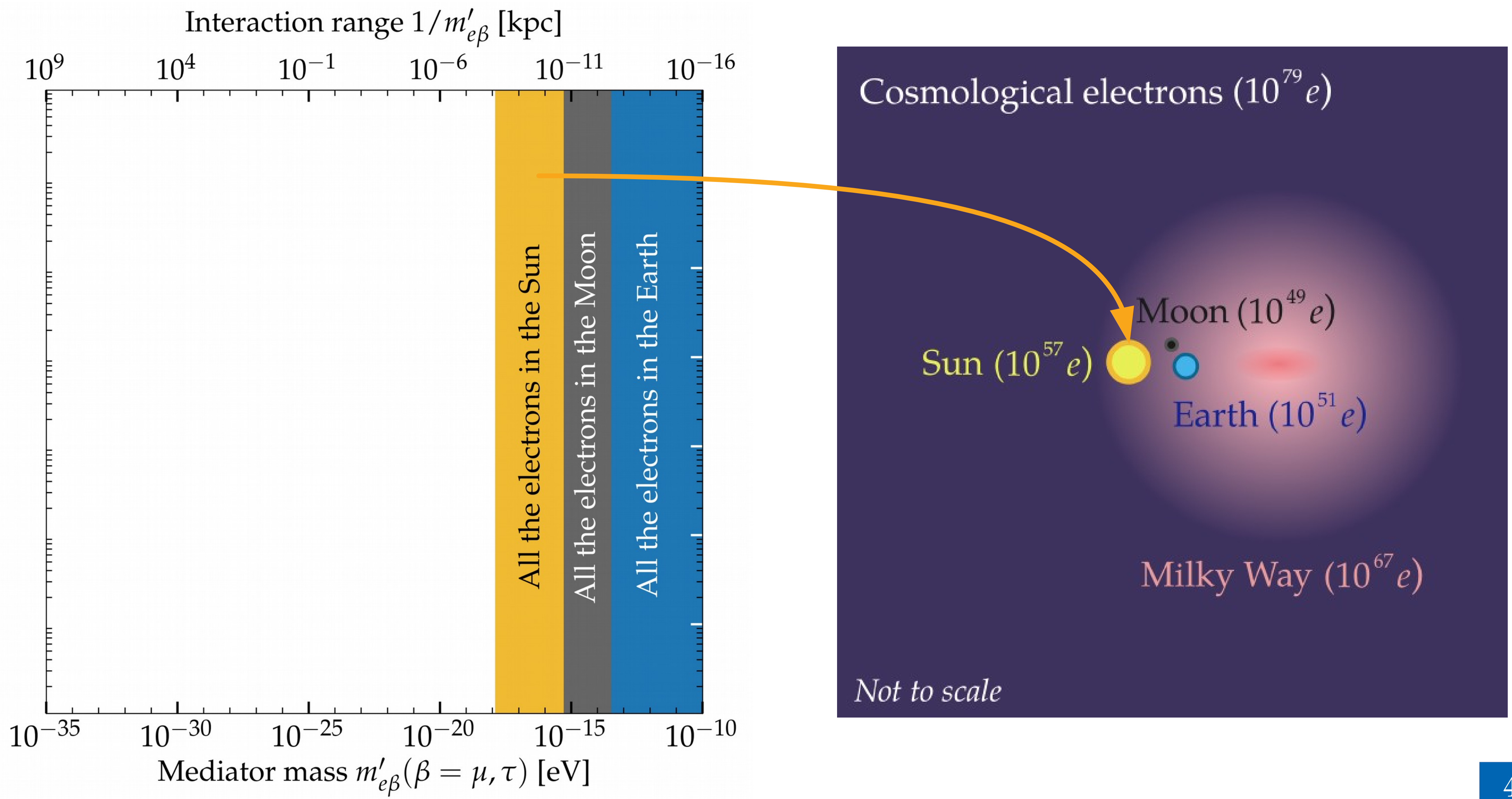



# Electrons in the local and distant Universe



# Electrons in the local and distant Universe



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