Pushing Neutrino Physics to the Cosmic Frontier

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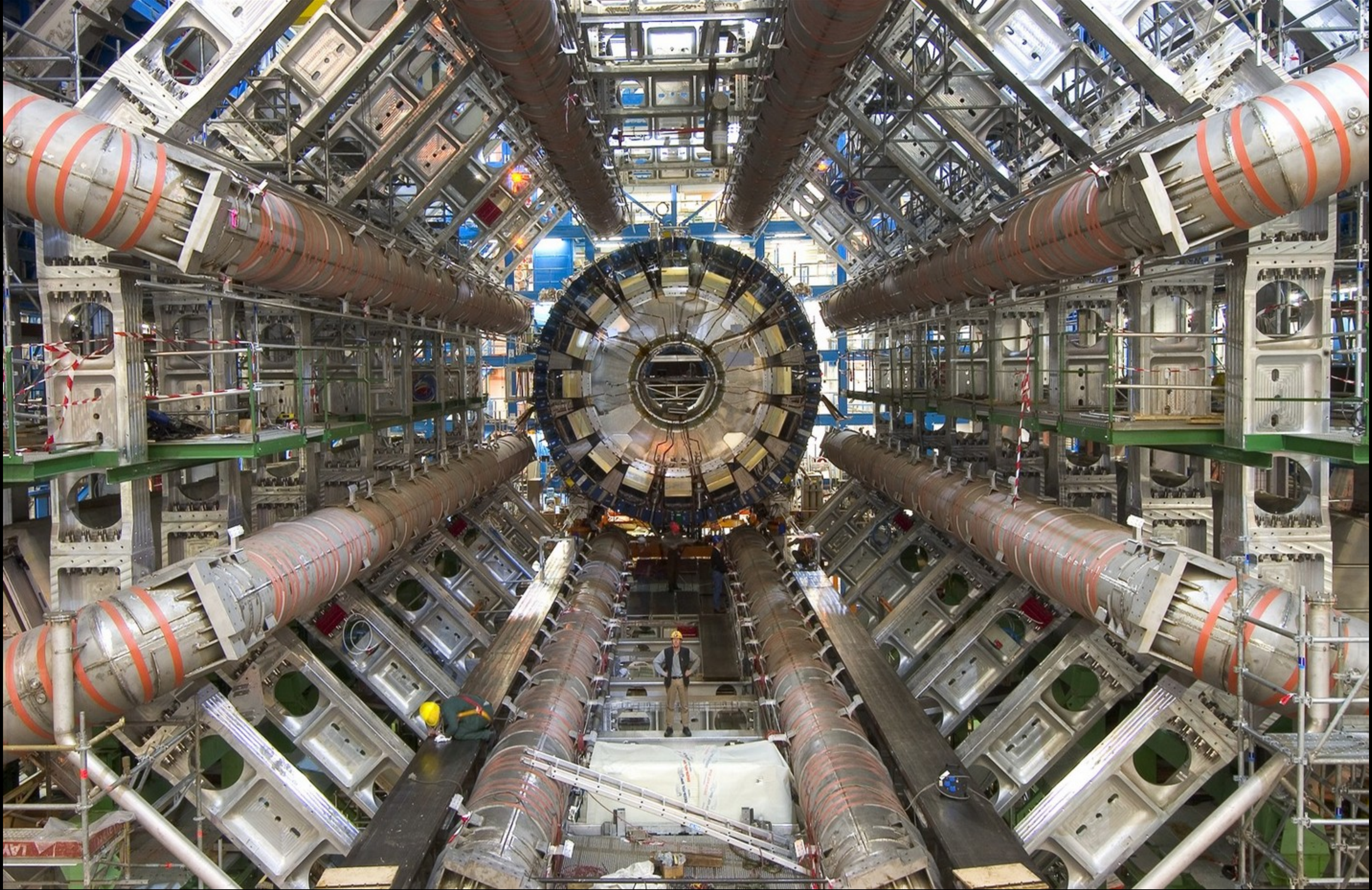
Niels Bohr Institute, University of Copenhagen

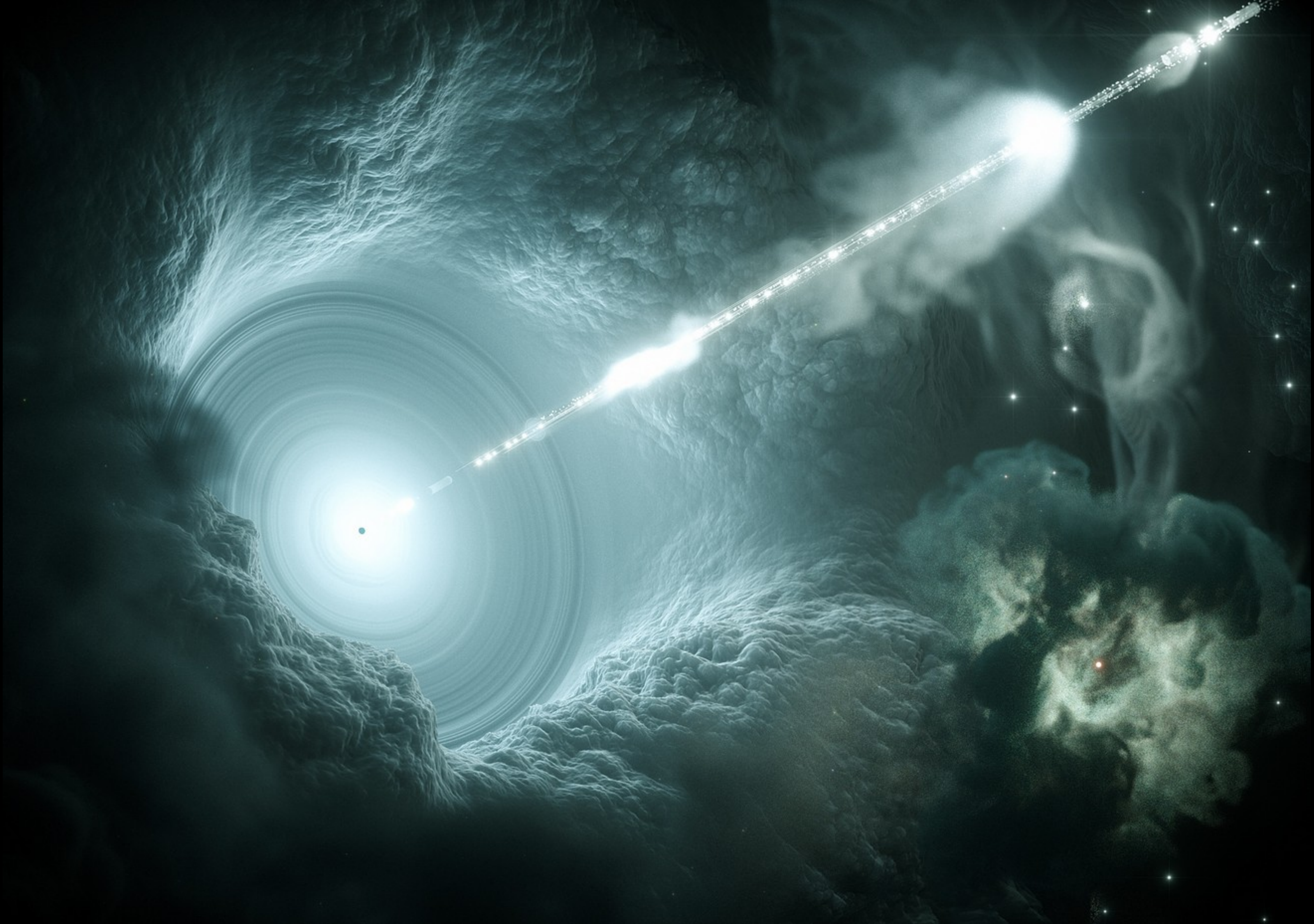
TTK Theory Seminar, RWTH Aachen
November 21, 2019

UNIVERSITY OF COPENHAGEN

VILLUM FONDEN



ATLAS



DESY

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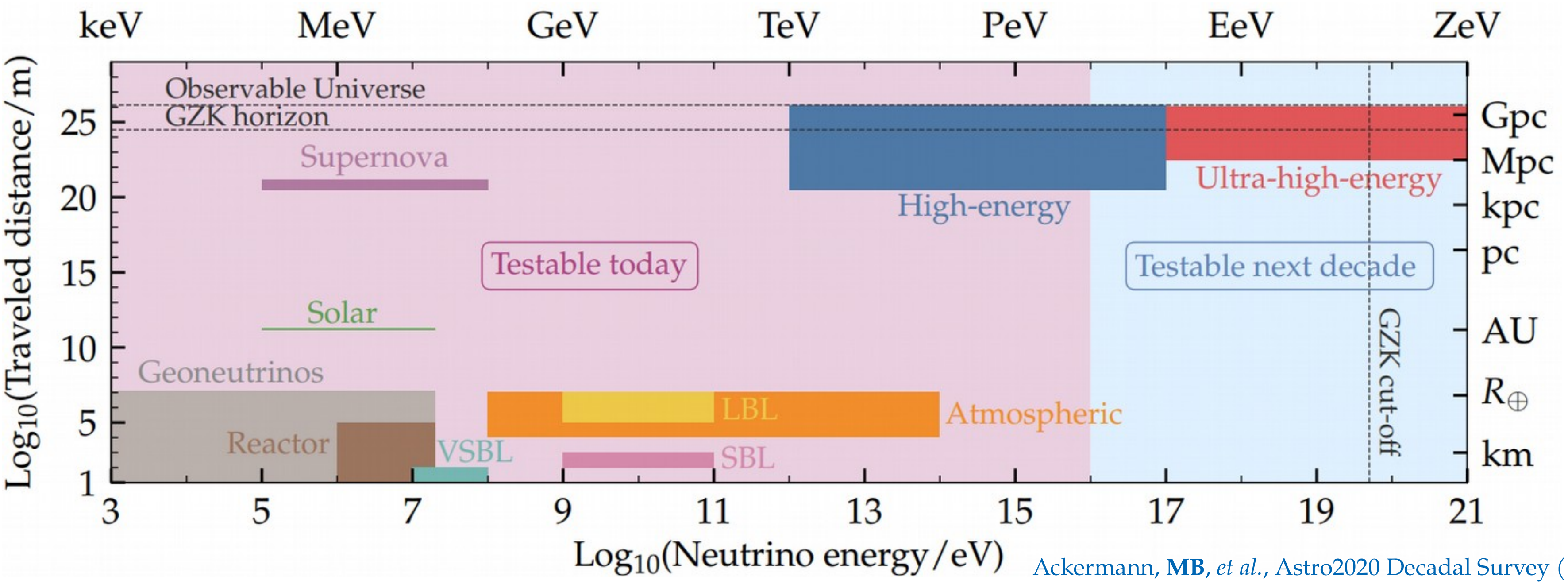

Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333)

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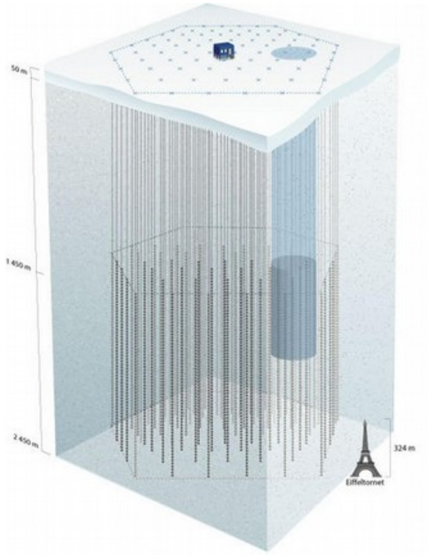
5 It comes *for free*

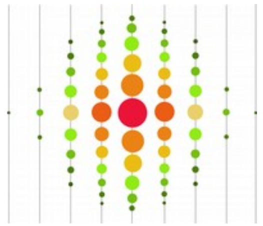
IceCube (8 years)

km³ in-ice
Cherenkov detector



Showers

(mostly from ν_e, ν_τ)



Tracks

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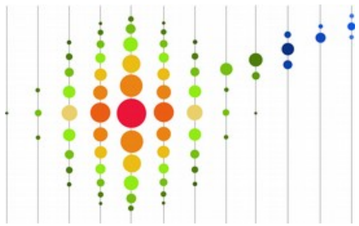
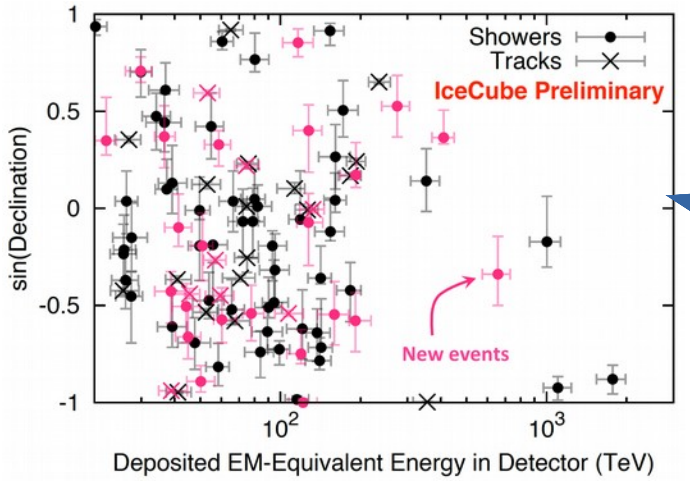


103 contained events, 15 TeV–2 PeV



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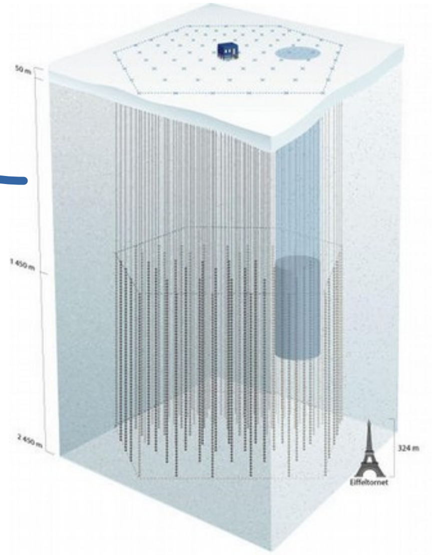

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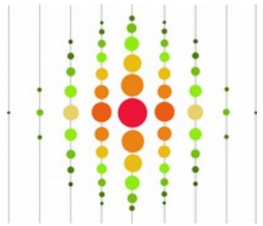

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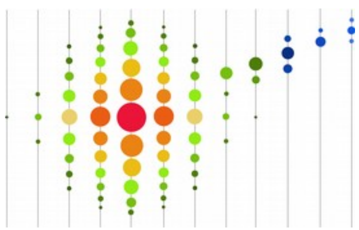

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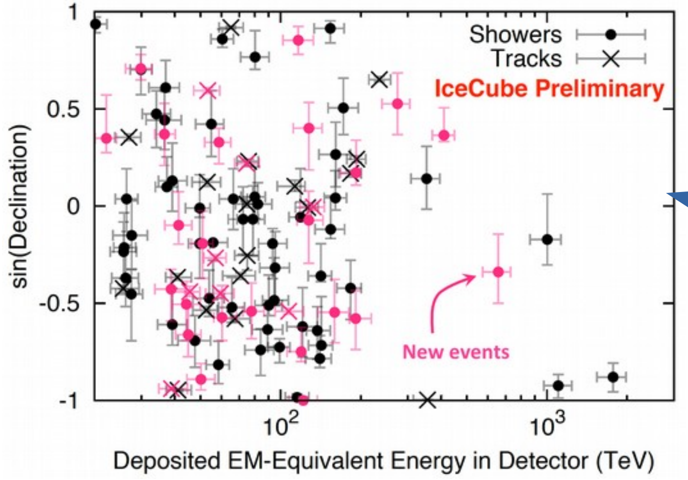

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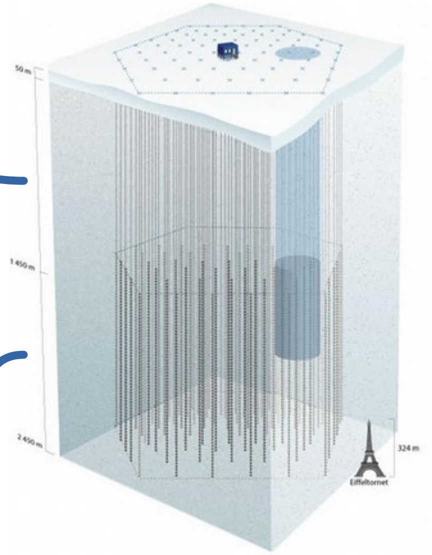
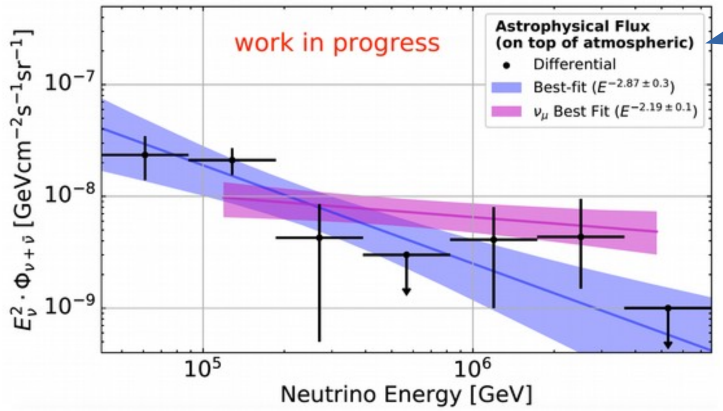


Astrophysical ν flux detected at $> 7\sigma$



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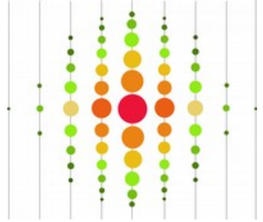

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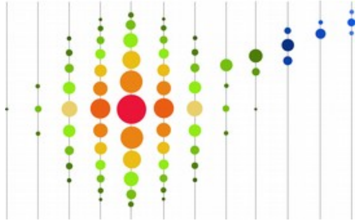

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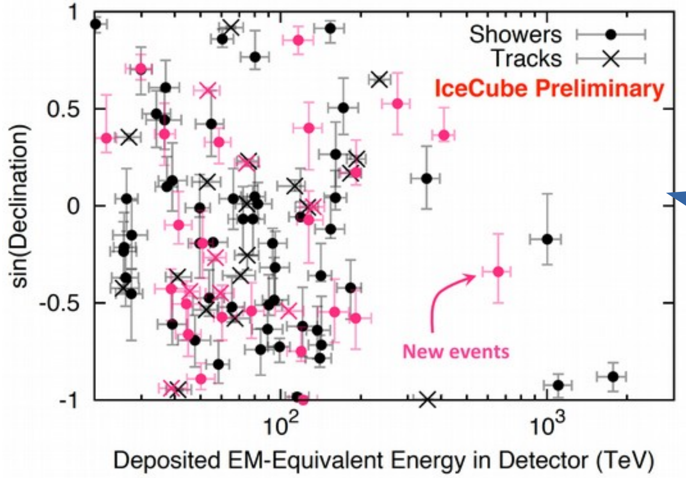

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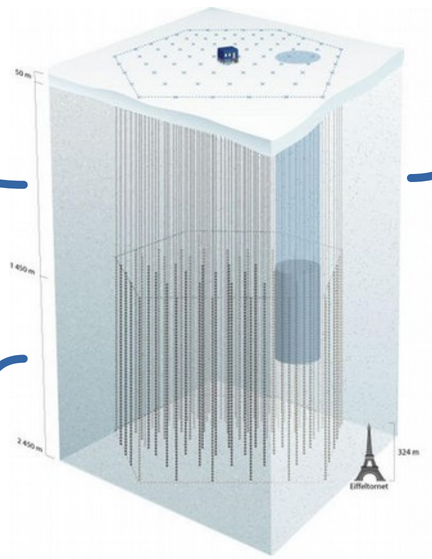
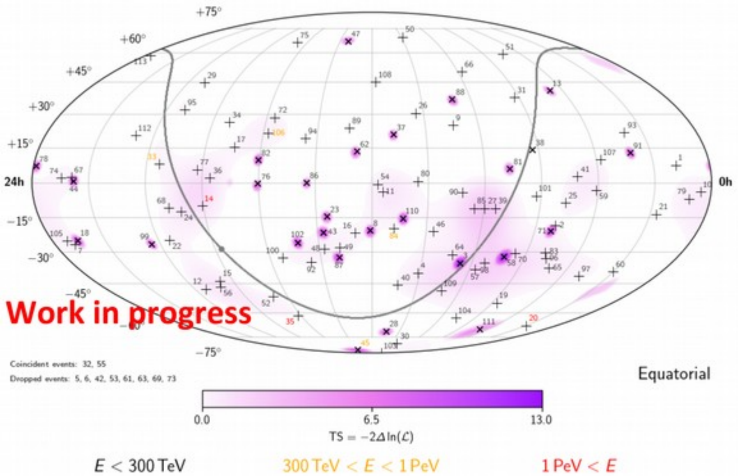


Arrival directions compatible with isotropy



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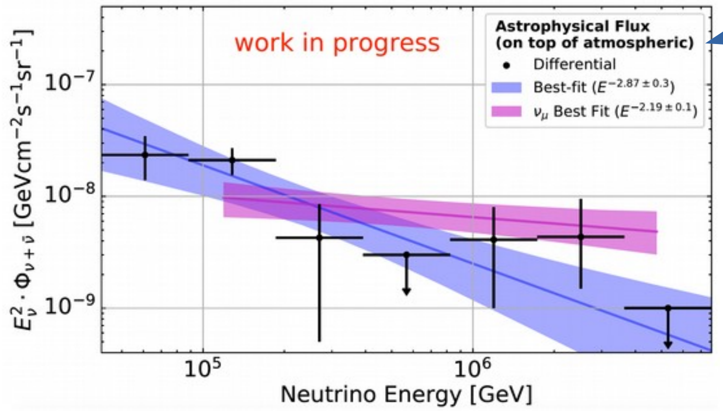

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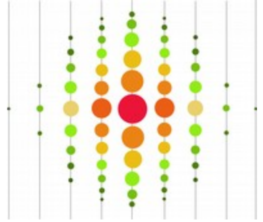

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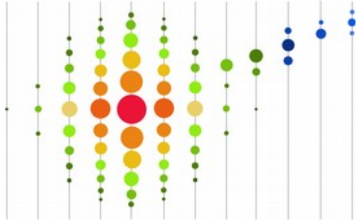

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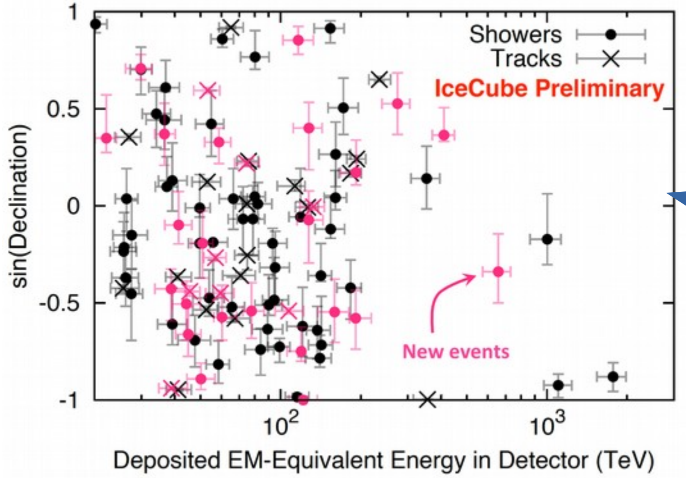

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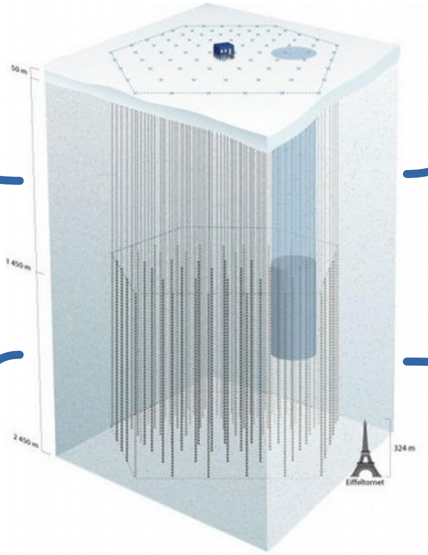

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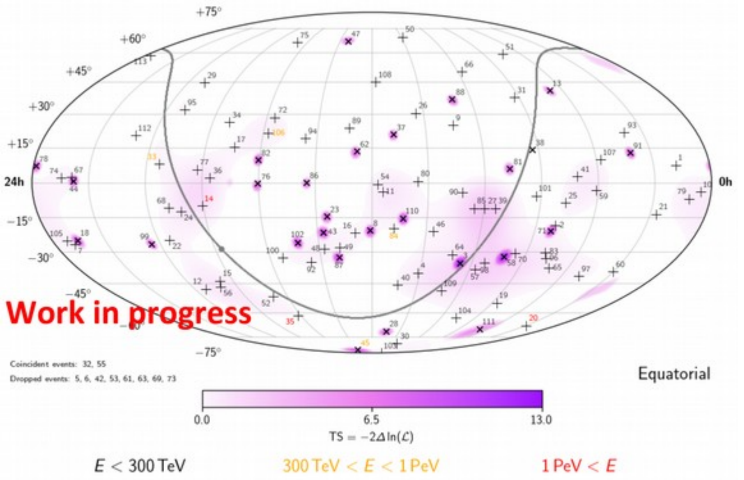

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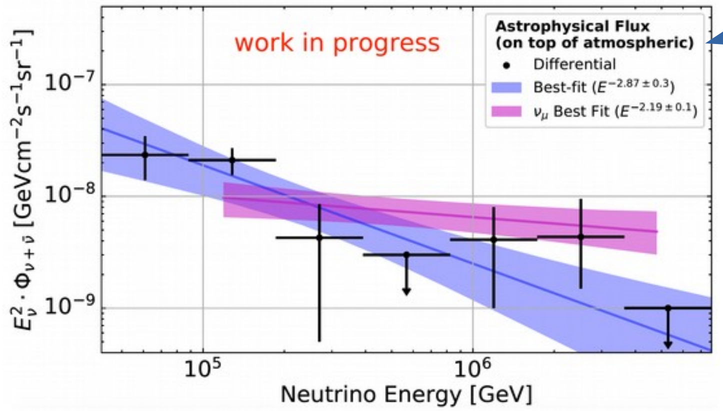

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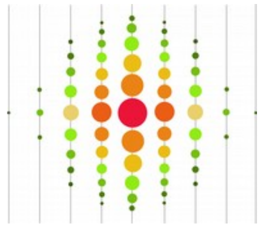

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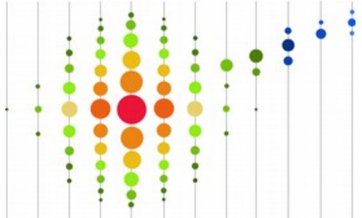
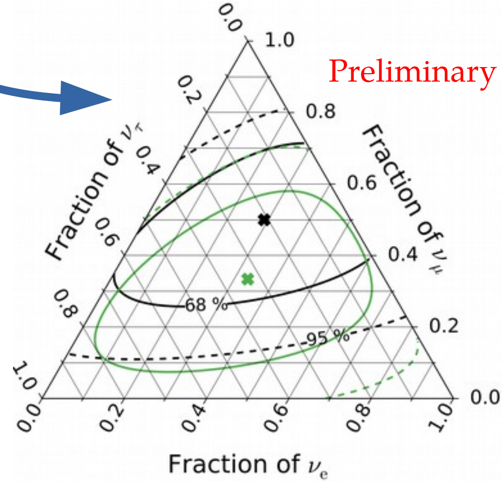


Flavor composition



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.

Netflix

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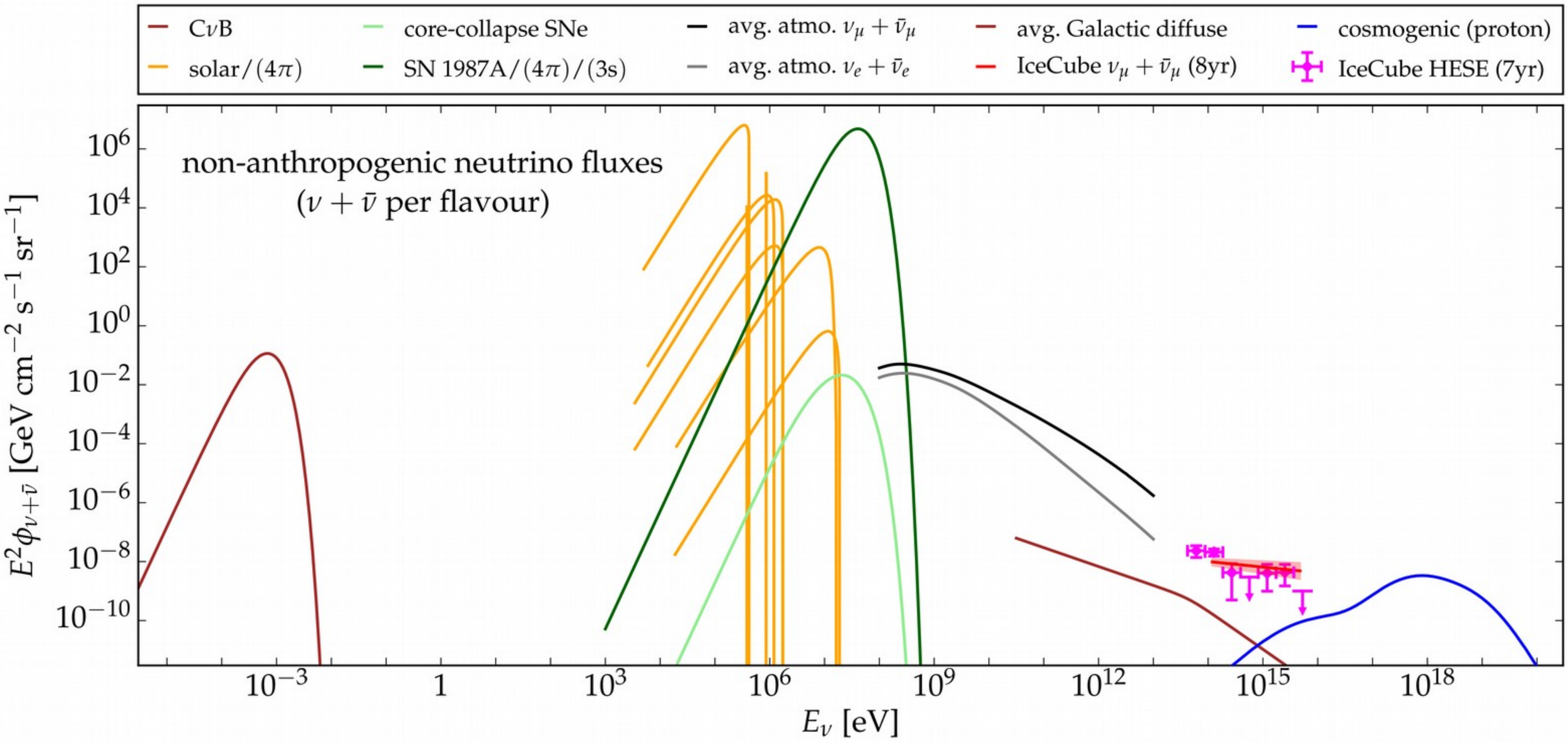
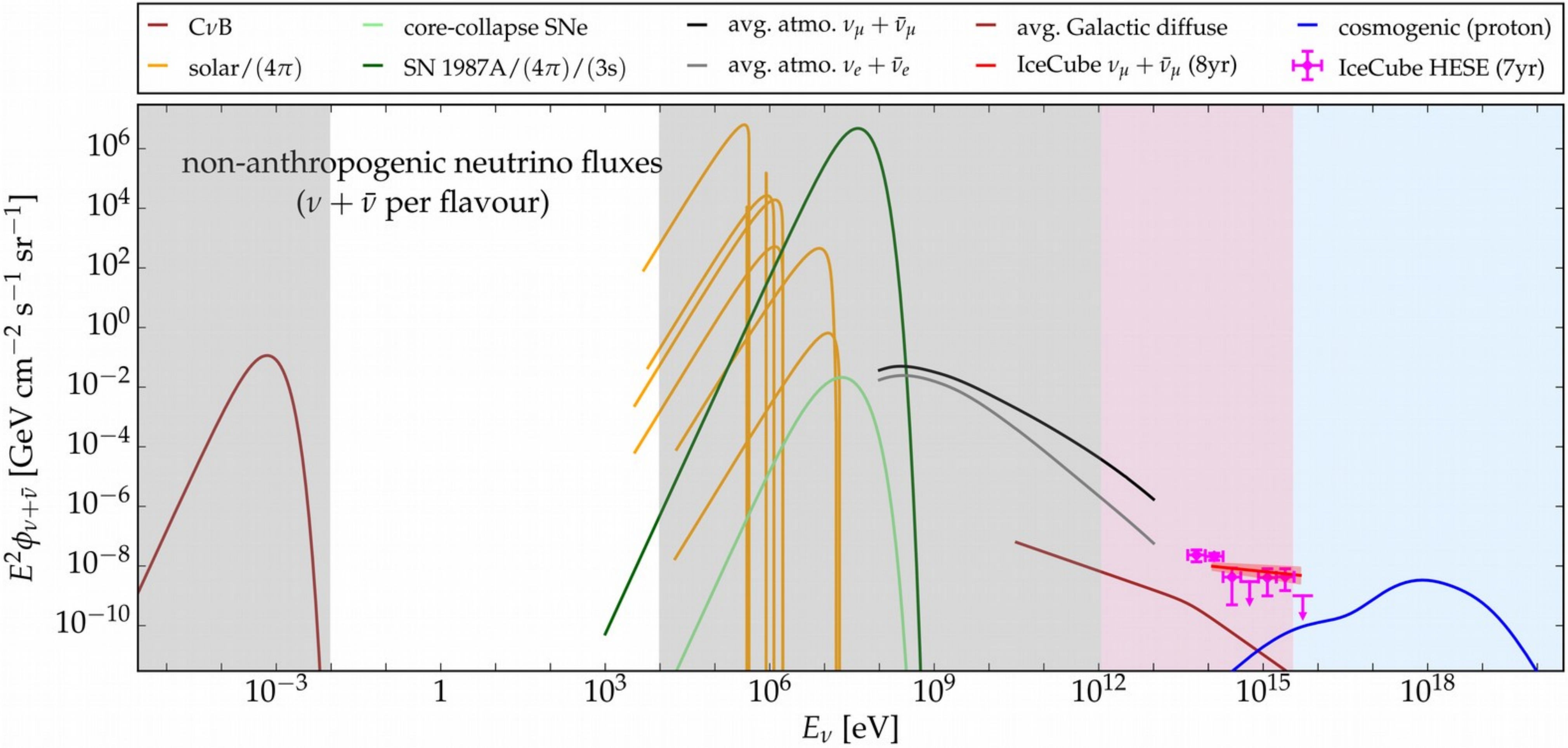


Figure courtesy of Markus Ahlers
Also in: Van Elewyck *et al.*, PoS(ICRC2019), 1023



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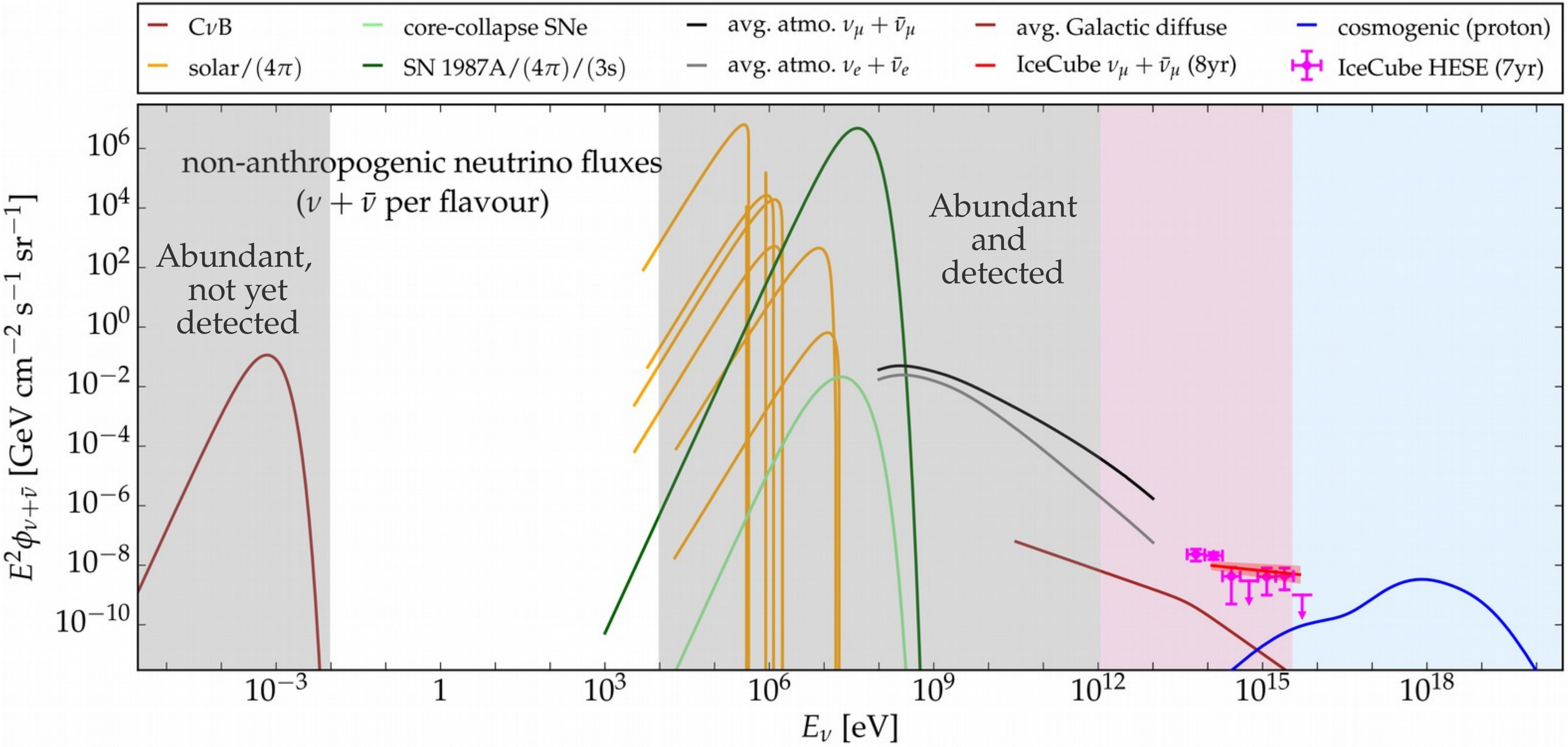

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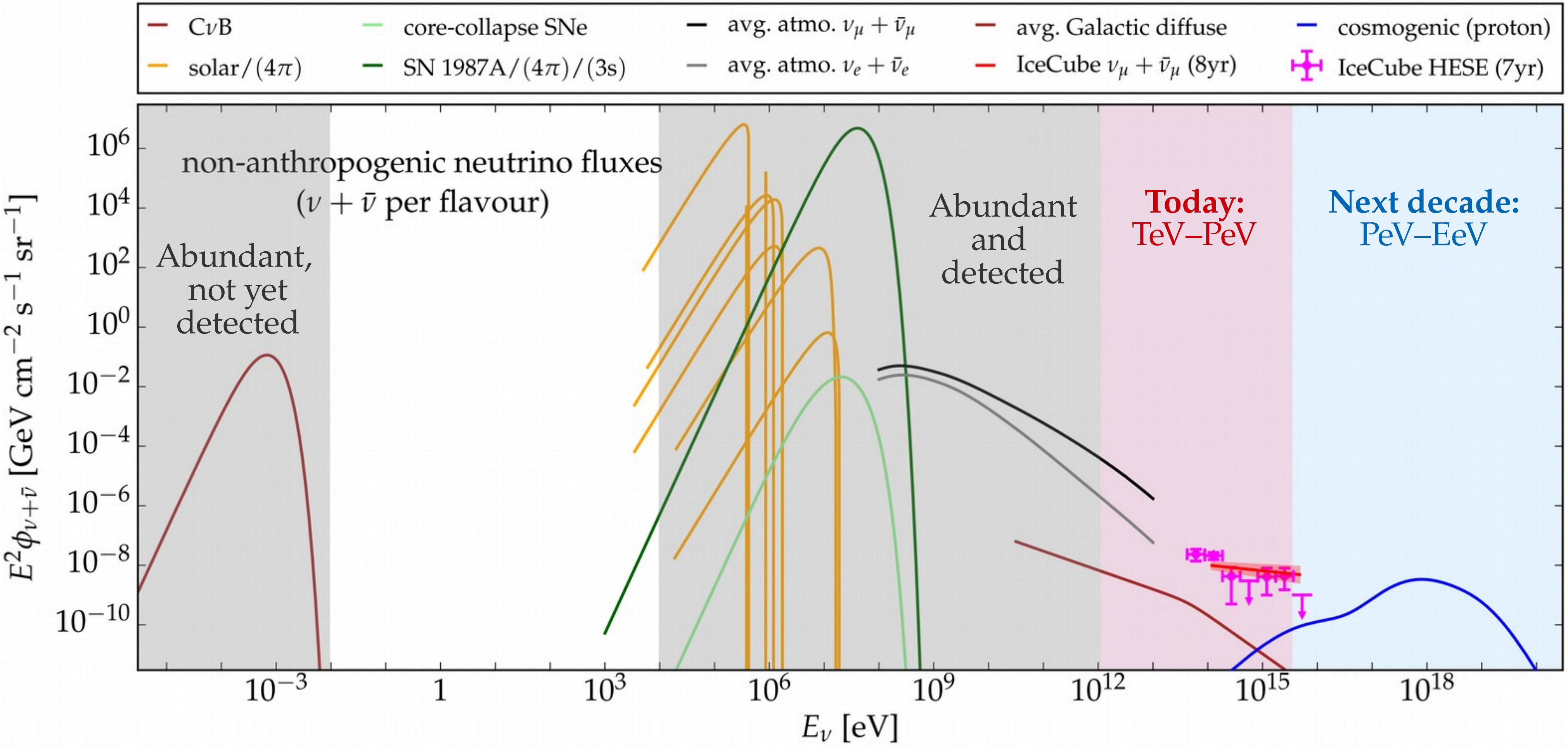

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The multi-messenger connection: a simple picture

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

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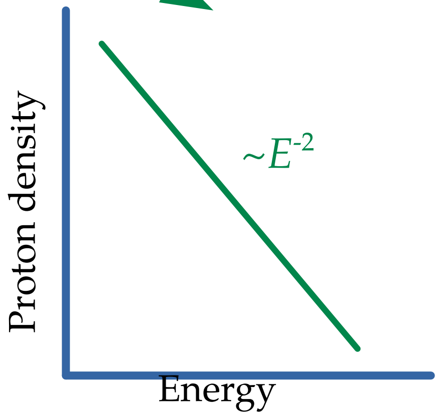

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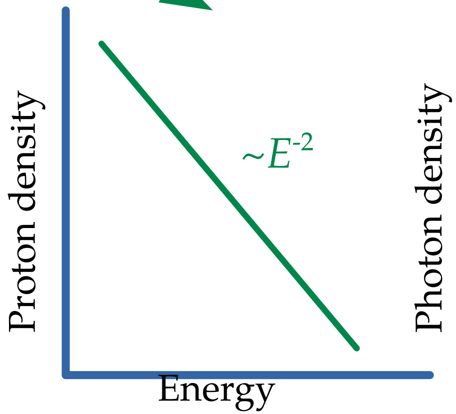

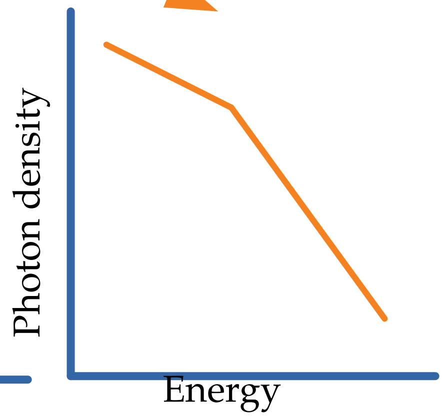

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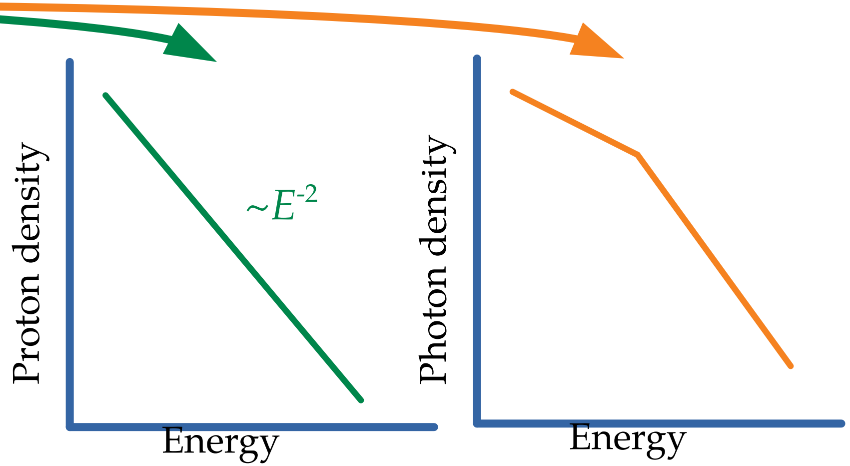
$$\pi^0 \rightarrow \gamma + \gamma$$

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

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



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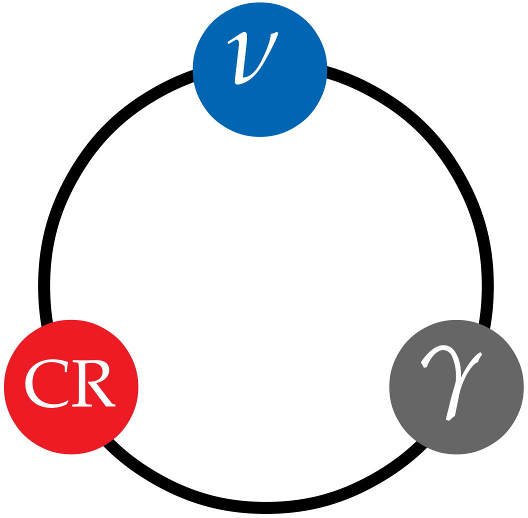

Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 10

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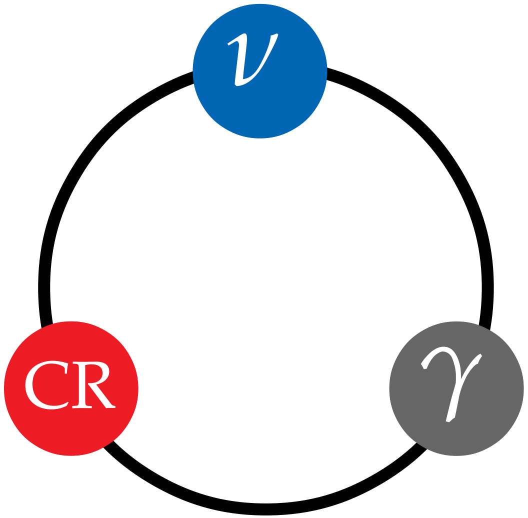

1 PeV 20 PeV

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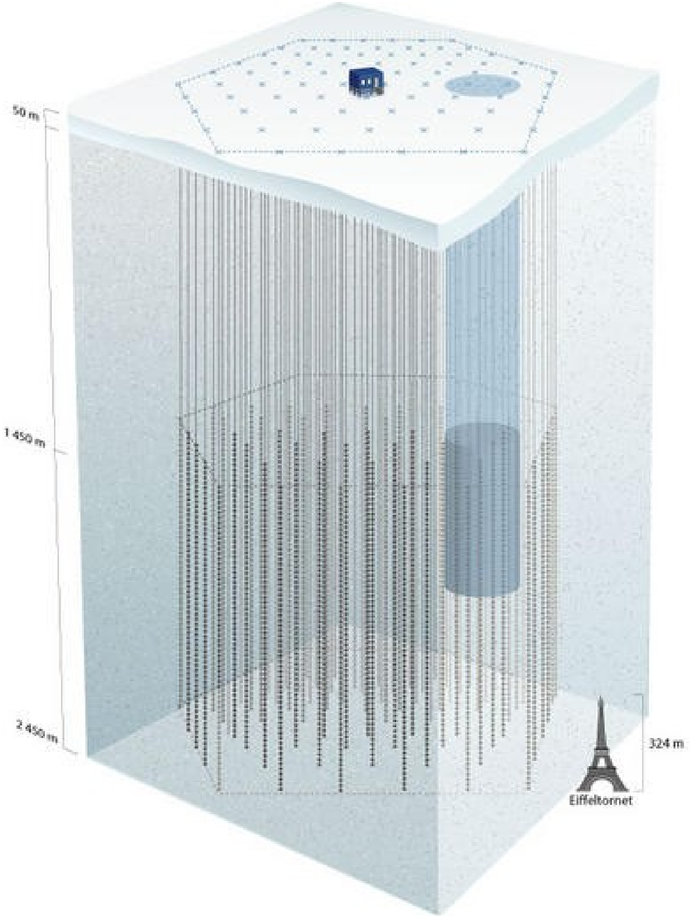
IceCube – What is it?



- 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)

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

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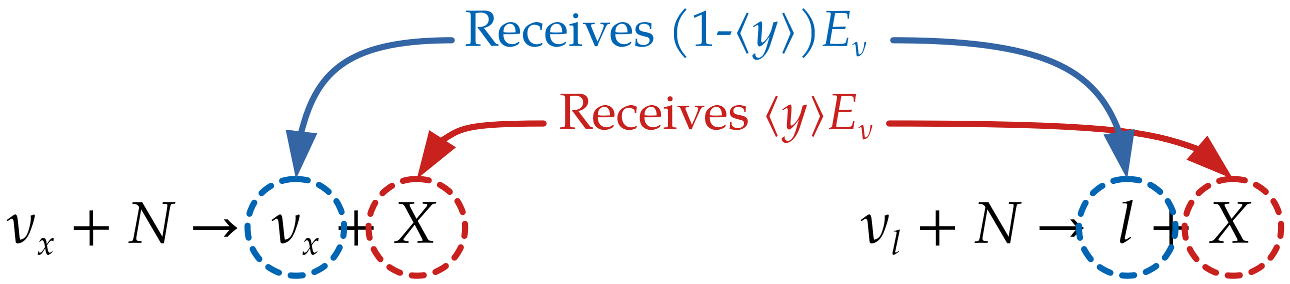

At TeV–PeV, the average inelasticity $\langle y \rangle = 0.25–0.30$

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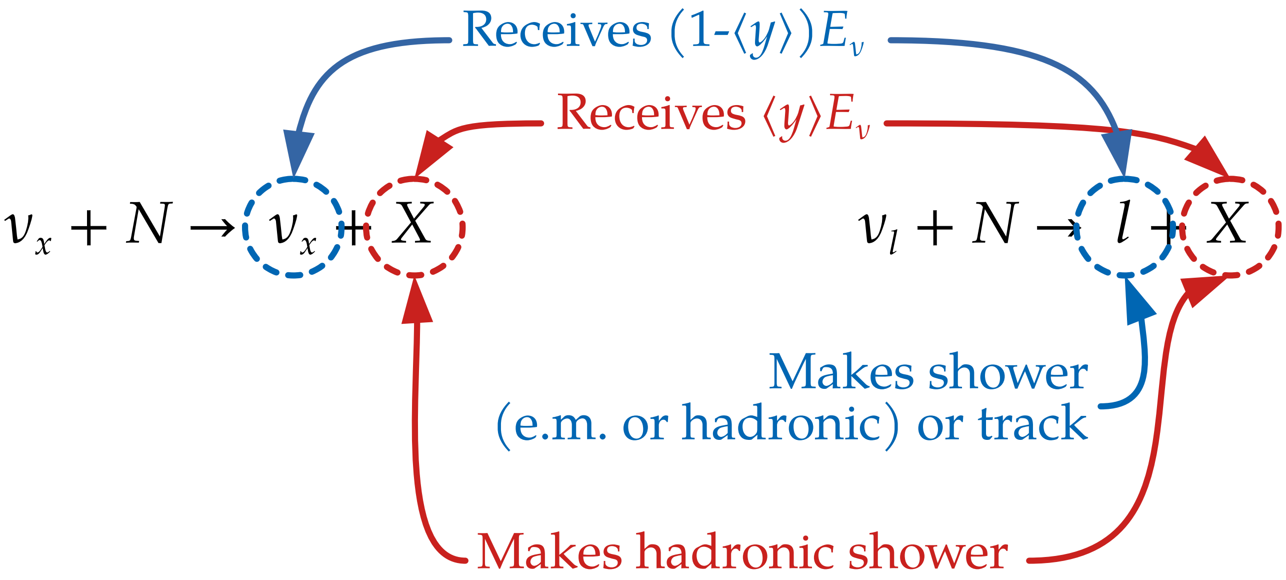

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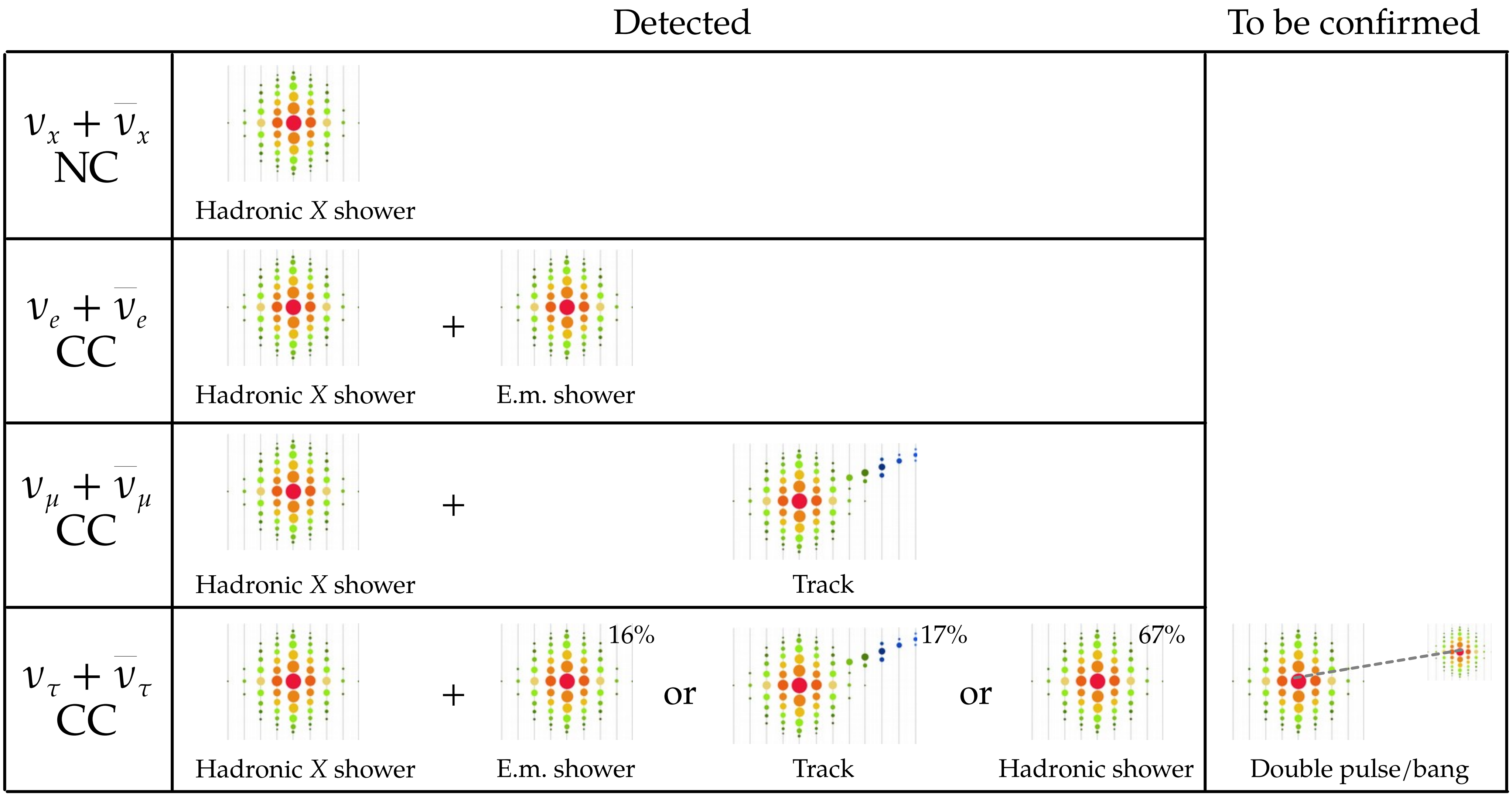

Detected
To be confirmed
$\nu_x + \bar{\nu}_x$ NC
Hadronic X shower
$\nu_e + \bar{\nu}_e$ CC
Hadronic X shower
+
E.m. shower
$\nu_\mu + \bar{\nu}_\mu$ CC
Hadronic X shower
+
Track
$\nu_\tau + \bar{\nu}_\tau$ CC
Hadronic X shower
+
16%
E.m. shower
or
17%
Track
or
67%
Hadronic shower
Double pulse/bang

Fundamental physics with HE cosmic neutrinos

- Numerous new-physics effects grow as $\sim \kappa_n \cdot E^n \cdot L$
- So we can probe $\kappa_n \sim 4 \cdot 10^{-47}\ (E/\text{PeV})^{-n}\ (L/\text{Gpc})^{-1}\ \text{PeV}^{1-n}$
- Improvement over current limits: $\kappa_0 < 10^{-29}$ PeV, $\kappa_1 < 10^{-33}$
- Fundamental physics can be extracted from four neutrino observables:
  - Spectral shape
  - Angular distribution
  - Flavor composition
  - Timing

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n = -1: neutrino decay
n = 0: CPT-odd Lorentz violation
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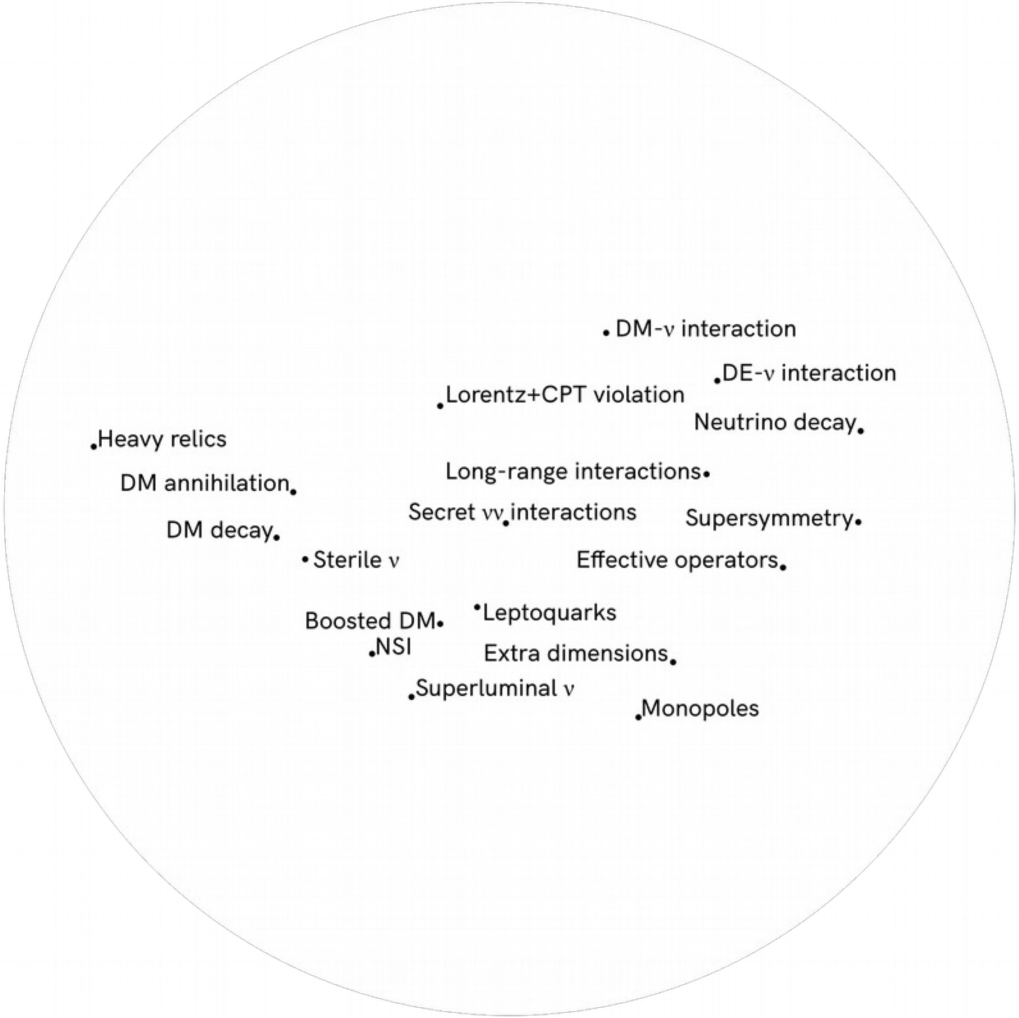
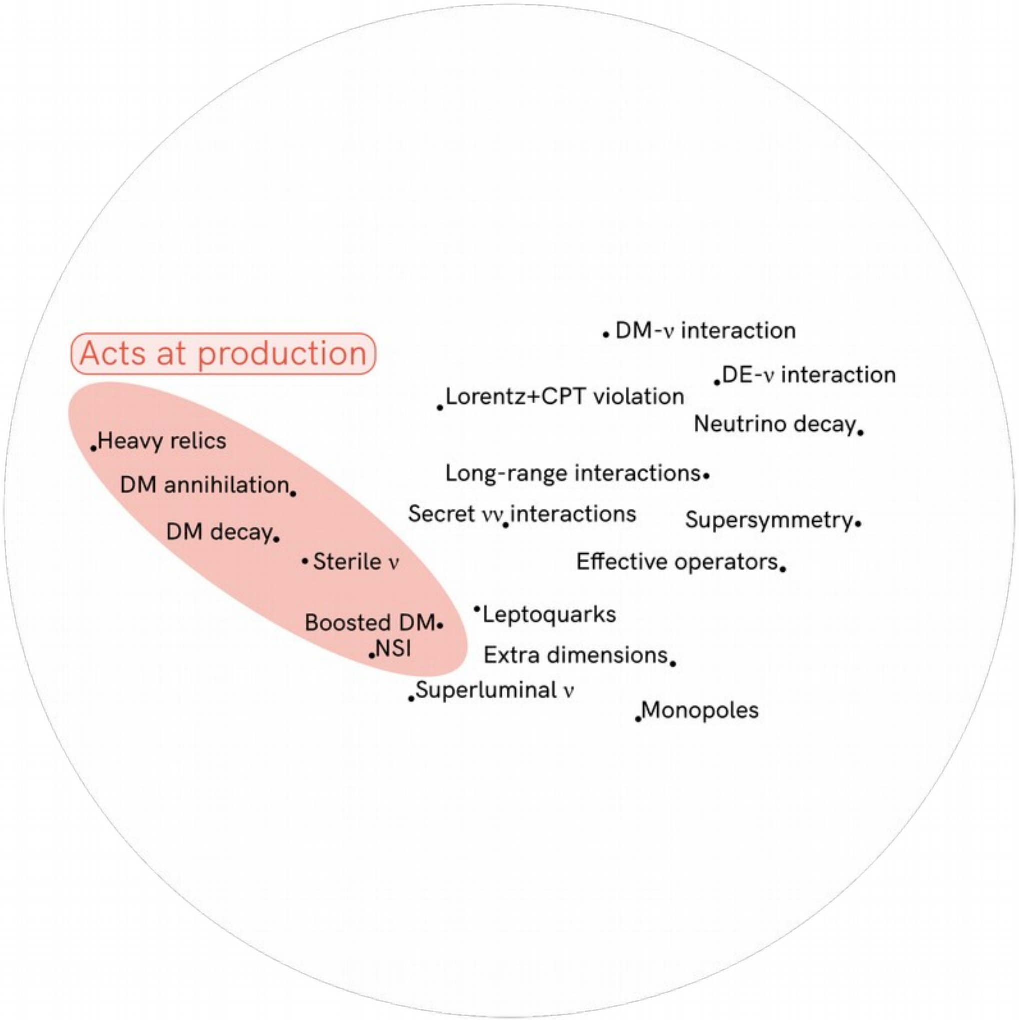
In spite of
poor energy, angular, flavor reconstruction
& astrophysical unknowns



Note: Not an exhaustive list



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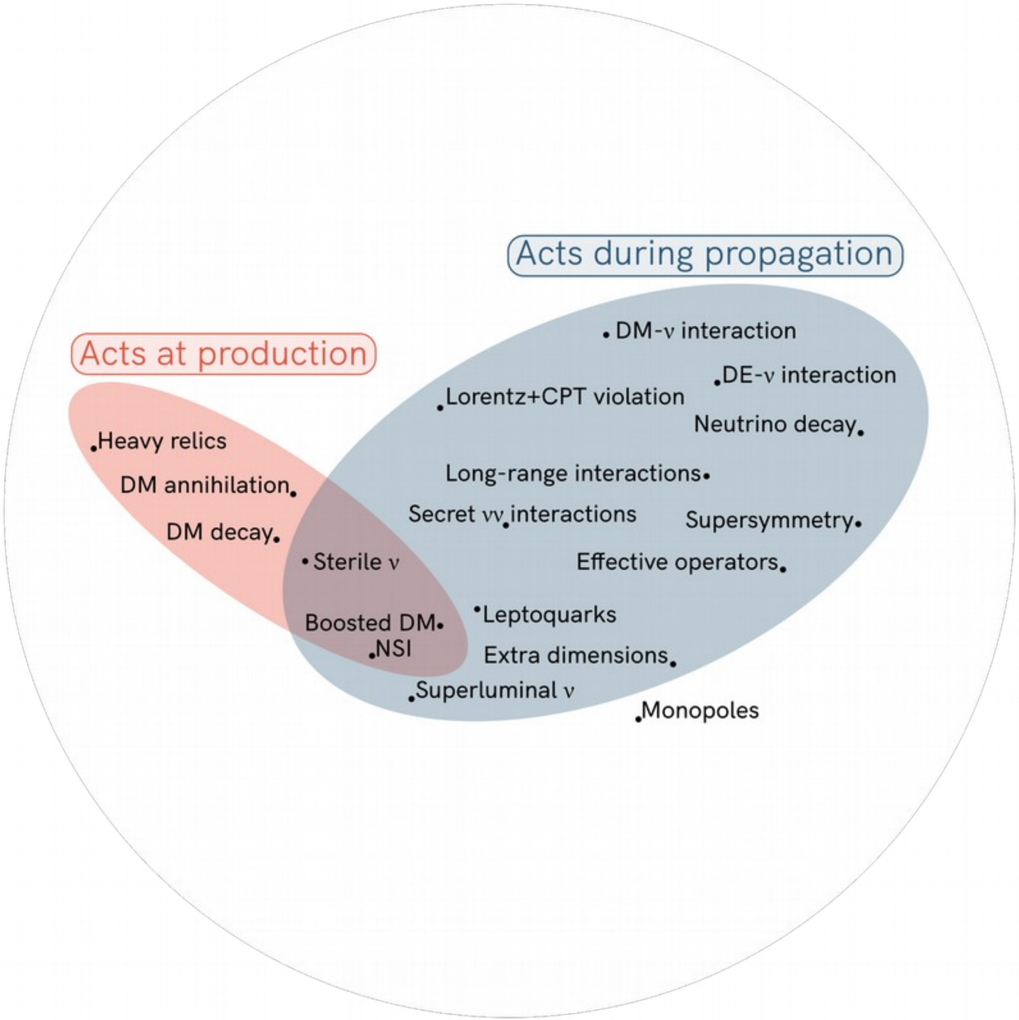

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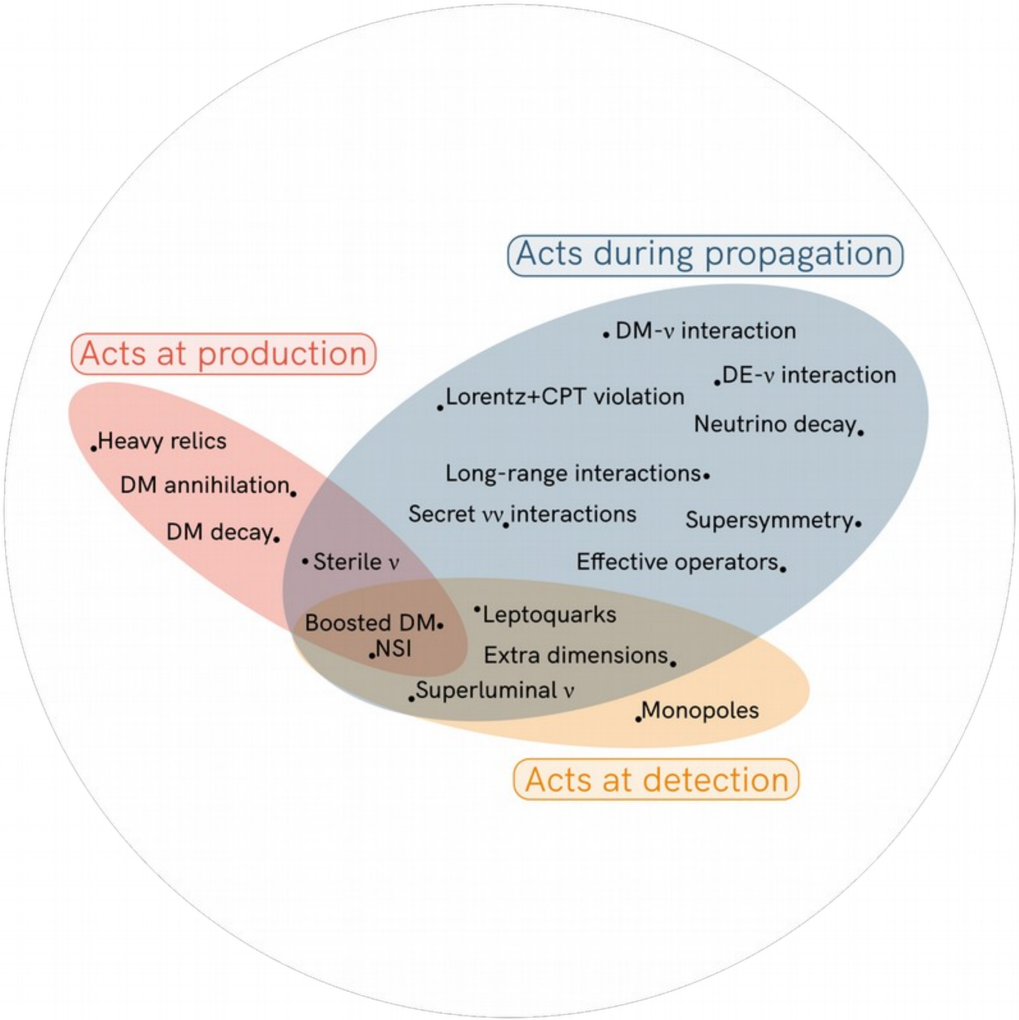

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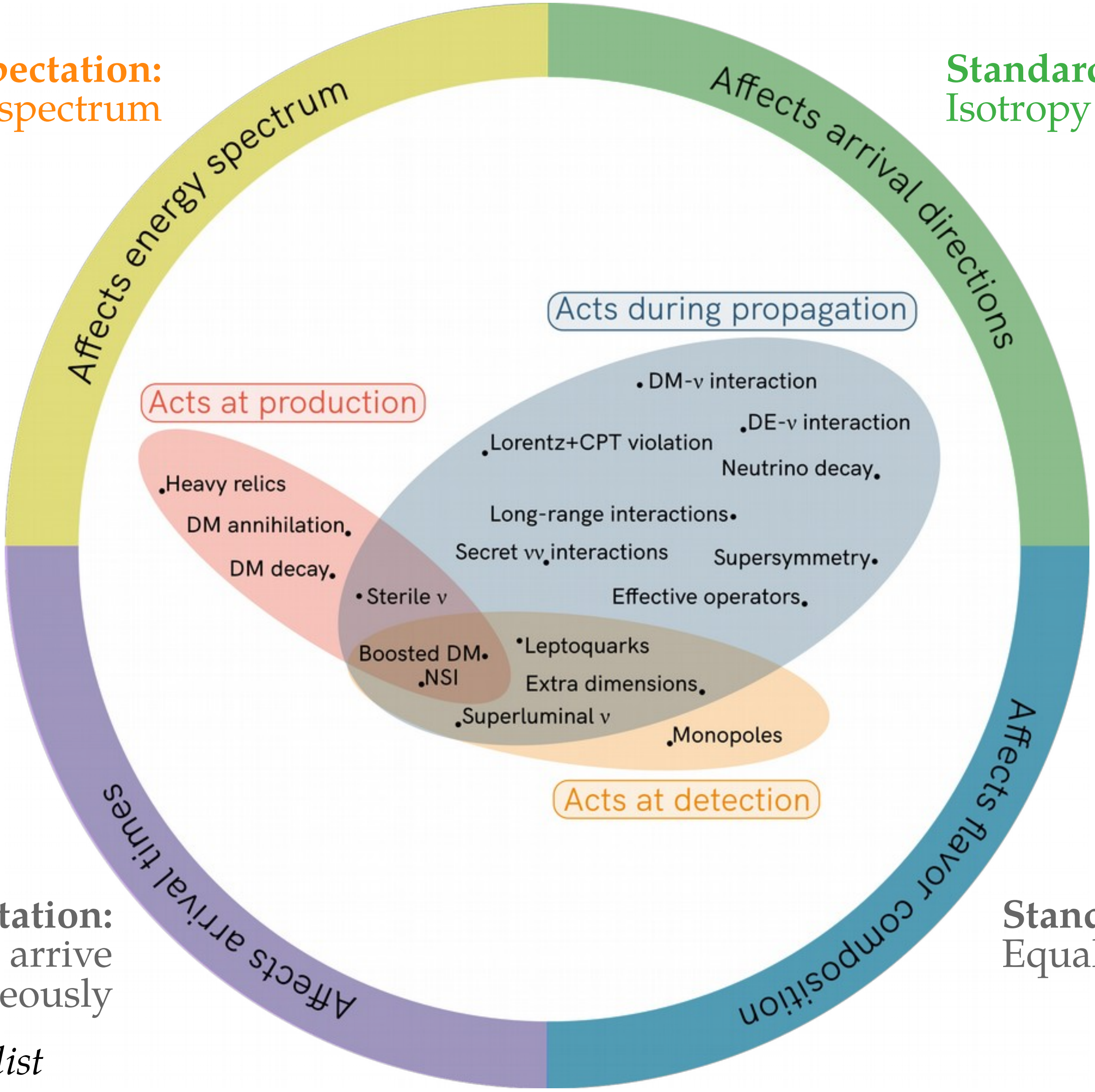
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



Standard expectation:
ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

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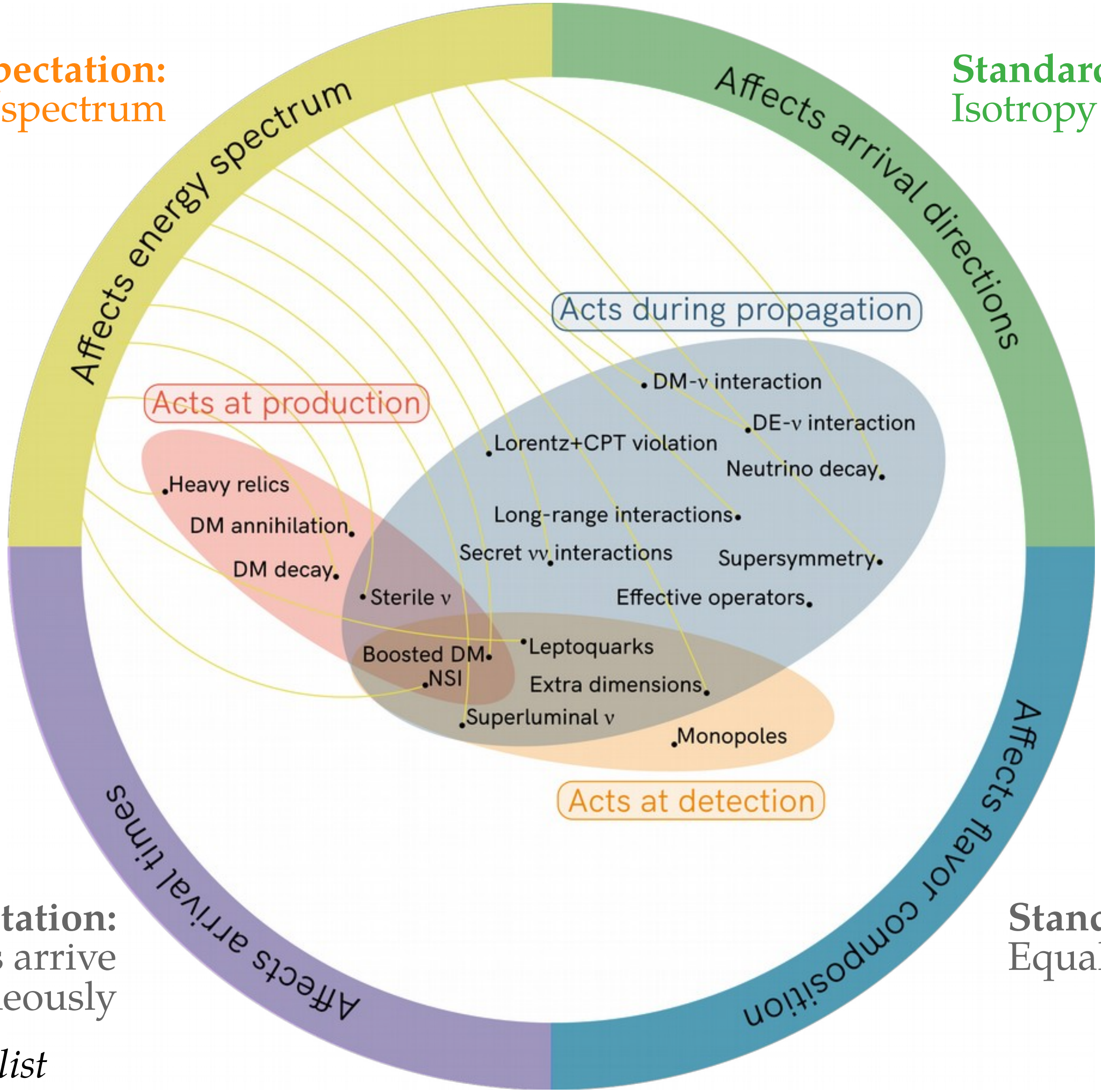
Isotropy (for diffuse flux)



