Fundamental Physics with High-Energy Cosmic Neutrinos

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UNIVERSITY OF COPENHAGEN

VILLUM FONDEN

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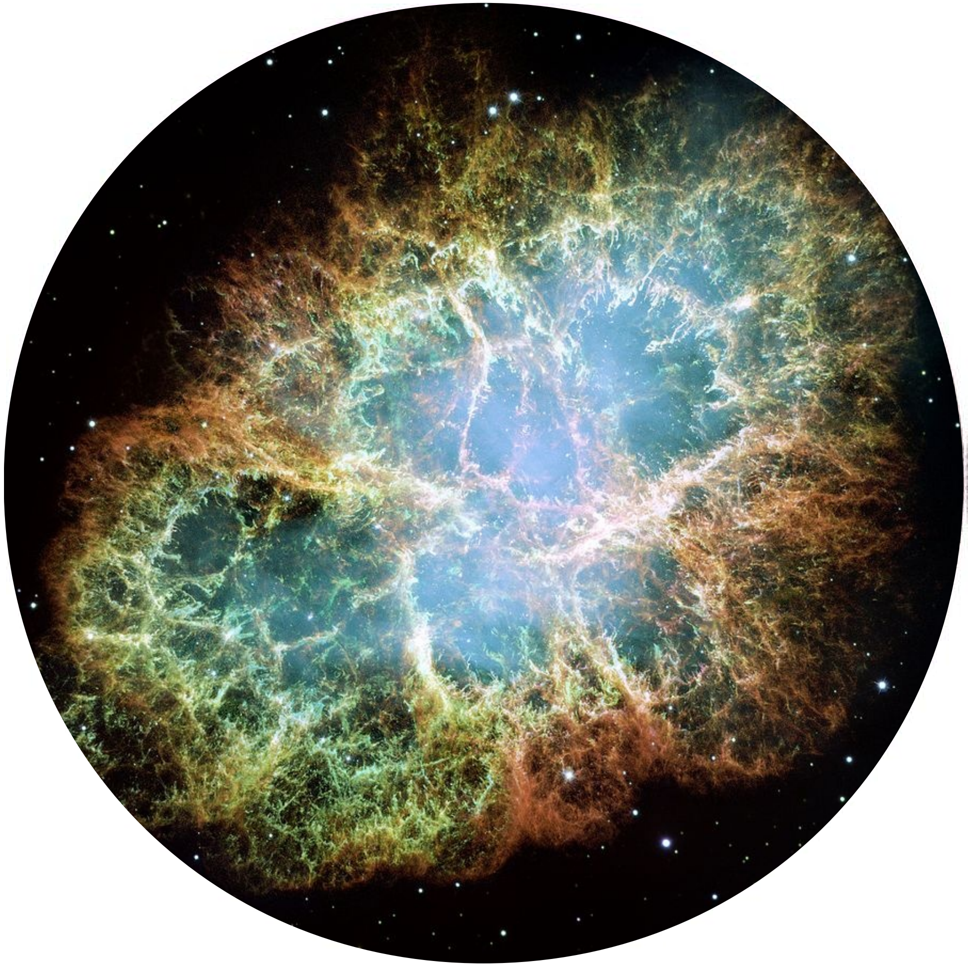

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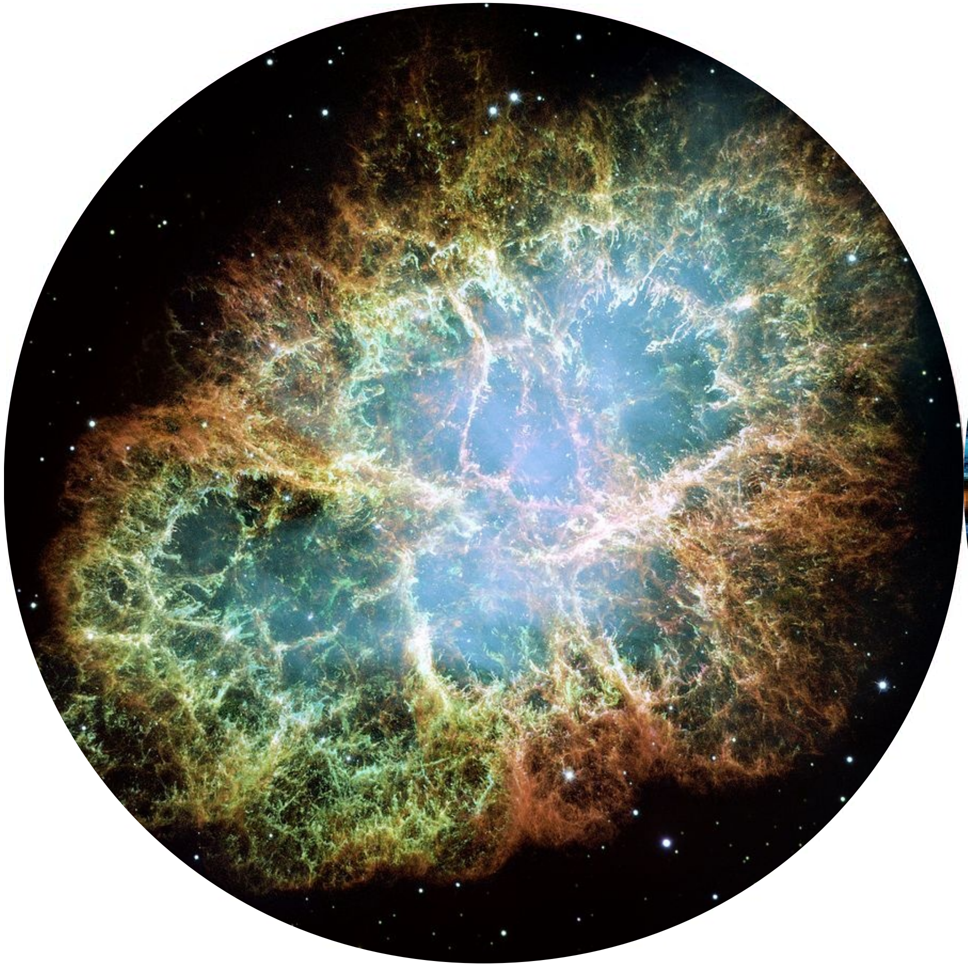

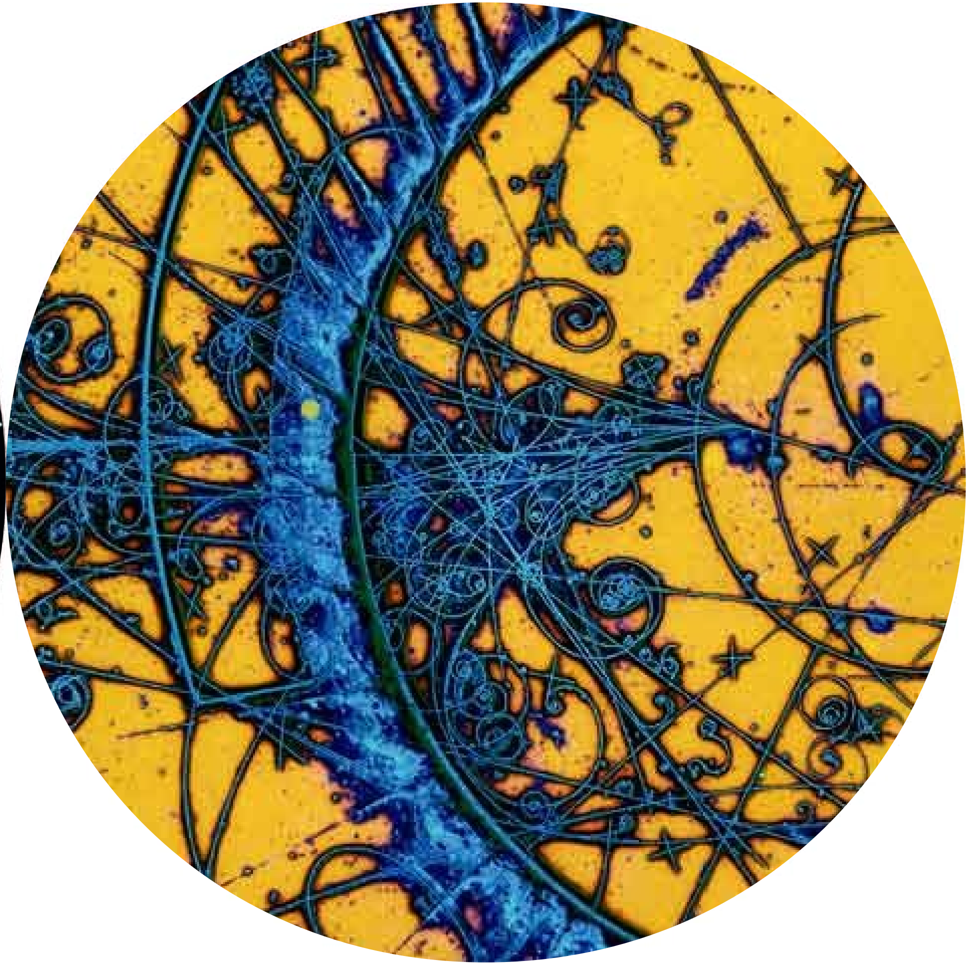

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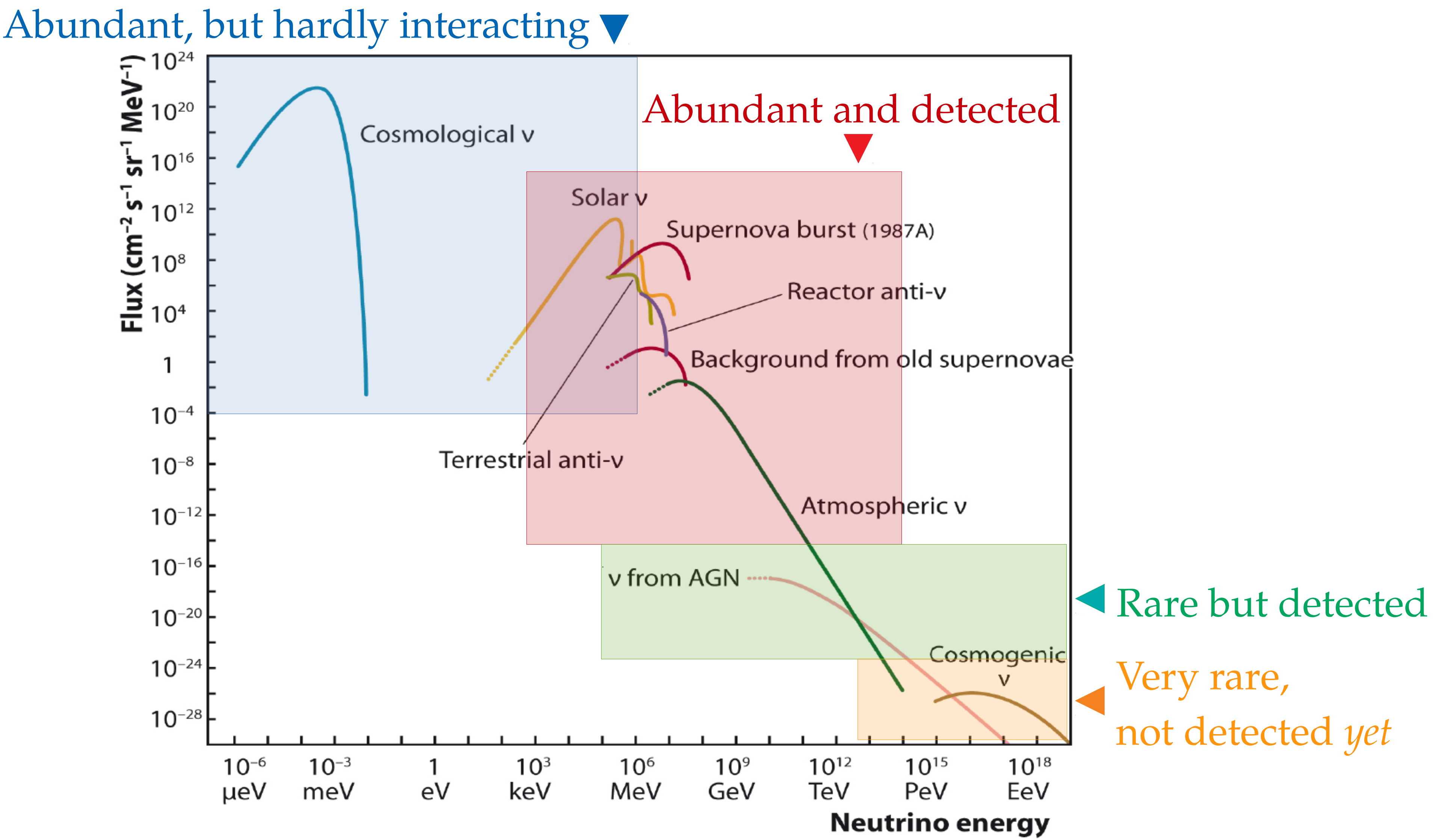

Abundant, but hardly interacting
Abundant and detected
Rare but detected
Very rare,
not detected *yet*
Flux (cm⁻² s⁻¹ sr⁻¹ MeV⁻¹)
10^24
10^20
10^16
10^12
10^8
10^4
1
10^-4
10^-8
10^-12
10^-16
10^-20
10^-24
10^-28
Cosmological ν
Solar ν
Supernova burst (1987A)
Reactor anti-ν
Background from old supernovae
Terrestrial anti-ν
Atmospheric ν
ν from AGN
Cosmogenic ν
10^-6 μeV
10^-3 meV
1 eV
10^3 keV
10^6 MeV
10^9 GeV
10^12 TeV
10^15 PeV
10^18 EeV
Neutrino energy

Why study fundamental physics with HE cosmic ν's?

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

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

3. Neutrinos are weakly interacting
   ↦ New effects may stand out more clearly

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4. 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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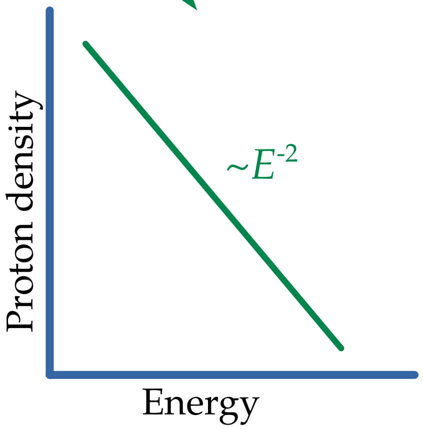

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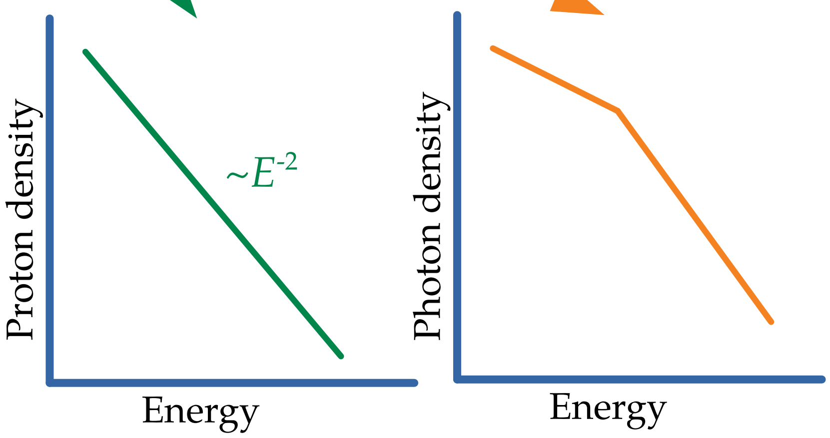

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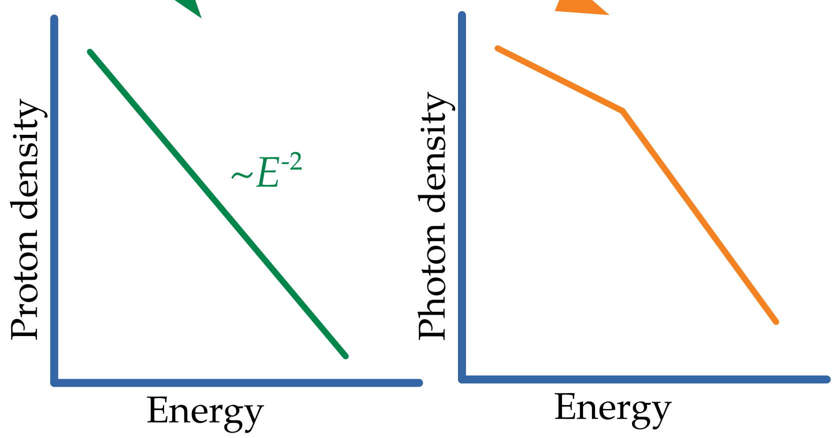
$$\pi^0 \rightarrow \gamma + \gamma$$

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

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



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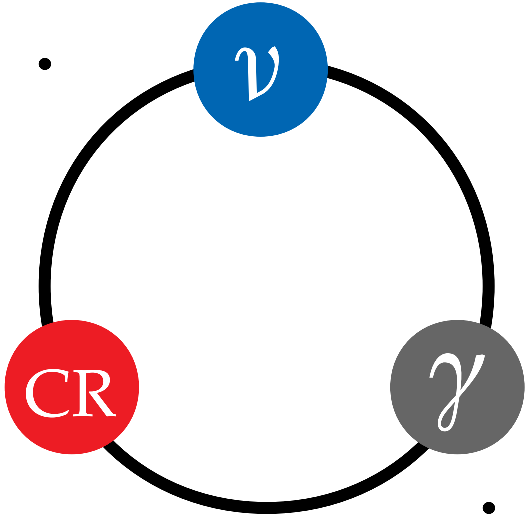

Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 10

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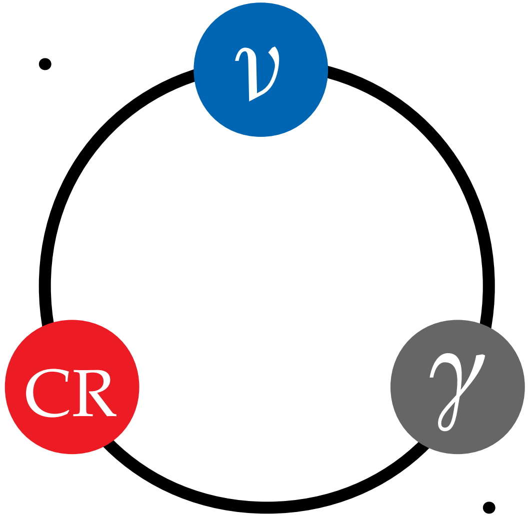

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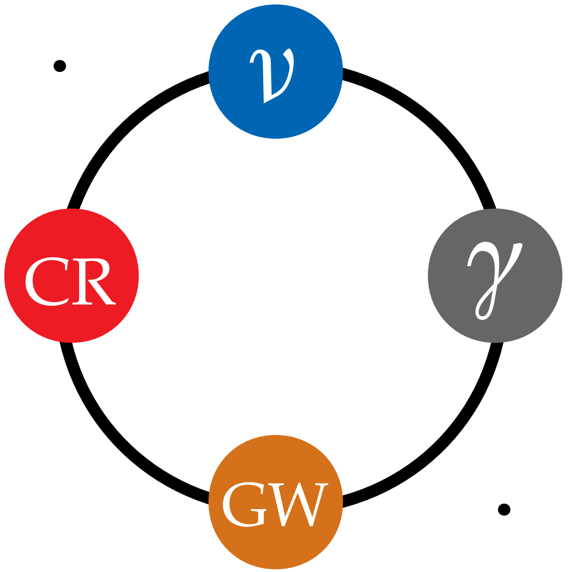

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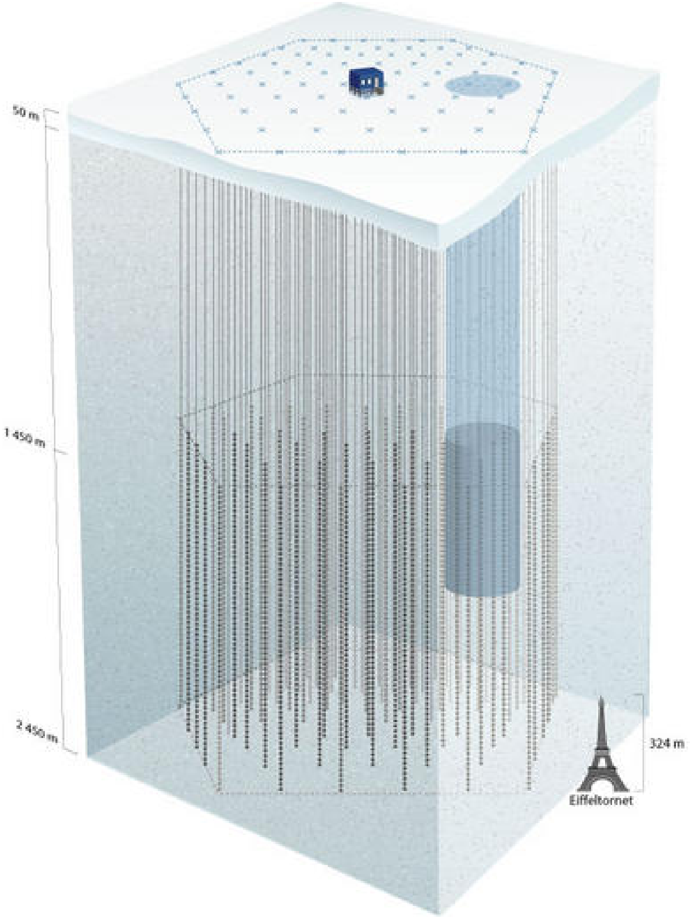
IceCube – What is it?



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

How does IceCube see neutrinos?

Two types of fundamental interactions …

Charged-current (CC)

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

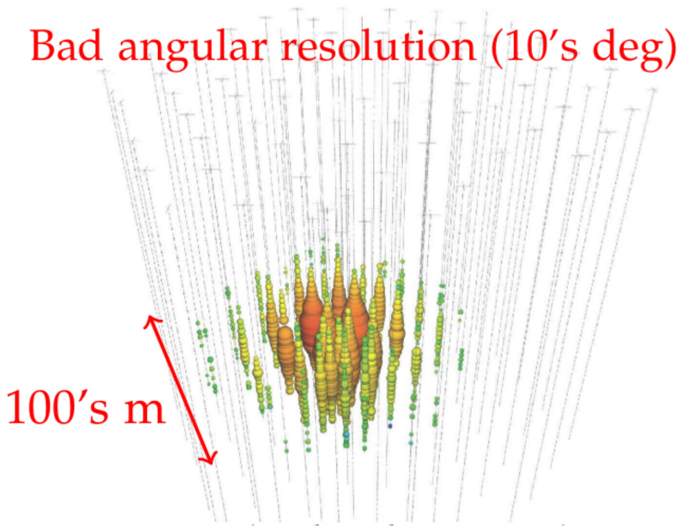
Neutral-current (NC)

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

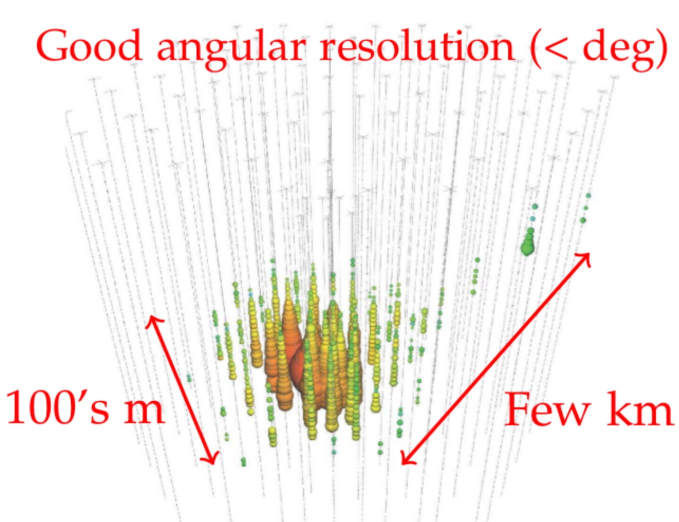
These shower and make light

… create two event topologies …

Showers — From CC ν_e or ν_τ, or NC ν_x



Tracks — From CC ν_μ mainly



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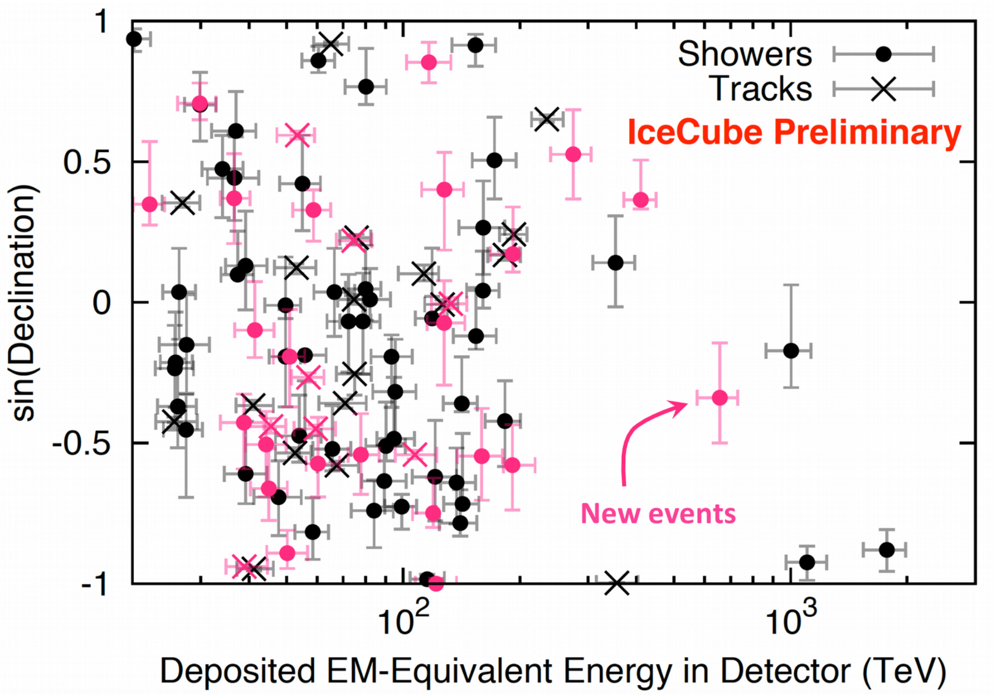

I. Taboada, Neutrino 2018

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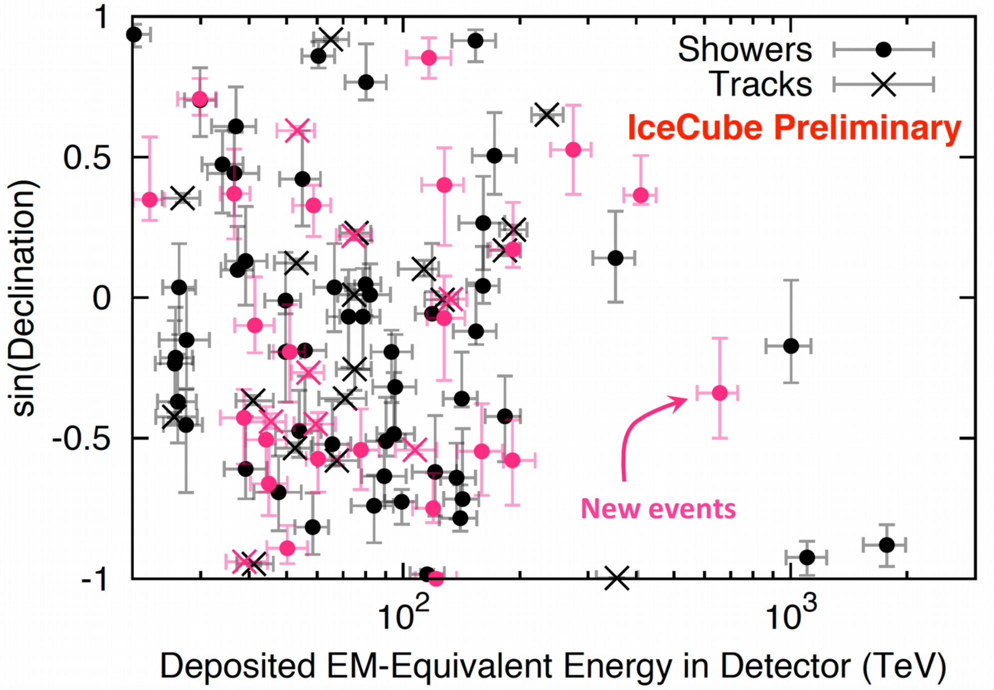
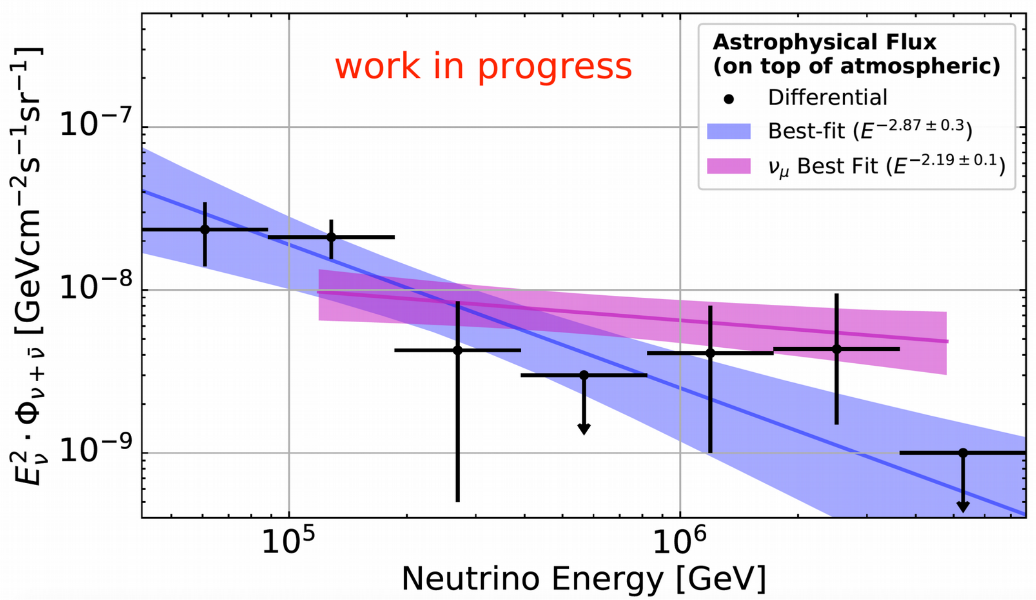


Astrophysical ν flux detected at > 7σ
(Normalization ok, but steep spectrum)



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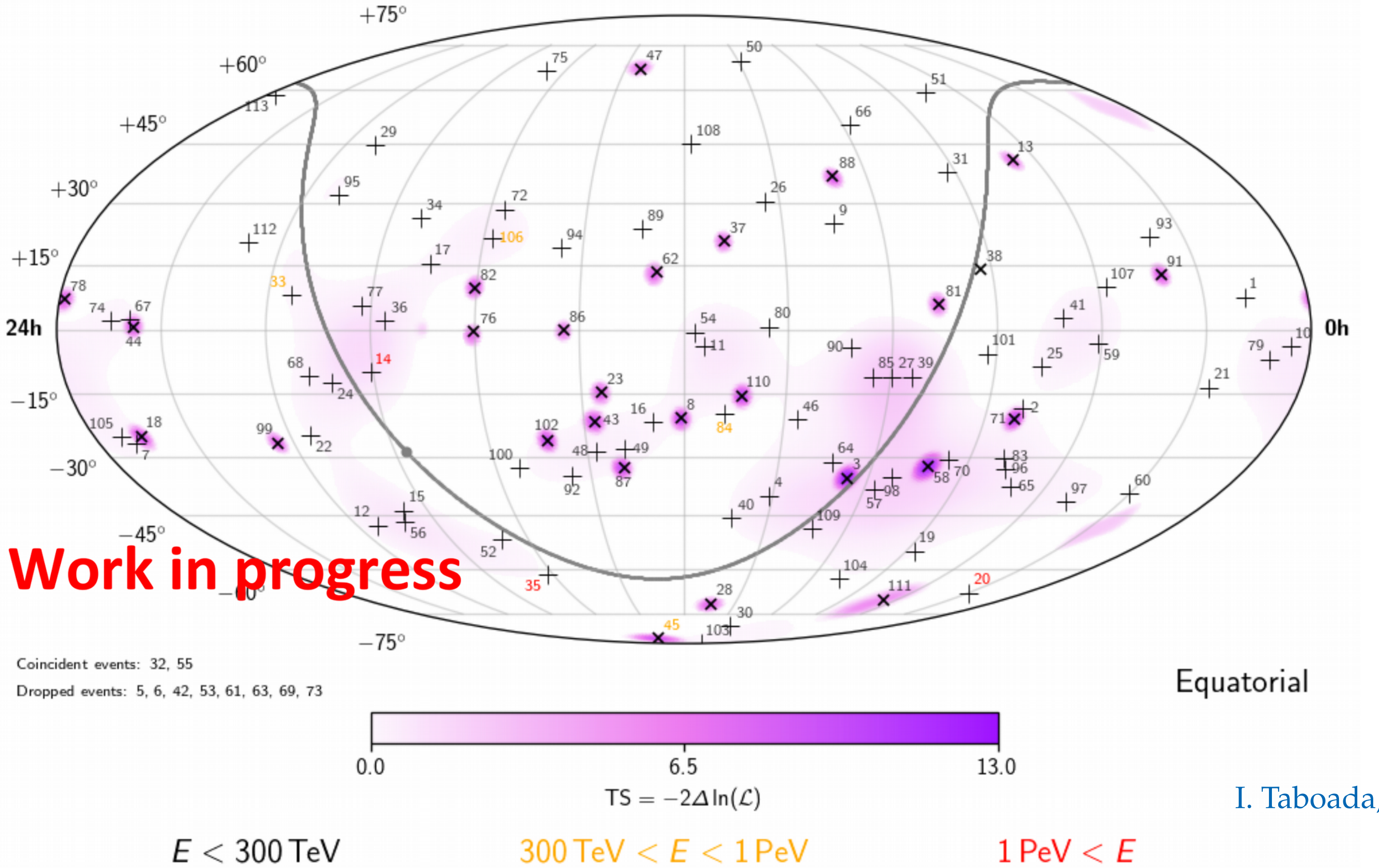
What has IceCube found so far (7.5 years)?

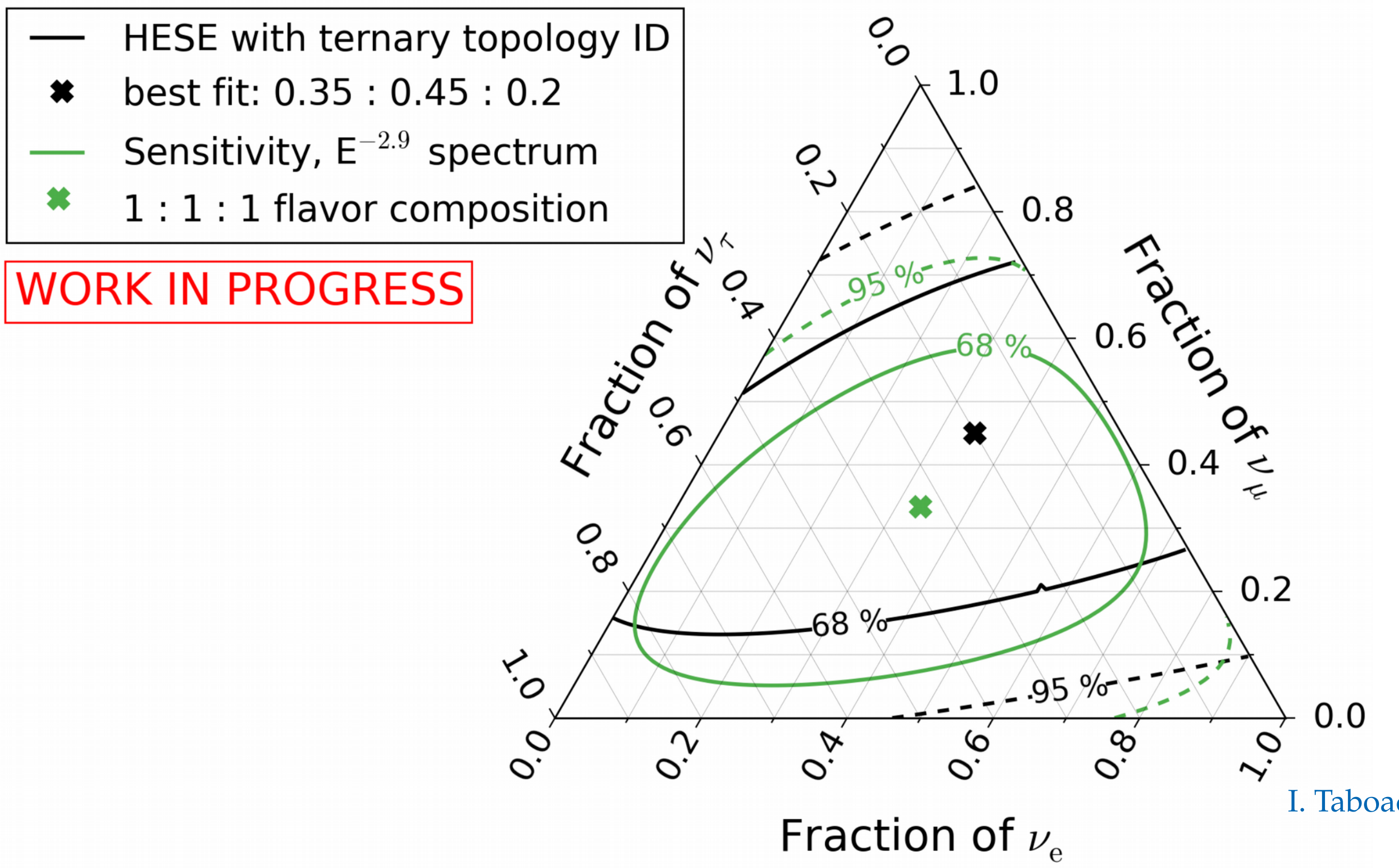
Arrival directions compatible with isotropy



I. Taboada, Neutrino 2018

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,
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 cosmic neutrinos

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

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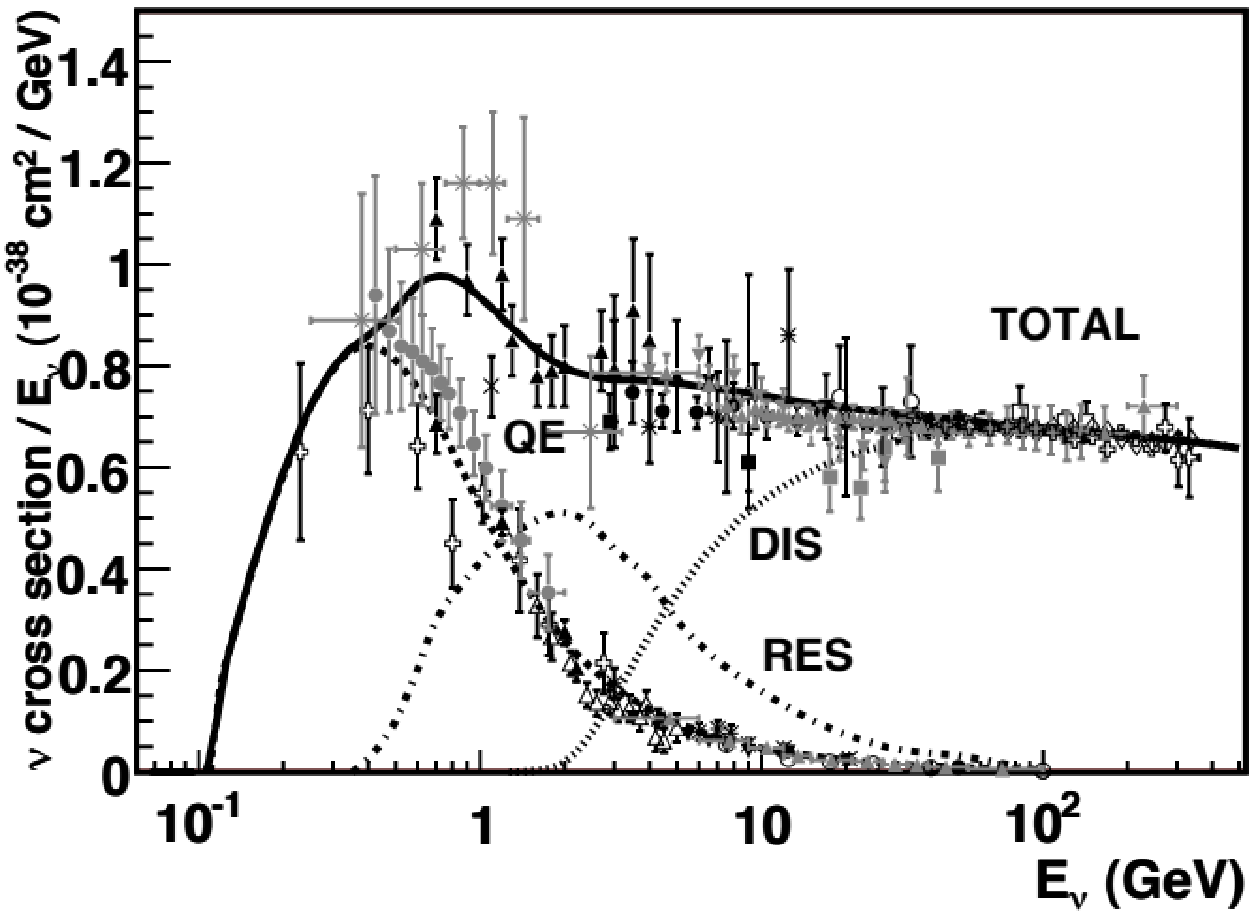
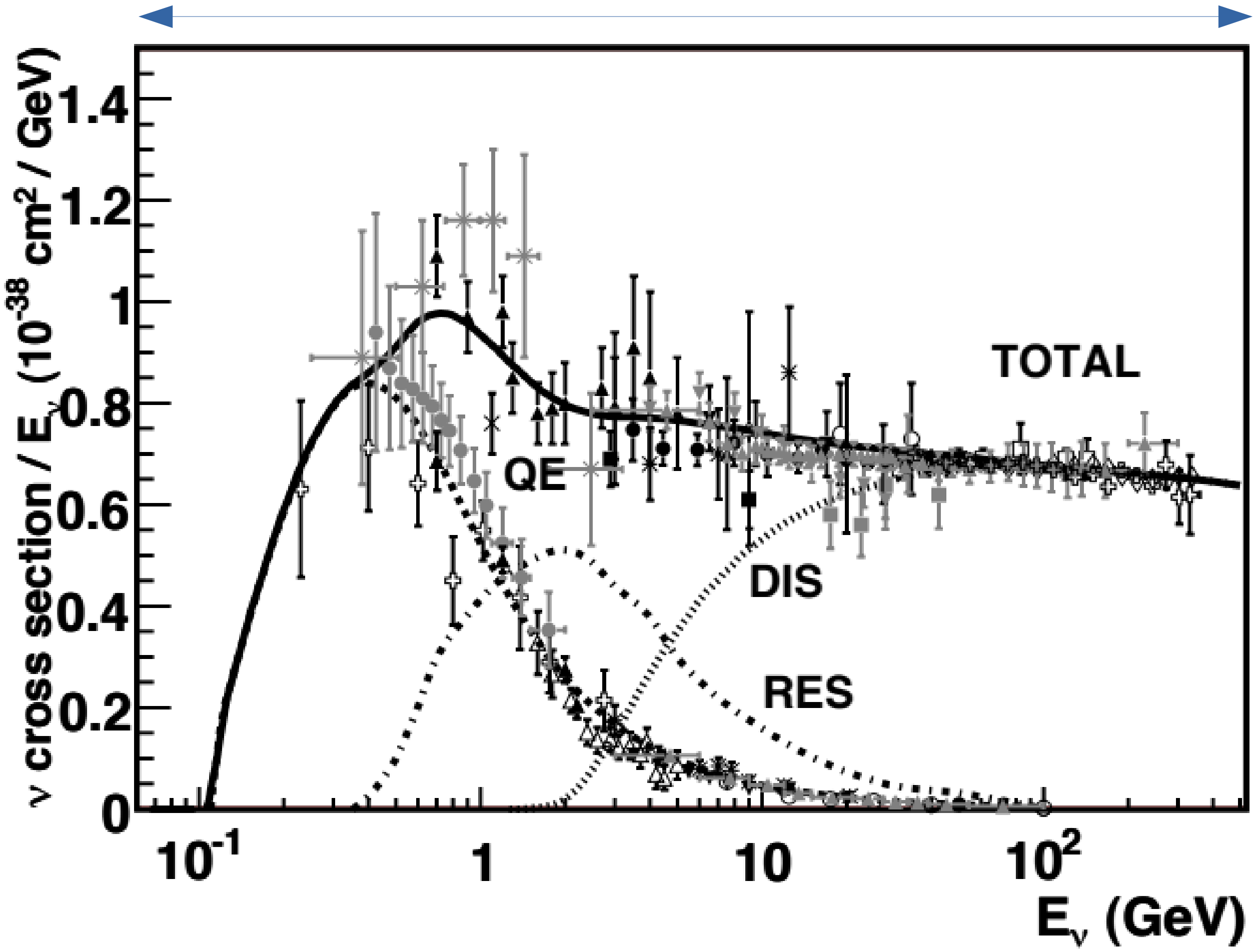
  In spite of
  poor energy, angular, flavor reconstruction
  & astrophysical unknowns



Particle Data Group

Accelerator experiments



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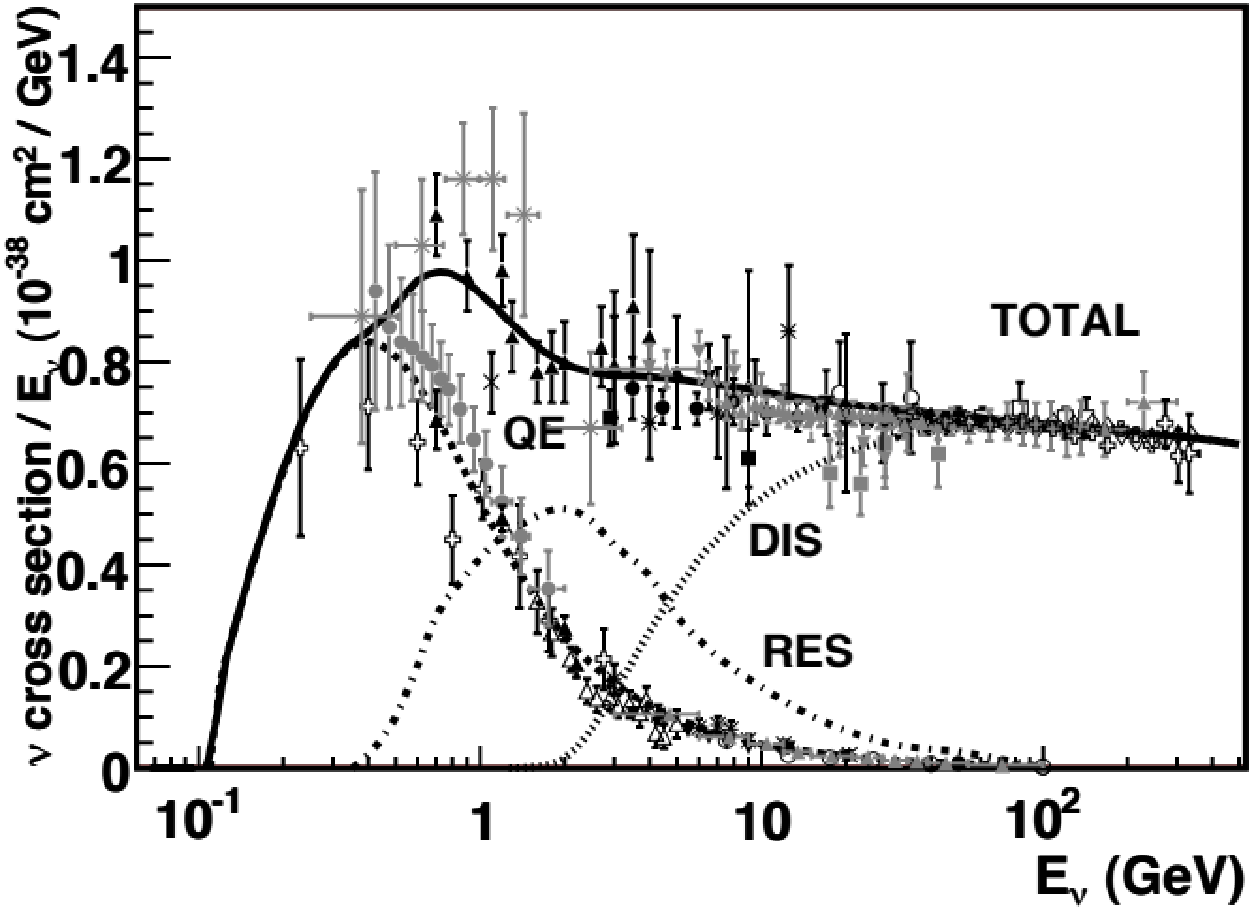
Accelerator experiments

One recent measurement (COHERENT)



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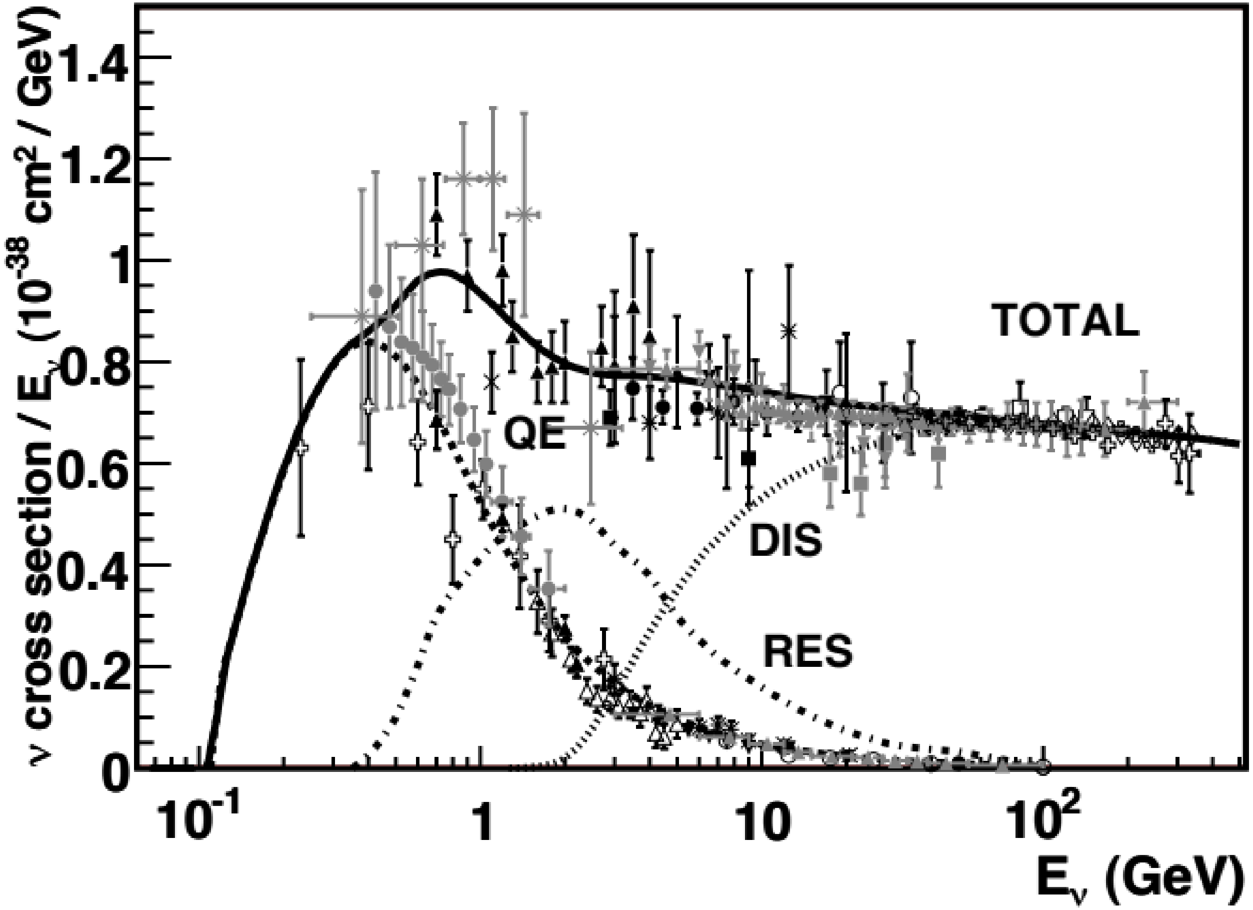

No measurements

… until now!

