

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

Mauricio Bustamante

Niels Bohr Institute, University of Copenhagen

Astroparticle Seminar

DESY, December 06, 2018

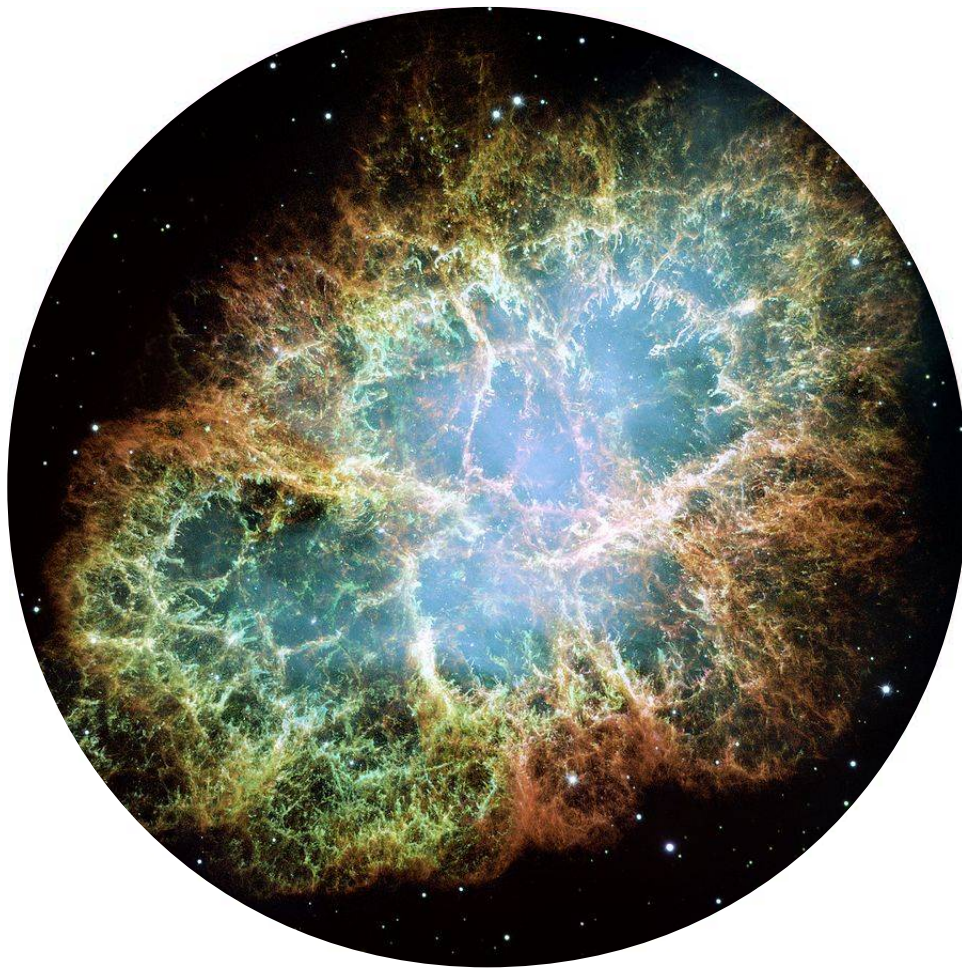
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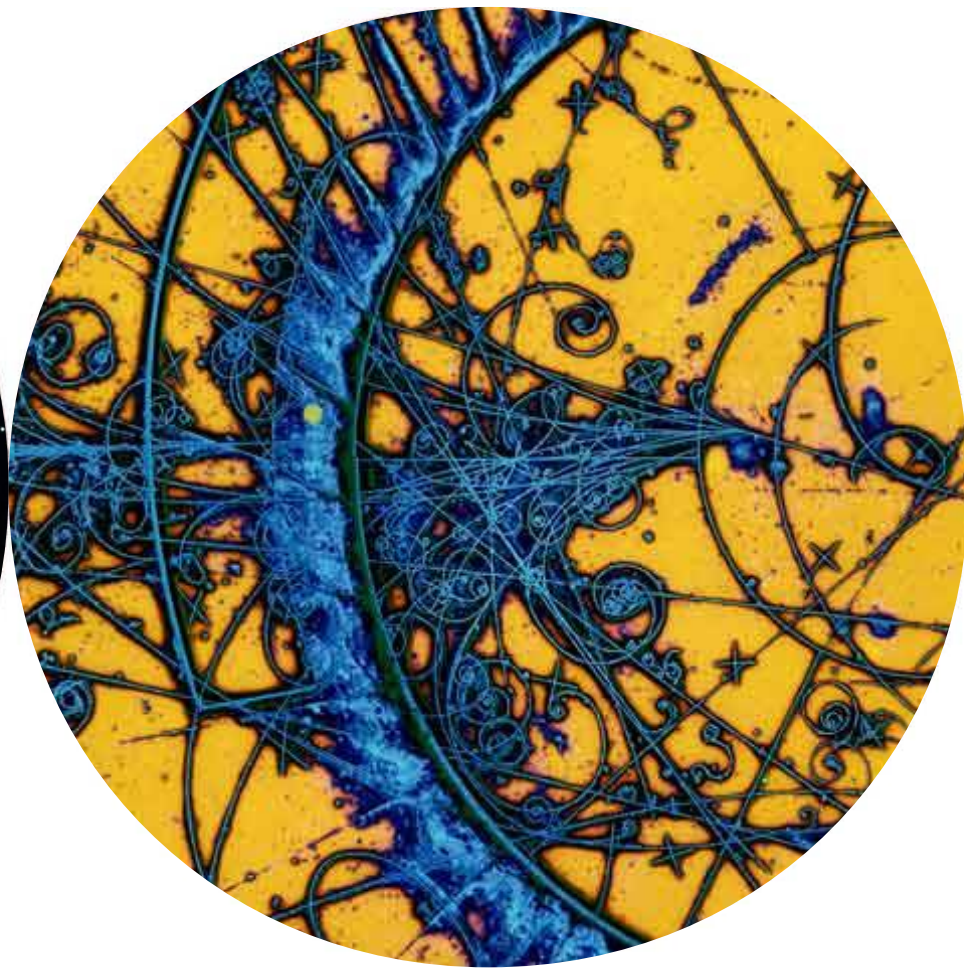
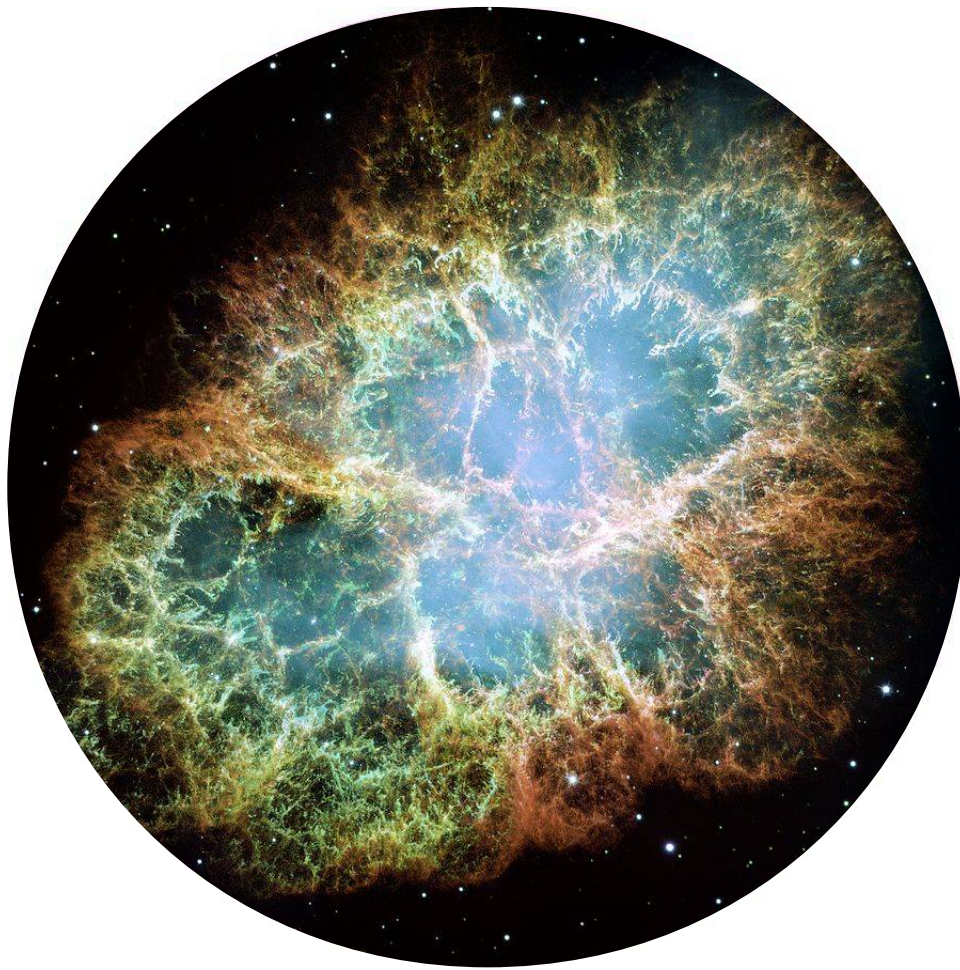


VILLUM FONDEN



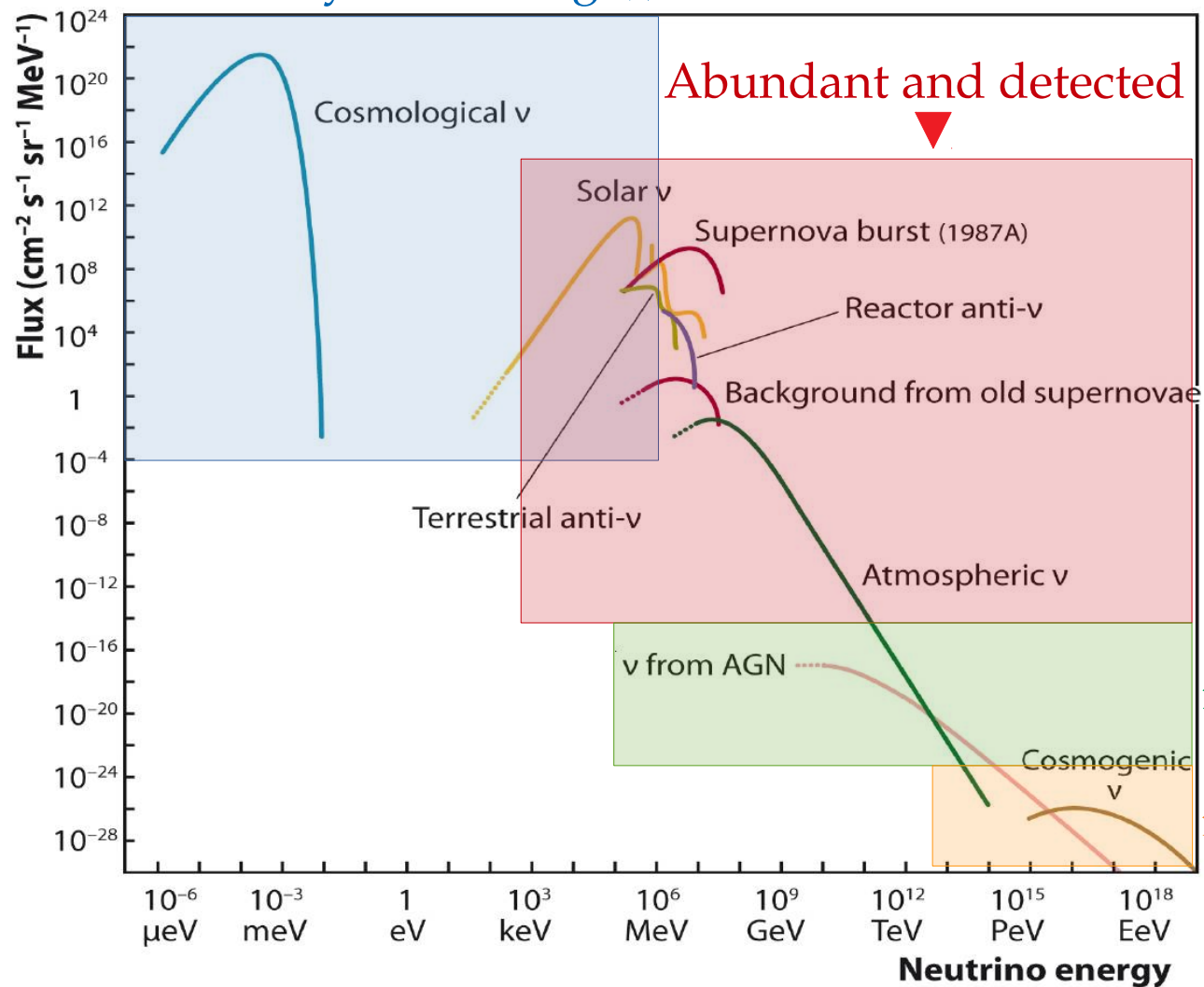








Abundant, but hardly interacting ▼



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

- 1 They have the **highest energies** ($\sim \text{PeV}$)
↳ Probe physics at new energy scales
- 2 They have the **longest baselines** ($\sim \text{Gpc}$)
↳ Tiny effects can accumulate and become observable

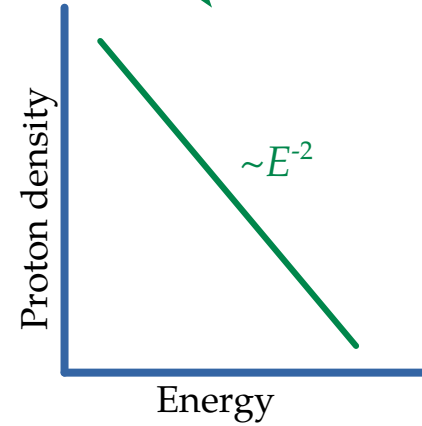
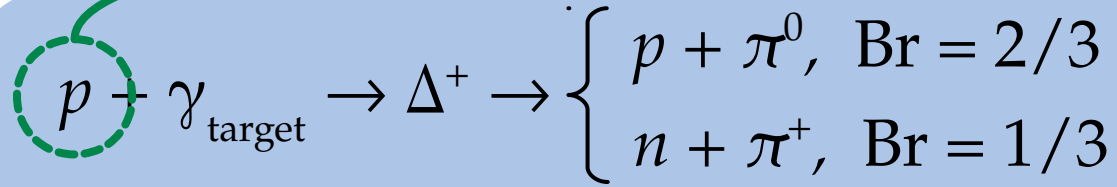
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- 1 They have the **highest energies** ($\sim \text{PeV}$)
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- 2 They have the **longest baselines** ($\sim \text{Gpc}$)
 $\rightarrow$ Tiny effects can accumulate and become observable
- 3 It comes *for free*

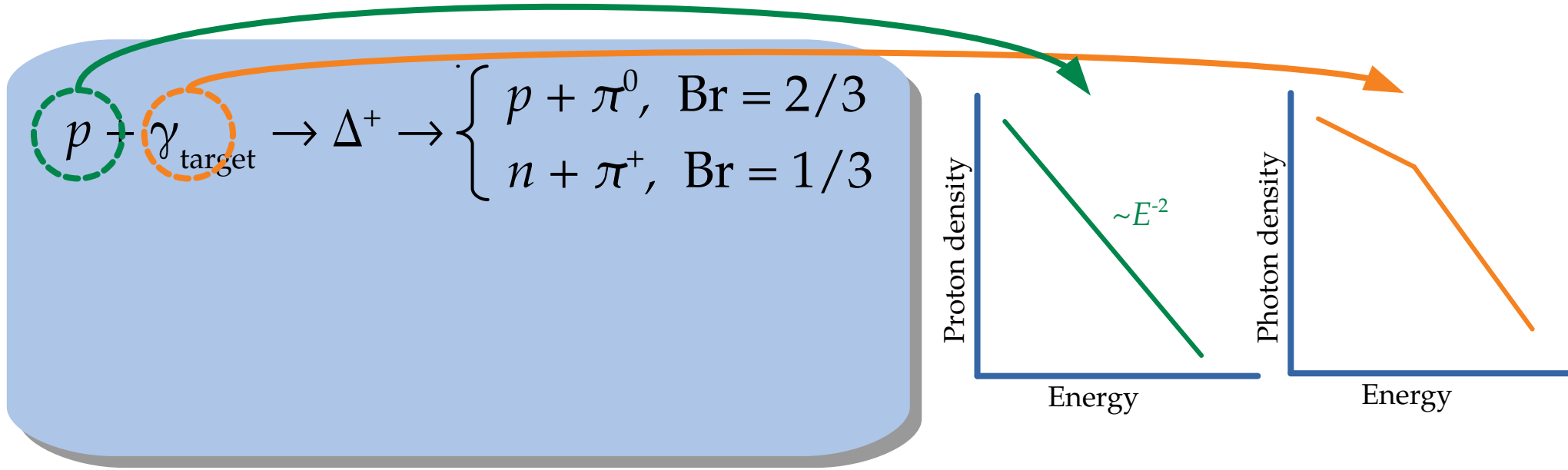
The multi-messenger connection

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

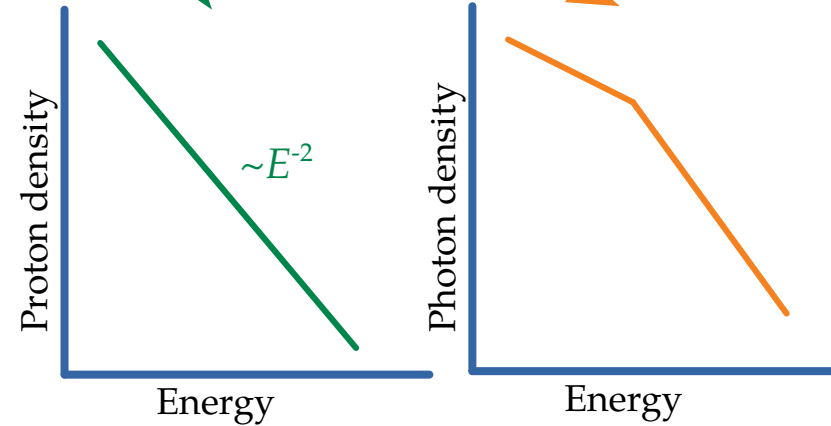
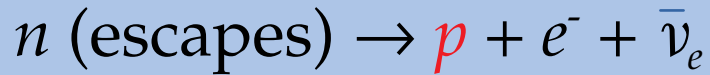
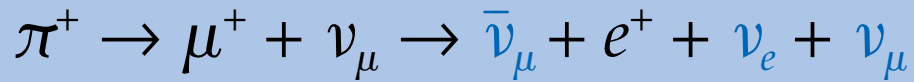
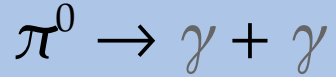
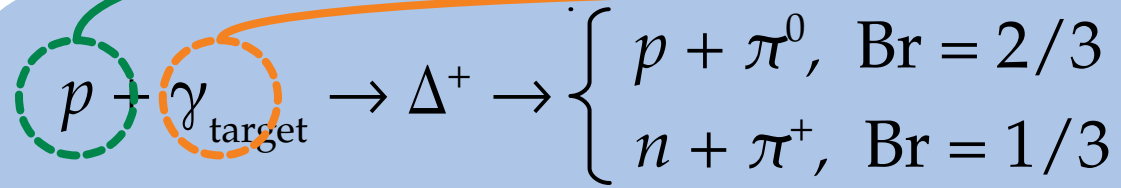
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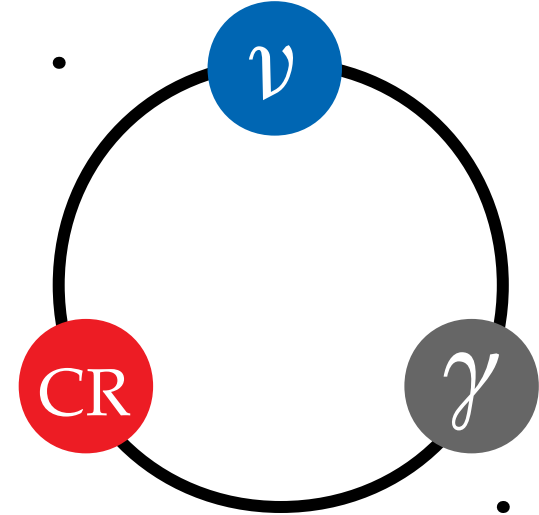
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$$\pi^0 \rightarrow \gamma + \gamma$$

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

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



$$\text{Neutrino energy} = \text{Proton energy} / 20$$

$$\text{Gamma-ray energy} = \text{Proton energy} / 10$$

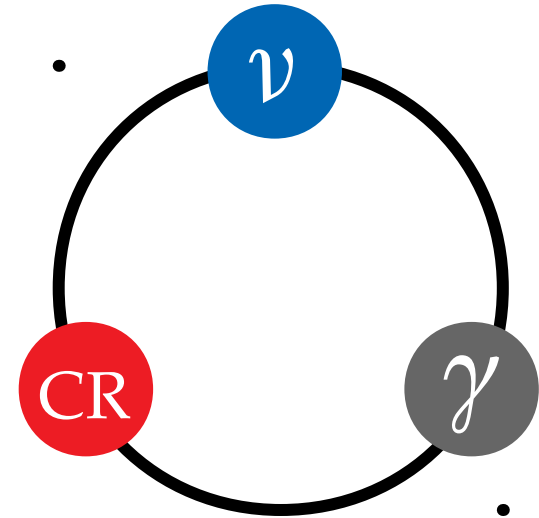
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1 PeV

20 PeV

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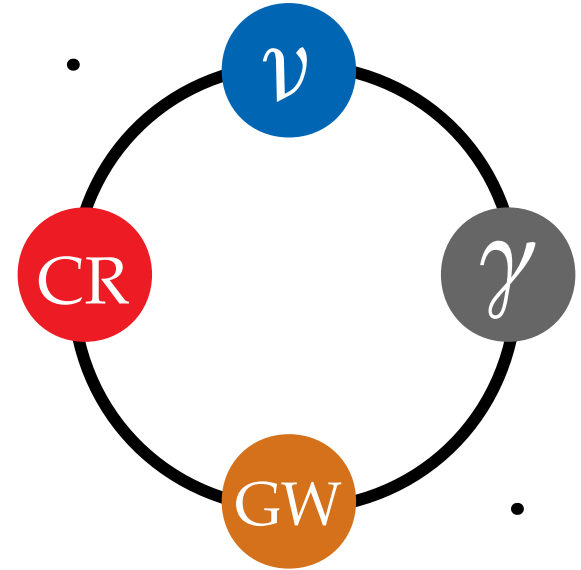
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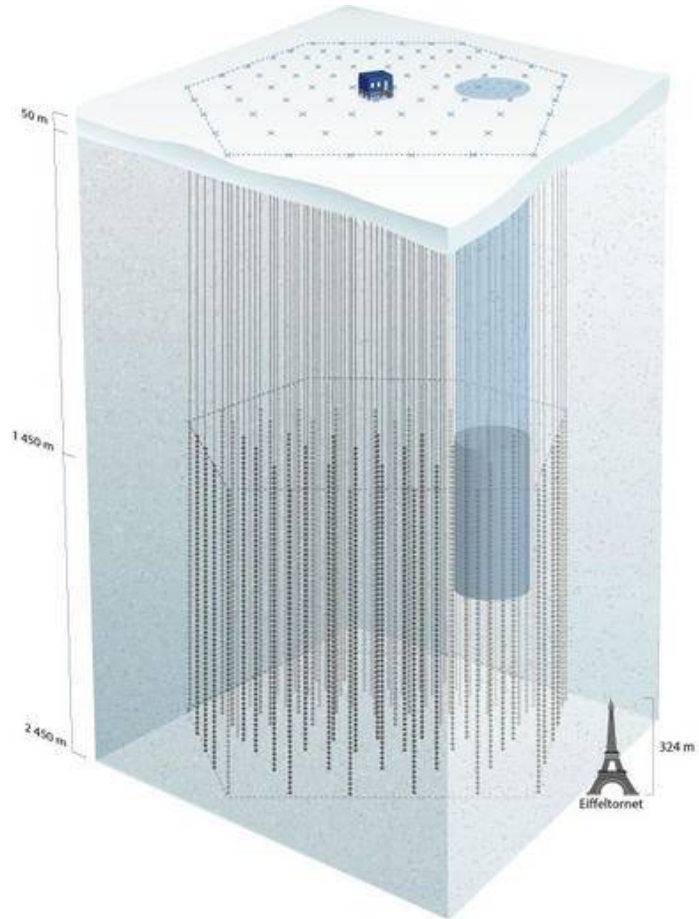
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IceCube – What is it?



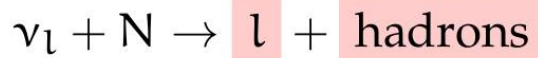
- ▶ Km^3 in-ice Cherenkov detector in Antarctica
- ▶ >5000 PMTs at 1.5–2.5 km of depth
- ▶ Sensitive to neutrino energies $> 10 \text{ GeV}$



How does IceCube see neutrinos?

Two types of fundamental interactions ...

Charged-current (CC)



Neutral-current (NC)



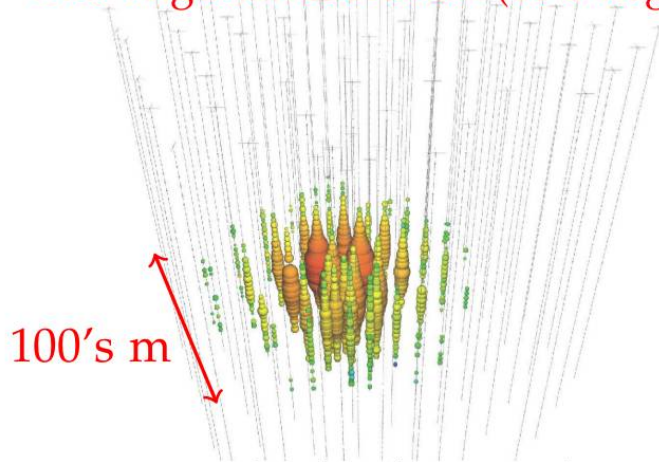
...create two event topologies ...

These shower and make light

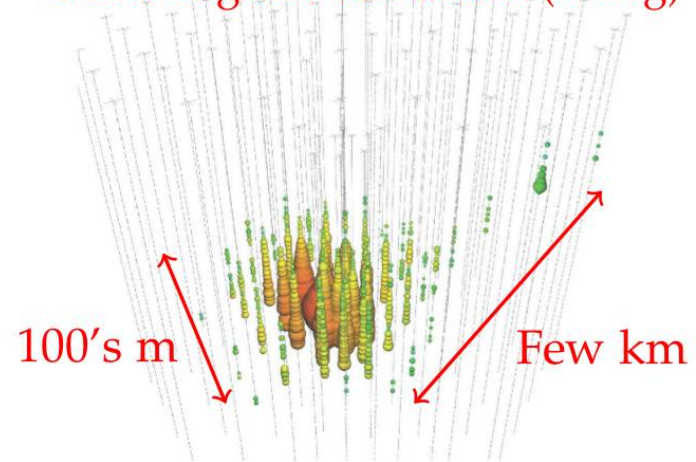
Showers — From CC ν_e or ν_τ , or NC ν_χ

Tracks — From CC ν_μ mainly

Bad angular resolution (10's deg)



Good angular resolution (< deg)

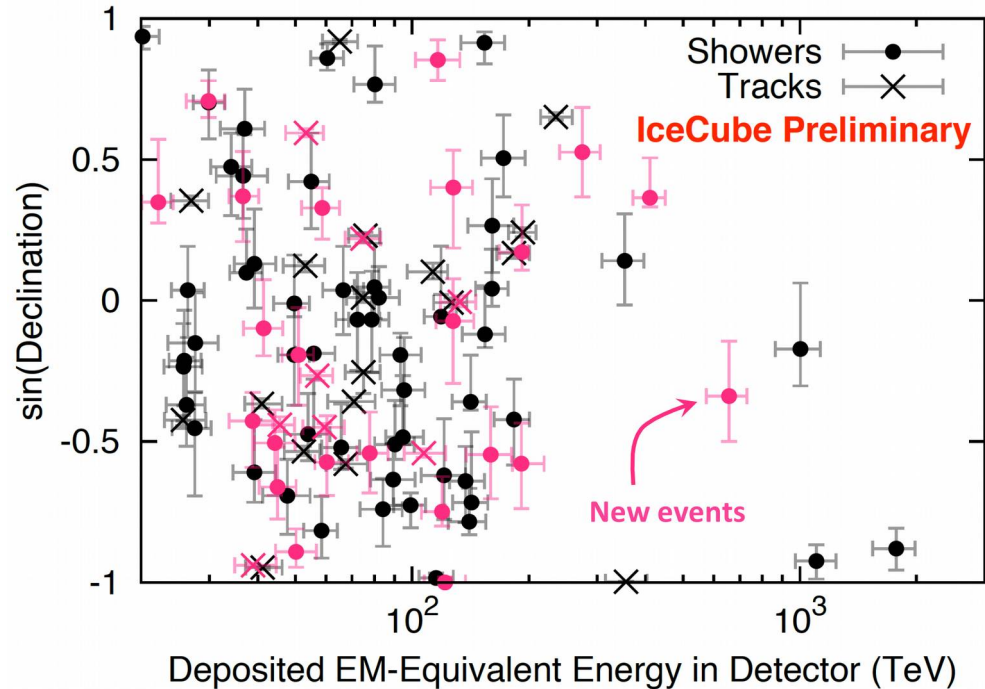


What has IceCube found so far (7.5 years)?

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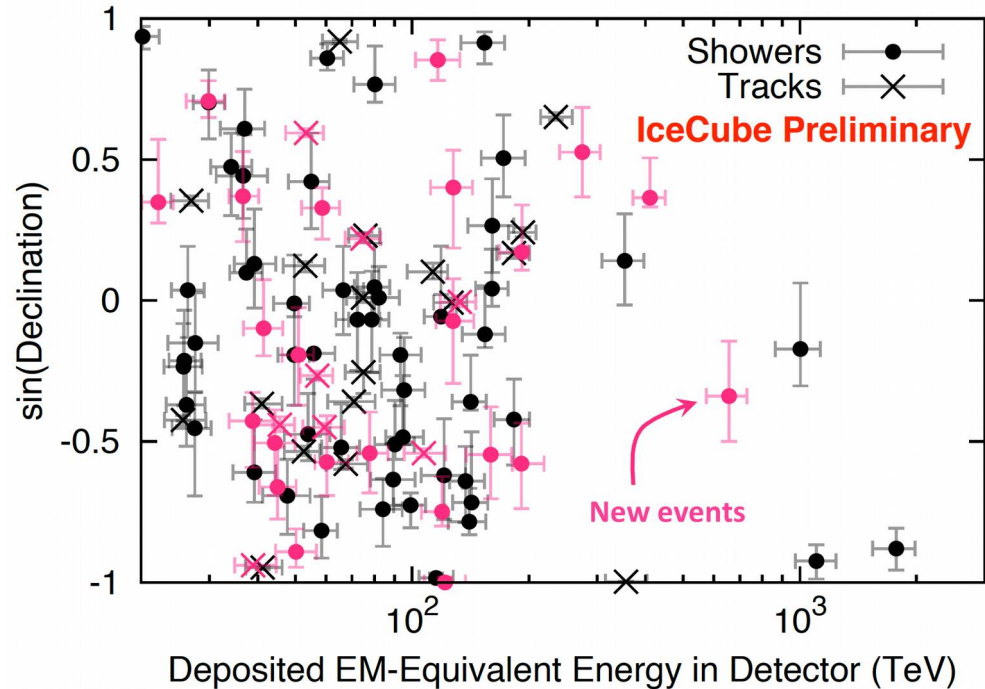
103 contained events between 15 TeV – 2 PeV



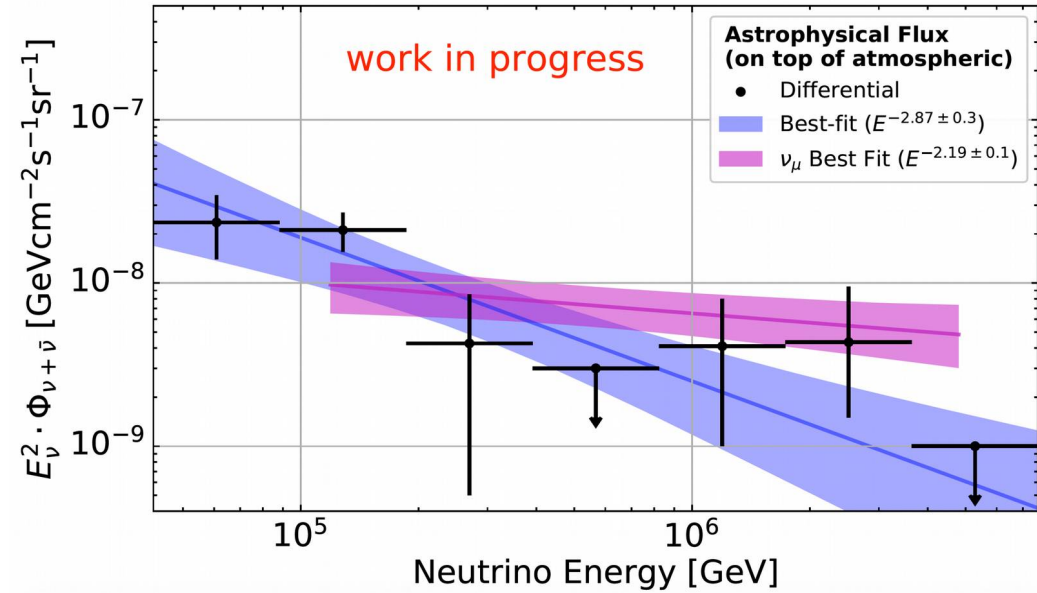
I. Taboada, Neutrino 2018

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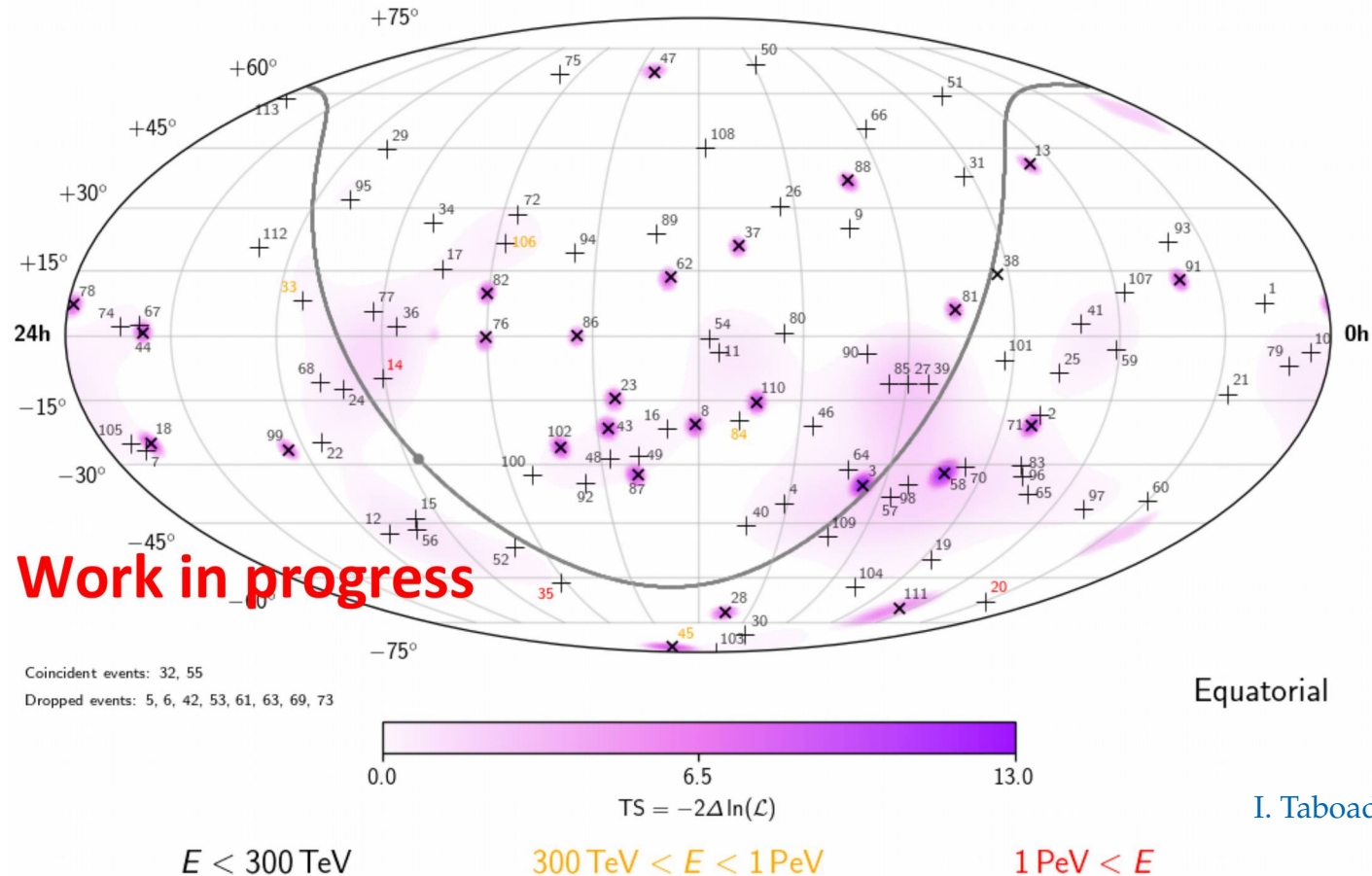
Astrophysical ν flux detected at $> 7\sigma$
(Normalization ok, but steep spectrum)



I. Taboada, Neutrino 2018

What has IceCube found so far (7.5 years)?

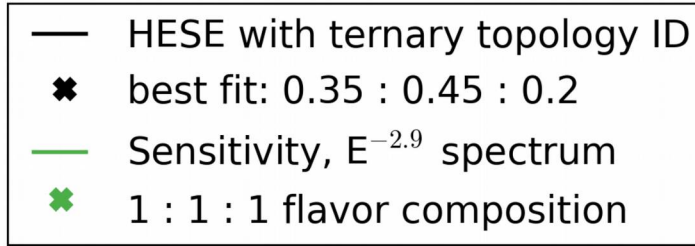
Arrival directions compatible with isotropy



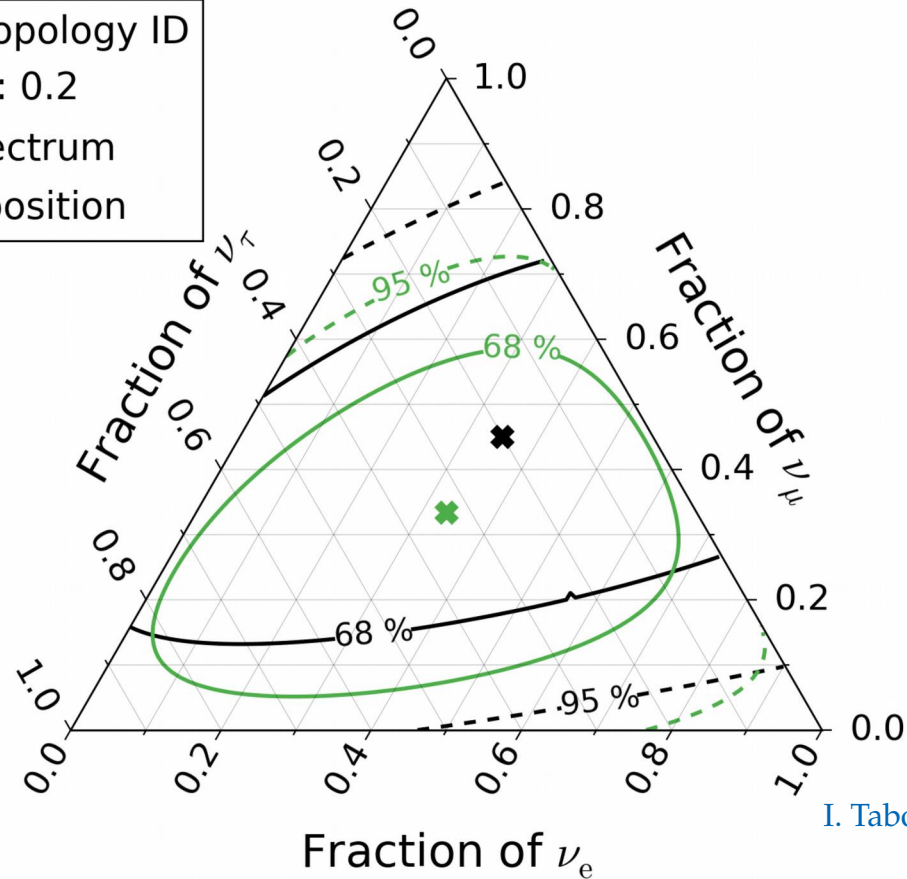
I. Taboada, Neutrino 2018

What has IceCube found so far (7.5 years)?

Flavor composition compatible with equal proportion of each flavor



WORK IN PROGRESS



I. Taboada, Neutrino 2018

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

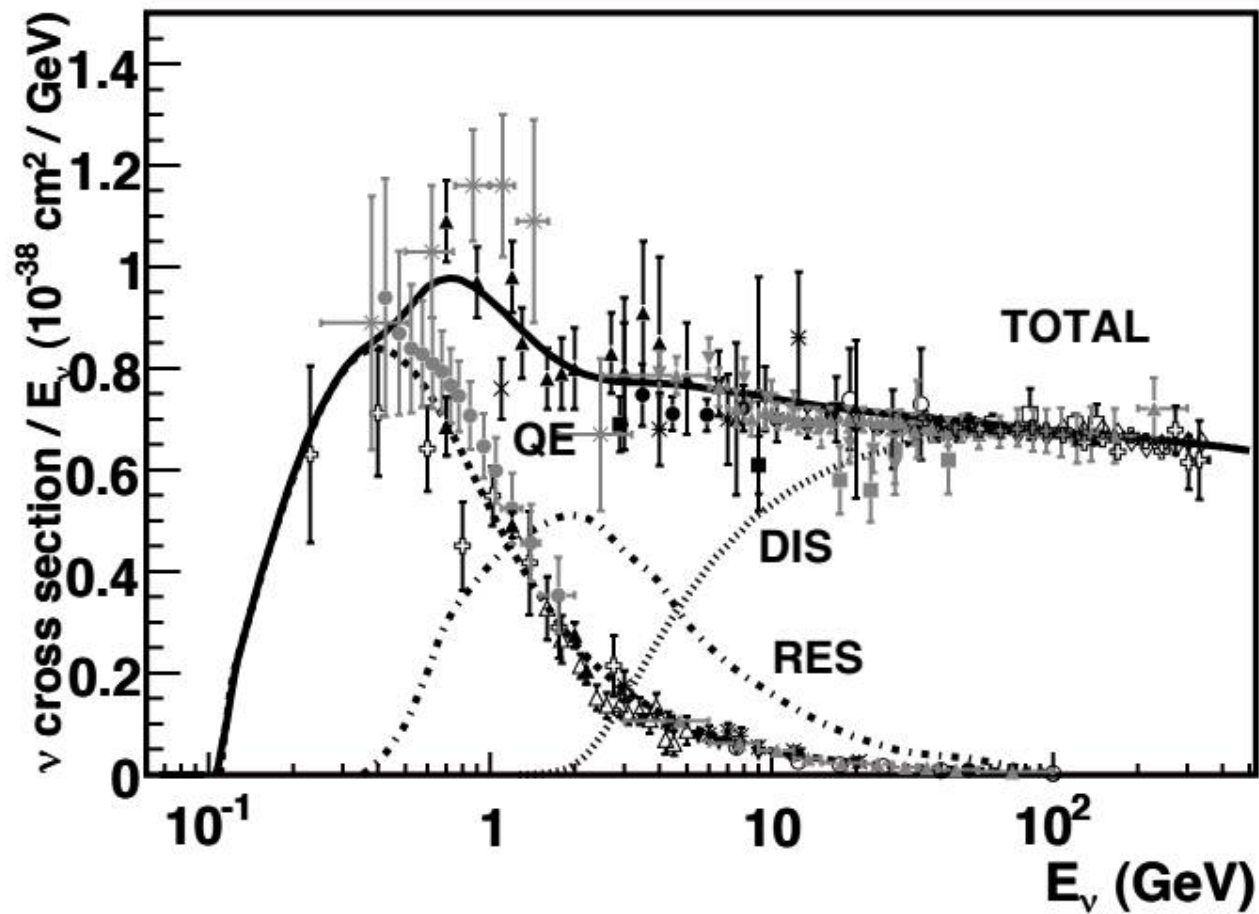
- ▶ Numerous new-physics effects grow as $\sim \kappa_n \cdot E^n \cdot L$
- ▶ So we can probe $\kappa_n \sim 4 \cdot 10^{-47} (E/\text{PeV})^{-n} (L/\text{Gpc})^{-1} \text{PeV}^{1-n}$
- ▶ Improvement over current limits: $\kappa_0 < 10^{-29} \text{PeV}$, $\kappa_1 < 10^{-33}$
- ▶ Fundamental physics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

Fundamental physics with HE astrophysical neutrinos

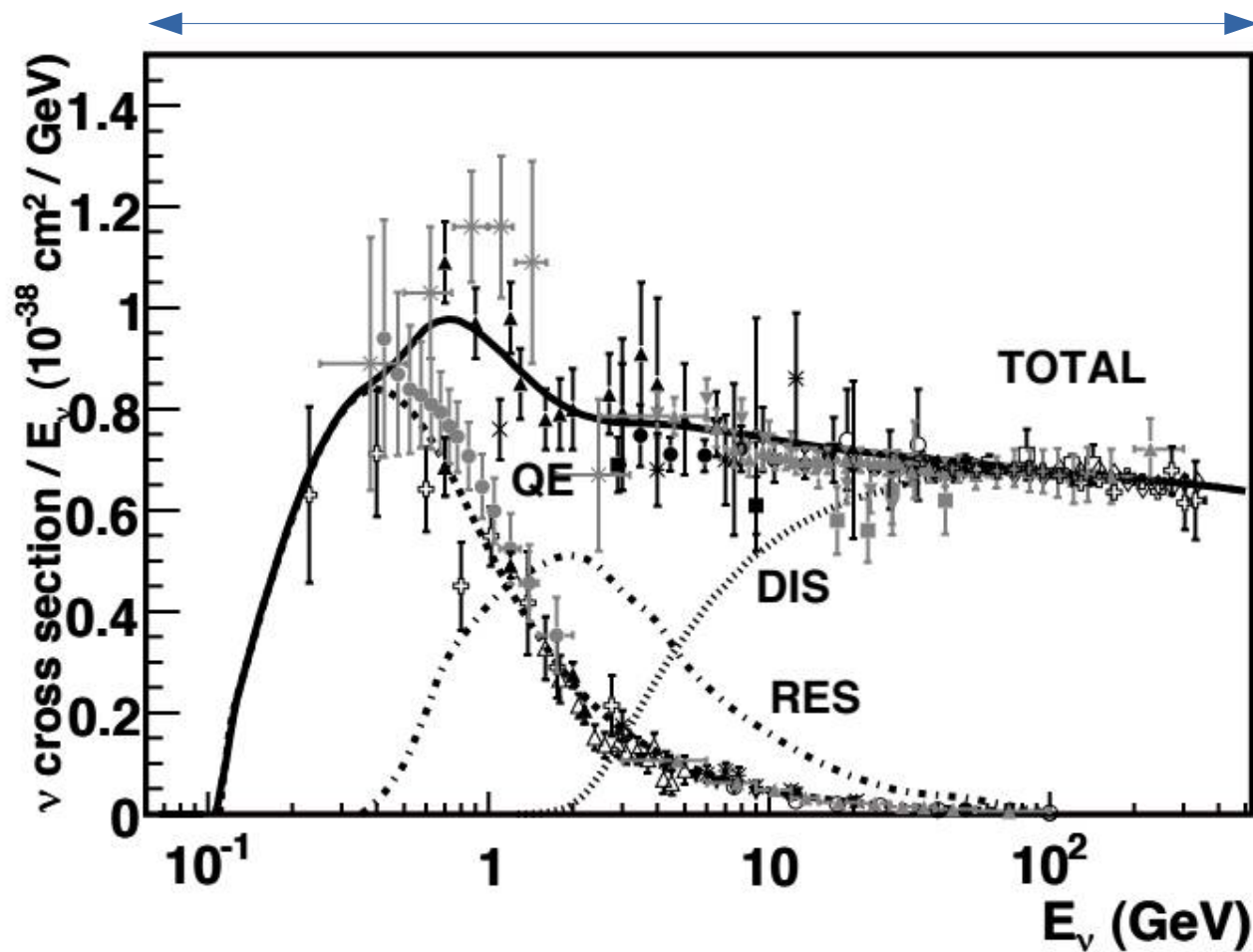
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 - $n = -1$: neutrino decay
 - $n = 0$: CPT-odd Lorentz violation
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Fundamental physics with HE astrophysical neutrinos

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- ▶ Fundamental physics can be extracted from:
 - ▶ Spectral shape
 - ▶ Angular distribution
 - ▶ Flavor information $\left. \begin{array}{l} \text{In spite of} \\ \text{poor energy, angular, flavor reconstruction} \\ \text{\& astrophysical unknowns} \end{array} \right\}$



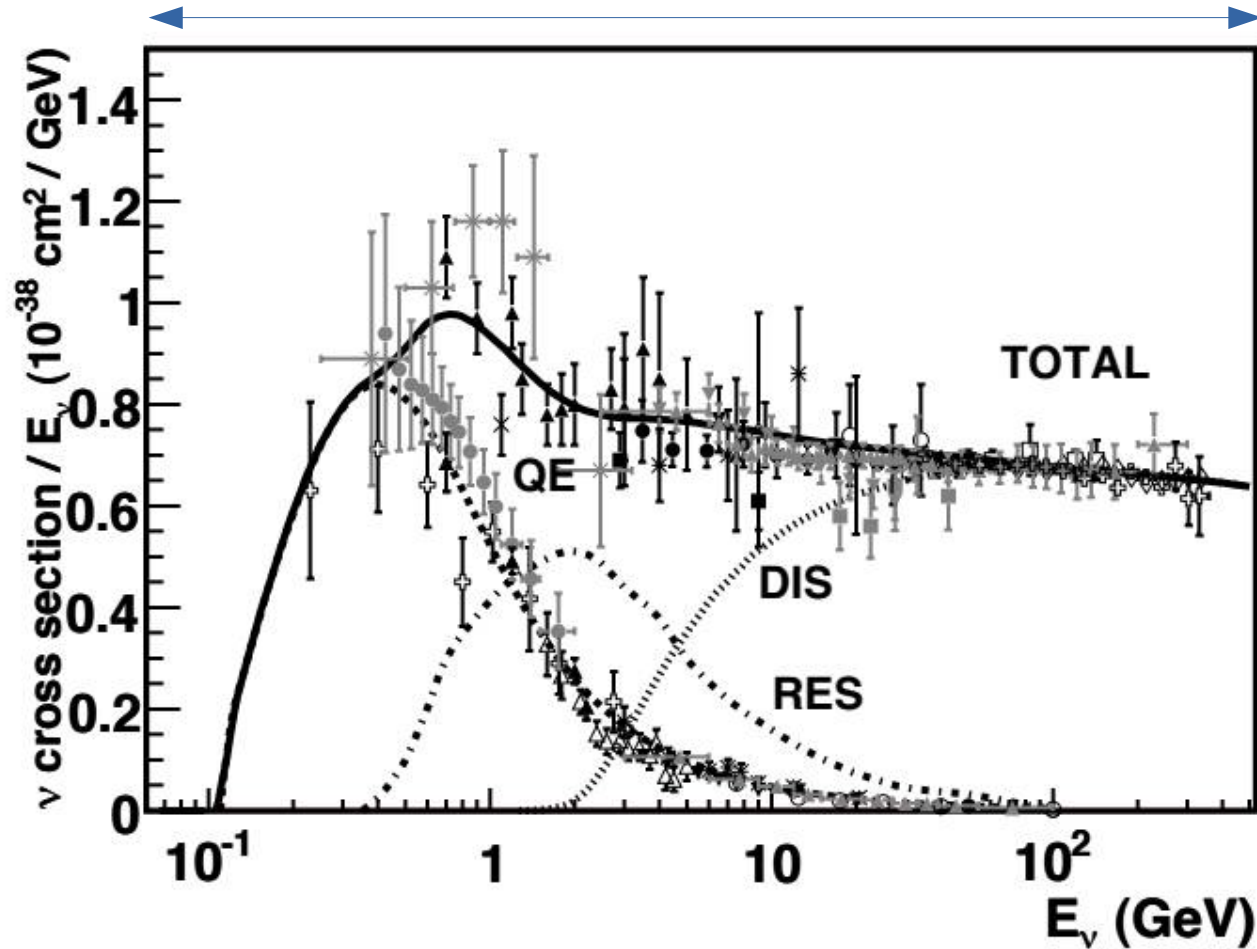
Accelerator experiments



Particle Data Group

Accelerator experiments

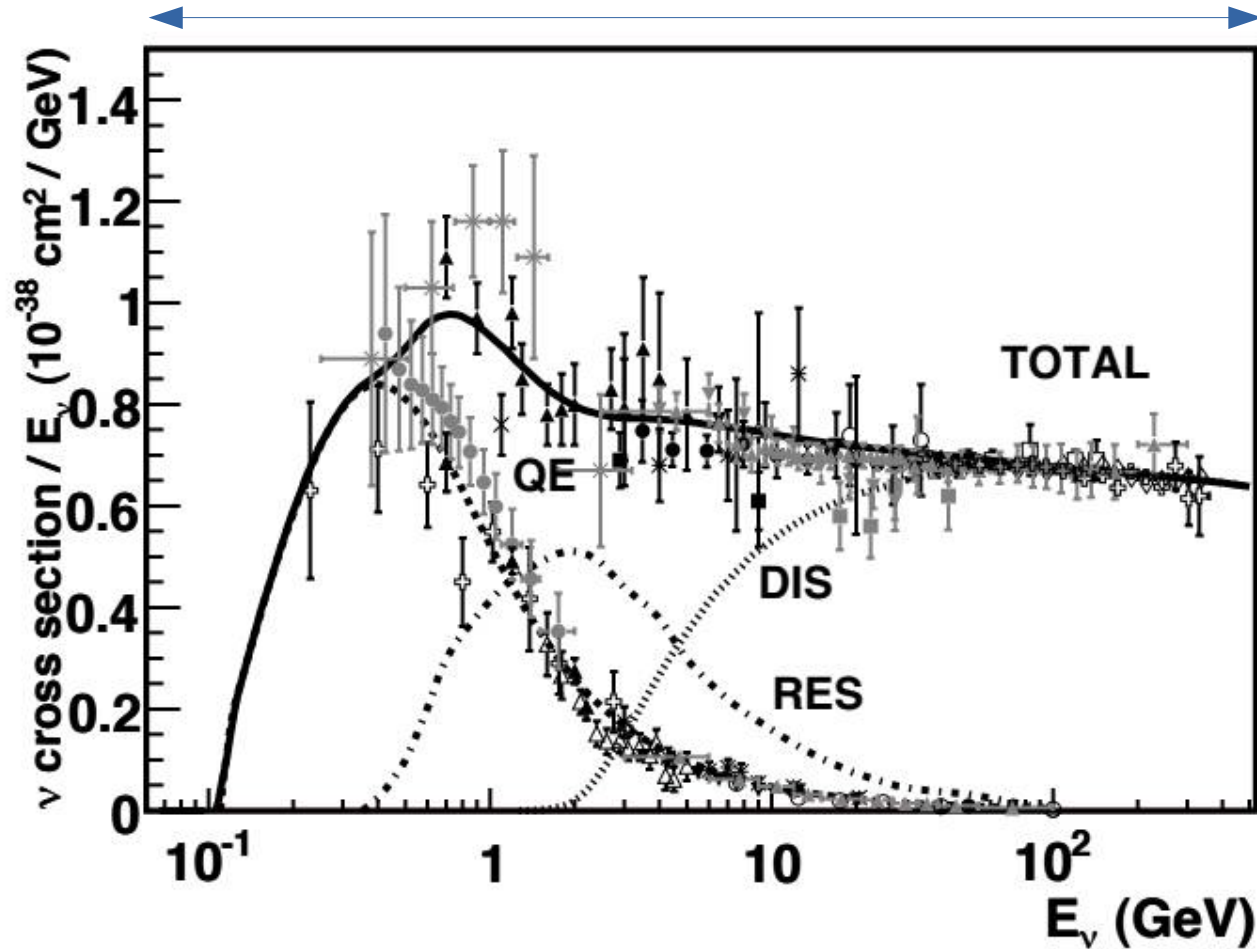
One recent
measurement
(COHERENT)



Particle Data Group

Accelerator experiments

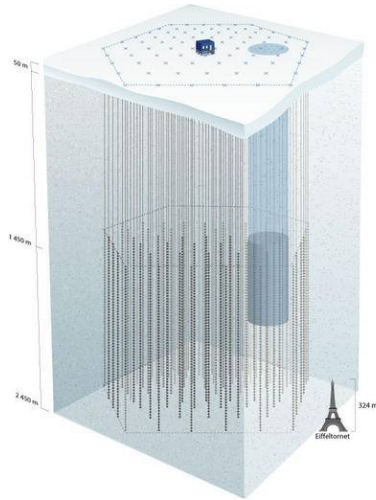
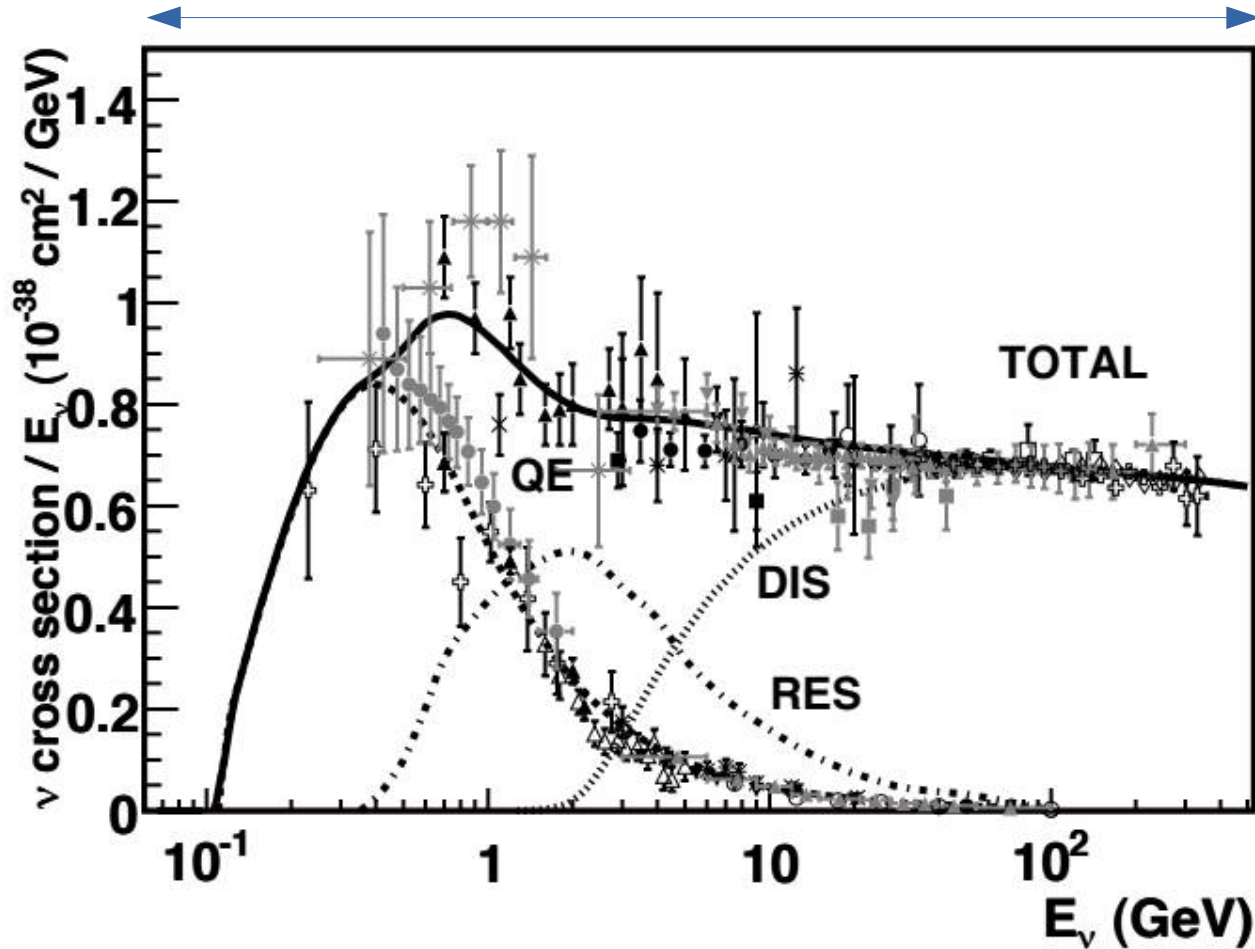
←
One recent
measurement
(COHERENT)



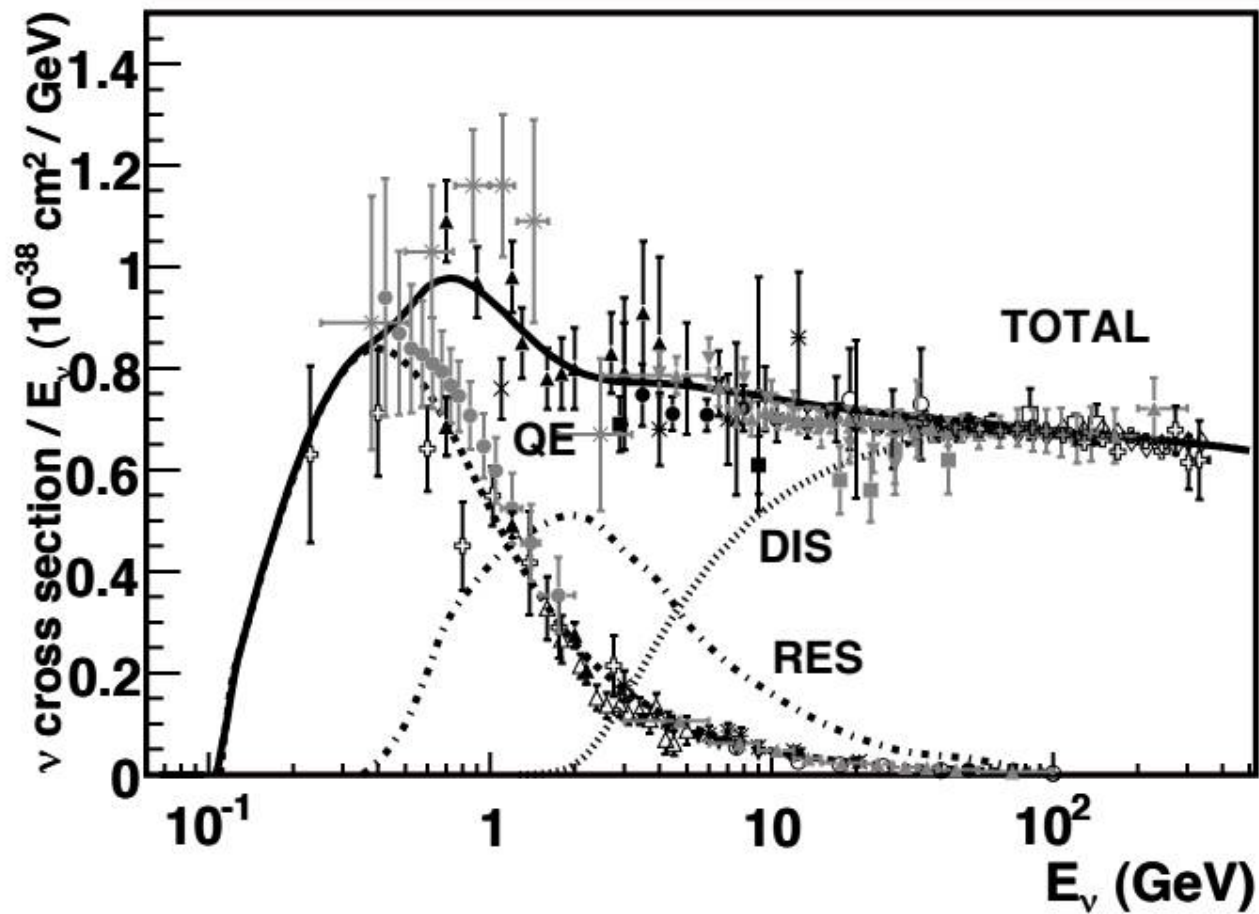
→
No
measurements
... until now!