Standard expectation:
ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Note: Not an exhaustive list

Standard expectation:
Power-law energy spectrum

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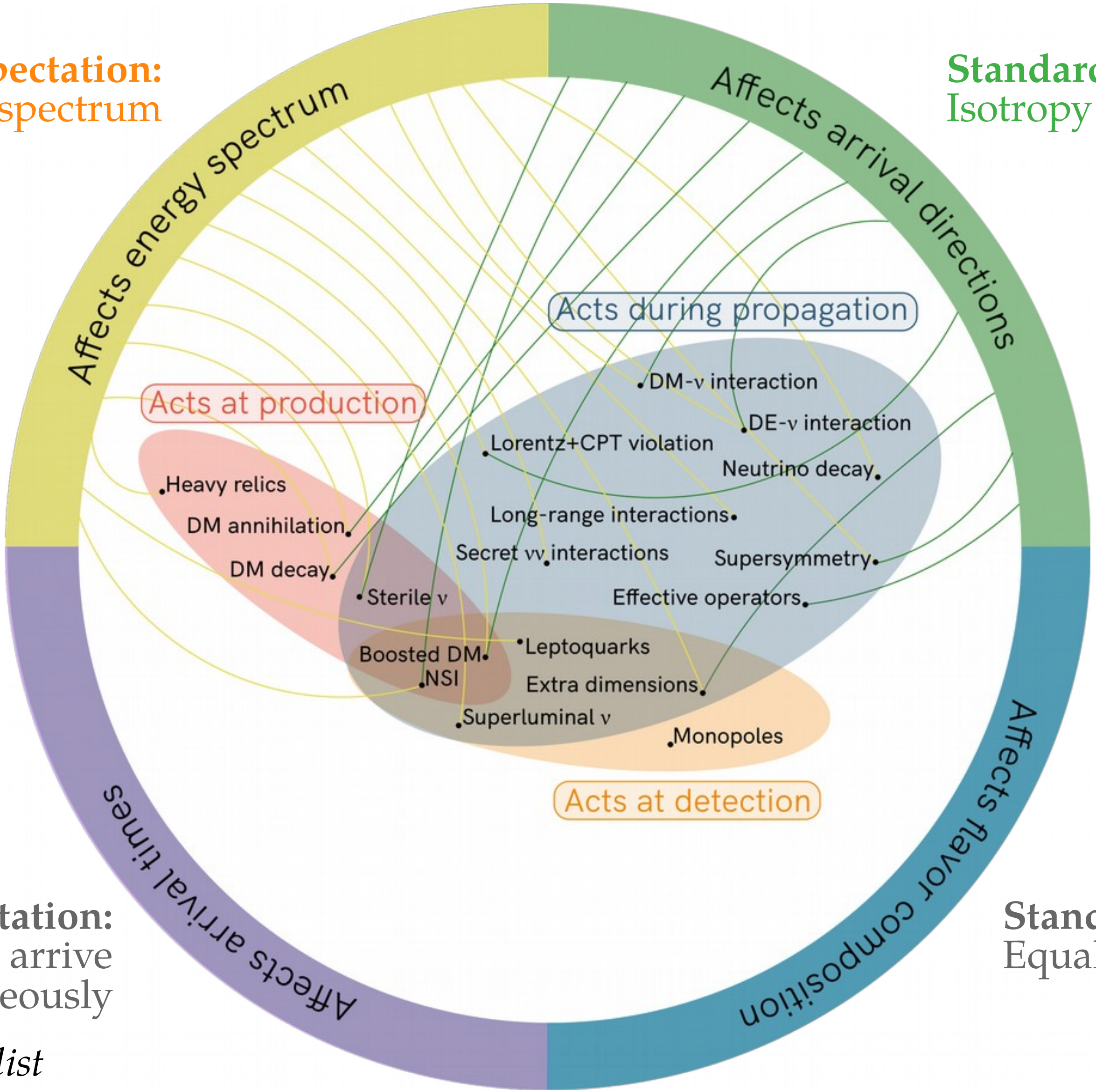

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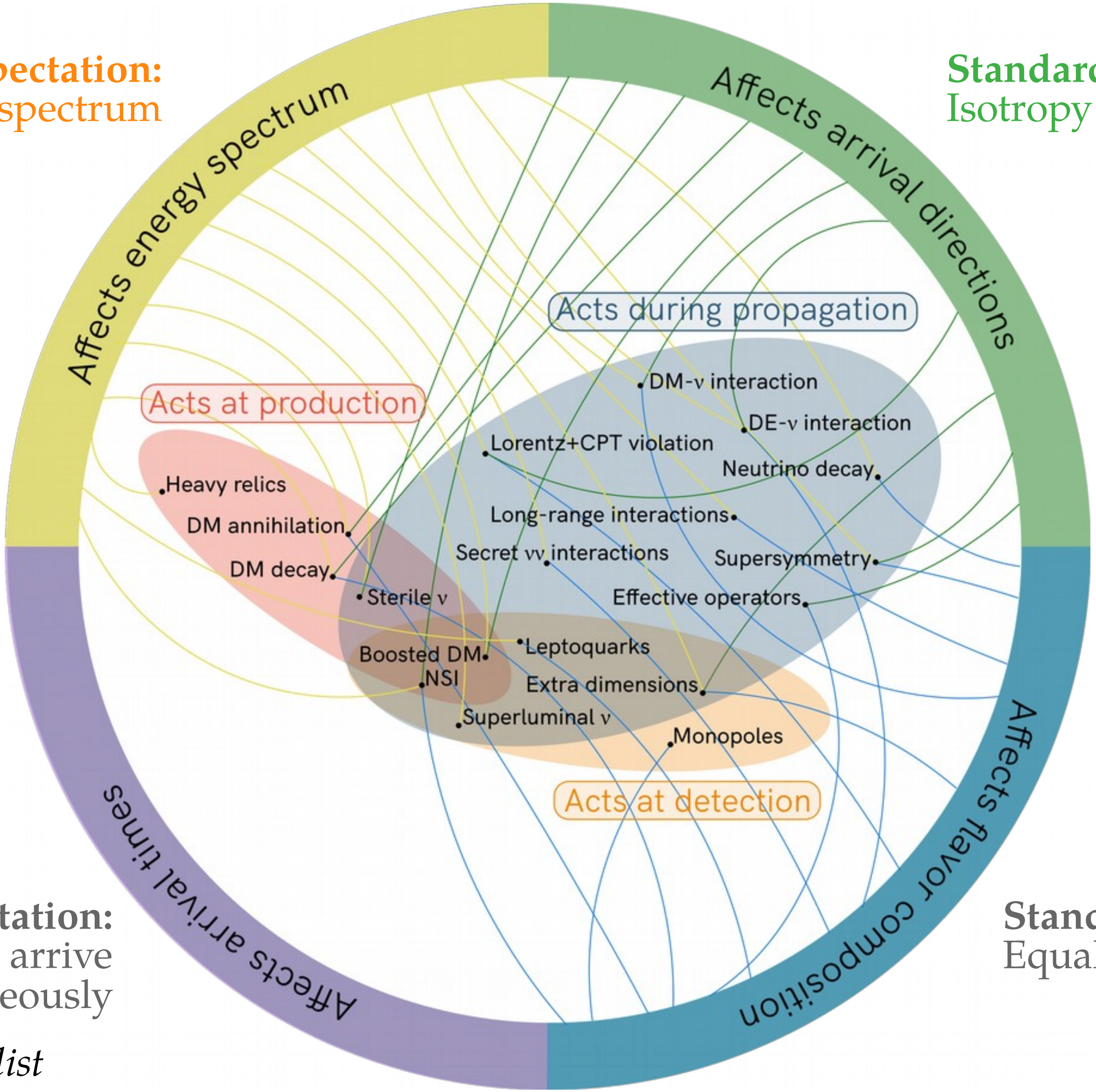

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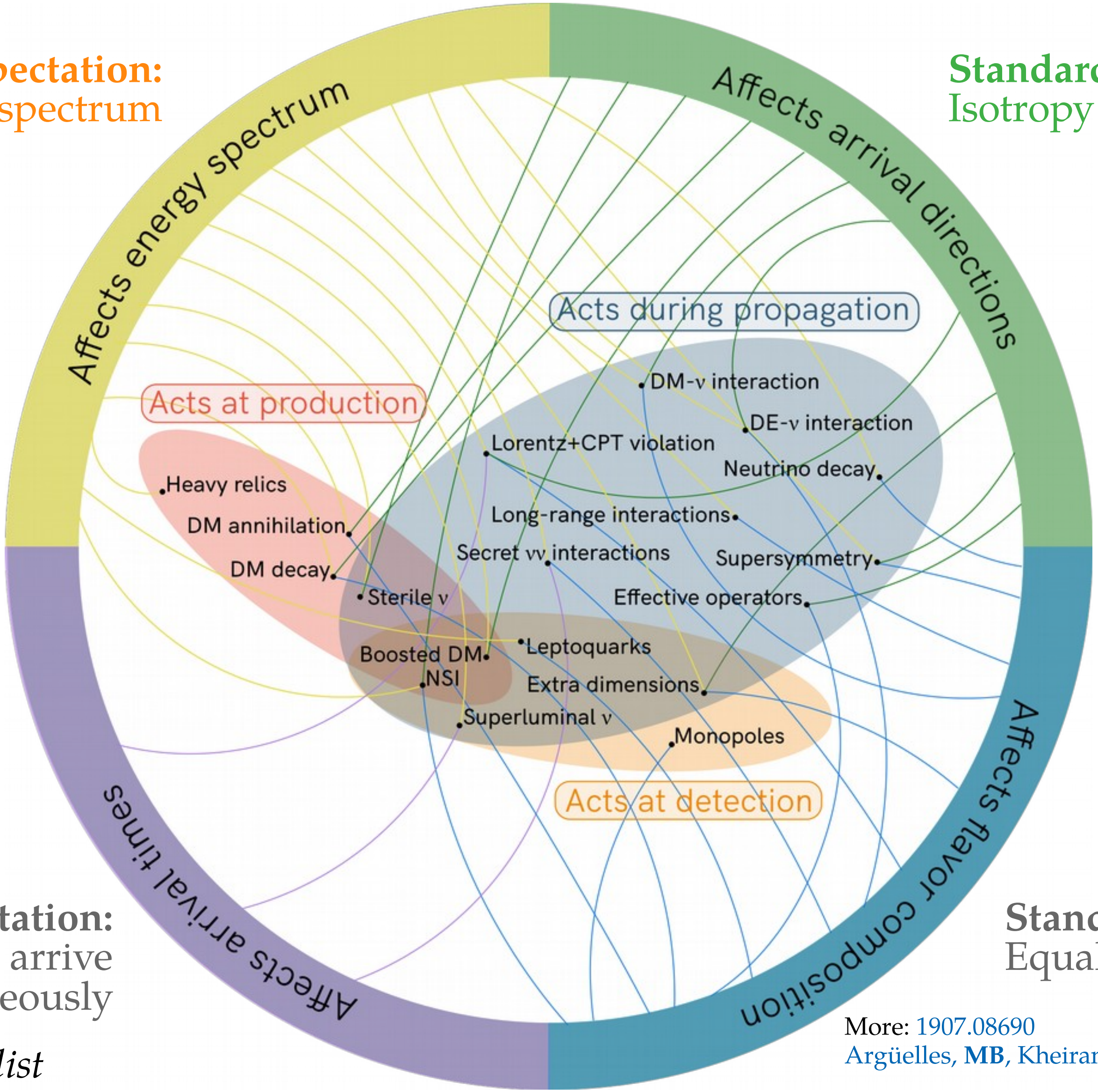

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More: 1907.08690
Argüelles, **MB**, Kheirandish, Palomares-Ruiz, Salvadó, Vincent

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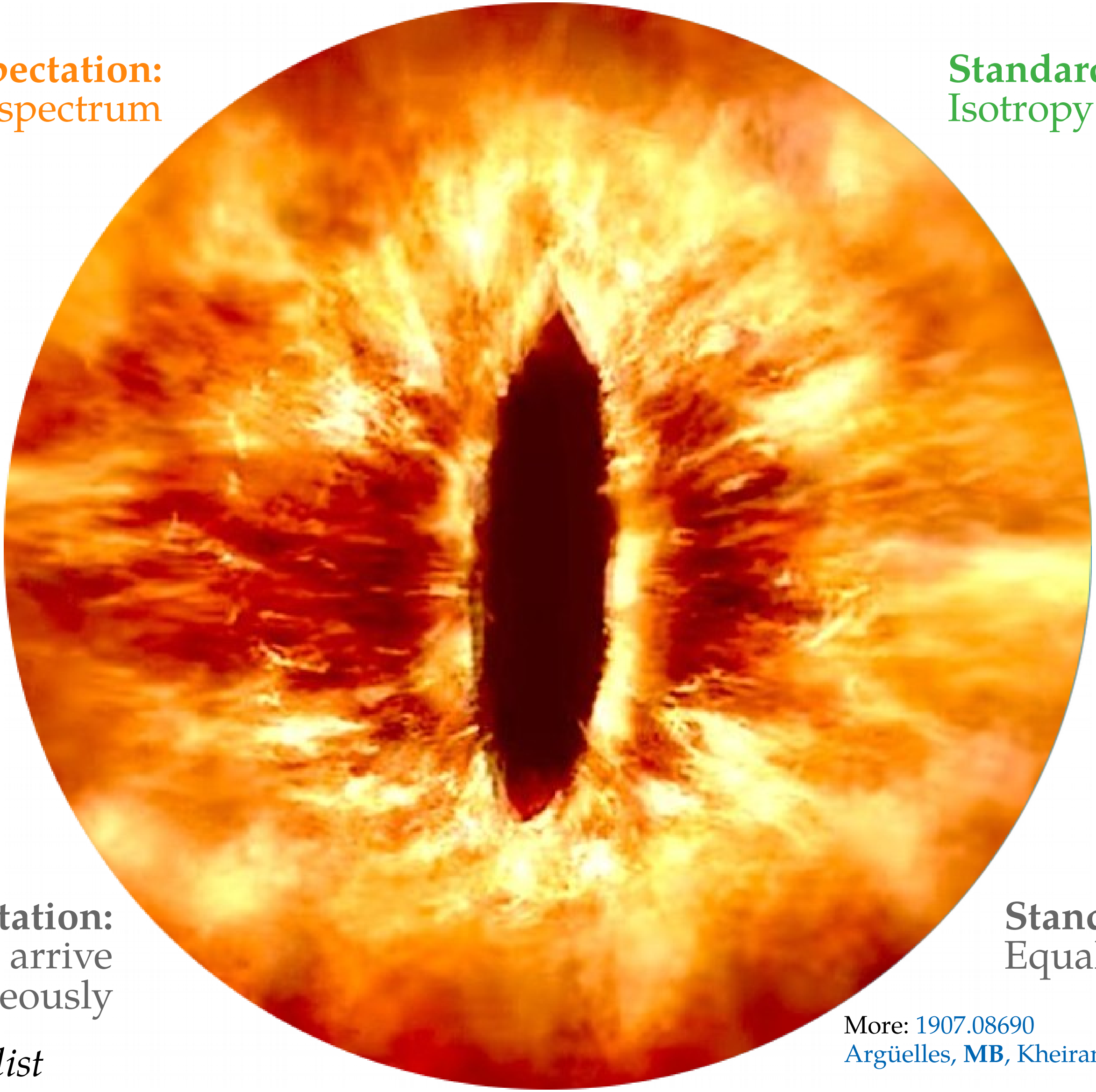

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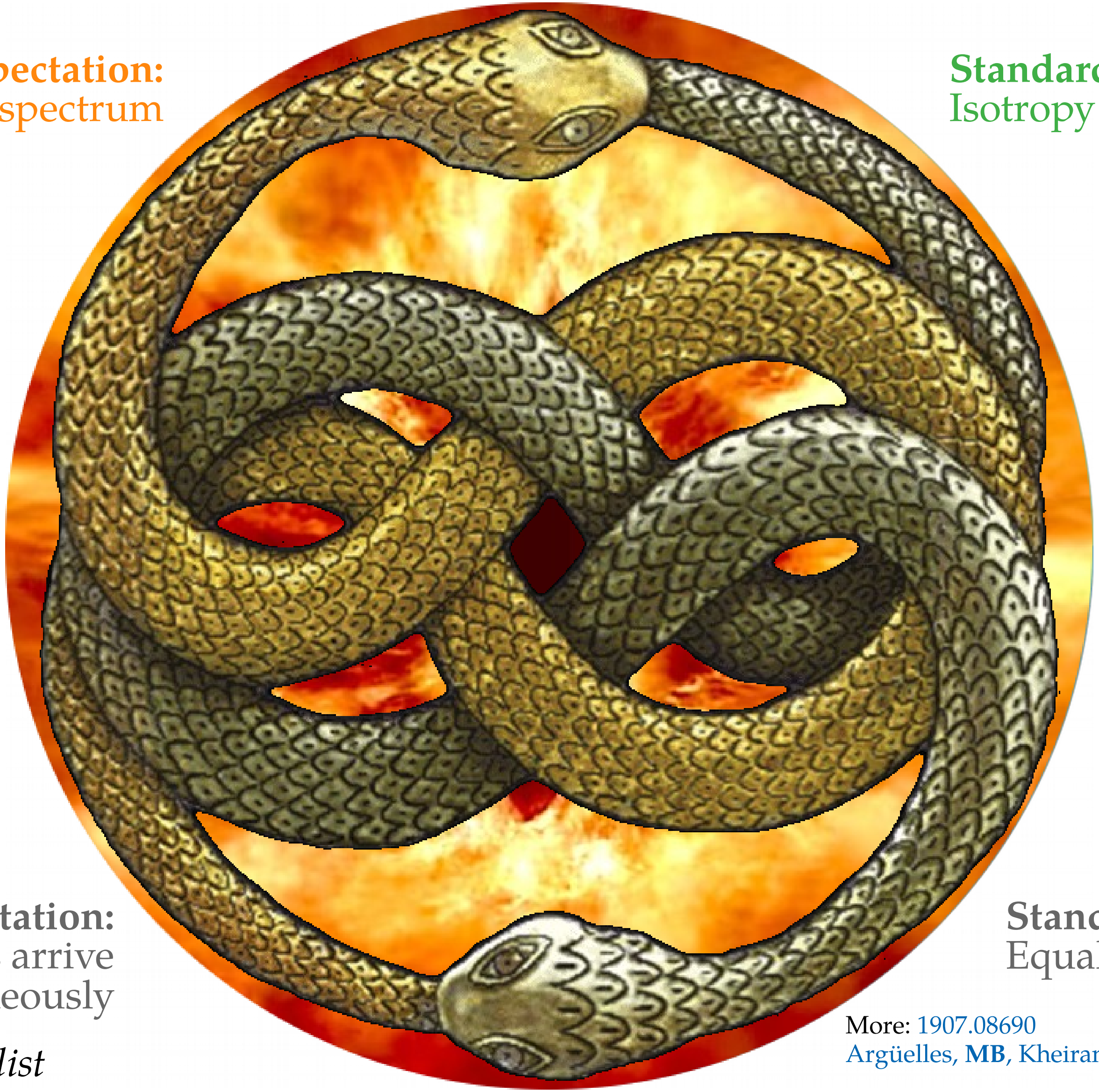

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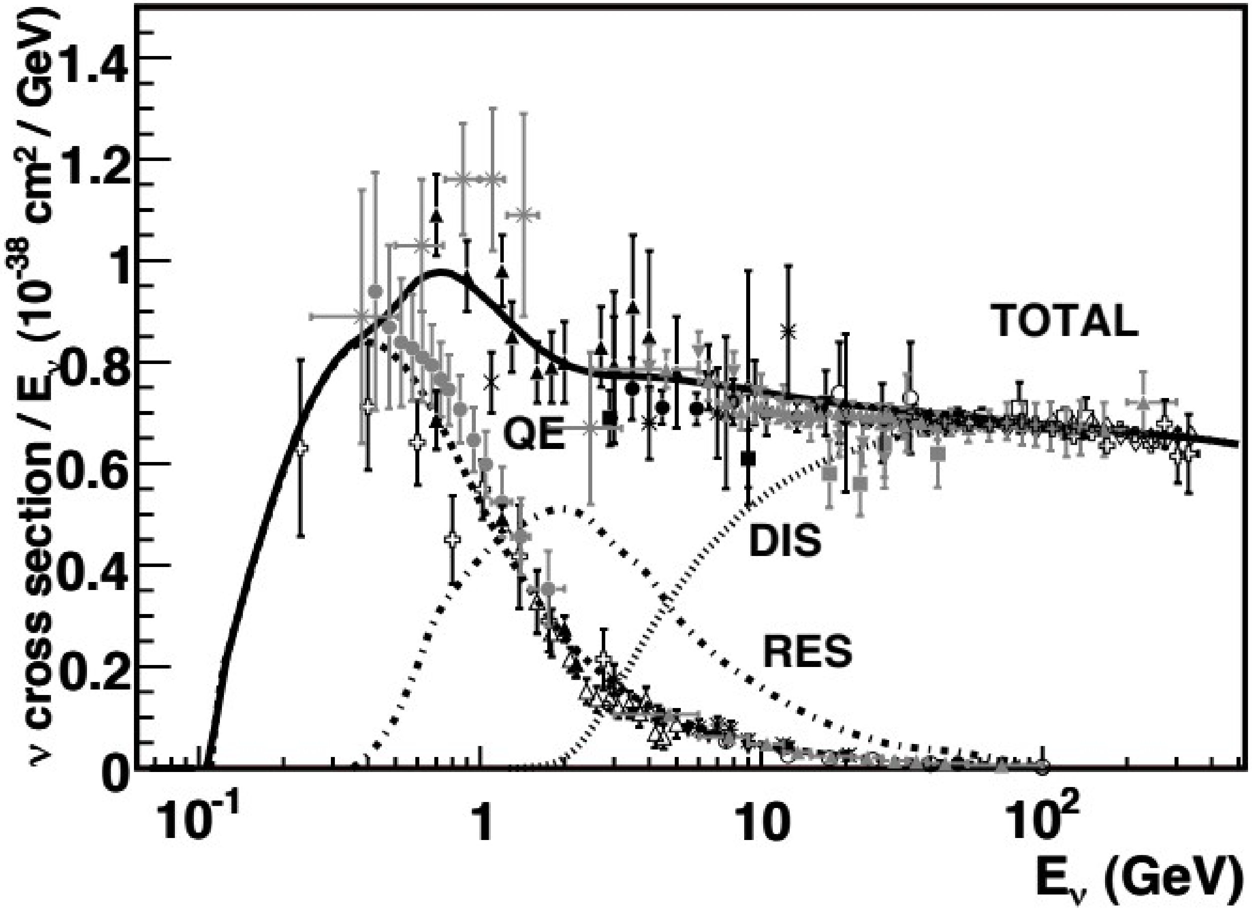
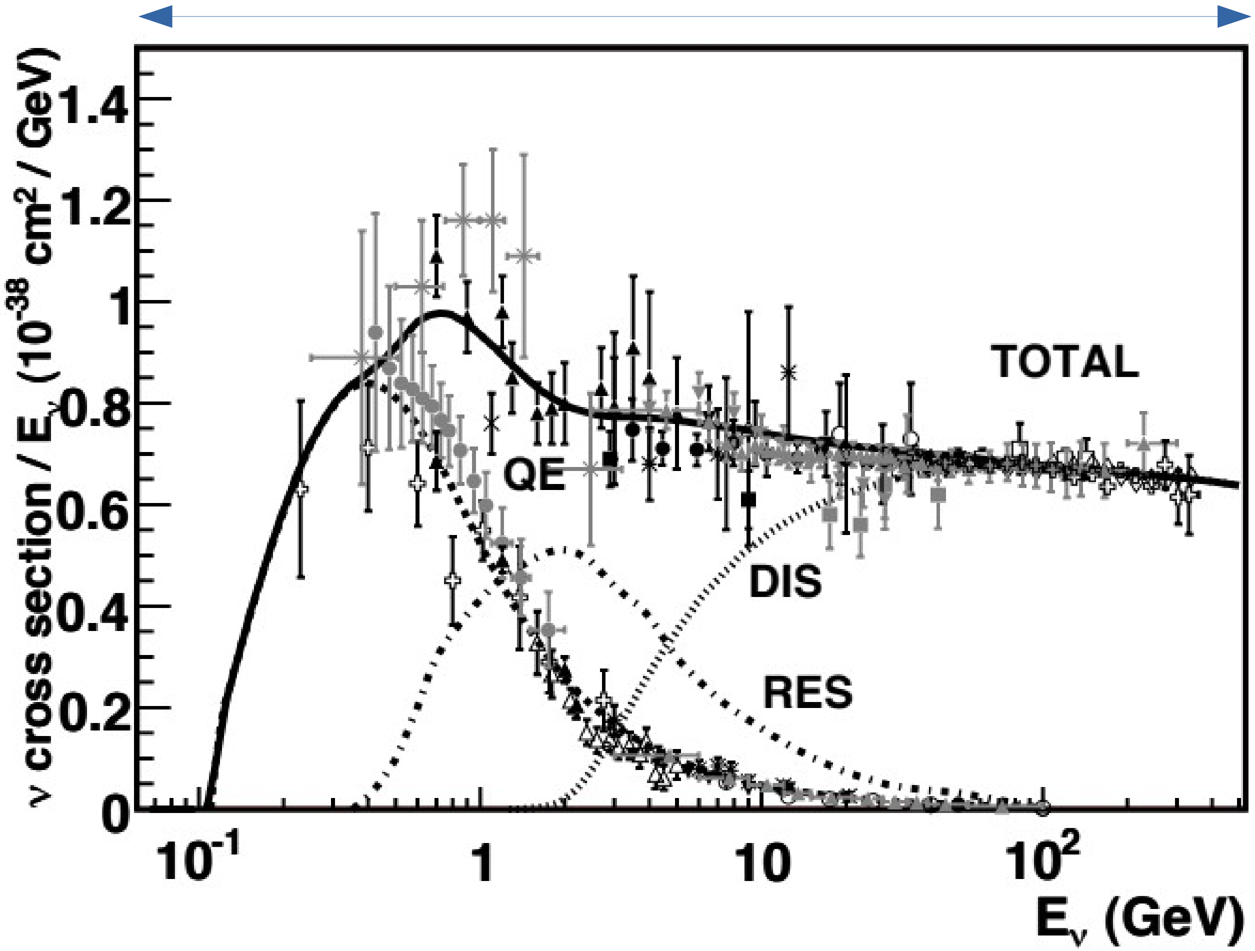


Particle Data Group

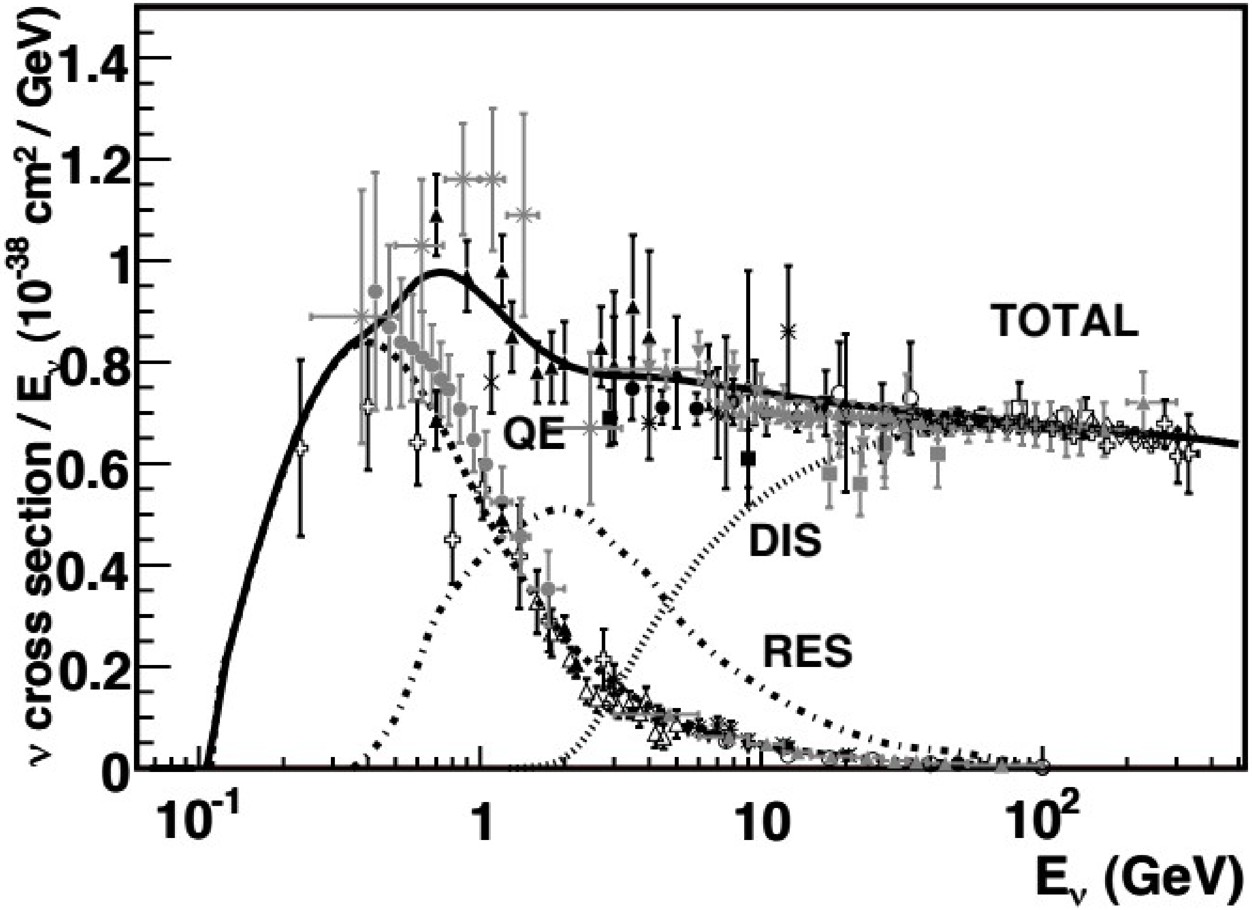
Accelerator experiments



Particle Data Group

Accelerator experiments

One recent measurement (COHERENT)



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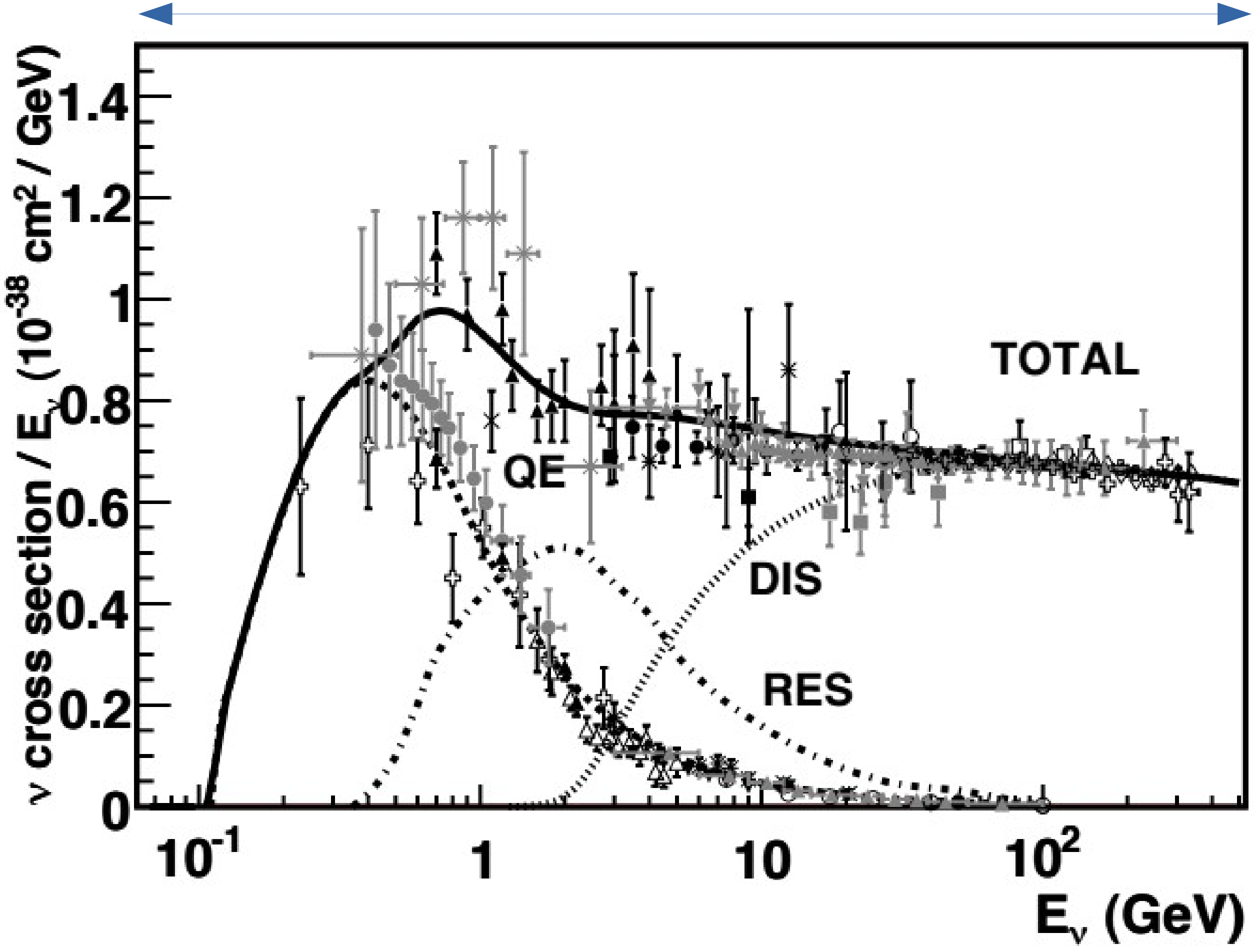


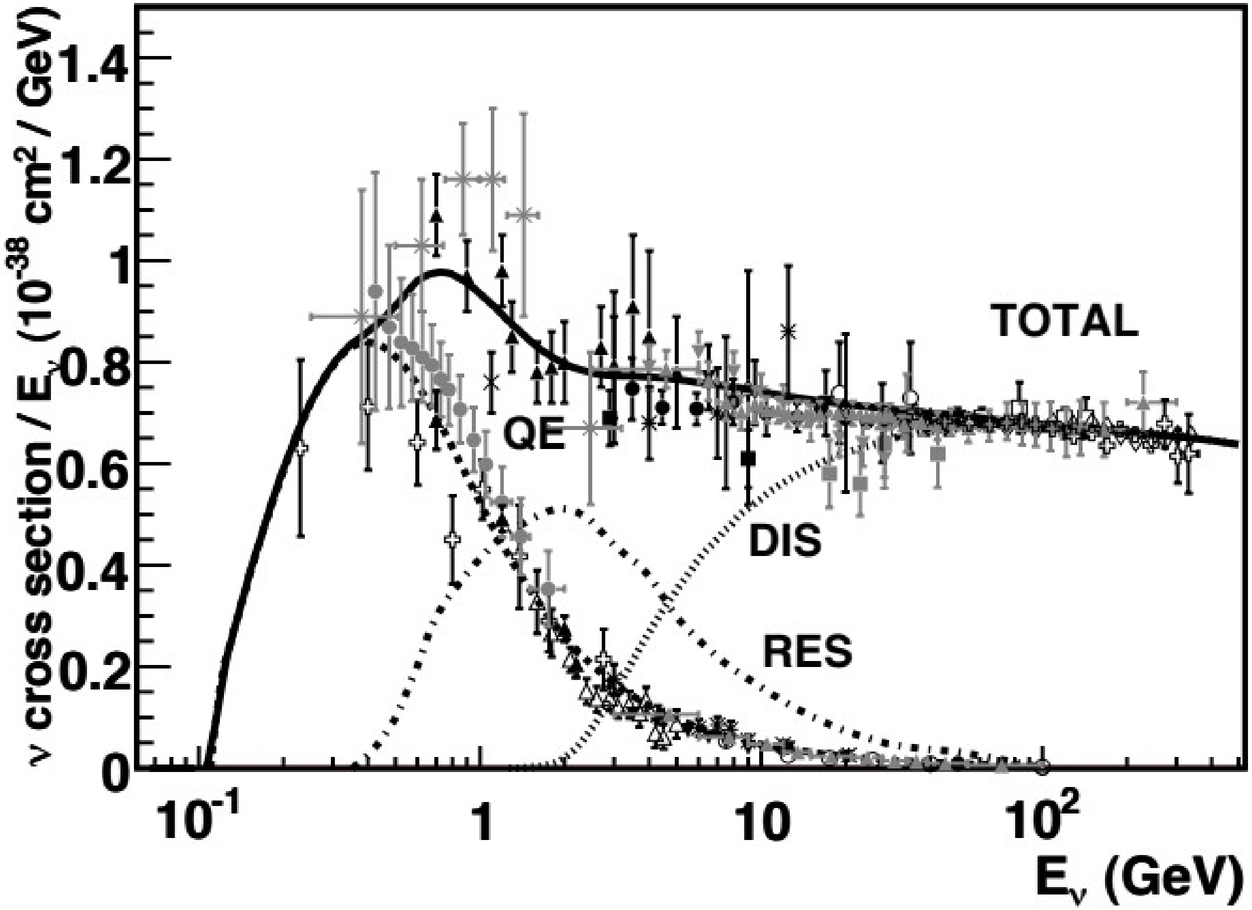
Particle Data Group

No measurements

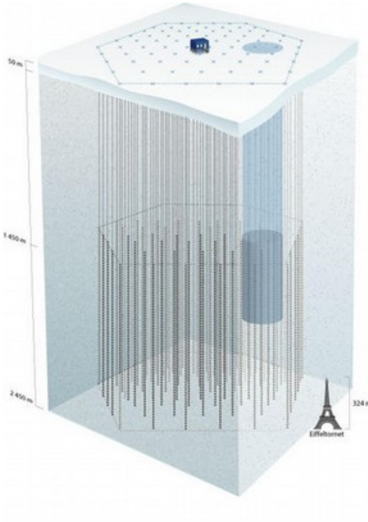
… until recently!

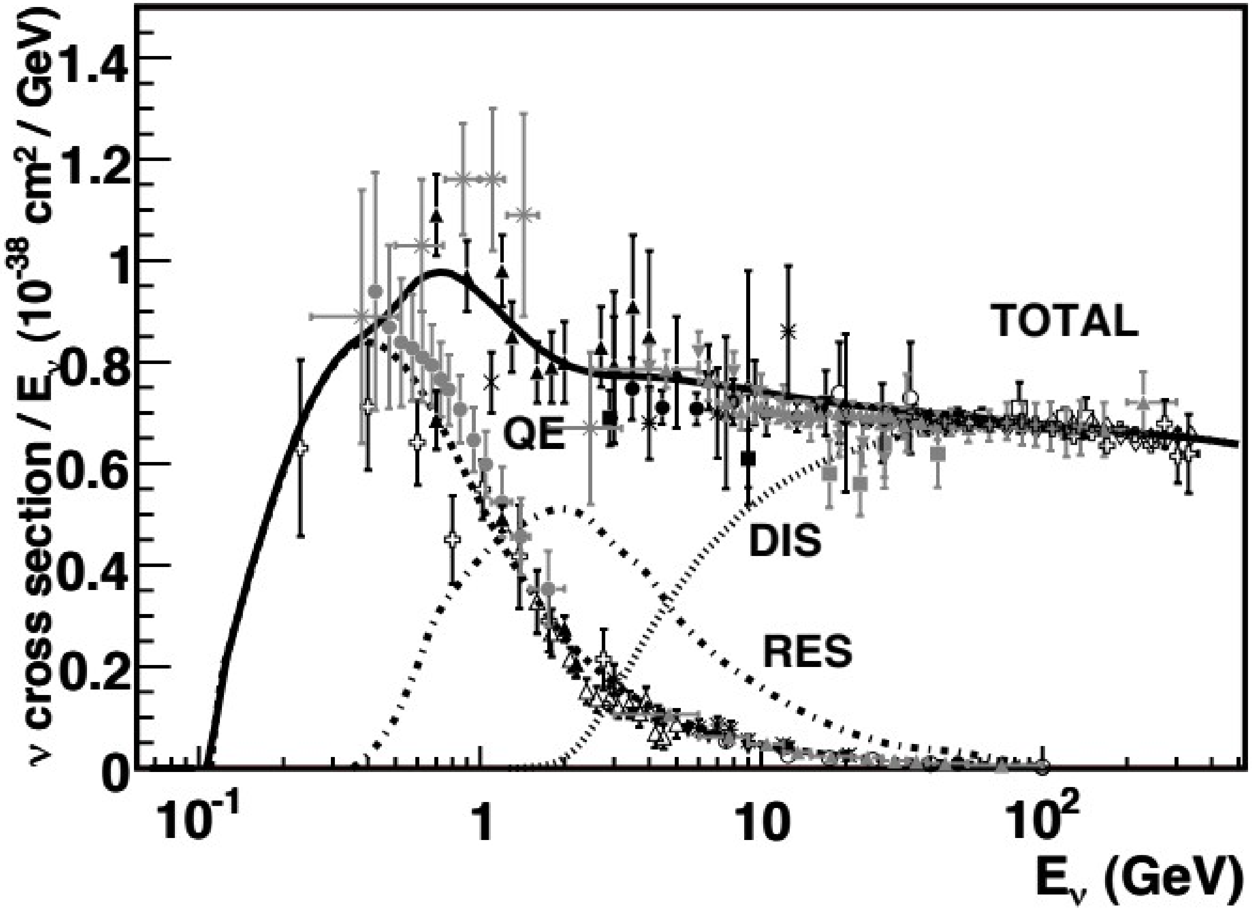
Accelerator experiments

One recent measurement (COHERENT)



Particle Data Group



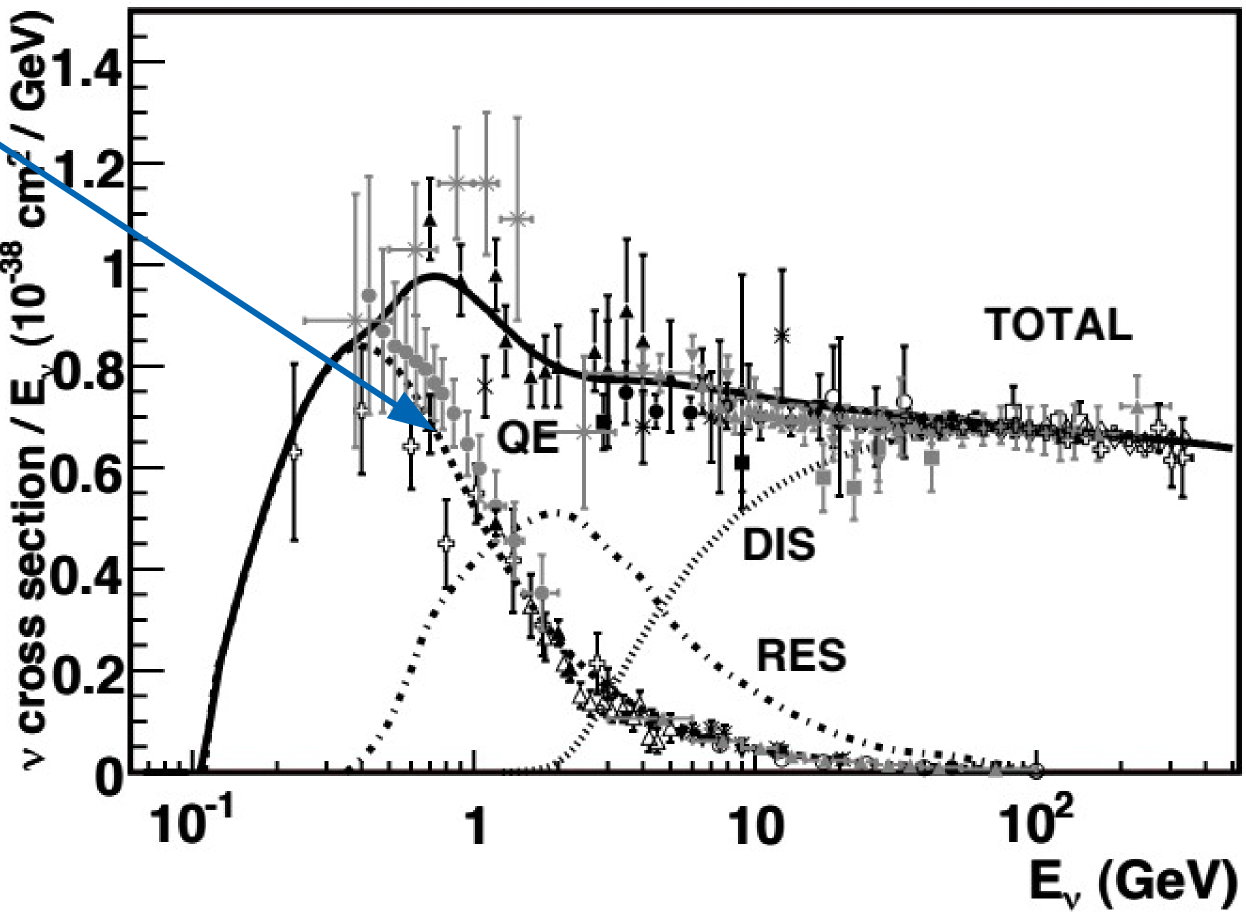


Particle Data Group

Quasi-elastic scattering:

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

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



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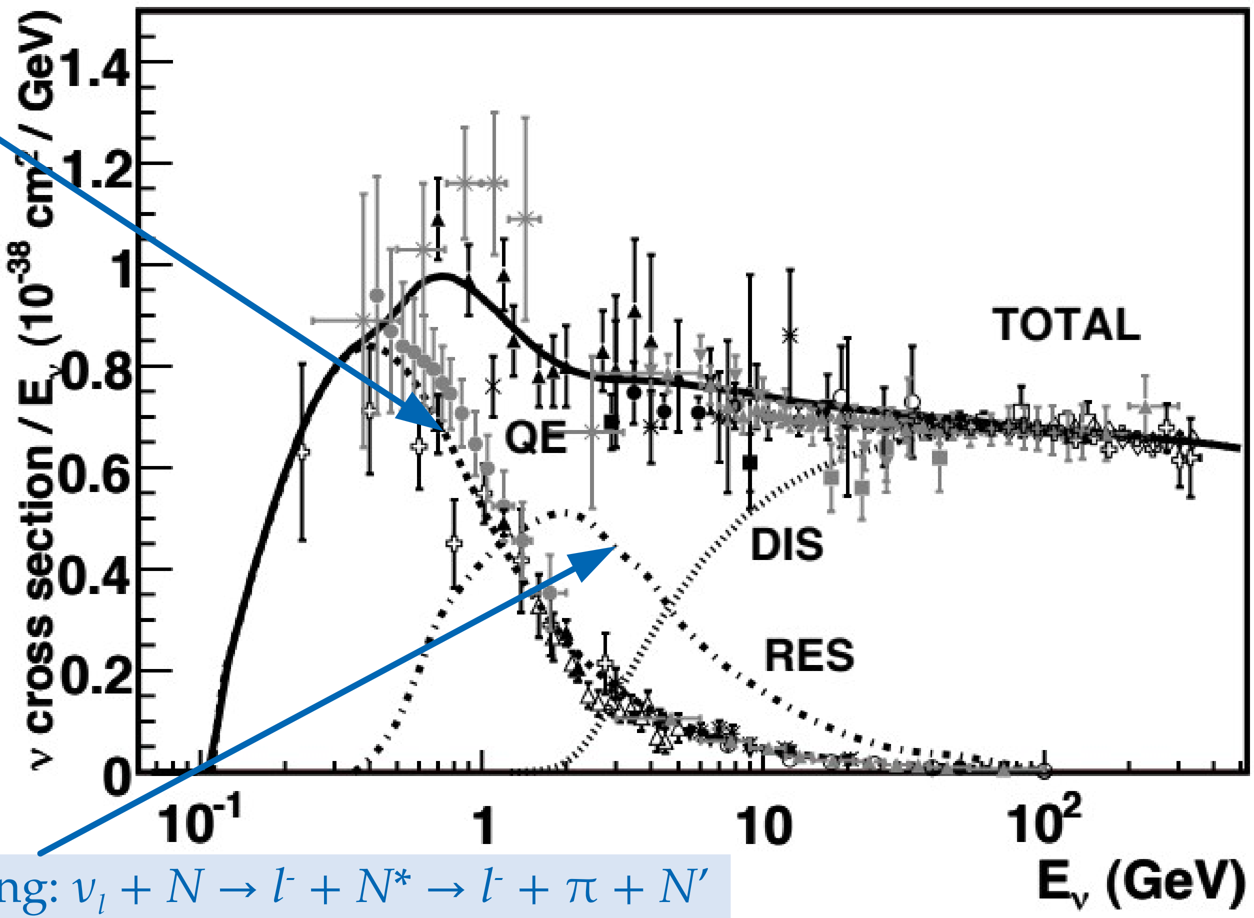

Resonant scattering: $\nu_l + N \rightarrow l^- + N^* \rightarrow l^- + \pi + N'$

Particle Data Group

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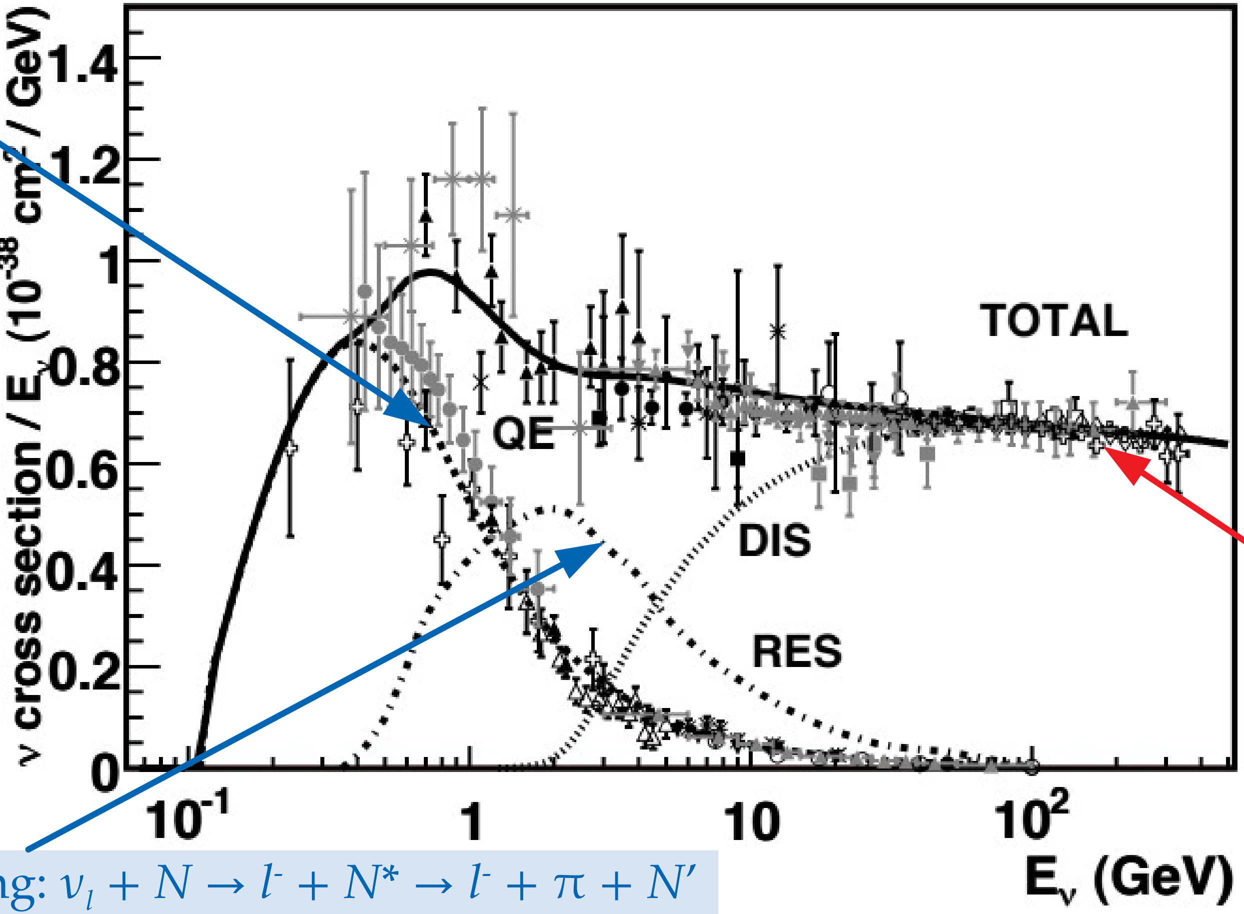


Particle Data Group

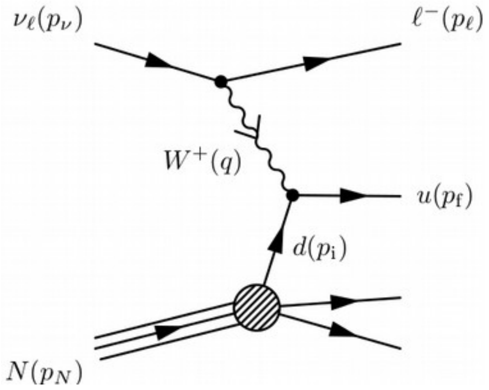
Resonant scattering: $\nu_l + N \rightarrow l^- + N^* \rightarrow l^- + \pi + N'$

Deep inelastic scattering:
$\nu_l + N \rightarrow l^- + X$
$\bar{\nu}_l + N \rightarrow l^+ + X$

Extrapolating the cross section to high energies

Extrapolating the cross section to high energies

SM



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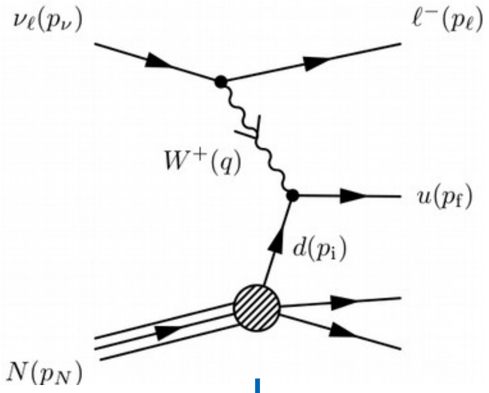
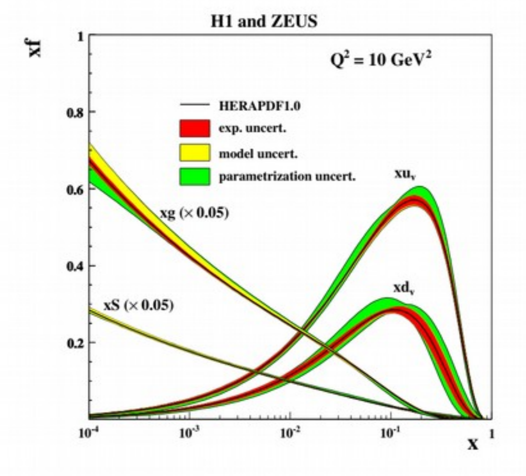
SM



+

PDFs



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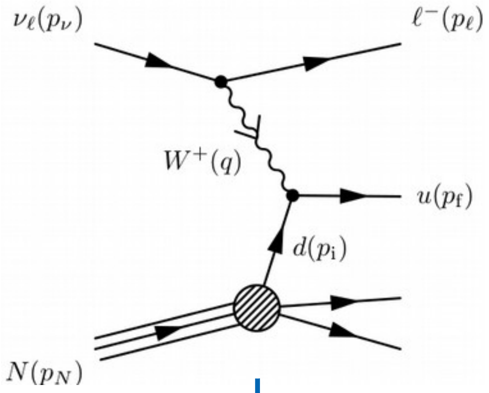

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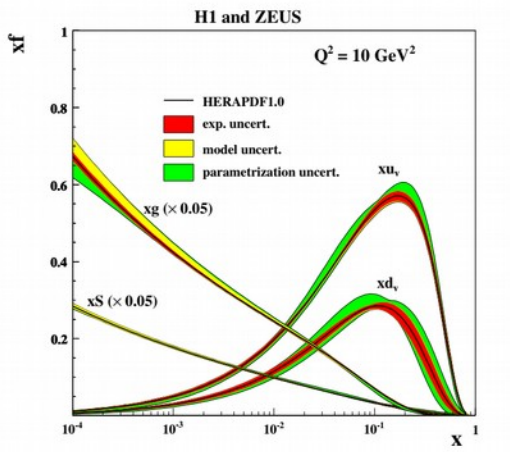

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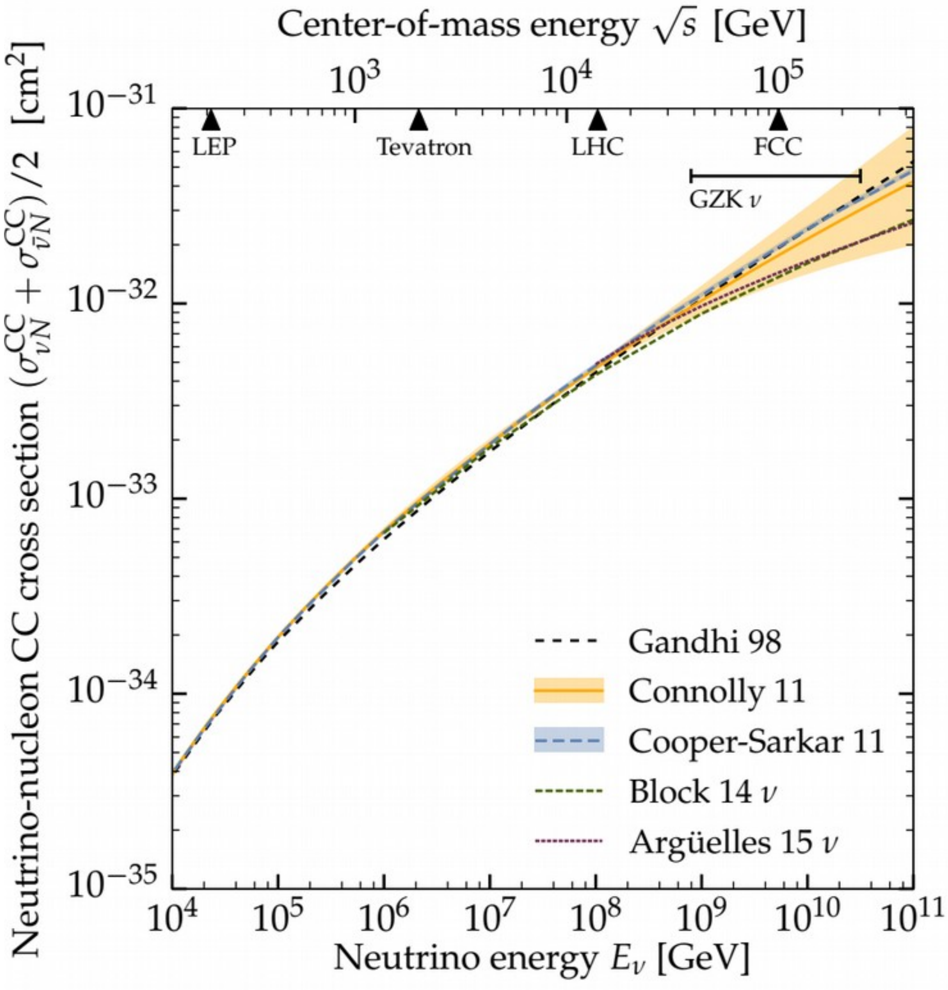

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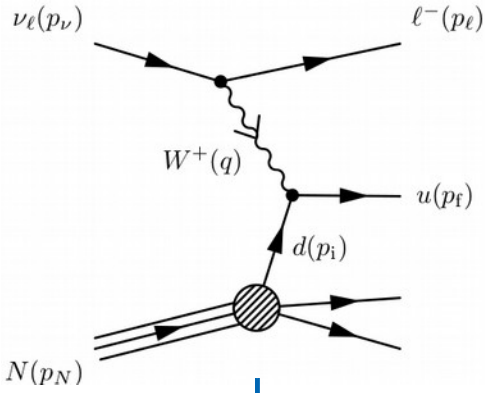

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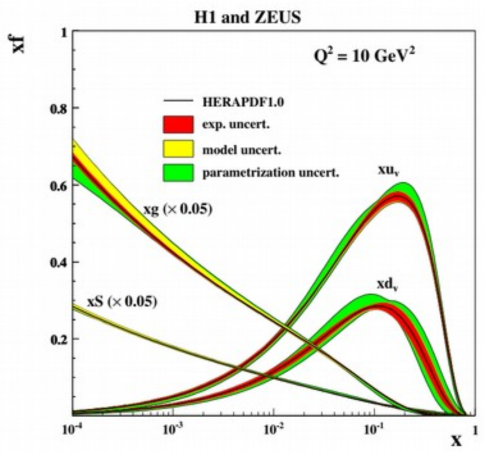

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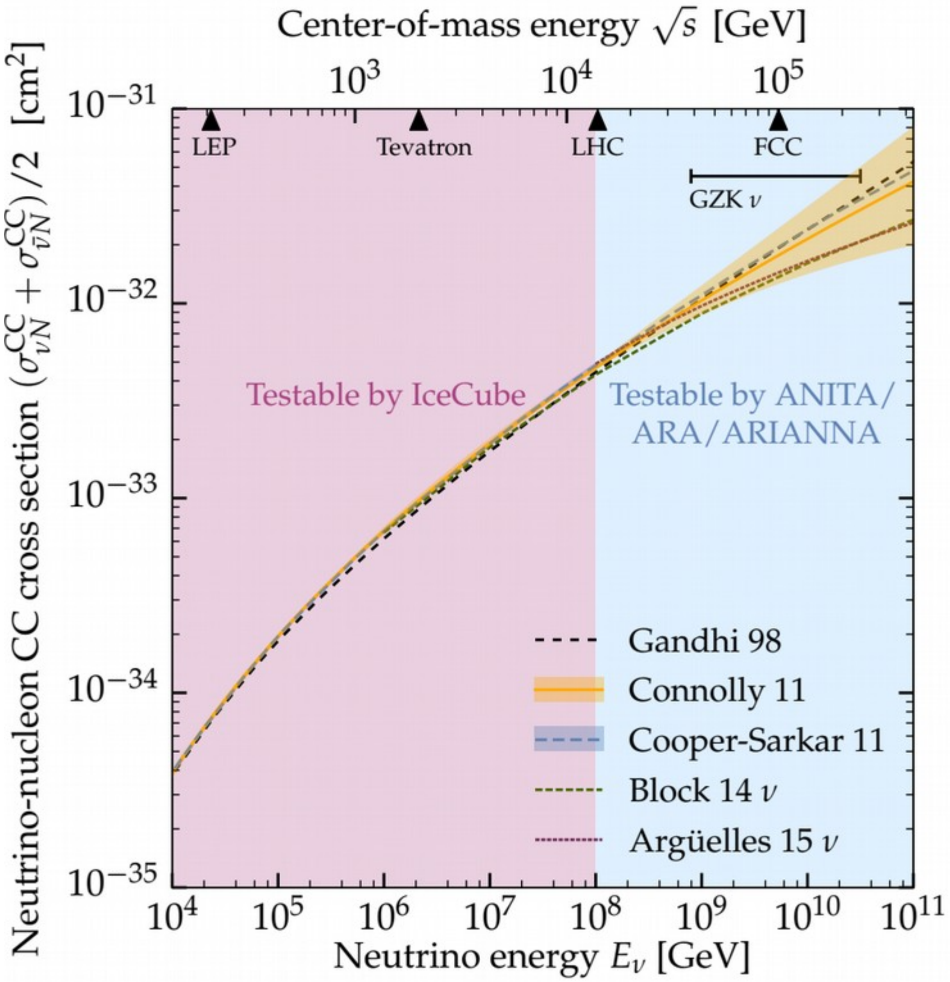
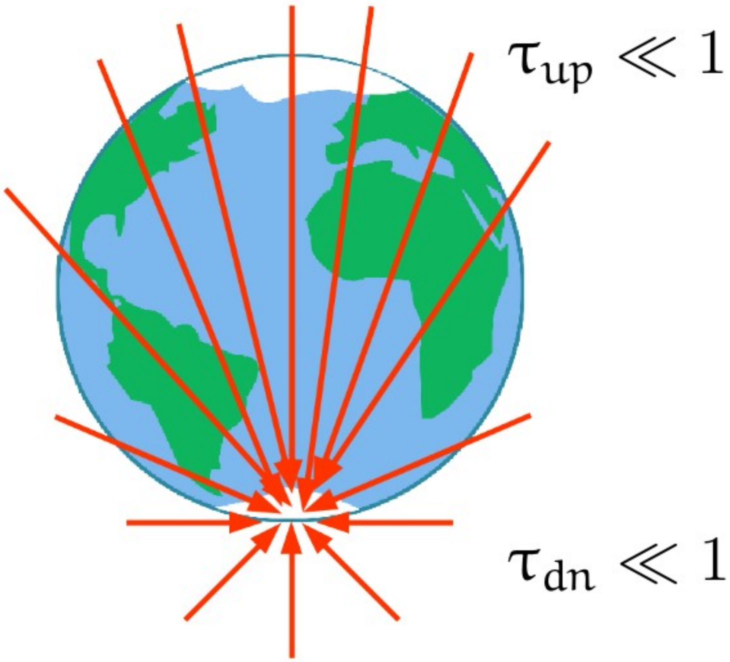


Measuring the high-energy cross section

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

Below ~ 10 TeV: Earth is transparent



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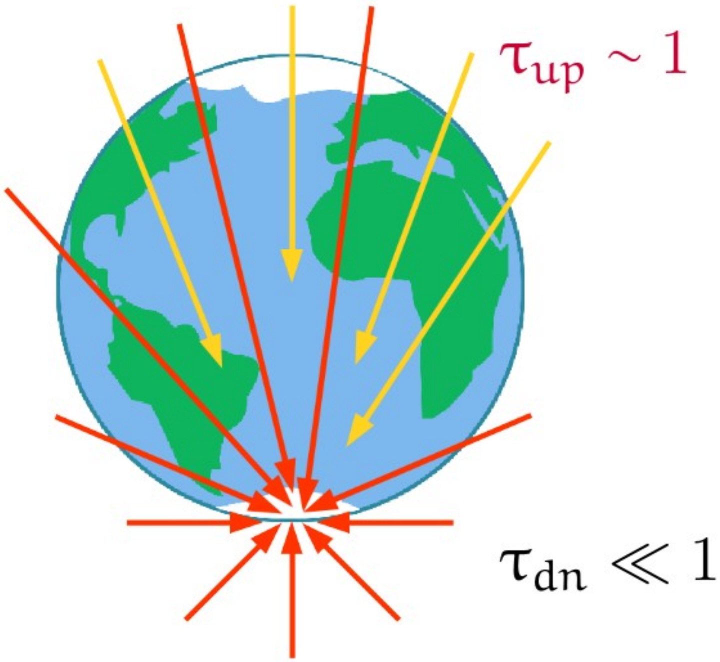

Hooper, *PRD* 2002; Hussain *et al.*, *PRL* 2006; Borriello *et al.*, *PRD* 2008
Hussain, Mafatia, McKay, *PRD* 2008 Connolly, Thorne, Waters, *PRD* 2011; Marfatia, McKay, Weiler, *PLB* 2015

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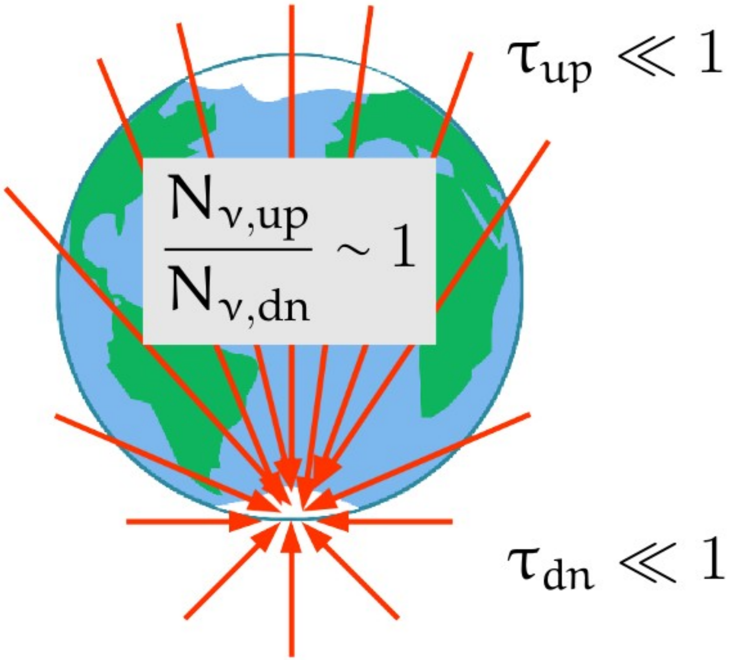

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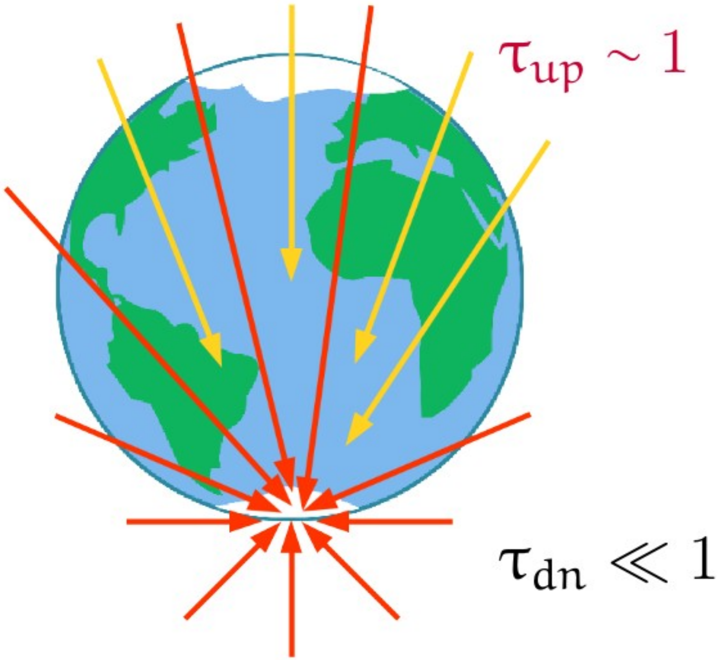

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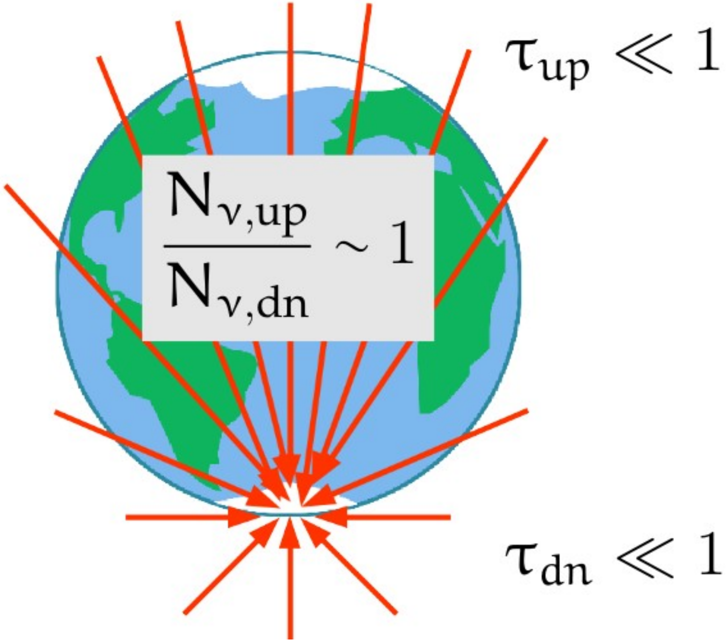

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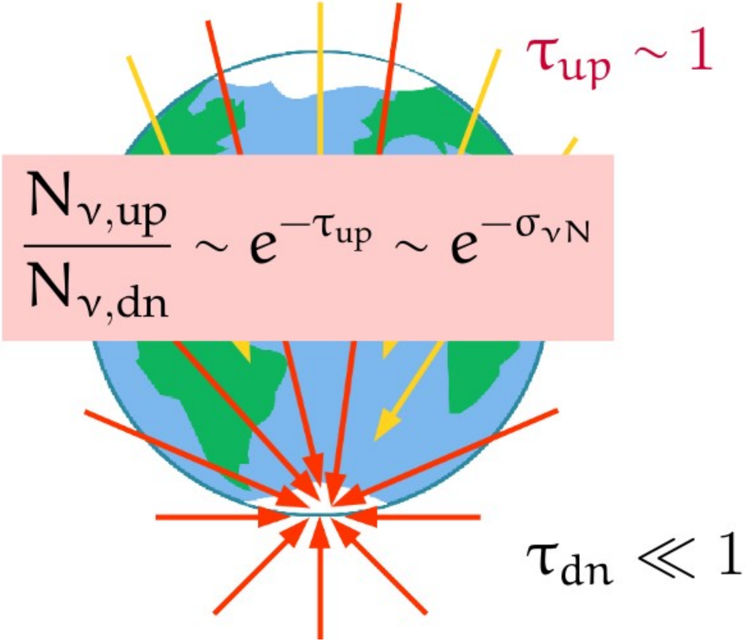