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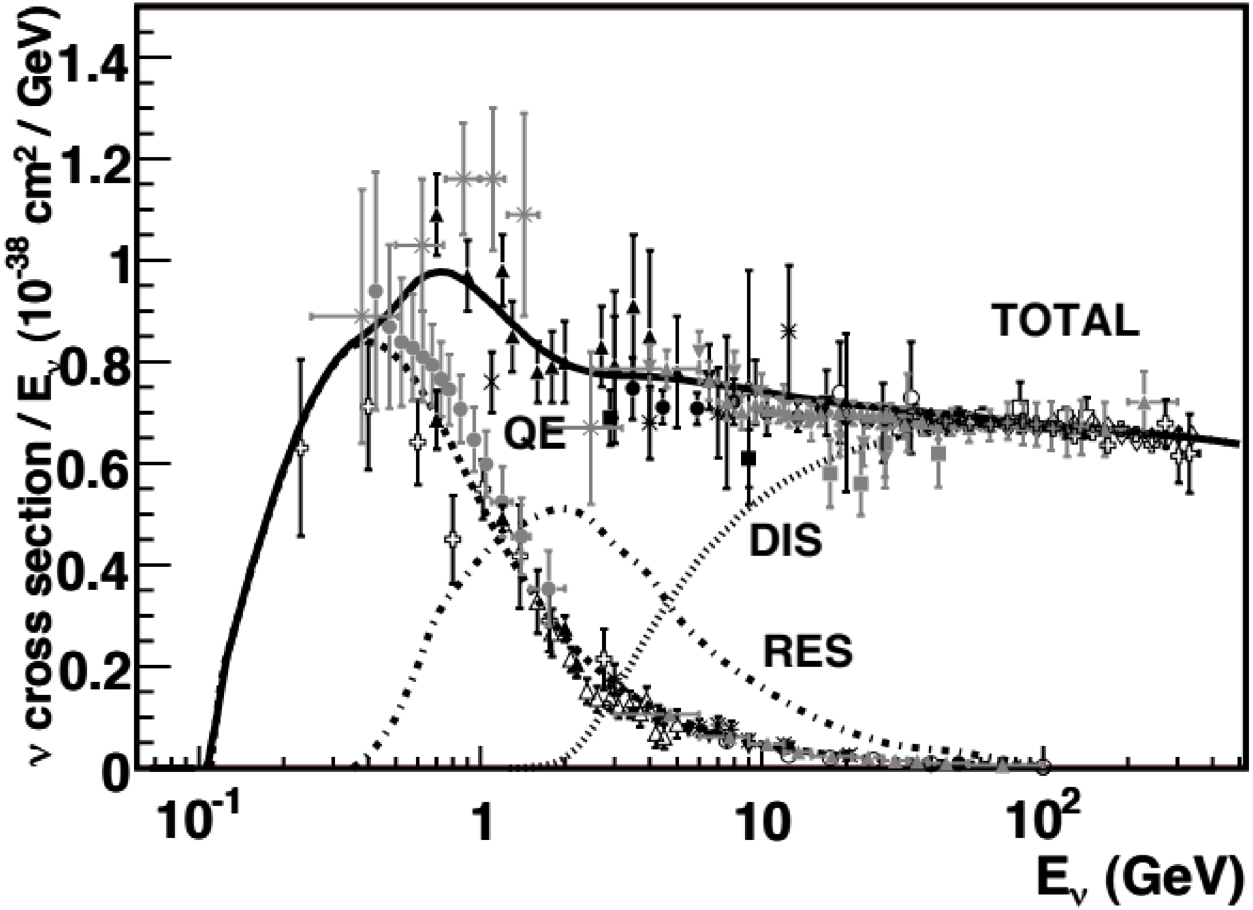

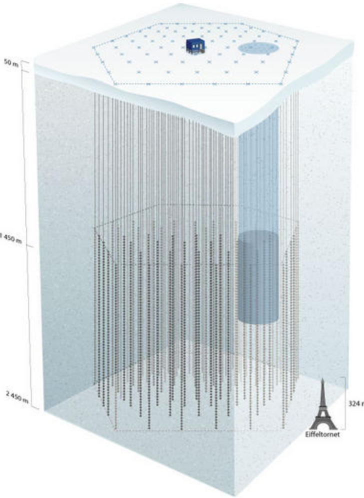

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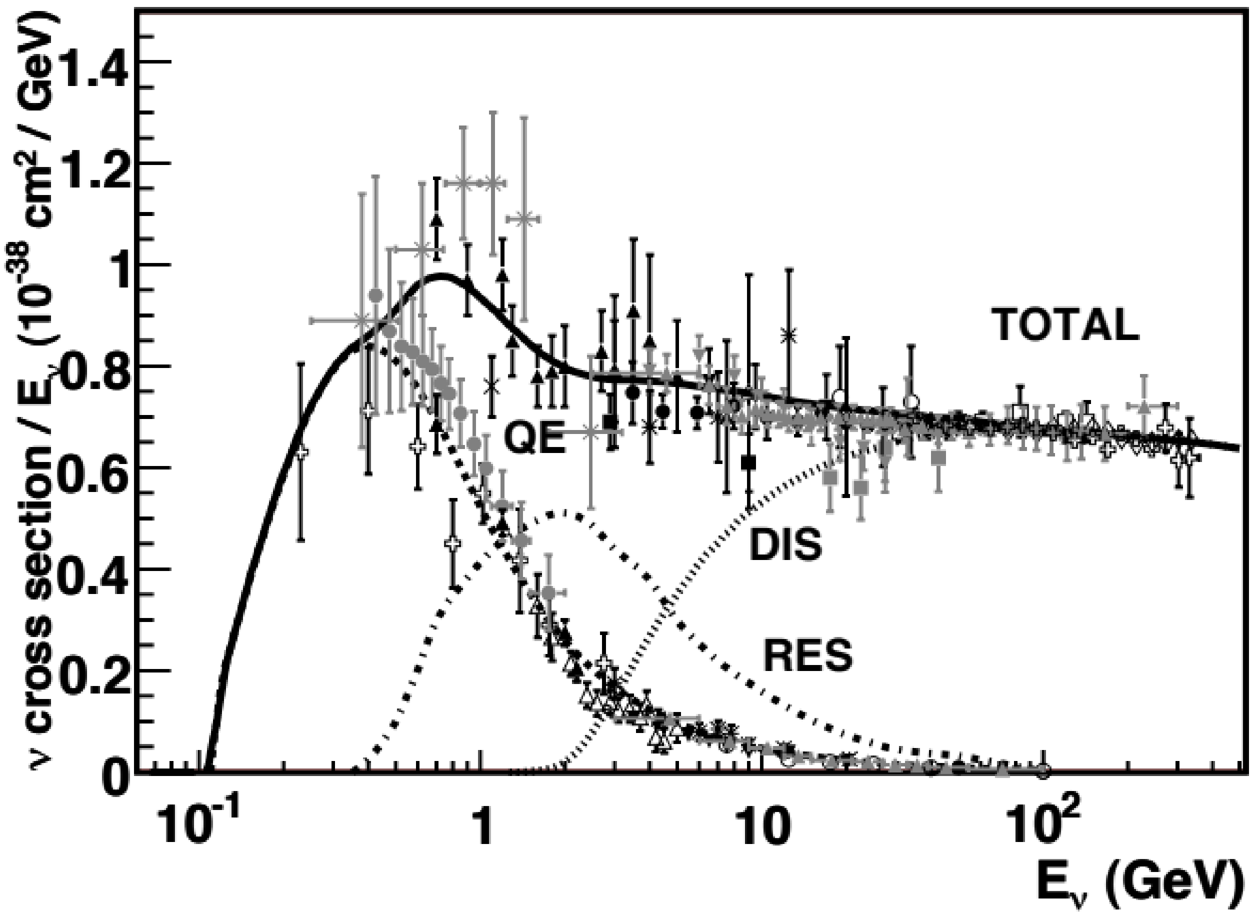
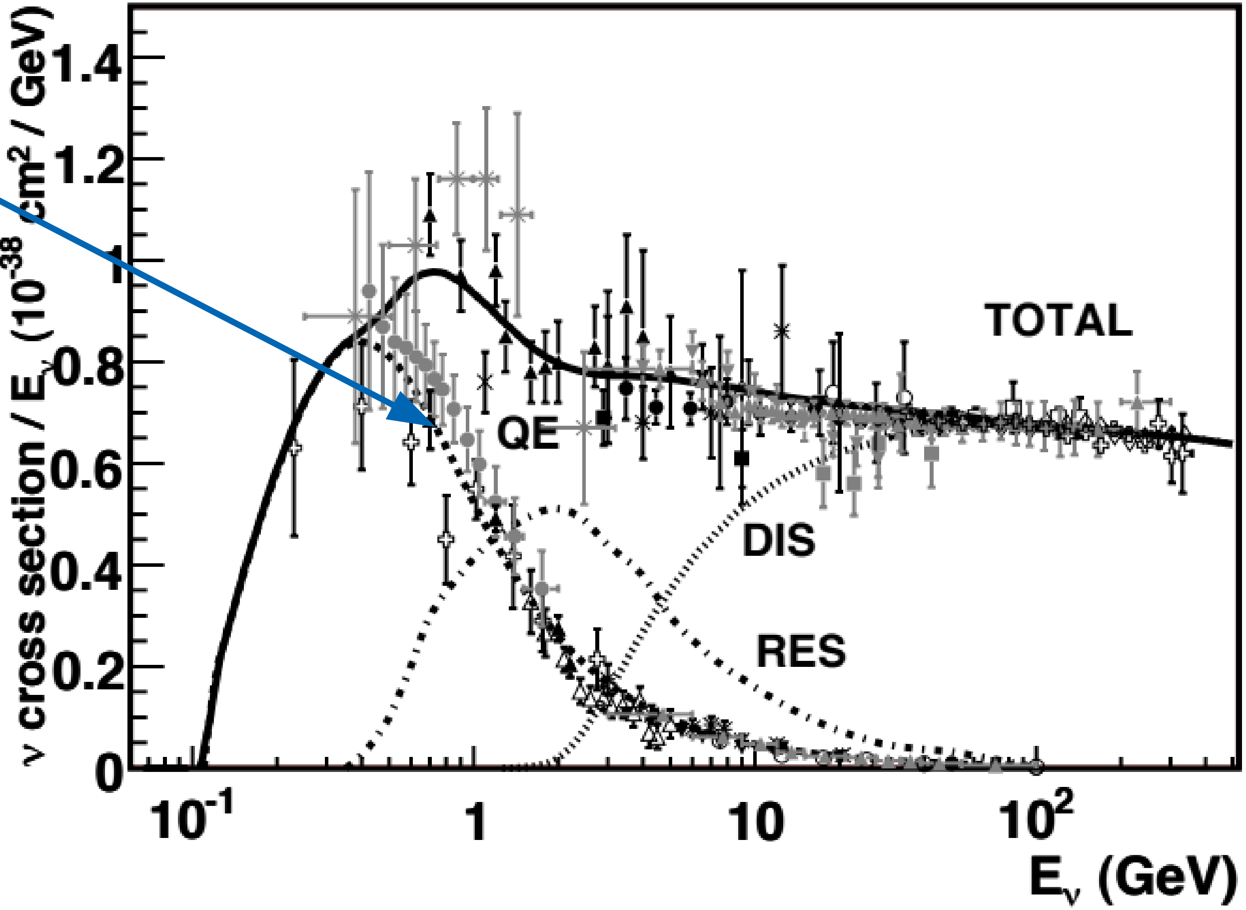


Particle Data Group

Quasi-elastic scattering:

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

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



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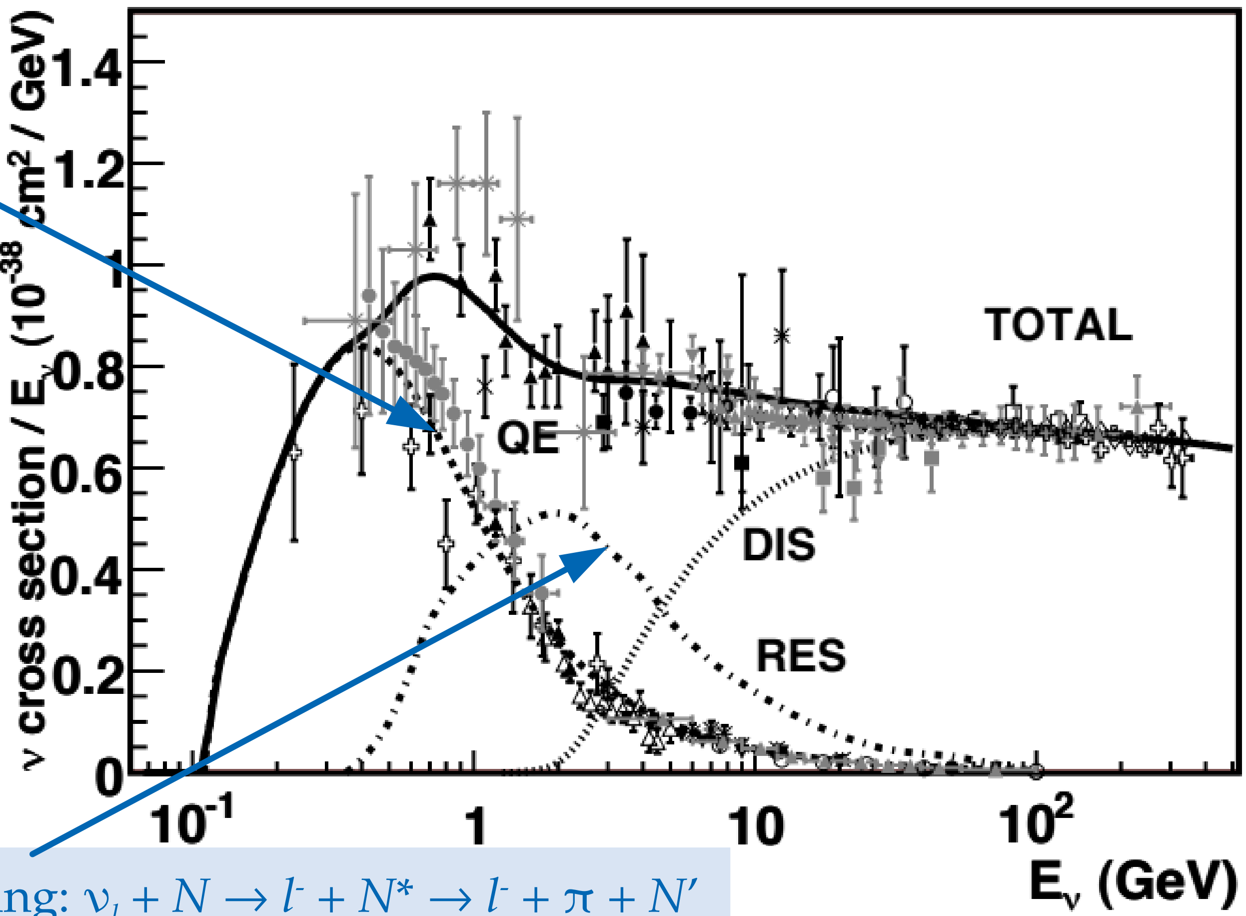

Resonant scattering: $\nu_l + N \rightarrow l^- + N^* \rightarrow l^- + \pi + N'$

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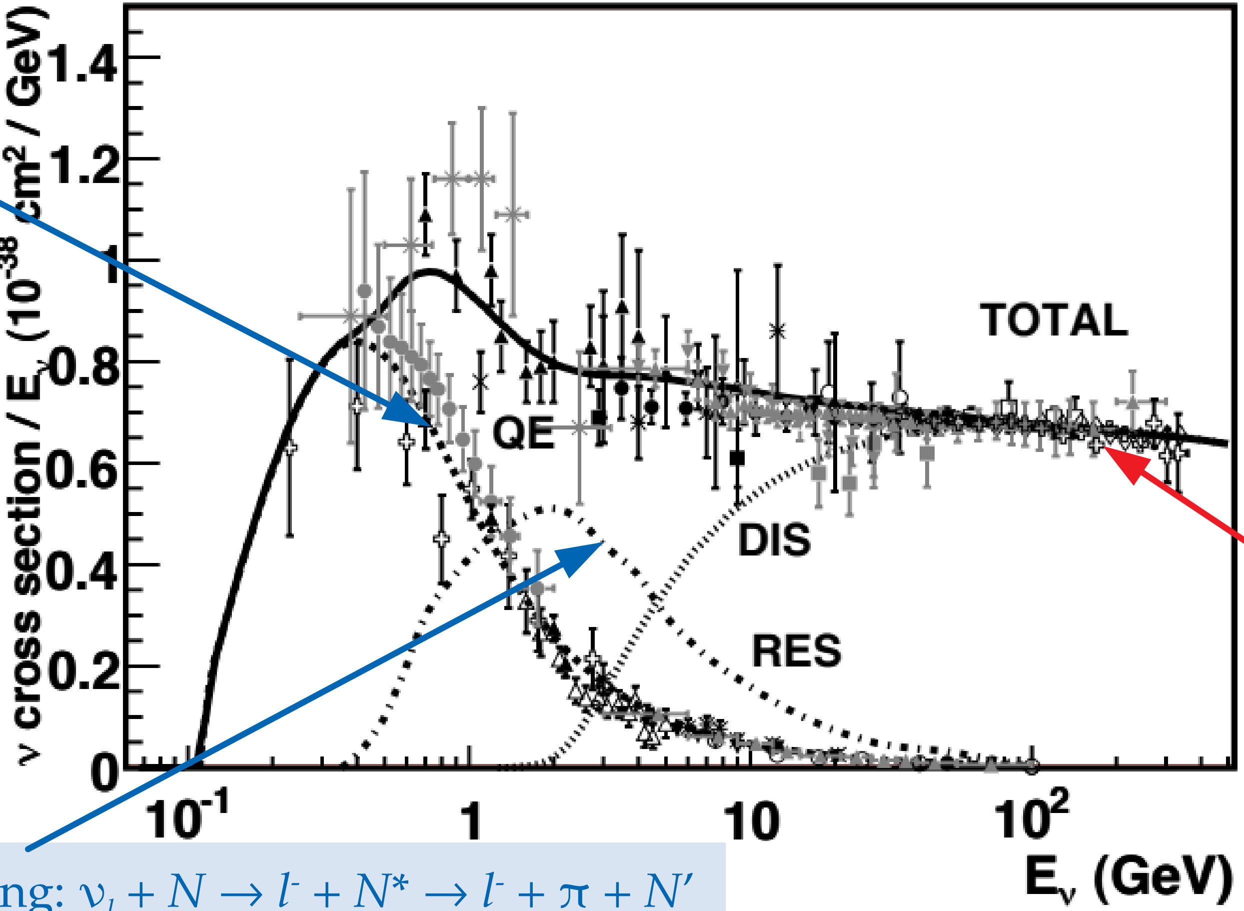

Particle Data Group

Deep inelastic scattering:

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

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

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

Extrapolating the cross section to high energies

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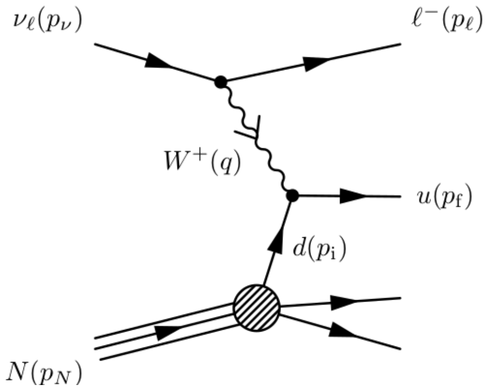
SM



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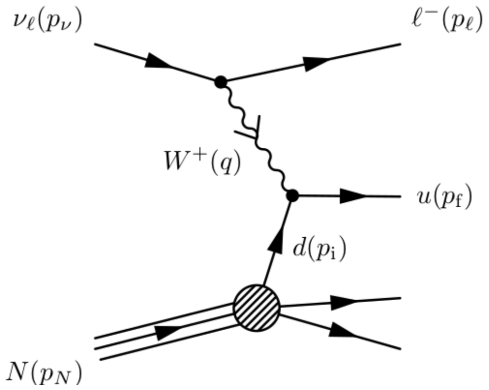

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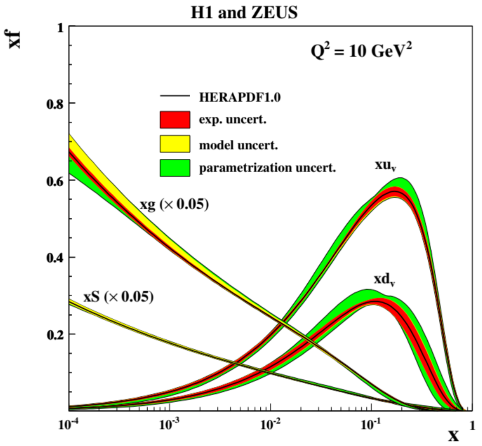
PDFs



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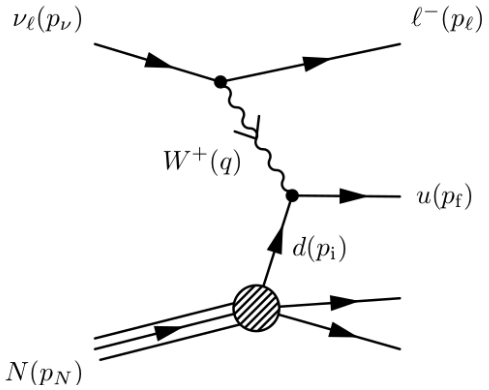

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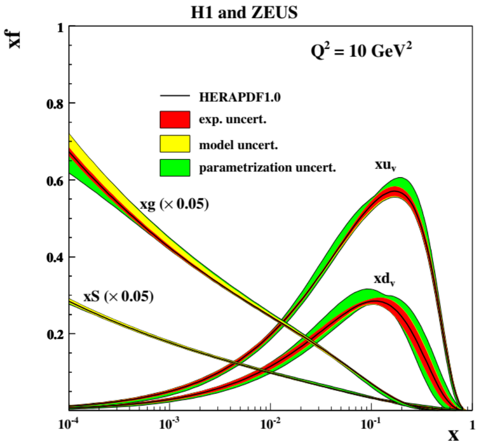

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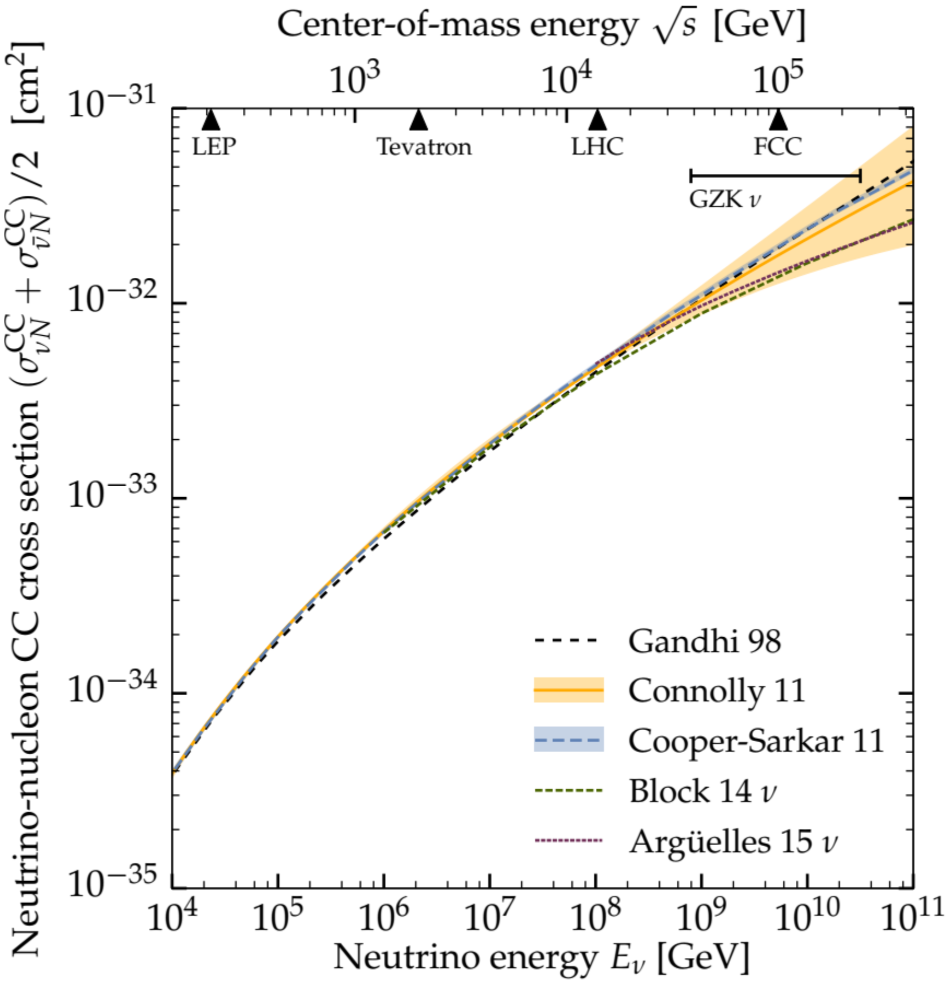

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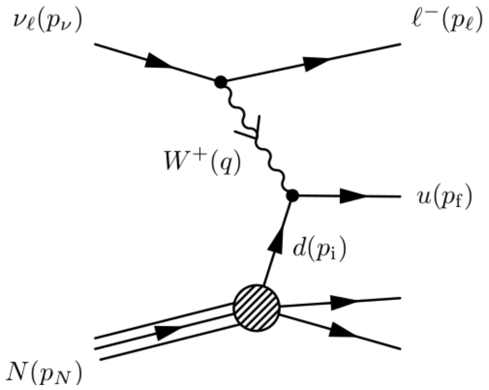

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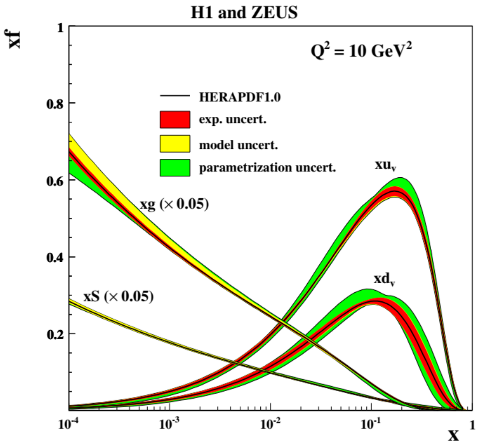

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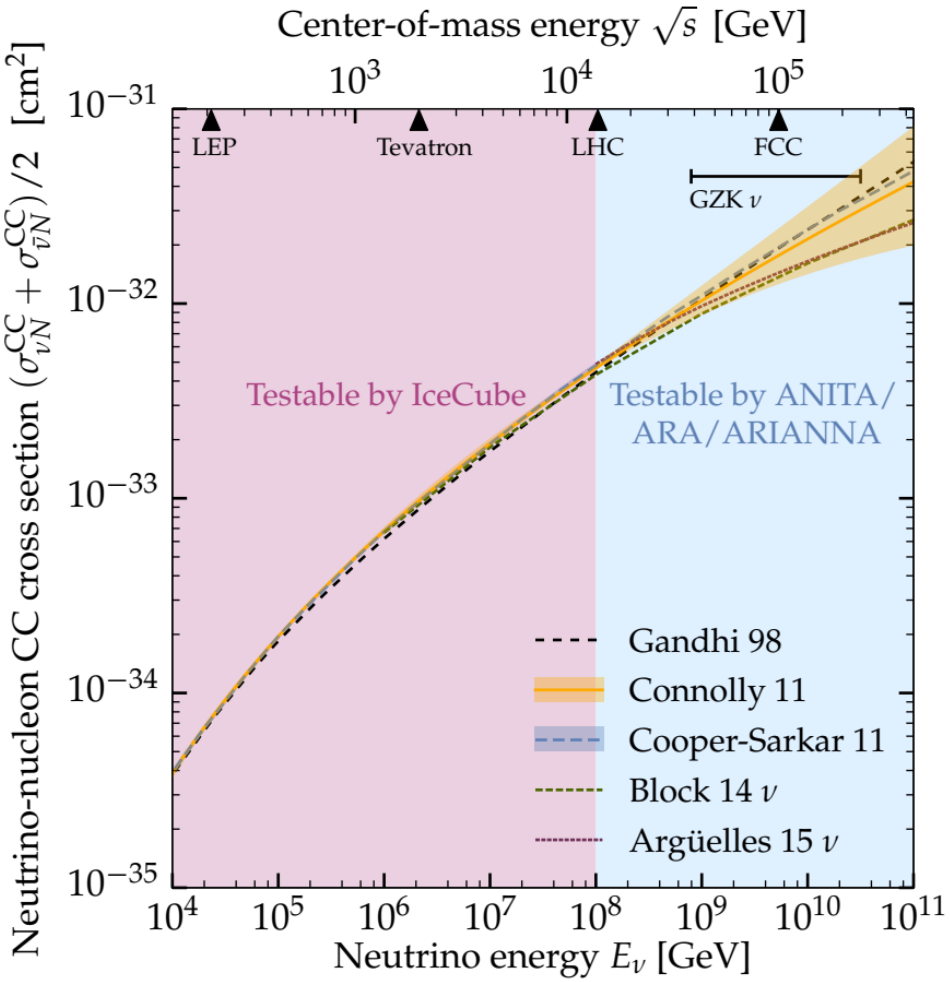
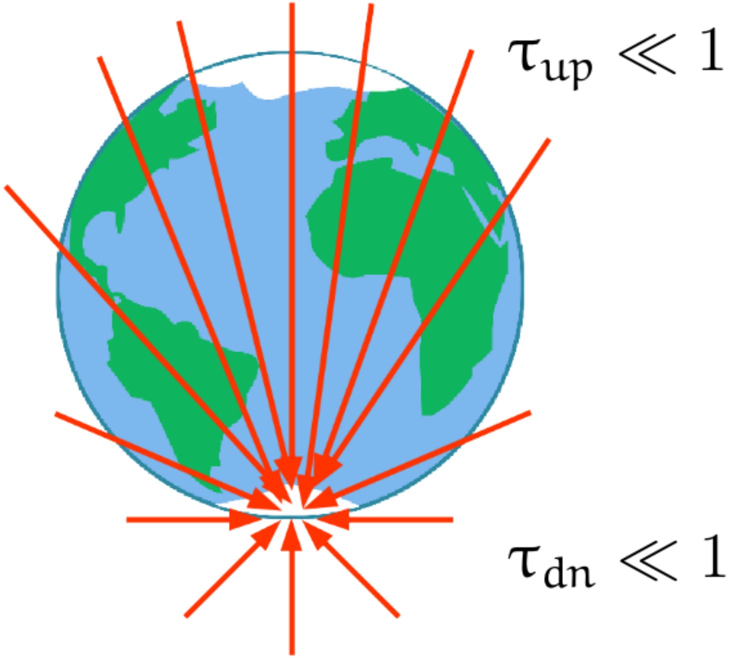


Measuring the high-energy cross section

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

Below ~ 10 TeV: Earth is transparent



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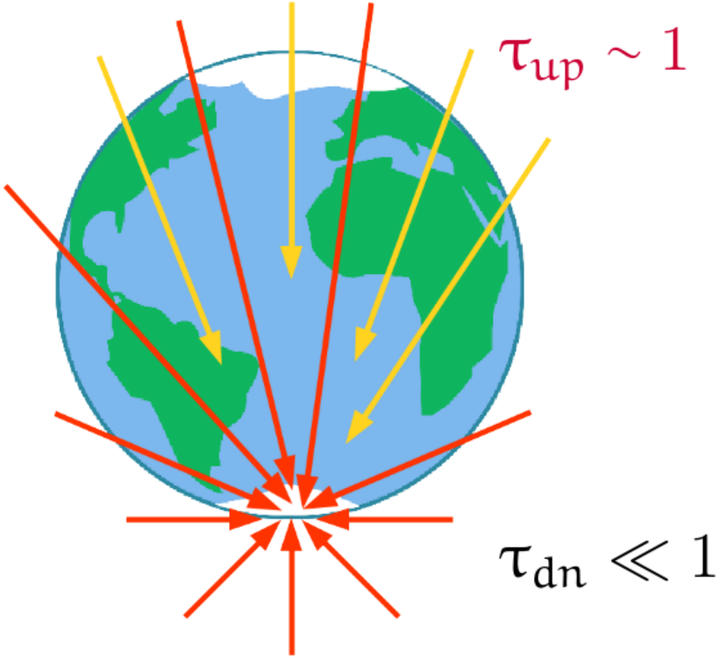

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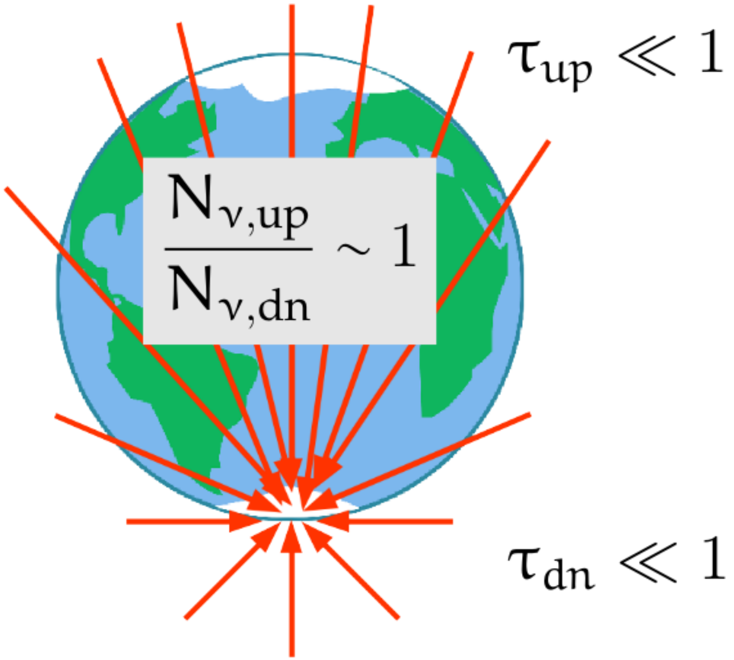

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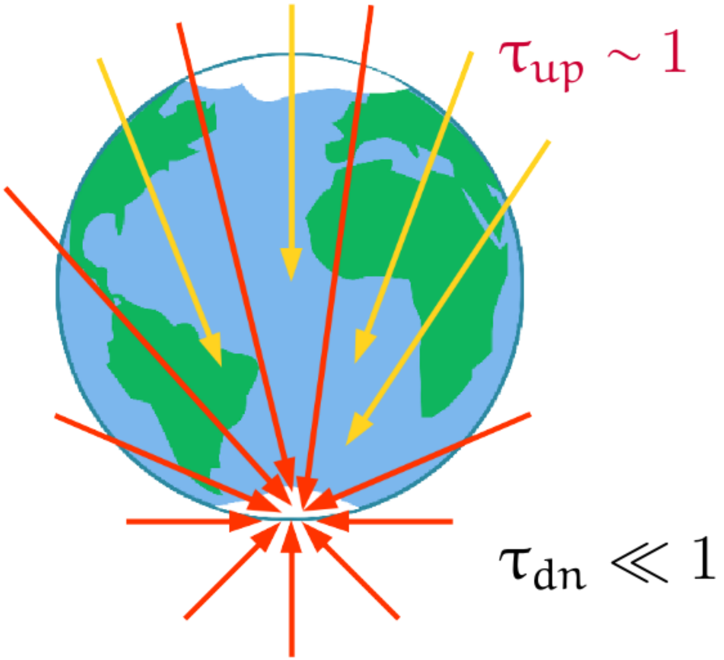

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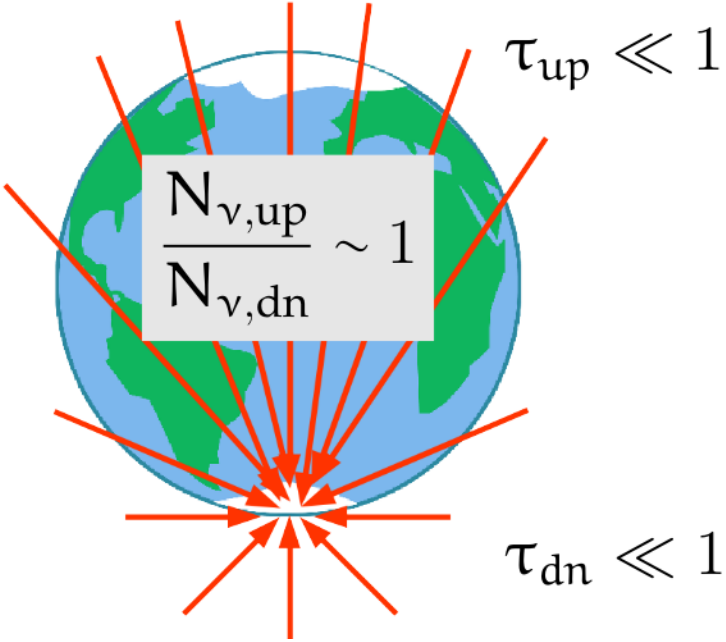

