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

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Niels Bohr Institute, University of Copenhagen

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Uppsala University, September 20, 2018

UNIVERSITY OF COPENHAGEN

VILLUM FONDEN

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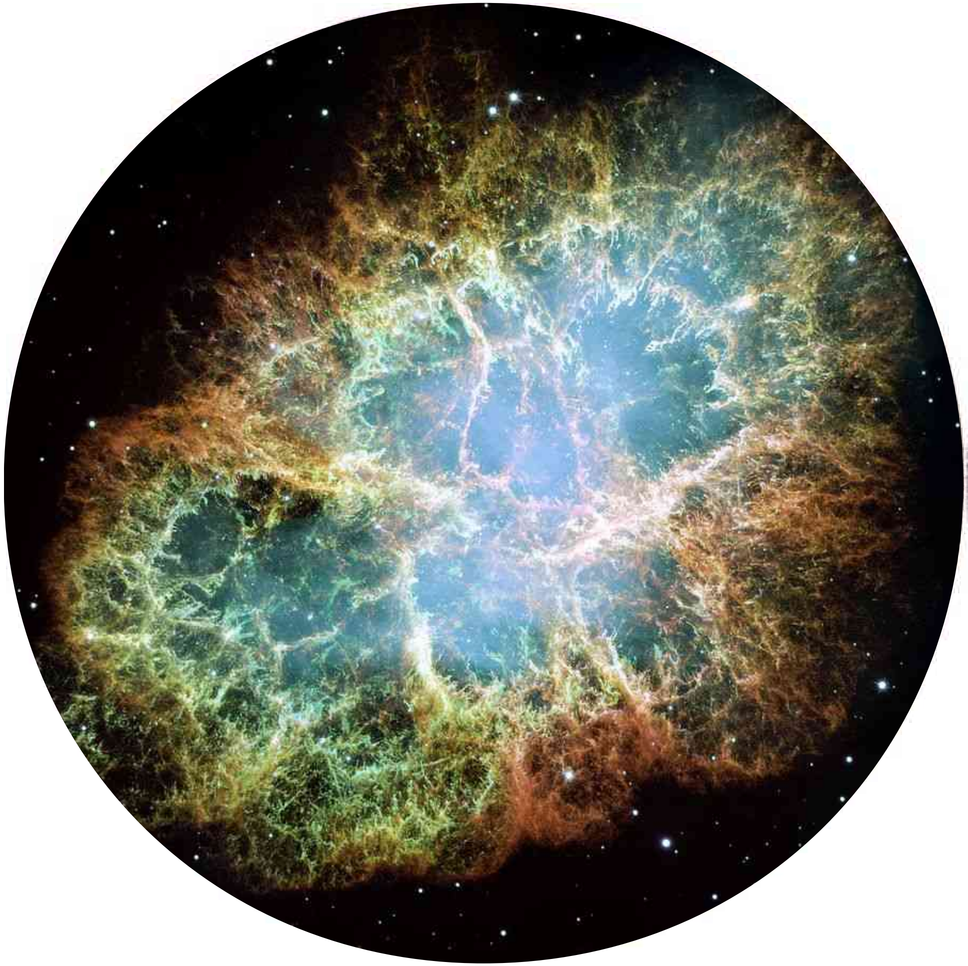

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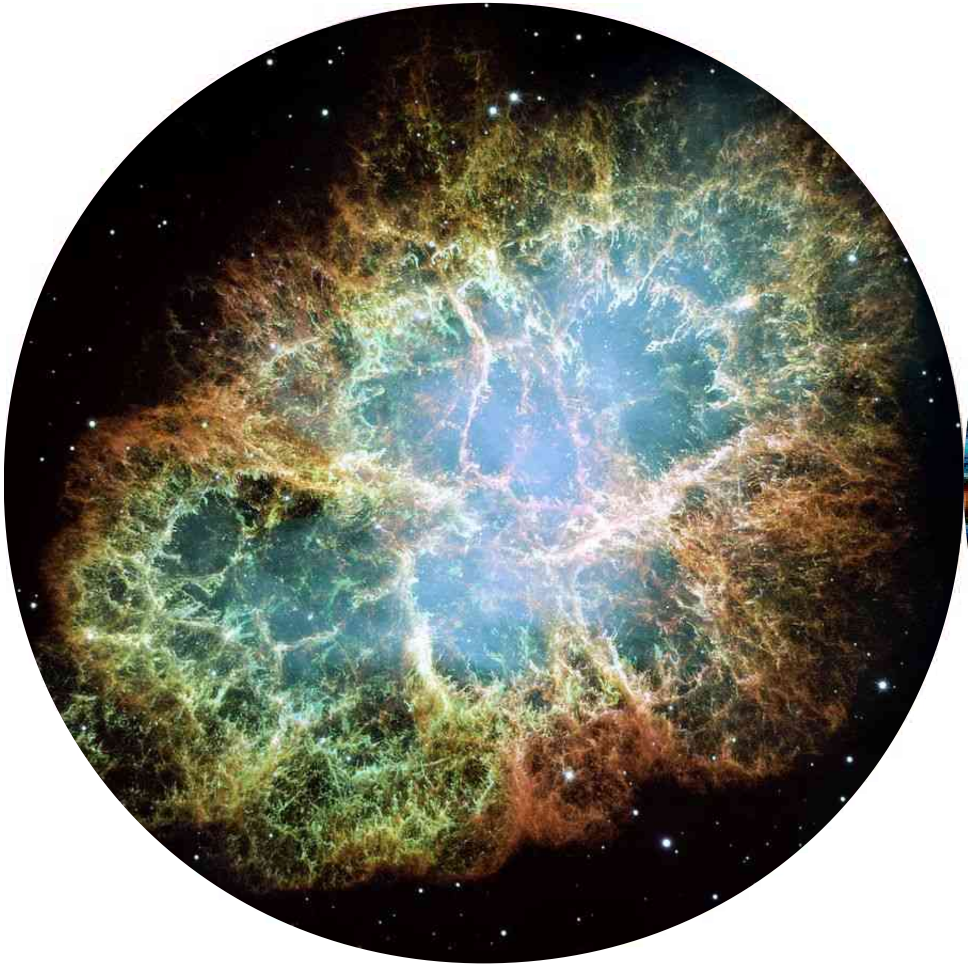
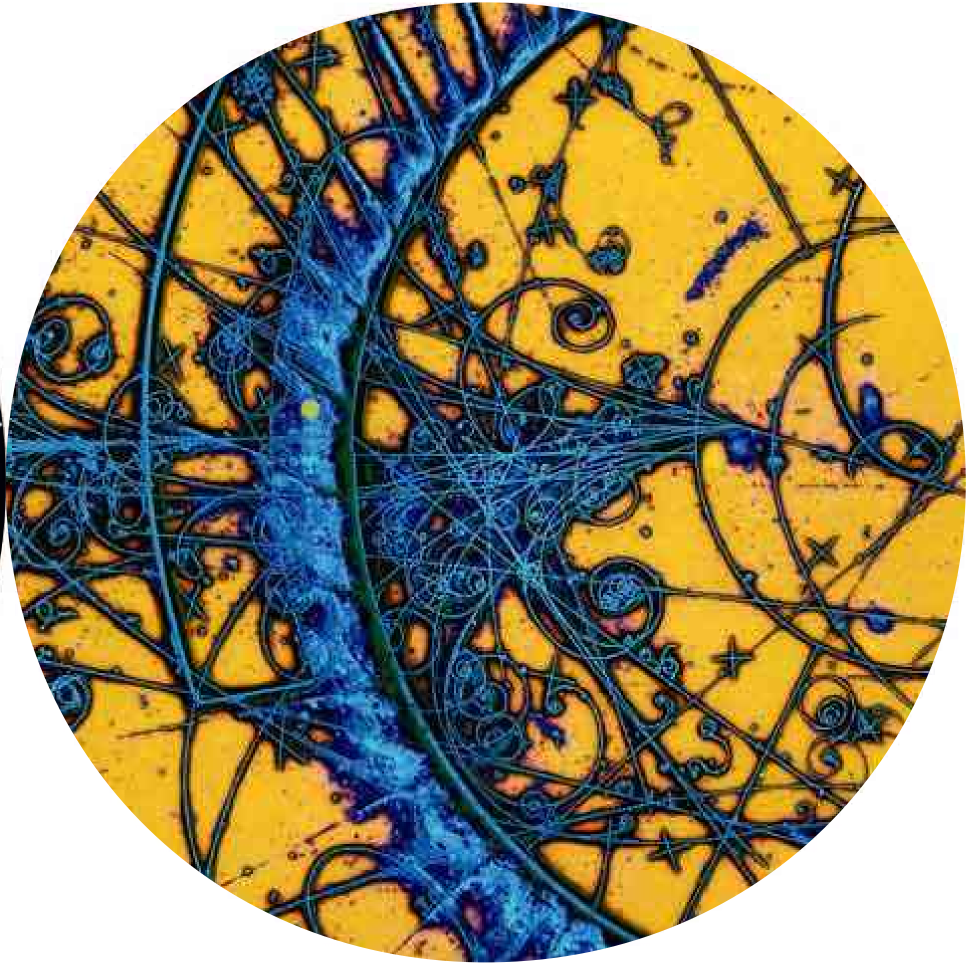

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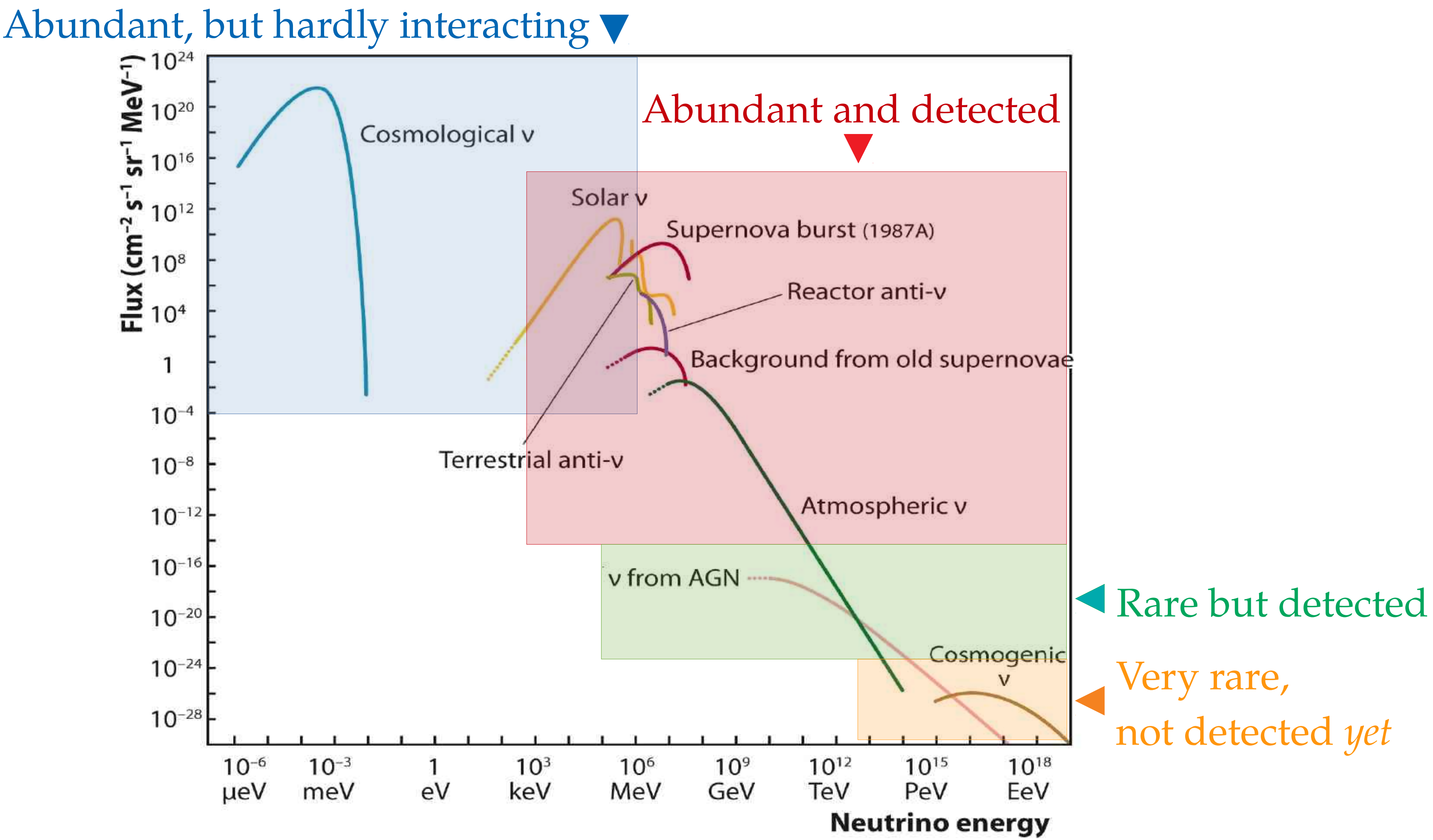

Abundant, but hardly interacting
Abundant and detected
Rare but detected
Very rare,
not detected *yet*
Cosmological ν
Solar ν
Supernova burst (1987A)
Reactor anti-ν
Background from old supernovae
Terrestrial anti-ν
Atmospheric ν
ν from AGN
Cosmogenic ν
Flux (cm⁻² s⁻¹ sr⁻¹ MeV⁻¹)
Neutrino energy
μeV
meV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

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

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

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

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   ↦ Tiny effects can accumulate and become observable

3. It comes *for free*

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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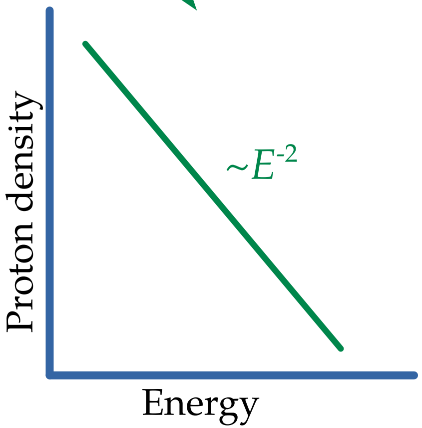

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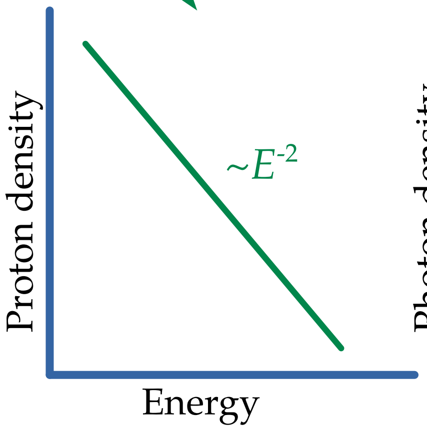

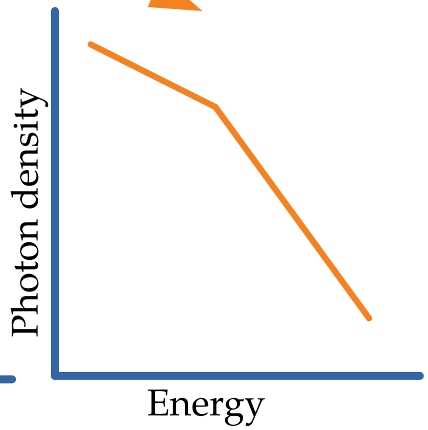

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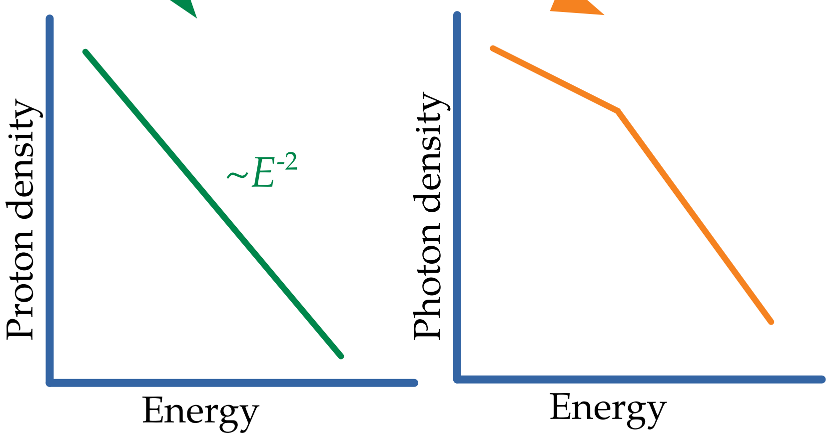
$$\pi^0 \rightarrow \gamma + \gamma$$

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

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



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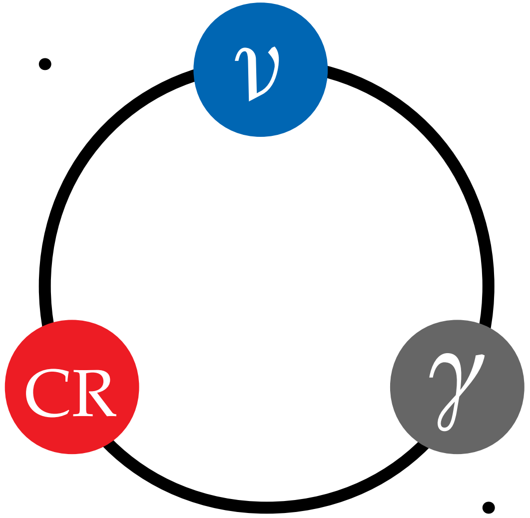

Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 20

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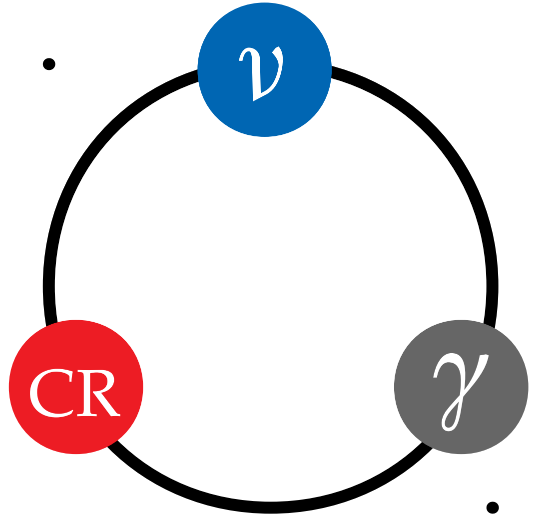

1 PeV　　　　　　　20 PeV

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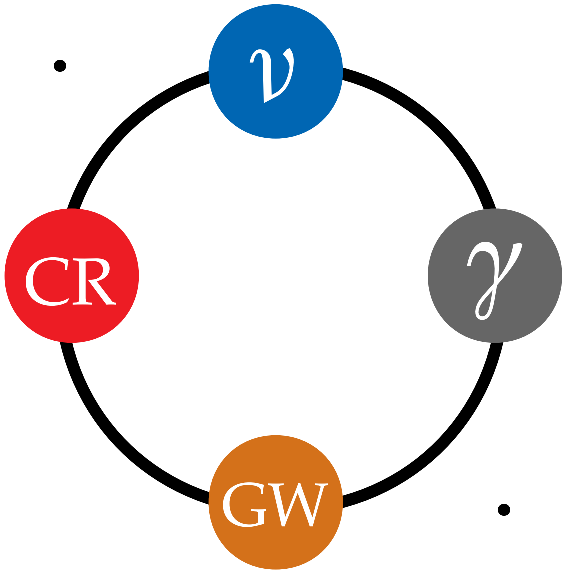

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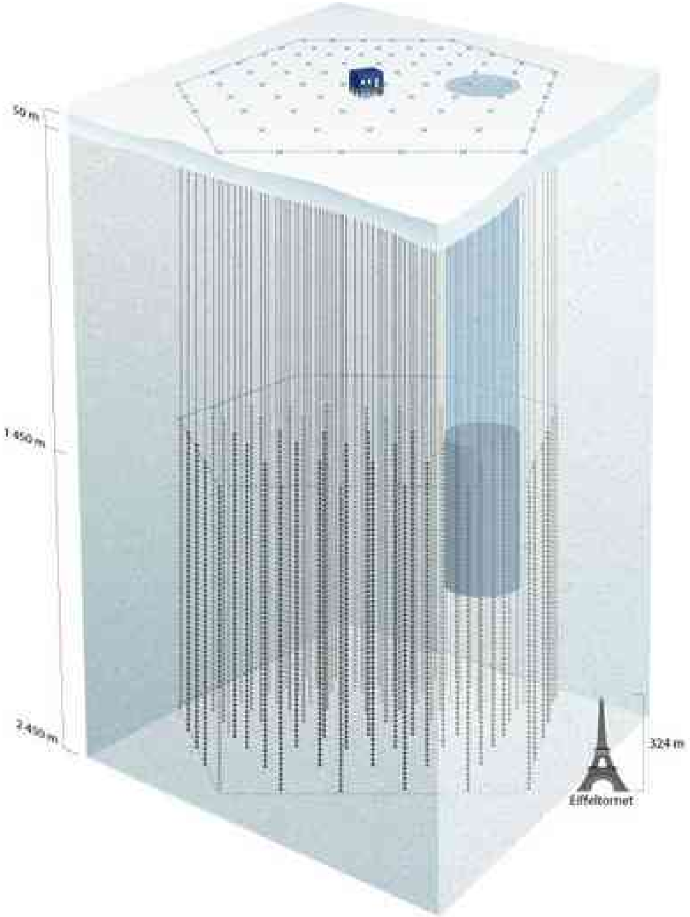
IceCube – What is it?



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

How does IceCube see neutrinos?

Two types of fundamental interactions . . .

Charged-current (CC)

$\nu_l + N \rightarrow l + \text{hadrons}$

Neutral-current (NC)

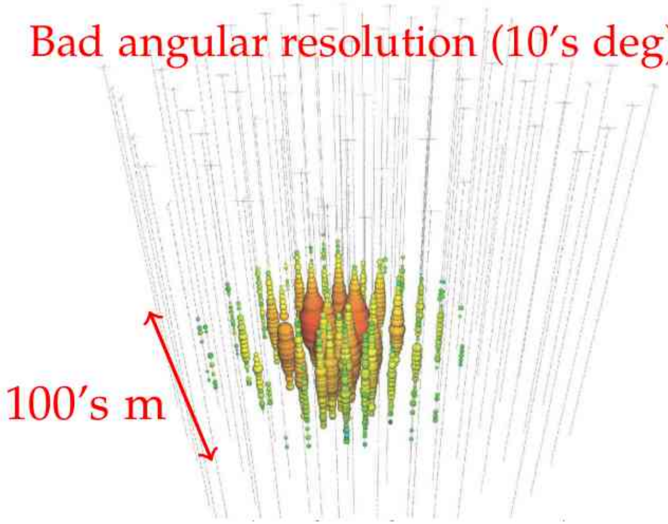
$\nu_l + N \rightarrow \nu_l + \text{hadrons}$

These shower and make light

. . . create two event topologies . . .

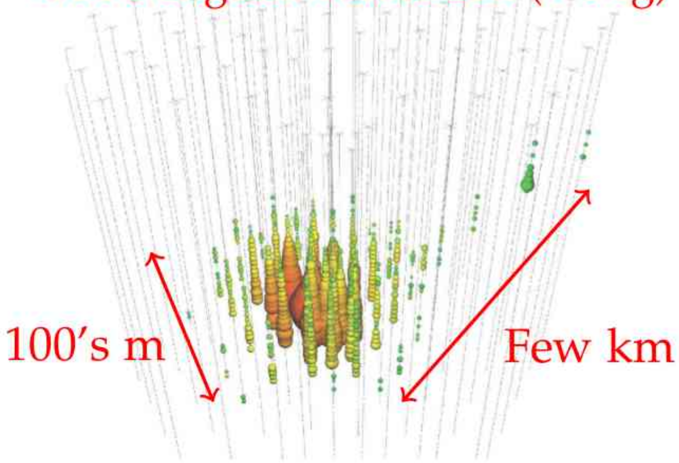
Showers — From CC ν_e or ν_τ, or NC ν_x

Bad angular resolution (10′s deg)



Tracks — From CC ν_μ mainly

Good angular resolution (< deg)



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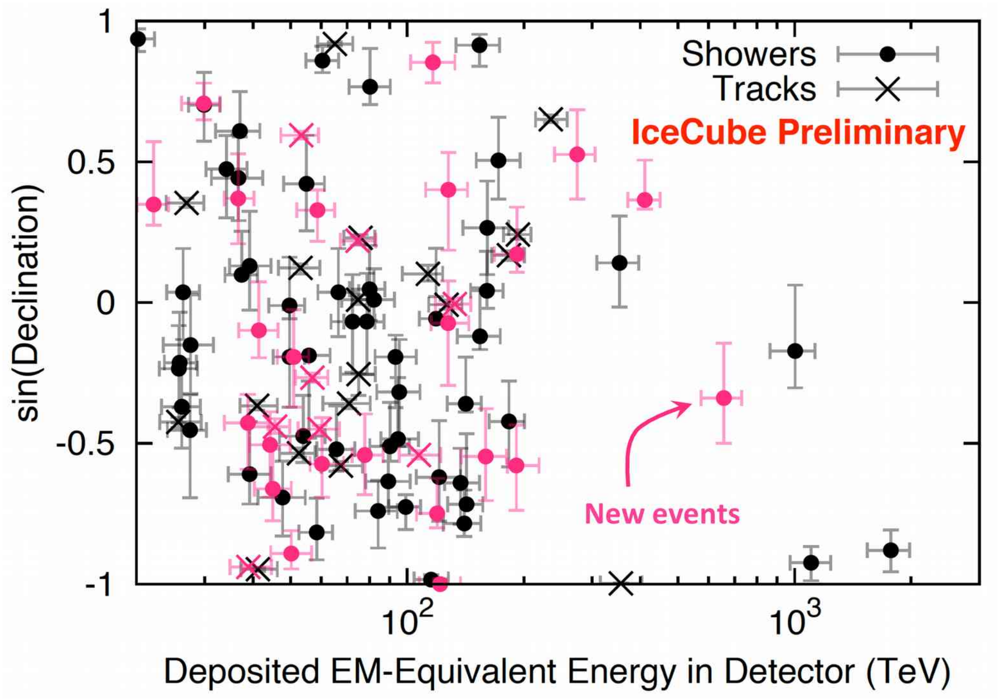

I. Taboada, Neutrino 2018

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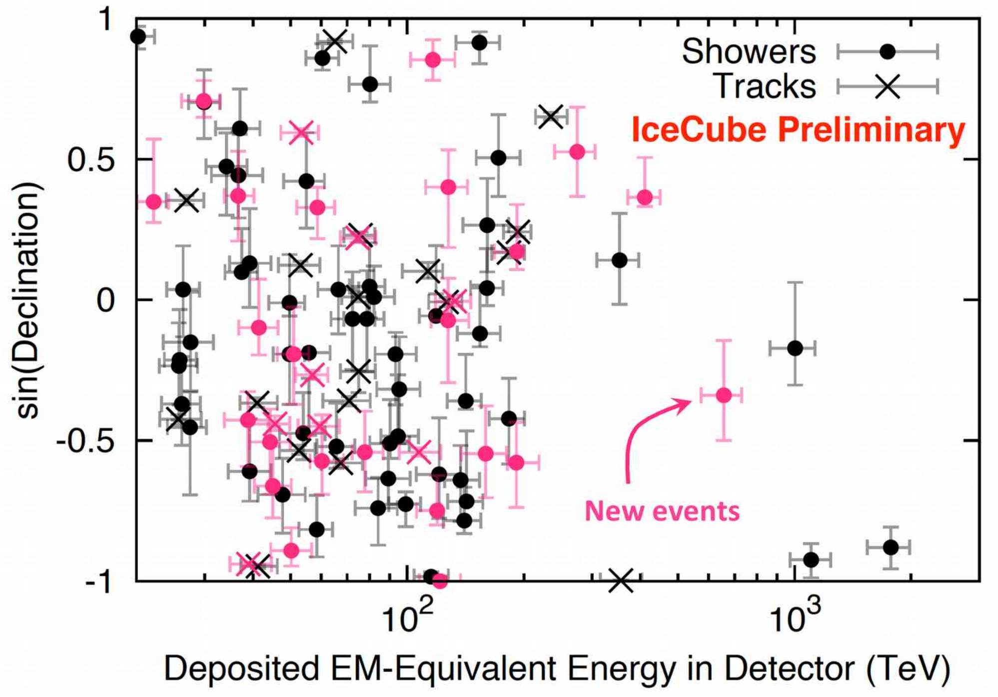
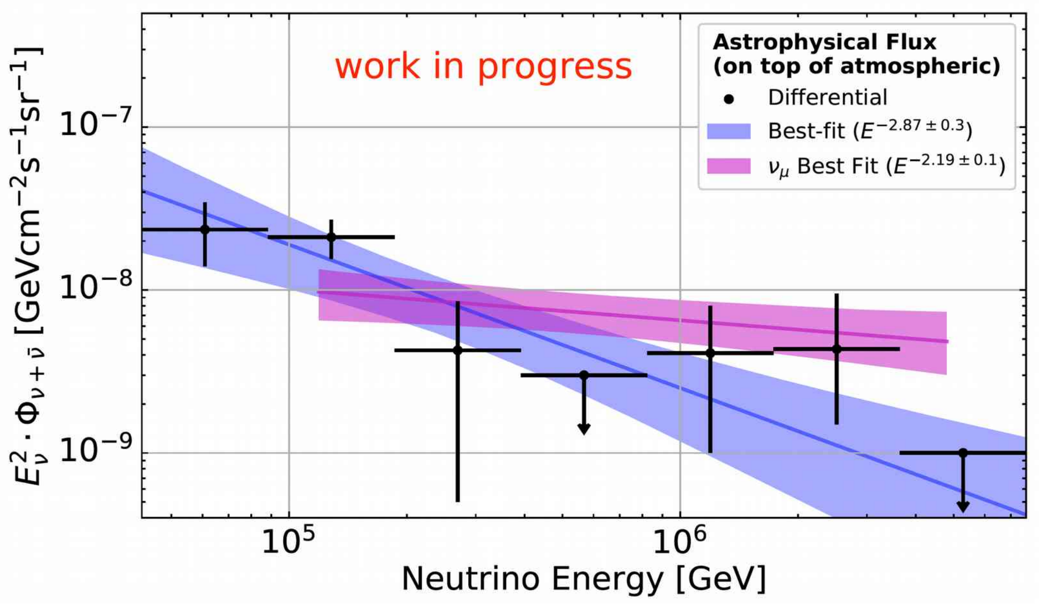


Astrophysical ν flux detected at > 7σ

(Normalization ok, but steep spectrum)



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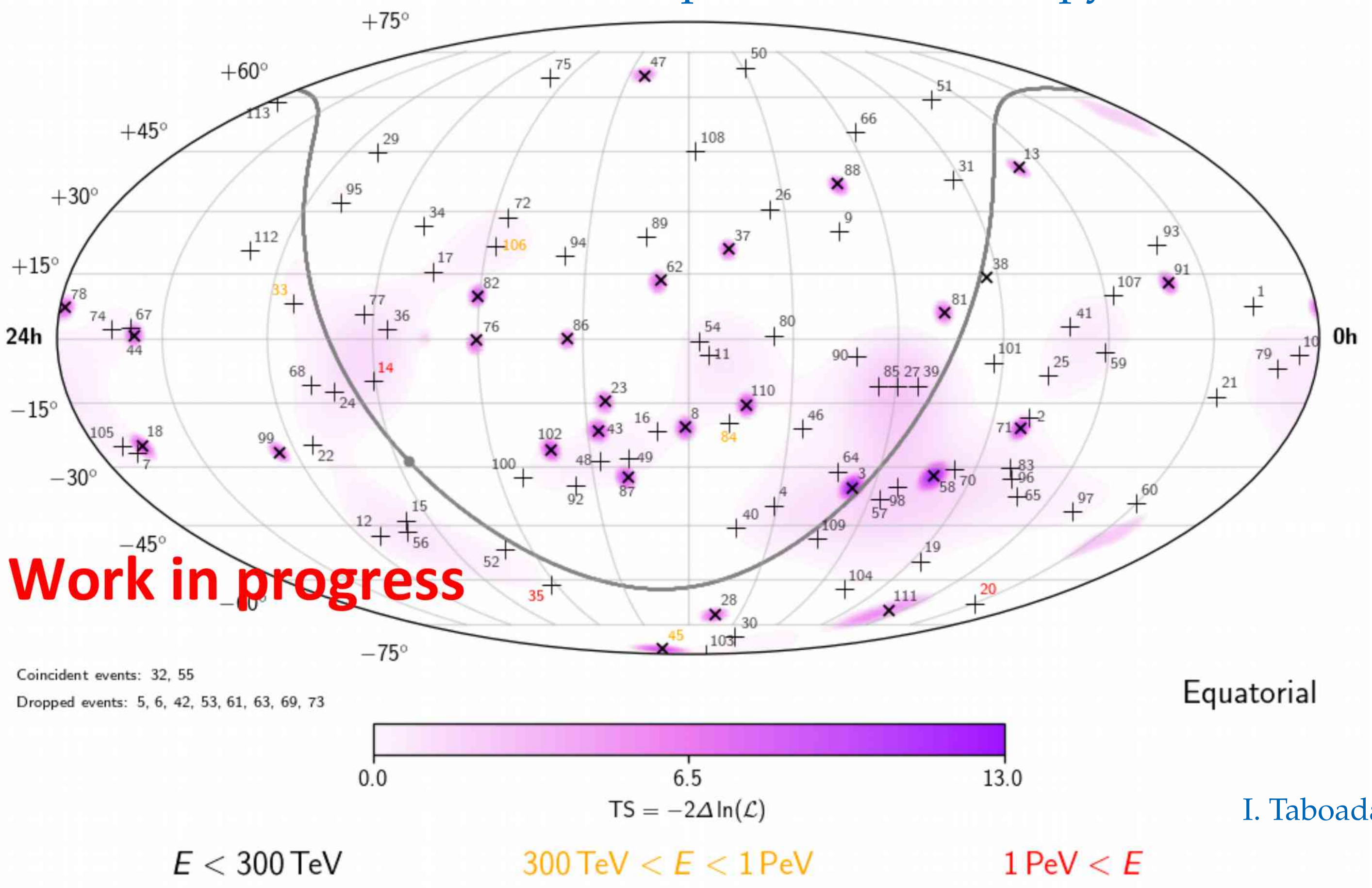
What has IceCube found so far (7.5 years)?

Arrival directions compatible with isotropy



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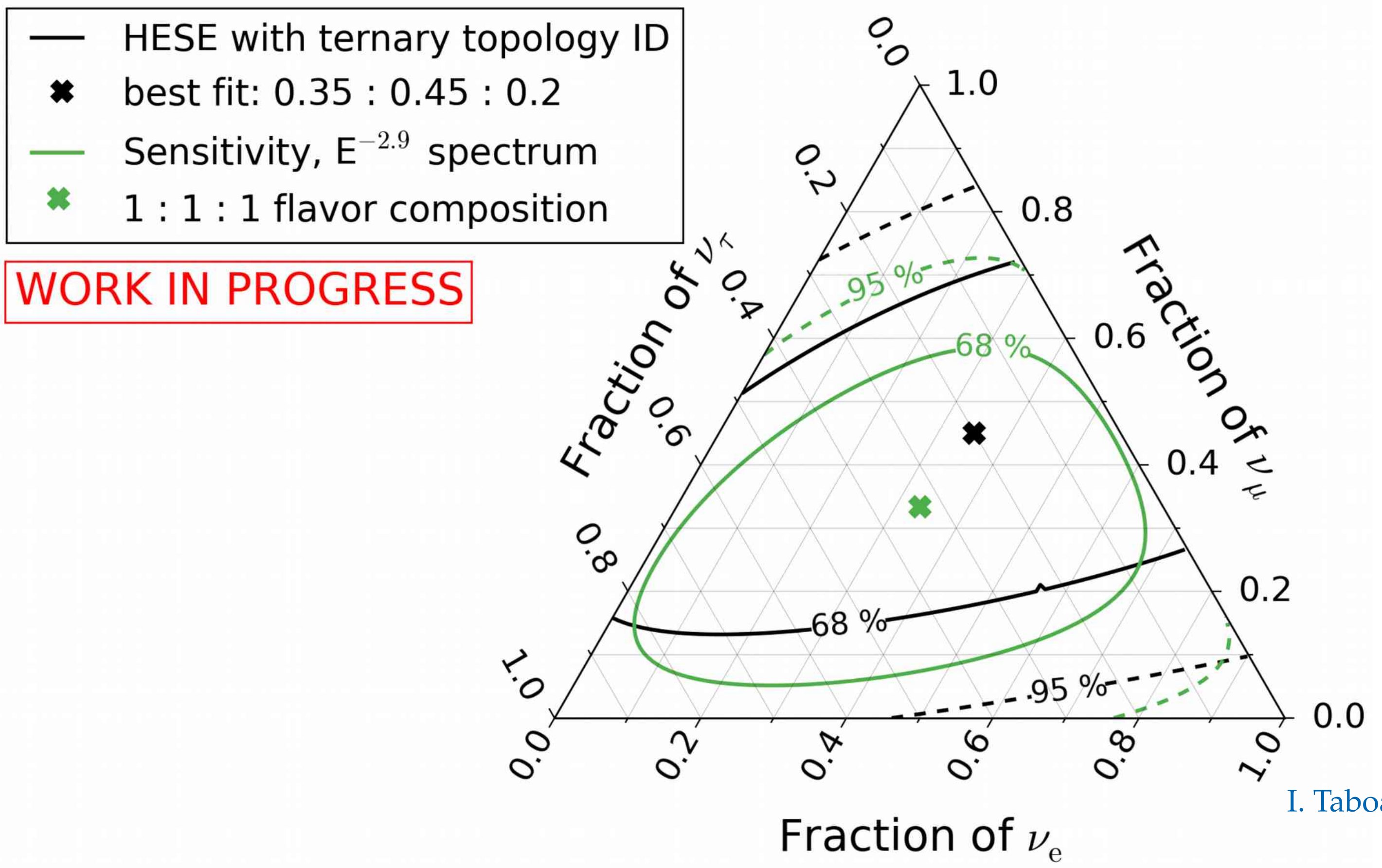
What has IceCube found so far (7.5 years)?

Flavor composition compatible with equal proportion of each flavor



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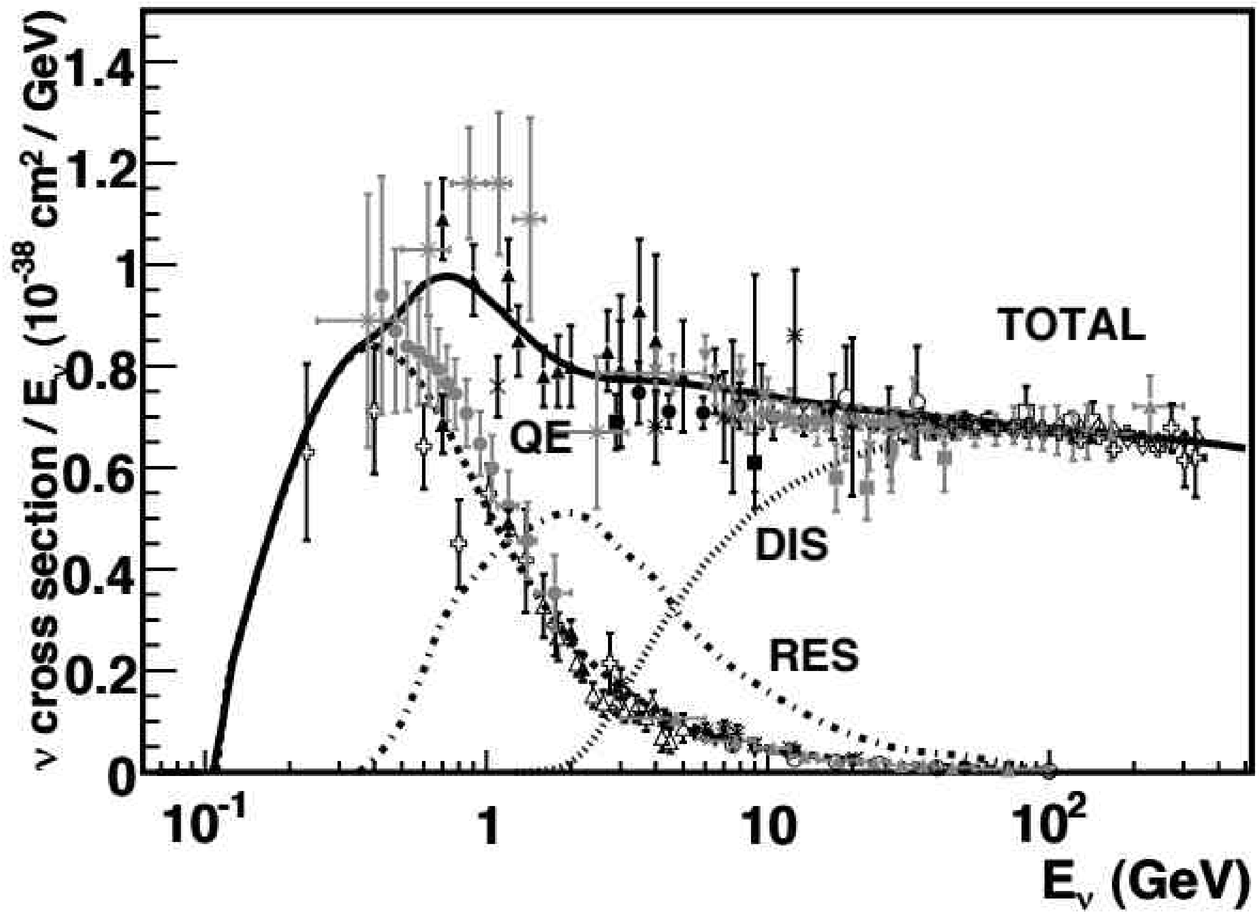
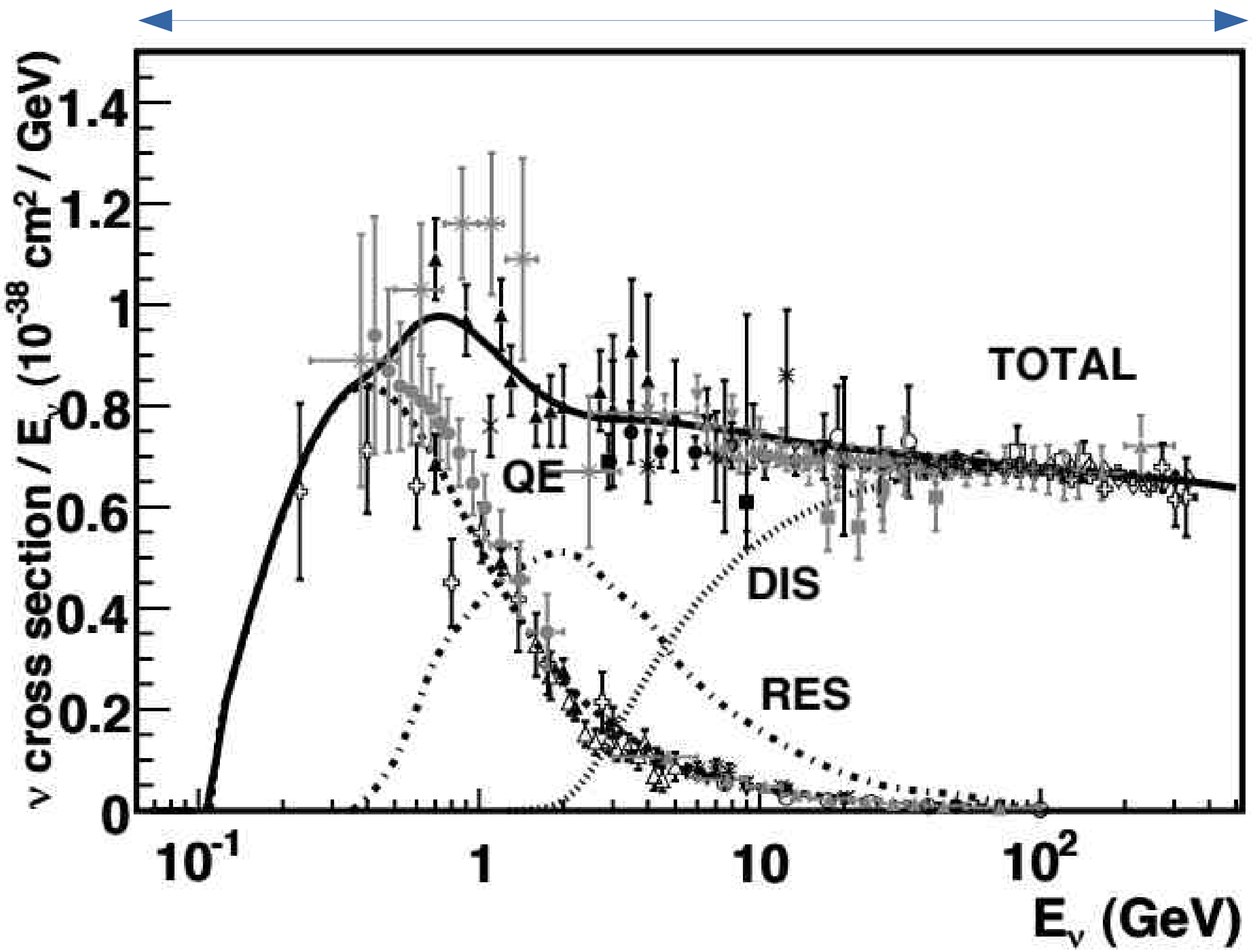
In spite of
poor energy, angular, flavor reconstruction
& astrophysical unknowns



Particle Data Group

Accelerator experiments



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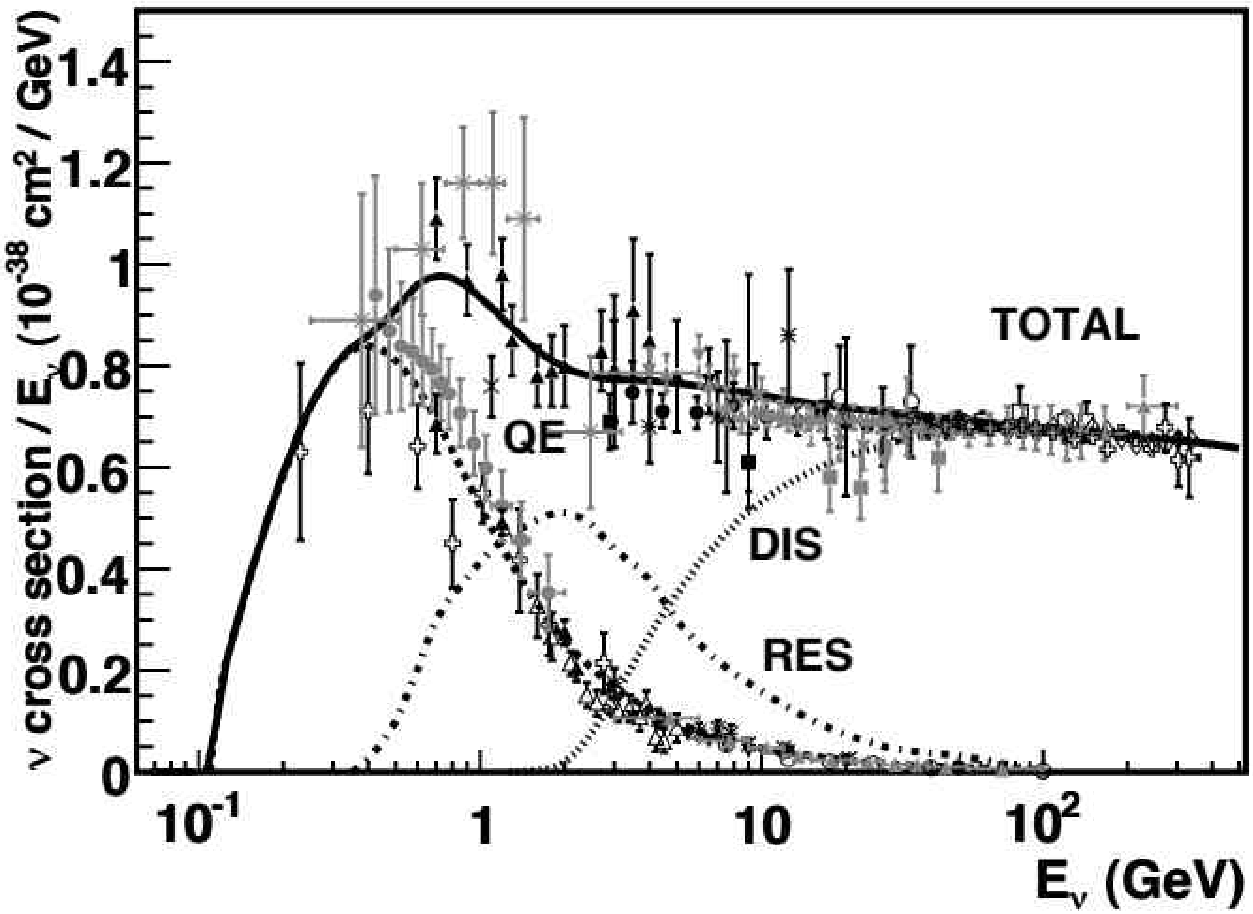
Accelerator experiments

One recent measurement (COHERENT)



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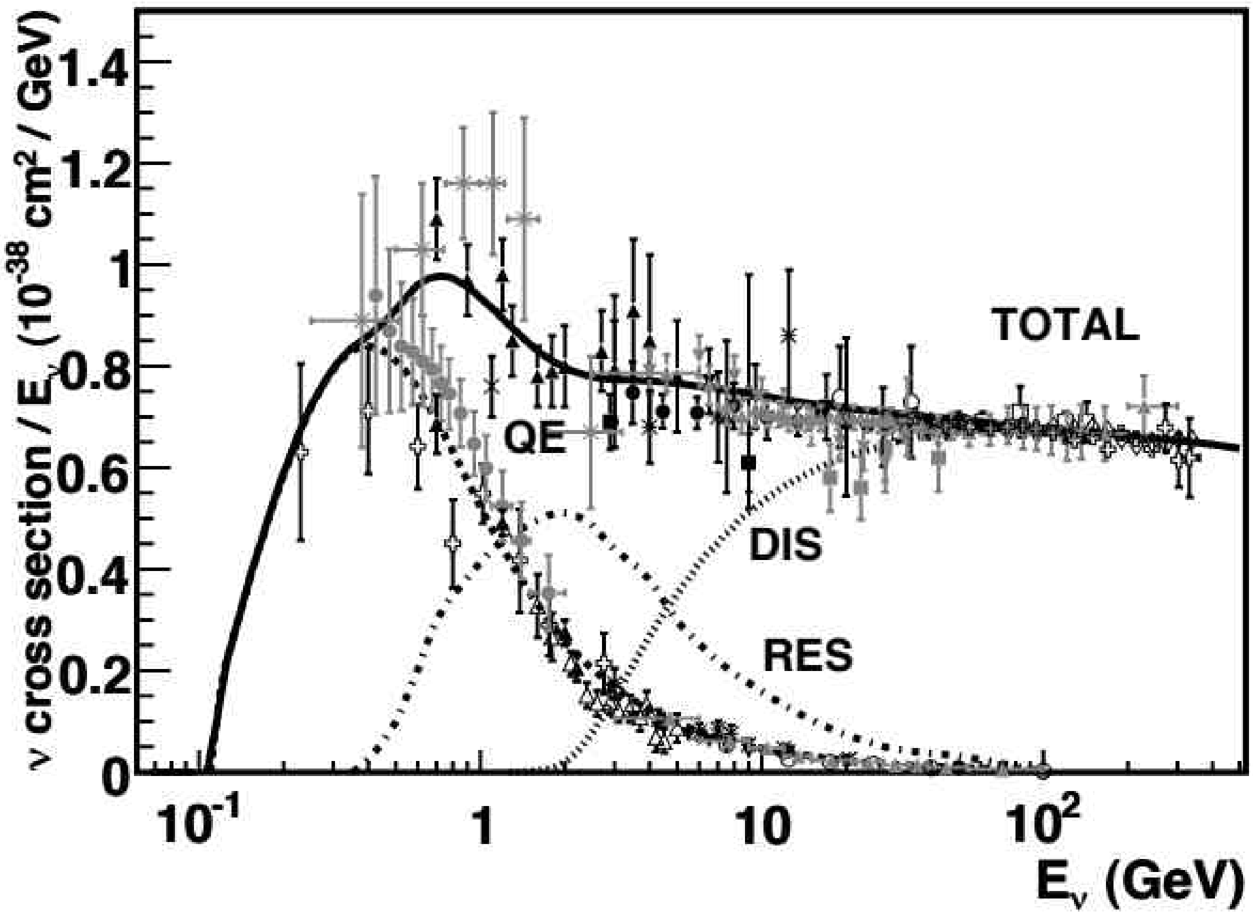

No measurements … until now!

Particle Data Group

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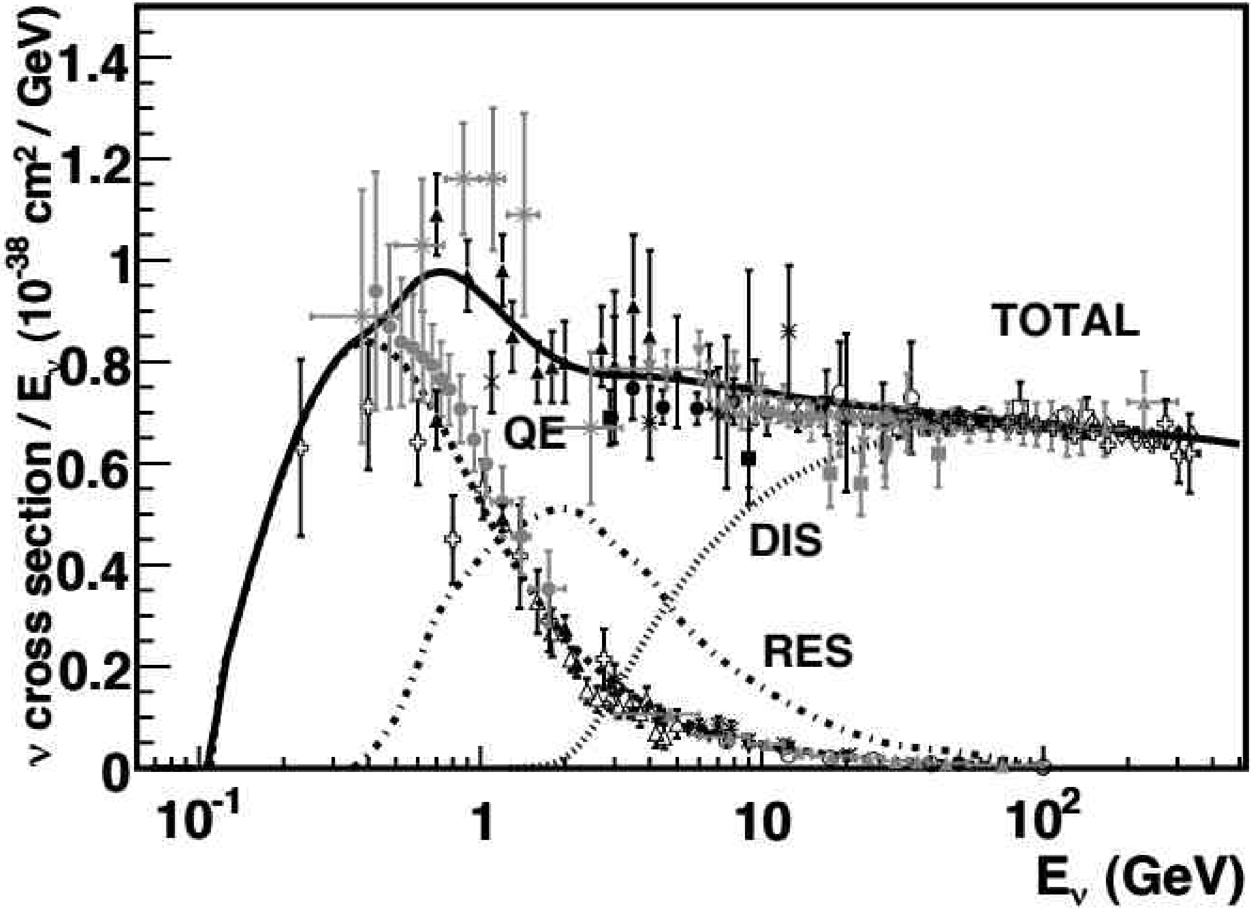
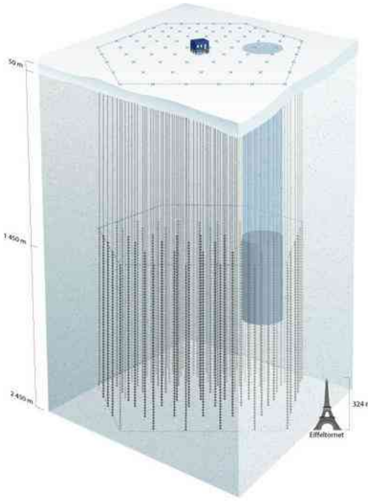
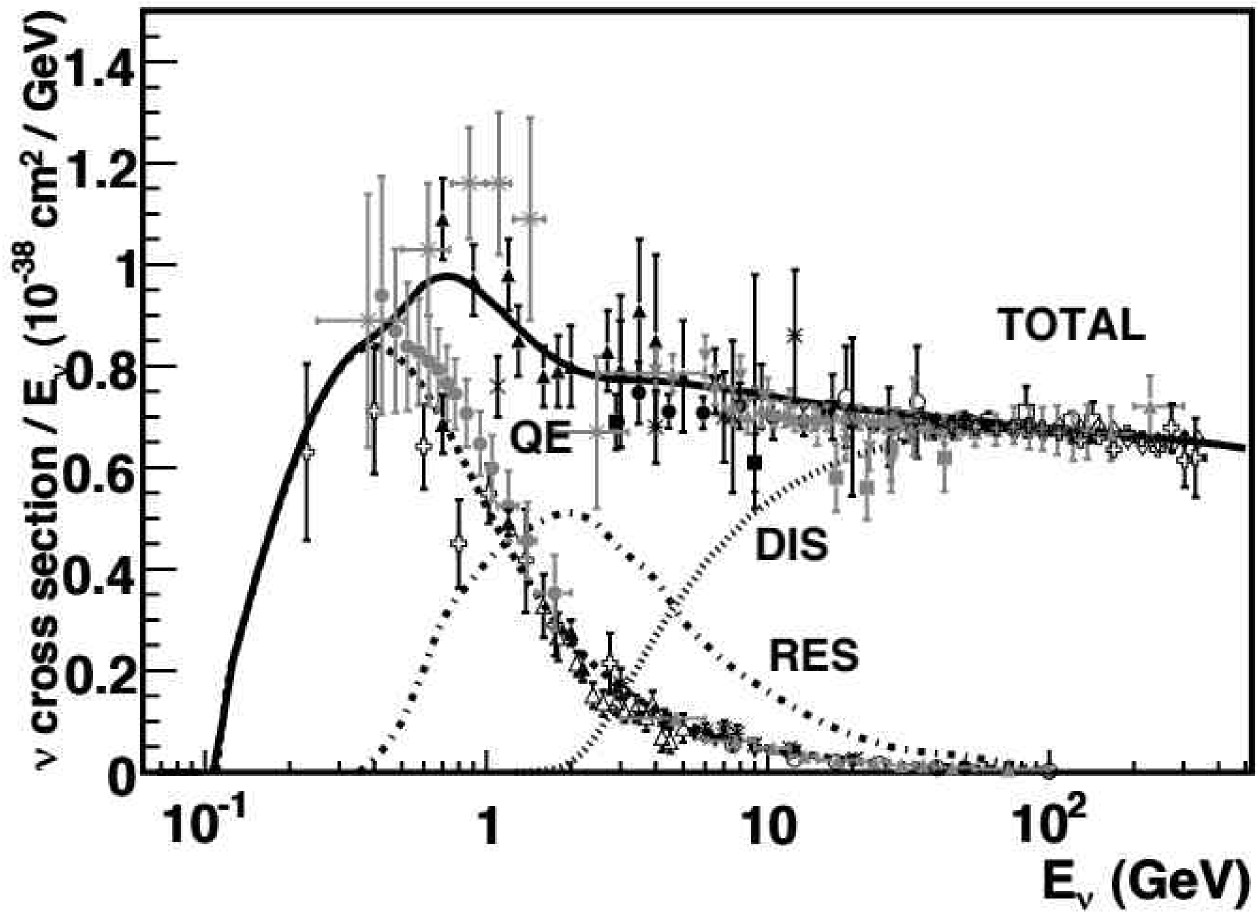


Particle Data Group



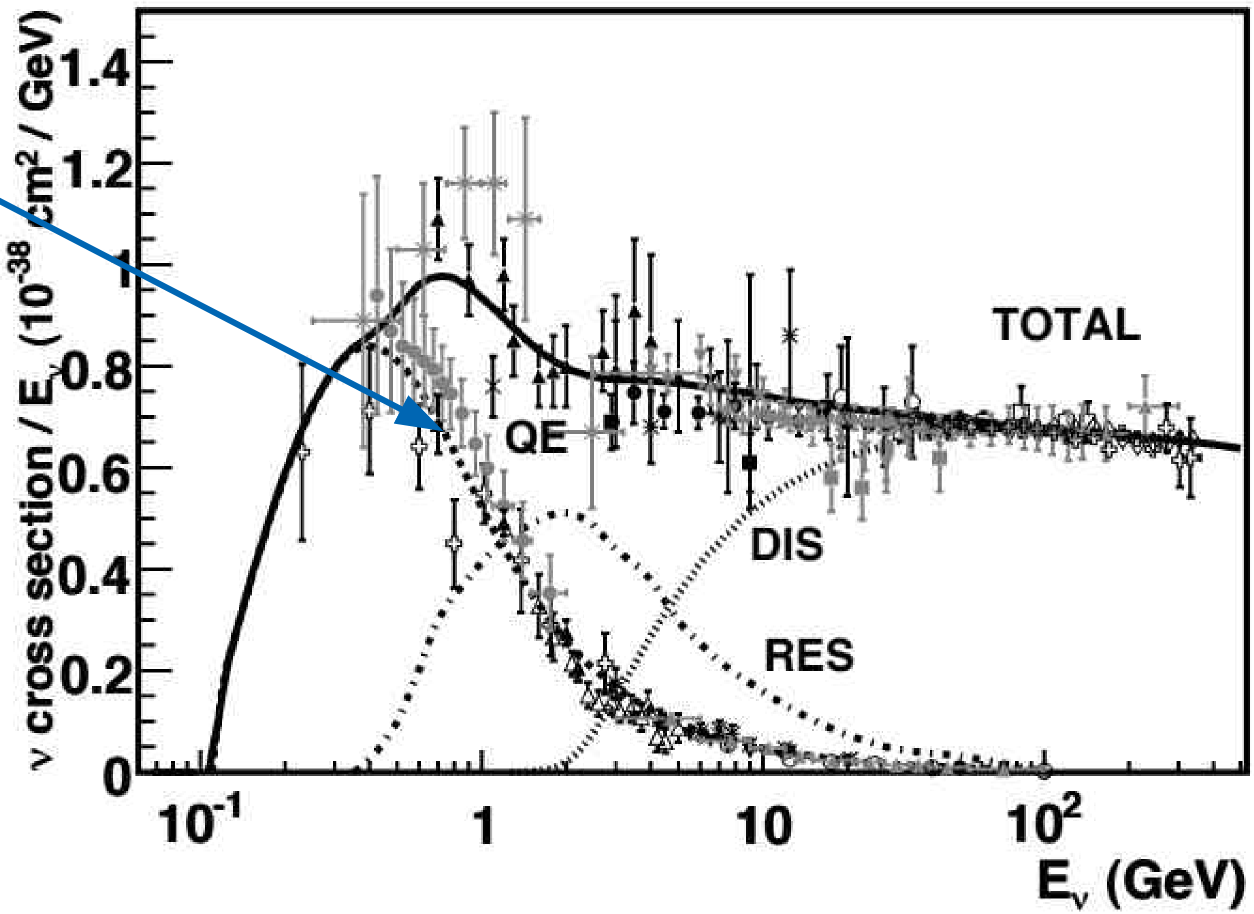


Particle Data Group

Quasi-elastic scattering:

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

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



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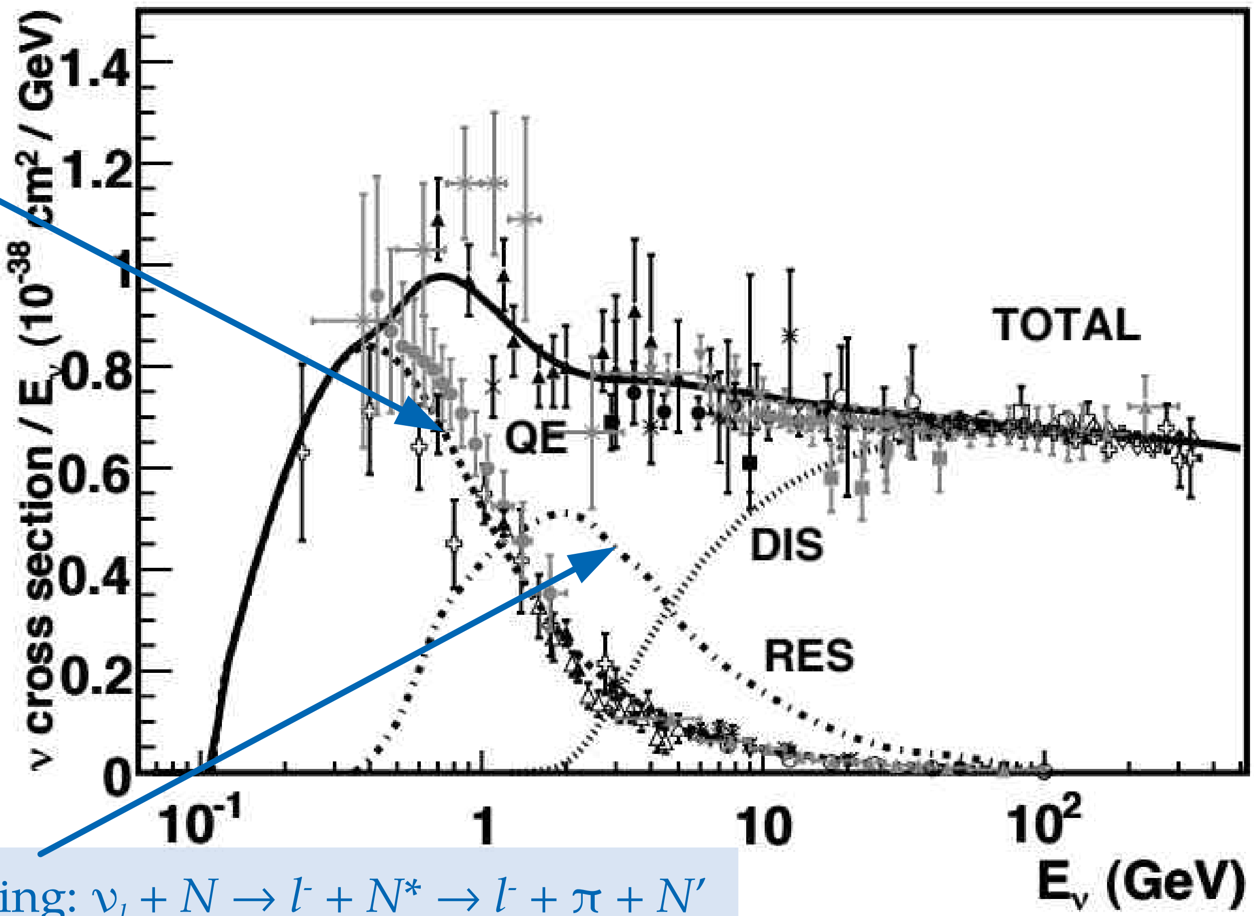

Resonant scattering: $\nu_l + N \rightarrow l^- + N^* \rightarrow l^- + \pi + N'$

Particle Data Group

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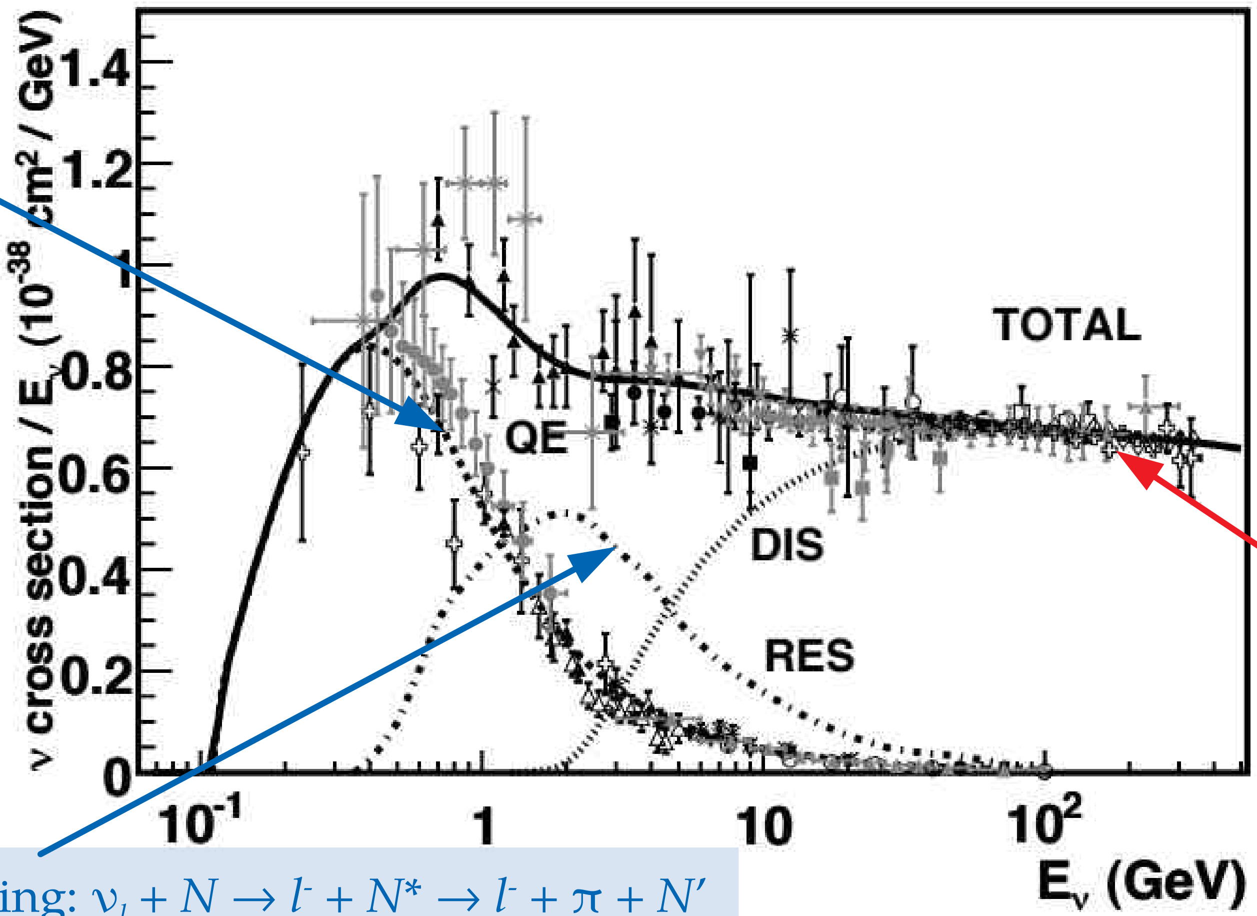
$\bar{\nu}_l + p \to l^+ + n$



Deep inelastic scattering:

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

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

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

Particle Data Group

Extrapolating the cross section to high energies

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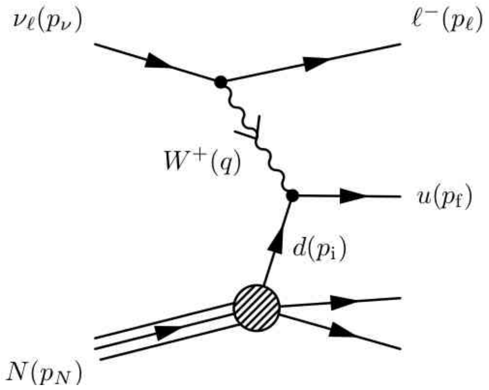
SM



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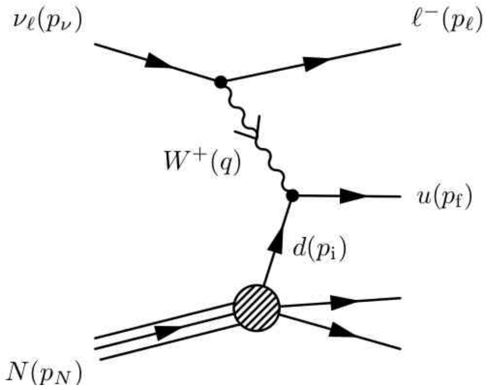

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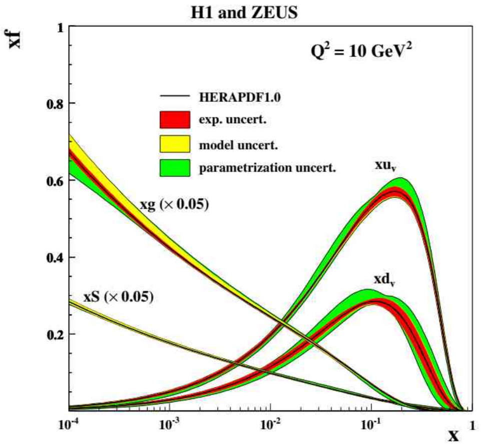
PDFs



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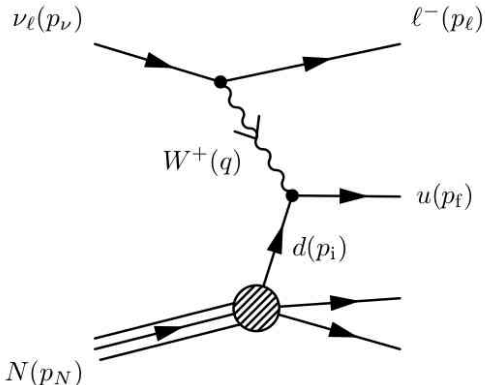

