Pushing Neutrino Physics to the Cosmic Frontier

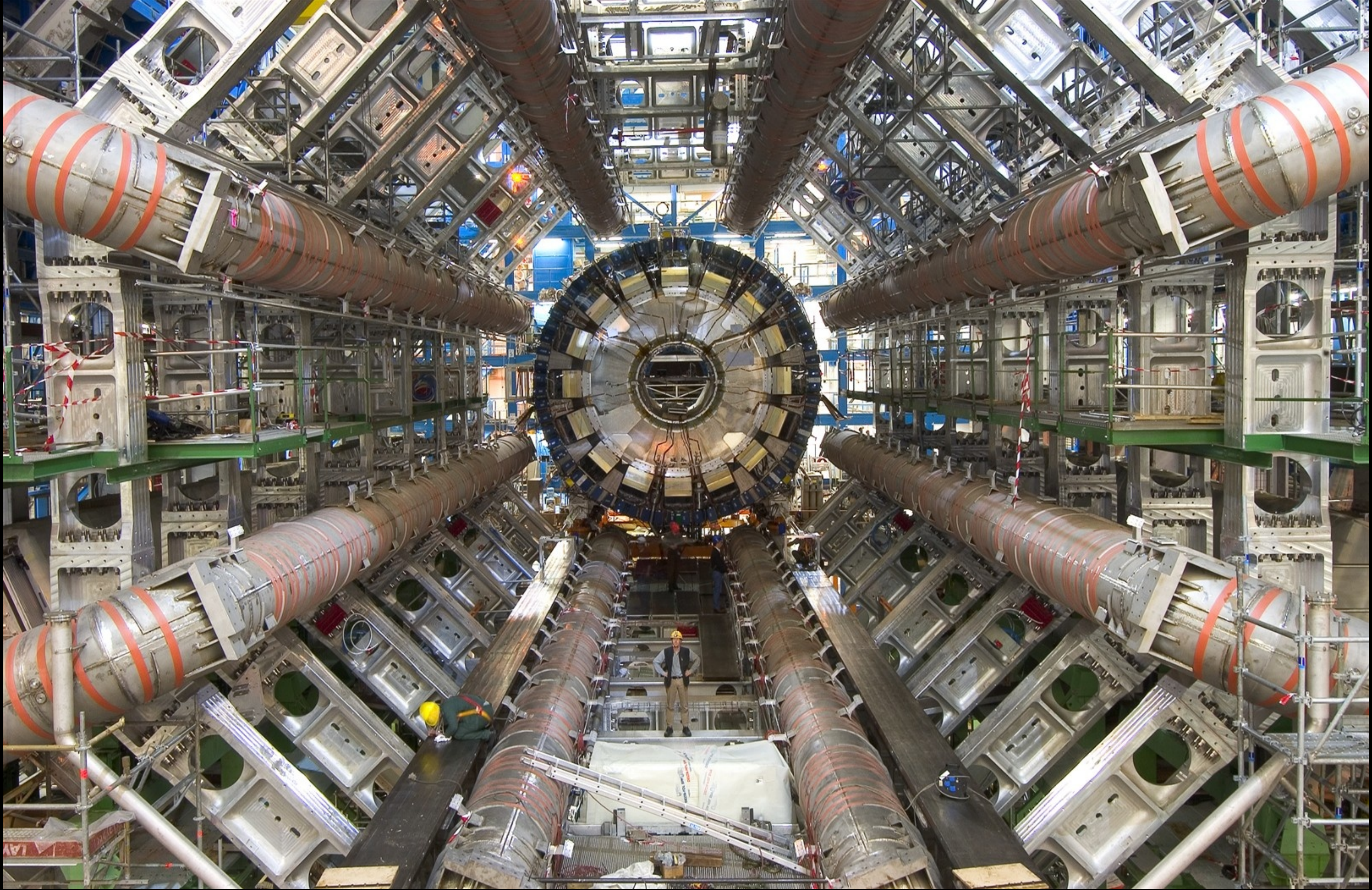
Mauricio Bustamante

Niels Bohr Institute, University of Copenhagen

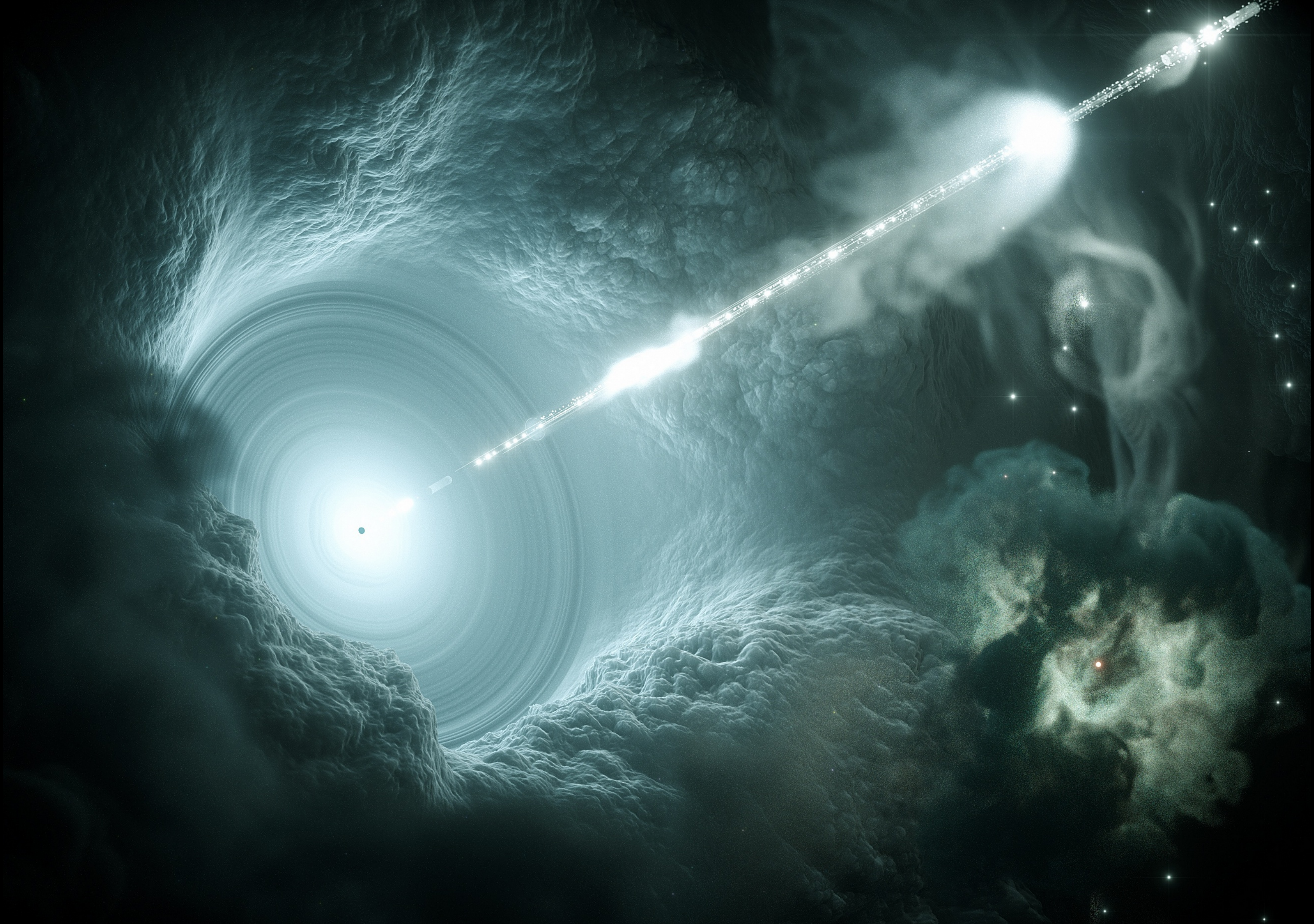
TPCC Seminar, King's College London
June 17, 2020

UNIVERSITY OF COPENHAGEN

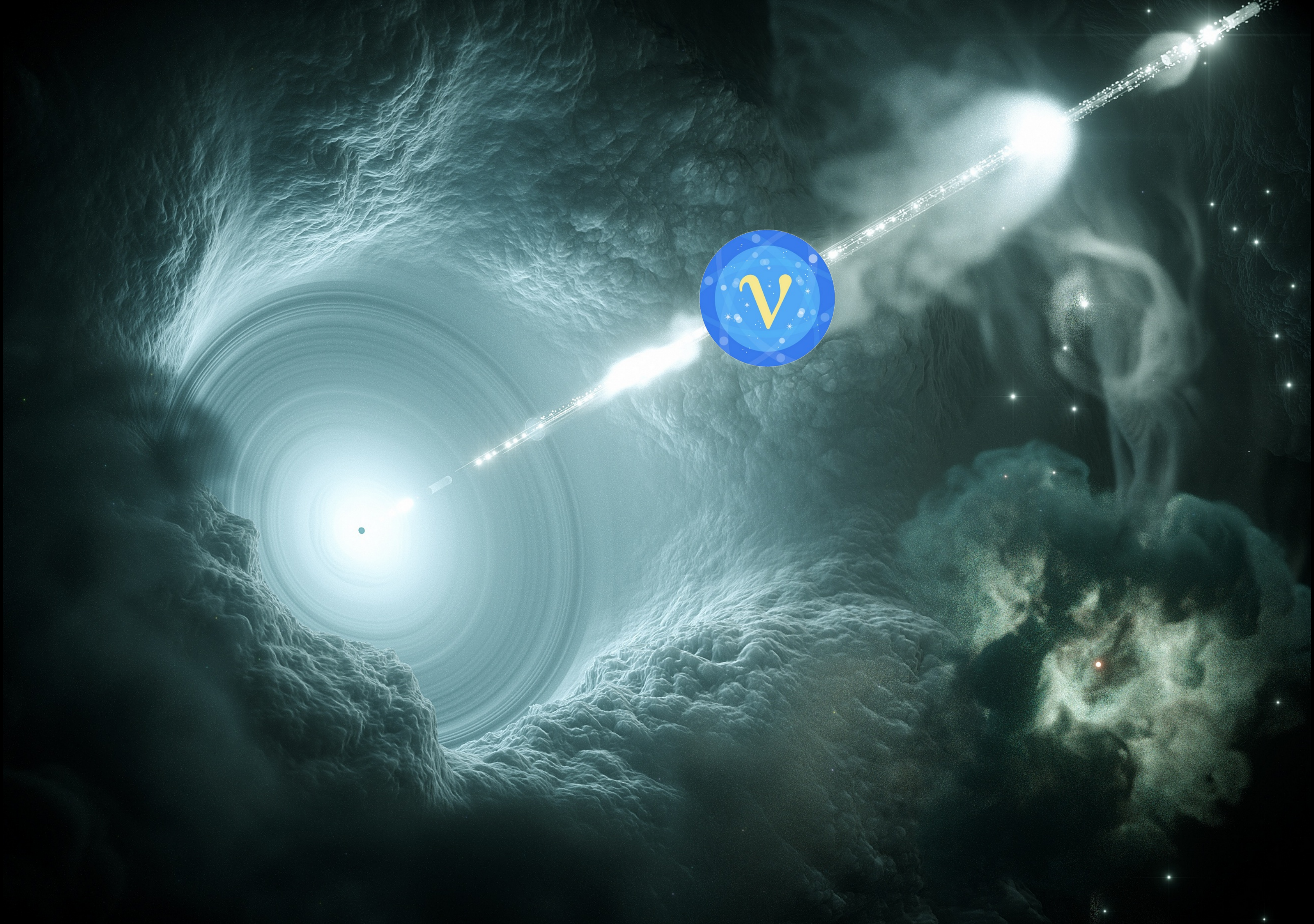
VILLUM FONDEN



ATLAS



DESY



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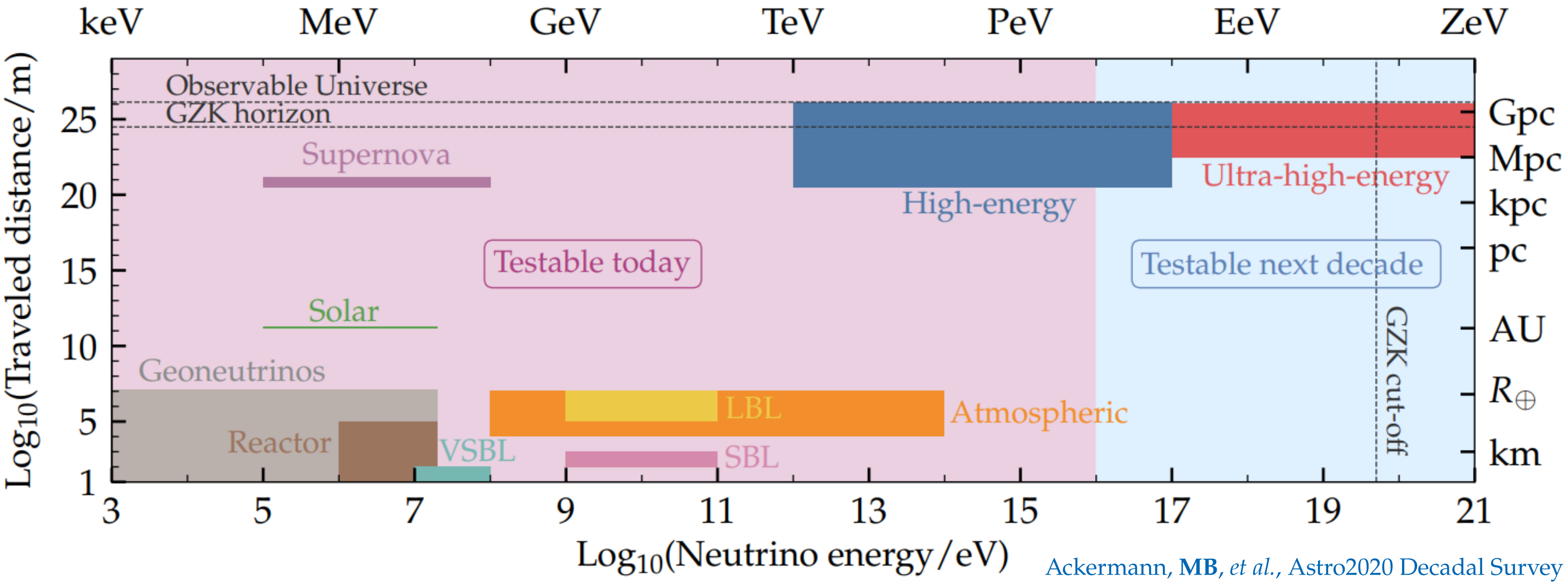

Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333)

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$\mapsto$ New effects may stand out more clearly

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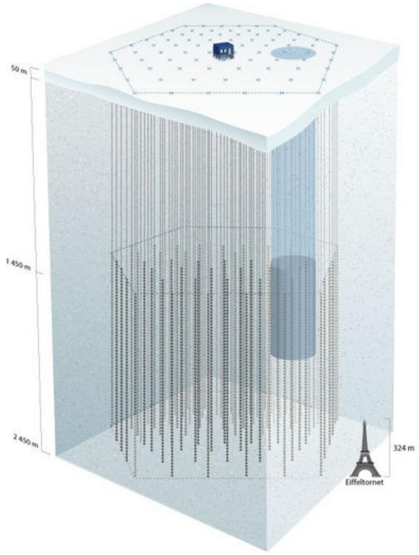
5 It comes *for free*

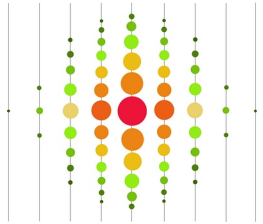
IceCube (8 years)

km^3 in-ice
Cherenkov detector



Showers

(mostly from ν_e, ν_τ)



Tracks

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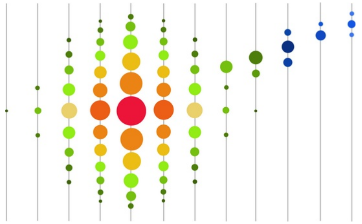
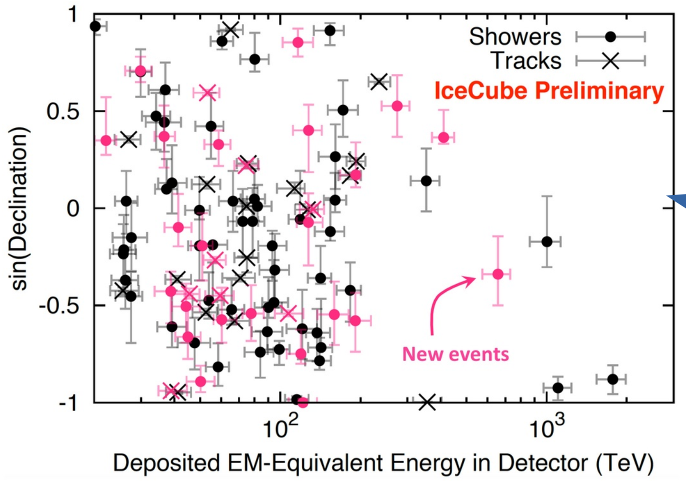


103 contained events, 15 TeV–2 PeV



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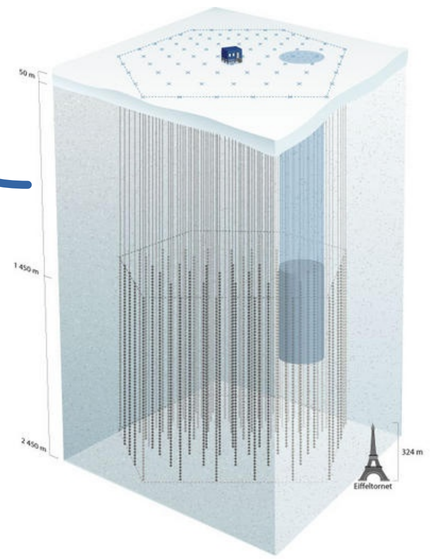

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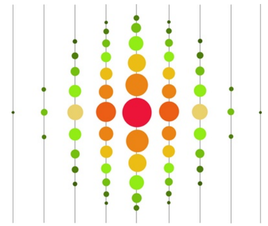

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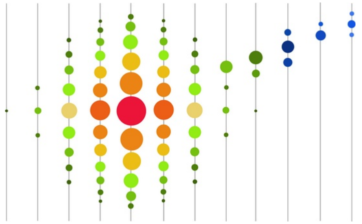

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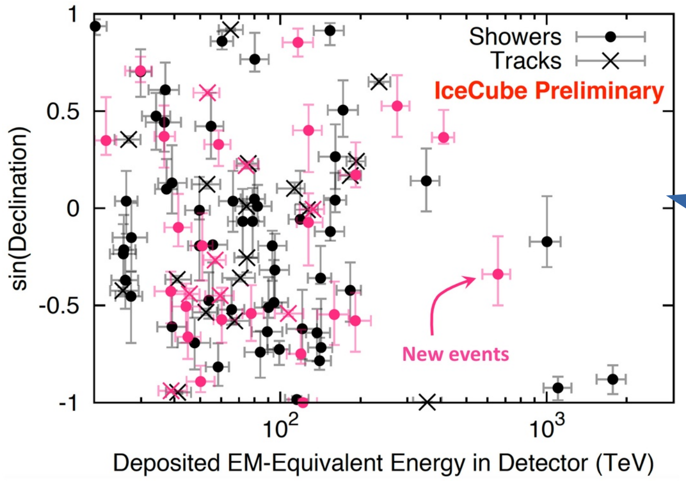

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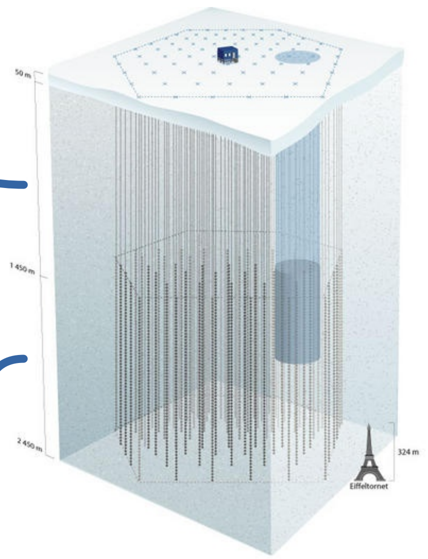
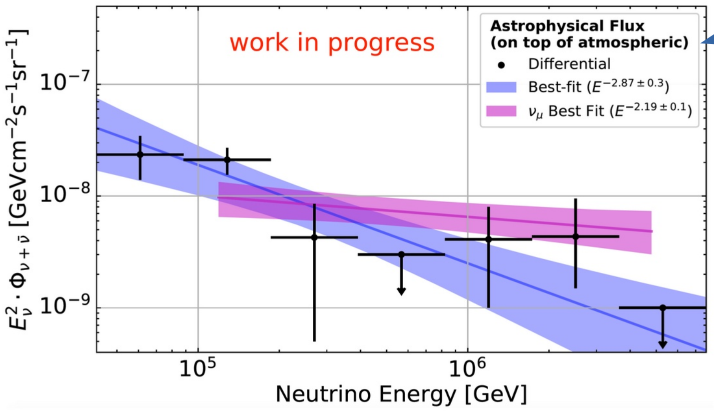


Astrophysical ν flux detected at > 7σ



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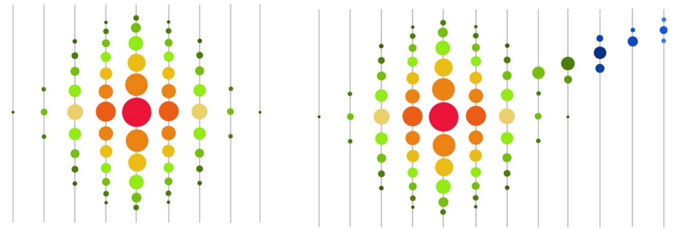

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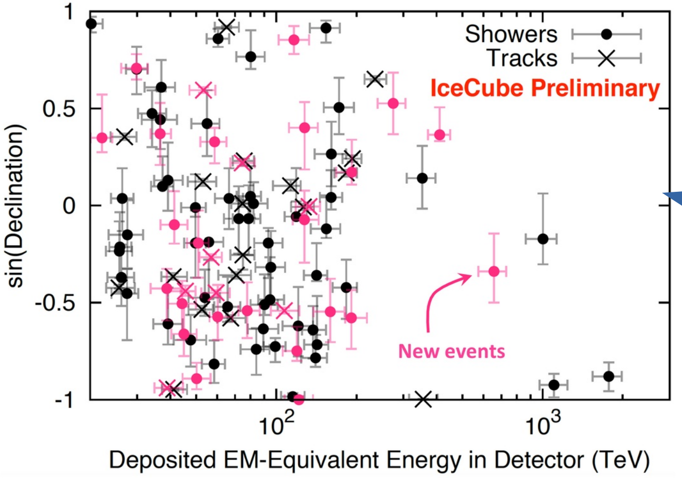

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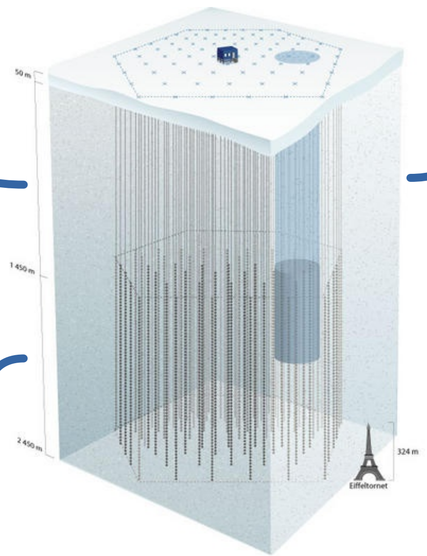
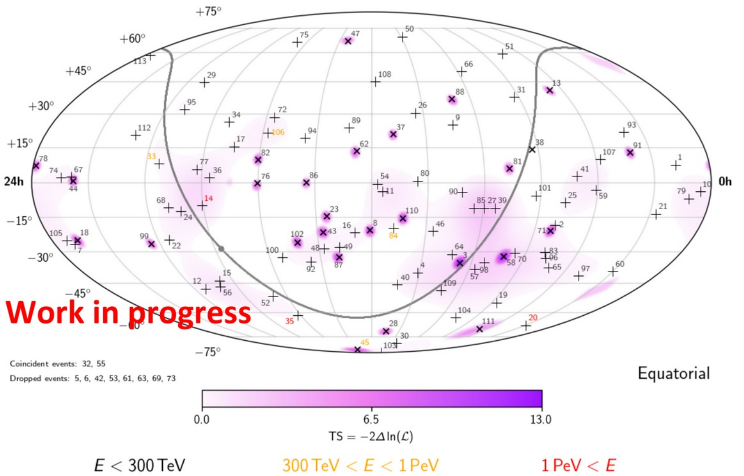


Arrival directions compatible with isotropy



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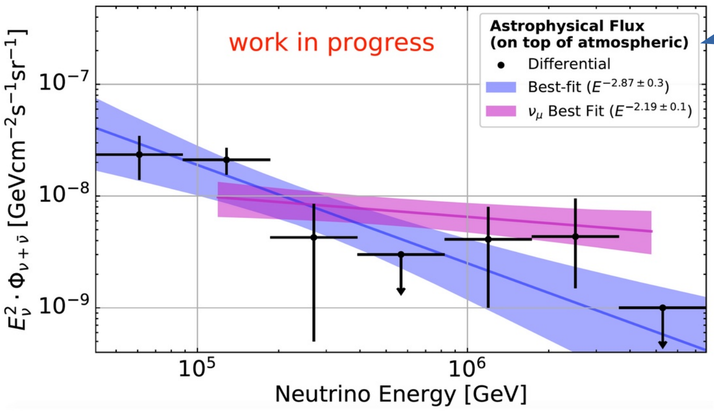

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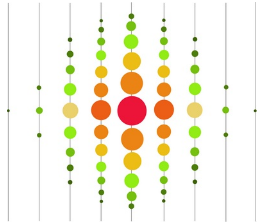

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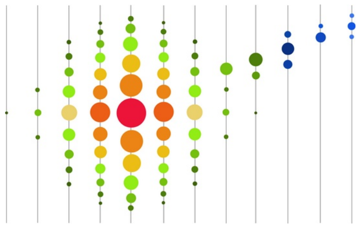

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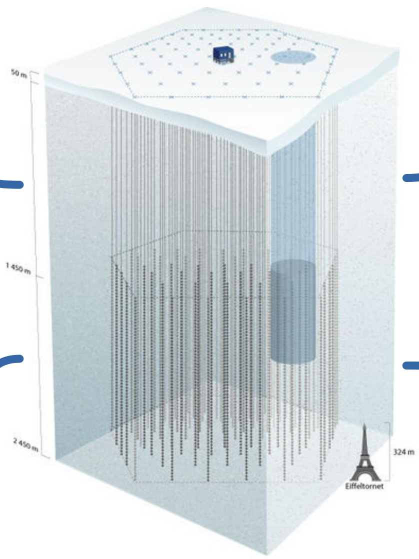

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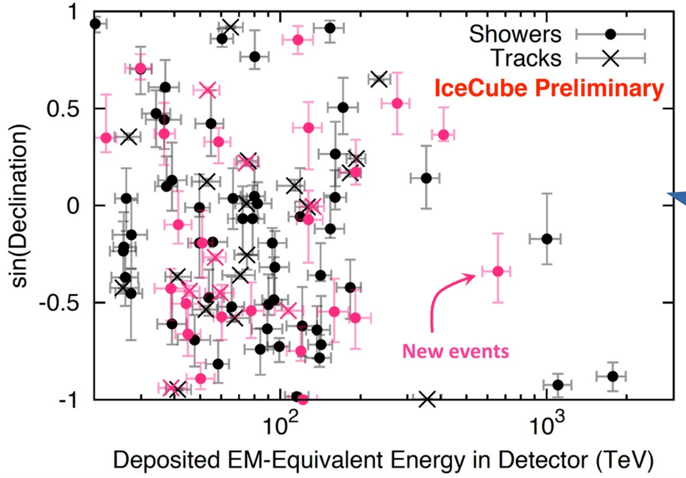

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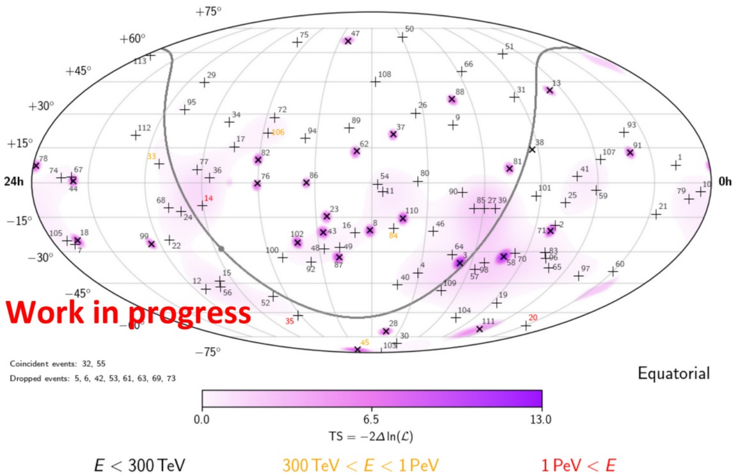

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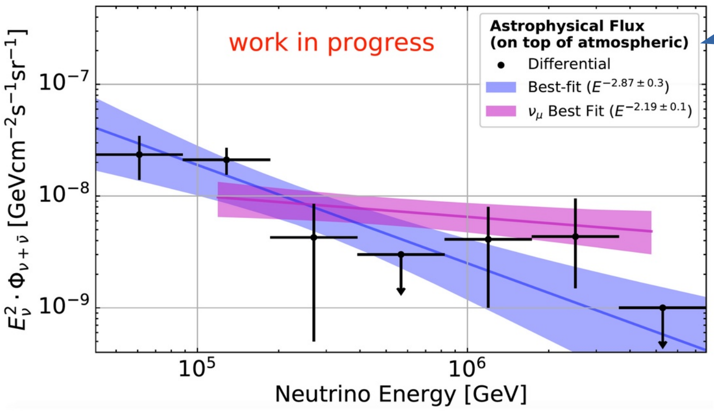

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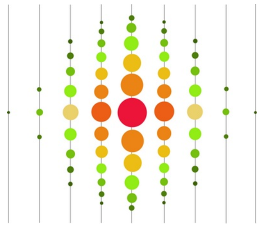

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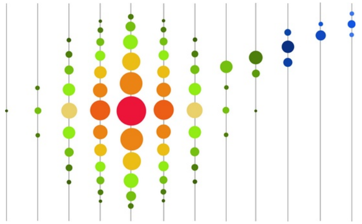
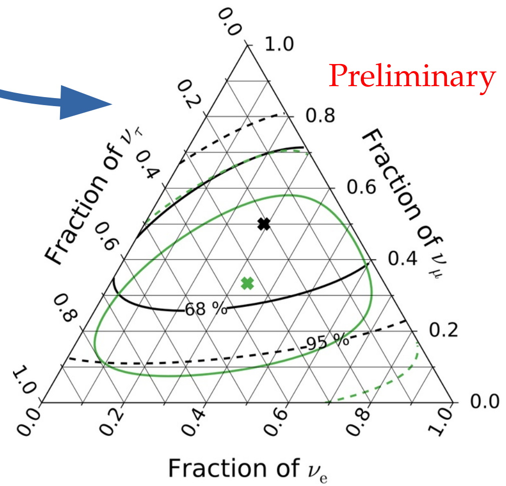


Flavor composition



Status quo of high-energy cosmic neutrinos

What we know

- Isotropic distribution of sources
- Spectrum is a power law $\propto E^{-p}$
- At least some sources are gamma-ray transients
- No correlation between directions of cosmic rays and neutrinos
- Flavor composition: compatible with equal number of ν_e, ν_μ, ν_τ
- No evident new physics

What we don't know

- The sources of the diffuse ν flux
- The ν production mechanism
- The spectral index of the spectrum
- A spectral cut-off at a few PeV?
- Are there Galactic ν sources?
- The precise flavor composition
- Is there new physics?

Status quo of high-energy cosmic neutrinos

But we have solid theory expectations
+ fast experimental progress

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Already today.


Neutrino physicist

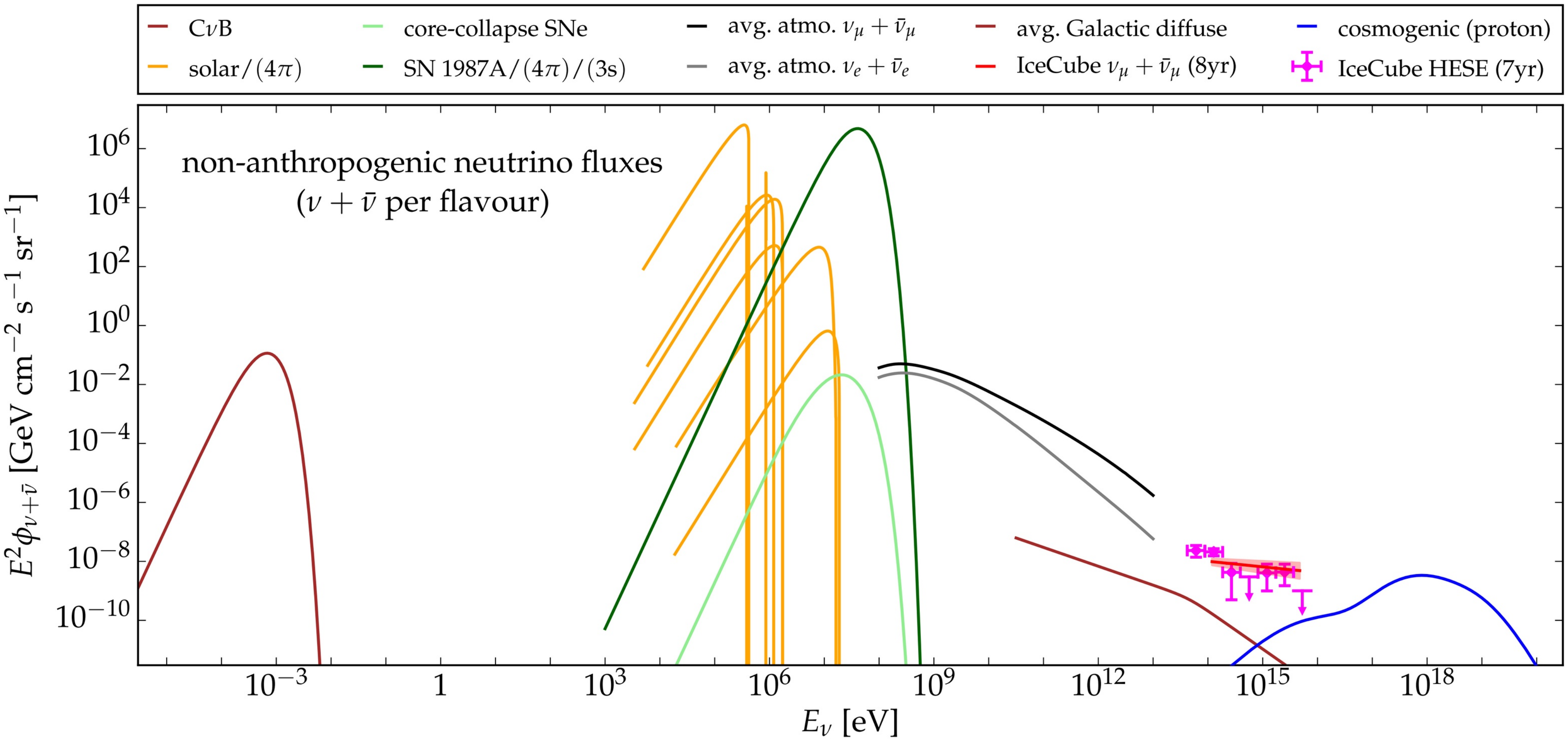
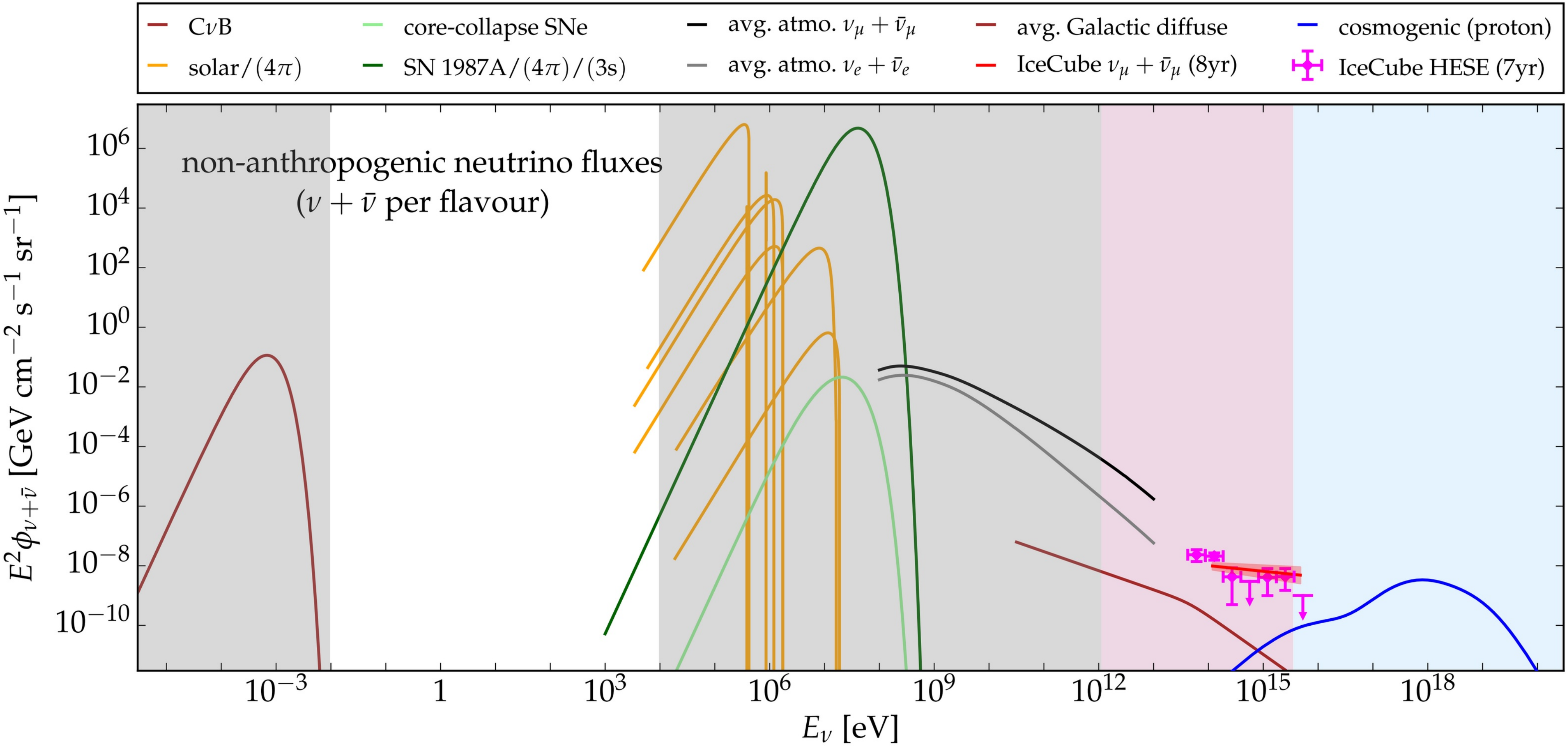


Figure courtesy of Markus Ahlers
Also in: Van Elewyck *et al.*, PoS(ICRC2019), 1023



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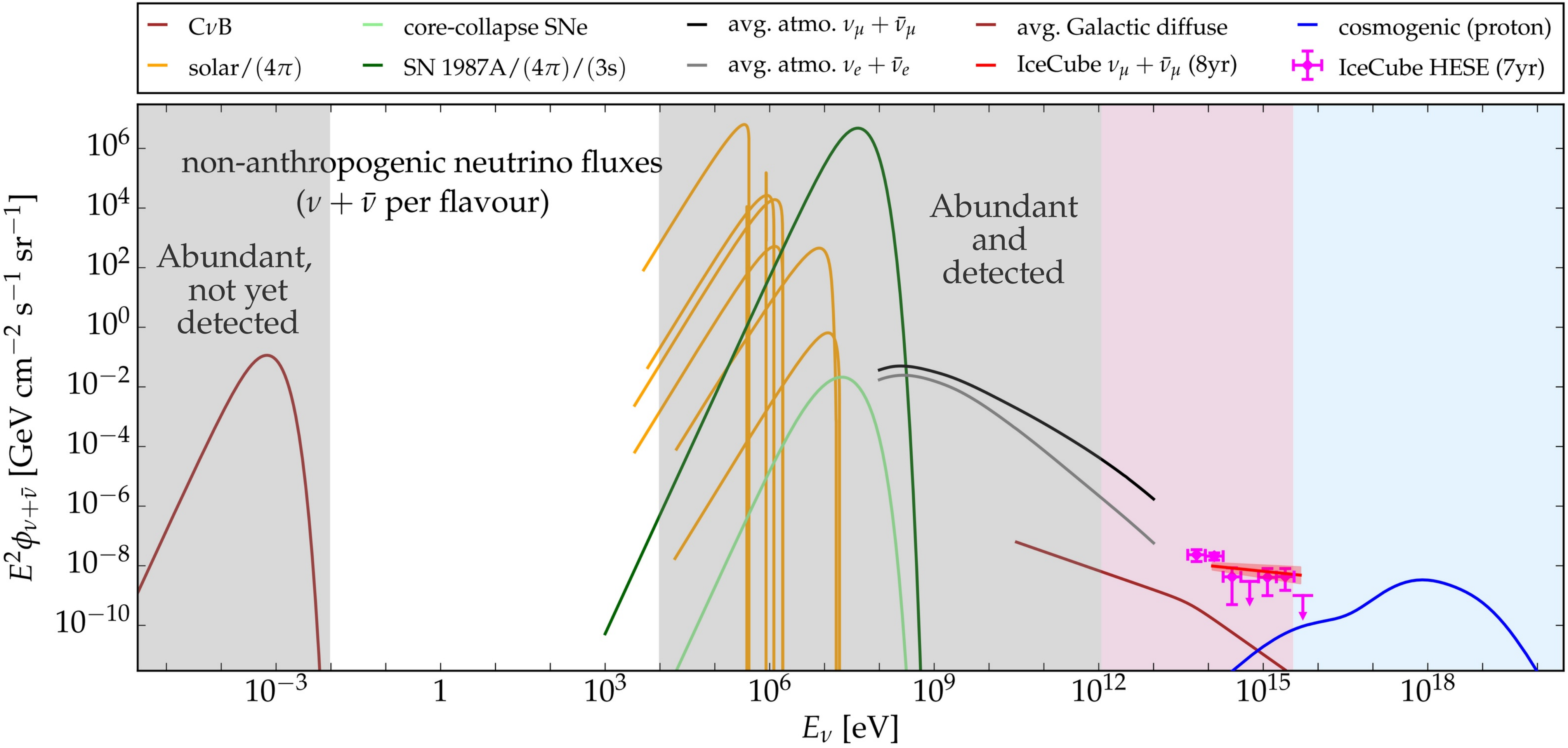

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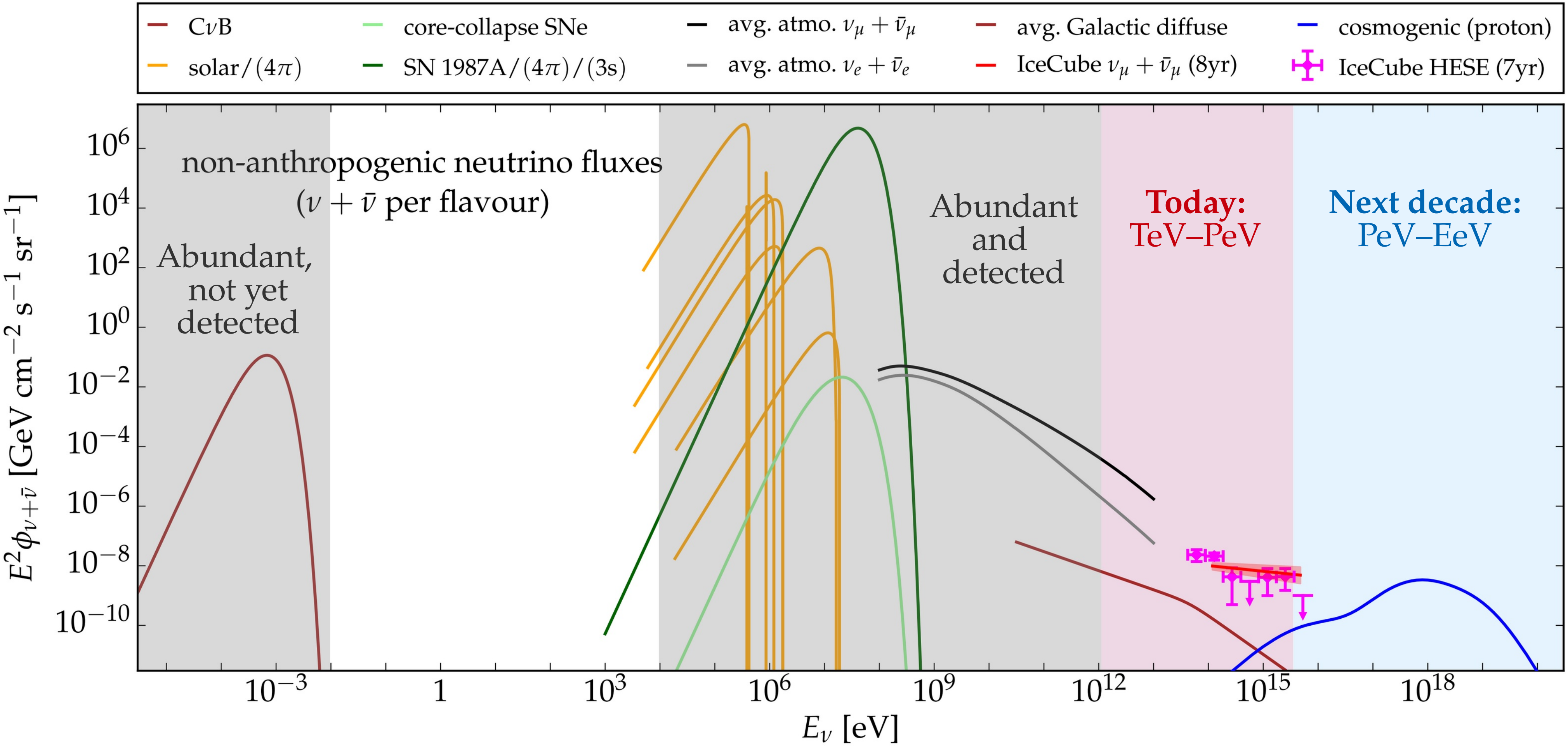

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The multi-messenger connection: a simple picture

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

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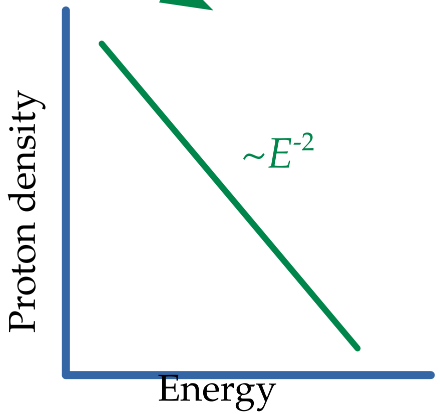

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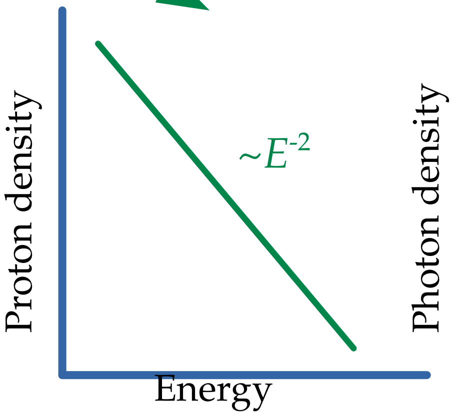

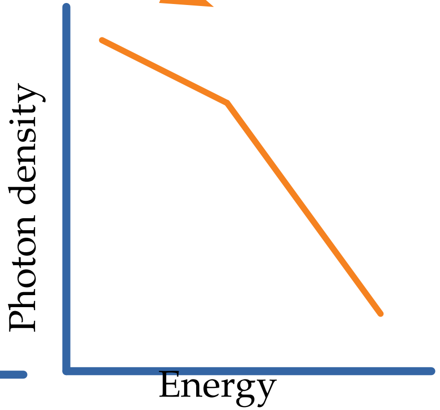

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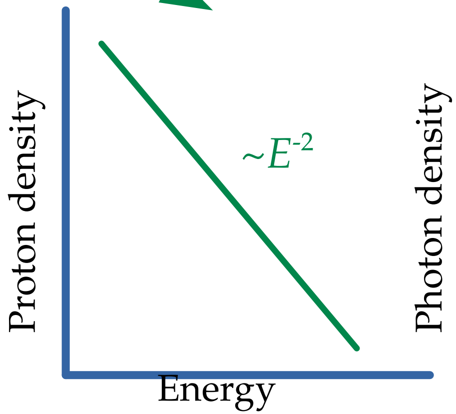
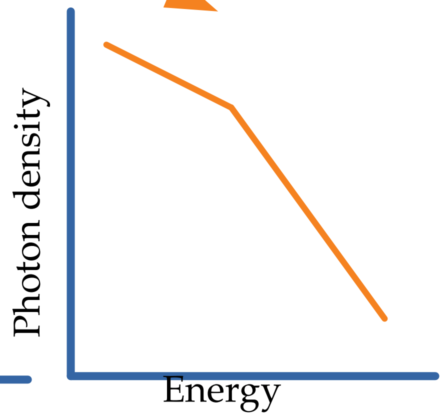
$$n \text{ (escapes)} \rightarrow p + e^{-} + \bar{\nu}_{e}$$





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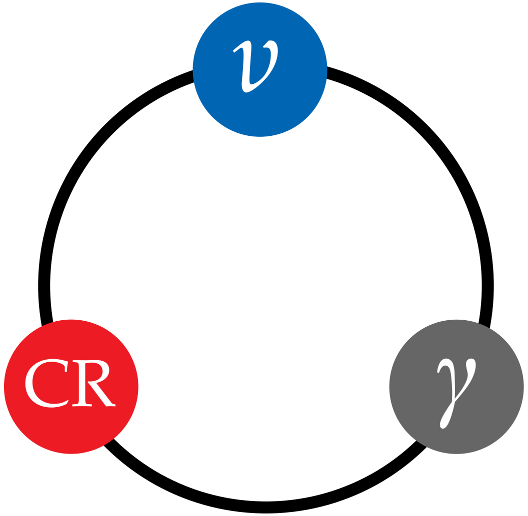

Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 10

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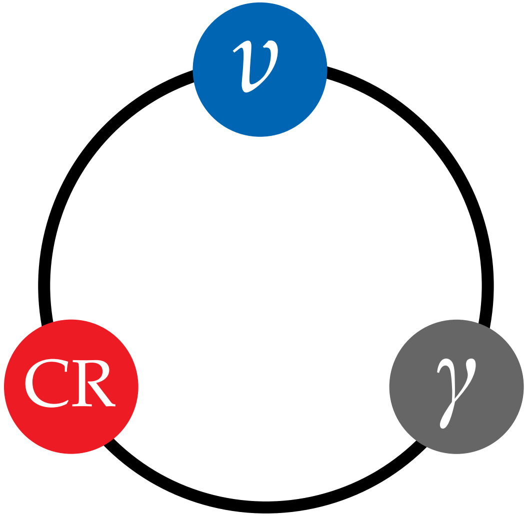

1 PeV 20 PeV

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Fundamental physics with HE cosmic neutrinos

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

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

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

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

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

Note: Not an exhaustive list

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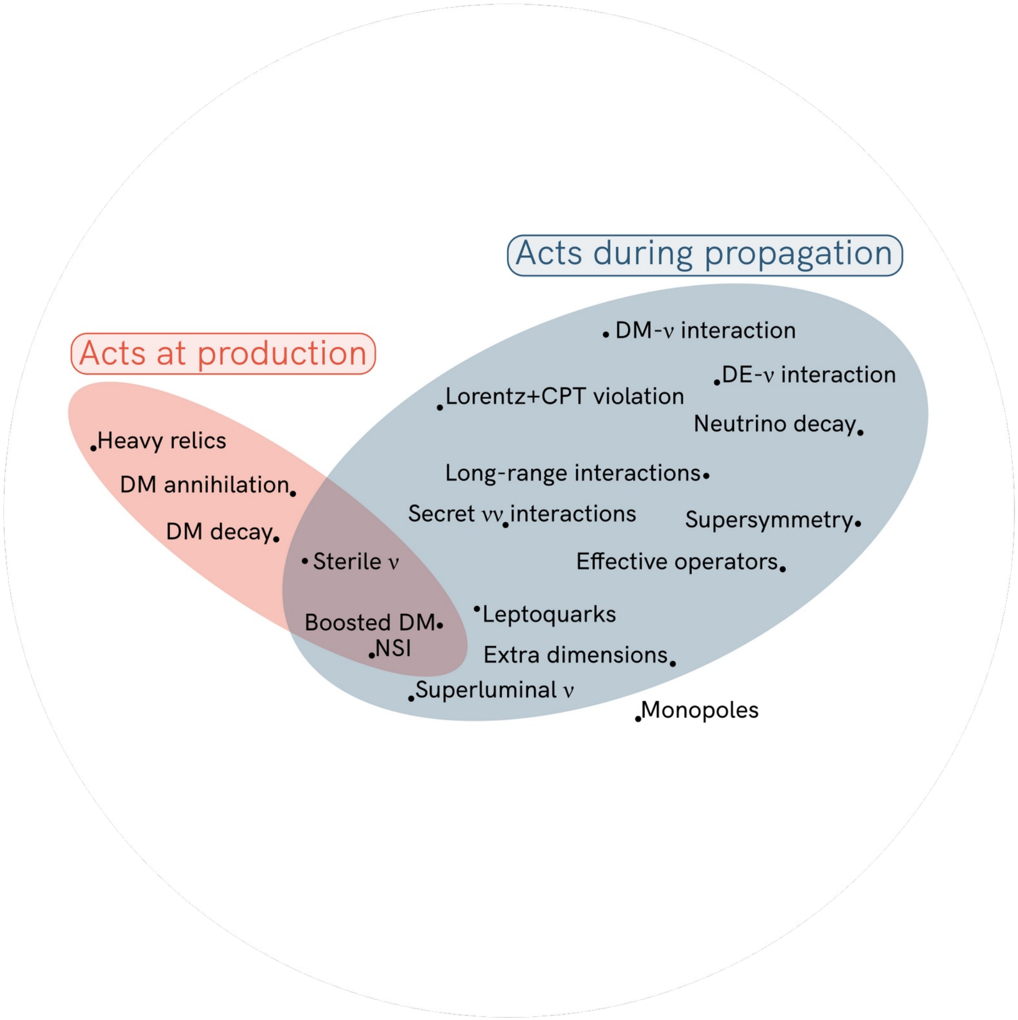

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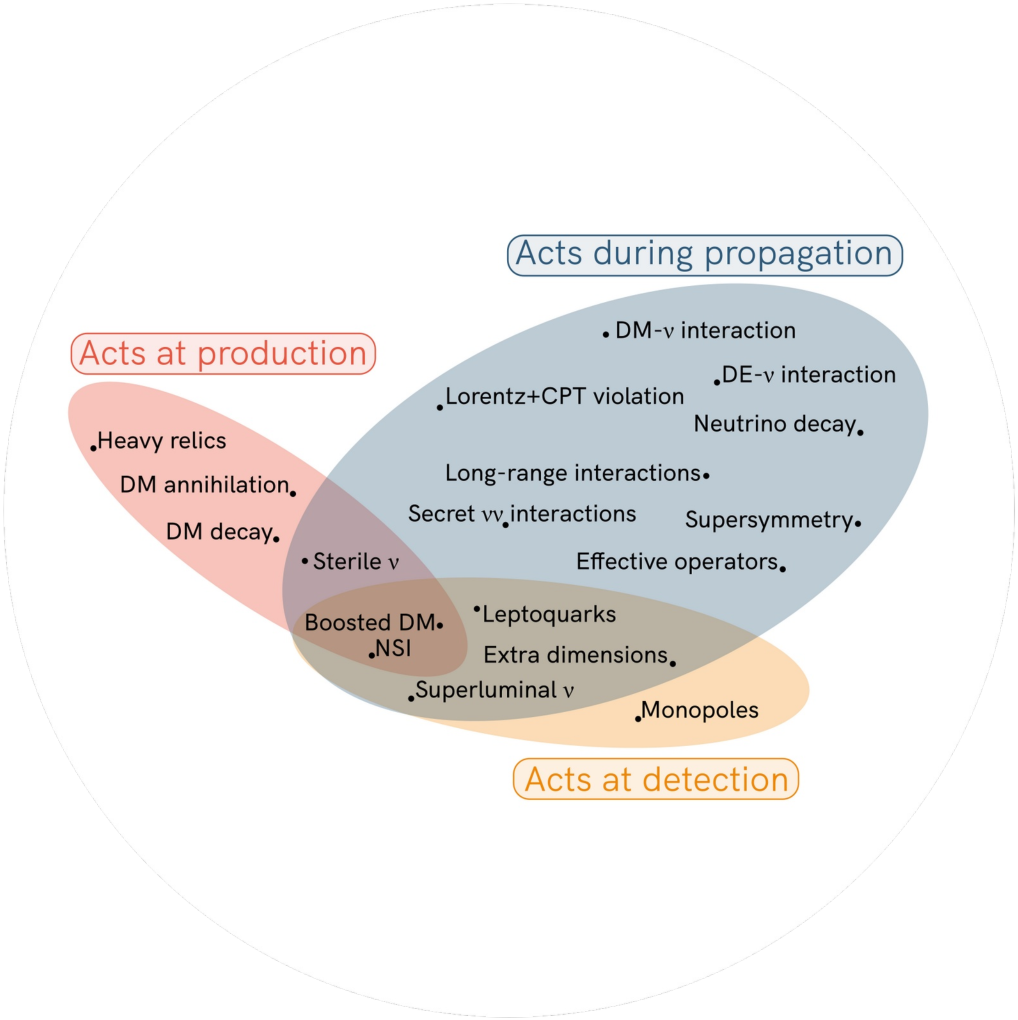

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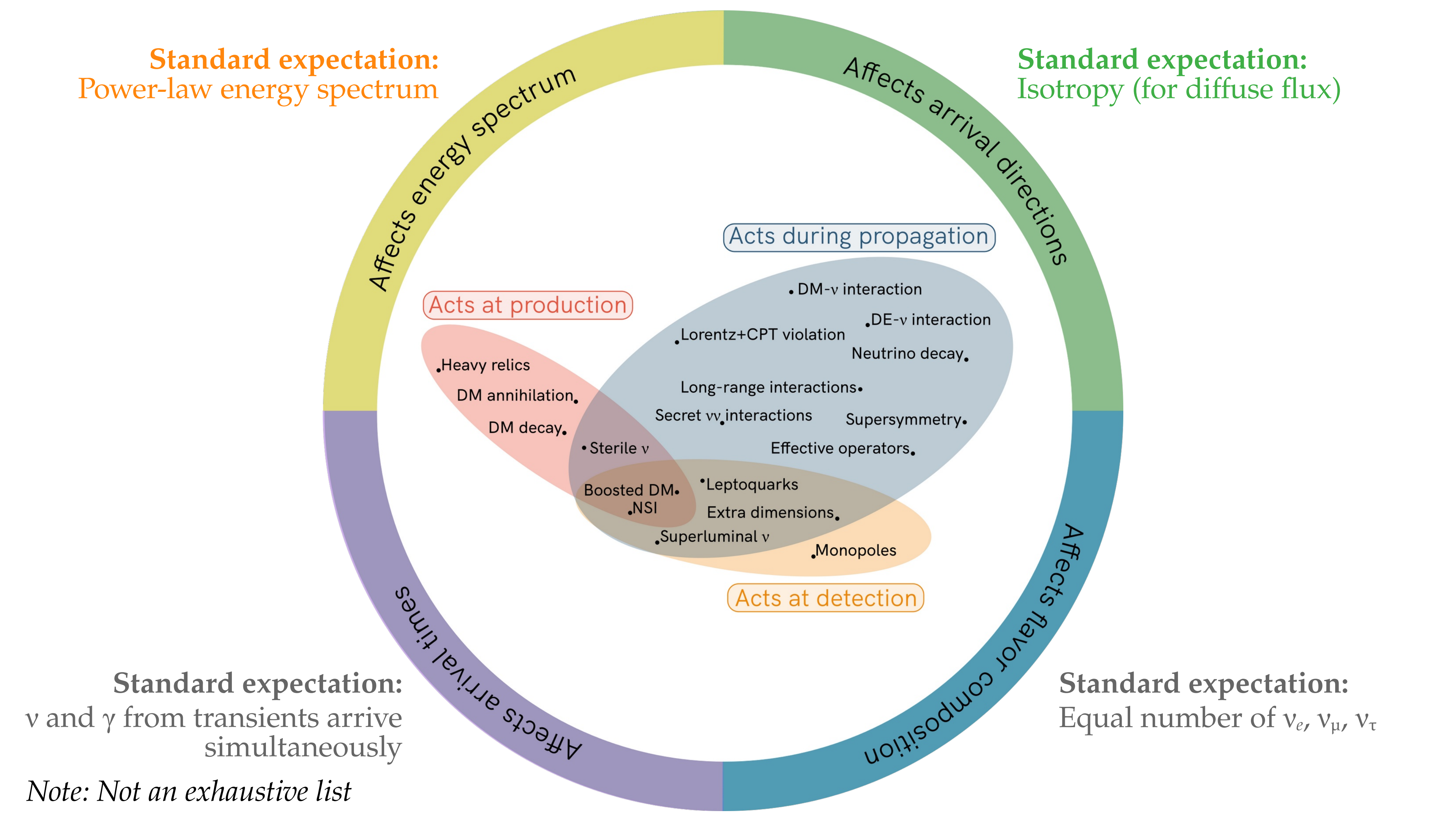

Standard expectation:
Power-law energy spectrum
Standard expectation:
Isotropy (for diffuse flux)
Affects energy spectrum
Affects arrival directions
Affects flavor composition
Affects arrival times
Acts during propagation
Acts at production
Acts at detection
DM-ν interaction
DE-ν interaction
Lorentz+CPT violation
Neutrino decay
Heavy relics
DM annihilation
DM decay
Long-range interactions
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ν and γ from transients arrive simultaneously
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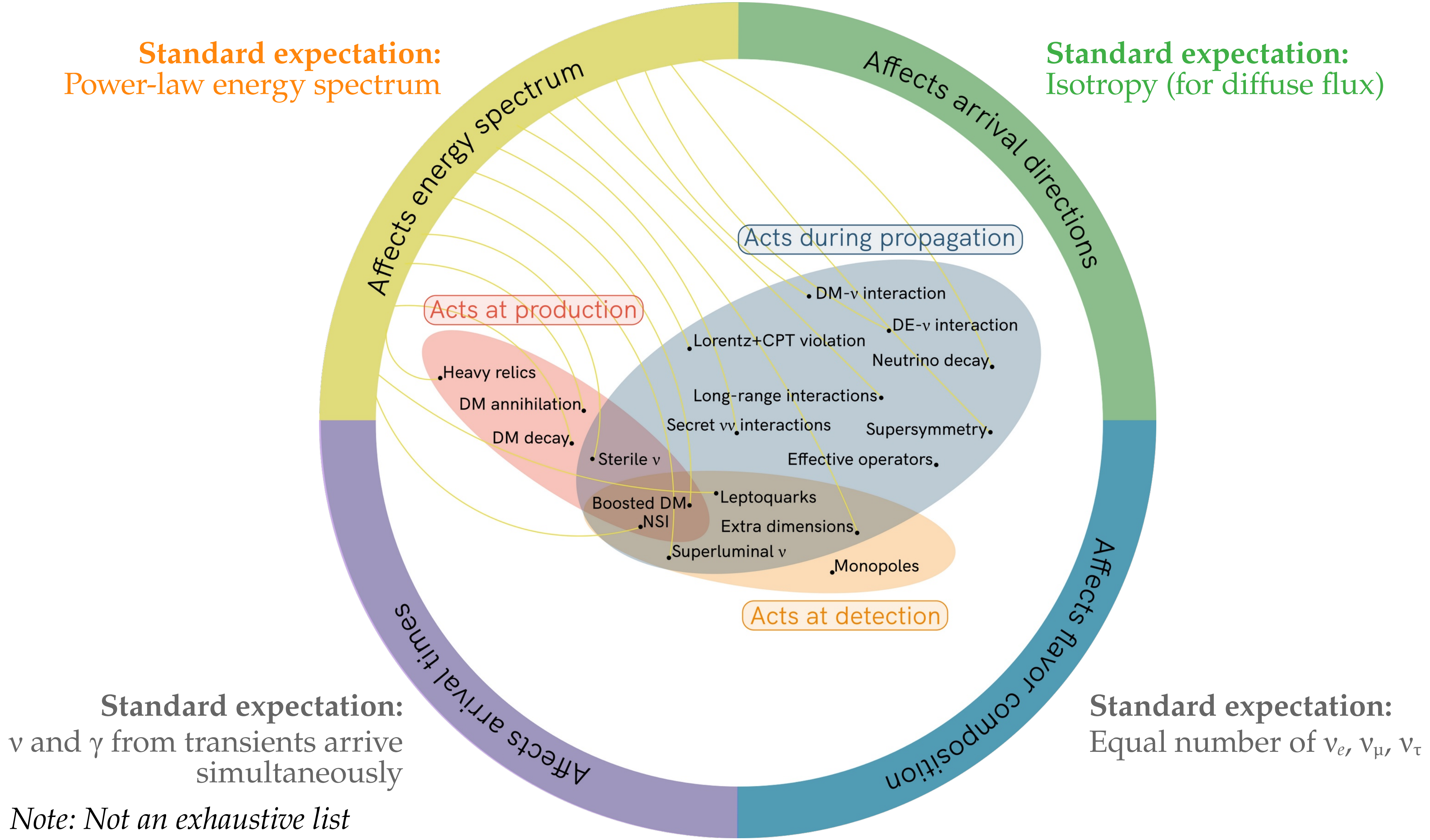
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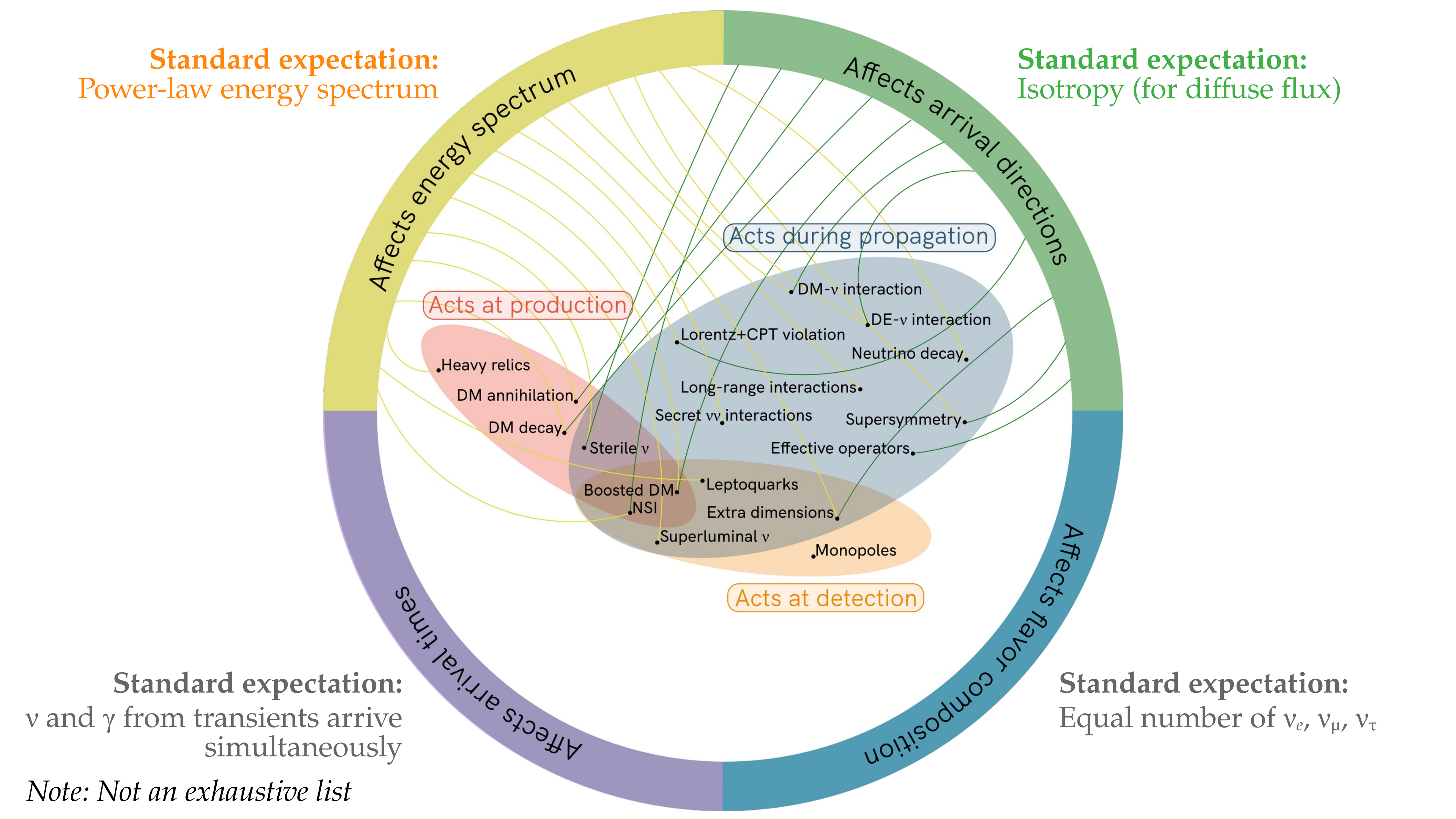

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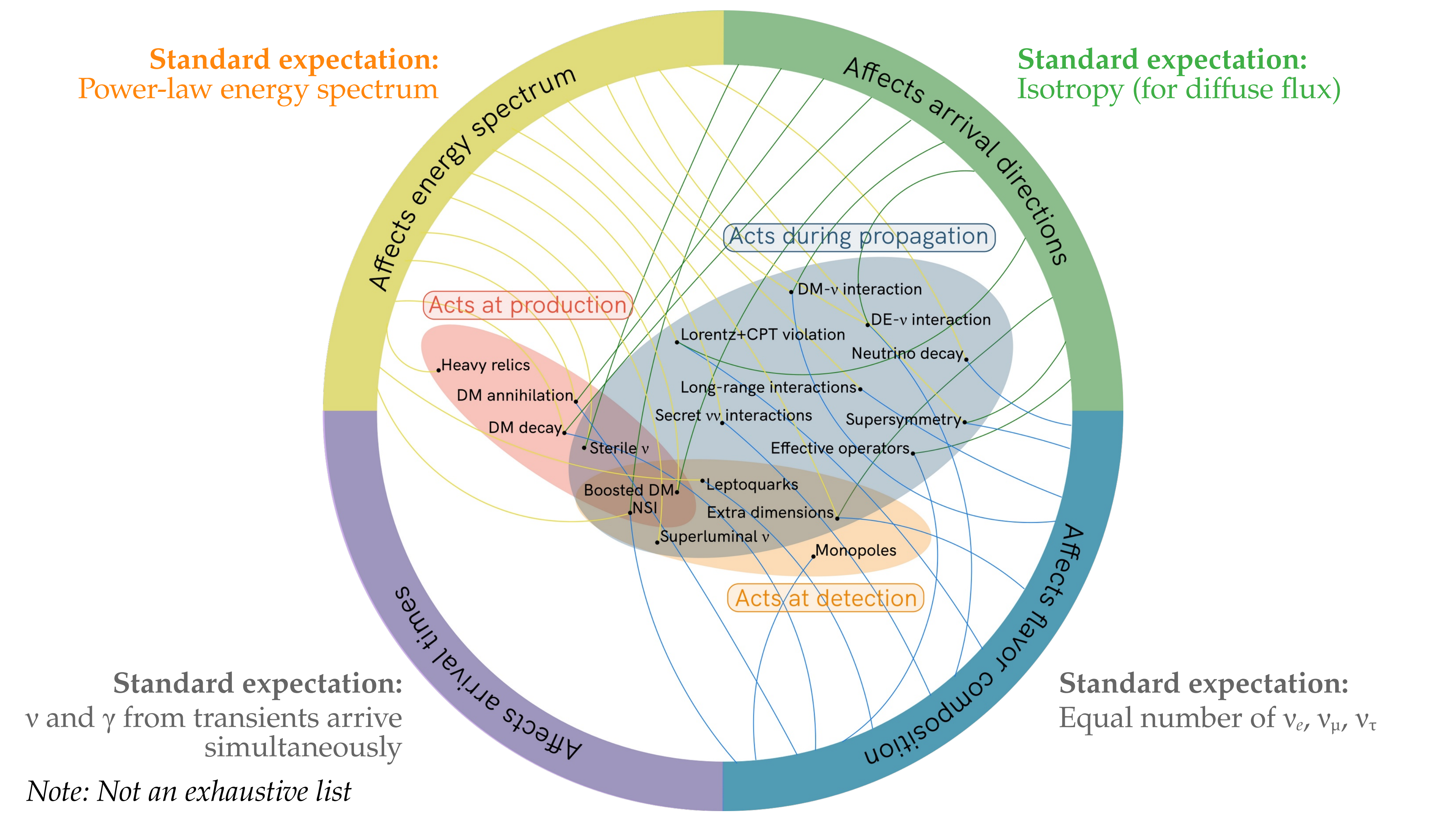
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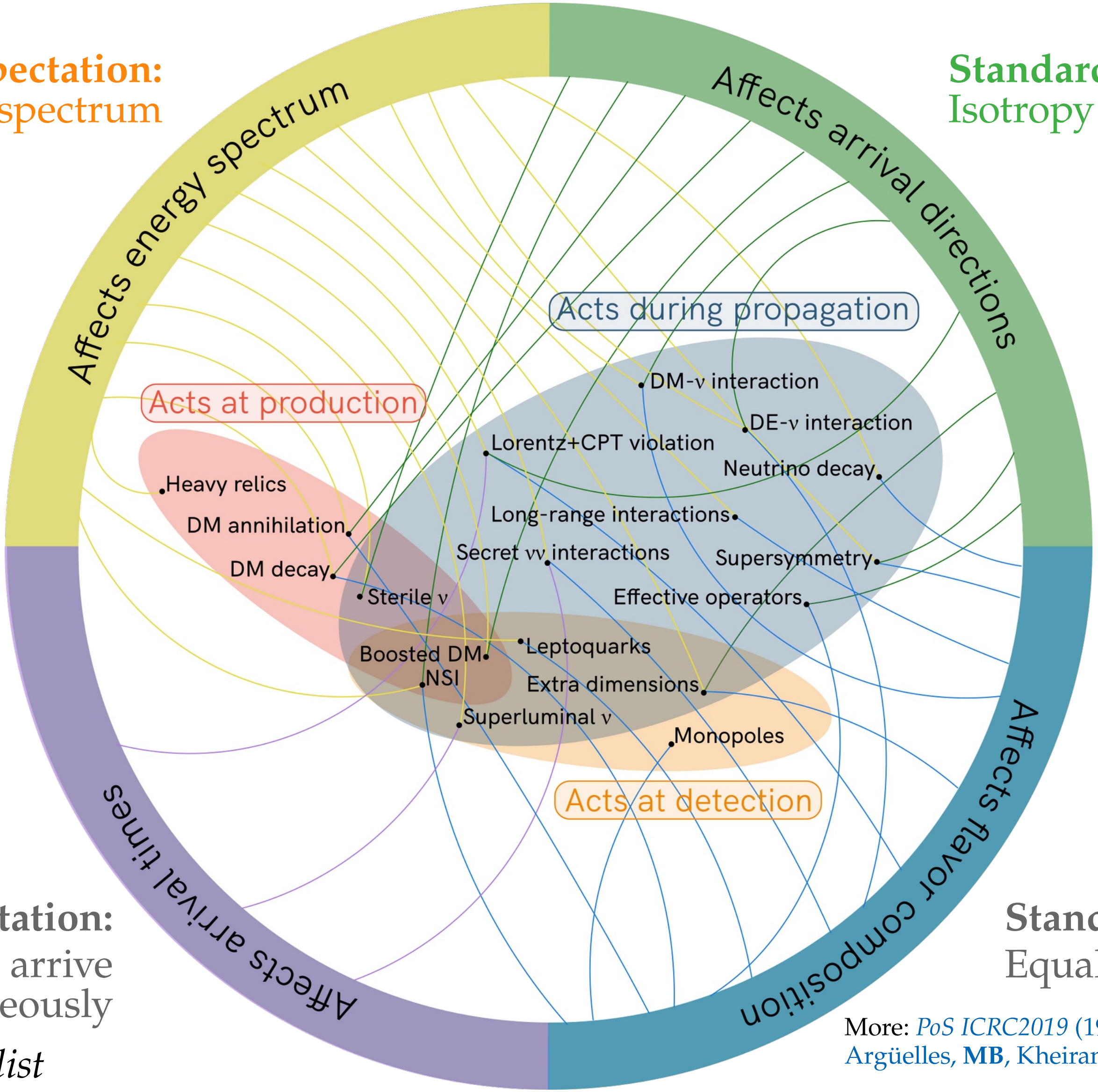
Leptoquarks
Boosted DM
NSI
Extra dimensions
Superluminal ν
Monopoles
Standard expectation:
ν and γ from transients arrive simultaneously
Standard expectation:
Equal number of ν_e, ν_μ, ν_τ
Note: Not an exhaustive list

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



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

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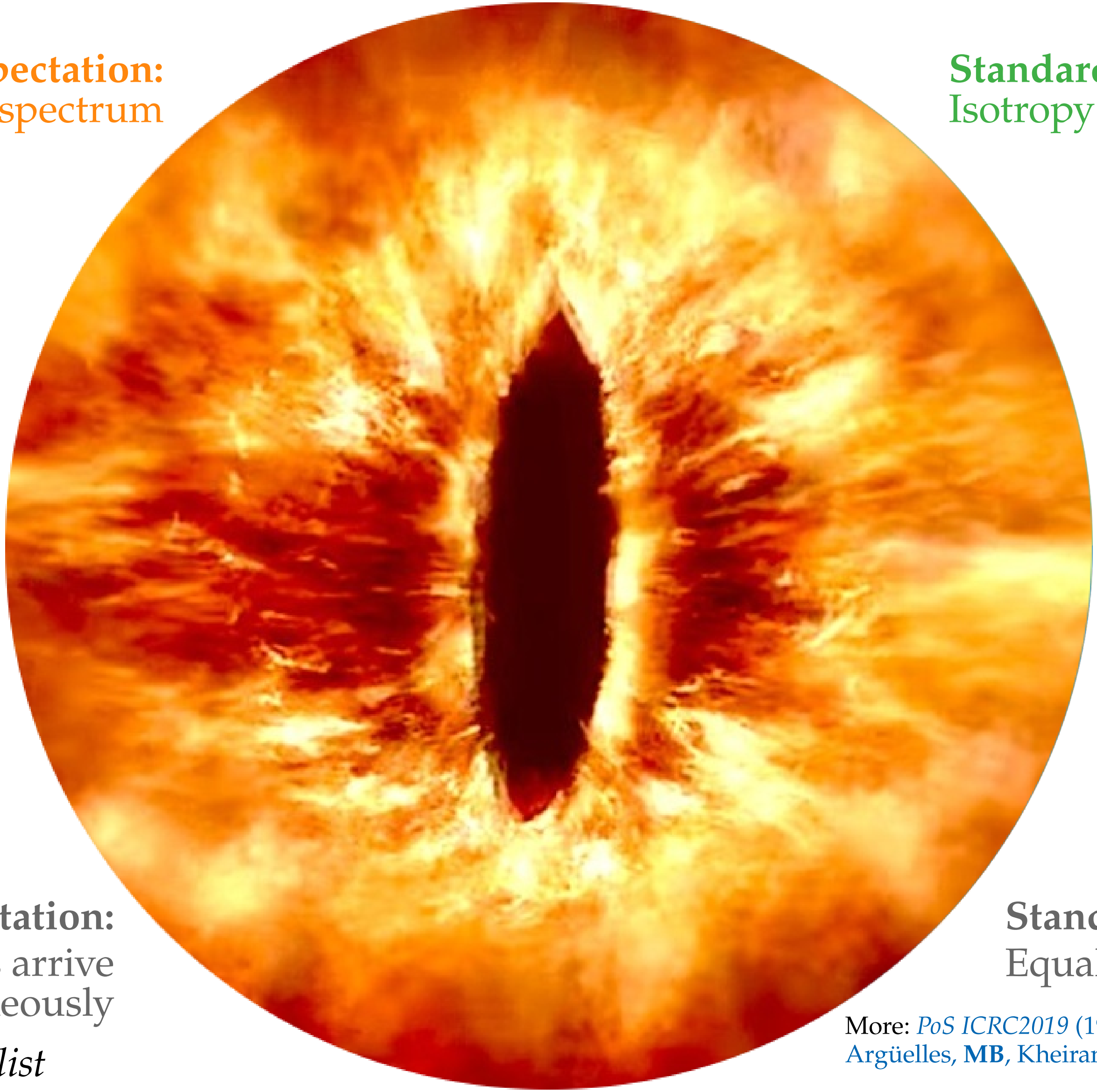

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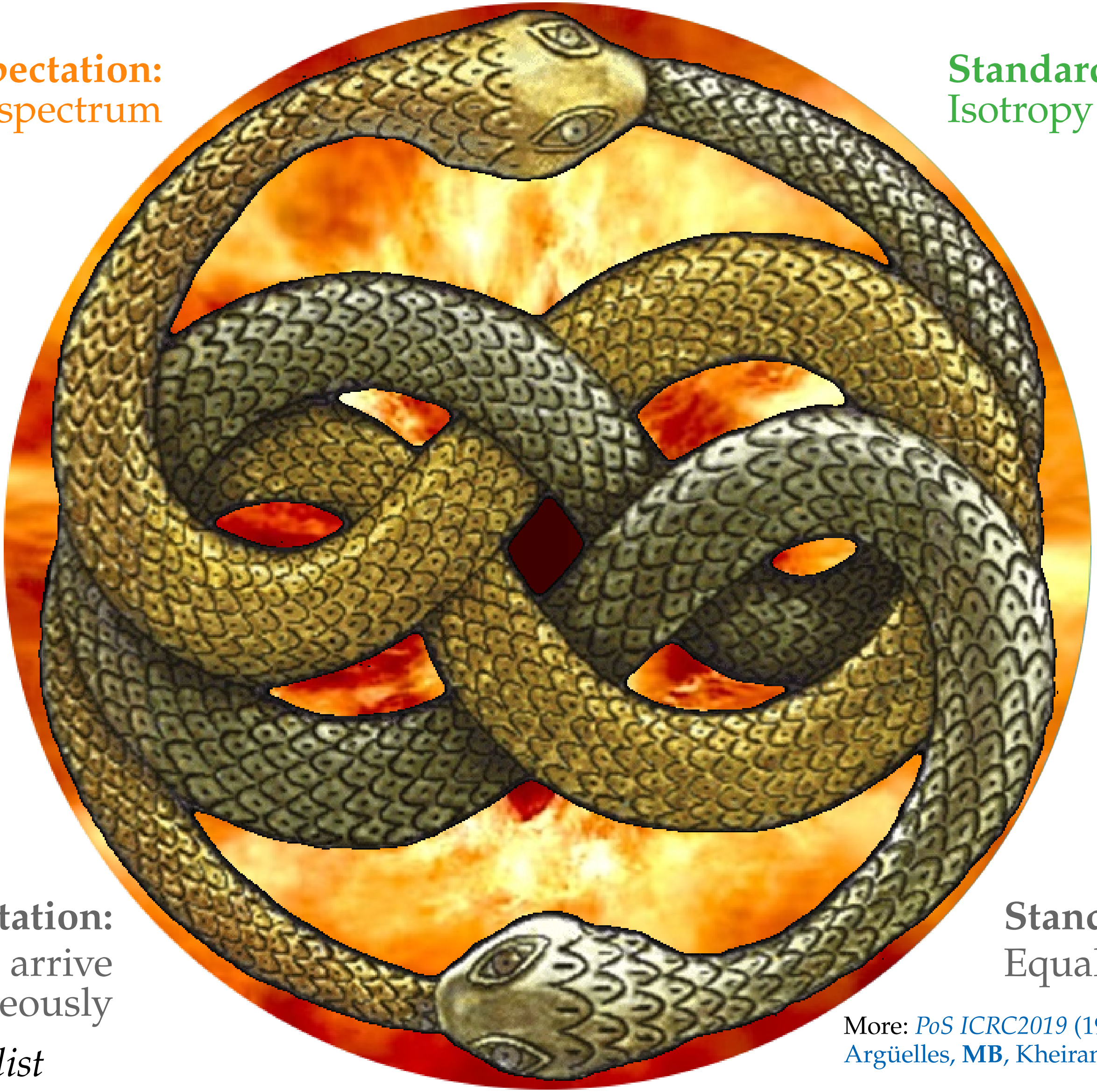