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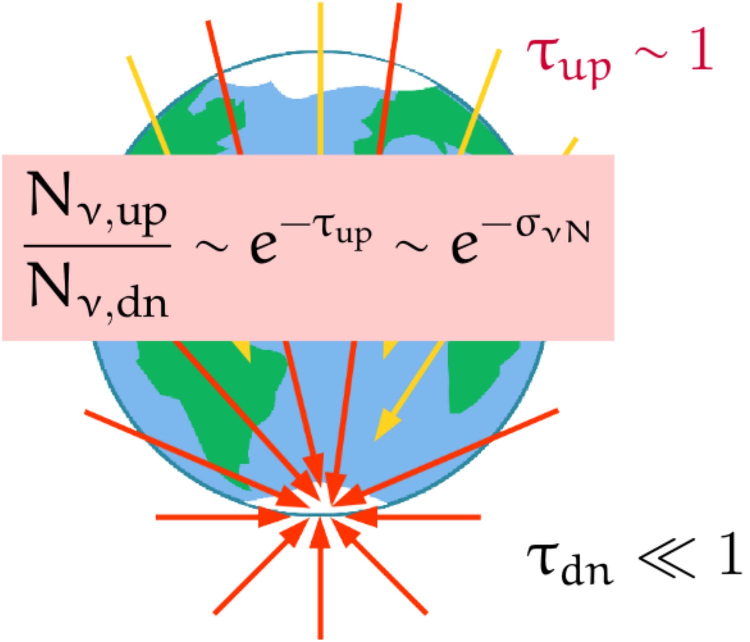
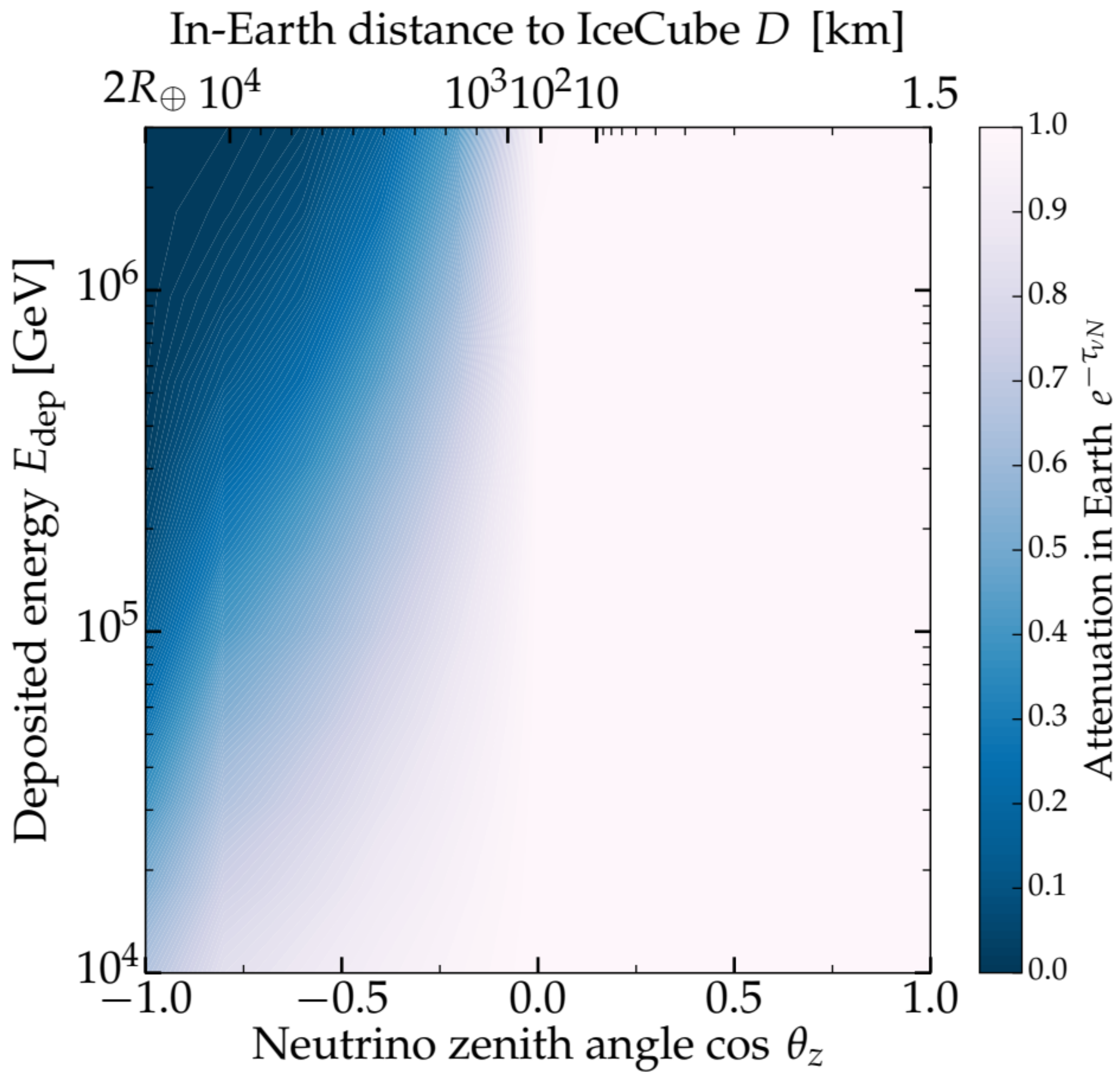
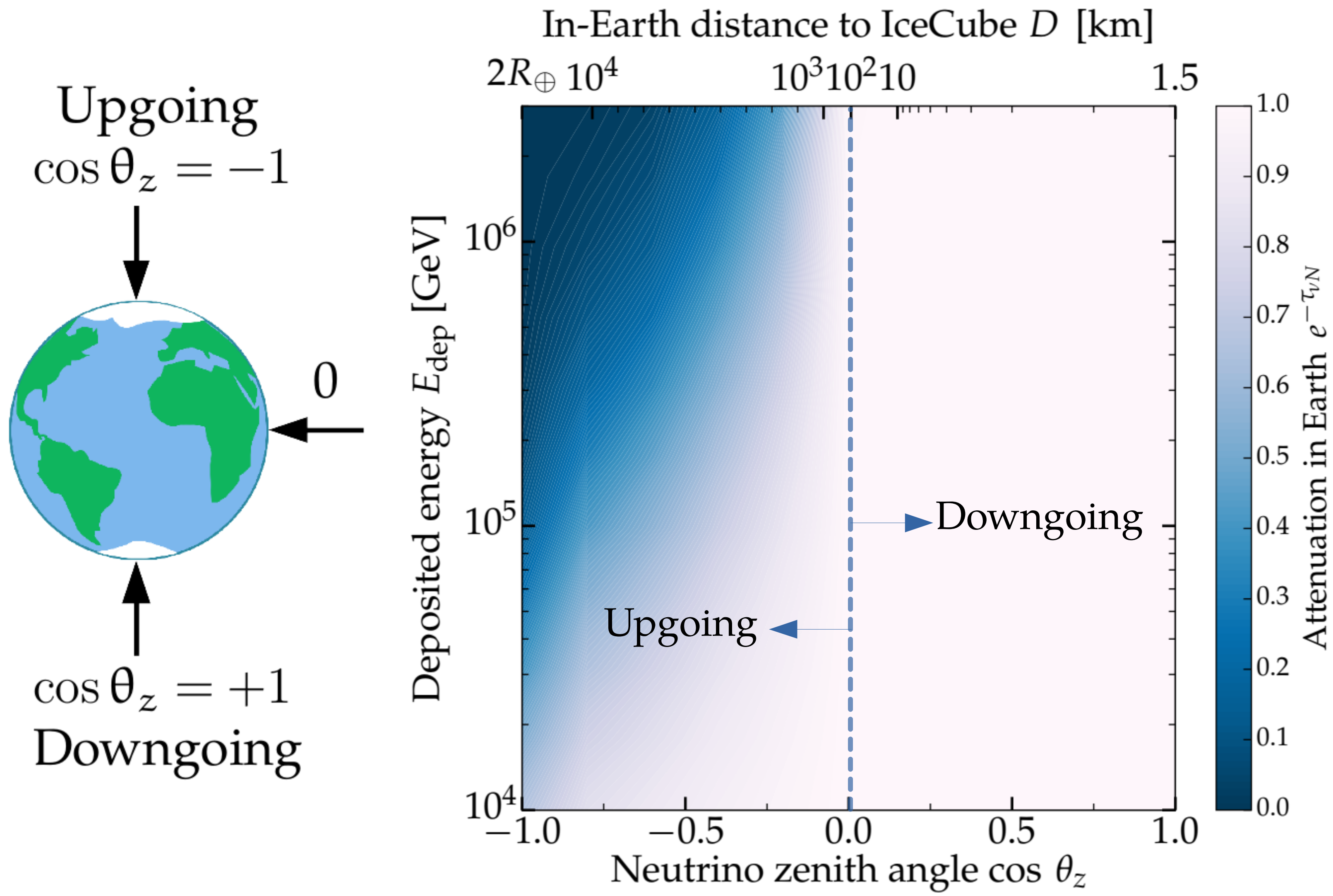
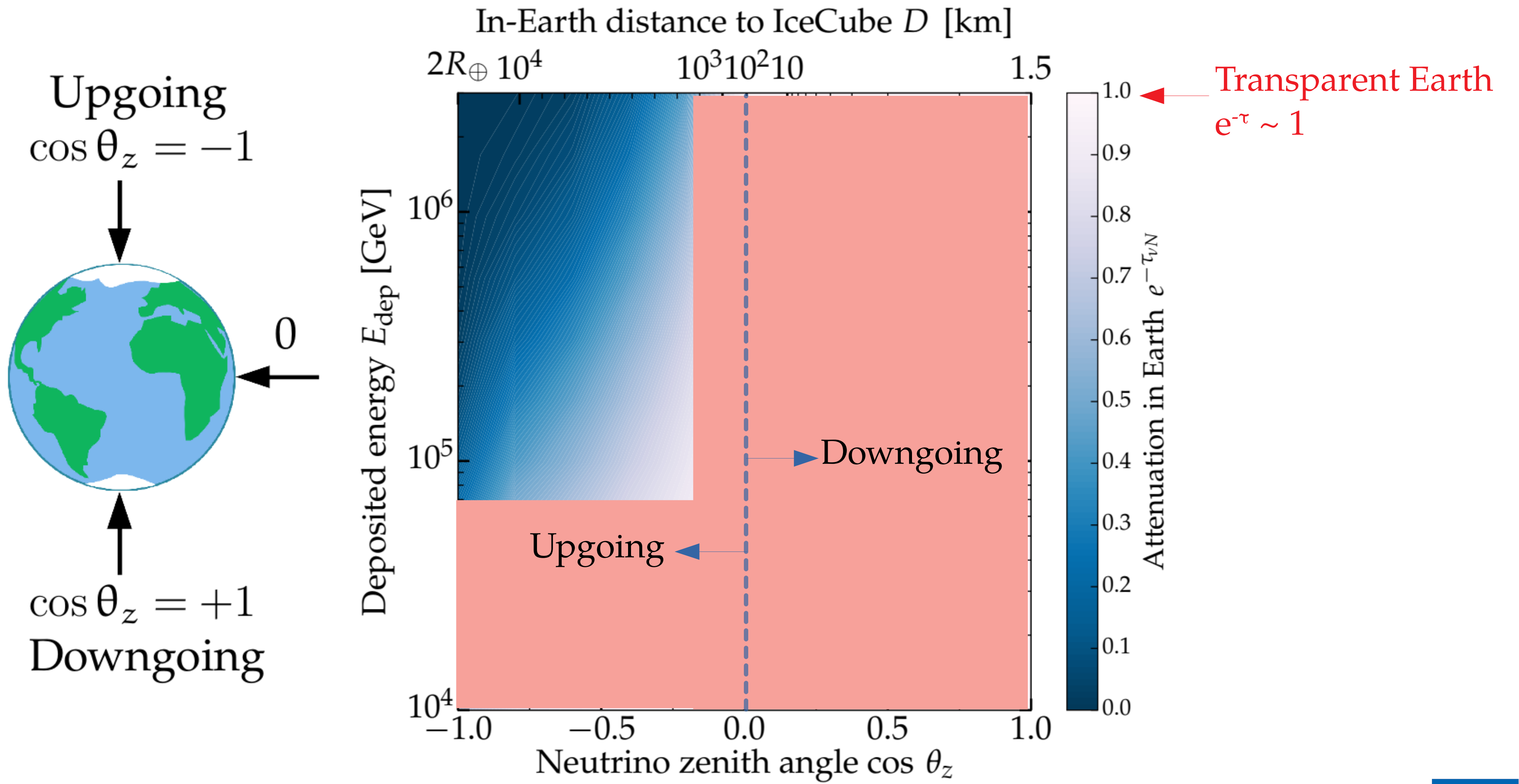


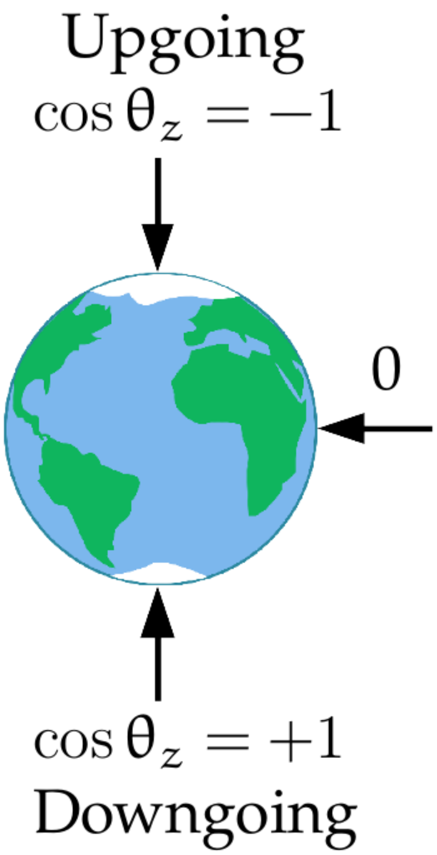

In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4 10^3 10^2 10 1.5
Deposited energy $E_{\rm dep}$ [GeV]
10^6
10^5
10^4
−1.0 −0.5 0.0 0.5 1.0
Neutrino zenith angle cos θ_z
1.0 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0.0
Attenuation in Earth $e^{-\tau_{\nu N}}$

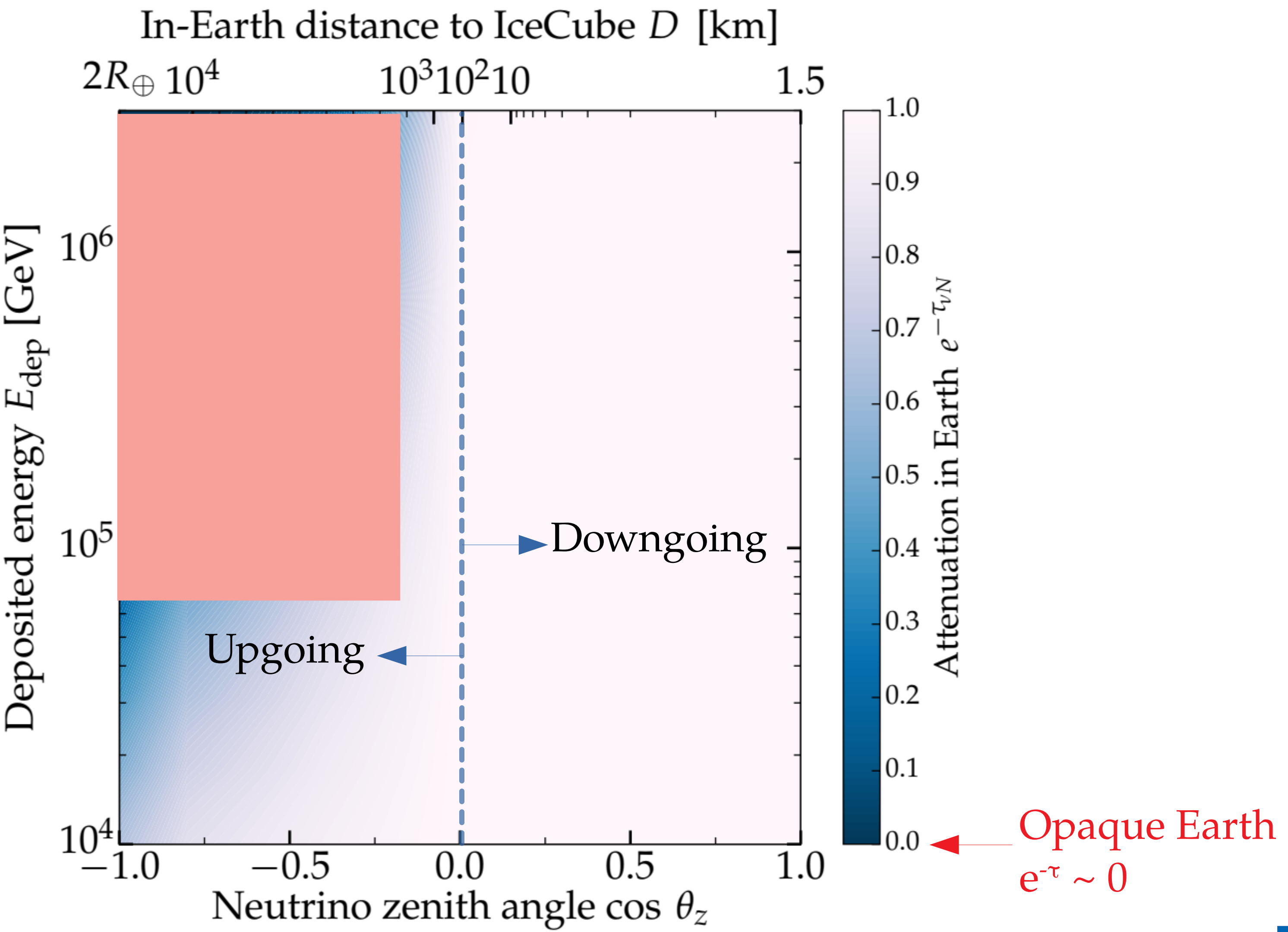


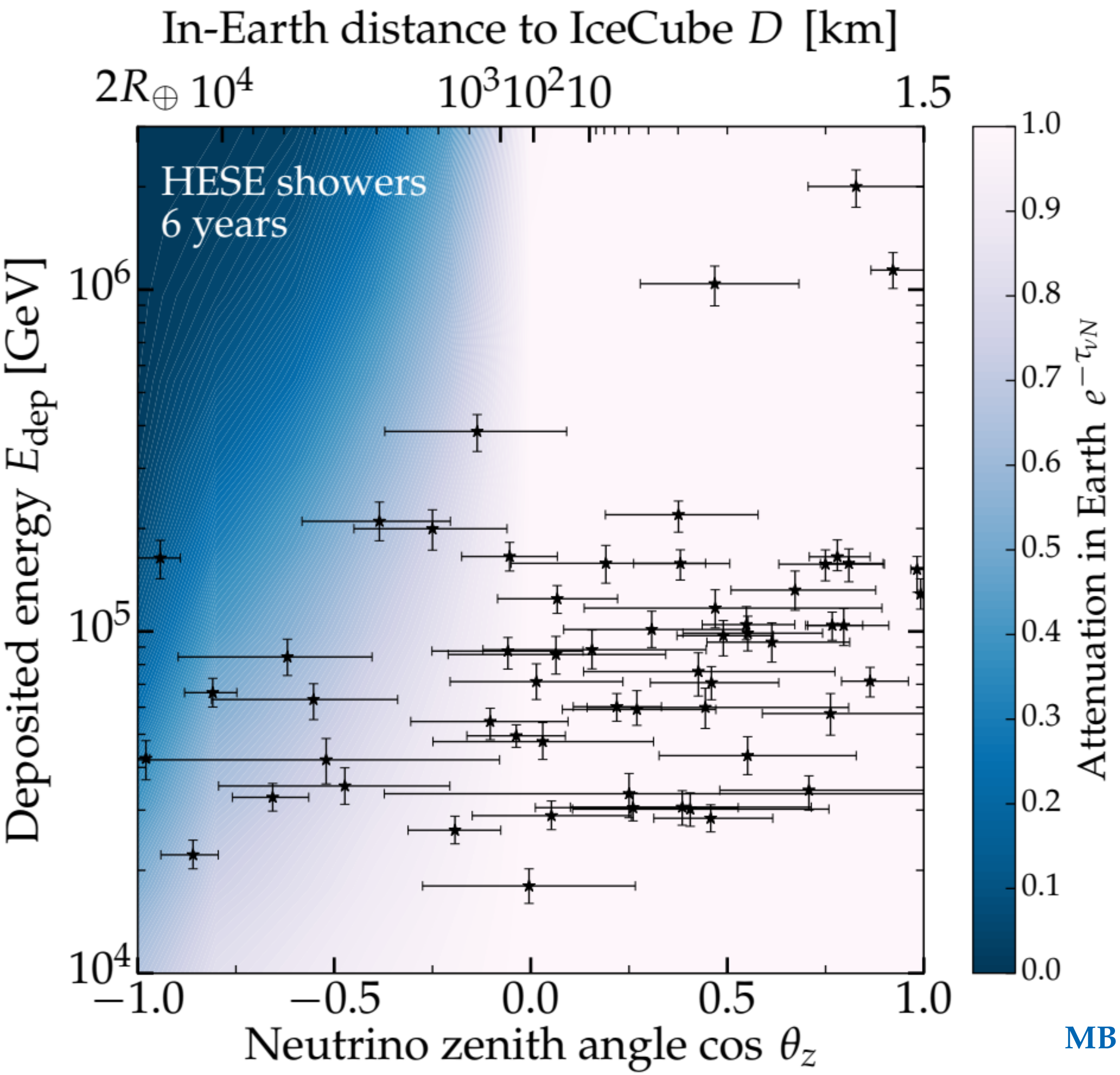
Upgoing
$\cos\theta_z = -1$
0
$\cos\theta_z = +1$
Downgoing
In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4 10^3 10^2 10 1.5
Deposited energy $E_{\rm dep}$ [GeV]
10^6
10^5
10^4
Downgoing
Upgoing
−1.0 −0.5 0.0 0.5 1.0
Neutrino zenith angle cos θ_z
Attenuation in Earth $e^{-\tau_{\nu N}}$
1.0 0.9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



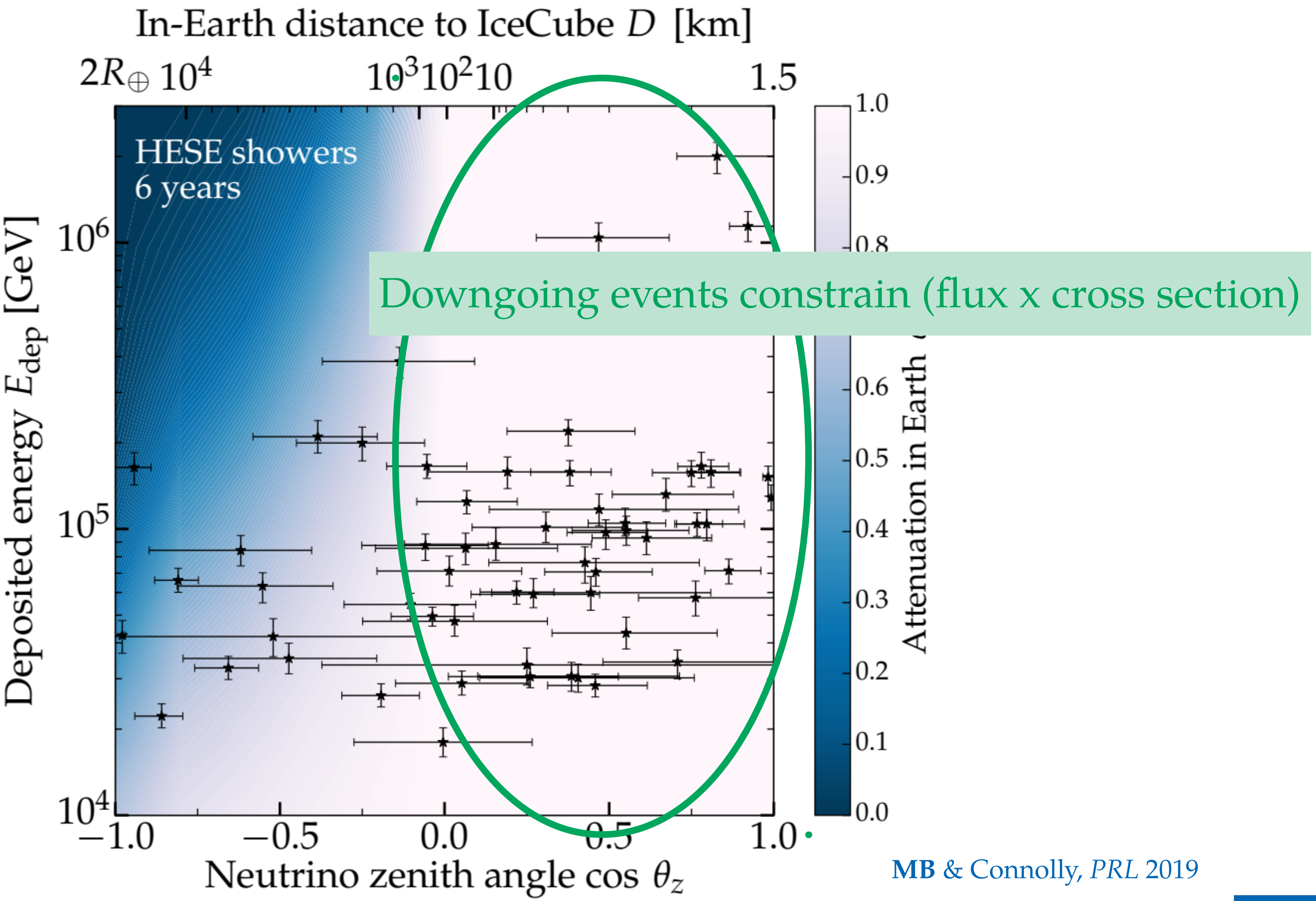
Upgoing
cos θz = −1
0
cos θz = +1
Downgoing
In-Earth distance to IceCube D [km]
2R⊕ 10^4
10^3 10^2 10
1.5
Deposited energy E_dep [GeV]
10^6
10^5
10^4
Downgoing
Upgoing
−1.0
−0.5
0.0
0.5
1.0
Neutrino zenith angle cos θz
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Attenuation in Earth e^−τνN
Transparent Earth
e^-τ ~ 1


Upgoing
$\cos\theta_z = -1$
0
$\cos\theta_z = +1$
Downgoing

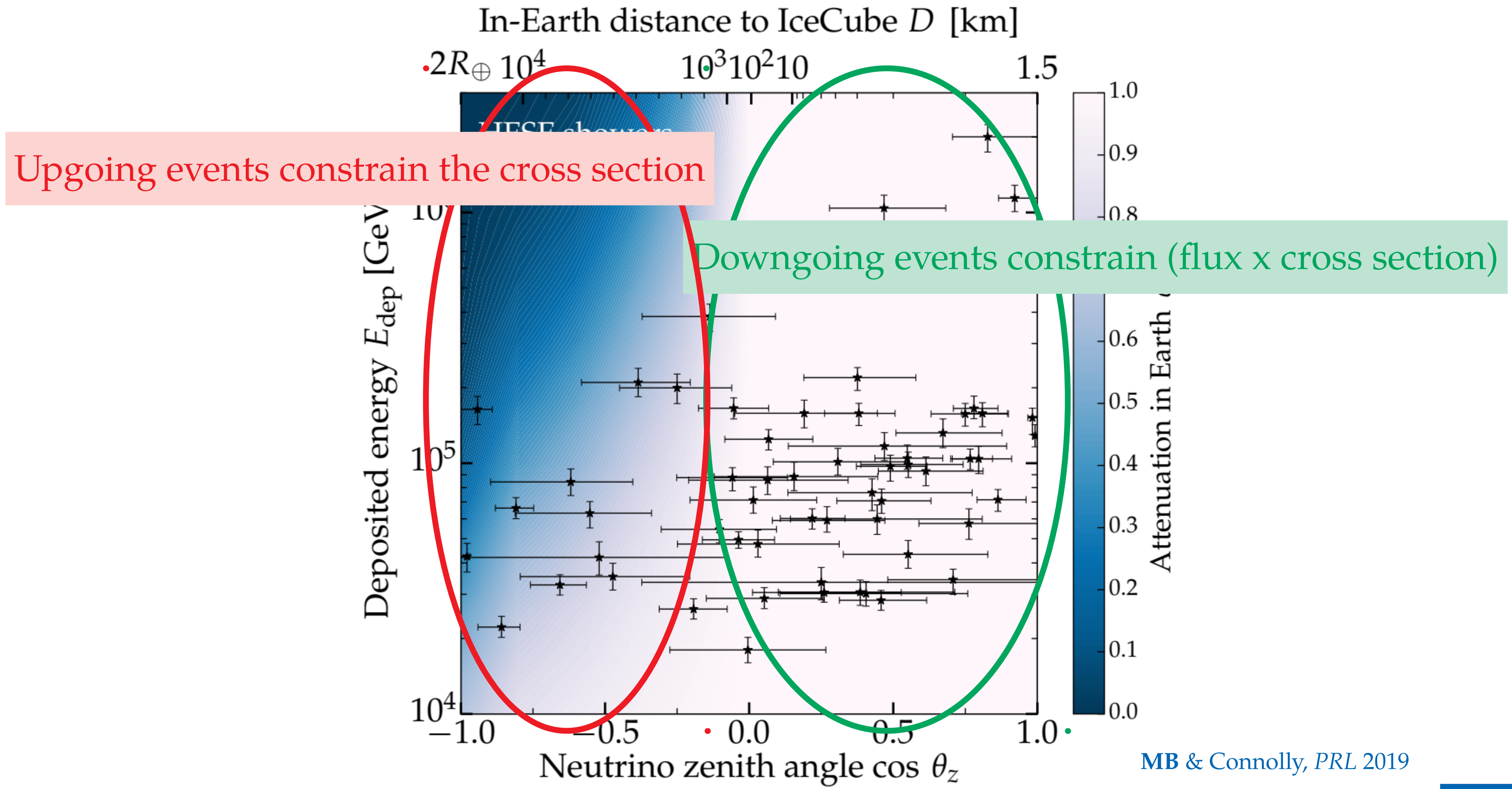

In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4 10^3 10^2 10 1.5
Deposited energy E_{dep} [GeV]
10^6
10^5
10^4
Downgoing
Upgoing
−1.0 −0.5 0.0 0.5 1.0
Neutrino zenith angle cos θ_z
Attenuation in Earth $e^{-\tau_{\nu N}}$
1.0 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0.0
Opaque Earth
$e^{-\tau} \sim 0$



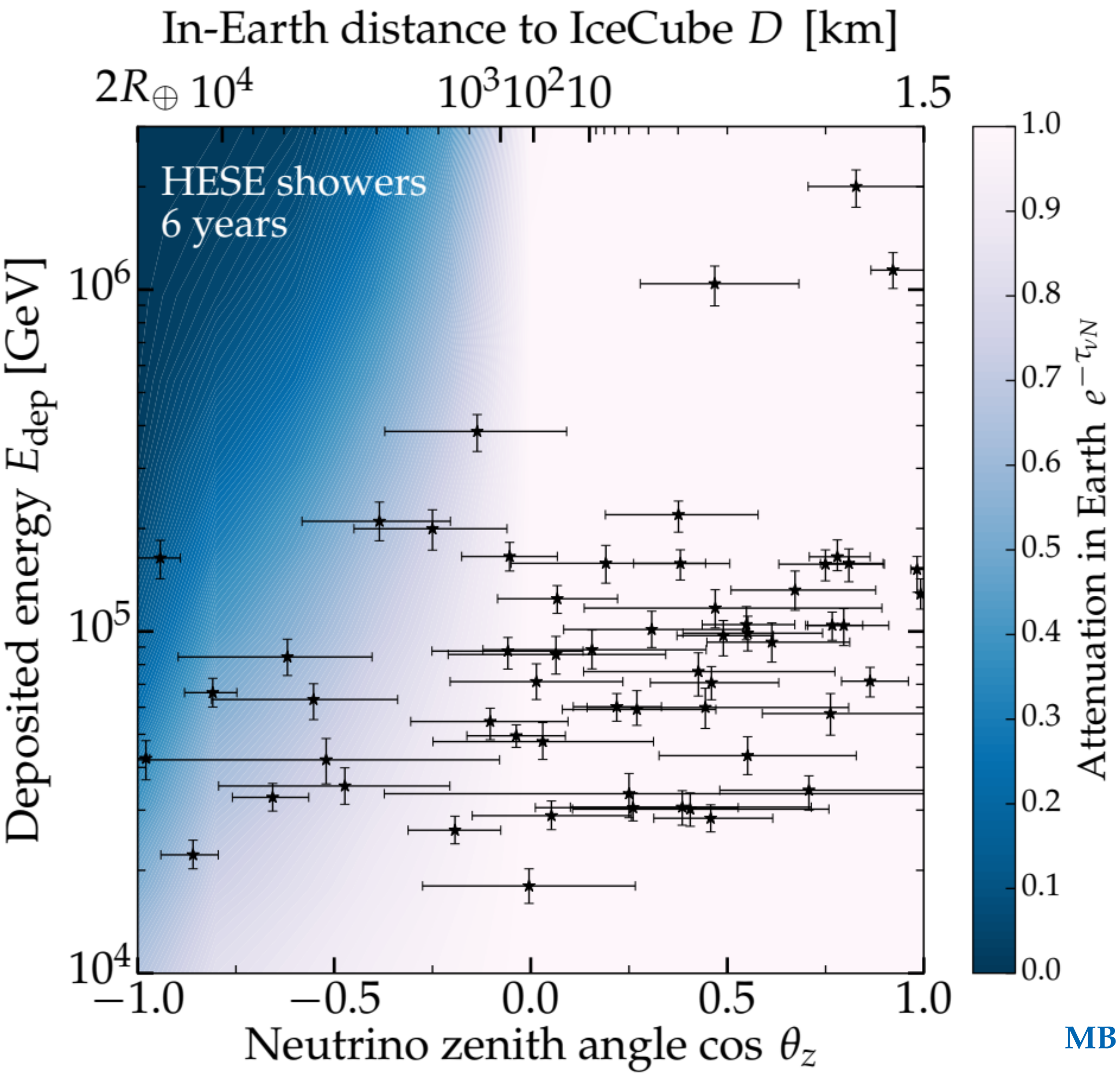
MB & Connolly, *PRL* 2019



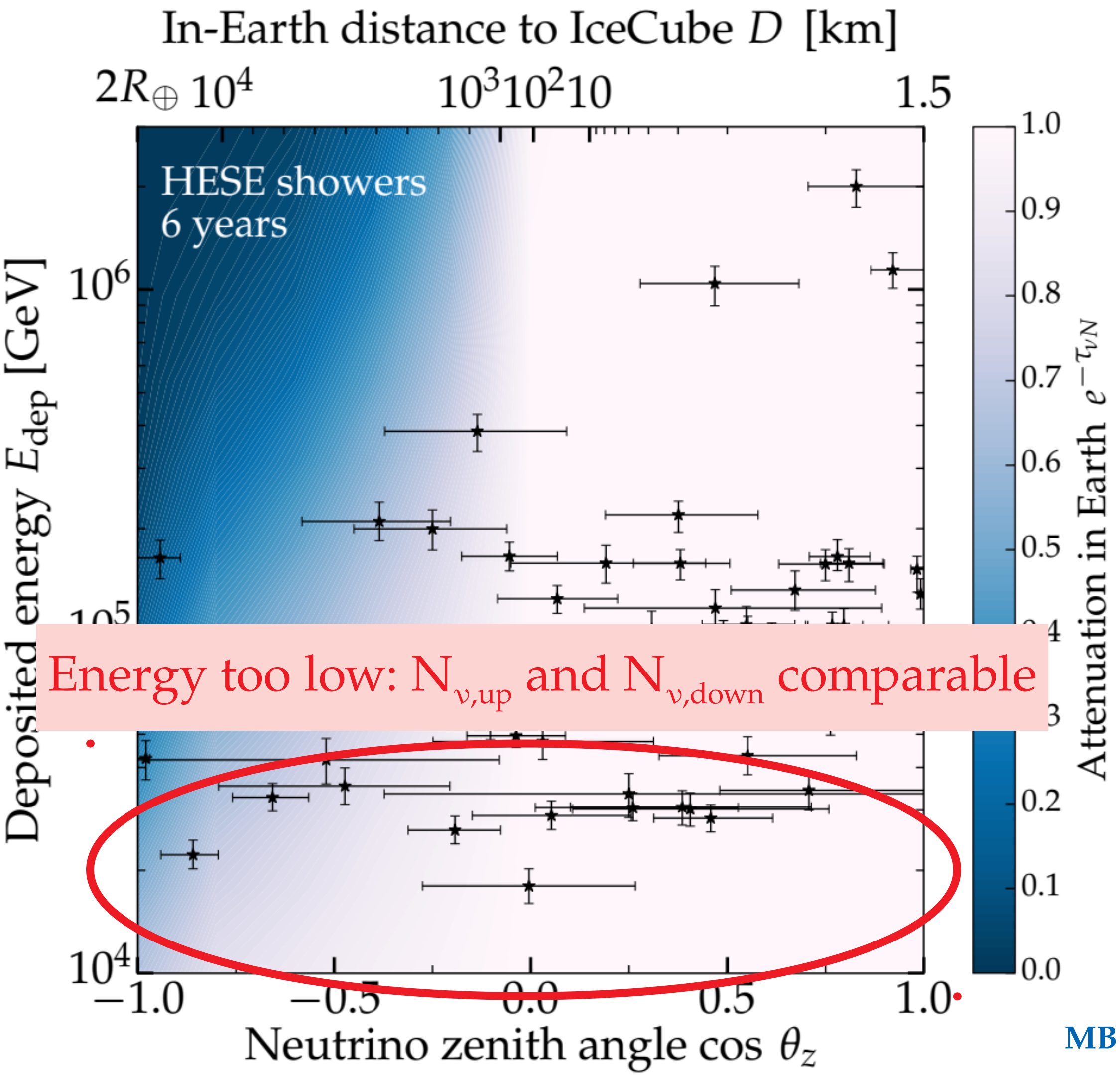
MB & Connolly, *PRL* 2019



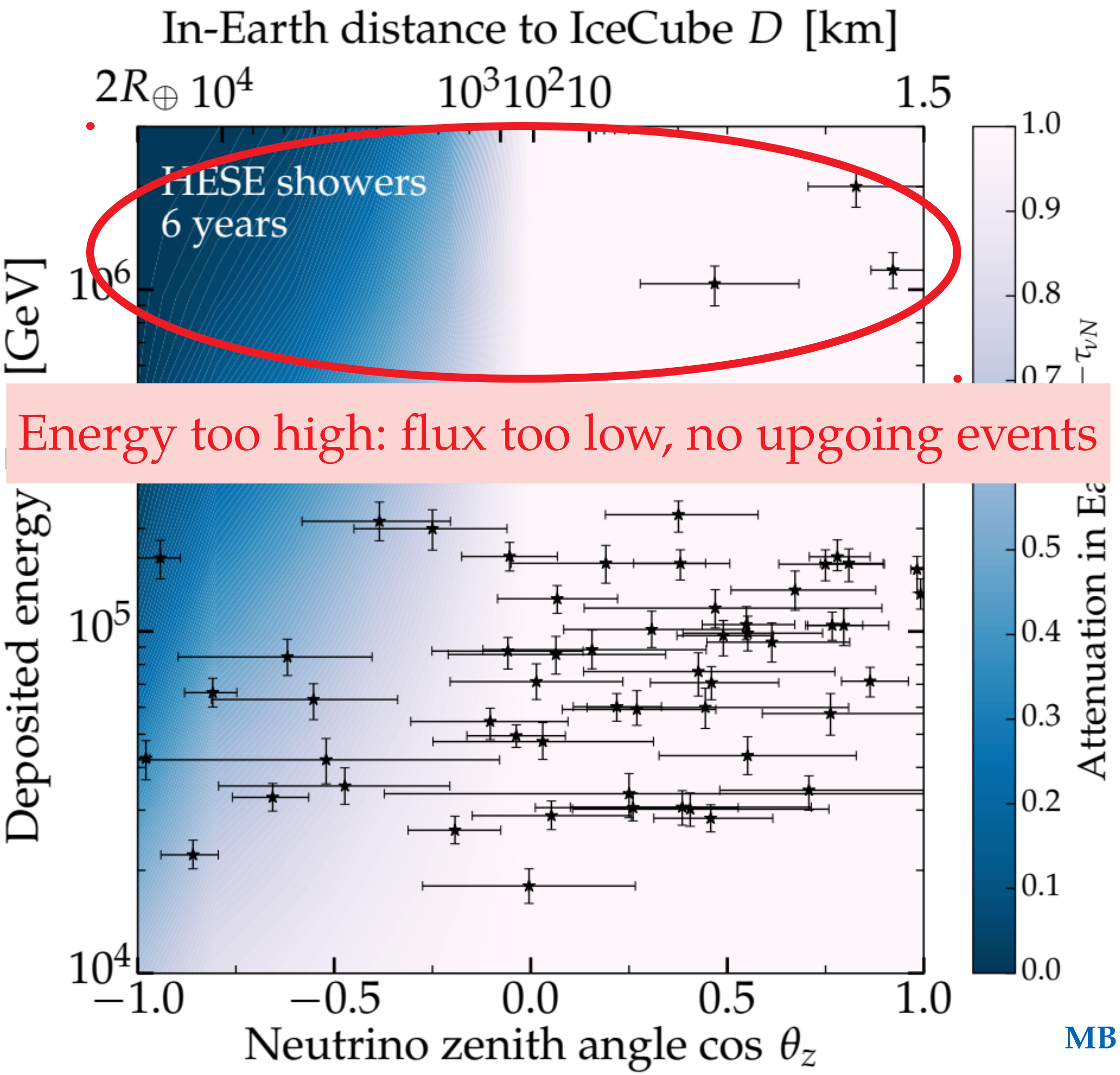
MB & Connolly, *PRL* 2019



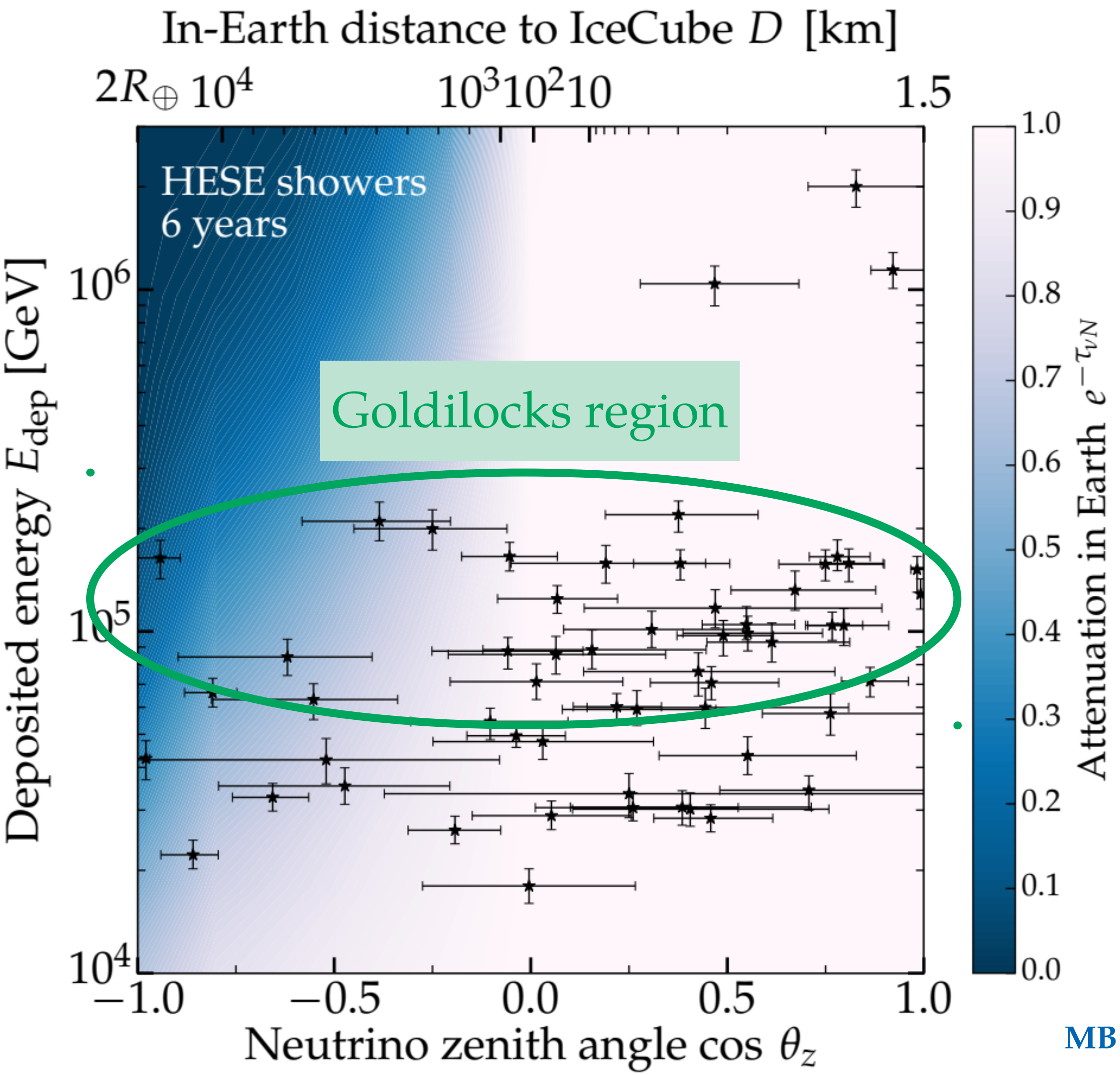
MB & Connolly, *PRL* 2019



MB & Connolly, *PRL* 2019

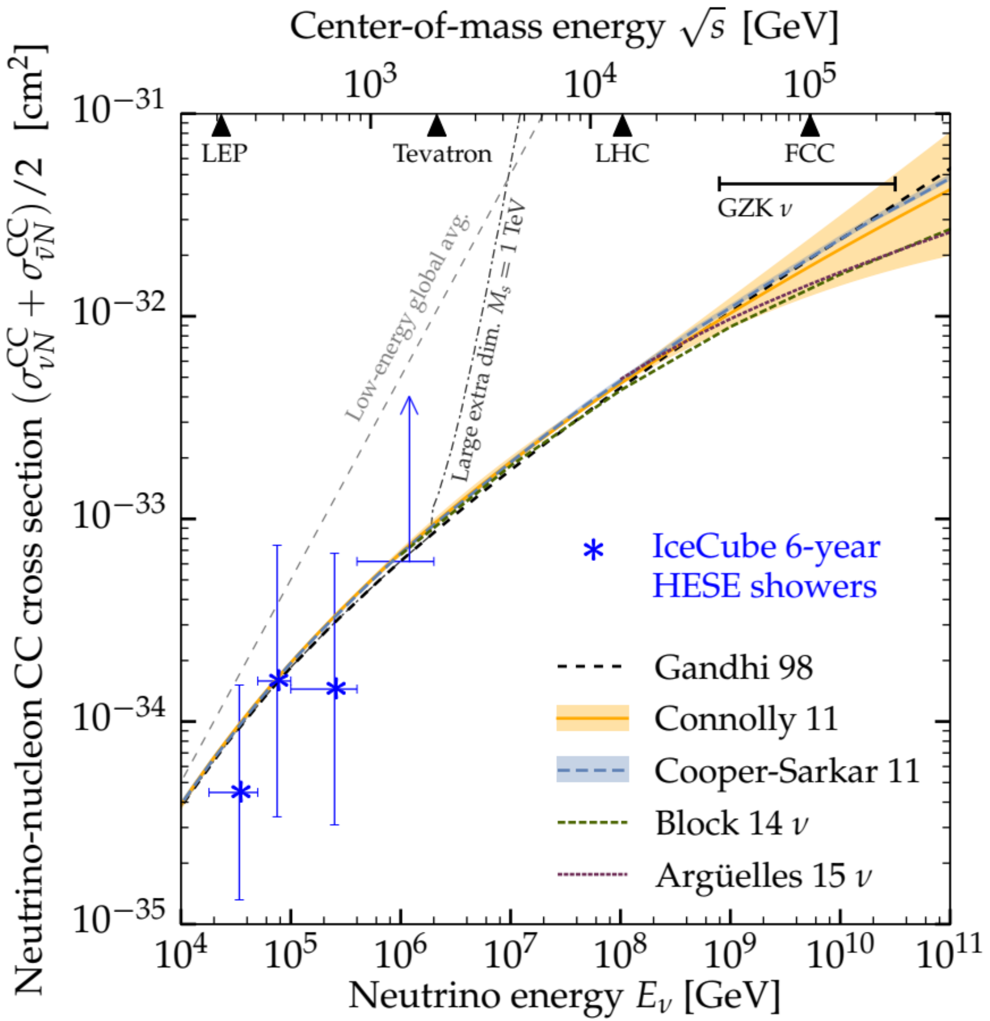


MB & Connolly, *PRL* 2019



MB & Connolly, *PRL* 2019

Our result



MB & A. Connolly *PRL* 2019

See also: IceCube, *Nature* 2017

Our result

MB & A. Connolly *PRL* 2019
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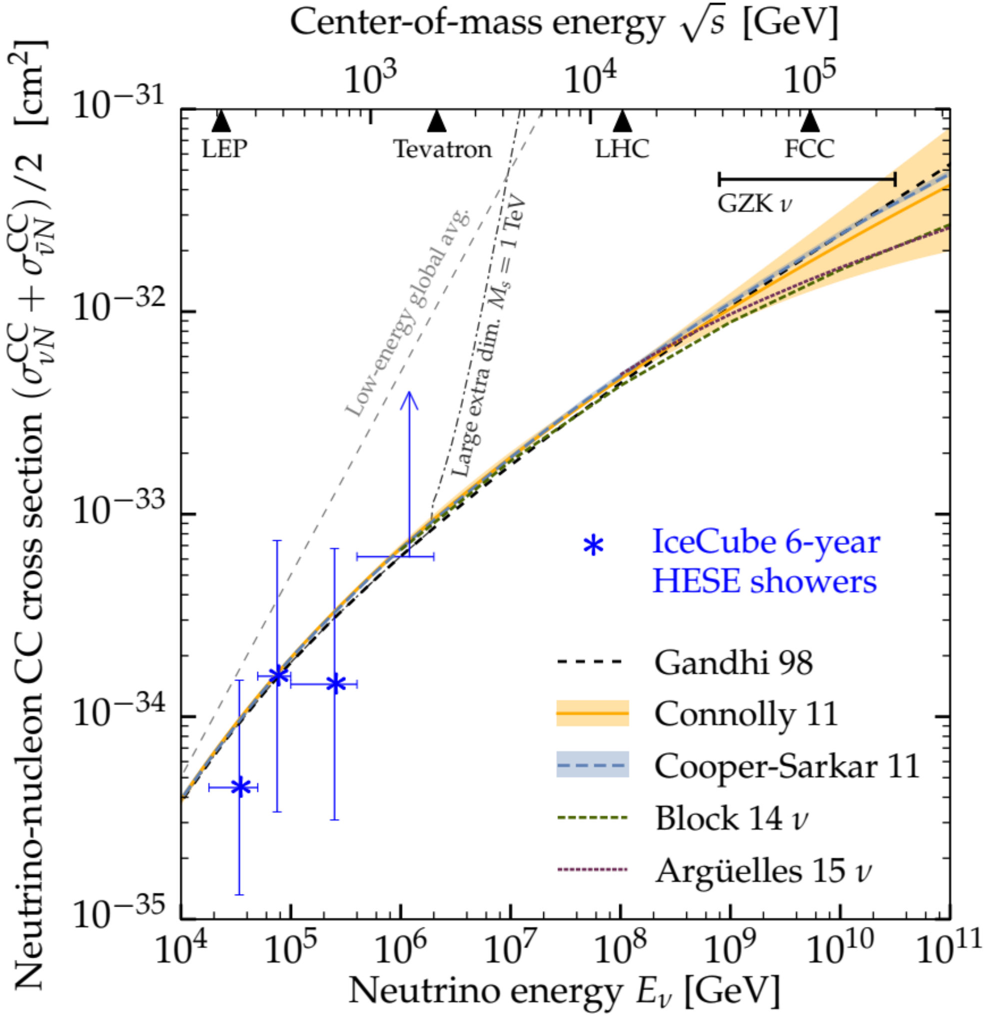