Accelerator experiments

One recent
measurement
(COHERENT)



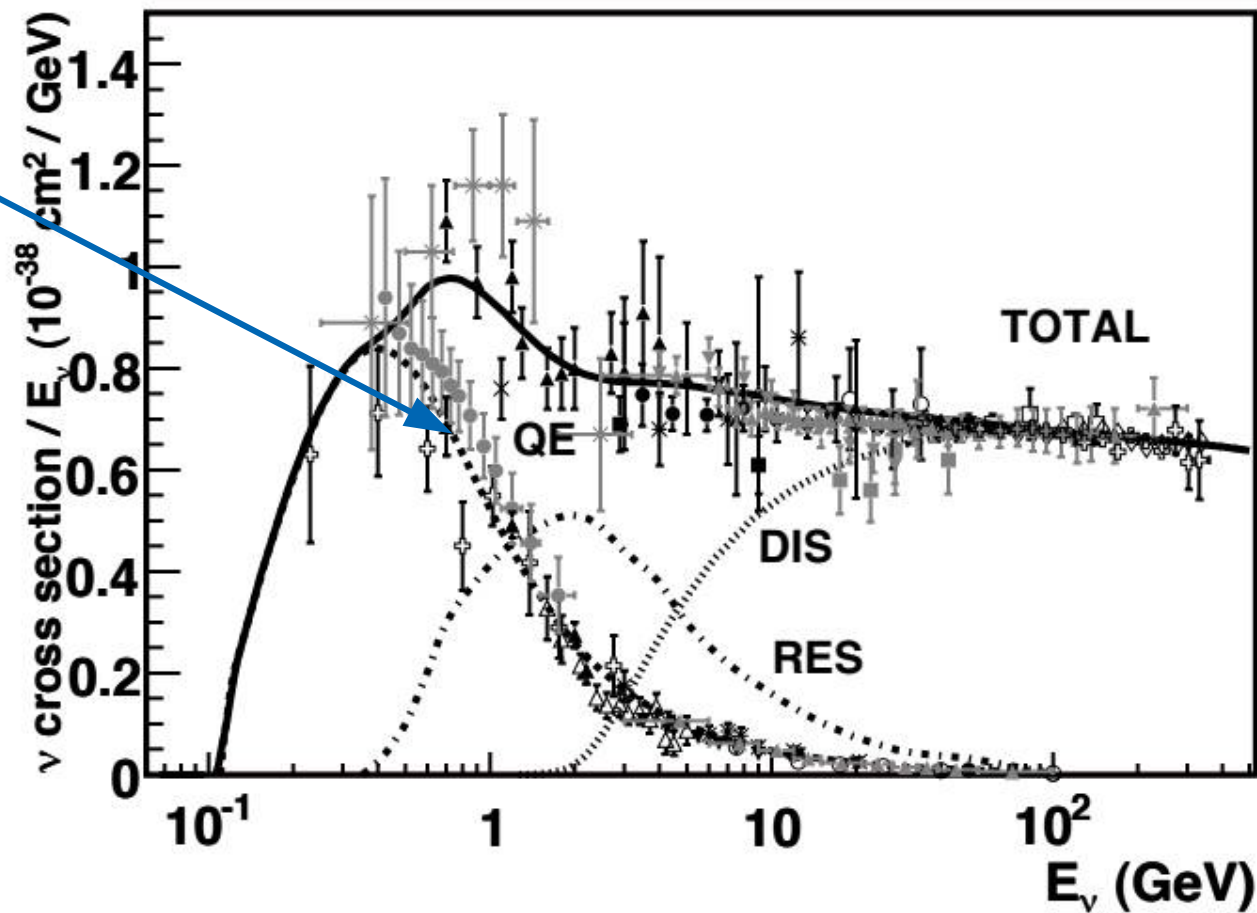
Particle Data Group



Quasi-elastic
scattering:

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

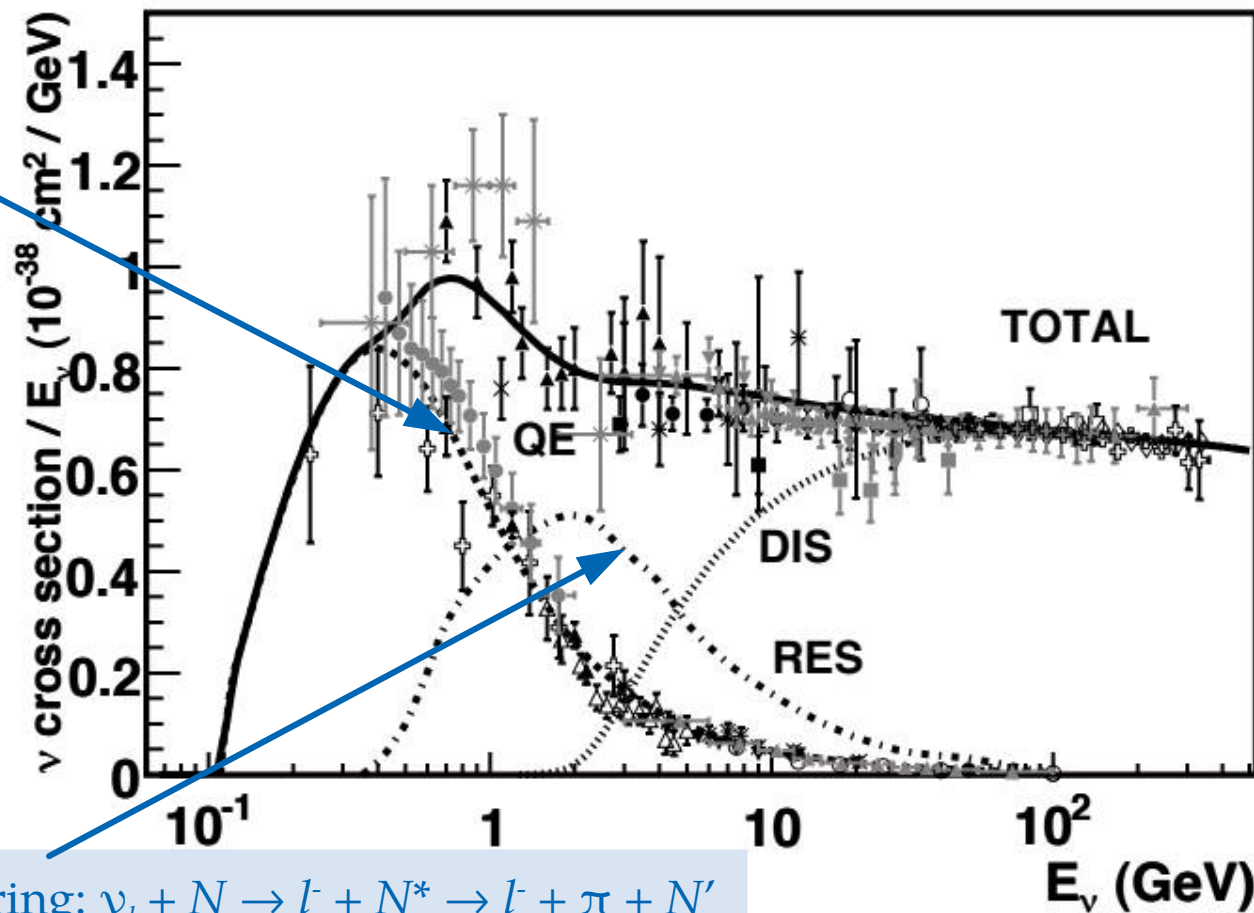
$$\bar{\nu}_l + p \rightarrow l^+ + n$$



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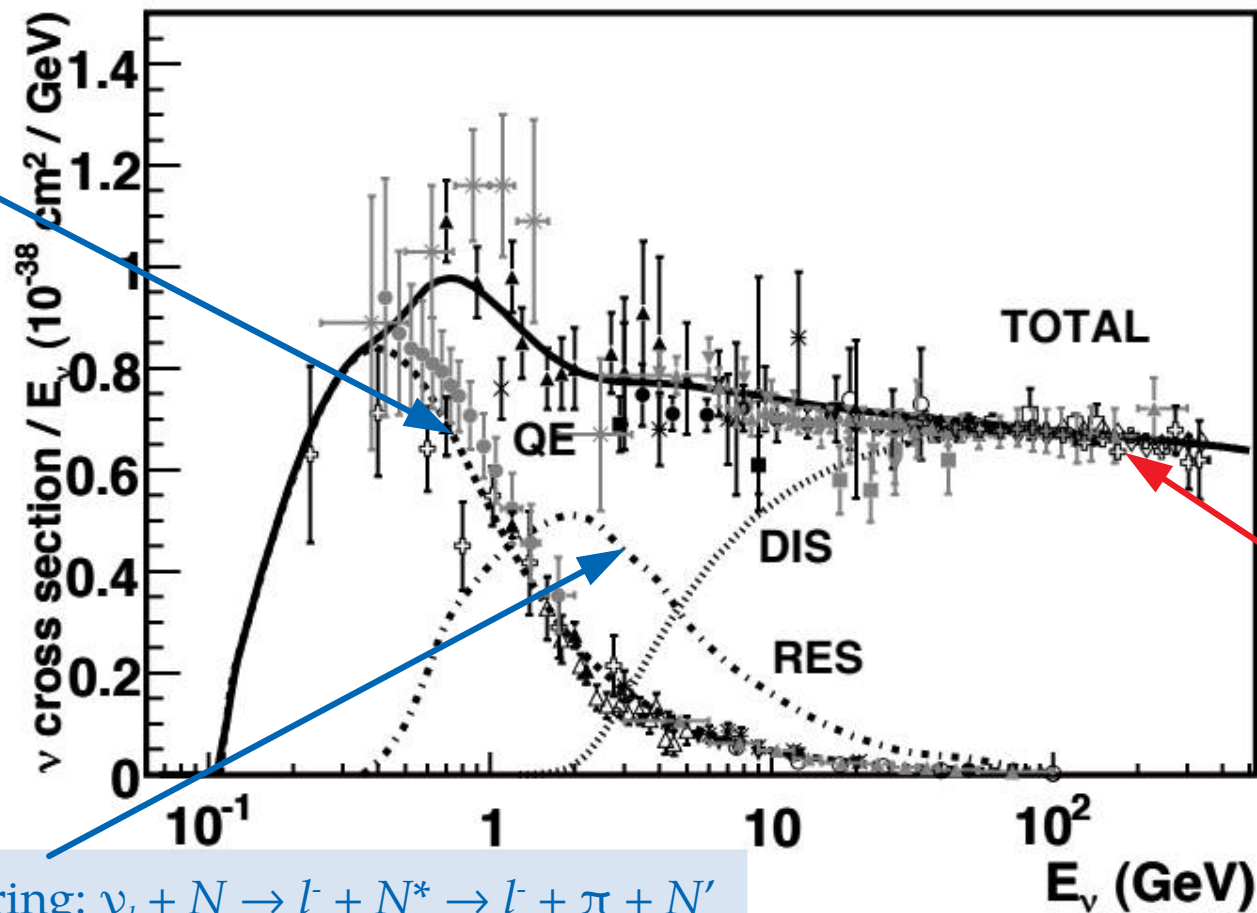
Resonant scattering: $\nu_l + N \rightarrow l^- + N^* \rightarrow l^- + \pi + N'$

Particle Data Group

Quasi-elastic
scattering:

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

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



Deep inelastic
scattering:

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

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

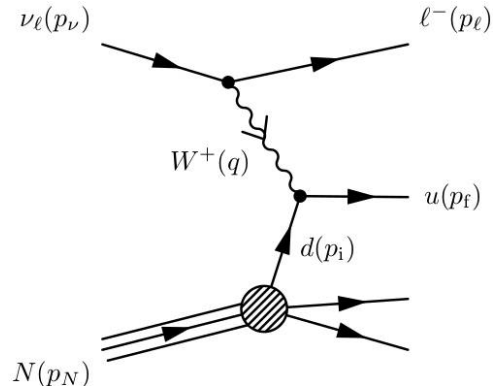
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Particle Data Group

Extrapolating the cross section to high energies

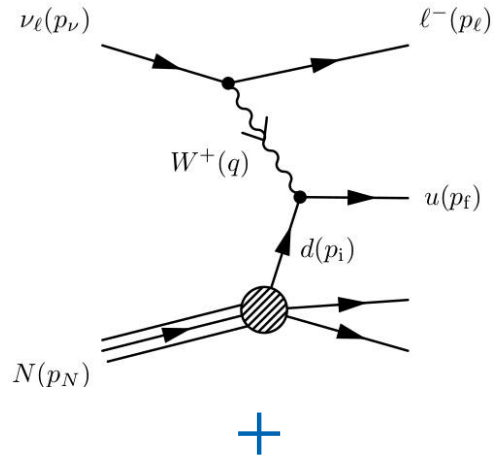
Extrapolating the cross section to high energies

SM



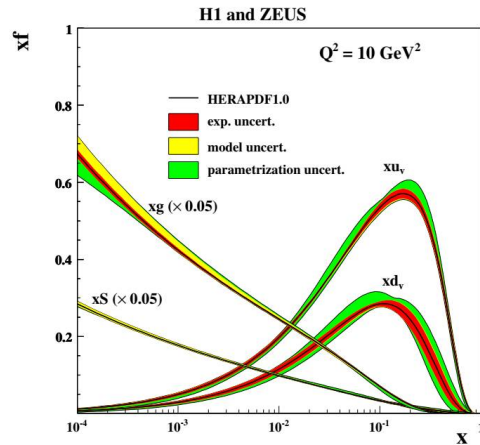
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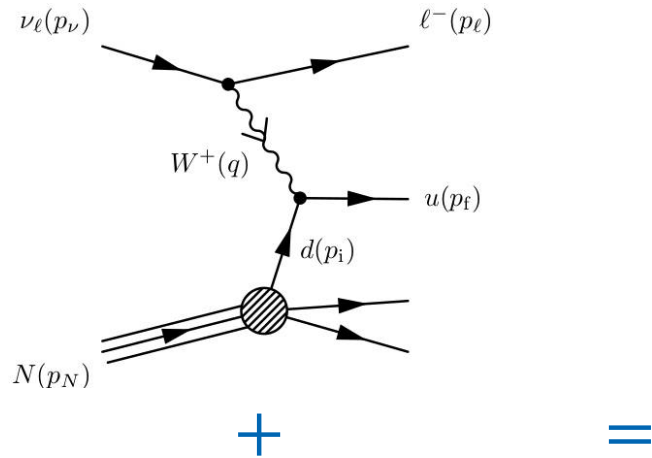
+

PDFs

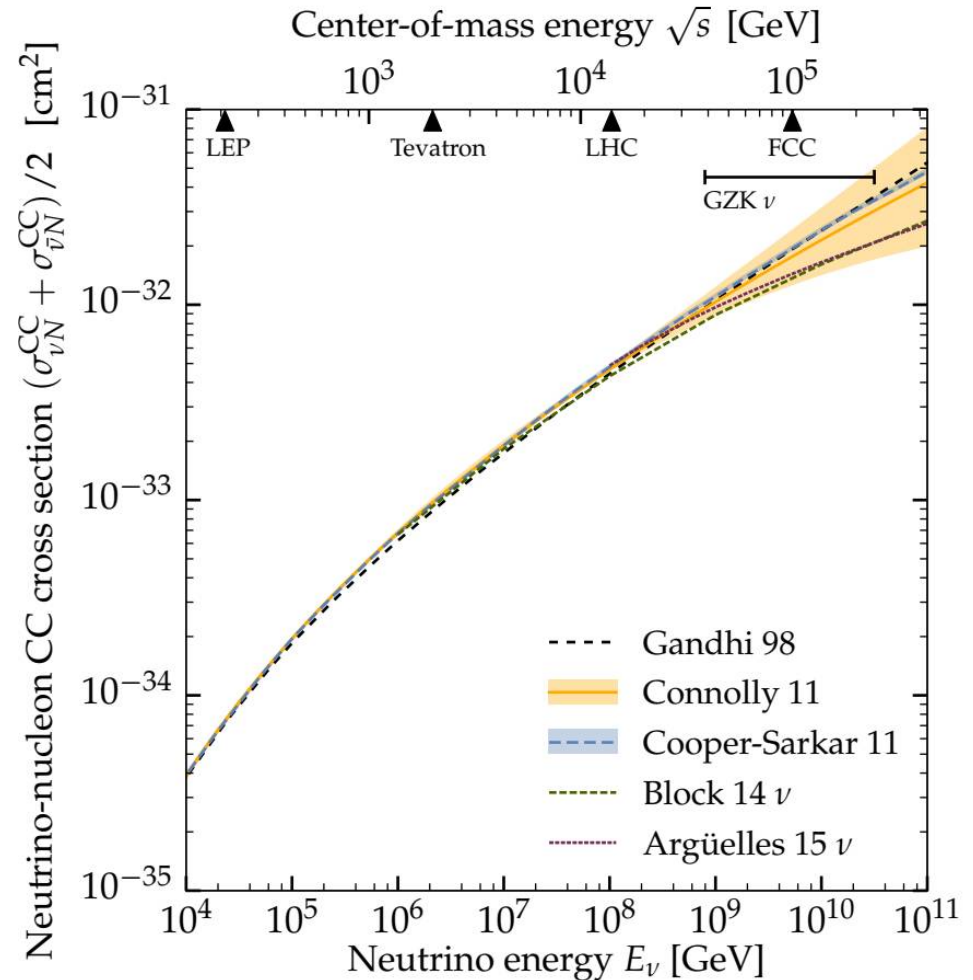
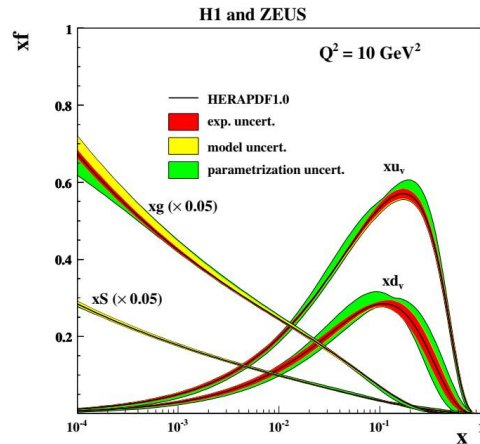


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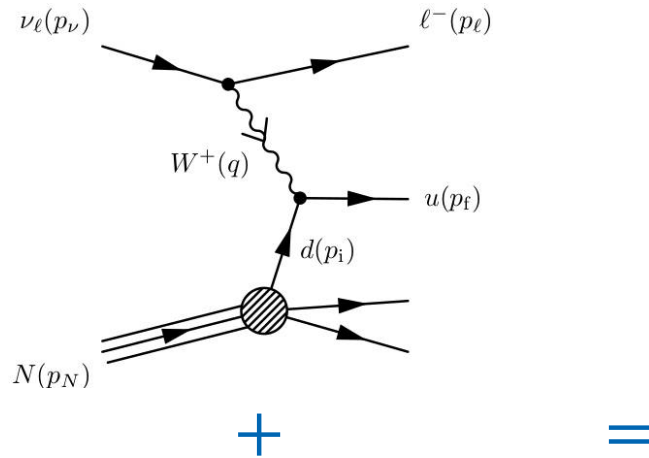


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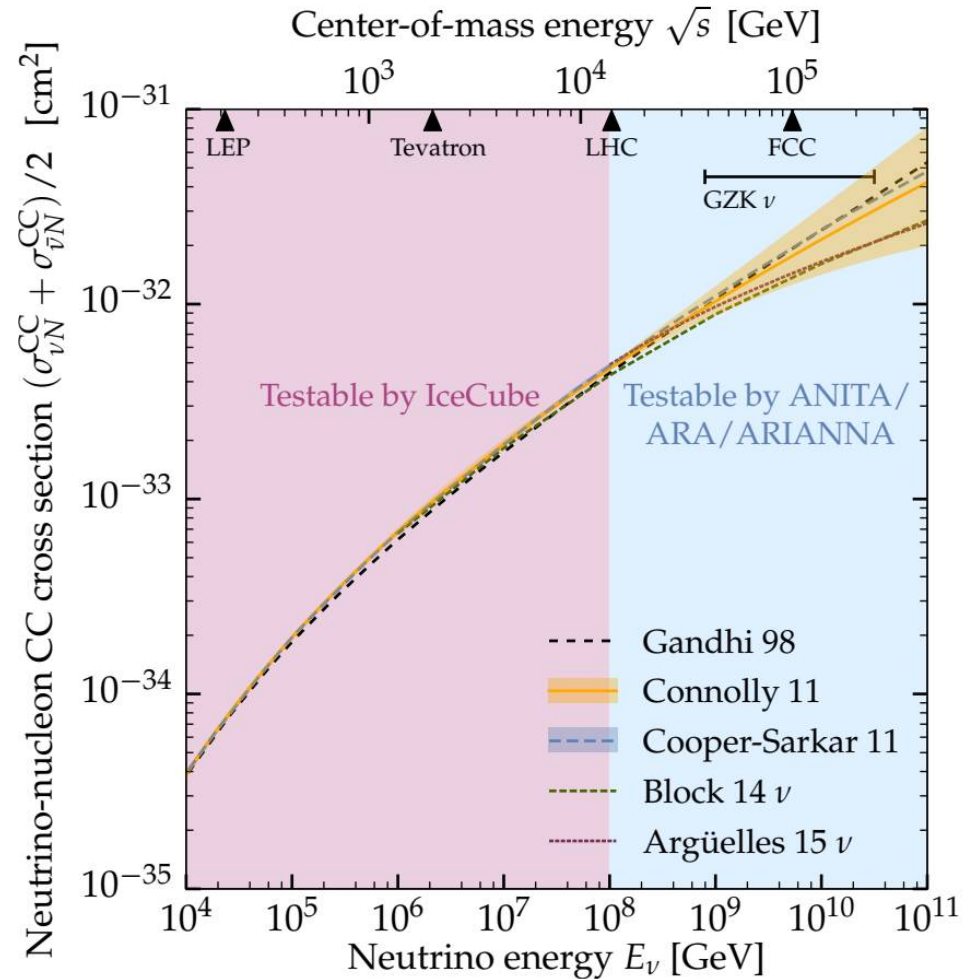
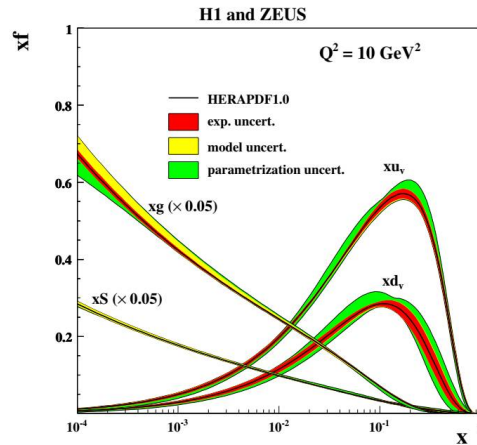


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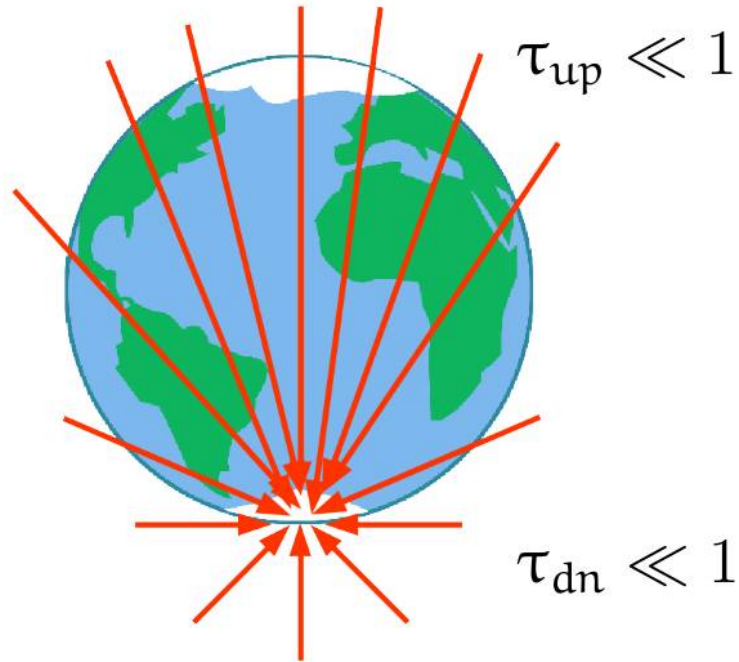
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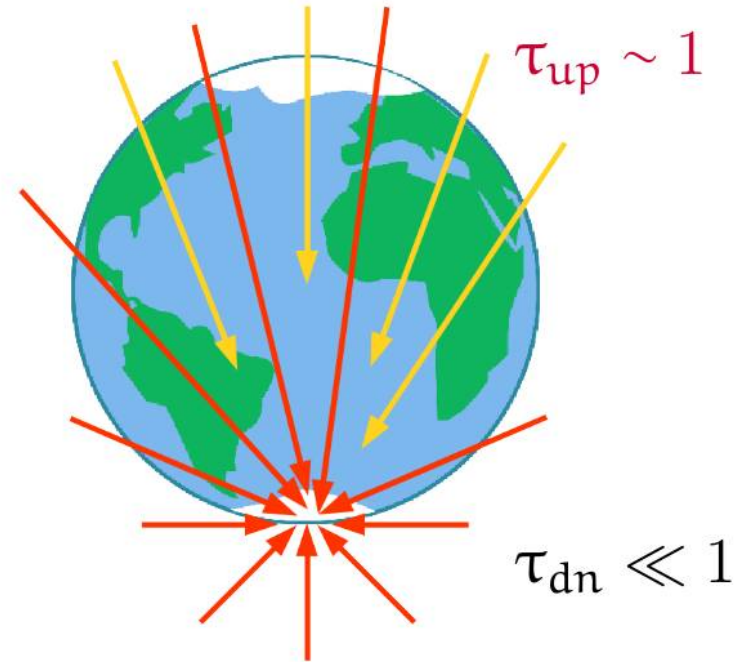
Measuring the high-energy cross section

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

Below ~ 10 TeV: Earth is transparent



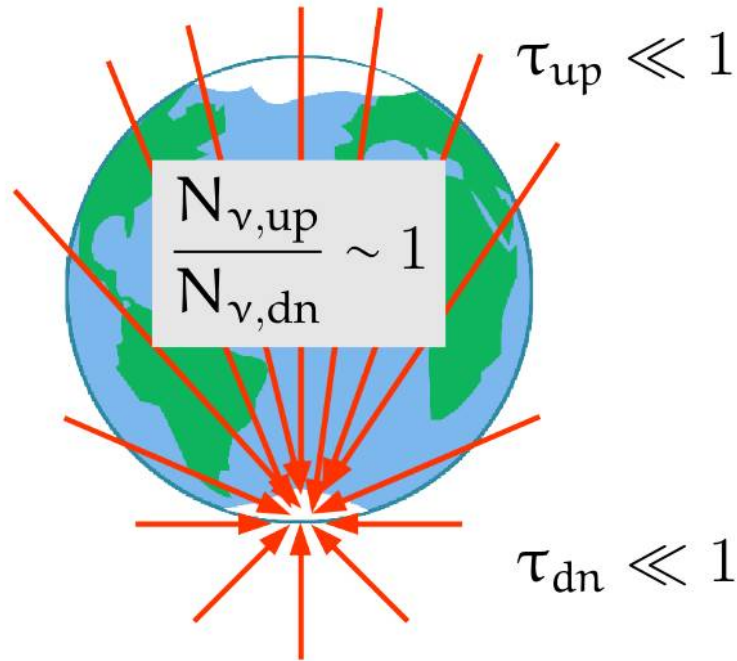
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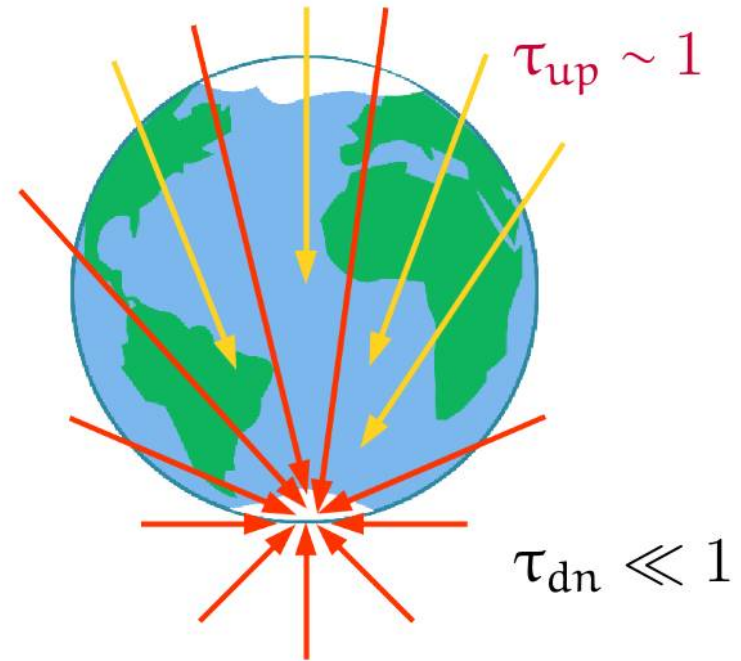
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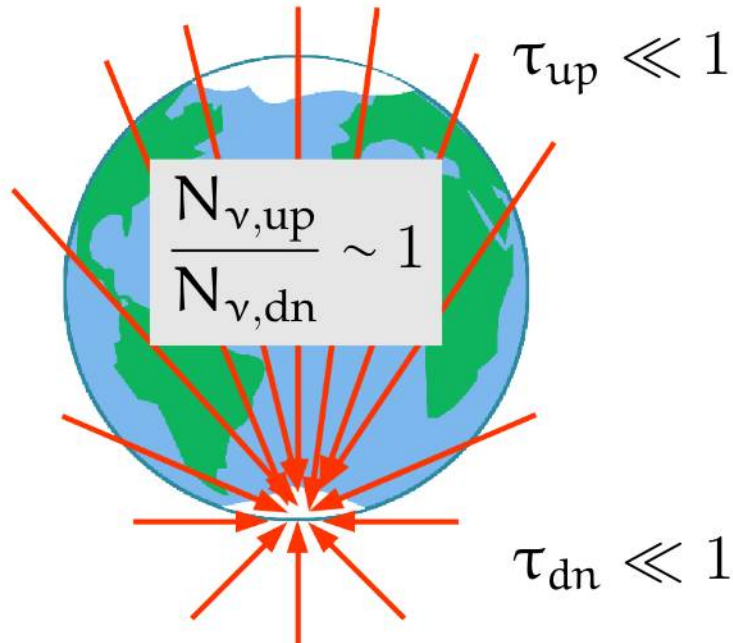
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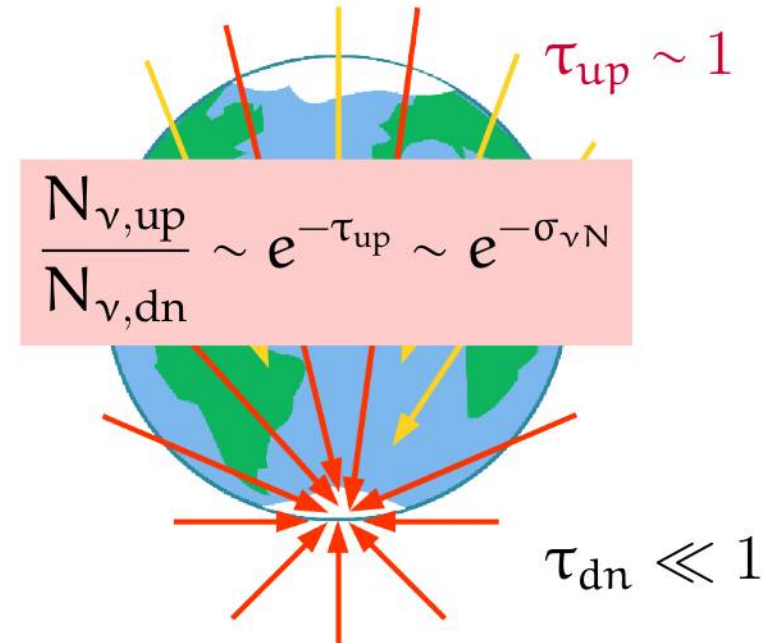
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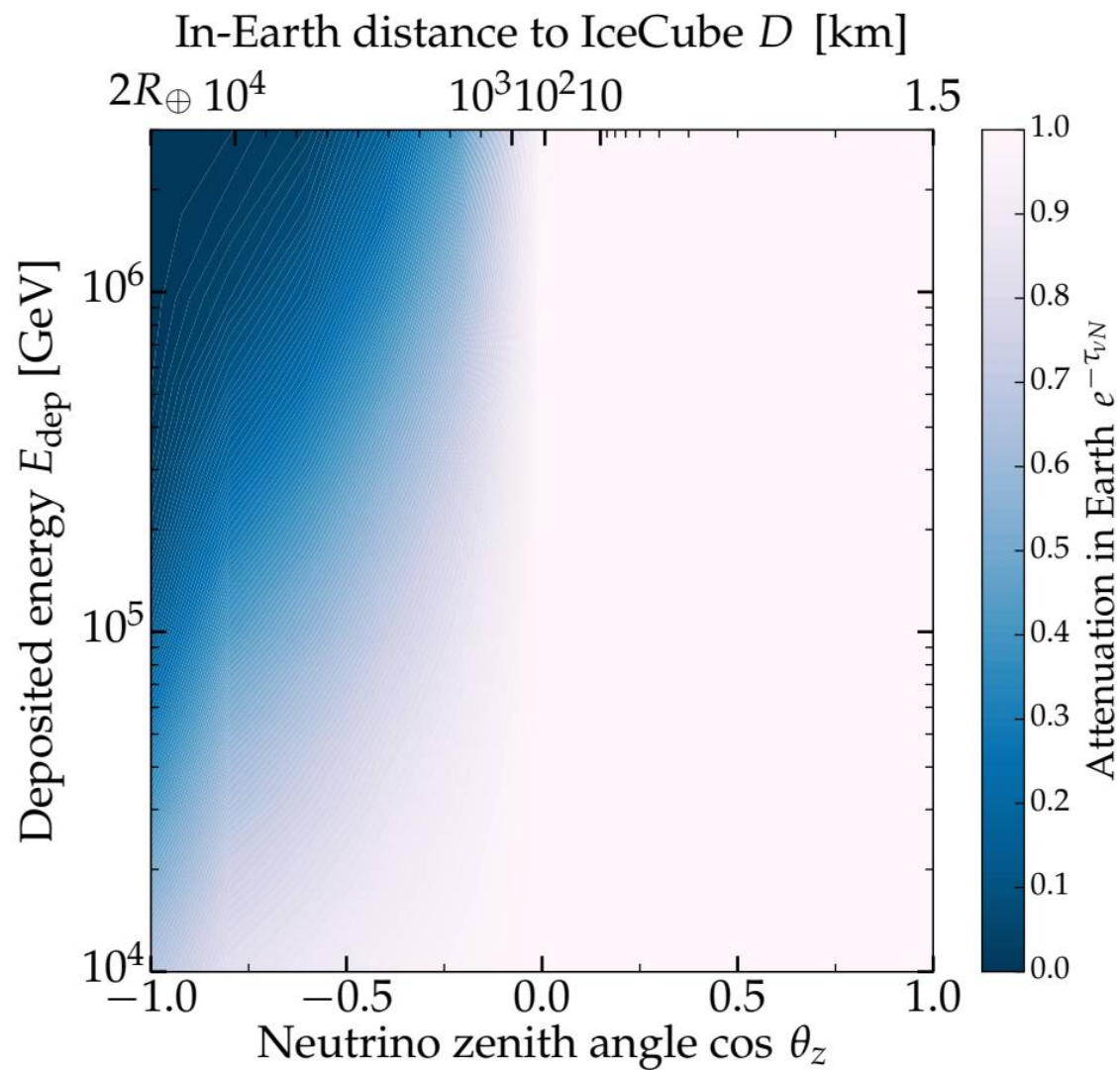
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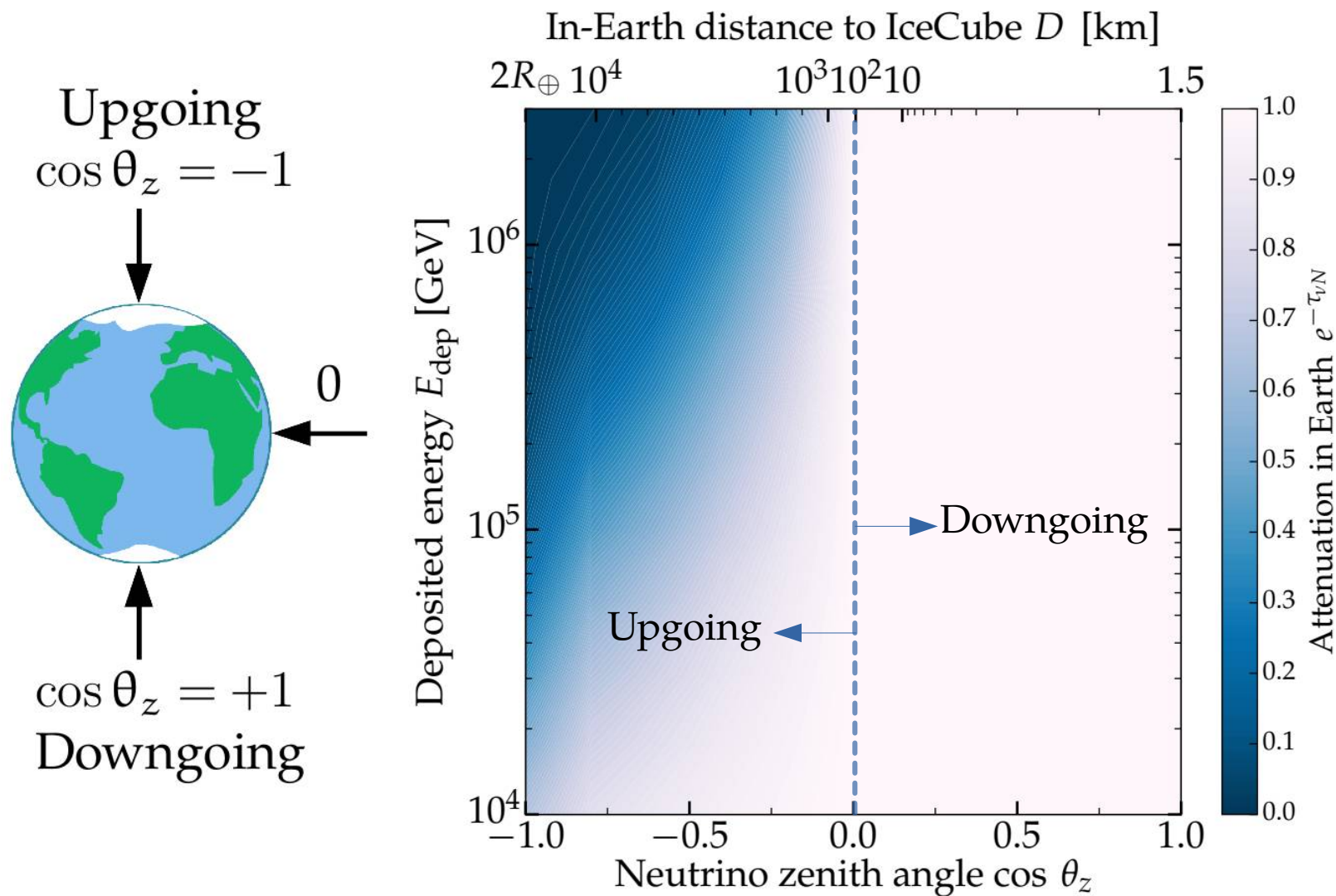
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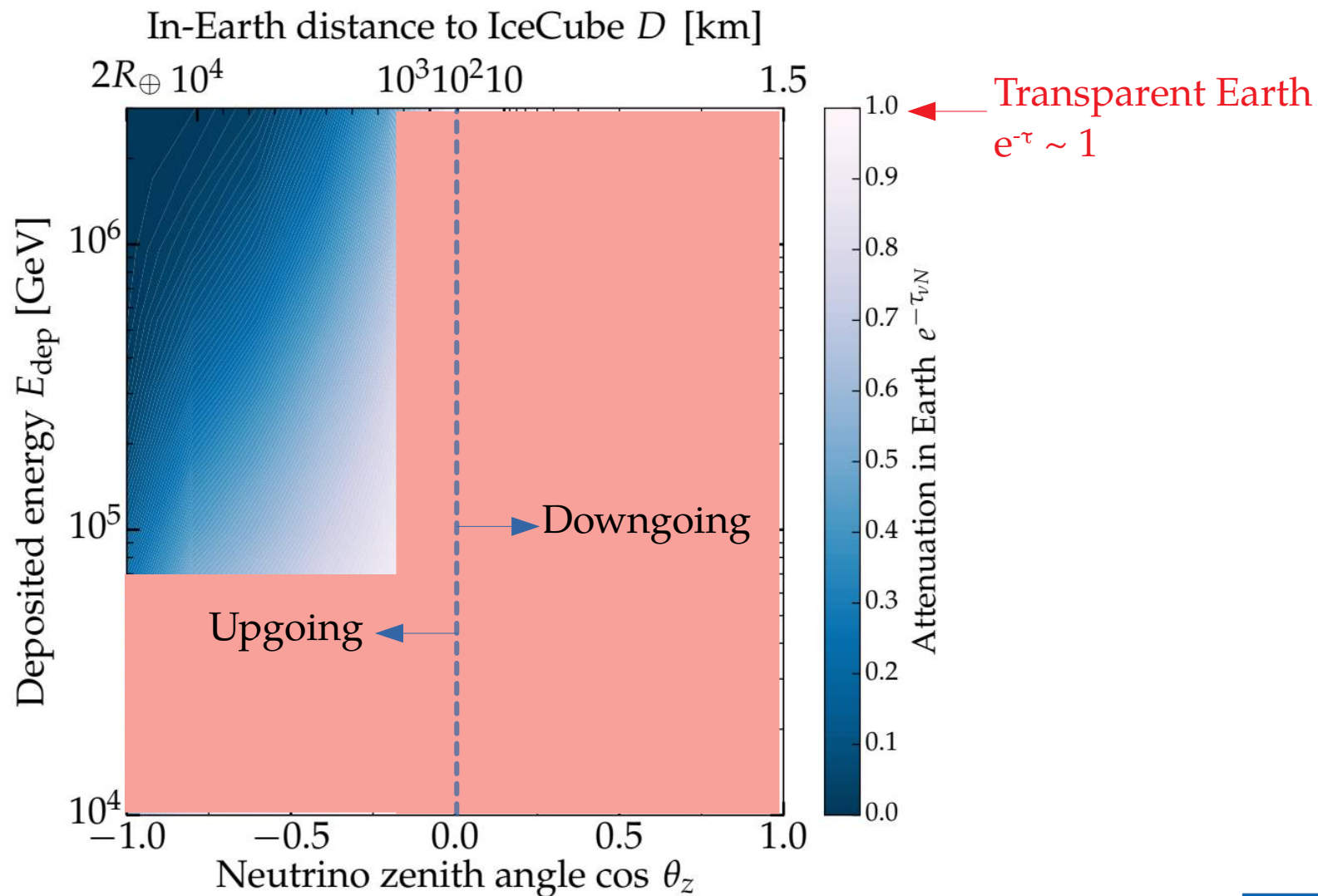
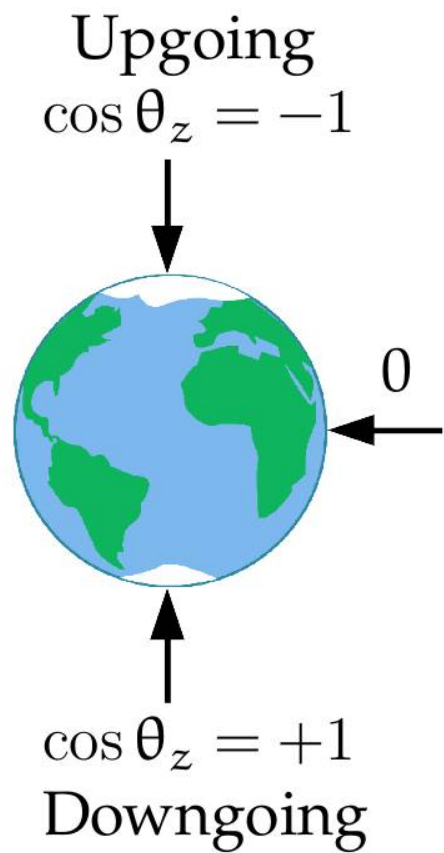


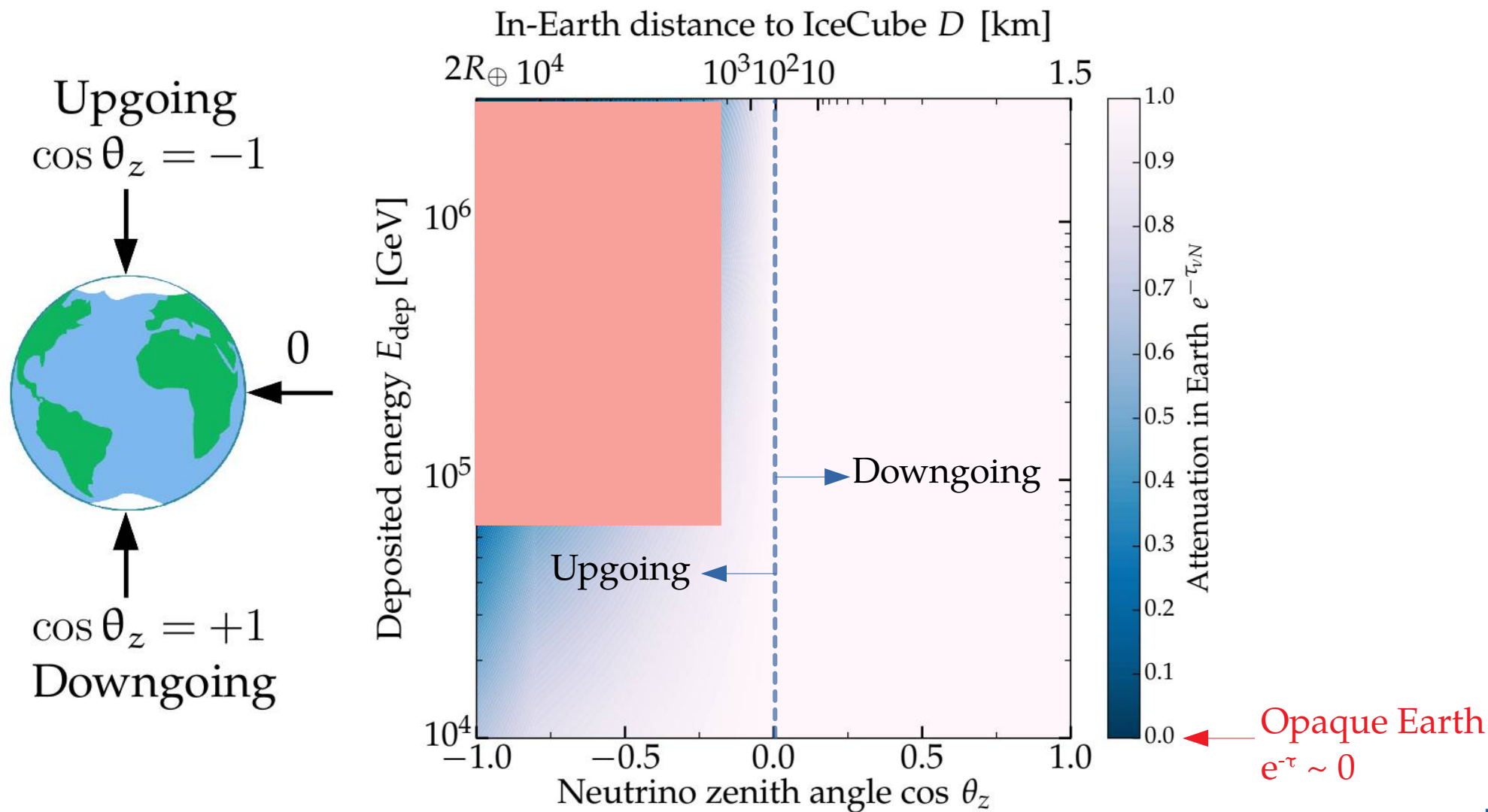
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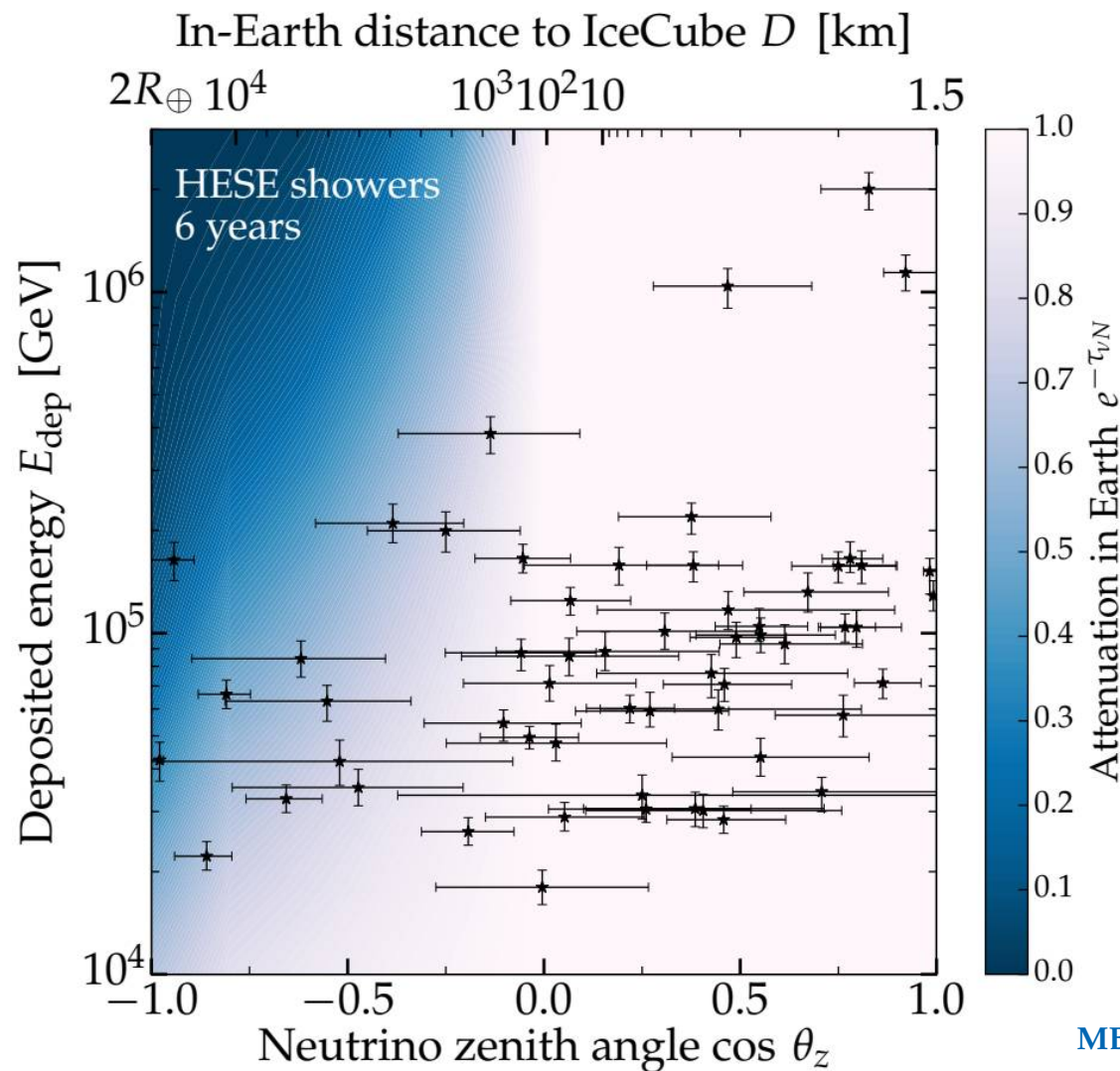




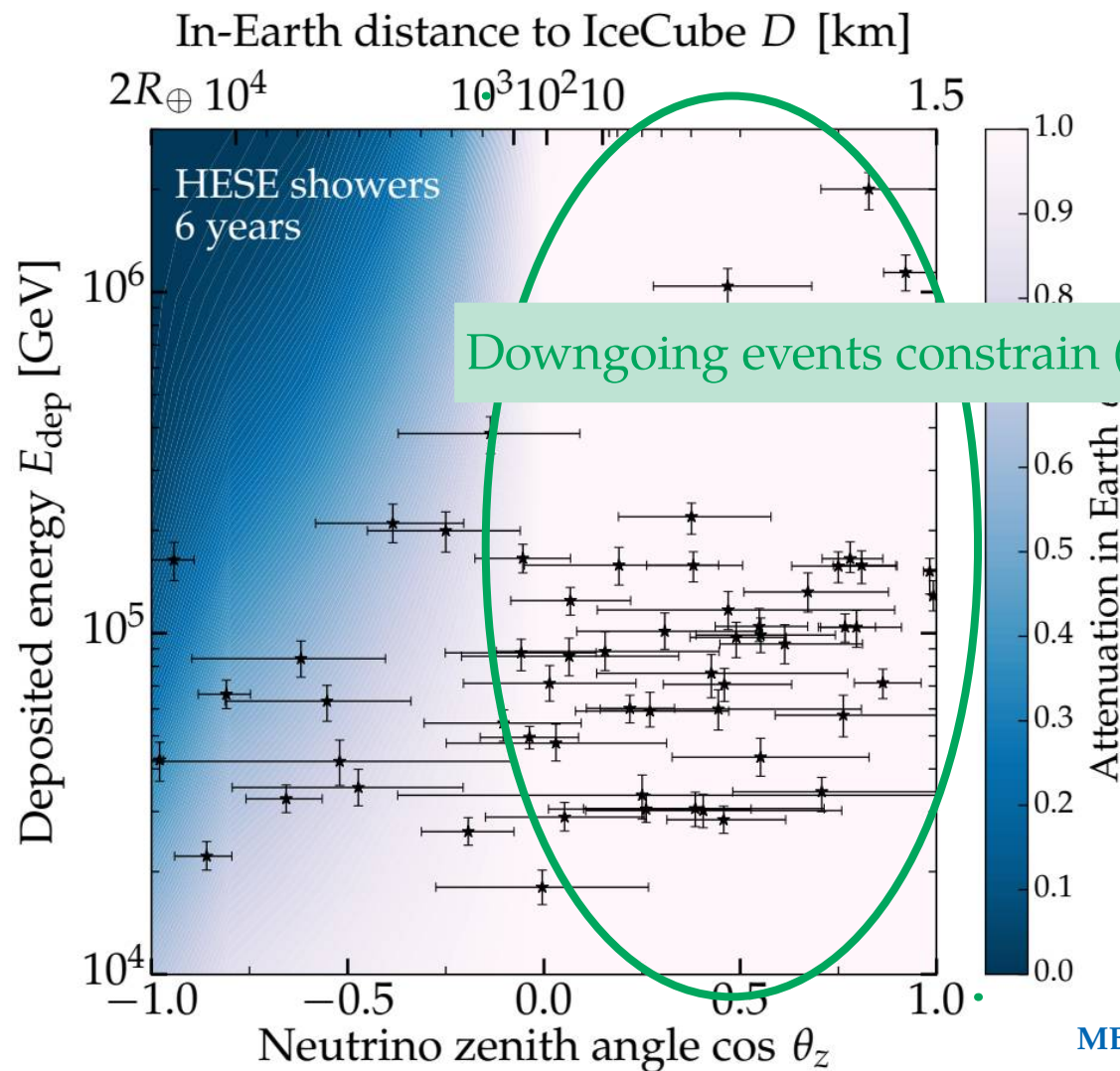








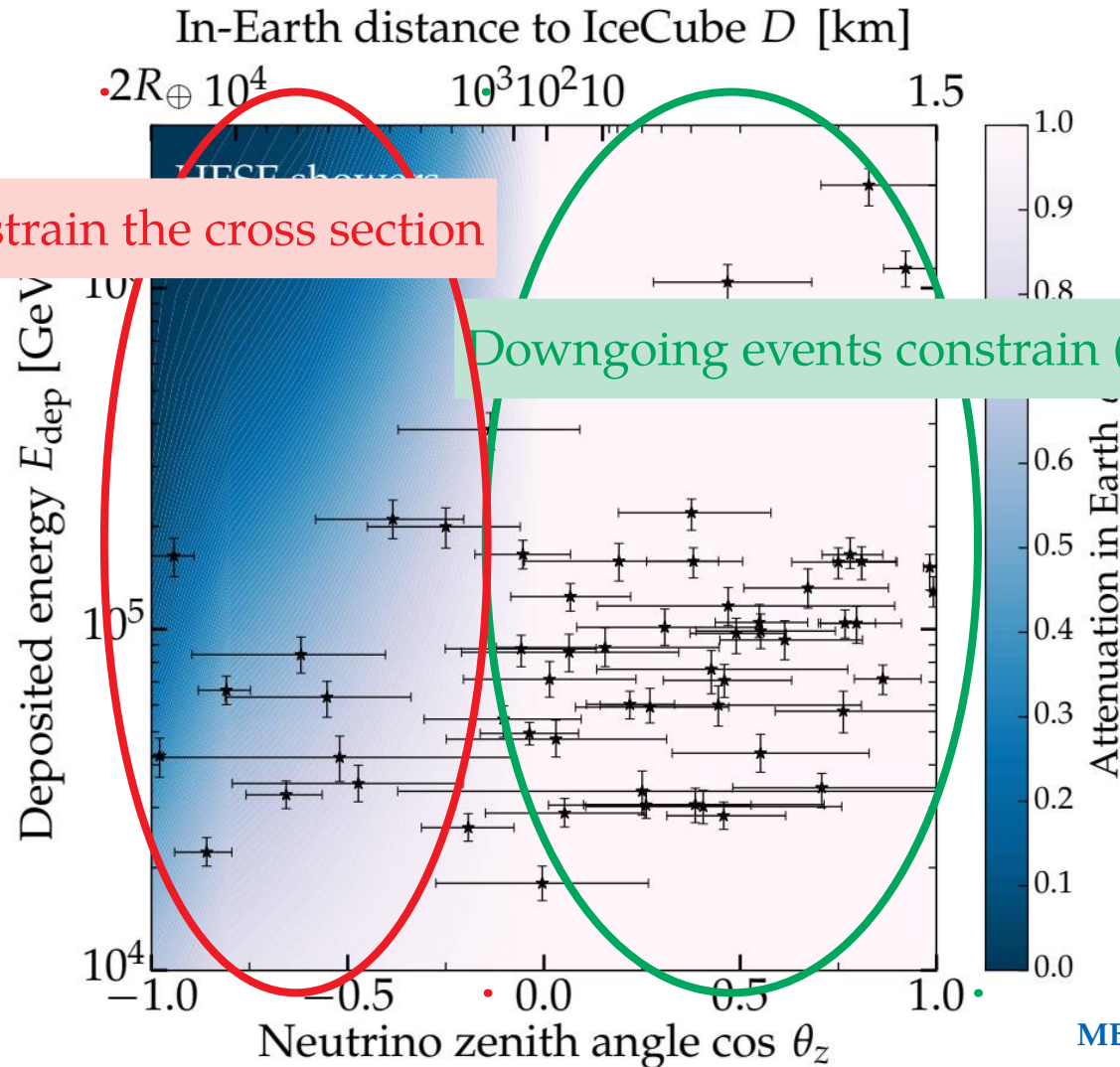
MB & Connolly, 2017



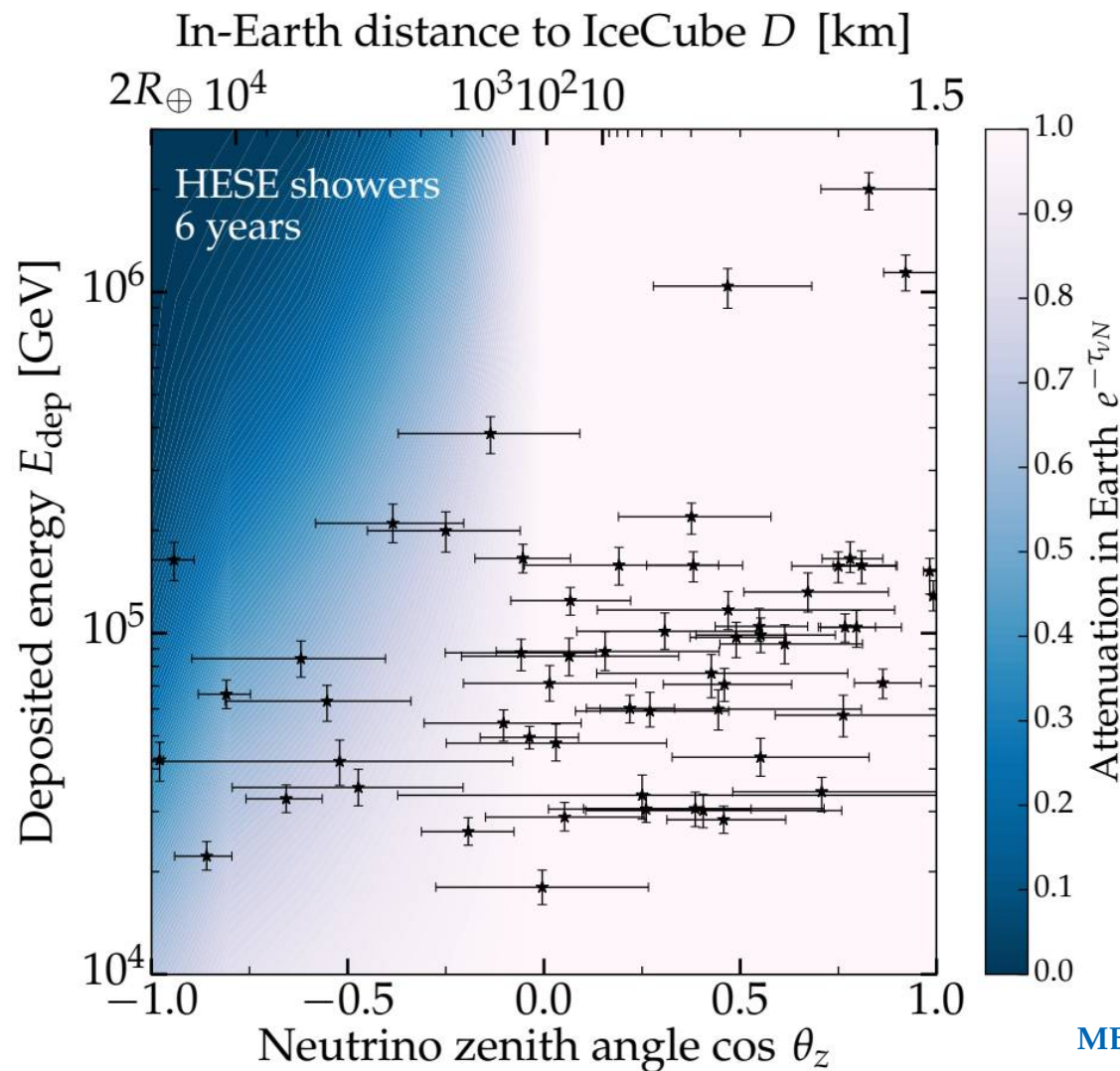
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Upgoing events constrain the cross section

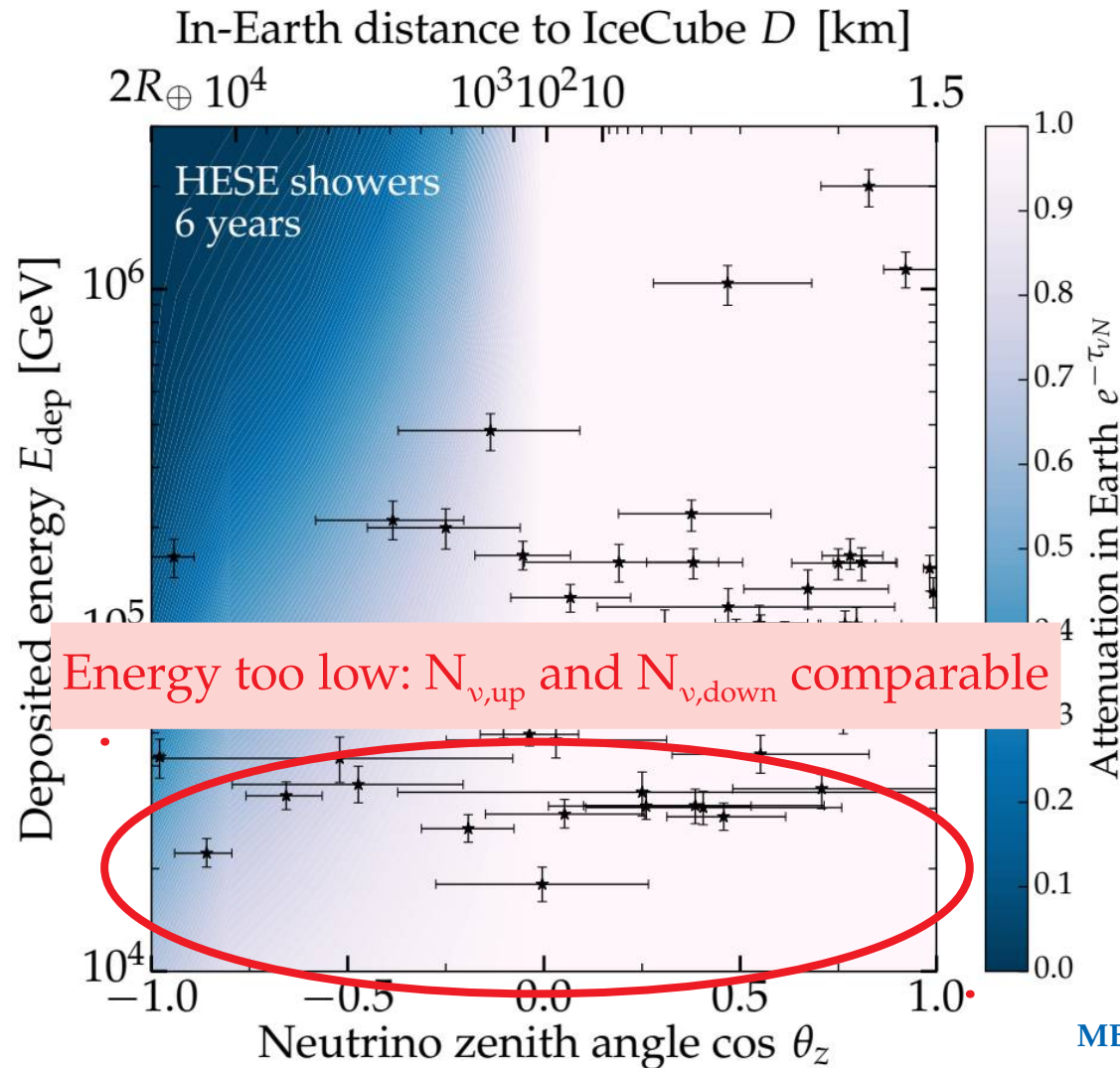
Downgoing events constrain (flux x cross section)



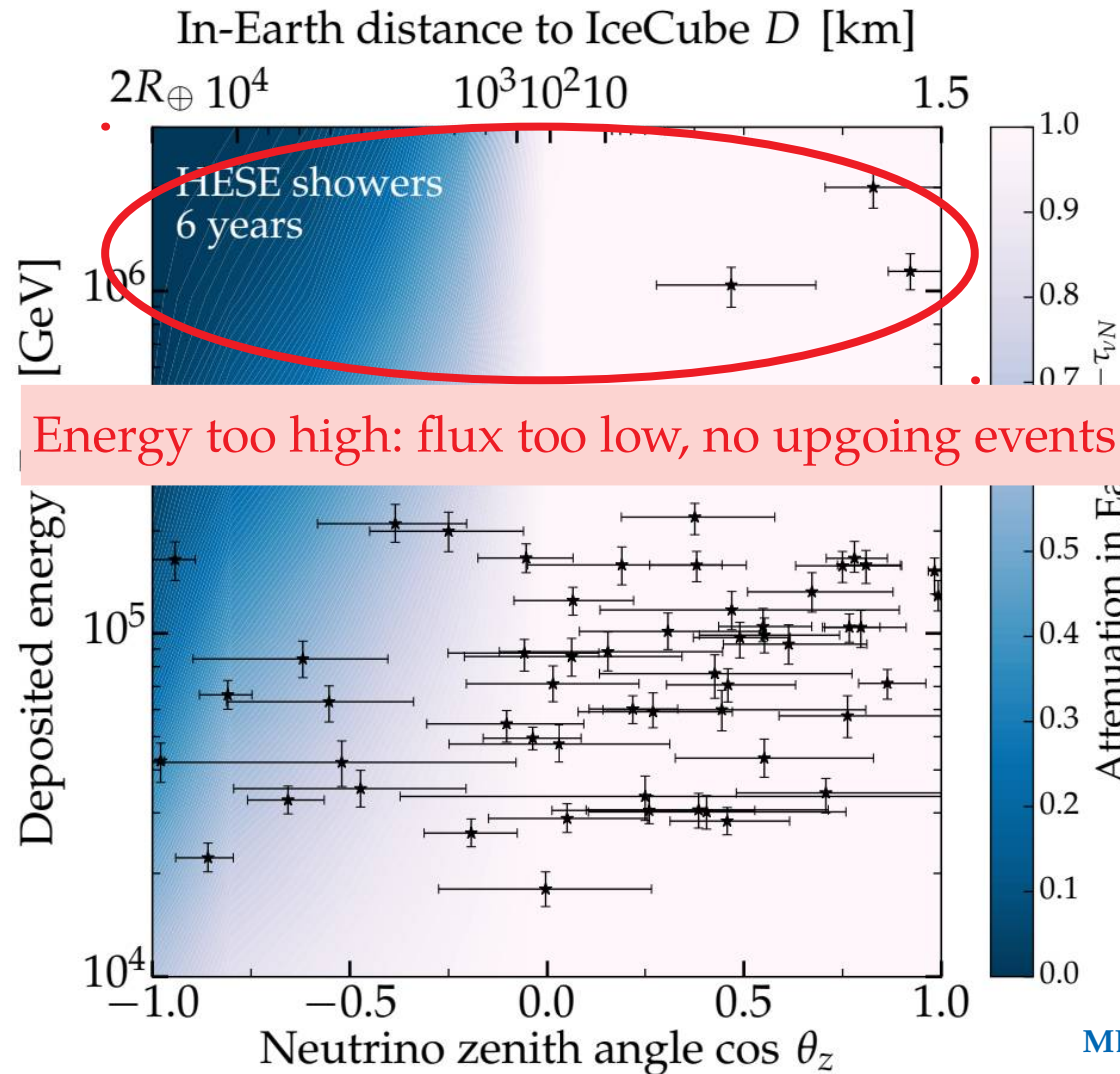
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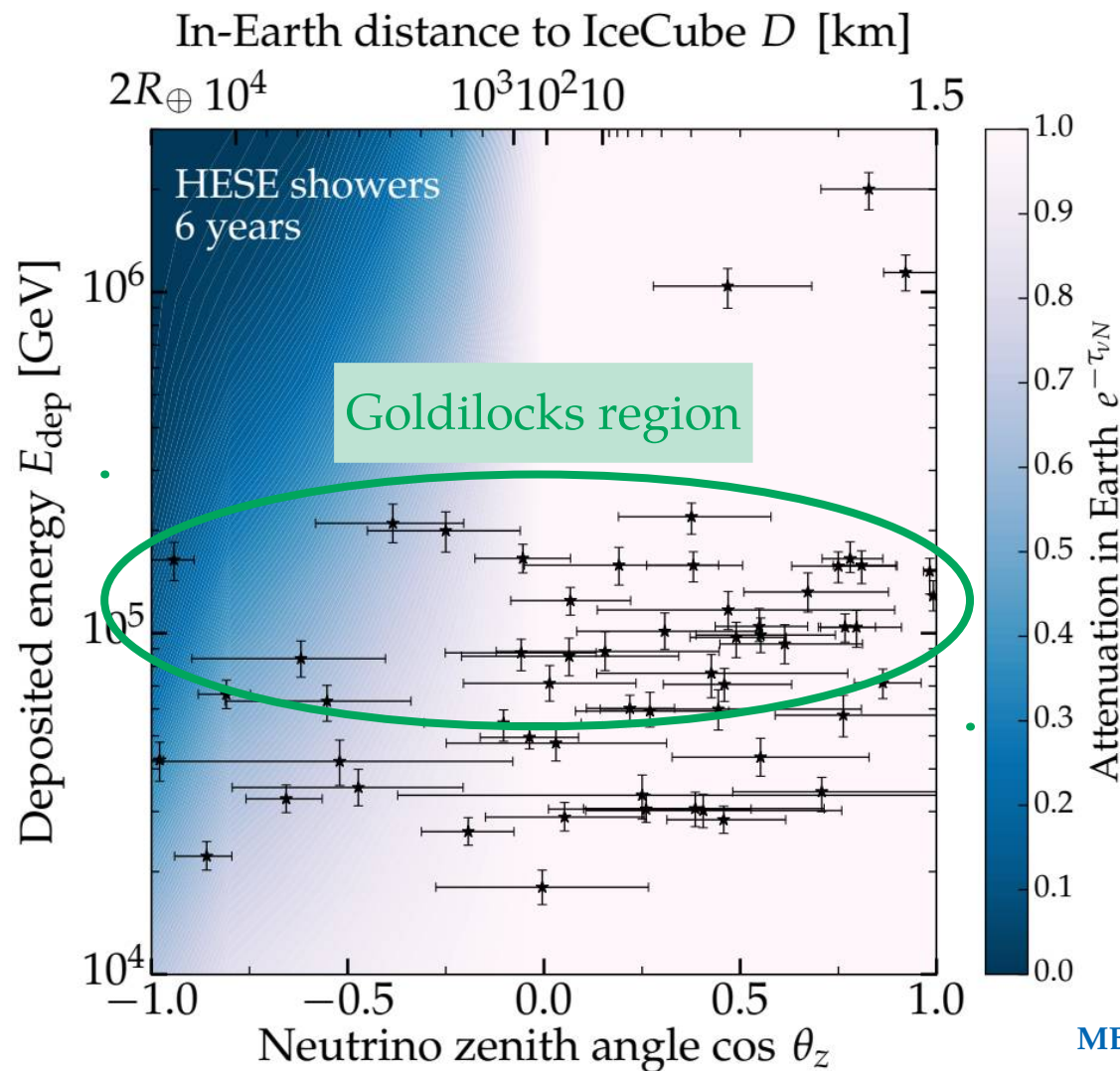
MB & Connolly, 2017



MB & Connolly, 2017

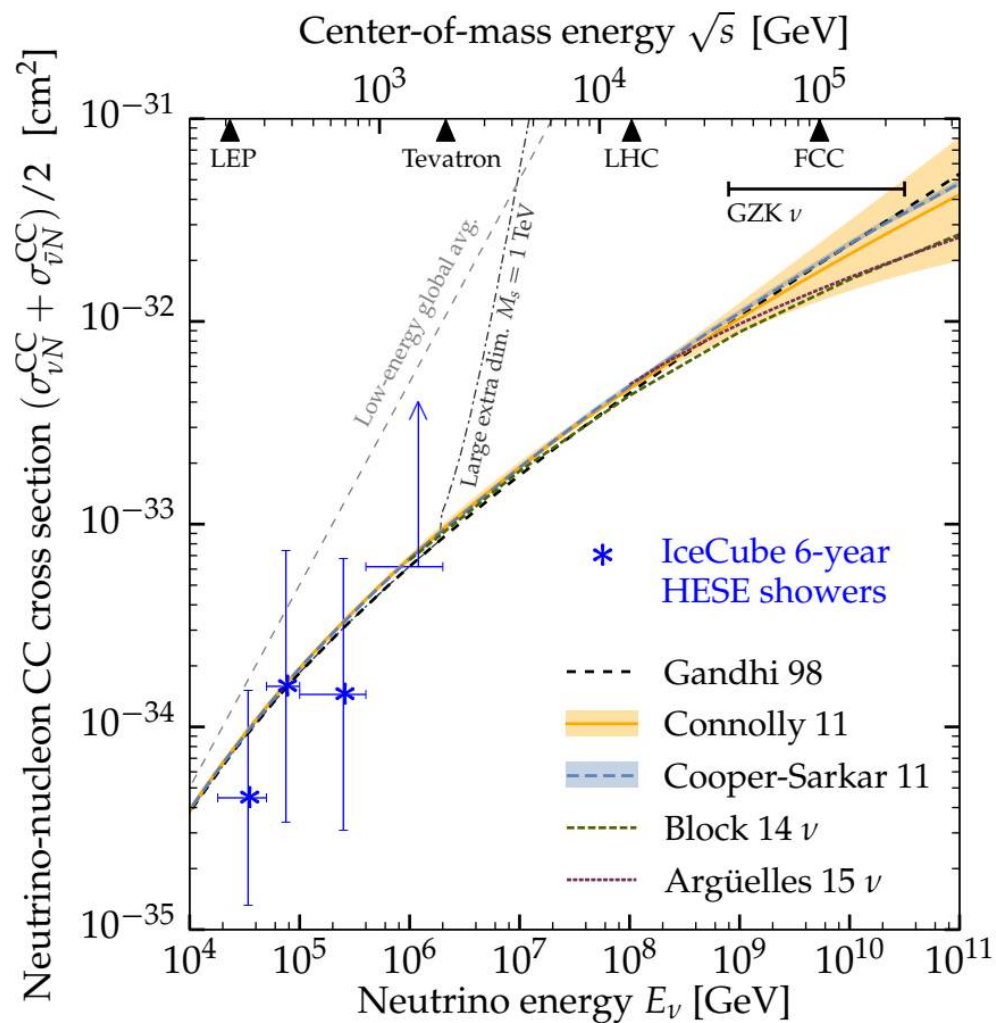


MB & Connolly, 2017



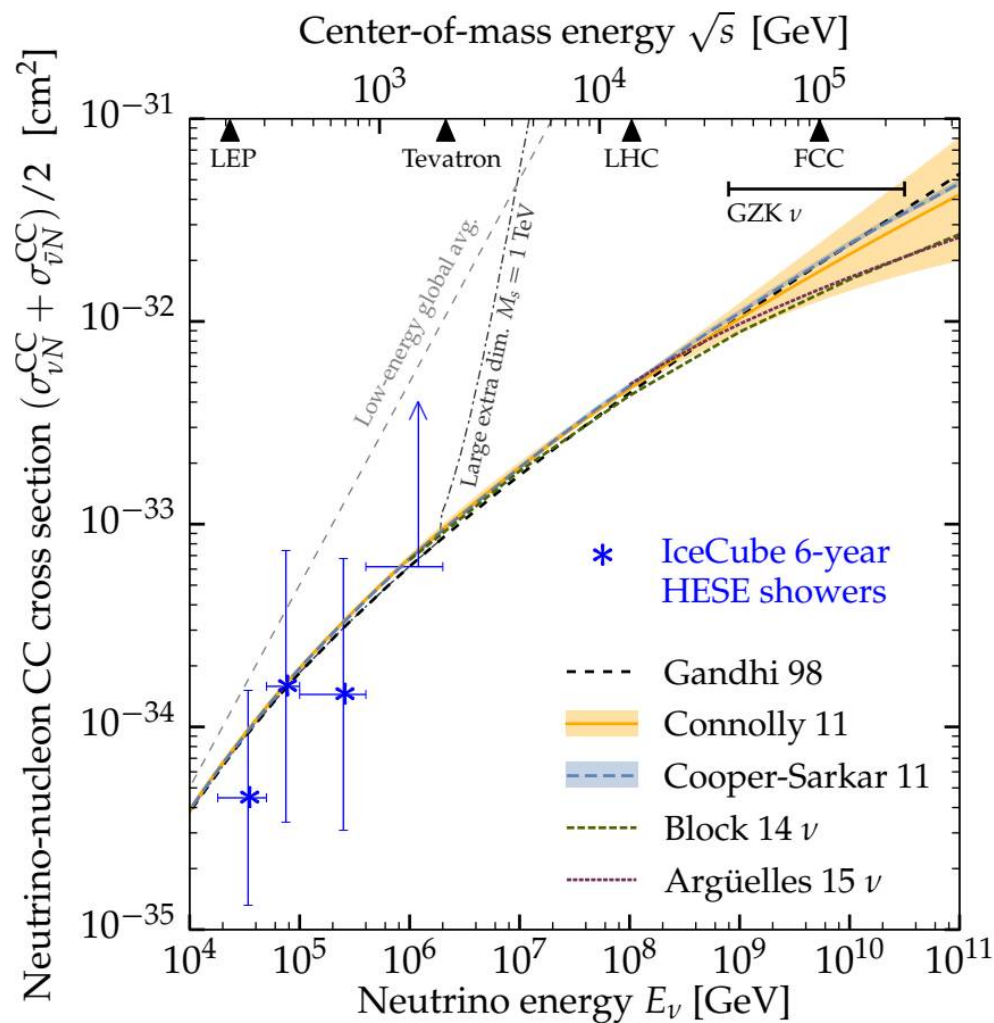
MB & Connolly, 2017

Our result



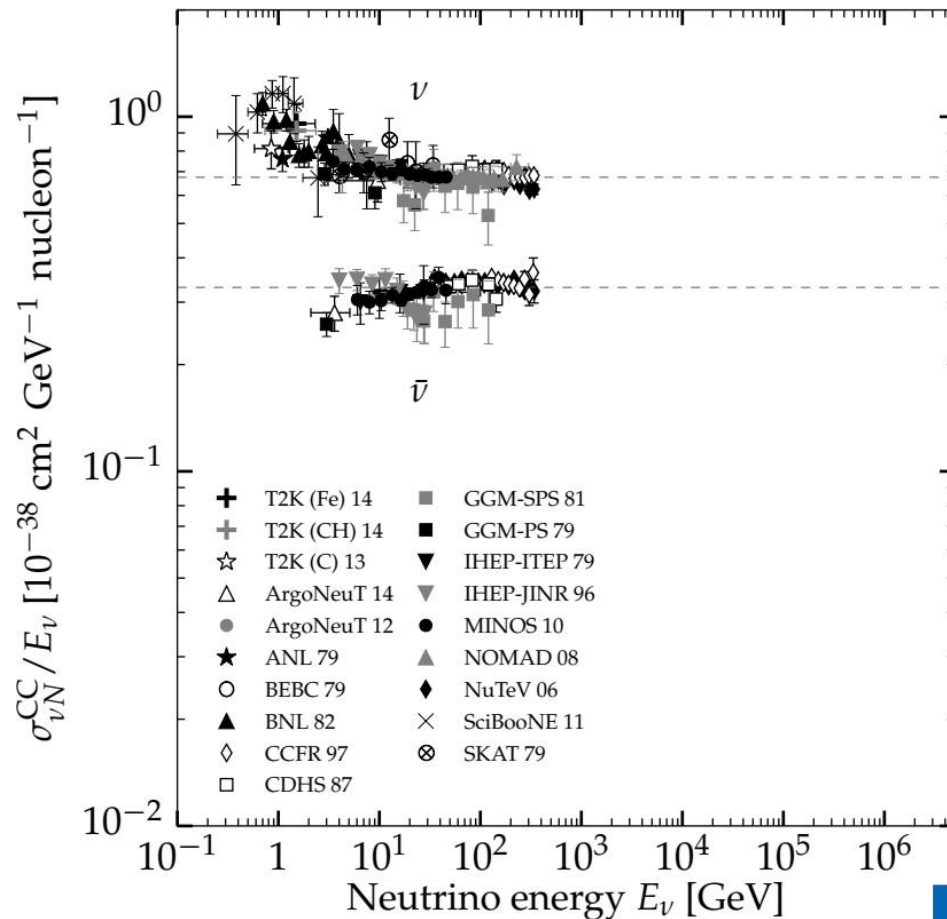
MB & A. Connolly 2017
See also: [IceCube, Nature 2017](#)