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Four examples

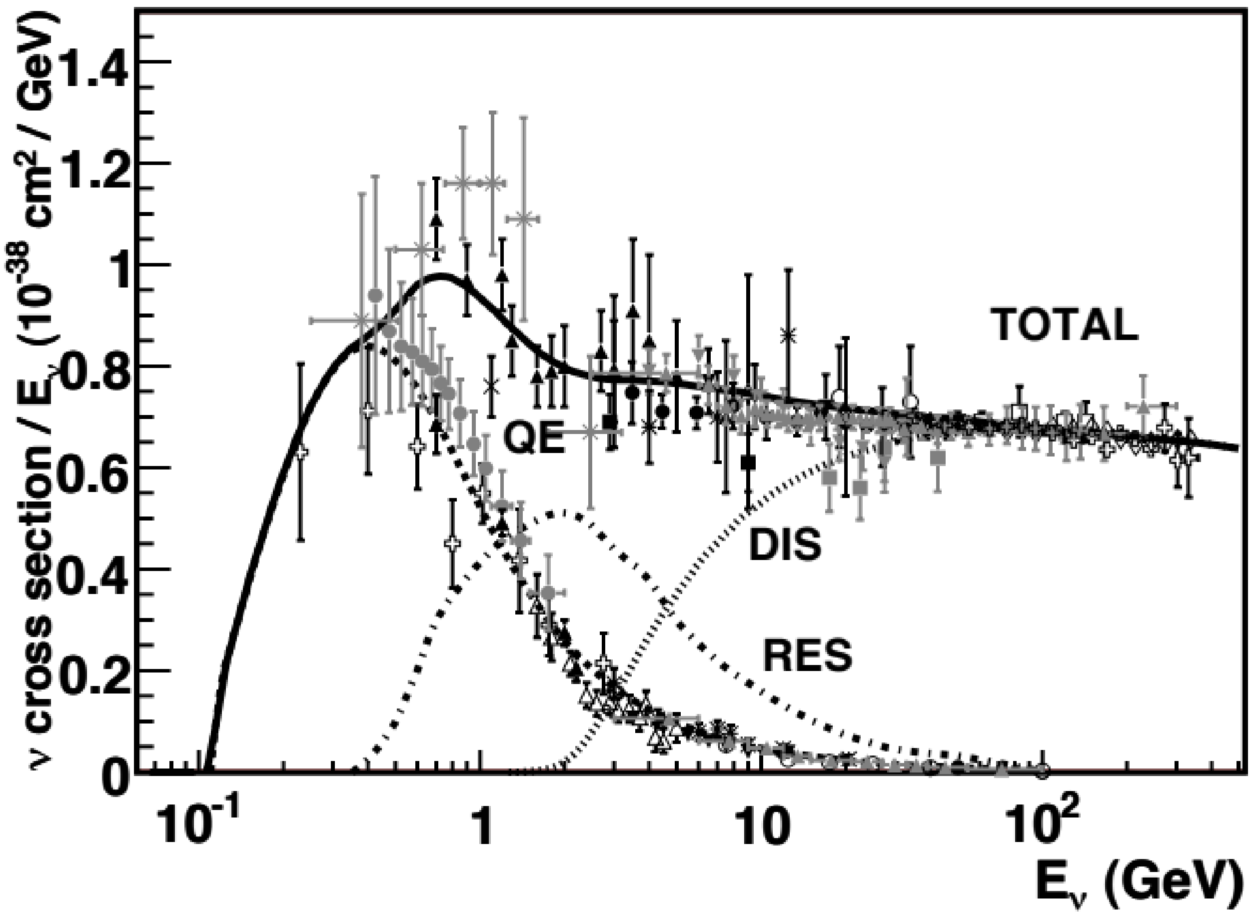
1. Measuring TeV–PeV neutrino cross sections

2. Secret neutrino interactions

3. The TeV–PeV neutrino flavor composition

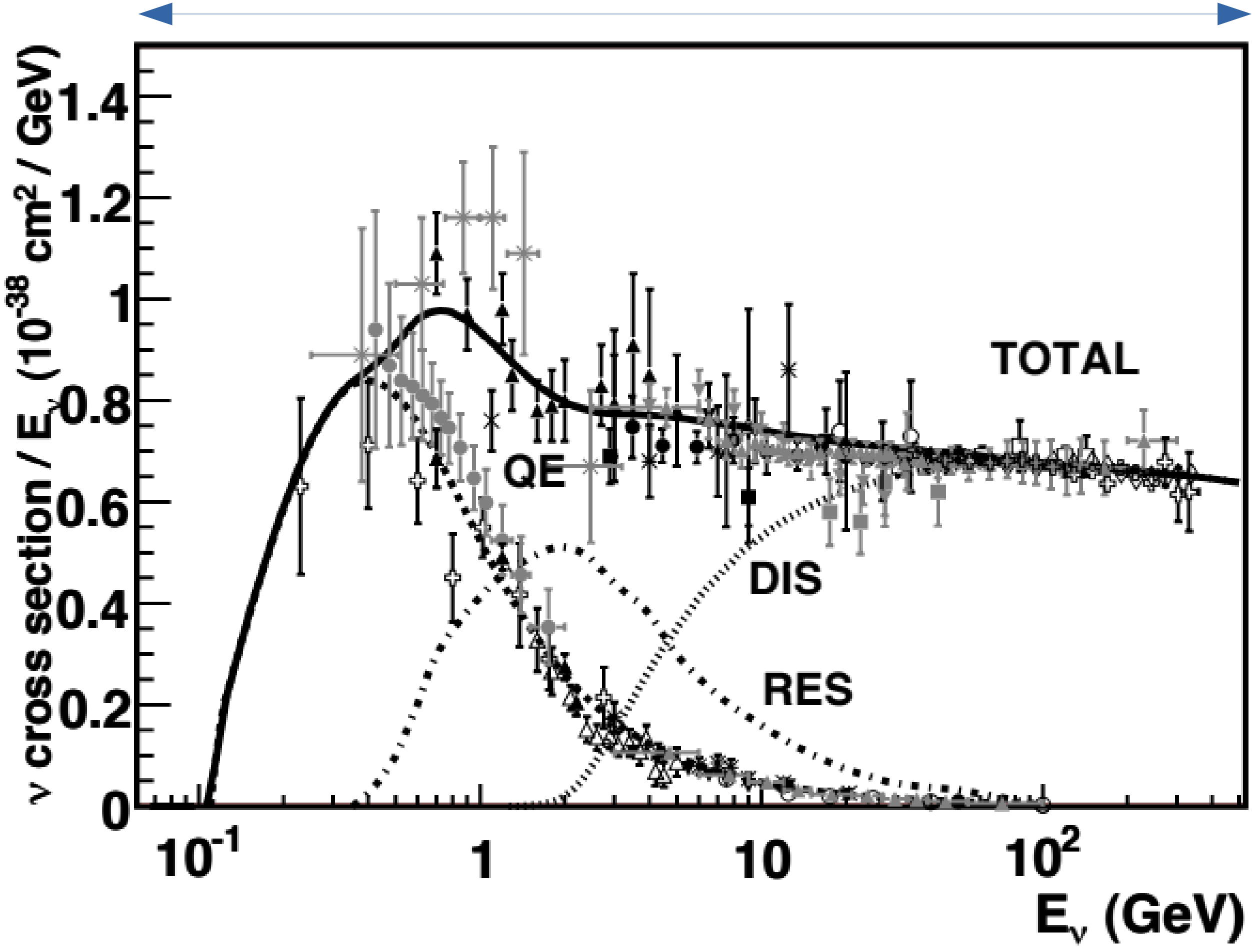
4. Neutrino decay (*if time allows*)

Measuring TeV–PeV ν cross sections



Particle Data Group

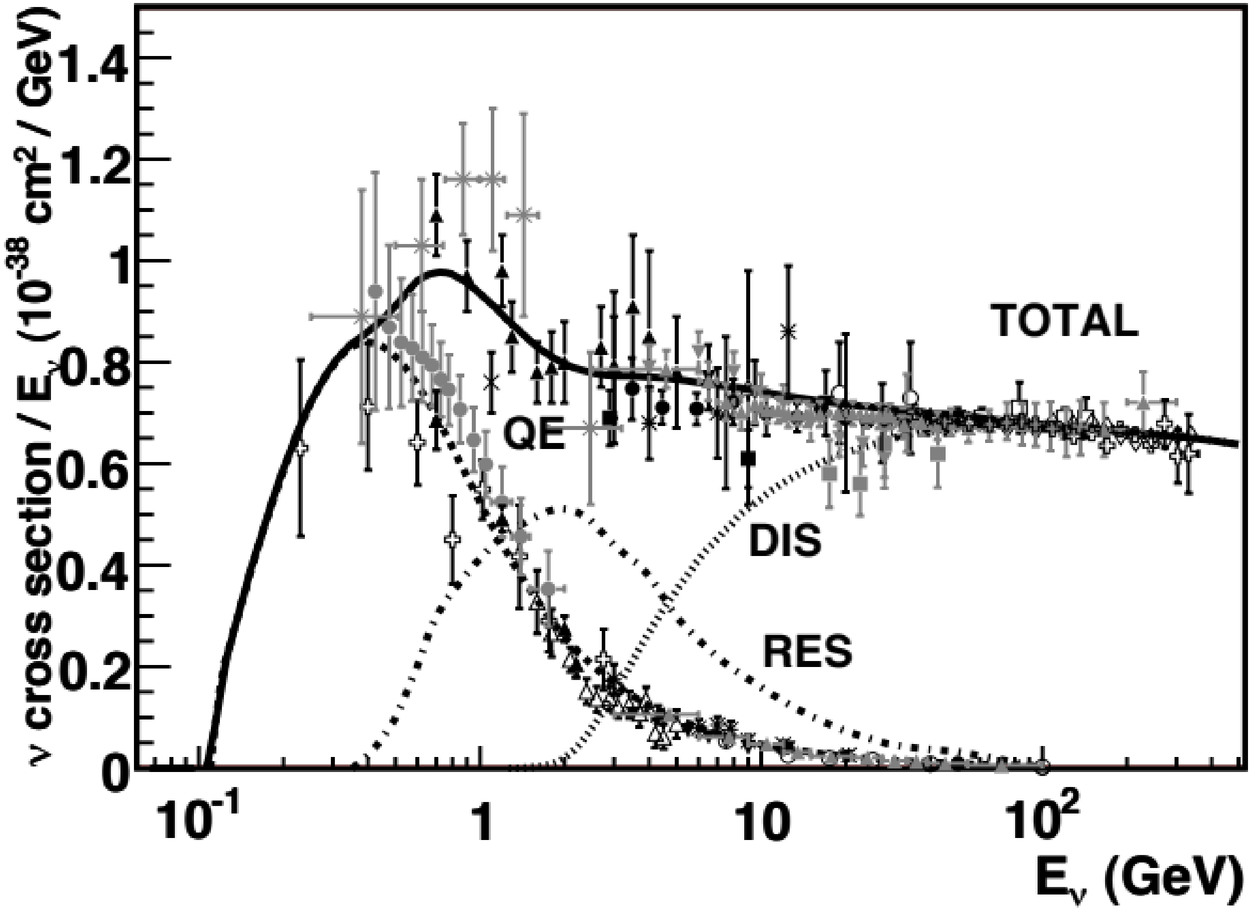
Accelerator experiments



Particle Data Group

Accelerator experiments

One recent measurement (COHERENT)



Particle Data Group

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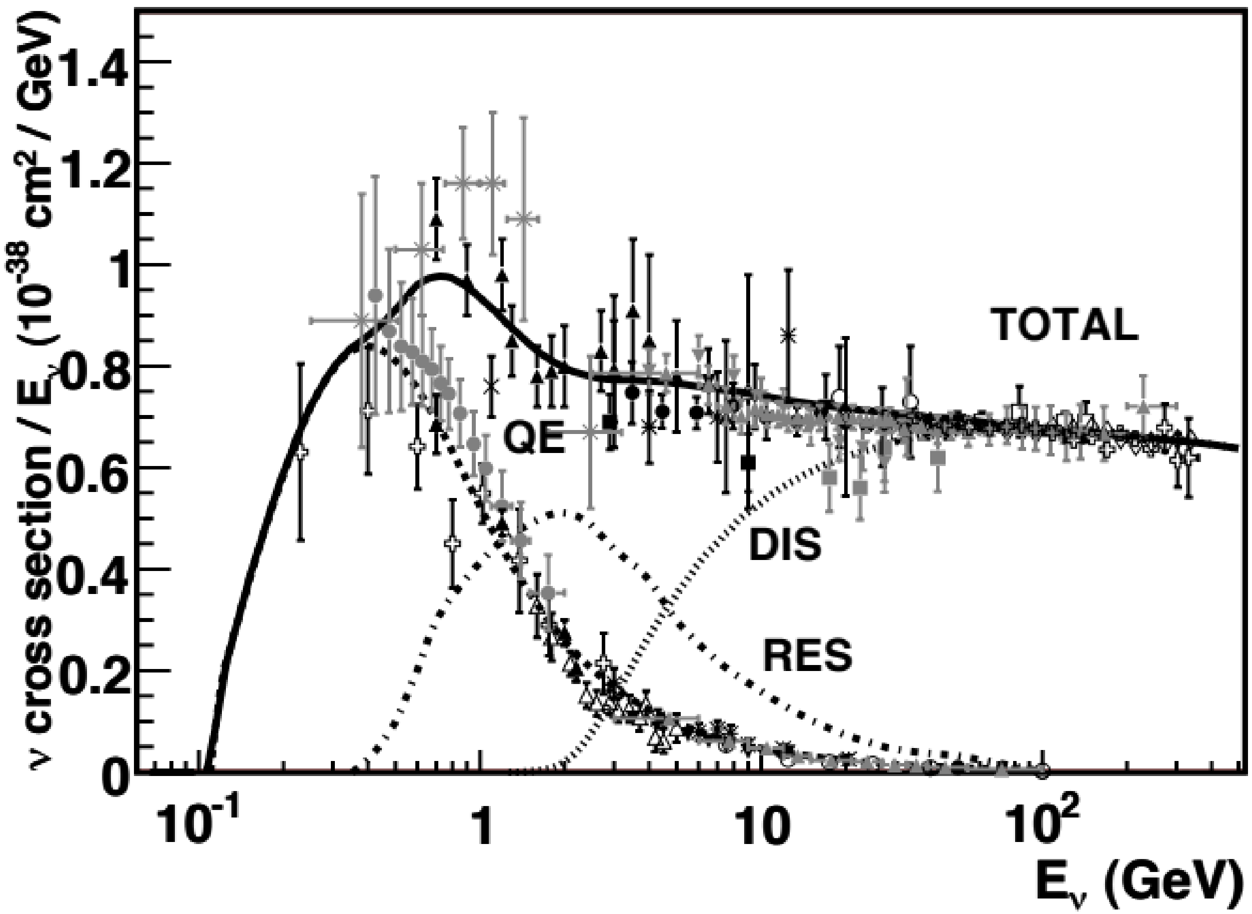


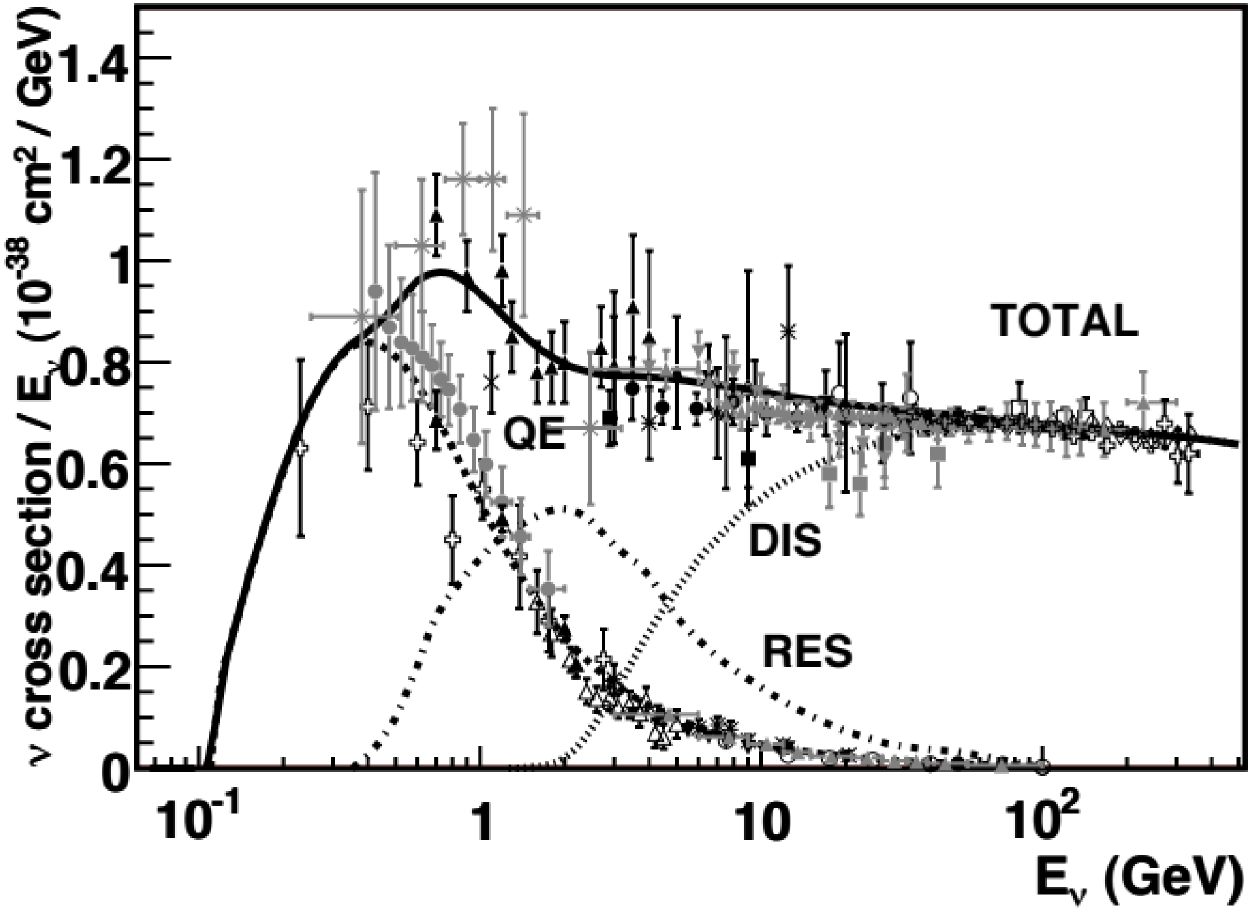
Particle Data Group

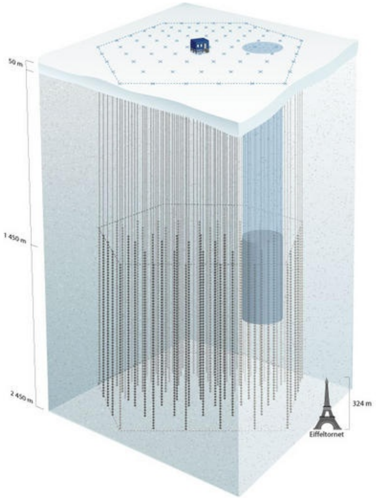
One recent measurement (COHERENT)

No measurements … until recently!

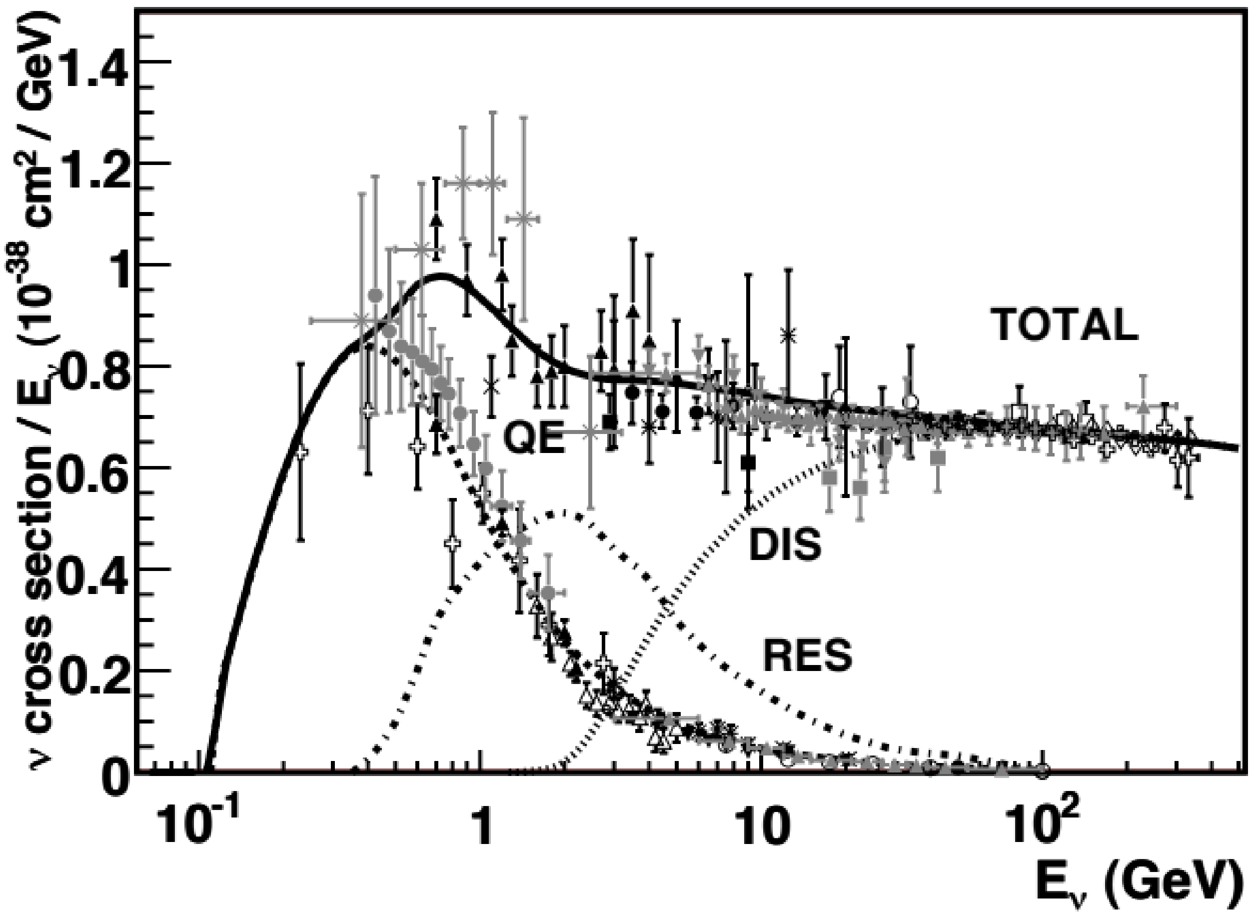
Accelerator experiments

One recent measurement (COHERENT)





Particle Data Group

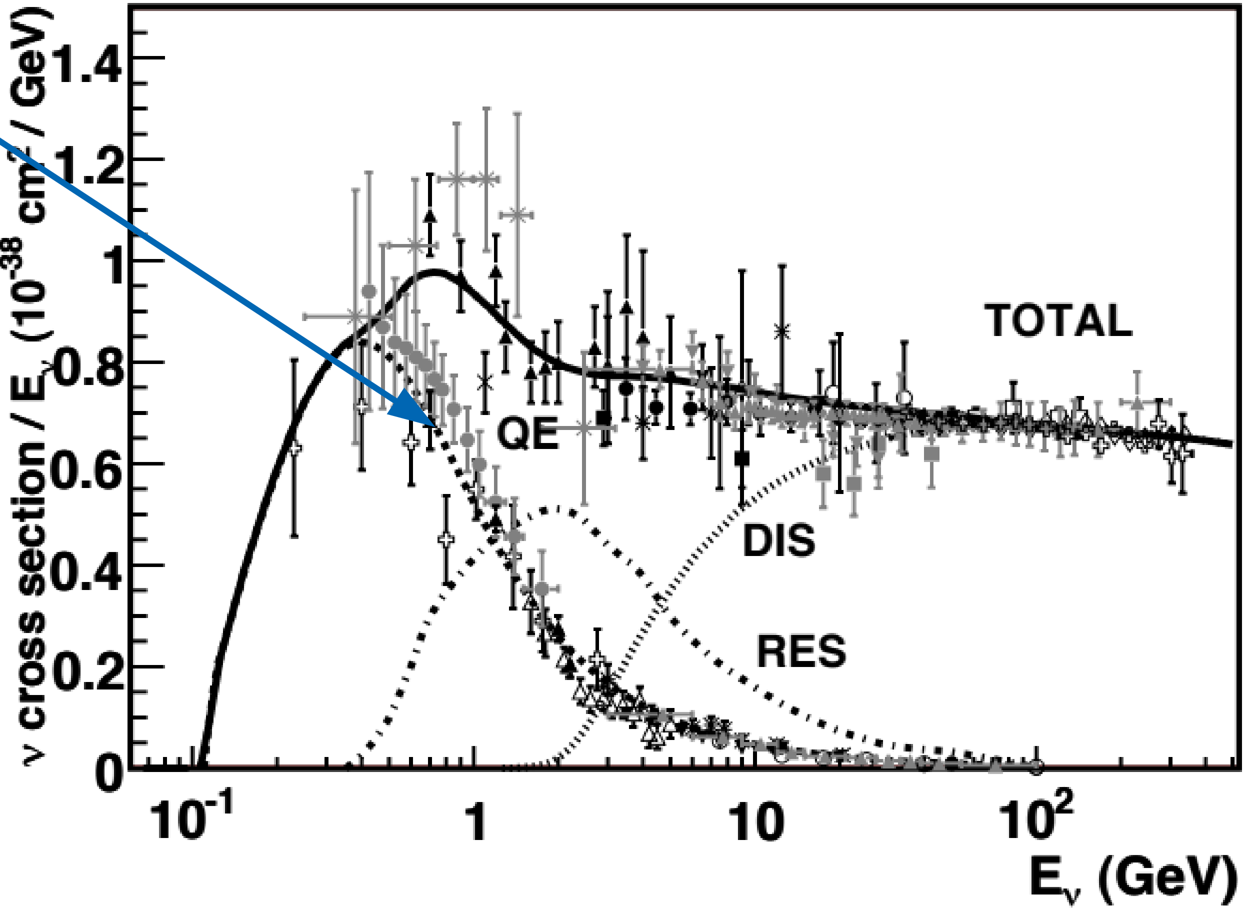


Particle Data Group

Quasi-elastic scattering:

$\nu_l + n \rightarrow l^- + p$

$\bar{\nu}_l + p \rightarrow l^+ + n$



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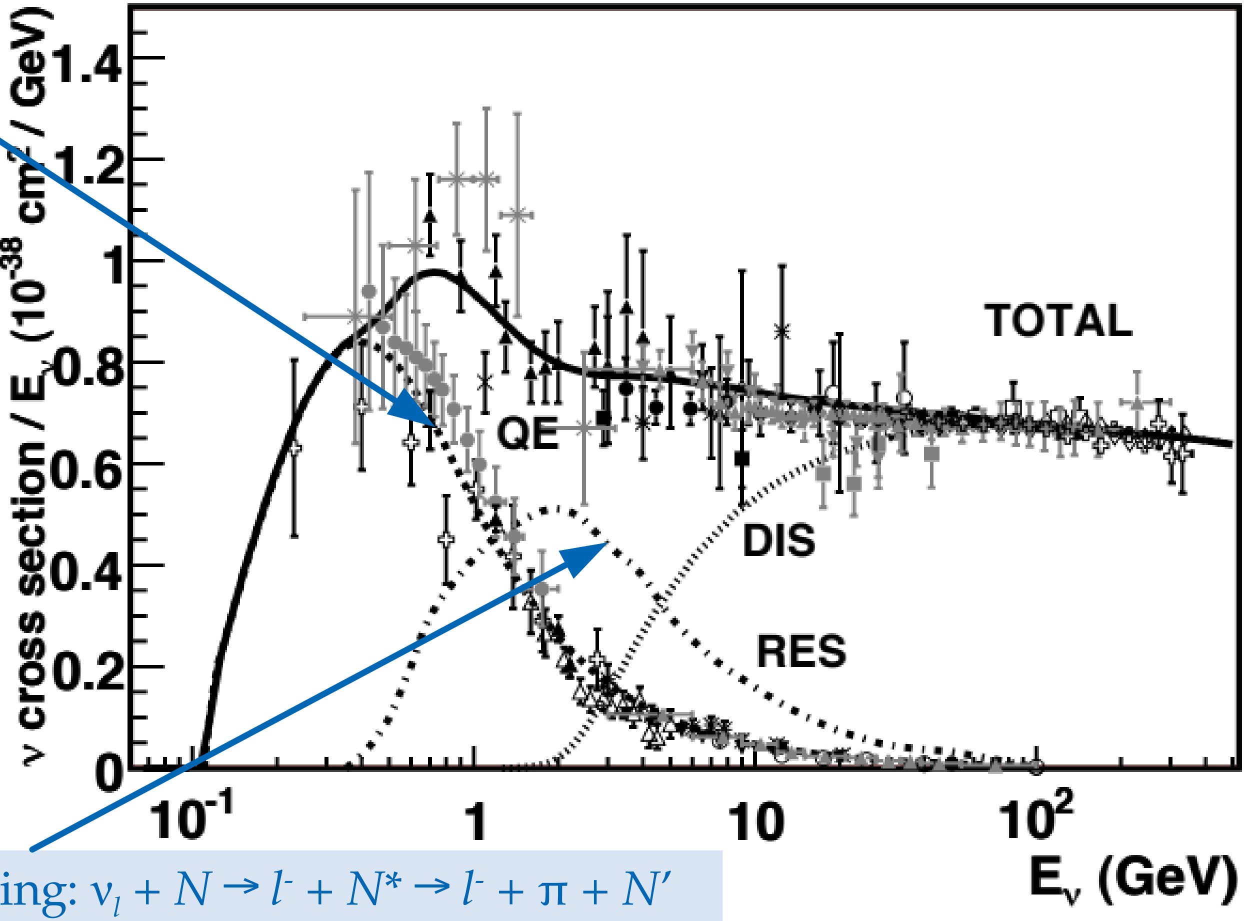

Resonant scattering: $\nu_l + N \rightarrow l^- + N^* \rightarrow l^- + \pi + N'$

Particle Data Group

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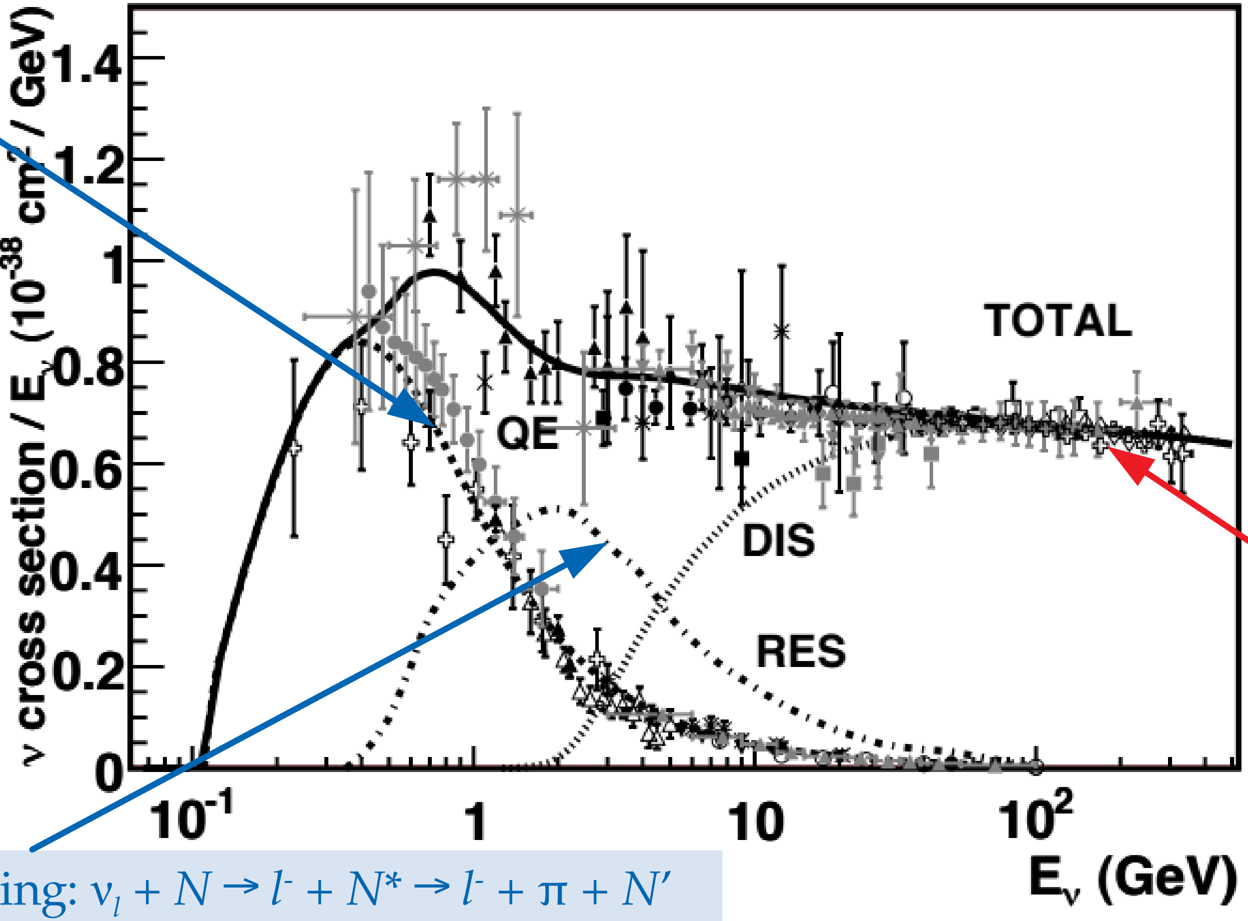


Particle Data Group

Deep inelastic scattering:

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

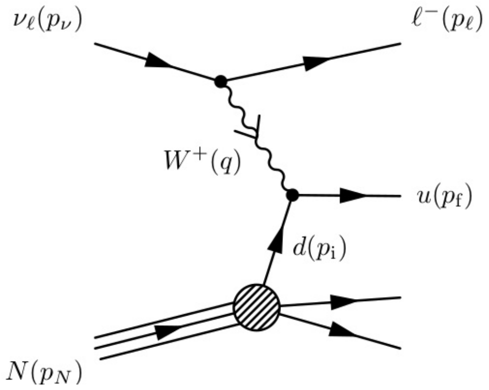
$\bar{\nu}_l + N \rightarrow l^+ + X$

Resonant scattering: $\nu_l + N \rightarrow l^- + N^* \rightarrow l^- + \pi + N'$

Extrapolating the cross section to high energies

Extrapolating the cross section to high energies

SM



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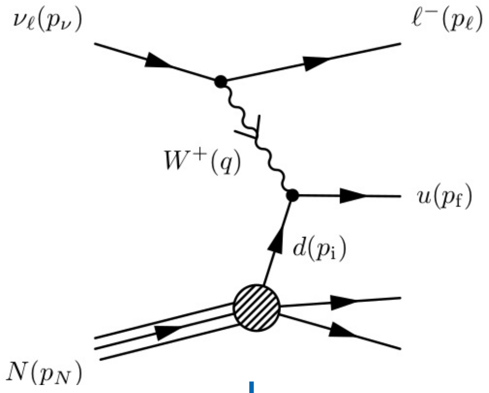
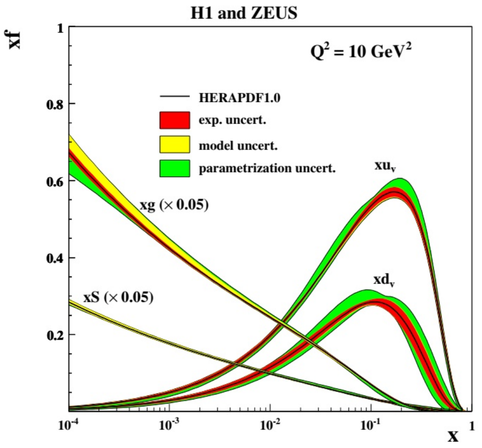


+

PDFs



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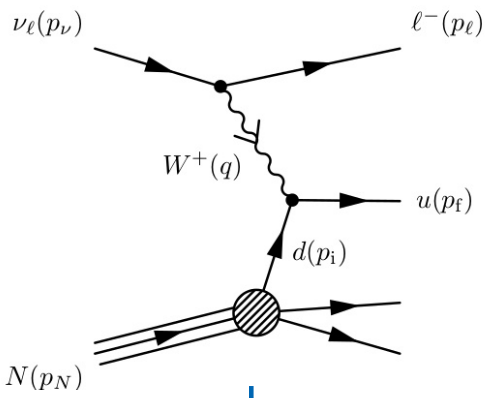

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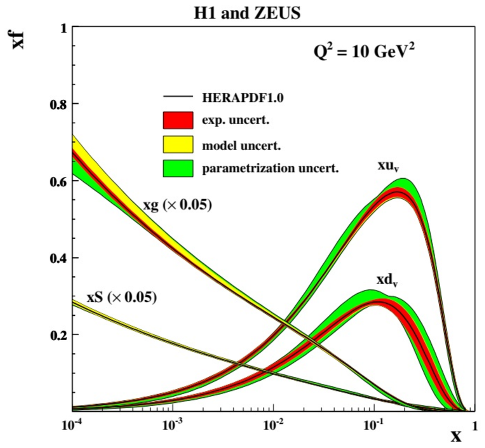

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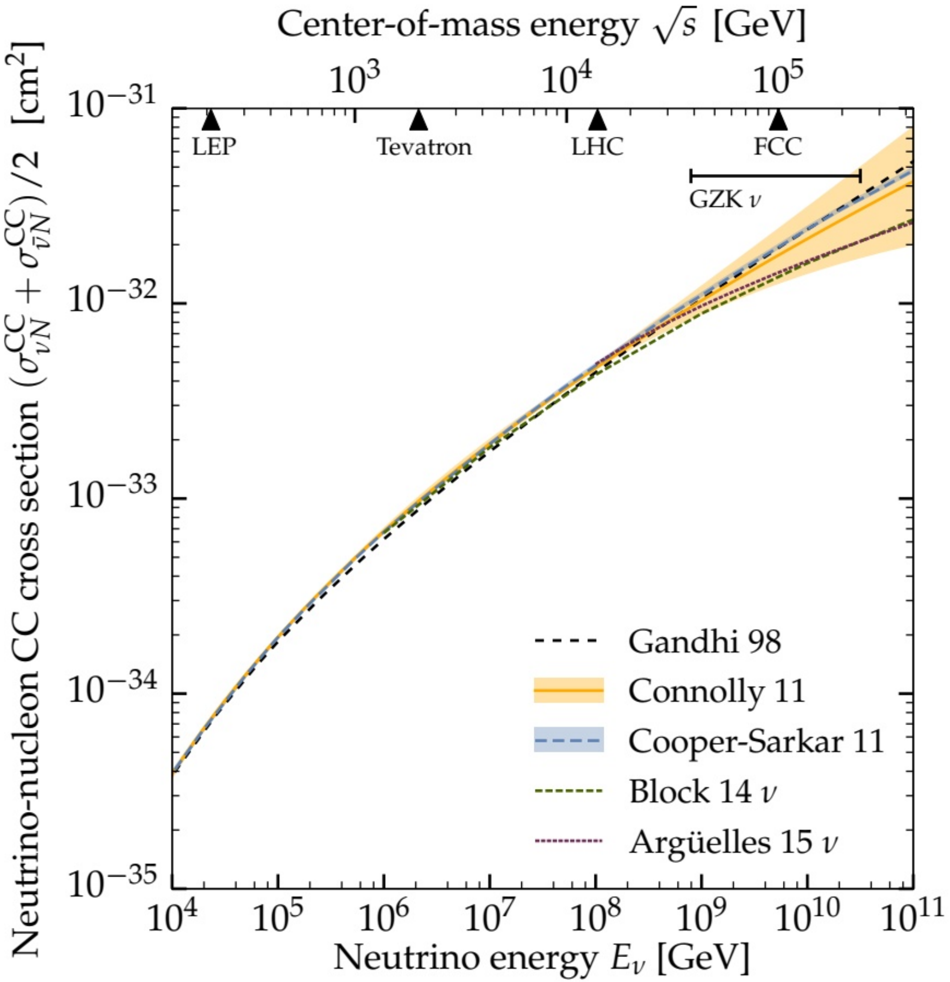

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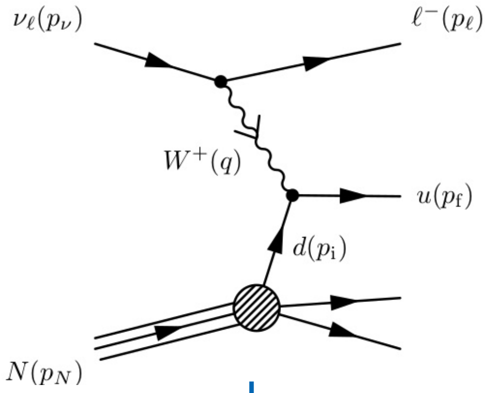

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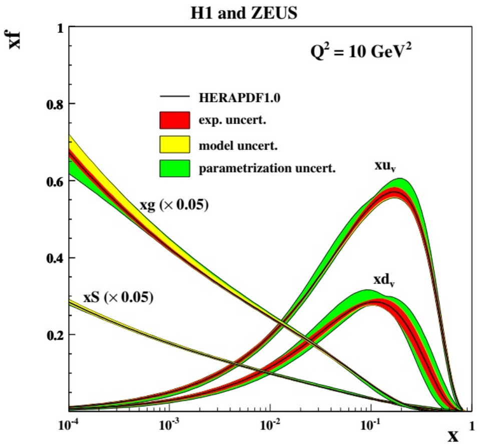

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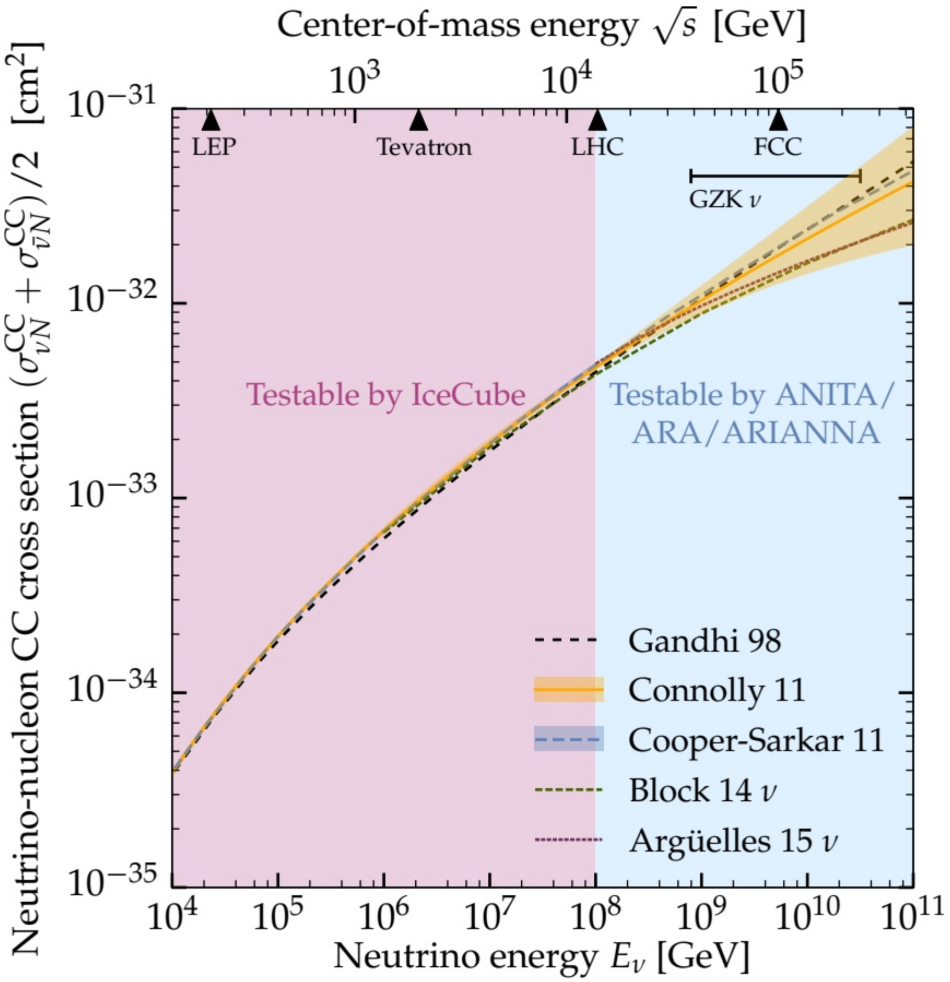
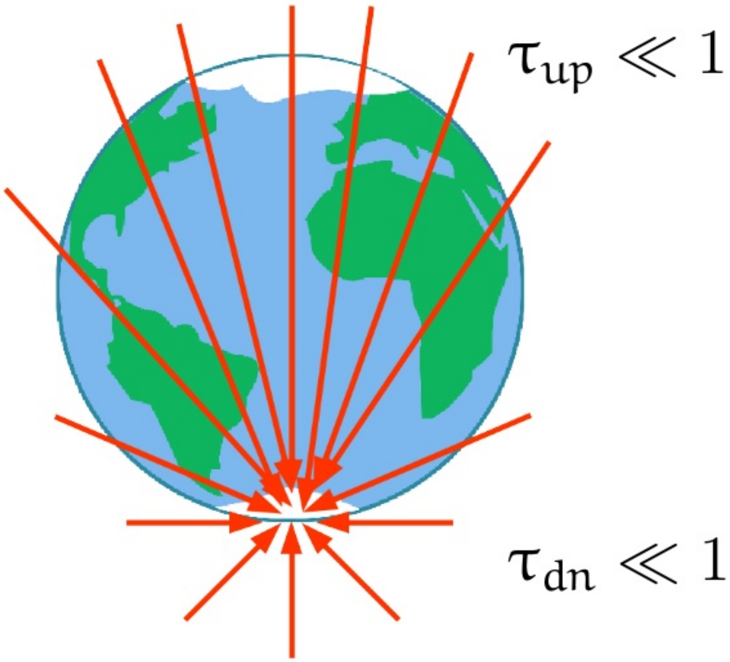


Measuring the high-energy cross section

$$\text{Optical depth to } \nu N \text{ int's} = \frac{\text{Distance from Earth's surface to IceCube}}{\text{Mean free path inside Earth}} \equiv \tau(E_\nu, \theta_z) \propto \sigma_{\nu N}$$

Below ~ 10 TeV: Earth is transparent



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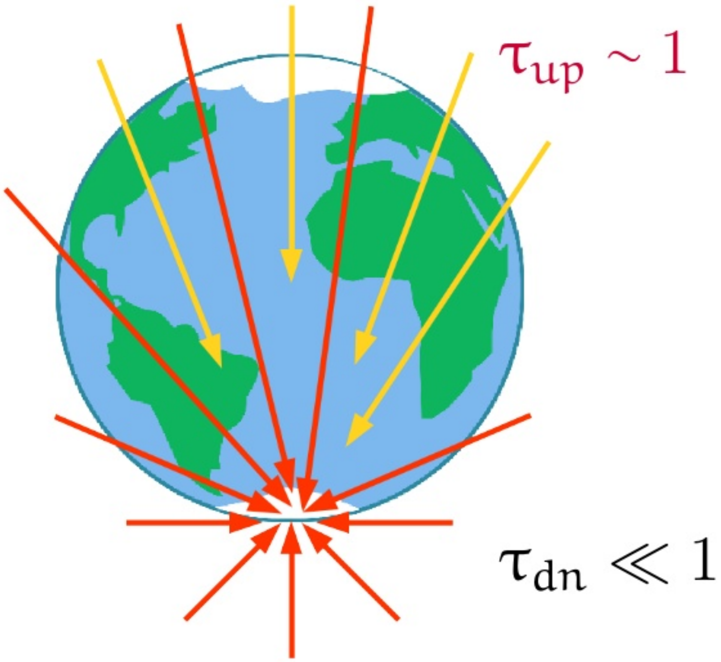

Hooper, *PRD* 2002; Hussain *et al.*, *PRL* 2006; Borriello *et al.*, *PRD* 2008
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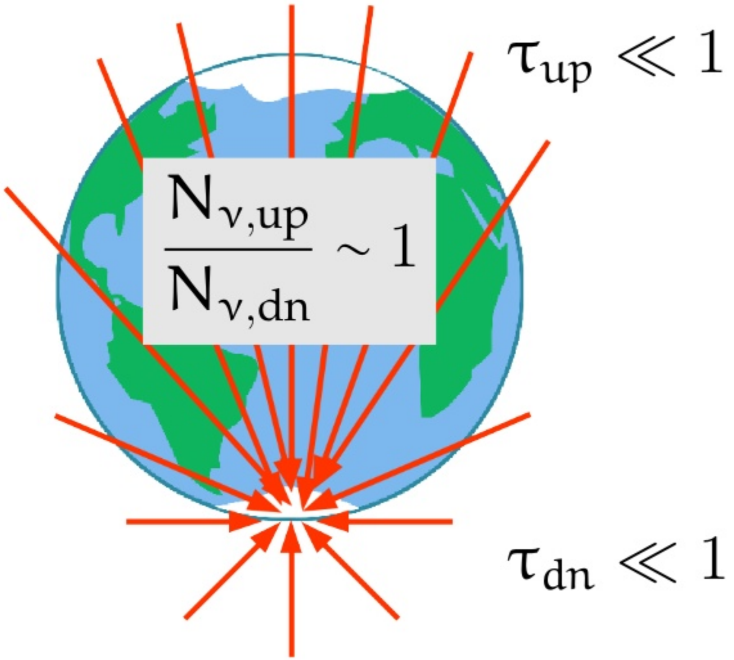

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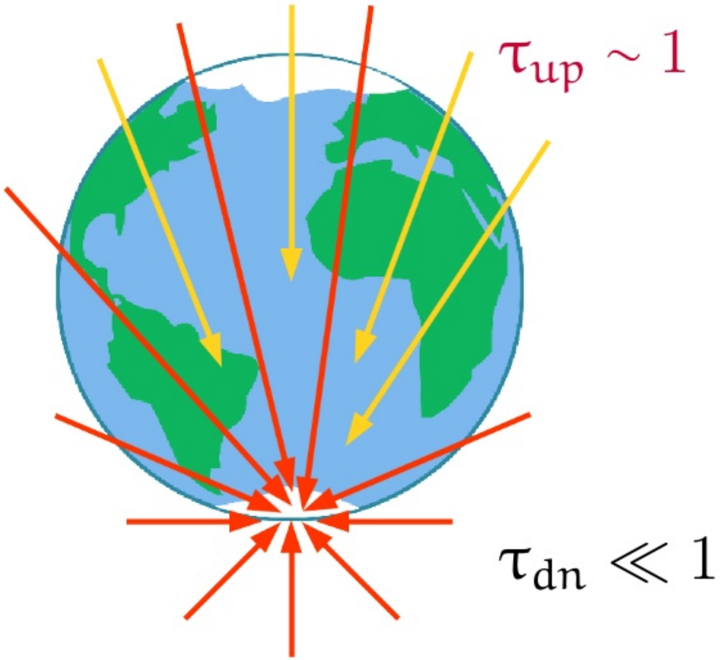

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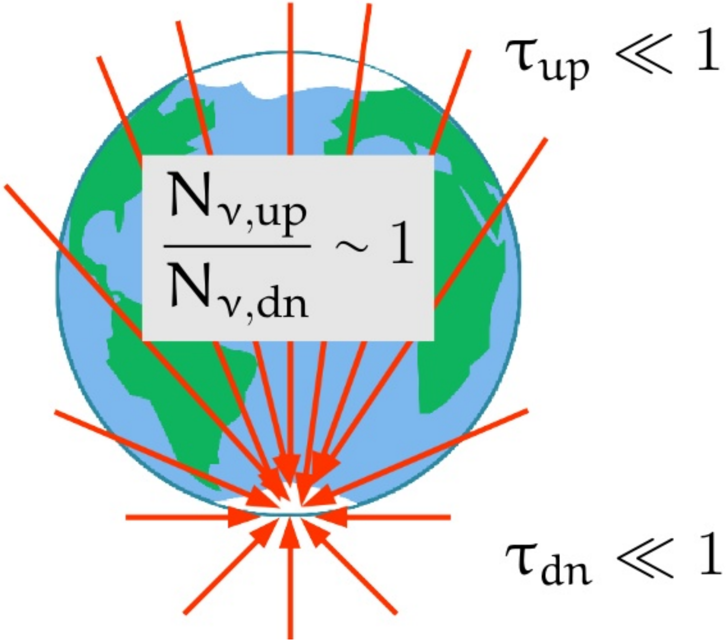

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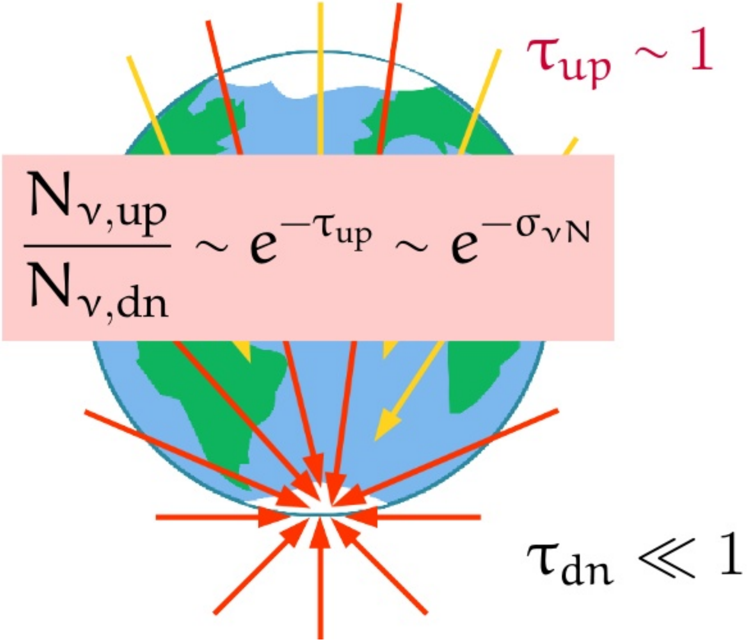

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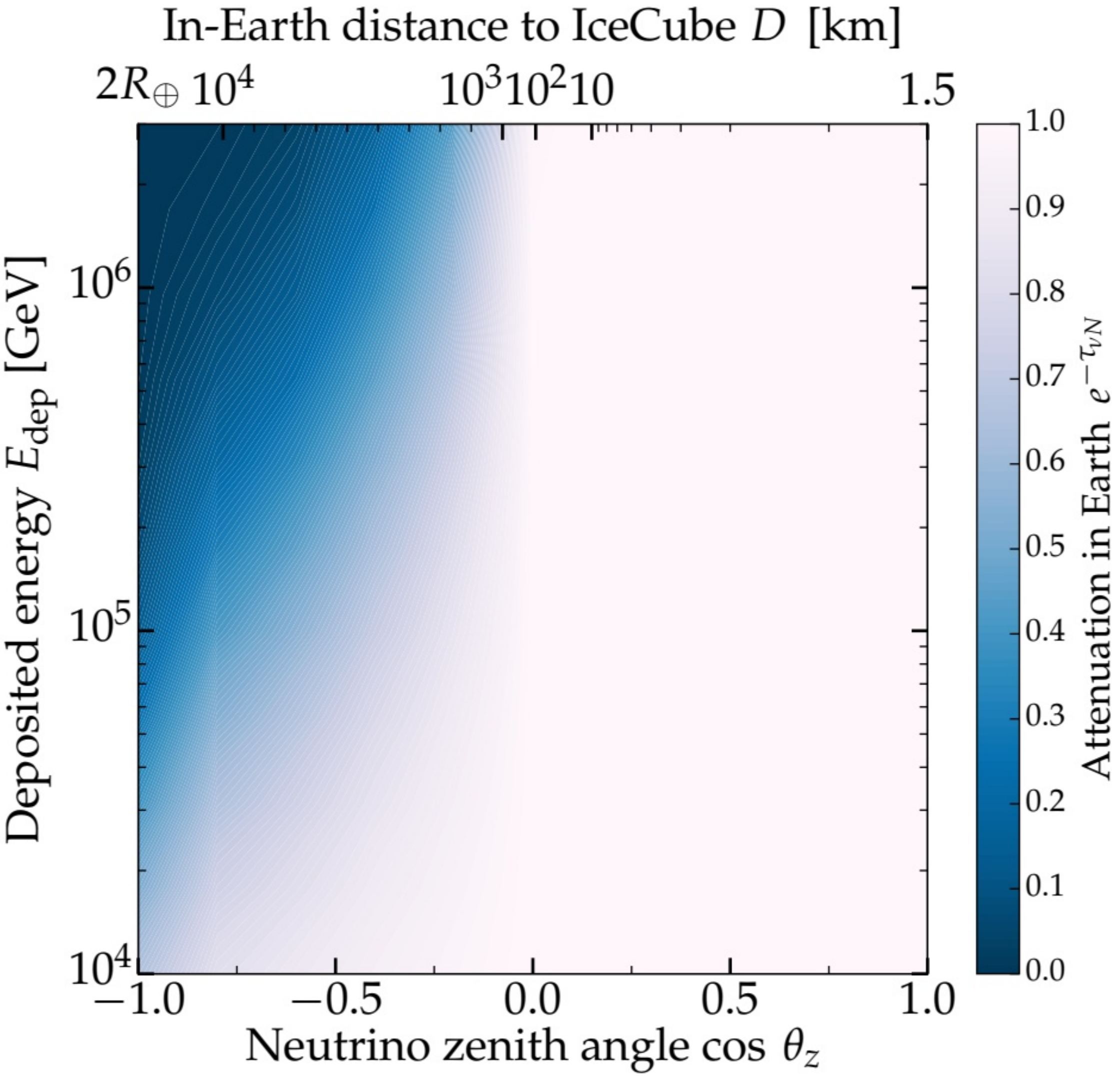
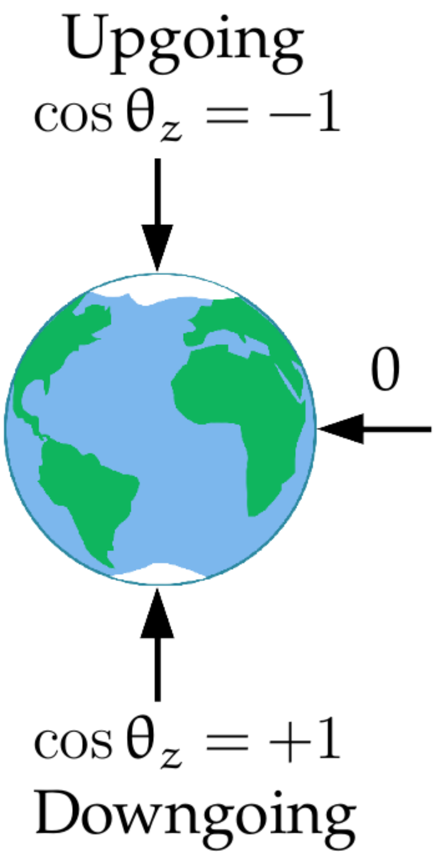
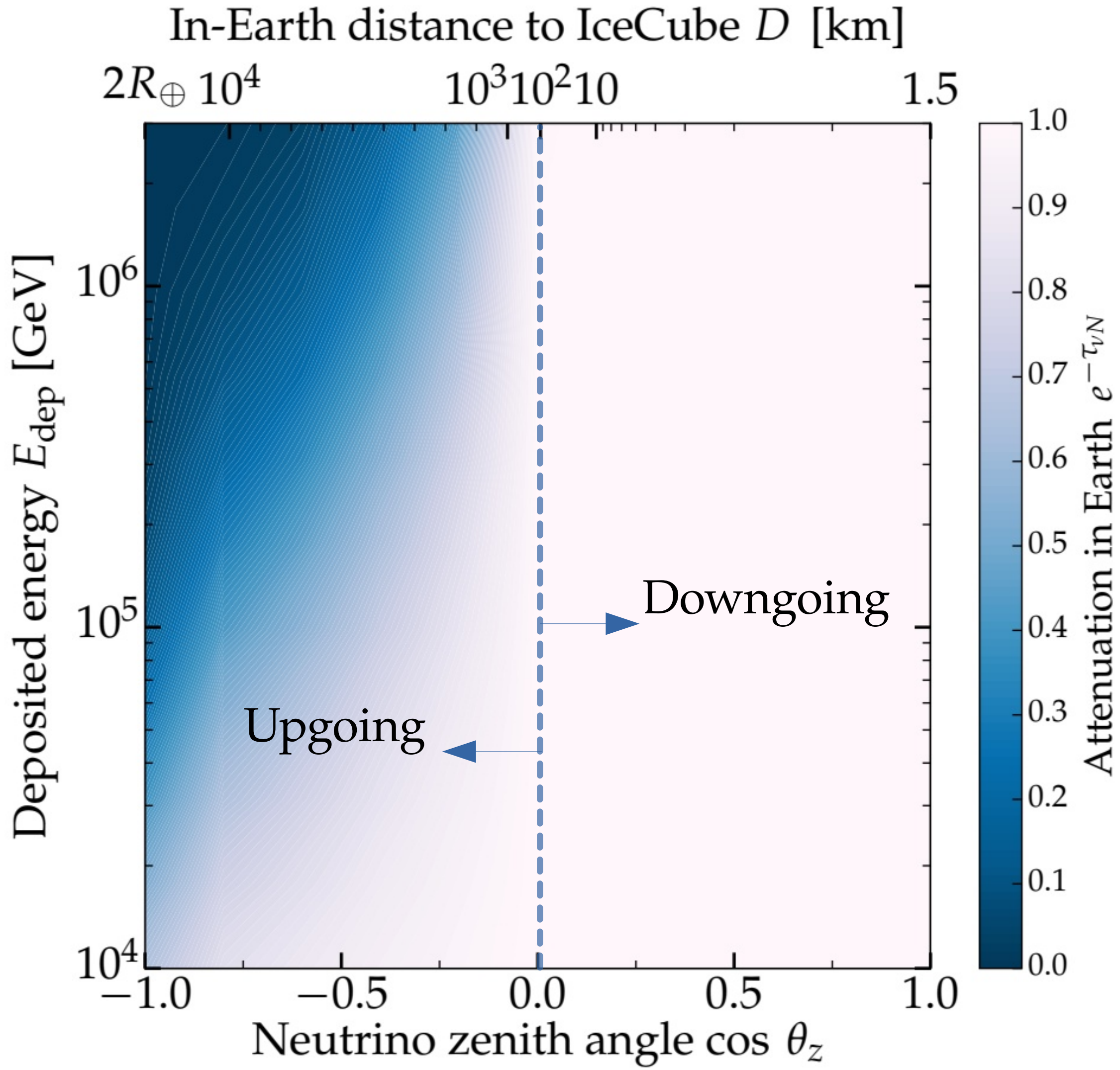

In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4 10^3 10^2 10 1.5
Deposited energy E_{dep} [GeV]
10^6
10^5
10^4
-1.0 -0.5 0.0 0.5 1.0
Neutrino zenith angle $\cos\theta_z$
Attenuation in Earth $e^{-\tau_{\nu N}}$
1.0 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0.0


Upgoing
$\cos\theta_z = -1$
0
$\cos\theta_z = +1$
Downgoing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10^3 10^2 10
1.5
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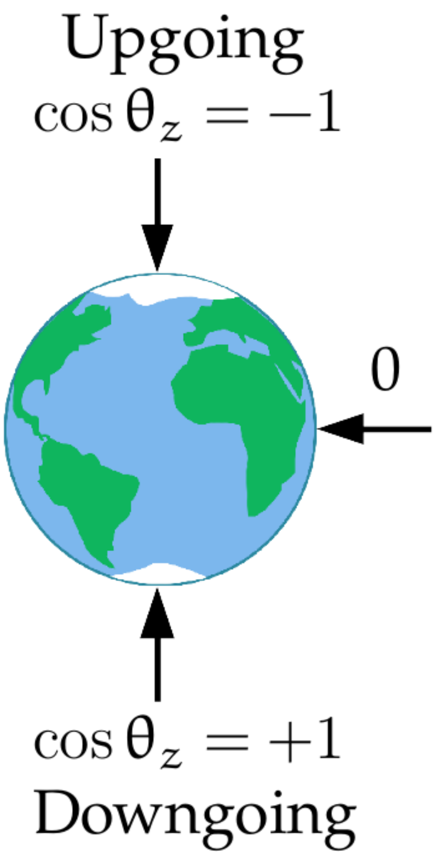
10^4
10^5
10^6
Downgoing
Upgoing
−1.0
−0.5
0.0
0.5
1.0
Neutrino zenith angle $\cos\theta_z$
Attenuation in Earth $e^{-\tau_{\nu N}}$
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0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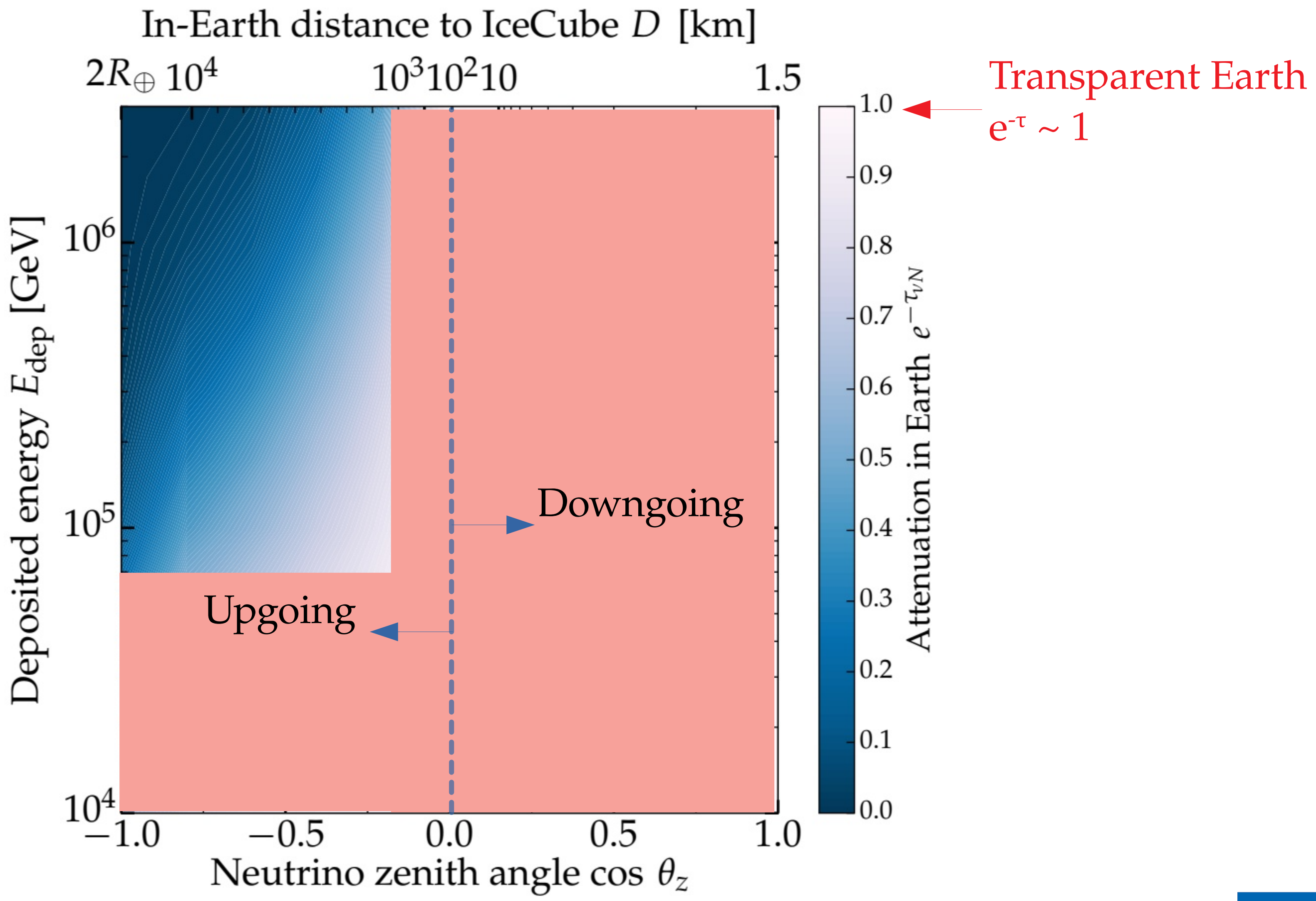
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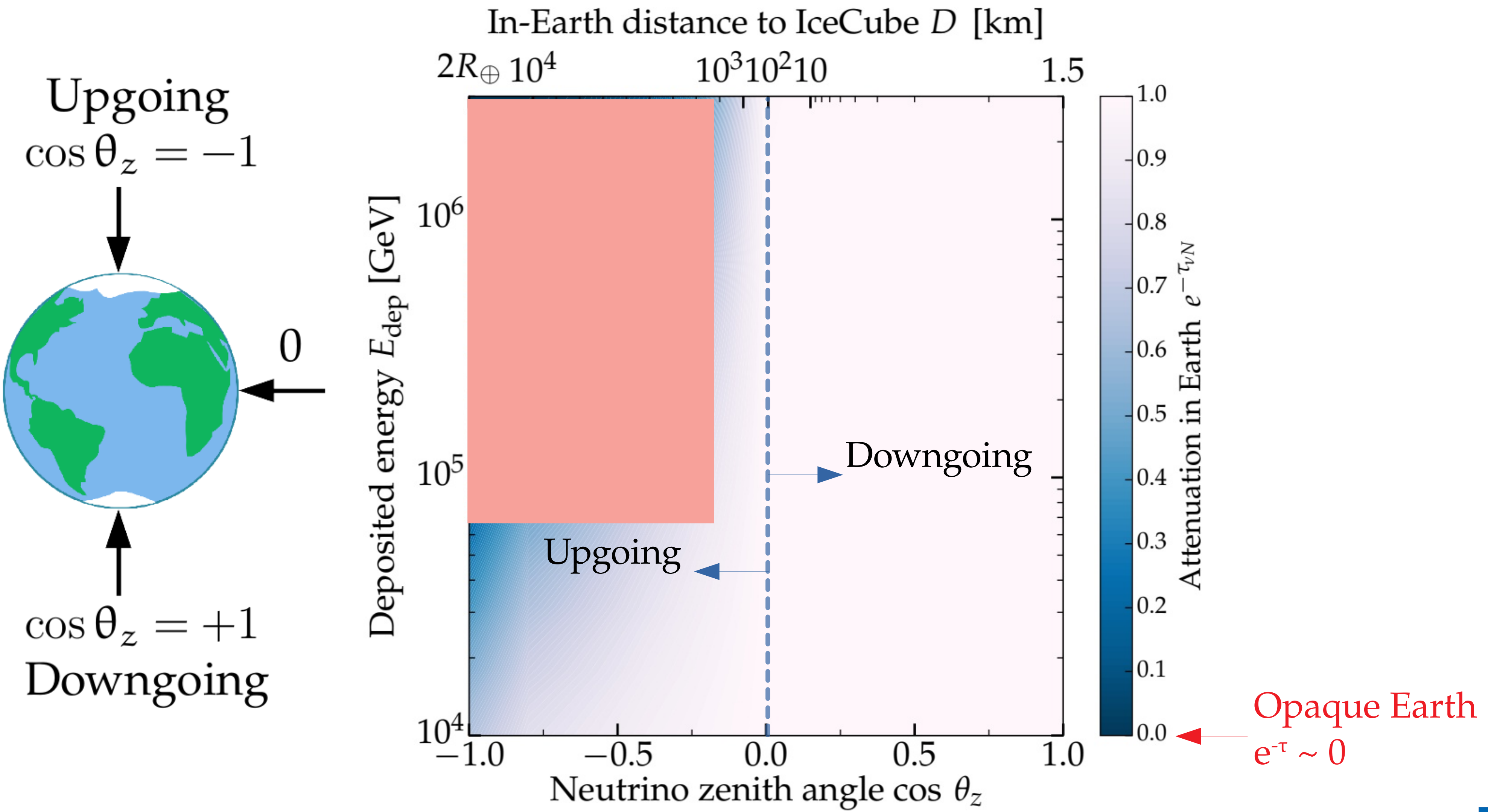
10^3 10^2 10
1.5
Deposited energy $E_{\rm dep}$ [GeV]
10^6
10^5
10^4
Downgoing
Upgoing
−1.0
−0.5
0.0
0.5
1.0
Neutrino zenith angle $\cos\theta_z$
Attenuation in Earth $e^{-\tau_{\nu N}}$
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Transparent Earth
$e^{-\tau} \sim 1$


Upgoing
$\cos\theta_z = -1$
0
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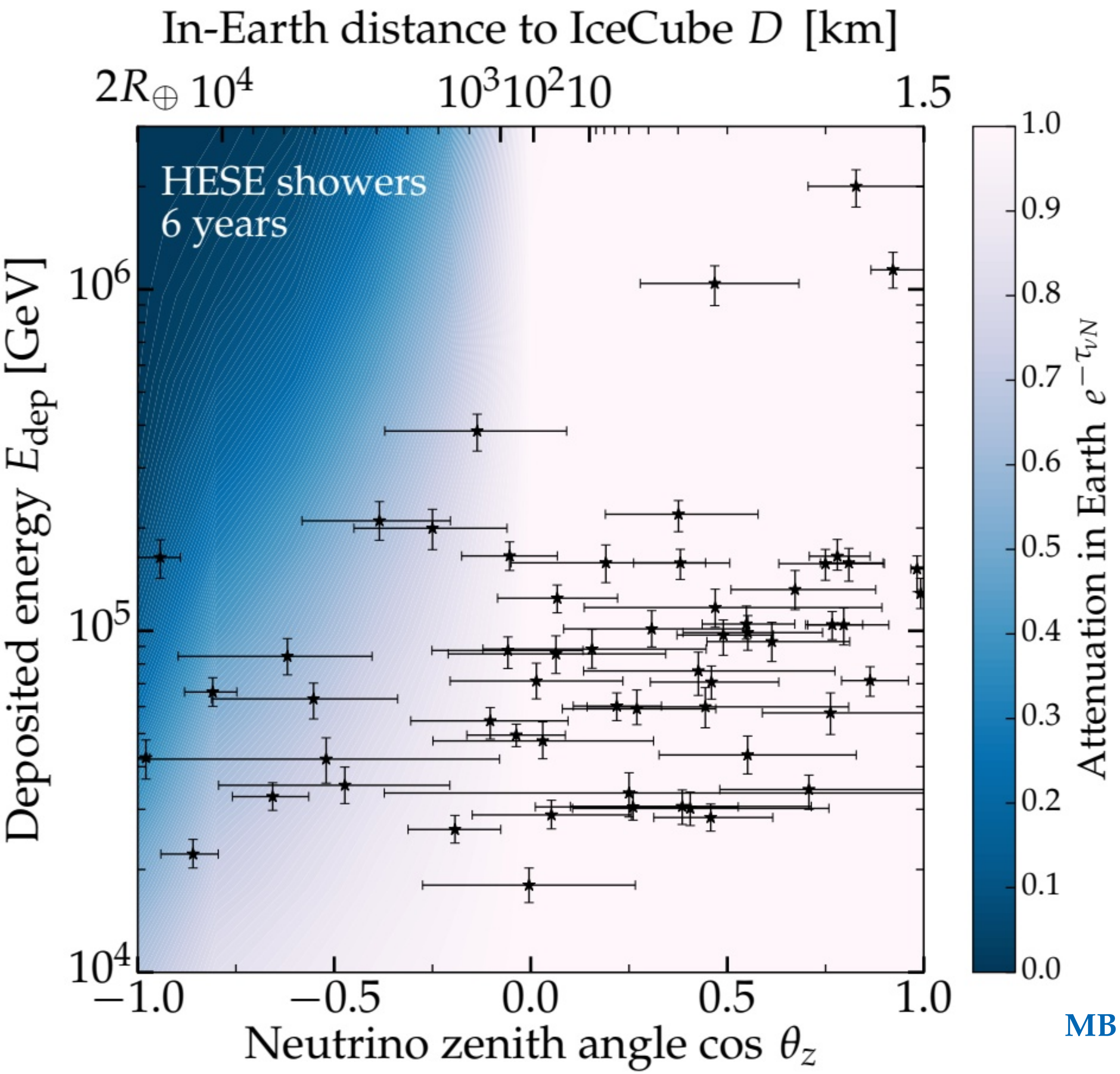
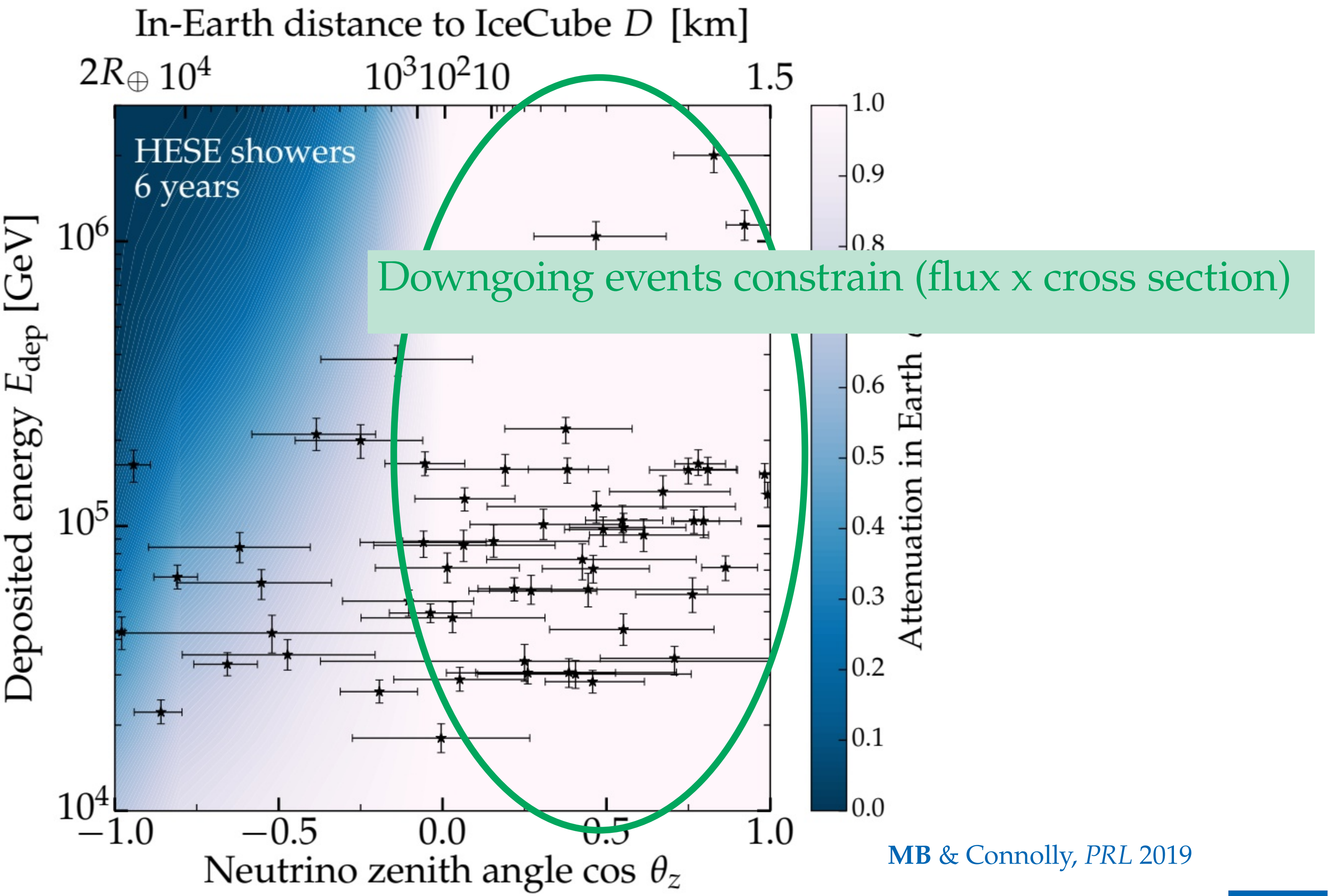
Downgoing
In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4 10^3 10^2 10 1.5
Deposited energy E_{dep} [GeV]
10^6
10^5
10^4
Downgoing
Upgoing
−1.0 −0.5 0.0 0.5 1.0
Neutrino zenith angle cos θ_z
1.0 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0.0
Attenuation in Earth $e^{-\tau_{\nu N}}$
Opaque Earth
$e^{-\tau} \sim 0$