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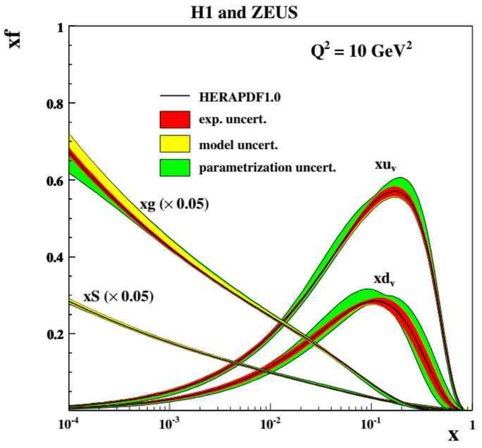

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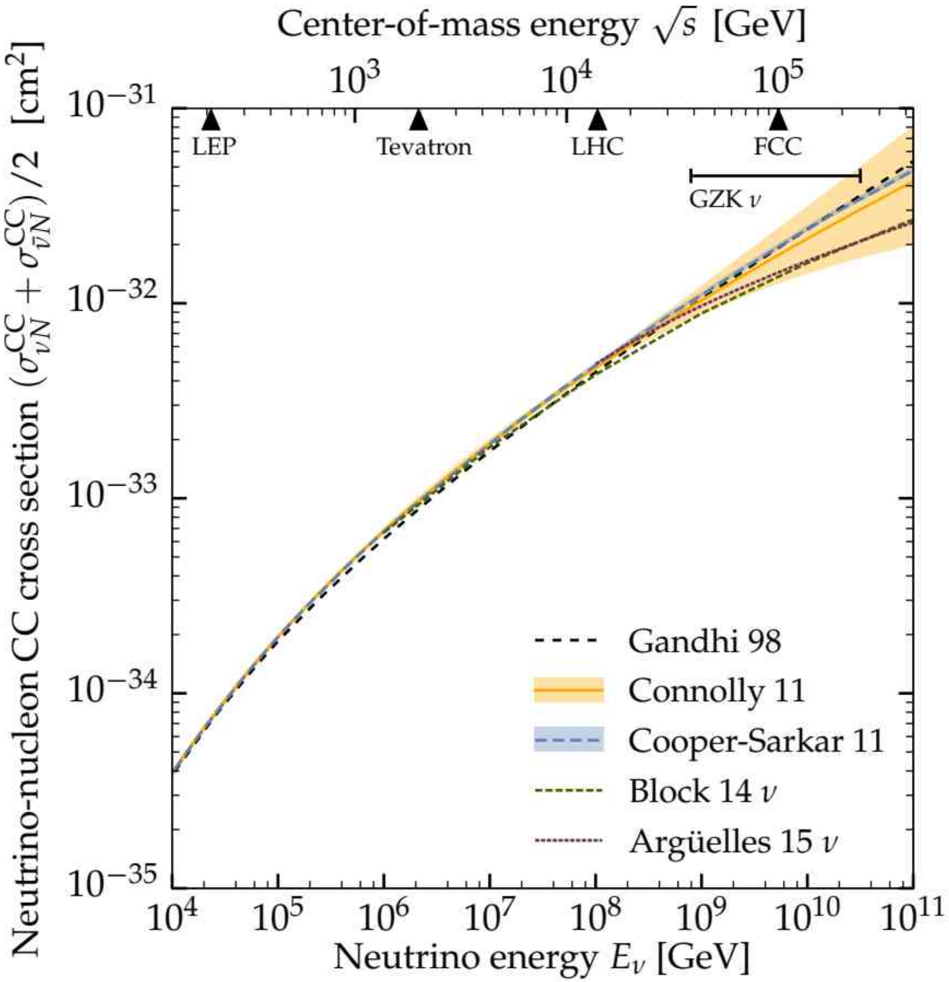

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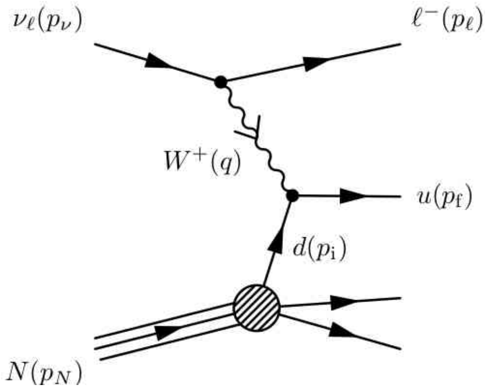

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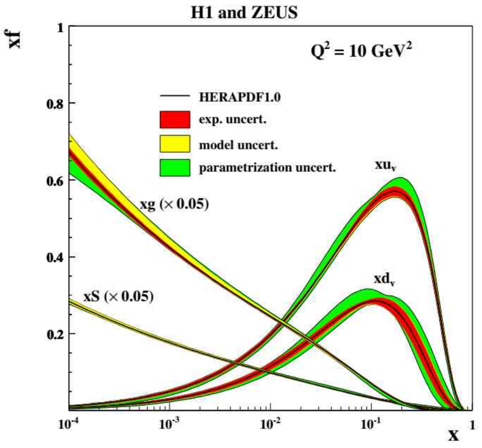

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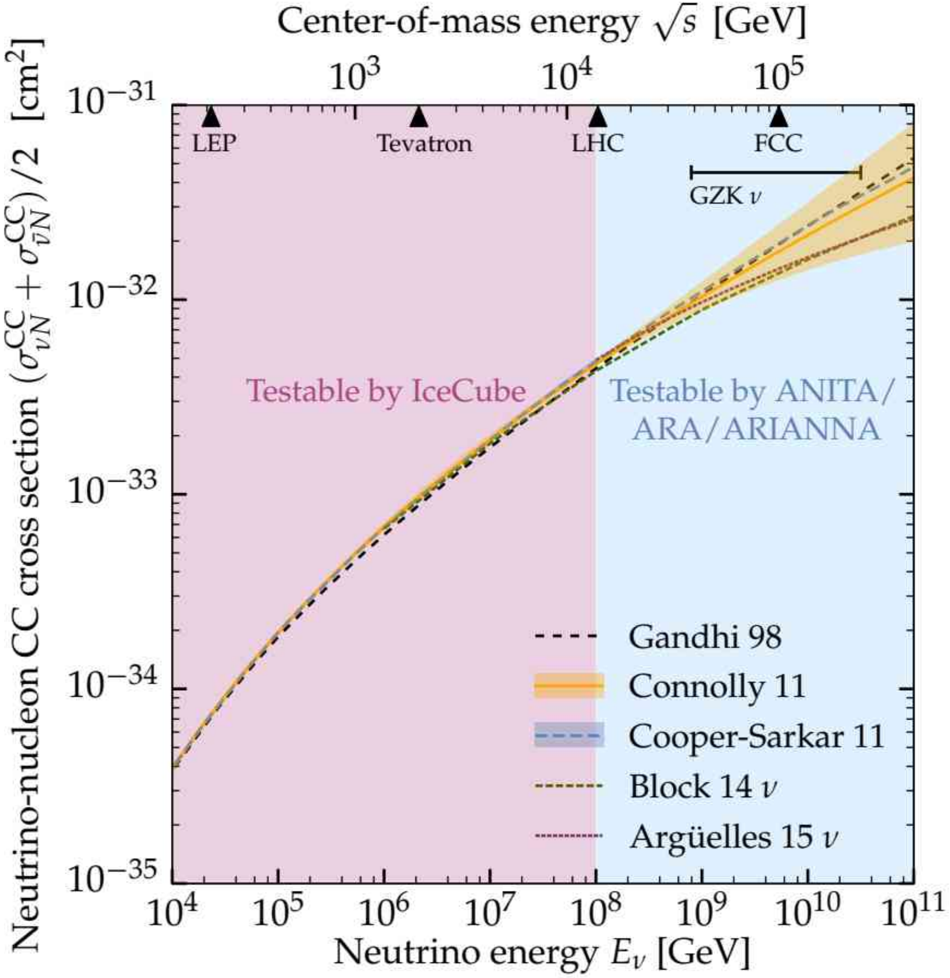
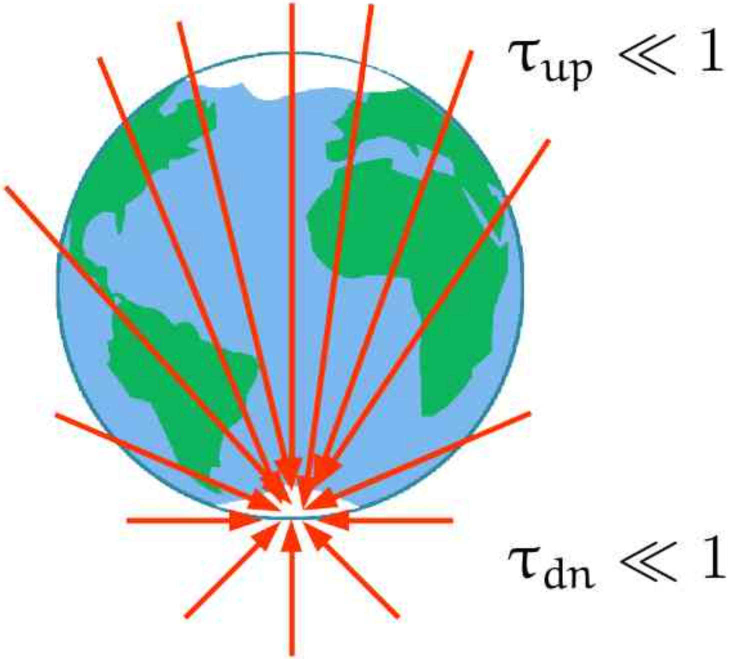


Measuring the high-energy cross section

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

Below ~ 10 TeV: Earth is transparent



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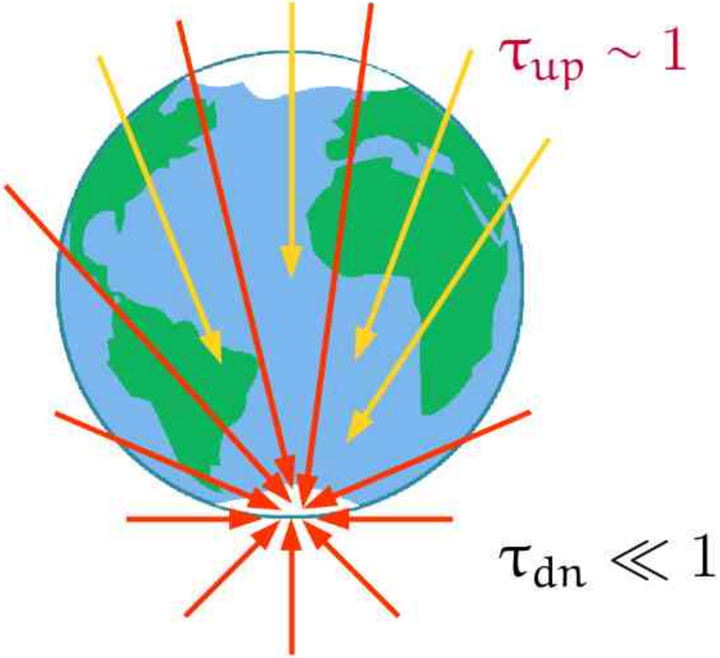

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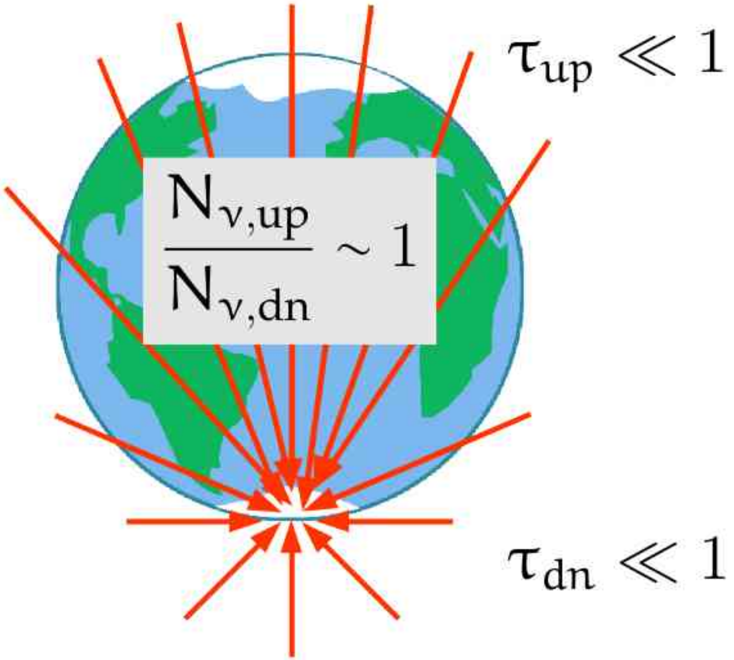

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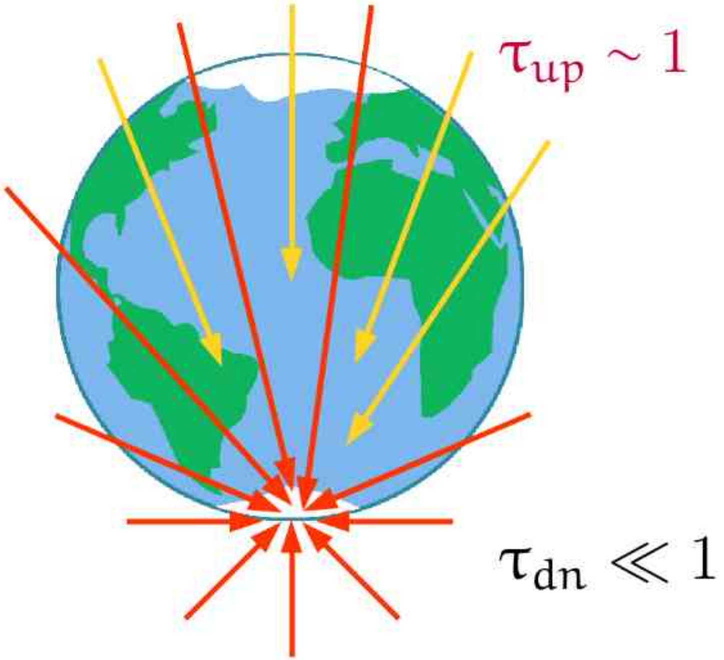

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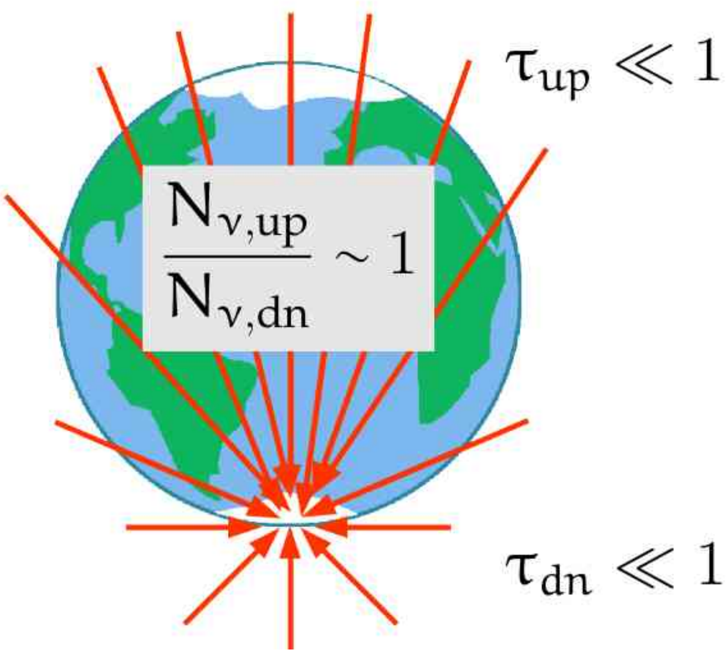

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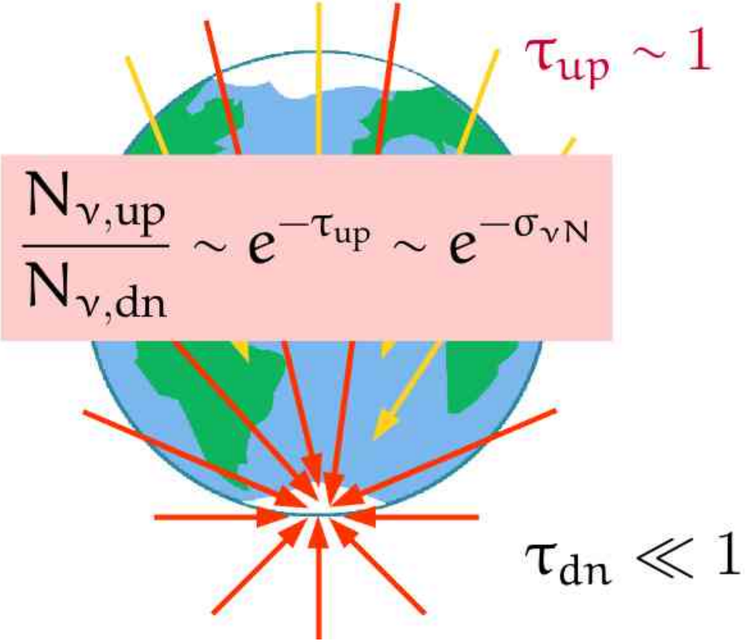
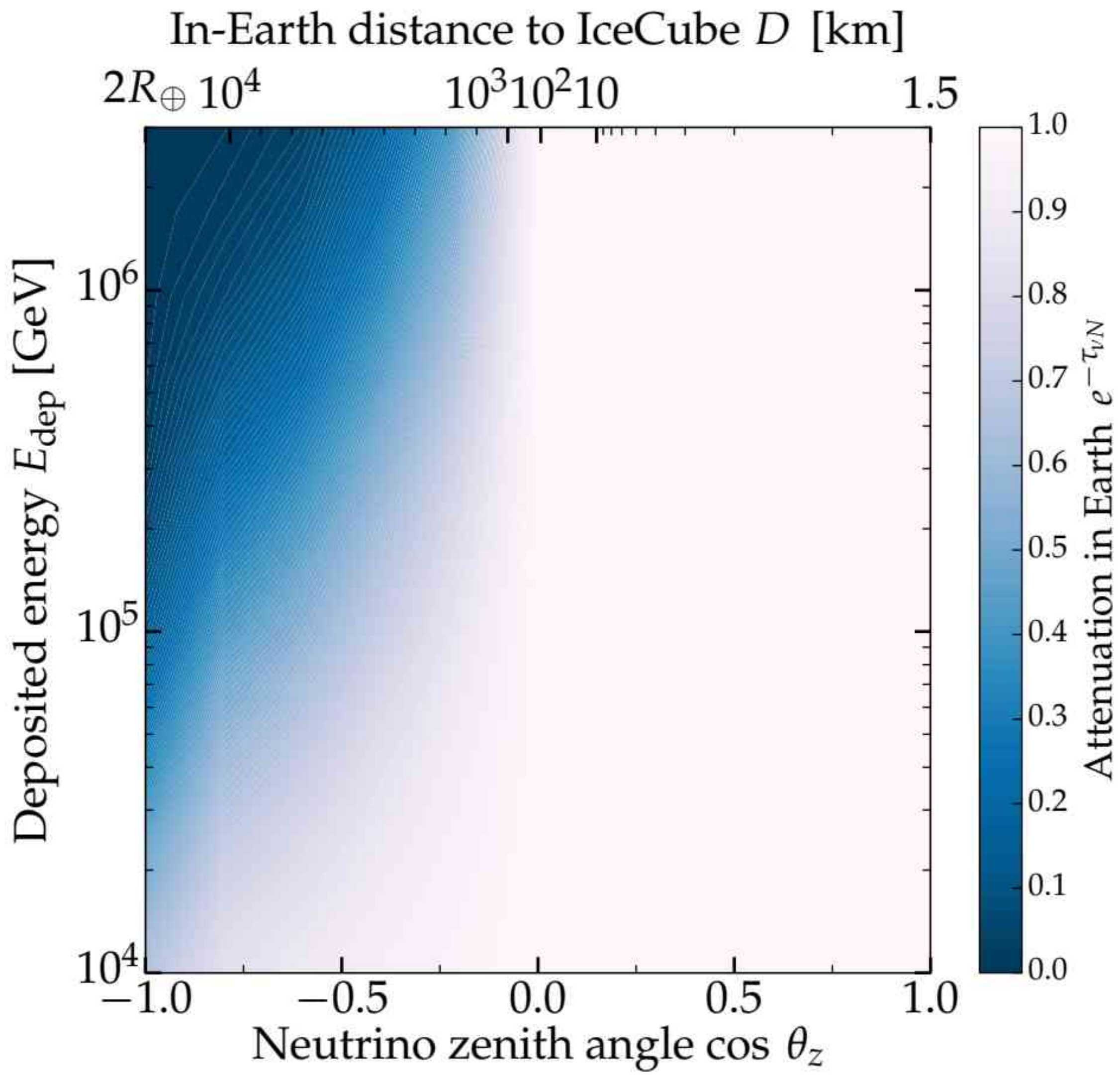
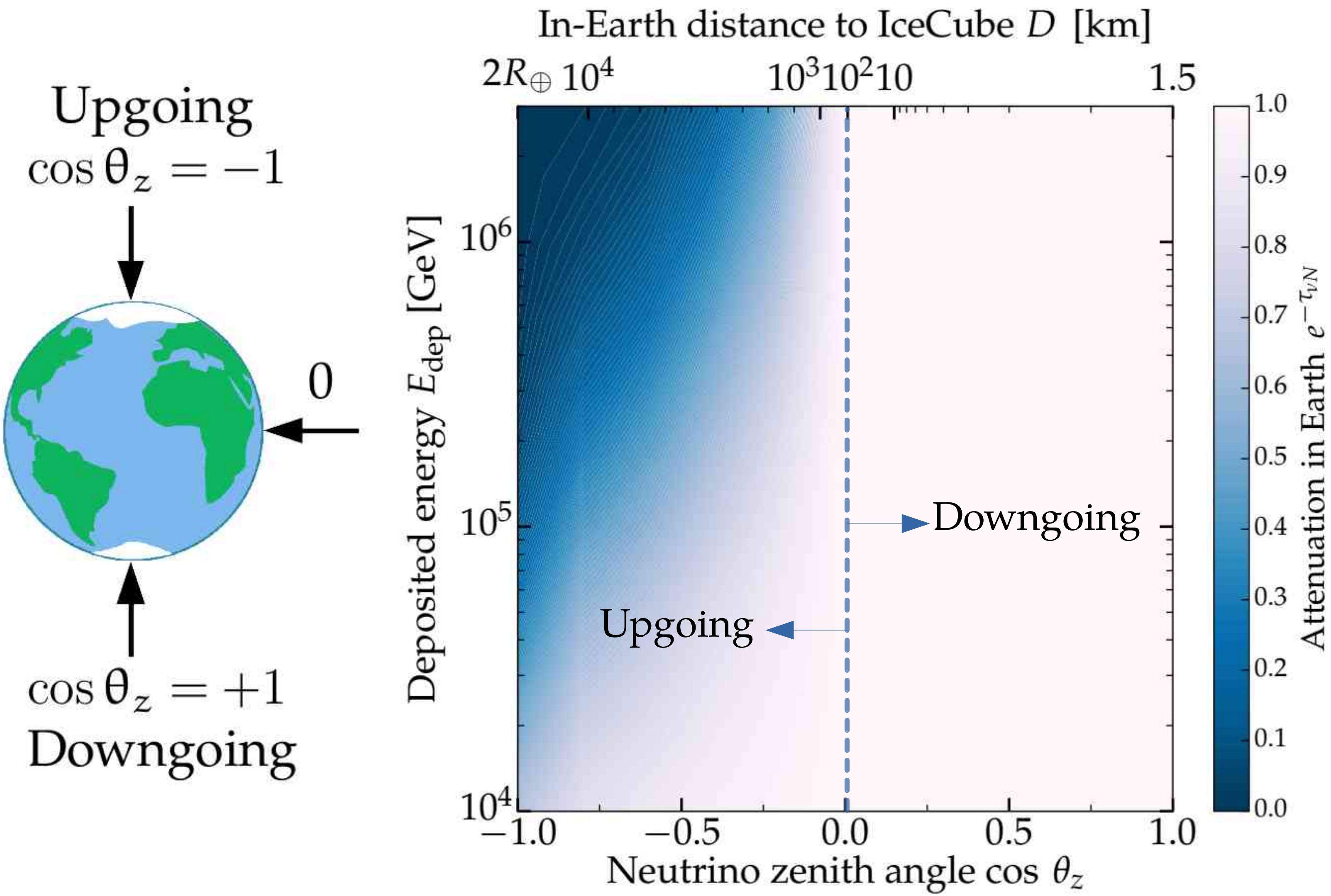
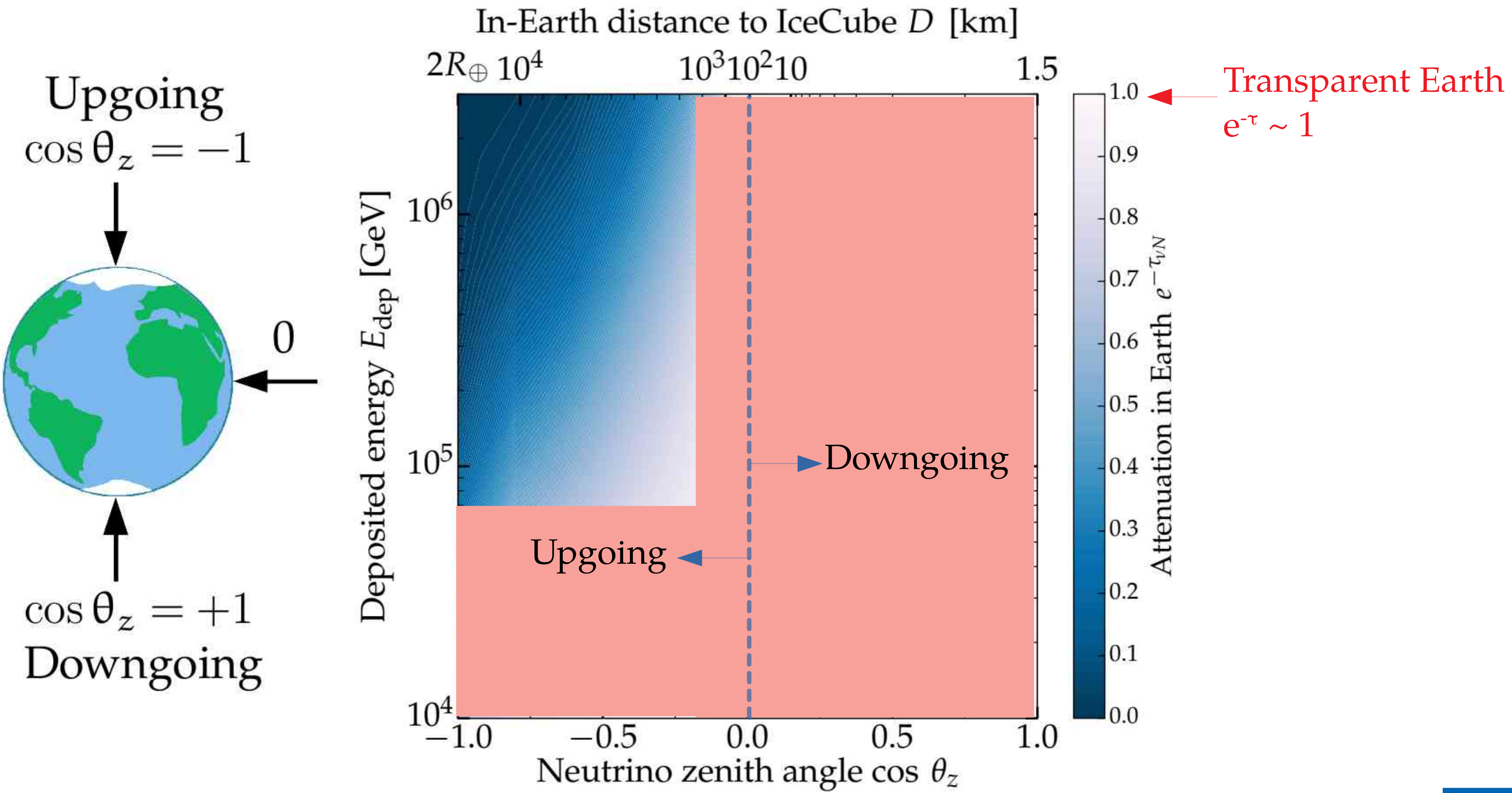


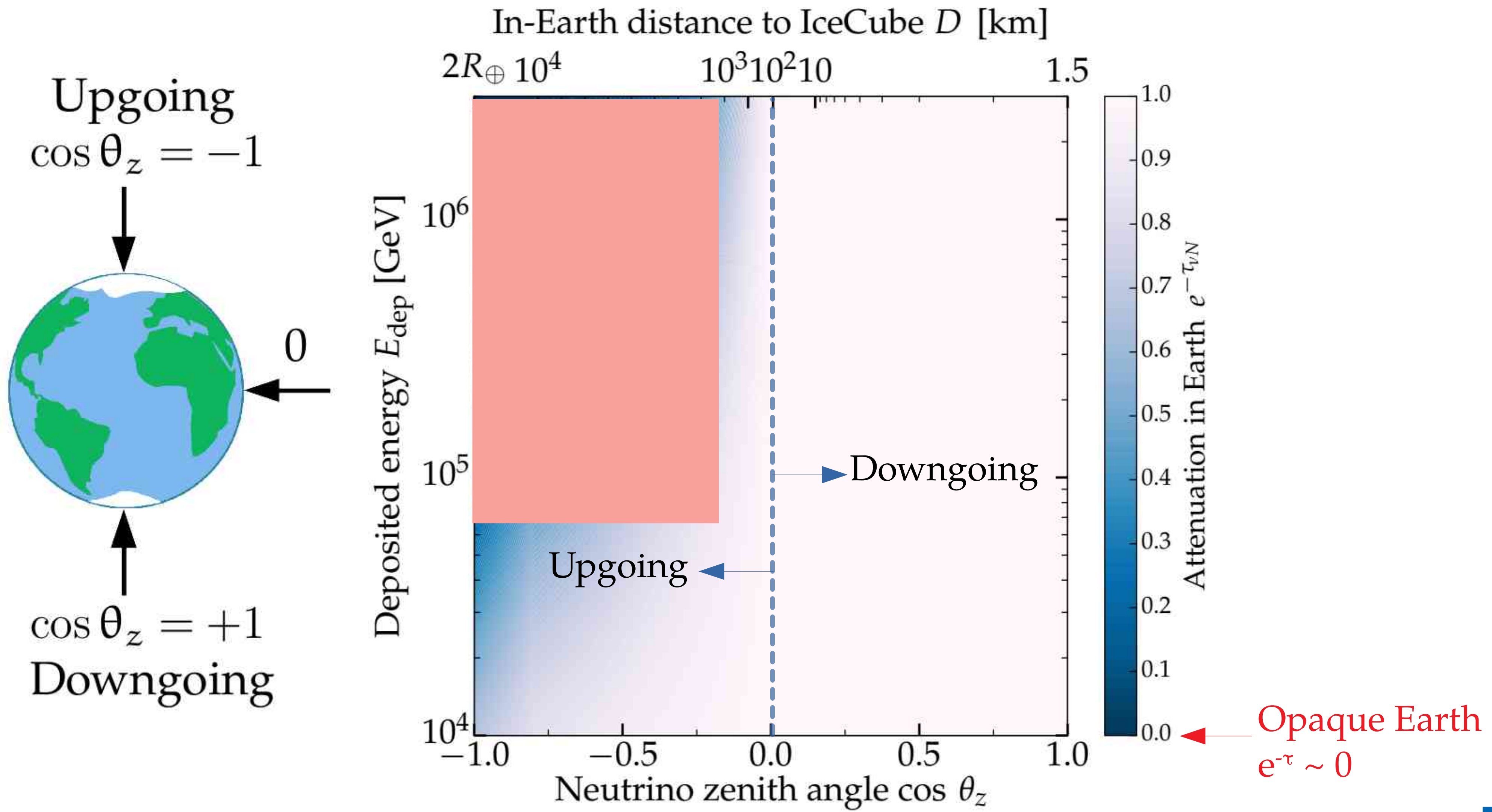


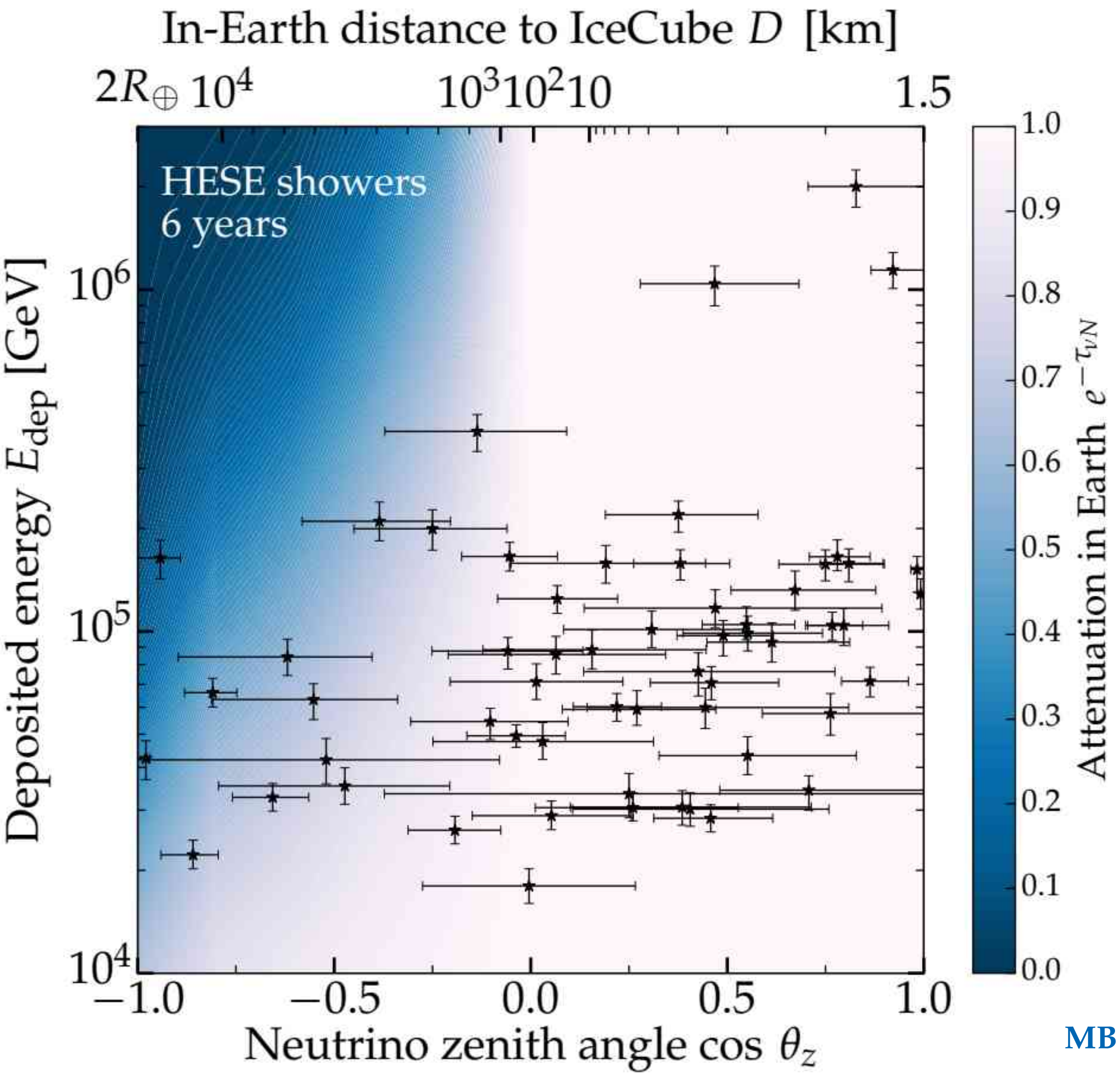
In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4
10^3 10^2 10
1.5
Deposited energy $E_{\rm dep}$ [GeV]
10^6
10^5
10^4
−1.0
−0.5
0.0
0.5
1.0
Neutrino zenith angle cos θ_z
Attenuation in Earth $e^{-\tau_{\nu N}}$
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0



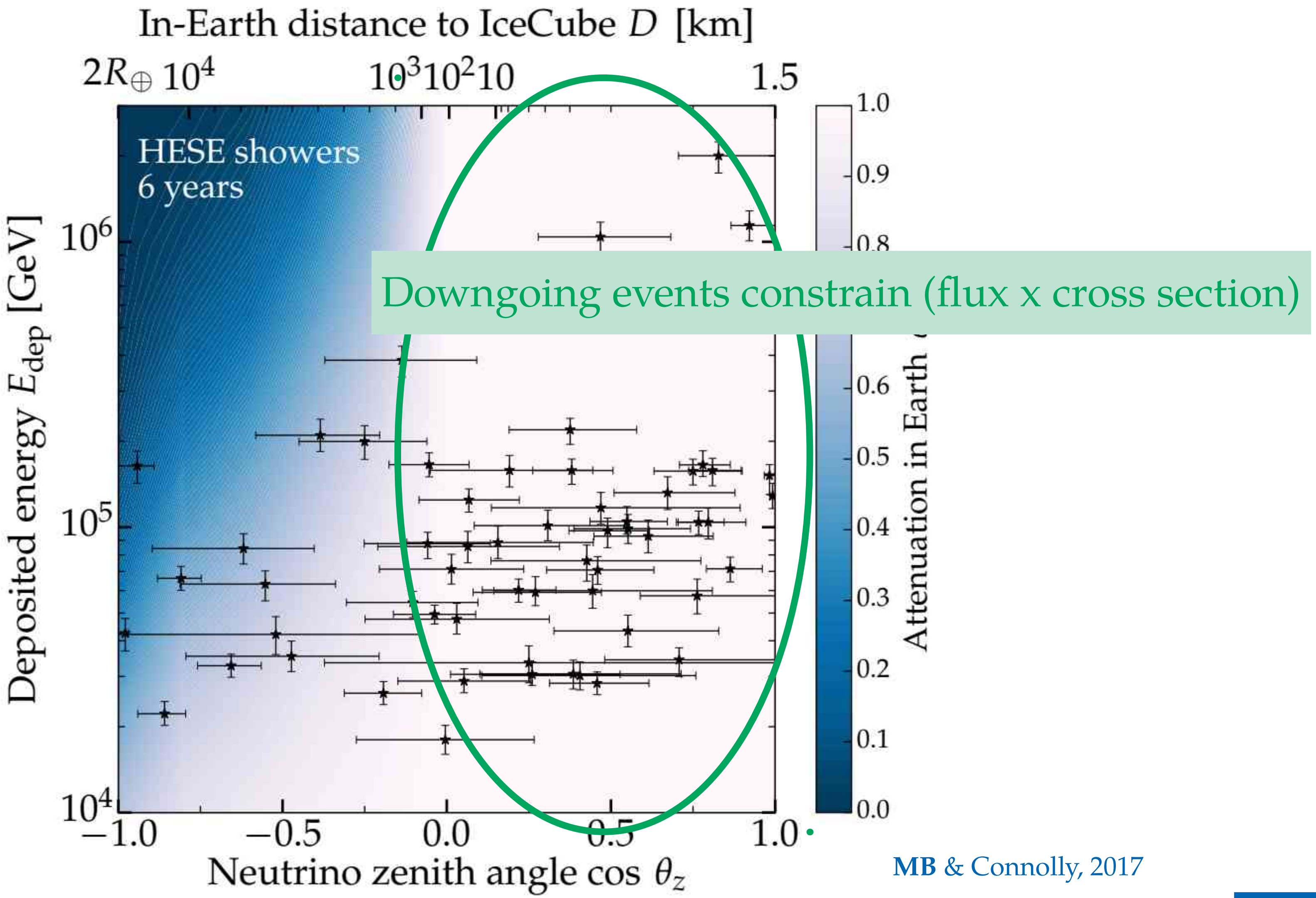
Upgoing
$\cos\theta_z = -1$
0
$\cos\theta_z = +1$
Downgoing
In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4 10^3 10^2 10 1.5
Deposited energy $E_{\rm dep}$ [GeV]
10^6
10^5
10^4
Downgoing
Upgoing
−1.0 −0.5 0.0 0.5 1.0
Neutrino zenith angle $\cos\theta_z$
Attenuation in Earth $e^{-\tau_{\nu N}}$
1.0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


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



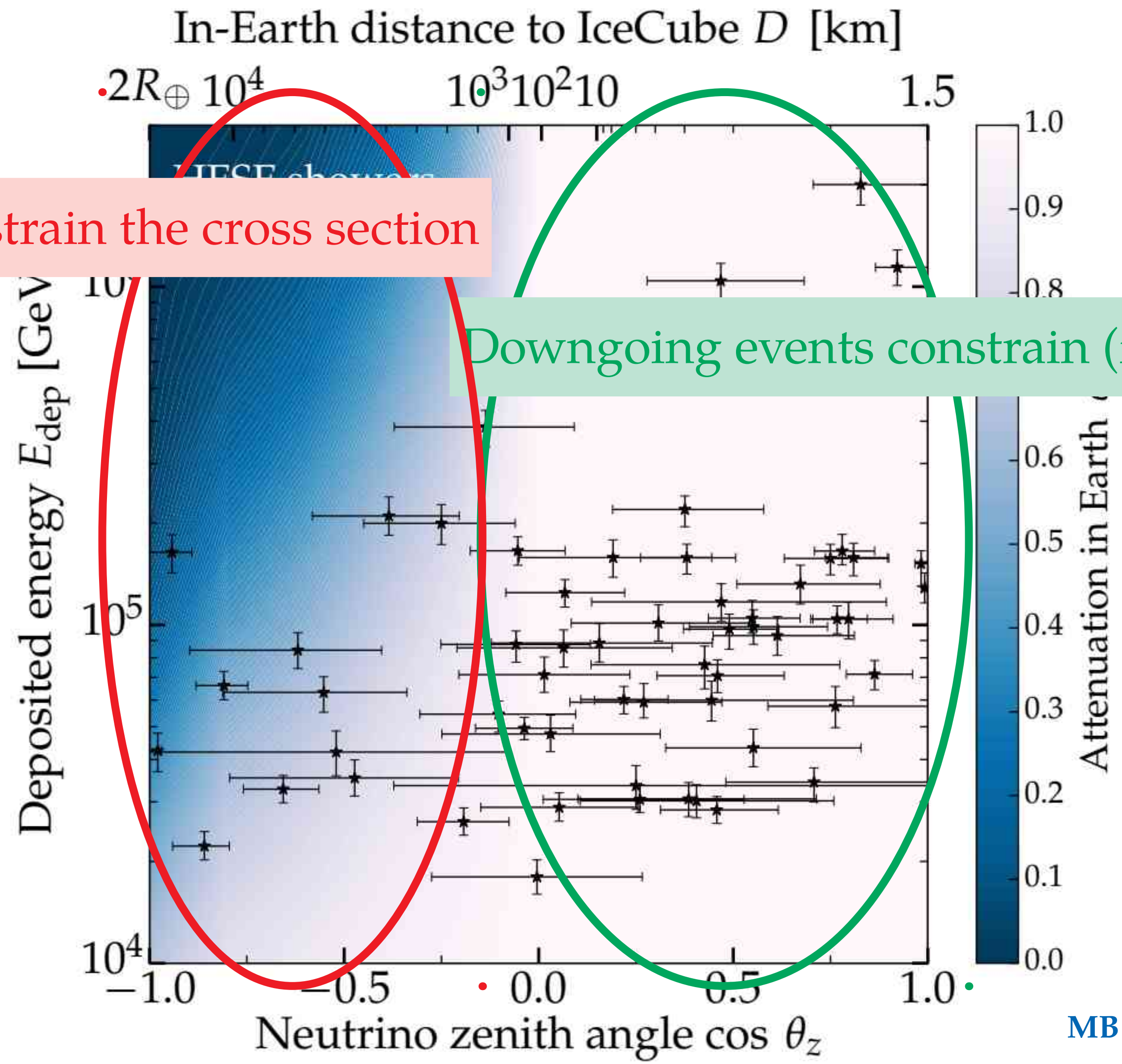
MB & Connolly, 2017



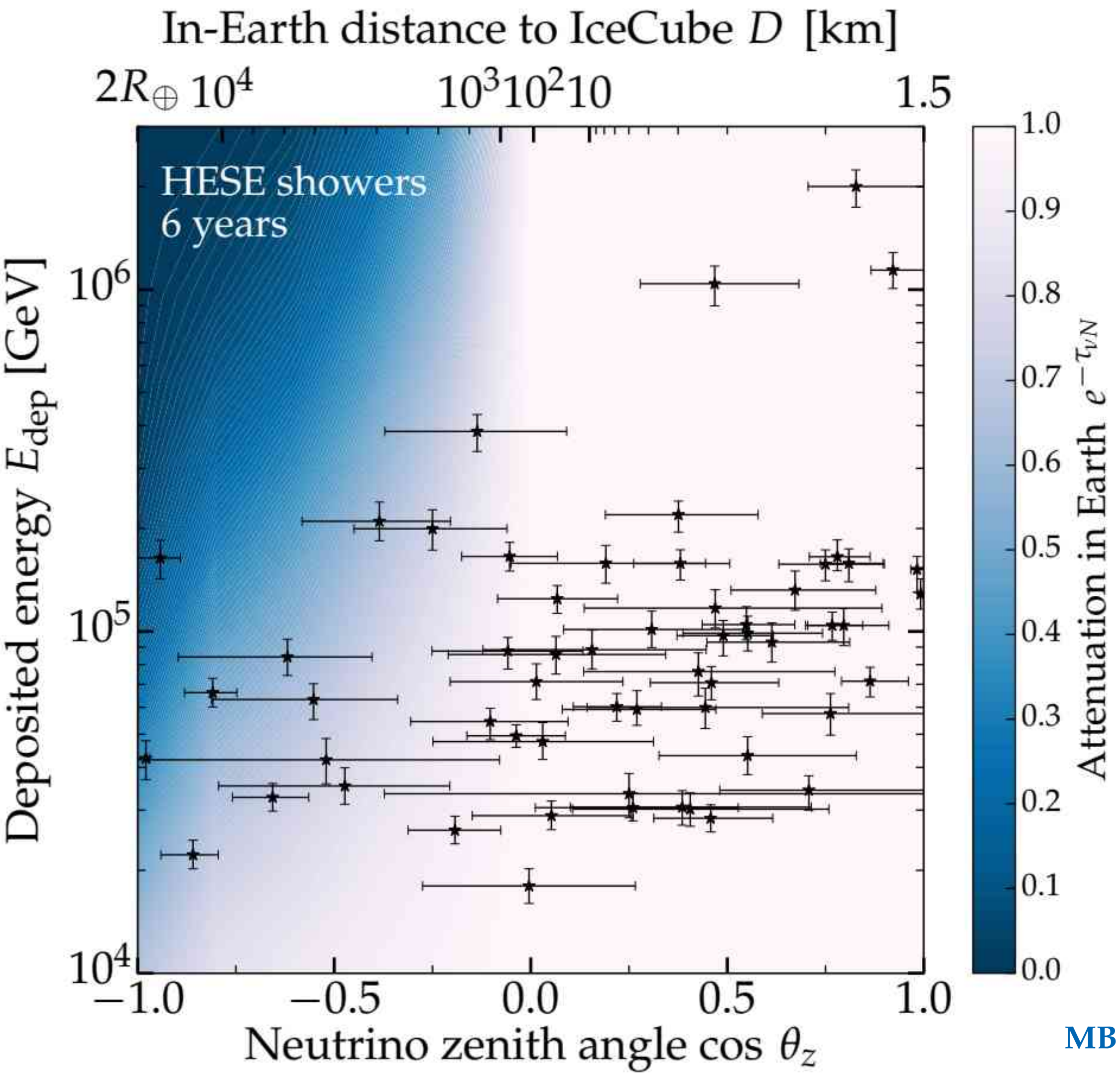
MB & Connolly, 2017

Upgoing events constrain the cross section

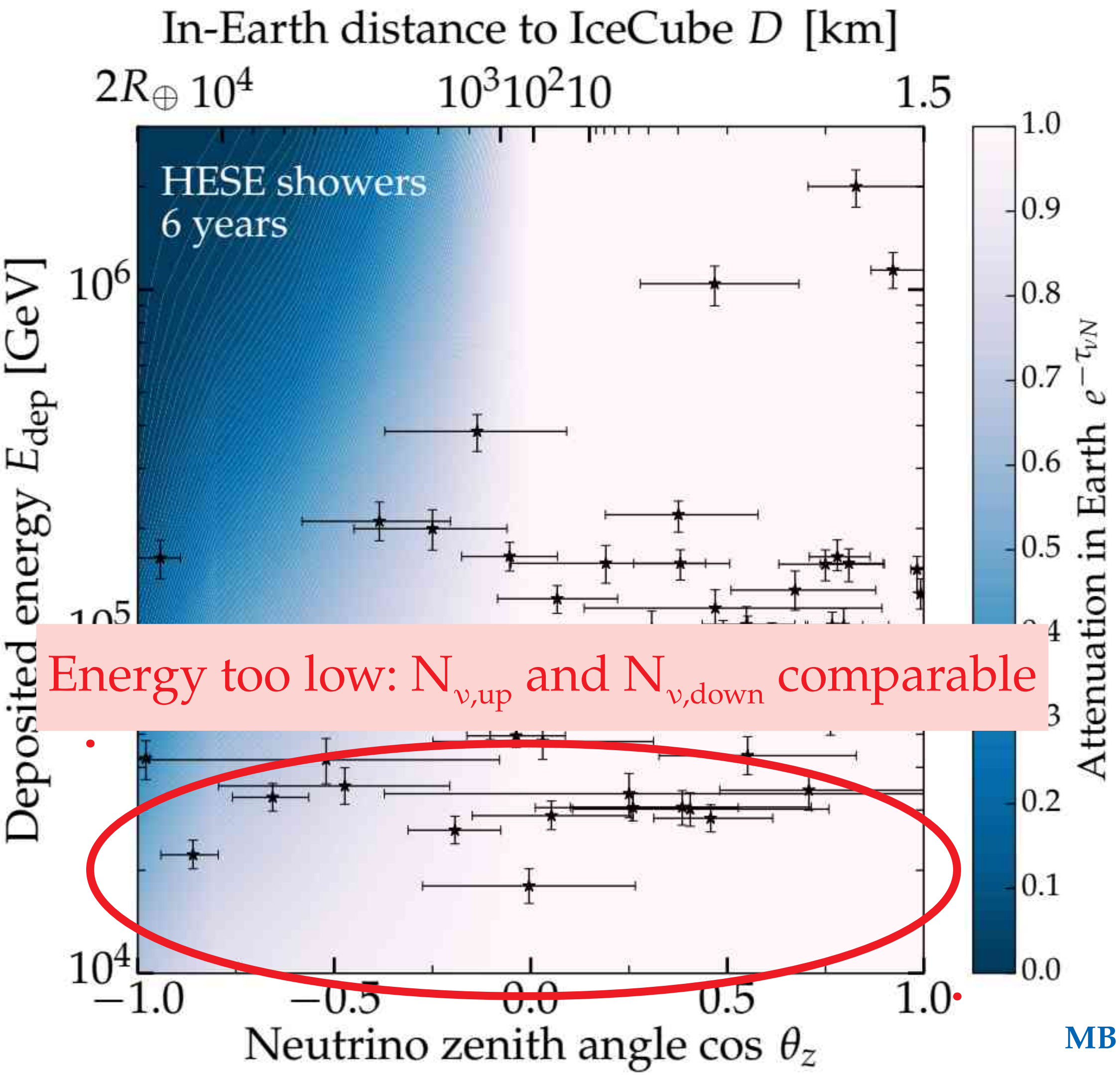
Downgoing events constrain (flux x cross section)



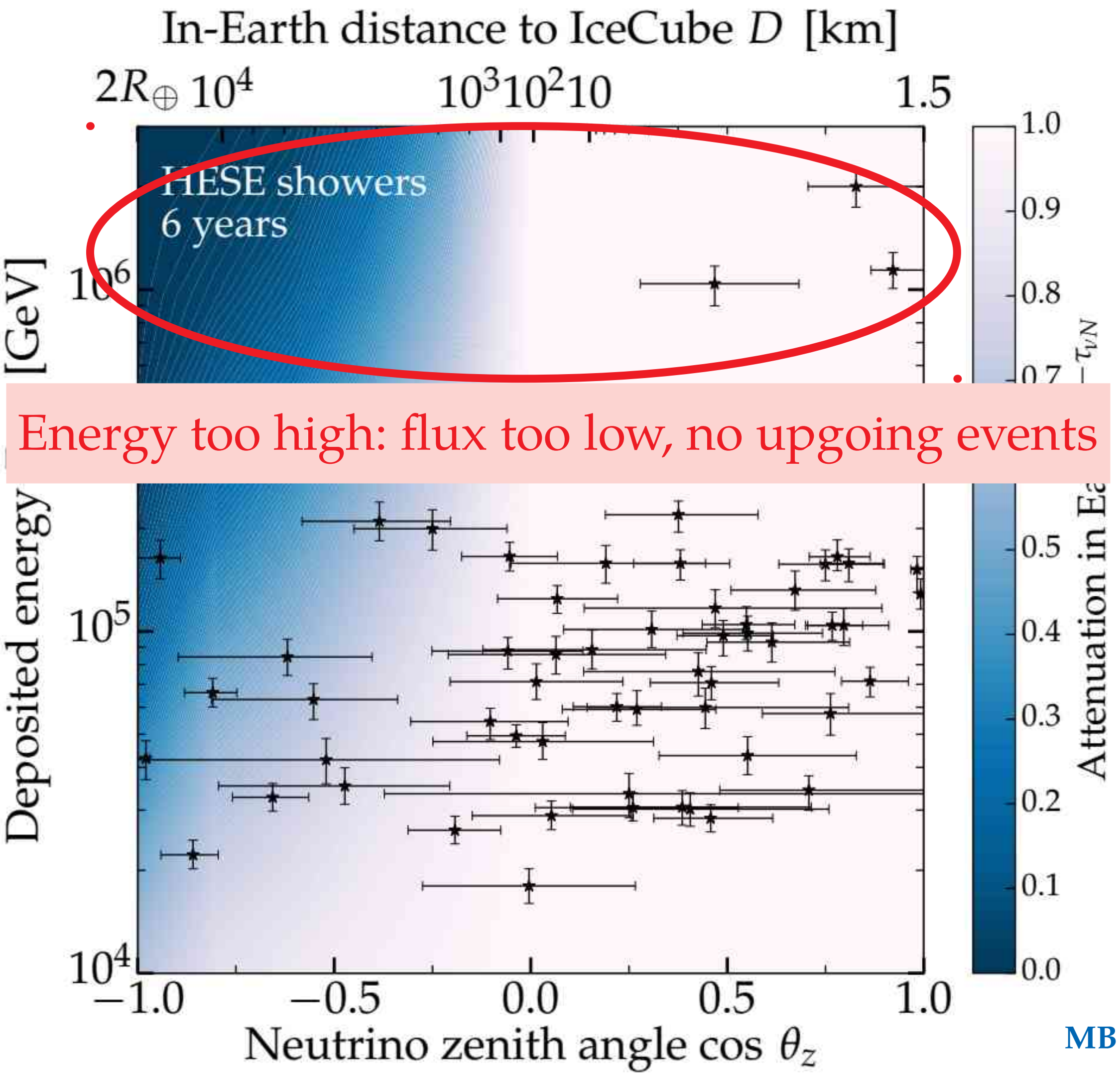
MB & Connolly, 2017



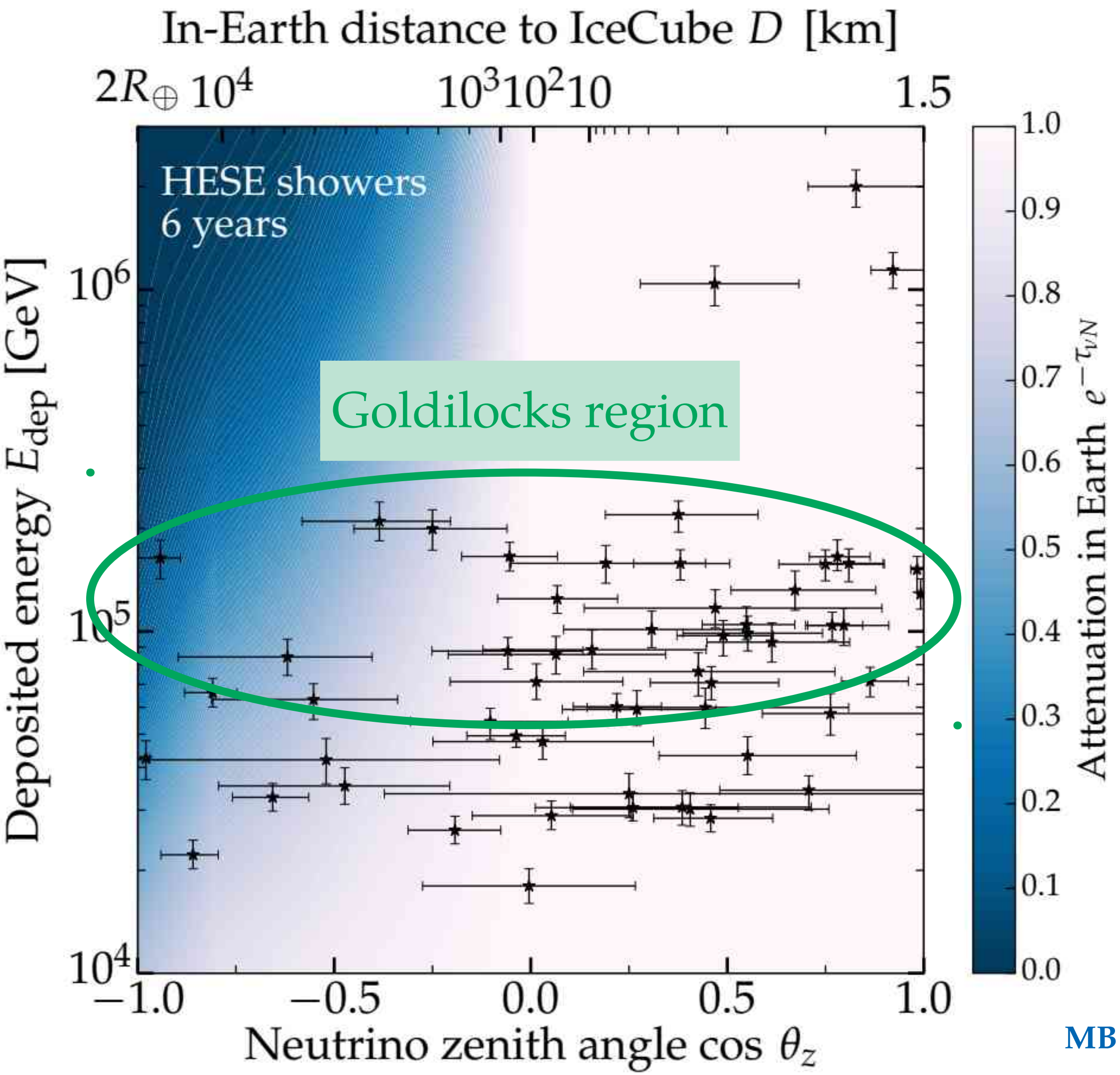
MB & Connolly, 2017



MB & Connolly, 2017

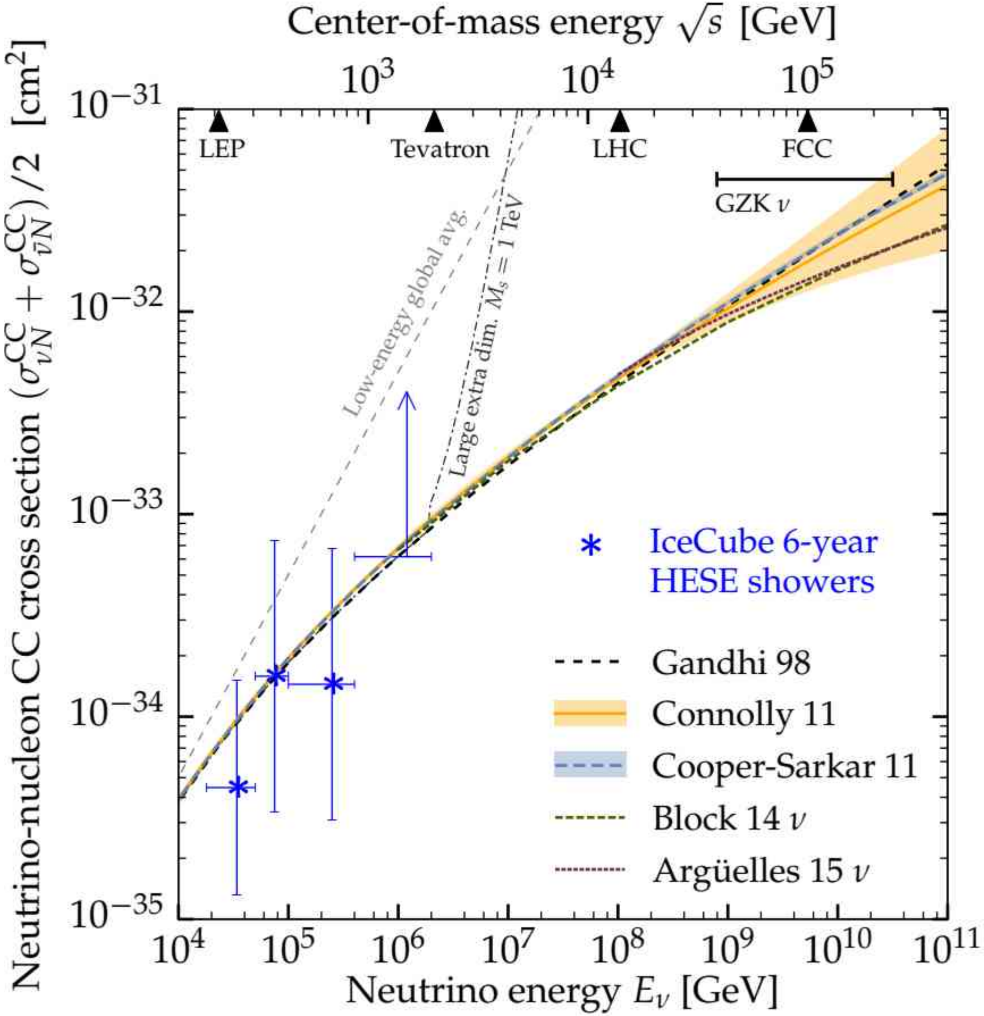


MB & Connolly, 2017



MB & Connolly, 2017

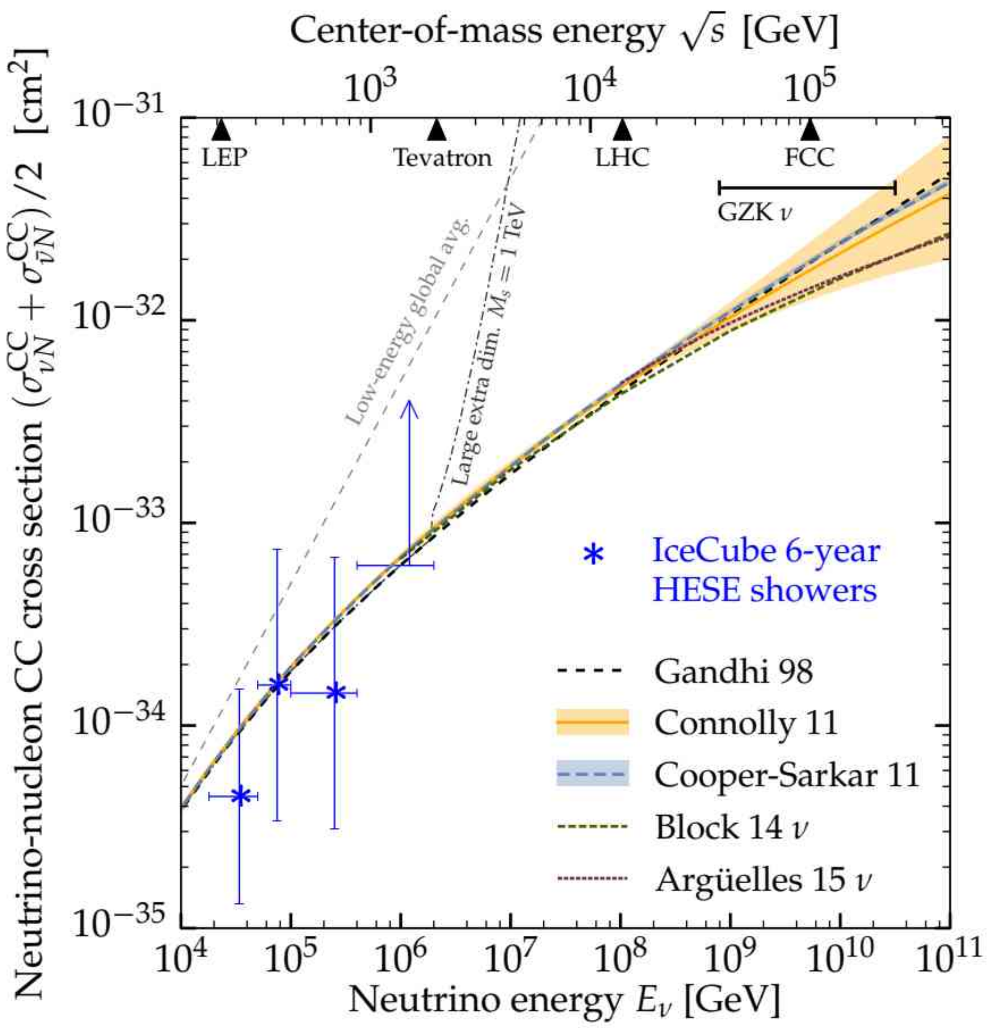
Our result

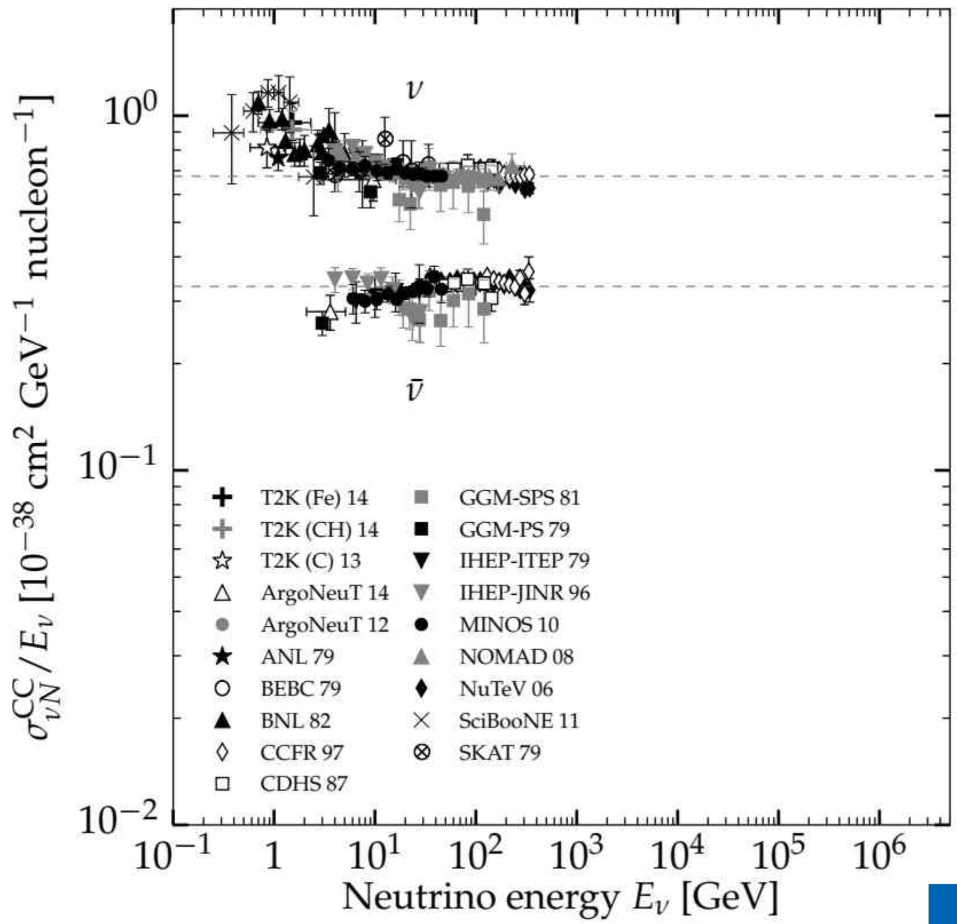


MB & A. Connolly 2017
See also: IceCube, *Nature* 2017

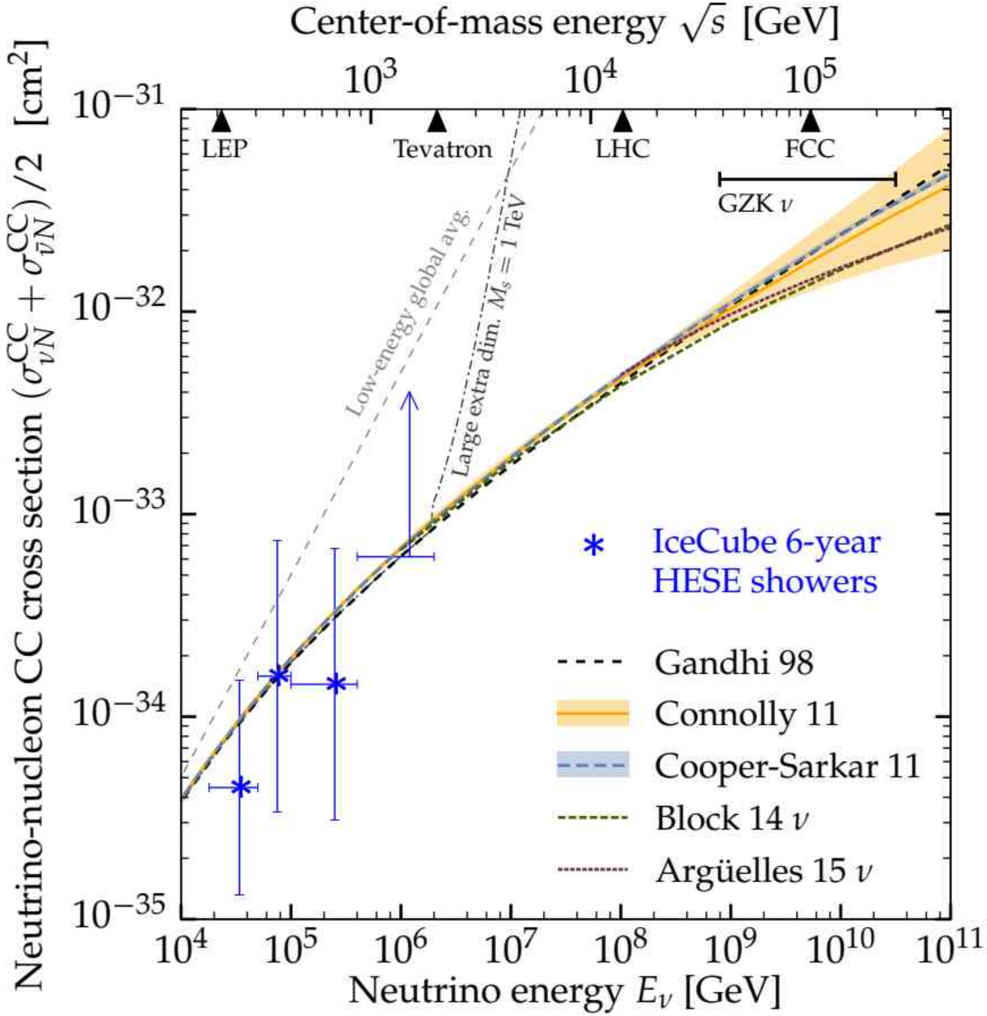
Our result

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



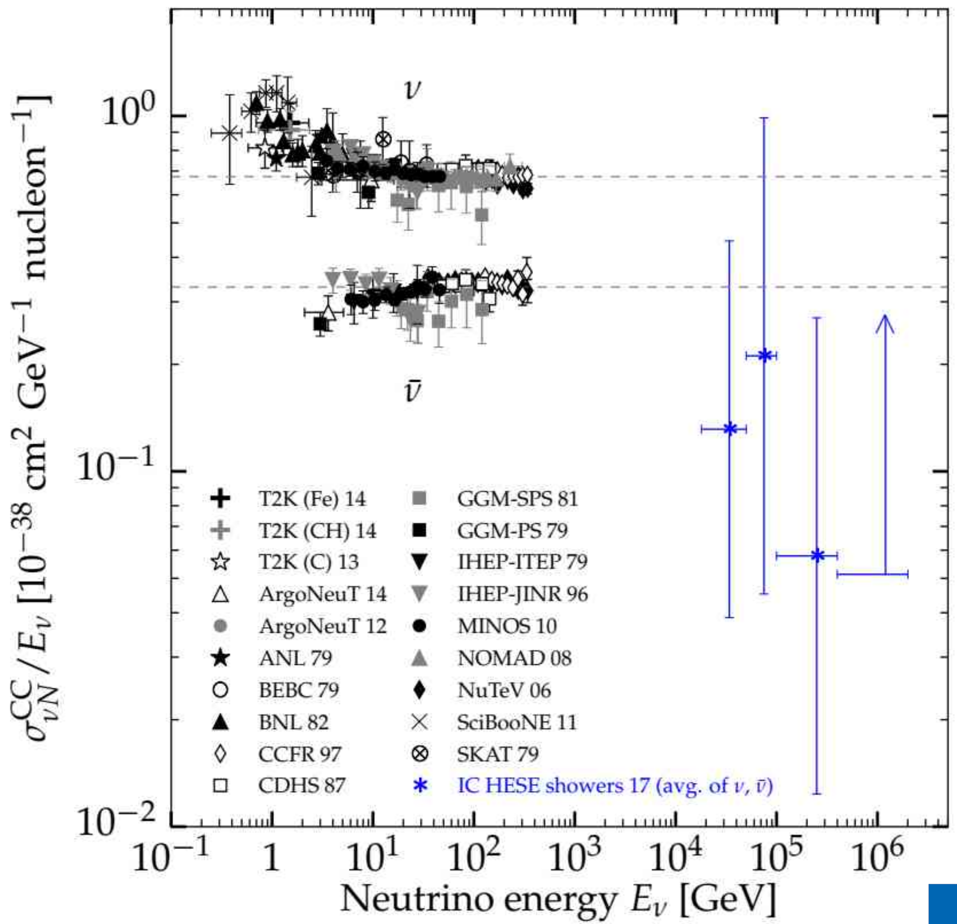


Our result

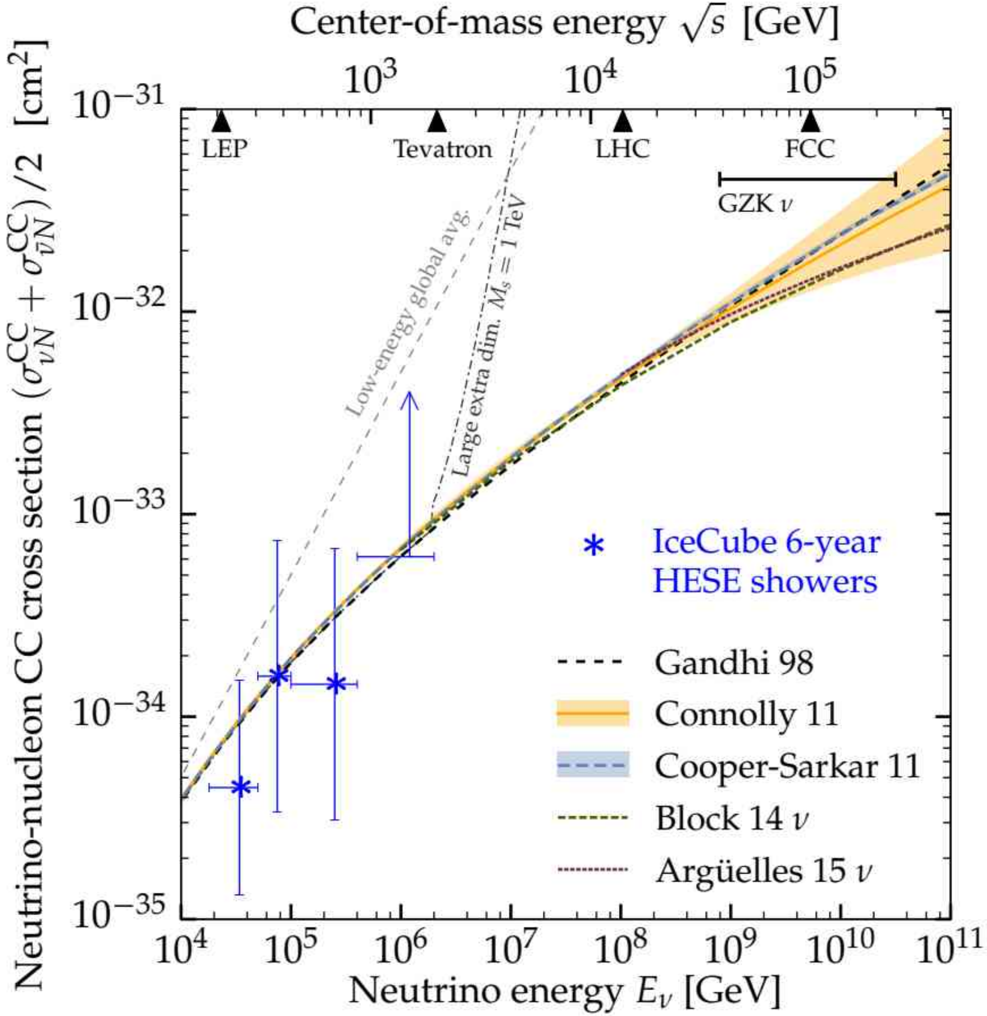


MB & A. Connolly 2017

See also: IceCube, *Nature* 2017

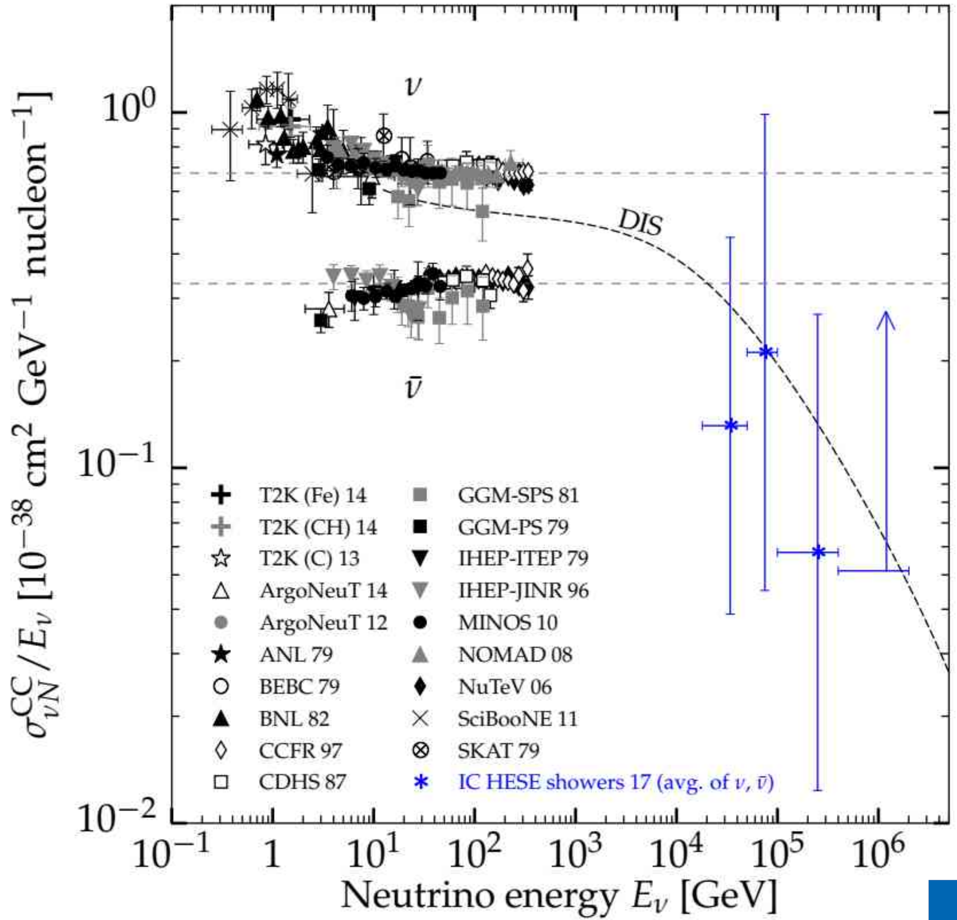


Our result



MB & A. Connolly 2017

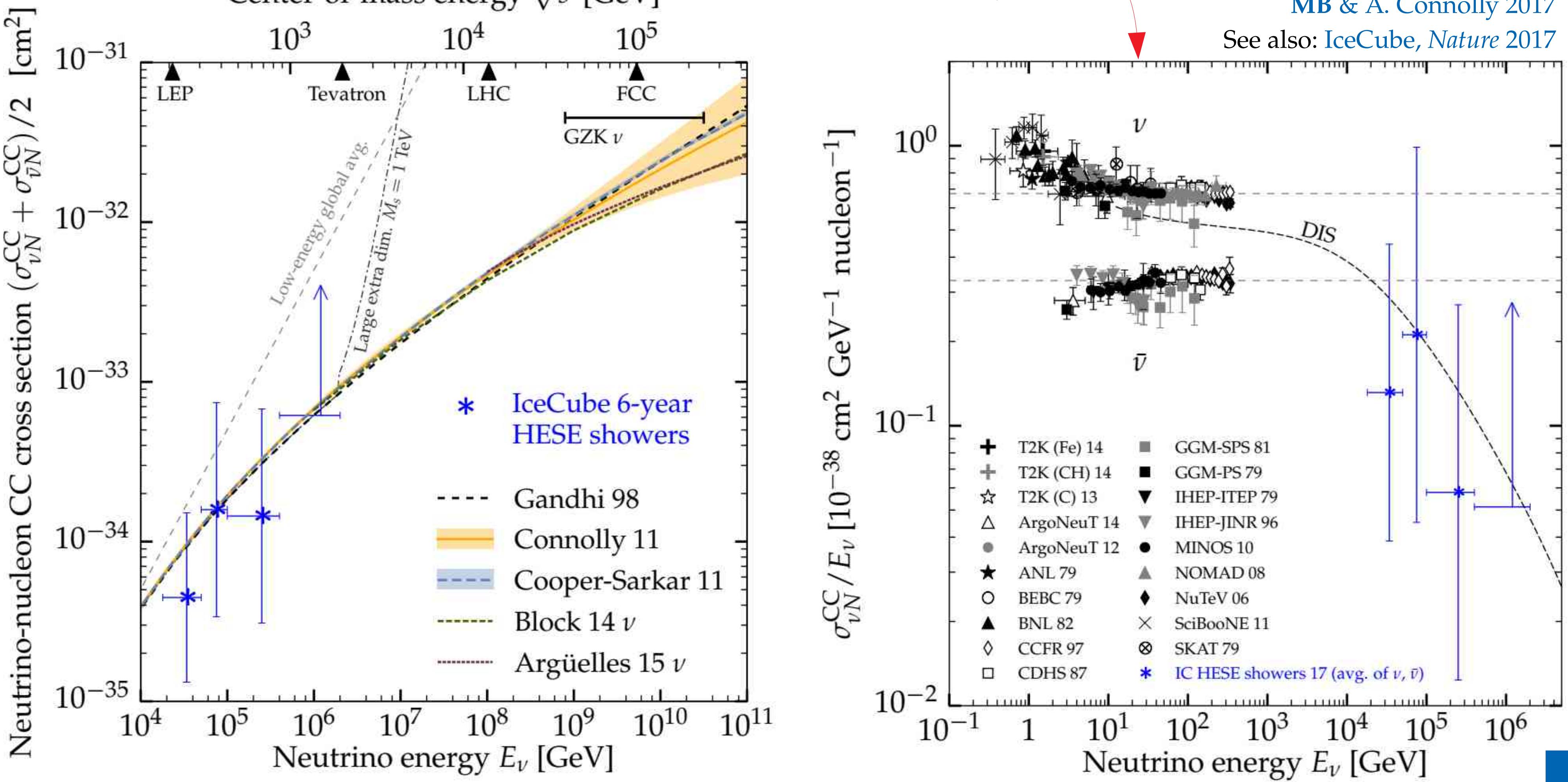
See also: IceCube, *Nature* 2017



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 $\nu_\mu + N \rightarrow \mu + X$:

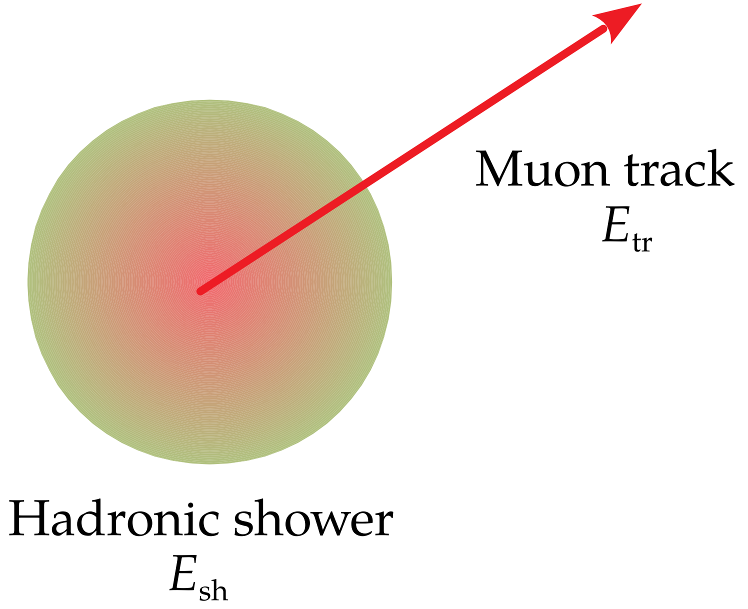
  $E_X = y\, E_\nu$ and $E_\mu = (1\text{-}y)\, E_\nu \Rightarrow y = (1 + E_\mu / E_X)^{-1}$

- The value of y follows a distribution $\mathrm{d}\sigma/\mathrm{d}y$

- In a HESE starting track:

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

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



IceCube, 1808.07629

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

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

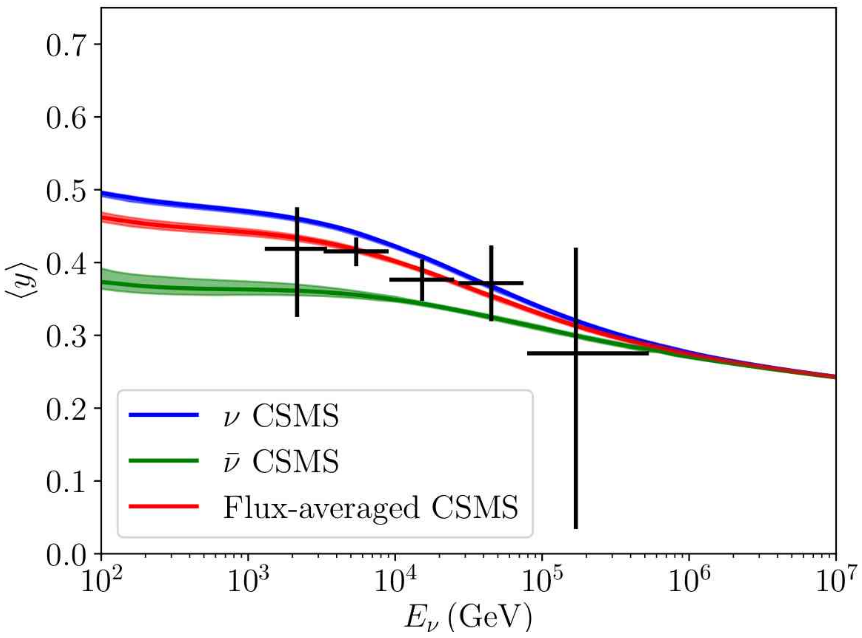
  $$E_X = y\,E_\nu \quad \text{and} \quad E_\mu = (1\text{-}y)\,E_\nu \quad \Rightarrow \quad y = (1 + E_\mu/E_X)^{-1}$$

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

- In a HESE starting track:

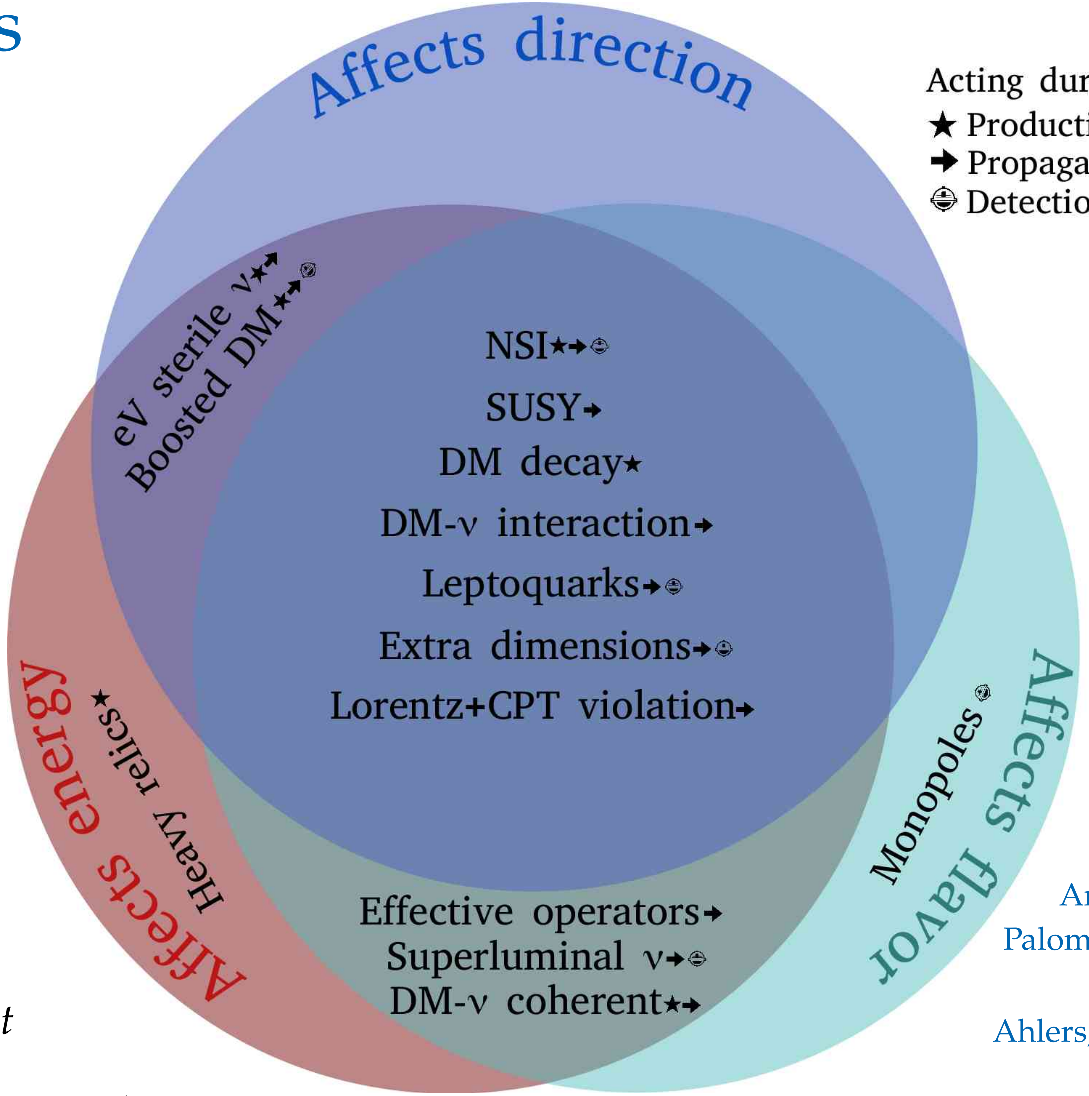
  $$\left.\begin{array}{l} E_X = E_{sh} \text{ (energy of shower)} \\ E_\mu = E_{tr} \text{ (energy of track)} \end{array}\right\} \; y = (1 + E_{tr}/E_{sh})^{-1}$$

- 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



Acting during
★ Production
➜ Propagation
Detection

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

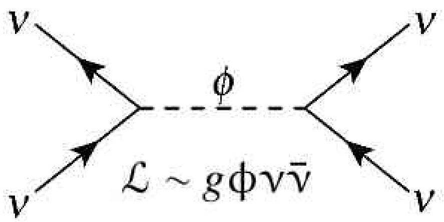
See also:

Ahlers, Helbing, De los Heros, 1806.05696

Note: Not an exhaustive list

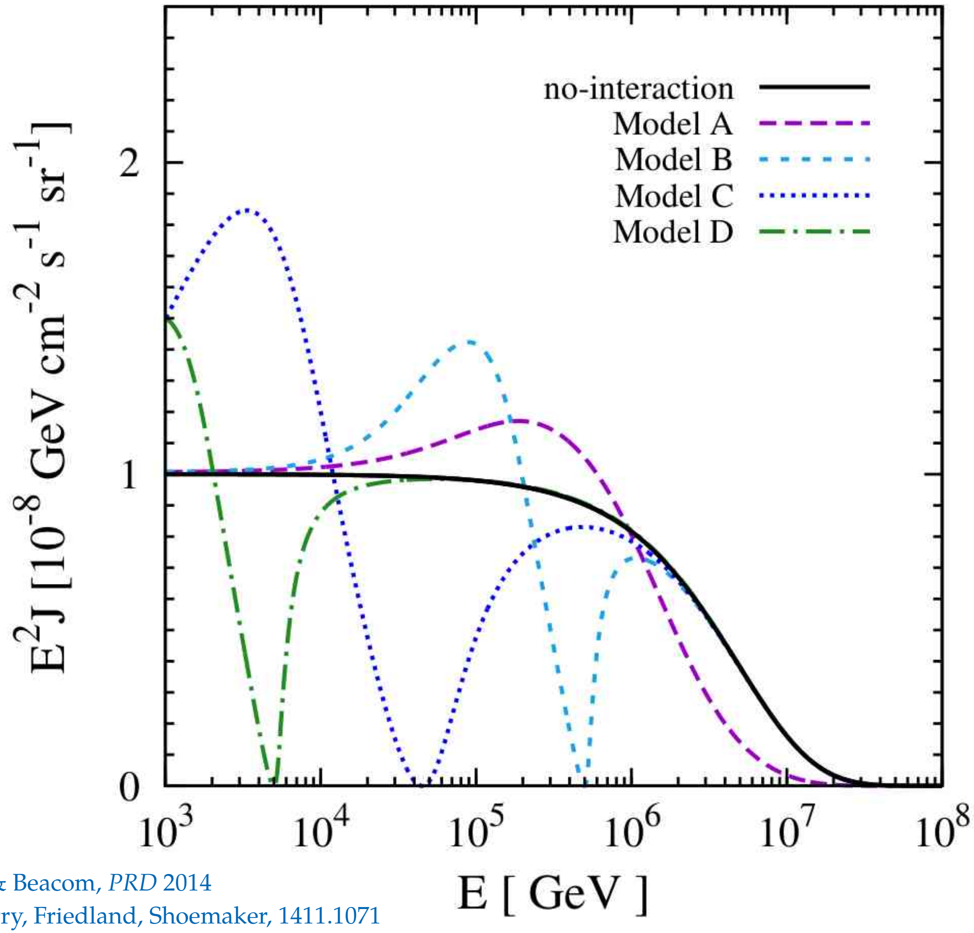
New physics in the spectral shape: $\nu\nu$ interactions

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



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

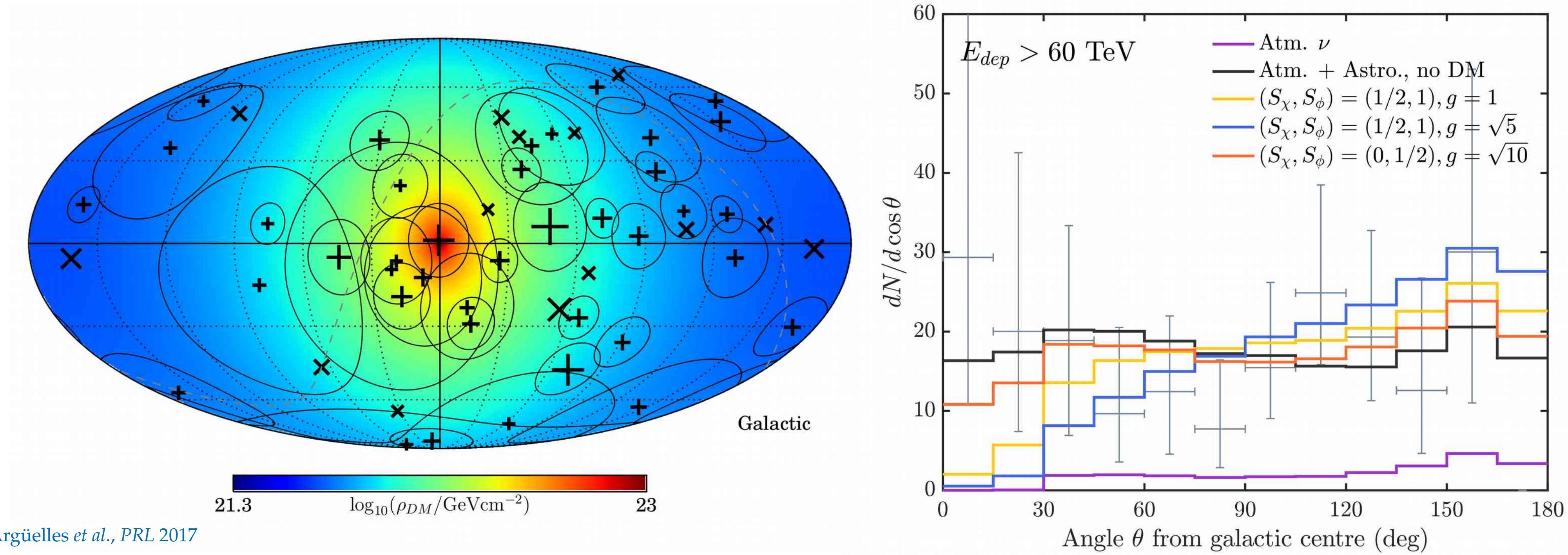
Resonance energy: $E_{\text{res}} = \frac{M^2}{2m_\nu}$



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 –



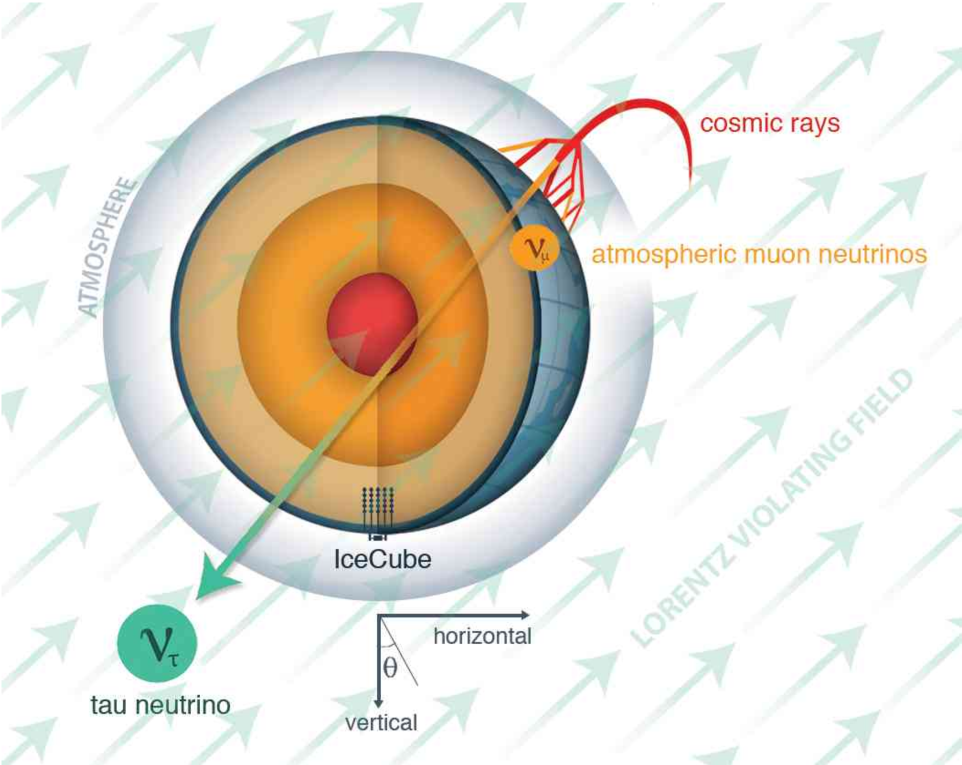
Argüelles *et al.*, *PRL* 2017

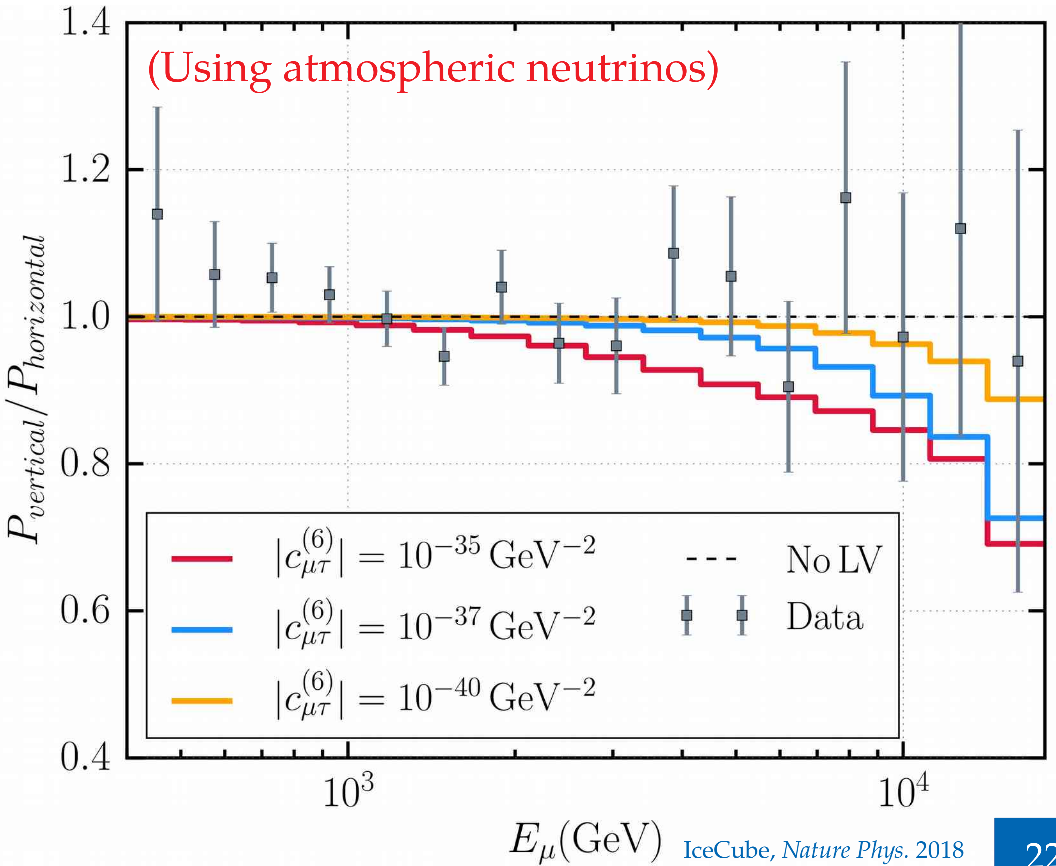
Expected: Fewer neutrinos coming from the Galactic Center

Observed: Isotropy

New physics in the energy & angular distribution

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





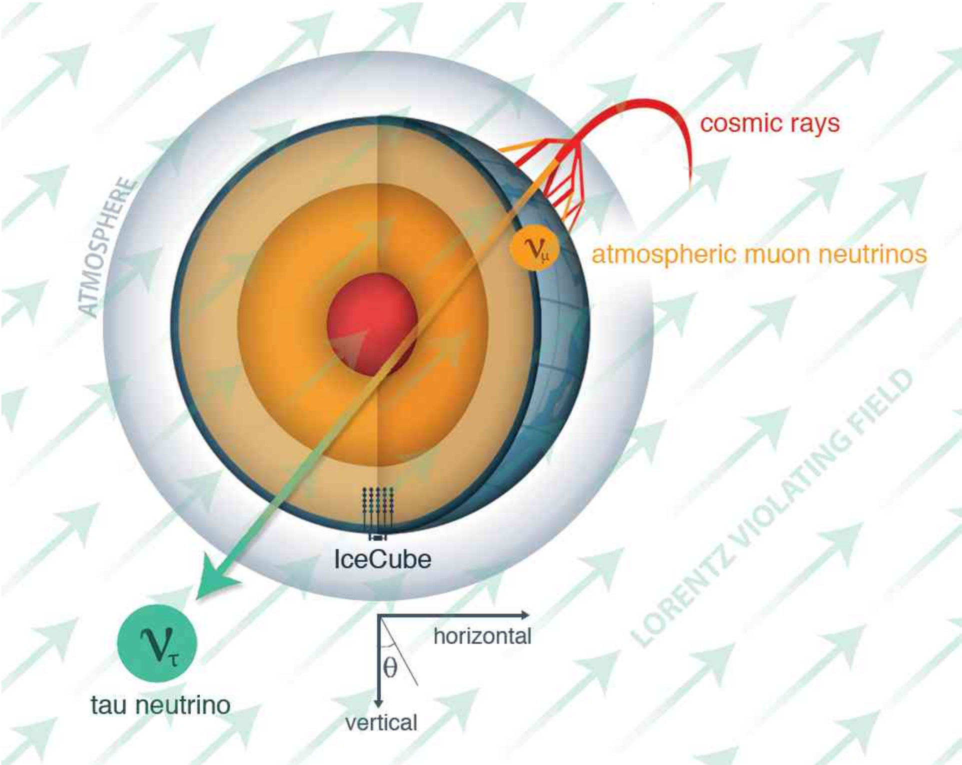
IceCube, *Nature Phys.* 2018

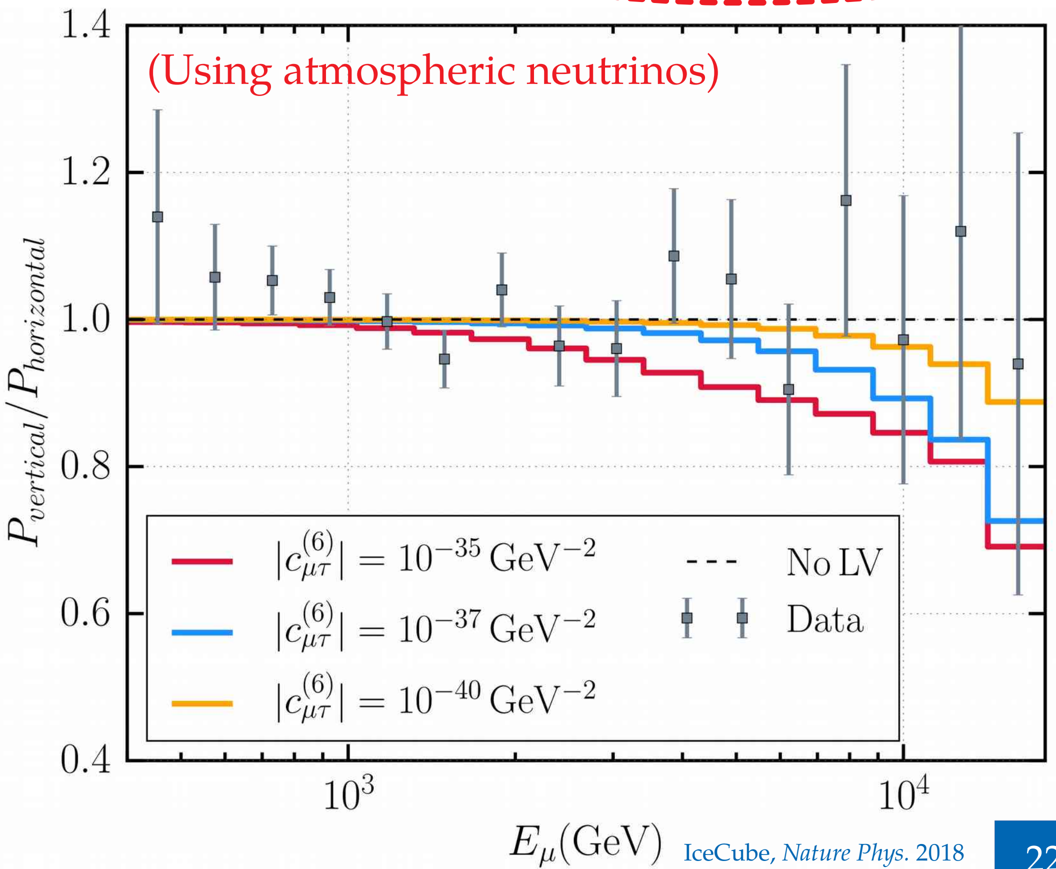
New physics in the energy & angular distribution

Lorentz violation

Standard oscillations

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

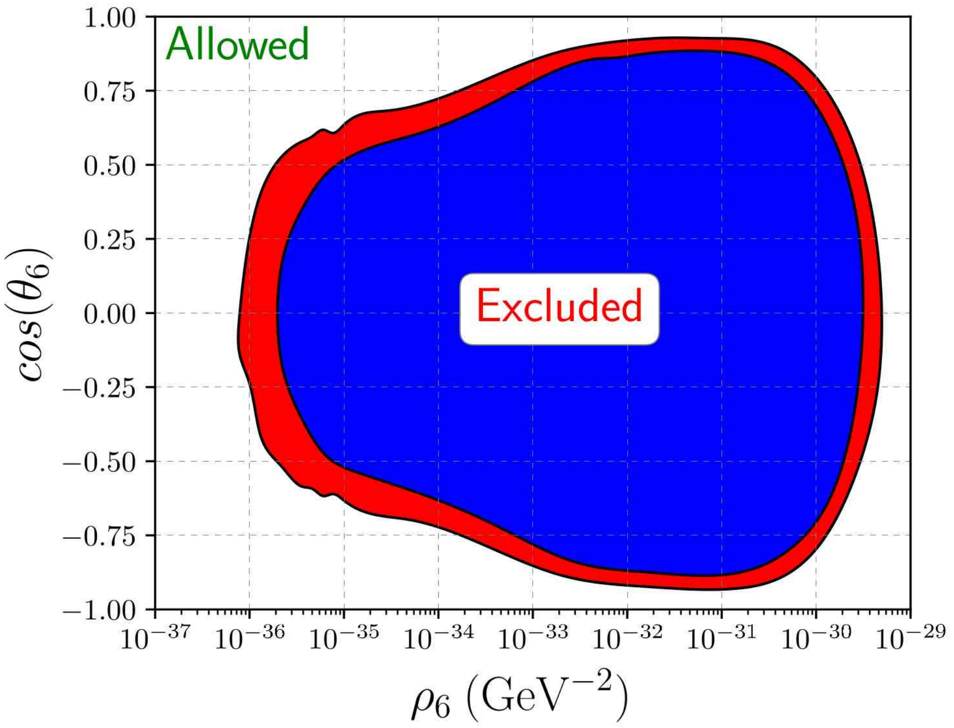
New physics in the energy & angular distribution

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

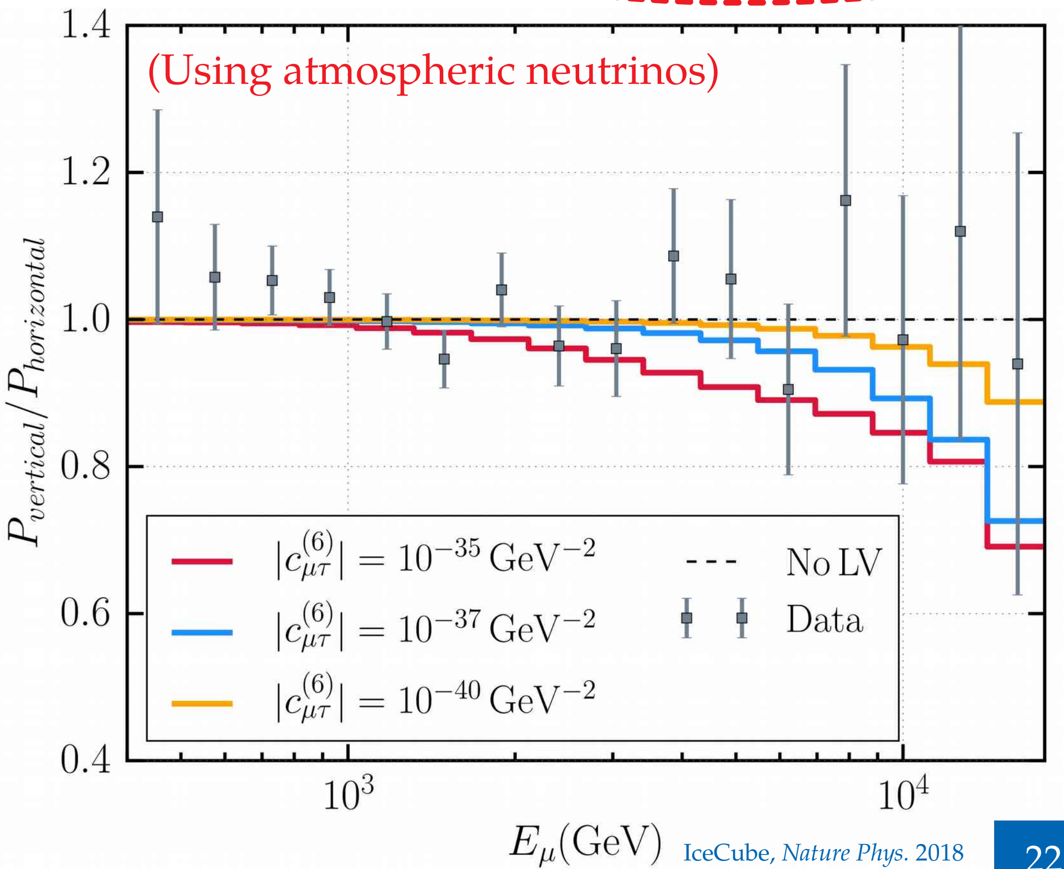
Standard oscillations: $m^2/(2E)$

Lorentz violation: $\mathring{a}^{(3)} - E \cdot \mathring{c}^{(4)} + E^2 \cdot \mathring{a}^{(5)} - E^3 \cdot \mathring{c}^{(6)}$

Best bounds come from IceCube

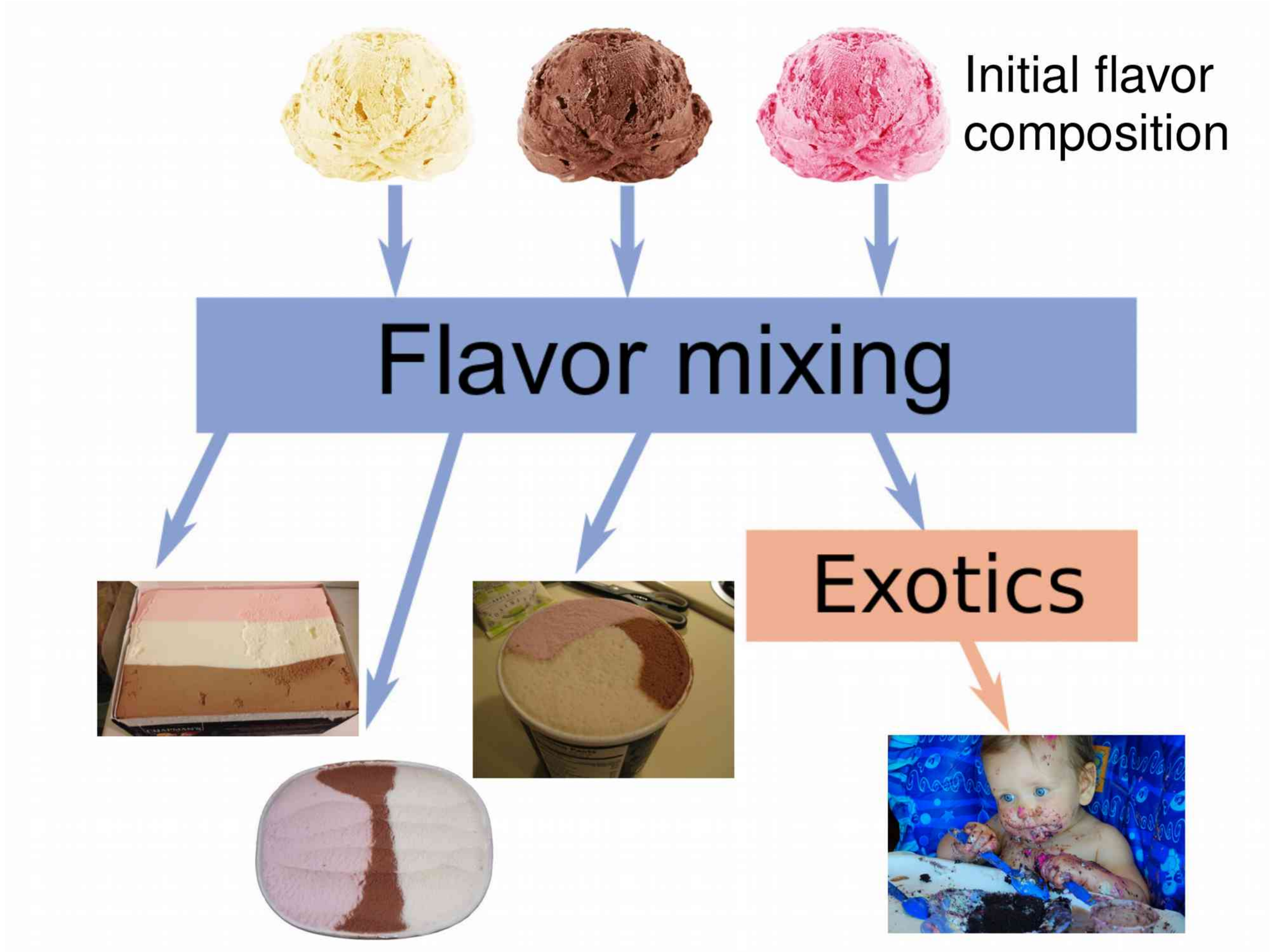


(Using atmospheric neutrinos)



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

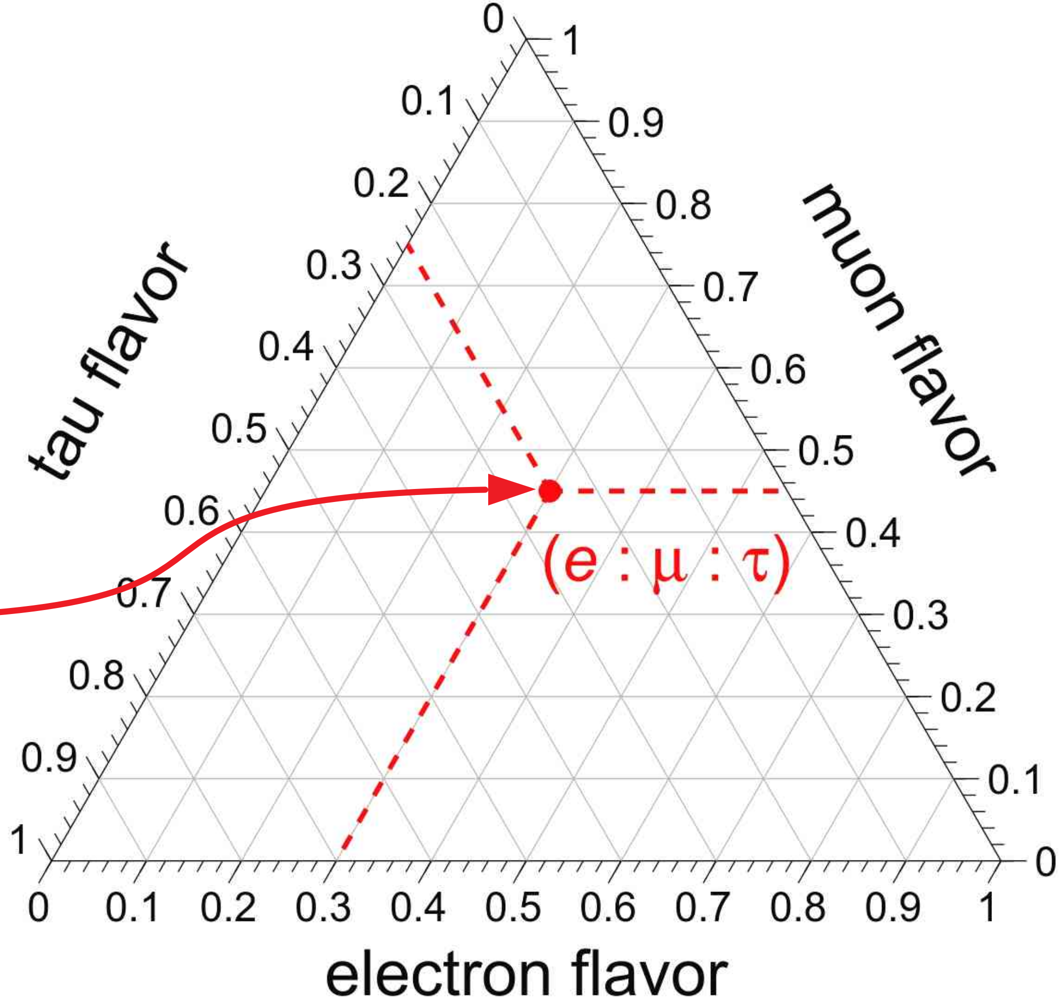
Note: Ratios are for $\nu + \bar{\nu}$, since neutrino telescopes cannot tell them apart

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*:μ:τ) = (0.30:0.45:0.25)



Flavor content of neutrino mass eigenstates

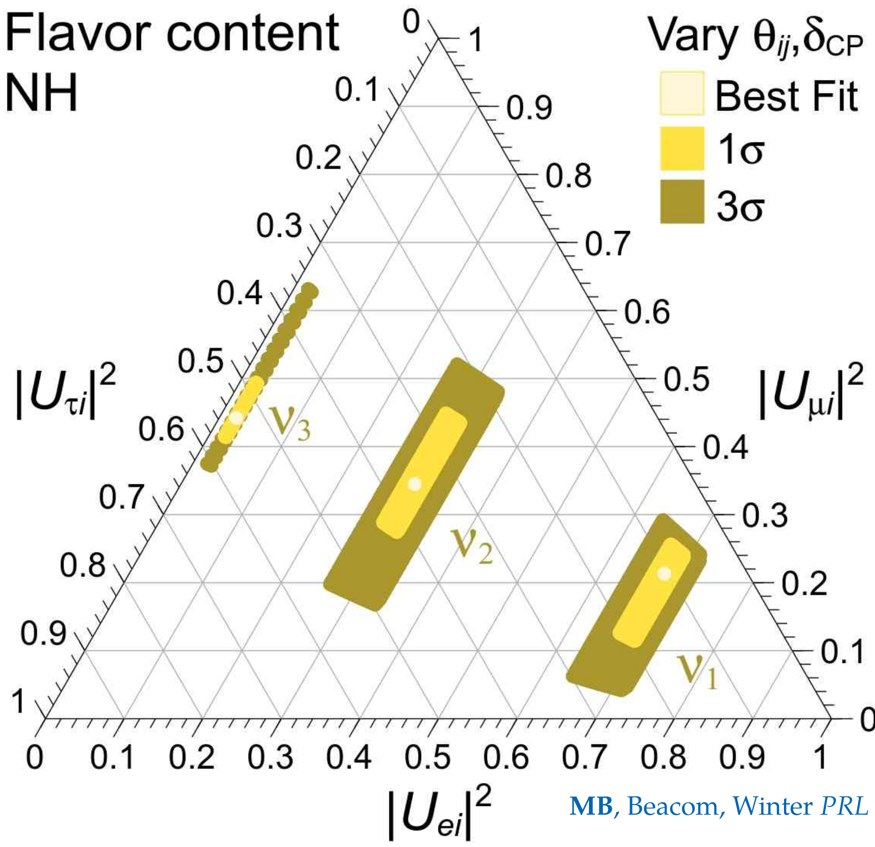
Flavor content for every allowed combination of mixing parameters –

Known to within 2%

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

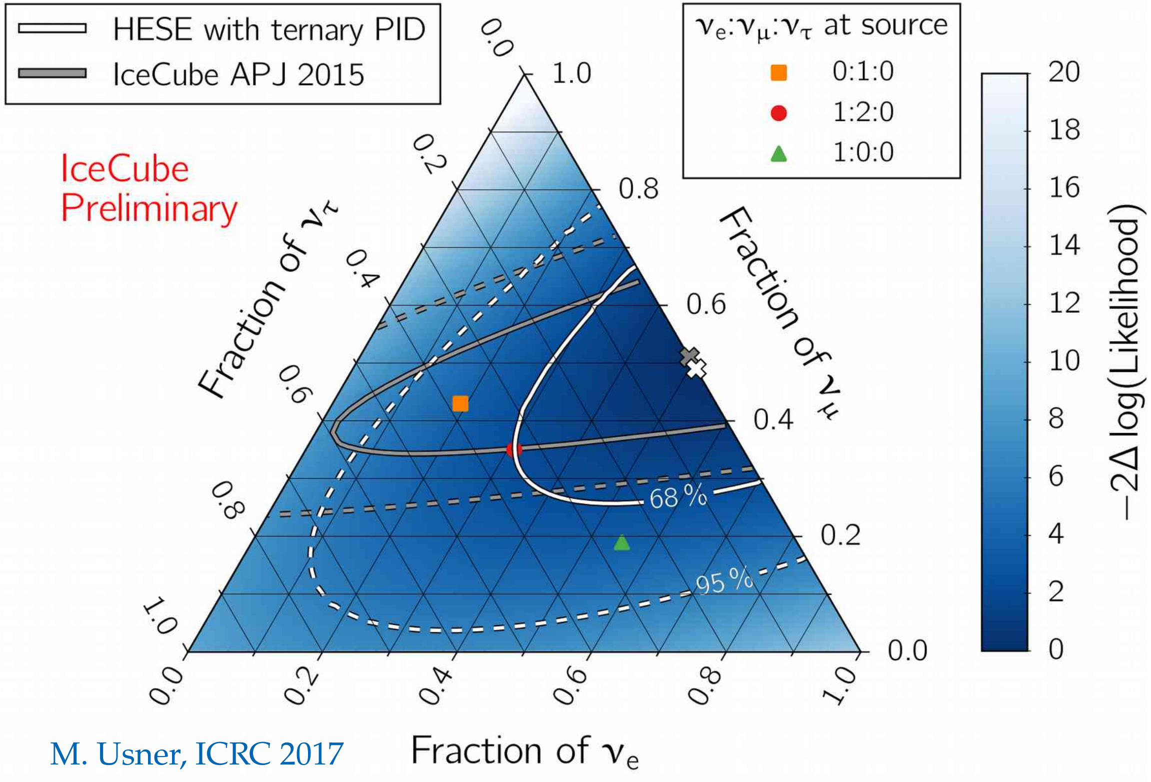
Known to within 8%

Known to within 20% (or worse)



MB, Beacom, Winter *PRL* 2015

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

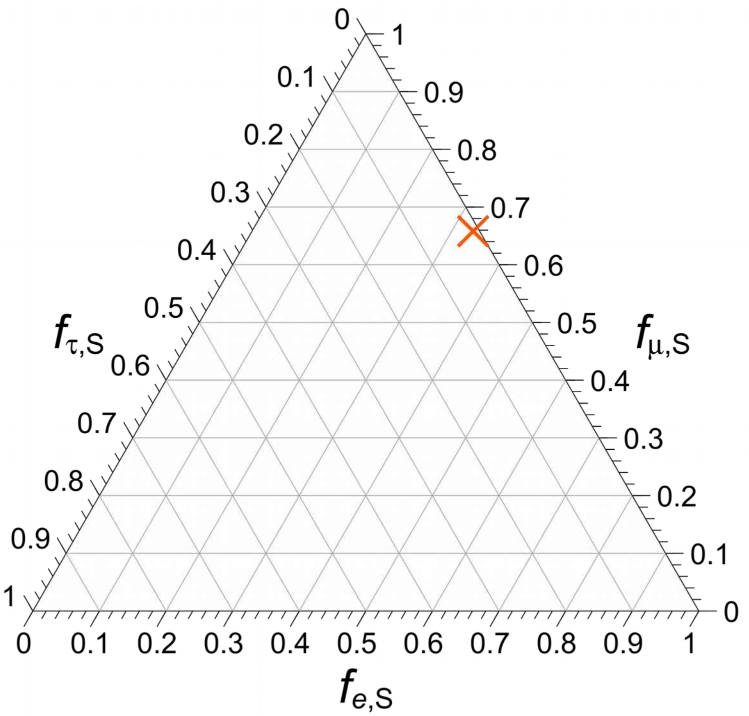
At the sources

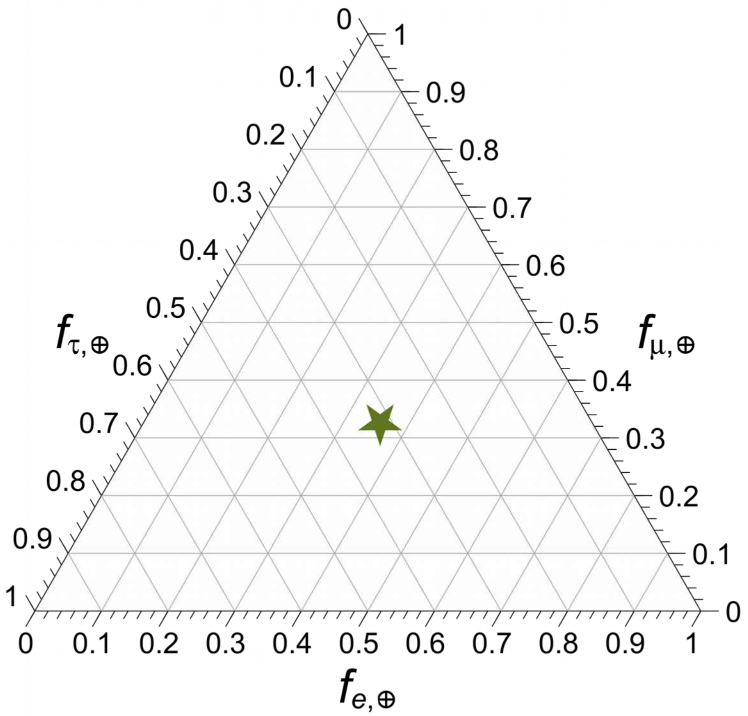
$(f_e{:}f_\mu{:}f_\tau)_S = (1/3 : 2/3 : 0)_S$

Neutrino oscillations

At Earth

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





Flavor – there and here

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

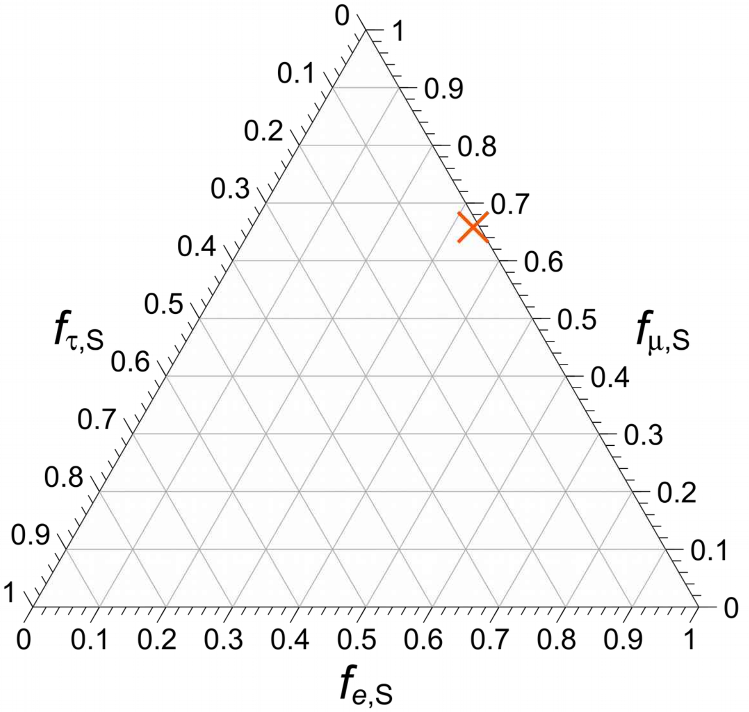
At the sources

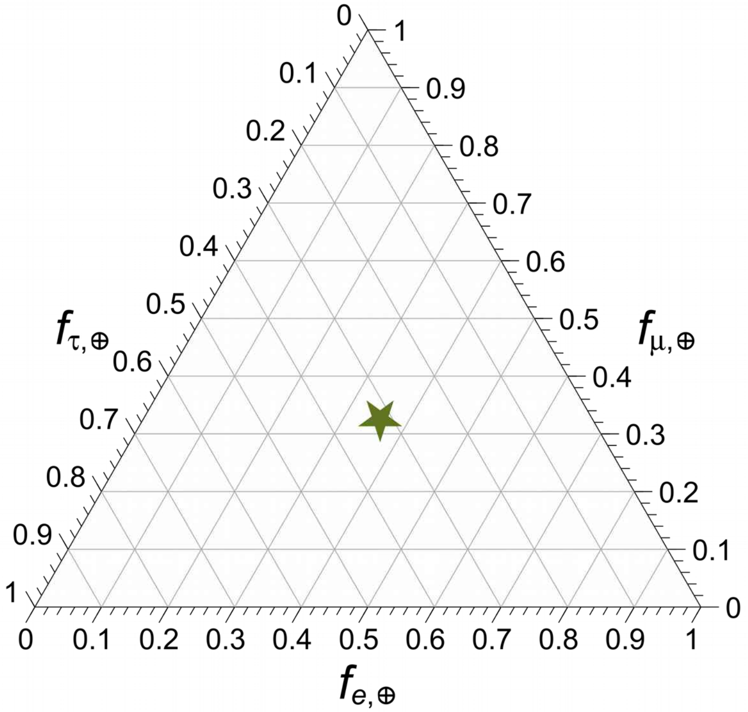
$(f_e\!:\!f_\mu\!:\!f_\tau)_S = (1/3 : 2/3 : 0)_S$

Neutrino oscillations

At Earth

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





Flavor – there and here

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

At the sources

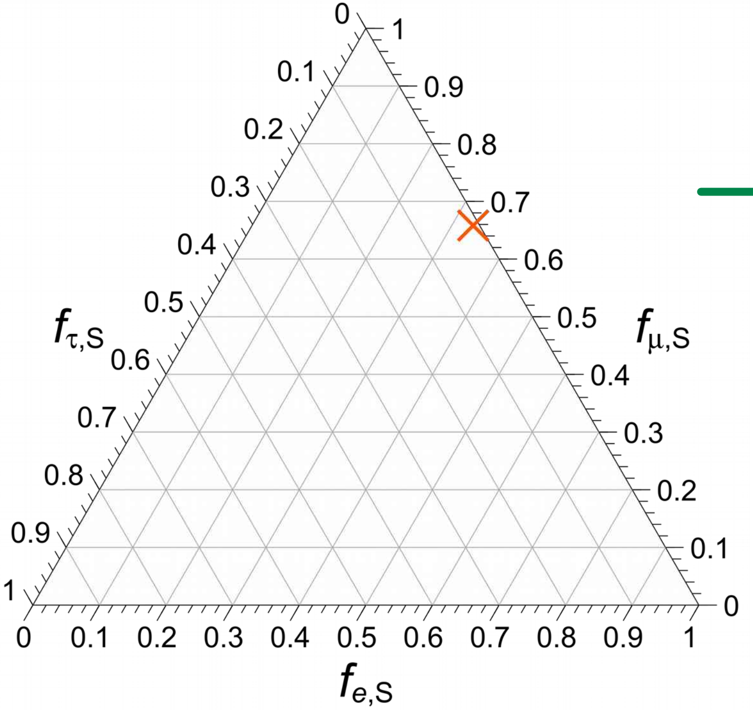
$(f_e:f_\mu:f_\tau)_S = (1/3 : 2/3 : 0)_S$

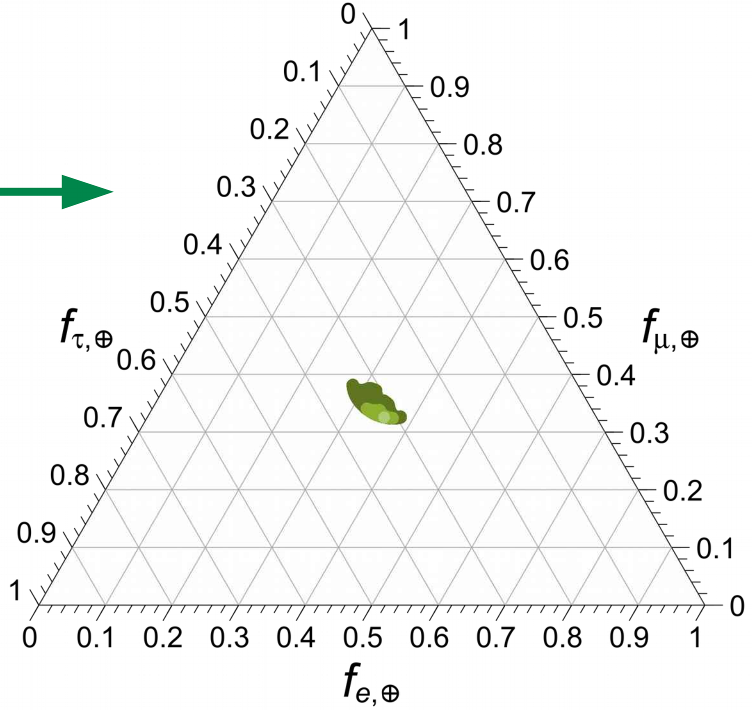
Neutrino oscillations

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

At Earth

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

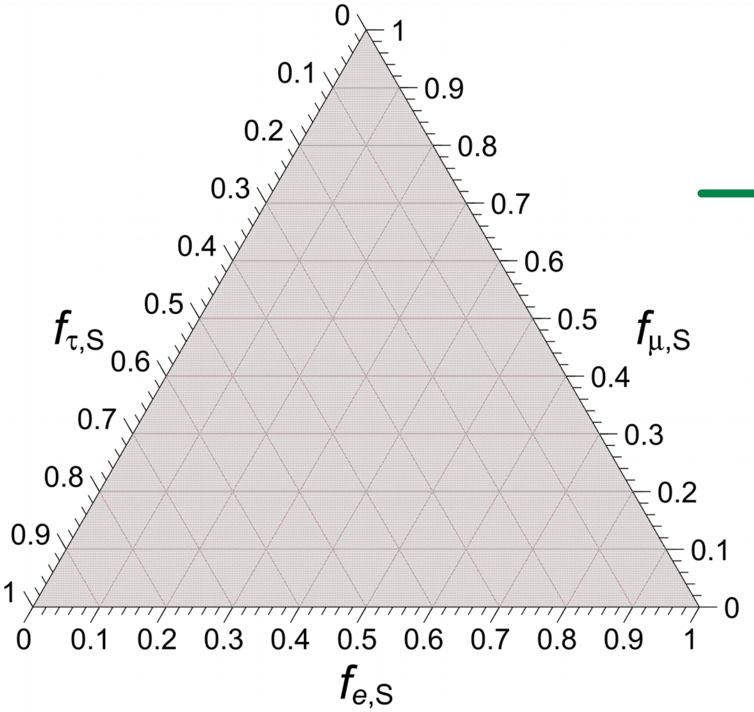




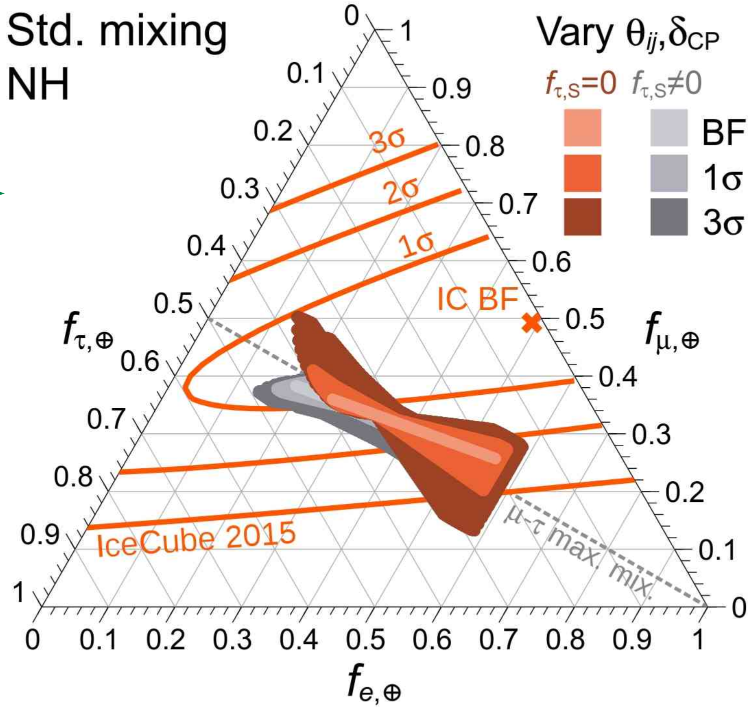
Flavor composition – Standard allowed region

At the sources

All possible flavor ratios



At Earth

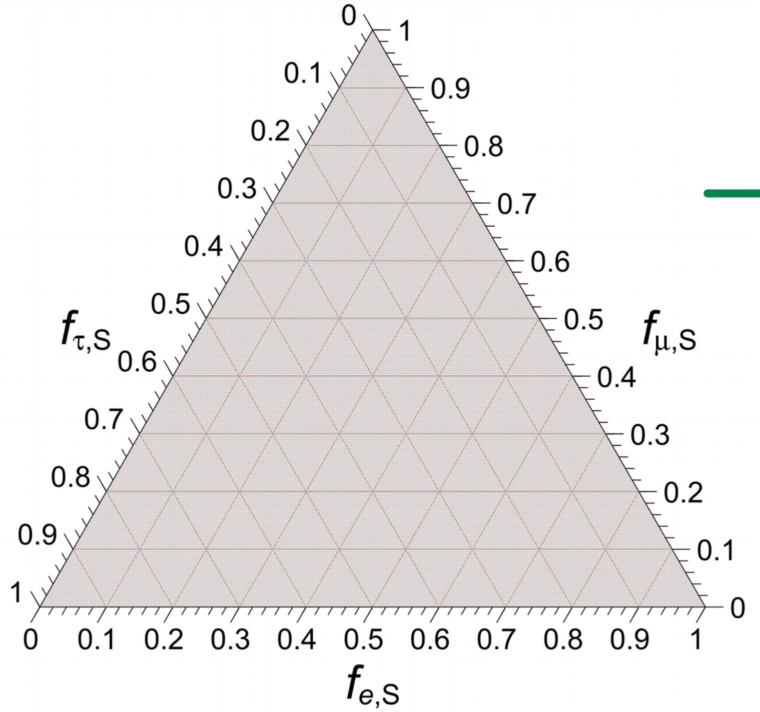


MB, Beacom, Winter *PRL* 2015

Flavor composition – Standard allowed region

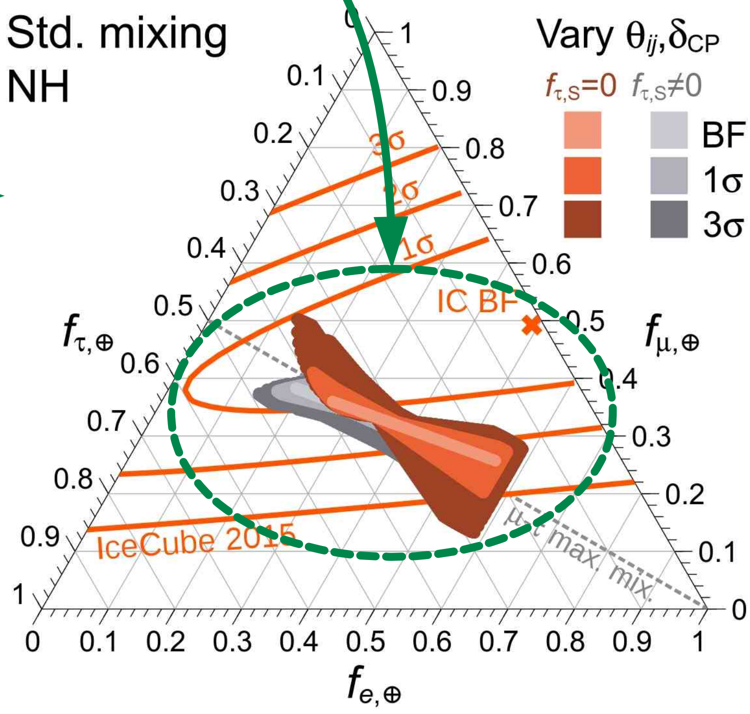
At the sources

All possible flavor ratios



Only 10% of parameter space

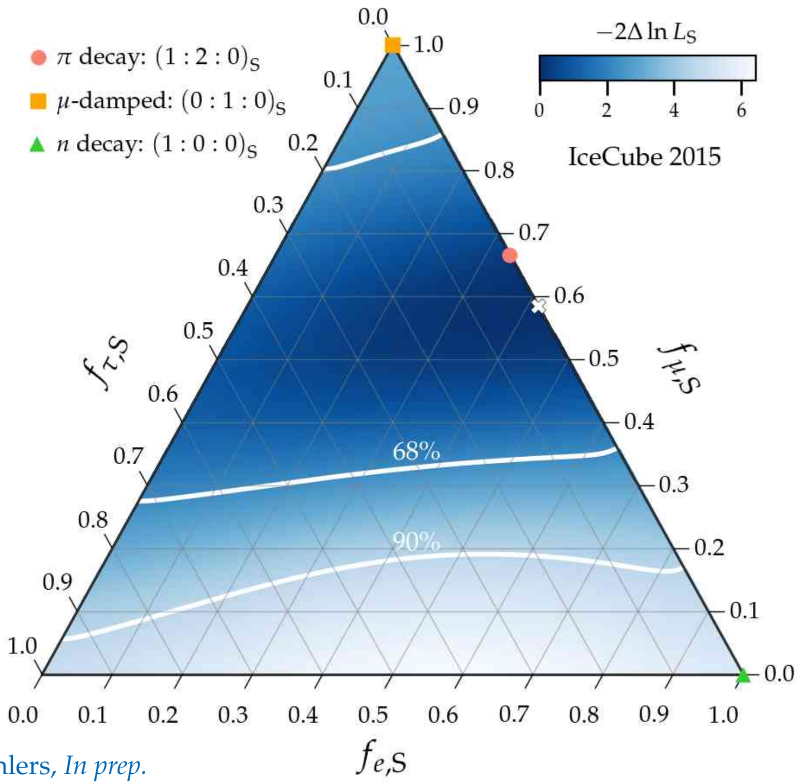
At Earth



MB, Beacom, Winter *PRL* 2015

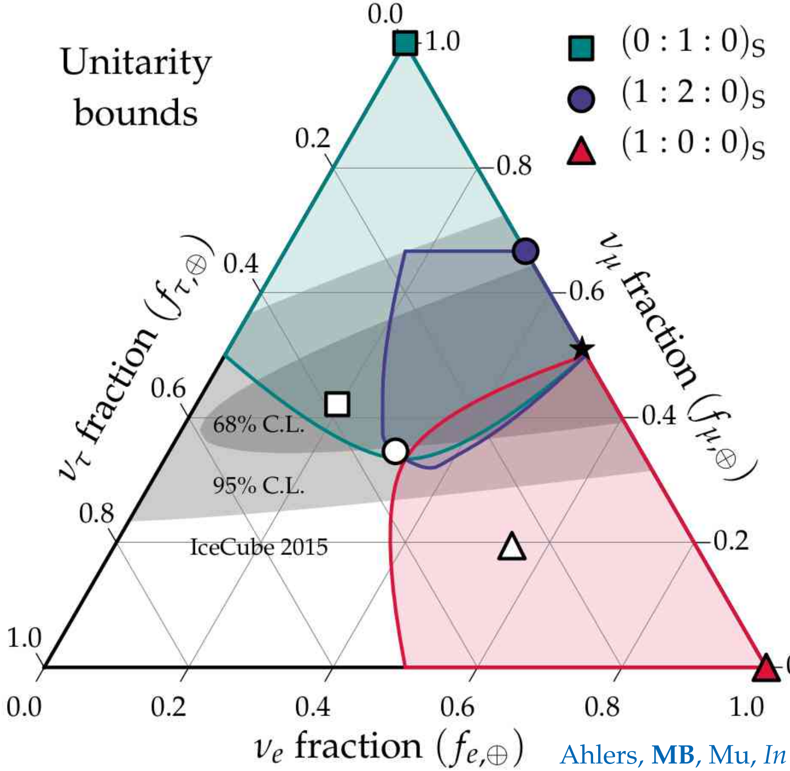
Flavor – What is it good for?