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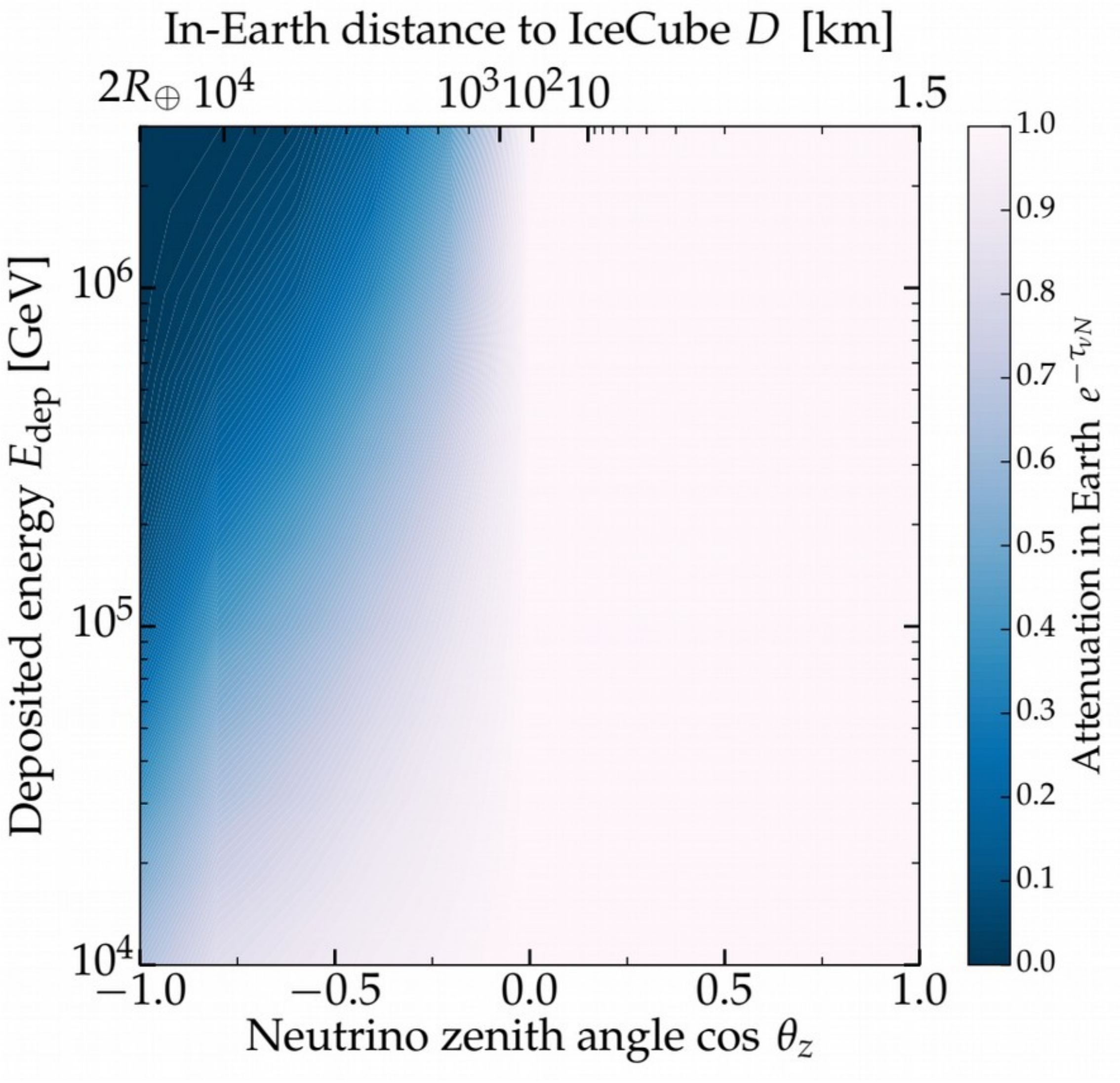
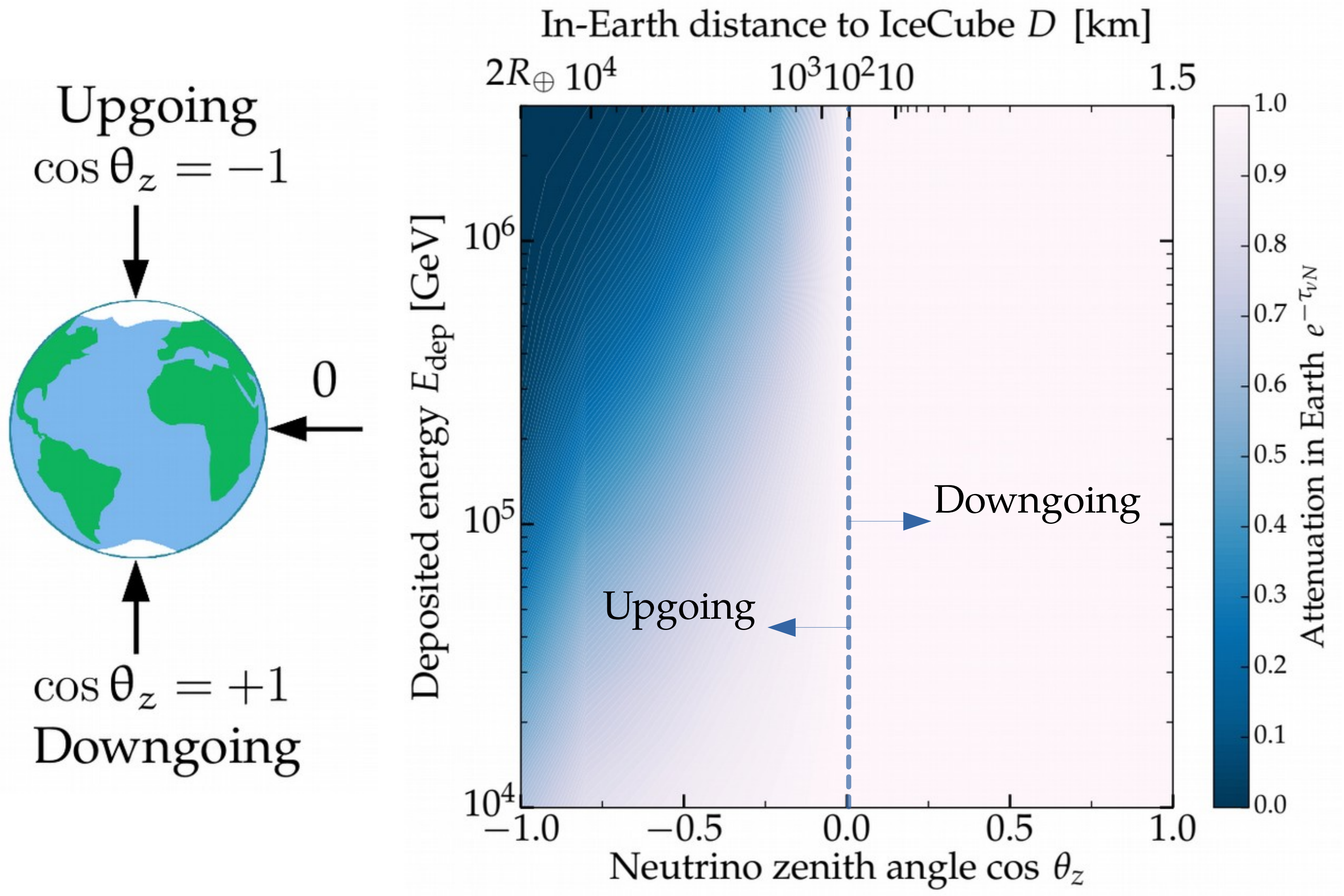
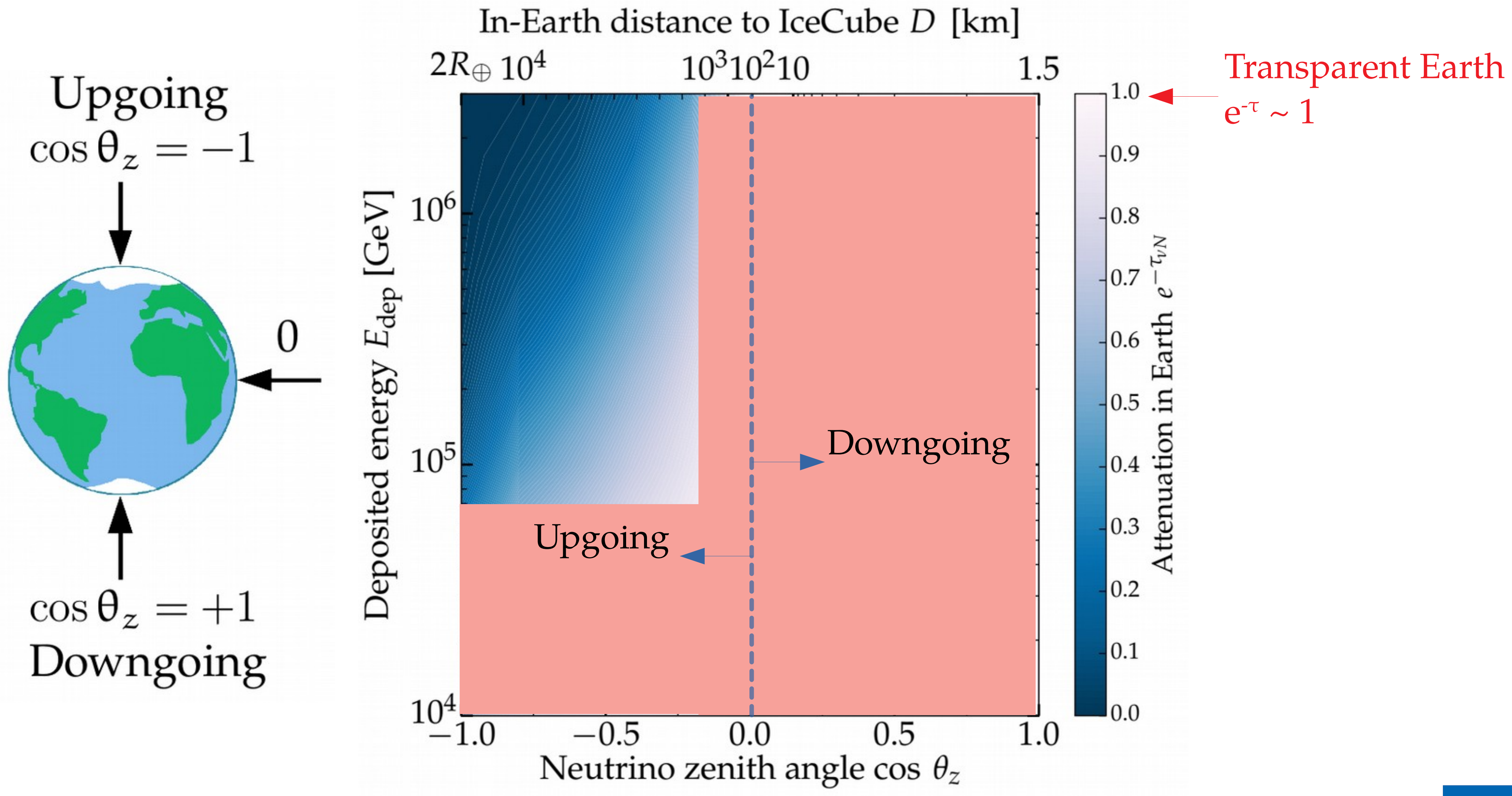
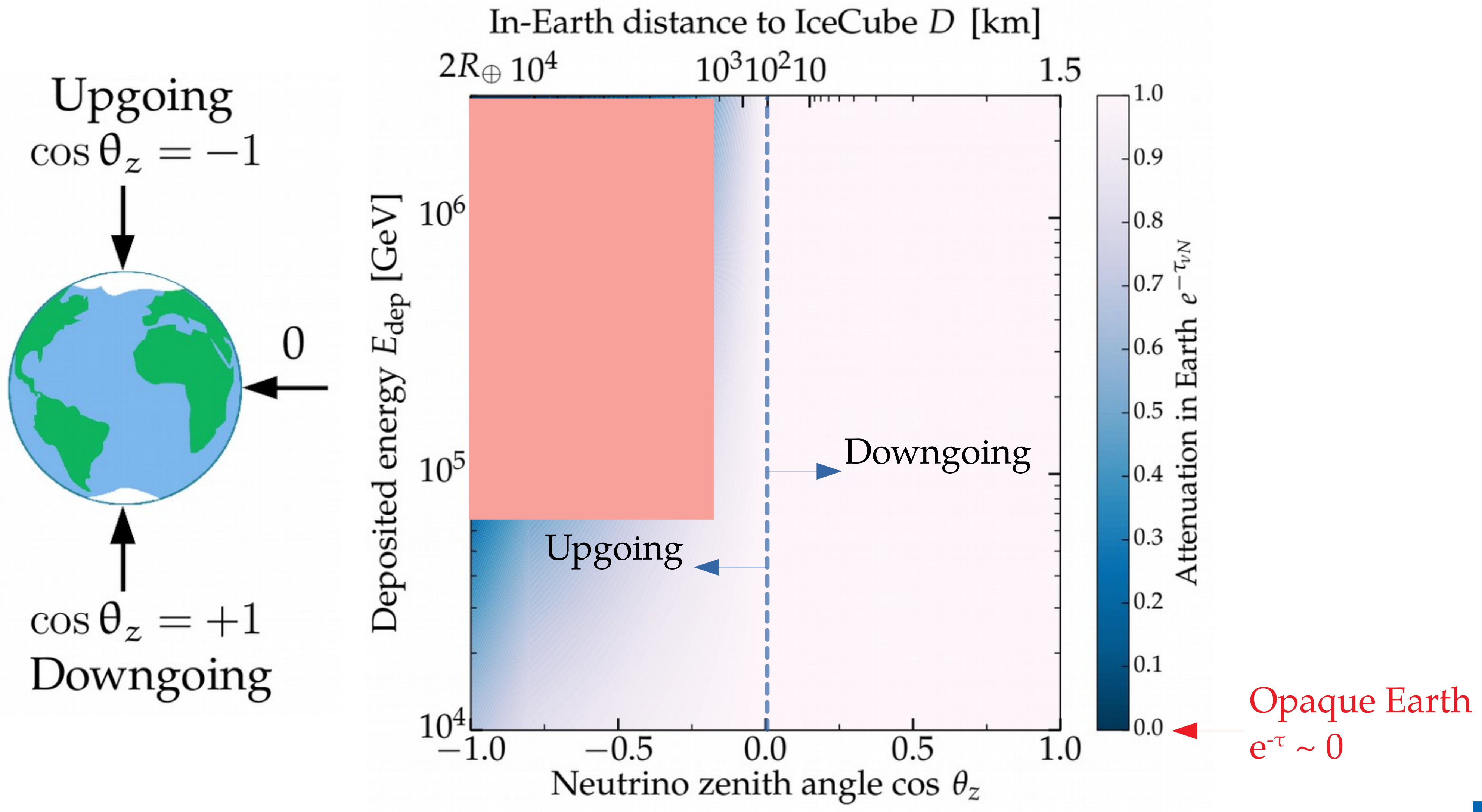
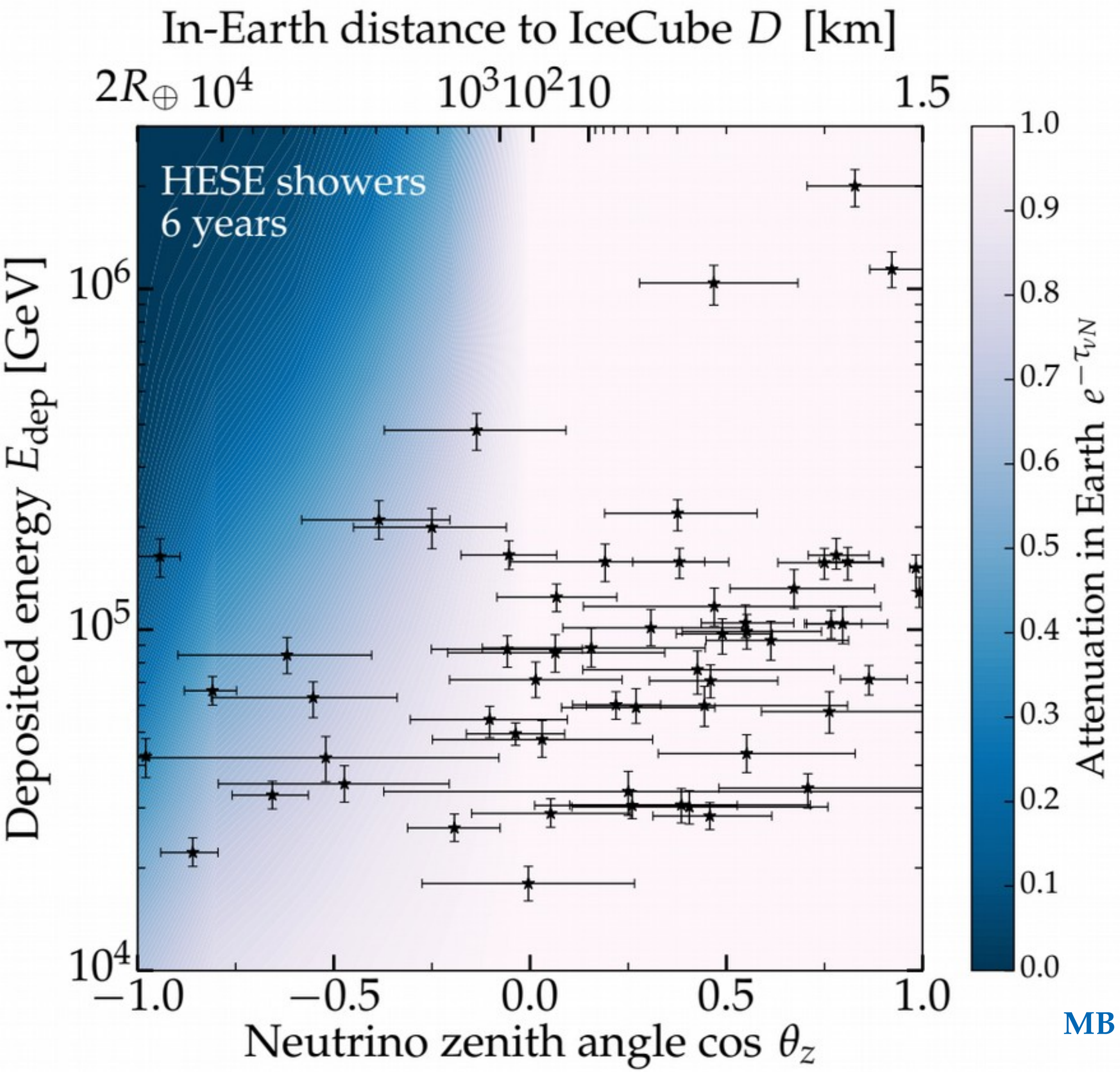

In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4
10^3 10^2 10
1.5
Deposited energy $E_{\rm dep}$ [GeV]
10^6
10^5
10^4
−1.0
−0.5
0.0
0.5
1.0
Neutrino zenith angle cos θ_z
Attenuation in Earth $e^{-\tau_{\nu N}}$
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0


Upgoing
$\cos\theta_z = -1$
0
$\cos\theta_z = +1$
Downgoing
In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4 10^3 10^2 10 1.5
Deposited energy E_{dep} [GeV]
10^4 10^5 10^6
Neutrino zenith angle $\cos\theta_z$
−1.0 −0.5 0.0 0.5 1.0
Upgoing
Downgoing
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

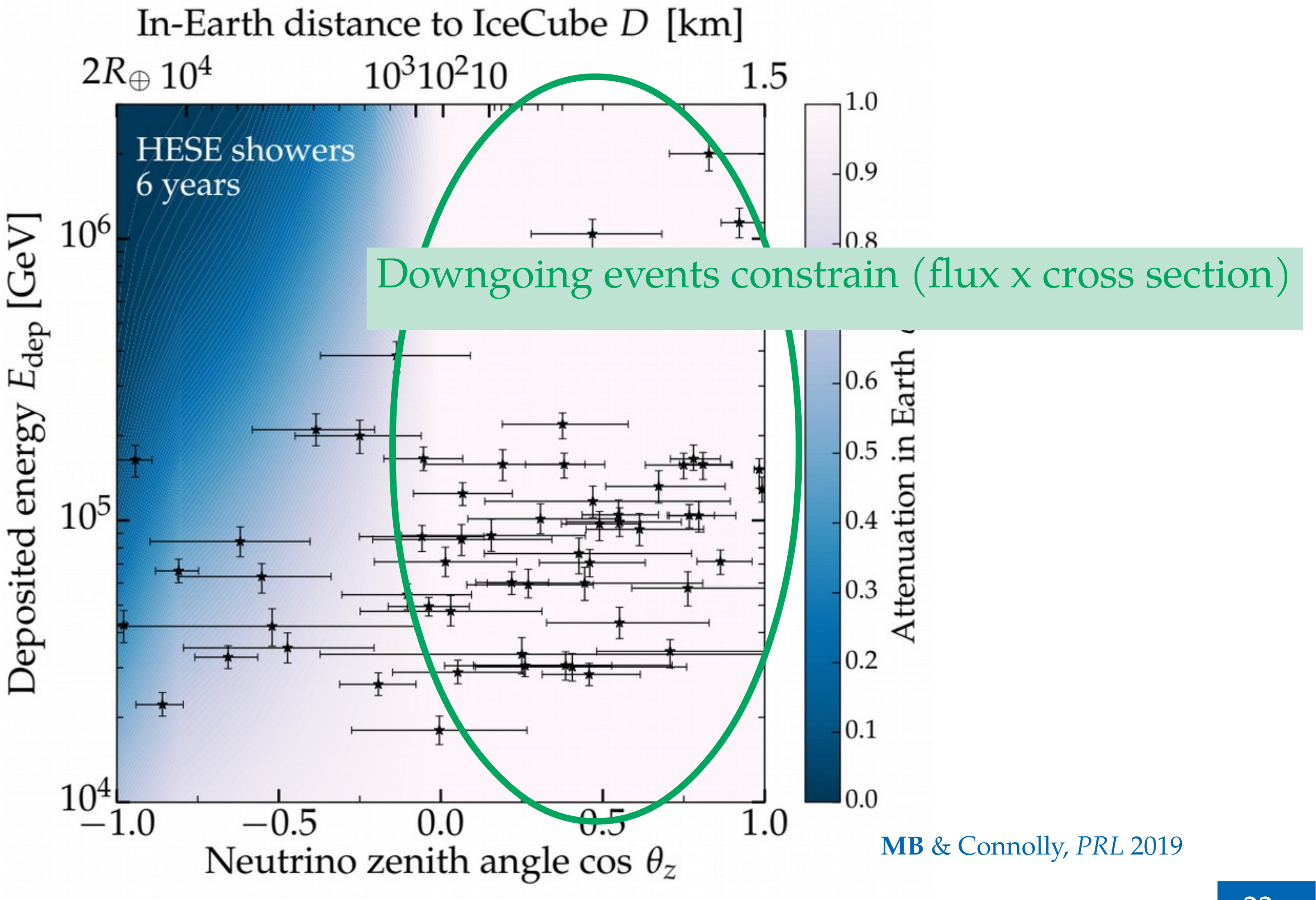


Upgoing
$\cos\theta_z = -1$
0
$\cos\theta_z = +1$
Downgoing
In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4 10^3 10^2 10 1.5
Deposited energy $E_{\rm dep}$ [GeV]
10^6
10^5
10^4
Downgoing
Upgoing
−1.0 −0.5 0.0 0.5 1.0
Neutrino zenith angle $\cos\theta_z$
1.0 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0.0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


Upgoing
cos θz = −1
0
cos θz = +1
Downgoing
In-Earth distance to IceCube D [km]
2R⊕ 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 θz
Attenuation in Earth e^{−τ_νN}
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Opaque Earth
e^{-τ} ~ 0



MB & Connolly, *PRL* 2019



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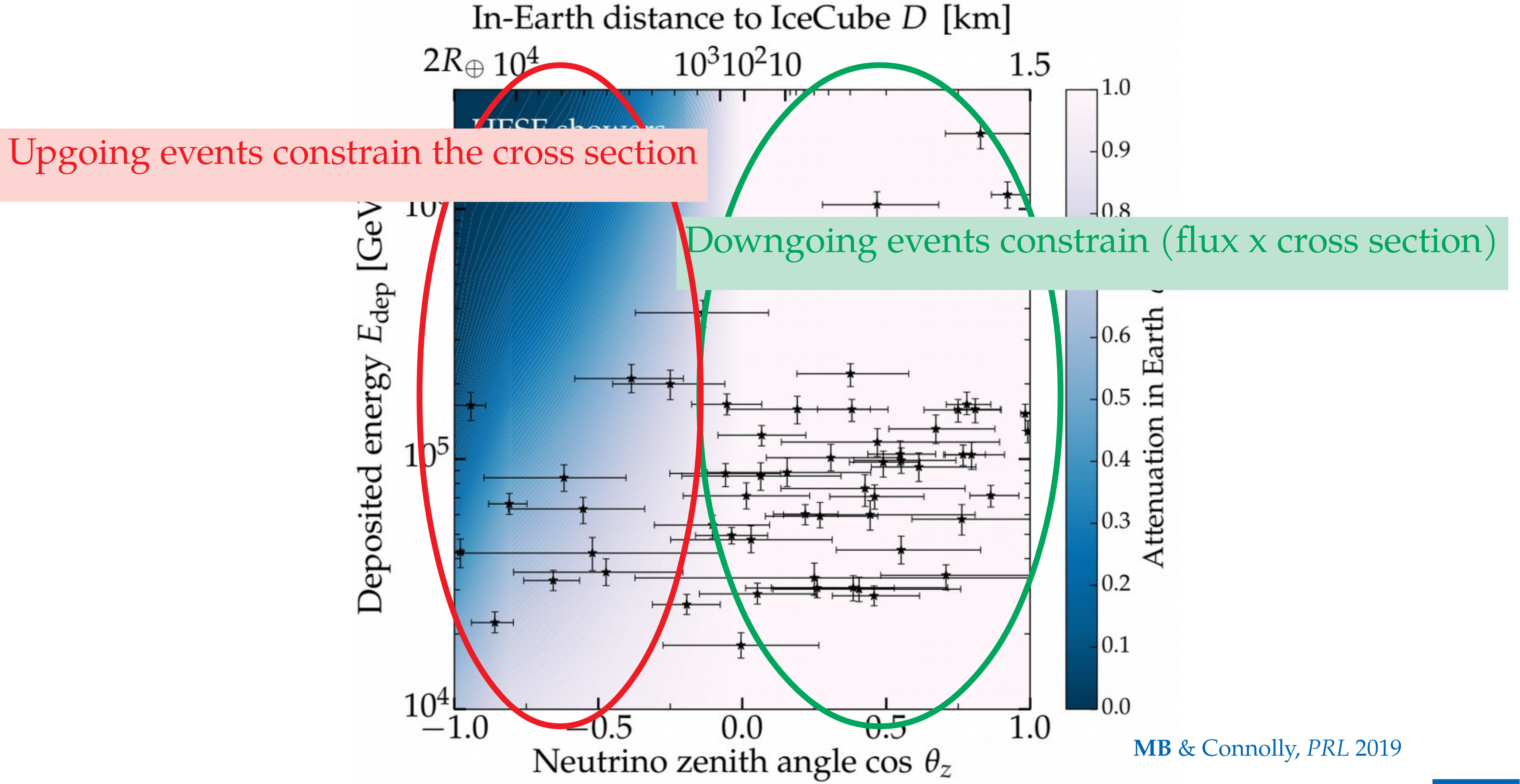

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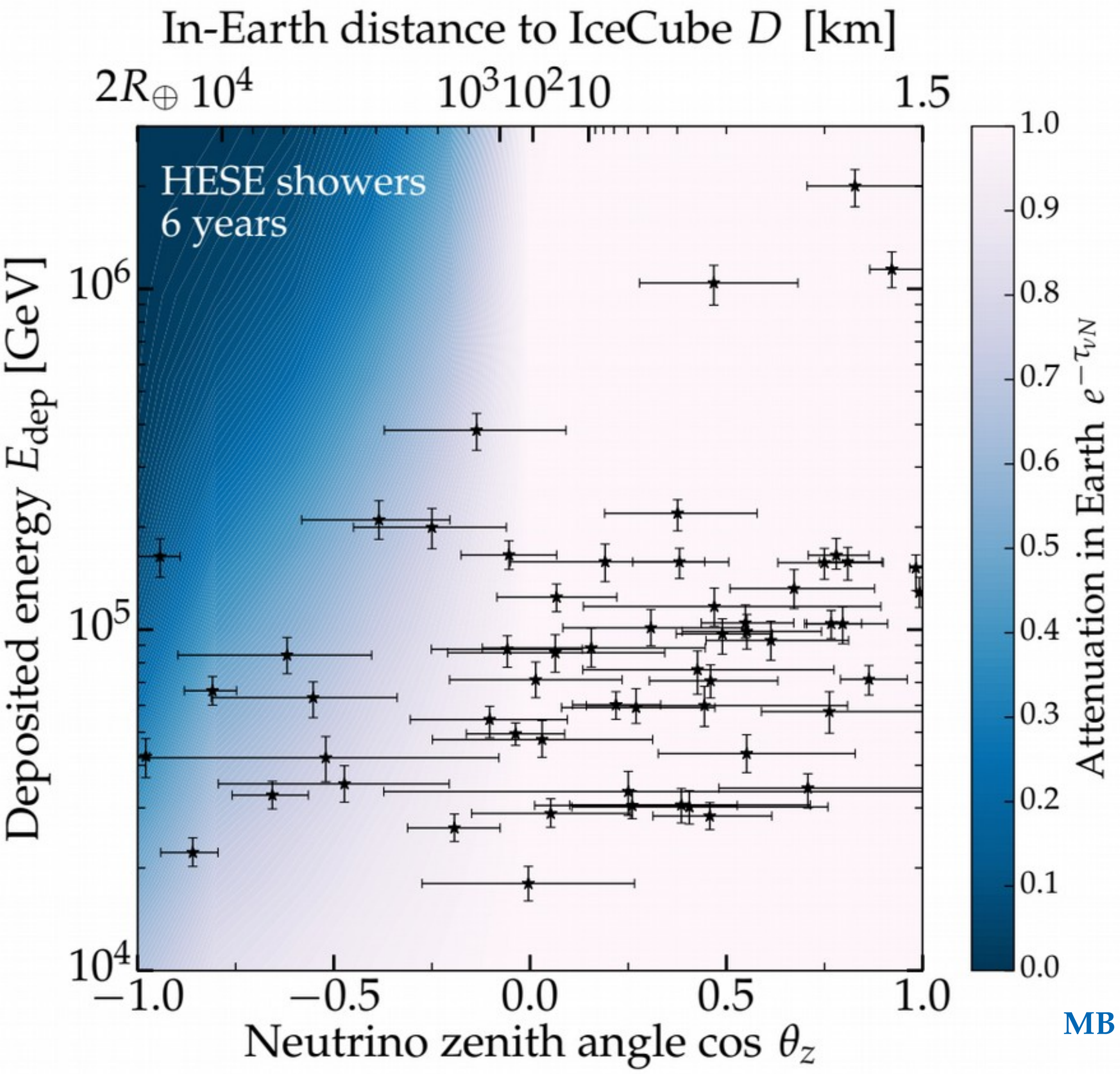

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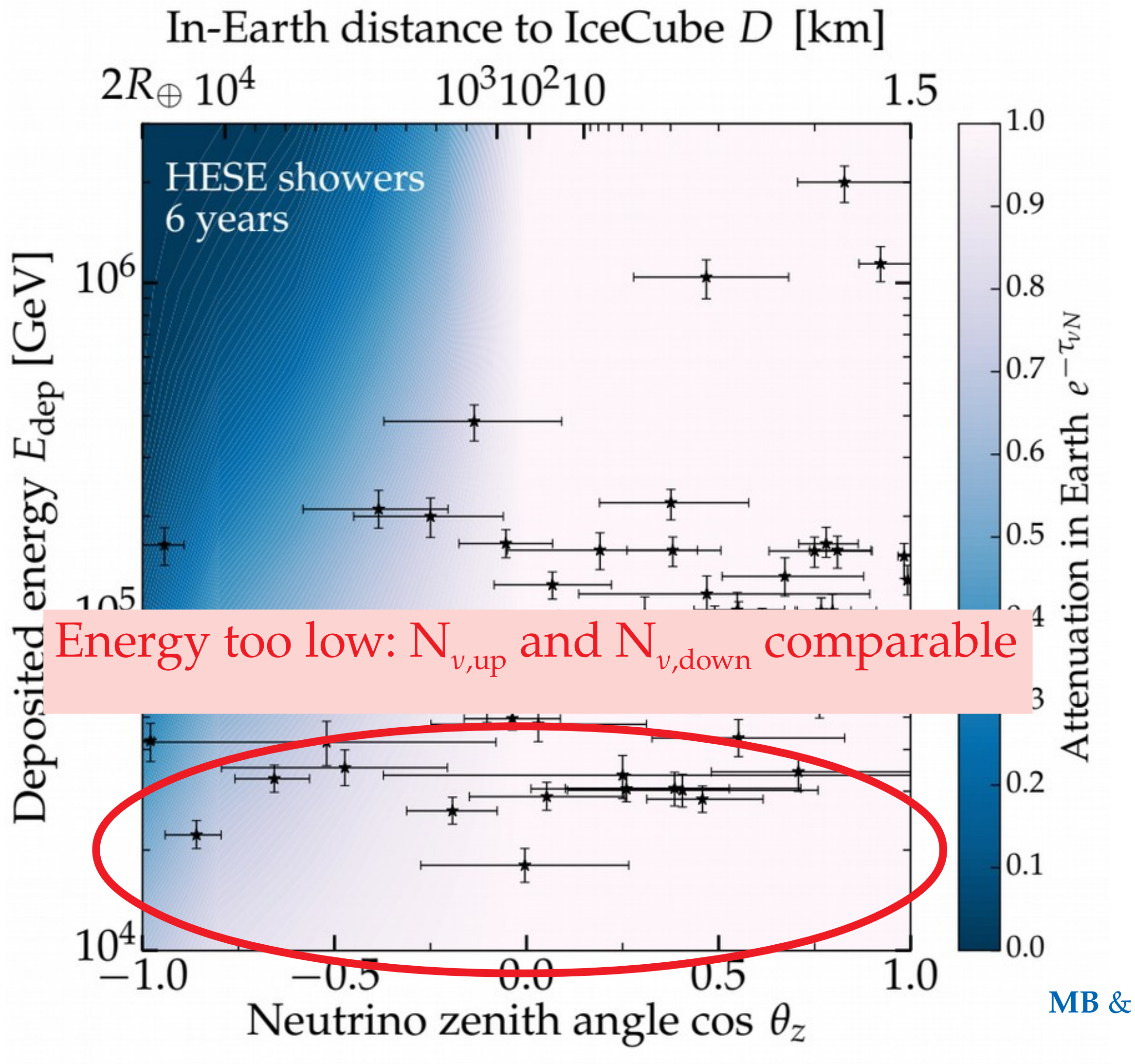
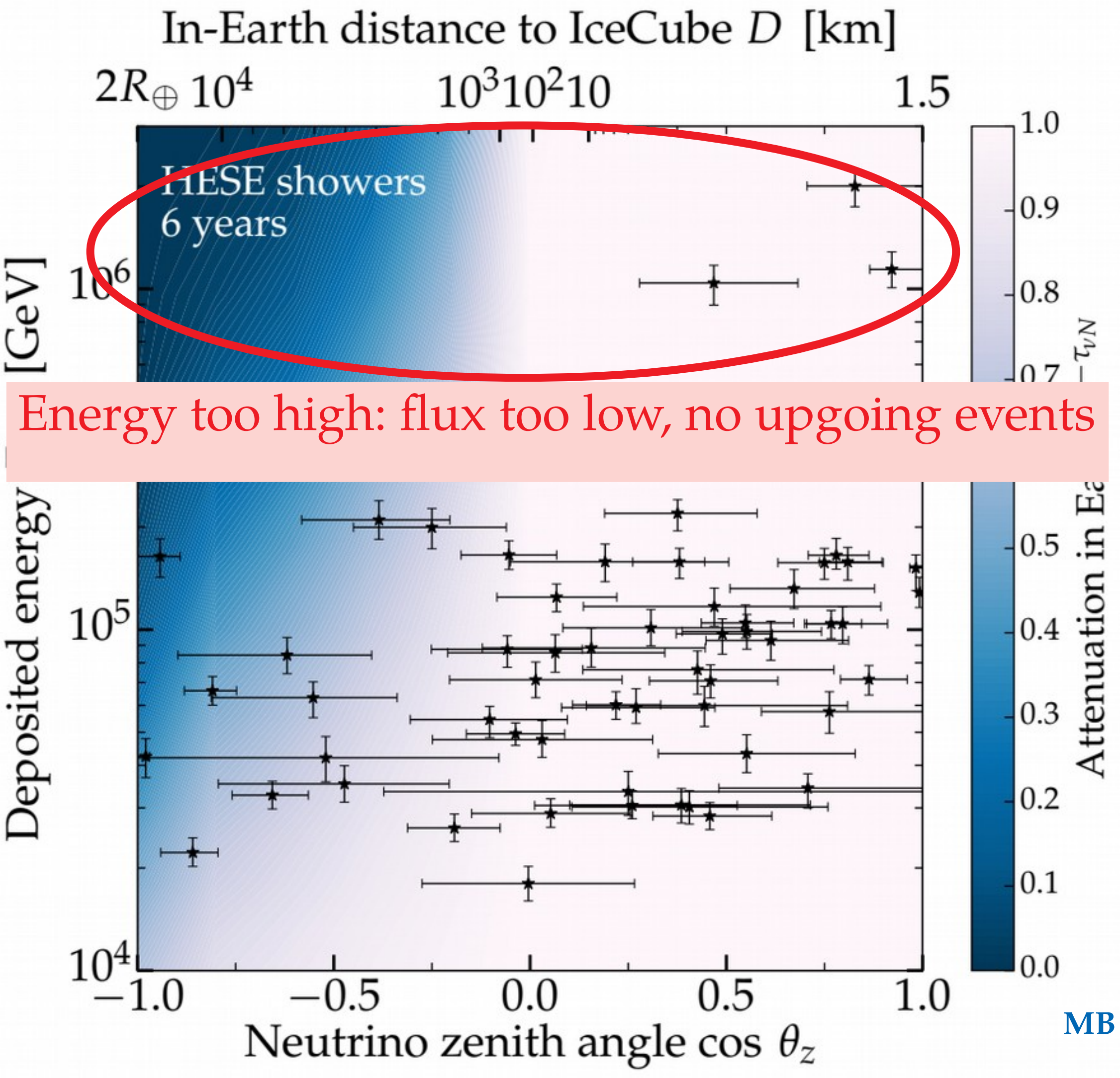
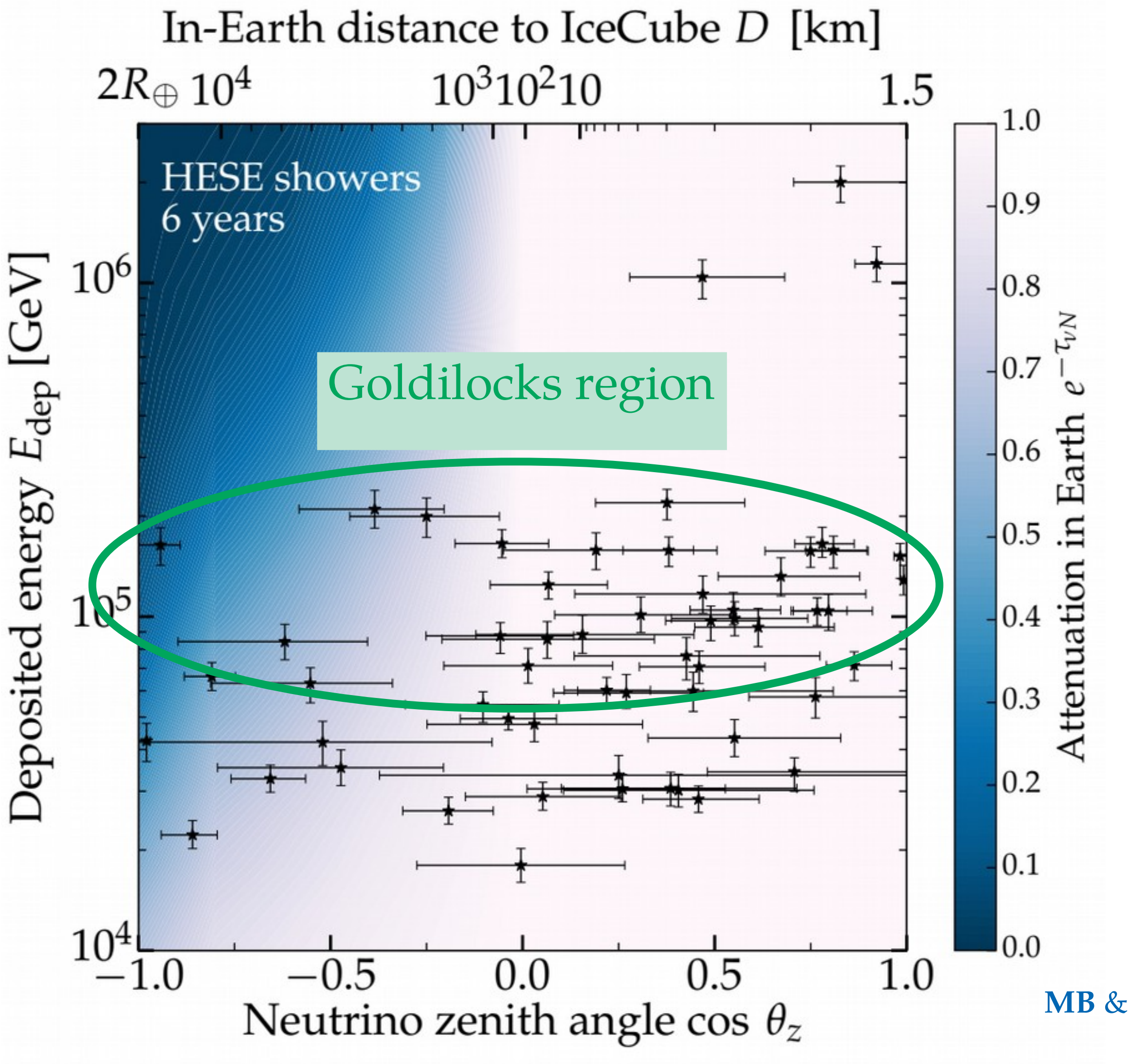


MB & Connolly, *PRL* 2019



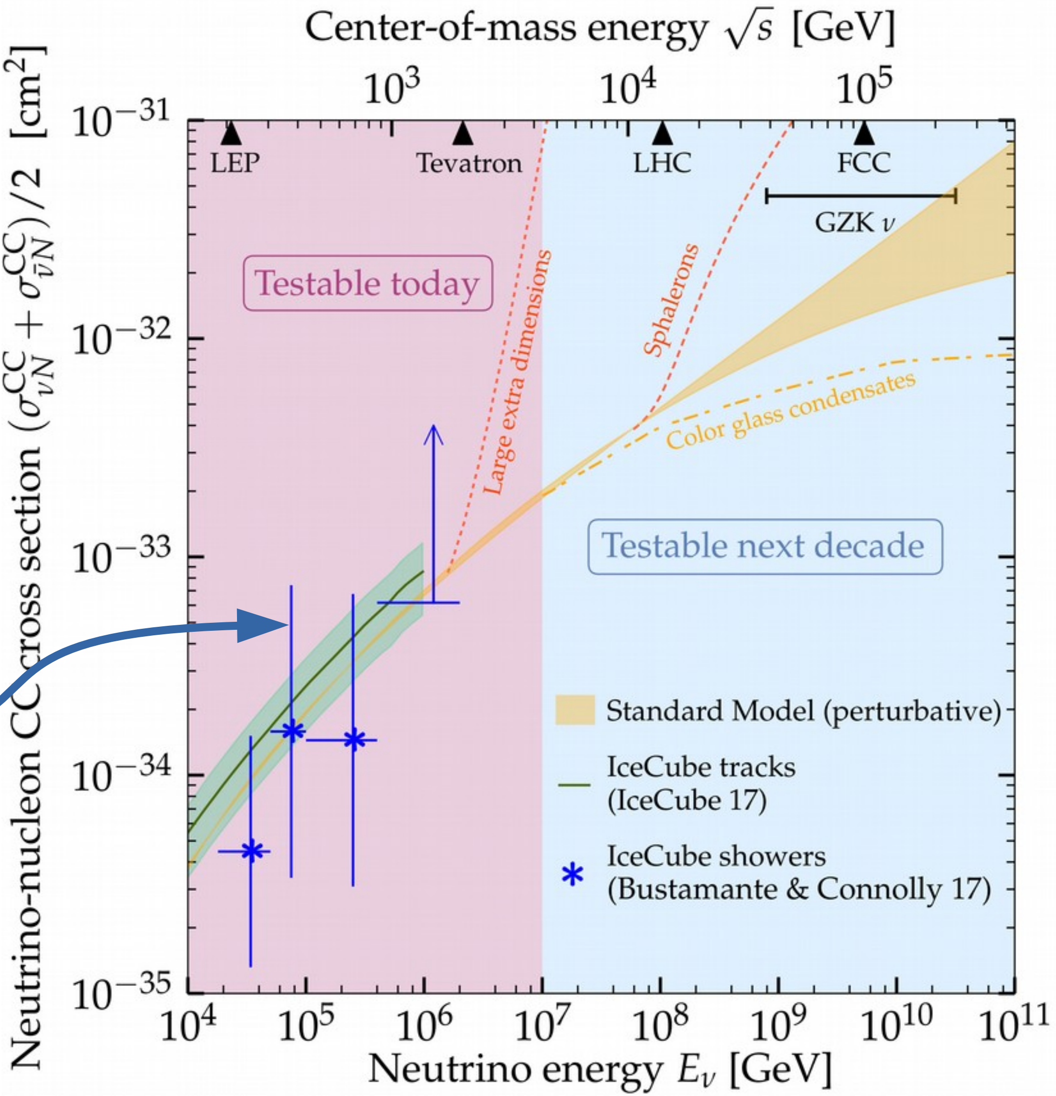
MB & Connolly, *PRL* 2019



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:
  - × 5 volume ⇒ 300 showers in 6 yr
  - Reduce statistical error by 40%

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



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

UHE uncertainties can be smaller:
Cooper-Sarkar, Mertsch, Sarkar *et al.*, *JHEP* 2011

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- Compatible with SM predictions
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- Today, using IceCube:
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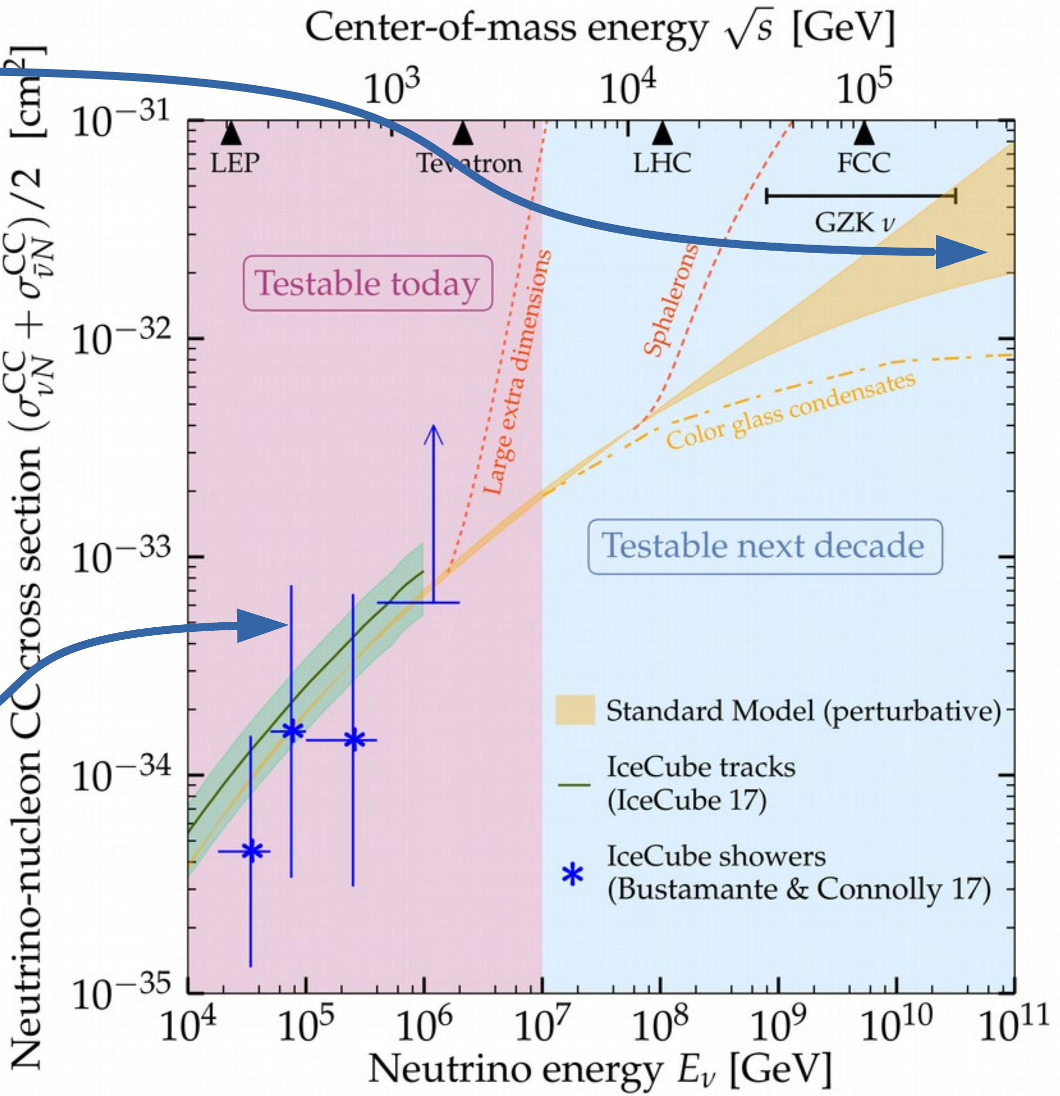

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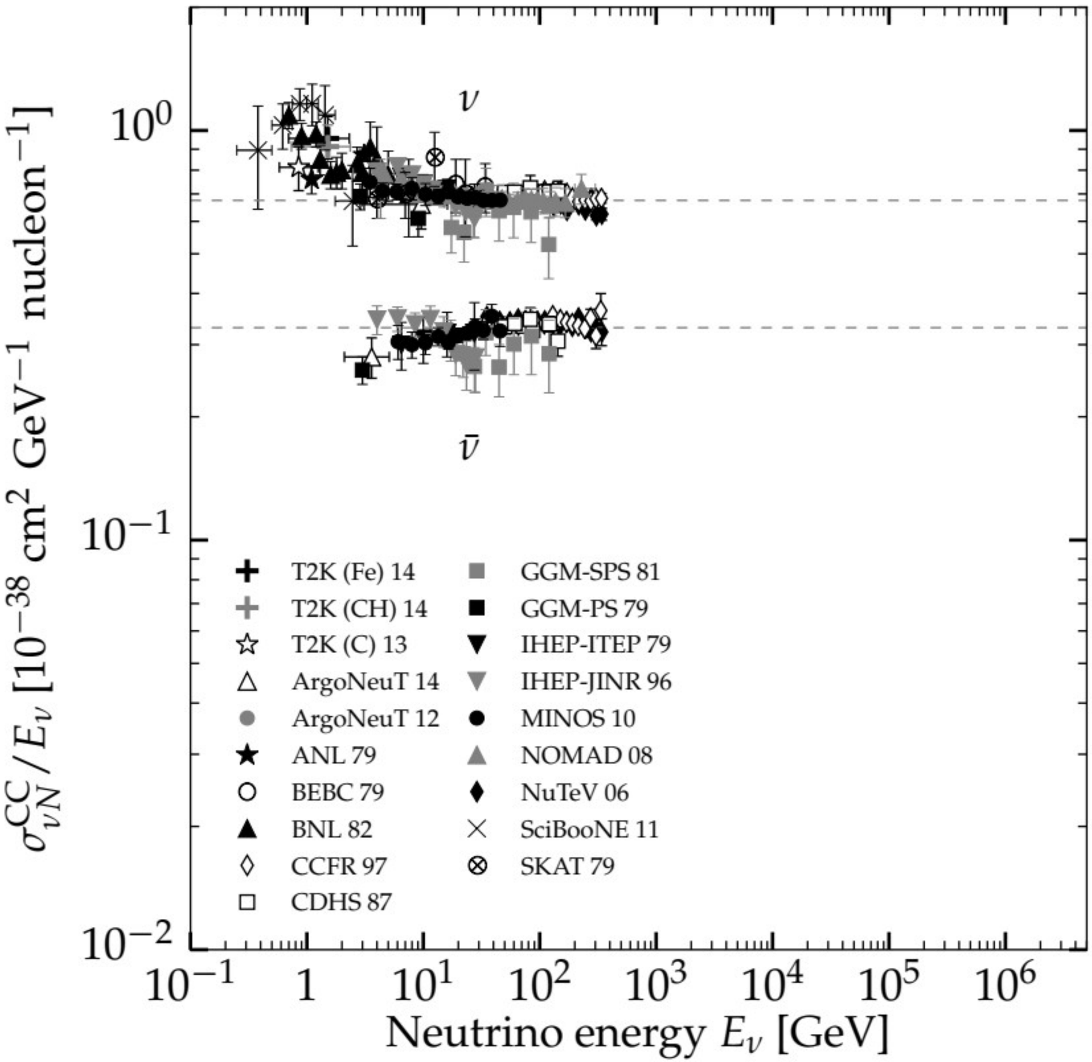

MB & A. Connolly *PRL* 2019
See also: IceCube, *Nature* 2017

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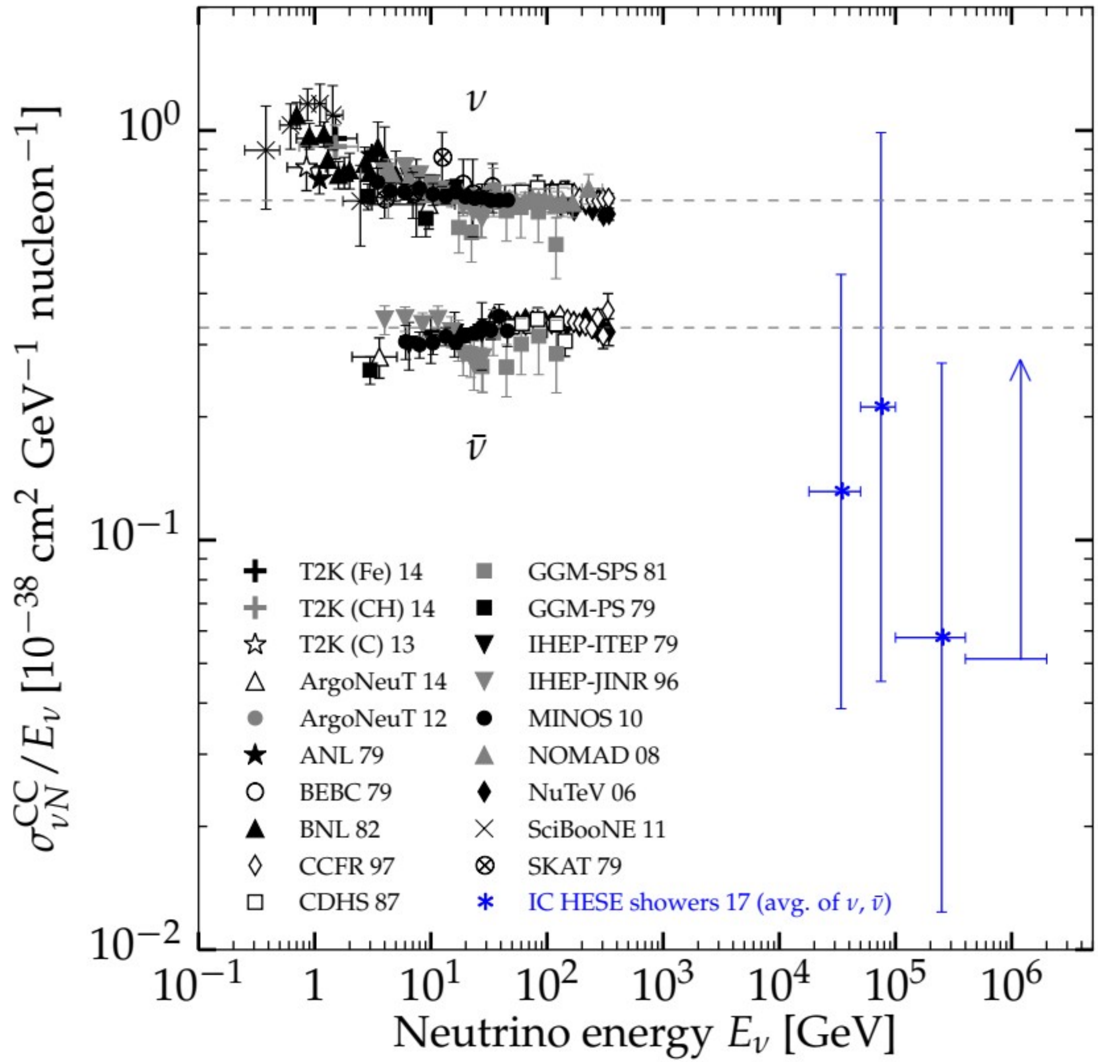

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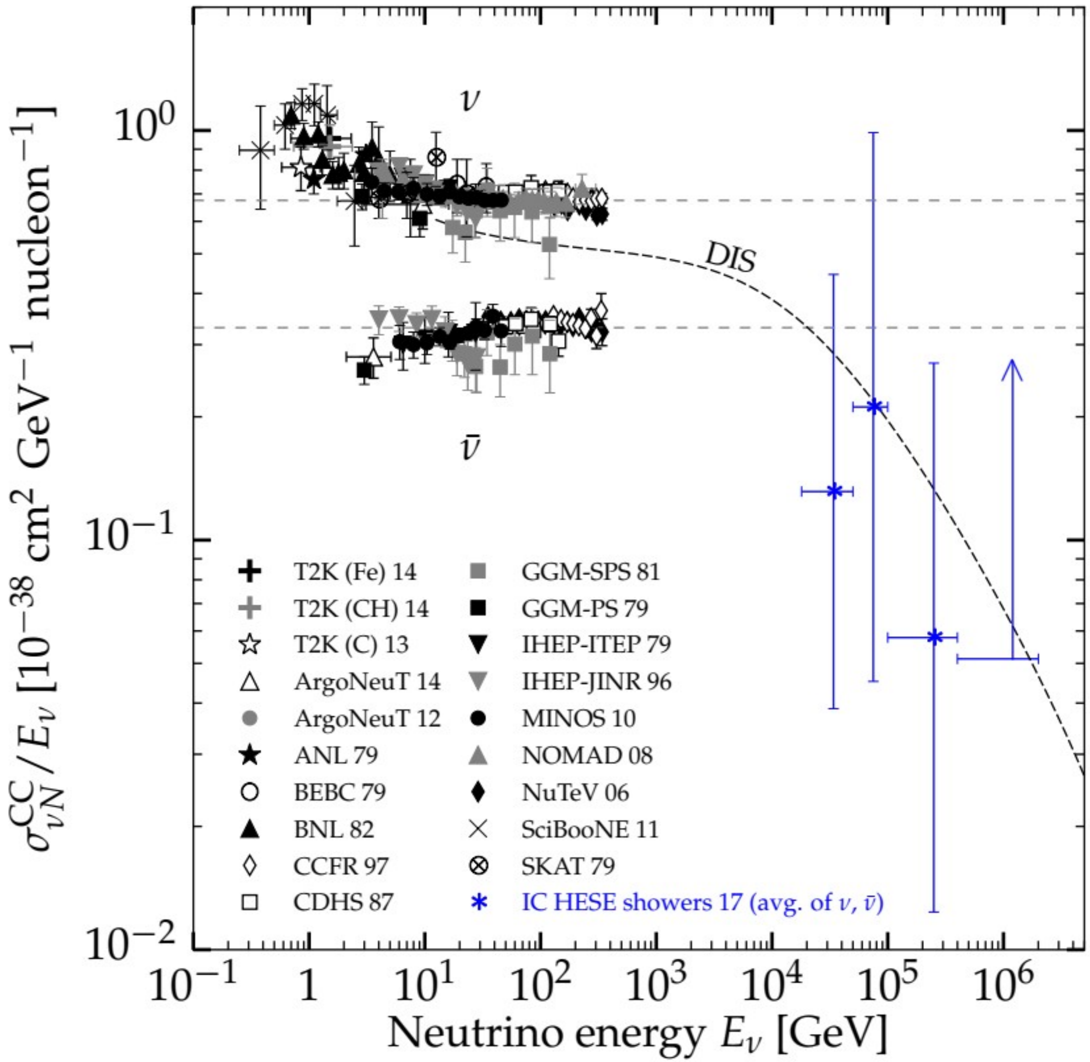
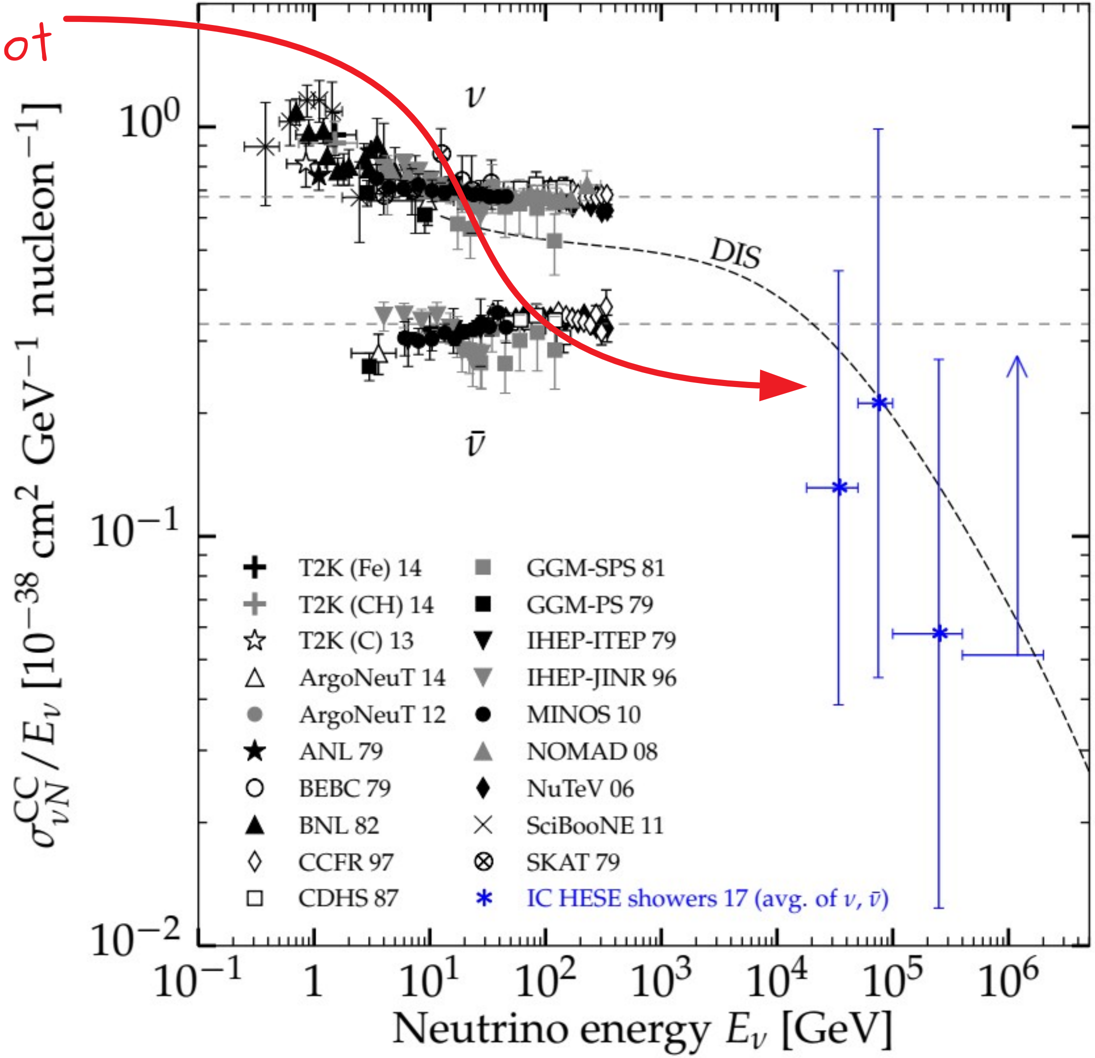


Extending the PDG cross-section plot



MB & A. Connolly *PRL* 2019
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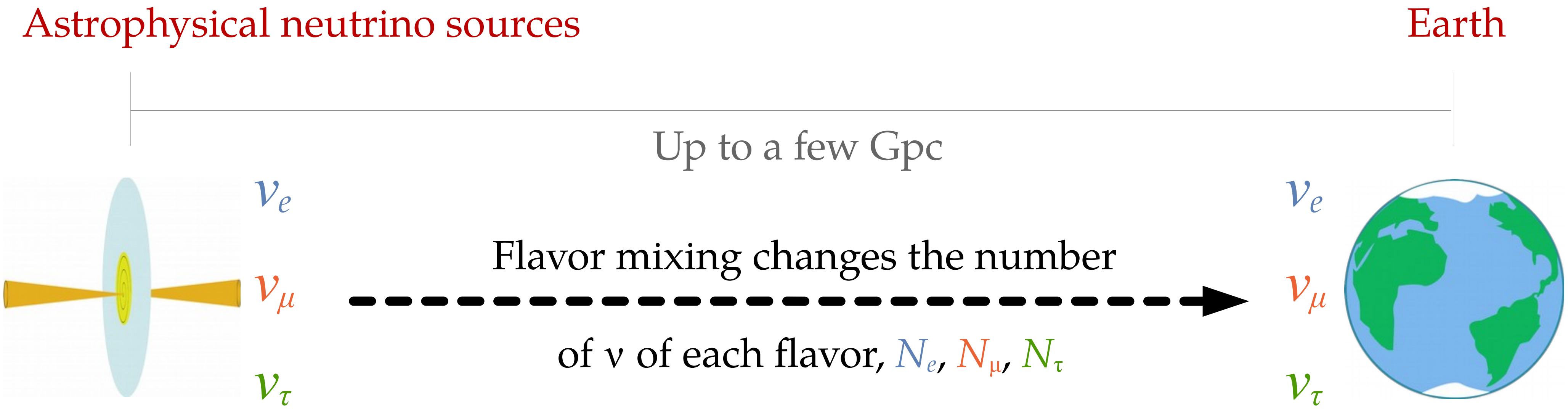
Flavor composition



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

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

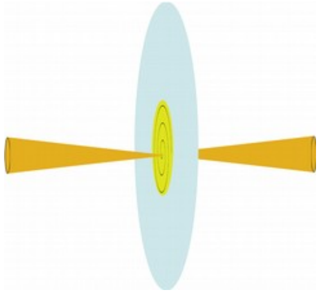
- Flavor ratios at Earth ($\alpha = e, \mu, \tau$):

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

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

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

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

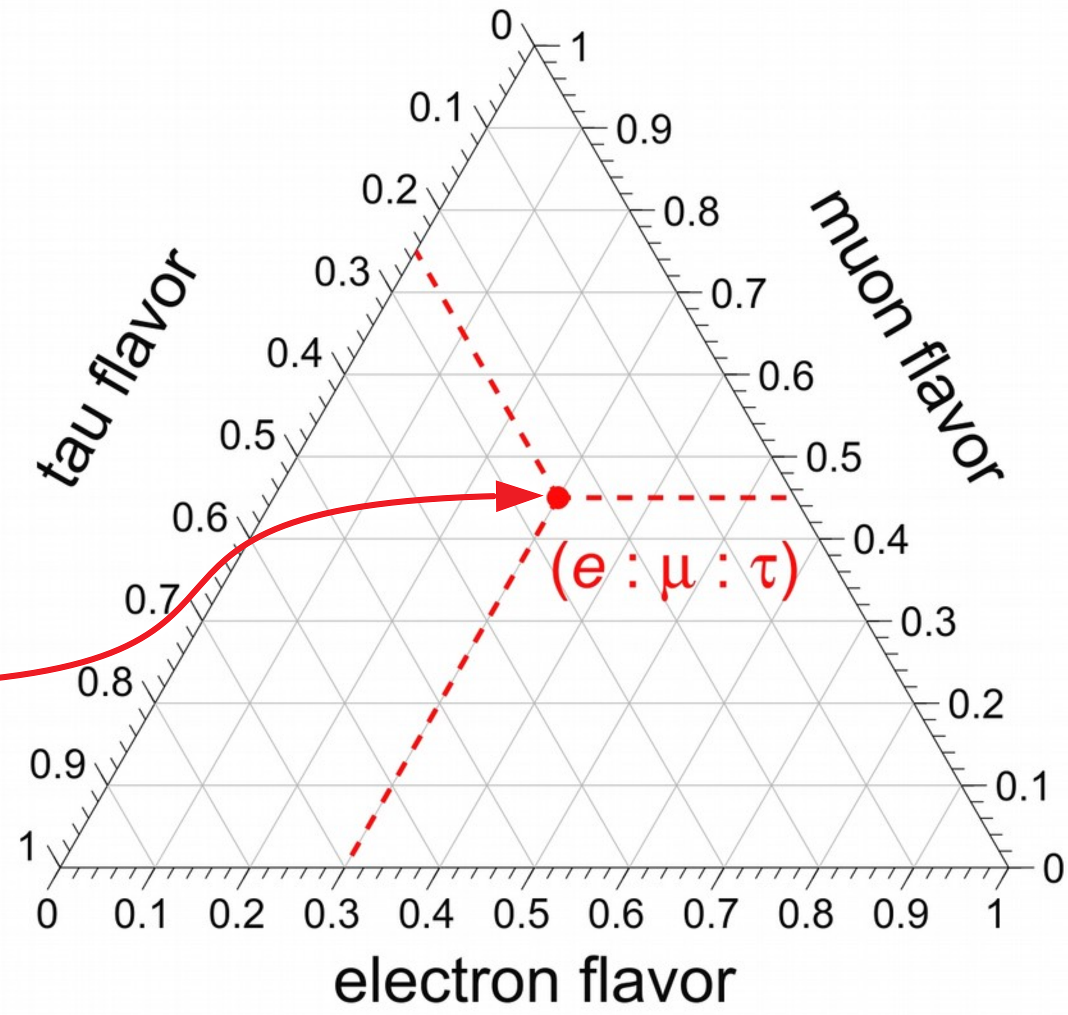
Standard oscillations
or
new physics

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:

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

Full π decay chain

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

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

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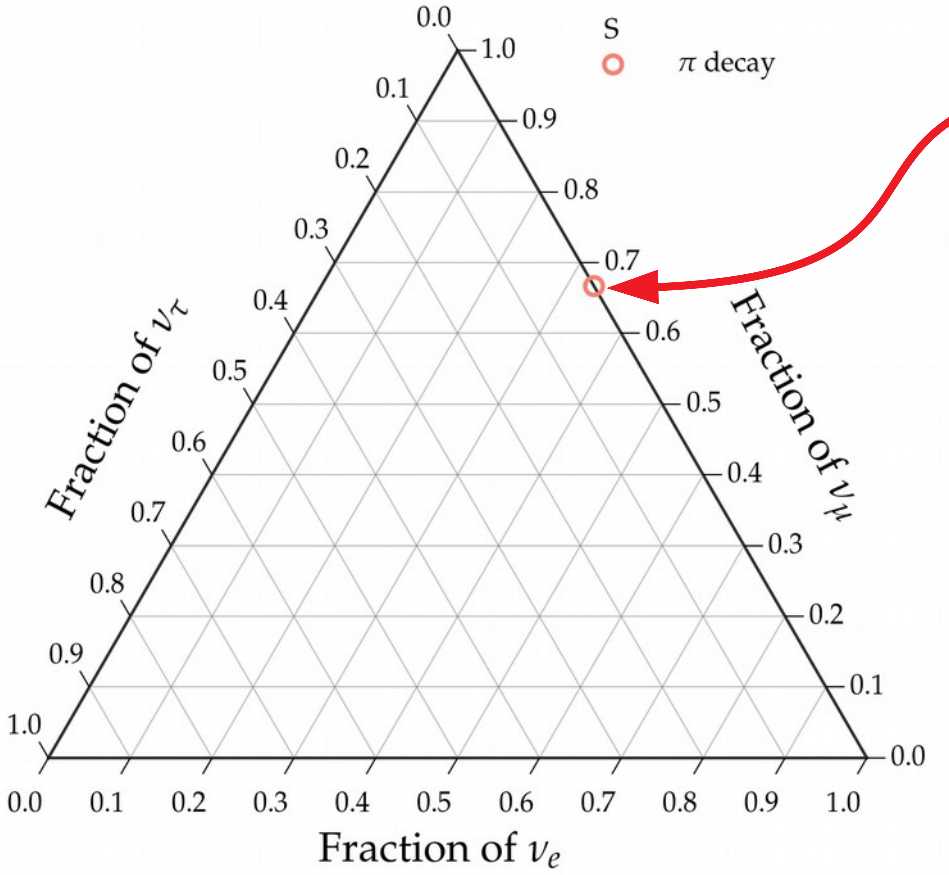

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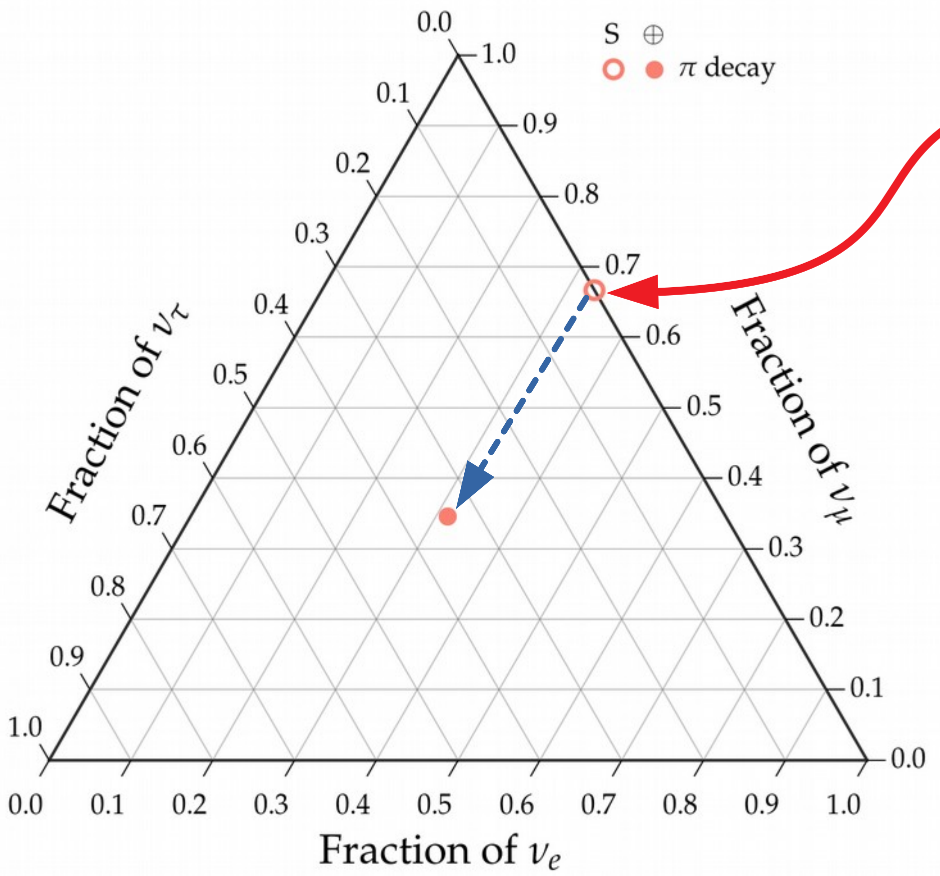

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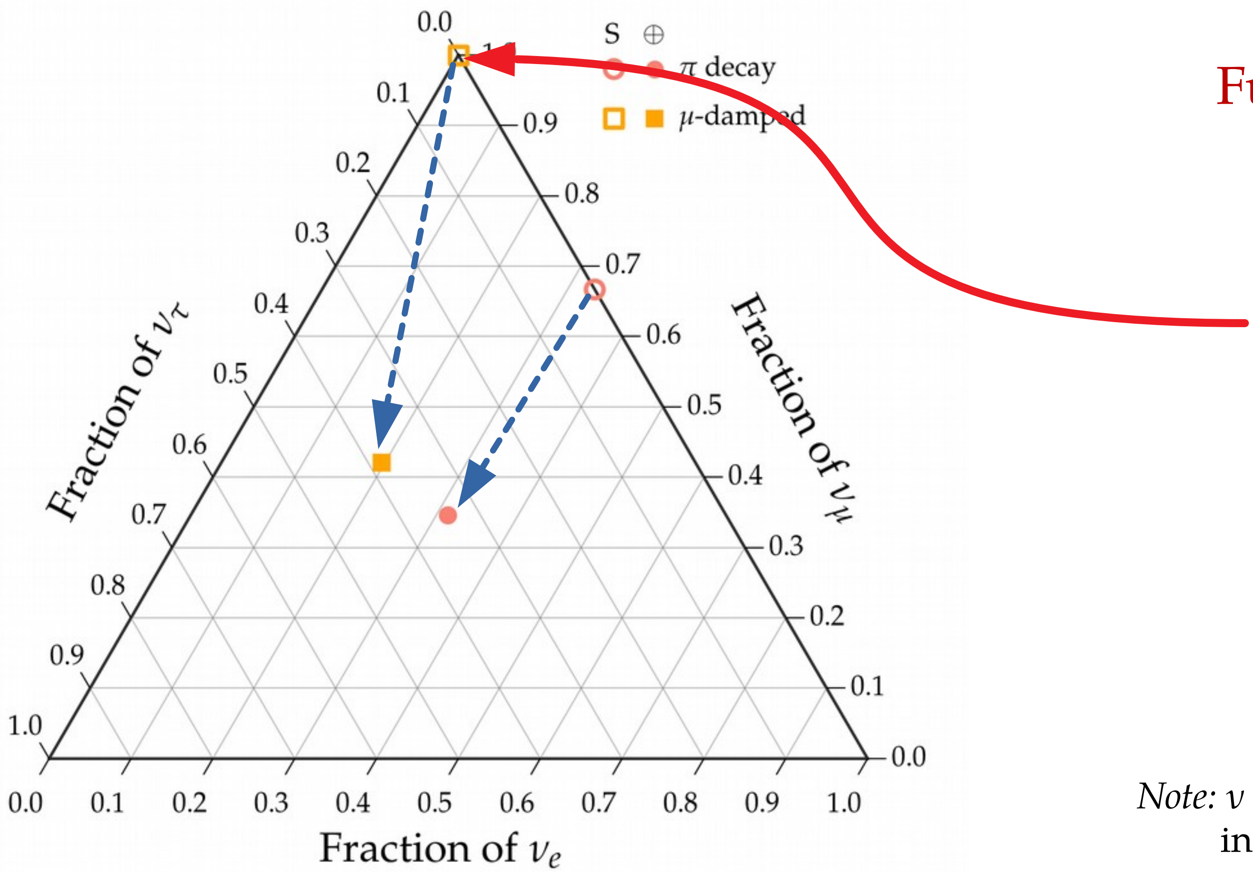

Full π decay chain

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Muon damped

$(0:1:0)_S$

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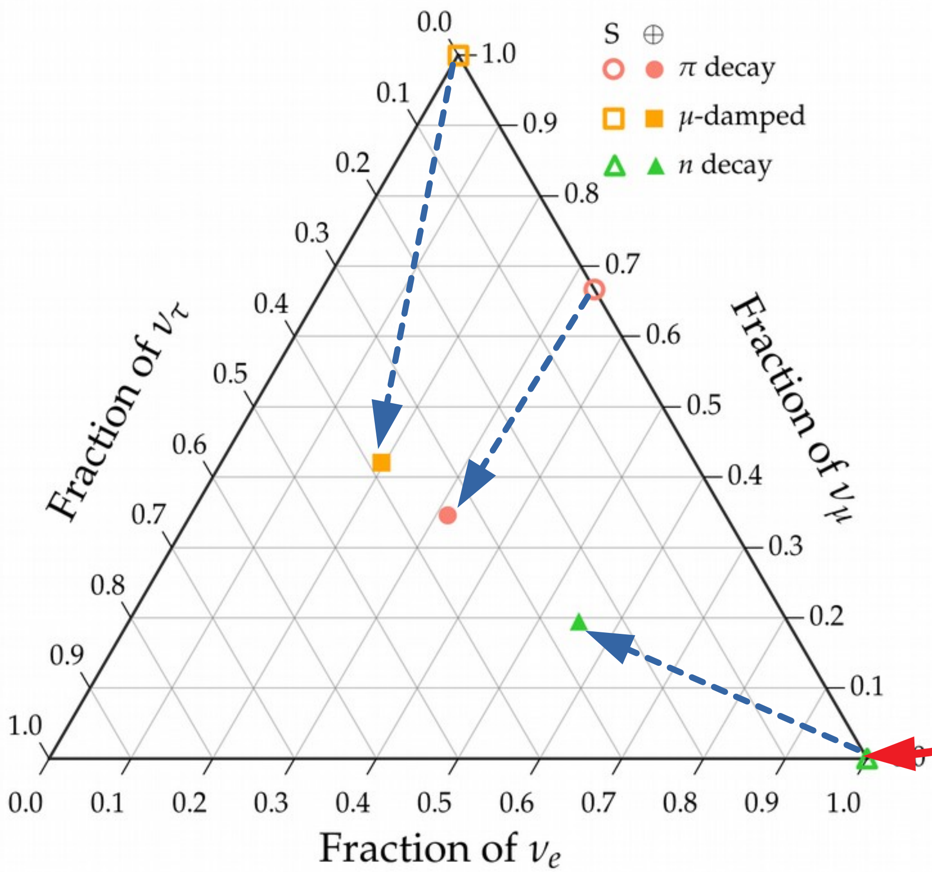