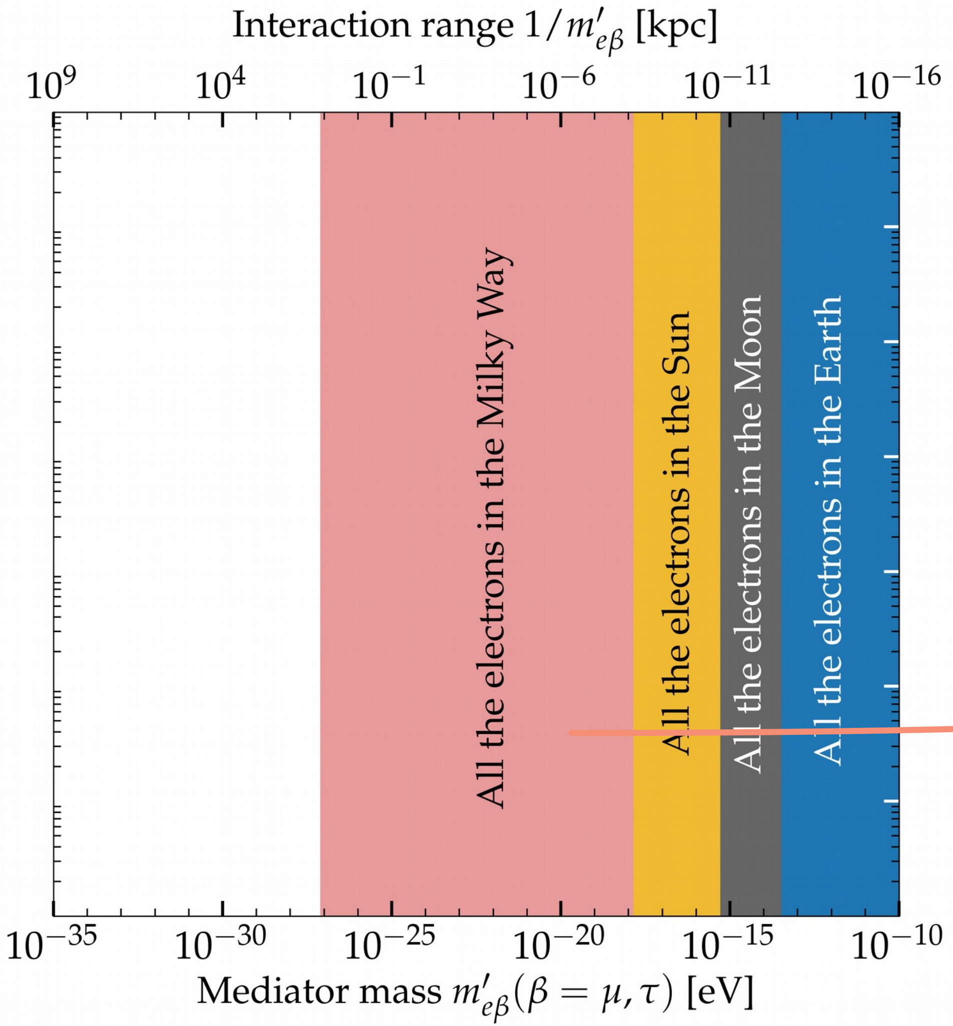
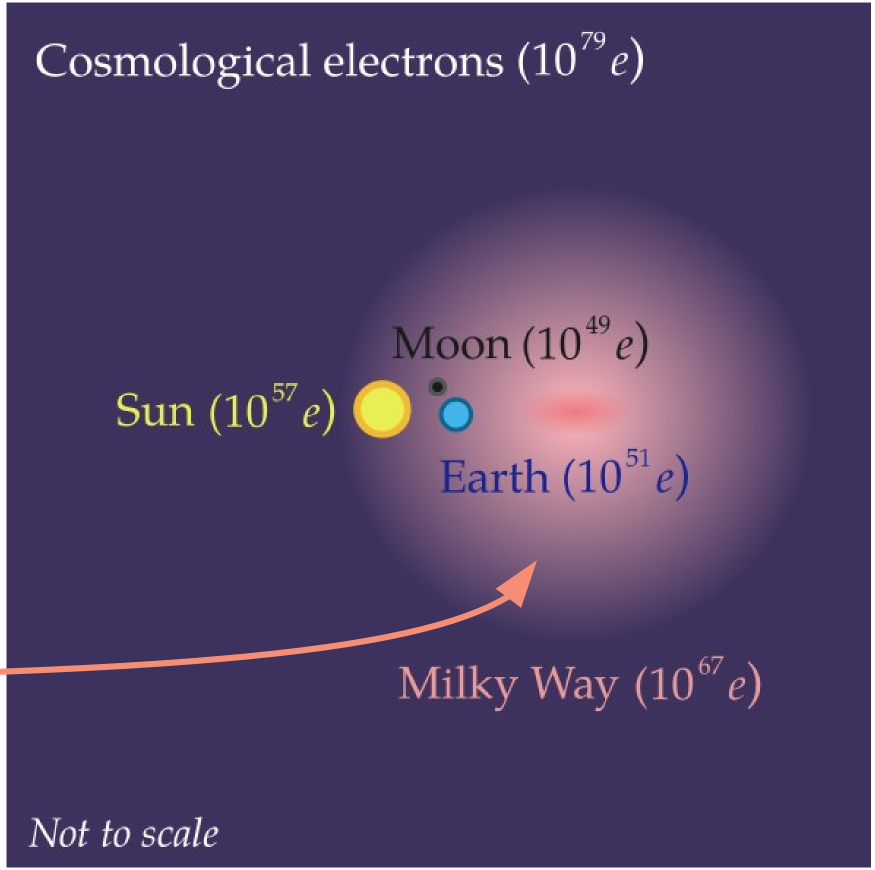
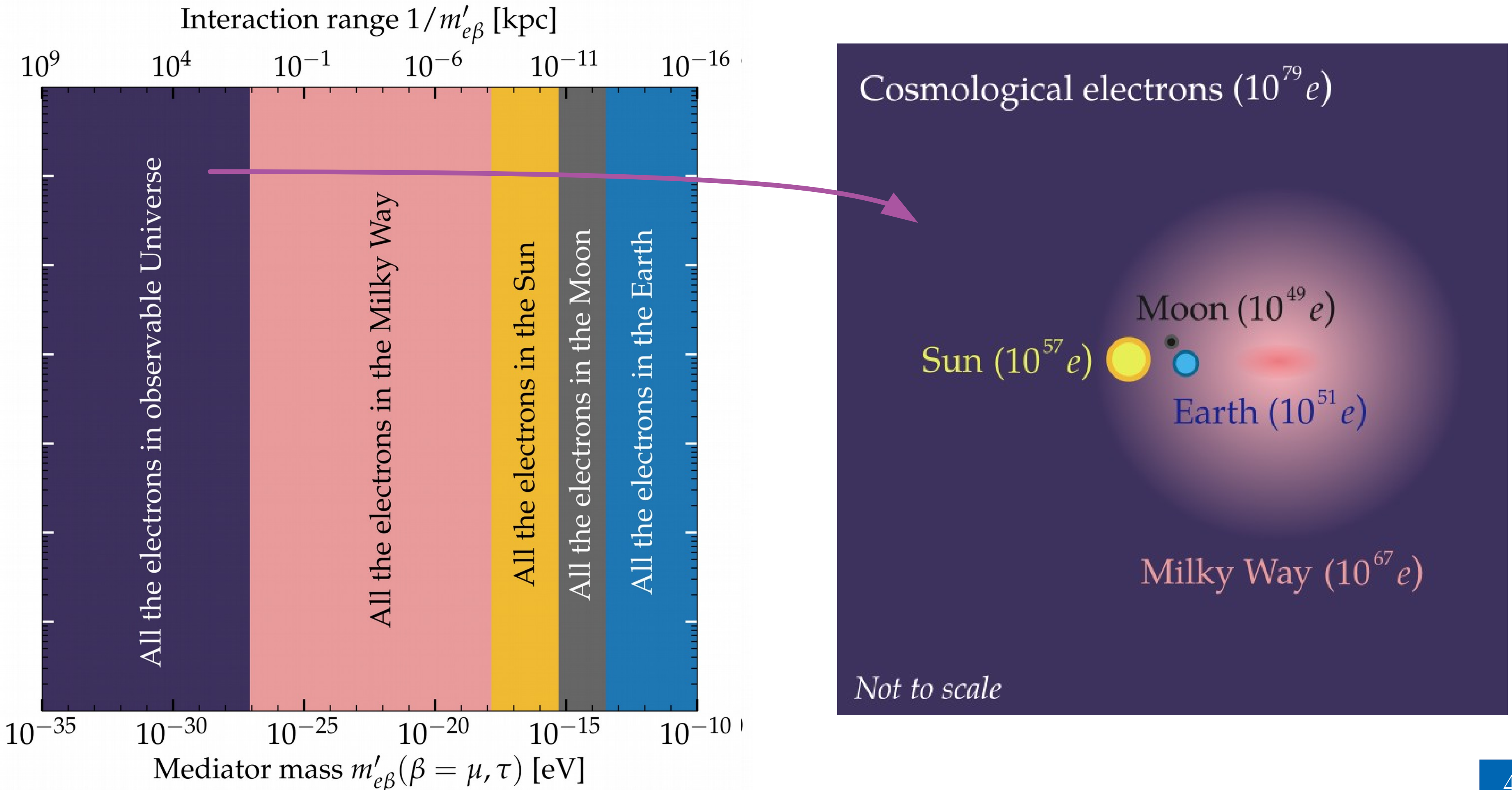
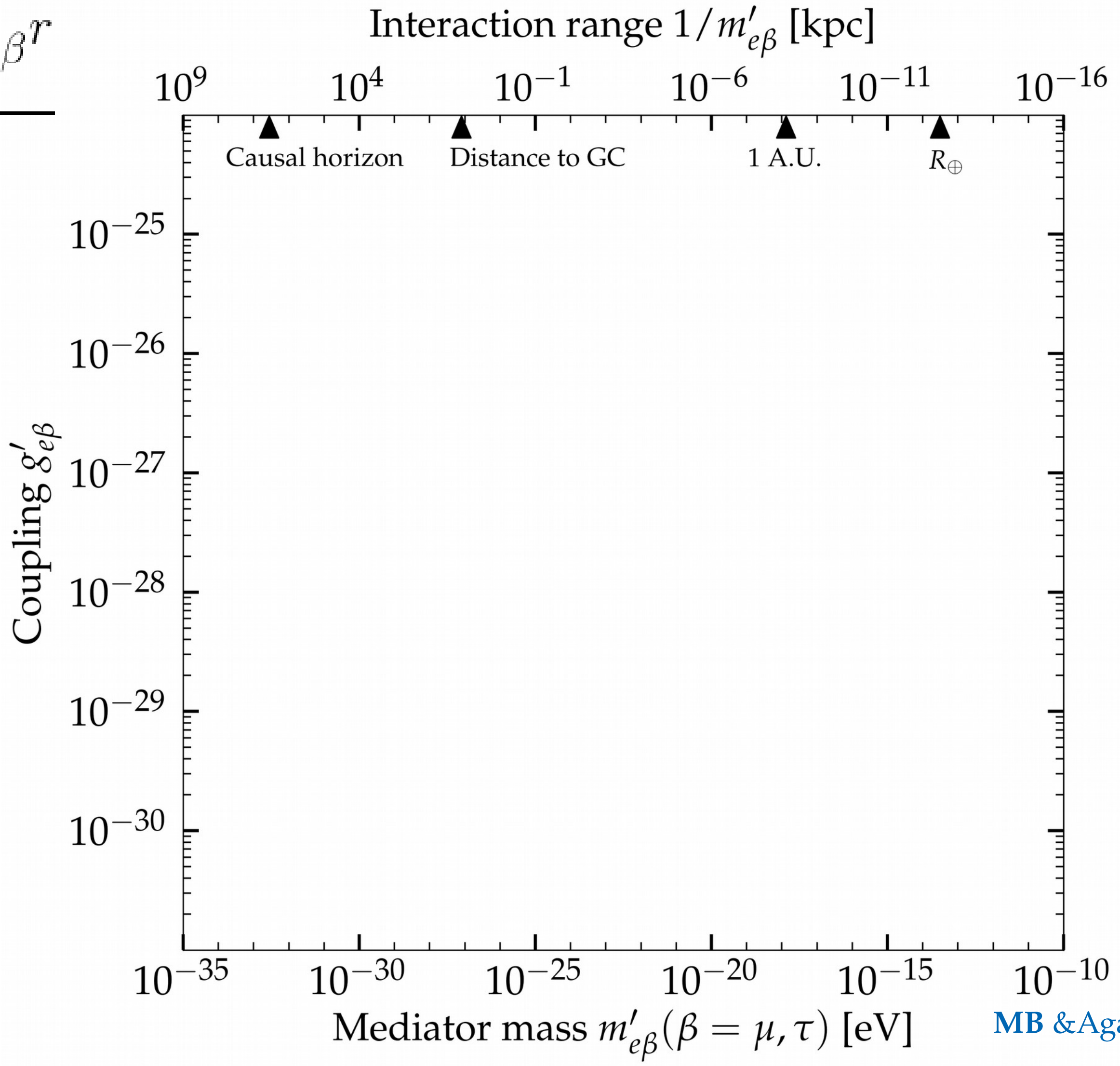


