Pushing the Energy and Cosmic Frontiers with High-Energy Astrophysical Neutrinos

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Niels Bohr Institute, University of Copenhagen

7th RICAP

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UNIVERSITY OF COPENHAGEN

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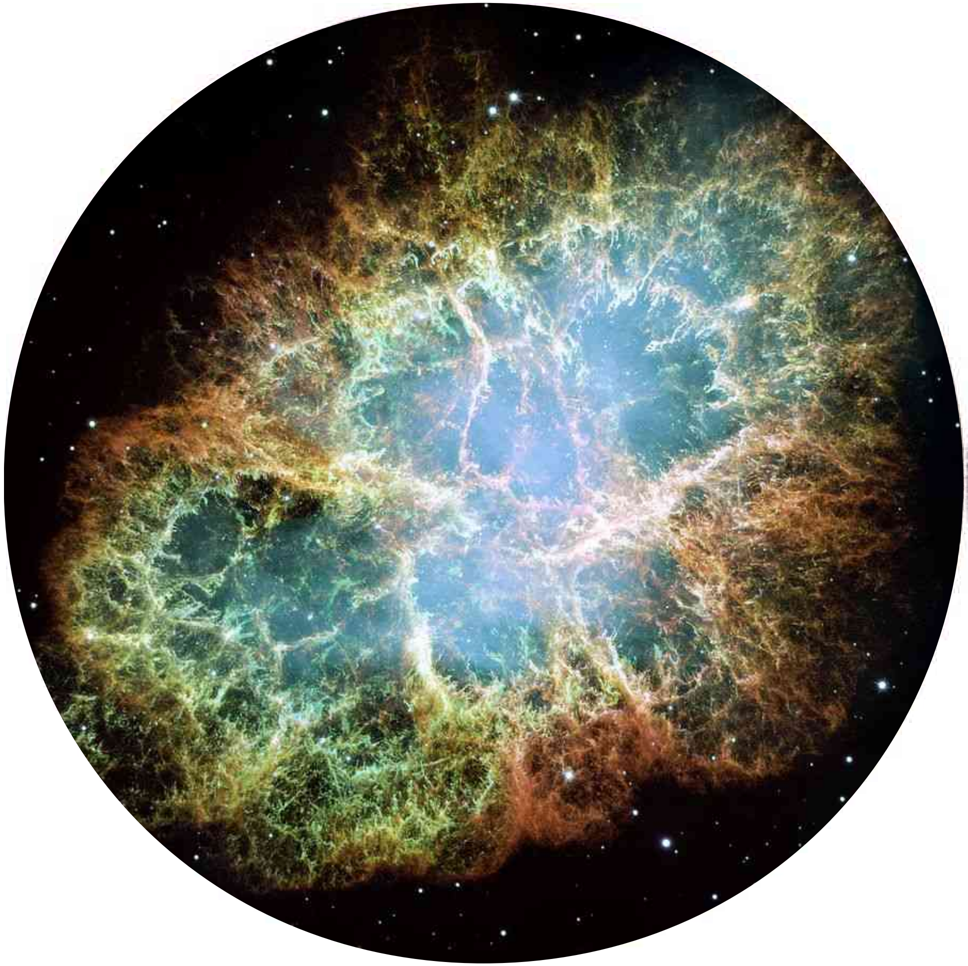

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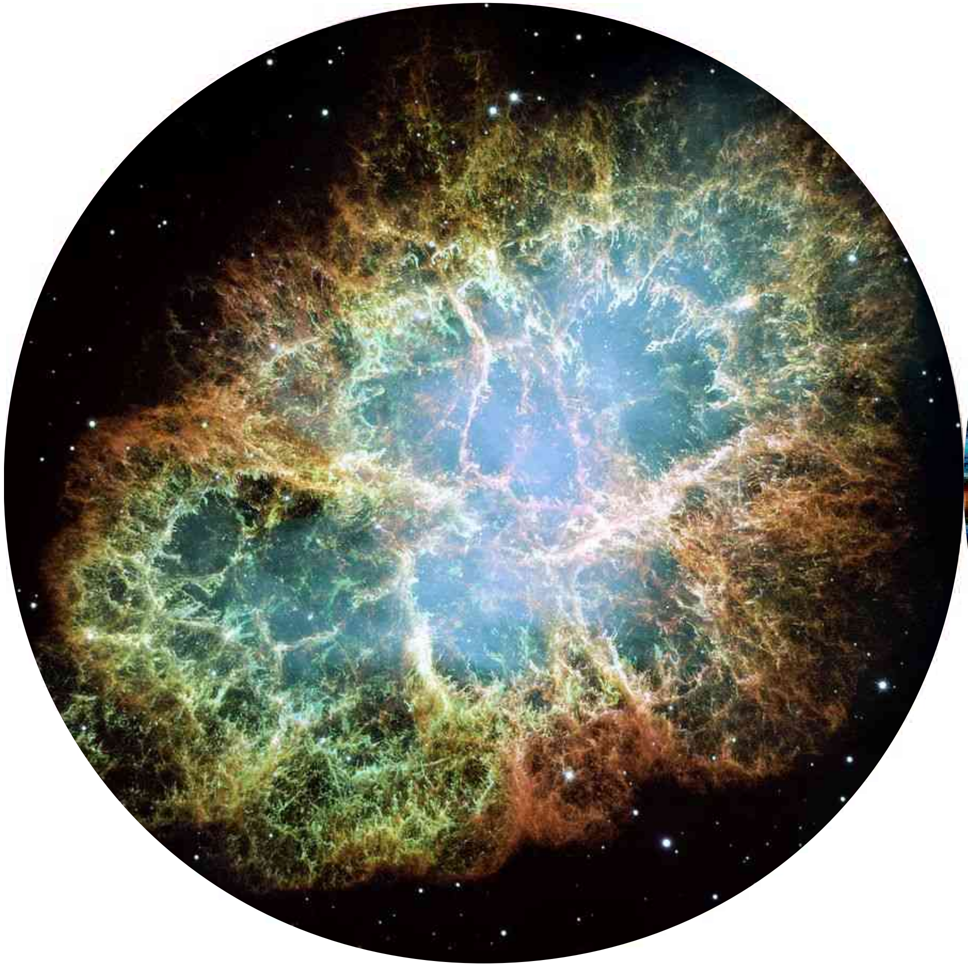
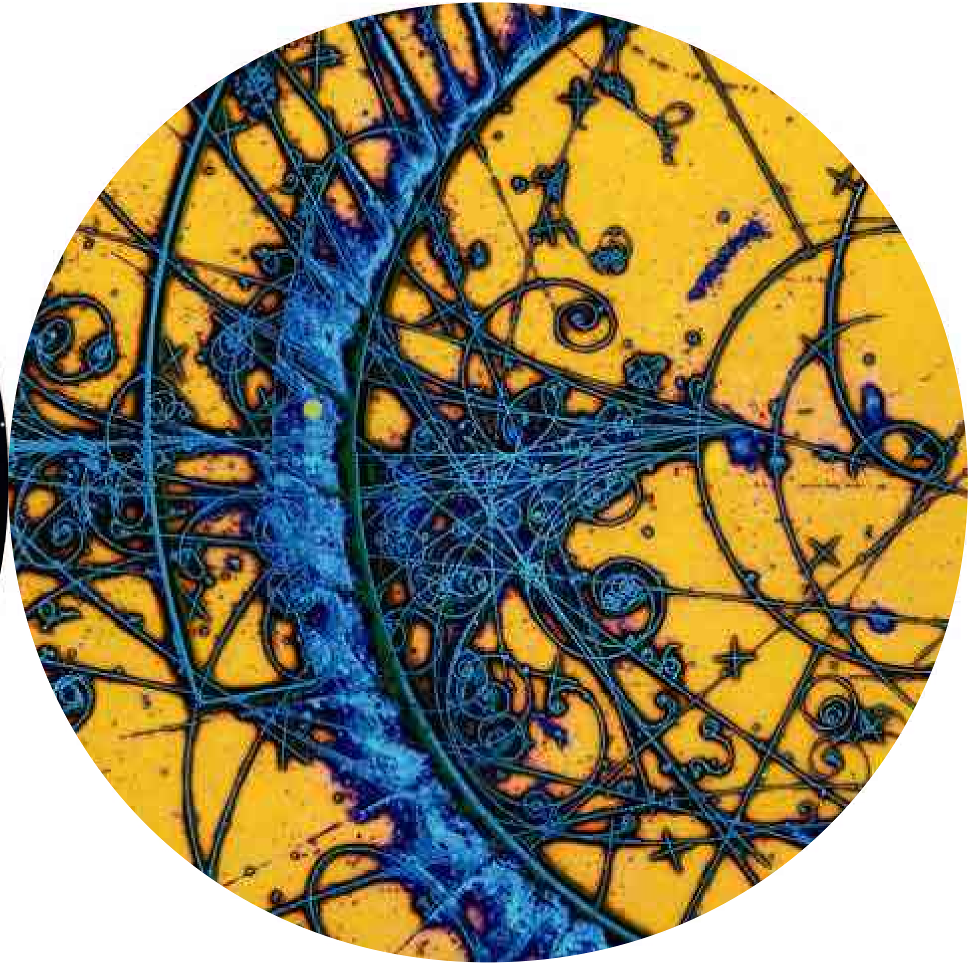

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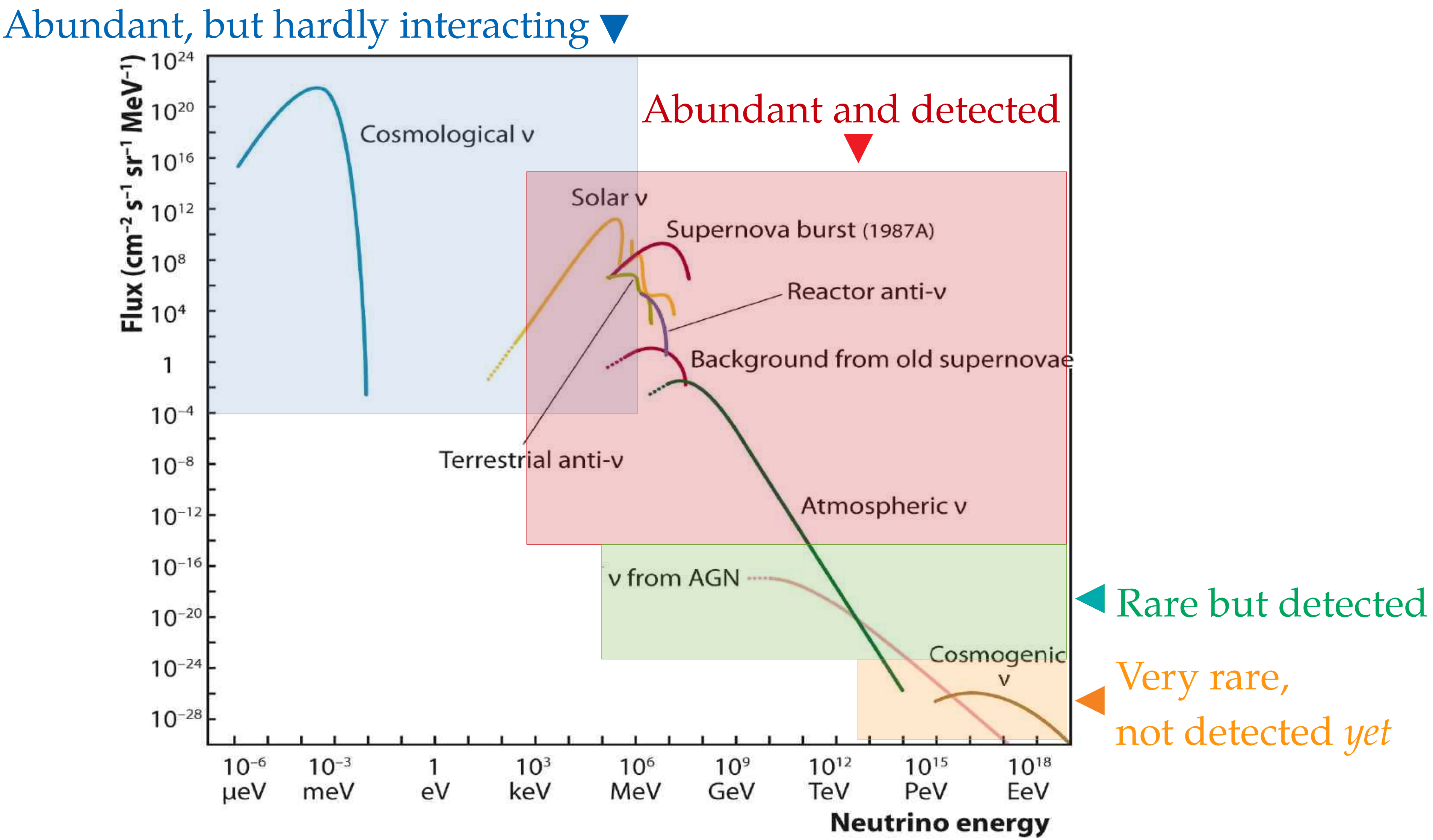

Abundant, but hardly interacting
Abundant and detected
Rare but detected
Very rare,
not detected *yet*
Flux (cm⁻² s⁻¹ sr⁻¹ MeV⁻¹)
Cosmological ν
Solar ν
Supernova burst (1987A)
Reactor anti-ν
Background from old supernovae
Terrestrial anti-ν
Atmospheric ν
ν from AGN
Cosmogenic ν
μeV
meV
eV
keV
MeV
GeV
TeV
PeV
EeV
Neutrino energy

Why study fundamental physics with HE astro. ν's?

1. They have the highest energies (~PeV)
   ↦ Probe physics at new energy scales

2. They have the longest baselines (~Gpc)
   ↦ Tiny effects can accumulate and become observable

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3. It comes *for free*

In the face of astrophysical unknowns,
can we extract fundamental TeV–PeV ν physics?

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can we extract fundamental TeV–PeV ν physics?

Yes.


Neutrino physicist

Fundamental physics with HE astrophysical neutrinos

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

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  n = 0: CPT-odd Lorentz violation
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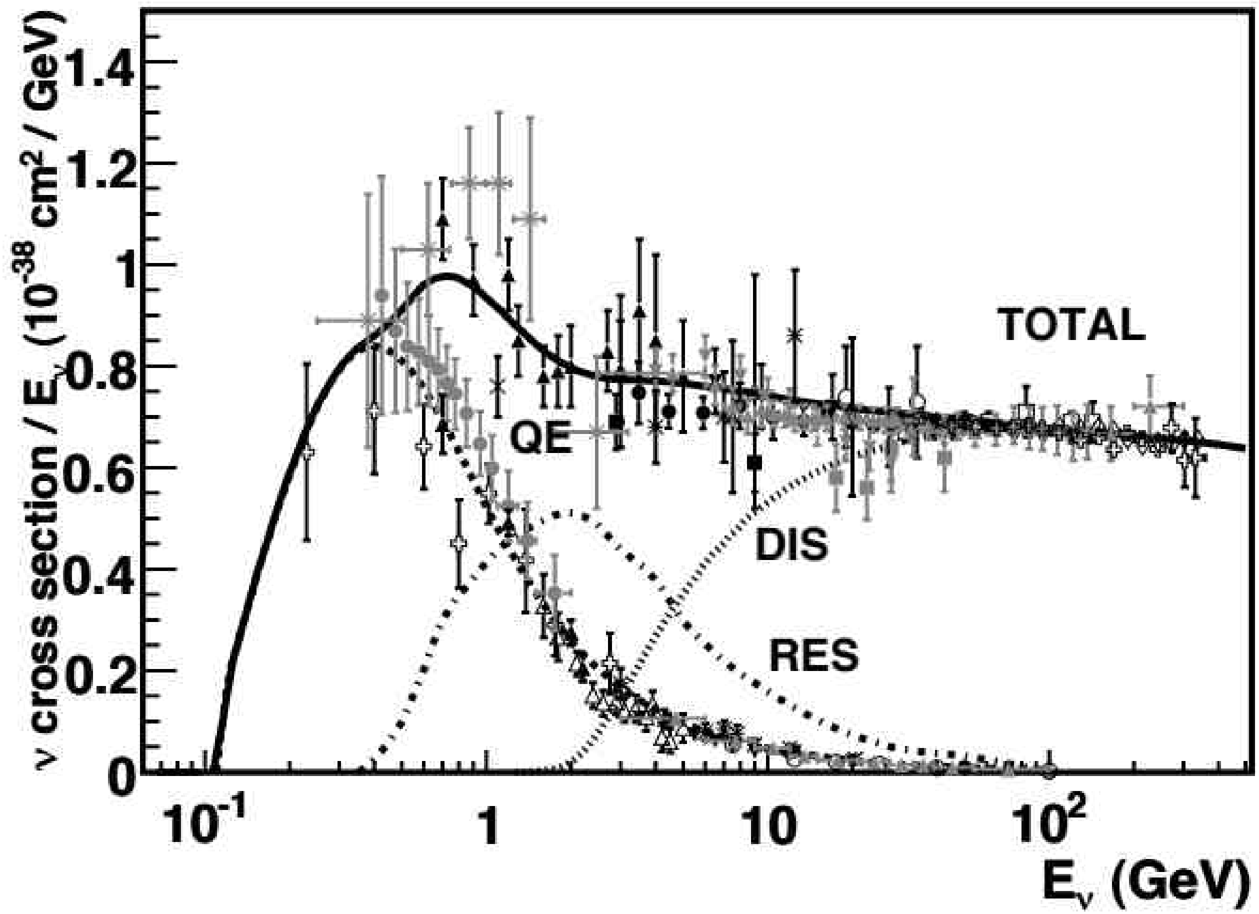
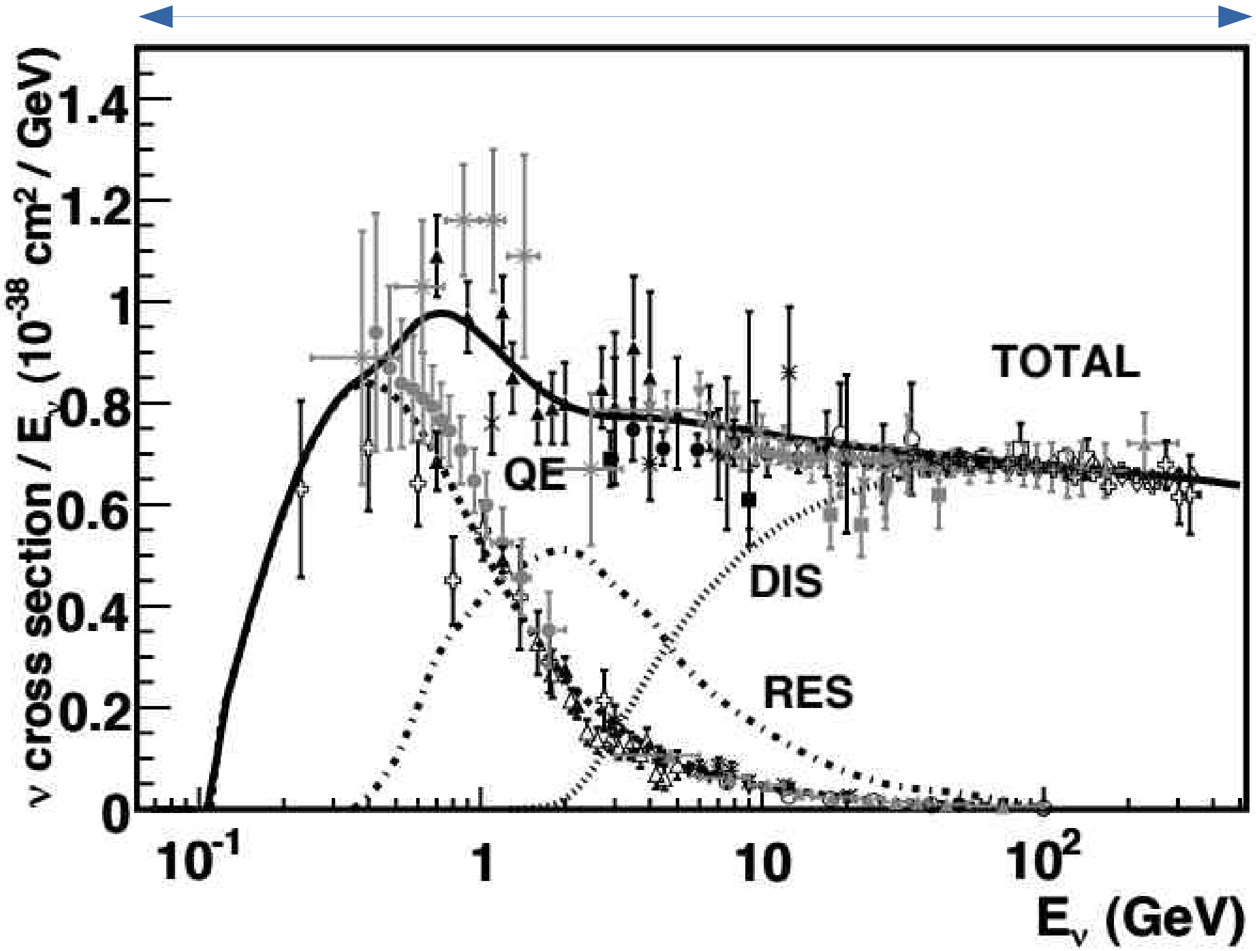
  - Spectral shape
  - Angular distribution
  - Flavor information

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



Particle Data Group

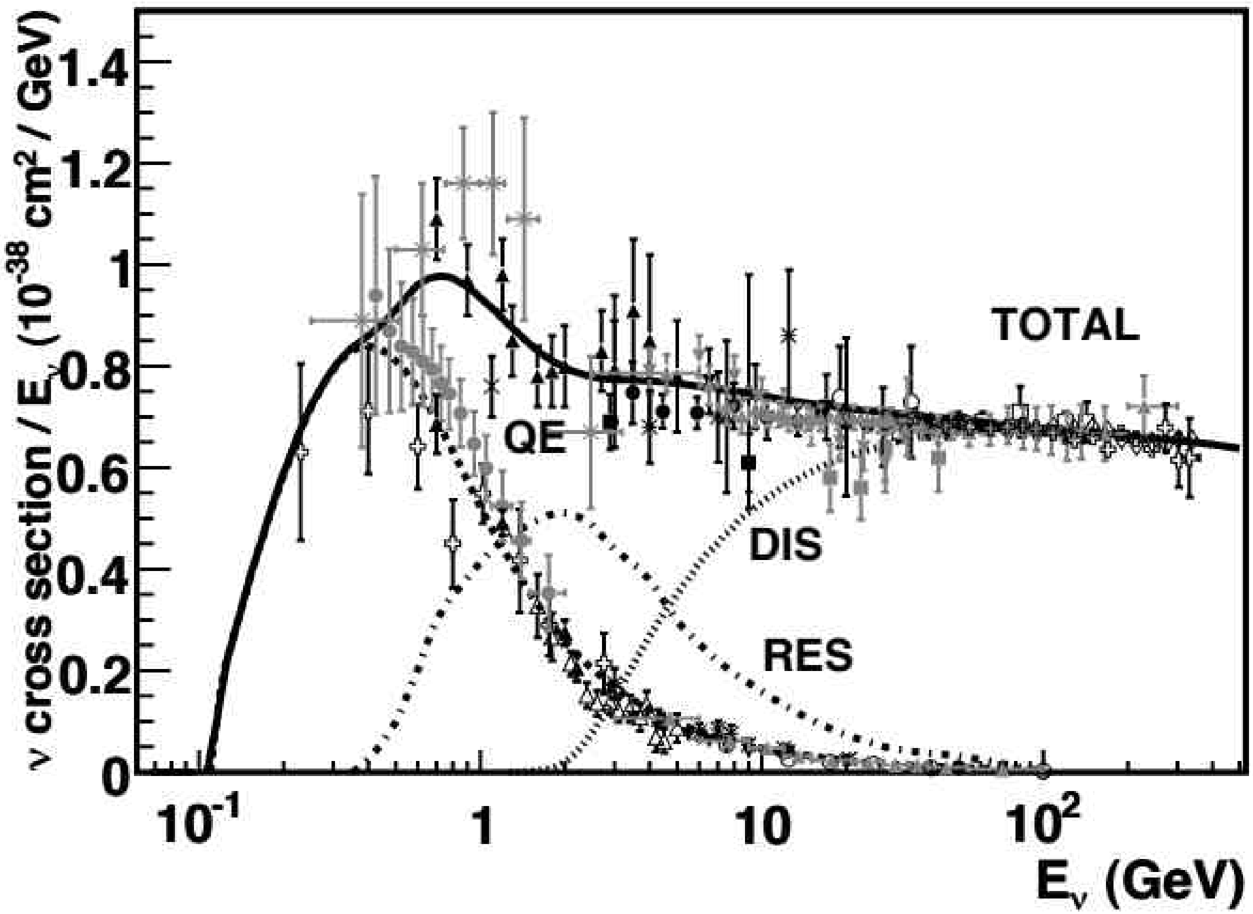
Accelerator experiments



Particle Data Group

Accelerator experiments

One recent measurement (COHERENT)



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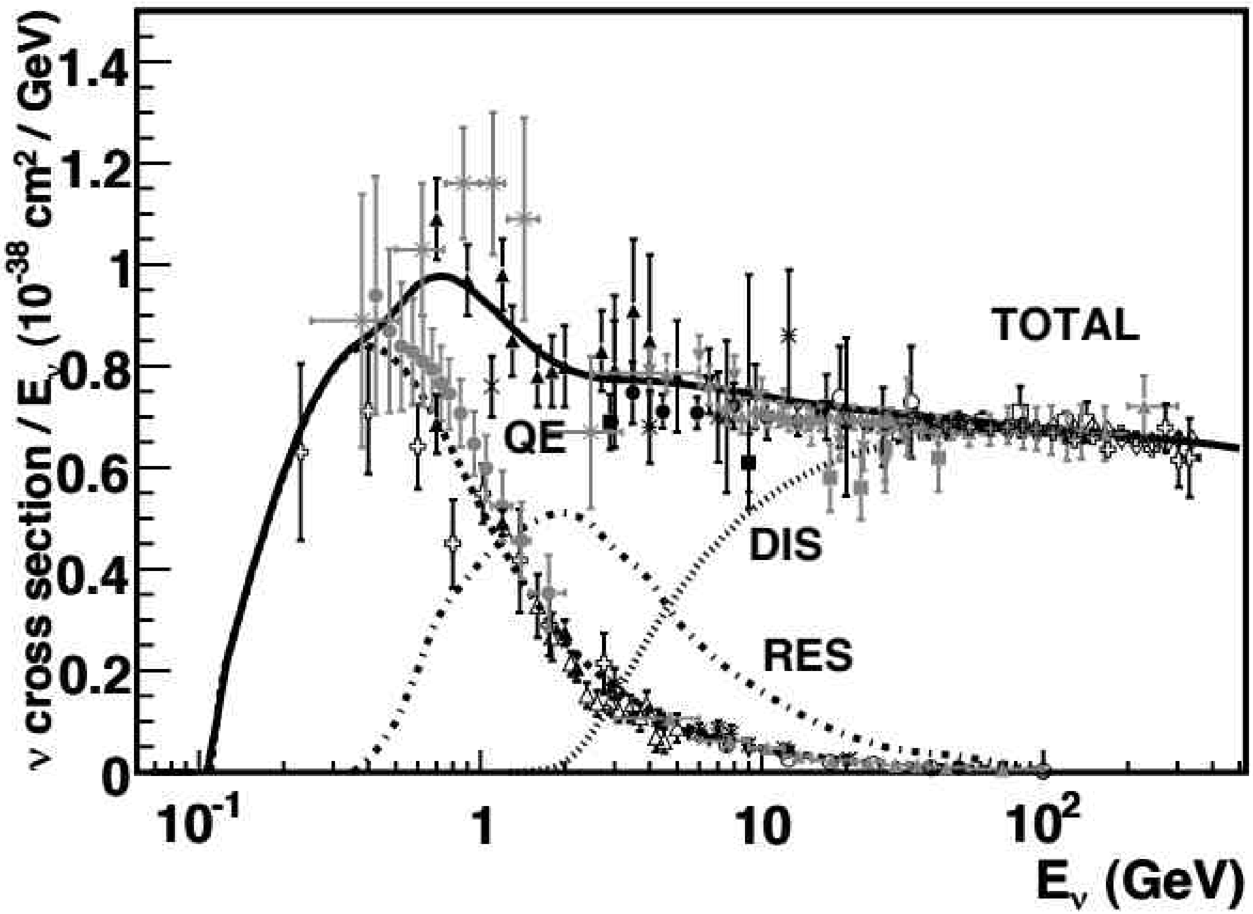


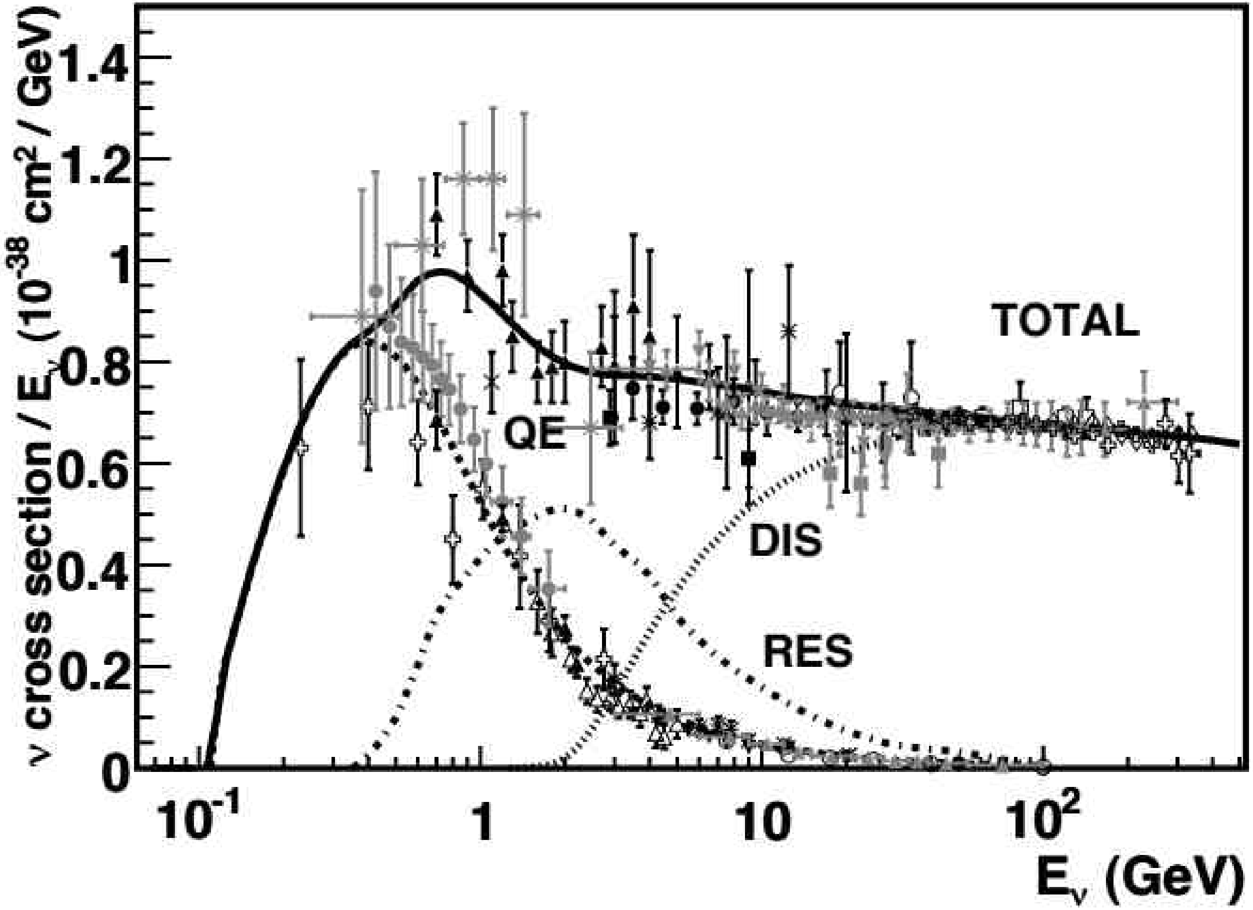
Particle Data Group

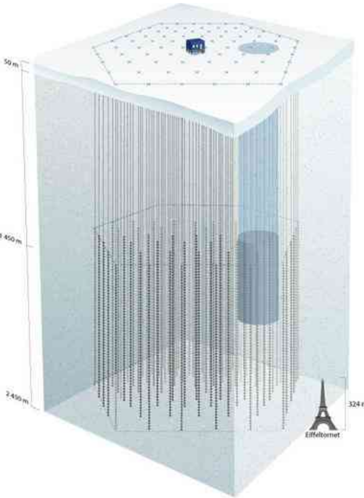
No measurements

… until now!

Accelerator experiments

One recent measurement (COHERENT)





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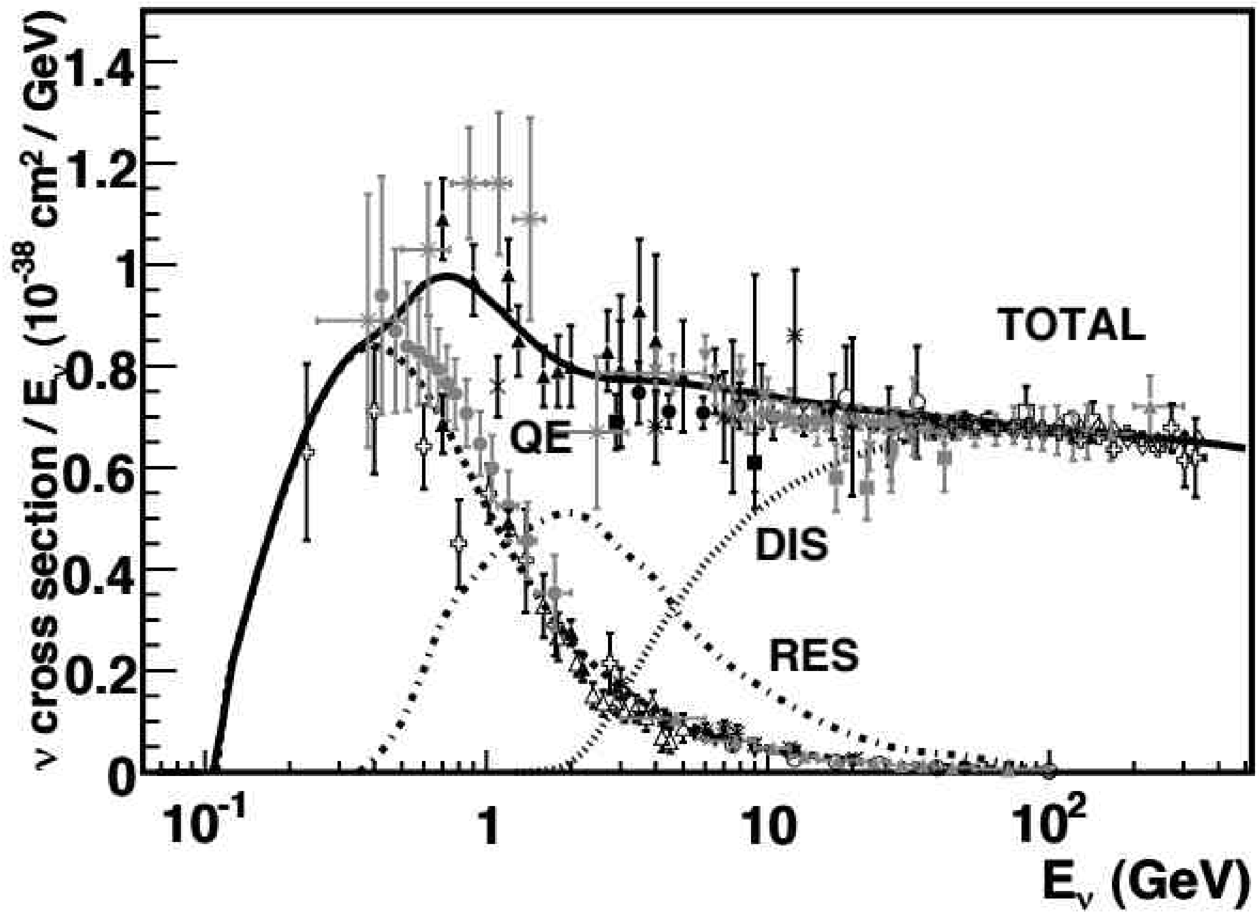
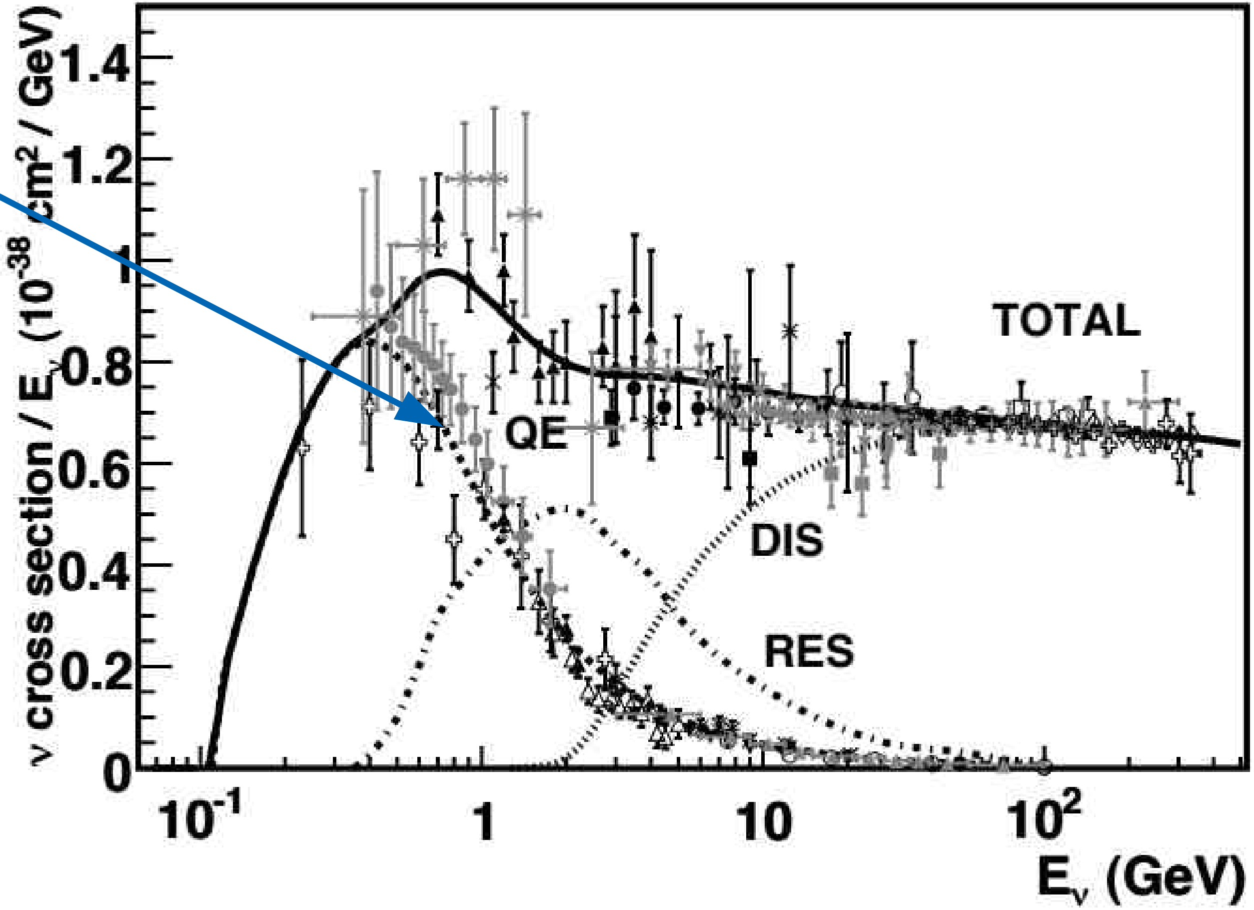


Particle Data Group

Quasi-elastic scattering:

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

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



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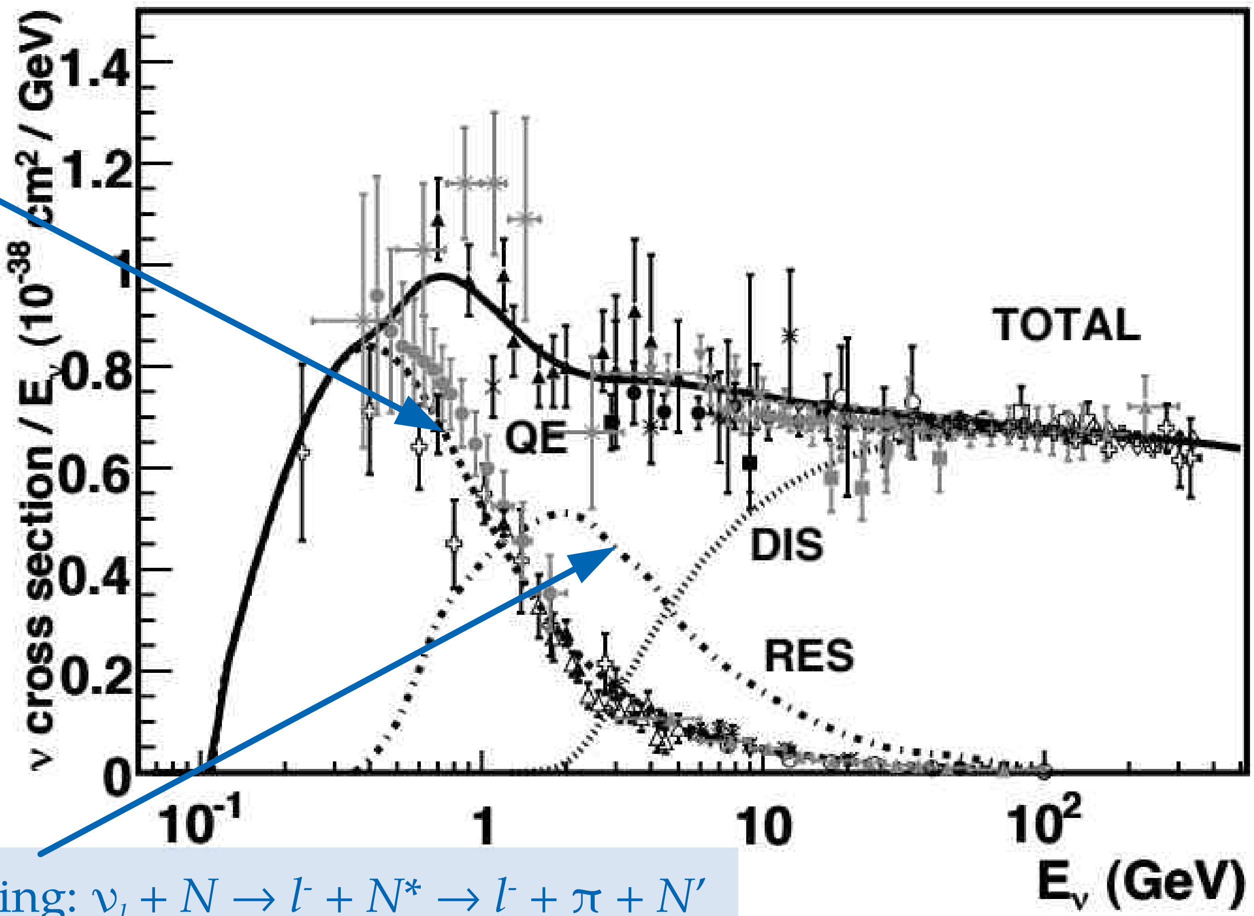

Resonant scattering: $\nu_l + N \rightarrow l^- + N^* \rightarrow l^- + \pi + N'$

Particle Data Group

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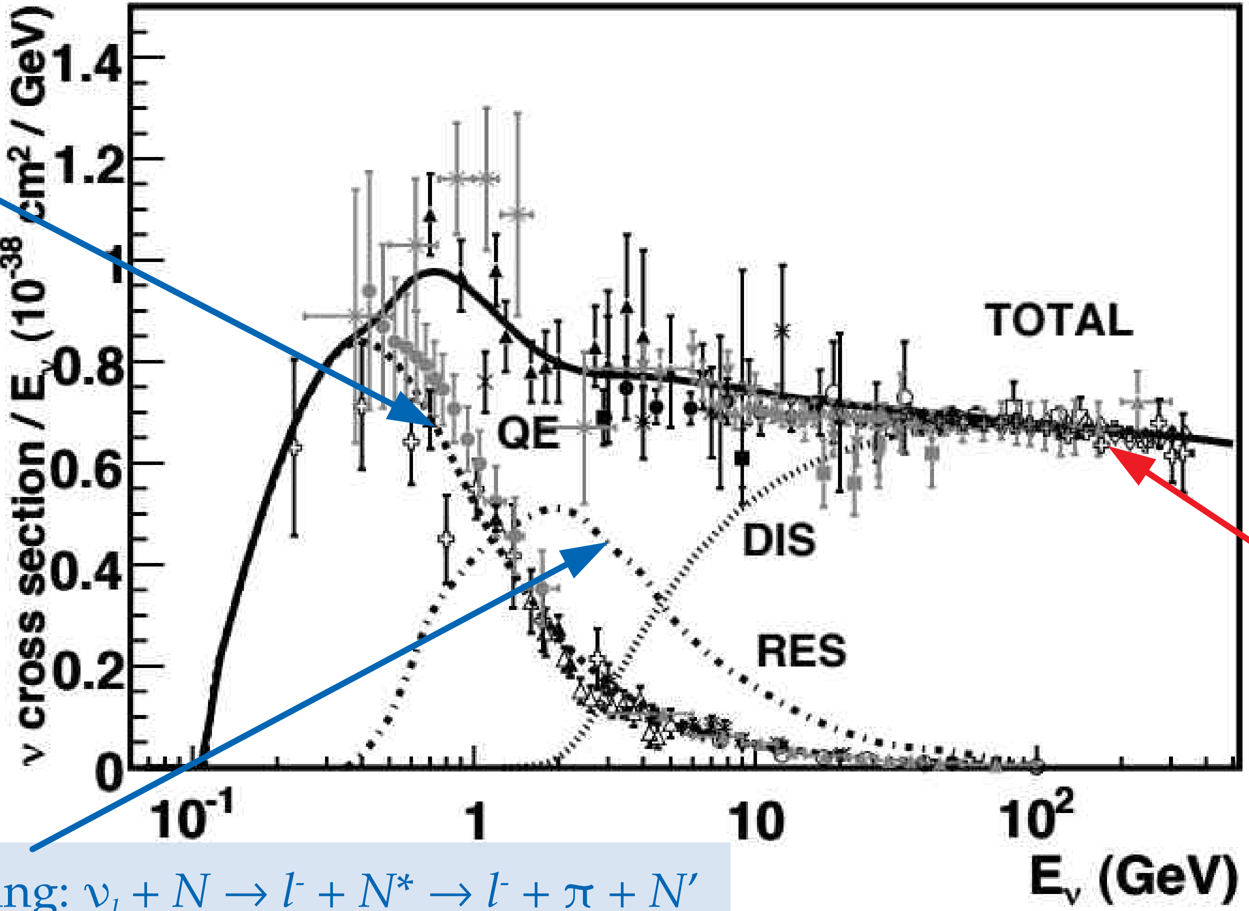

Particle Data Group

Deep inelastic scattering:

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

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

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

Extrapolating the cross section to high energies

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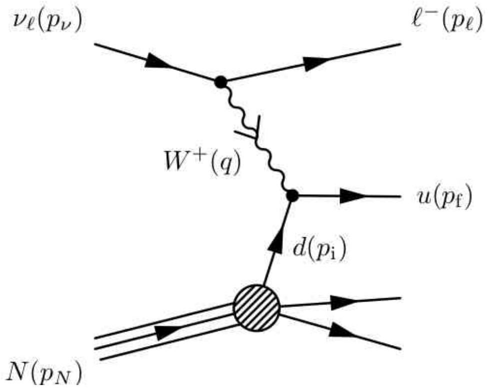
SM



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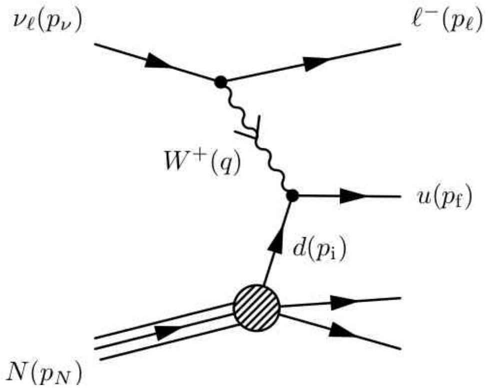

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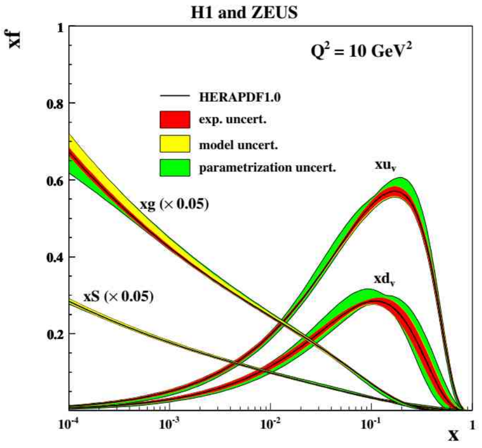
PDFs



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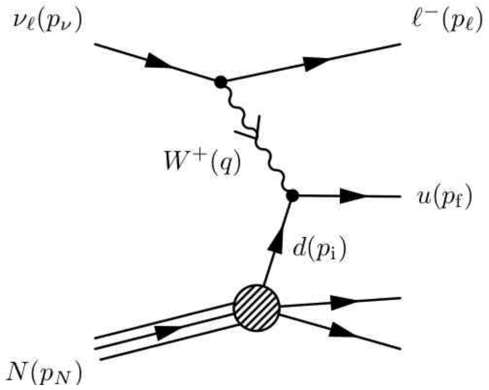

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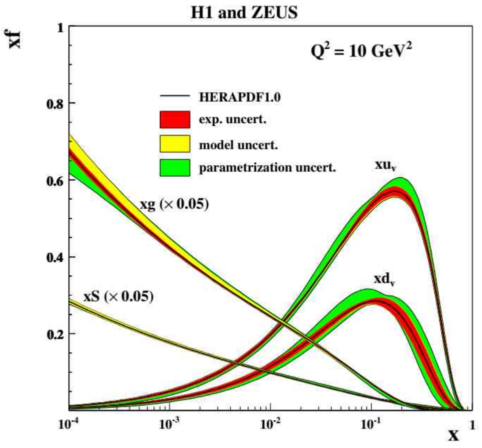

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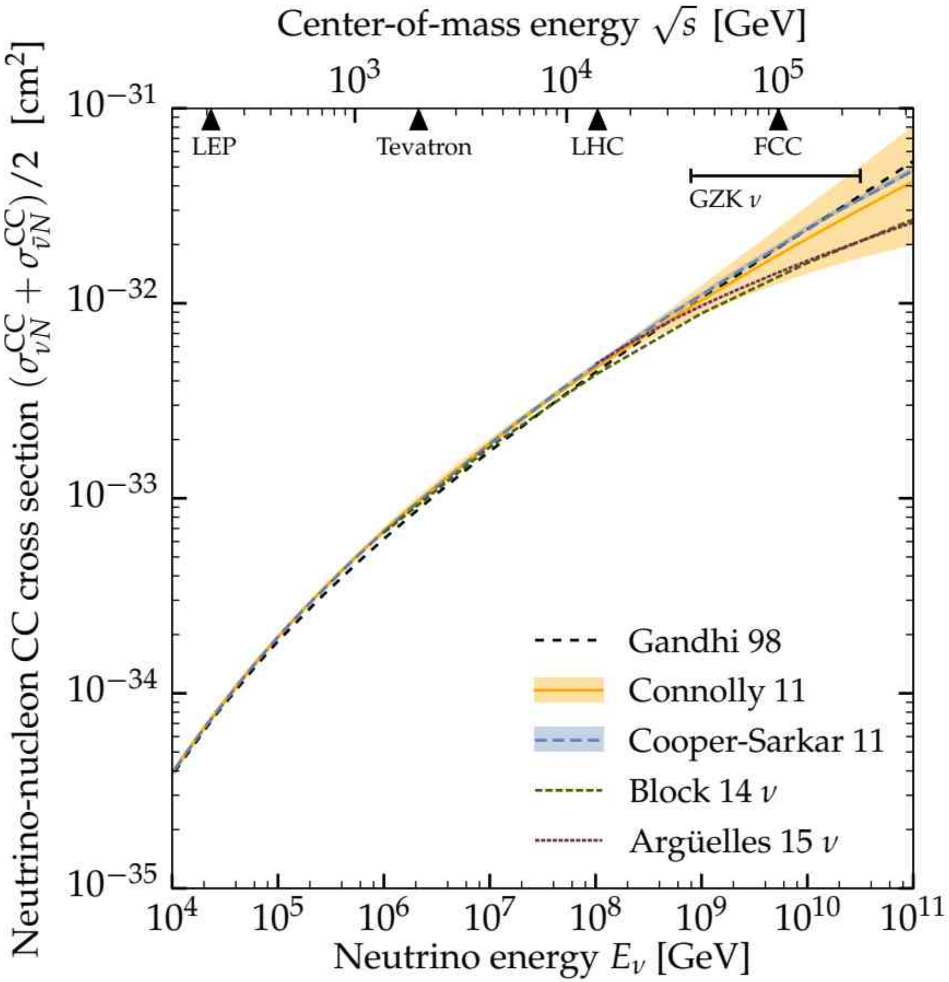

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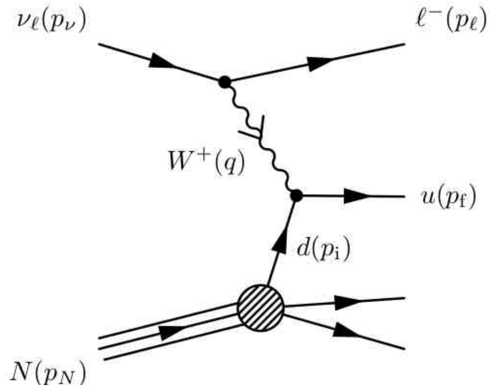

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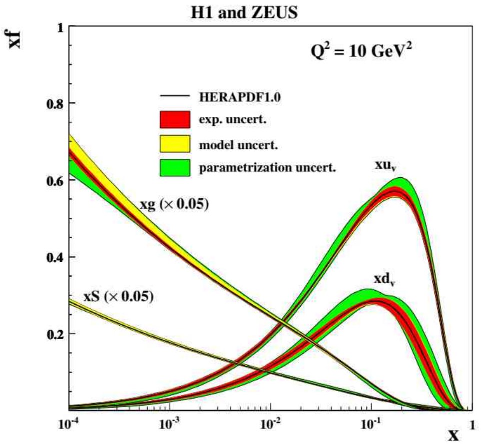

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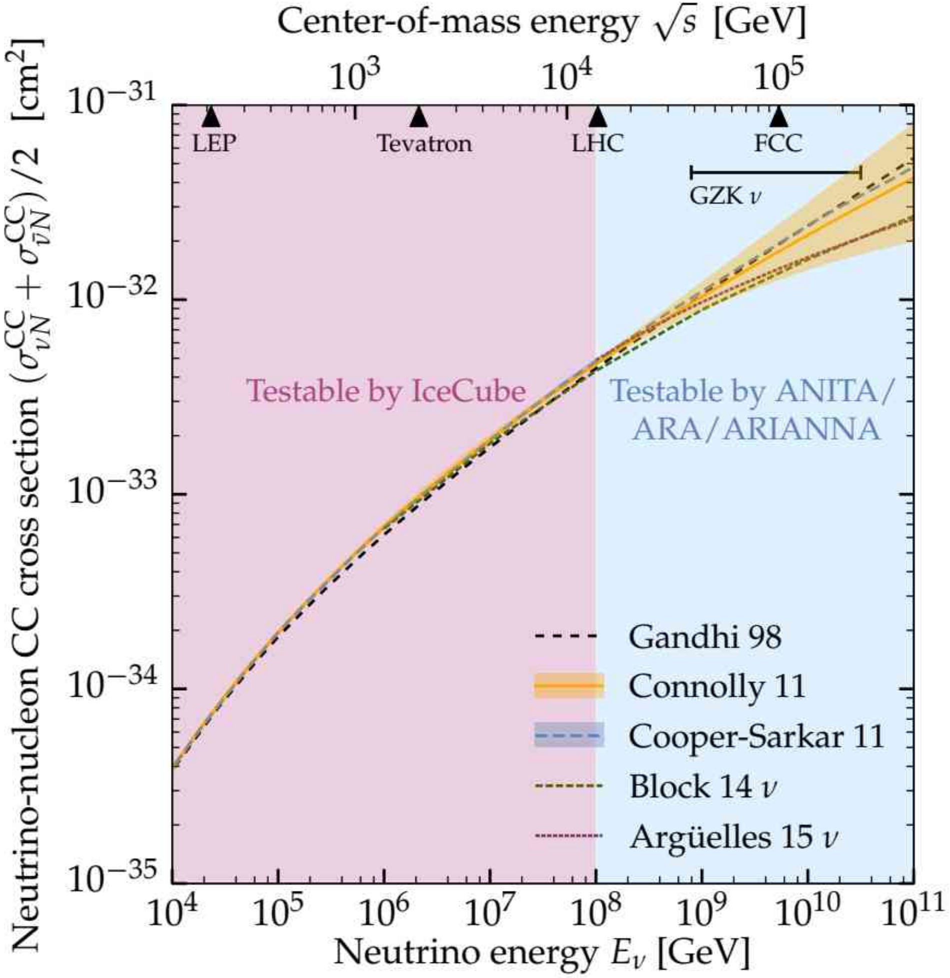
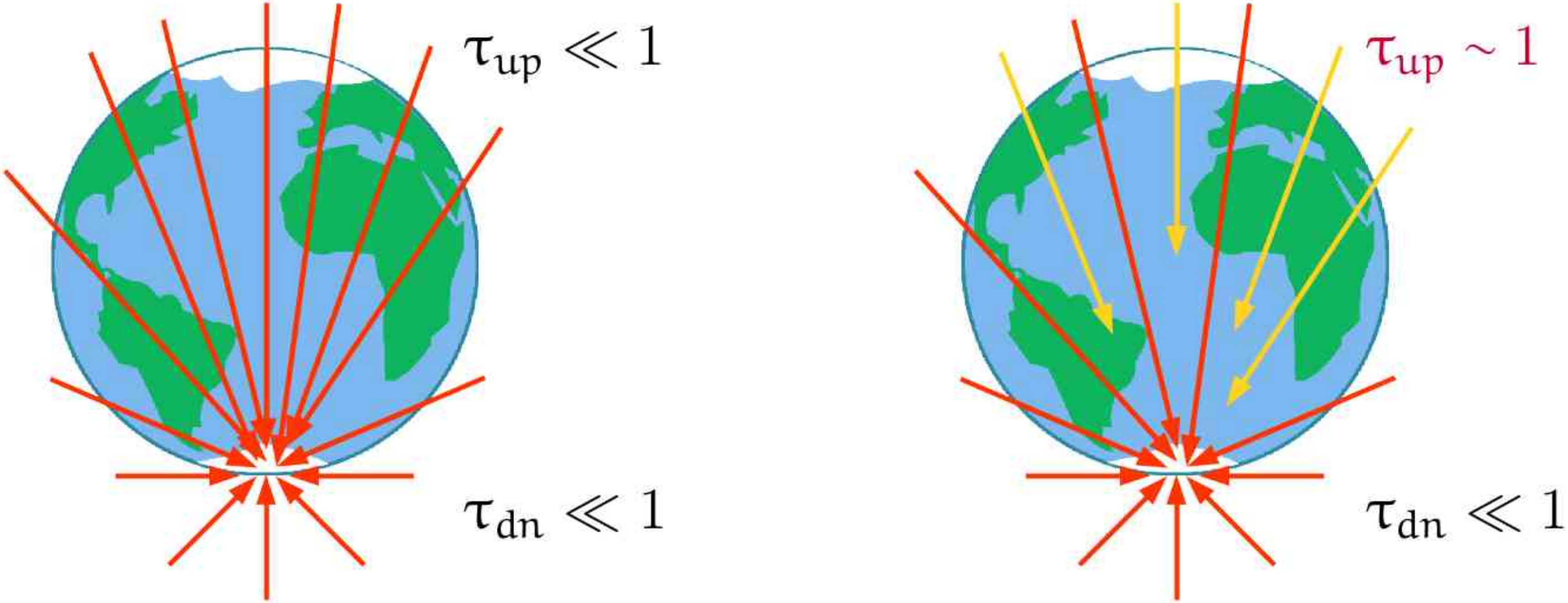


Measuring the high-energy cross section

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

Below ~ 10 TeV: Earth is transparent

Above ~ 10 TeV: Earth is opaque



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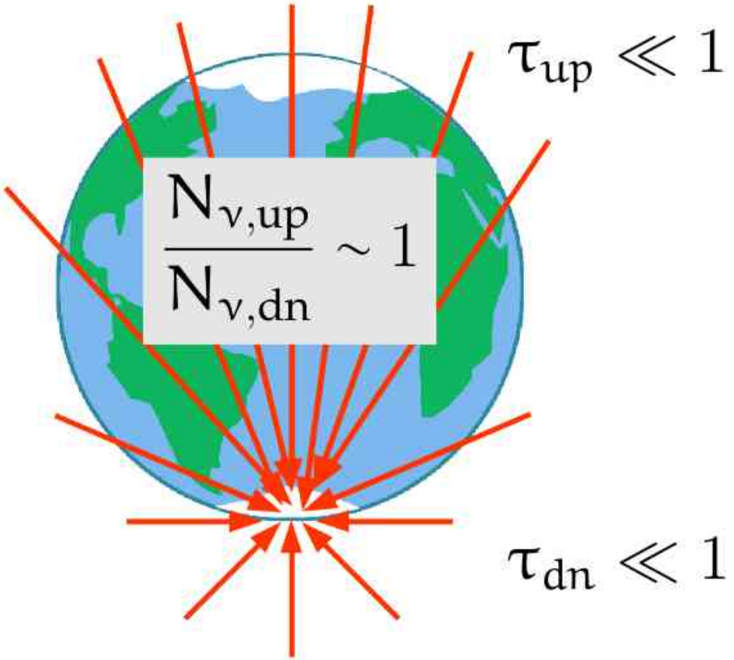

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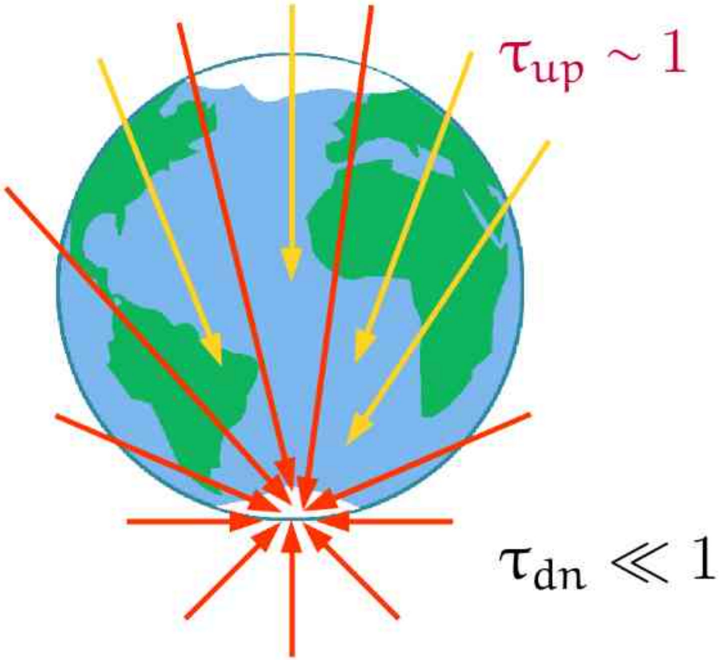

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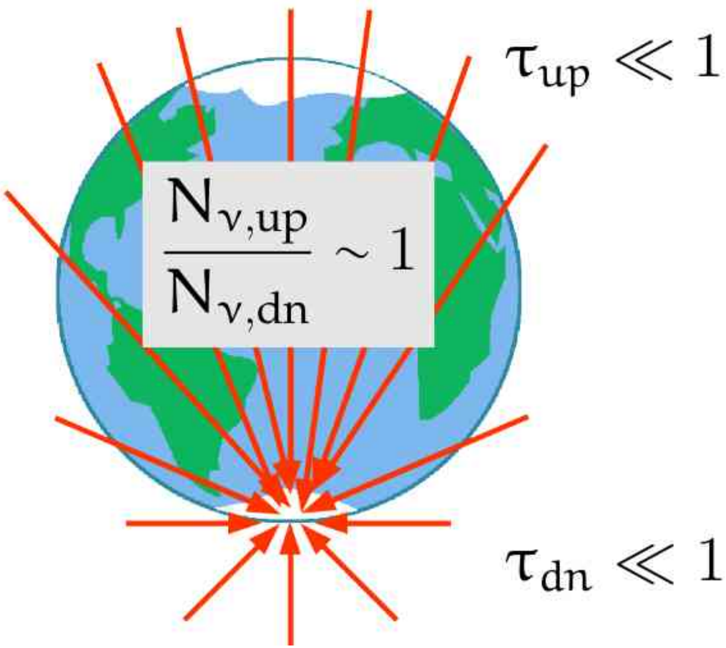

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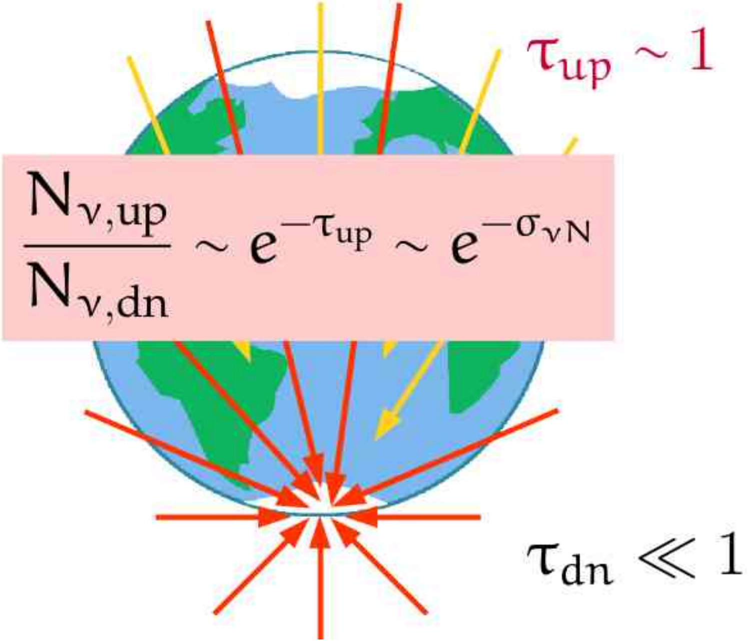
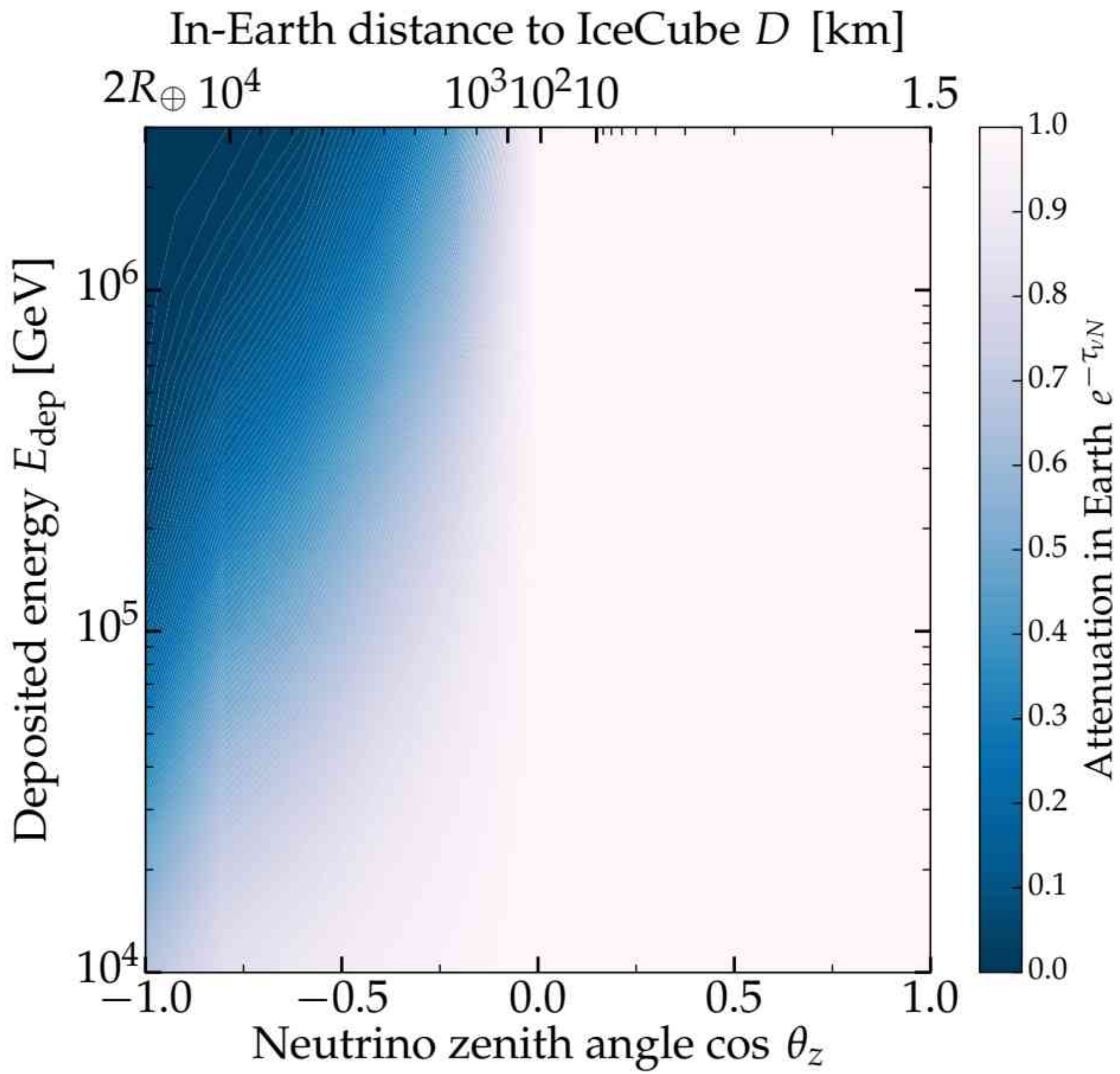
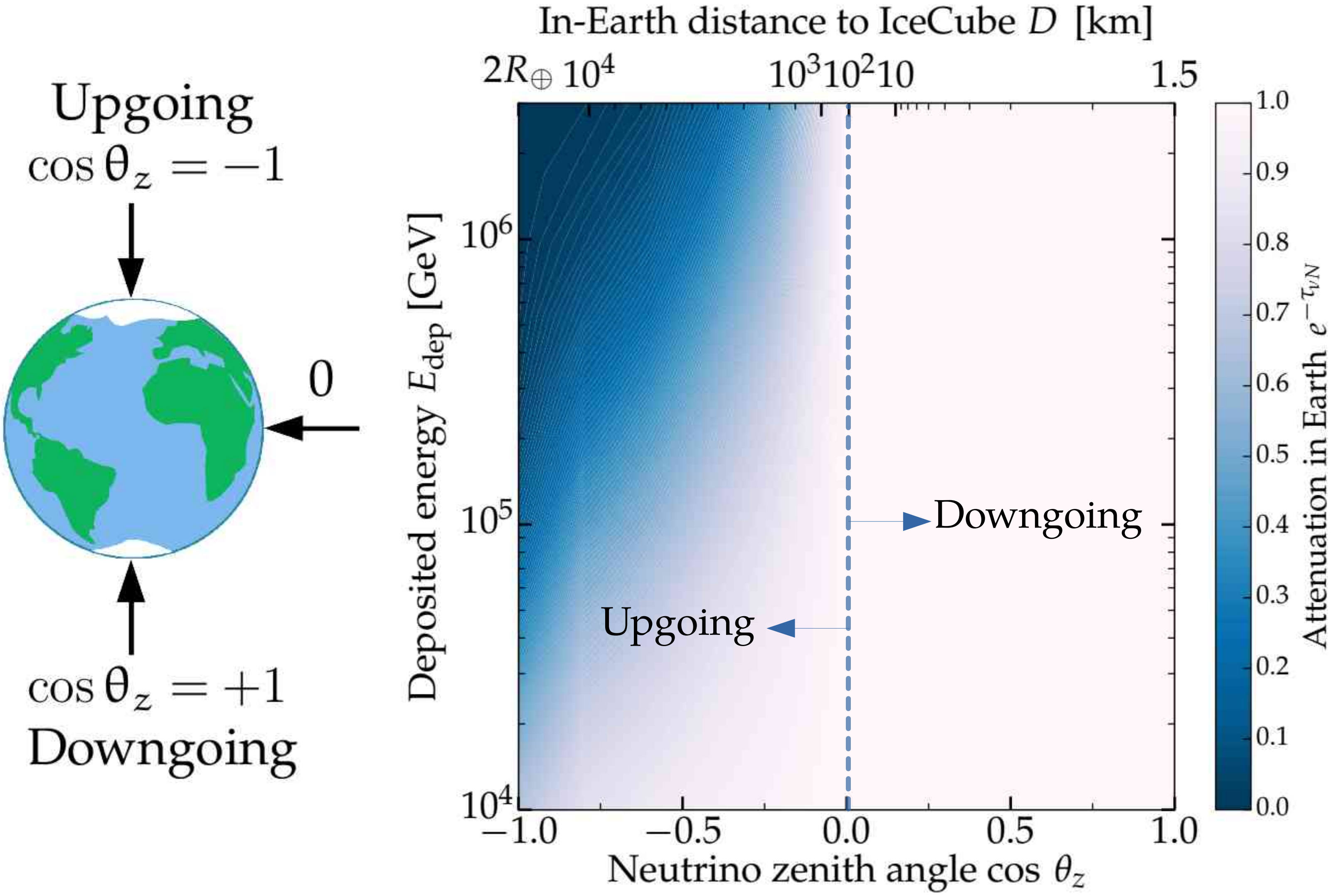



In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4 10^3 10^2 10 1.5
Deposited energy $E_{\rm dep}$ [GeV]
10^4 10^5 10^6
-1.0 -0.5 0.0 0.5 1.0
Neutrino zenith angle cos θ_z
Attenuation in Earth $e^{-\tau_{\nu N}}$
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0