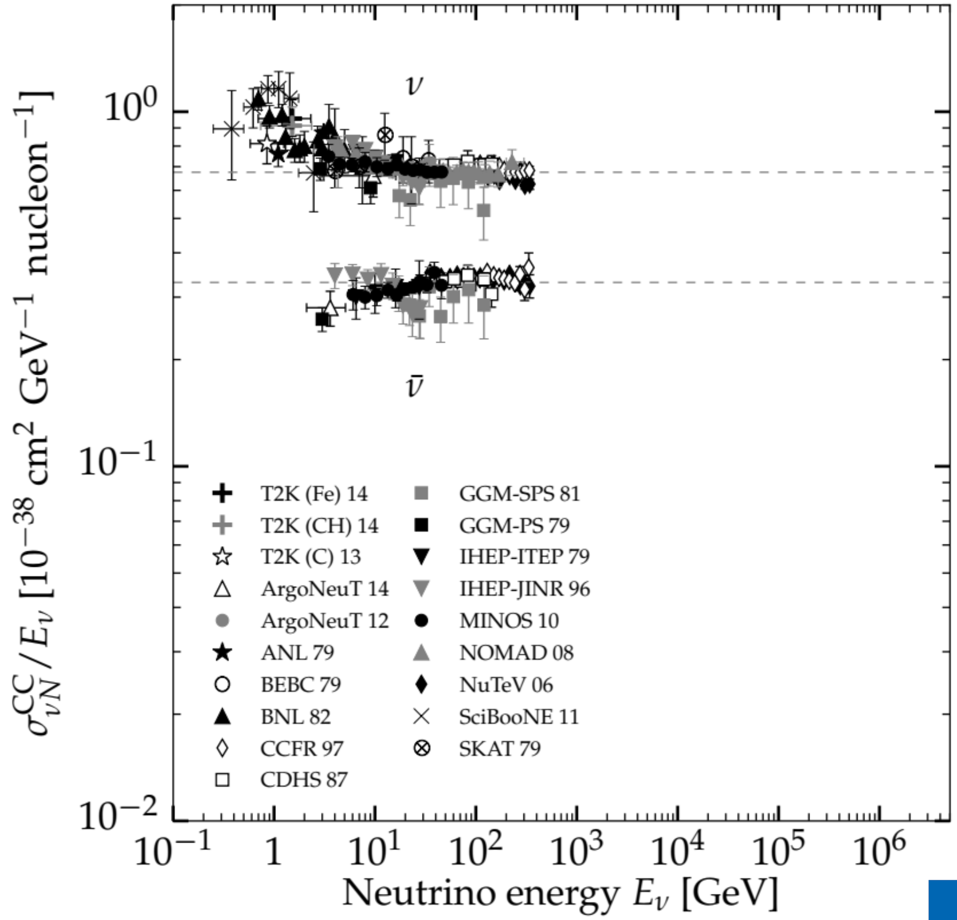

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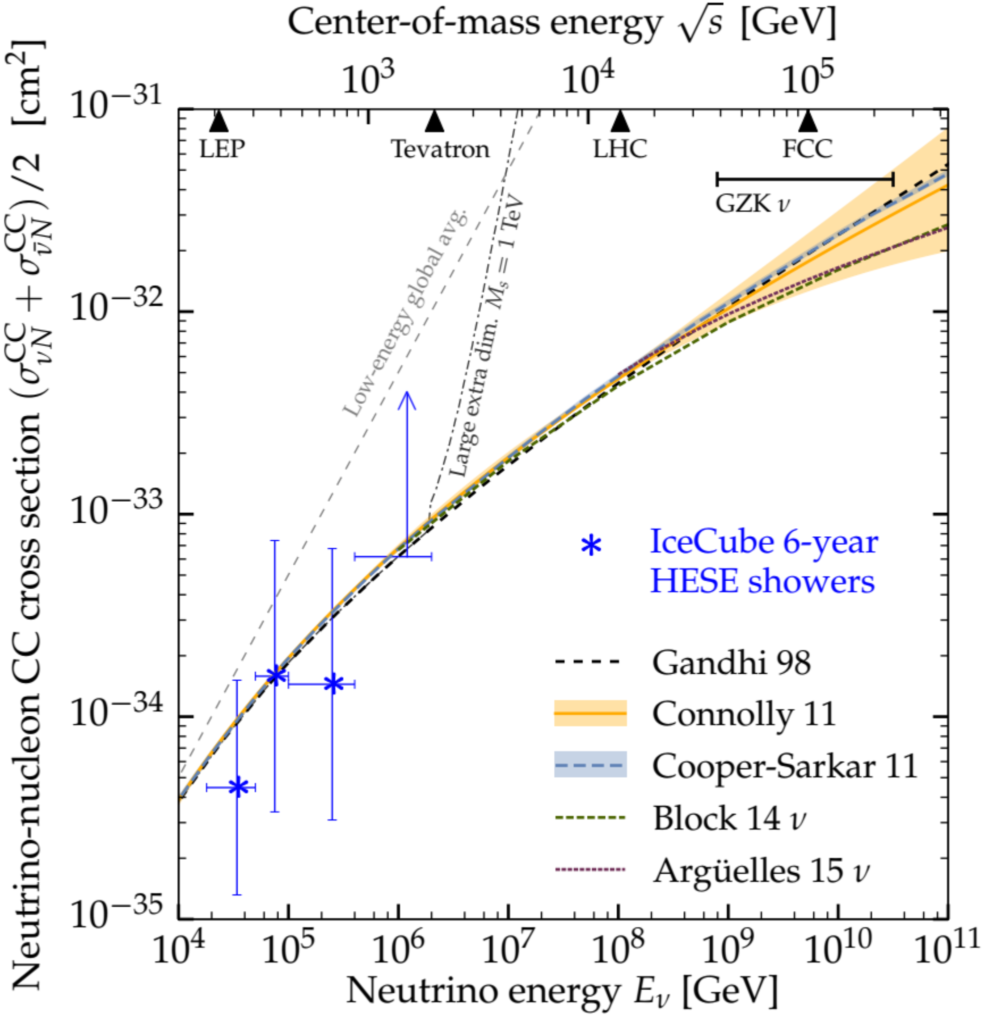

MB & A. Connolly *PRL* 2019

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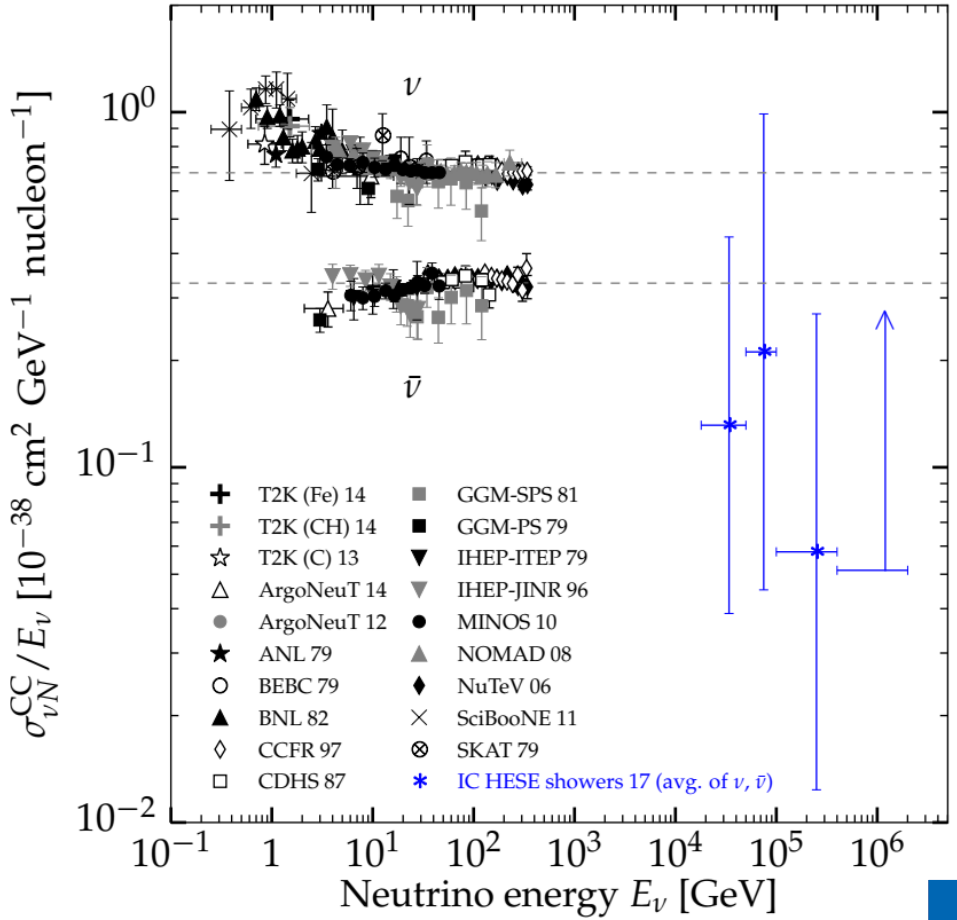
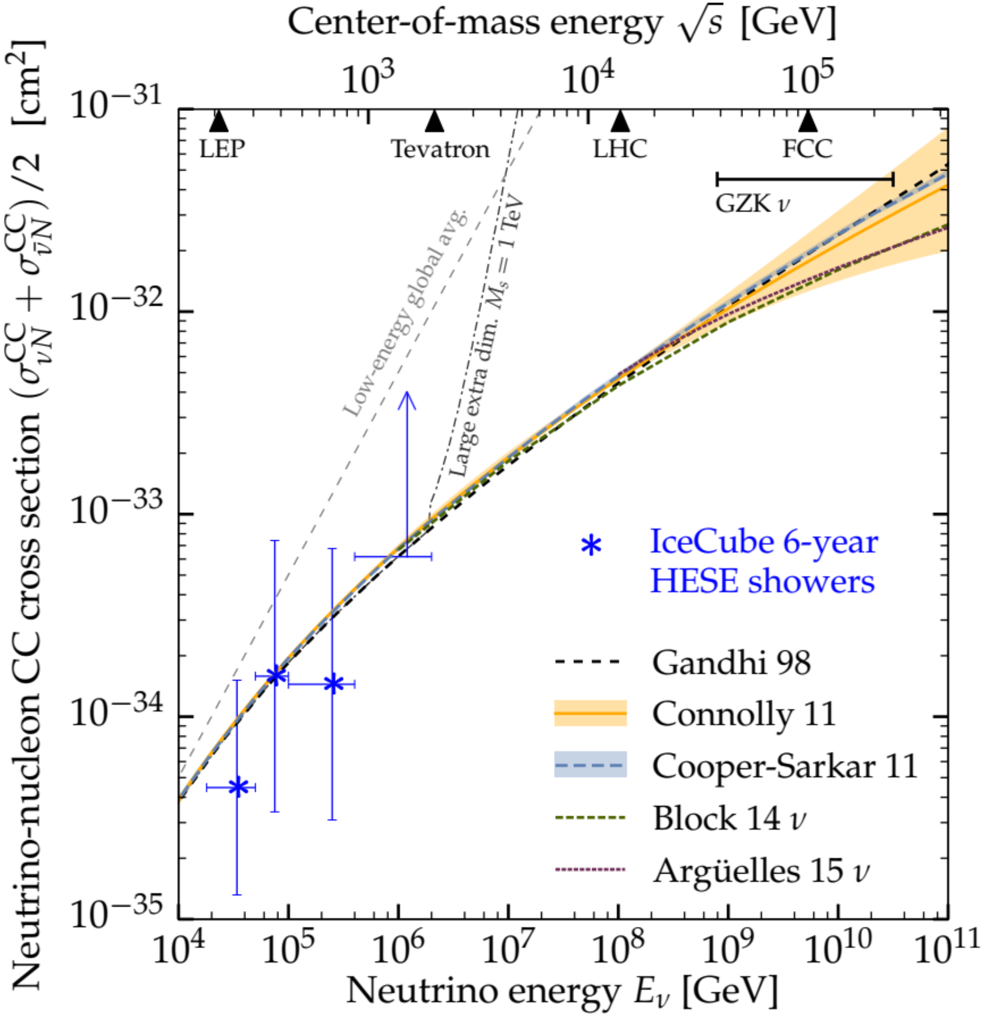
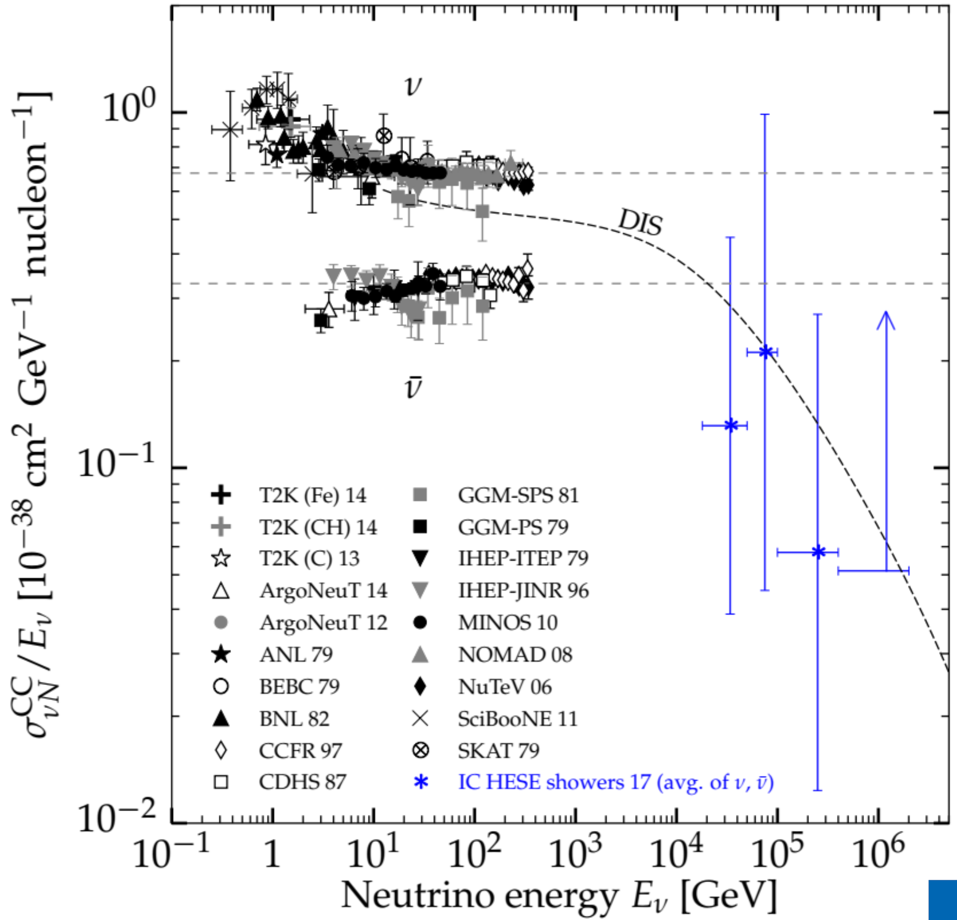


Our result

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

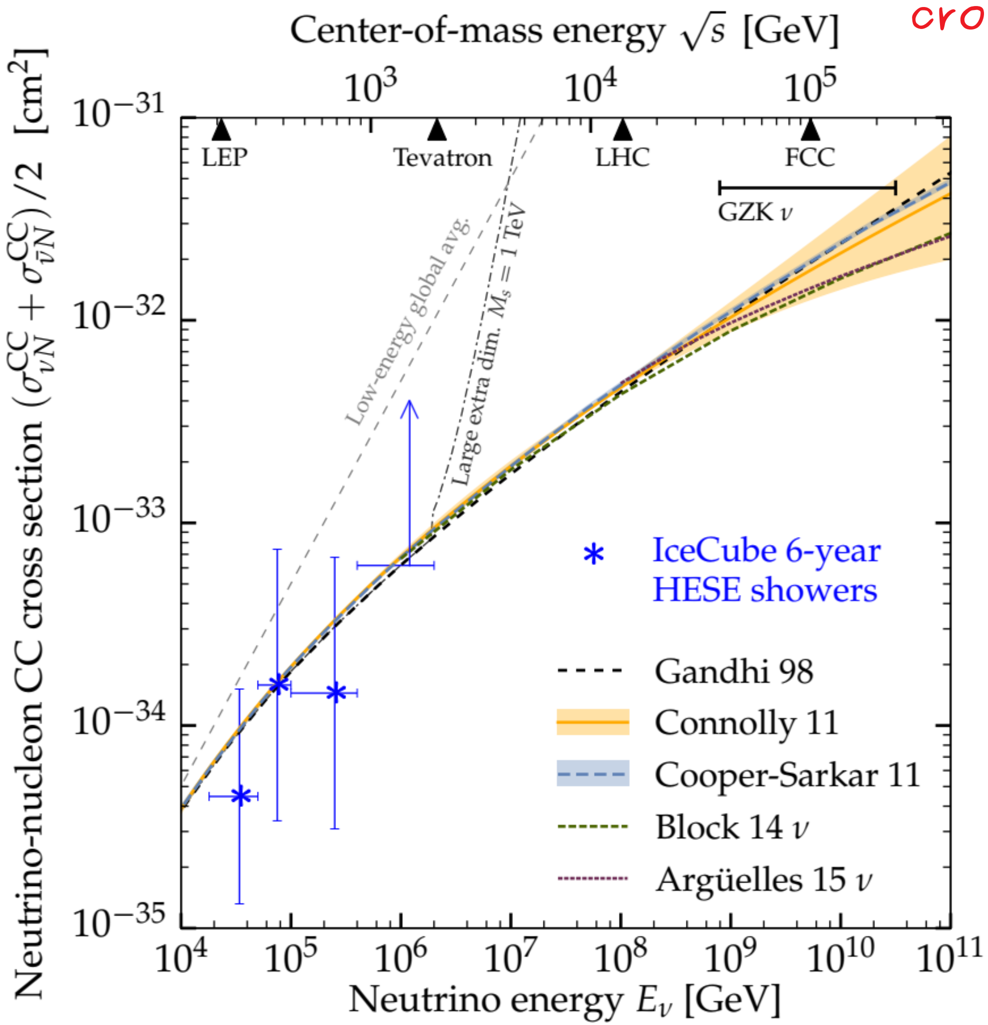


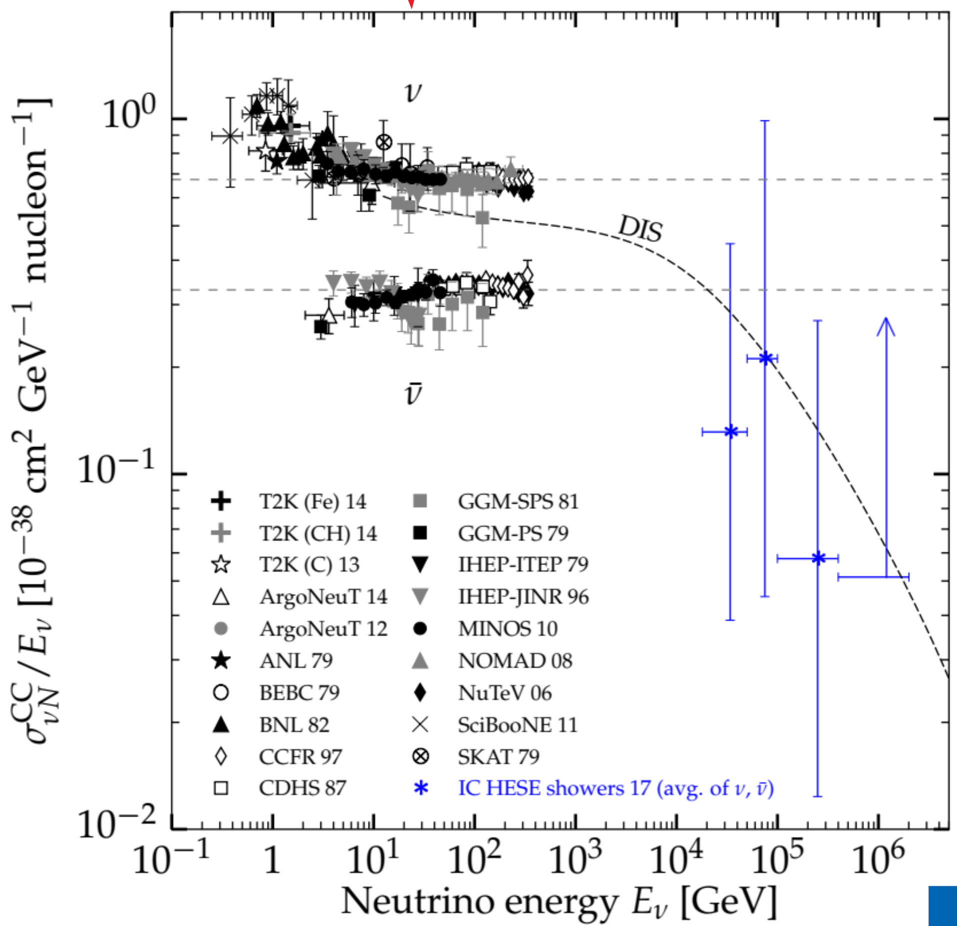


Our result

Extending the PDG cross-section plot

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





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

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

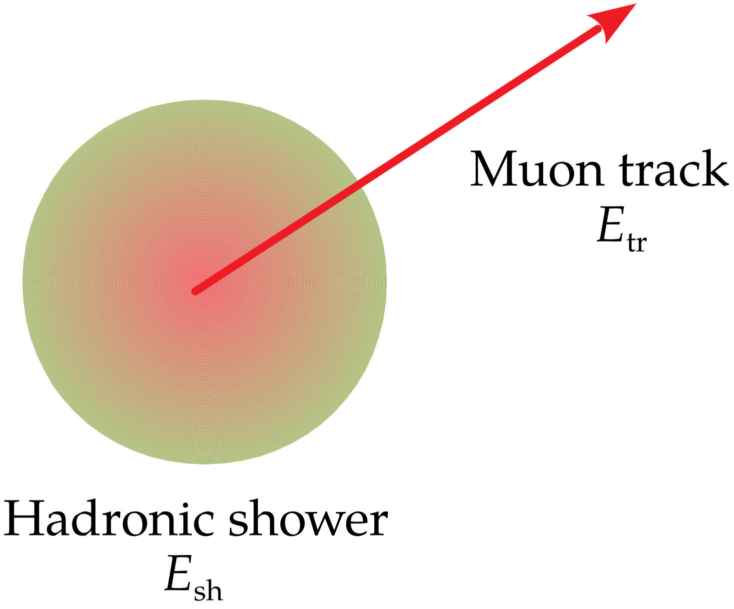
  $E_X = y\, E_\nu$ and $E_\mu = (1\text{-}y)\, E_\nu \;\Rightarrow\; y = (1 + E_\mu/E_X)^{-1}$

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

- 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, *PRD* 2019

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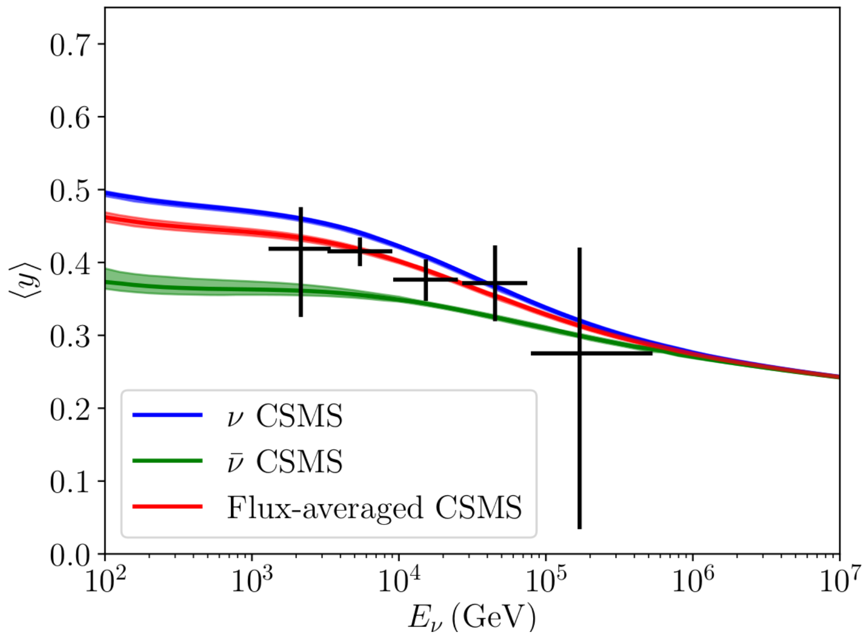
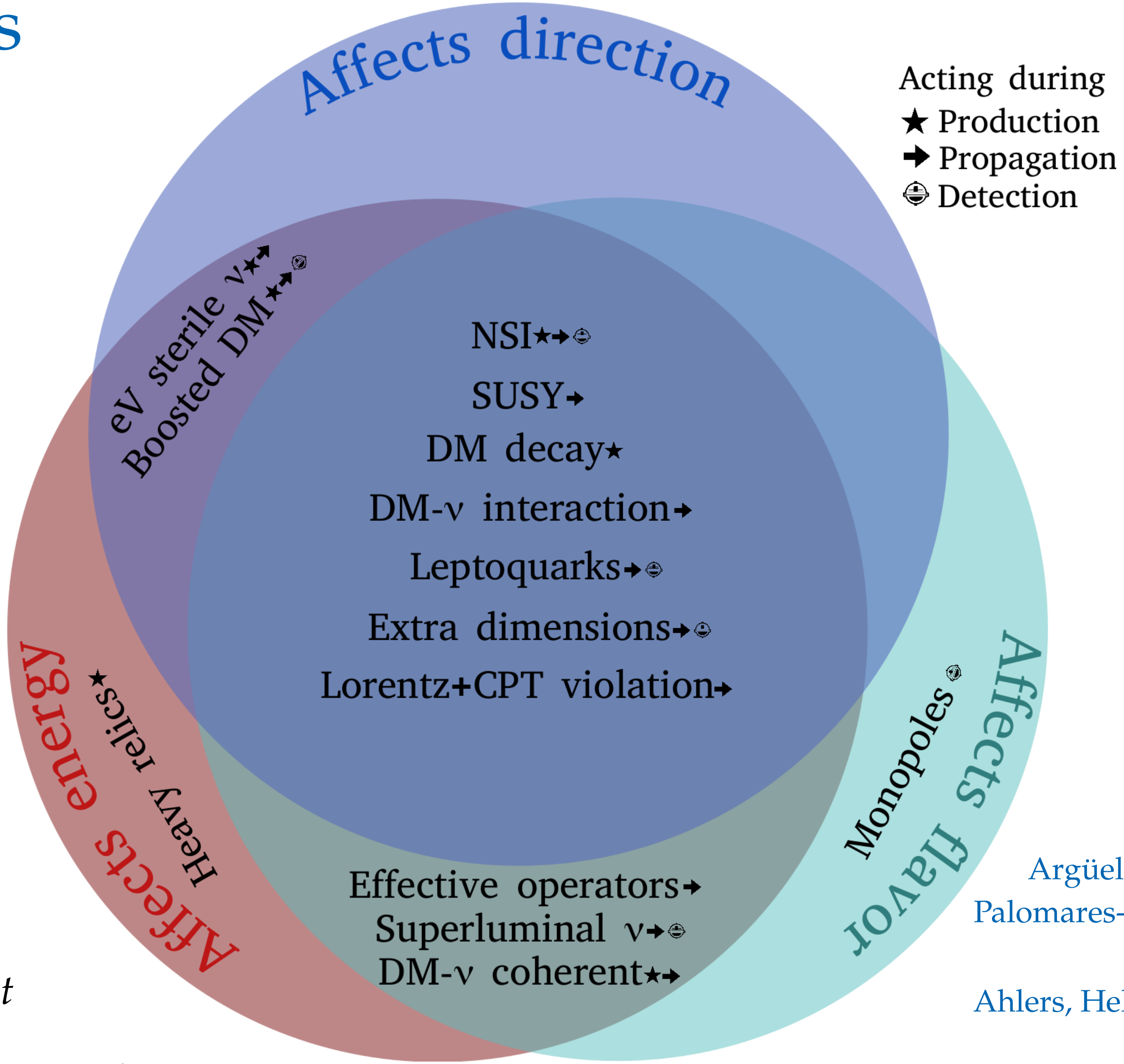


IceCube, *PRD* 2019

New ν physics



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

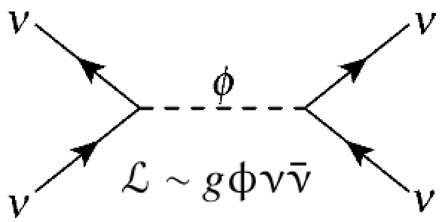
See also:

Ahlers, Helbing, De los Heros, *EPJC* 2018

Note: Not an exhaustive list

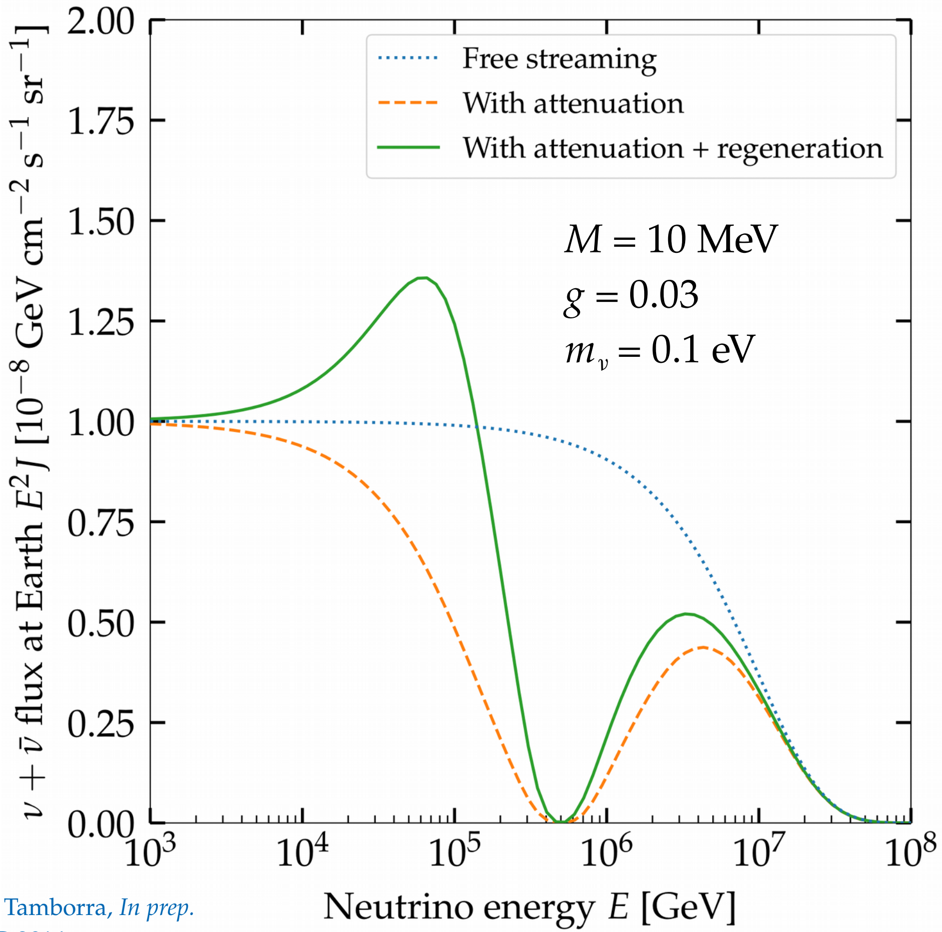
New physics in the spectral shape: $\nu\nu$ interactions

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



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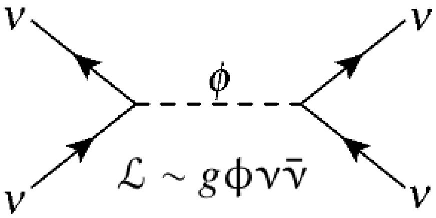
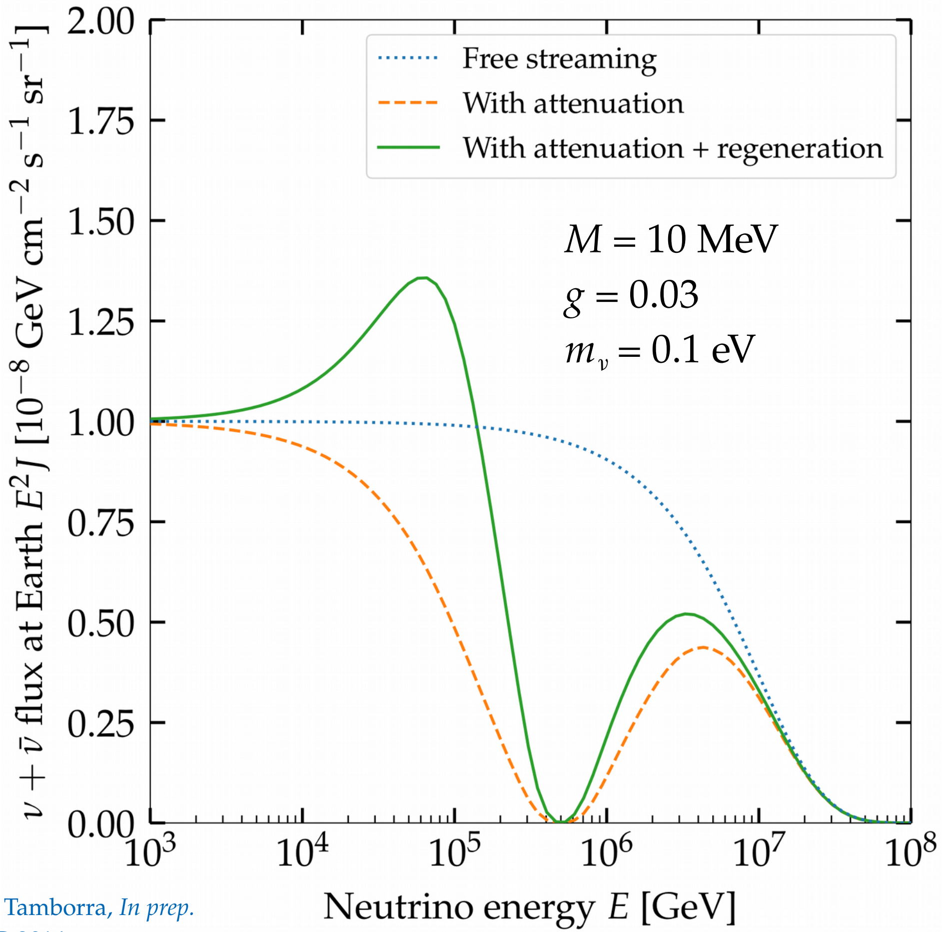


New coupling

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

Mediator mass

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



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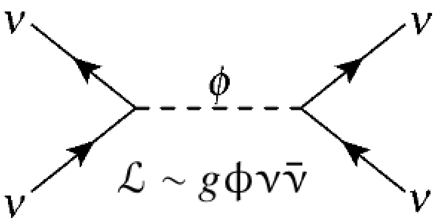

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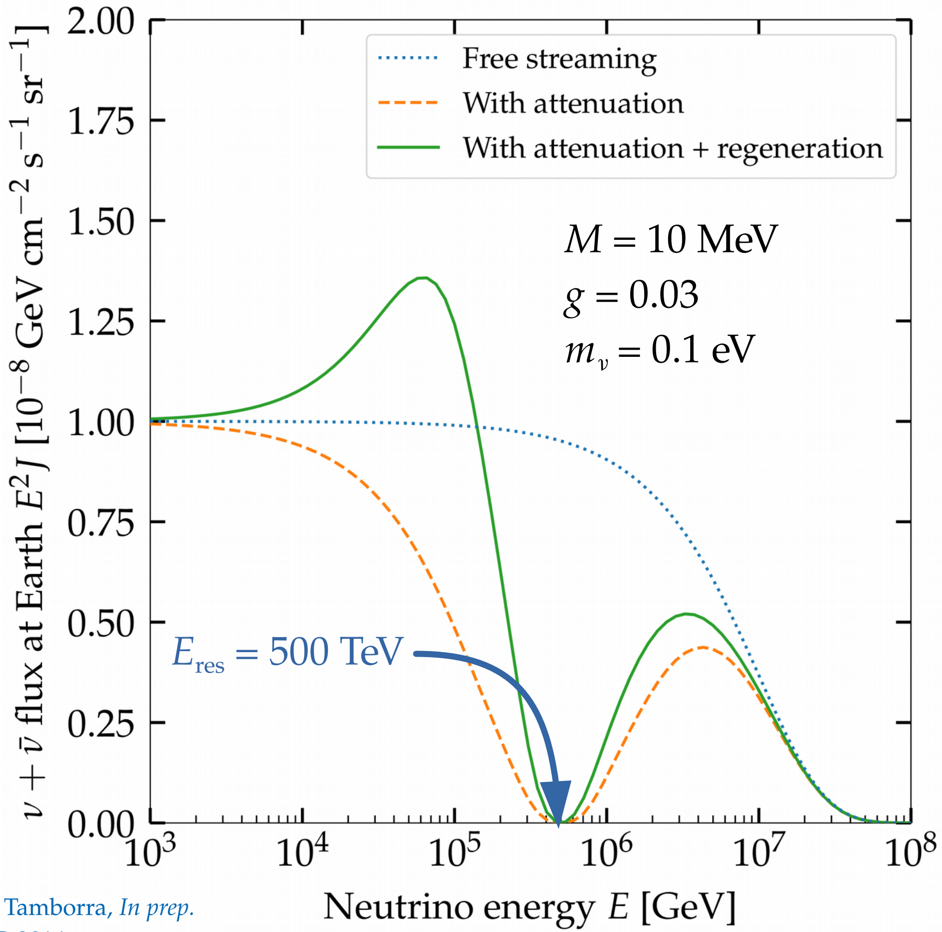

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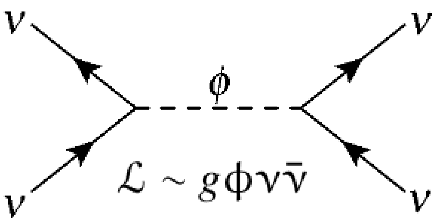

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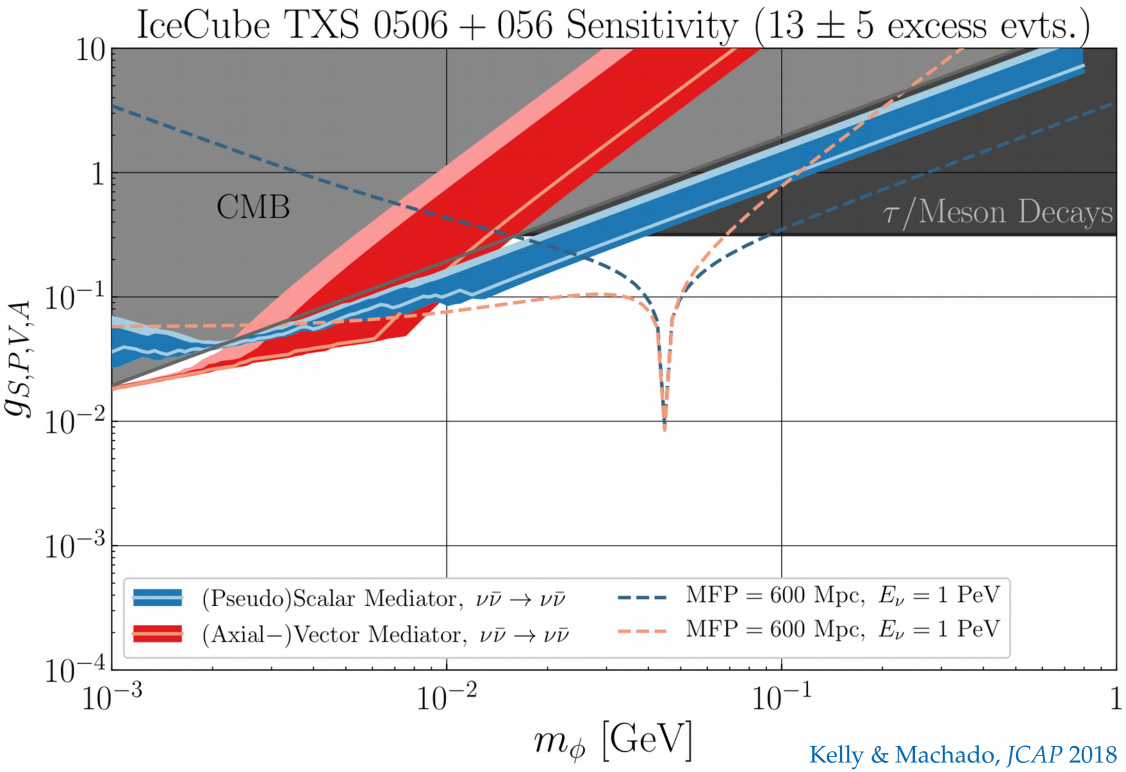
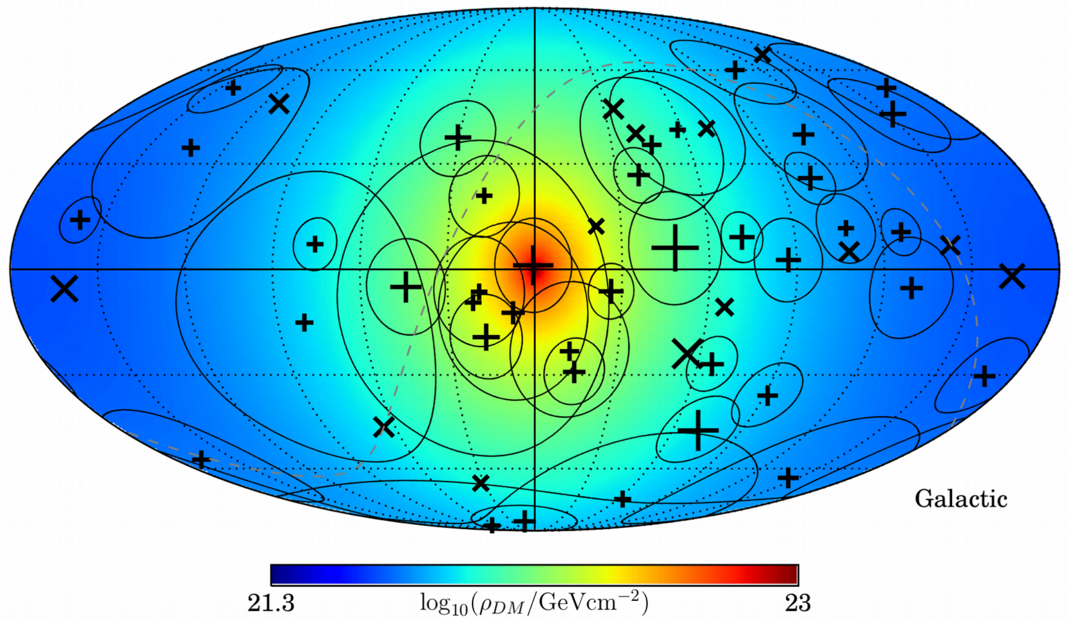