# Electrons in the local and distant Universe



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




**MB** &Agarwalla, *PRL* 2019

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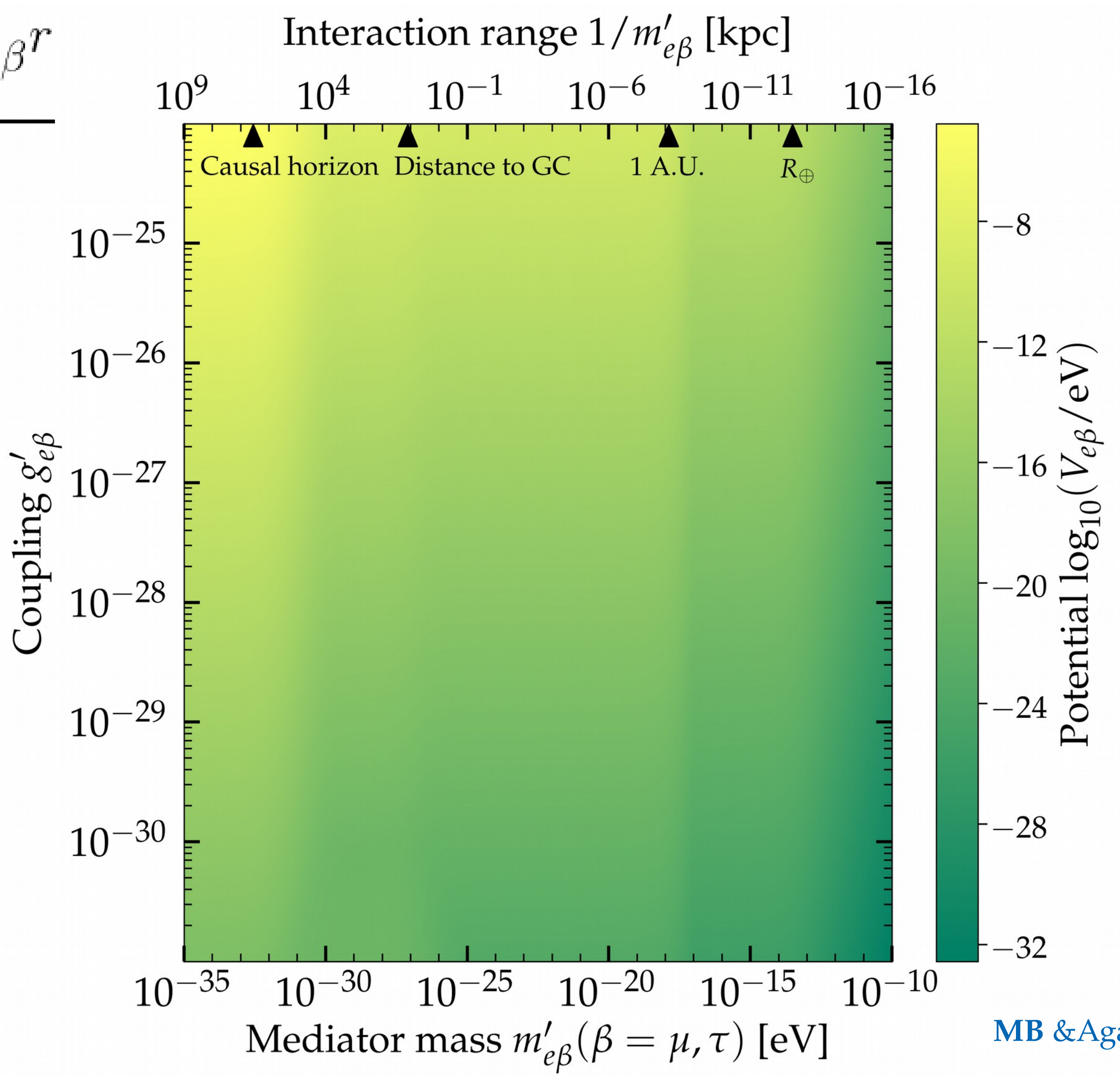
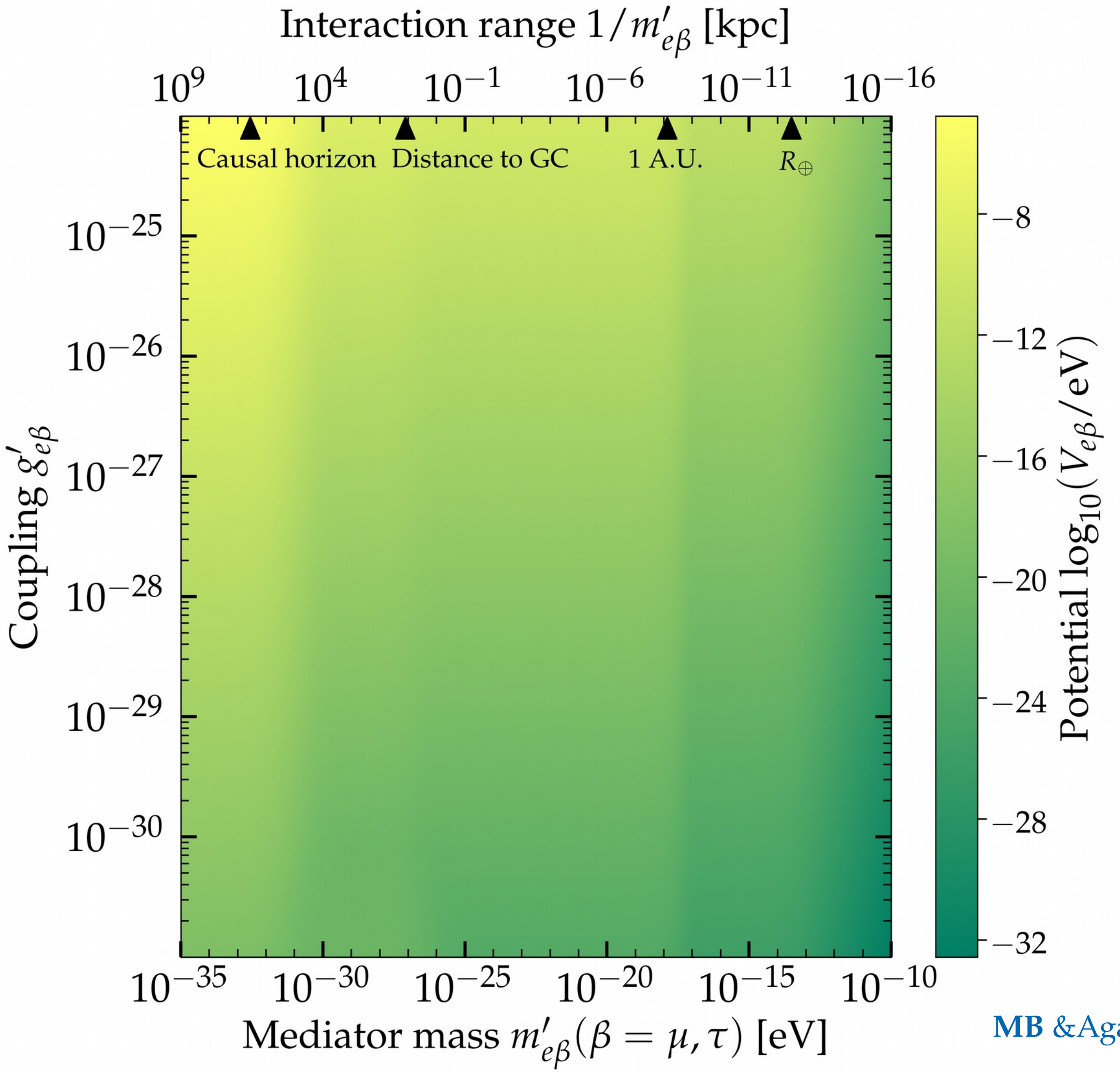