Trusting particle physics
and learning about astrophysics



MB, Ahlers, *In prep.*

Trusting astrophysics
and learning about particle physics

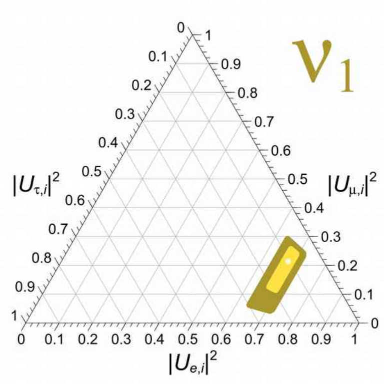


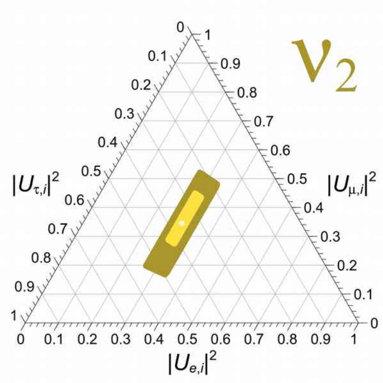
Ahlers, **MB**, Mu, *In prep.*

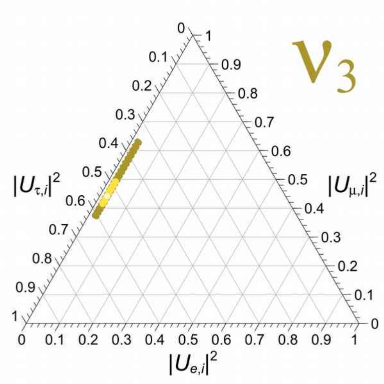
Two classes of new physics

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

- Each one has a different flavor content:







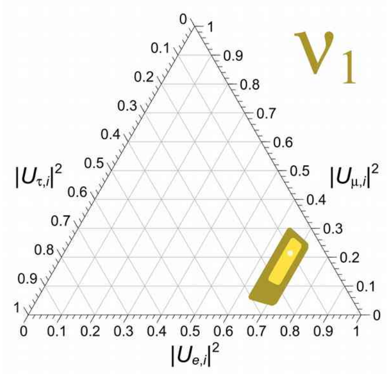
- Flavor ratios at Earth are the result of their combination

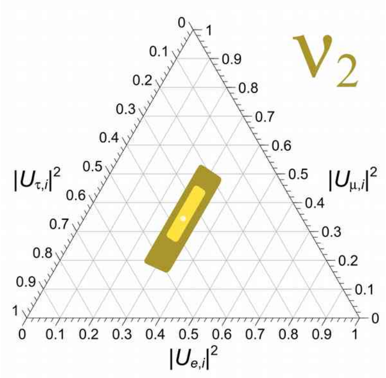
- New physics may:
  - Only reweigh the proportion of each ν_i reaching Earth (*e.g.*, ν decay)
  - Redefine the propagation states (*e.g.*, Lorentz-invariance violation)

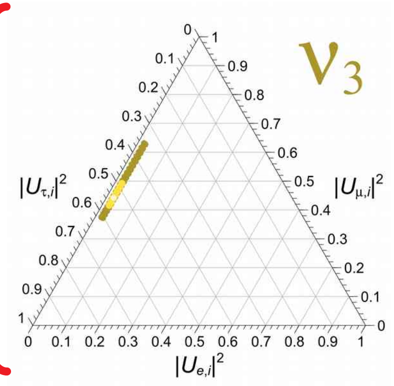
Two classes of new physics

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

- Each one has a different flavor content:

w_1 [

] + w_2 [

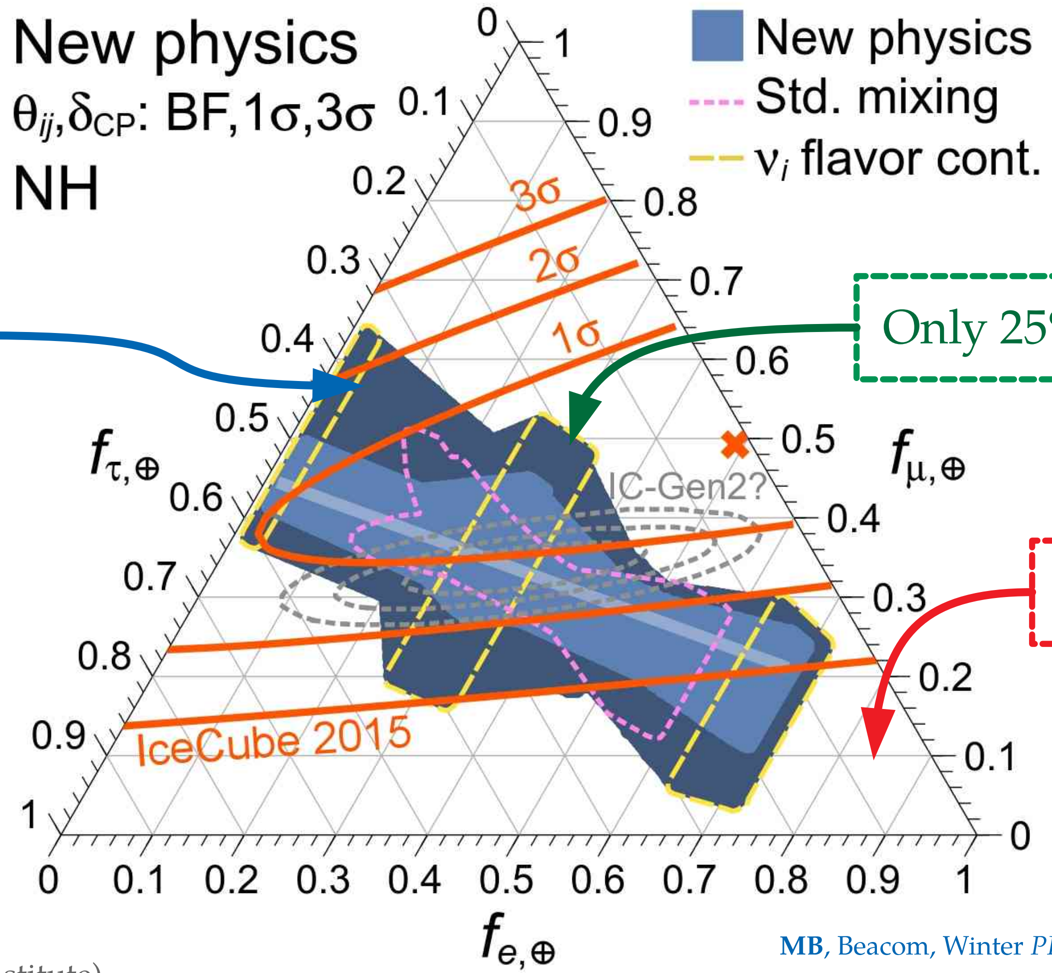
] + w_3 [

]

- Flavor ratios at Earth are the result of their combination

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

Flavor ratios accessible with decay-like physics



Region of all linear combinations of ν_1, ν_2, ν_3

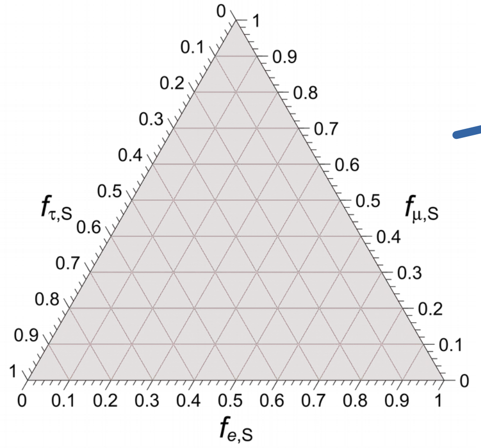
Only 25% of parameter space

What lies outside?

MB, Beacom, Winter *PRL* 2015

Measuring the neutrino lifetime

Sources



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

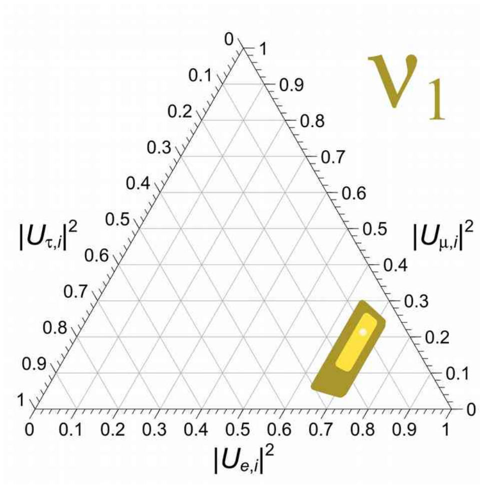
ν_1 lightest and stable

If all unstable neutrinos decay

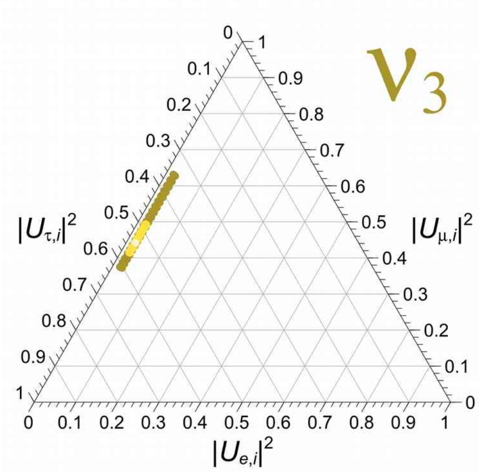
$\underbrace{\nu_1, \nu_2 \to \nu_3}$

ν_3 lightest and stable

Earth



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



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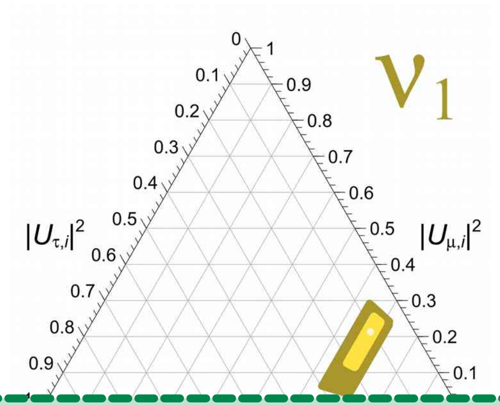
Measuring the neutrino lifetime

Earth



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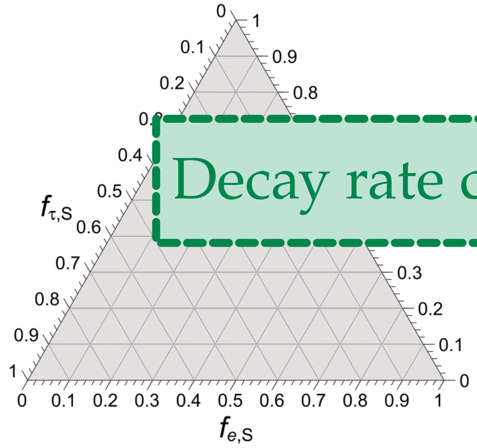
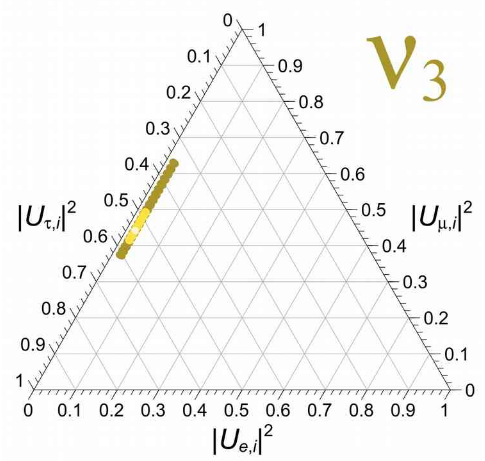


Decay rate depends on $\exp[-\, t\, /\, (\gamma\tau_i)] = \exp[-\, (L/E) \cdot (m_i/\tau_i)]$

neutrinos decay



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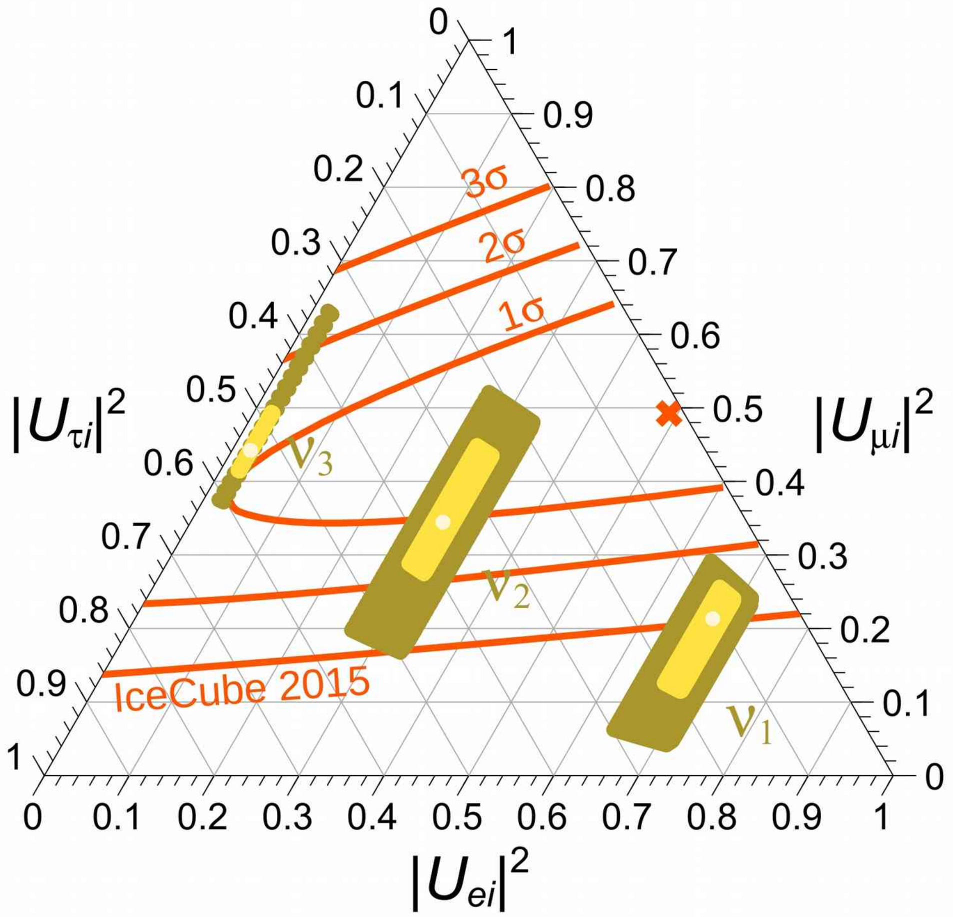
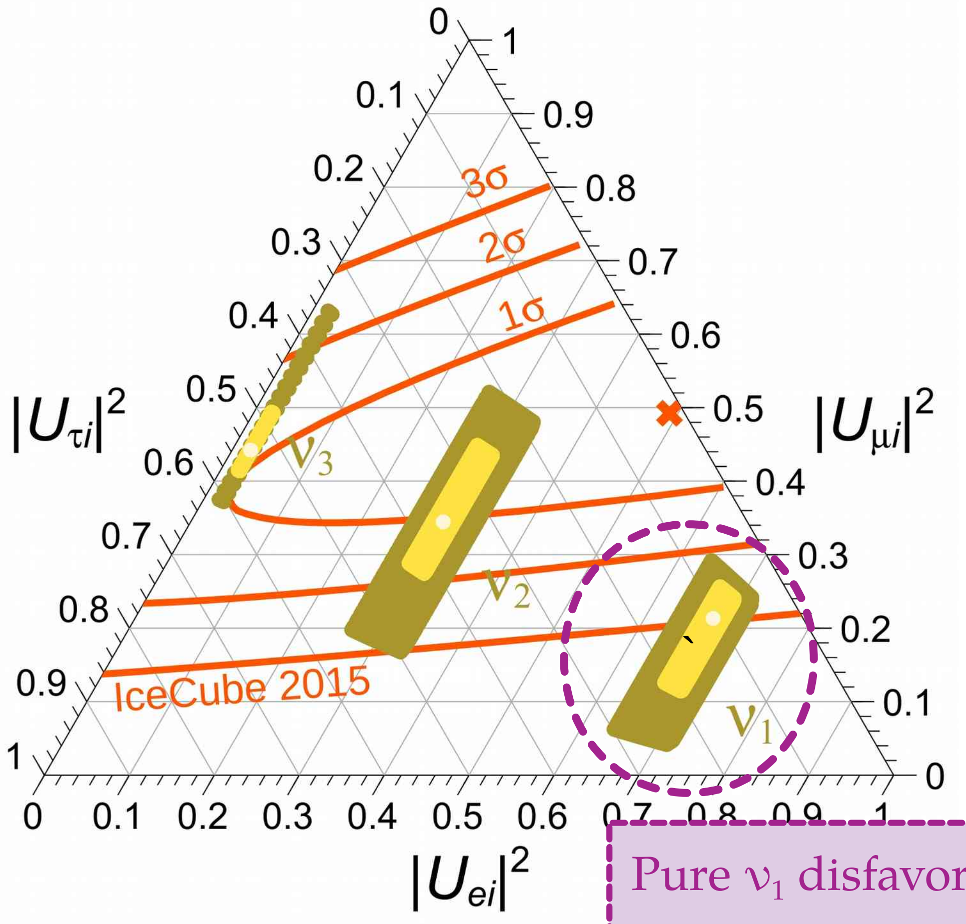


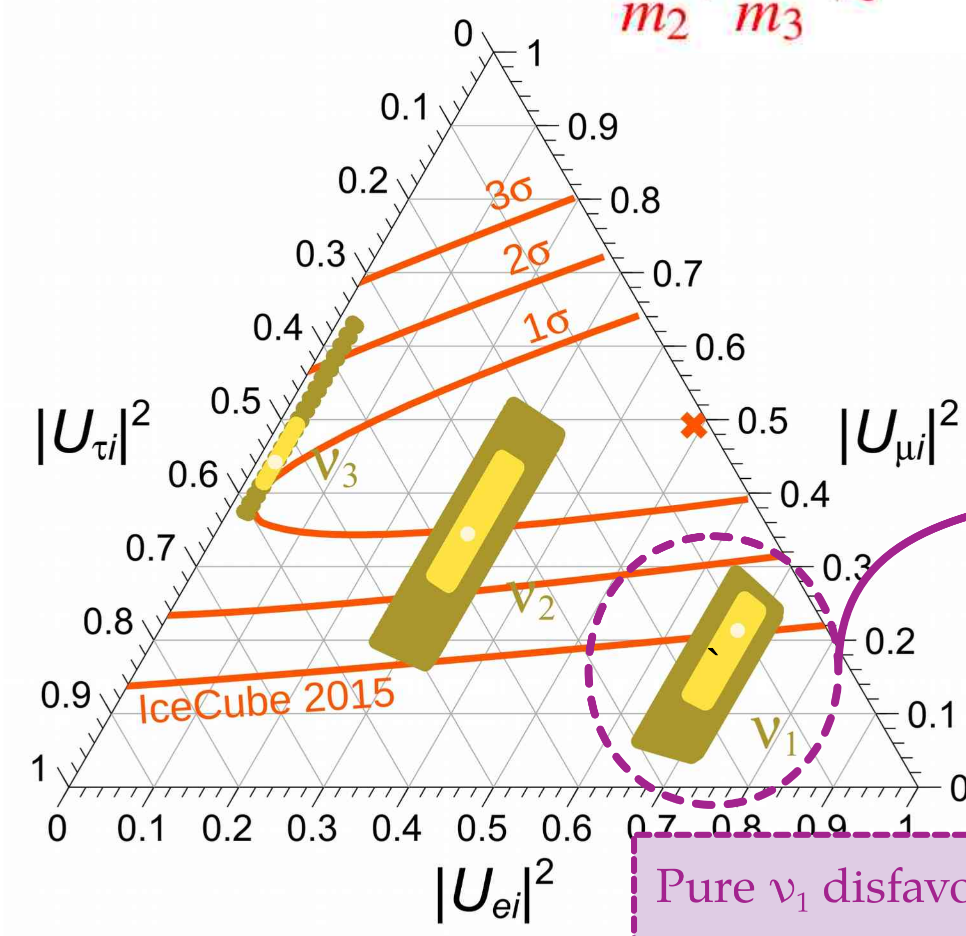
MB, Beacom, Murase, *PRD* 2017

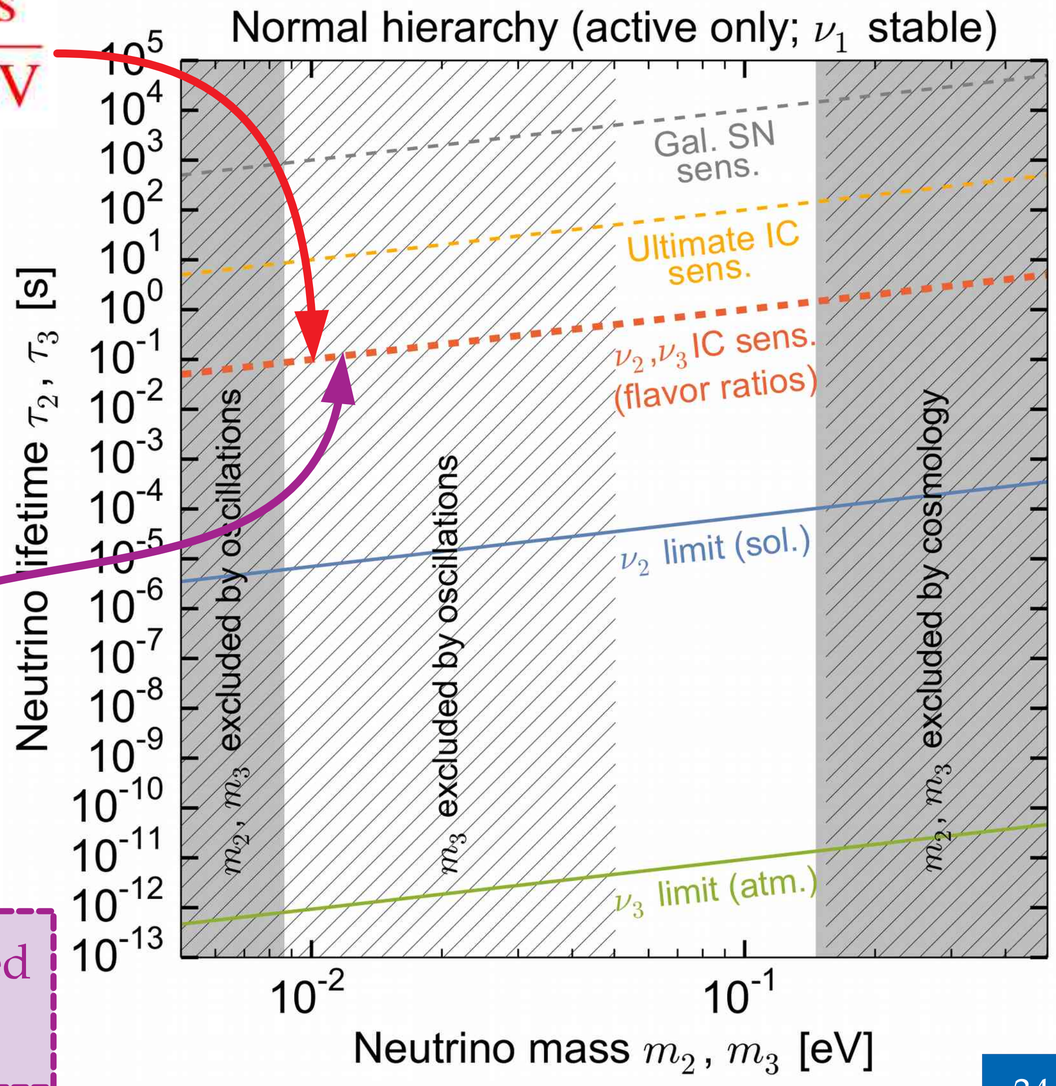


Pure ν_1 disfavored at > 2σ

MB, Beacom, Murase, *PRD* 2017

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





Pure ν_1 disfavored at > 2σ

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]

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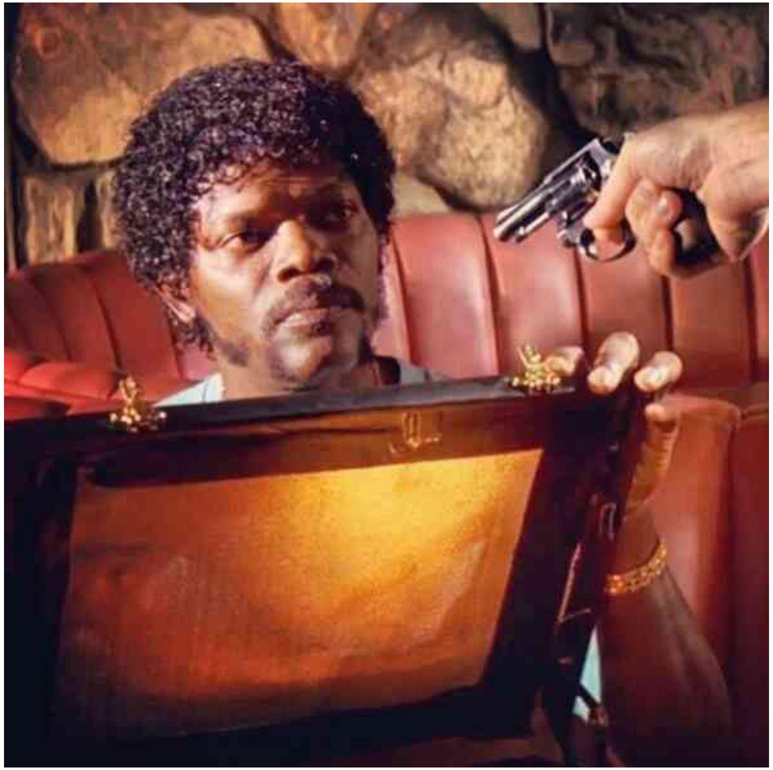

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New physics – High-energy effects

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

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

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

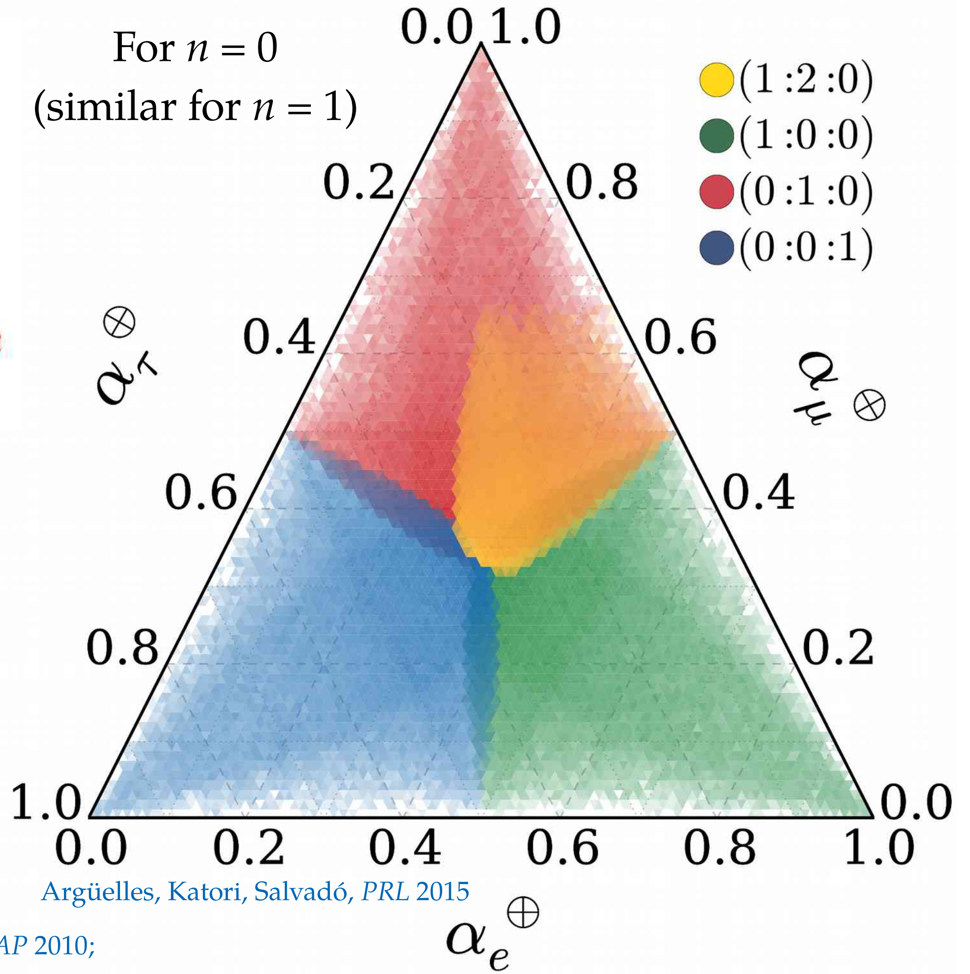
This can populate *all* of the triangle –

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

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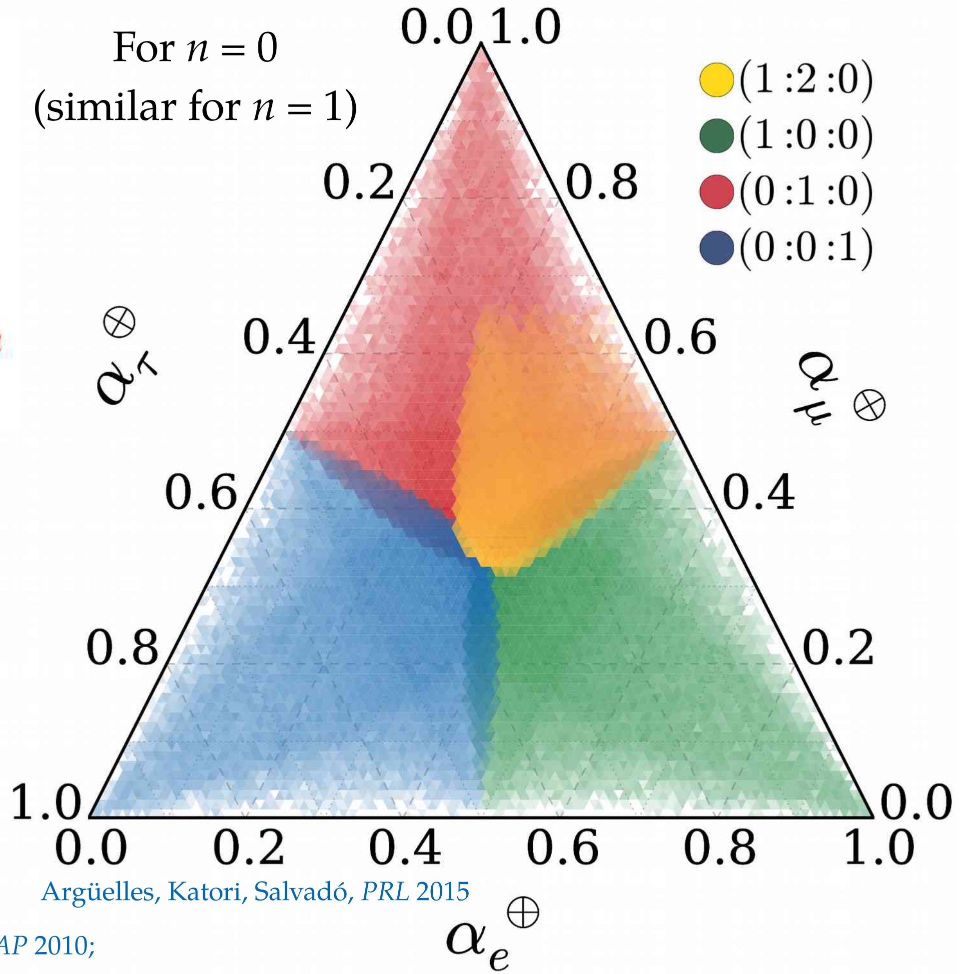

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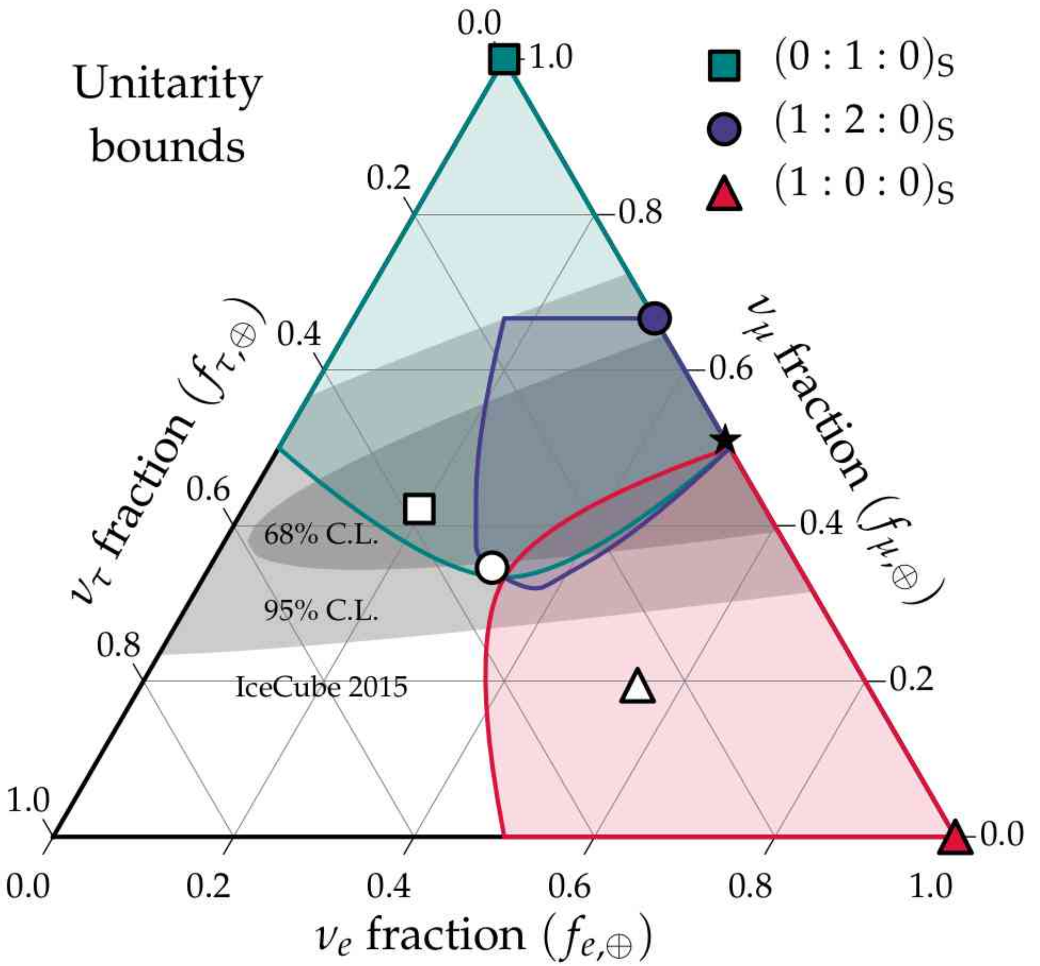
Using unitarity to constrain new physics

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

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

Ahlers, **MB**, Mu, *In prep.*



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 $\sim(1/m')$

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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 ~$(1/m')$

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

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

New neutrino-electron interaction:
This is diagonal

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Z' parameters

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

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Z' parameters

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

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

Electron-neutrino interactions can kill oscillations

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

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

$\sim 1/E$

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

Electrons in the local and distant Universe

Potential:

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

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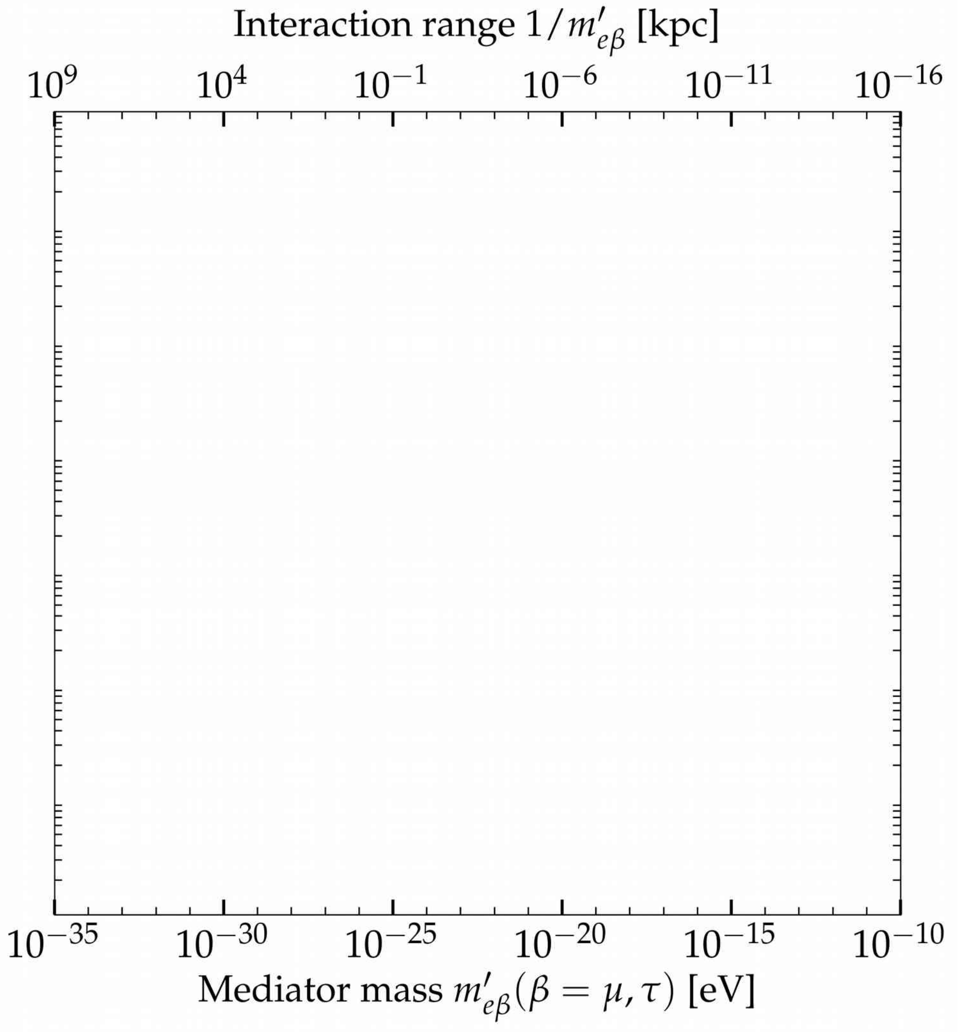
Electrons in the local and distant Universe



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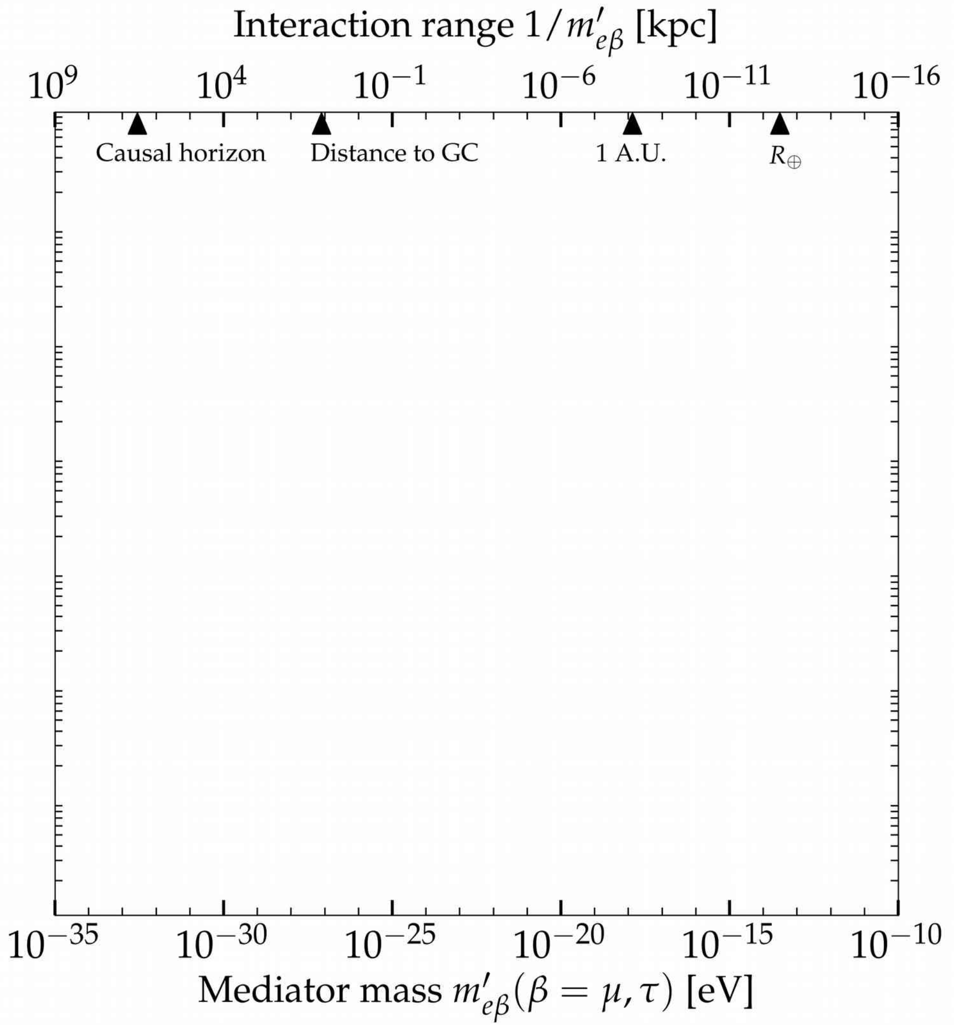

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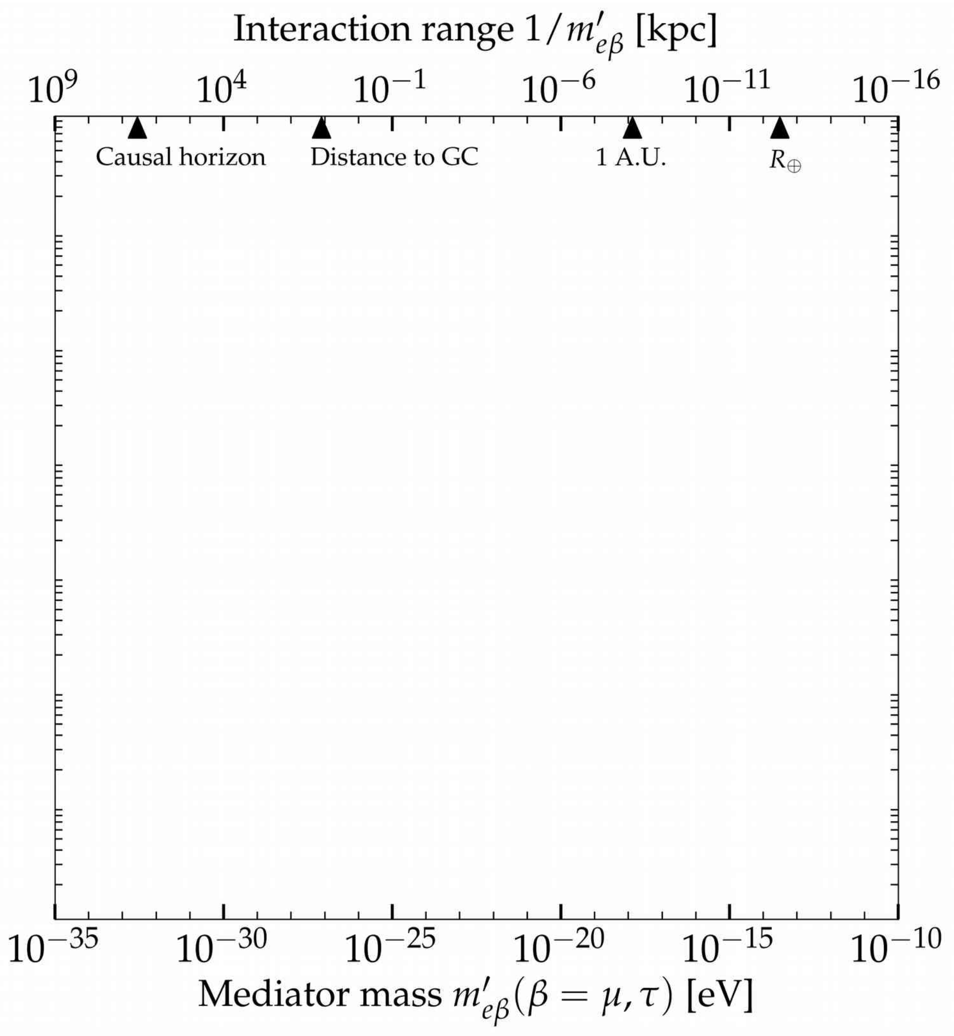

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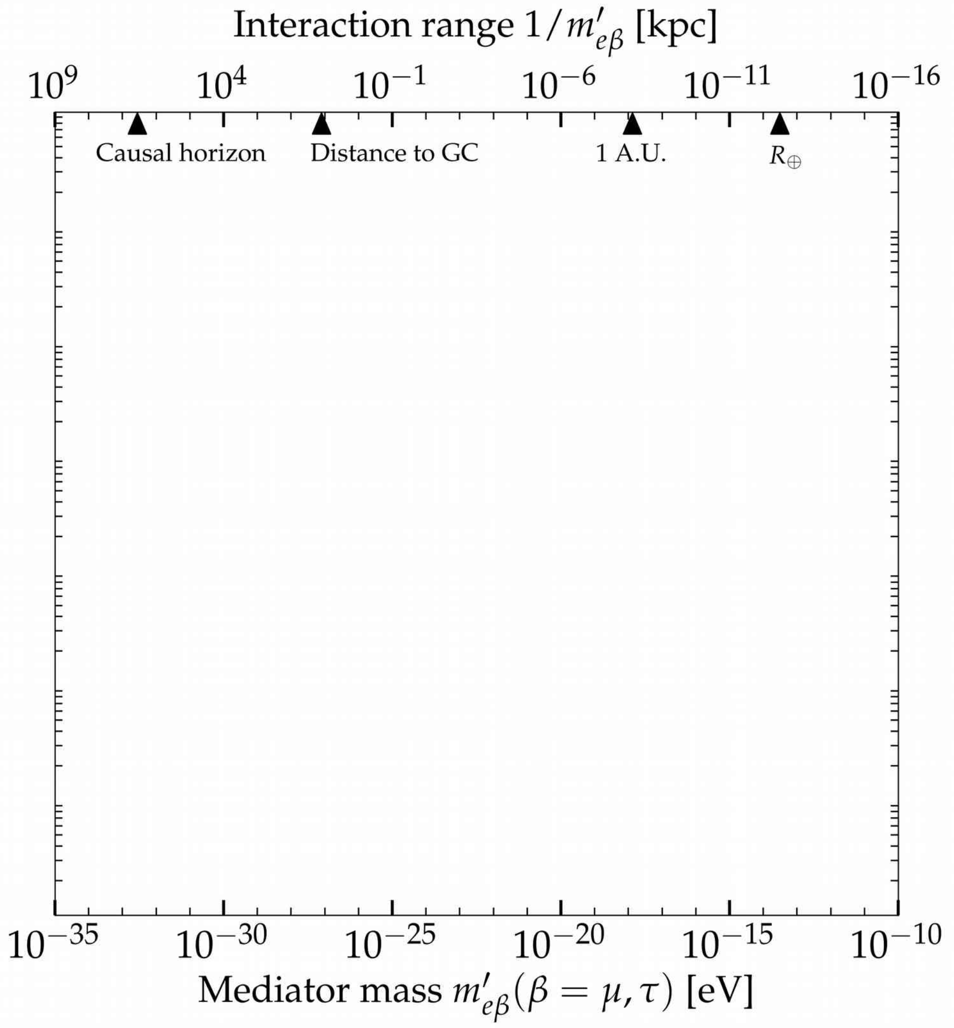
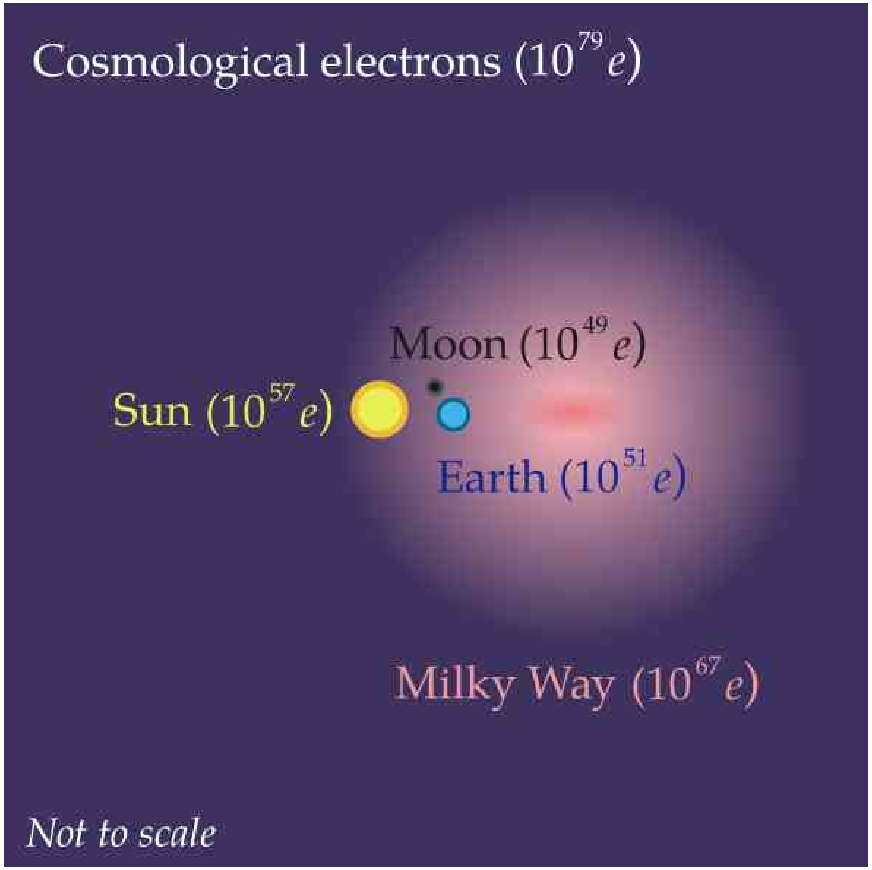
Interaction range: $\dfrac{1}{m'_{e\beta}}$

Light mediators
⇒ Long interaction ranges

Electrons in the local and distant Universe





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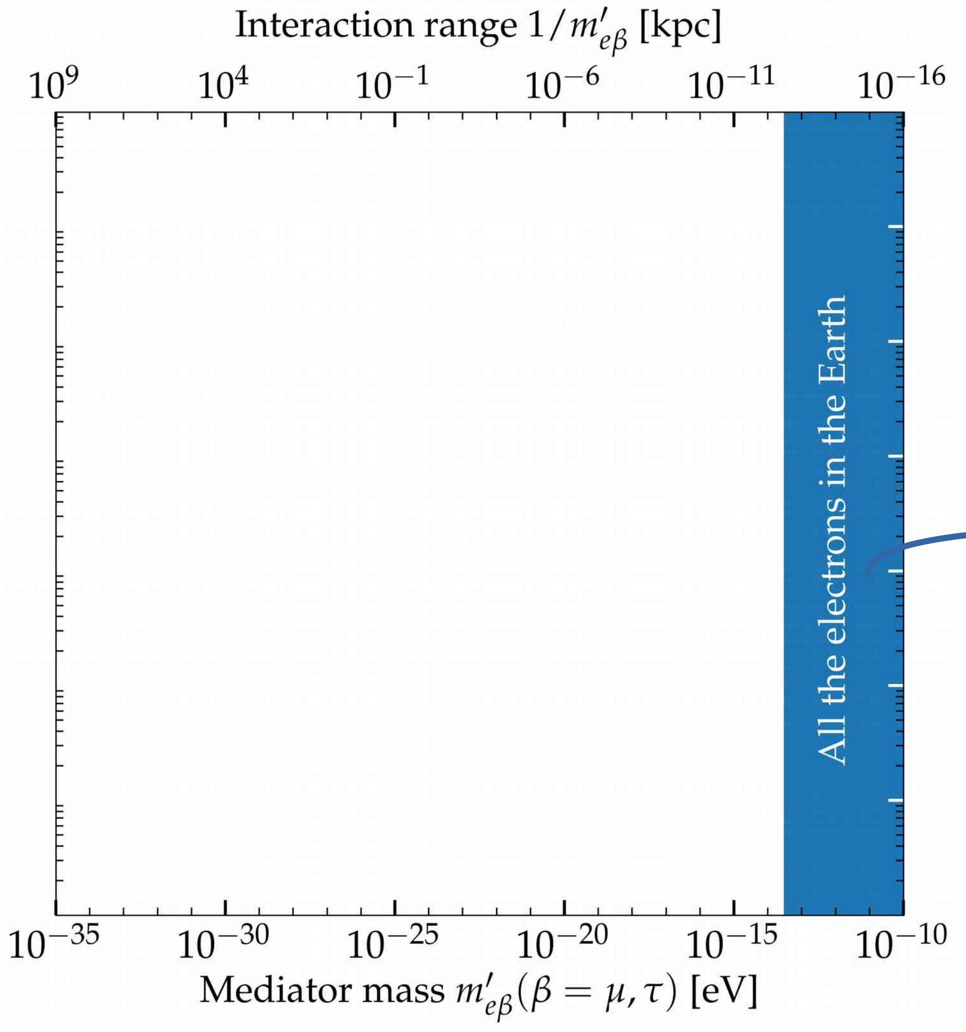

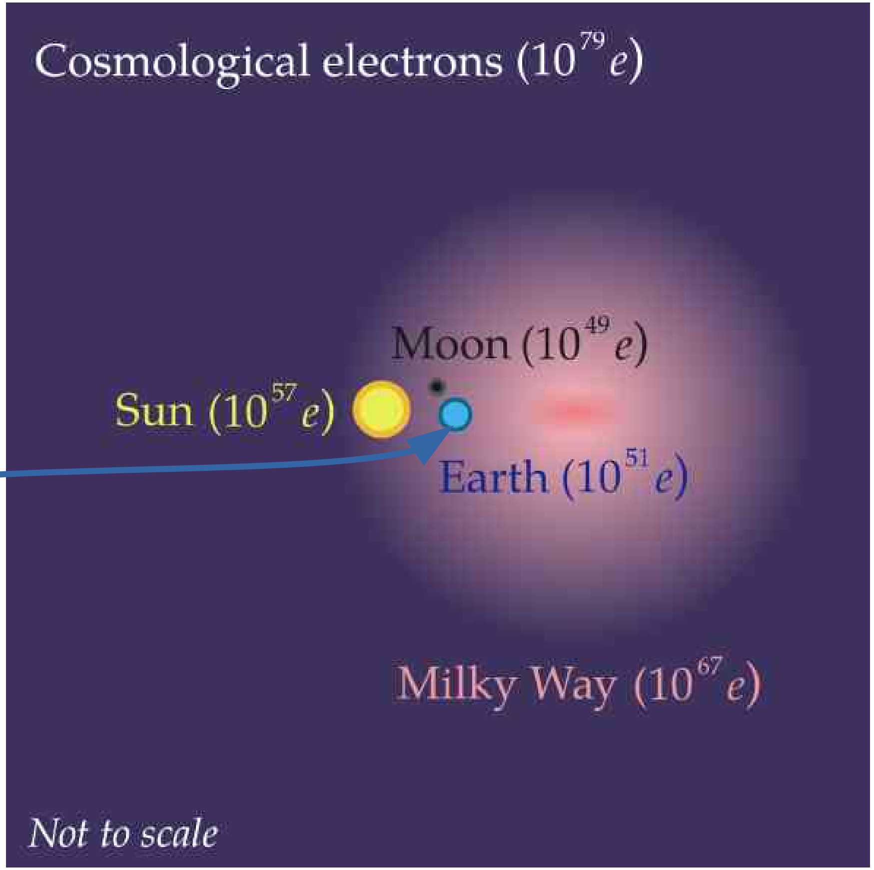

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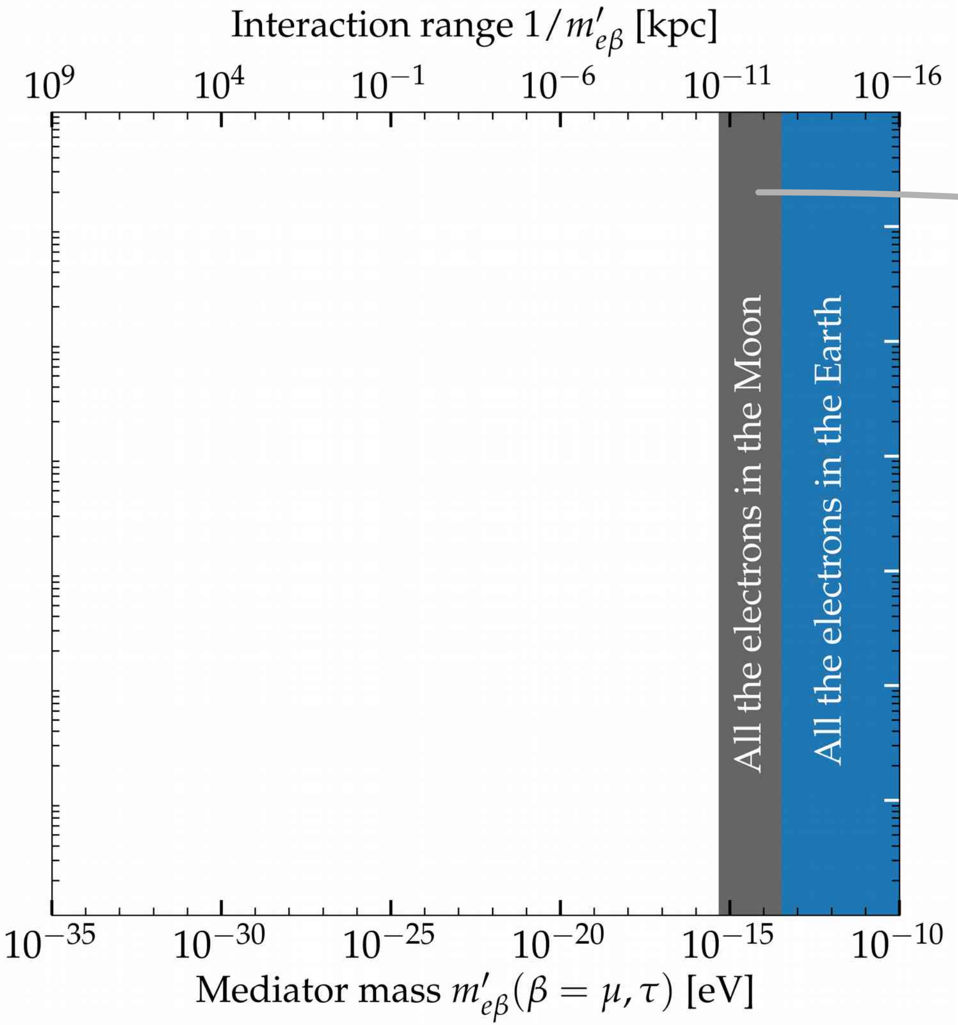

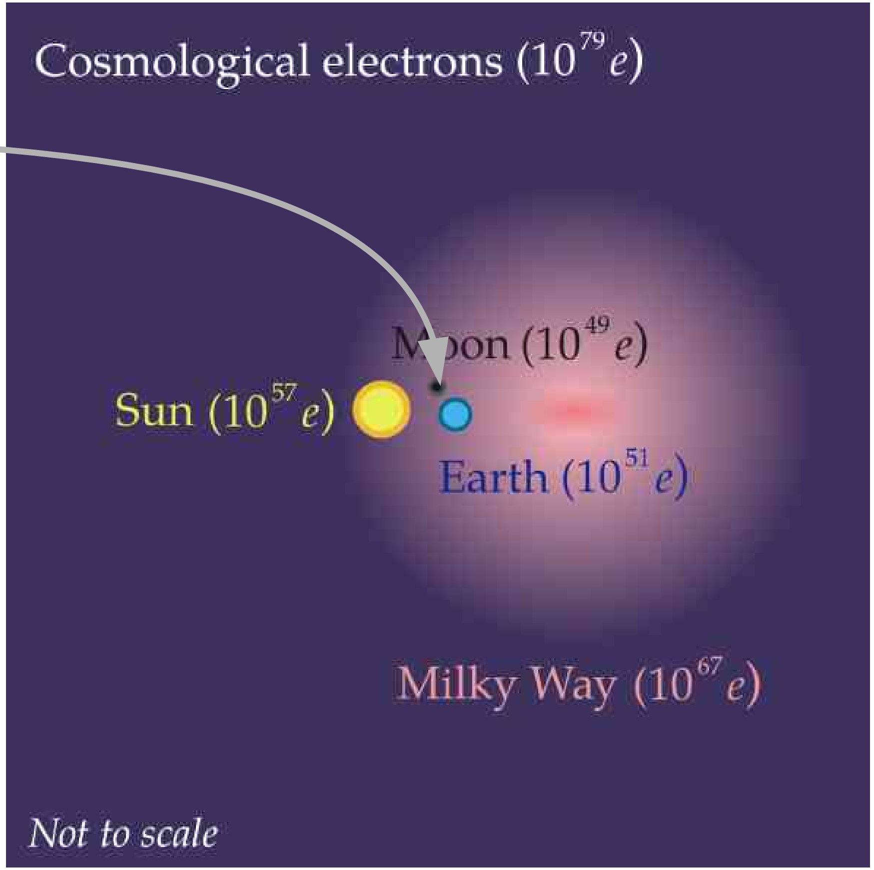

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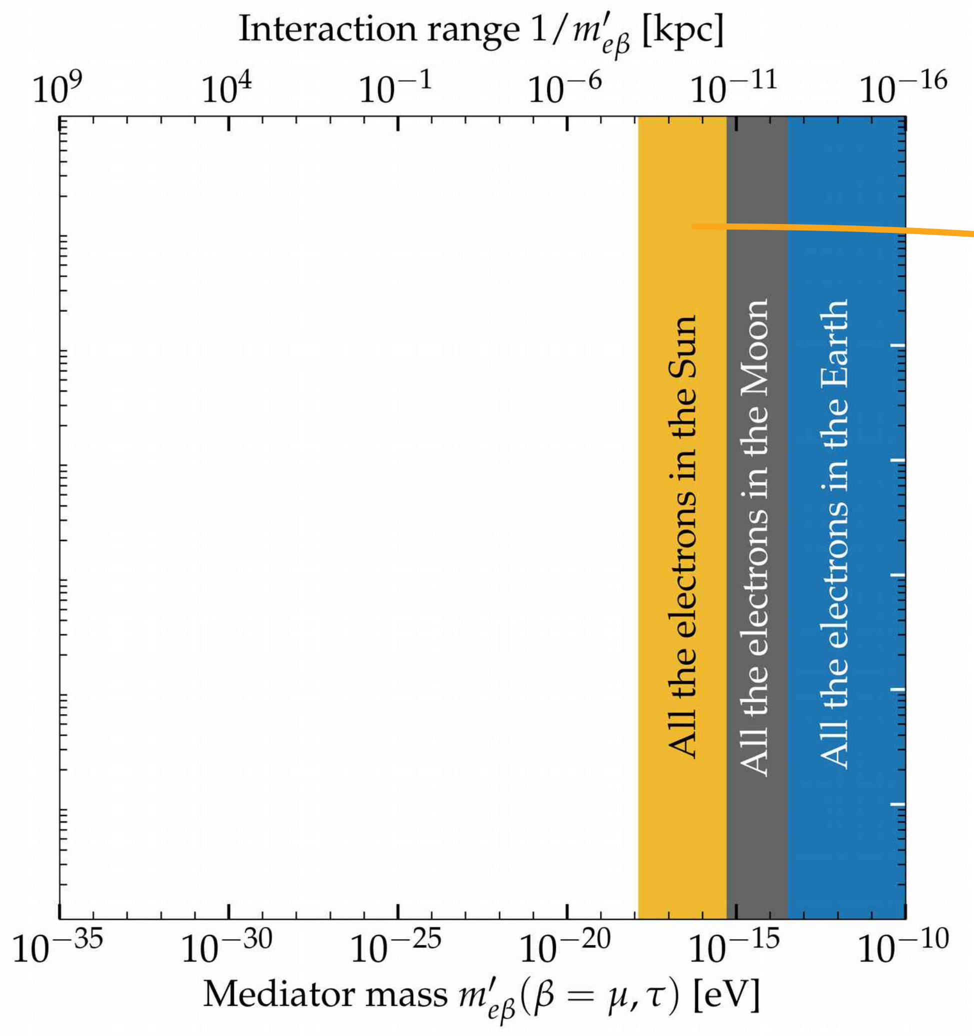

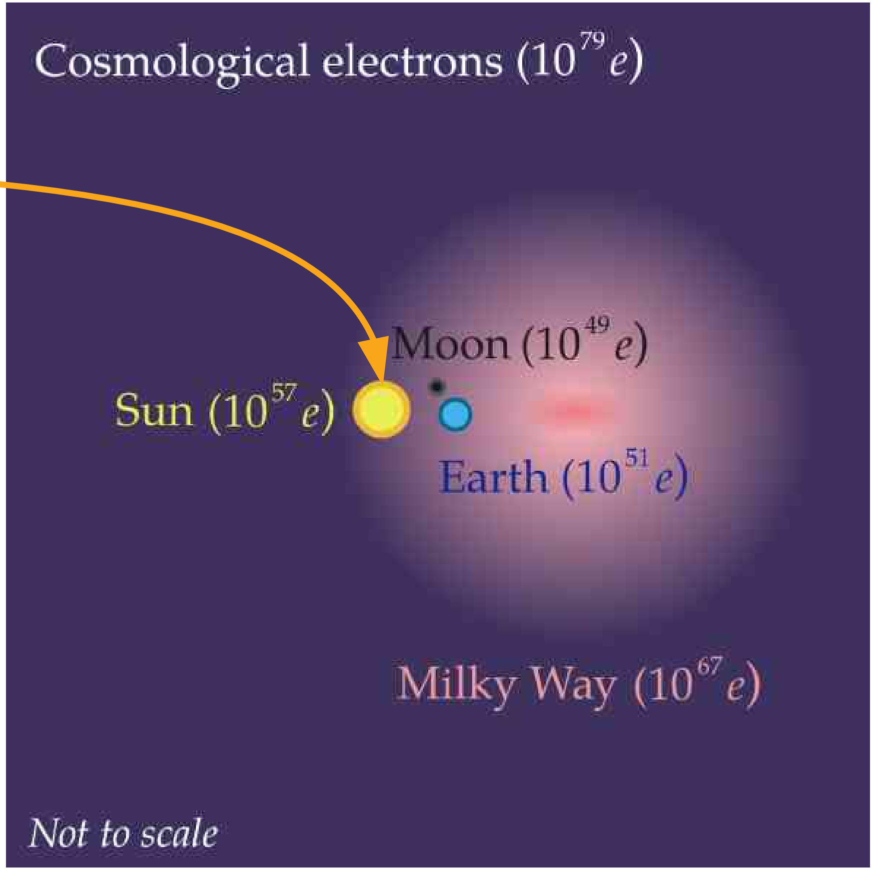

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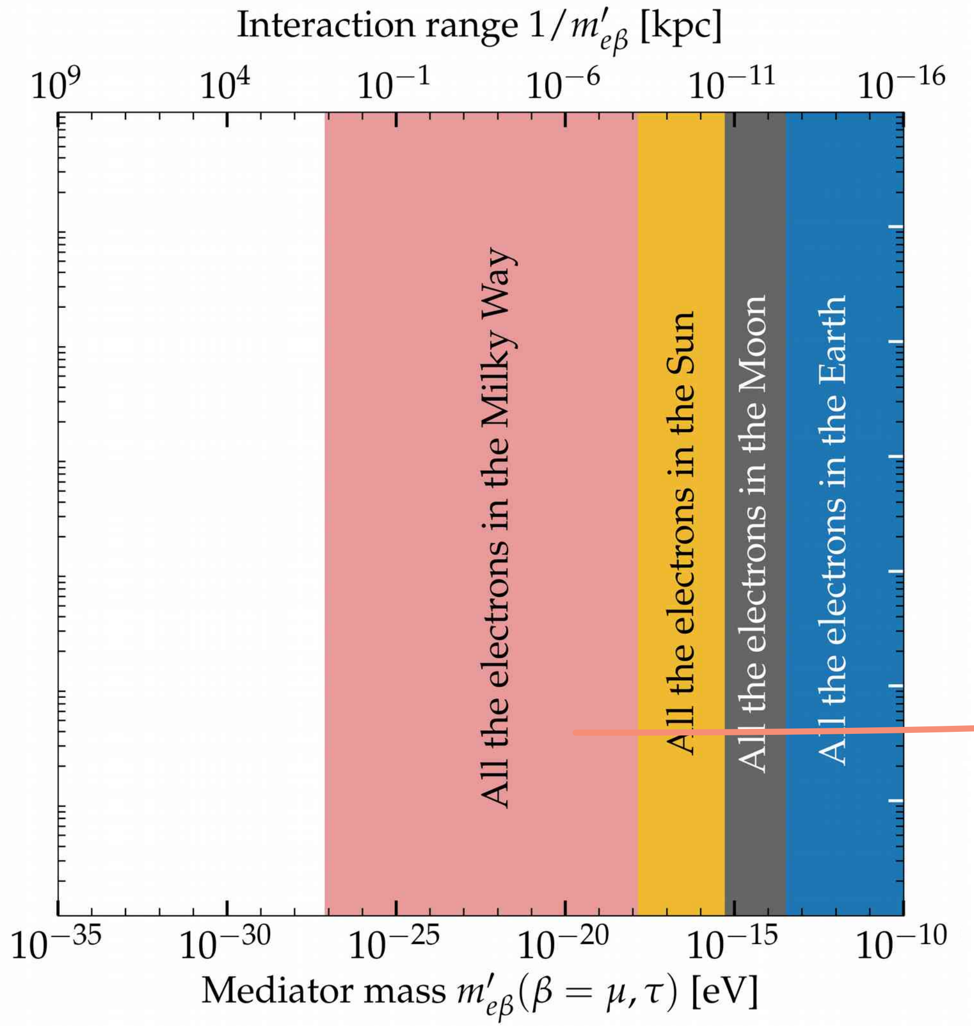