Our result

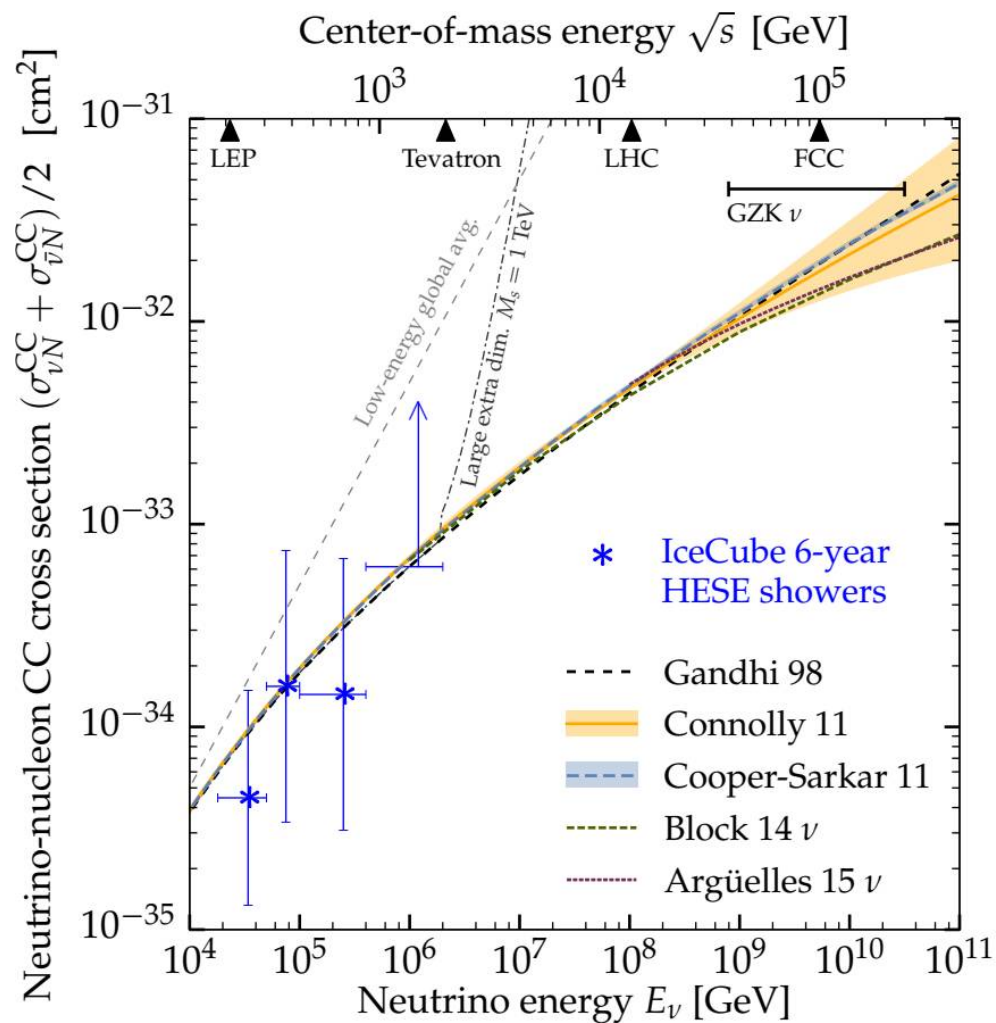


MB & A. Connolly 2017

See also: *IceCube, Nature* 2017

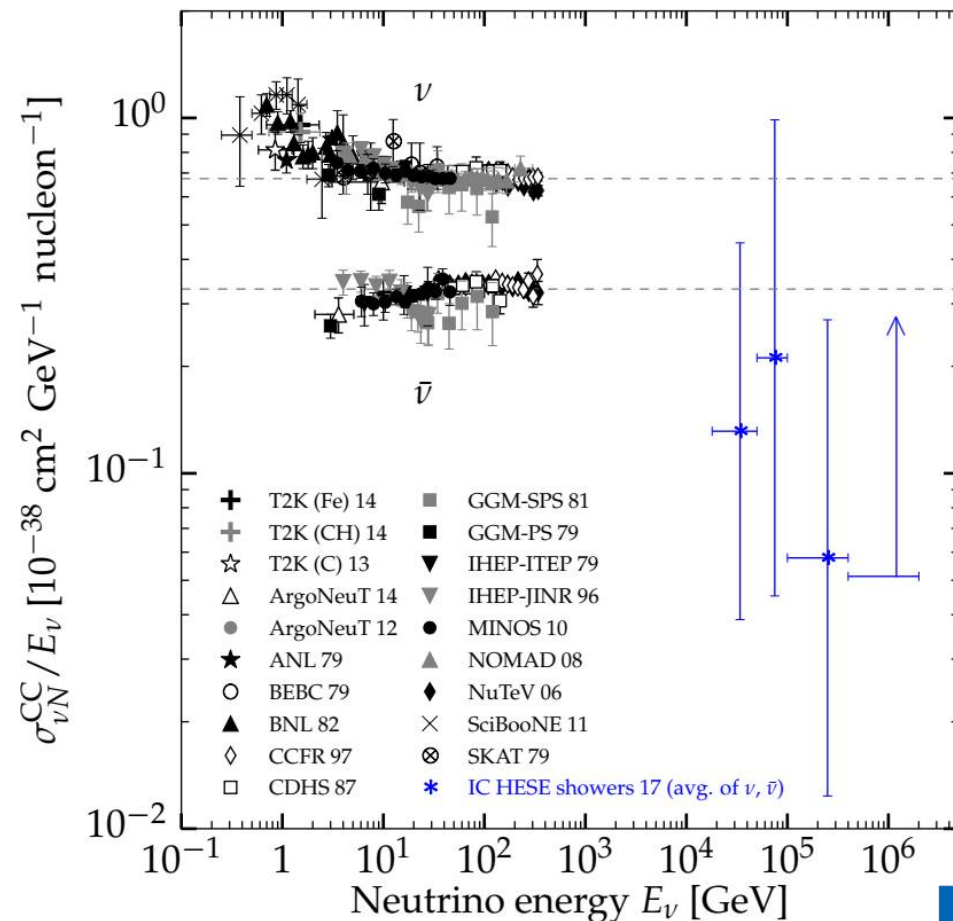


Our result

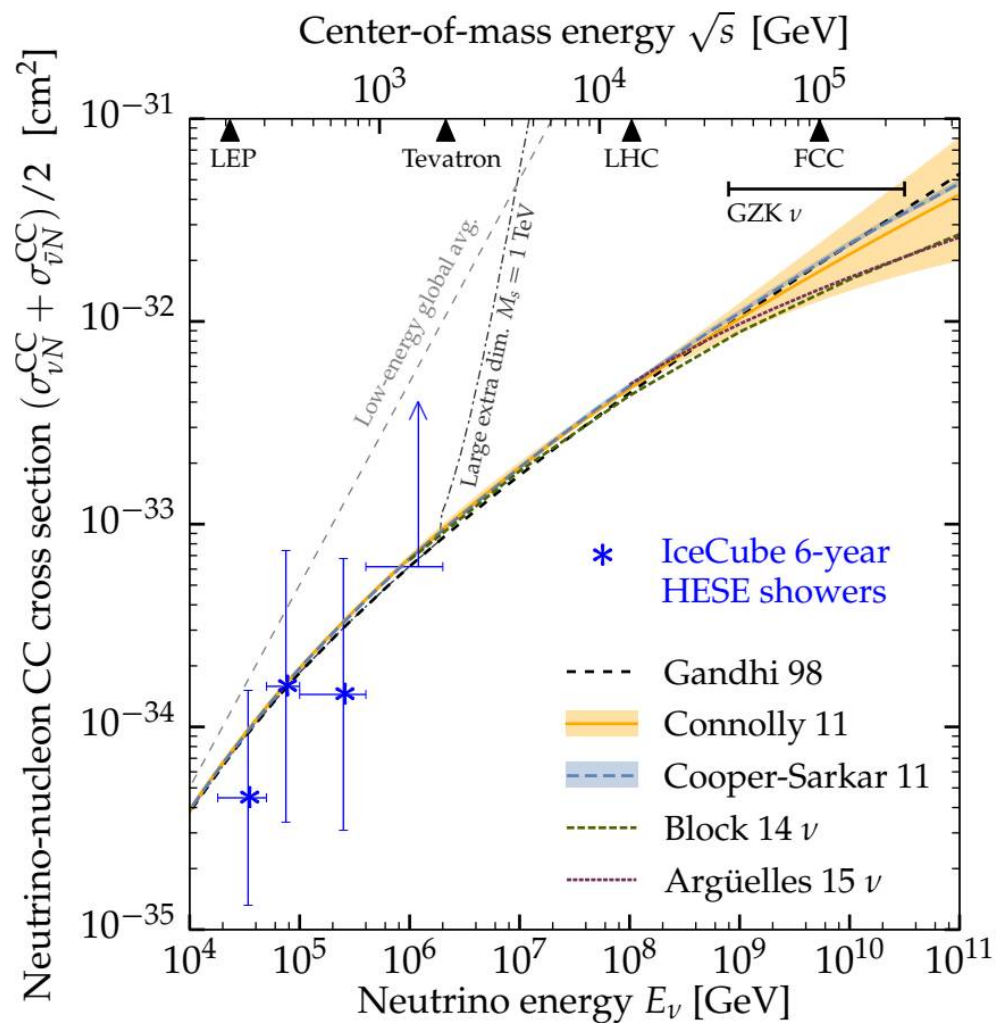


MB & A. Connolly 2017

See also: *IceCube, Nature* 2017

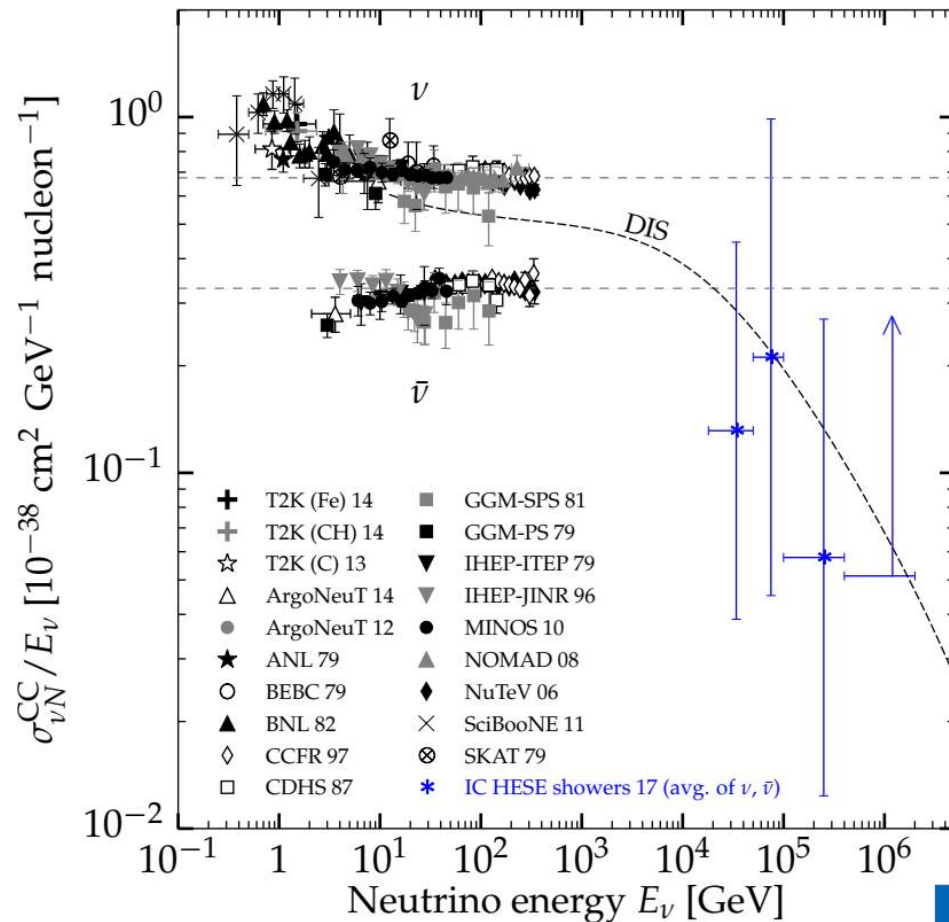


Our result

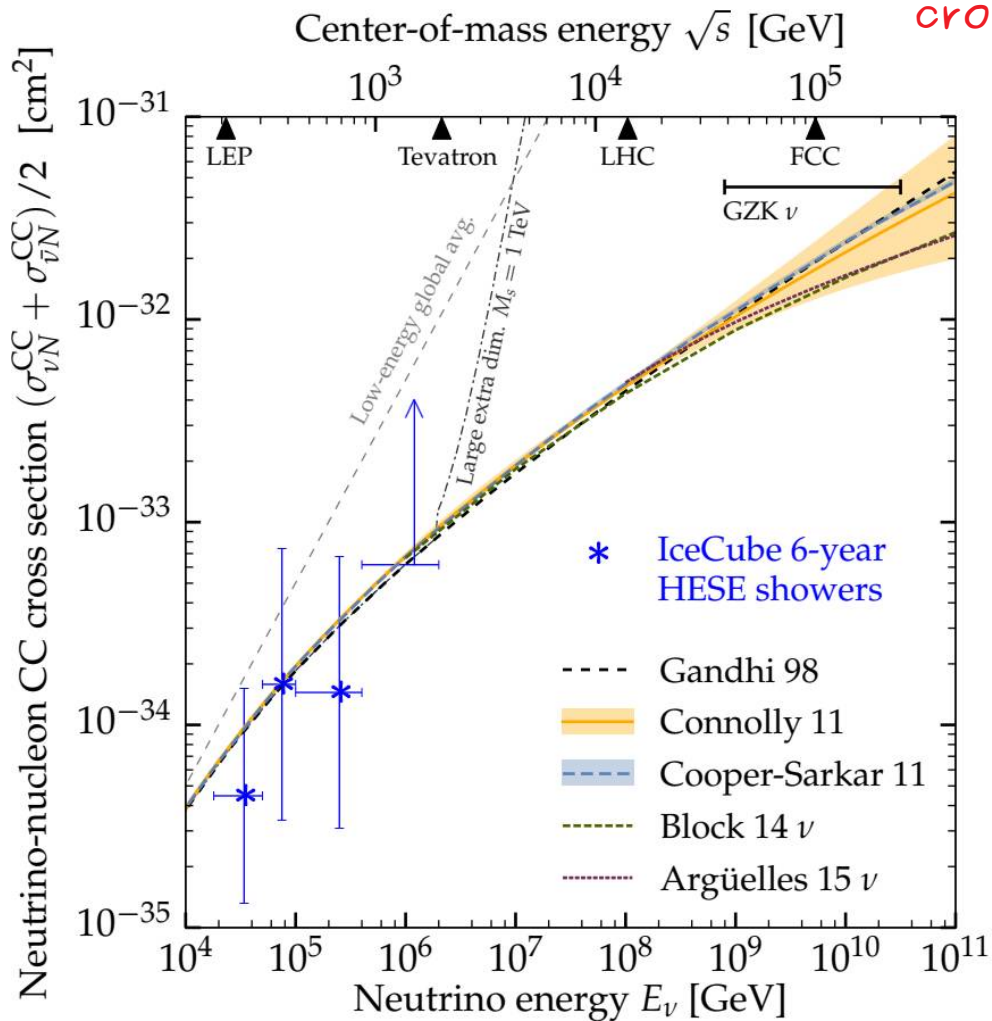


MB & A. Connolly 2017

See also: *IceCube, Nature* 2017



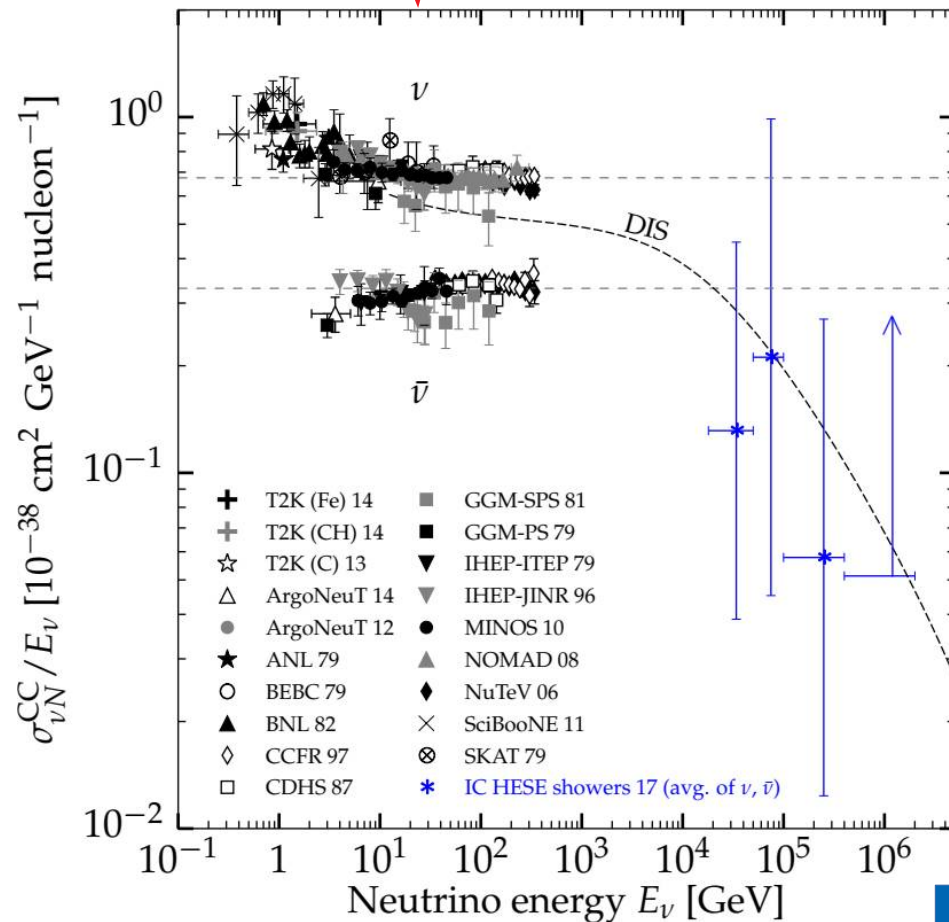
Our result



Extending the PDG
cross-section plot

MB & A. Connolly 2017

See also: *IceCube, Nature* 2017



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

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

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

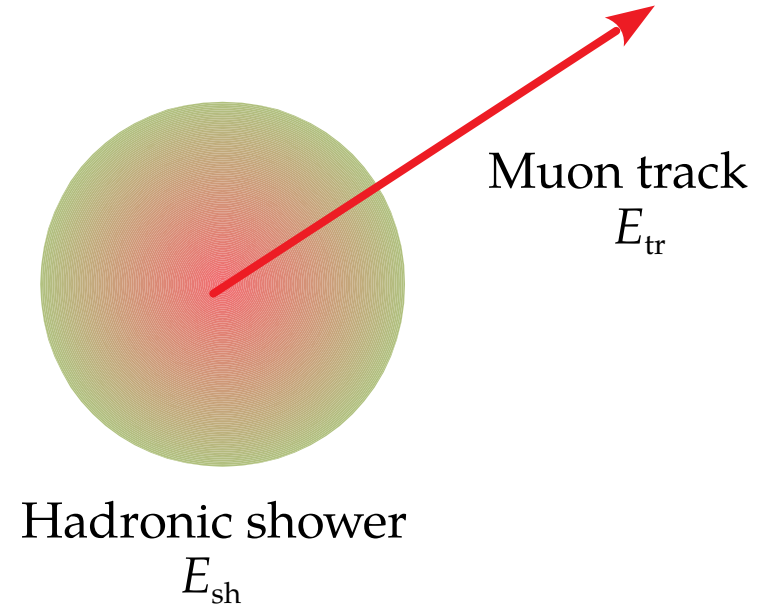
- ▶ The value of y follows a distribution $d\sigma/dy$

- ▶ In a HESE starting track:

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

- ▶ 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 $\langle y \rangle$

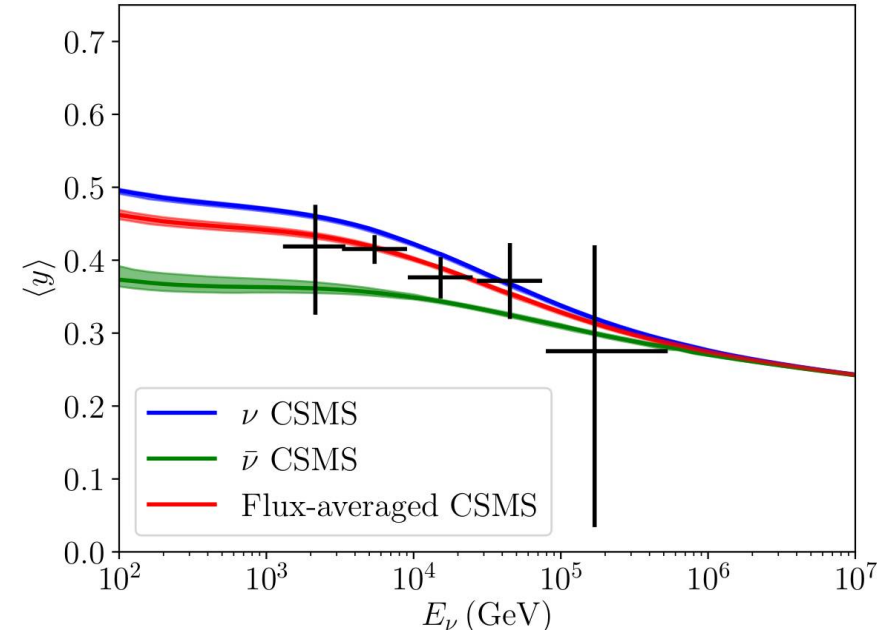
- ▶ Inelasticity in CC ν_μ interaction $\nu_\mu + N \rightarrow \mu + X$:

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

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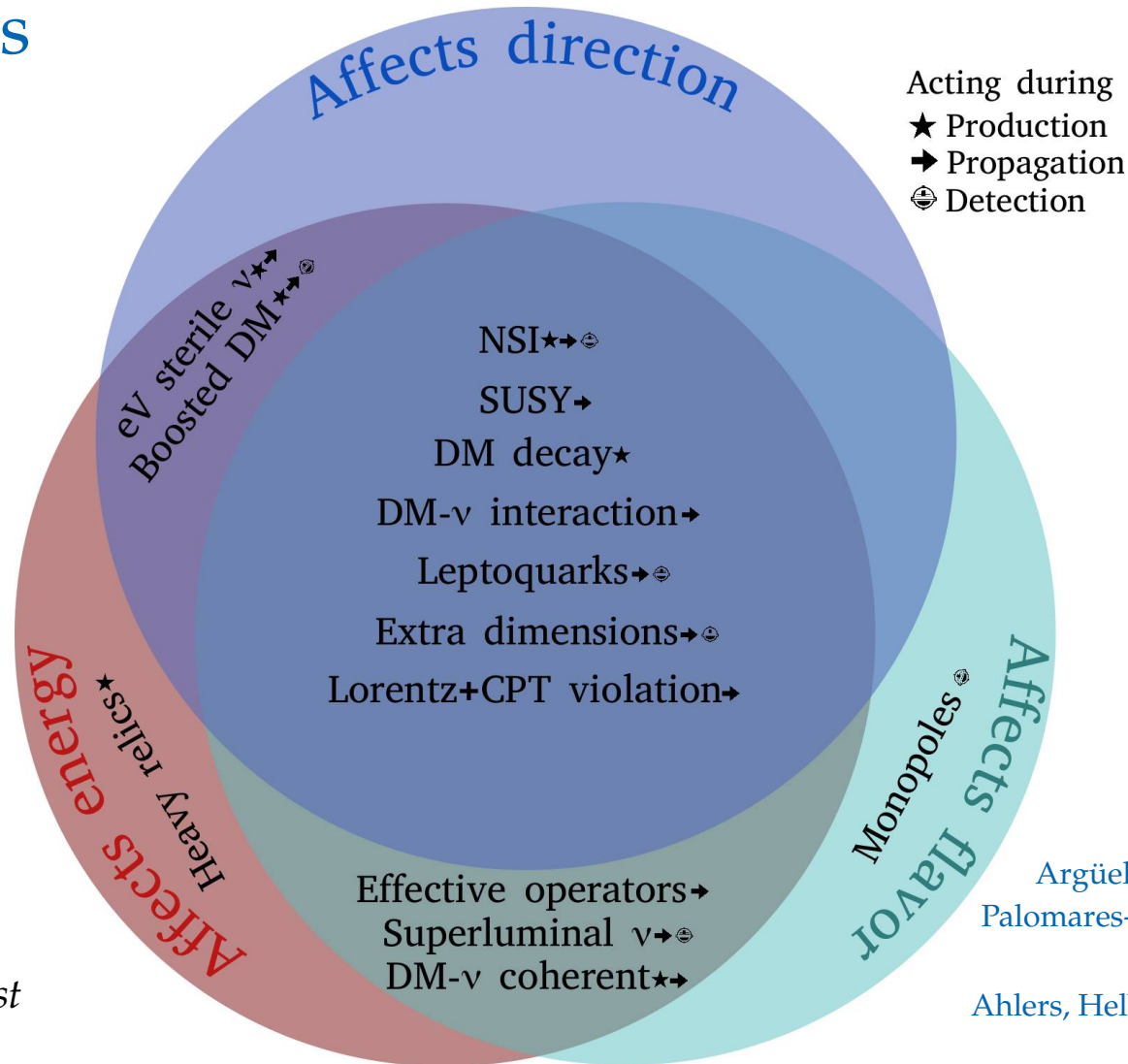
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[IceCube, 1808.07629](#)

New ν physics



Note: Not an exhaustive list

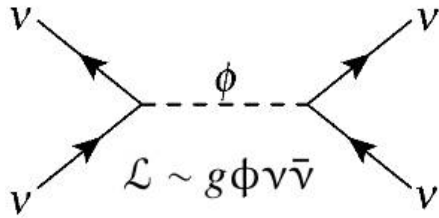
Argüelles, **MB**, Conrad, Kheirandish, Palomares-Ruiz, Salvadó, Vincent, *In prep.*

See also:

Ahlers, Helbing, De los Heros, 1806.05696

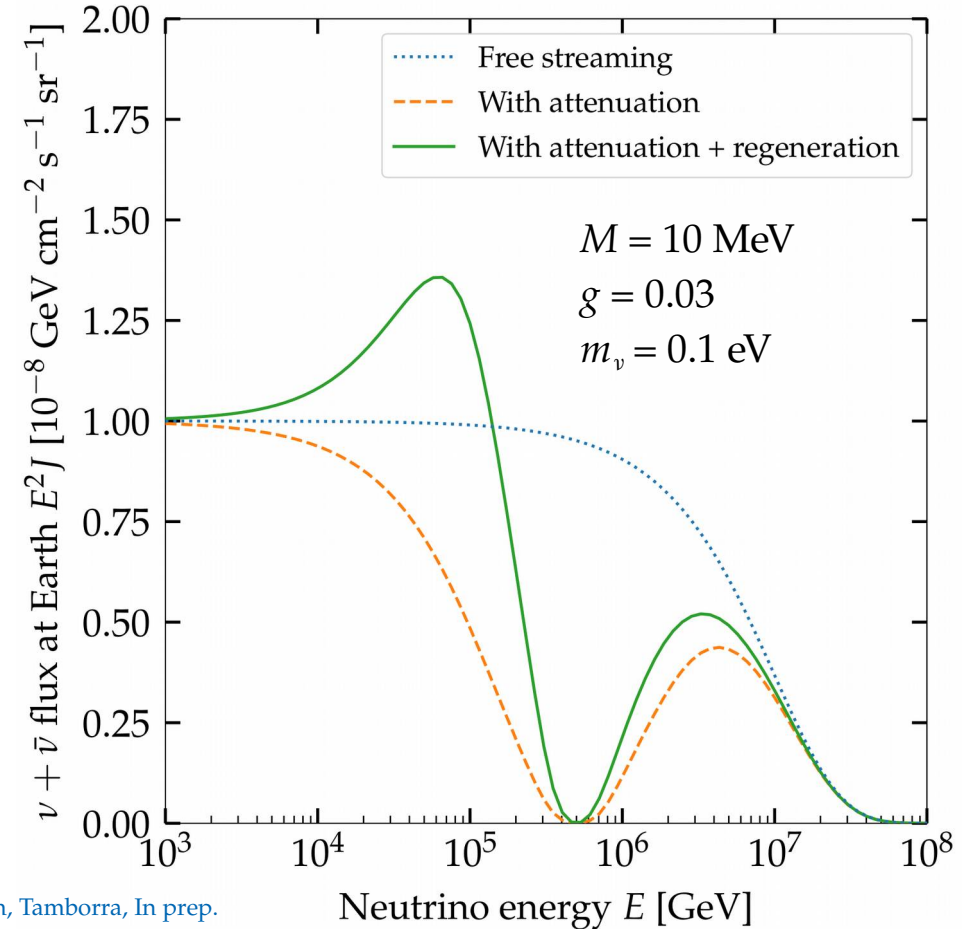
New physics in the spectral shape: $\nu\nu$ interactions

“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.

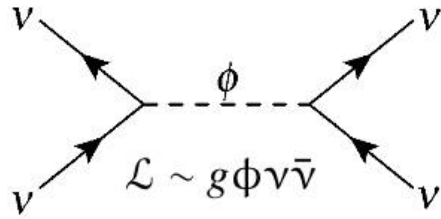
Ng & Beacom, *PRD* 2014

Cherry, Friedland, Shoemaker, 1411.1071

Blum, Hook, Murase, 1408.3799

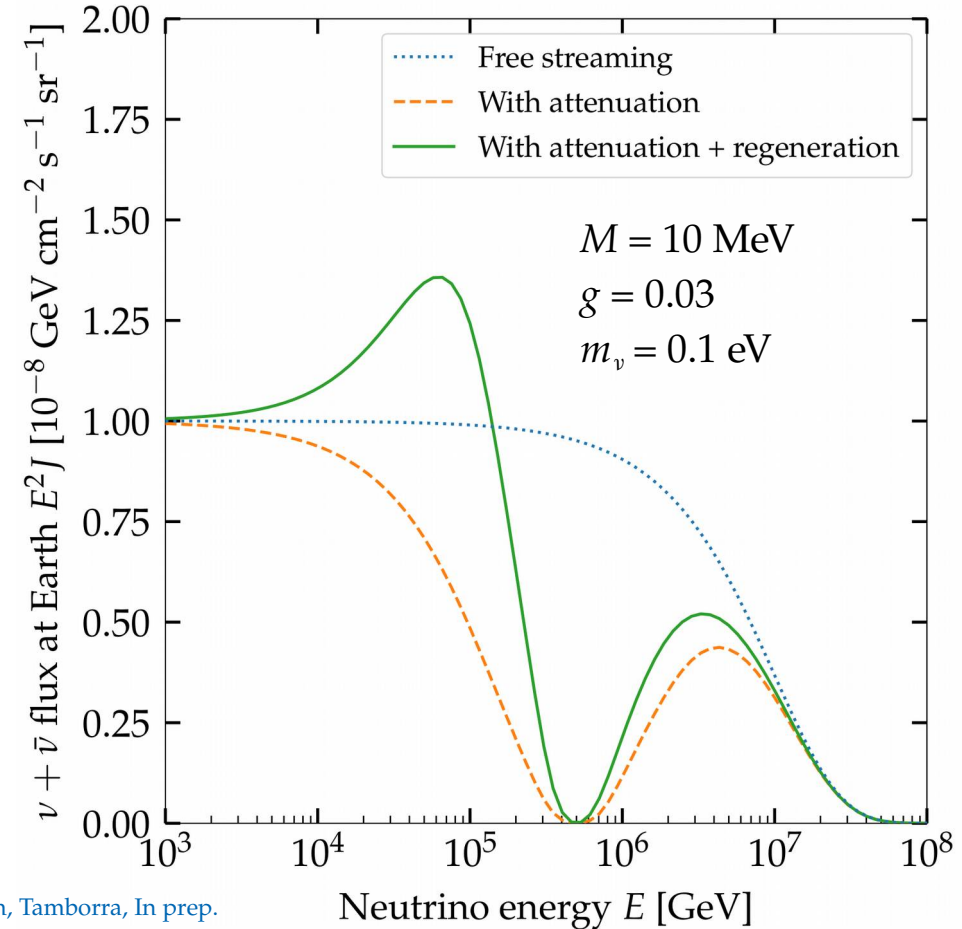
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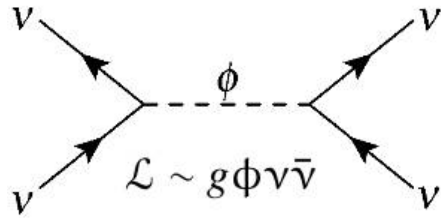
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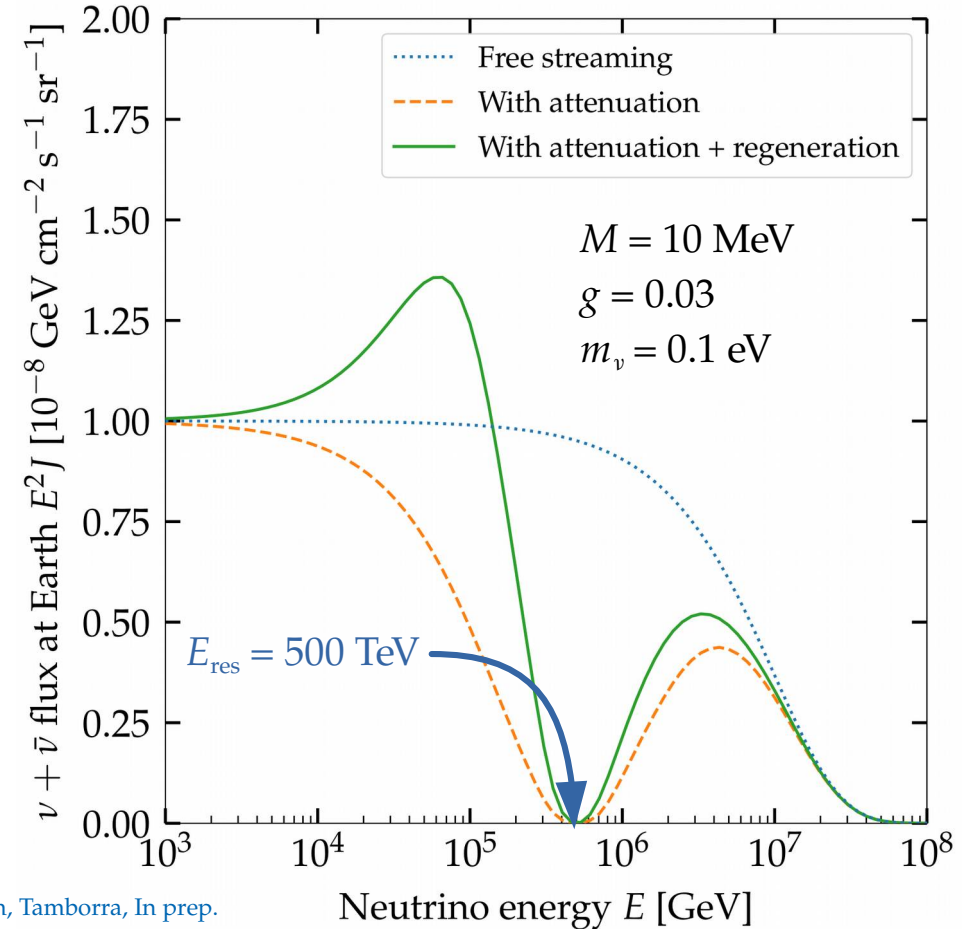
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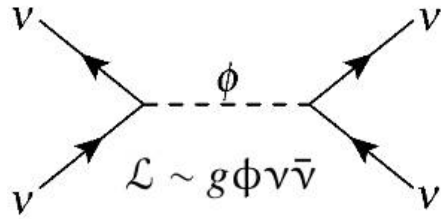
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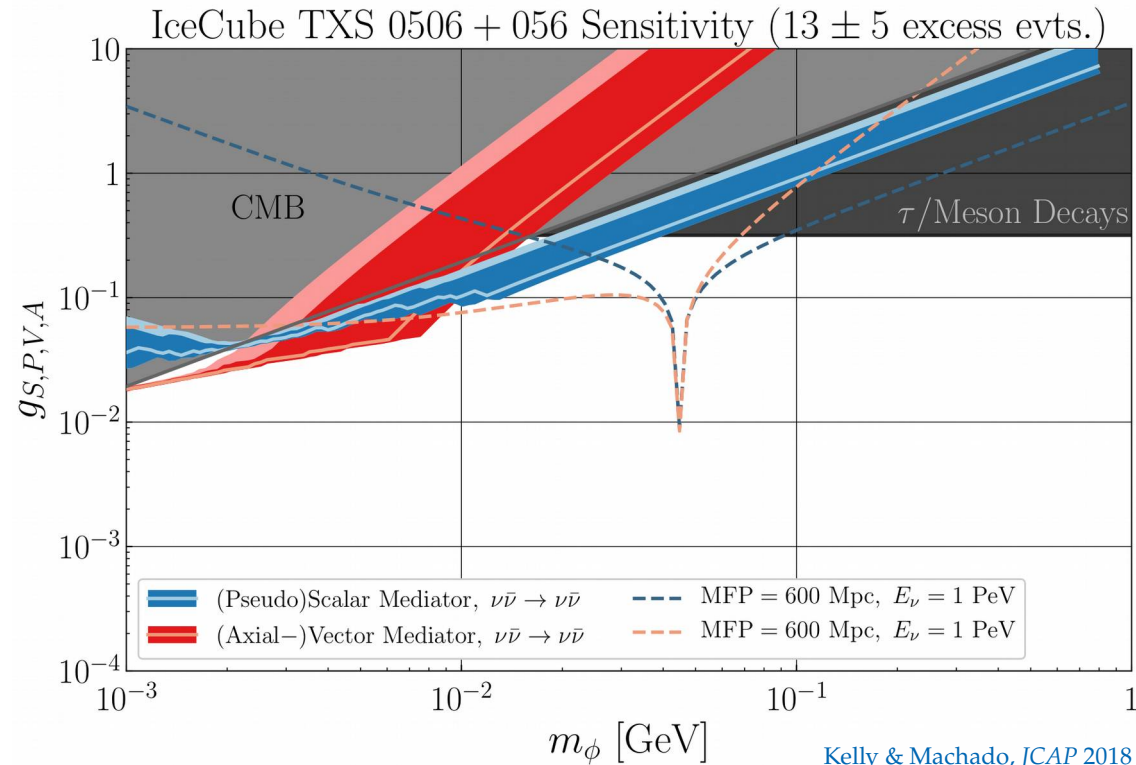
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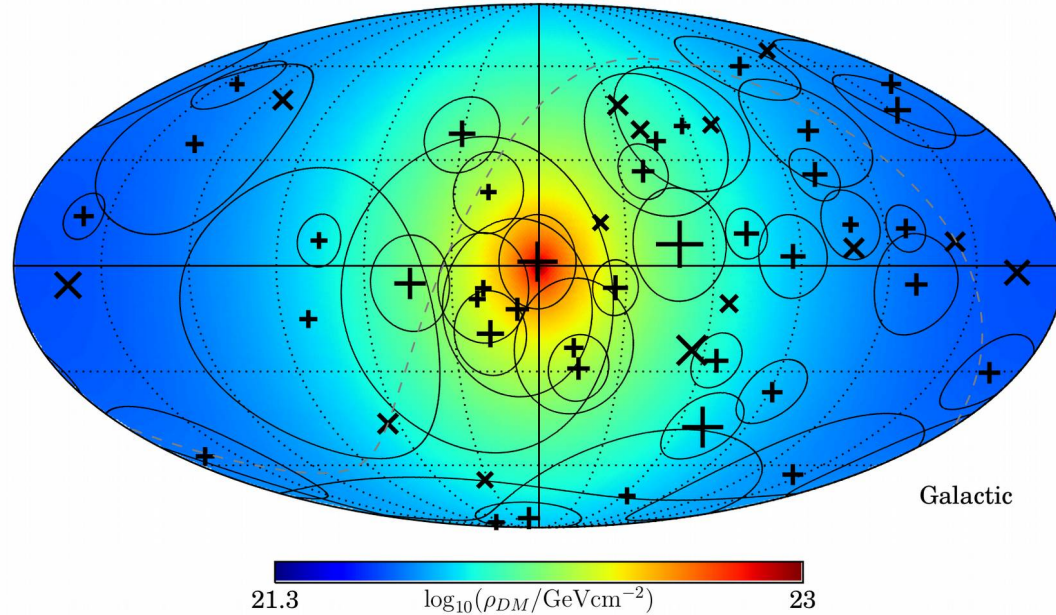
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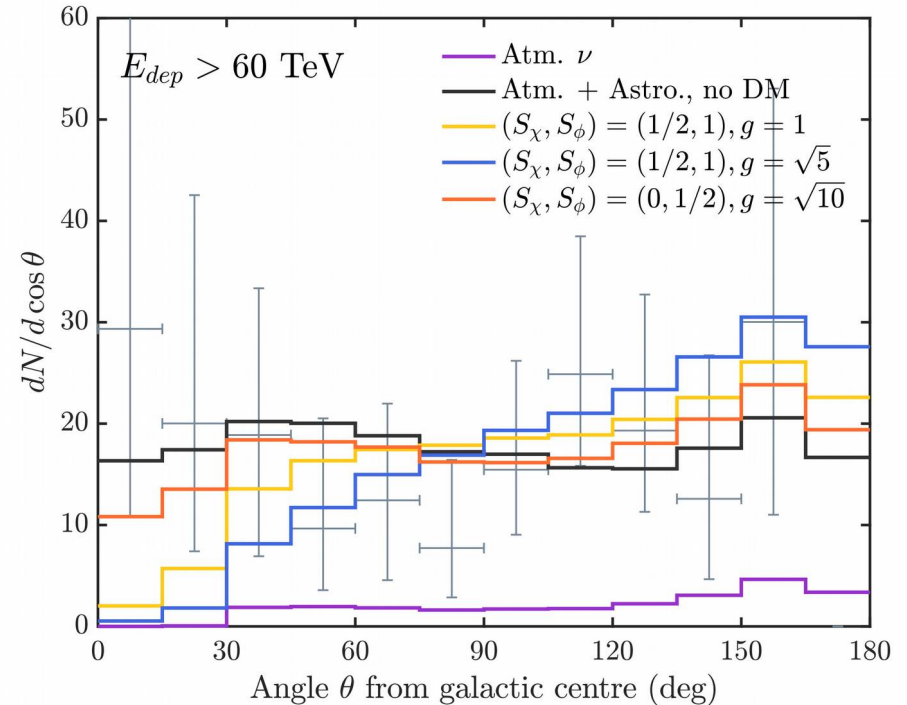
Kelly & Machado, JCAP 2018

New physics in the angular distribution: ν -DM interactions

Interaction between astrophysical neutrinos and the Galactic dark matter profile –



Argüelles *et al.*, PRL 2017

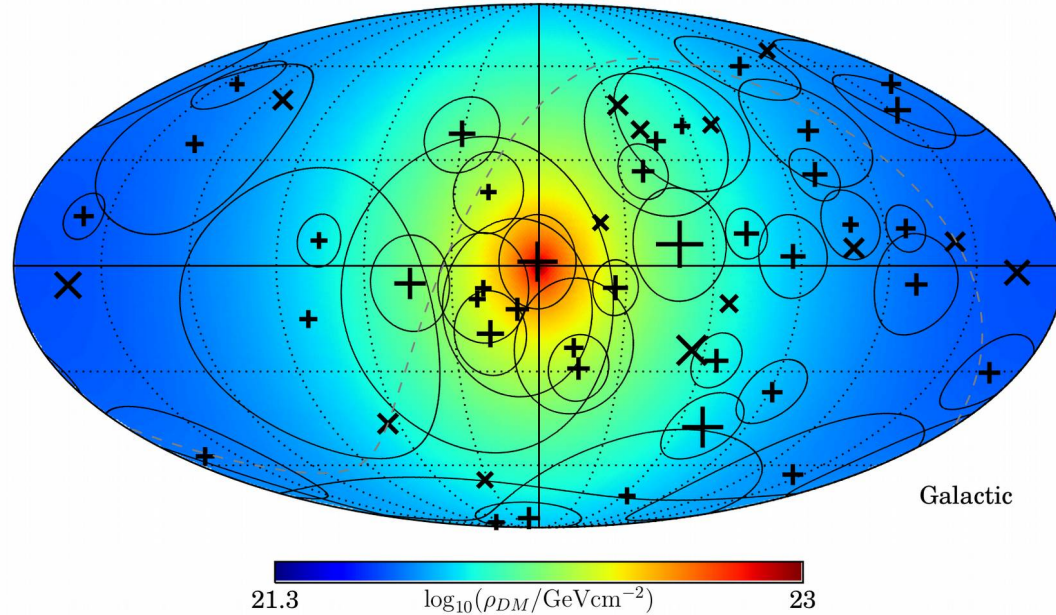


Expected: Fewer neutrinos coming from the Galactic Center

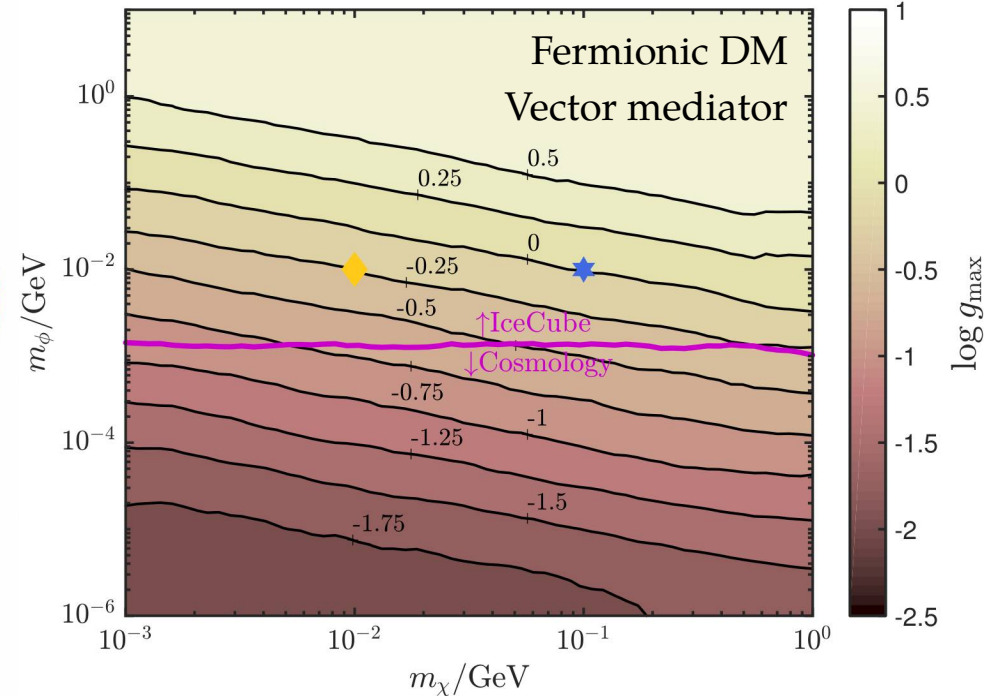
Observed: Isotropy

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Interaction between astrophysical neutrinos and the Galactic dark matter profile –



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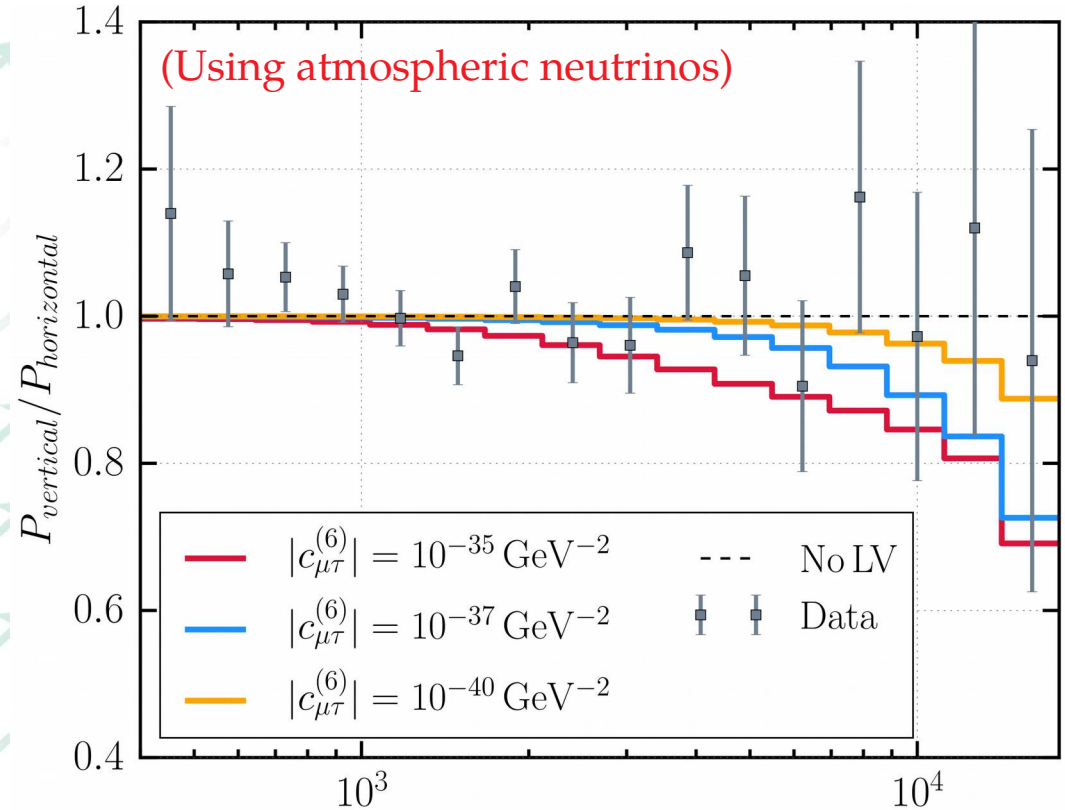
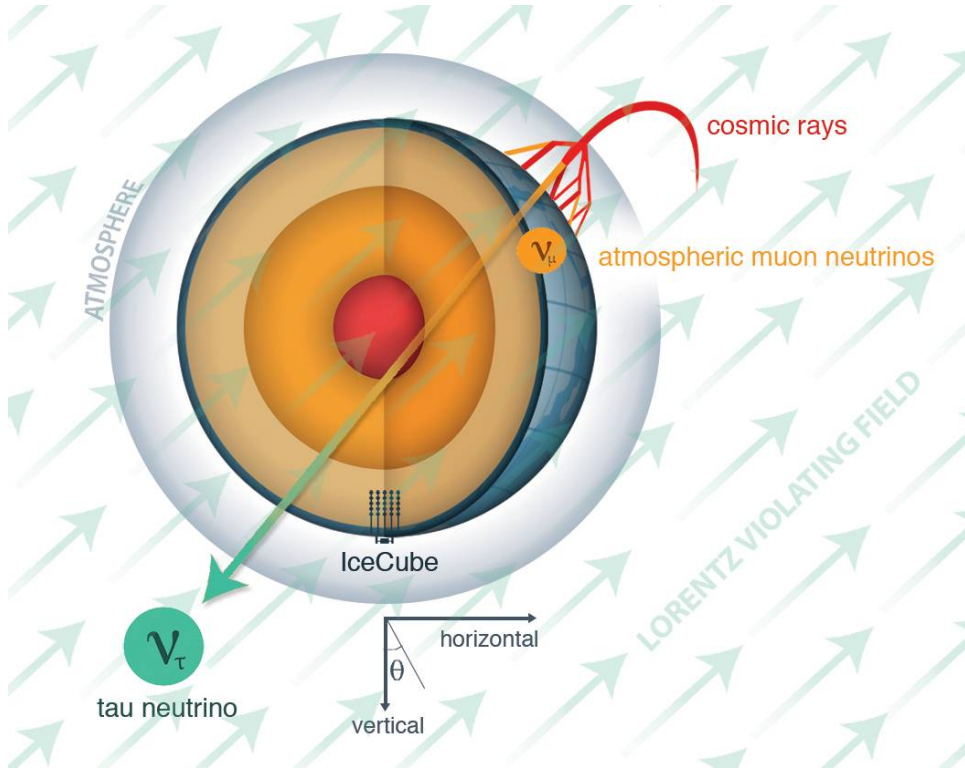


Expected: Fewer neutrinos coming from the Galactic Center

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New physics in the energy & angular distribution

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

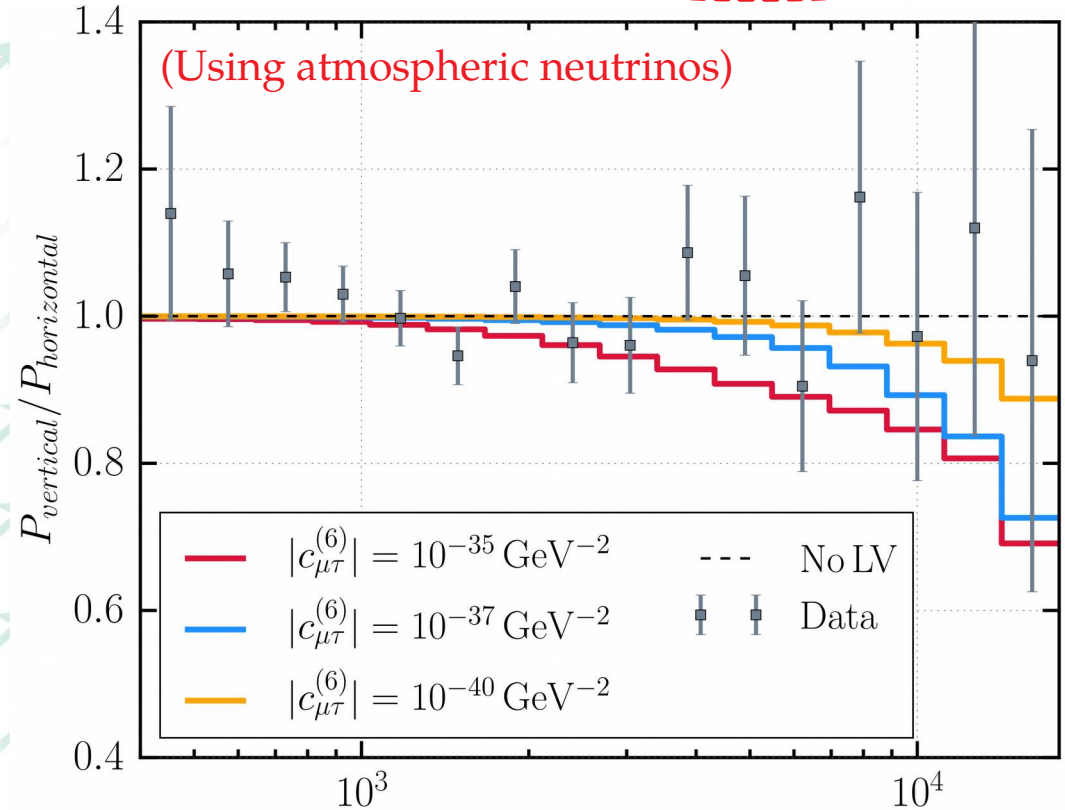
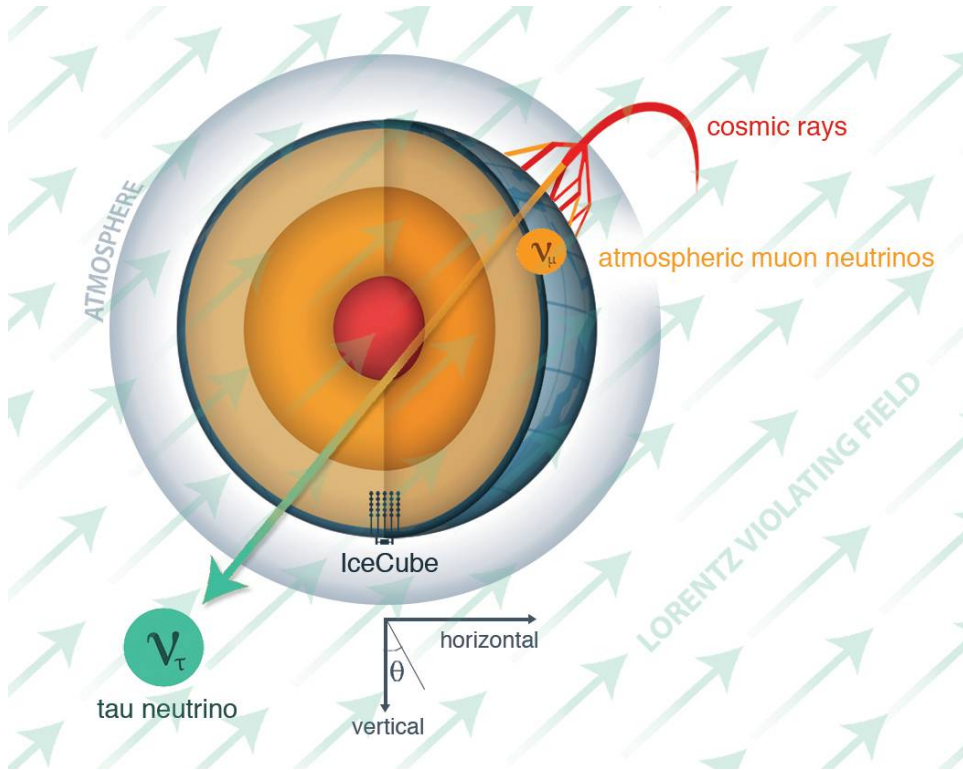


New physics in the energy & angular distribution

Standard oscillations

Lorentz violation

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



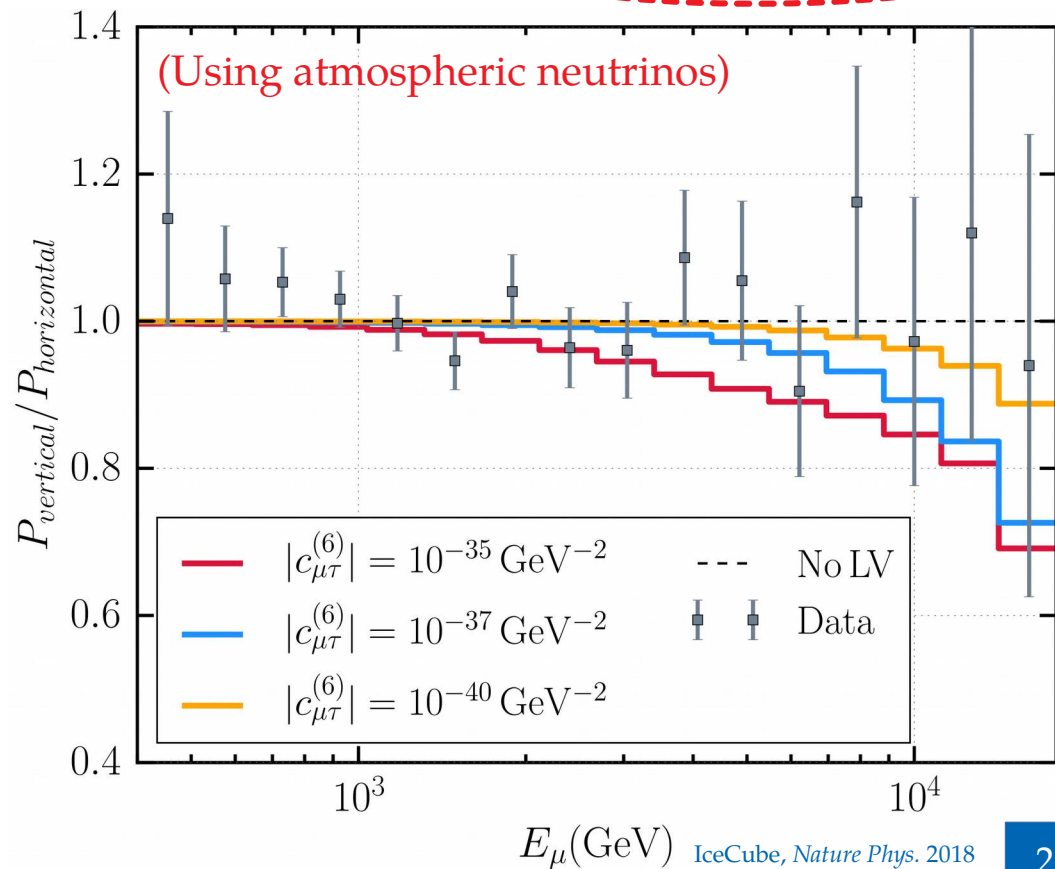
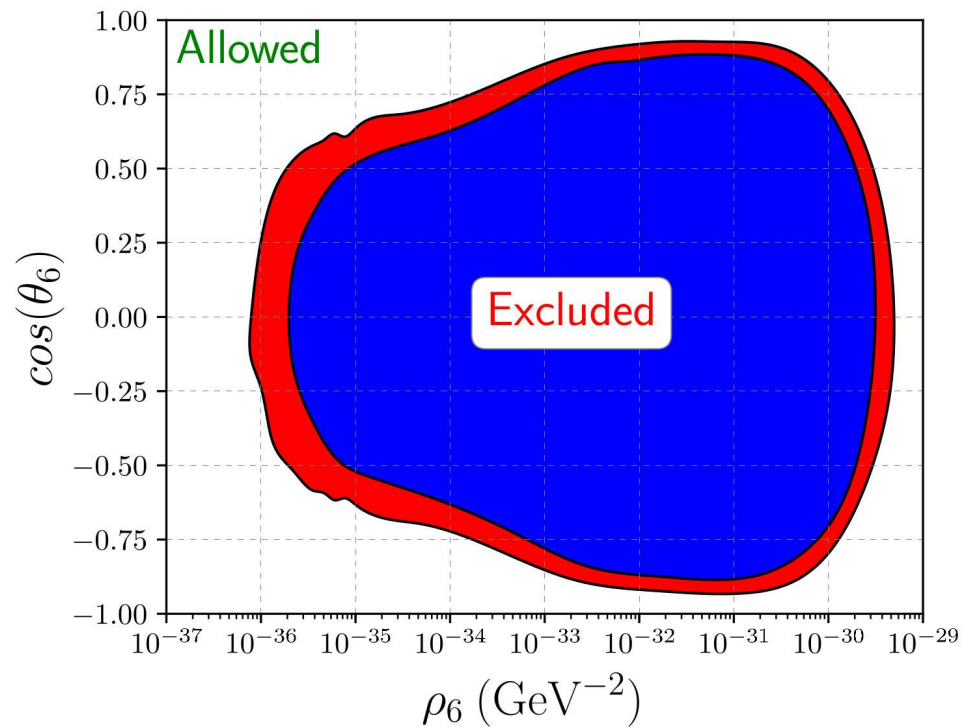
New physics in the energy & angular distribution

Standard oscillations

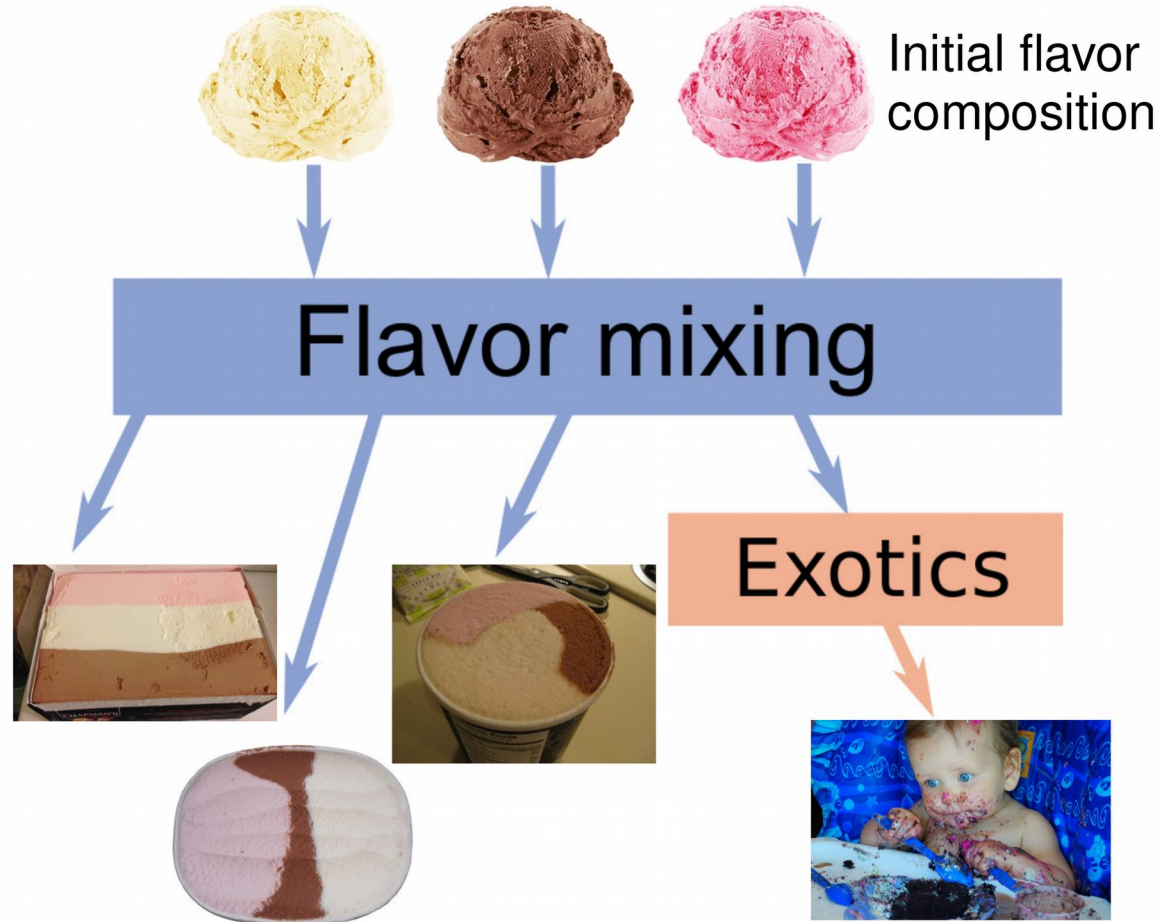
Lorentz violation

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

Best bounds come from IceCube



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

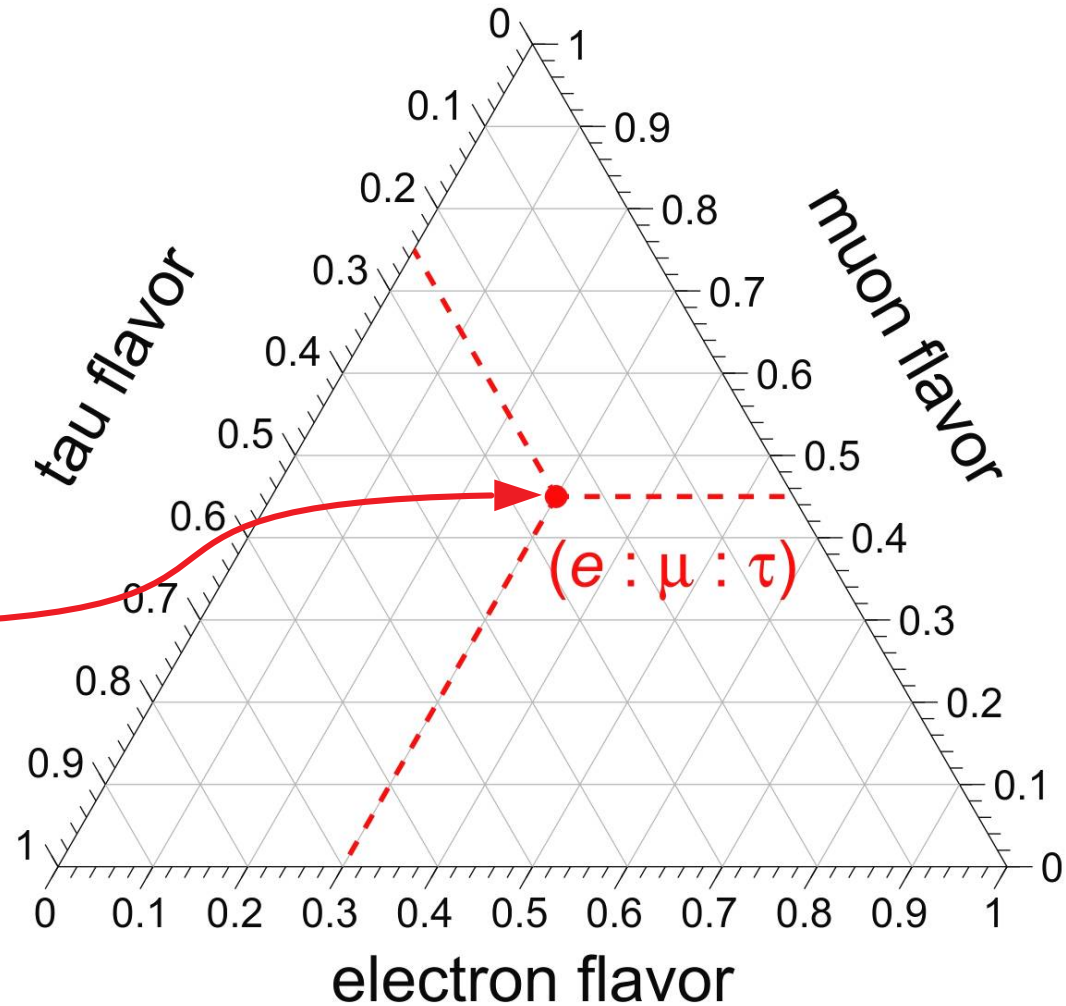
Note: Ratios are for $\nu + \bar{\nu}$, since neutrino telescopes cannot tell them apart

Reading a ternary plot

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

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

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



Flavor content of neutrino mass eigenstates

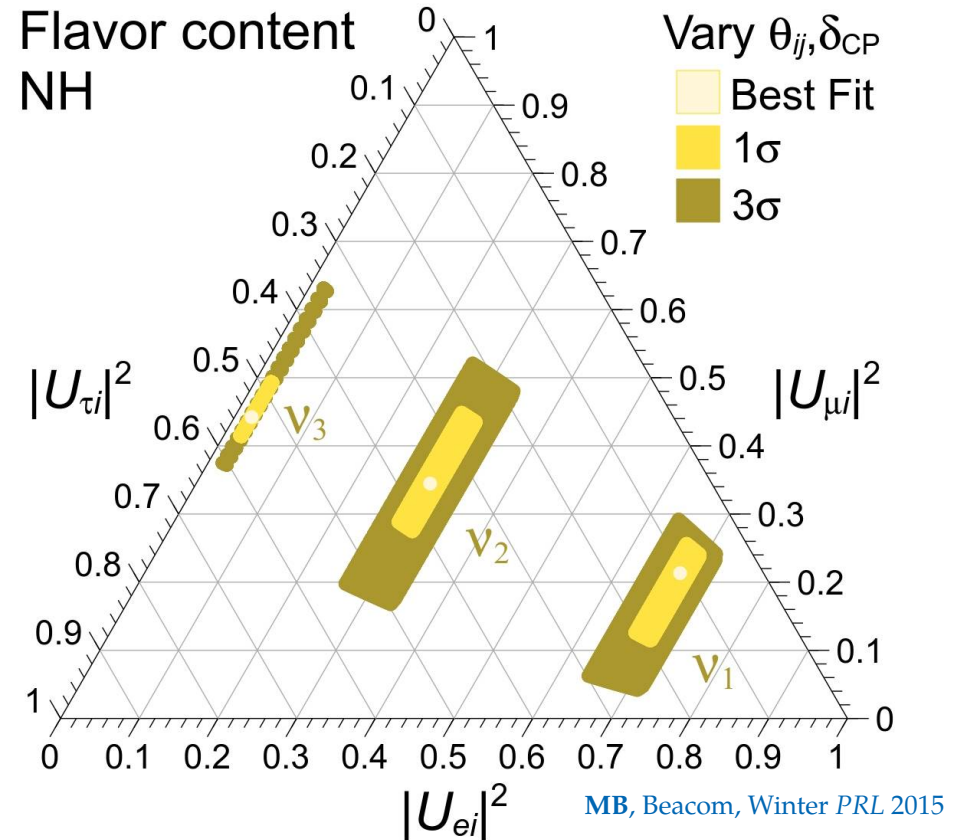
Flavor content for every allowed combination of mixing parameters –

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

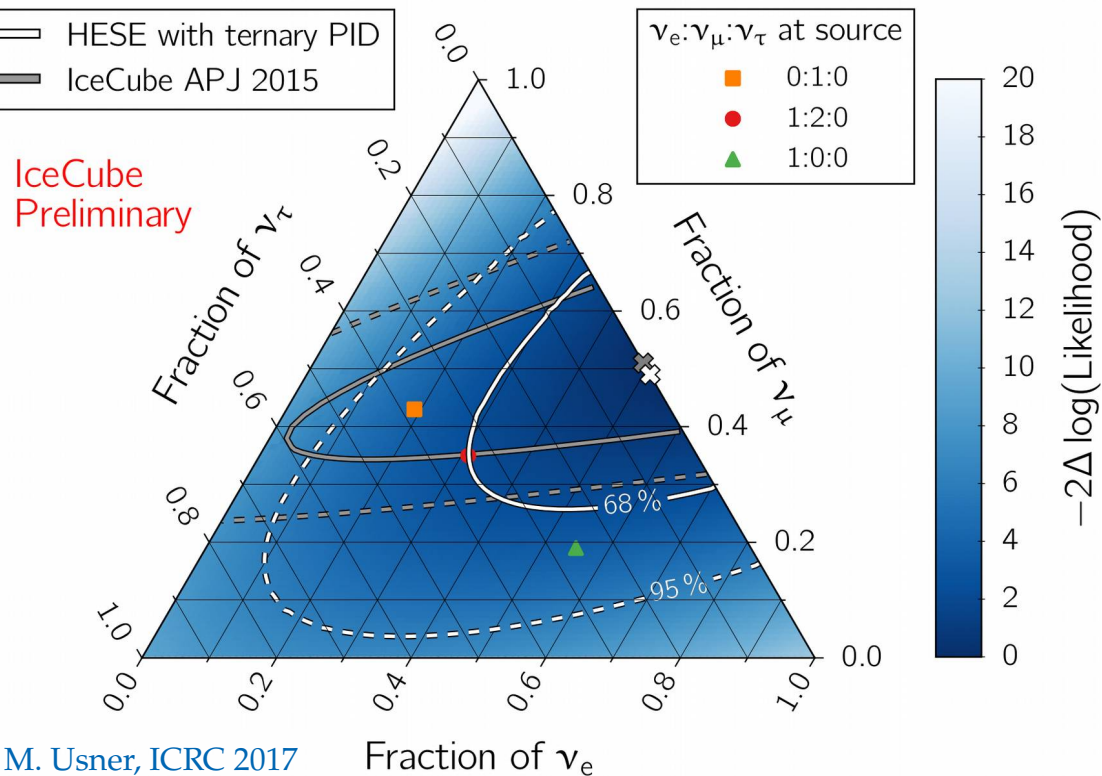
Known to within 2%

Known to within 8%

Known to within 20% (or worse)



IceCube flavor composition (pre-Neutrino 2018)



M. Usner, ICRC 2017

Fraction of ν_e

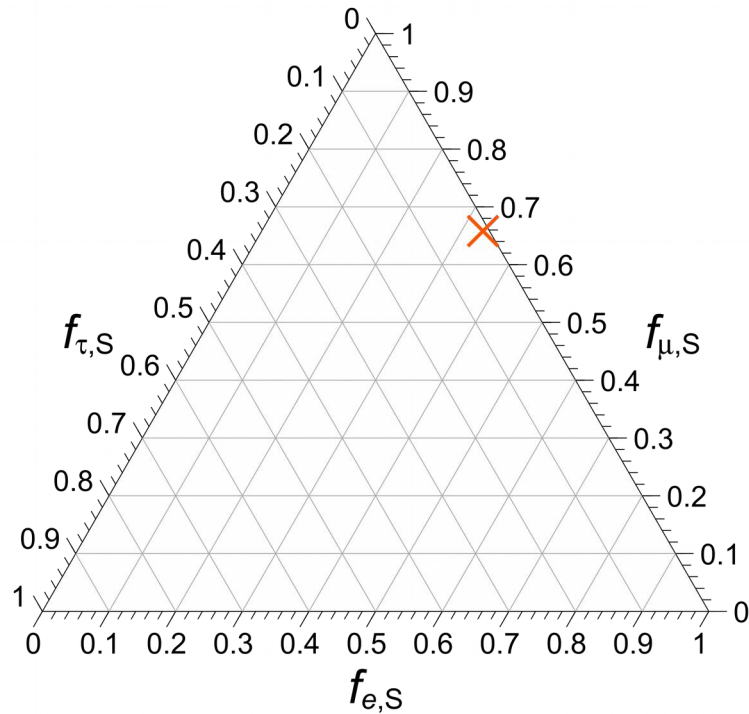
- ▶ Compare number of tracks (ν_μ) vs. showers (**all flavors**)
- ▶ Best fit: $(f_e:f_\mu:f_\tau)_\oplus = (0.49:0.51:0)_\oplus$
- ▶ Compatible with standard source compositions
- ▶ Lots of room for improvement: more statistics, better flavor-tagging