**MB** &Agarwalla, *PRL* 2019

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

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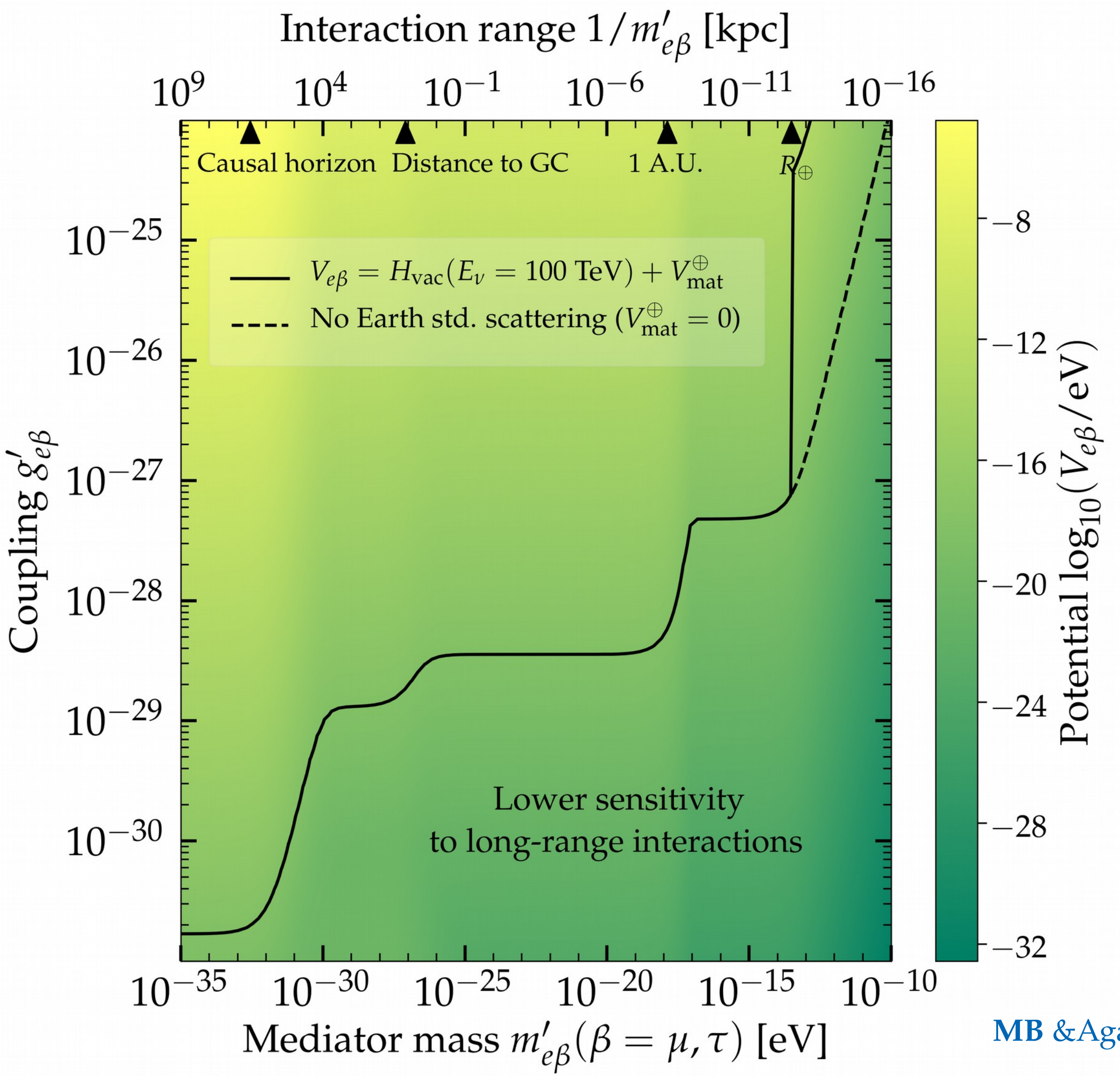


**MB** &Agarwalla, *PRL* 2019

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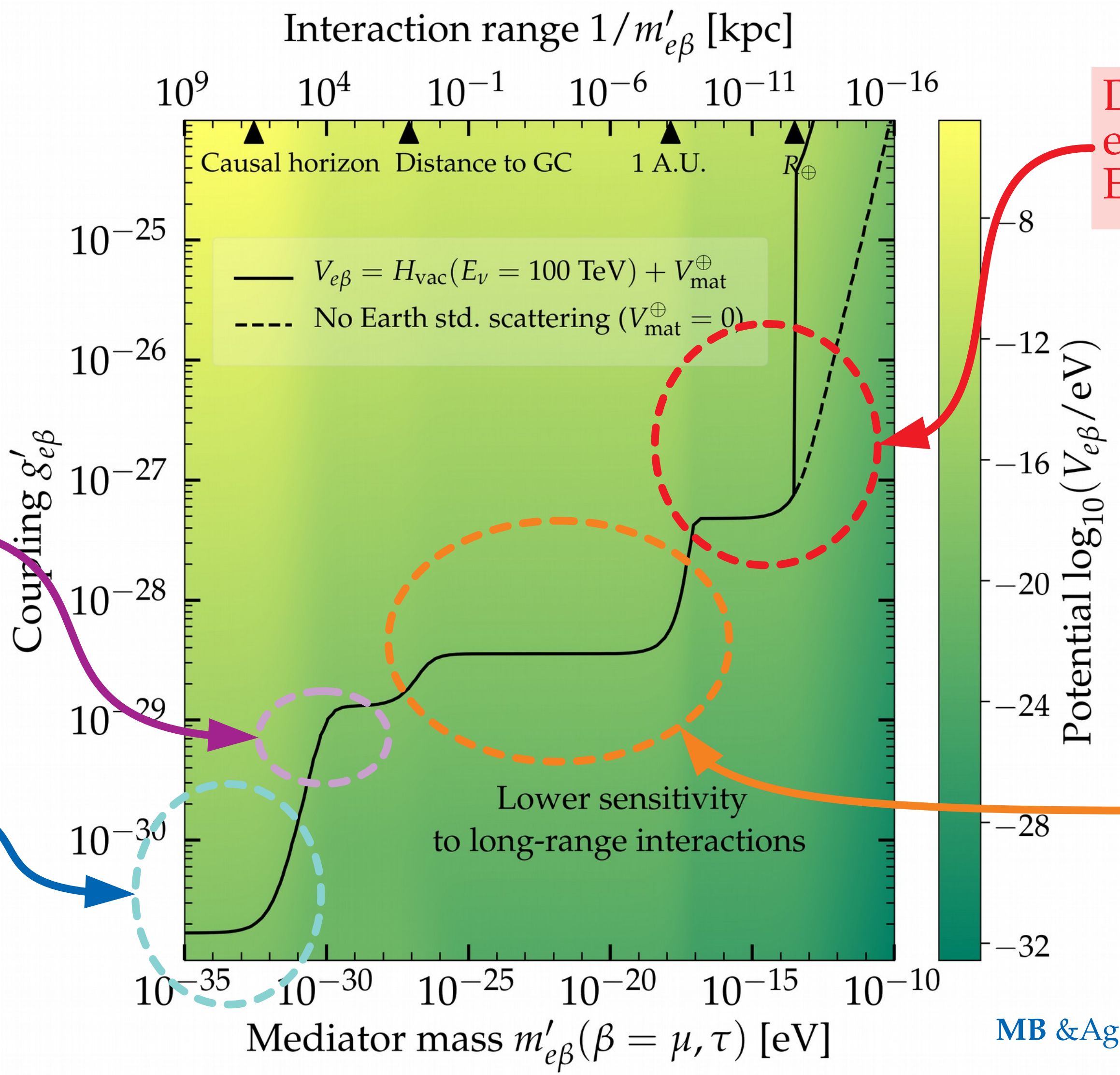
Dominated by Milky-Way *e*