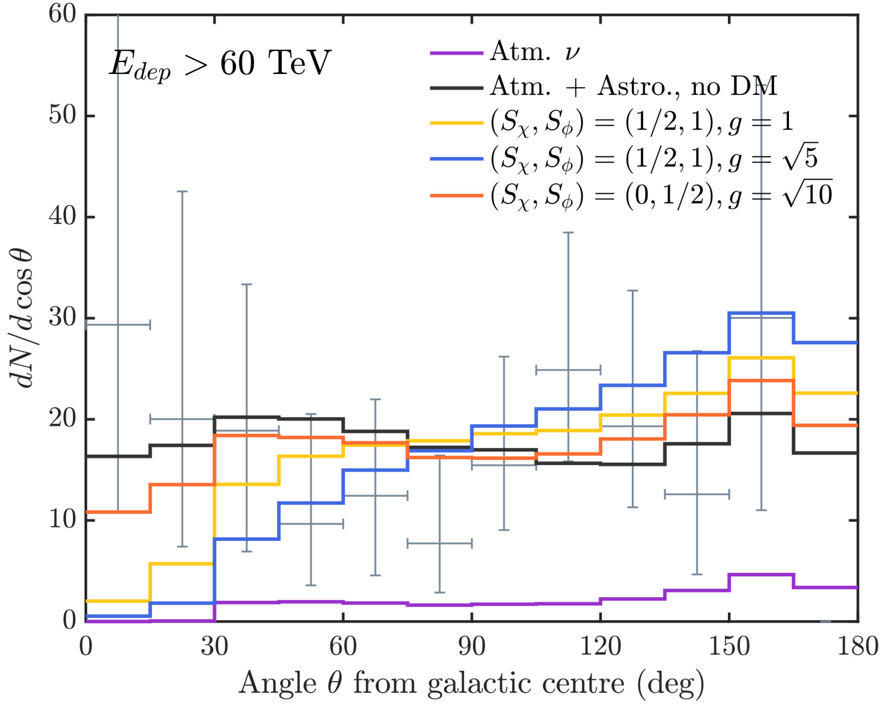
Kelly & Machado, *JCAP* 2018

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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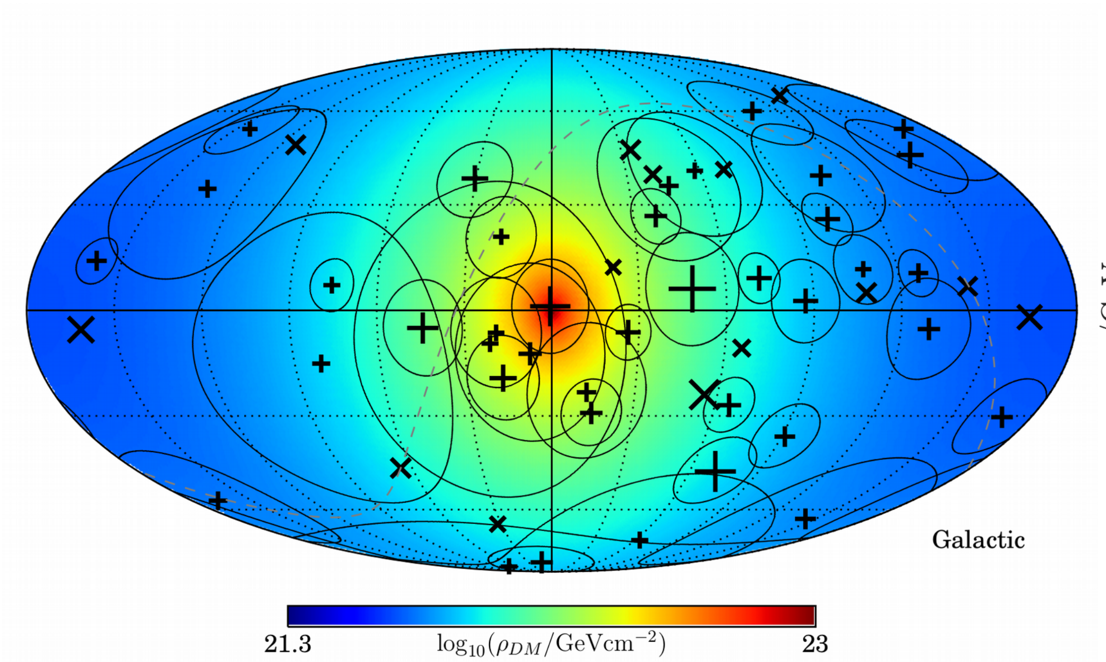
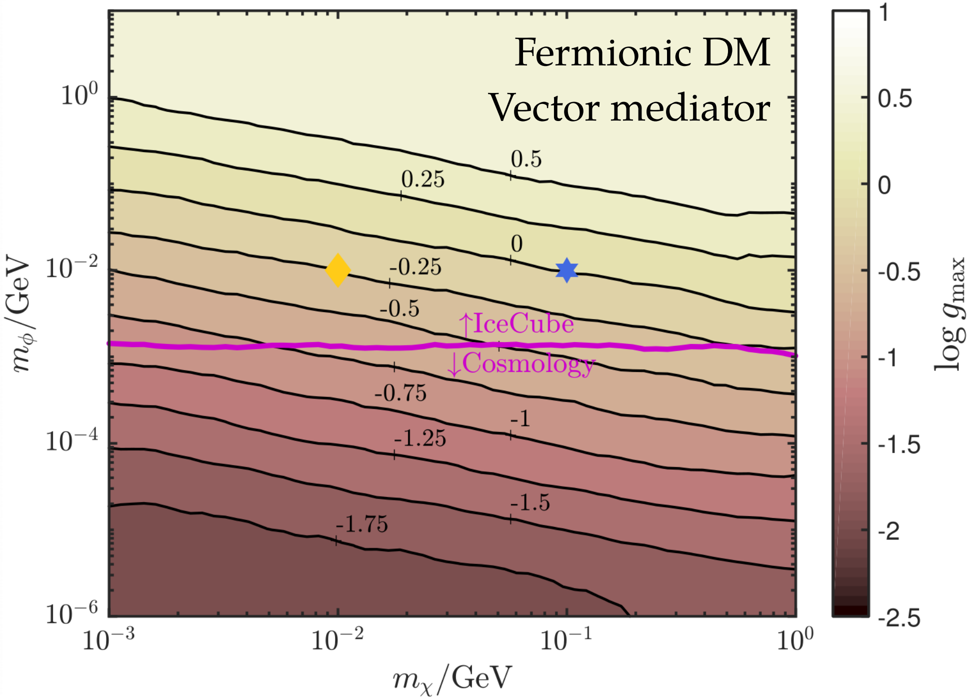


Argüelles *et al.*, *PRL* 2017



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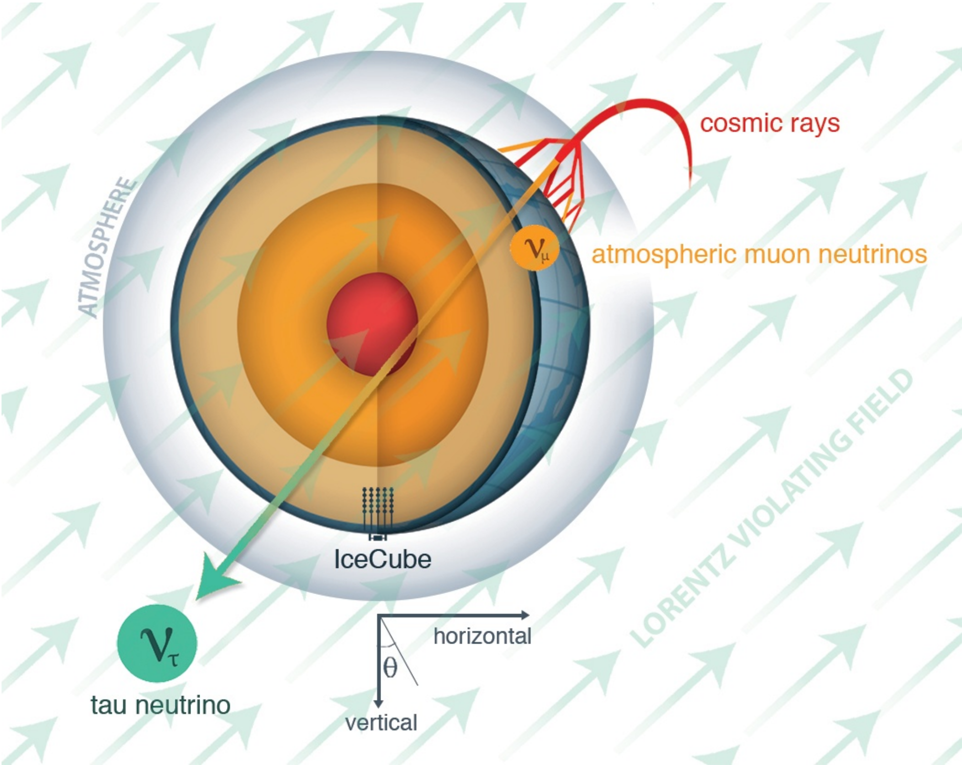
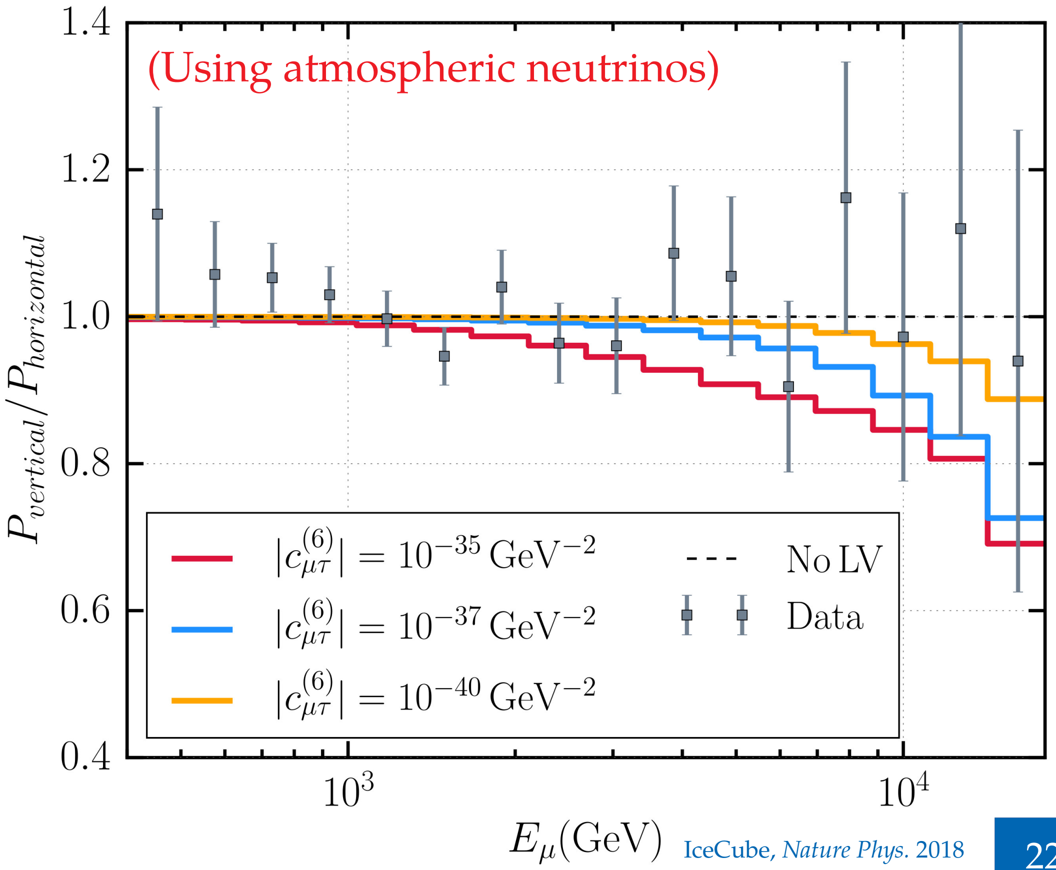
New physics in the energy & angular distribution

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





IceCube, *Nature Phys.* 2018

New physics in the energy & angular distribution

Lorentz violation

Standard oscillations

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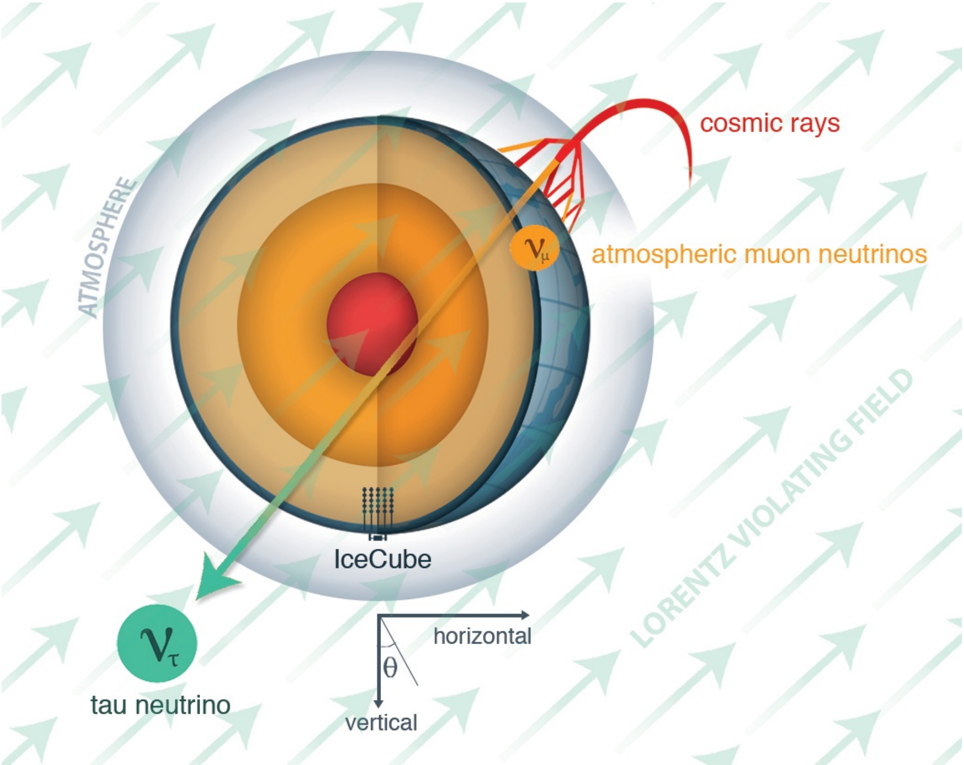

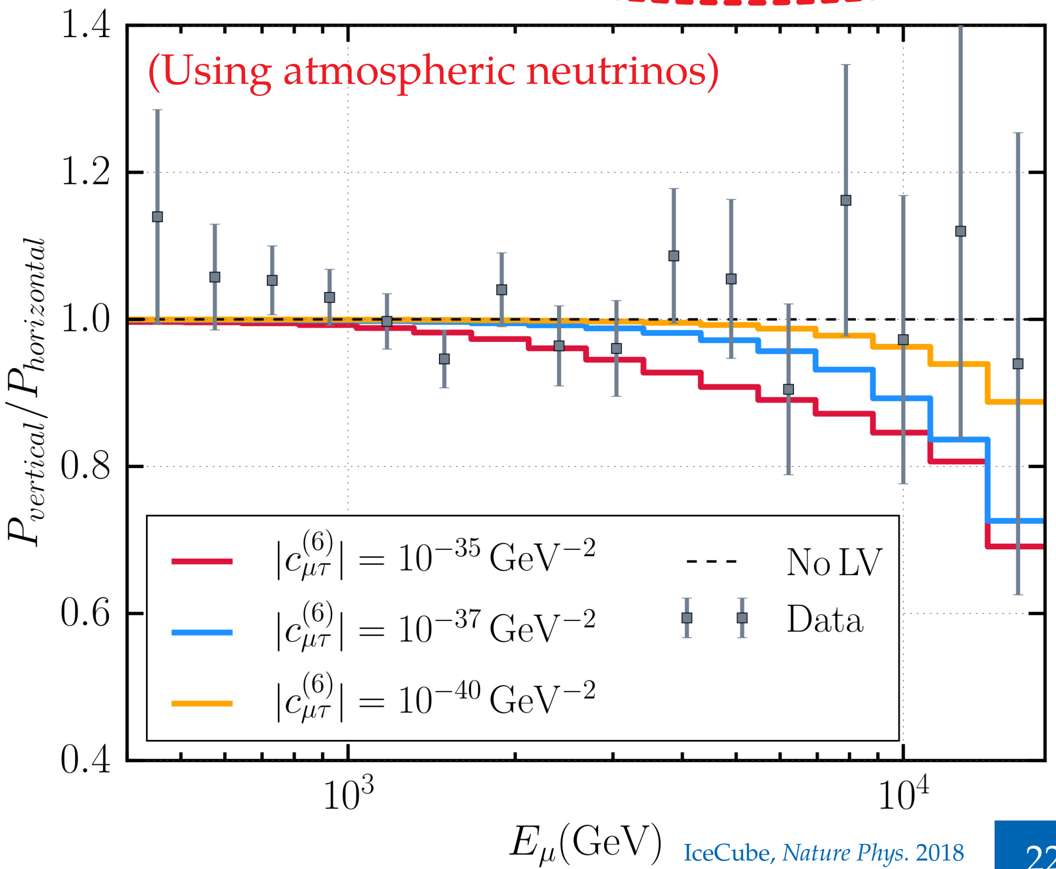

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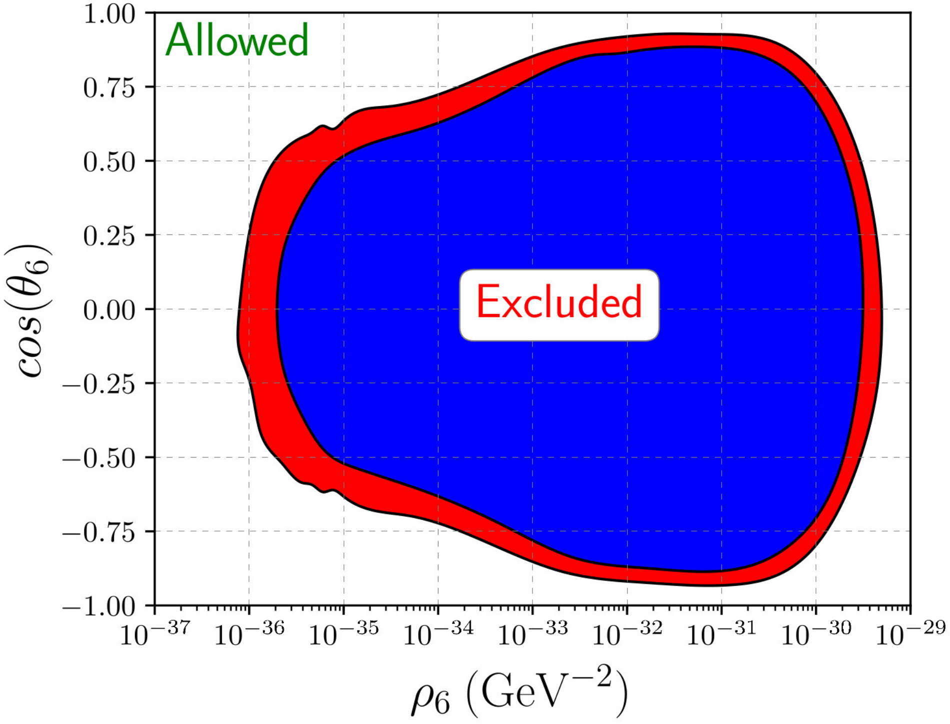
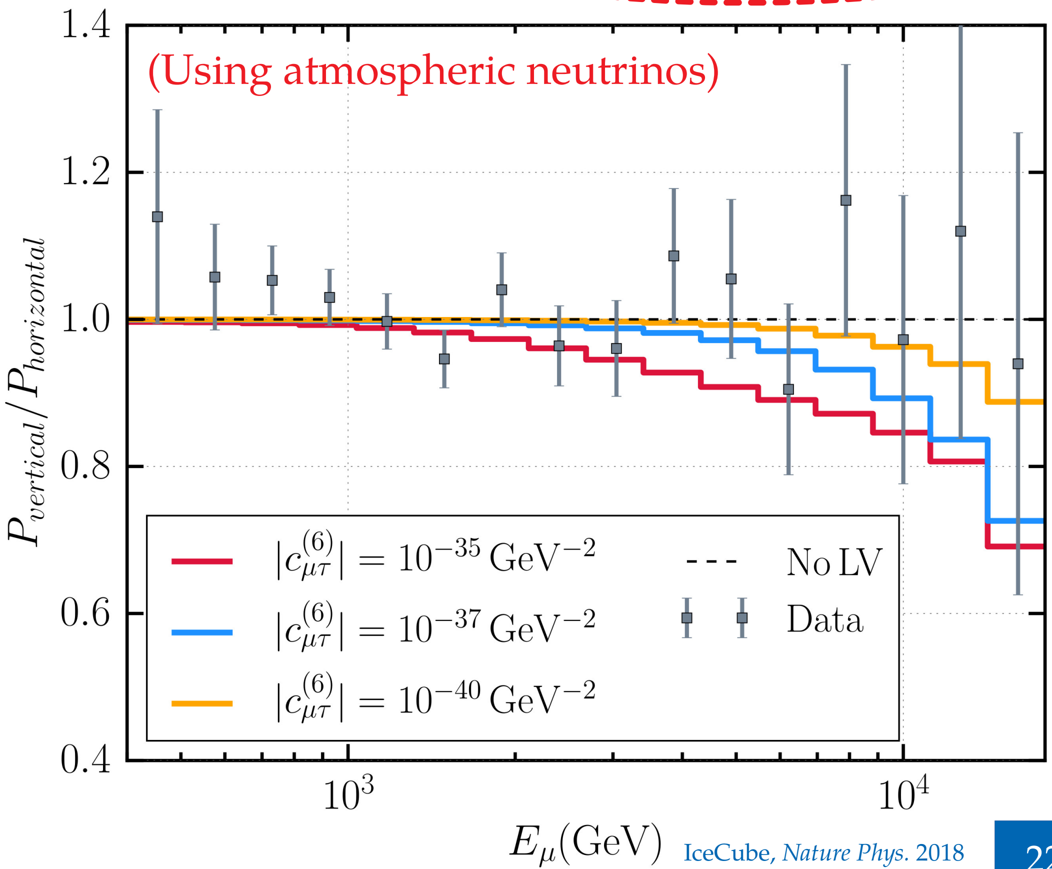
Best bounds come from IceCube

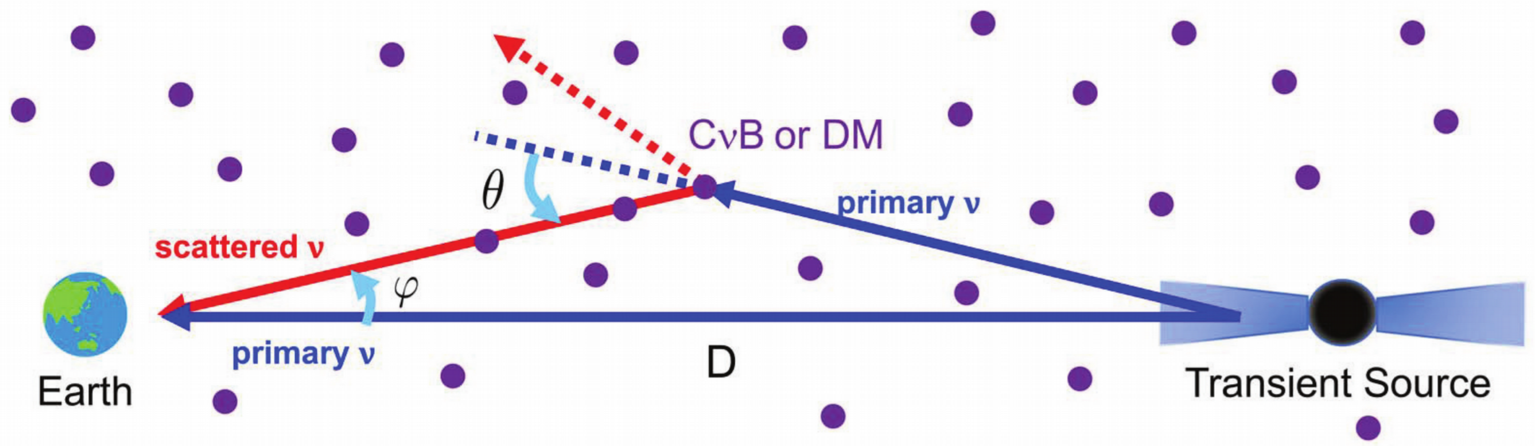




IceCube, *Nature Phys.* 2018

New physics in timing — TeV–PeV

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



Shoemaker & Murase, 1903.08607

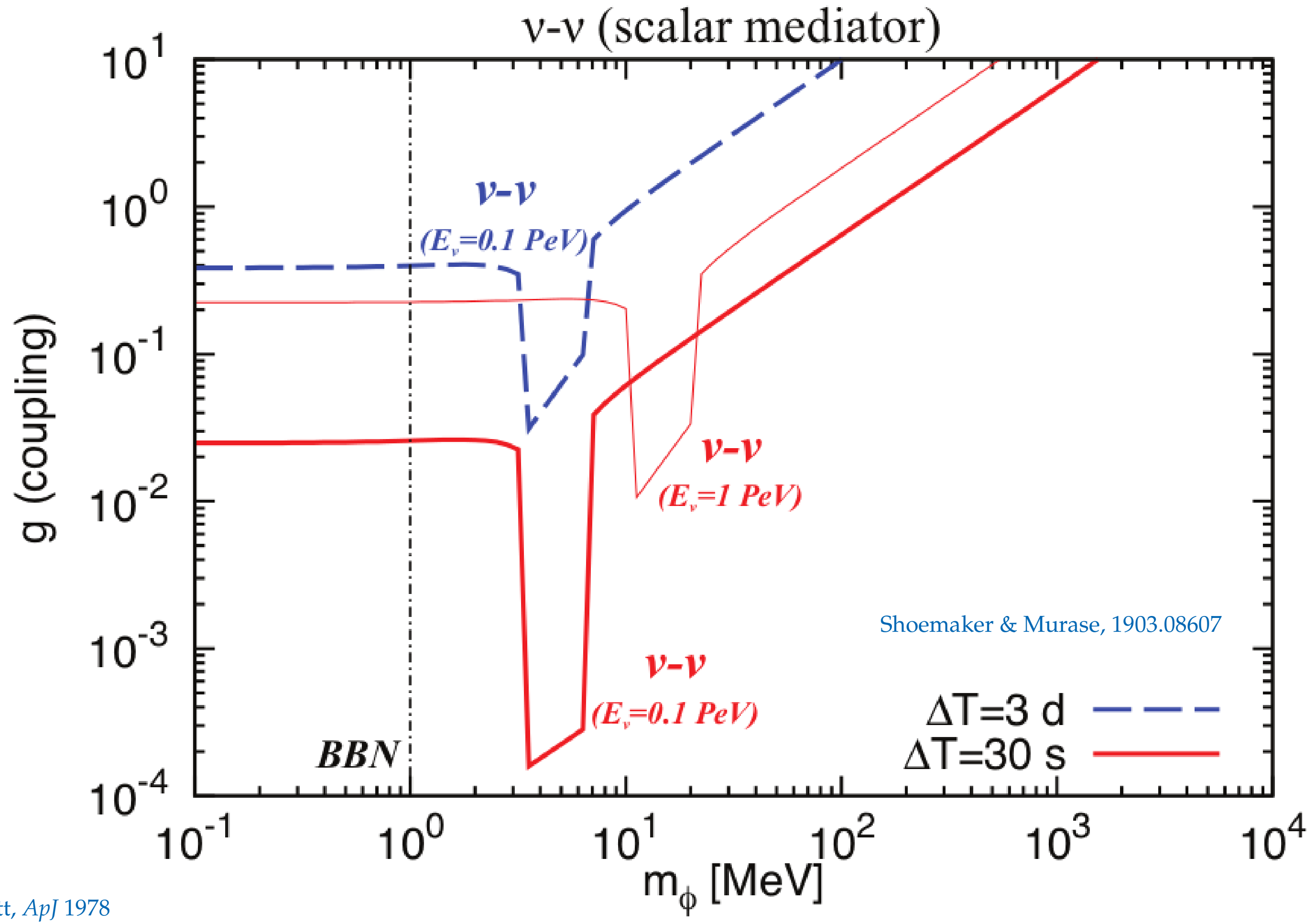
Characteristic time delay —

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

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

See also: Alcock & Hatchett, *ApJ* 1978

New physics in timing — TeV–PeV



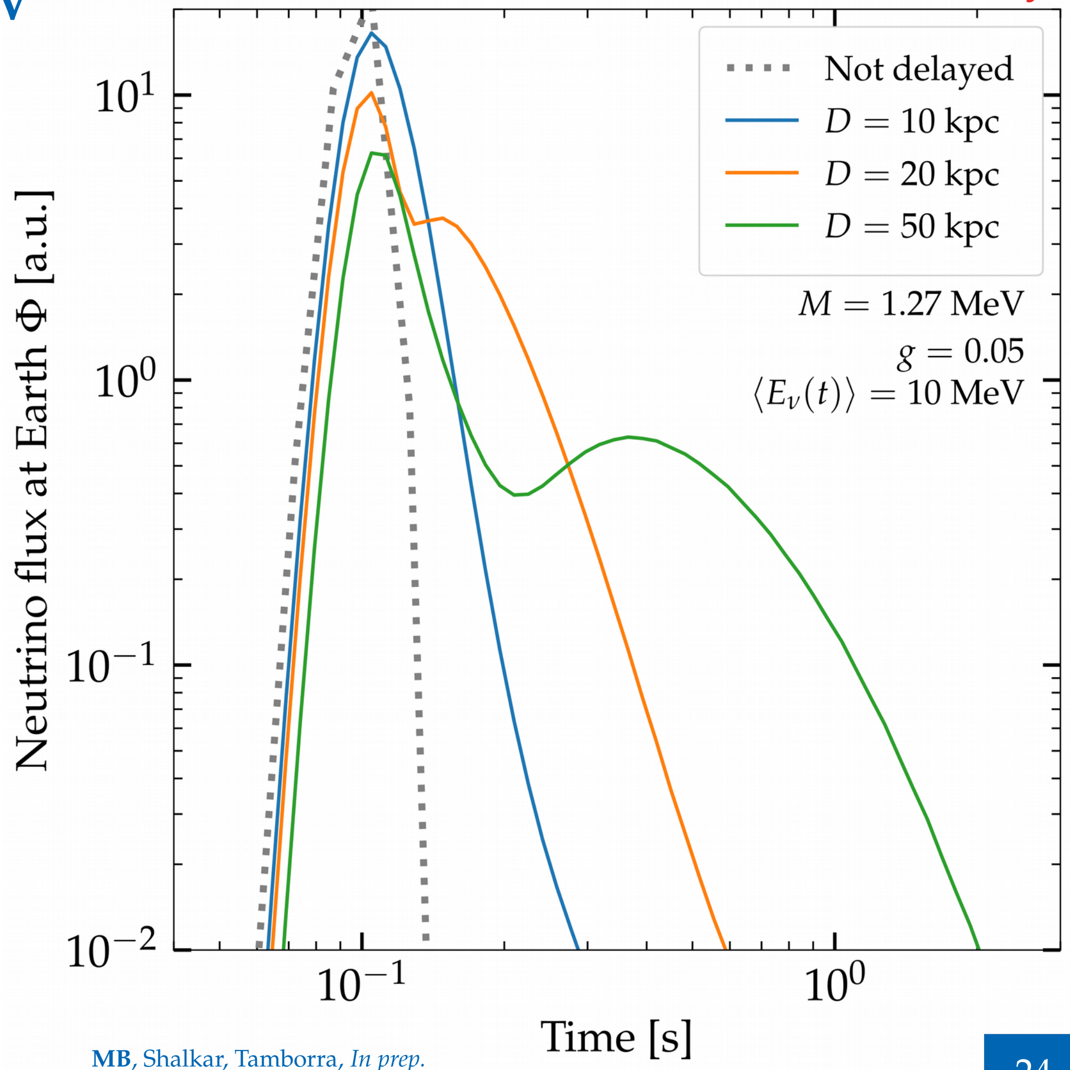
See also: Alcock & Hatchett, *ApJ* 1978

New physics in timing — MeV

- Secret $\nu\nu$ interactions delay the arrival of the burst of supernova ν
- Look for changes in:
  - *Start time* of the ν light curve (hard)
  - *Shape* of the ν light curve (easier)
- Sensitive to mediator masses of keV
- Probes the same parameter as $\nu\nu$ in early Universe, but differently

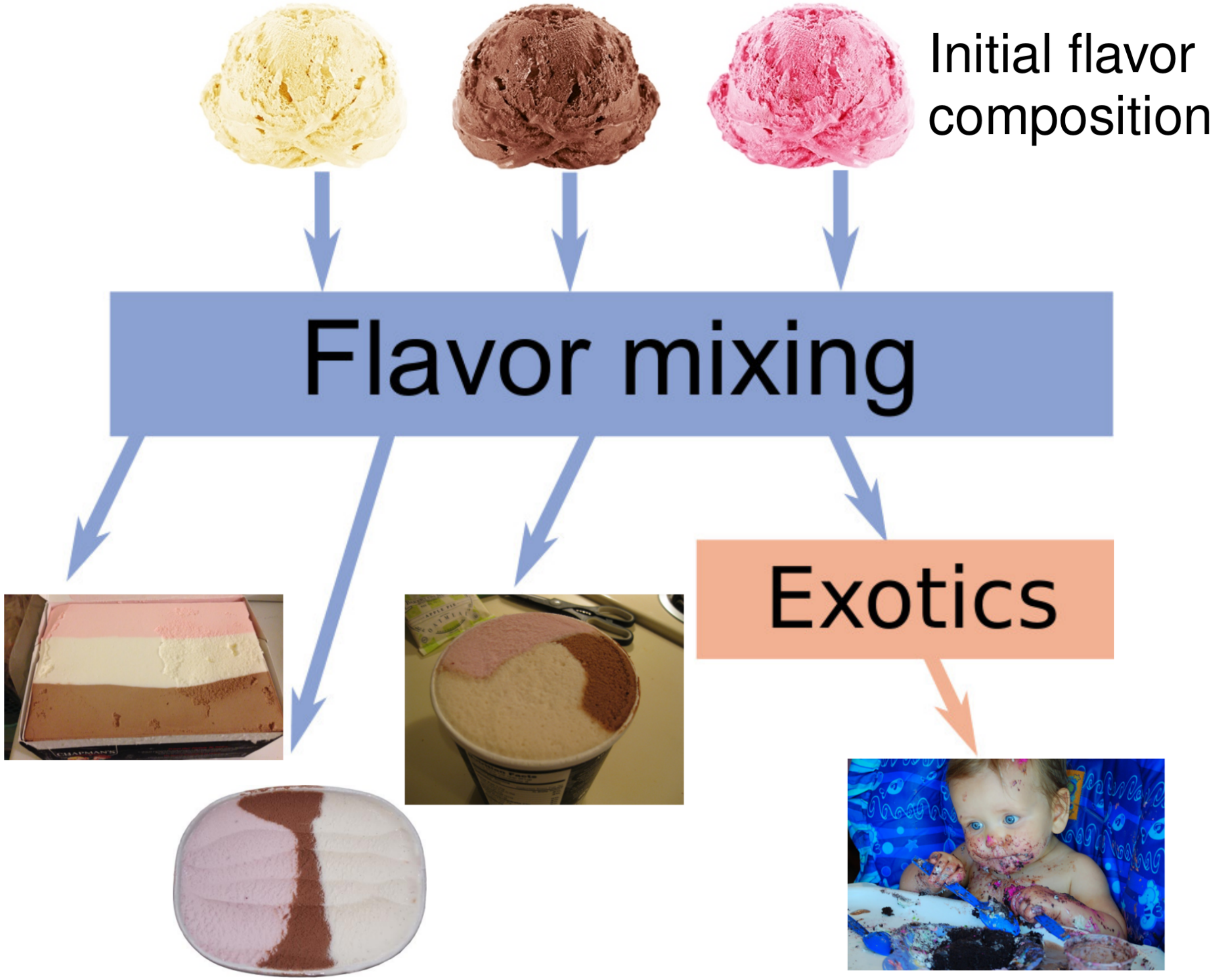
(Ahlgren, Ohlsson, Zhou, *PRL* 2013)

Preliminary



MB, Shalkar, Tamborra, *In prep.*

New physics in the flavor composition

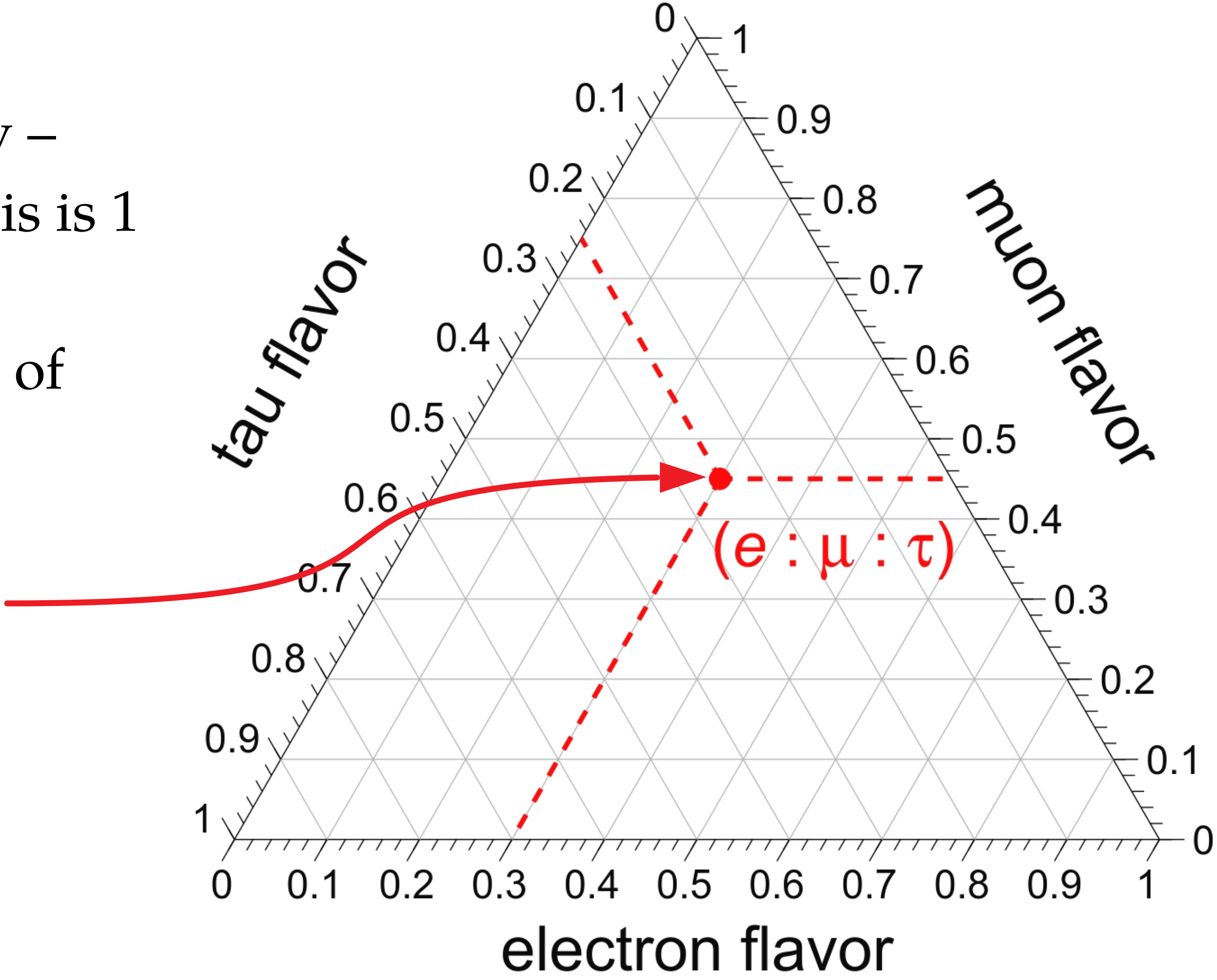


Reading a ternary plot

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

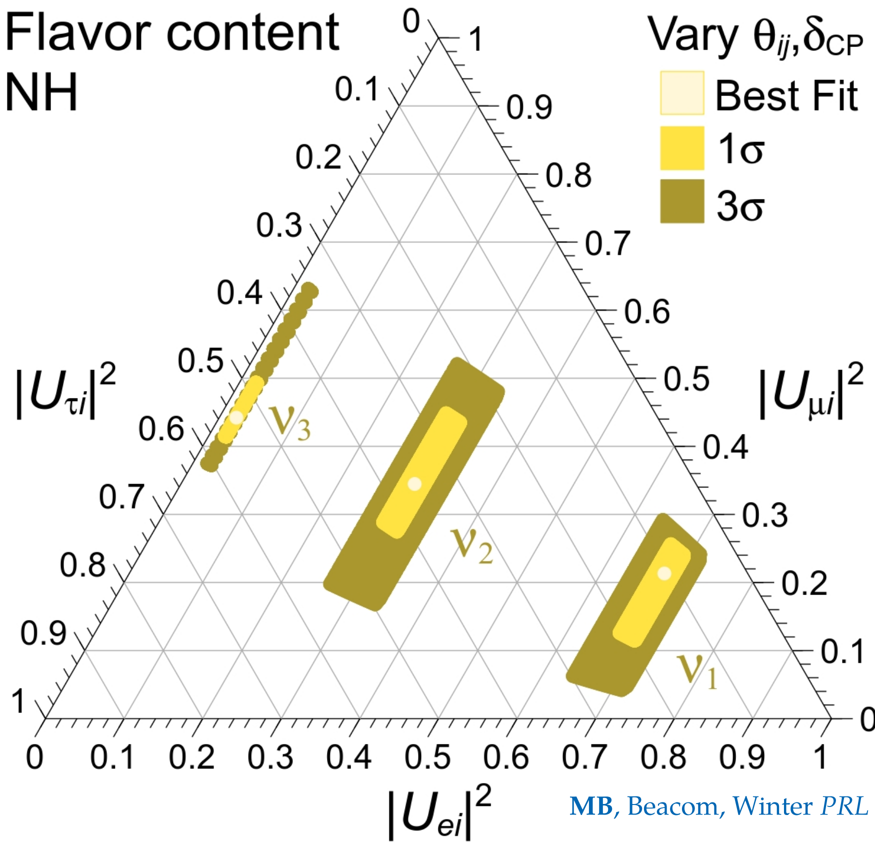
Flavor content for every allowed combination of mixing parameters –

Known to within 2%

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

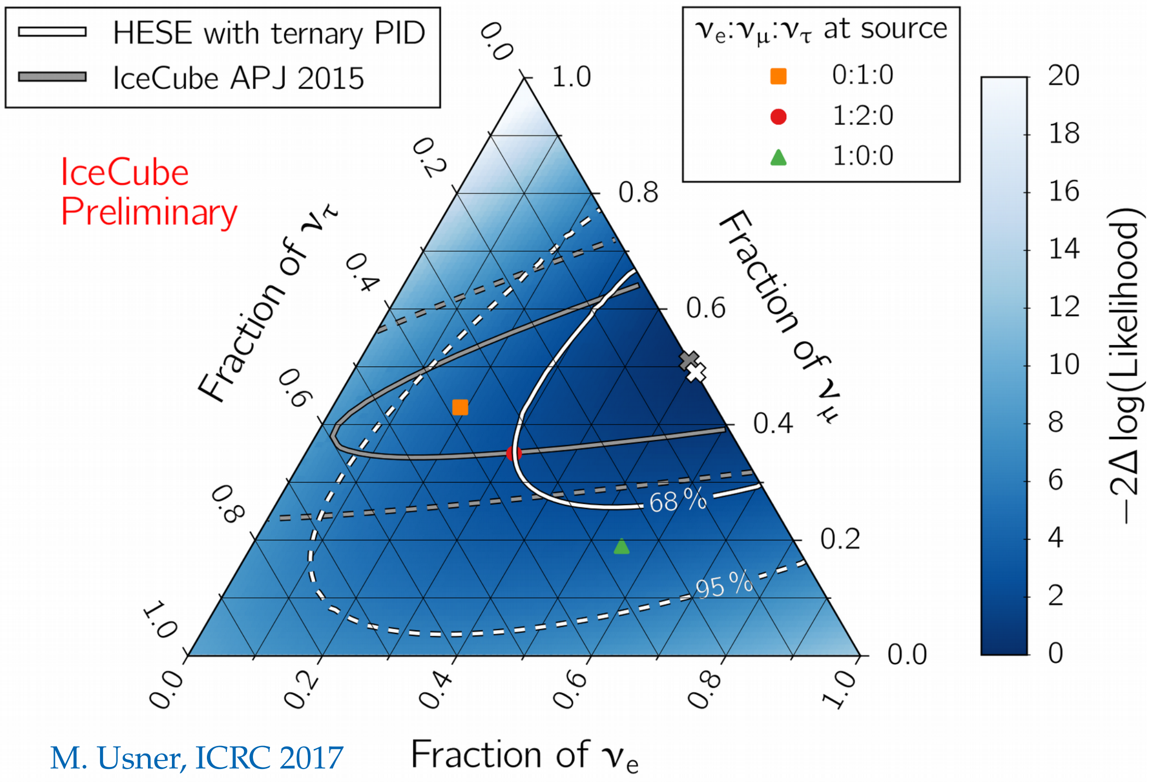
Known to within 8%

Known to within 20% (or worse)



MB, Beacom, Winter *PRL* 2015

IceCube flavor composition



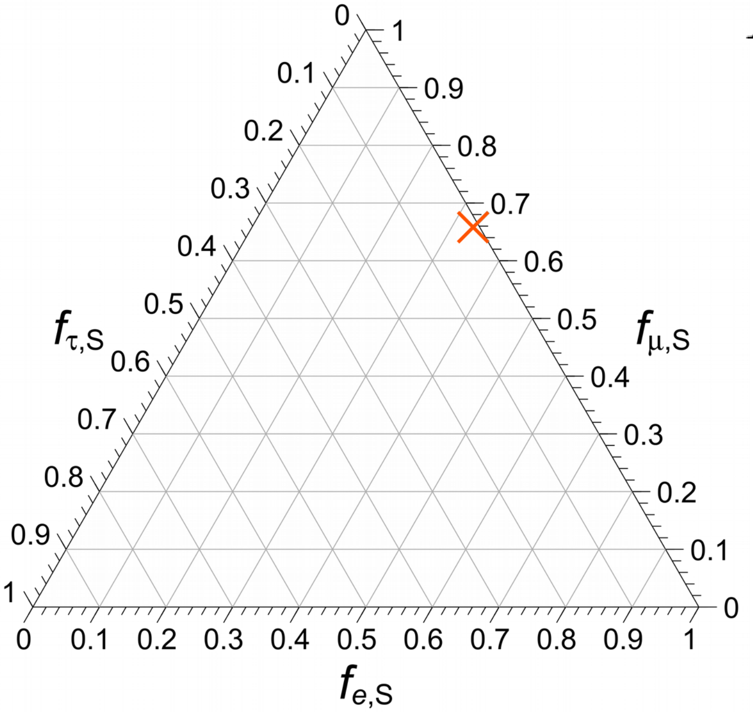
- Compare number of tracks (ν_μ) *vs.* showers (all flavors)
- Best fit: $(f_e : f_\mu : f_\tau)_\oplus = (0.49 : 0.51 : 0)_\oplus$
- Compatible with standard source compositions
- Lots of room for improvement: more statistics, better flavor-tagging