Li, MB, Beacom 2016

Flavor – there and here

At the sources

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

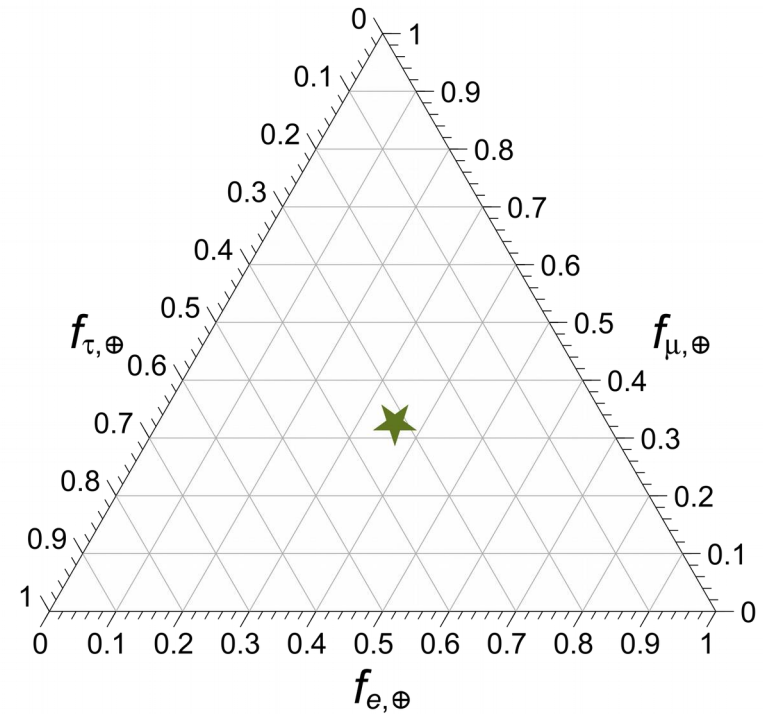


Neutrino oscillations



At Earth

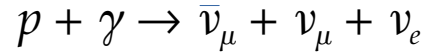
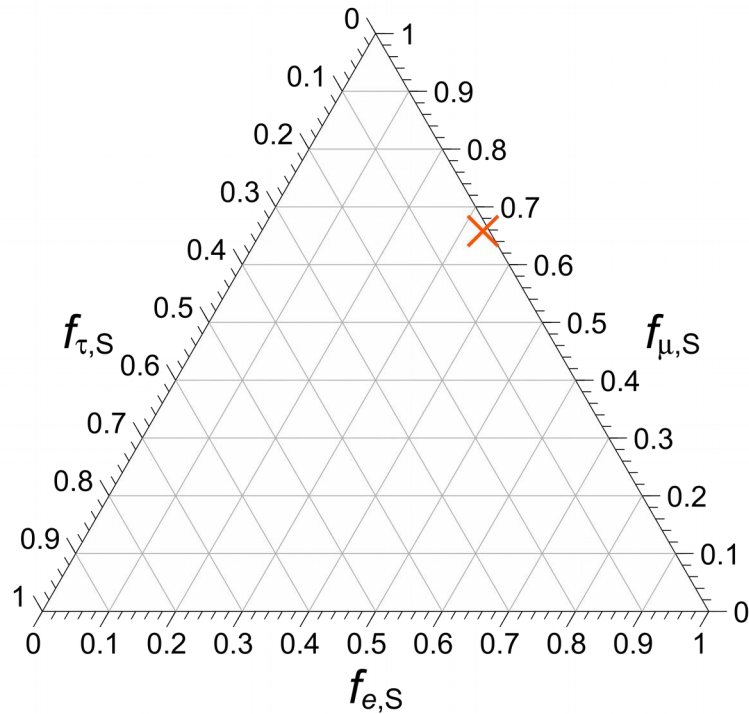
$$(0.36 : 0.32 : 0.32)_\oplus$$



Flavor – there and here

At the sources

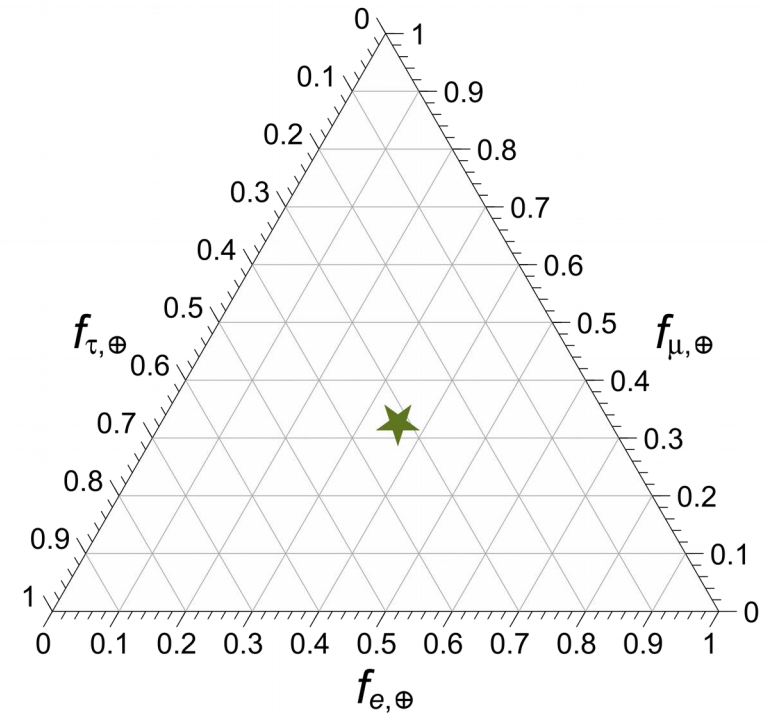
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Neutrino oscillations

At Earth

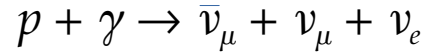
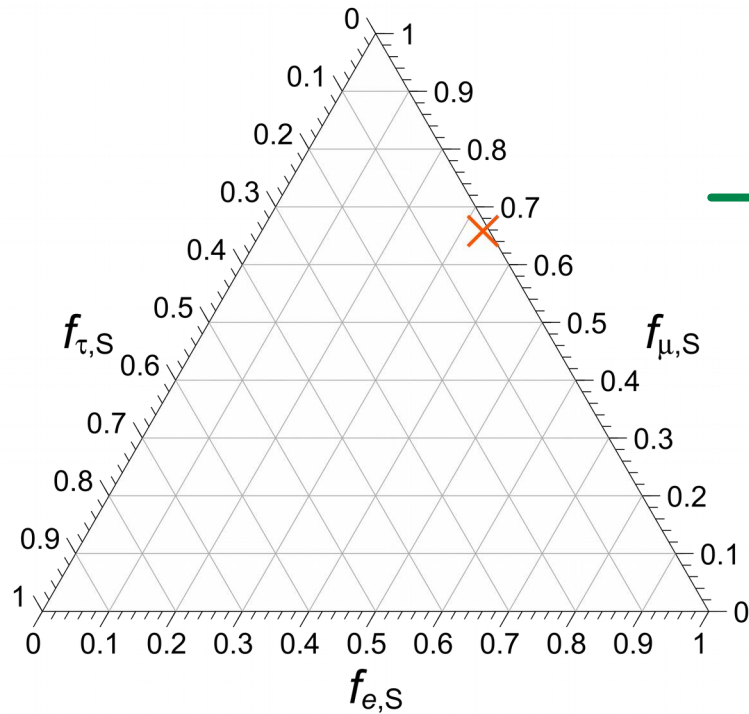
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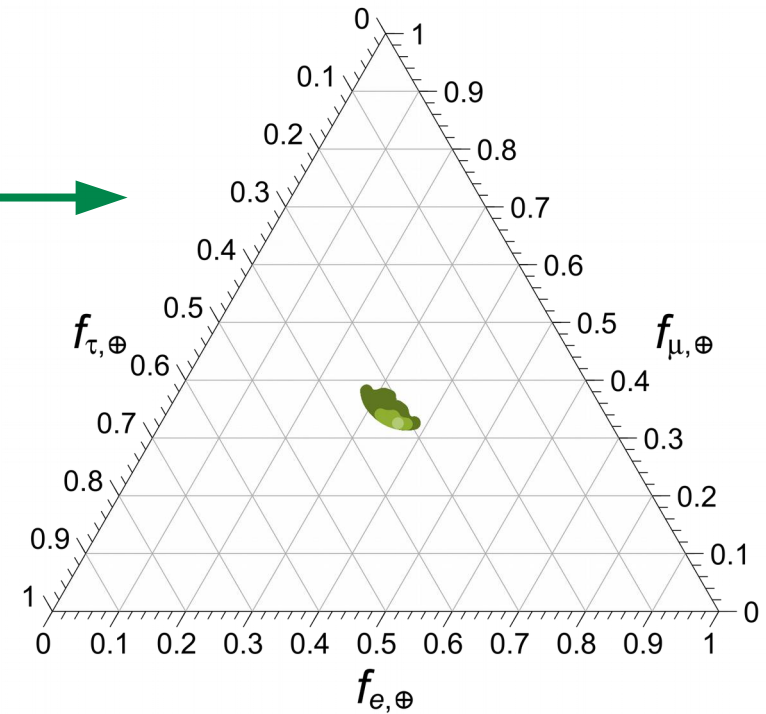


Neutrino oscillations

At Earth

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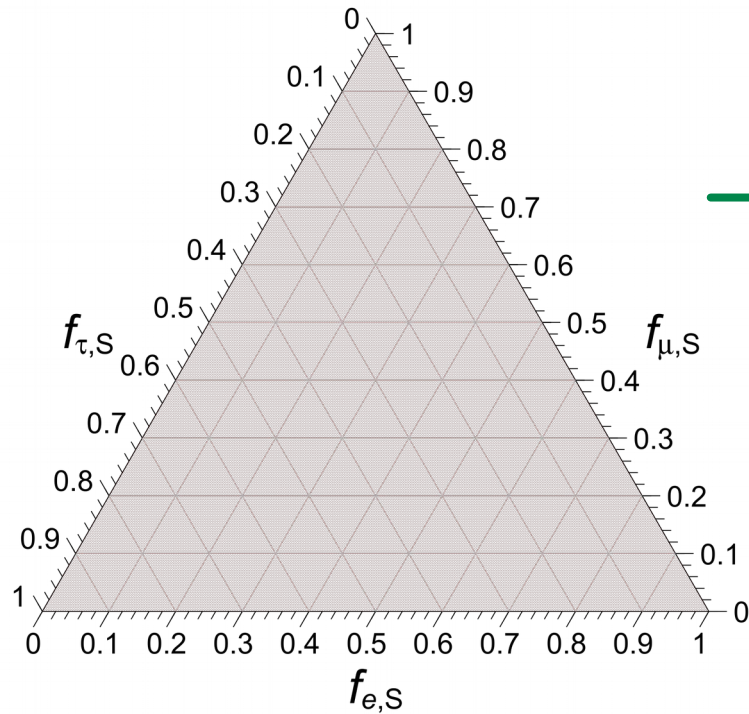
Uncertainties in values of
mixing parameter ($1\sigma, 3\sigma$)



Flavor composition – Standard allowed region

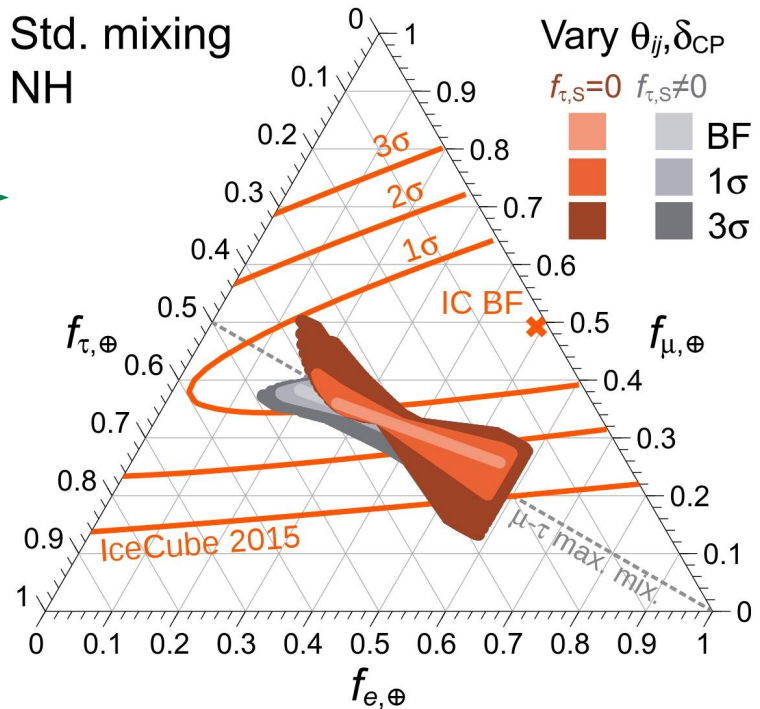
At the sources

All possible flavor ratios



At Earth

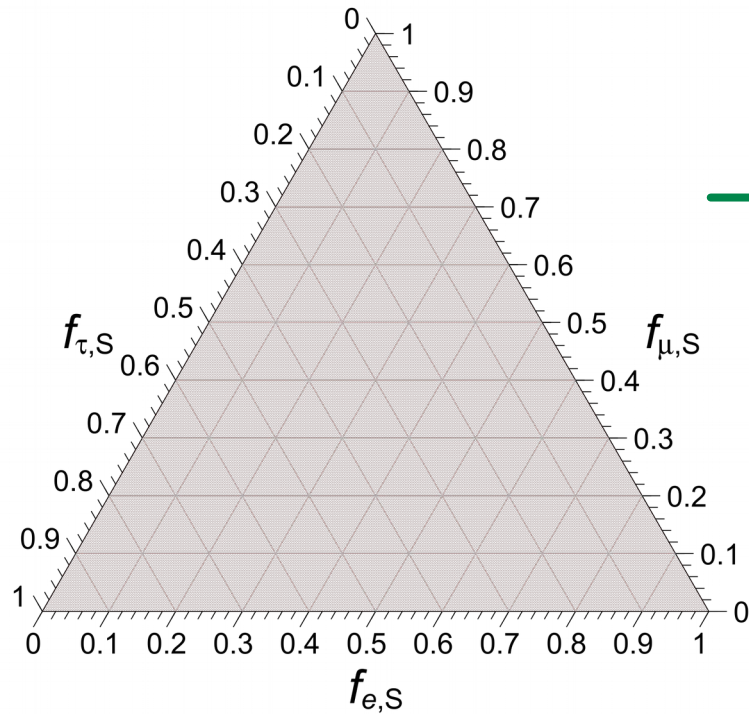
Std. mixing
NH



Flavor composition – Standard allowed region

At the sources

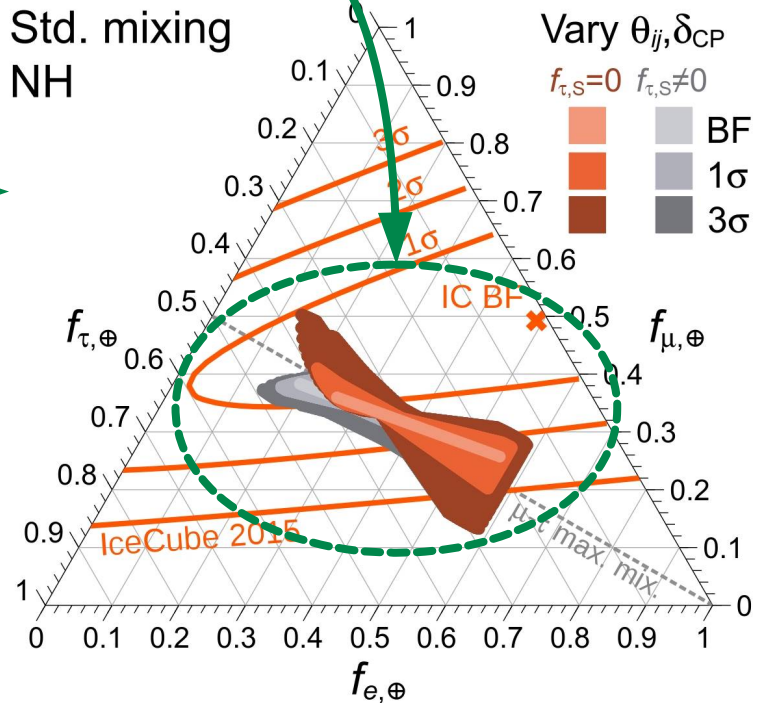
All possible flavor ratios



Only 10% of parameter space

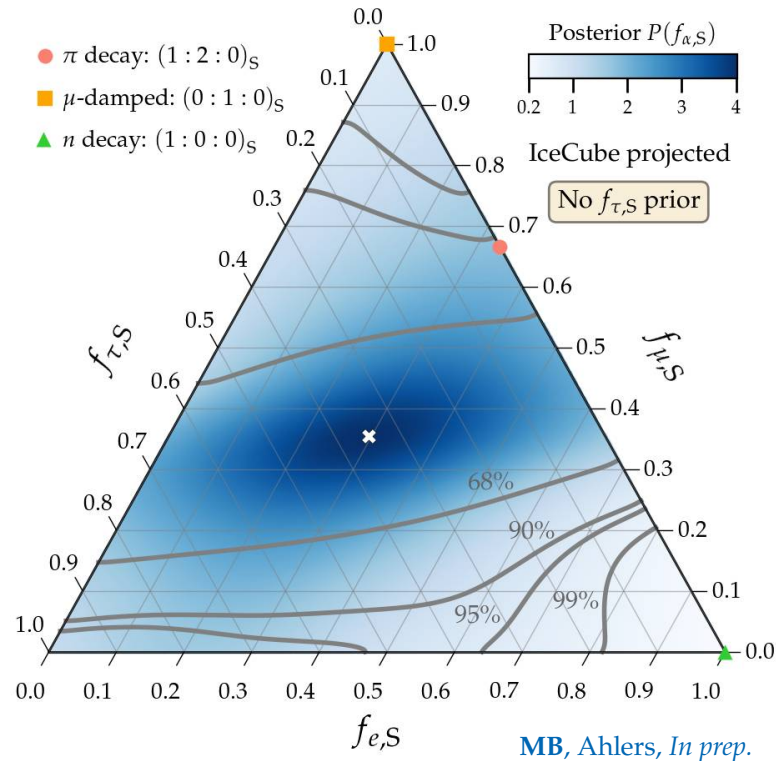
At Earth

Std. mixing
NH

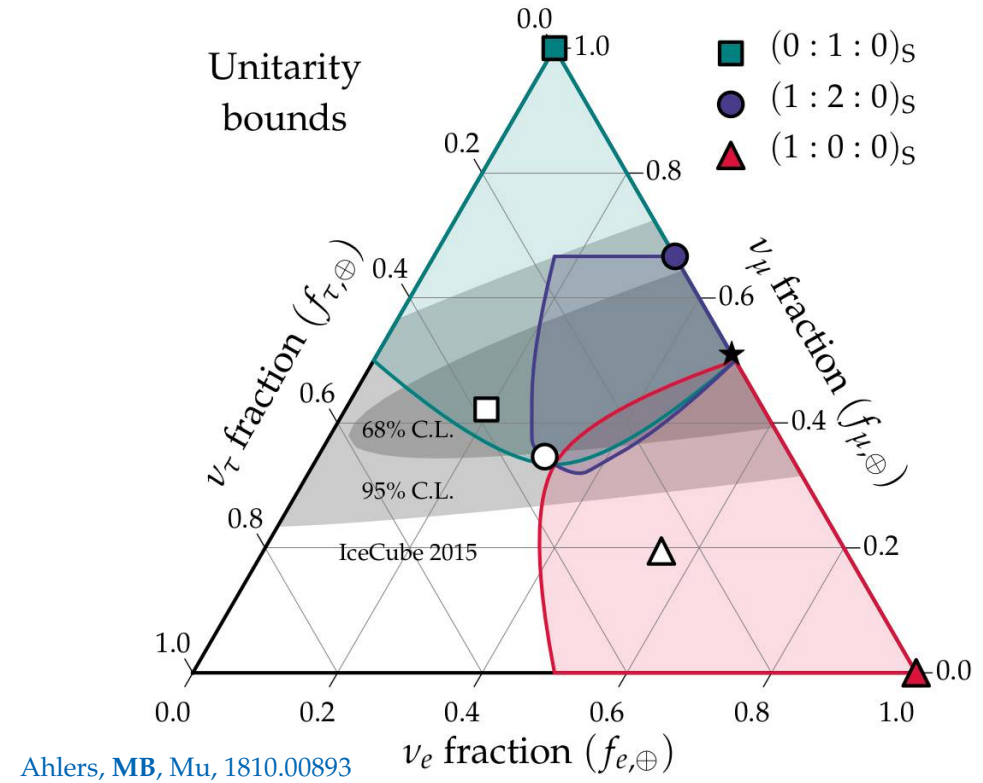


Flavor – What is it good for?

Trusting **particle physics**
and learning about **astrophysics**



Trusting **astrophysics**
and learning about **particle physics**

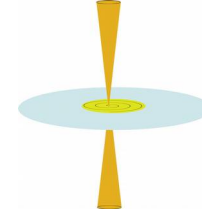


Inferring flavor composition at the sources

Measured:
Flavor ratios at Earth



Invert flavor oscillations



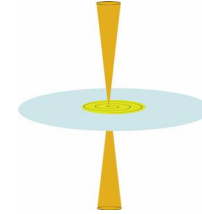
Inferred:
Flavor ratios at
astrophysical sources

Inferring flavor composition at the sources

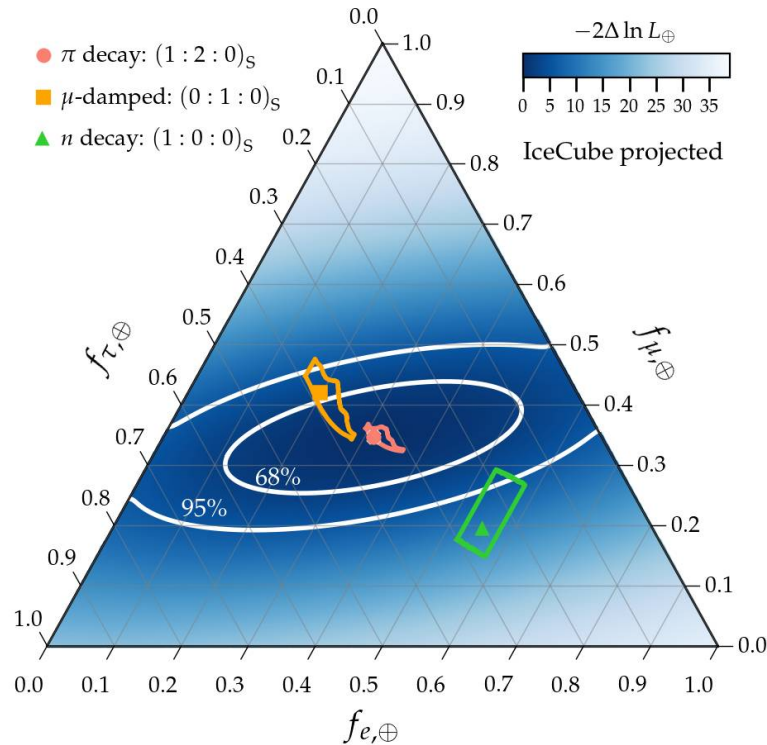
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Invert flavor oscillations



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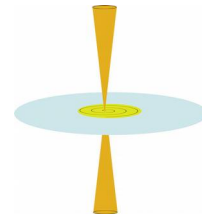


Inferring flavor composition at the sources

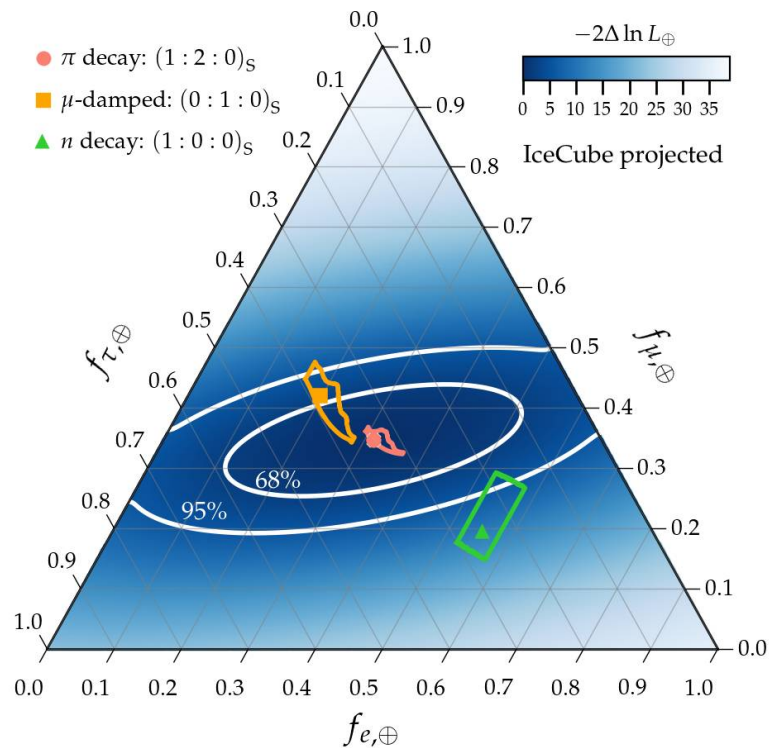
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Invert flavor oscillations



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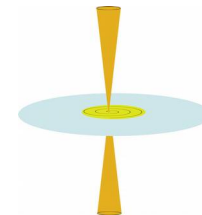


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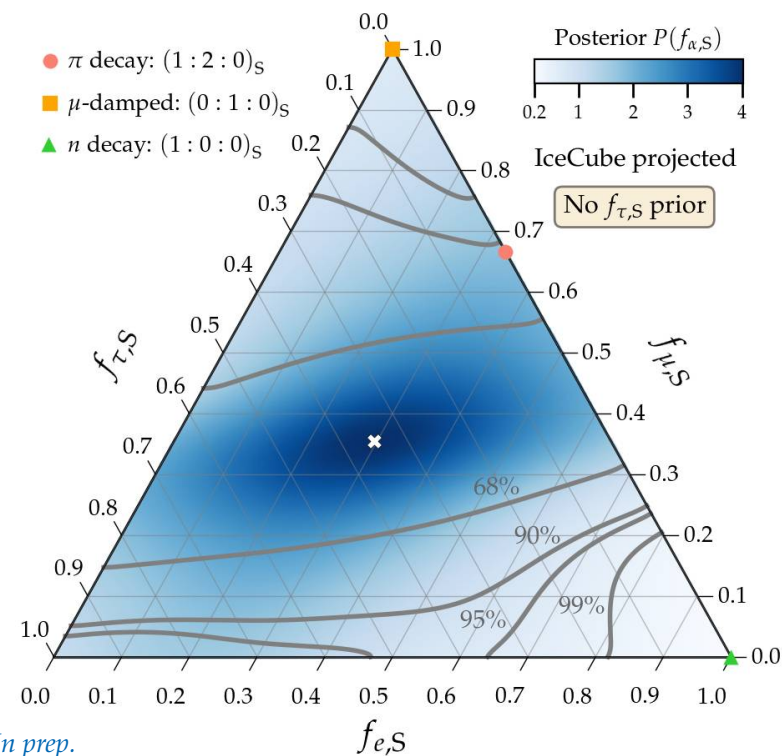
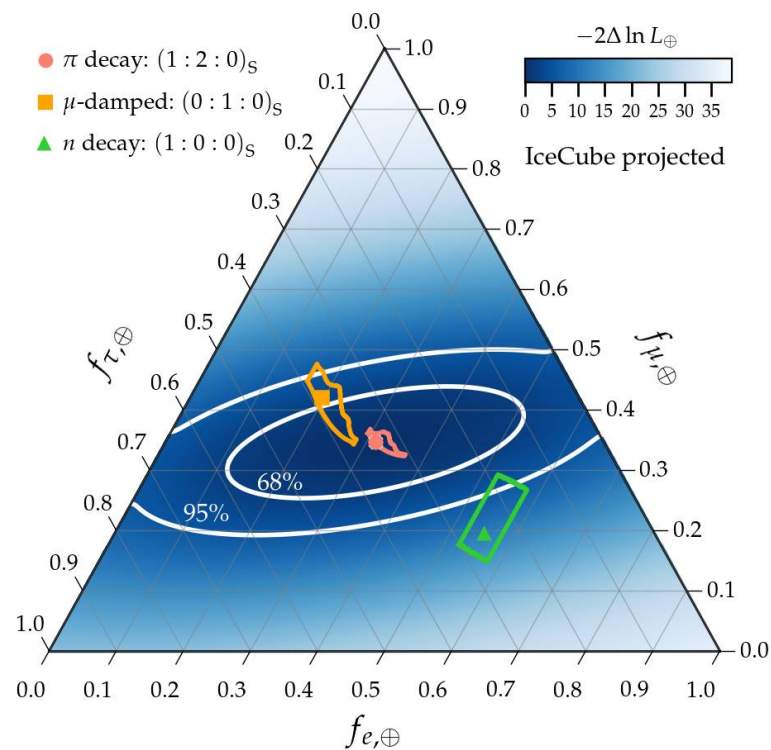
Measured:
Flavor ratios at Earth



Invert flavor oscillations



Inferred:
Flavor ratios at
astrophysical sources



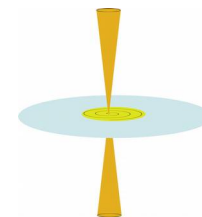
MB, Ahlers, *In prep.*

Inferring flavor composition at the sources

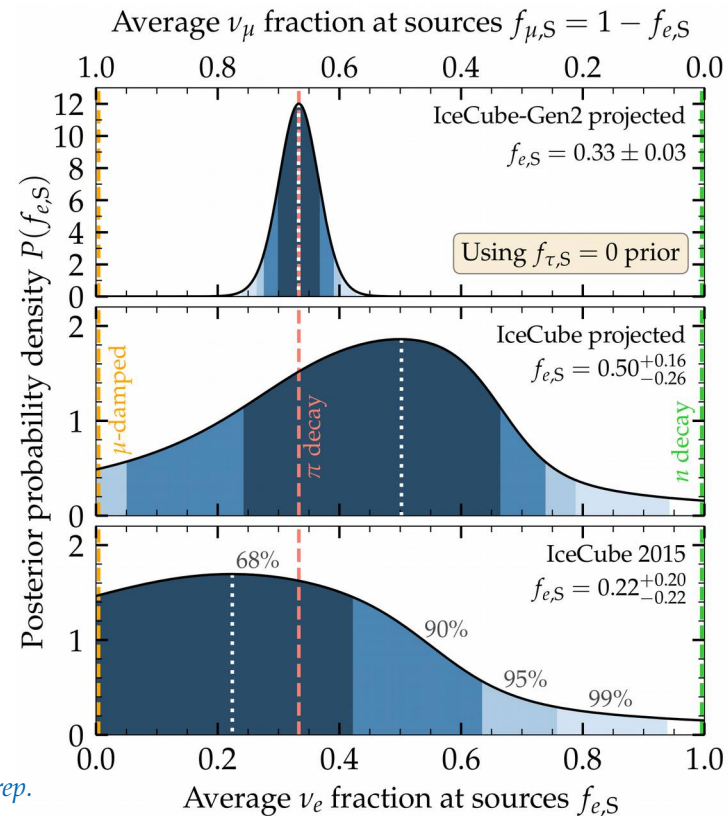
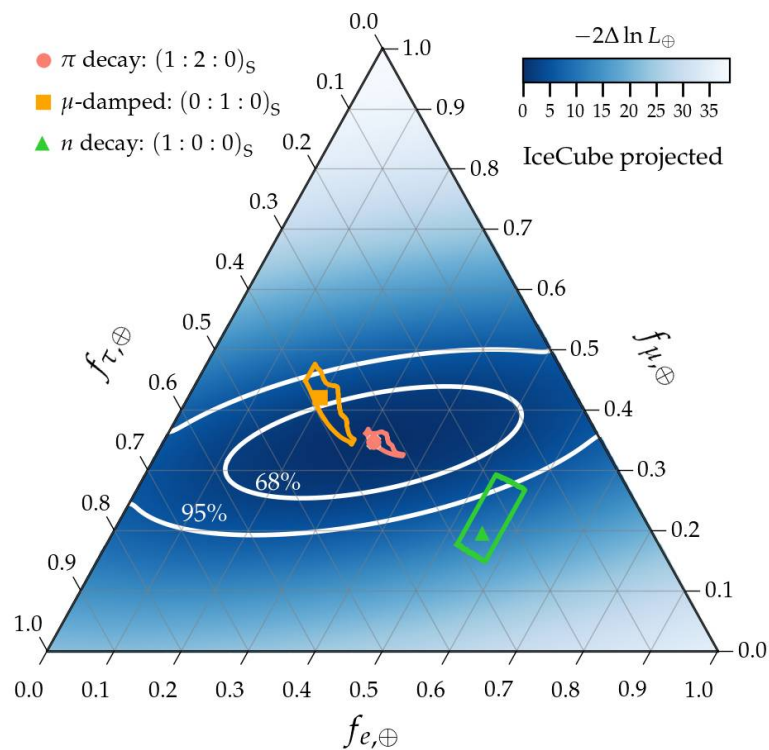
Measured:
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Invert flavor oscillations



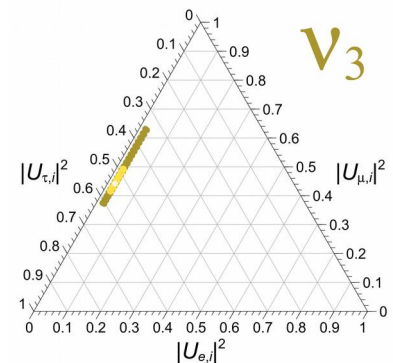
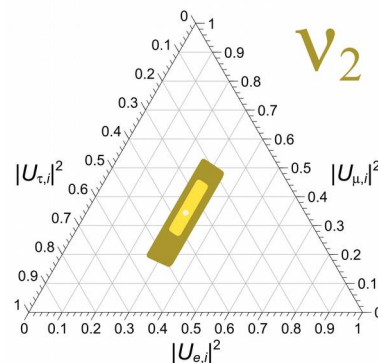
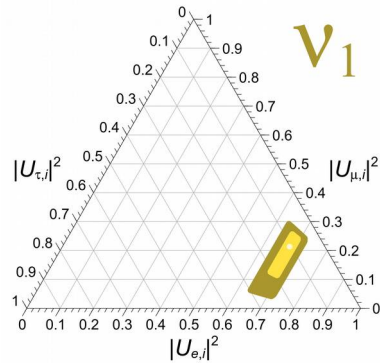
Inferred:
Flavor ratios at
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MB, Ahlers, *In prep.*

Two classes of new physics

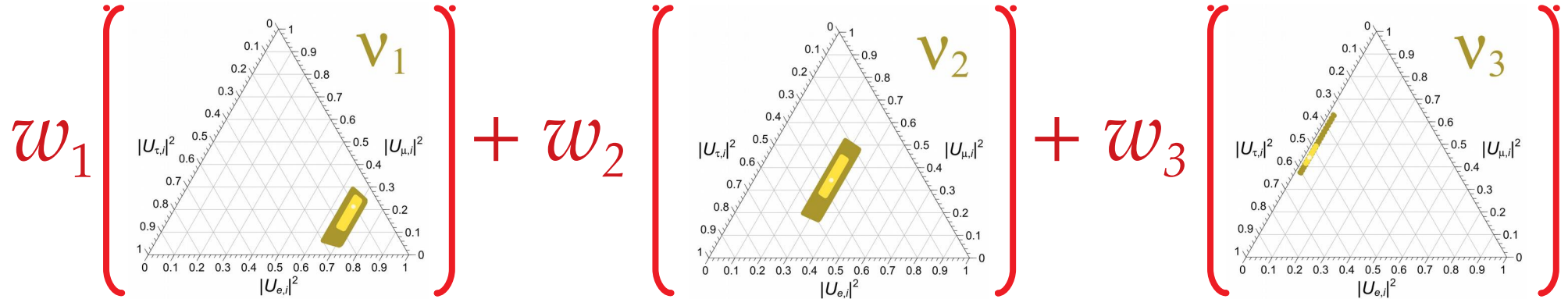
- ▶ Neutrinos propagate as an incoherent mix of ν_1, ν_2, ν_3
- ▶ Each one has a different flavor content:



- ▶ 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)

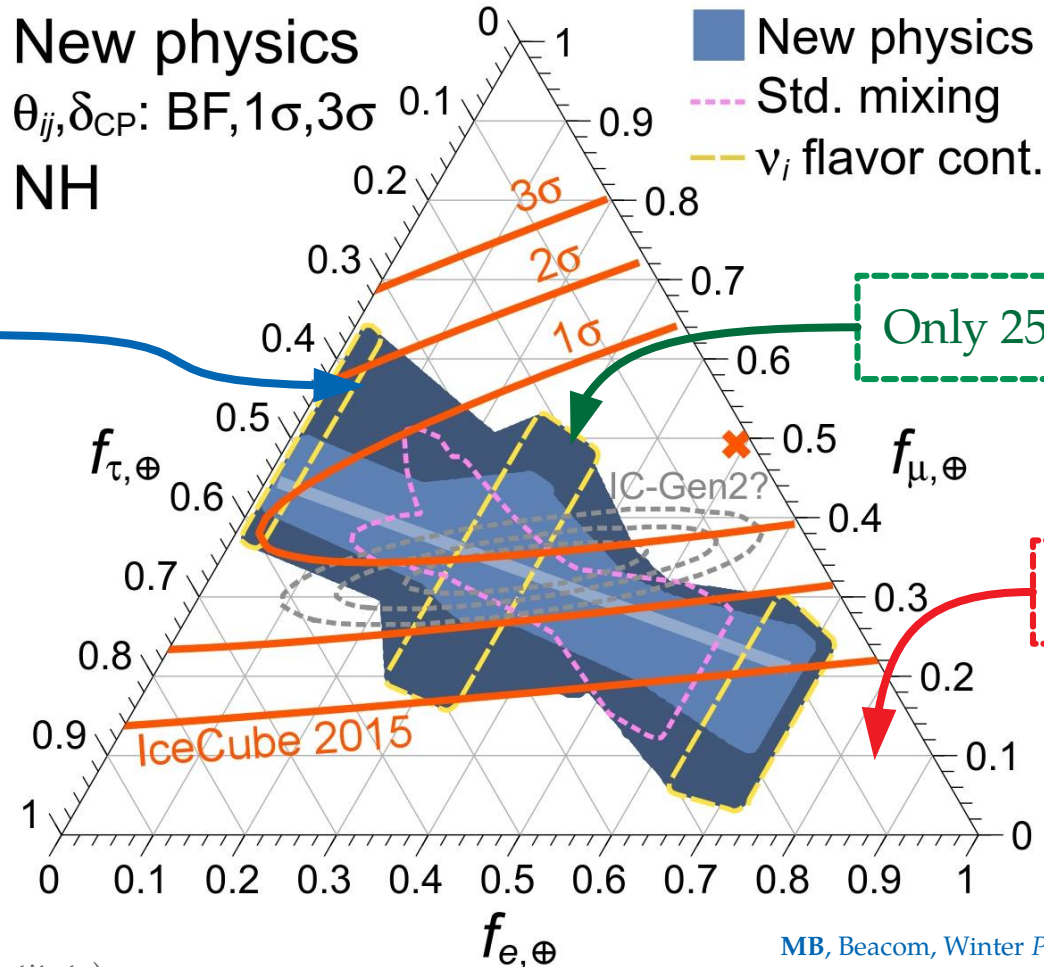
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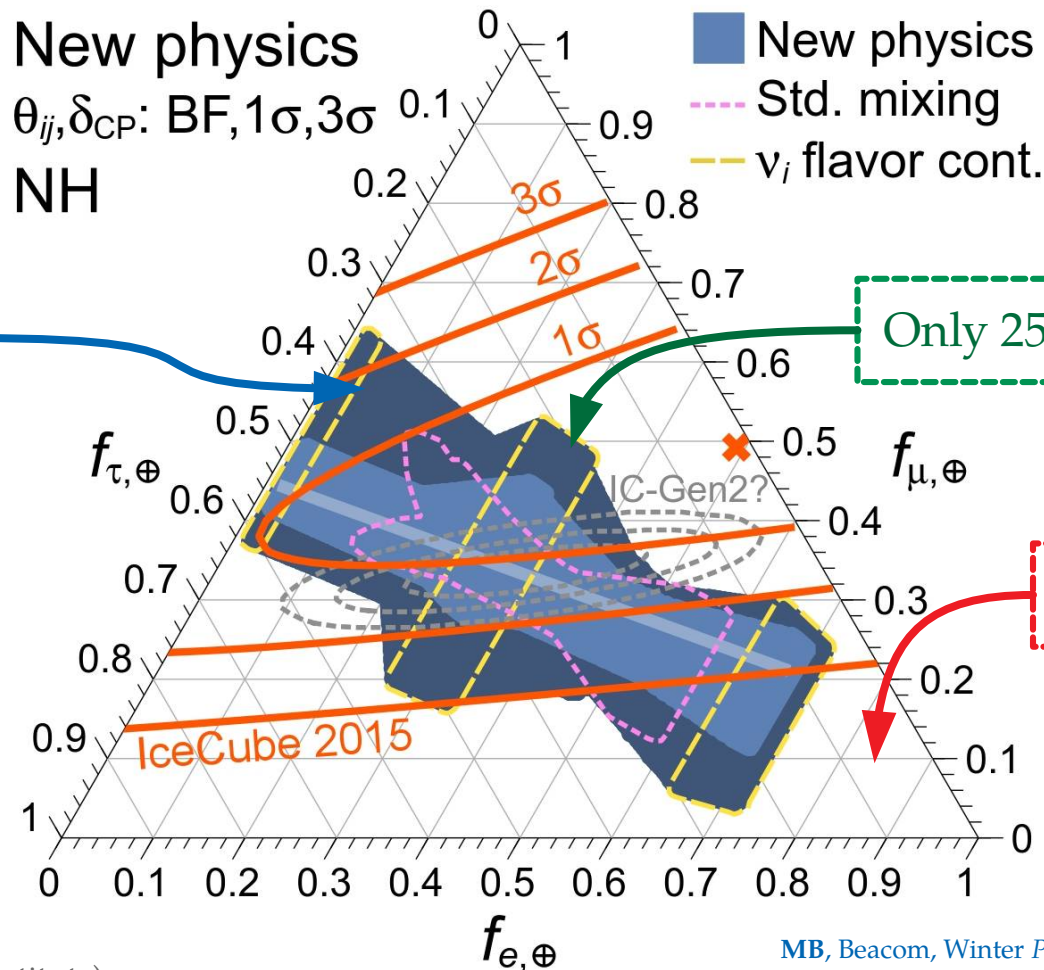


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Flavor ratios accessible with decay-like physics

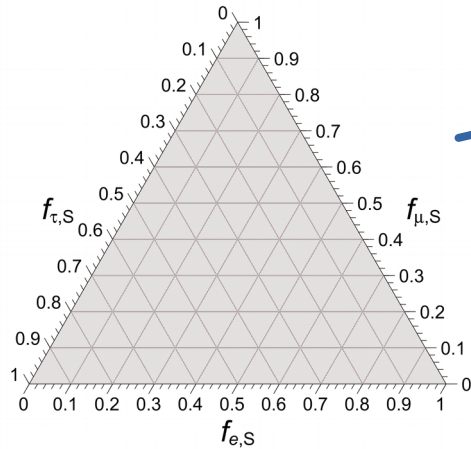


Flavor ratios accessible with decay-like physics



Measuring the neutrino lifetime

Sources

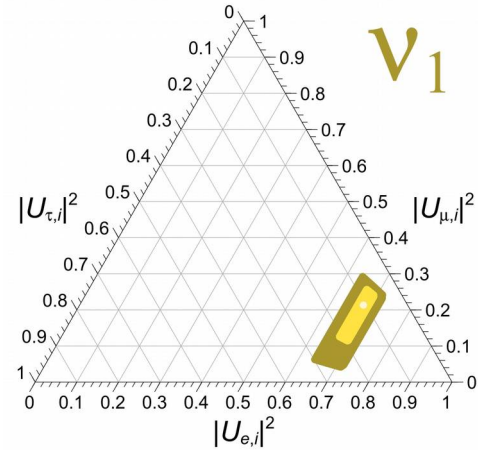


$\nu_{2'}, \nu_3 \rightarrow \nu_1$
 ν_1 lightest and stable

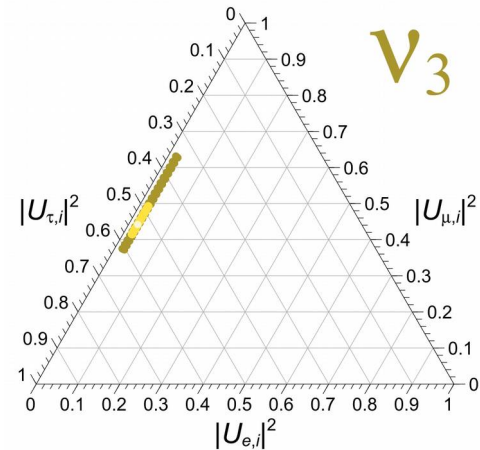
If all unstable
 neutrinos decay

$\nu_{1'}, \nu_2 \rightarrow \nu_3$
 ν_3 lightest and stable

Earth

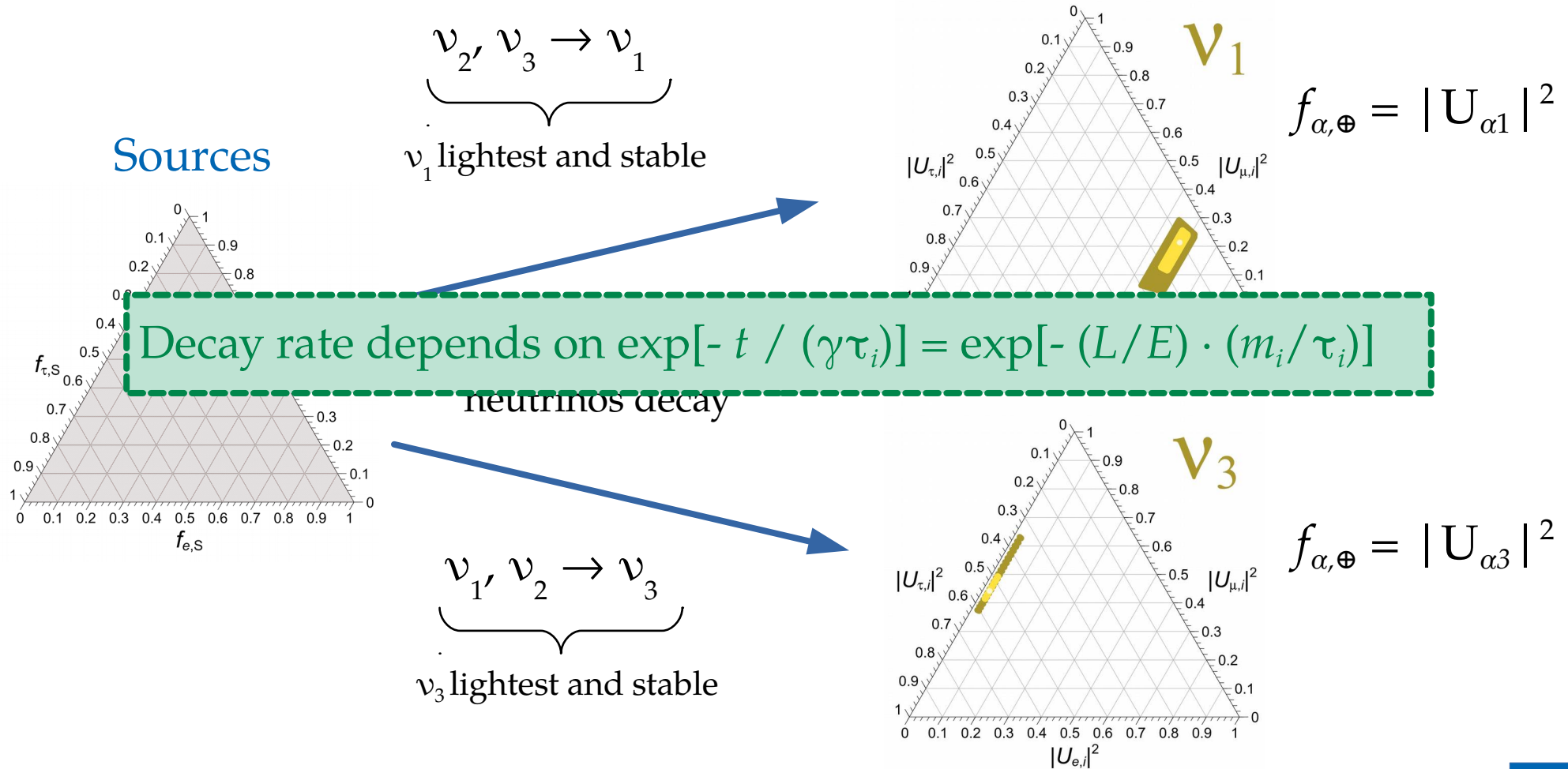


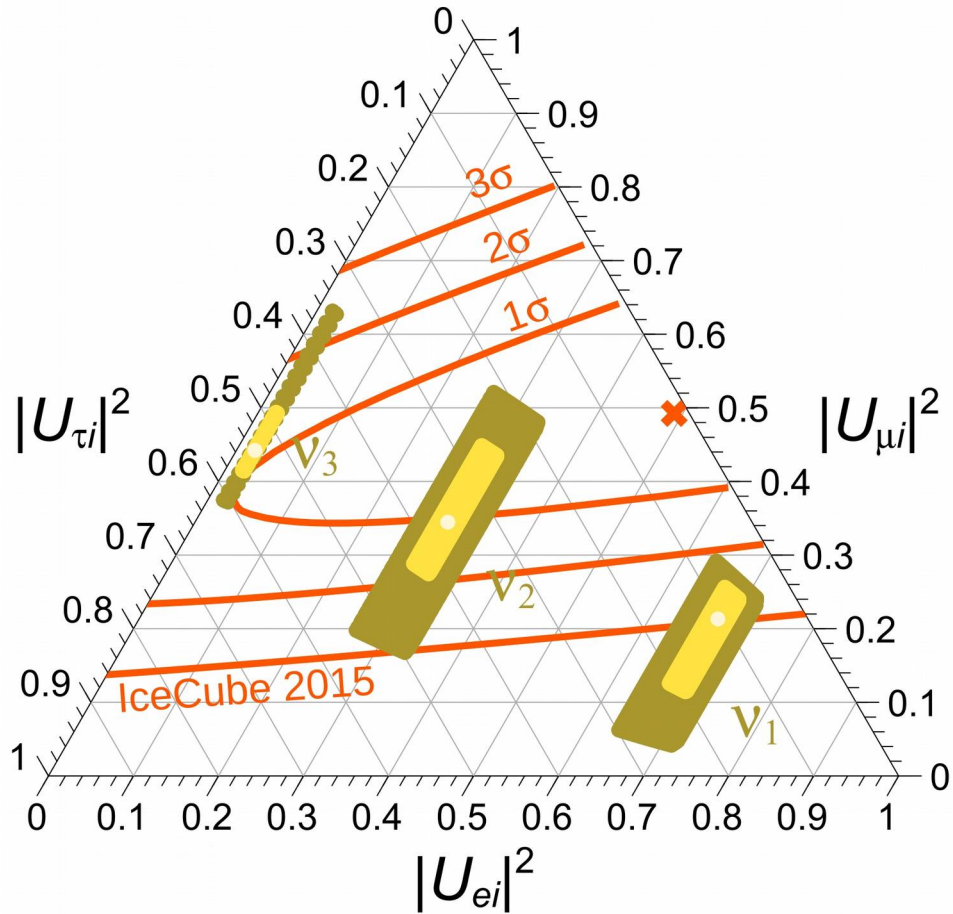
$$f_{\alpha,\oplus} = |U_{\alpha 1}|^2$$



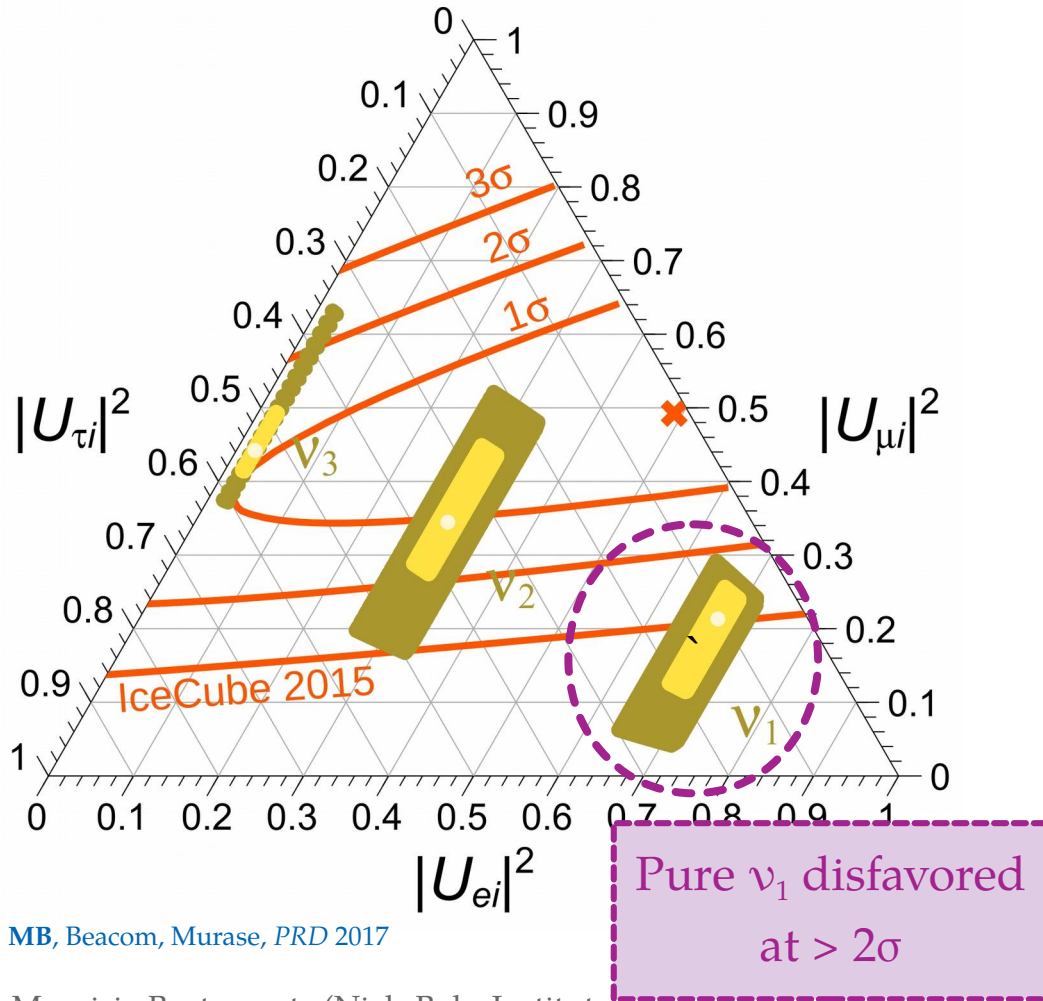
$$f_{\alpha,\oplus} = |U_{\alpha 3}|^2$$

Measuring the neutrino lifetime

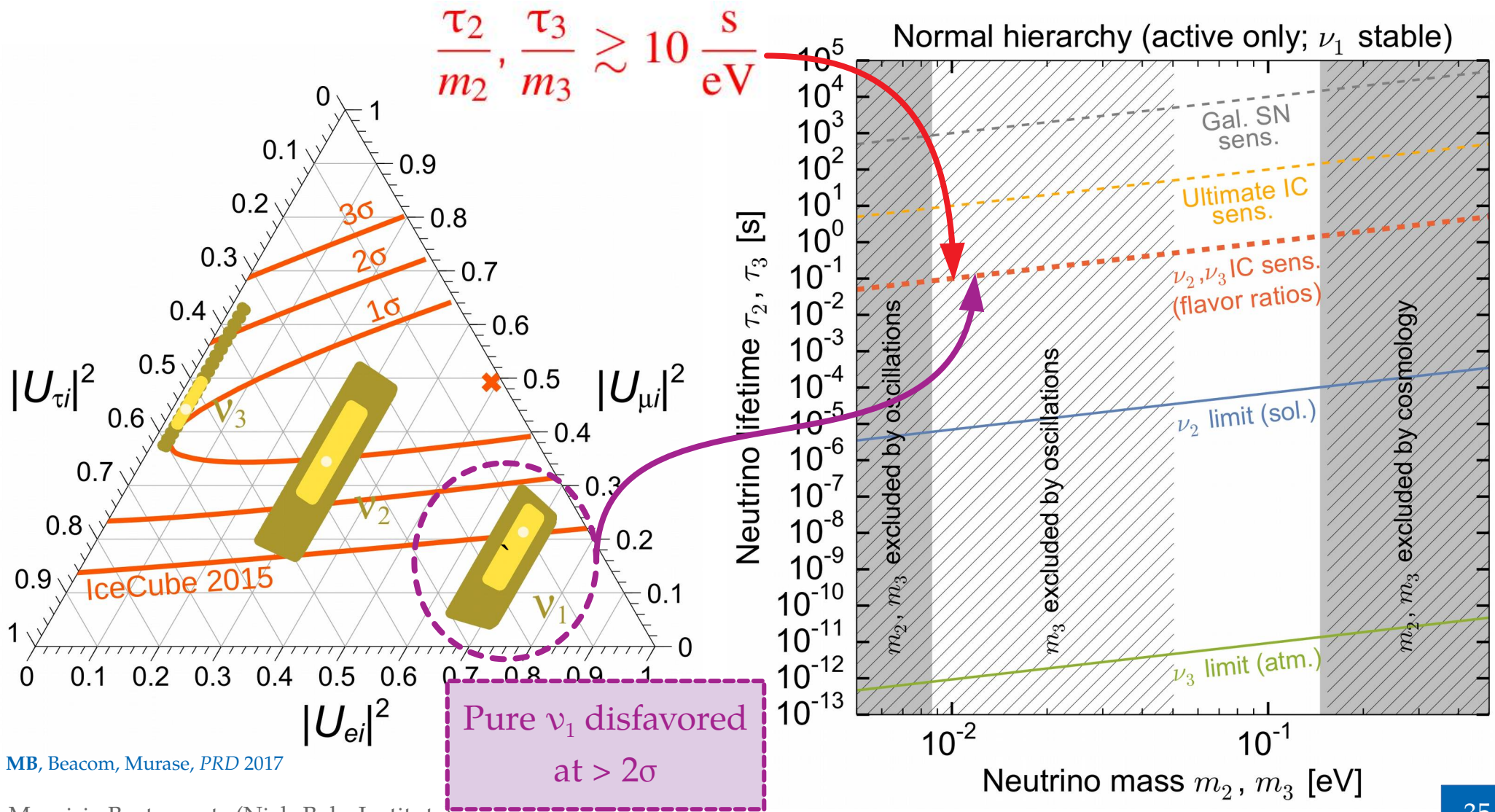




MB, Beacom, Murase, *PRD* 2017



MB, Beacom, Murase, PRD 2017



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]
- ▶ Active-sterile mixing
[Aeikens *et al.*, *JCAP* 2015; V. Brdar, *JCAP* 2017]
- ▶ Flavor-violating physics
 - ▶ New $\nu\nu$ interactions
[Ng & Beacom, *PRD* 2014; Cherry, Friedland, Shoemaker, 1411.1071; Blum, Hook, Murase, 1408.3799]
 - ▶ New neutrino-electron interactions
[**MB** & Agarwalla, 1808.02042]



Toho Company Ltd.

New physics – High-energy effects

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

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

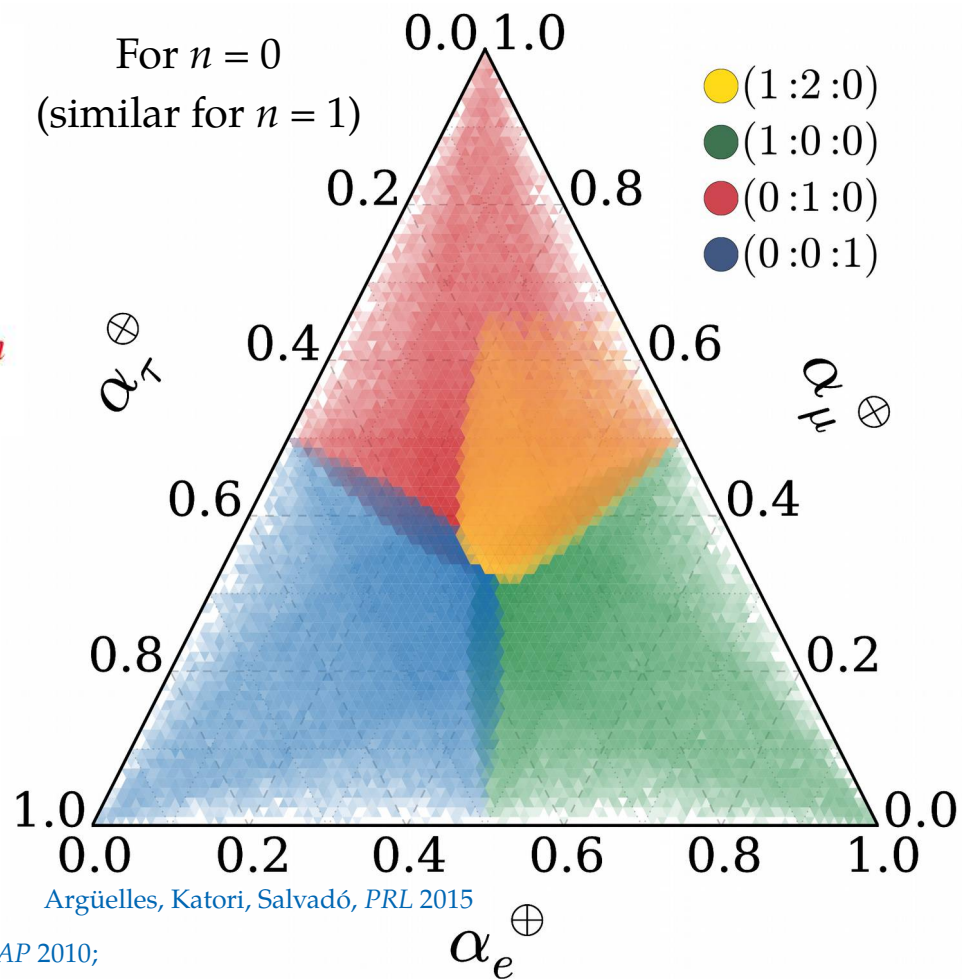
$$H_{\text{NP}} = \sum_n \left(\frac{E}{\Lambda_n} \right)^n U_n^\dagger \text{diag} (O_{n,1}, O_{n,2}, O_{n,3}) U_n$$

This can populate *all* of the triangle –

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

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

- Sample the unknown new mixing angles



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

Bazo, **MB**, Gago, Miranda *IJMPA* 2009; + many others

Mauricio Bustamante (Niels Bohr Institute)

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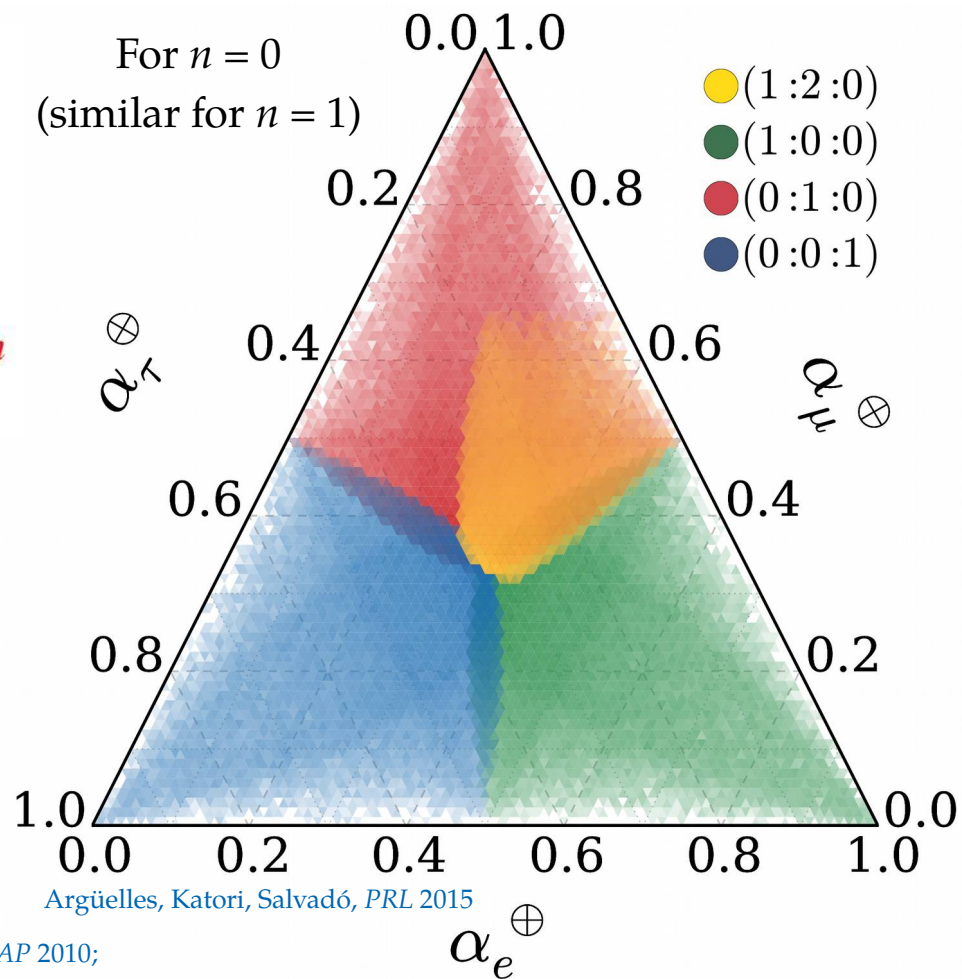
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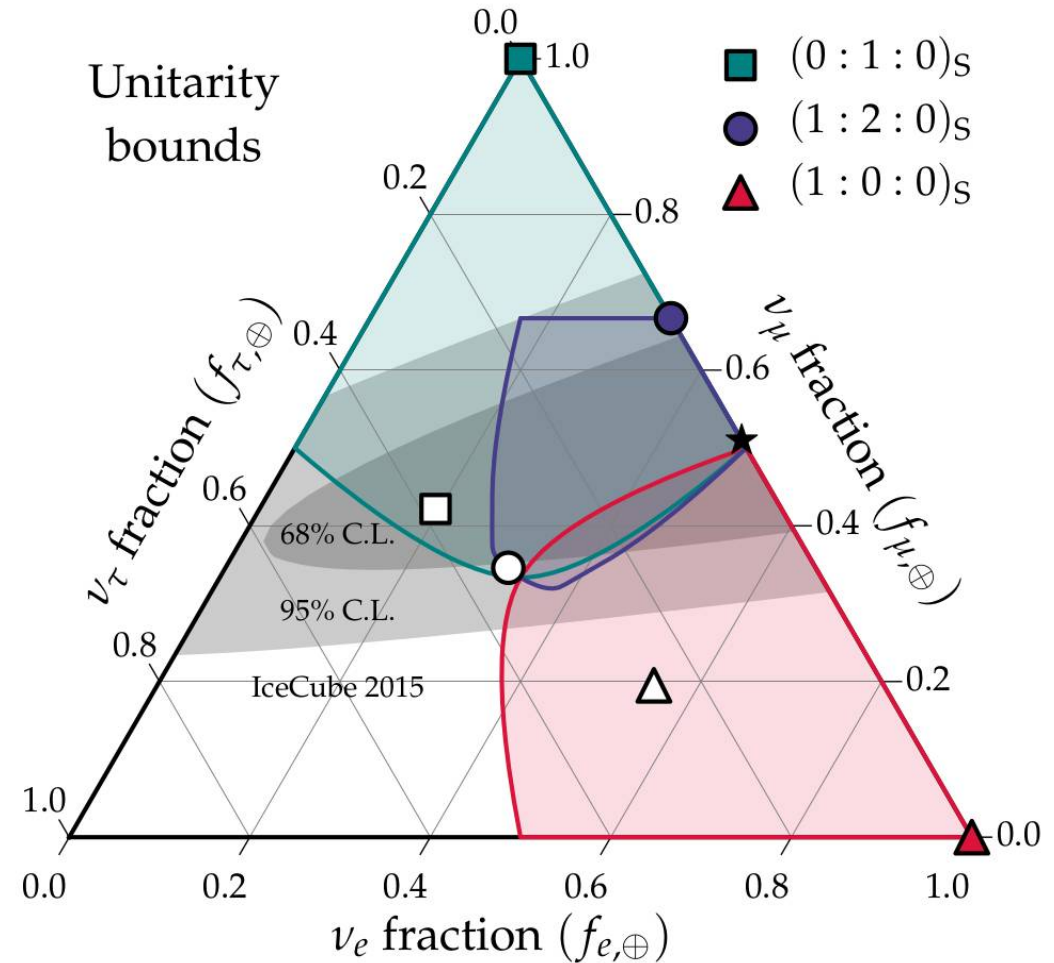
Mauricio Bustamante (Niels Bohr Institute)

Using unitarity to constrain new physics

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

- ▶ New mixing angles unconstrained
- ▶ Use unitarity to bound all possible flavor ratios at Earth
- ▶ Can be used as prior in new-physics searches in IceCube

Ahlers, MB, Mu, 1810.00893



Ultra-long-range flavorful interactions

- ▶ Simple extension of the SM: Promote the global lepton-number symmetries L_e-L_μ, L_e-L_τ to local symmetries
- ▶ They introduce new interaction between electrons and ν_e and ν_μ or ν_τ mediated by a new neutral vector boson (Z'):
 - ▶ Affects oscillations
 - ▶ If the Z' is *very* light, *many* electrons can contribute

X.-G. He, G.C. Joshi, H. Lew, R. R. Volkas, *PRD* 1991 / R. Foot, X.-G. He, H. Lew, R. R. Volkas, *PRD* 1994
A. Joshipura, S. Mohanty, *PLB* 2004 / J. Grifols & E. Massó, *PLB* 2004 / A. Bandyopadhyay, A. Dighe, A. Joshipura, *PRD* 2007
M.C. González-García, P.C. de Holanda, E. Massó, R. Zukanovich Funchal, *JCAP* 2007 / A. Samanta, *JCAP* 2011
S.-S. Chatterjee, A. Dasgupta, S. Agarwalla, *JHEP* 2015

The new potential sourced by an electron

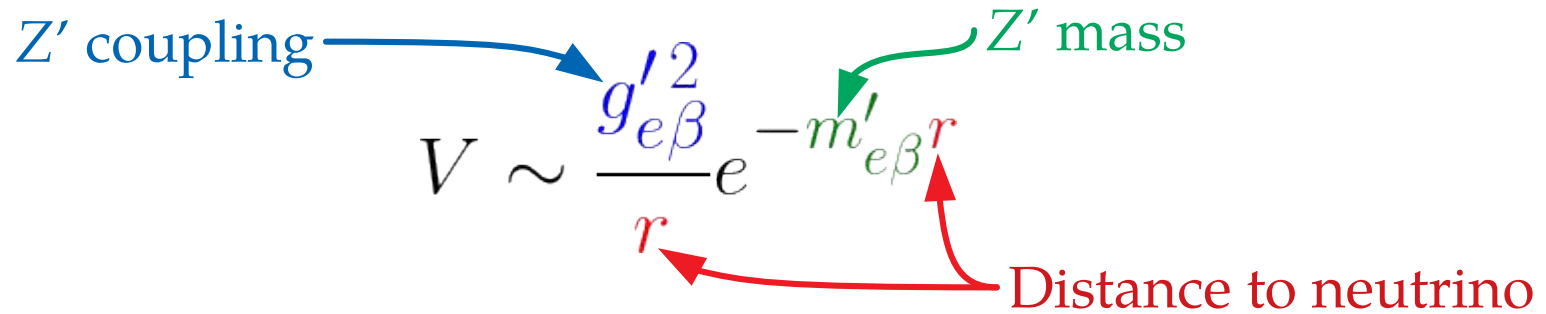
Under the L_e - L_μ or L_e - L_τ symmetry, an electron sources a Yukawa potential —

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

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

The new potential sourced by an electron

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



The diagram shows the Yukawa potential equation $V \sim \frac{g'^2_{e\beta}}{r} e^{-m'_{e\beta} r}$ with three color-coded annotations: a blue arrow points from the text "Z' coupling" to the coupling term $g'^2_{e\beta}$; a green arrow points from the text "Z' mass" to the mass term $m'_{e\beta}$; and a red arrow points from the text "Distance to neutrino" to the distance variable r .