MB & Connolly, *PRL* 2019



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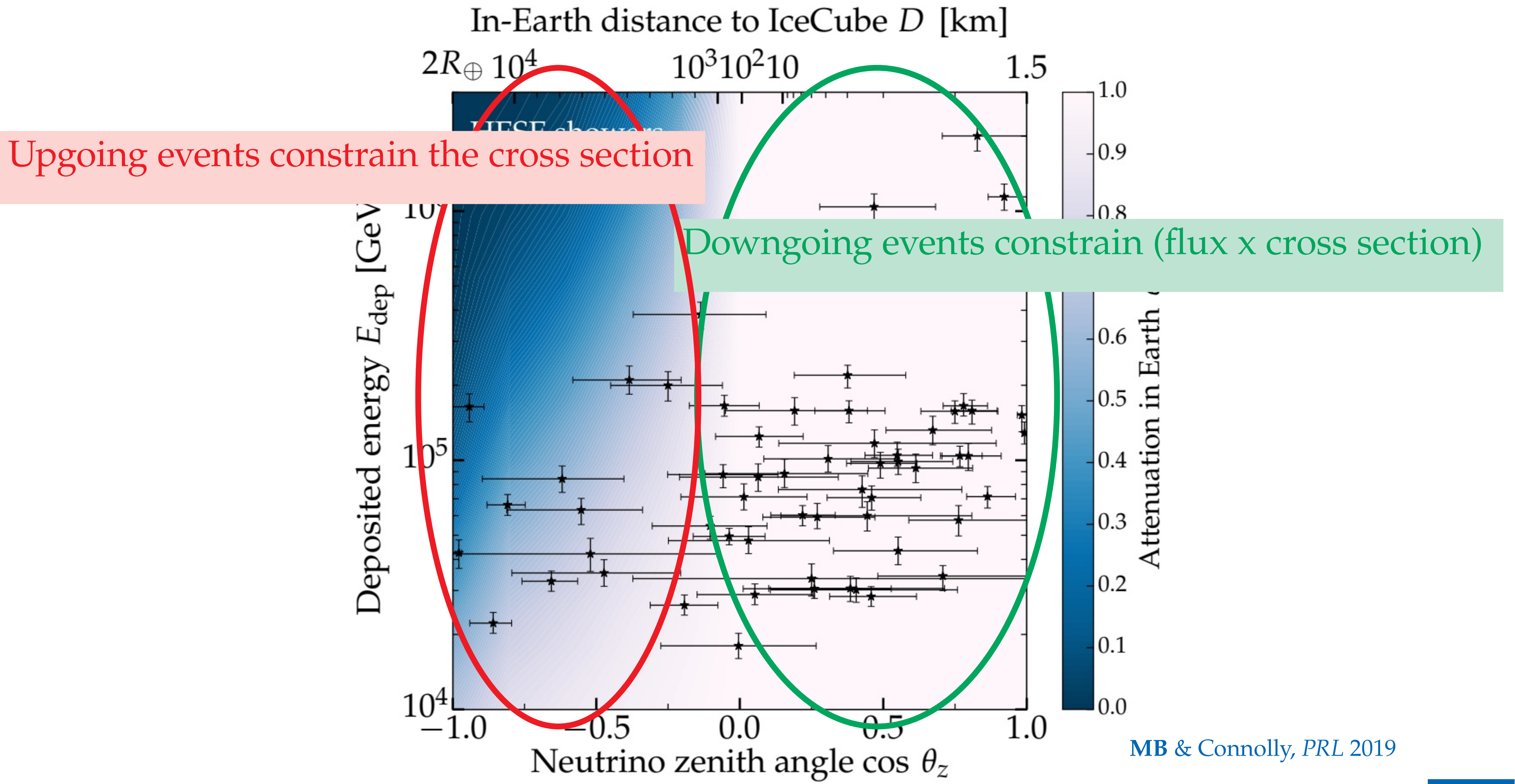

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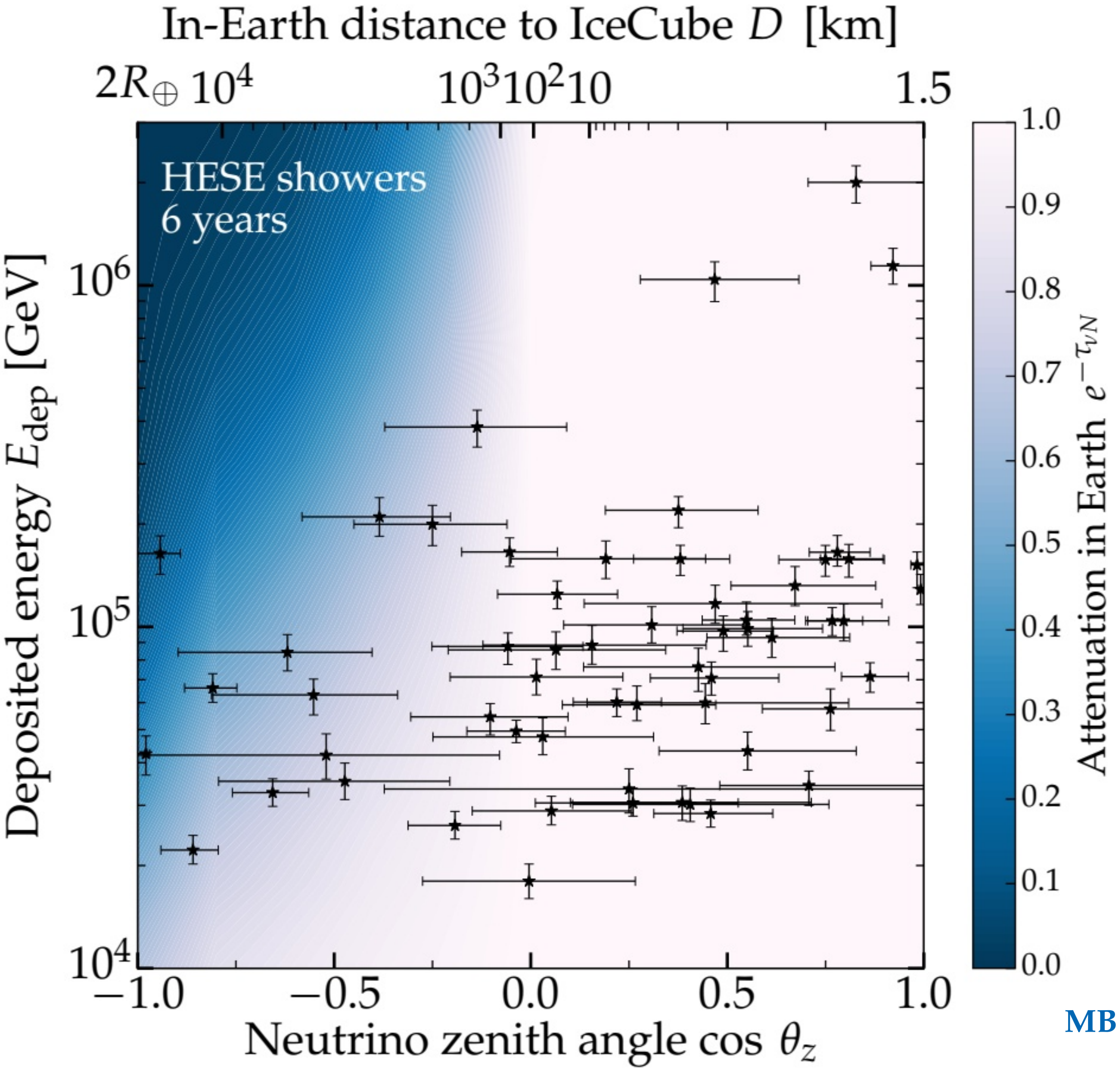

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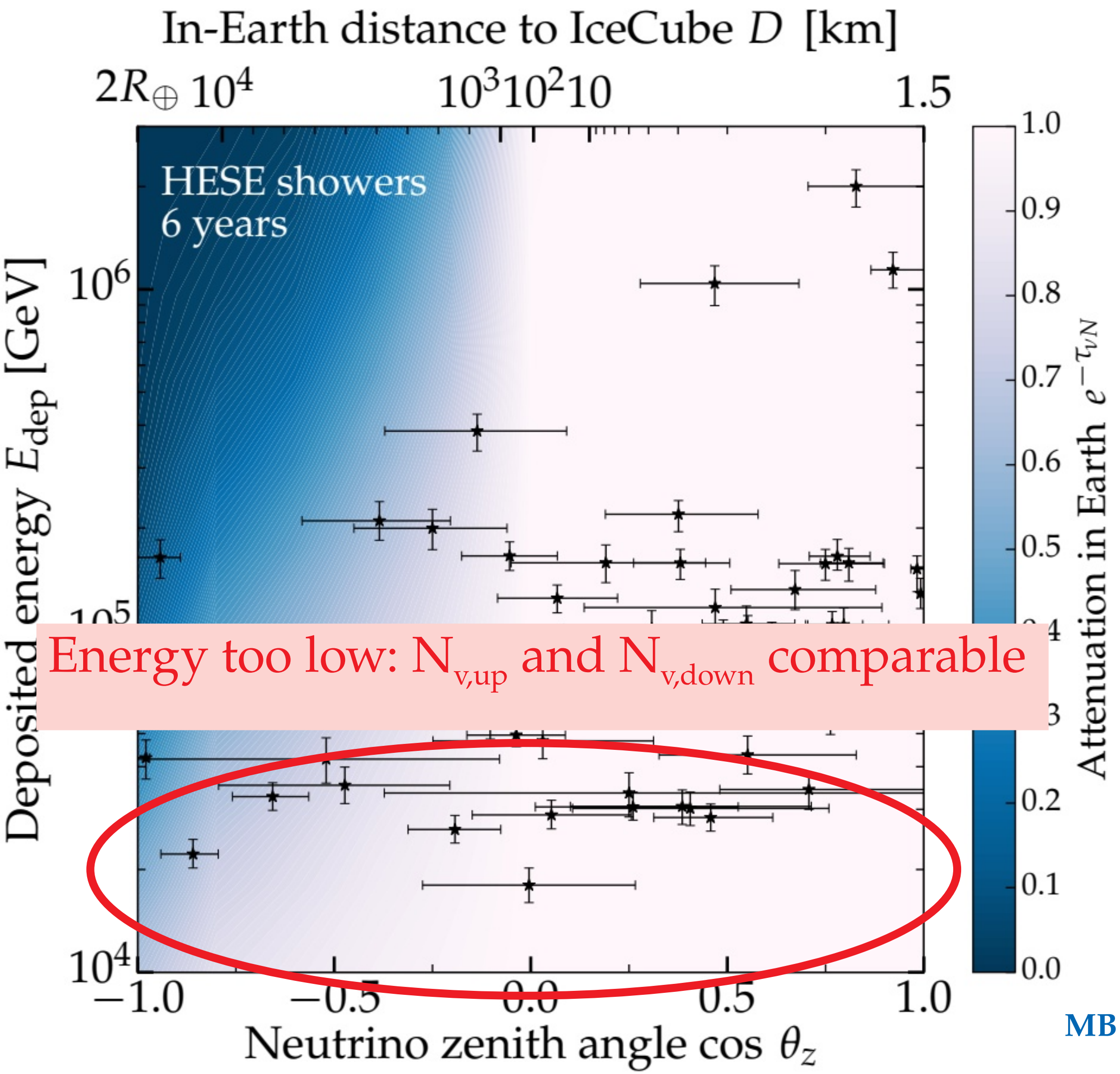

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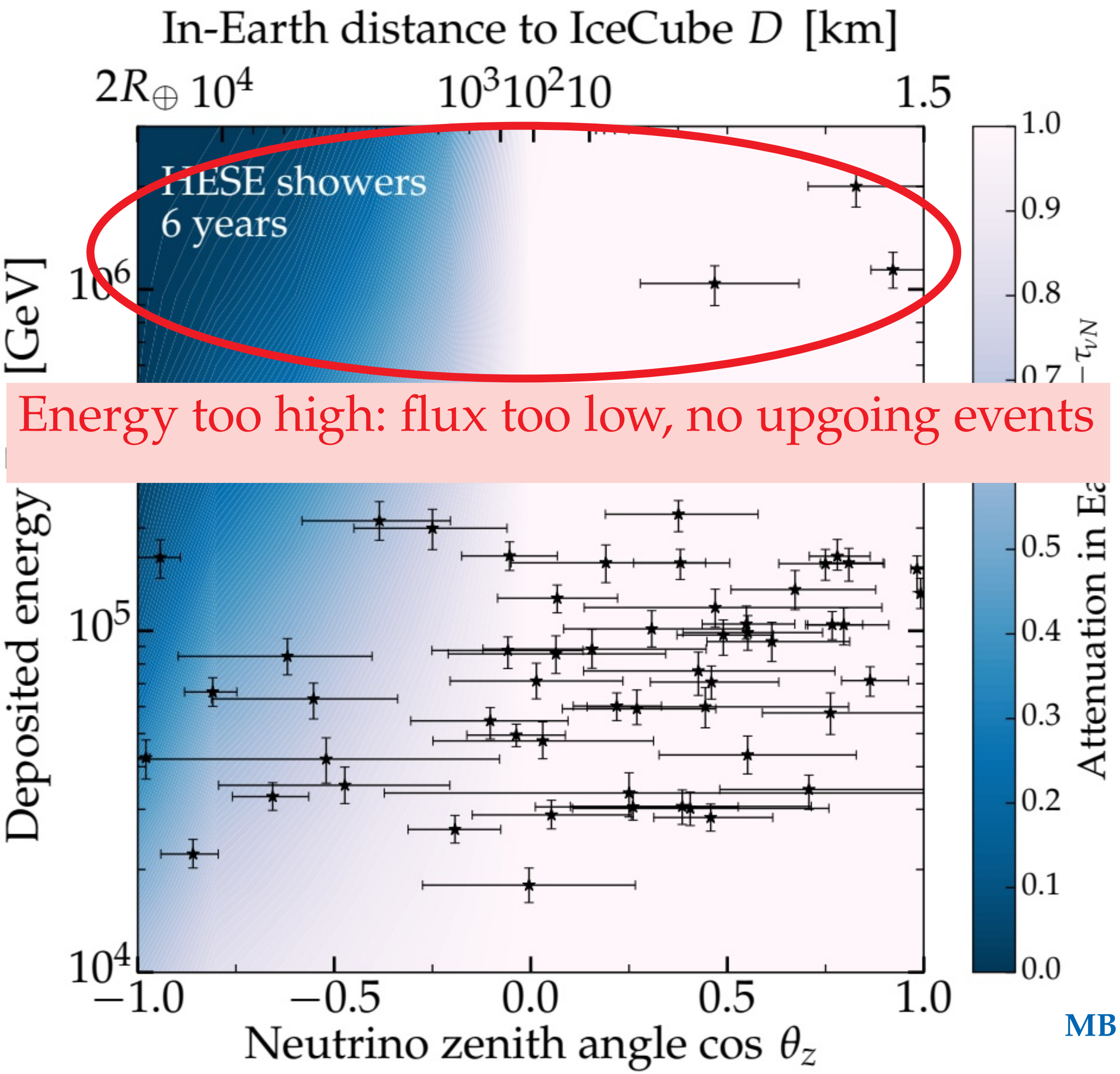
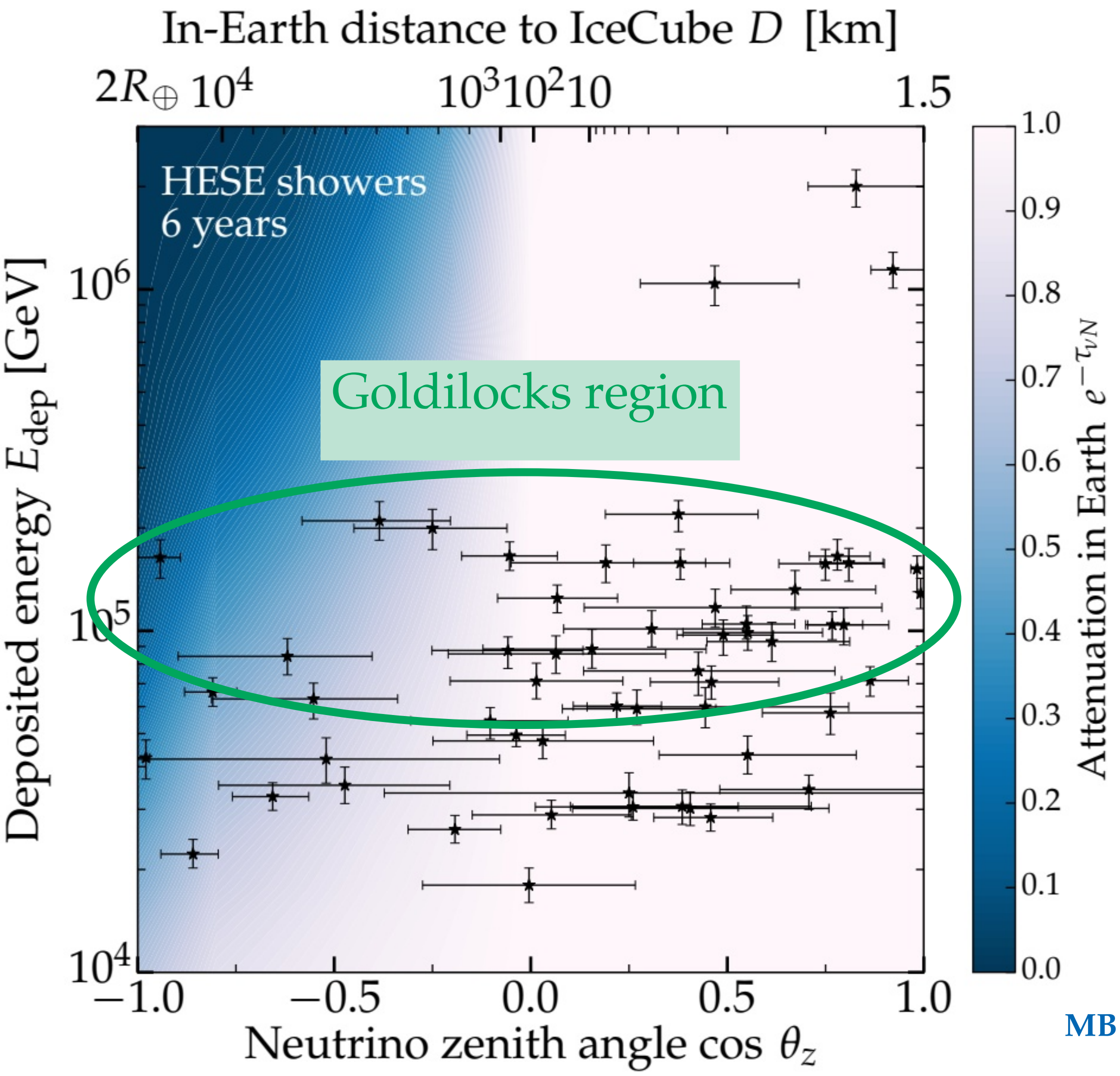
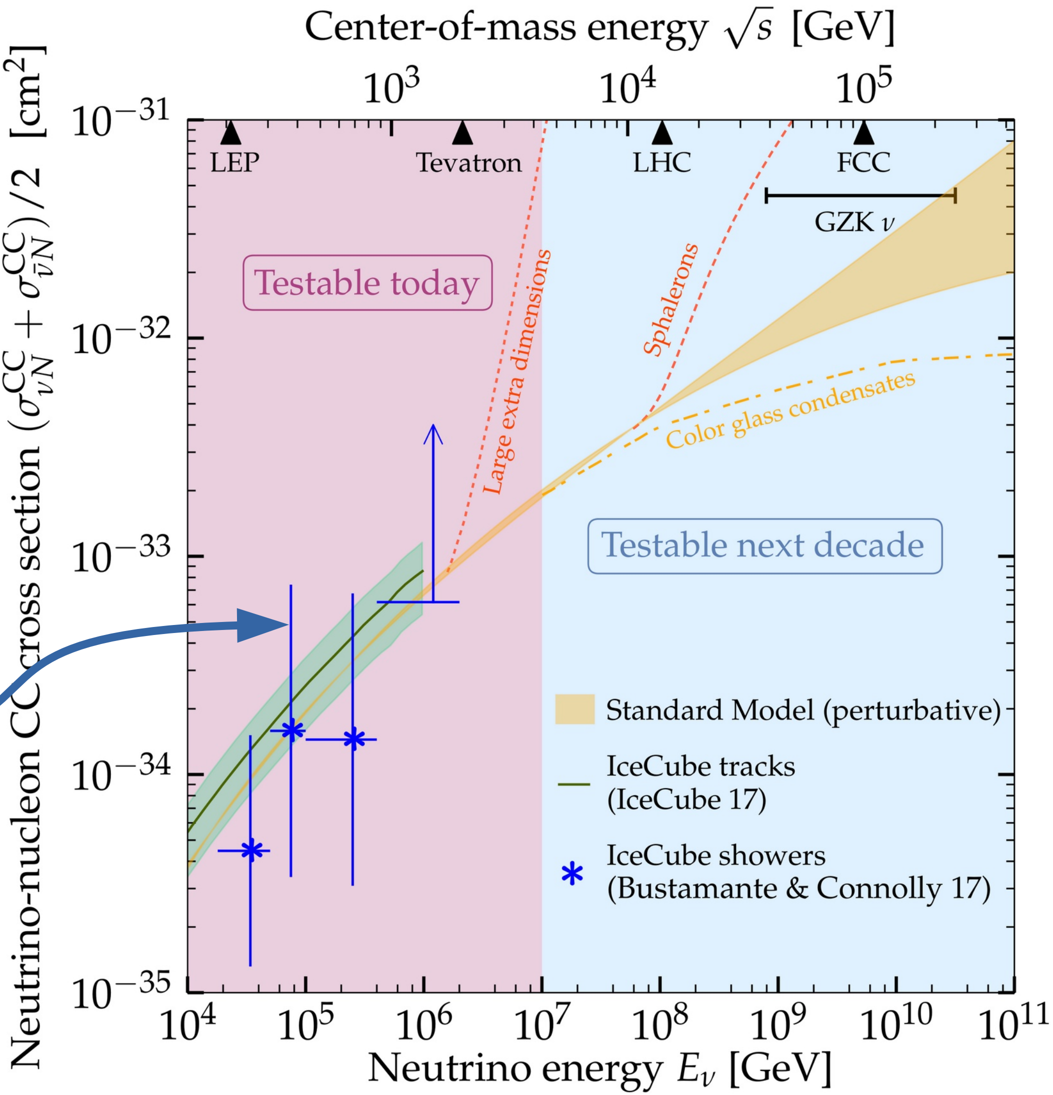


MB & Connolly, *PRL* 2019



MB & Connolly, *PRL* 2019

- Fold in astrophysical unknowns (spectral index, normalization)
- Compatible with SM predictions
- Still room for new physics
- Today, using IceCube:
  - Extracted from ~60 showers in 6 yr
  - Limited by statistics
- Future, using IceCube-Gen2:
  - $\times$ 5 volume $\Rightarrow$ 300 showers in 6 yr
  - Reduce statistical error by 40%



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

Cross sections from:
MB & Connolly *PRL* 2019
IceCube, *Nature* 2017

UHE uncertainties are actually smaller:
Cooper-Sarkar, Mertsch, Sarkar *et al.*, *JHEP* 2011

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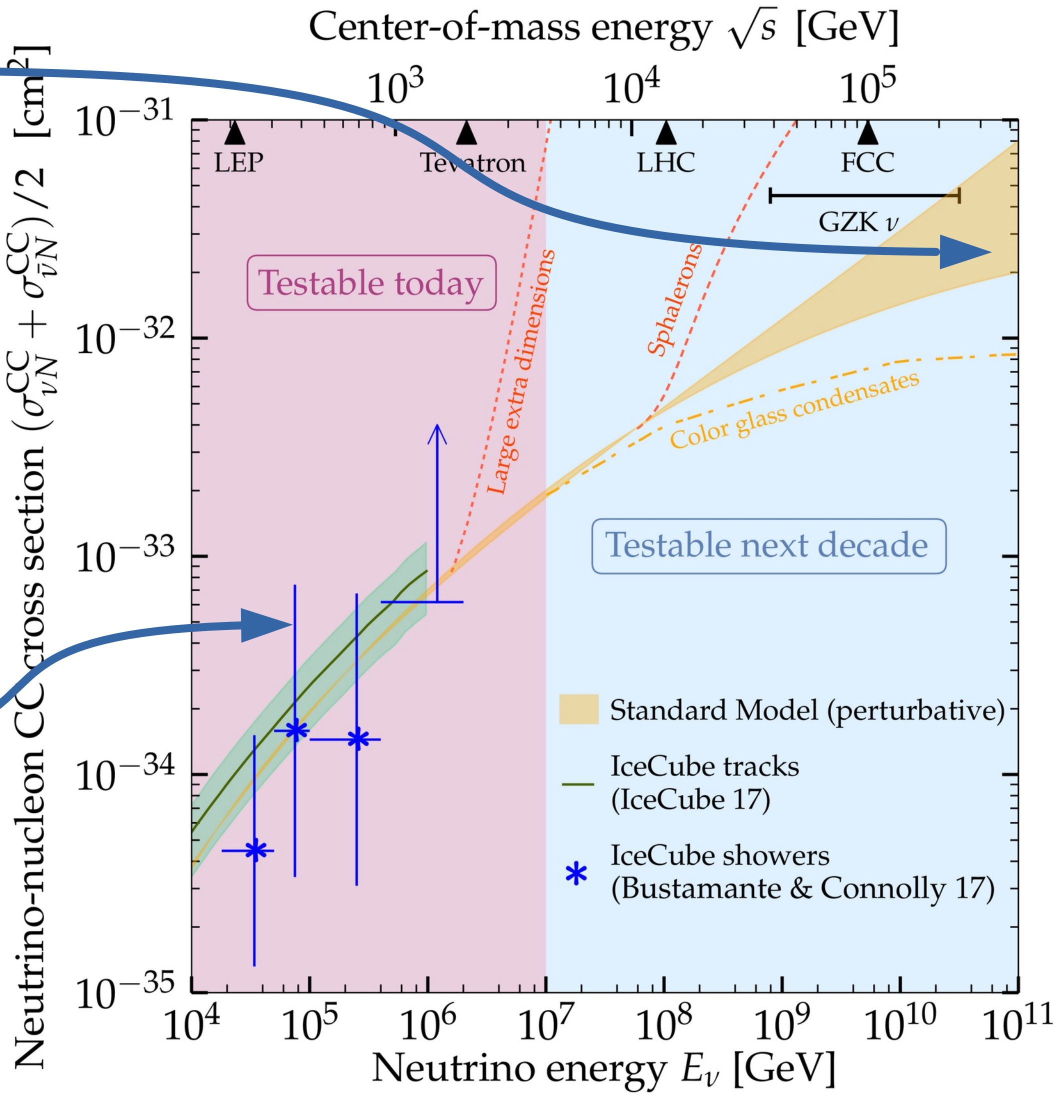

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Secret neutrino interactions

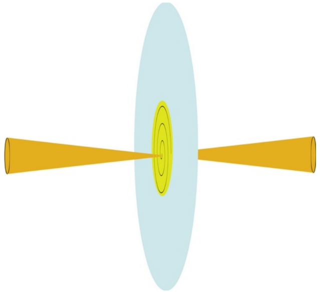
Astrophysical neutrino sources

Earth

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

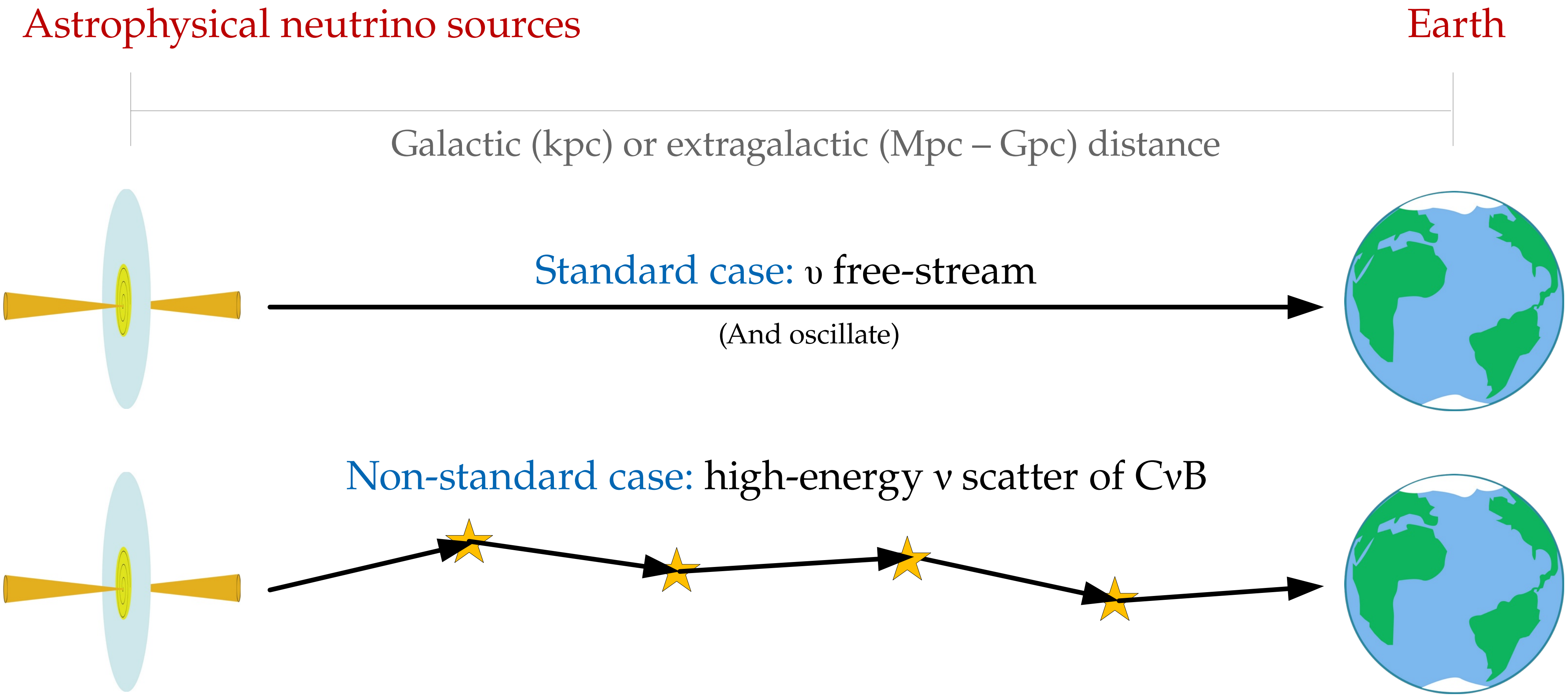
Astrophysical neutrino sources   Earth

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

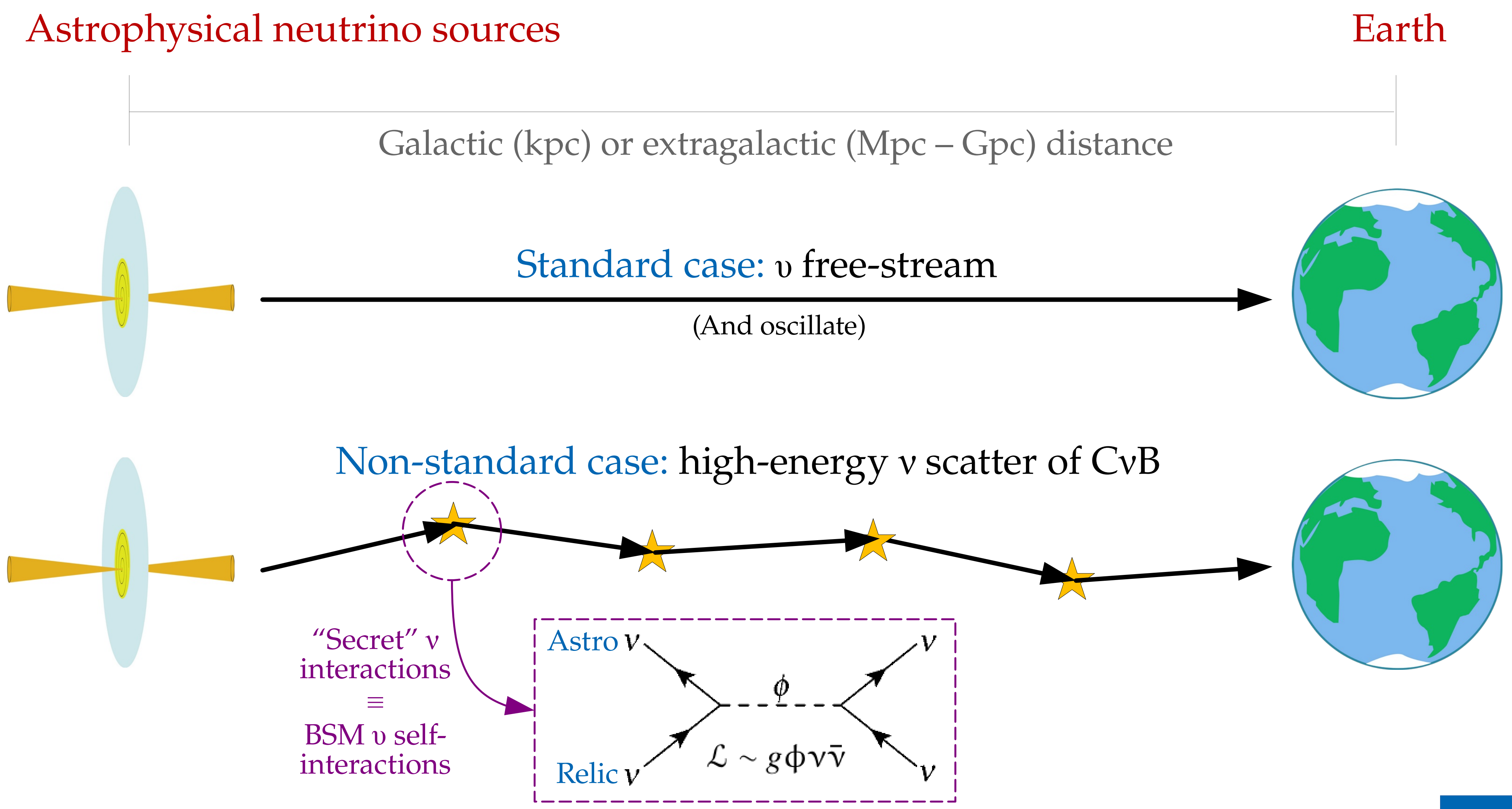


Standard case: υ free-stream

(And oscillate)



Astrophysical neutrino sources
Earth
Galactic (kpc) or extragalactic (Mpc – Gpc) distance
Standard case: υ free-stream
(And oscillate)
Non-standard case: high-energy ν scatter of CνB


Astrophysical neutrino sources
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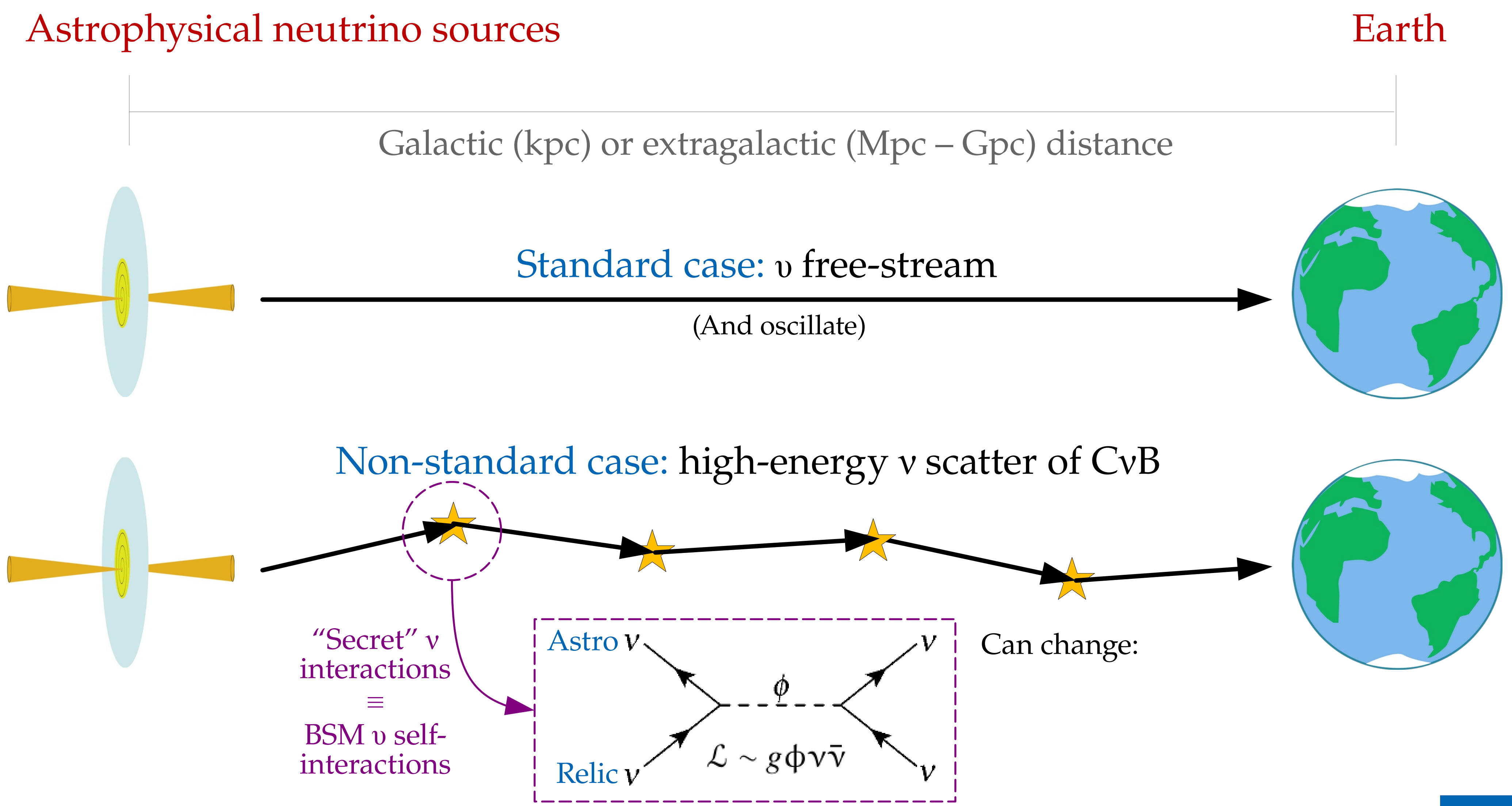
Non-standard case: high-energy ν scatter of CνB
"Secret" ν interactions ≡ BSM υ self-interactions
Astro ν
Relic ν
ν
ν
ϕ
$\mathcal{L} \sim g\phi\nu\bar{\nu}$



Astrophysical neutrino sources
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≡
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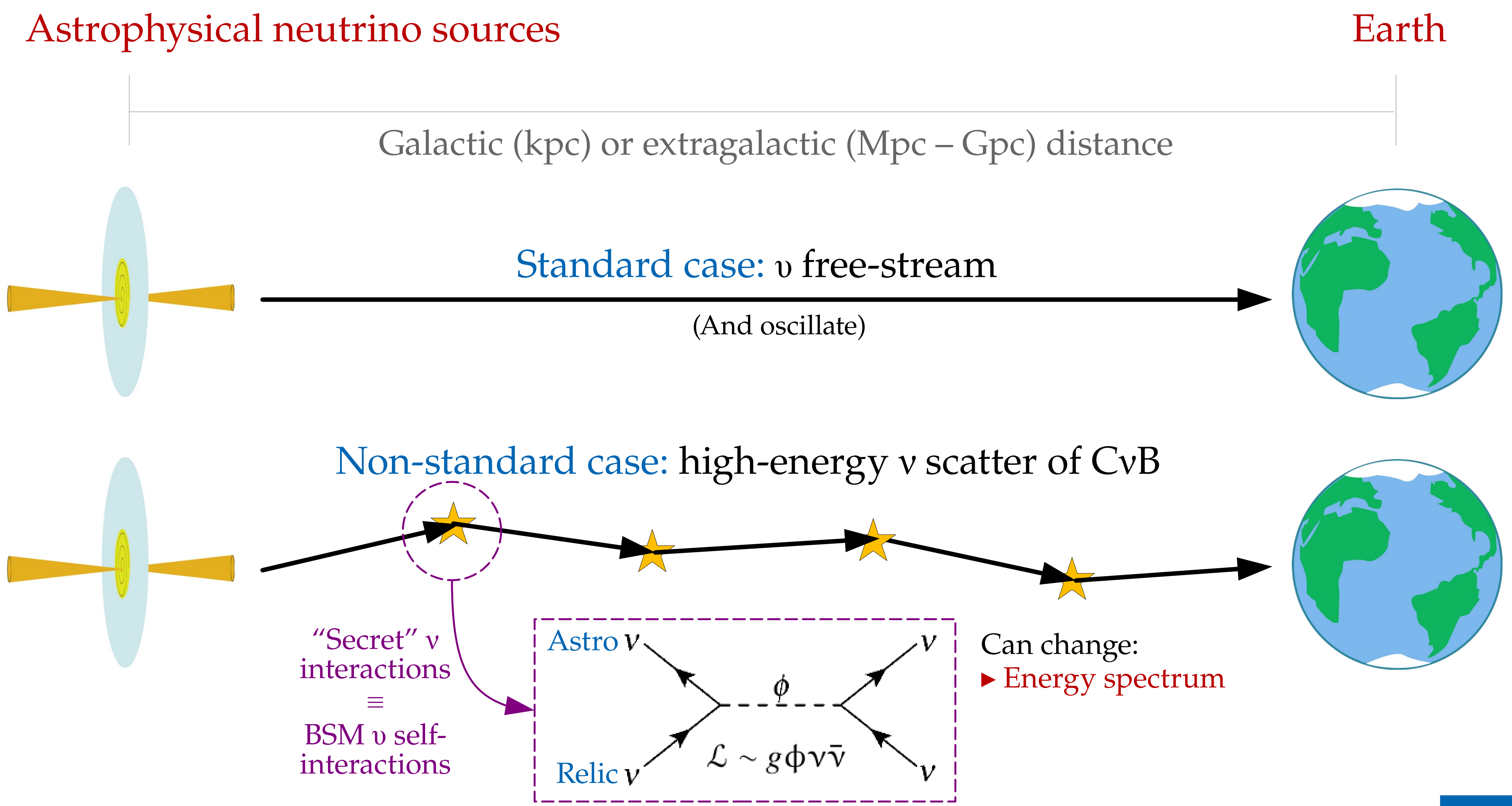
Can change: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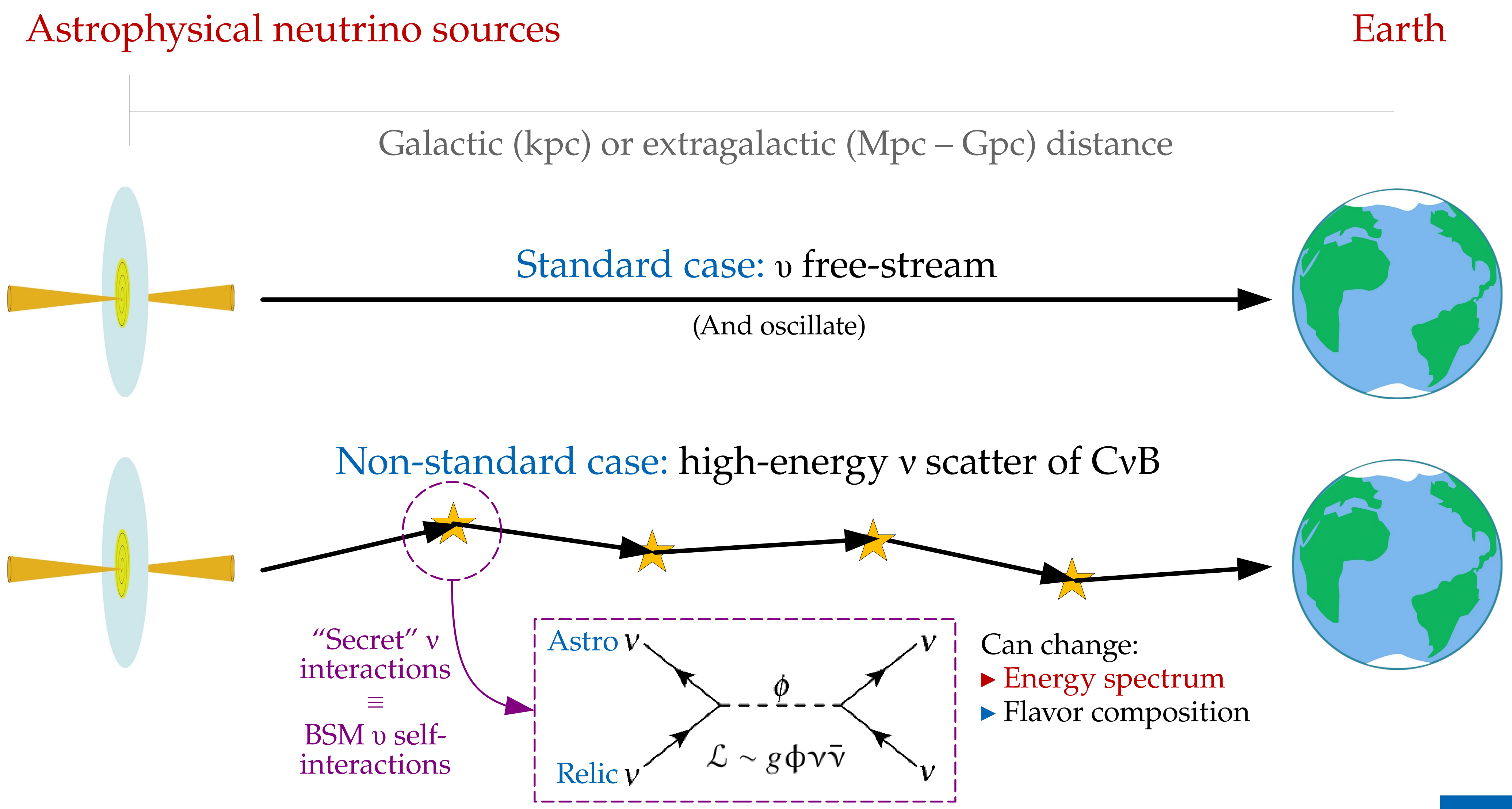
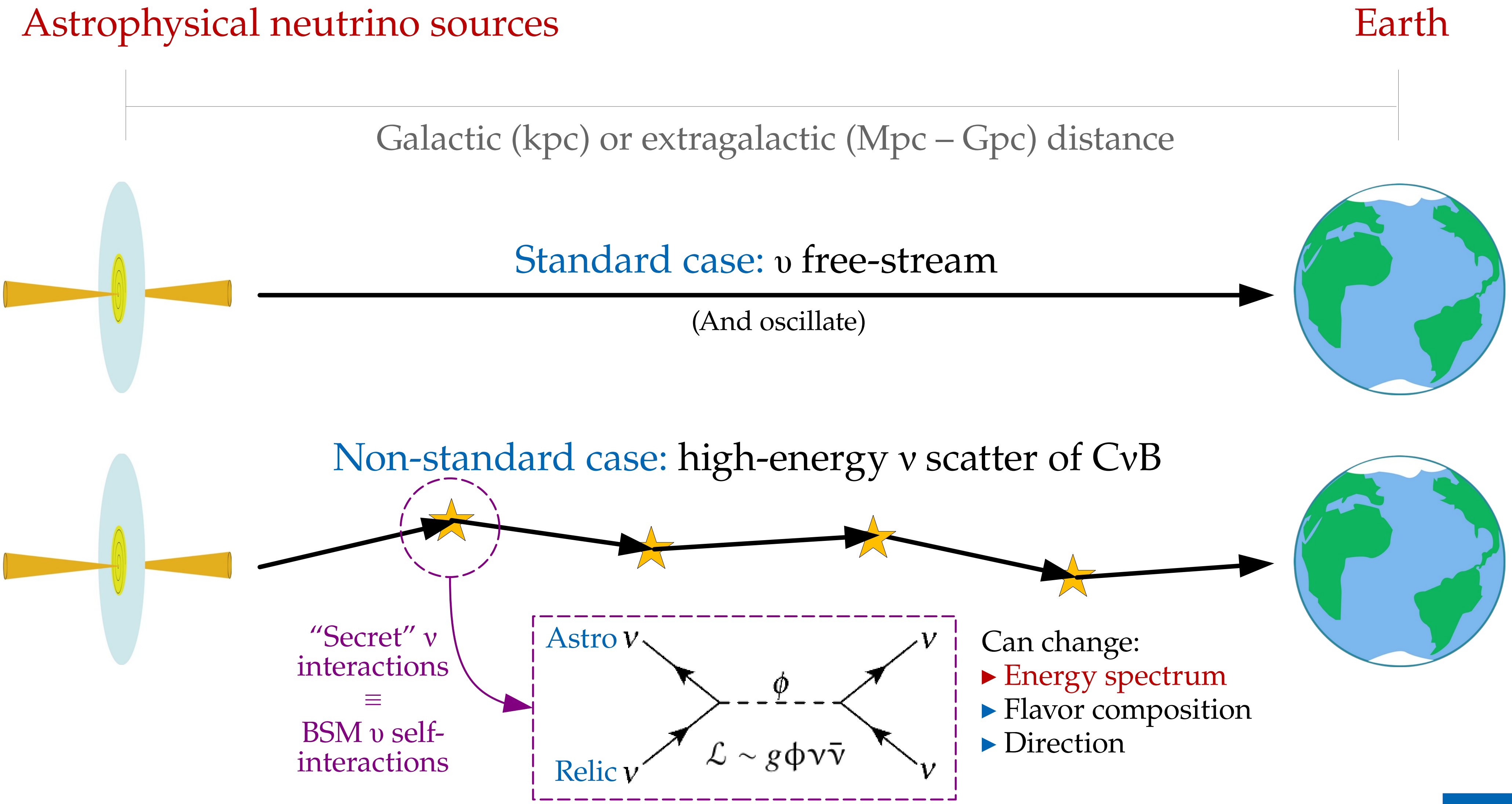
$\mathcal{L} \sim g\phi\nu\bar{\nu}$
Can change:
▸ Energy spectrum



Astrophysical neutrino sources
Earth
Galactic (kpc) or extragalactic (Mpc – Gpc) distance
Standard case: υ free-stream
(And oscillate)
Non-standard case: high-energy ν scatter of CνB
"Secret" ν interactions ≡ BSM υ self-interactions
Astro ν
Relic ν
ϕ
ν
ν
$\mathcal{L} \sim g\phi\nu\bar{\nu}$
Can change:
▸ Energy spectrum
▸ Flavor composition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▸ Direction

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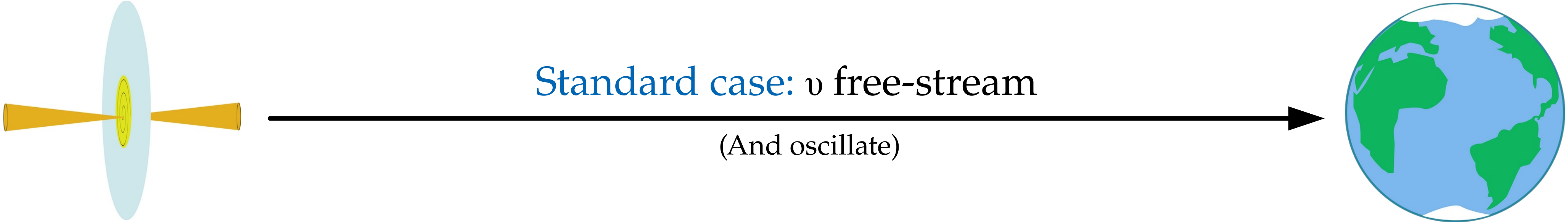

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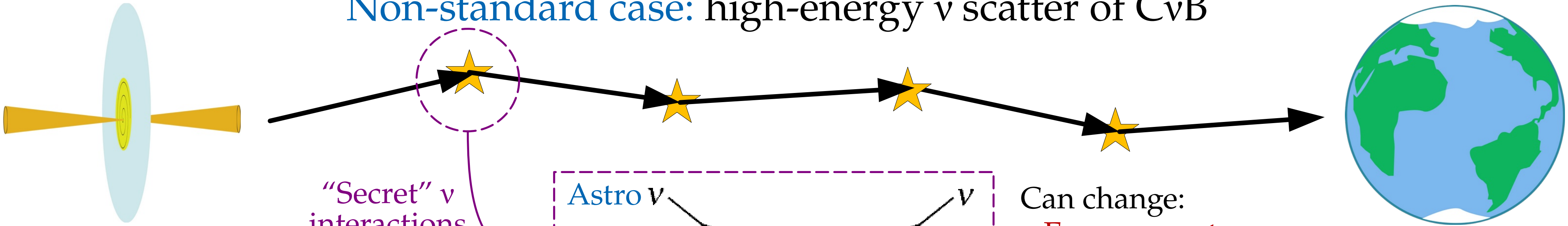

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≡
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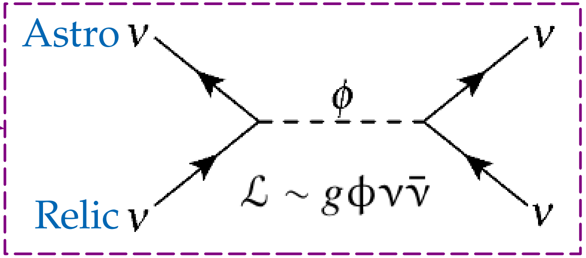
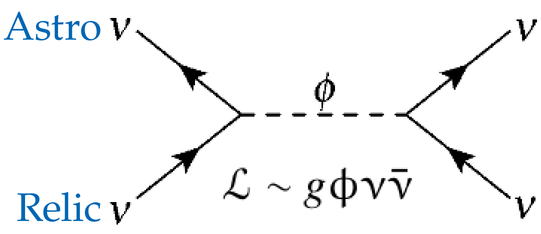


Can change:

- Energy spectrum
- Flavor composition
- Direction
- Arrival times

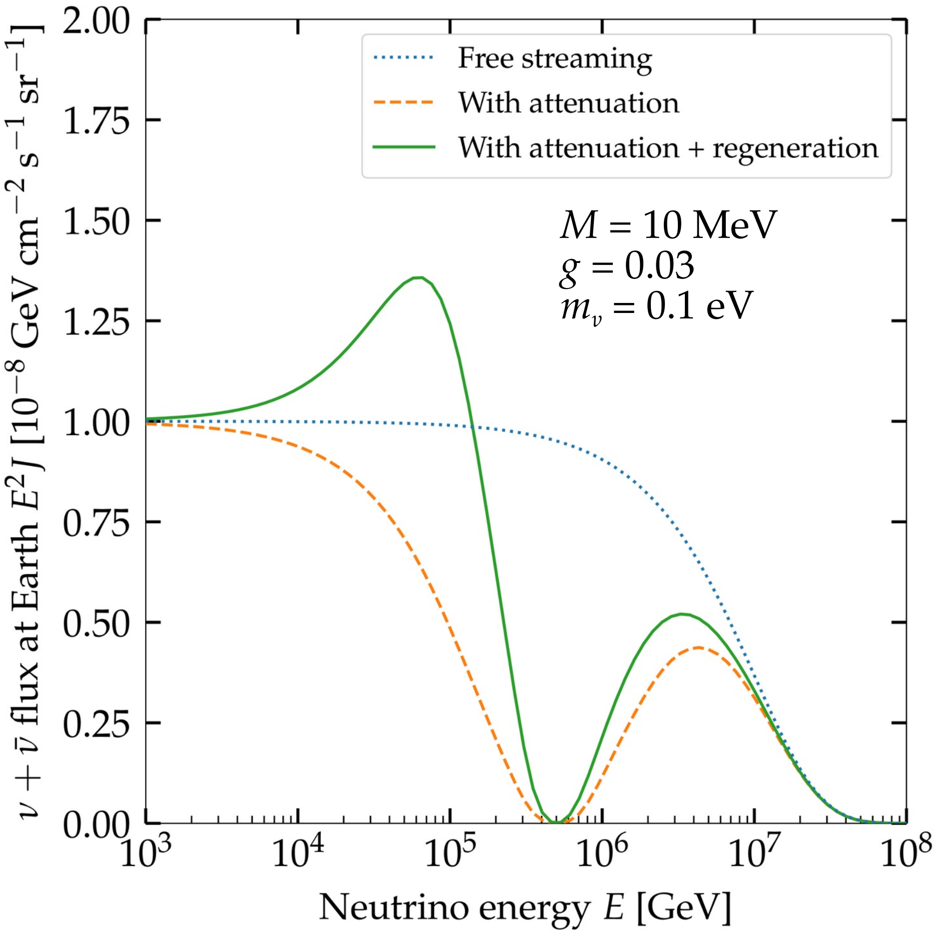
Secret interactions of high-energy astrophysical neutrinos

"Secret" neutrino interactions between astrophysical ν (PeV) and relic ν (0.1 meV):



Cross section: $\sigma = \frac{g^4}{4\pi}\frac{s}{(s-M^2)^2 + M^2\Gamma^2}$

Resonance energy: $E_{\rm res} = \frac{M^2}{2m_\nu}$



MB, Rosenstroem, Shalgar, Tamborra, *PRD* 2020 (to appear)
See also: Ng & Beacom, *PRD* 2014
Cherry, Friedland, Shoemaker, 1411.1071
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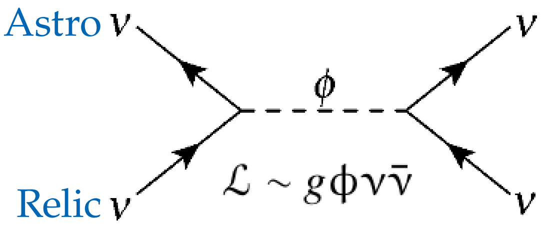

New coupling

Cross section: $$\sigma = \frac{g^4}{4\pi} \frac{s}{(s - M^2)^2 + M^2\Gamma^2}$$

Mediator mass

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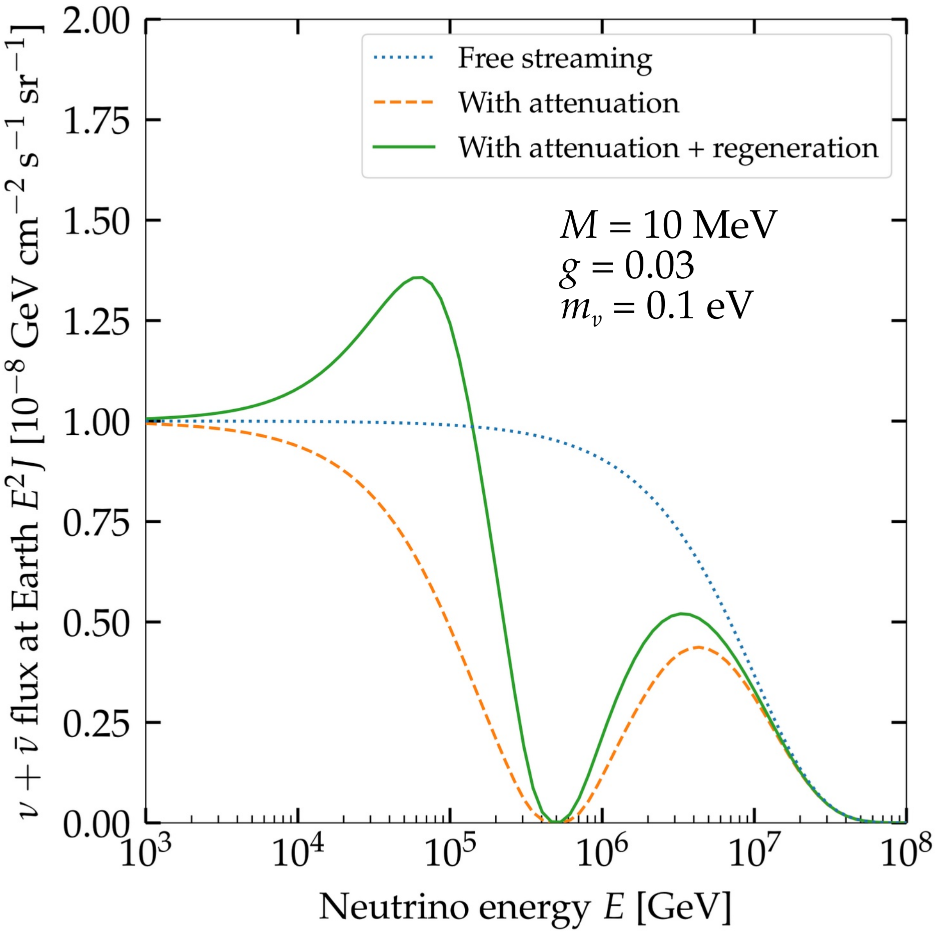

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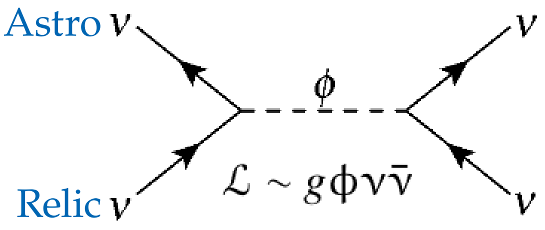

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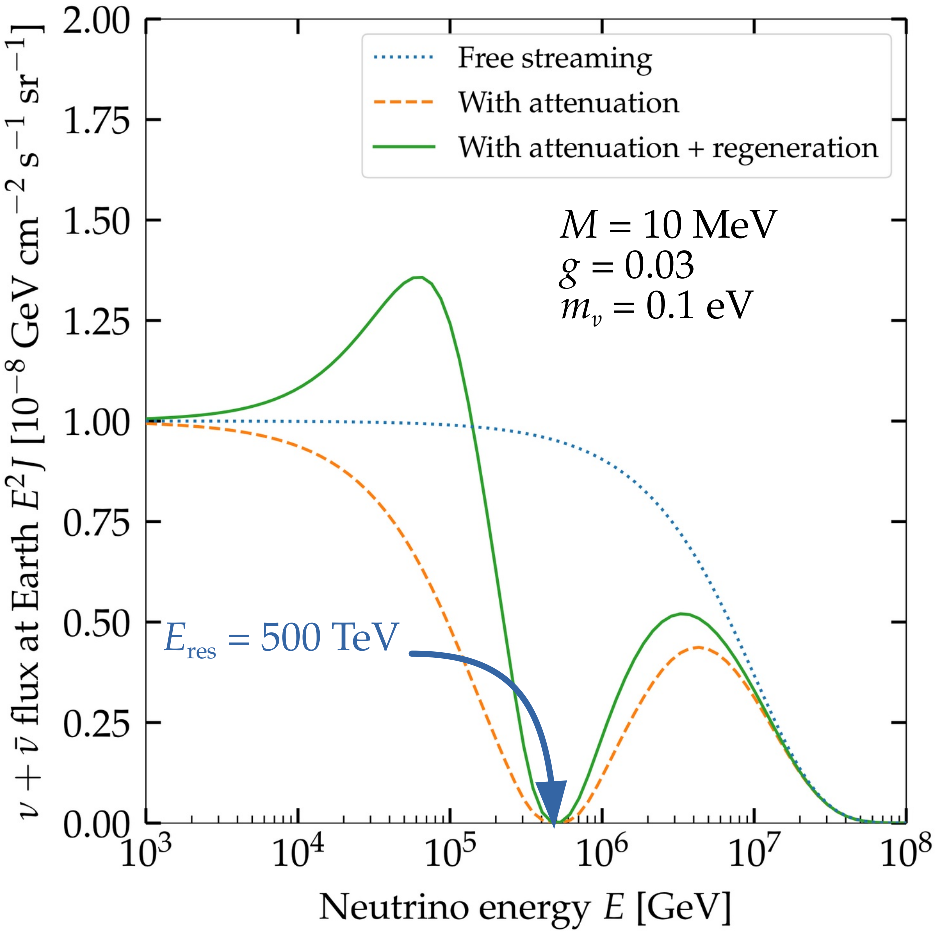

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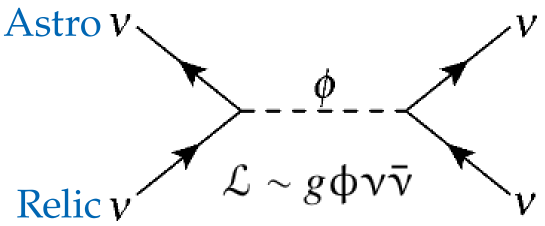

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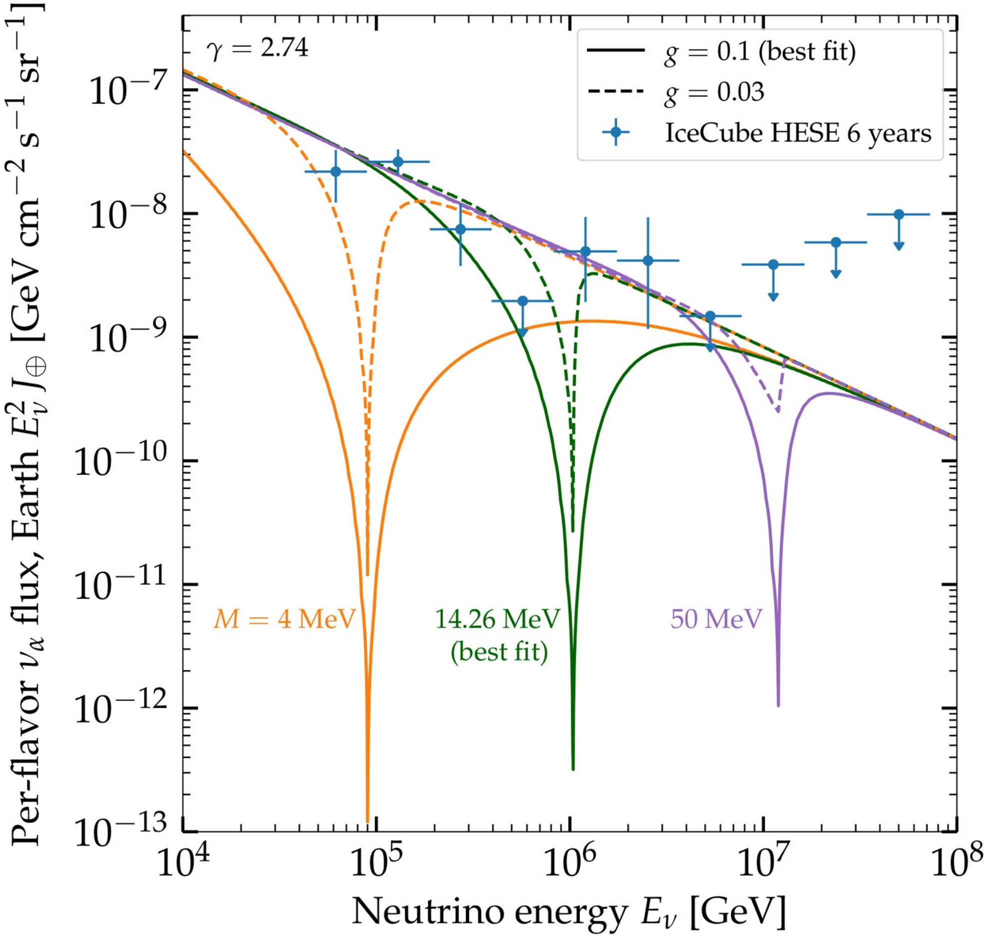

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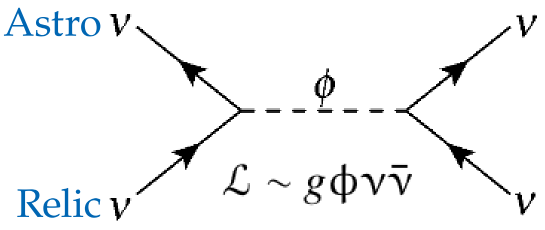

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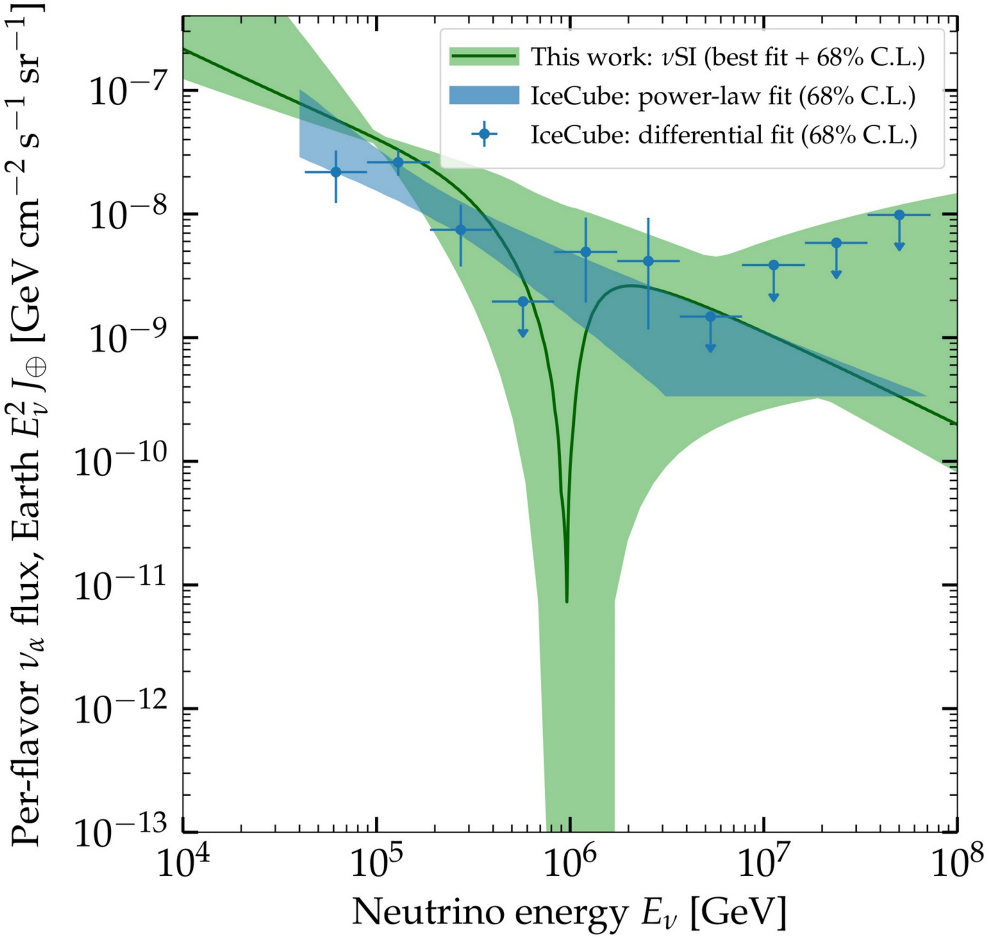
Looking for evidence of υSI

- Look for dips in 6 years of public IceCube data (HESE)
- 80 events, 18 TeV–2 PeV
- Assume flavor-diagonal and universal: $g_{\alpha\alpha} = g\,\delta_{\alpha\alpha}$
- Bayesian analysis varying M, g, shape of emitted flux (γ)
- Account for atmospheric υ, in-Earth propagation, detector uncertainties

No significant (> 3σ) evidence for a spectral dip …



MB, Rosenstroem, Shalgar, Tamborra, *PRD* 2020 (to appear)
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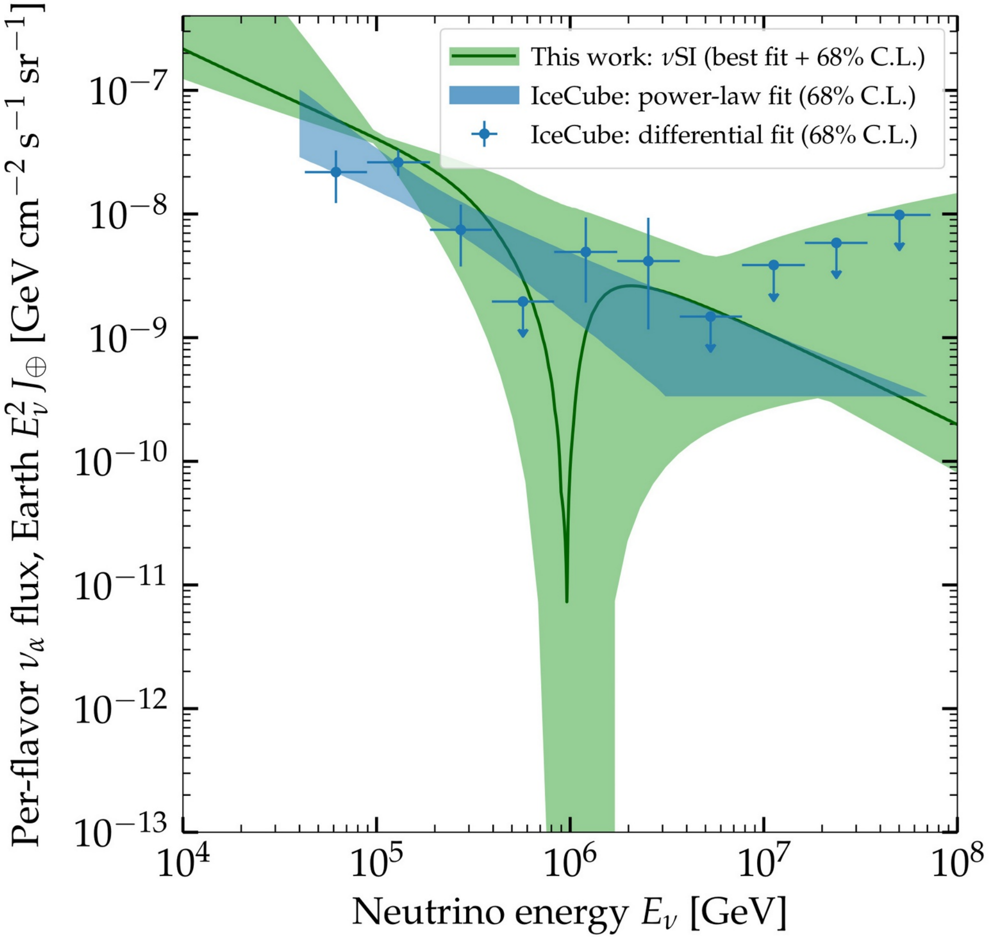

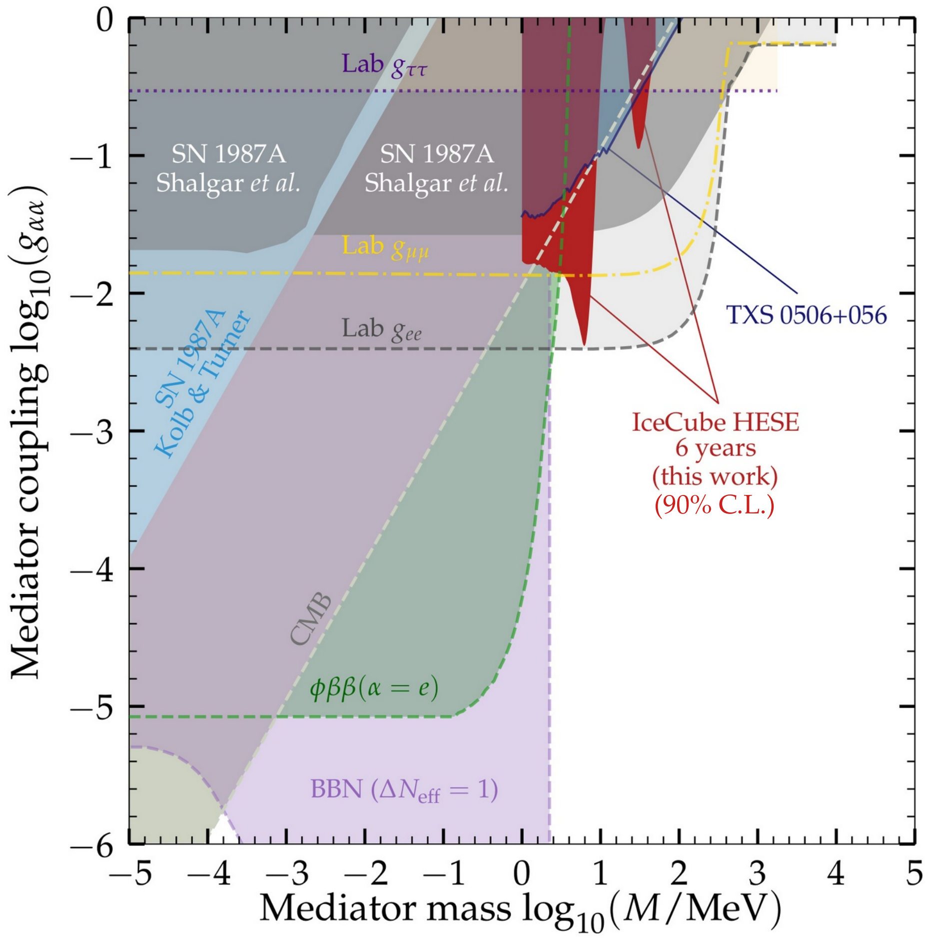

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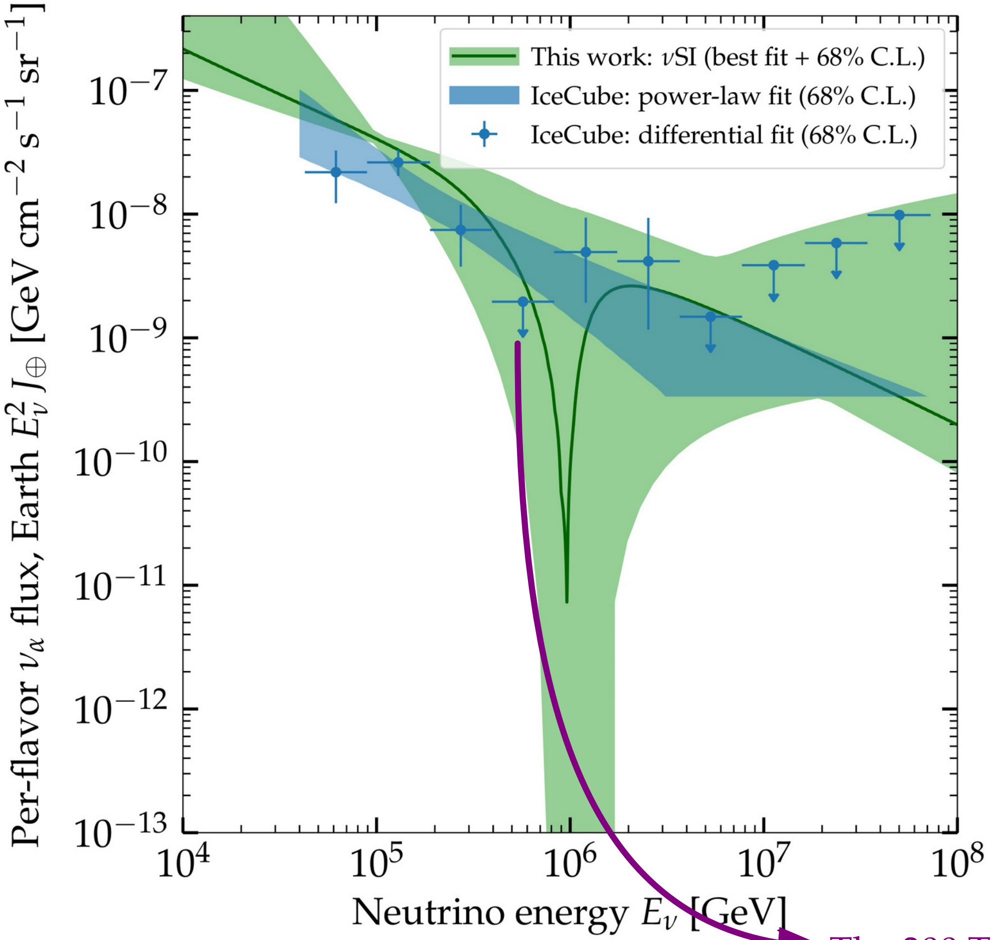
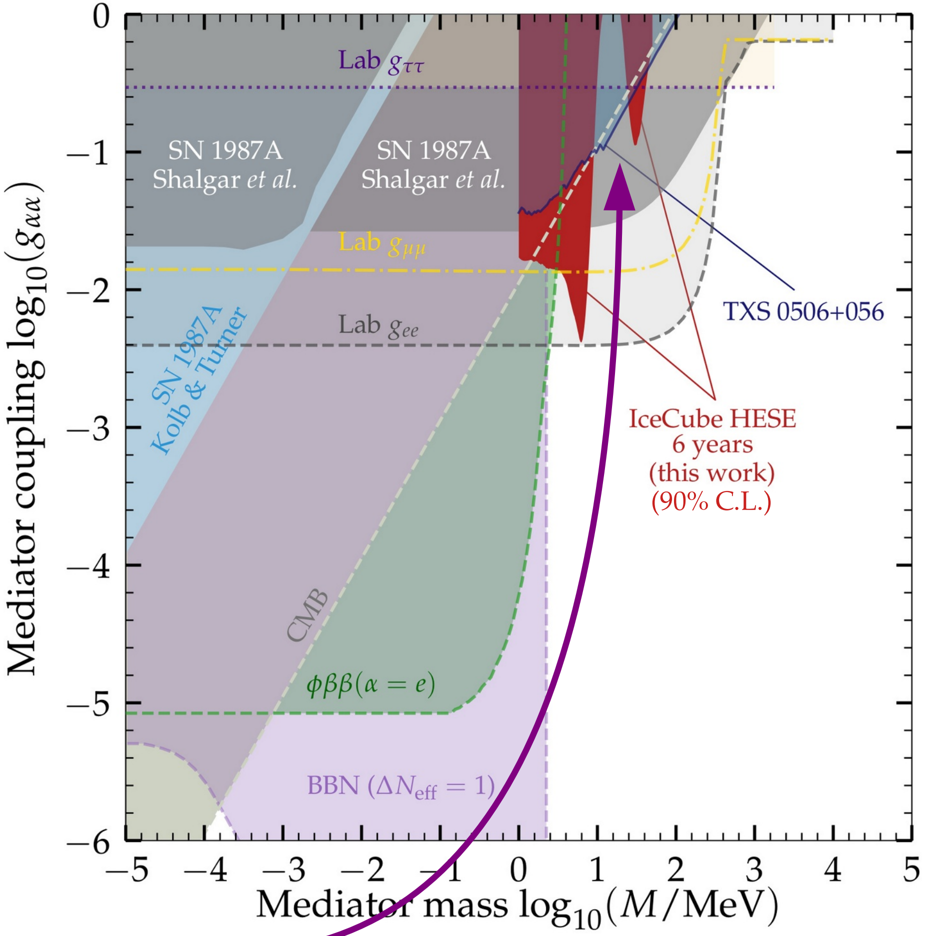


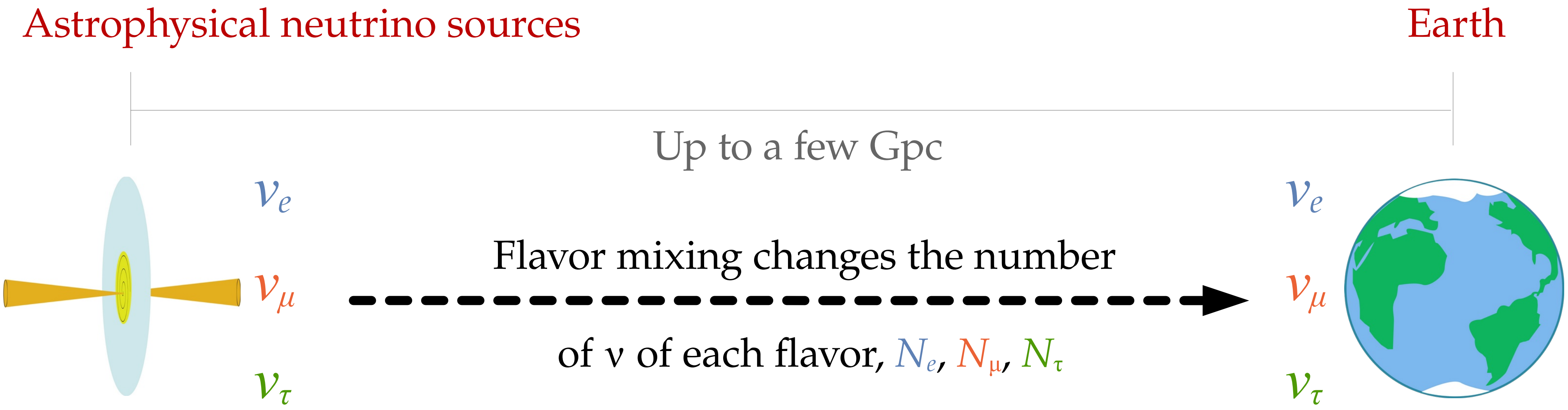


The 300 TeV–1 PeV "gap" degrades the limit at ~10 MeV

MB, Rosenstroem, Shalgar, Tamborra, *PRD* 2020 (to appear)
See also: Shalgar, **MB**, Tamborra, 1912.09115

The TeV–PeV ν flavor composition

Flavor composition



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

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

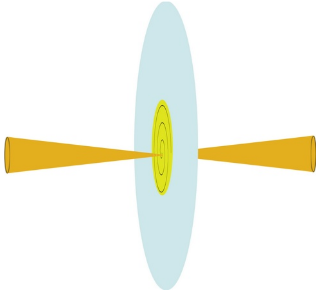
- Flavor ratios at Earth ($\alpha = e, \mu, \tau$):