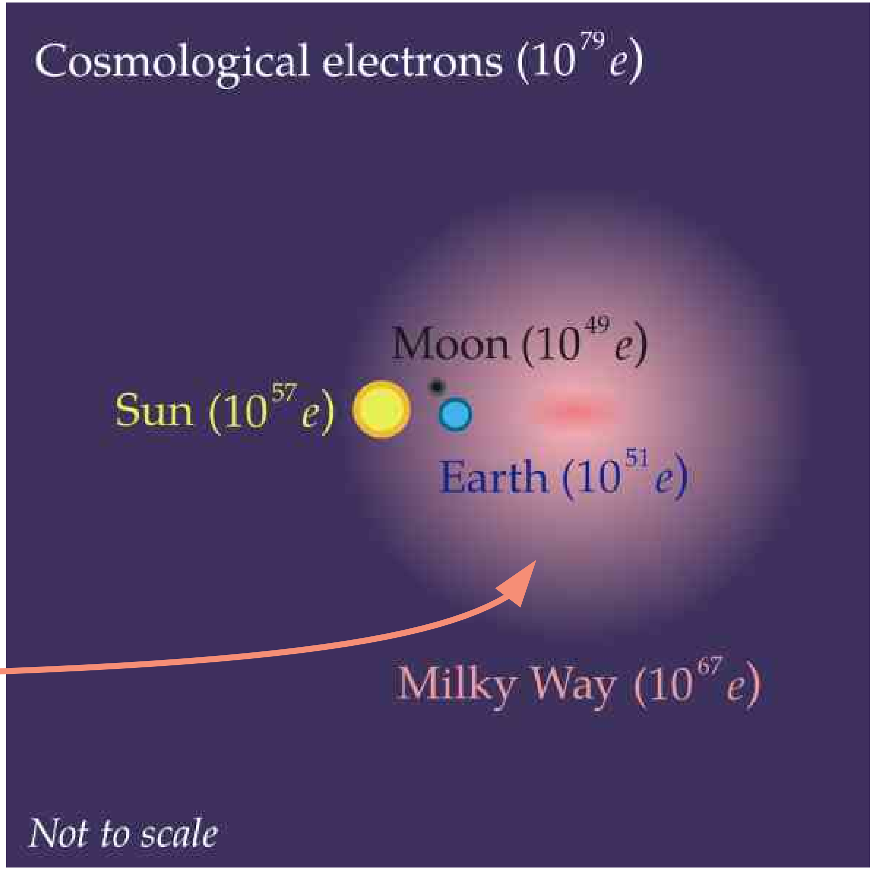

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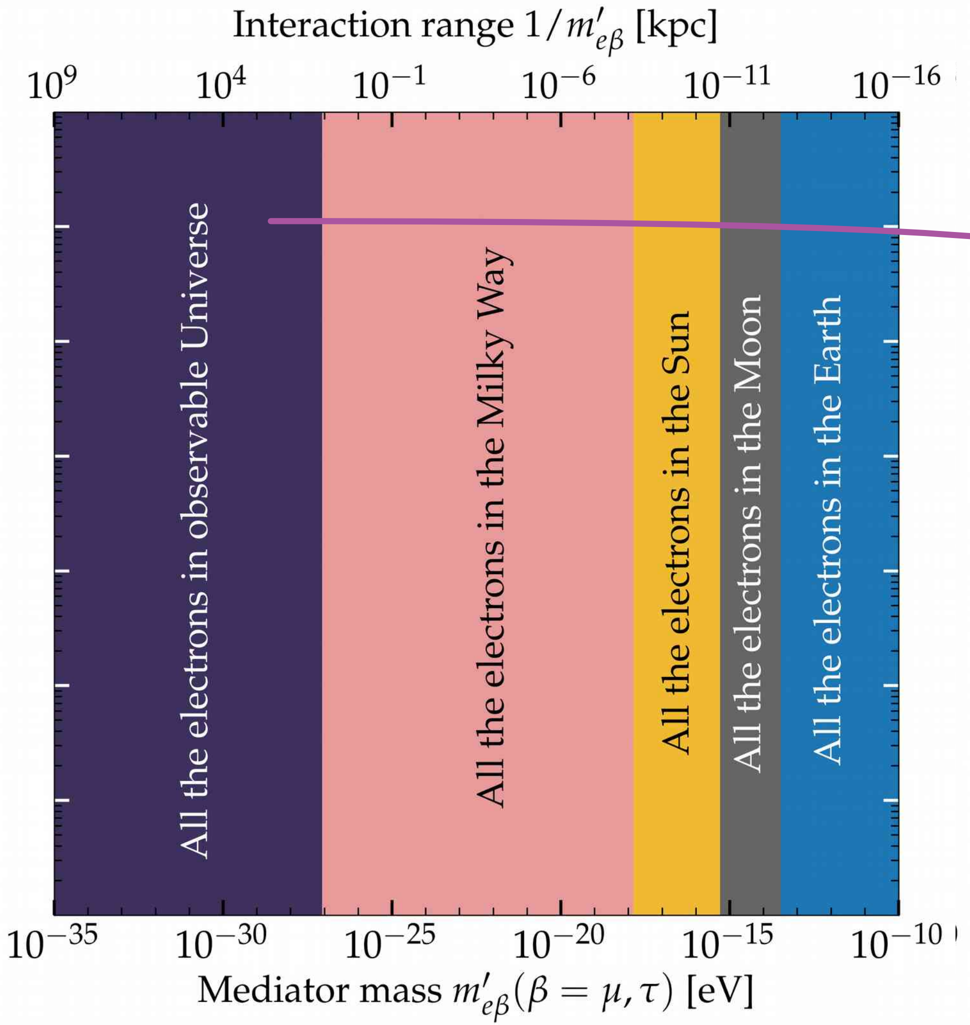
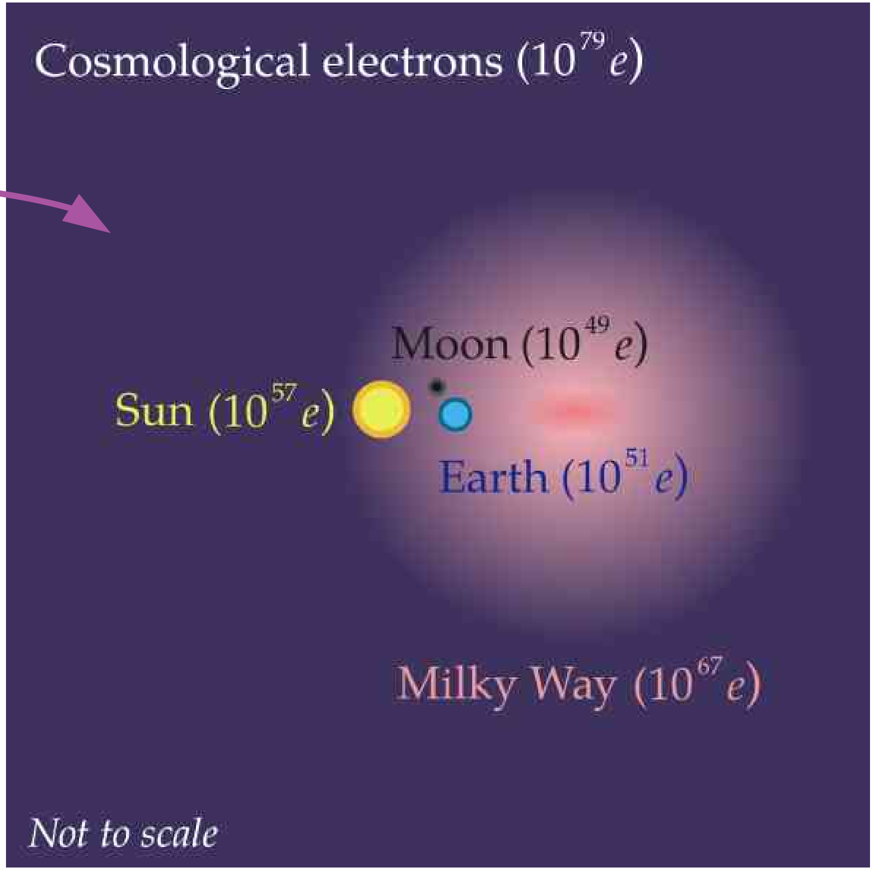
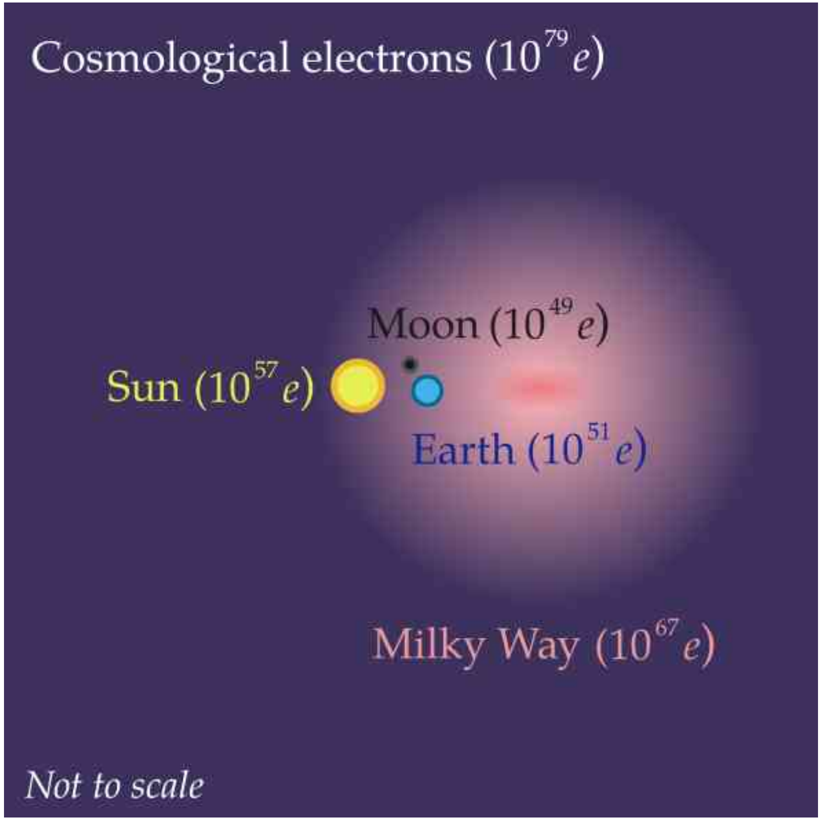




The total potential



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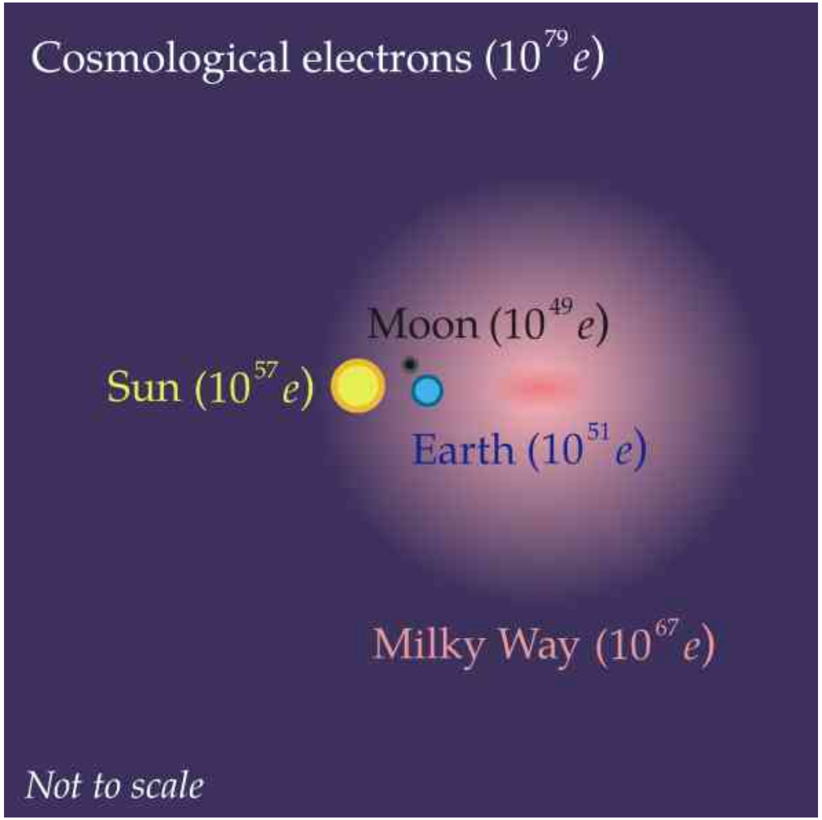
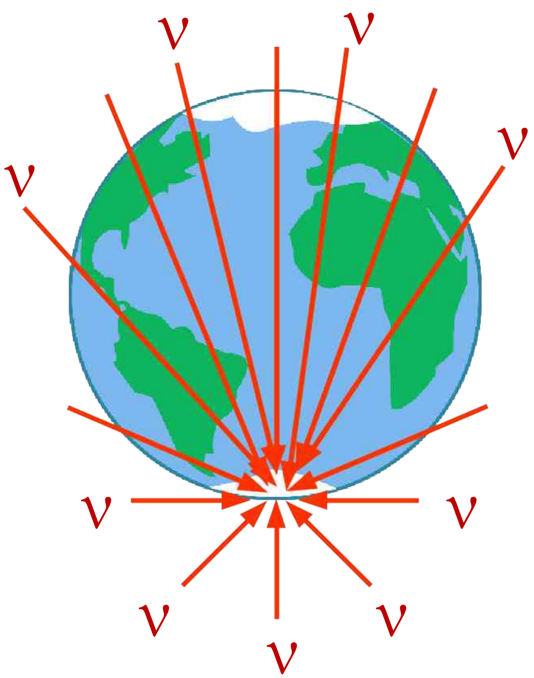
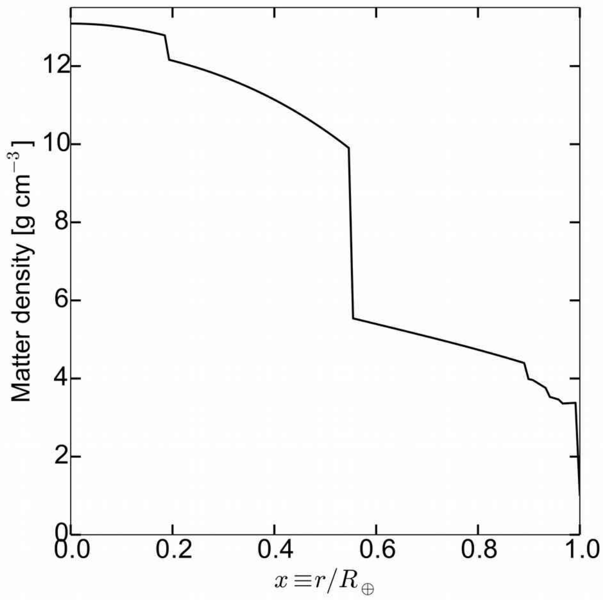


Earth:



Preliminary Reference Earth Model

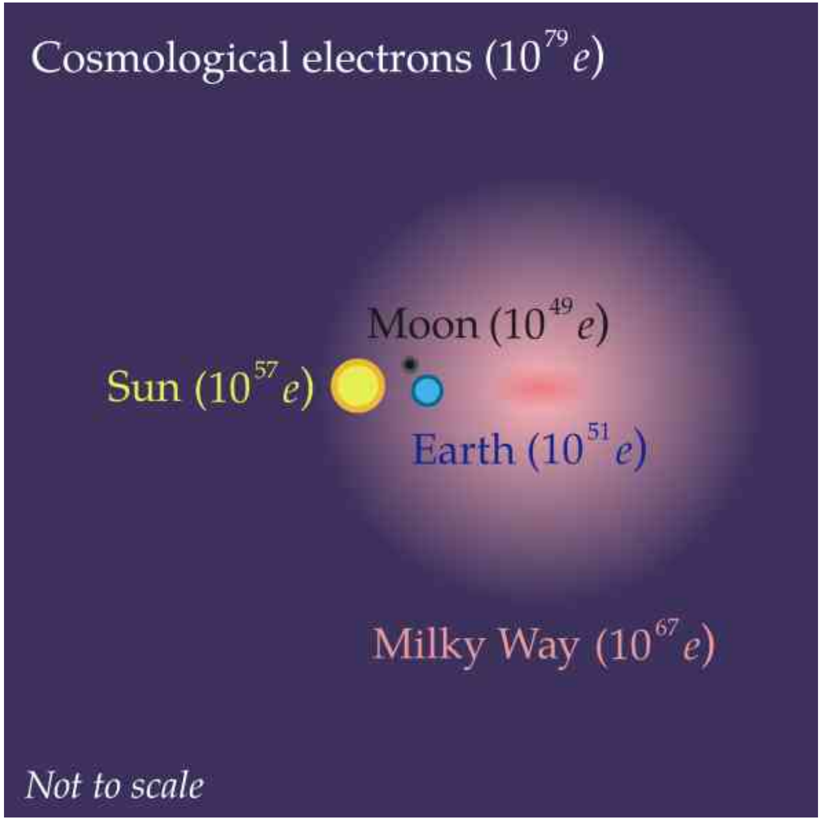
Dziewonski & Anderson 1981



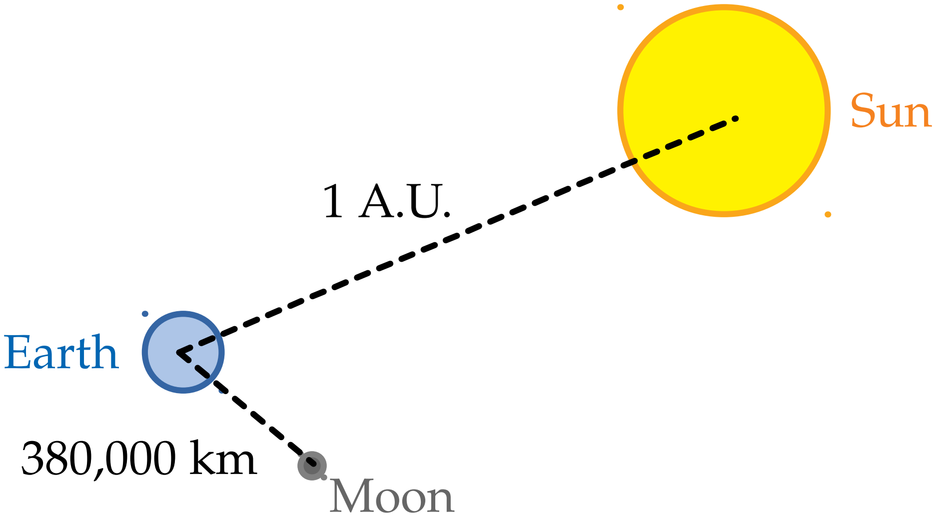
Neutrinos traverse different electron column depths

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

The total potential



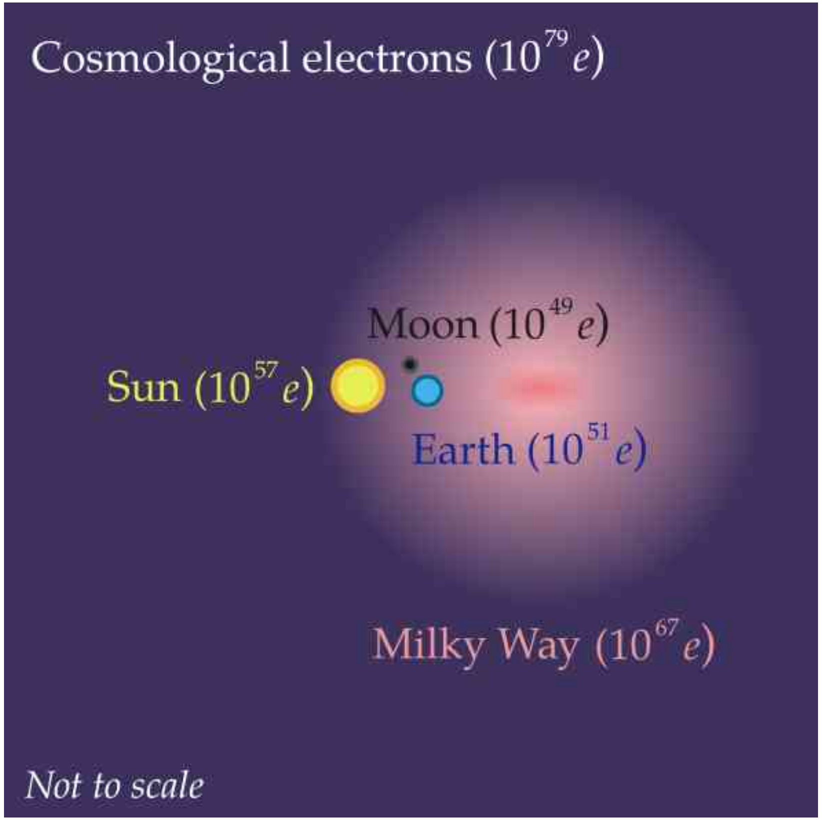
Moon and Sun:



Treated as point sources of electrons

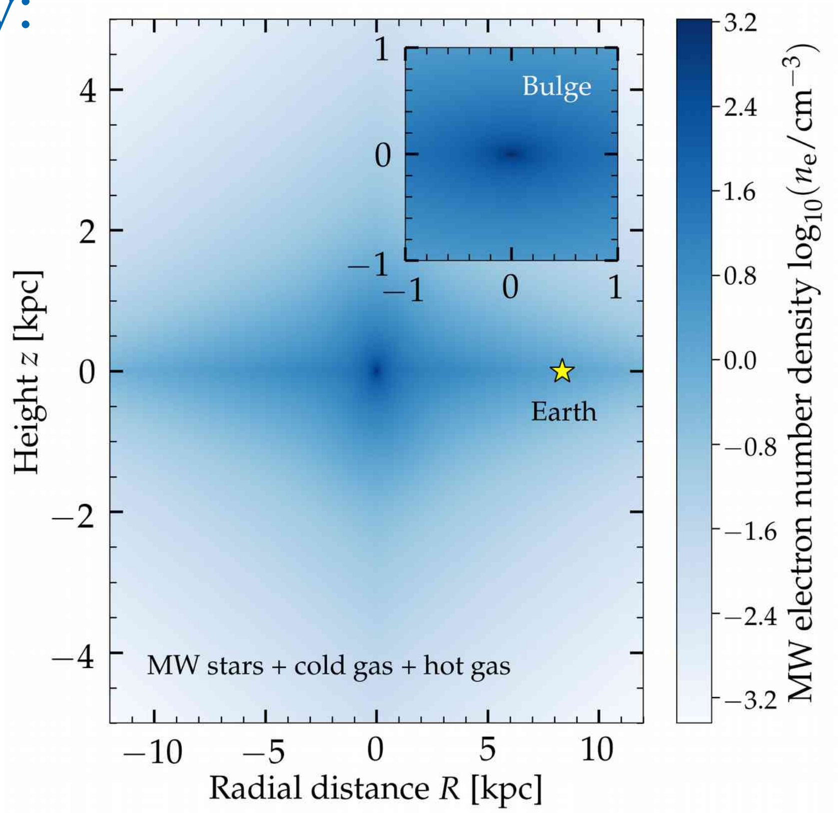
$$V_{e\beta} = V_{e\beta}^{\oplus} + V_{e\beta}^{\text{Moon}} + V_{e\beta}^{\odot}$$

The total potential



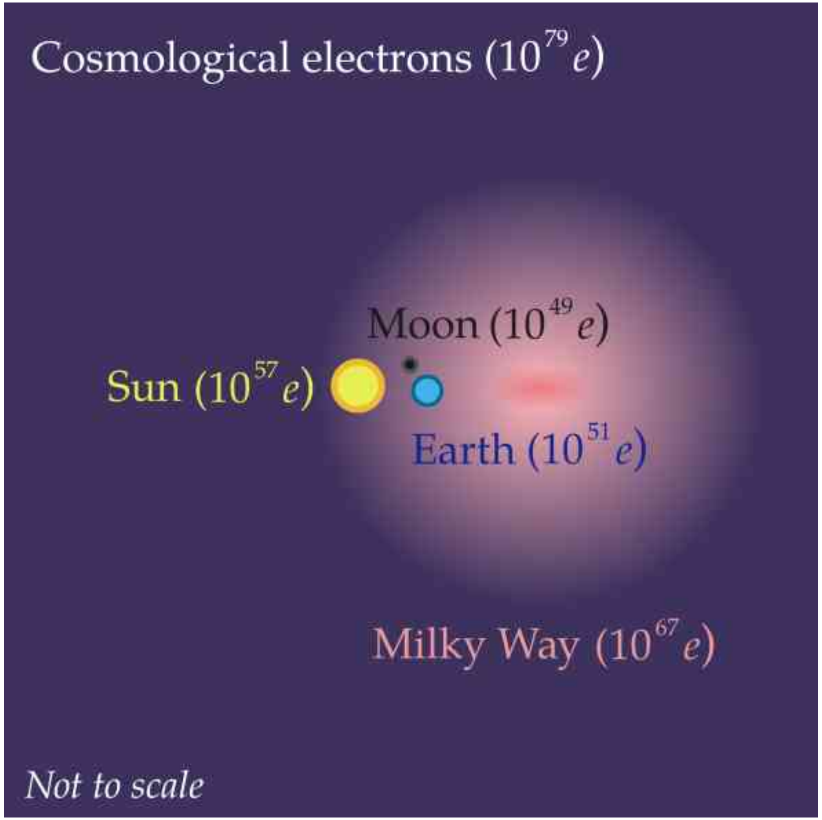
Milky Way:

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



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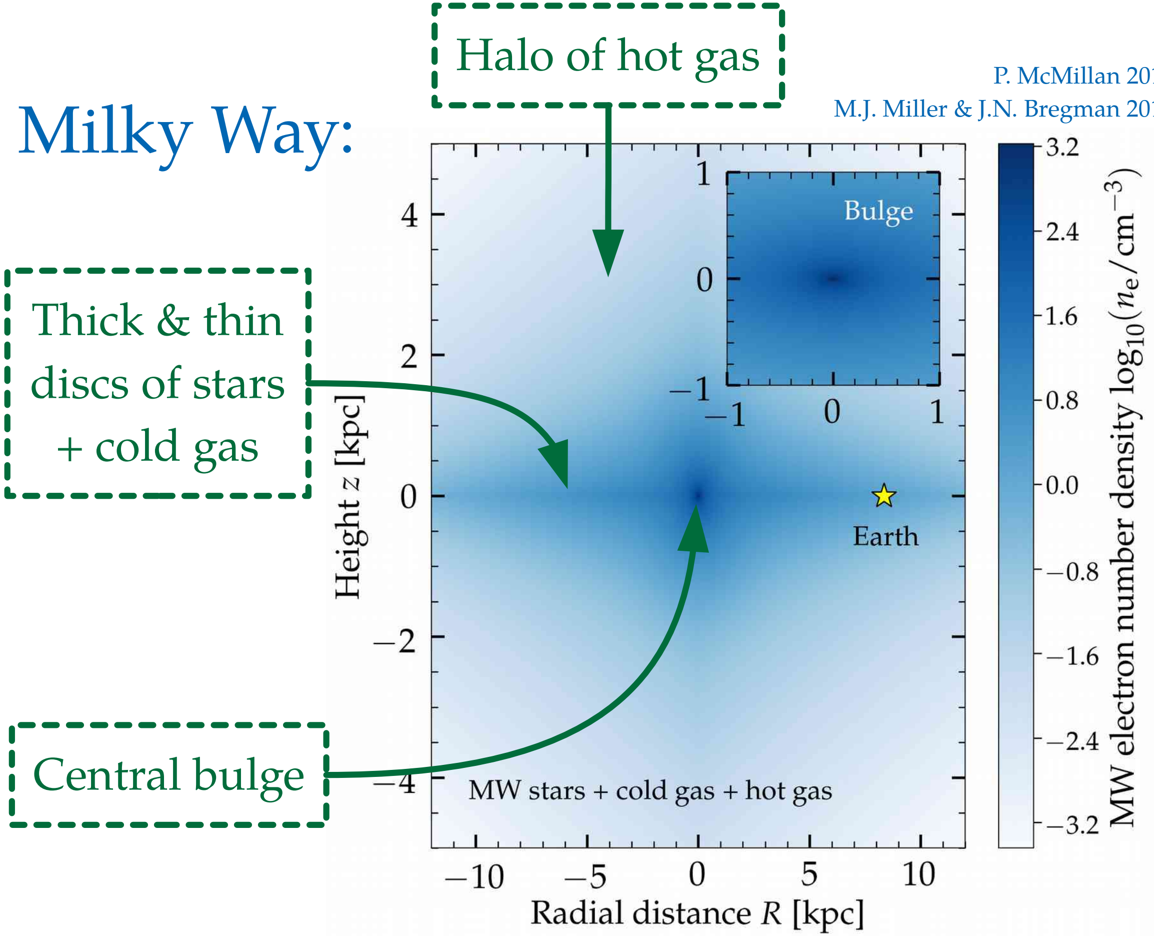
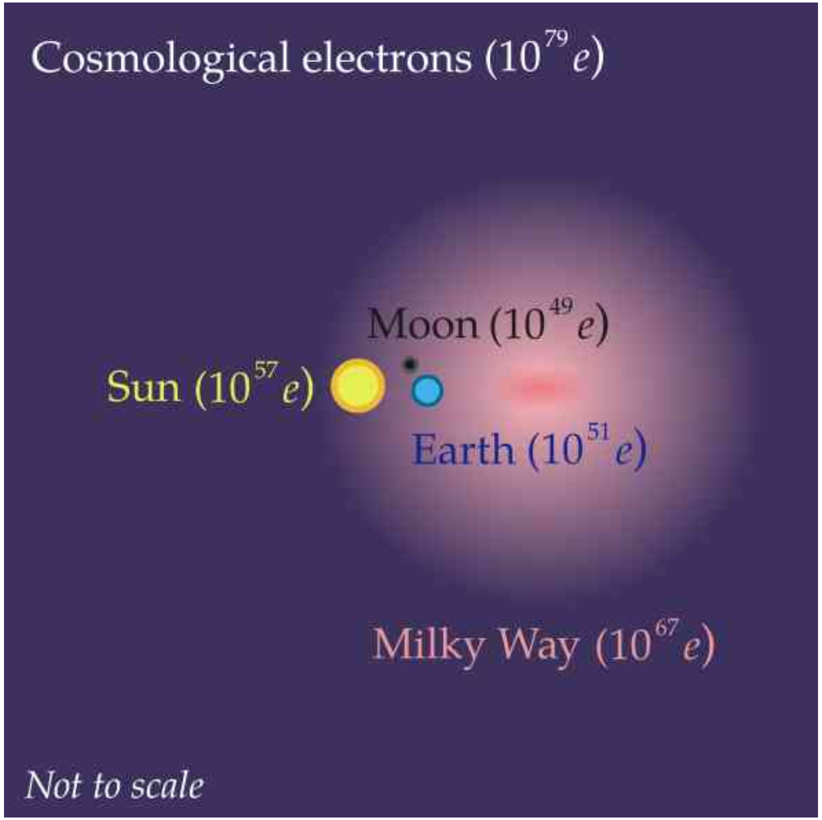
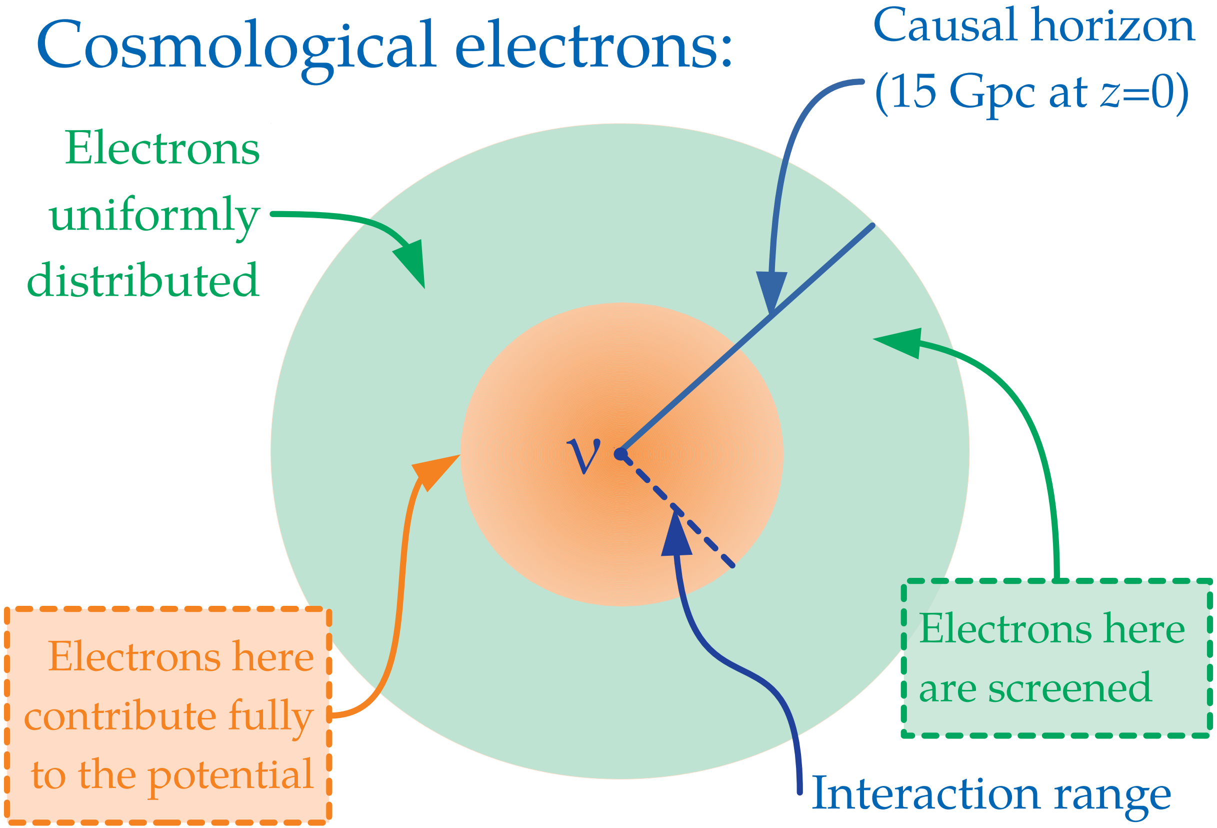


$$V_{e\beta} = V_{e\beta}^{\oplus} + V_{e\beta}^{\text{Moon}} + V_{e\beta}^{\odot} + V_{e\beta}^{\text{MW}}$$

The total potential

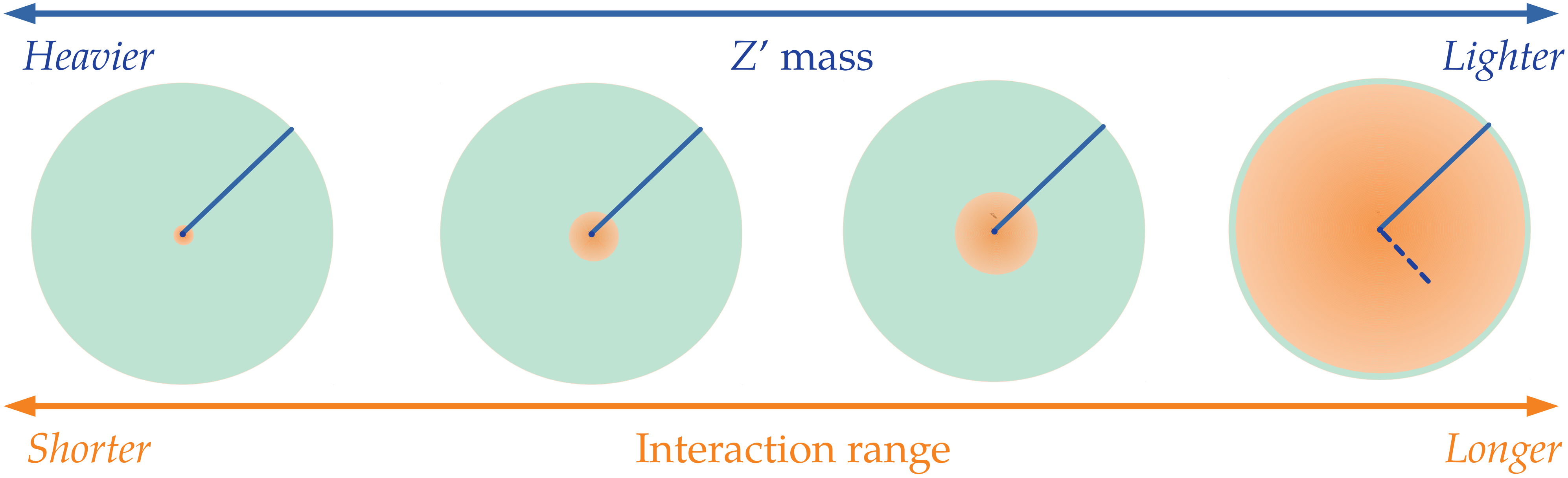


Cosmological electrons:



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

The total potential



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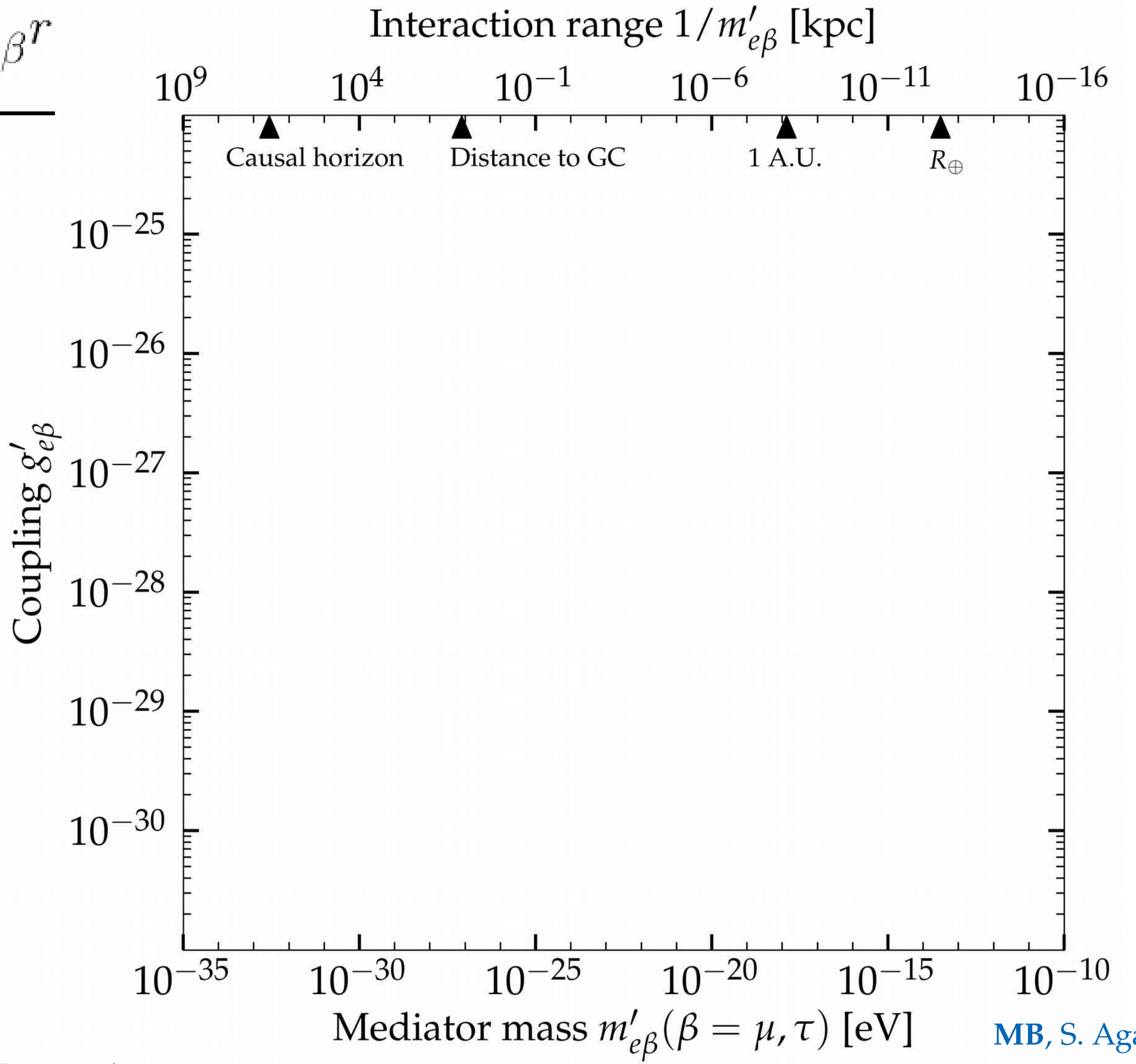
$$V_{e\beta} = \frac{g'^2_{e\beta}}{4\pi} \frac{e^{-m'_{e\beta} r}}{r}$$



MB, S. Agarwalla, 1808.02042

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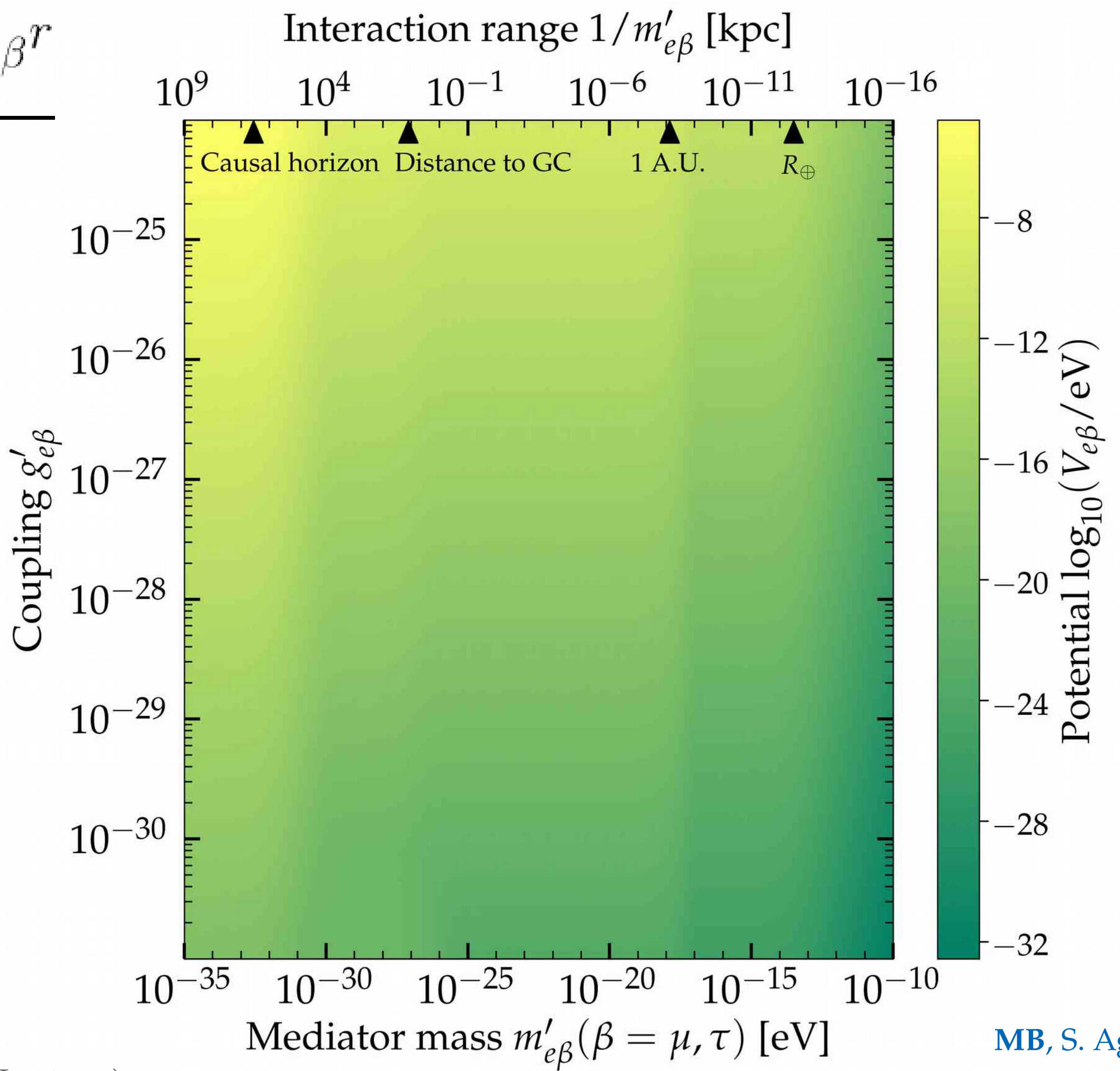


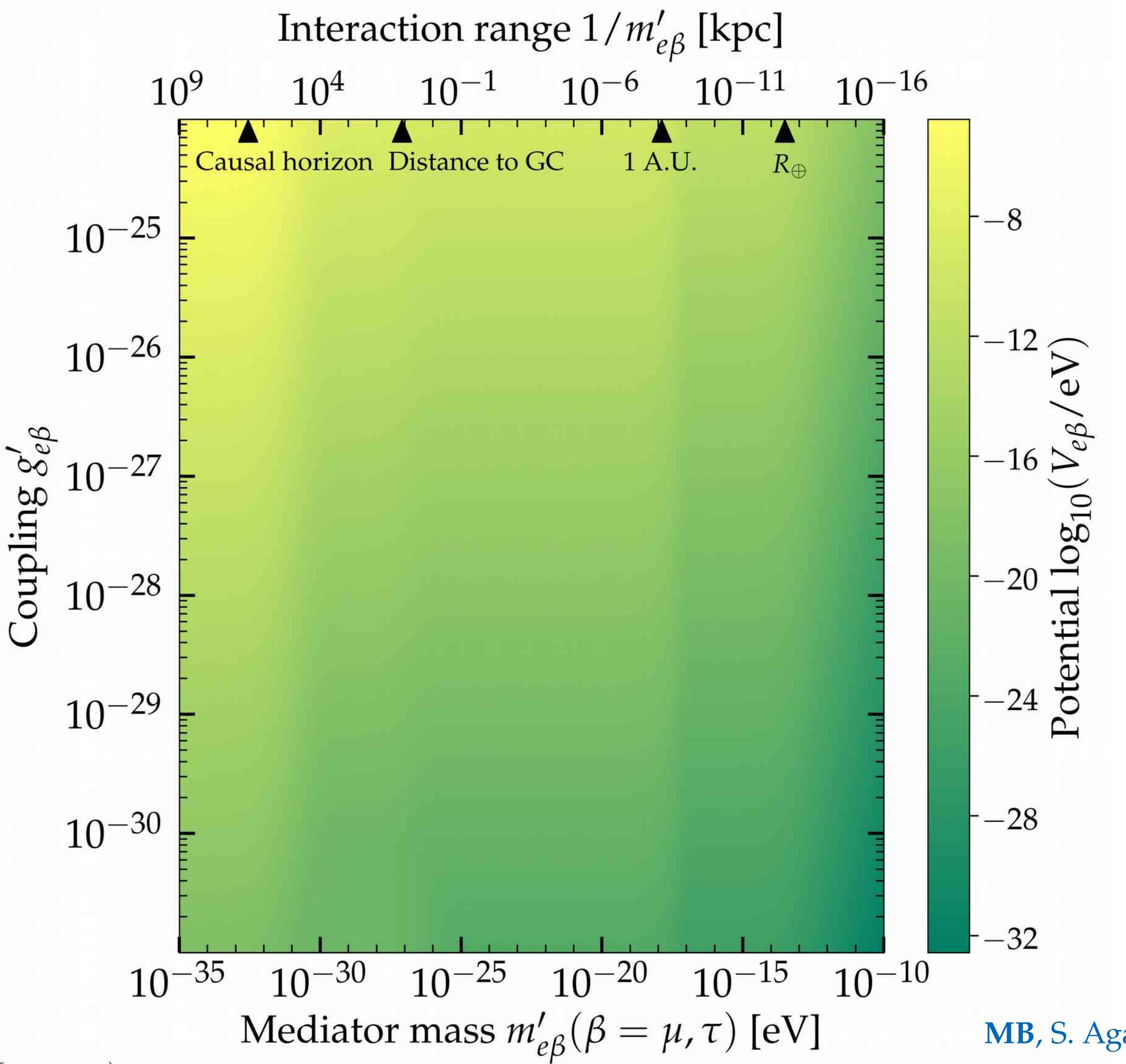
MB, S. Agarwalla, 1808.02042

$g_{strong} \sim 13.5$

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

$g_{weak} \sim 0.01$

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



MB, S. Agarwalla, 1808.02042

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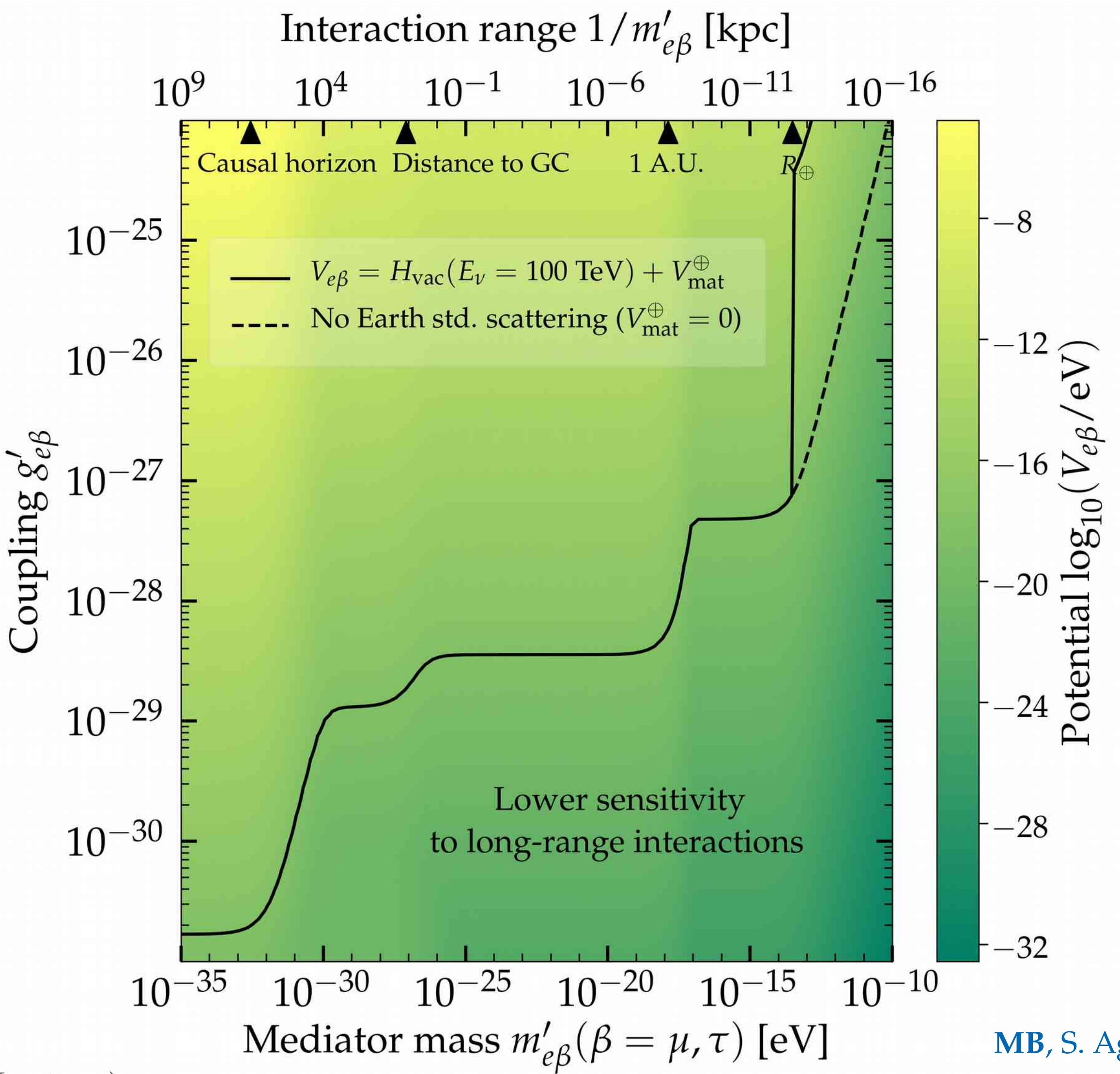

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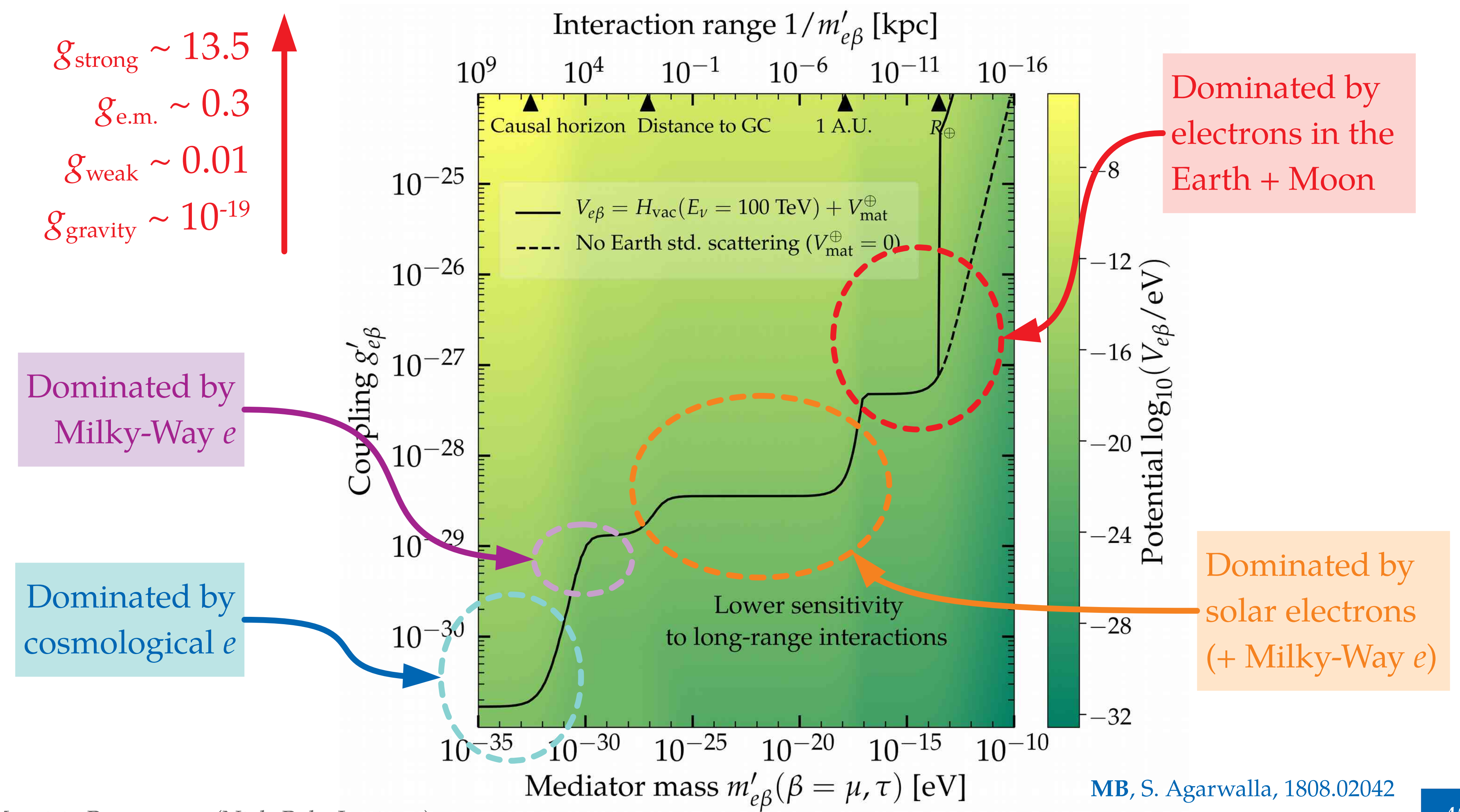
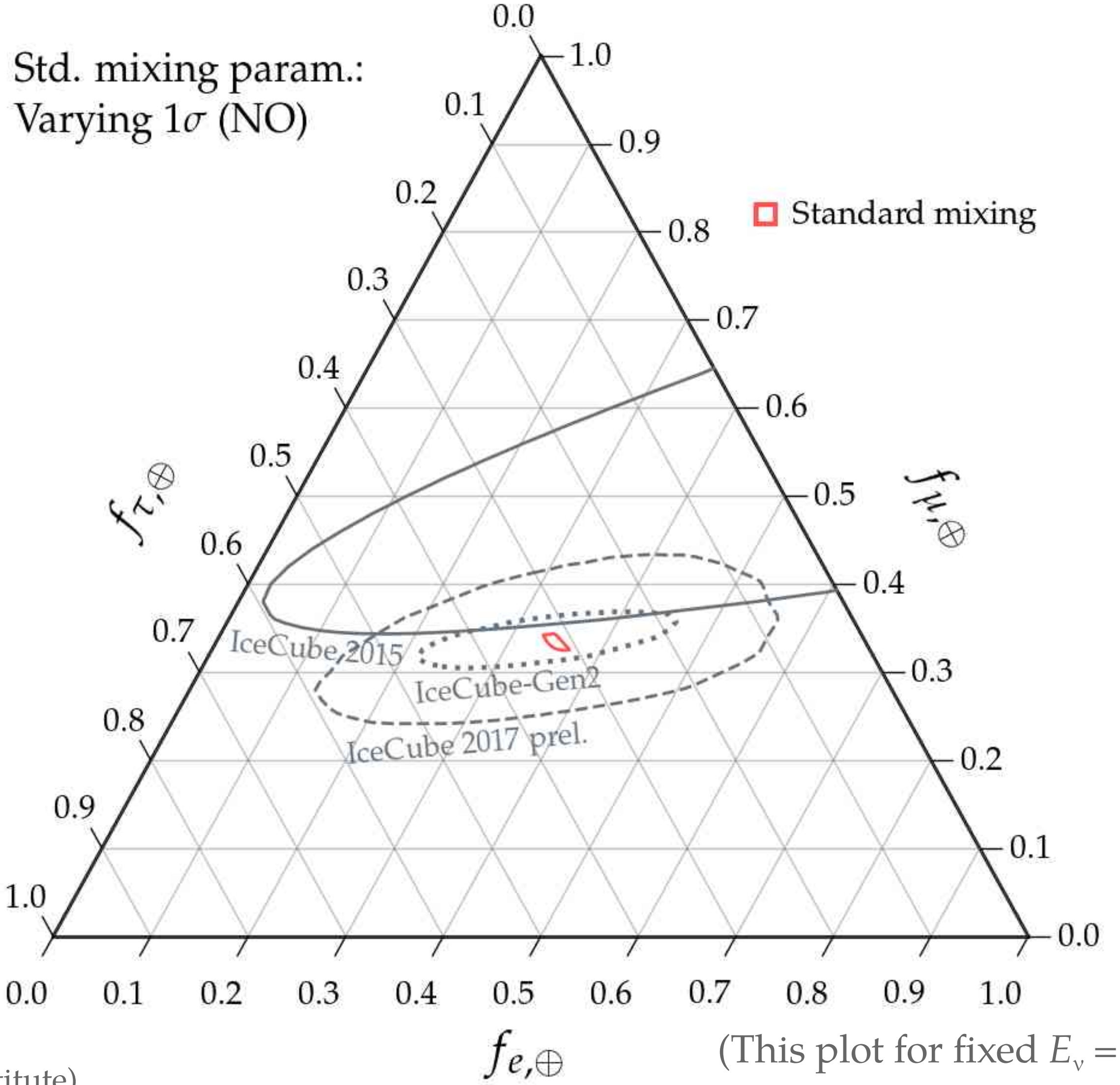
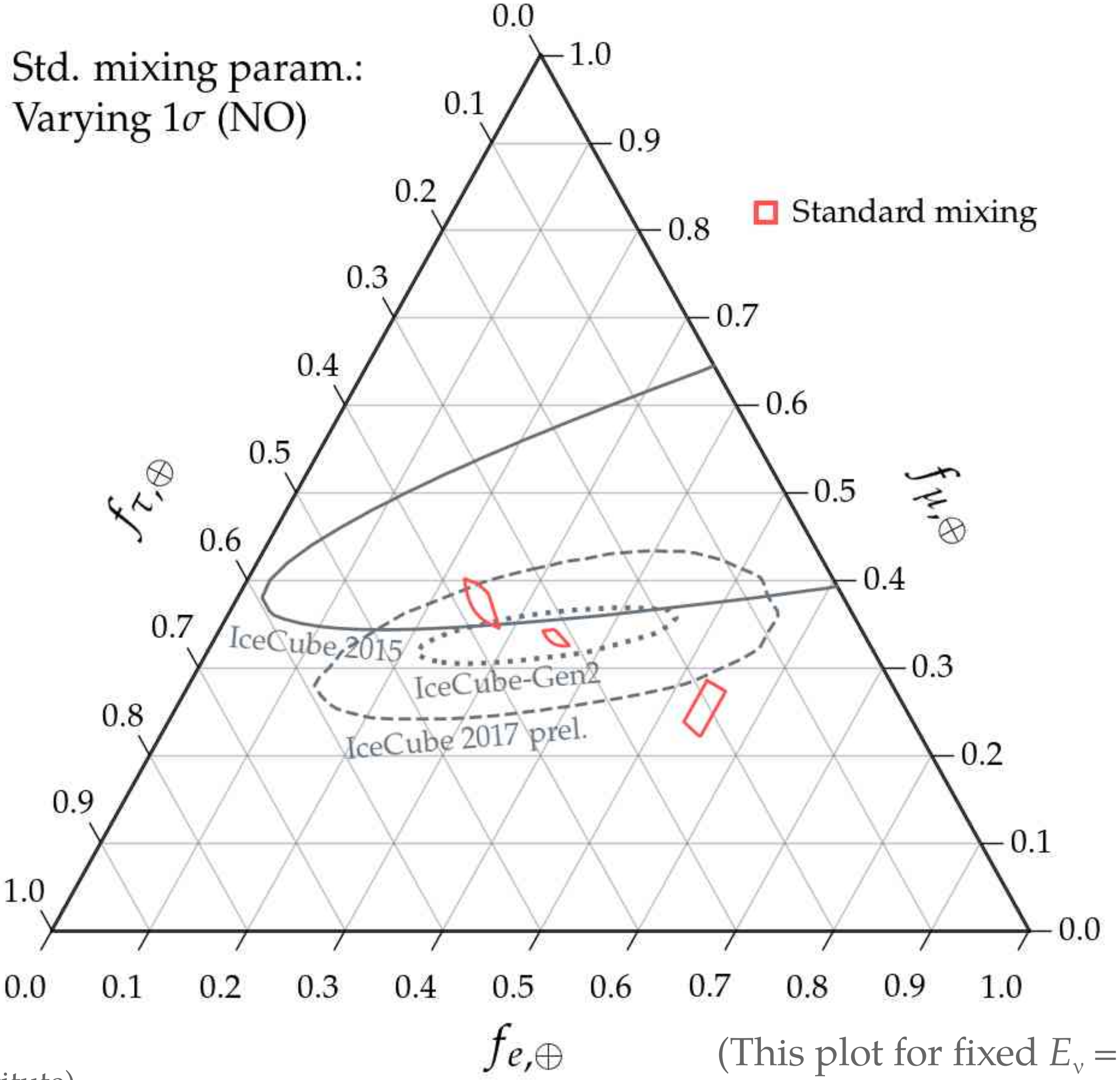


MB, S. Agarwalla, 1808.02042



MB, S. Agarwalla, 1808.02042

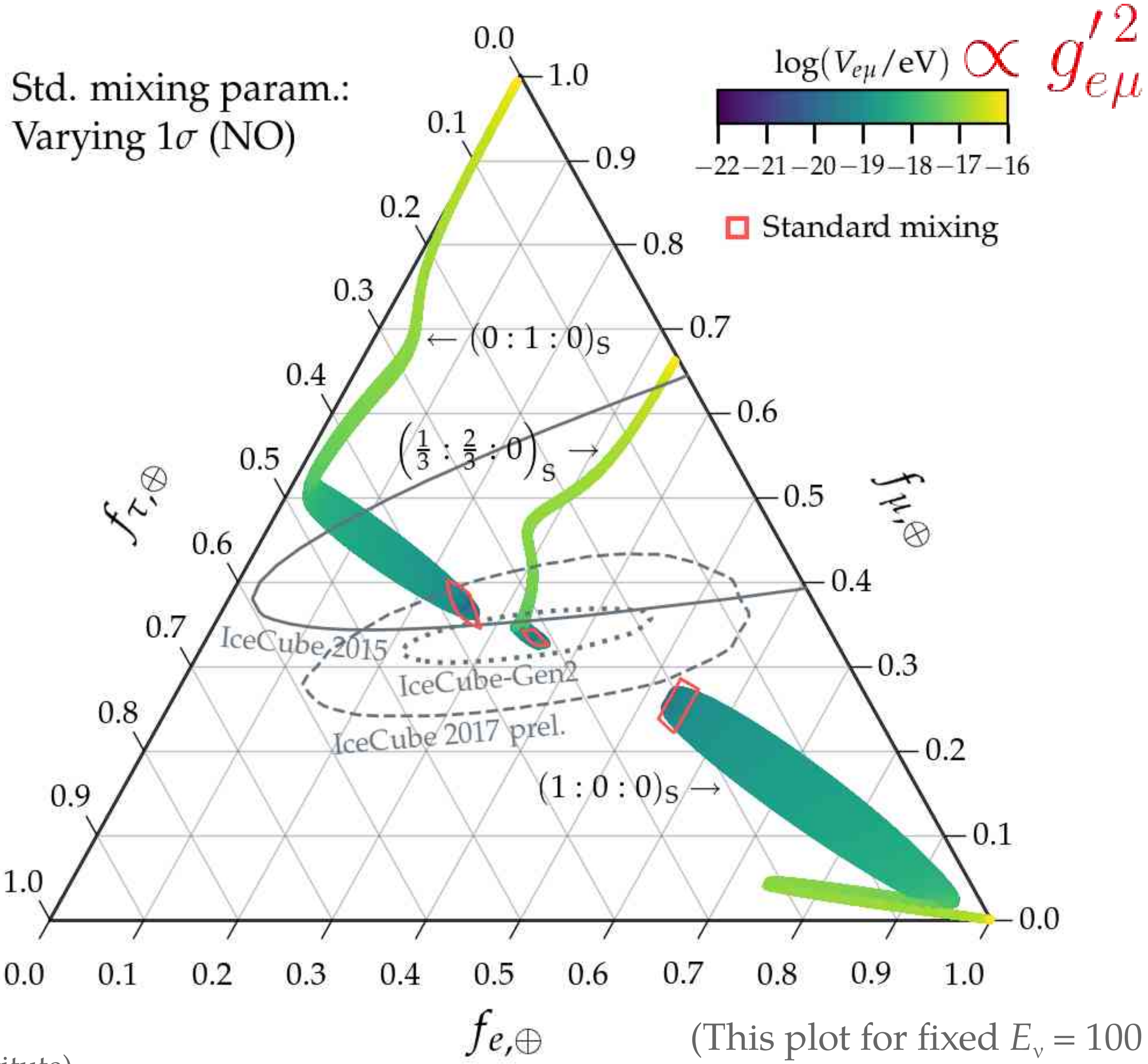
(This plot for fixed E_ν = 100 TeV)



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*)



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MB, S. Agarwalla, 1808.02042

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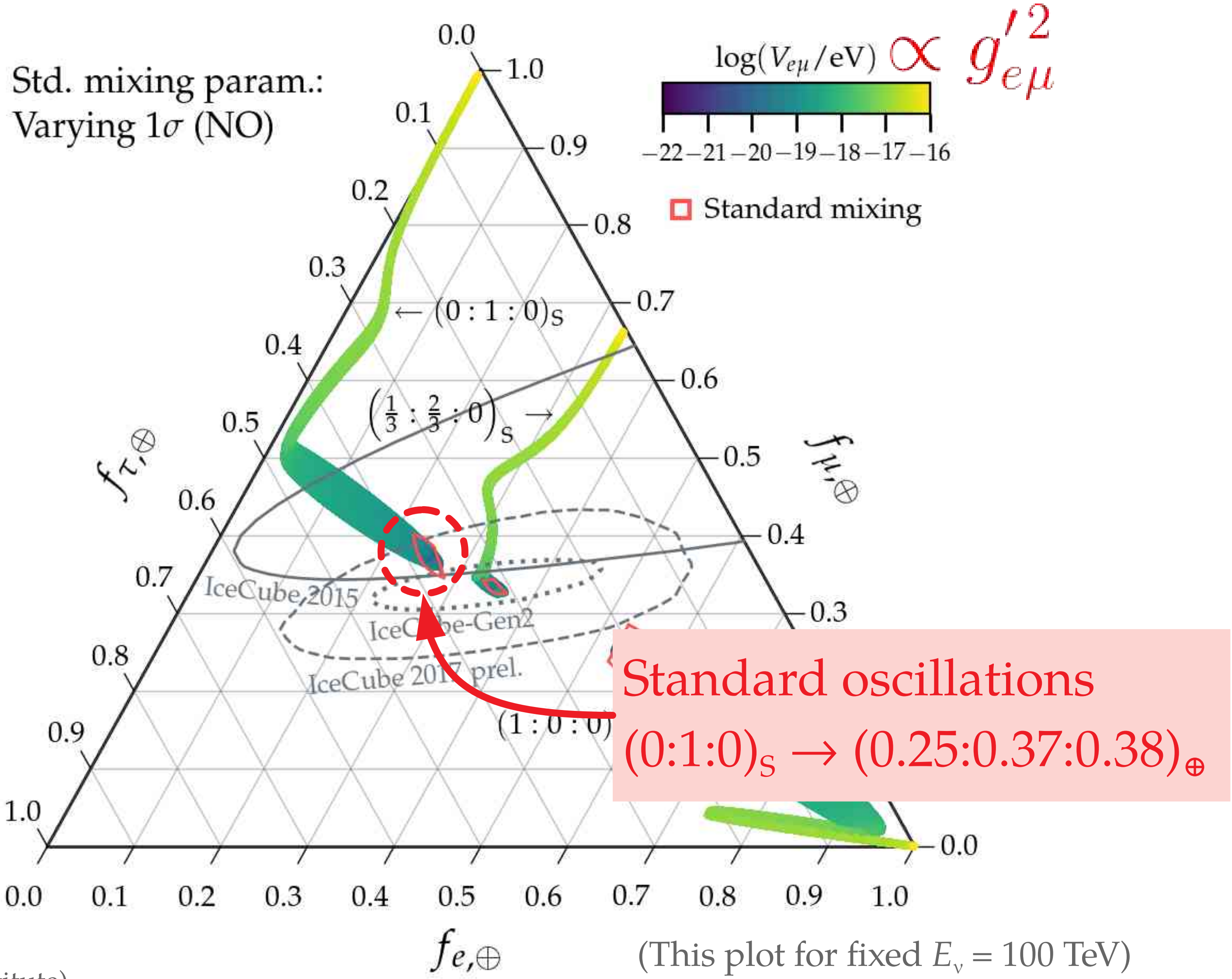

MB, S. Agarwalla, 1808.02042

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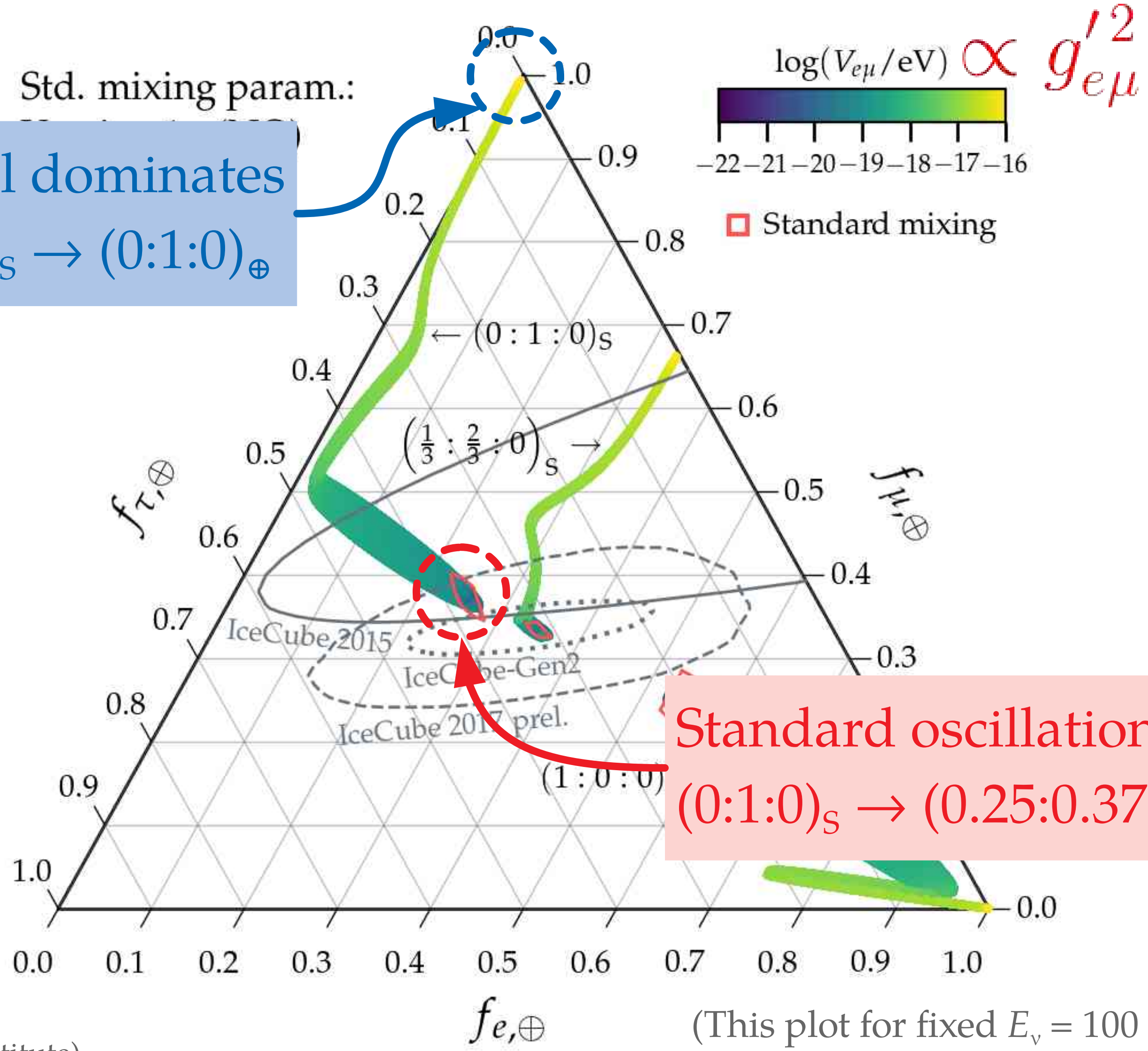
We assume equal
proportions of ν and ν
(e.g., pr

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

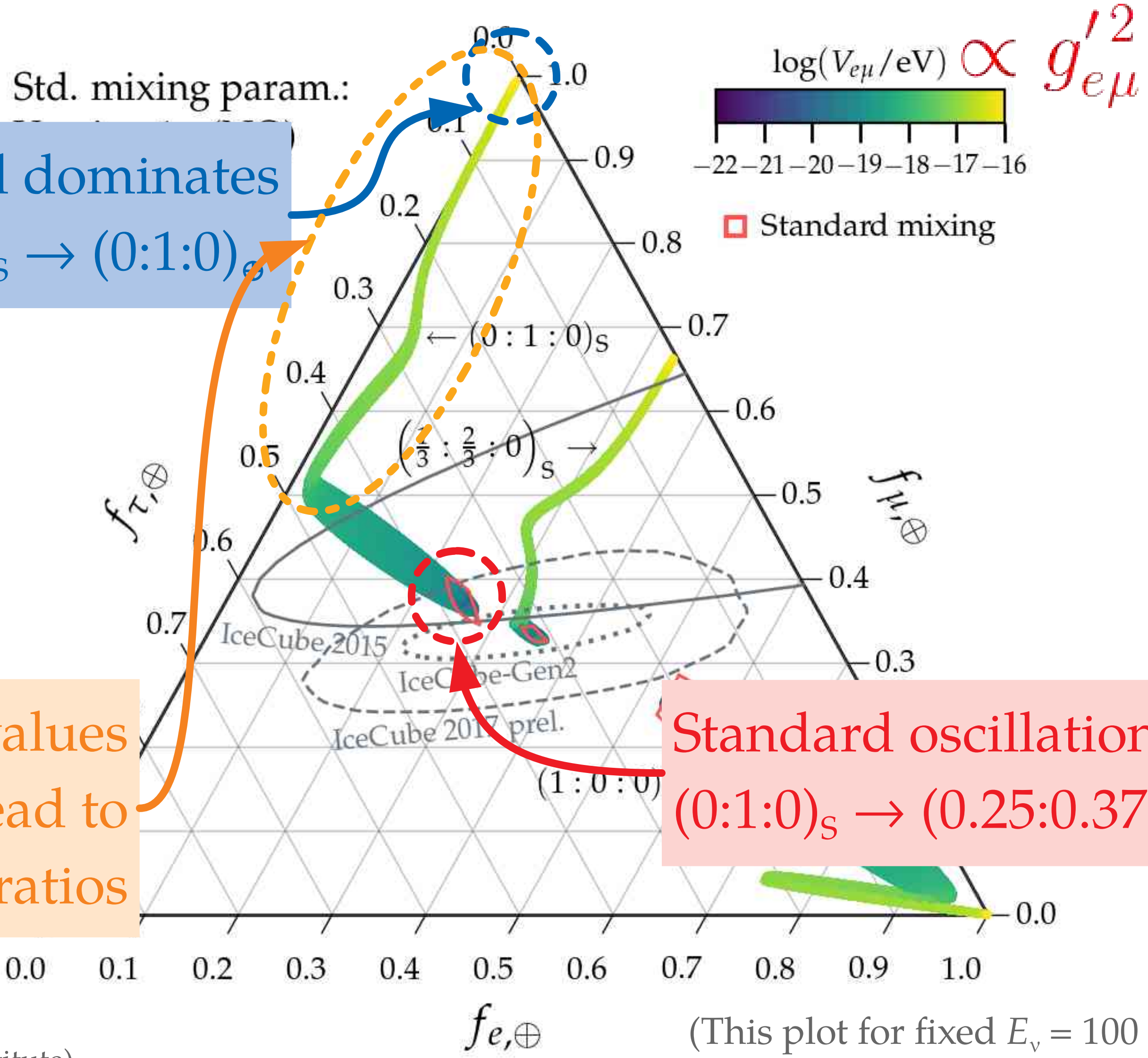


Standard oscillations
$(0:1:0)_S \to (0.25:0.37:0.38)_\oplus$

MB, S. Agarwalla, 1808.02042

(This plot for fixed E_ν = 100 TeV)