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

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

Electron-neutrino interactions can kill oscillations

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


Standard oscillations:

Neutrinos change flavor
because this is non-diagonal

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$$P_{\nu_\alpha \rightarrow \nu_\beta}(\theta_{ij}, \delta_{\text{CP}})$$

Electron-neutrino interactions can kill oscillations

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

New neutrino-electron interaction:

This is diagonal

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

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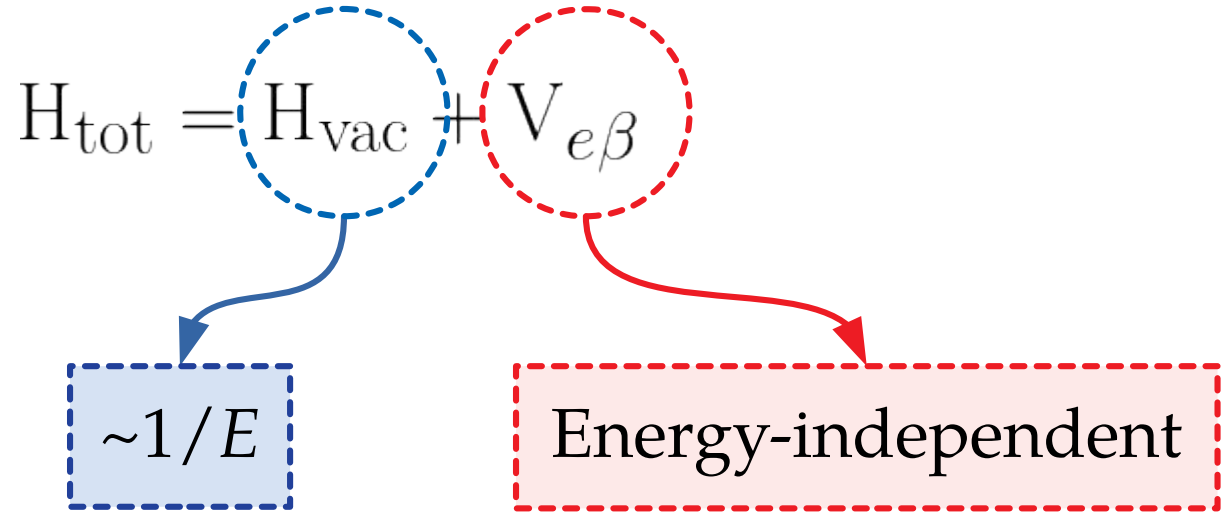
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If $V_{e\beta}$ dominates ($g' \gg 1, m' \ll 1$), oscillations turn off

Electron-neutrino interactions can kill oscillations

$$H_{\text{tot}} = H_{\text{vac}} + V_{e\beta}$$

Electron-neutrino interactions can kill oscillations



Electron-neutrino interactions can kill oscillations

$$H_{\text{tot}} = H_{\text{vac}} + V_{e\beta}$$

The diagram illustrates the components of the total Hamiltonian H_{tot} . It is split into two terms: H_{vac} (vacuum Hamiltonian) and $V_{e\beta}$ (interaction potential). H_{vac} is enclosed in a blue dashed circle, and $V_{e\beta}$ is enclosed in a red dashed circle. A blue arrow points from the H_{vac} circle to a blue dashed box containing the expression $\sim 1/E$, indicating its energy dependence. A red arrow points from the $V_{e\beta}$ circle to a red dashed box containing the text "Energy-independent", indicating its lack of energy dependence.

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

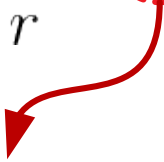
Electrons in the local and distant Universe

Potential:

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

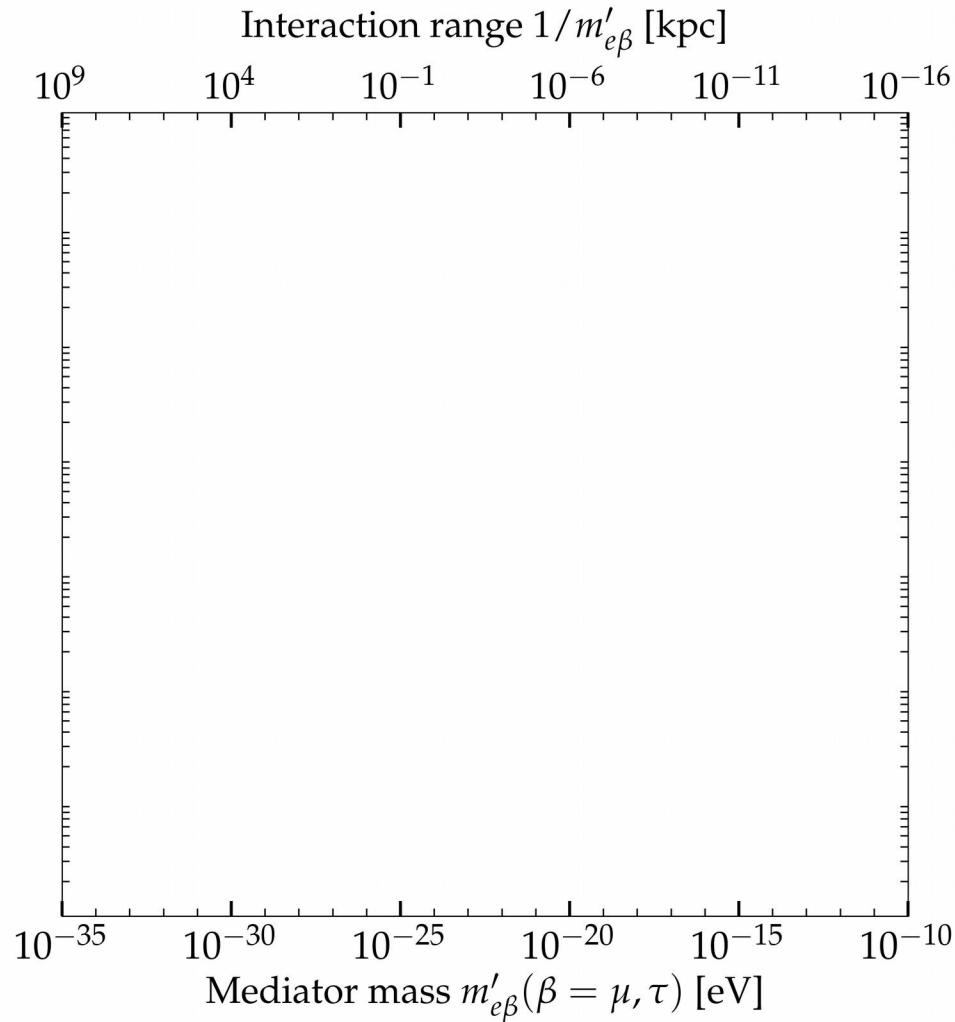
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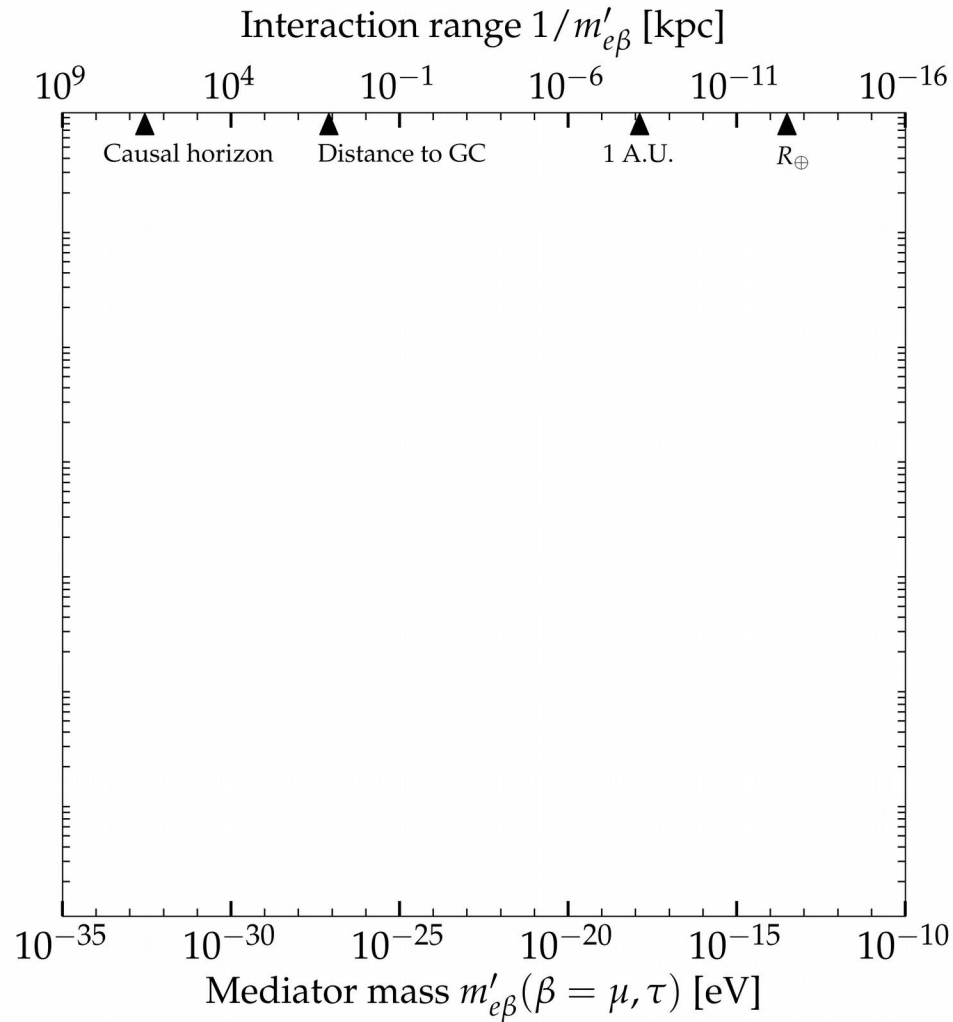


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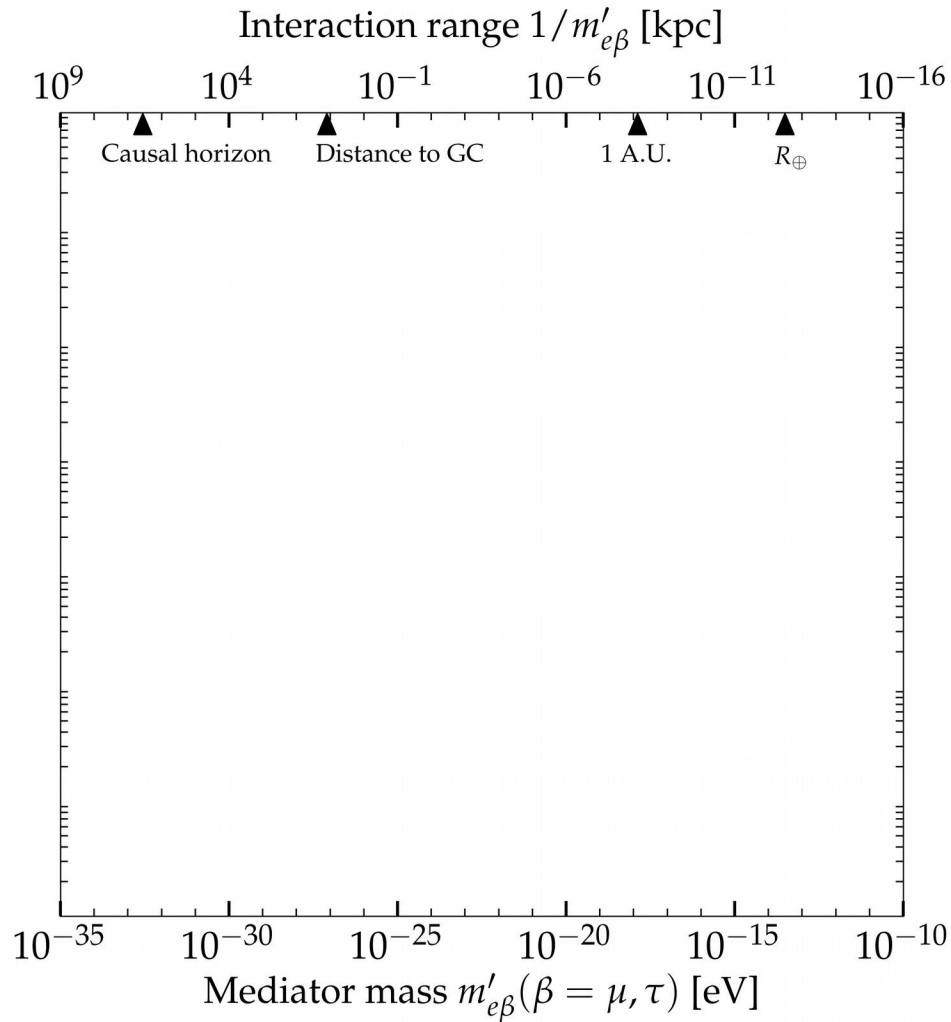


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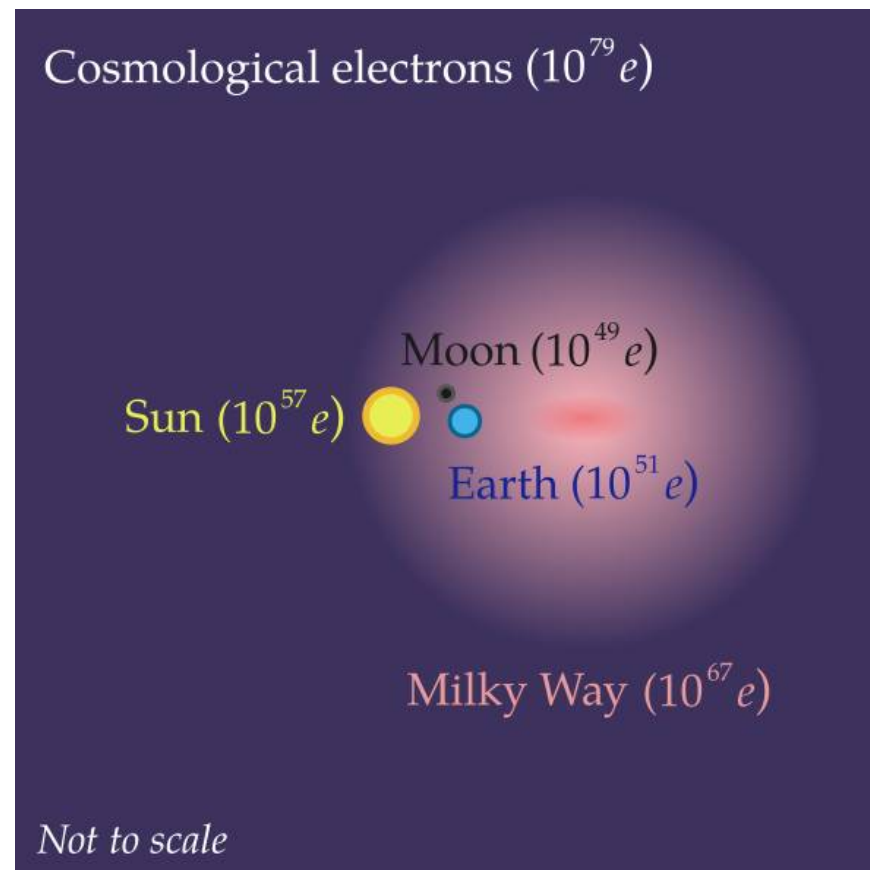
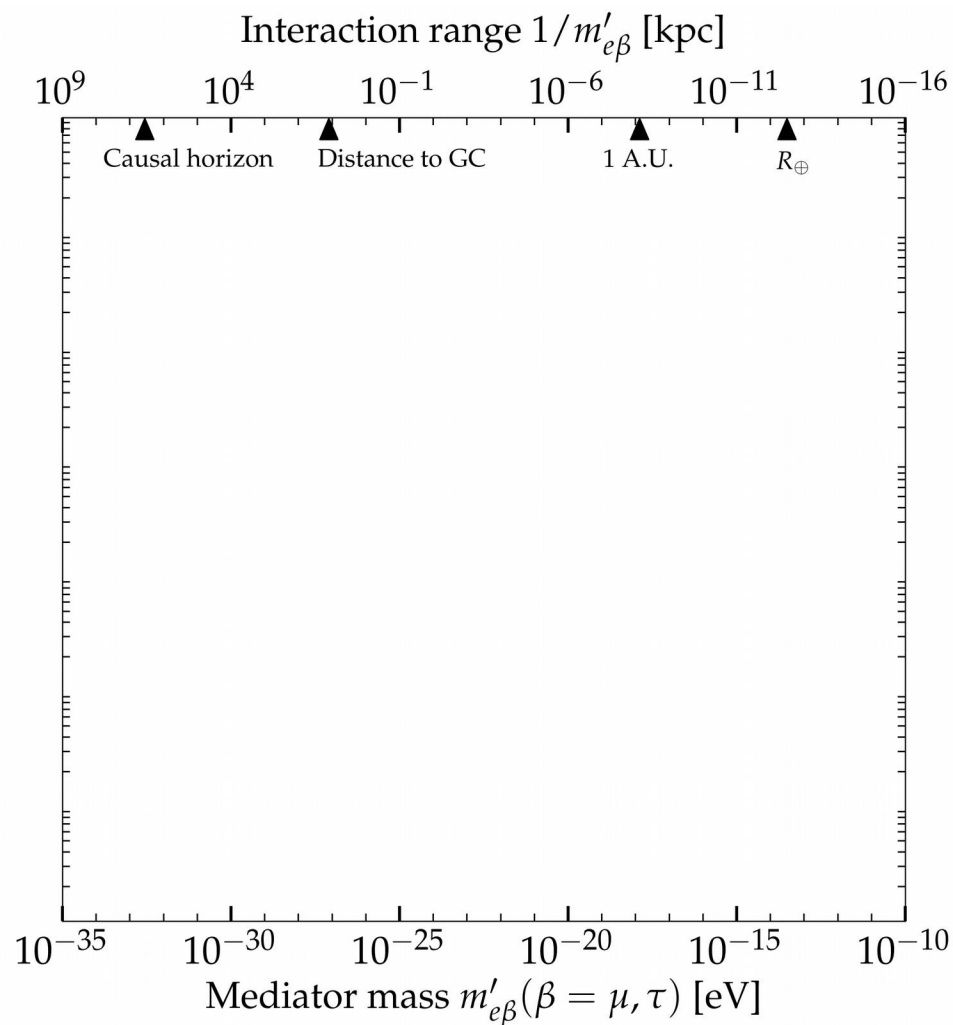
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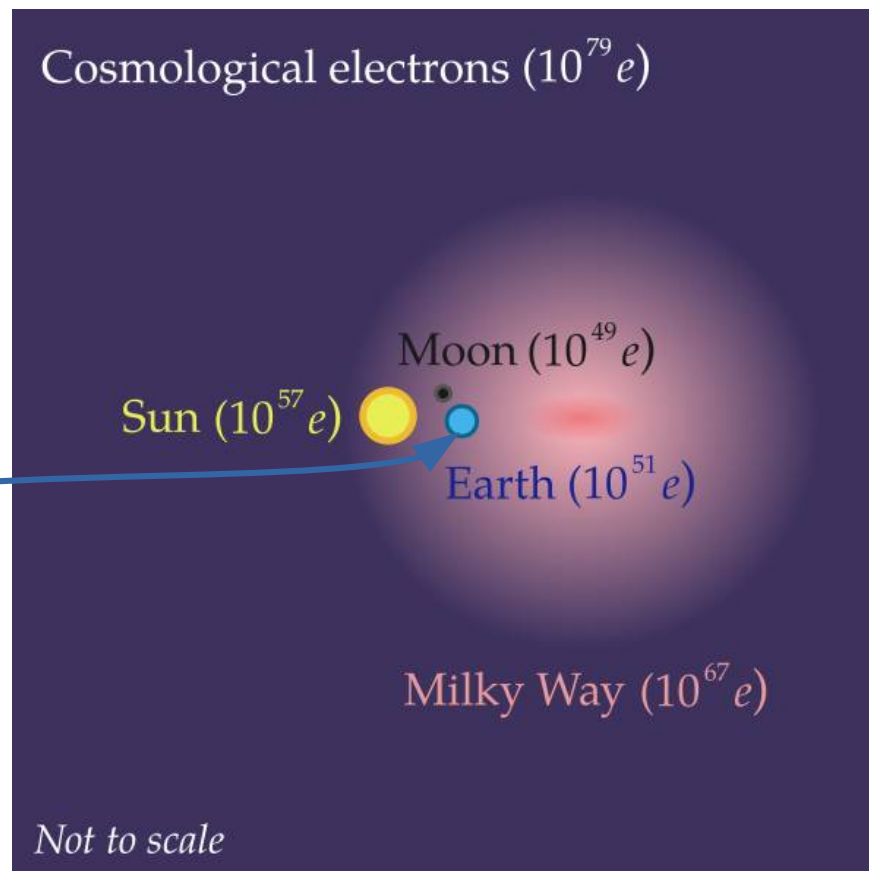
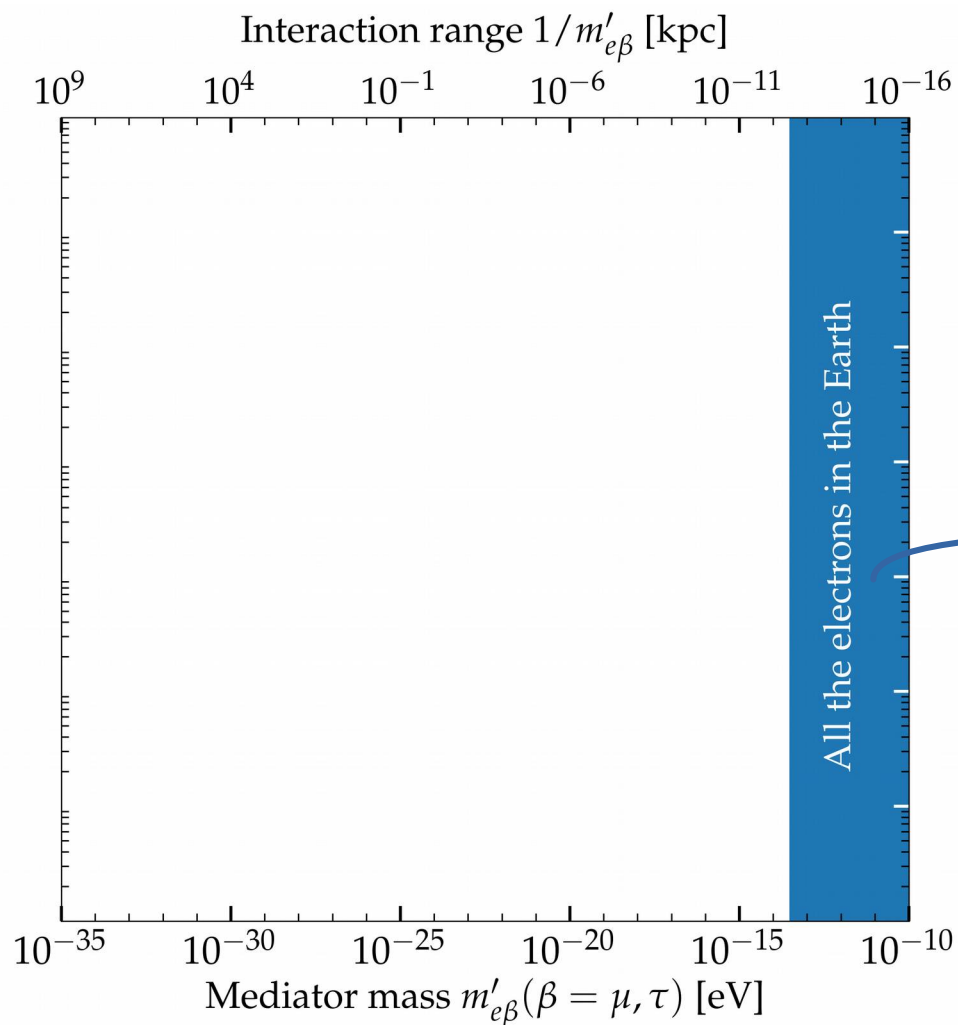
Interaction range: $\frac{1}{m'_{e\beta}}$

Light mediators
 $\Rightarrow$ Long interaction ranges

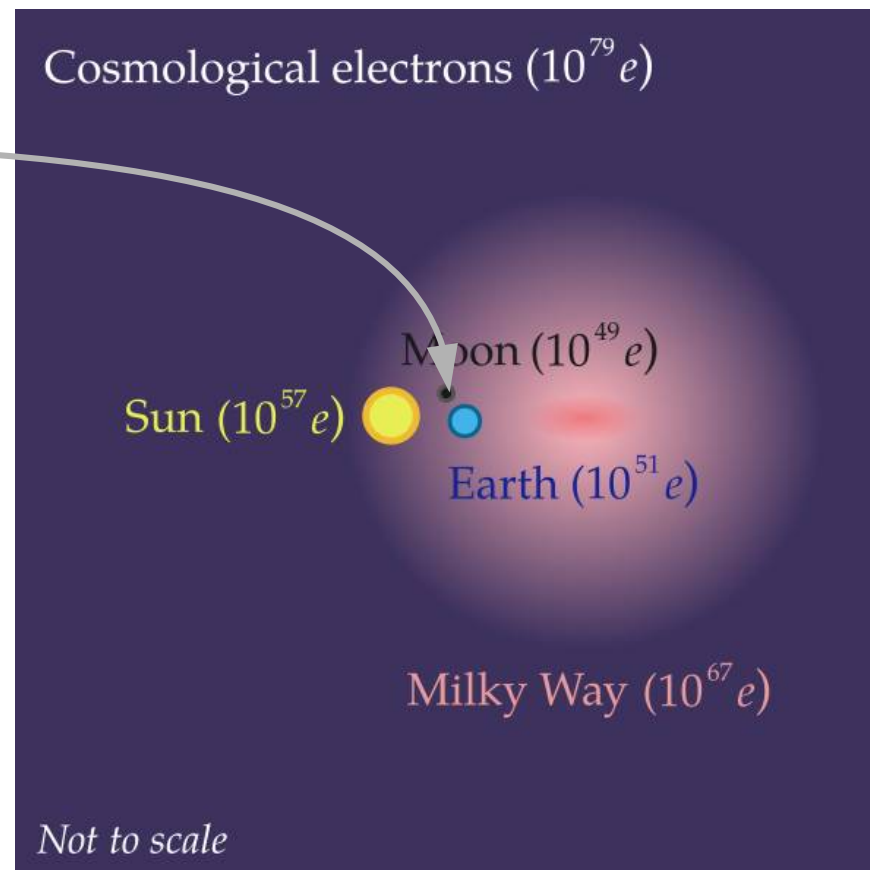
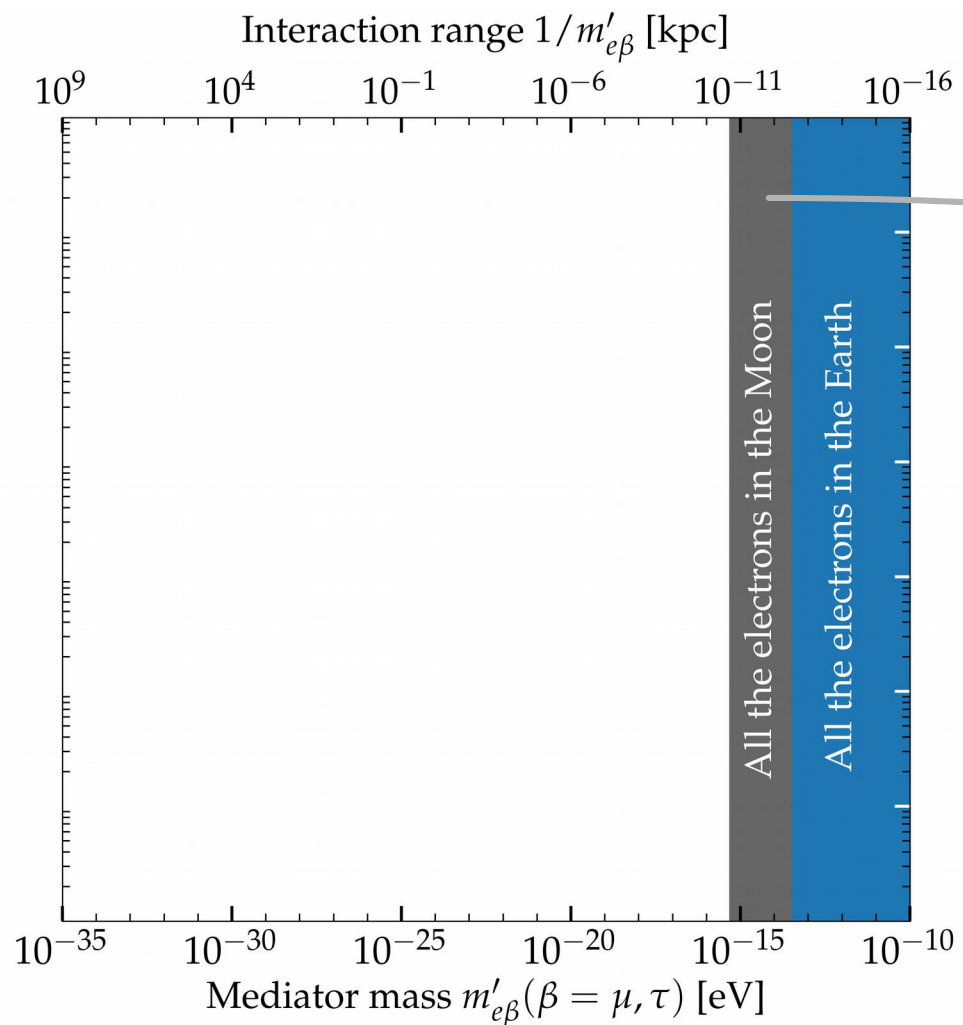
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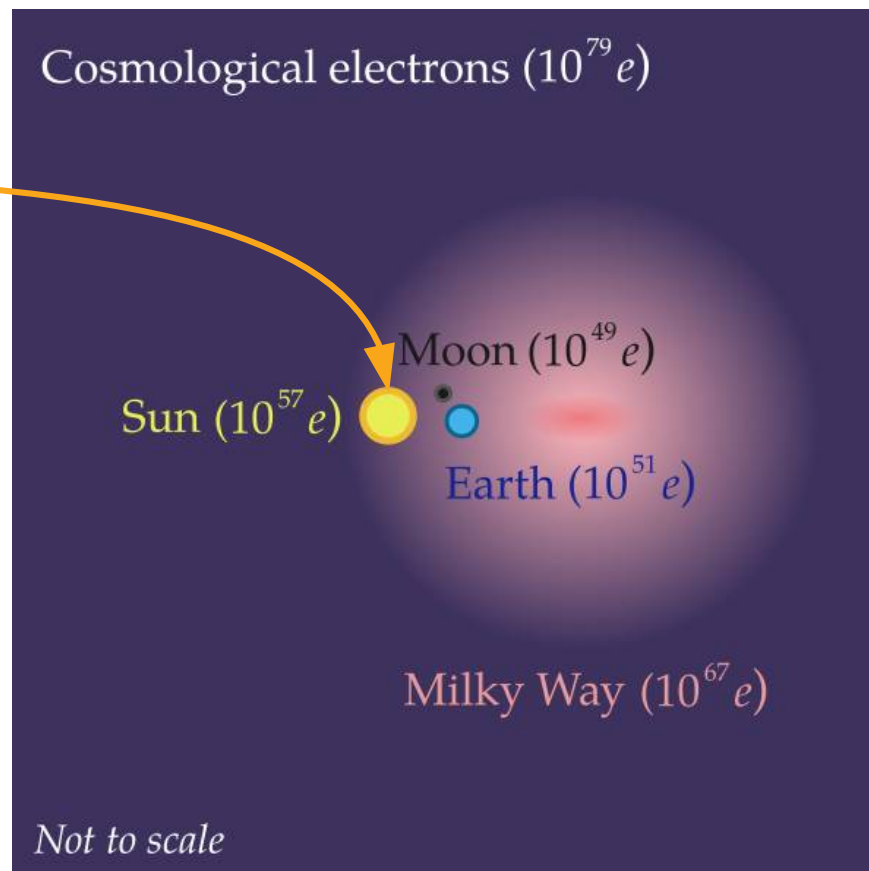
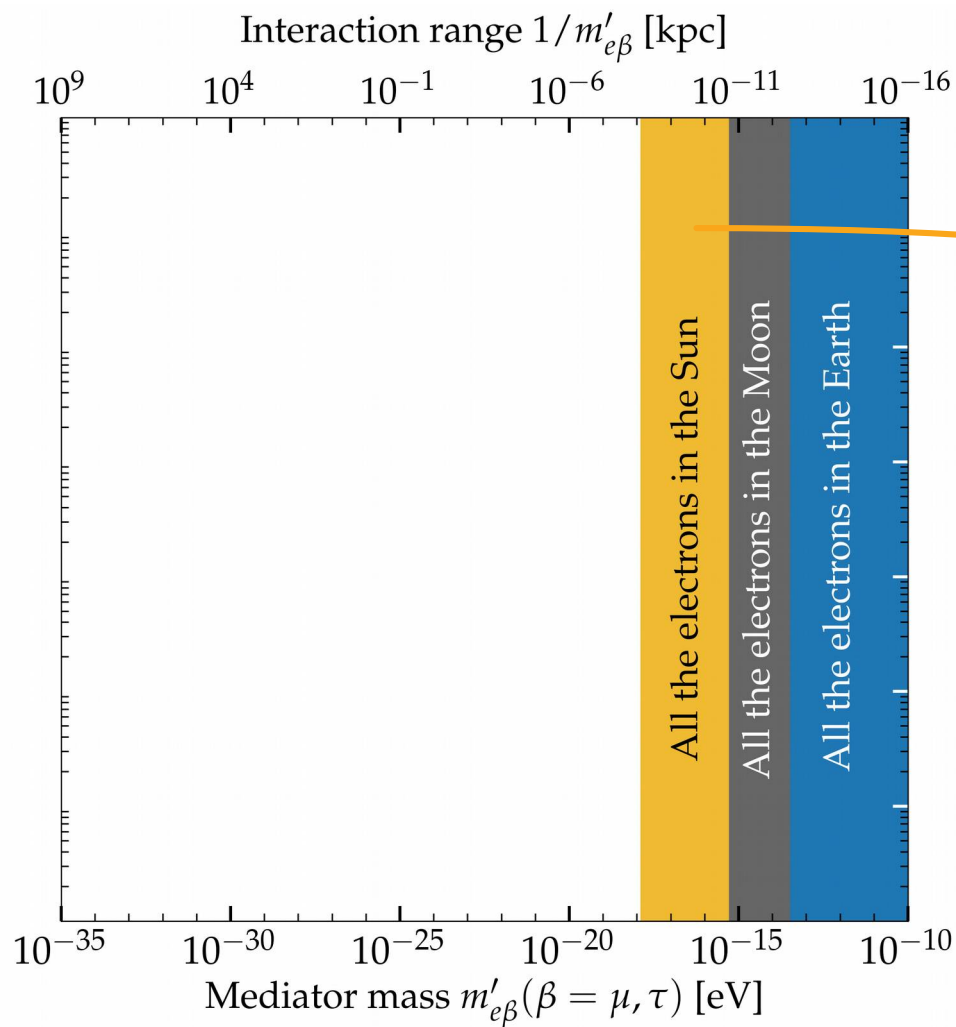
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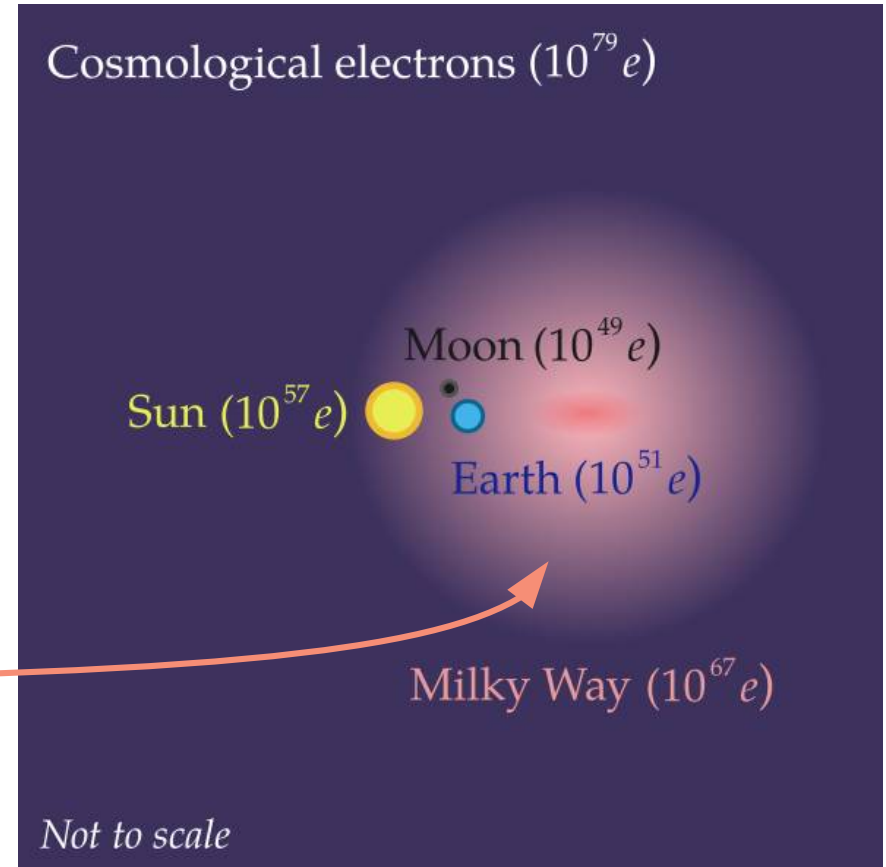
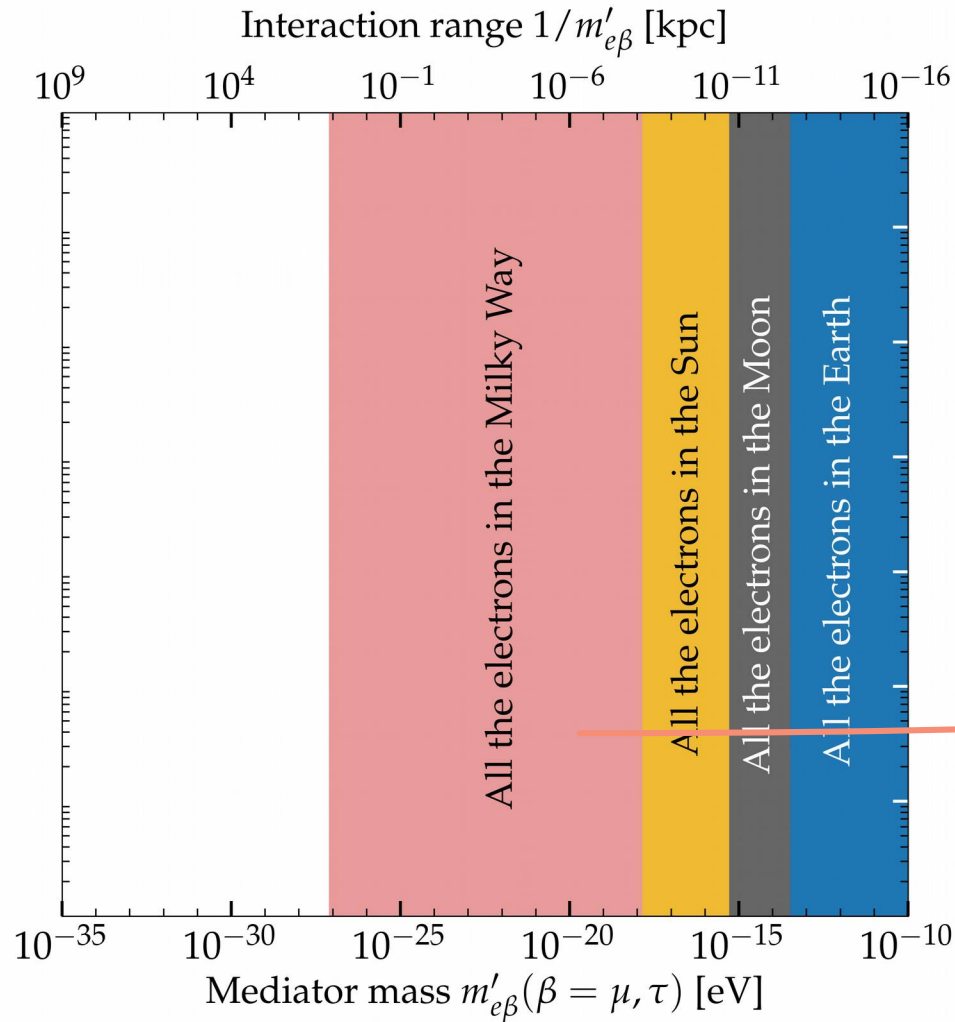
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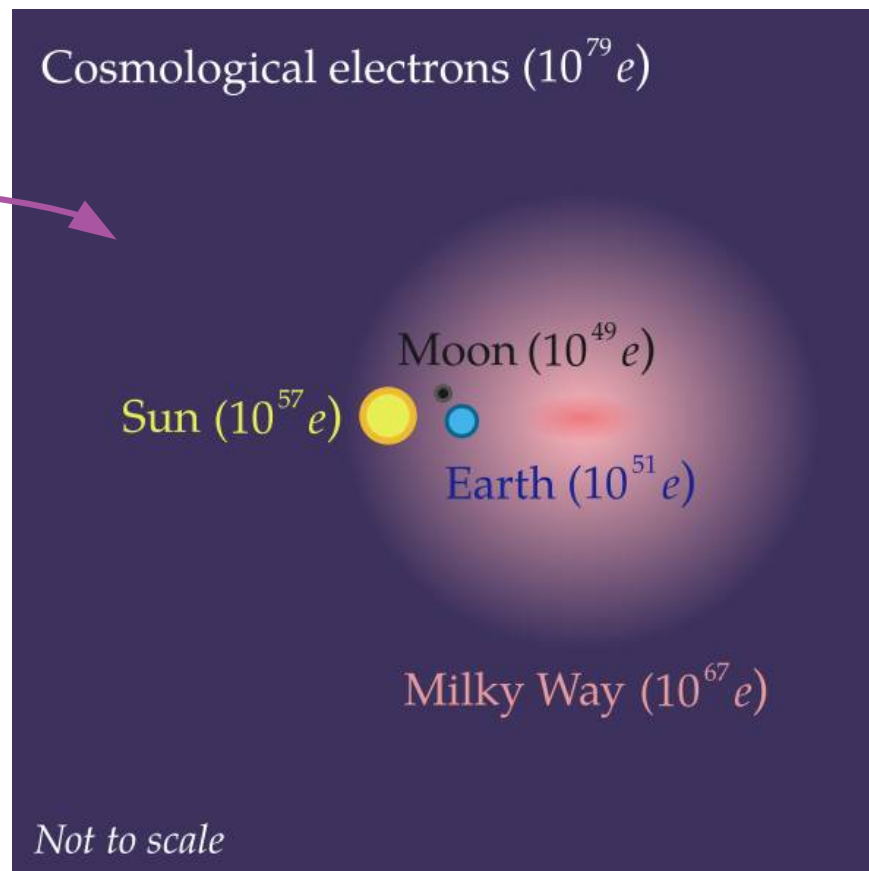
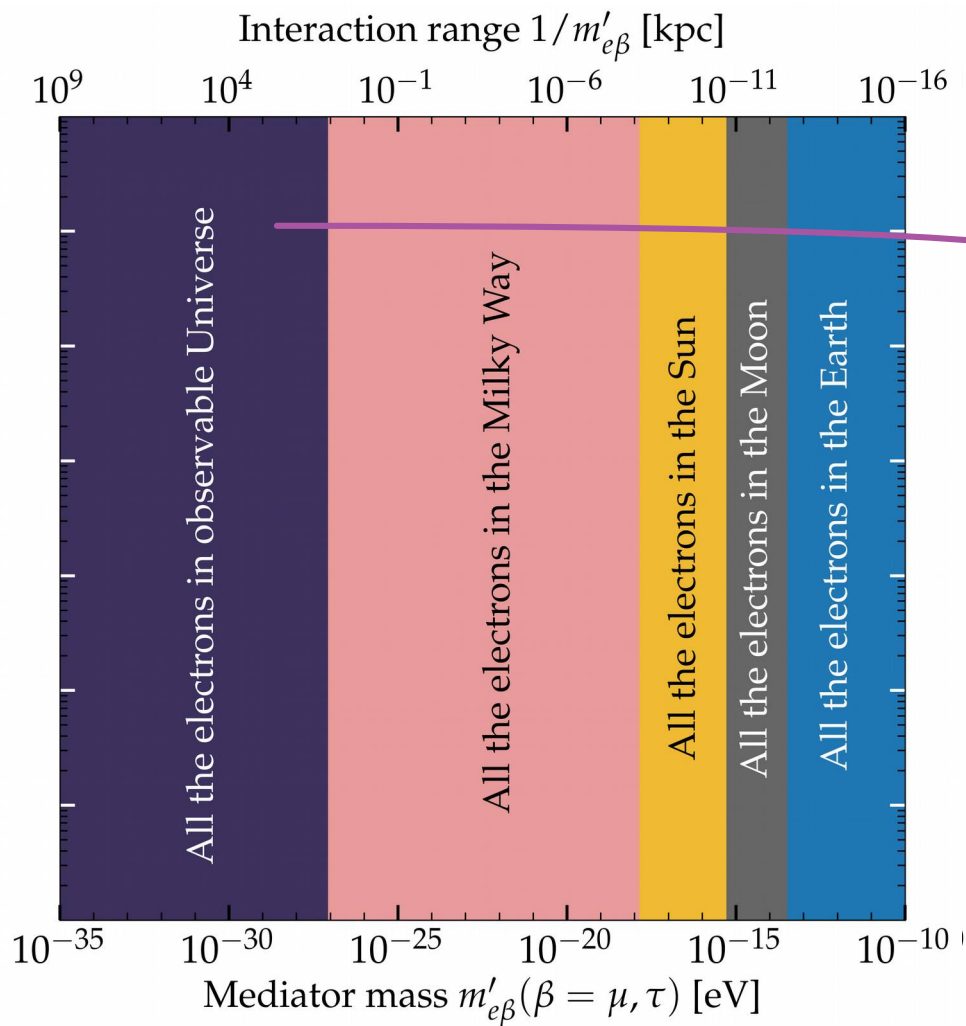
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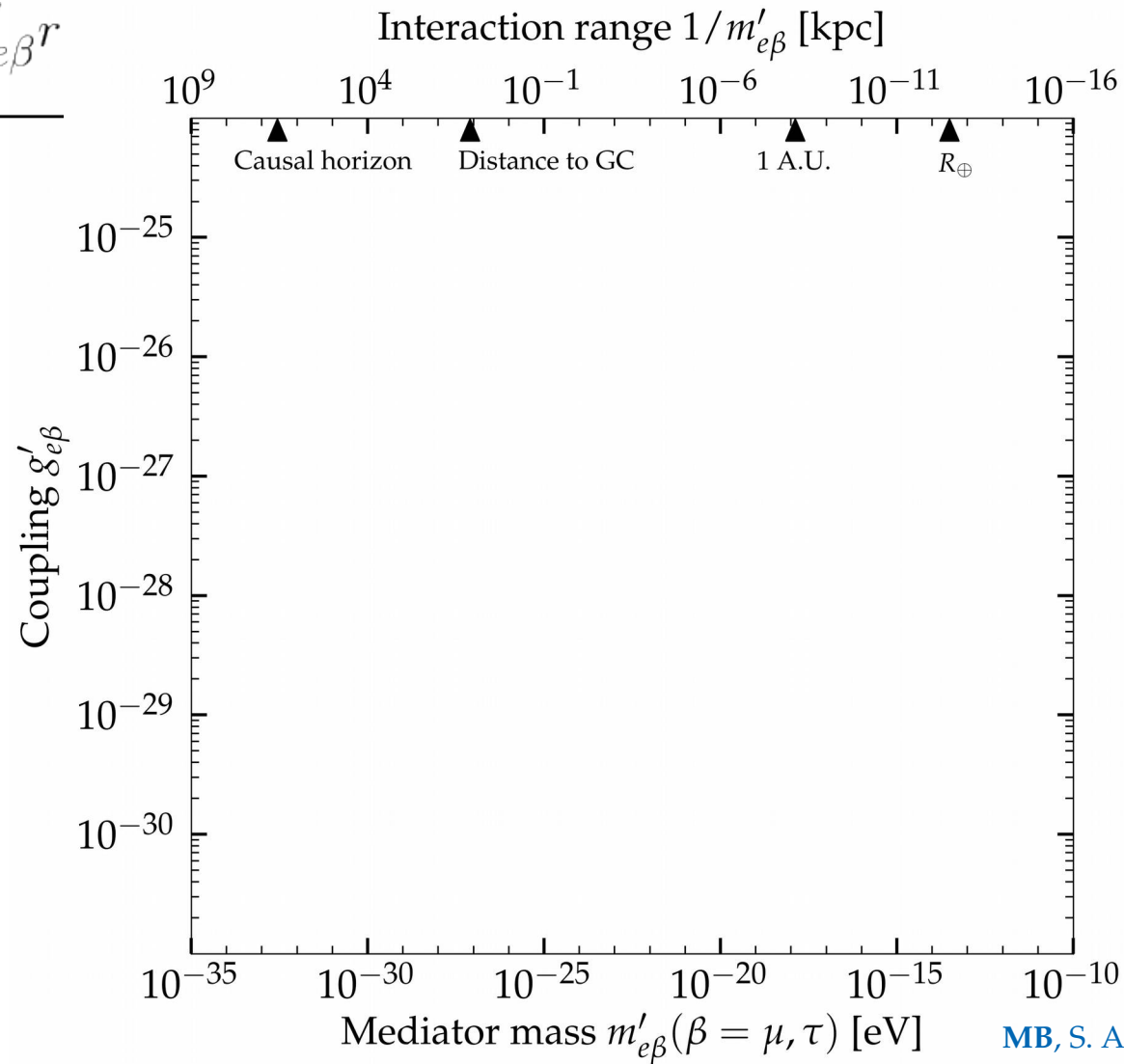
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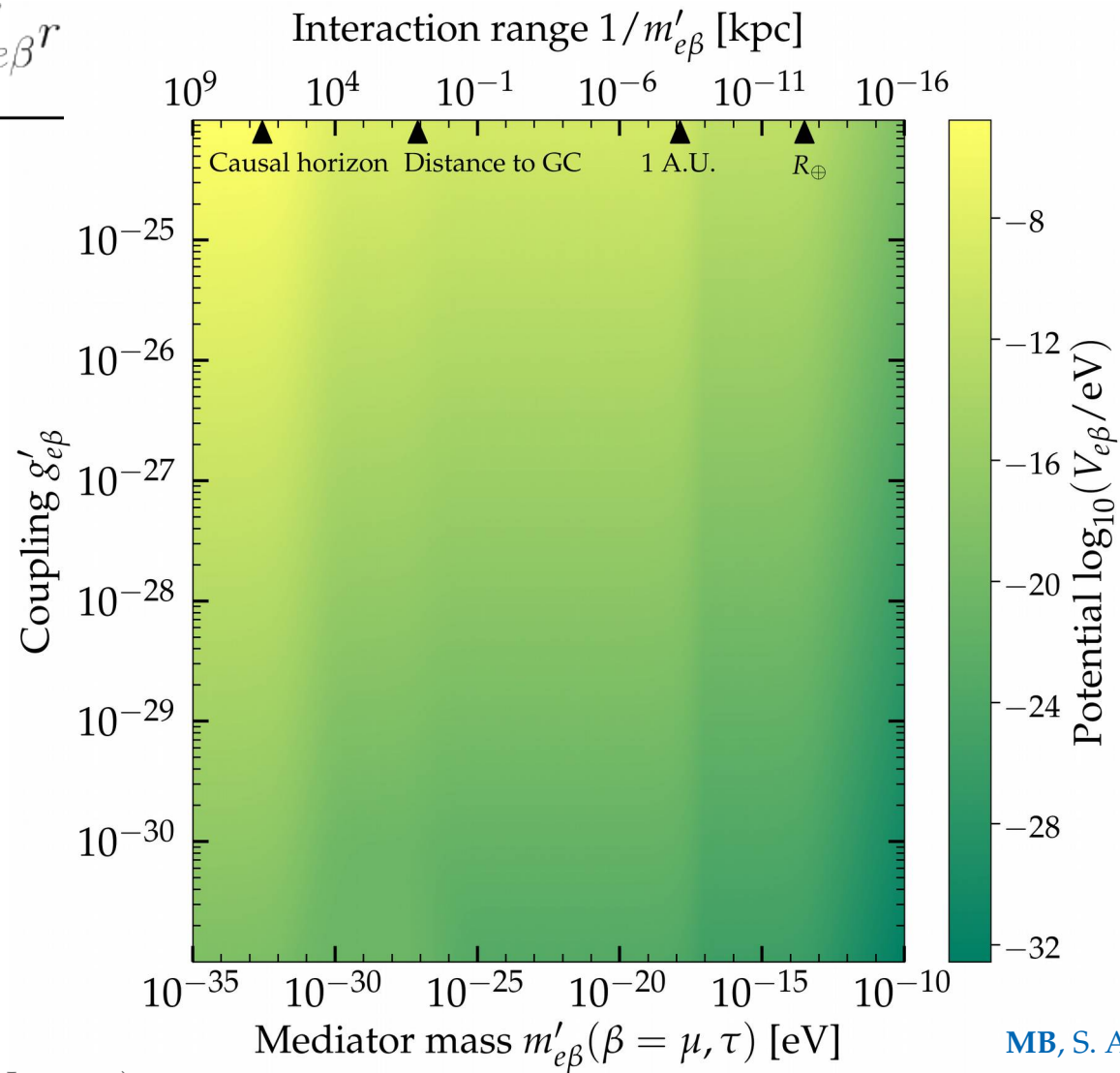


$$V_{e\beta} = \frac{g_{e\beta}'^2}{4\pi} \frac{e^{-m'_{e\beta} r}}{r}$$



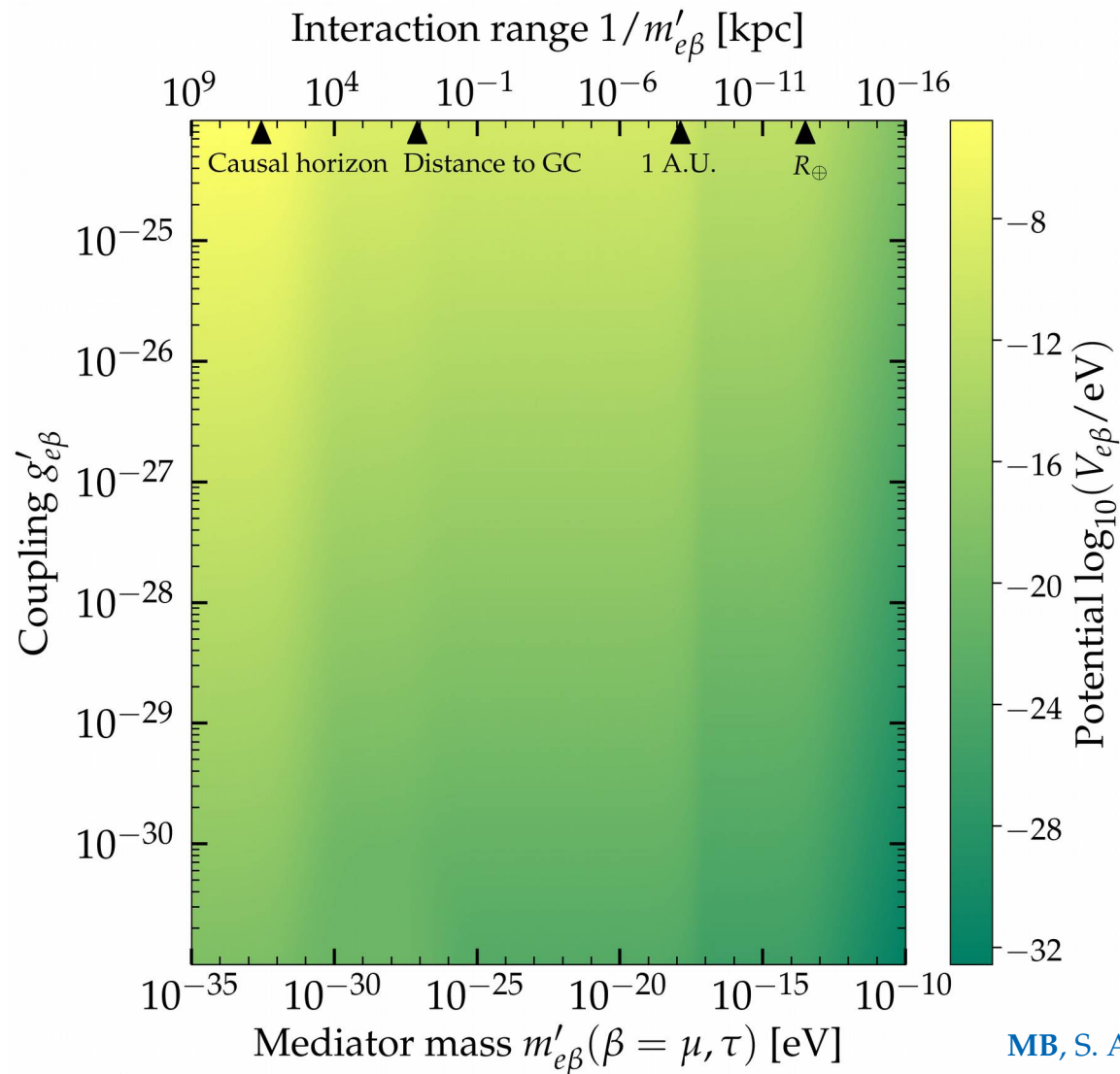
MB, S. Agarwalla, 1808.02042

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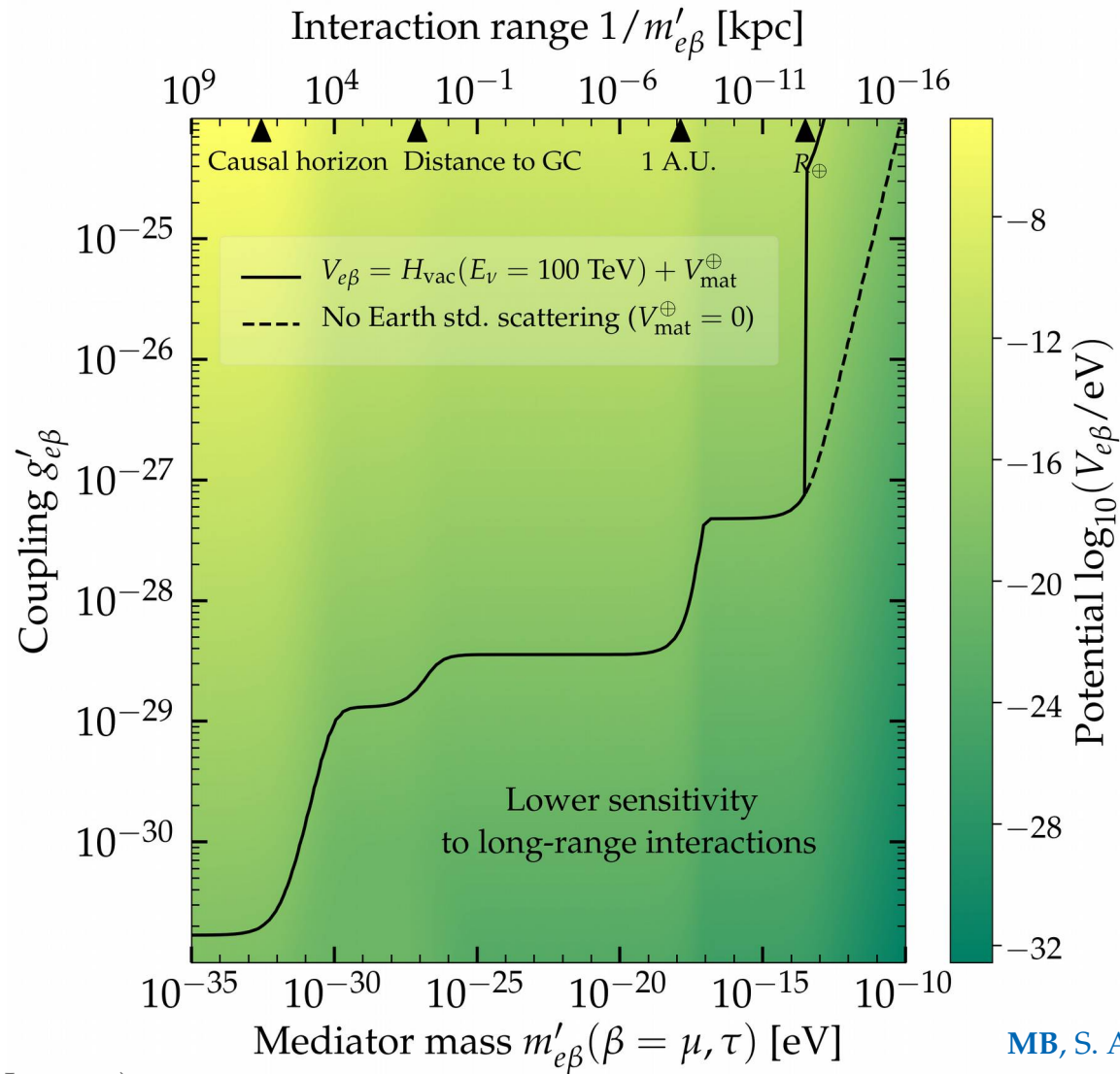
$g_{\text{strong}} \sim 13.5$
 $g_{\text{e.m.}} \sim 0.3$
 $g_{\text{weak}} \sim 0.01$
 $g_{\text{gravity}} \sim 10^{-19}$

↑

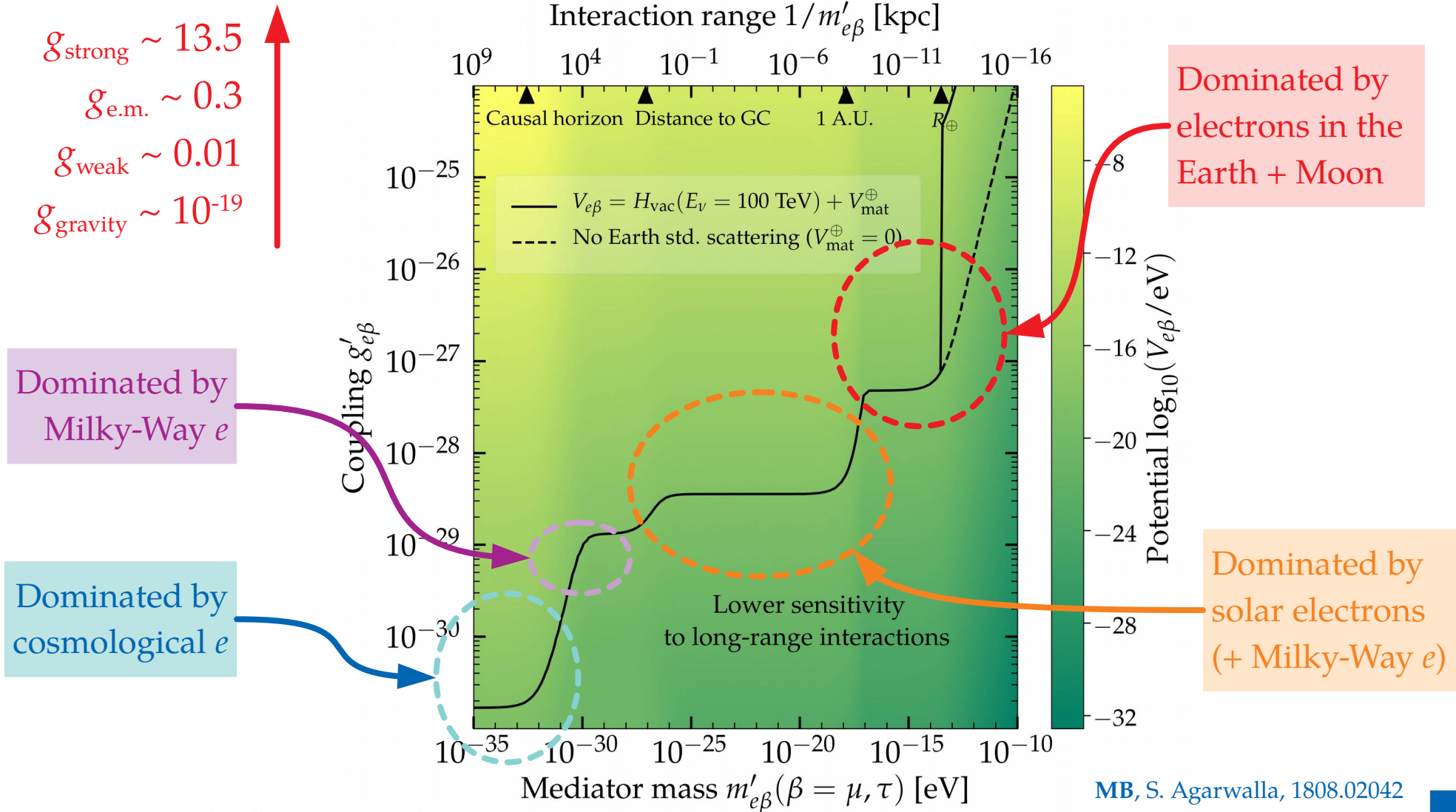


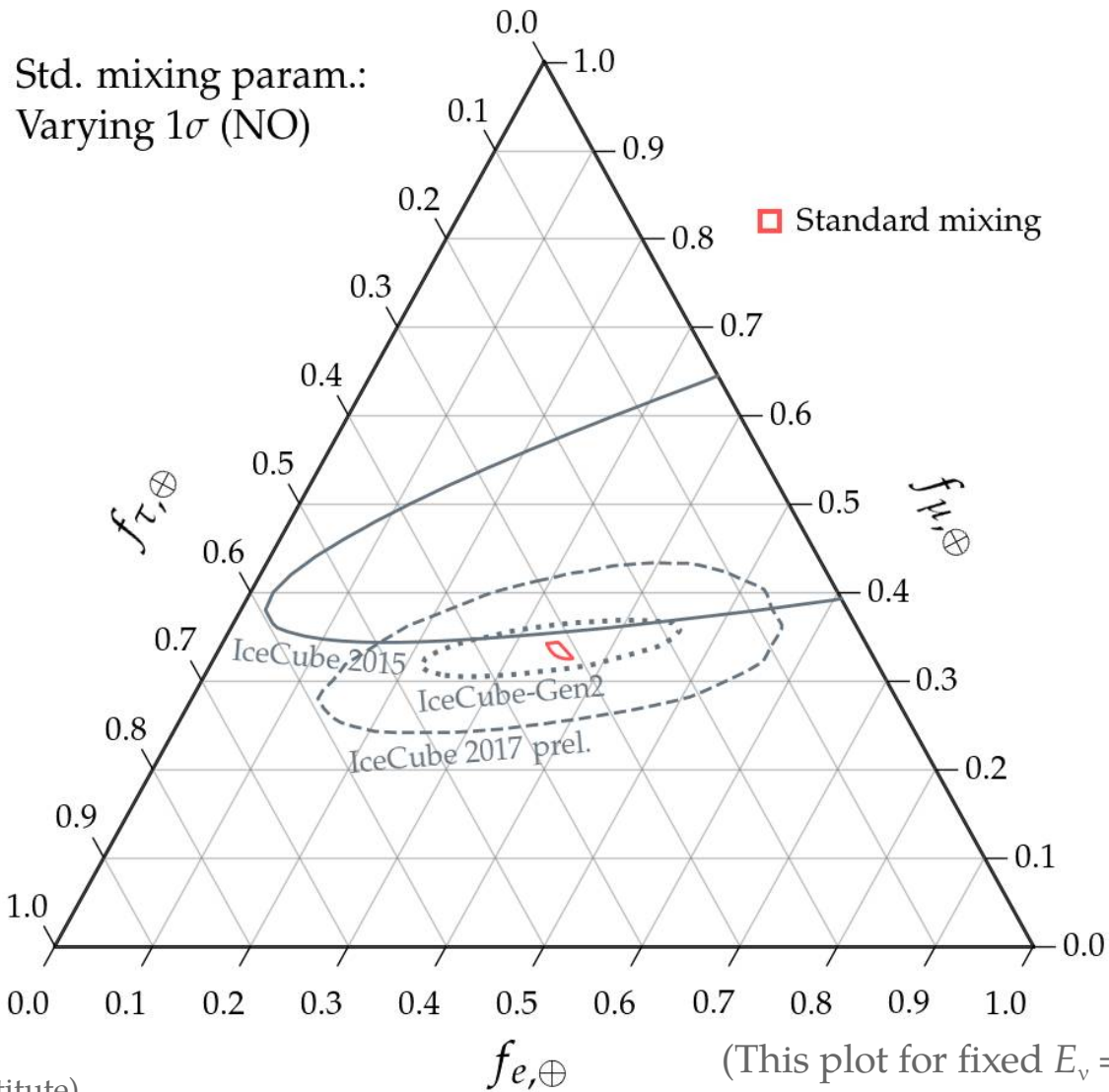
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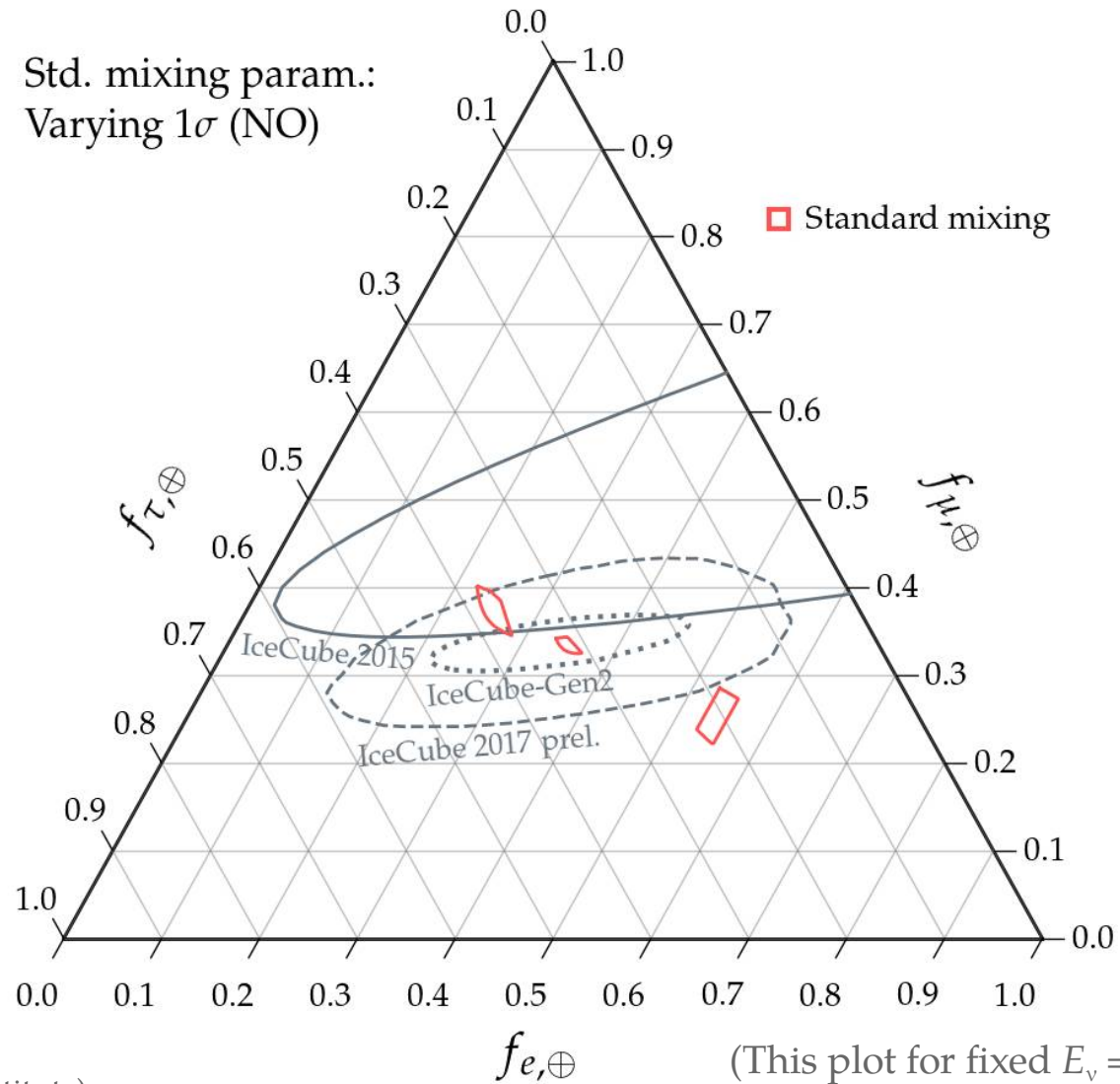
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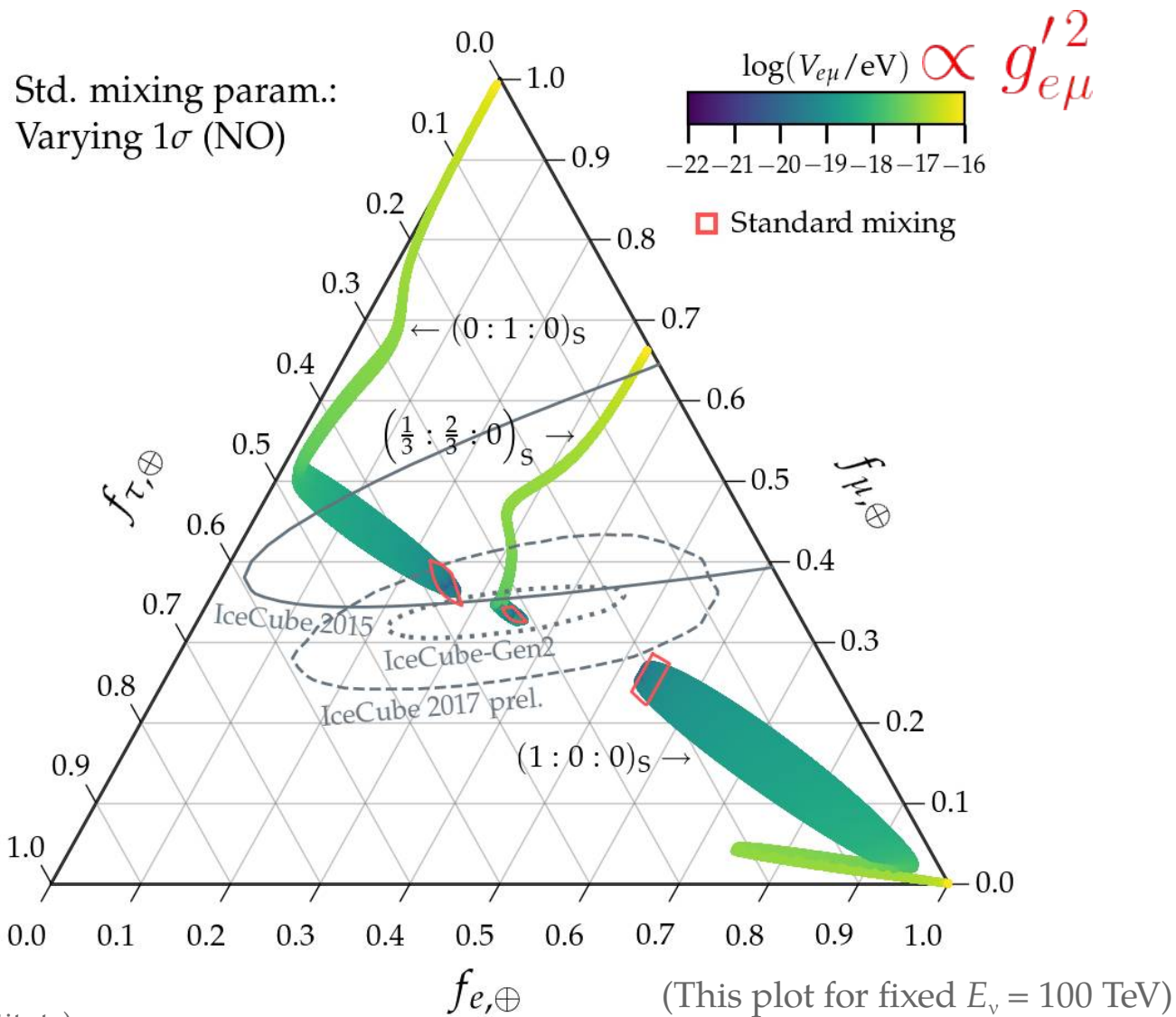