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]
10^4 10^5 10^6
Downgoing
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−1.0 −0.5 0.0 0.5 1.0
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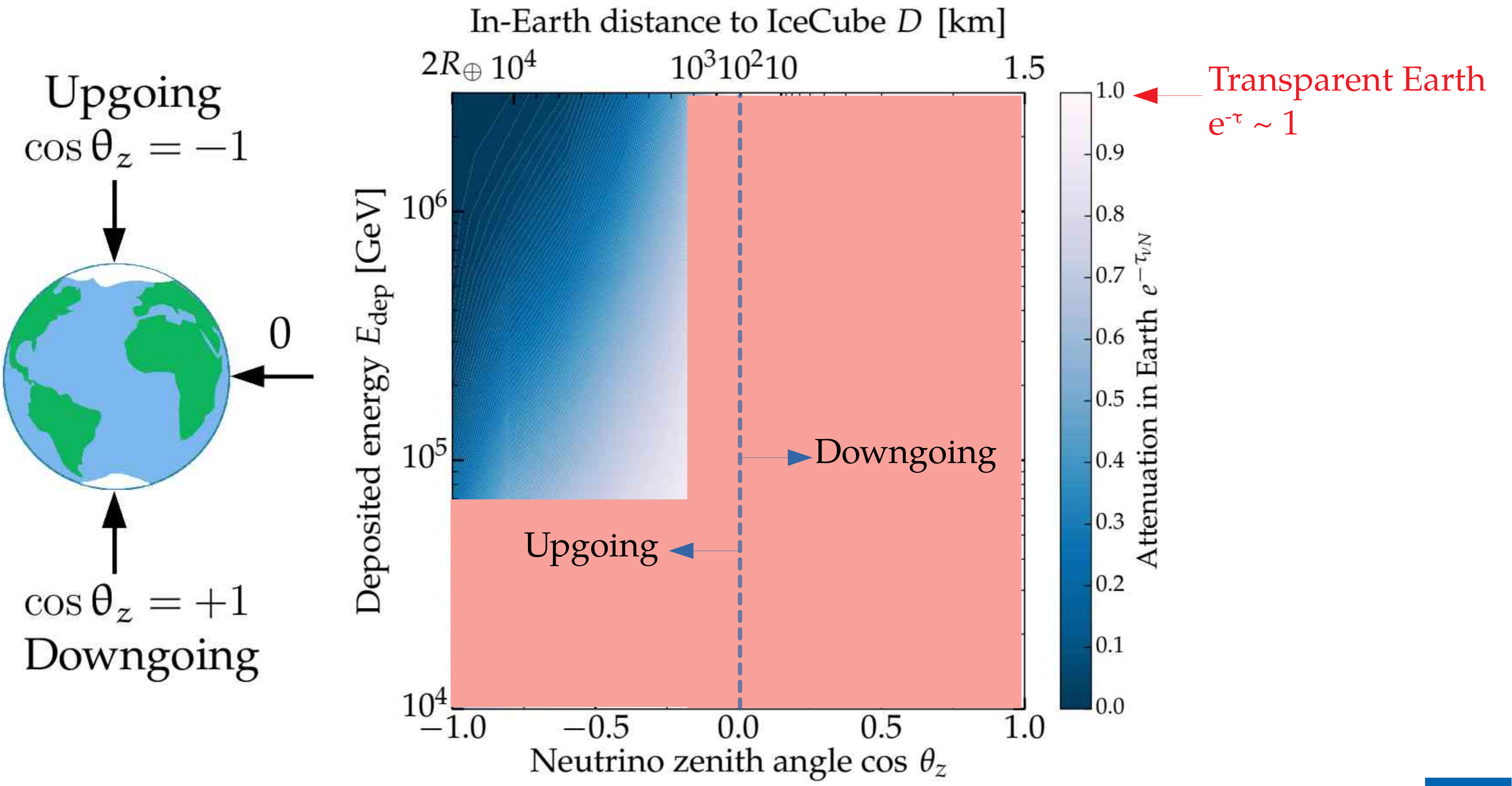
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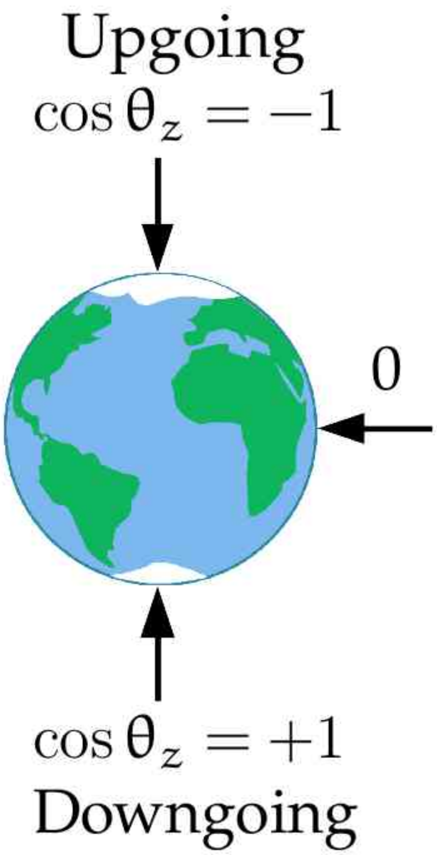
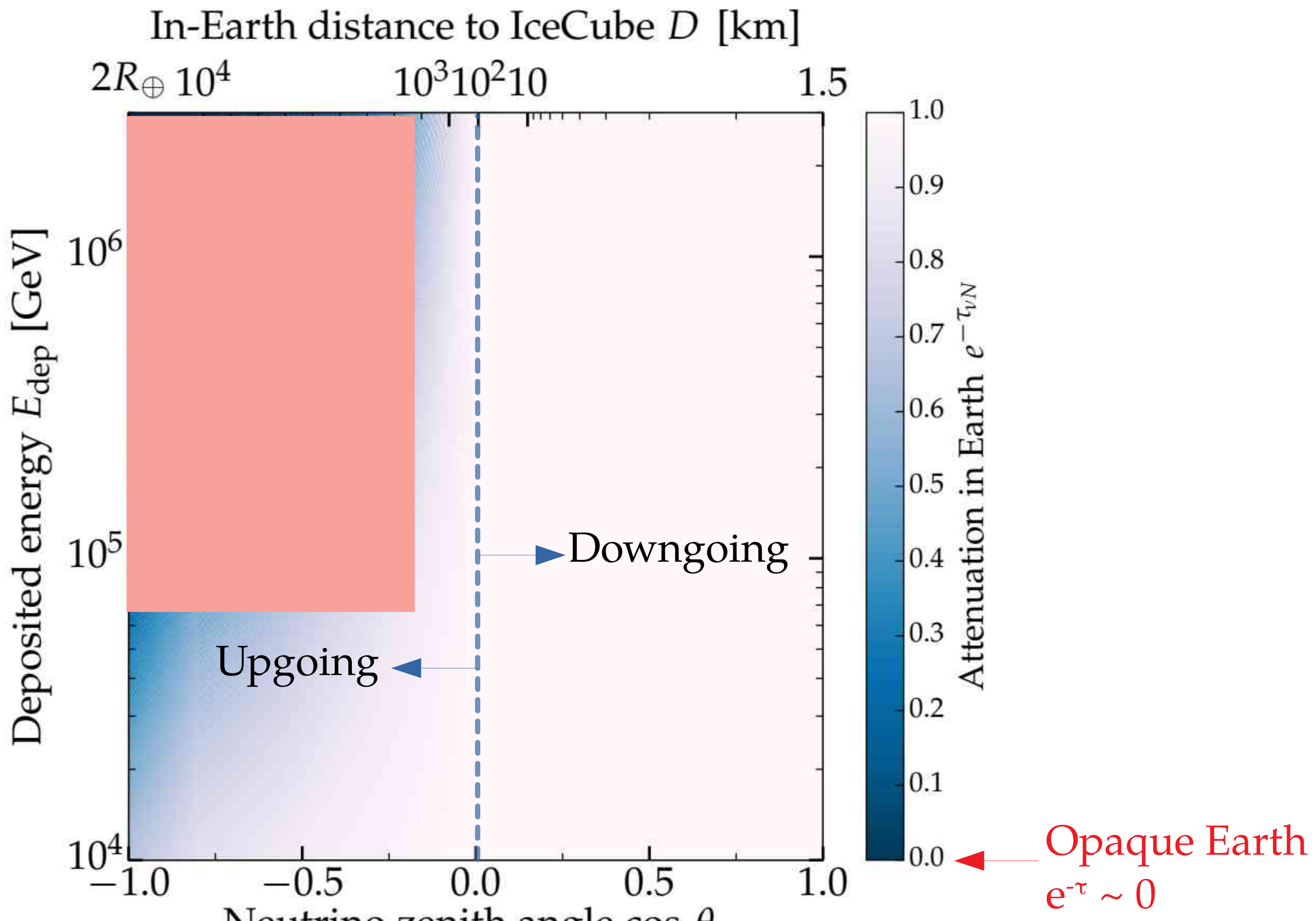
0.0
0.5
1.0
Neutrino zenith angle $\cos\theta_z$
Downgoing
Upgoing
Attenuation in Earth $e^{-\tau_{\nu N}}$
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Transparent Earth
$e^{-\tau} \sim 1$


Upgoing
cos θ_z = −1
0
cos θ_z = +1
Downgoing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2R⊕ 10^4
10^3 10^2 10
1.5
Deposited energy E_dep [GeV]
10^6
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Downgoing
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−1.0
−0.5
0.0
0.5
1.0
Neutrino zenith angle cos θ_z
Attenuation in Earth e^{−τ_νN}
1.0
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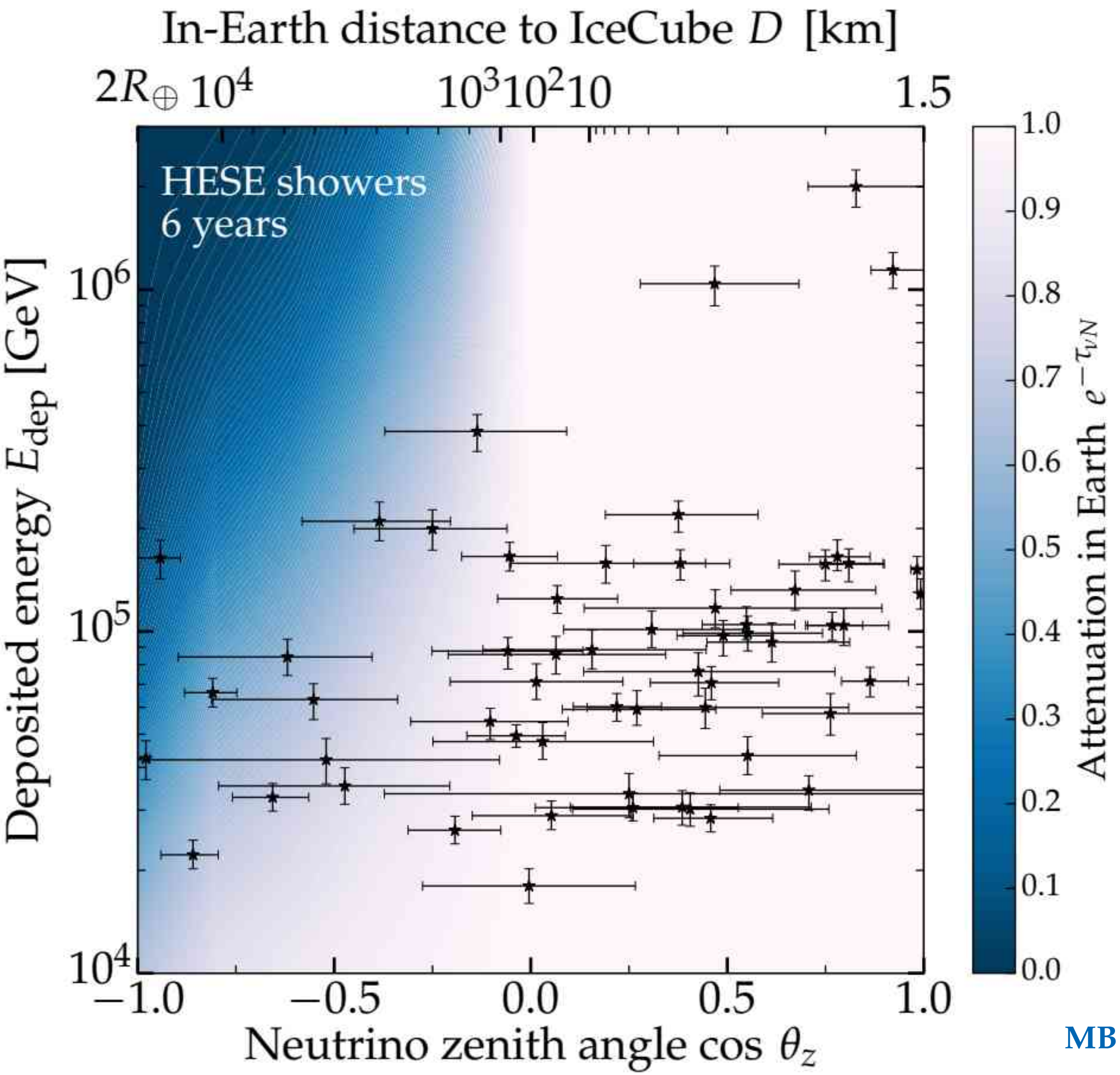
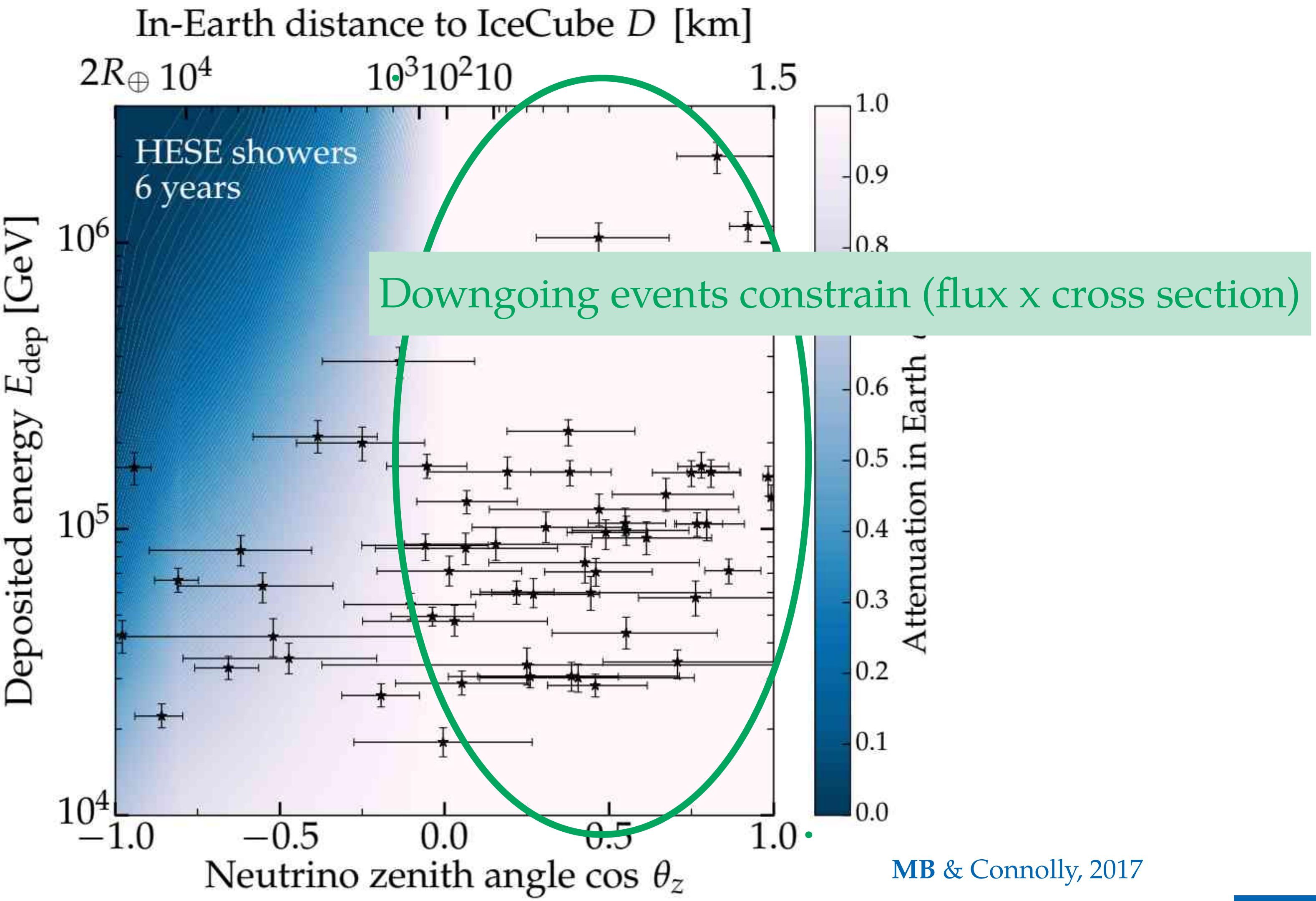
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Opaque Earth
e^{-τ} ~ 0



MB & Connolly, 2017



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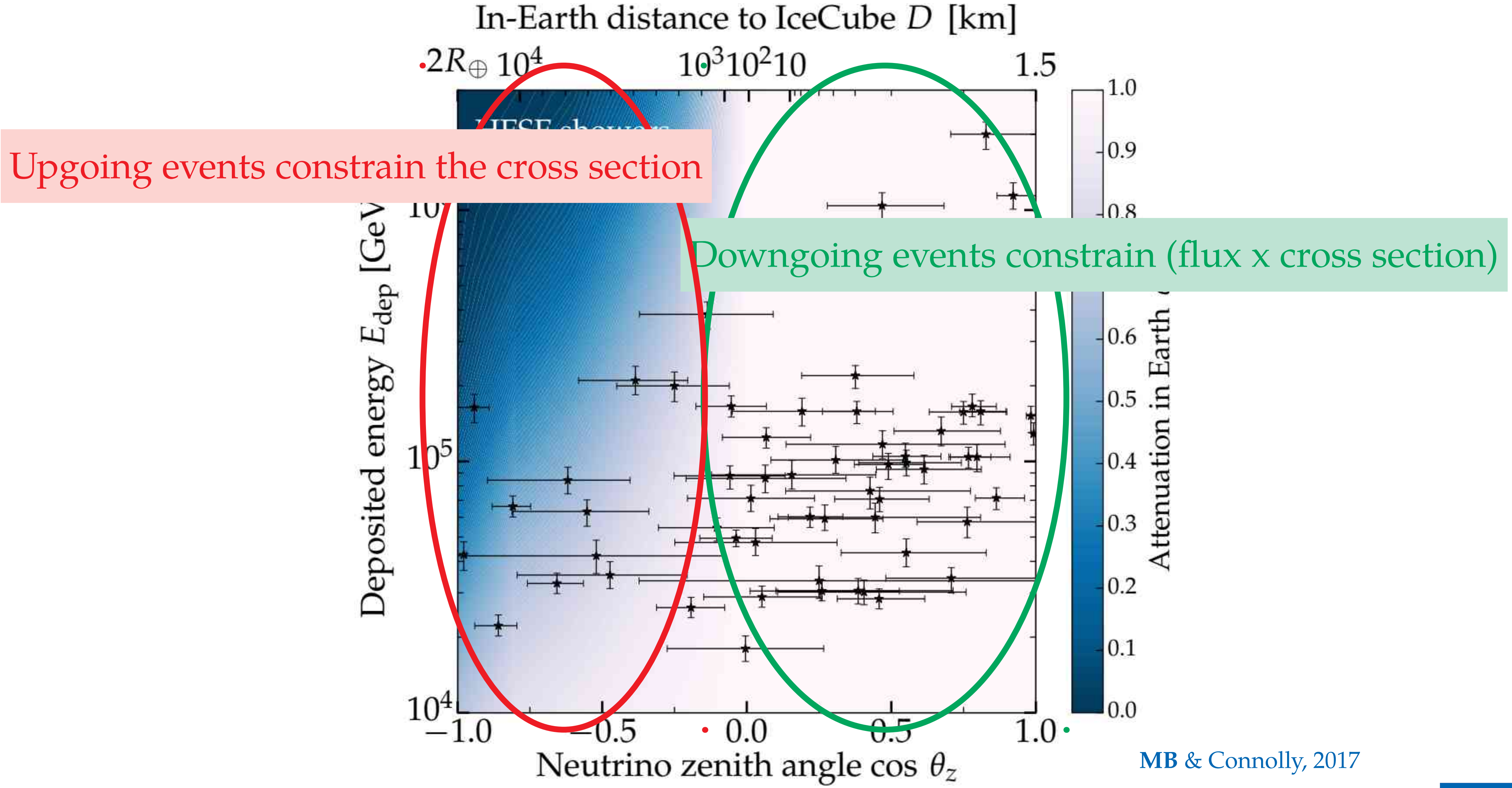

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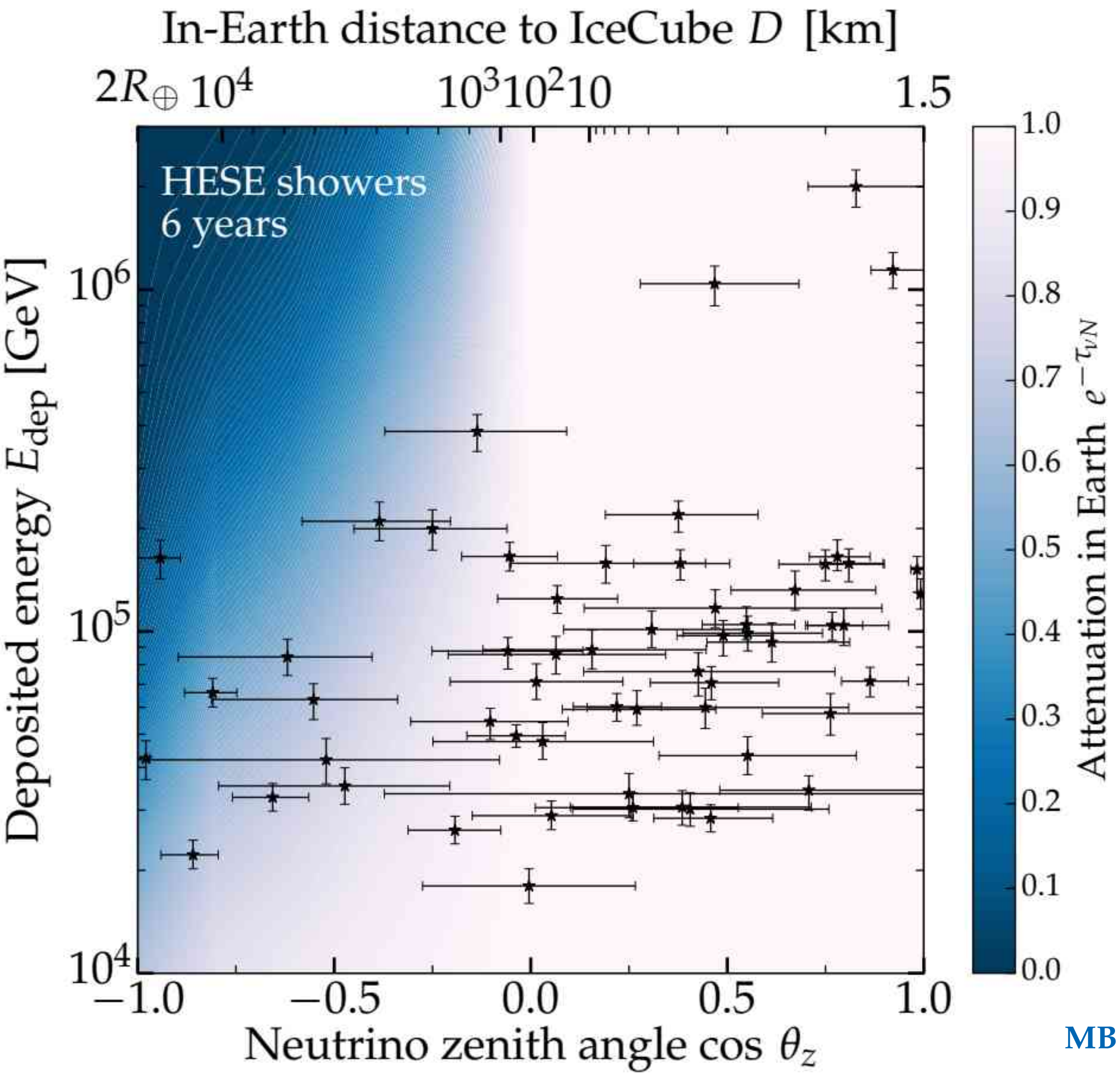

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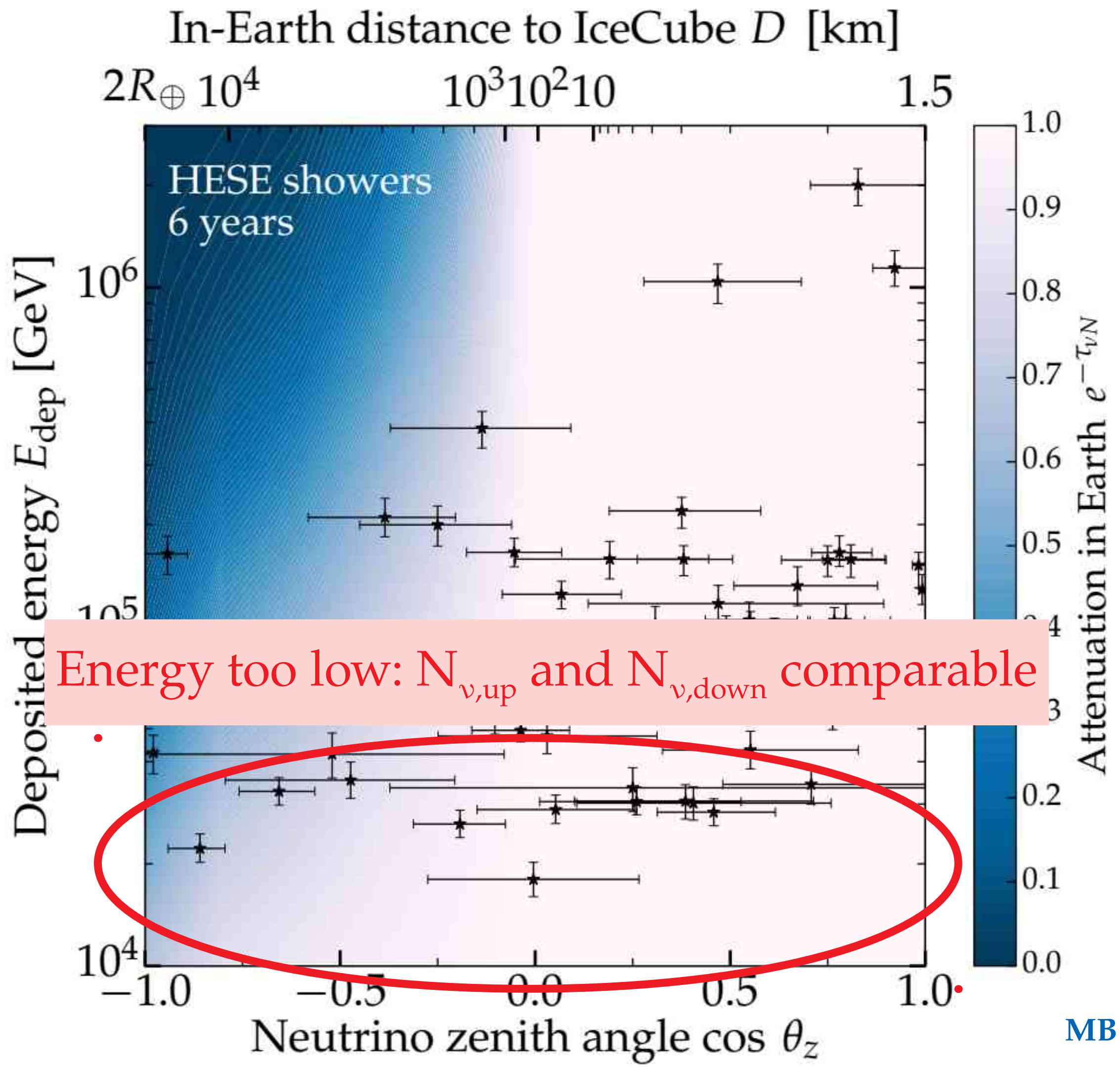
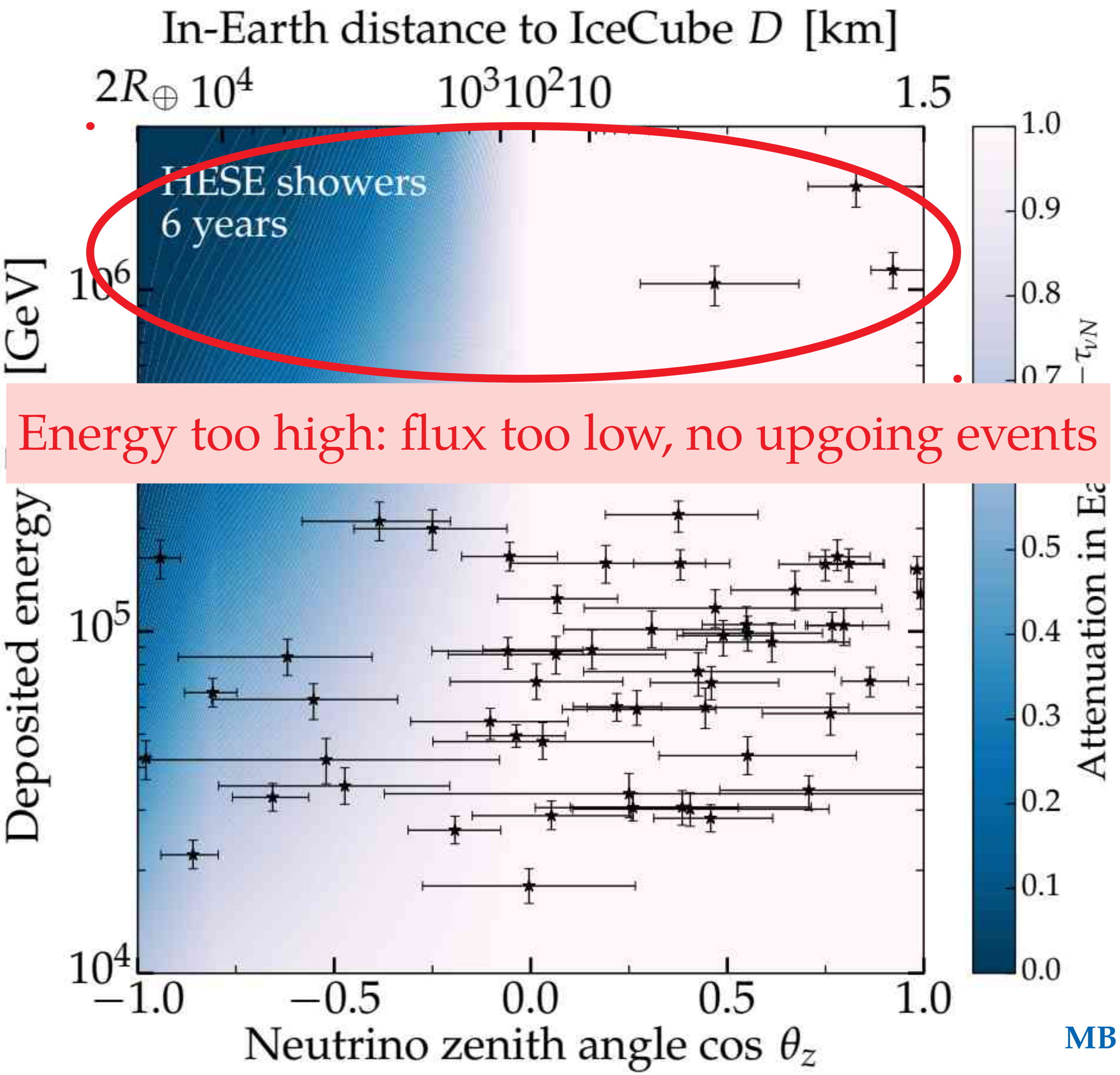
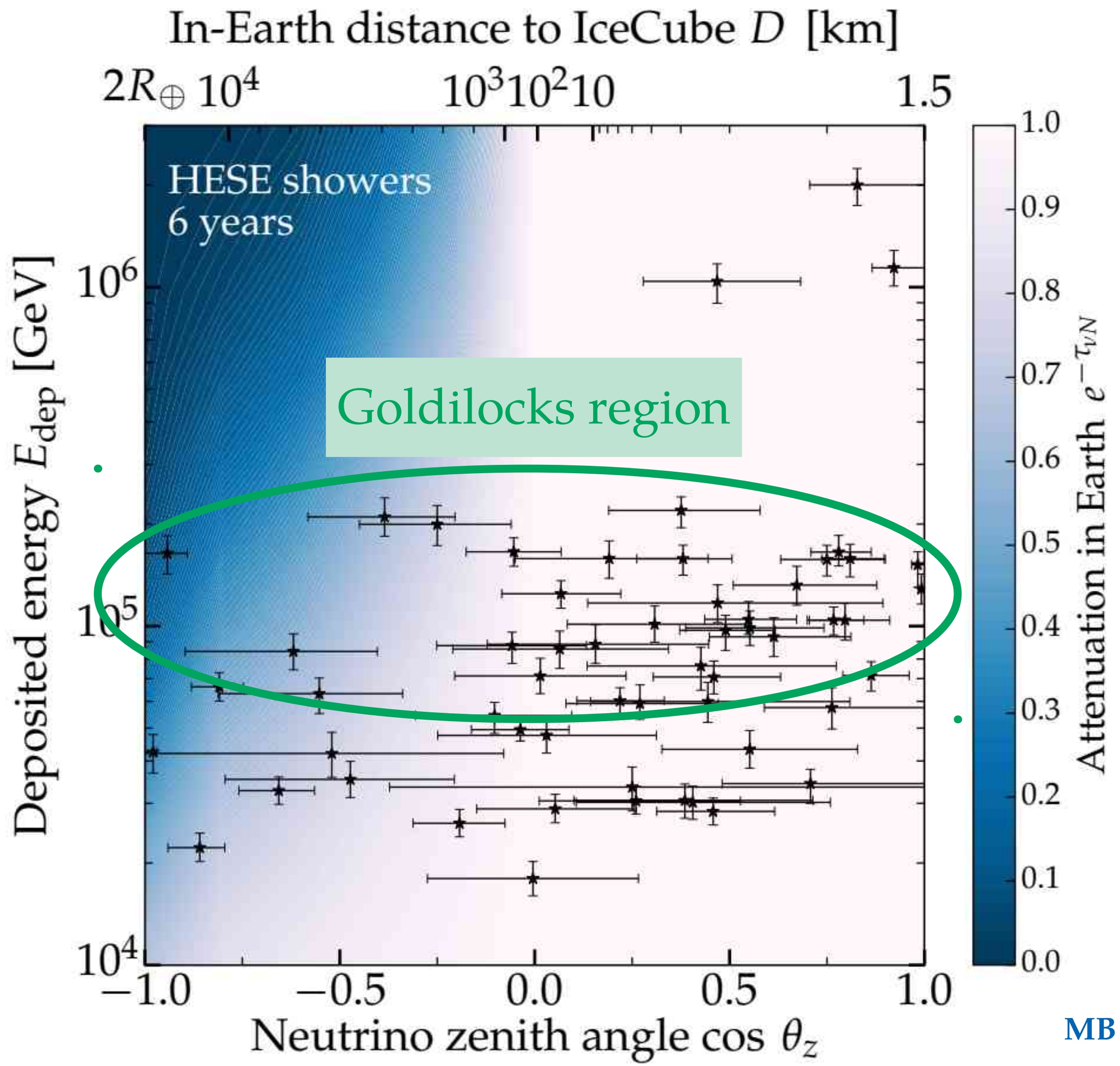


MB & Connolly, 2017



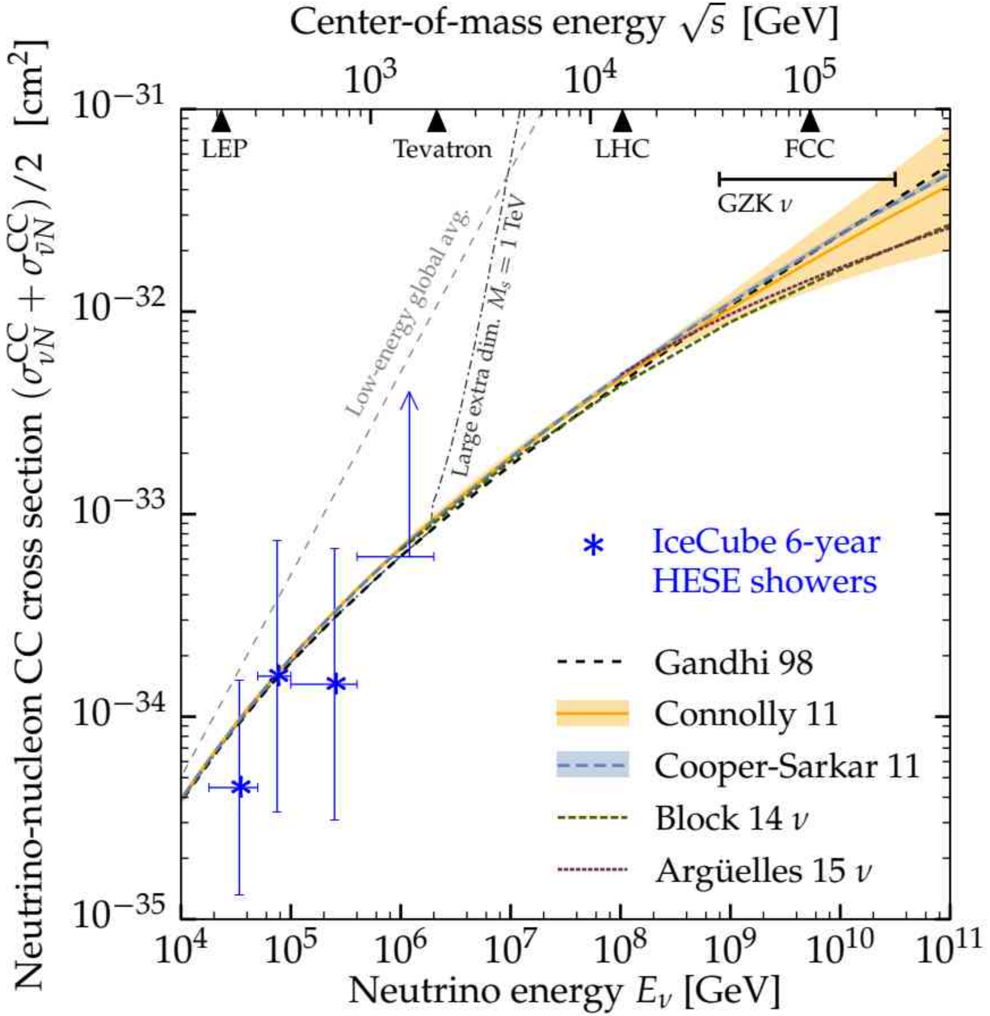
Energy too high: flux too low, no upgoing events

MB & Connolly, 2017



MB & Connolly, 2017

Our result



MB & A. Connolly 2017

See also: IceCube, *Nature* 2017

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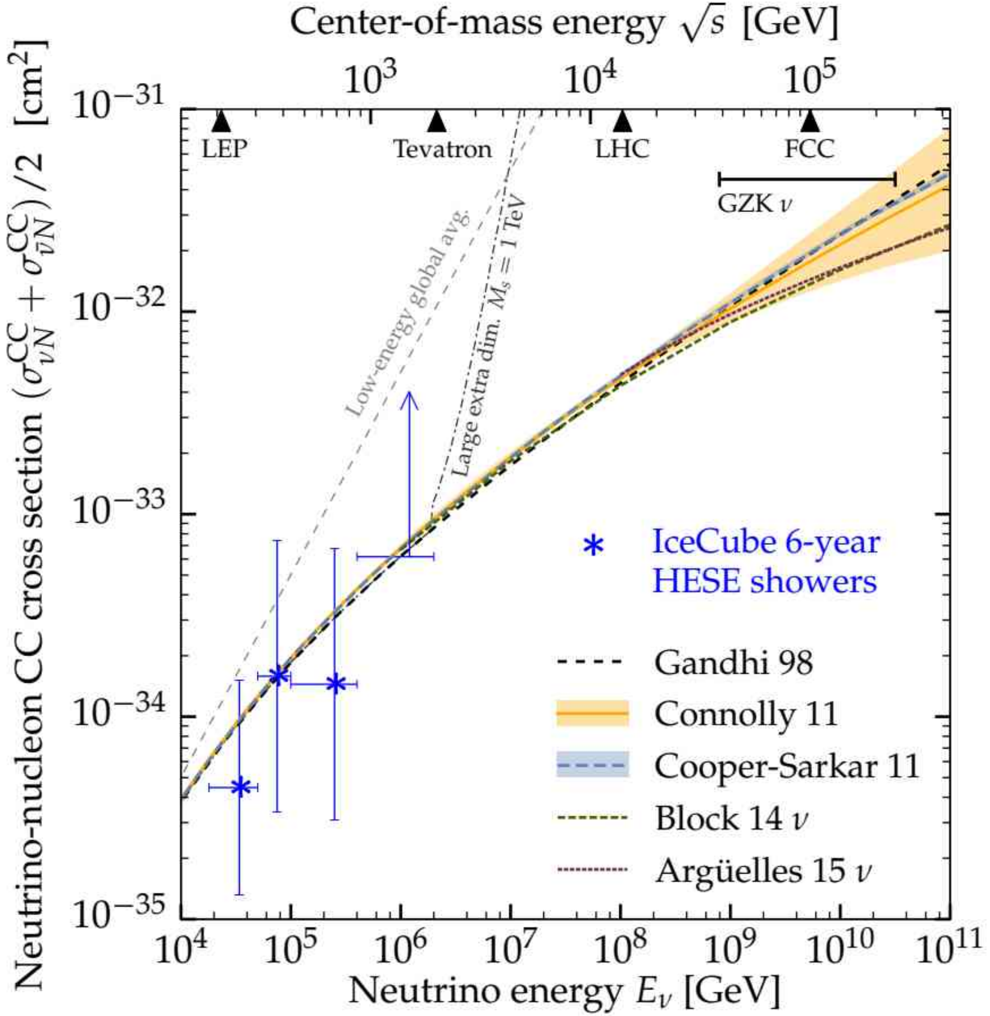

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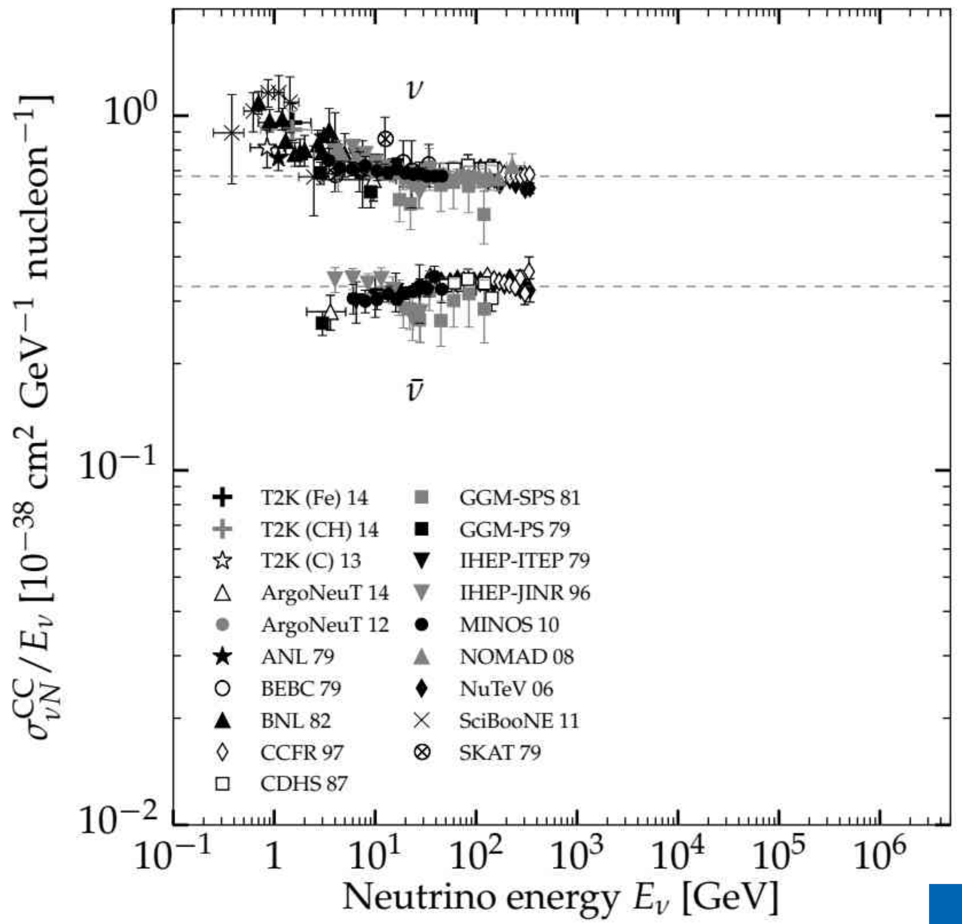

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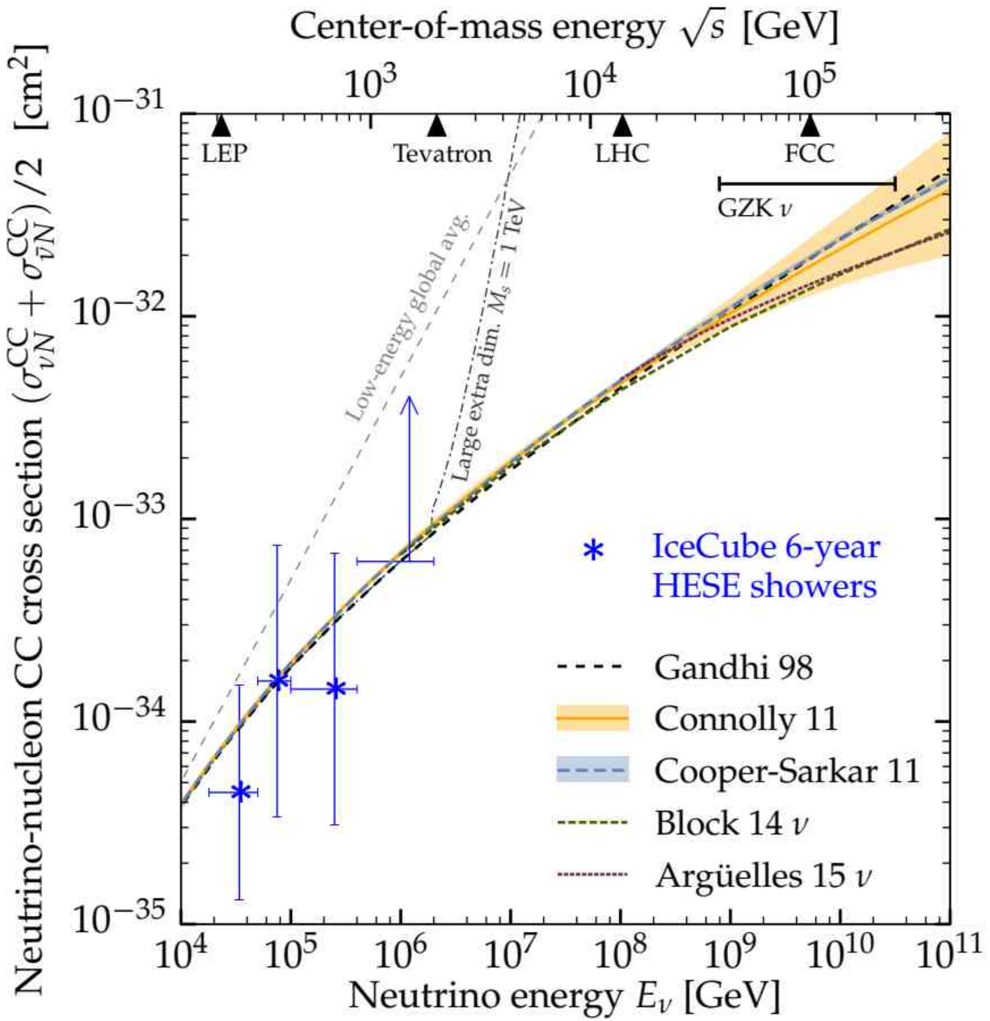

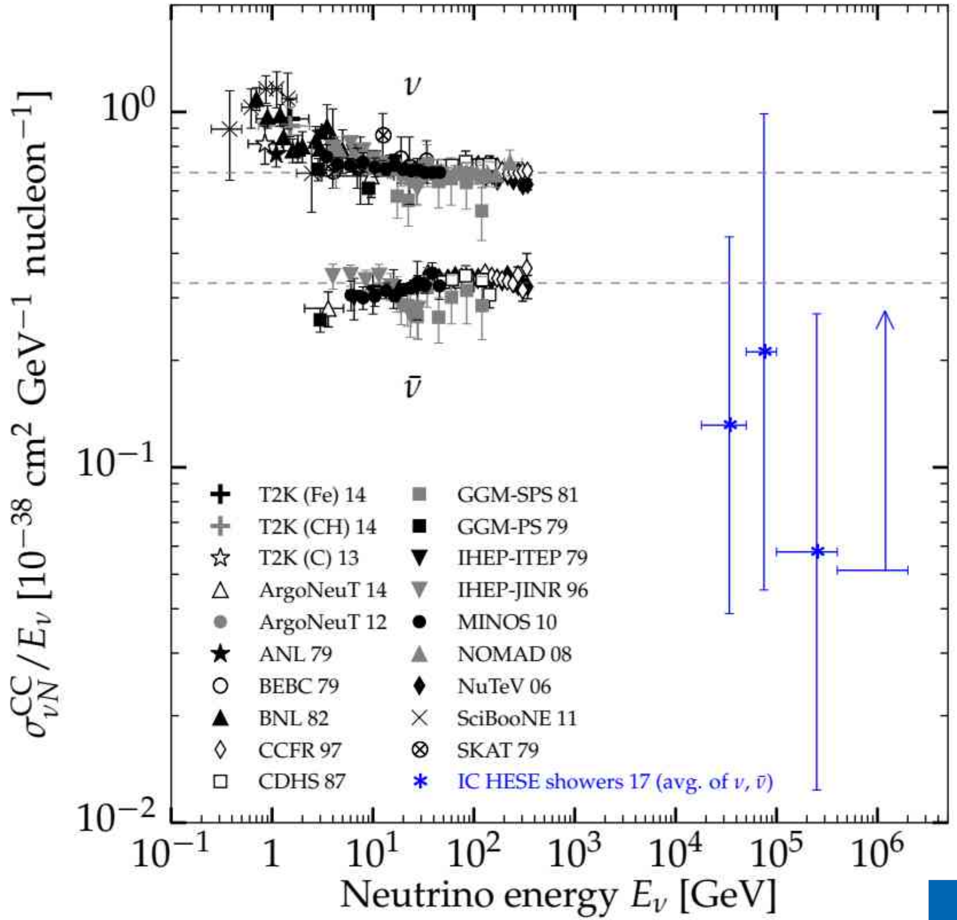

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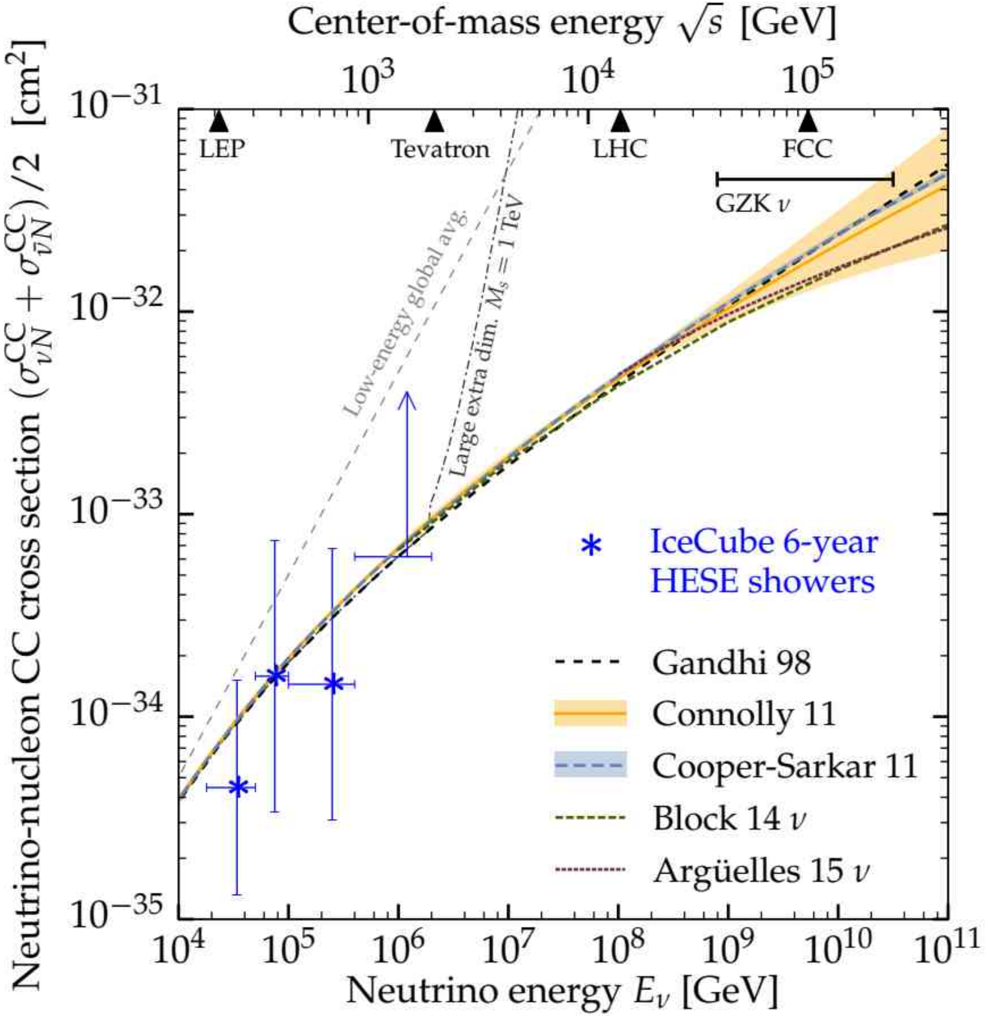
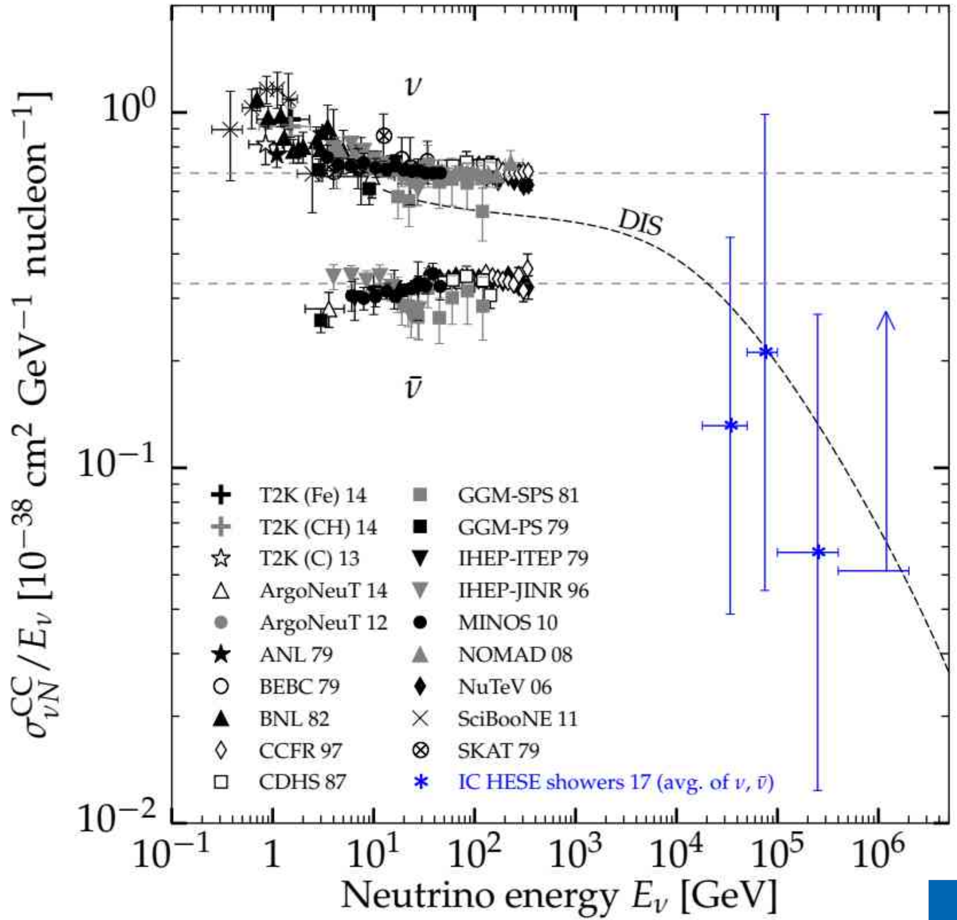
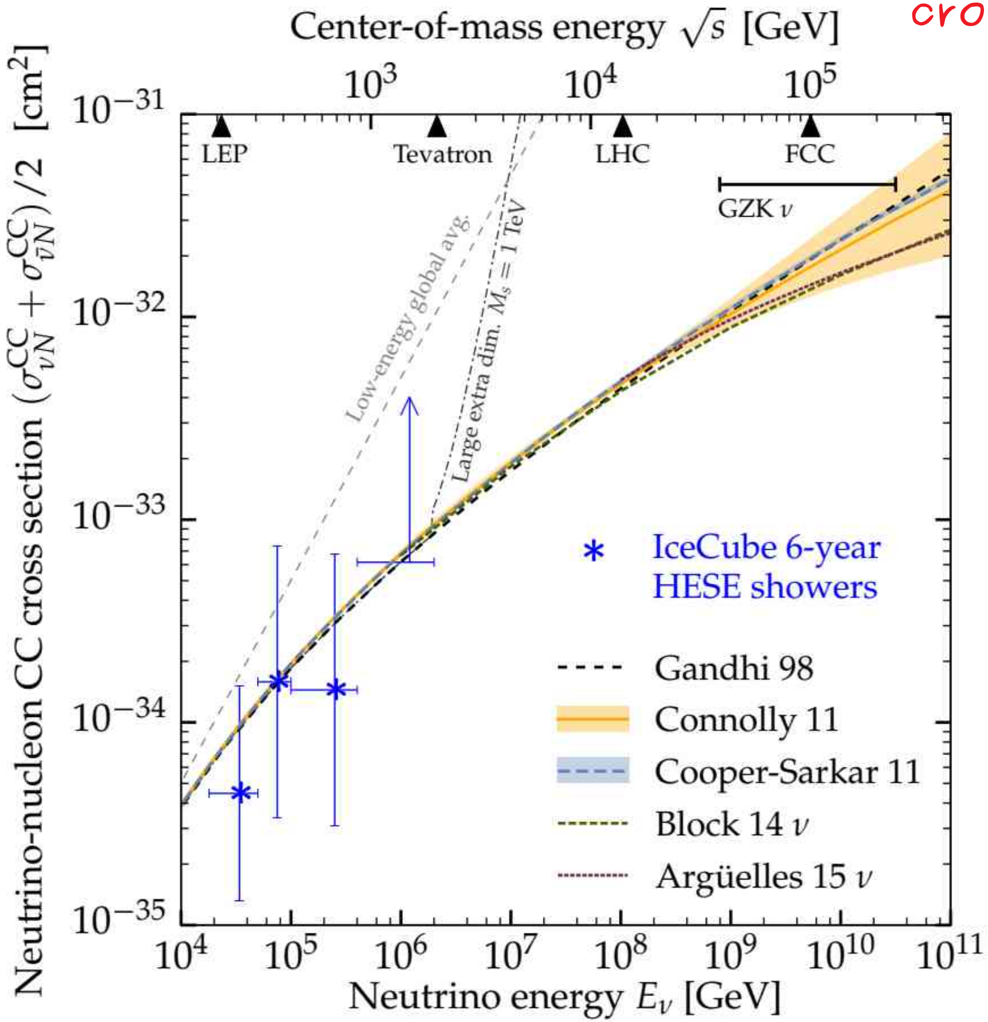




Our result

Extending the PDG cross-section plot



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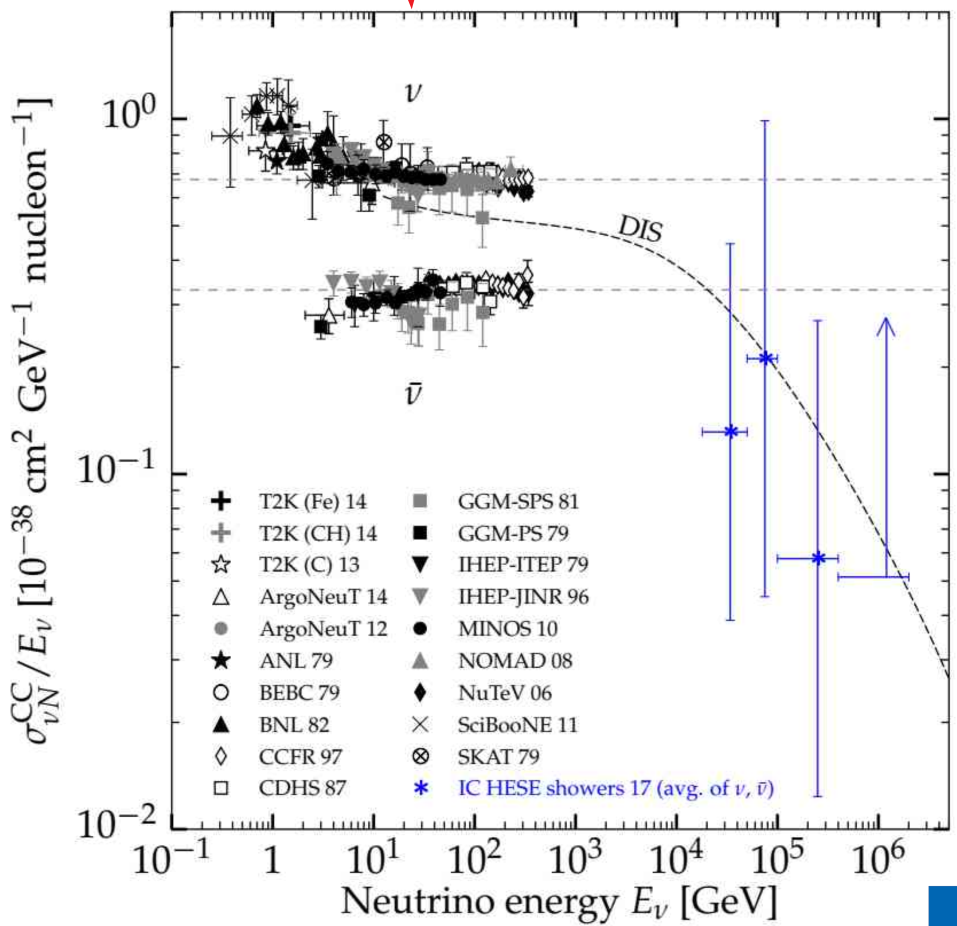


Bonus: Measuring the inelasticity $\langle y \rangle$

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

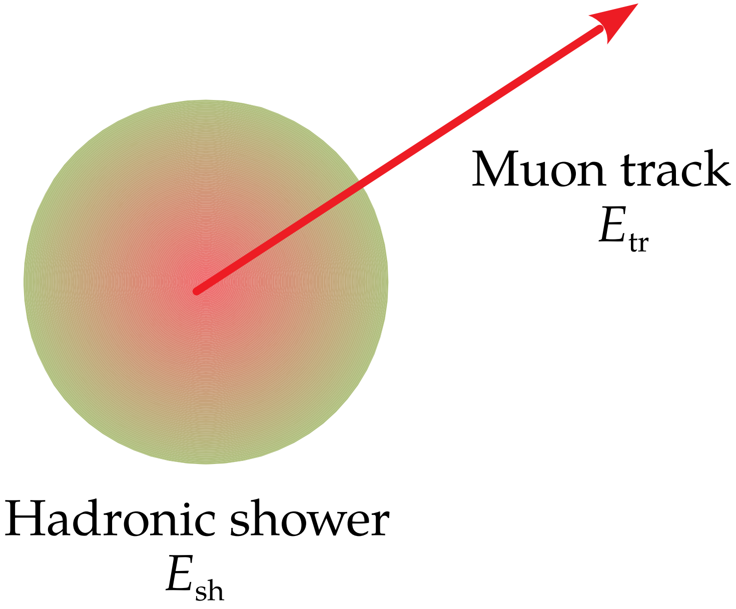
  $$E_X = y\, E_\nu \quad \text{and} \quad E_\mu = (1-y)\, E_\nu \;\Rightarrow\; y = (1 + E_\mu / E_X)^{-1}$$

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

- In a HESE starting track:

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

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



IceCube, 1808.07629

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

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

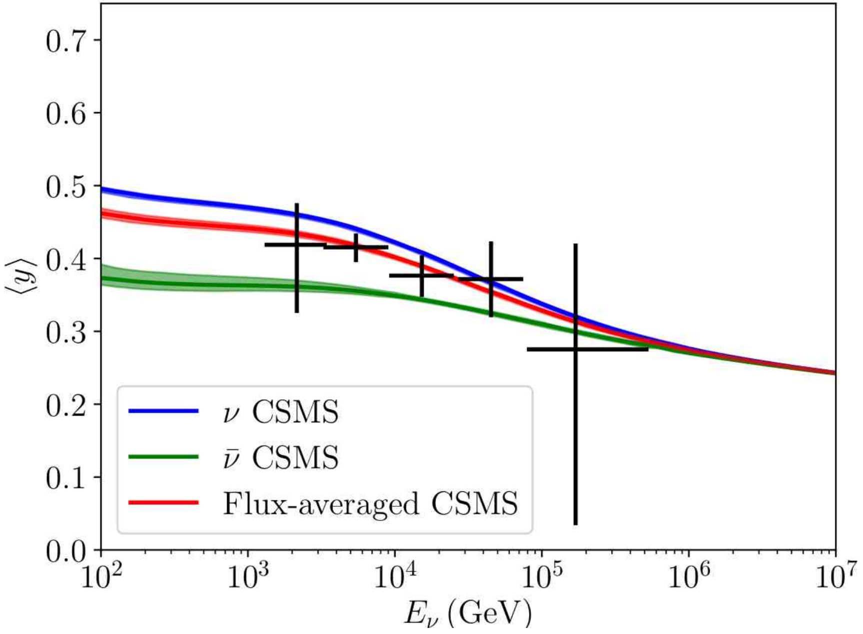
  $E_X = y\, E_\nu$ and $E_\mu = (1-y)\, E_\nu \Rightarrow y = (1 + E_\mu/E_X)^{-1}$

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

- In a HESE starting track:

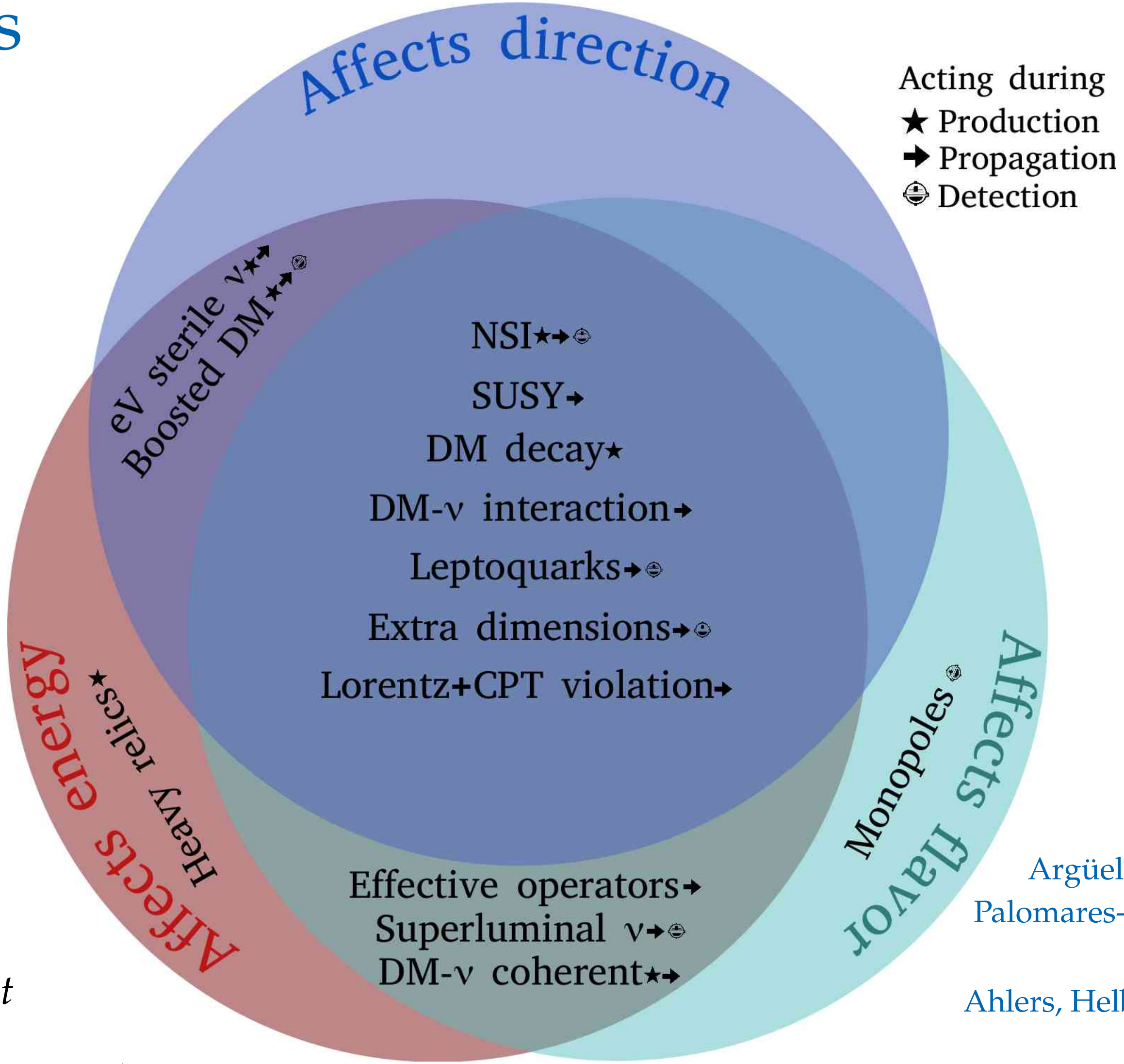
  $$\left.\begin{array}{l} E_X = E_{sh} \text{ (energy of shower)} \\ E_\mu = E_{tr} \text{ (energy of track)} \end{array}\right\} y = (1 + E_{tr}/E_{sh})^{-1}$$

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



IceCube, 1808.07629

New ν physics



Argüelles, **MB**, Conrad, Kheirandish, Palomares-Ruiz, Salvadó, Vincent, *In prep.*

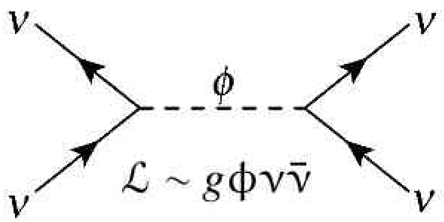
See also:

Ahlers, Helbing, De los Heros, 1806.05696

Note: Not an exhaustive list

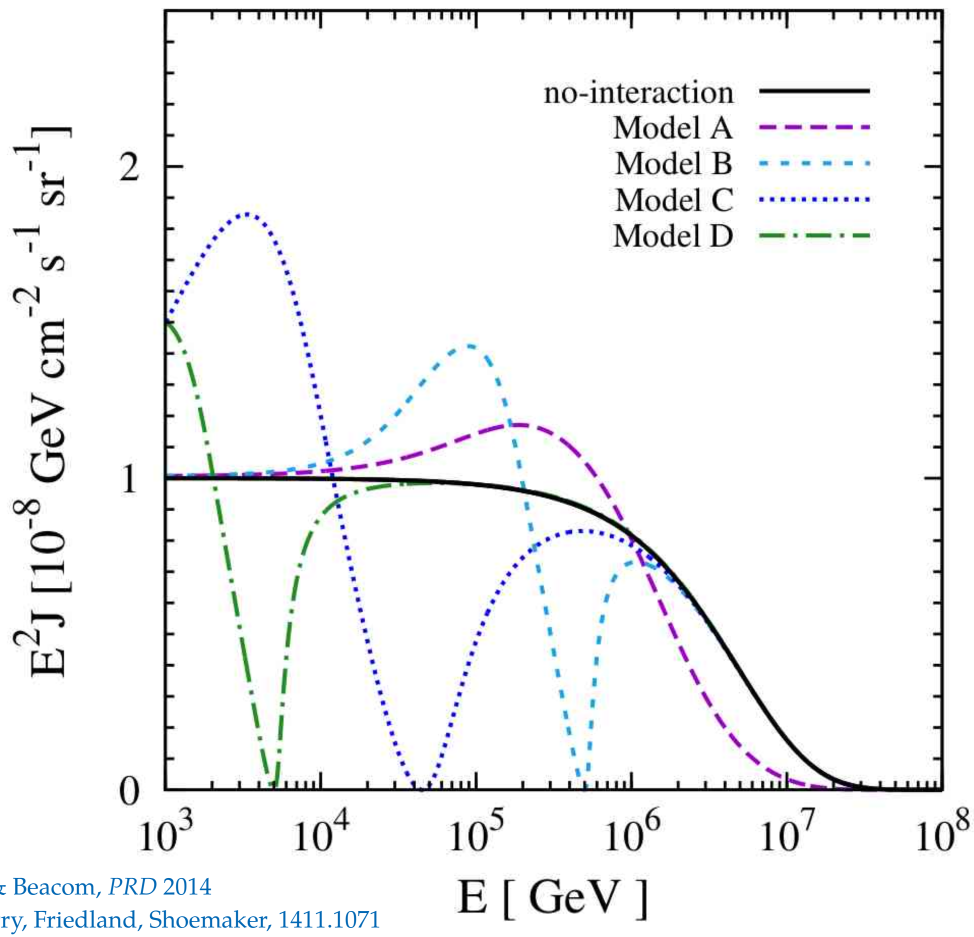
New physics in the spectral shape: $\nu\nu$ interactions

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



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

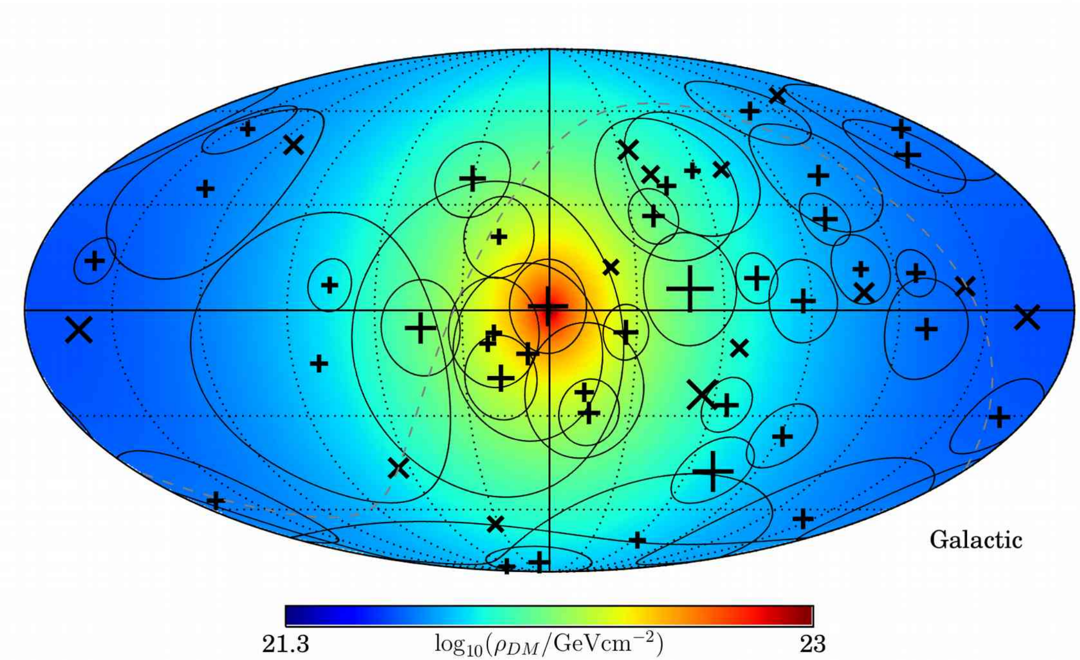
Resonance energy: $E_{\text{res}} = \frac{M^2}{2m_\nu}$

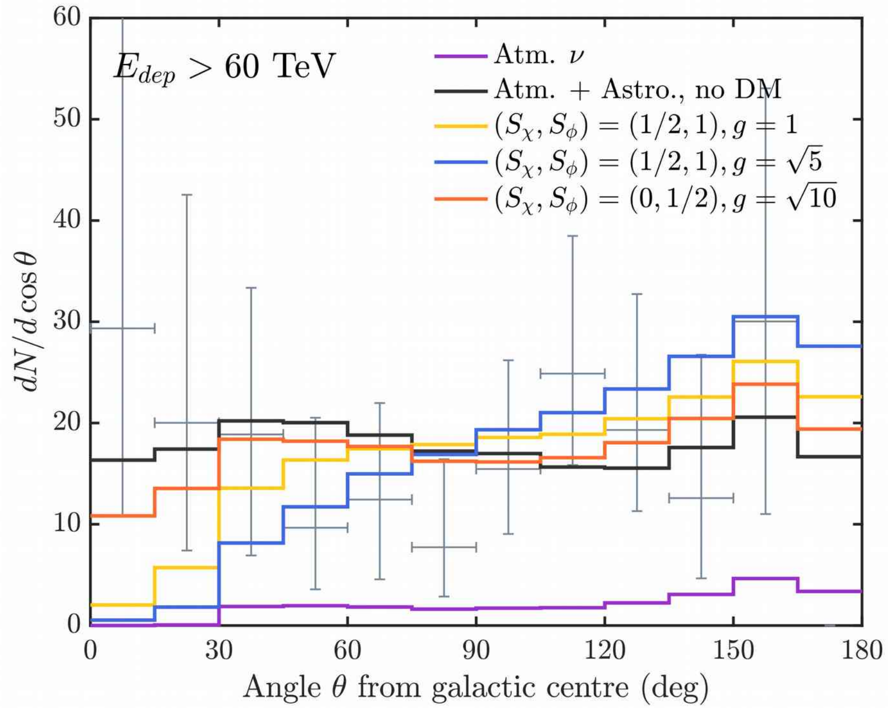


Ng & Beacom, *PRD* 2014
Cherry, Friedland, Shoemaker, 1411.1071
Blum, Hook, Murase, 1408.3799

New physics in the angular distribution: ν-DM interactions

Interaction between astrophysical neutrinos and the Galactic dark matter profile –