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

Flavor composition

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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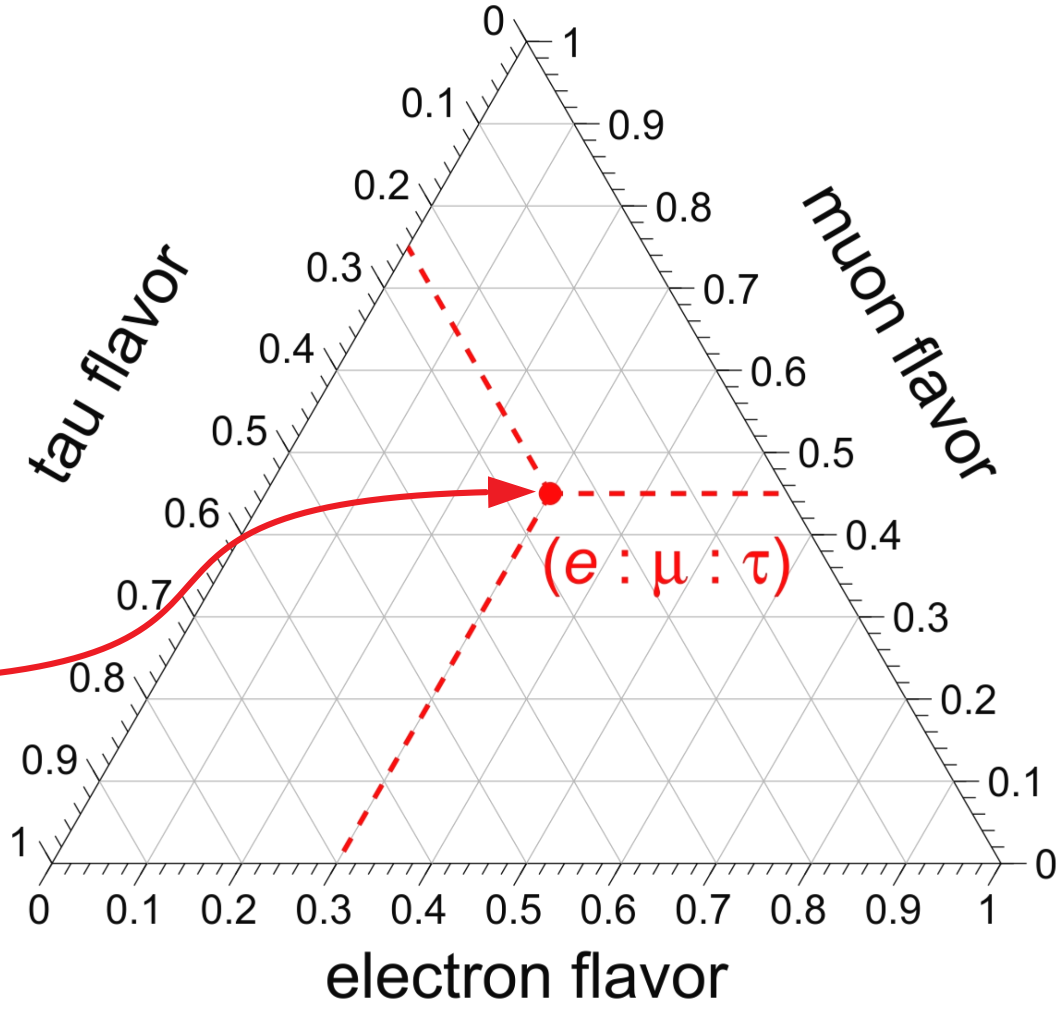
Standard oscillations
or
new physics

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.*,

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



One likely TeV–PeV ν production scenario:

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

Full π decay chain

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

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

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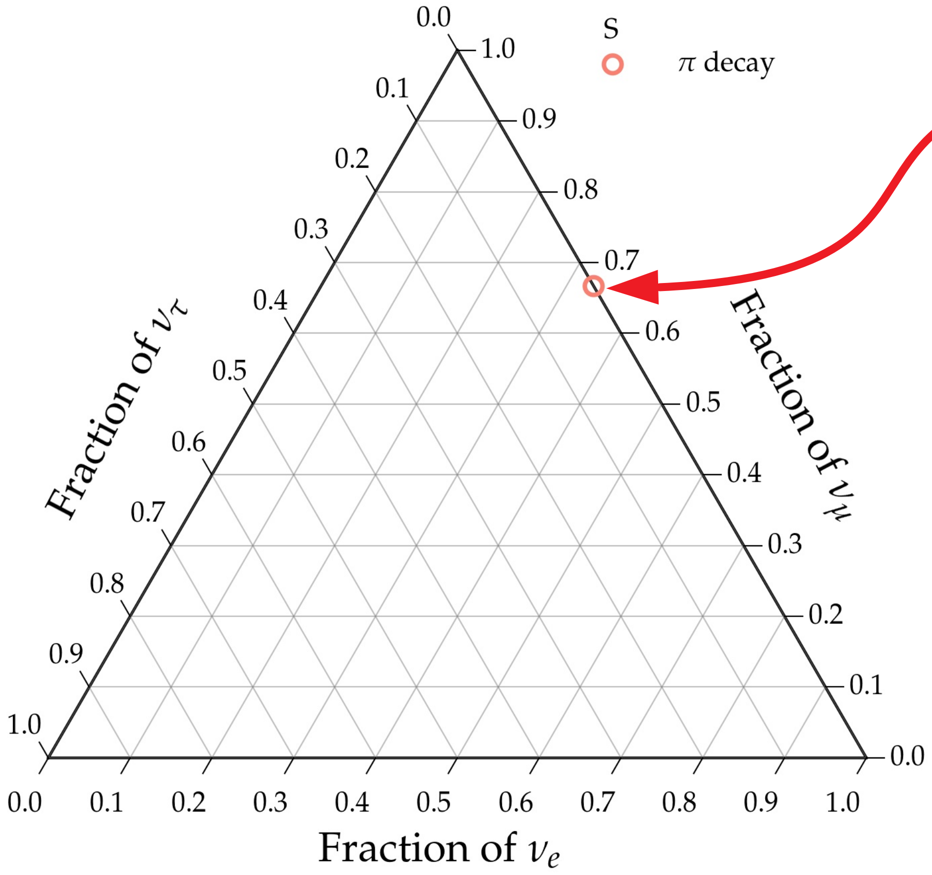

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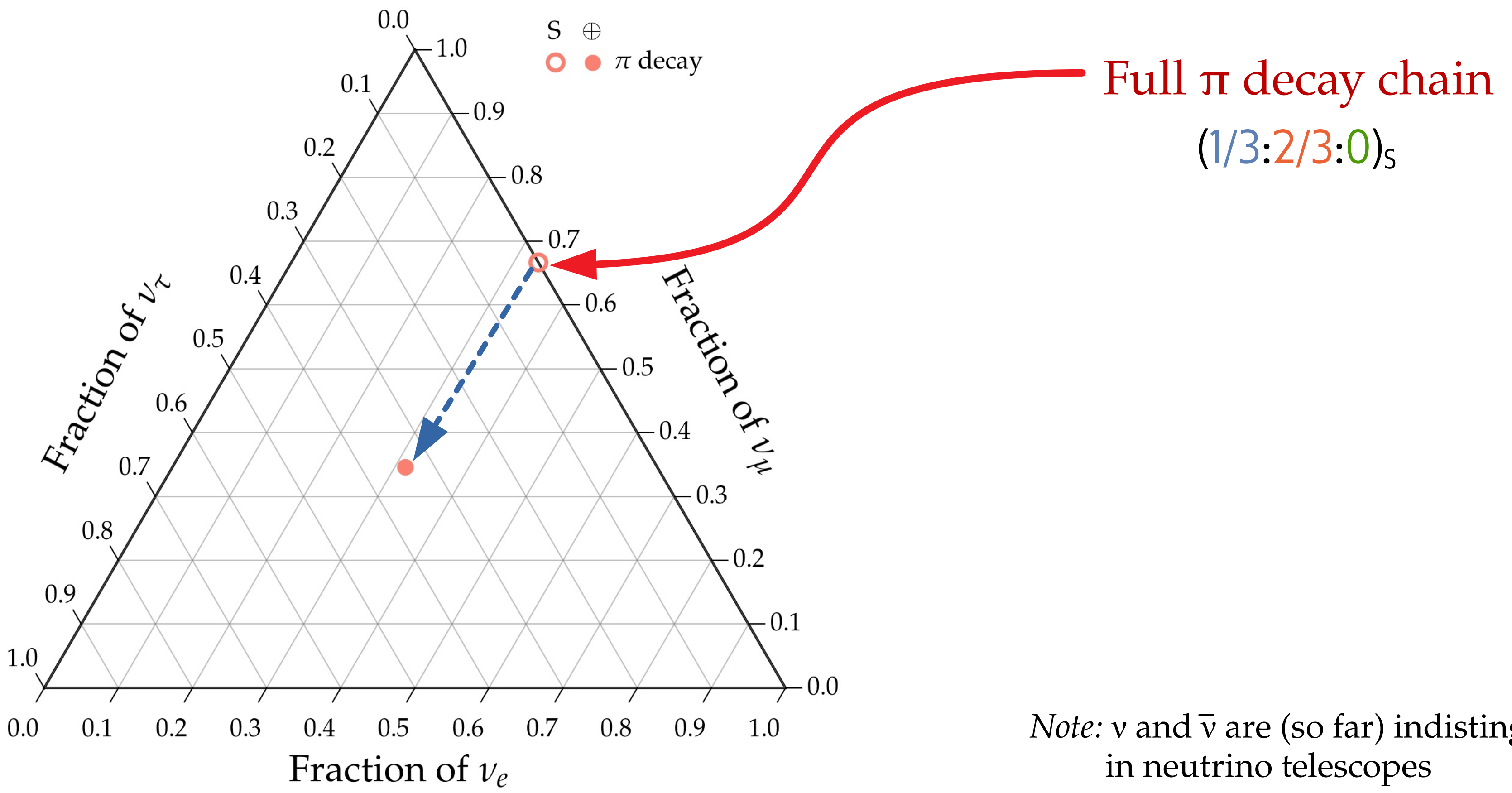

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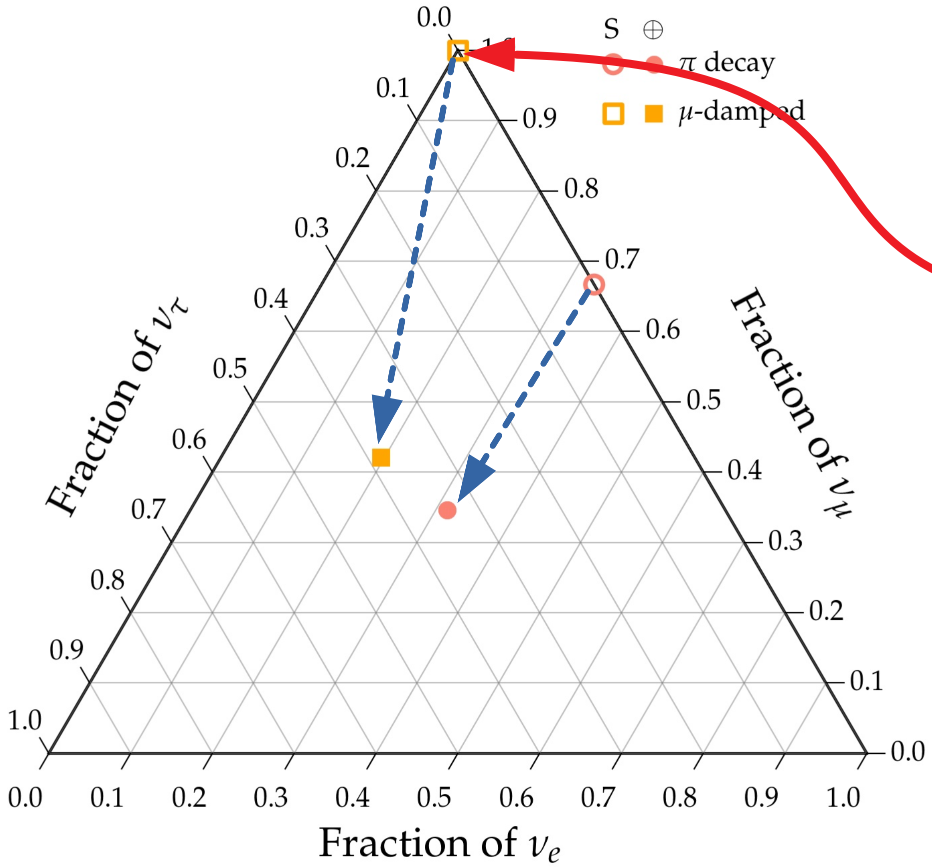

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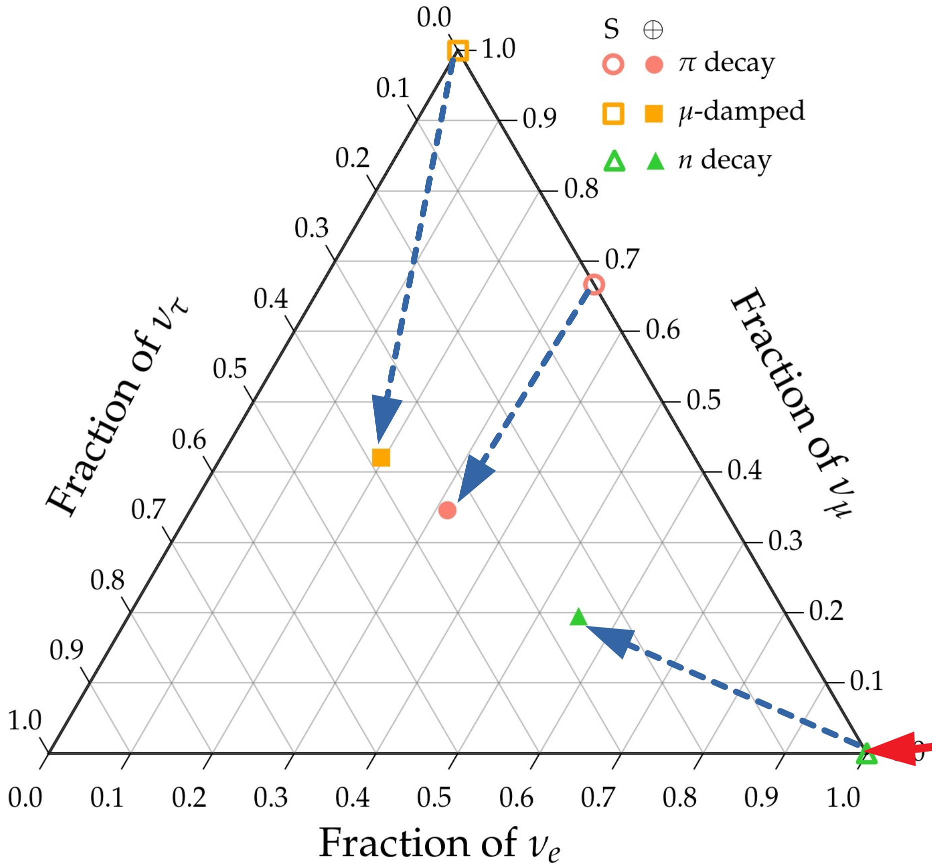

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Neutron decay

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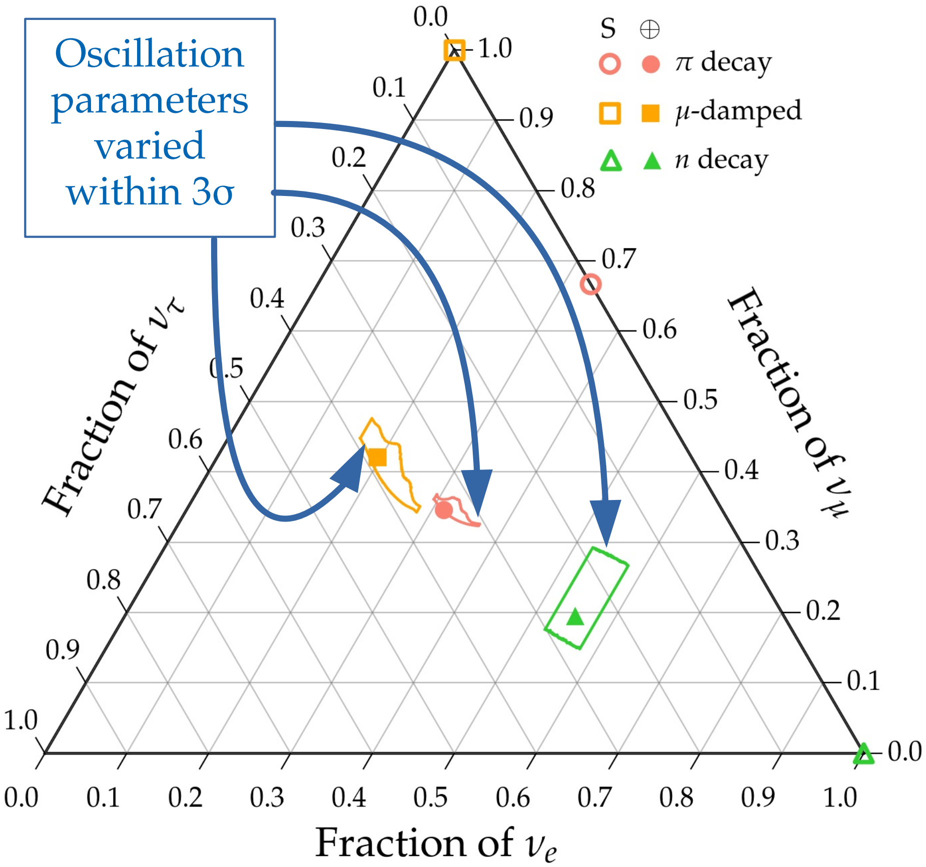

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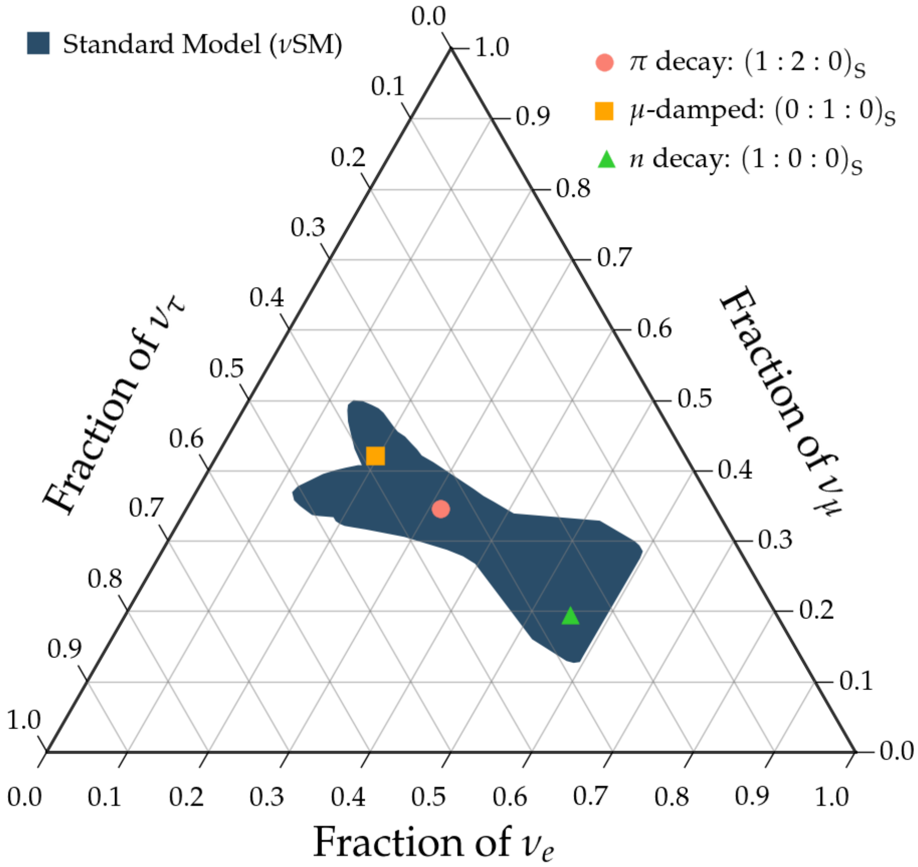


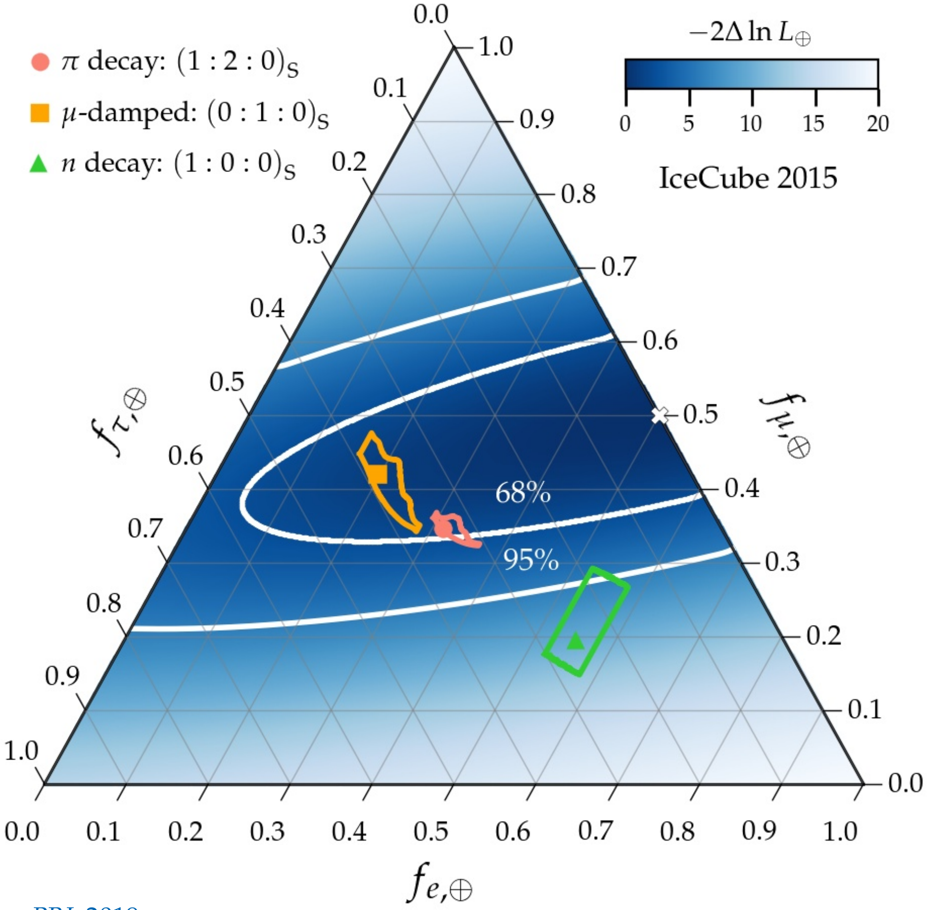
All possible flavor ratios at the sources

+

Vary oscillation parameters within 3σ

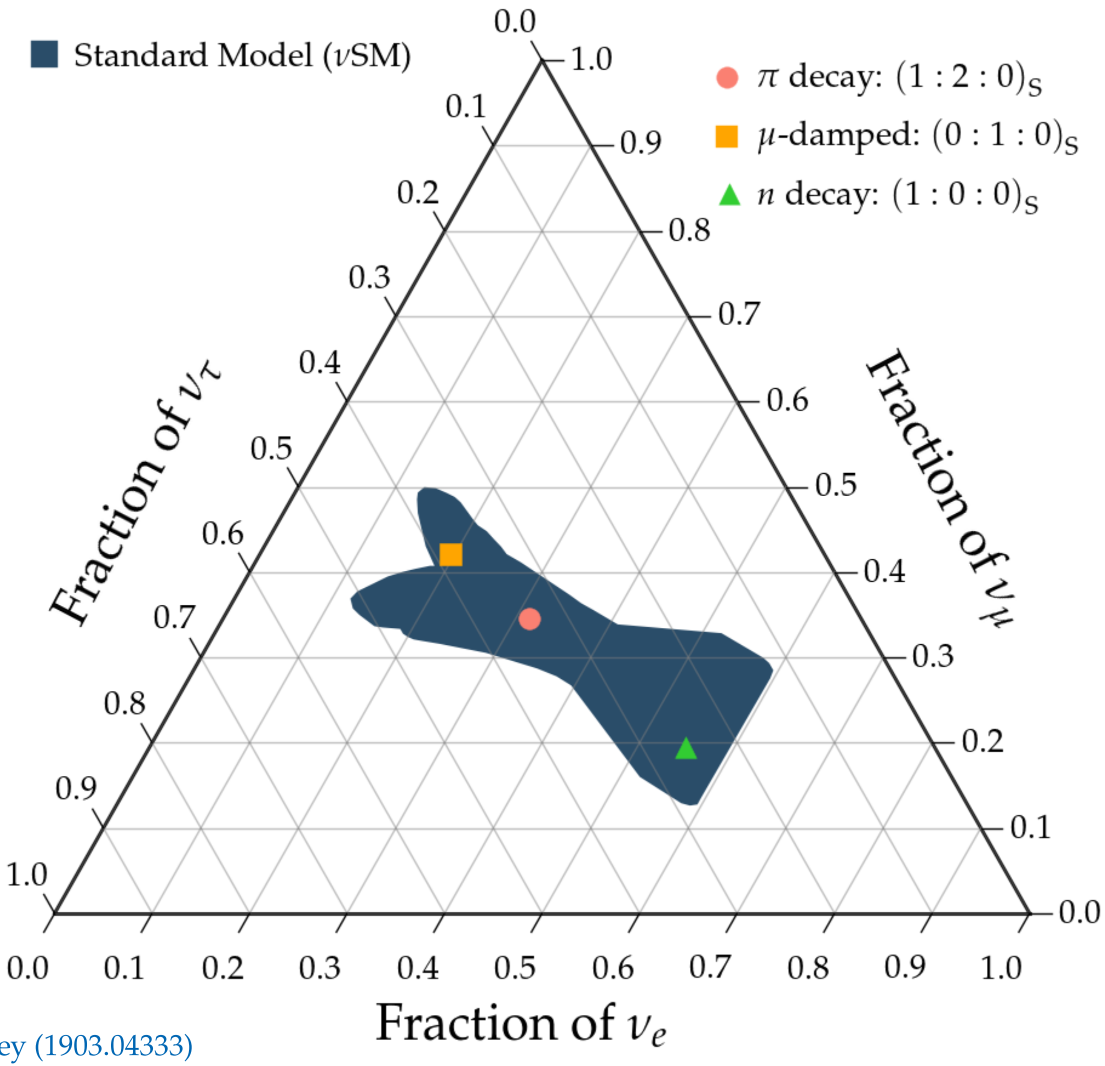
Note: ν and $\bar{\nu}$ are (so far) indistinguishable in neutrino telescopes

IceCube flavor composition

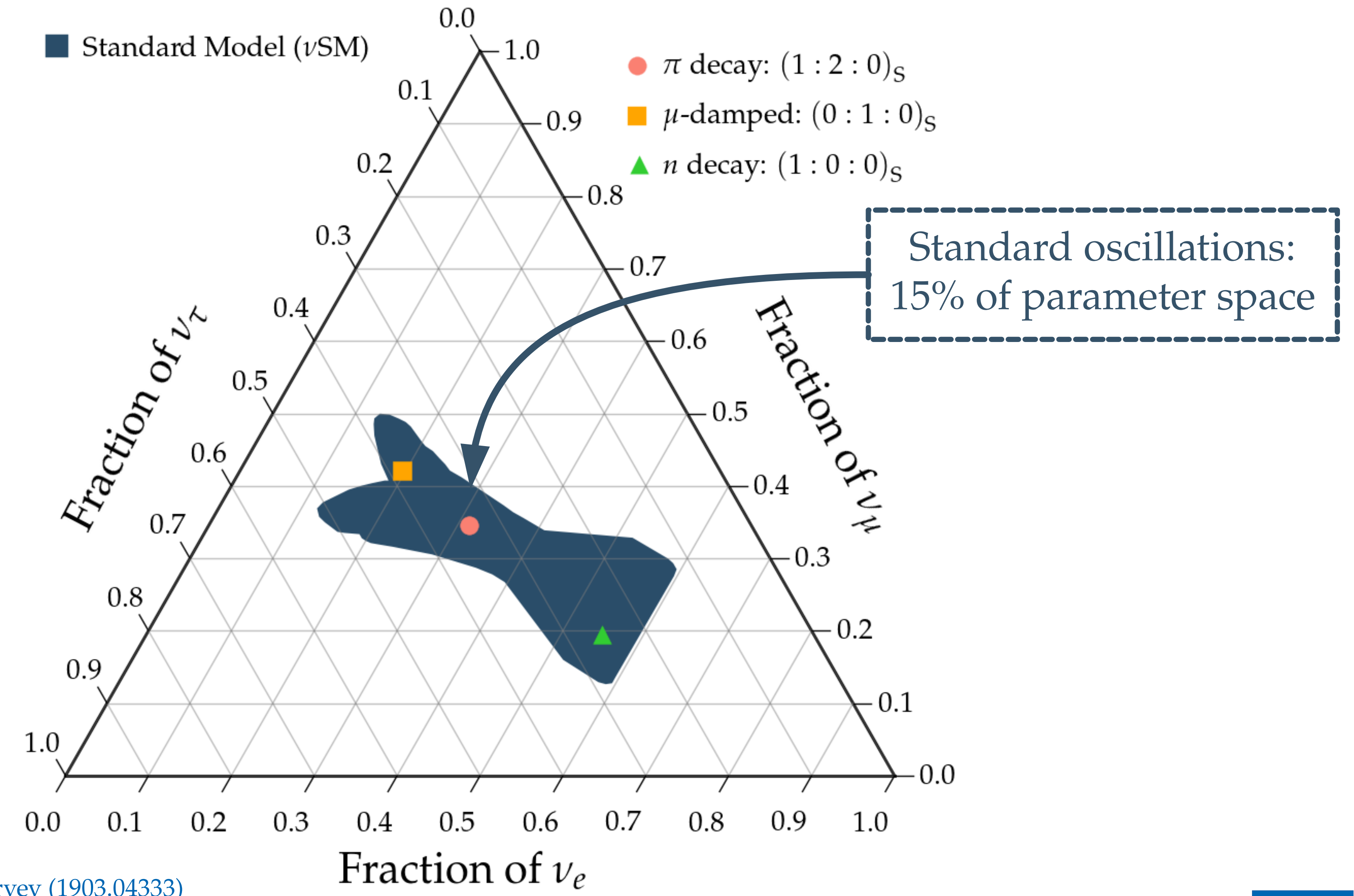


- Compare number of tracks (υ_μ) *vs.* showers (all flavors)
- Best fit: $(f_e : f_\mu : f_\tau)_\oplus = (0.5 : 0.5 : 0)_\oplus$
- Compatible with standard source compositions
- Lots of room for improvement: more statistics, better flavor-tagging

MB & Ahlers, *PRL* 2019
Adapted from: IceCube, *ApJ* 2015



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



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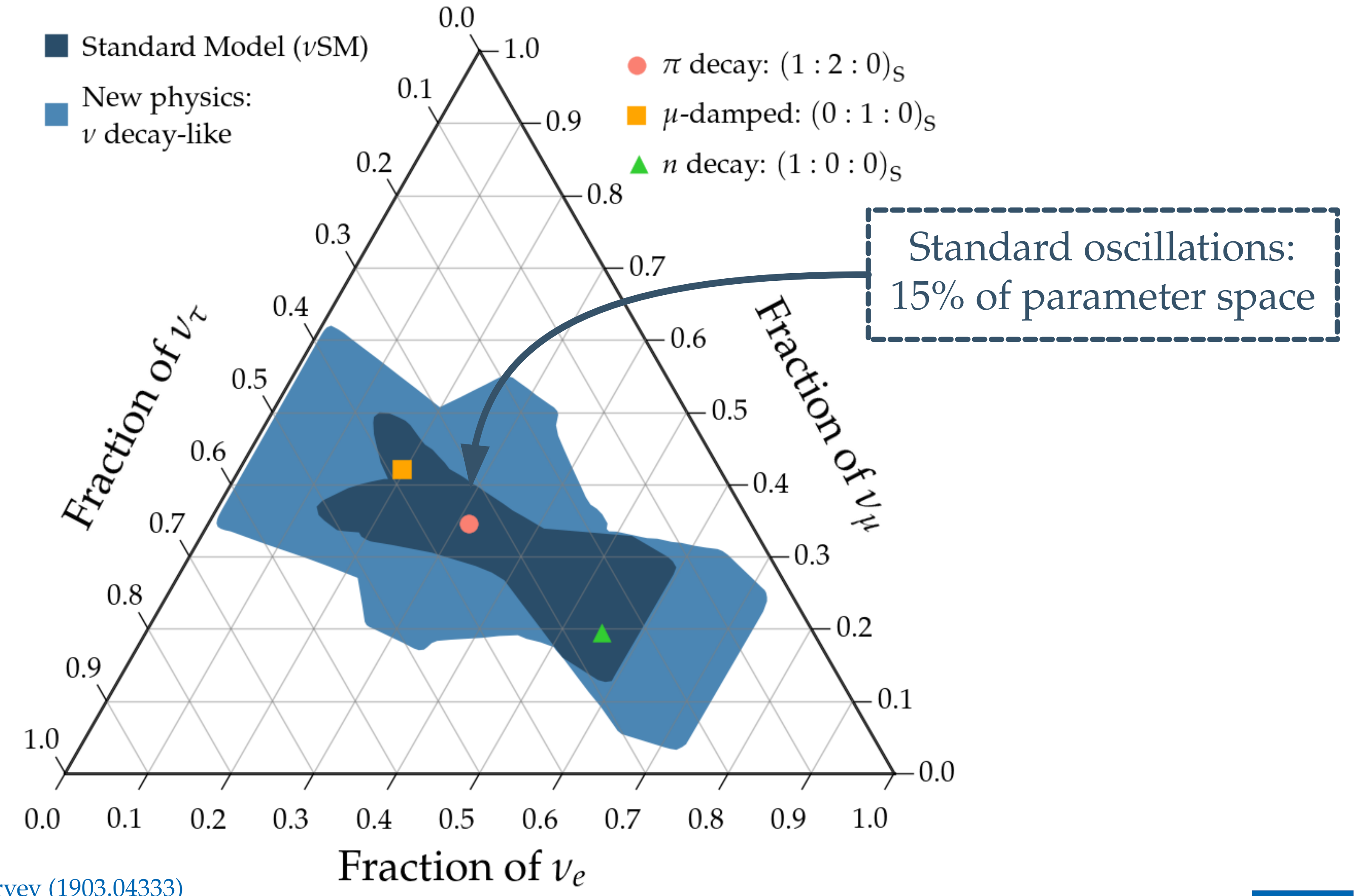

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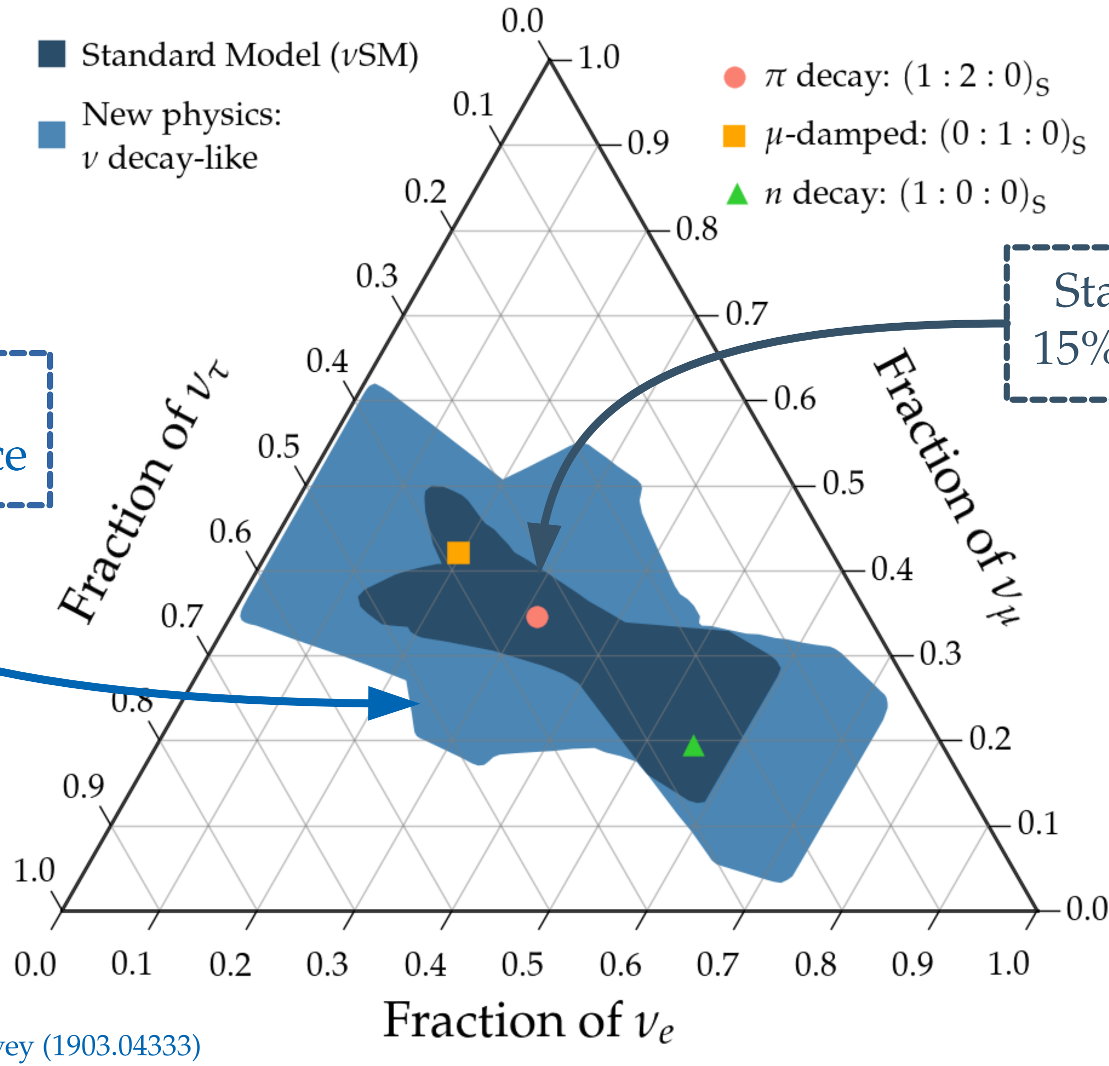
Neutrino decay
30% of parameter space



Standard oscillations:
15% of parameter space

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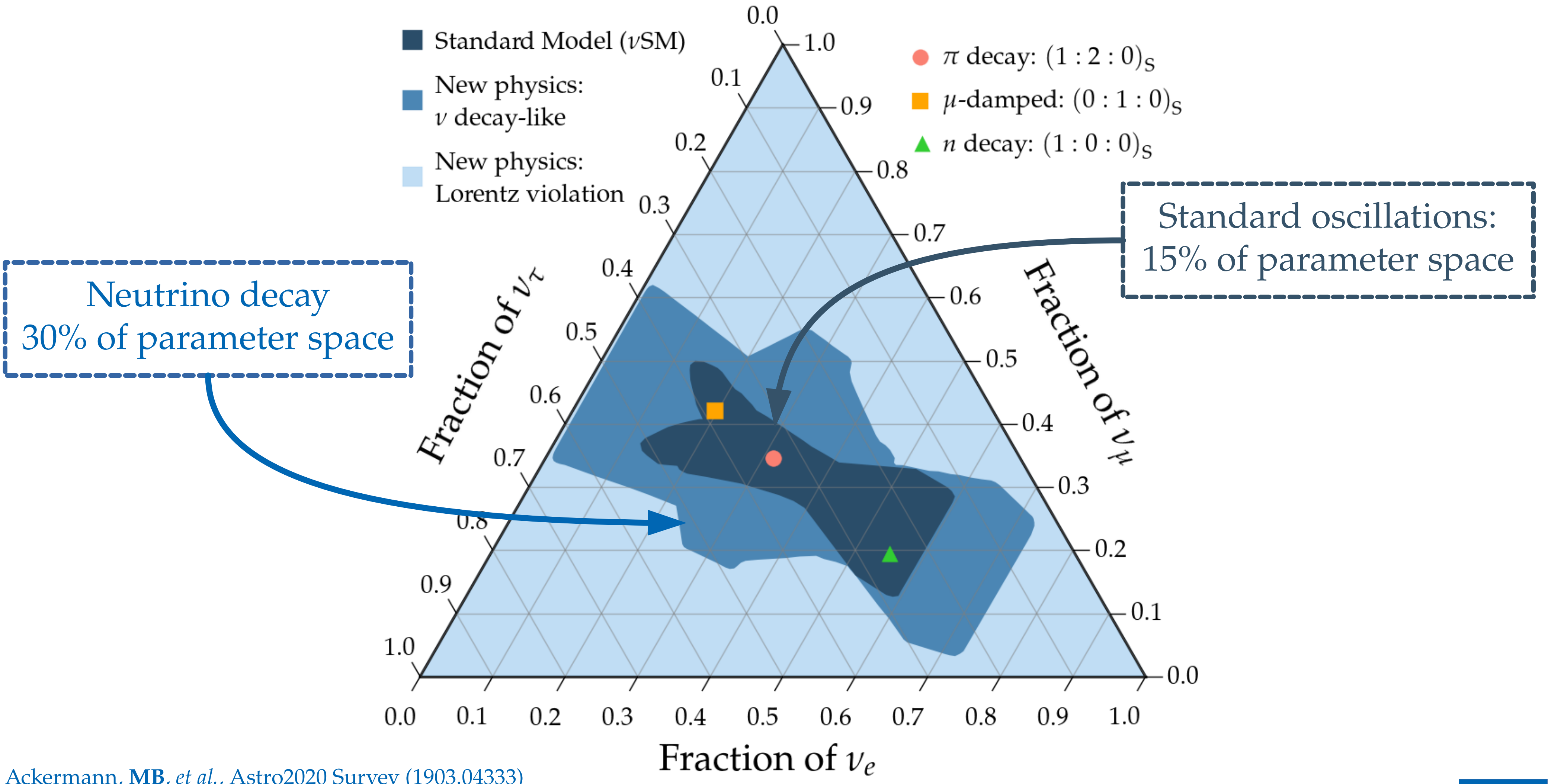

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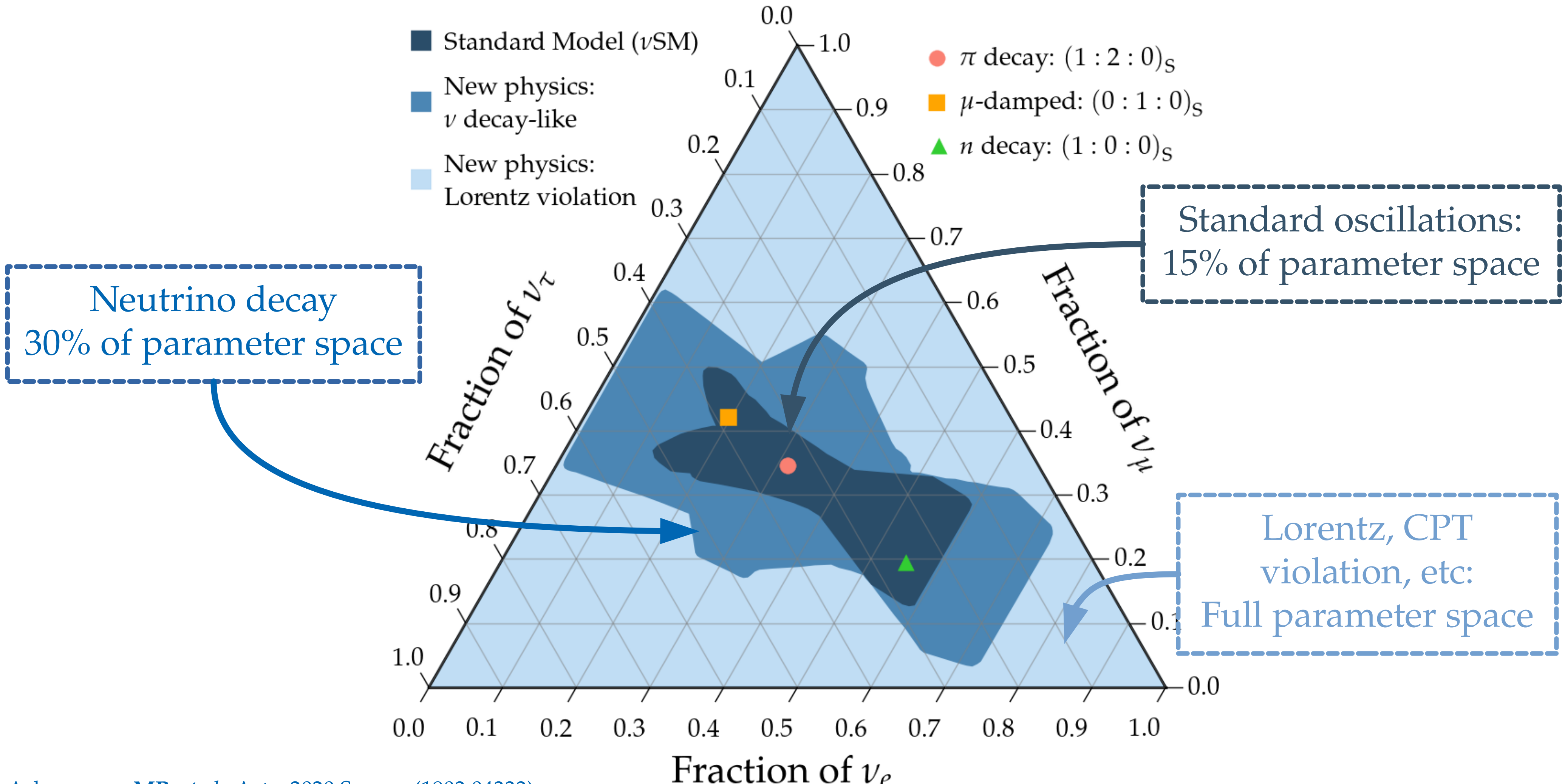

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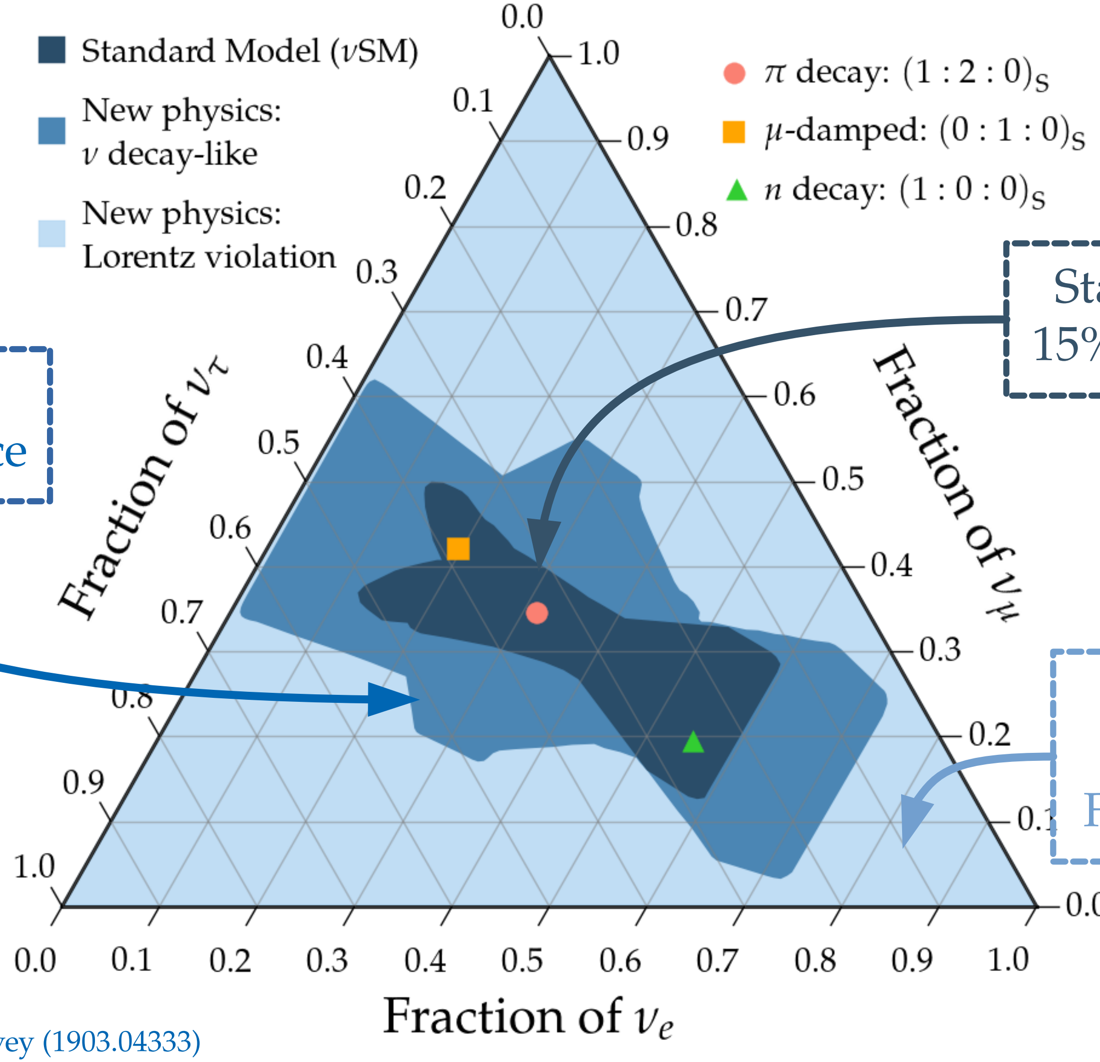

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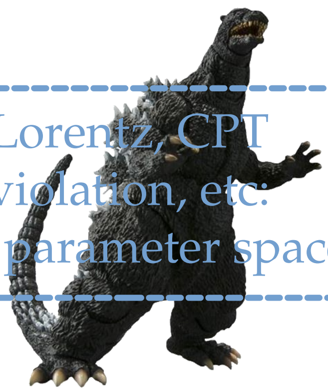


Lorentz, CPT violation, etc:
Full parameter space

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

There be dragons

- High-energy effective field theories
  - Violation of Lorentz and CPT invariance
    [Barenboim & Quigg, *PRD* 2003; **MB**, Gago, Peña-Garay, *JHEP* 2010; Kostelecky & Mewes 2004]
  - 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]

- Flavor-violating physics
  - New neutrino-electron interactions
    [**MB** & Agarwalla, *PRL* 2019]
  - New νν interactions
    [**MB** *et al.*, *PRD* 2020; Ng & Beacom, *PRD* 2014; Cherry, Friedland, Shoemaker, 1411.1071; Blum, Hook, Murase, 1408.3799]

- …

Toho Company Ltd.

How to fill out the flavor triangle?

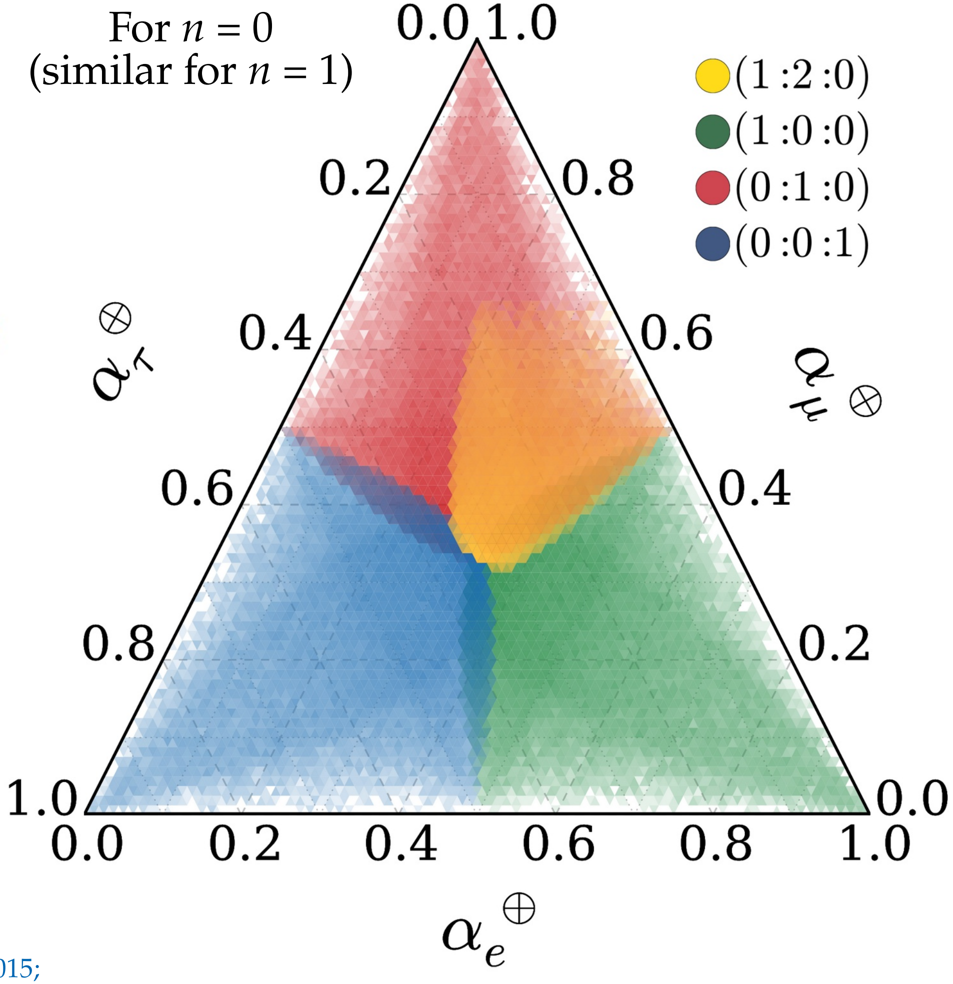
$$H_{\text{tot}} = H_{\text{std}} + H_{\text{NP}}$$

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

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

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



Argüelles, Katori, Salvadó, *PRL* 2015

See also: Ahlers, **MB**, Mu, *PRD* 2018; Rasmusen *et al.*, *PRD* 2017; **MB**, Beacom, Winter *PRL* 2015; **MB**, Gago, Peña-Garay *JCAP* 2010; Bazo, **MB**, Gago, Miranda *IJMPA* 2009; + many others

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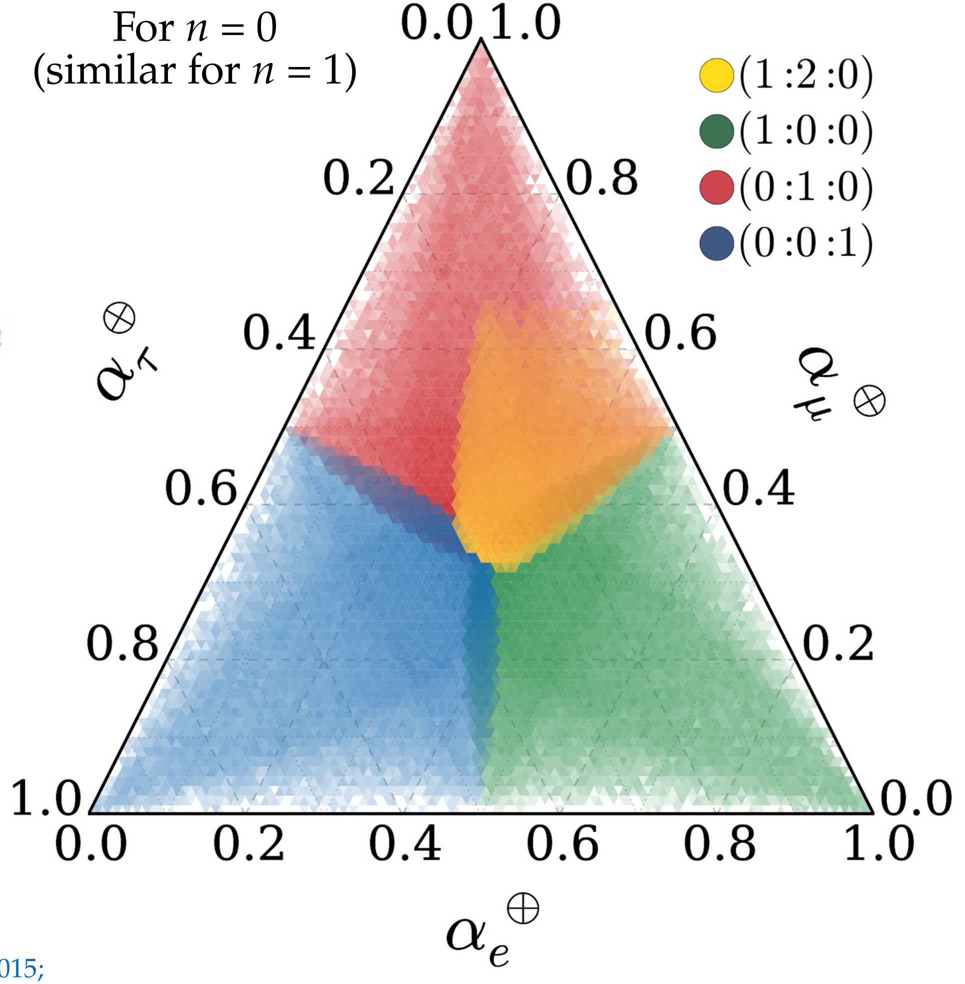
- Sample the unknown new mixing angles



See also: Ahlers, **MB**, Mu, *PRD* 2018; Rasmusen *et al.*, *PRD* 2017; **MB**, Beacom, Winter *PRL* 2015; **MB**, Gago, Peña-Garay *JCAP* 2010; Bazo, **MB**, Gago, Miranda *IJMPA* 2009; + many others

Argüelles, Katori, Salvadó, *PRL* 2015

Neutrino decay

Are neutrinos forever?

- In the Standard Model (νSM), neutrinos are essentially stable ($\tau > 10^{36}$ yr):
  - One-photon decay ($\nu_i \to \nu_j + \gamma$): $\tau > 10^{36}\,(m_i/\mathrm{eV})^{-5}$ yr
  - Two-photon decay ($\nu_i \to \nu_j + \gamma + \gamma$): $\tau > 10^{57}\,(m_i/\mathrm{eV})^{-9}$ yr
  - Three-neutrino decay ($\nu_i \to \nu_j + \nu_k + \bar{\nu}_k$): $\tau > 10^{55}\,(m_i/\mathrm{eV})^{-5}$ yr

  » Age of Universe (~ 14.5 Gyr)

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

- φ: Nambu-Goldstone boson of a broken symmetry (*e.g.*, Majoron)

- We work in a model-independent way:
  the nature of φ is unimportant if it is invisible to neutrino detectors

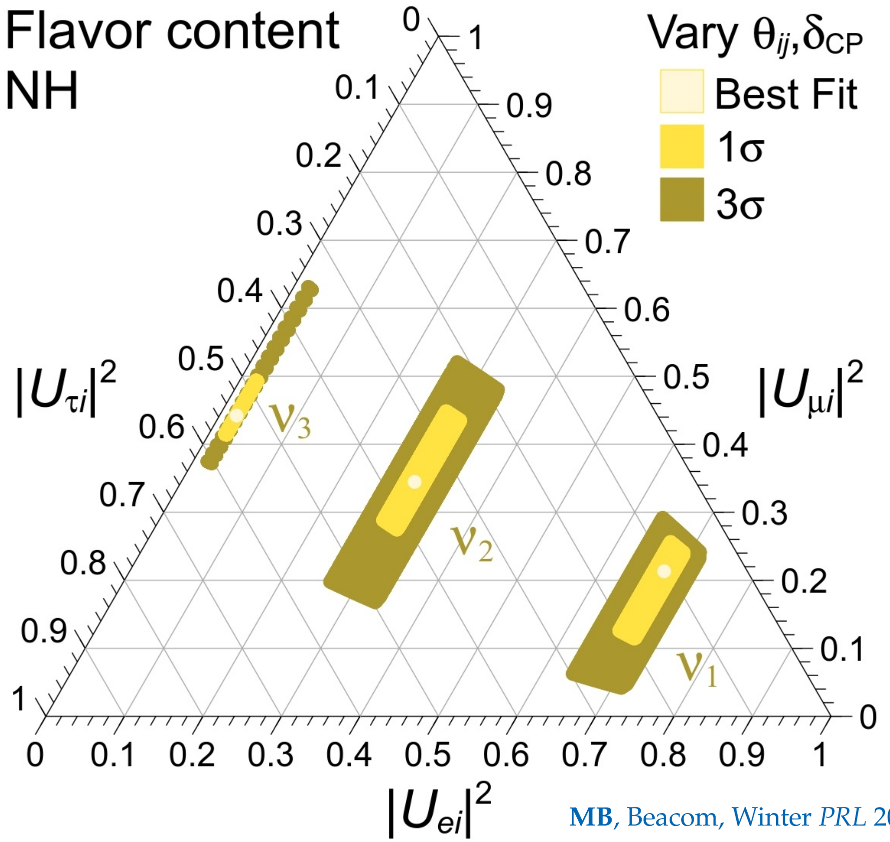
Flavor content of neutrino mass eigenstates

Known to within 2%

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

Known to within 8%

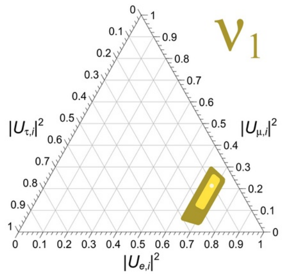
Known to within 20% (or worse)



MB, Beacom, Winter *PRL* 2015

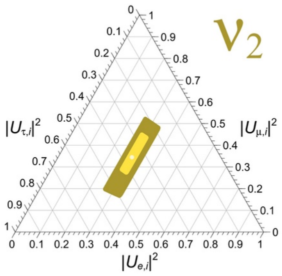
Neutrinos propagate as an incoherent mix of ν_1, ν_2, ν_3 —

w_1



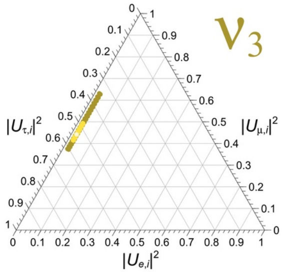
+

w_2

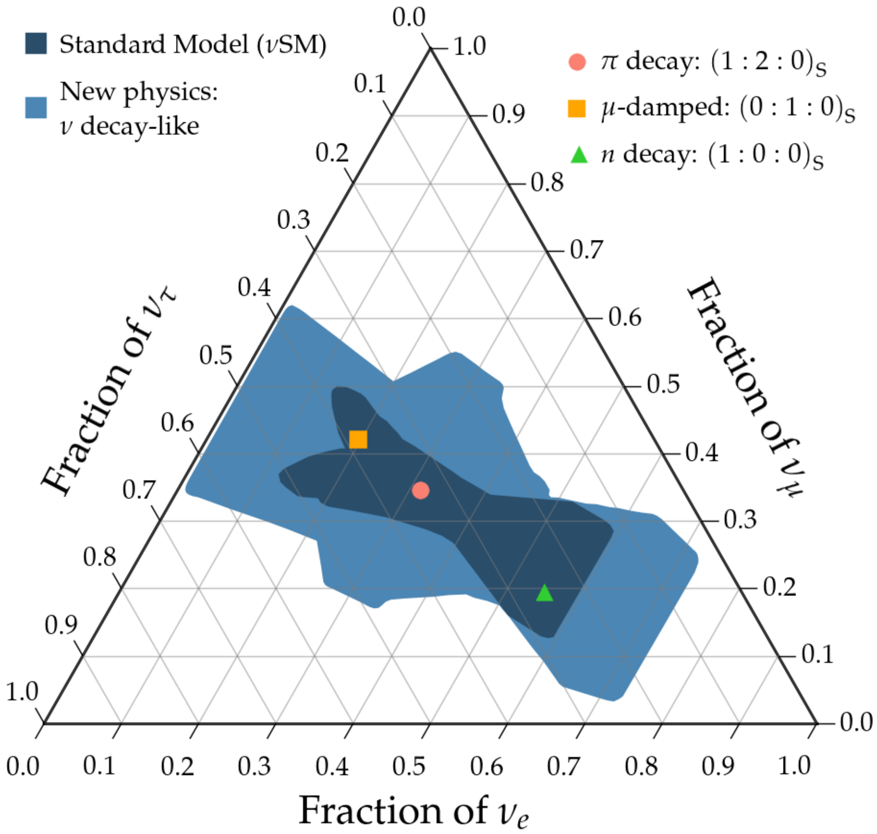


+

w_3



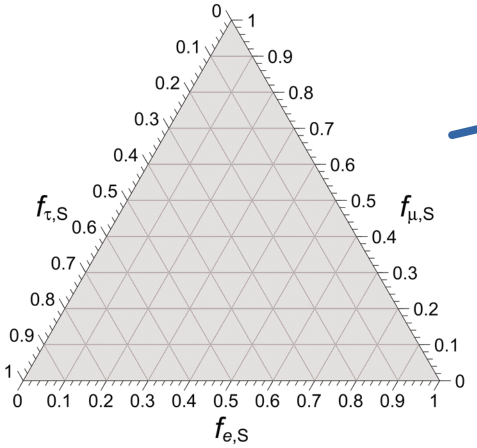
Varying all possible combinations of weights w_i and mixing parameters



Complete decay selects particular weights ▸ with striking consequences for flavor

Measuring the neutrino lifetime

Sources



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

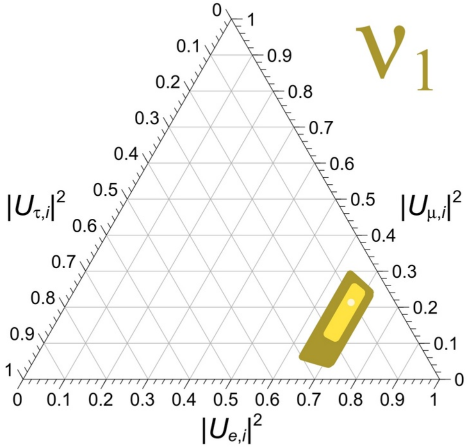
ν_1 lightest and stable
(normal mass ordering)

If all unstable
neutrinos decay

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

ν_3 lightest and stable
(inverted mass ordering)

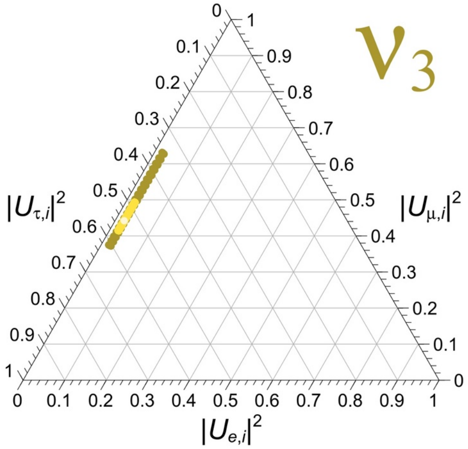
Earth



ν_1

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

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



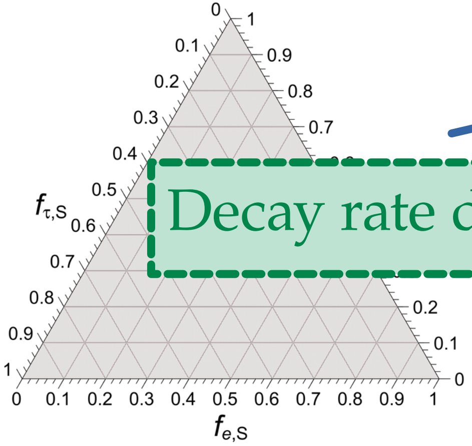
ν_3

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

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

Measuring the neutrino lifetime

Sources



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

ν_1 lightest and stable
(normal mass ordering)

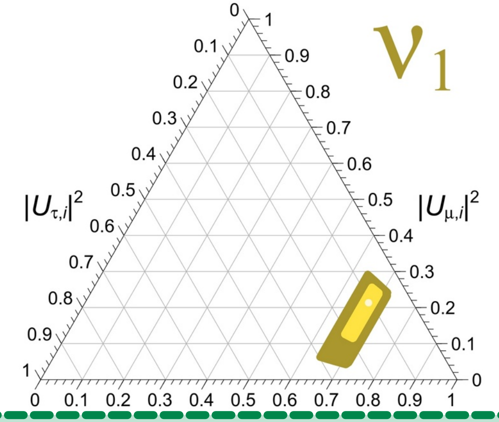
If all unstable

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

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

ν_3 lightest and stable
(inverted mass ordering)

Earth



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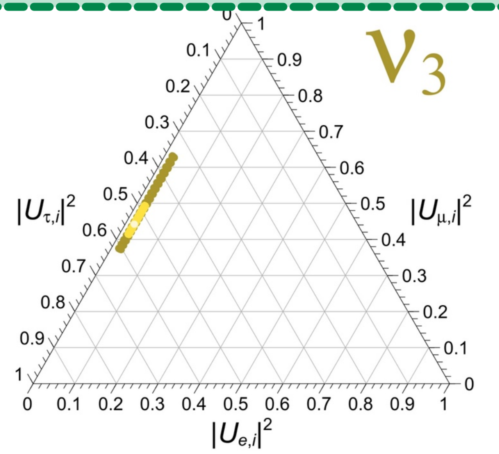

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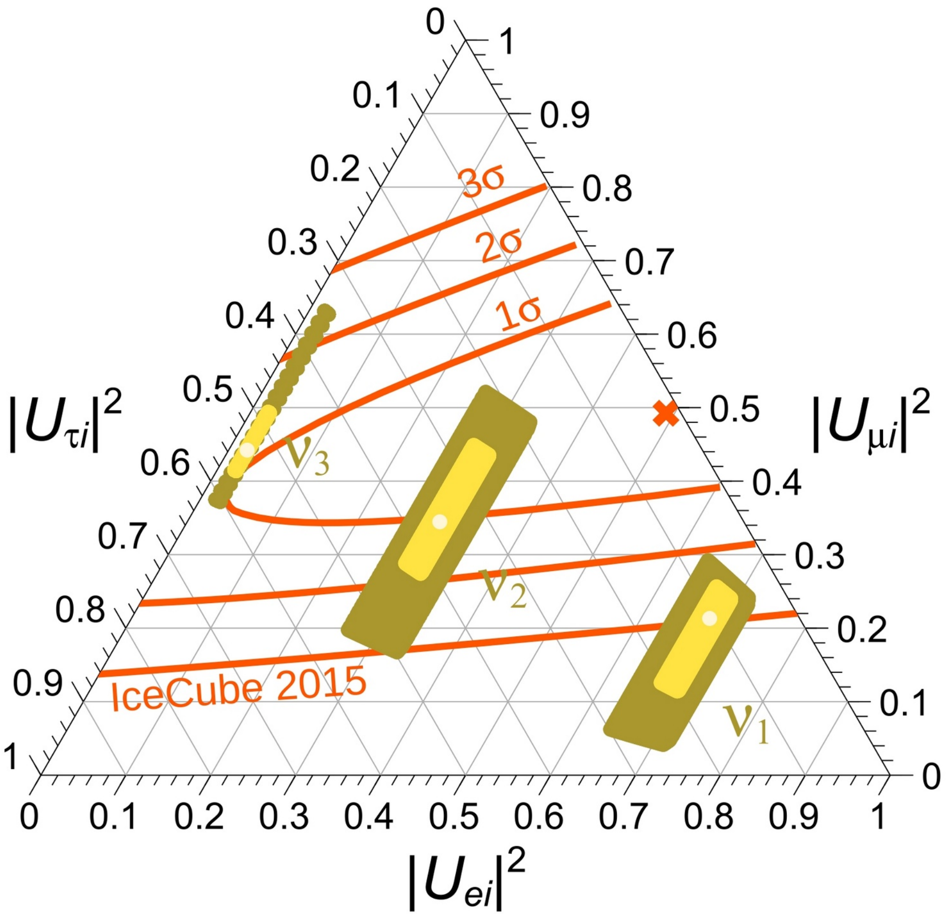
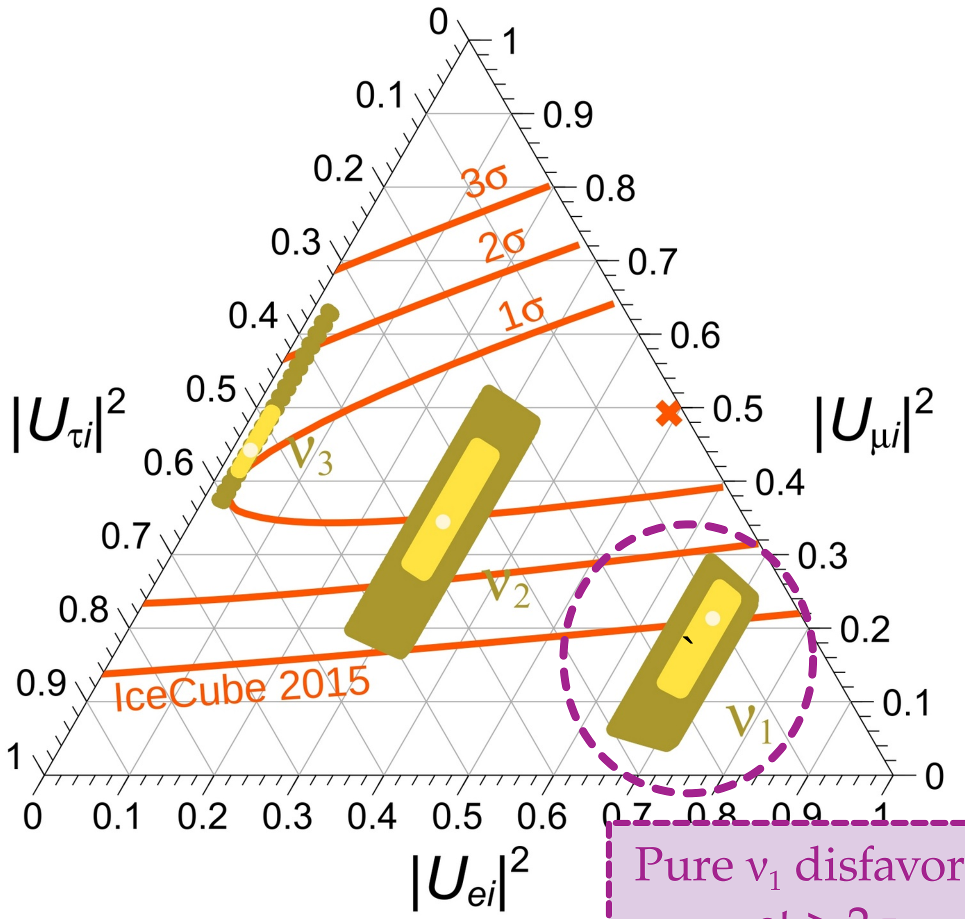


MB, Beacom, Murase, *PRD* 2017

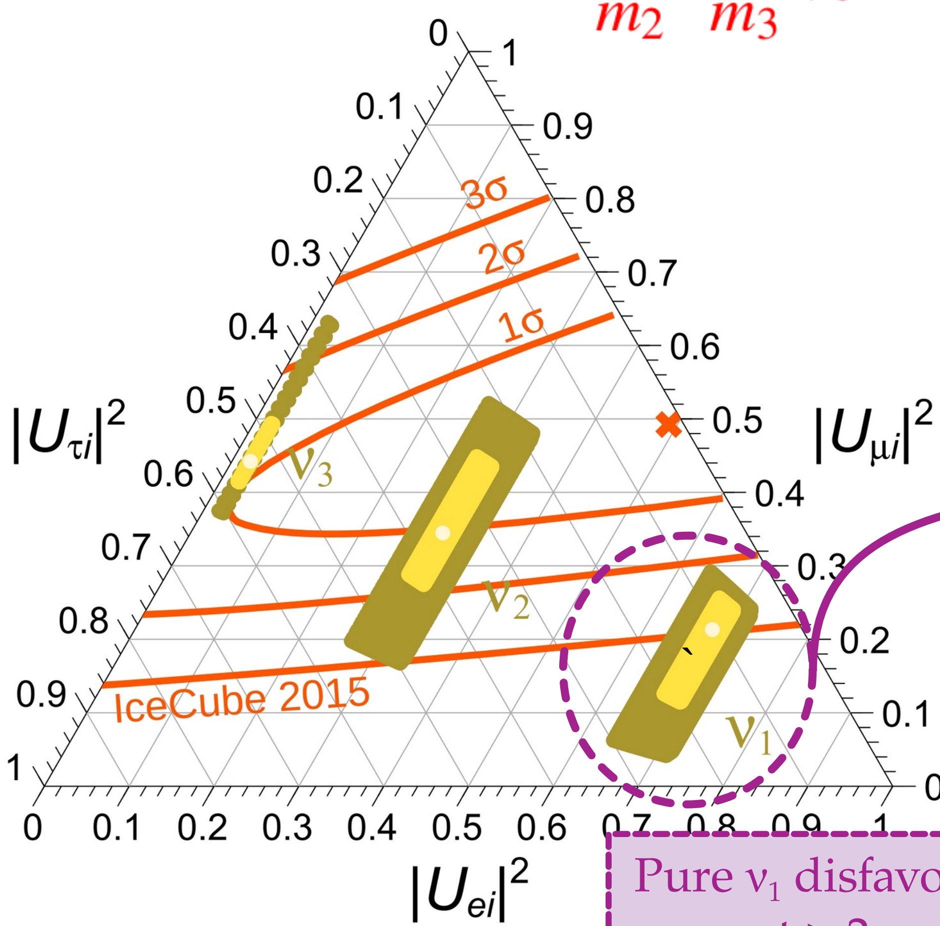
Baerwald, **MB**, Winter, *JCAP* 2012

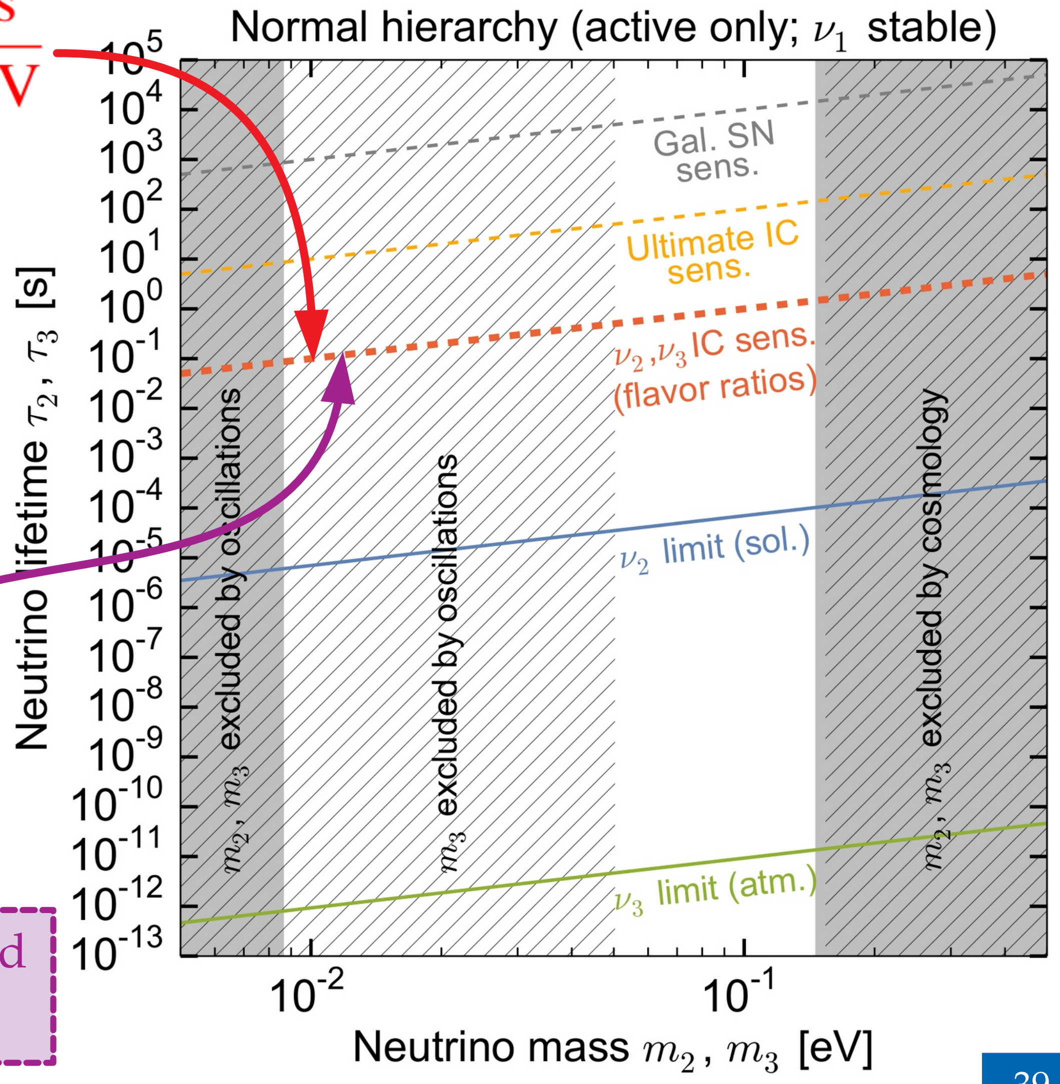


Pure ν_1 disfavored at > 2σ

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

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





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Using the Glashow resonance to test decay

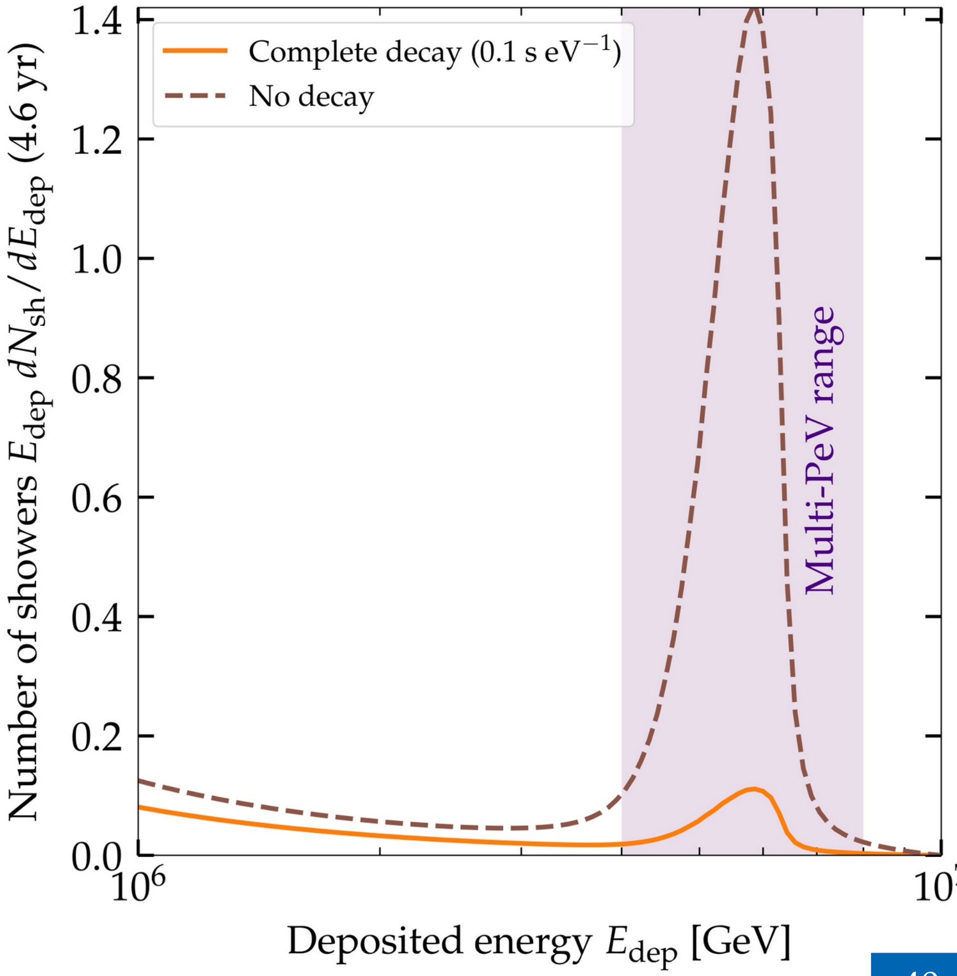
- At 6.3 PeV, the Glashow resonance ($\bar{\nu}_e + e \to W$) should trigger showers in IceCube

- … unless ν_1, ν_2 decay to ν_3 en route to Earth (the surviving ν_3 have little electron content)

- IceCube has seen 1 shower in the 4–8 PeV range, so ν_1, ν_2 *must* make it to Earth

- So we set *lower* limits on their lifetimes (in the inverted mass ordering)

- Translated into *upper* limits on coupling



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

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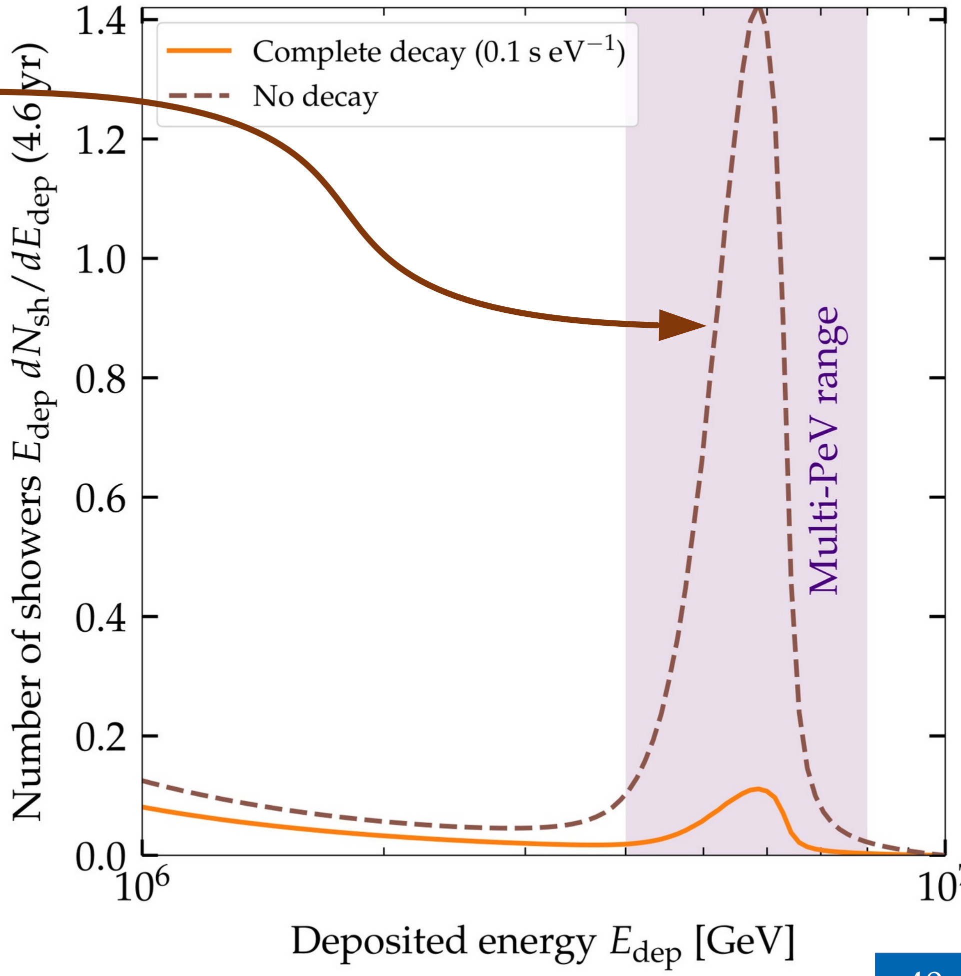

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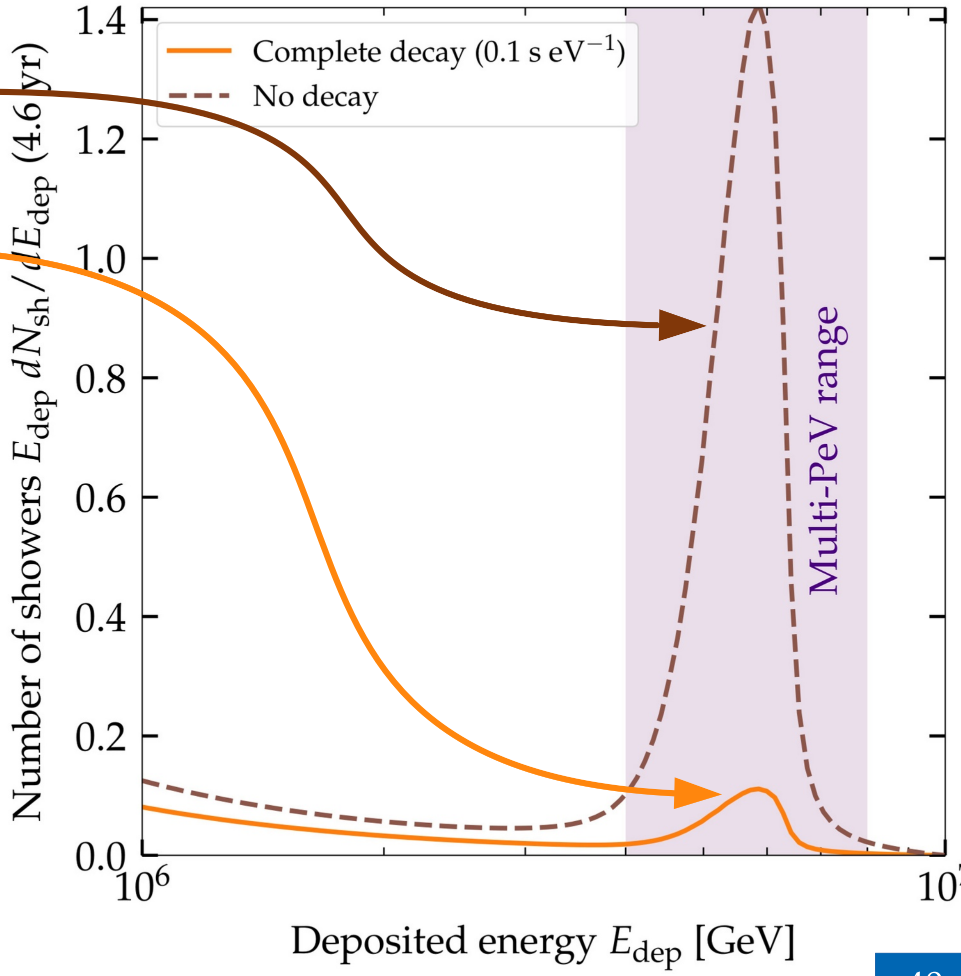

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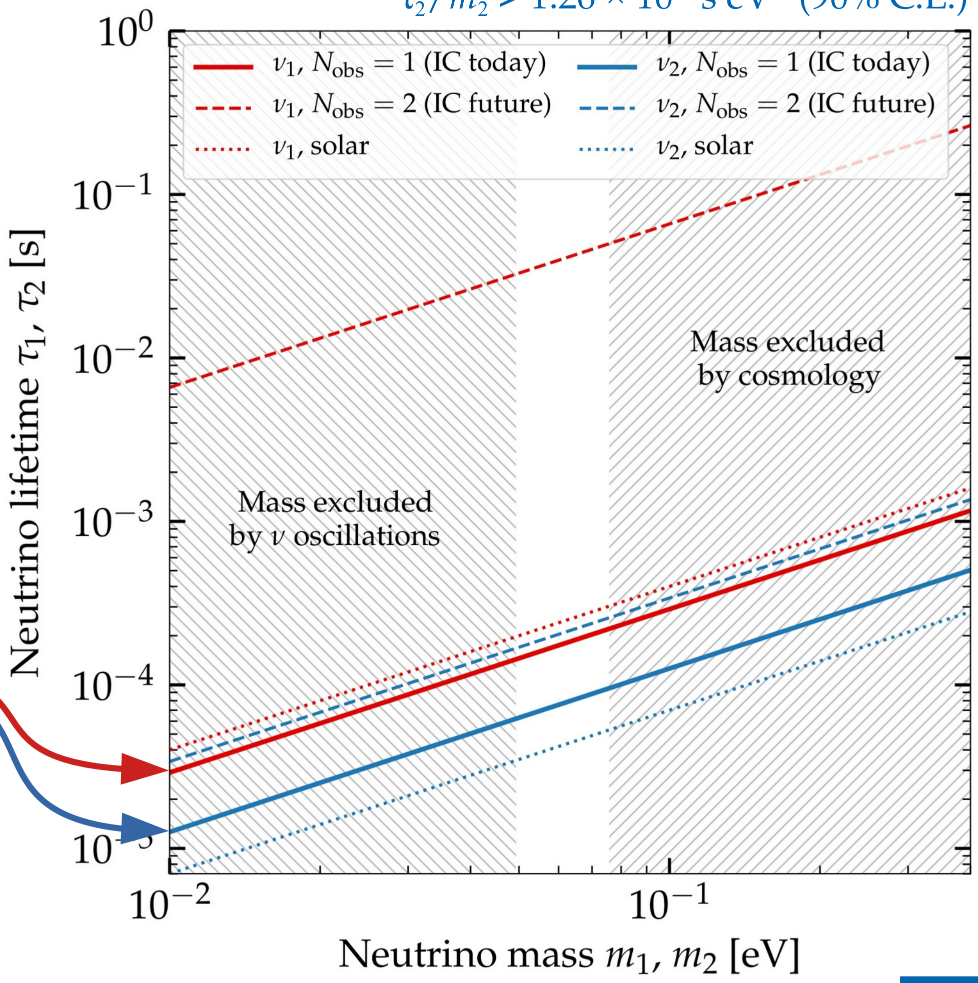
$\tau_1/m_1 > 2.91 \times 10^{-3}$ s eV^{-1} (90% C.L.)
$\tau_2/m_2 > 1.26 \times 10^{-3}$ s eV^{-1} (90% C.L.)