Dominated by cosmological *e*

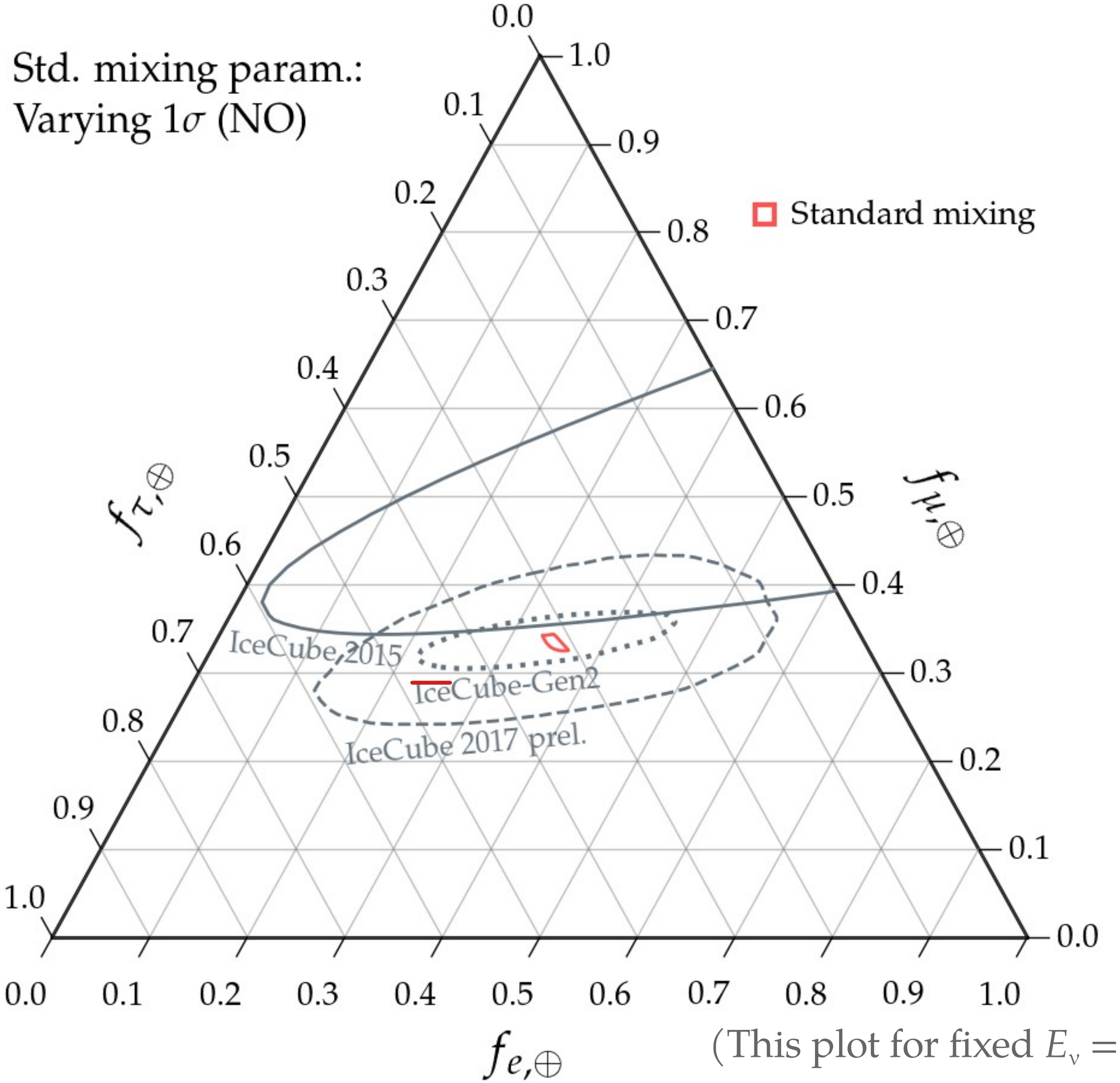



Dominated by electrons in the Earth + Moon

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

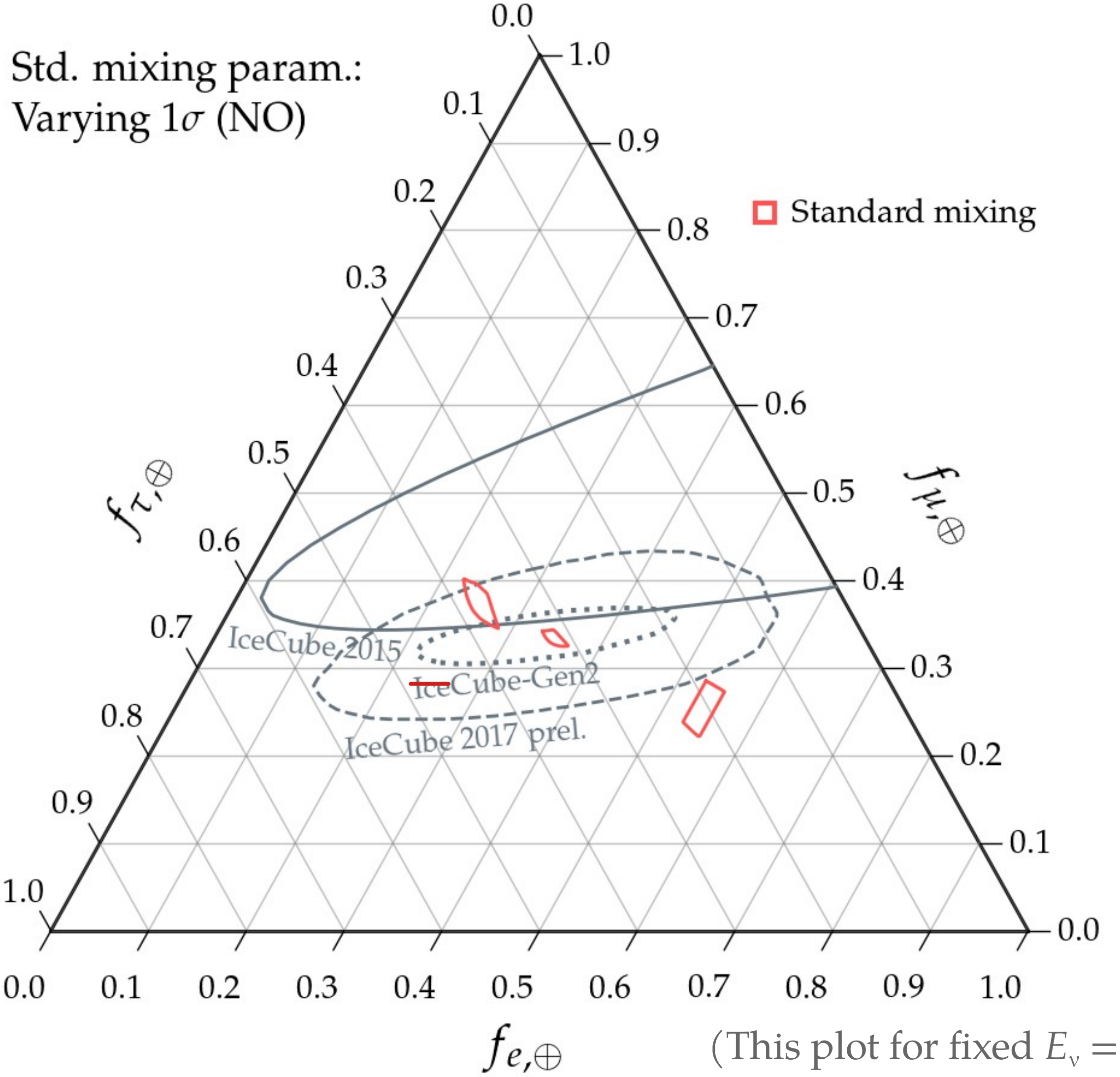
**MB** &Agarwalla, *PRL* 2019

Std. mixing param.:
Varying $1\sigma$ (NO)