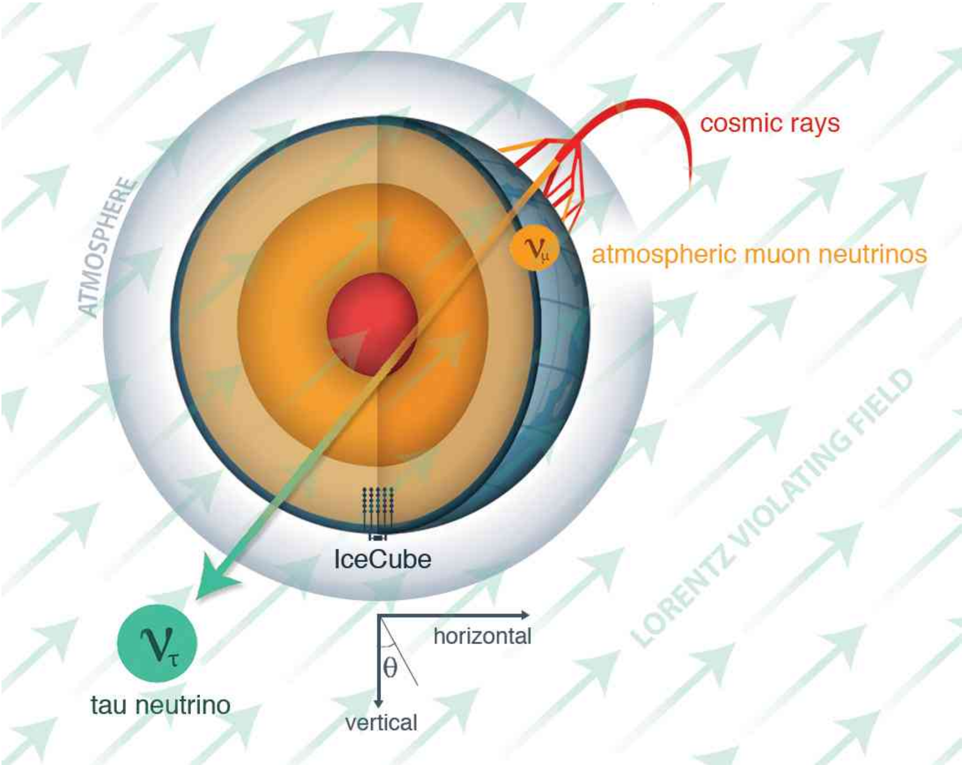
Argüelles *et al.*, *PRL* 2017

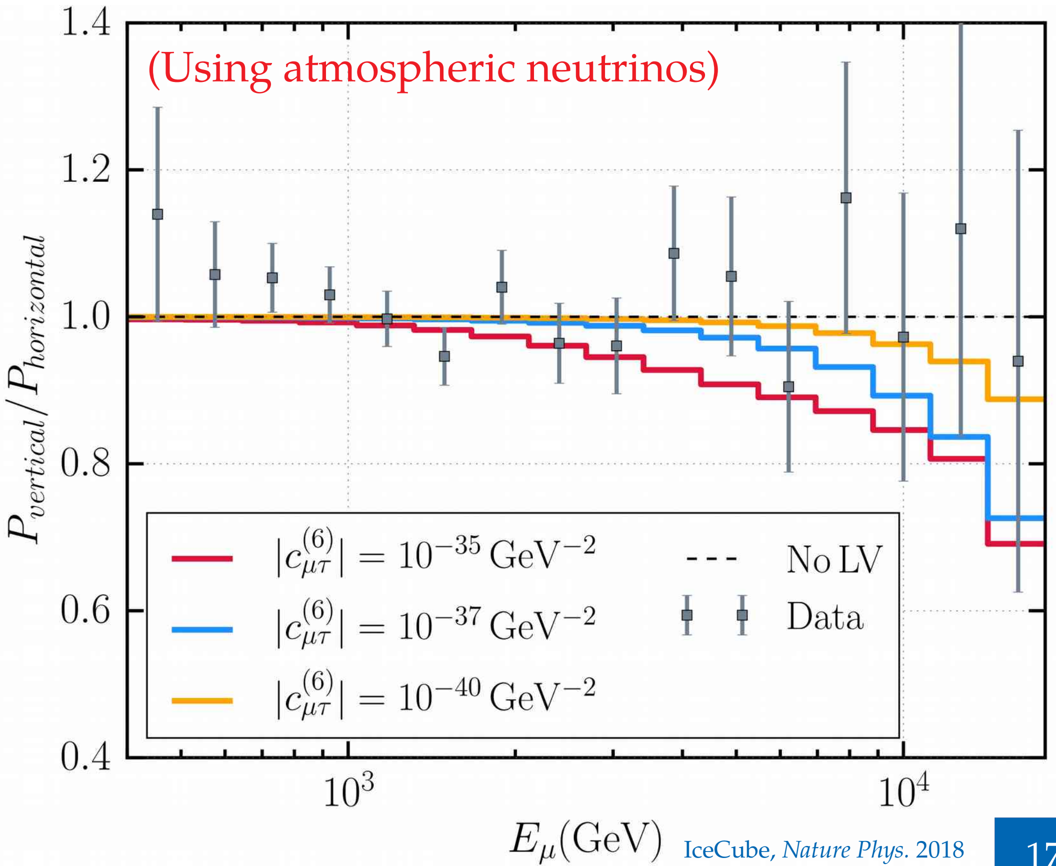
Expected: Fewer neutrinos coming from the Galactic Center

Observed: Isotropy

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

New physics in the energy & angular distribution

Lorentz violation

Standard oscillations

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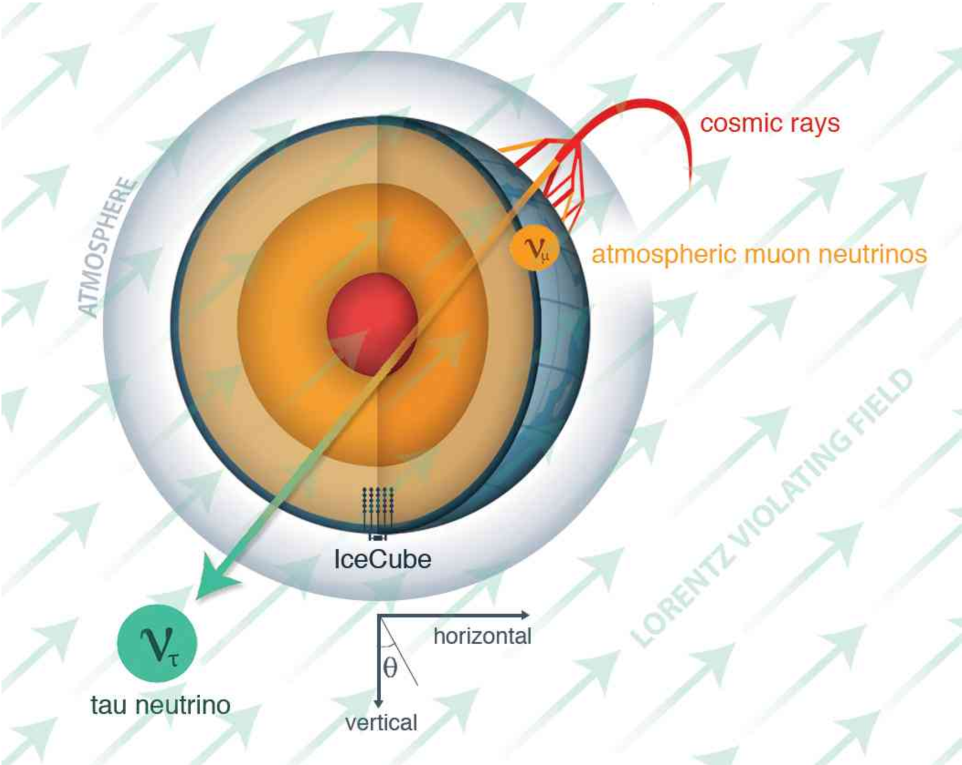

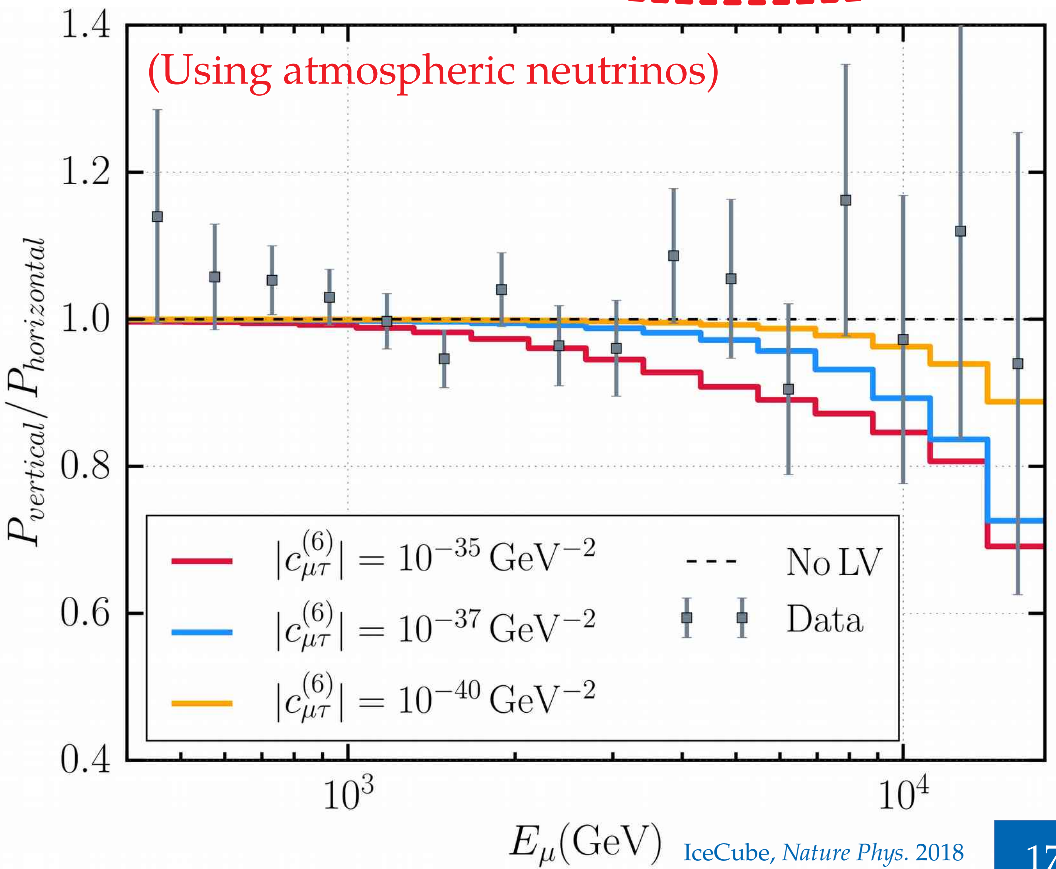

IceCube, *Nature Phys.* 2018

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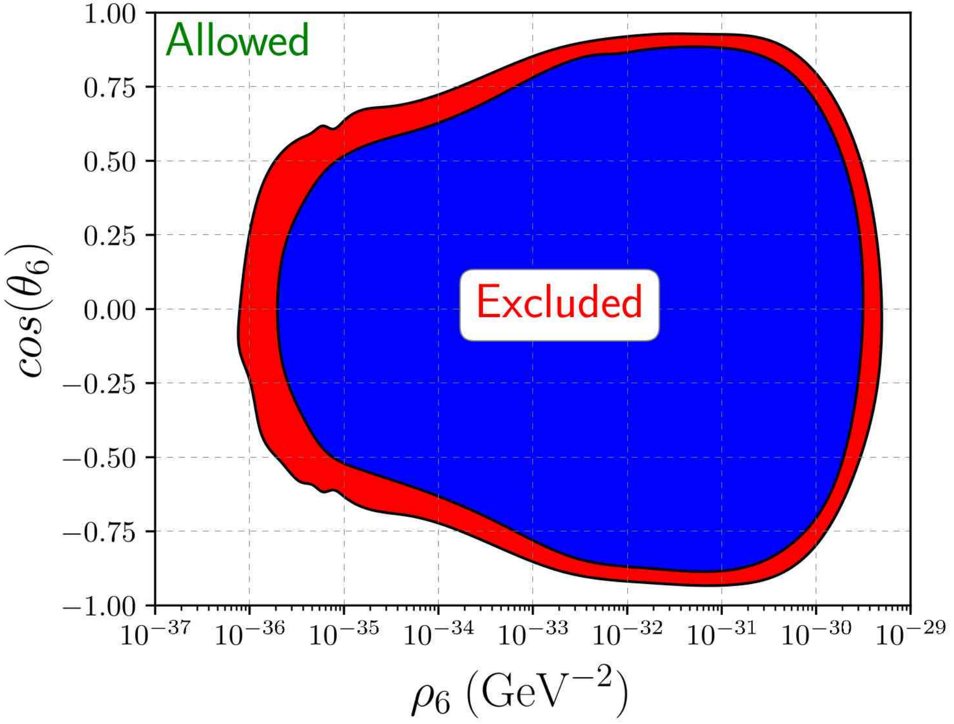
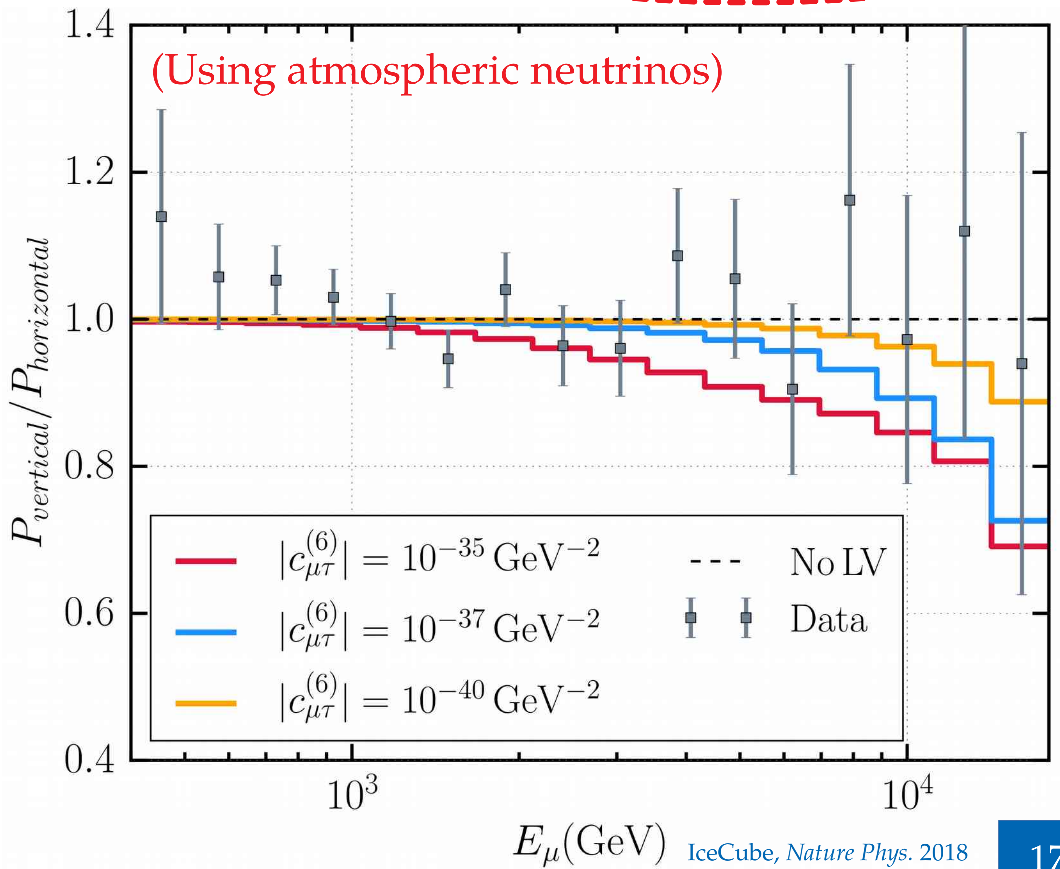
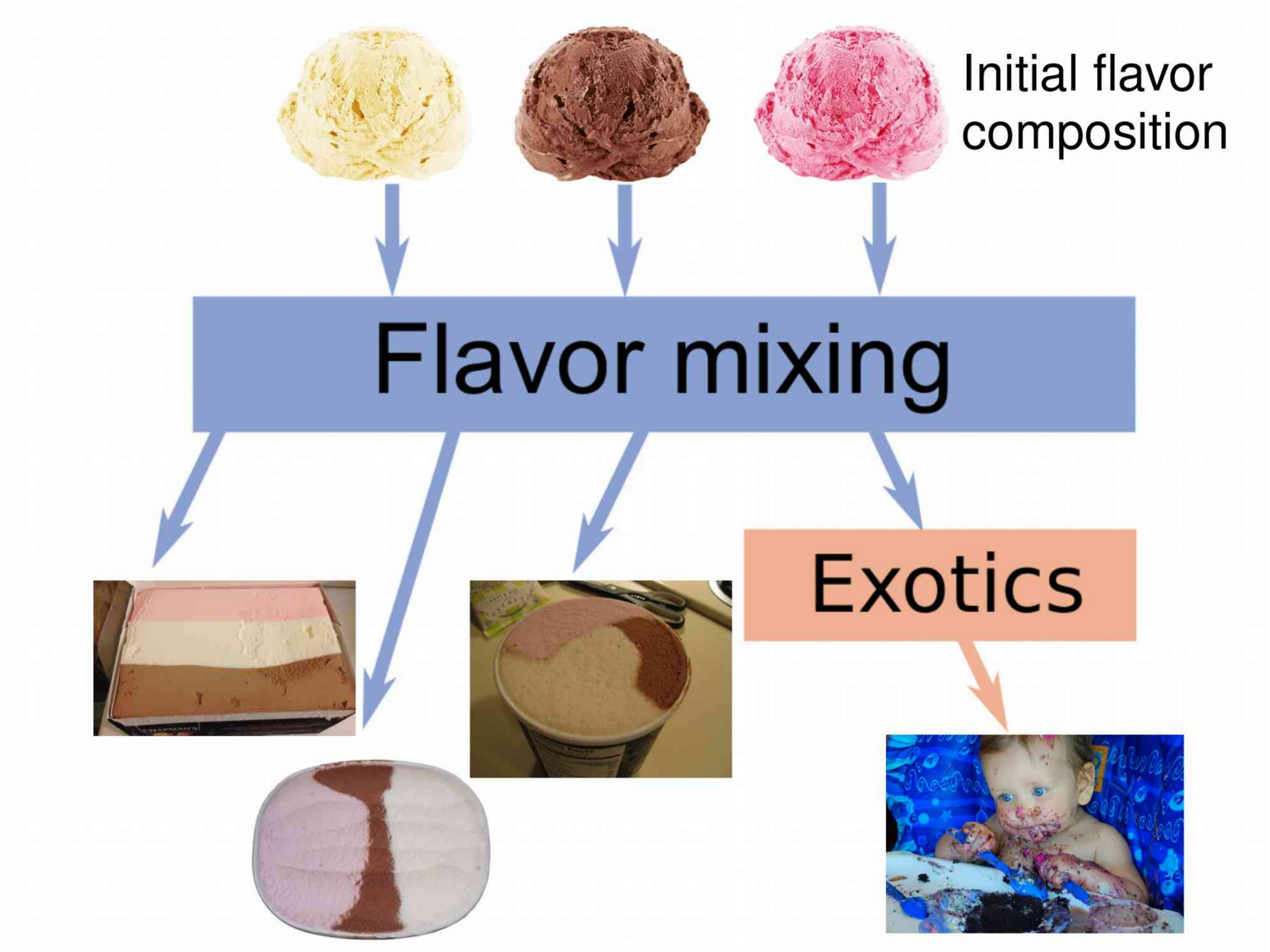
Best bounds come from IceCube





IceCube, *Nature Phys.* 2018

New physics in the flavor composition



Why are flavor ratios useful?

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

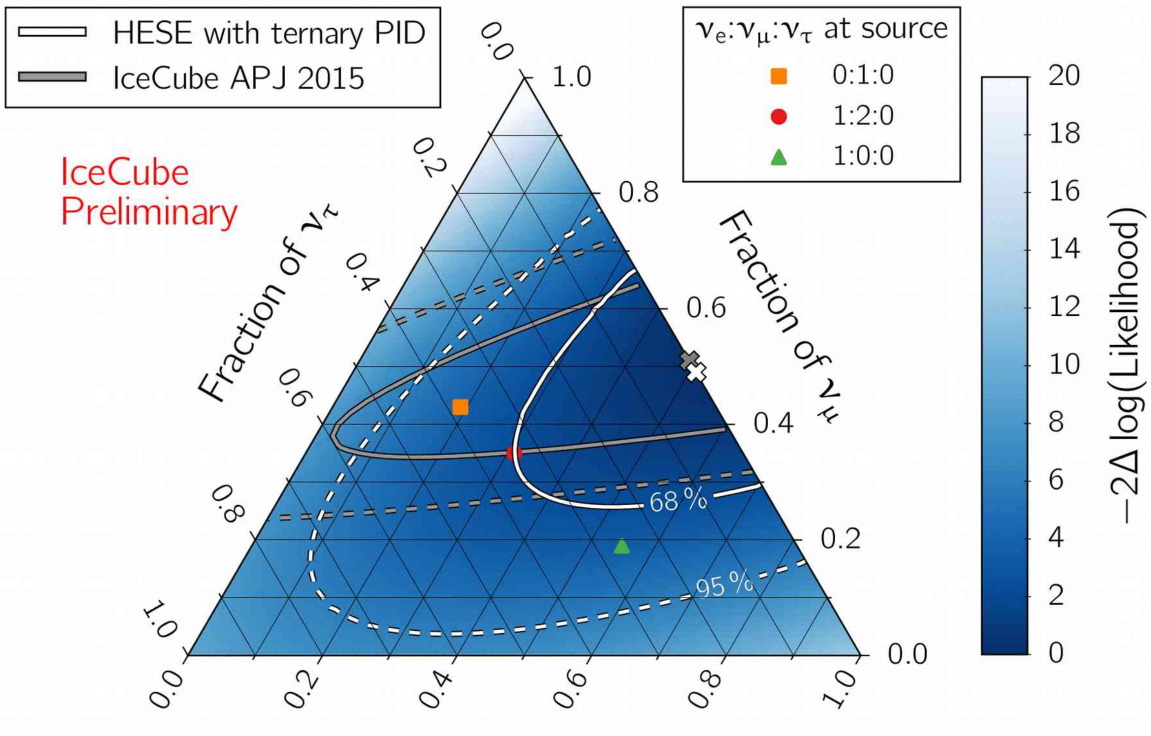
$$\alpha\text{-flavor ratio at Earth } (f_{\alpha,\oplus}) = \frac{\text{Flux at Earth of } \nu_\alpha \ (\alpha = e, \mu, \tau)}{\text{Sum of fluxes of all flavors}}$$

- Ratios remove systematic uncertainties common to all flavors

- Flavor ratios are useful in astrophysics and particle physics

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

IceCube flavor composition (pre-Neutrino 2018)



M. Usner, ICRC 2017

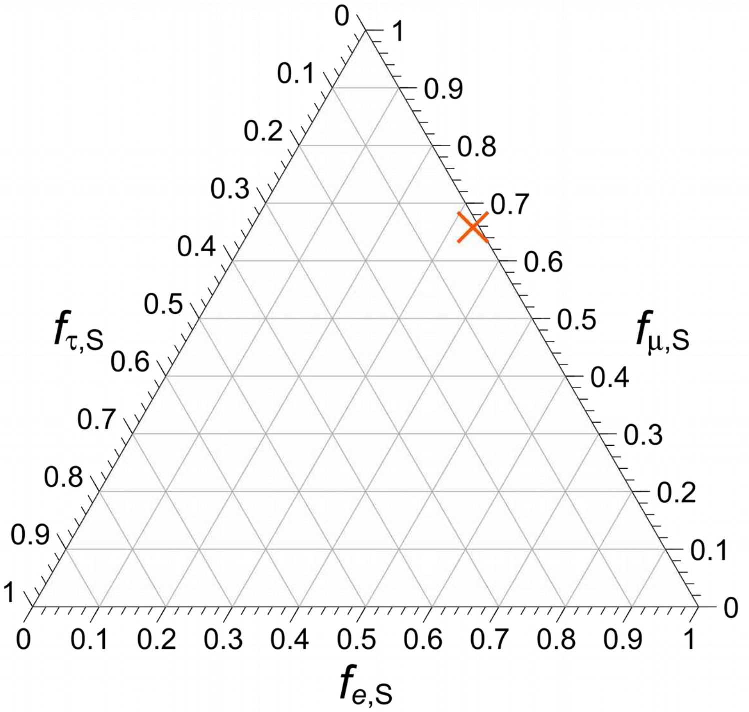
- Compare number of tracks (ν_μ) *vs.* showers (all flavors)
- Best fit: $(f_e : f_\mu : f_\tau)_\oplus = (0.49 : 0.51 : 0)_\oplus$
- Compatible with standard source compositions
- Lots of room for improvement: more statistics, better flavor-tagging

Li, **MB**, Beacom 2016

Flavor – there and here

At the sources

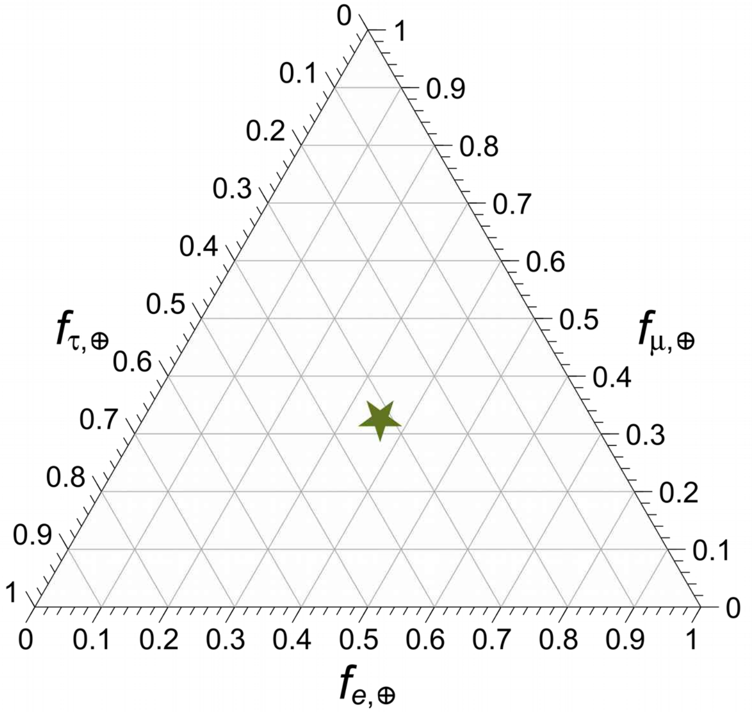
$(f_e{:}f_\mu{:}f_\tau)_S = (1/3 : 2/3 : 0)_S$



Neutrino oscillations

At Earth

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



Flavor – there and here

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

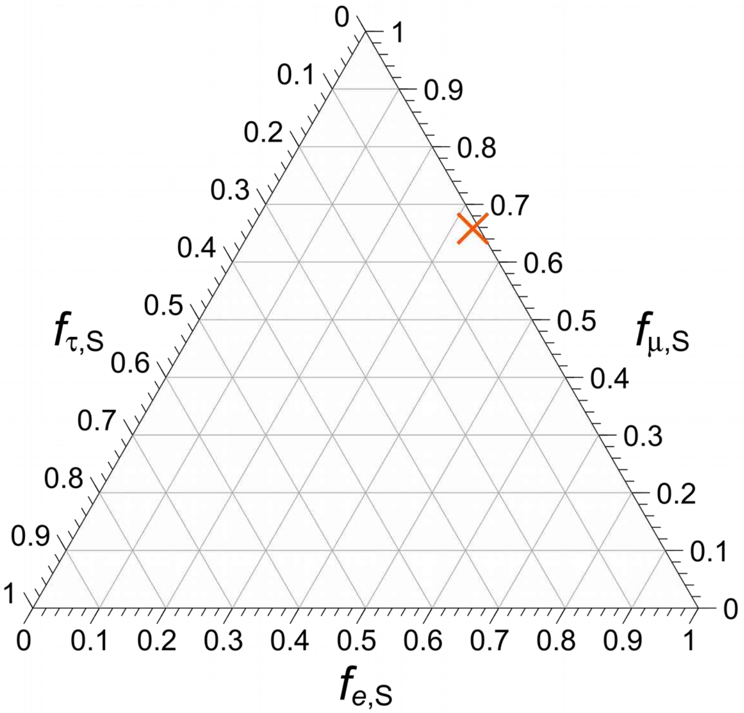
At the sources

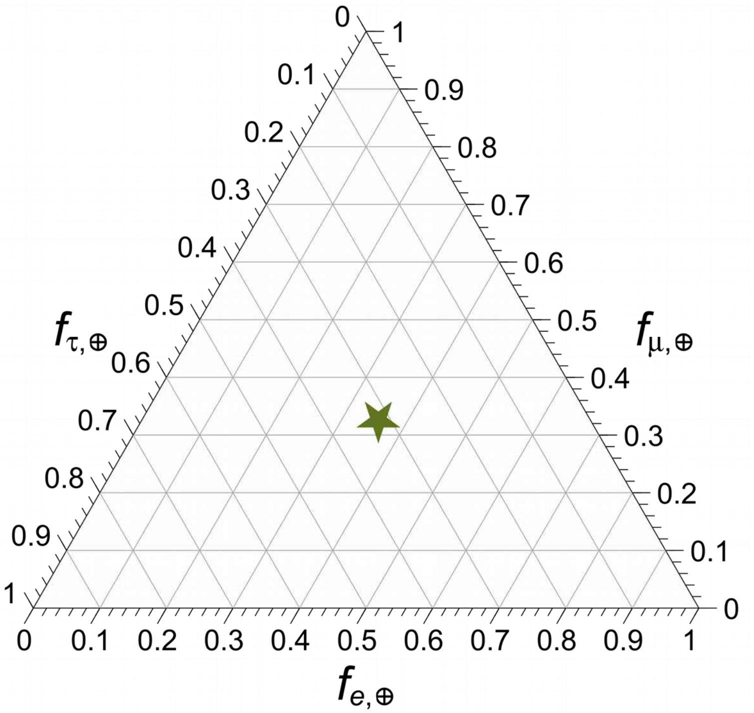
$$(f_e:f_\mu:f_\tau)_S = (1/3 : 2/3 : 0)_S$$

Neutrino oscillations

At Earth

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





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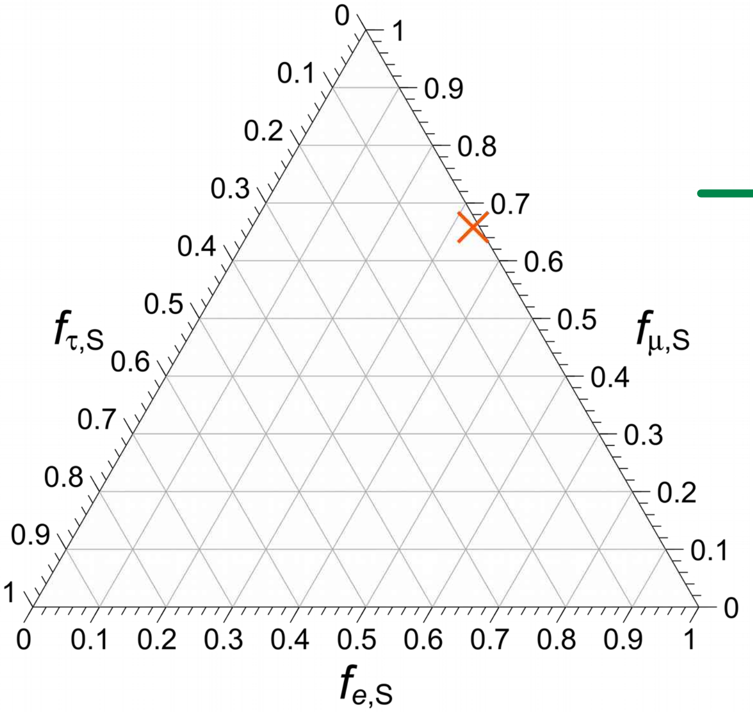
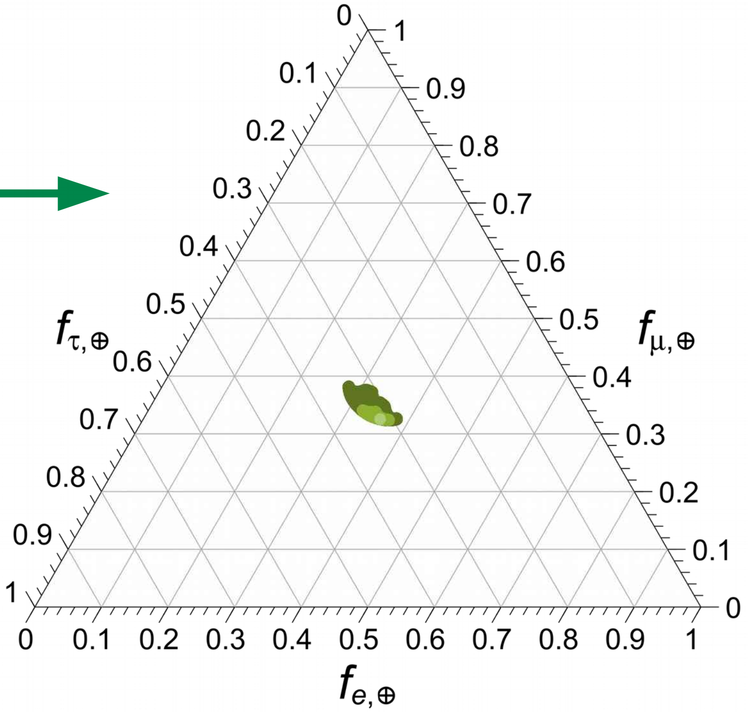


Uncertainties in values of mixing parameter (1σ, 3σ)

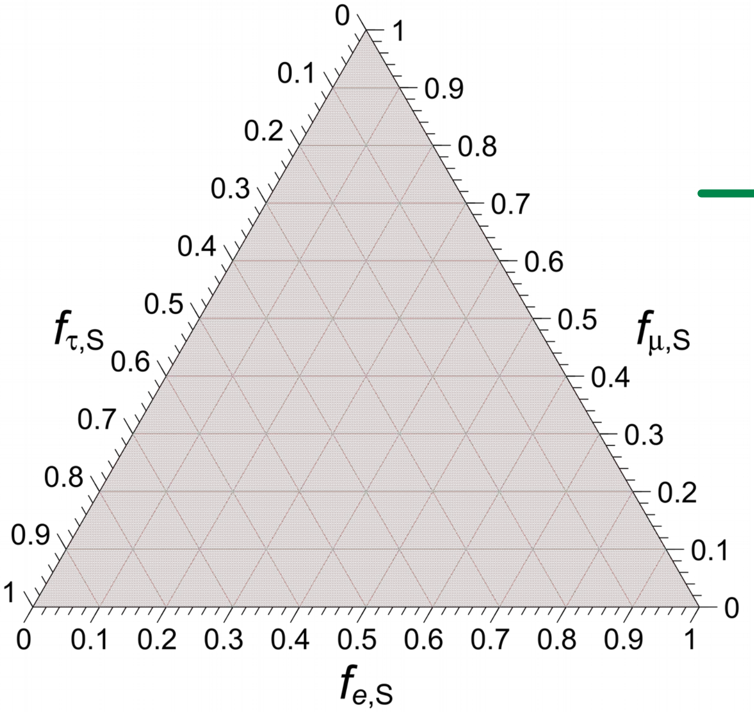


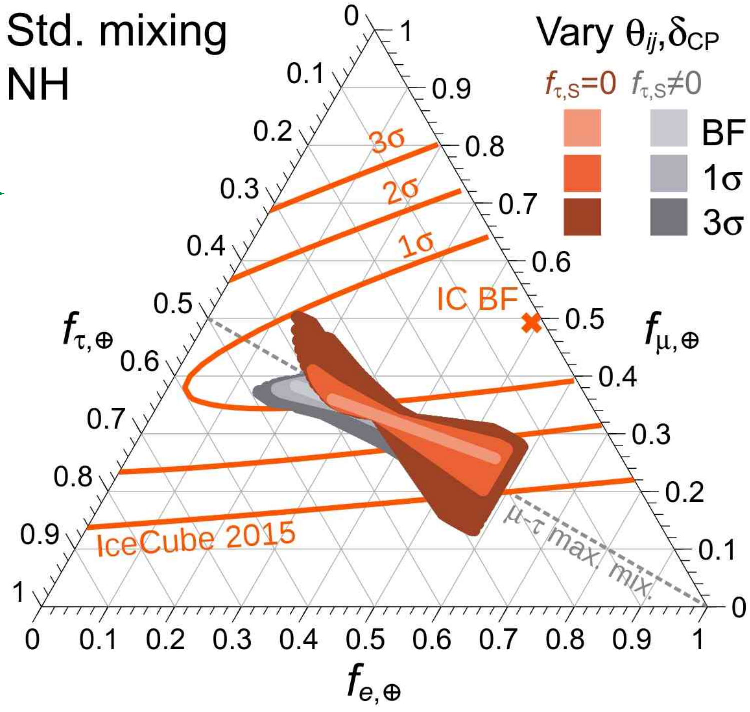
Flavor composition – Standard allowed region

At the sources

At Earth

All possible flavor ratios





MB, Beacom, Winter *PRL* 2015

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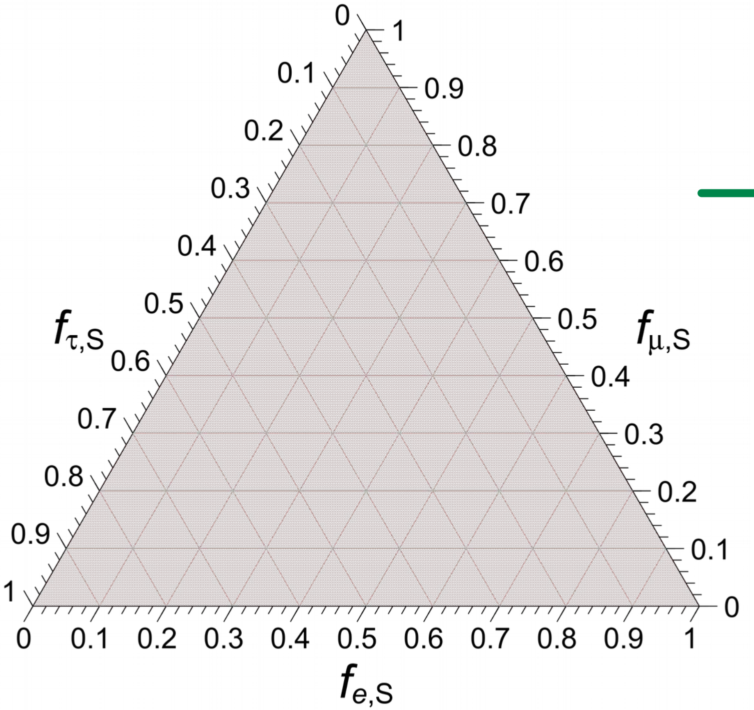
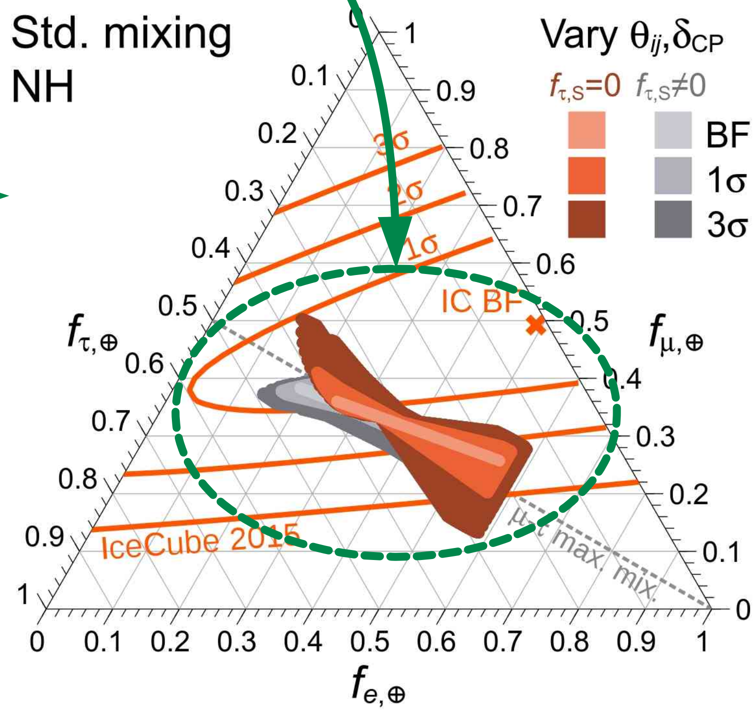


Only 10% of parameter space

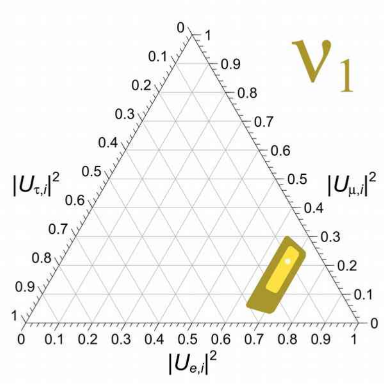
At Earth

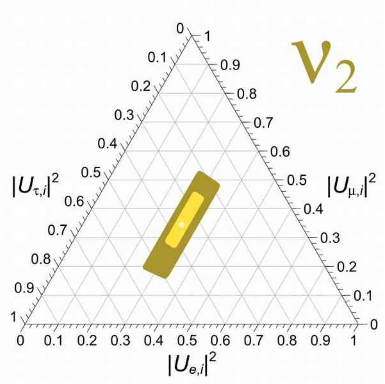


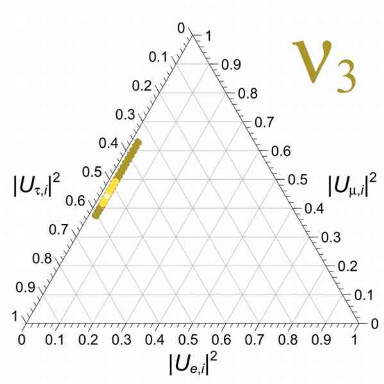
MB, Beacom, Winter *PRL* 2015

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

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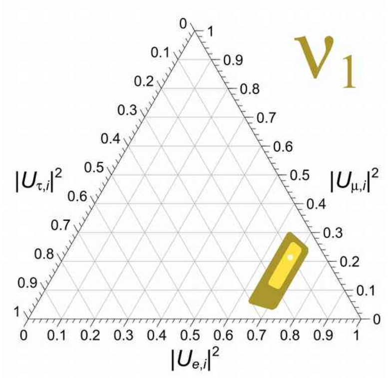
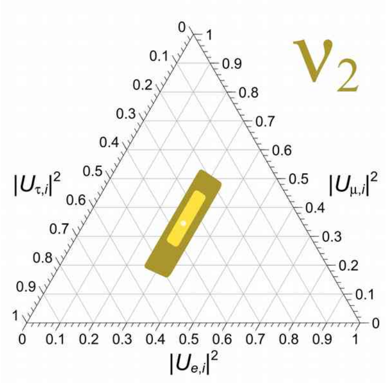
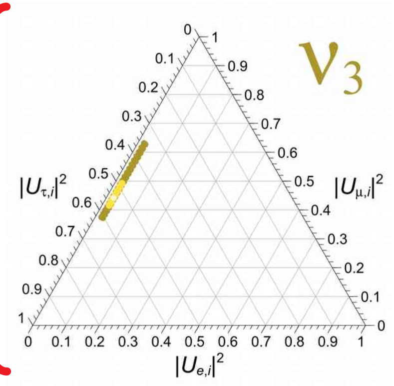
w_1 [

] + w_2 [

] + w_3 [

]

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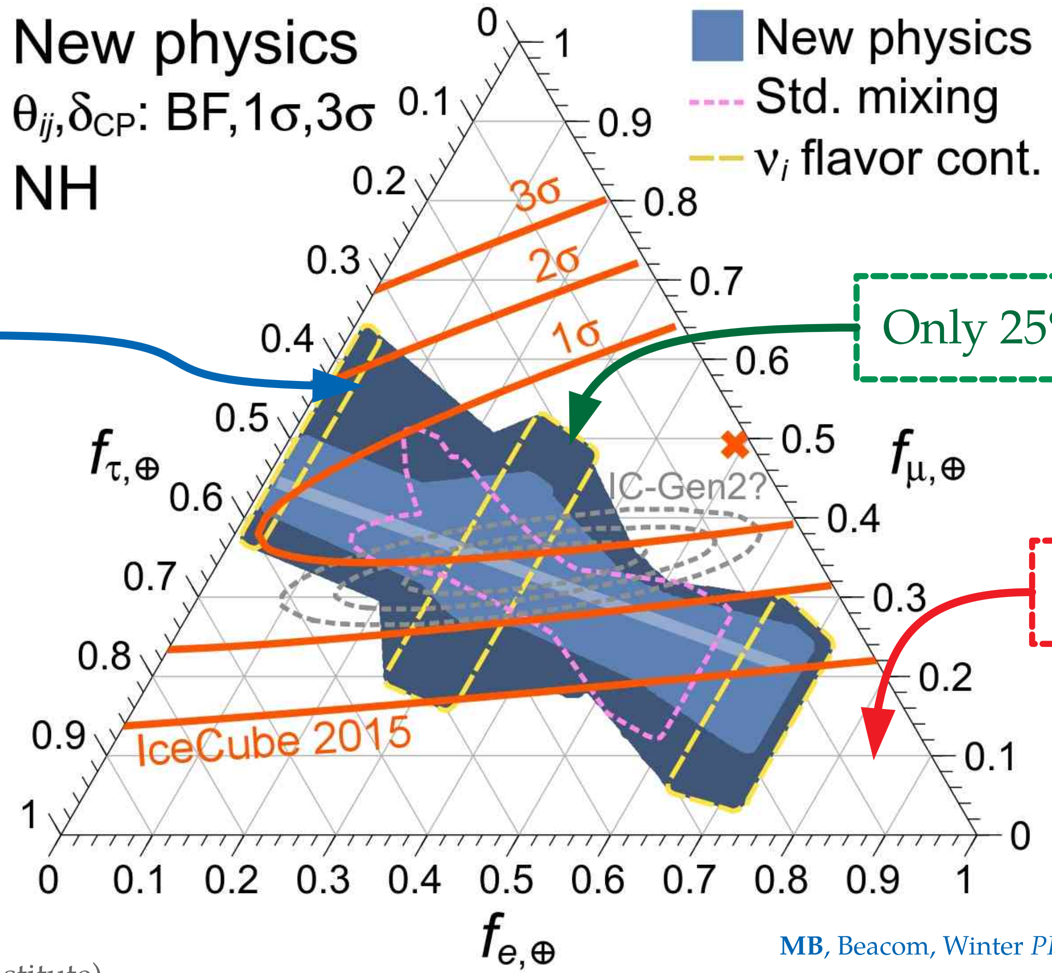
Flavor ratios accessible with decay-like physics

Region of all linear combinations of ν_1, ν_2, ν_3



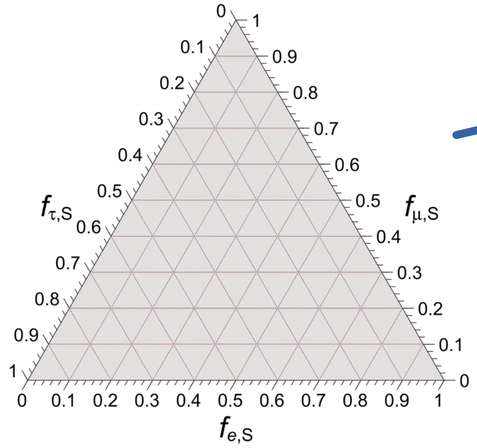
Only 25% of parameter space

What lies outside?

MB, Beacom, Winter *PRL* 2015

Measuring the neutrino lifetime

Sources

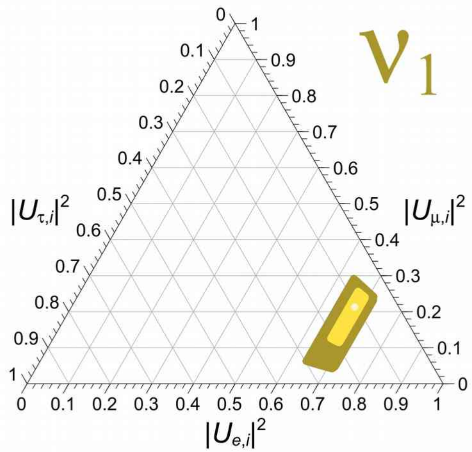


$$\underbrace{\nu_2, \nu_3 \to \nu_1}_{\nu_1 \text{ lightest and stable}}$$

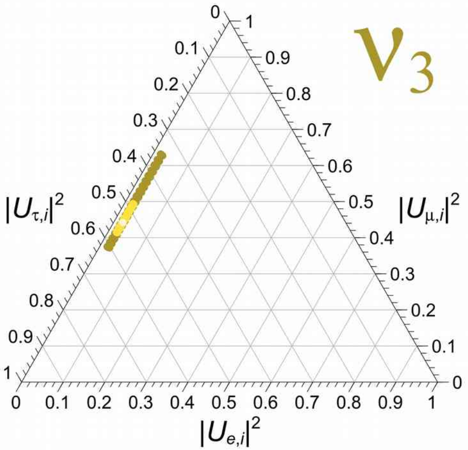
If all unstable neutrinos decay

$$\underbrace{\nu_1, \nu_2 \to \nu_3}_{\nu_3 \text{ lightest and stable}}$$

Earth



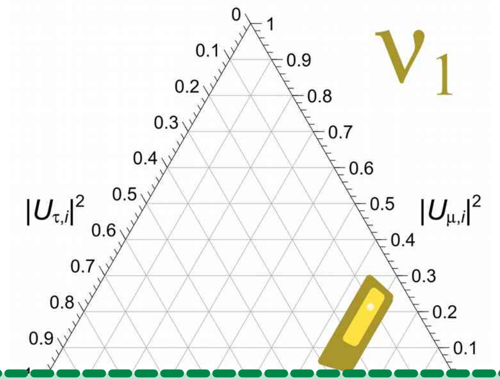
$$f_{\alpha,\oplus} = |U_{\alpha 1}|^2$$



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

Measuring the neutrino lifetime

Earth



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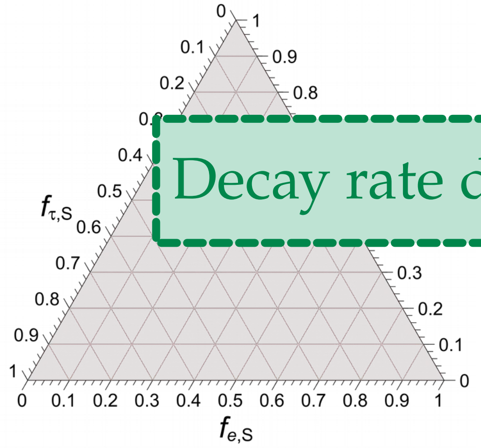
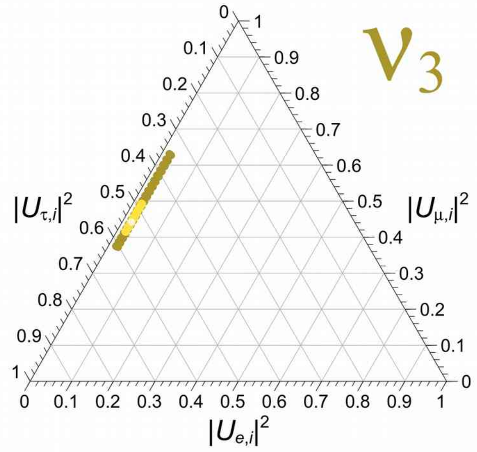
Sources



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

neutrinos decay



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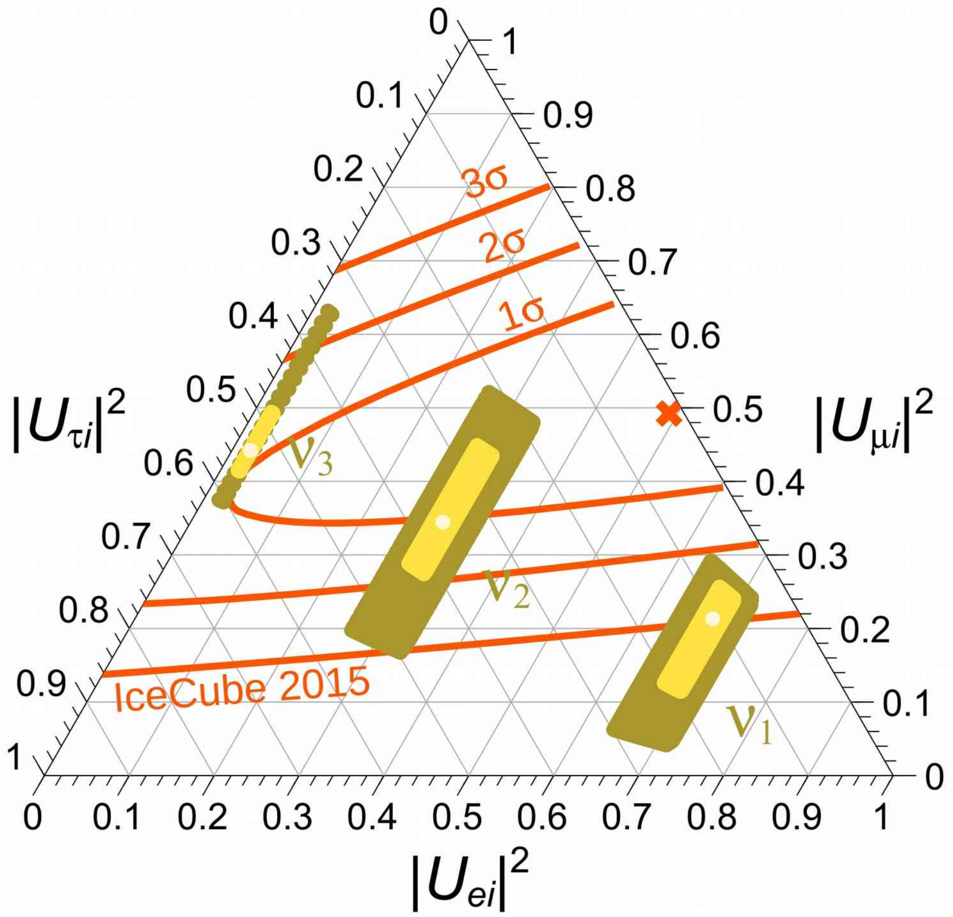
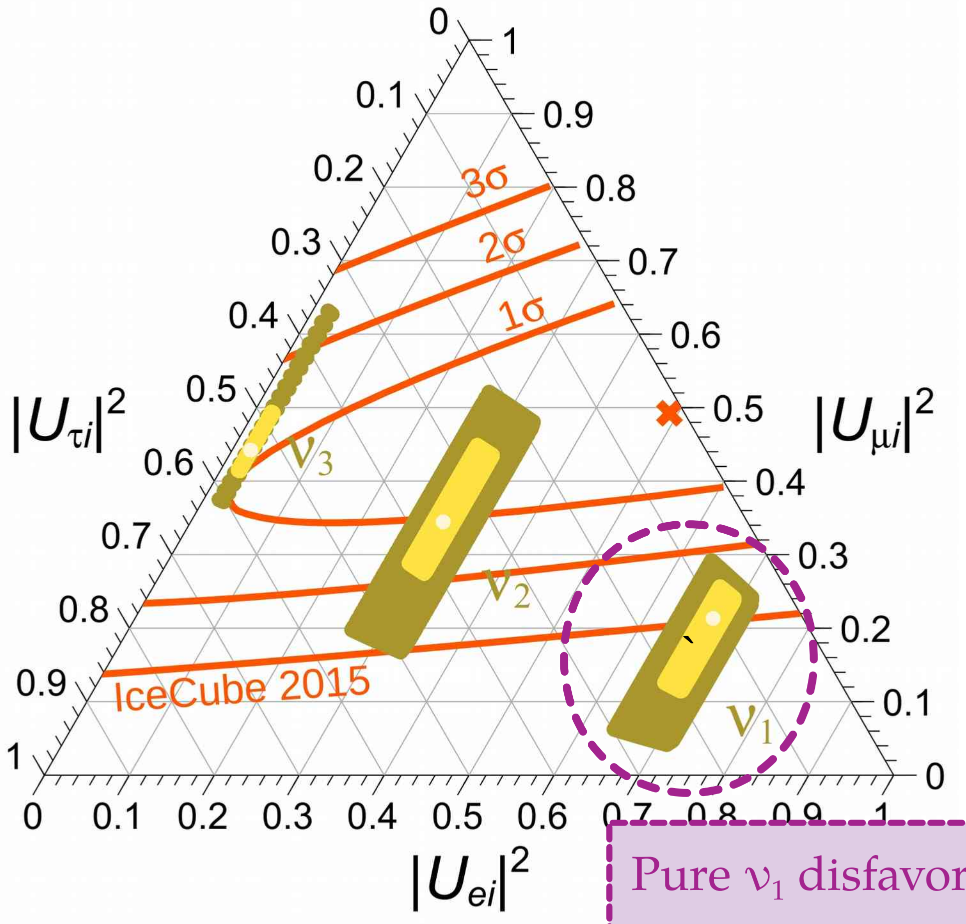


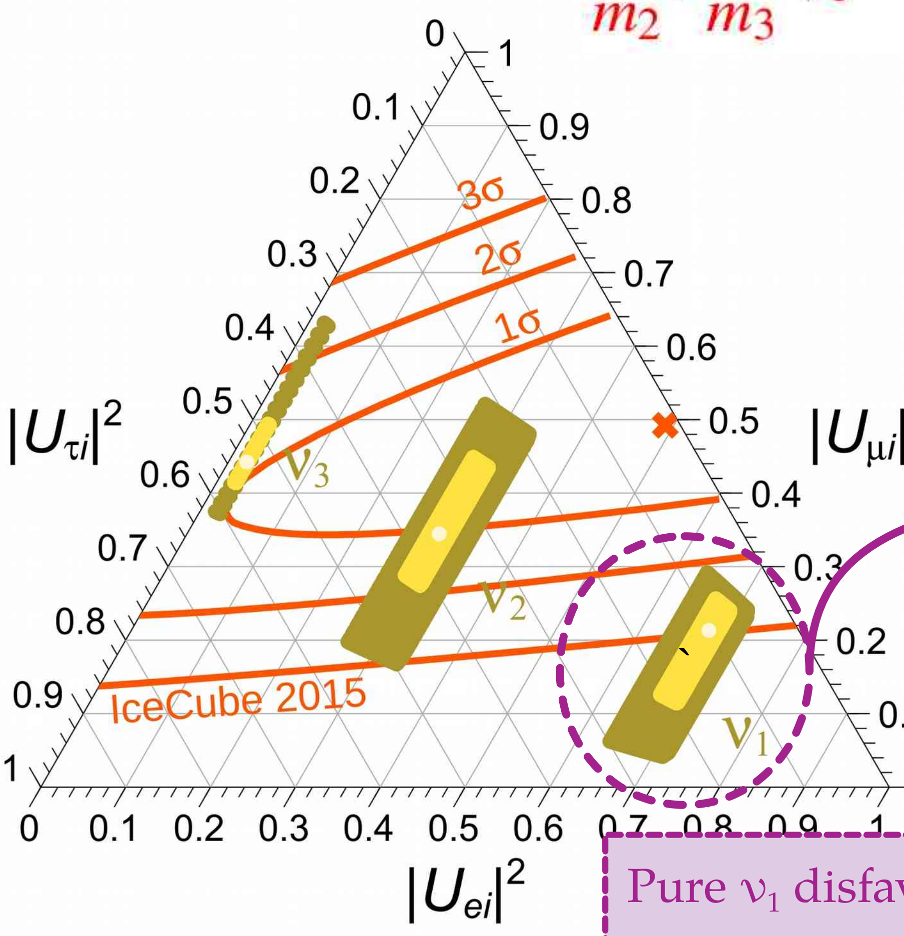
MB, Beacom, Murase, *PRD* 2017



Pure ν_1 disfavored at > 2σ

MB, Beacom, Murase, *PRD* 2017

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



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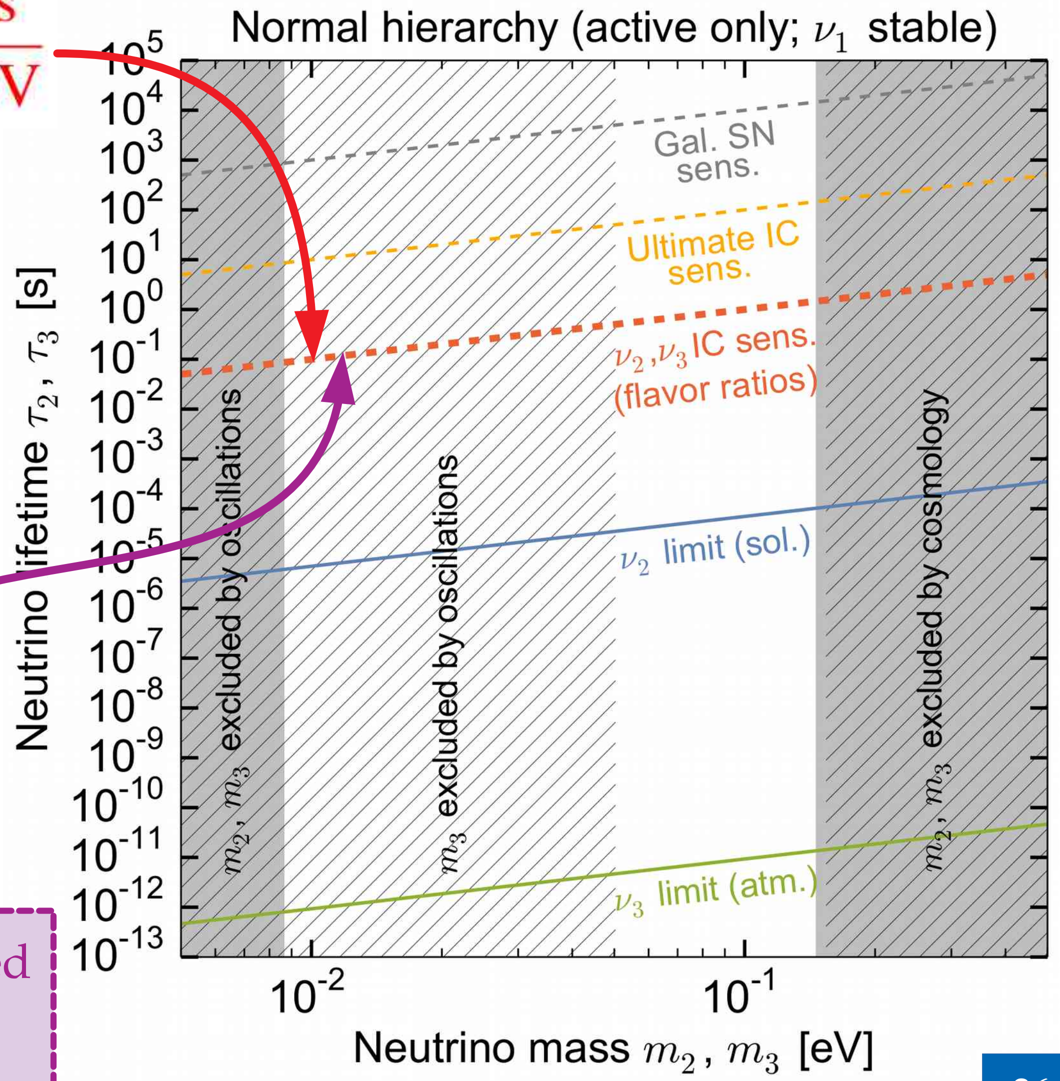

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What lies beyond? *Take your pick*

- 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
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  - Coupling to a gravitational torsion field
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  - Renormalization-group-running of mixing parameters
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- Active-sterile mixing
  [Aeikens *et al.*, *JCAP* 2015; V. Brdar, *JCAP* 2017]

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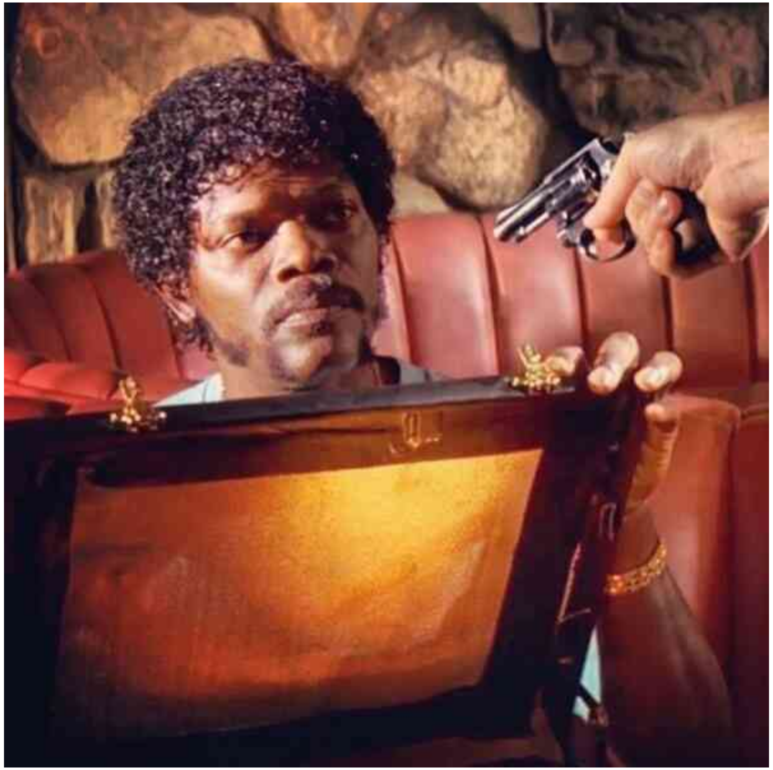


New physics – High-energy effects

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

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

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

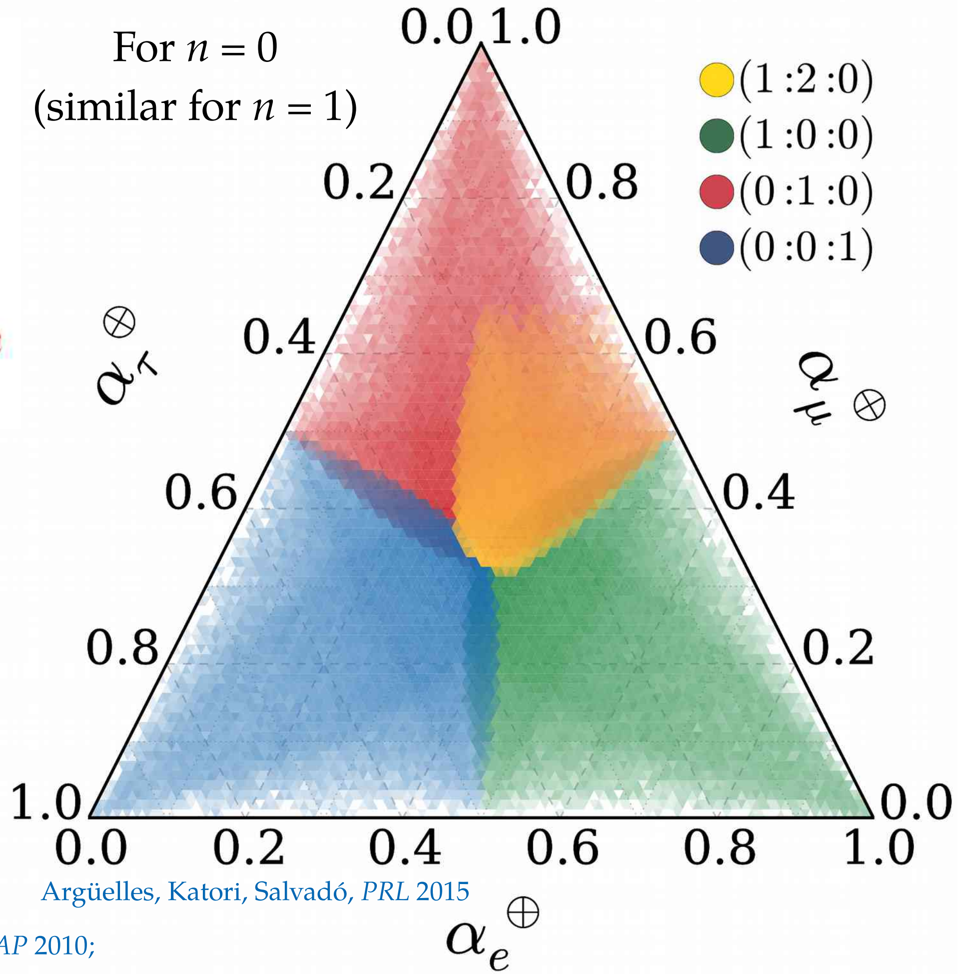
This can populate *all* of the triangle –

- Use current atmospheric bounds on $O_{n,i}$:

  $O_0 < 10^{-23}$ GeV, $O_1/\Lambda_1 < 10^{-27}$ GeV

- Sample the unknown new mixing angles

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



Argüelles, Katori, Salvadó, *PRL* 2015

See also: Rasmusen *et al.*, *PRD* 2017; **MB**, Beacom, Winter *PRL* 2015; **MB**, Gago, Peña-Garay *JCAP* 2010;
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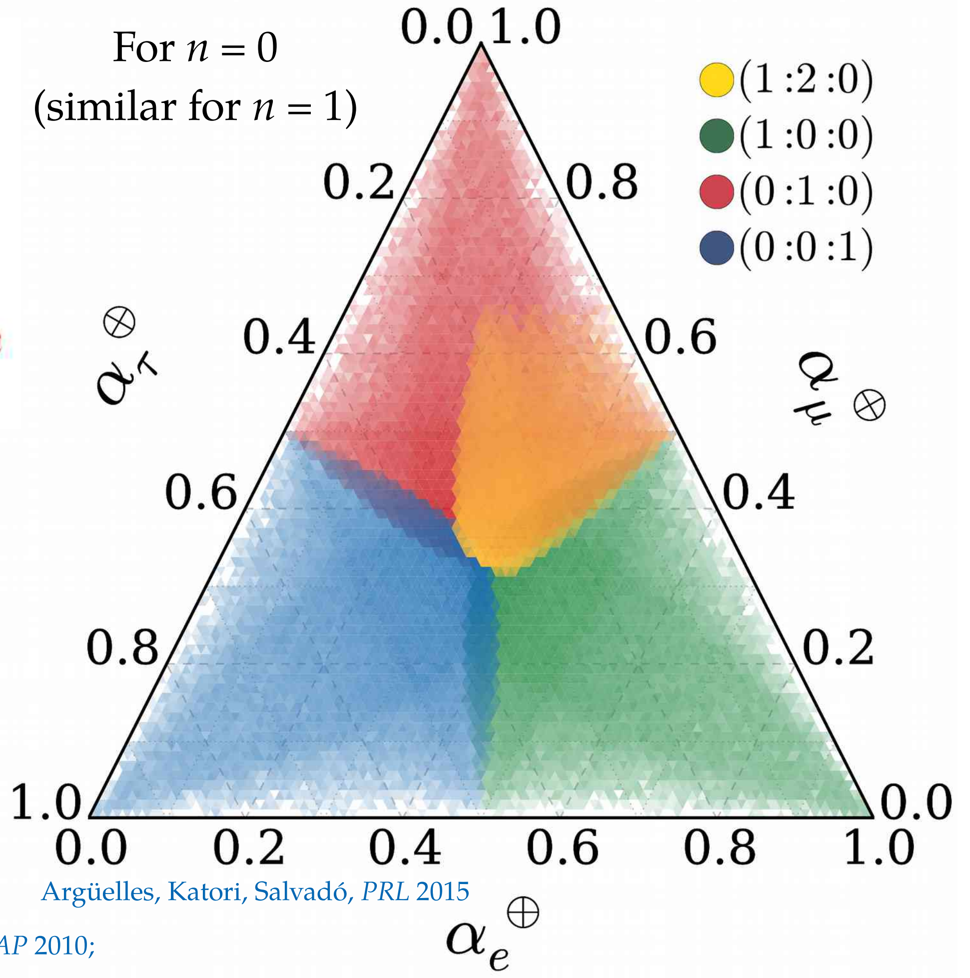

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Ultra-long-range flavorful interactions

- 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

Electrons in the local and distant Universe

Potential:

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

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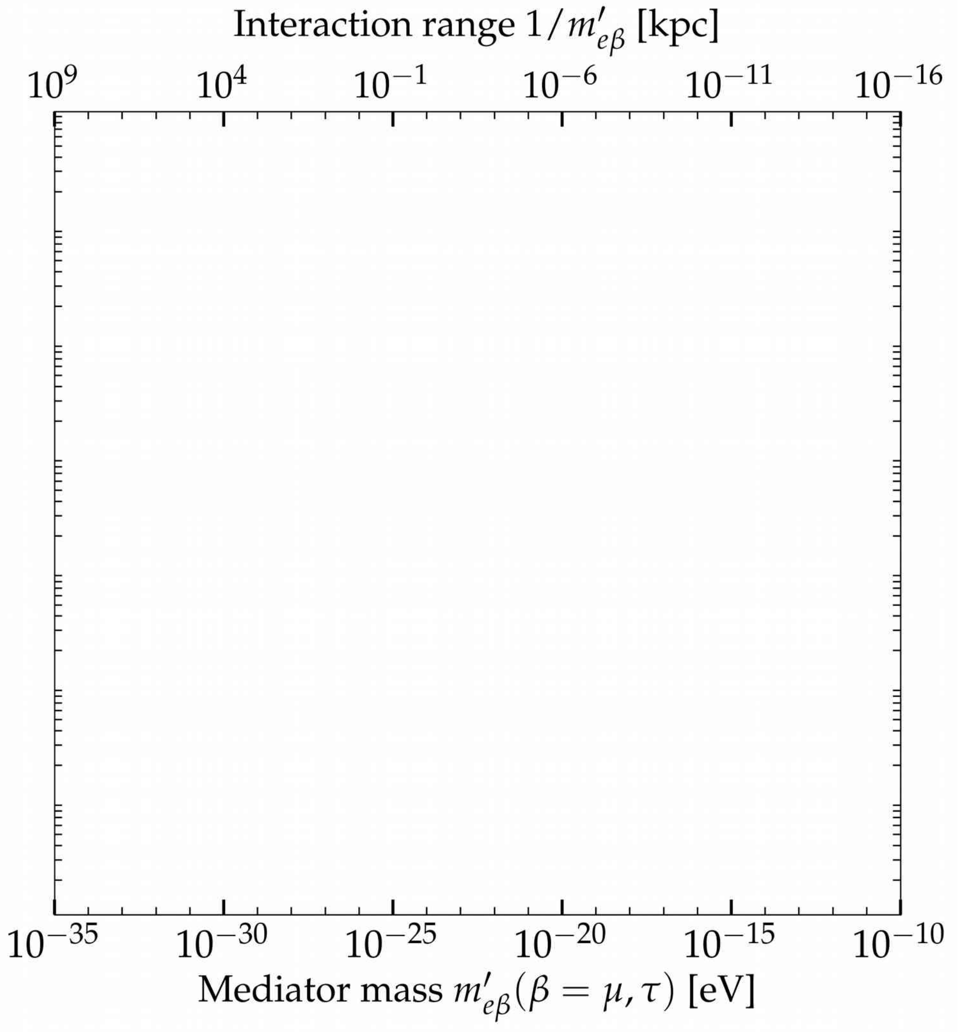
Electrons in the local and distant Universe



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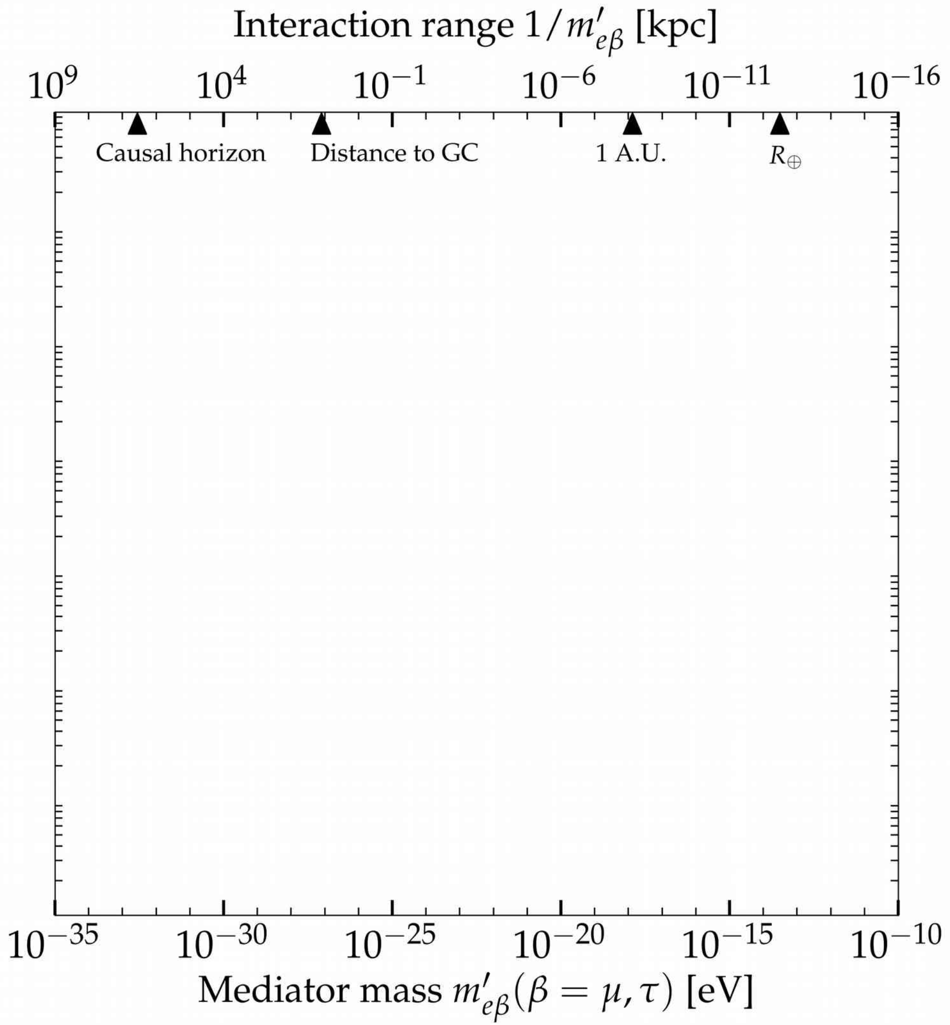