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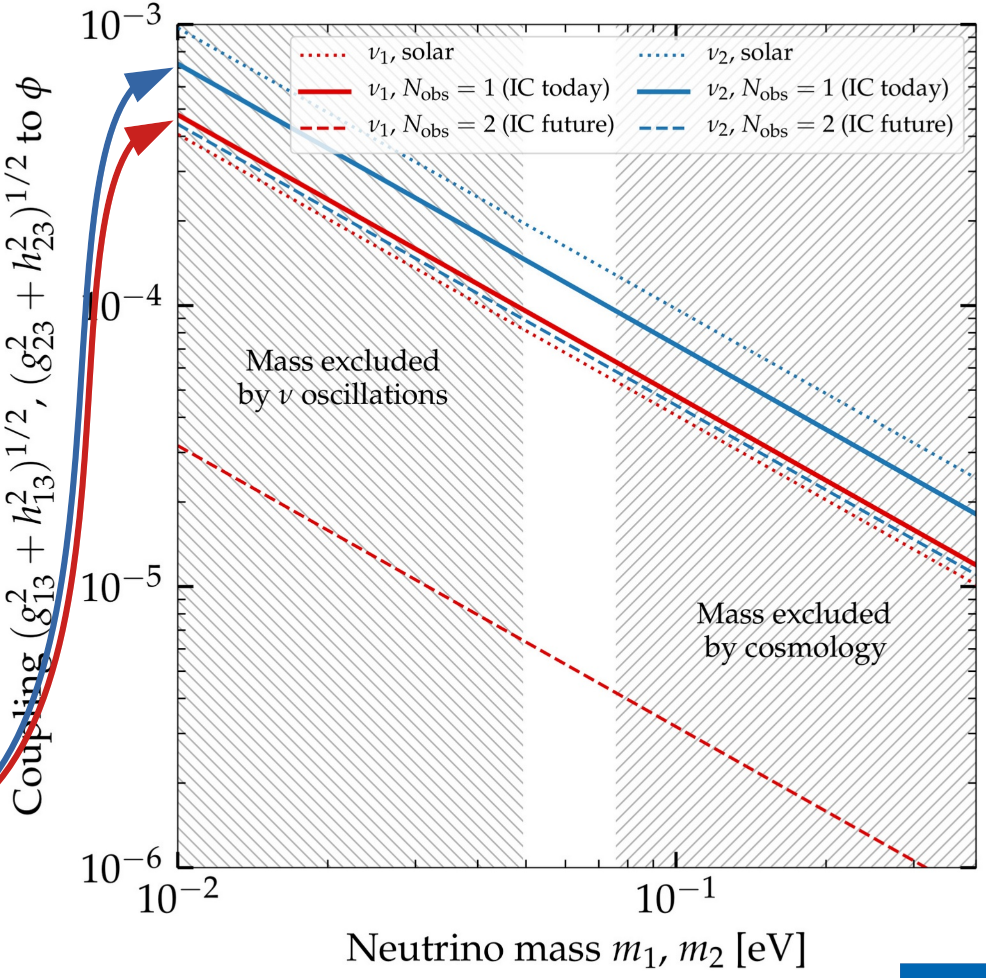
$$\mathcal{L} = g_{ij}\bar{\nu}_i\nu_j\phi + h_{ij}\bar{\nu}_i\gamma_5\nu_j\phi + \text{h.c.}$$



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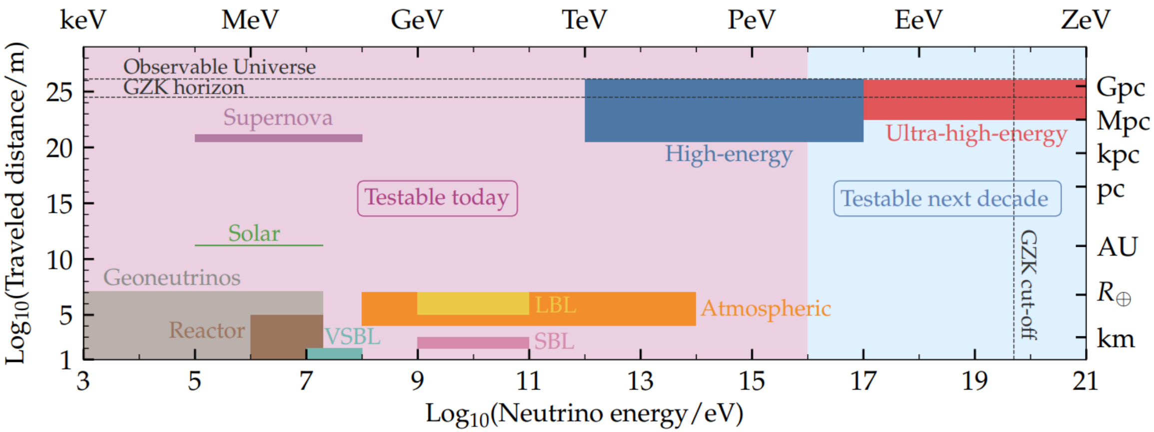
An exciting decade ahead



Today: TeV–PeV astrophysical ν

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

Next decade: EeV cosmogenic ν

$\kappa_n \sim 4 \cdot 10^{-50}\,(E/\mathrm{EeV})^{-n}\,(L/\mathrm{Gpc})^{-1}\,\mathrm{EeV}^{1-n}$

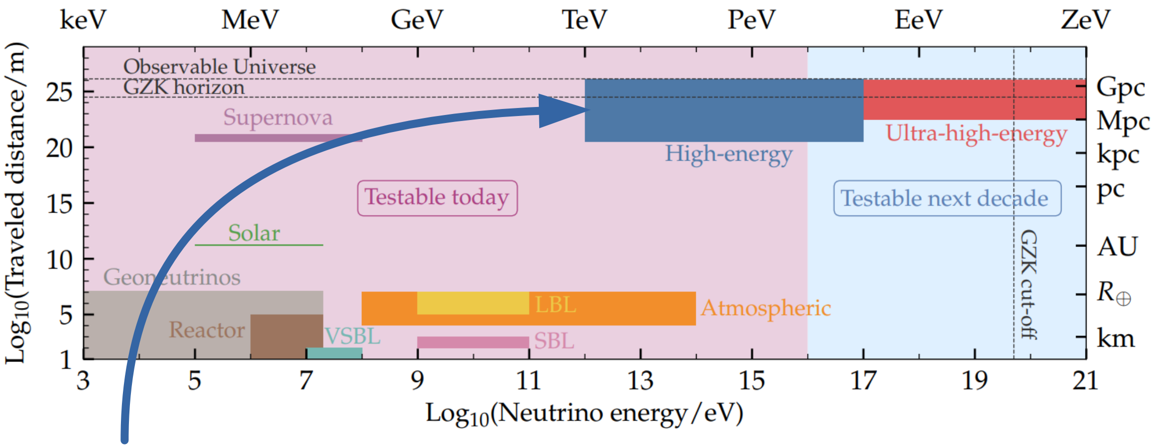
IceCube + ANTARES + Baikal

+ Growing statistics

+ Improved systematics

IceCube upgrade
IceCube-Gen2
KM3NeT
ANITA
ARA
ARIANNA
Baikal-GVD
BEACON
GRAND
POEMMA
TRINITY

An exciting decade ahead



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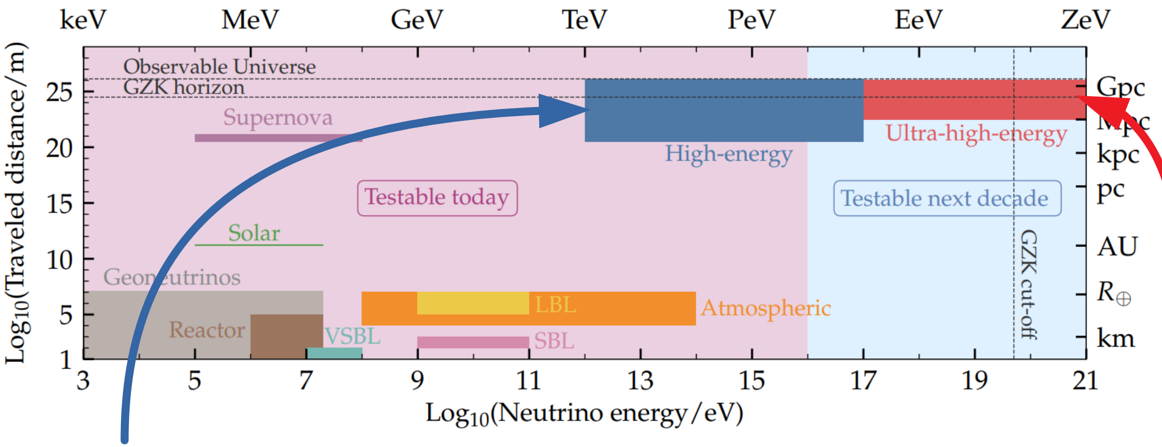

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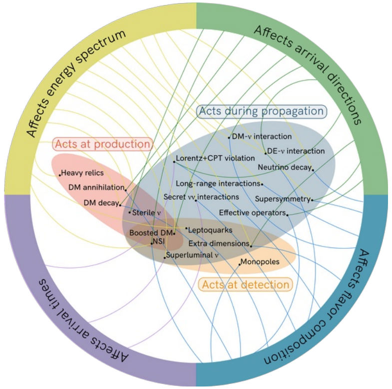
What are you taking home?

- Cosmic neutrinos are incisive probes of TeV–PeV physics
- We can do this *already today*, in spite of unknowns
- New physics comes in many shapes — so we need to be thorough
- Exciting prospects: larger statistics, better reconstruction, higher energies

More?

- *Fundamental physics with high-energy cosmic neutrinos today and in the future*, 1907.08690
- *Astro2020: Fundamental physics with high-energy cosmic neutrinos*, 1903.04333
- *Astro2020: Astrophysics uniquely enabled by observations of high-energy cosmic neutrinos*, 1903.04334

What are you taking home?



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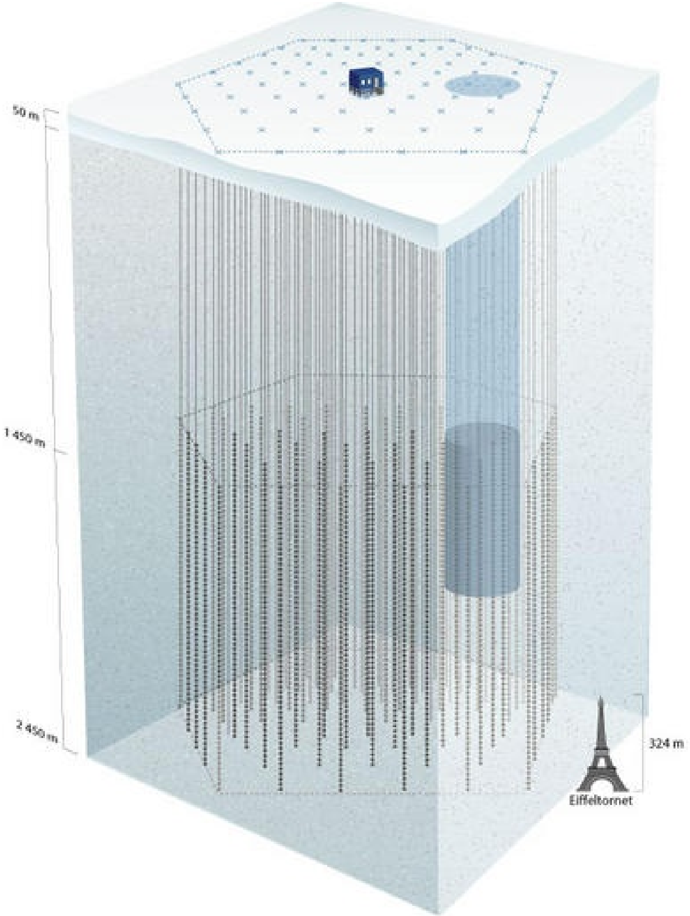
- *Astro2020: Astrophysics uniquely enabled by observations of high-energy cosmic neutrinos*, 1903.04334

Backup slides

IceCube – What is it?



- Km^3 in-ice Cherenkov detector in Antarctica
- >5000 PMTs at 1.5–2.5 km of depth
- Sensitive to neutrino energies > 10 GeV

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 $\langle y \rangle E_\nu$

$$\nu_x + N \to \nu_x + X$$

$$\nu_l + N \to l + X$$

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

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Charged current (CC)

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

Receives $\langle y \rangle E_\nu$

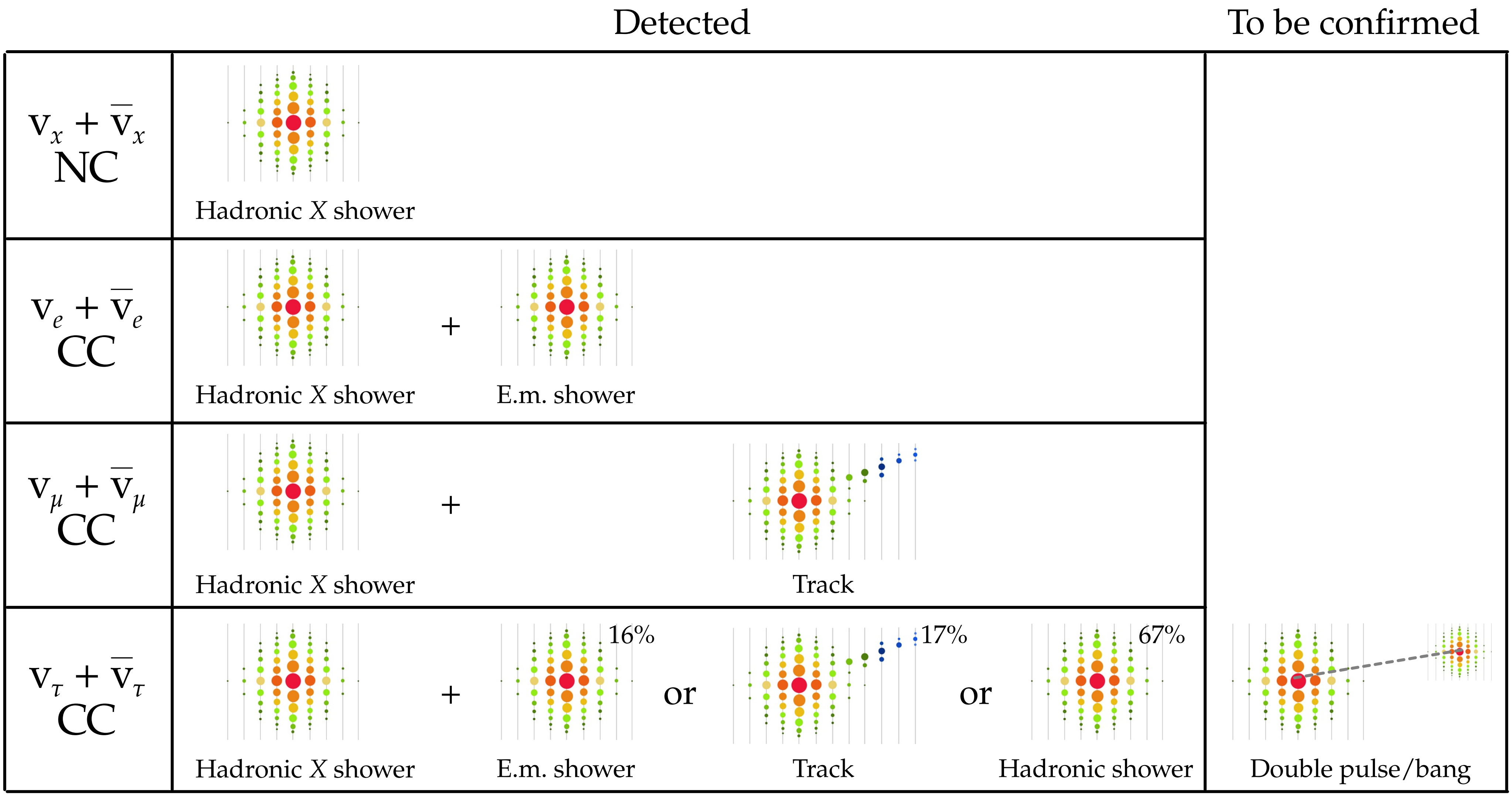
$$\nu_x + N \rightarrow \nu_x + X$$

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

Makes shower
(e.m. or hadronic) or track

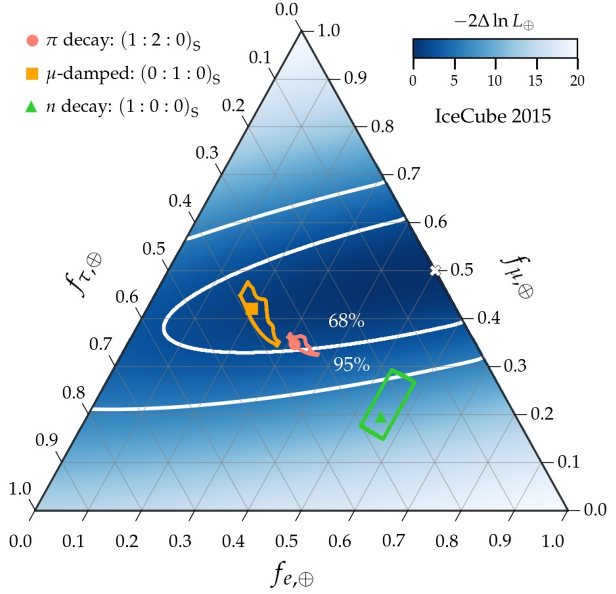
Makes hadronic shower

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

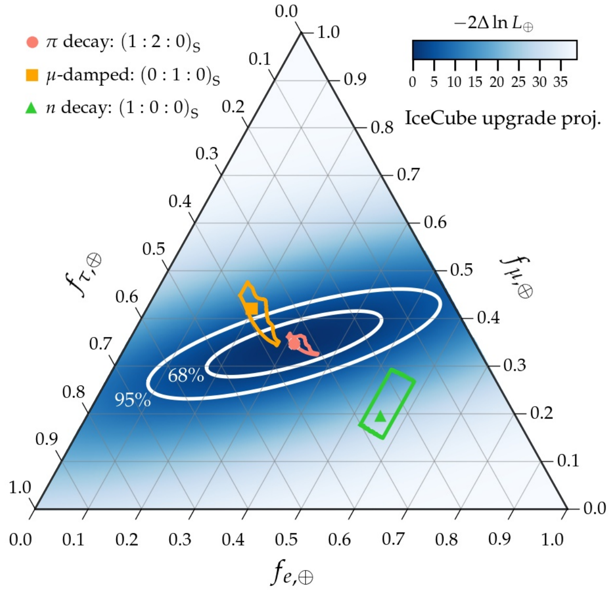

Detected
To be confirmed
$\nu_x + \bar{\nu}_x$
NC
Hadronic X shower
$\nu_e + \bar{\nu}_e$
CC
Hadronic X shower
+
E.m. shower
$\nu_\mu + \bar{\nu}_\mu$
CC
Hadronic X shower
+
Track
$\nu_\tau + \bar{\nu}_\tau$
CC
Hadronic X shower
+
16%
E.m. shower
or
17%
Track
or
67%
Hadronic shower
Double pulse/bang

IceCube flavor composition

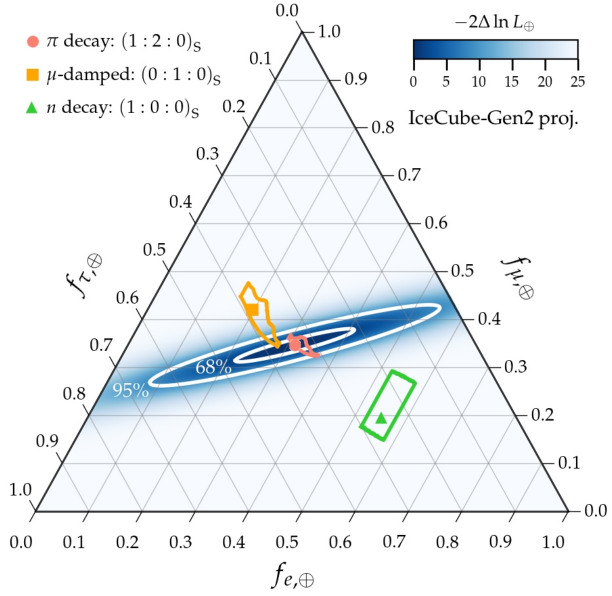
Today
IceCube



Near future (2022)
IceCube upgrade



In 10 years (2030s)
IceCube-Gen2



- Best fit: $(f_e : f_\mu : f_\tau)_\oplus = (0.49 : 0.51 : 0)_\oplus$
- Compatible with standard source compositions
- Hints of one ν_τ (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]

Neutrinos – The ultimate smoking gun of cosmic accelerators

	Gamma rays	Neutrinos	UHE Cosmic rays
Point back at sources			
Size of horizon			
Energy degradation			
Relative ease to detect			

Note: This is a simplified view

Neutrinos – The ultimate smoking gun of cosmic accelerators

	Gamma rays	Neutrinos	UHE Cosmic rays
Point back at sources	Yes	Yes	No
Size of horizon			
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Relative ease to detect			

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Neutrinos – The ultimate smoking gun of cosmic accelerators

	Gamma rays	Neutrinos	UHE Cosmic rays
Point back at sources	Yes	Yes	No
Size of horizon	10 Mpc (at EeV)	Size of the Universe	100 Mpc (> 40 EeV)
Energy degradation			
Relative ease to detect			

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Size of horizon	10 Mpc (at EeV)	Size of the Universe	100 Mpc (> 40 EeV)
Energy degradation	Severe	Tiny	Severe
Relative ease to detect			

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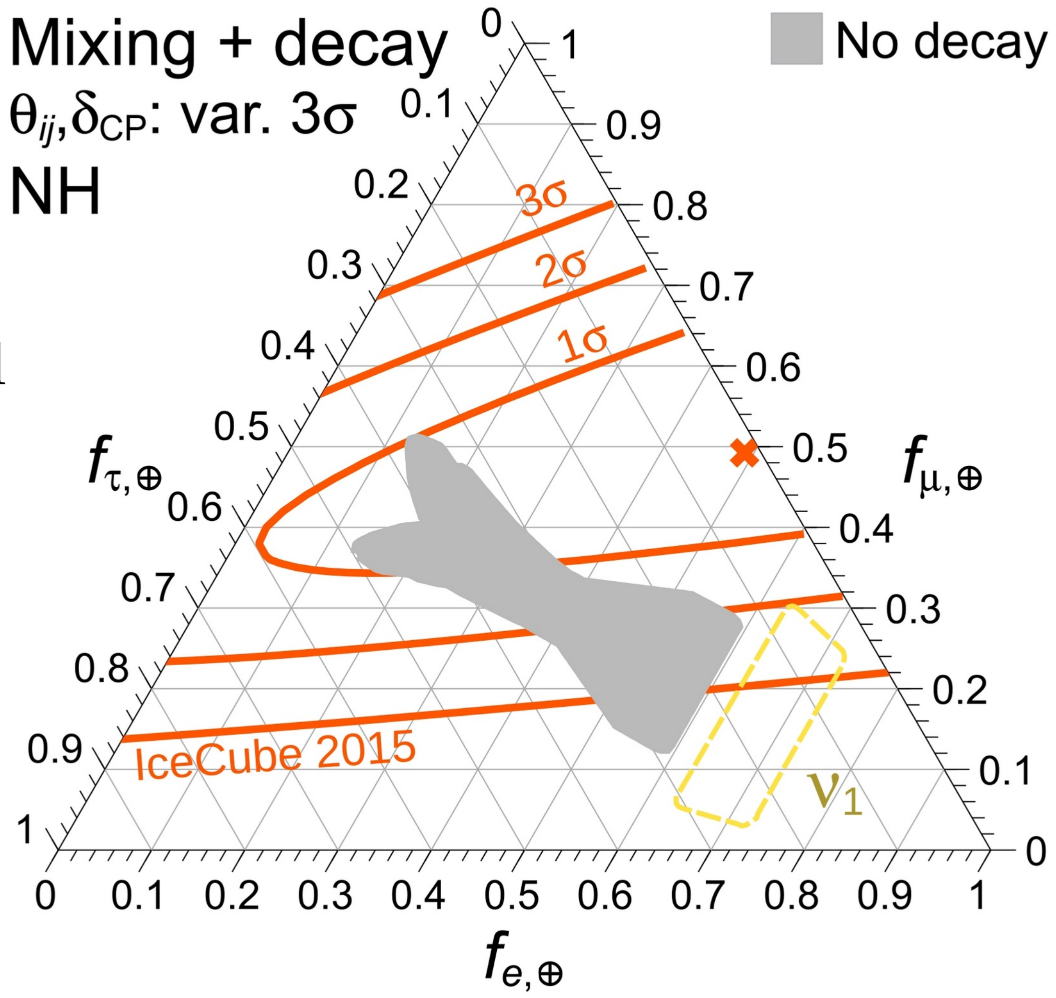
Note: This is a simplified view

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

Measuring the neutrino lifetime

Fraction of ν_2, ν_3 remaining at Earth

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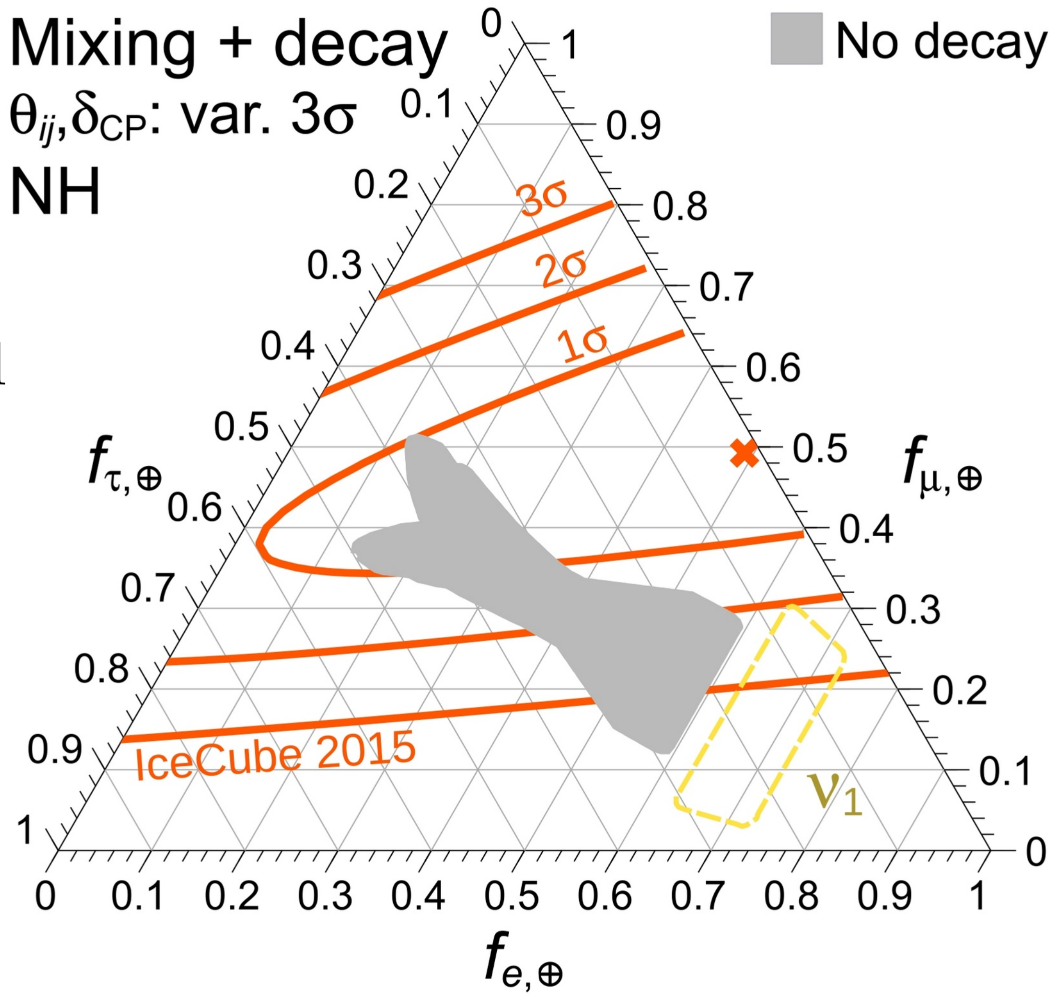

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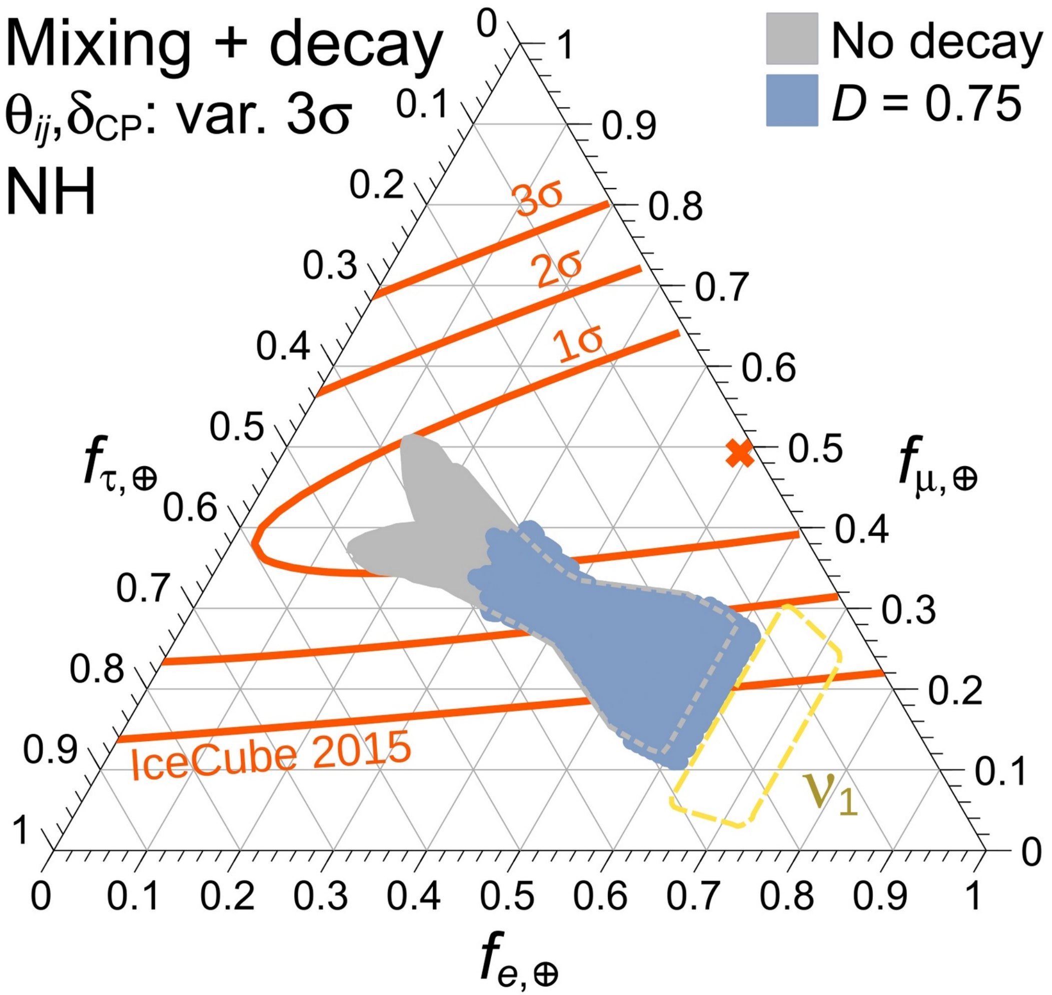

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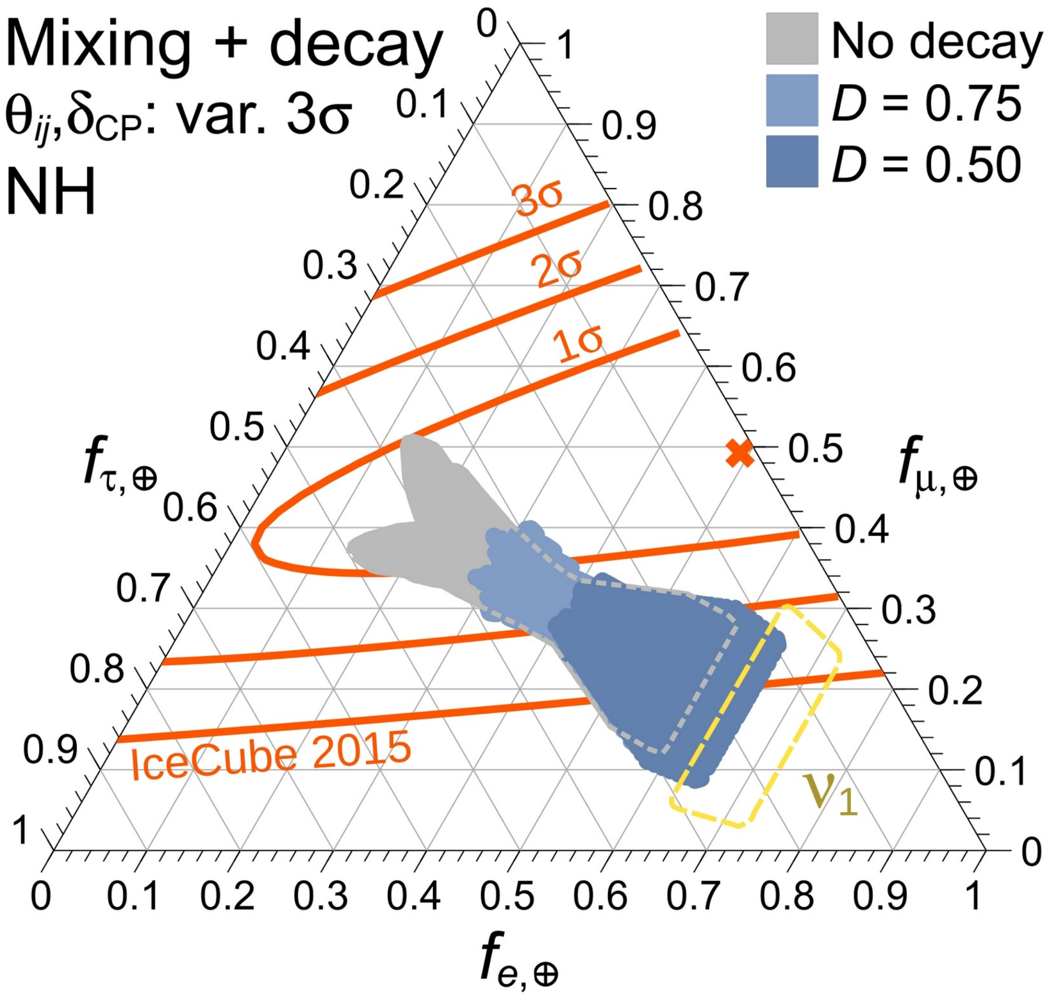

MB, Beacom, Murase, *PRD* 2017
Baerwald, **MB**, Winter, *JCAP* 2012

Measuring the neutrino lifetime

Fraction of ν_2, ν_3 remaining at Earth

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

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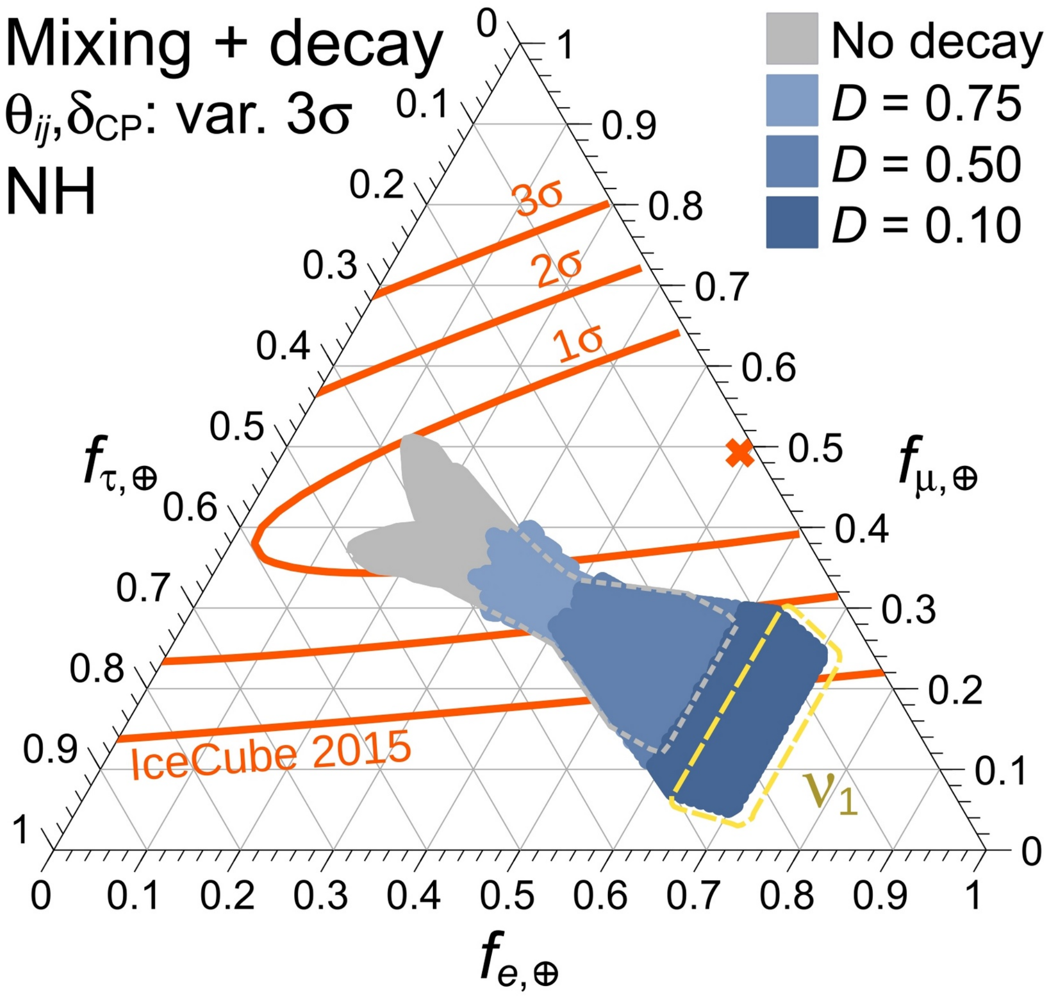

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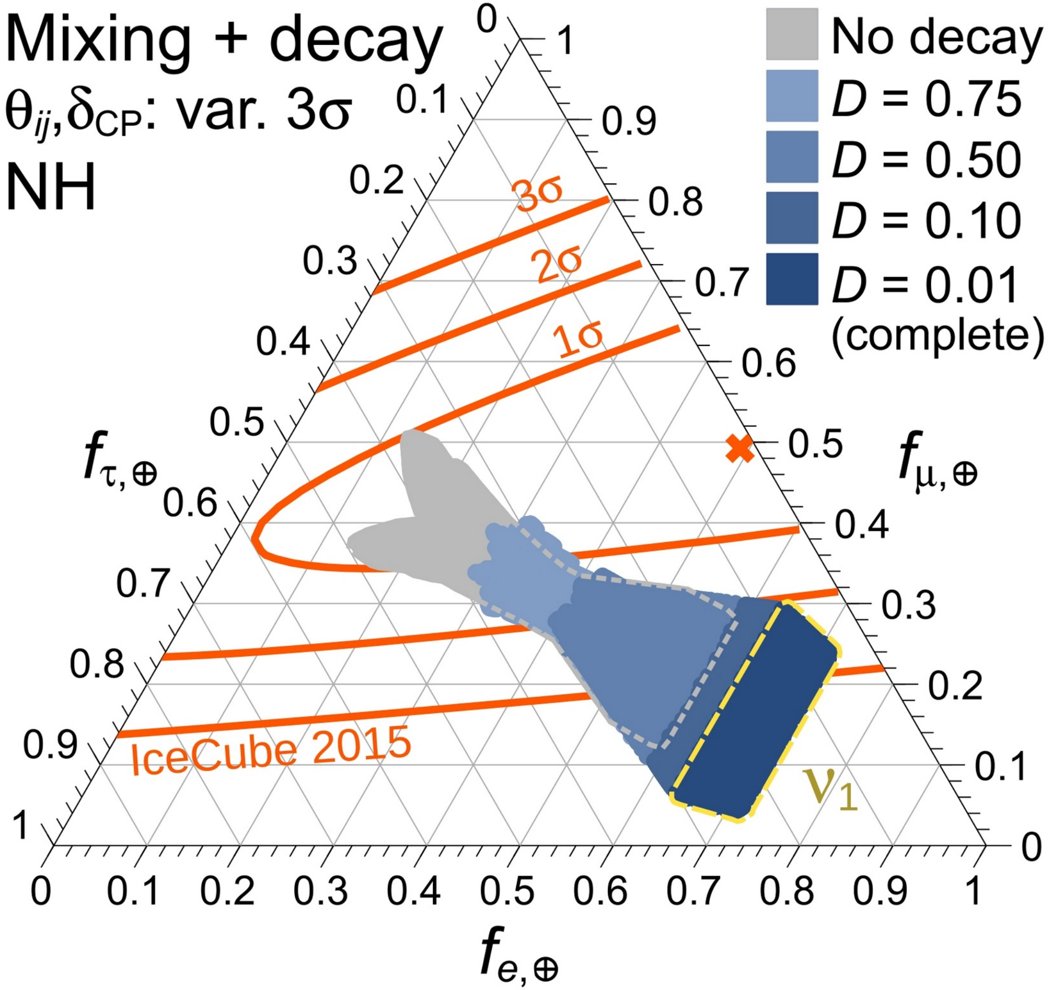

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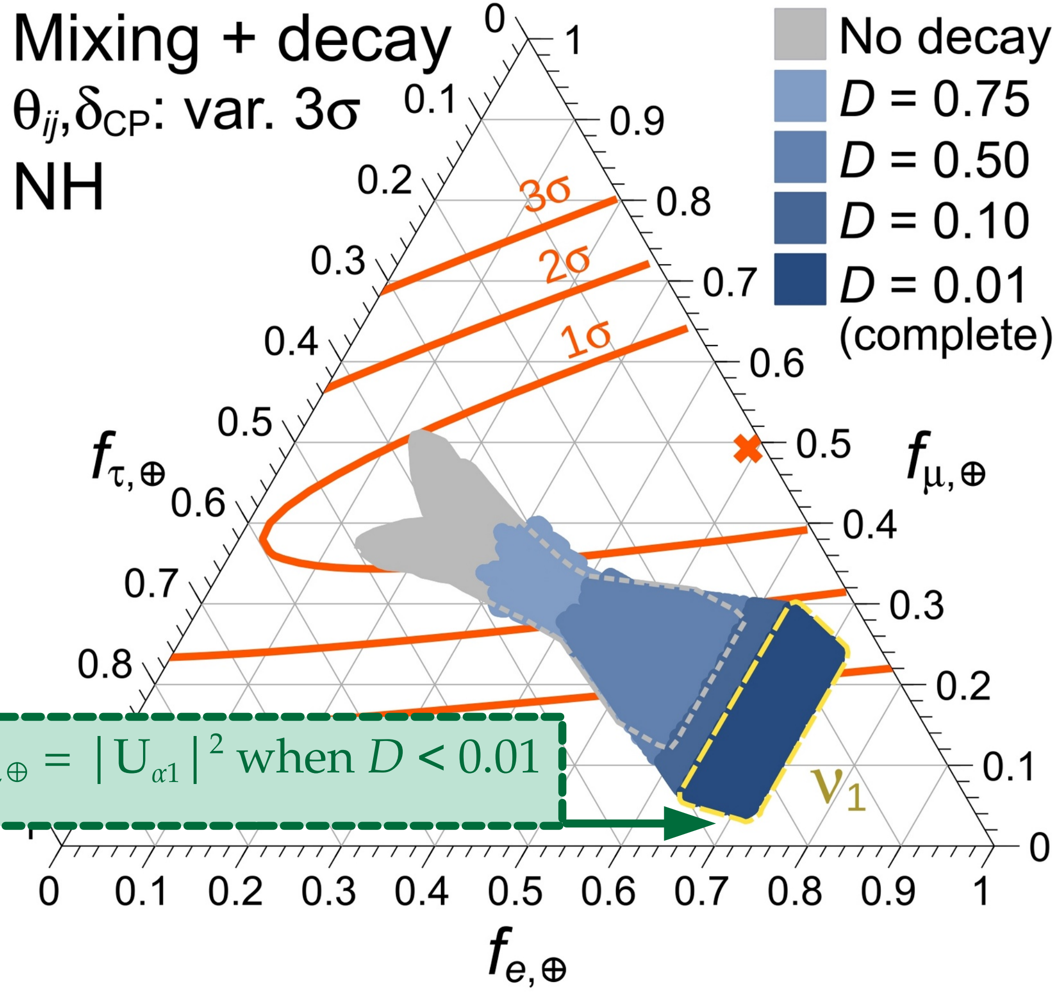
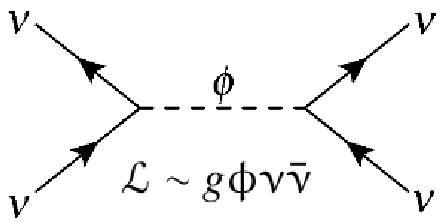


$f_{\alpha,\oplus} = |U_{\alpha 1}|^2$ when $D < 0.01$

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

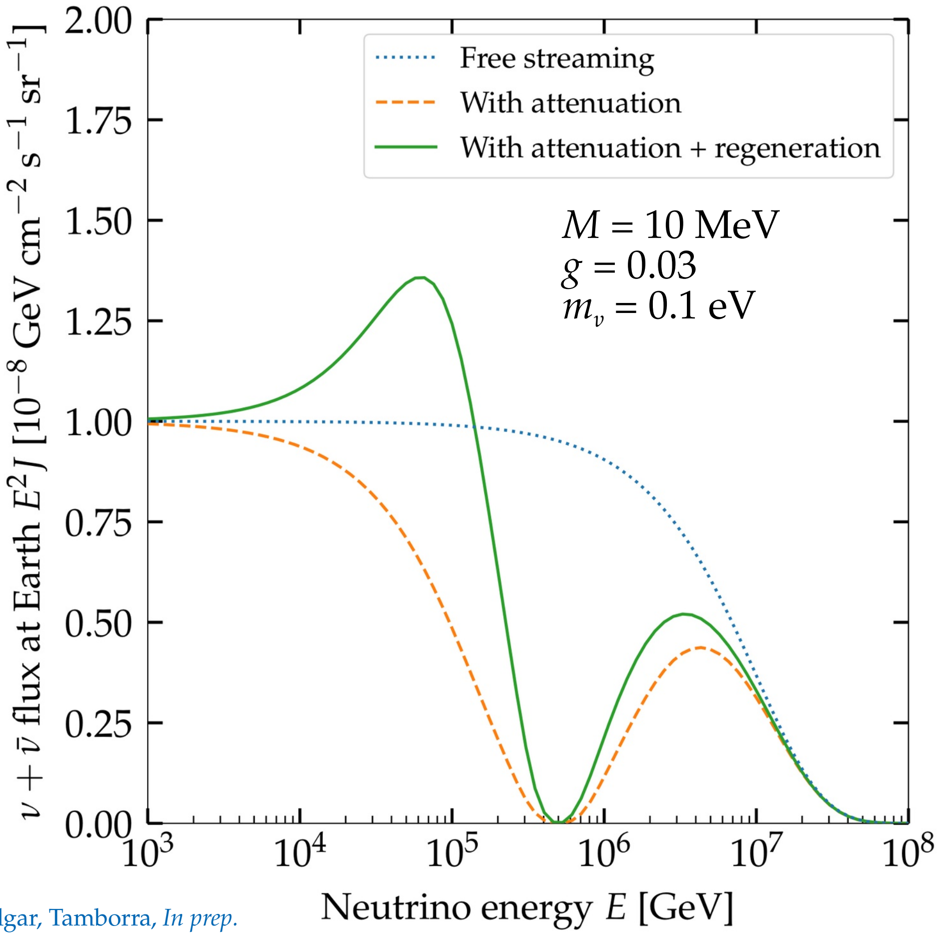
New physics in the spectral shape: νν interactions

"Secret" neutrino interactions between astrophysical ν (PeV) and relic ν (0.1 meV):



Cross section: $$\sigma = \frac{g^4}{4\pi}\frac{s}{(s-M^2)^2+M^2\Gamma^2}$$

Resonance energy: $$E_{\text{res}} = \frac{M^2}{2m_\nu}$$



MB, Rosenstroem, Shalgar, Tamborra, *In prep.*
Ng & Beacom, *PRD* 2014
Cherry, Friedland, Shoemaker, 1411.1071
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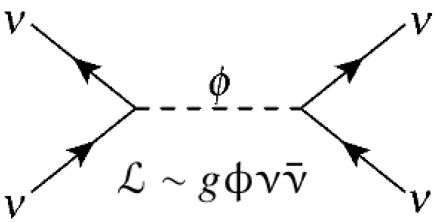

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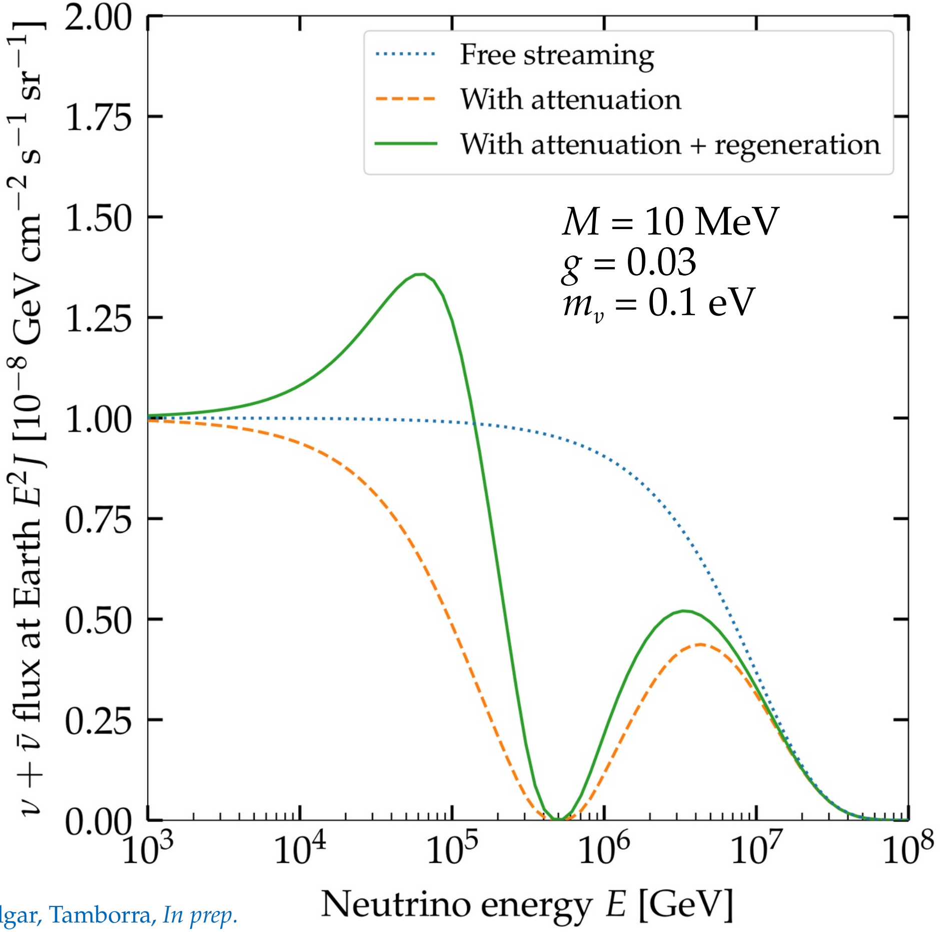

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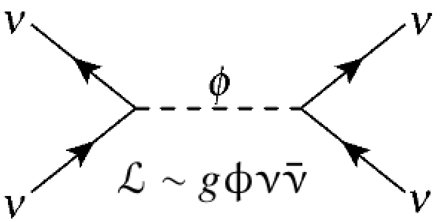

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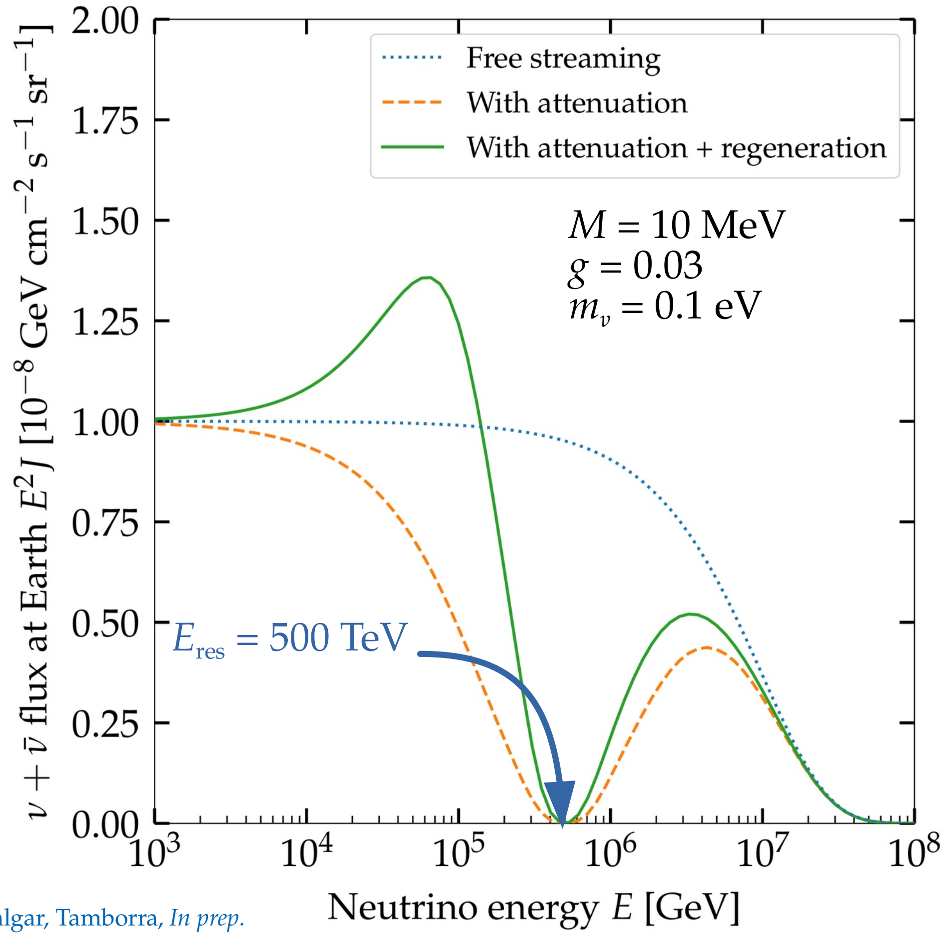

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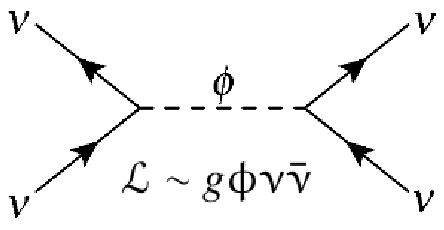

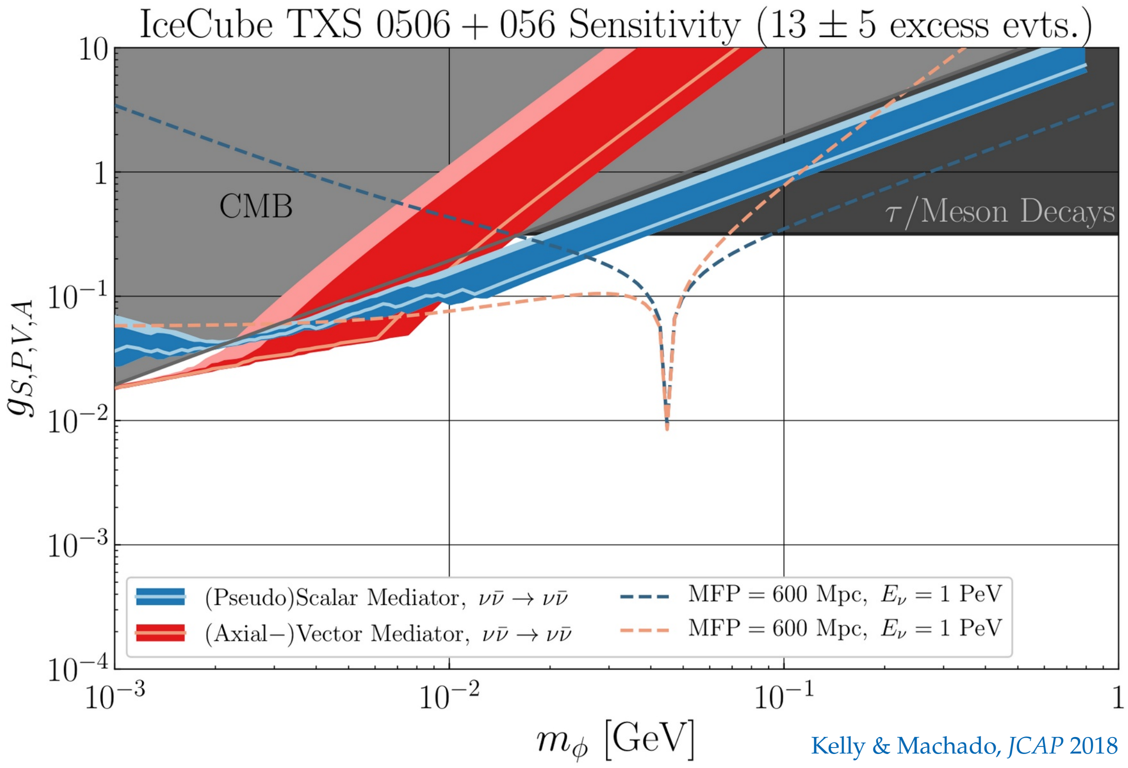

Kelly & Machado, *JCAP* 2018

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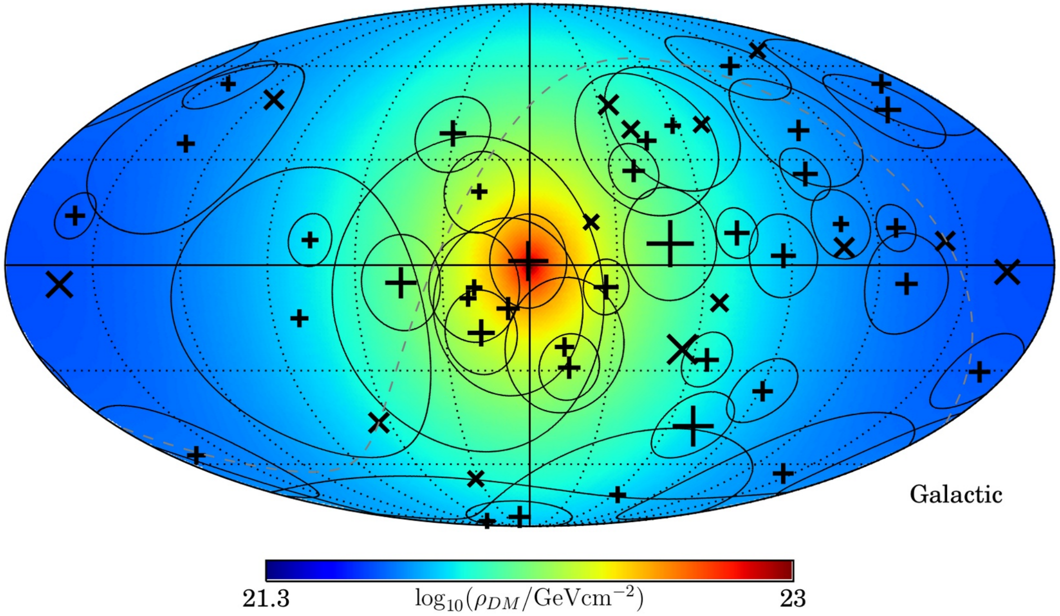

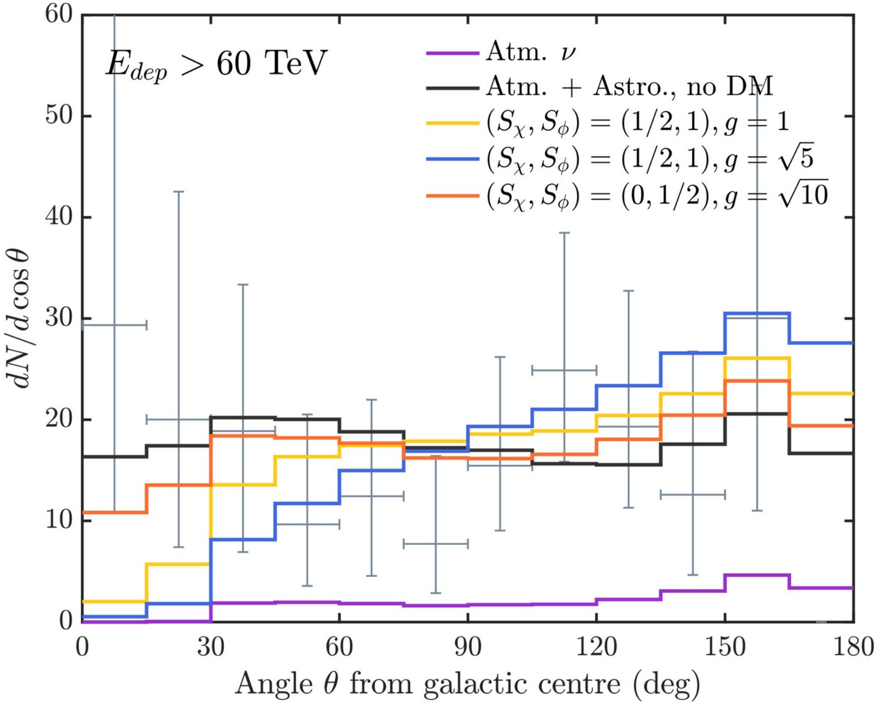

Expected: Fewer neutrinos coming from the Galactic Center

Observed: Isotropy

Argüelles, Kheirandish, Vincent, *PRL* 2017

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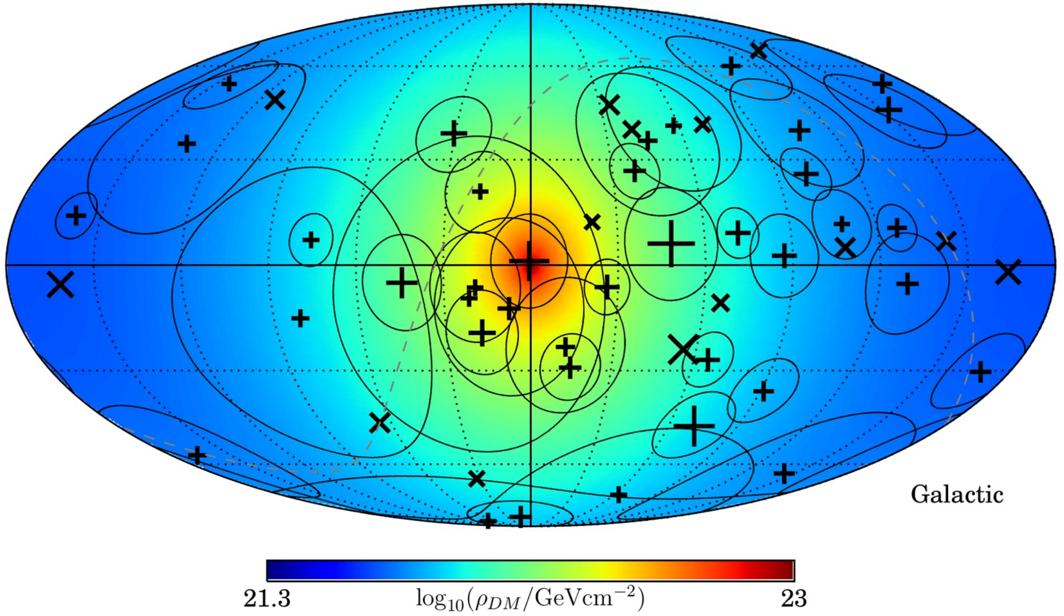

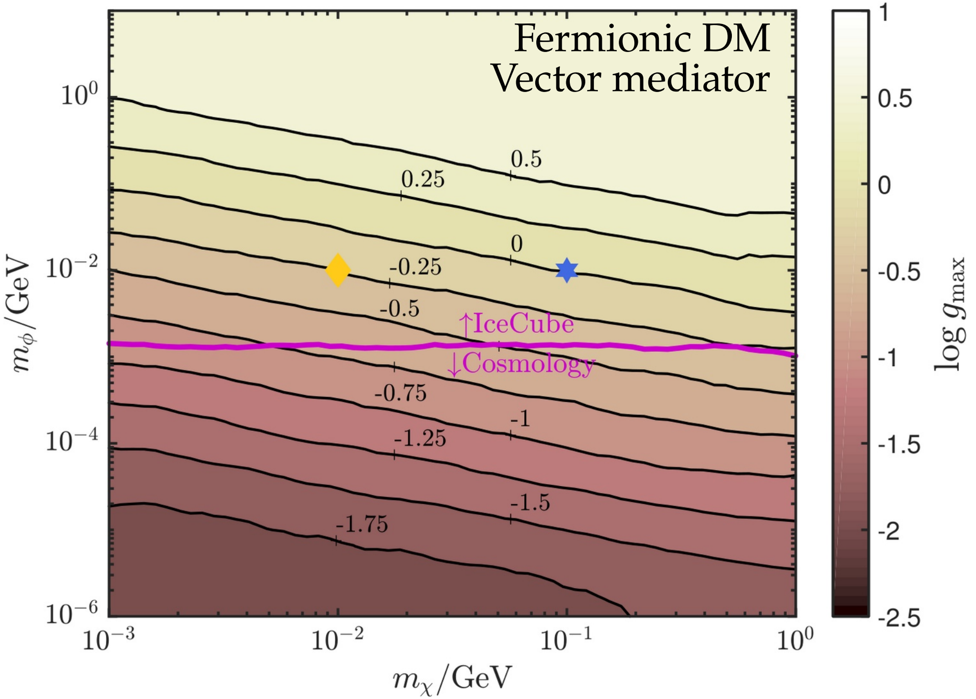

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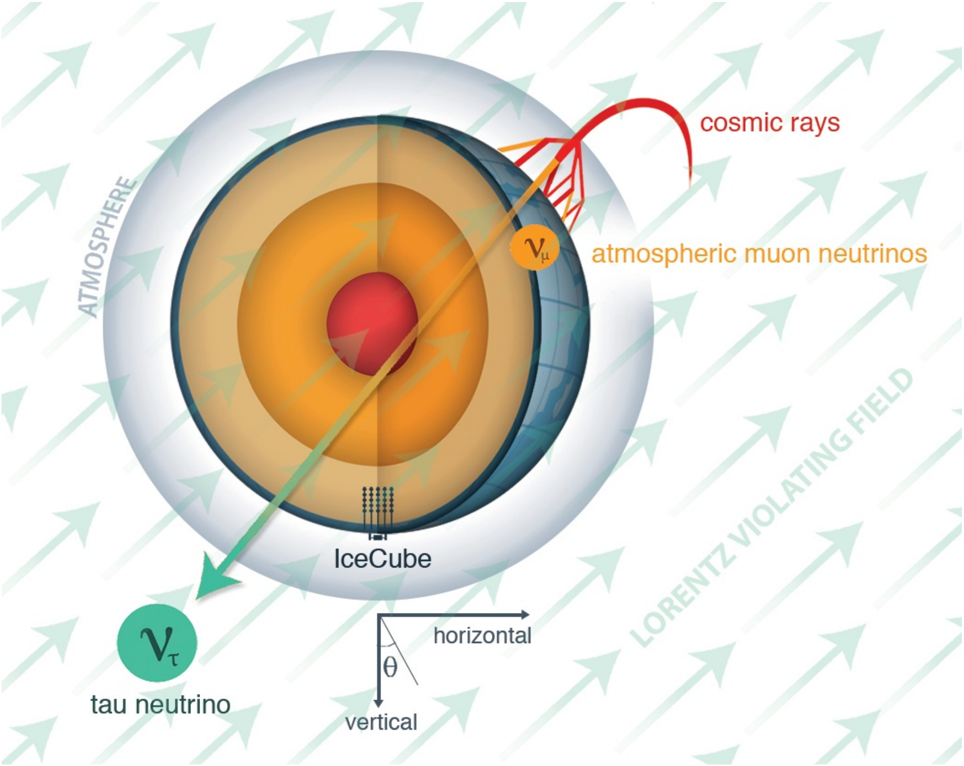
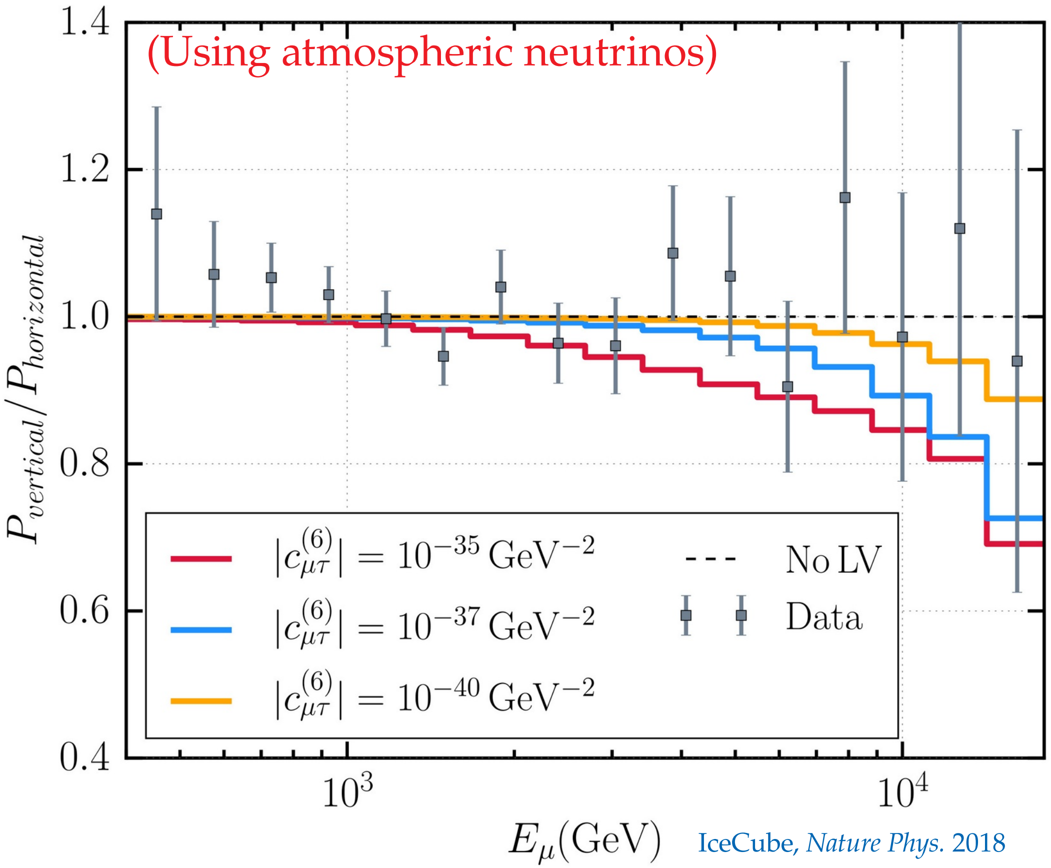
New physics in the energy & angular distribution

Lorentz invariance violation – Hamiltonian: $H \sim m^2/(2E) + a^{(3)} - E \cdot c^{(4)} + E^2 \cdot a^{(5)} - E^3 \cdot c^{(6)}$





IceCube, *Nature Phys.* 2018

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Standard oscillations

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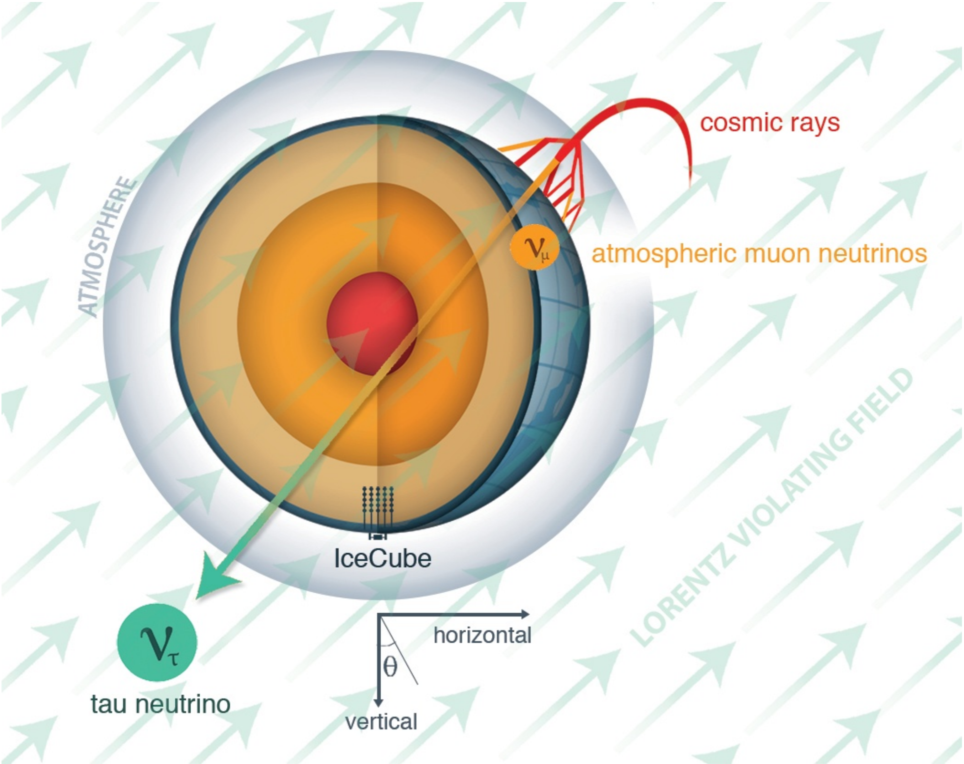