We assume equal proportions of ν and ν̄ (*e.g.*, pr



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

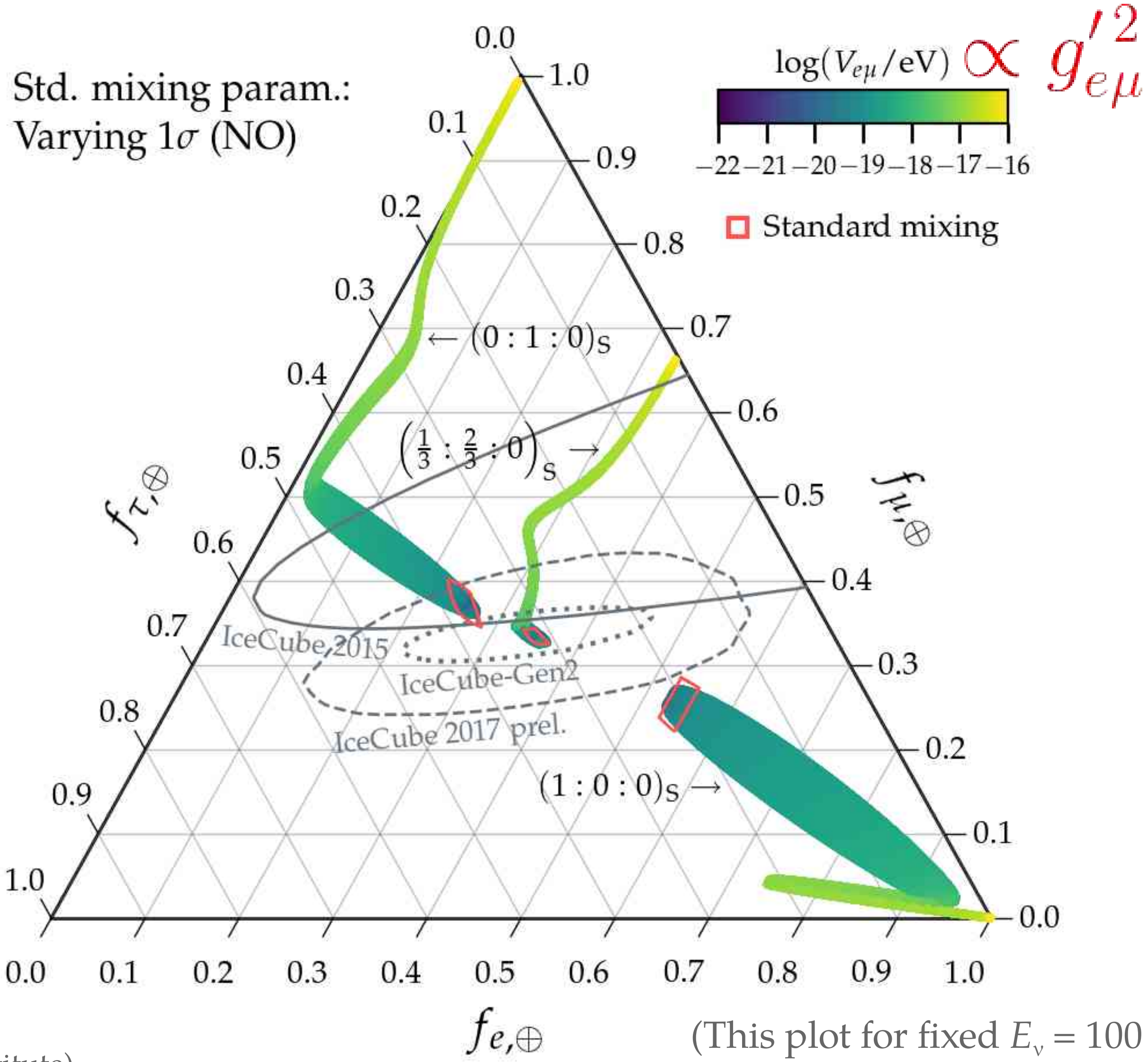
We can disfavor all values of m' and g' that lead to these flavor ratios

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

MB, 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*)



MB, S. Agarwalla, 1808.02042

(This plot for fixed E_ν = 100 TeV)

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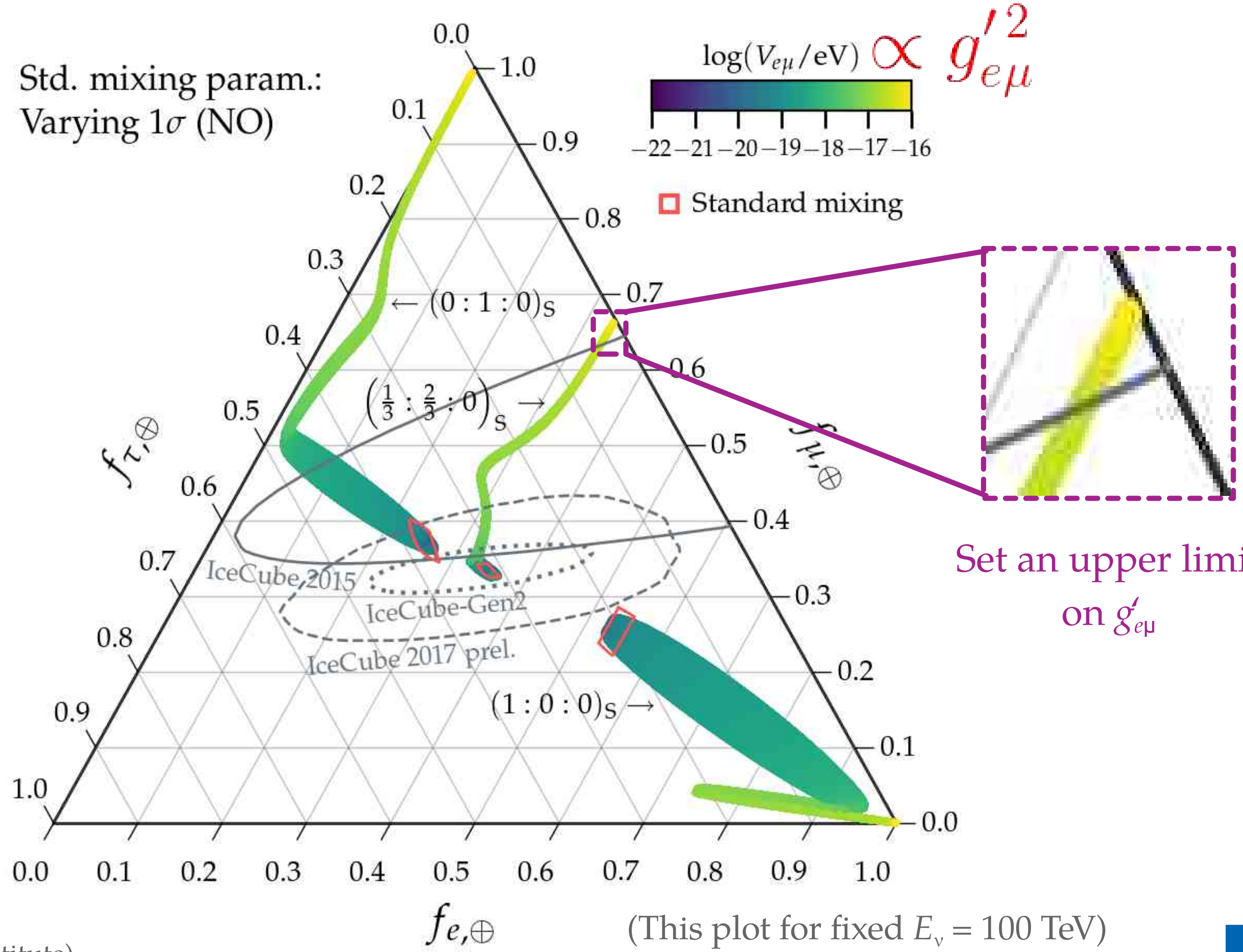
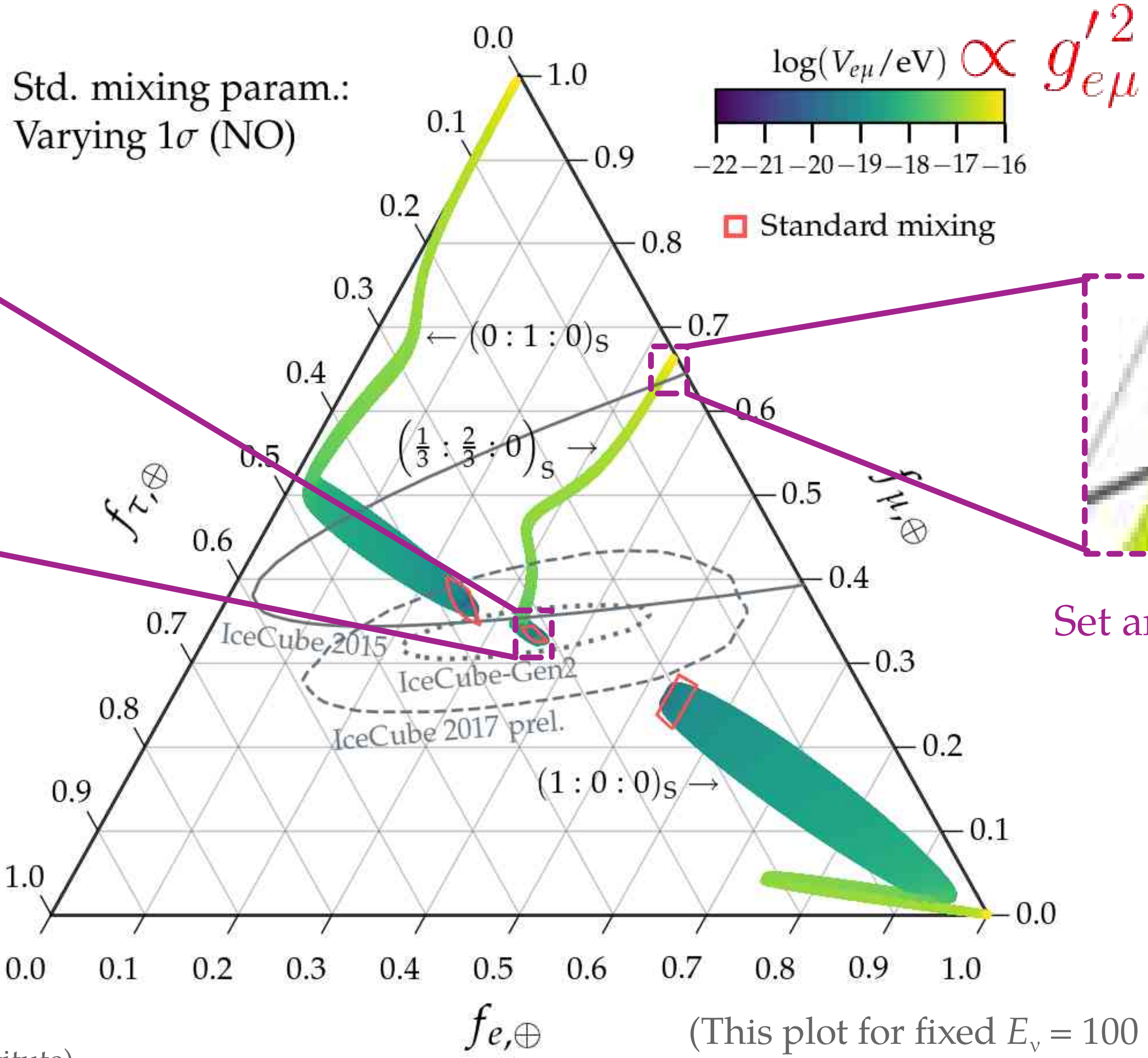


Set an upper limit on $g'_{e\mu}$

MB, S. Agarwalla, 1808.02042

(This plot for fixed E_ν = 100 TeV)

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



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

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

MB, S. Agarwalla, 1808.02042

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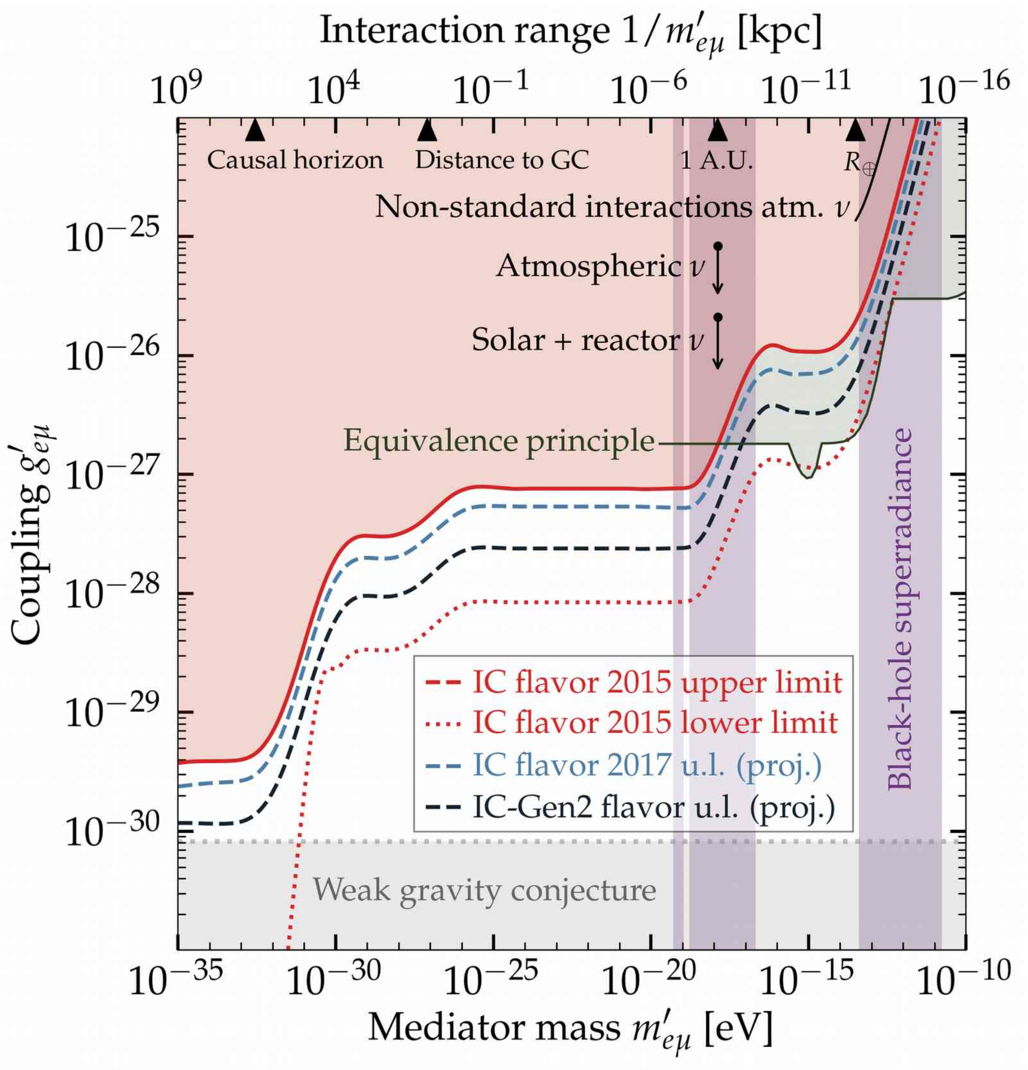


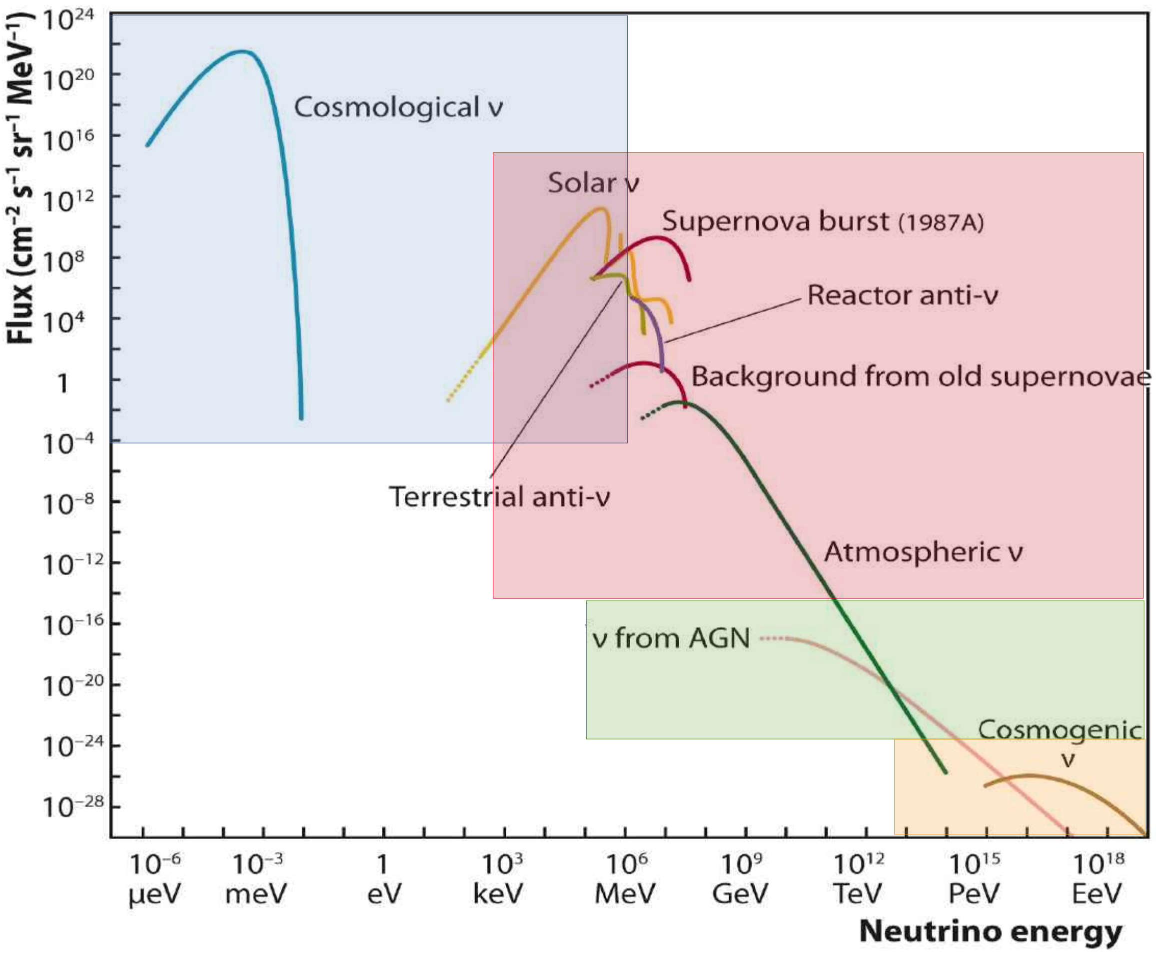
The result

- Best sensitivity at low Z' masses
- But significance is low (1σ) because of difficulty in measuring flavor
- Results are robust against:
  - Uncertainty in mixing parameters
  - Uncertainty in ν spectral index
  - Choice of neutrino mass ordering
- Similar results for L_e-L_τ

← For this plot, mass ordering is normal and flavor at sources is $(1/3 : 2/3 : 0)_S$

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

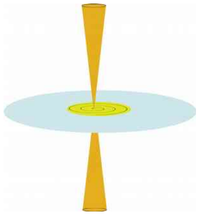
Adapted from
DC Comics, *World's Finest* #153

Backup slides

Inferring flavor composition at the sources

Measured:
Flavor ratios at Earth

Invert flavor oscillations



Inferred:
Flavor ratios at astrophysical sources

MB, Ahlers, *In prep.*

Inferring flavor composition at the sources

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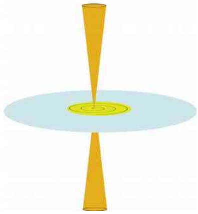

Inferred:
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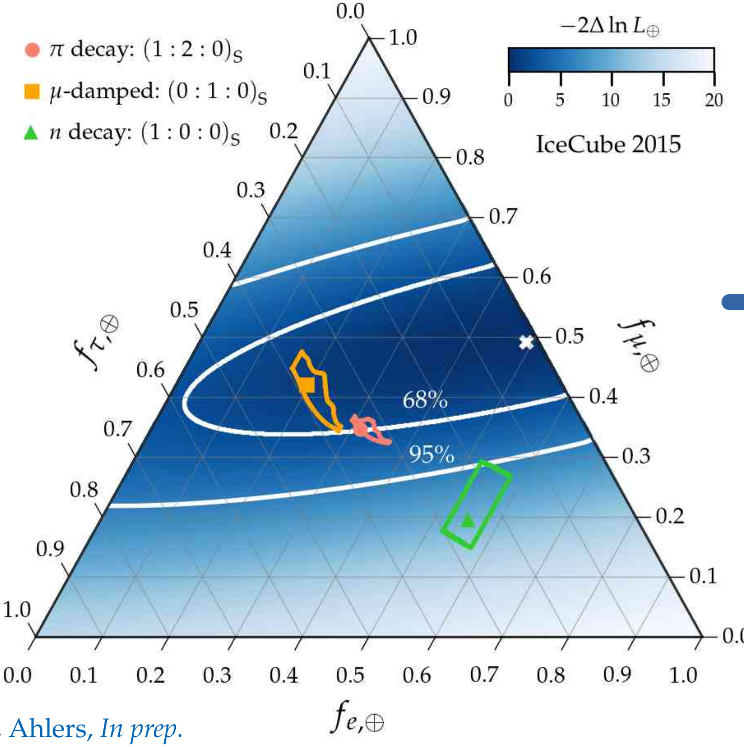

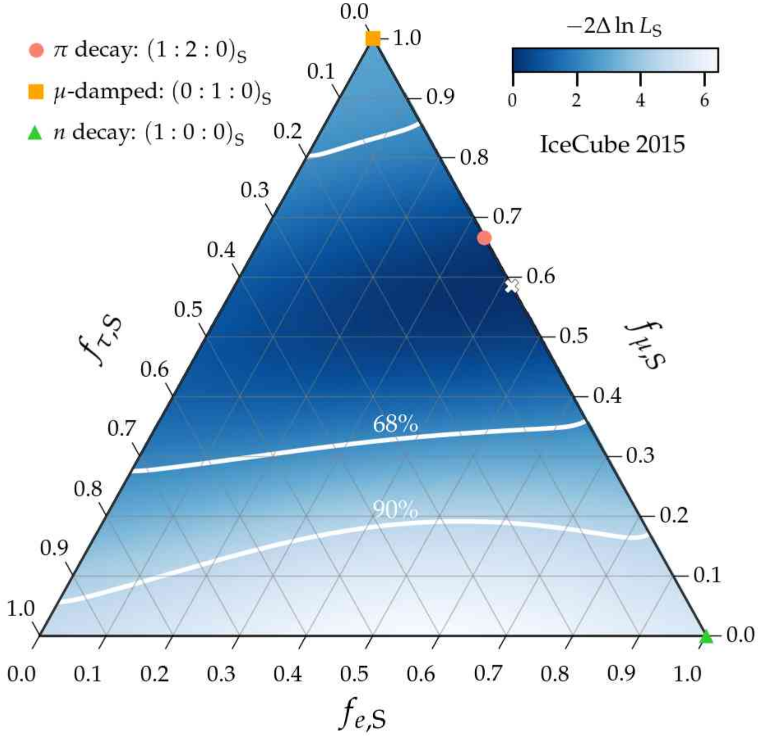

MB, Ahlers, *In prep.*

Inferring flavor composition at the sources

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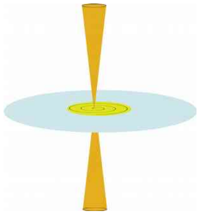

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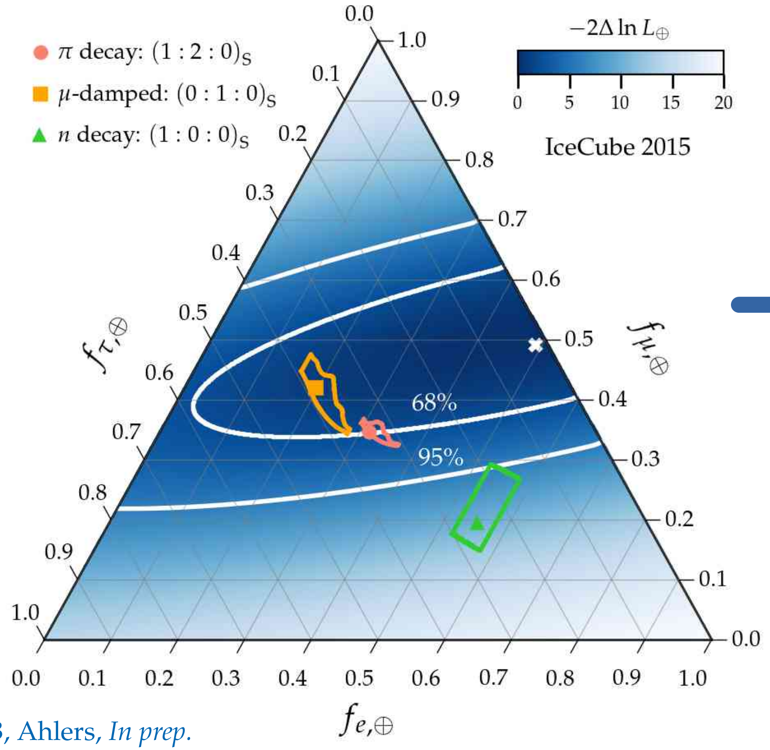
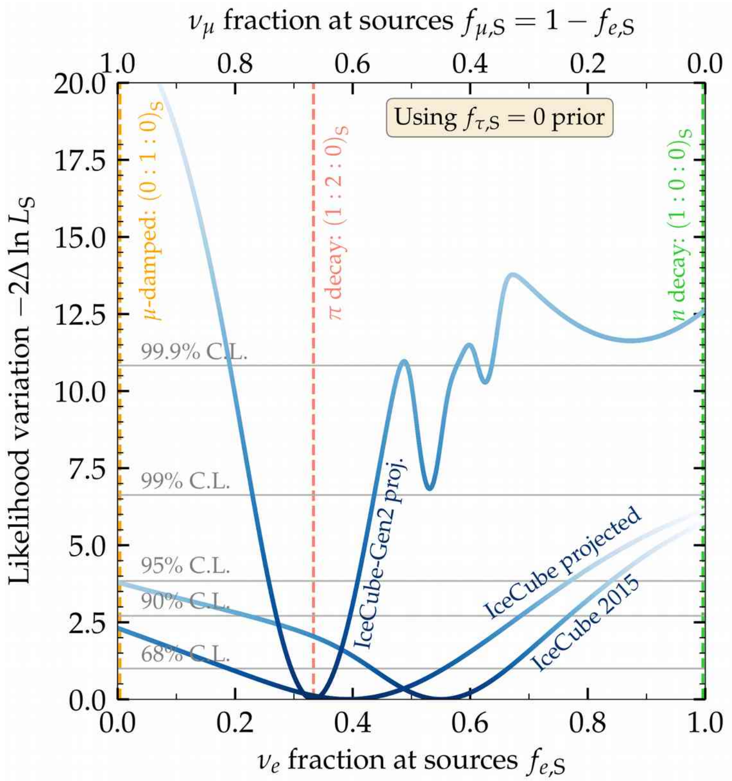
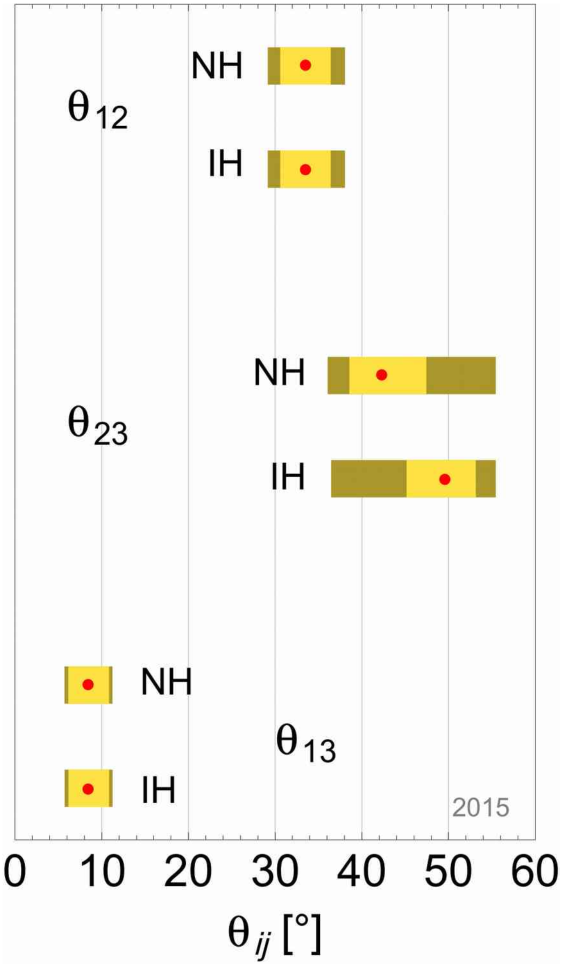




MB, Ahlers, *In prep.*

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...	... 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 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 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.

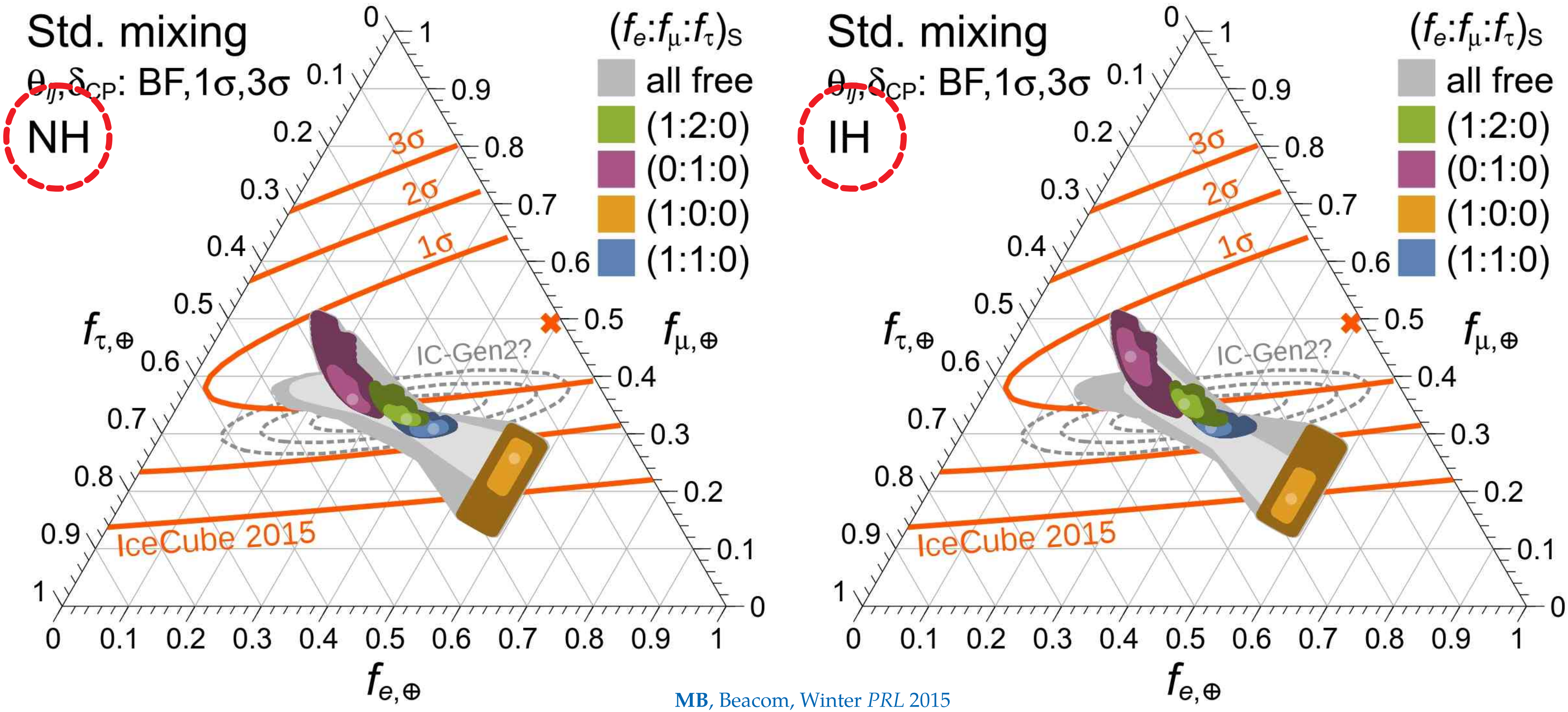
But we can thoroughly explore new physics

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 composition – a few source choices

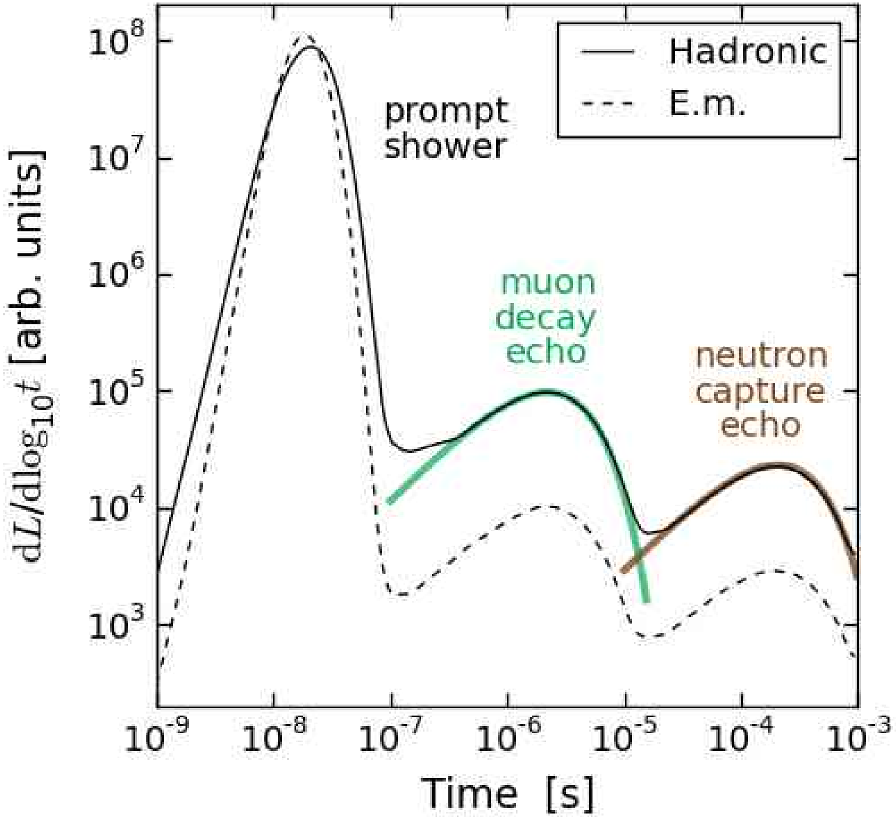
Flavor composition – a few source choices

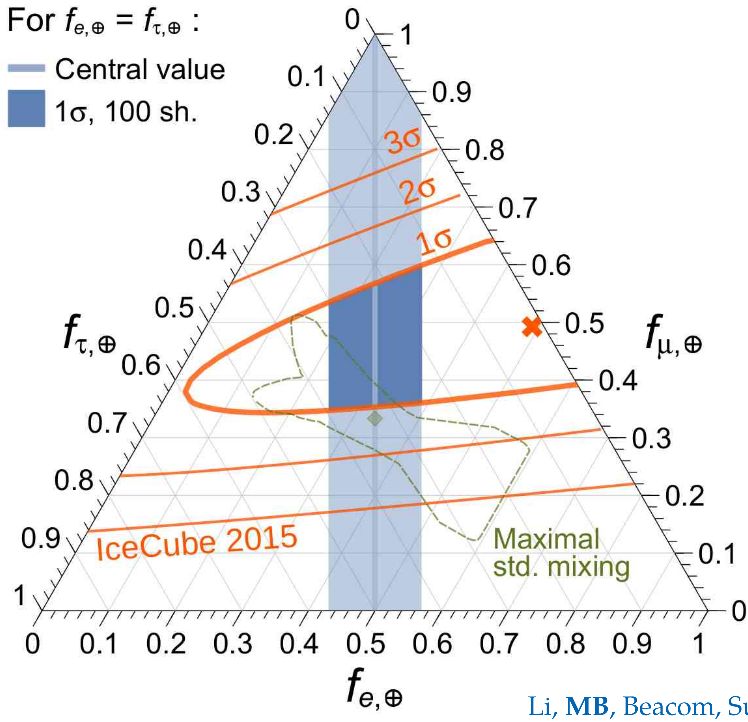


MB, Beacom, Winter *PRL* 2015

Side note: Improving flavor-tagging using *echoes*

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





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

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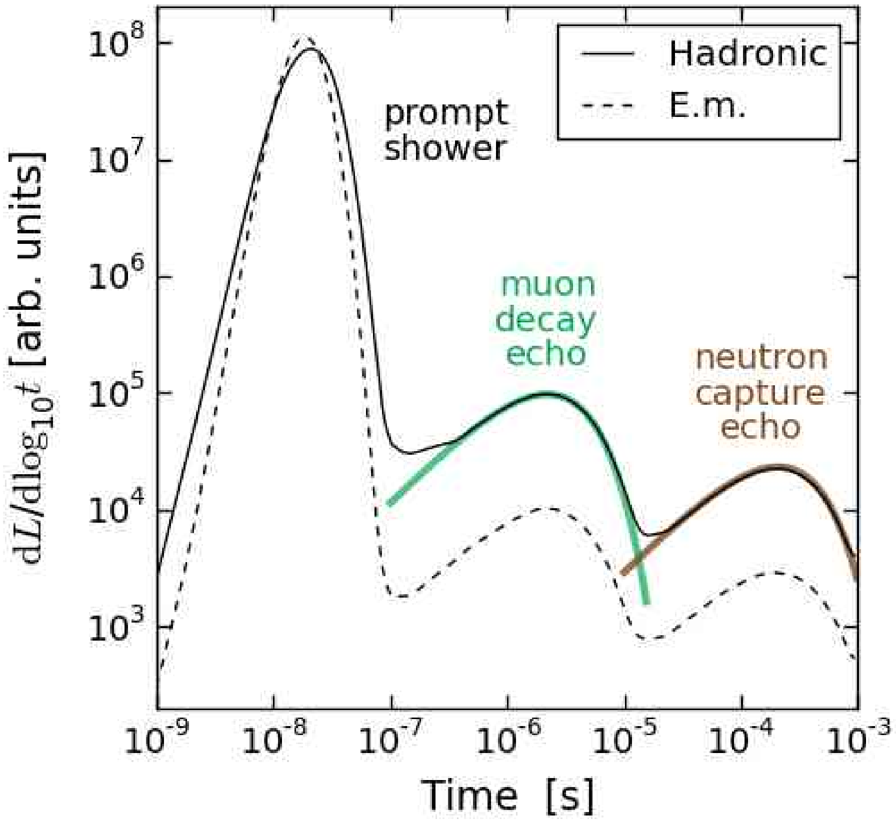
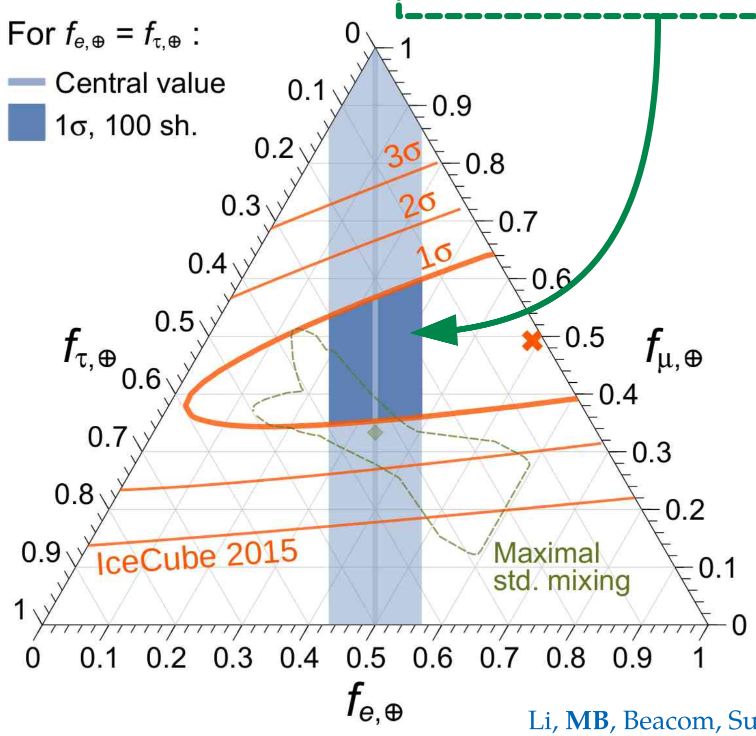


~10 × improvement over current measurement



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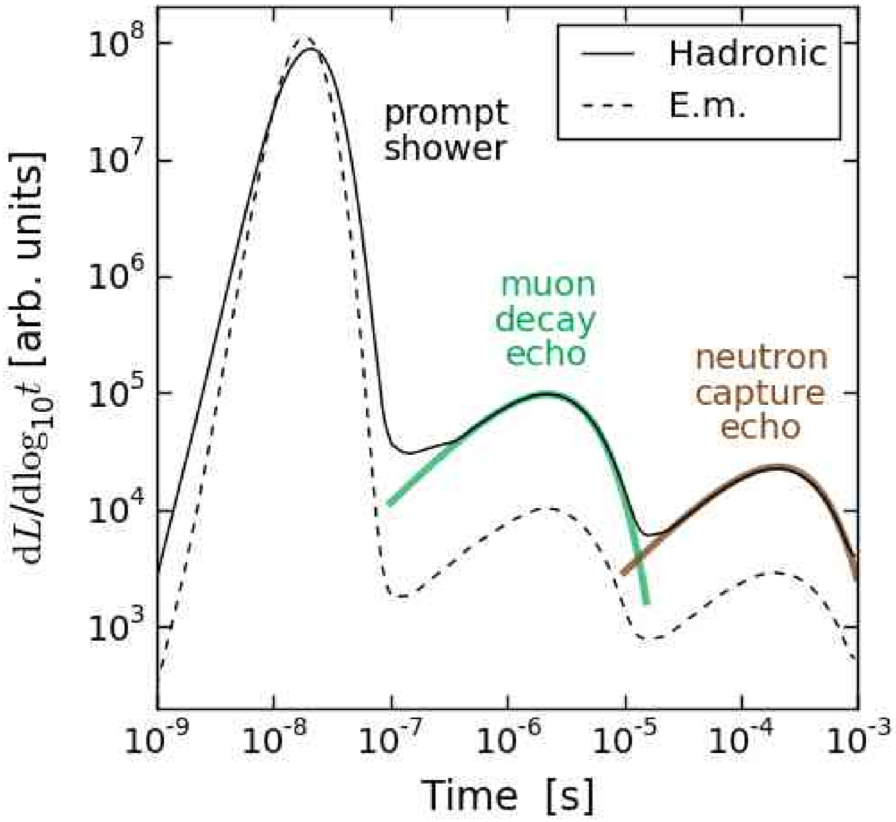
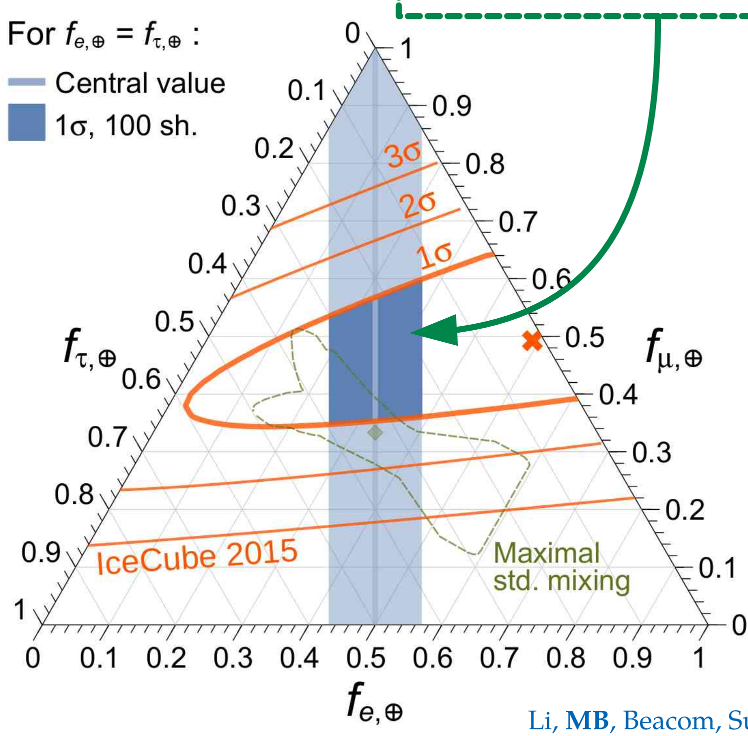
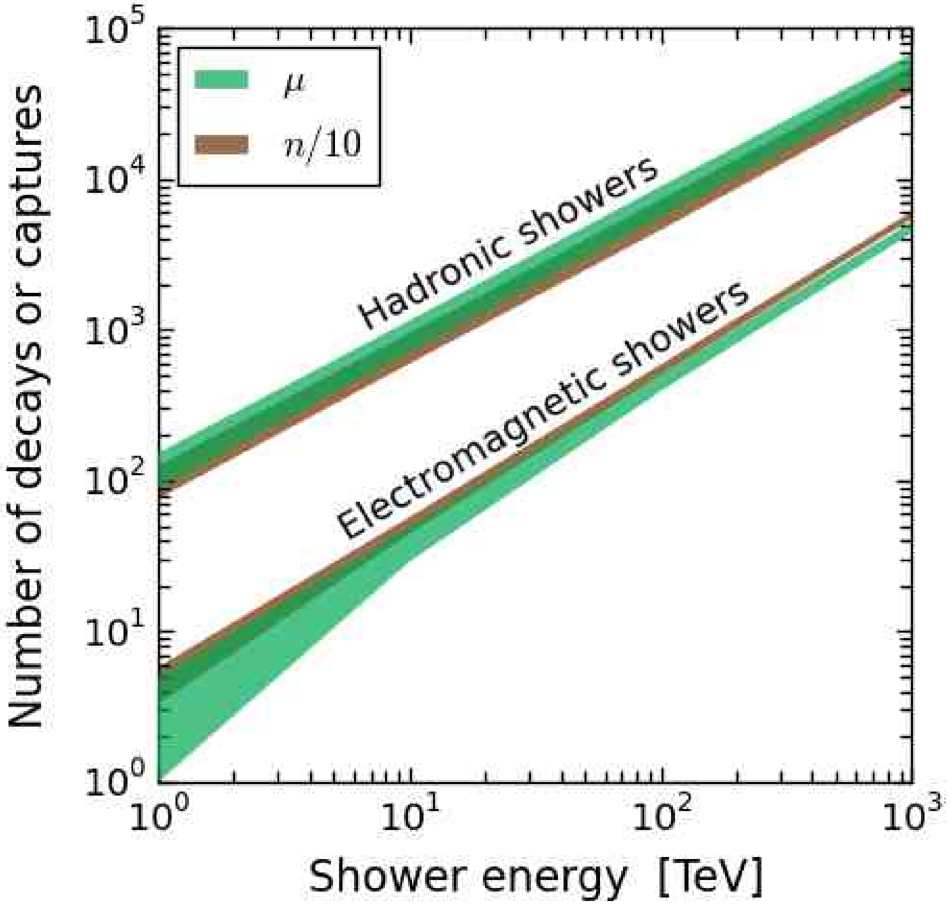


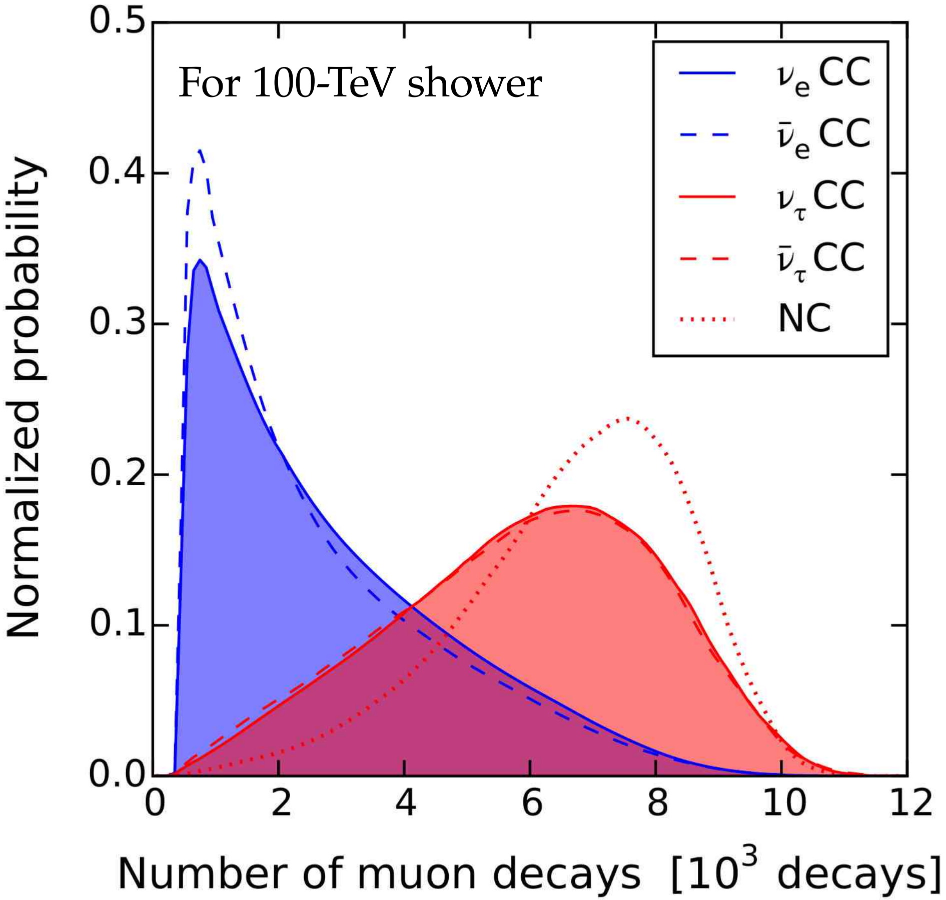


~10 × improvement over current measurement

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

Hadronic *vs.* electromagnetic showers

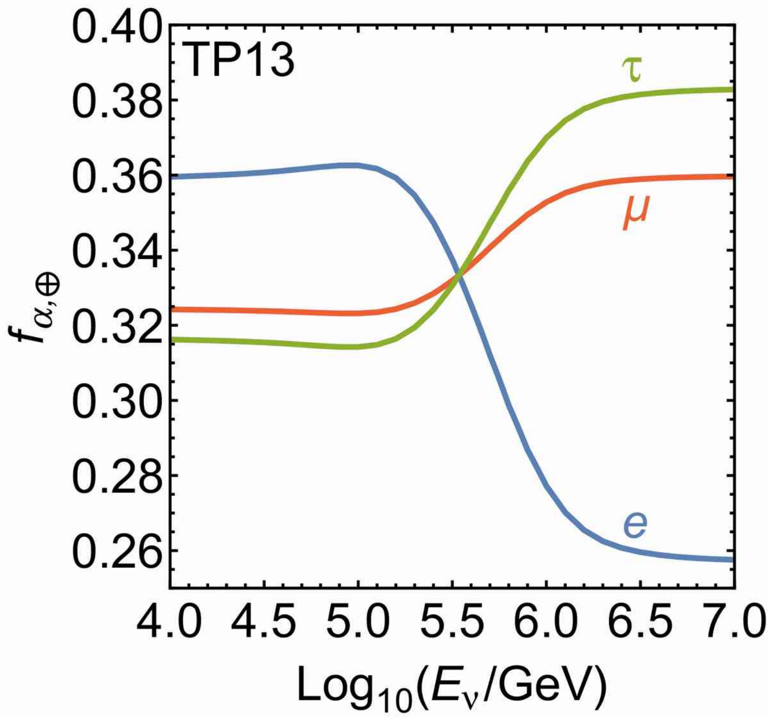


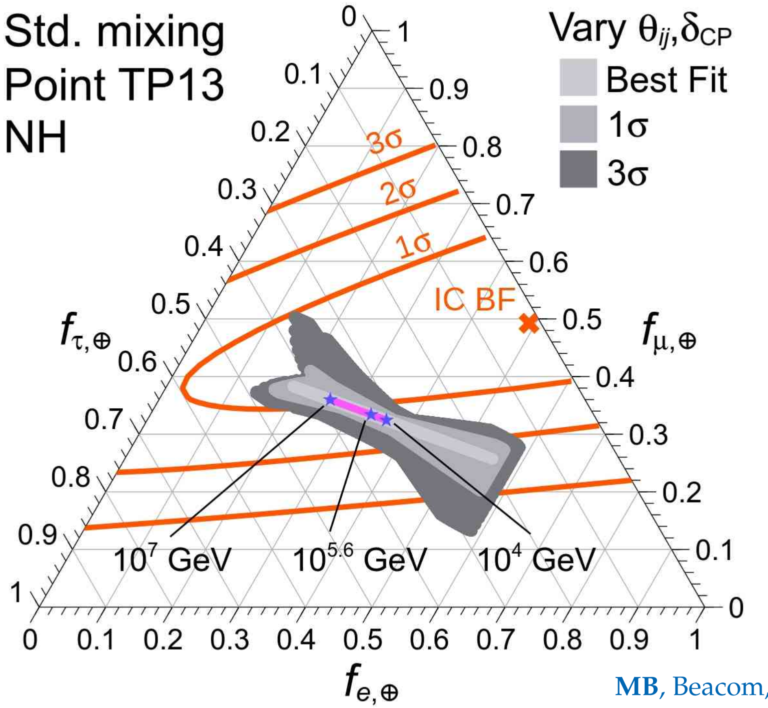


Li, **MB**, Beacom, Sub. to *PRL*

Energy dependence of the flavor composition?

Different neutrino production channels accessible at different energies –

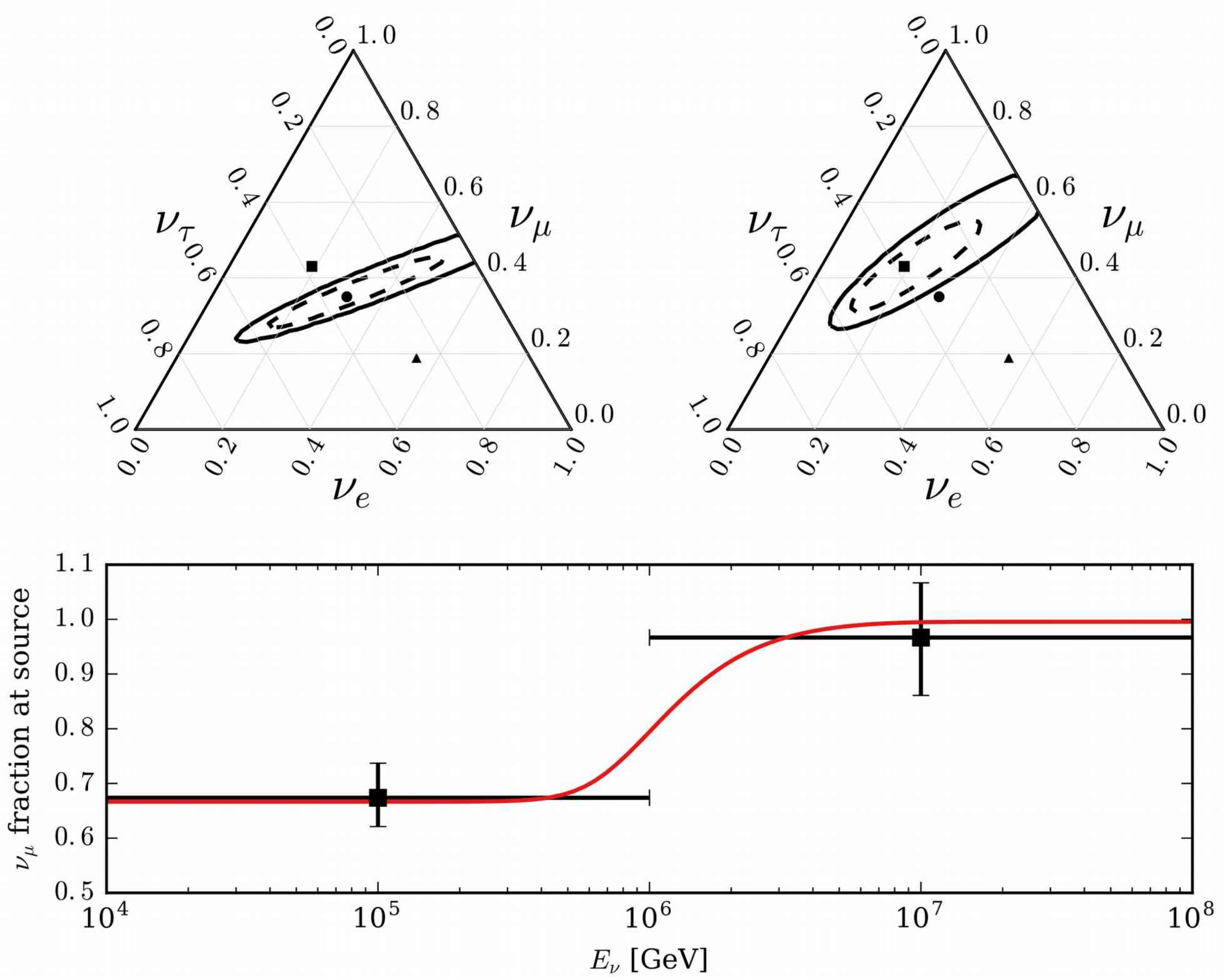




MB, Beacom, Winter *PRL* 2015

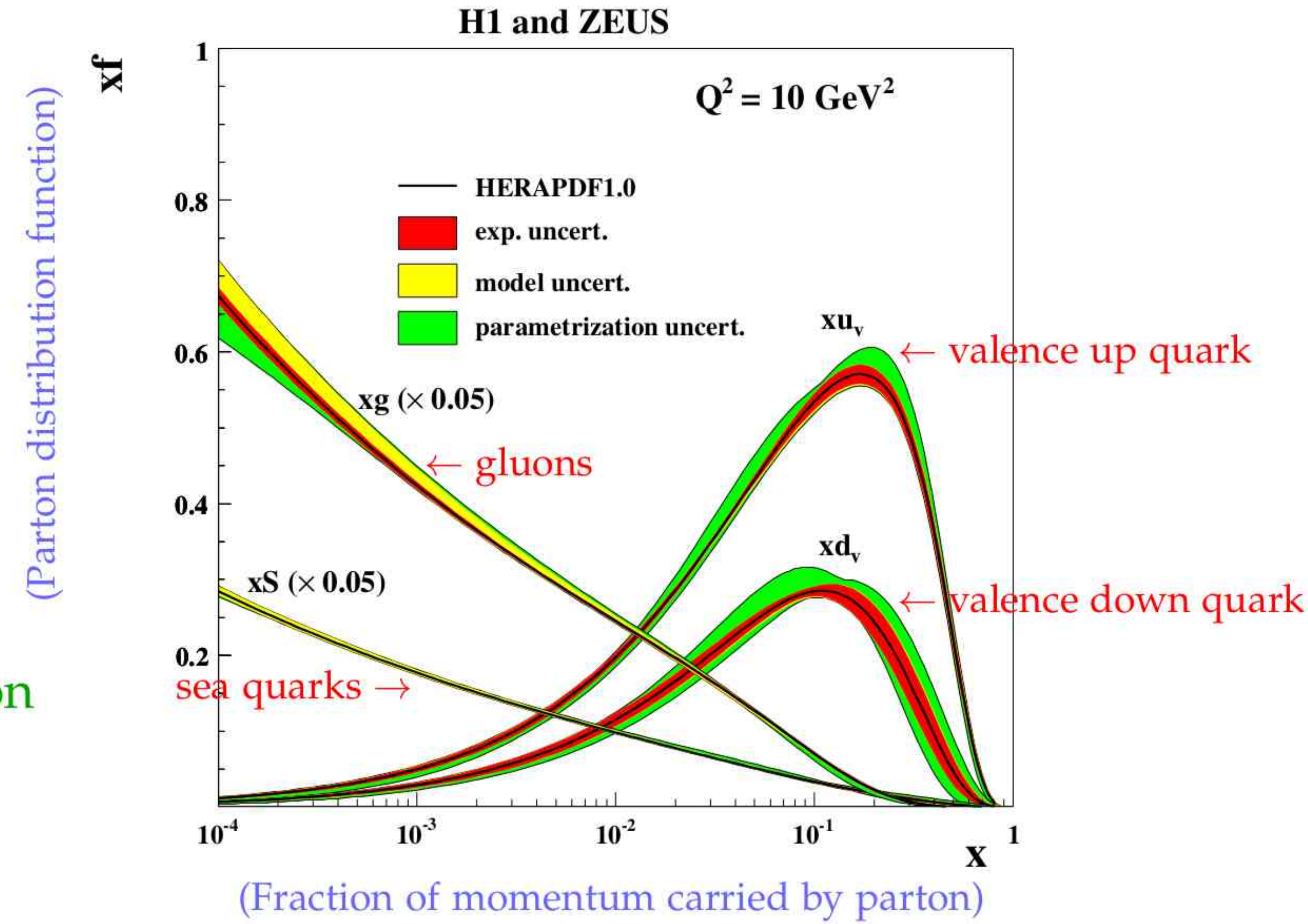
- TP13: $p\gamma$ model, target photons from electron-positron annihilation [Hümmer+, *Astropart. Phys.* 2010]
- Will be difficult to resolve [Kashti, Waxman, *PRL* 2005; Lipari, Lusignoli, Meloni, *PRD* 2007]

… Observable in IceCube-Gen2?



Borrowed from M. Kowalski

Peeking inside a proton



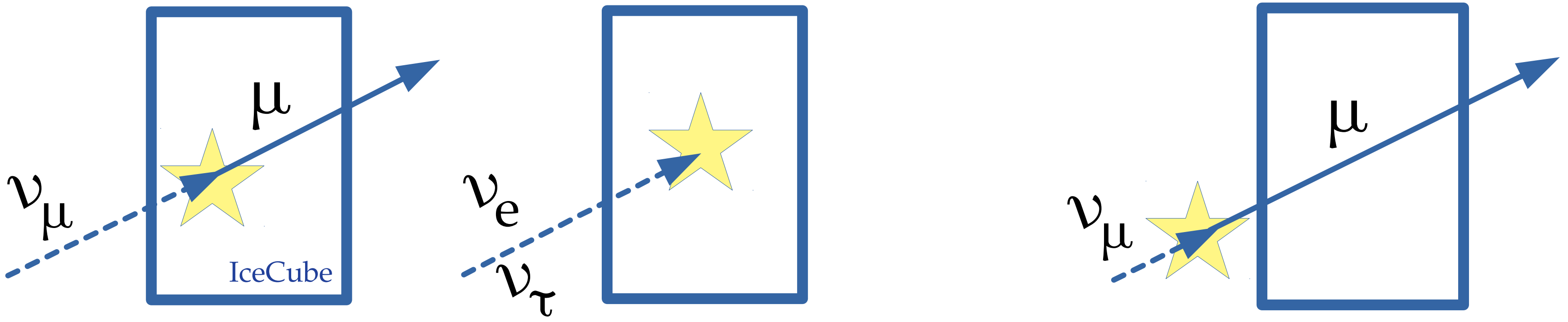
← Extrapolation

A. Cooper-Sarkar 2012

Contained *vs.* uncontained νN interactions

Contained events

Uncontained events



Starting track

Shower

Through-going muon

Pro: Clean determination of E_ν

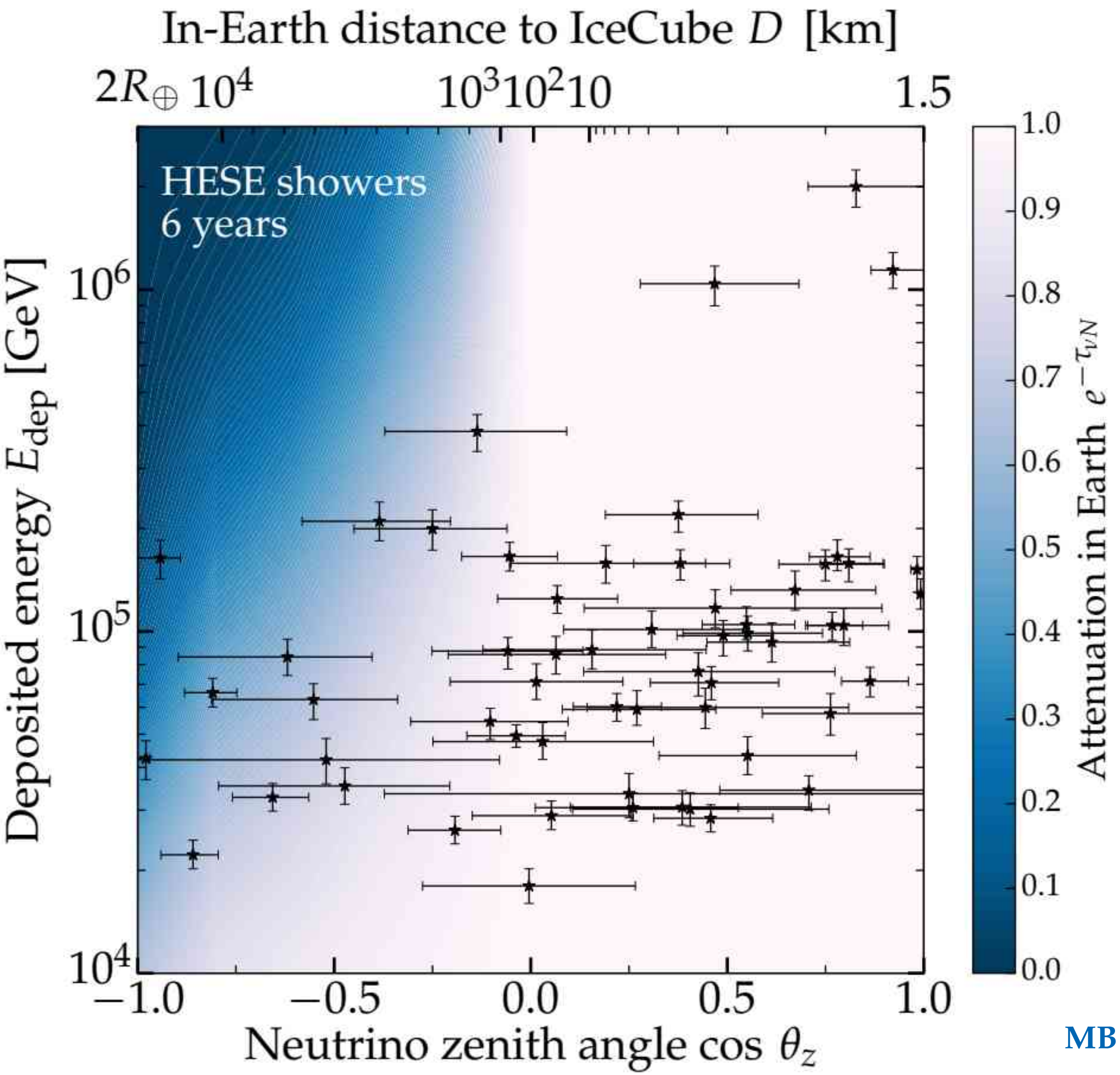
Con: Few events (<100)

Ref.: MB & A. Connolly, 1711.11043

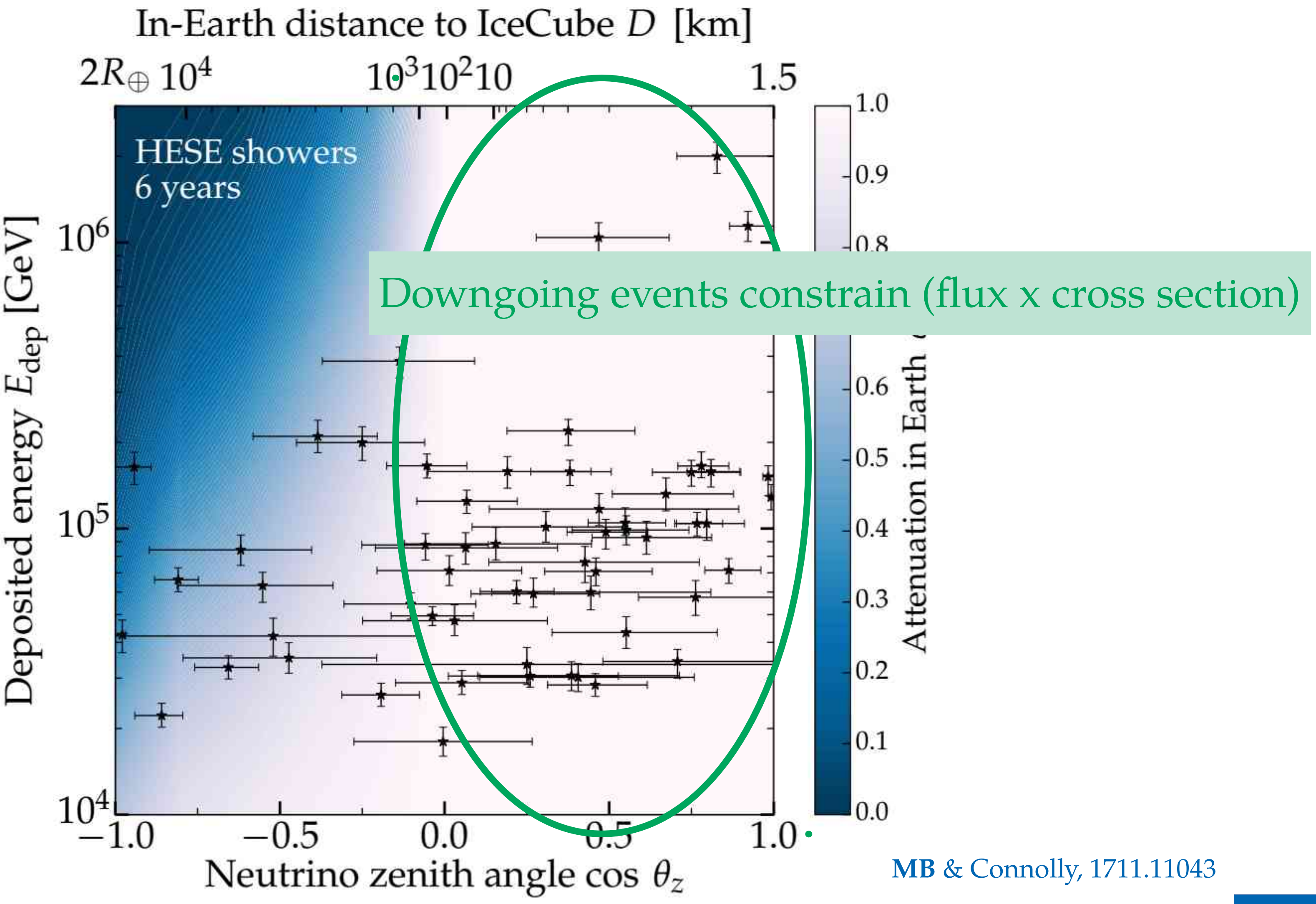
Pro: Lots of events (~10k used)

Con: Uncertain estimates of E_ν

Ref.: IceCube, *Nature* 2017, 1711.08119



MB & Connolly, 1711.11043



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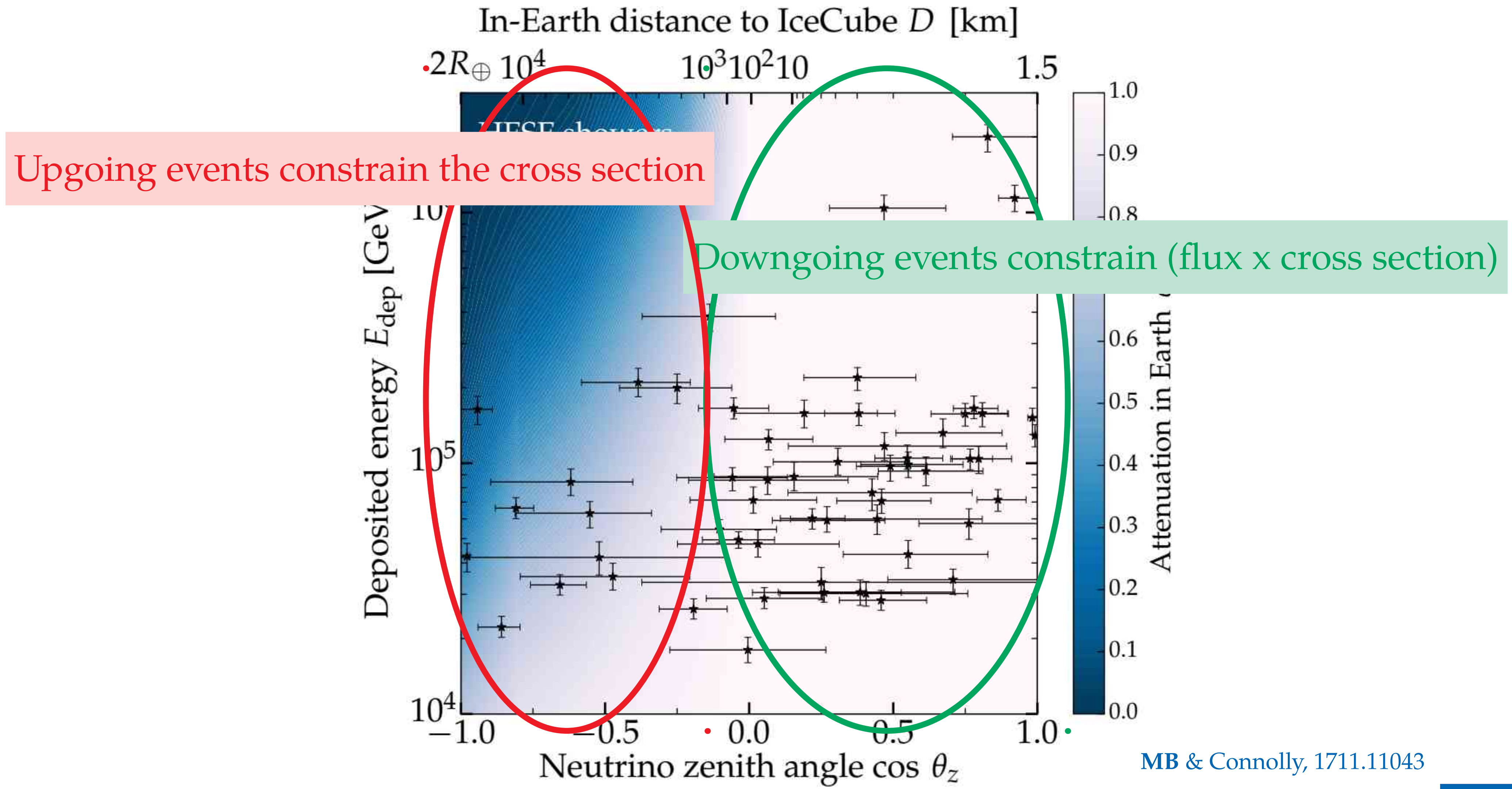