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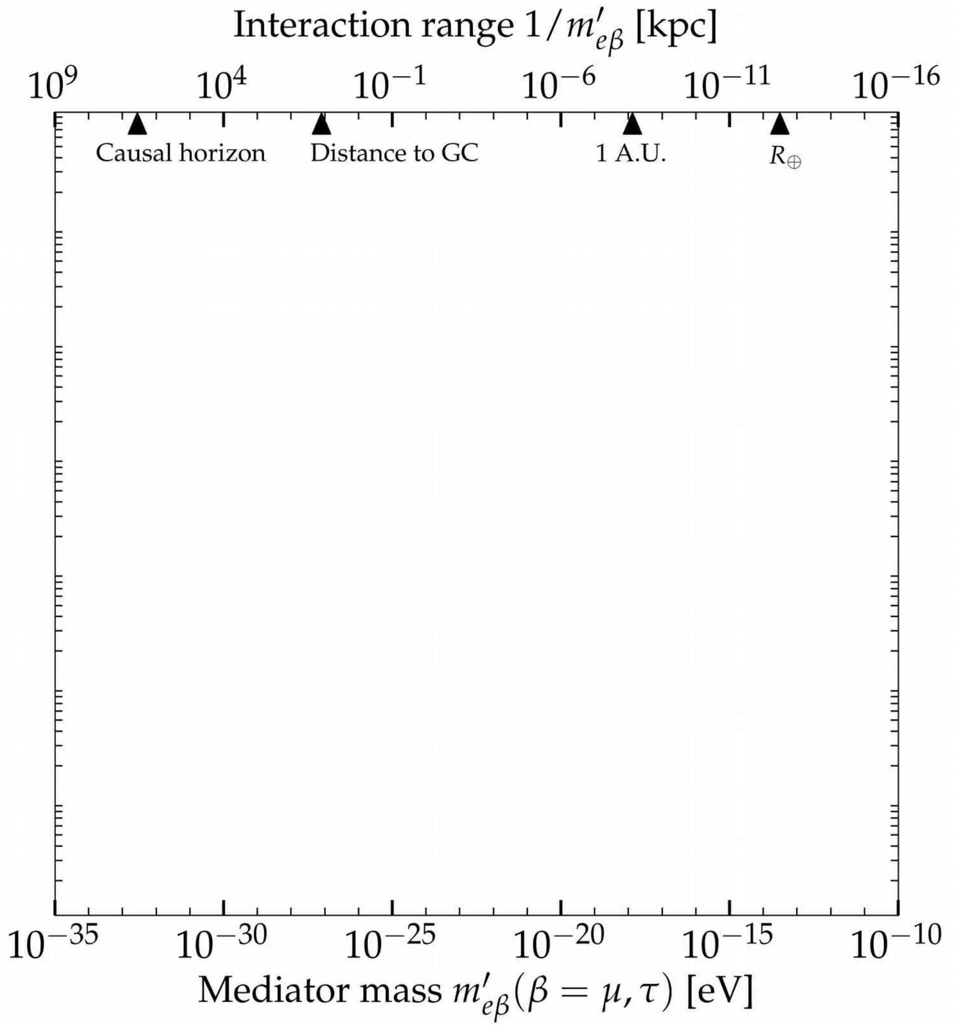

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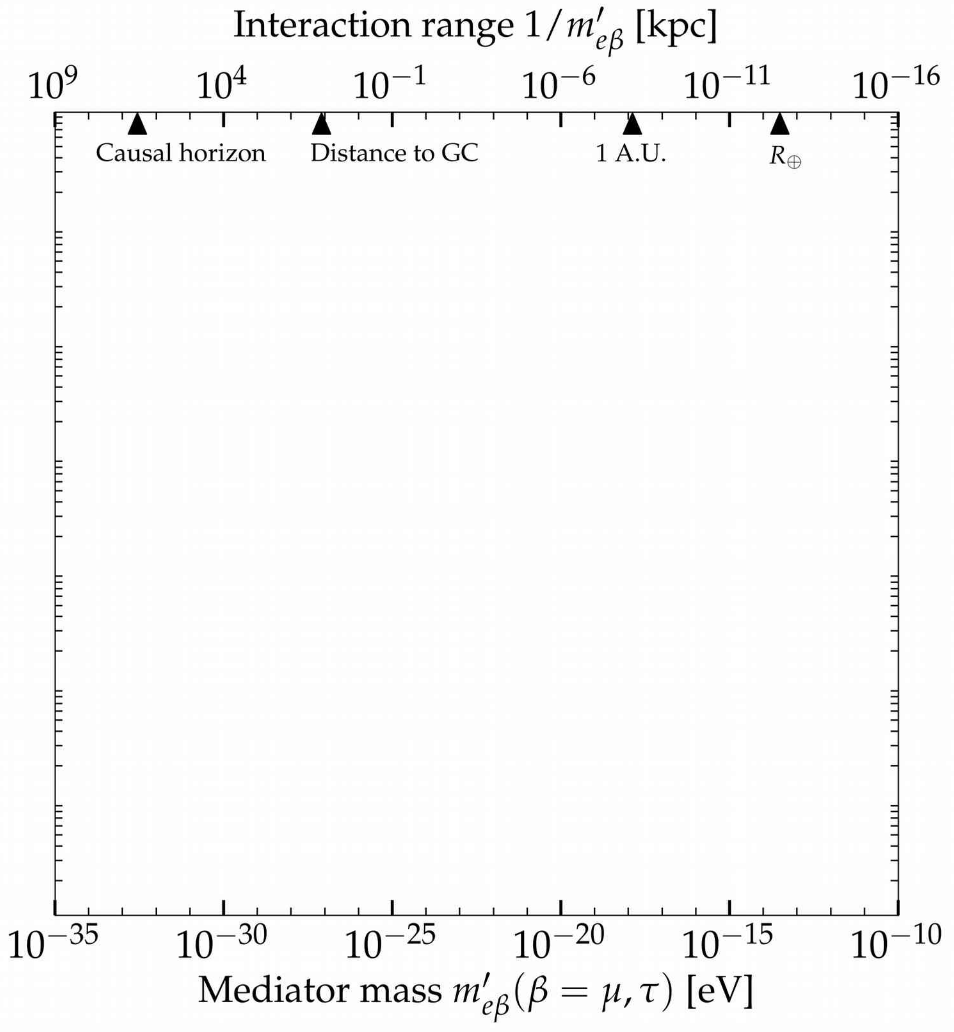
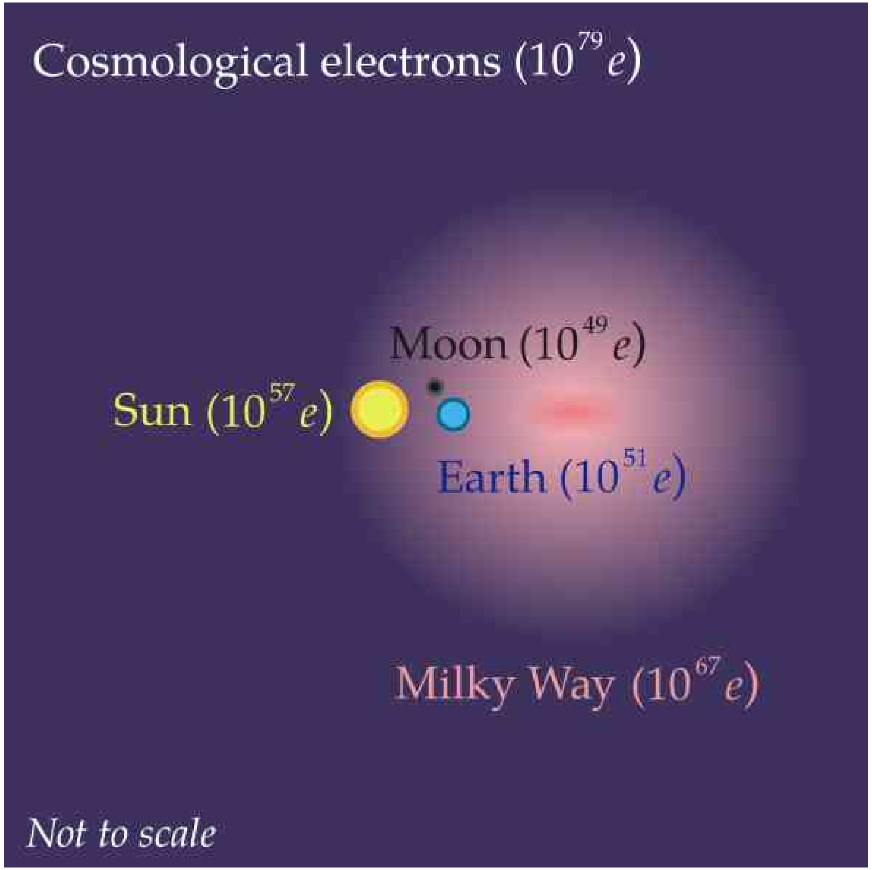
$$V_{e\beta} \propto \frac{1}{r} e^{-m'_{e\beta} r}$$

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

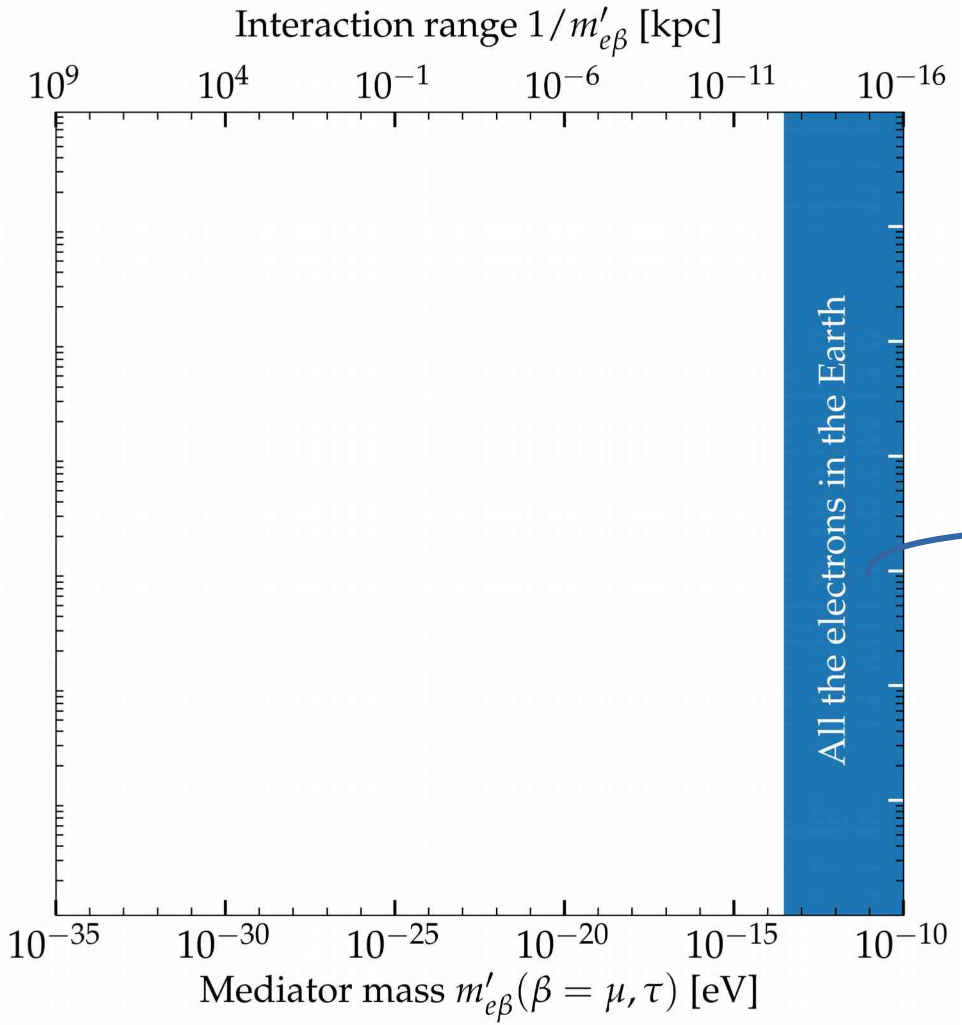
Light mediators
$\Rightarrow$ Long interaction ranges

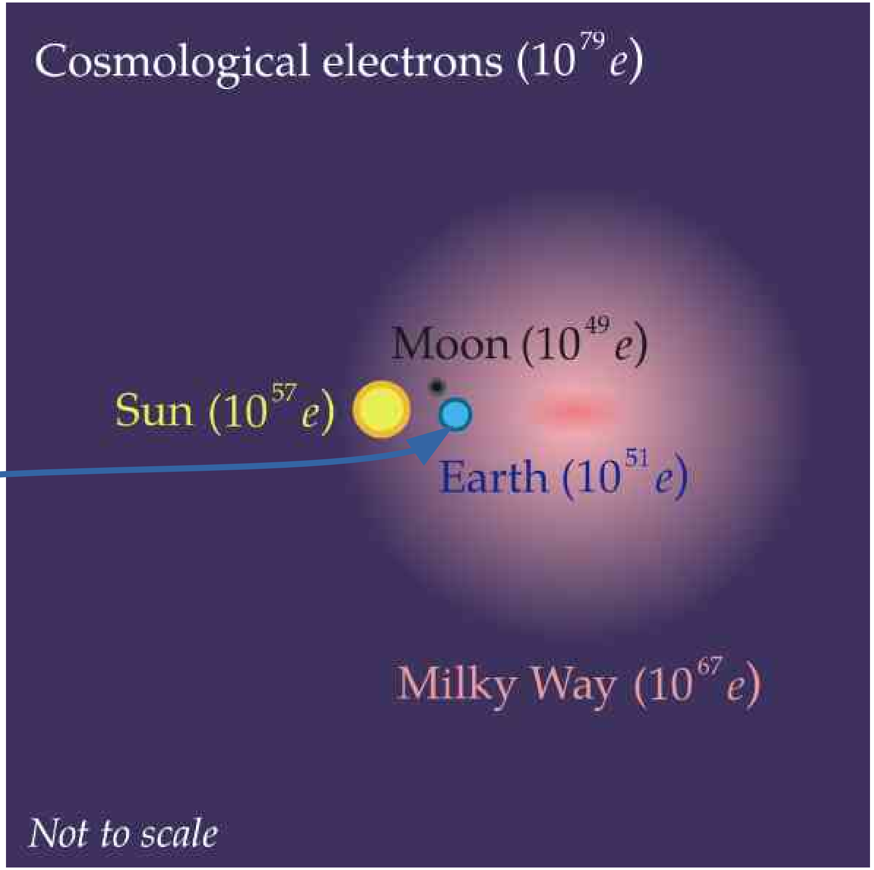
Electrons in the local and distant Universe





Electrons in the local and distant Universe





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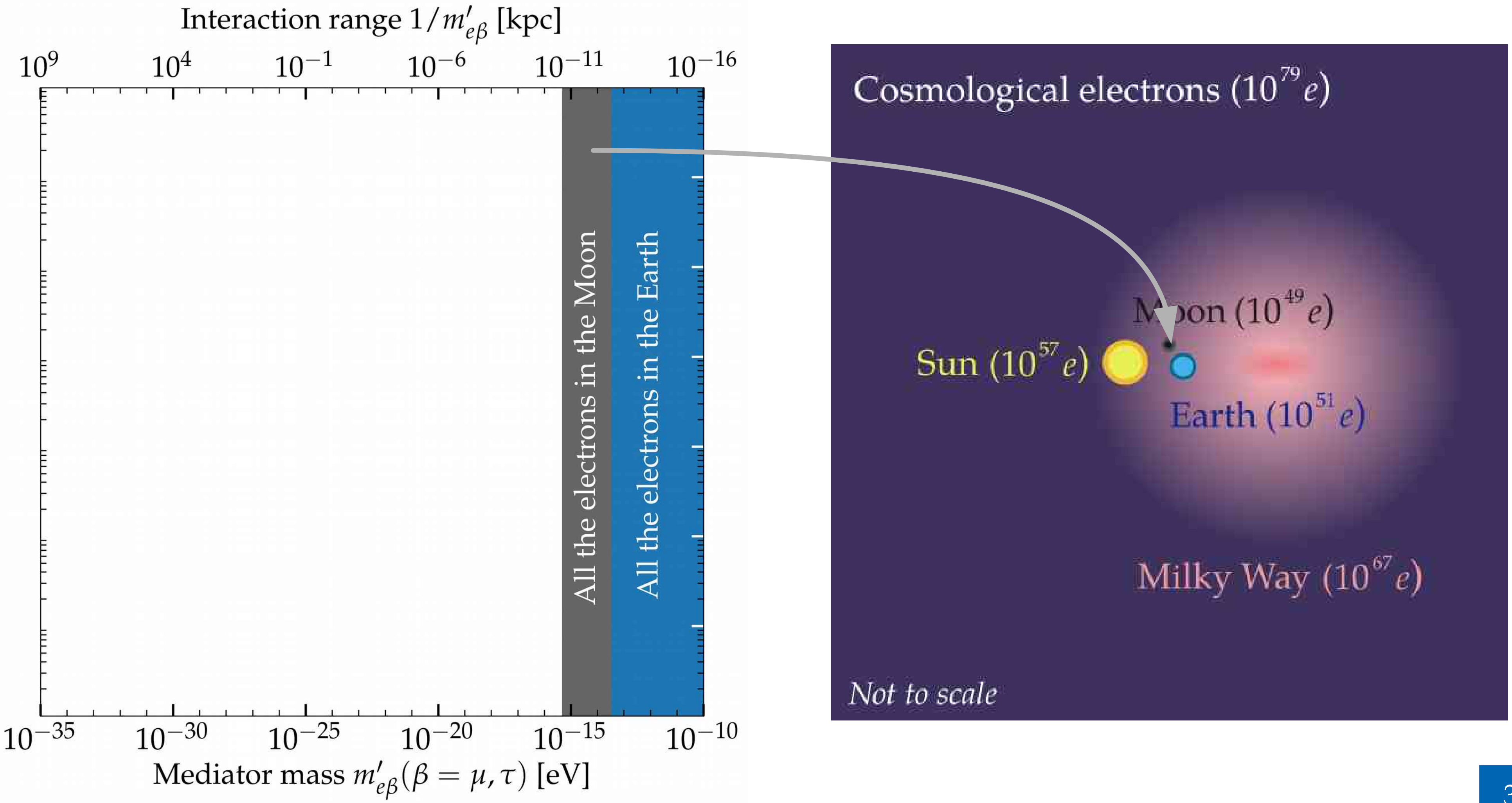

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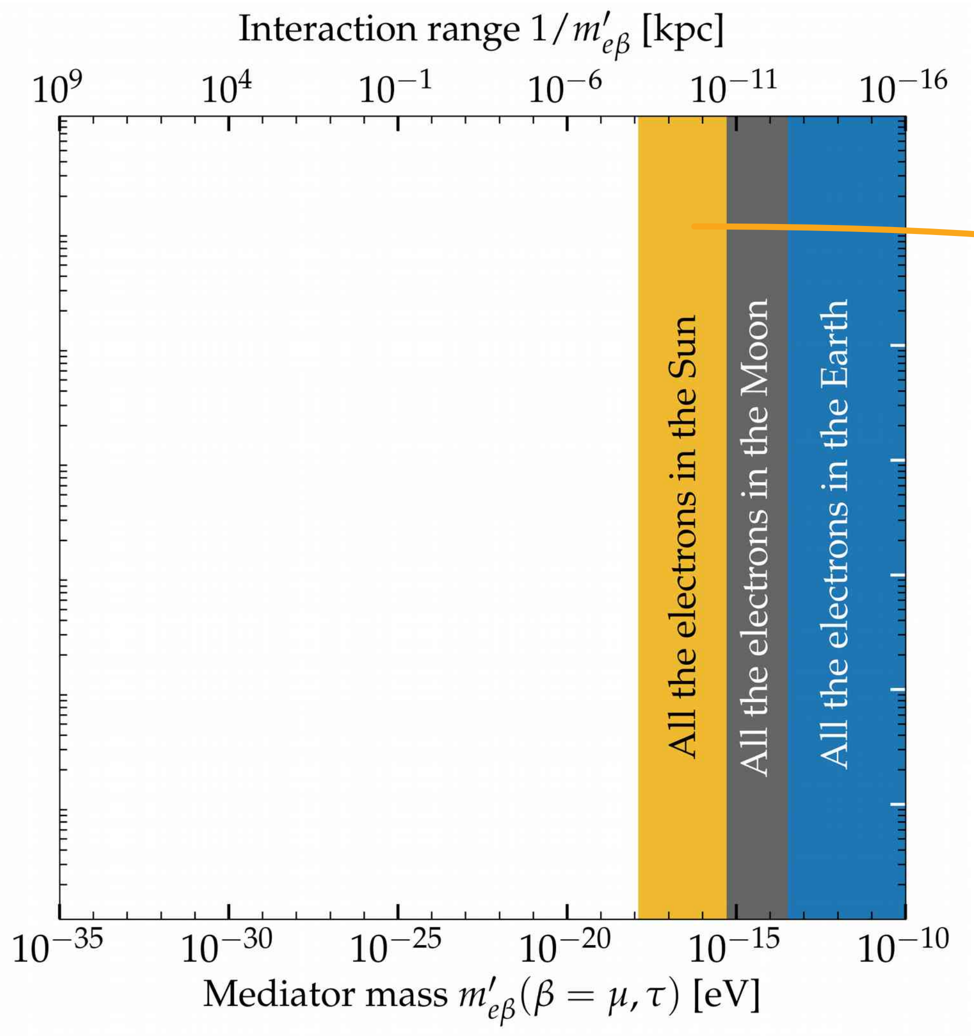

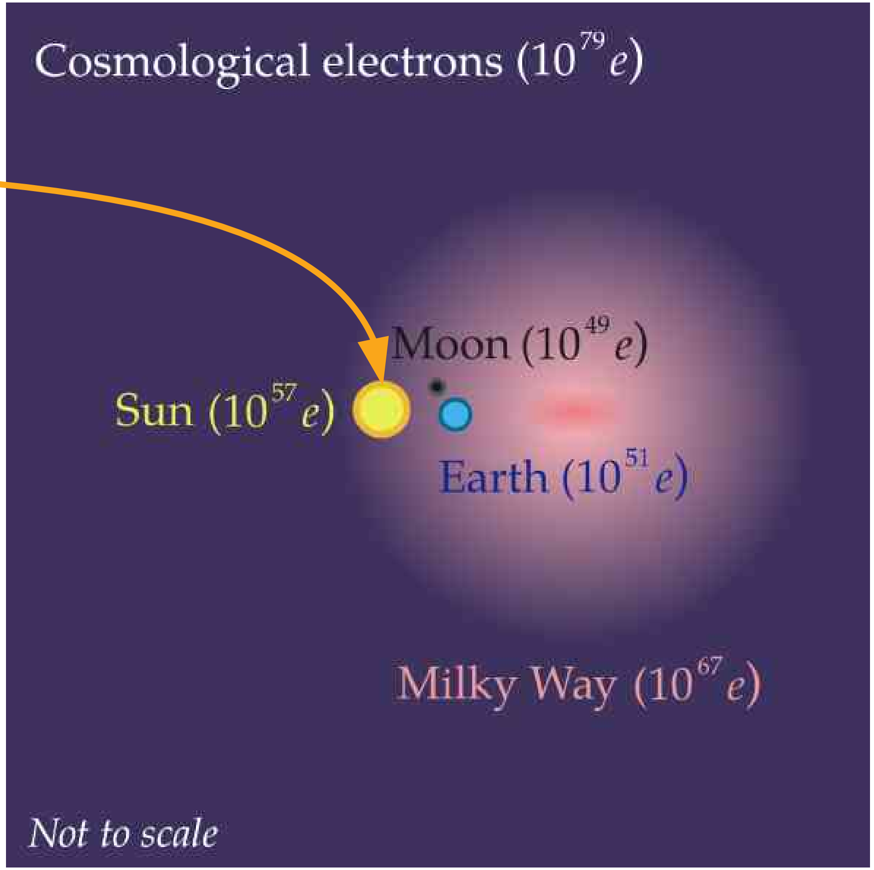

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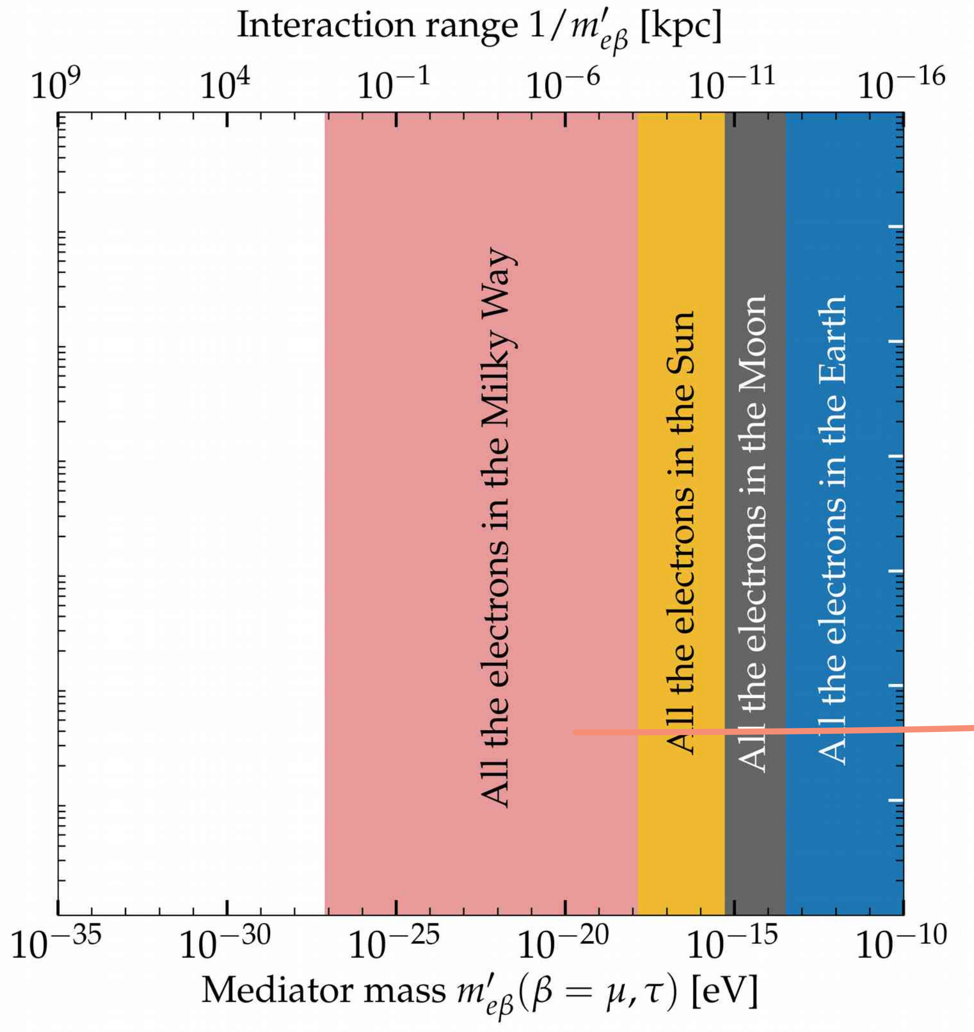

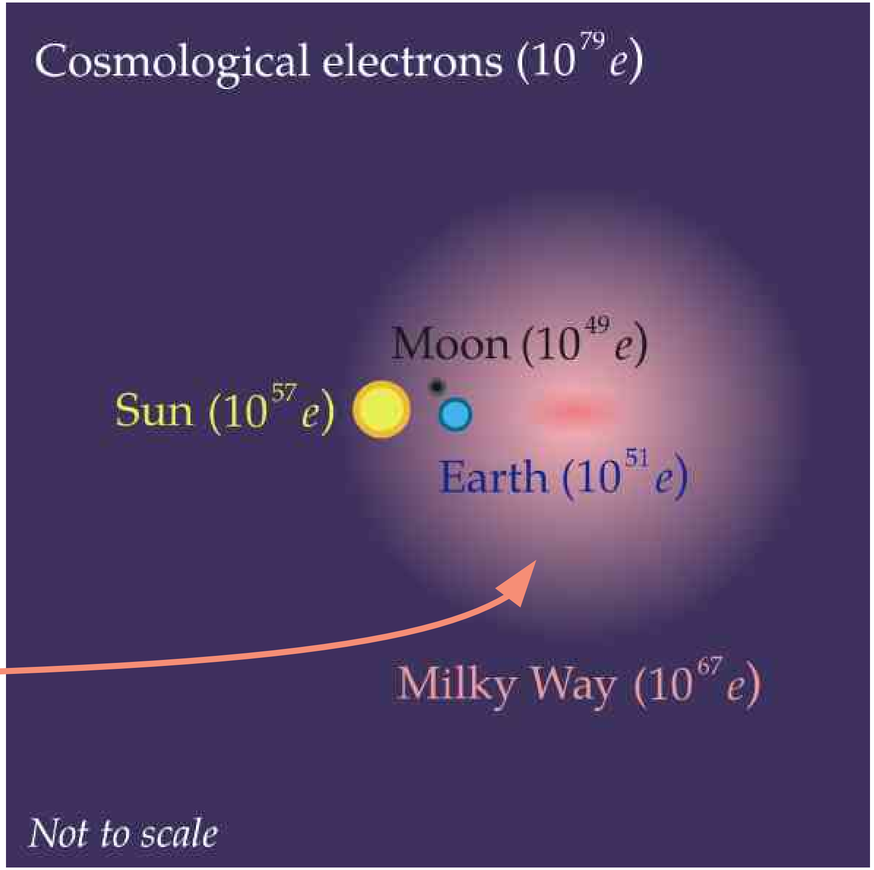

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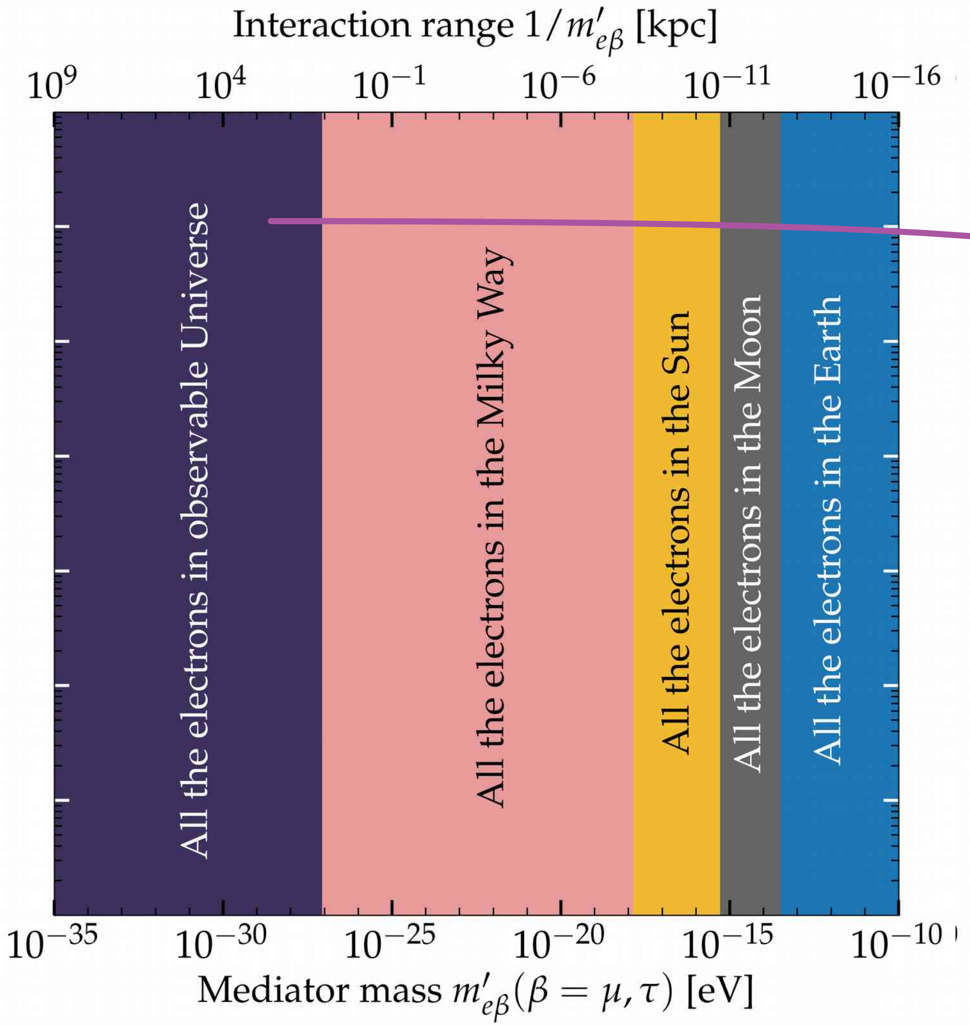
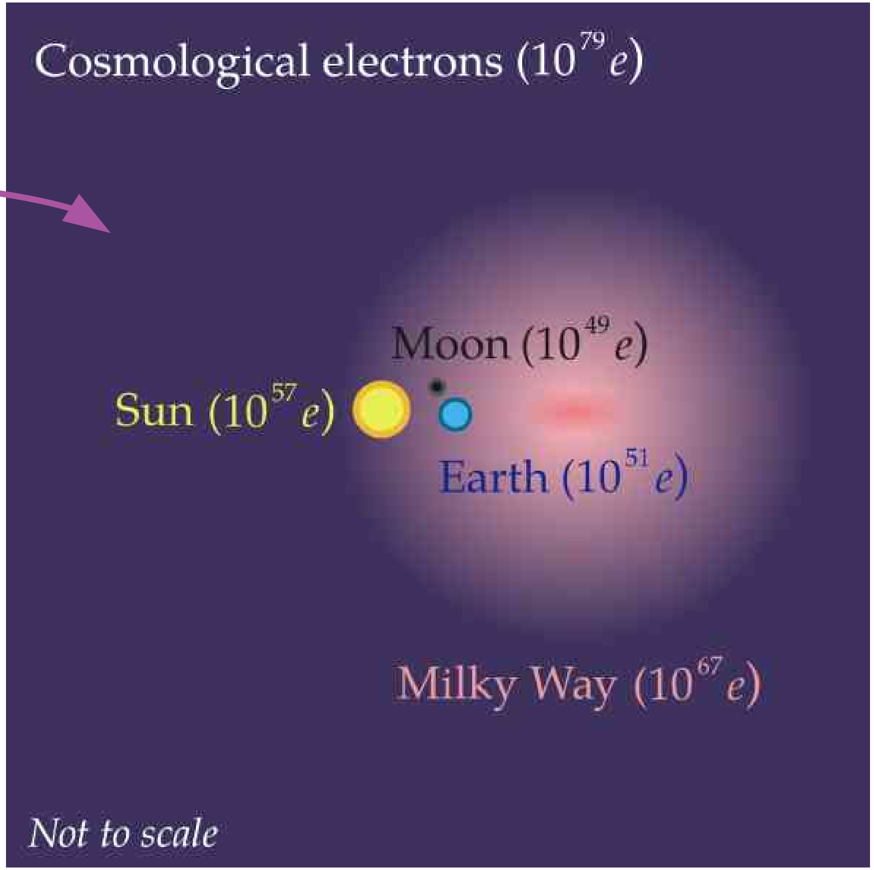
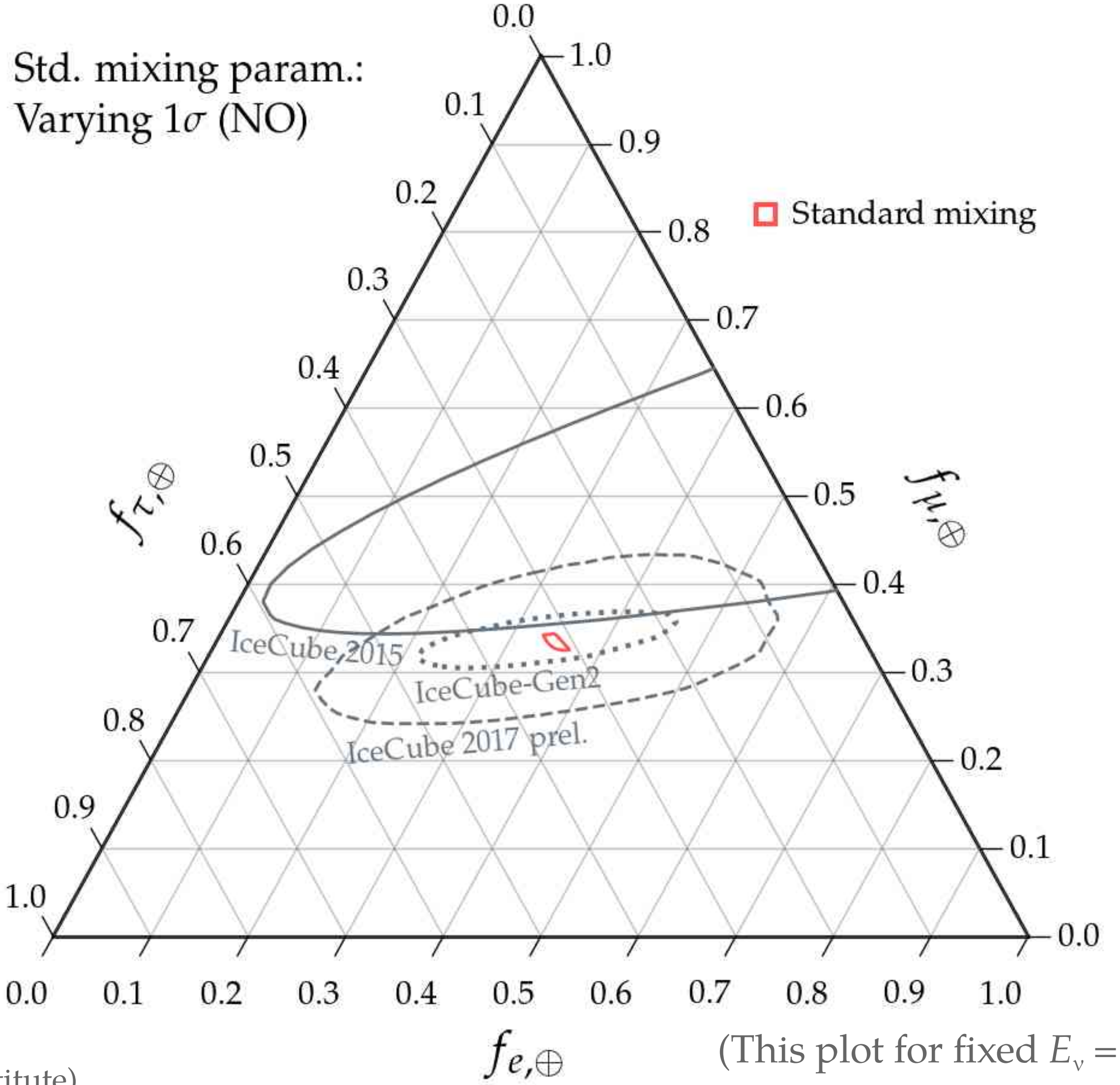
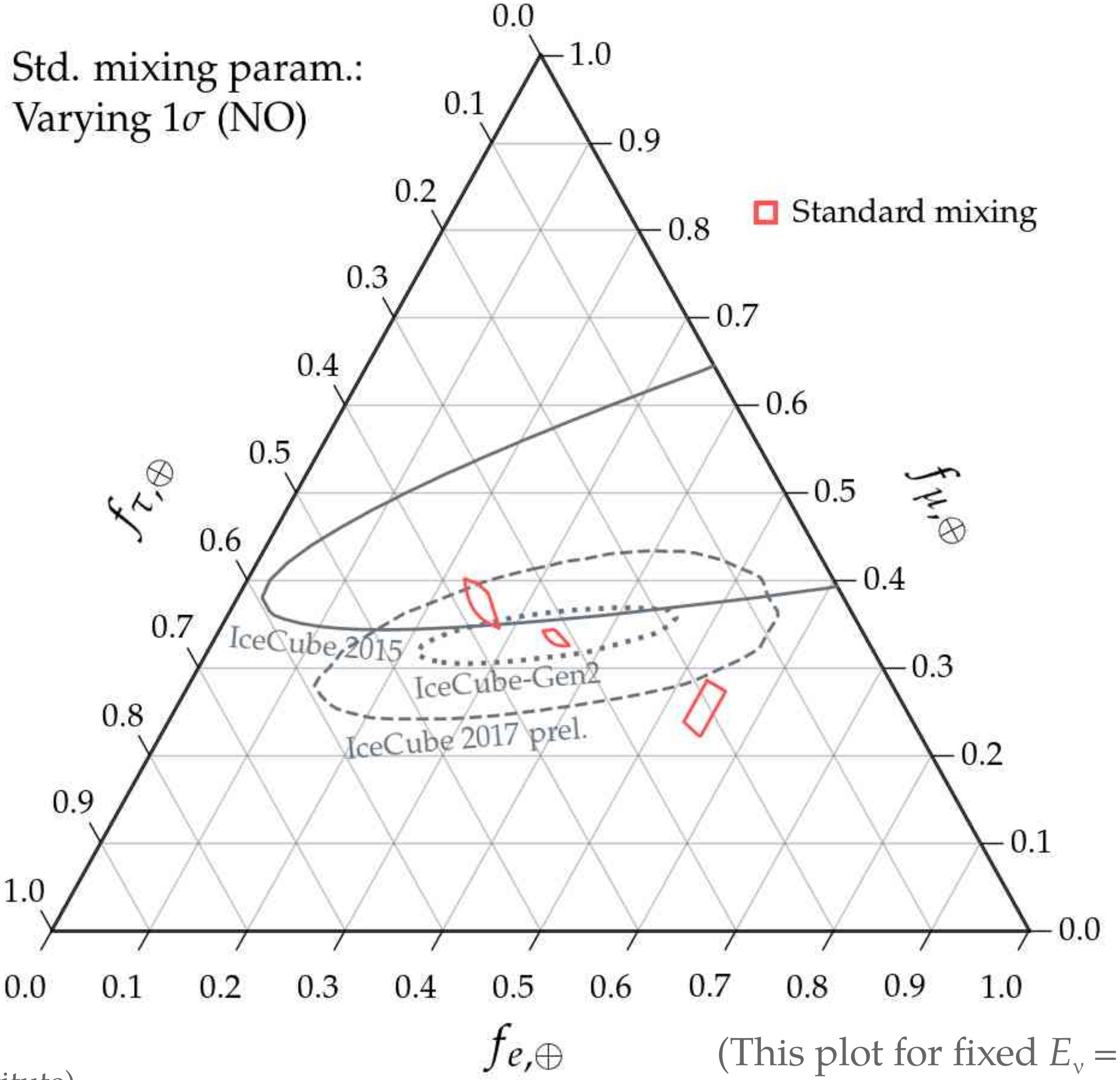






MB, S. Agarwalla, 1808.02042

(This plot for fixed E_ν = 100 TeV)



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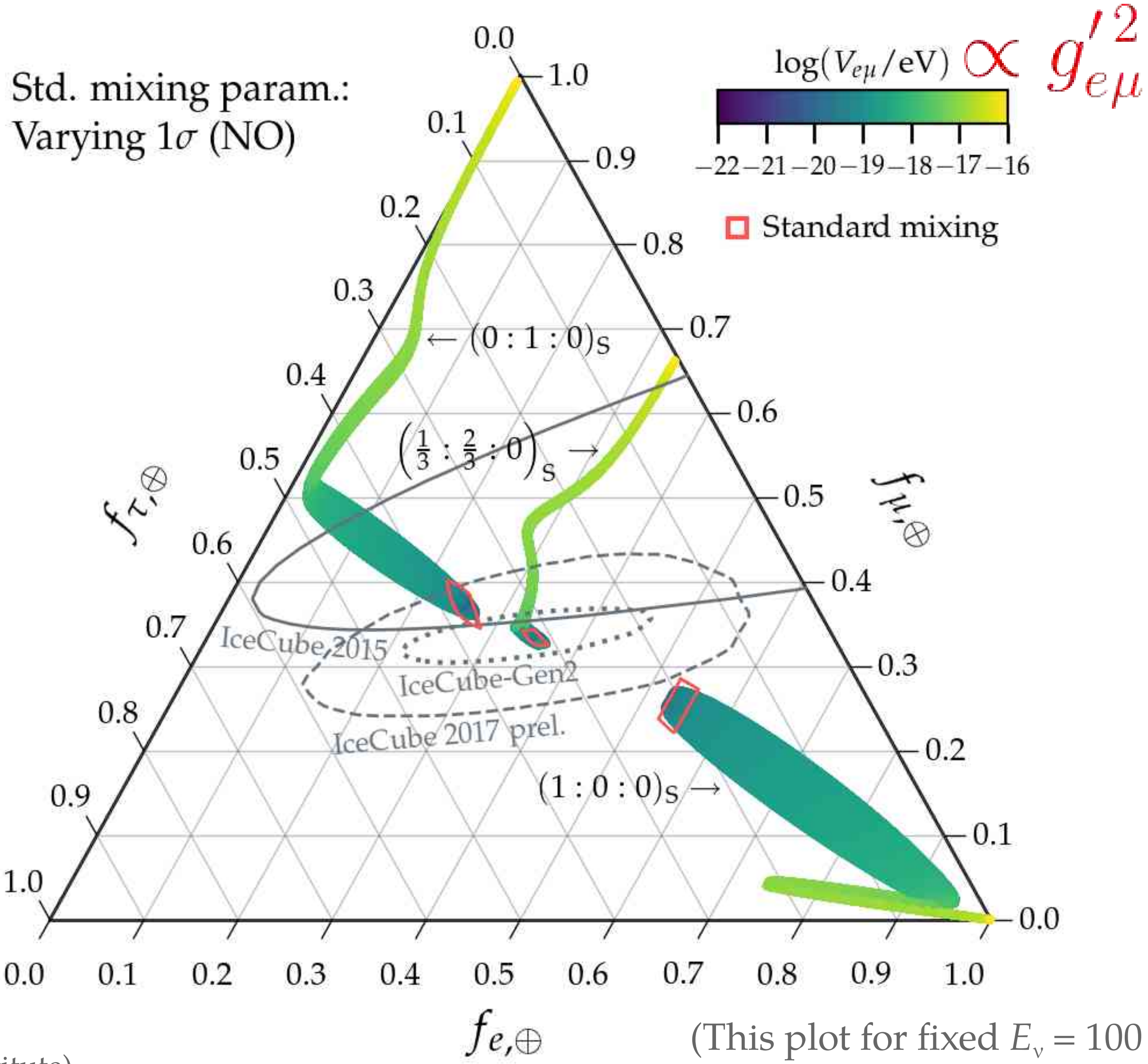

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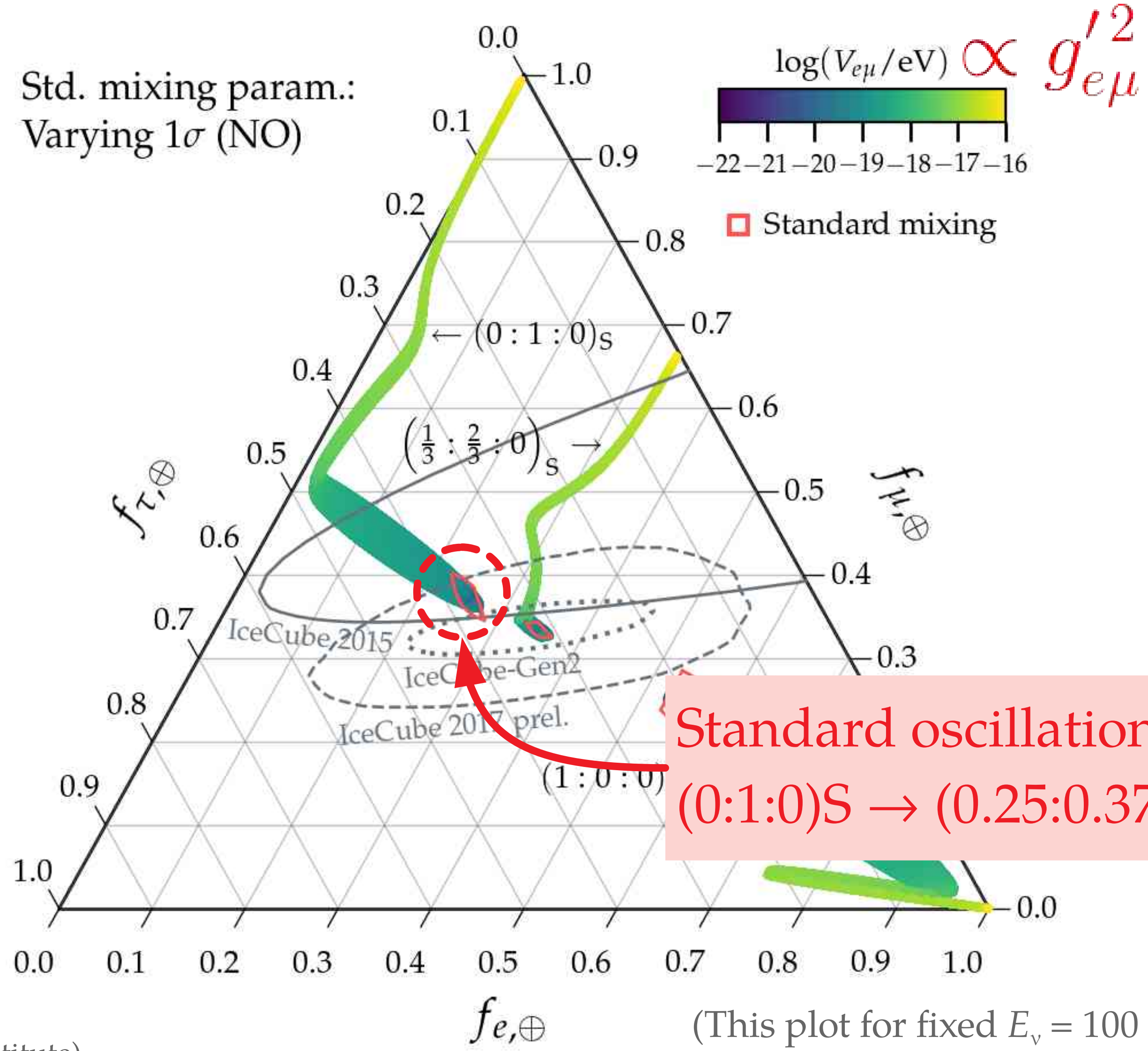

Standard oscillations
(0:1:0)S → (0.25:0.37:0.38)⊕

MB, S. Agarwalla, 1808.02042

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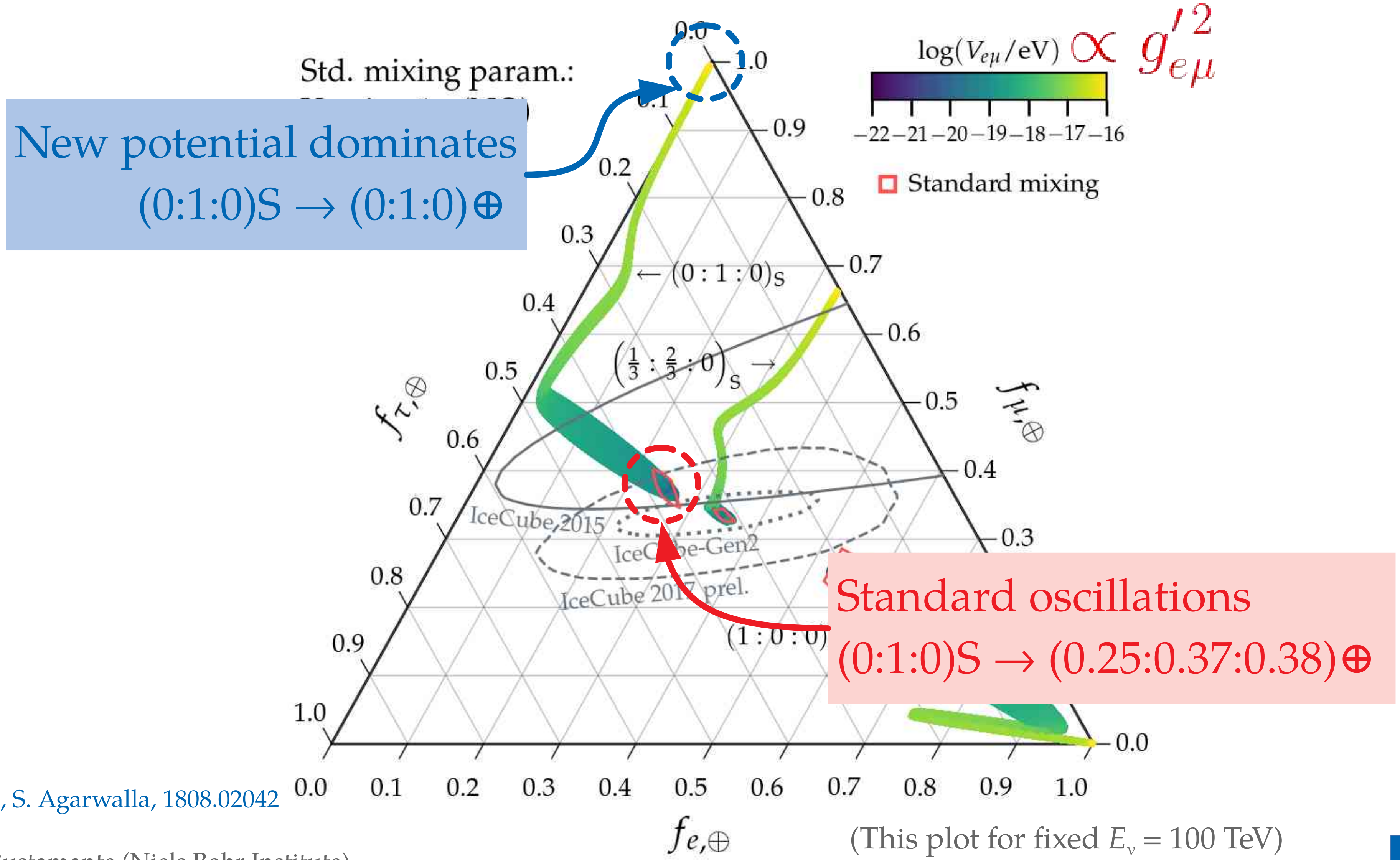
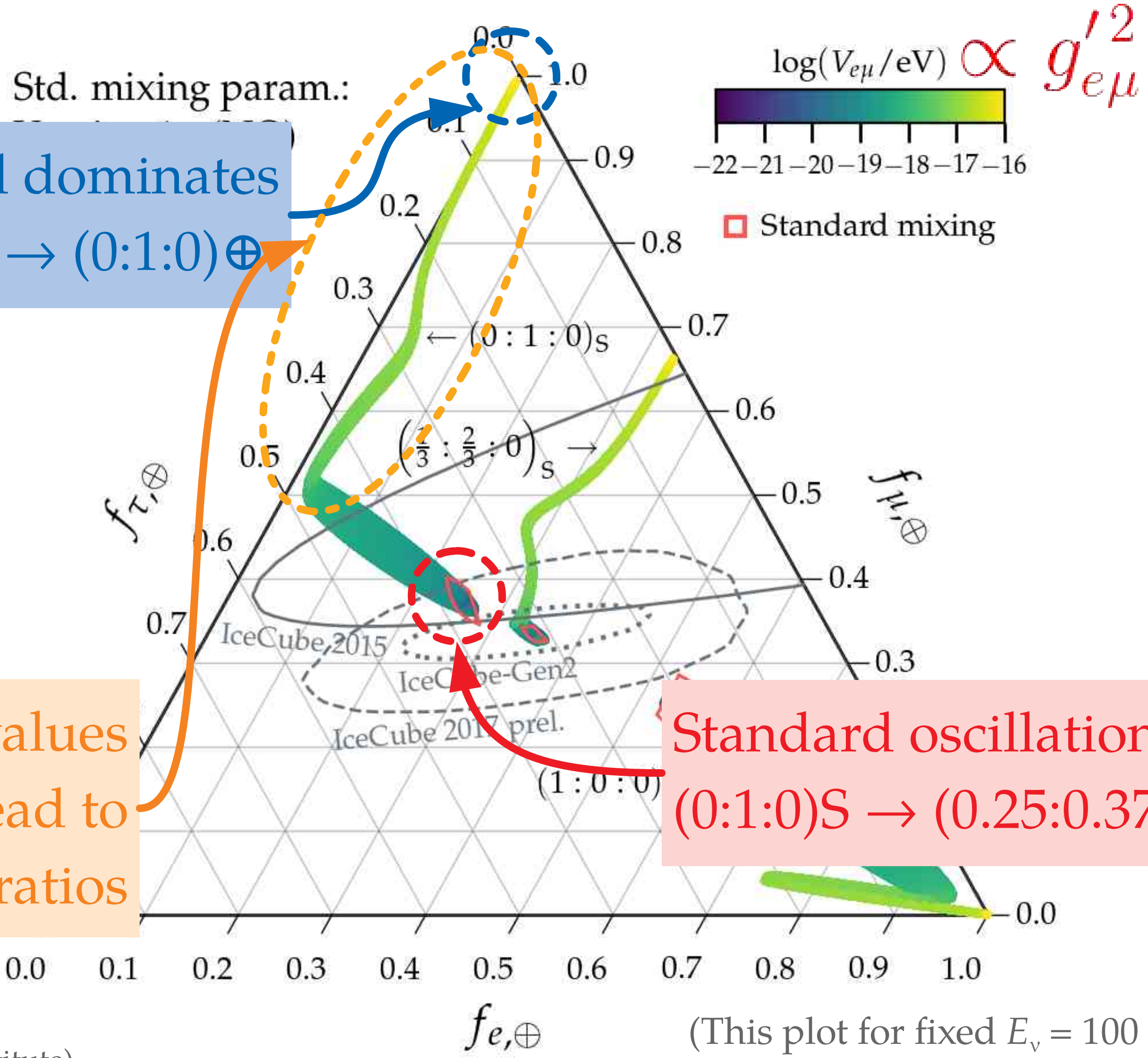


MB, S. Agarwalla, 1808.02042

(This plot for fixed E_ν = 100 TeV)

New potential dominates
(0:1:0)S → (0:1:0)⊕



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

Standard oscillations
(0:1:0)S → (0.25:0.37:0.38)⊕

MB, S. Agarwalla, 1808.02042

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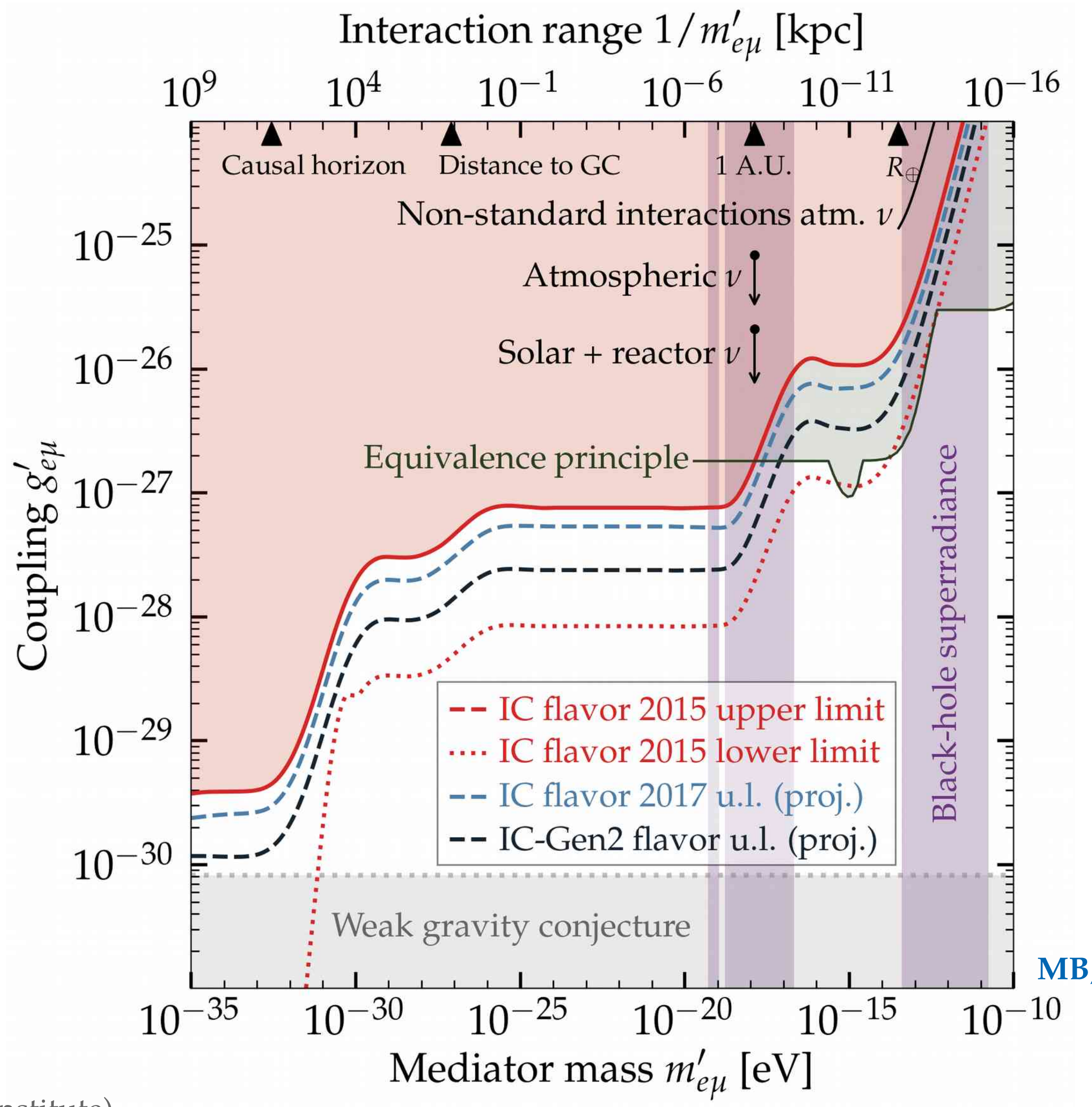
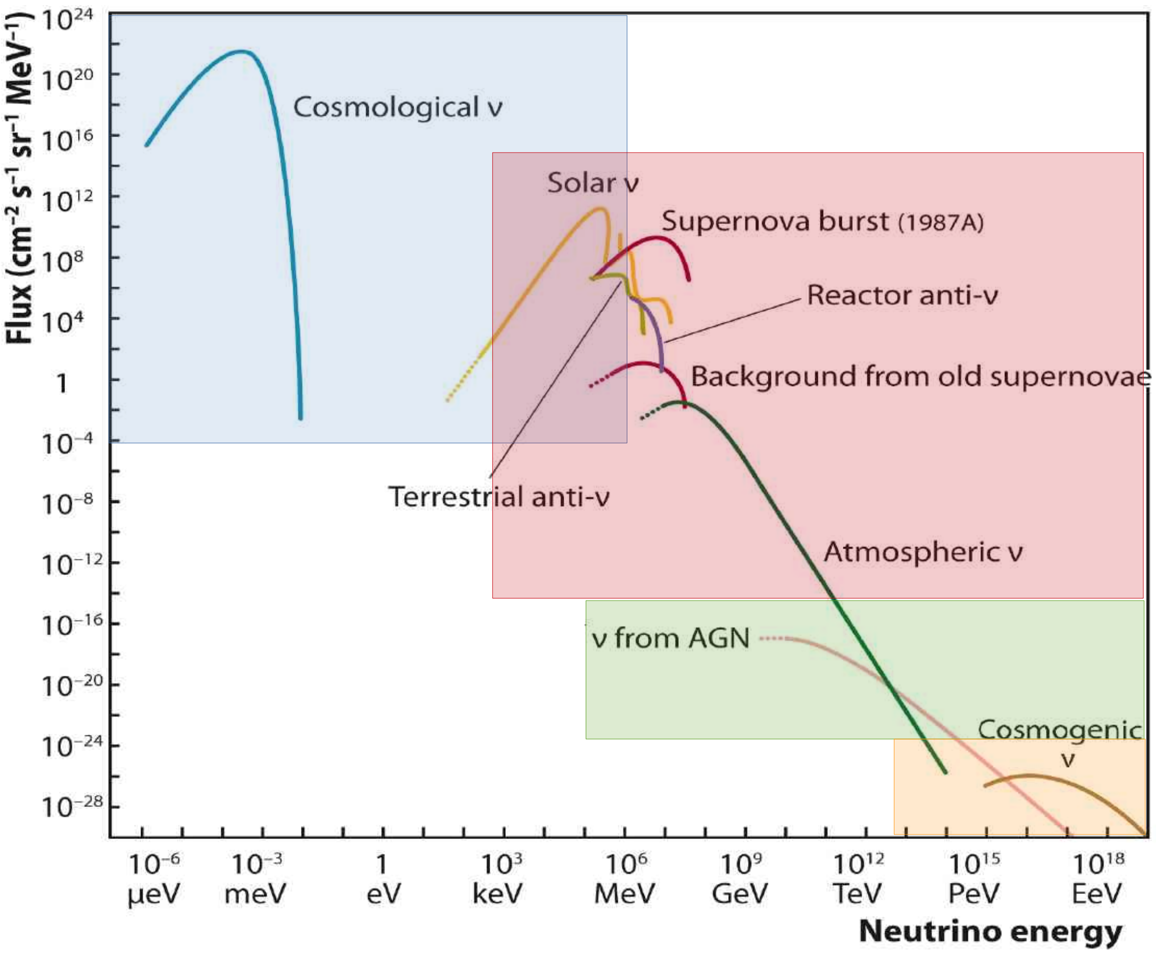


MB, S. Agarwalla, 1808.02042

Quo vadis? Ultra-high-energy neutrinos



Very rare,
not detected *yet*

Quo vadis? Ultra-high-energy neutrinos

Present

IceCube:

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

Future

ARA/ARIANNA/ANITA/GRAND/POEMMA/BEACON/*etc.*:

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

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GRAND

Giant Radio Array for Neutrino Detection

Web: grand.cnrs.fr

What are you taking home?

- Astrophysical neutrinos are the *only* feasible way to probe TeV–PeV physics
- New physics is possibly sub-dominant – so we need to be thorough
- We can extract TeV–PeV ν physics *now*, in spite of astrophysical unknowns
- Forthcoming improvements: statistics, better reconstruction, higher energies

xkcd

Backup slides

What has IceCube found so far (7.5 years)?

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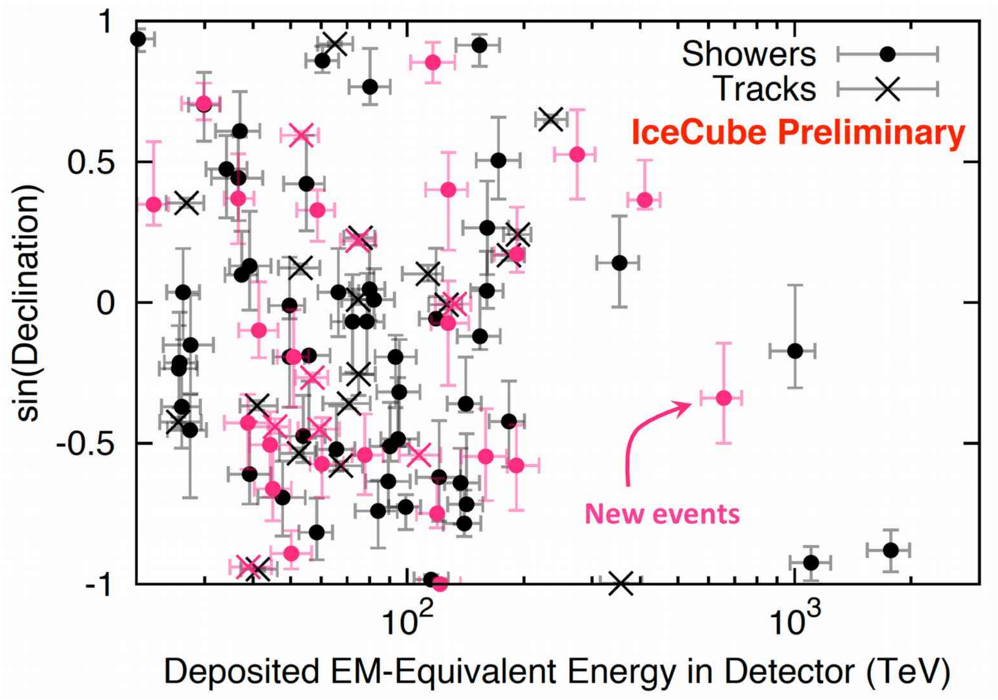
103 contained events between 15 TeV – 2 PeV



I. Taboada, Neutrino 2018

What has IceCube found so far (7.5 years)?

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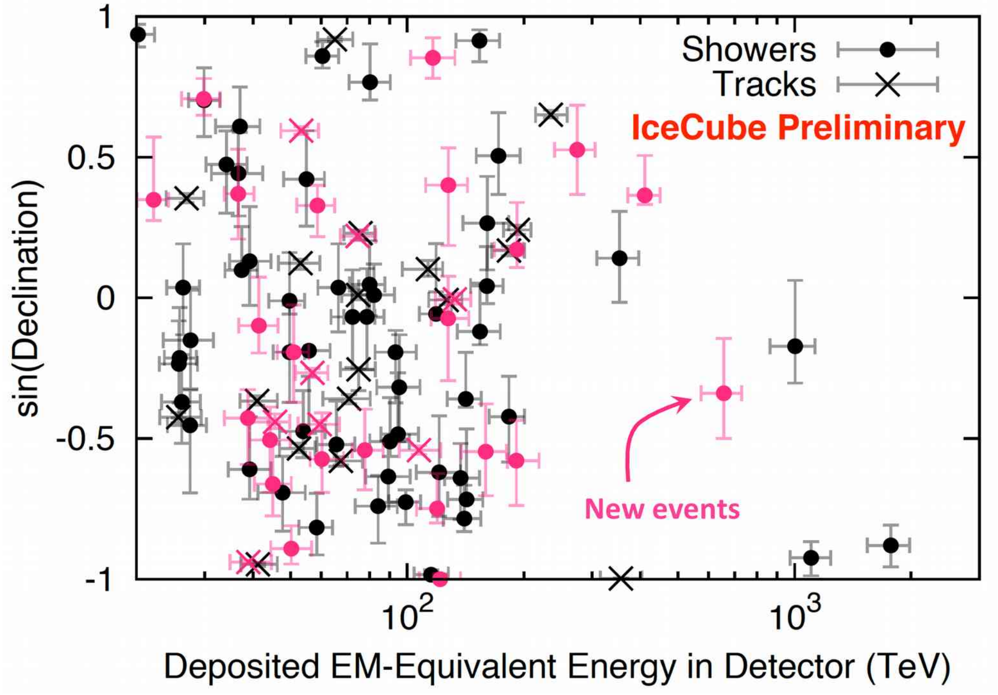
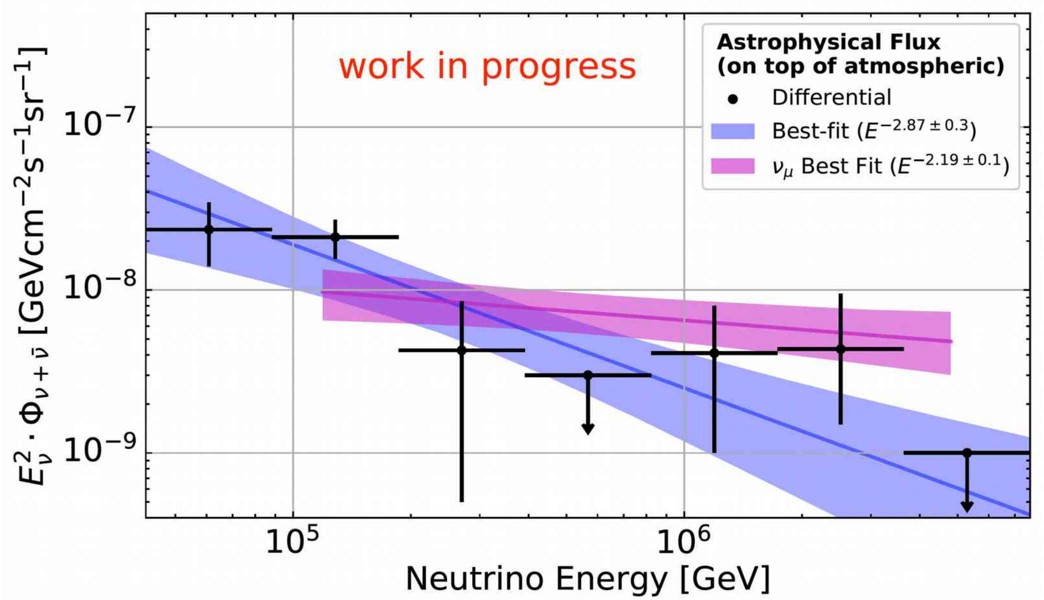


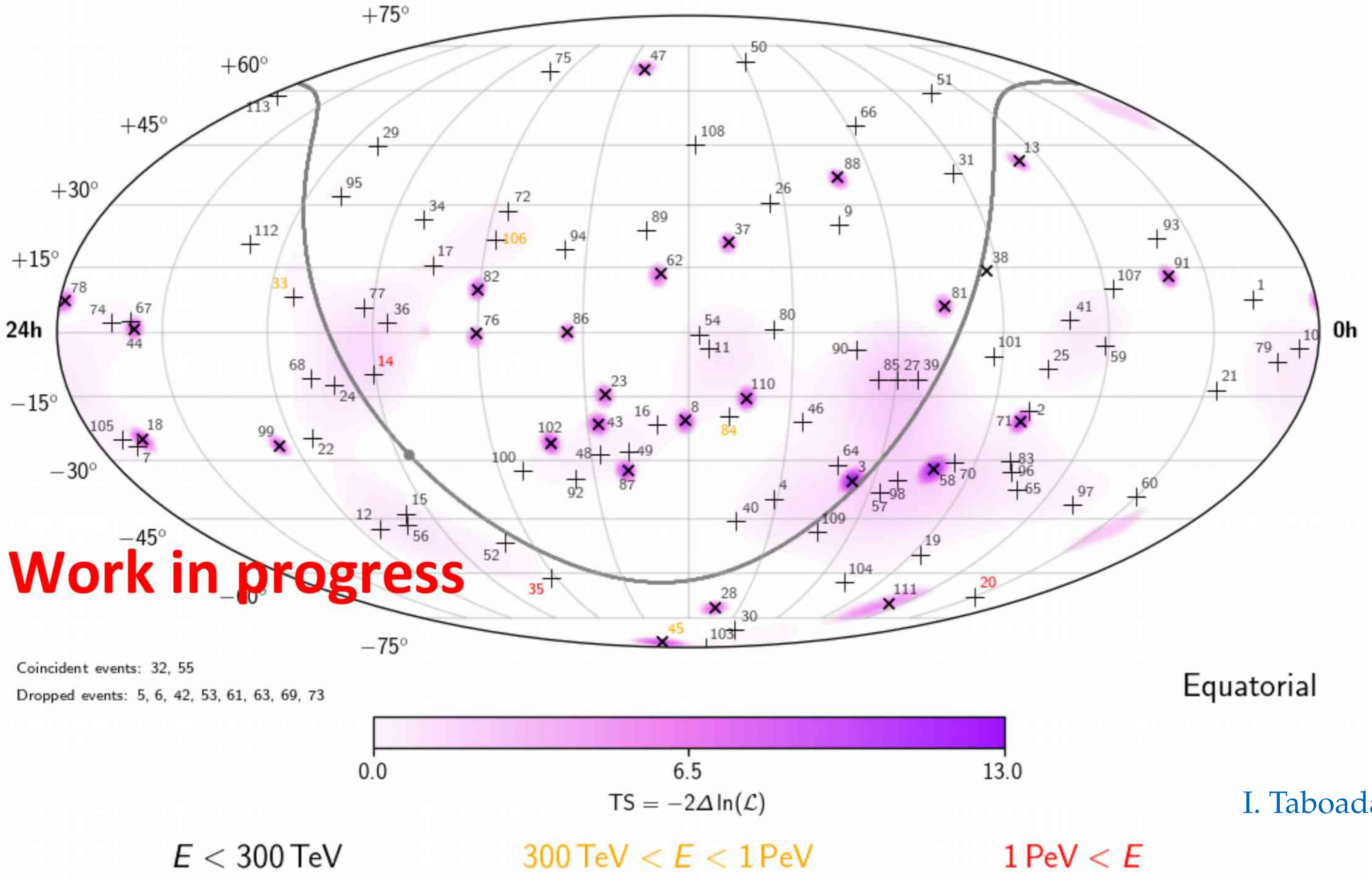
Astrophysical ν flux detected at > 7σ
(Normalization ok, but steep spectrum)



I. Taboada, Neutrino 2018

What has IceCube found so far (7.5 years)?