MB, S. Agarwalla, 1808.02042

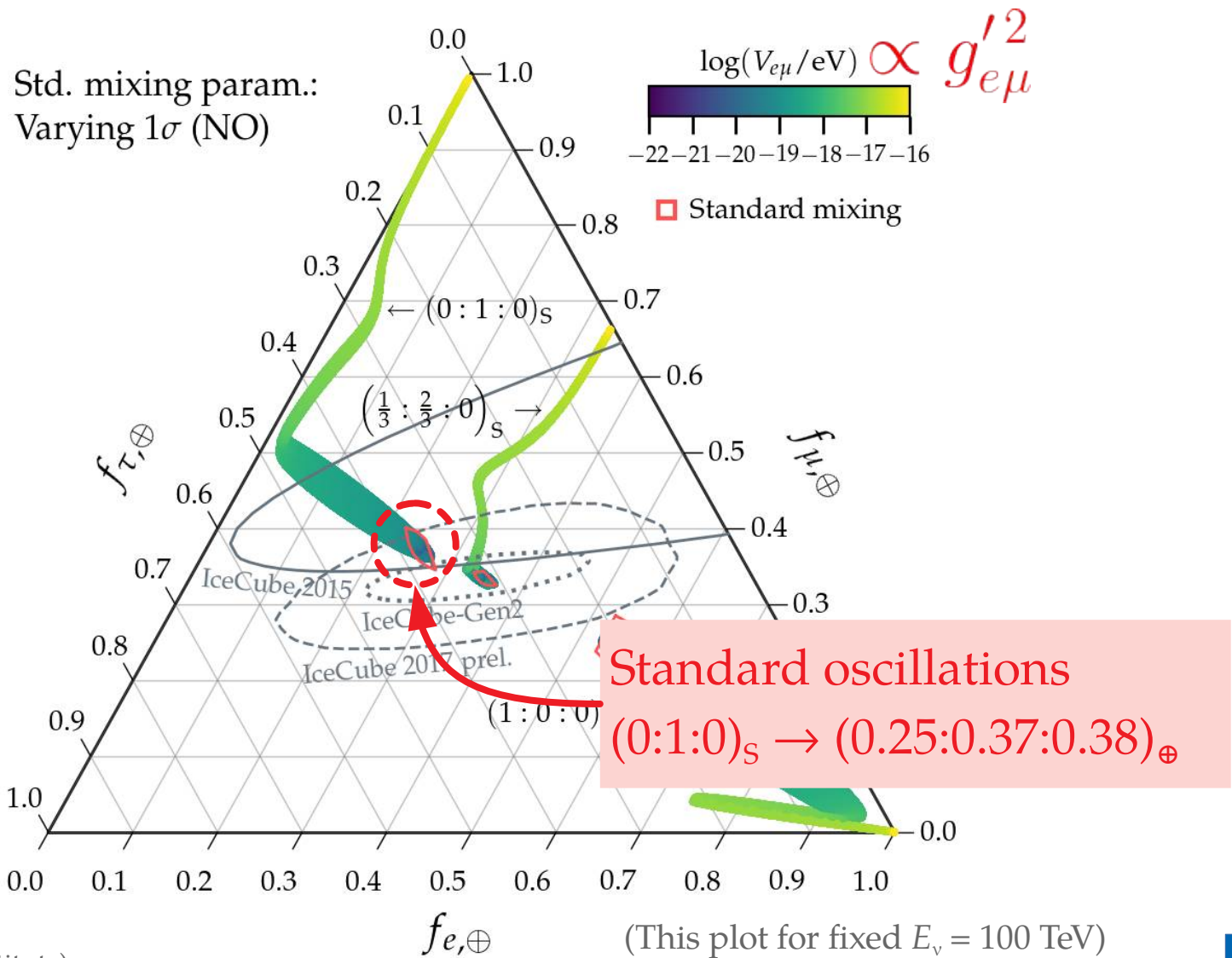
Std. mixing param.:
Varying 1σ (NO)



MB, S. Agarwalla, 1808.02042



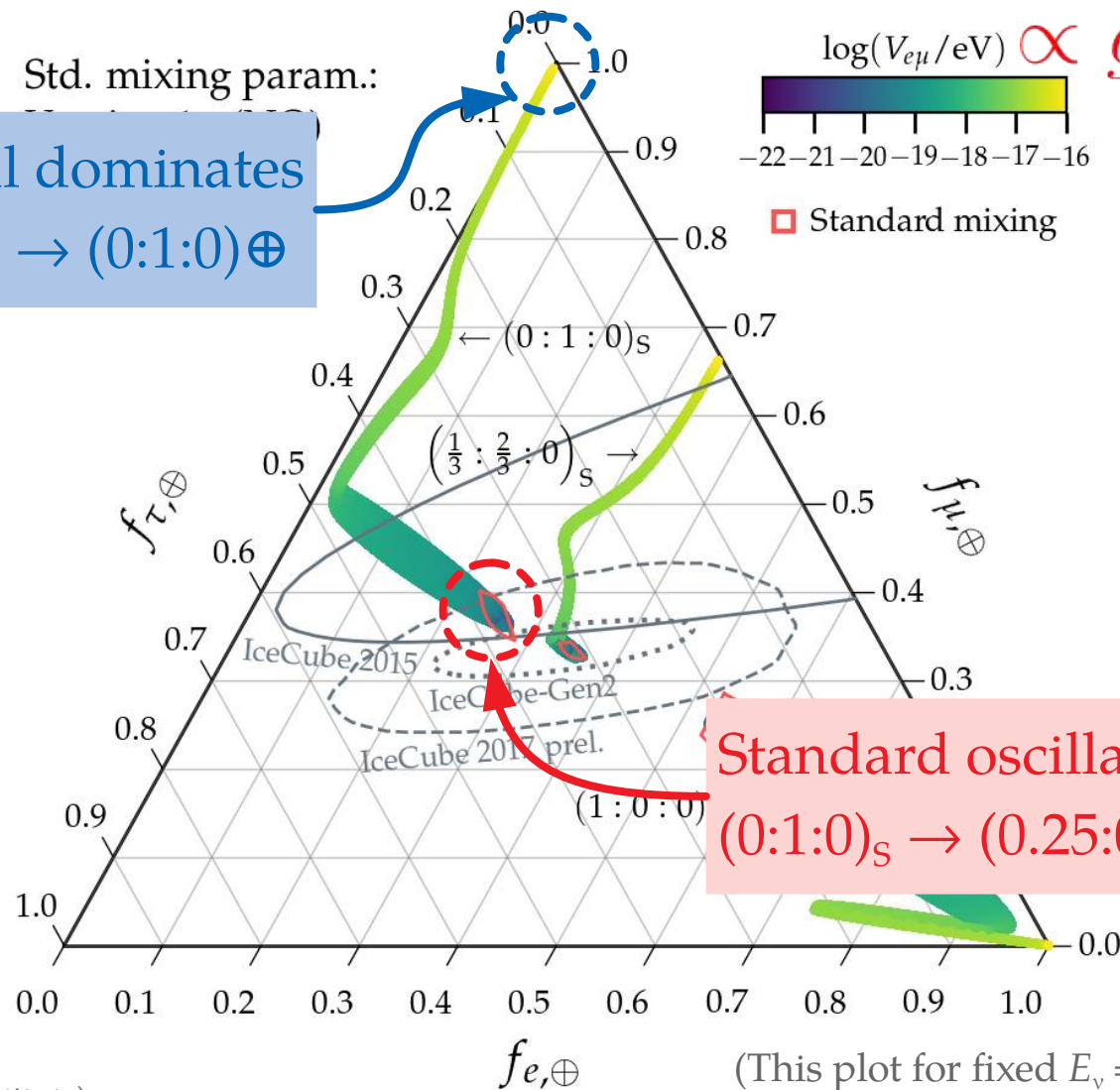
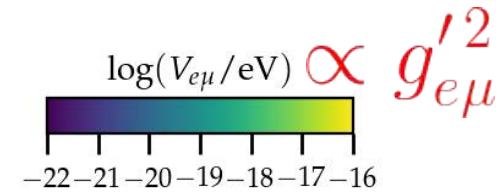
MB, S. Agarwalla, 1808.02042



MB, S. Agarwalla, 1808.02042

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

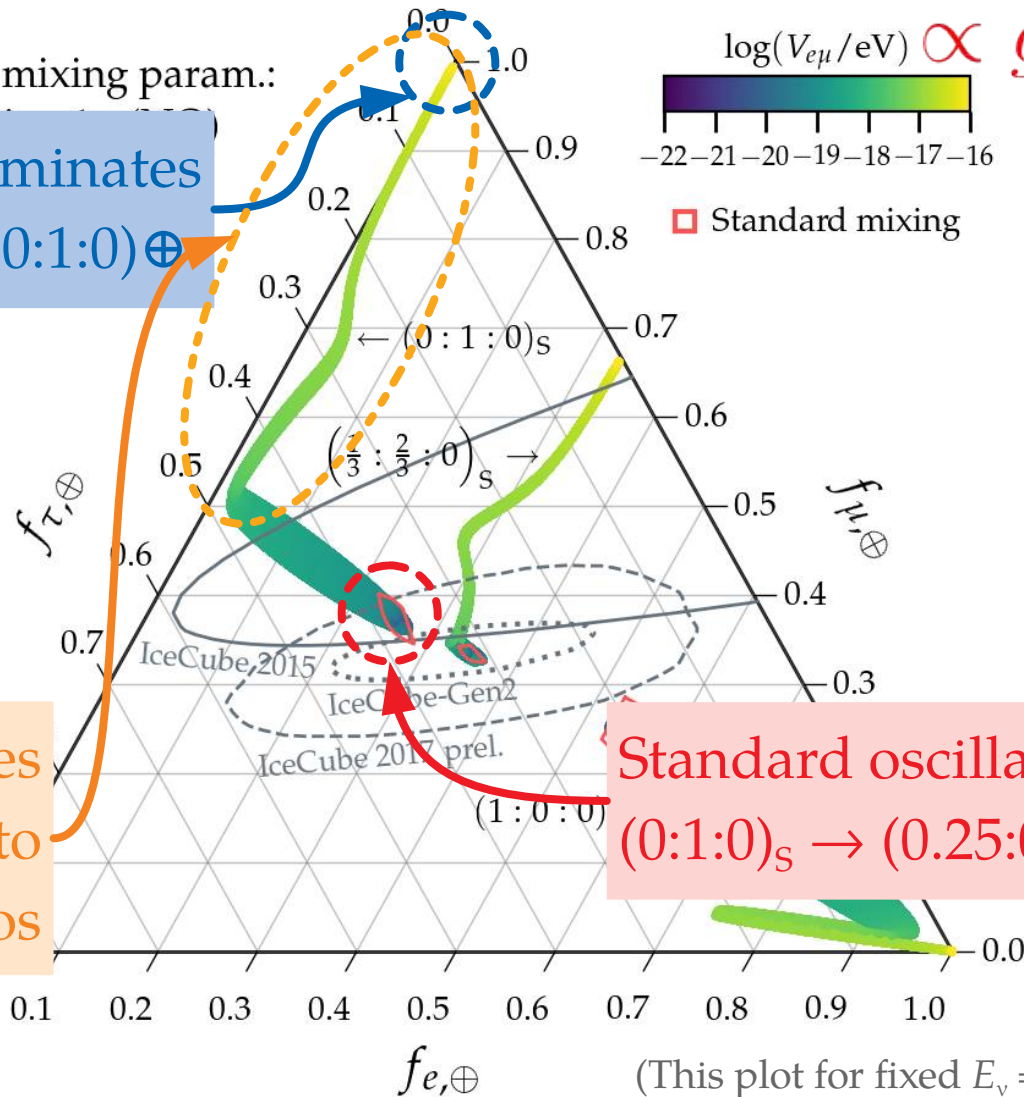
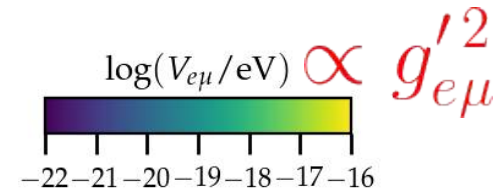
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MB, S. Agarwalla, 1808.02042

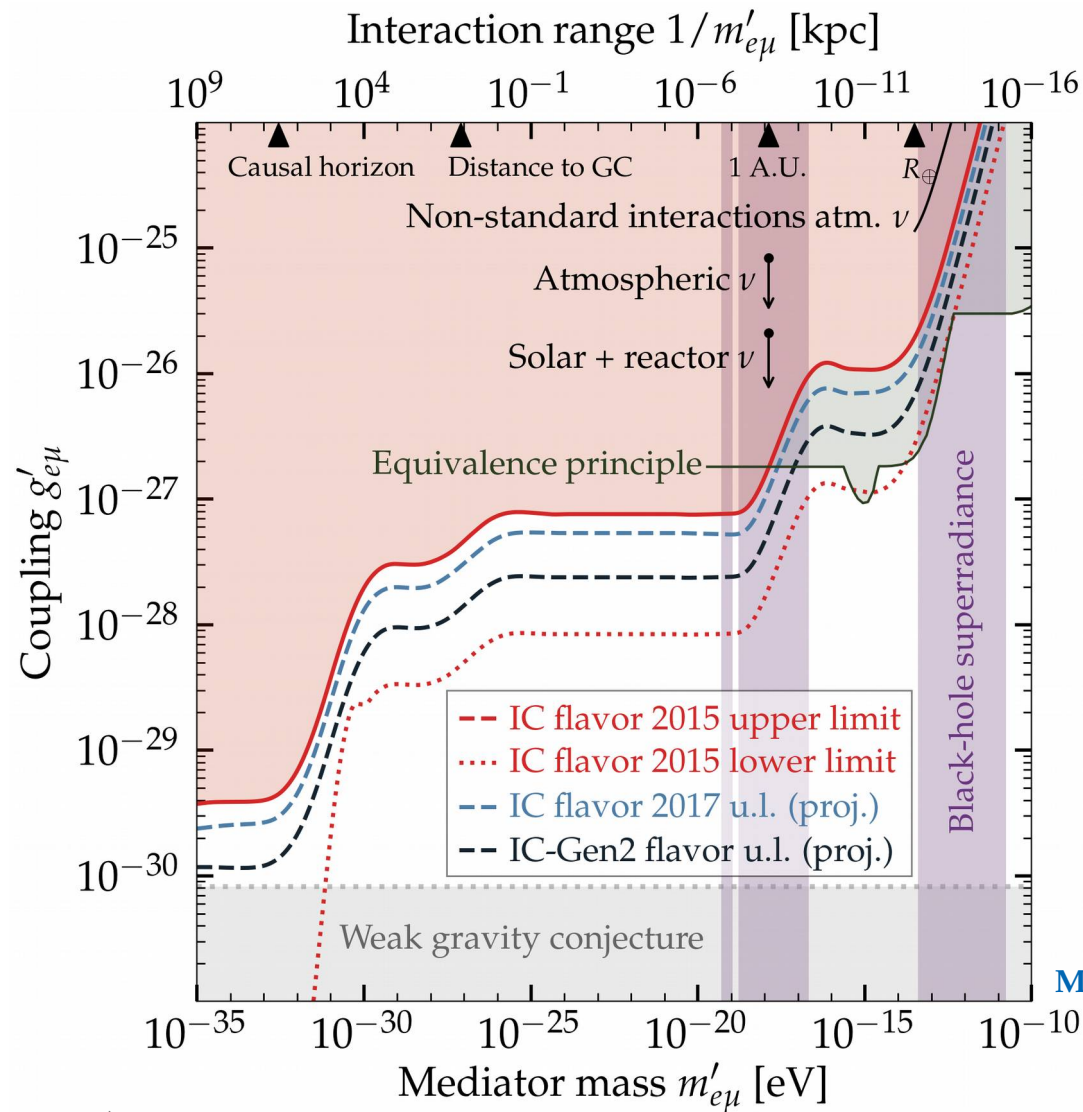
New potential dominates
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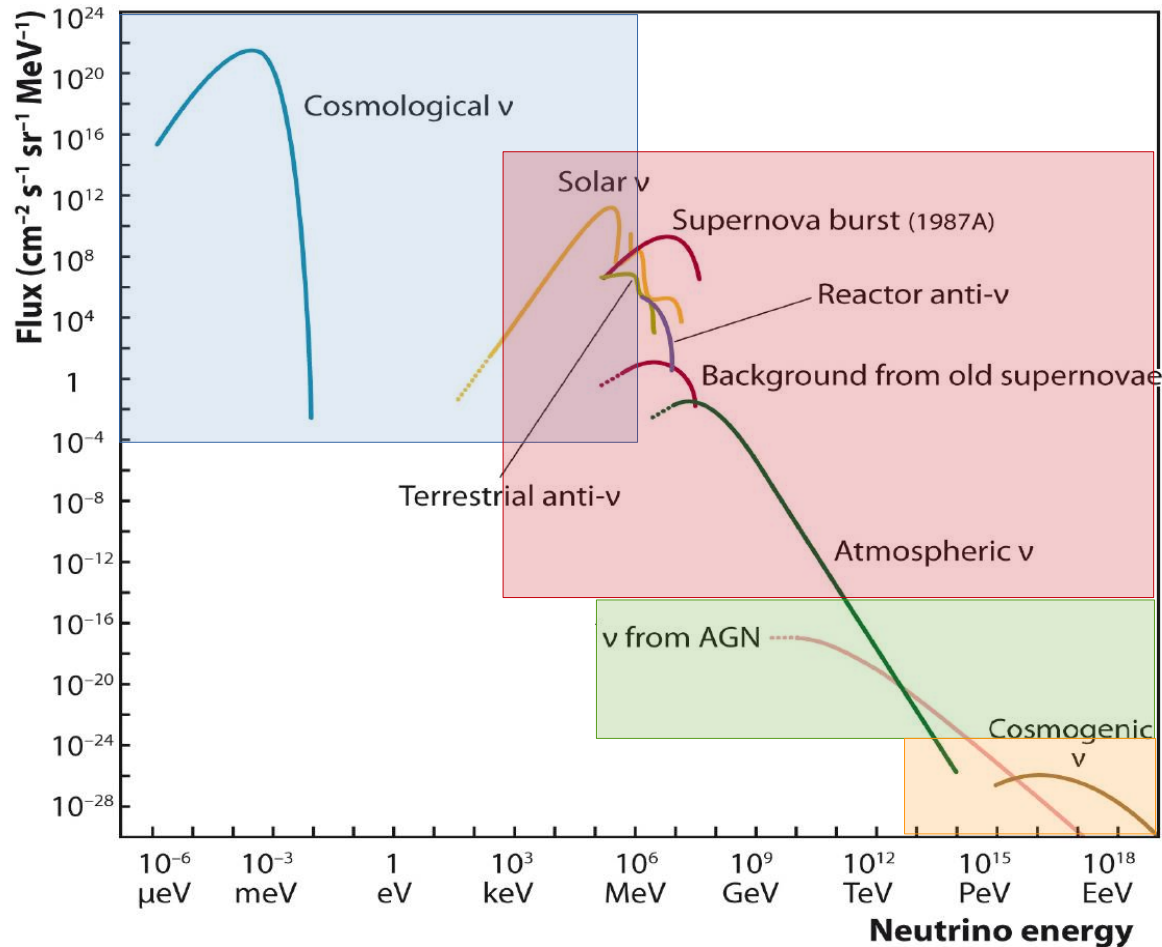
Standard oscillations
 $(0:1:0)_S \rightarrow (0.25:0.37:0.38)_\oplus$

MB, S. Agarwalla, 1808.02042



MB, S. Agarwalla, 1808.02042

Quo vadis? Ultra-high-energy neutrinos



Very rare,
not detected yet

Quo vadis? Ultra-high-energy neutrinos

Present

IceCube:

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



Future

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

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

Quo vadis? Ultra-high-energy neutrinos

Present

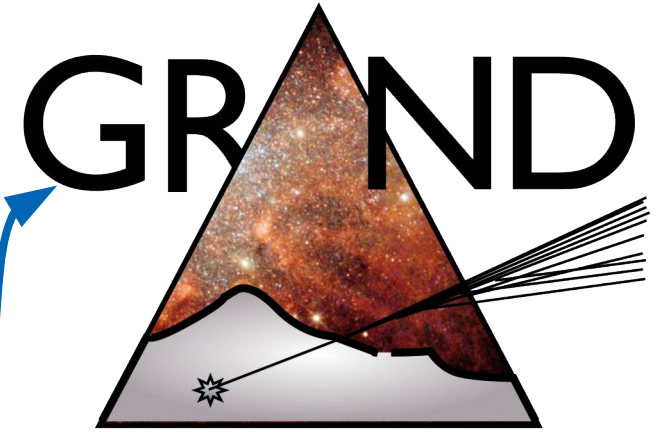
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Giant Radio Array for
Neutrino Detection

White paper: 1810.09994

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

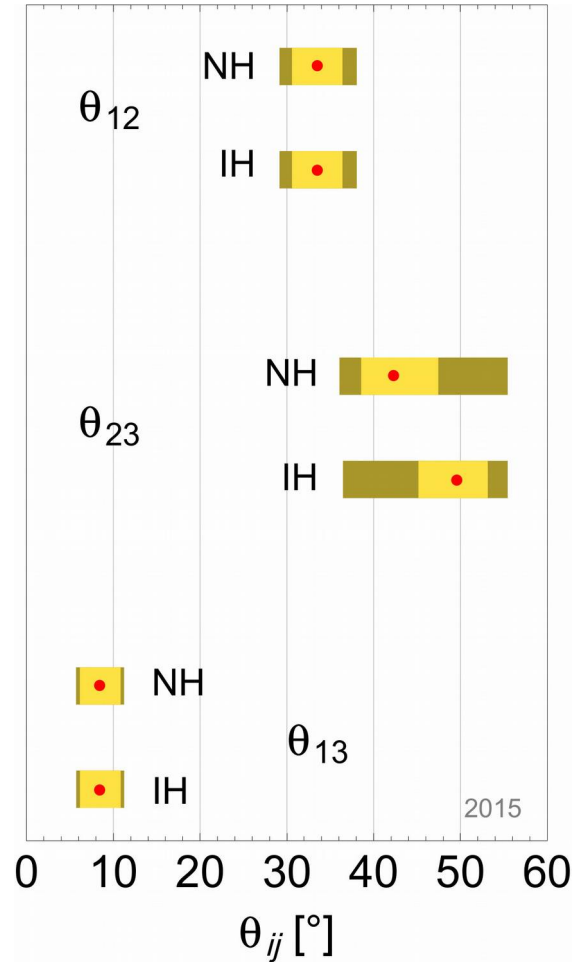




Backup slides

Uncertainties in lepton mixing angles

As of 2015 –



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...

...the neutrino mixing parameters...

...the neutrino production mechanism...

... then you can infer *very* precisely...

... flavor ratios emitted by sources

... values of the mixing parameters

vs.

The real world

You measure flavor ratios at Earth *poorly* and...

... you know ...

...mixing parameters up to a few deg...

... little about ν production scenarios...

... then you can ...

... disfavor a few ν production scenarios

... say nothing about mixing parameters

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

The ideal world

If you measure *very* precisely the flavor ratios at Earth and...

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... values of the mixing parameters

vs.

But we can thoroughly explore new physics

The real world

You measure flavor ratios at Earth *poorly* and...

... you know ...

...mixing parameters up to a few deg...

... little about ν production scenarios...

... then you can ...

... disfavor a few ν production scenarios

... say nothing about mixing parameters

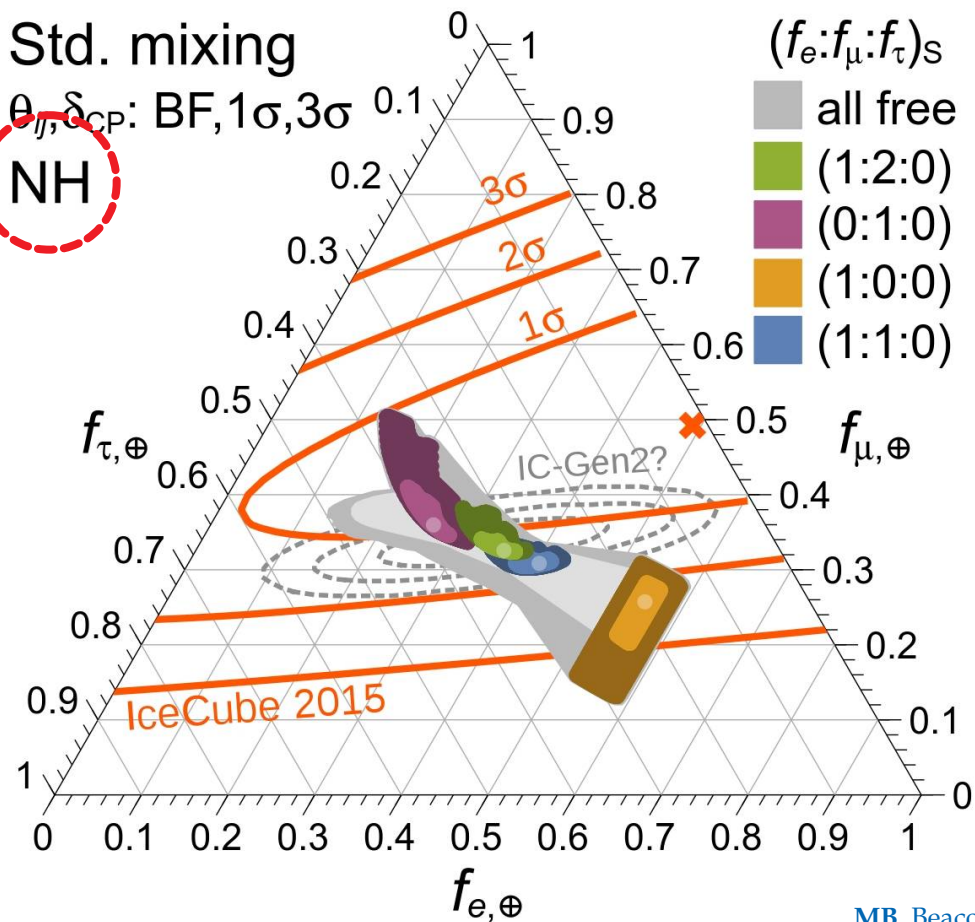
Flavor composition – a few source choices

Flavor composition – a few source choices

Std. mixing

θ_{12}, δ_{CP} : BF, $1\sigma, 3\sigma$

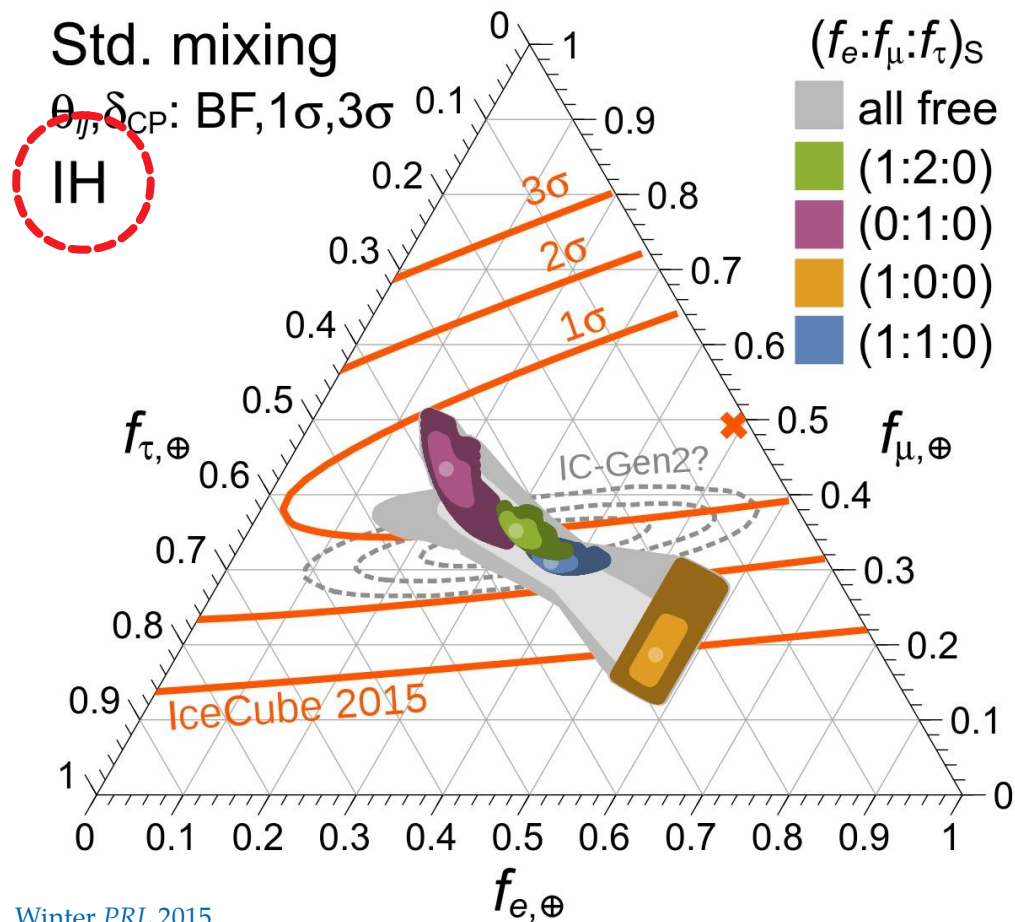
NH



Std. mixing

θ_{12}, δ_{CP} : BF, $1\sigma, 3\sigma$

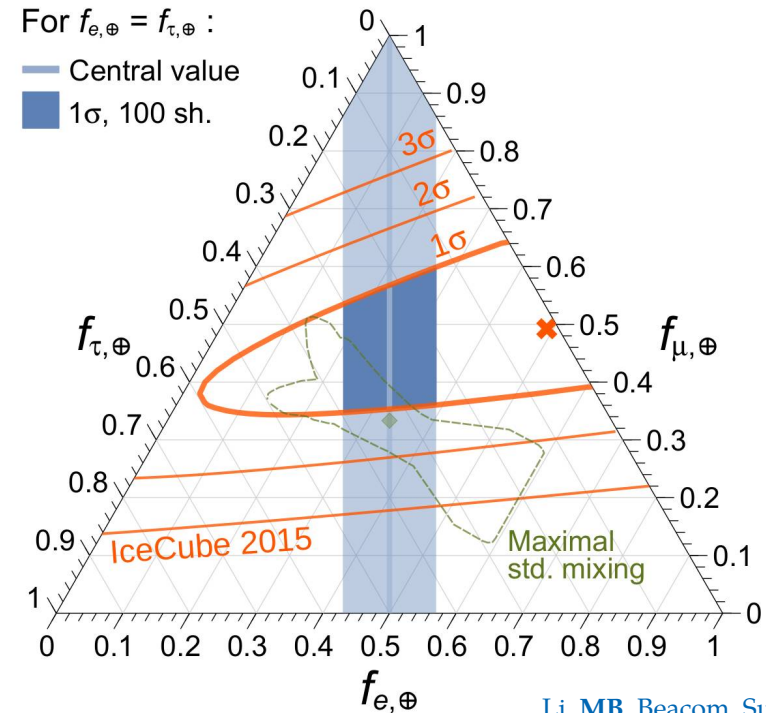
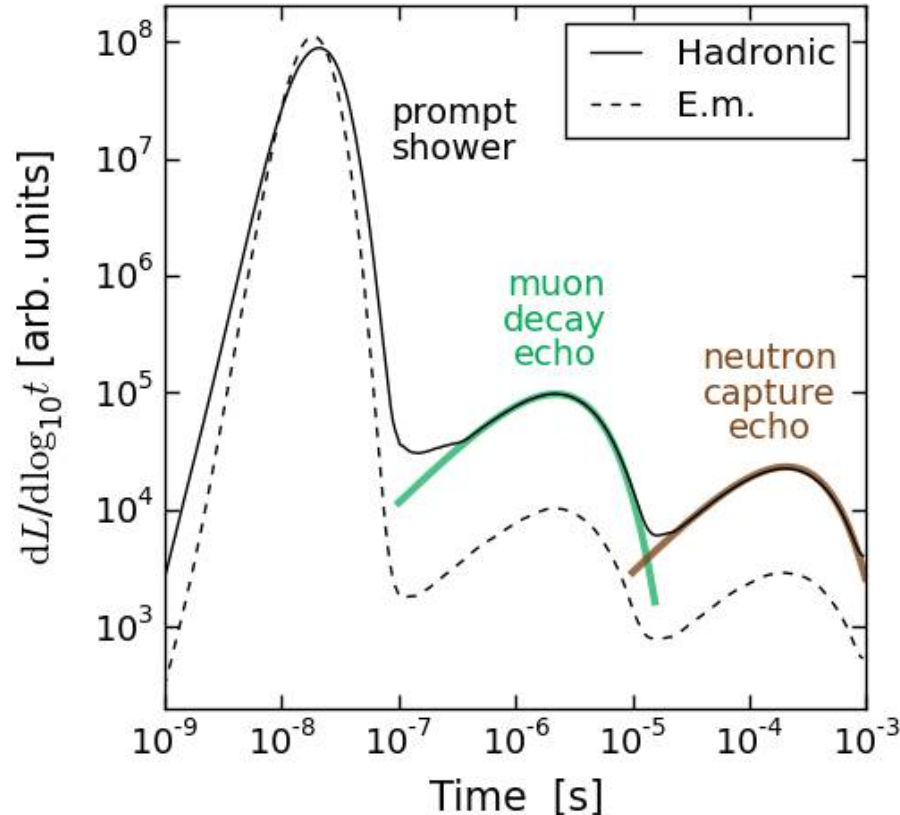
IH



MB, Beacom, Winter PRL 2015

Side note: Improving flavor-tagging using *echoes*

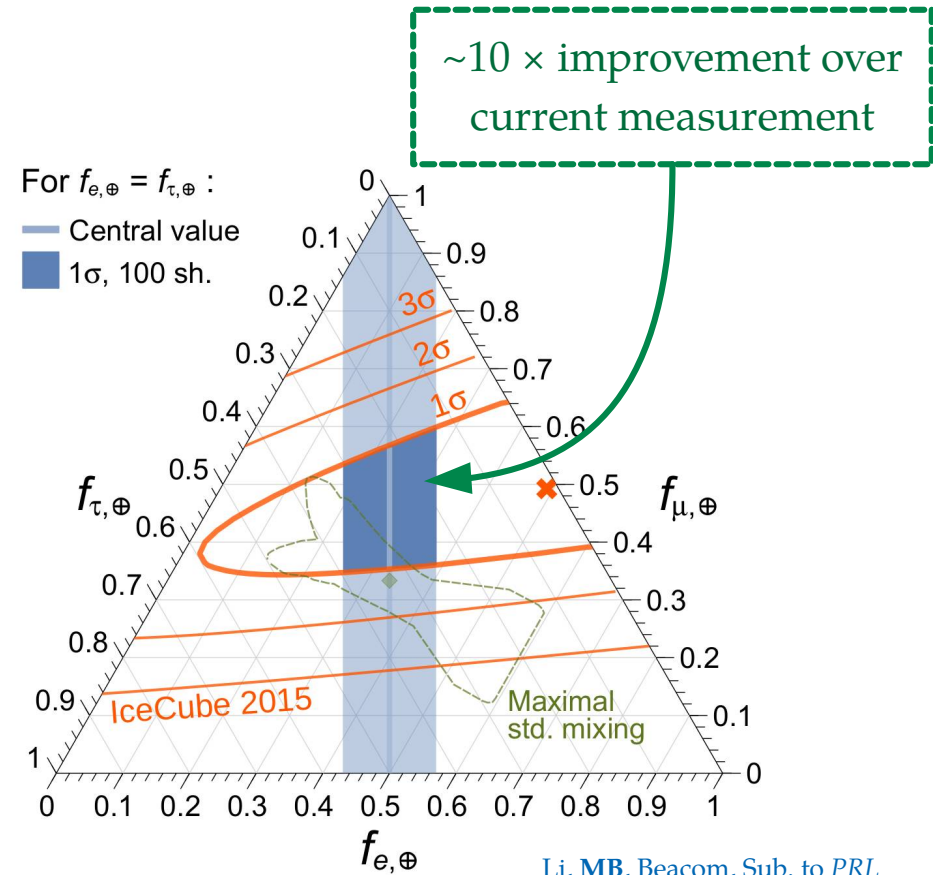
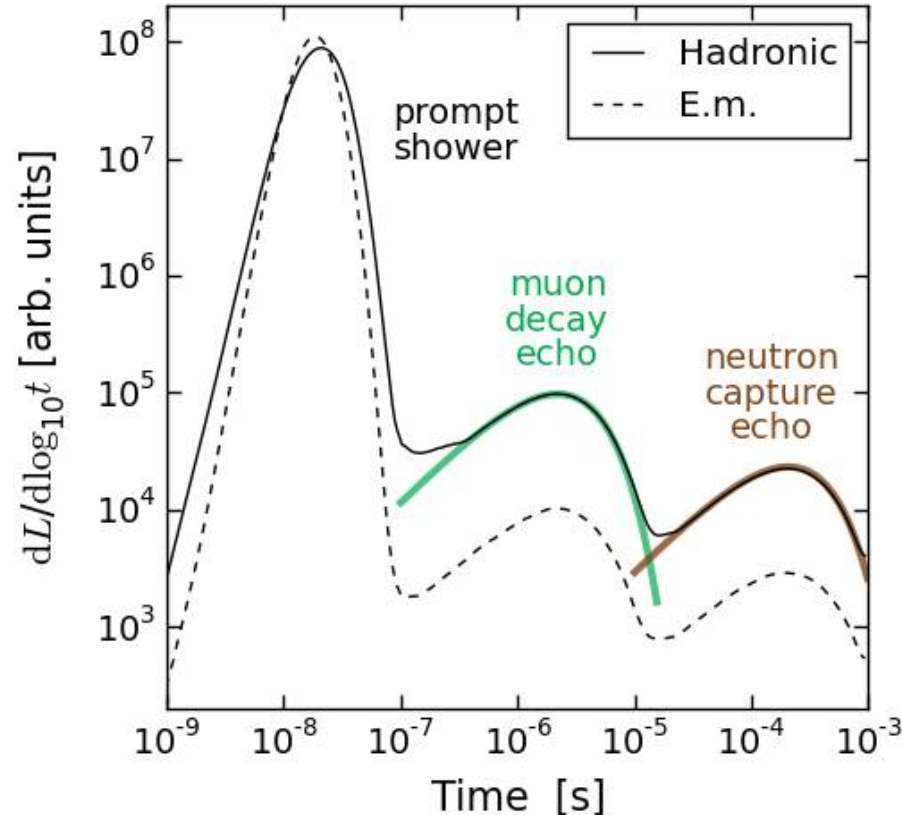
Late-time light (*echoes*) from muon decays and neutron captures can separate showers made by ν_e and ν_τ –



Li, MB, Beacom, Sub. to PRL

Side note: Improving flavor-tagging using *echoes*

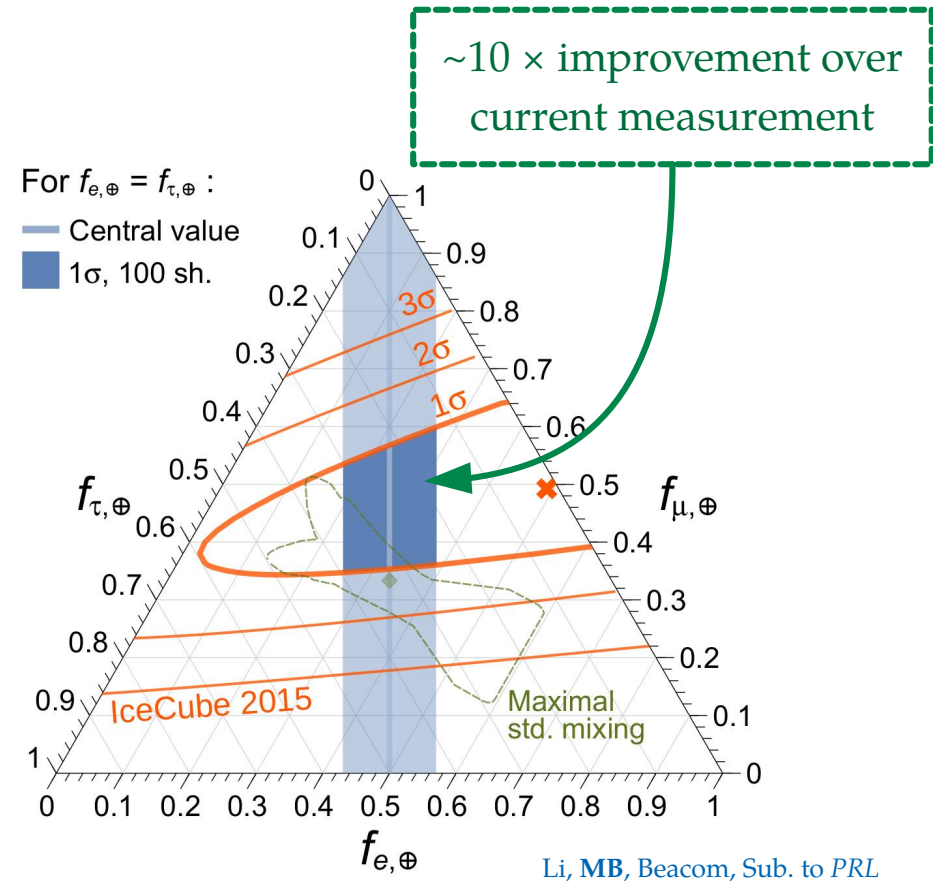
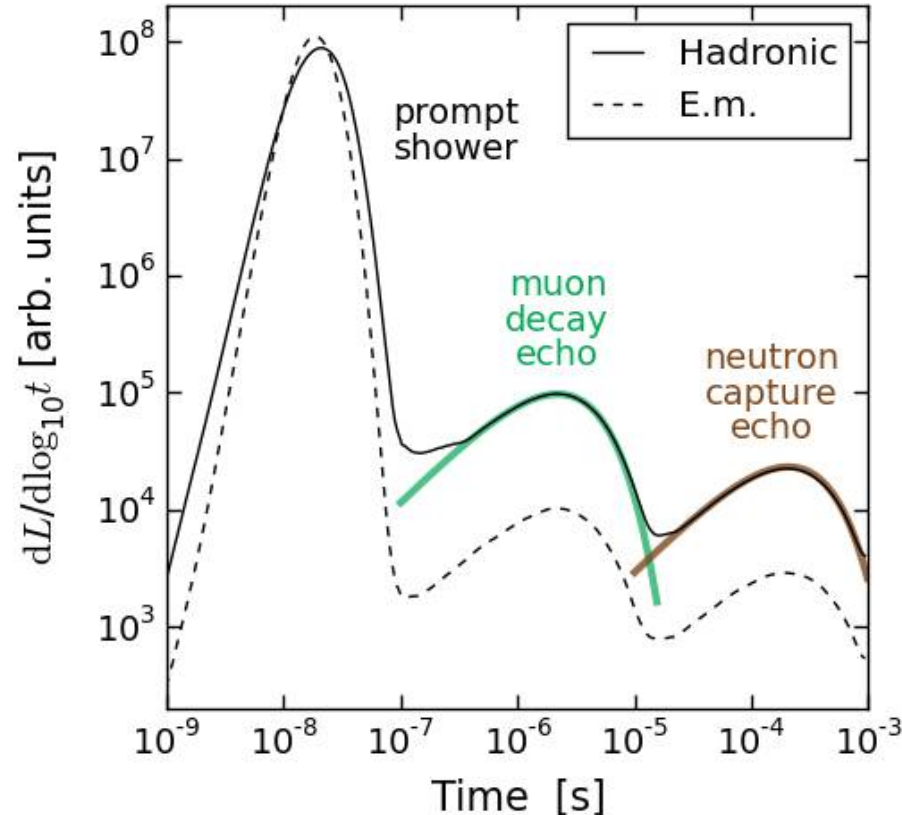
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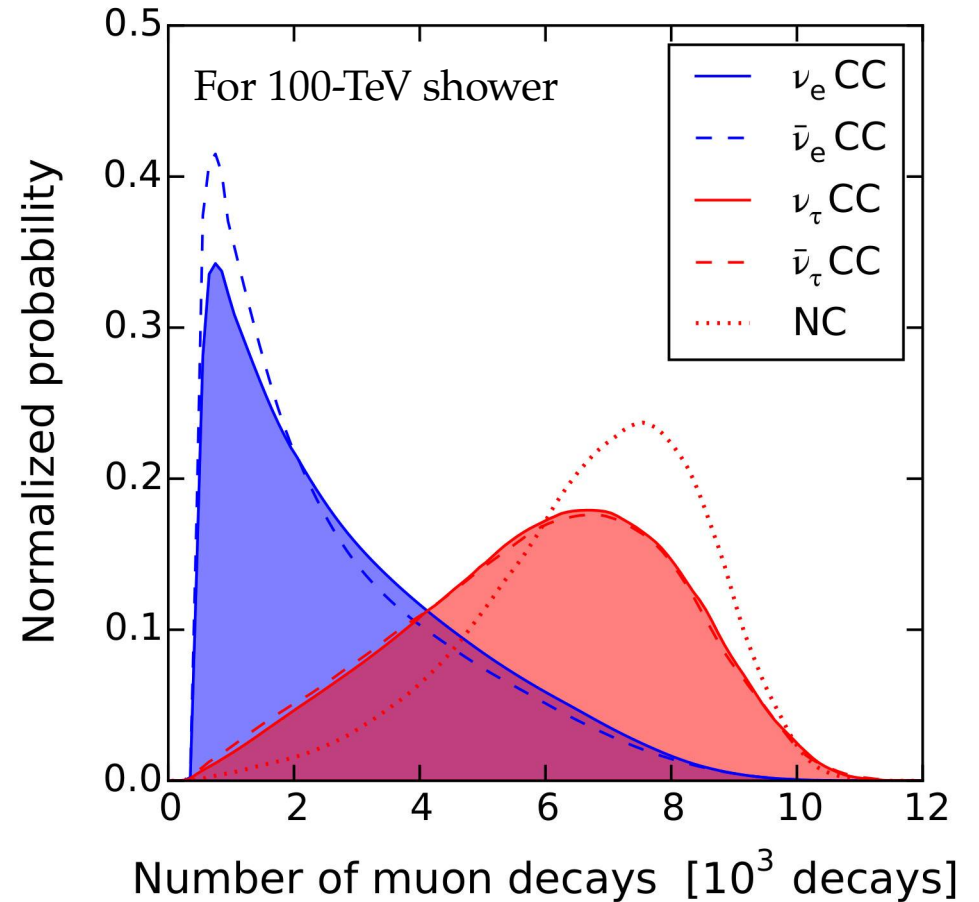
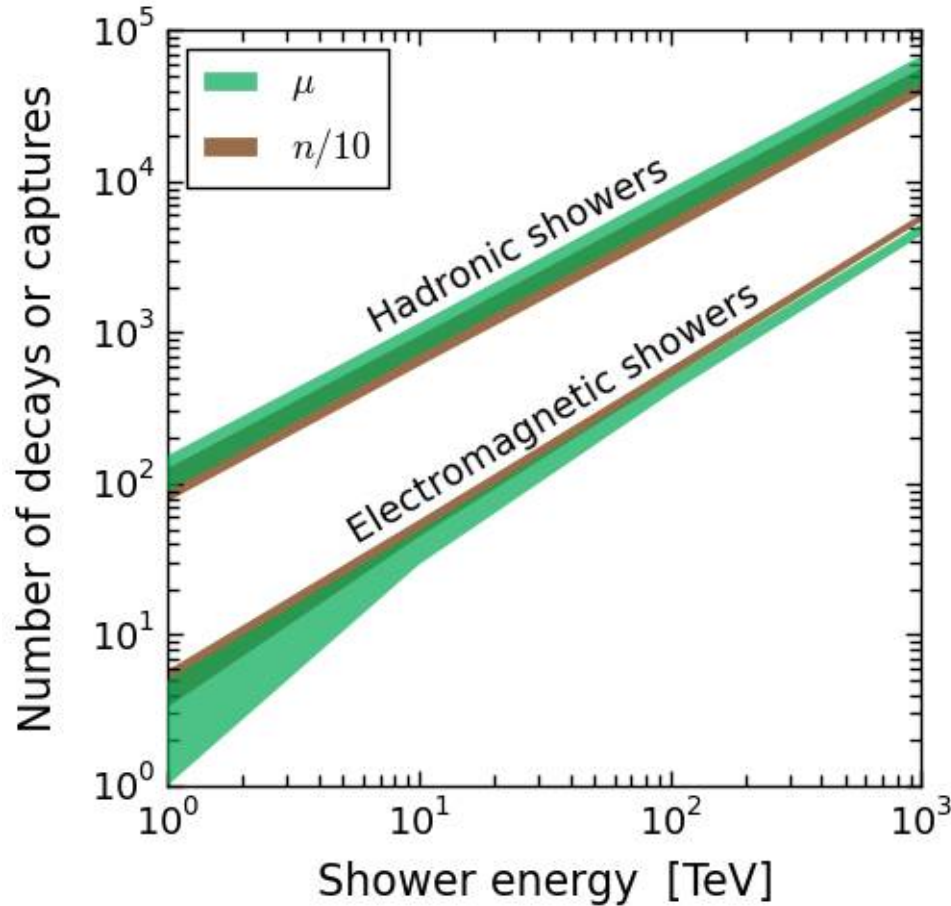
Side note: Improving flavor-tagging using *echoes*

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



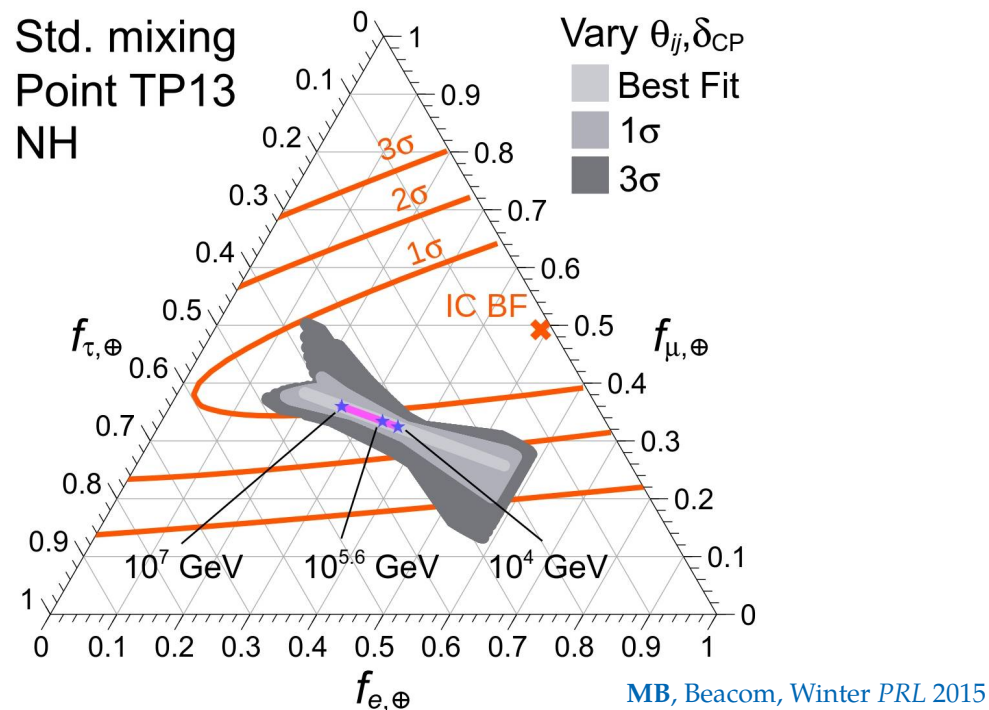
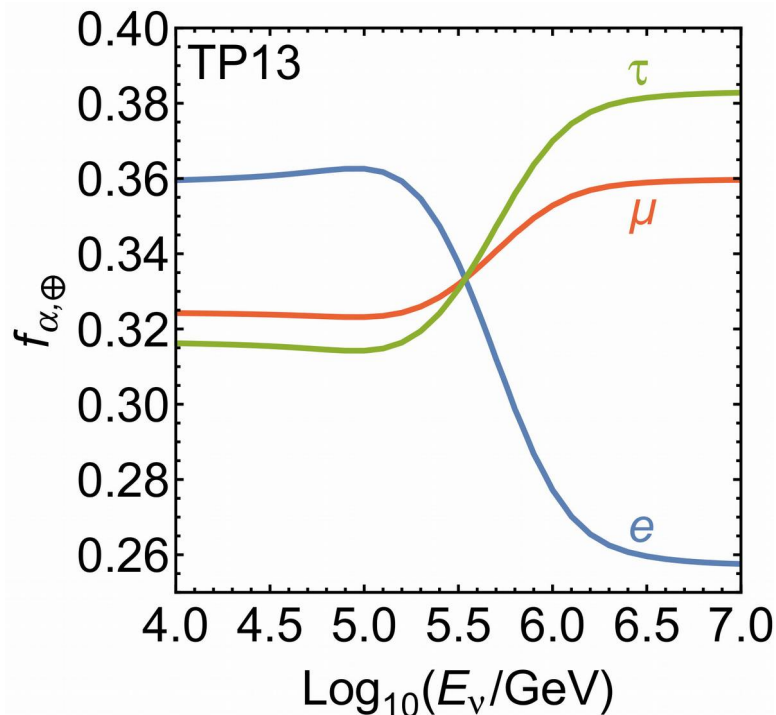
Li, MB, Beacom, Sub. to PRL

Hadronic *vs.* electromagnetic showers



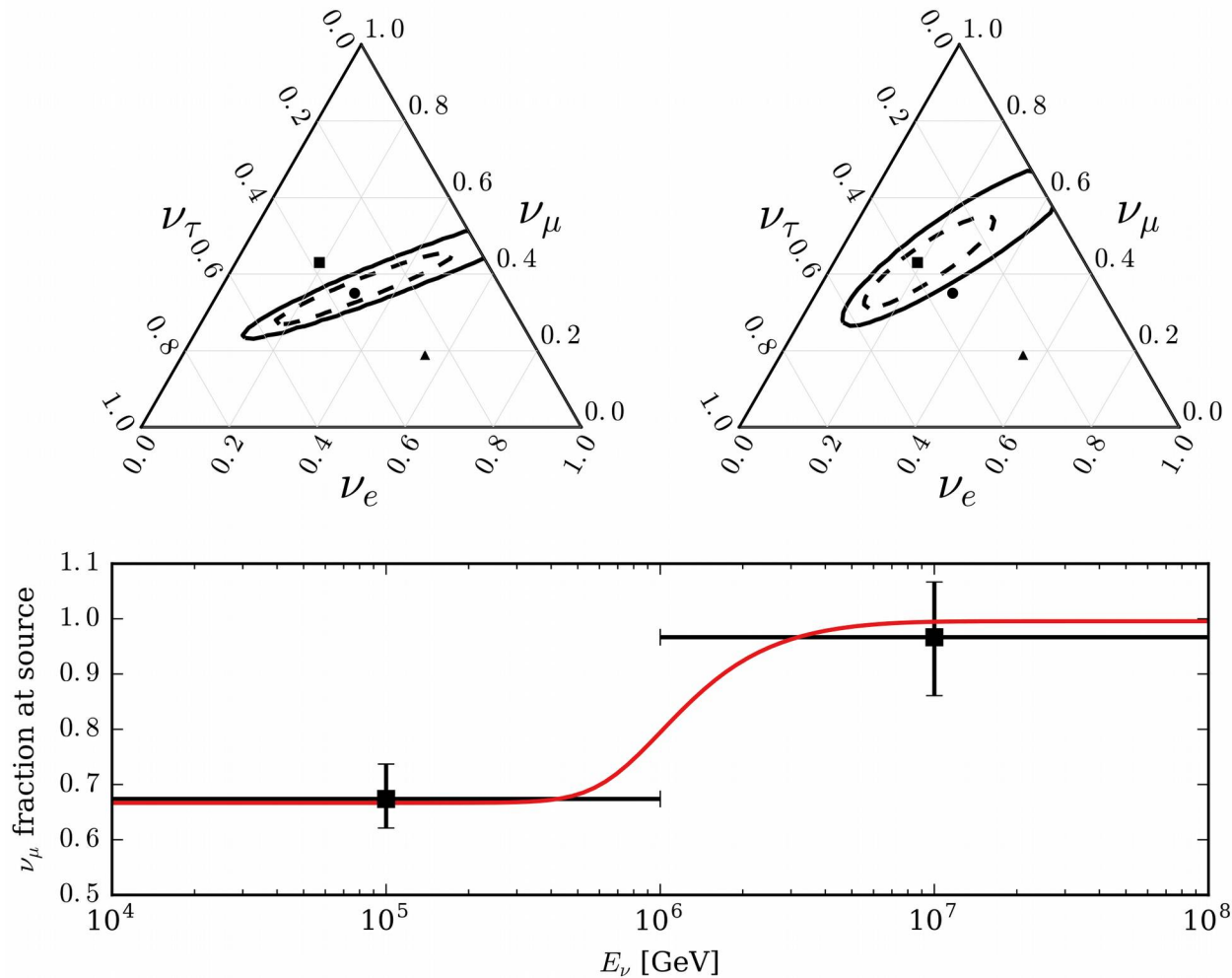
Energy dependence of the flavor composition?

Different neutrino production channels accessible at different energies –



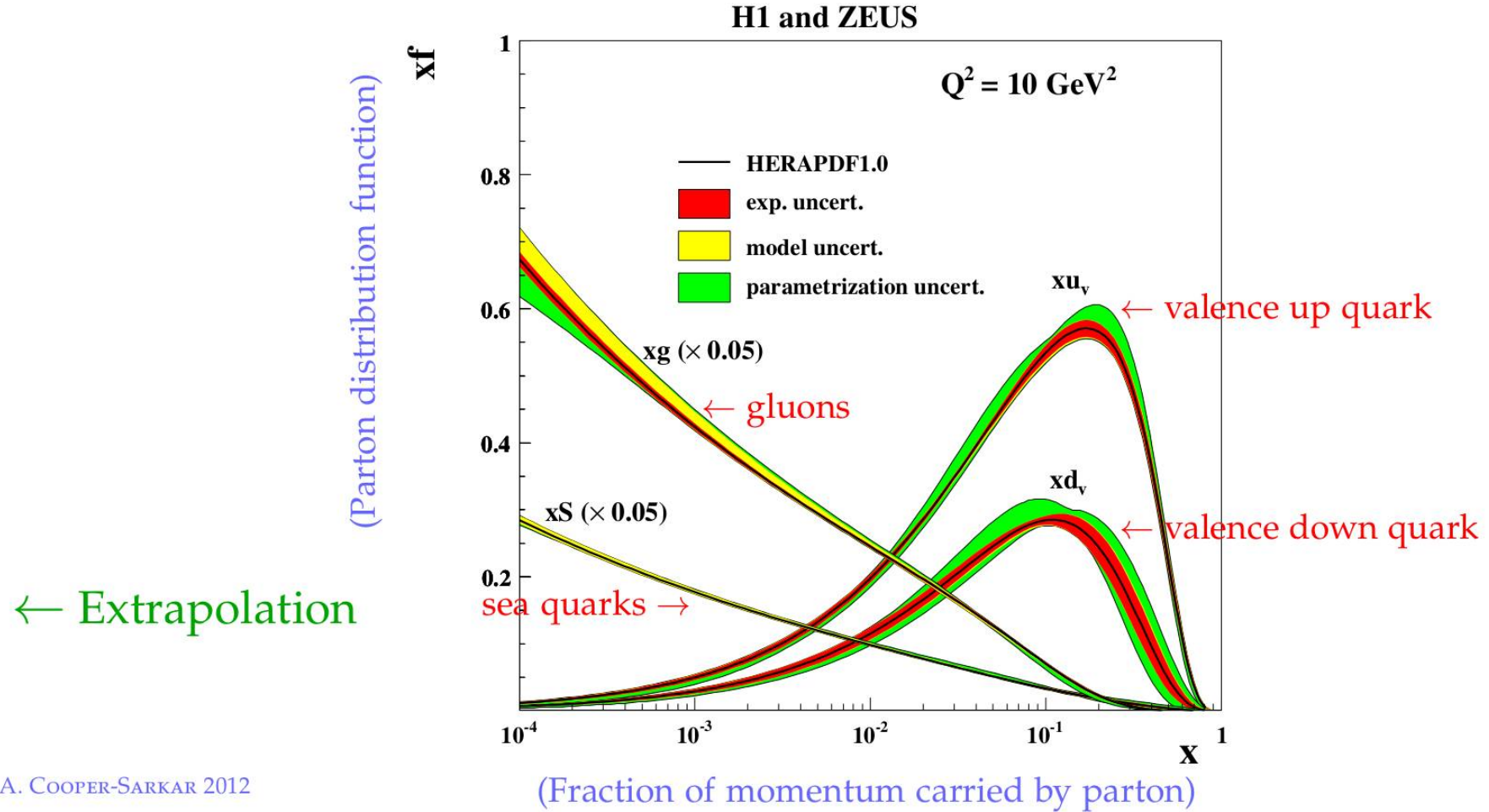
- ▶ TP13: $p\gamma$ model, target photons from electron-positron annihilation [Hümmer+, *Astropart. Phys.* 2010]
- ▶ Will be difficult to resolve [Kashti, Waxman, *PRL* 2005; Lipari, Lusignoli, Meloni, *PRD* 2007]

... Observable in IceCube-Gen2?



Borrowed from M. Kowalski

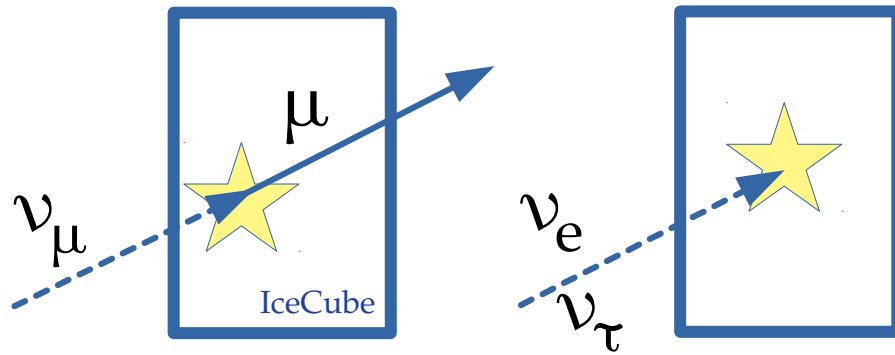
Peeking inside a proton



A. COOPER-SARKAR 2012

Contained *vs.* uncontained νN interactions

Contained events



Starting track

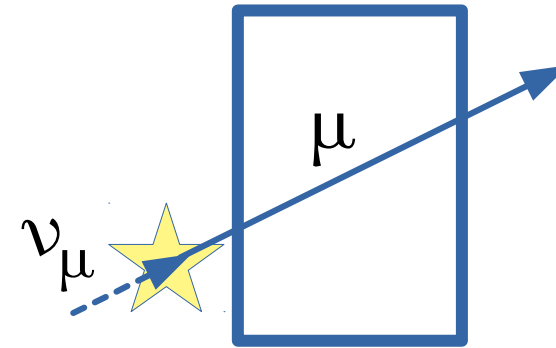
Shower

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 ($\sim 10\text{k}$ used)

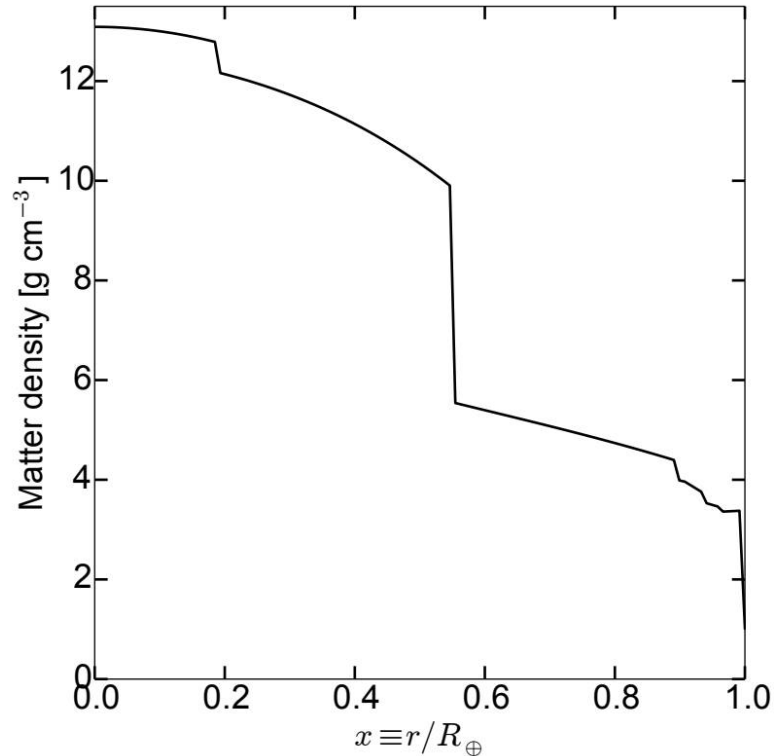
Con: Uncertain estimates of E_ν

Ref.: IceCube, *Nature* 2017, 1711.08119

A feel for the in-Earth attenuation

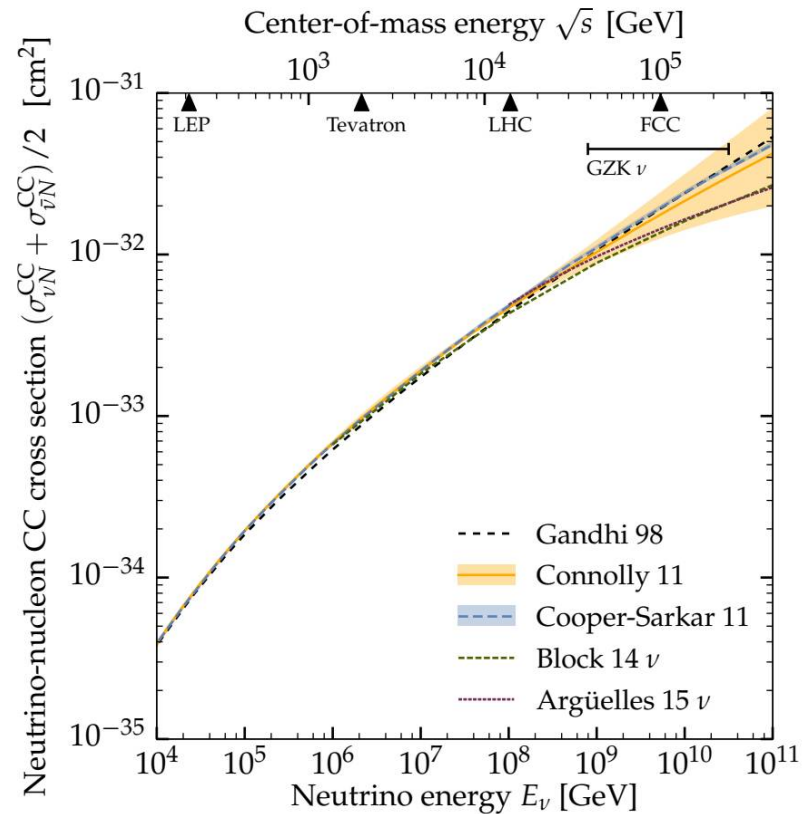
Earth matter density

(Preliminary Reference Earth Model)

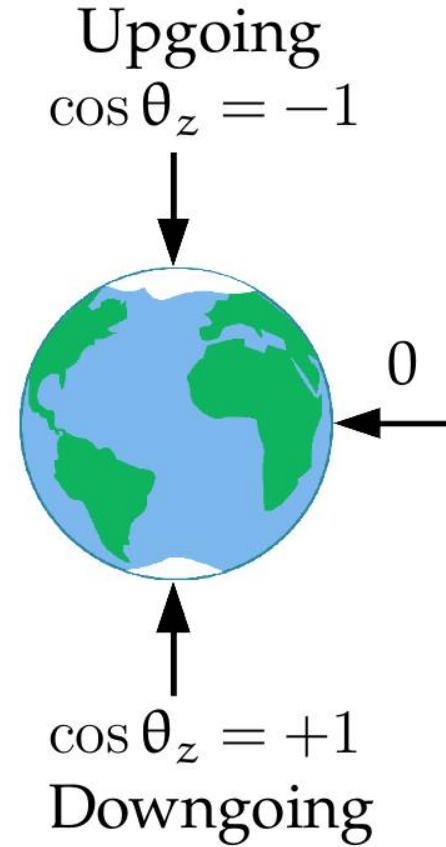
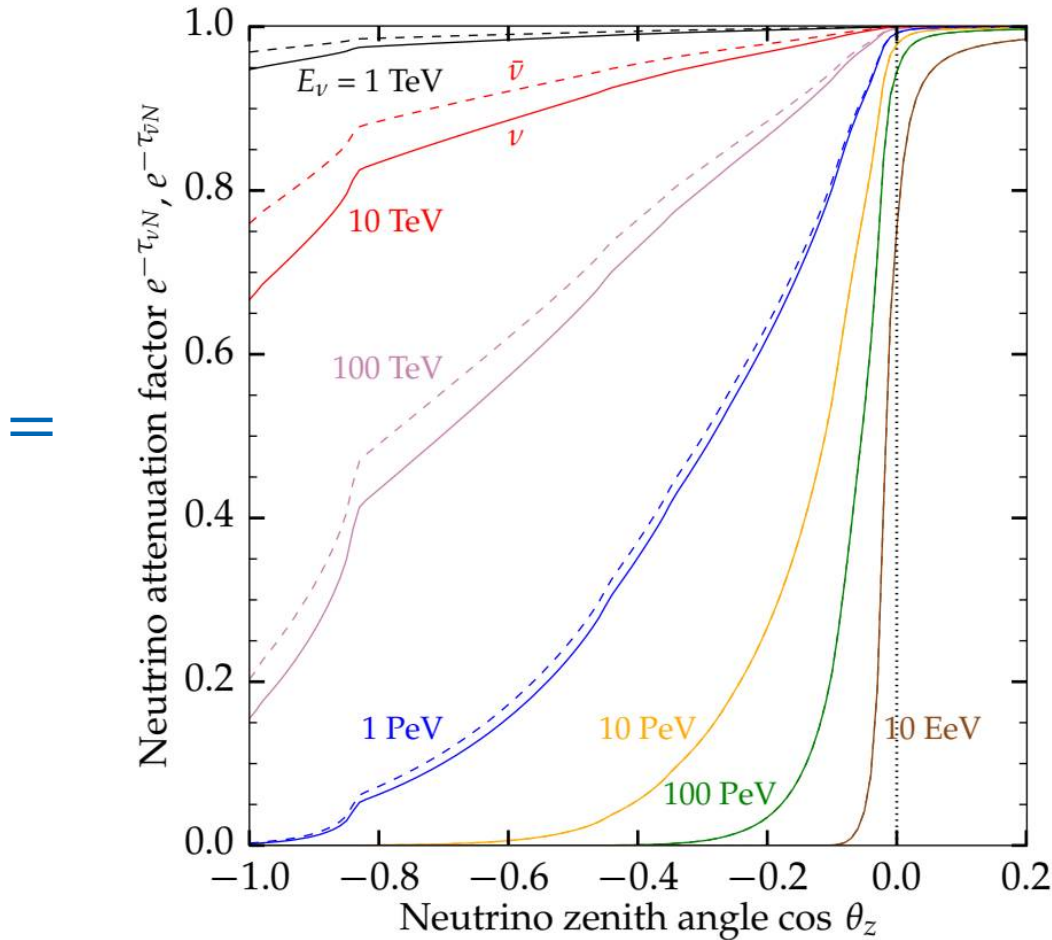


+

Neutrino-nucleon cross section



A feel for the in-Earth attenuation



Cross section from contained events

- ▶ $\sigma_{\nu N}$ varies with neutrino energy $\Rightarrow$ 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 ($E_{\text{dep}} \approx E_\nu$)
 - ▶ ☐ **Tracks:** partially contained ($E_{\text{dep}} < E_\nu$)
- ▶ 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)

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

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

Upgoing (lots of matter)

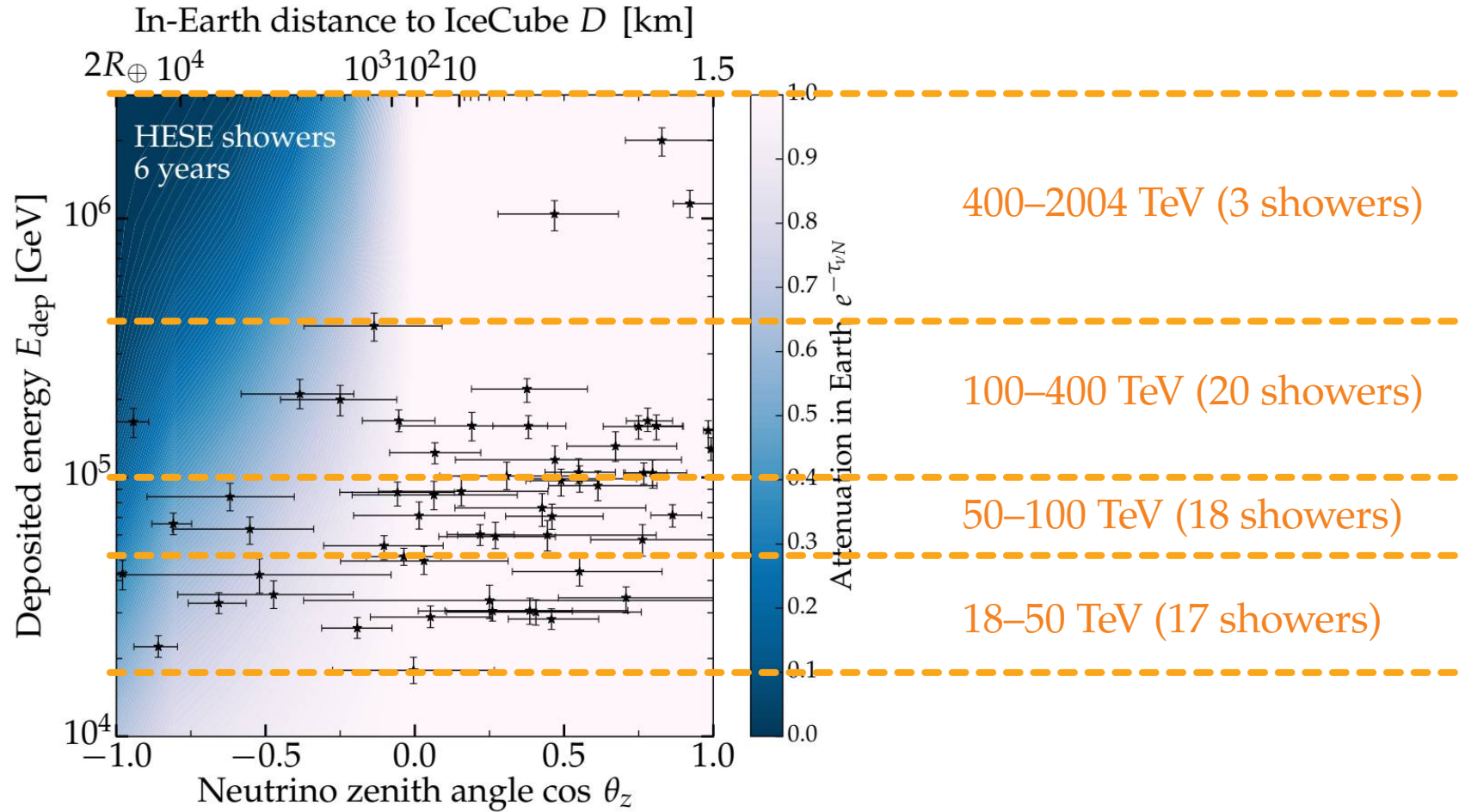
$$N_{\nu,\text{up}} \sim N_{\nu,\text{dn}} \cdot e^{-\tau}$$

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

Reality check:

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

Bin-by-bin analysis



The fine print

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

What goes into the (likelihood) mix?