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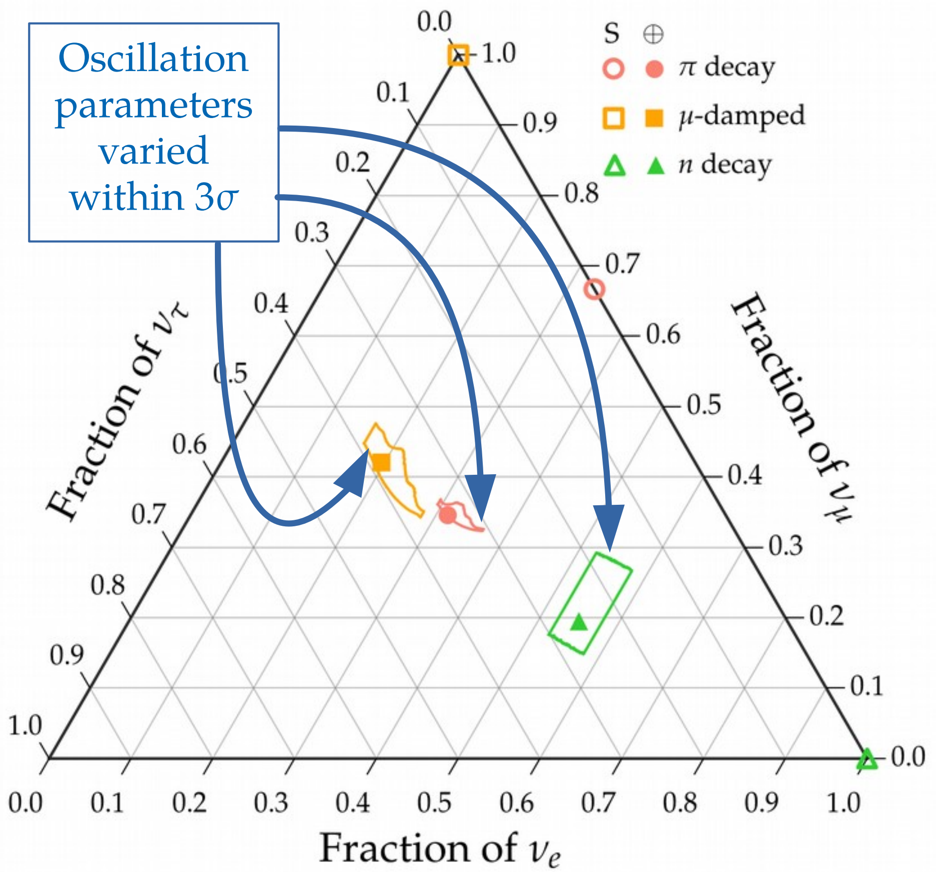

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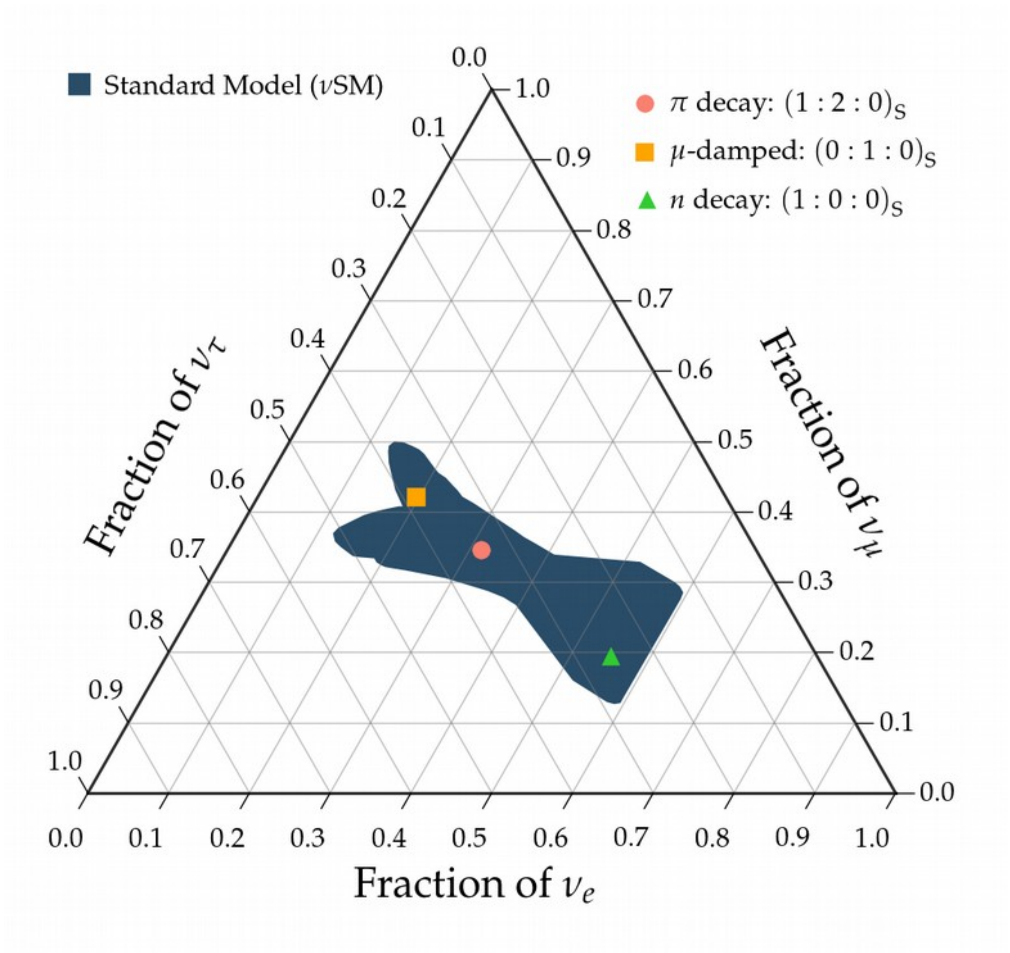


All possible flavor ratios at the sources

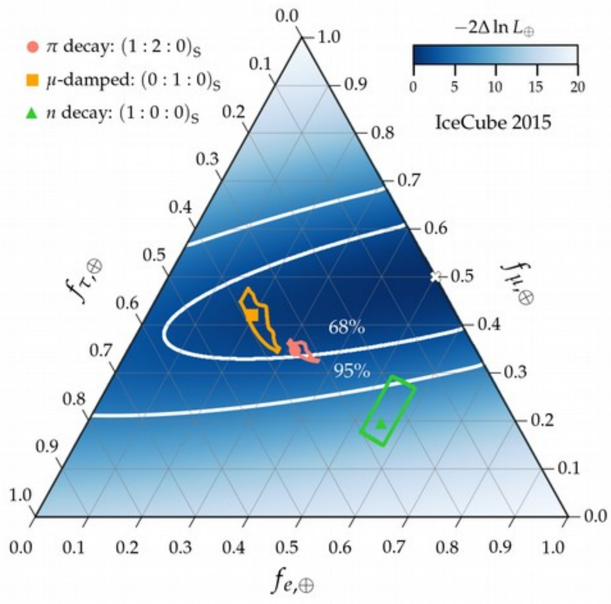
+

Vary oscillation parameters within 3σ

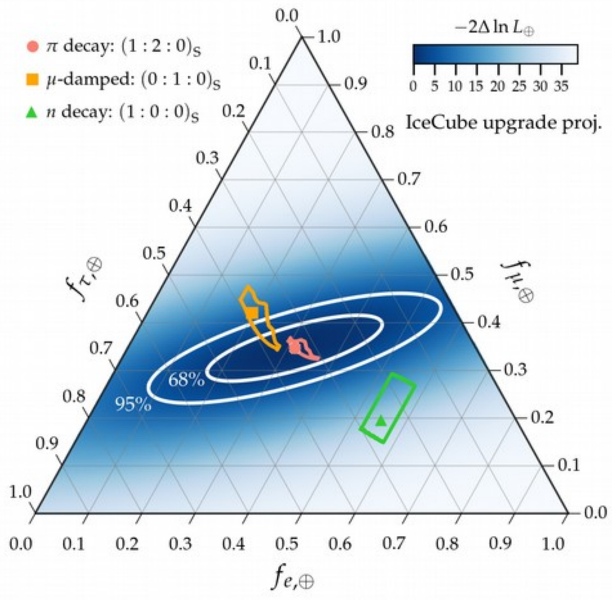
Note: ν and $\bar{\nu}$ are (so far) indistinguishable in neutrino telescopes

IceCube flavor composition

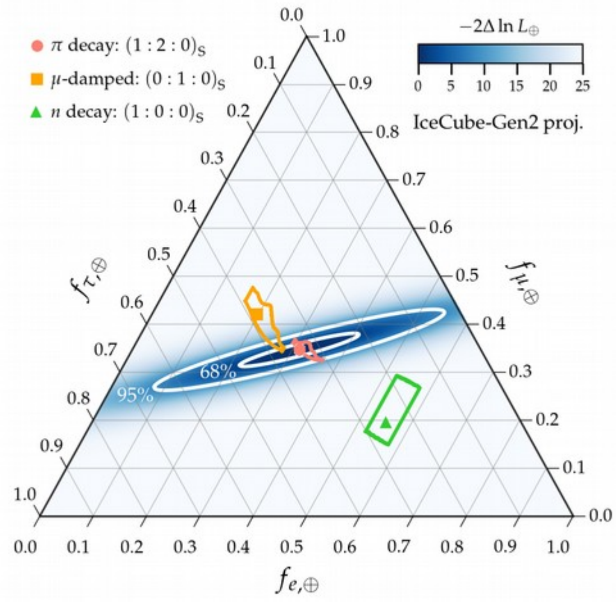
Today
IceCube



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)

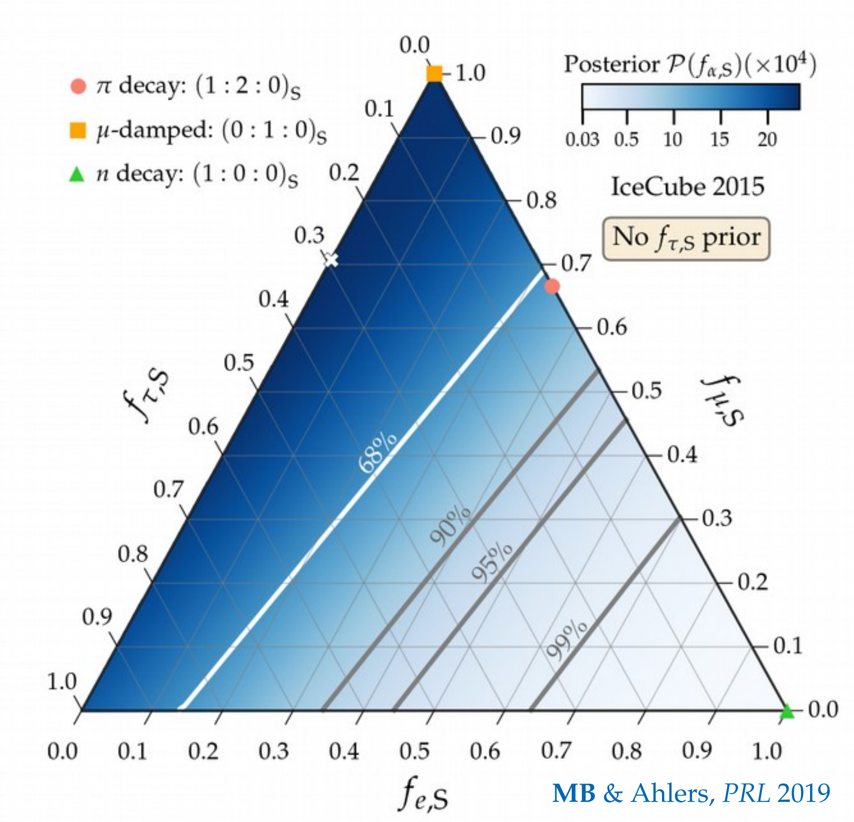
Assuming production by the full pion decay chain

Plus possibly better flavor-tagging, *e.g.*, muon and neutron echoes

[Li, **MB**, Beacom *PRL* 2019]

Flavor – What is it good for?

Trusting particle physics
and learning about astrophysics



MB & Ahlers, *PRL* 2019

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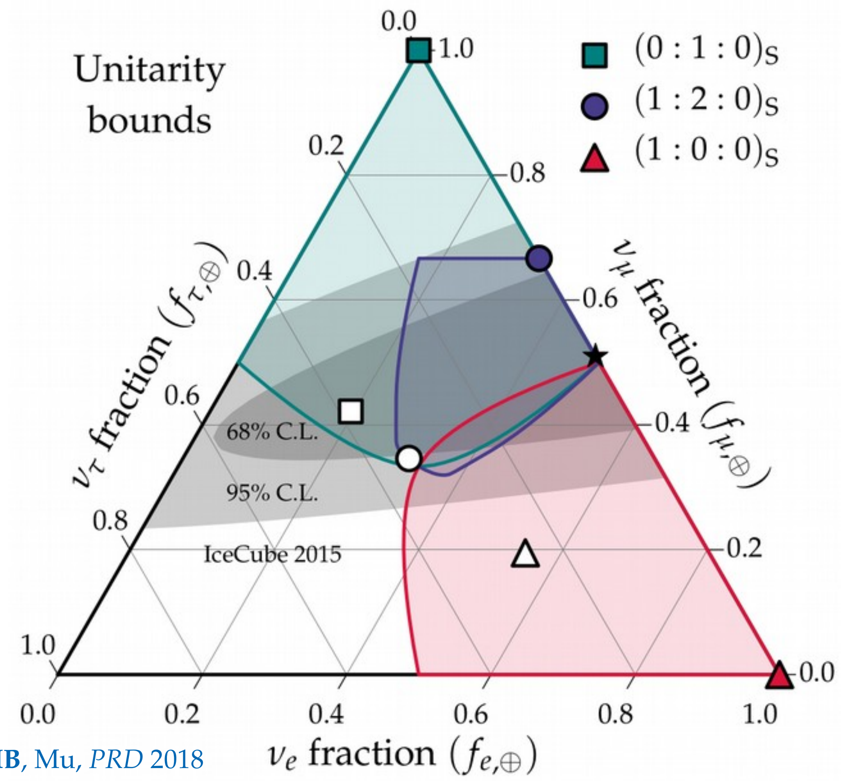
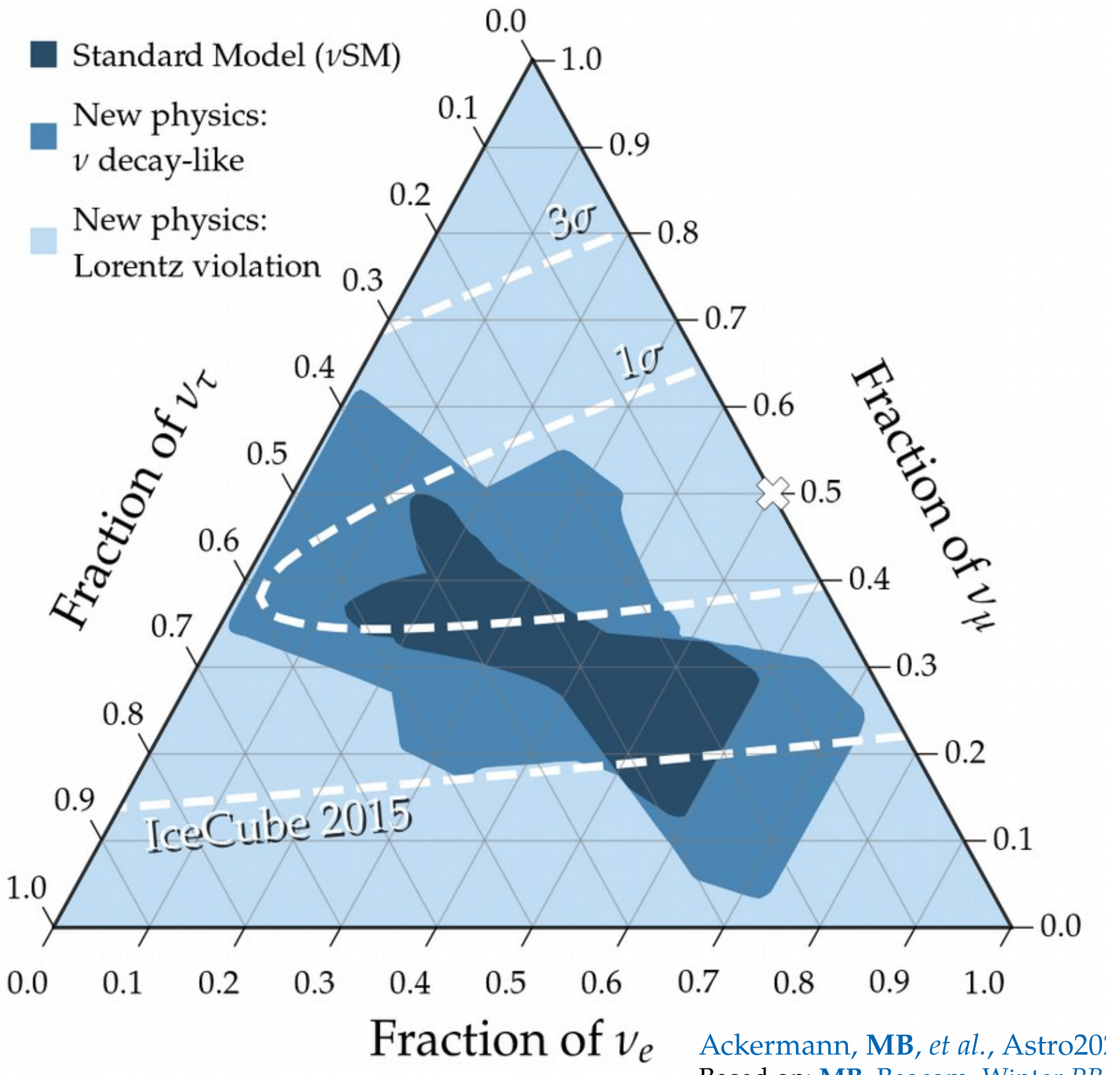
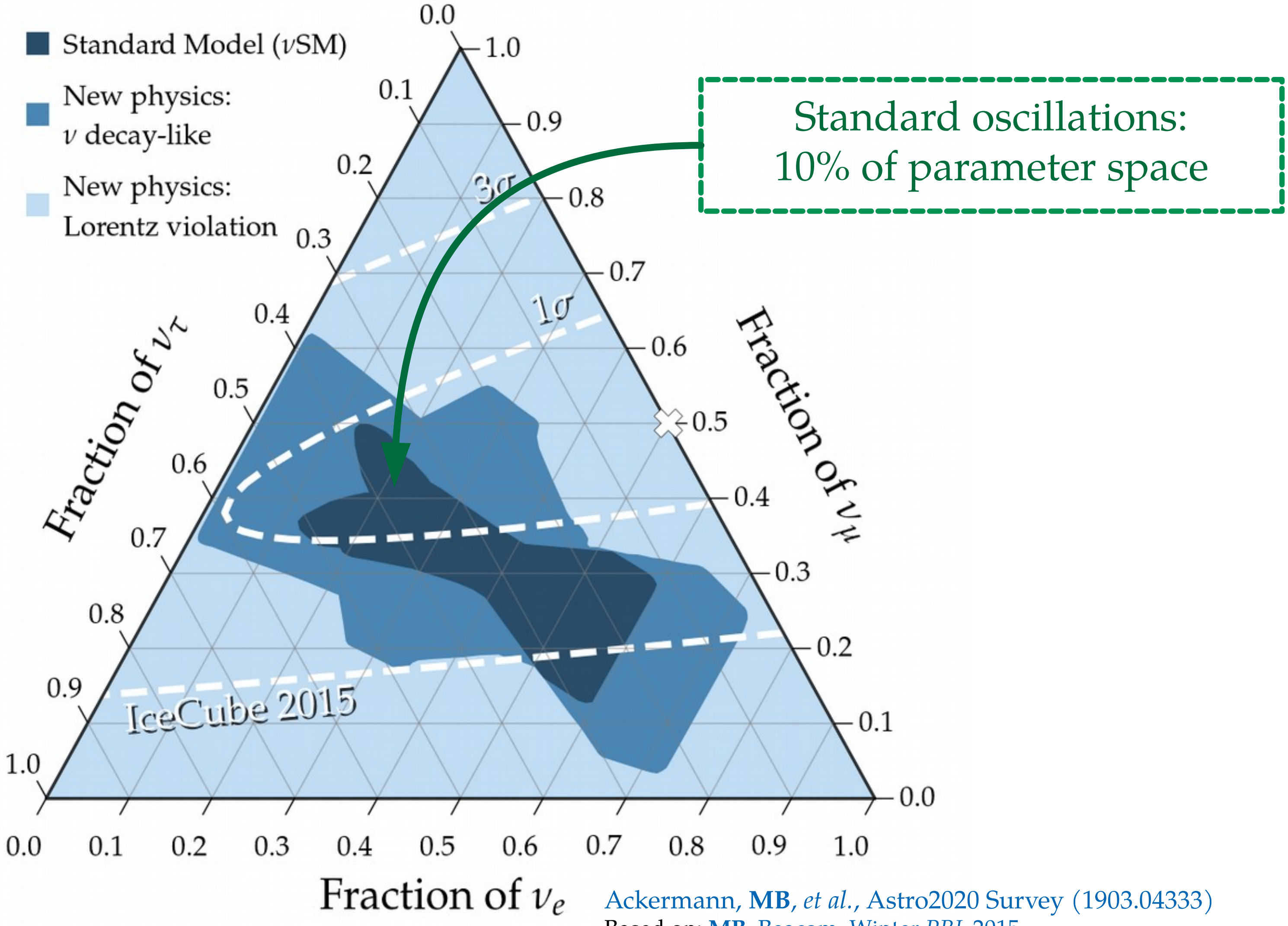


Ahlers, **MB**, Mu, *PRD* 2018



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



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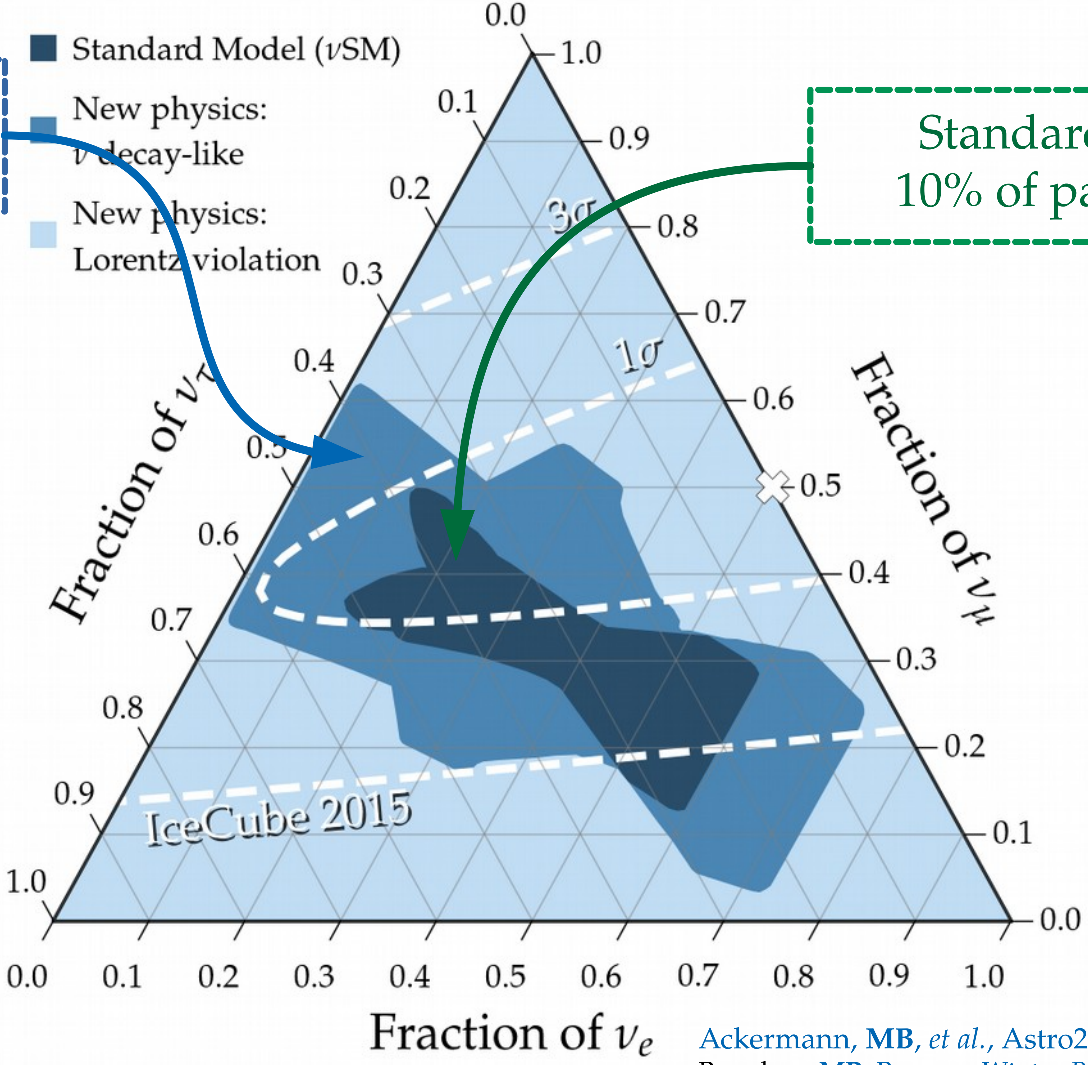
Neutrino decay
30% of parameter space



Standard oscillations:
10% of parameter space

Ackermann, **MB**, *et al.*, Astro2020 Survey (1903.04333)
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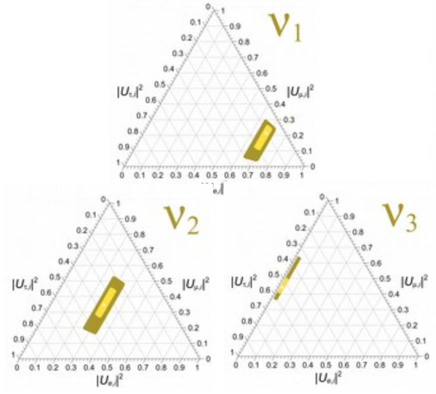
Neutrino decay
30% of parameter space

$\nu_2, \nu_3 \to \nu_1$ or $\nu_1, \nu_2 \to \nu_3$

Flavor ratios determined by how many ν_1, ν_2, ν_3 survive:



$\tau_2/m_2, \tau_3/m_3 > 10$ s eV^{-1}

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

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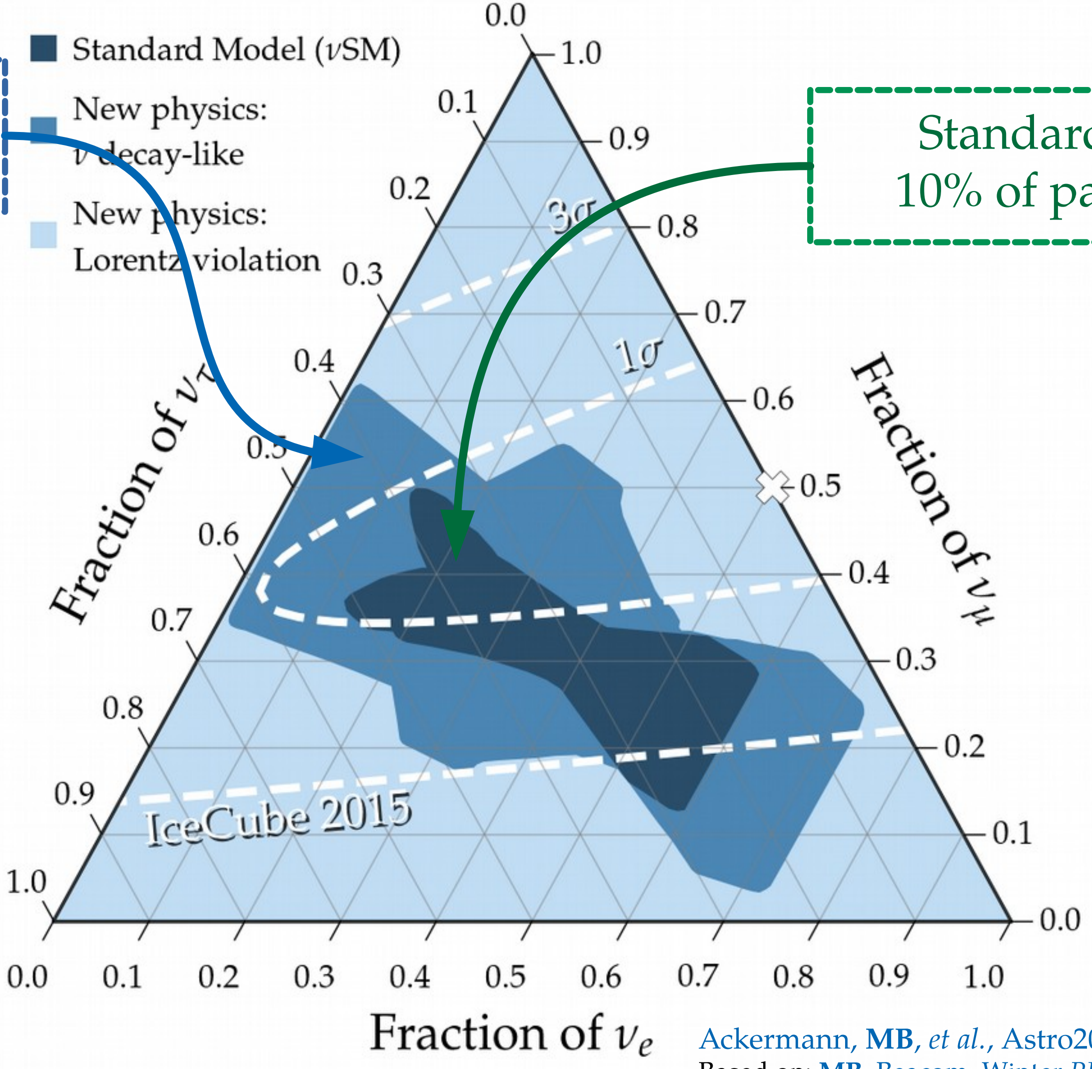

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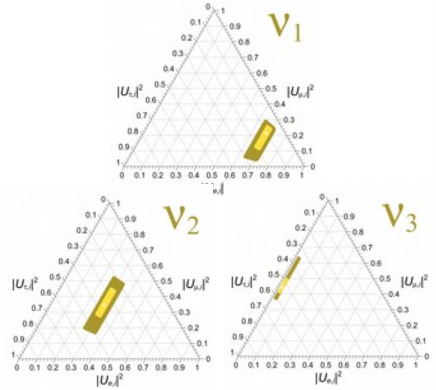

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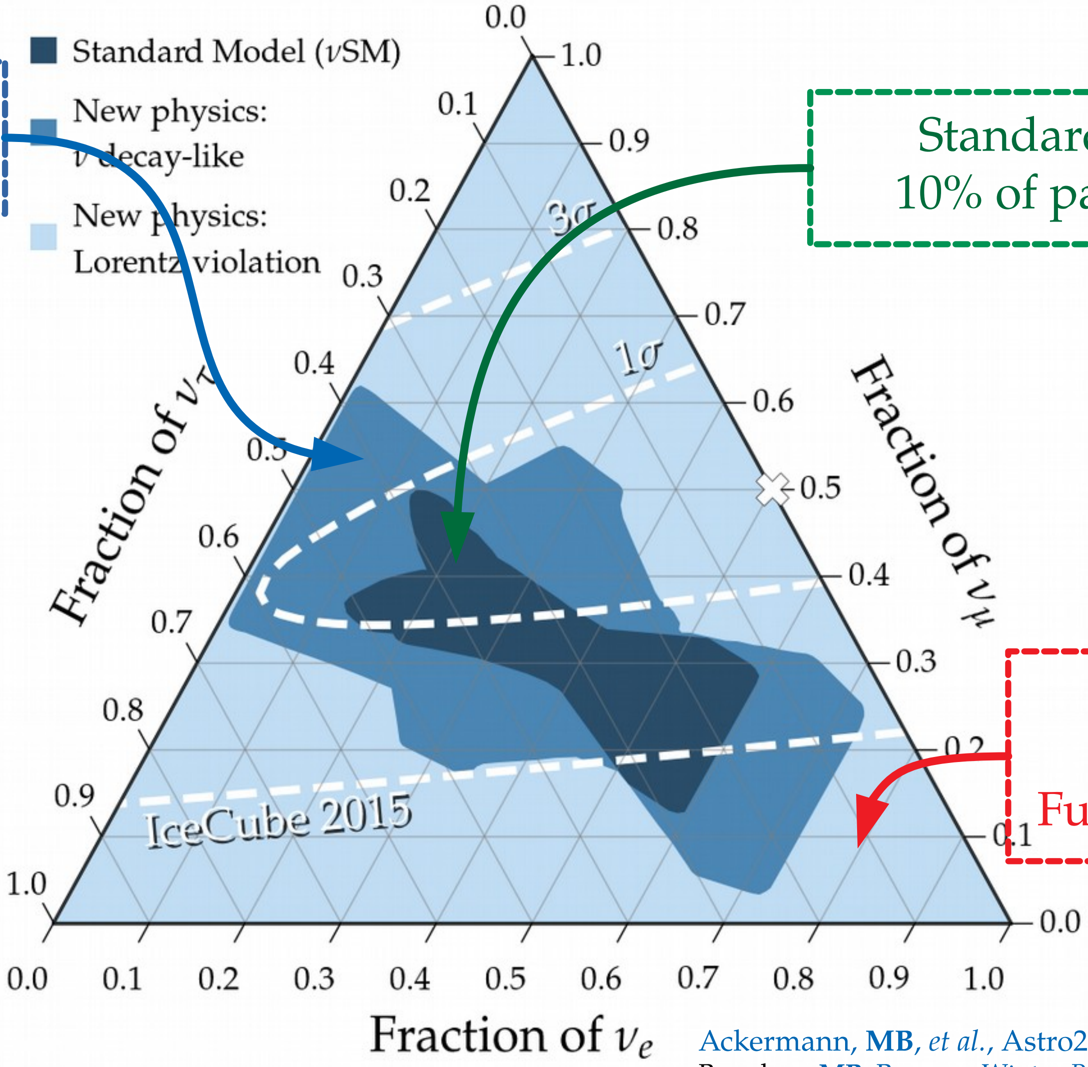

Standard oscillations:
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Lorentz, CPT violation, etc:
Full parameter space

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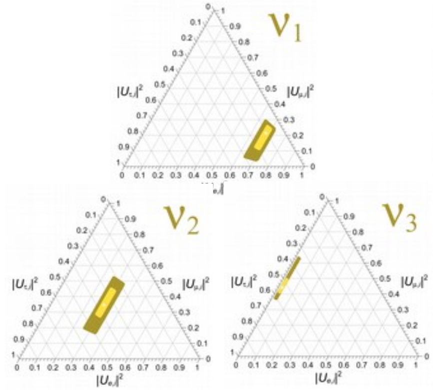

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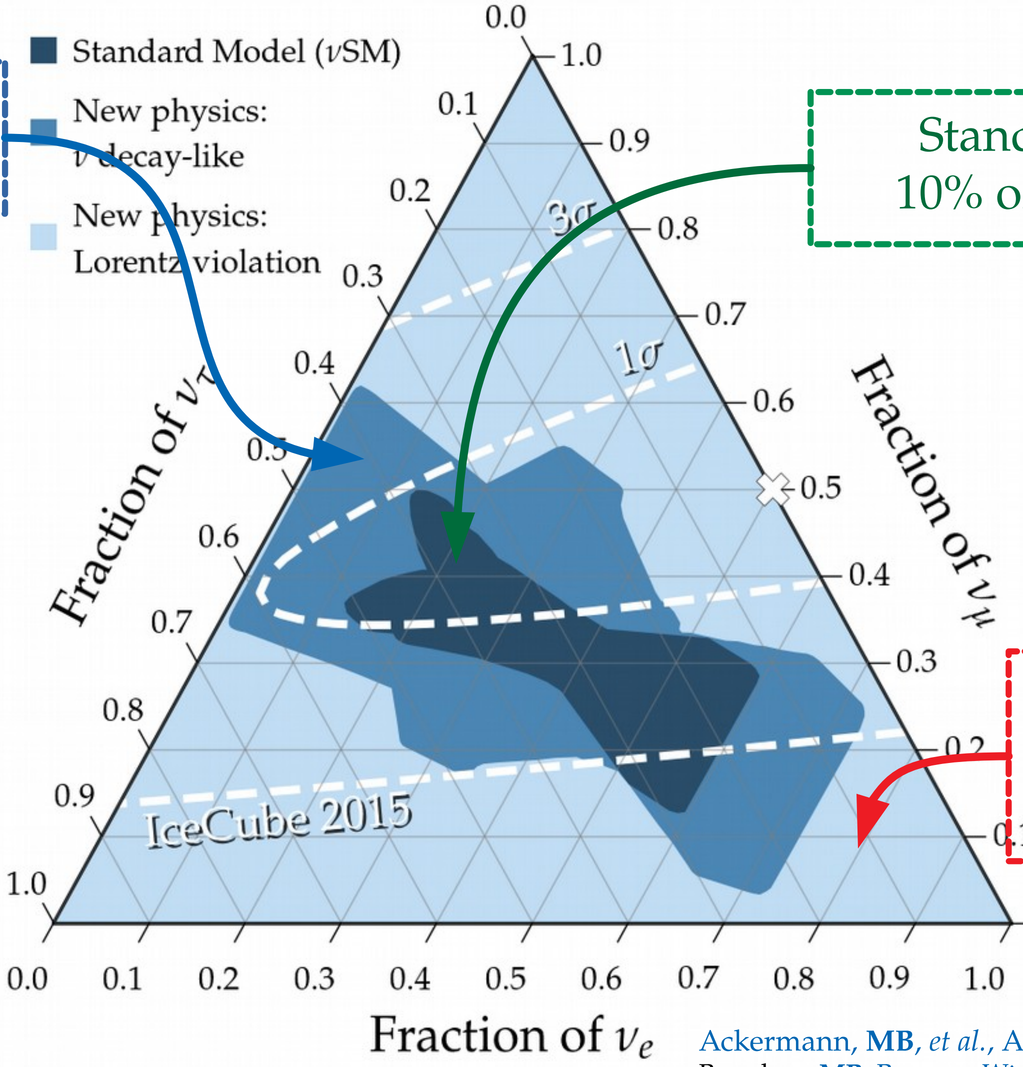

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Ackermann, **MB**, *et al.*, Astro2020 Survey (1903.04333)
Based on: **MB**, Beacom, Winter *PRL* 2015

What lies beyond? *Take your pick*

- 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 $\nu\nu$ interactions
    [Ng & Beacom, *PRD* 2014; Cherry, Friedland, Shoemaker, 1411.1071; Blum, Hook, Murase, 1408.3799]

- …

Toho Company Ltd.

New physics – High-energy effects

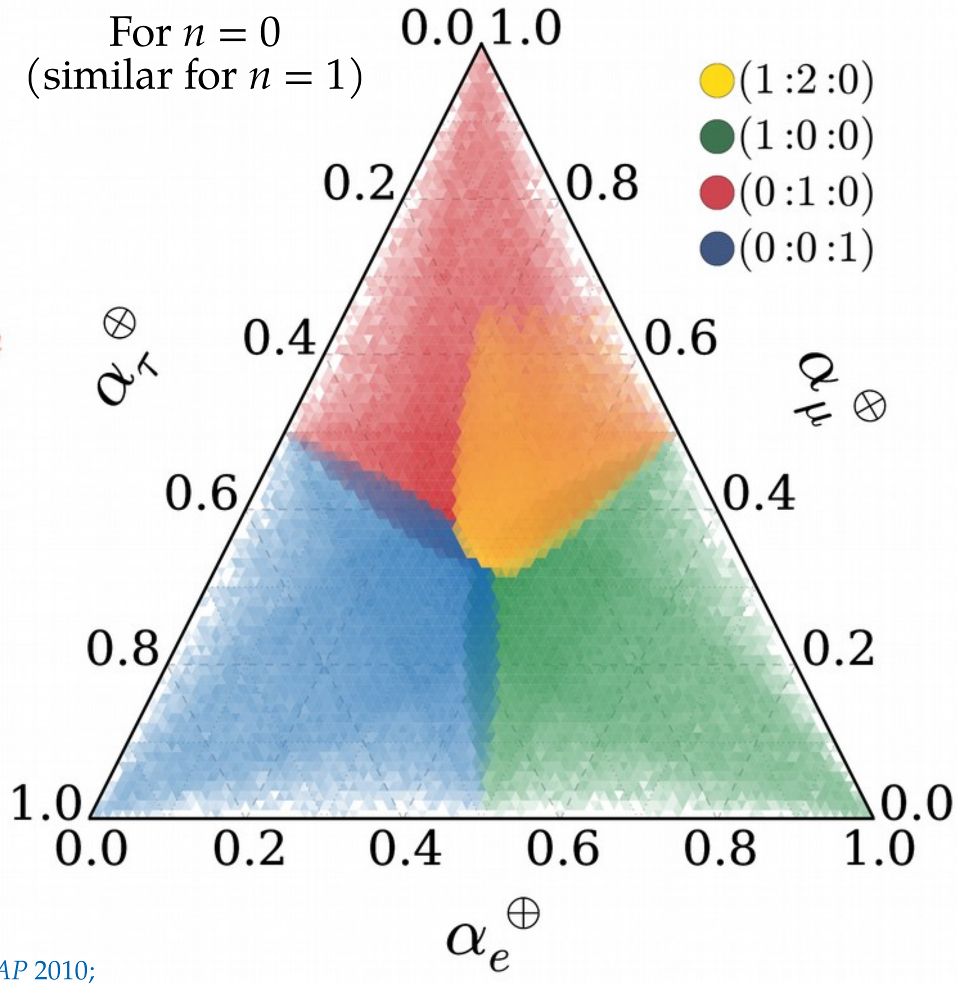
$$H_{\text{tot}} = H_{\text{std}} + H_{\text{NP}}$$

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

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

This can populate *all* of the triangle –

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



Argüelles, Katori, Salvadó, *PRL* 2015

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

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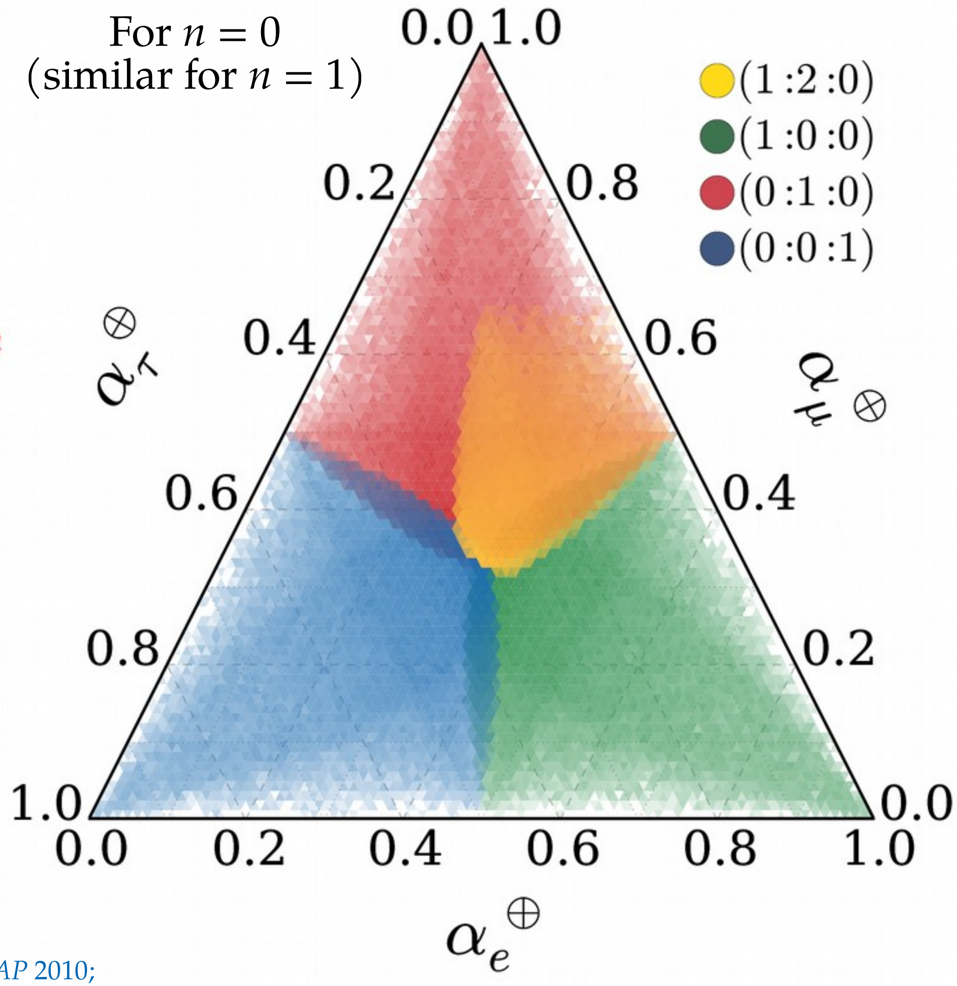

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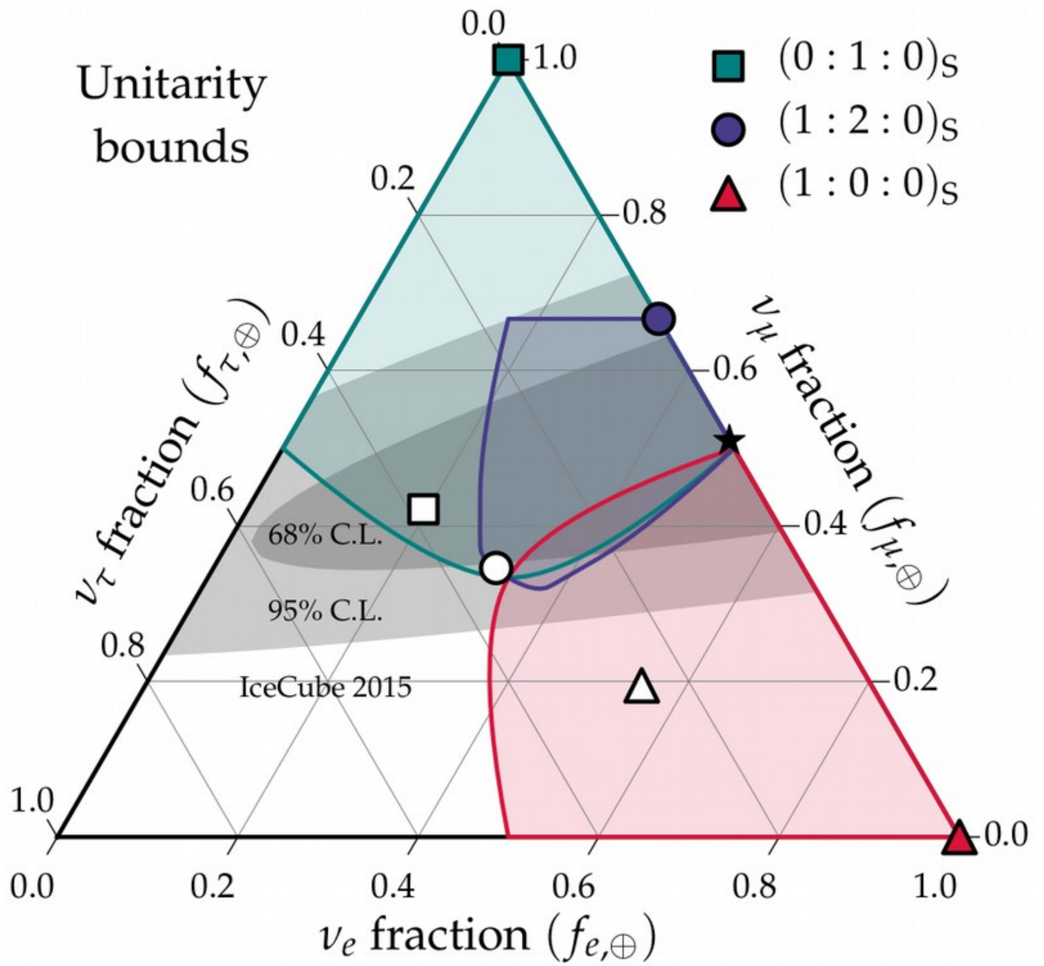
Using unitarity to constrain new physics

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

- 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 —

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

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

The new potential sourced by an electron

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

Z′ coupling

Z′ mass

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

Distance to neutrino

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

Electron-neutrino interactions can kill oscillations

Electron-neutrino interactions can kill oscillations

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

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

Electron-neutrino interactions can kill oscillations

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

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

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

Electron-neutrino interactions can kill oscillations

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

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

New neutrino-electron interaction:
This is diagonal

Electron-neutrino interactions can kill oscillations

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

New neutrino-electron interaction:
This is diagonal

Z′ parameters

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

Electron-neutrino interactions can kill oscillations

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

New neutrino-electron interaction:
This is diagonal

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

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

Electron-neutrino interactions can kill oscillations

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

Electron-neutrino interactions can kill oscillations

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

~$1/E$

Energy-independent

Electron-neutrino interactions can kill oscillations

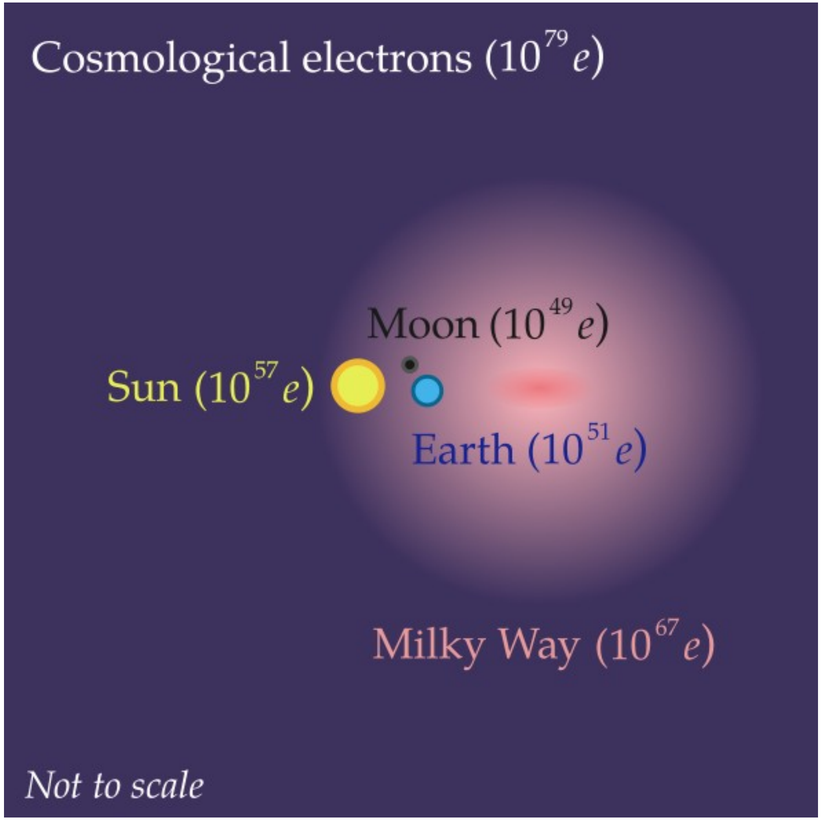
$$\mathrm{H}_{\mathrm{tot}} = \mathrm{H}_{\mathrm{vac}} + \mathrm{V}_{e\beta}$$

$\sim 1/E$

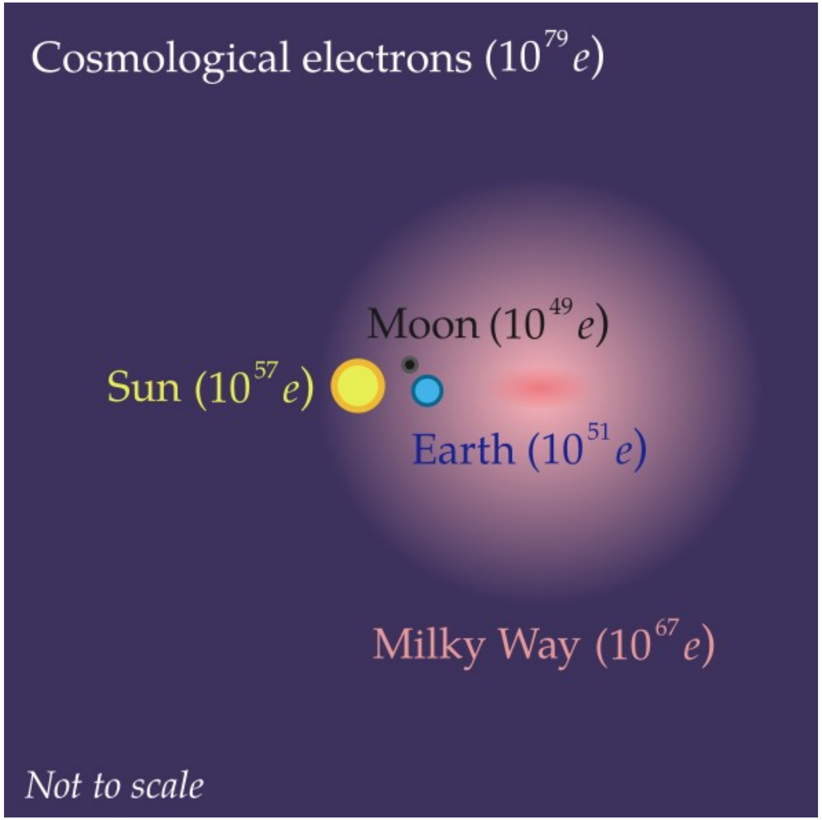
Energy-independent

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

The total potential

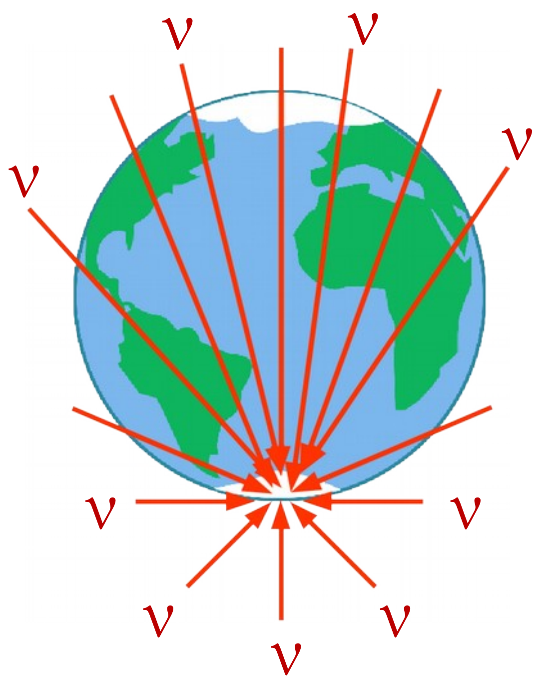


The total potential

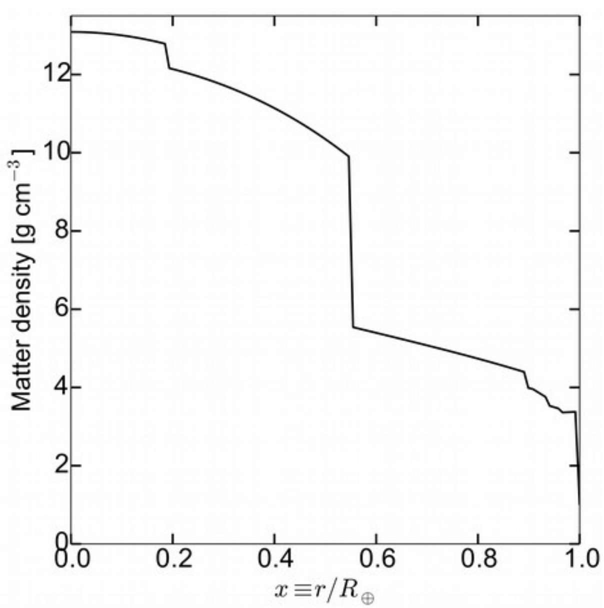


$$V_{e\beta} = V_{e\beta}^{\oplus}$$

Earth:

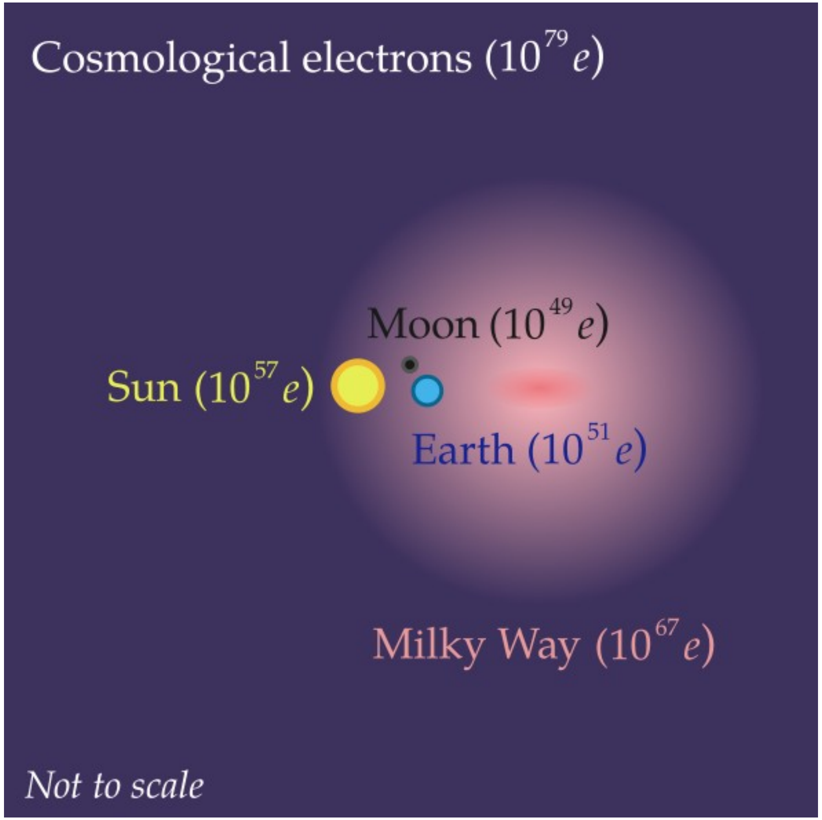


Preliminary Reference Earth Model
Dziewonski & Anderson 1981

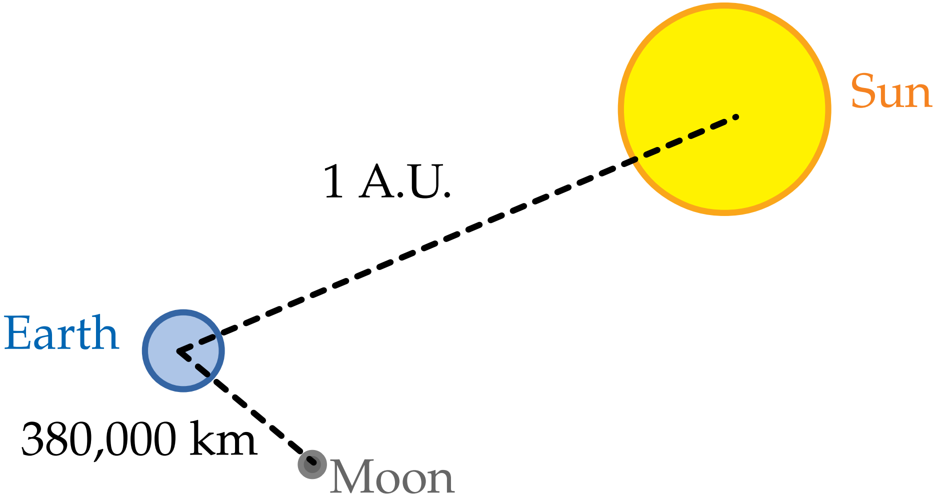


Neutrinos traverse different electron column depths

The total potential



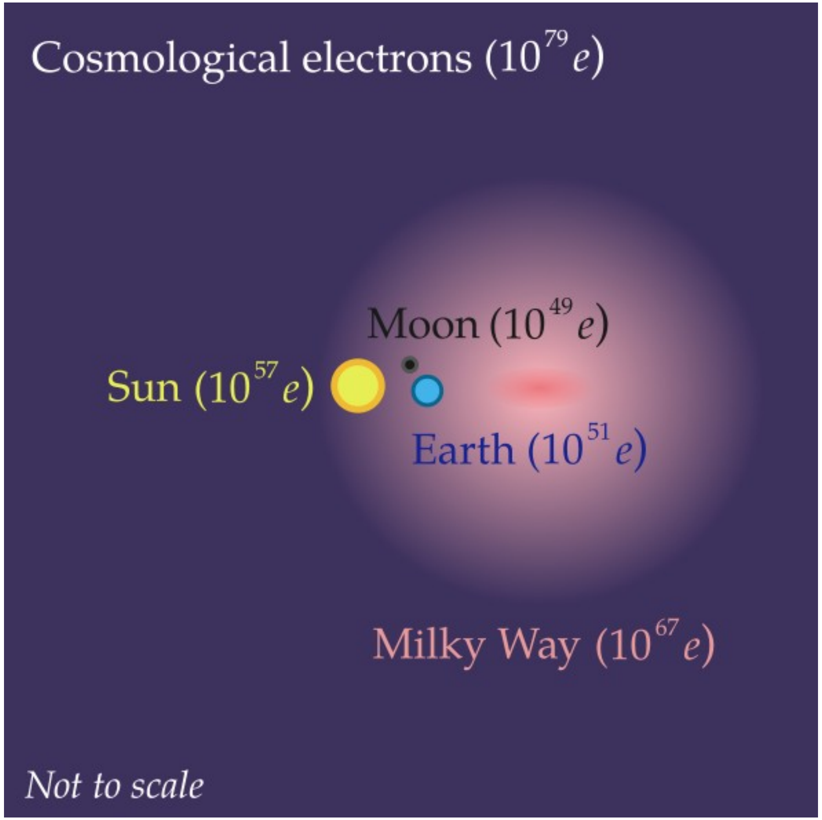
Moon and Sun:



Treated as point sources of electrons

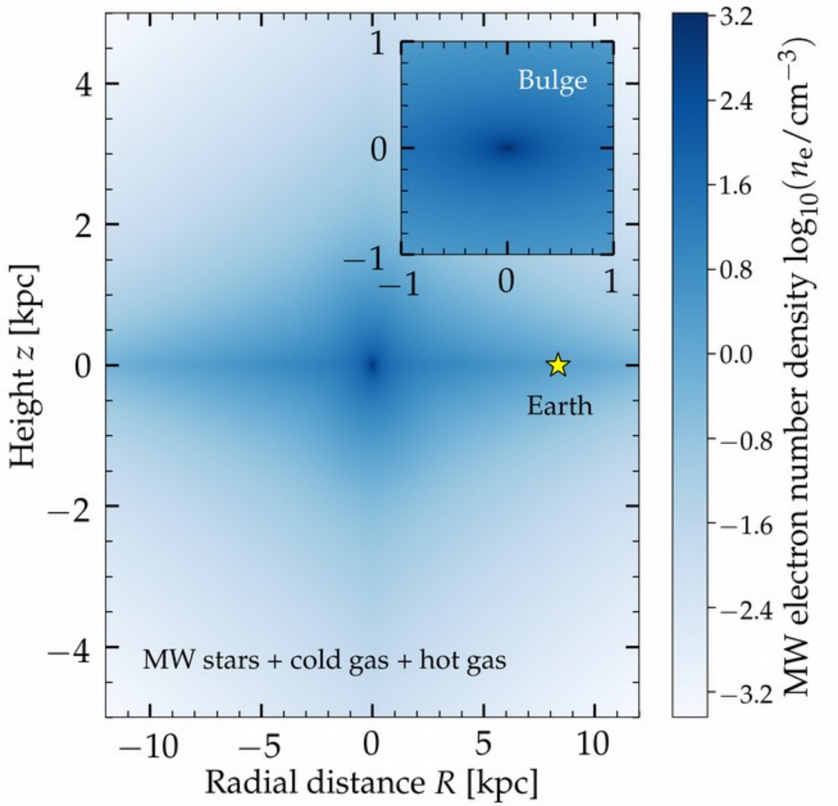
$$V_{e\beta} = V_{e\beta}^{\oplus} + V_{e\beta}^{\text{Moon}} + V_{e\beta}^{\odot}$$

The total potential



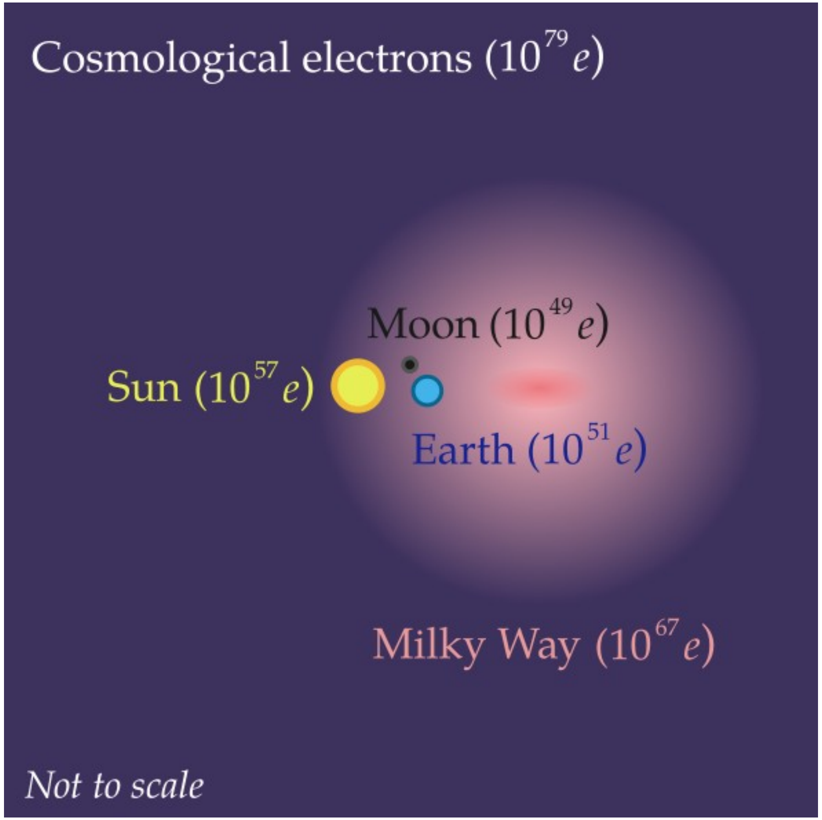
Milky Way:

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



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

The total potential



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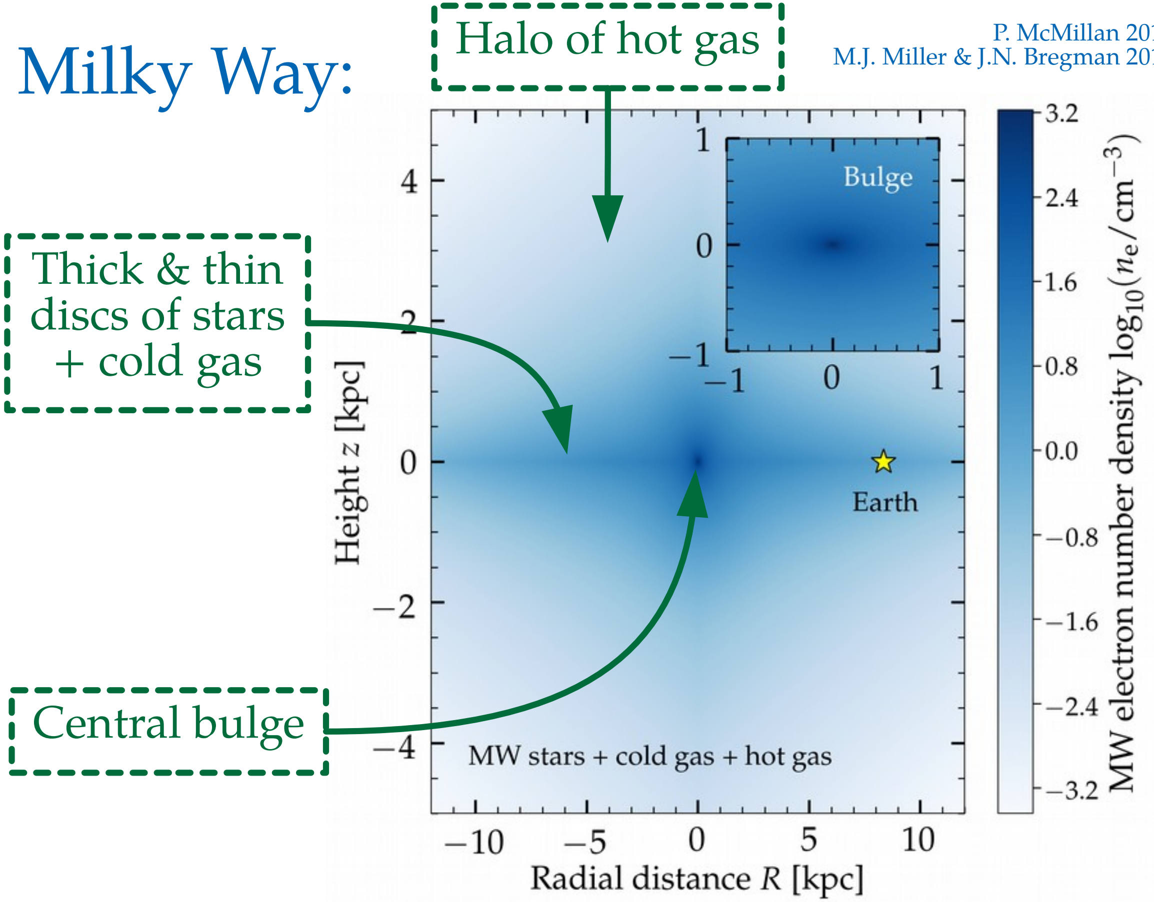

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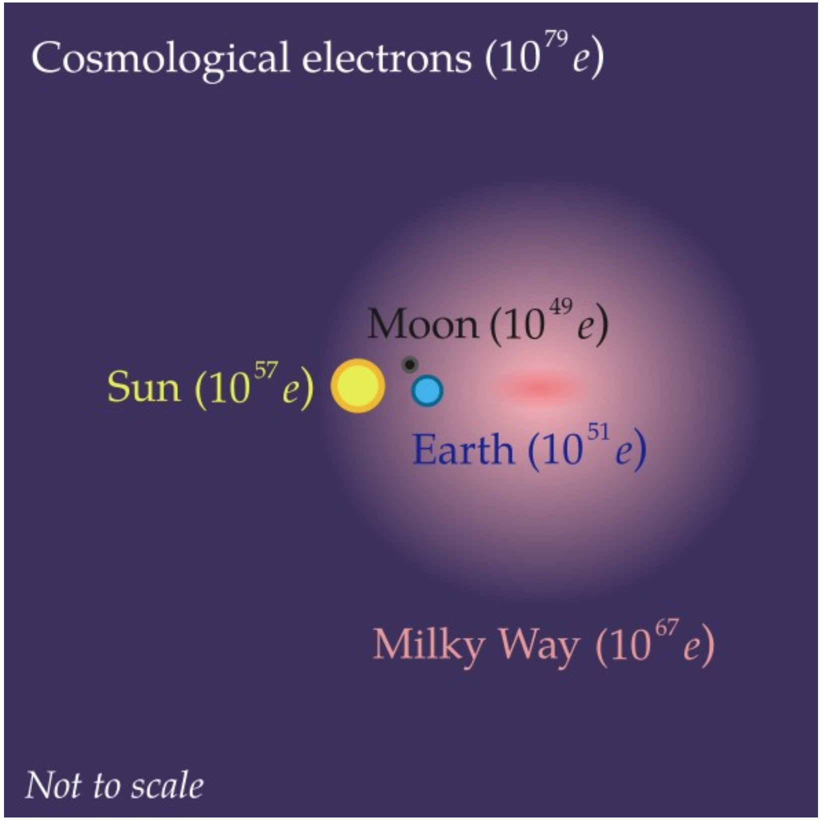
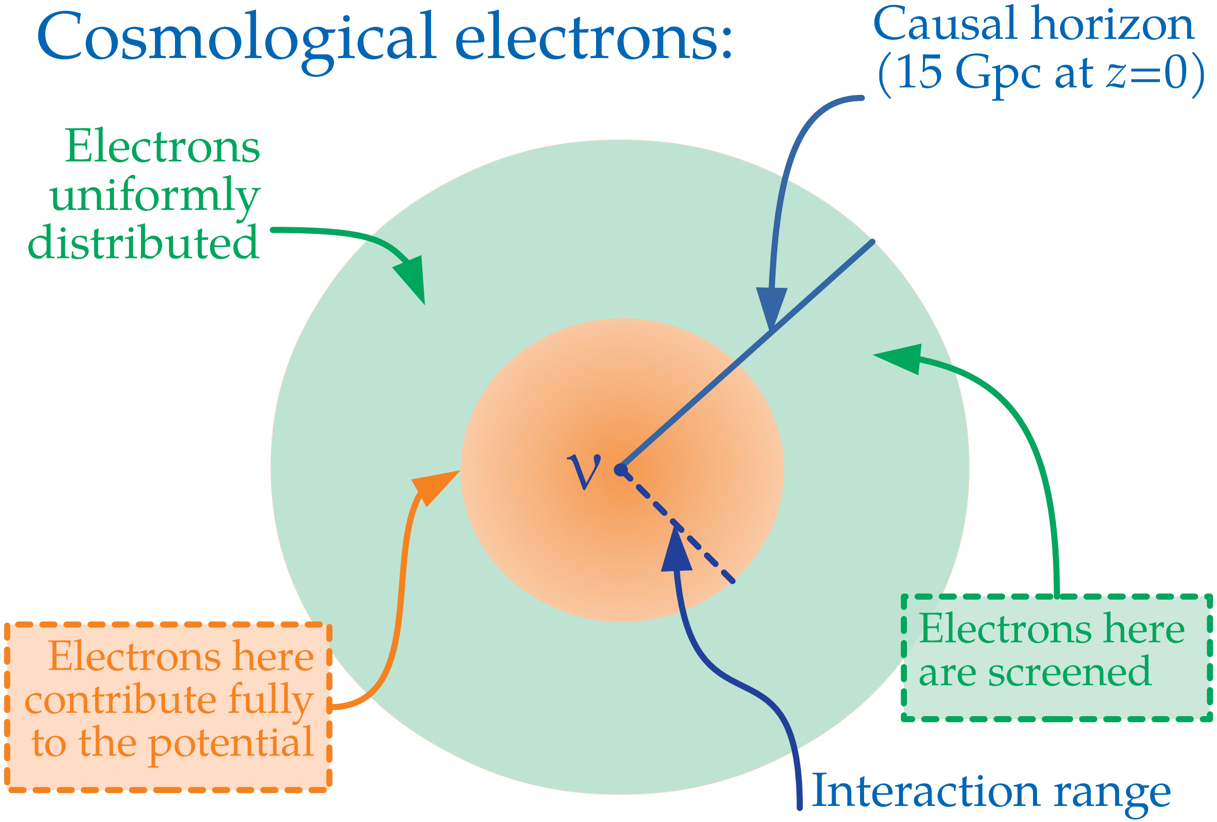
The total potential

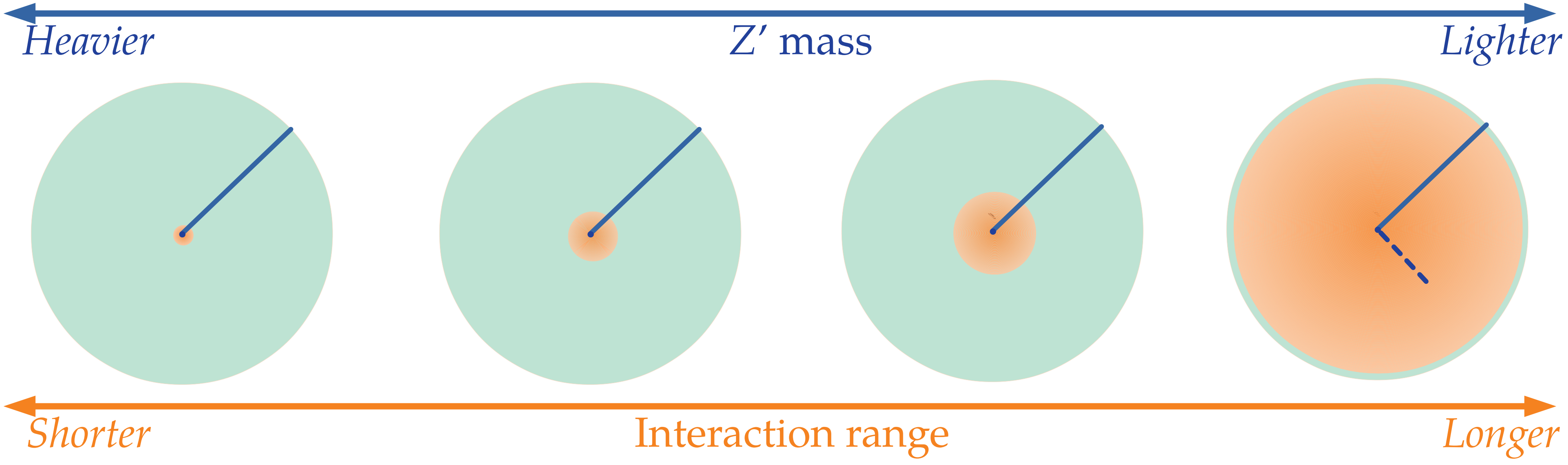


Cosmological electrons:



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

The total potential



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Electrons in the local and distant Universe

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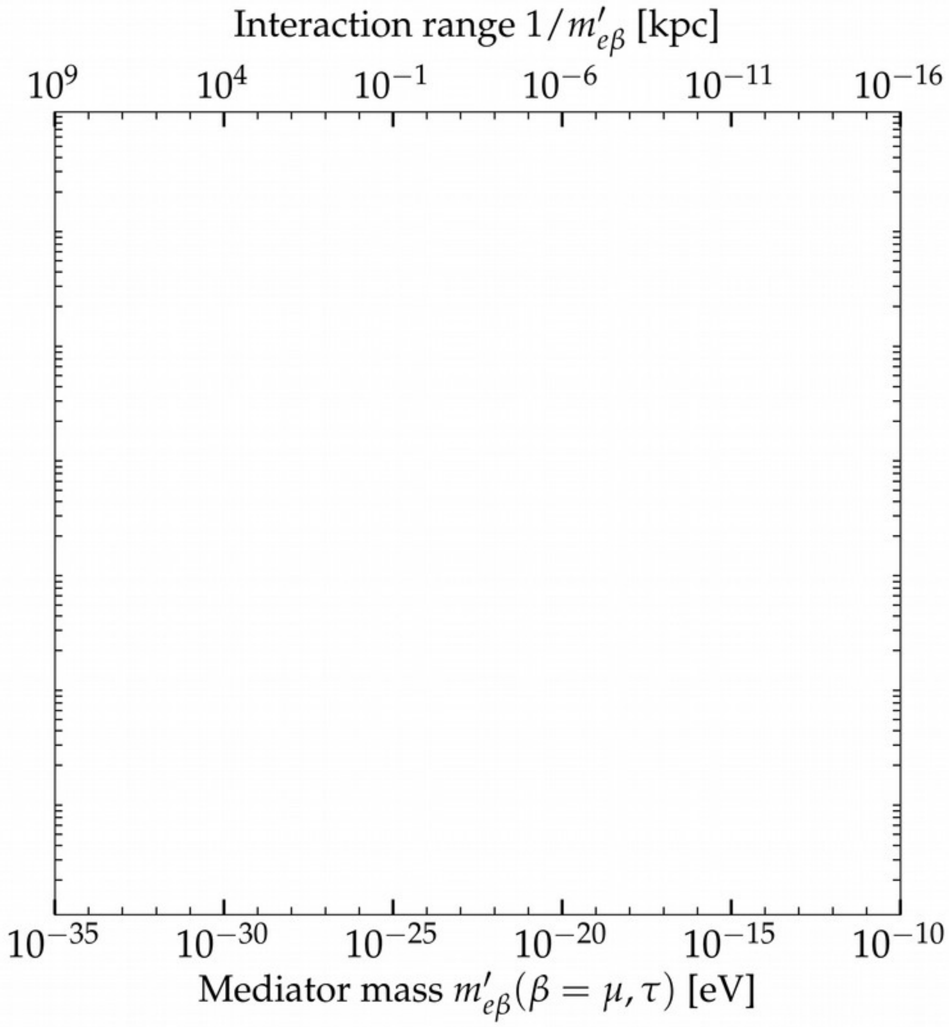

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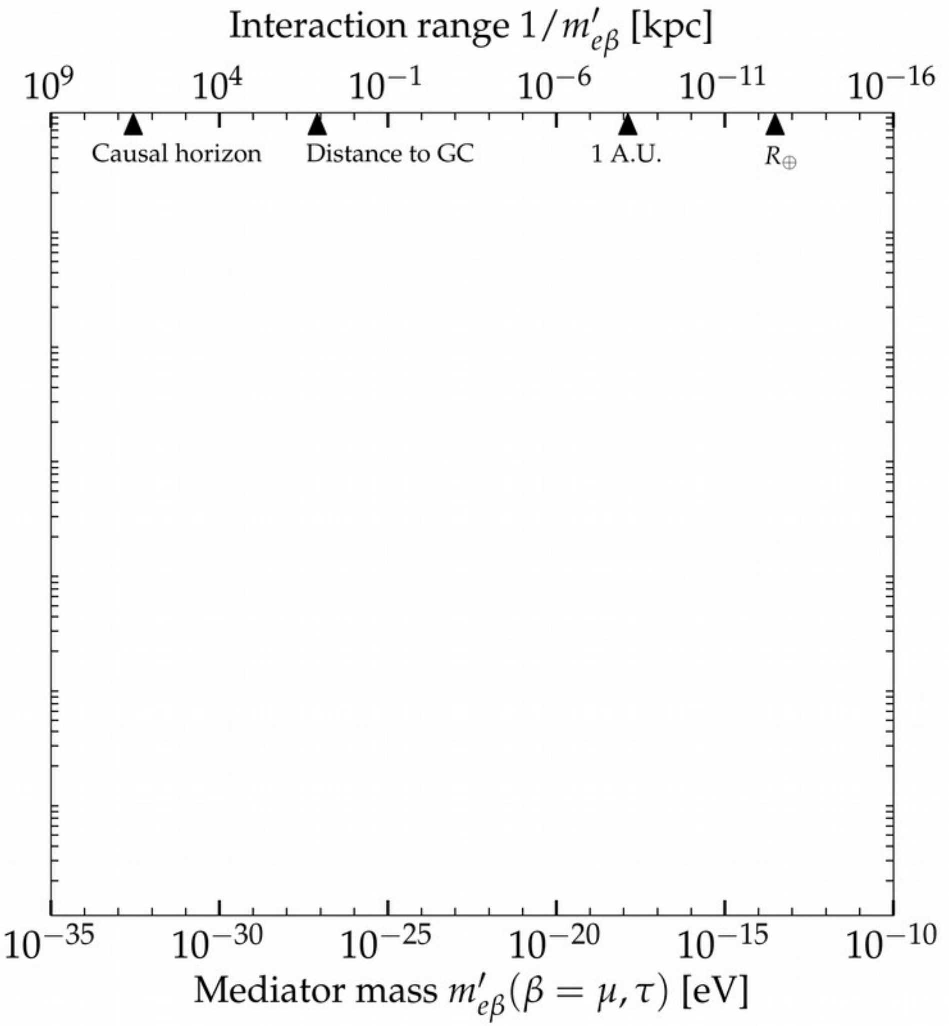

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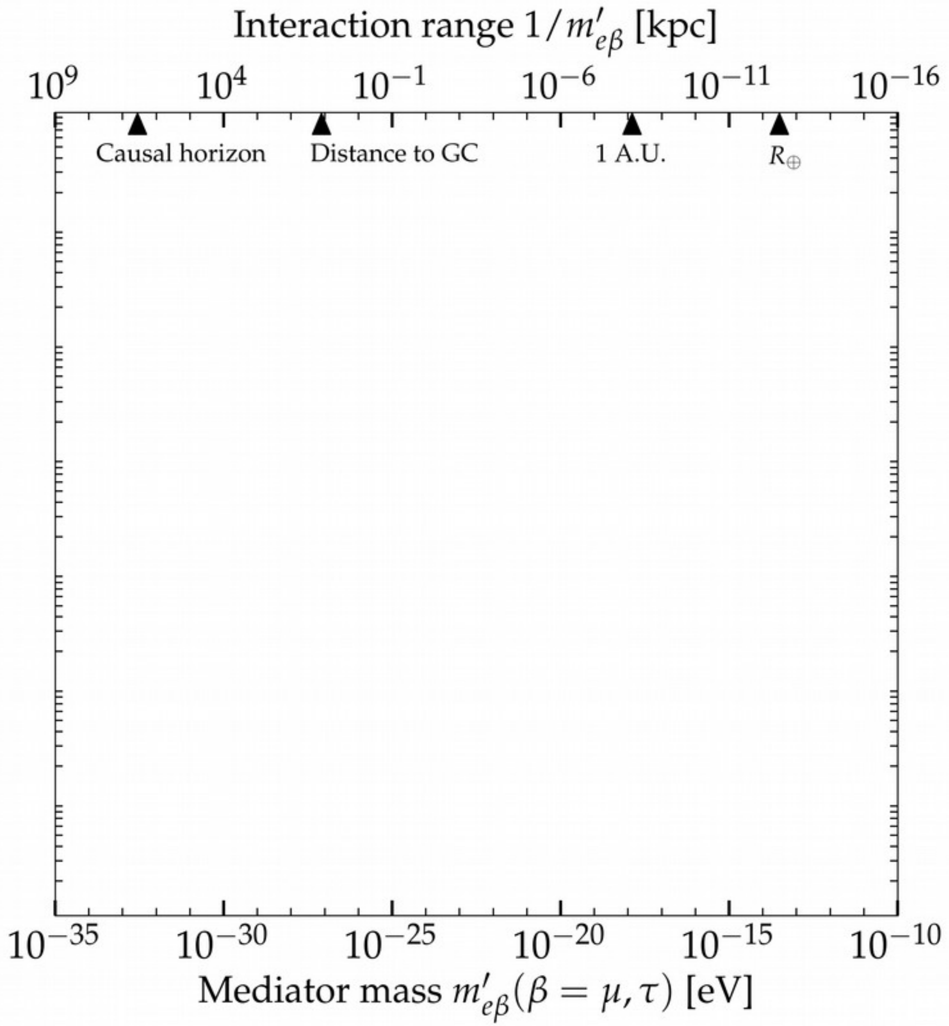

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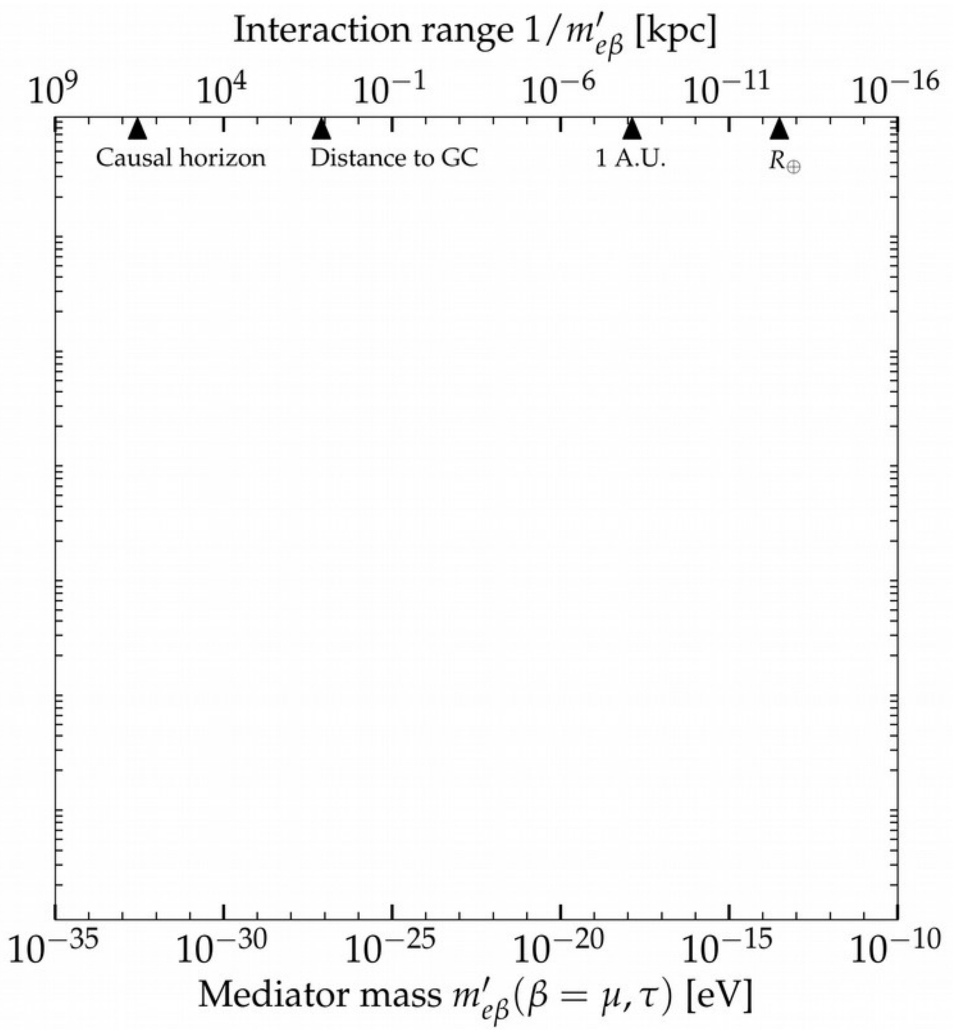
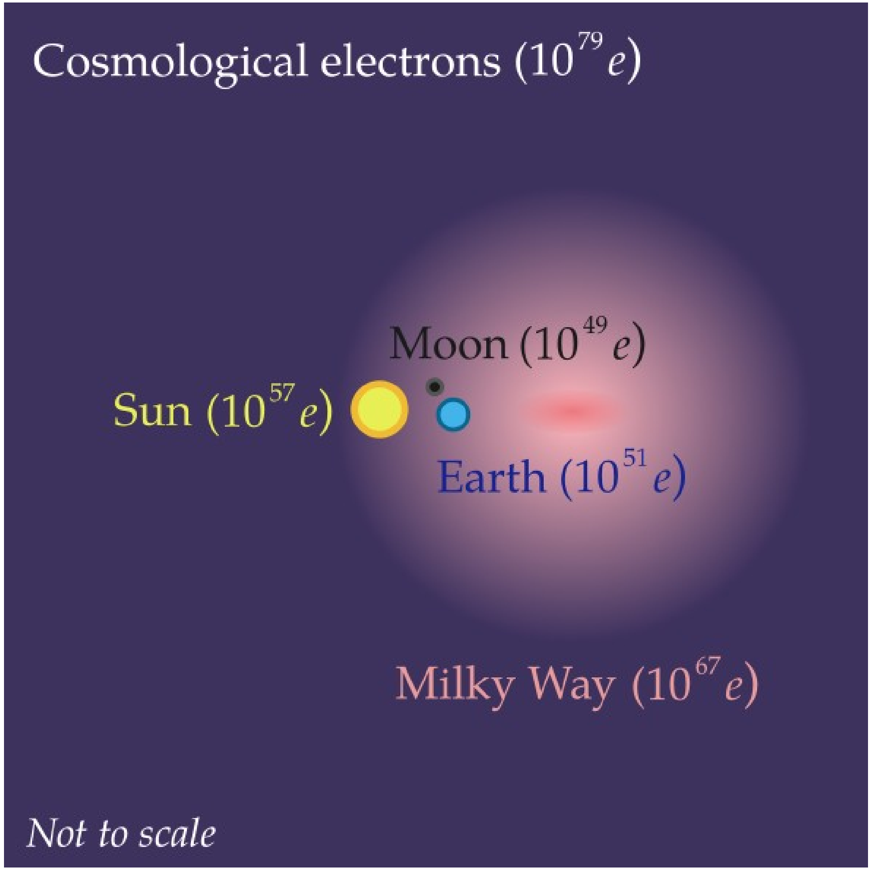
Light mediators
⇒ Long interaction ranges

Electrons in the local and distant Universe





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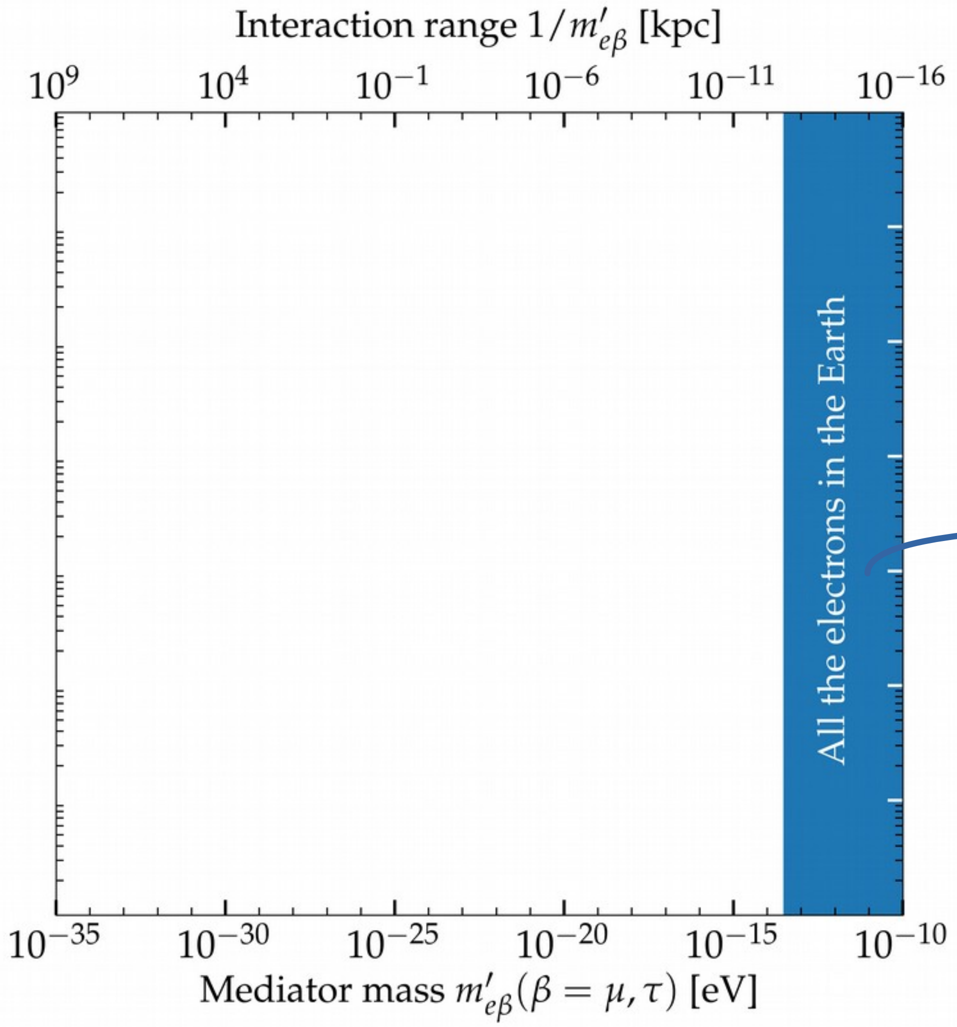

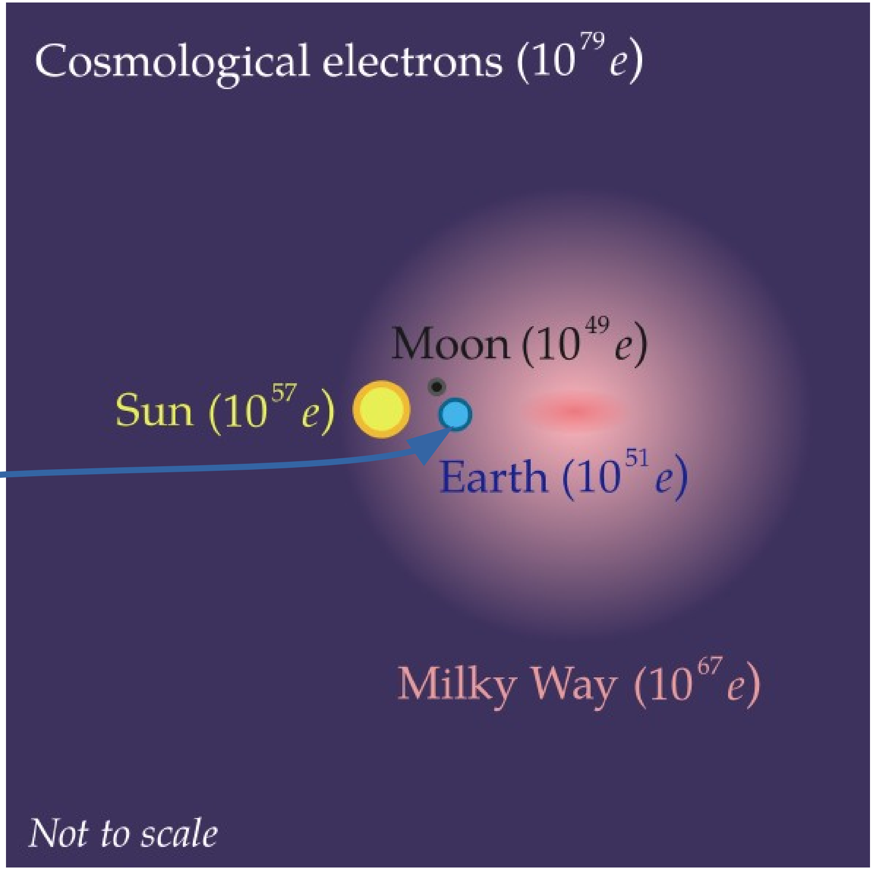

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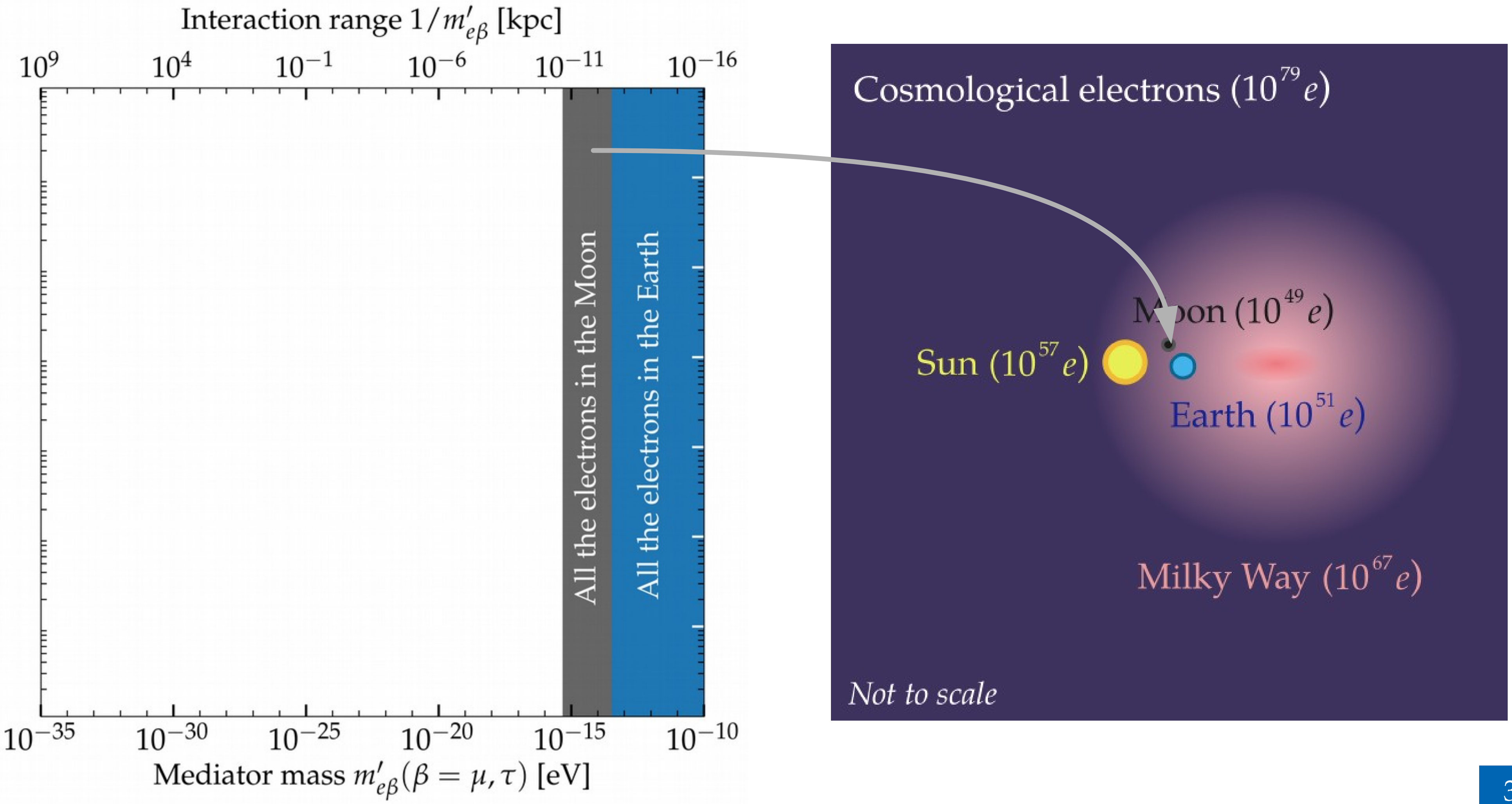

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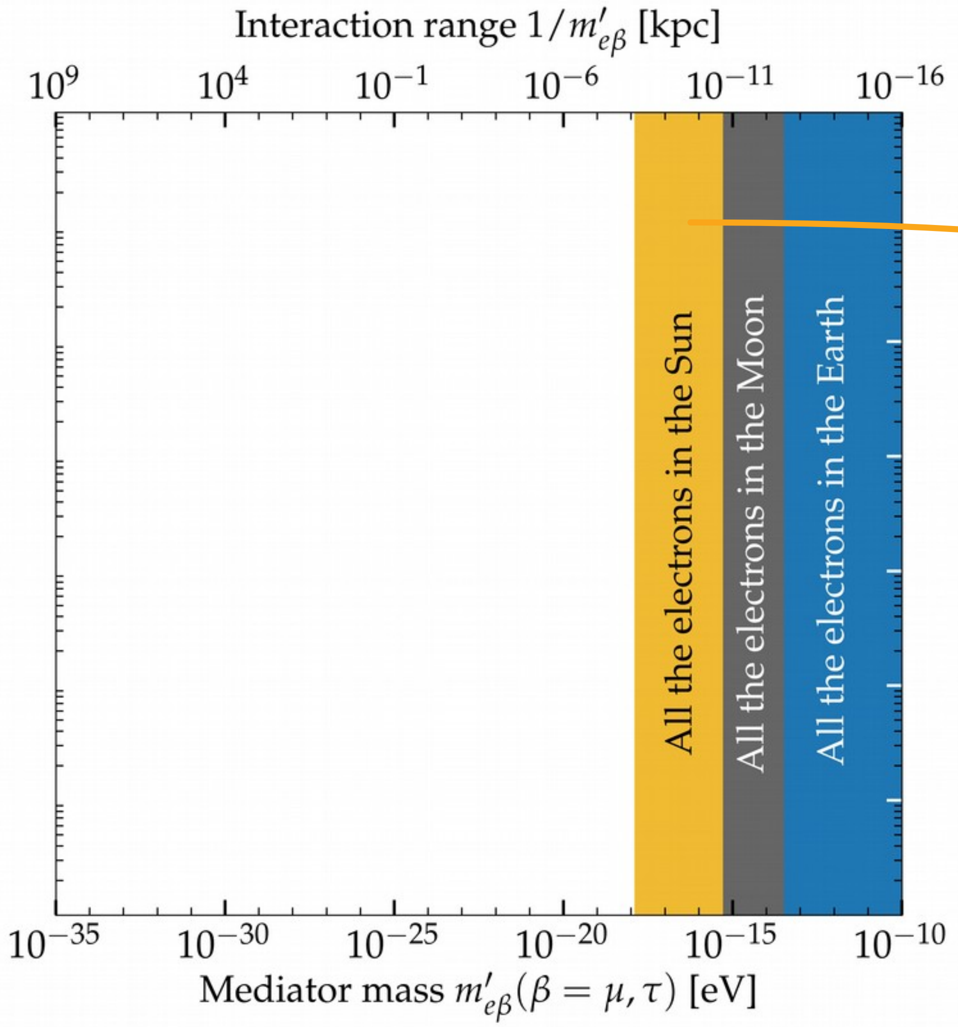

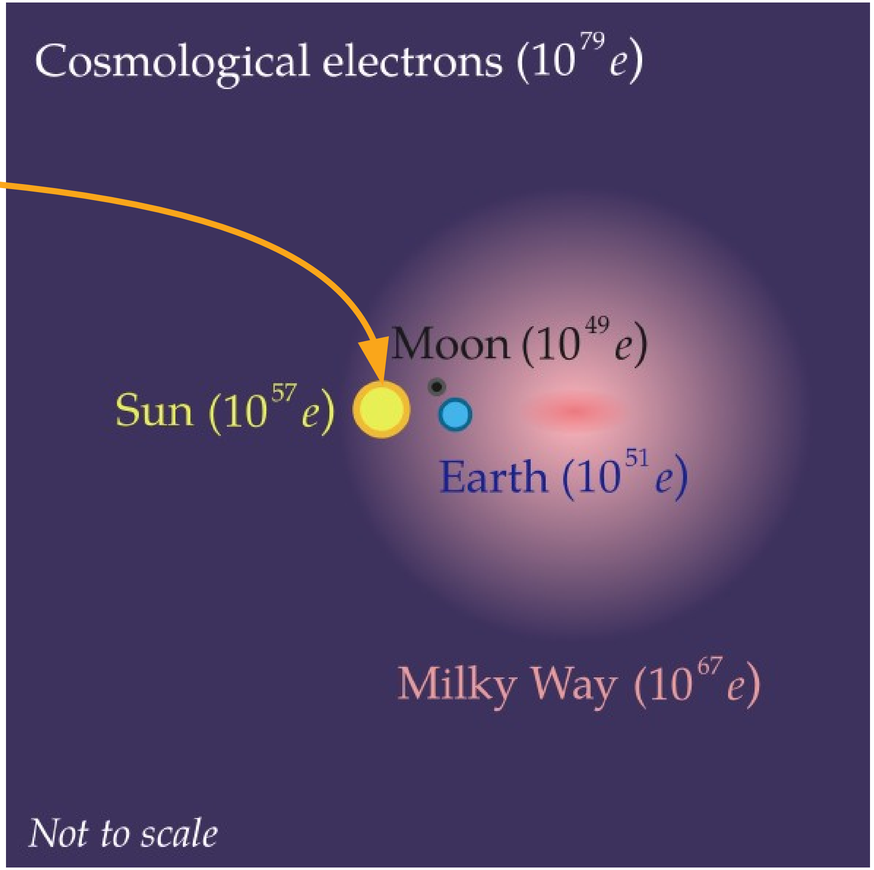

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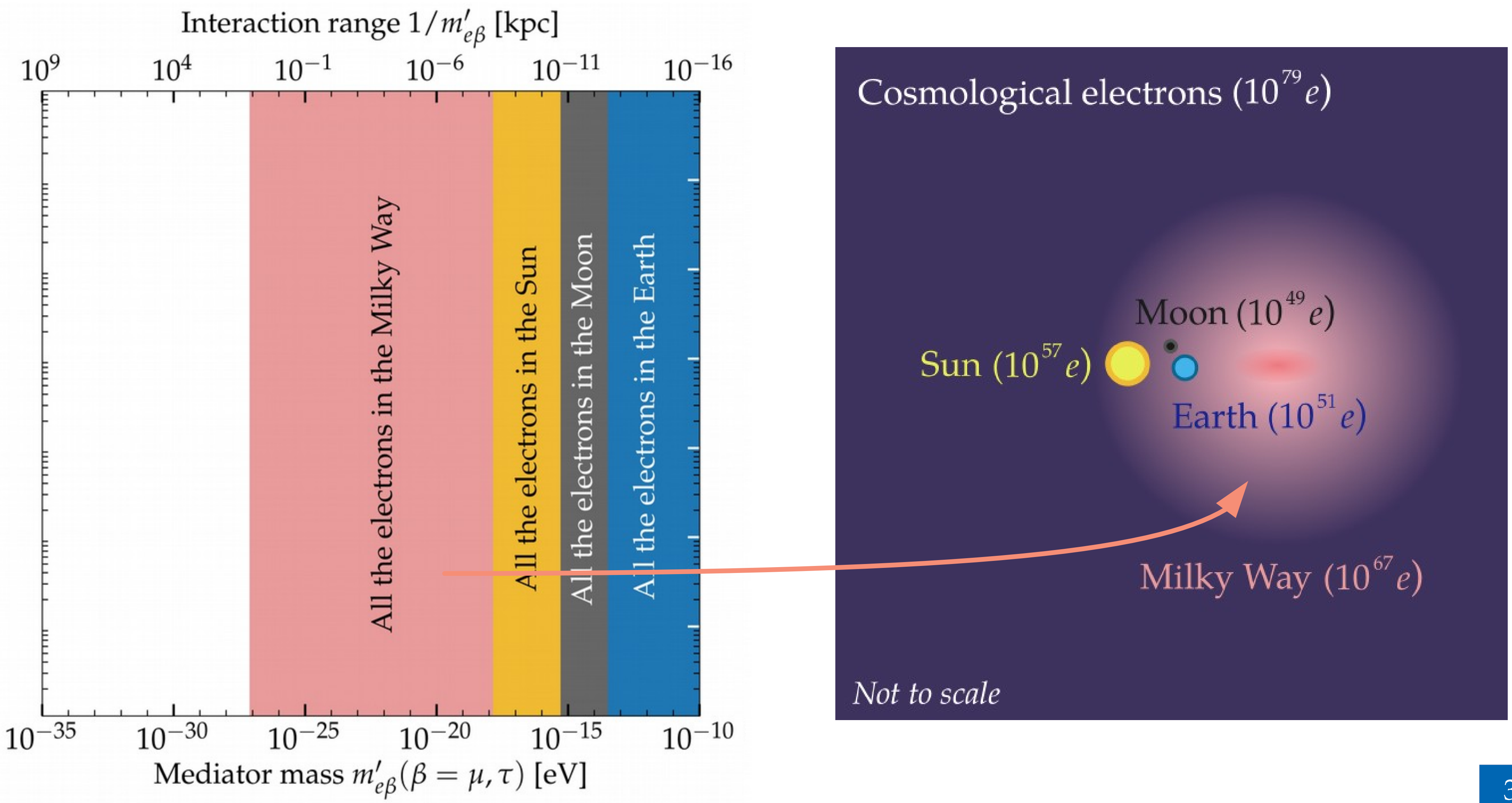

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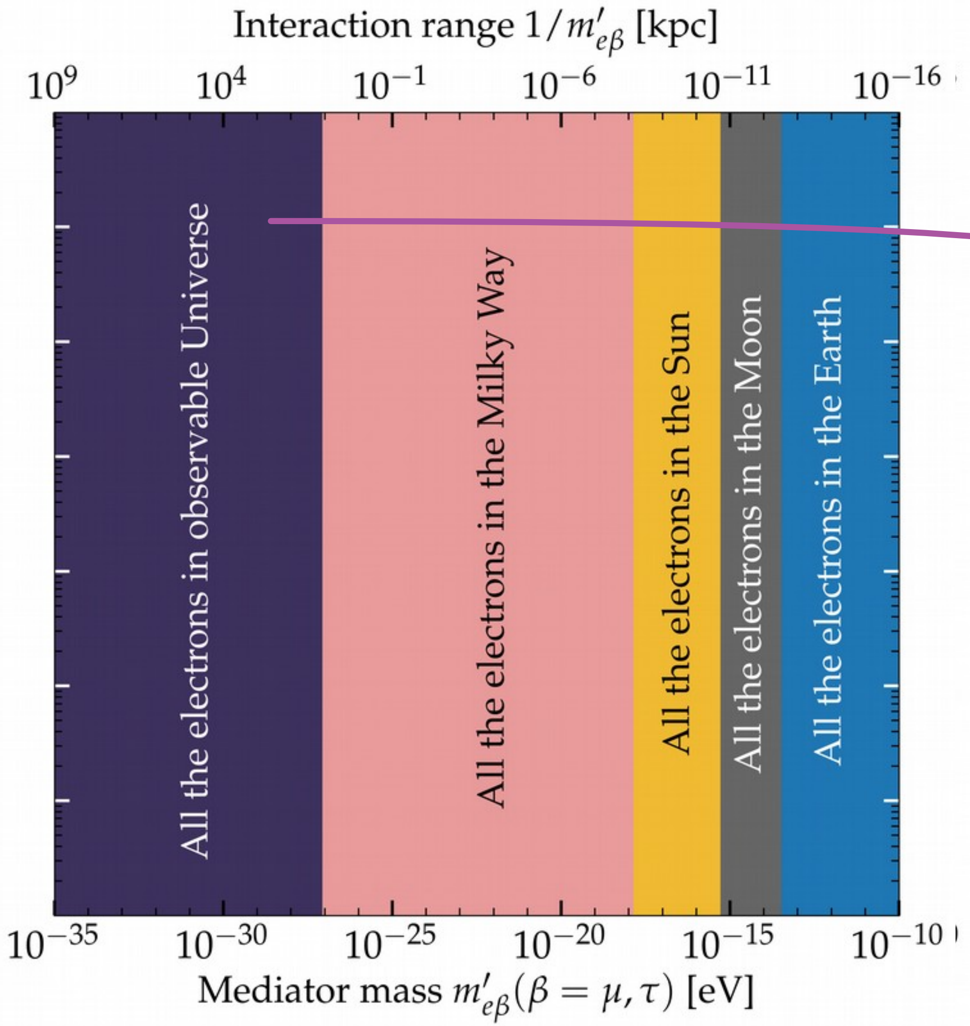

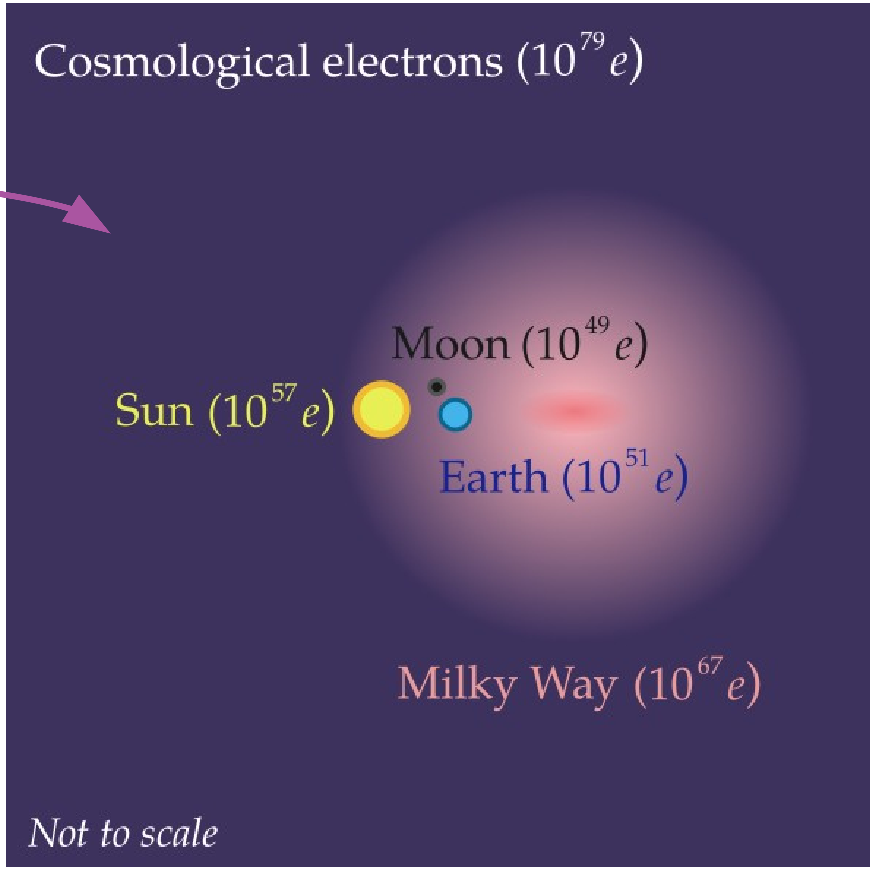

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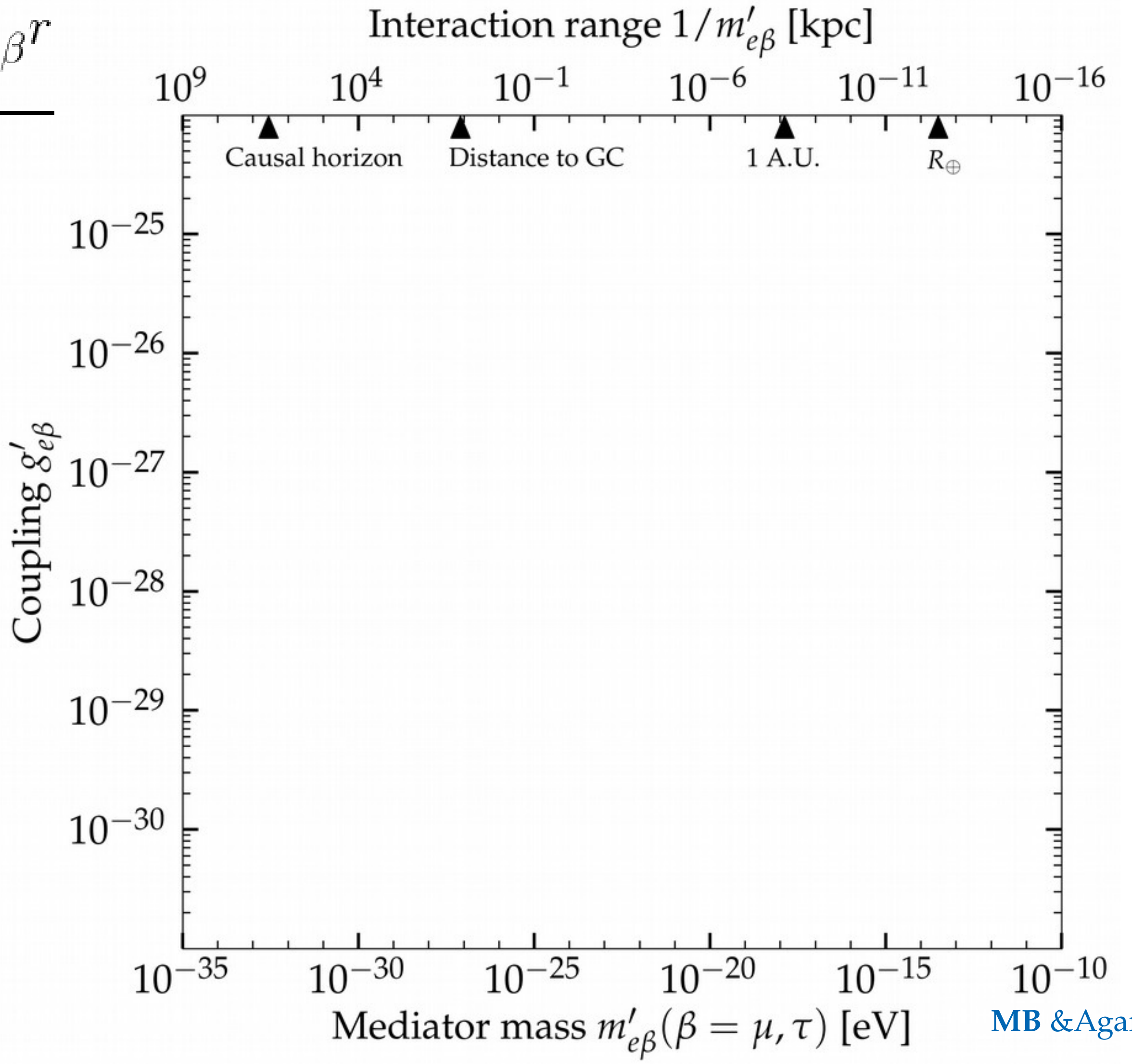

MB &Agarwalla, *PRL* 2019

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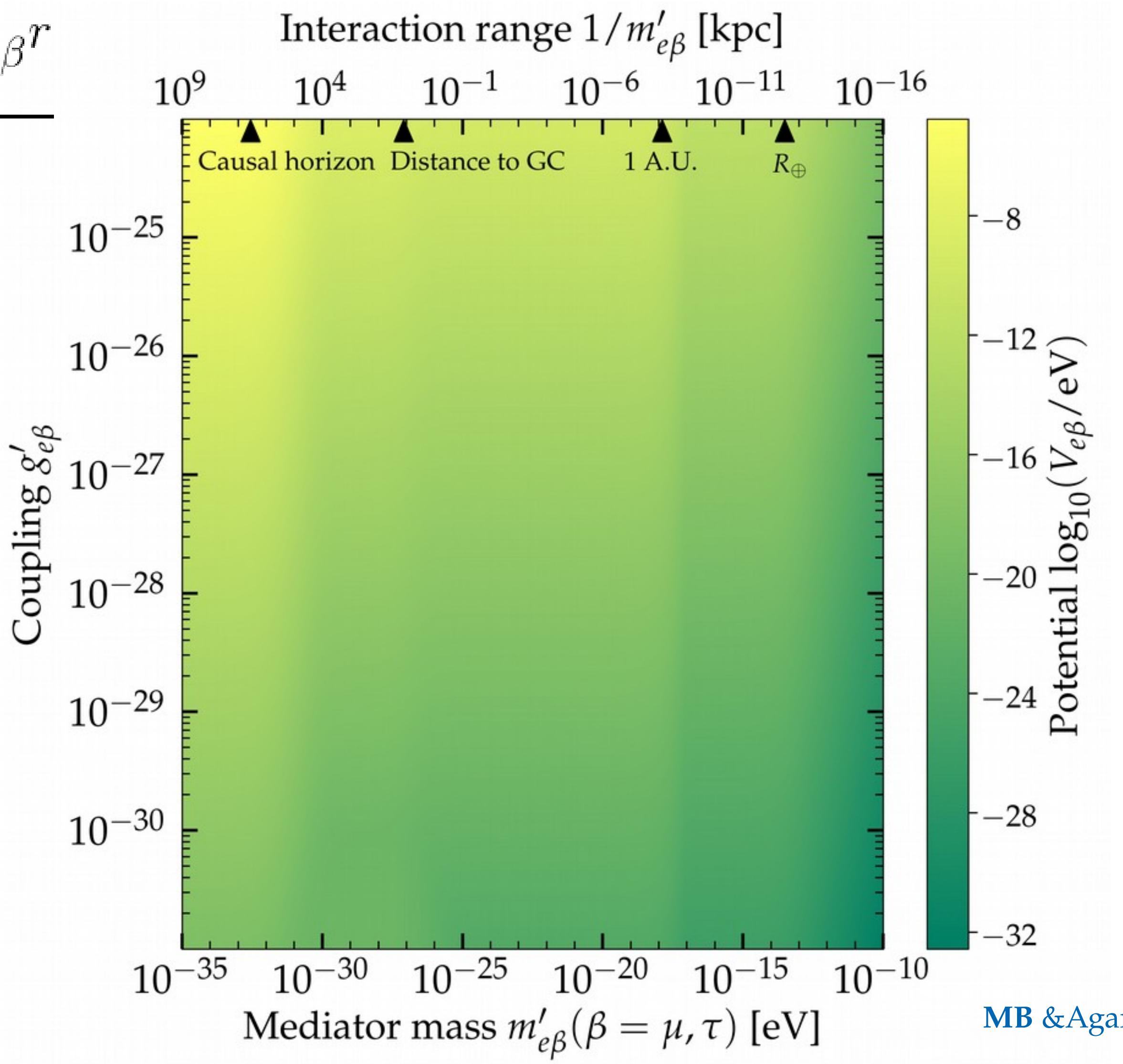

MB &Agarwalla, *PRL* 2019

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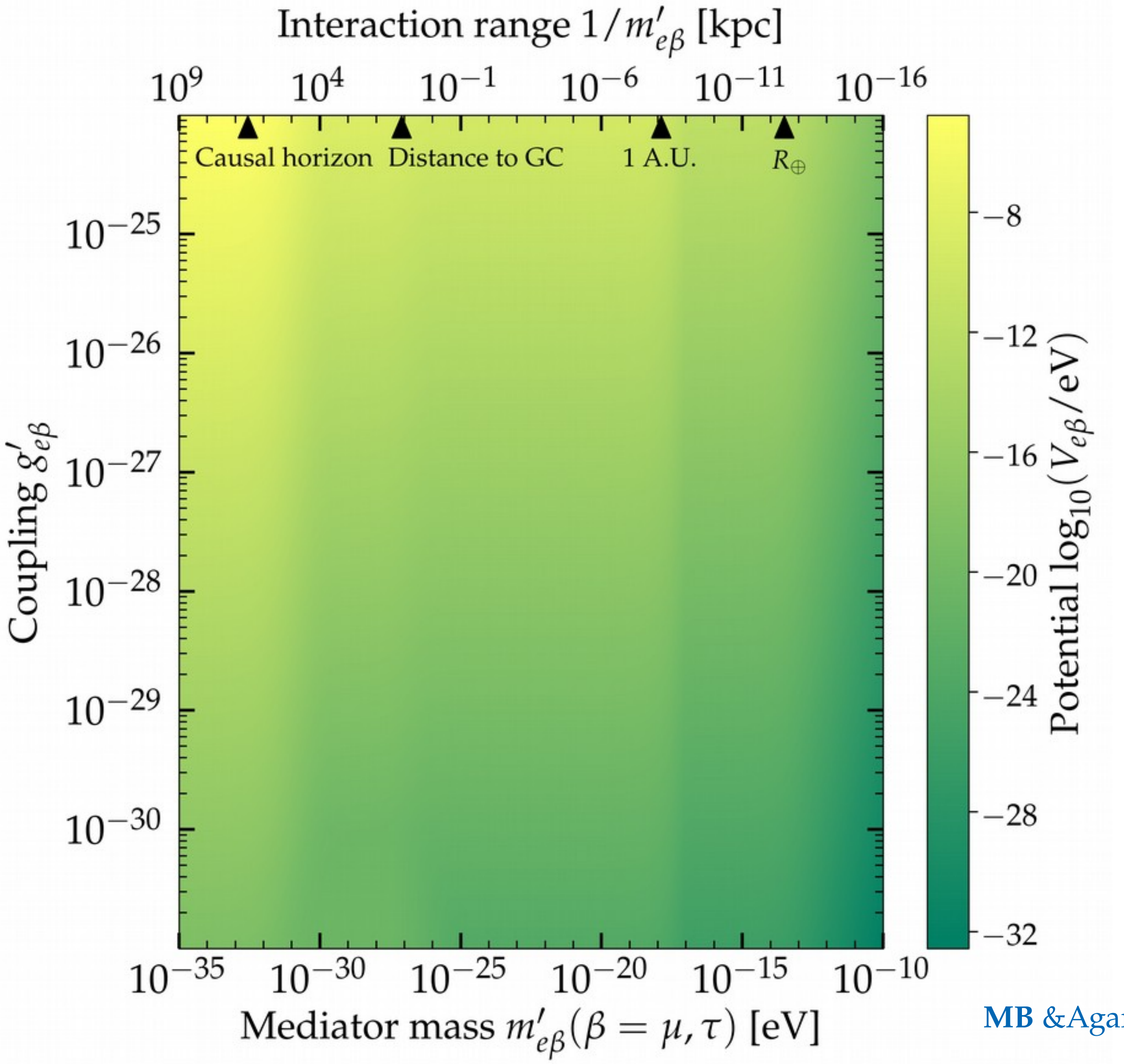

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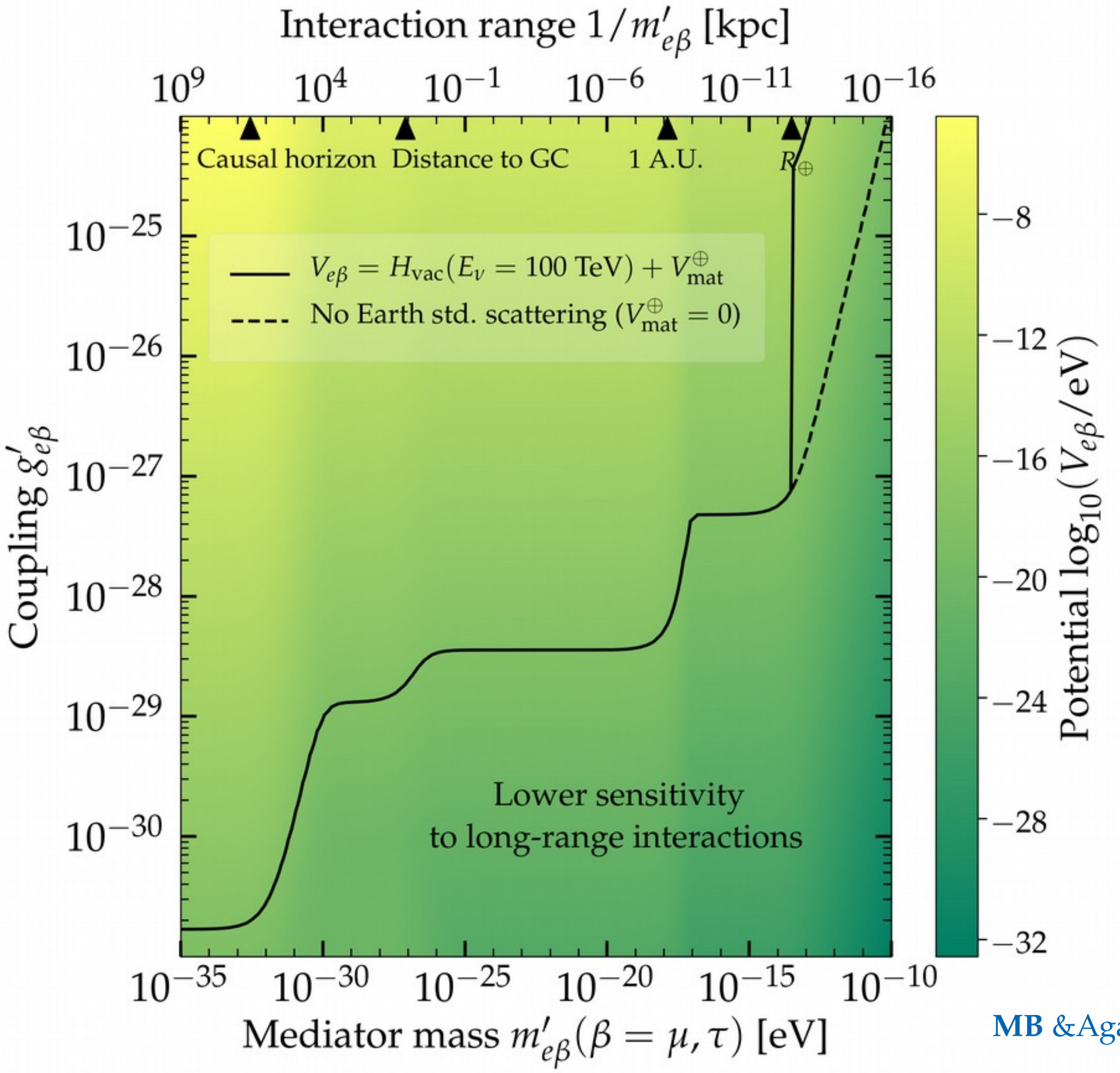

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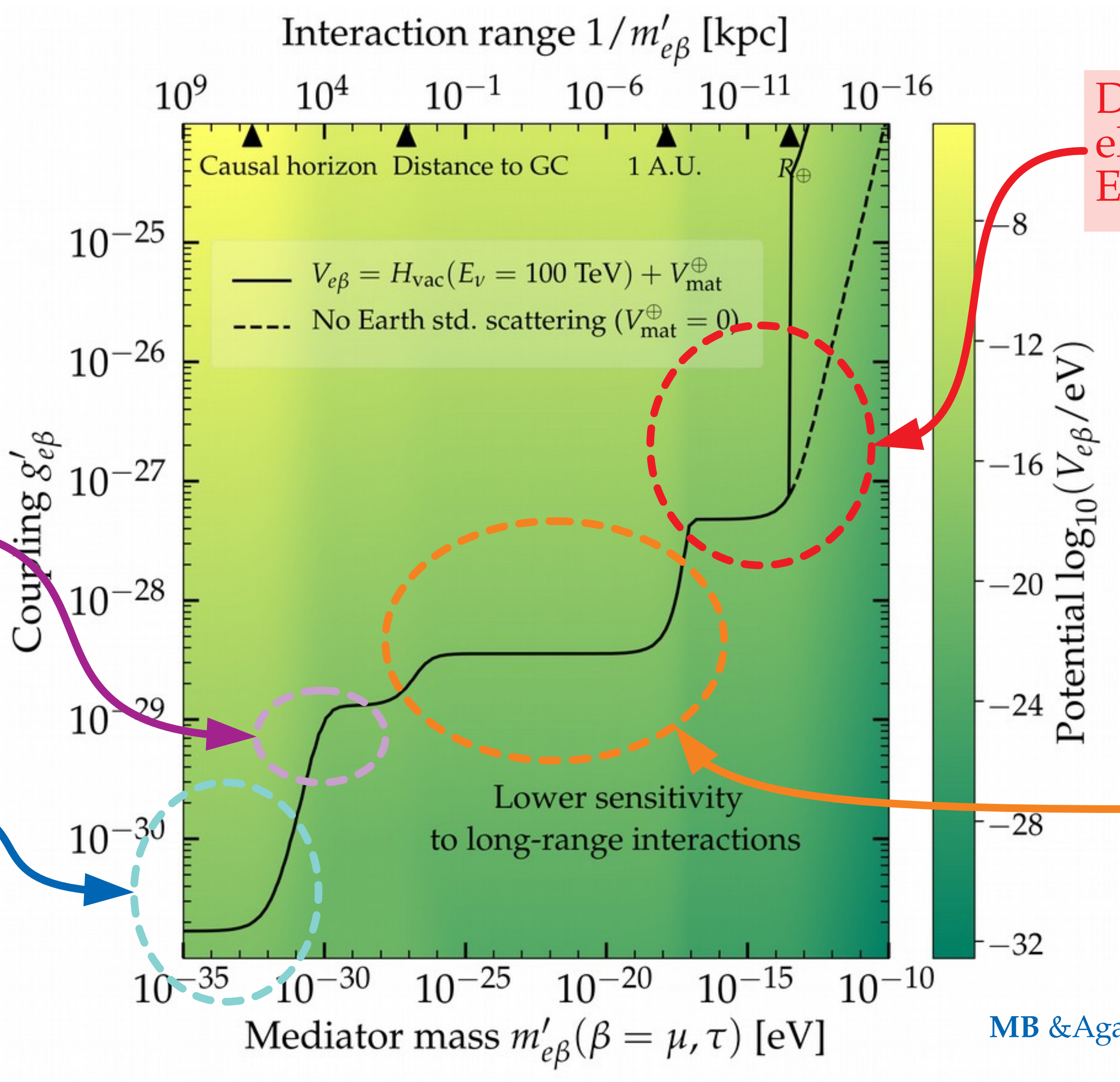
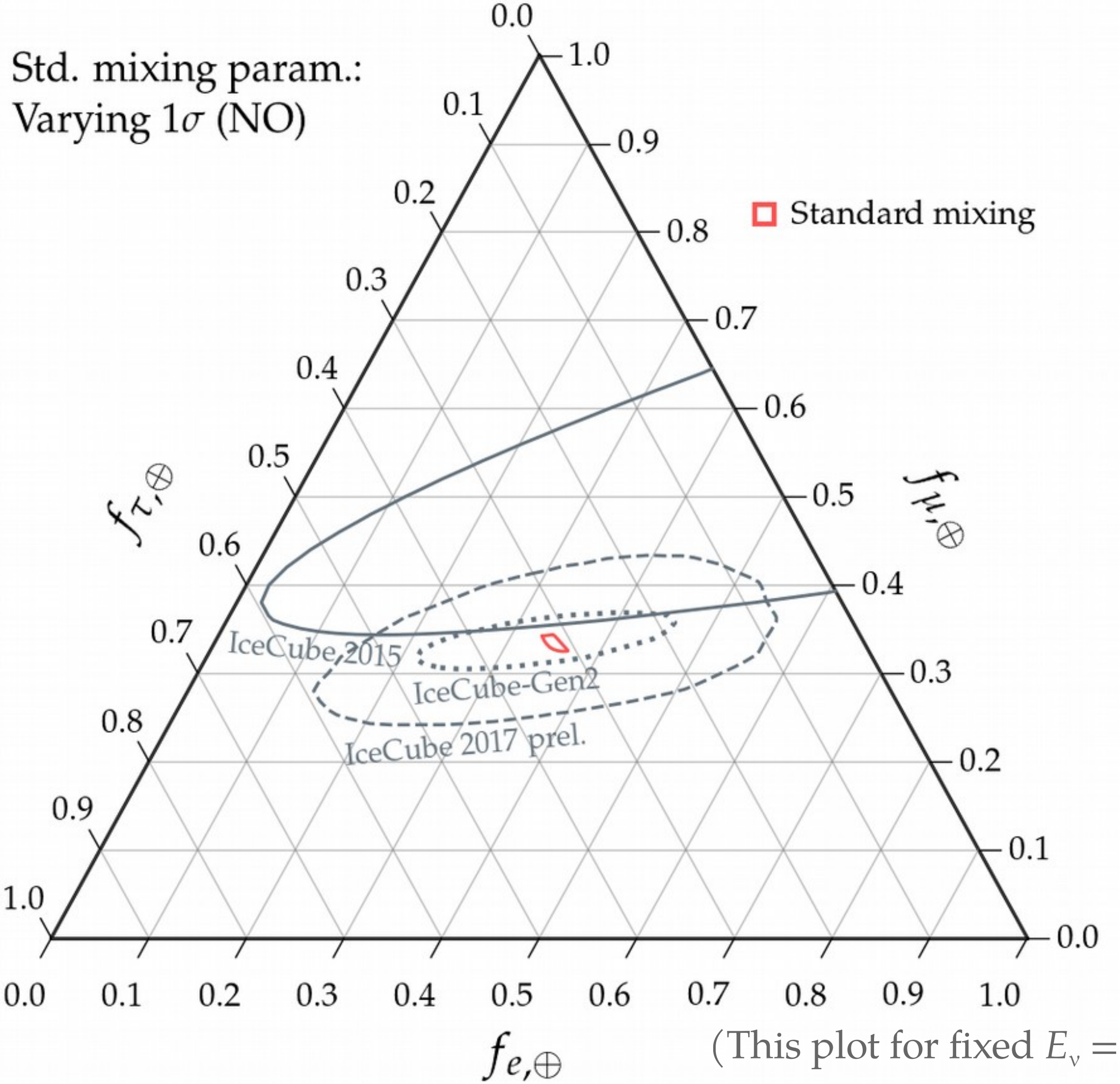
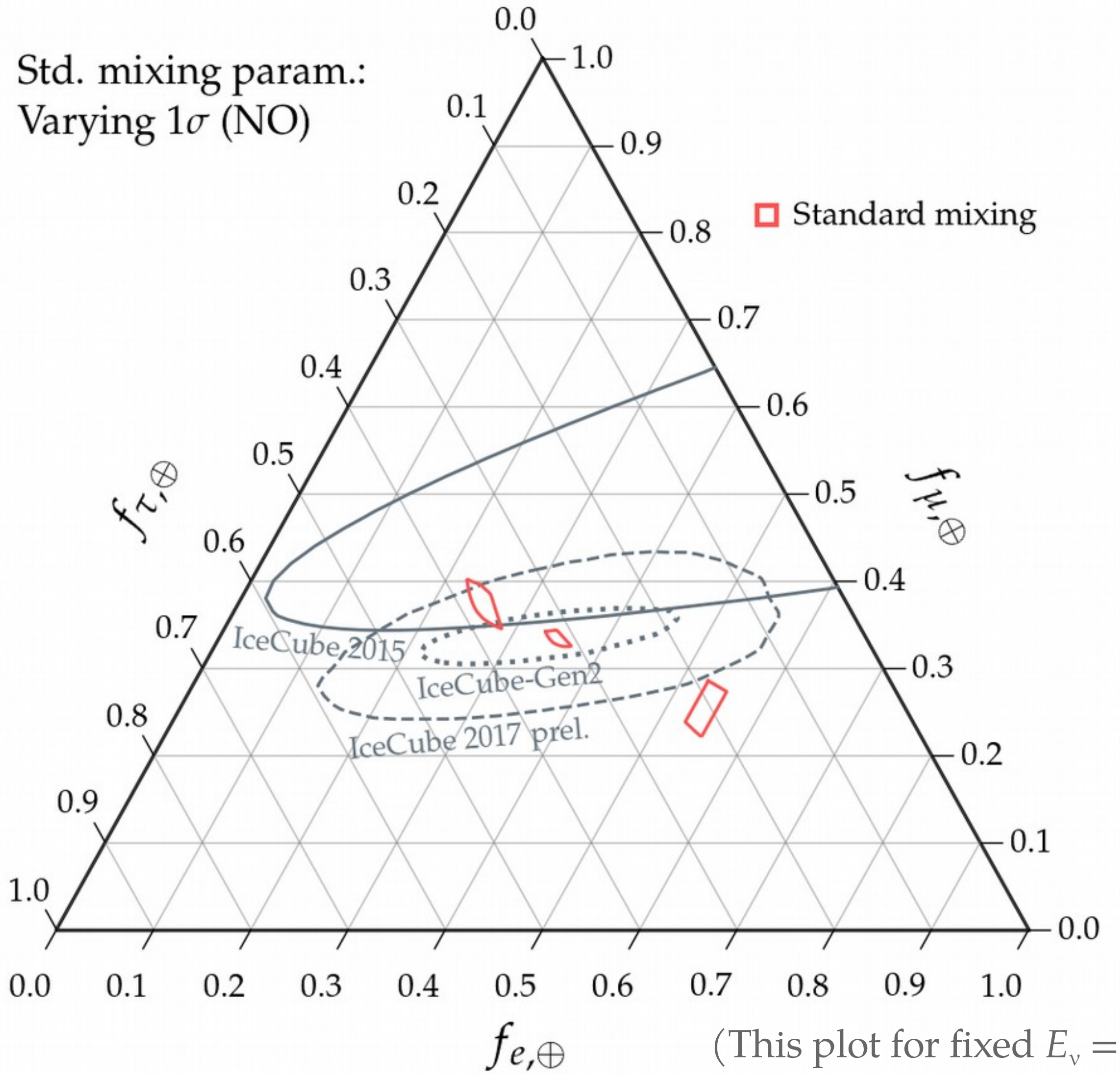


MB &Agarwalla, *PRL* 2019



MB & Agarwalla, *PRL* 2019

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



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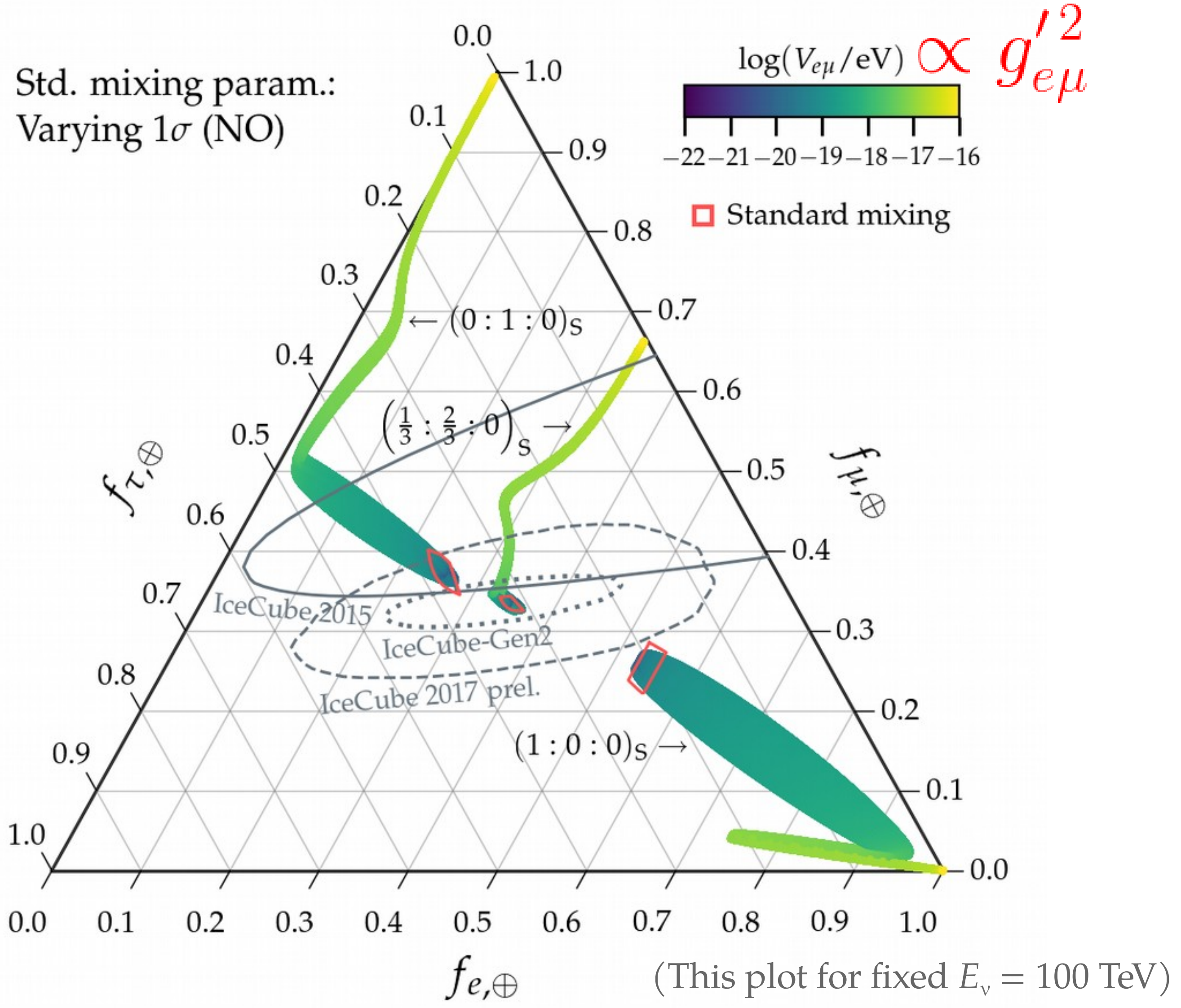

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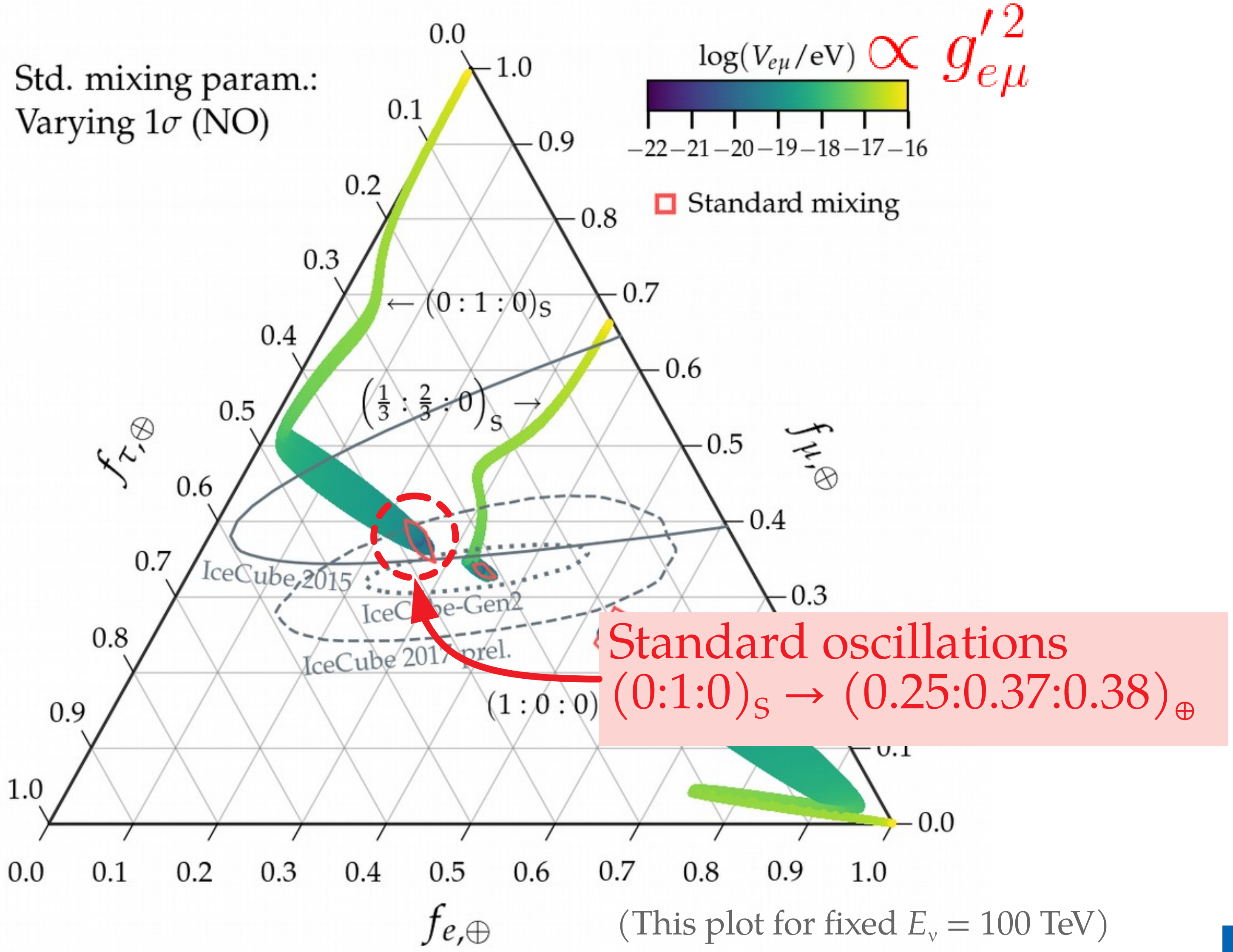

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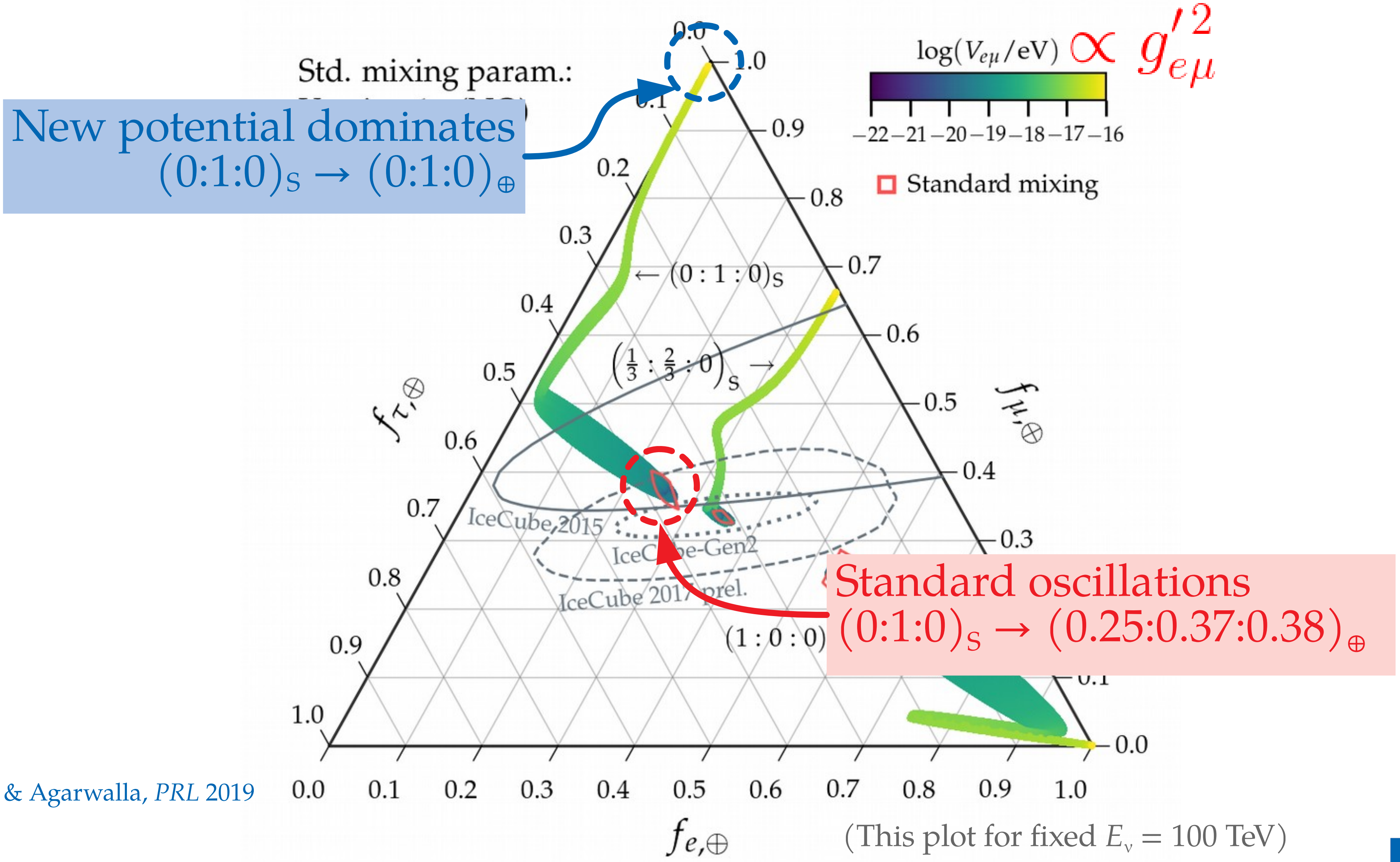