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

Flavor – there and here

At the sources

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

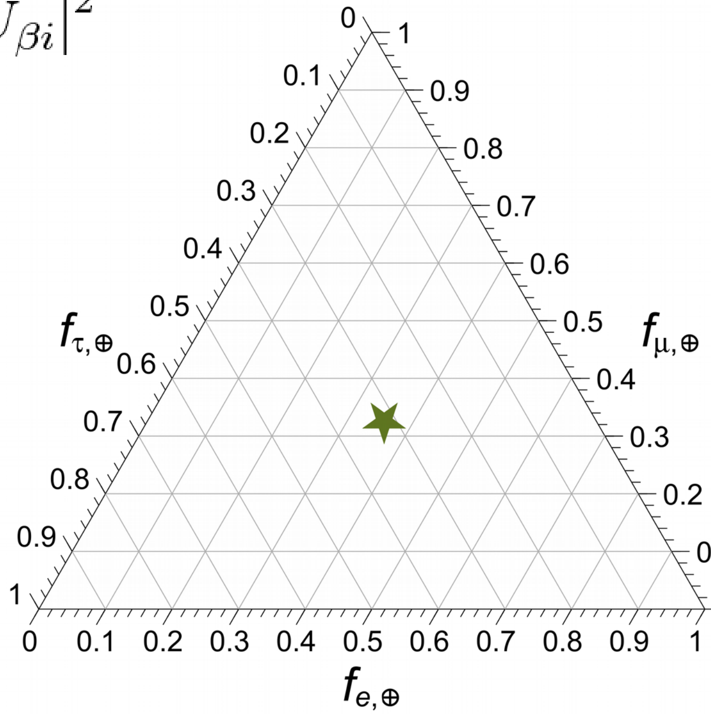


Neutrino oscillations

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

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

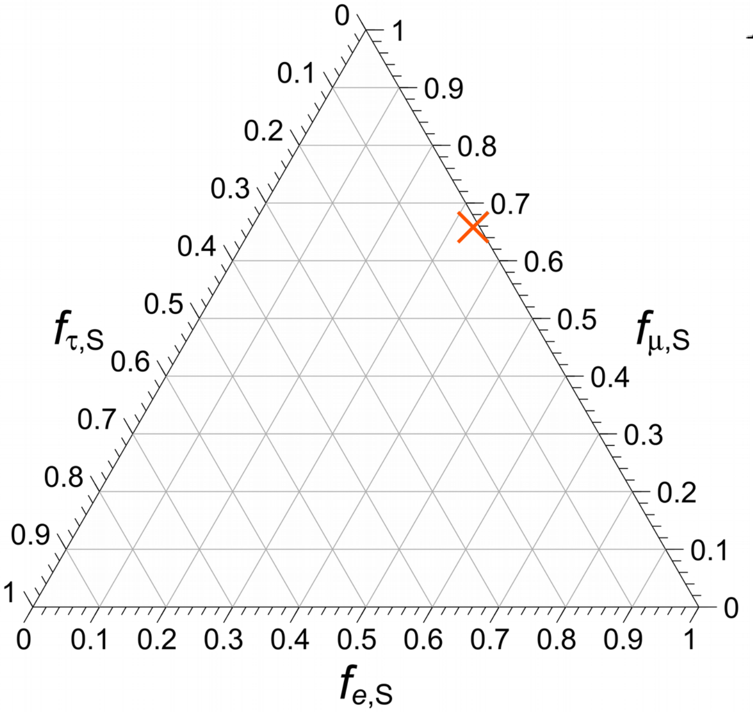
$(f_e:f_\mu:f_\tau)_S = (1/3 : 2/3 : 0)_S$

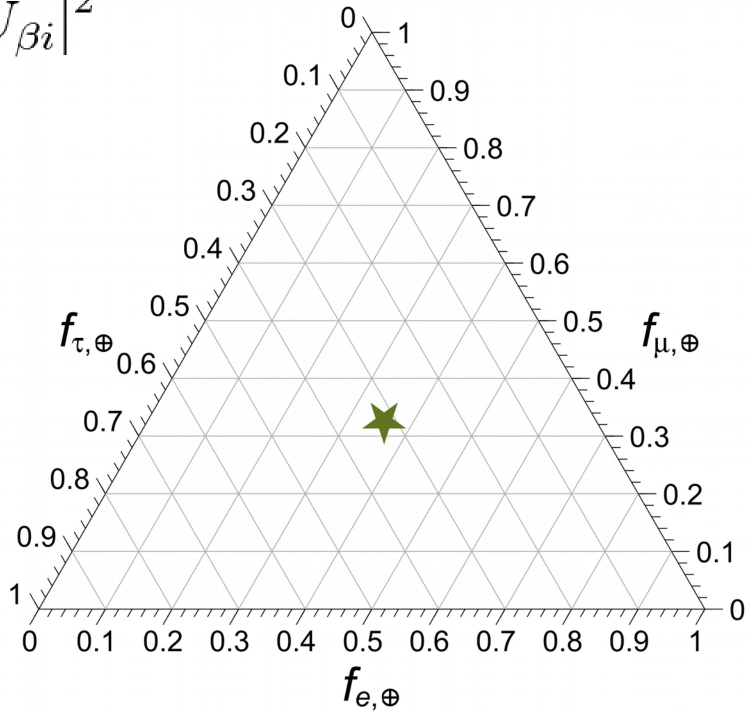
Neutrino oscillations

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

At Earth

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





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

At Earth

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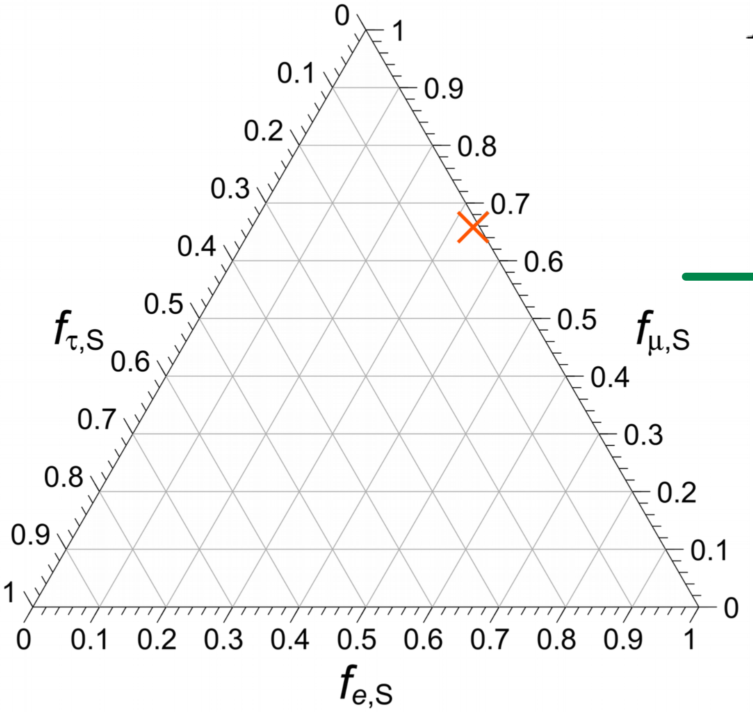
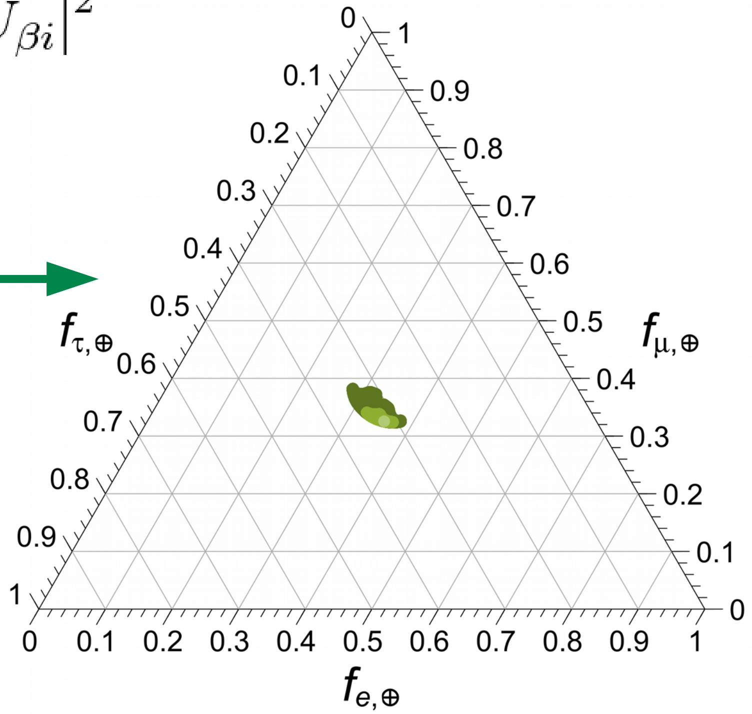
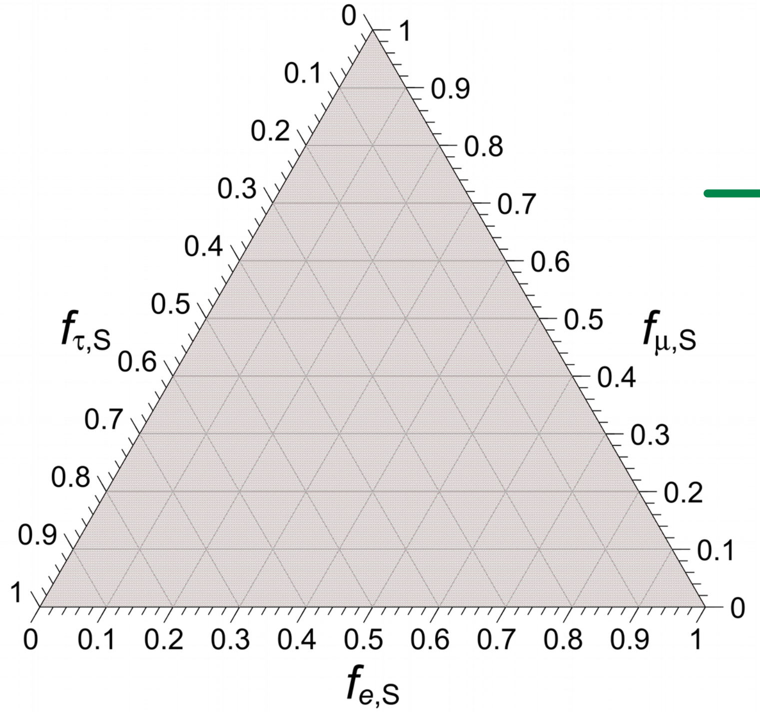




Flavor composition – Standard allowed region

At the sources

All possible flavor ratios



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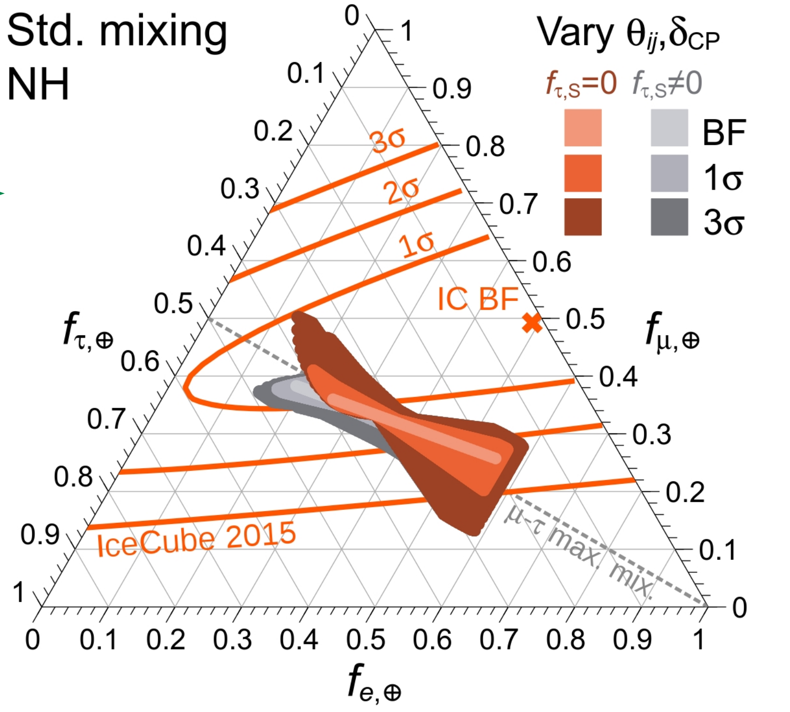

MB, Beacom, Winter *PRL* 2015

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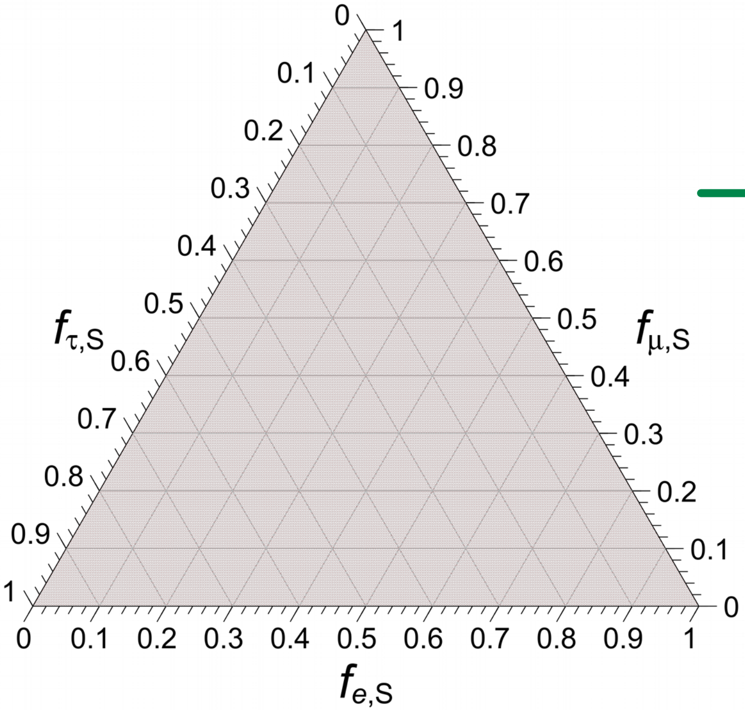
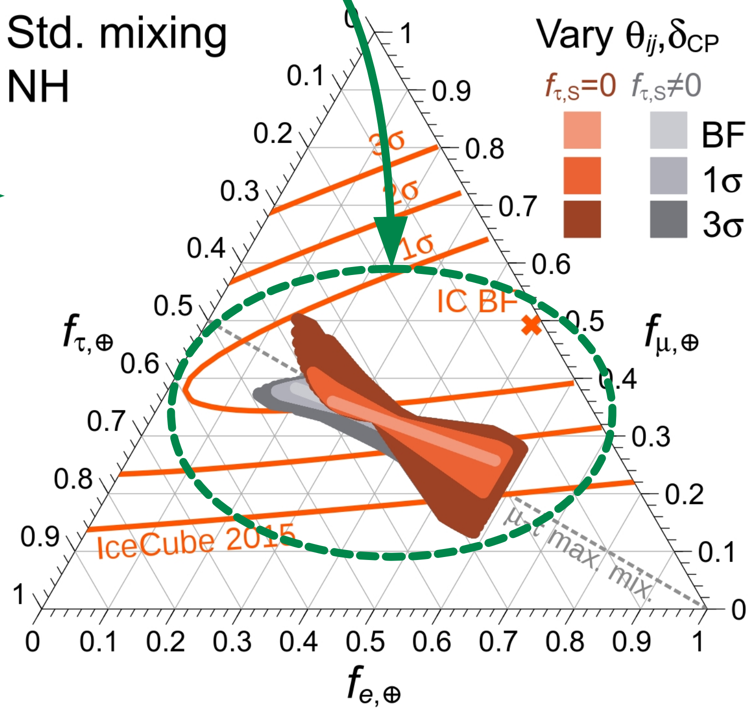


Only 10% of parameter space

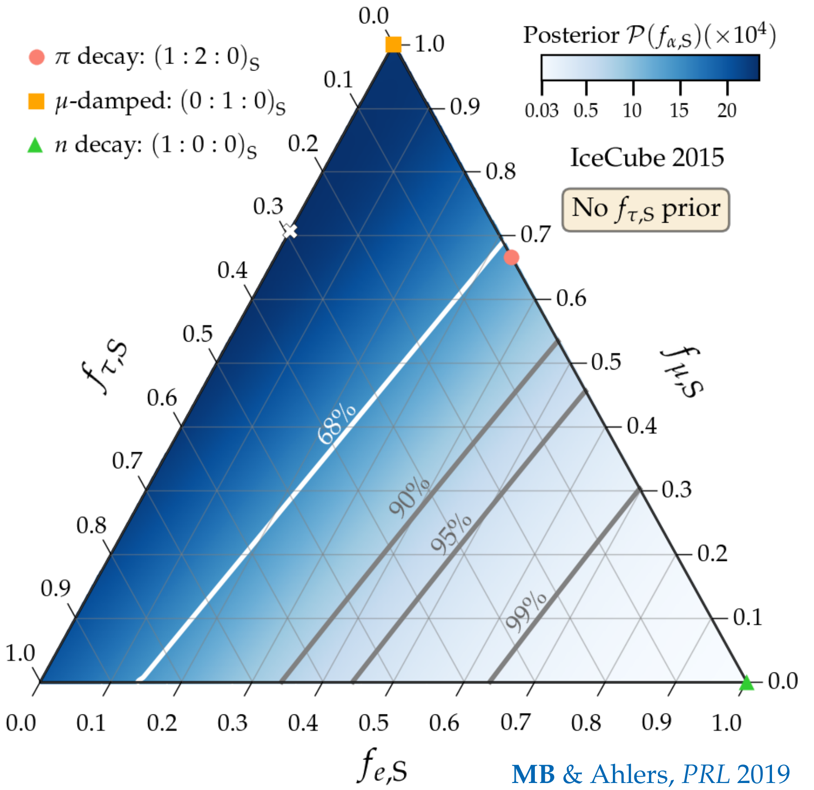
At Earth



MB, Beacom, Winter *PRL* 2015

Flavor – What is it good for?

Trusting particle physics
and learning about astrophysics



MB & Ahlers, *PRL* 2019

Trusting astrophysics
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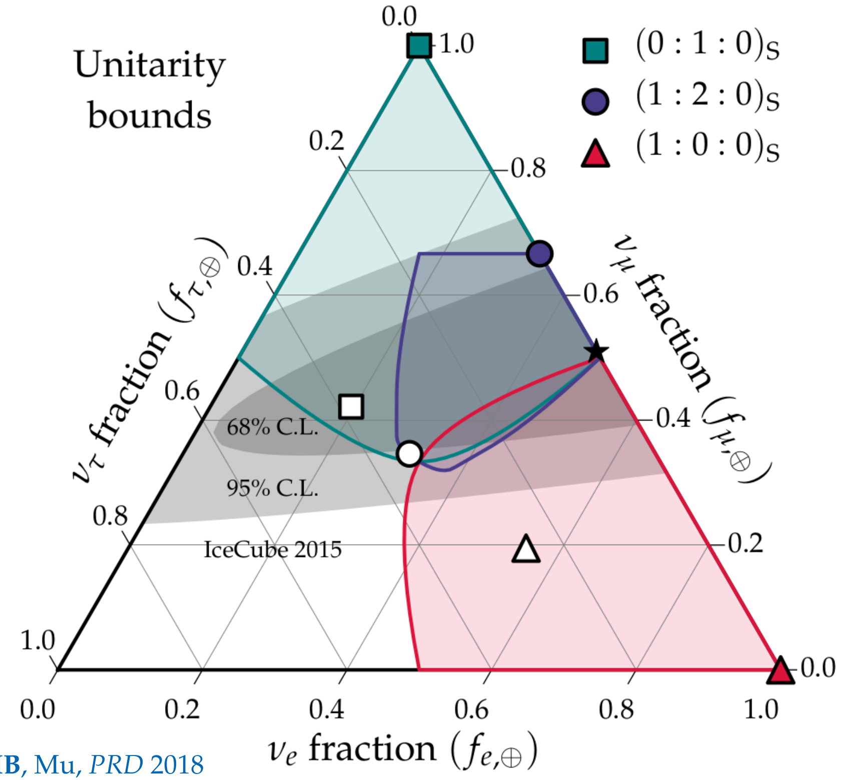
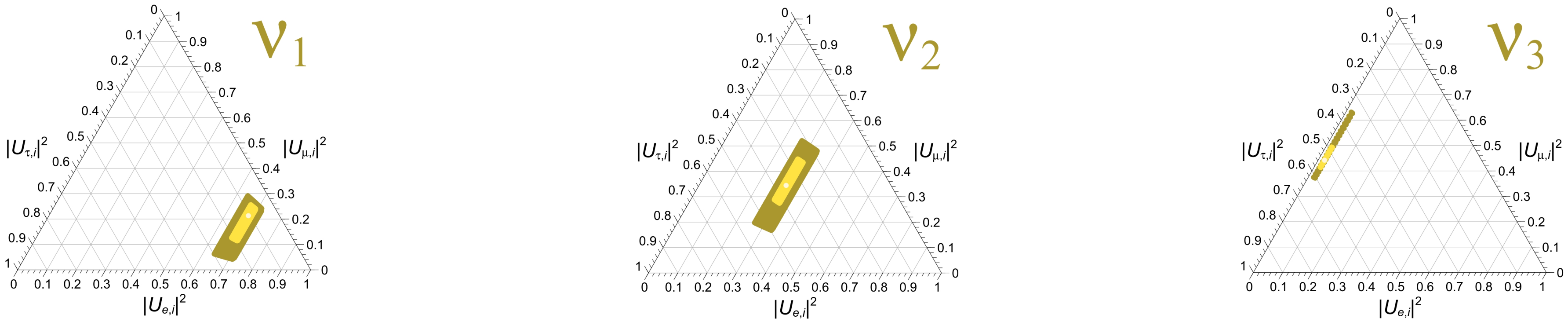


Ahlers, **MB**, Mu, *PRD* 2018

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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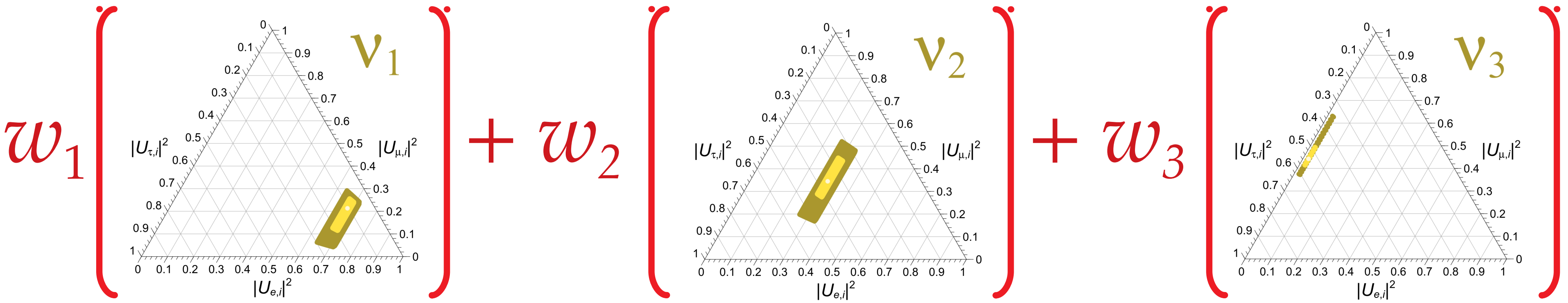

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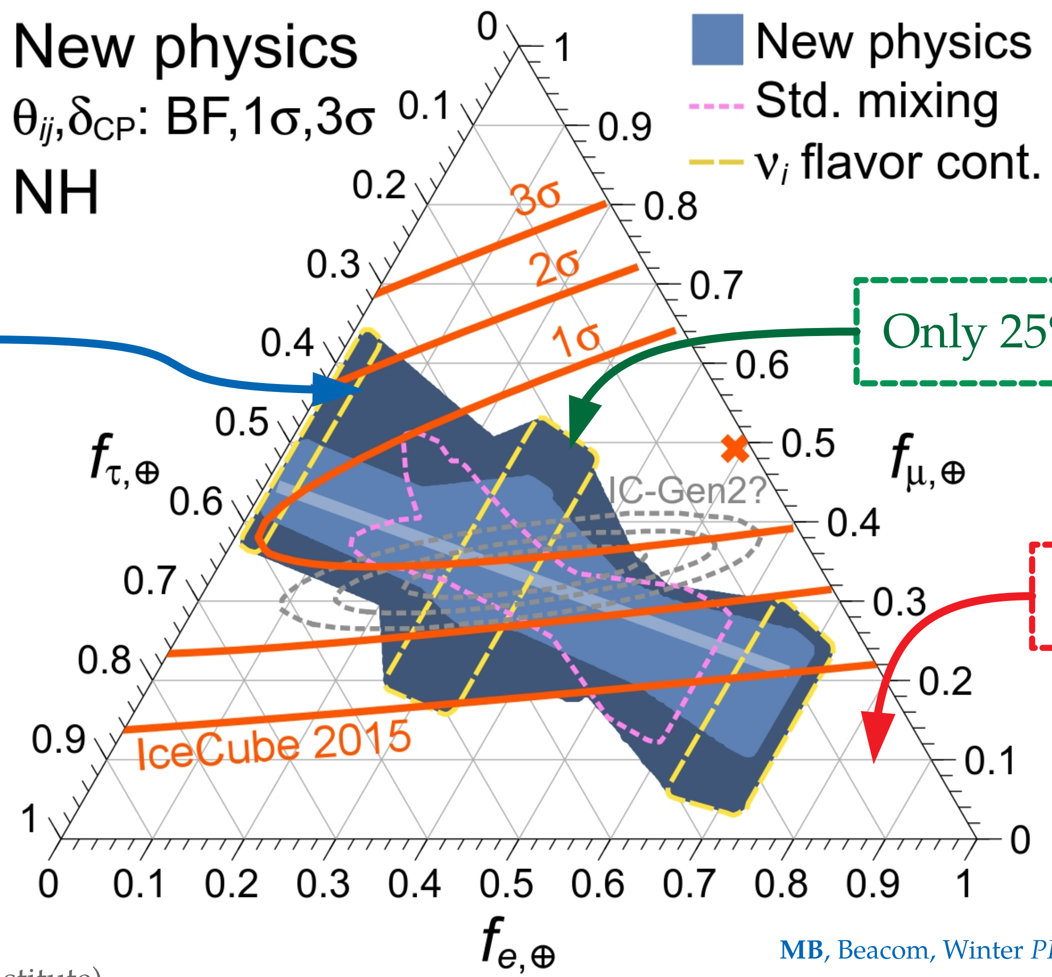
Flavor ratios accessible with decay-like physics

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

Flavor ratios accessible with decay-like physics

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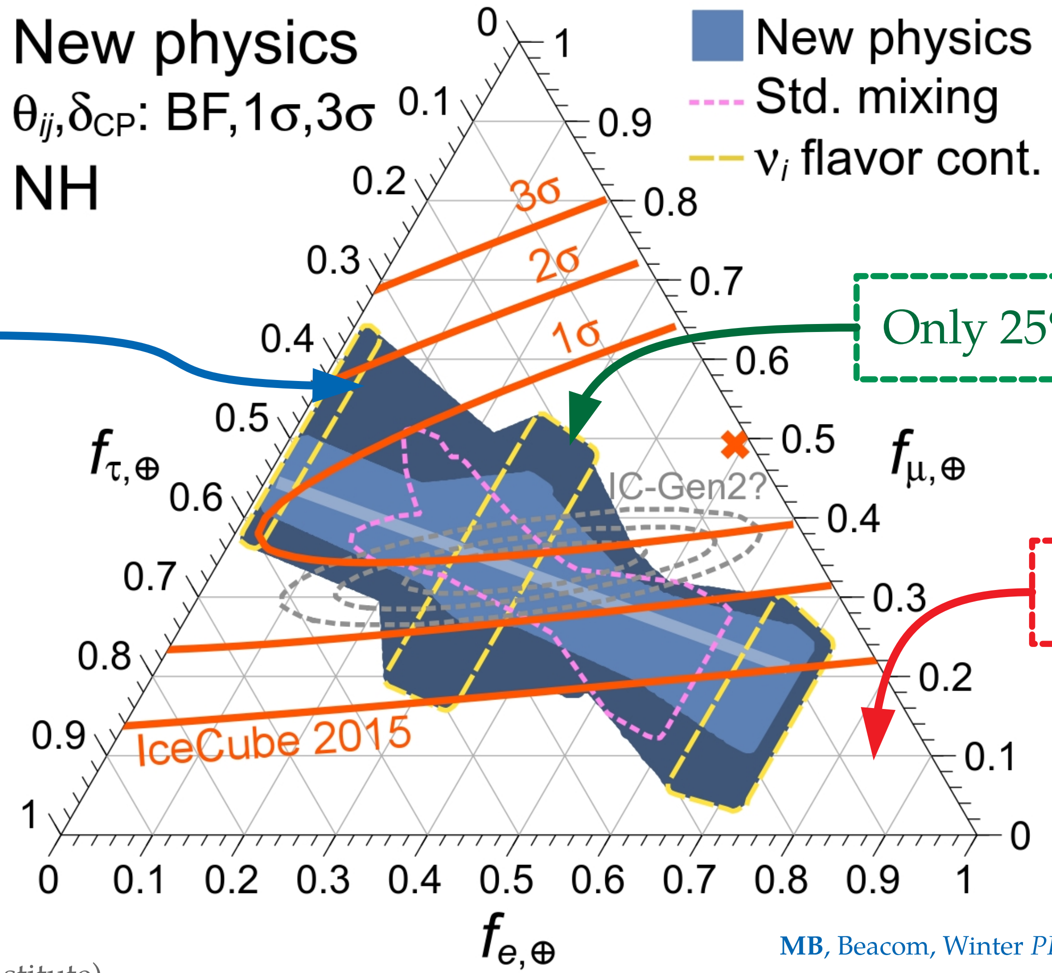

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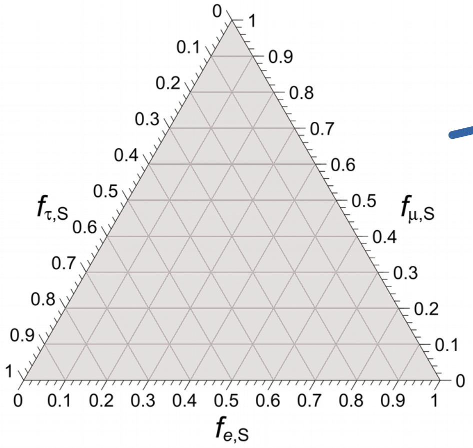
MB, Beacom, Winter *PRL* 2015

Measuring the neutrino lifetime

Sources



$\nu_2, \nu_3 \to \nu_1$

ν_1 lightest and stable

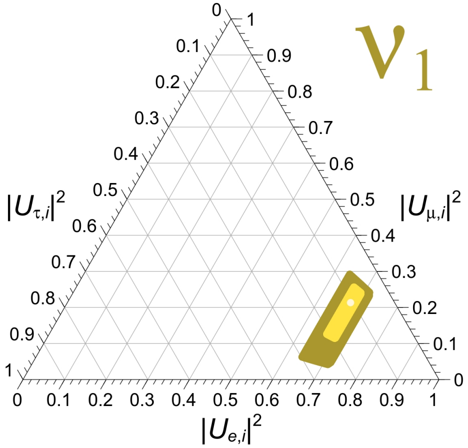
If all unstable neutrinos decay

$\nu_1, \nu_2 \to \nu_3$

ν_3 lightest and stable

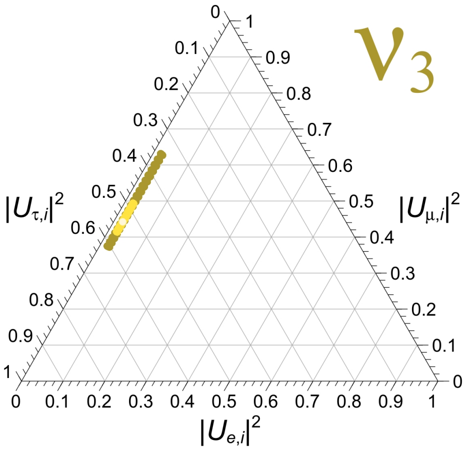
Earth

ν_1



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

ν_3

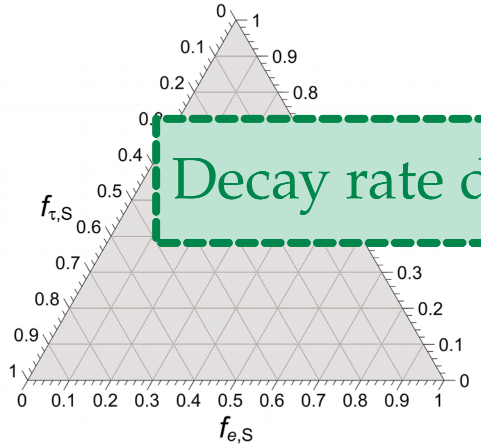


$$f_{\alpha,\oplus} = |U_{\alpha 3}|^2$$

Measuring the neutrino lifetime

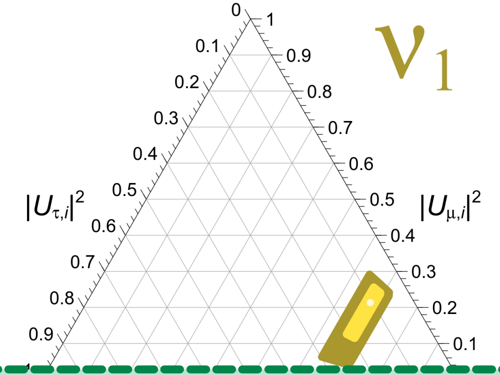
Earth

Sources



$\nu_2, \nu_3 \to \nu_1$

ν_1 lightest and stable



ν_1

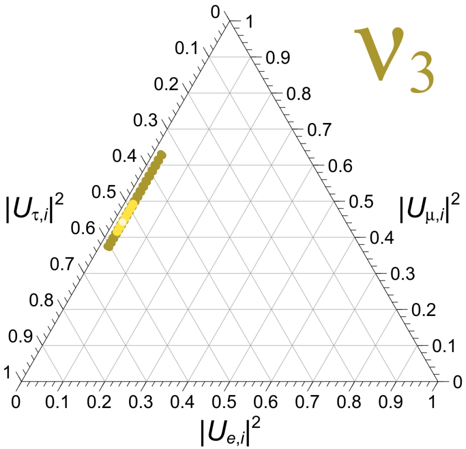
$f_{\alpha,\oplus} = |U_{\alpha 1}|^2$

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

neutrinos decay

$\nu_1, \nu_2 \to \nu_3$

ν_3 lightest and stable



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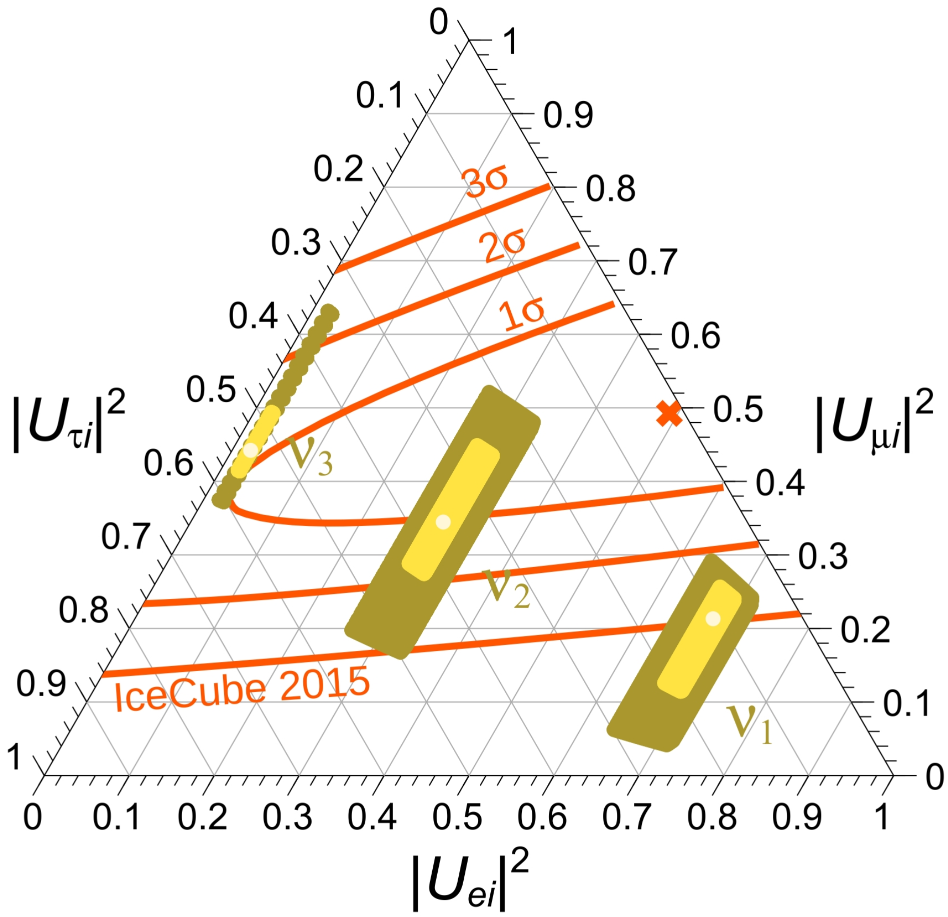
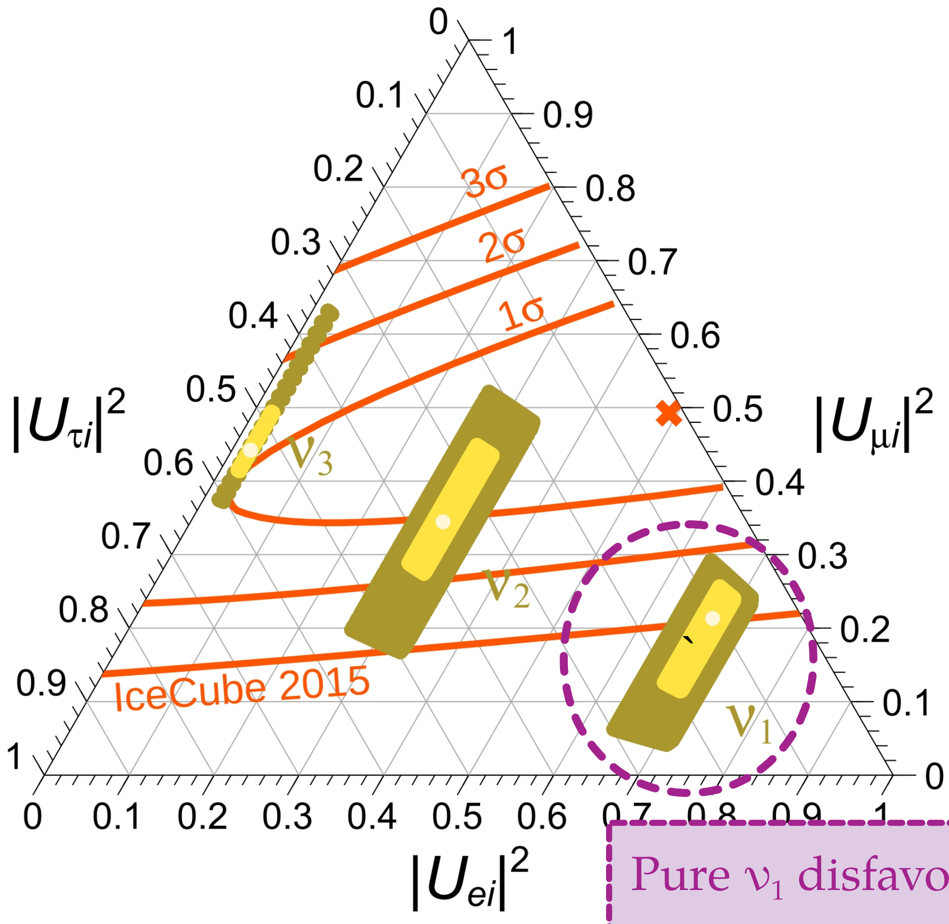


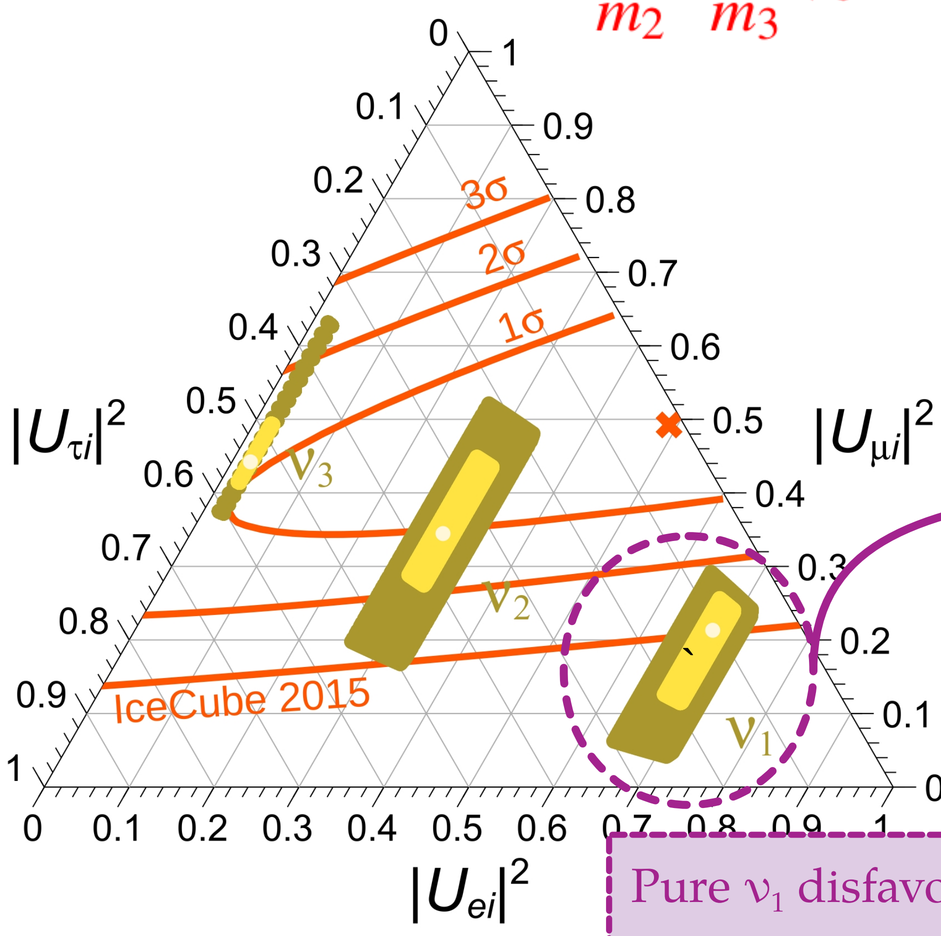
MB, Beacom, Murase, *PRD* 2017

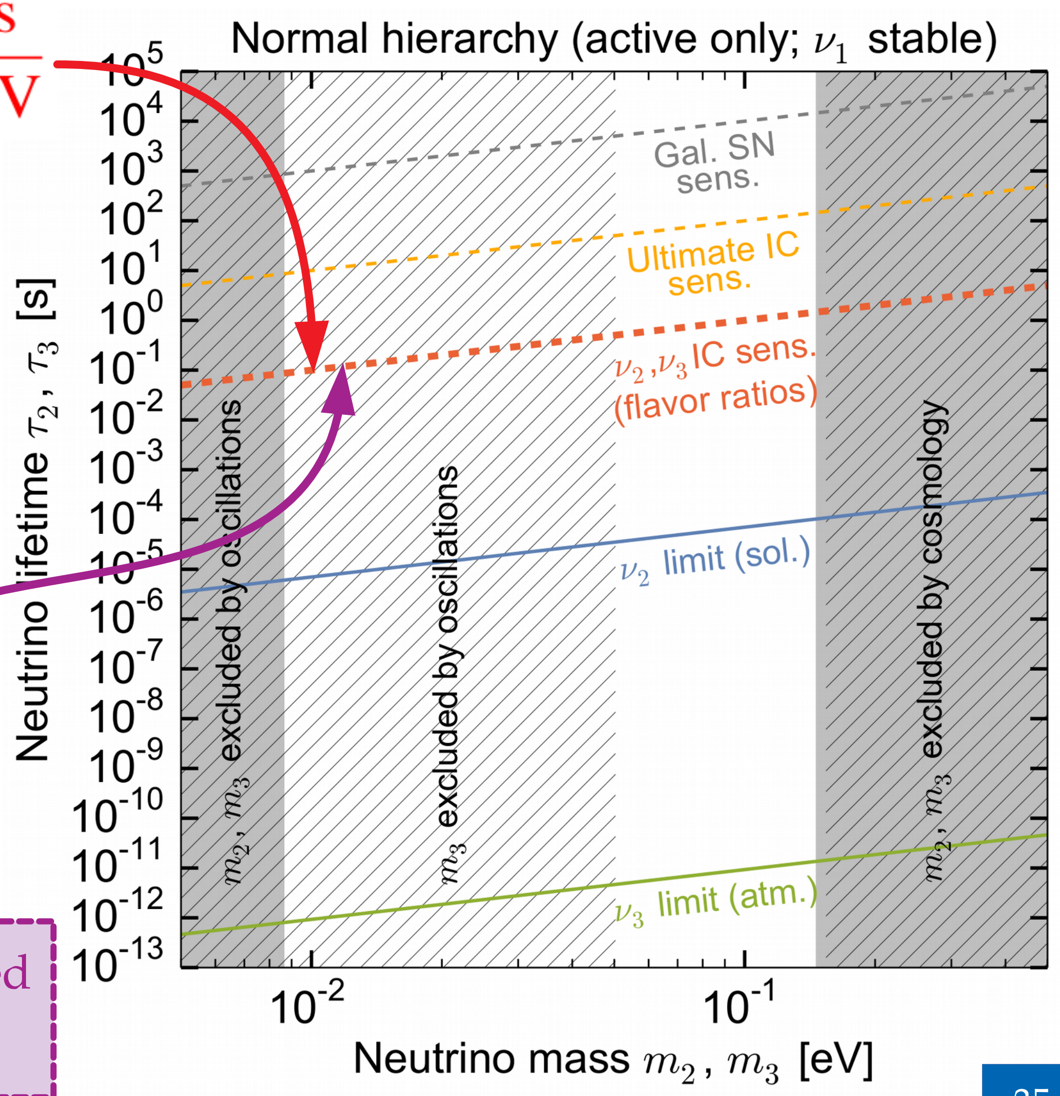


Pure ν_1 disfavored at > 2σ

MB, Beacom, Murase, *PRD* 2017

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





MB, Beacom, Murase, *PRD* 2017

Pure ν_1 disfavored at > 2σ

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; 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, *PRL* 2019]

Toho Company Ltd.