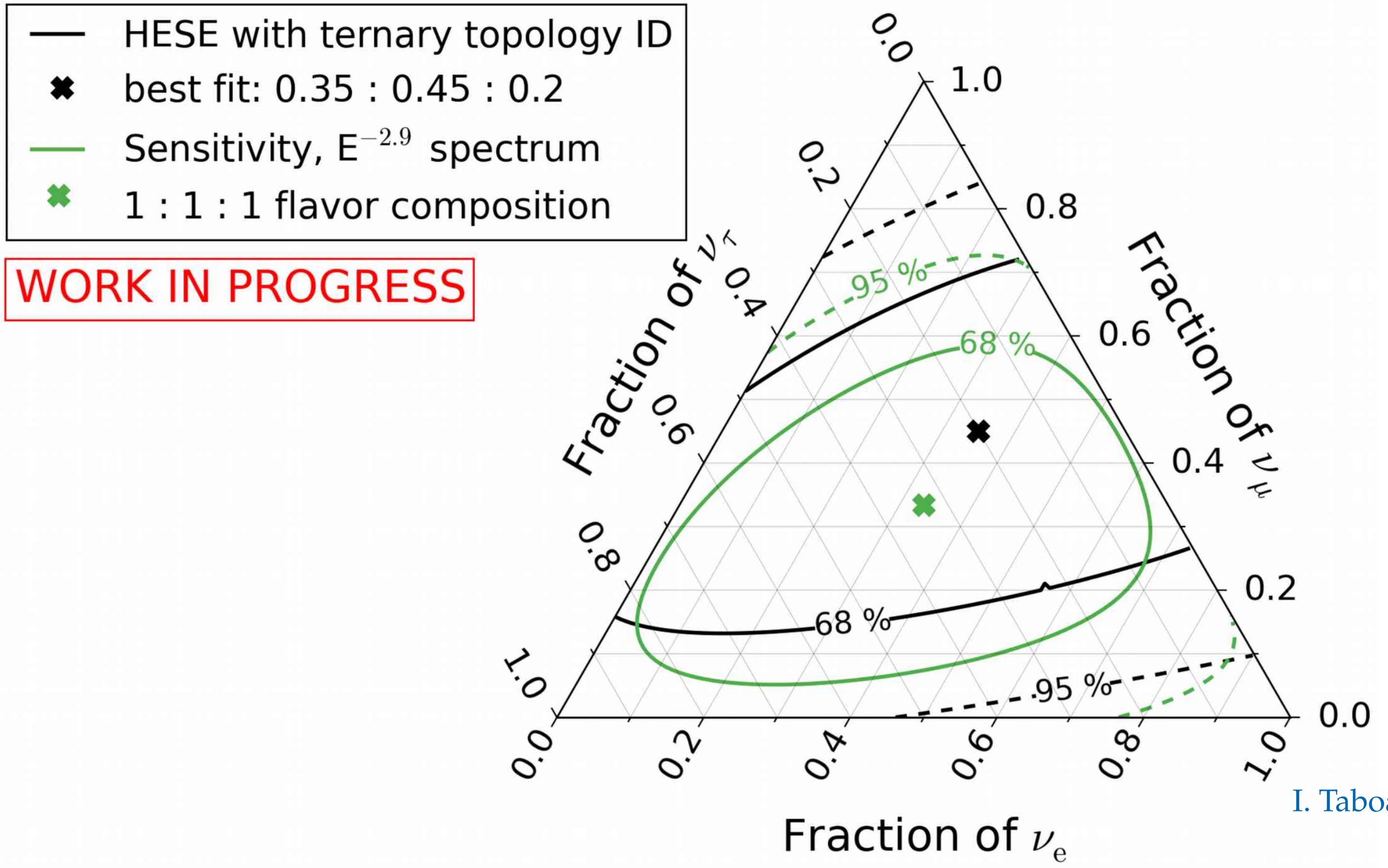
Arrival directions compatible with isotropy



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

The multi-messenger connection

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

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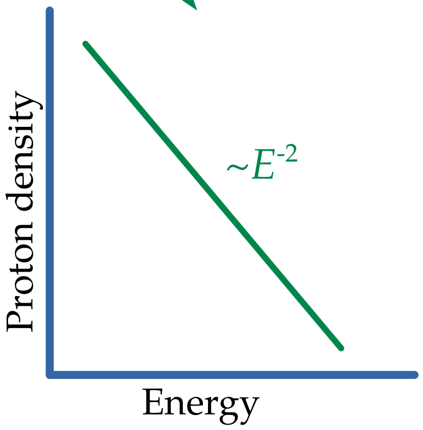

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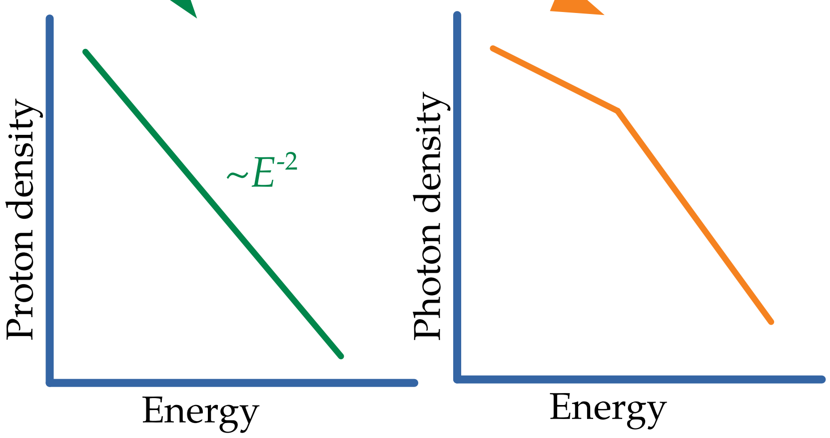

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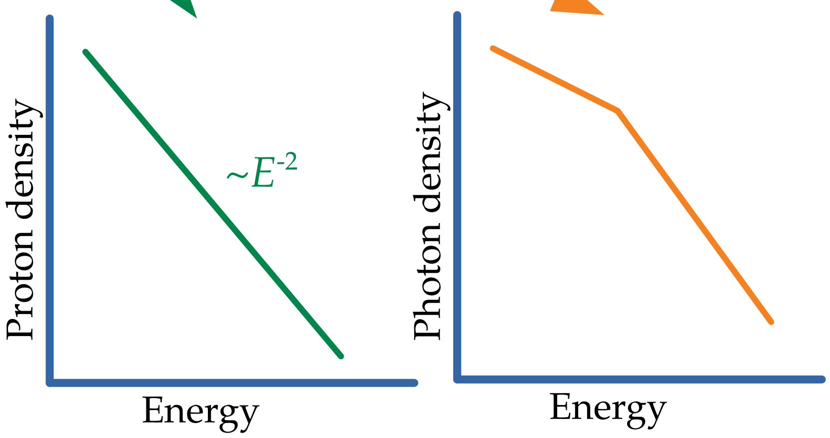
$$\pi^0 \to \gamma + \gamma$$

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

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



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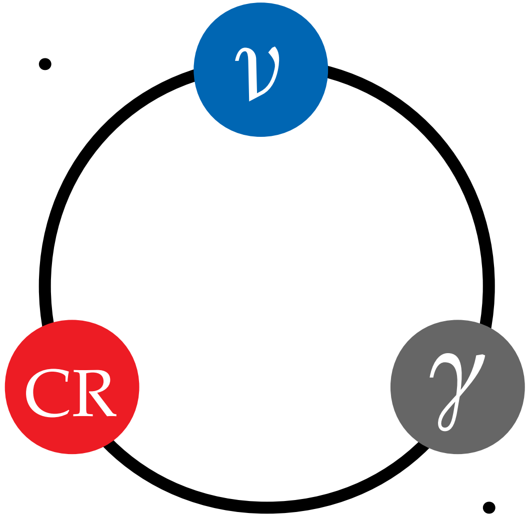

Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 20

The multi-messenger connection

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

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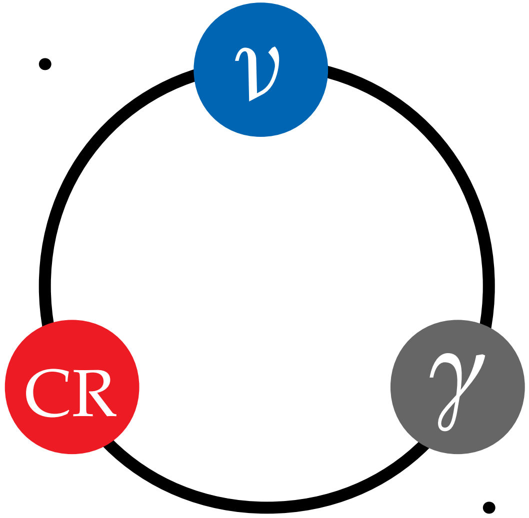

1 PeV 20 PeV

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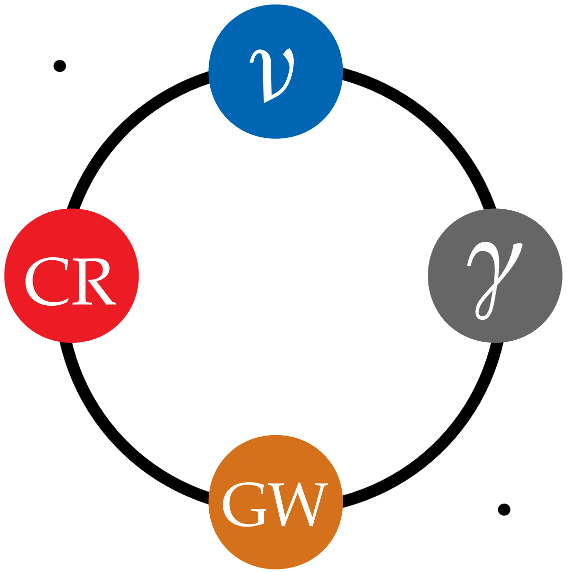

1 PeV 20 PeV

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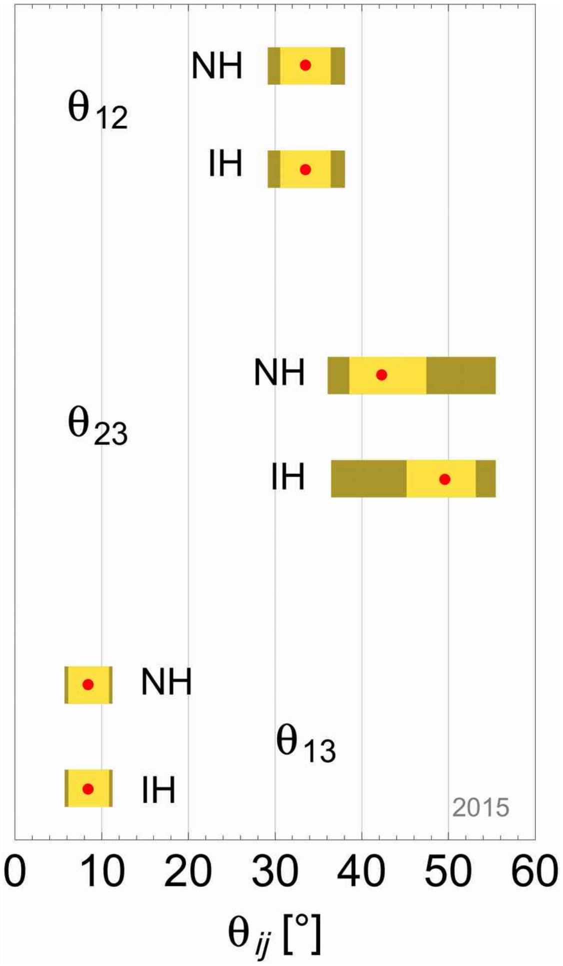
Uncertainties in lepton mixing angles

As of 2015 –



How does IceCube see neutrinos?

Two types of fundamental interactions ...

Charged-current (CC)

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

Neutral-current (NC)

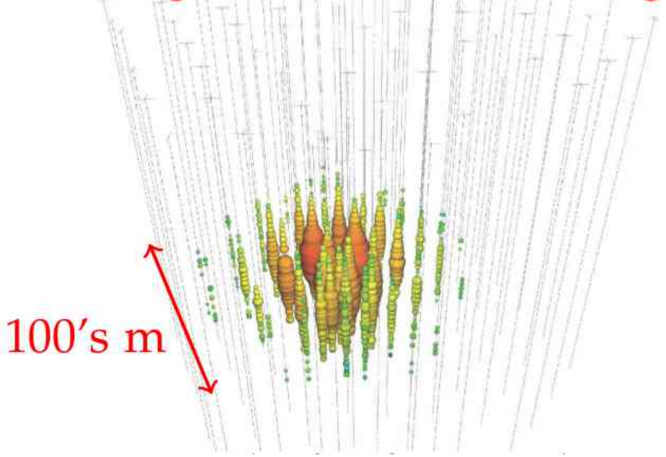
$$\nu_l + N \to \nu_l + \boxed{\text{hadrons}}$$

These shower and make light

... create two event topologies ...

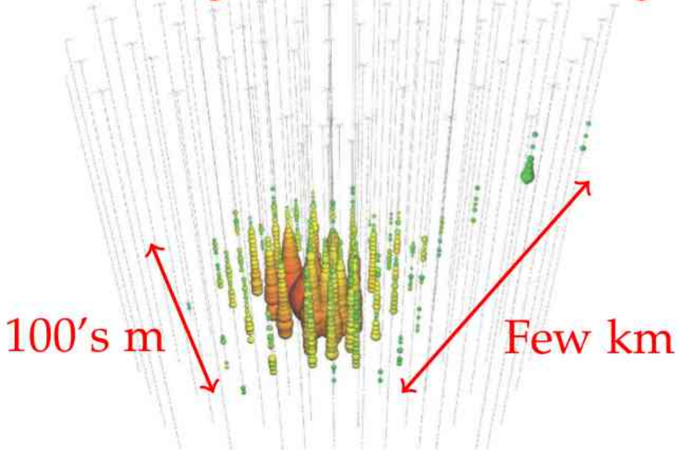
Showers — From CC ν_e or ν_τ, or NC ν_x

Bad angular resolution (10's deg)



Tracks — From CC ν_μ mainly

Good angular resolution (< deg)

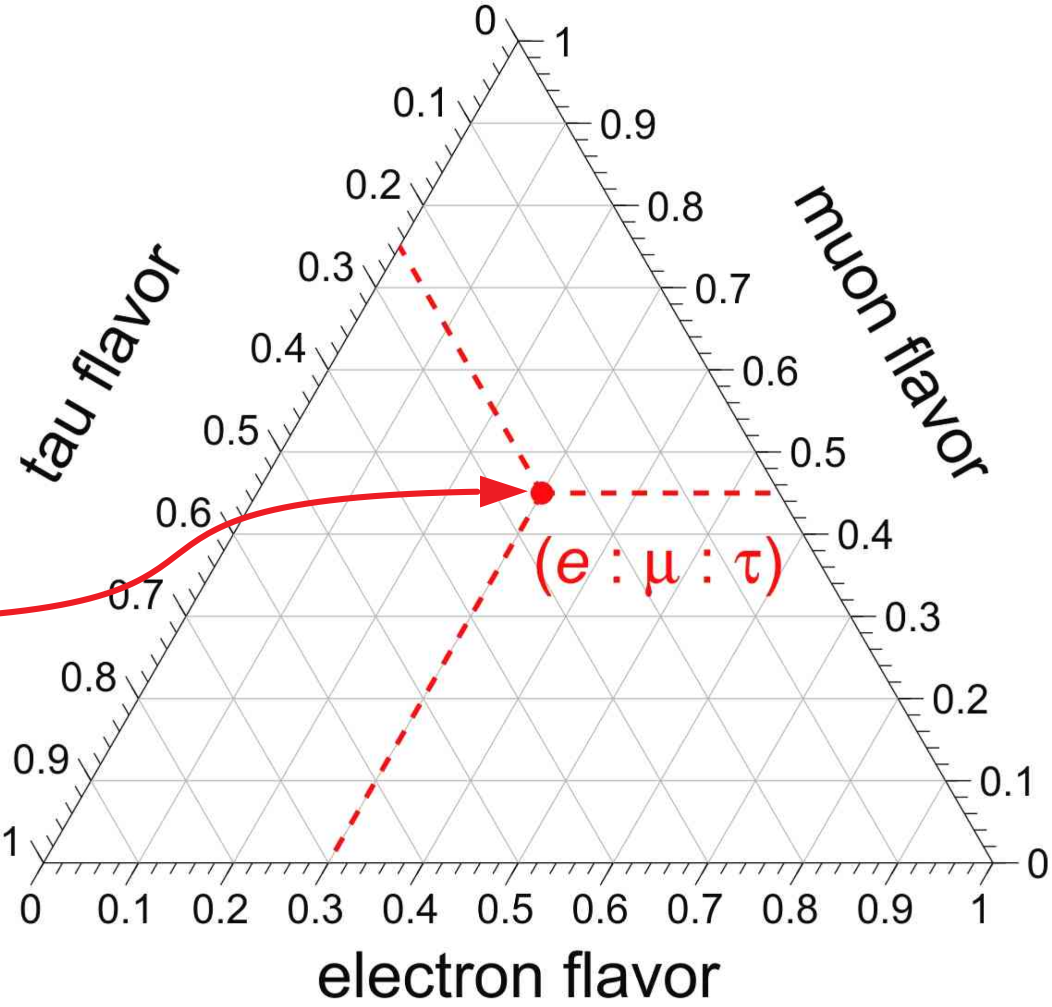


Reading a ternary plot

Assumes underlying unitarity – sum of projections on each axis is 1

How to read it: Follow the tilt of the tick marks, *e.g.*,

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



Flavor ratios – The ideal world *vs.* the real world

The ideal world

If you measure *very* precisely the flavor ratios at Earth and...	... you know *very* precisely...	... then you can infer *very* precisely...
	...the neutrino mixing parameters... →	... flavor ratios emitted by sources
	...the neutrino production mechanism... →	... values of the mixing parameters

vs.

The <u>real</u> world

You measure flavor ratios at Earth *poorly* and...	... you know ...	... then you can ...
	...mixing parameters up to a few deg... →	... disfavor a few ν production scenarios
	... little about ν production scenarios... →	... say nothing about mixing parameters

Flavor ratios – The ideal world *vs.* the real world

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If you measure *very* precisely the flavor ratios at Earth and...	… you know *very* precisely...	… then you can infer *very* precisely...
	…the neutrino mixing parameters… →	… flavor ratios emitted by sources
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vs.

But we can thoroughly explore new physics

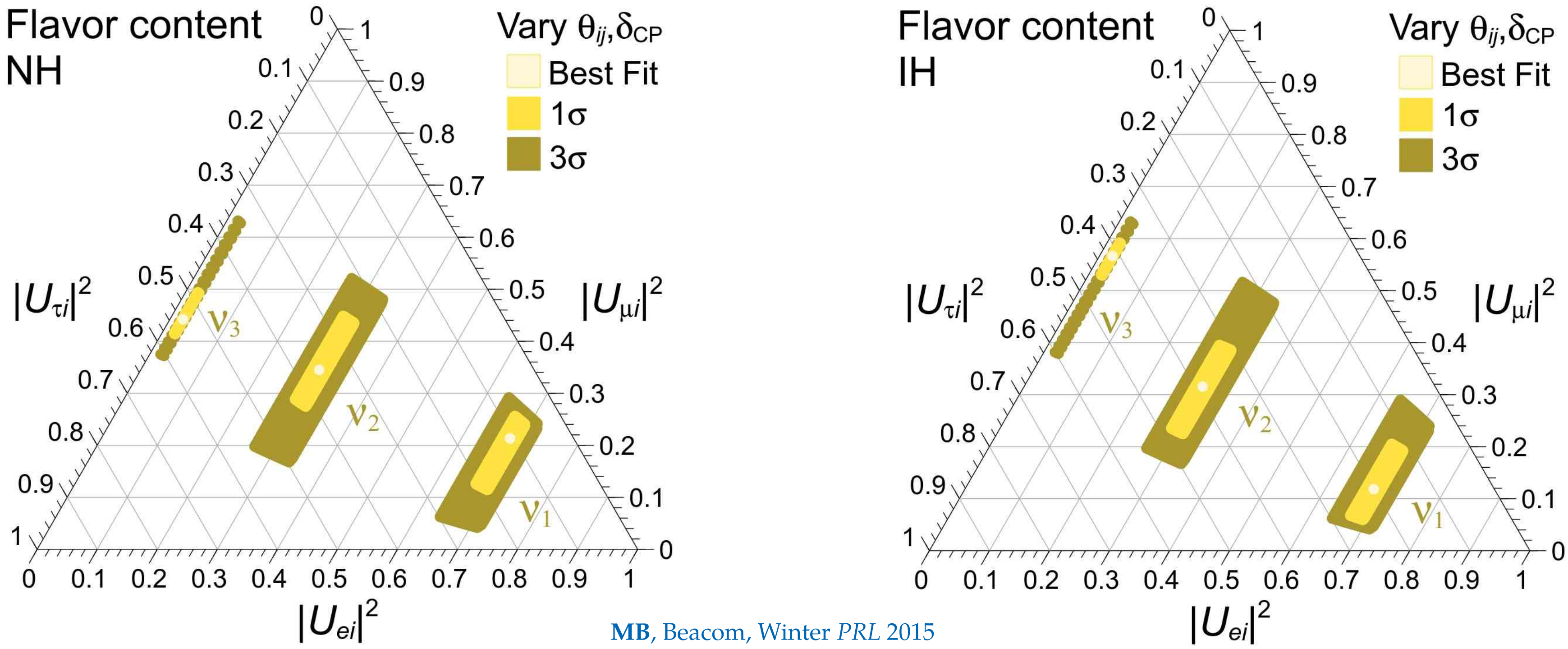
The real world

You measure flavor ratios at Earth *poorly* and...	… you know …	… then you can …
	…mixing parameters up to a few deg… →	… disfavor a few ν production scenarios
	… little about ν production scenarios… →	… say nothing about mixing parameters

Flavor content of neutrino mass eigenstates

Flavor content for every allowed combination of mixing parameters –

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



MB, Beacom, Winter *PRL* 2015

Flavor composition – a few source choices

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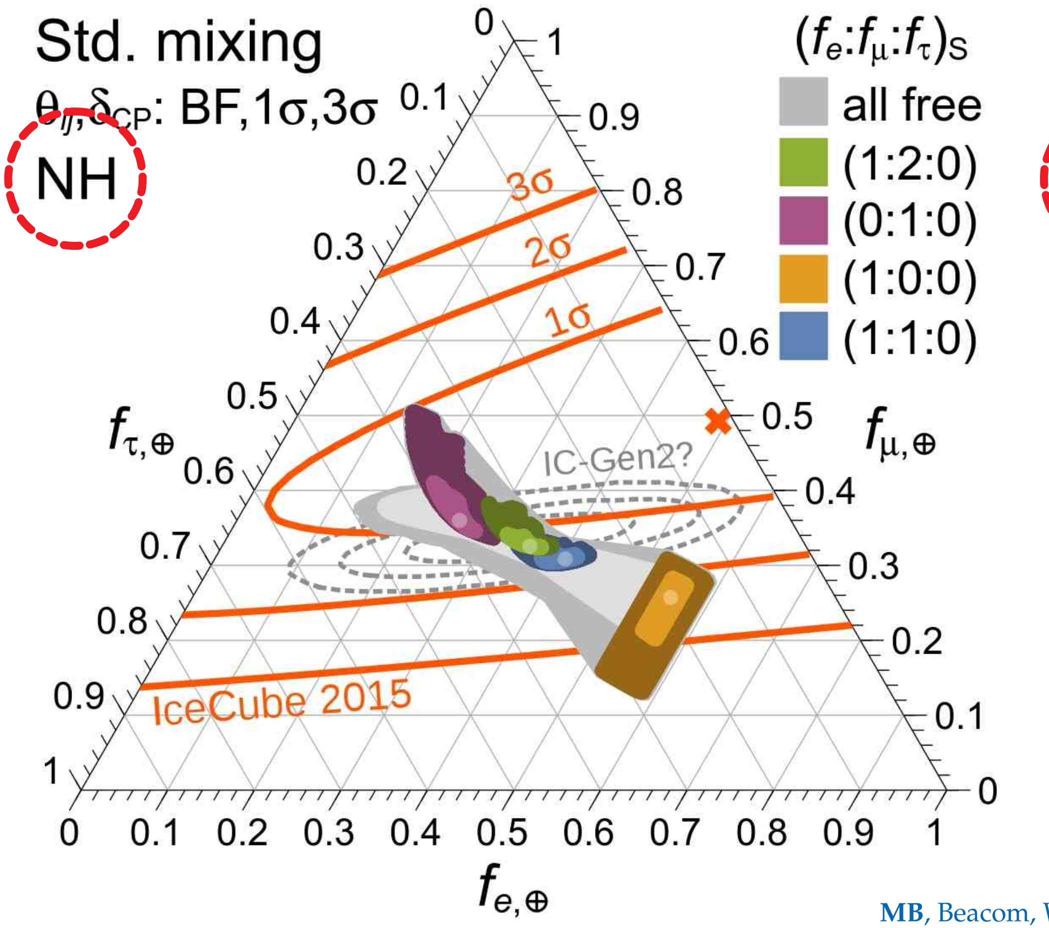
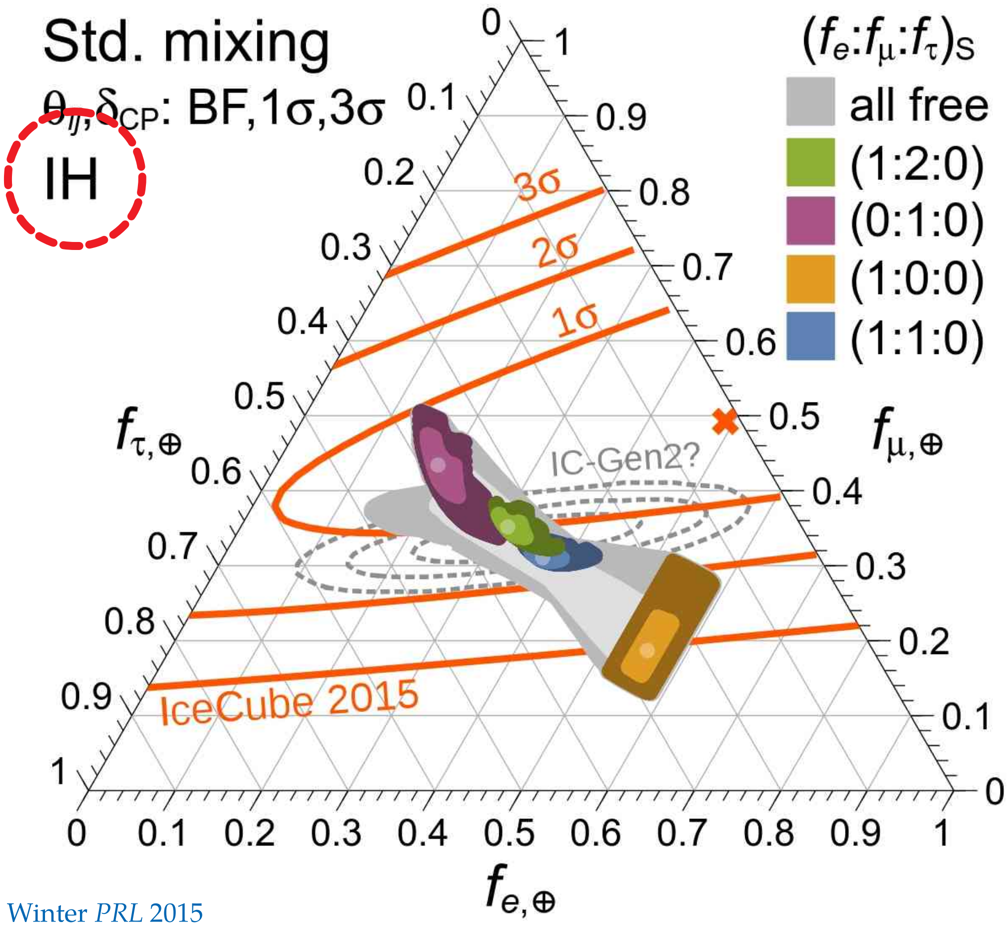
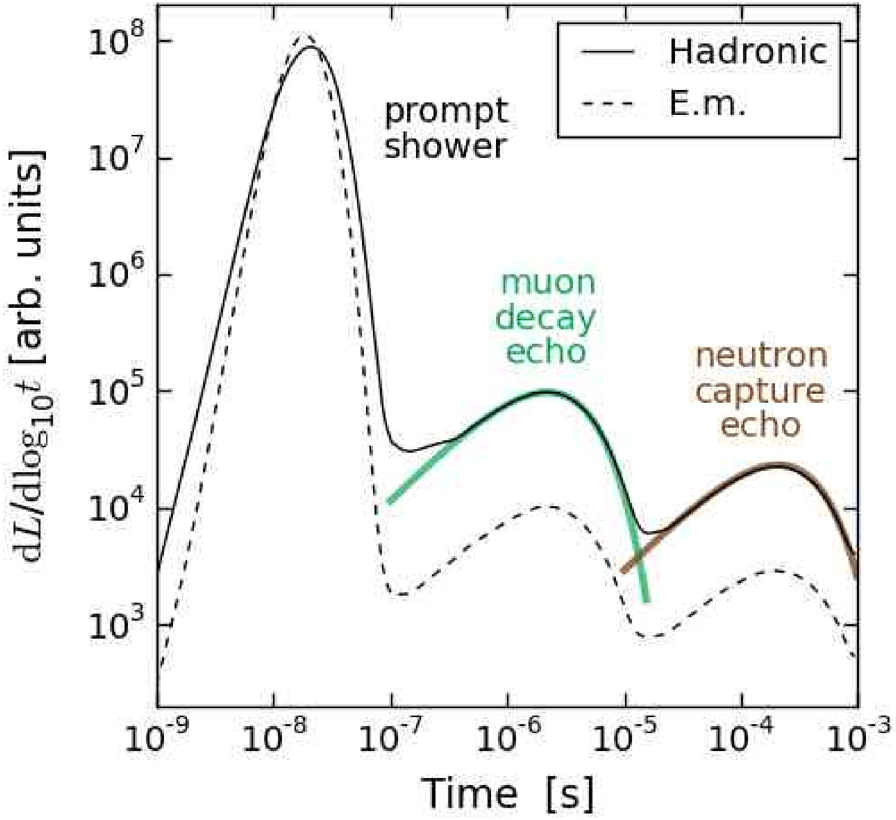


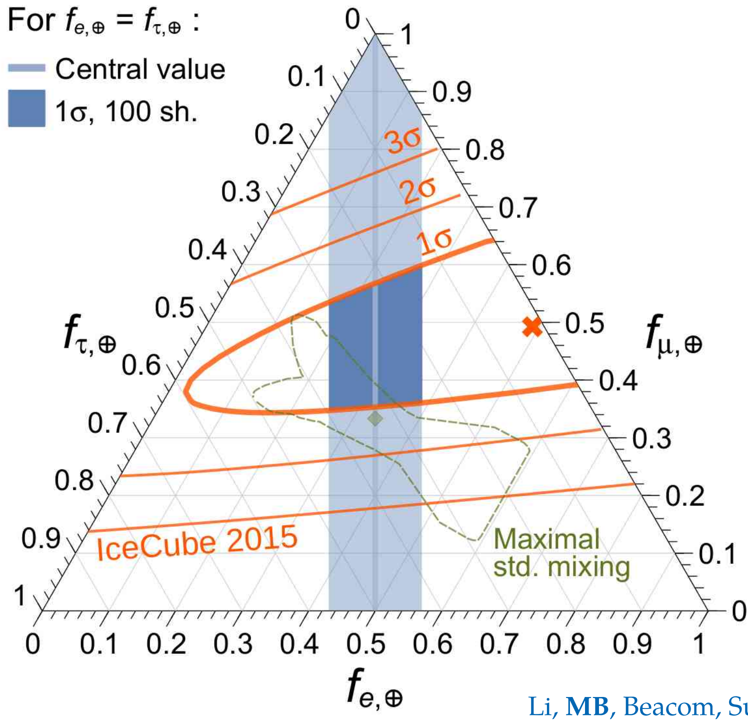


MB, Beacom, Winter *PRL* 2015

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, Sub. to *PRL*

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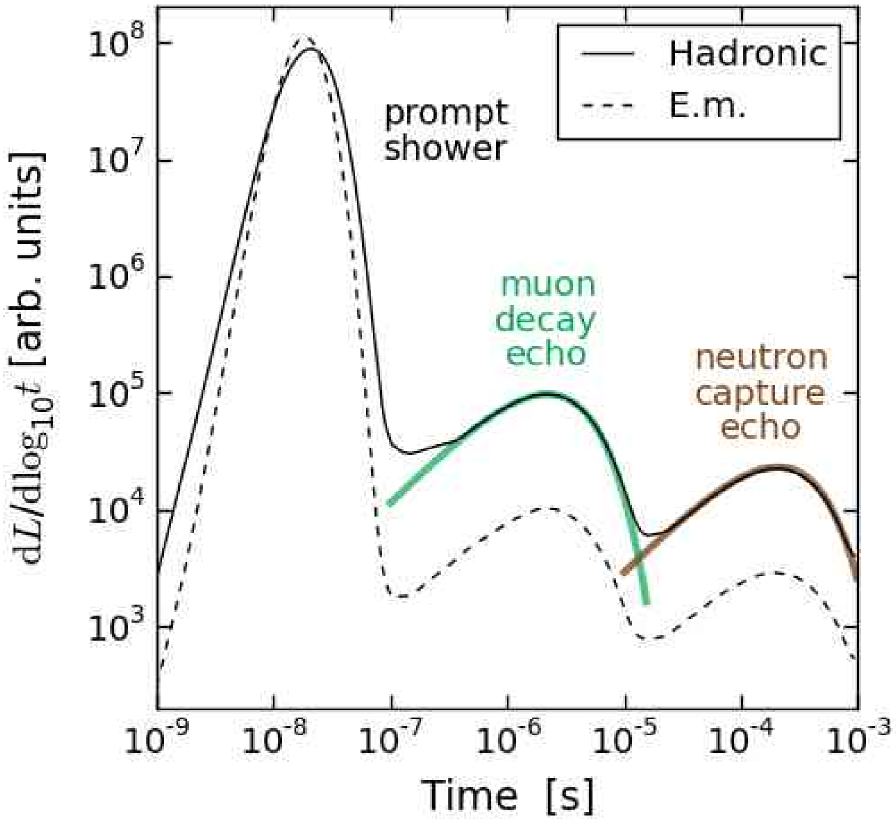
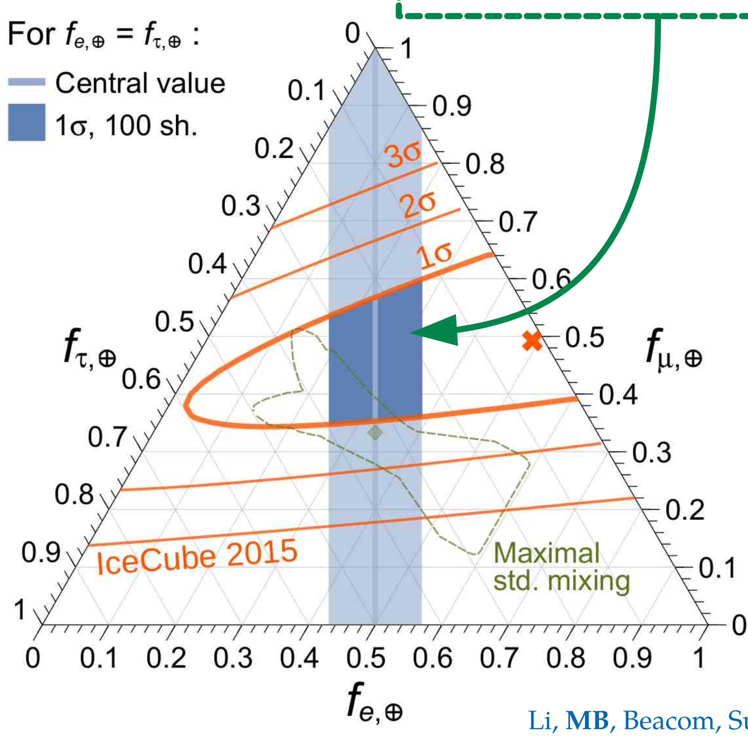
Late-time light (*echoes*) from muon decays and neutron captures can separate showers made by ν_e and ν_τ –

~10 × improvement over current measurement





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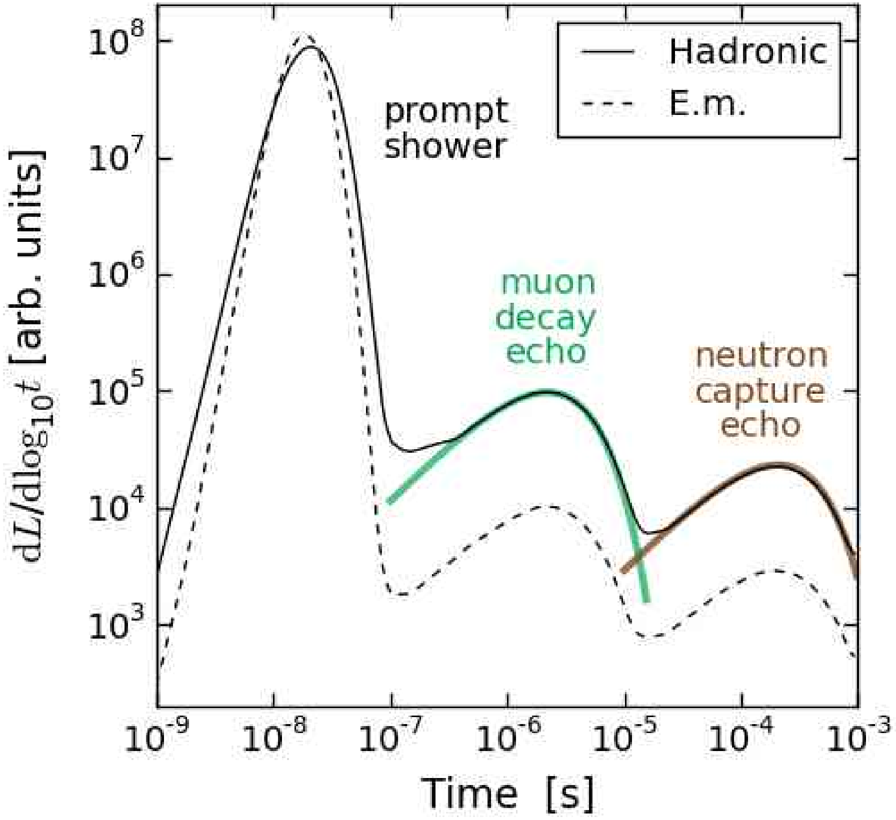
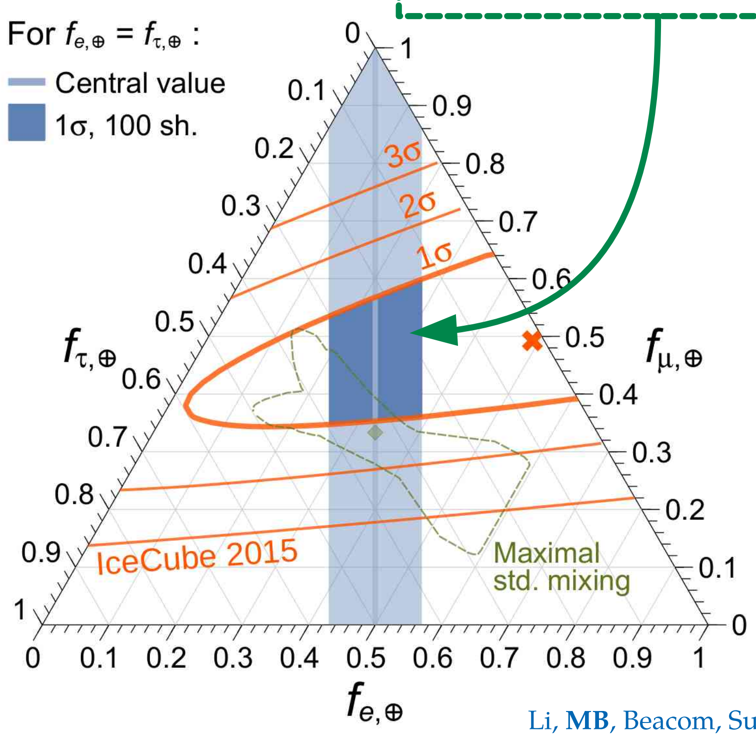
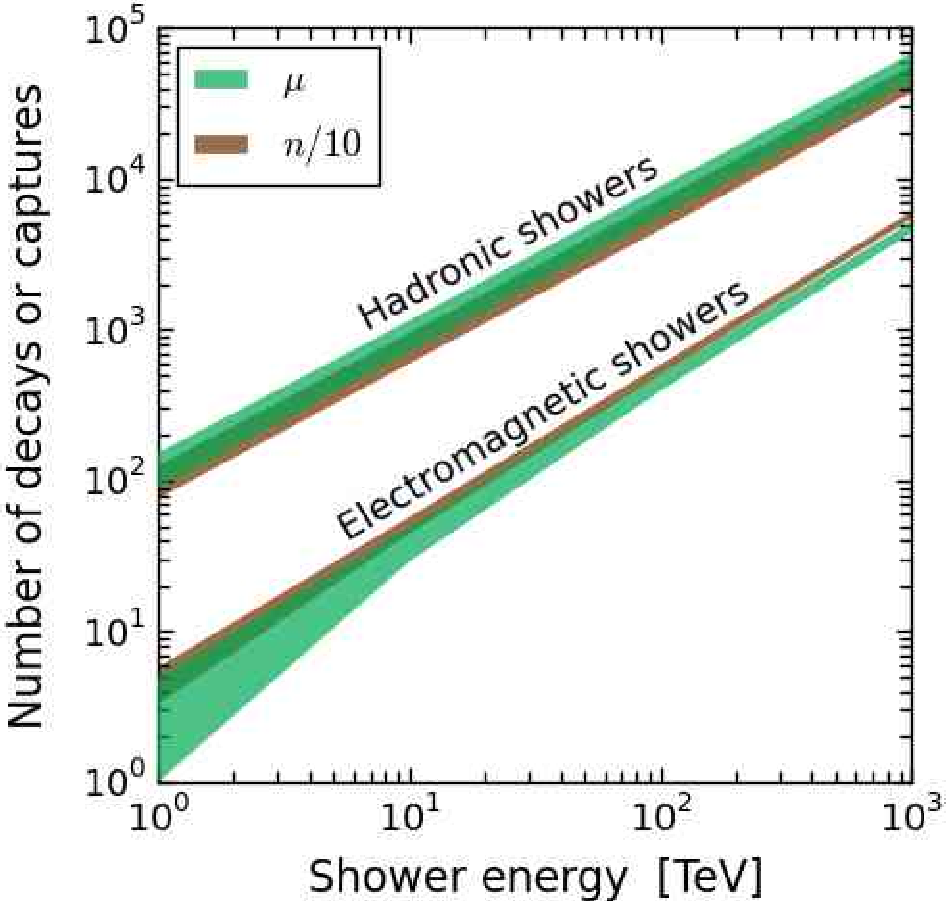
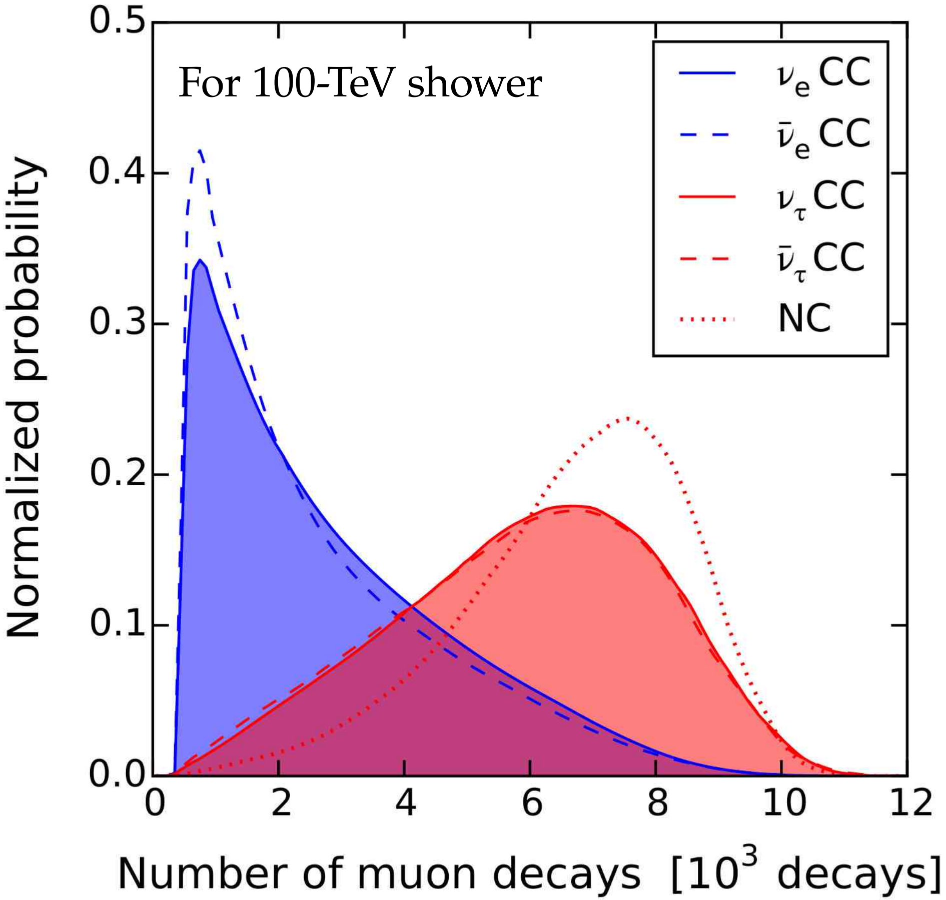




Li, **MB**, Beacom, Sub. to *PRL*

Hadronic *vs.* electromagnetic showers

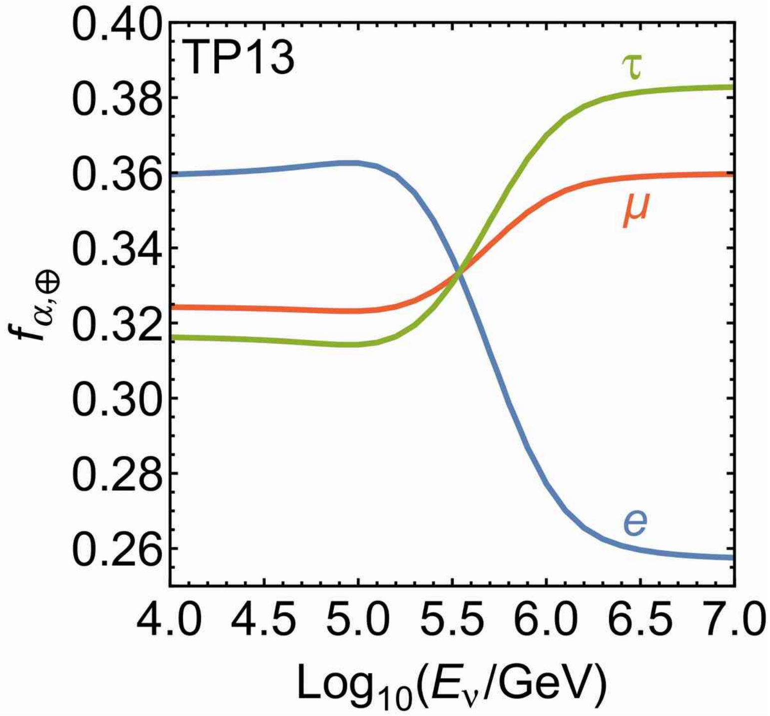


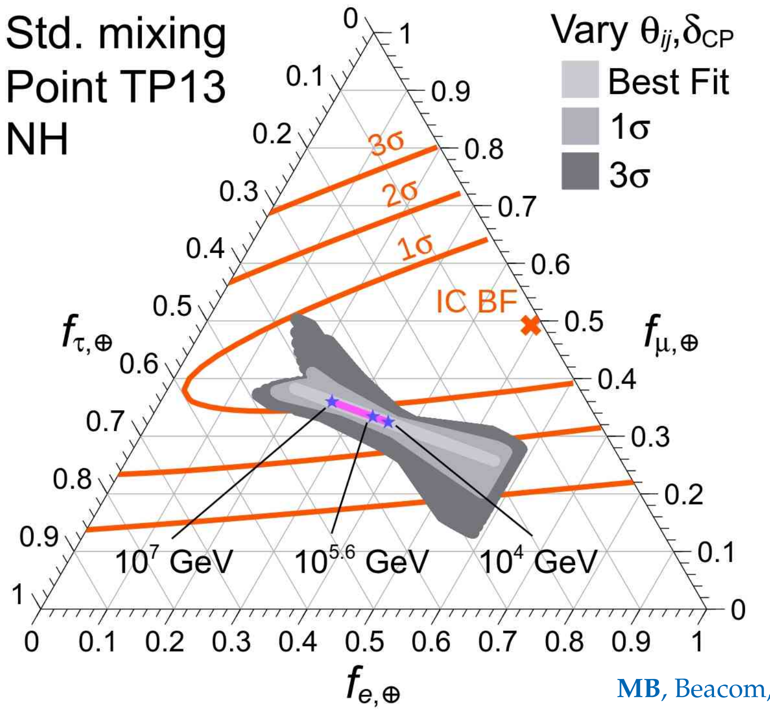


Li, **MB**, Beacom, Sub. to *PRL*

Energy dependence of the flavor composition?

Different neutrino production channels accessible at different energies –

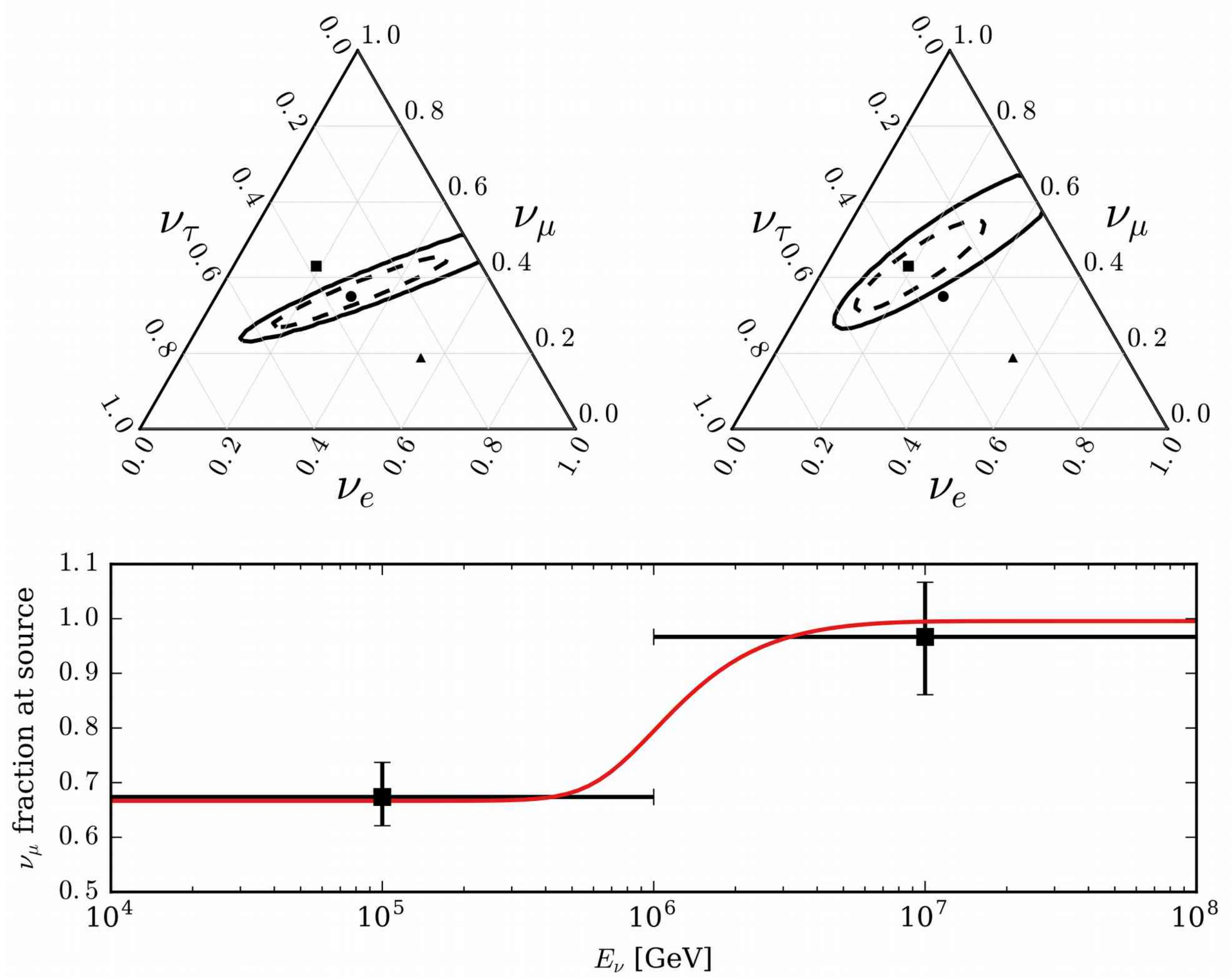




MB, Beacom, Winter *PRL* 2015

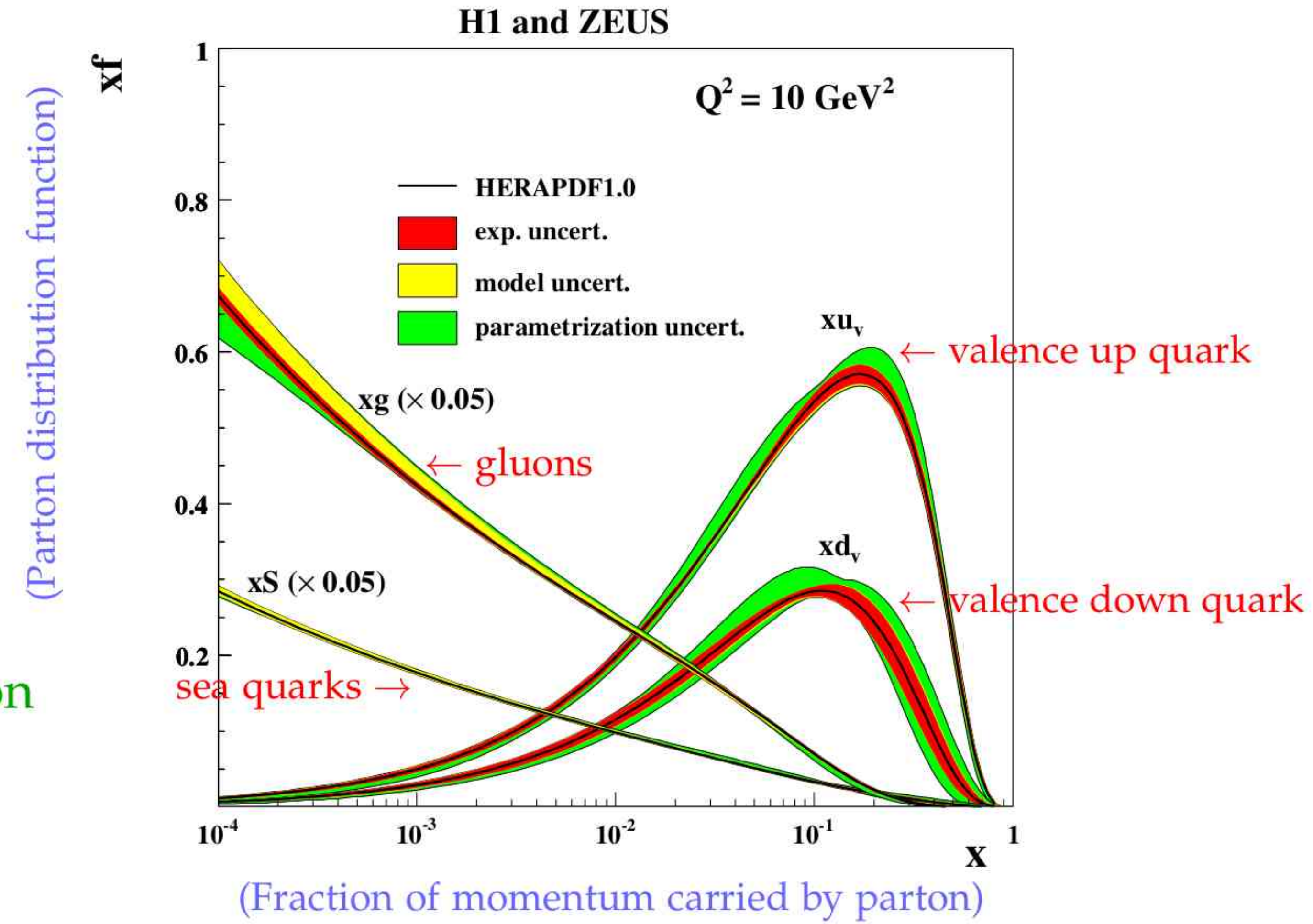
- TP13: $p\gamma$ model, target photons from electron-positron annihilation [Hümmer+, *Astropart. Phys.* 2010]
- Will be difficult to resolve [Kashti, Waxman, *PRL* 2005; Lipari, Lusignoli, Meloni, *PRD* 2007]

… Observable in IceCube-Gen2?



Borrowed from M. Kowalski

Peeking inside a proton



← Extrapolation

A. Cooper-Sarkar 2012

How does IceCube see neutrinos?

Two types of fundamental interactions …

Charged-current (CC)

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

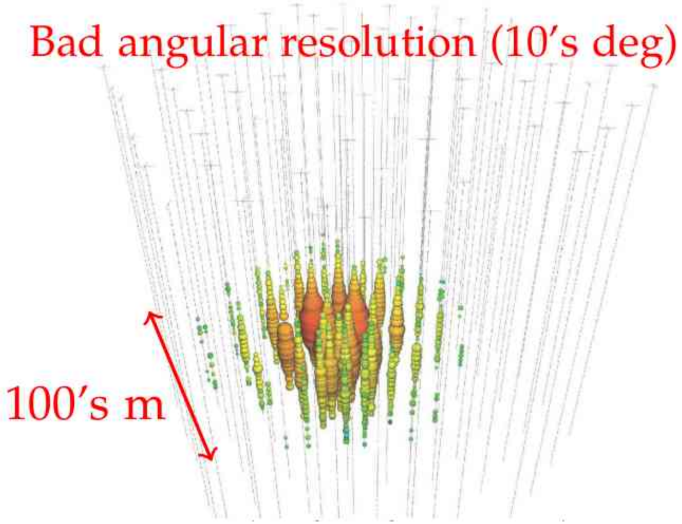
Neutral-current (NC)

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

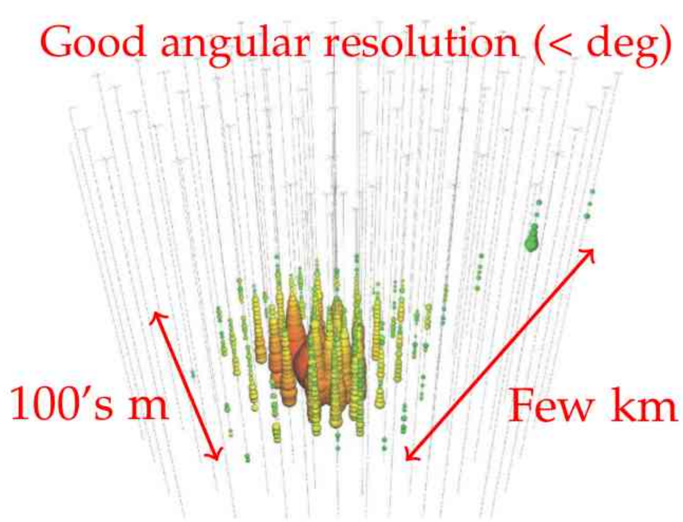
These shower and make light

… create two event topologies …

Showers — From CC ν_e or ν_τ, or NC ν_x

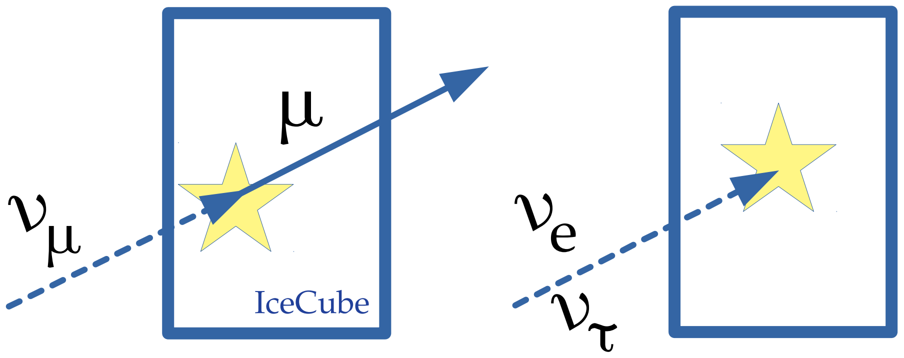


Tracks — From CC ν_μ mainly



Contained *vs.* uncontained νN interactions

Contained events



Starting track

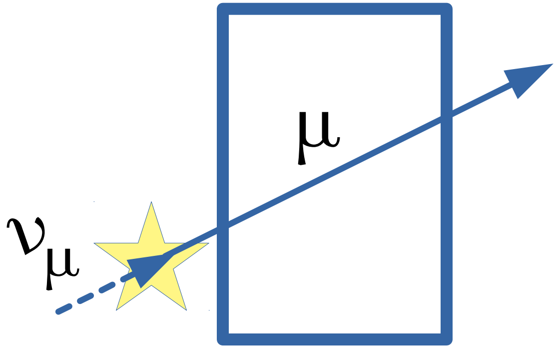
Shower

Pro: Clean determination of E_ν

Con: Few events (<100)

Ref.: MB & A. Connolly, 1711.11043

Uncontained events

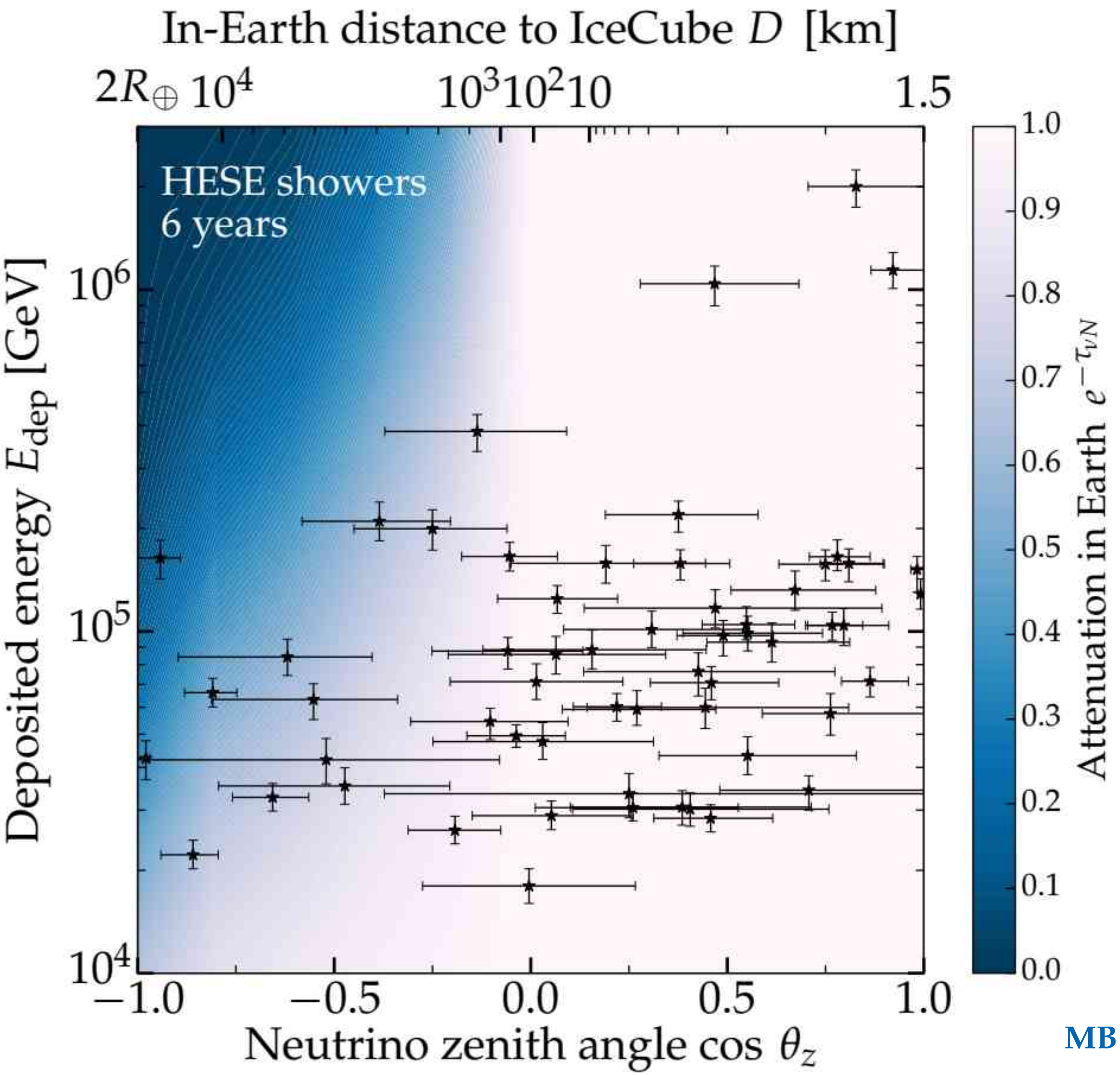


Through-going muon

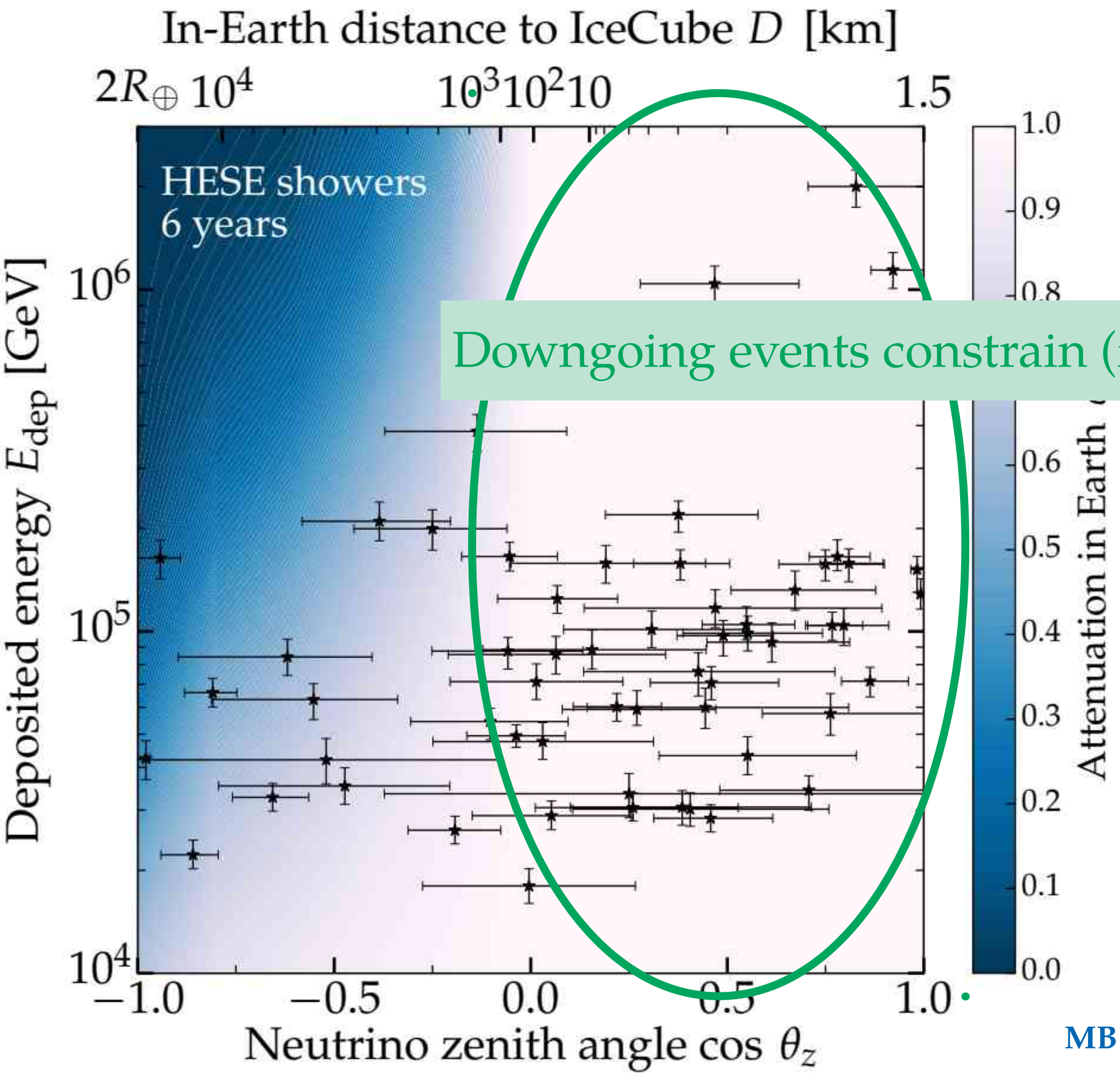
Pro: Lots of events (~10k used)

Con: Uncertain estimates of E_ν

Ref.: IceCube, *Nature* 2017, 1711.08119



MB & Connolly, 1711.11043

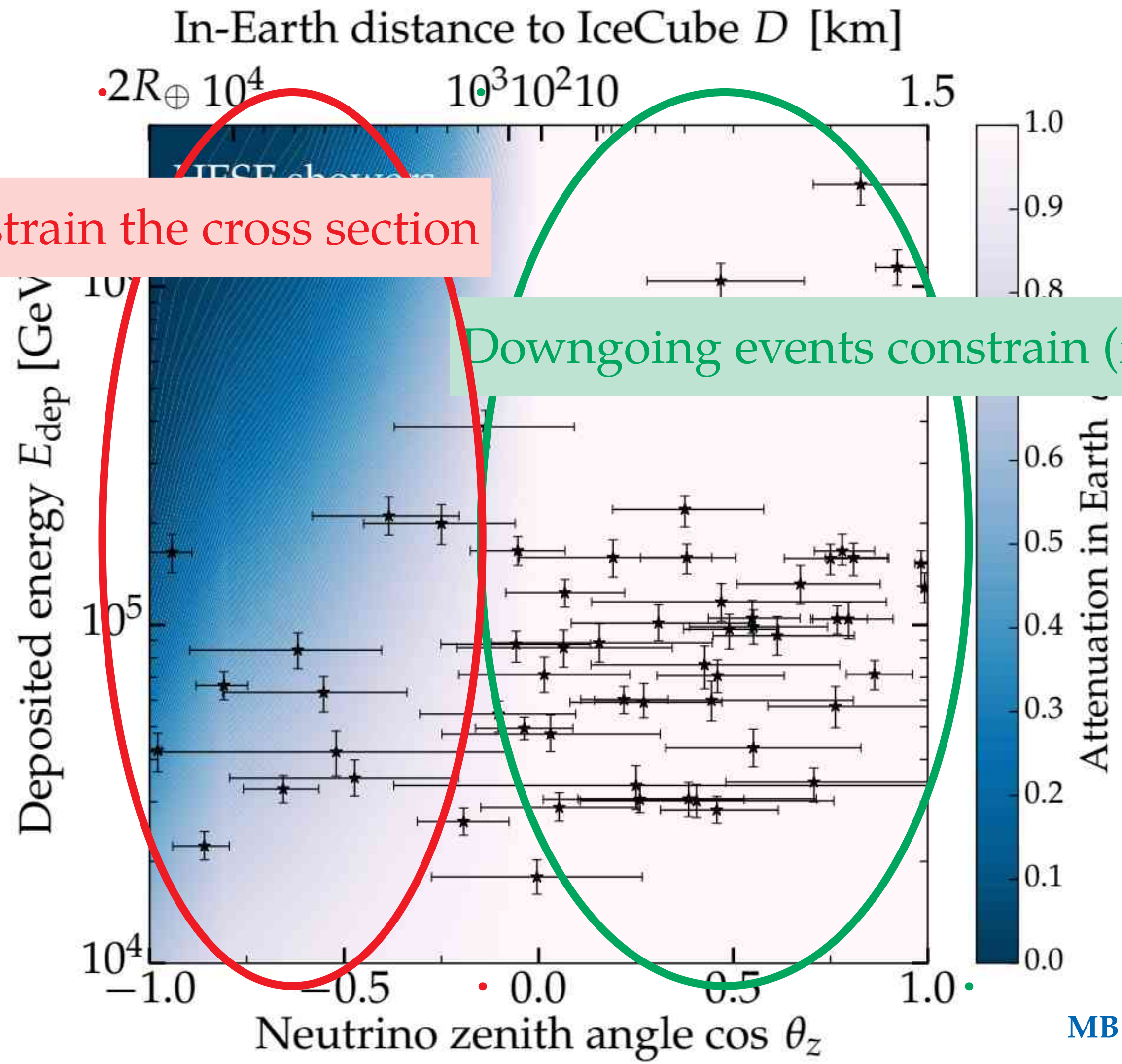


Downgoing events constrain (flux x cross section)