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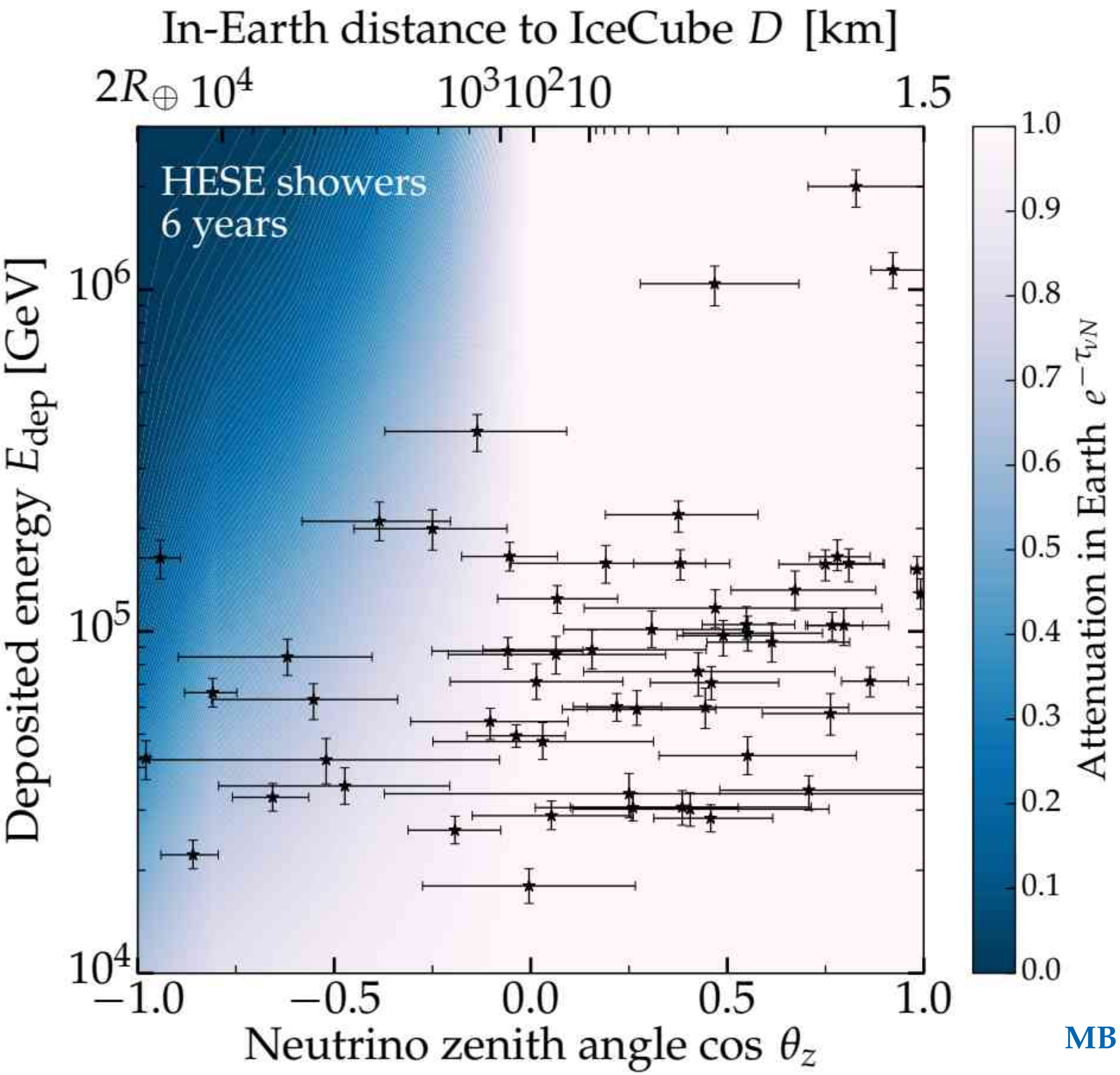
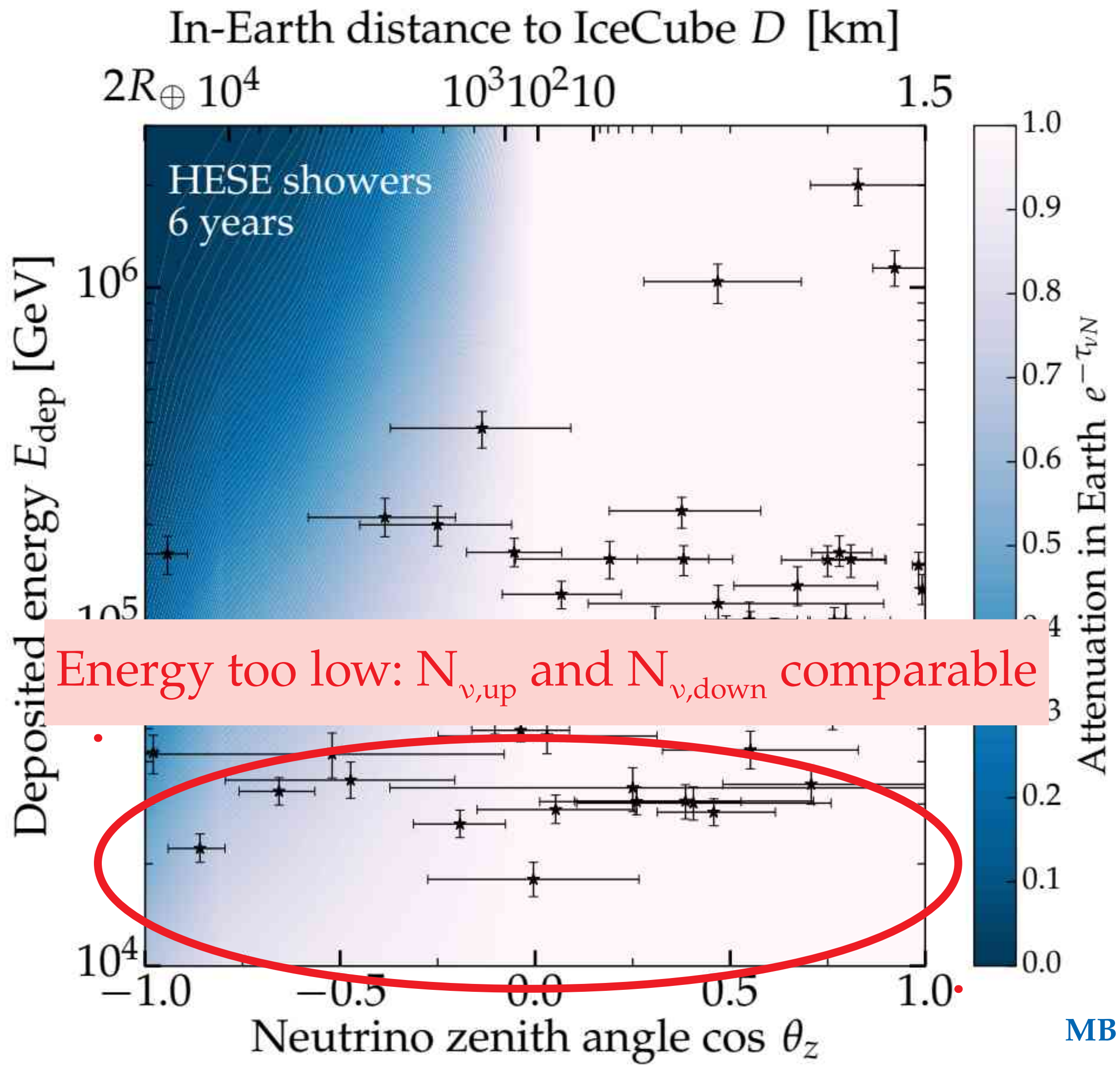
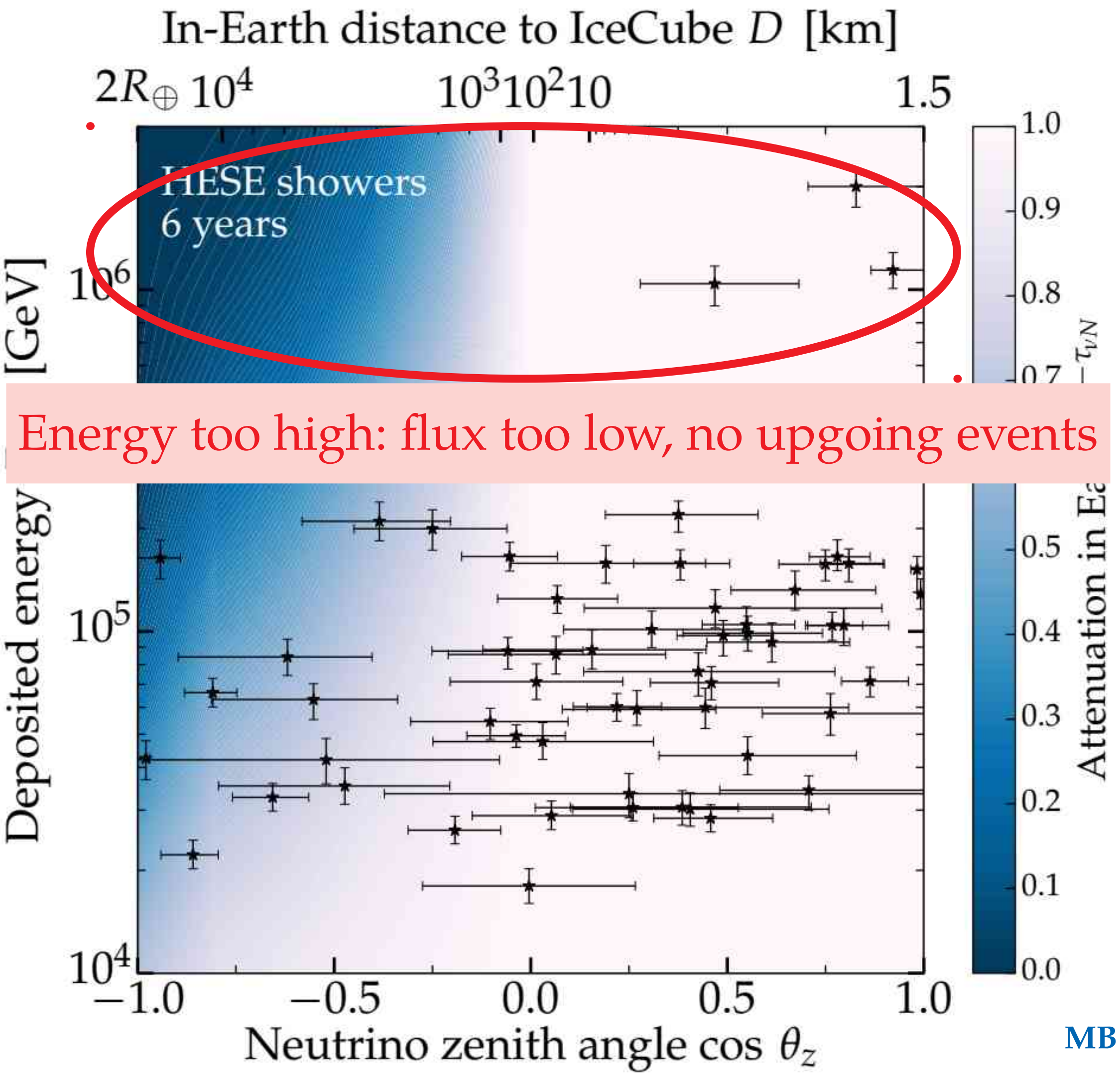


MB & Connolly, 1711.11043

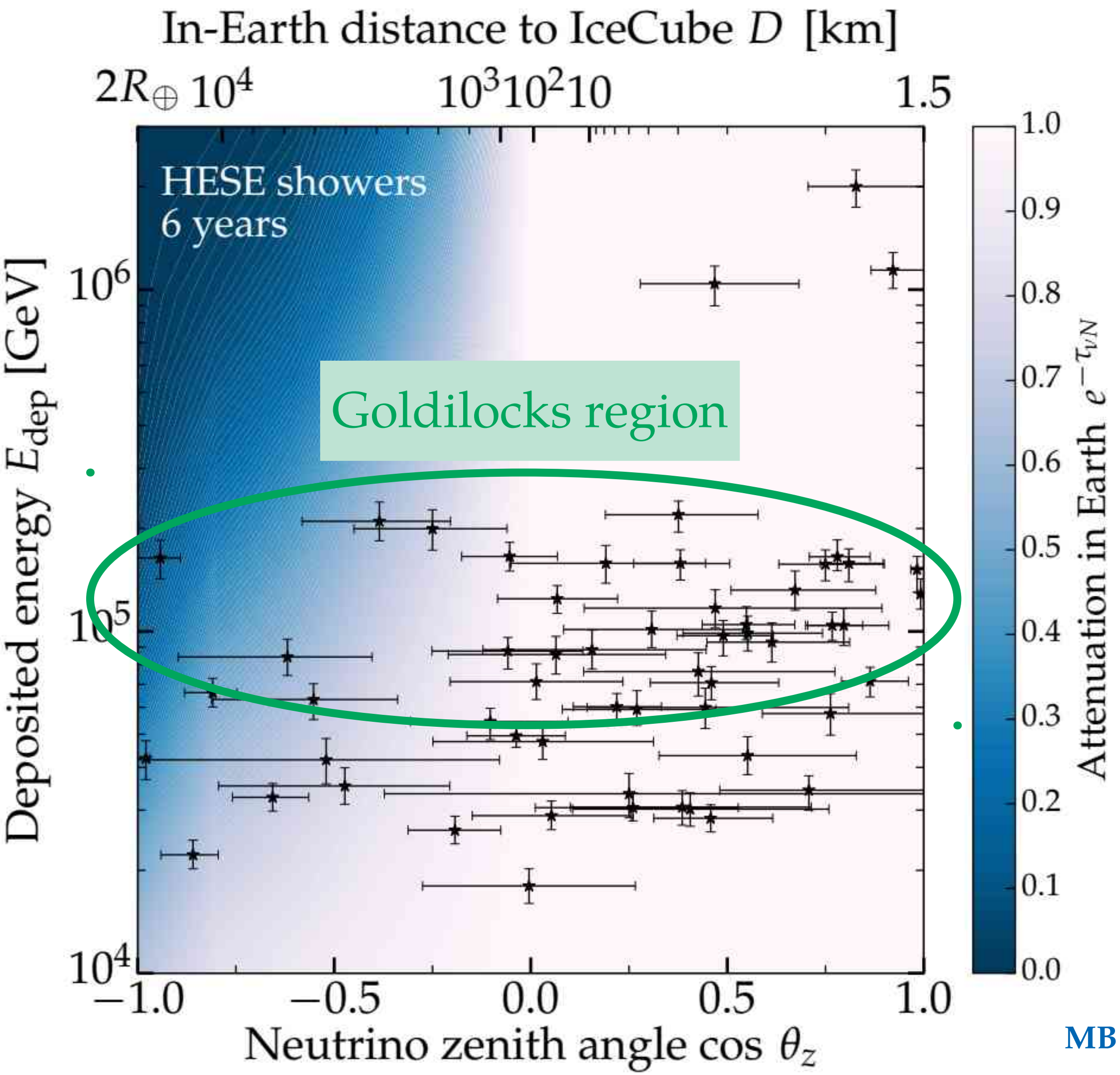


Energy too low: $N_{\nu,up}$ and $N_{\nu,down}$ comparable

MB & Connolly, 1711.11043



MB & Connolly, 1711.11043

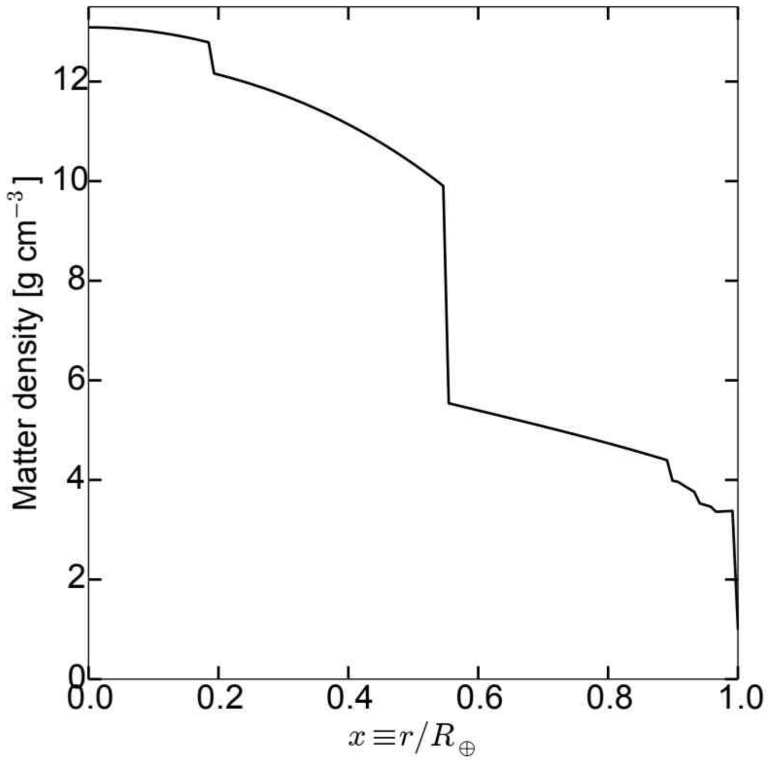


MB & Connolly, 1711.11043

A feel for the in-Earth attenuation

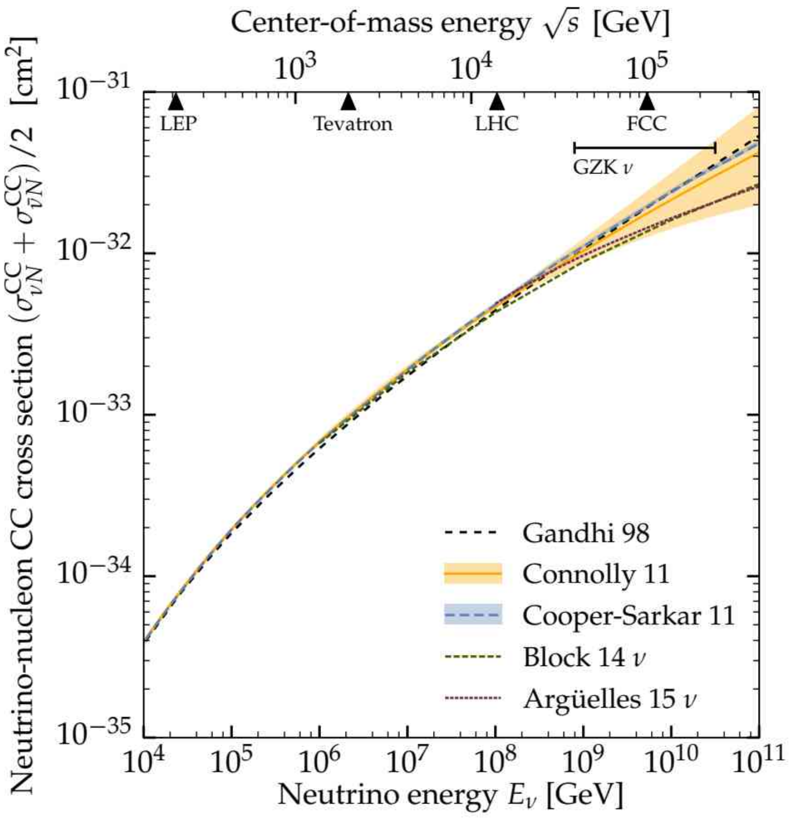
Earth matter density

(Preliminary Reference Earth Model)



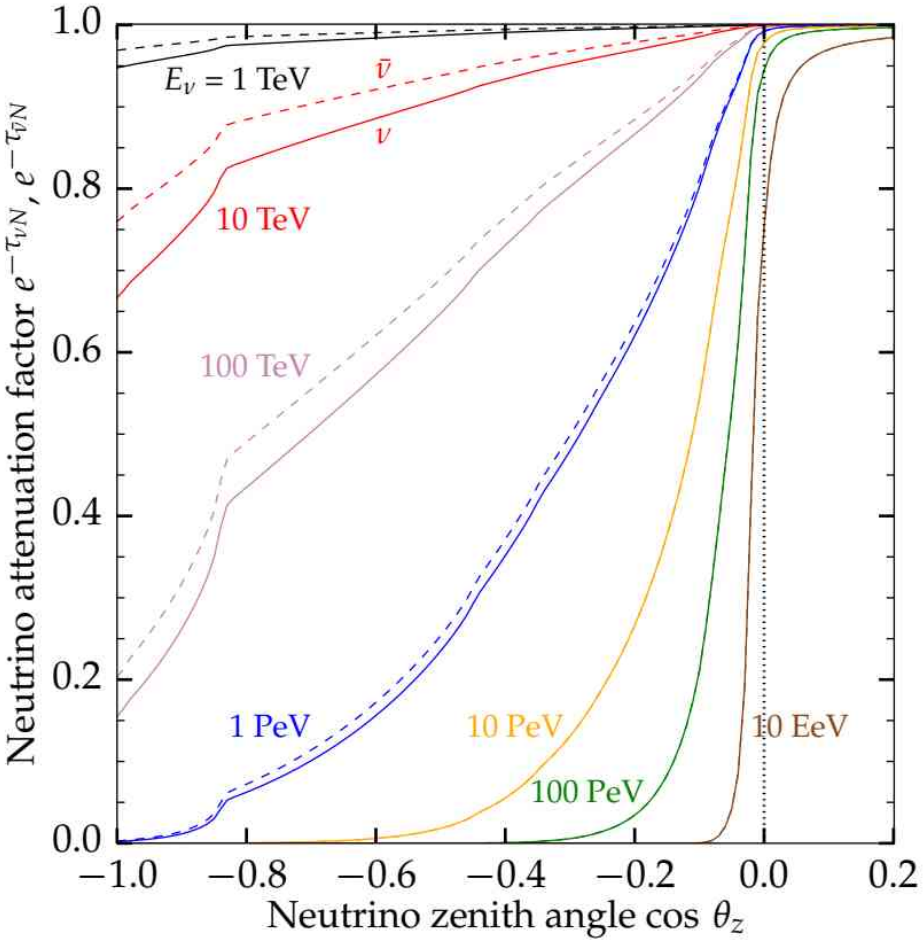
+

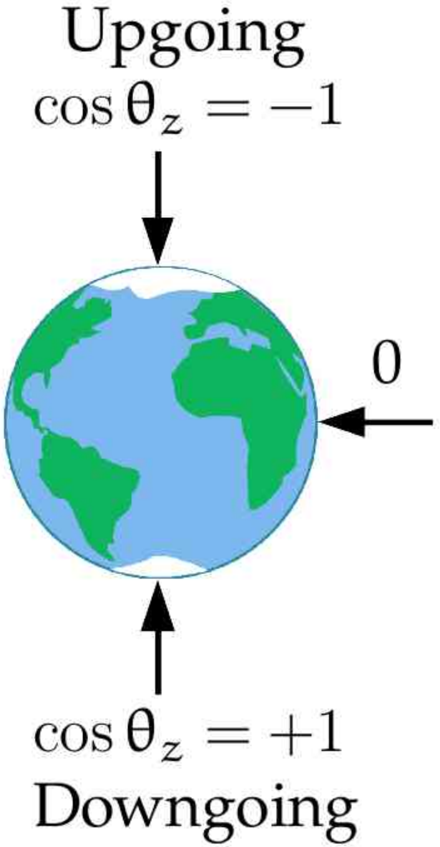
Neutrino-nucleon cross section



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 $\Phi_\nu \cdot \sigma_{\nu N}$

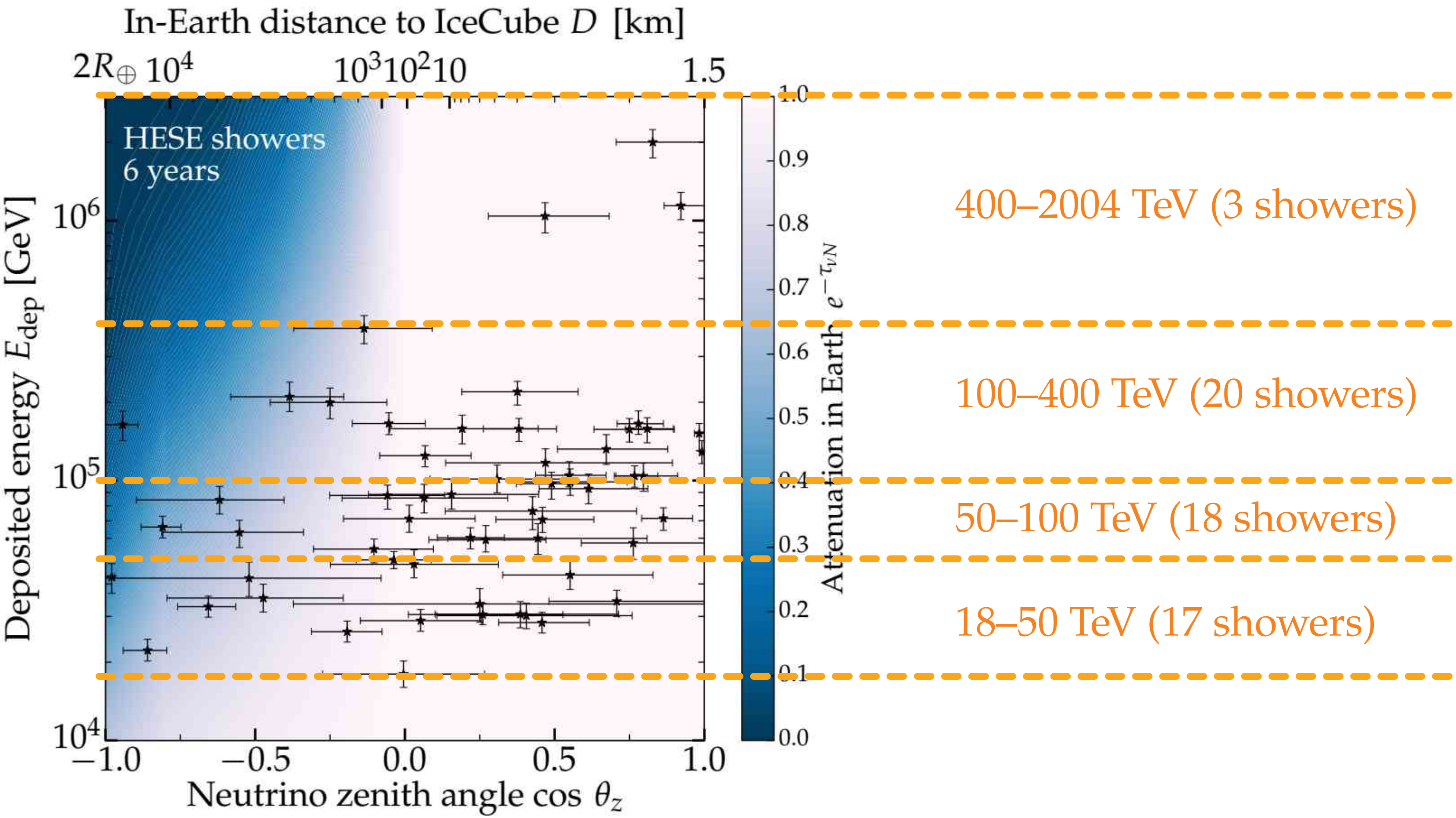
Upgoing (lots of matter)

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

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

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

Bin-by-bin analysis



The fine print

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

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)

- 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)
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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:

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

MB & A. Connolly, 1711.11043

Detector resolution

Number of contained showers:

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

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

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

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
  ↦ Solvable with more data from IceCube, IceCube-Gen2, KM3NeT
- Large errors in arrival direction (~10°) 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

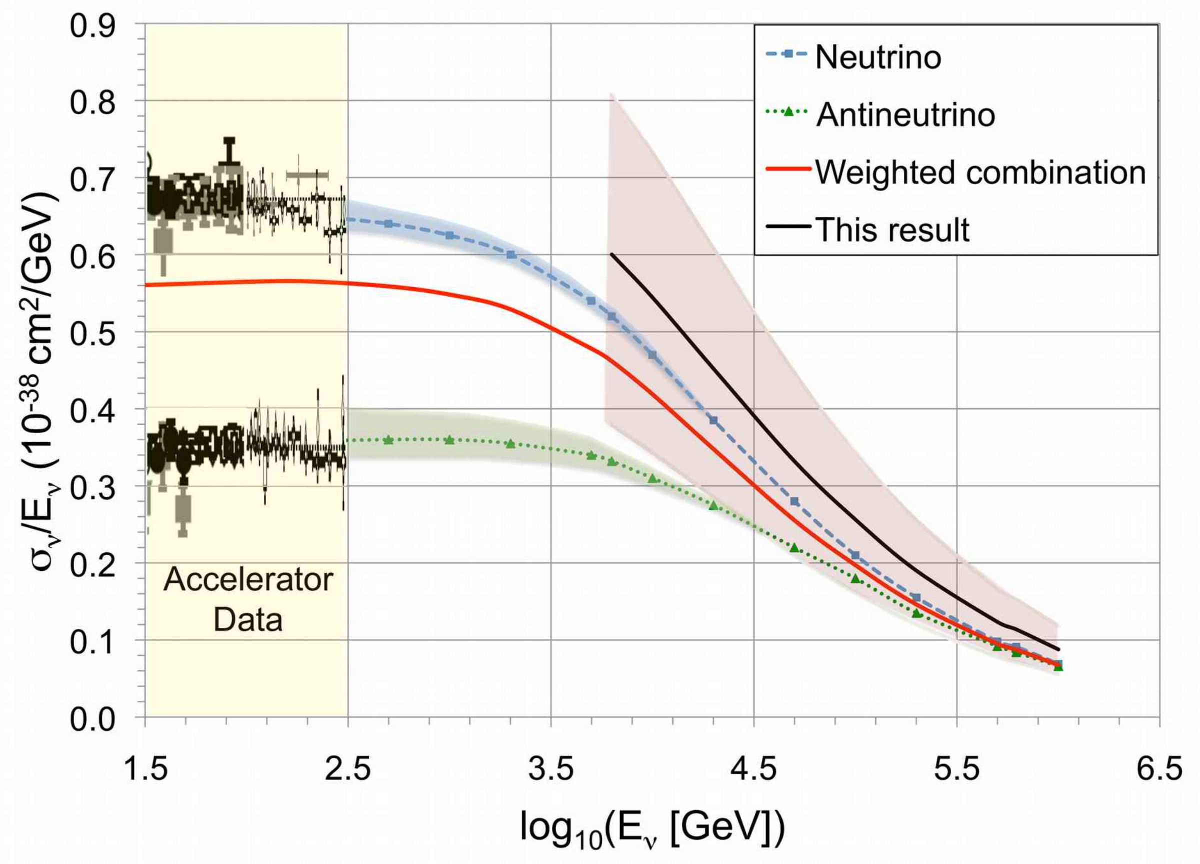
TABLE I. Neutrino-nucleon charged-current inclusive cross sections, averaged between neutrinos ($\sigma_{\nu N}^{\rm CC}$) and anti-neutrinos ($\sigma_{\bar{\nu} N}^{\rm CC}$), extracted from 6 years of IceCube HESE showers. To obtain these results, we fixed $\sigma_{\bar{\nu} N}^{\rm CC} = \langle \sigma_{\bar{\nu} N}^{\rm CC} / \sigma_{\nu N}^{\rm CC} \rangle \cdot \sigma_{\nu N}^{\rm CC}$ — 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

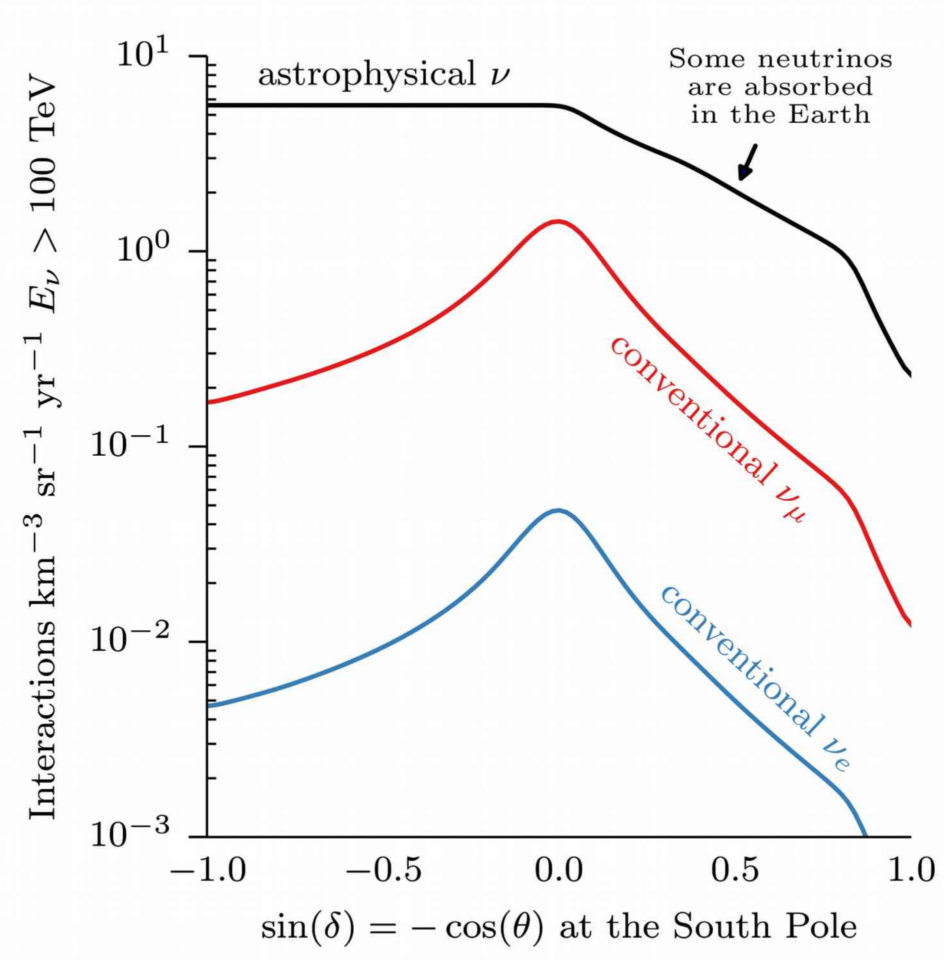
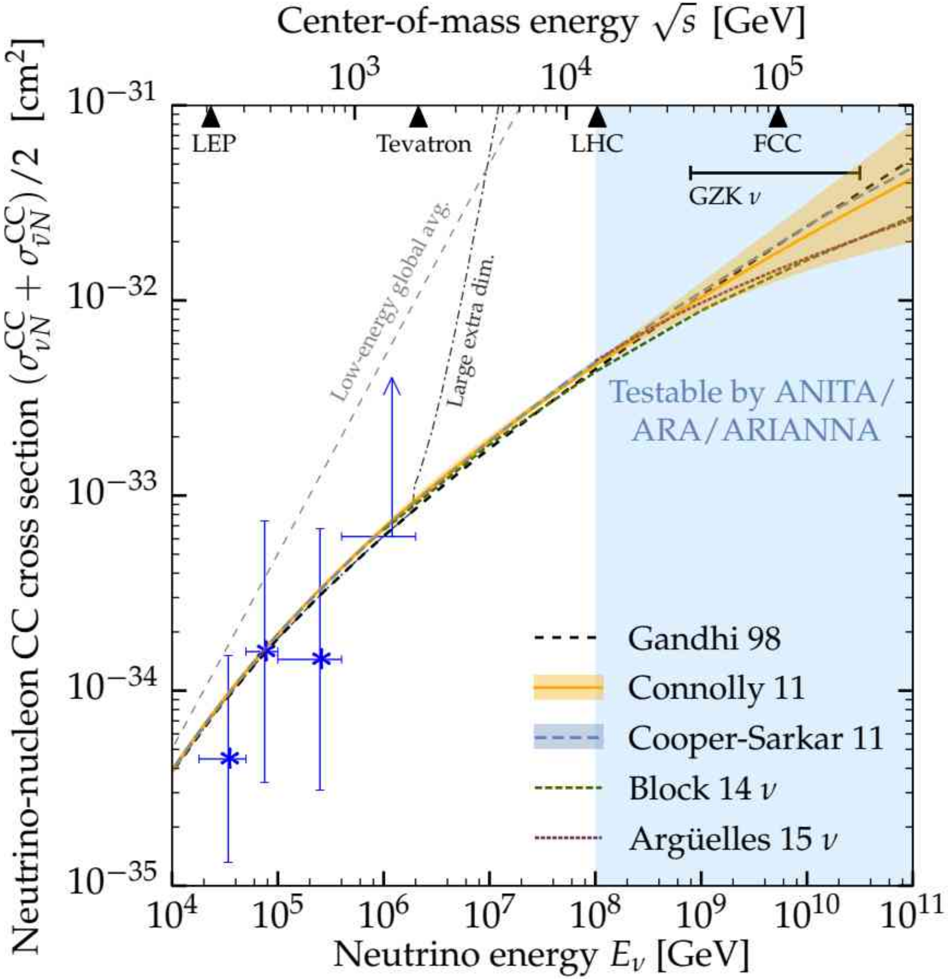


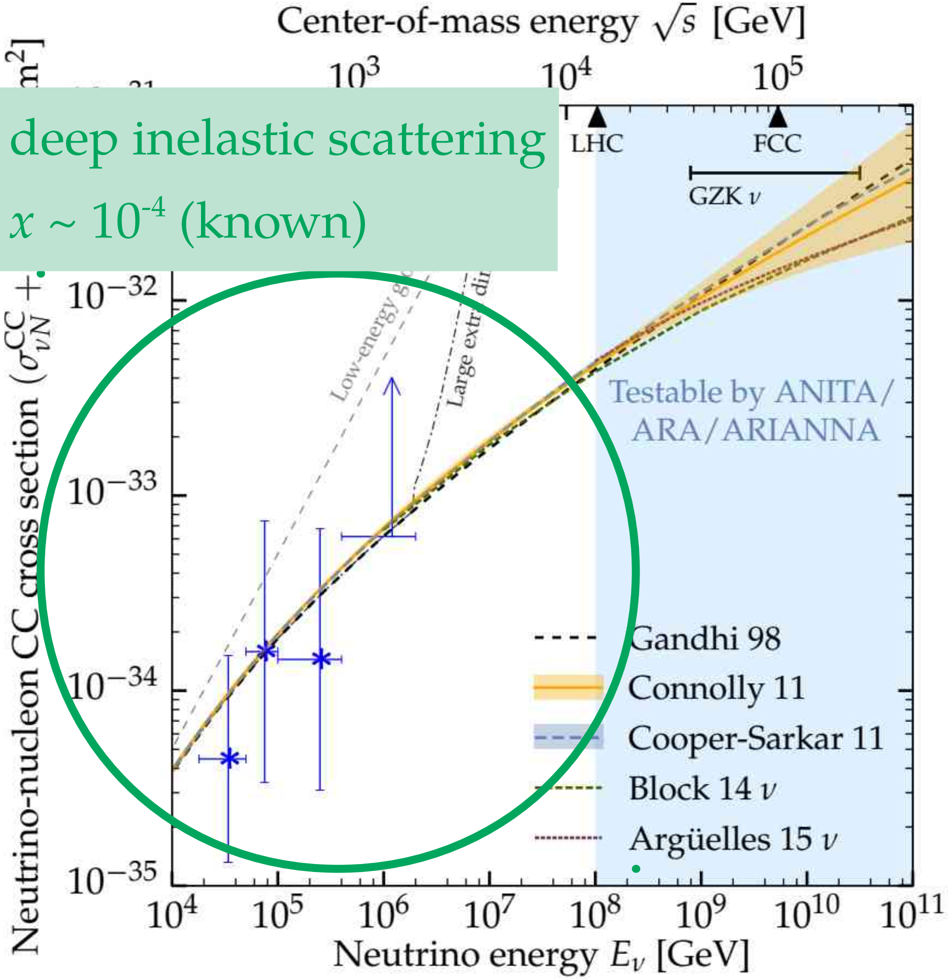
Figure by
Jakob Van Santen
ICRC 2017

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

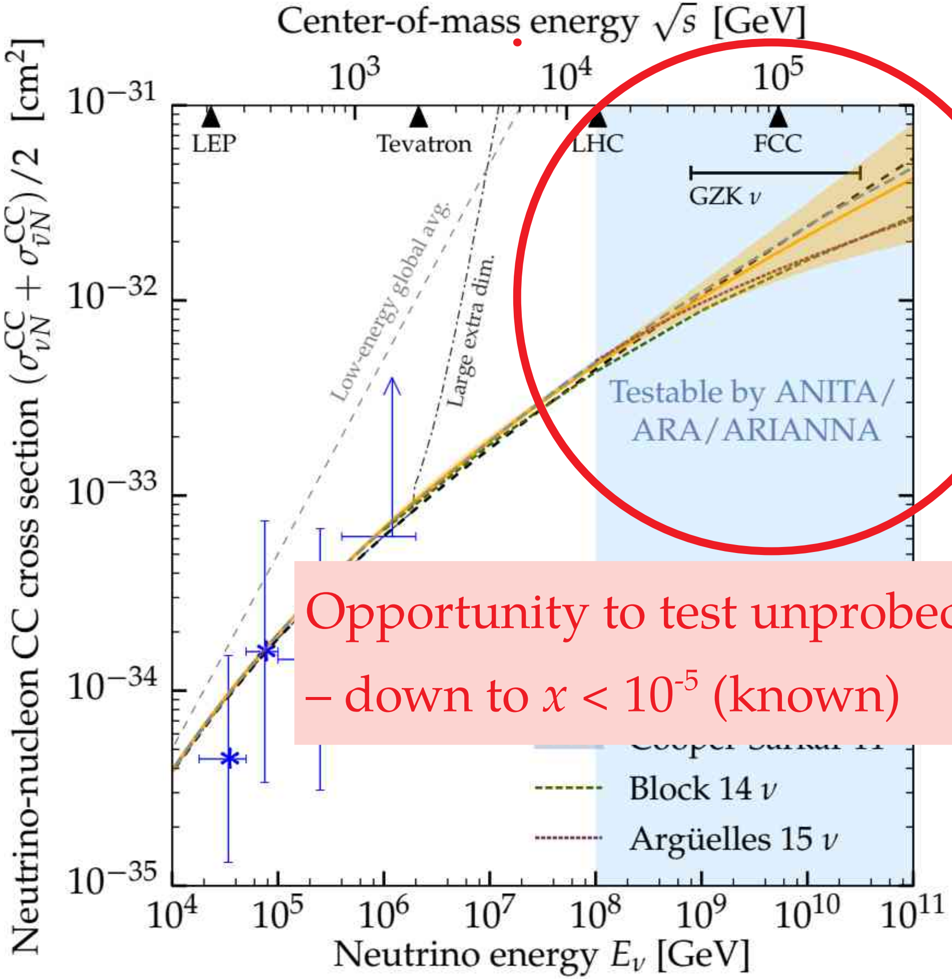


IceCube *now* vs. ANITA/ARA/ARIANNA *in the future*

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)

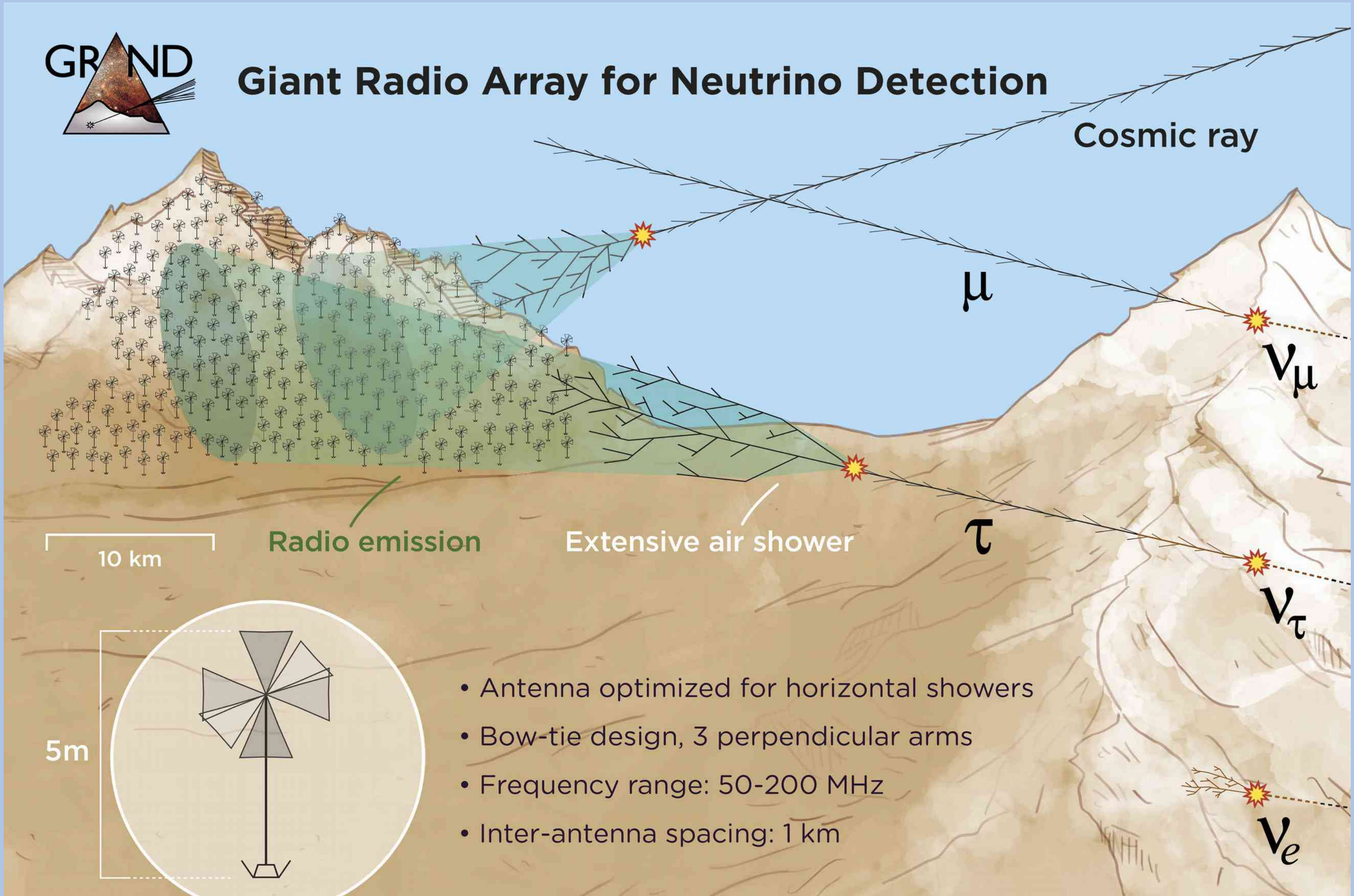
The new ν physics matrix

Where it happens

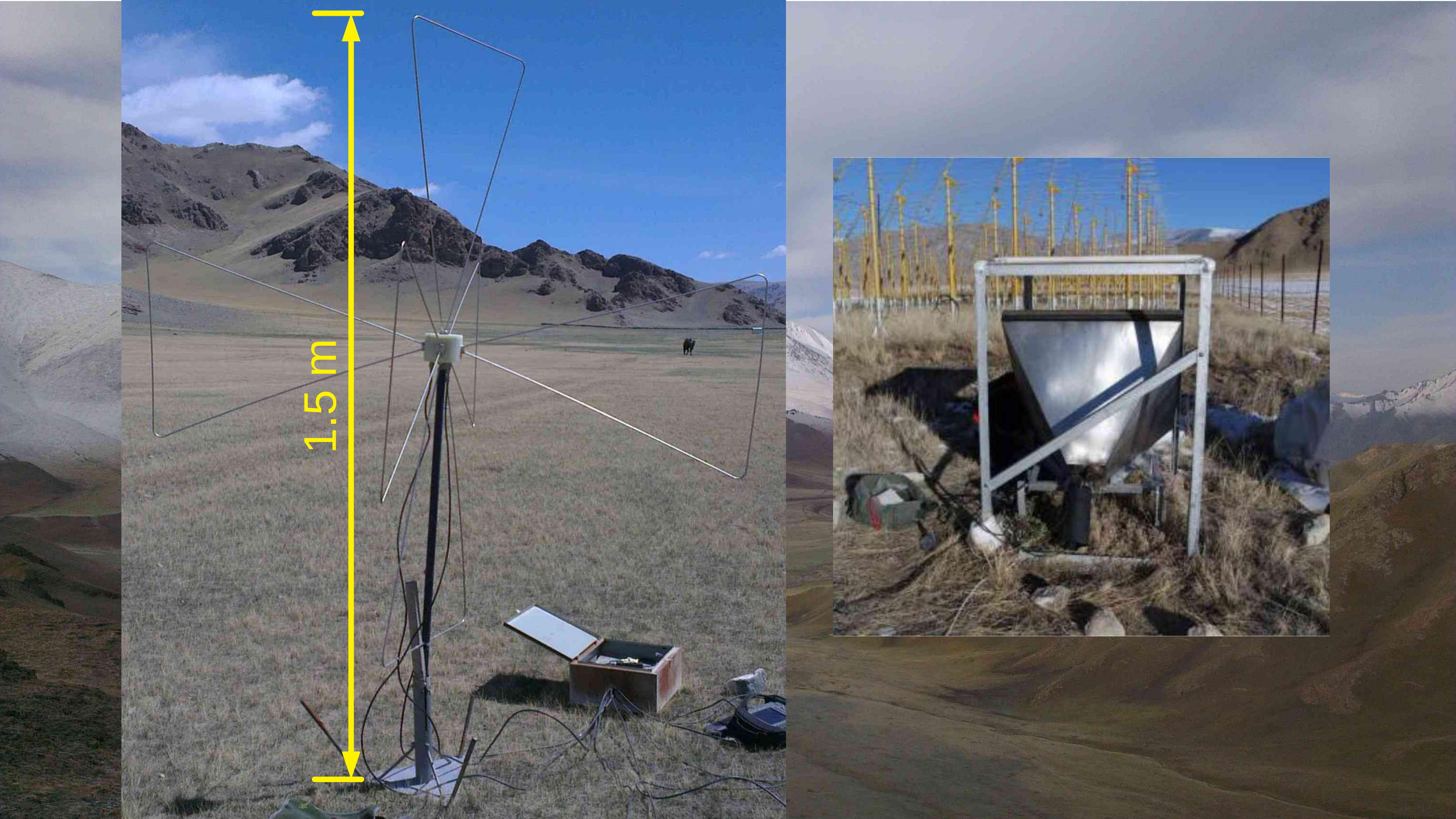
What it changes

	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	

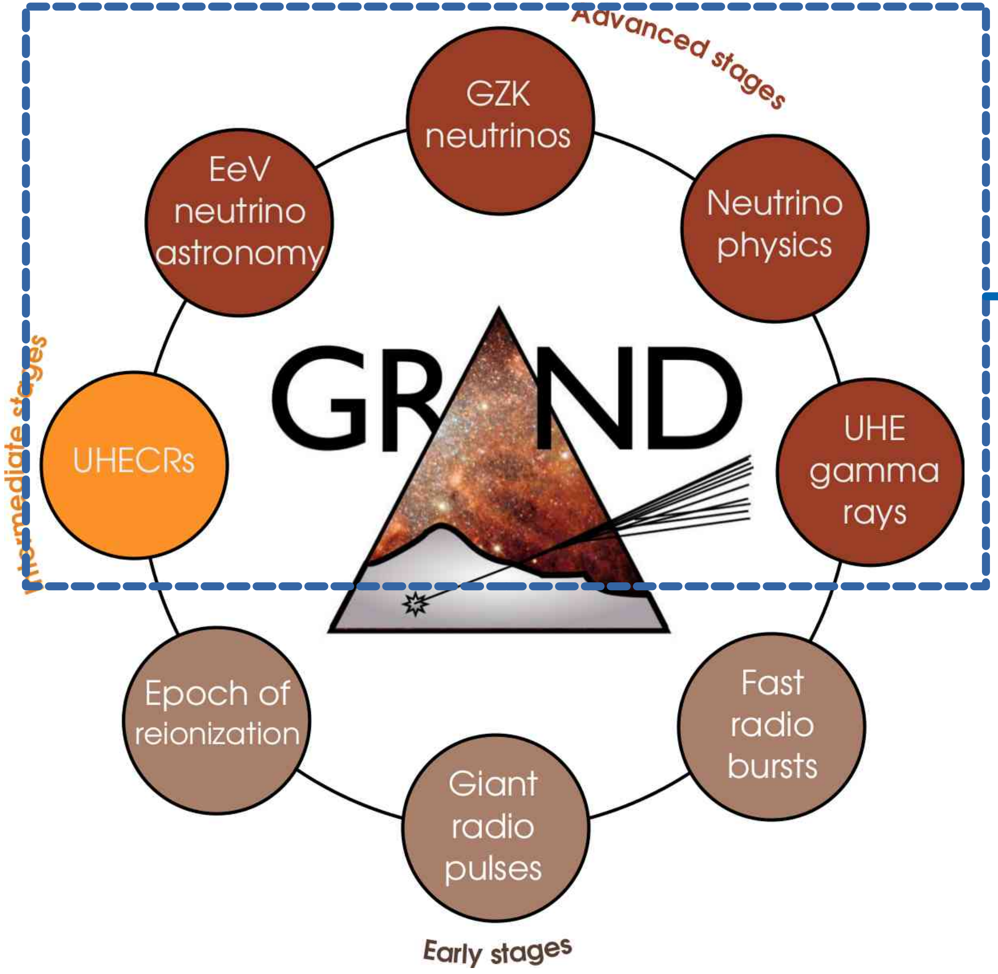
Argüelles, MB, Conrad, Kheirandish, Palomares-Ruiz, Salvadó, Vincent, *In prep.*



More information about GRAND: 1708.05128

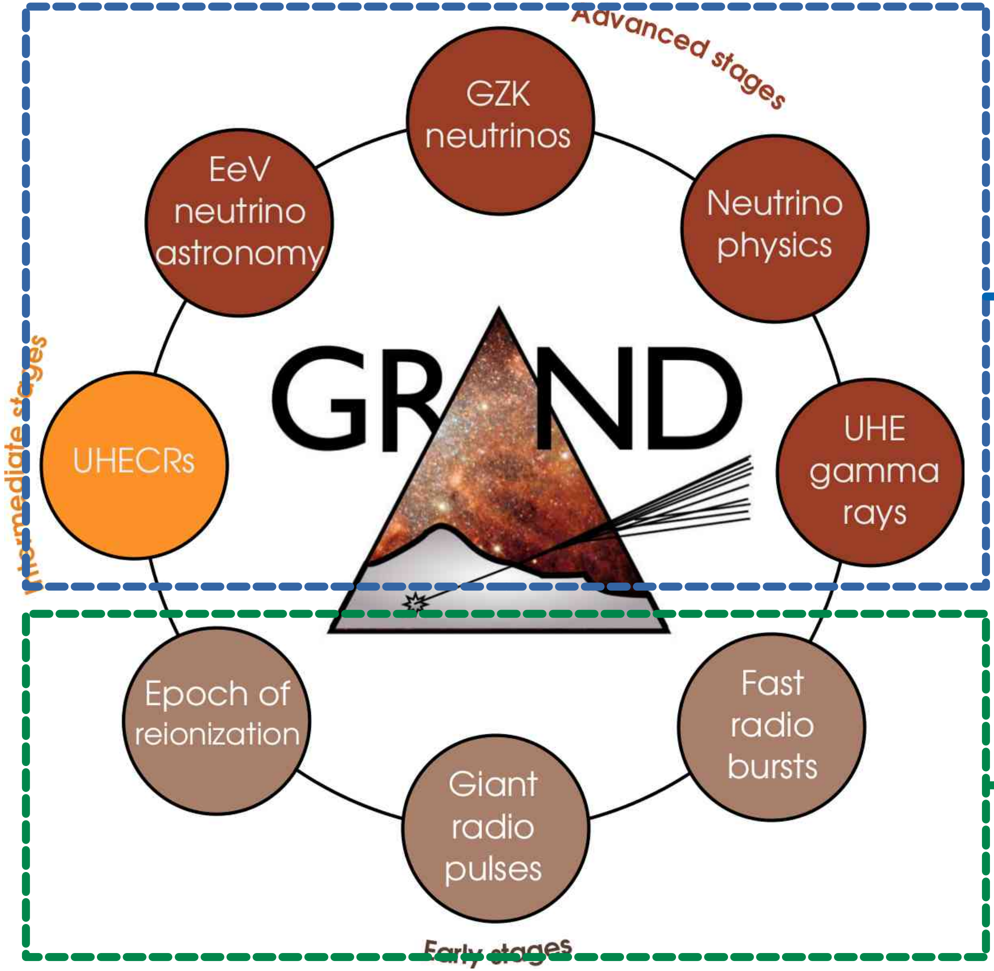

1.5 m


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



Main goal:

Finding the sources of UHECRs above 10^9 GeV

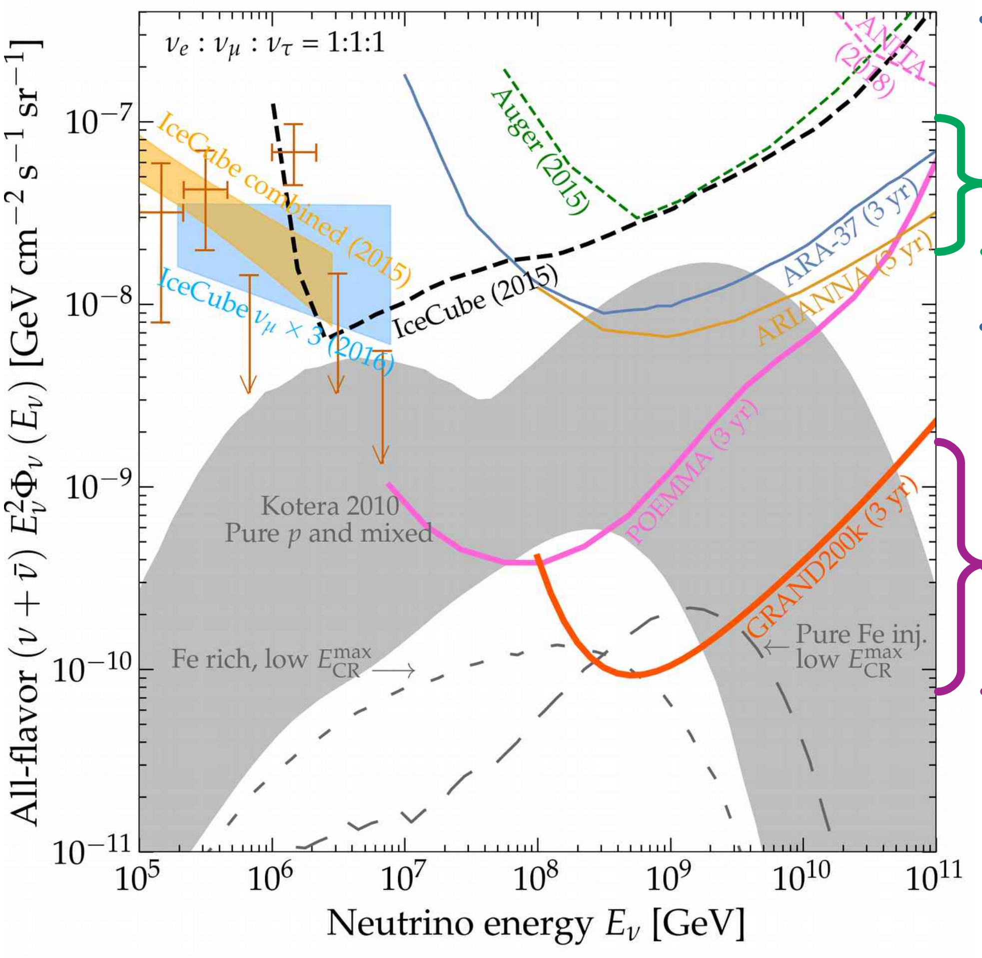


Main goal:
Finding the sources of UHECRs above 10^9 GeV

Secondary goal:
Radioastronomy and cosmology

UHE Neutrinos – Where Do We Go?

Flux predictions (Kotera 2010)

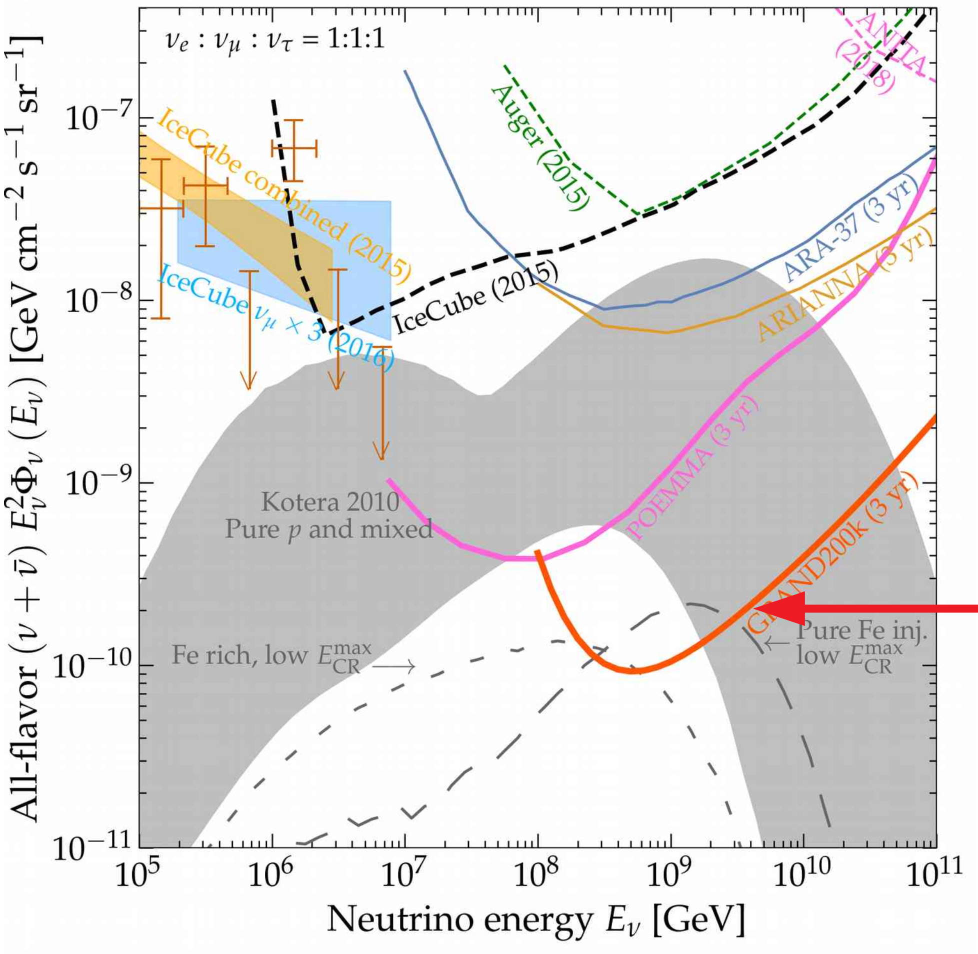


Existing upper limits

Future reach of existing in-ice radio detectors

Next-gen air-radio and space detectors

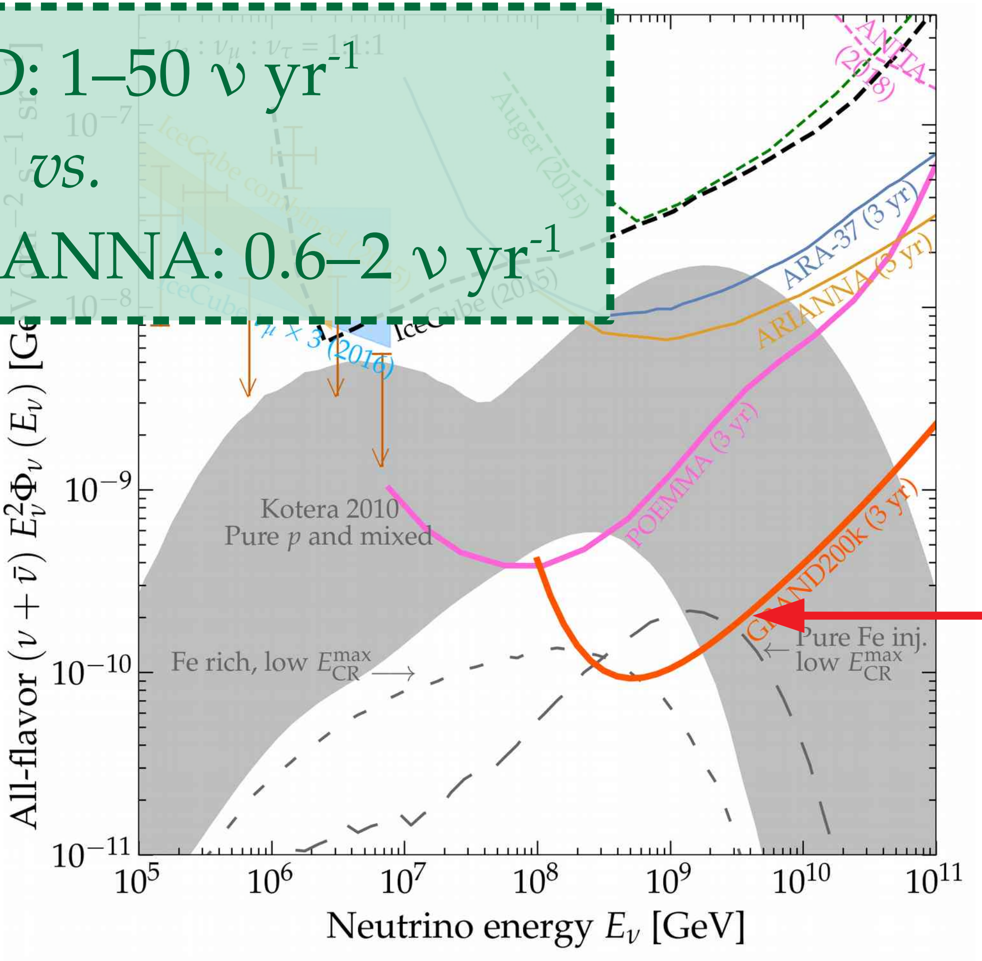
UHE Neutrinos – Where Do We Go?