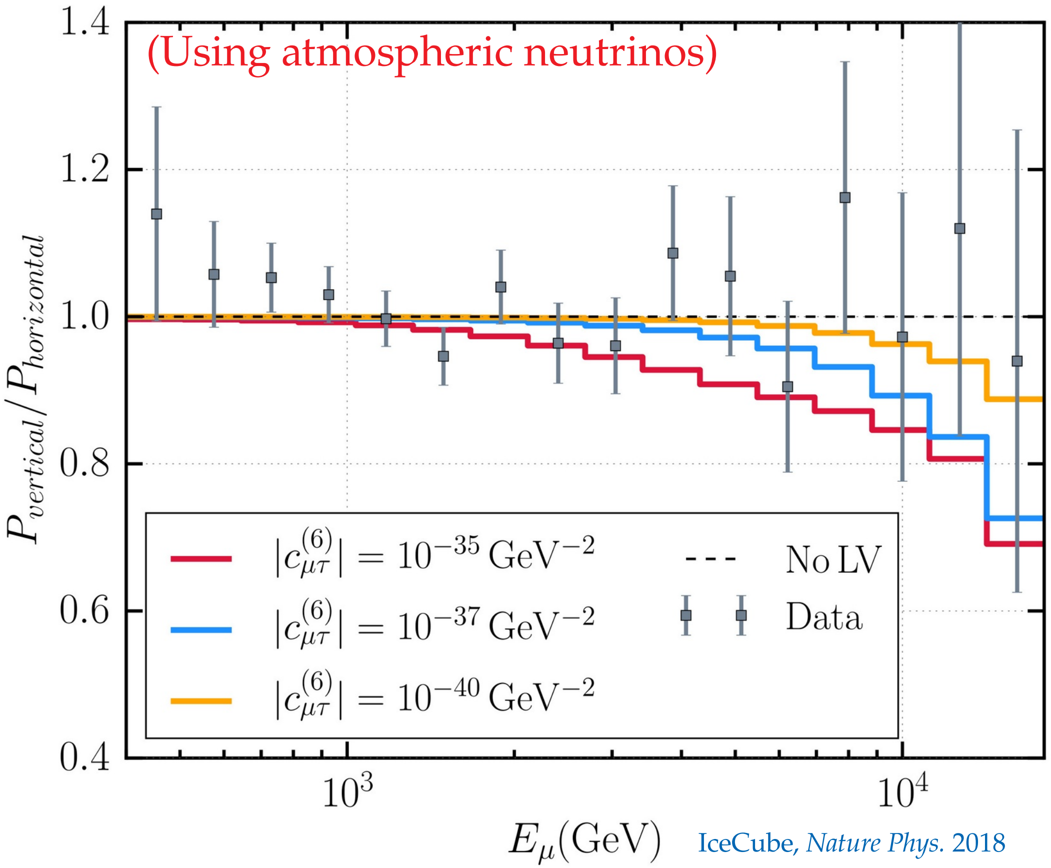

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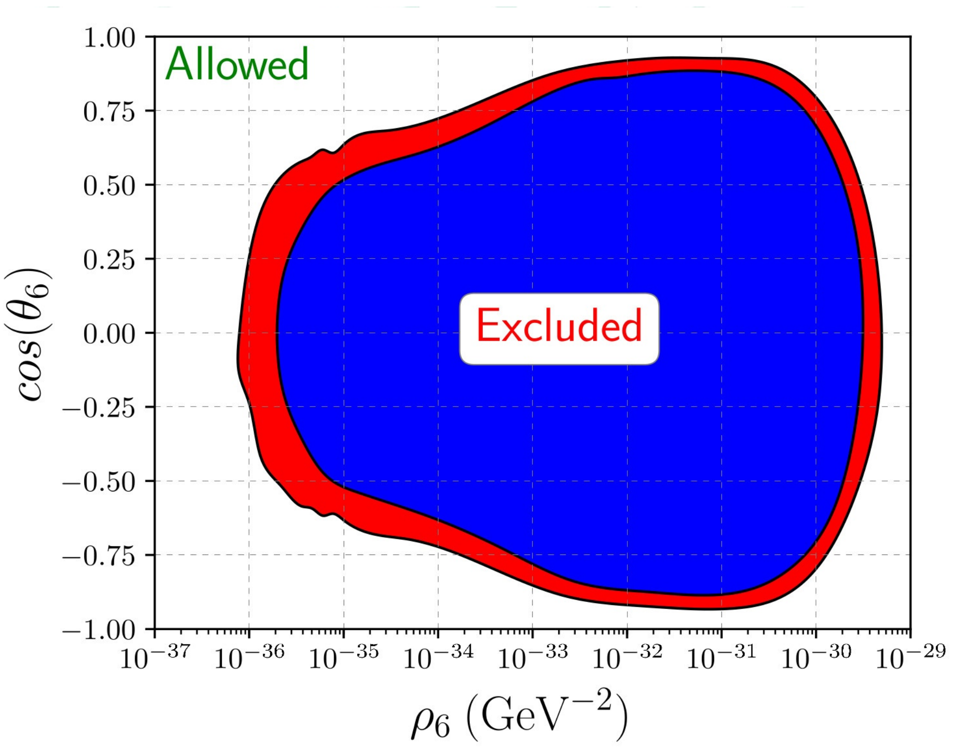
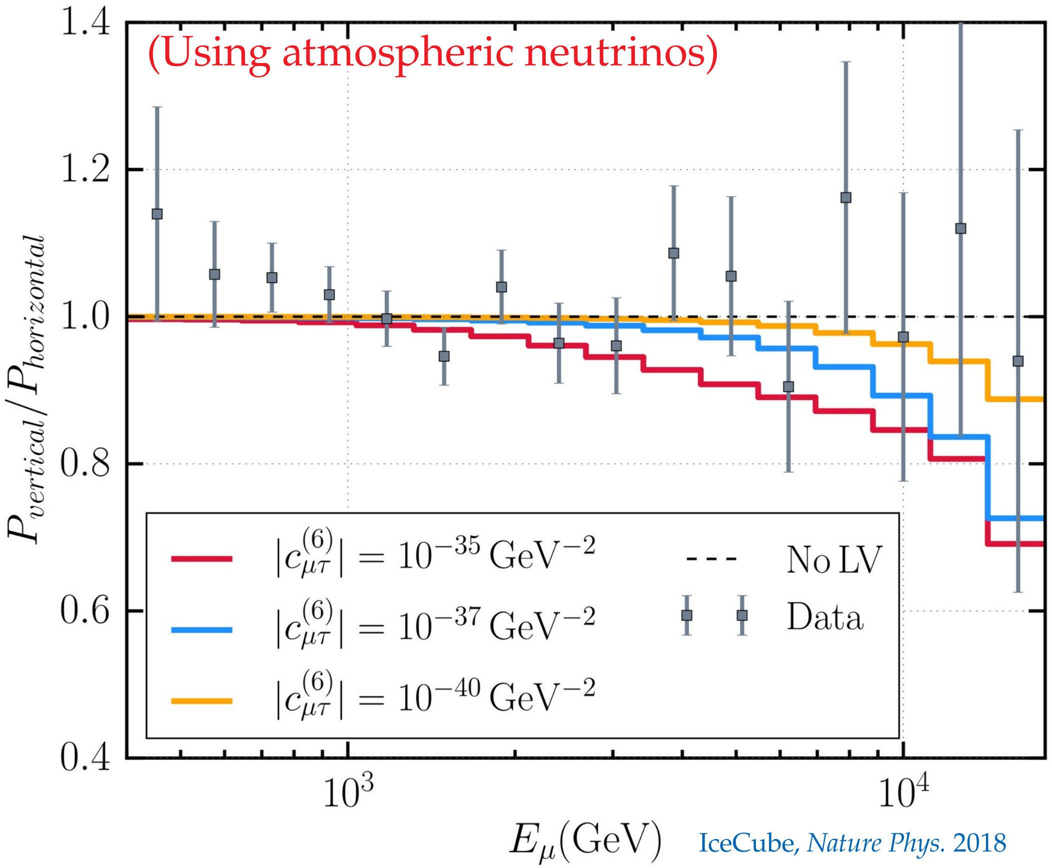
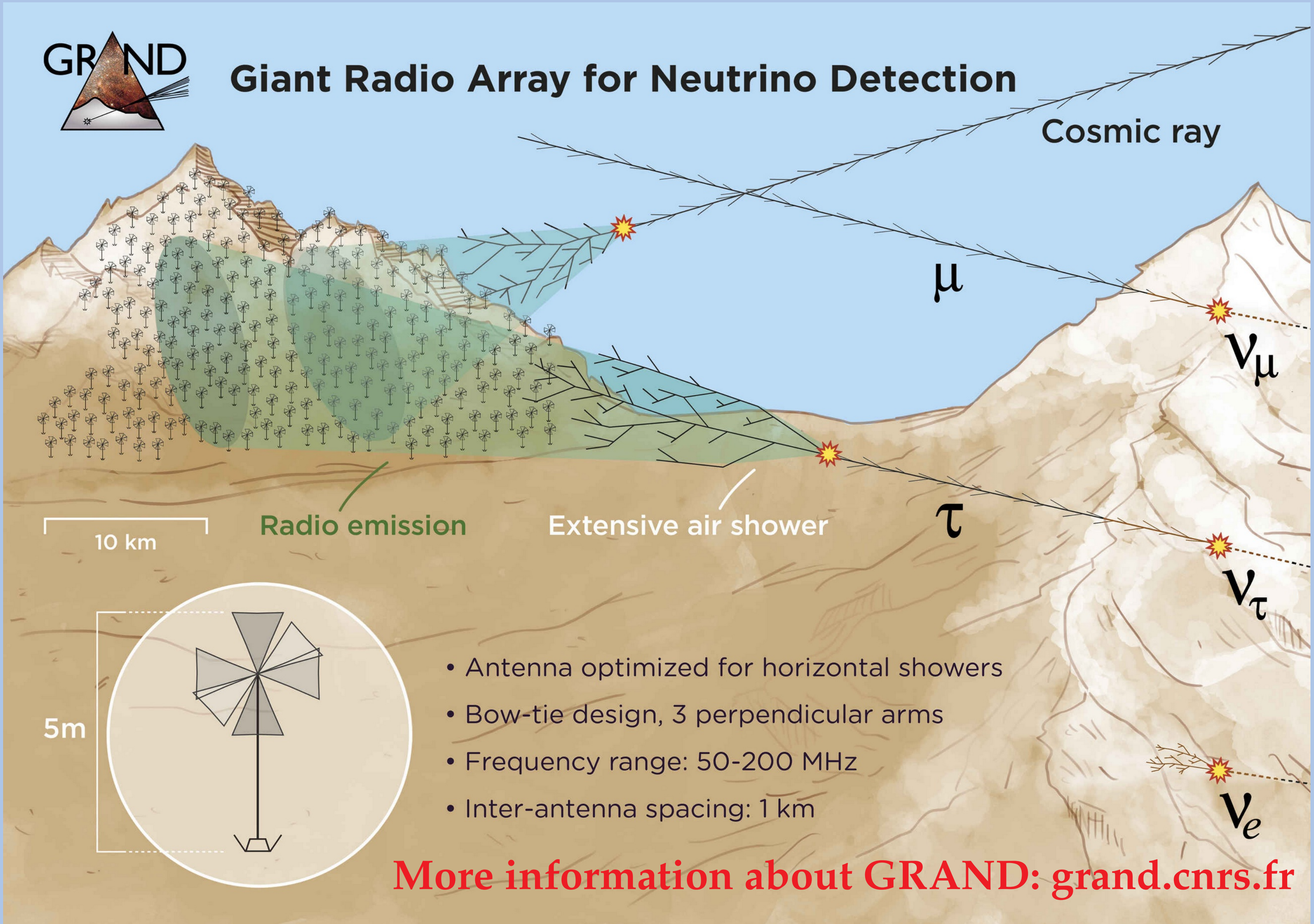
Best bounds come from IceCube





IceCube, *Nature Phys.* 2018


GRAND
Giant Radio Array for Neutrino Detection
Cosmic ray
μ
ν_μ
τ
ν_τ
ν_e
10 km
Radio emission
Extensive air shower
5m
• Antenna optimized for horizontal showers
• Bow-tie design, 3 perpendicular arms
• Frequency range: 50-200 MHz
• Inter-antenna spacing: 1 km
More information about GRAND: grand.cnrs.fr

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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$\theta_{23} \approx 48^\circ$

$\theta_{13} \approx 9^\circ$

$\theta_{12} \approx 34^\circ$

$\delta \approx 222^\circ$

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… But high-energy neutrinos oscillate *fast*

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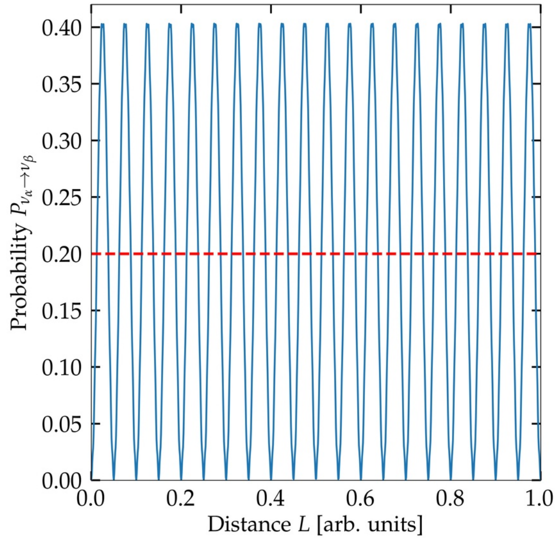

Oscillation length for 1-TeV ν: $2\pi \times 2E/\Delta m^2 \sim 0.1$ pc

~ 8% of the way to Proxima Centauri

≪ Distance to Galactic Center (8 kpc)

≪ Distance to Andromeda (1 Mpc)

≪ Cosmological distances (few Gpc)

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

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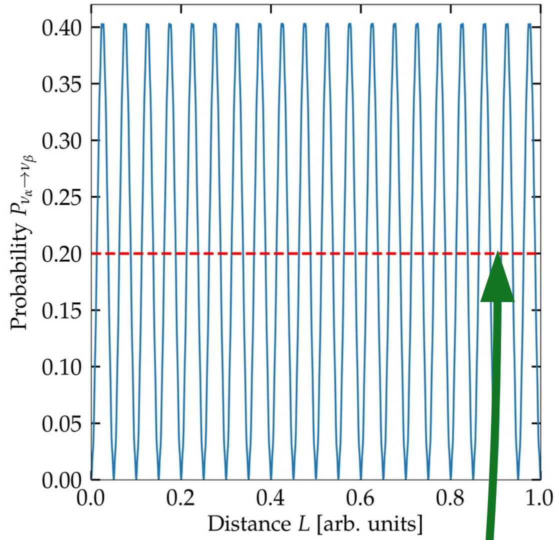

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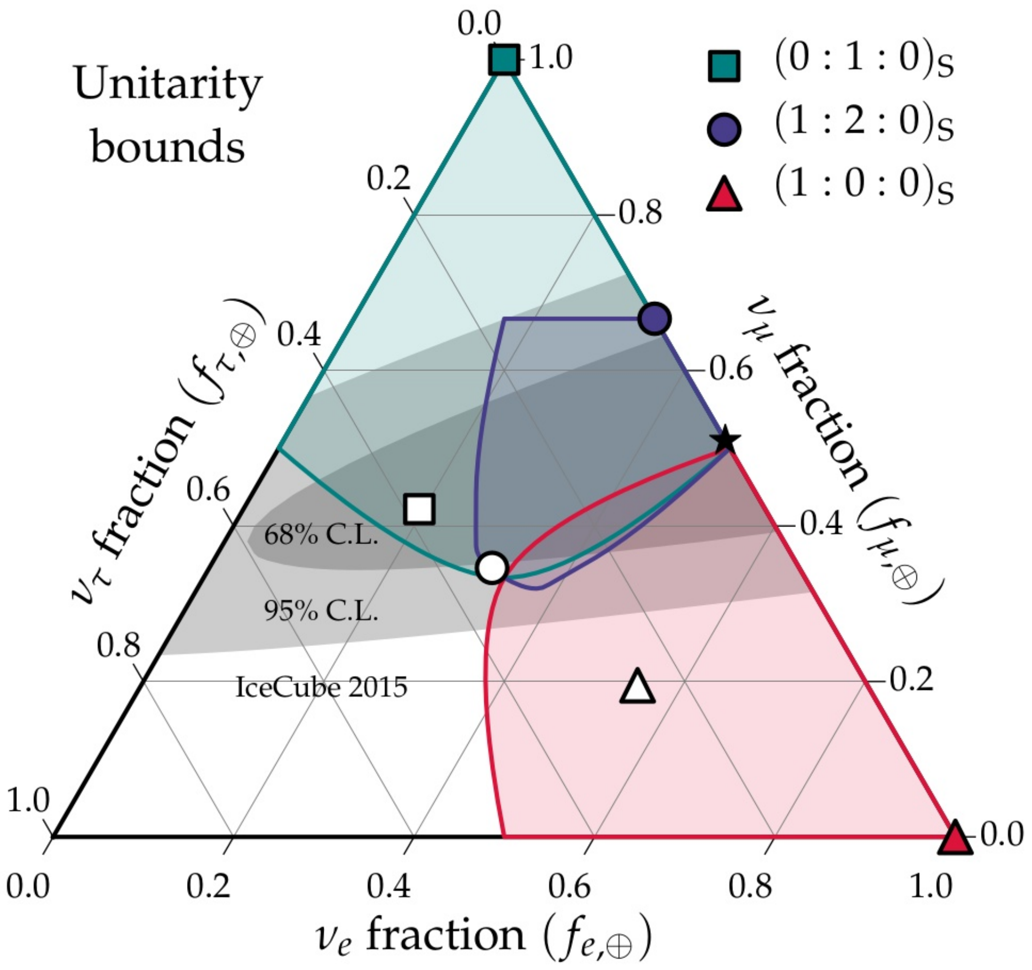
Using unitarity to constrain new physics

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

- 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

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 —

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

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

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

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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

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

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

Electron-neutrino interactions can kill oscillations

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

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New neutrino-electron interaction:
This is diagonal

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

Electron-neutrino interactions can kill oscillations

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

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

$\sim 1/E$

Energy-independent

Electron-neutrino interactions can kill oscillations

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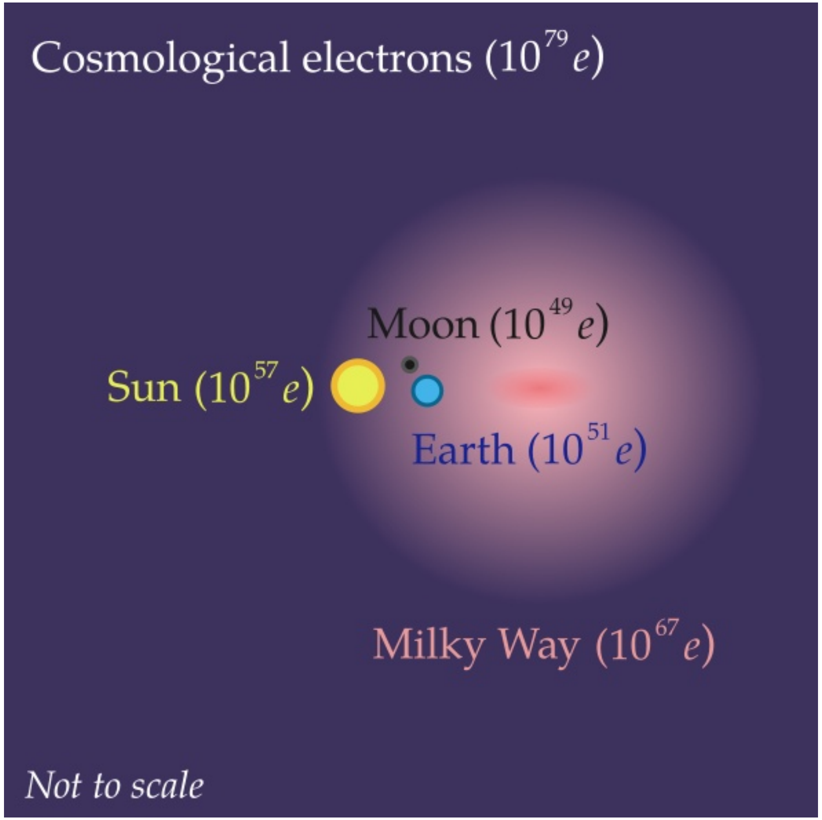
$\sim 1/E$

Energy-independent

∴ We can use high-energy astrophysical neutrinos

The total potential



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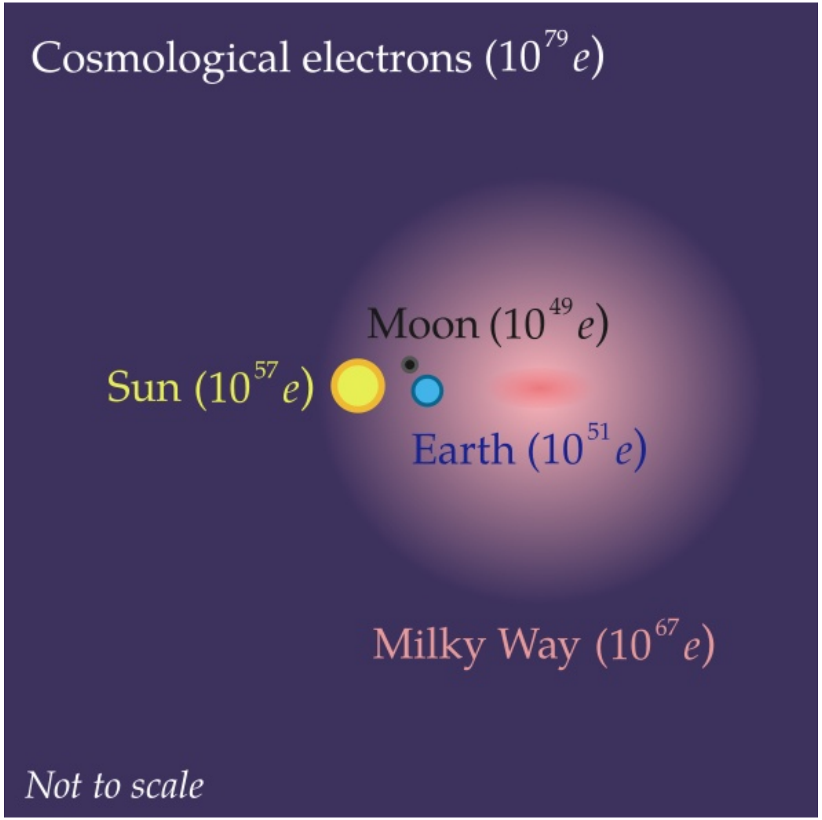
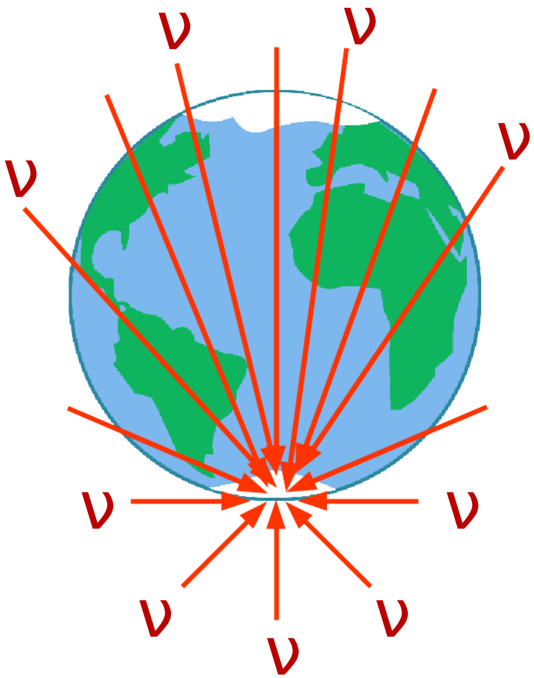


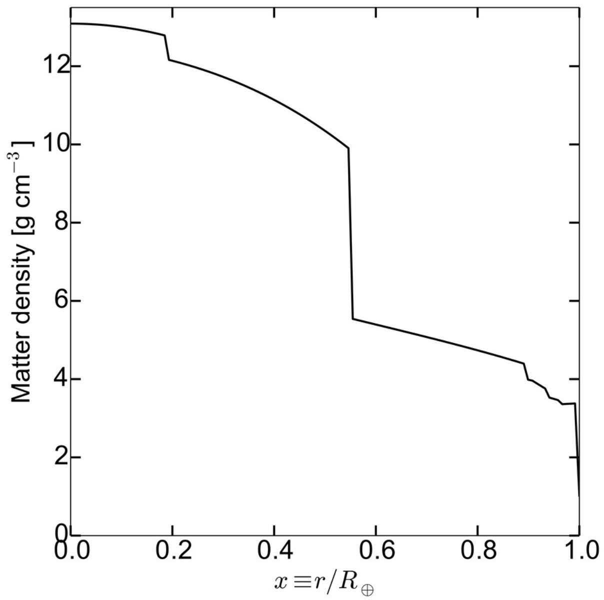
$$V_{e\beta} = V_{e\beta}^{\oplus}$$

Earth:



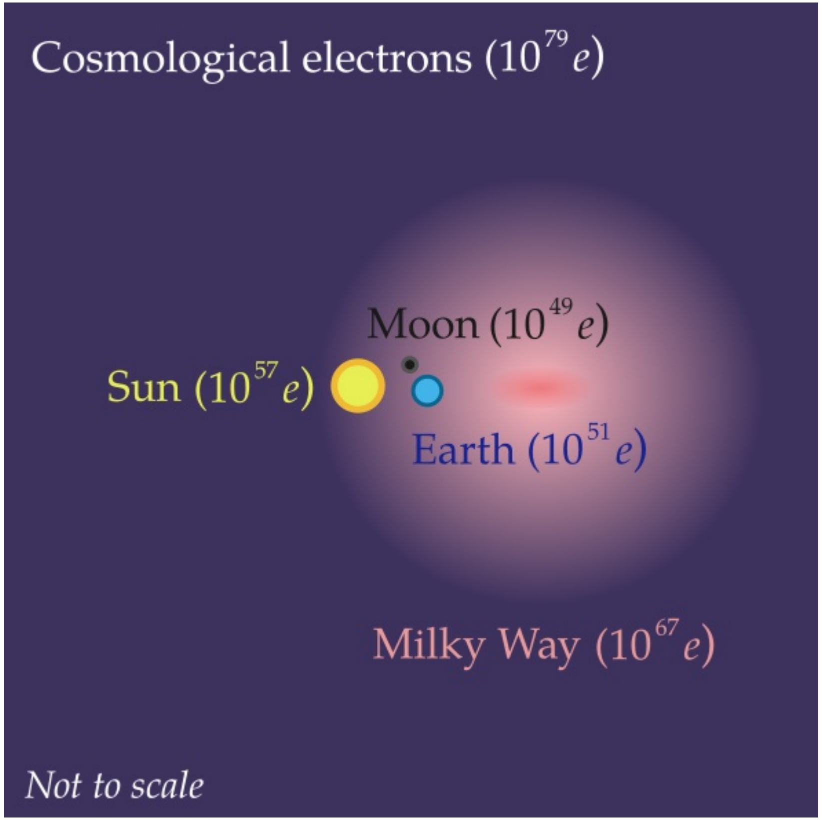
Preliminary Reference Earth Model

Dziewonski & Anderson 1981

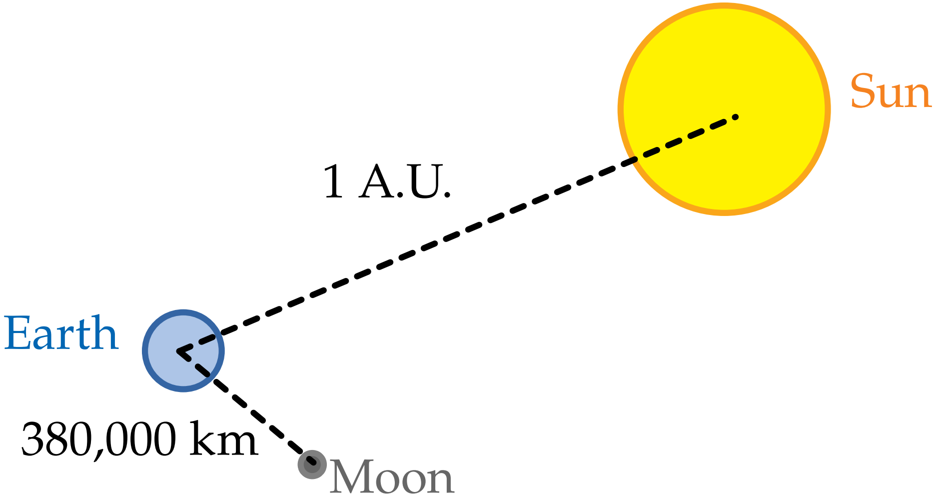


Neutrinos traverse different electron column depths

The total potential



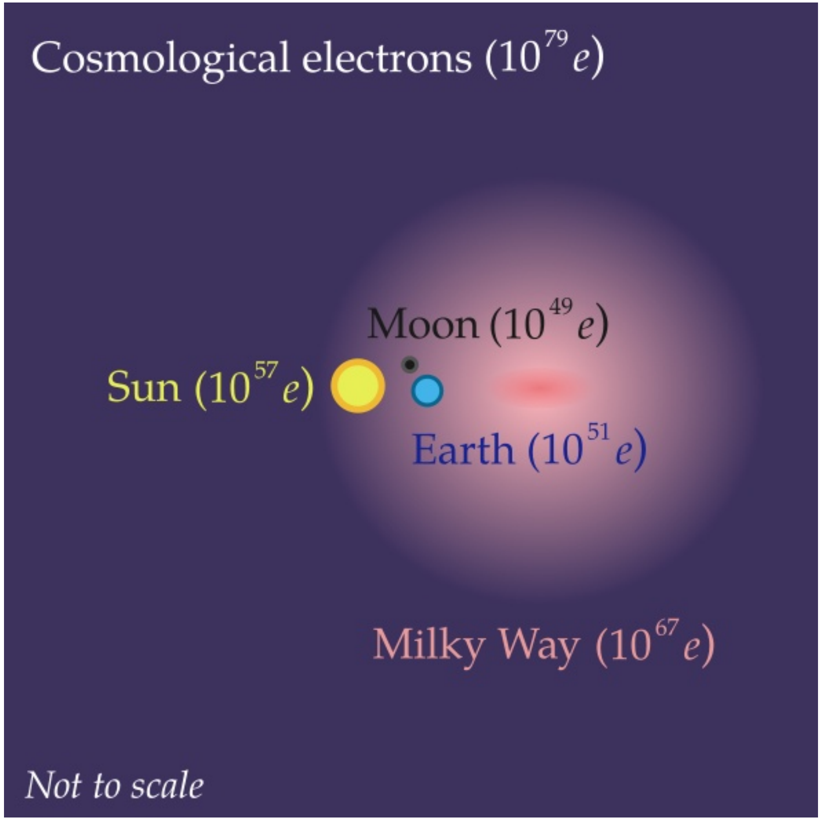
Moon and Sun:



Treated as point sources of electrons

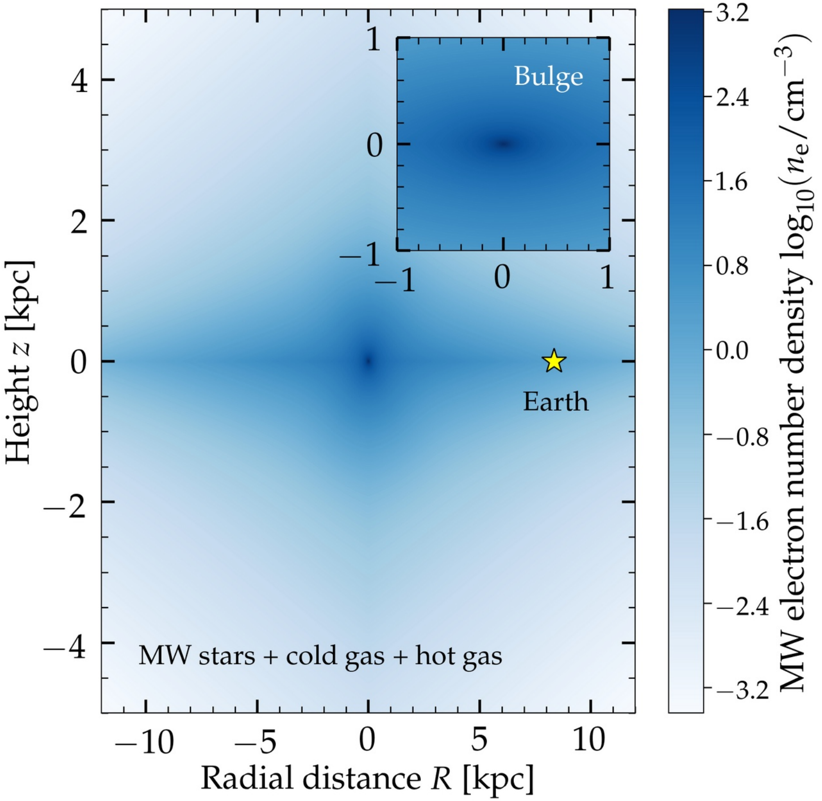
$$V_{e\beta} = V_{e\beta}^{\oplus} + V_{e\beta}^{\mathrm{Moon}} + V_{e\beta}^{\odot}$$

The total potential



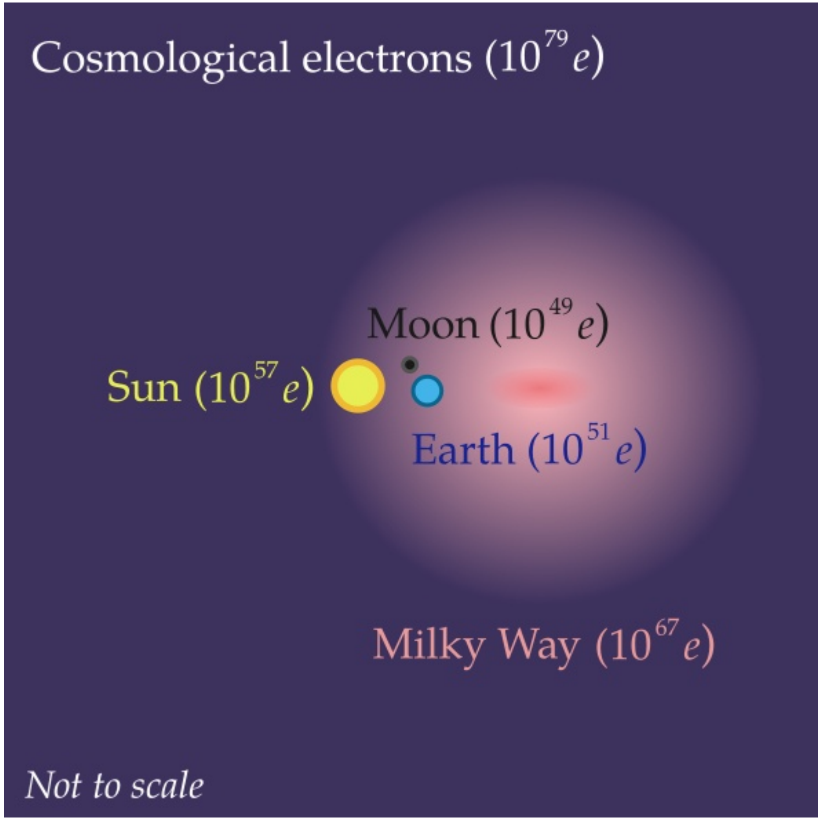
Milky Way:

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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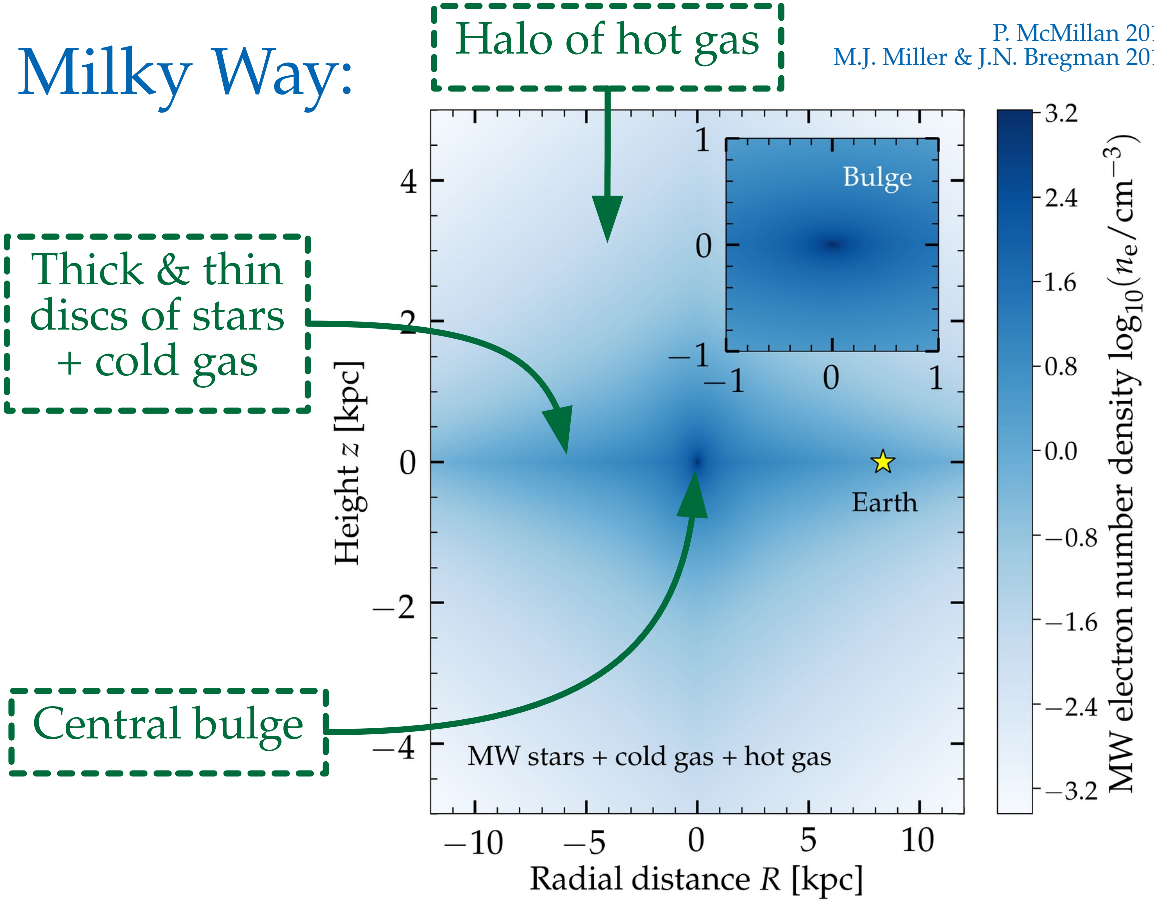

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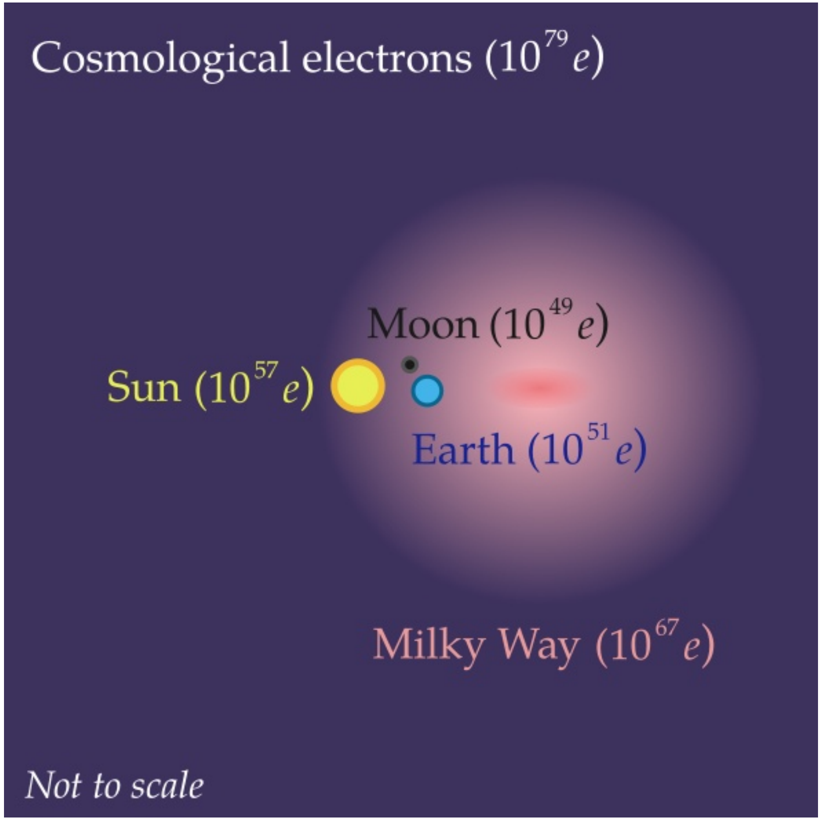
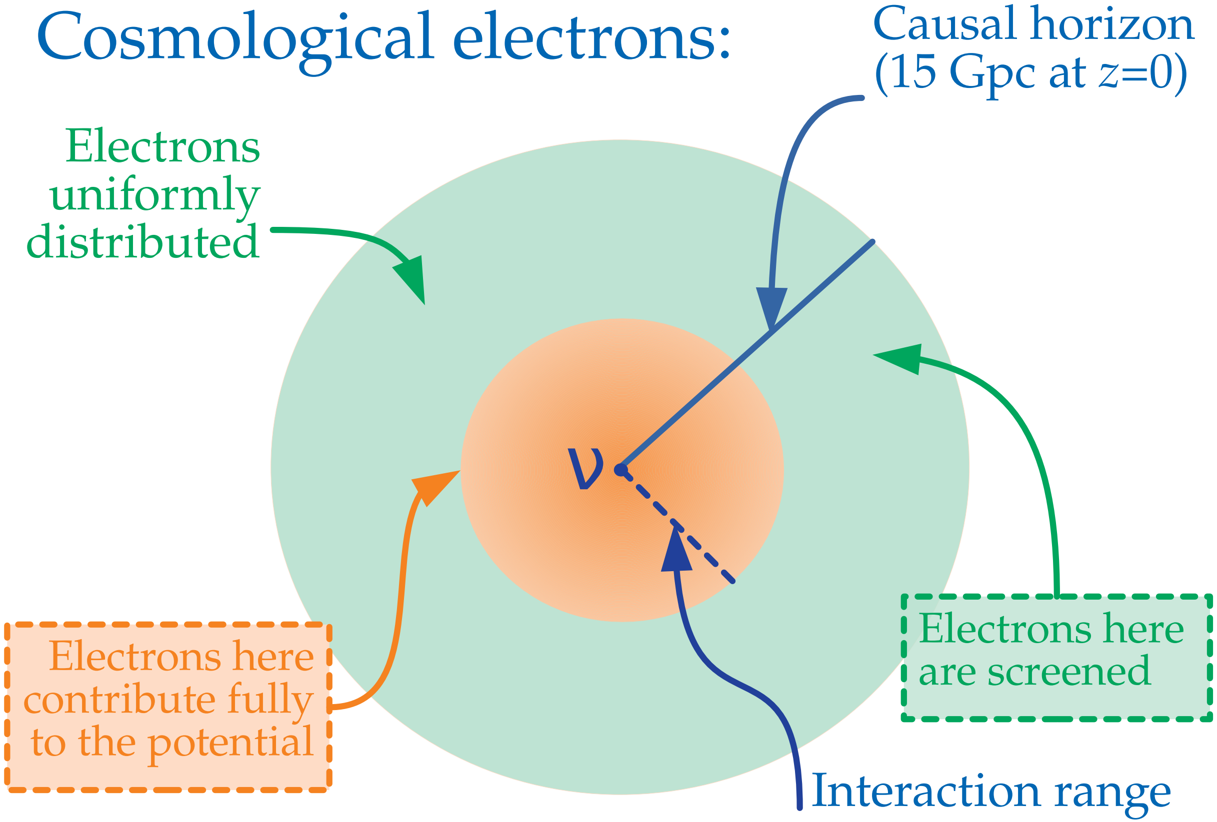
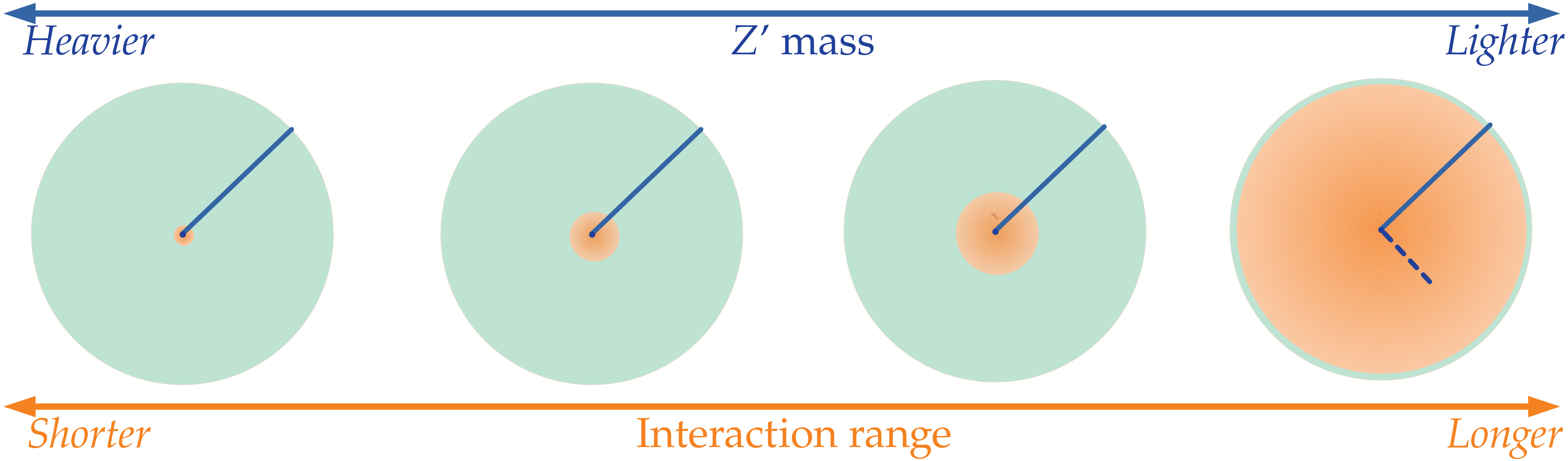


Cosmological electrons:



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

The total potential



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Electrons in the local and distant Universe

Potential:

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

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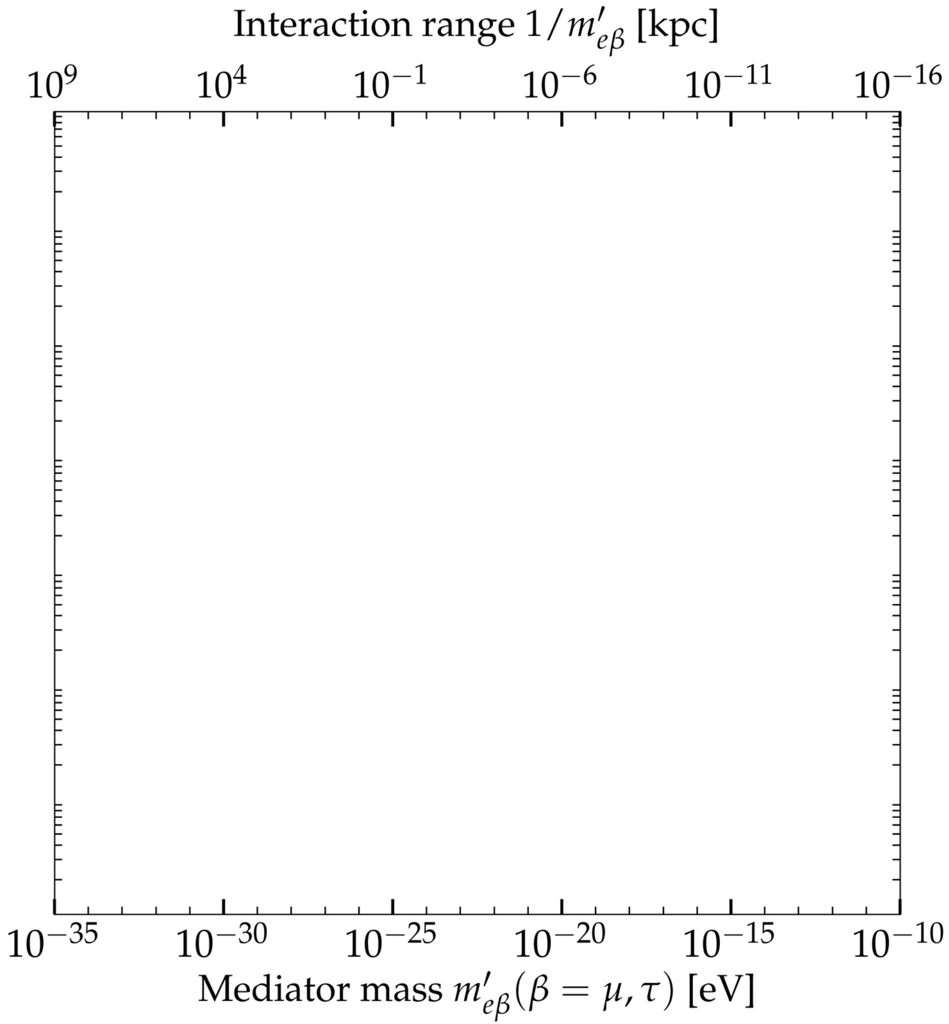

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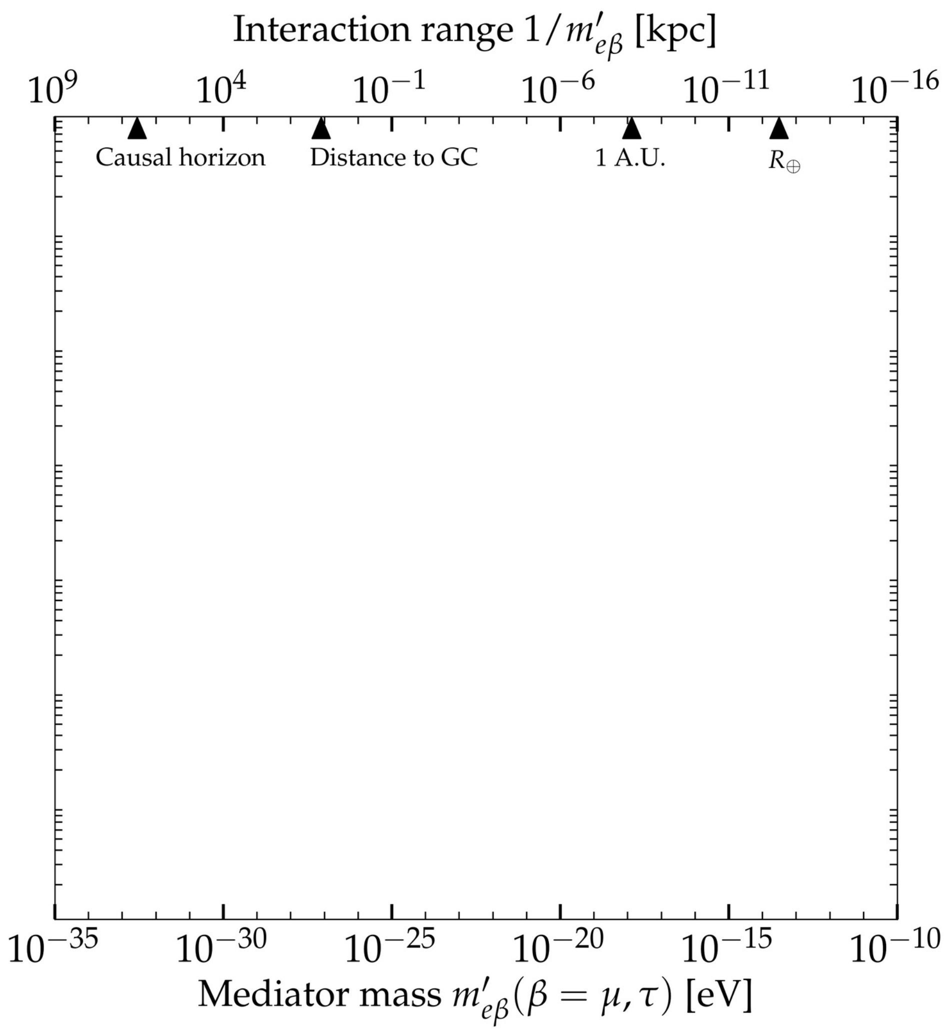

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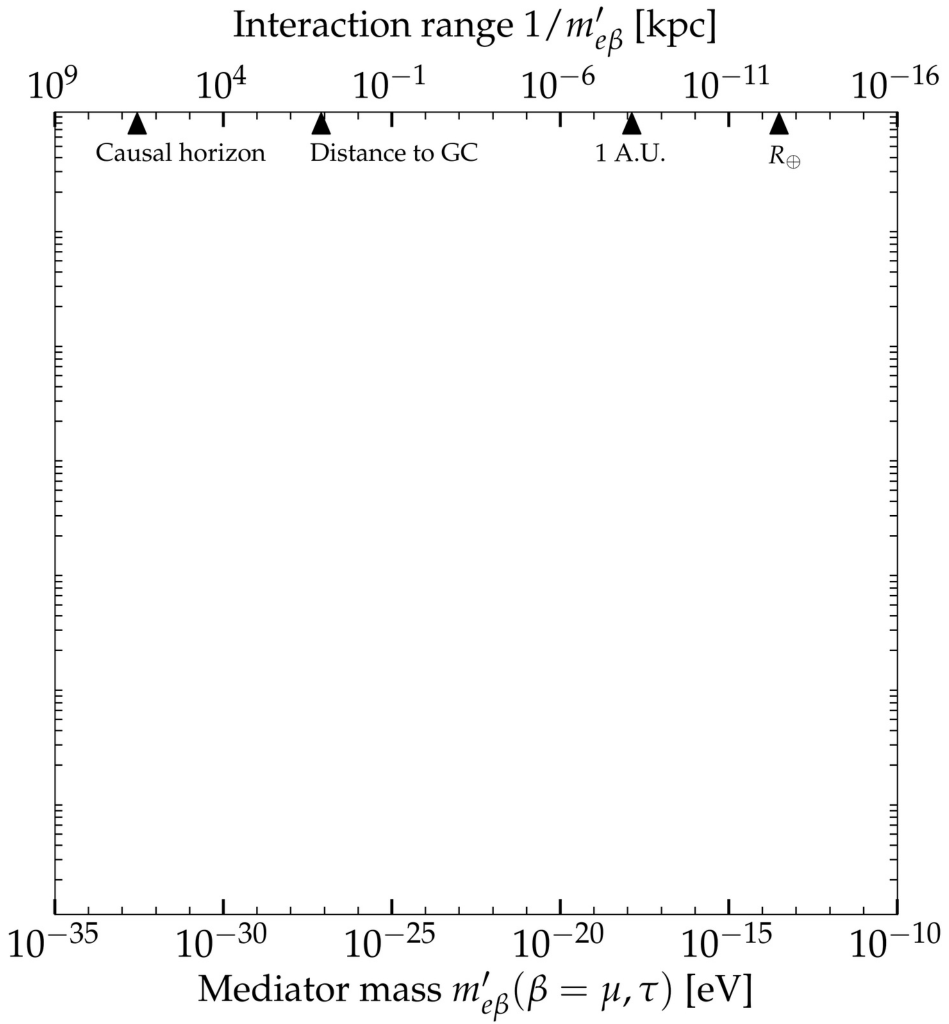

Potential:

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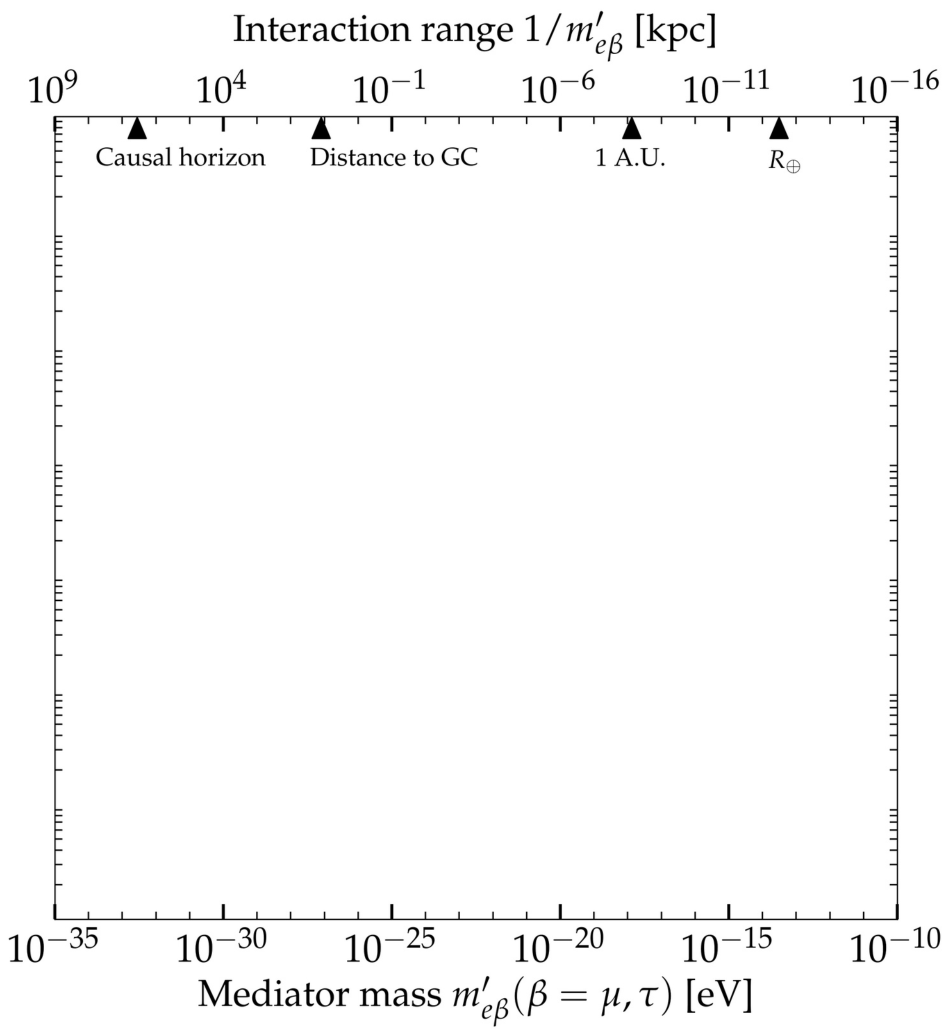
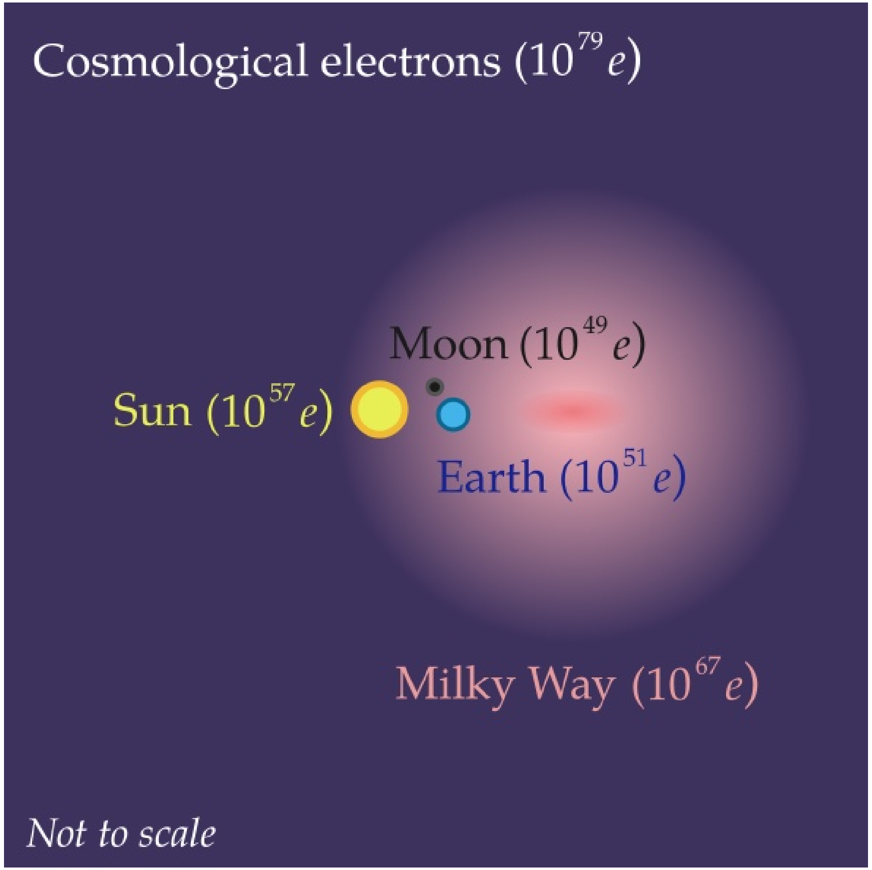
Interaction range: $\dfrac{1}{m'_{e\beta}}$

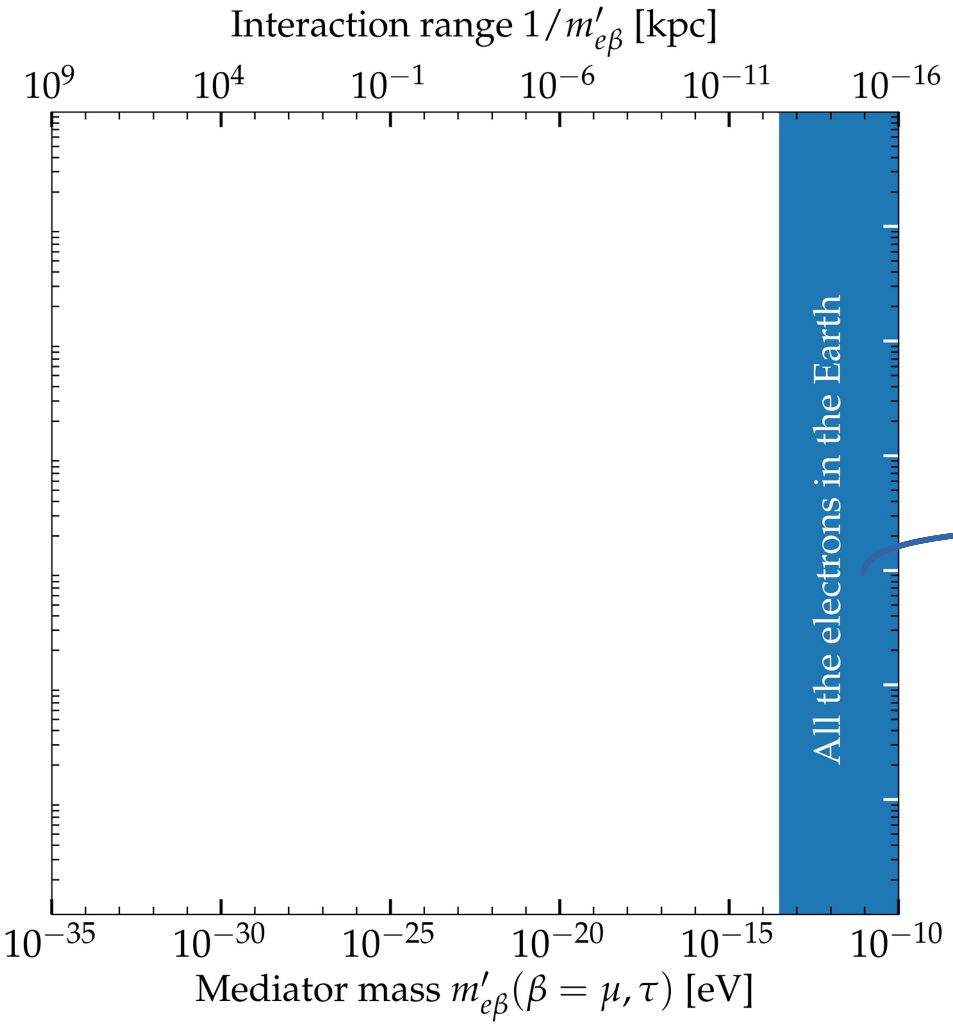
Light mediators
$\Rightarrow$ Long interaction ranges

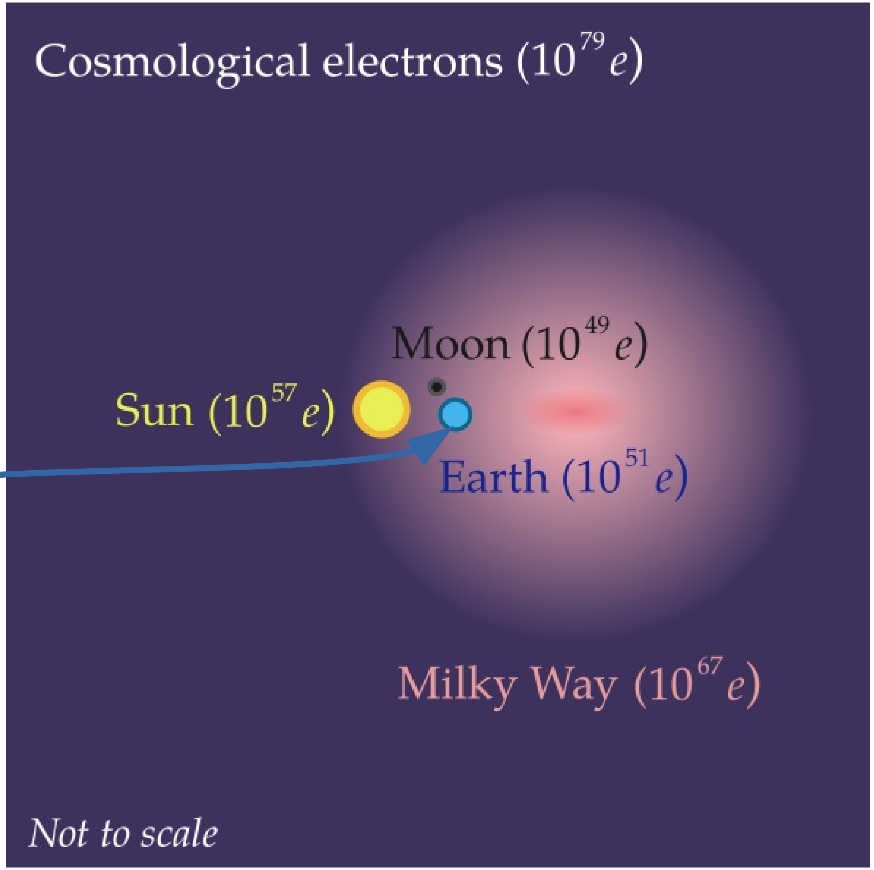
Electrons in the local and distant Universe





Electrons in the local and distant Universe





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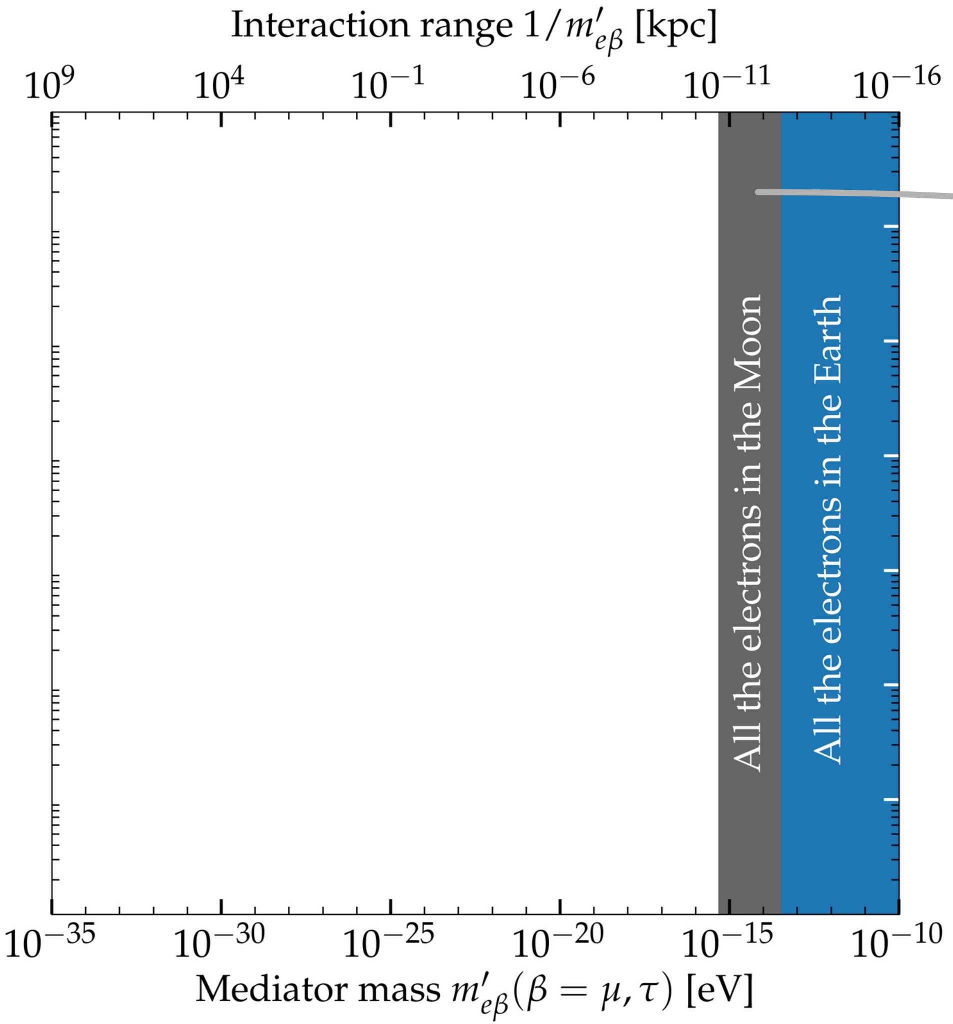

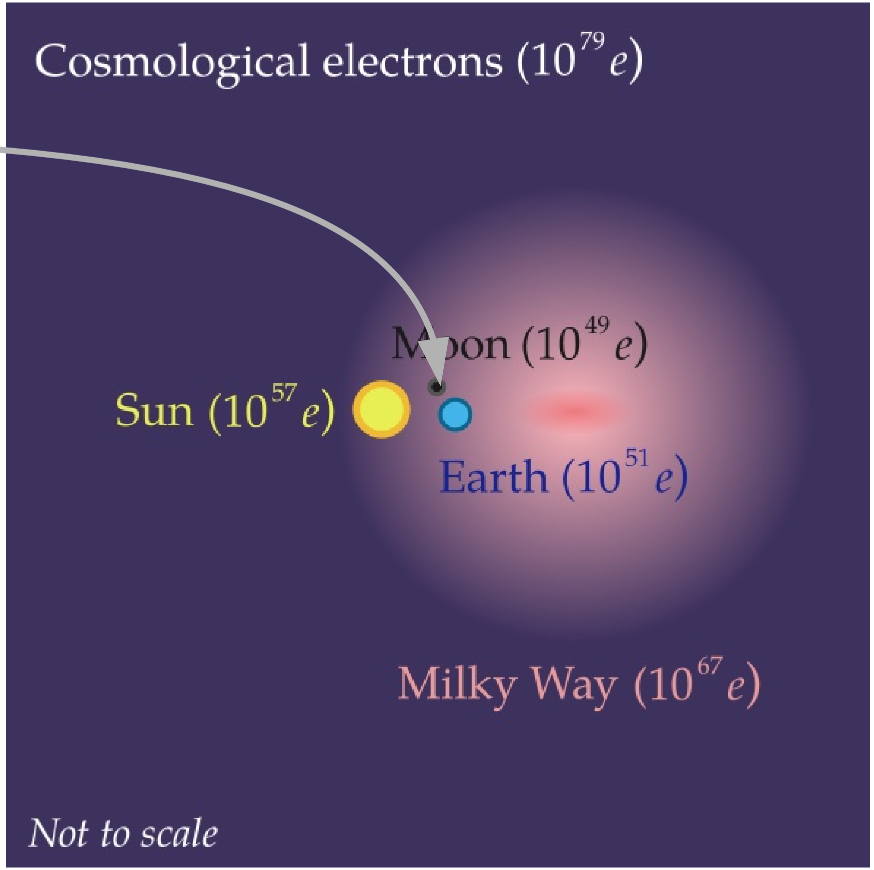

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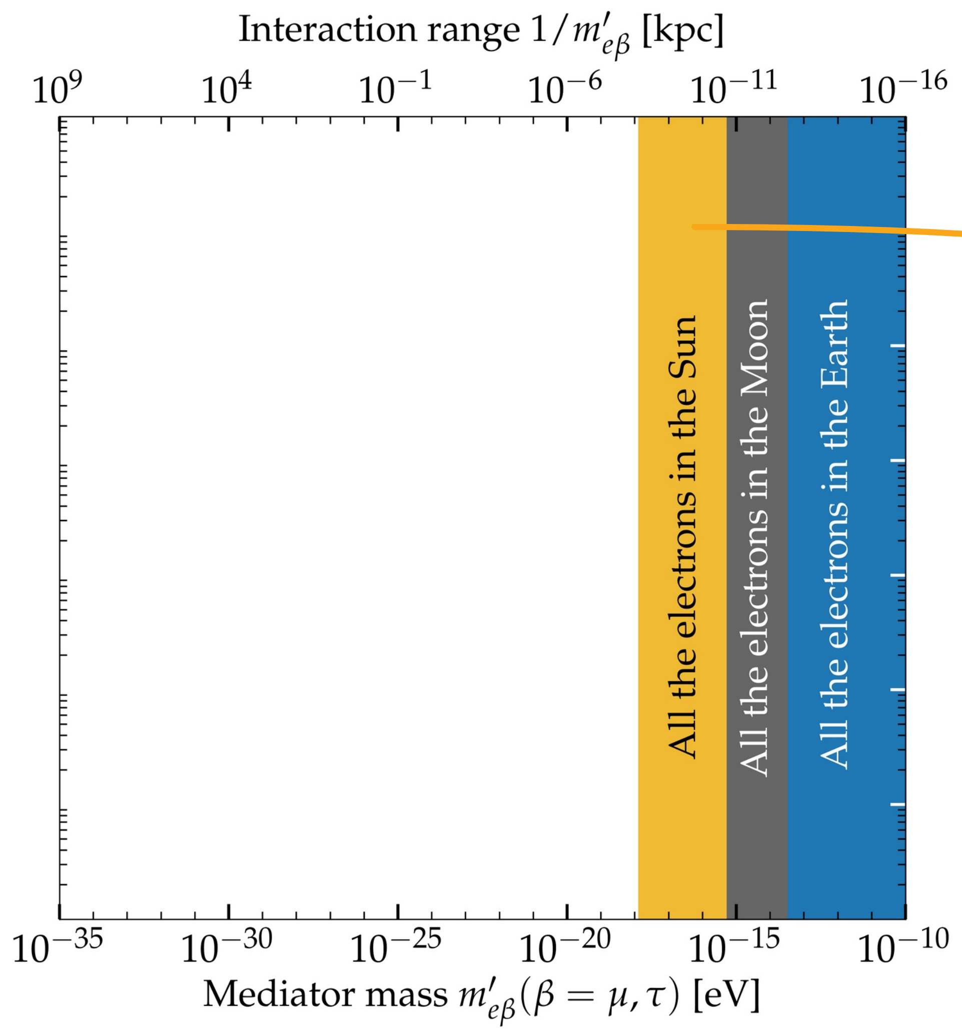
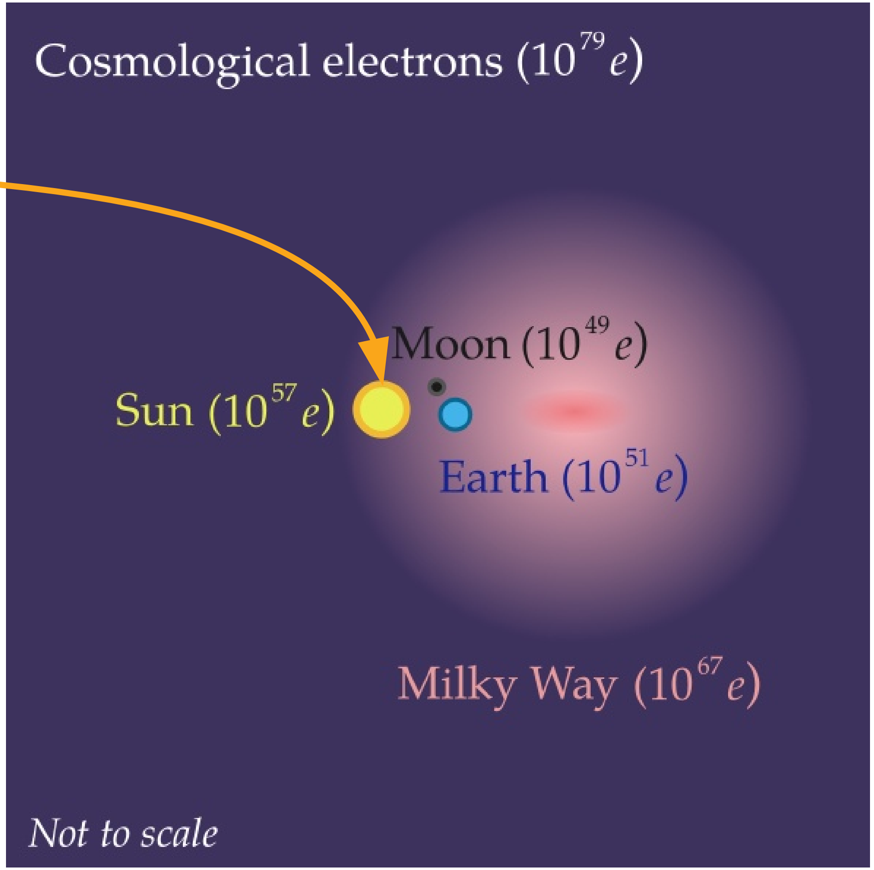
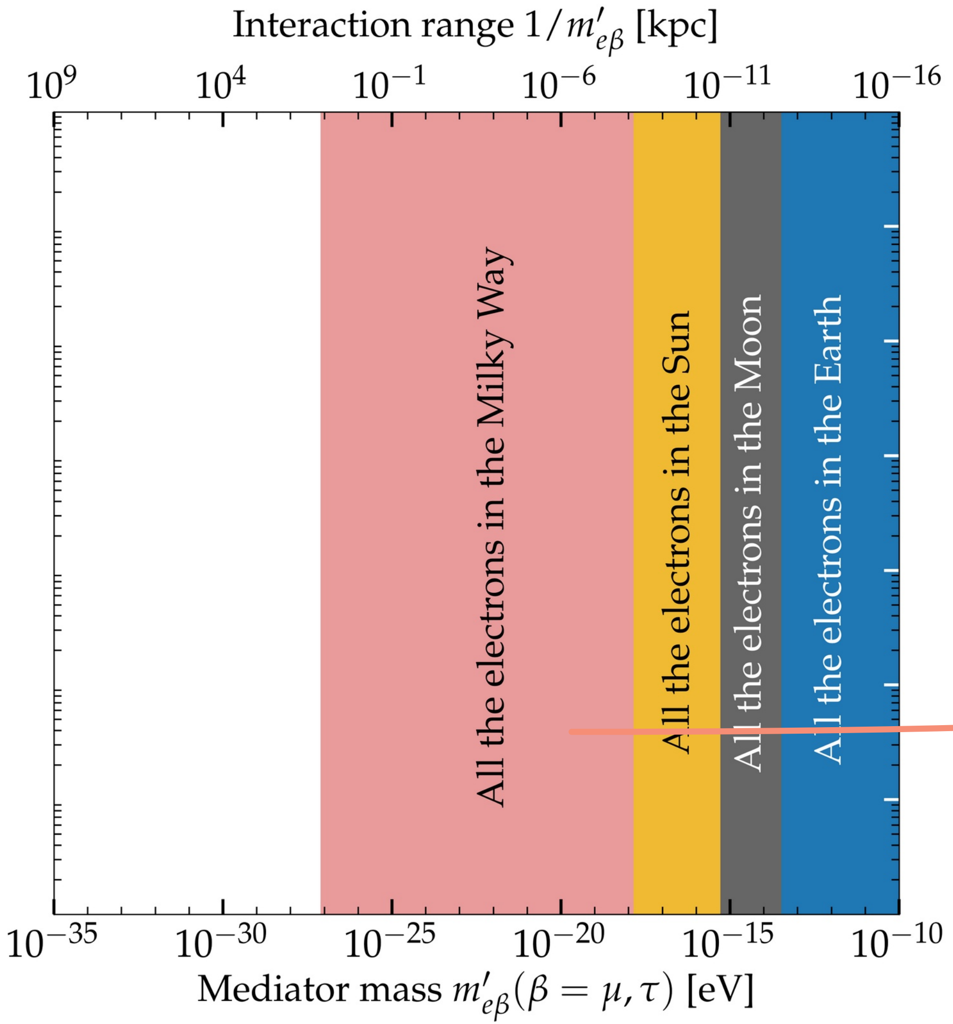
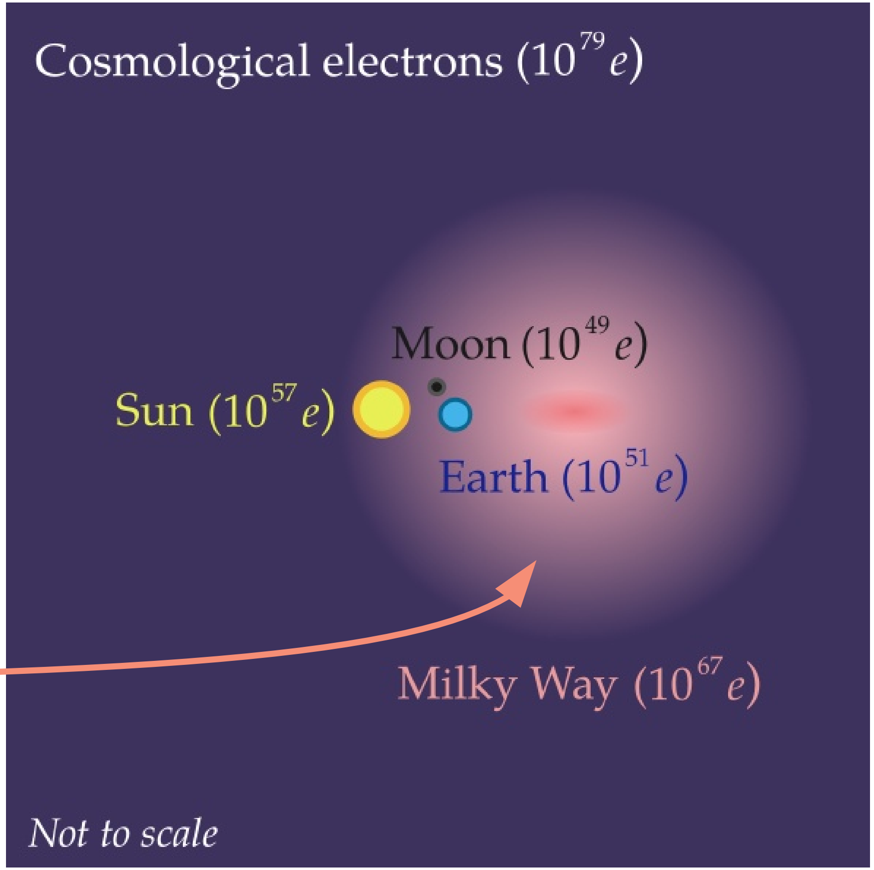