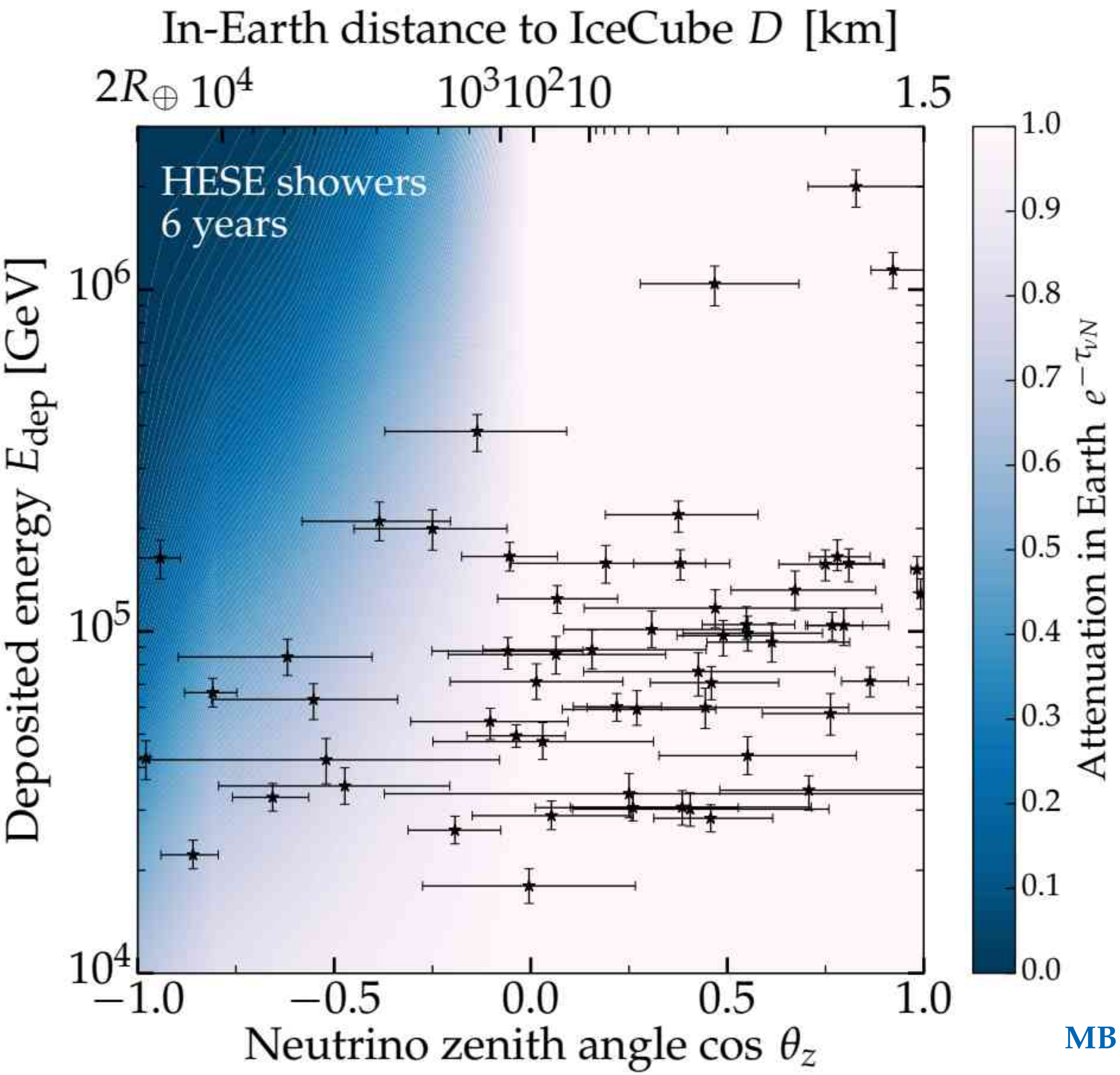
MB & Connolly, 1711.11043

Upgoing events constrain the cross section

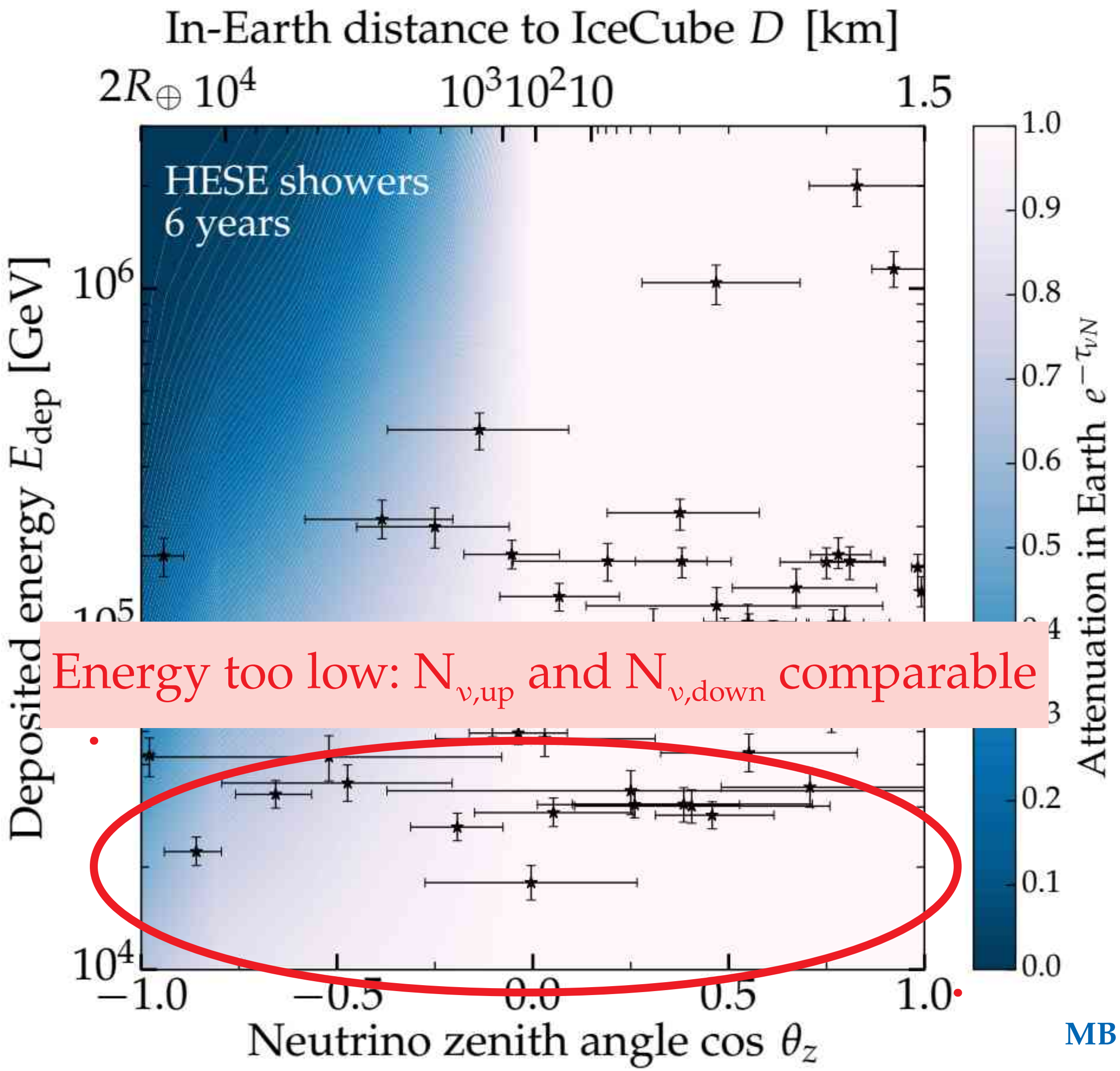
Downgoing events constrain (flux x cross section)



MB & Connolly, 1711.11043

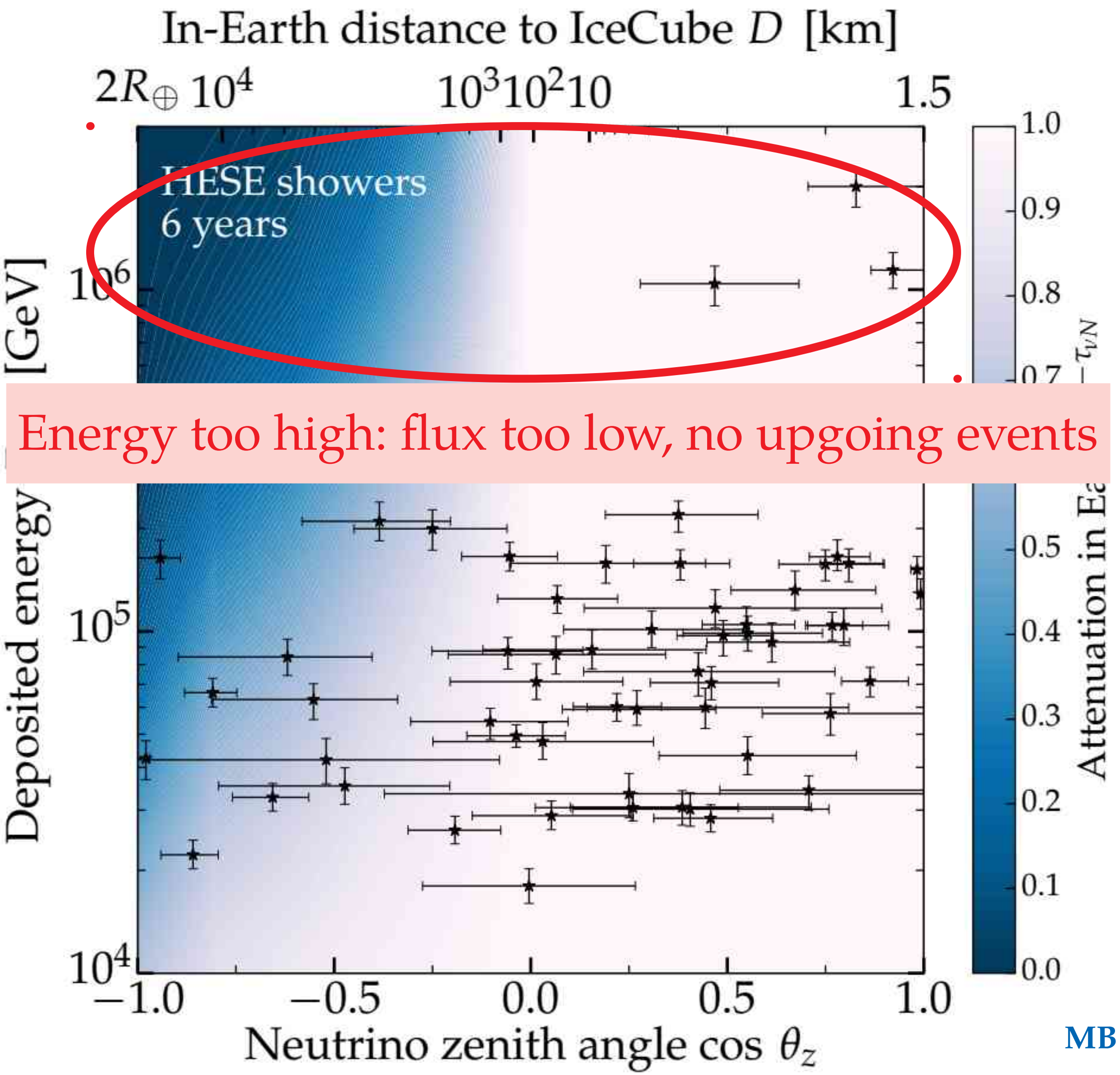


MB & Connolly, 1711.11043

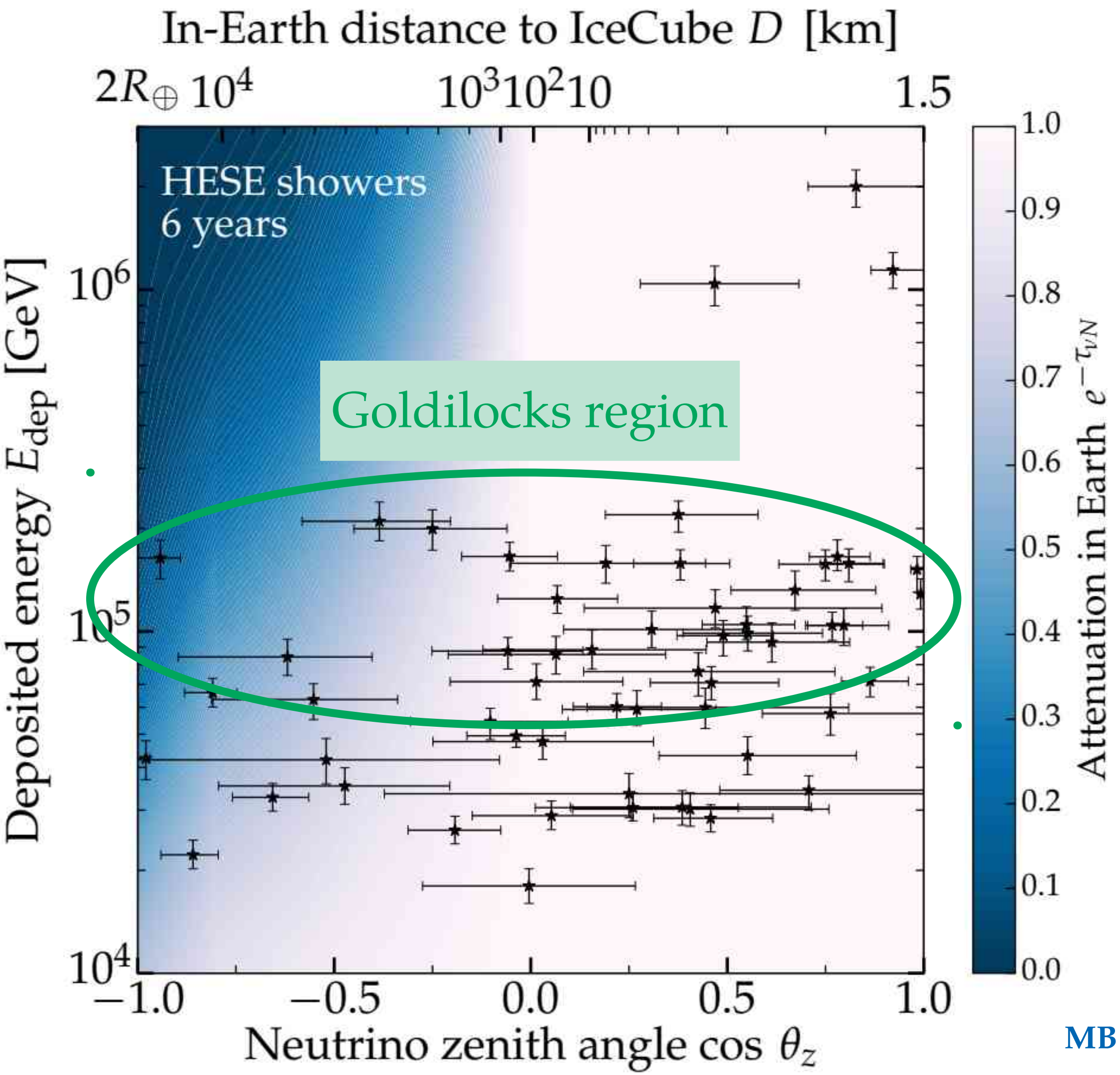


Energy too low: $N_{\nu,up}$ and $N_{\nu,down}$ comparable

MB & Connolly, 1711.11043



MB & Connolly, 1711.11043

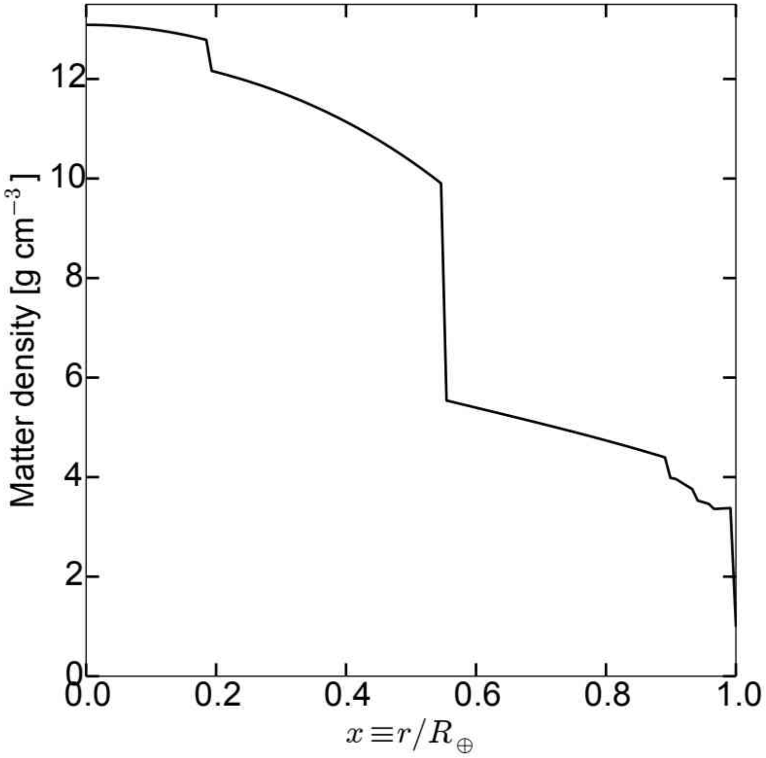


MB & Connolly, 1711.11043

A feel for the in-Earth attenuation

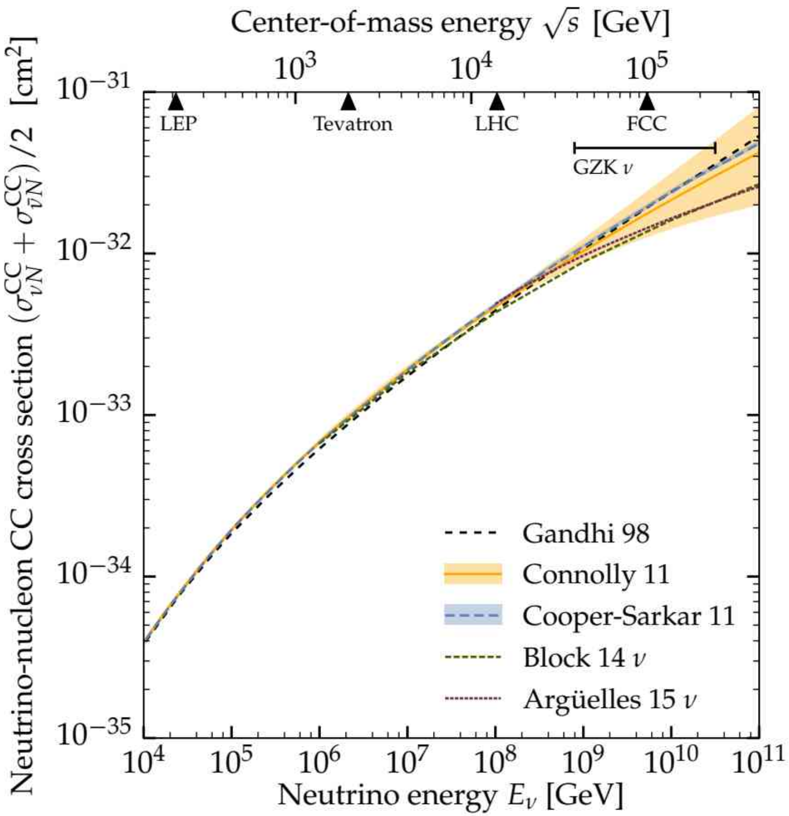
Earth matter density

(Preliminary Reference Earth Model)



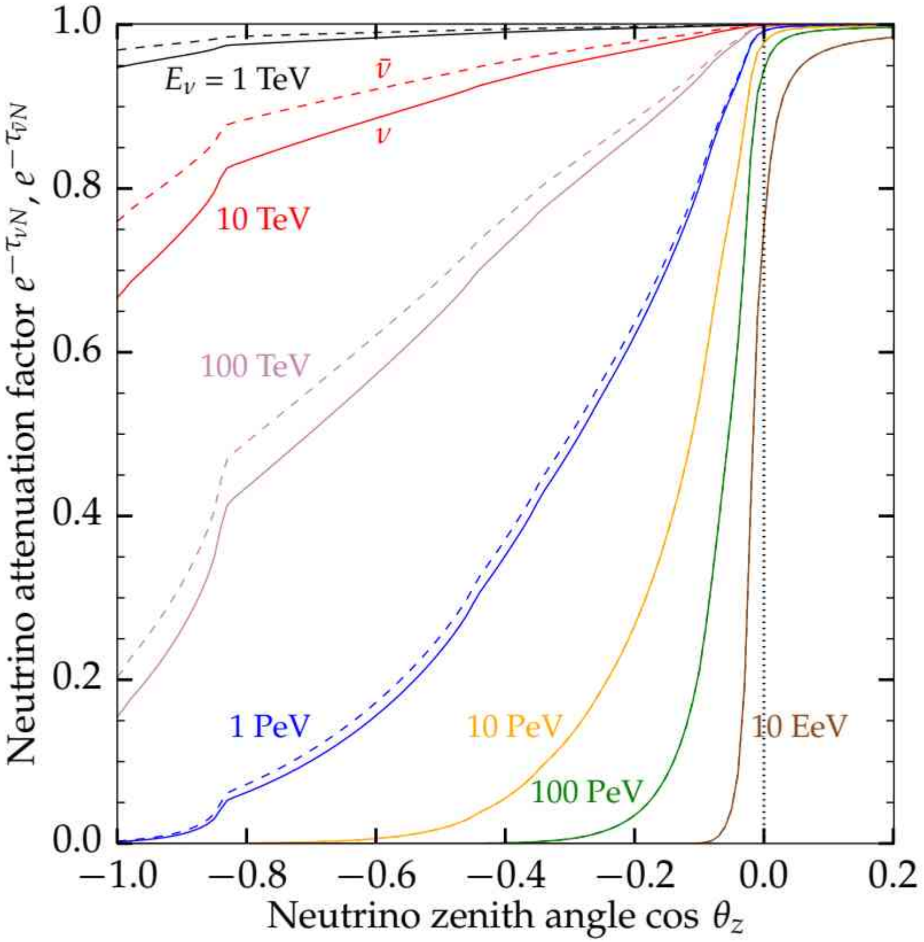
+

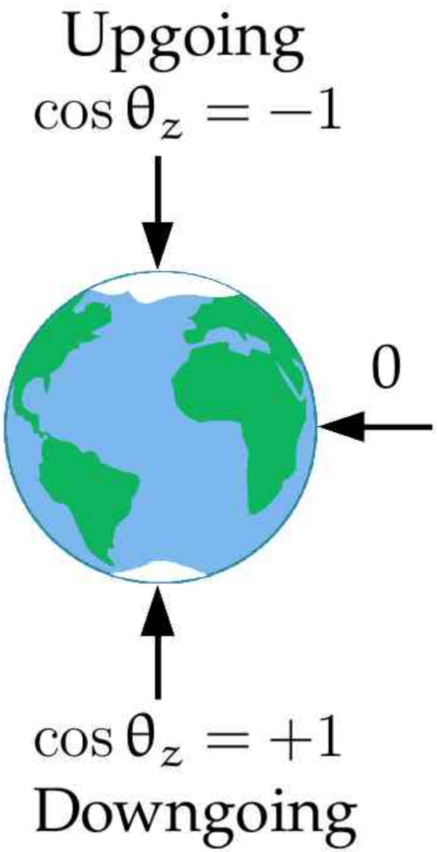
Neutrino-nucleon cross section



A feel for the in-Earth attenuation

=





Cross section from contained events

- $\sigma_{\nu N}$ varies with neutrino energy ⇒ use events where E_ν is well-reconstructed

- These are IceCube High-Energy Starting Events (HESE):
  - νN interaction occurs inside the detector
  - ☑ **Showers:** completely contained in the detector ($E_{dep} \approx E_\nu$)
  - ☒ **Tracks:** partially contained ($E_{dep} < E_\nu$)

- We use the 58 publicly available HESE showers (6-year sample)

- HESE tracks *could* be used
  – but we would need non-public data to reconstruct E_ν without bias

Sensitivity to σ in each bin

Number of contained events in an energy bin:

$$N_\nu \sim \Phi_\nu \cdot \sigma_{\nu N} \cdot e^{-\tau} = \Phi_\nu \cdot \sigma_{\nu N} \cdot e^{-L\sigma_{\nu N} n_N}$$

Downgoing (no matter)

$$N_{\nu,\mathrm{dn}} \sim \Phi_\nu \cdot \sigma_{\nu N}$$

Downgoing events fix the product $\Phi_\nu \cdot \sigma_{\nu N}$

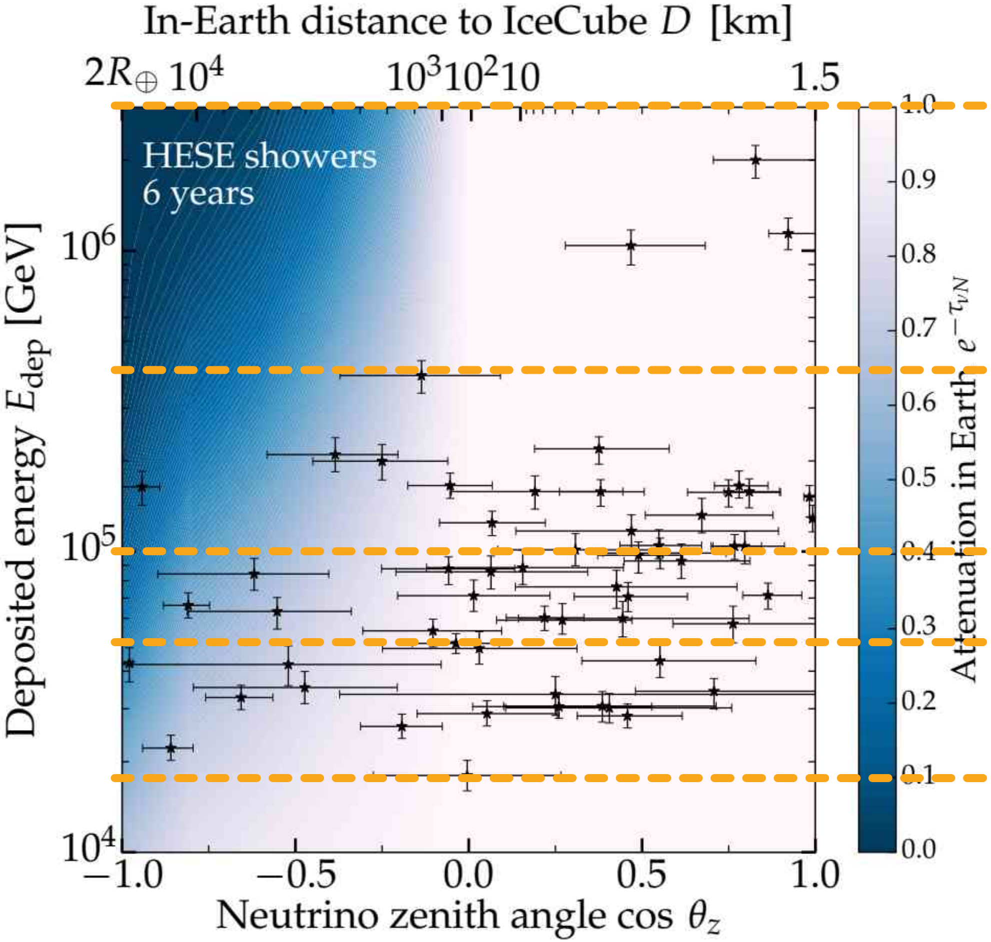
Upgoing (lots of matter)

$$N_{\nu,\mathrm{up}} \sim N_{\nu,\mathrm{dn}} \cdot e^{-\tau}$$

Upgoing events measure $\sigma_{\nu N}$ via τ

Reality check:
Few events (per energy bin), so we are statistics-limited

Bin-by-bin analysis



400–2004 TeV (3 showers)

100–400 TeV (20 showers)

50–100 TeV (18 showers)

18–50 TeV (17 showers)

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 $\sigma_{NC} = \sigma_{CC}/3$

- IceCube does not **distinguish ν from $\bar{\nu}$**, and their cross-sections are different

  $\mapsto$ We assume equal fluxes, expected from production via pp collisions

  $\mapsto$ We assume the avg. ratio $\langle\sigma_{\bar{\nu}N}/\sigma_{\nu N}\rangle$ in each bin known, from SM predictions

- The **flavor composition** of astrophysical neutrinos is still uncertain

  $\mapsto$ We assume equal flux of each flavor, compatible with theory and observations

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
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  - 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

Energy and angular shower spectra

Rate from all flavors, CC + NC:

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

Contribution from one flavor CC:

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

Conversion between shower energy and neutrino energy:

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

MB & A. Connolly, 1711.11043

Detector resolution

Number of contained showers:

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

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

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

IceCube, *JINST* 2014

Angular resolution:

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

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

MB & A. Connolly, 1711.11043

Likelihood

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

Each energy bin is independent

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

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

Depends on $\sigma_{\nu N}$

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

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

PDF for this shower to be made by an atmospheric ν

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

PDF for this shower to be made by an astrophysical ν

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

Best-fit values and uncertainties

TABLE II. Best-fit values and 1σ uncertainties of the nuisance parameters in each energy bin: number of showers due to atmospheric neutrinos $N_{\rm sh}^{\rm atm}$, number of showers due to astrophysical neutrinos $N_{\rm sh}^{\rm ast}$, and astrophysical spectral index γ.

E_ν [TeV]	$N_{\rm sh}^{\rm atm}$	$N_{\rm sh}^{\rm ast}$	γ
18–50	4.2 ± 4.9	11.4 ± 3.5	2.38 ± 0.31
50–100	6.3 ± 5.3	11.7 ± 4.5	2.43 ± 0.31
100–400	6.4 ± 6.0	12.9 ± 5.2	2.49 ± 0.31
400–2004	1.2 ± 1.0	1.73 ± 0.89	2.37 ± 0.32

MB & A. Connolly, 1711.11043

How to do better / more?

- Currently, we are statistics-limited
  $\mapsto$ Solvable with more data from IceCube, IceCube-Gen2, KM3NeT
- Large errors in arrival direction (~10°) give errors in attenuation
  $\mapsto$ Solvable with ongoing IceCube improvements + KM3NeT
- Charged-current + neutral-current cross sections are indistinguishable
  $\mapsto$ Solvable (?) with muon and neutron echoes (Li, MB, Beacom 16)
- Cannot separate ν from $\bar{\nu}$
  $\mapsto$ Wait to detect Glashow resonance (~6.3 PeV), sensitive only to $\bar{\nu}_e$
- Use starting tracks / through-going muons
  $\mapsto$ Doable / done by IceCube (more next)

Marginalized cross section in each bin

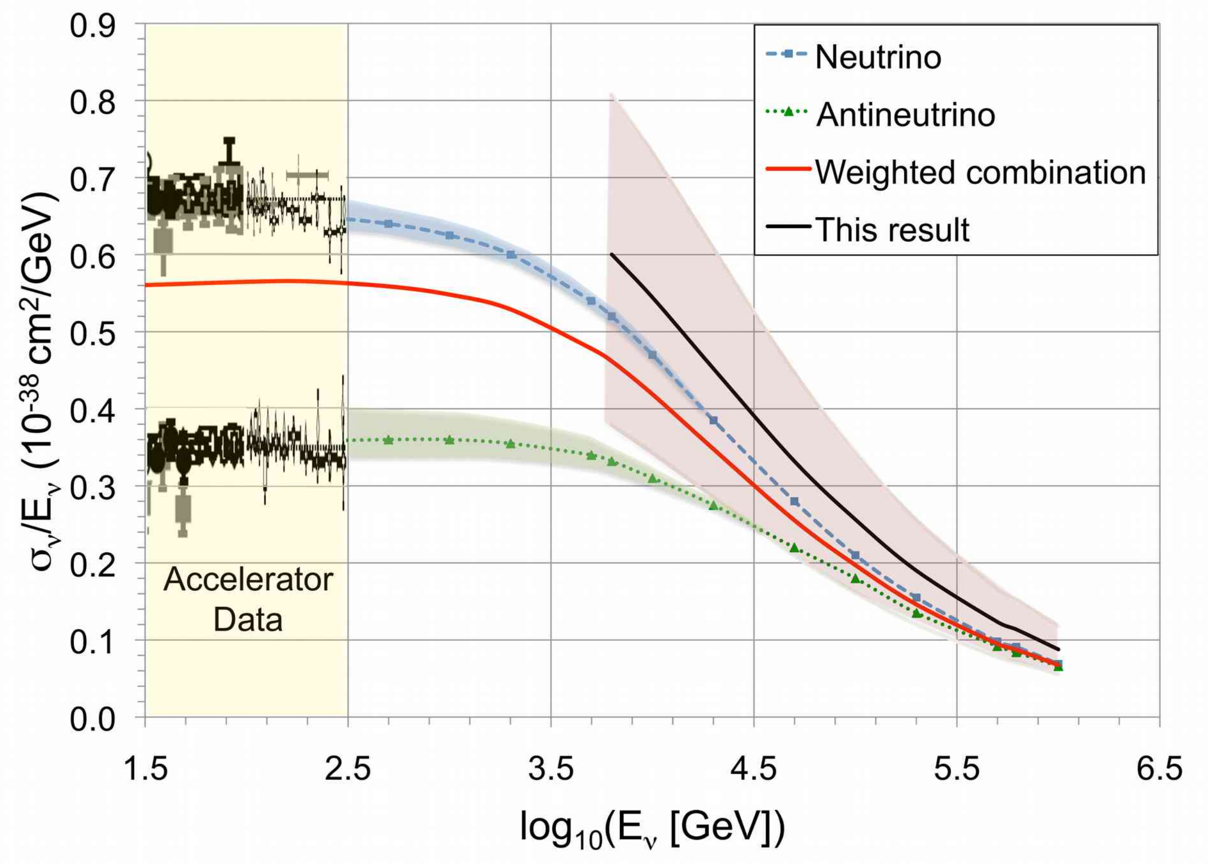
TABLE I. Neutrino-nucleon charged-current inclusive cross sections, averaged between neutrinos ($\sigma_{\nu N}^{\rm CC}$) and anti-neutrinos ($\sigma_{\bar{\nu} N}^{\rm CC}$), extracted from 6 years of IceCube HESE showers. To obtain these results, we fixed $\sigma_{\bar{\nu} N}^{\rm CC} = \langle \sigma_{\bar{\nu}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

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

MB & A. Connolly, 1711.11043

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}
  $1.30^{+0.21}_{-0.19}$ (stat.)$^{+0.39}_{-0.43}$ (syst.)
- All events grouped in a single energy bin 6–980 TeV



IceCube, *Nature* 2017

Neutrino zenith angle distribution

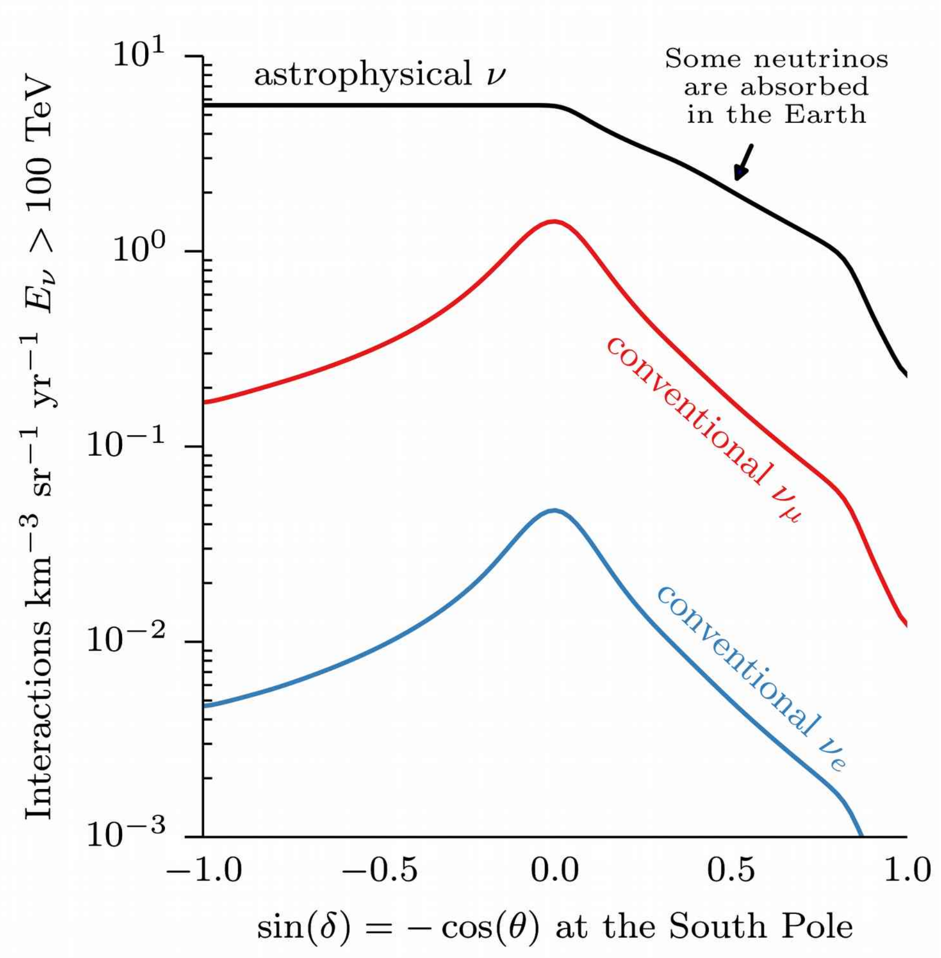
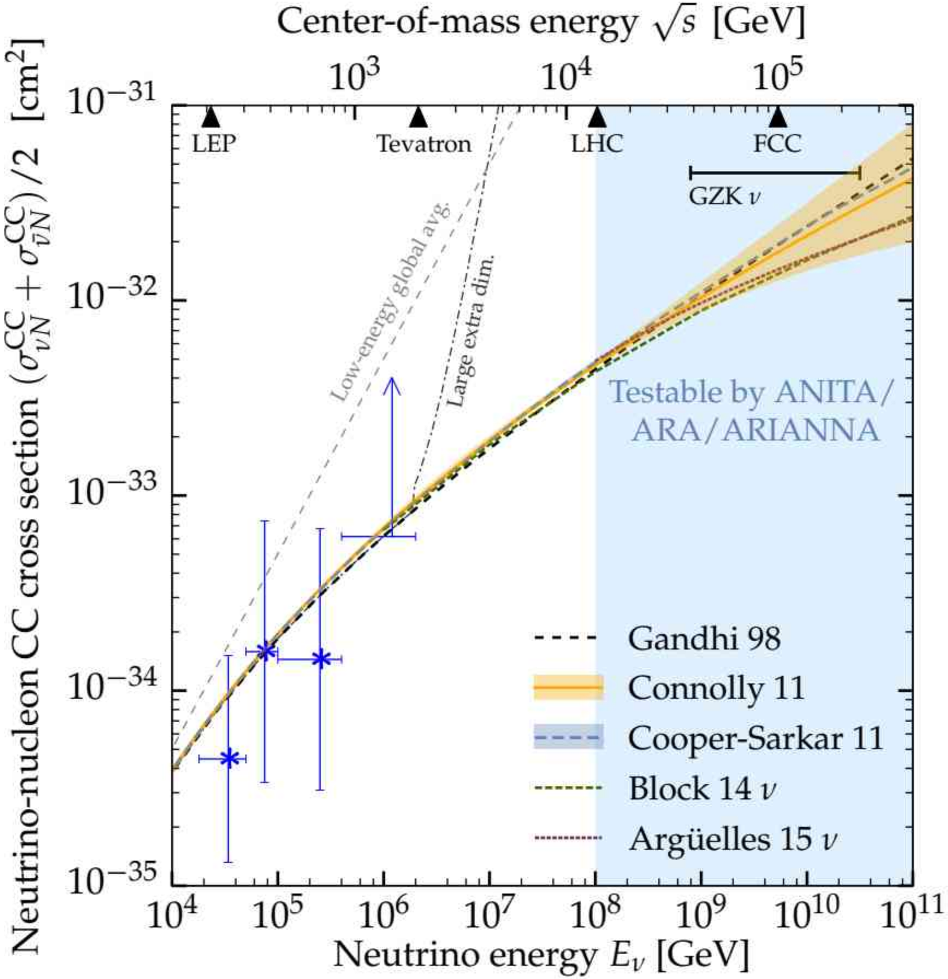
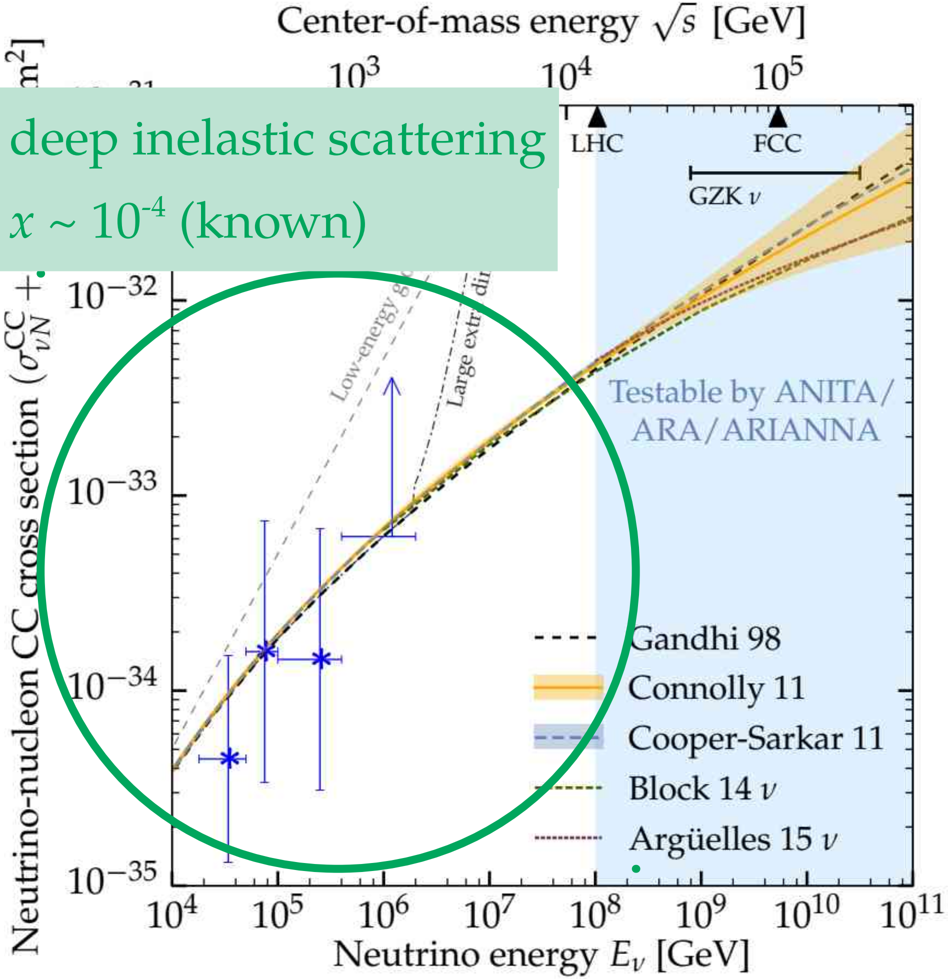


Figure by
Jakob Van Santen
ICRC 2017

IceCube *now* vs. ANITA / ARA / ARIANNA *in the future*

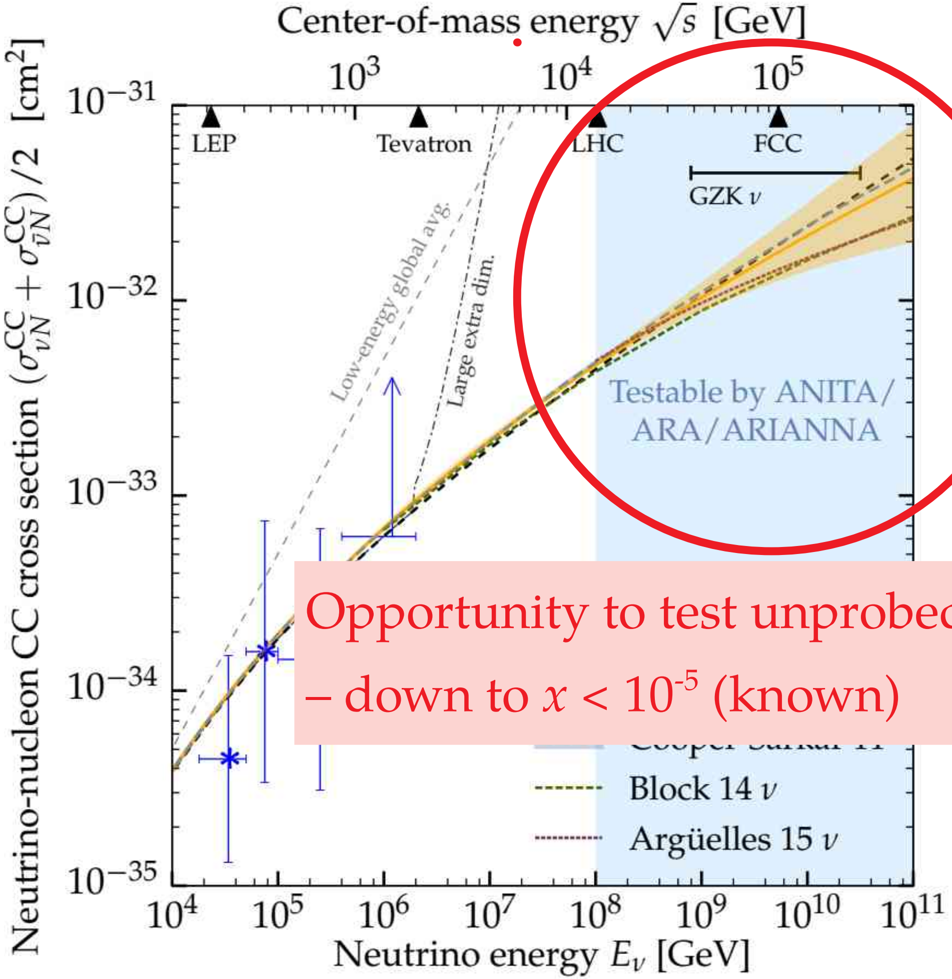


IceCube *now* vs. ANITA/ARA/ARIANNA *in the future*



Test predictions of deep inelastic scattering
– down to PDFs at $x \sim 10^{-4}$ (known)

IceCube *now* vs. ANITA / ARA / ARIANNA *in the future*



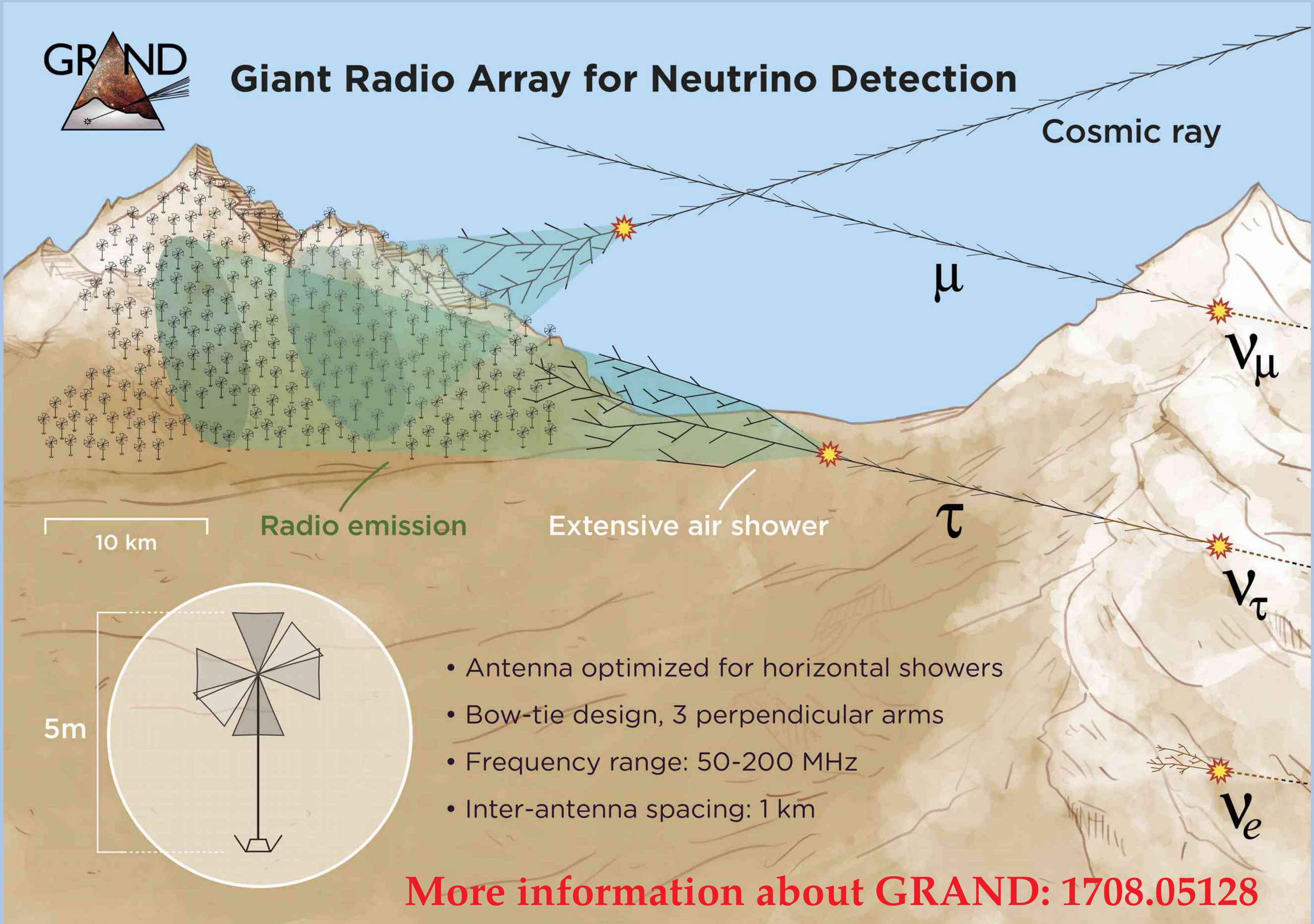
Opportunity to test unprobed nucleon structure – down to $x < 10^{-5}$ (known)

The new ν physics matrix

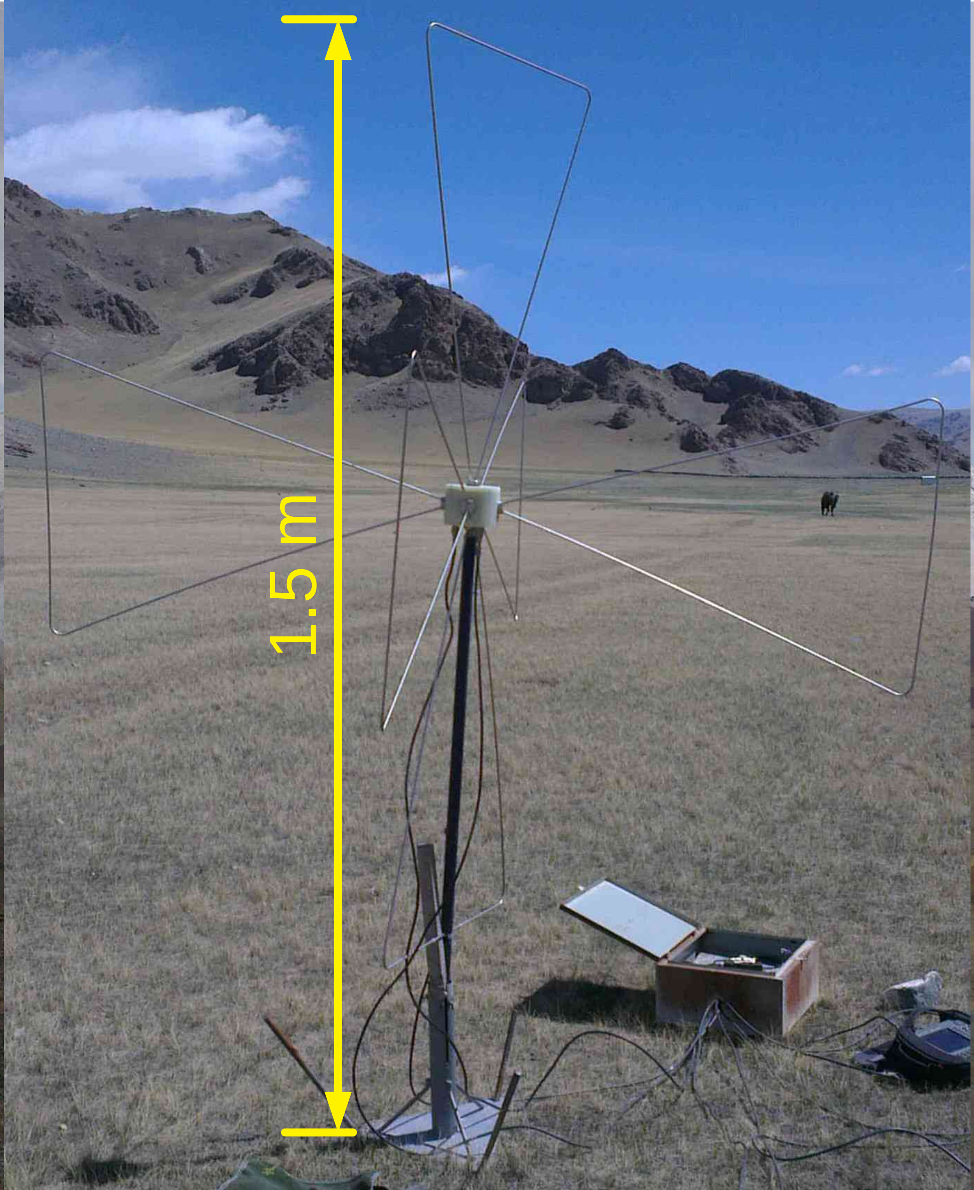
Where it happens

What it changes	At source	During propagation	At detection
Energy	Matter effects	New interactions, sterile neutrinos	New resonances
Direction	DM decay / annihilation	New ν-N, ν-DM interactions	Anomalous ν magnetic moment
Topology / flavor	Matter effects	ν decay, sterile ν, new operators	Non-standard interactions
Time		Lorentz-invariance violation	

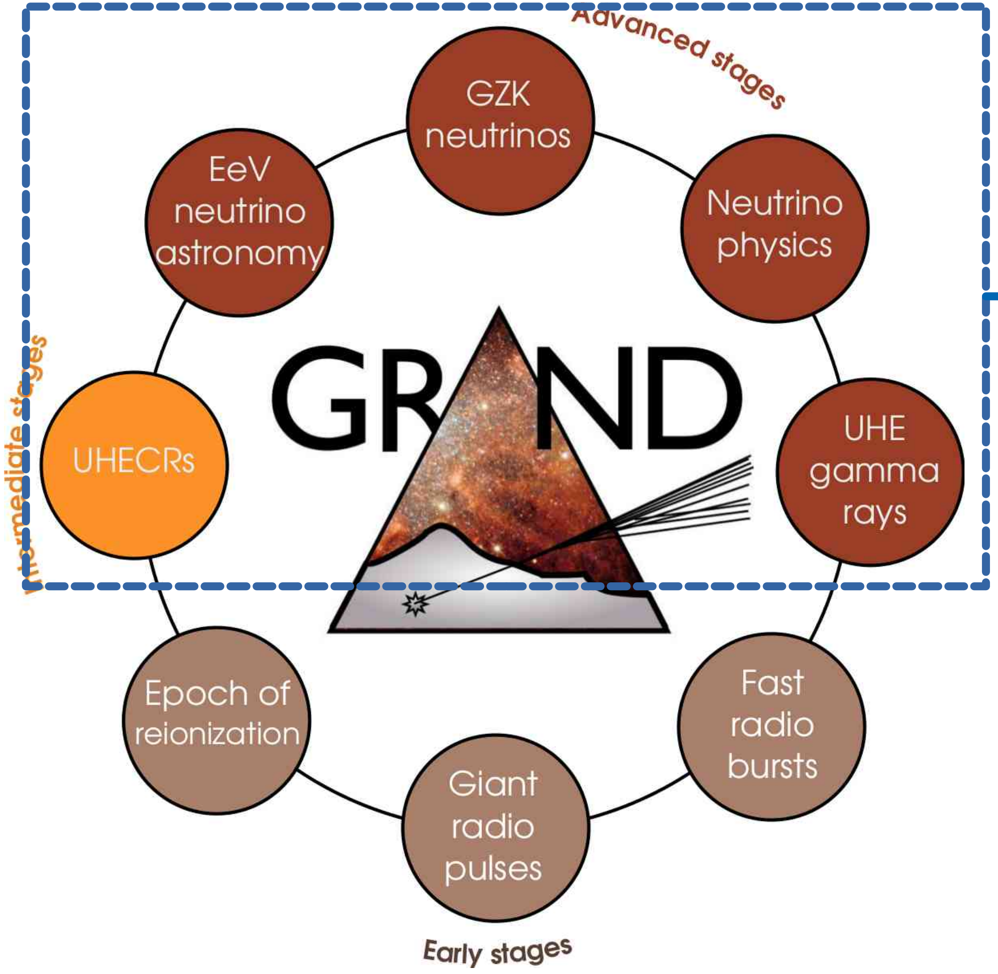
Argüelles, MB, Conrad, Kheirandish, Palomares-Ruiz, Salvadó, Vincent, *In prep.*



More information about GRAND: 1708.05128

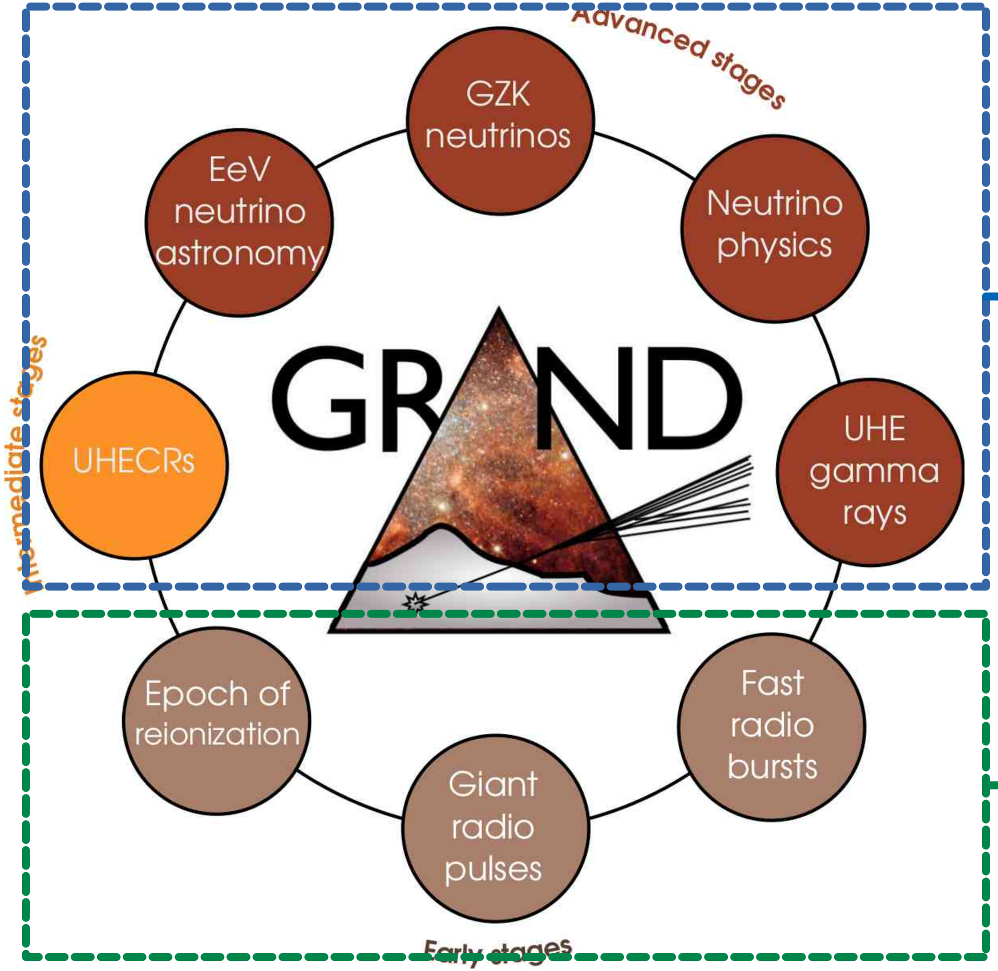

1.5 m


Advanced stages
GZK neutrinos
Neutrino physics
UHE gamma rays
Fast radio bursts
Giant radio pulses
Early stages
Epoch of reionization
UHECRs
Intermediate stages
EeV neutrino astronomy
GRAND



Main goal:

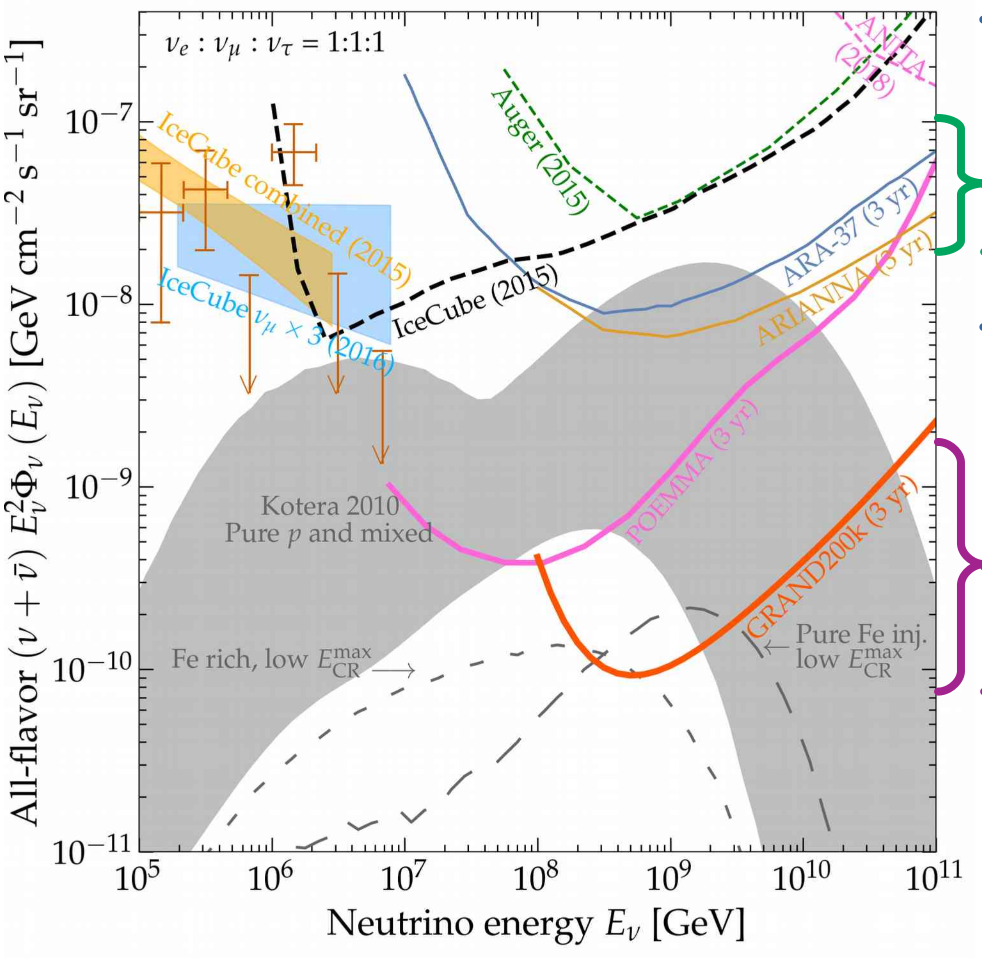
Finding the sources of UHECRs above 10^9 GeV



Main goal:
Finding the sources of UHECRs above 10^9 GeV

Secondary goal:
Radioastronomy and cosmology

UHE Neutrinos – Where Do We Go?



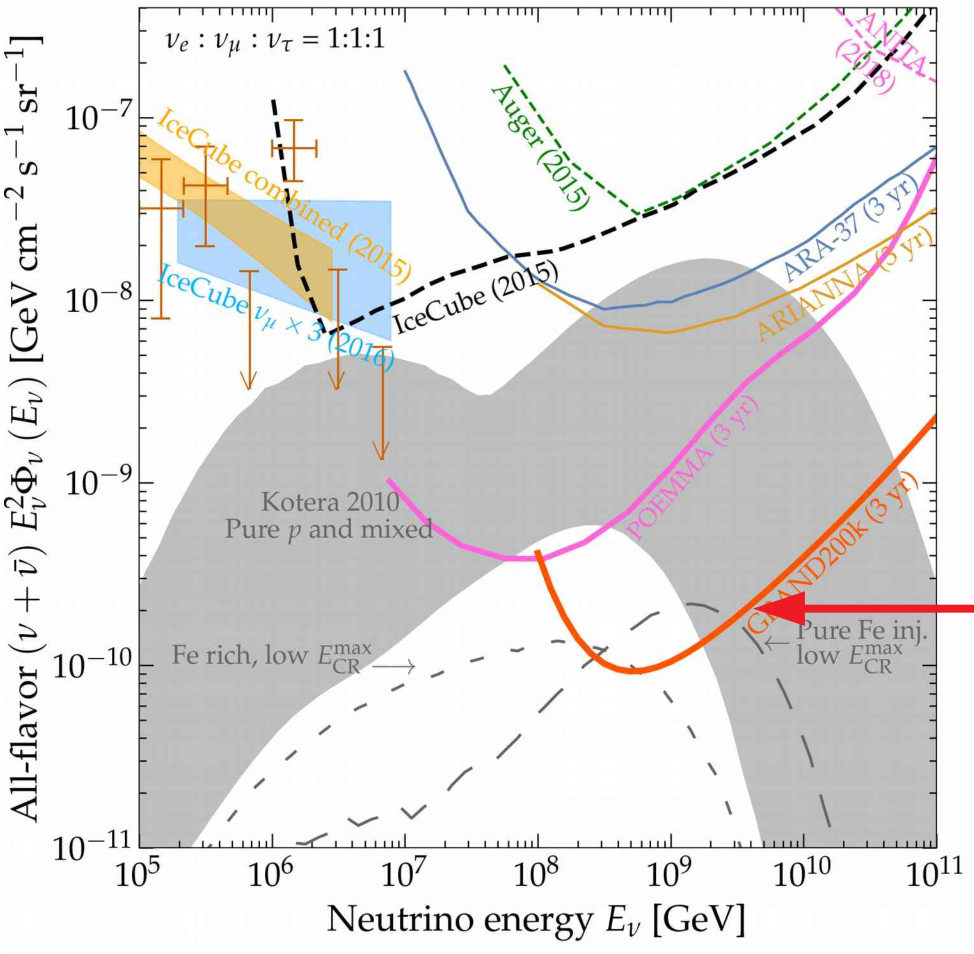
Flux predictions (Kotera 2010)

Existing upper limits

Future reach of existing in-ice radio detectors

Next-gen air-radio and space detectors

UHE Neutrinos – Where Do We Go?



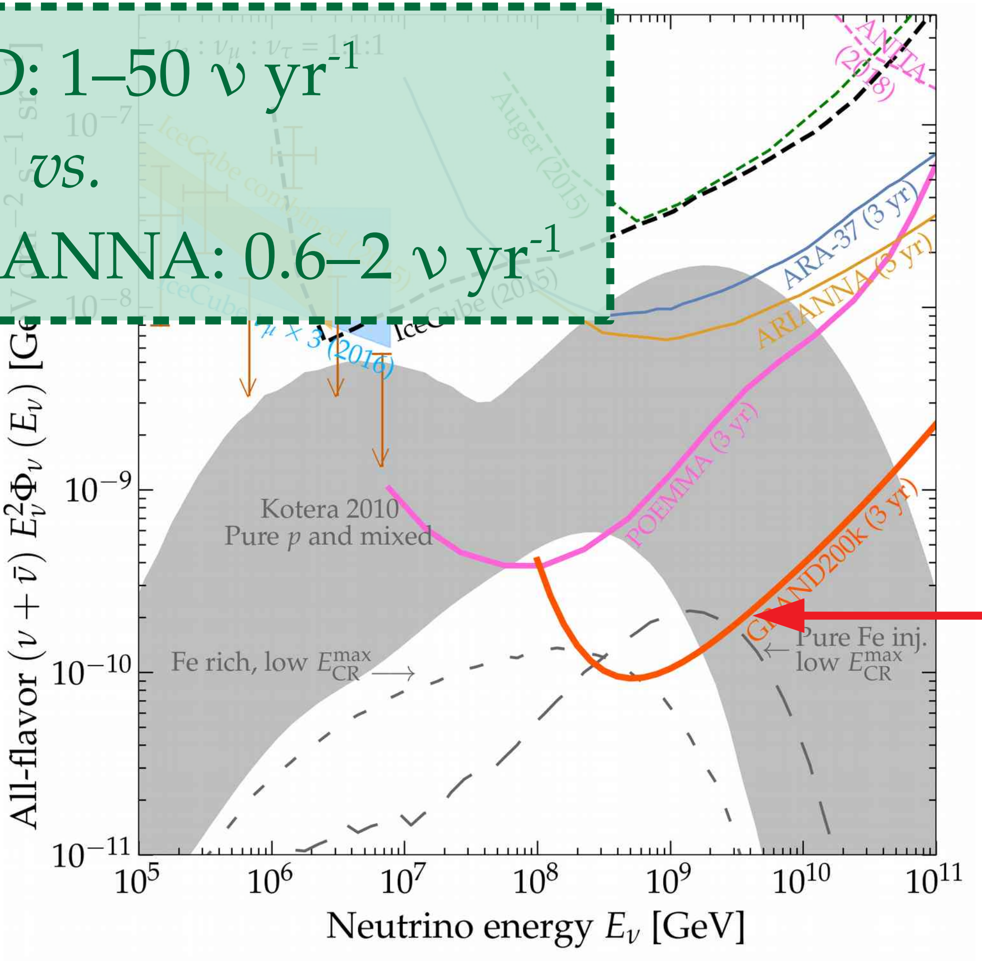
GRAND will probe *very* low fluxes at ~10^9 GeV

UHE Neutrinos – Where Do We Go?

GRAND: 1–50 ν yr^{-1}

vs.