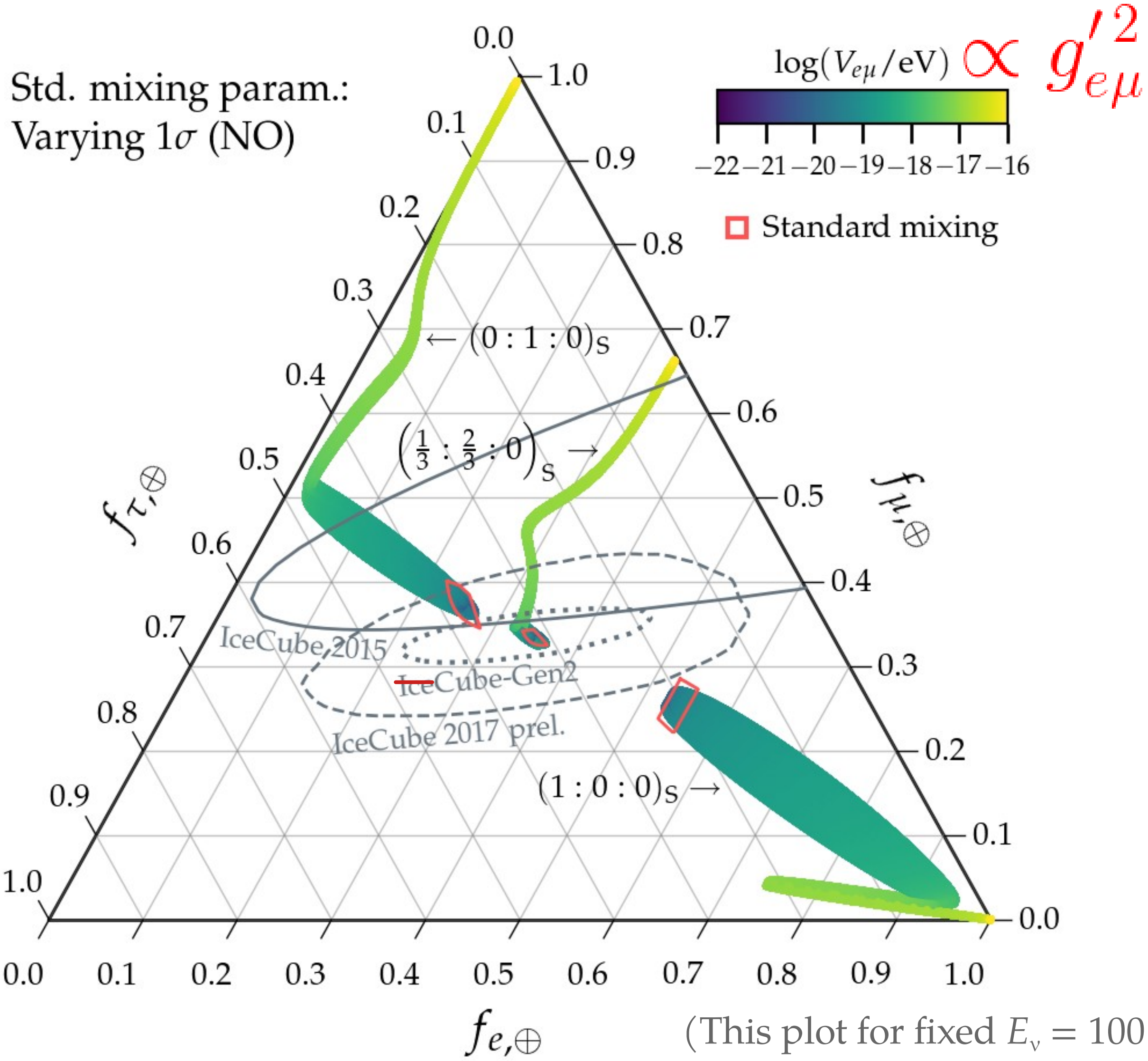

**MB** & Agarwalla, *PRL* 2019

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




**MB** & Agarwalla, *PRL* 2019

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




MB & Agarwalla, *PRL* 2019

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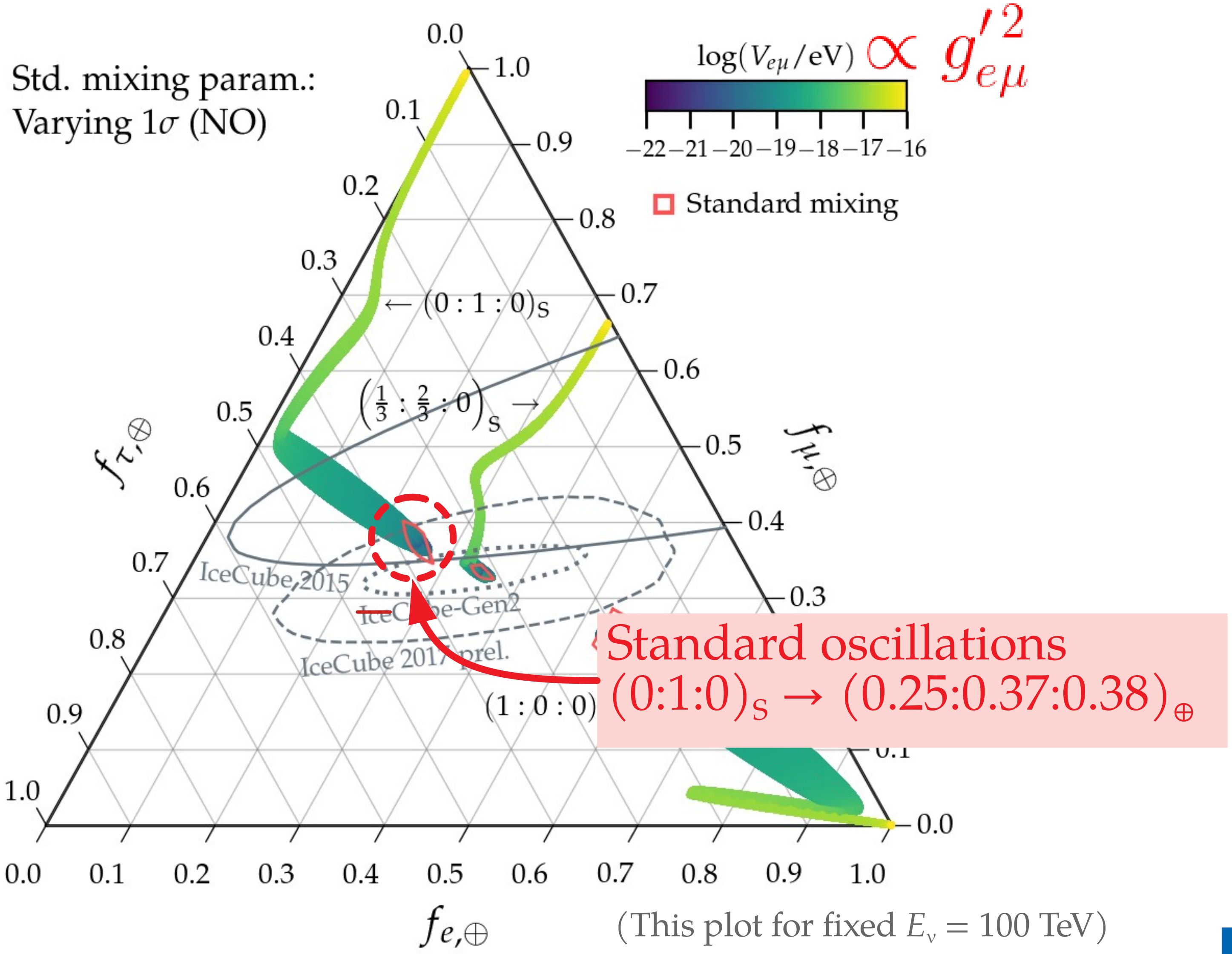


**MB** & Agarwalla, *PRL* 2019

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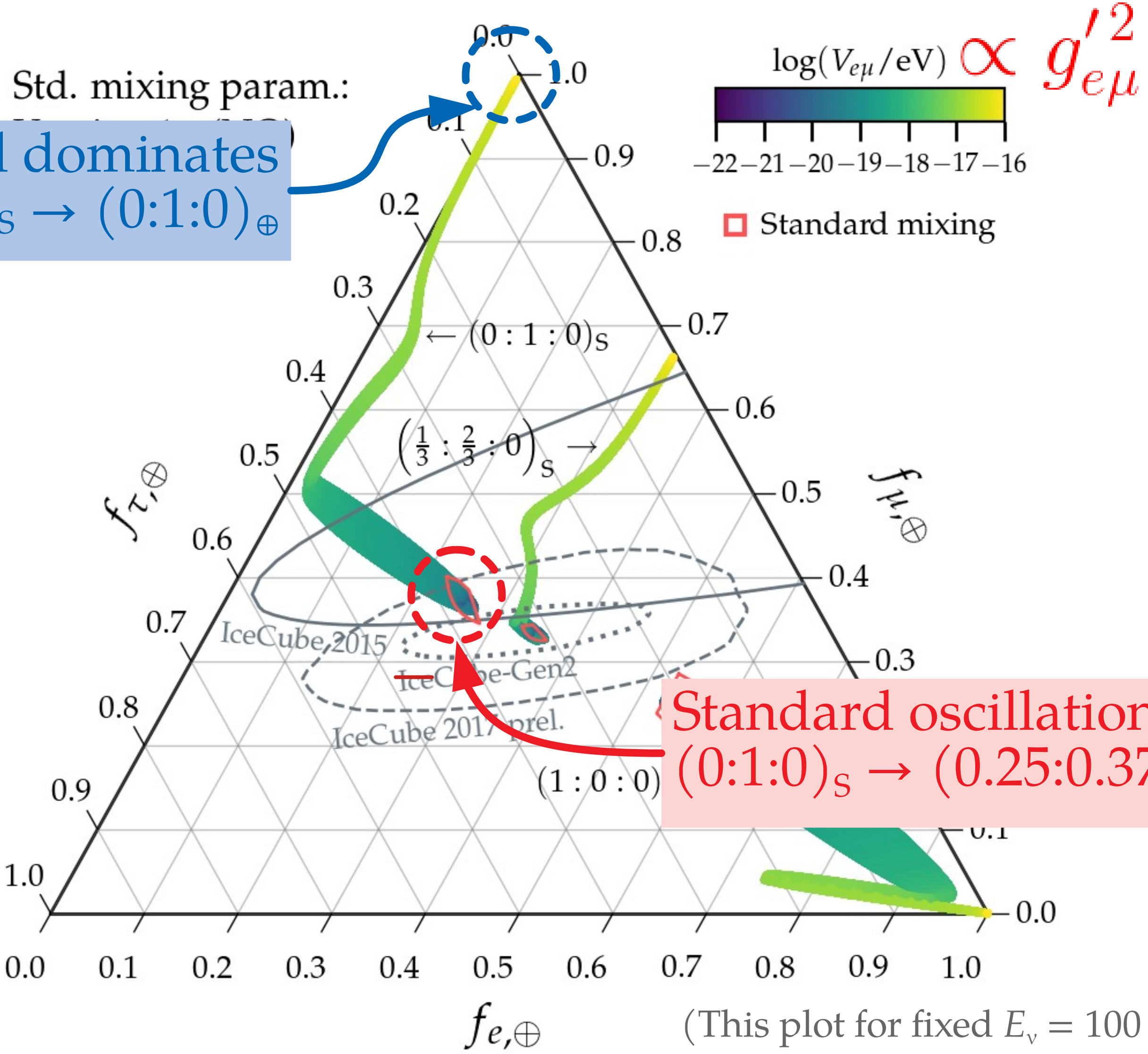