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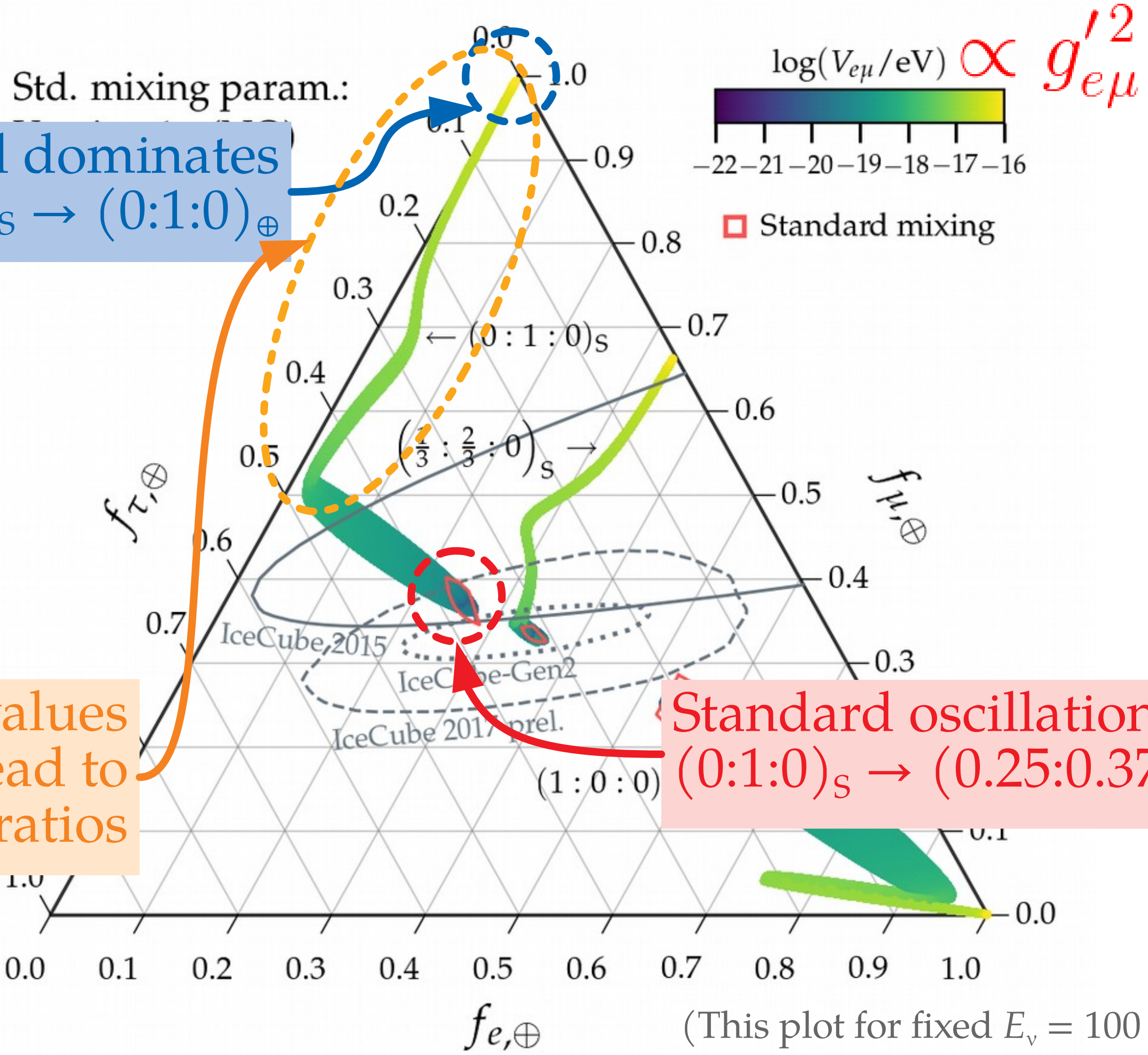

New potential dominates
$(0:1:0)_S \rightarrow (0:1:0)_\oplus$

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

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

MB & Agarwalla, *PRL* 2019

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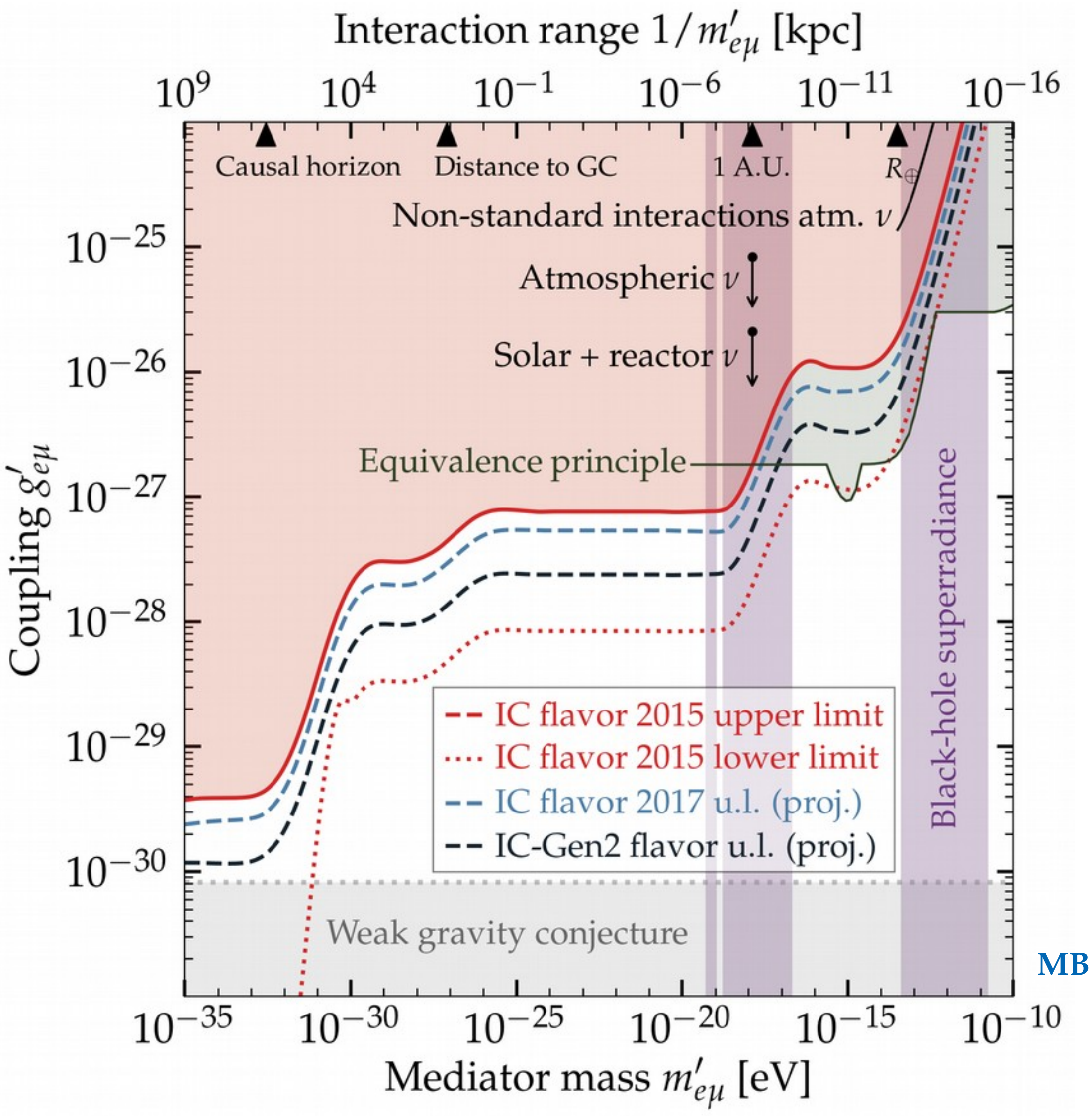
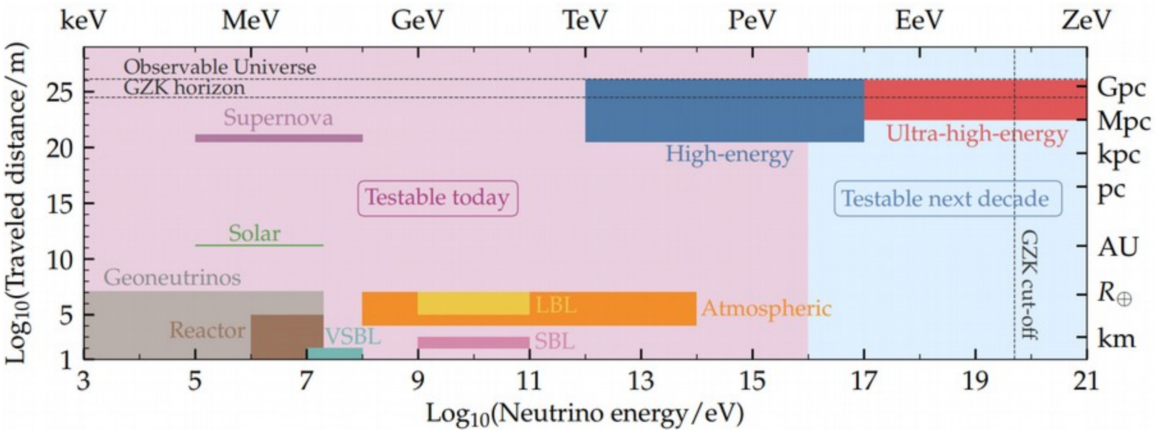


MB &Agarwalla, *PRL* 2019

An exciting decade ahead



Today: TeV–PeV astrophysical ν

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

IceCube + ANTARES + Baikal

+ Growing statistics

+ Improved systematics

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 upgrade
IceCube-Gen2
KM3NeT
ANITA
ARA
ARIANNA
Baikal-GVD
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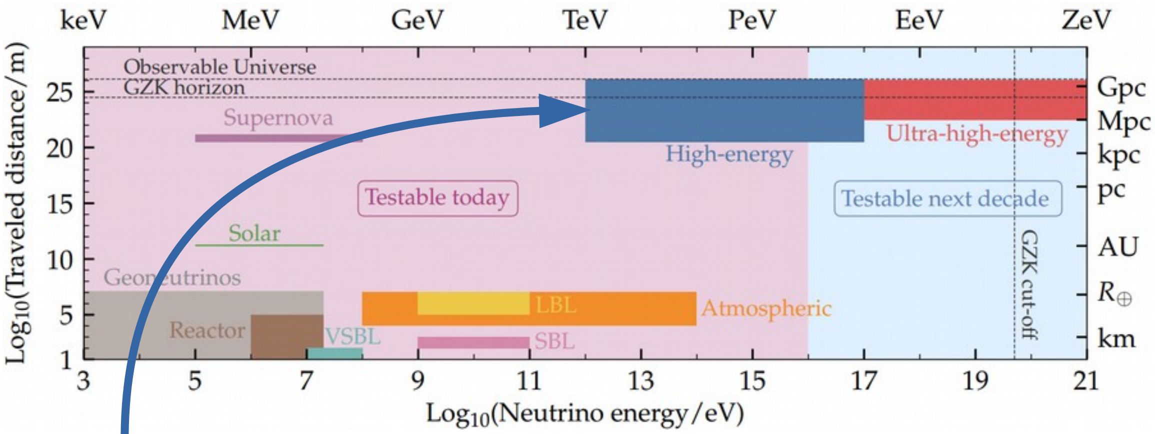

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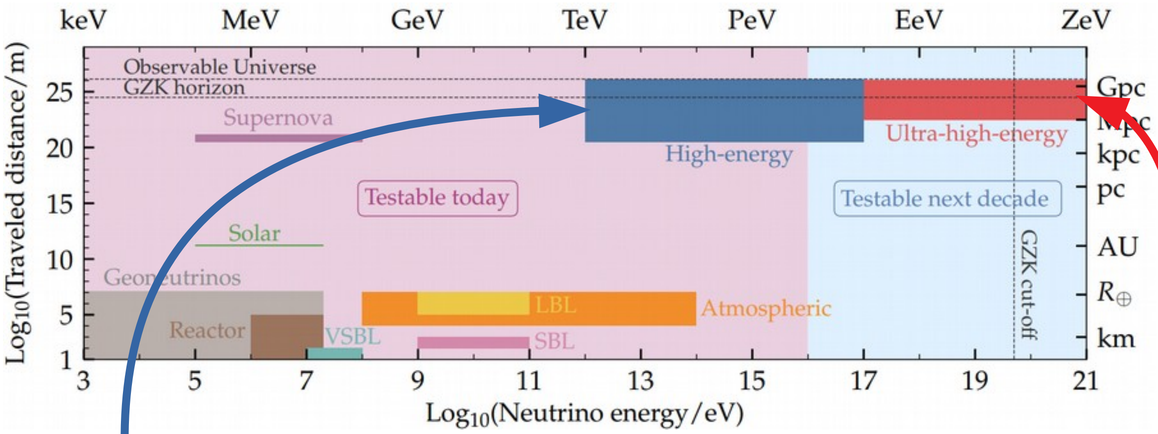

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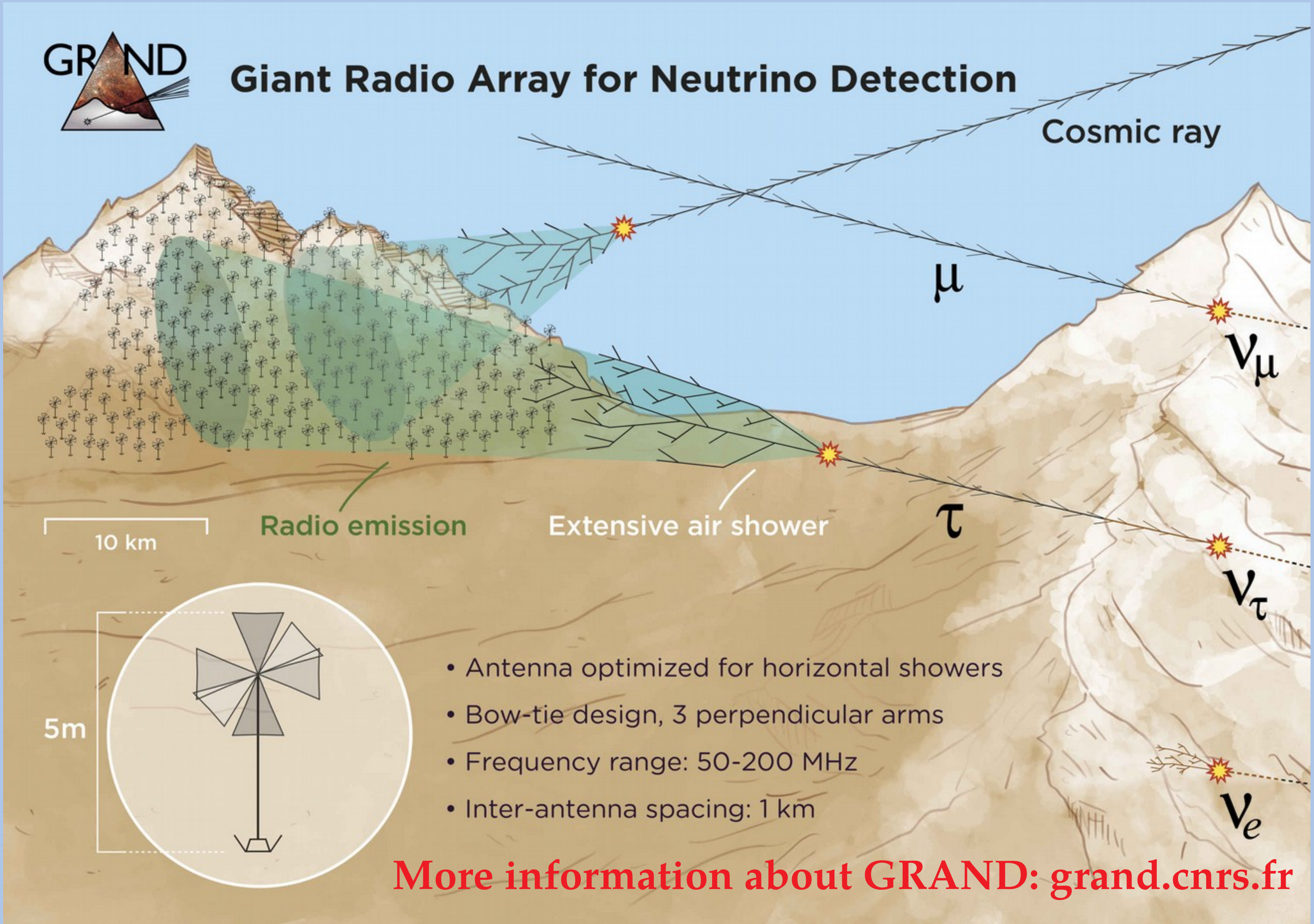

GRAND
Giant Radio Array for Neutrino Detection
Cosmic ray
μ
νμ
Radio emission
Extensive air shower
10 km
τ
ντ
νe
5m
• Antenna optimized for horizontal showers
• Bow-tie design, 3 perpendicular arms
• Frequency range: 50-200 MHz
• Inter-antenna spacing: 1 km
More information about GRAND: grand.cnrs.fr

What are you taking home?

- Cosmic neutrinos are incisive probes of TeV–PeV physics
- We can do this *now*, in spite of astrophysical 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

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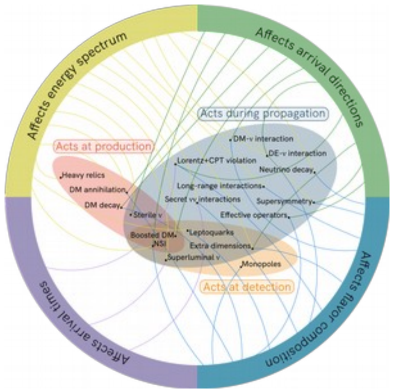

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Backup slides

Flavor-transition probability: the quick and dirty of it

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

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

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

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

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

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Atmospheric | Cross mixing | Solar | Majorana CP phases

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… But high-energy neutrinos oscillate *fast*

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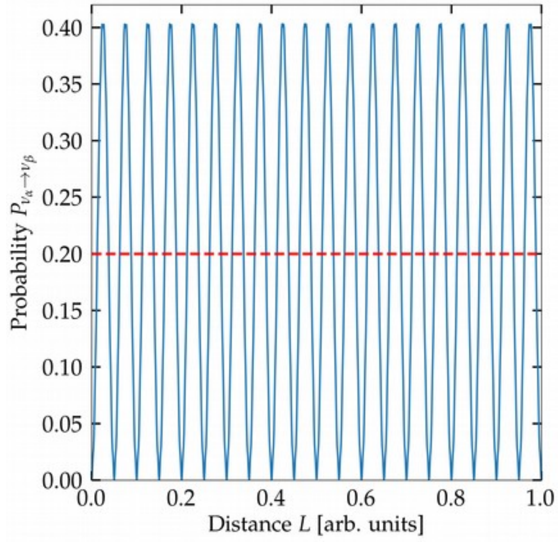

Oscillation length for 1-TeV ν: $2\pi \times 2E/\Delta m^2 \sim 0.1$ pc

~ 8% of the way to Proxima Centauri

≪ Distance to Galactic Center (8 kpc)

≪ Distance to Andromeda (1 Mpc)

≪ Cosmological distances (few Gpc)

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

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

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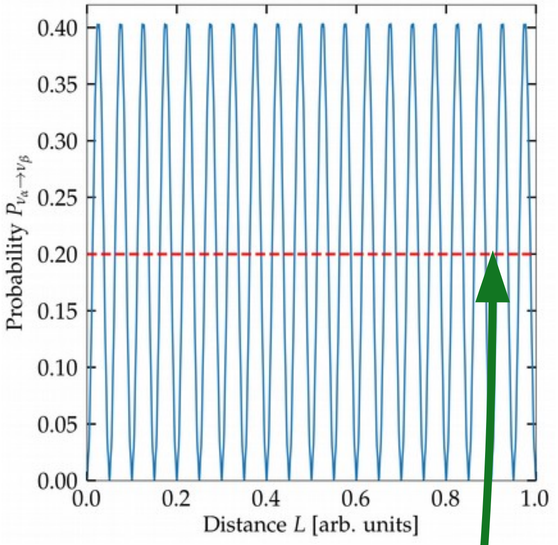

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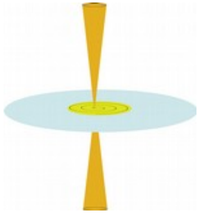
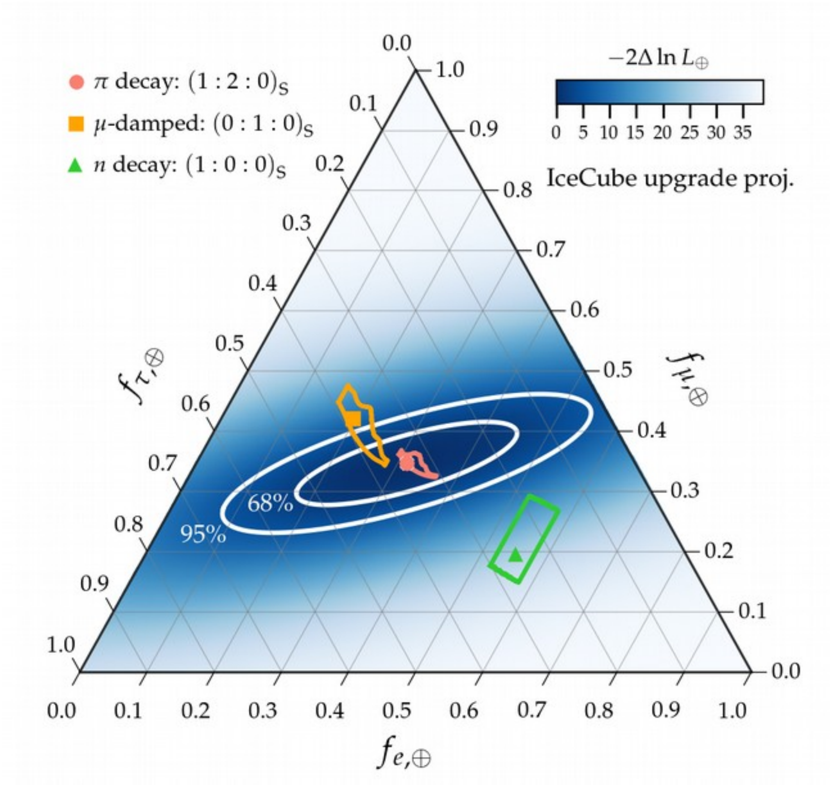
Inferring the flavor composition at the sources

Measured:
Flavor ratios at Earth

Invert flavor oscillations



Inferred:
Flavor ratios at astrophysical sources



MB & Ahlers, *PRL* 2019

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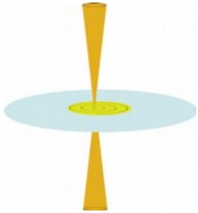

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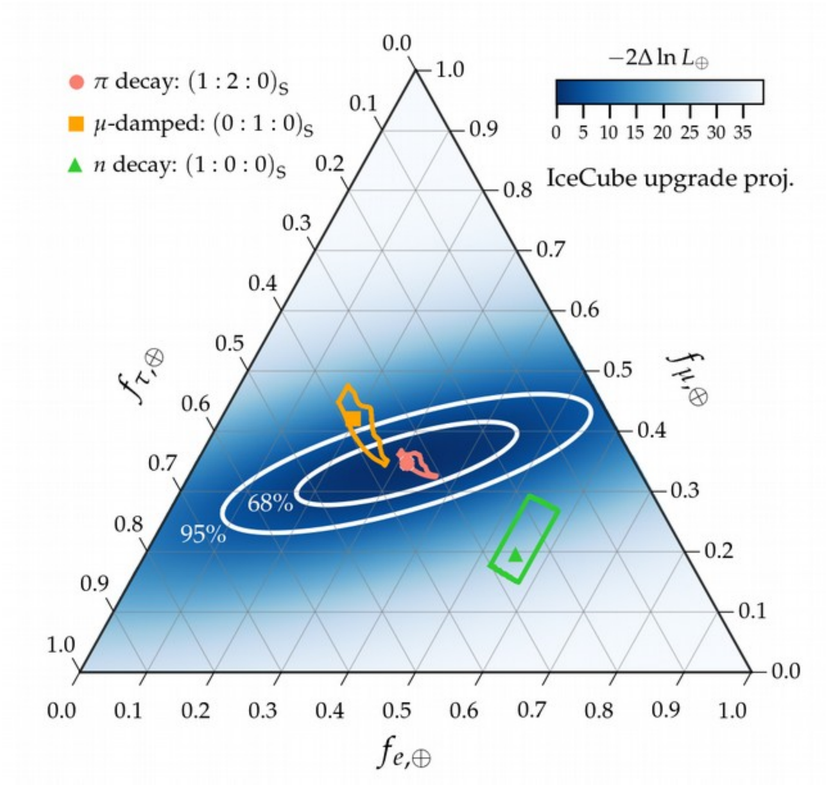

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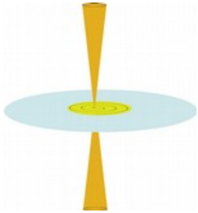

Inferred:
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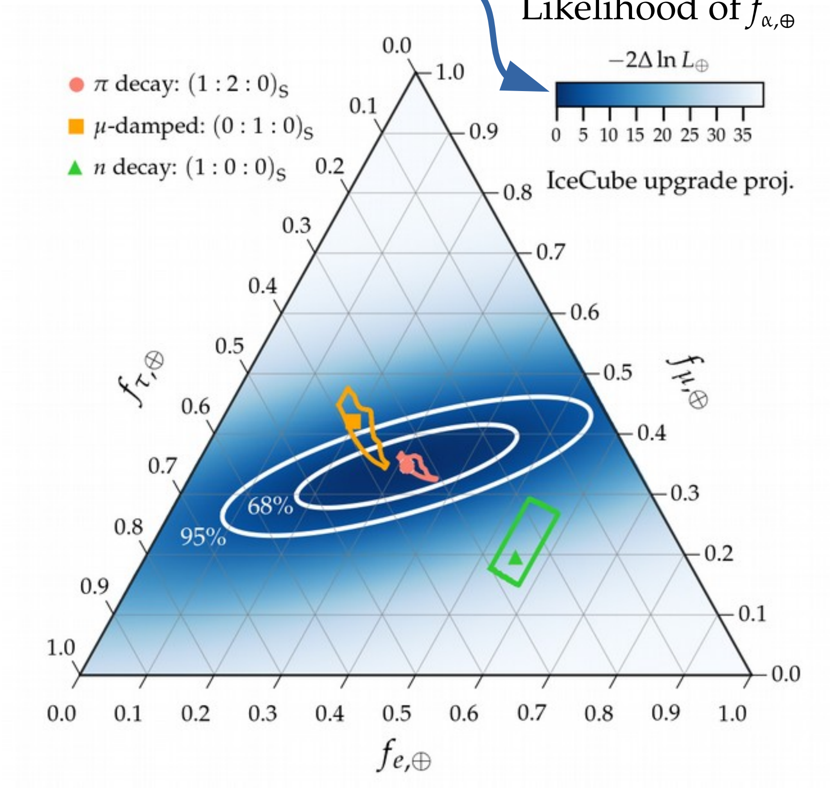
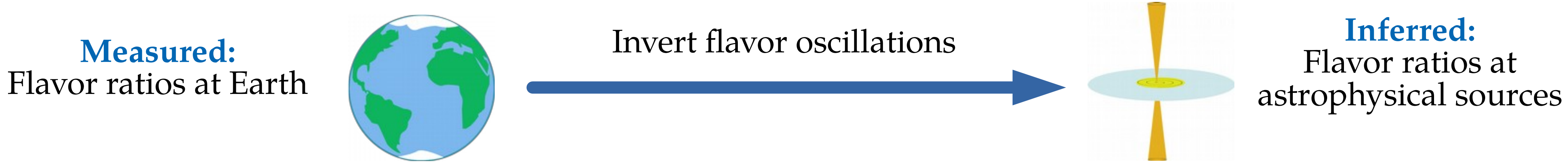
More likely

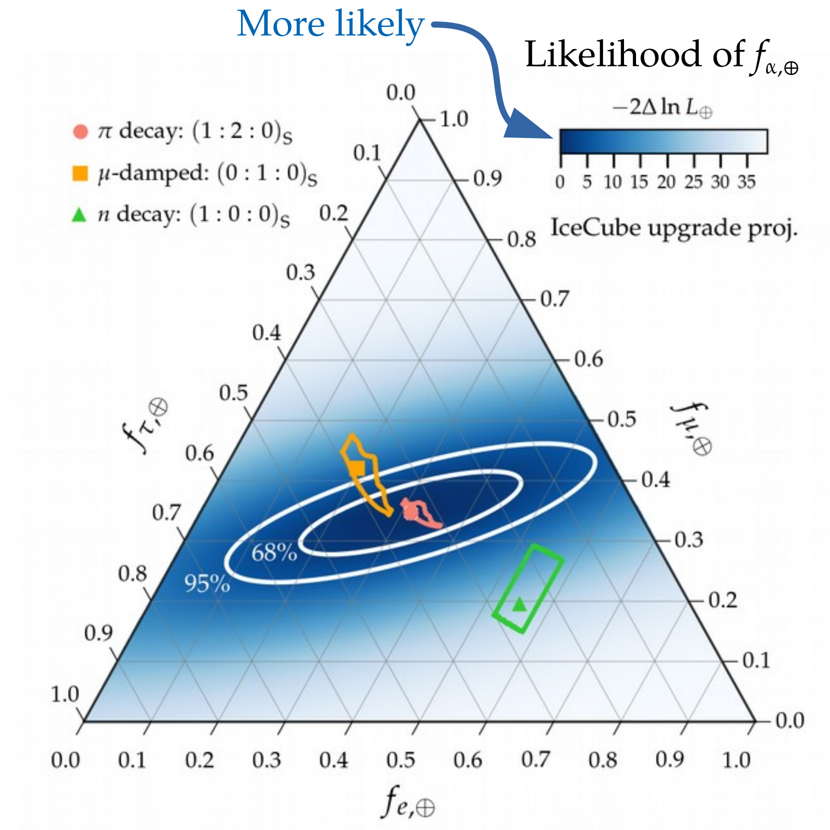
Likelihood of $f_{\alpha,\oplus}$

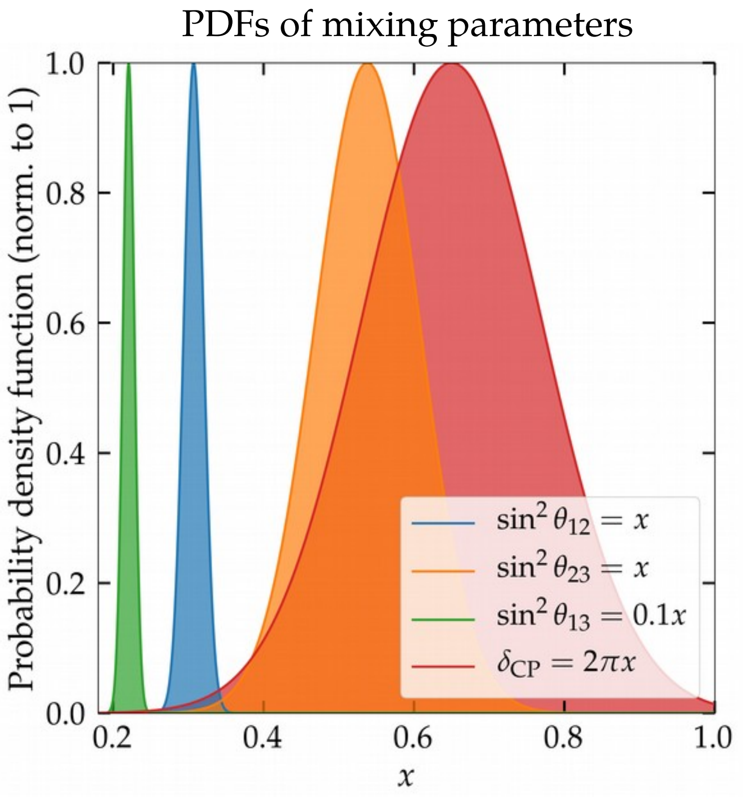


MB & Ahlers, *PRL* 2019

Inferring the flavor composition at the sources





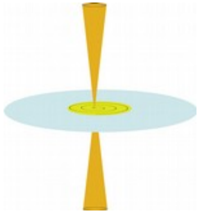


MB & Ahlers, *PRL* 2019

Inferring the flavor composition at the sources

Measured:
Flavor ratios at Earth

Invert flavor oscillations



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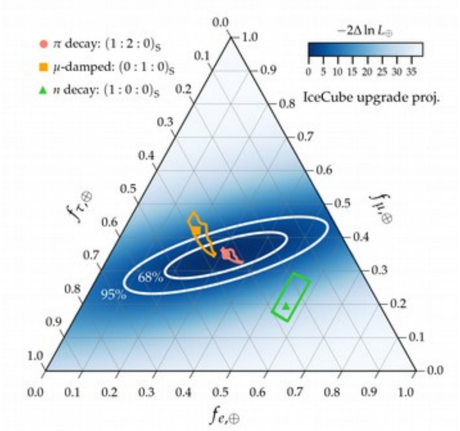

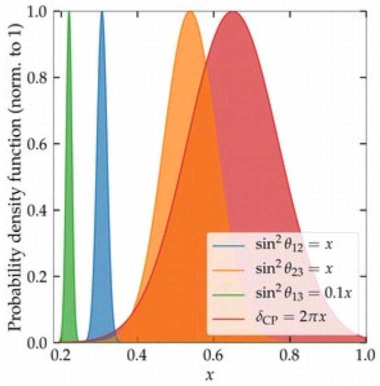

Posterior probability density of $f_{\alpha,\mathrm{S}}$ being the flavor ratios at the sources:

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

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

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

MB & Ahlers, *PRL* 2019

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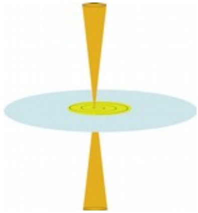

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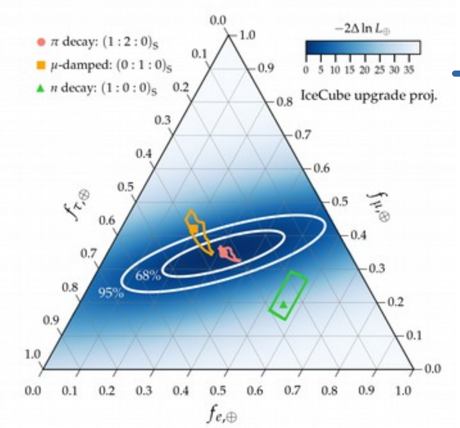

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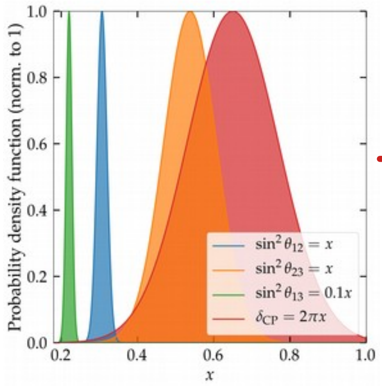

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MB & Ahlers, *PRL* 2019

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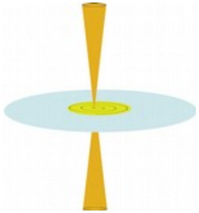

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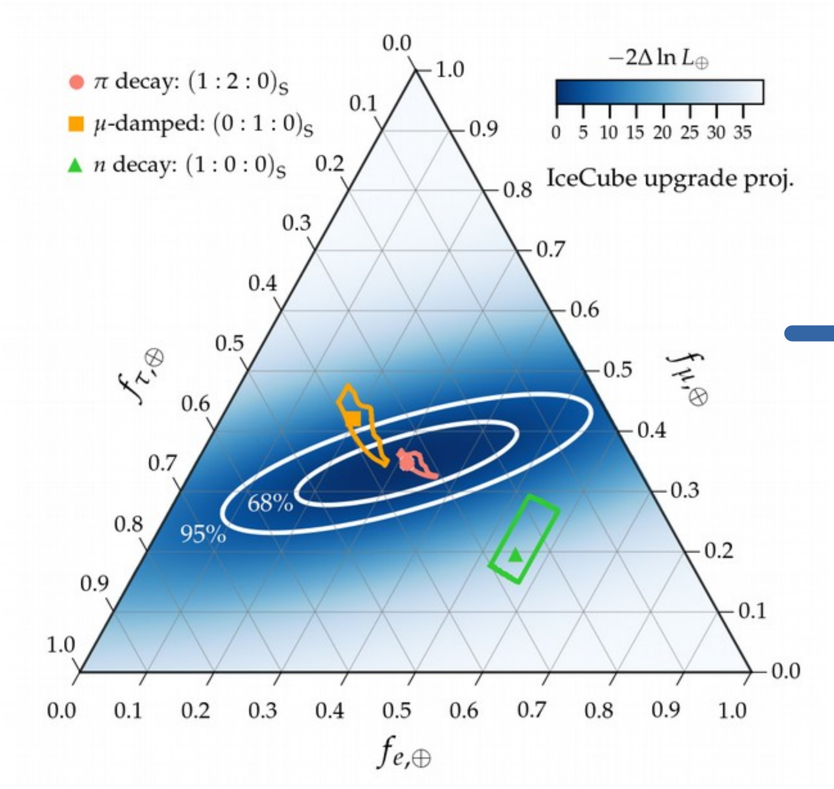

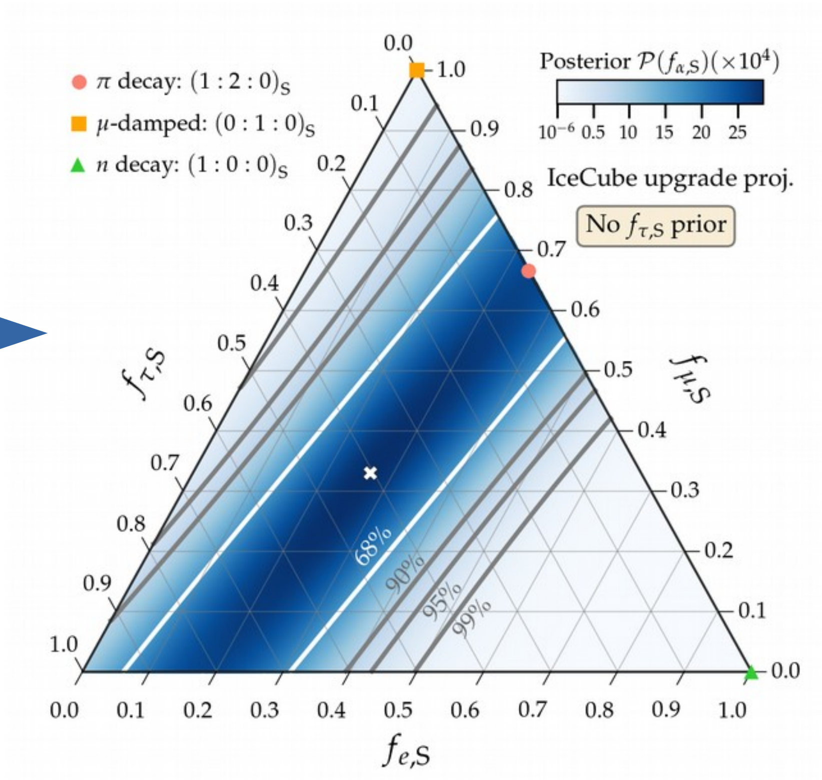

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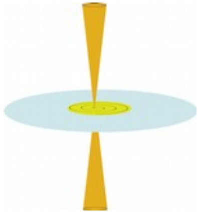

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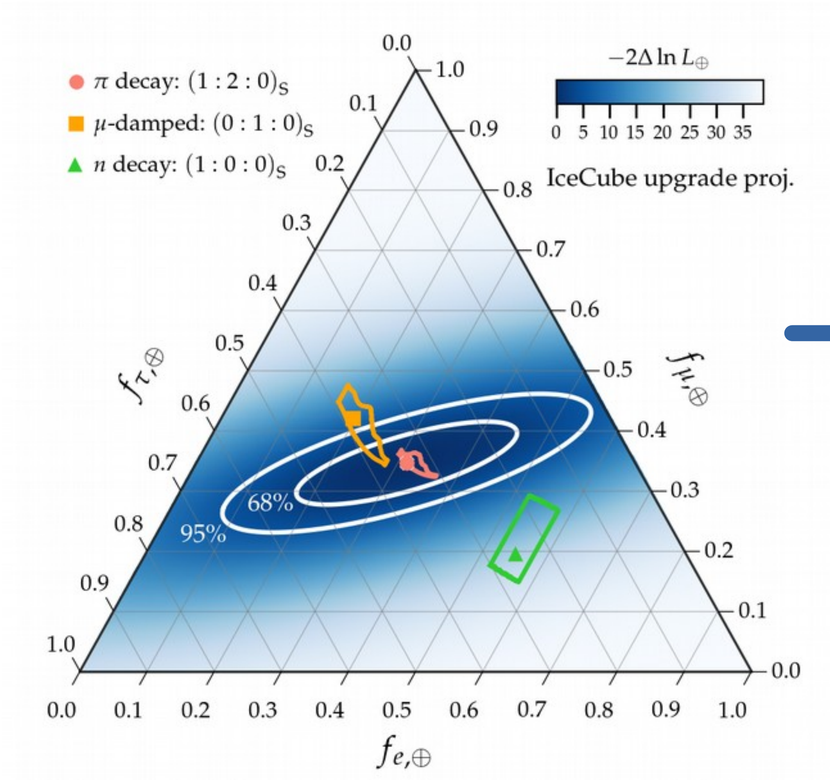

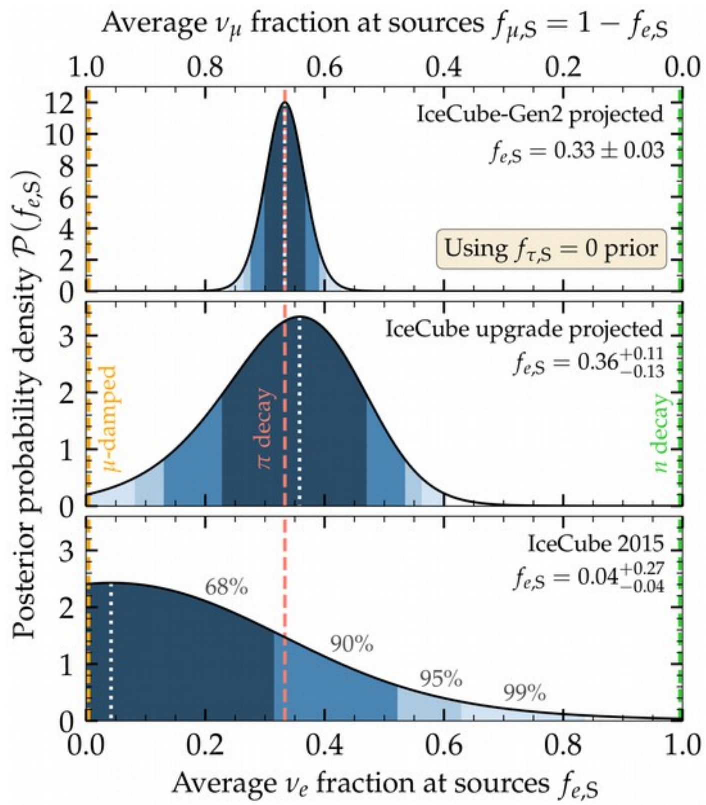

MB & Ahlers, *PRL* 2019

What has IceCube found so far (7.5 years)?

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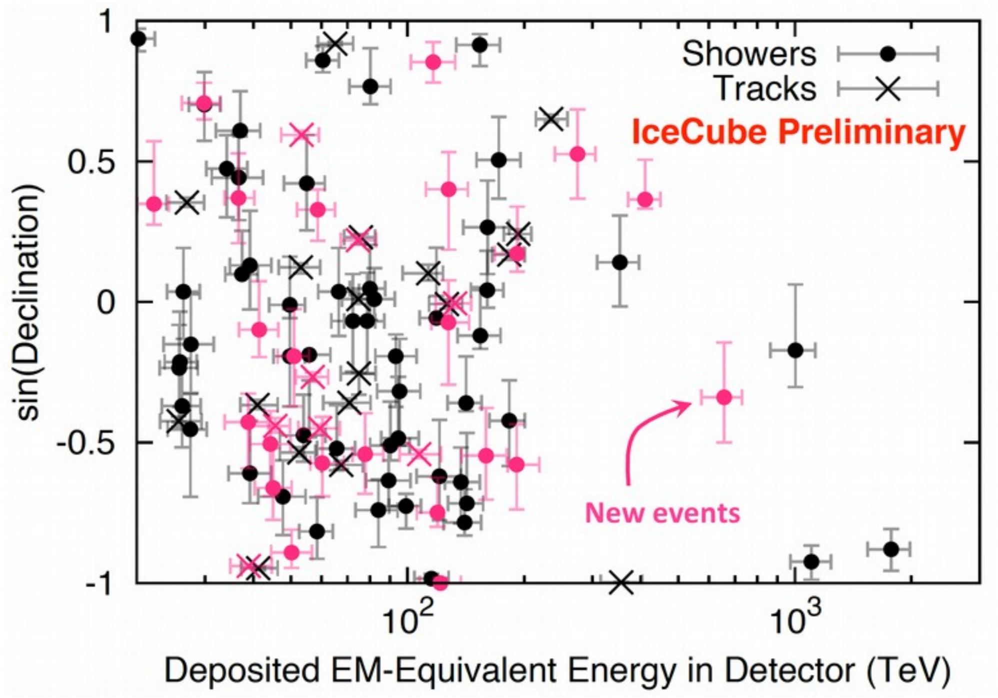
103 contained events between 15 TeV – 2 PeV



I. Taboada, Neutrino 2018

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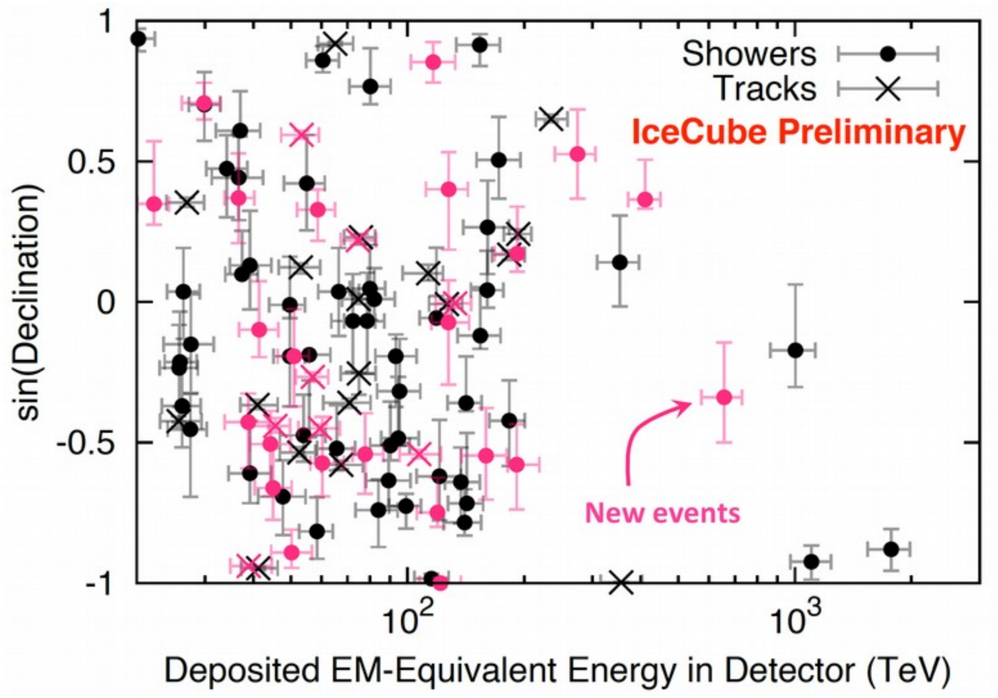
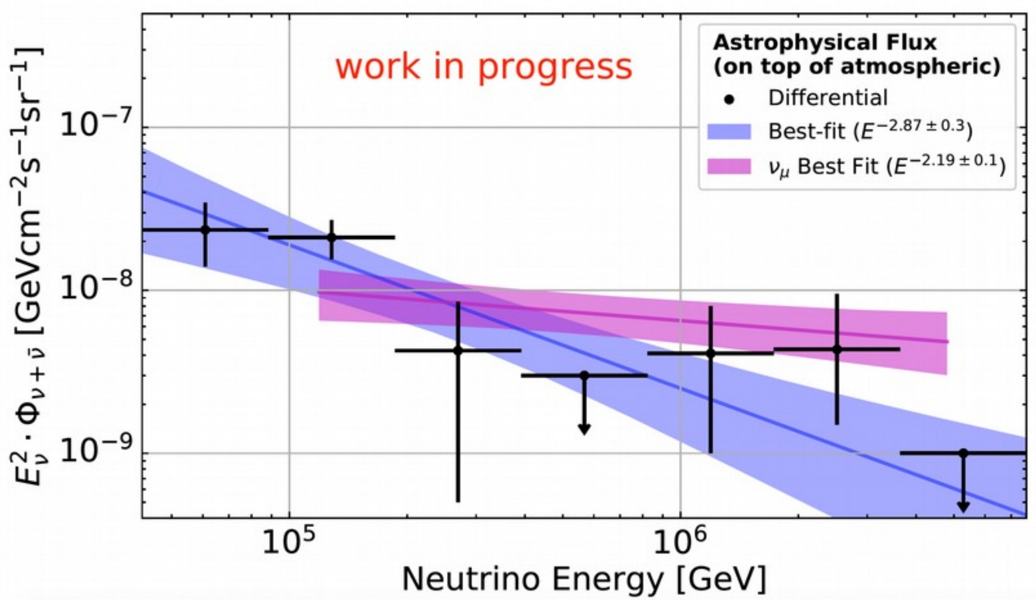


Astrophysical ν flux detected at > 7σ

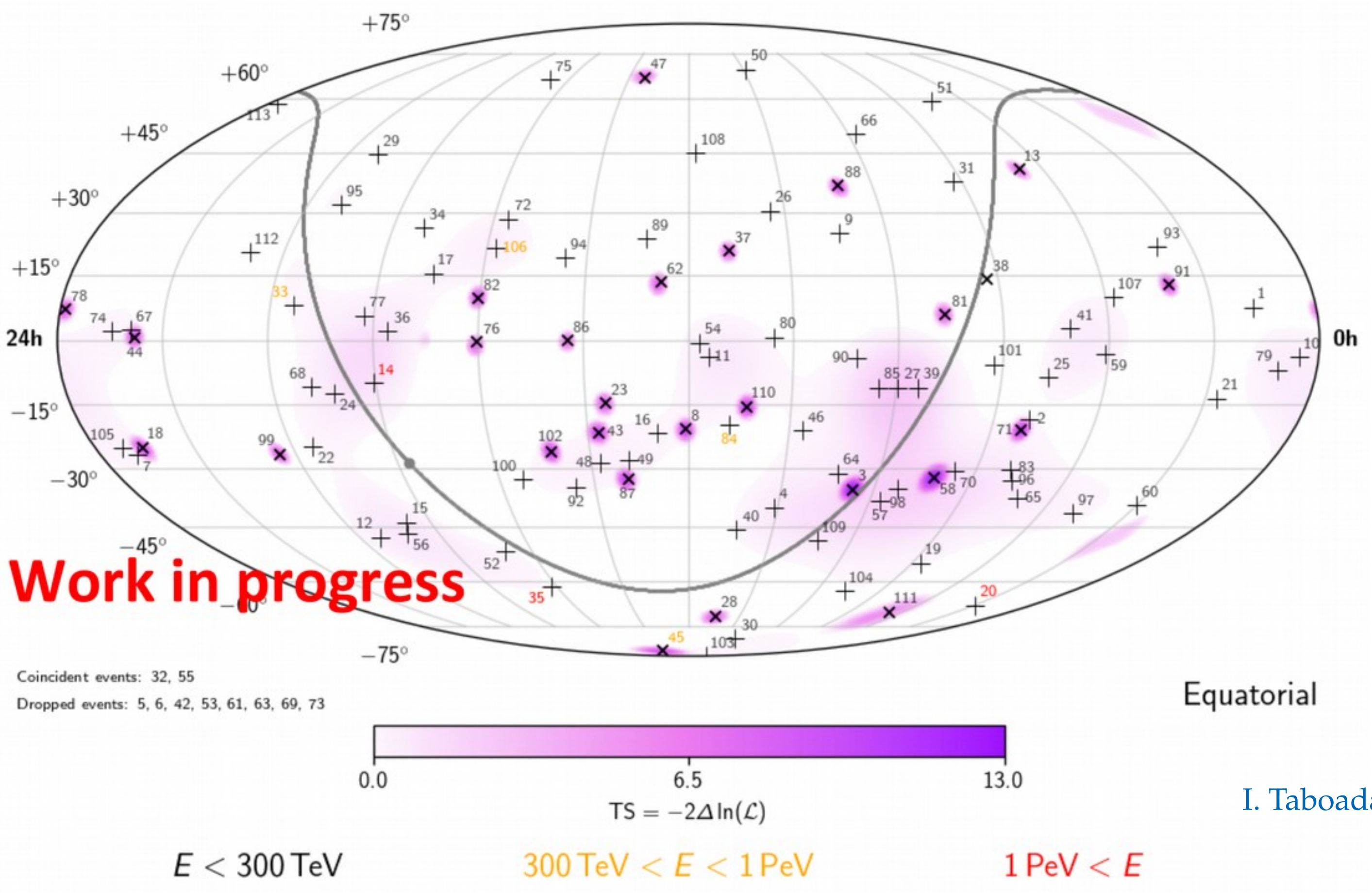
(Normalization ok, but steep spectrum)



I. Taboada, Neutrino 2018

What has IceCube found so far (7.5 years)?

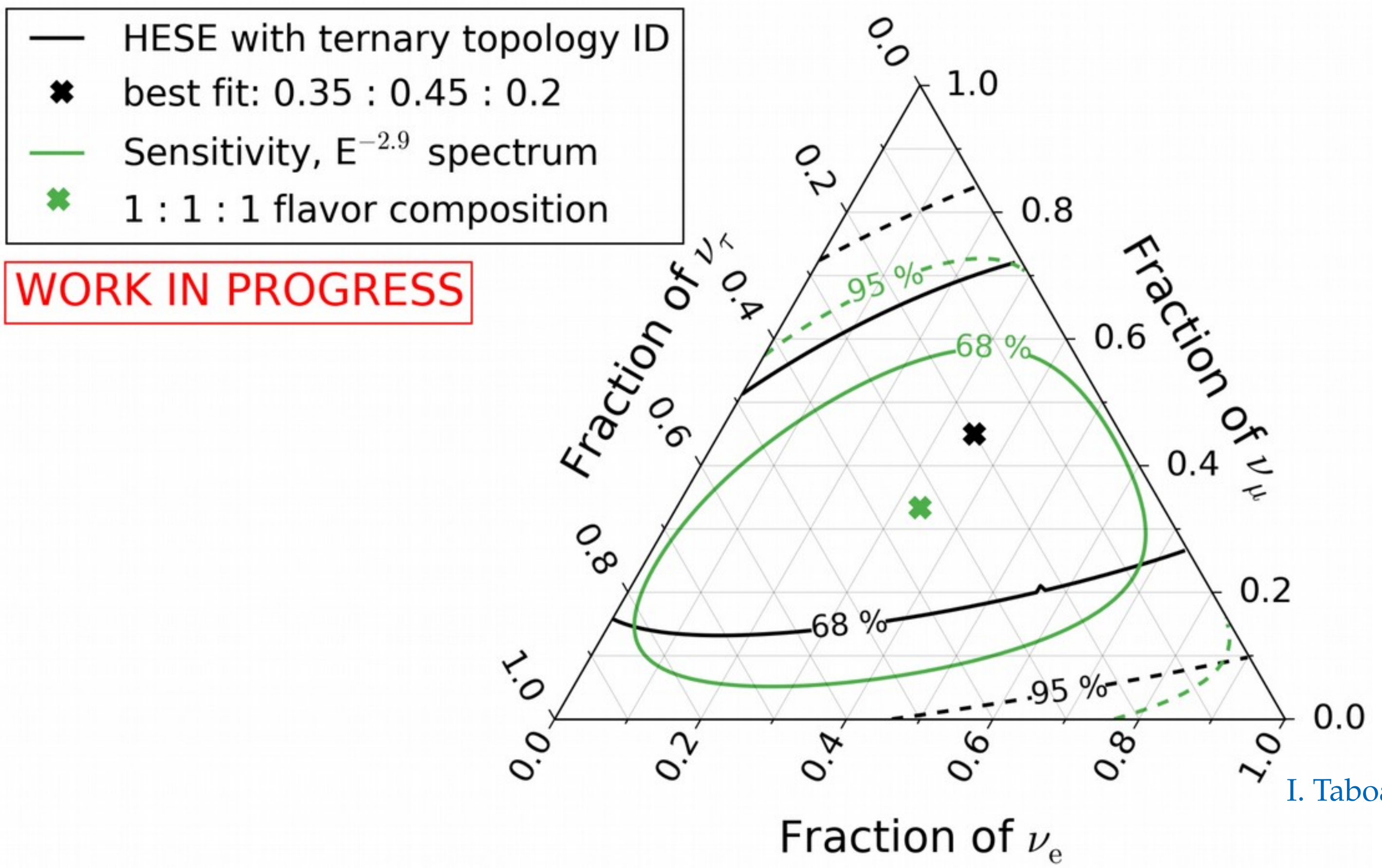
Arrival directions compatible with isotropy



I. Taboada, Neutrino 2018

What has IceCube found so far (7.5 years)?

Flavor composition compatible with equal proportion of each flavor



I. Taboada, Neutrino 2018

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 $\mathrm{d}\sigma/\mathrm{d}y$

- In a HESE starting track:

  $E_X = E_{sh}$ (energy of shower)
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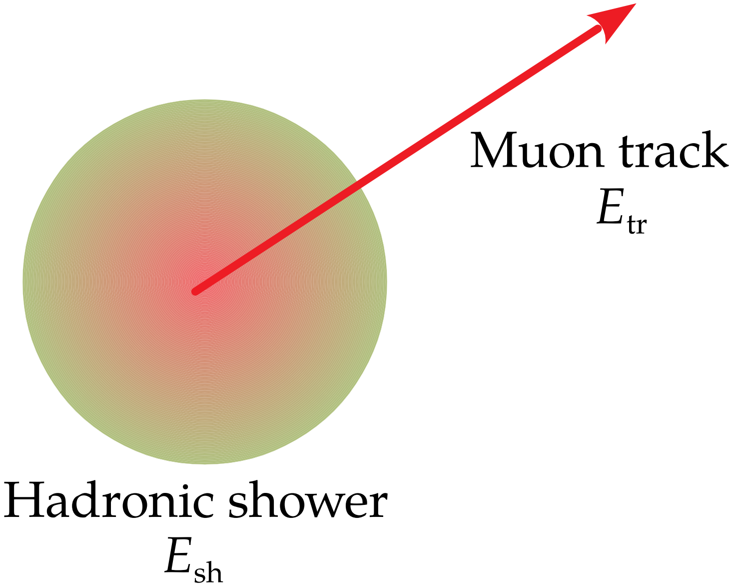
  $\Big\}\; y = (1 + E_{tr}/E_{sh})^{-1}$

- 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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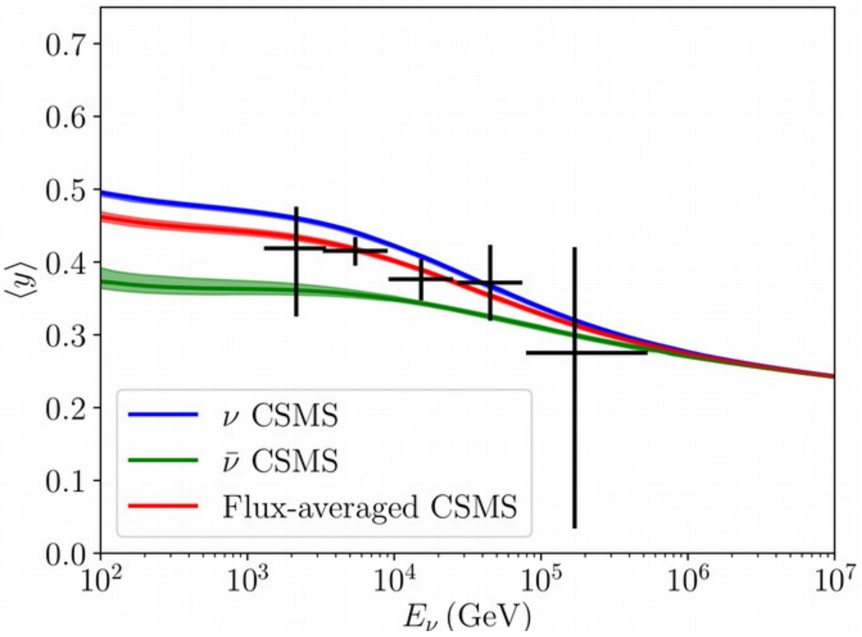
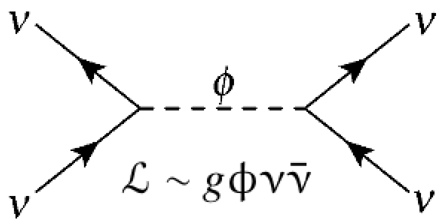


IceCube, *PRD* 2019

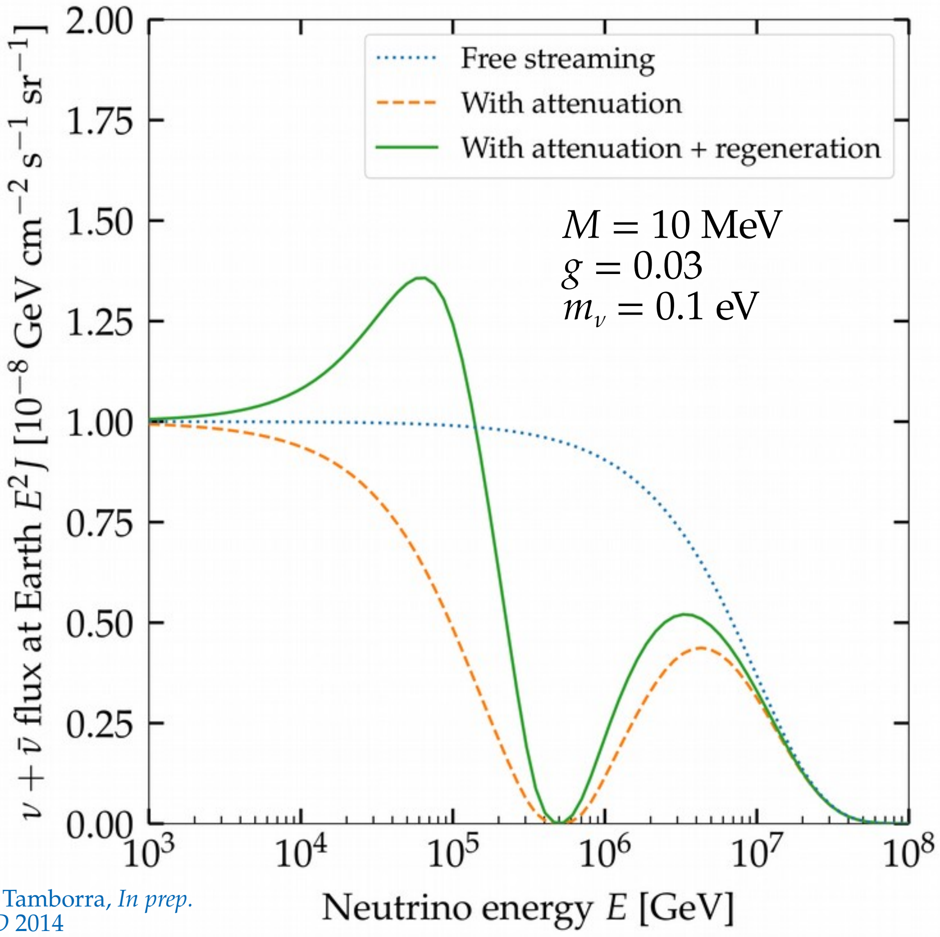
New physics in the spectral shape: $\nu\nu$ interactions

"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, Tamborra, *In prep.*
Ng & Beacom, *PRD* 2014
Cherry, Friedland, Shoemaker, 1411.1071
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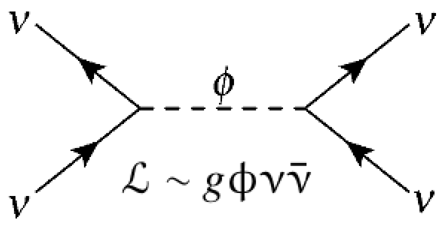

New coupling

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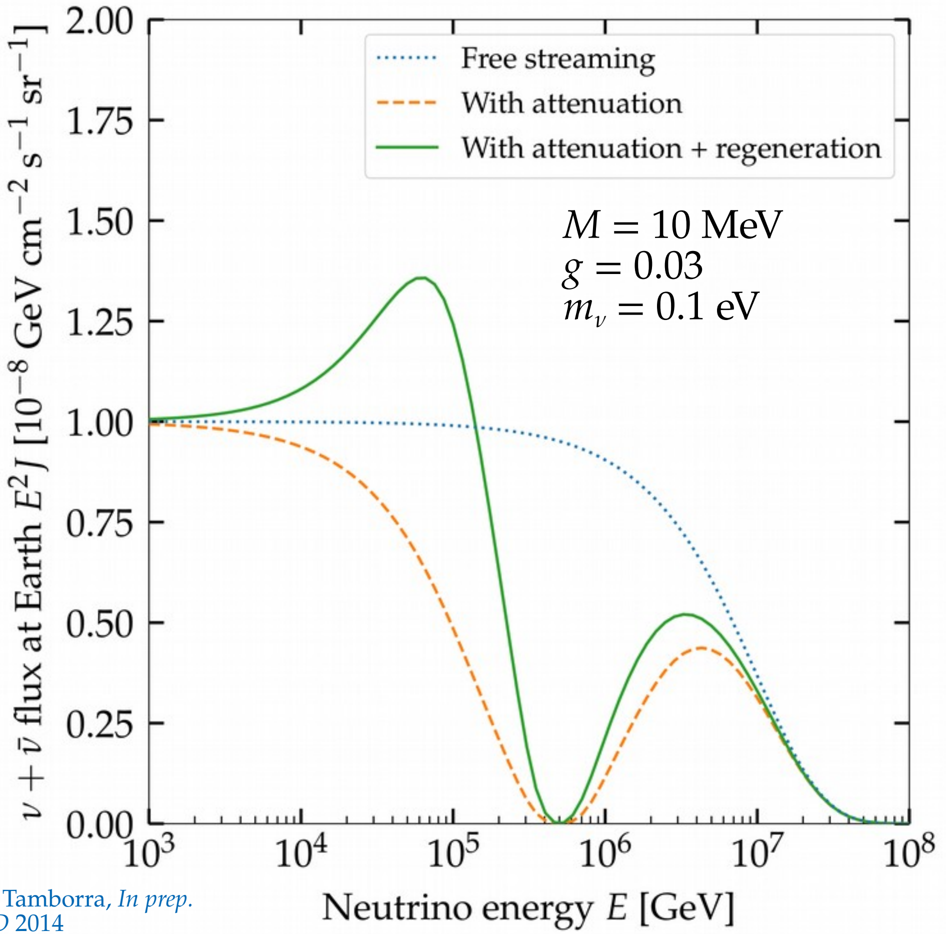

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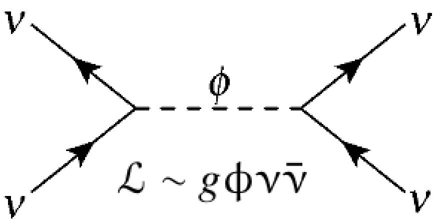

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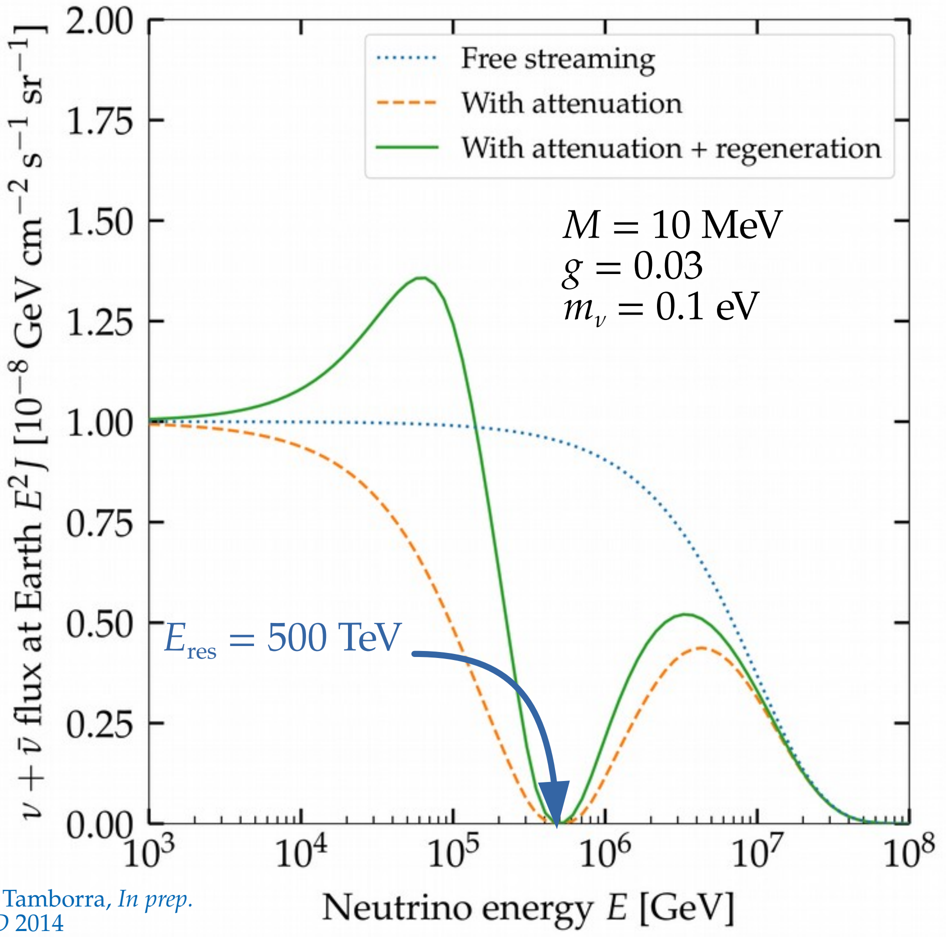

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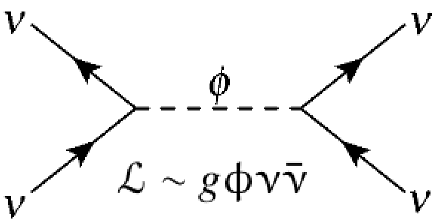

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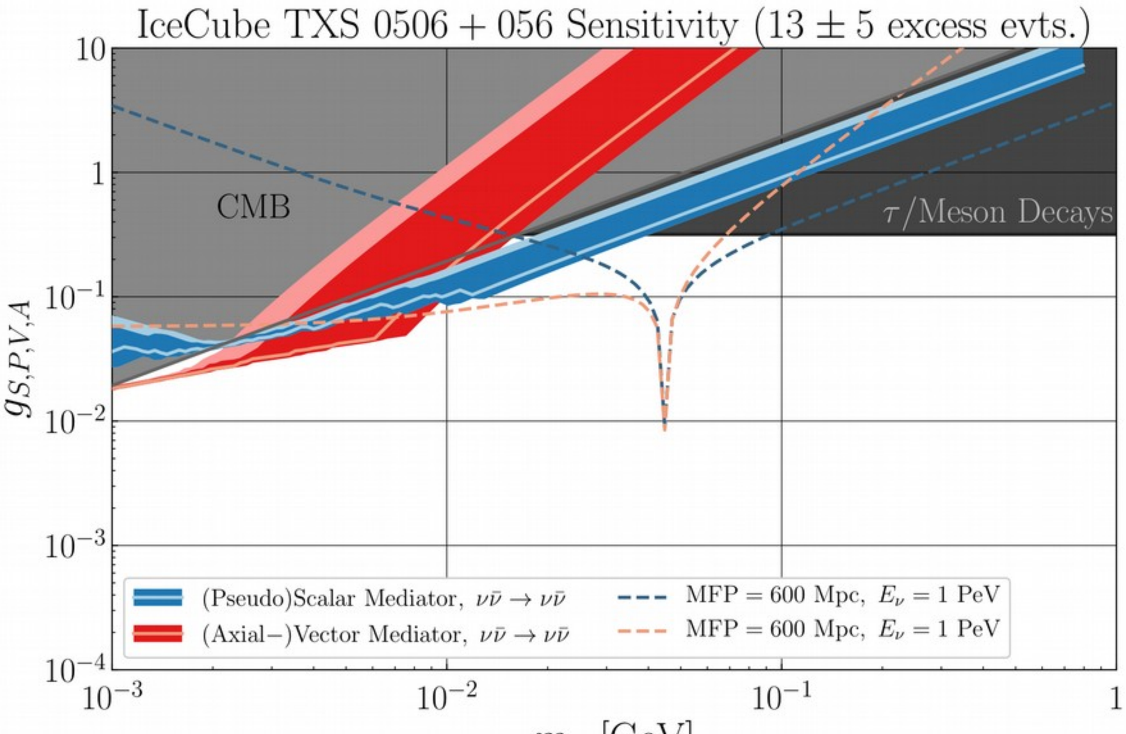
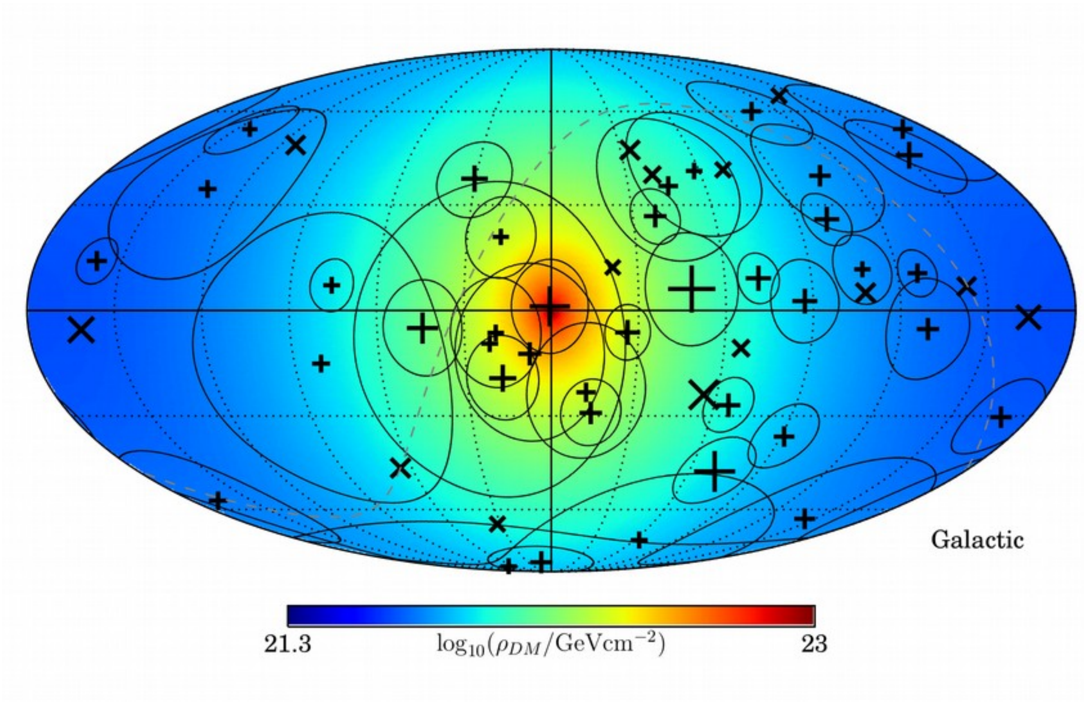
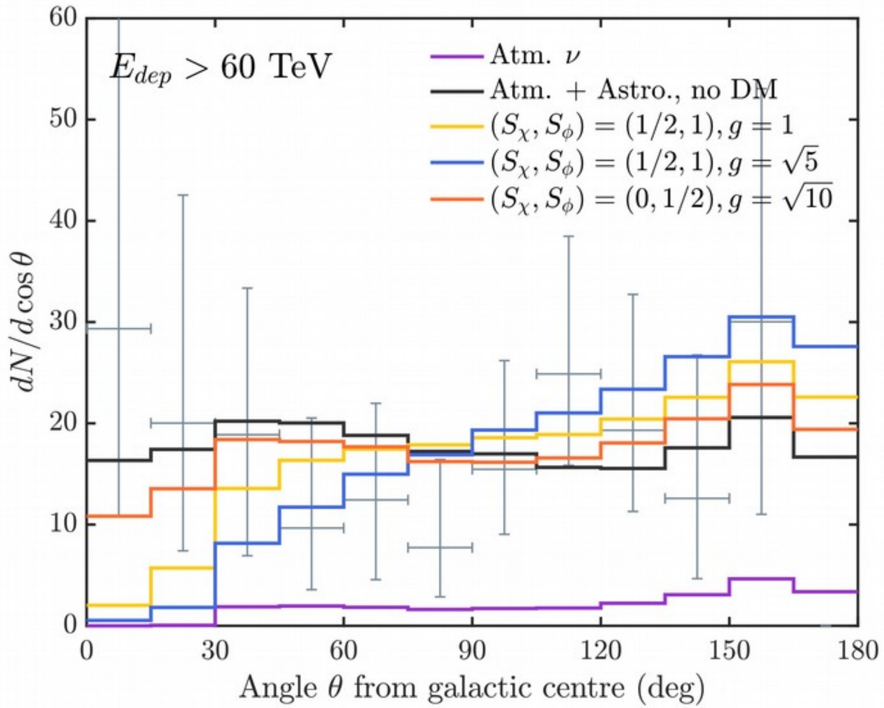


Kelly & Machado, *JCAP* 2018

New physics in the angular distribution: ν-DM interactions

Interaction between astrophysical neutrinos and the Galactic dark matter profile –