Full ARA, ARIANNA: 0.6–2 ν yr^{-1}



GRAND will probe *very* low fluxes at ~10^9 GeV

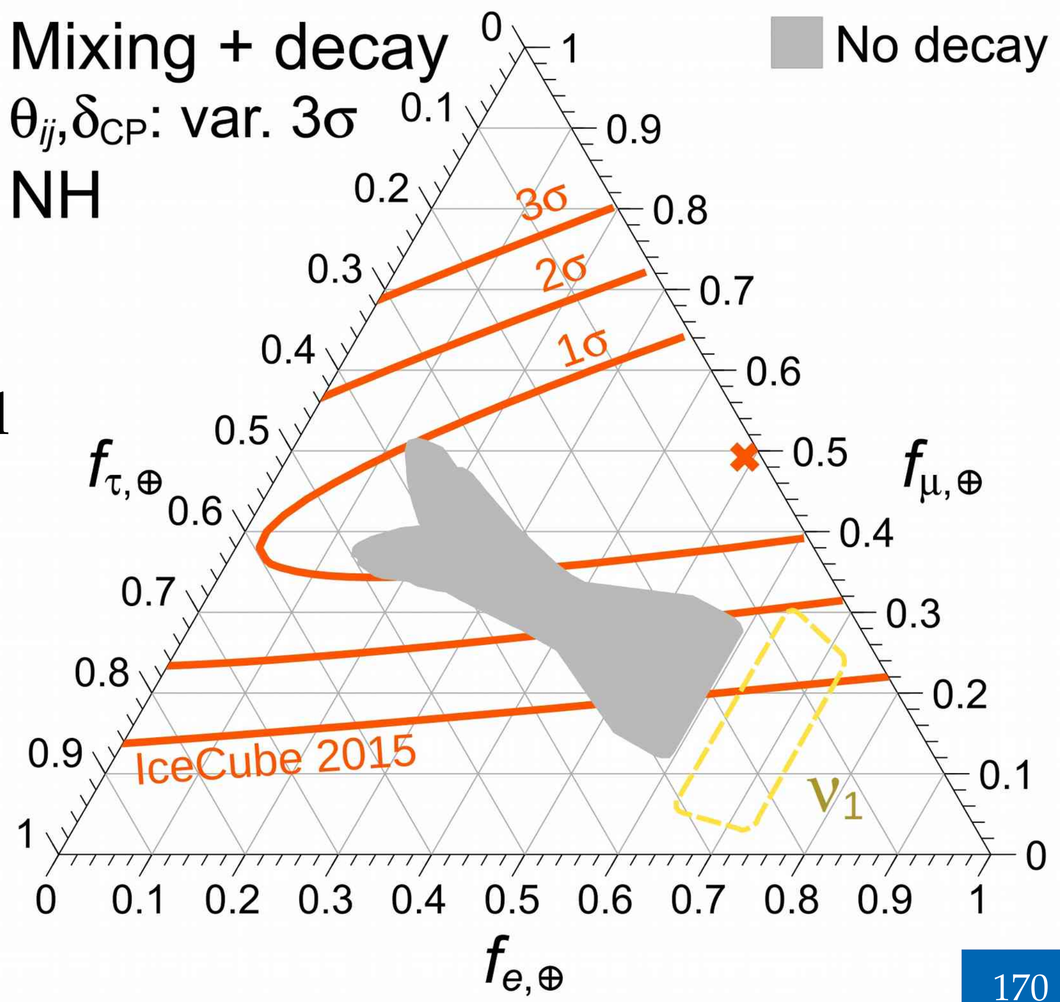
Measuring the neutrino lifetime

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

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

(Assume equal lifetimes of ν_2, ν_3)

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



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Fraction of ν_2, ν_3 remaining at Earth

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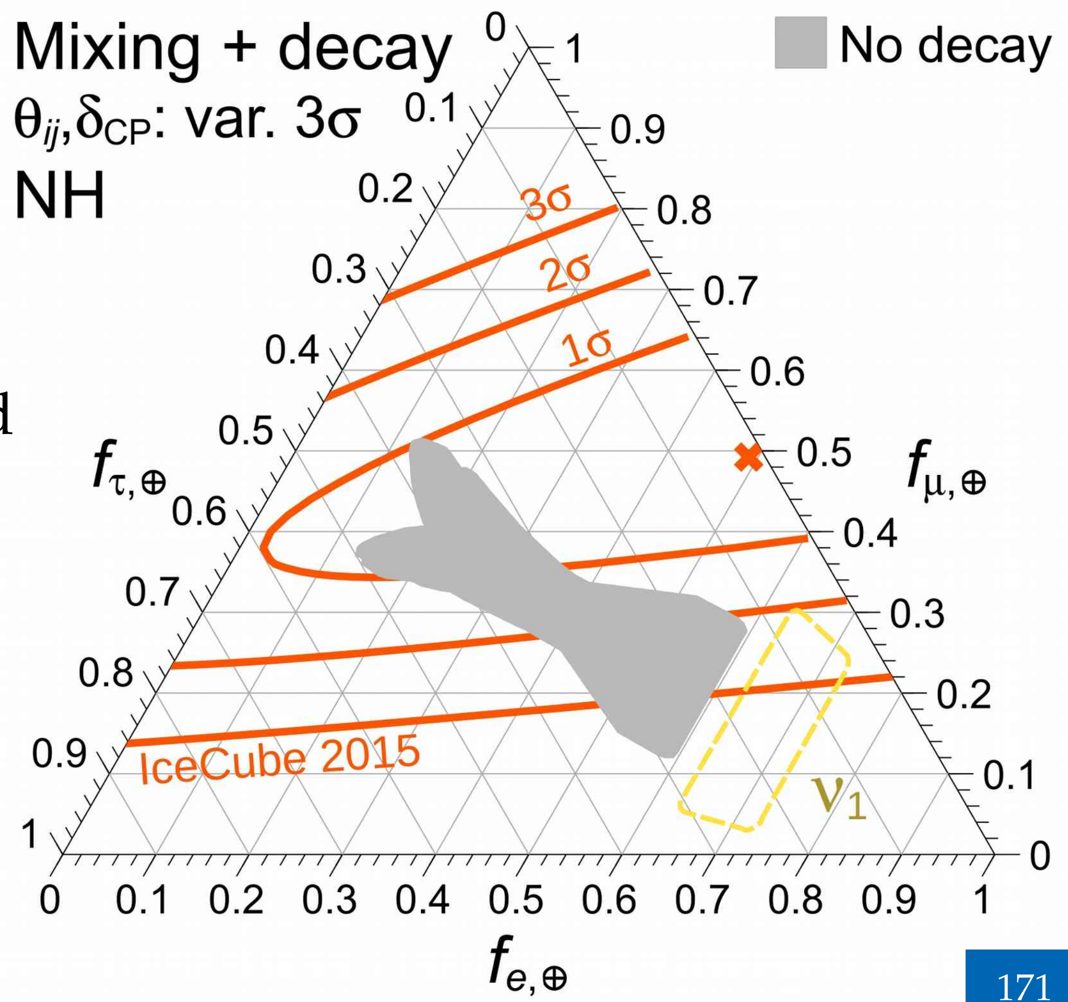

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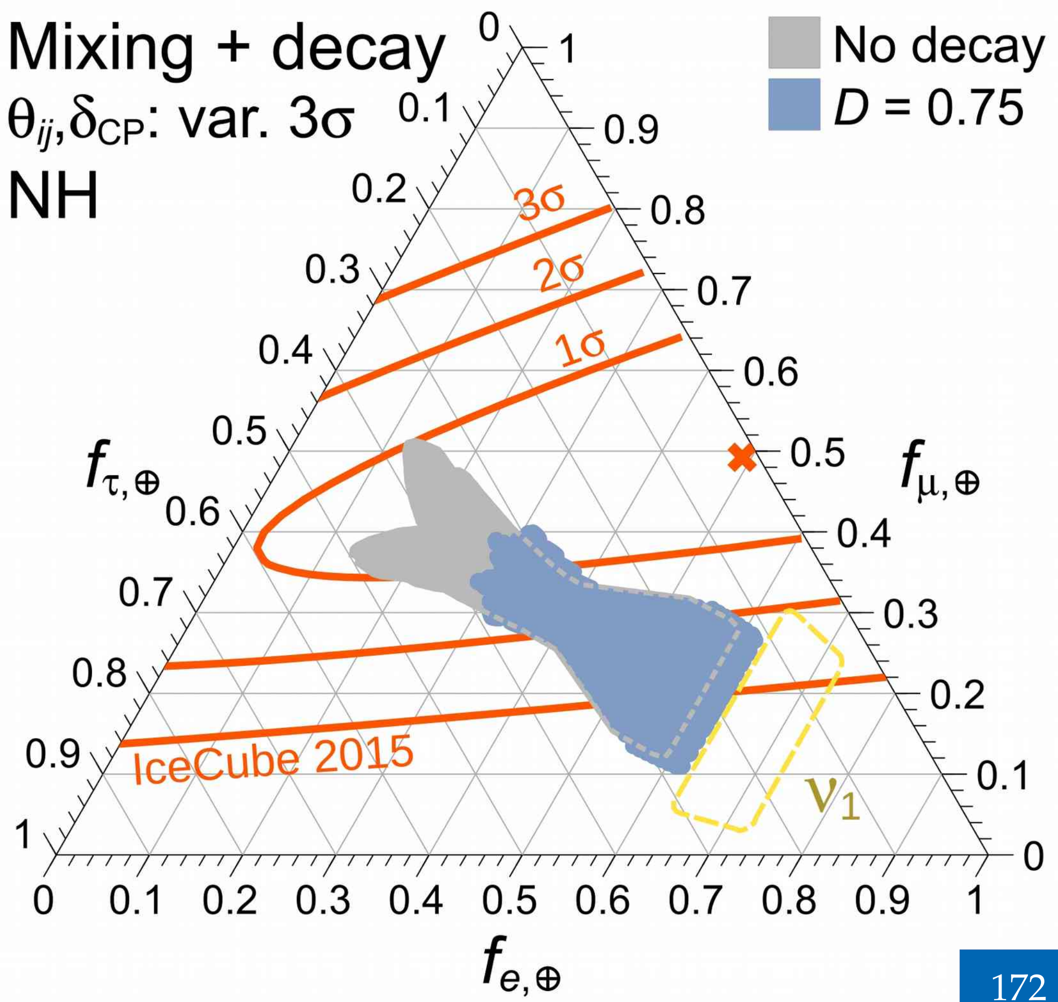

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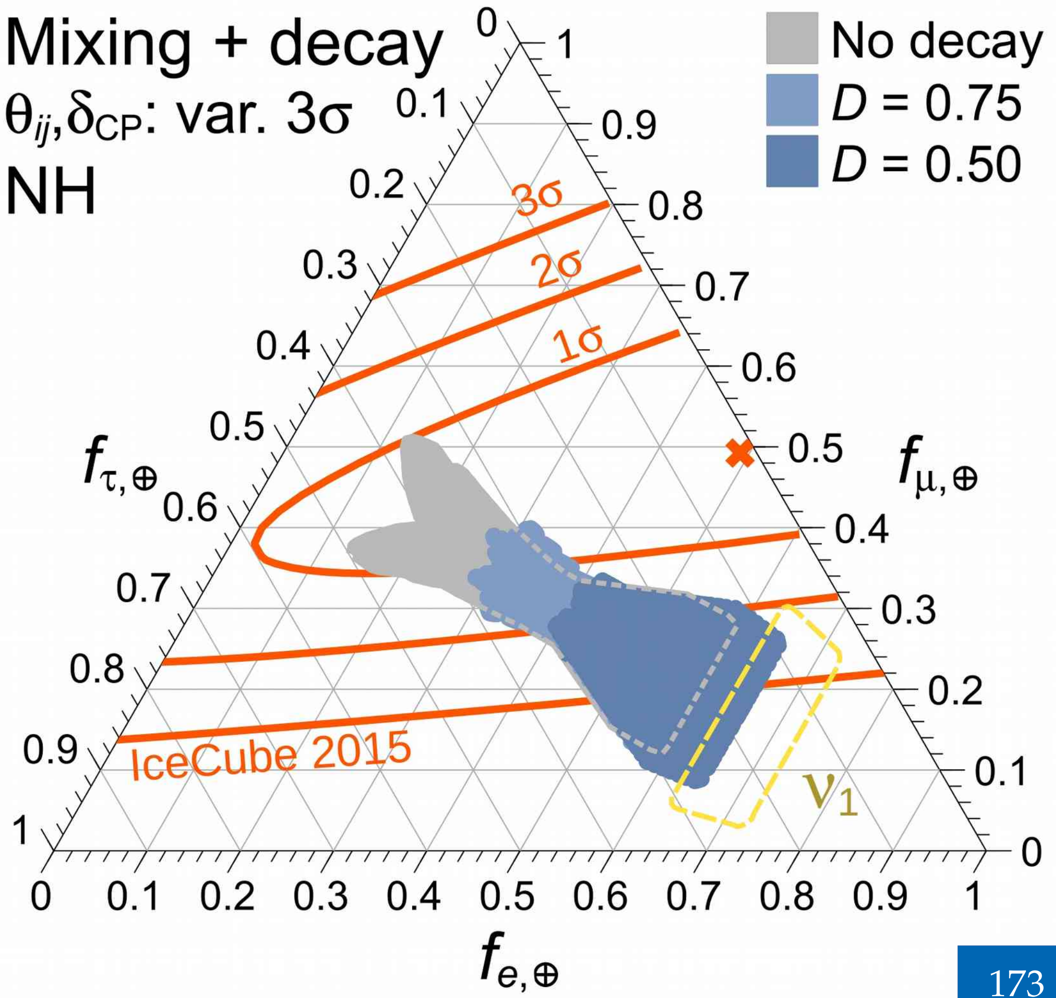

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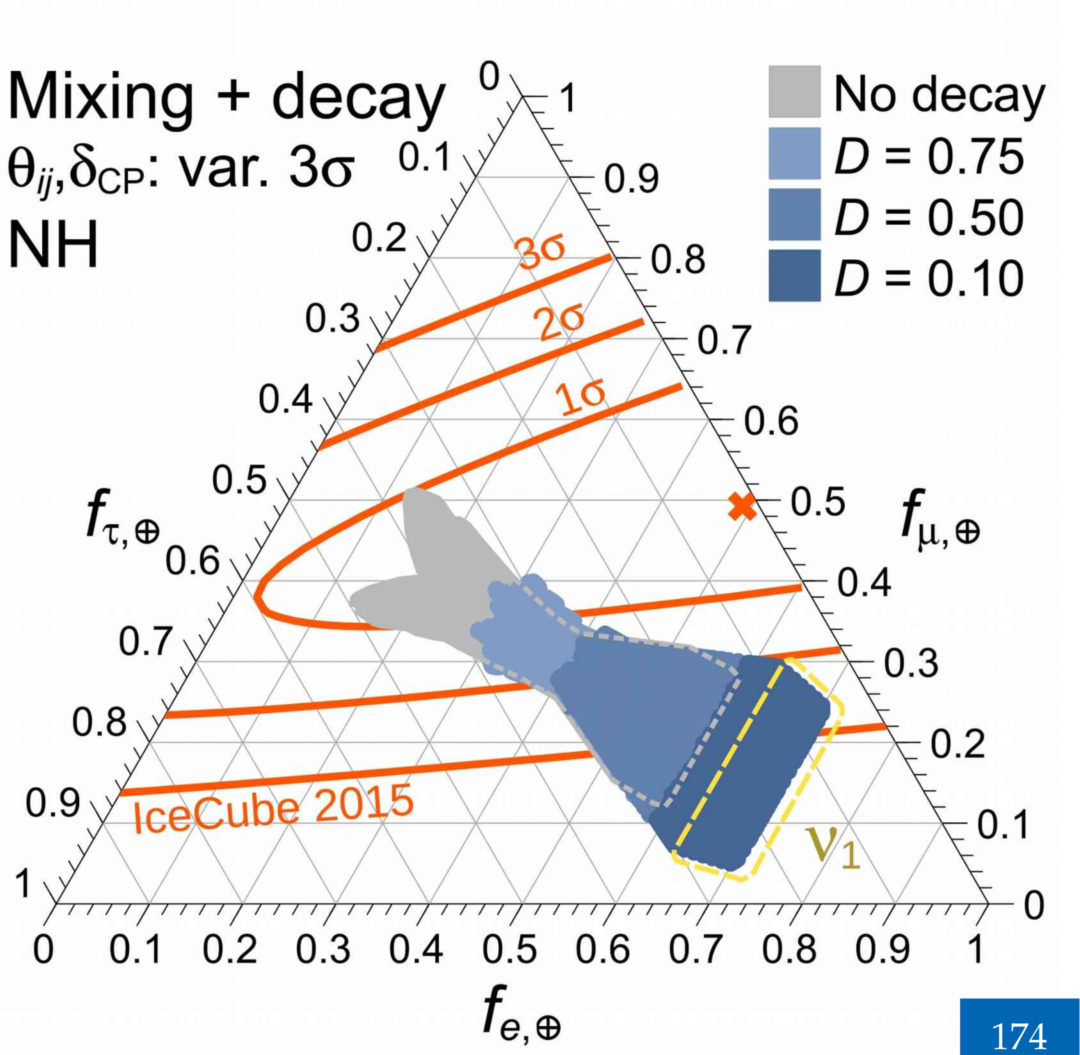

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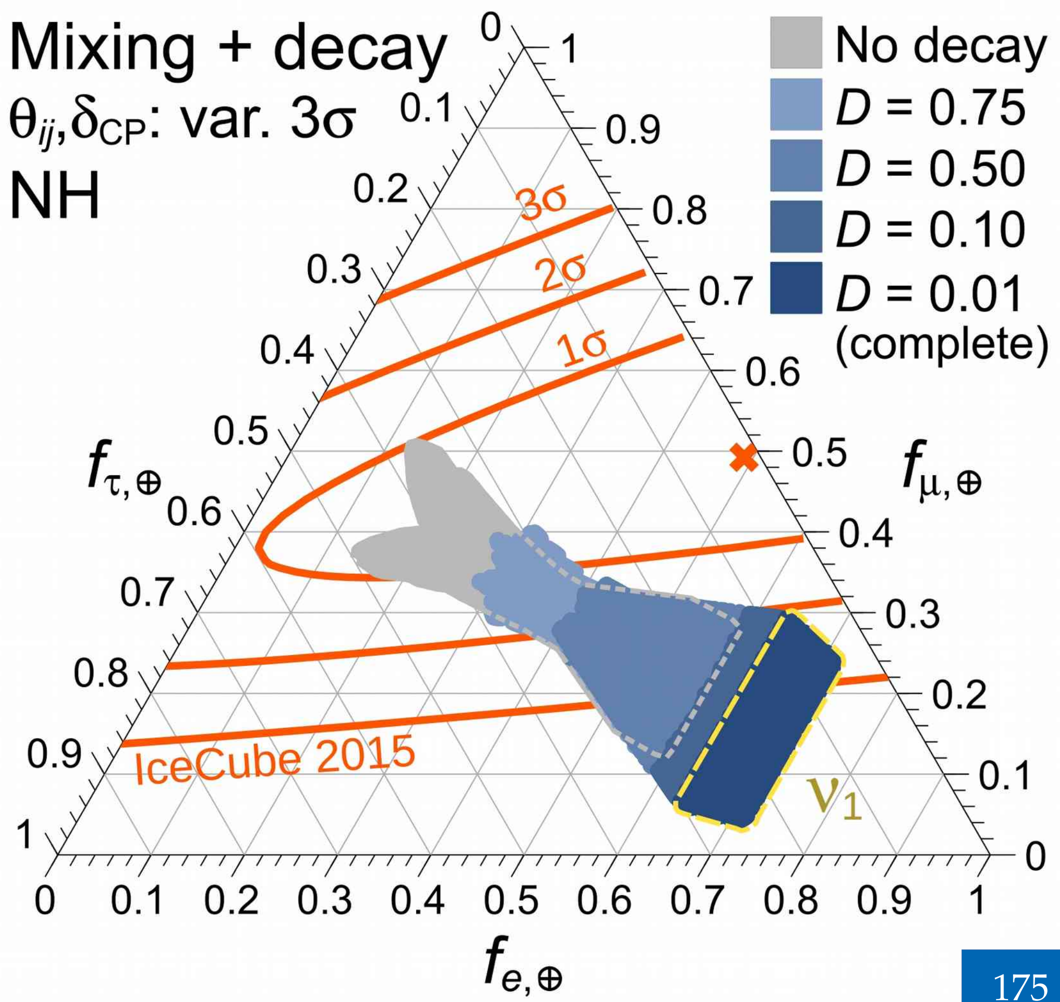

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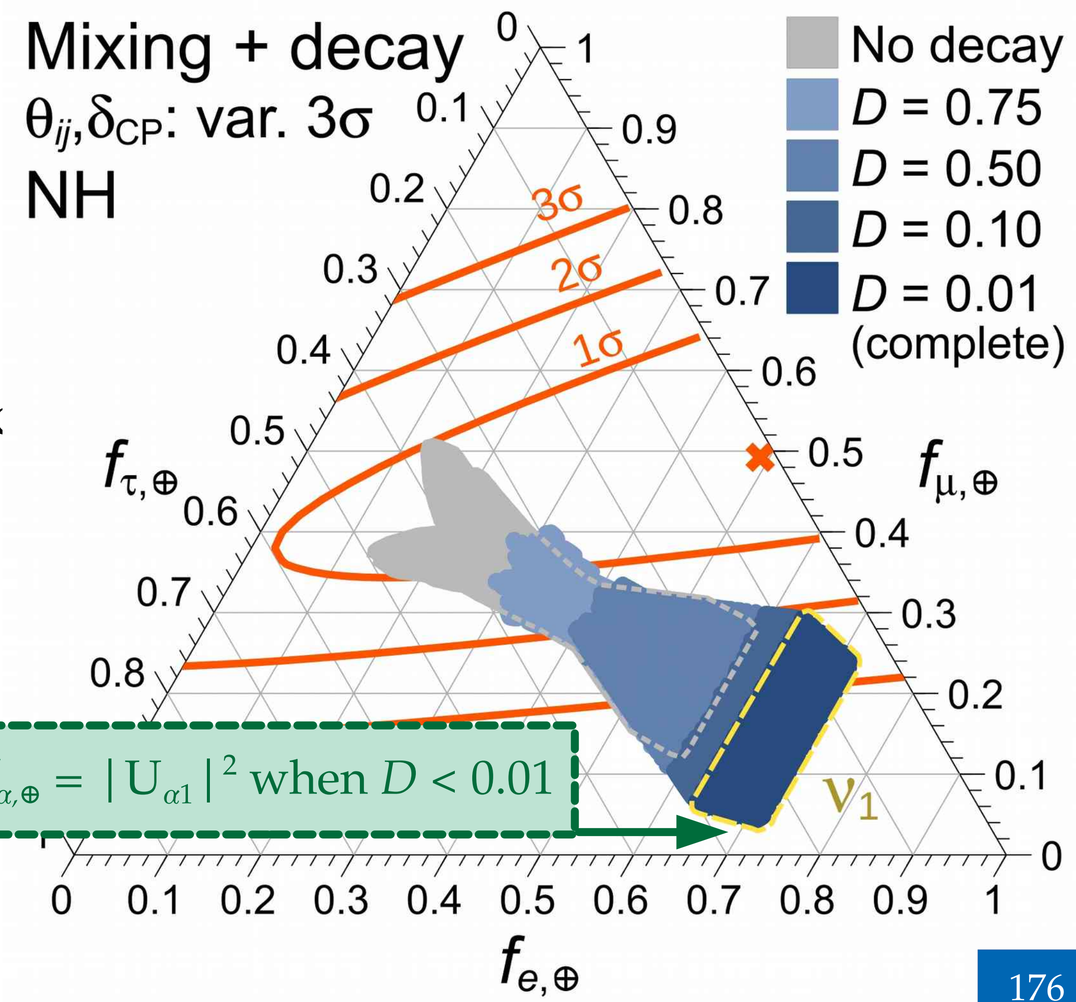

$f_{\alpha,\oplus} = |U_{\alpha 1}|^2$ when $D < 0.01$

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

Electron-neutrino interactions can kill oscillations

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

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

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

Electron-neutrino interactions can kill oscillations

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

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New neutrino-electron interaction:

This is diagonal

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

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

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

Electron-neutrino interactions can kill oscillations

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

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$\sim 1/E$

Energy-independent

Electron-neutrino interactions can kill oscillations

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

$\sim 1/E$

Energy-independent

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

The new potential sourced by an electron

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

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

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

The new potential sourced by an electron

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

Z′ coupling

Z′ mass

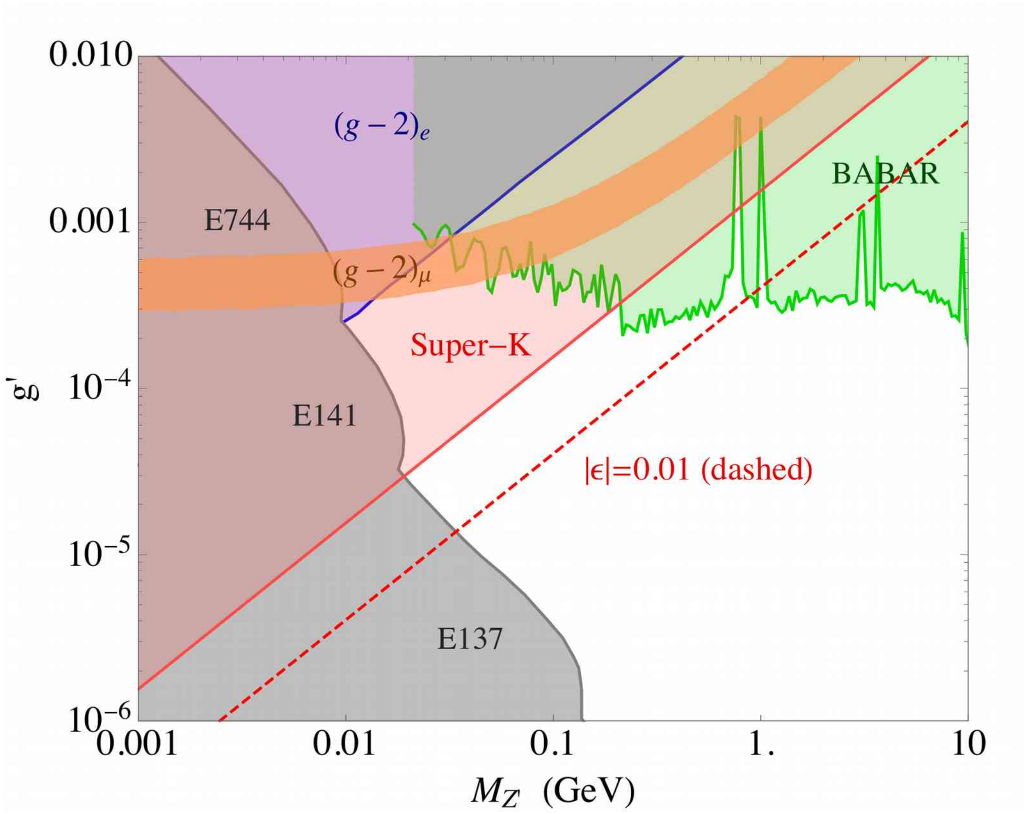
$$V \sim \frac{g'^{2}_{e\beta}}{r} e^{-m'_{e\beta} r}$$

Distance to neutrino

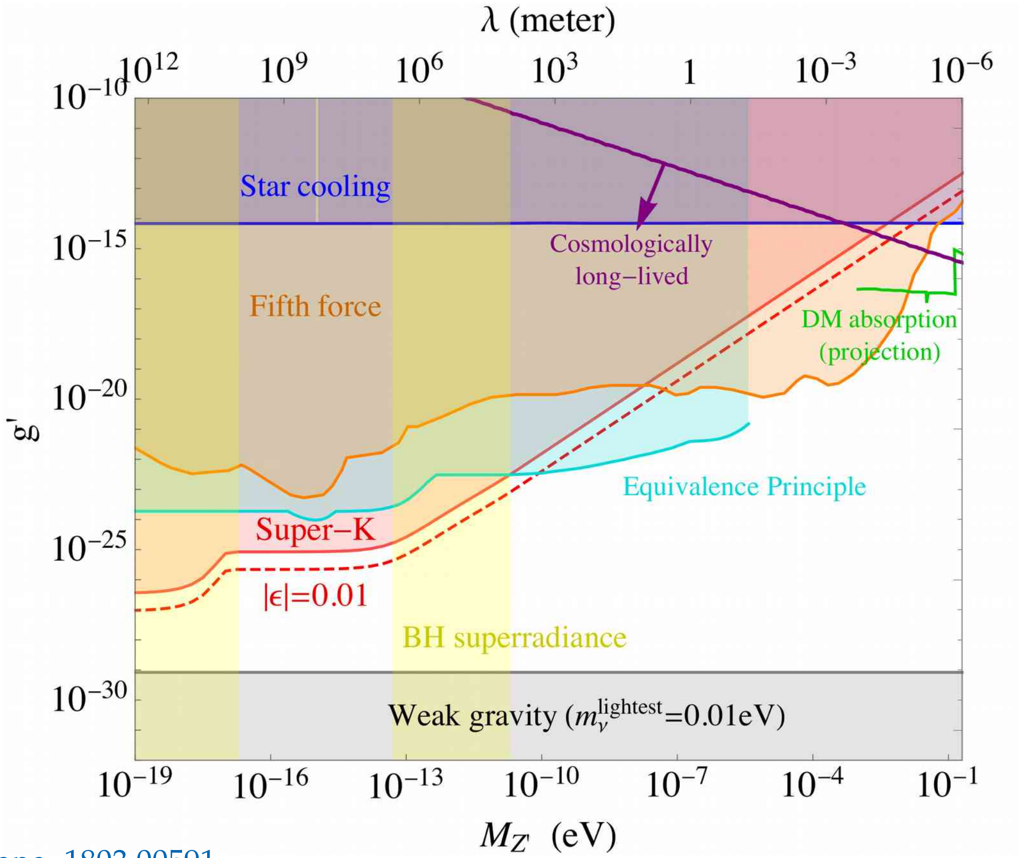
A neutrino "feels" all the electrons within the interaction range ~$(1/m')$

Current limits on the Z'

MeV–GeV masses

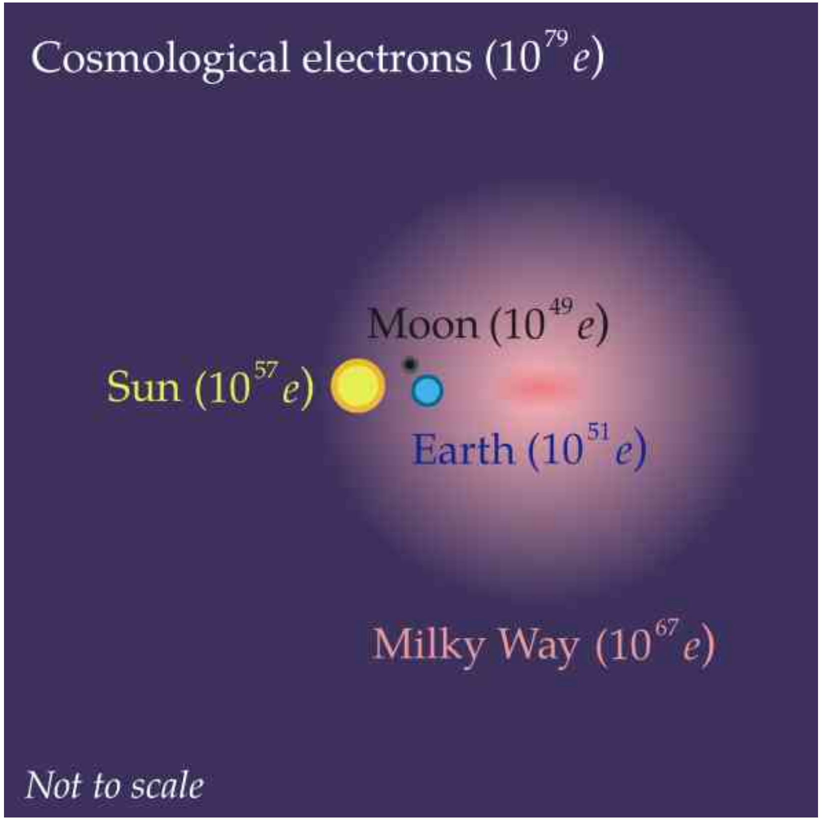


Sub-eV masses



M. Wise & Y. Zhang, 1803.00591

The total potential



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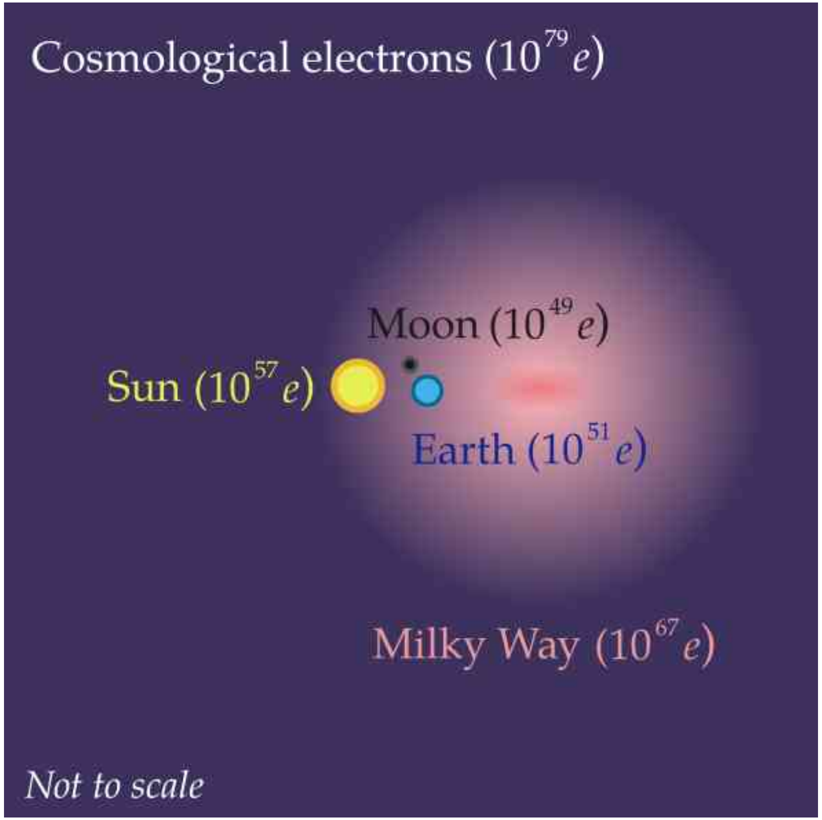
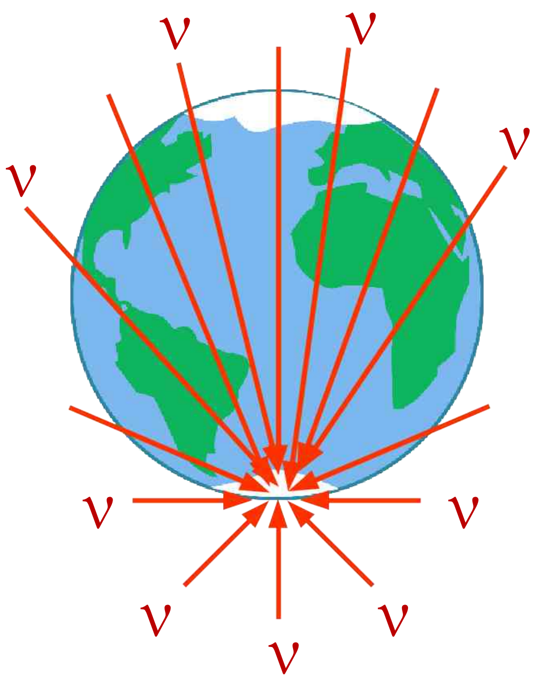


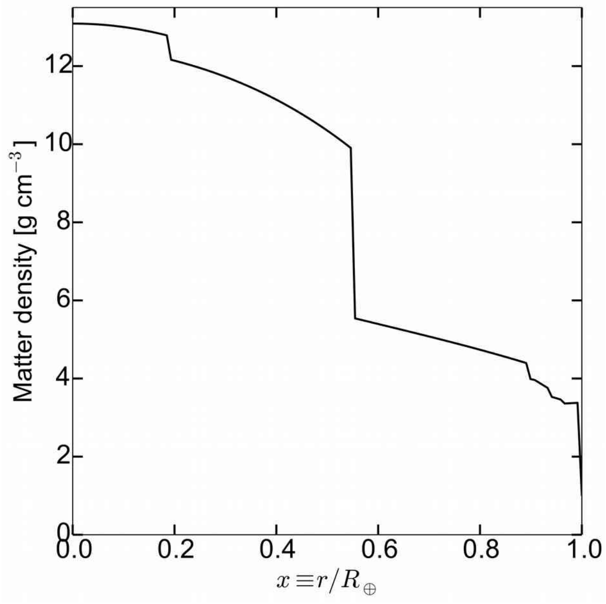
$$V_{e\beta} = V_{e\beta}^{\oplus}$$

Earth:



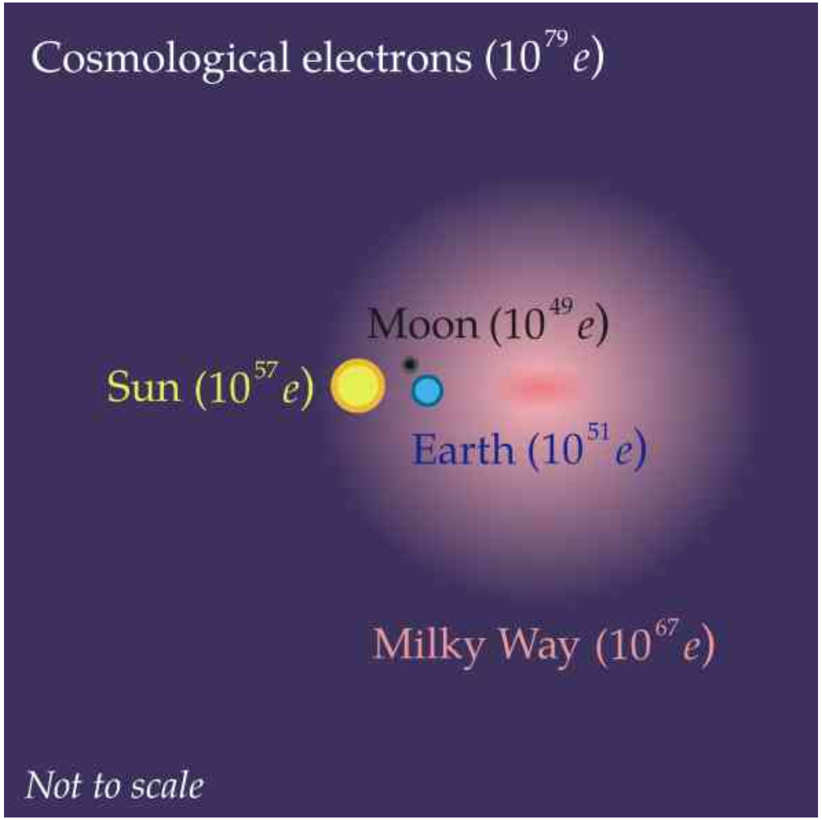
Preliminary Reference Earth Model

Dziewonski & Anderson 1981

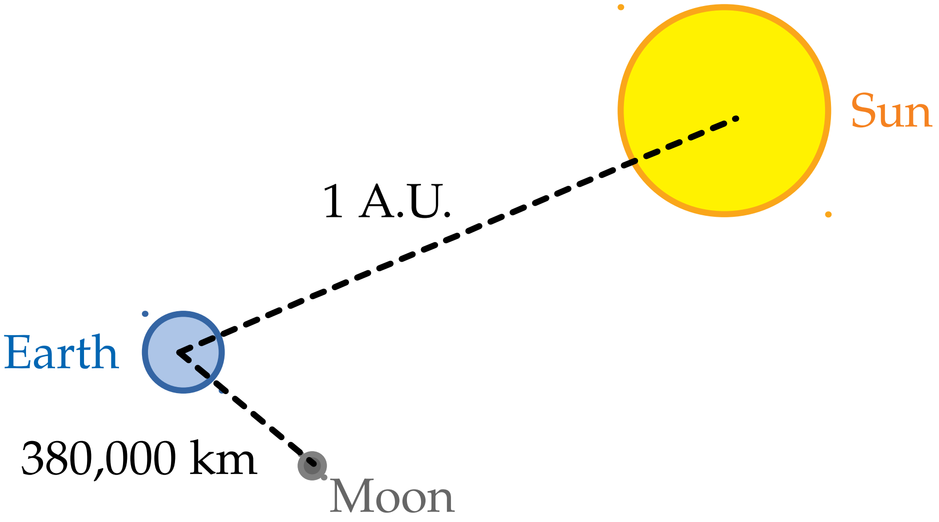


Neutrinos traverse different electron column depths

The total potential



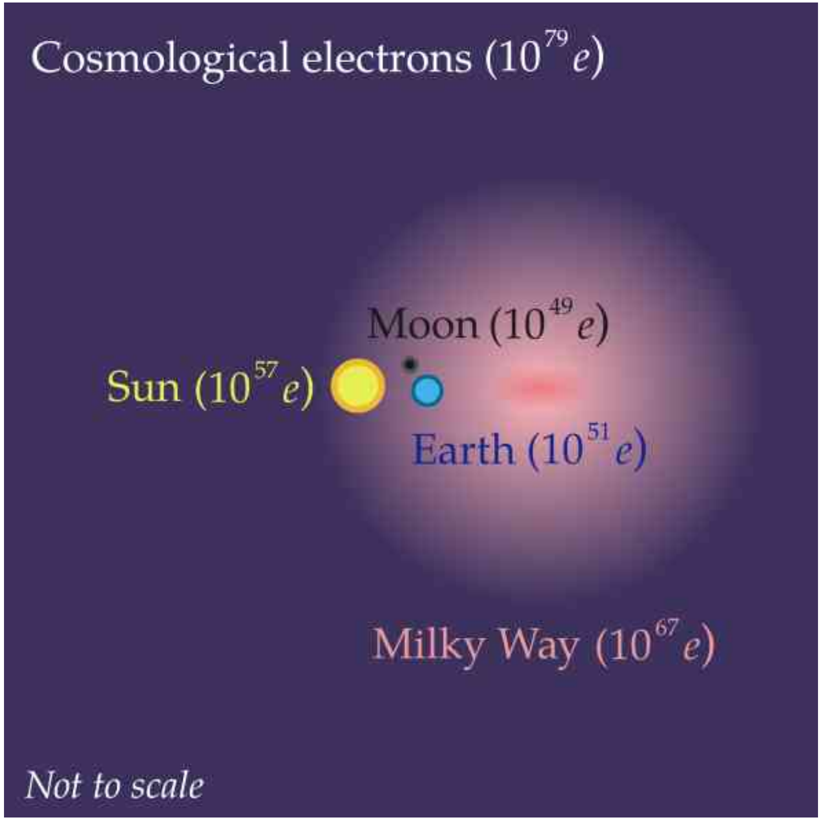
Moon and Sun:



Treated as point sources of electrons

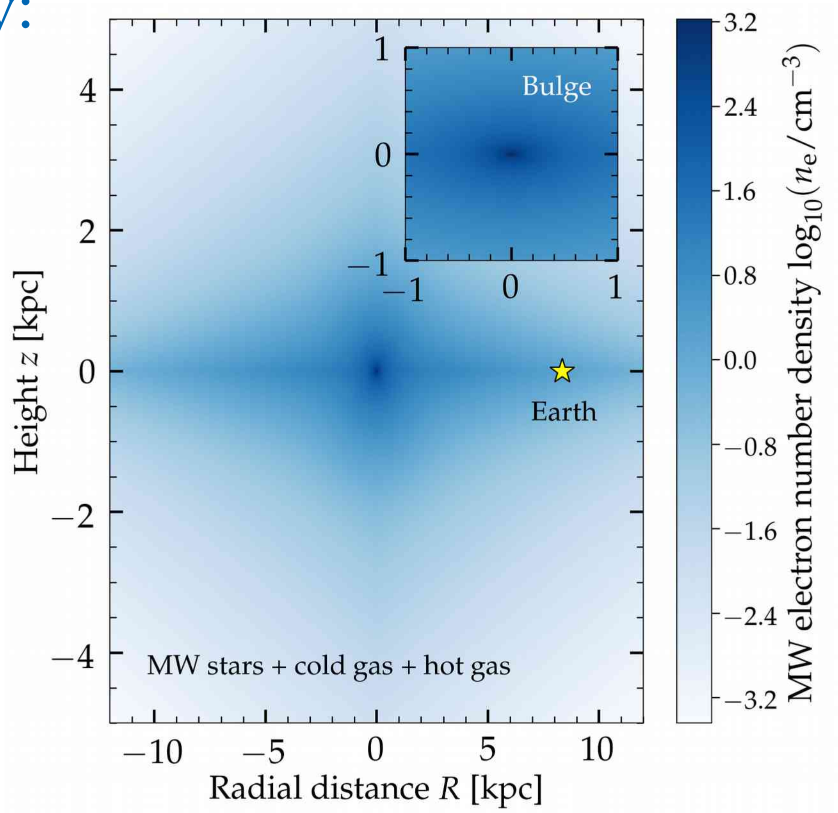
$$V_{e\beta} = V_{e\beta}^{\oplus} + V_{e\beta}^{\rm Moon} + V_{e\beta}^{\odot}$$

The total potential



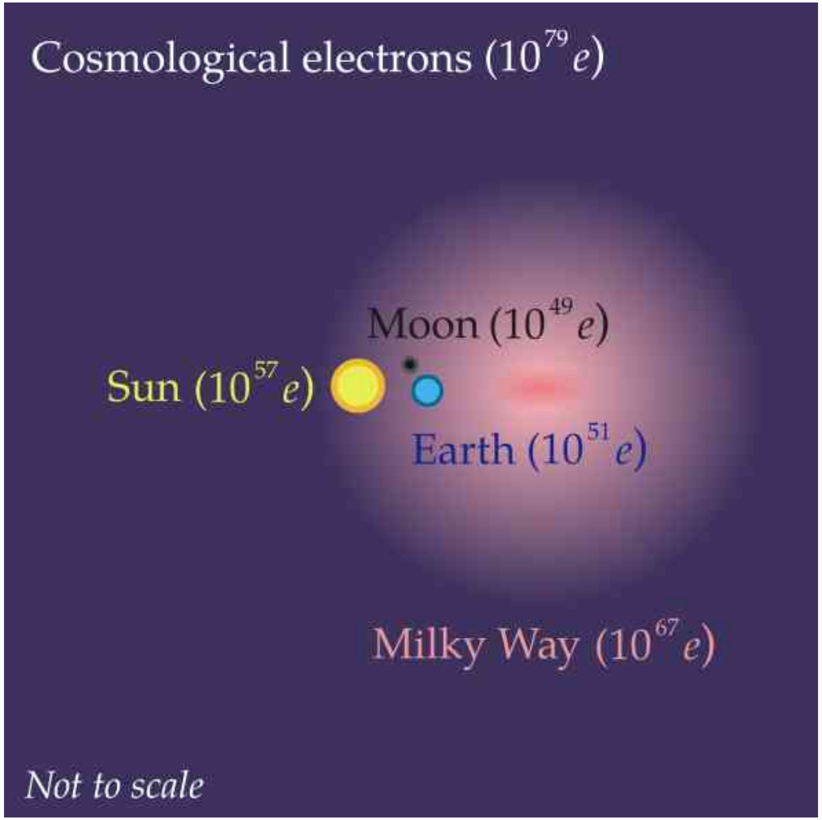
Milky Way:

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



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

The total potential



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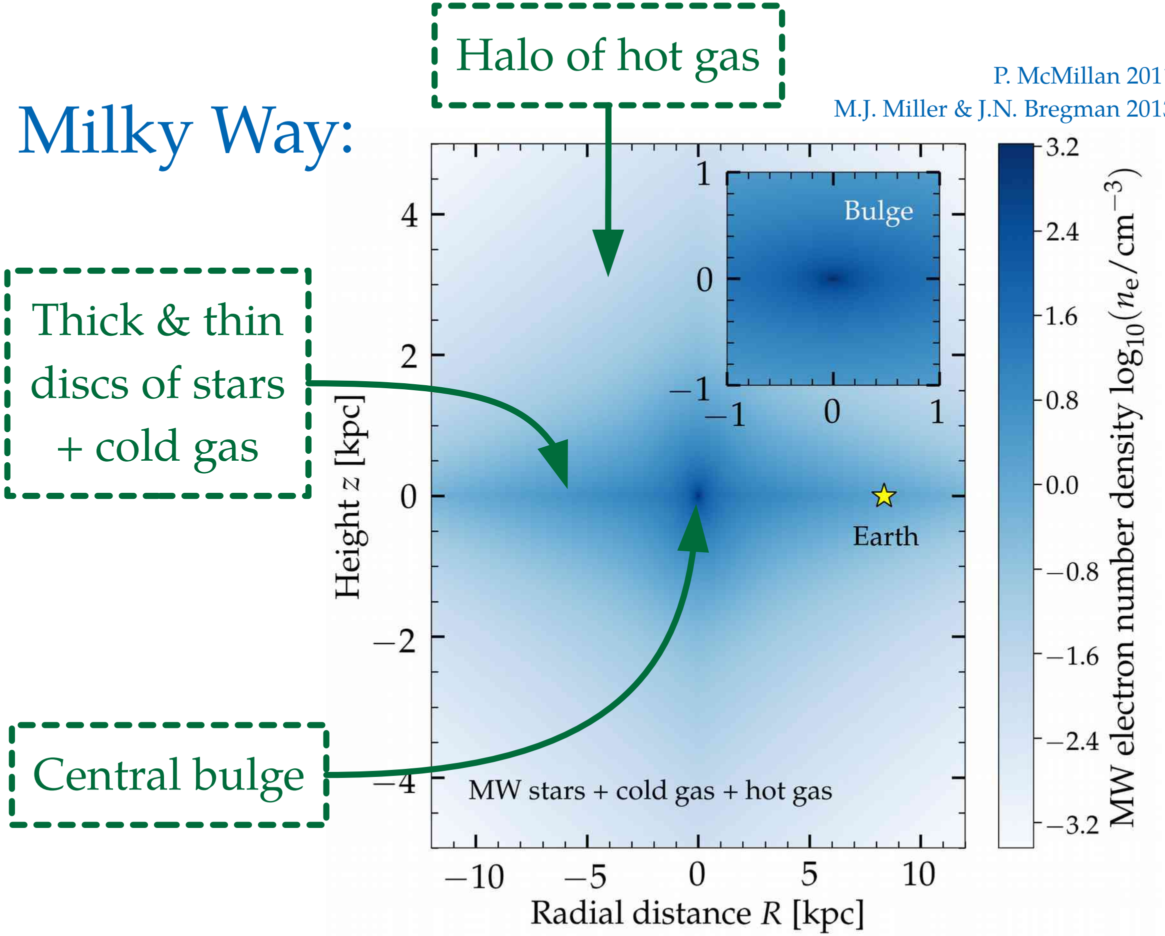

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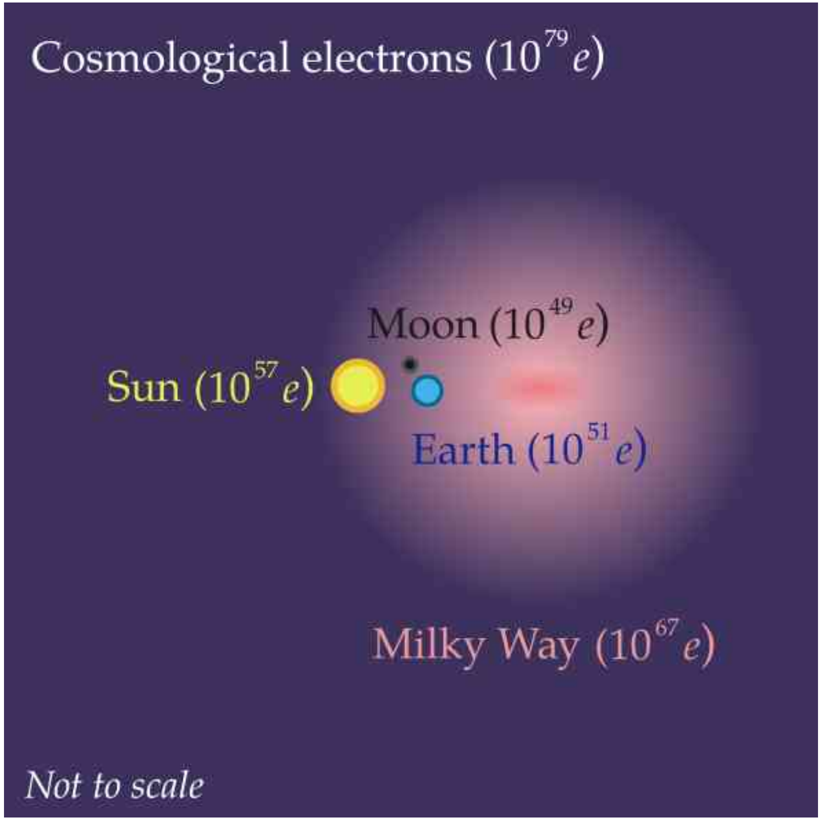
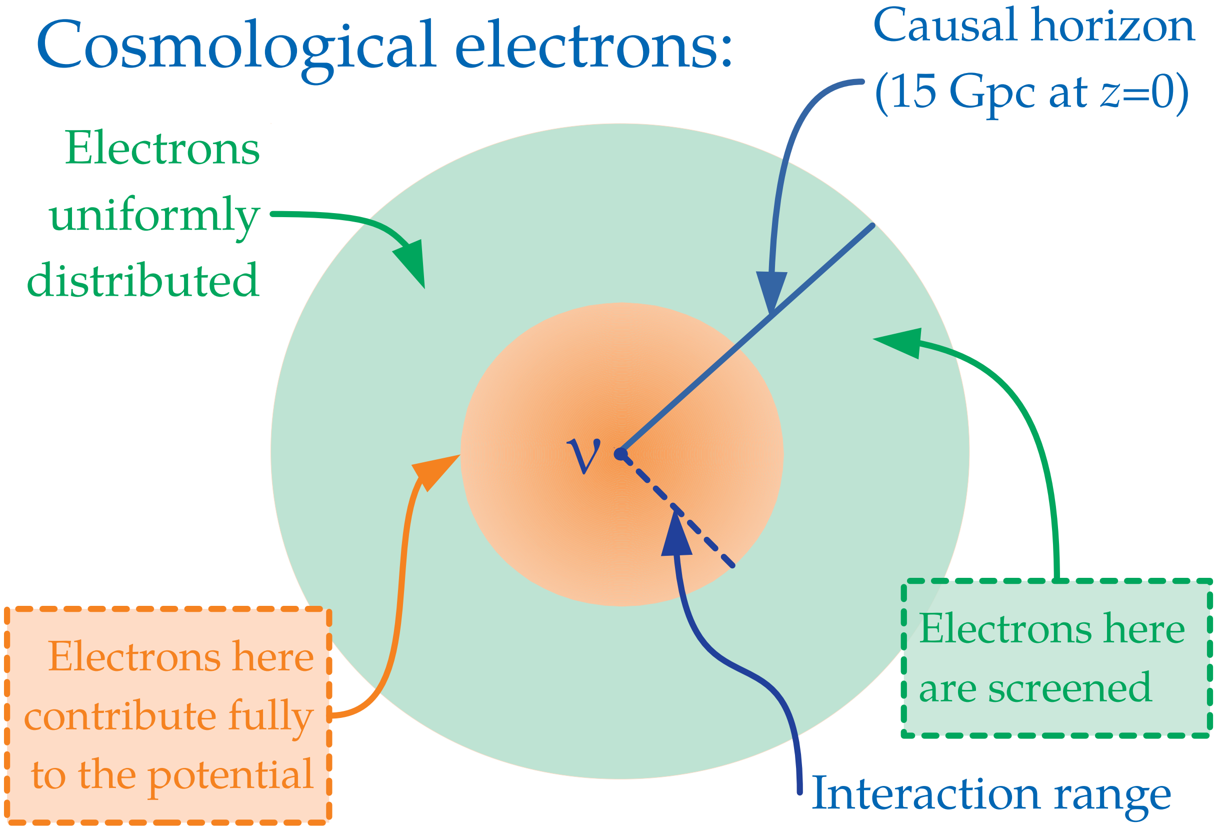


Cosmological electrons:



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

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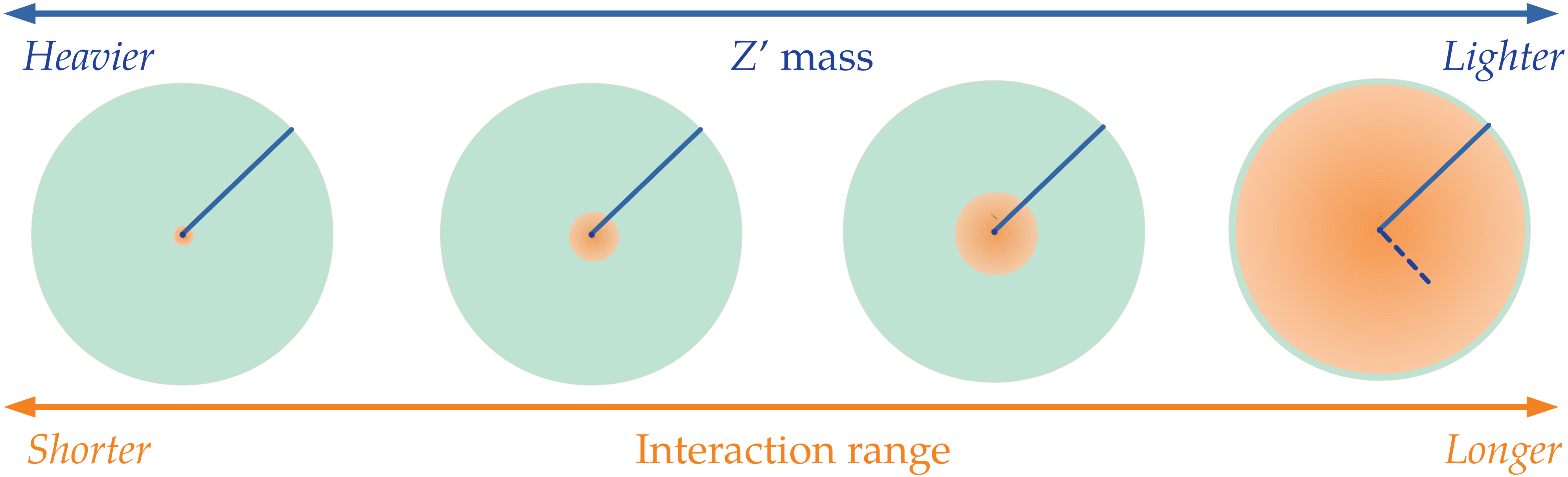

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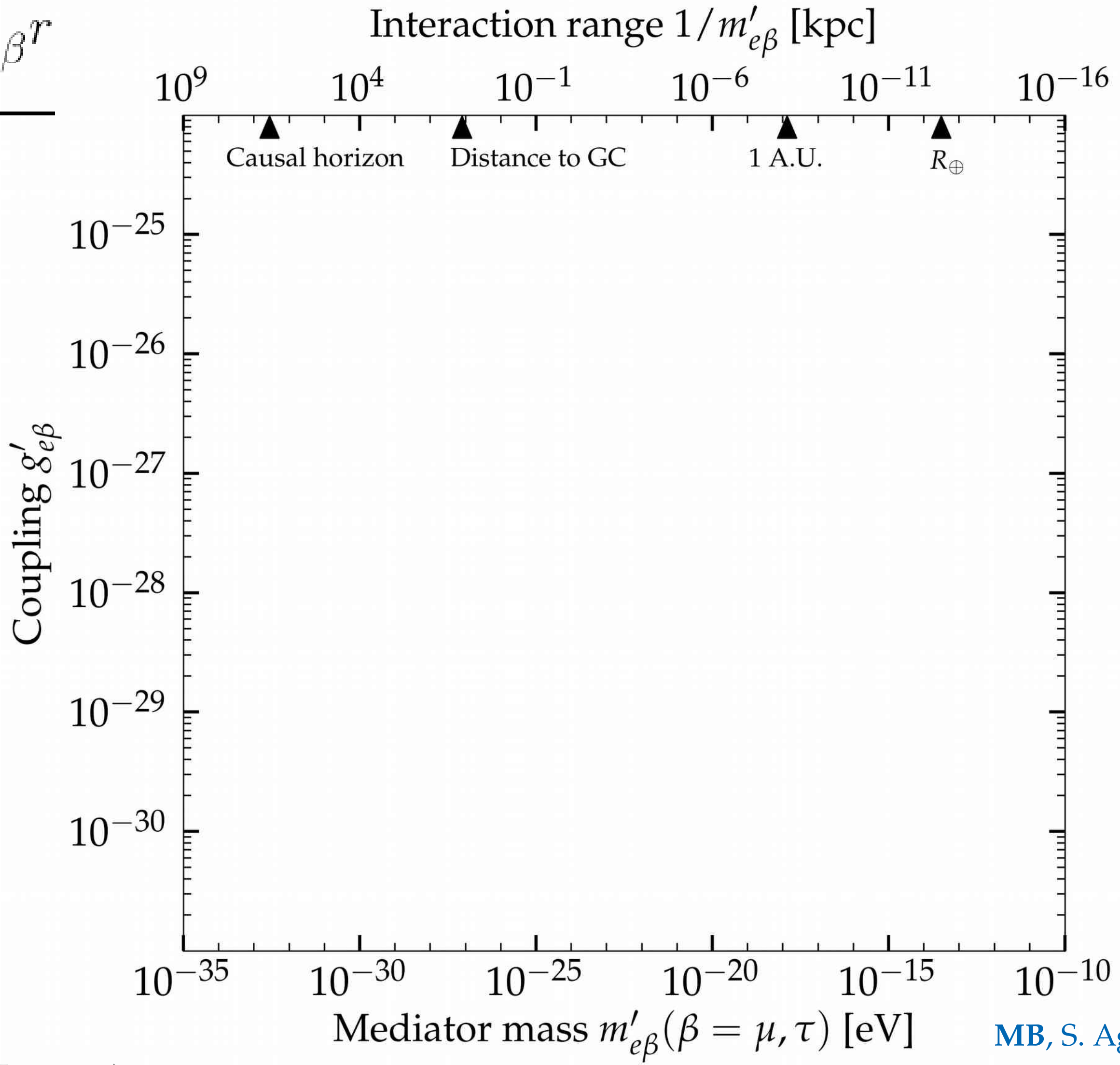
$$V_{e\beta} = \frac{g'^2_{e\beta}}{4\pi} \frac{e^{-m'_{e\beta} r}}{r}$$



MB, S. Agarwalla, 1808.02042

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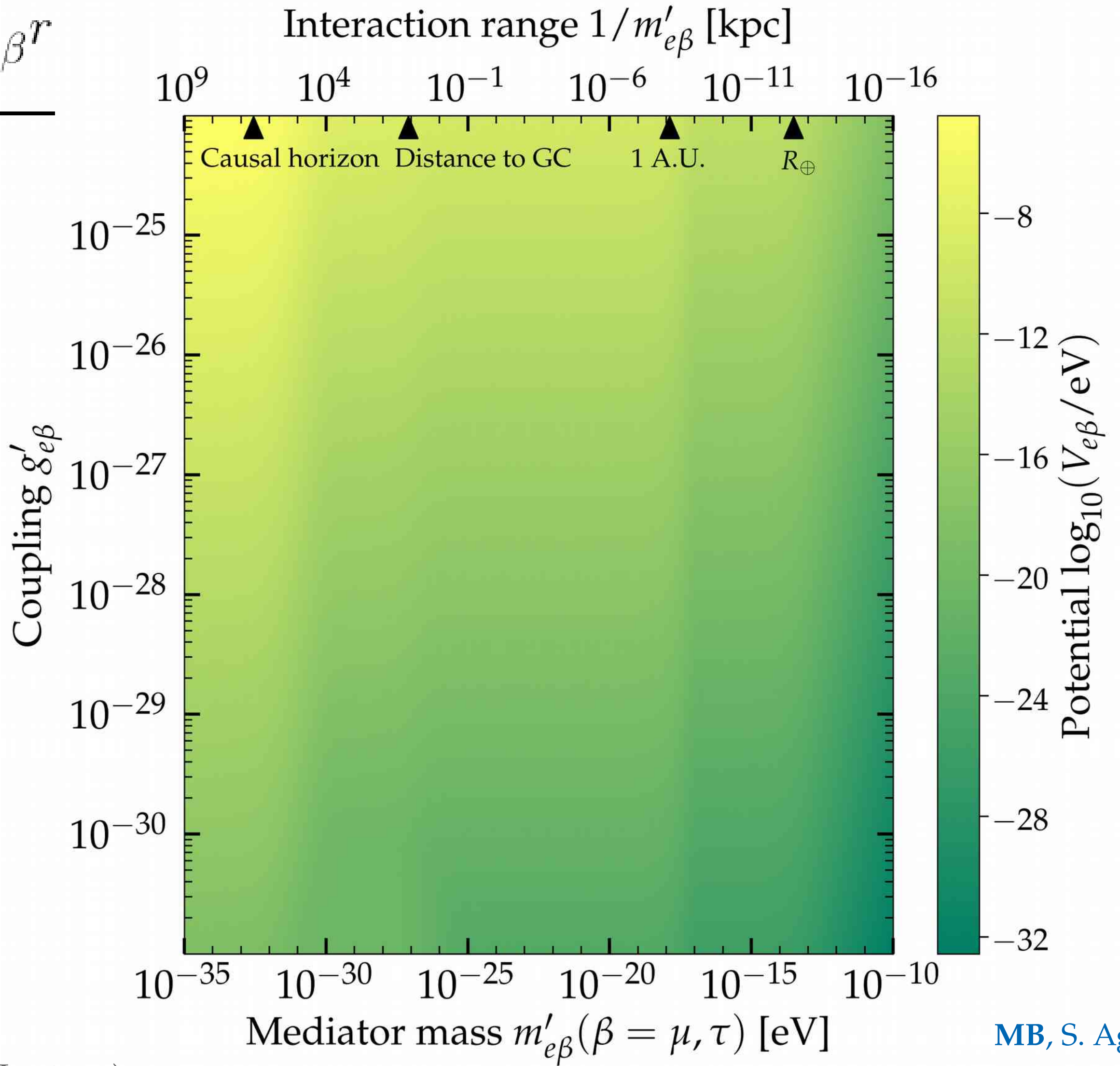


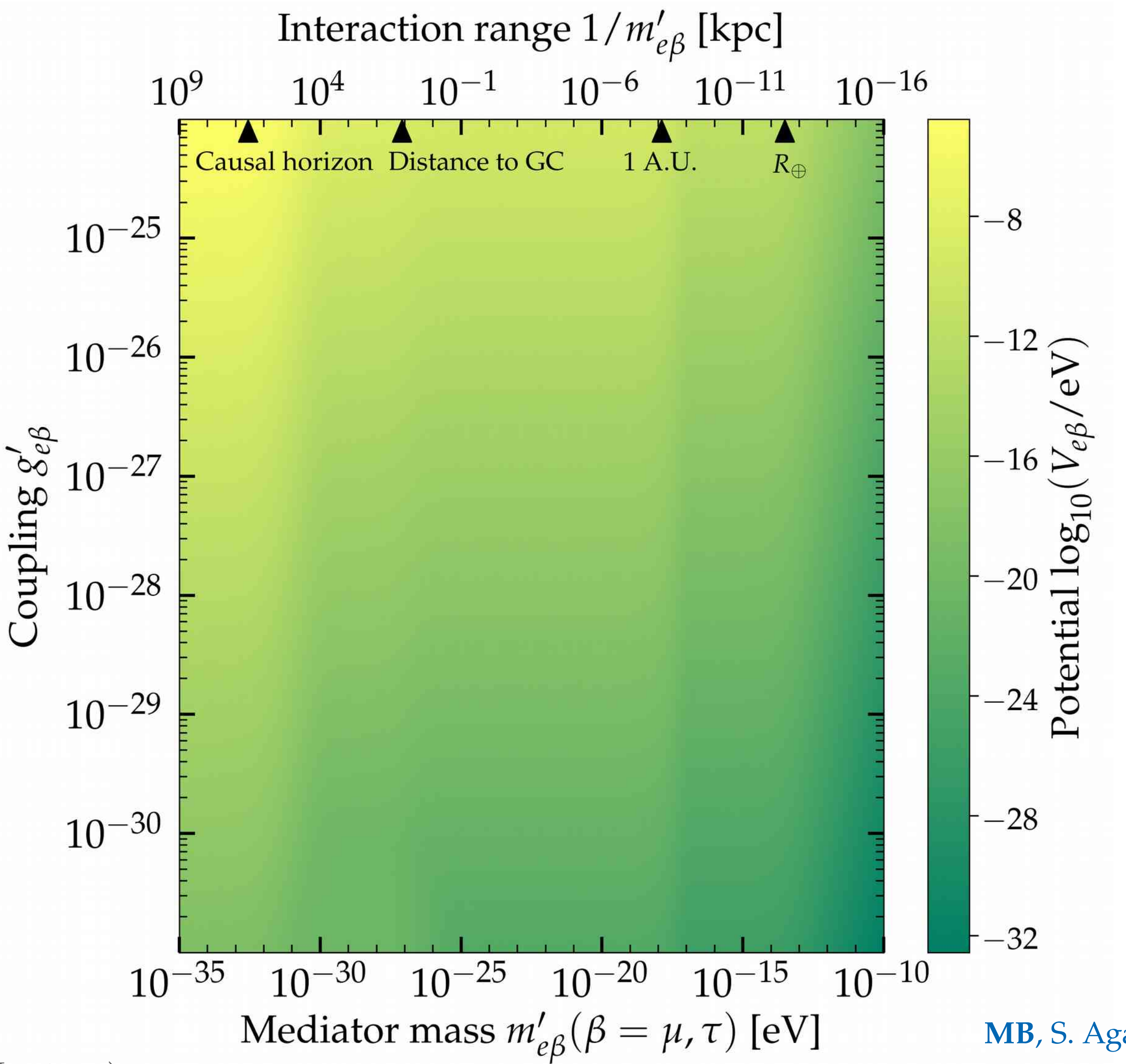
MB, S. Agarwalla, 1808.02042

$g_{\text{strong}} \sim 13.5$

$g_{\text{e.m.}} \sim 0.3$

$g_{\text{weak}} \sim 0.01$

$g_{\text{gravity}} \sim 10^{-19}$



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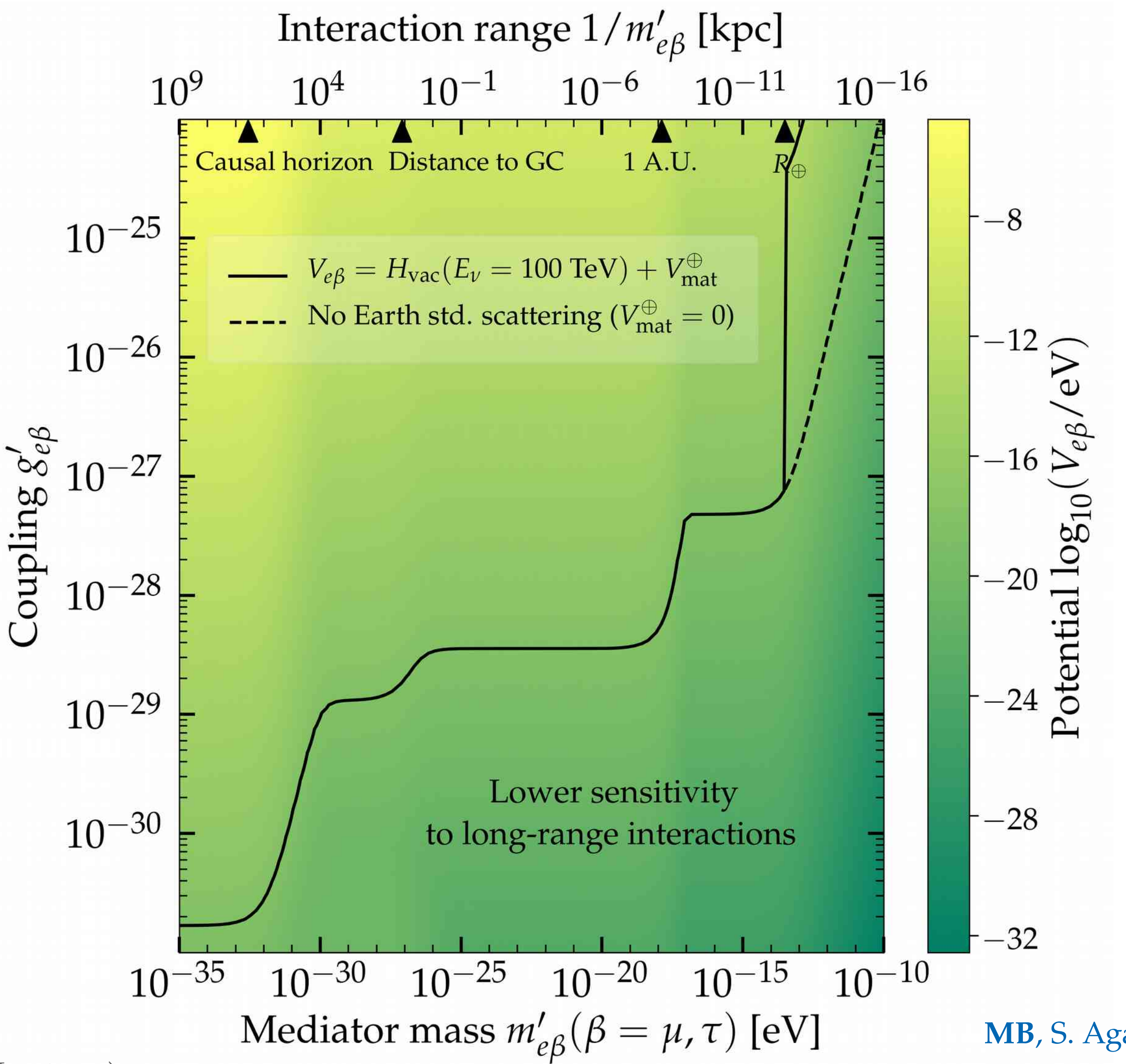

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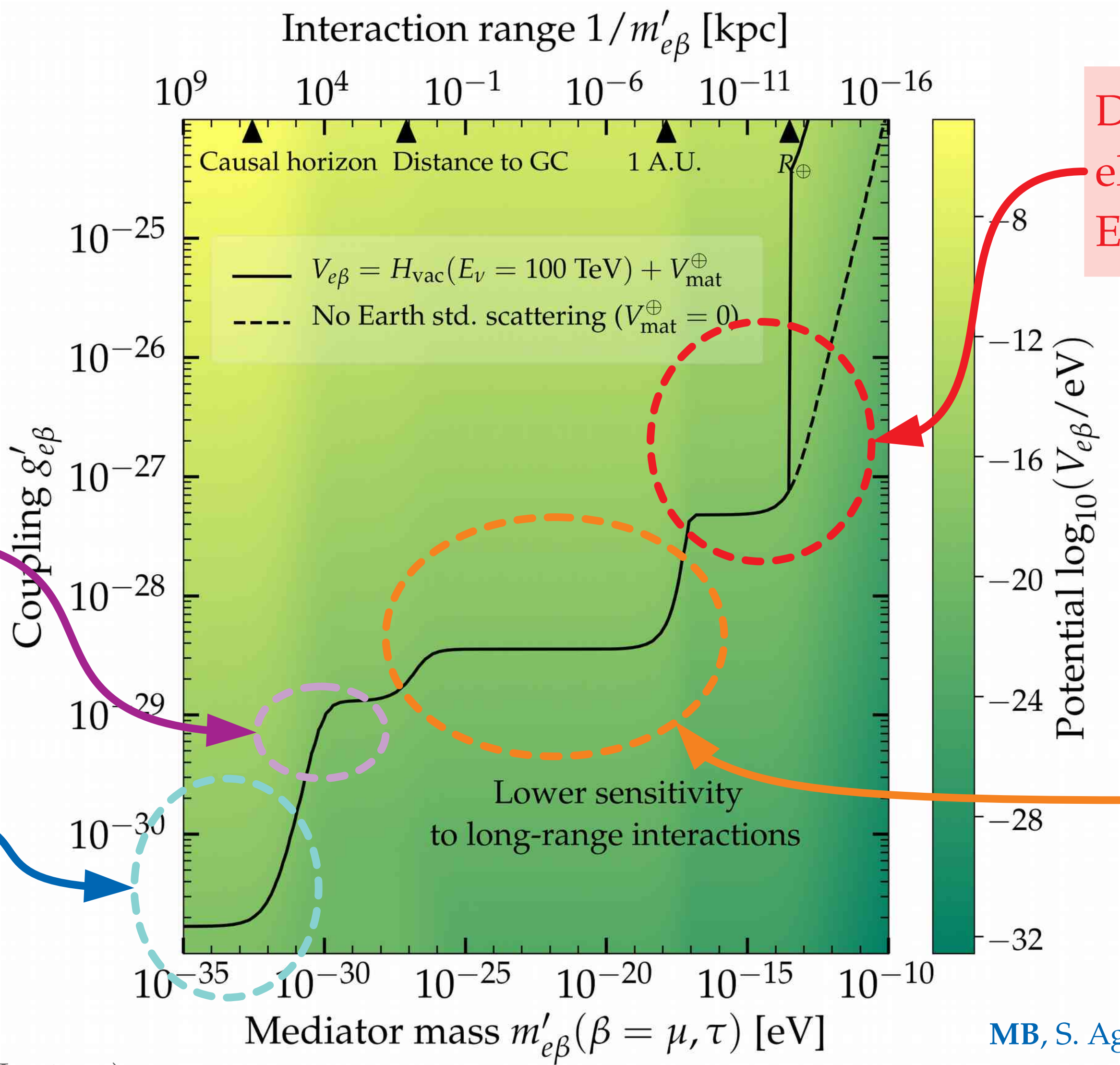
Dominated by Milky-Way e

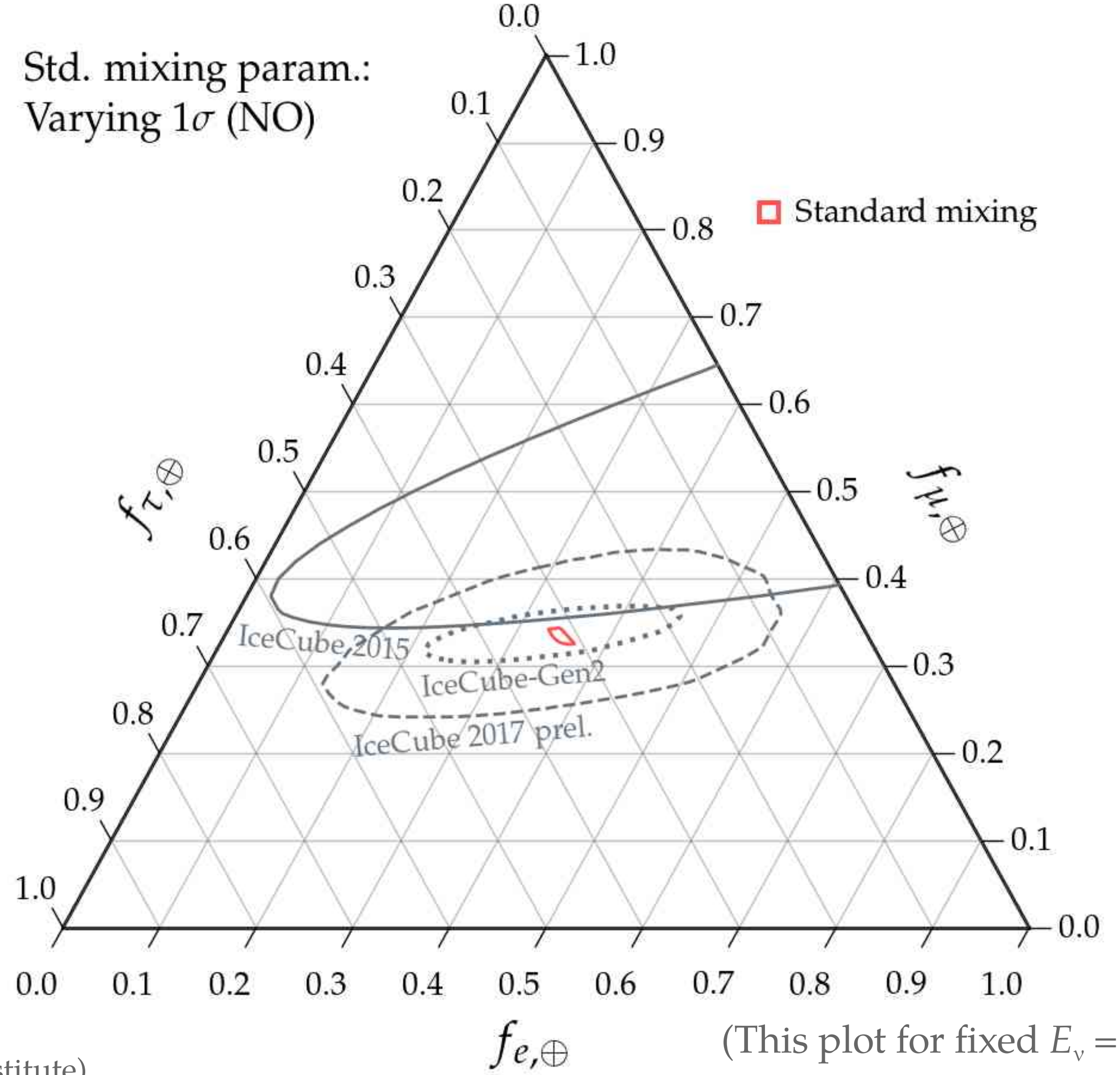
Dominated by cosmological e



Dominated by electrons in the Earth + Moon

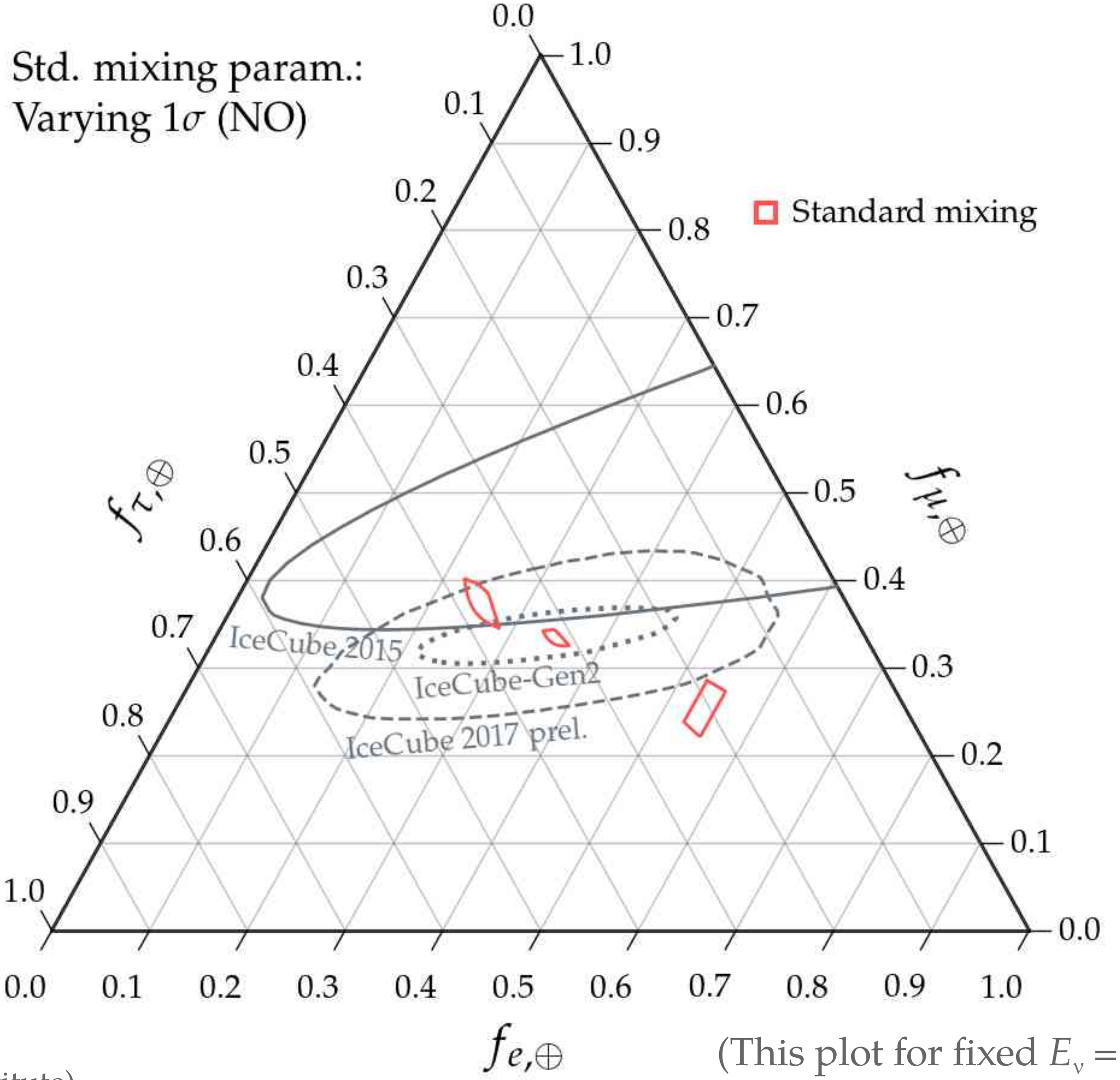
Dominated by solar electrons (+ Milky-Way e)

MB, S. Agarwalla, 1808.02042



MB, S. Agarwalla, 1808.02042

(This plot for fixed E_ν = 100 TeV)