New potential dominates
$(0{:}1{:}0)_S \rightarrow (0{:}1{:}0)_\oplus$

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

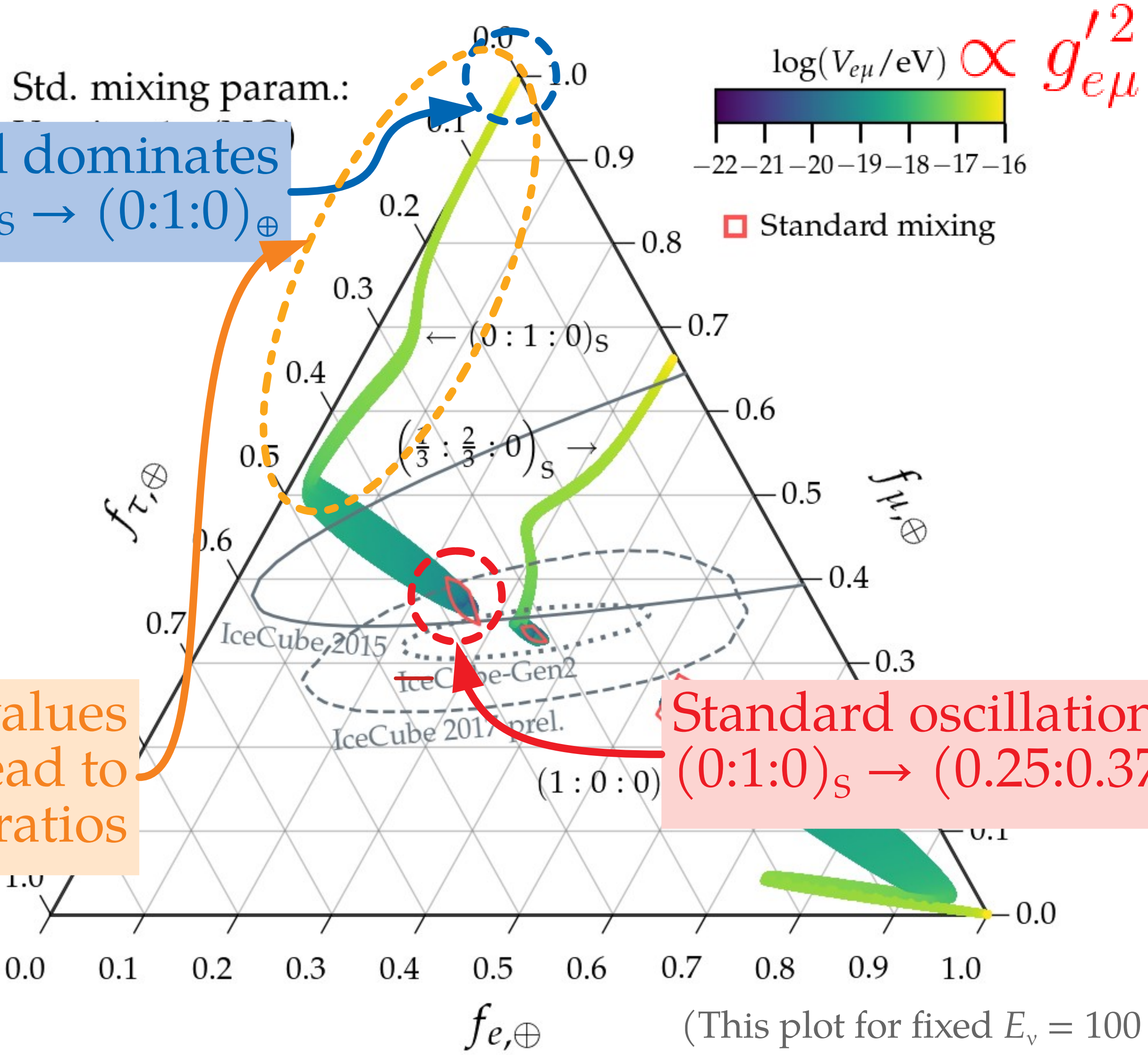
**MB** & Agarwalla, *PRL* 2019

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

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

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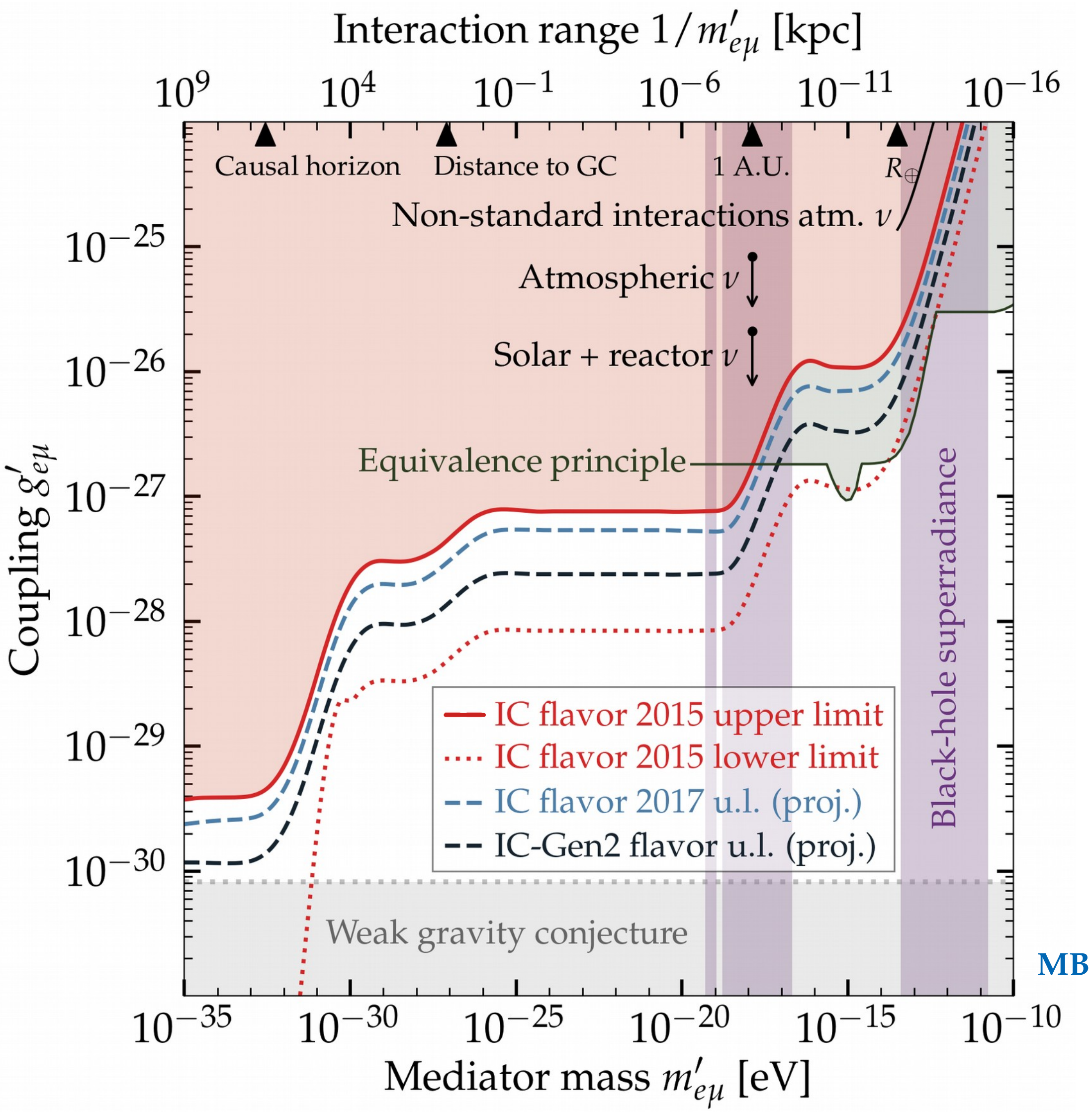
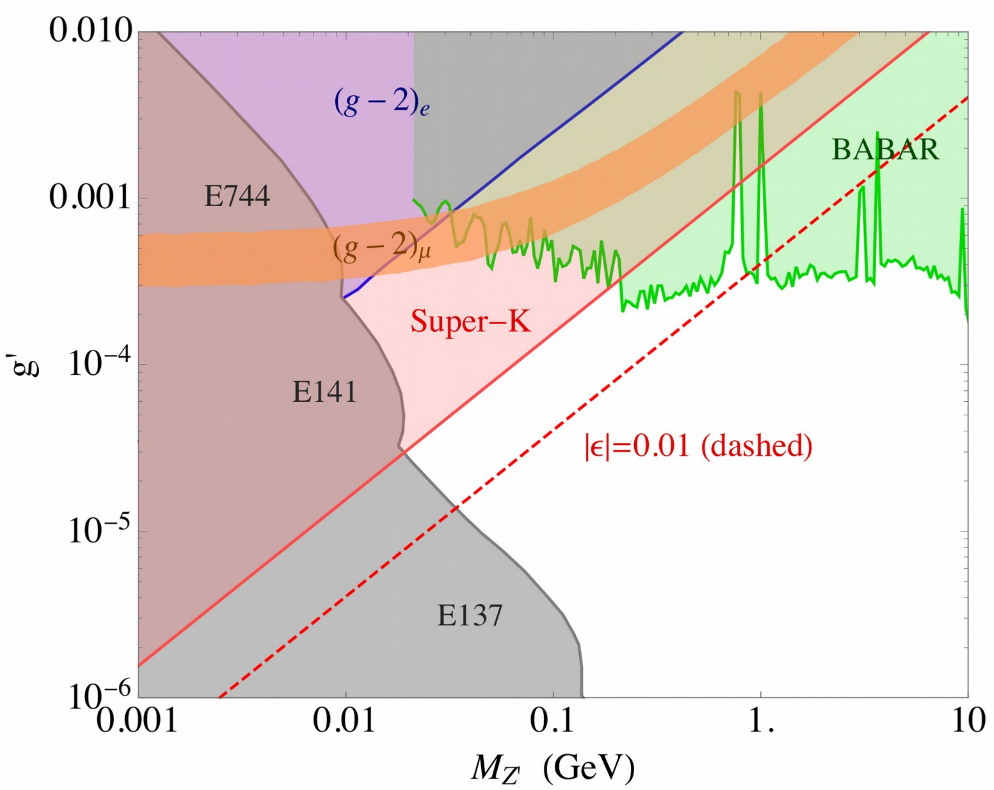
**MB** & Agarwalla, *PRL* 2019