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

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

Energy and angular shower spectra

Rate from all flavors, CC + NC:

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

$= 0.83$

Contribution from one flavor CC:

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

Conversion between shower energy and neutrino energy:

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

MB & A. Connolly, 1711.11043

Detector resolution

Number of contained showers:

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

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

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

IceCube, *JINST* 2014

Angular resolution:

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

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

MB & A. Connolly, 1711.11043

Likelihood

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

Each energy bin is independent

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

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

Depends on $\sigma_{\nu N}$

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

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

PDF for this shower to be made by an atmospheric ν

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

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

Mauricio Bustamante (Niels Bohr Institute)

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 $N_{\text{sh}}^{\text{atm}}$, number of showers due to astrophysical neutrinos $N_{\text{sh}}^{\text{ast}}$, and astrophysical spectral index γ .

E_ν [TeV]	$N_{\text{sh}}^{\text{atm}}$	$N_{\text{sh}}^{\text{ast}}$	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
 - ↳ Solvable with more data from IceCube, IceCube-Gen2, KM3NeT
- ▶ Large errors in arrival direction ($\sim 10^\circ$) give errors in attenuation
 - ↳ Solvable with ongoing IceCube improvements + KM3NeT
- ▶ Charged-current + neutral-current cross sections are indistinguishable
 - ↳ Solvable (?) with muon and neutron echoes (Li, MB, Beacom 16)
- ▶ Cannot separate ν from $\bar{\nu}$
 - ↳ Wait to detect Glashow resonance (~ 6.3 PeV), sensitive only to $\bar{\nu}_e$
- ▶ Use starting tracks / through-going muons
 - ↳ Doable / done by IceCube (more next)

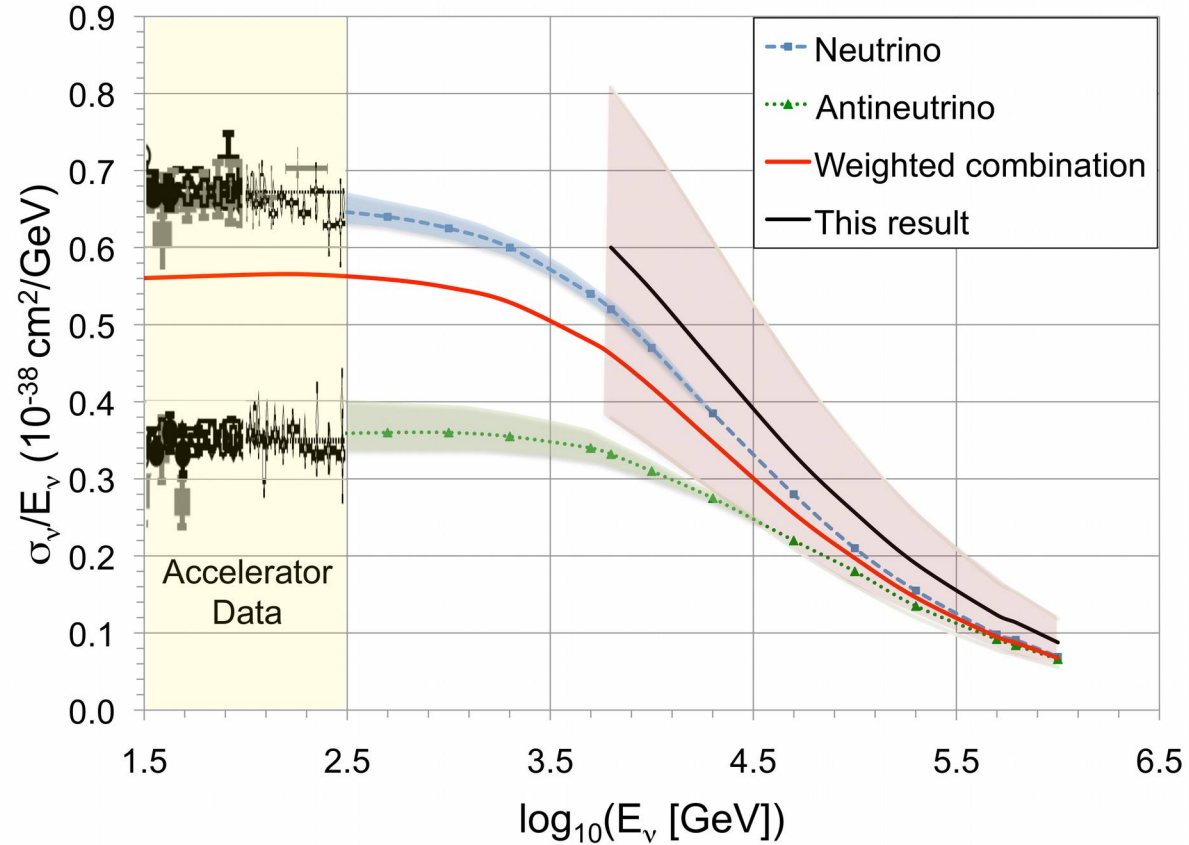
Marginalized cross section in each bin

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

E_ν [TeV]	$\langle E_\nu \rangle$ [TeV]	$\langle \sigma_{\bar{\nu} N}^{\text{CC}} / \sigma_{\nu N}^{\text{CC}} \rangle$	$\log_{10}[\frac{1}{2}(\sigma_{\nu N}^{\text{CC}} + \sigma_{\bar{\nu} N}^{\text{CC}})/\text{cm}^2]$
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	$> -33.21 (1\sigma)$

Using through-going muons instead

- ▶ Use $\sim 10^4$ 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 $\sigma_{\text{obs}}/\sigma_{\text{SM}}$
 $1.30_{-0.19}^{+0.21}$ (stat.) $_{-0.43}^{+0.39}$ (syst.)
- ▶ All events grouped in a single
energy bin 6–980 TeV



IceCube, *Nature* 2017

Neutrino zenith angle distribution

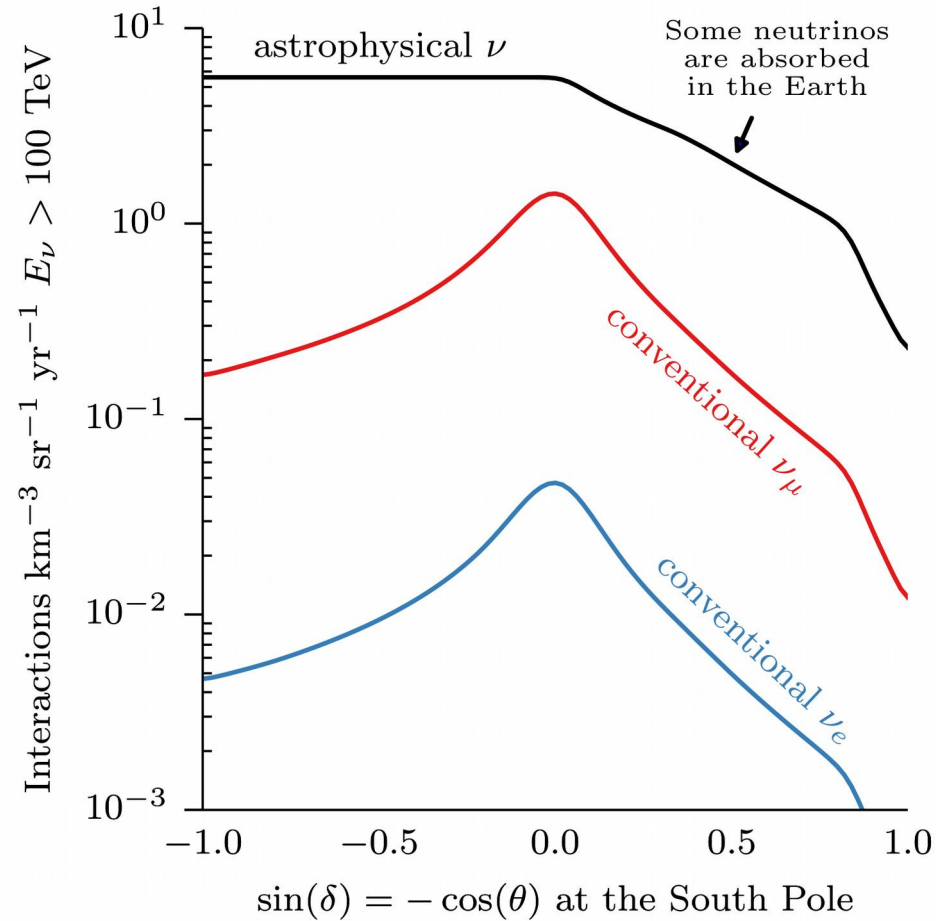
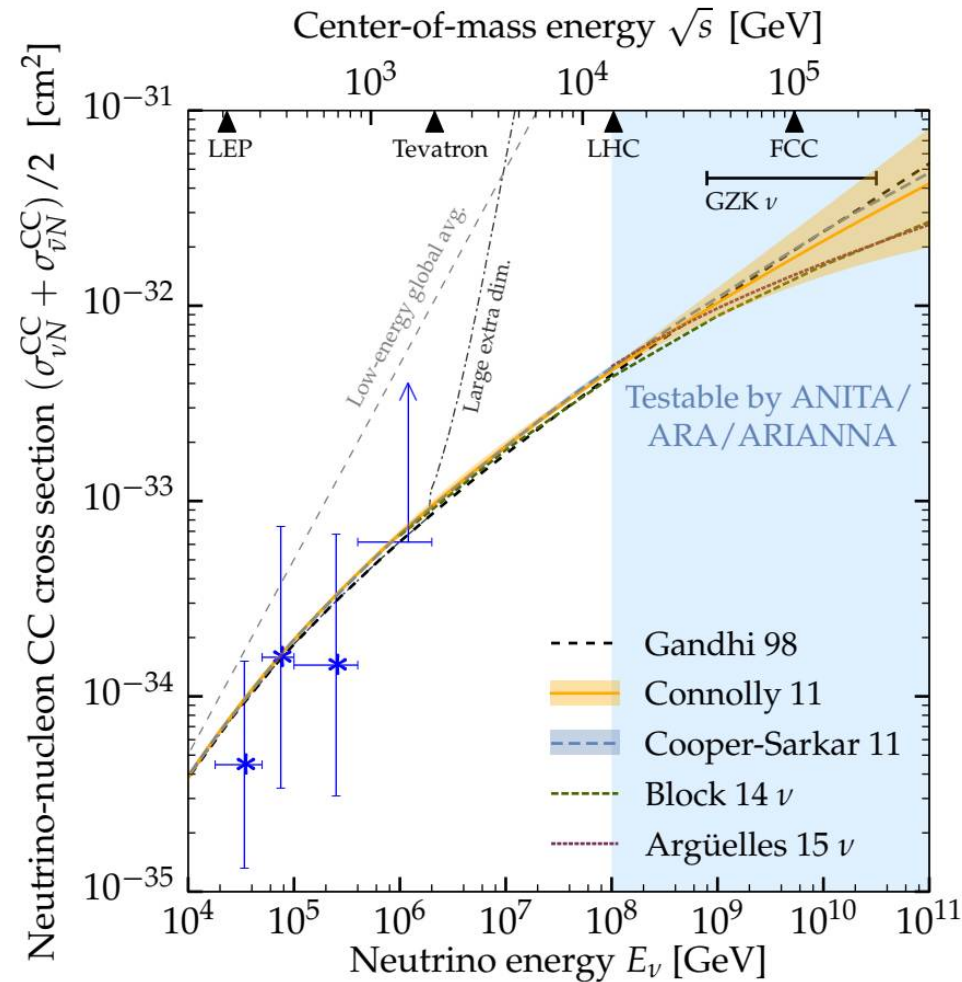


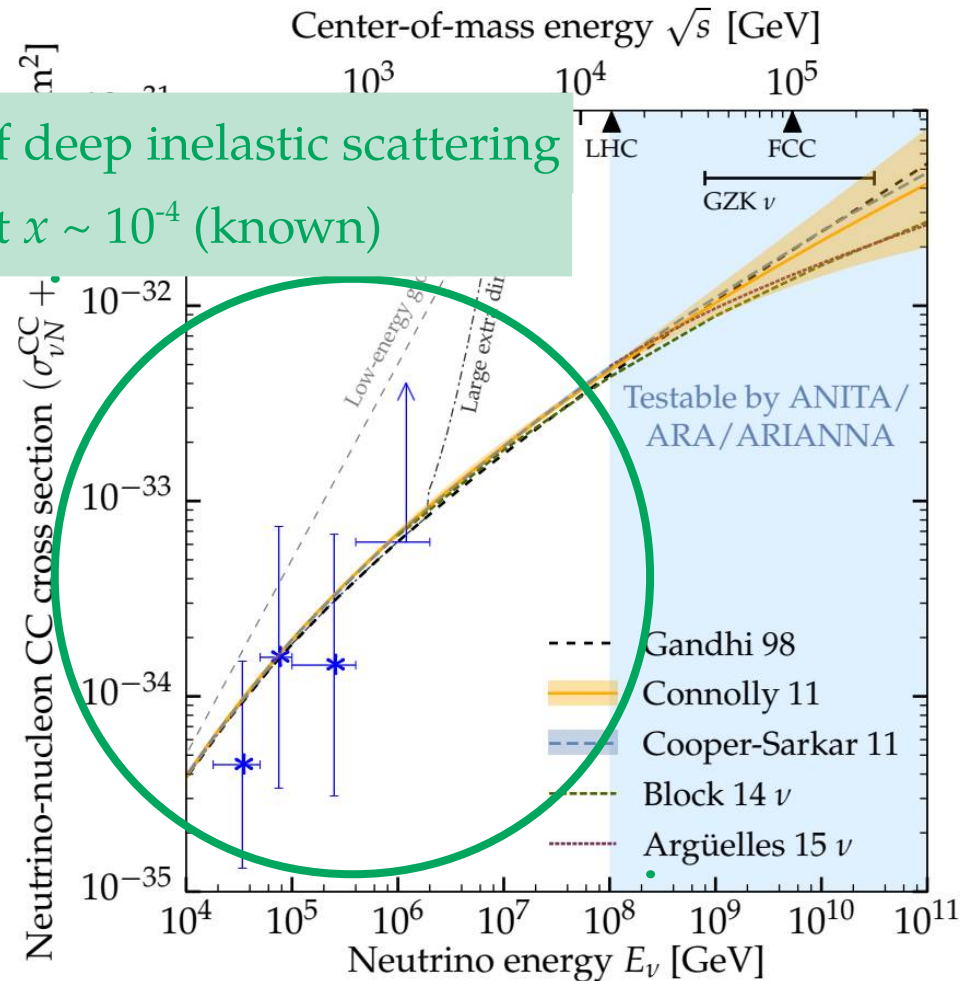
Figure by
Jakob Van Santen
ICRC 2017

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

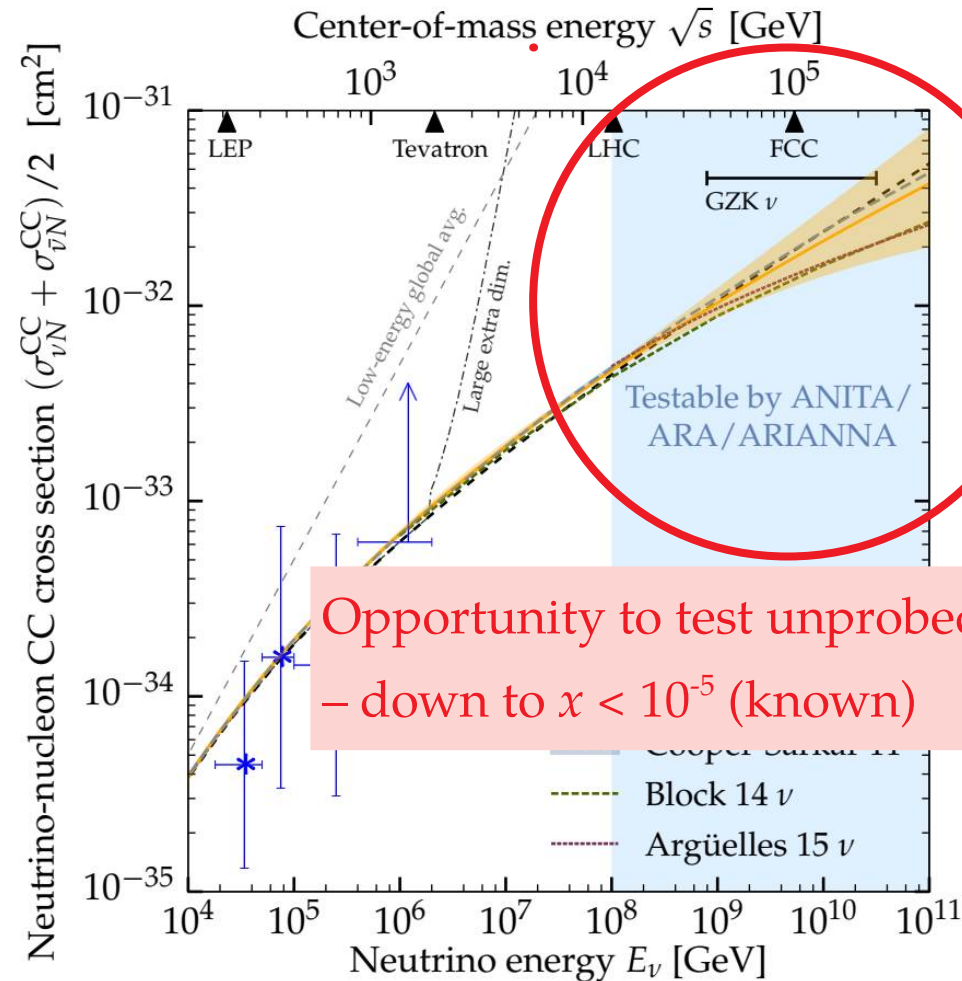


IceCube *now* vs. ANITA/ARA/ARIANNA *in the future*

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)

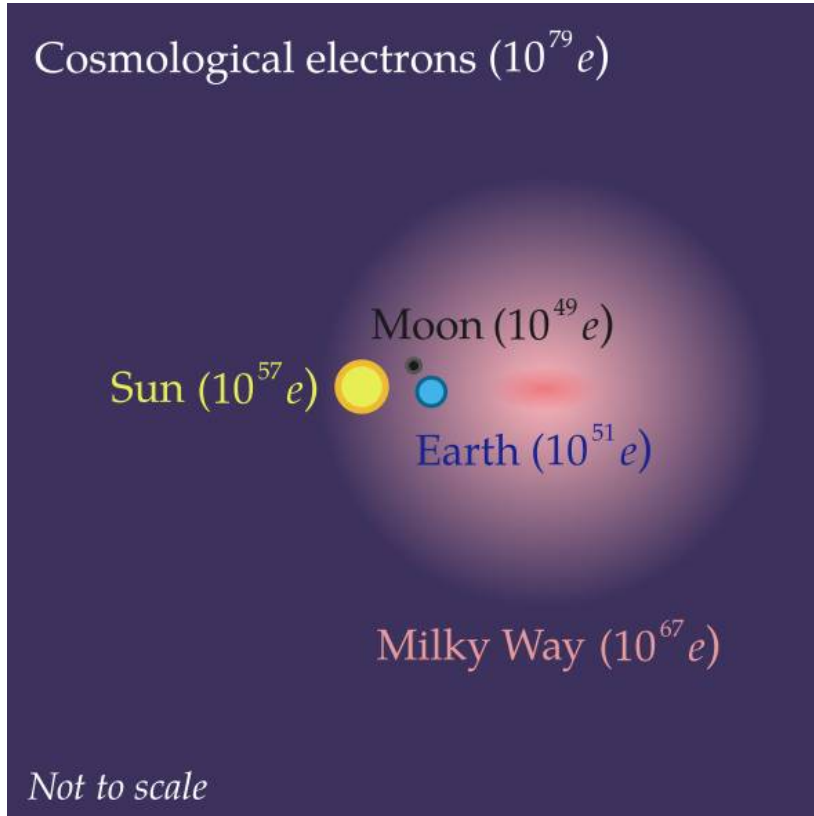
The new ν physics matrix

Where it happens

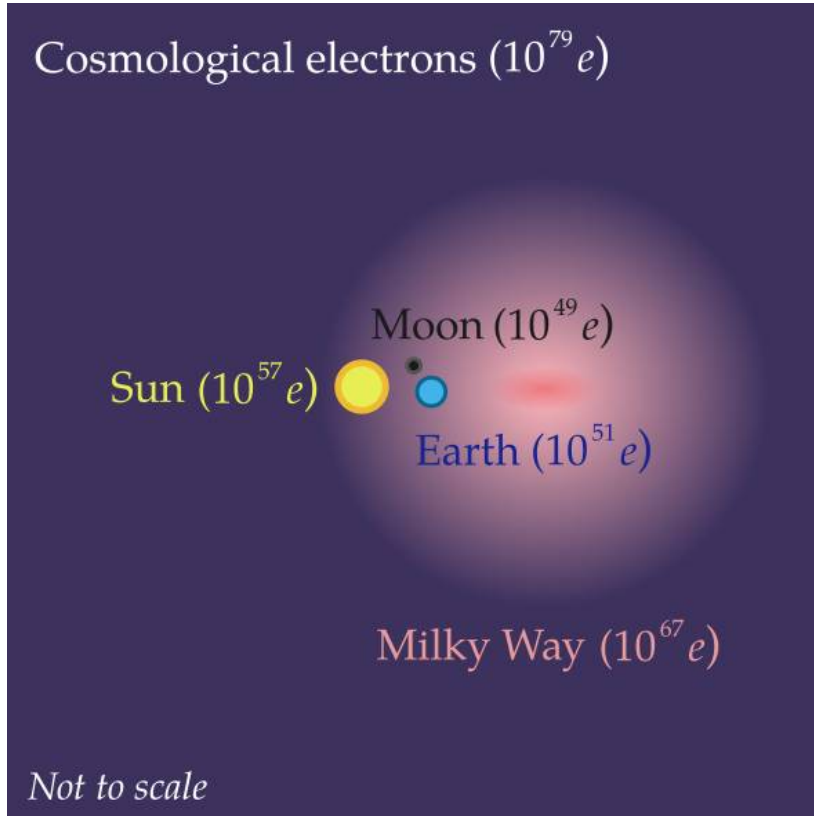
What it changes		At source	During propagation	At detection
	Energy	Matter effects	New interactions, sterile neutrinos	New resonances
	Direction	DM decay / annihilation	New ν -N, ν -DM interactions	Anomalous ν magnetic moment
	Topology / flavor	Matter effects	ν decay, sterile ν , new operators	Non-standard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

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

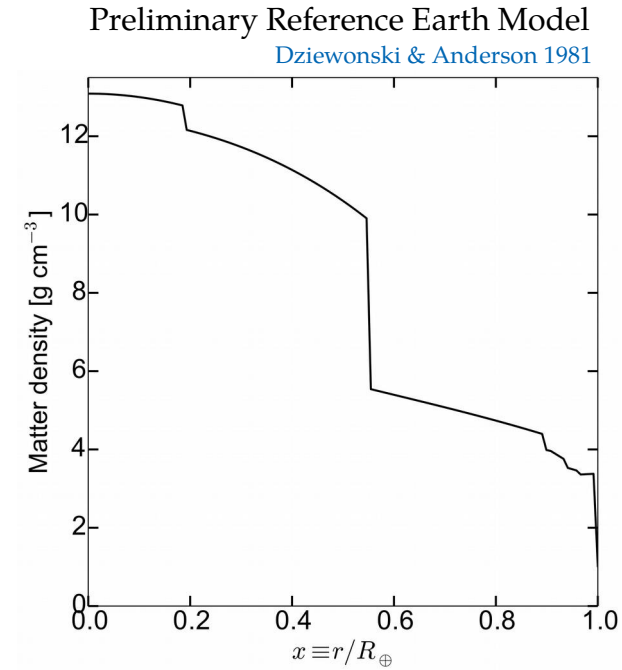
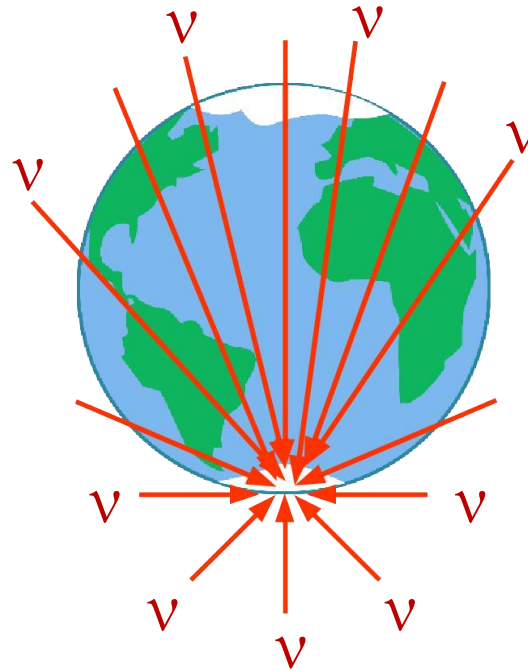
The total potential



The total potential



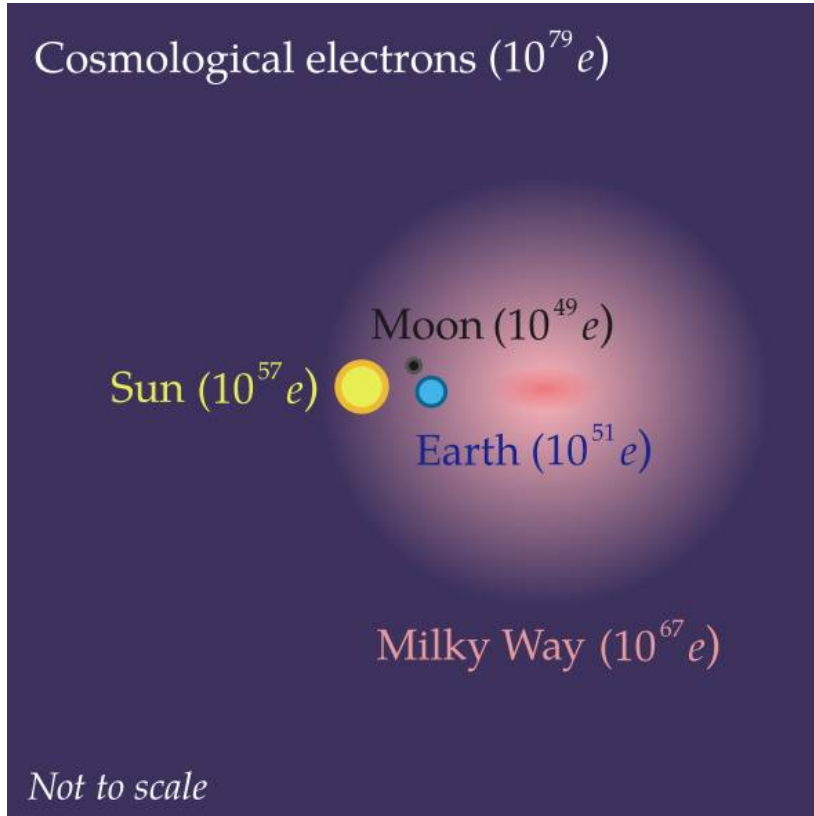
Earth:



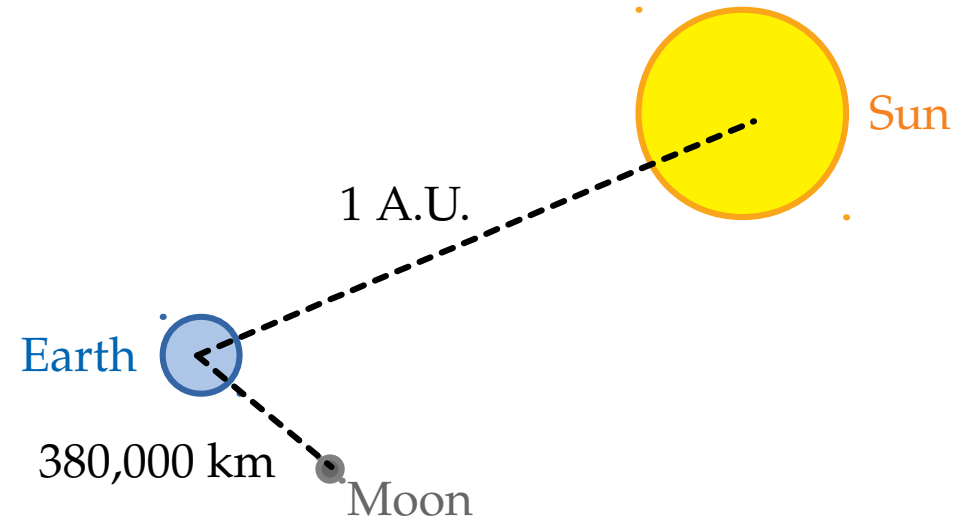
Neutrinos traverse different electron column depths

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

The total potential



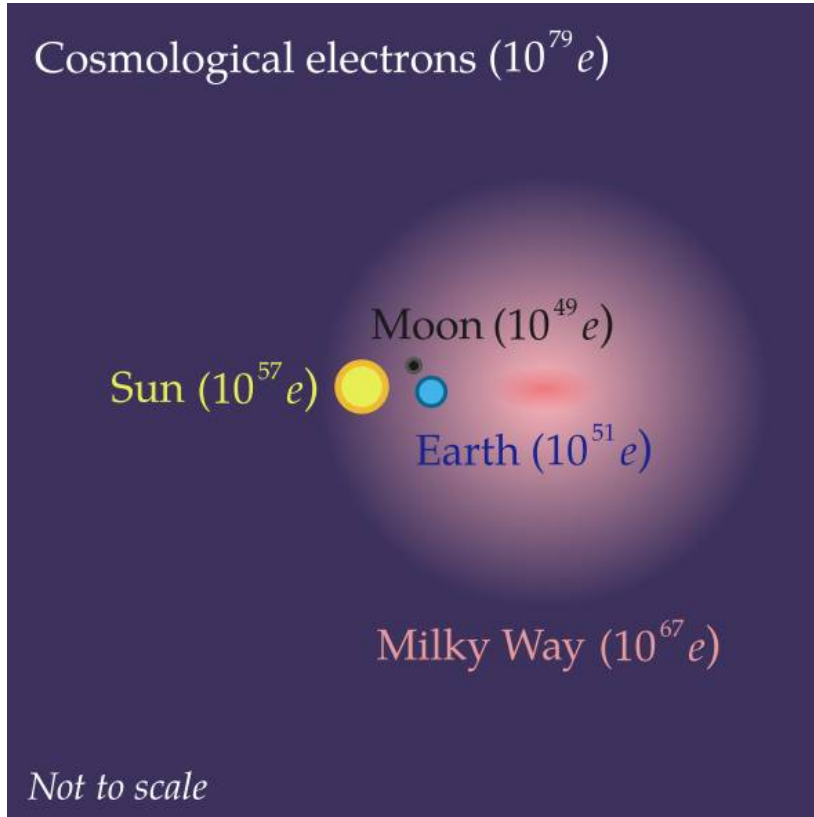
Moon and Sun:



Treated as point sources of electrons

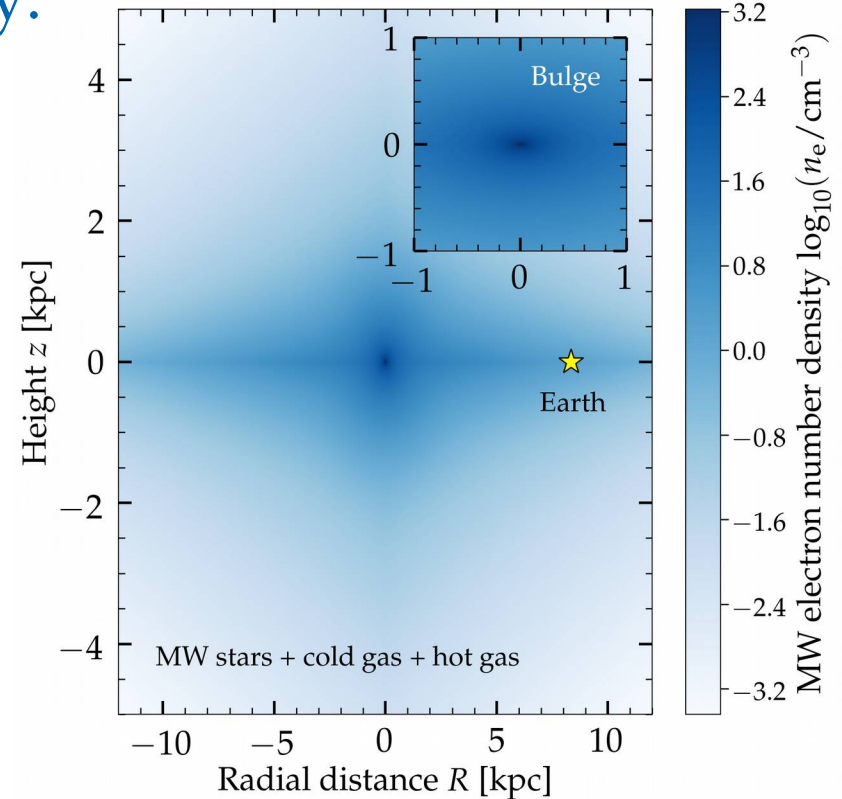
$$V_{e\beta} = V_{e\beta}^{\oplus} + V_{e\beta}^{\text{Moon}} + V_{e\beta}^{\odot}$$

The total potential



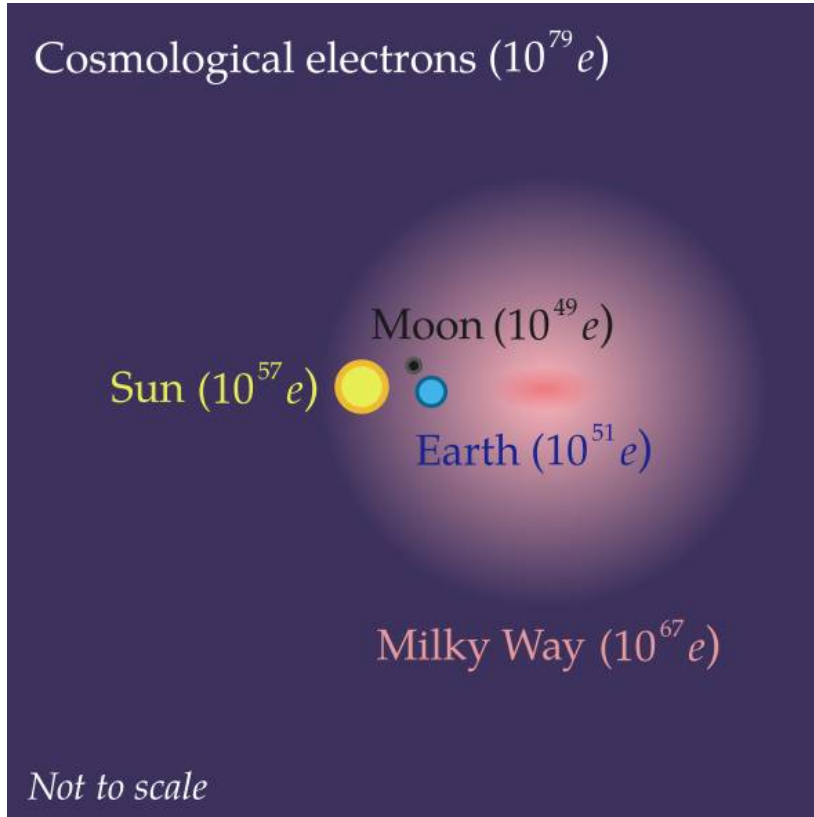
Milky Way:

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



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

The total potential

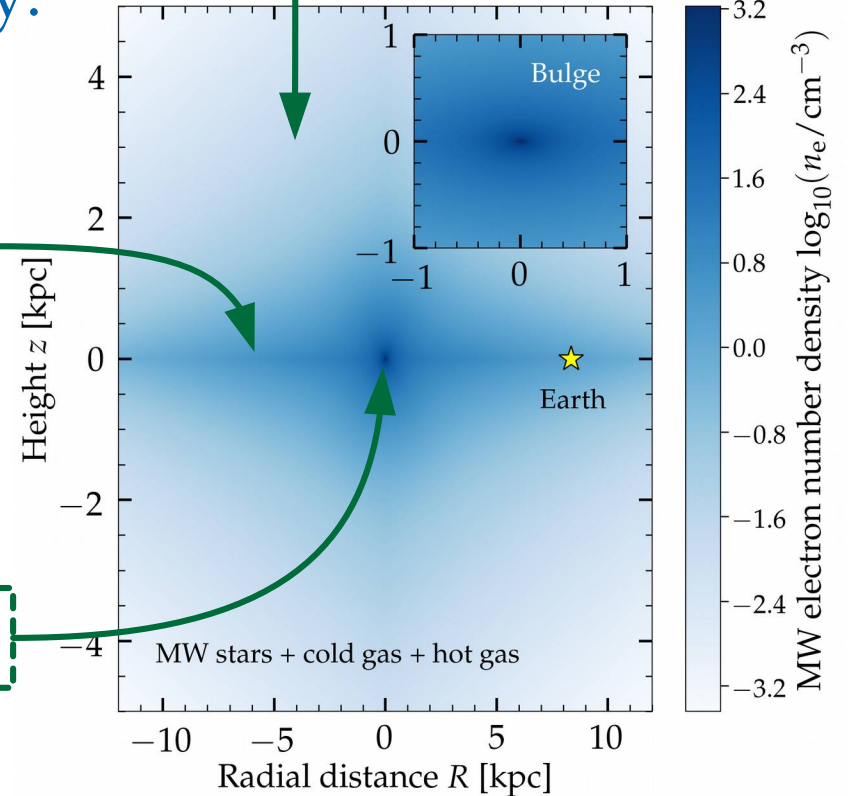


Milky Way:

Thick & thin discs of stars
+ cold gas

Central bulge

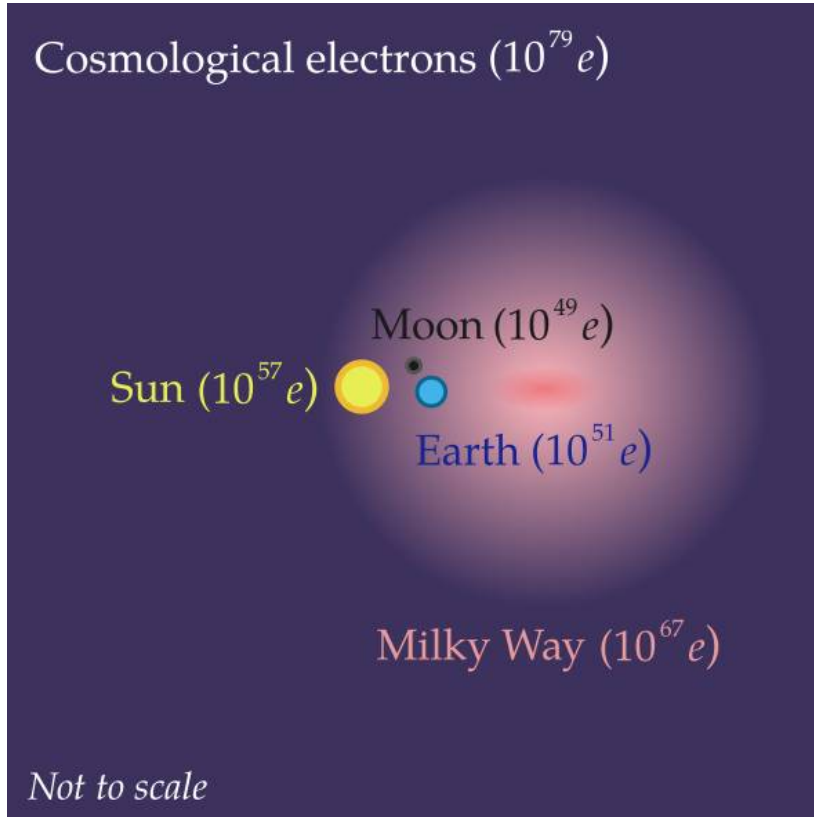
Halo of hot gas



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

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

The total potential



Cosmological electrons:

Electrons
uniformly
distributed

Causal horizon
(15 Gpc at $z=0$)

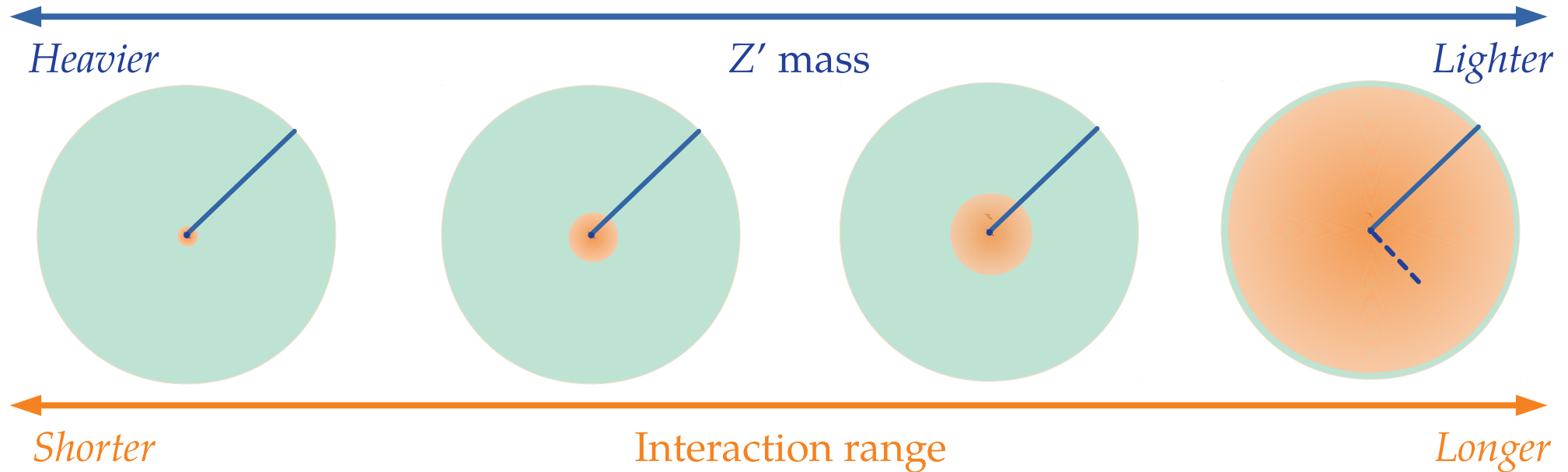
Electrons here
contribute fully
to the potential

Electrons here
are screened

Interaction range

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

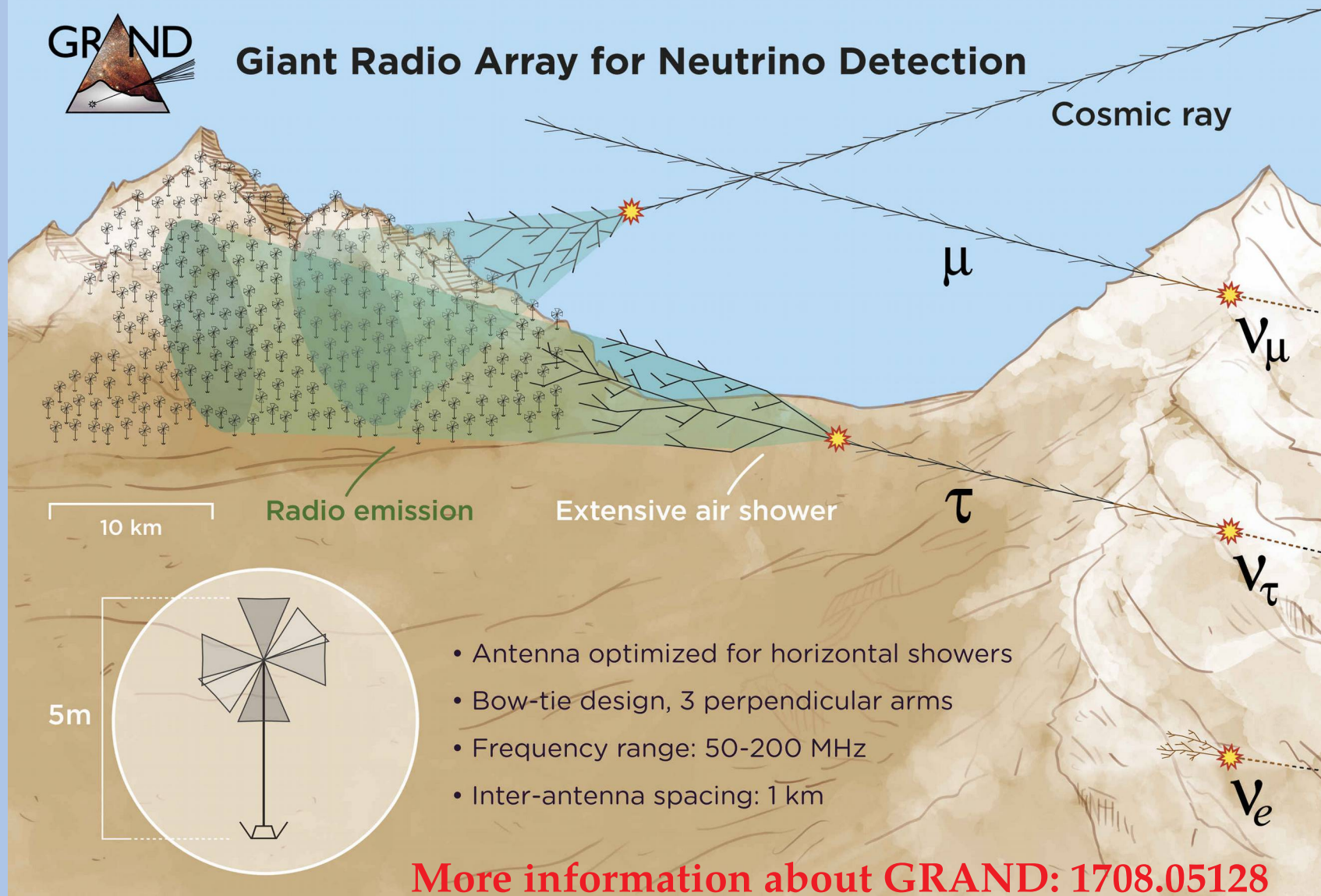
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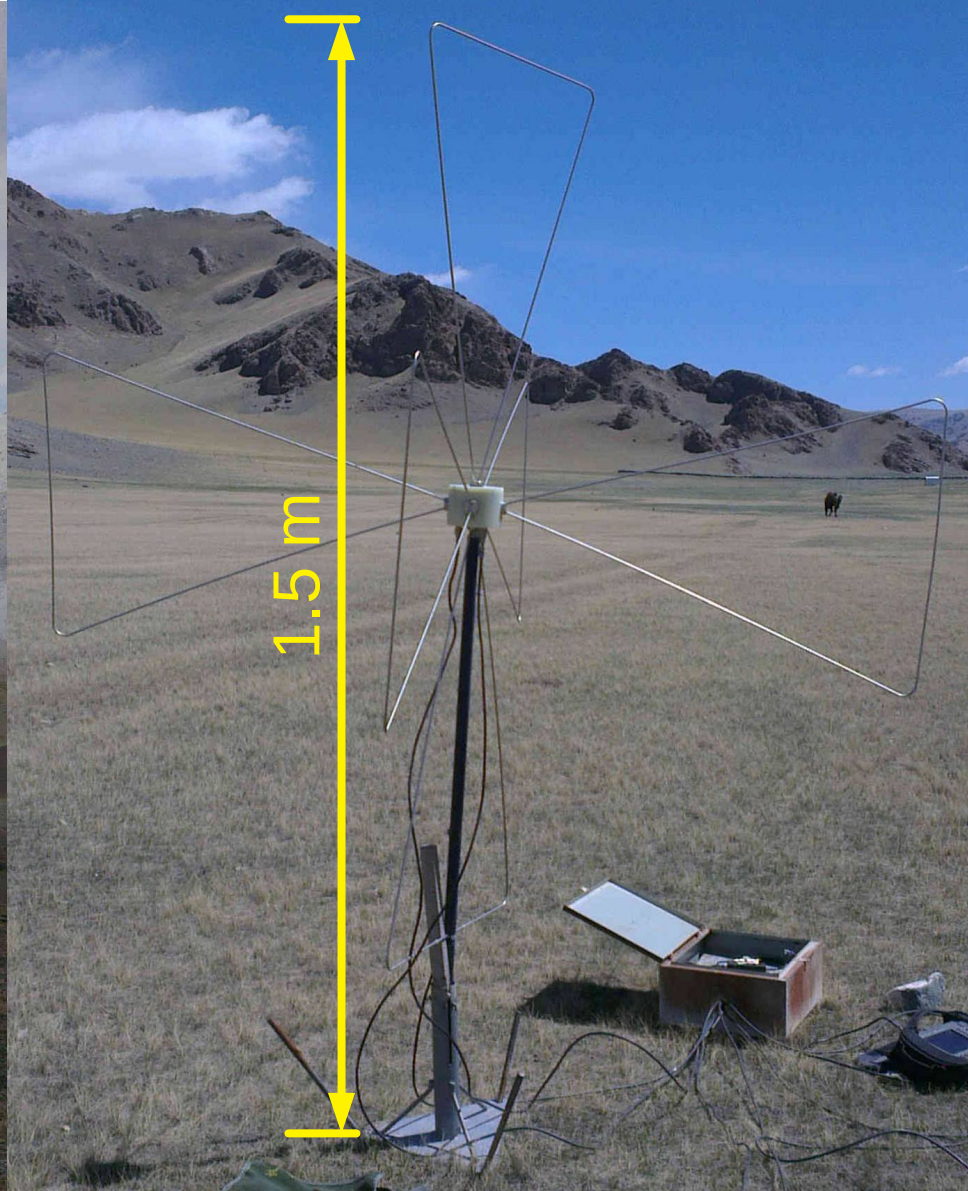


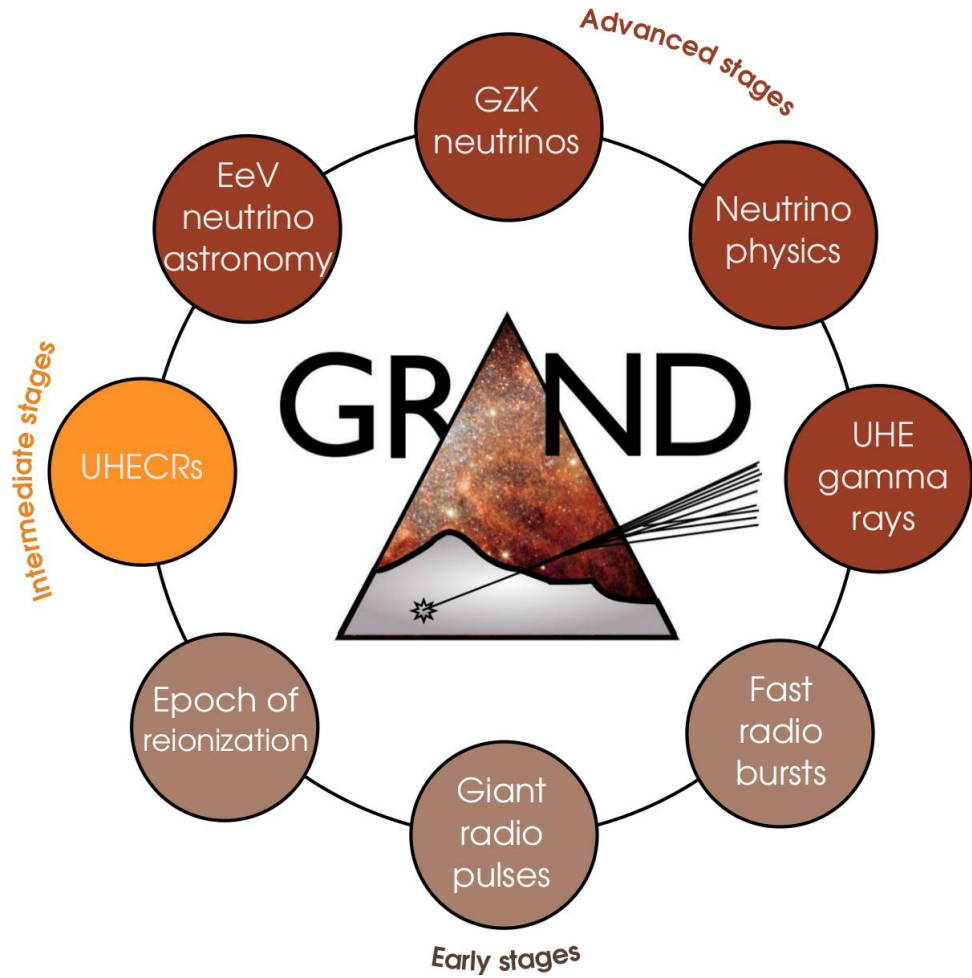
Giant Radio Array for Neutrino Detection

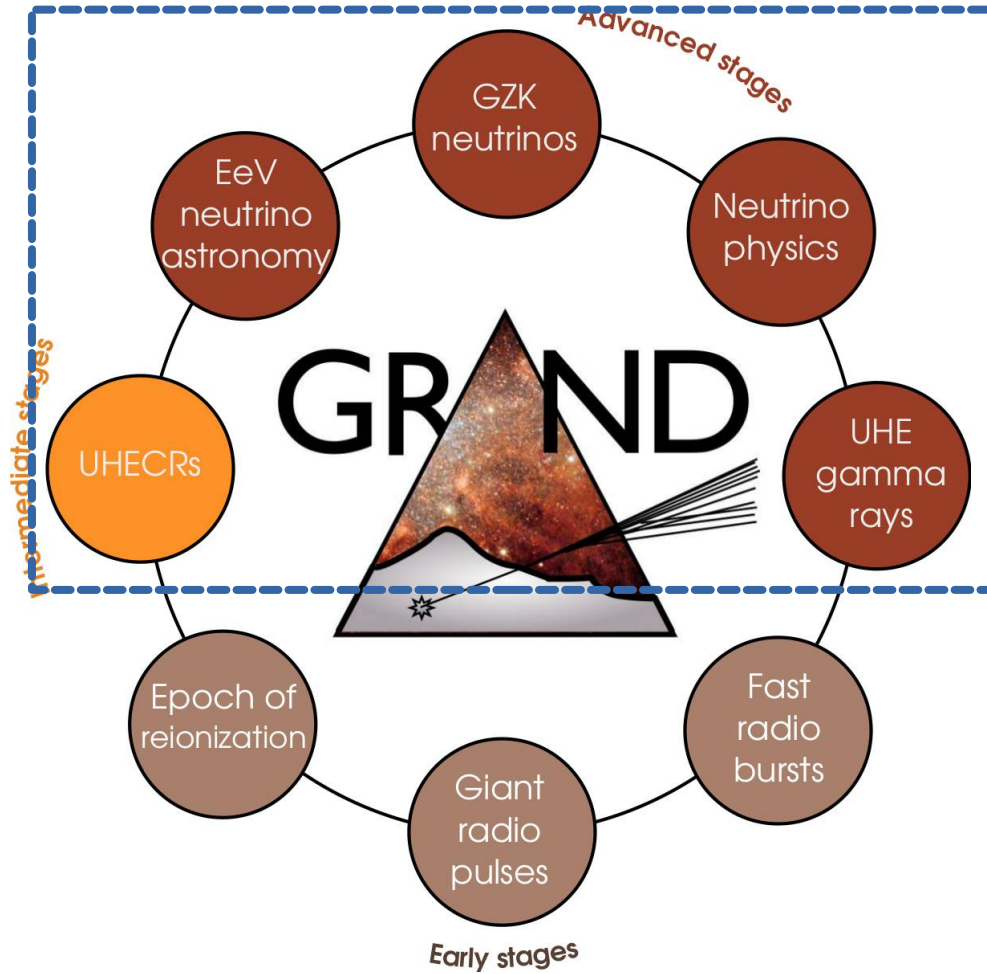


More information about GRAND: 1708.05128

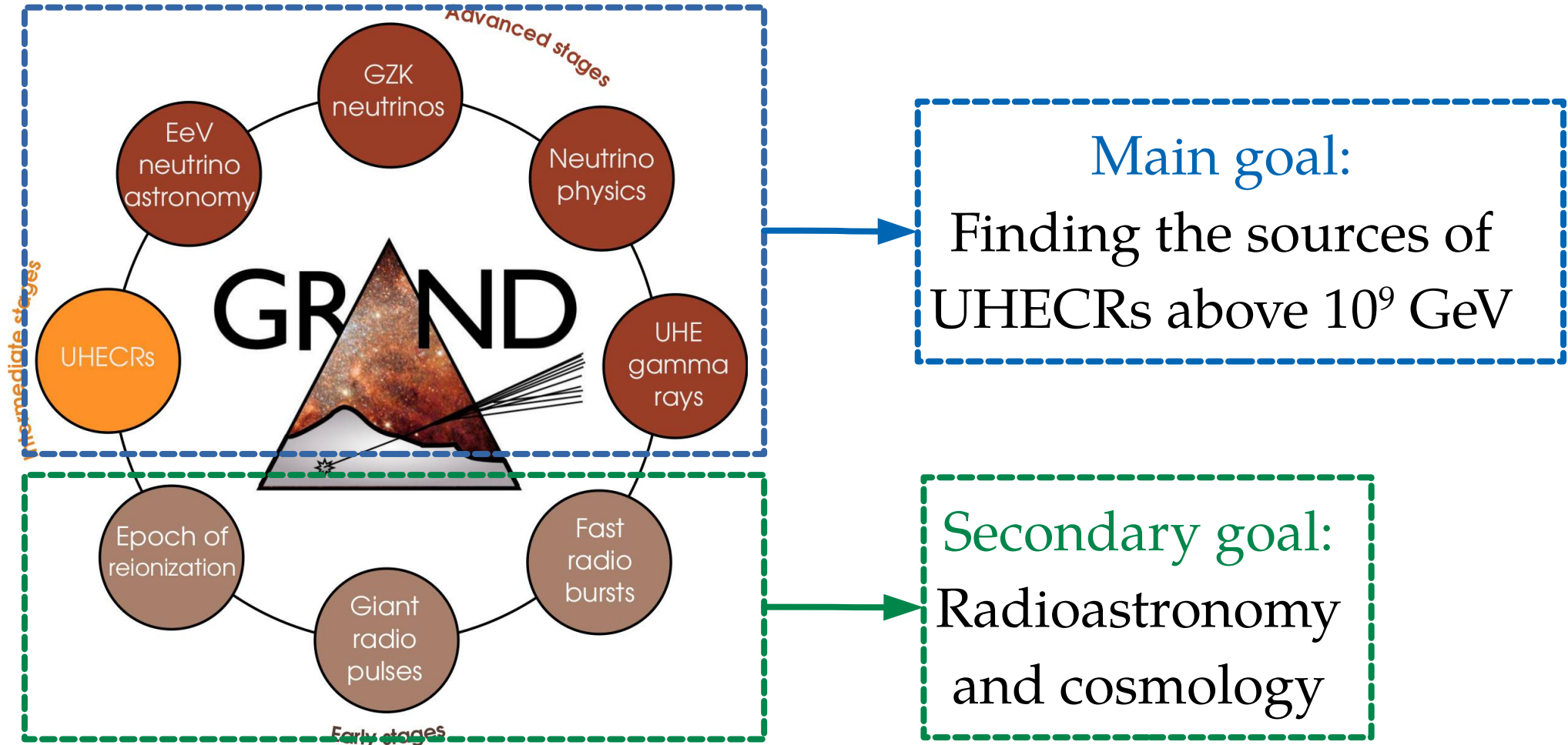




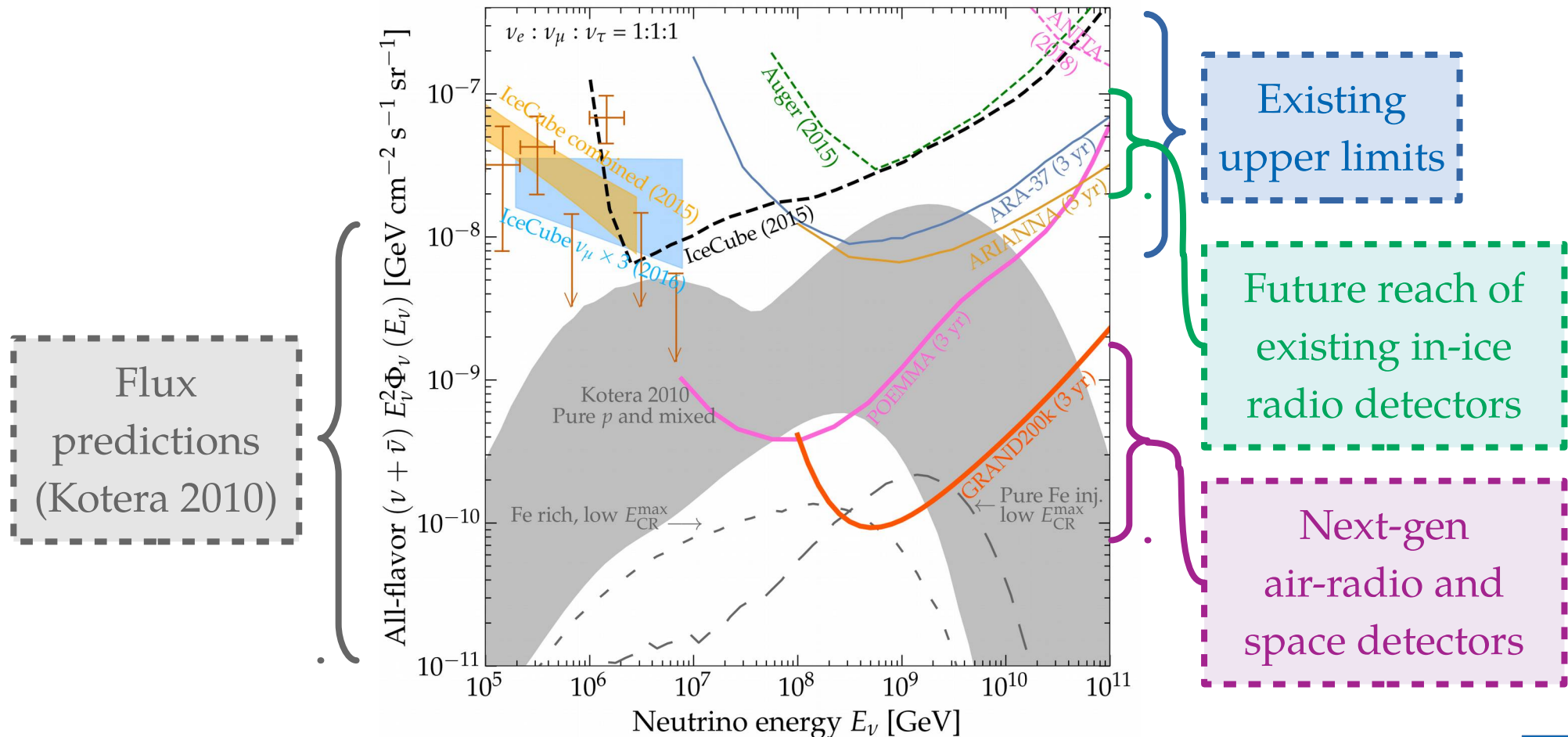




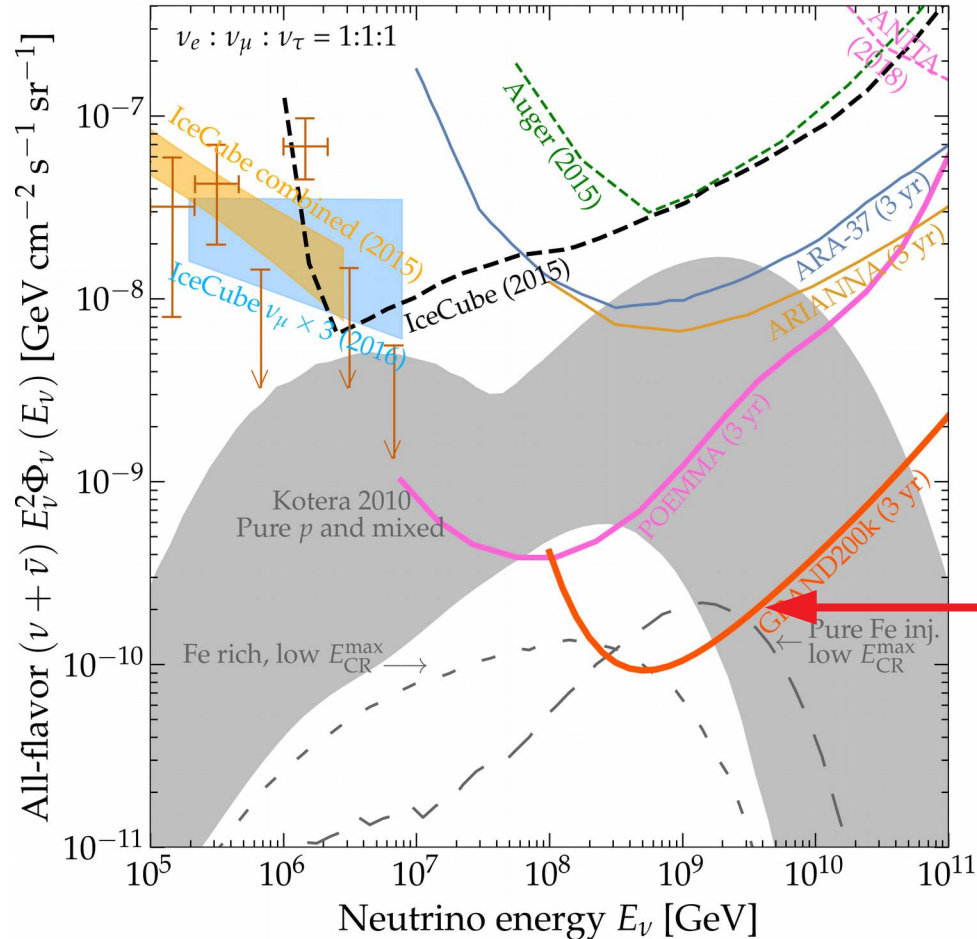
Main goal:
Finding the sources of
UHECRs above 10^9 GeV



UHE Neutrinos – Where Do We Go?



UHE Neutrinos – Where Do We Go?



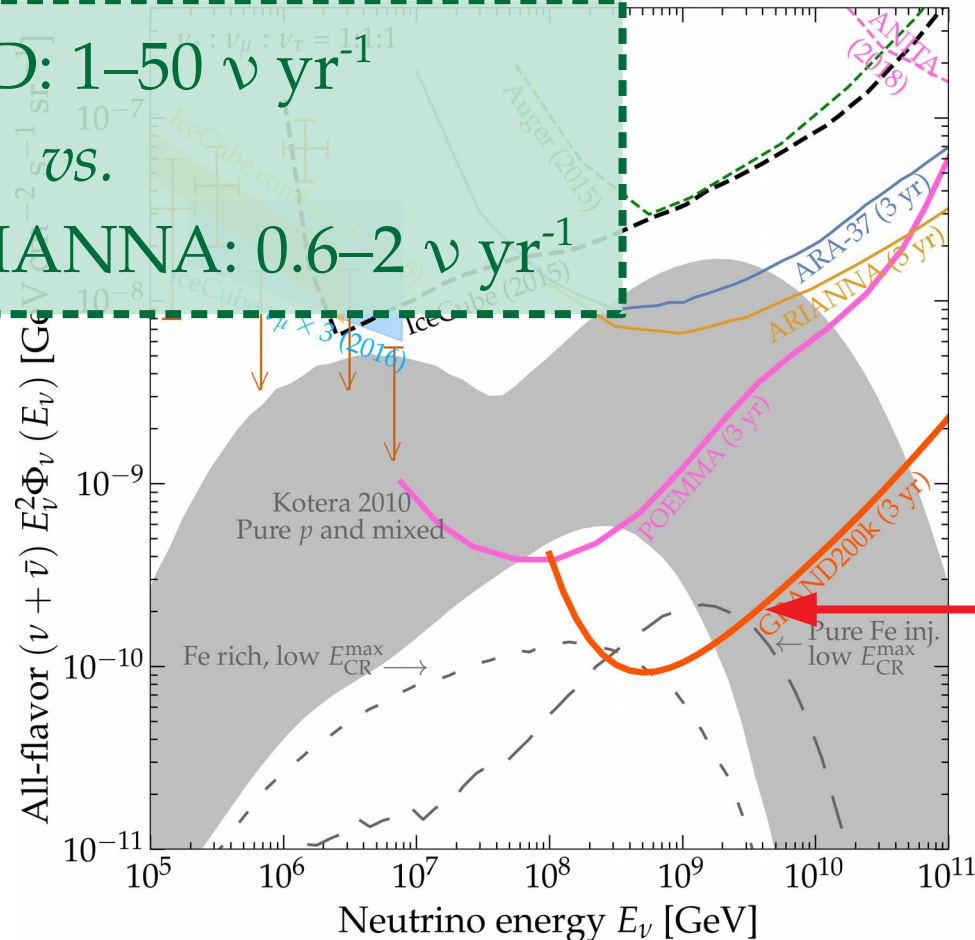
GRAND will probe
very low fluxes at
 $\sim 10^9$ GeV

UHE Neutrinos – Where Do We Go?

GRAND: $1\text{--}50 \nu \text{ yr}^{-1}$

vs.