New physics – High-energy effects

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

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

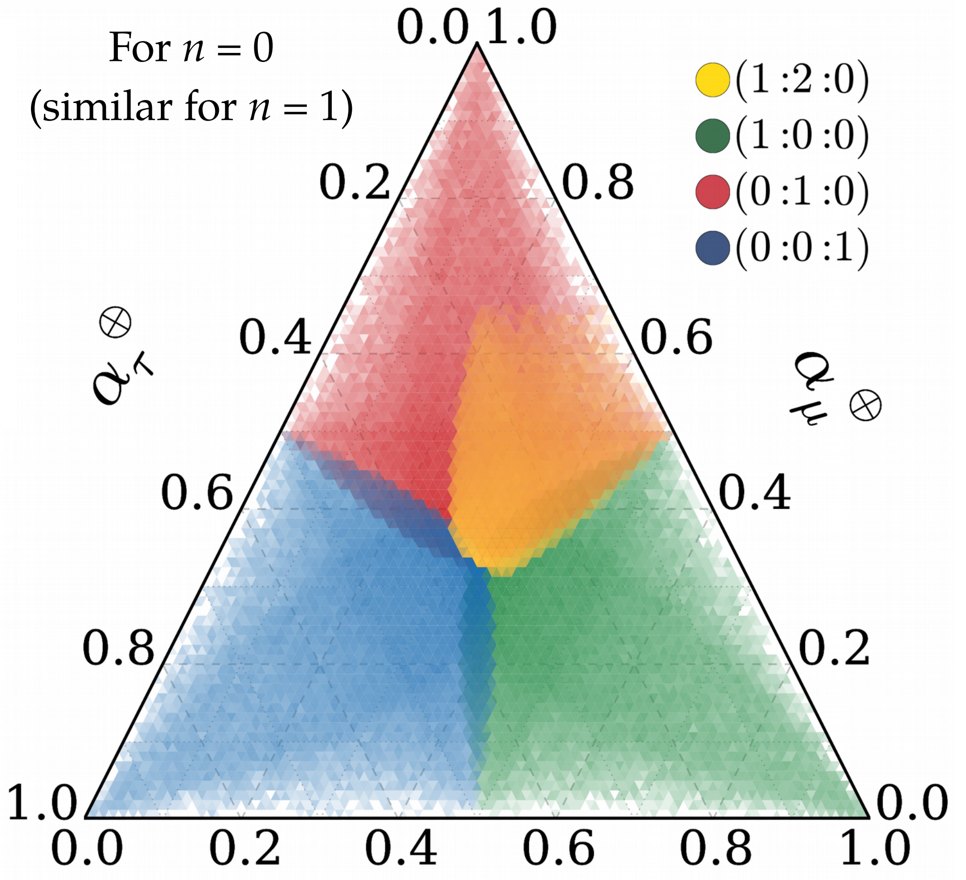
$$H_{\rm NP} = \sum_n \left(\frac{E}{\Lambda_n}\right)^n U_n^\dagger \,{\rm diag}\left(O_{n,1}, O_{n,2}, O_{n,3}\right) U_n$$

This can populate *all* of the triangle –

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

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

- Sample the unknown new mixing angles



Argüelles, Katori, Salvadó, *PRL* 2015

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

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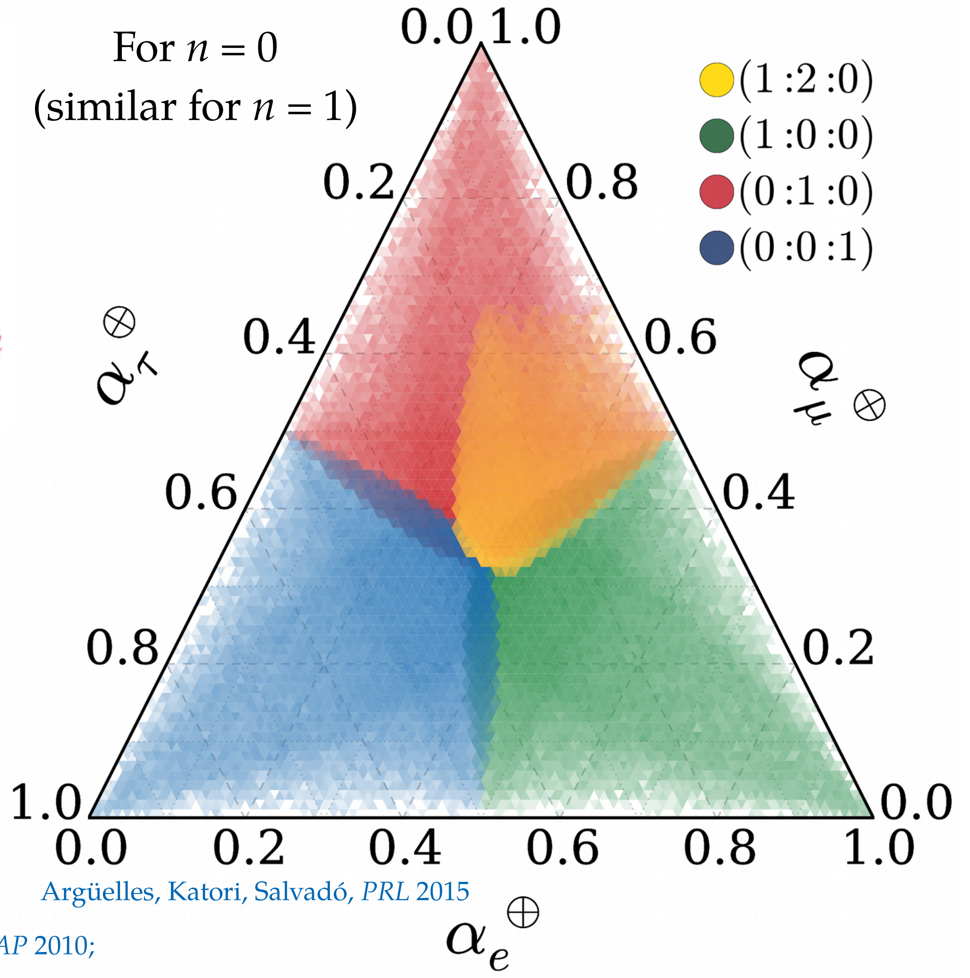

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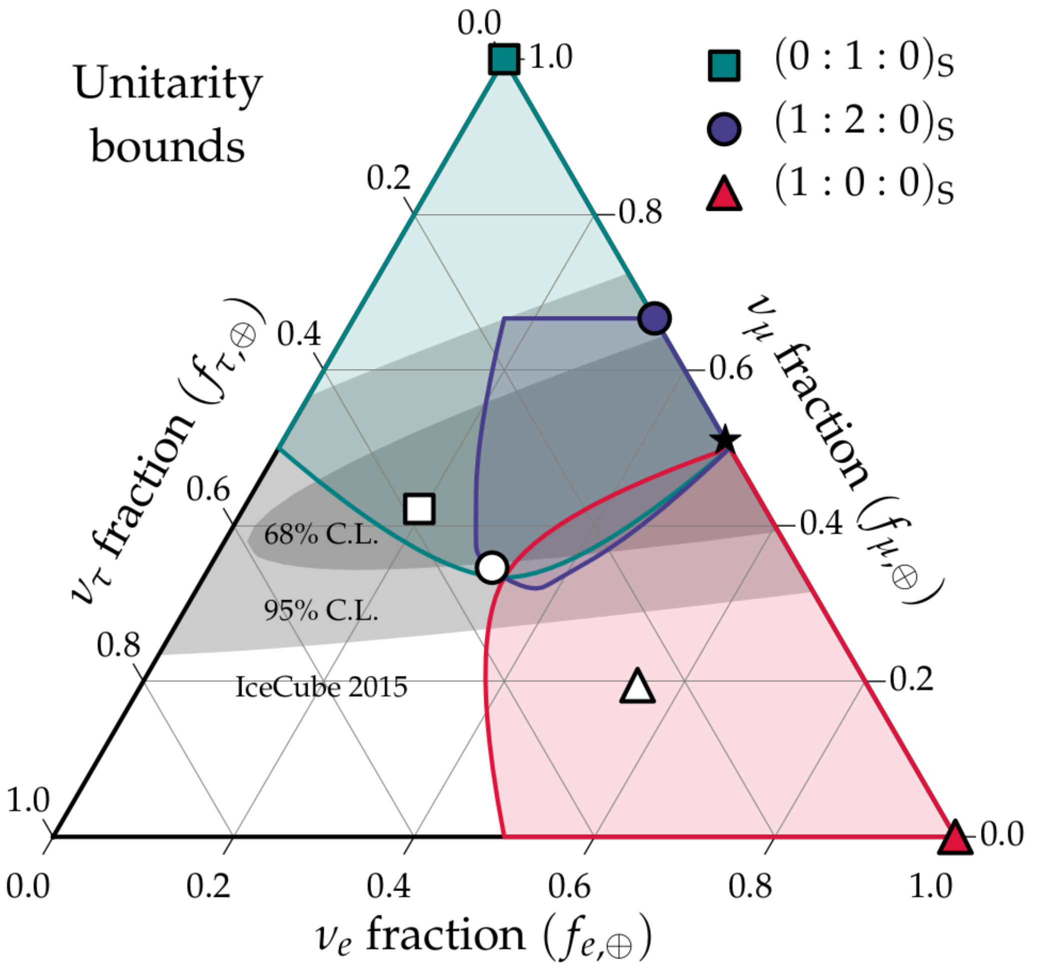
Using unitarity to constrain new physics

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

- New mixing angles unconstrained
- Use unitarity ($U_{NP}U_{NP}^{\dagger} = 1$) to bound all possible flavor ratios at Earth
- Can be used as prior in new-physics searches in IceCube



Ahlers, **MB**, Mu, *PRD* 2018
See also: Xu, He, Rodejohann, *JCAP* 2014

Ultra-long-range flavorful interactions

- Simple extension of the SM: Promote the global lepton-number symmetries L_e-L_μ, L_e-L_τ to local symmetries

- They introduce new interaction between electrons and ν_e and ν_μ or ν_τ mediated by a new neutral vector boson (Z'):
  - Affects oscillations
  - If the Z' is *very* light, *many* electrons can contribute

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

The new potential sourced by an electron

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

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

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

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

Z' coupling → $g'^2_{e\beta}$

Z' mass → $m'_{e\beta}$

Distance to neutrino → r

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

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

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

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

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Z' parameters

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

Electron-neutrino interactions can kill oscillations

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

Electron-neutrino interactions can kill oscillations

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

$\mathrm{H}_{\mathrm{vac}}$: $\sim 1/E$

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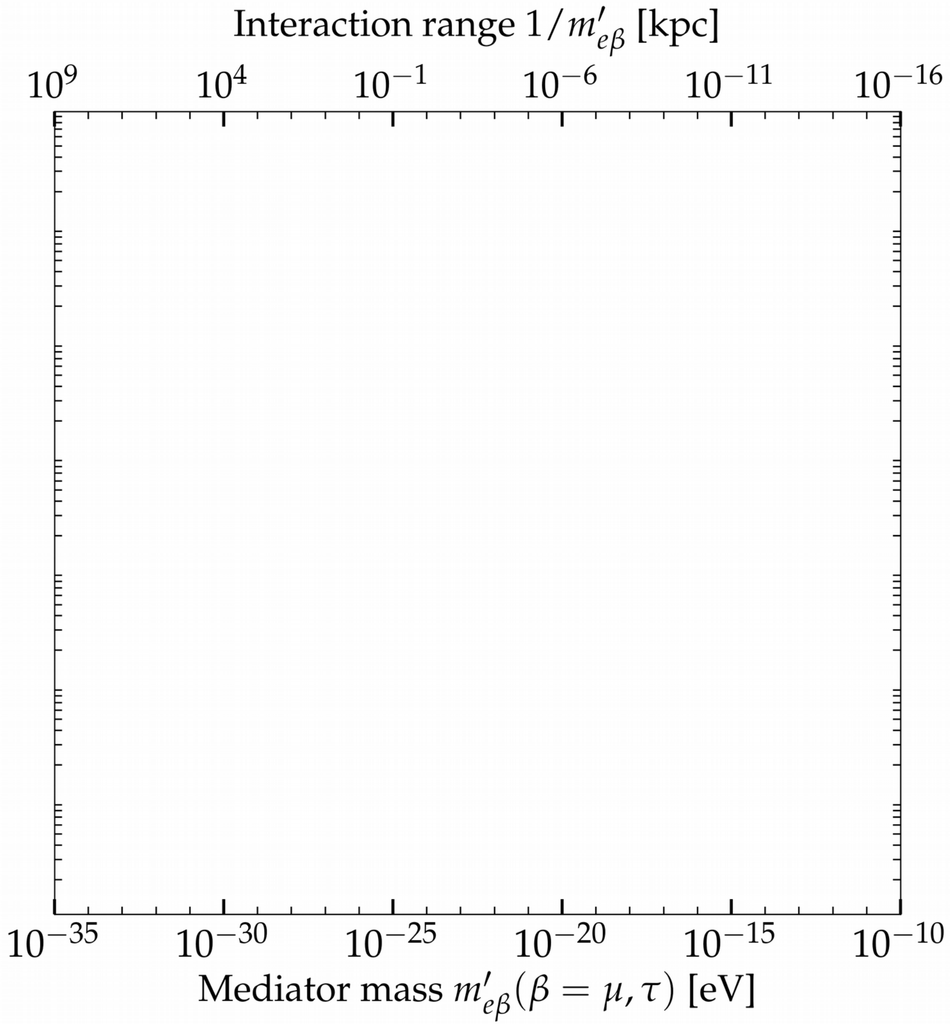
Interaction range: $\frac{1}{m'_{e\beta}}$

Electrons in the local and distant Universe



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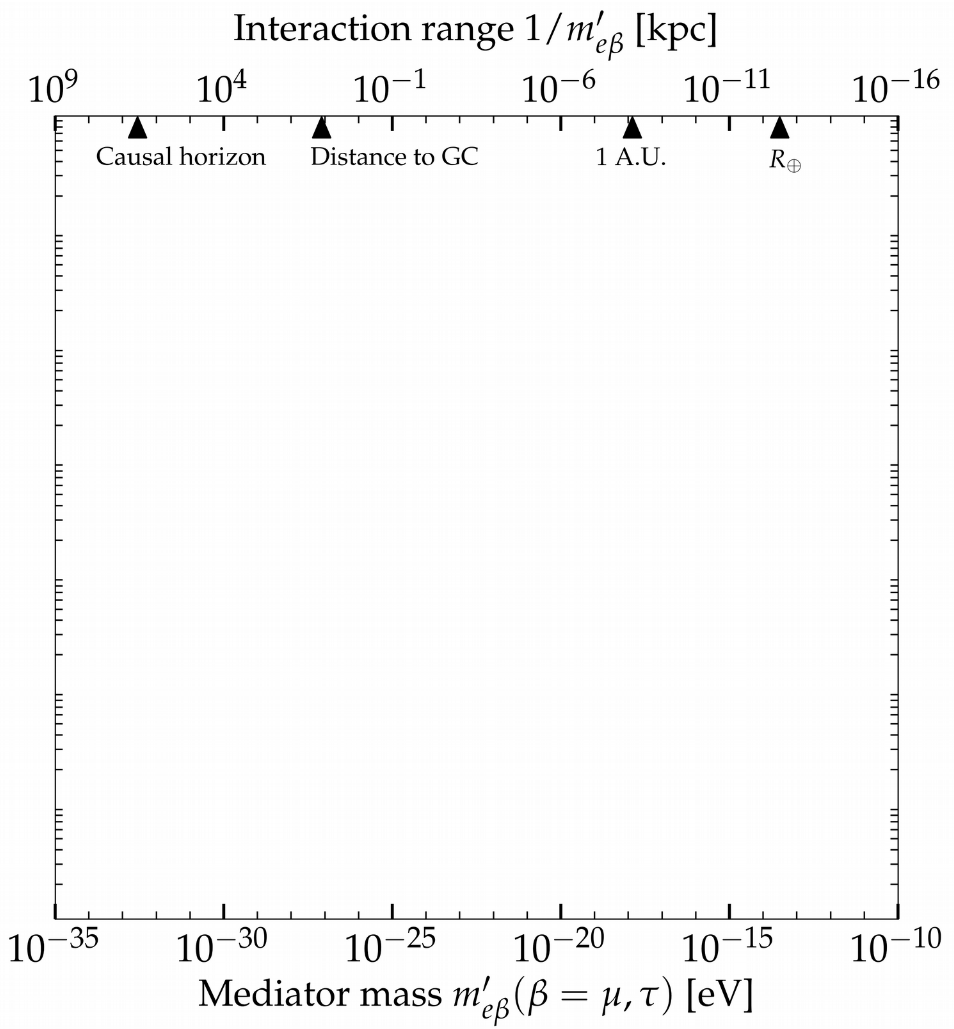

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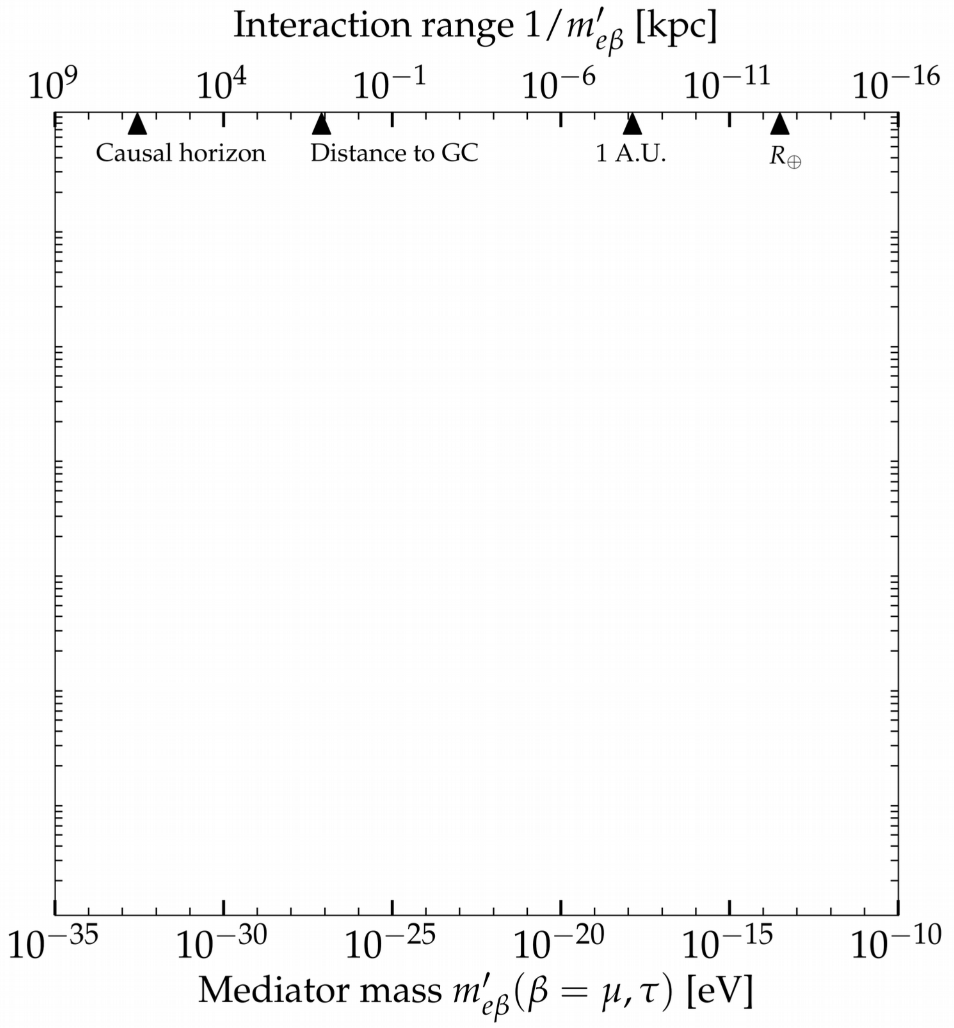

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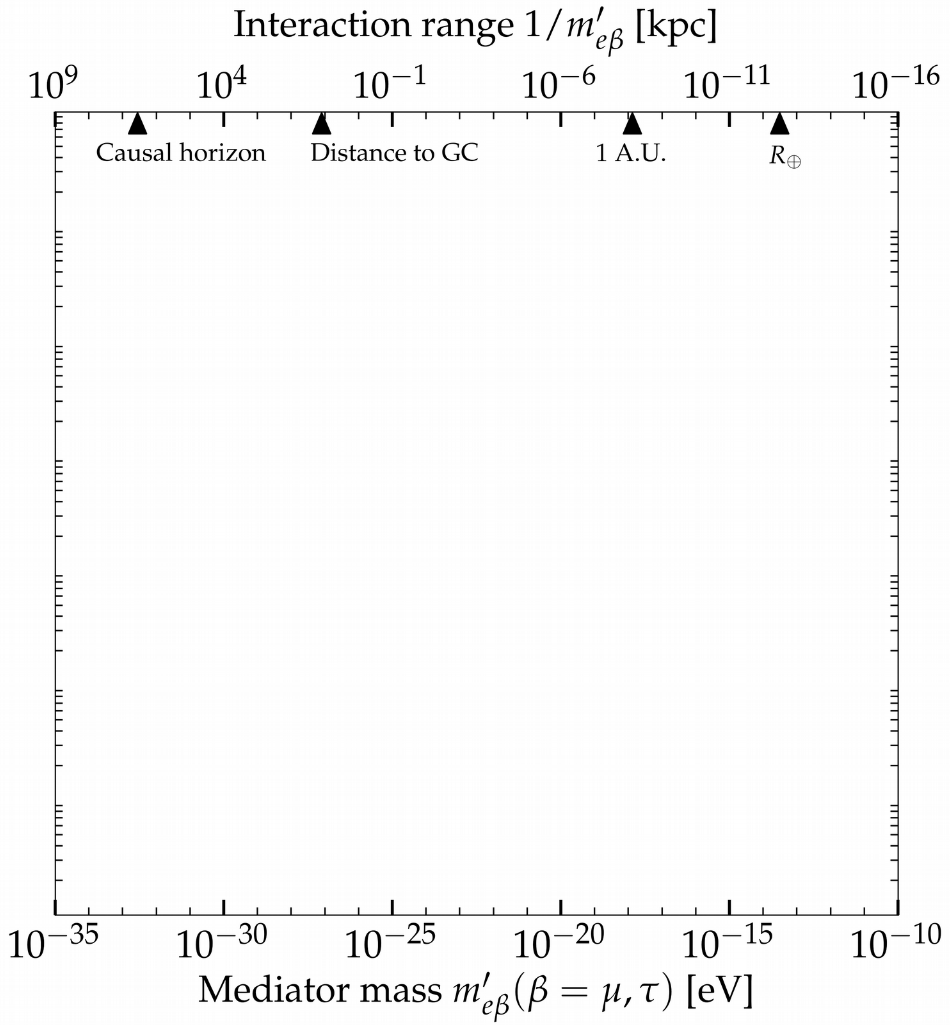
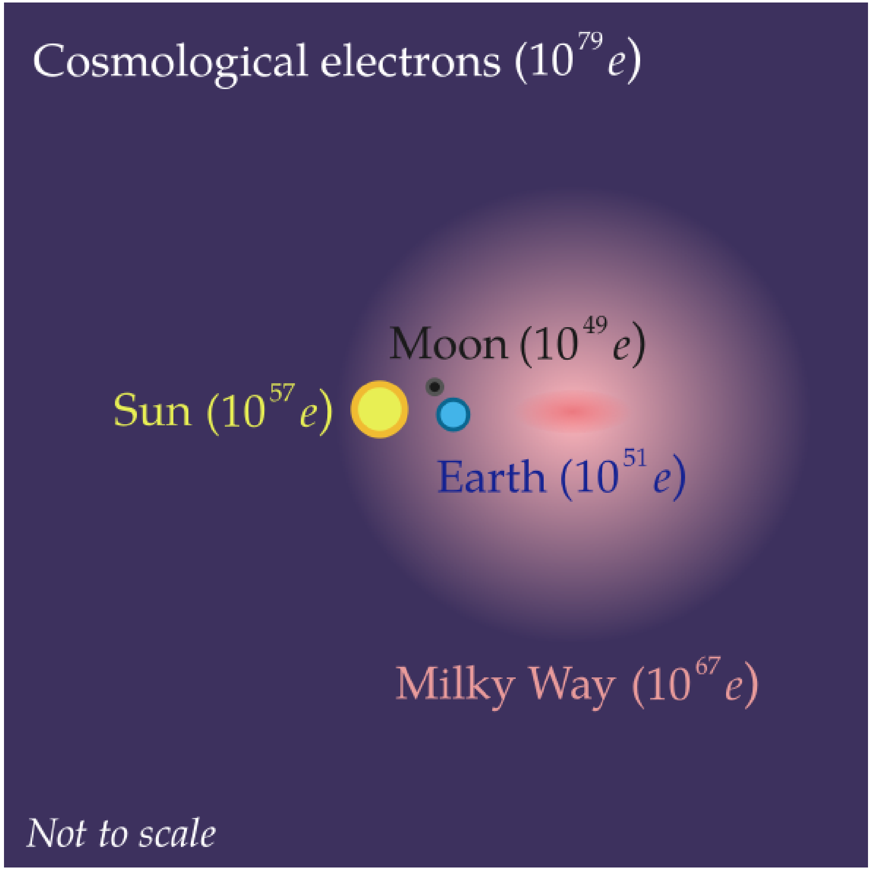
Light mediators
$\Rightarrow$ Long interaction ranges

Electrons in the local and distant Universe





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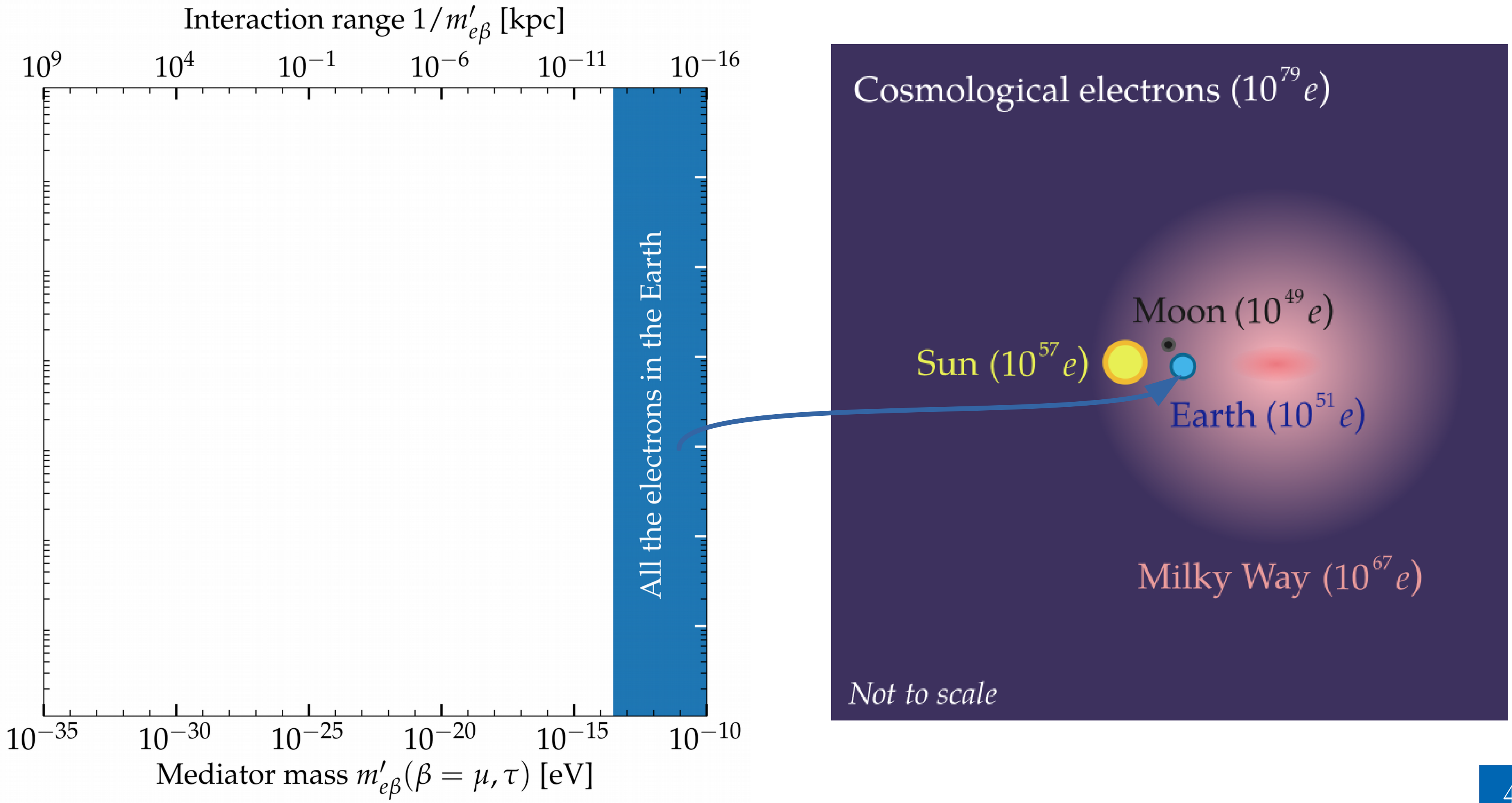

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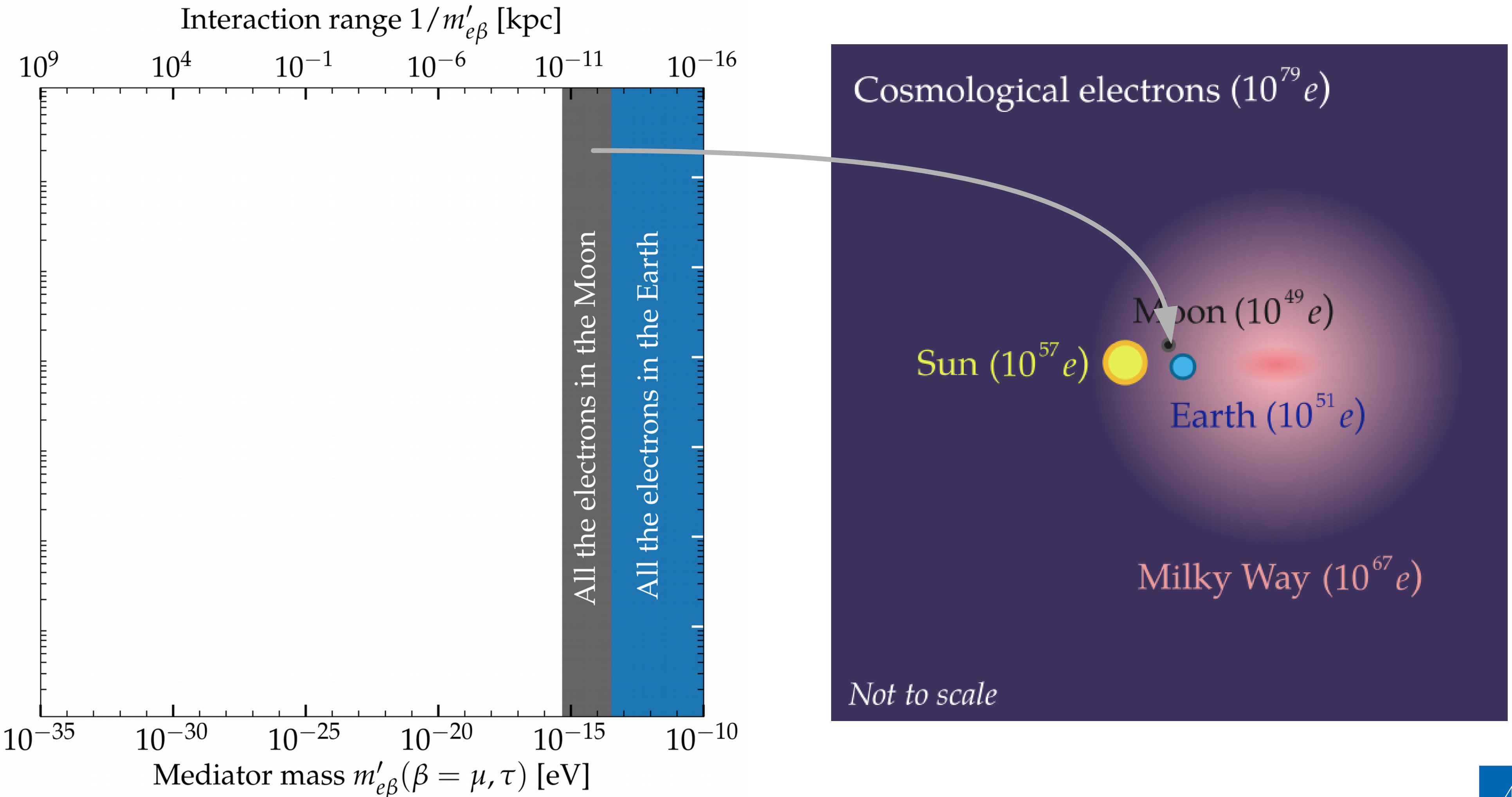

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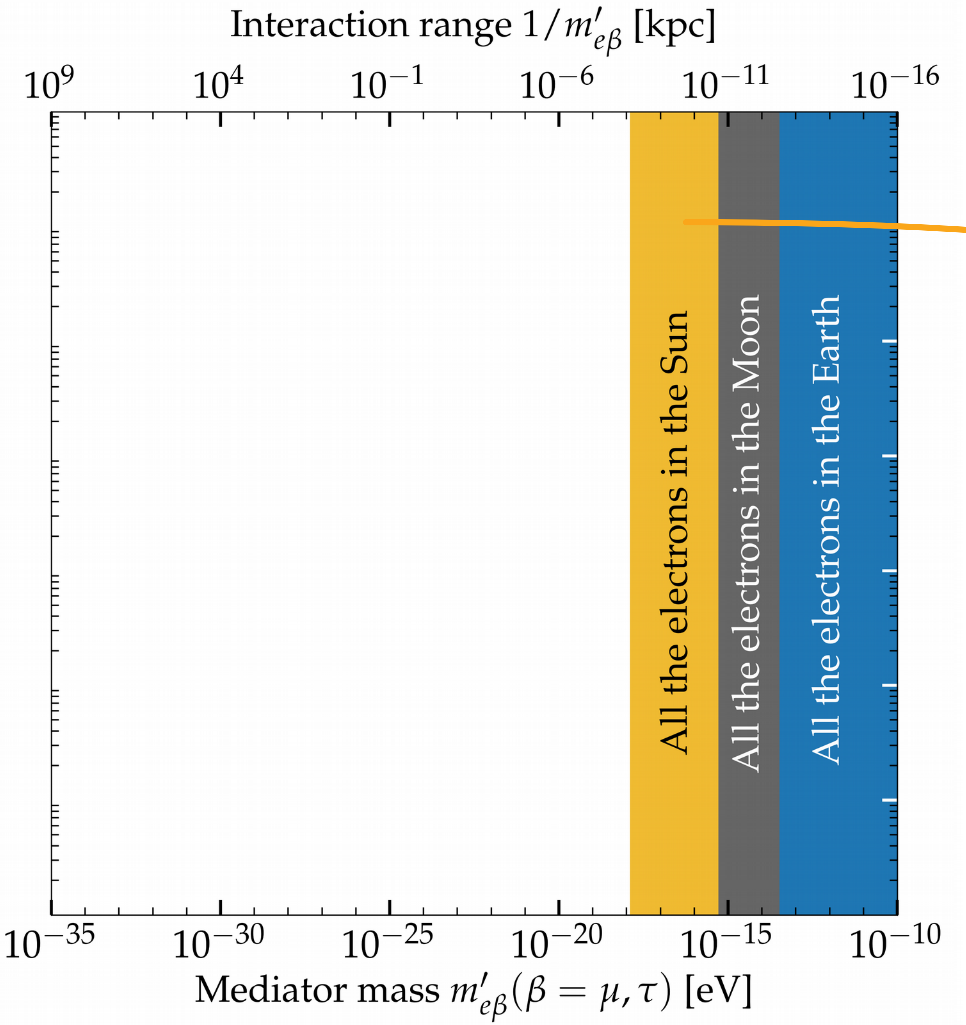

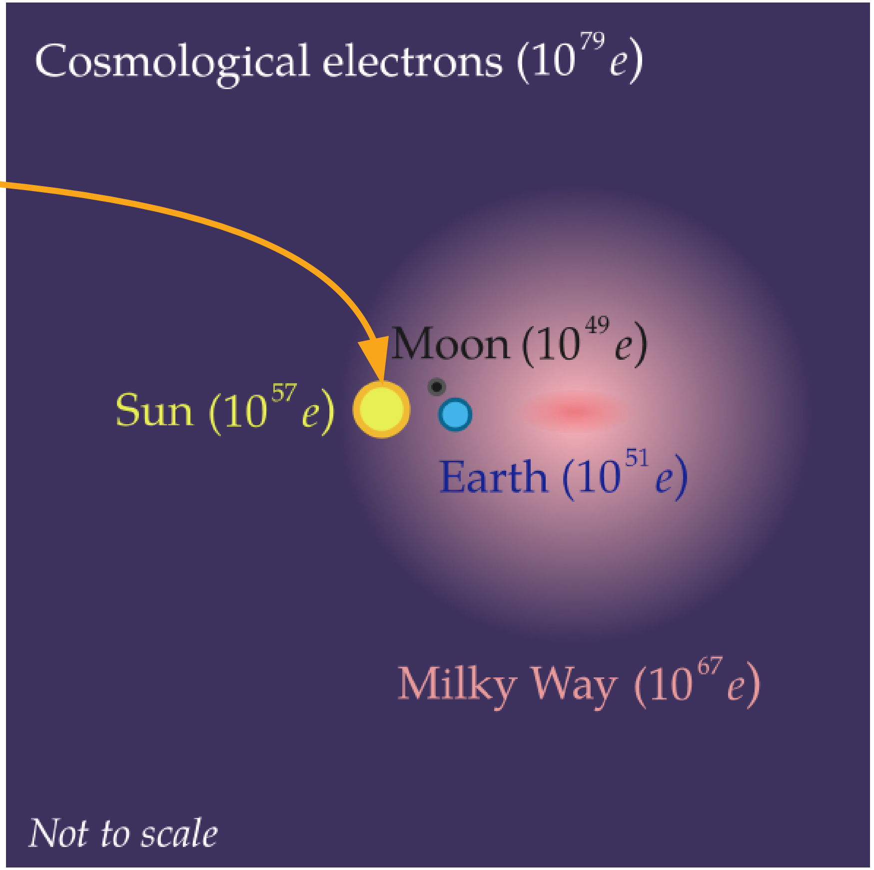

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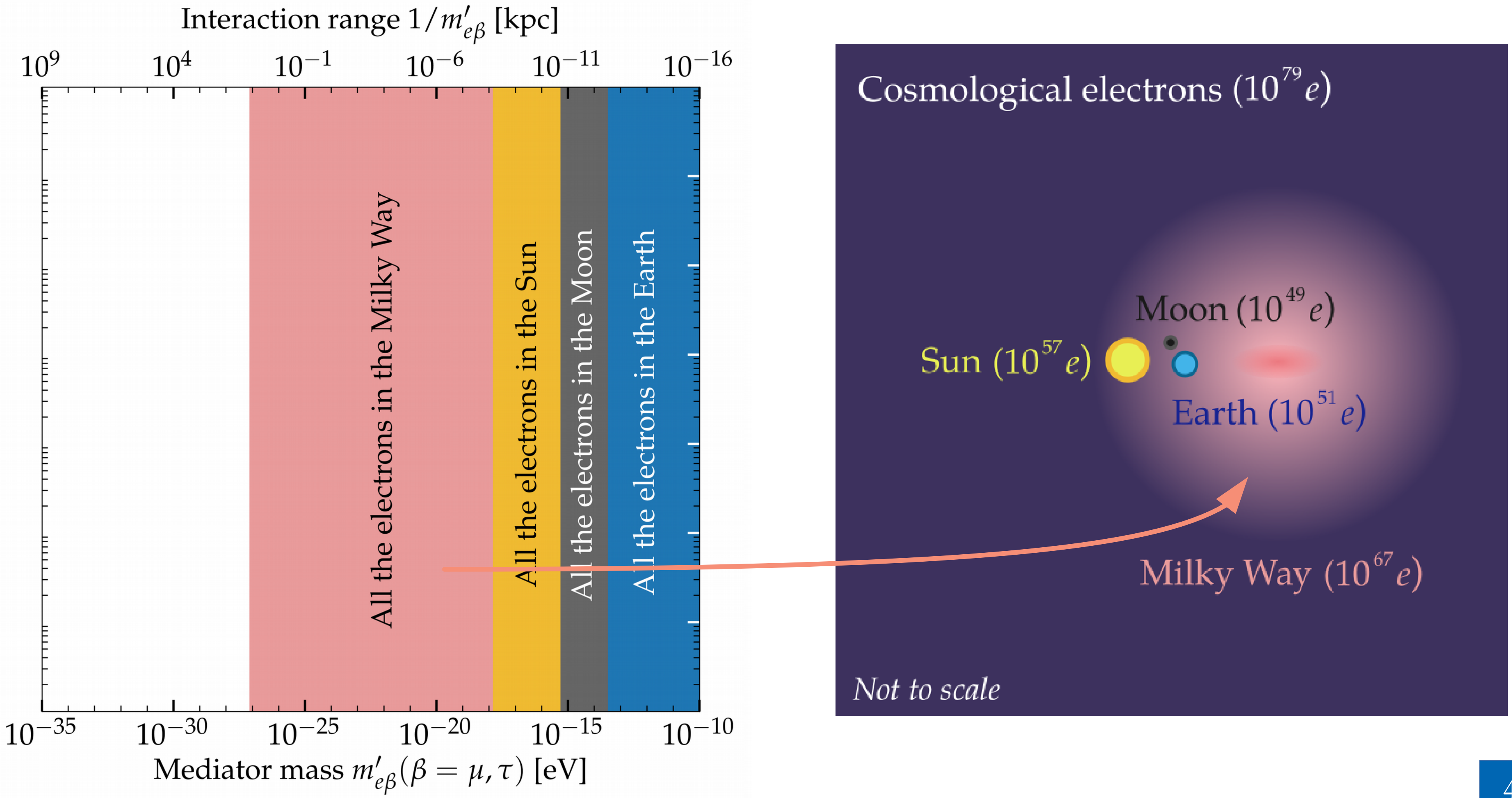

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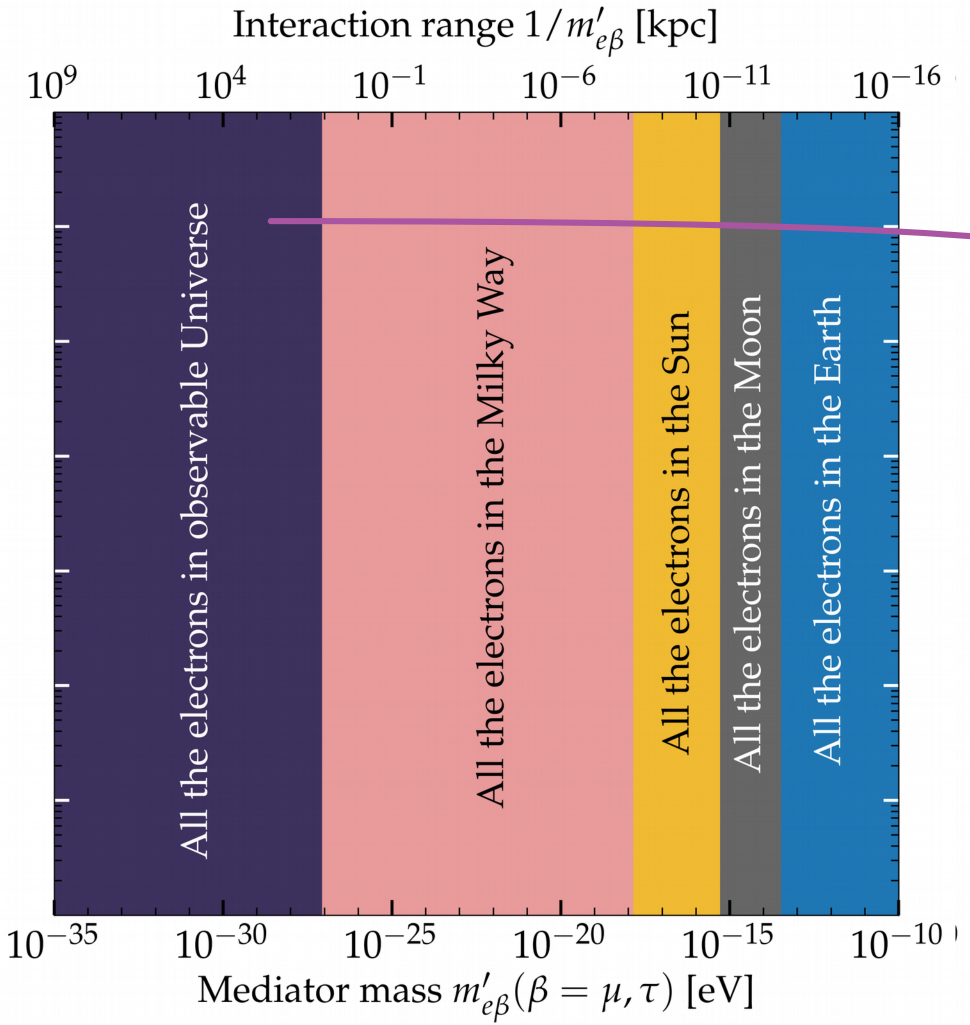