Expected: Fewer neutrinos coming from the Galactic Center

Observed: Isotropy

Argüelles, Kheirandish, Vincent, *PRL* 2017

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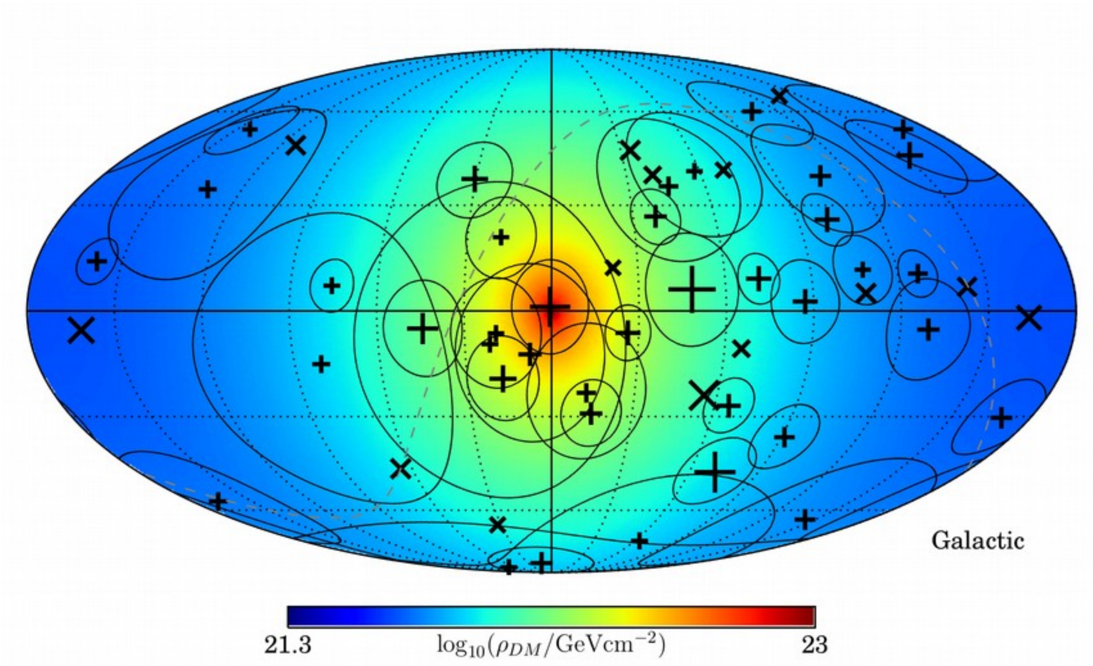

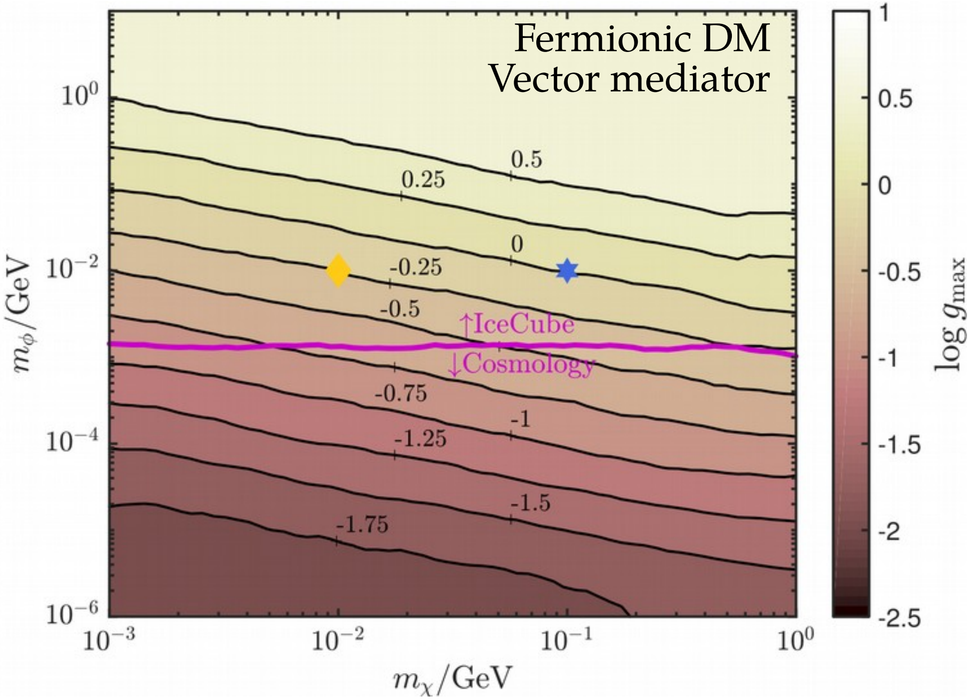

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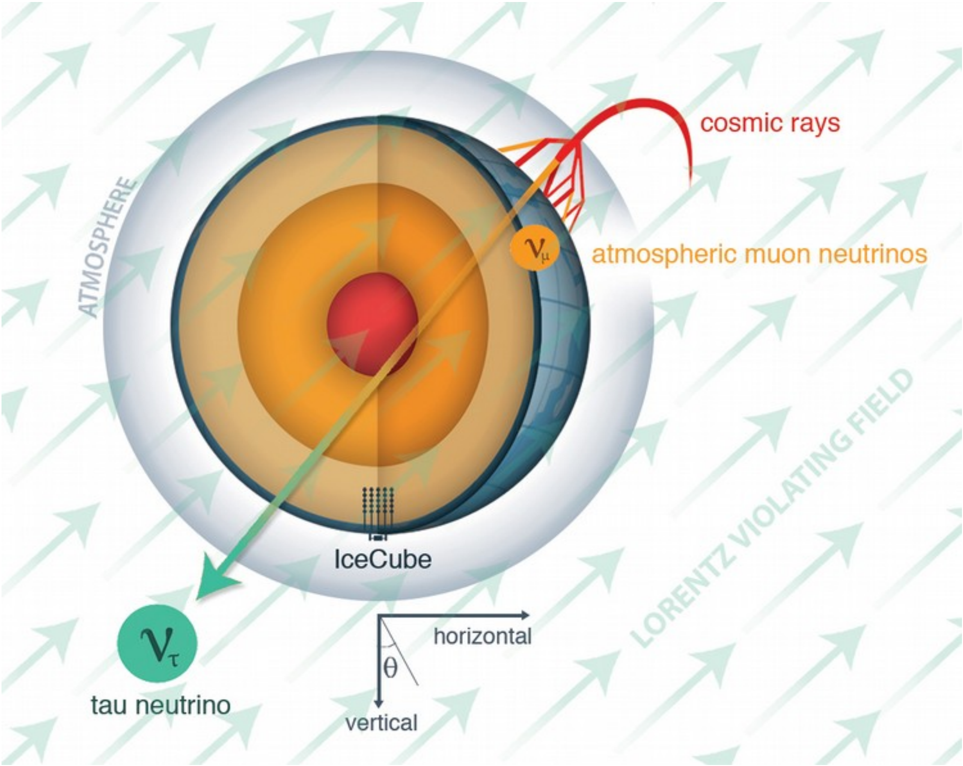
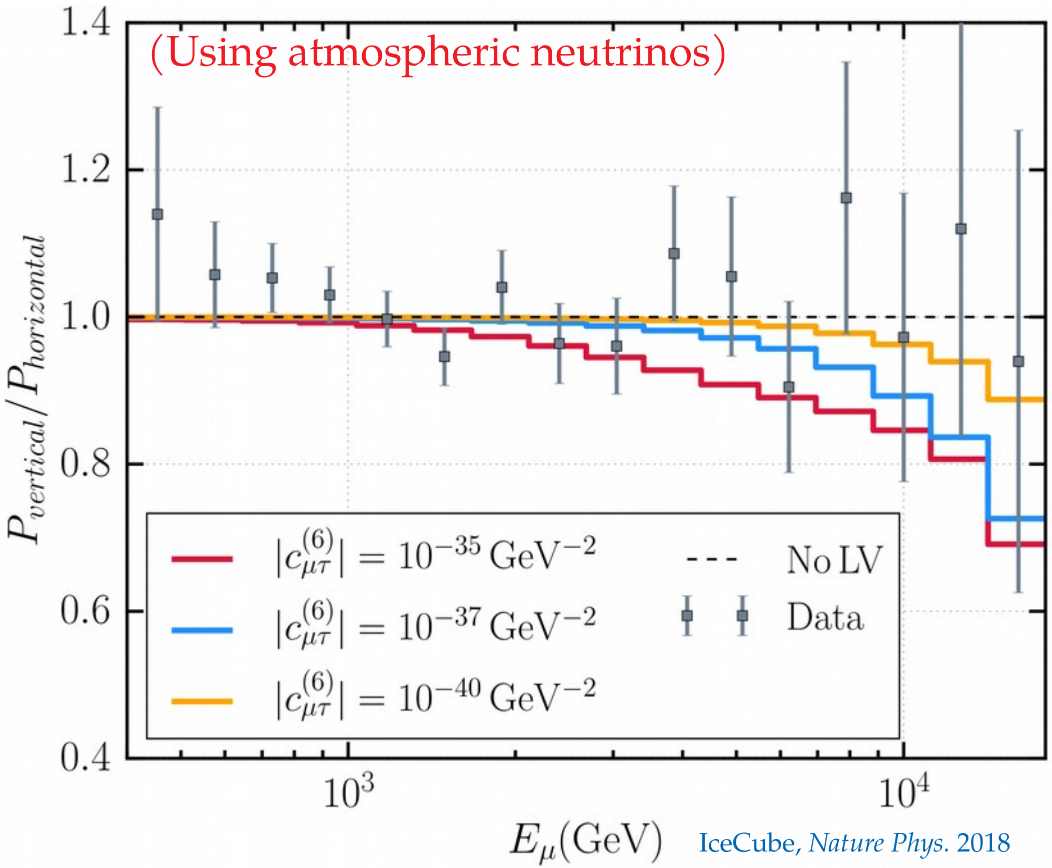
New physics in the energy & angular distribution

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





IceCube, *Nature Phys.* 2018

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Standard oscillations

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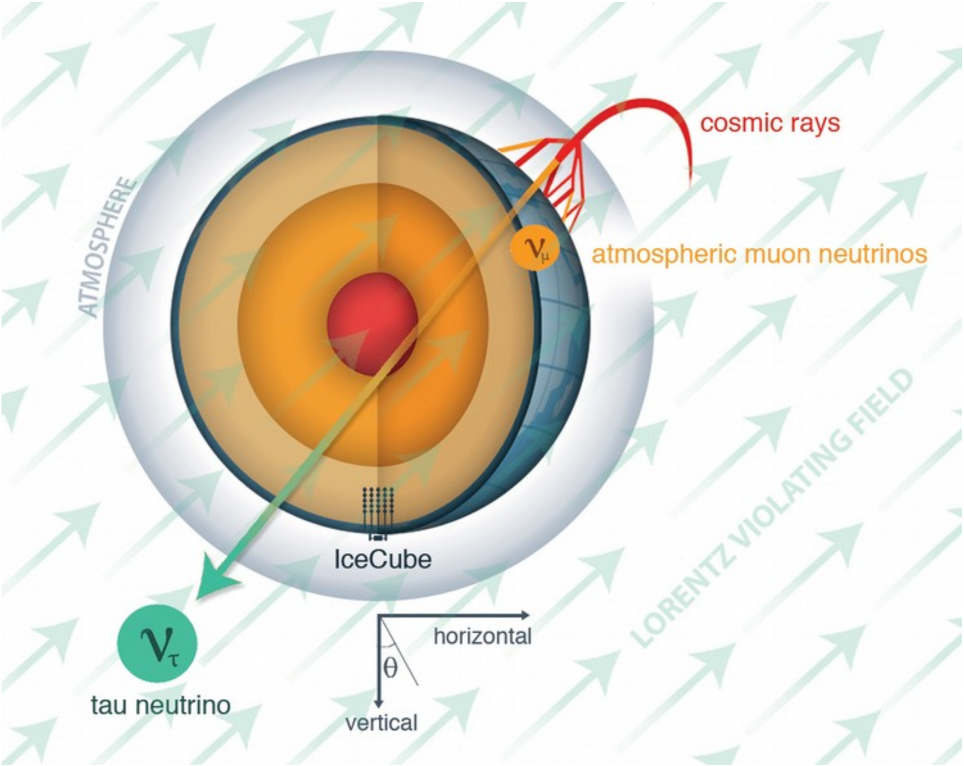

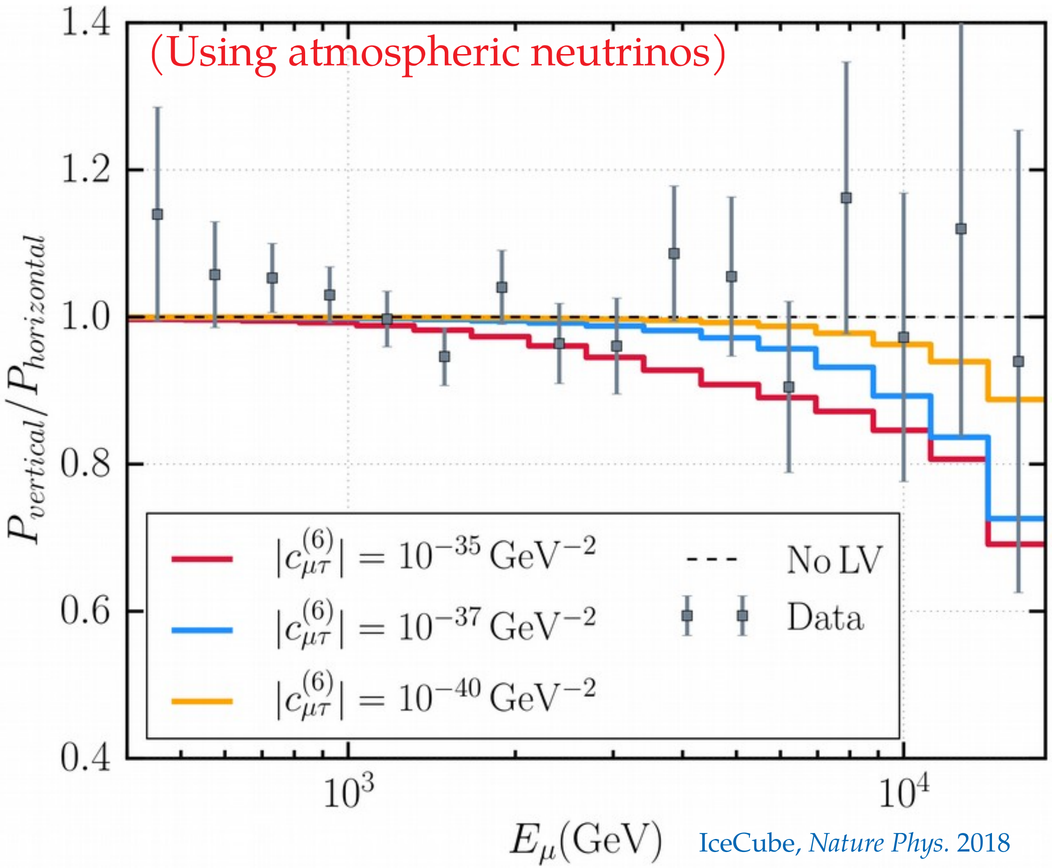

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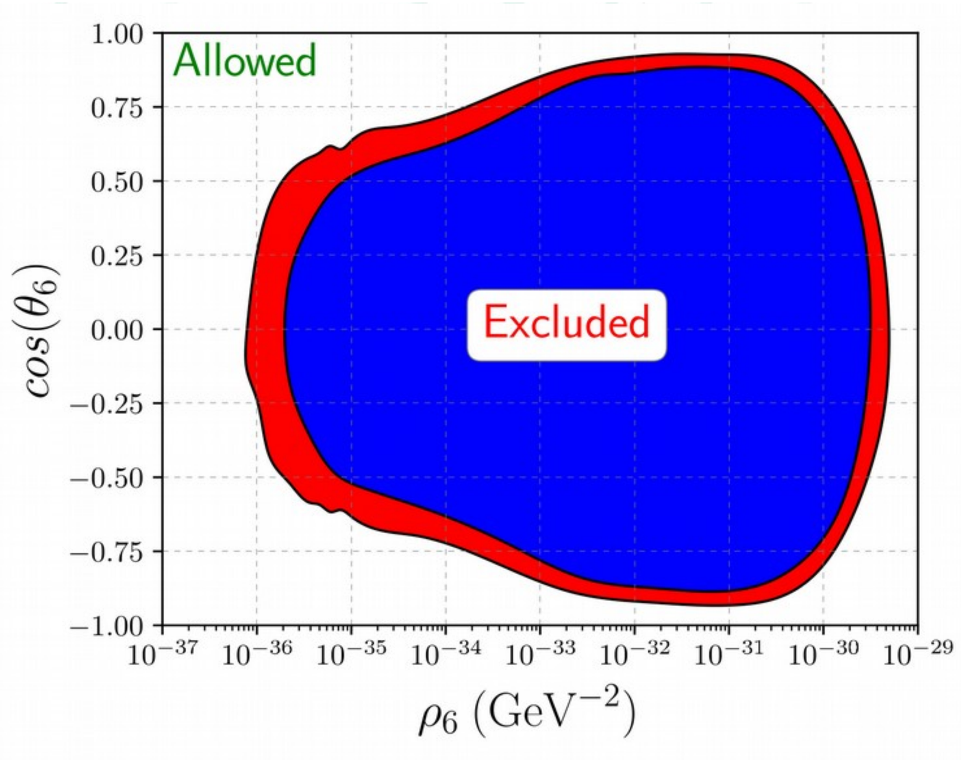
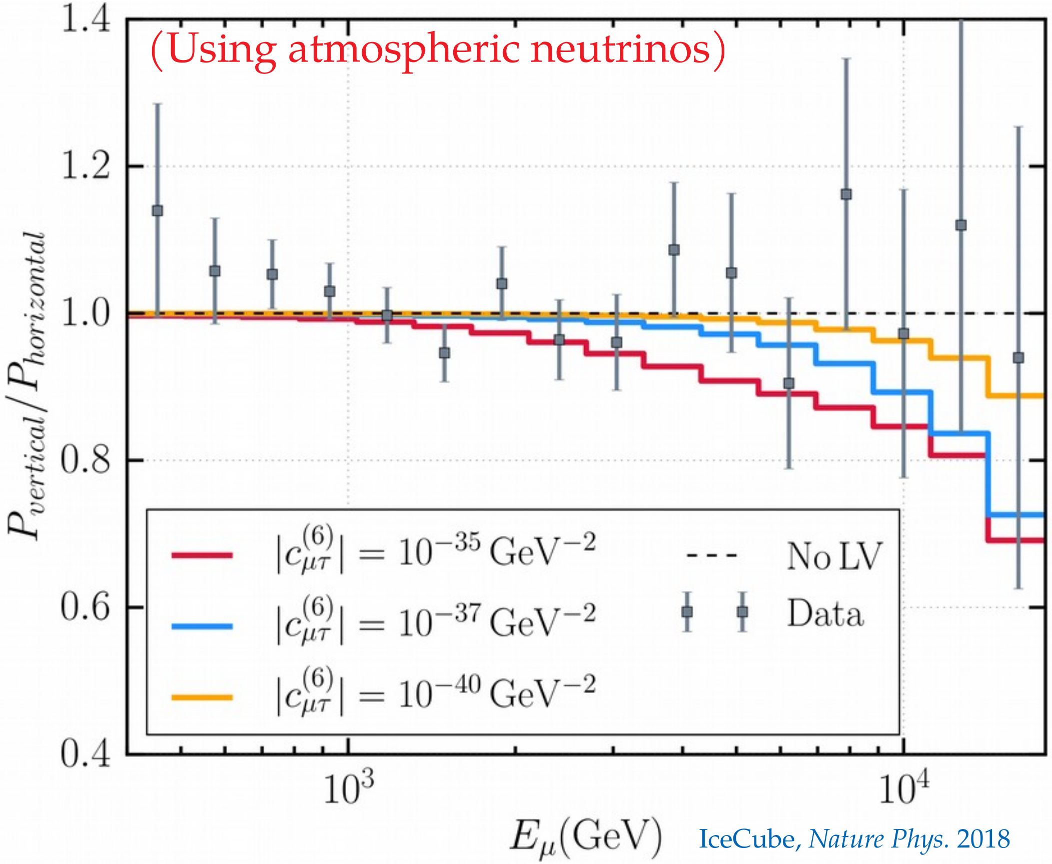
Best bounds come from IceCube

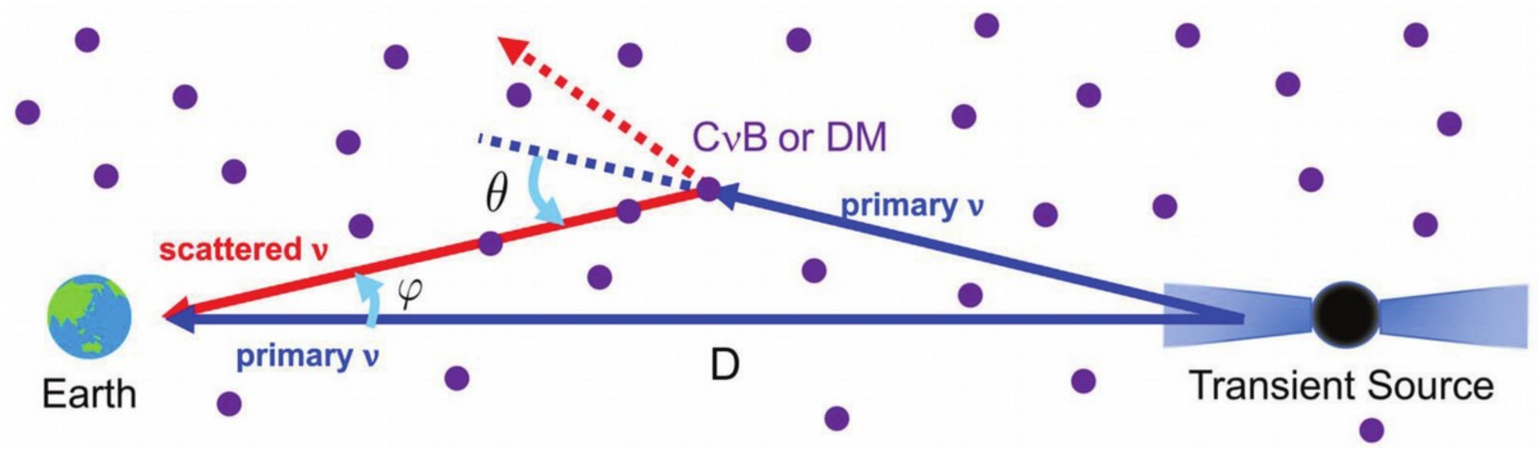




IceCube, *Nature Phys.* 2018

New physics in timing — TeV–PeV

Multiple secret $\nu\nu$ scatterings may delay the arrival of neutrinos from a transient



Shoemaker & Murase, 1903.08607

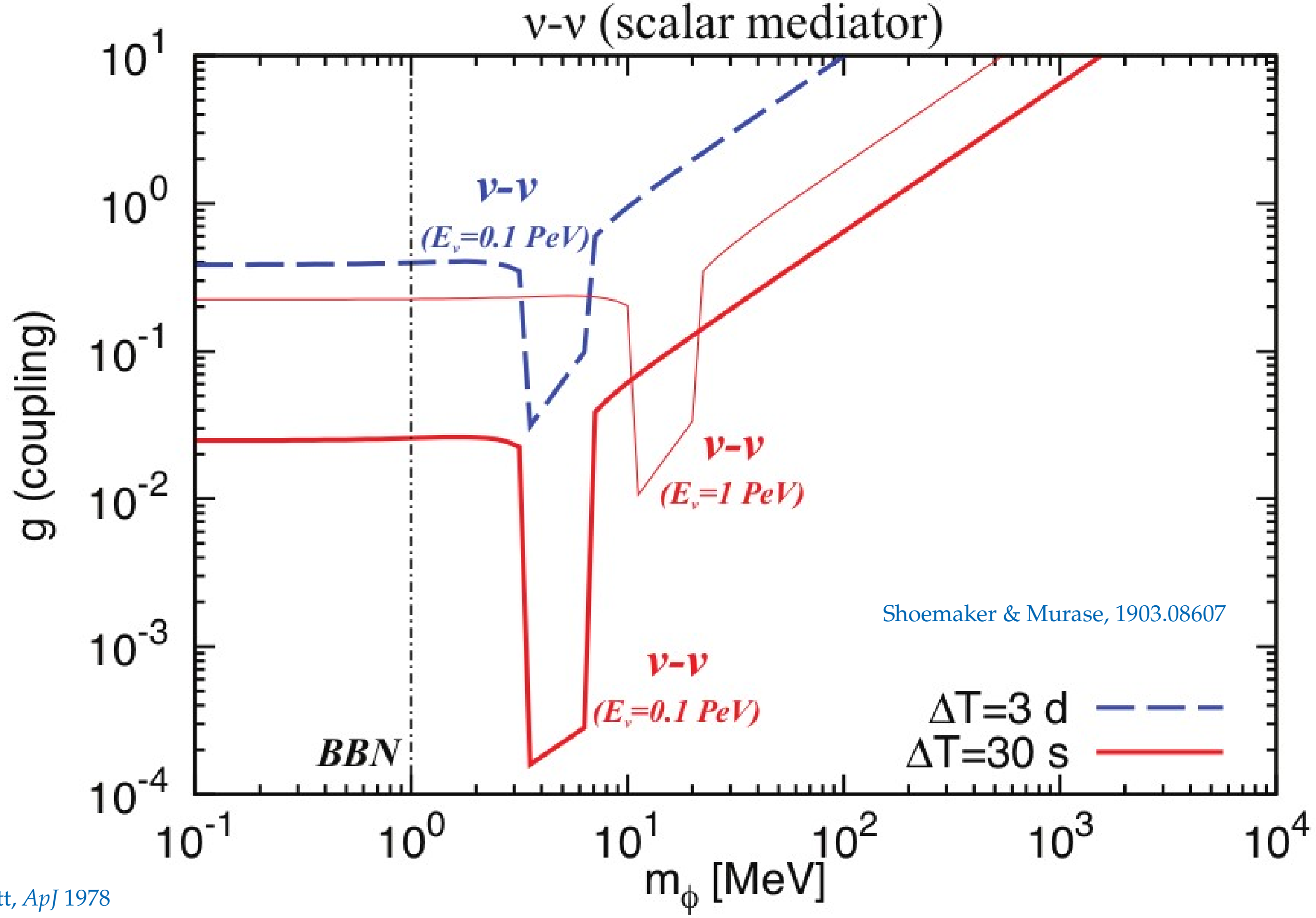
Characteristic time delay —

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

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

See also: Alcock & Hatchett, *ApJ* 1978

New physics in timing — TeV–PeV



See also: Alcock & Hatchett, *ApJ* 1978

Neutrino zenith angle distribution

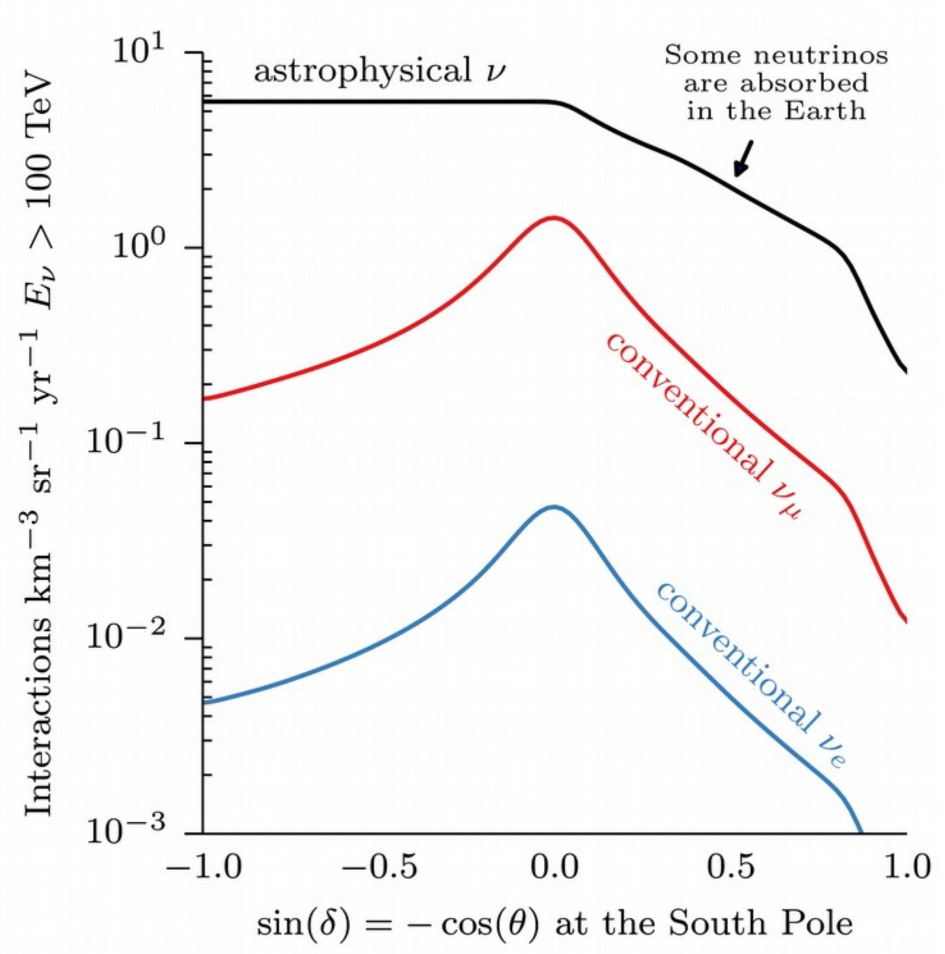
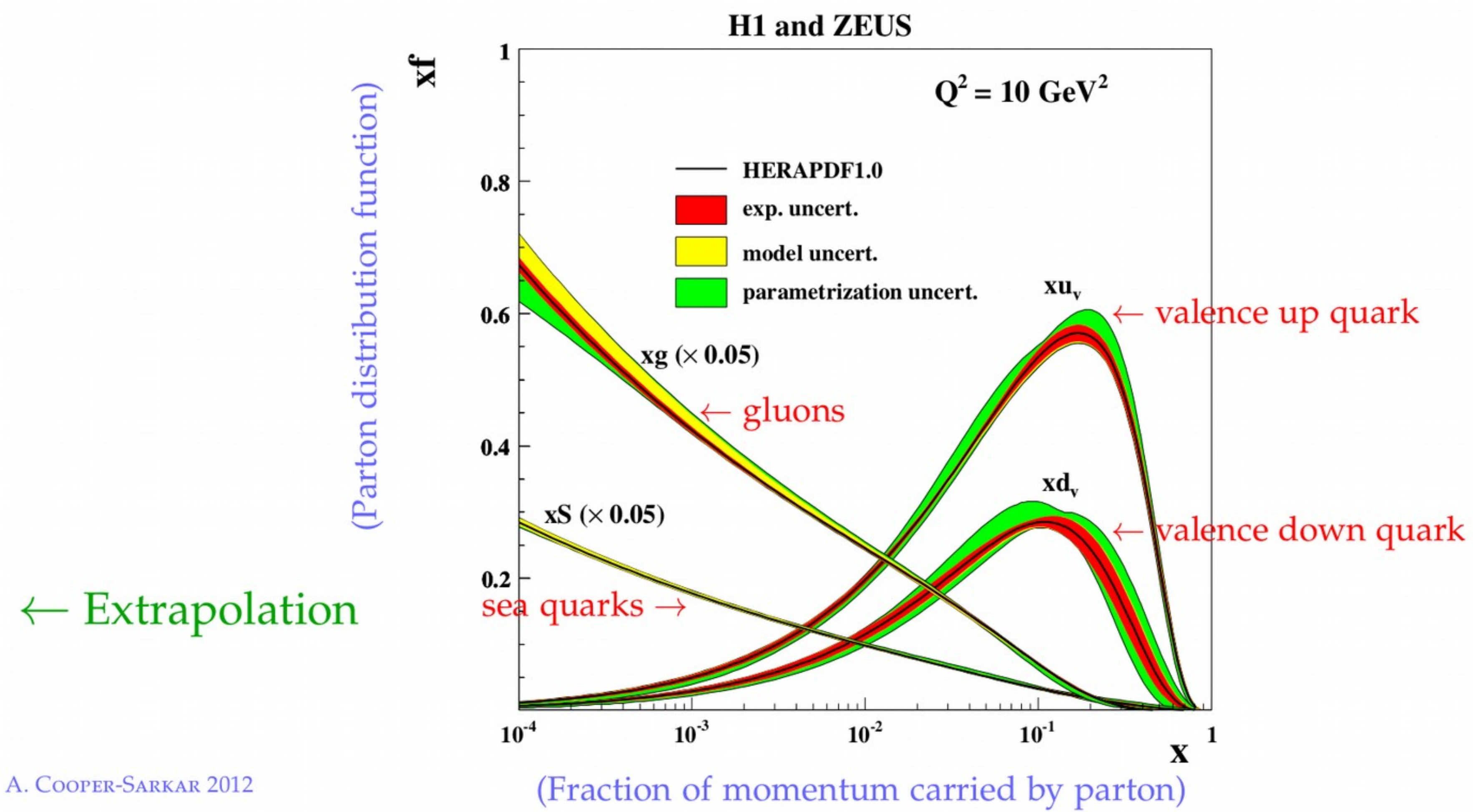


Figure by
Jakob Van Santen
ICRC 2017

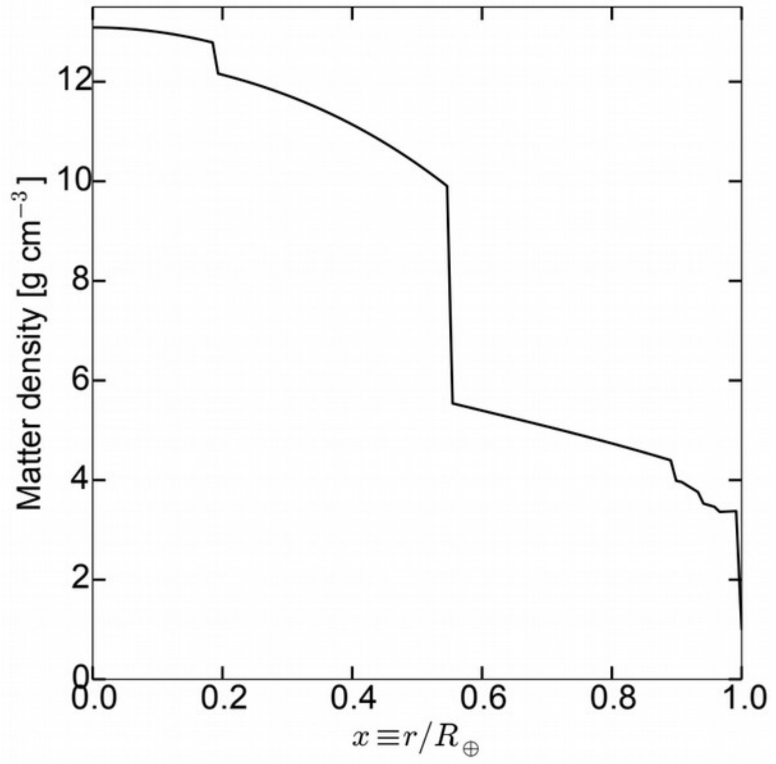
Peeking inside a proton



A feel for the in-Earth attenuation

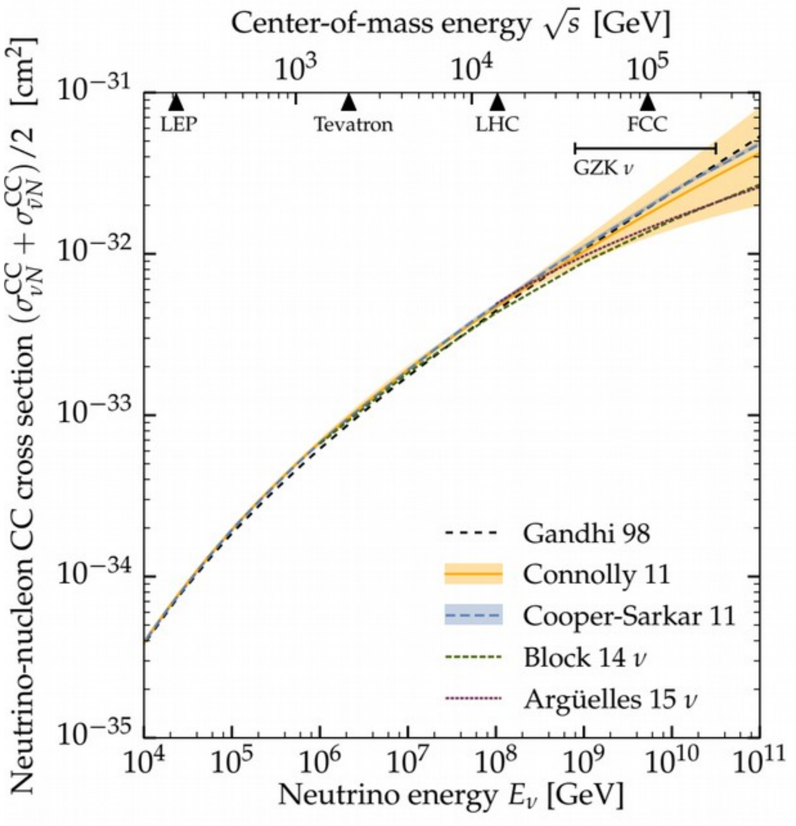
Earth matter density

(Preliminary Reference Earth Model)



+

Neutrino-nucleon cross section



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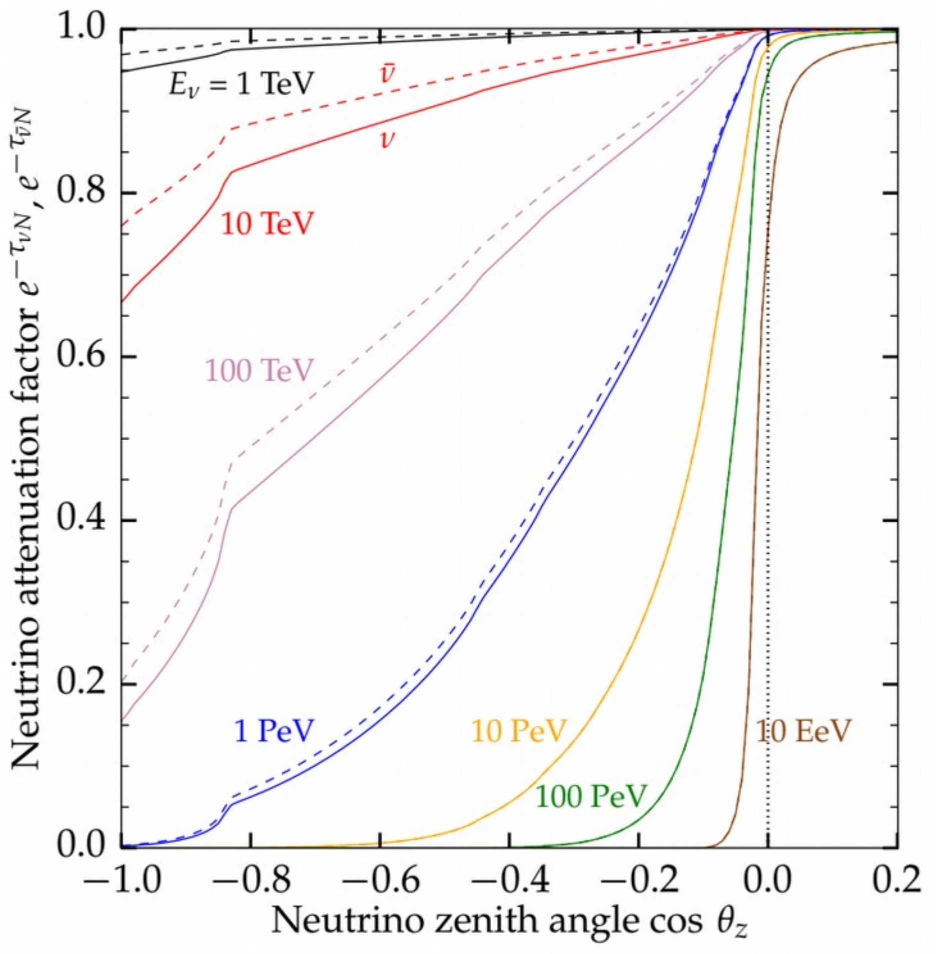

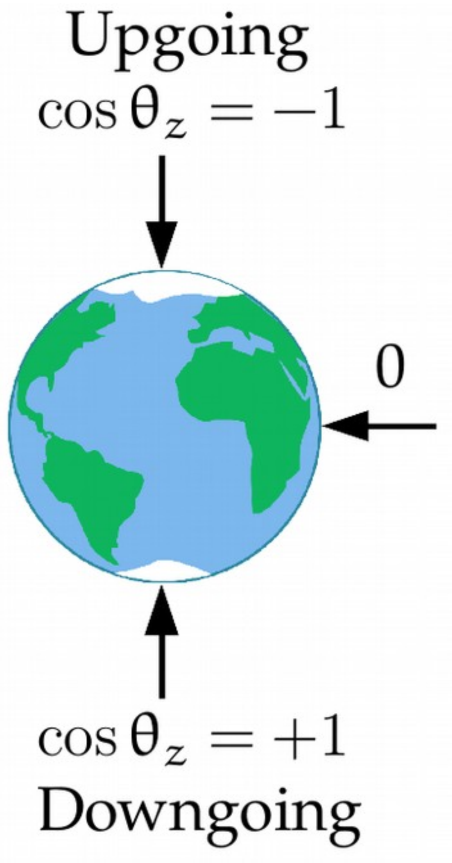

What goes into the (likelihood) mix?

- 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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- 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)

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

- 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

Marginalized cross section in each bin

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

E_ν [TeV]	$\langle E_\nu \rangle$ [TeV]	$\langle \sigma_{\bar{\nu} N}^{CC} / \sigma_{\nu N}^{CC} \rangle$	$\log_{10}[\frac{1}{2}(\sigma_{\nu N}^{CC} + \sigma_{\bar{\nu} N}^{CC})/\text{cm}^2]$
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:

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

Contribution from one flavor CC:

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

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]

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

IceCube, *JINST* 2014

Angular resolution:

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

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 $\sigma_{\nu N}$

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

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

PDF for this shower to be made by an atmospheric ν

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

PDF for this shower to be made by an astrophysical ν

Depends on γ and $\sigma_{\nu N}$

MB & A. Connolly, 1711.11043

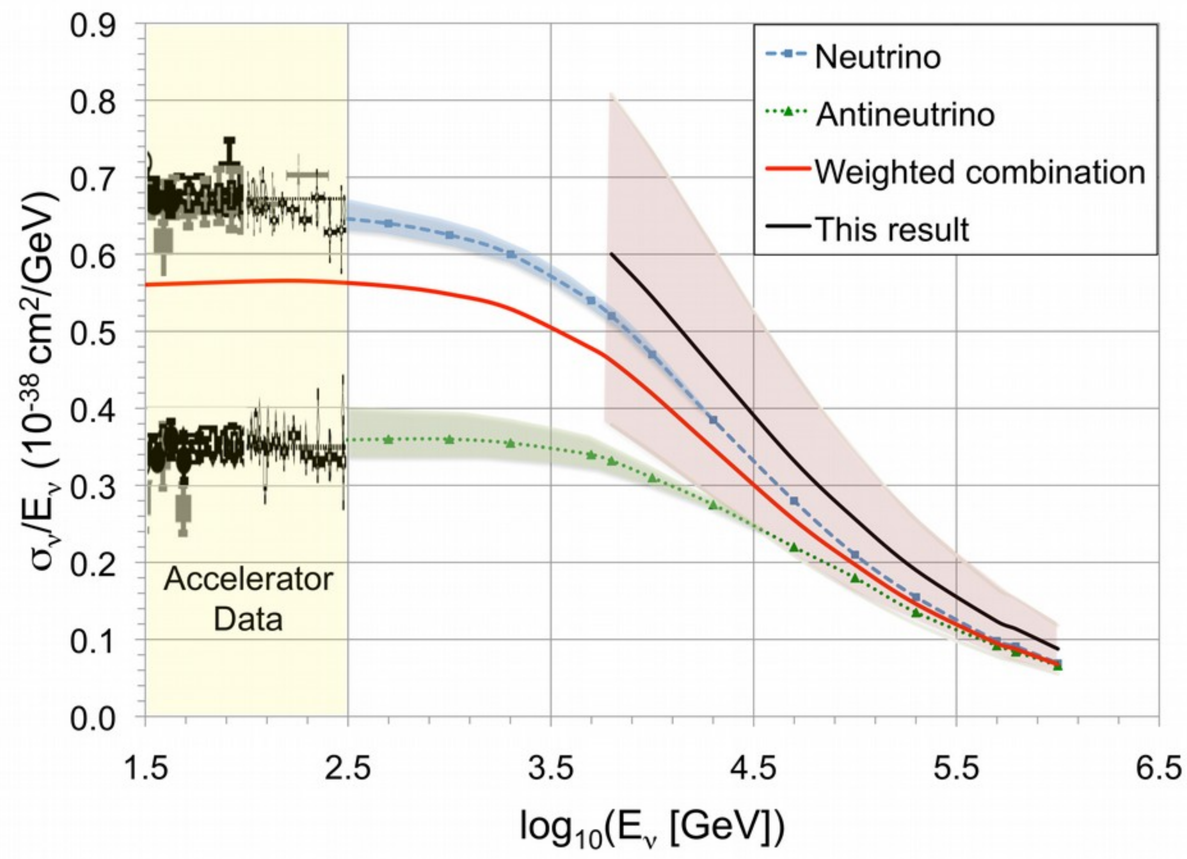
See also: Palomares-Ruiz, Vincent, Mena *PRD* 2015; Vincent, Palomares-Ruiz, Mena *PRD* 2016

The fine print

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

Using through-going muons instead

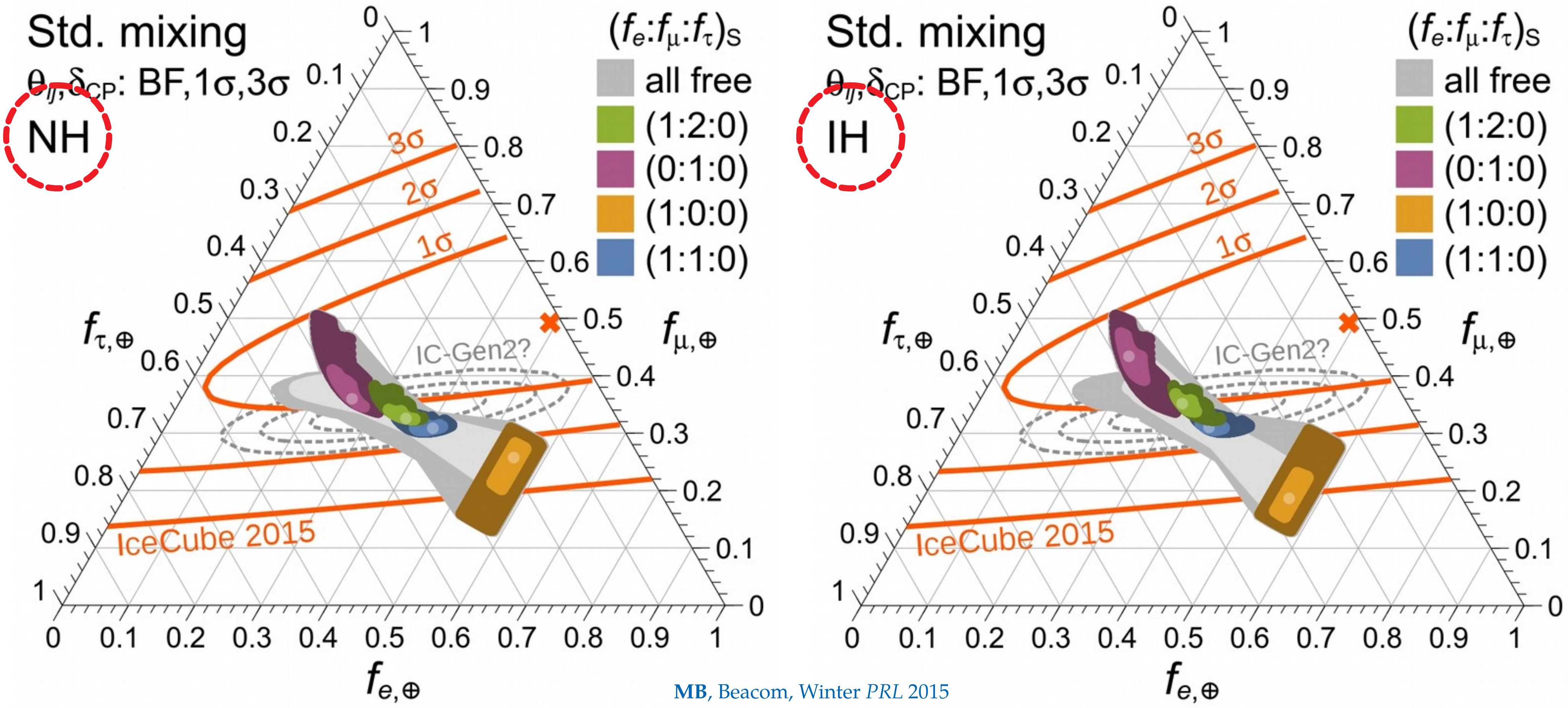
- Use ~10^4 through-going muons
- Measured: dE_μ/dx
- Inferred: $E_\mu \approx dE_\mu/dx$
- From simulations (uncertain): most likely E_ν given E_μ
- Fit the ratio σ_{obs}/σ_{SM}
  $1.30^{+0.21}_{-0.19}(\text{stat.})^{+0.39}_{-0.43}(\text{syst.})$
- All events grouped in a single energy bin 6–980 TeV



IceCube, *Nature* 2017

Flavor composition – a few source choices

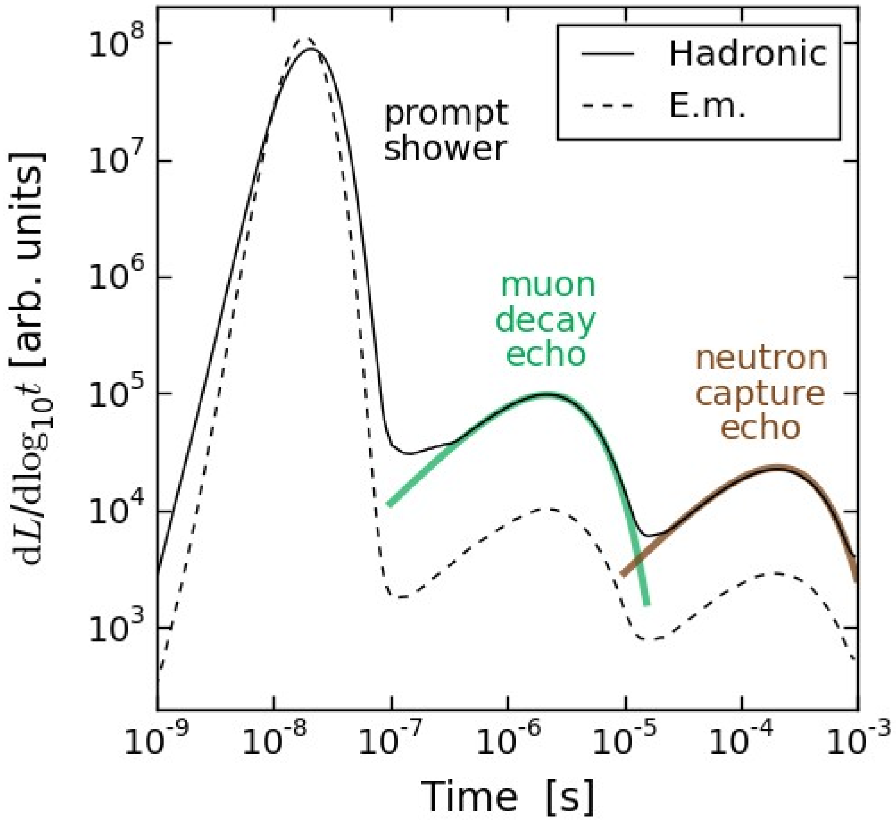
Flavor composition – a few source choices

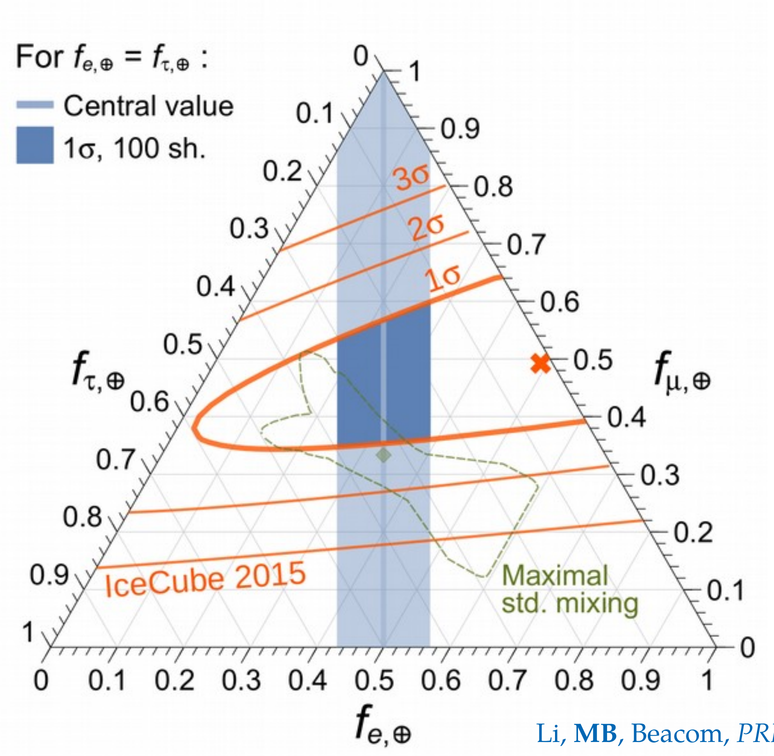


MB, Beacom, Winter *PRL* 2015

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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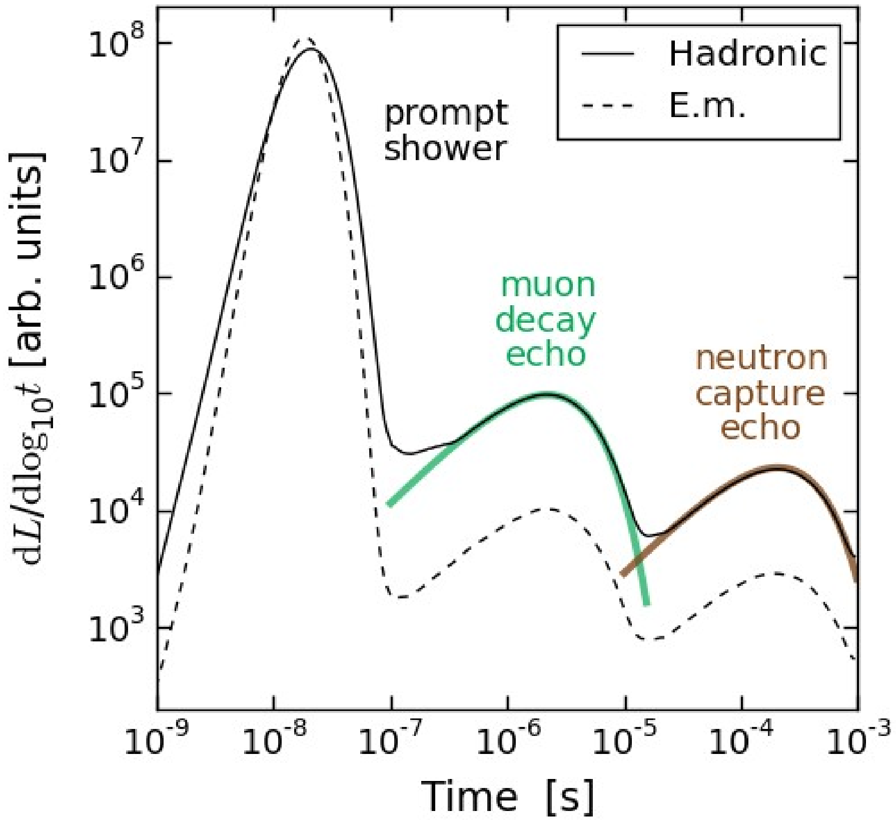
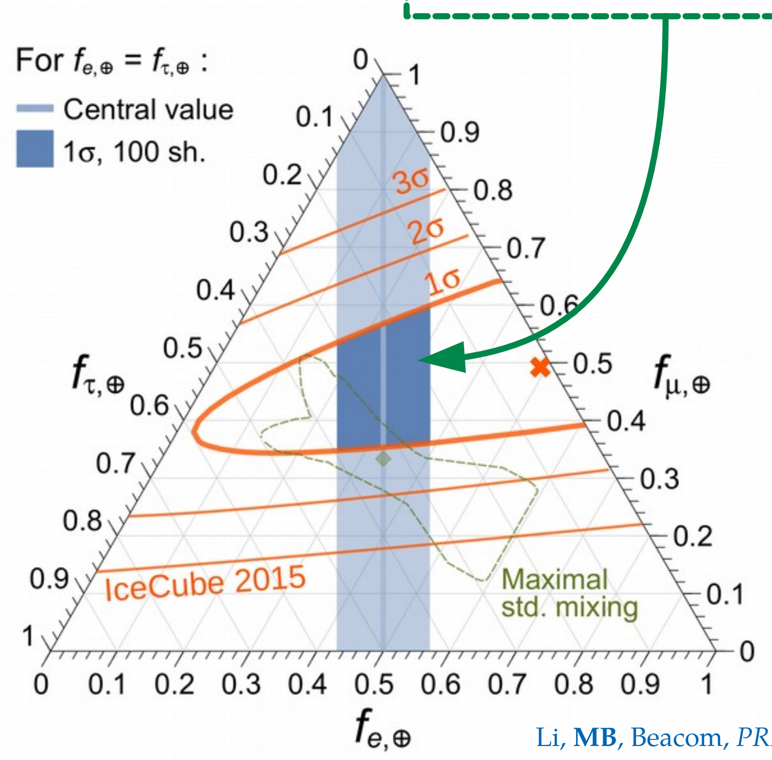


~10 × improvement over current measurement



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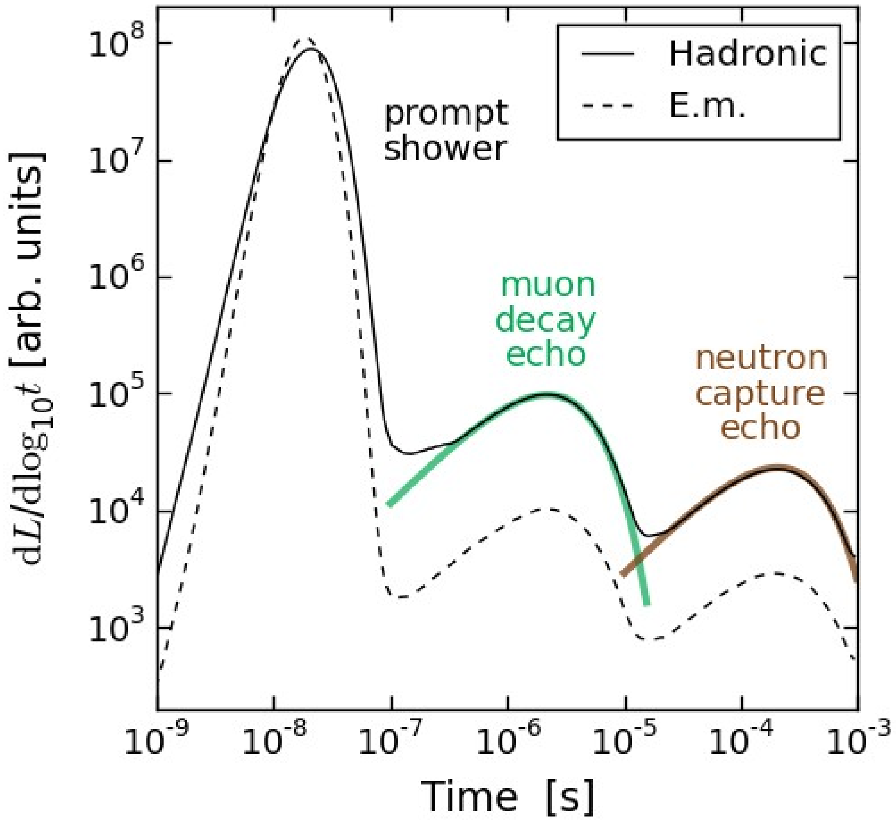

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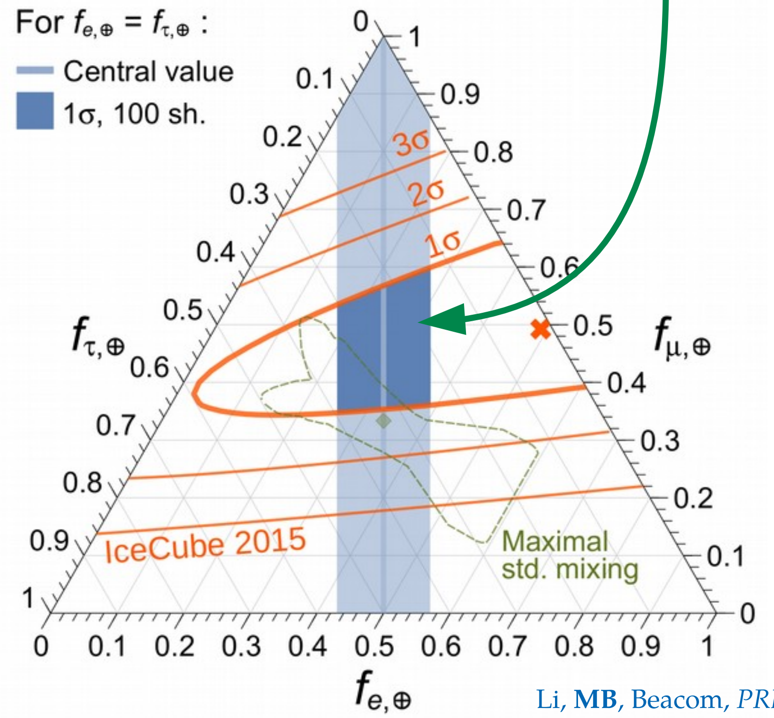
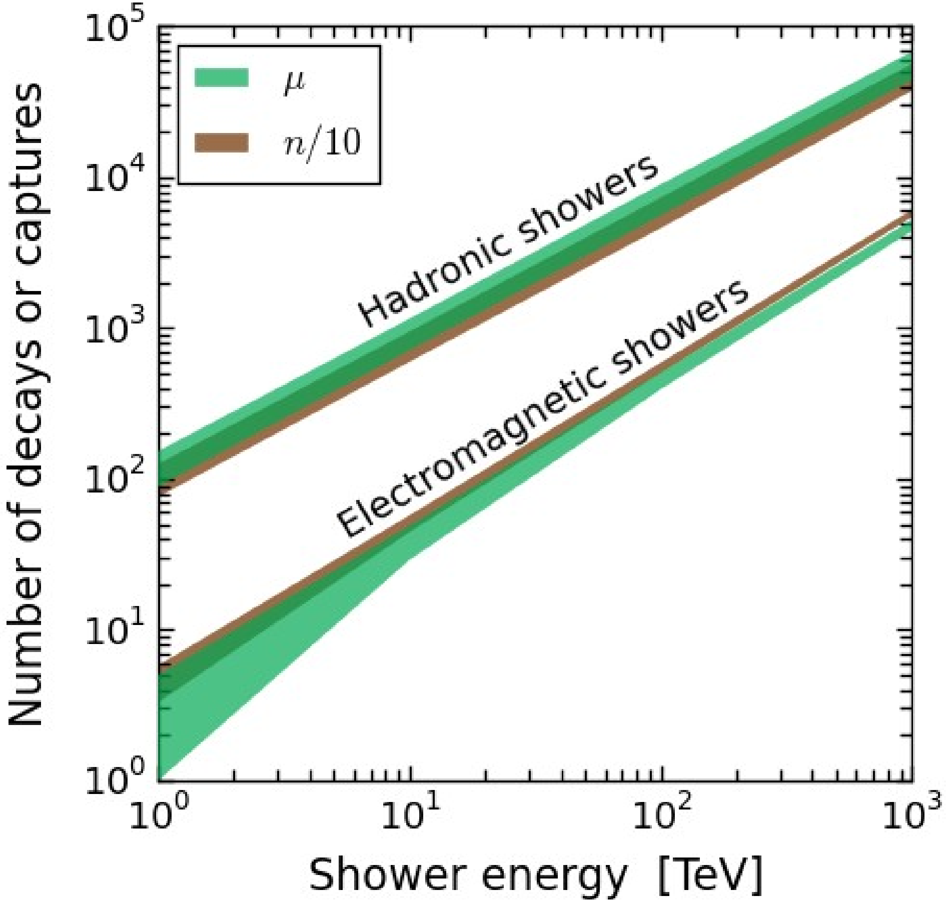
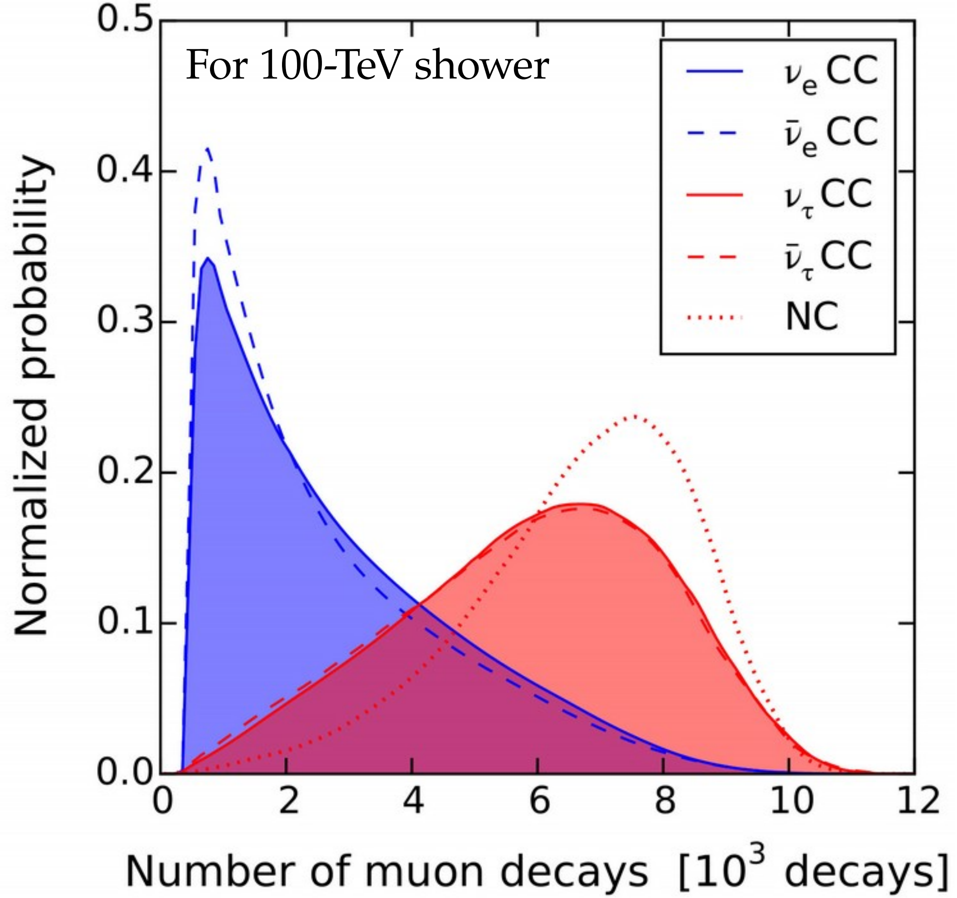


Li, **MB**, Beacom, *PRL* 2019

Hadronic *vs.* electromagnetic showers

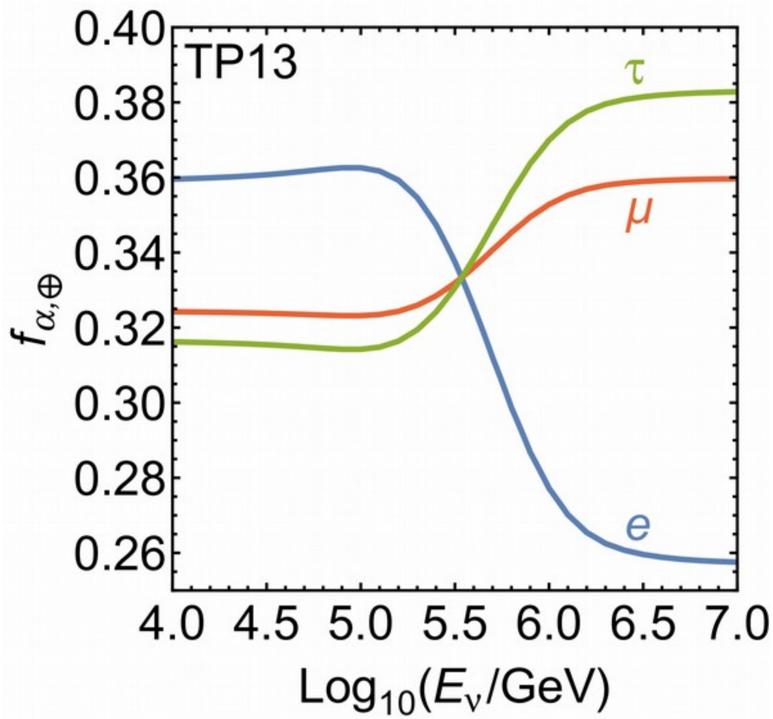


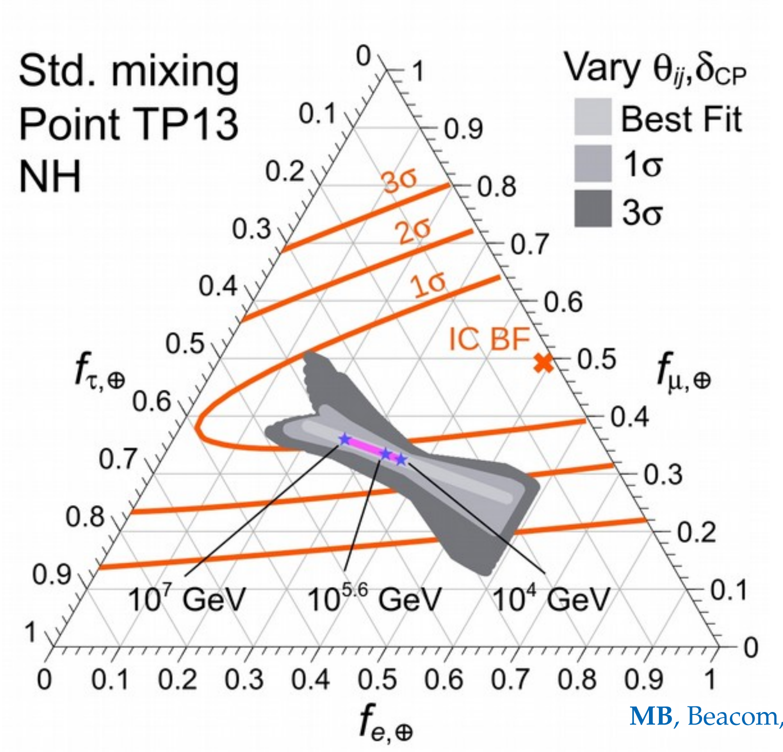


Li, **MB**, Beacom, *PRL* 2019

Energy dependence of the flavor composition?