Full ARA, ARIANNA: $0.6\text{--}2 \nu \text{ yr}^{-1}$



GRAND will probe
very low fluxes at
 $\sim 10^9$ GeV

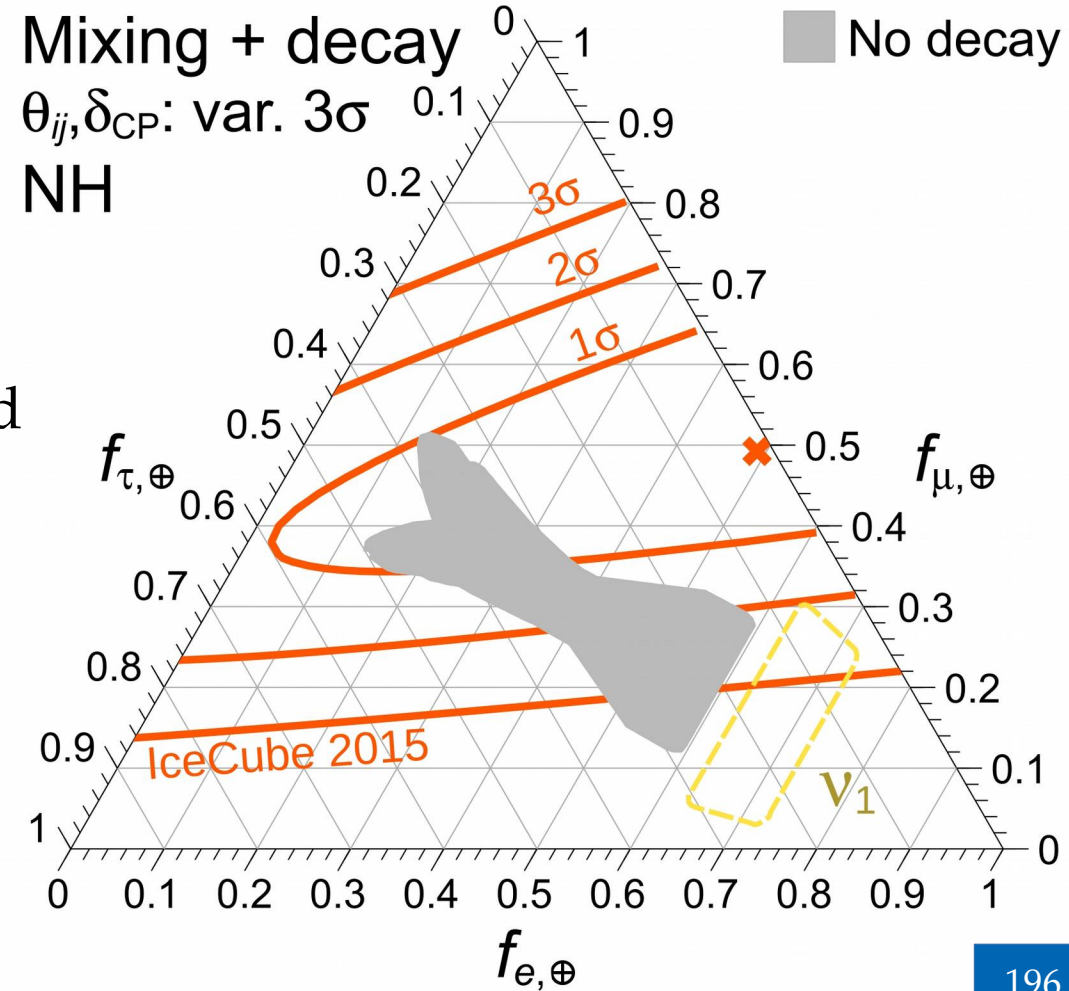
Measuring the neutrino lifetime

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



Measuring the neutrino lifetime

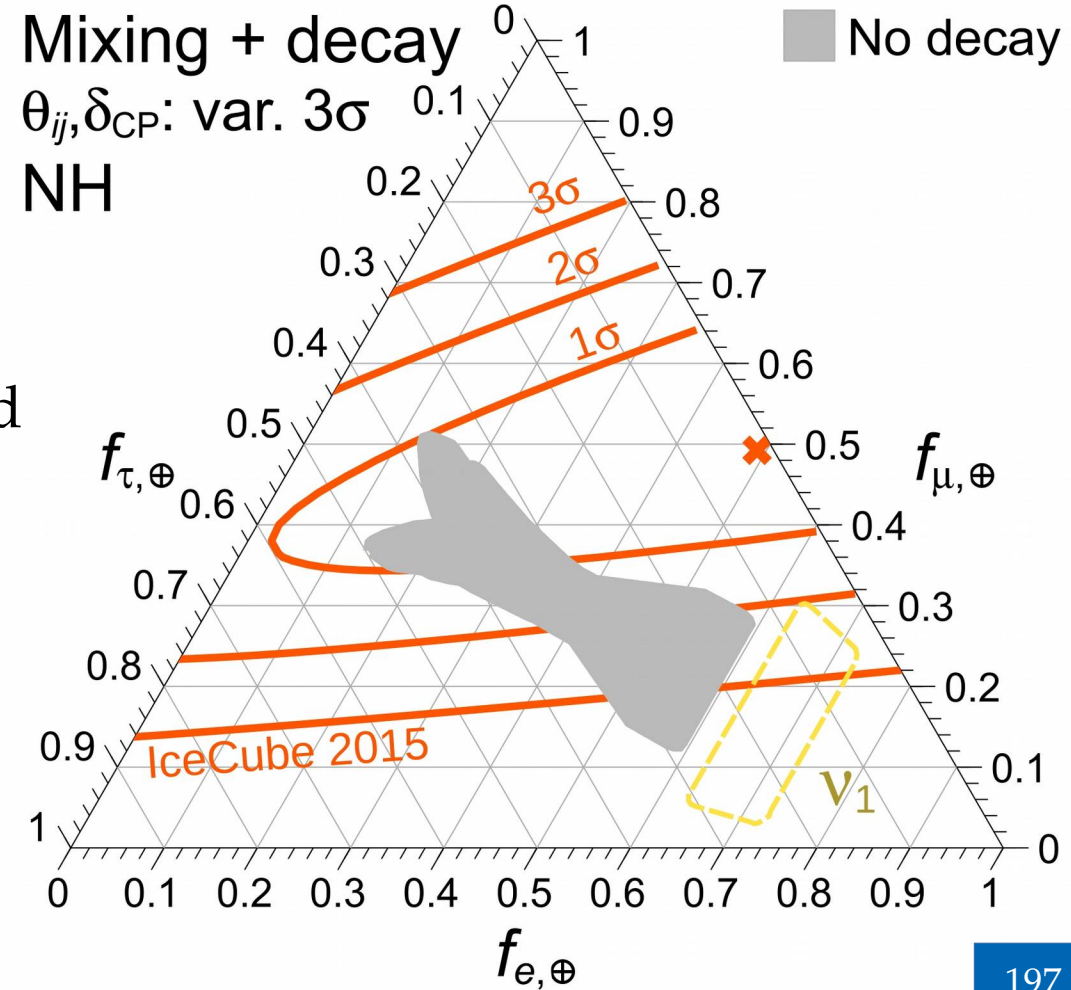
Fraction of ν_2, ν_3 remaining at Earth

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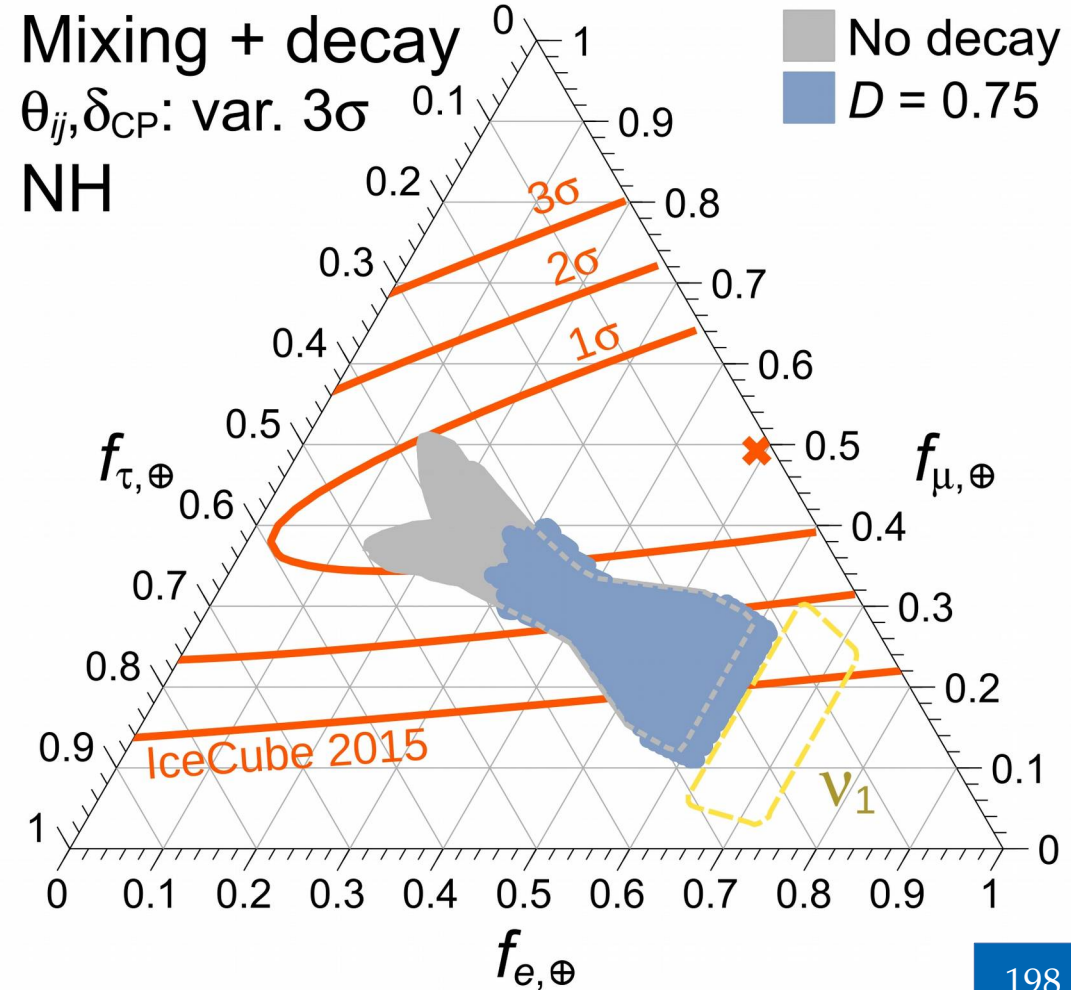
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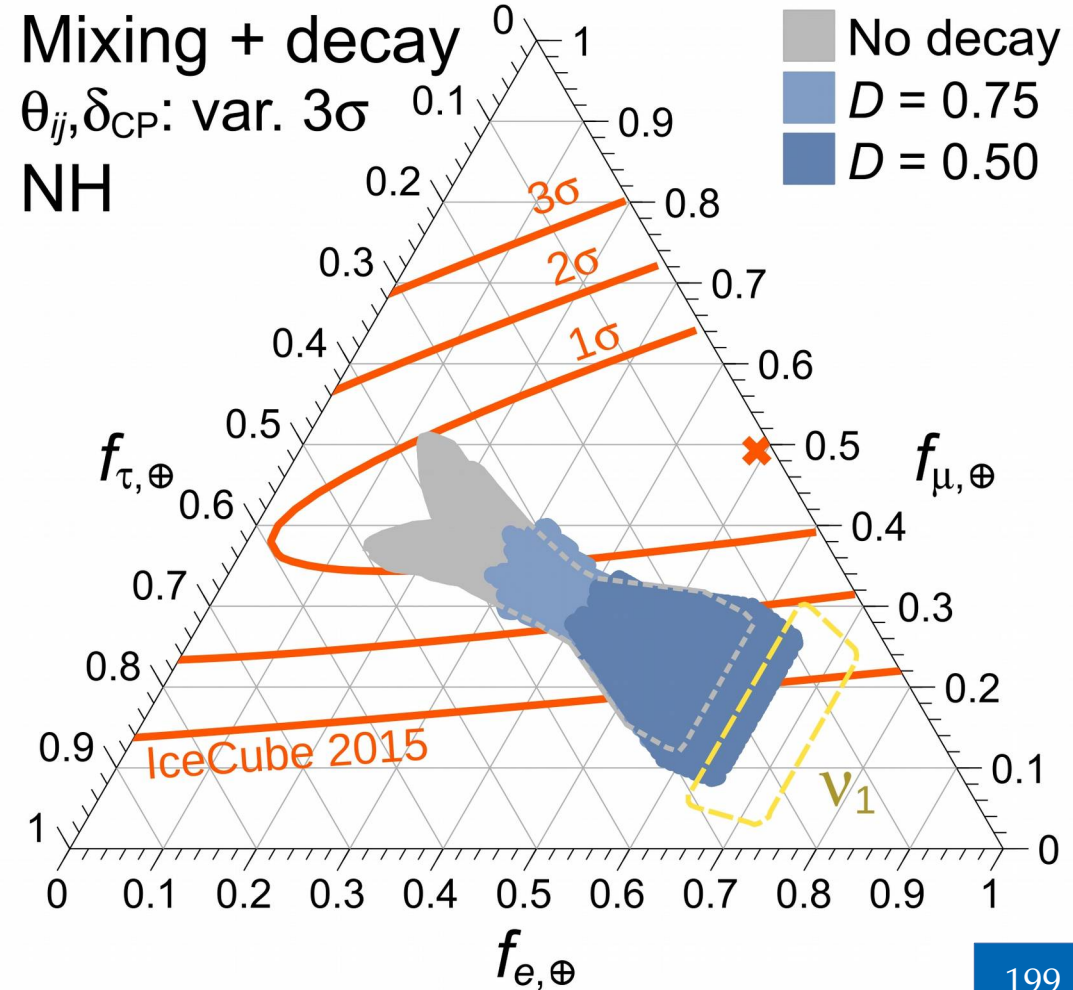
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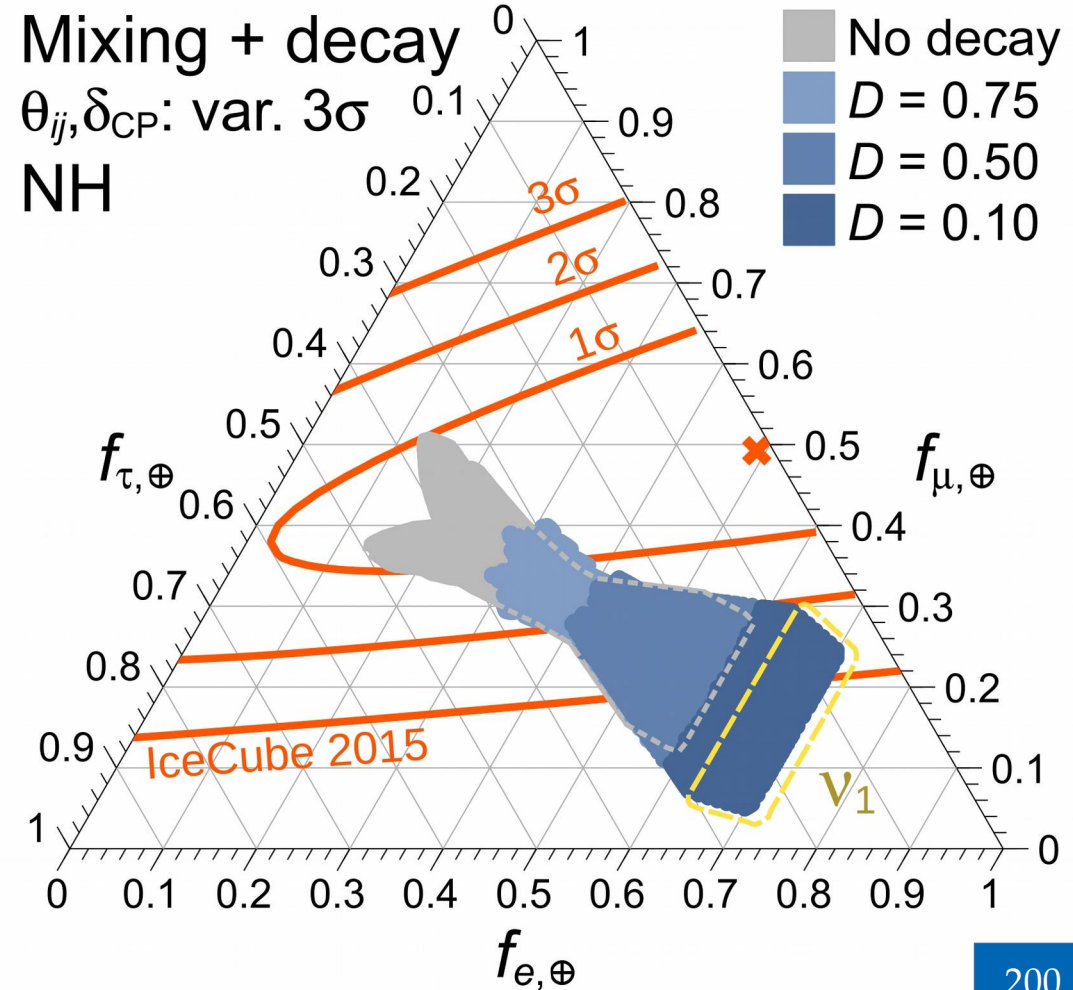
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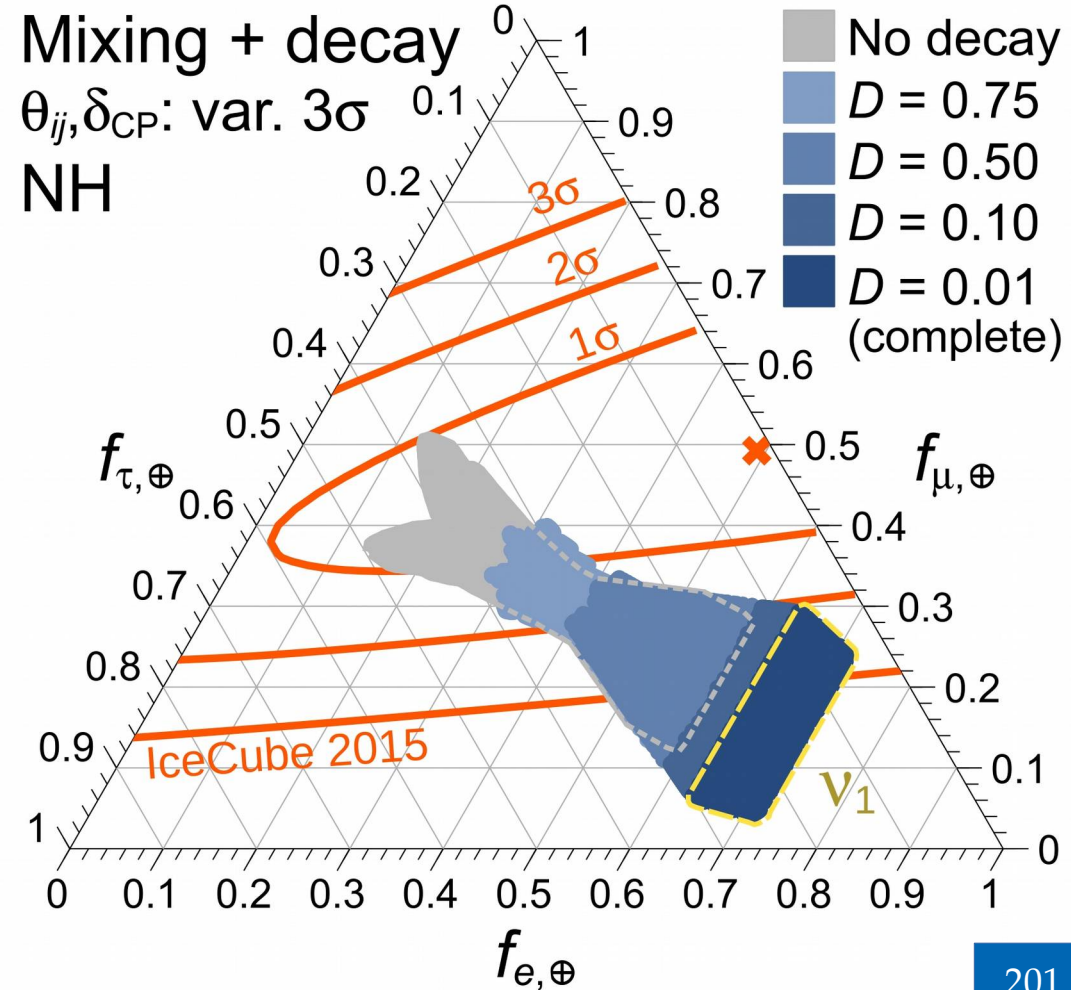
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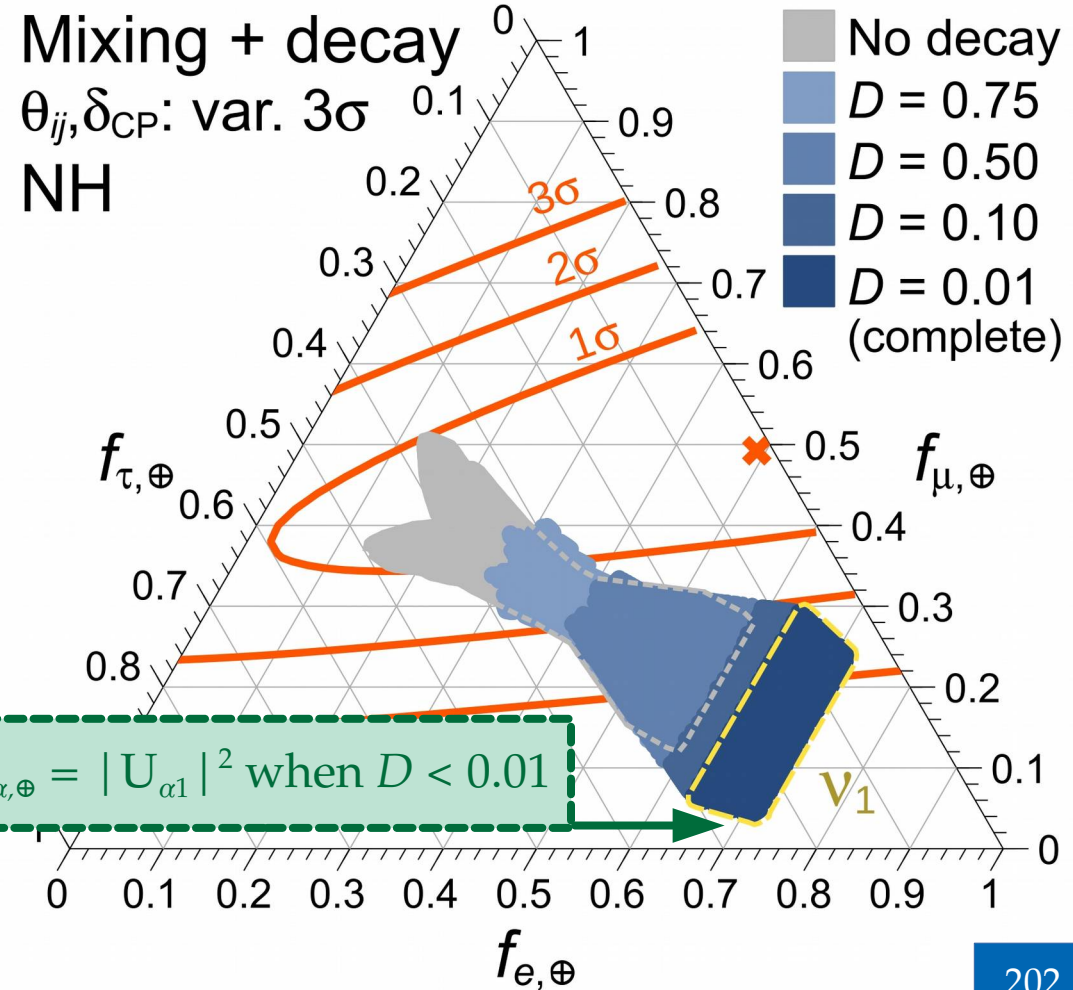
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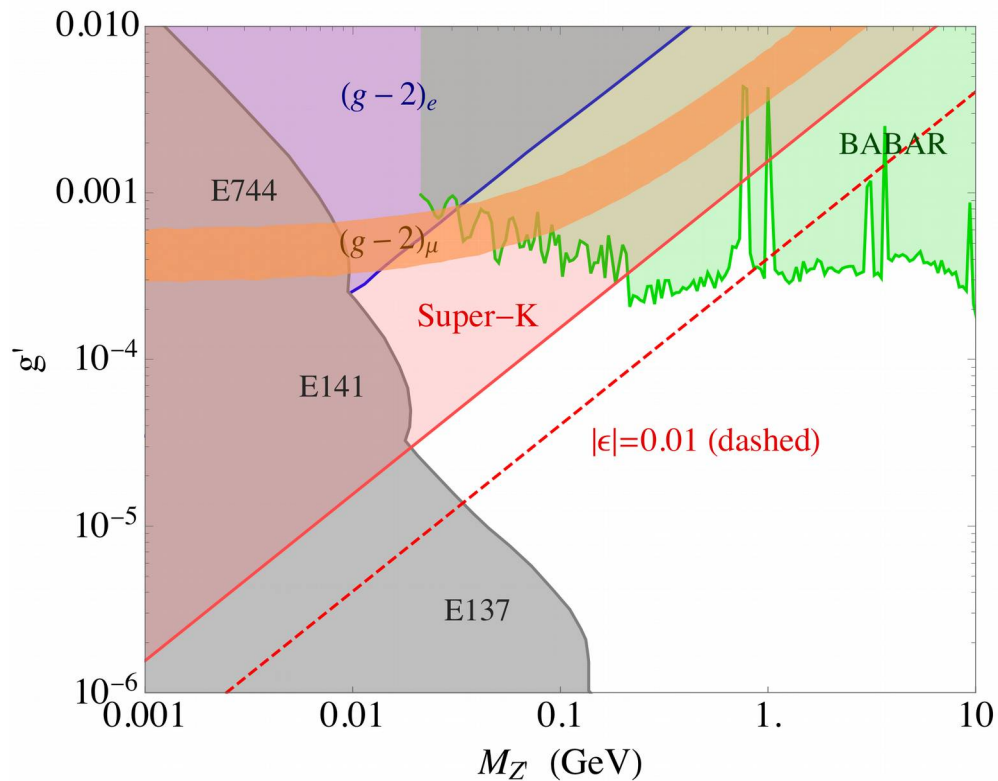
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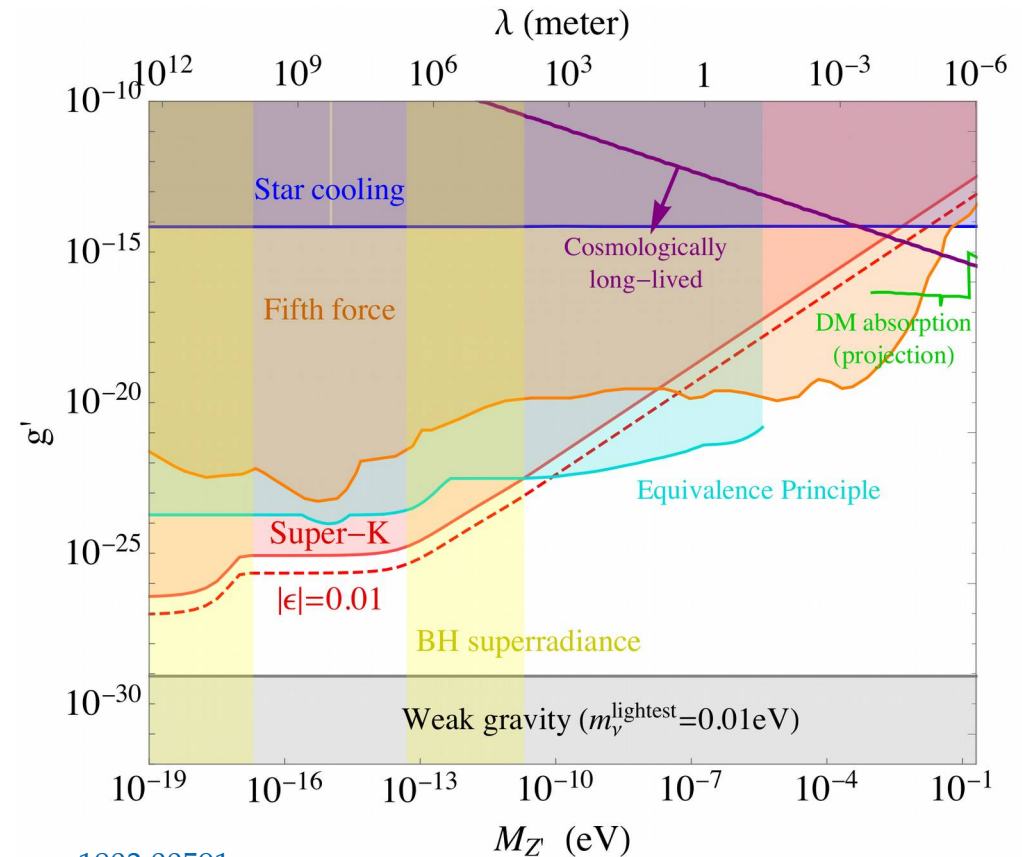
MB, Beacom, Murase, *PRD* 2017
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Current limits on the Z'

MeV–GeV masses



Sub-eV masses



M. Wise & Y. Zhang, 1803.00591

Connecting flavor-ratio predictions to experiment

- 1 Integrate potential in redshift, weighed by source number density
→ Assume star formation rate

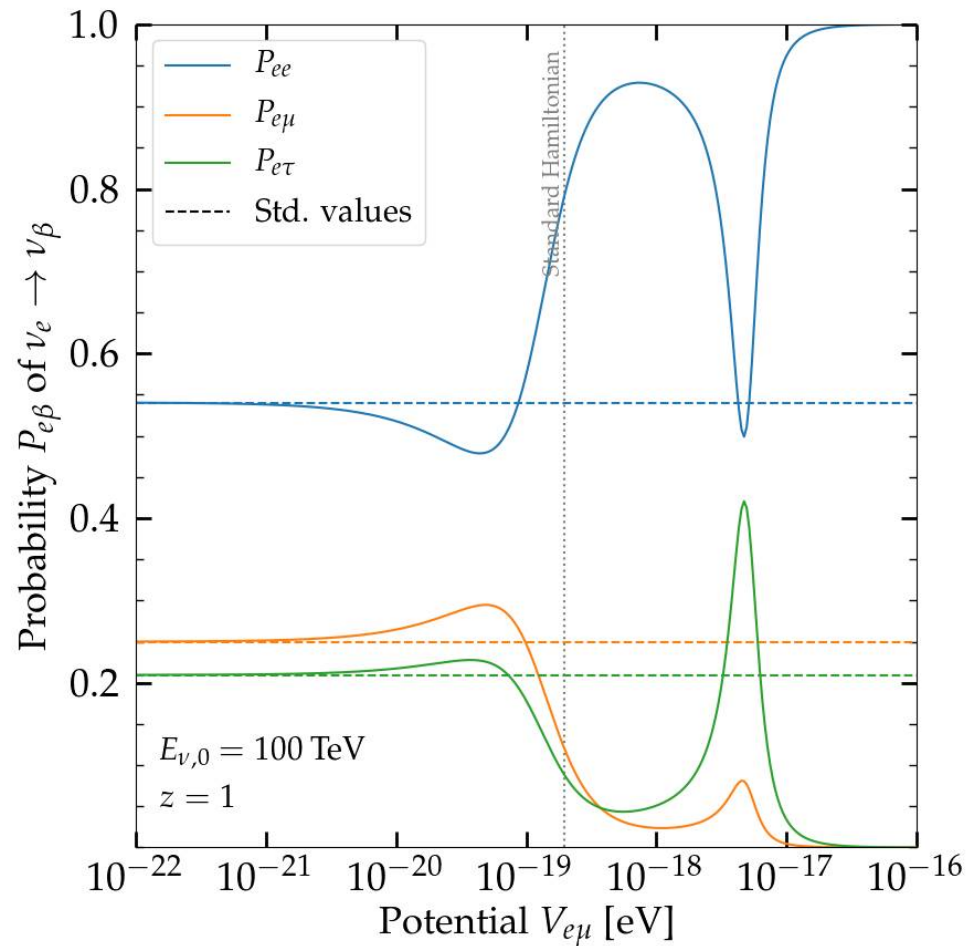
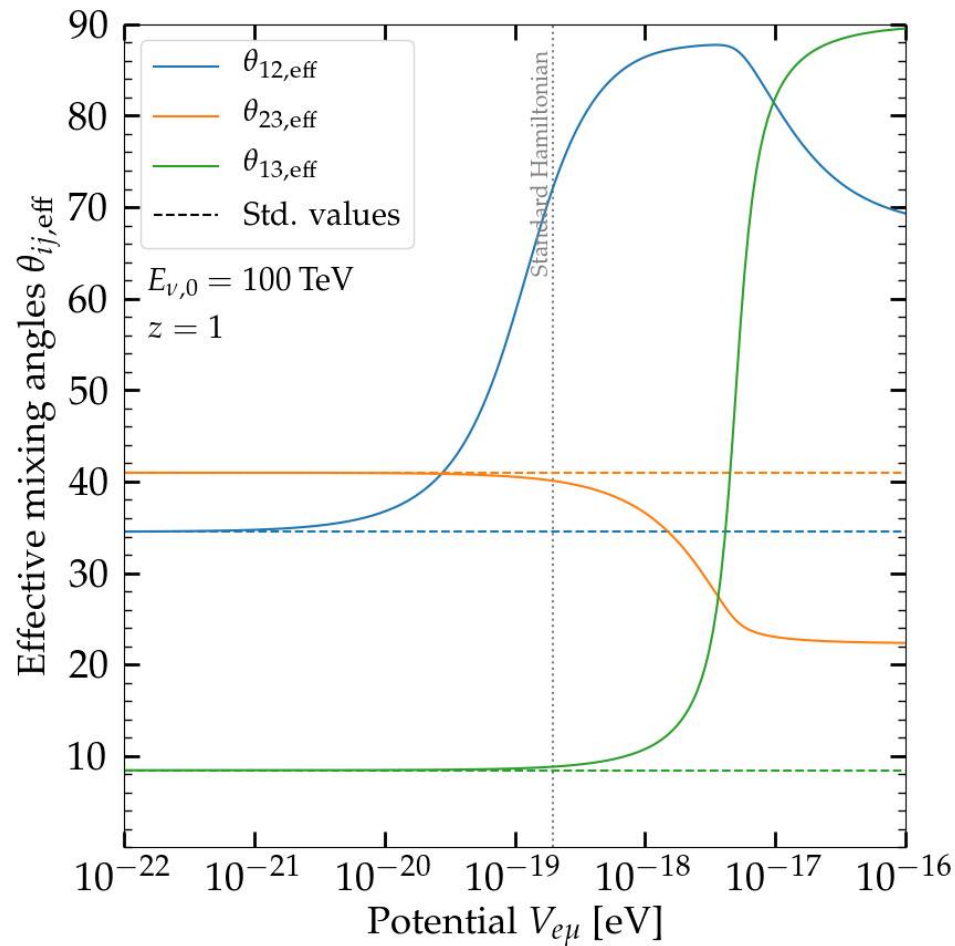
$$\langle V_{e\beta}^{\cos} \rangle \propto \int dz \, \rho_{\text{SFR}}(z) \cdot \frac{dV_c}{dz} \cdot V_{e\beta}^{\cos}(z)$$

Density of cosmological e grows with z

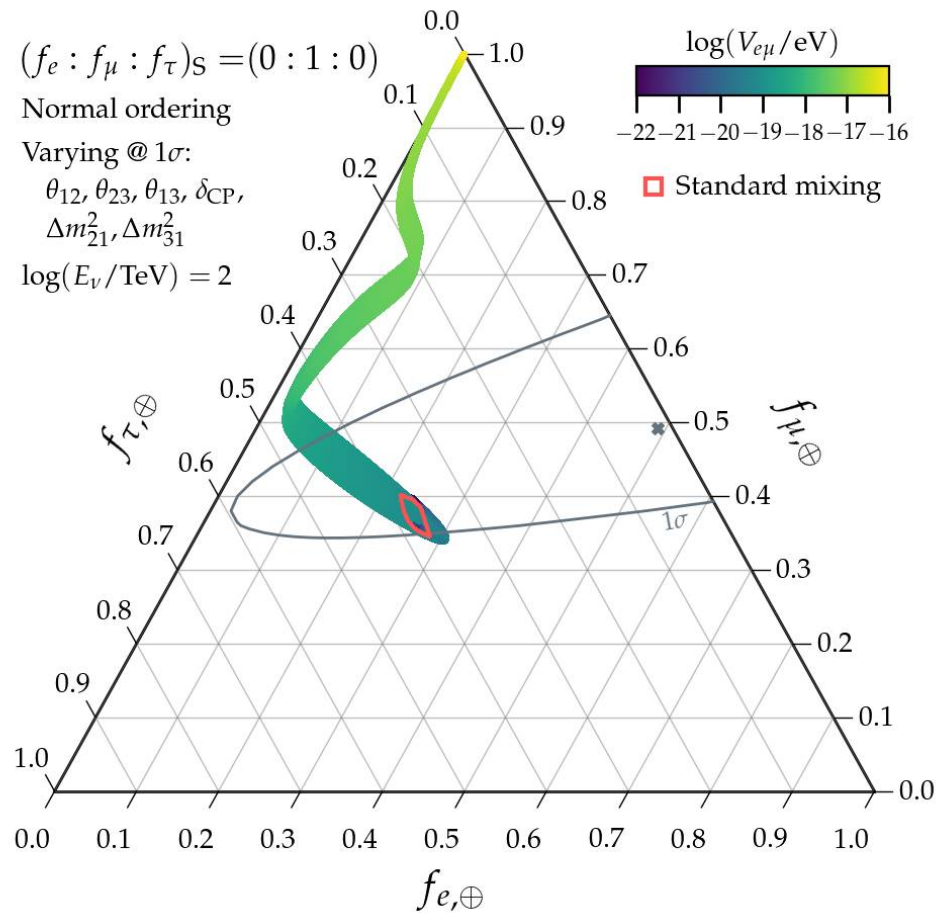
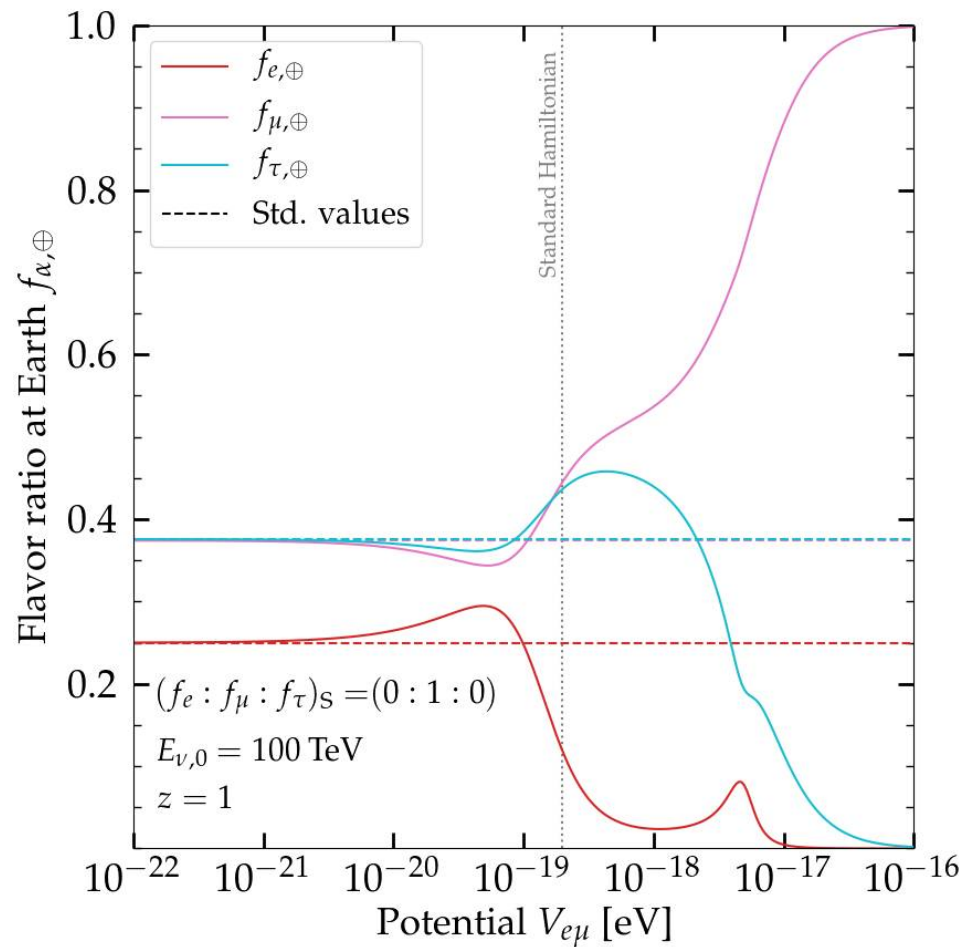
- 2 Convolve flavor ratios with observed neutrino energy spectrum
→ Either $E^{-2.50}$ (combined analysis) or $E^{-2.13}$ (through-going muons)

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

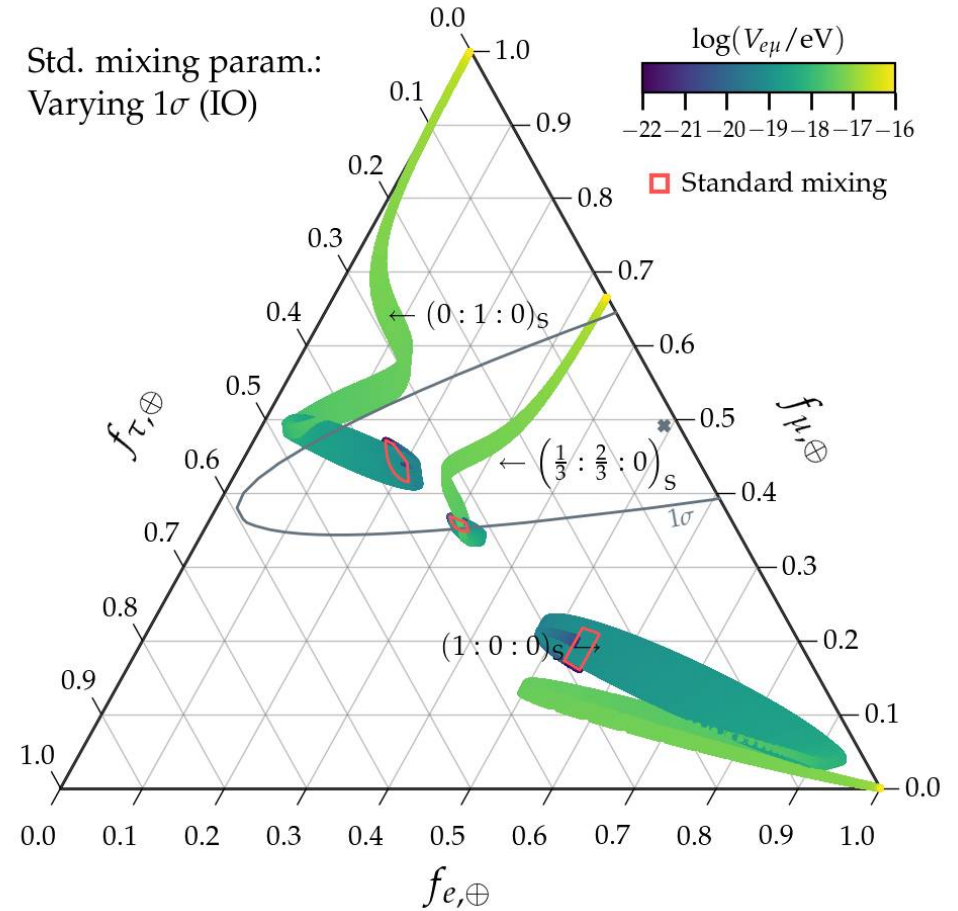
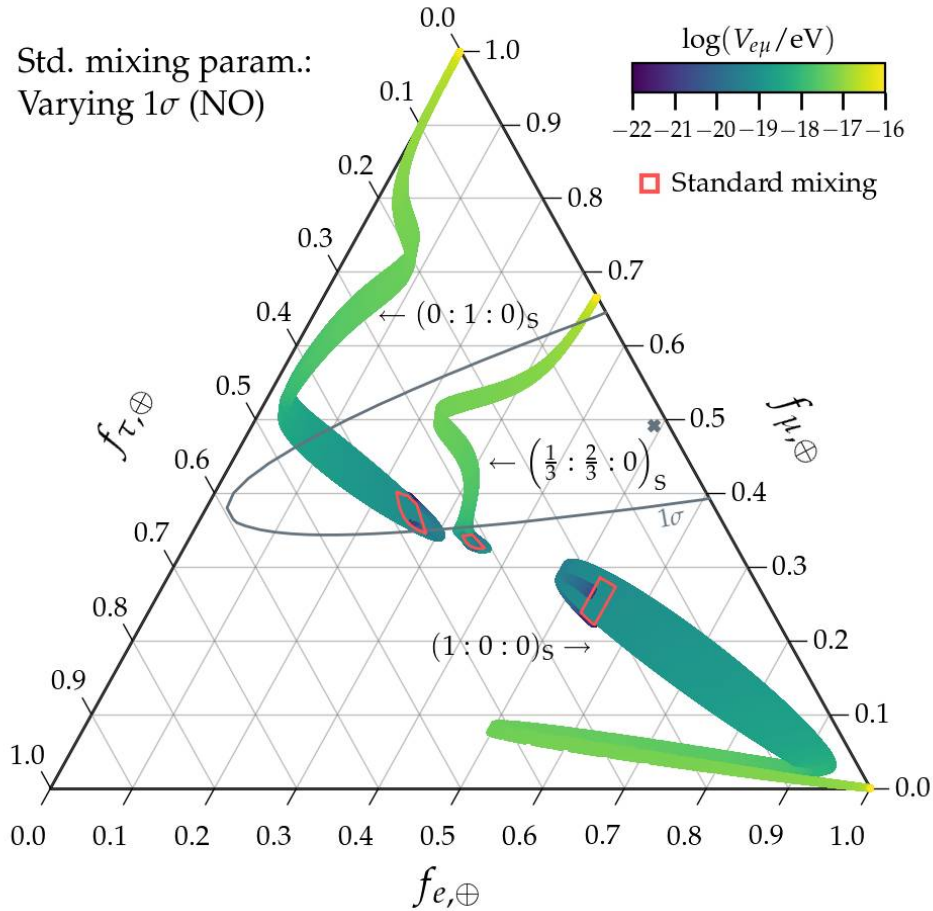
Resonance due to the L_e - L_μ symmetry



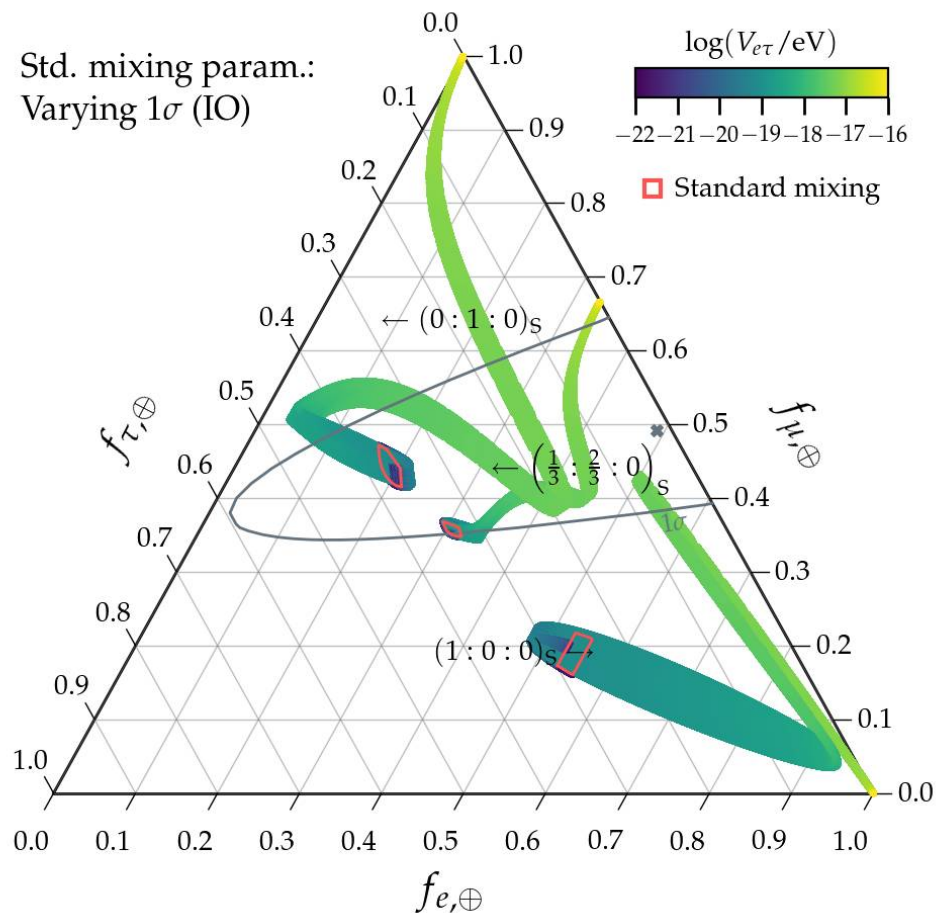
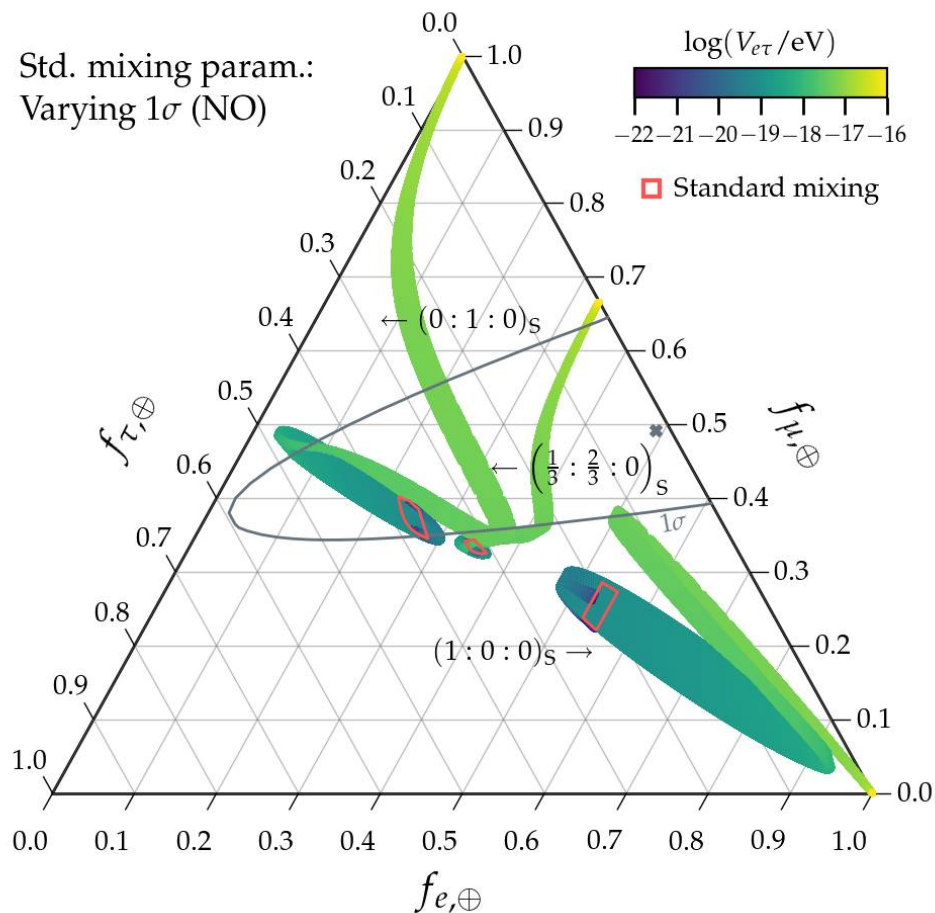
Resonance due to the L_e - L_μ symmetry (*cont.*)



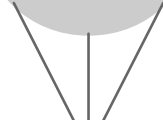
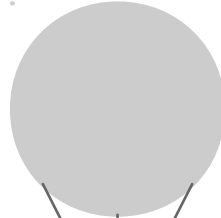
Flavor ratios for the L_e - L_μ symmetry: NO *vs.* IO



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



ANITA



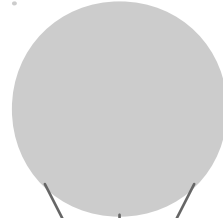
35–40 km



Ice

Not to scale

ANITA



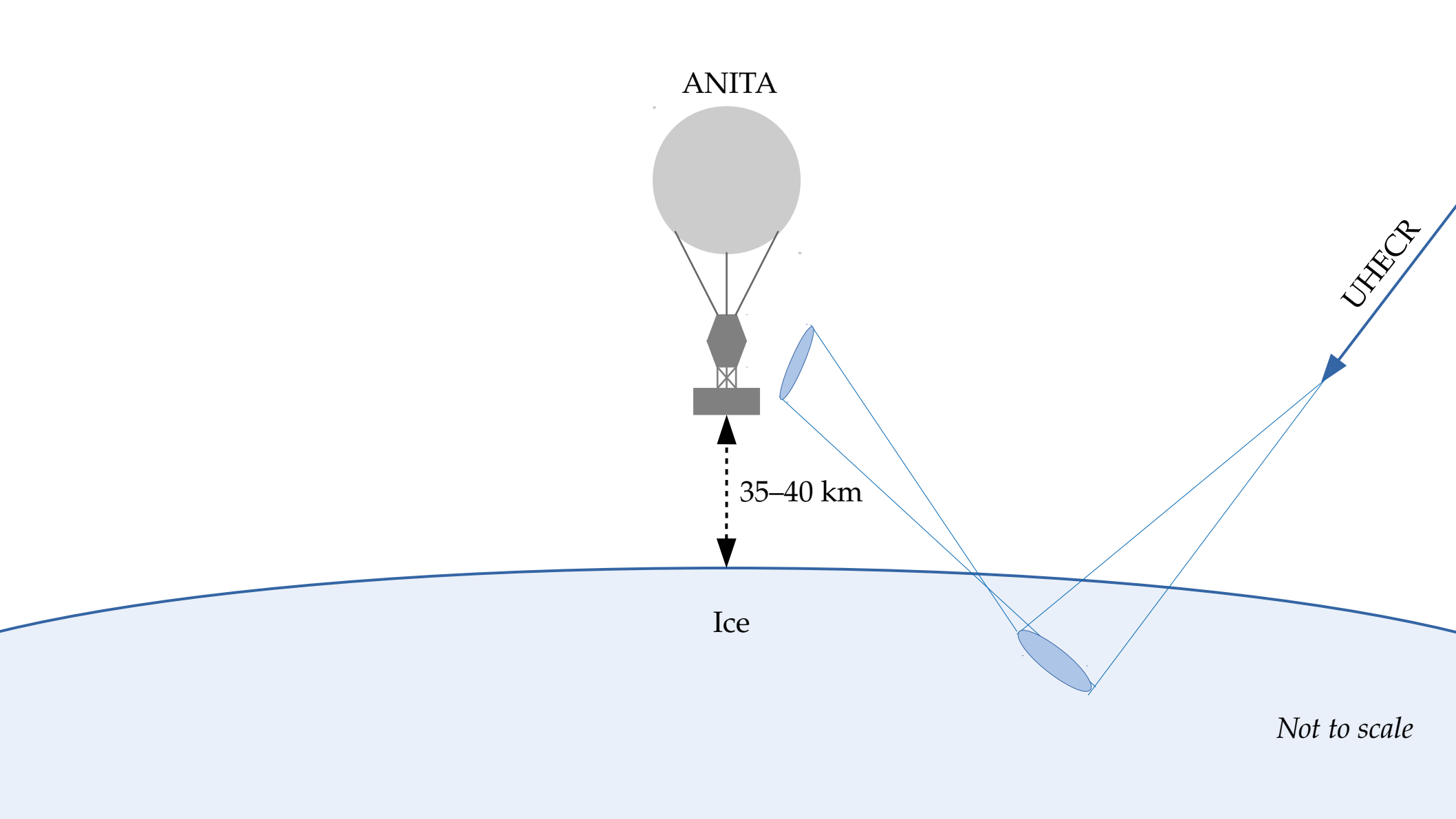
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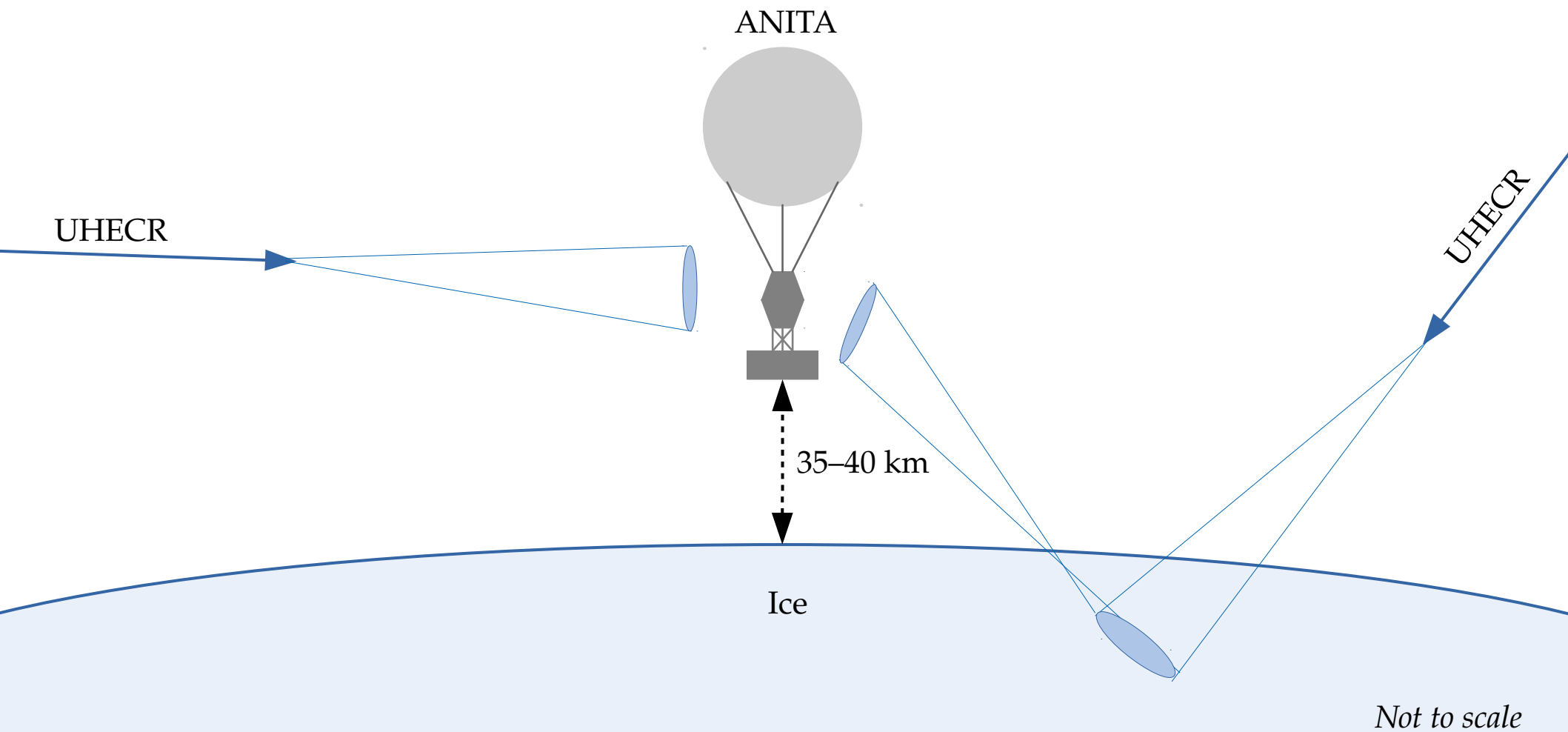
Ice

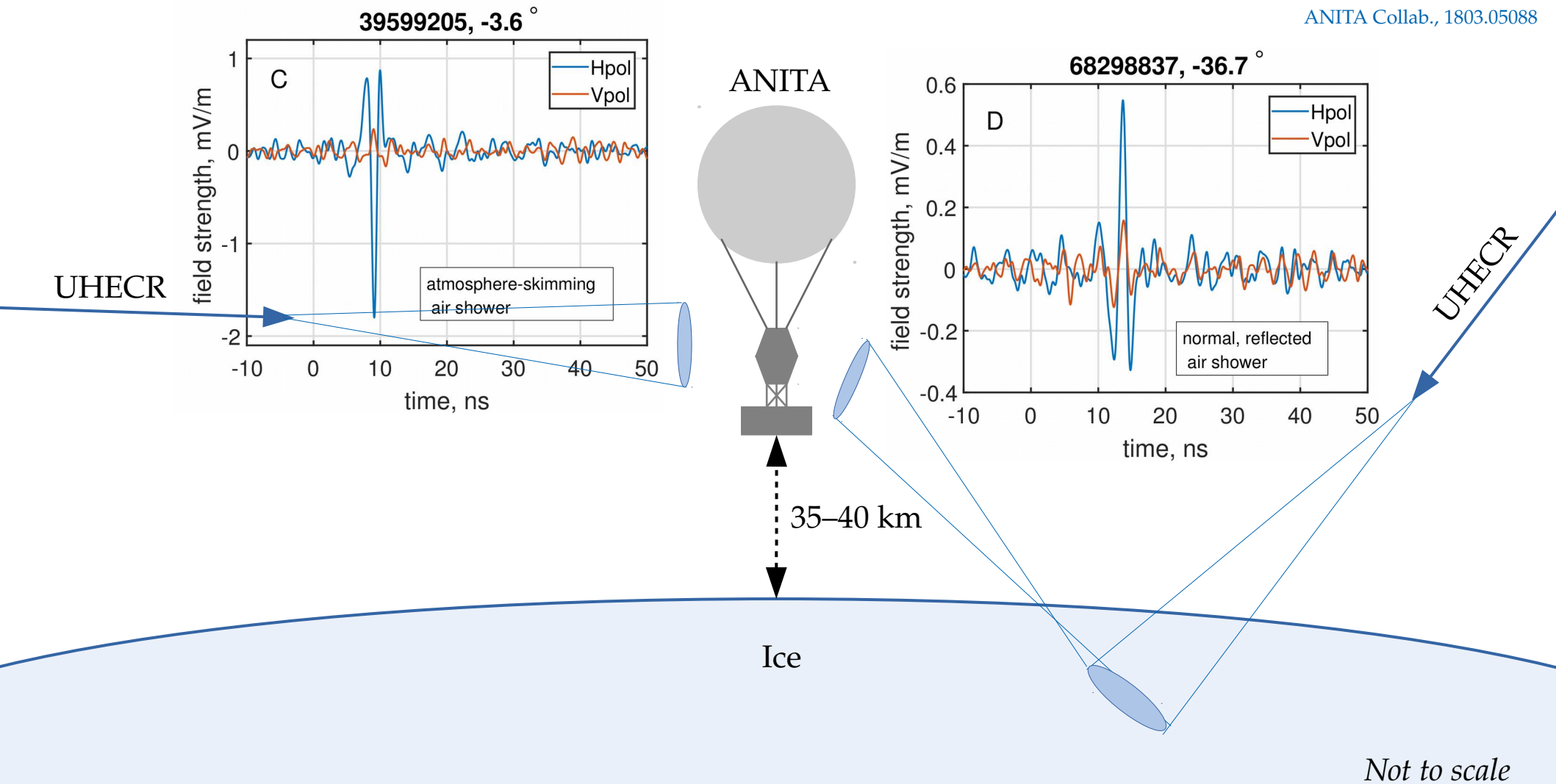


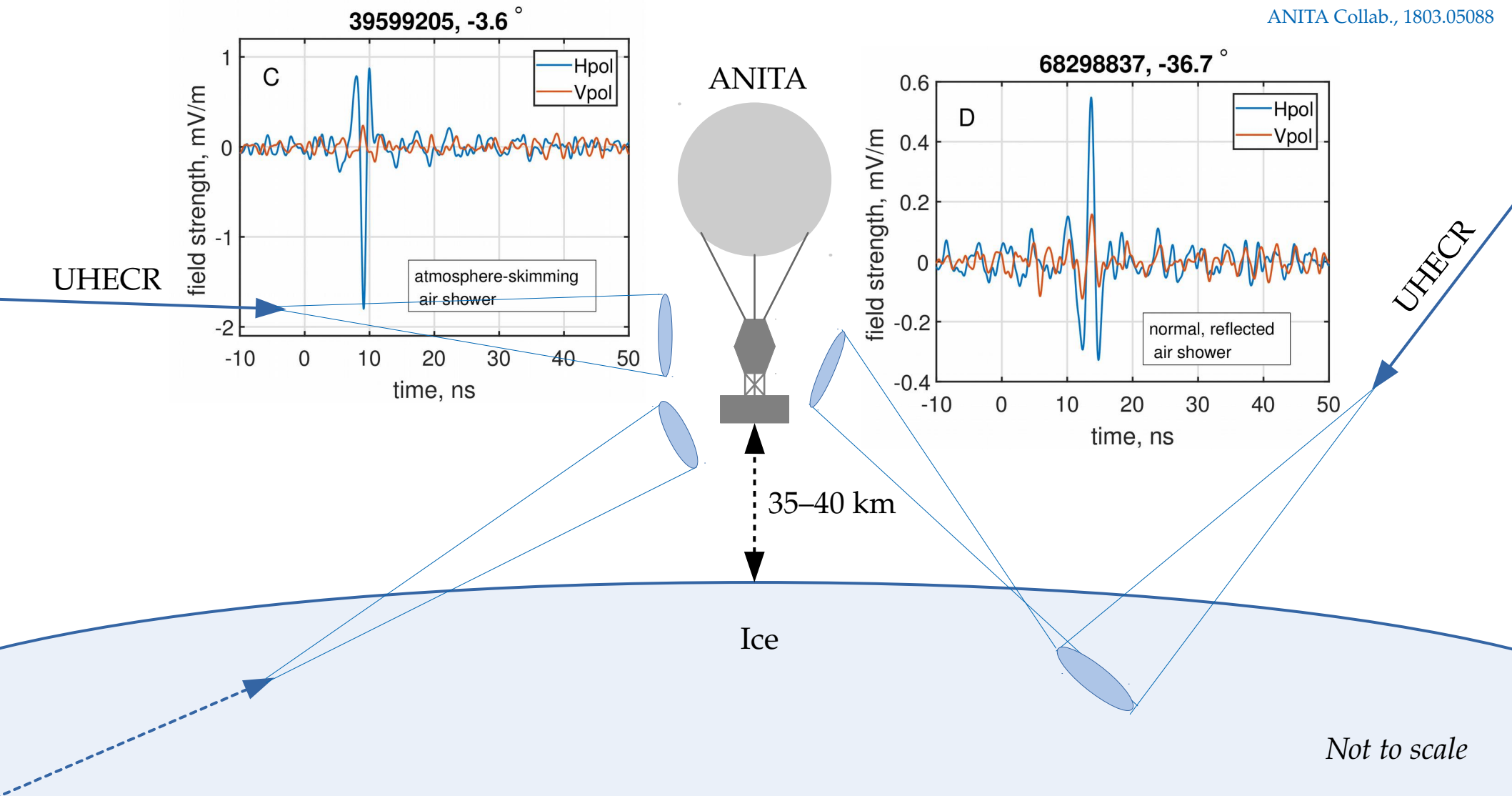
UHECR

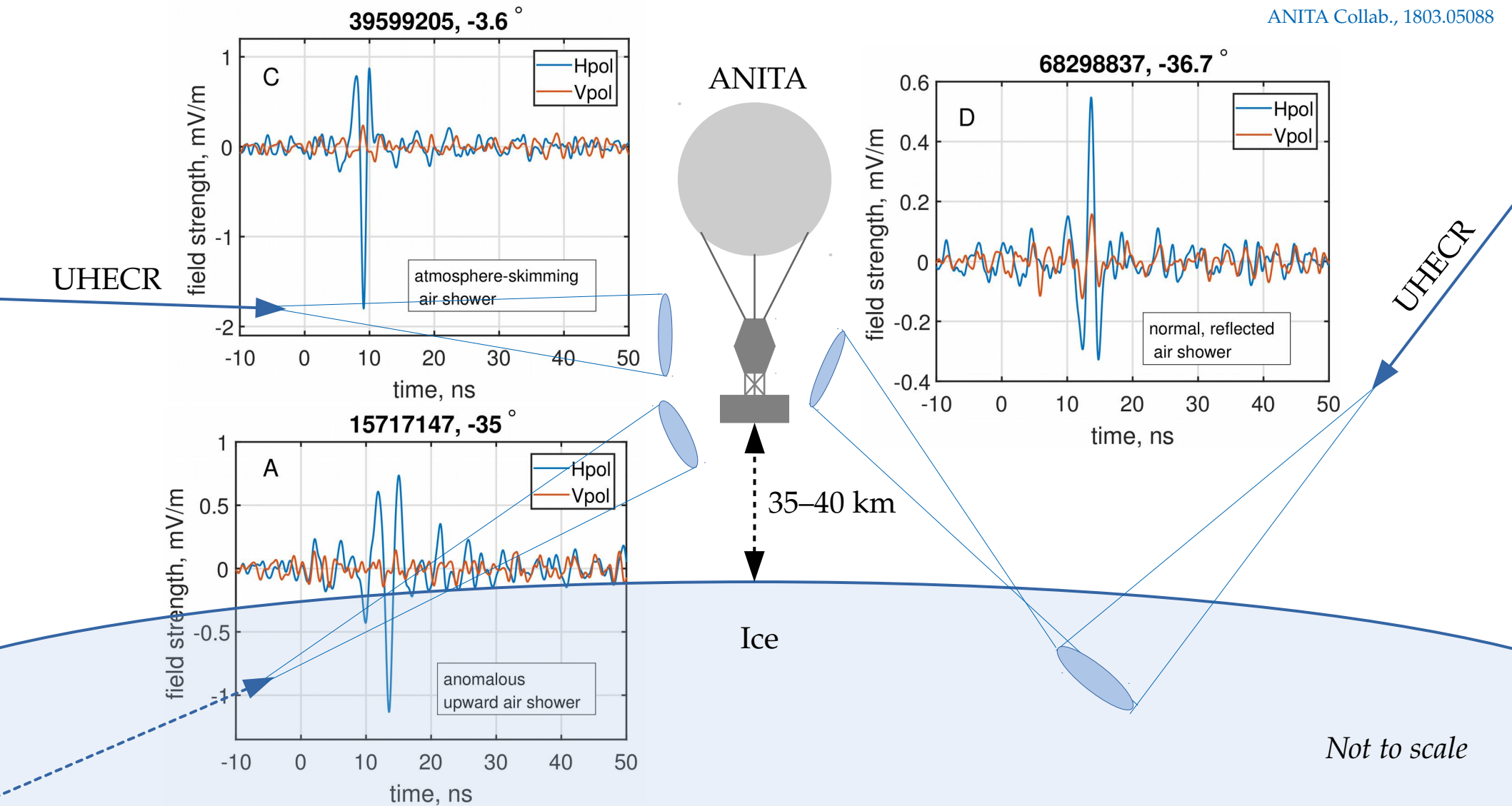
Not to scale

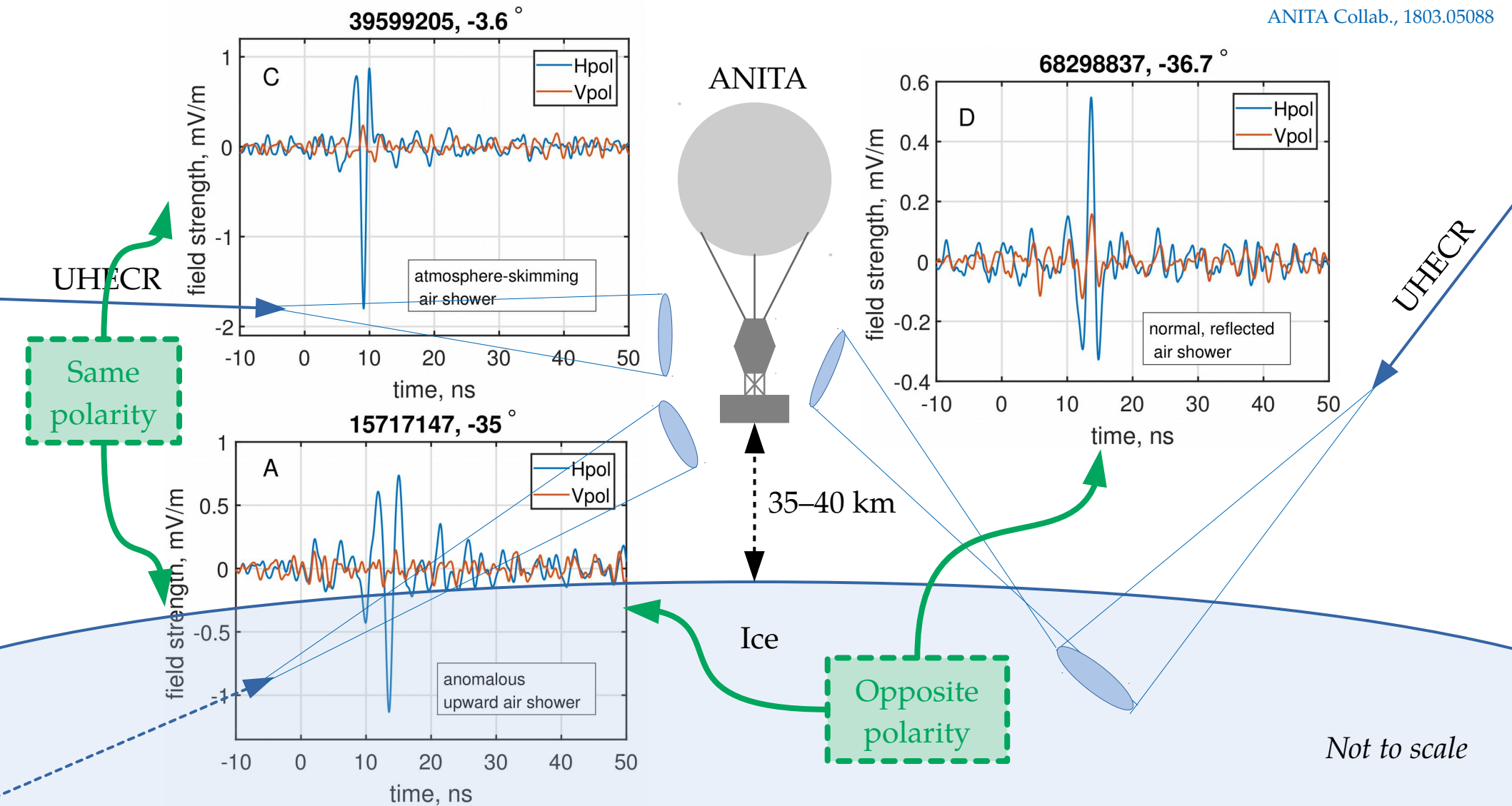


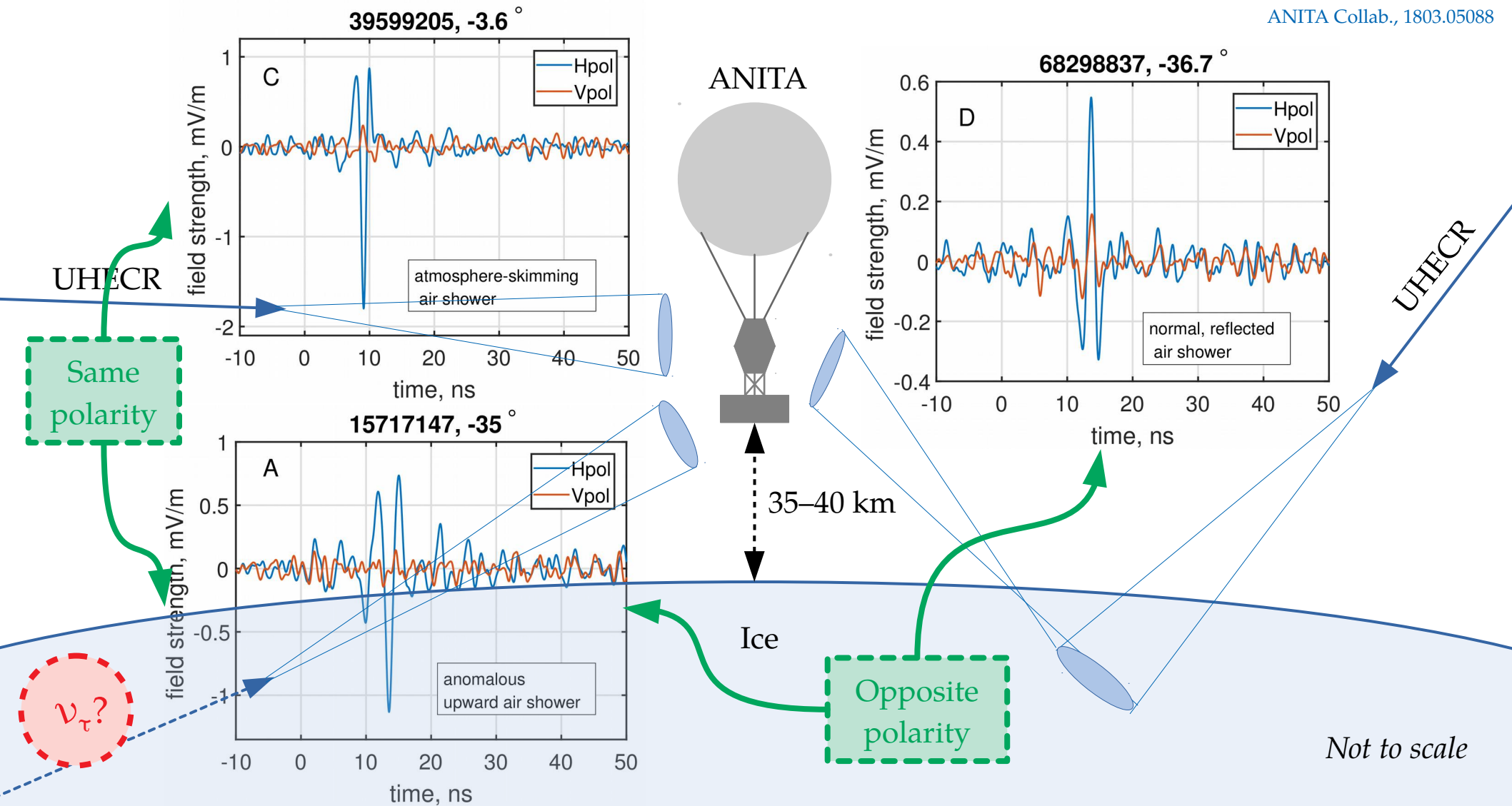












Mystery ANITA events – First UHE ν detected?

- ▶ Two upgoing, unflipped-polarity showers:
 - ▶ ANITA-1 (2006): $20^\circ \pm 0.3^\circ$ dec., 0.60 ± 0.4 EeV
 - ▶ ANITA-3 (2014): $38^\circ \pm 0.3^\circ$ 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:

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

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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 $4 \times 10^{42} \text{ erg s}^{-1}$

So what is ANITA seeing?

► Transition radiation [Motloch *et al.*, PRD 2017]:

- Wide-angle emission 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 $\nu_s \rightarrow \nu_\tau$
- **Assessment:** Model predicts more (unseen) events at shallower angles

► Dark matter decay in Earth core [Anchordoqui *et al.*, 1803.11554]:

- Decay of 480-PeV sterile right-handed ν_r (relic DM) trapped “puffy” Earth core: $\nu_r \rightarrow \text{Higgs} + \nu_\tau$
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Mean free path $\sim$ Earth radius Decay length $\sim$ Earth radius

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