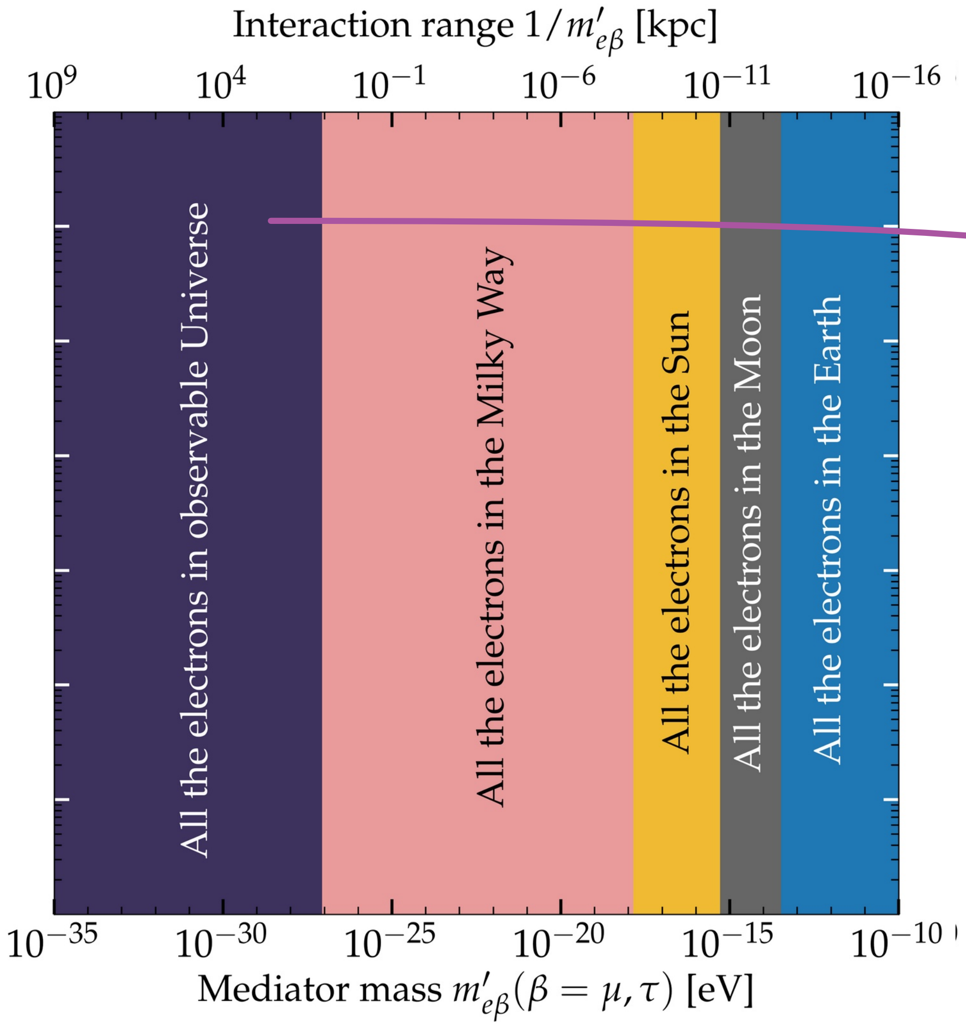


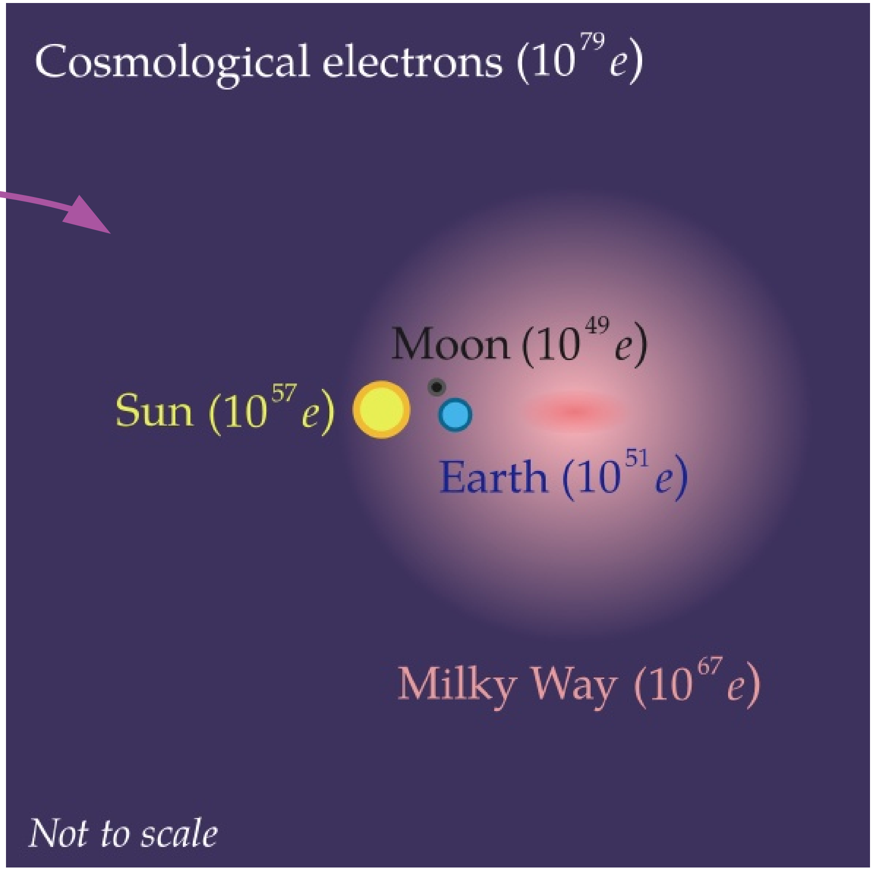
Electrons in the local and distant Universe



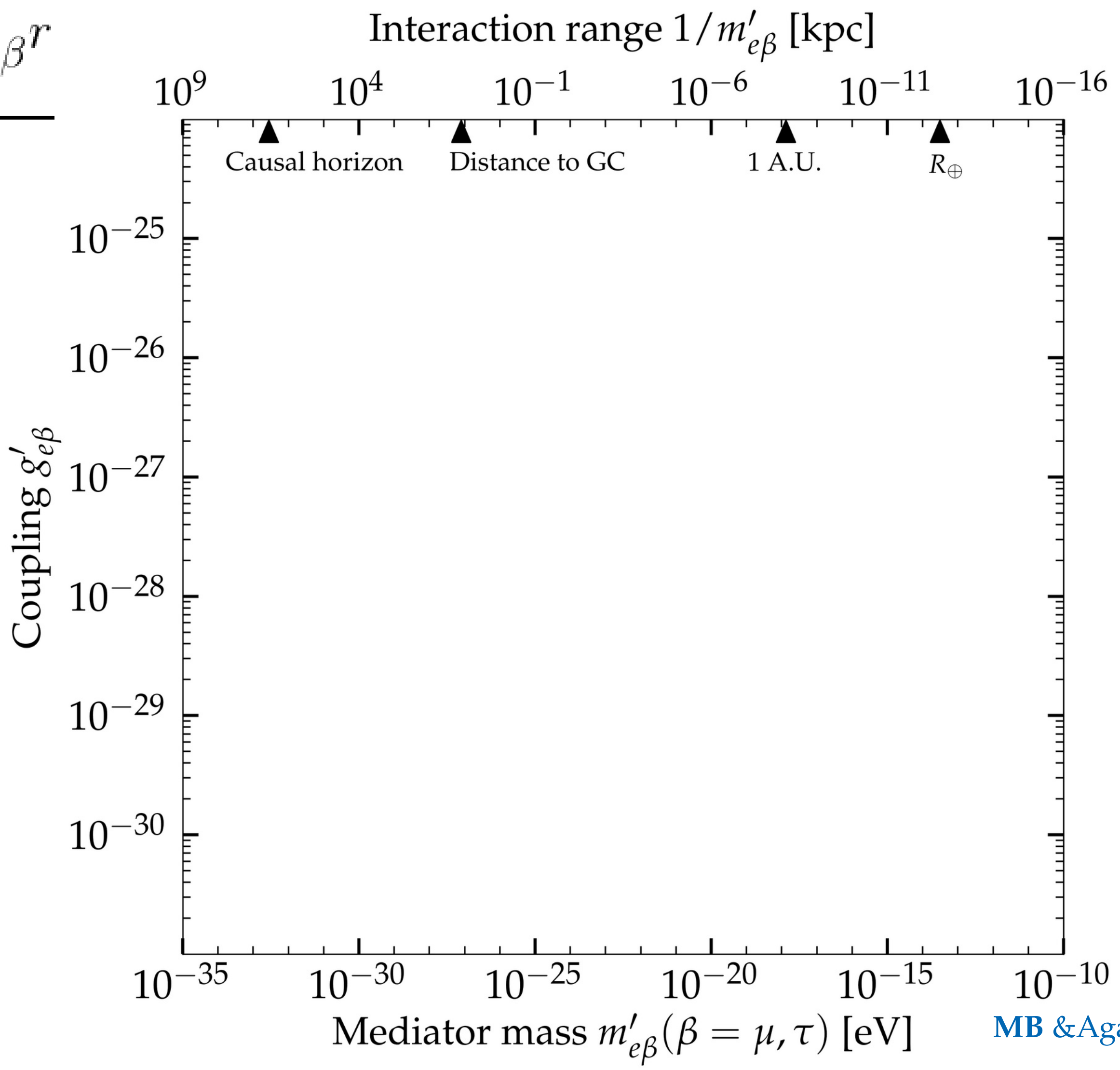


Electrons in the local and distant Universe





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



MB &Agarwalla, *PRL* 2019

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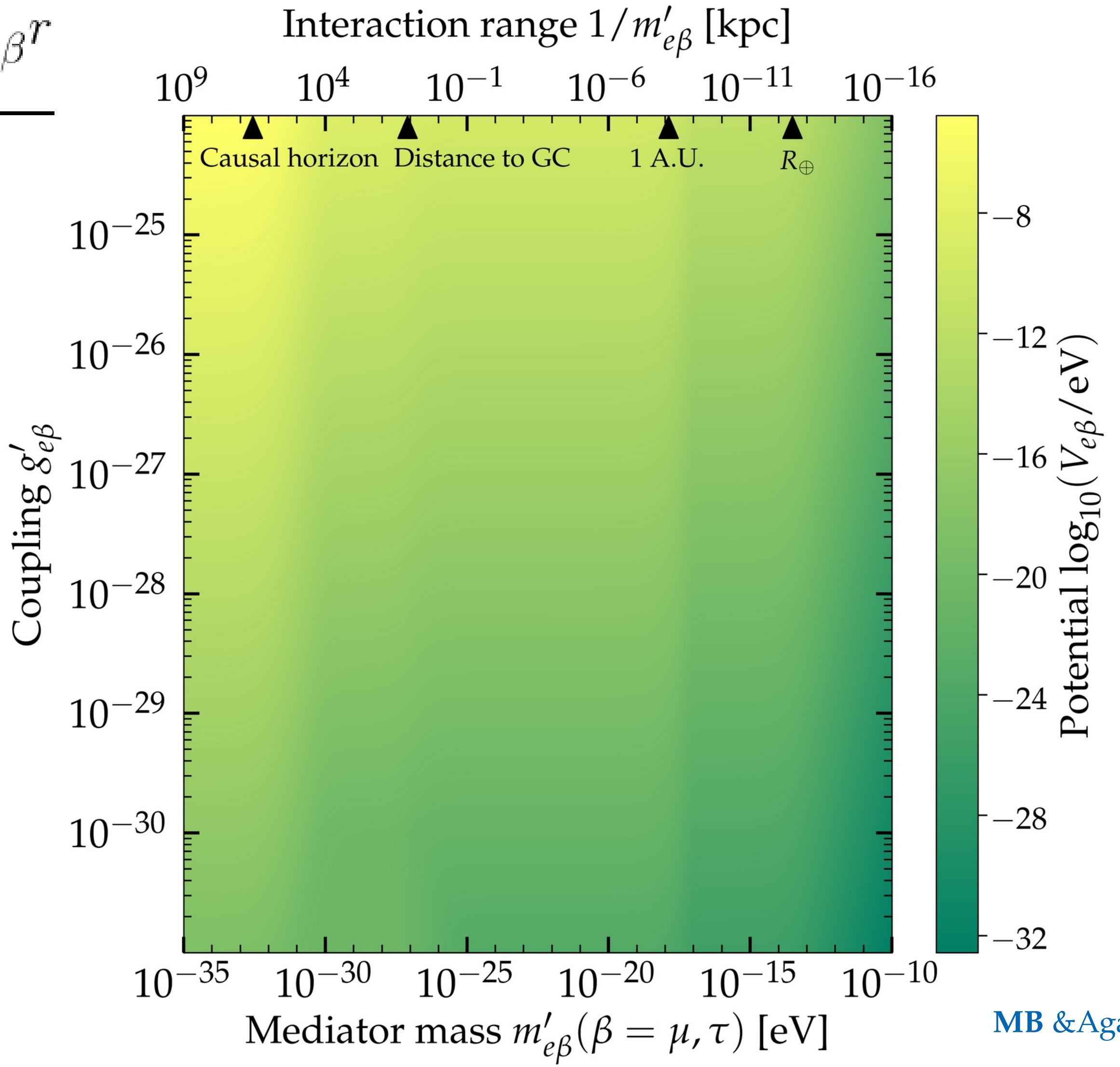
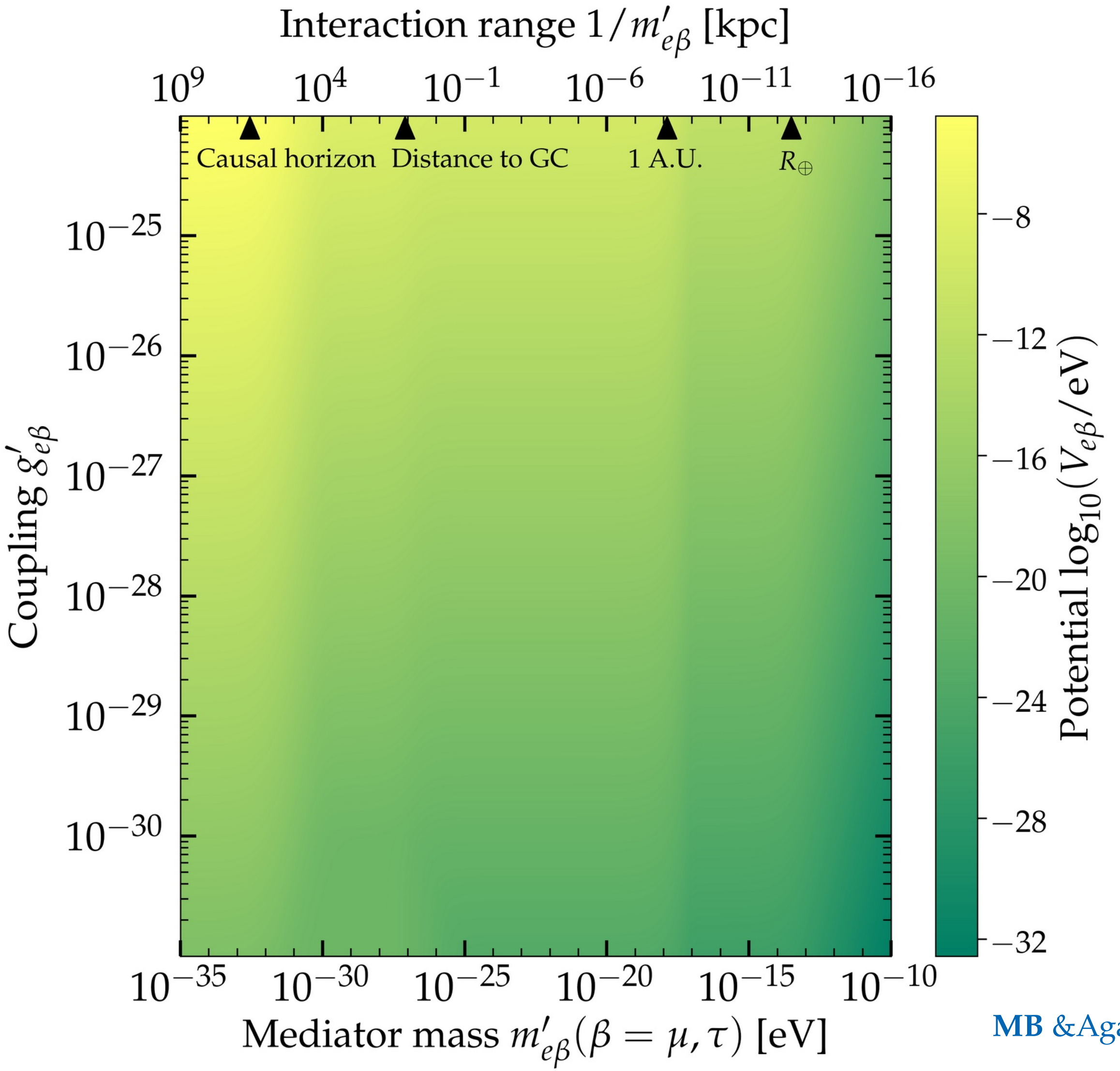


MB &Agarwalla, *PRL* 2019

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



MB &Agarwalla, *PRL* 2019

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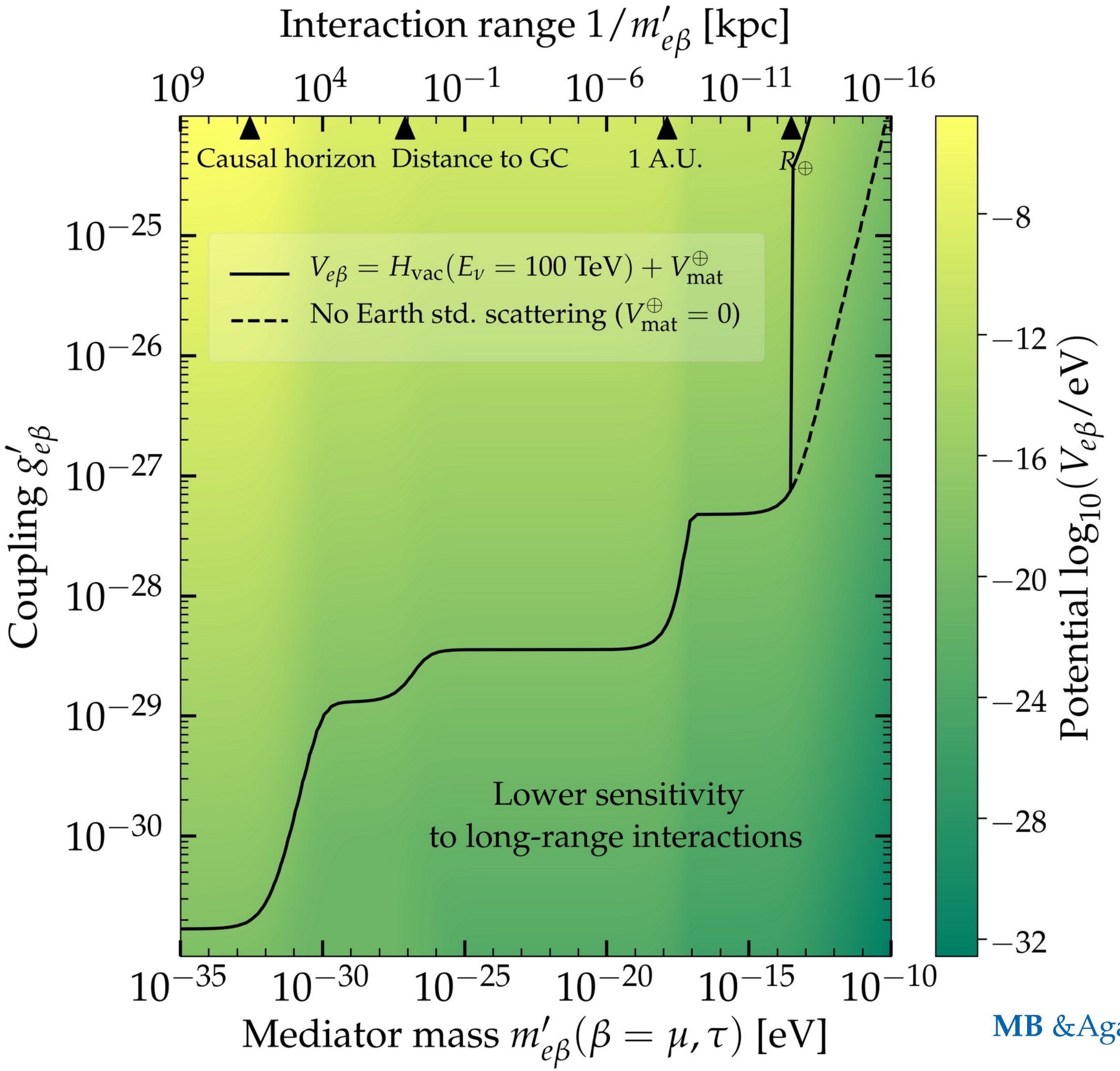
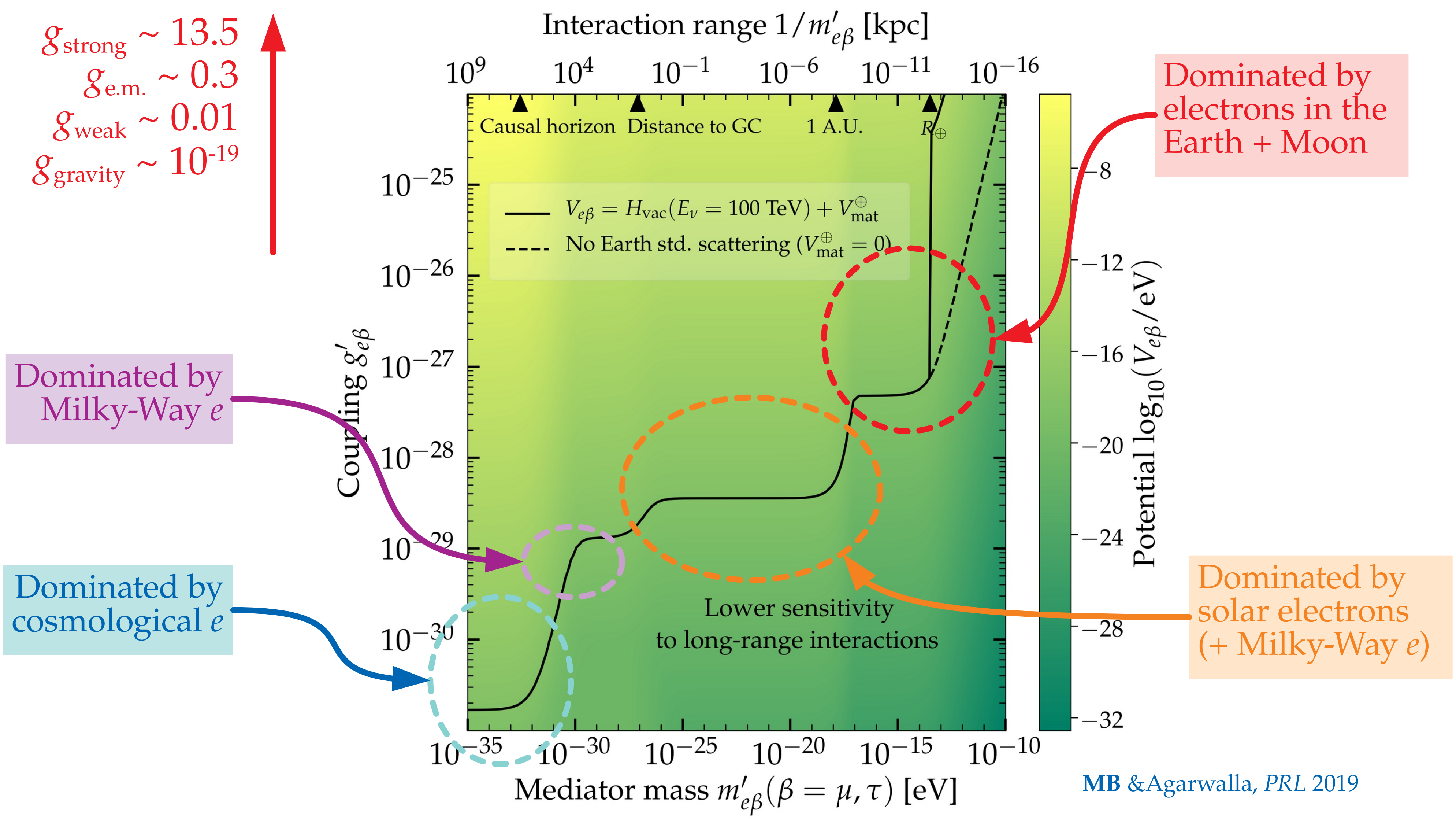
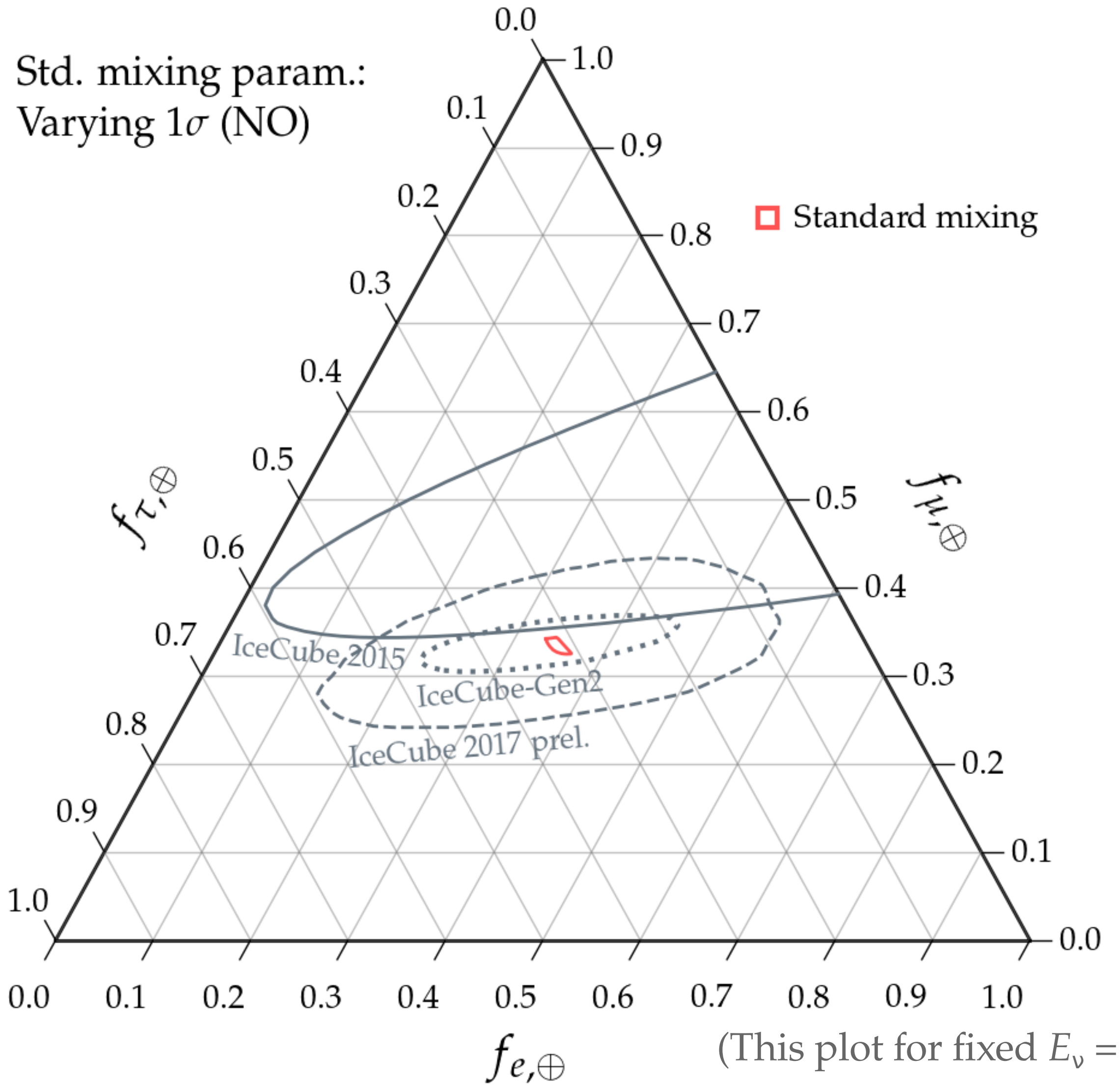


MB &Agarwalla, *PRL* 2019

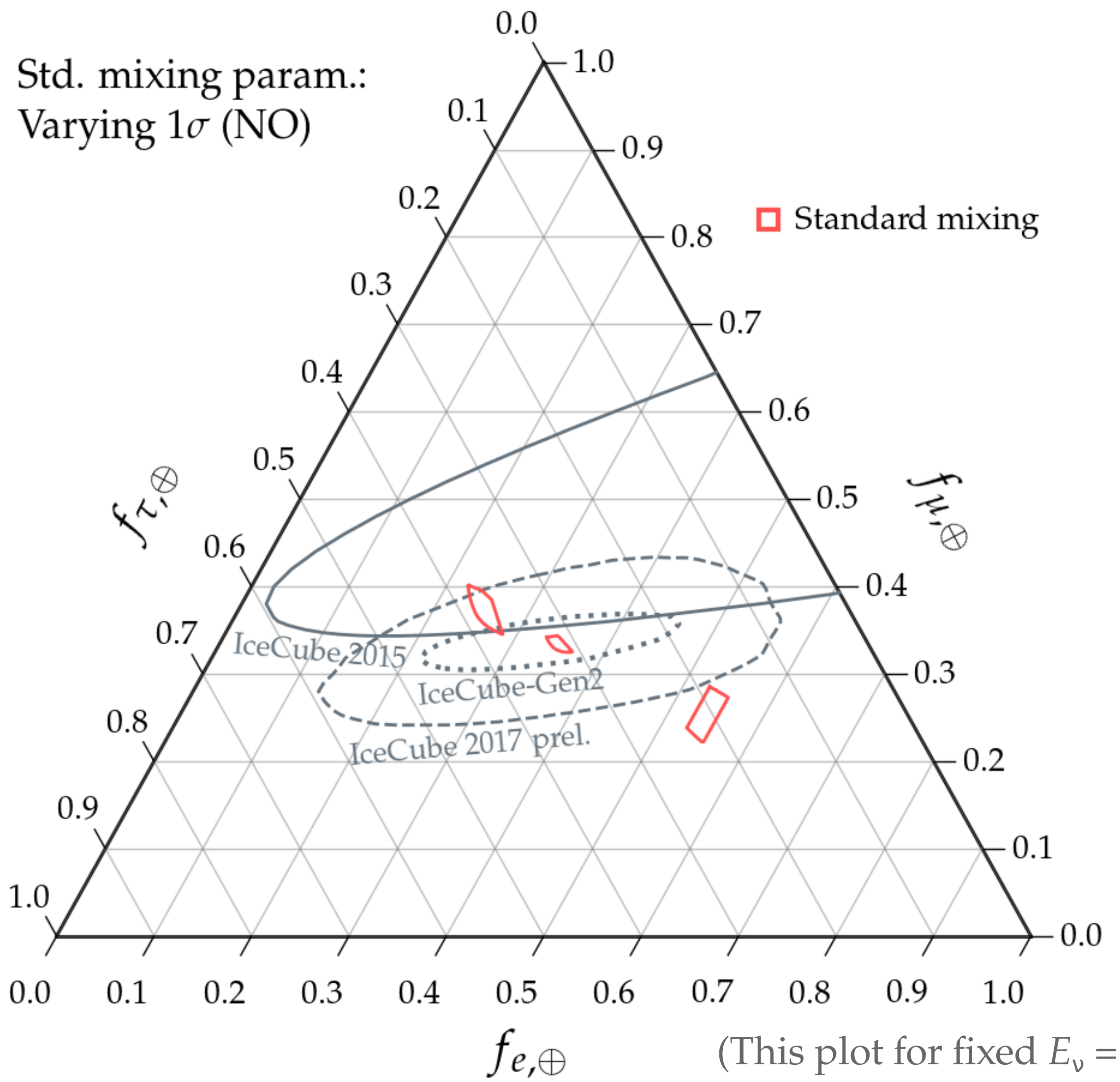


$g_{\text{strong}} \sim 13.5$
$g_{\text{e.m.}} \sim 0.3$
$g_{\text{weak}} \sim 0.01$
$g_{\text{gravity}} \sim 10^{-19}$
Interaction range $1/m'_{e\beta}$ [kpc]
10^{9} 10^{4} 10^{-1} 10^{-6} 10^{-11} 10^{-16}
Causal horizon
Distance to GC
1 A.U.
$R_\oplus$
$V_{e\beta} = H_{\text{vac}}(E_\nu = 100\text{ TeV}) + V^{\oplus}_{\text{mat}}$
No Earth std. scattering ($V^{\oplus}_{\text{mat}} = 0$)
Coupling $g'_{e\beta}$
10^{-25} 10^{-26} 10^{-27} 10^{-28} 10^{-29} 10^{-30}
Lower sensitivity
to long-range interactions
10^{-35} 10^{-30} 10^{-25} 10^{-20} 10^{-15} 10^{-10}
Mediator mass $m'_{e\beta}(\beta = \mu, \tau)$ [eV]
Potential $\log_{10}(V_{e\beta}/\text{eV})$
-8 -12 -16 -20 -24 -28 -32
Dominated by electrons in the Earth + Moon
Dominated by Milky-Way e
Dominated by cosmological e
Dominated by solar electrons (+ Milky-Way e)
MB &Agarwalla, *PRL* 2019



MB & Agarwalla, *PRL* 2019

(This plot for fixed E_ν = 100 TeV)



MB & Agarwalla, *PRL* 2019

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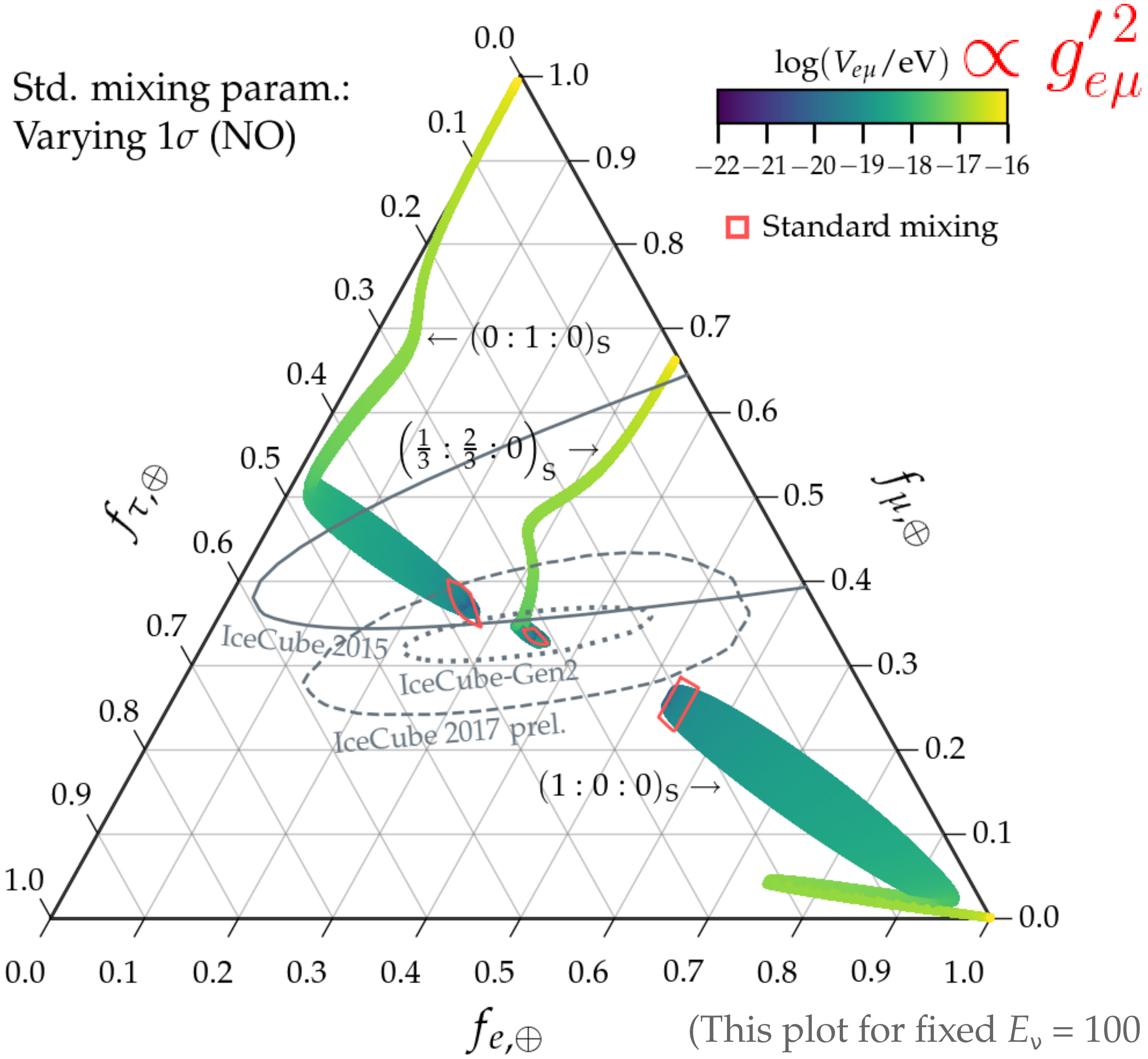

MB & Agarwalla, *PRL* 2019

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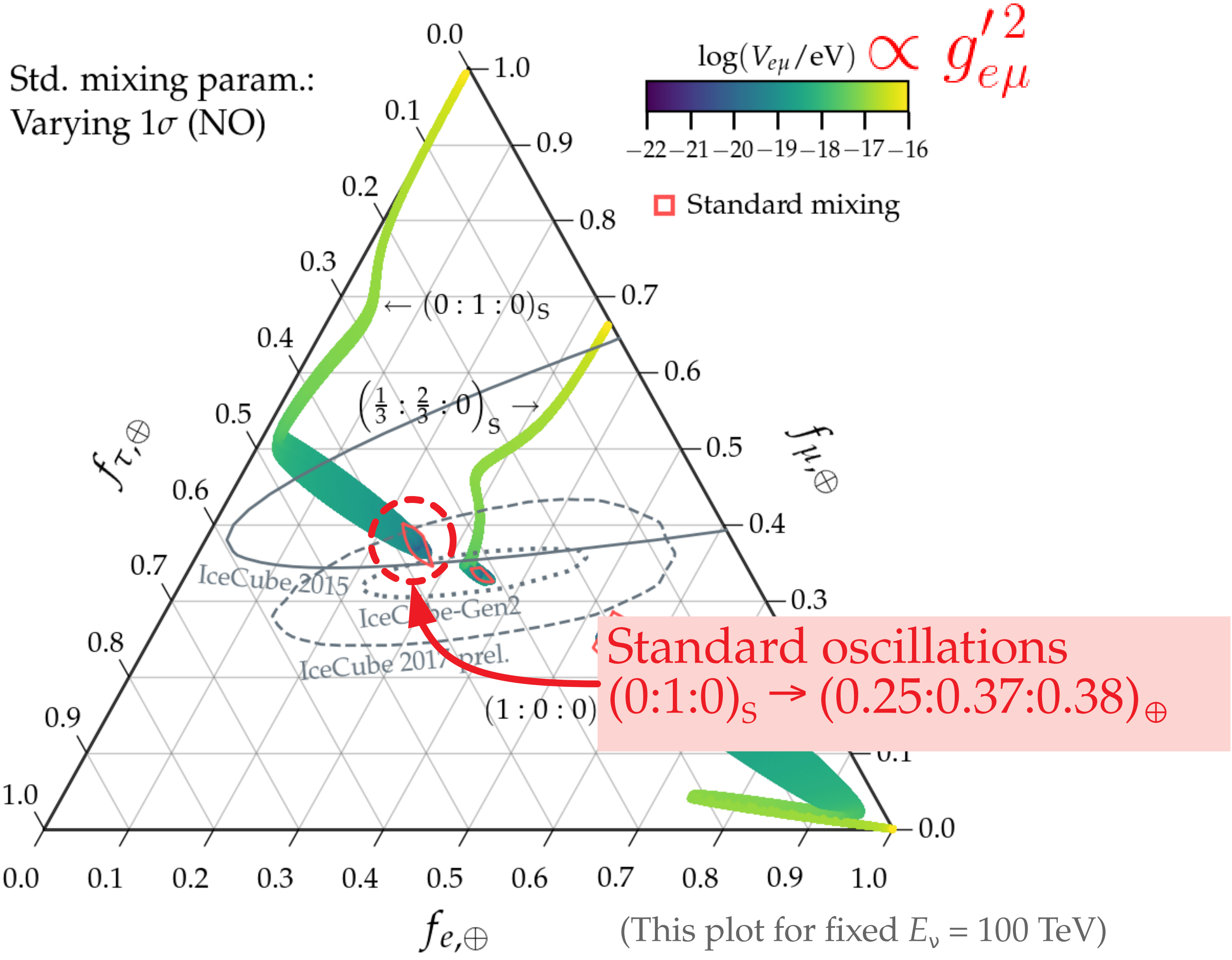
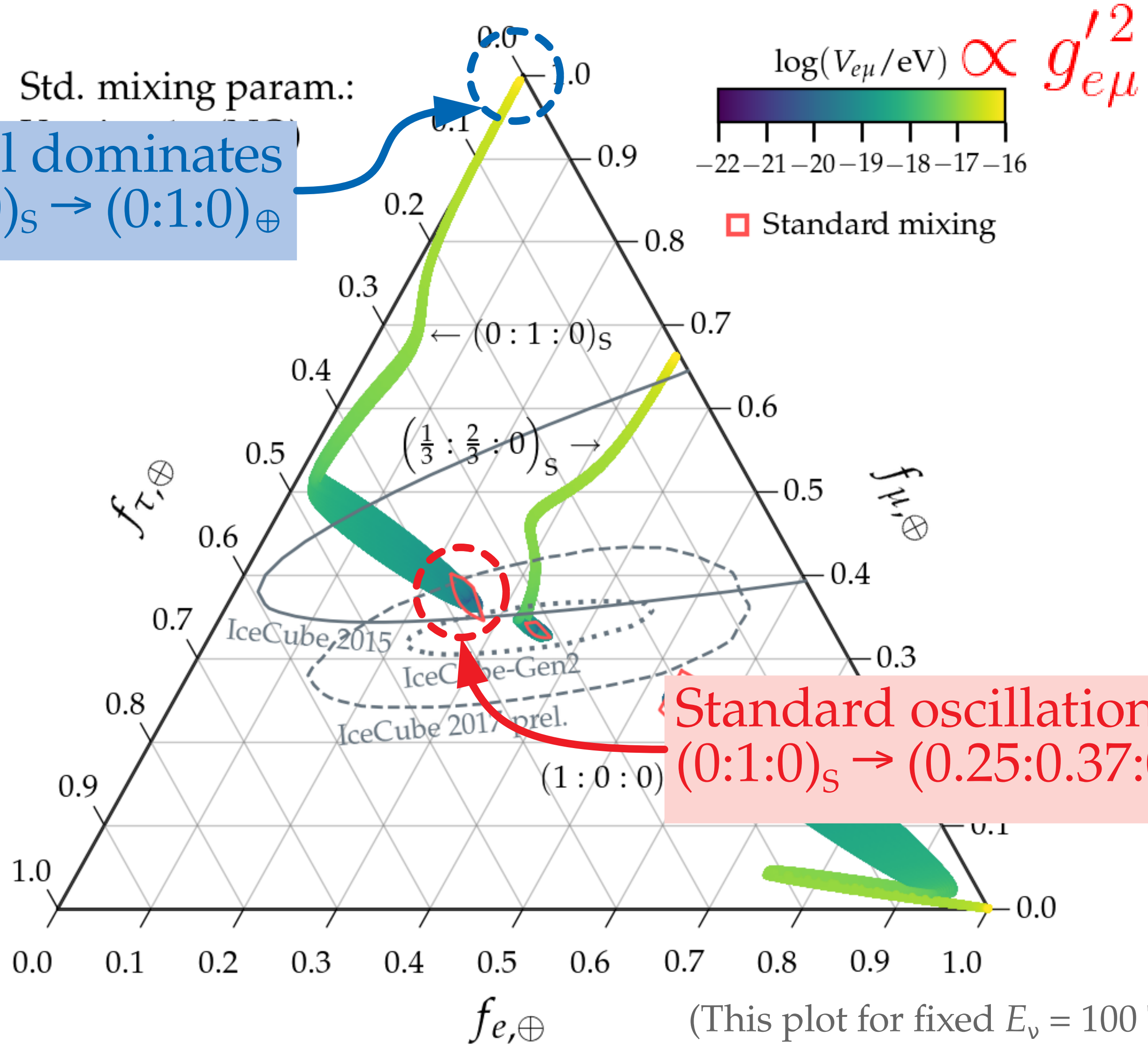


MB & Agarwalla, *PRL* 2019

(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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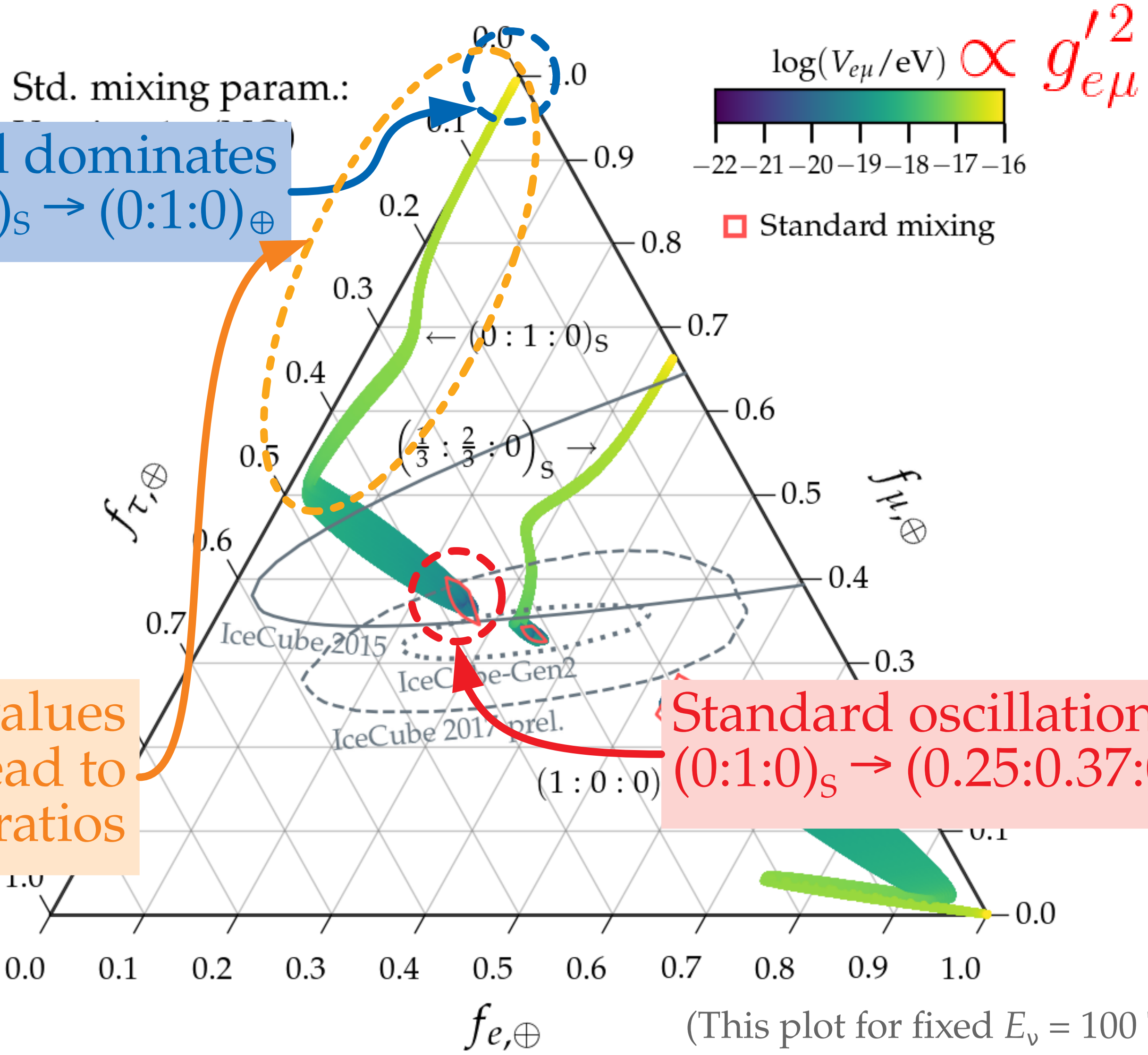

We can disfavor all values of m' and g' that lead to these flavor ratios

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

MB & Agarwalla, *PRL* 2019

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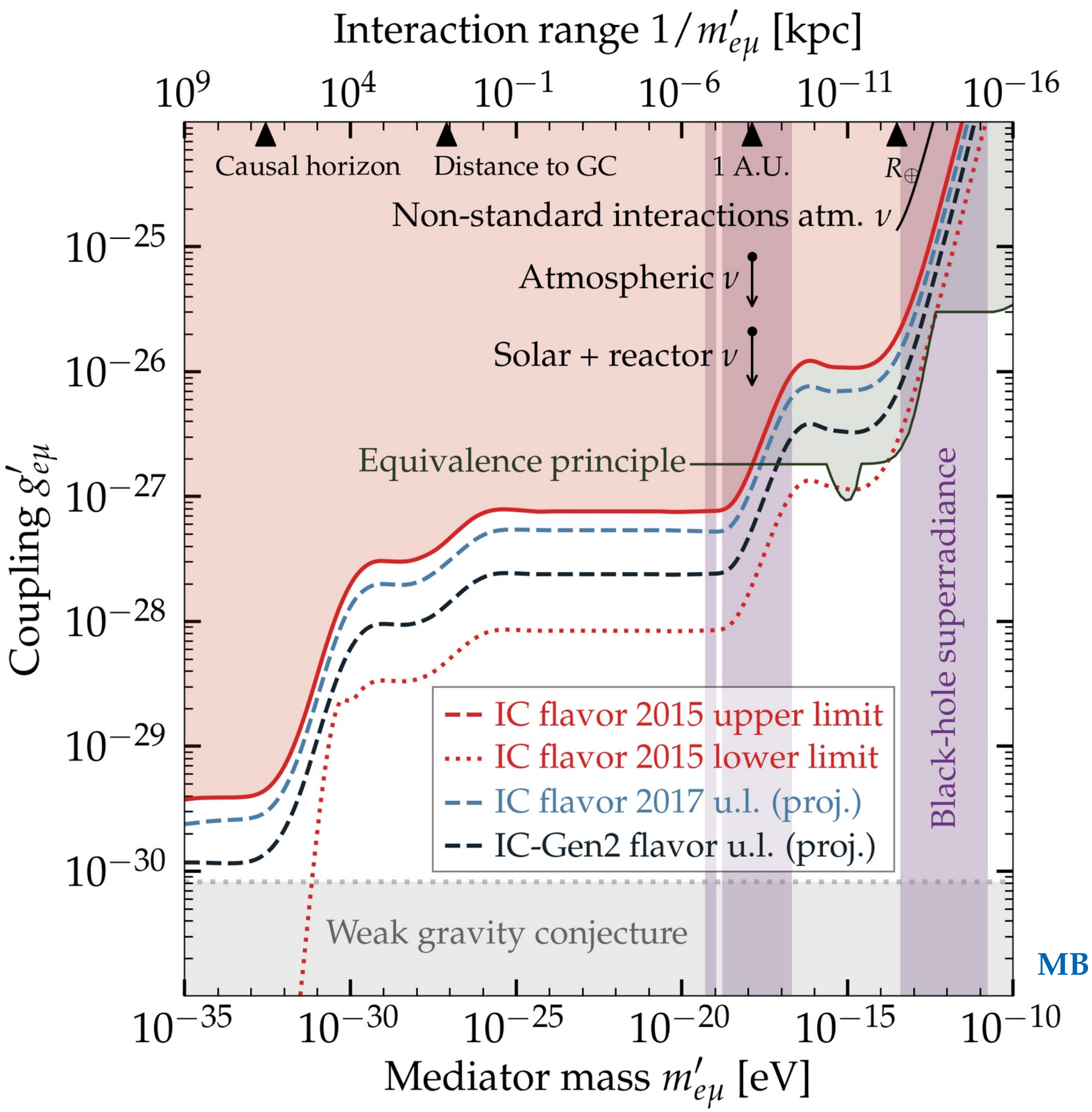


MB &Agarwalla, *PRL* 2019

Bonus: Measuring the inelasticity $\langle y \rangle$

- Inelasticity in CC ν_μ interaction $\nu_\mu + N \to \mu + X$:

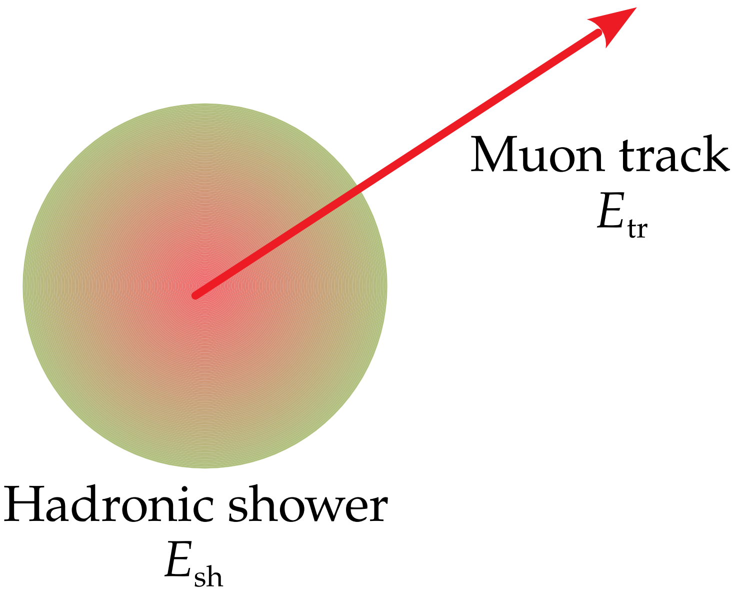
  $E_X = y\, E_\nu$ and $E_\mu = (1\text{-}y)\, E_\nu \;\Rightarrow\; y = (1 + E_\mu / E_X)^{-1}$

- The value of y follows a distribution $d\sigma/dy$

- In a HESE starting track:

  $$\left.\begin{array}{l} E_X = E_{sh} \text{ (energy of shower)} \\ E_\mu = E_{tr} \text{ (energy of track)} \end{array}\right\} \; y = (1 + E_{tr}/E_{sh})^{-1}$$

- New IceCube analysis:
  - 5 years of starting-track data (2650 tracks)
  - Machine learning separates shower from track
  - Different y distributions for ν and $\bar{\nu}$



IceCube, *PRD* 2019

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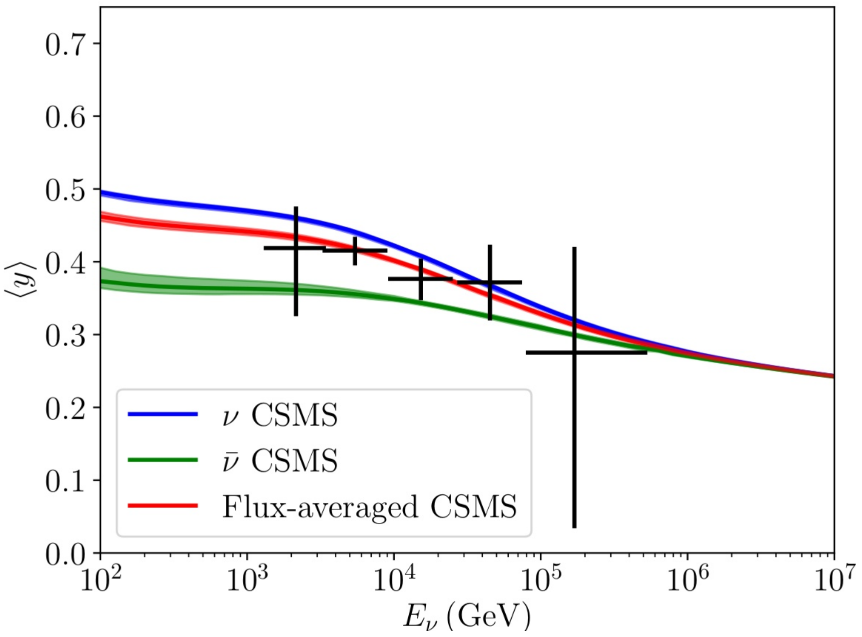
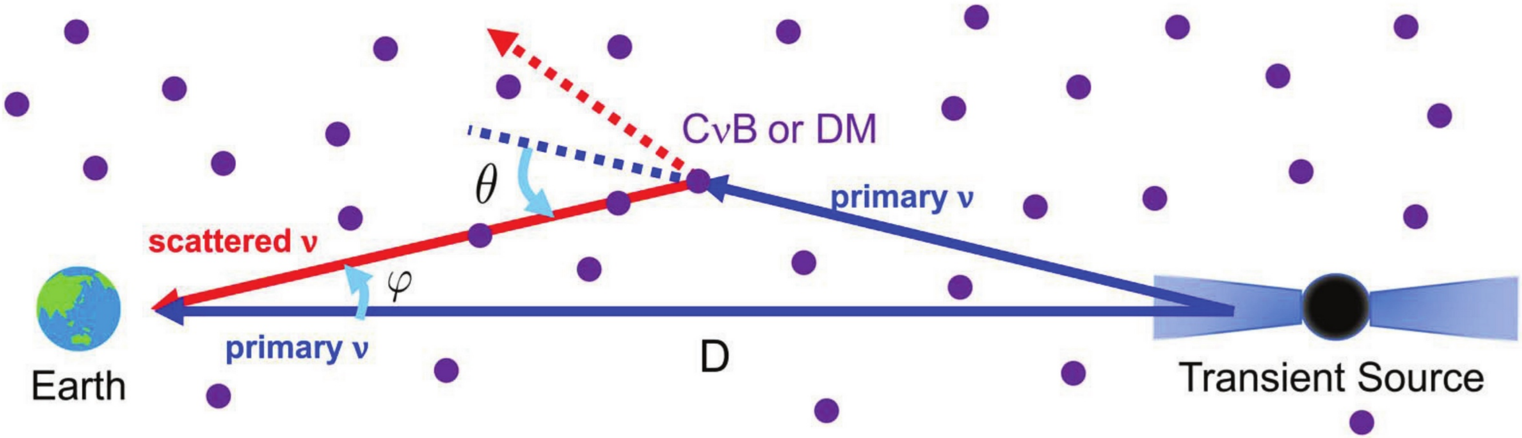


IceCube, *PRD* 2019

New physics in timing — TeV–PeV

Multiple secret νν scatterings may delay the arrival of neutrinos from a transient



Shoemaker & Murase, 1903.08607

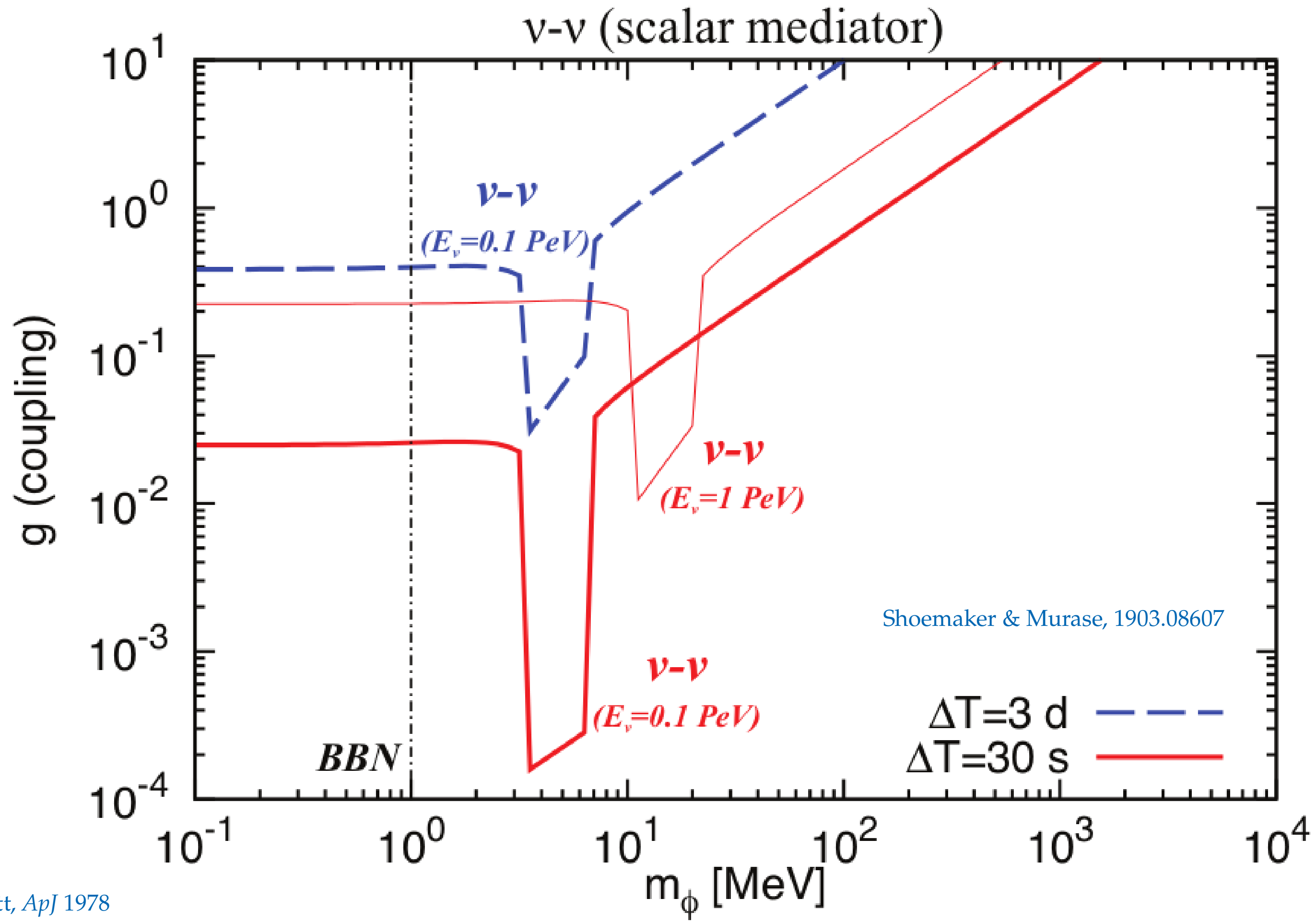
Characteristic time delay —

Optical depth to νν: $\tau_{\nu\nu} = n_\nu \sigma_{\nu\nu} D$

$$\Delta t \approx 1500\,\mathrm{s} \left(\frac{\tau_{\nu\nu}}{30}\right) \left(\frac{D}{3\ \mathrm{Gpc}}\right) \left(\frac{m_\nu}{0.1\ \mathrm{eV}}\right) \left(\frac{0.1\ \mathrm{PeV}}{E_\nu}\right)$$

See also: Alcock & Hatchett, *ApJ* 1978

New physics in timing — TeV–PeV



See also: Alcock & Hatchett, *ApJ* 1978

Neutrino zenith angle distribution

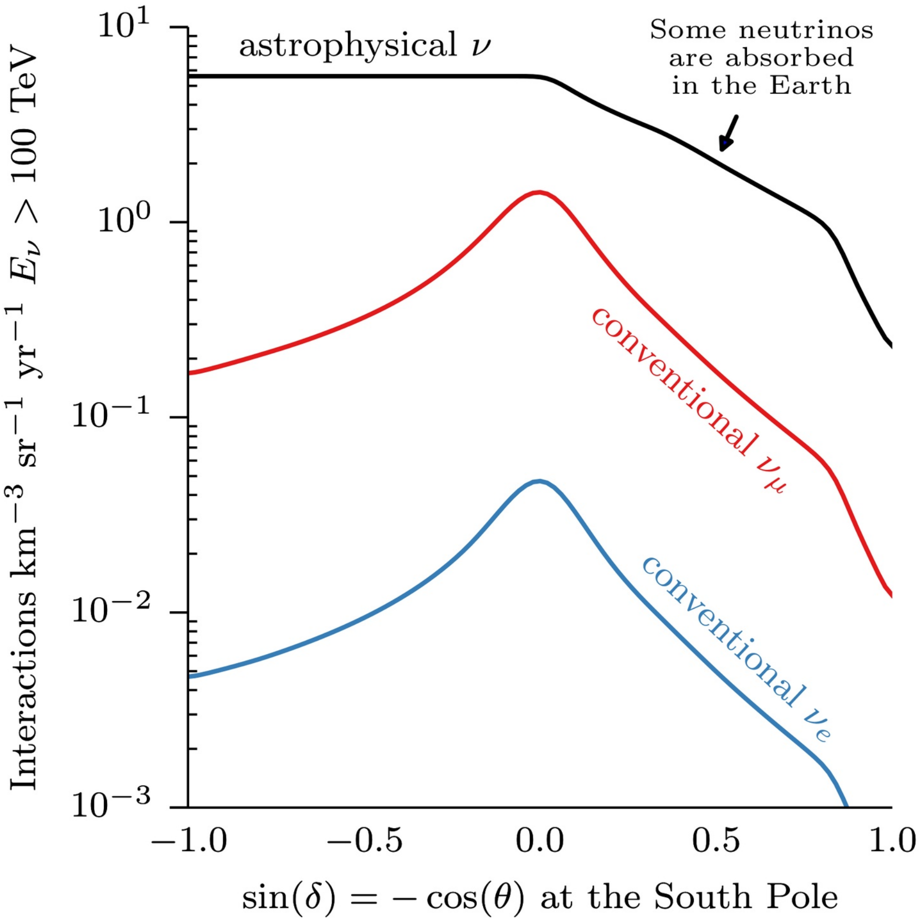
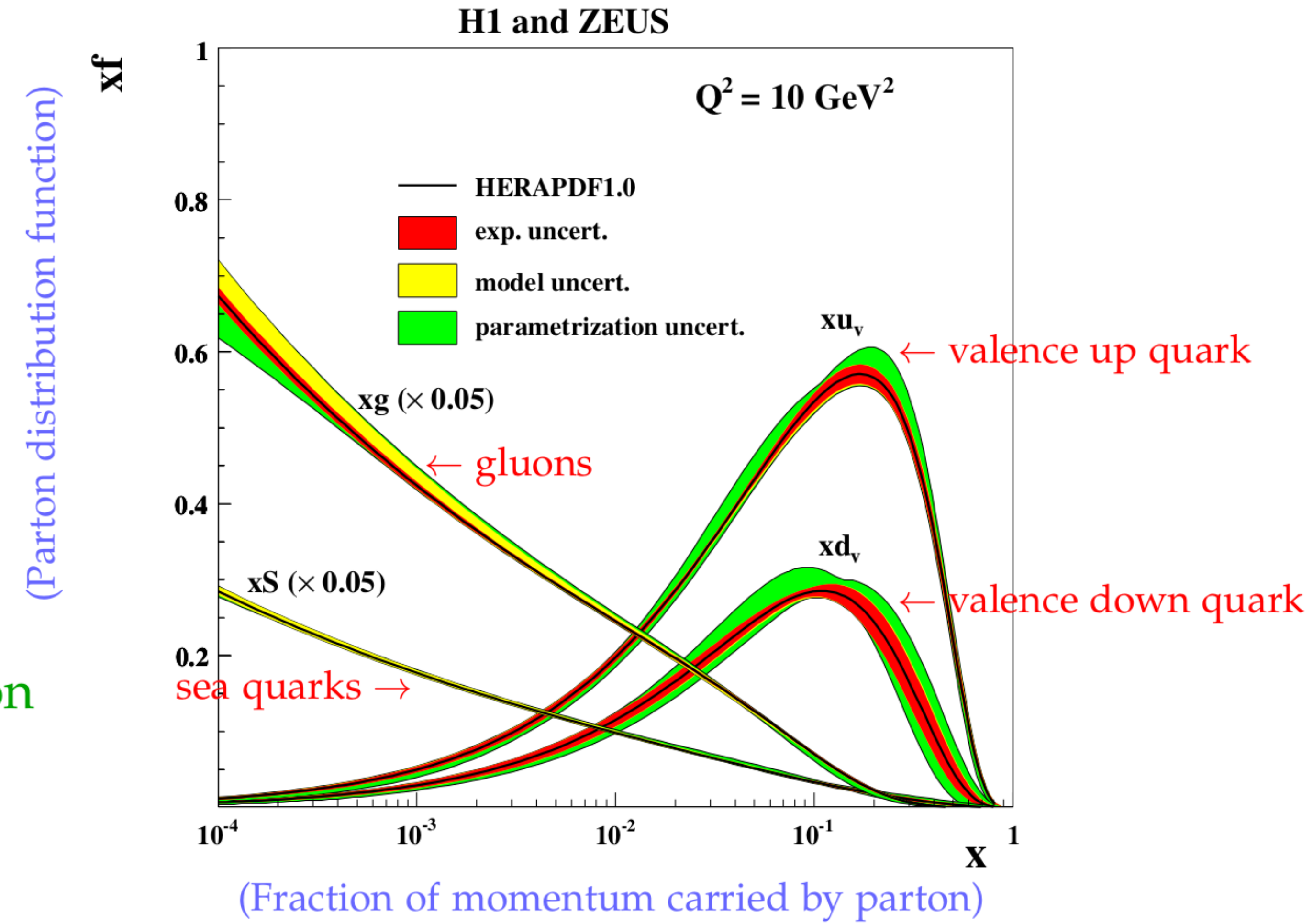


Figure by
Jakob Van Santen
ICRC 2017

Peeking inside a proton



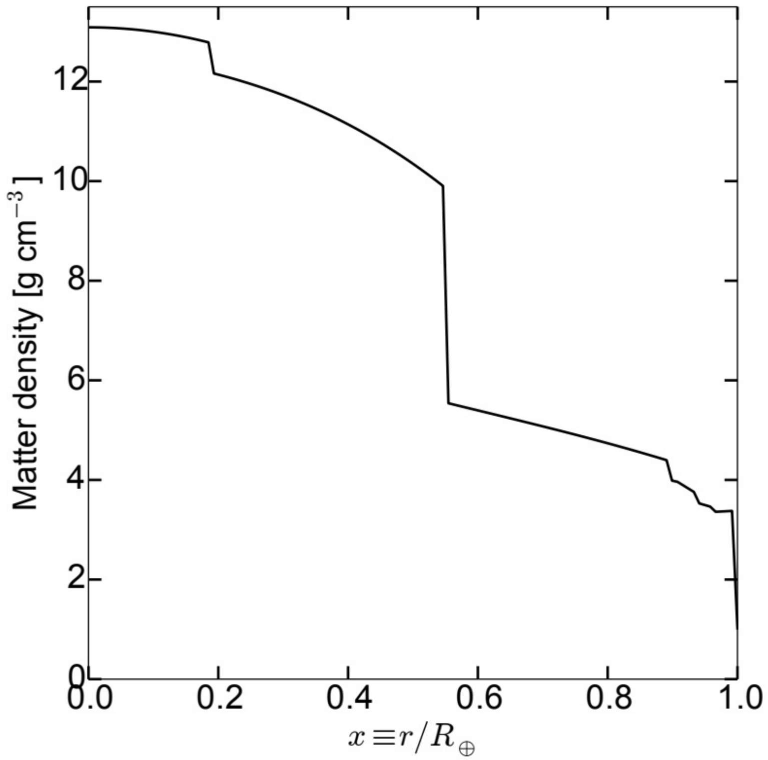
← Extrapolation

A. Cooper-Sarkar 2012

A feel for the in-Earth attenuation

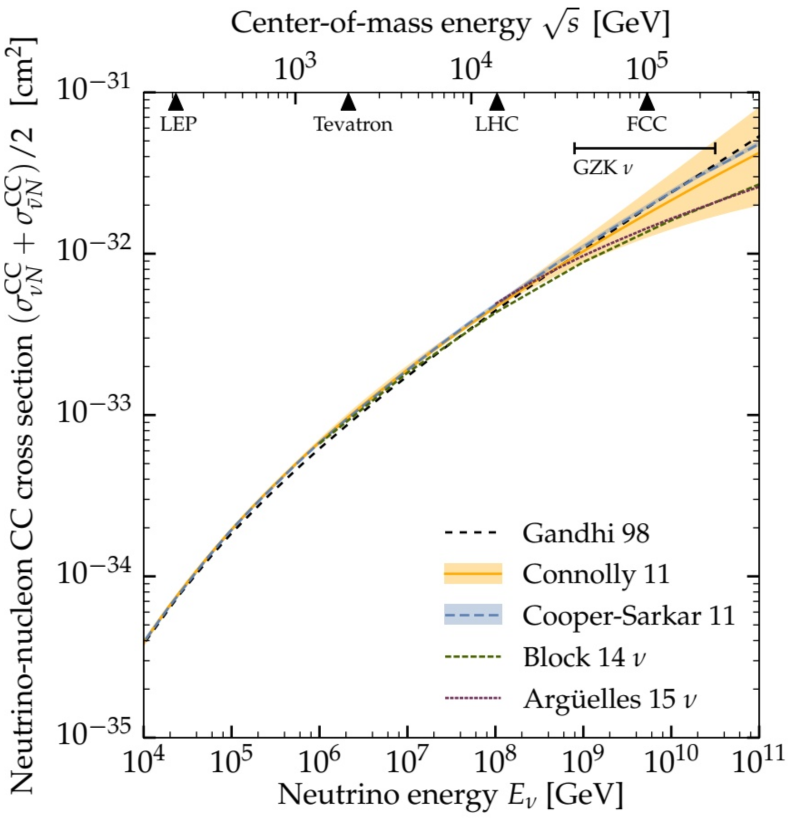
Earth matter density

(Preliminary Reference Earth Model)



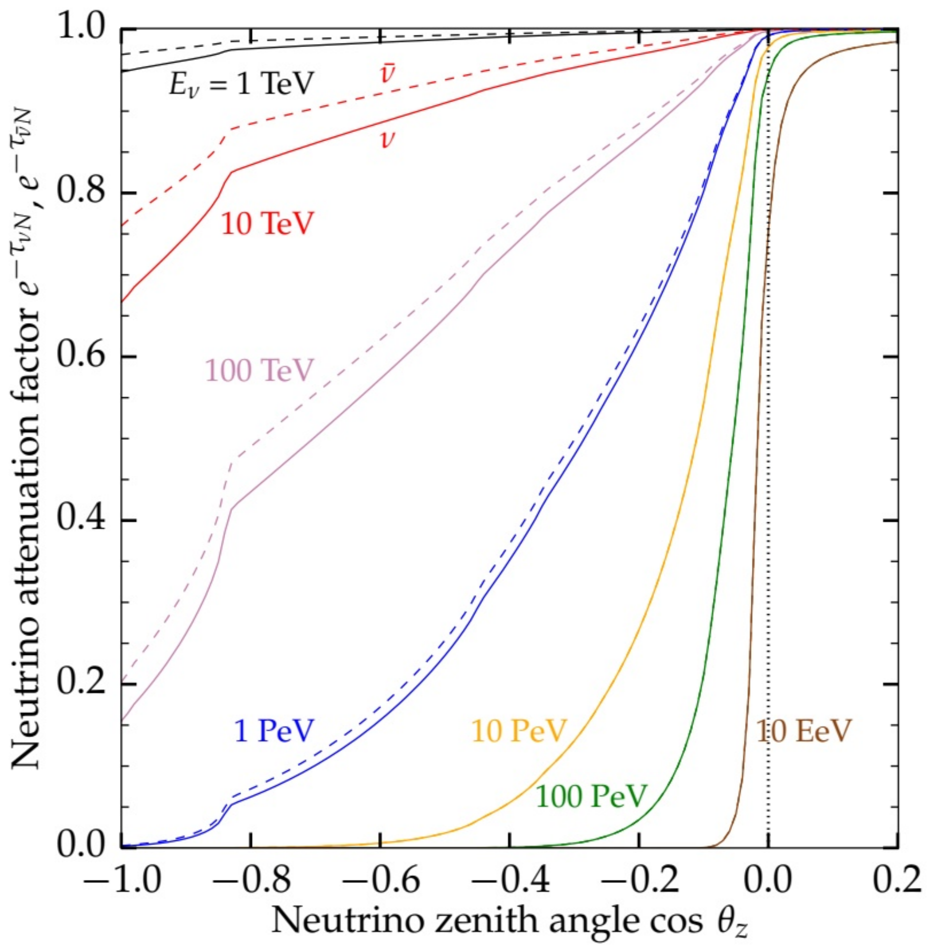
+

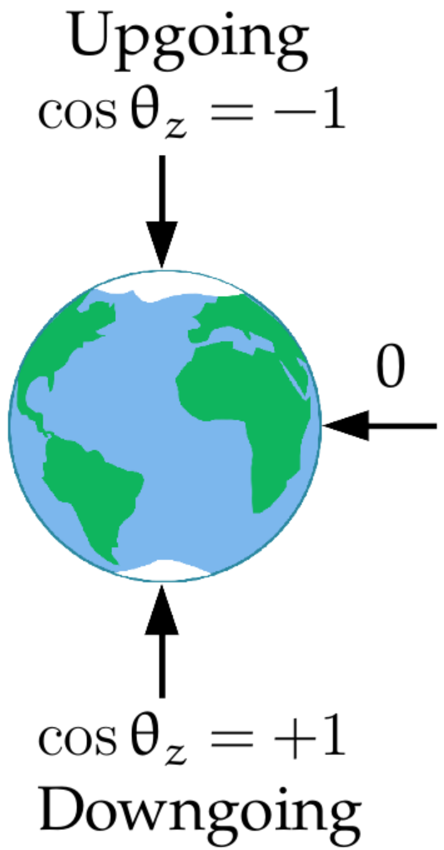
Neutrino-nucleon cross section



A feel for the in-Earth attenuation

=





What goes into the (likelihood) mix?

- Inside each energy bin, we freely vary
  - N_{ast} (showers from astrophysical neutrinos)
  - N_{atm} (showers from atmospheric neutrinos)
  - γ (astrophysical spectral index)
  - σ_{CC} (neutrino-nucleon charged-current cross section)
- For each combination, we generate the angular and energy shower spectrum…
- … and compare it to the observed HESE spectrum via a likelihood
- Maximum likelihood yields σ_{CC} (marginalized over nuisance parameters)
- Bins are independent of each other – there are no (significant) cross-bin correlations

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Including detector resolution
(10% in energy, 15° in direction)

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Marginalized cross section in each bin

TABLE I. Neutrino-nucleon charged-current inclusive cross sections, averaged between neutrinos ($\sigma_{\nu N}^{\rm CC}$) and anti-neutrinos ($\sigma_{\bar{\nu} N}^{\rm CC}$), extracted from 6 years of IceCube HESE showers. To obtain these results, we fixed $\sigma_{\bar{\nu} N}^{\rm CC} = \langle \sigma_{\bar{\nu} N}^{\rm CC} / \sigma_{\nu N}^{\rm CC} \rangle \cdot \sigma_{\nu N}^{\rm CC}$ — where $\langle \sigma_{\bar{\nu} N}^{\rm CC} / \sigma_{\nu N}^{\rm CC} \rangle$ is the average ratio of $\bar{\nu}$ to ν cross sections calculated using the standard prediction from Ref. [60] — and $\sigma_{\nu N}^{\rm NC} = \sigma_{\nu N}^{\rm CC}/3$, $\sigma_{\bar{\nu} N}^{\rm NC} = \sigma_{\bar{\nu} N}^{\rm CC}/3$. Uncertainties are statistical plus systematic, added in quadrature.