MB, S. Agarwalla, 1808.02042

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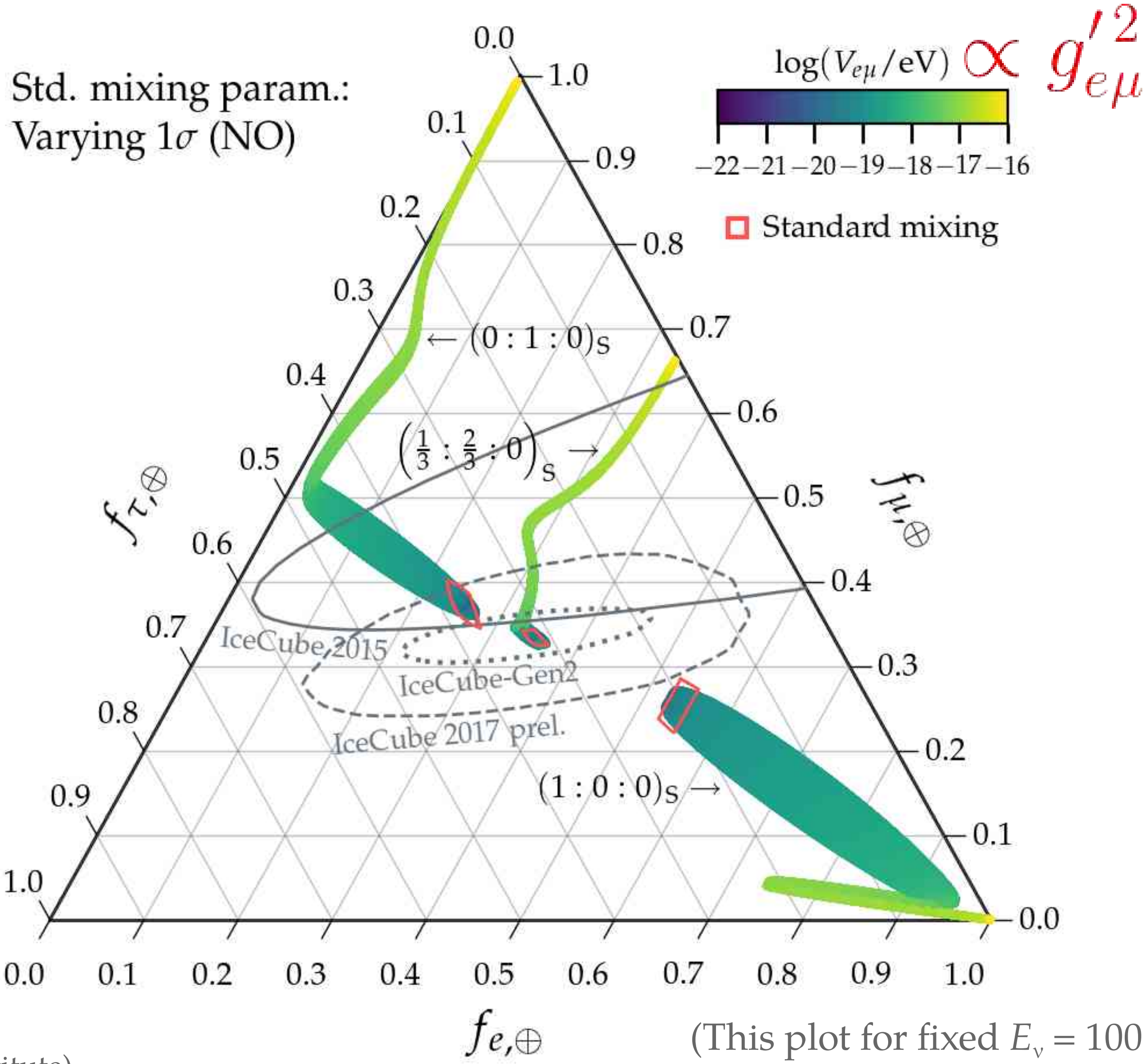
We assume equal proportions of ν and ν (*e.g.*, production via *pp*)



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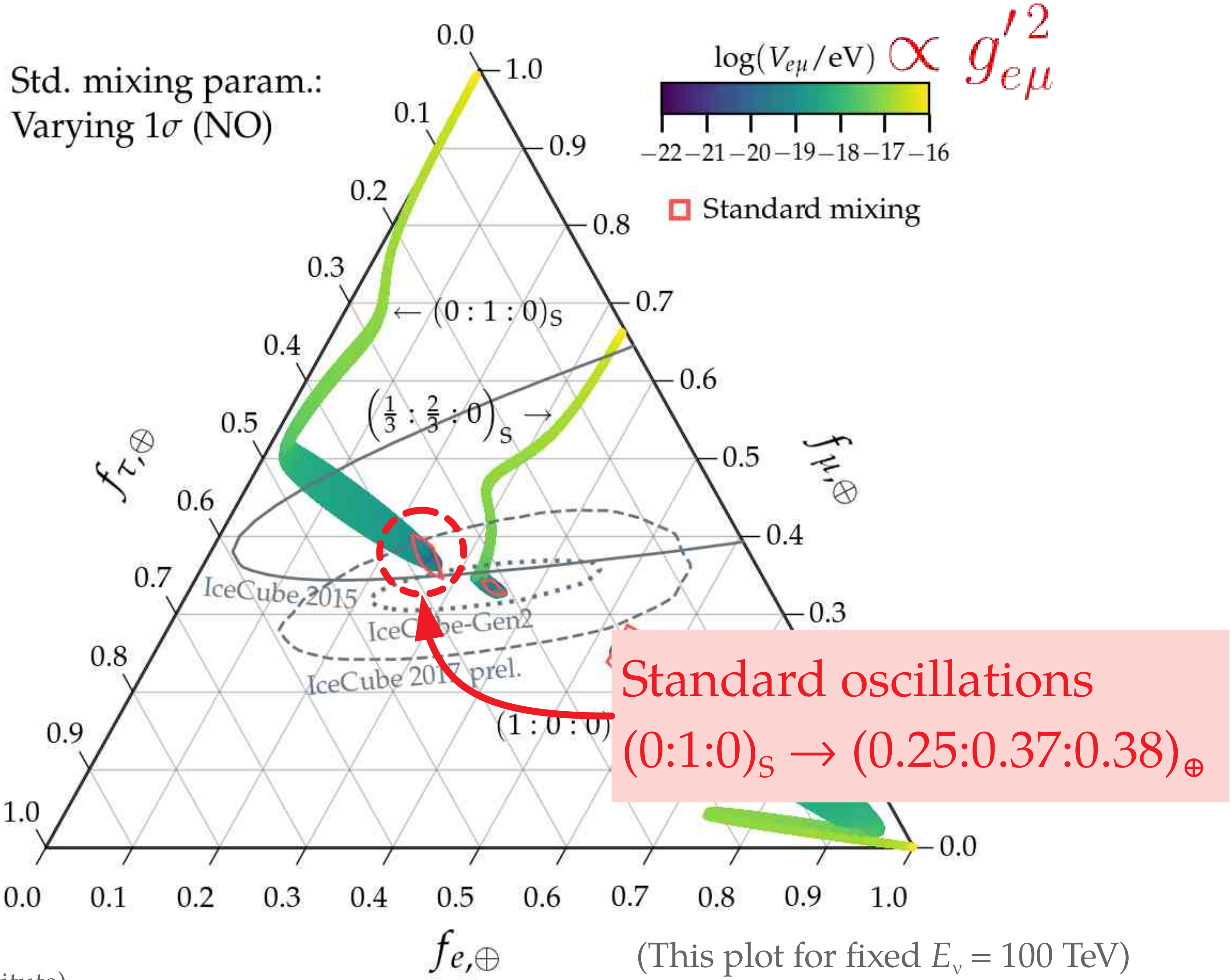

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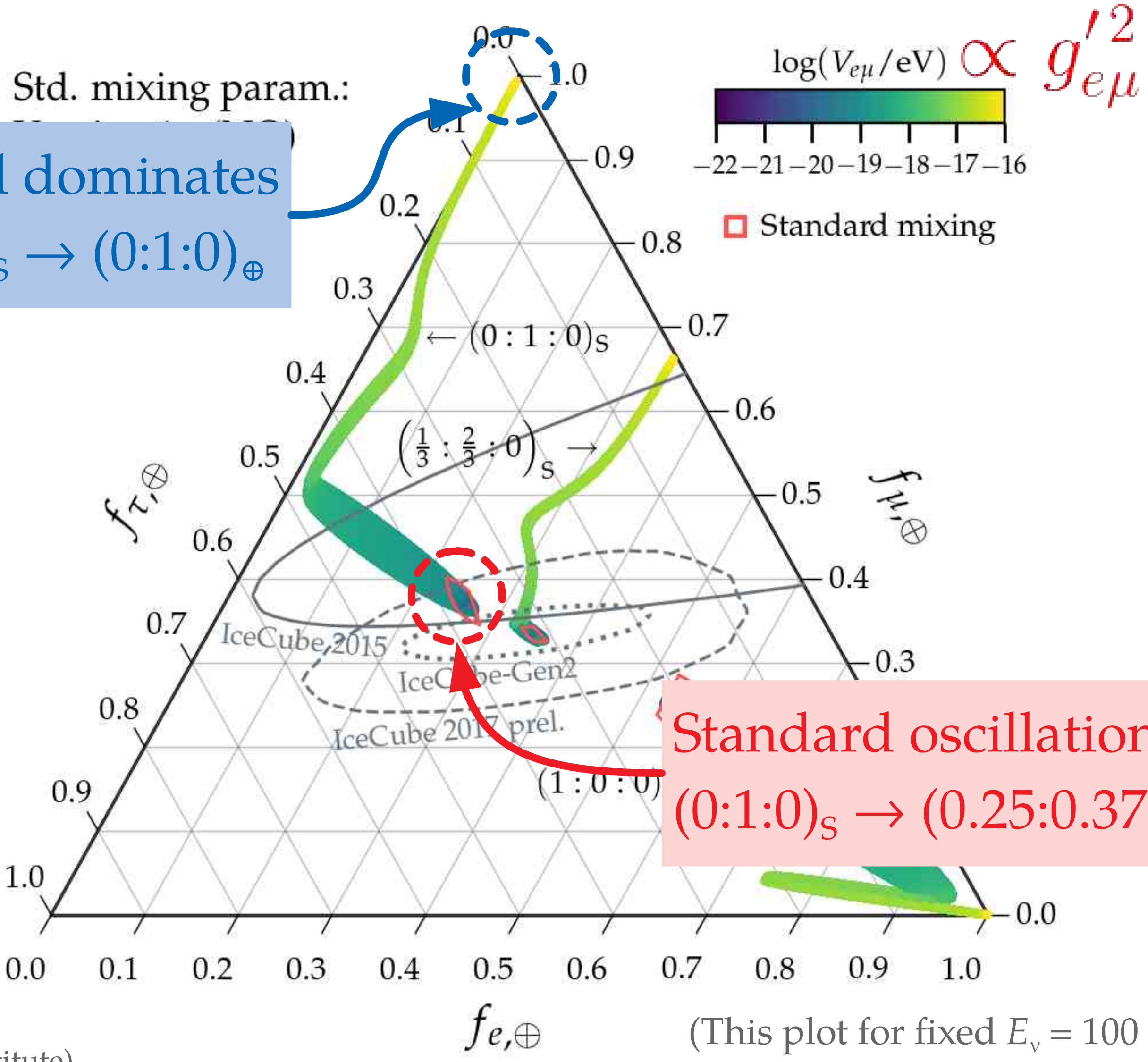

New potential dominates

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

Standard oscillations

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

MB, S. Agarwalla, 1808.02042

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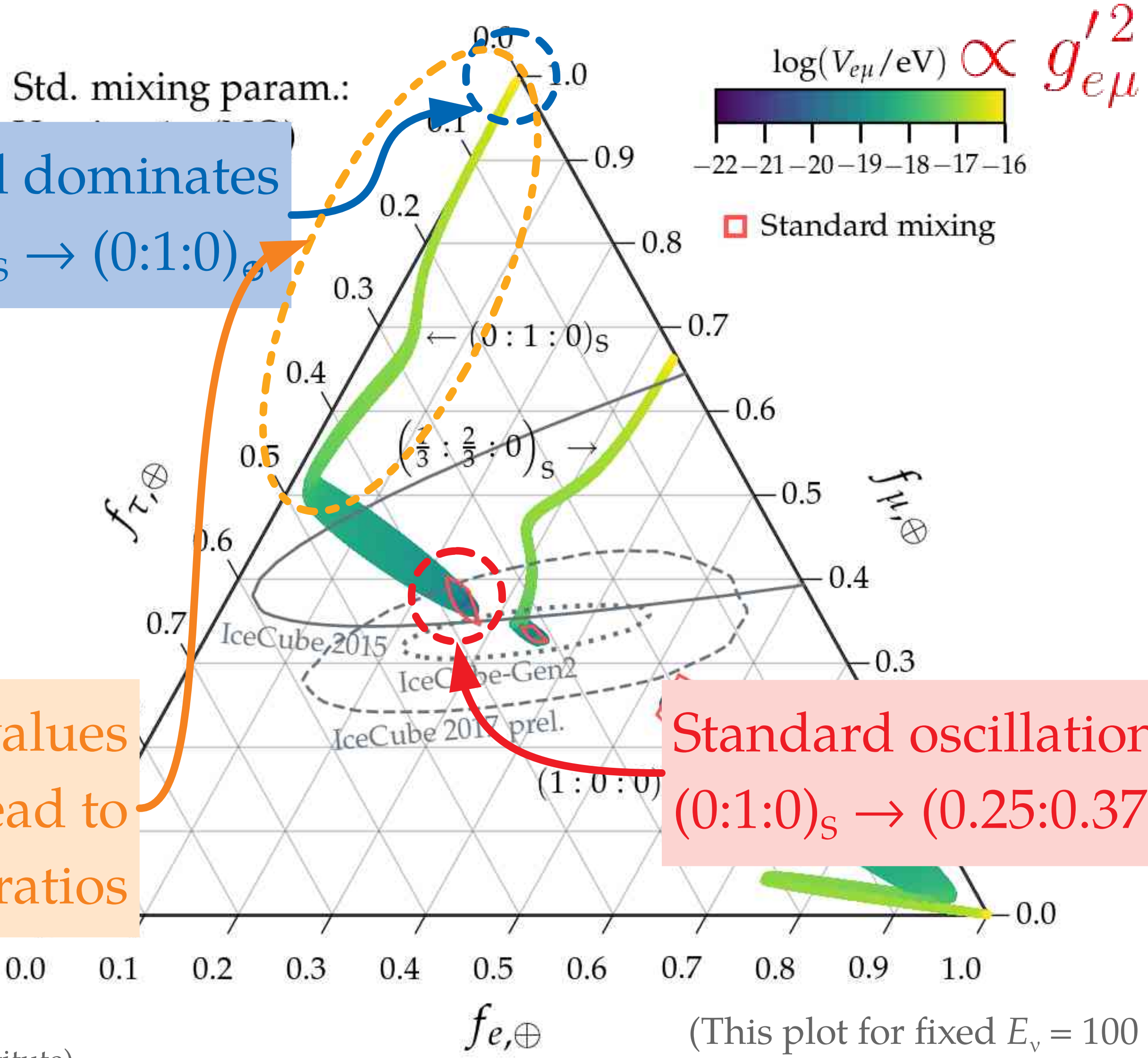

We can disfavor all values of *m*′ and *g*′ that lead to these flavor ratios

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

MB, S. Agarwalla, 1808.02042

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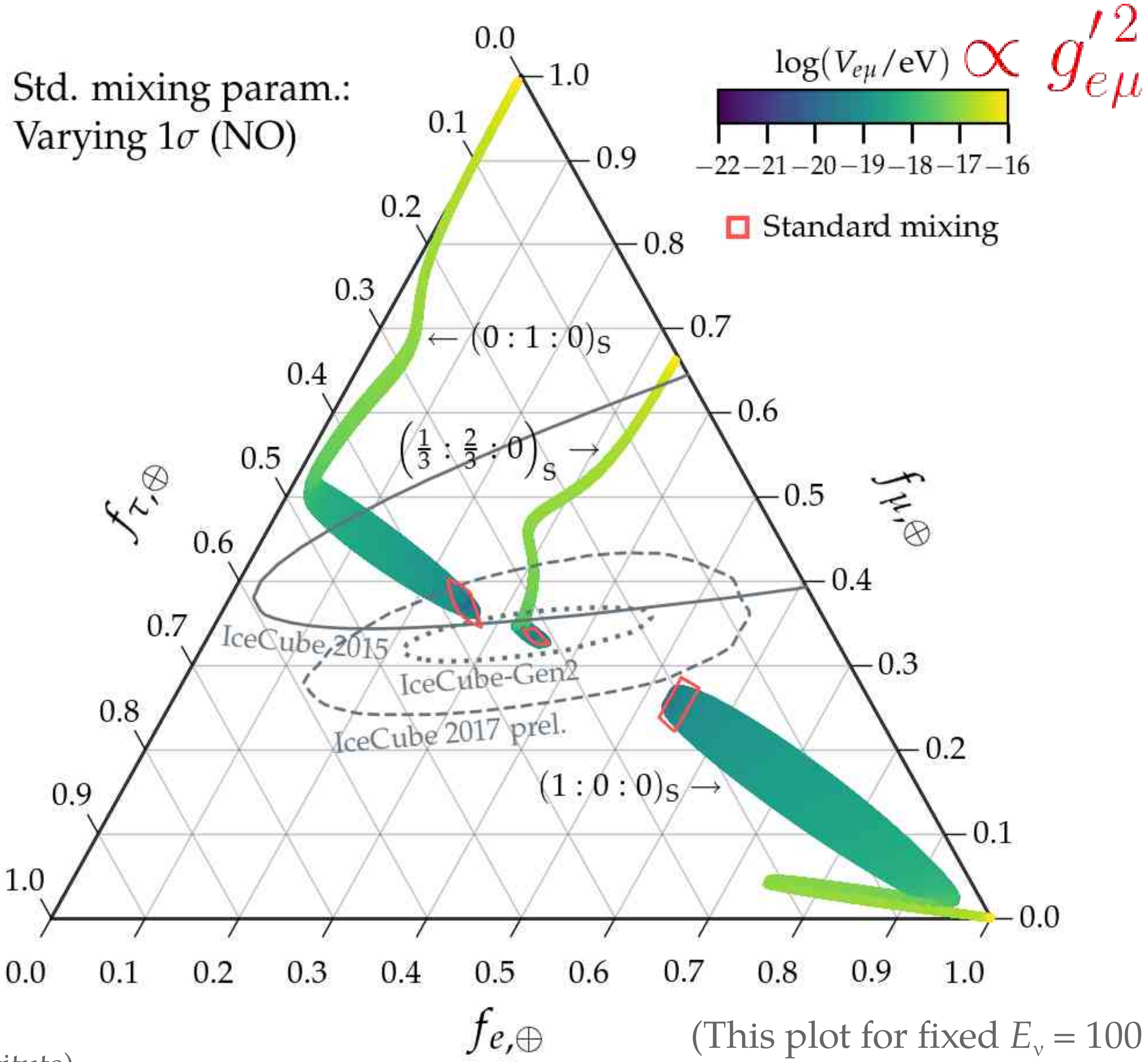

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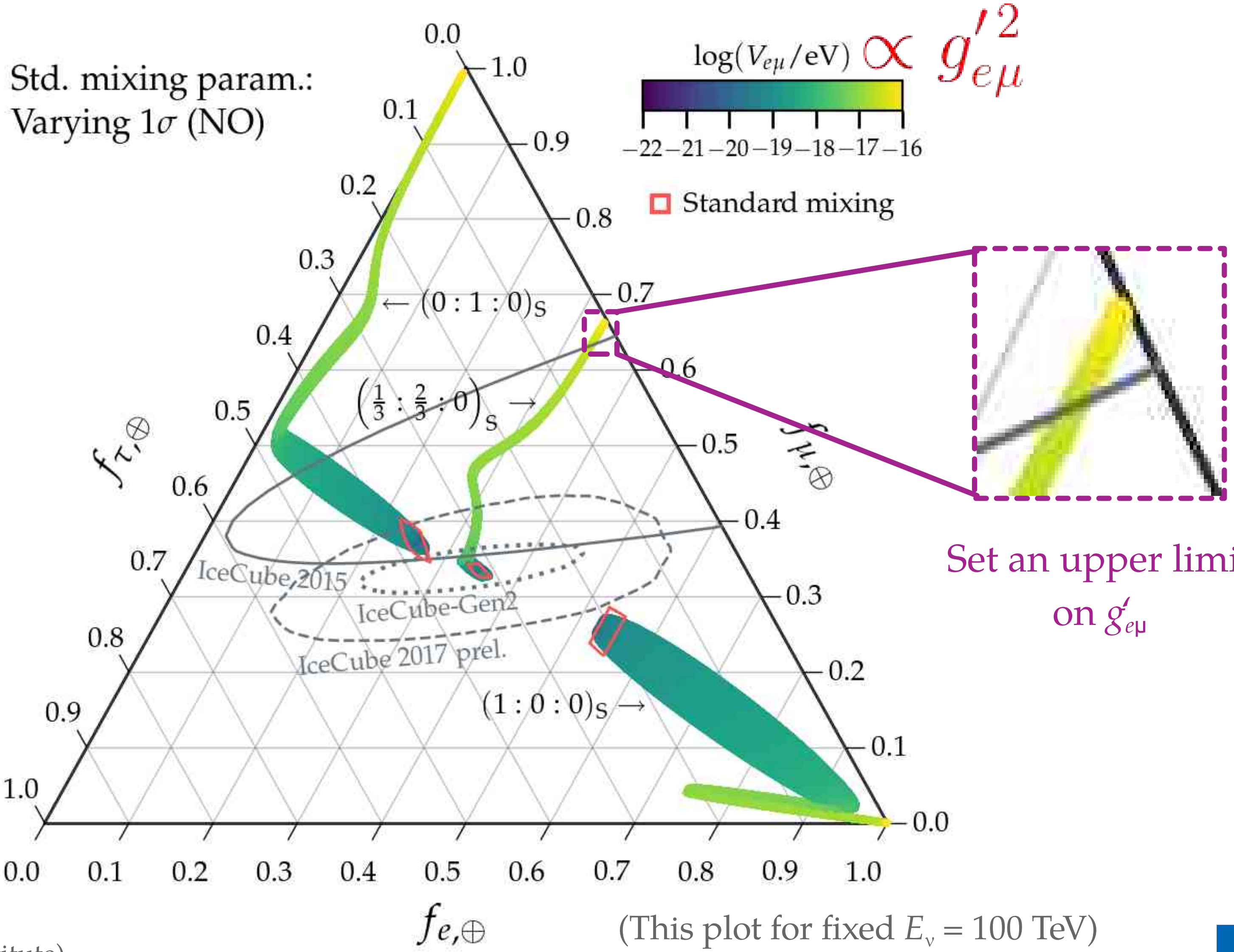
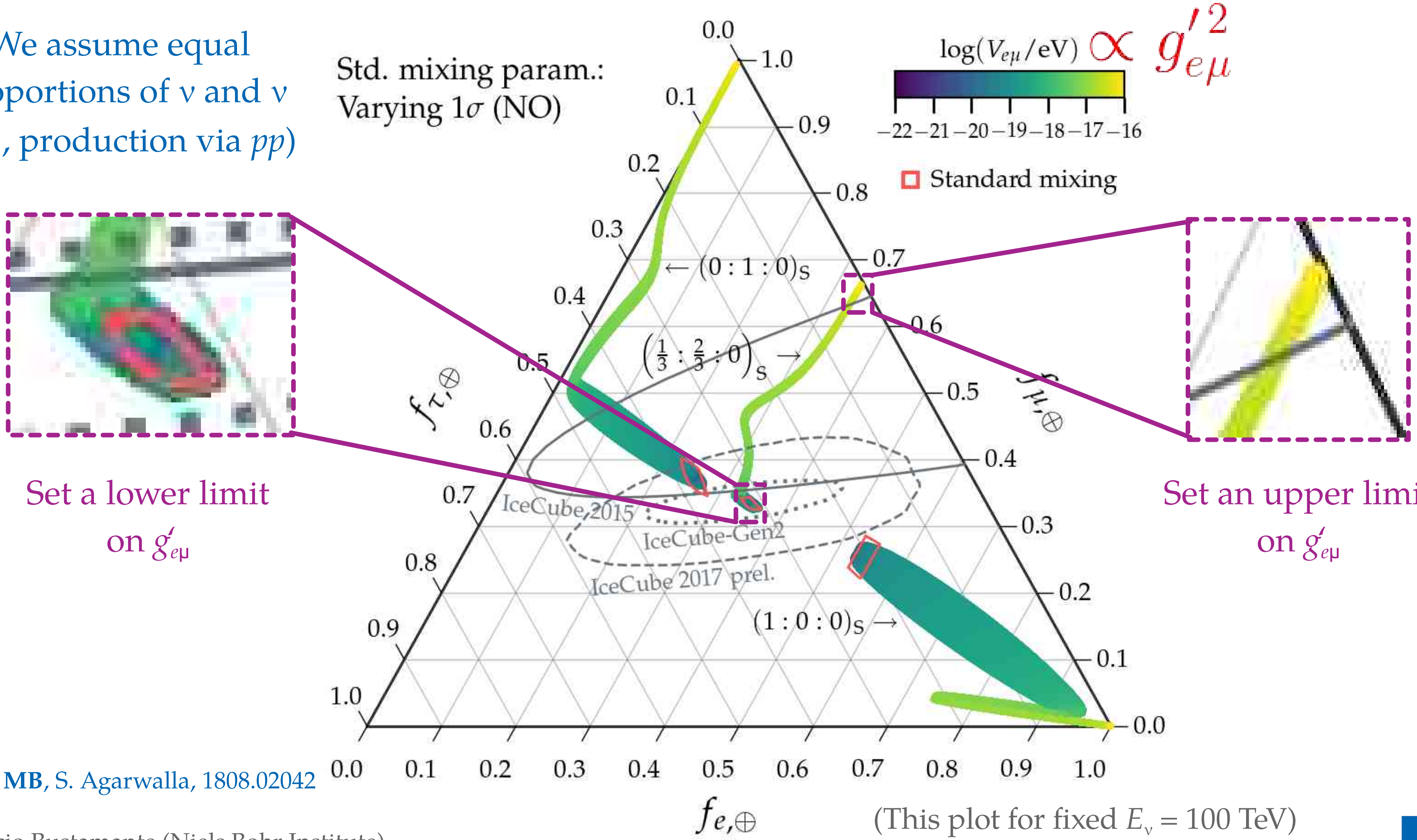


MB, S. Agarwalla, 1808.02042

(This plot for fixed E_ν = 100 TeV)

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

Std. mixing param.:
Varying 1σ (NO)



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

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

MB, S. Agarwalla, 1808.02042

(This plot for fixed E_ν = 100 TeV)

Connecting flavor-ratio predictions to experiment

1 Integrate potential in redshift, weighed by source number density

↦ Assume star formation rate

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

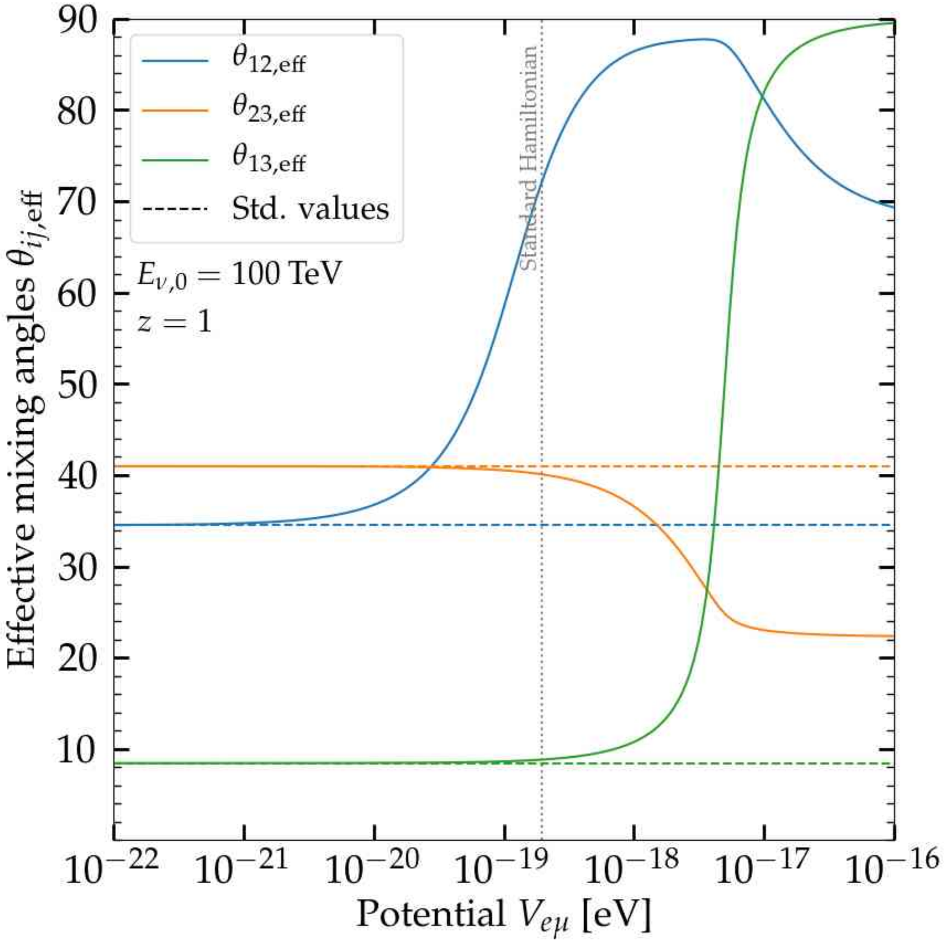
Density of cosmological *e* grows with *z*

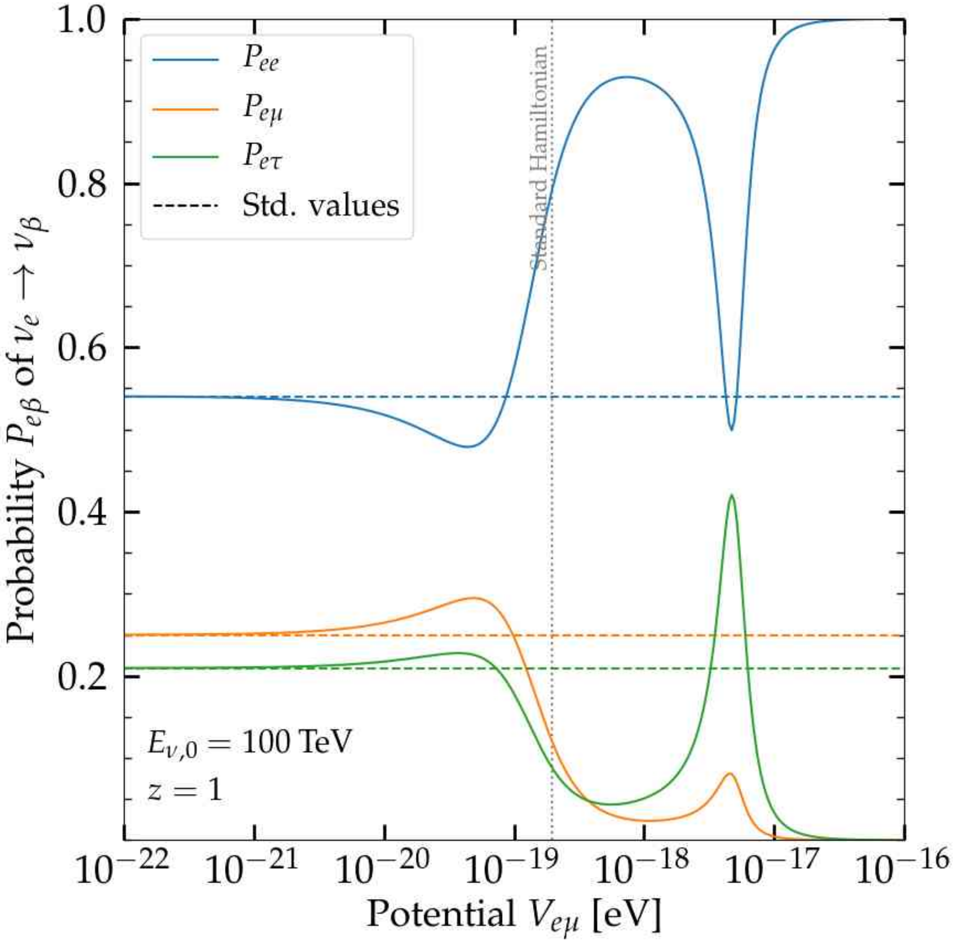
2 Convolve flavor ratios with observed neutrino energy spectrum

↦ Either $E^{-2.50}$ (combined analysis) or $E^{-2.13}$ (through-going muons)

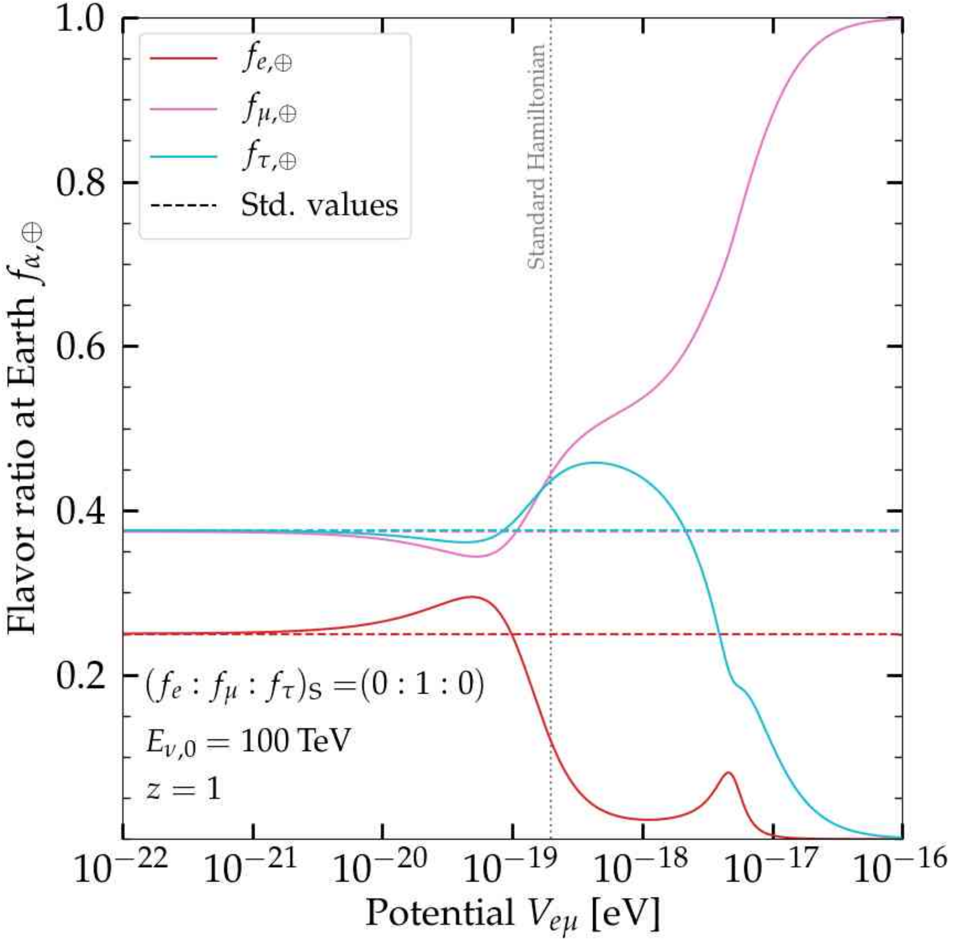
$$\underbrace{\langle \Phi_\alpha \rangle \propto \int dE_\nu \; f_{\alpha,\oplus}(E_\nu) \; E_\nu^{-\gamma}}_{\text{Energy-averaged flux}} \Rightarrow \underbrace{\langle f_{\alpha,\oplus} \rangle \equiv \frac{\langle \Phi_\alpha \rangle}{\sum_{\beta=e,\mu,\tau} \langle \Phi_\beta \rangle}}_{\text{Energy-averaged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

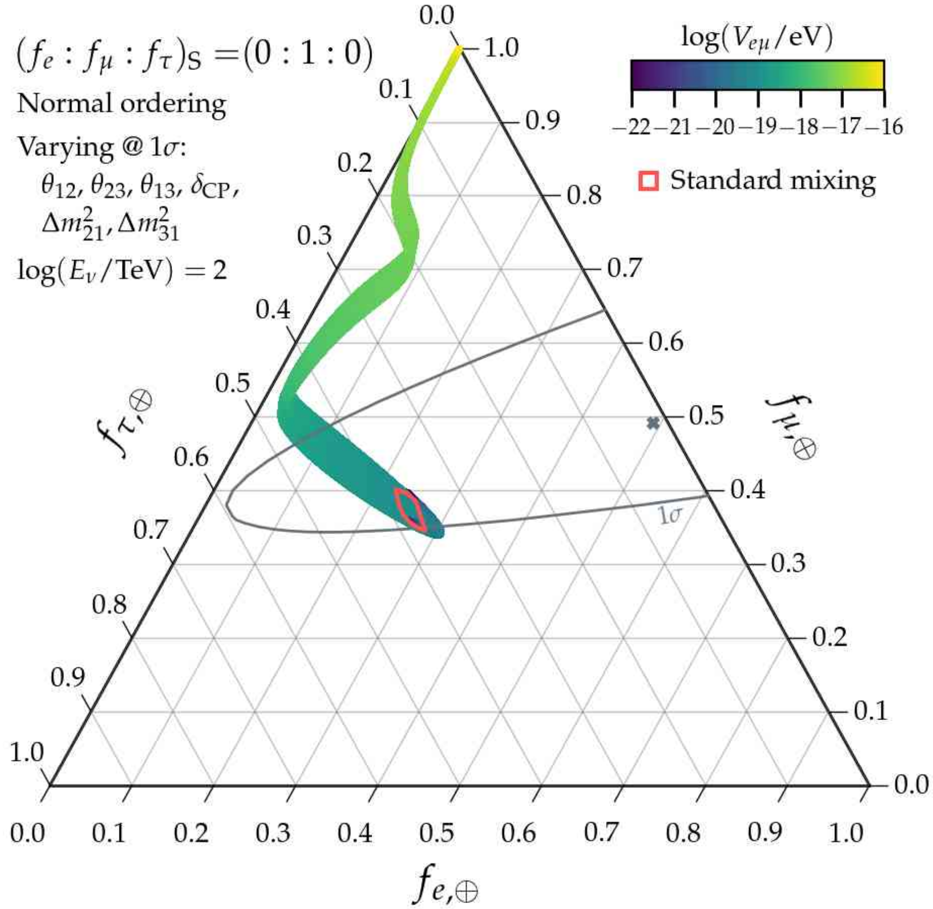
Resonance due to the L_e-L_μ symmetry



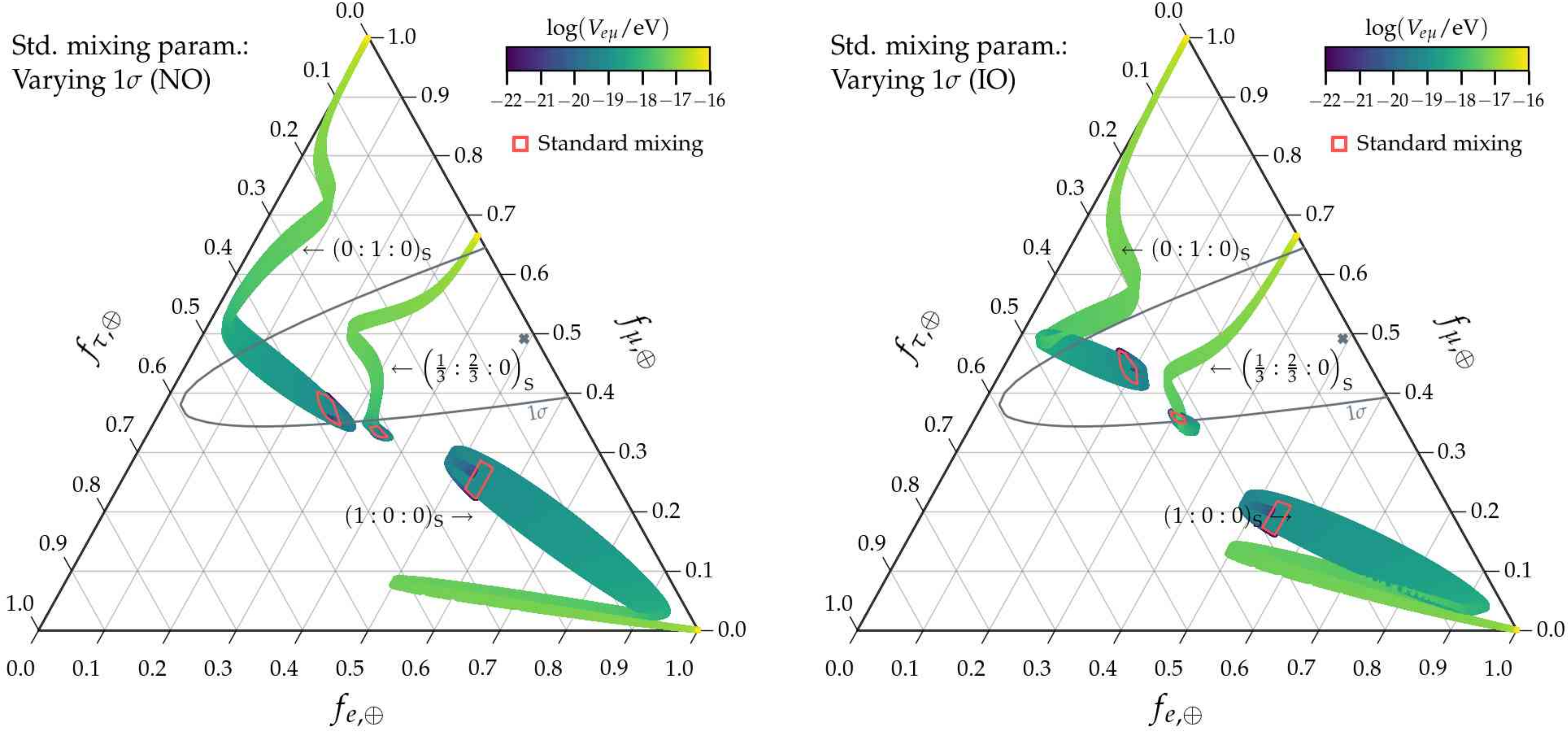


Resonance due to the L_e-L_μ symmetry (*cont.*)

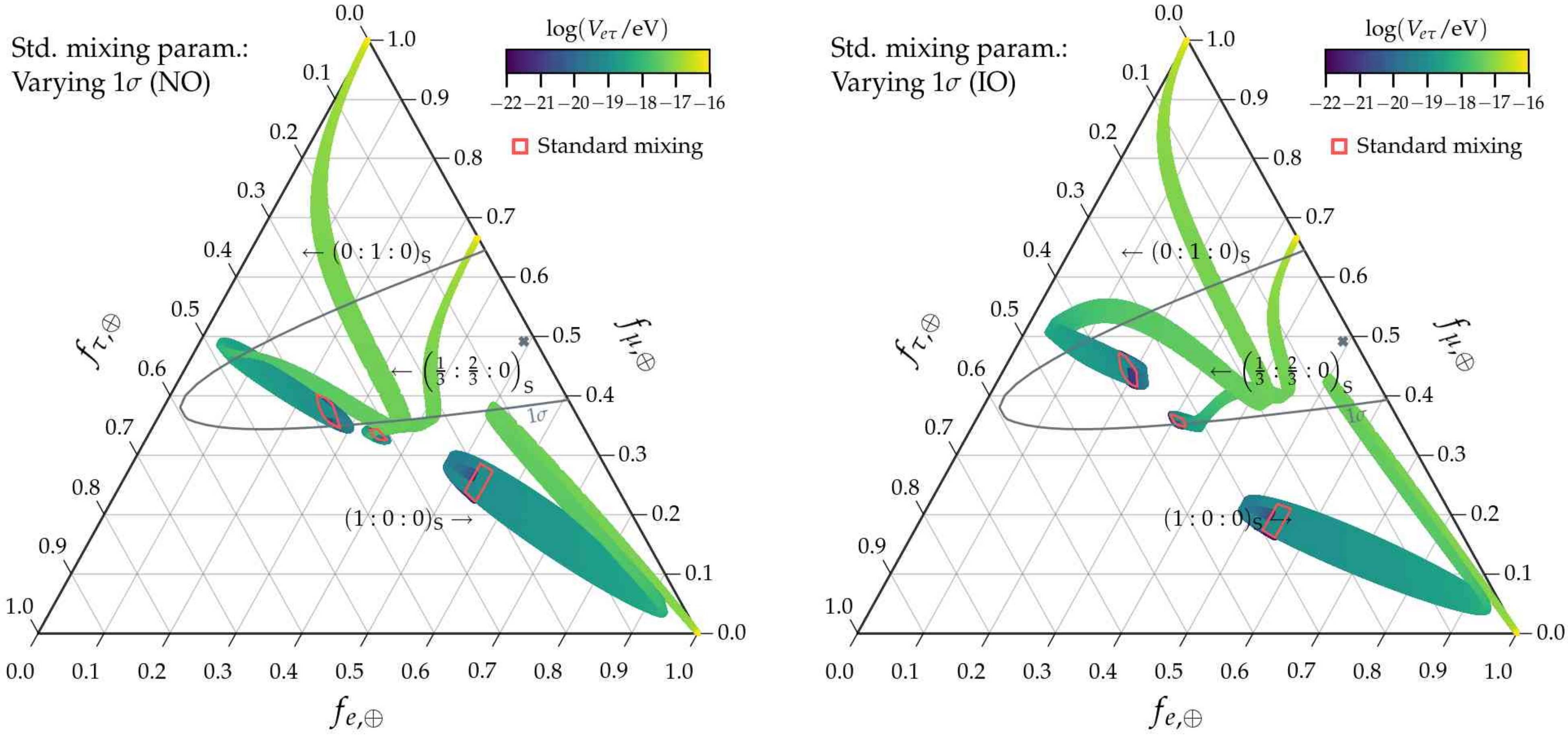


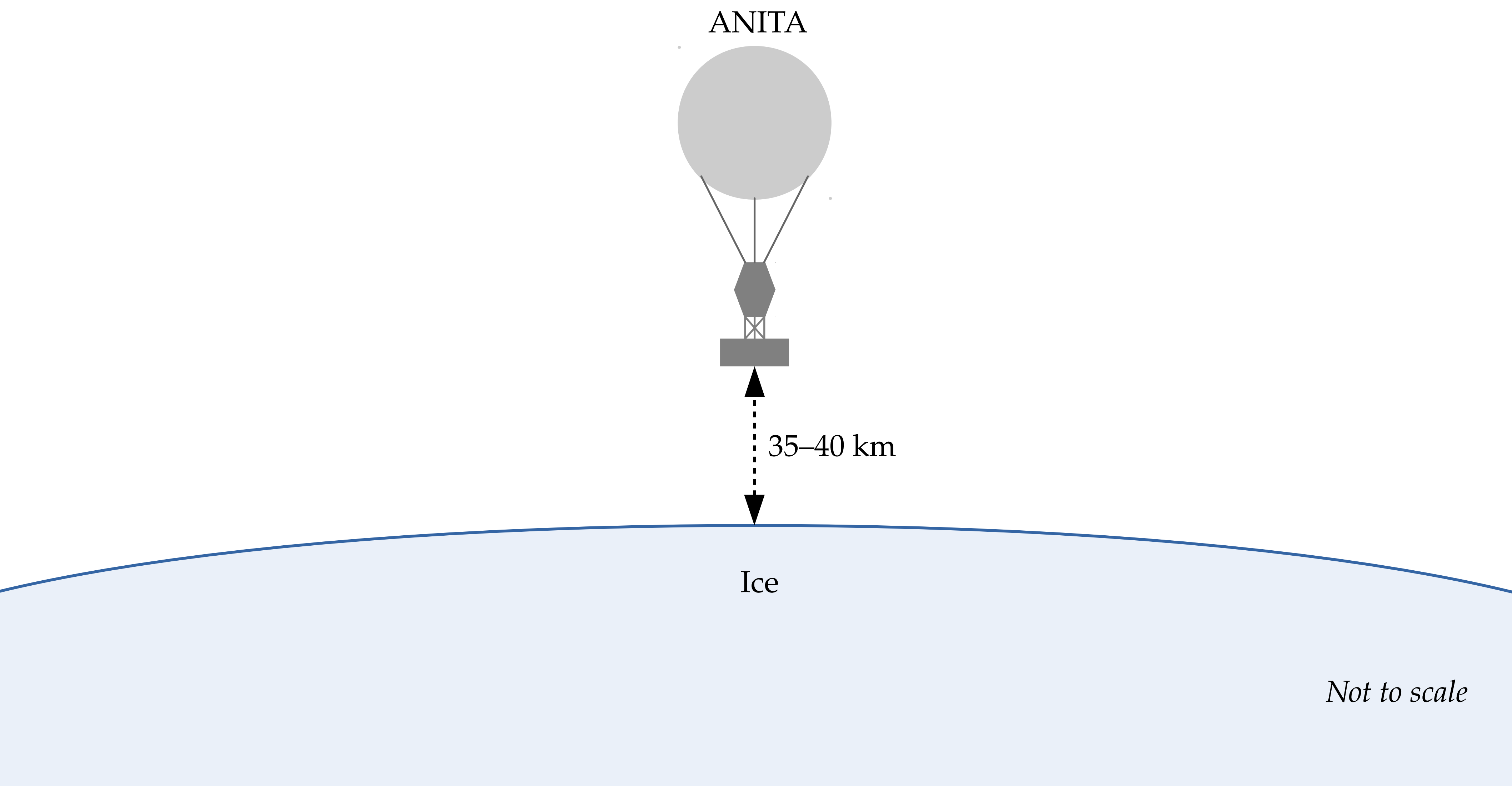


Flavor ratios for the L_e-L_μ symmetry: NO *vs.* IO

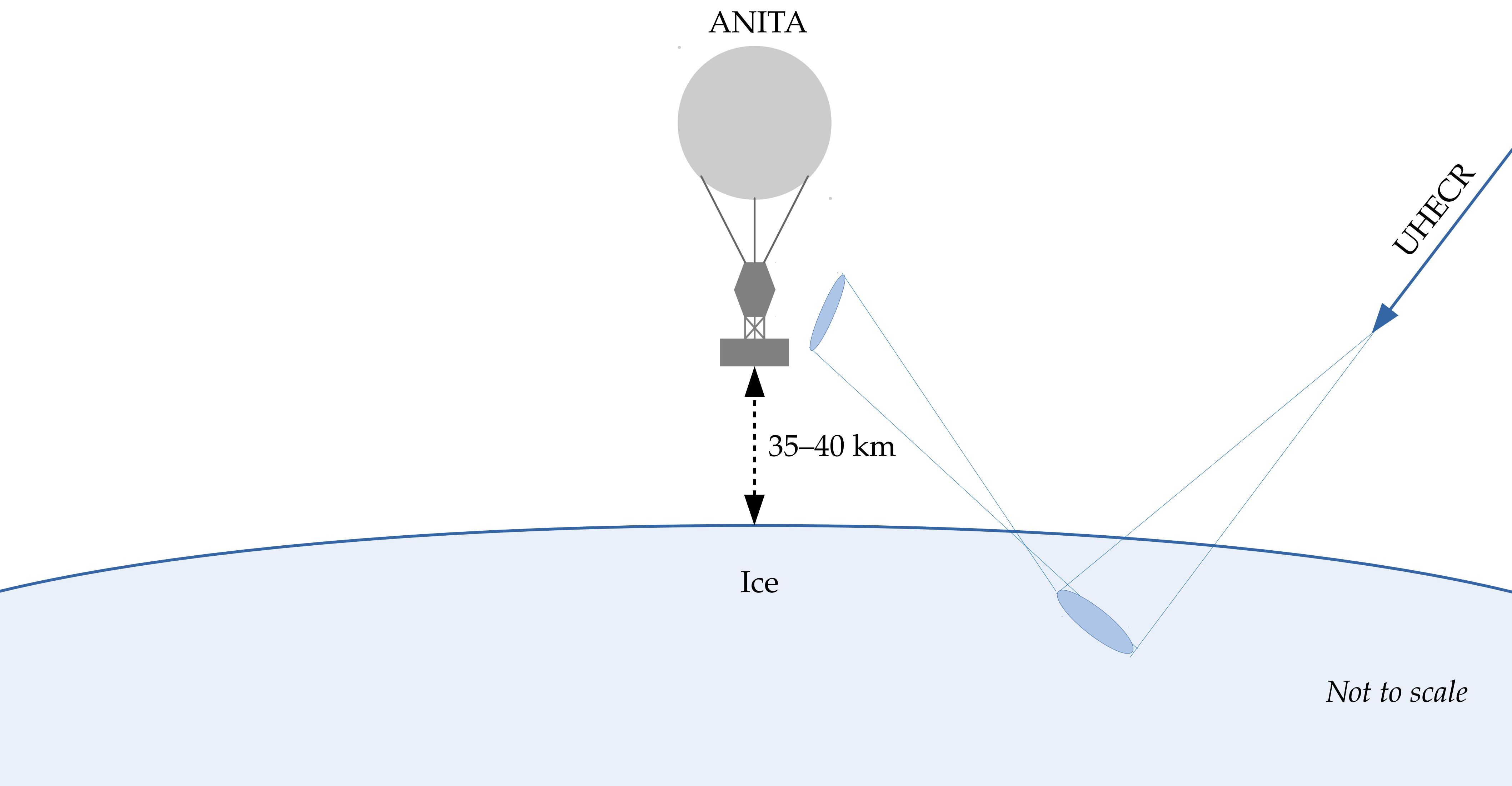


Flavor ratios for the L_e-L_τ symmetry: NO *vs.* IO





ANITA
35–40 km
Ice
Not to scale


ANITA
UHECR
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Ice
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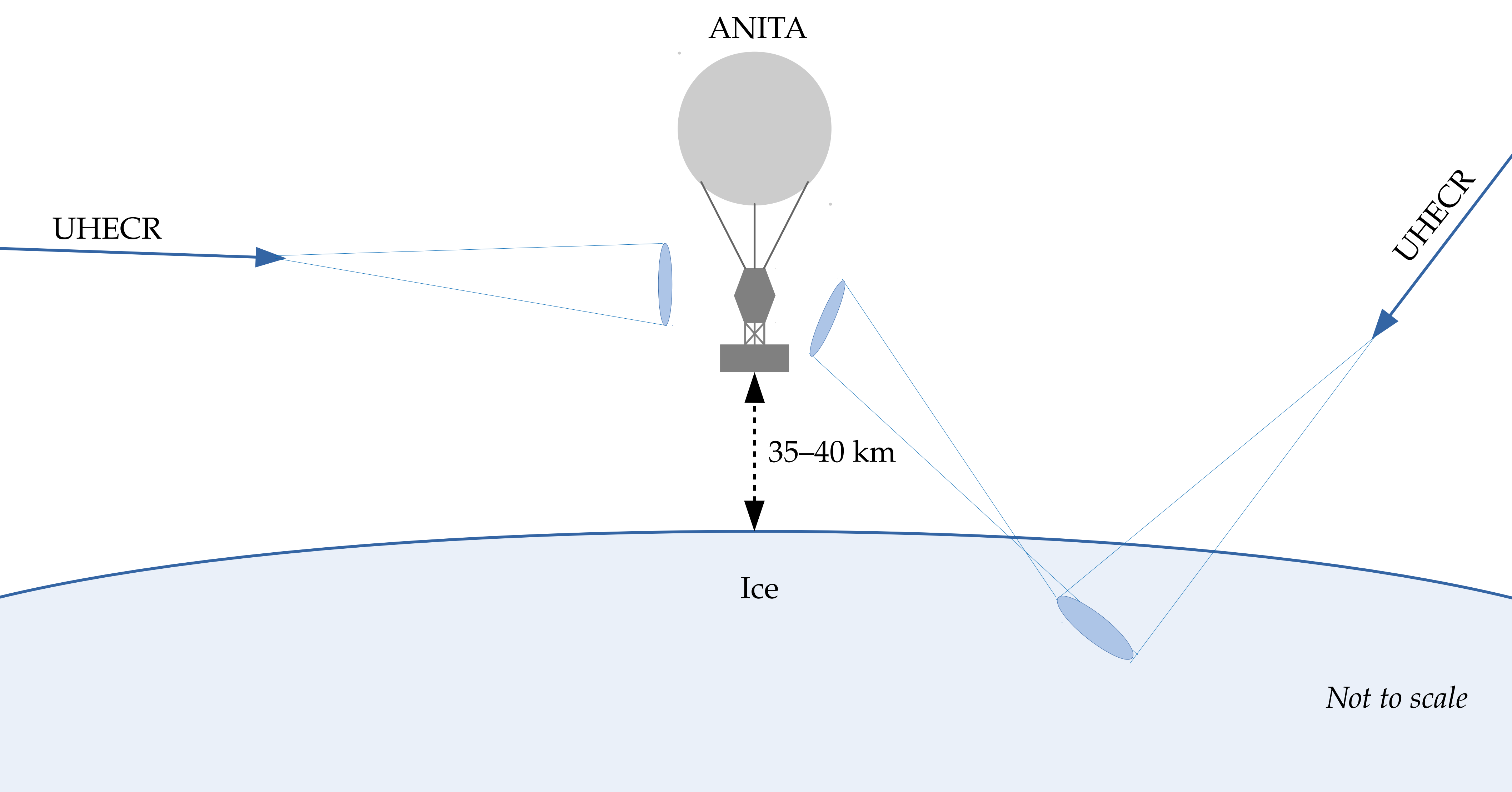
ANITA
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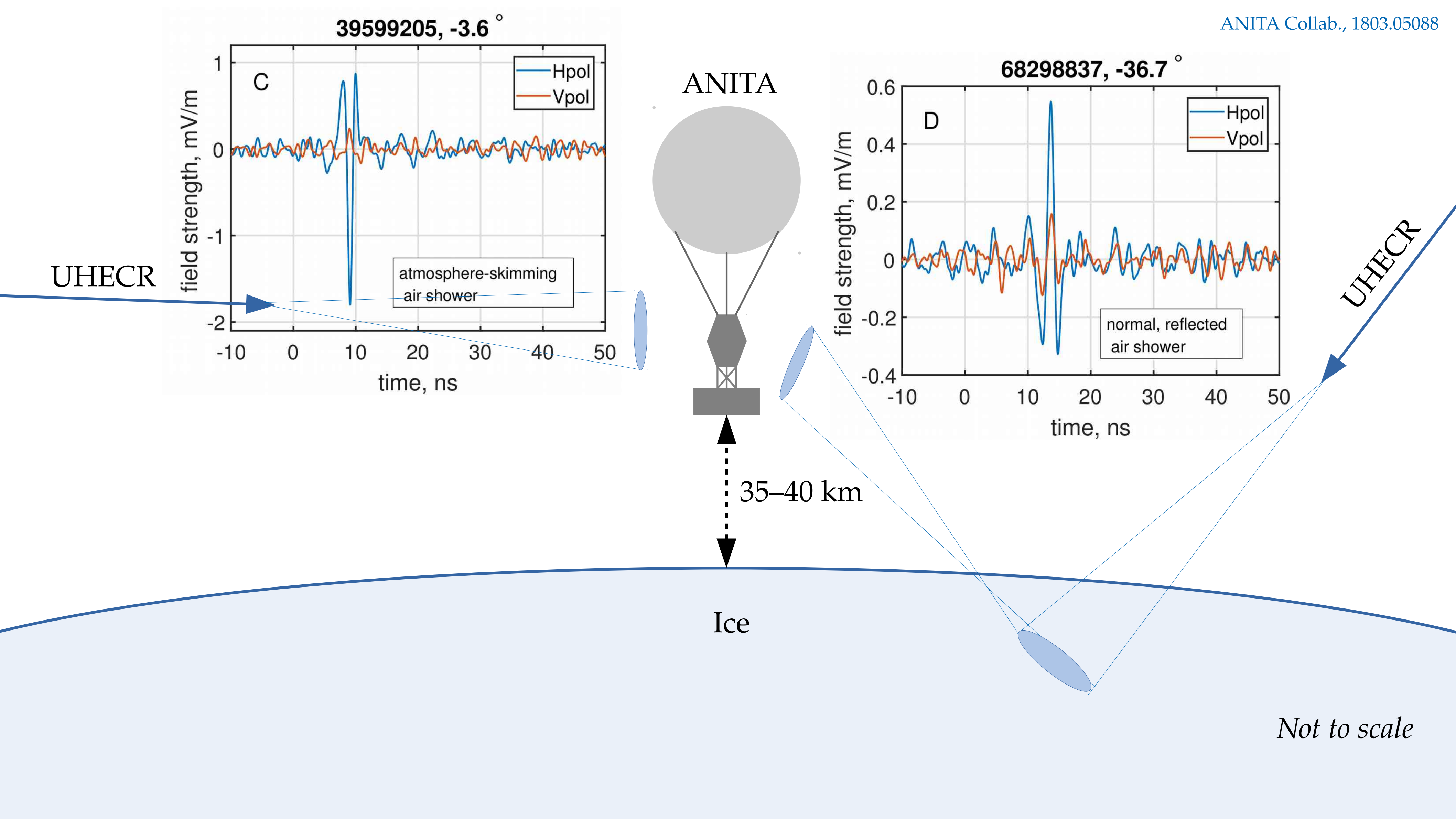
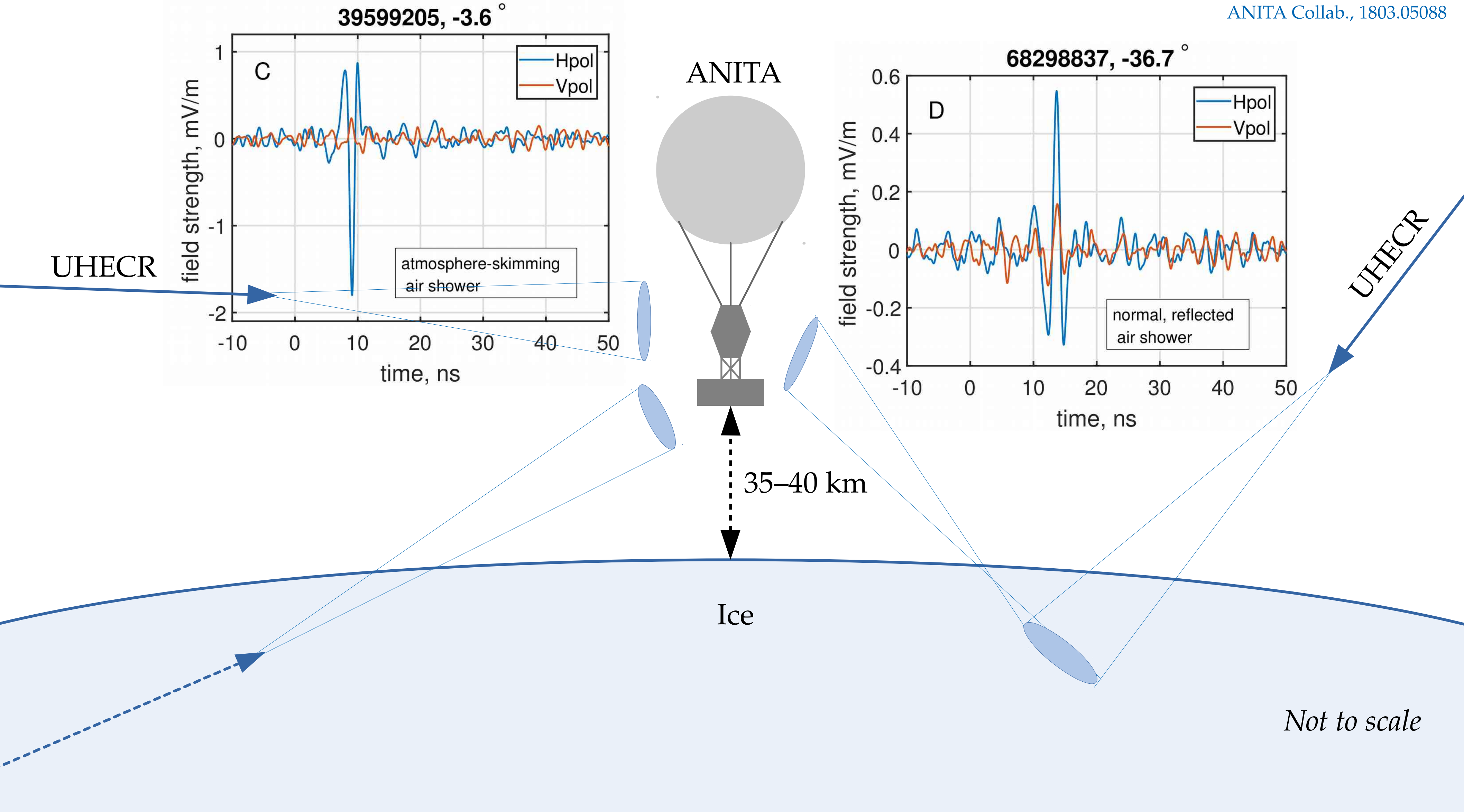
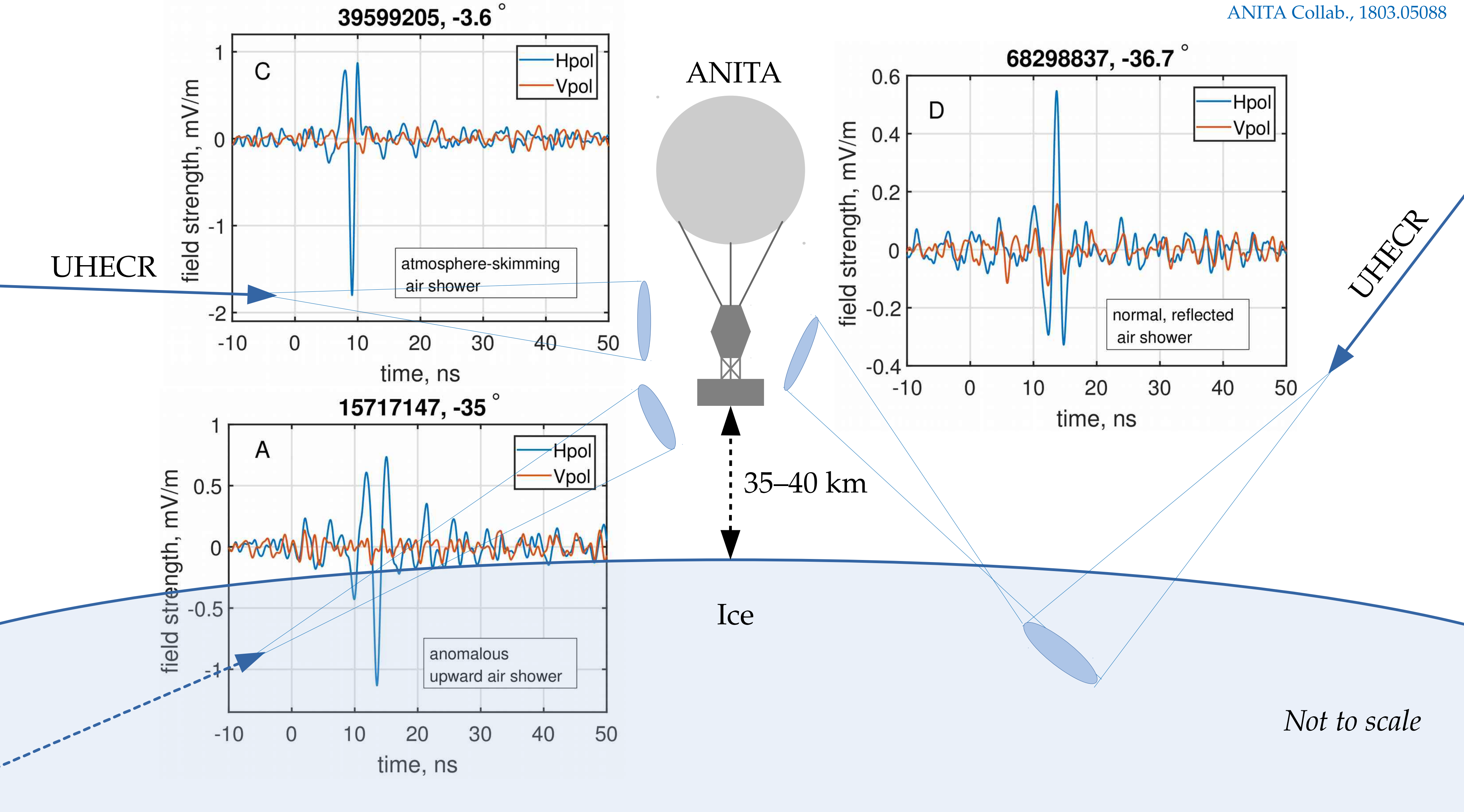

ANITA Collab., 1803.05088
39599205, -3.6 °
C
Hpol
Vpol
field strength, mV/m
time, ns
atmosphere-skimming air shower
UHECR
ANITA
68298837, -36.7 °
D
normal, reflected air shower
35–40 km
Ice
Not to scale

ANITA Collab., 1803.05088




39599205, -3.6 °
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field strength, mV/m
time, ns
15717147, -35 °
A
Hpol
Vpol
anomalous upward air shower
field strength, mV/m
time, ns
68298837, -36.7 °
D
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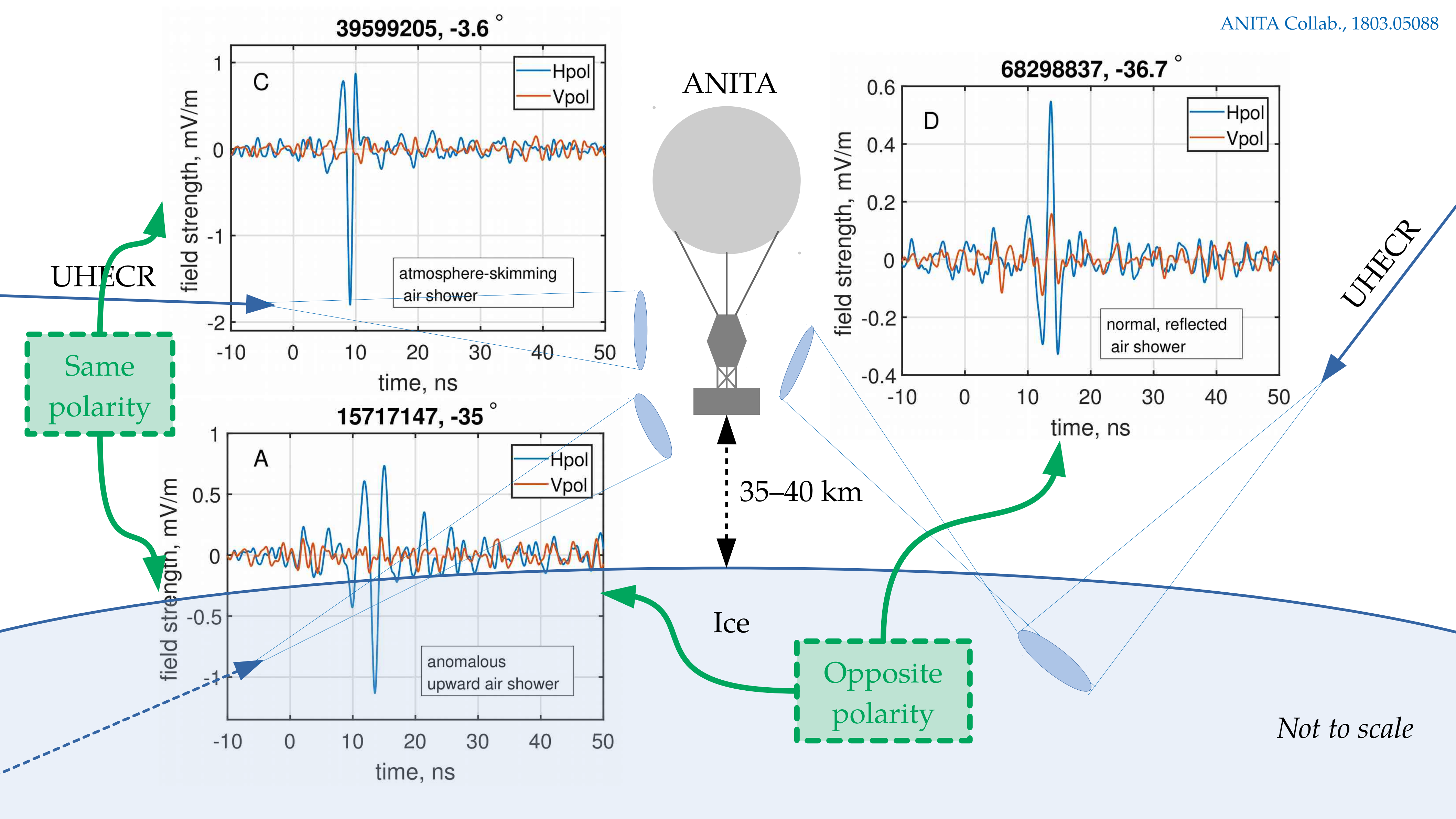

ANITA Collab., 1803.05088
39599205, -3.6 °
C
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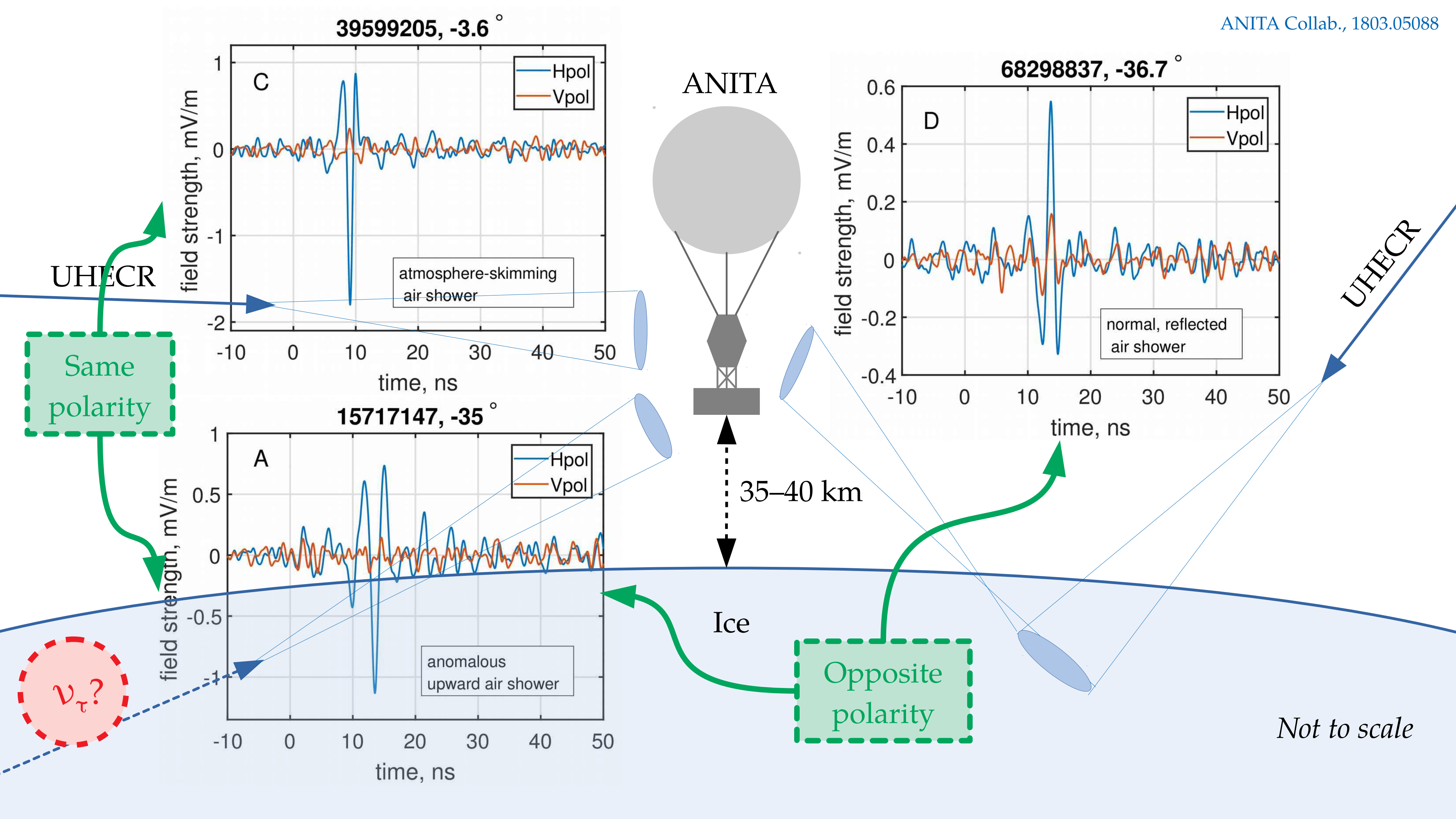
Vpol
atmosphere-skimming
air shower
field strength, mV/m
time, ns
15717147, -35 °
A
anomalous
upward air shower
68298837, -36.7 °
D
normal, reflected
air shower
ANITA
35–40 km
UHECR
UHECR
Same
polarity
Opposite
polarity
Ice
Not to scale



ANITA Collab., 1803.05088
39599205, -3.6 °
C
Hpol
Vpol
atmosphere-skimming
air shower
field strength, mV/m
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UHECR
Same
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upward air shower
ν_τ?
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Opposite
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Mystery ANITA events – First UHE ν detected?

- Two upgoing, unflipped-polarity showers:
  - ANITA-1 (2006): 20°±0.3° dec., 0.60±0.4 EeV
  - ANITA-3 (2014): 38°±0.3° dec., 0.56±0.2 EeV

- Estimated background rate: < 10^{-2} events

- Were these showers due to ν_τ? *Unlikely*

- Optical depth to νN interactions at EeV:

$$\frac{\text{Chord inside Earth}}{\text{Interaction length in Earth}} = \frac{7000\ \text{km}}{390\ \text{km}} = 18$$

- Flux is suppressed by $e^{-18} = 10^{-8}$

ANITA Collab., *PRL* 2016 + 1803.05088

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Transient astrophysical event?

- **ANITA-1 event:** none associated
- **ANITA-3 event:**
  - Type-Ia SN2014dz ($z = 0.017$)
  - Within 1.9°, 5 hours before event
  - Probability of chance SN: 3×10^{-3}
  - ν luminosity must exceed bolometric luminosity of 4×10^{42} erg s^{-1}

Mystery ANITA events – What are they?

- Transition radiation [Motloch *et al.*, *PRD* 2017]:
  - Refraction of radio waves at ice-air interface could make horizontal ν_τ look upgoing
  - Assessment: Needs too large a diffuse flux of ν_τ, because transition radiation is a small effect

- Sterile neutrinos [Cherry & Shoemaker, 1802.01611; Huang, 1804.05362]:
  - Sterile neutrinos propagate in Earth, then convert $\nu_s \to \nu_\tau$
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- Dark matter decay in Earth core [Anchordoqui *et al.*, 1803.11554]:
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