Different neutrino production channels accessible at different energies –

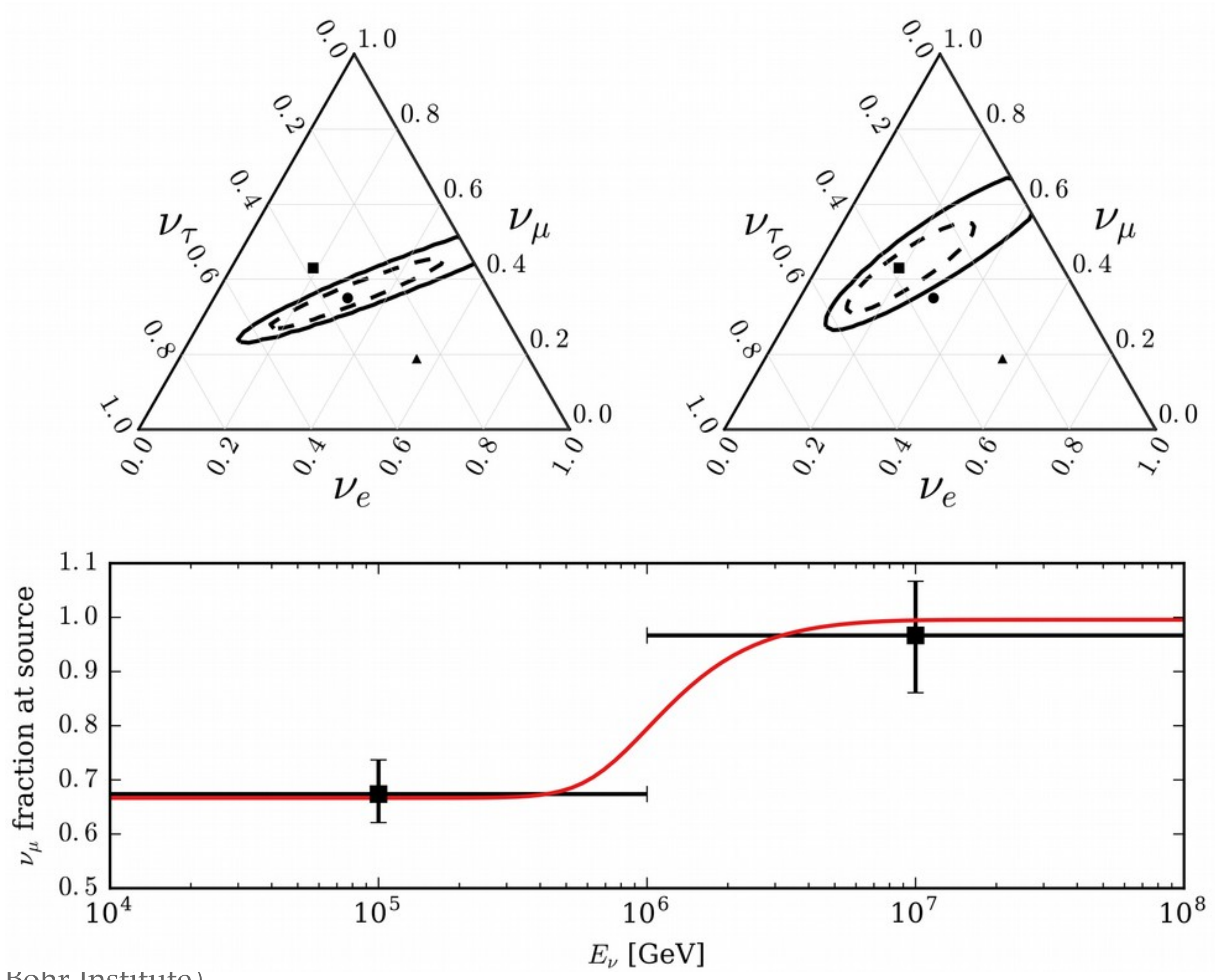




MB, Beacom, Winter *PRL* 2015

- 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

Flavor content of neutrino mass eigenstates

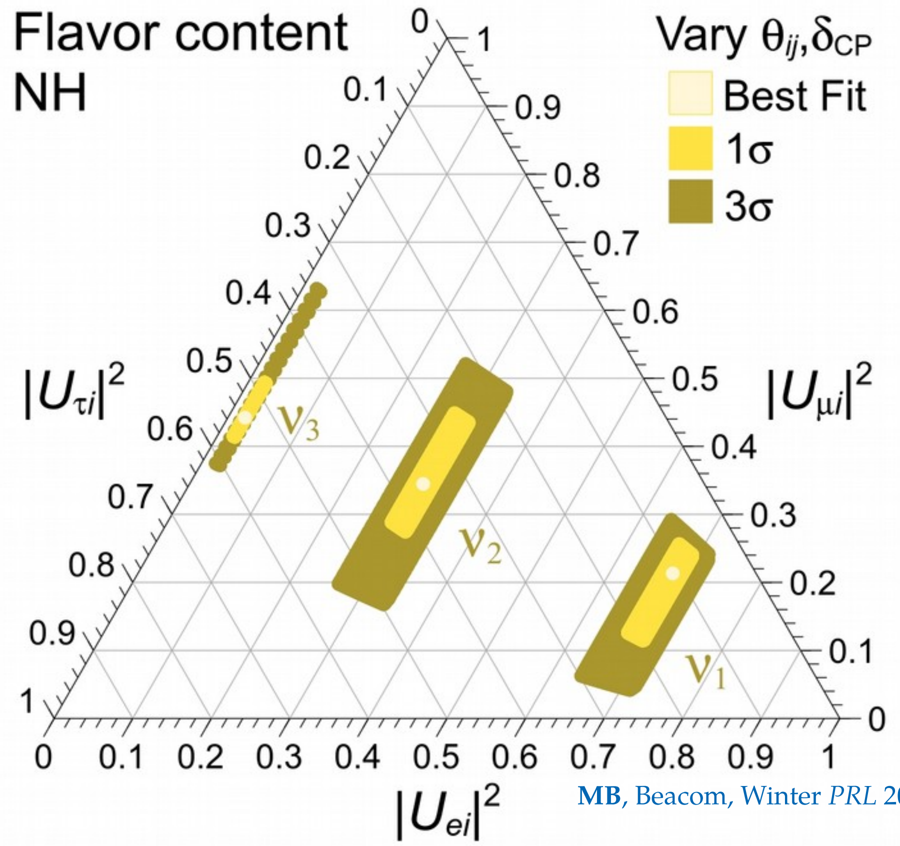
Flavor content for every allowed combination of mixing parameters –

Known to within 2%

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

Known to within 8%

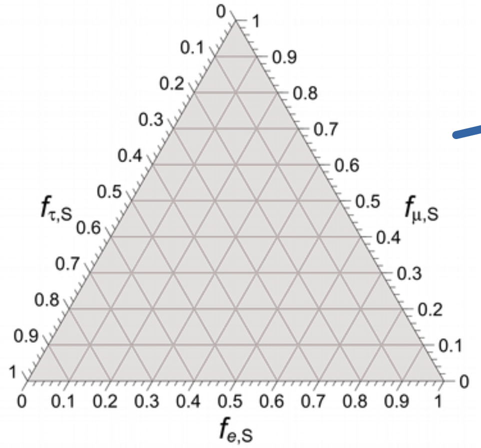
Known to within 20% (or worse)



MB, Beacom, Winter *PRL* 2015

Measuring the neutrino lifetime

Sources



$\nu_2, \nu_3 \to \nu_1$

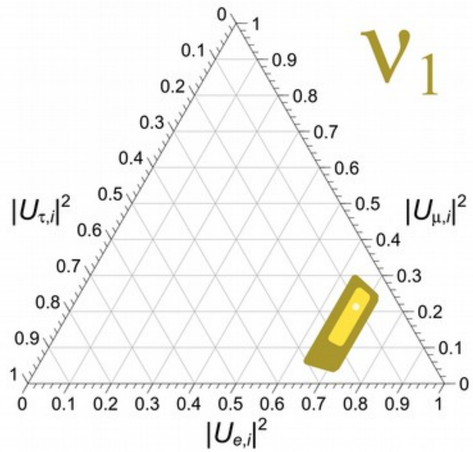
ν_1 lightest and stable

If all unstable neutrinos decay

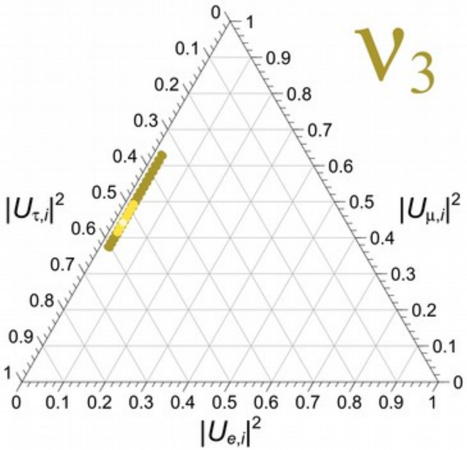
$\nu_1, \nu_2 \to \nu_3$

ν_3 lightest and stable

Earth



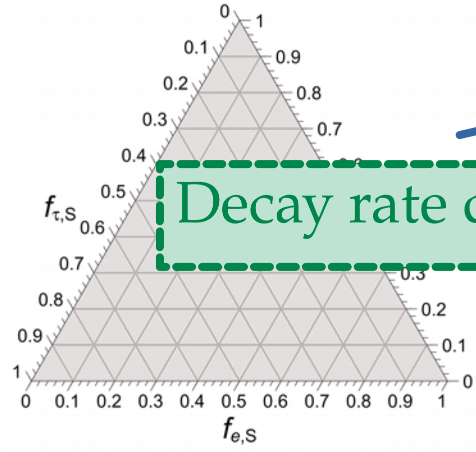
$$f_{\alpha,\oplus} = |U_{\alpha 1}|^2$$



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

Measuring the neutrino lifetime

Sources



$\nu_2, \nu_3 \rightarrow \nu_1$

ν_1 lightest and stable

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ν_3 lightest and stable

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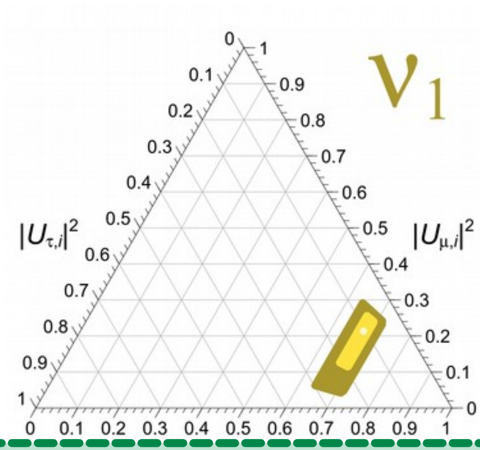
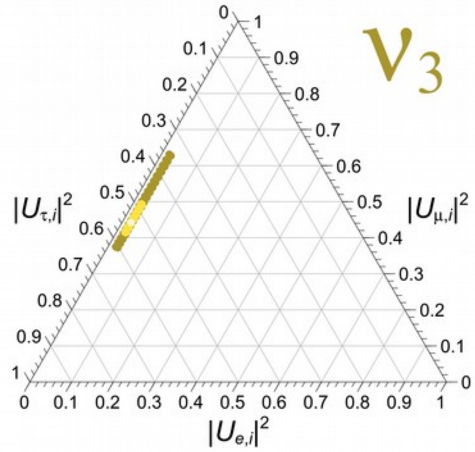


$f_{\alpha,\oplus} = |U_{\alpha 1}|^2$

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



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

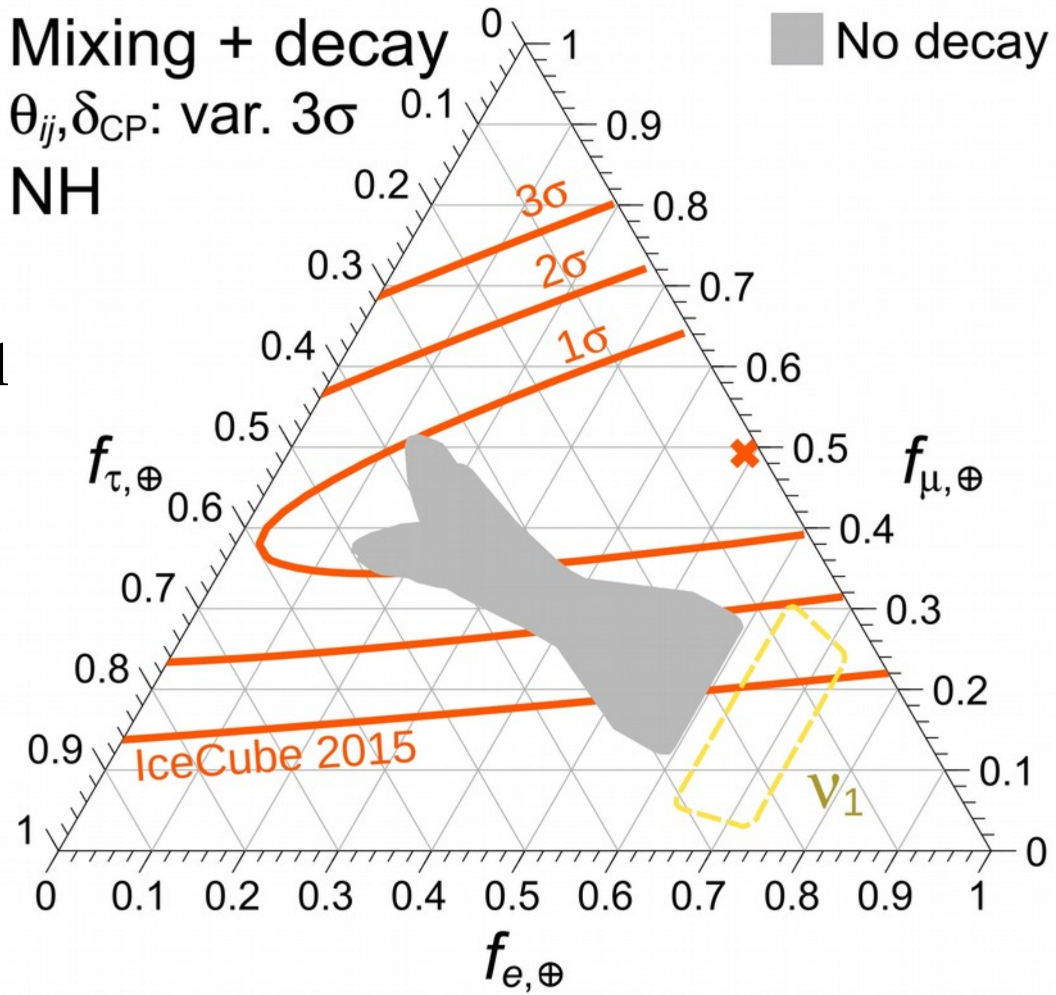
Measuring the neutrino lifetime

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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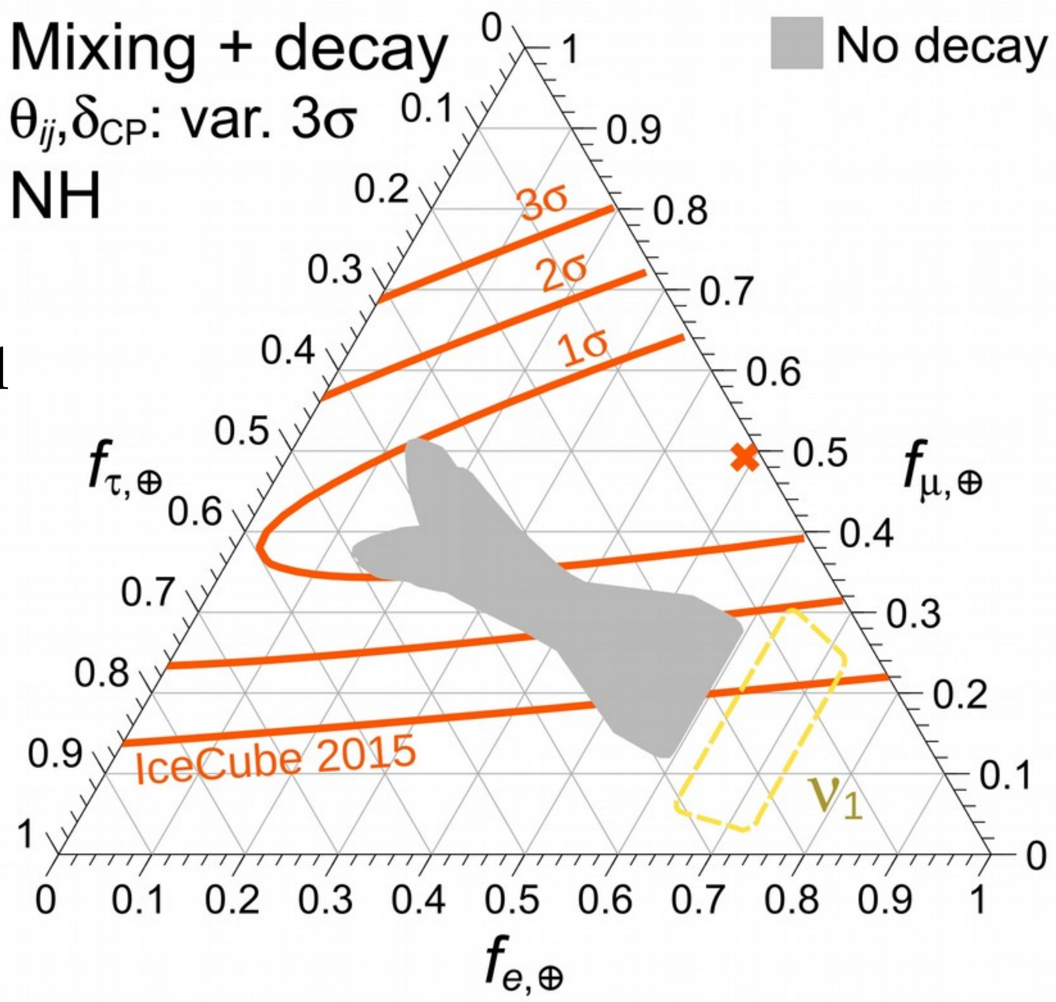

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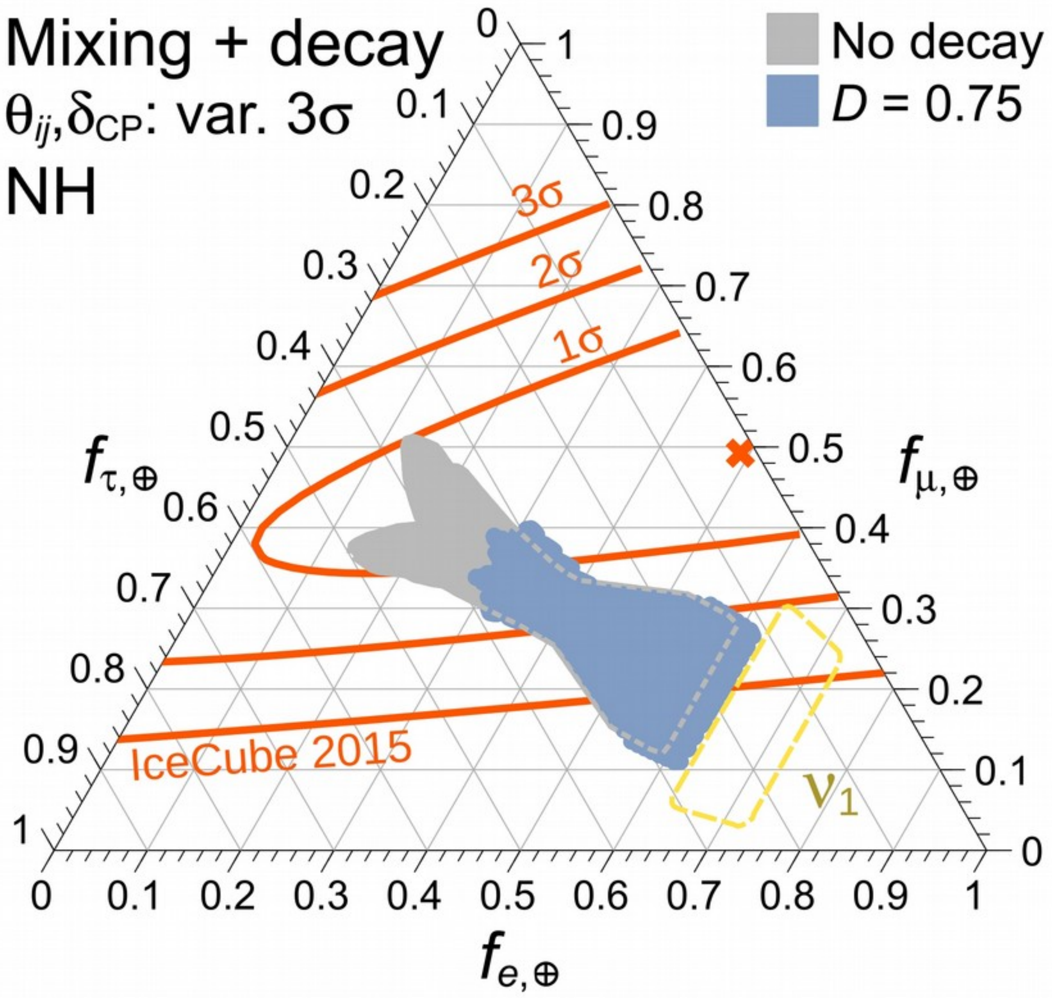

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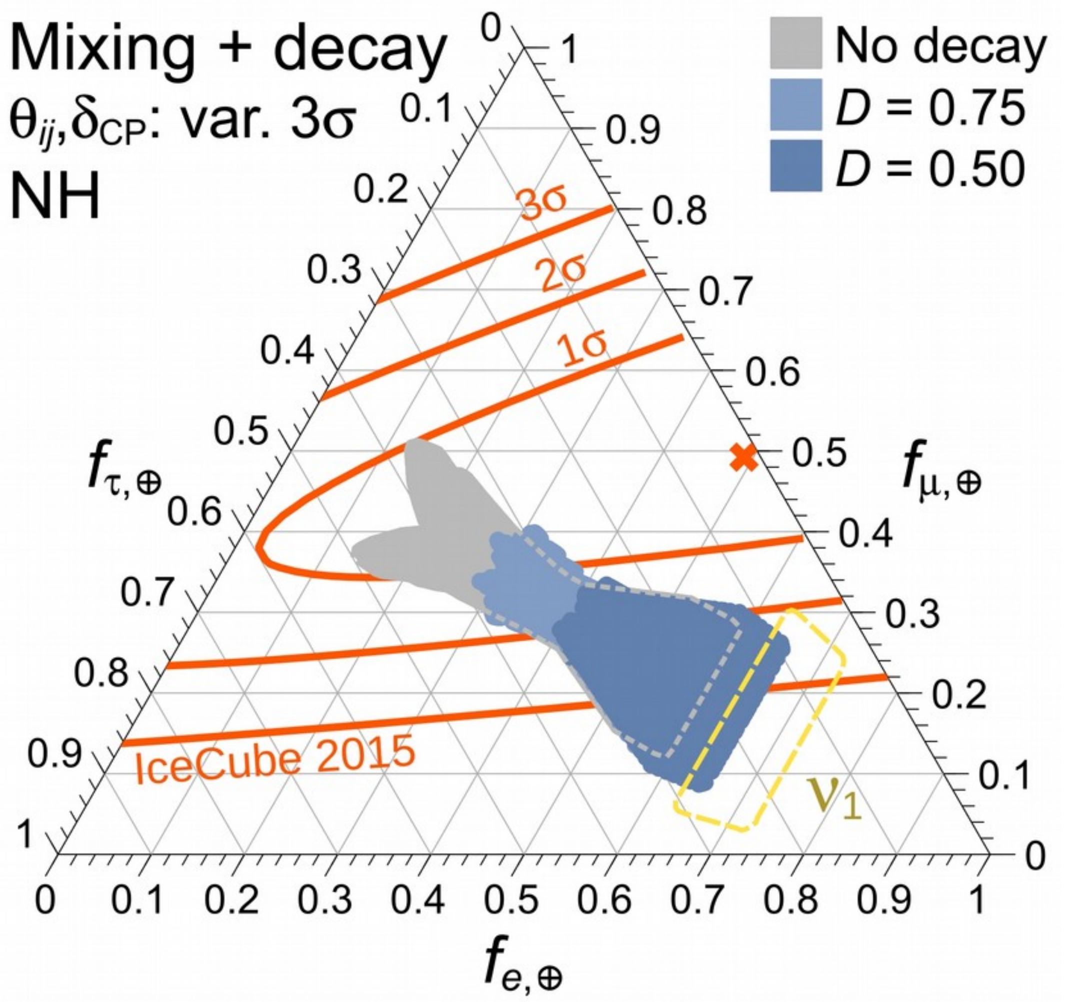

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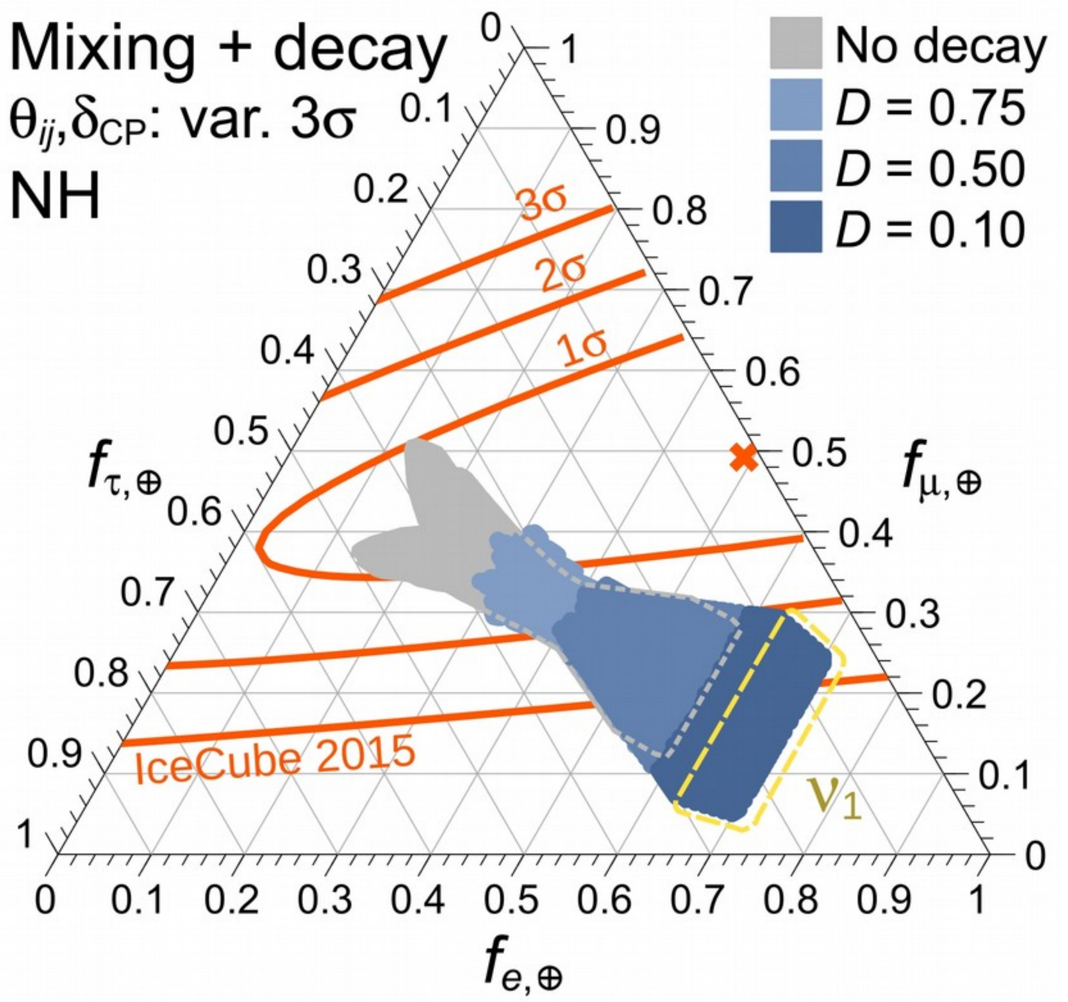

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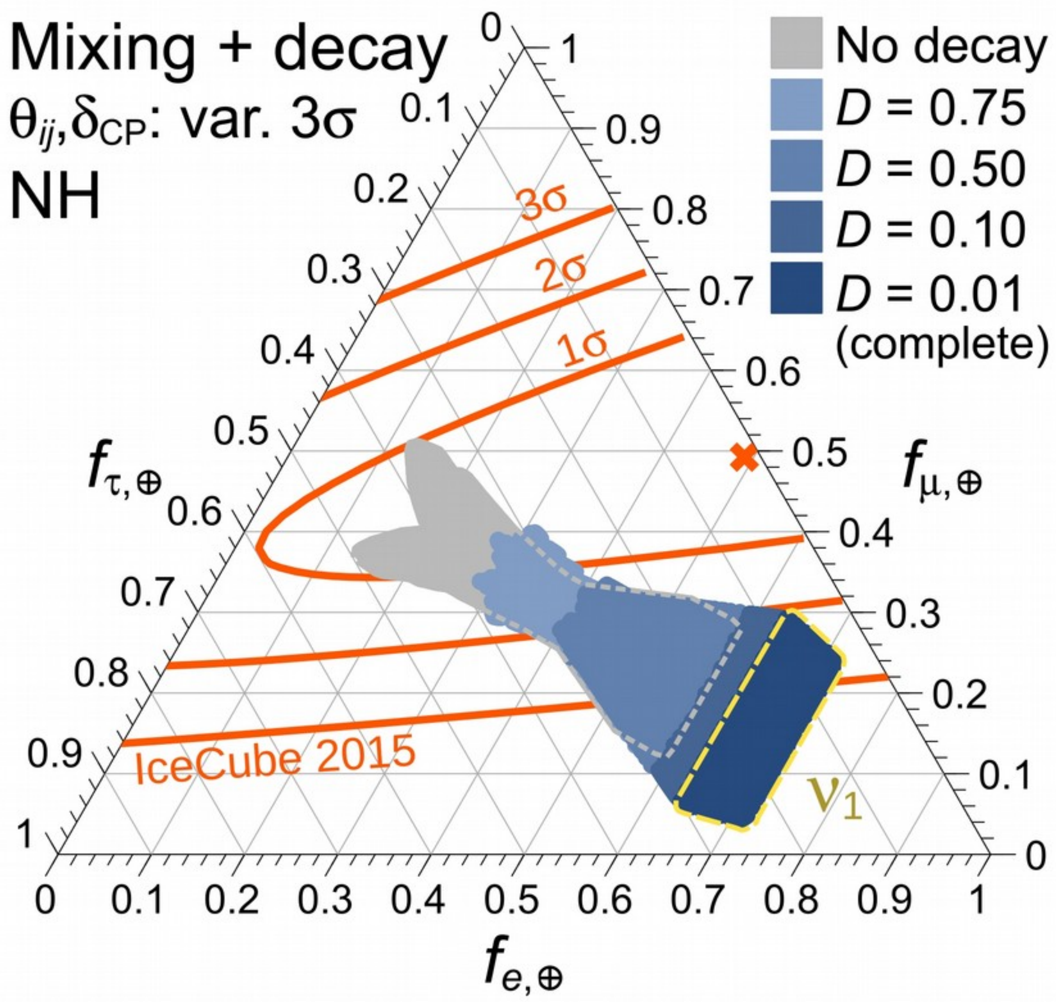

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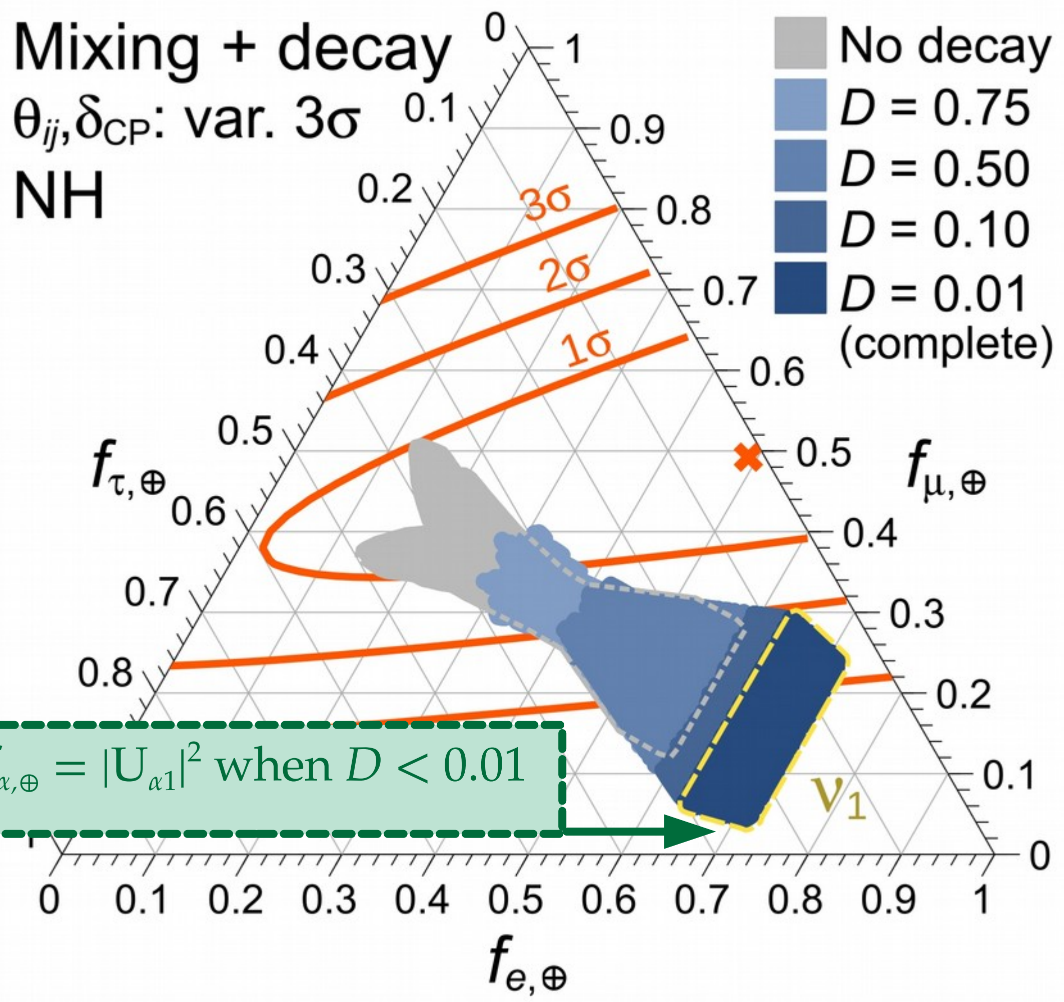
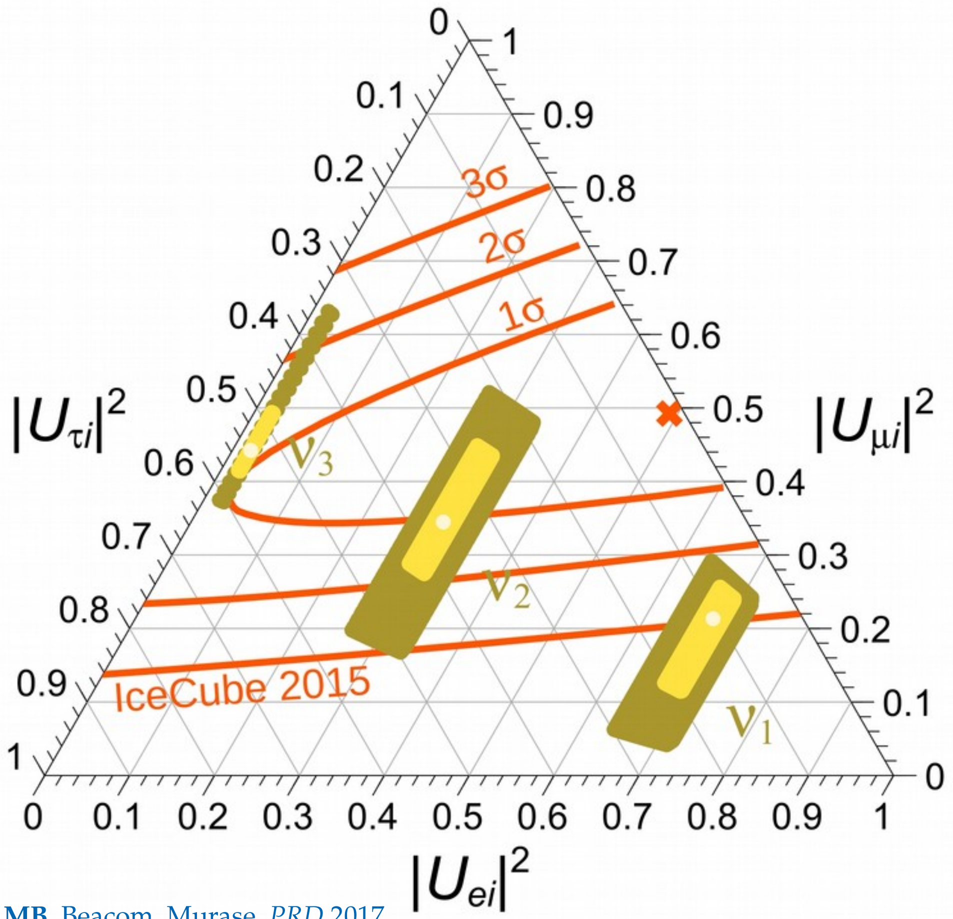
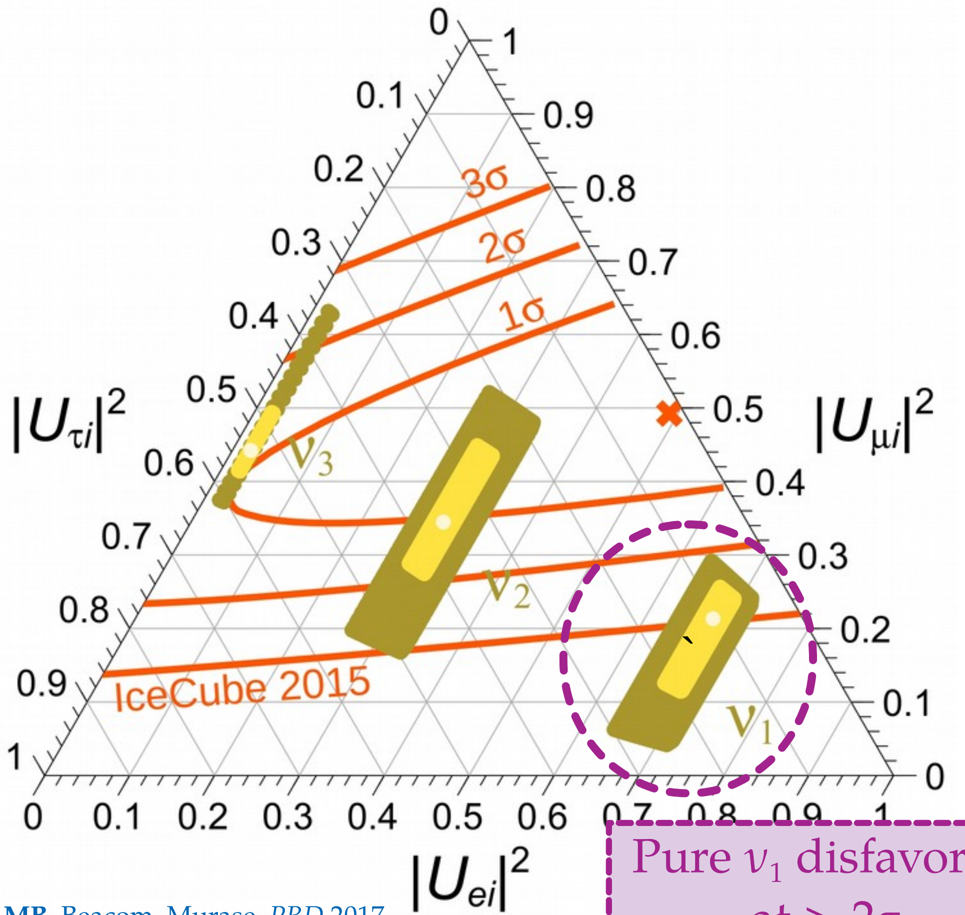


$f_{\alpha,\oplus} = |U_{\alpha 1}|^2$ when $D < 0.01$

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



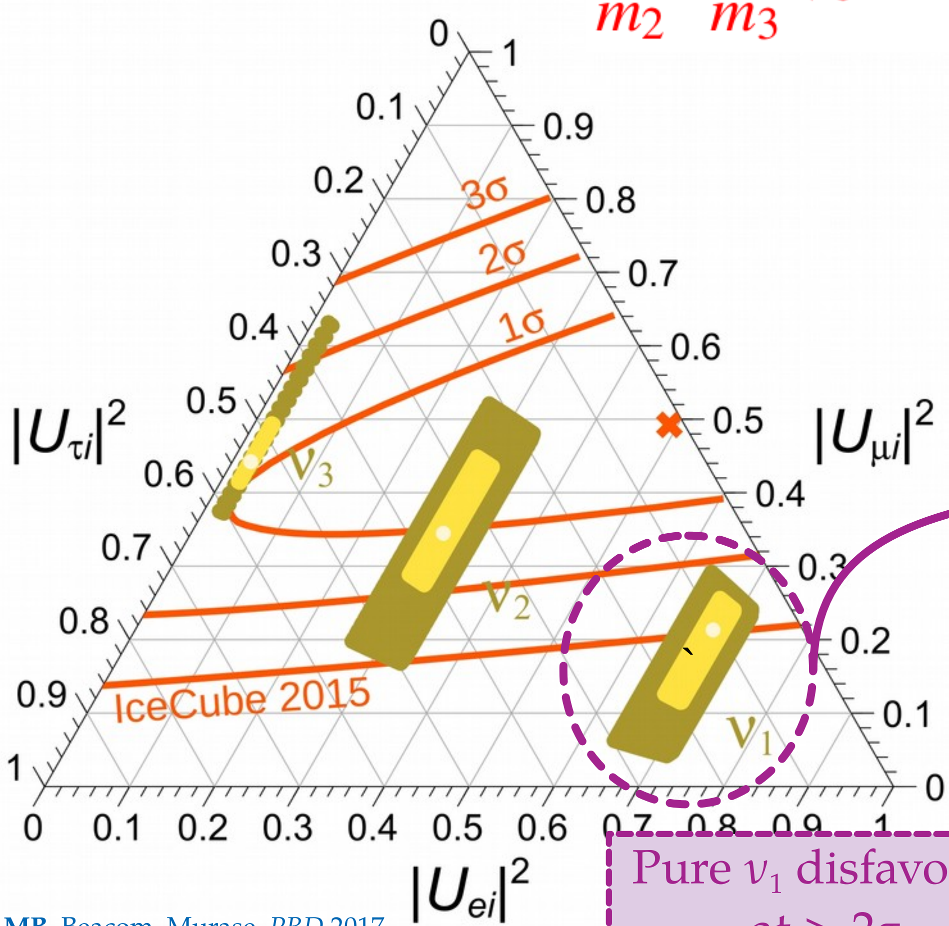
MB, Beacom, Murase, *PRD* 2017



MB, Beacom, Murase, *PRD* 2017

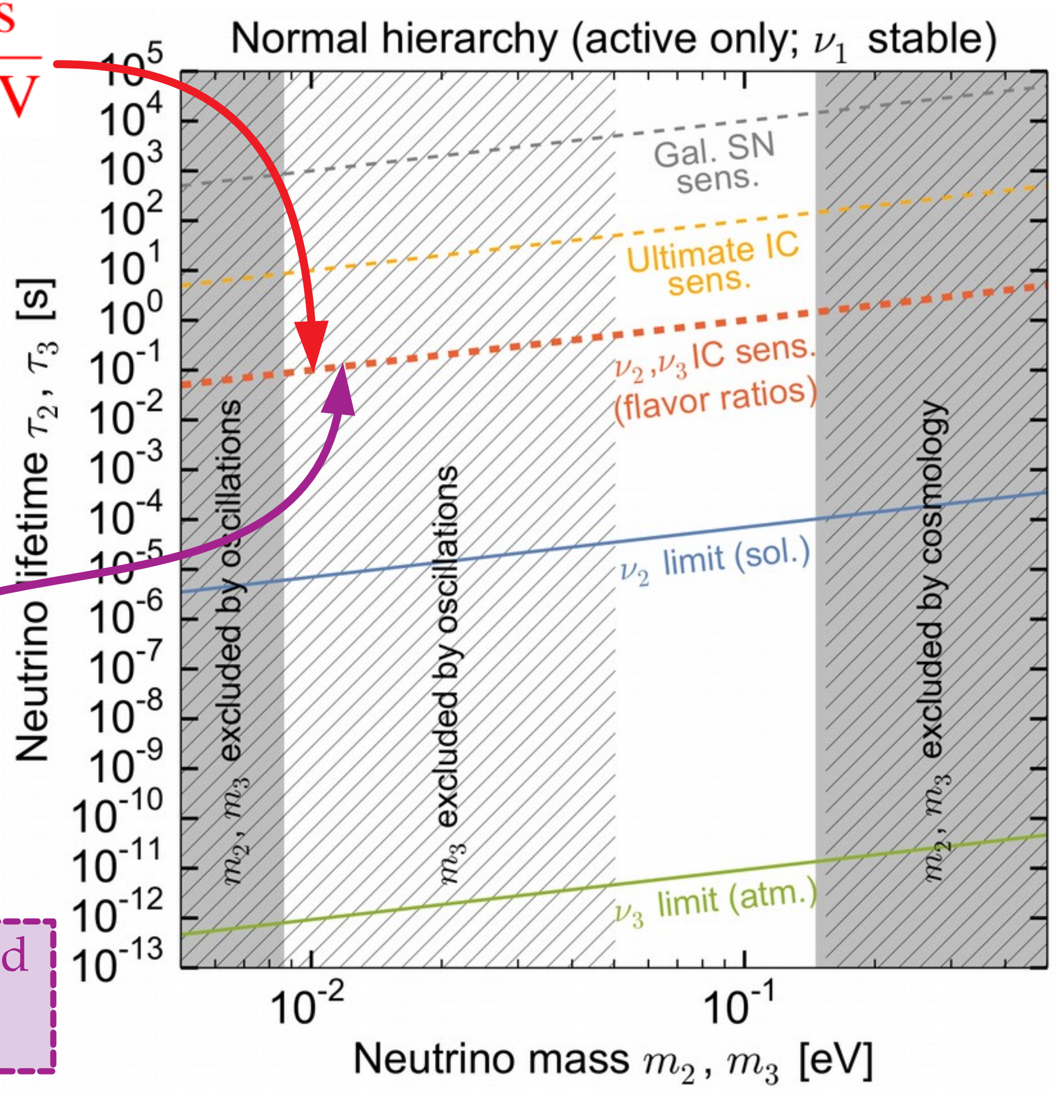
Pure ν_1 disfavored at > 2σ

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



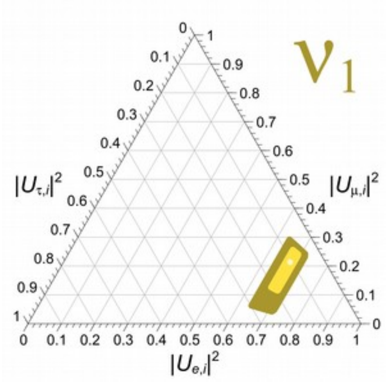
MB, Beacom, Murase, *PRD* 2017

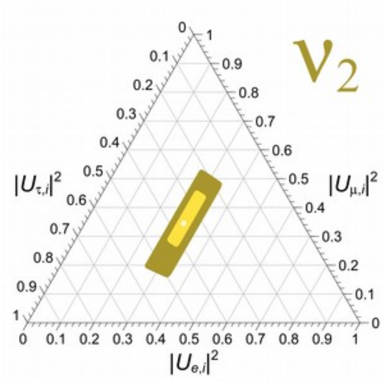
Pure ν_1 disfavored at $> 2\sigma$

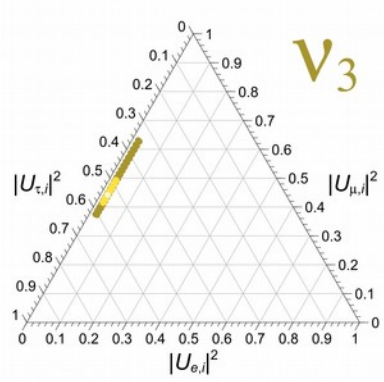


Two classes of new physics

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



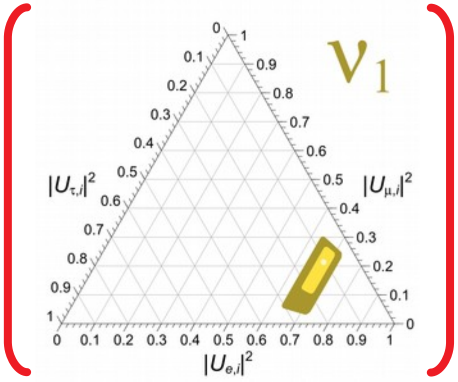


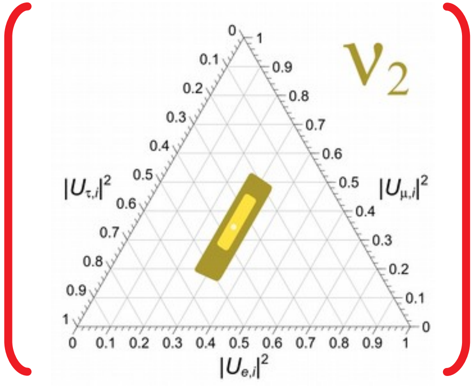


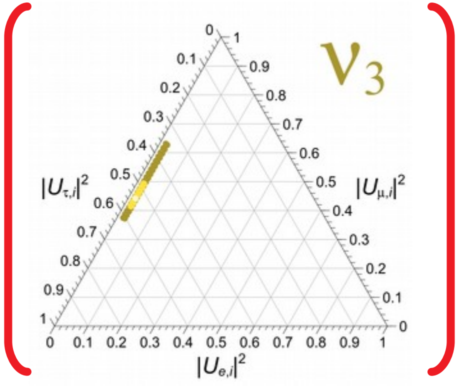
- Flavor ratios at Earth are the result of their combination
- New physics may:
  - Only reweigh the proportion of each ν_i reaching Earth (*e.g.*, ν decay)
  - Redefine the propagation states (*e.g.*, Lorentz-invariance violation)

Two classes of new physics

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

w_1 

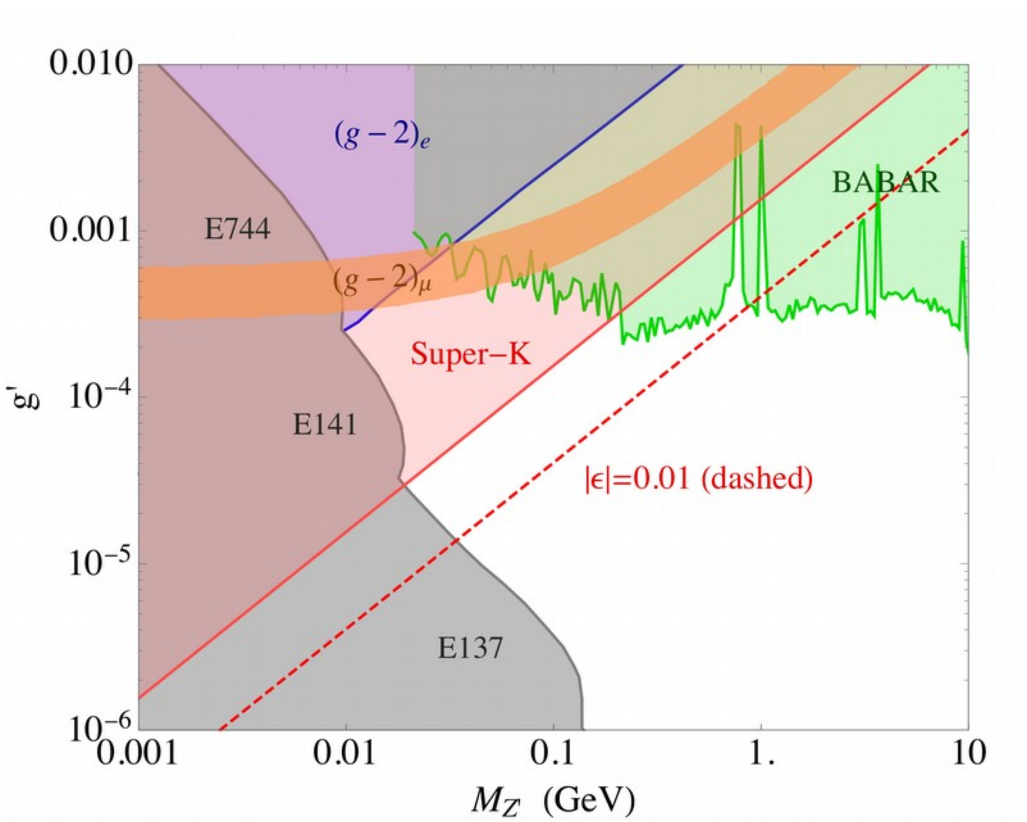
$+w_2$ 

$+w_3$ 

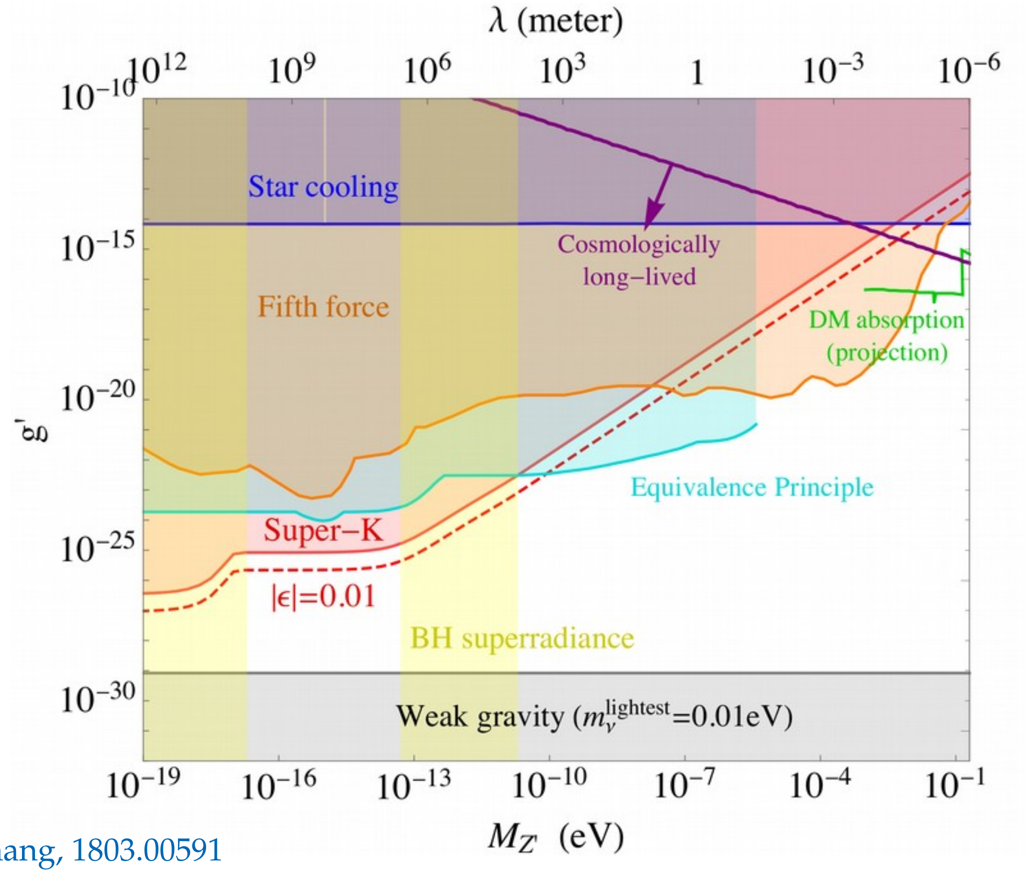
- Flavor ratios at Earth are the result of their combination
- New physics may:
  - Only reweigh the proportion of each ν_i reaching Earth (*e.g.*, ν decay)
  - Redefine the propagation states (*e.g.*, Lorentz-invariance violation)

Current limits on the Z'

MeV–GeV masses



Sub-eV masses



M. Wise & Y. Zhang, 1803.00591

Connecting flavor-ratio predictions to experiment

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

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

Density of cosmological *e* grows with *z*

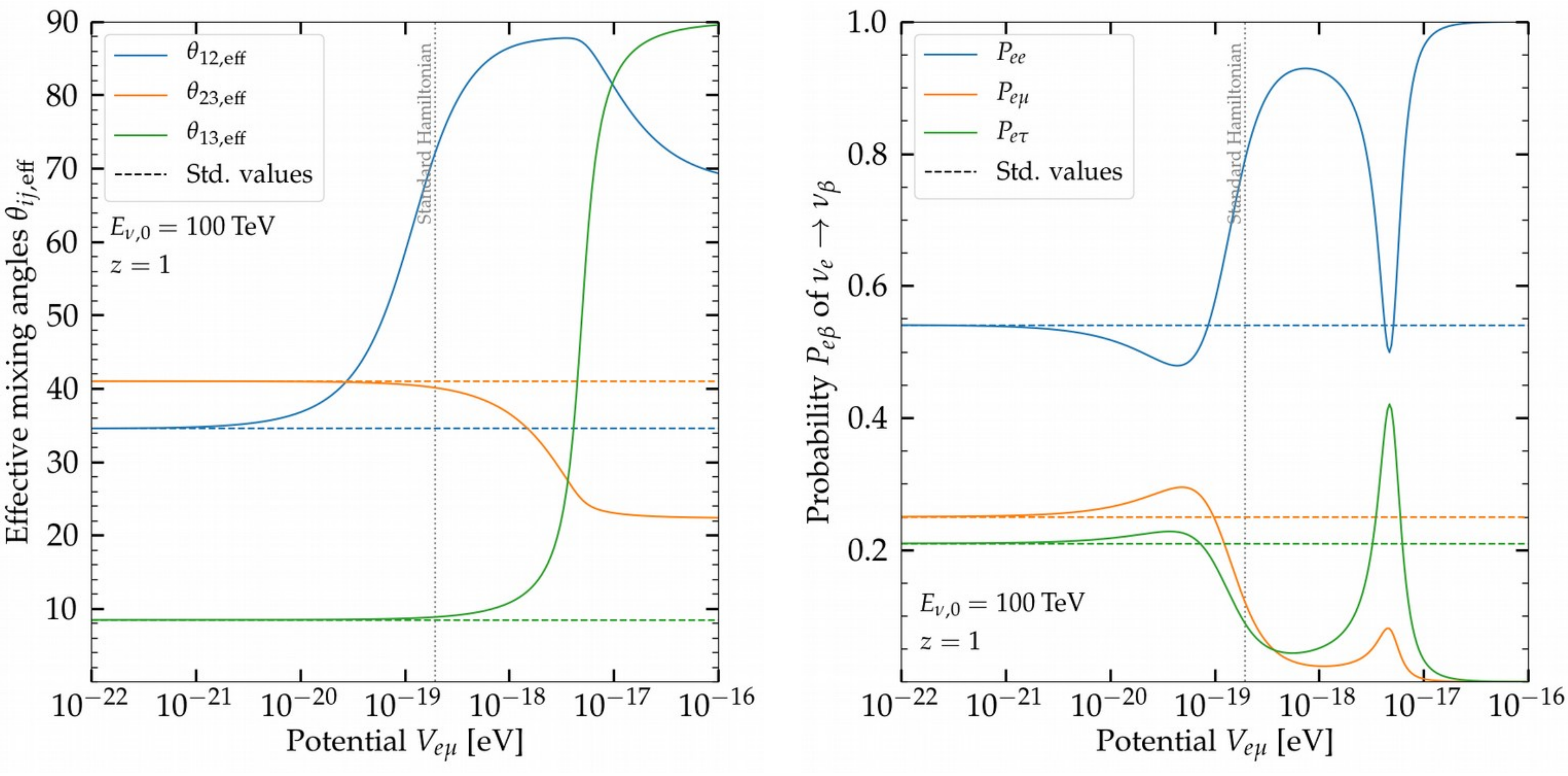
2. Convolve flavor ratios with observed neutrino energy spectrum
   $\mapsto$ Either $E^{-2.50}$ (combined analysis) or $E^{-2.13}$ (through-going muons)

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

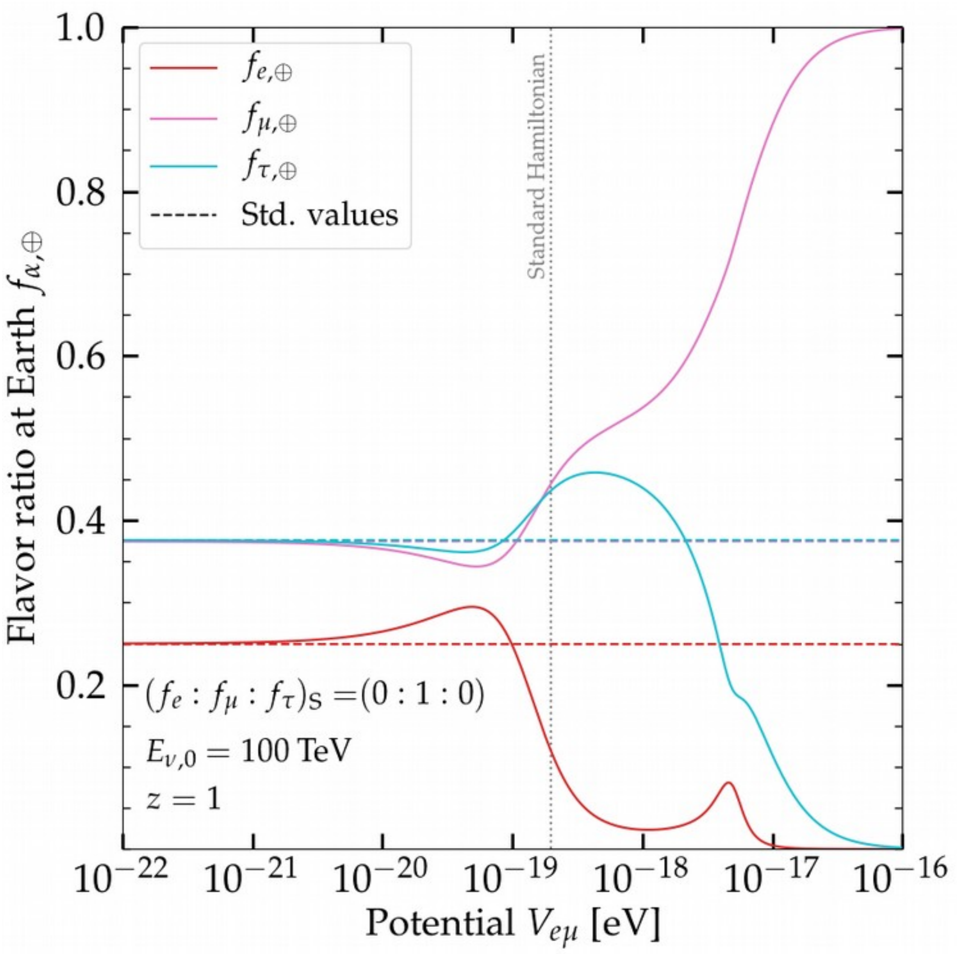
Energy-averaged flux

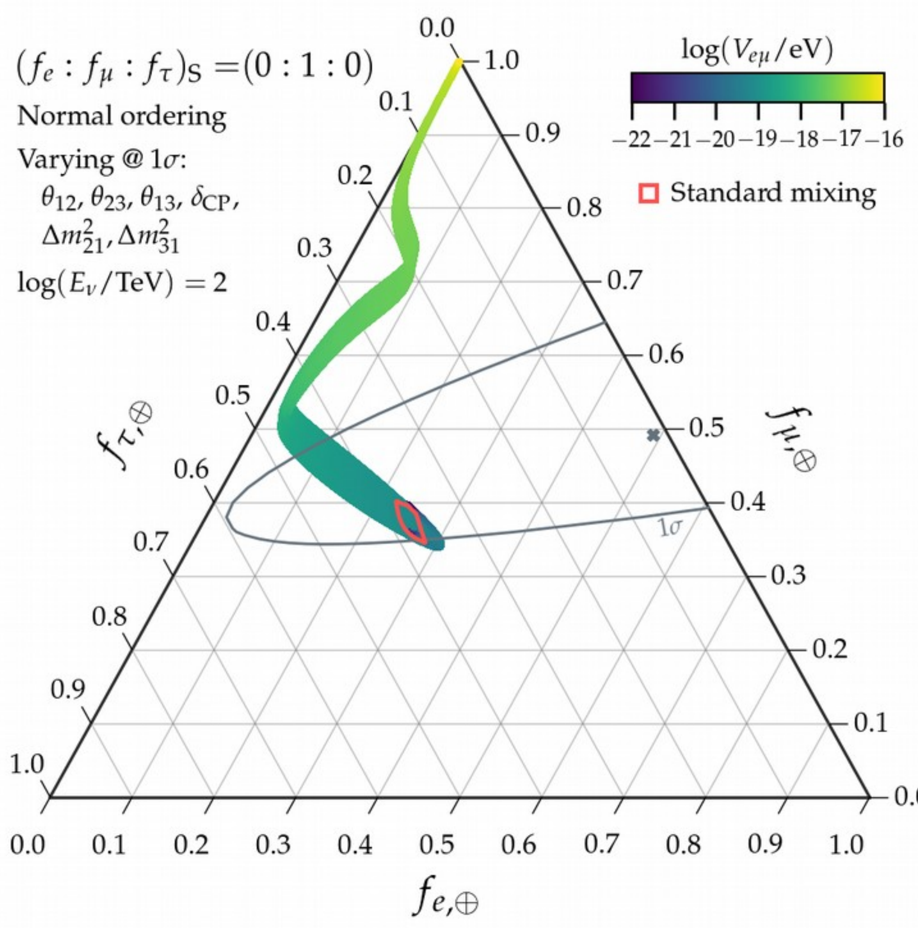
Energy-averaged flavor ratios

Resonance due to the L_e-L_μ symmetry



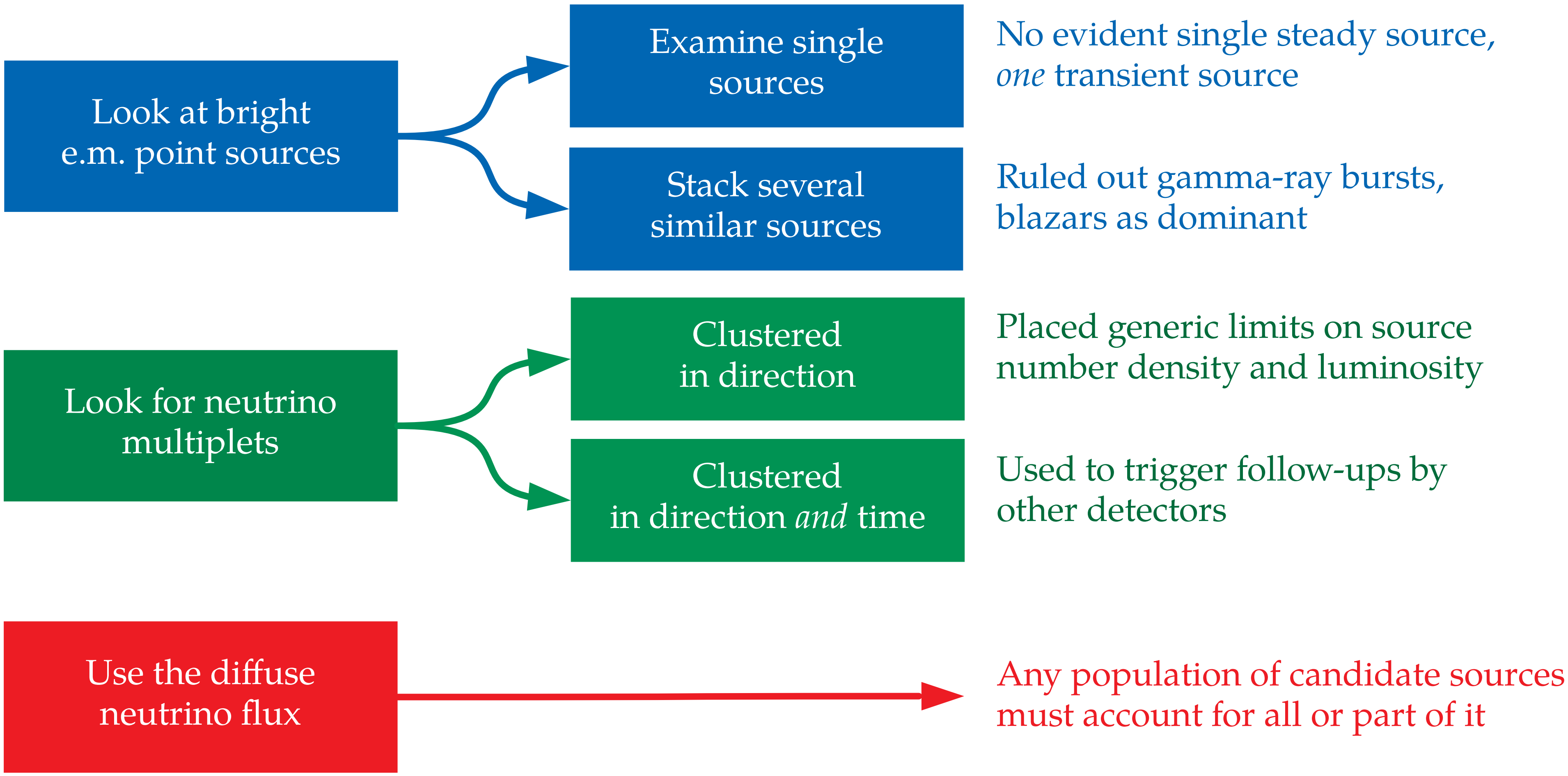
Resonance due to the L_e-L_μ symmetry (*cont.*)





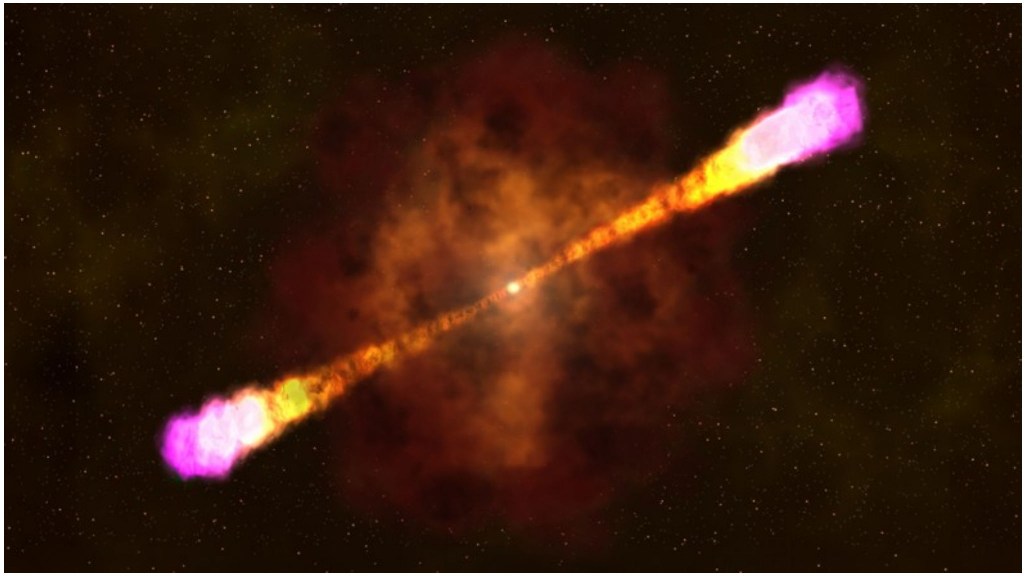
Looking for the sources

Three Strategies to Reveal Sources Using TeV–PeV ν



Gamma-ray bursts and blazars – *not* dominant

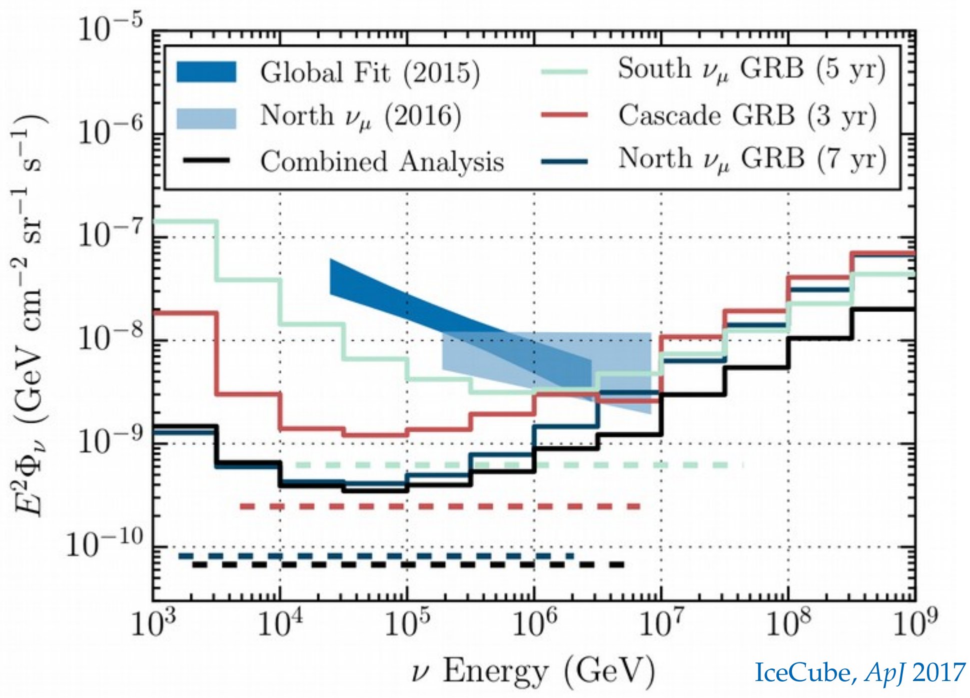
Gamma-ray bursts



Blazars

Gamma-ray bursts and blazars – *not* dominant

Gamma-ray bursts

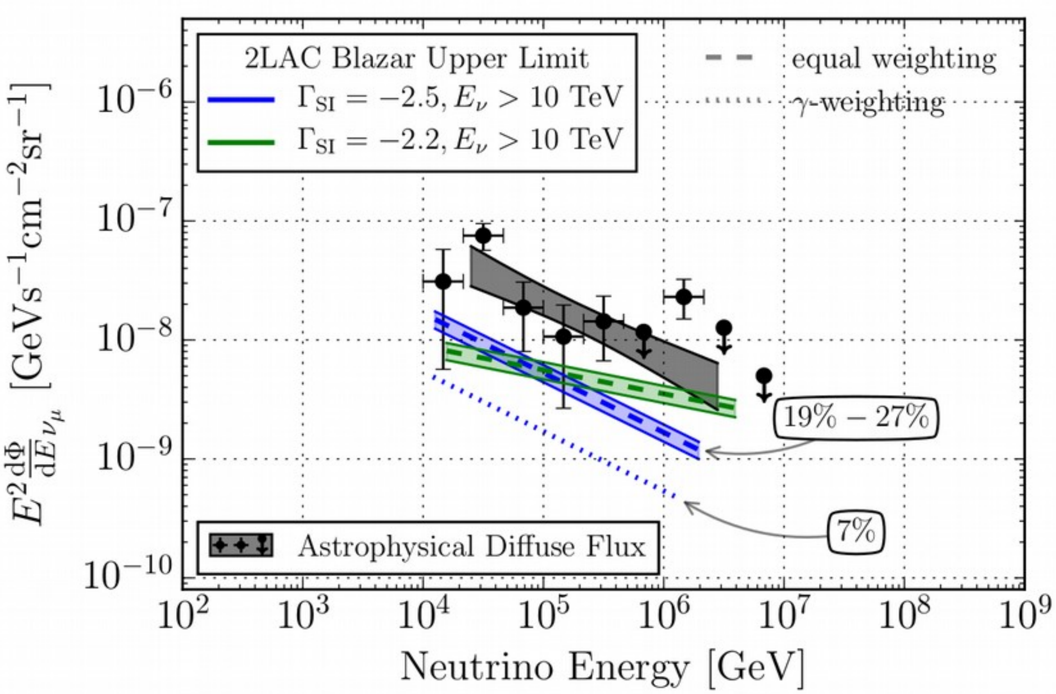


IceCube, *ApJ* 2017

1172 GRBs inspected, no correlation found

< 1% contribution to diffuse flux

Blazars



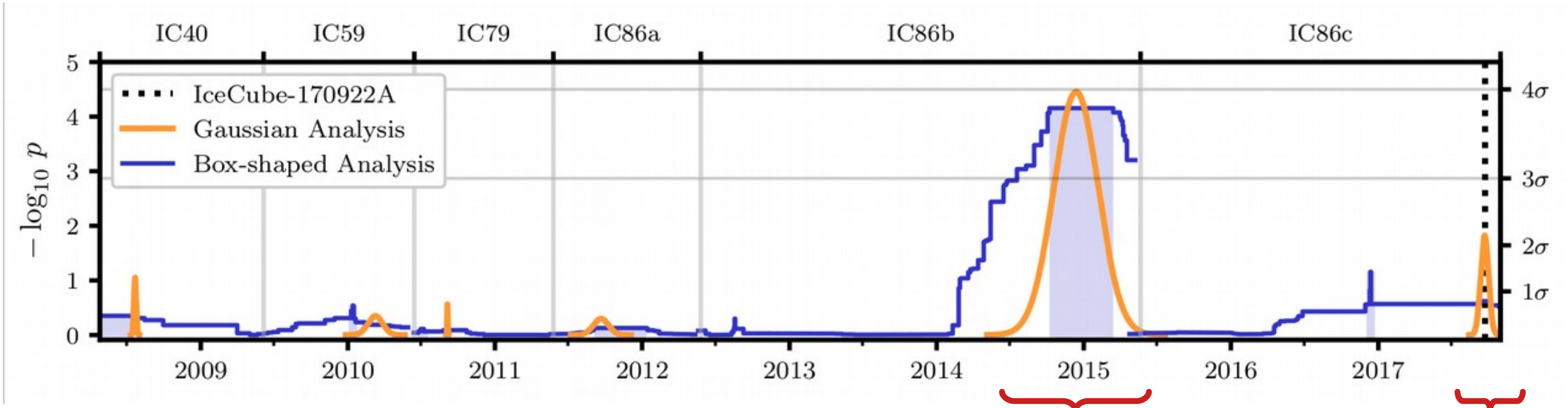
862 blazars inspected, no correlation found

< 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

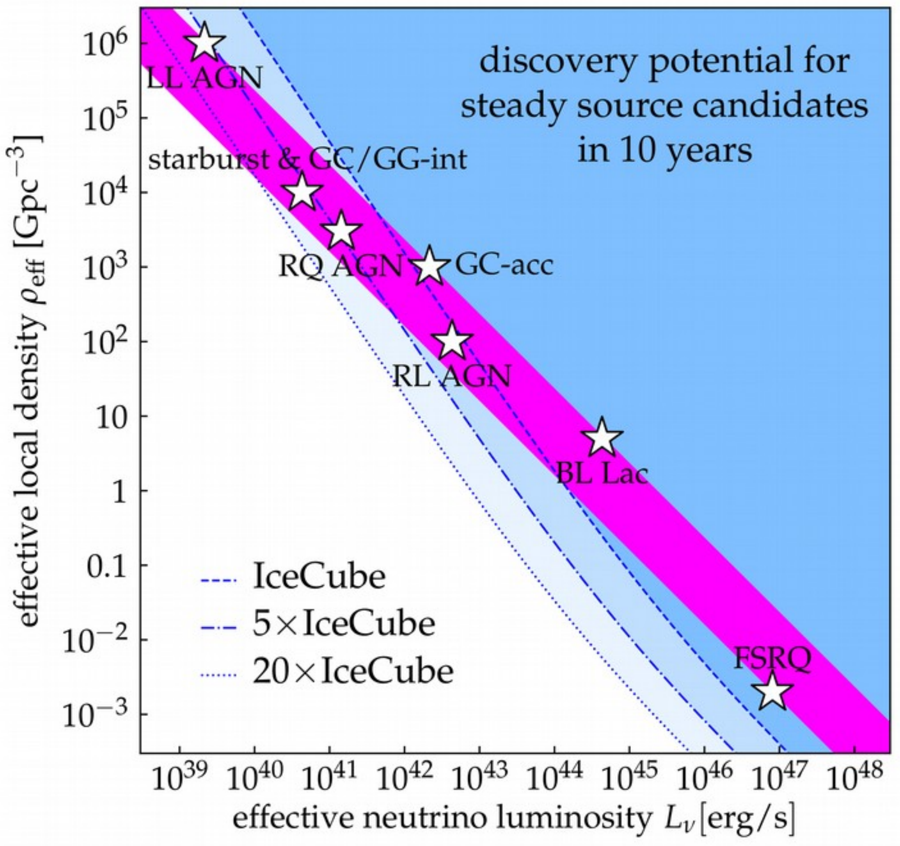
Hard fluence: $E^2 J_{100} = 2.1^{+0.9}_{-0.7} \left(\frac{E}{100 \text{ TeV}}\right)^{-2.1\pm0.2} \text{ TeV cm}^{-2}$

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

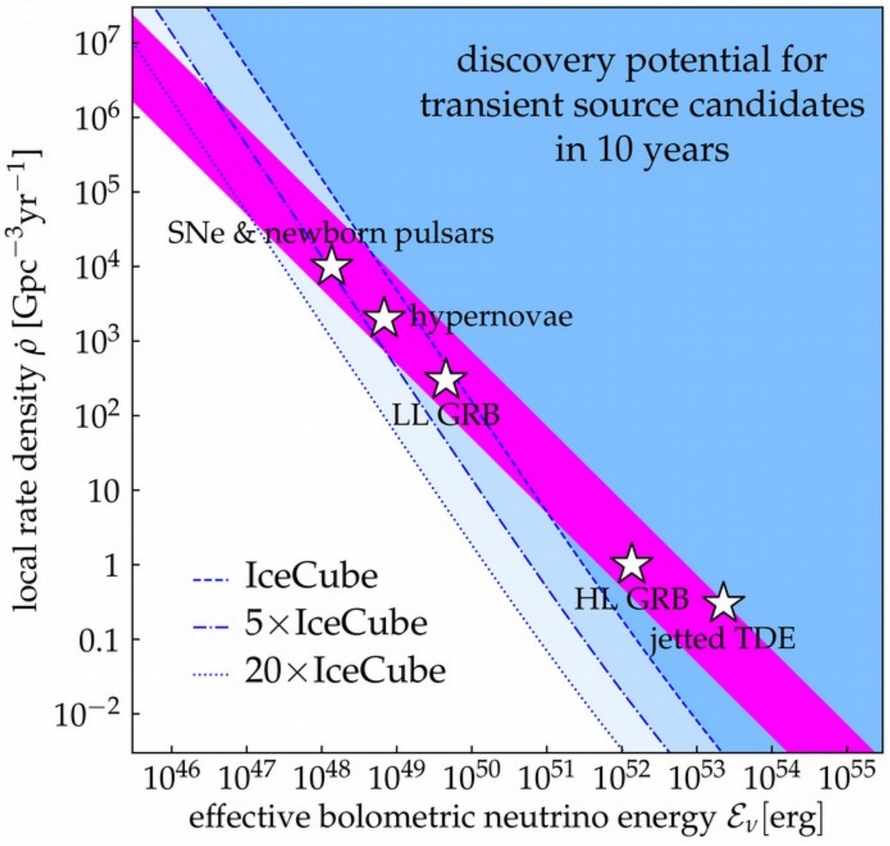
Source discovery potential: today and in the future

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