E_ν [TeV]	$\langle E_\nu \rangle$ [TeV]	$\langle \sigma_{\bar{\nu} N}^{\rm CC} / \sigma_{\nu N}^{\rm CC} \rangle$	$\log_{10}[\frac{1}{2}(\sigma_{\nu N}^{\rm CC} + \sigma_{\bar{\nu} N}^{\rm CC})/{\rm cm}^2]$
18–50	32	0.752	-34.35 ± 0.53
50–100	75	0.825	-33.80 ± 0.67
100–400	250	0.888	-33.84 ± 0.67
400–2004	1202	0.957	> -33.21 (1σ)

MB & A. Connolly, 1711.11043

Energy and angular shower spectra

Rate from all flavors, CC + NC:

$$\frac{d^2 N_{\rm sh}}{dE_{\rm sh}\, d\cos\theta_z} = \frac{d^2 N^{\rm CC}_{{\rm sh},e}}{dE_{\rm sh}\, d\cos\theta_z} + \underbrace{\mathrm{Br}_{\tau\to{\rm sh}}}_{= 0.83} \frac{d^2 N^{\rm CC}_{{\rm sh},\tau}}{dE_{\rm sh}\, d\cos\theta_z} + \sum_{l=e,\mu,\tau} \frac{d^2 N^{\rm NC}_{{\rm sh},l}}{dE_{\rm sh}\, d\cos\theta_z}$$

Contribution from one flavor CC:

$$\frac{d^2 N^{\rm CC}_{{\rm sh},l}}{dE_{\rm sh}\, d\cos\theta_z}(E_{\rm sh}, \cos\theta_z) \simeq -2\pi \rho_{\rm ice} N_A V T \left\{ \Phi_l(E_\nu) \sigma^{\rm CC}_{\nu N}(E_\nu) e^{-\tau_{\nu N}(E_\nu,\theta_z)} + \Phi_{\bar{l}}(E_\nu) \sigma^{\rm CC}_{\bar{\nu} N}(E_\nu) e^{-\tau_{\bar{\nu} N}(E_\nu,\theta_z)} \right\} \Big|_{E_\nu = E_{\rm sh}/f_{l,{\rm CC}}}$$

Conversion between shower energy and neutrino energy:

$$f_{l,t} \equiv \frac{E_{\rm sh}}{E_\nu} \simeq \begin{cases} 1 & \text{for } l = e \ \text{ and } \ t = \text{CC} \\ [\langle y \rangle + 0.7\,(1 - \langle y \rangle)] \simeq 0.8 & \text{for } l = \tau \ \text{ and } \ t = \text{CC} \\ \langle y \rangle \simeq 0.25 & \text{for } l = e,\mu,\tau \ \text{ and } \ t = \text{NC} \end{cases}$$

MB & A. Connolly, 1711.11043

Detector resolution

Number of contained showers:

$$\frac{d^2 N_{\rm sh}}{dE_{\rm dep} d\cos\theta_z} = \int dE_{\rm sh} \int d\cos\theta'_z \frac{d^2 N_{\rm sh}}{dE_{\rm sh} d\cos\theta'_z} R_E(E_{\rm sh}, E_{\rm dep}, \sigma_E(E_{\rm sh})) R_\theta(\cos\theta'_z, \cos\theta_z, \sigma_{\cos\theta_z})$$

Energy resolution: [Palomares-Ruiz, Vincent, Mena *PRD* 2015; Vincent, Palomares-Ruiz, Mena *PRD* 2016; MB, Beacom. Murase, *PRD* 2016]

$$R_E(E_{\rm sh}, E_{\rm dep}, \sigma_E(E_{\rm sh})) = \frac{1}{\sqrt{2\pi\sigma_E^2(E_{\rm sh})}} \exp\left[-\frac{(E_{\rm sh} - E_{\rm dep})^2}{2\sigma_E^2(E_{\rm sh})}\right] \quad \text{with} \quad \sigma_E(E_{\rm sh}) = 0.1 E_{\rm sh}$$

IceCube, *JINST* 2014

Angular resolution:

$$R_\theta(\cos\theta'_z, \cos\theta_z, \sigma_{\cos\theta_z}) = \frac{1}{\sqrt{2\pi\sigma^2_{\cos\theta_z}}} \exp\left[-\frac{(\cos\theta'_z - \cos\theta_z)^2}{2\sigma^2_{\cos\theta_z}}\right]$$

with $\sigma_{\cos\theta_z} \equiv \frac{1}{2}\left[\left|\cos(\theta_z + \sigma_{\theta_z}) - \cos\theta_z\right| + \left|\cos(\theta_z - \sigma_{\theta_z}) - \cos\theta_z\right|\right]$ and $\sigma_{\theta_z} = 15^\circ$

MB & A. Connolly, 1711.11043

Likelihood

In an energy bin containing $N_{\rm sh}^{\rm obs}$ observed showers, the likelihood is

Each energy bin is independent

$$\mathcal{L} = \frac{e^{-(N_{\rm sh}^{\rm atm}+N_{\rm sh}^{\rm ast})}}{N_{\rm sh}^{\rm obs}!}\prod_{i=1}^{N_{\rm sh}^{\rm obs}} \mathcal{L}_i$$

Partial likelihood, *i.e.*, relative probability of the *i*-th shower being from an atmospheric neutrino or an astrophysical neutrino:

Depends on $\sigma_{\nu N}$

$$\mathcal{L}_i = N_{\rm sh}^{\rm atm}\,\mathcal{P}_i^{\rm atm} + N_{\rm sh}^{\rm ast}\,\mathcal{P}_i^{\rm ast}$$

$$\mathcal{P}_i^{\rm atm} = \left(\int_{E_{\rm dep}^{\rm min}}^{E_{\rm dep}^{\rm max}} dE_{\rm dep}\int_{-1}^{1} d\cos\theta_z\,\frac{d^2N_{\rm sh}^{\rm atm}}{dE_{\rm dep}d\cos\theta_z}\right)^{-1}\left(\left.\frac{d^2N_{\rm sh}^{\rm atm}}{dE_{\rm dep}d\cos\theta_z}\right|_{E_{{\rm dep},i},\cos\theta_{z,i}}\right)$$

PDF for this shower to be made by an atmospheric ν

$$\mathcal{P}_i^{\rm ast} = \left(\int_{E_{\rm dep}^{\rm min}}^{E_{\rm dep}^{\rm max}} dE_{\rm dep}\int_{-1}^{1} d\cos\theta_z\,\frac{d^2N_{\rm sh}^{\rm ast}}{dE_{\rm dep}d\cos\theta_z}\right)^{-1}\left(\left.\frac{d^2N_{\rm sh}^{\rm ast}}{dE_{\rm dep}d\cos\theta_z}\right|_{E_{{\rm dep},i},\cos\theta_{z,i}}\right)$$

PDF for this shower to be made by an astrophysical ν

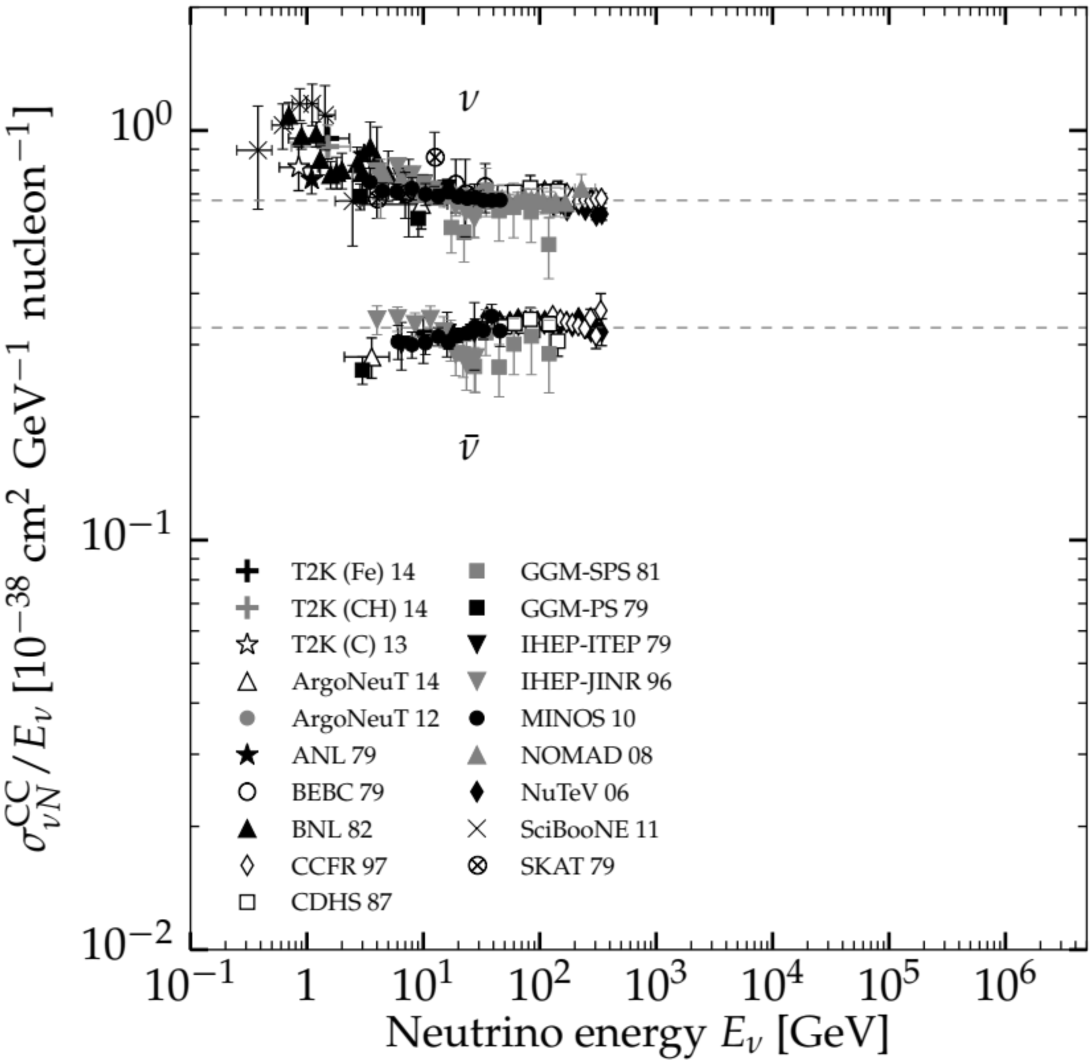
MB & A. Connolly, 1711.11043

See also: Palomares-Ruiz, Vincent, Mena *PRD* 2015; Vincent, Palomares-Ruiz, Mena *PRD* 2016

Depends on γ and $\sigma_{\nu N}$

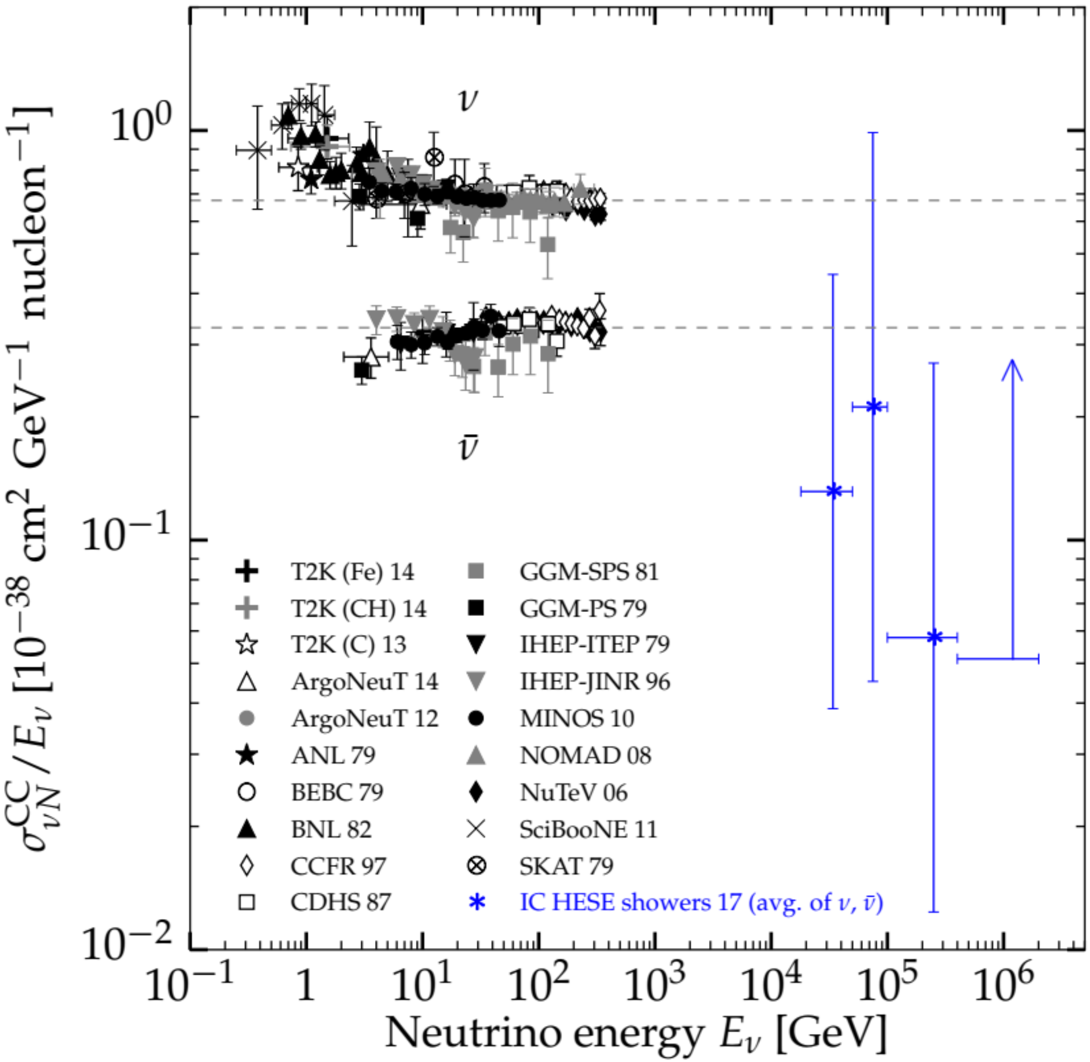
The fine print

- High-energy ν's: astrophysical (isotropic) + atmospheric (**anisotropic**)
  ↦ We take into account the shape of the atmospheric contribution
- The shape of the astrophysical ν **energy spectrum** is still uncertain
  ↦ We take a $E^{-\gamma}$ spectrum in *narrow* energy bins
- **NC showers** are sub-dominant to **CC showers**, but they are indistinguishable
  ↦ Following Standard-Model predictions, we take $\sigma_{NC} = \sigma_{CC}/3$
- IceCube does not **distinguish ν from $\bar{\nu}$**, and their cross-sections are different
  ↦ We assume equal fluxes, expected from production via pp collisions
  ↦ We assume the avg. ratio $\langle\sigma_{\bar{\nu}N}/\sigma_{\nu N}\rangle$ in each bin known, from SM predictions
- The **flavor composition** of astrophysical neutrinos is still uncertain
  ↦ We assume equal flux of each flavor, compatible with theory and observations

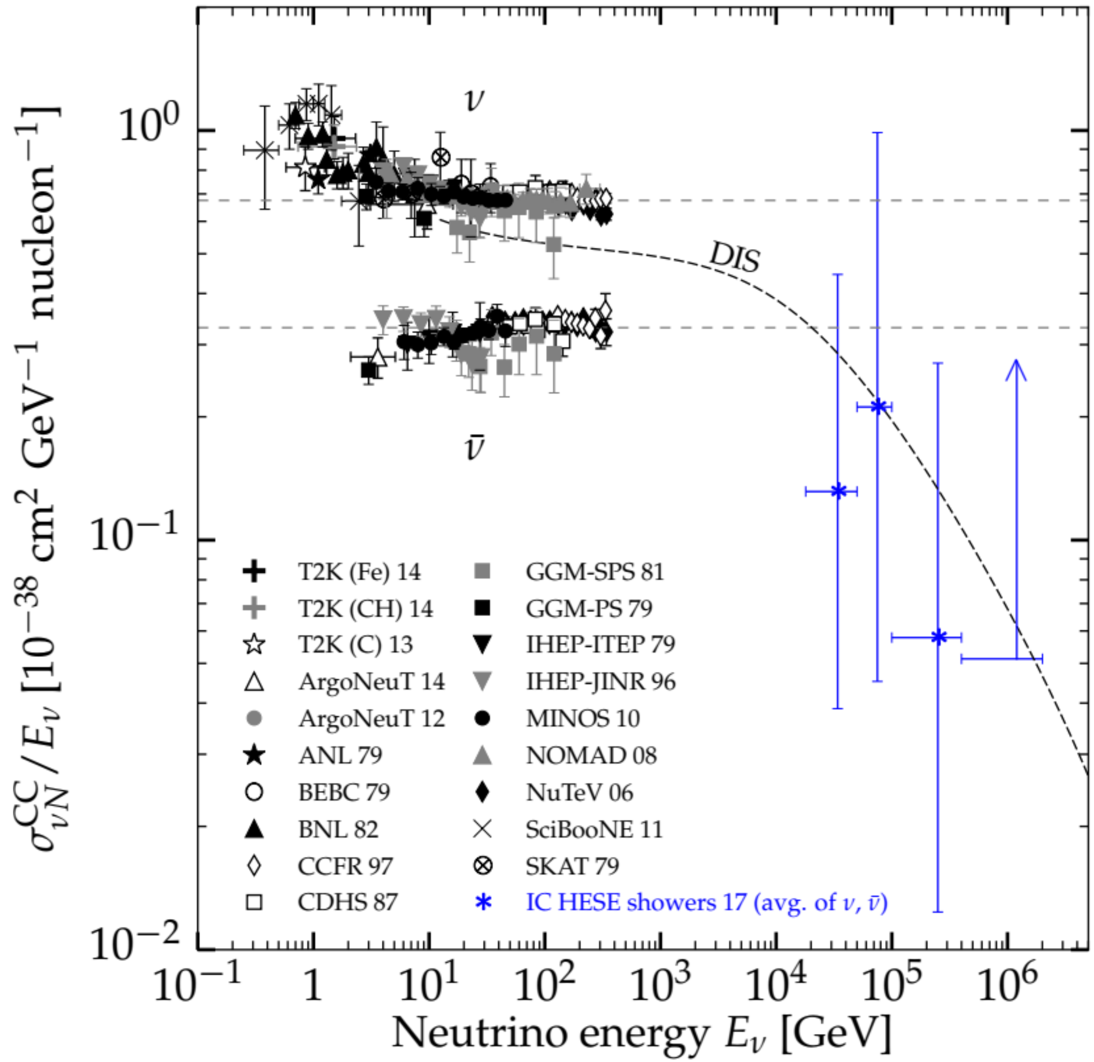


MB & Connolly *PRL* 2019
See also: IceCube, *Nature* 2017

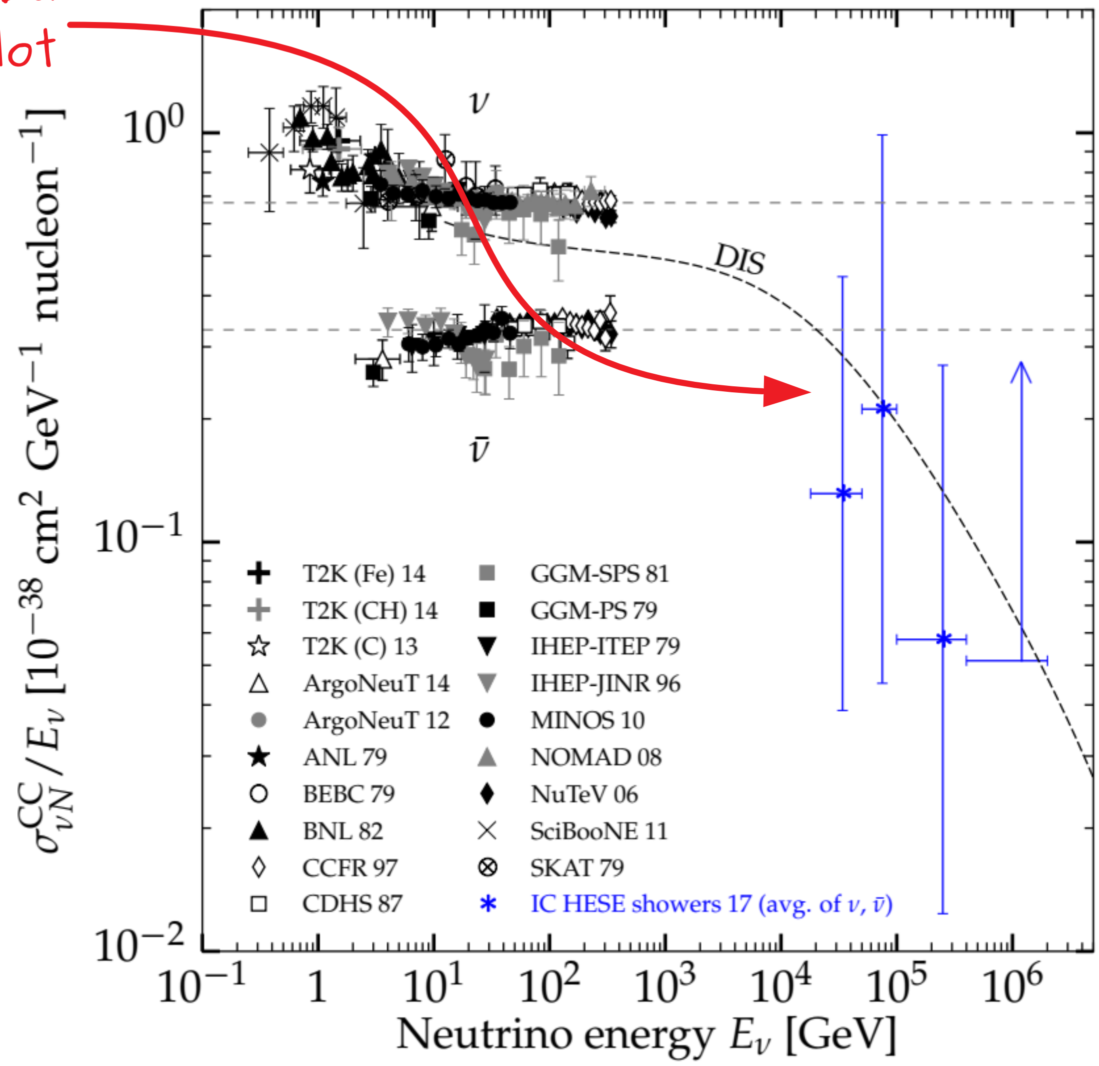
MB & Connolly *PRL* 2019
See also: IceCube, *Nature* 2017



MB & Connolly *PRL* 2019
See also: IceCube, *Nature* 2017



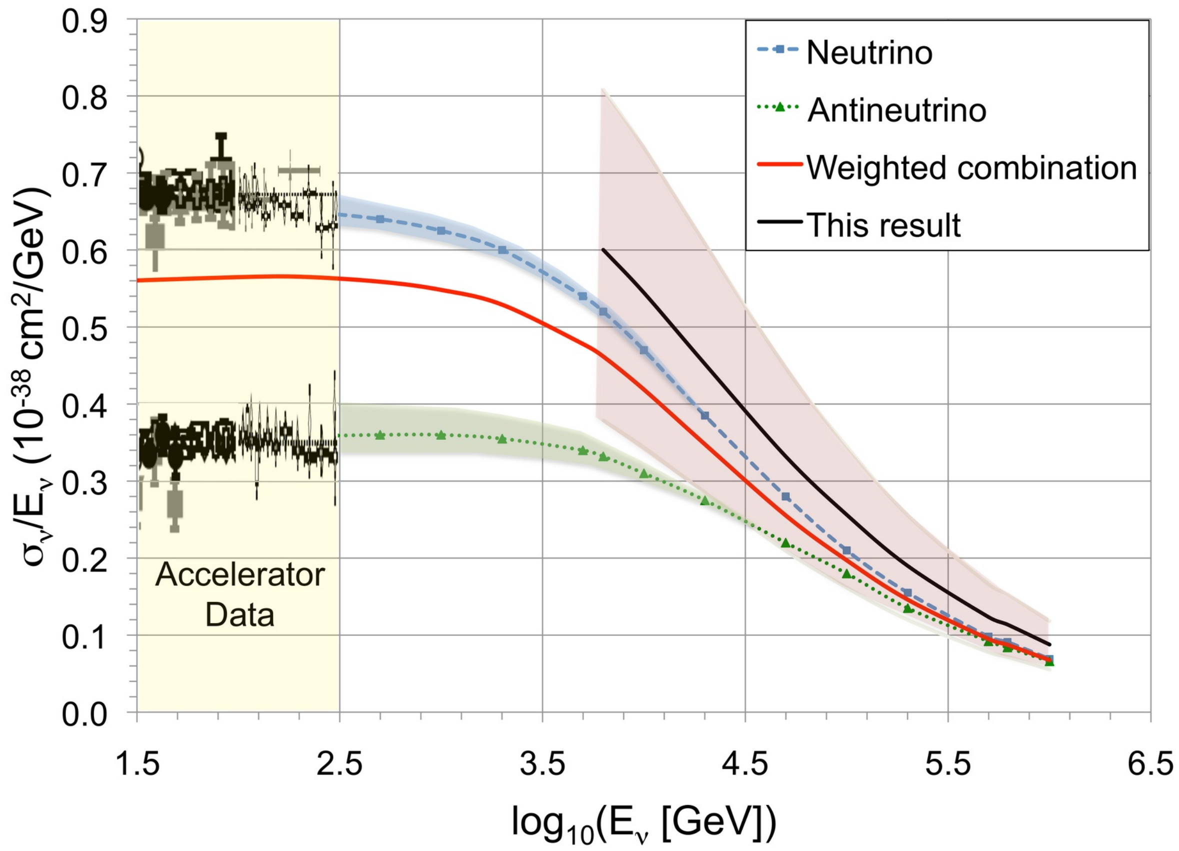
Extending the PDG cross-section plot



MB & Connolly *PRL* 2019
See also: IceCube, *Nature* 2017

Using through-going muons instead

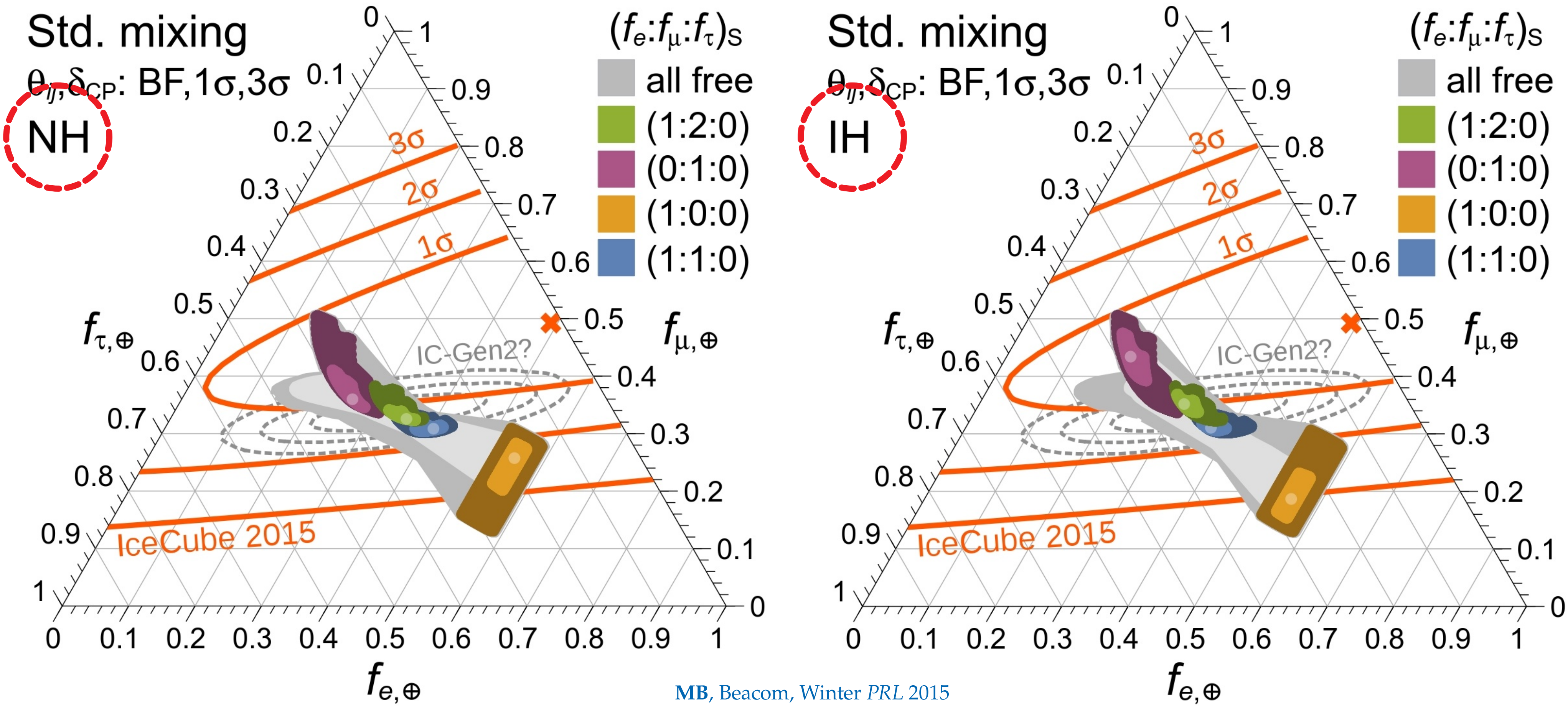
- Use ~10^4 through-going muons
- Measured: $\mathrm{d}E_\mu/\mathrm{d}x$
- Inferred: $E_\mu \approx \mathrm{d}E_\mu/\mathrm{d}x$
- From simulations (uncertain): most likely E_ν given E_μ
- Fit the ratio σ_{obs}/σ_{SM}
  $1.30\,^{+0.21}_{-0.19}\text{(stat.)}\,^{+0.39}_{-0.43}\text{(syst.)}$
- All events grouped in a single energy bin 6–980 TeV



IceCube, *Nature* 2017

Flavor composition – a few source choices

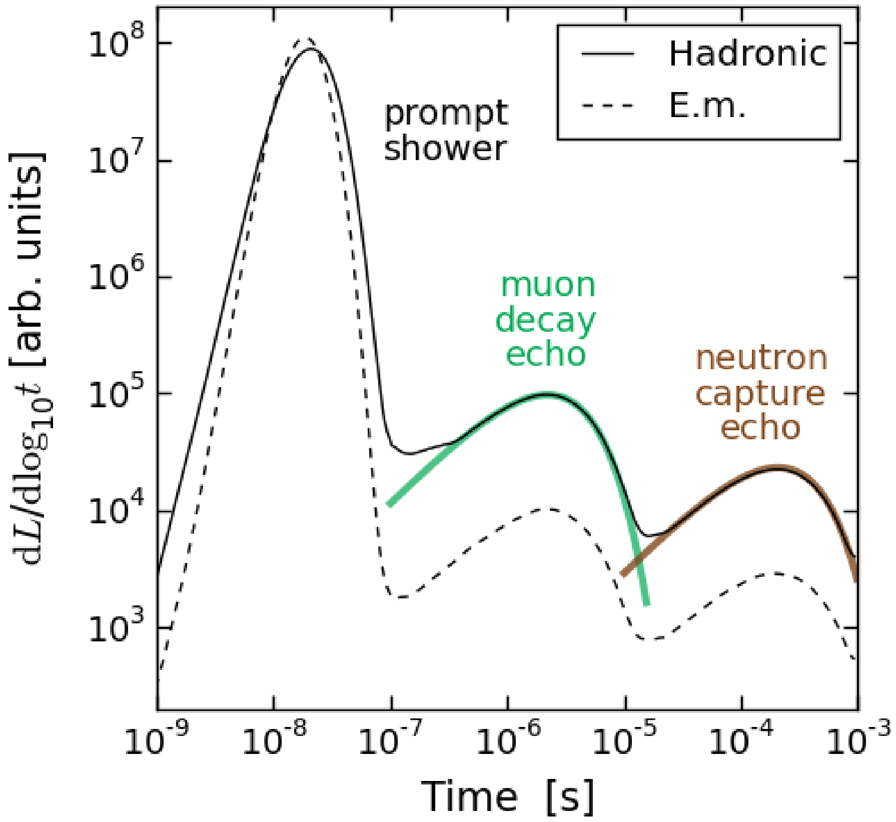
Flavor composition – a few source choices

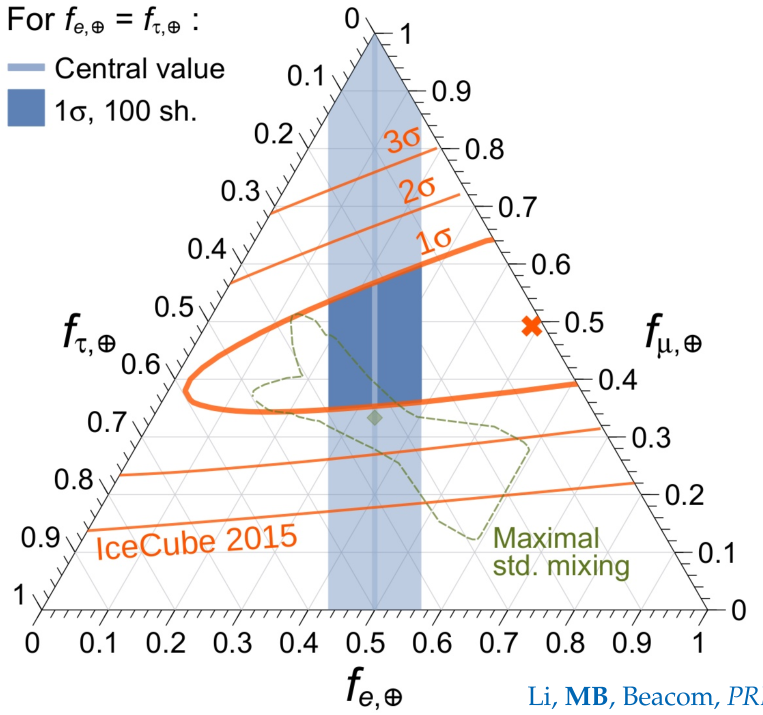


MB, Beacom, Winter *PRL* 2015

Side note: Improving flavor-tagging using *echoes*

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





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

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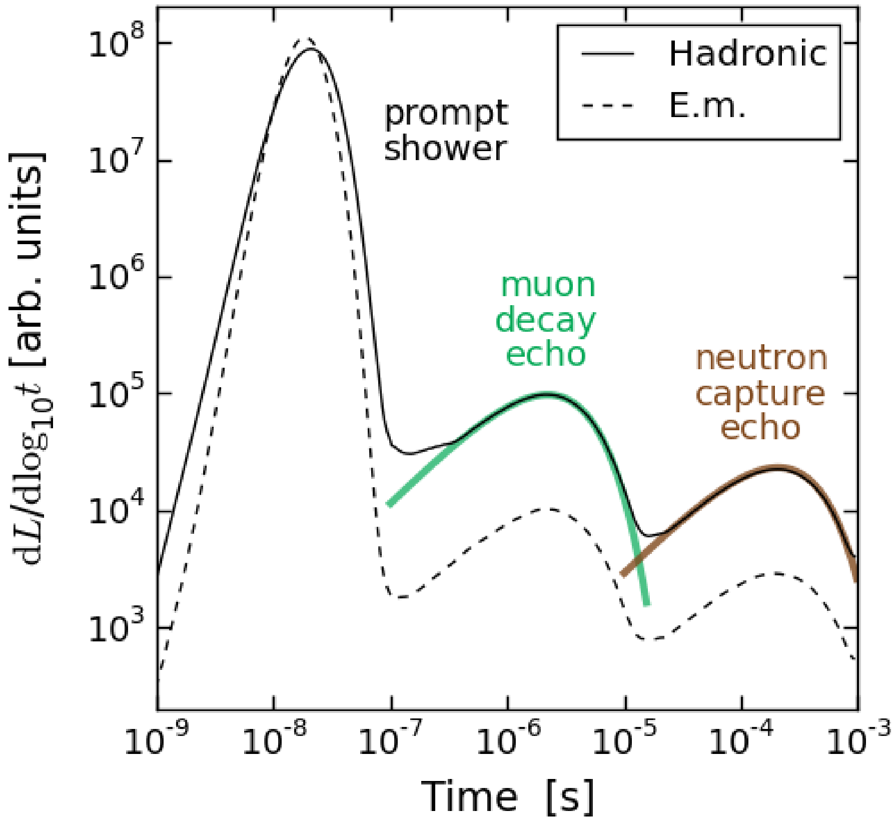
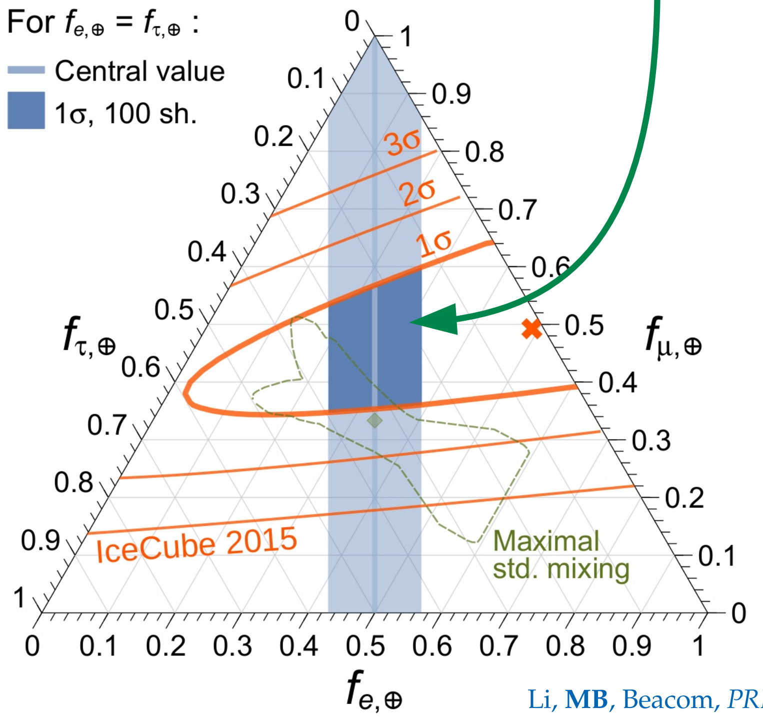


~10 × improvement over current measurement



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

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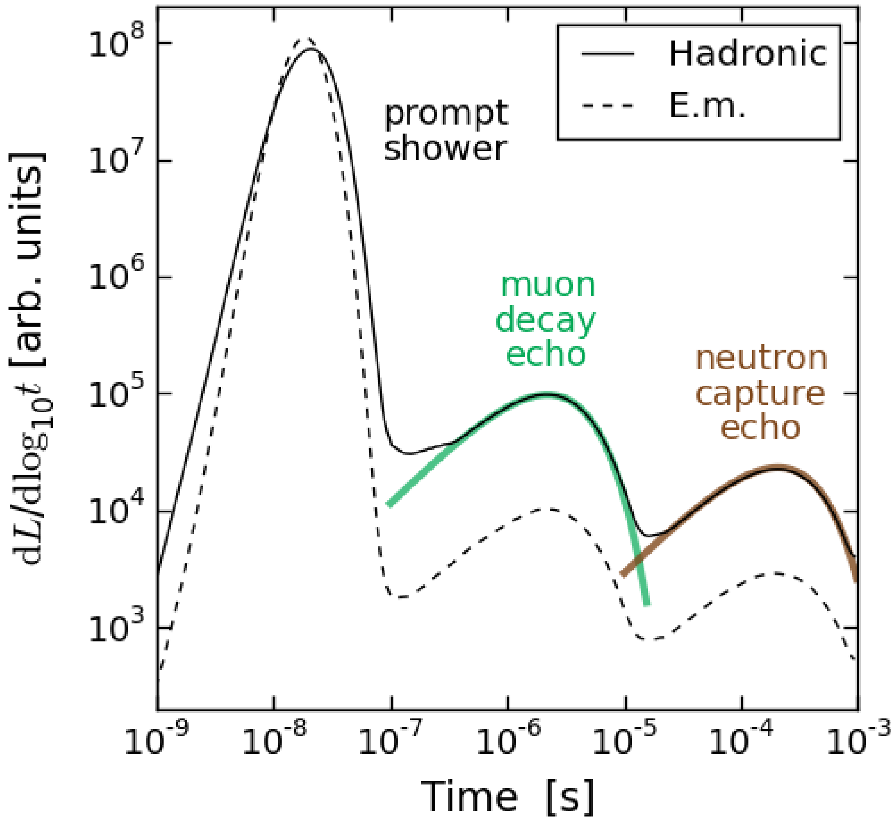
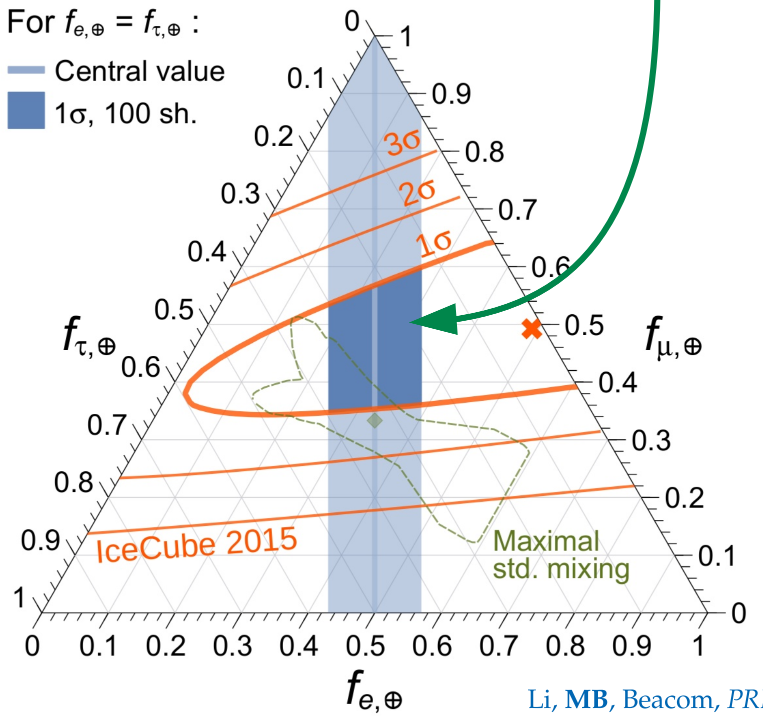
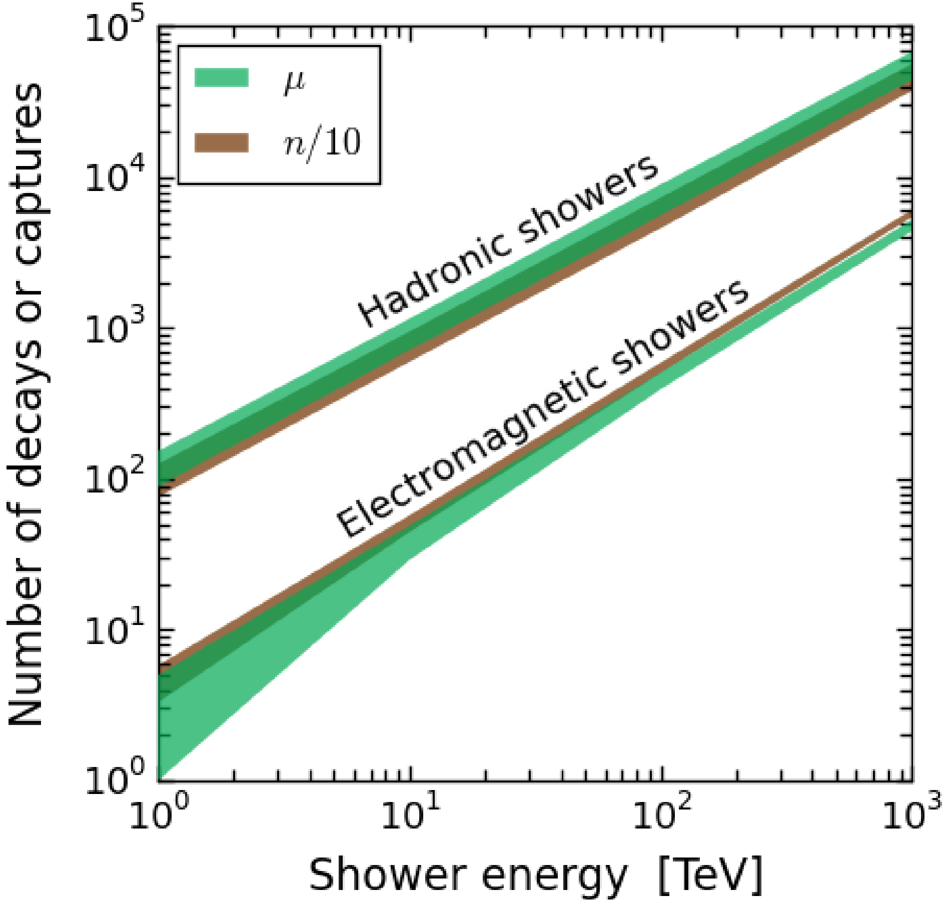
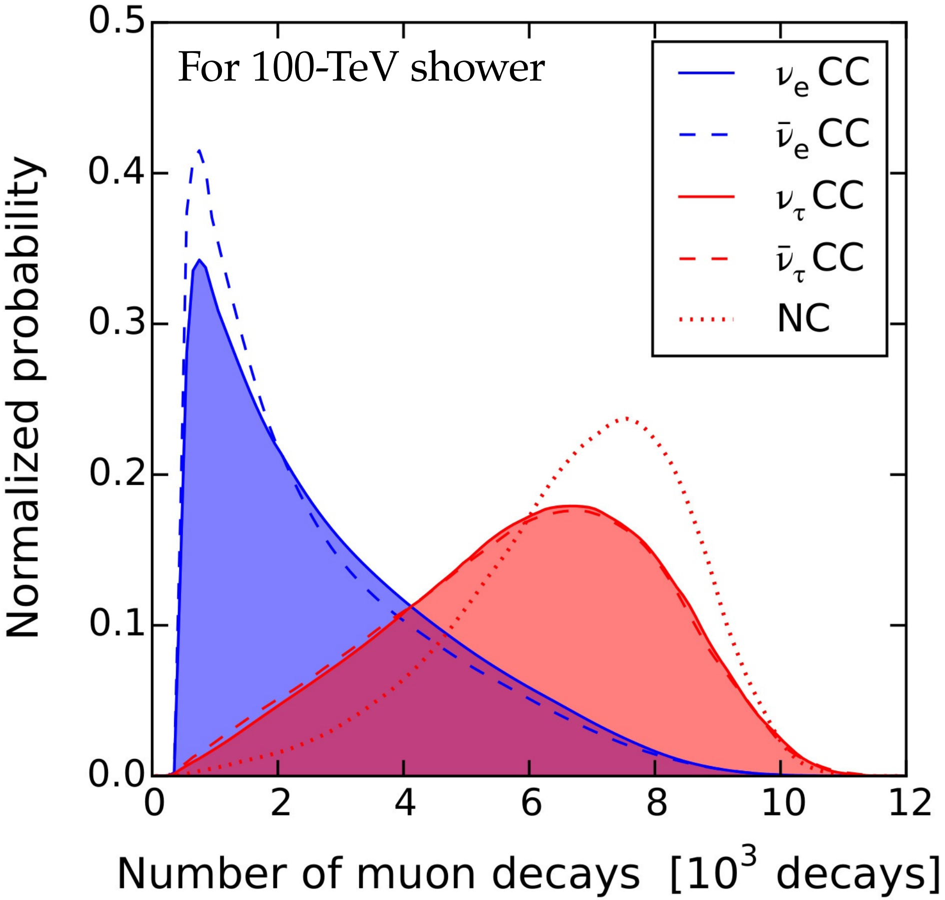




Li, **MB**, Beacom, *PRL* 2019

Hadronic *vs.* electromagnetic showers

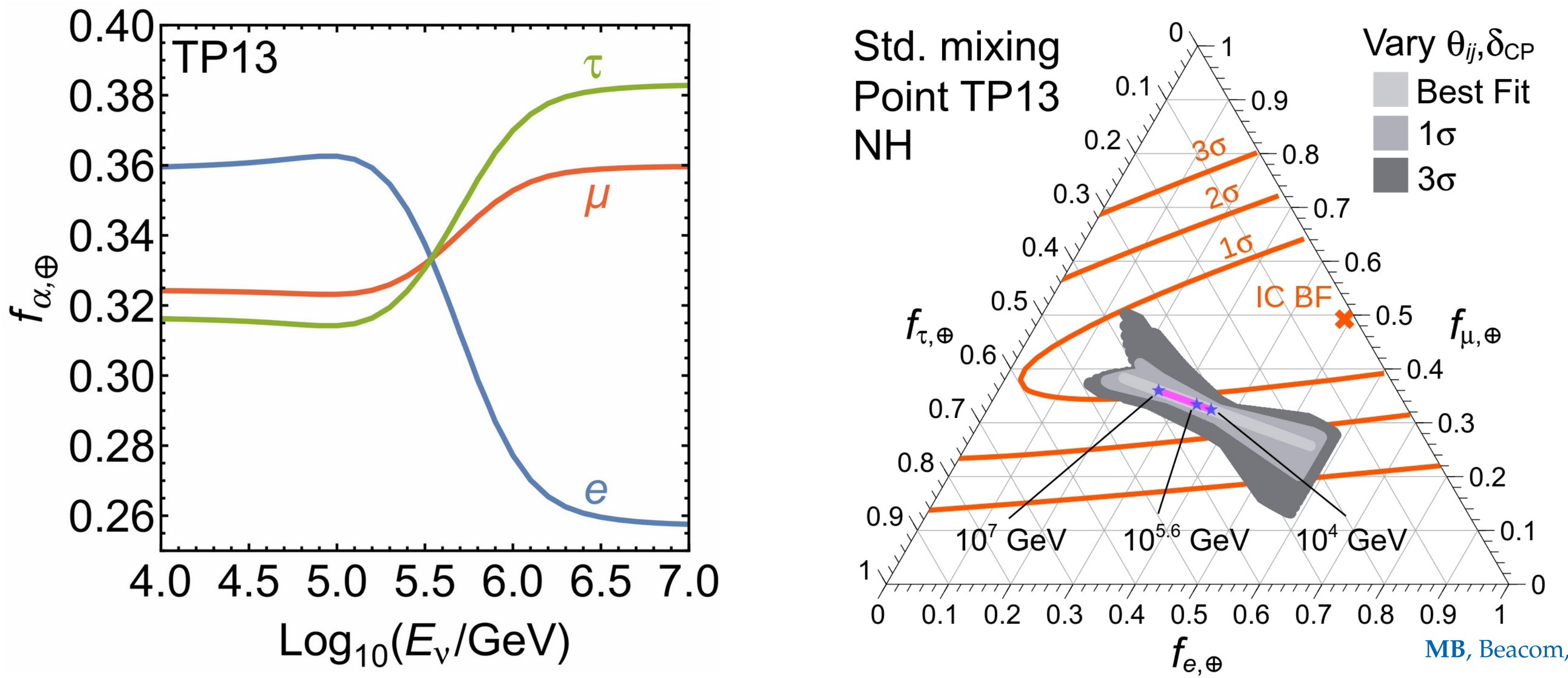




Li, **MB**, Beacom, *PRL* 2019

Energy dependence of the flavor composition?

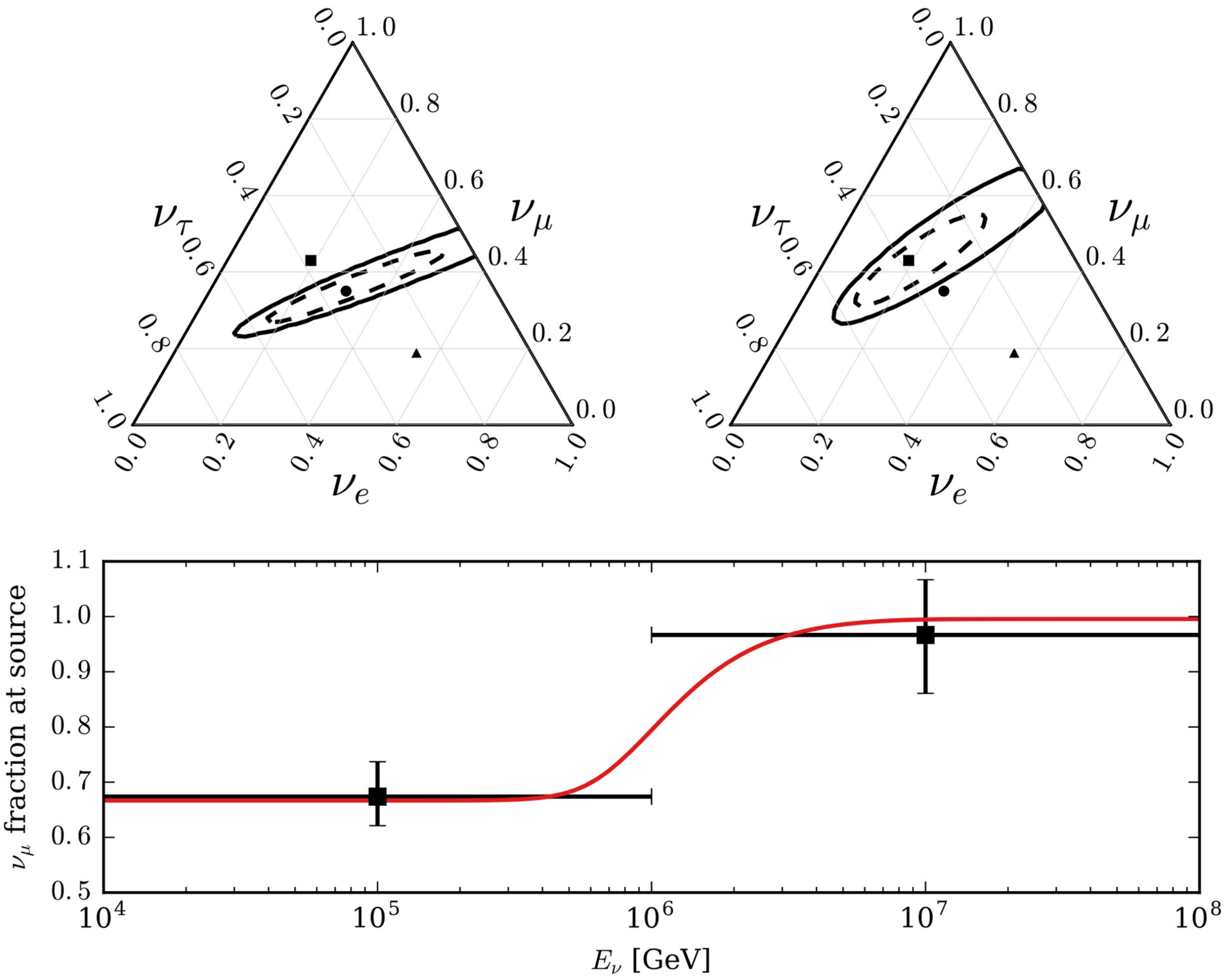
Different neutrino production channels accessible at different energies –



MB, Beacom, Winter *PRL* 2015

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

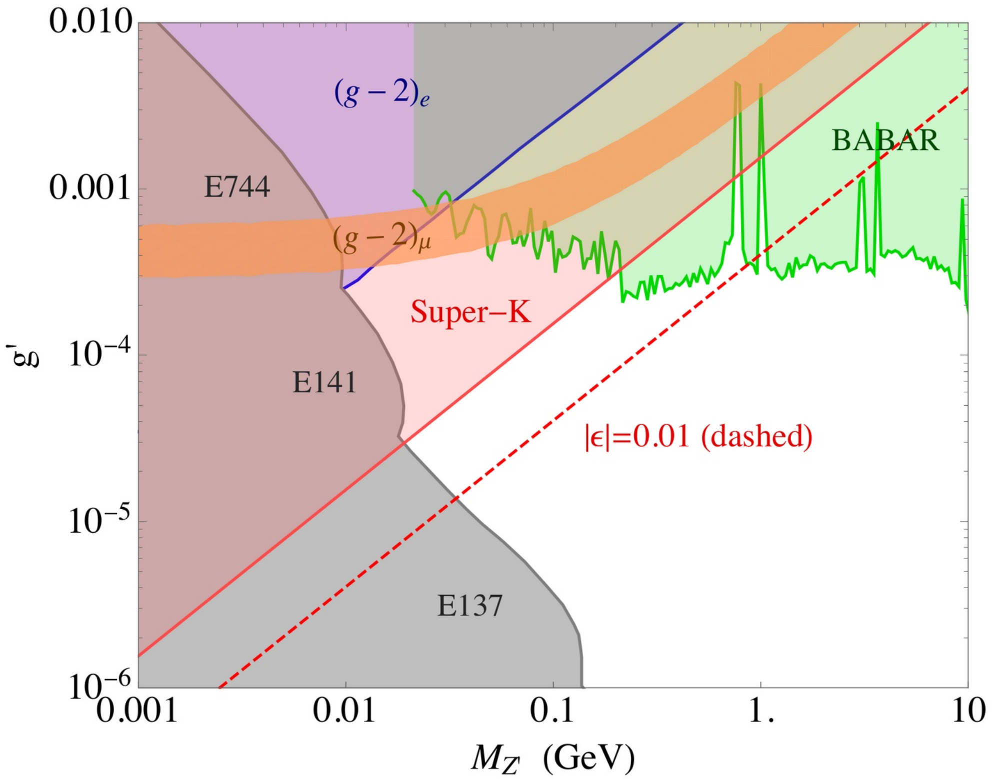
… Observable in IceCube-Gen2?



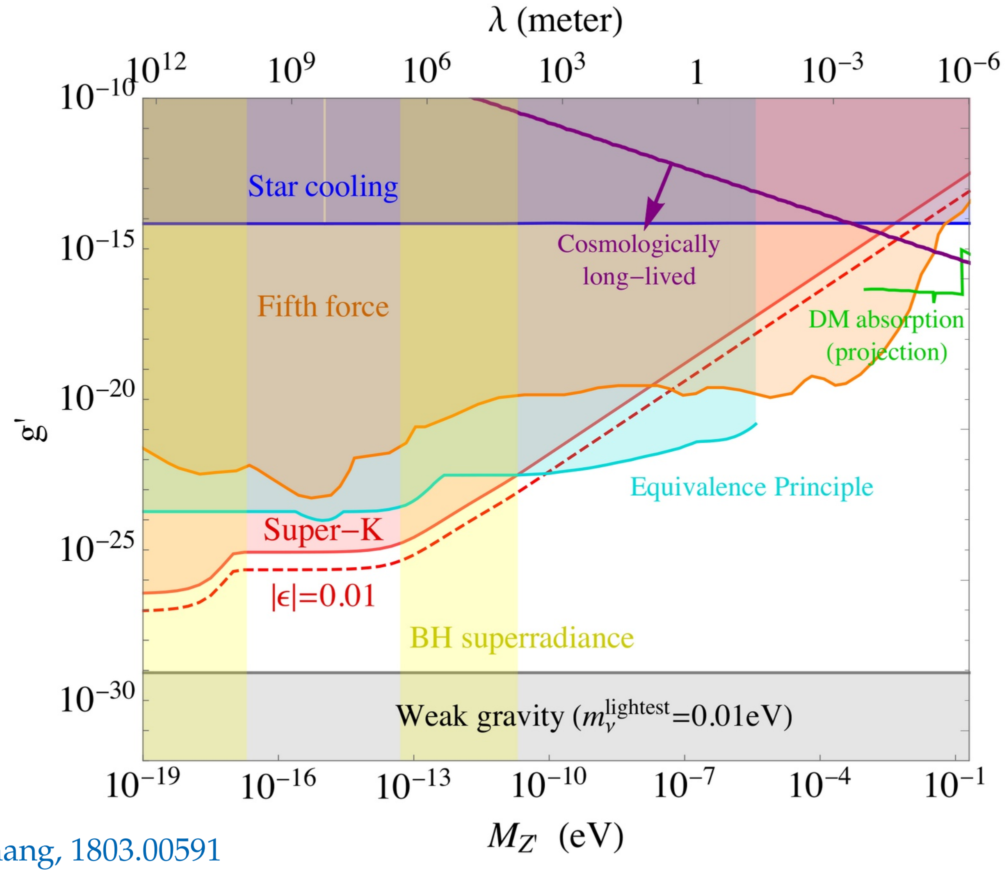
Borrowed from M. Kowalski

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

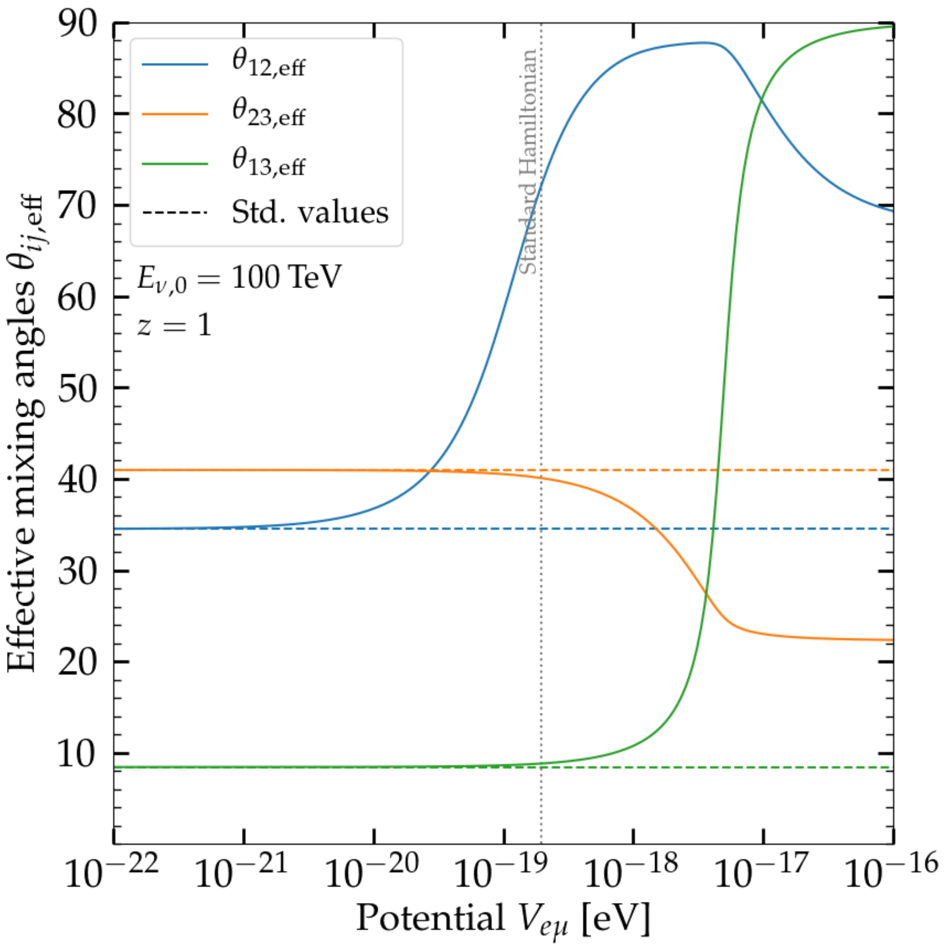
$$\langle V_{e\beta}^{\cos} \rangle \propto \int dz \, \rho_{\rm SFR}(z) \cdot \frac{dV_c}{dz} \cdot V_{e\beta}^{\cos}(z)$$

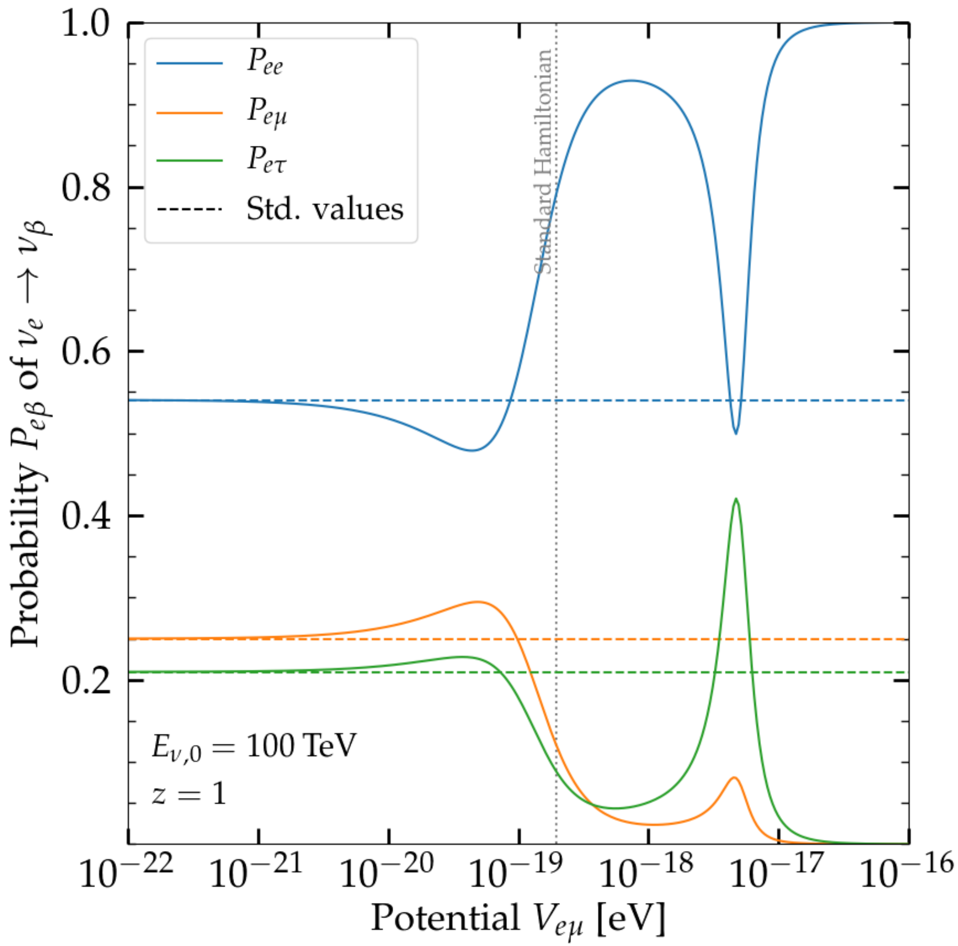
Density of cosmological *e* grows with *z*

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

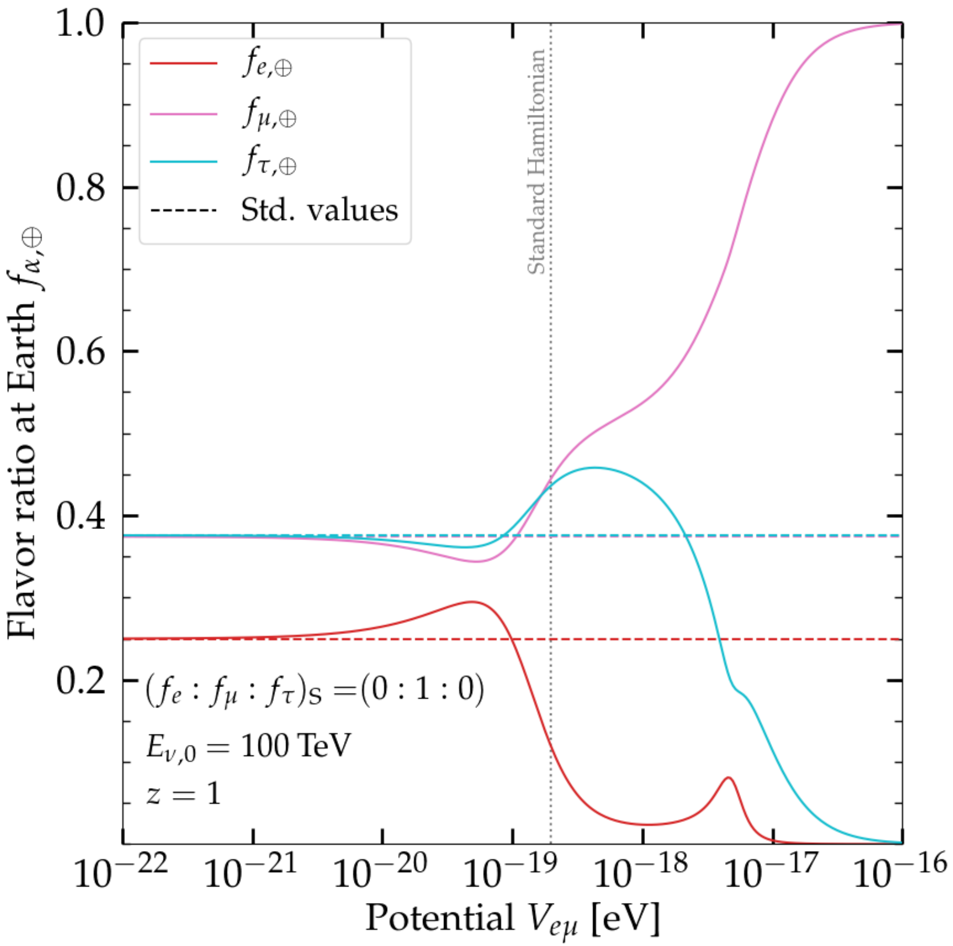
$$\underbrace{\langle \Phi_\alpha \rangle \propto \int dE_\nu \, f_{\alpha,\oplus}(E_\nu) \, E_\nu^{-\gamma}}_{\text{Energy-averaged flux}} \quad \Rightarrow \quad \underbrace{\langle f_{\alpha,\oplus} \rangle \equiv \frac{\langle \Phi_\alpha \rangle}{\sum_{\beta=e,\mu,\tau} \langle \Phi_\beta \rangle}}_{\text{Energy-averaged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

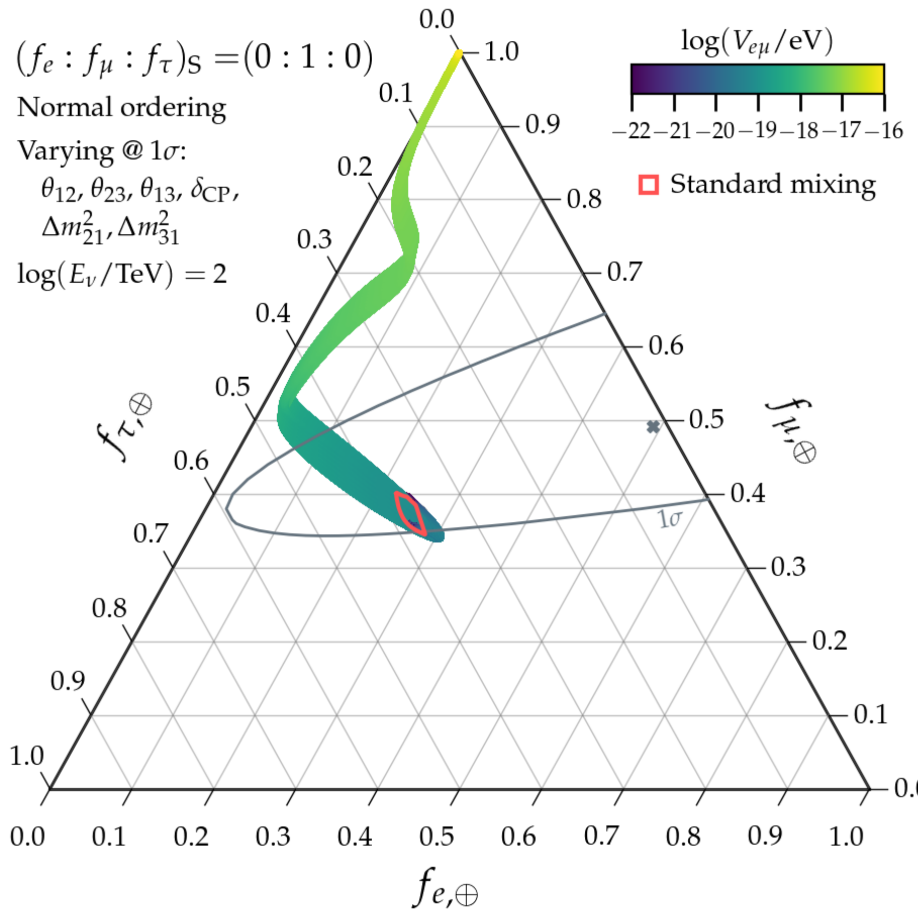
Resonance due to the L_e-L_μ symmetry





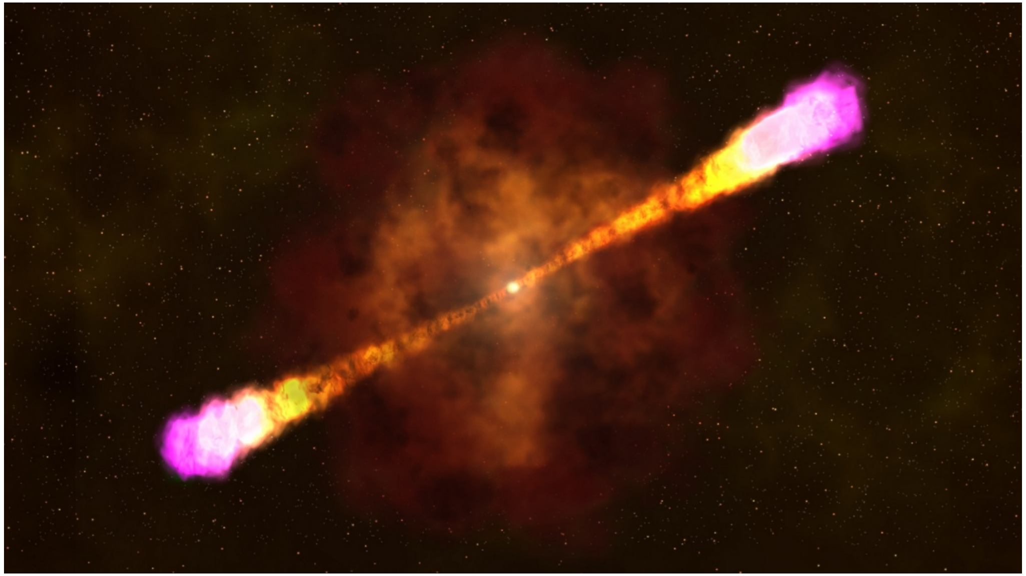
Resonance due to the L_e-L_μ symmetry (*cont.*)





Gamma-ray bursts and blazars – *not* dominant

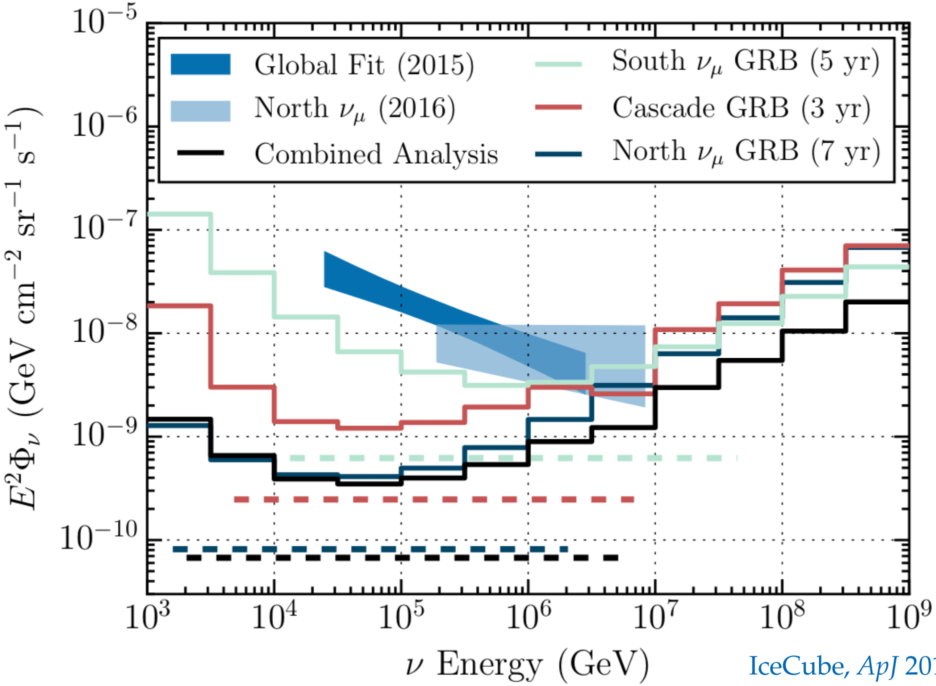
Gamma-ray bursts



Blazars

Gamma-ray bursts and blazars – *not* dominant

Gamma-ray bursts

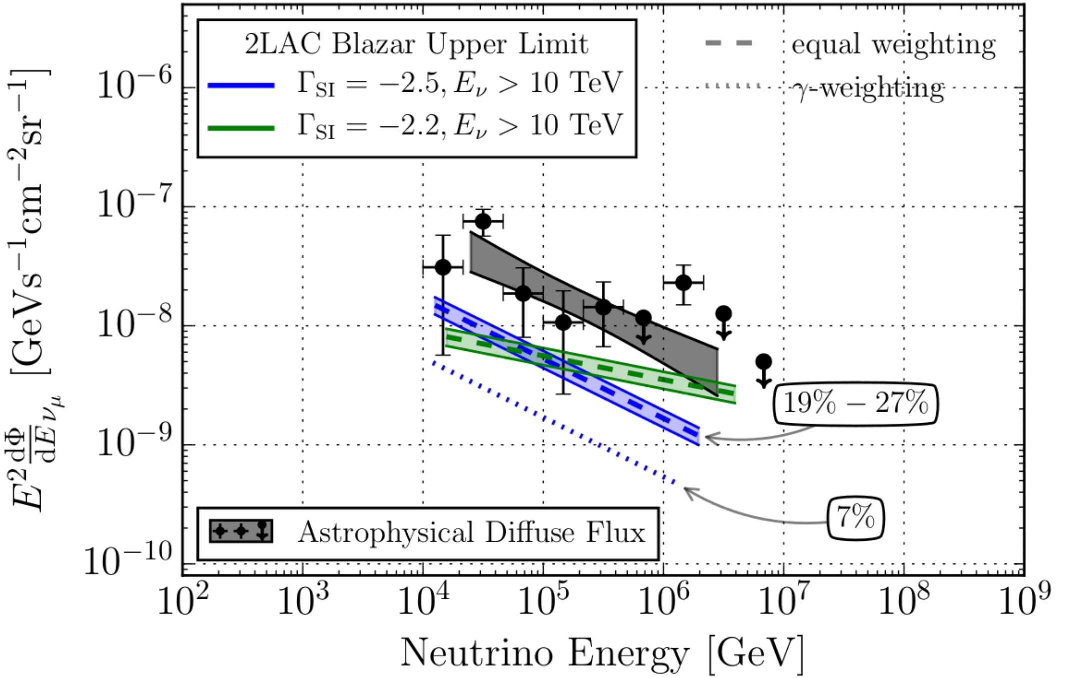


IceCube, *ApJ* 2017

1172 GRBs inspected, no correlation found

< 1% contribution to diffuse flux

Blazars



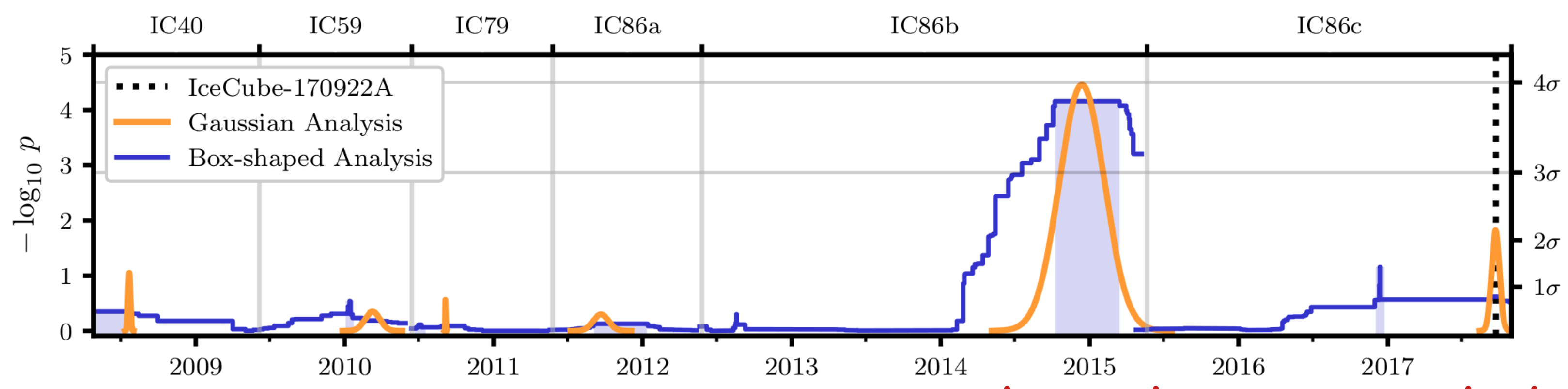
862 blazars inspected, no correlation found

< 27% contribution to diffuse flux

… but we have seen *one* blazar neutrino flare!

Recent news:
The starburst Seyfert galaxy NGC 1068 is also a potential neutrino source candidate (1908.05993)

Blazar TXS 0506+056:



Important:
If every blazar produced neutrinos as TXS 0506+056, the diffuse neutrino flux would be 20x higher than observed!

2014–2015: 13±5 ν flare, no X-ray flare
3.5σ significance of correlation (post-trial)

2017: one 290-TeV ν + X-ray flare
1.4σ significance of correlation

Combined (pre-trial): 4.1σ

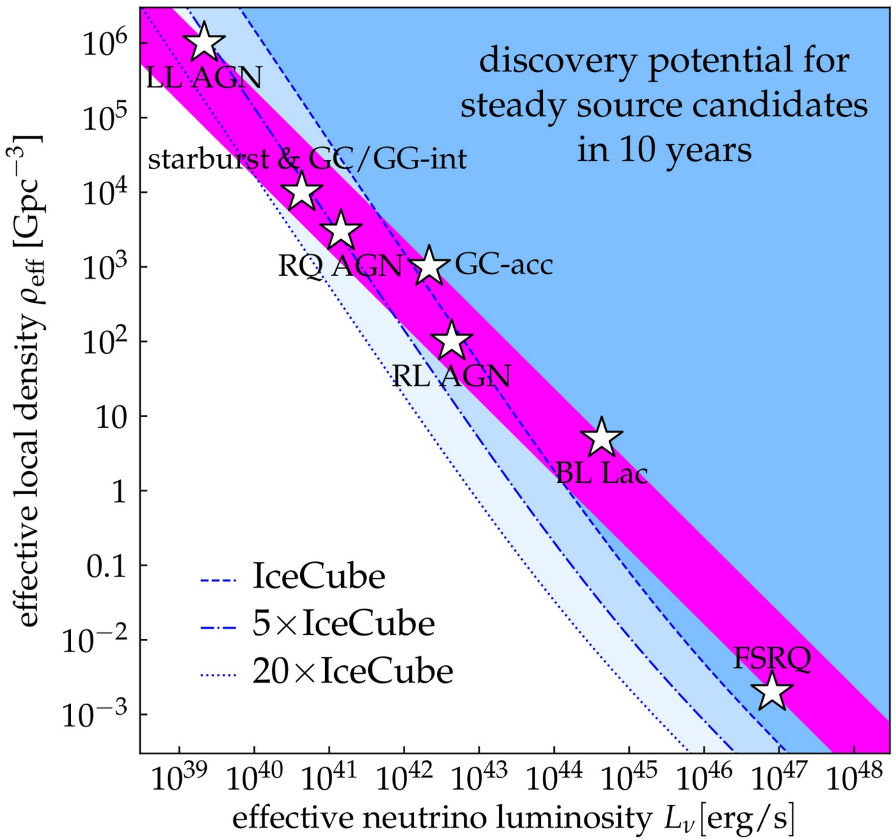
Hard fluence: $E^2 J_{100} = 2.1^{+0.9}_{-0.7} \left(\frac{E}{100\ \mathrm{TeV}}\right)^{-2.1\pm0.2}\ \mathrm{TeV\ cm^{-2}}$

Joint modeling of the two periods is challenging; see ICRC 2019 talk by Walter Winter

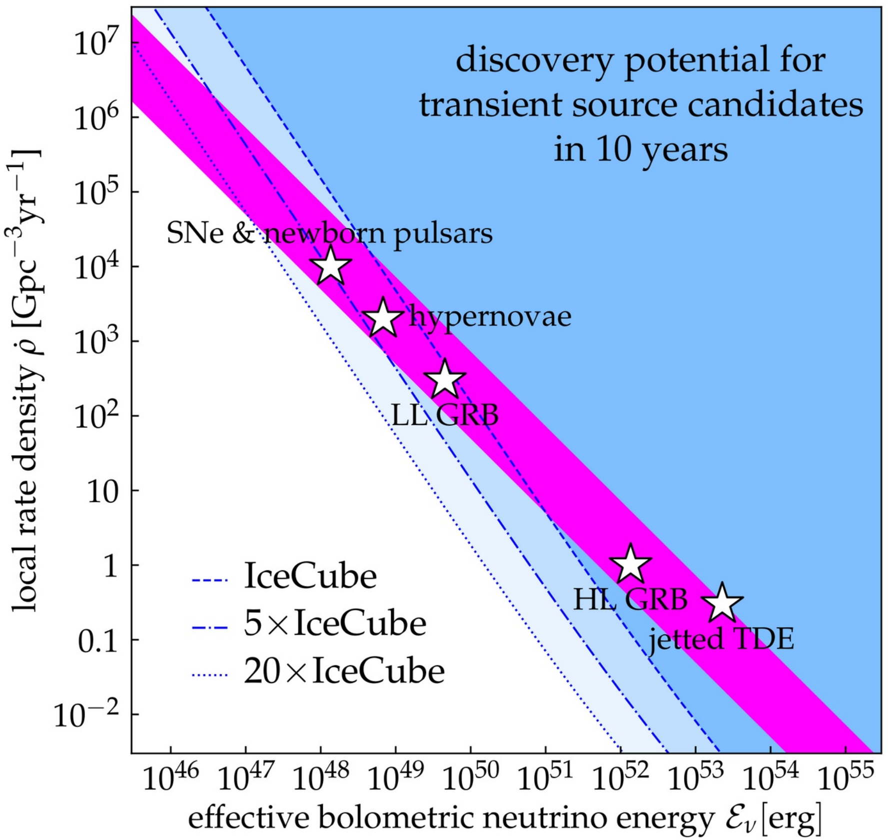
Source discovery potential: today and in the future

Accounts for the observed diffuse ν flux (lower/upper edge: rapid/no redshift evolution)

Closest source with $E^2\Phi_{\nu_\mu+\bar{\nu}_\mu} = 10^{-12}$ TeV cm^{-2} s^{-1}



Closest source with $E^2F_{\nu_\mu+\bar{\nu}_\mu} = 0.1$ GeV cm^{-2}



Ackermann, **MB** *et al.*, Astro2020 Survey (1903.04333) – See also: Silvestri & Barwick, *PRD* 2010; Murase & Waxman, *PRD* 2016