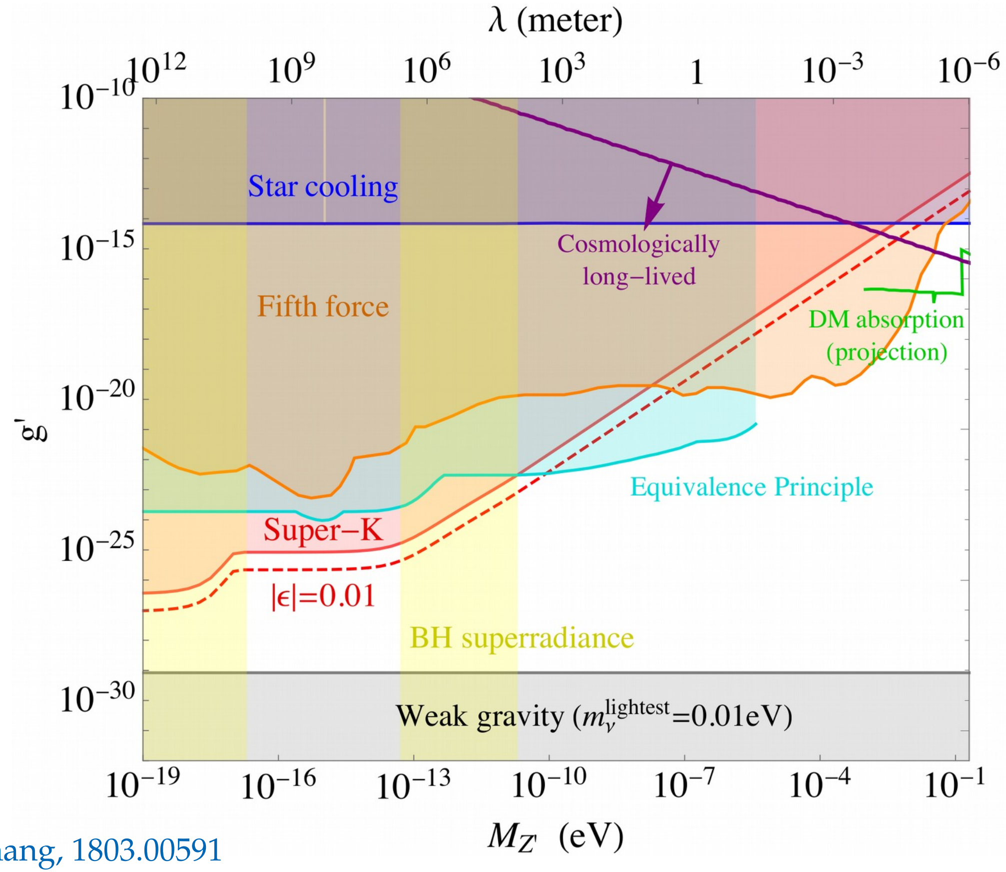

**MB** &Agarwalla, *PRL* 2019

# 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
   ↦ Assume star formation rate

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

Density of cosmological $e$ grows with $z$

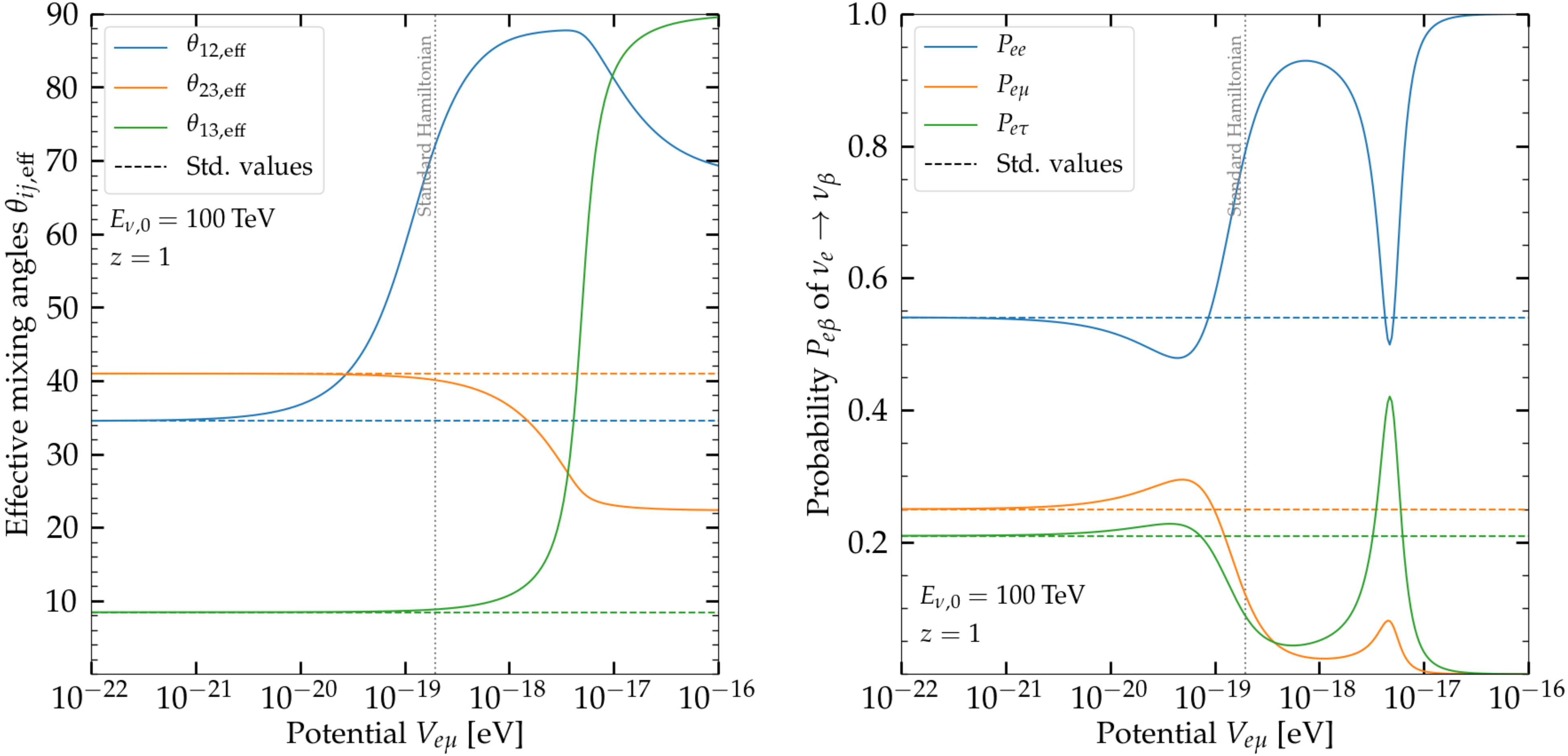
2. Convolve flavor ratios with observed neutrino energy spectrum
   ↦ Either $E^{-2.50}$ (combined analysis) or $E^{-2.13}$ (through-going muons)

$$\langle \Phi_\alpha \rangle \propto \int dE_\nu \, f_{\alpha,\oplus}(E_\nu) \, E_\nu^{-\gamma} \Rightarrow \langle f_{\alpha,\oplus} \rangle \equiv \frac{\langle \Phi_\alpha \rangle}{\sum_{\beta=e,\mu,\tau} \langle \Phi_\beta \rangle}$$

Energy-averaged flux

Energy-averaged flavor ratios

# Resonance due to the $L_e$-$L_\mu$ symmetry



# Resonance due to the $L_e$-$L_\mu$ symmetry (*cont.*)