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}



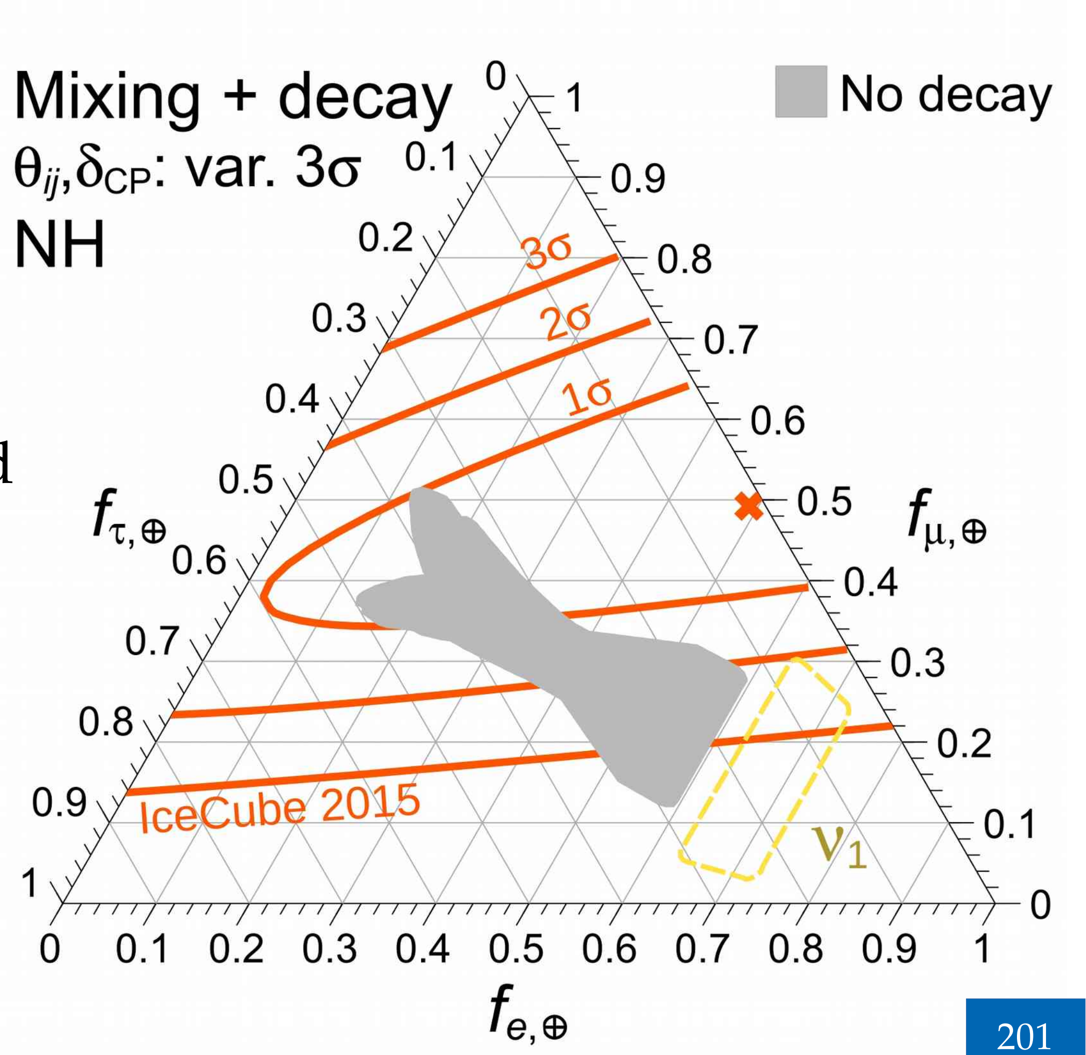
GRAND will probe *very* low fluxes at ~10^9 GeV

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

Measuring the neutrino lifetime

Fraction of ν_2, ν_3 remaining at Earth

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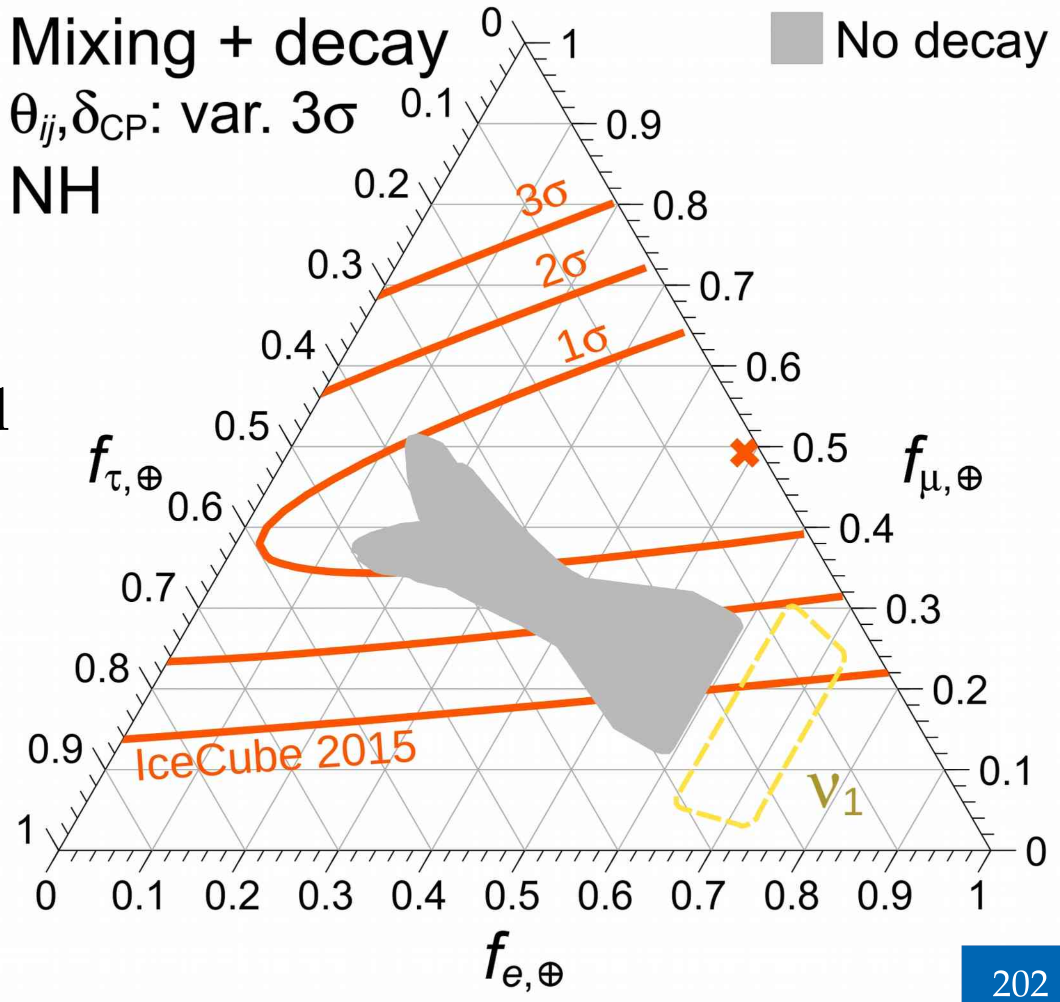

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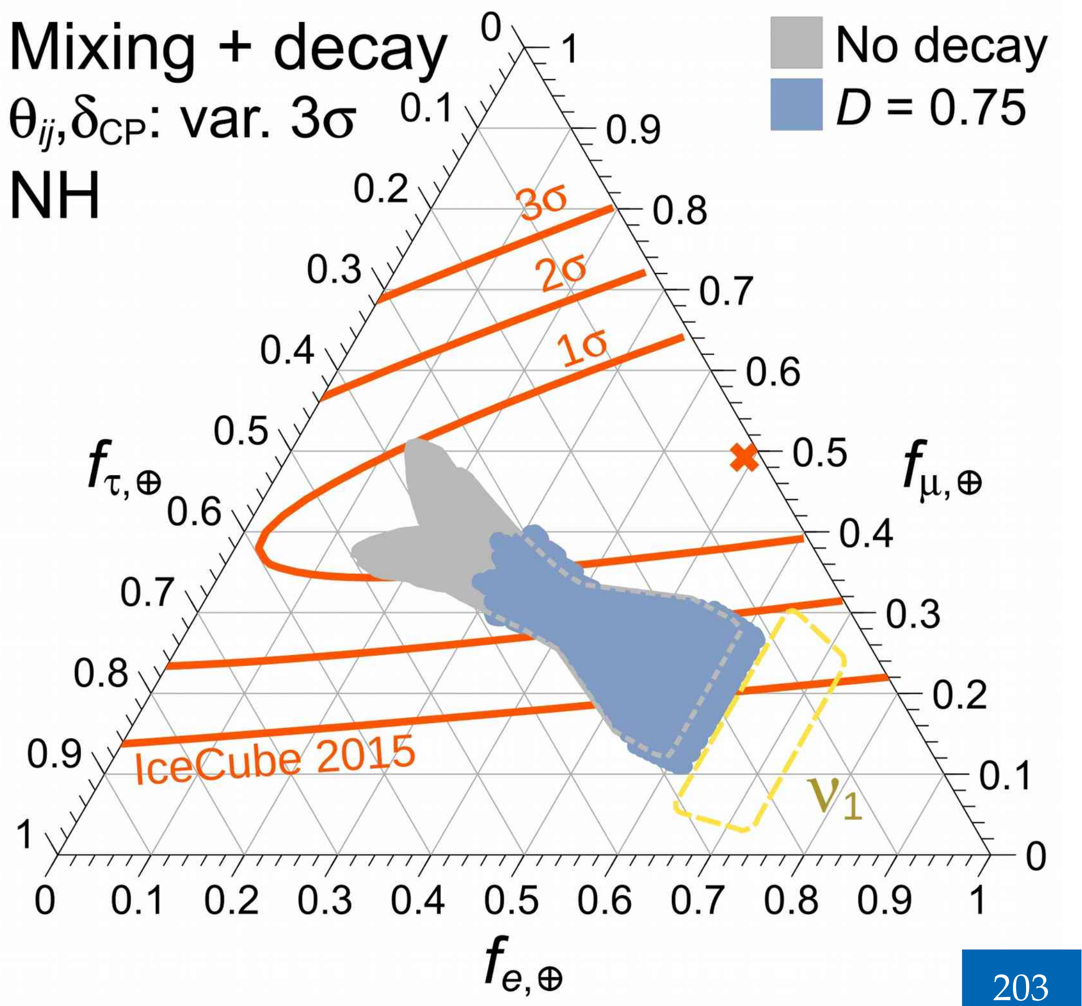

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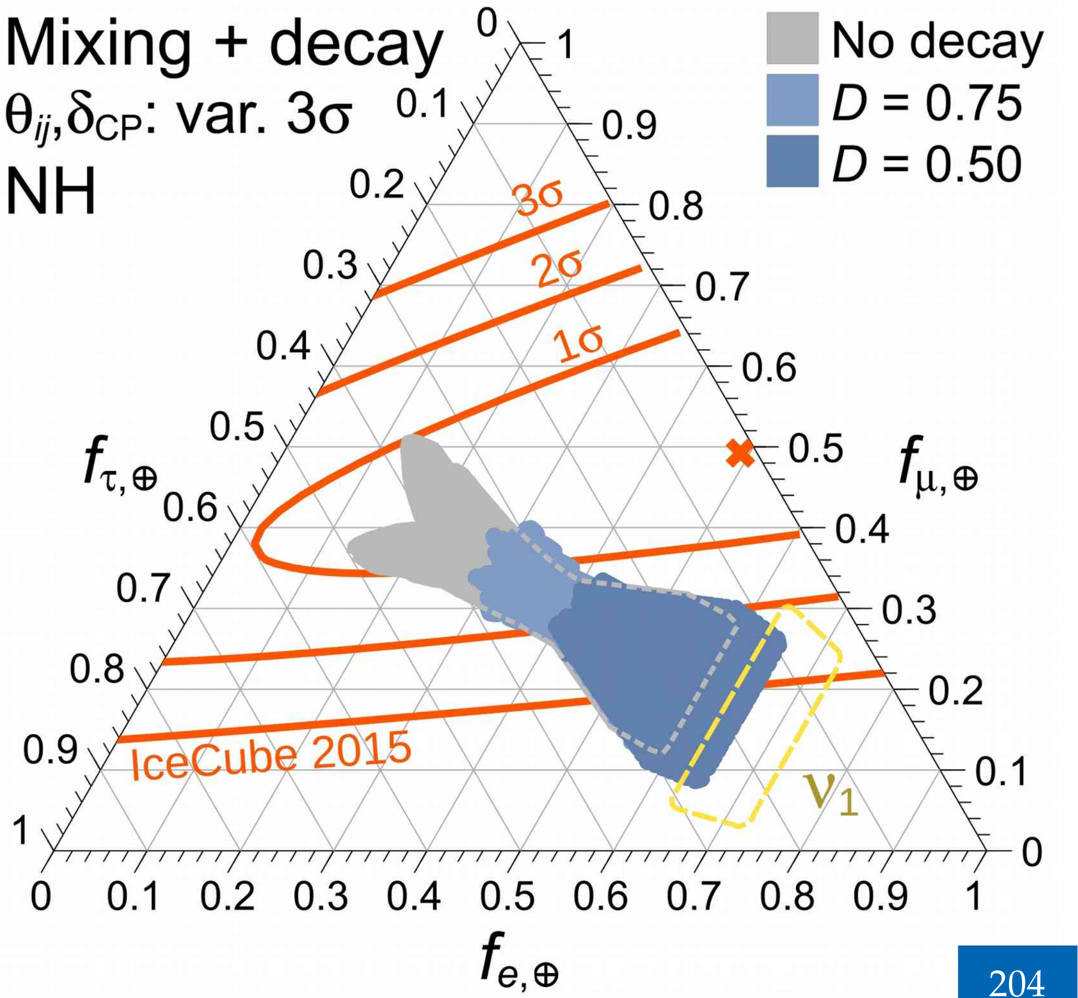

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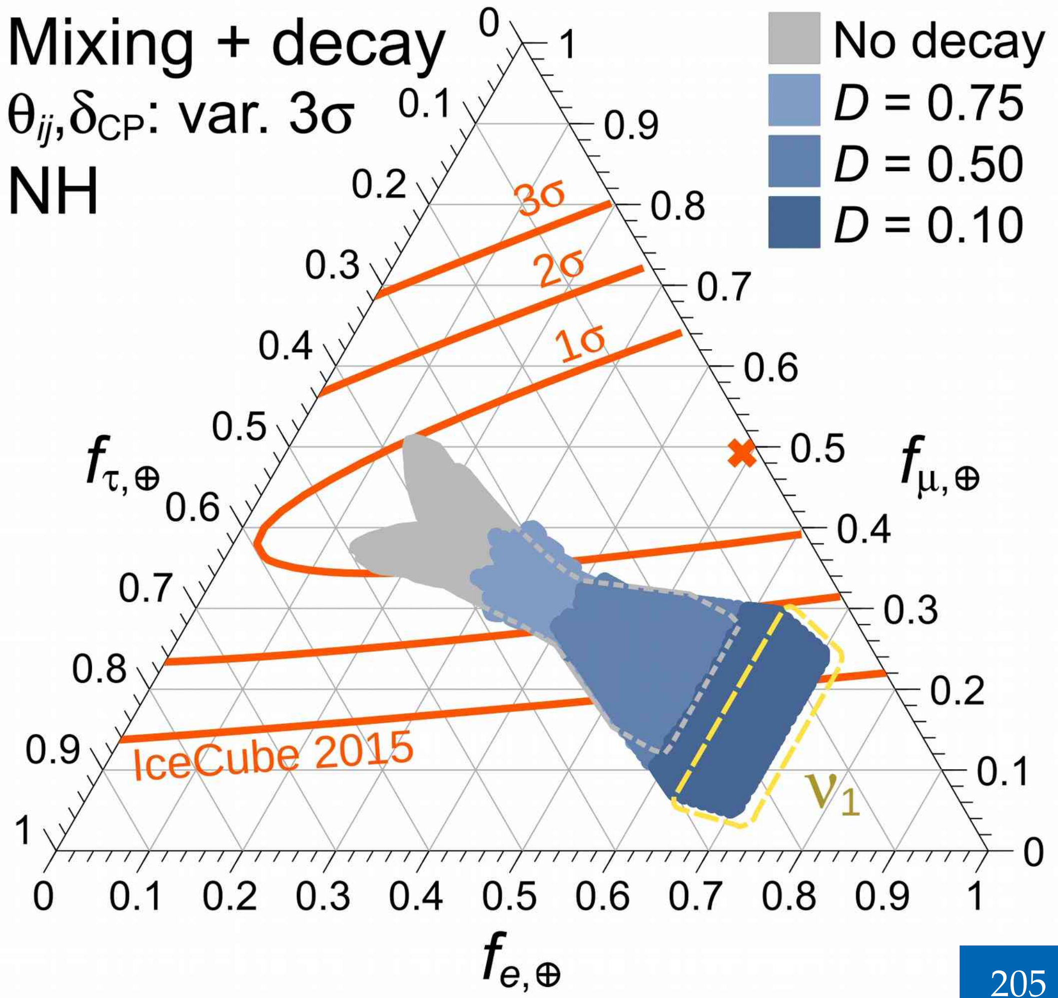

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MB, Beacom, Murase, *PRD* 2017
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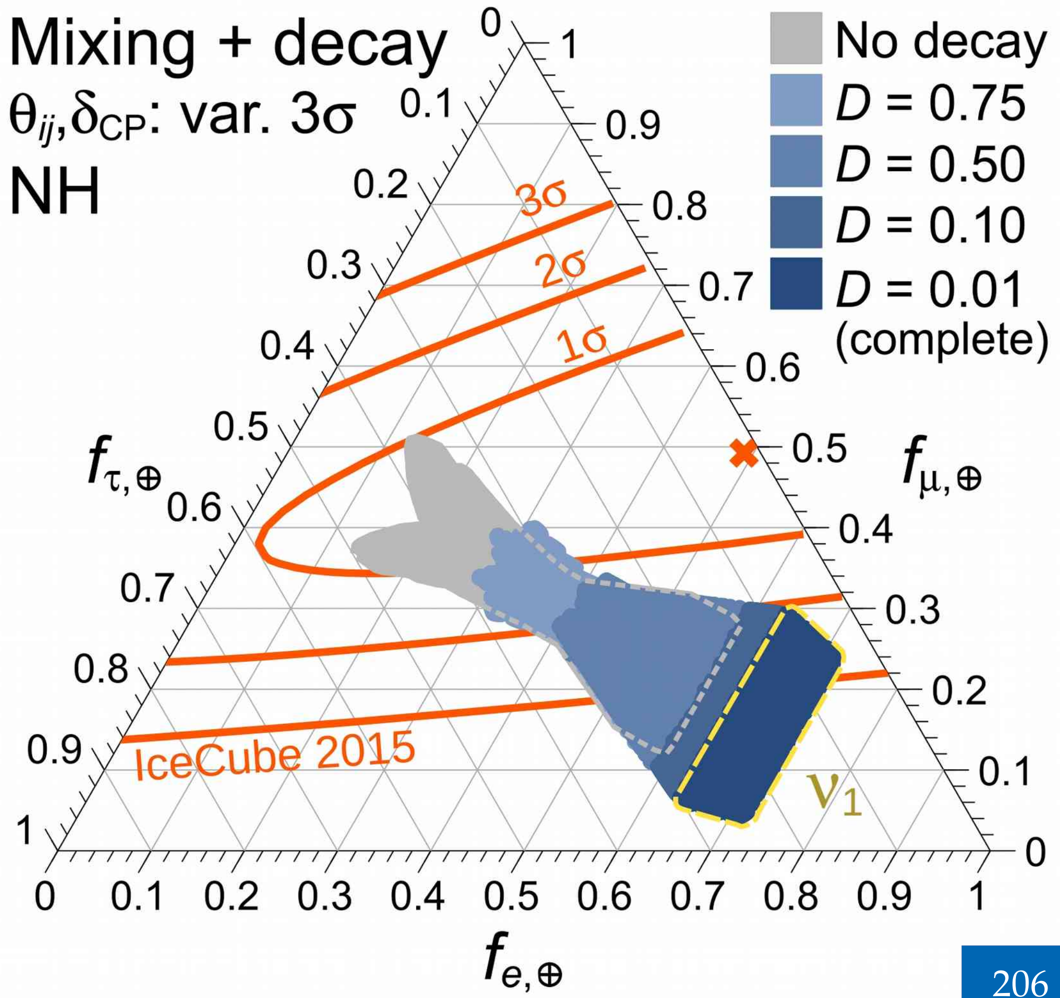

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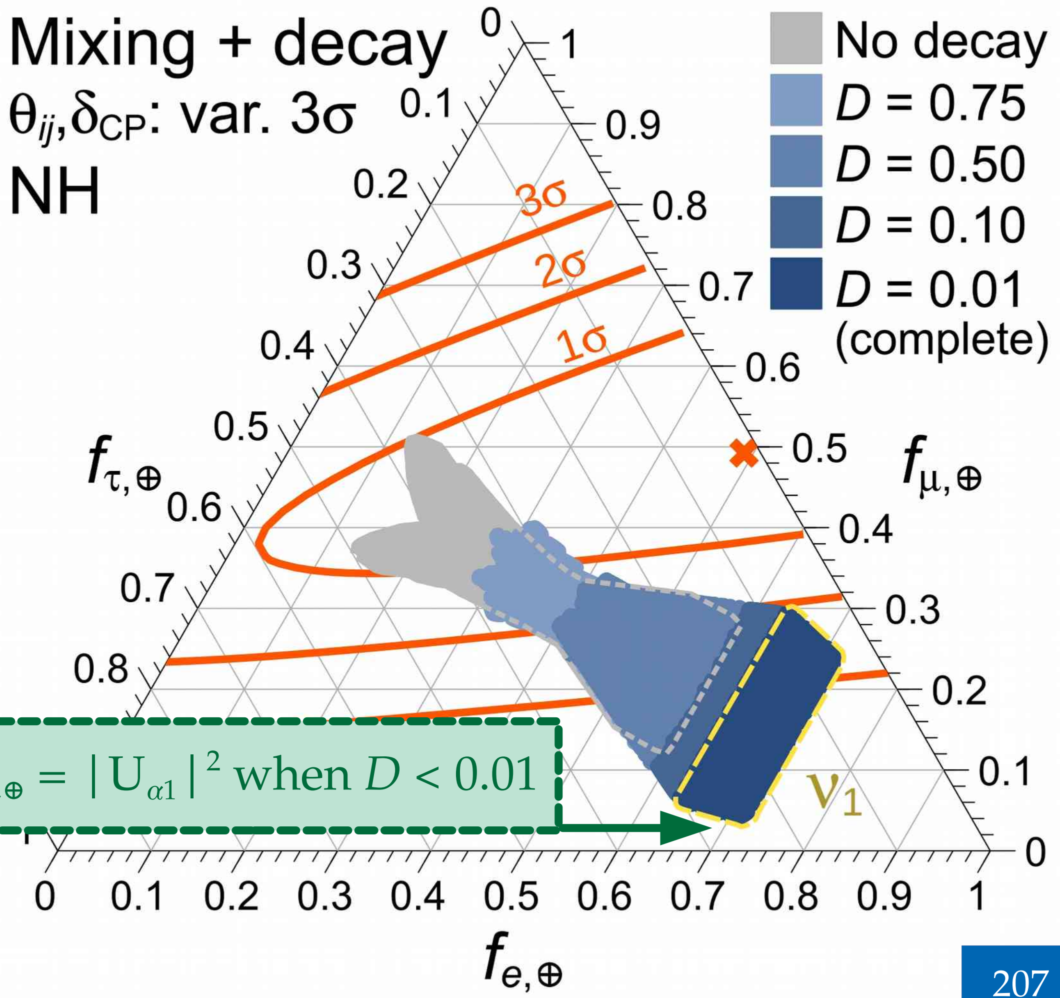
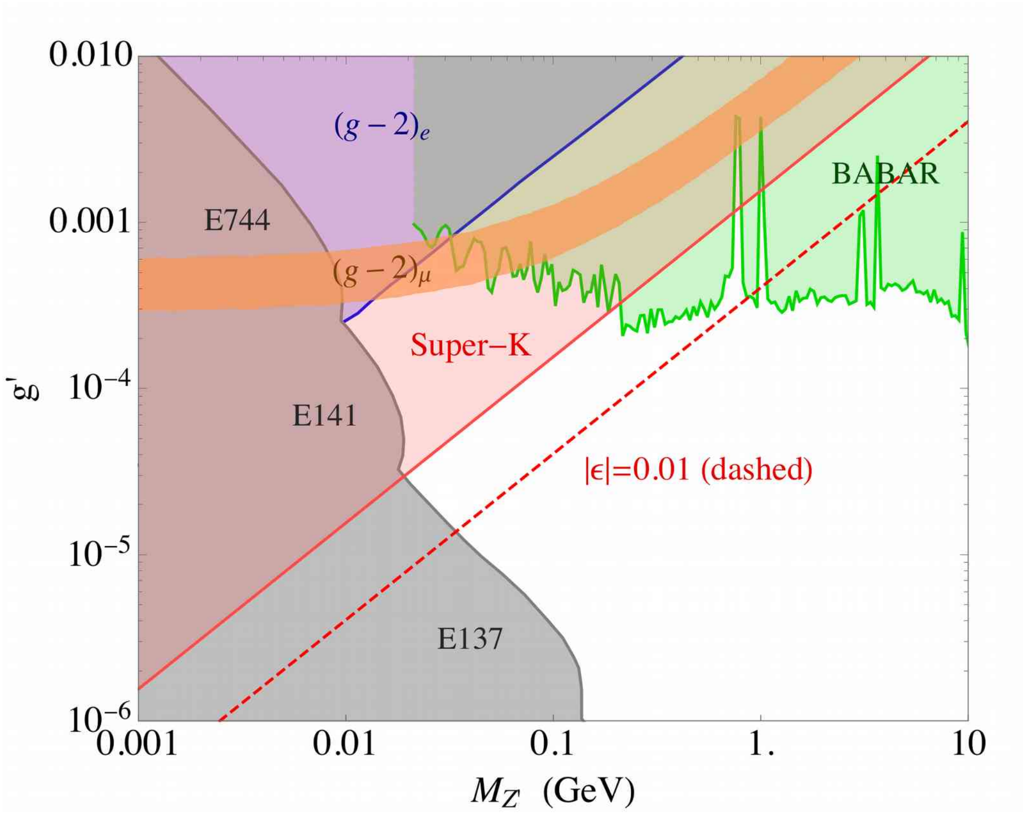


$f_{\alpha,\oplus} = |U_{\alpha 1}|^2$ when $D < 0.01$

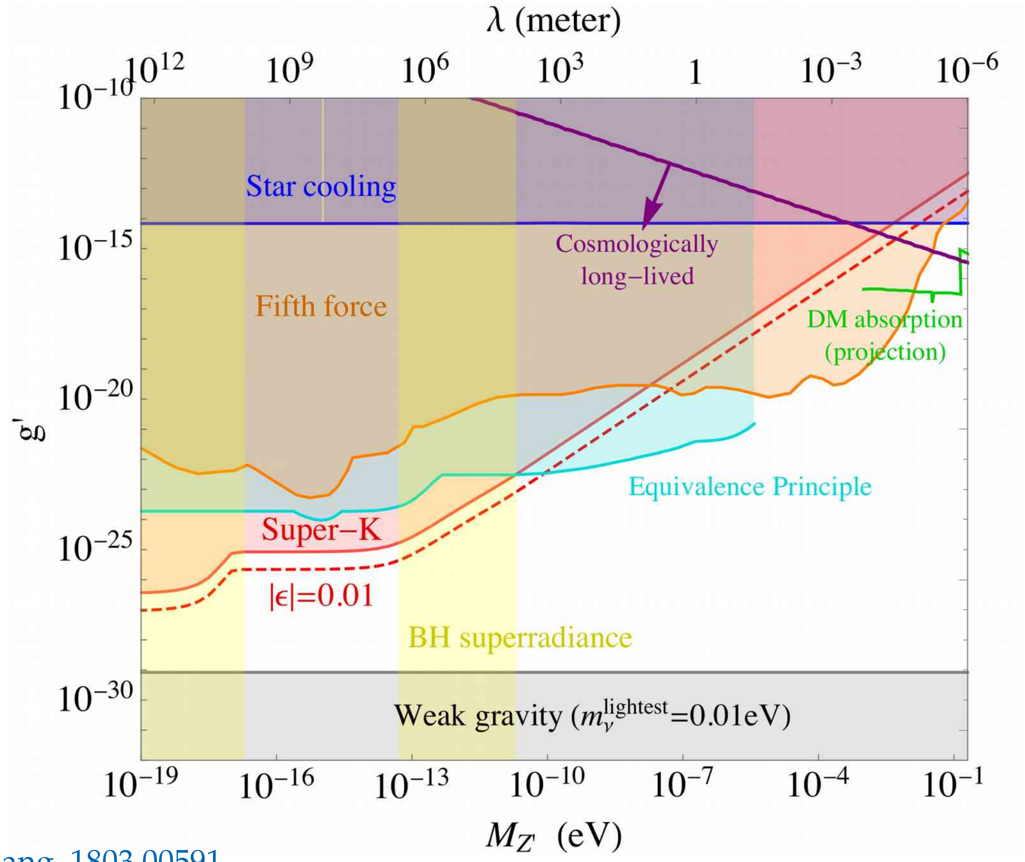
MB, Beacom, Murase, *PRD* 2017
Baerwald, **MB**, Winter, *JCAP* 2012

Current limits on the Z'

MeV–GeV masses



Sub-eV masses



M. Wise & Y. Zhang, 1803.00591

Connecting flavor-ratio predictions to experiment

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

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

Density of cosmological *e* grows with *z*

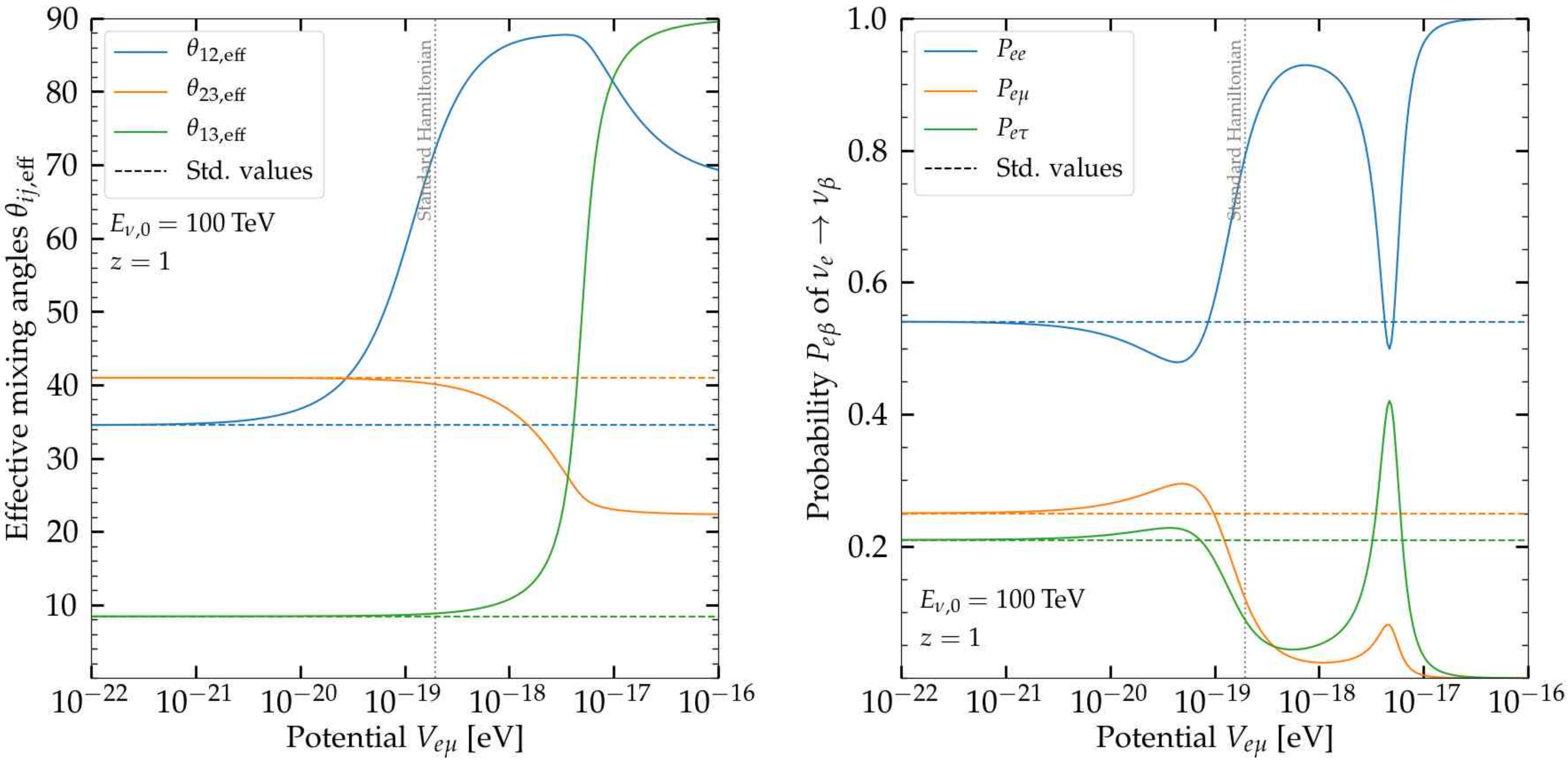
2. Convolve flavor ratios with observed neutrino energy spectrum
   ↦ Either $E^{-2.50}$ (combined analysis) or $E^{-2.13}$ (through-going muons)

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

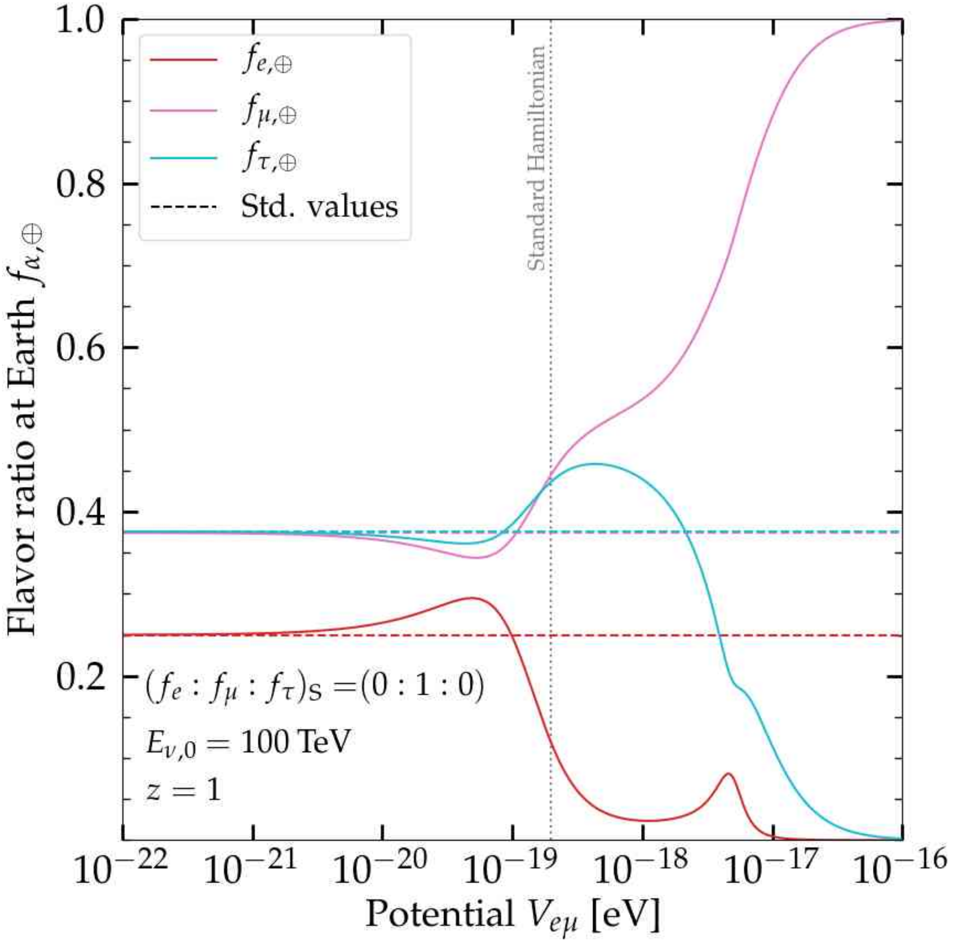
Energy-averaged flux

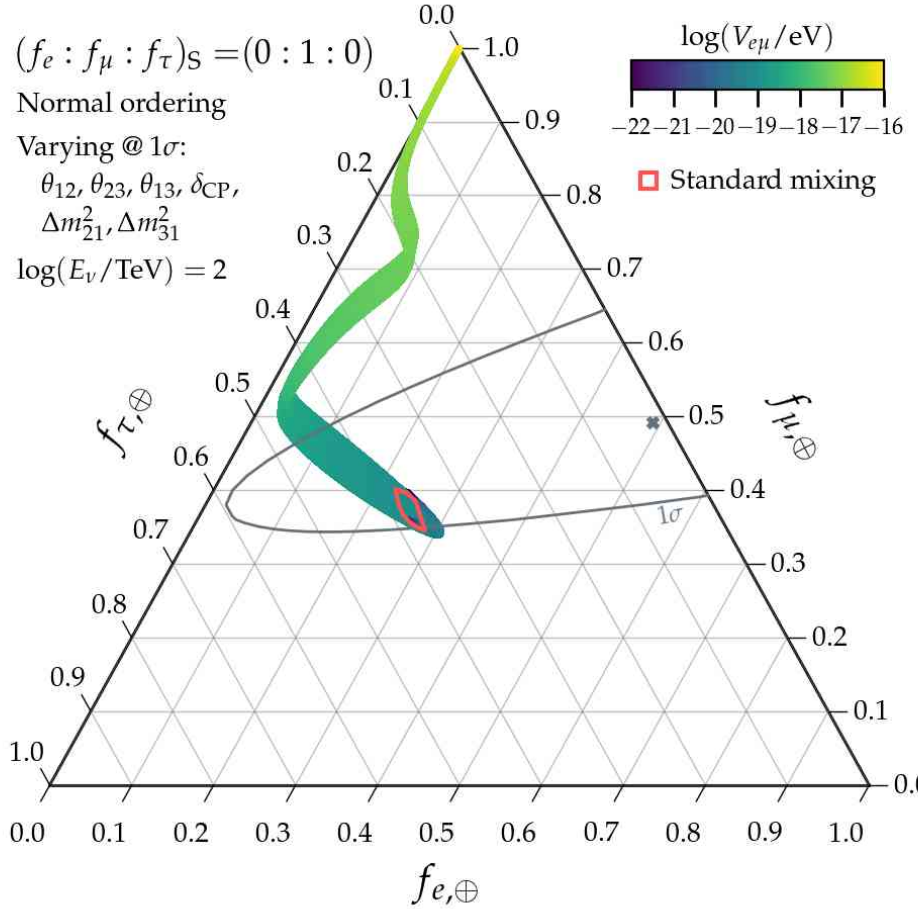
Energy-averaged flavor ratios

Resonance due to the L_e-L_μ symmetry

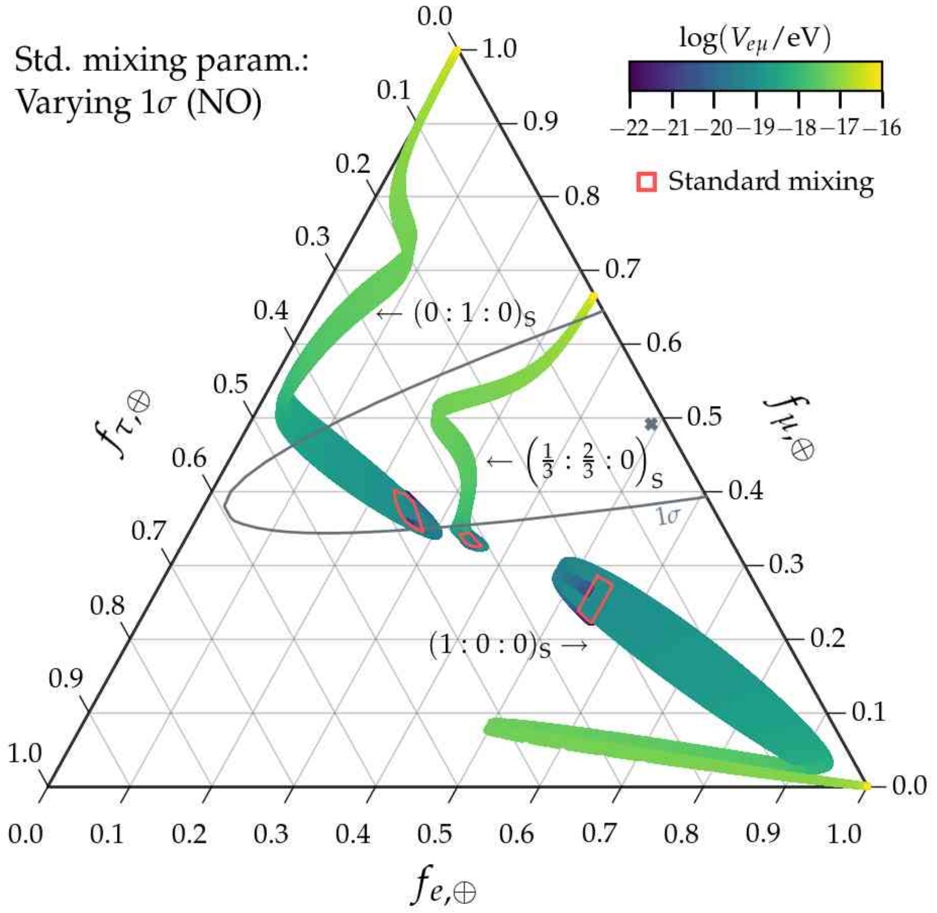


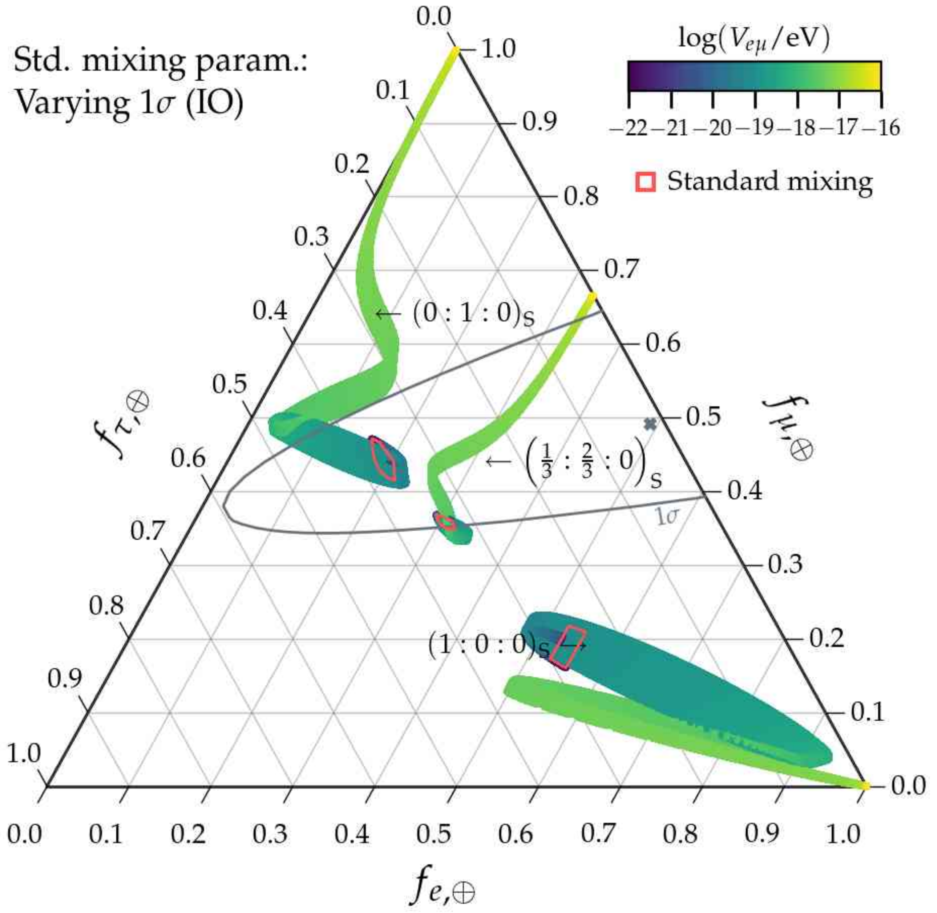
Resonance due to the L_e-L_μ symmetry (*cont.*)



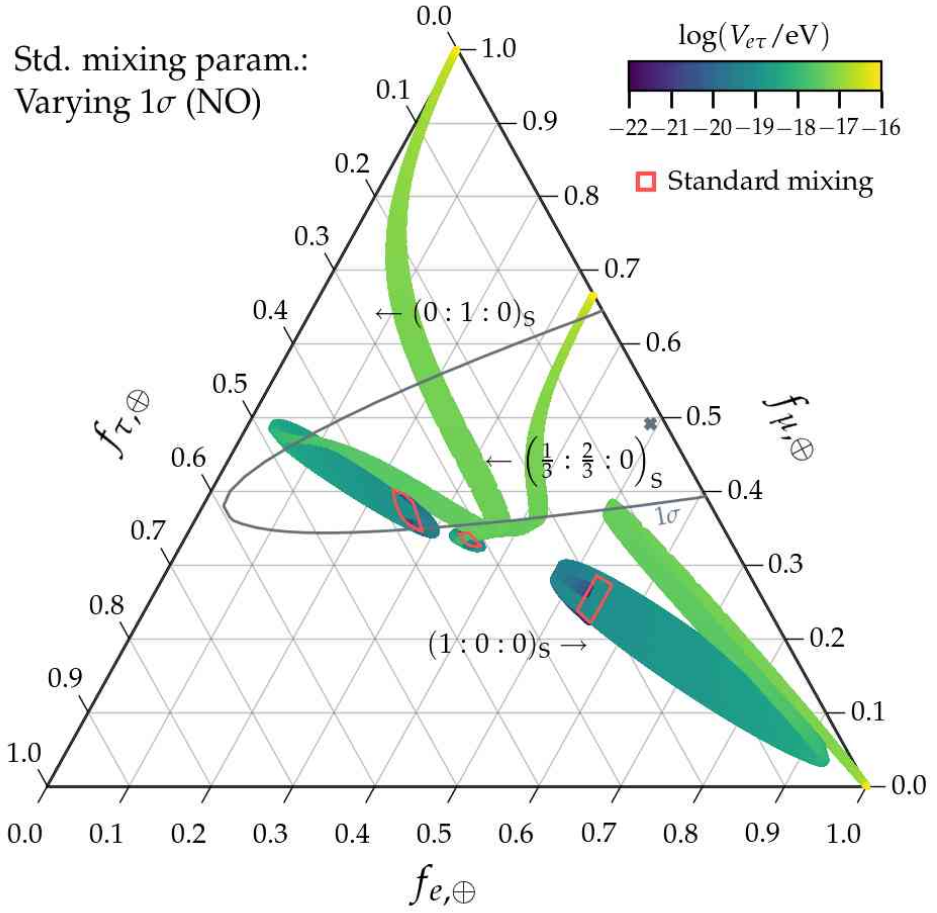


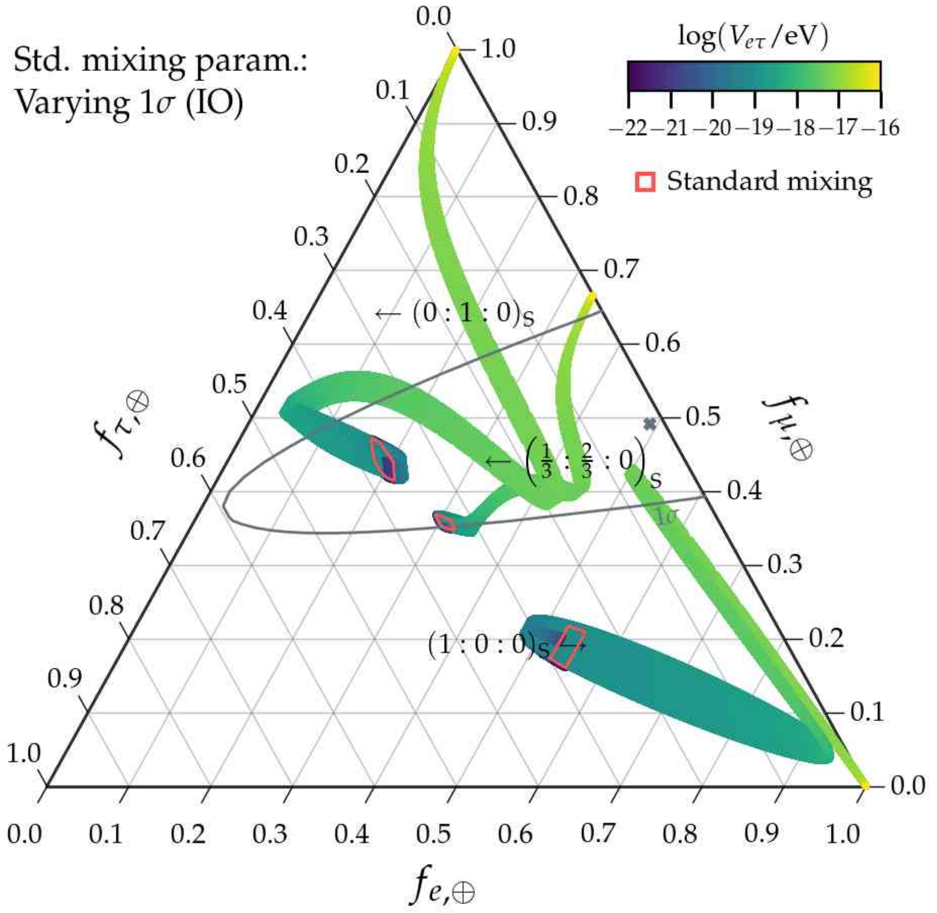
Flavor ratios for the L_e-L_μ symmetry: NO *vs.* IO

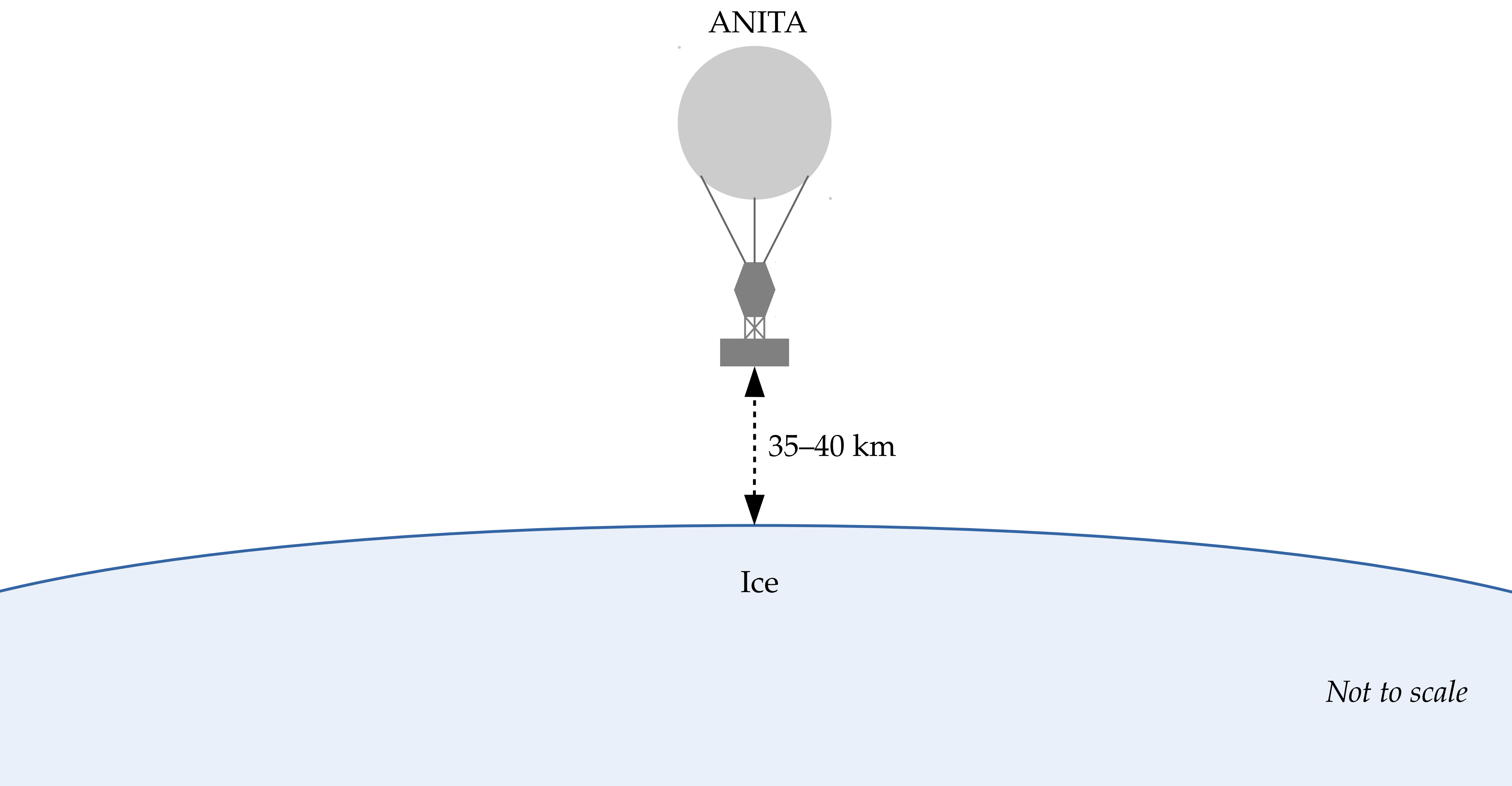


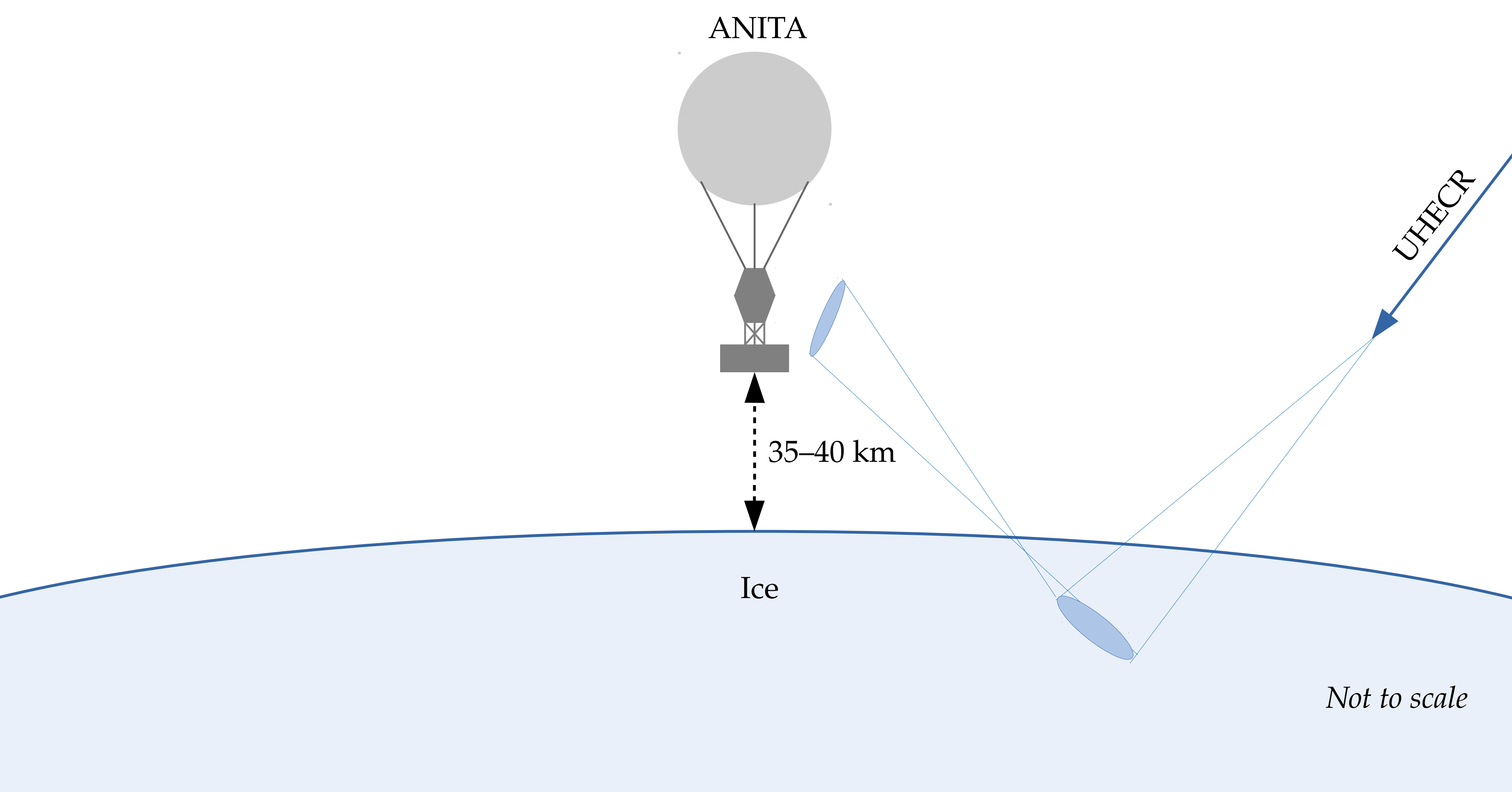


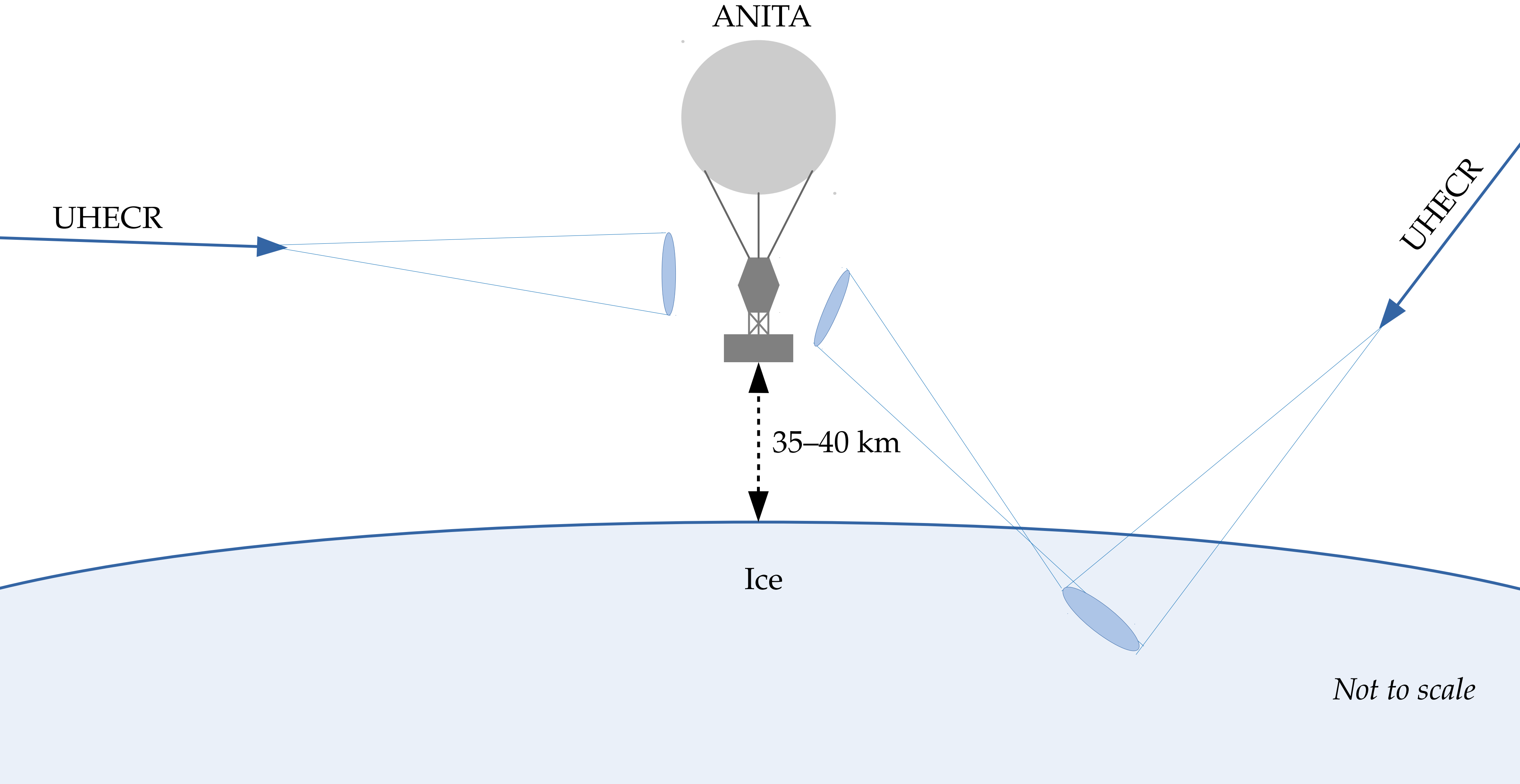
Flavor ratios for the L_e-L_τ symmetry: NO *vs.* IO






ANITA
35–40 km
Ice
Not to scale


ANITA
UHECR
35–40 km
Ice
Not to scale



ANITA
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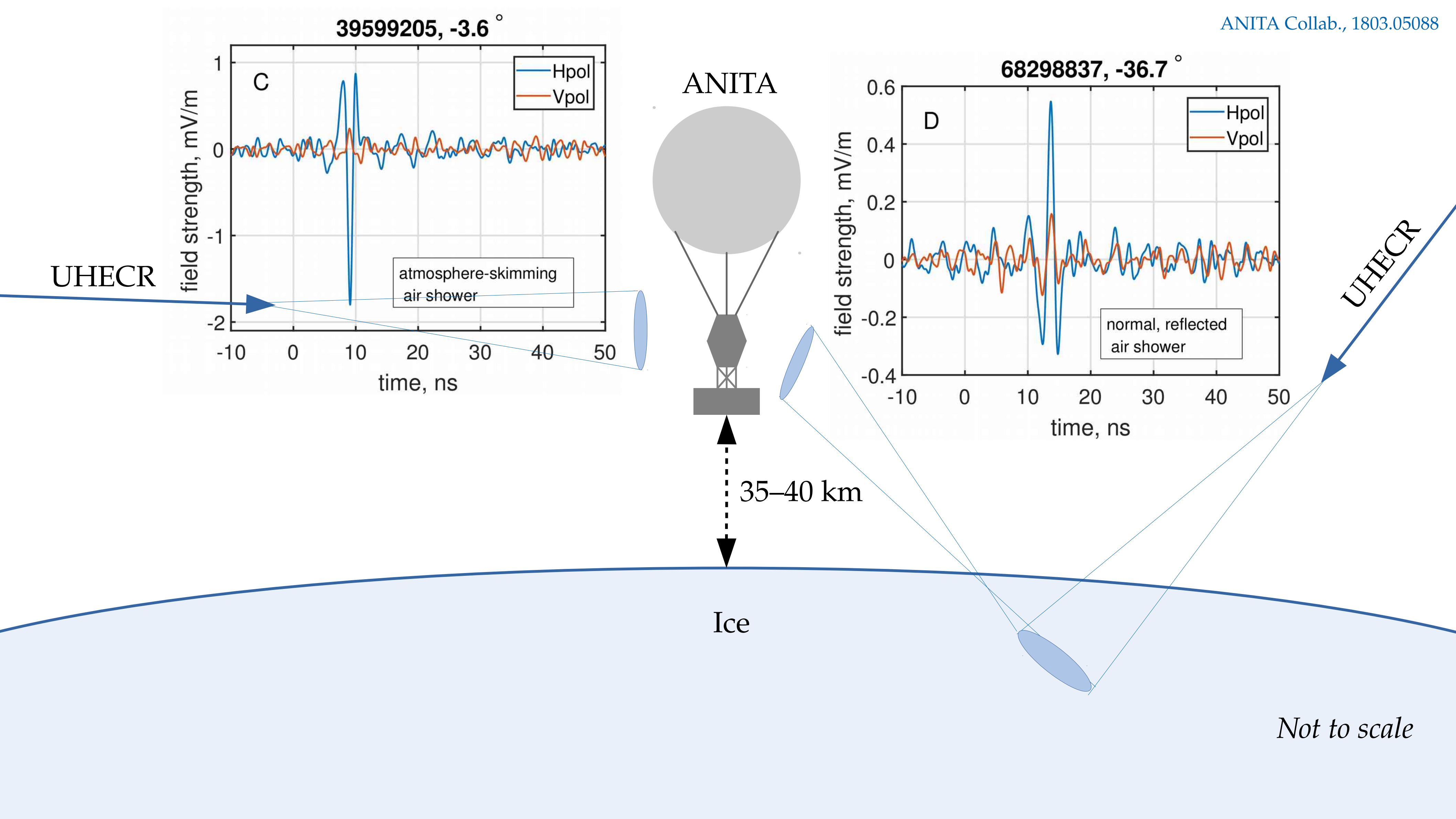
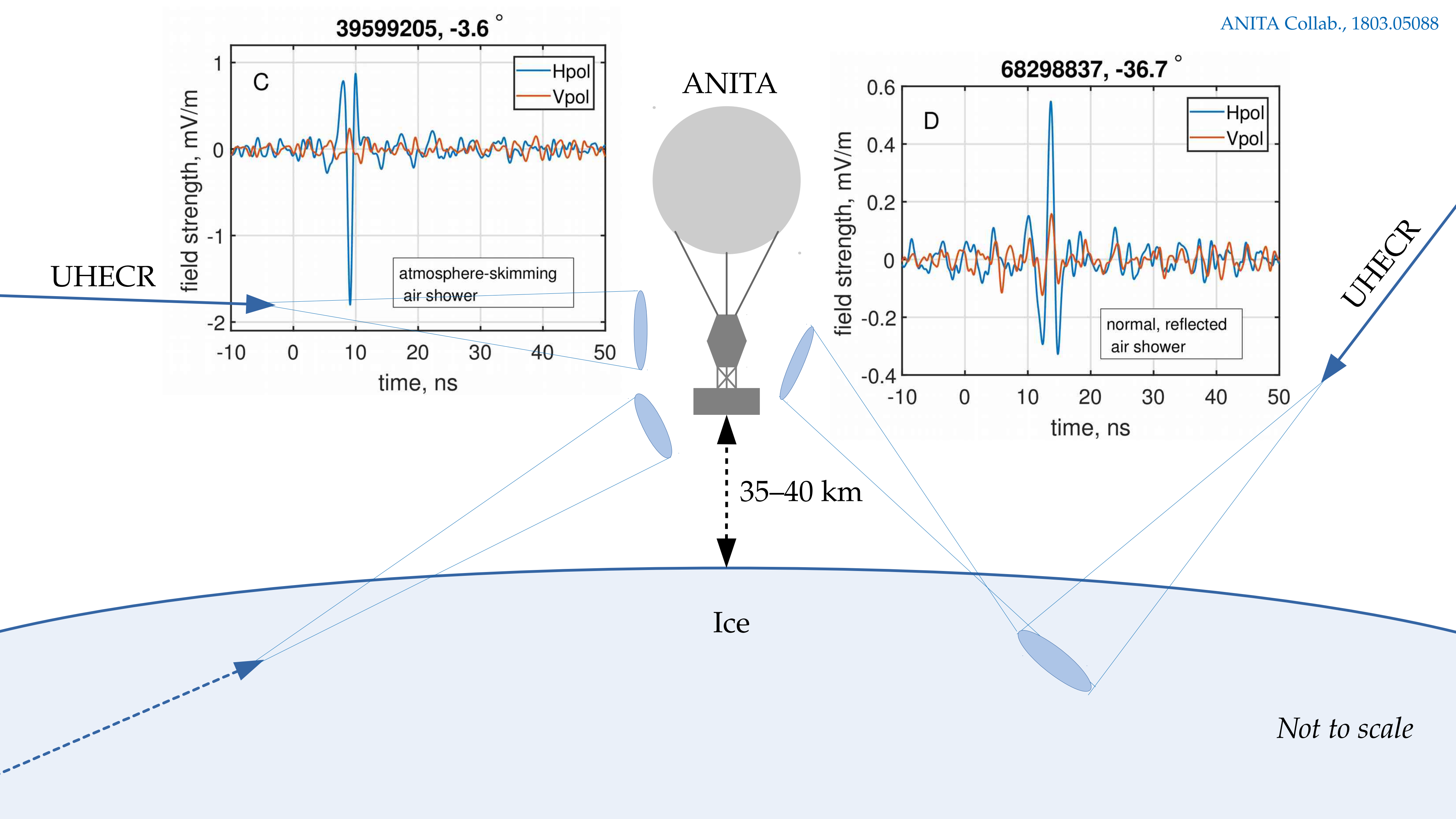
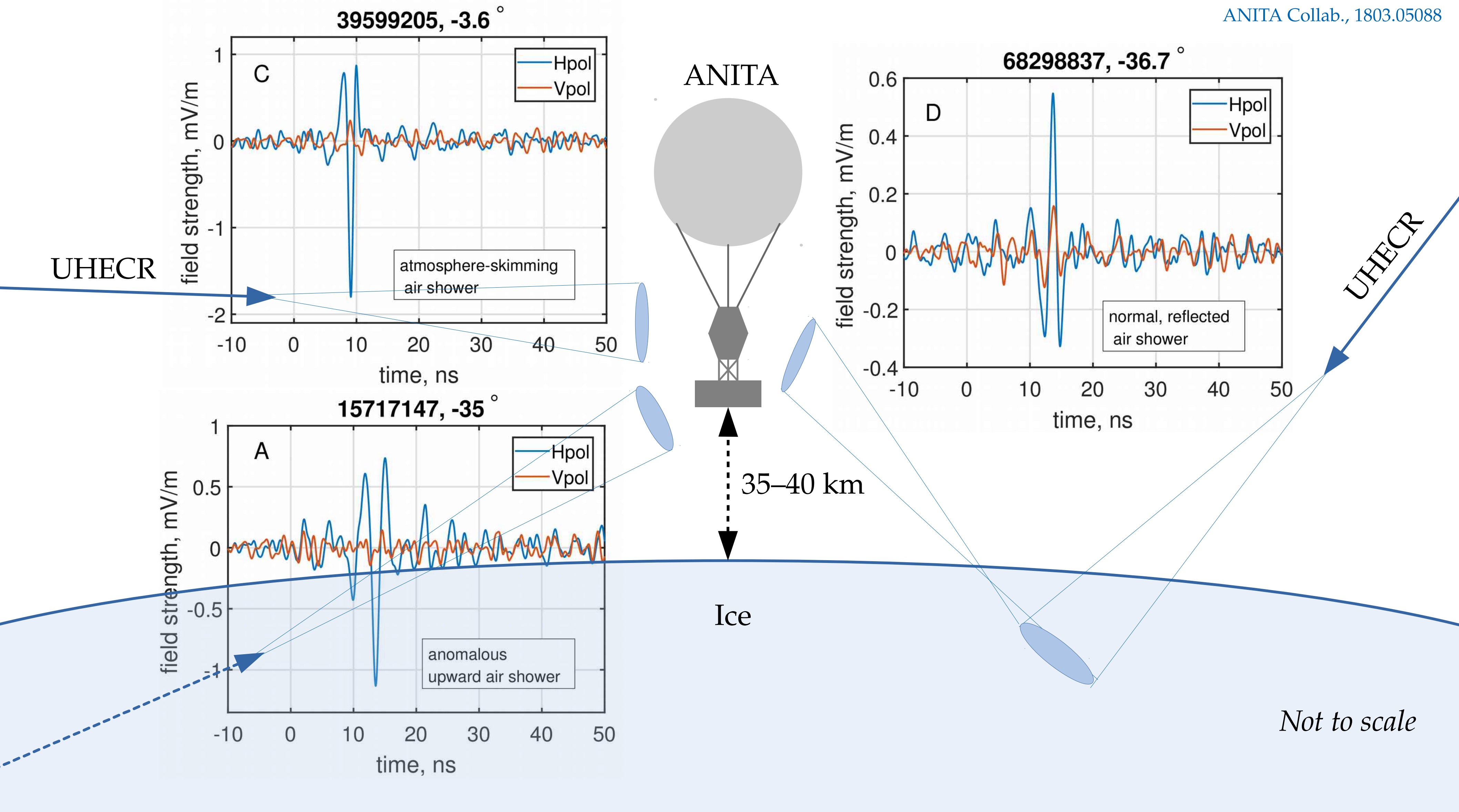
ANITA Collab., 1803.05088

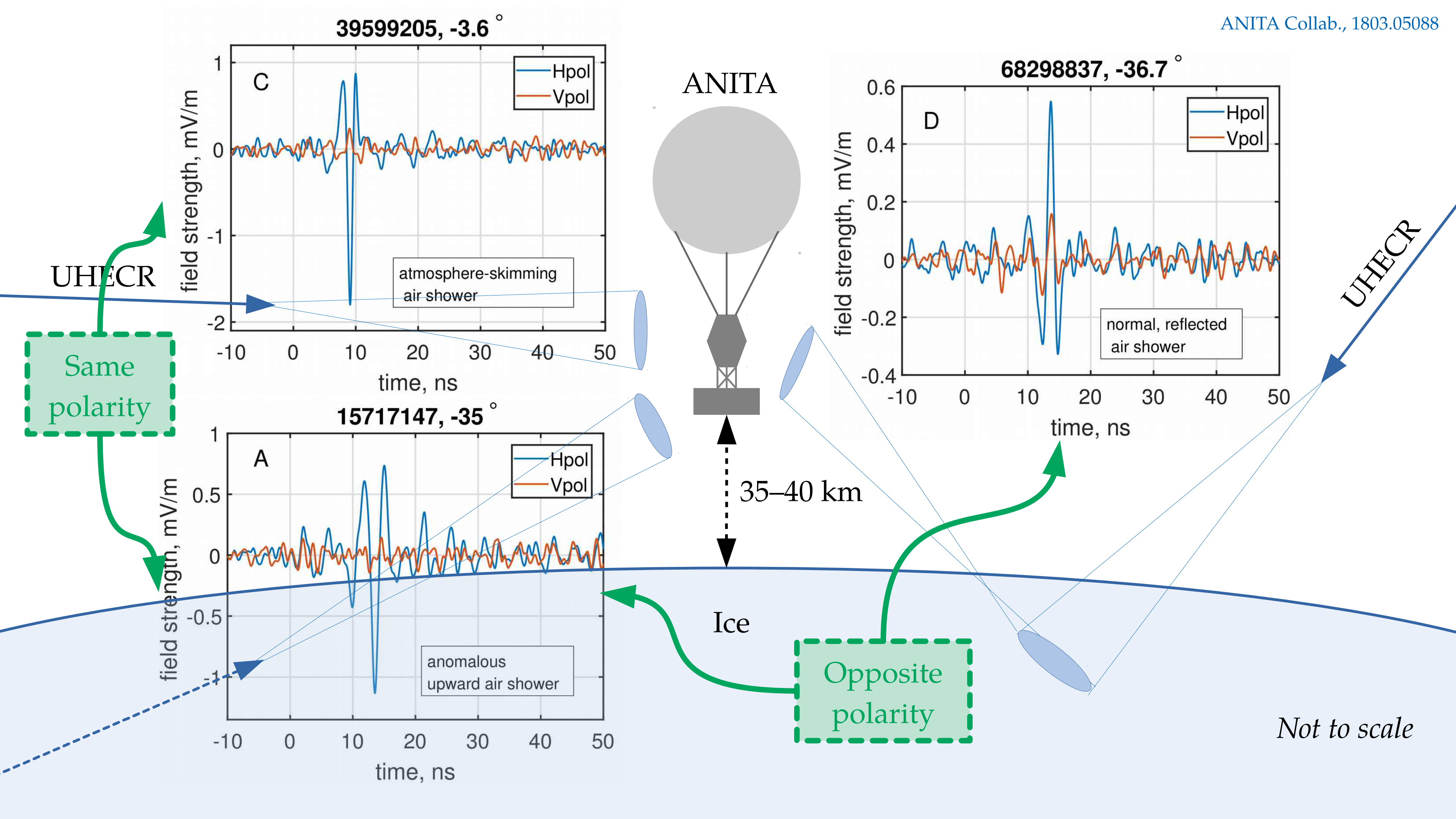




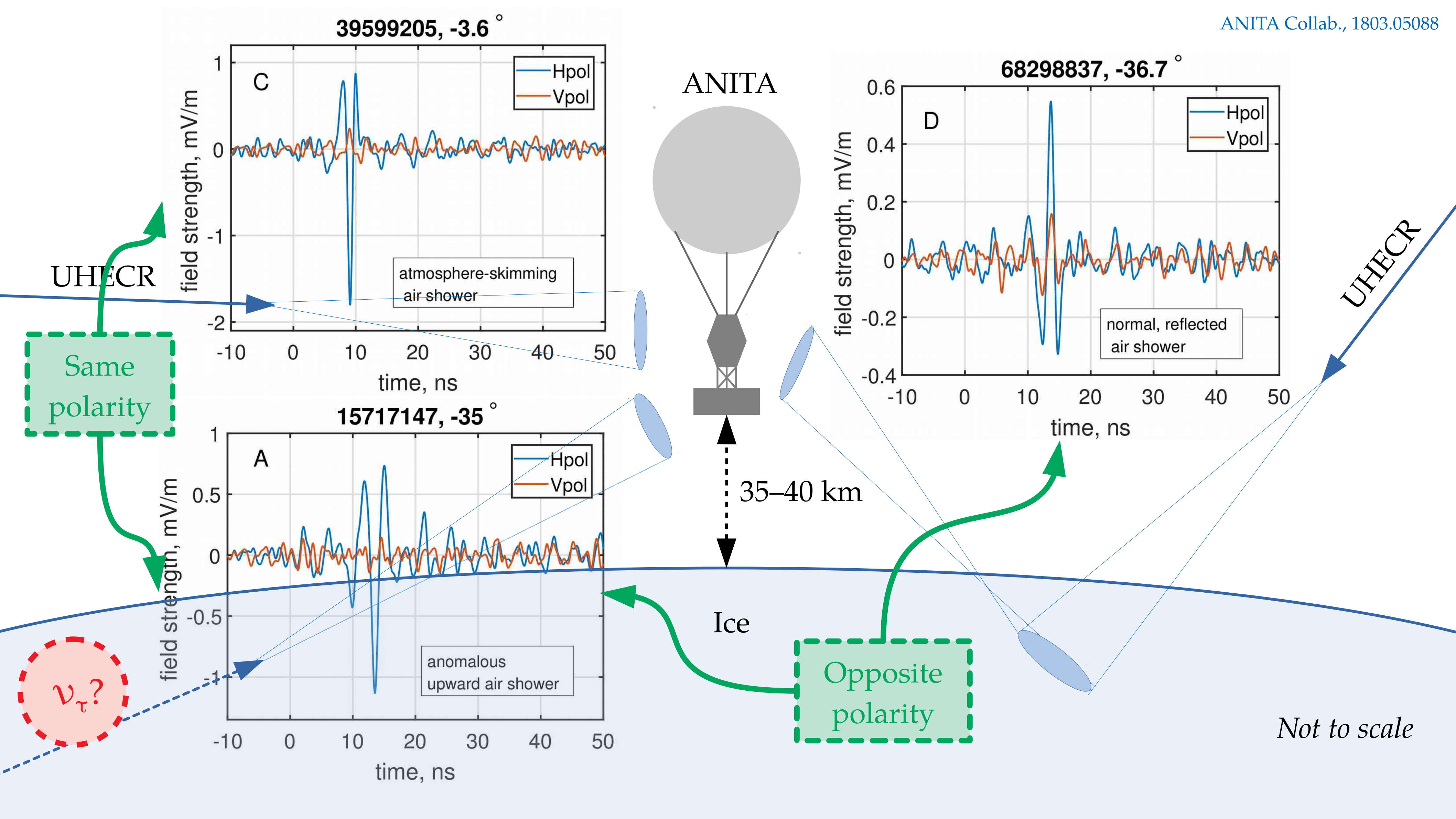
ANITA Collab., 1803.05088
39599205, -3.6 °
C
Hpol
Vpol
field strength, mV/m
time, ns
atmosphere-skimming air shower
UHECR
ANITA
68298837, -36.7 °
D
normal, reflected air shower
UHECR
35–40 km
Ice
Not to scale

ANITA Collab., 1803.05088





ANITA Collab., 1803.05088
39599205, -3.6 °
C
Hpol
Vpol
field strength, mV/m
time, ns
atmosphere-skimming air shower
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
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ν_τ?
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Ice
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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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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