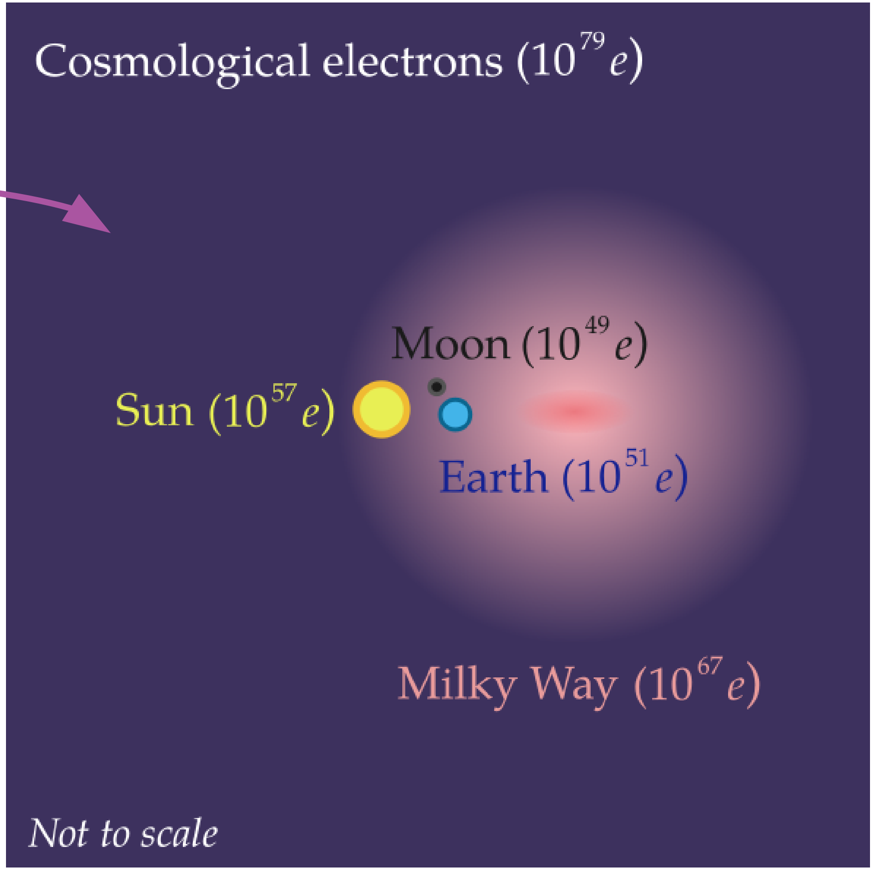

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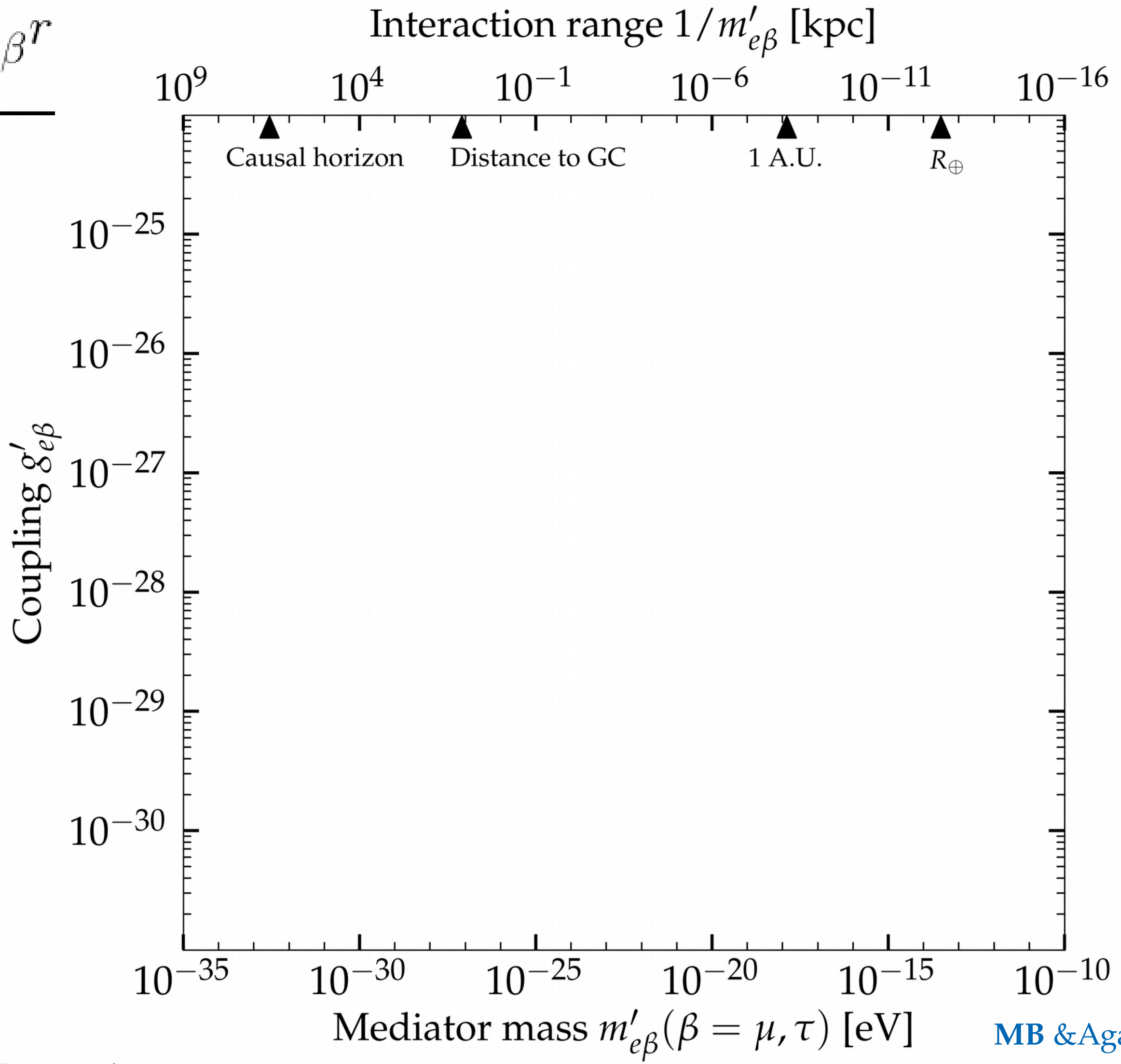
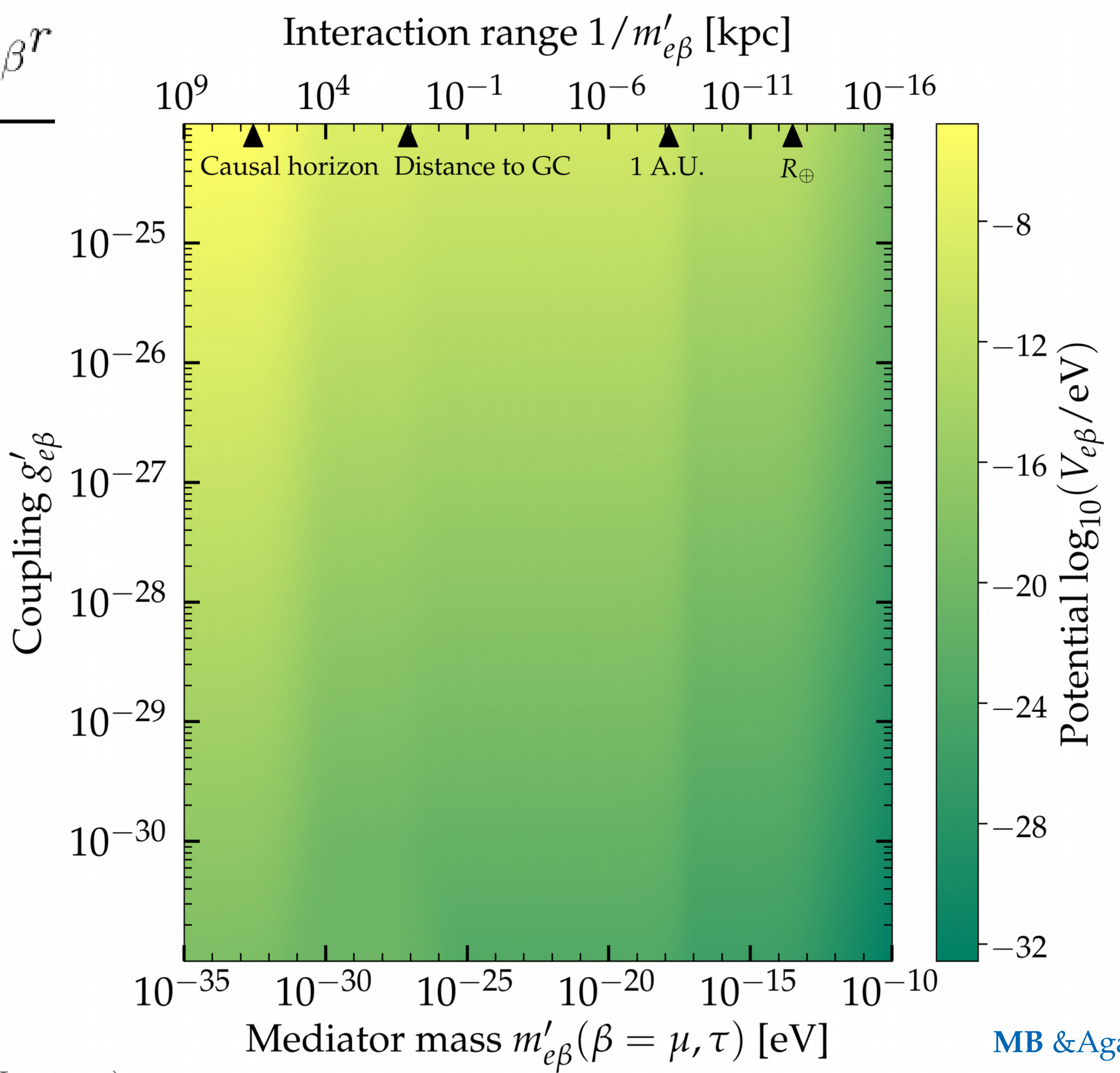


MB &Agarwalla, *PRL* 2019

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



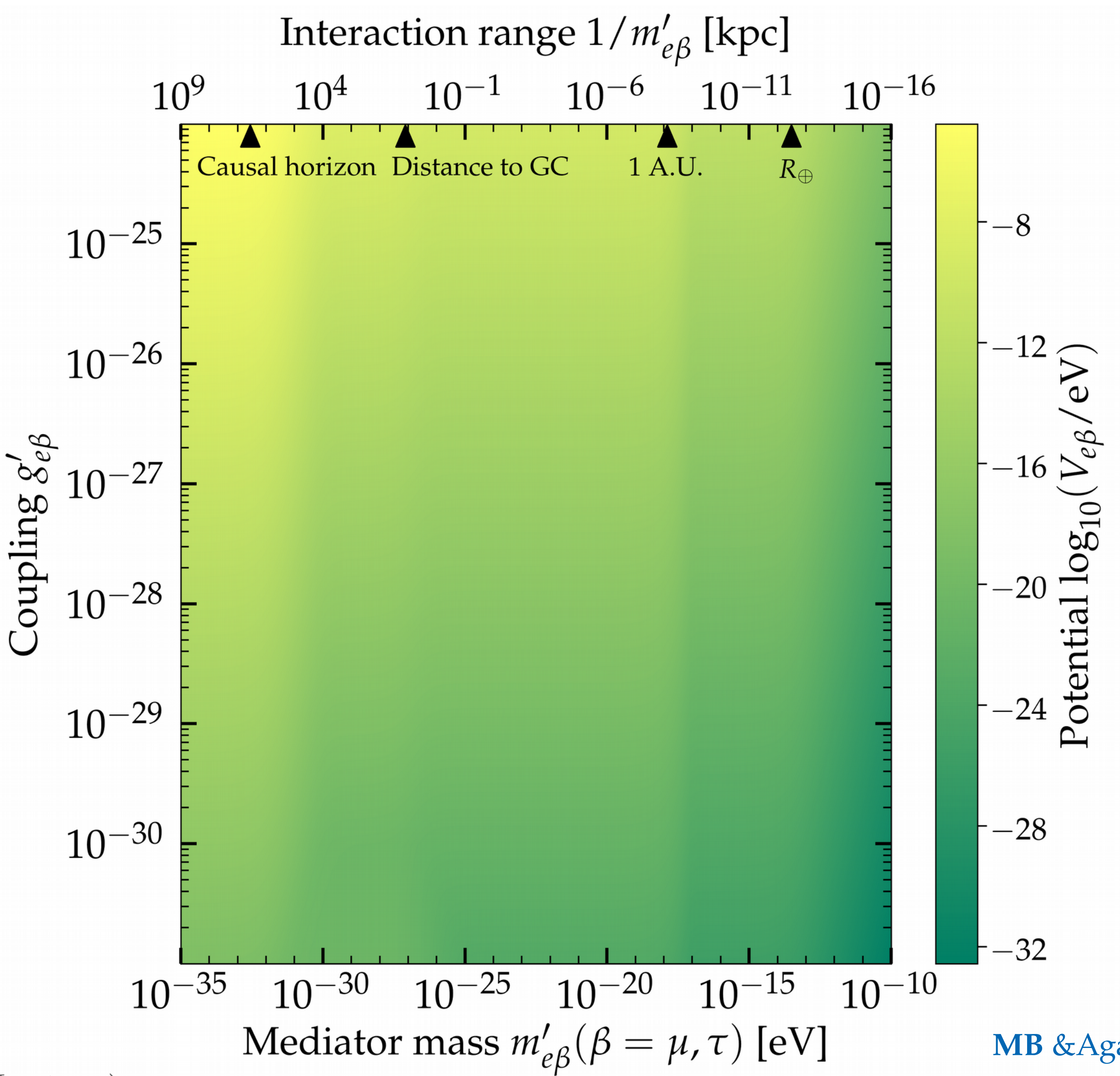
MB &Agarwalla, *PRL* 2019

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

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

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

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



MB &Agarwalla, *PRL* 2019

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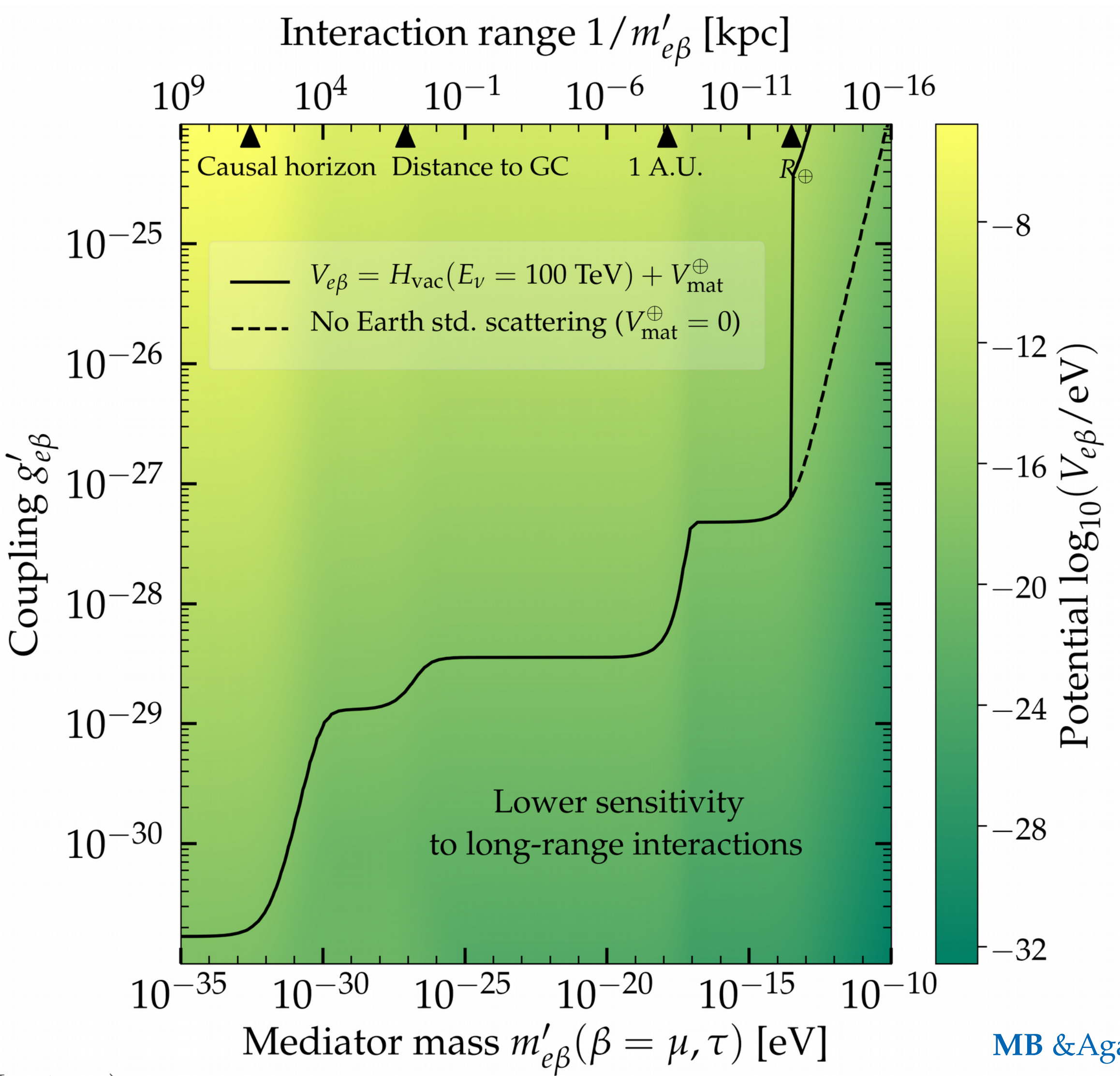

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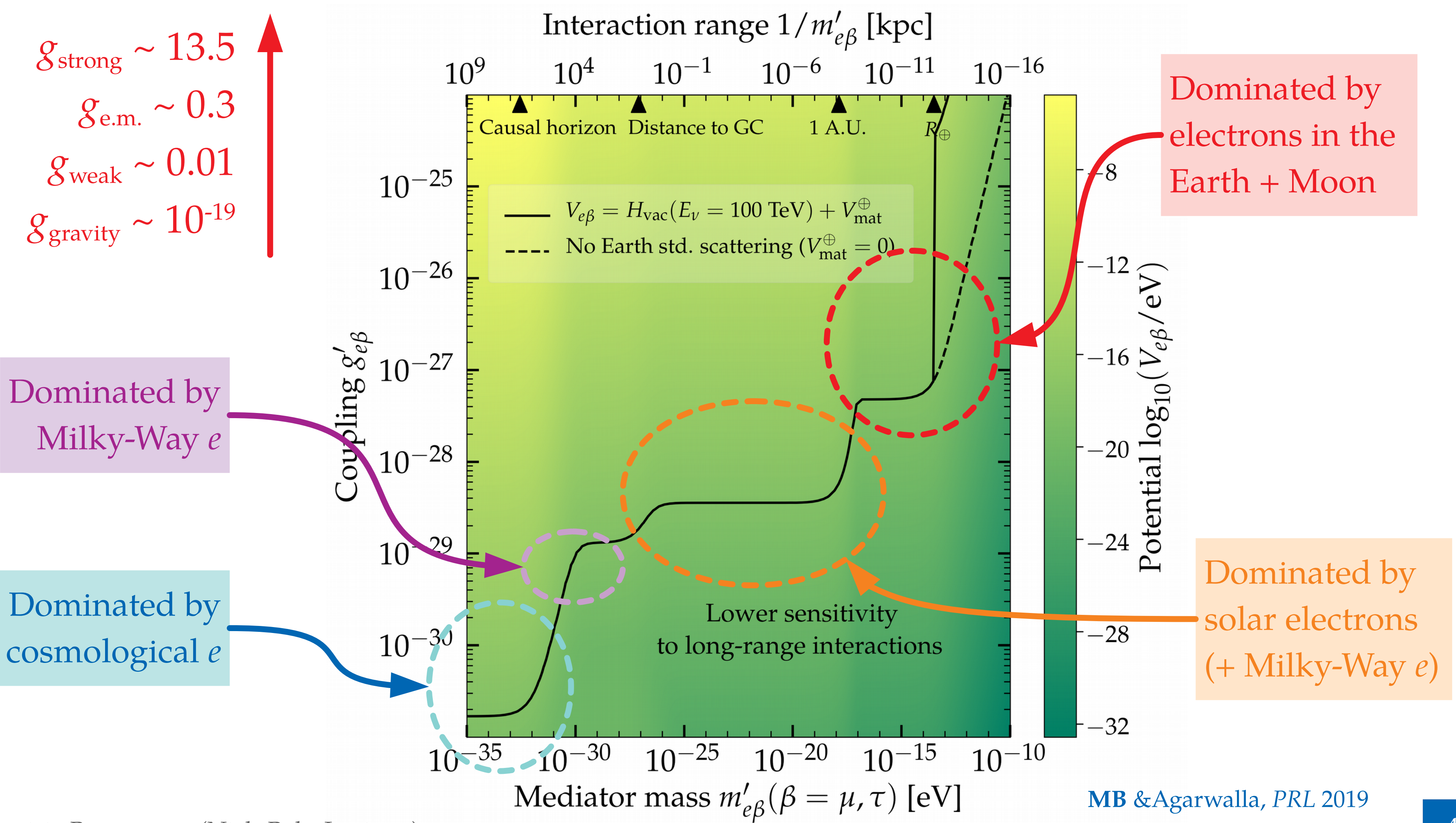

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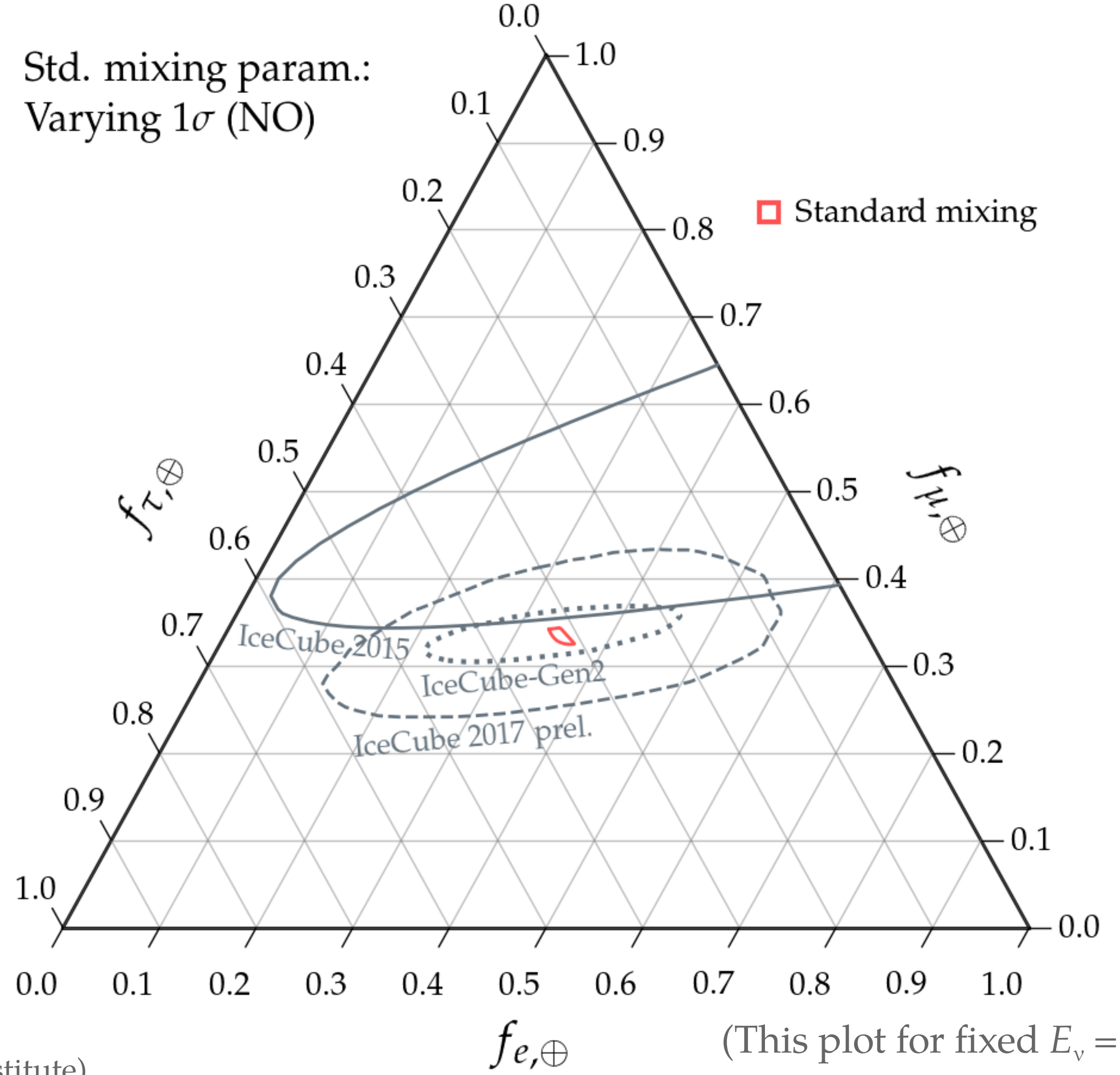

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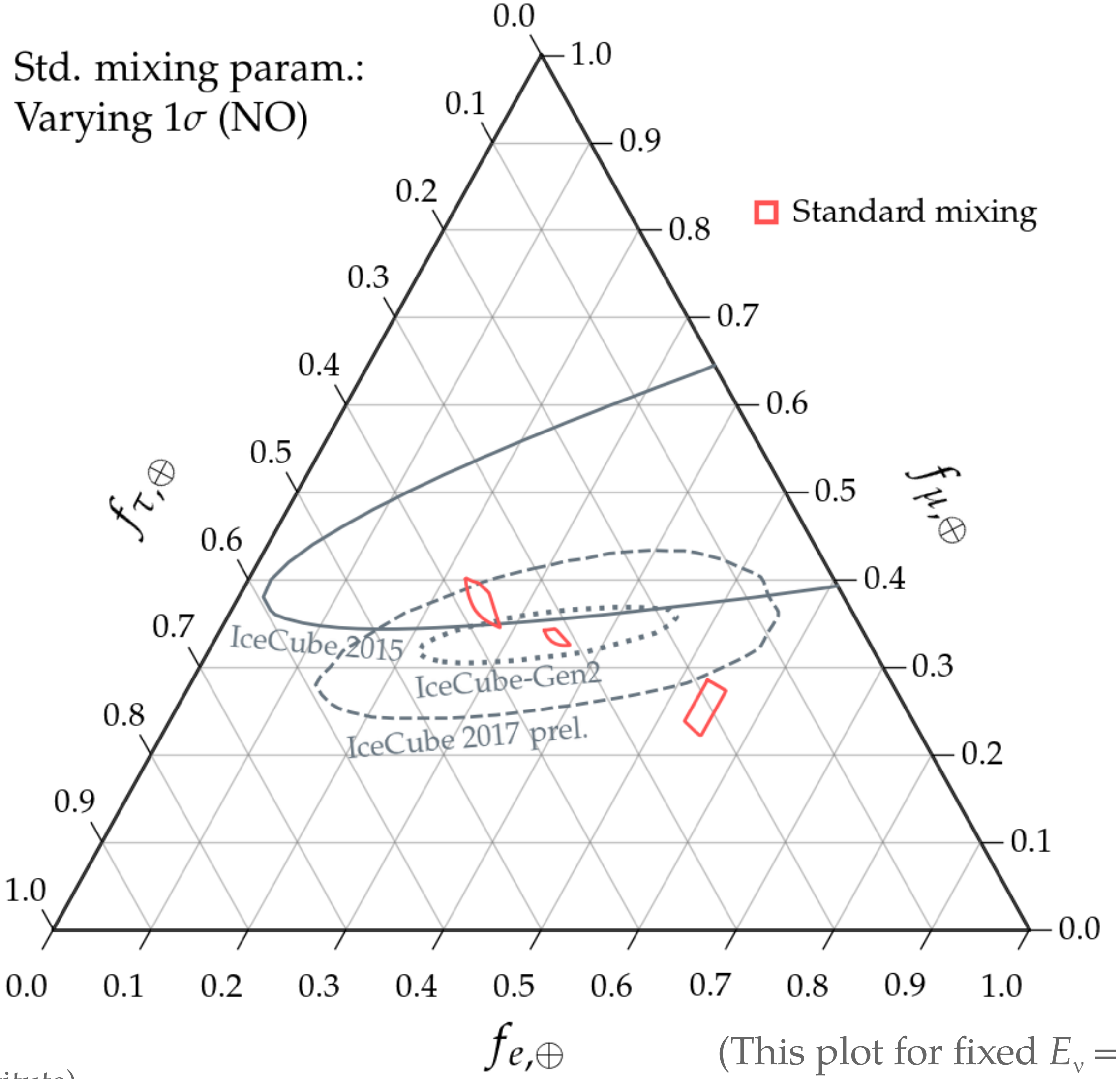
(This plot for fixed E_ν = 100 TeV)



MB & Agarwalla, *PRL* 2019

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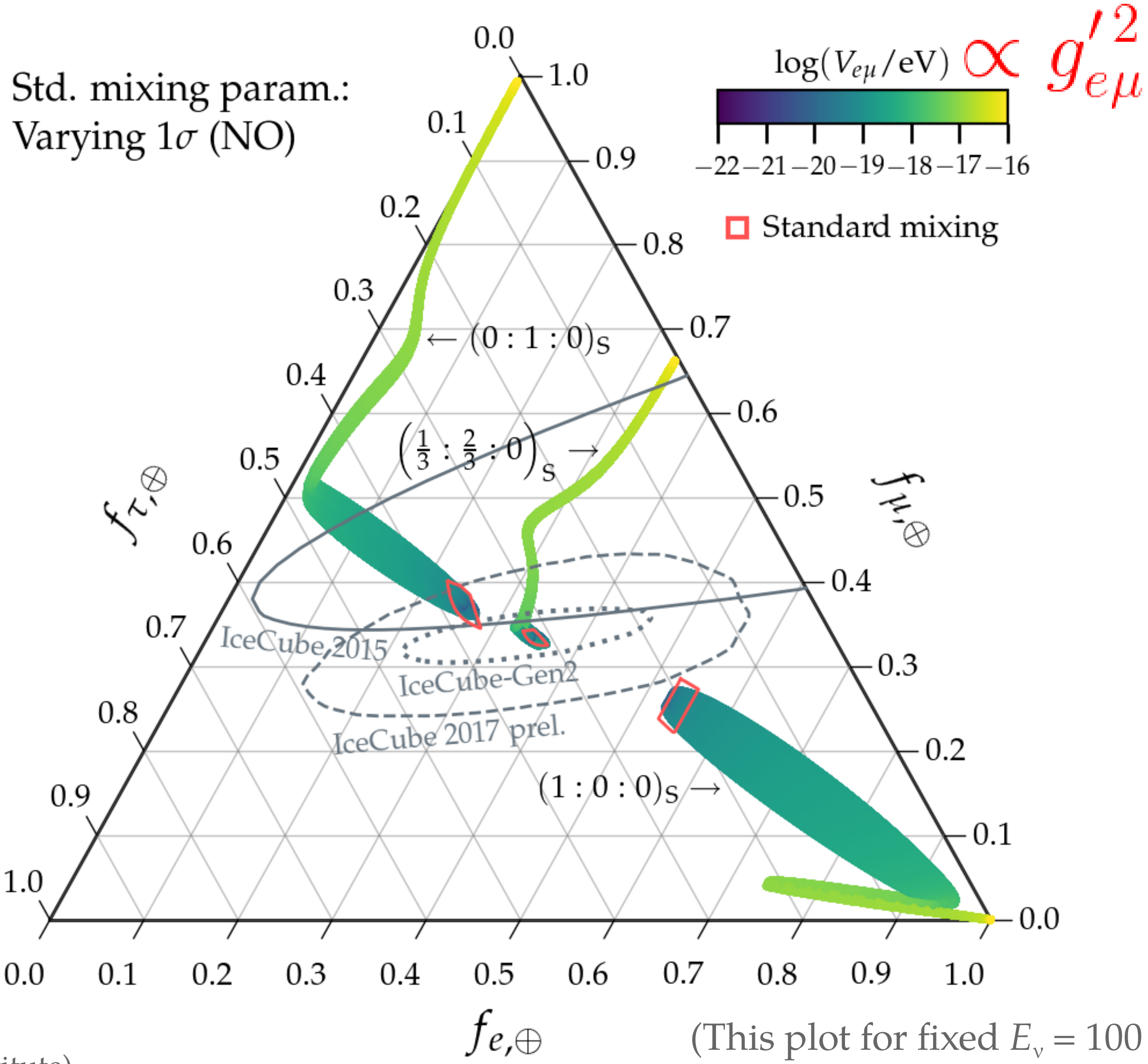

MB & Agarwalla, *PRL* 2019

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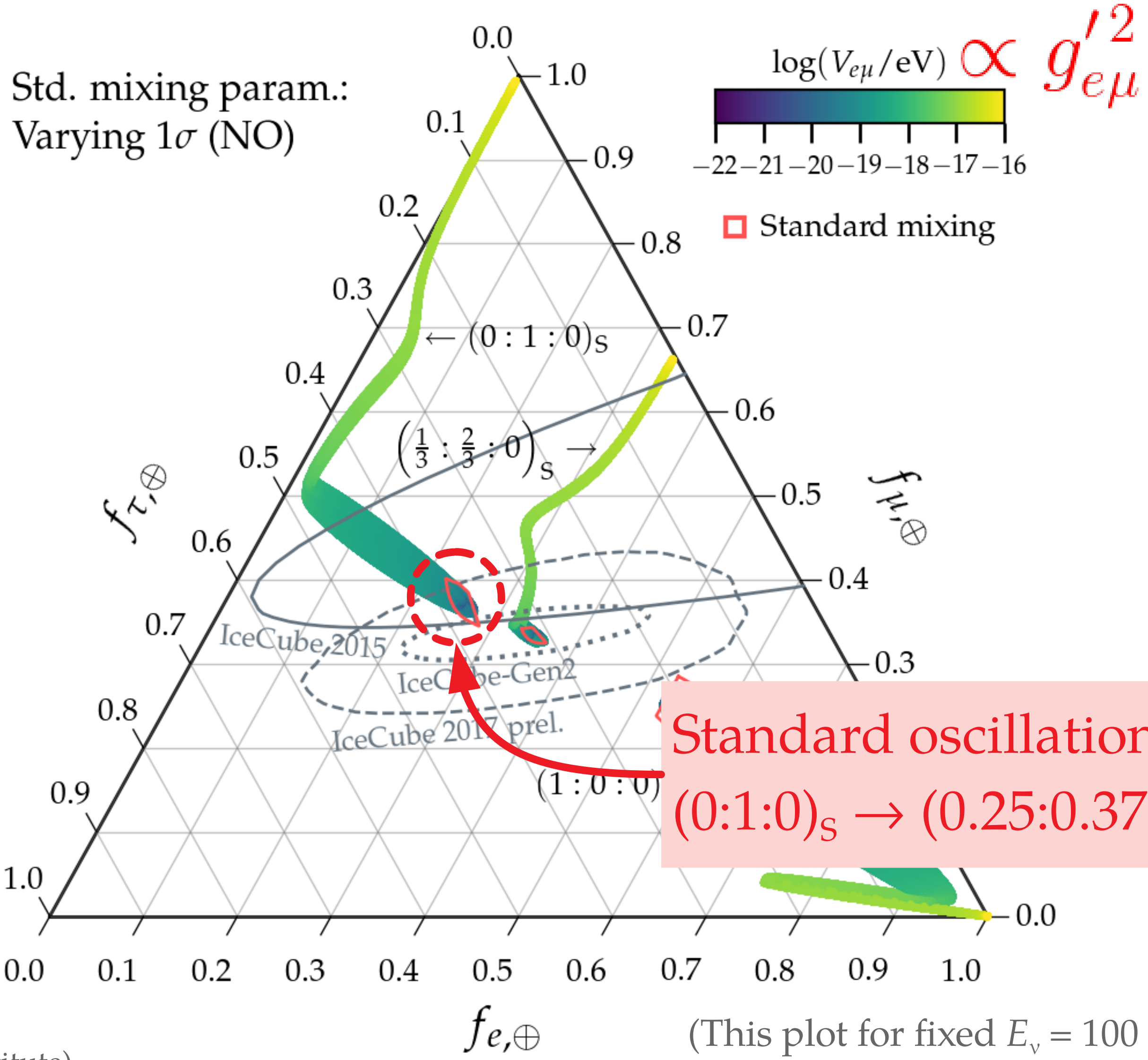
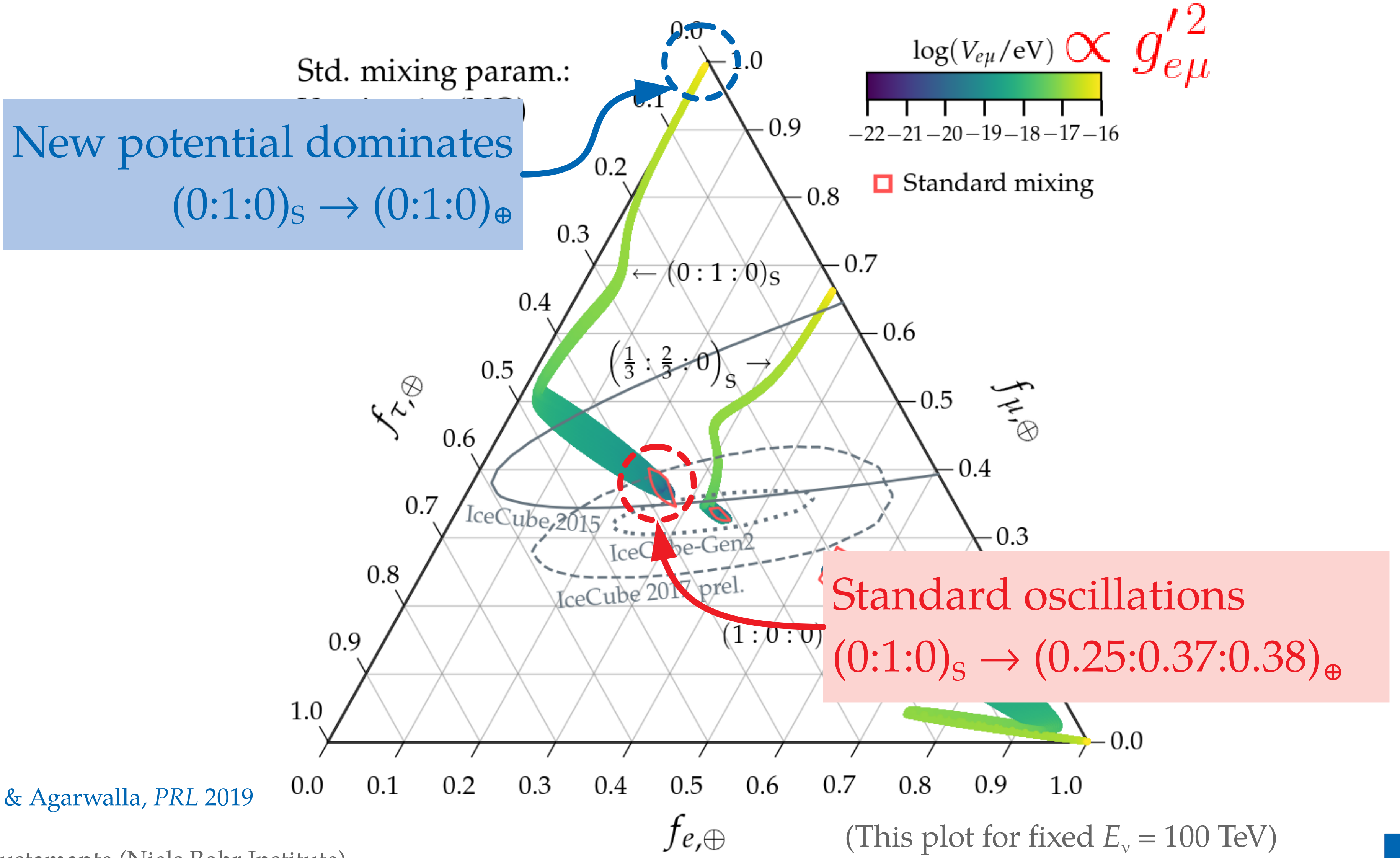


Standard oscillations
$(0{:}1{:}0)_S \rightarrow (0.25{:}0.37{:}0.38)_\oplus$

MB & Agarwalla, *PRL* 2019

(This plot for fixed E_ν = 100 TeV)



MB & Agarwalla, *PRL* 2019

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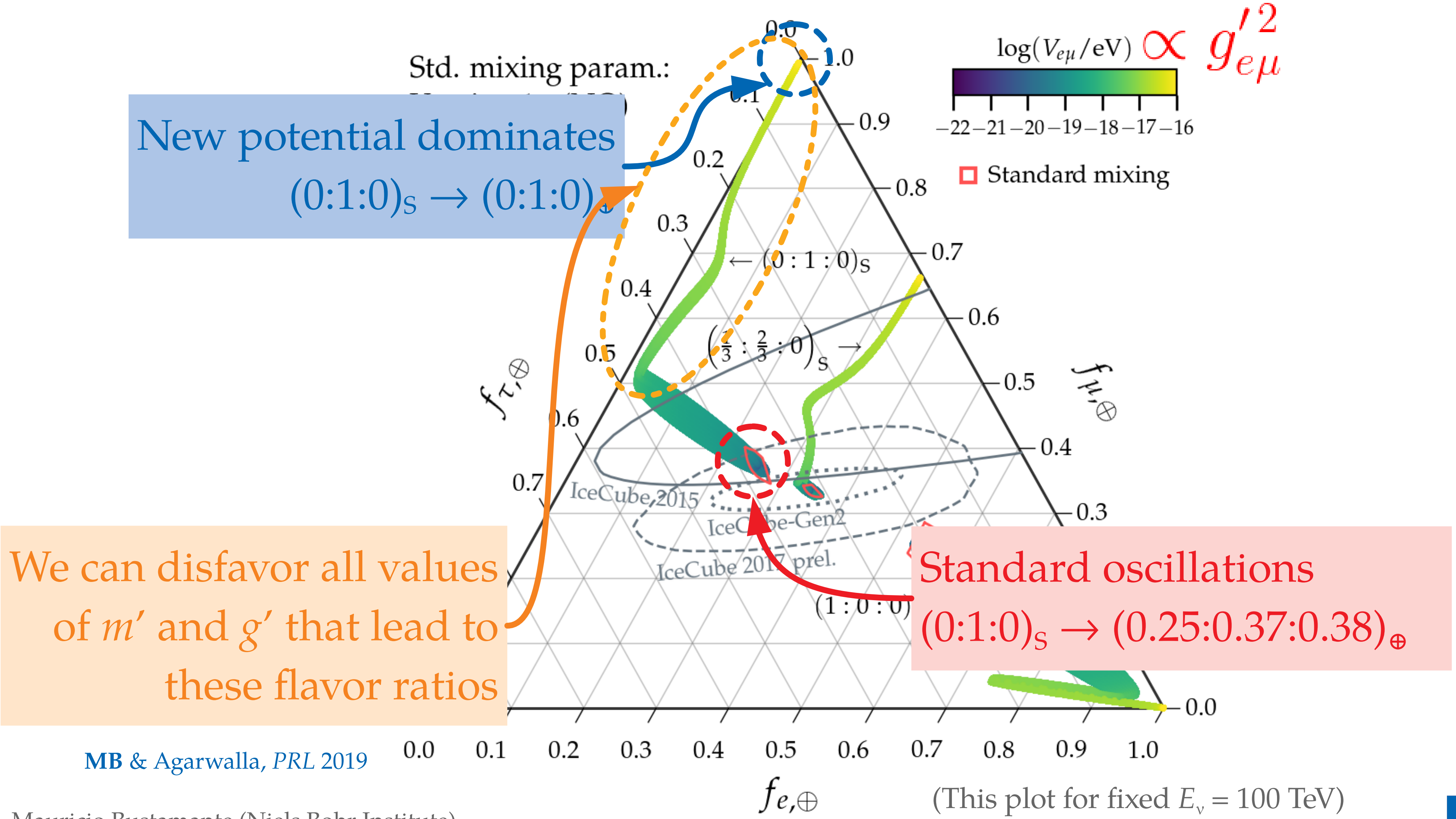
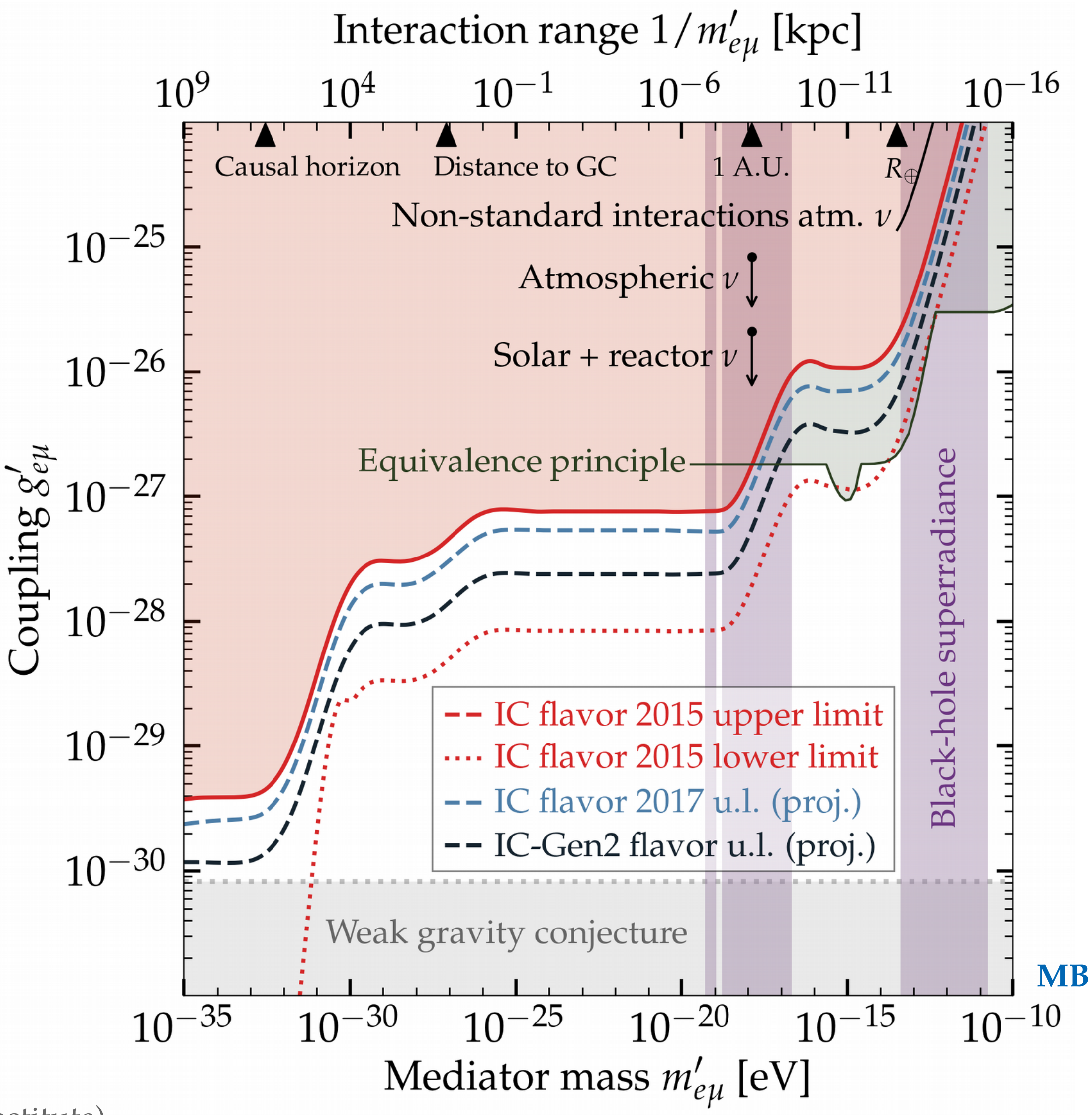


MB & Agarwalla, *PRL* 2019



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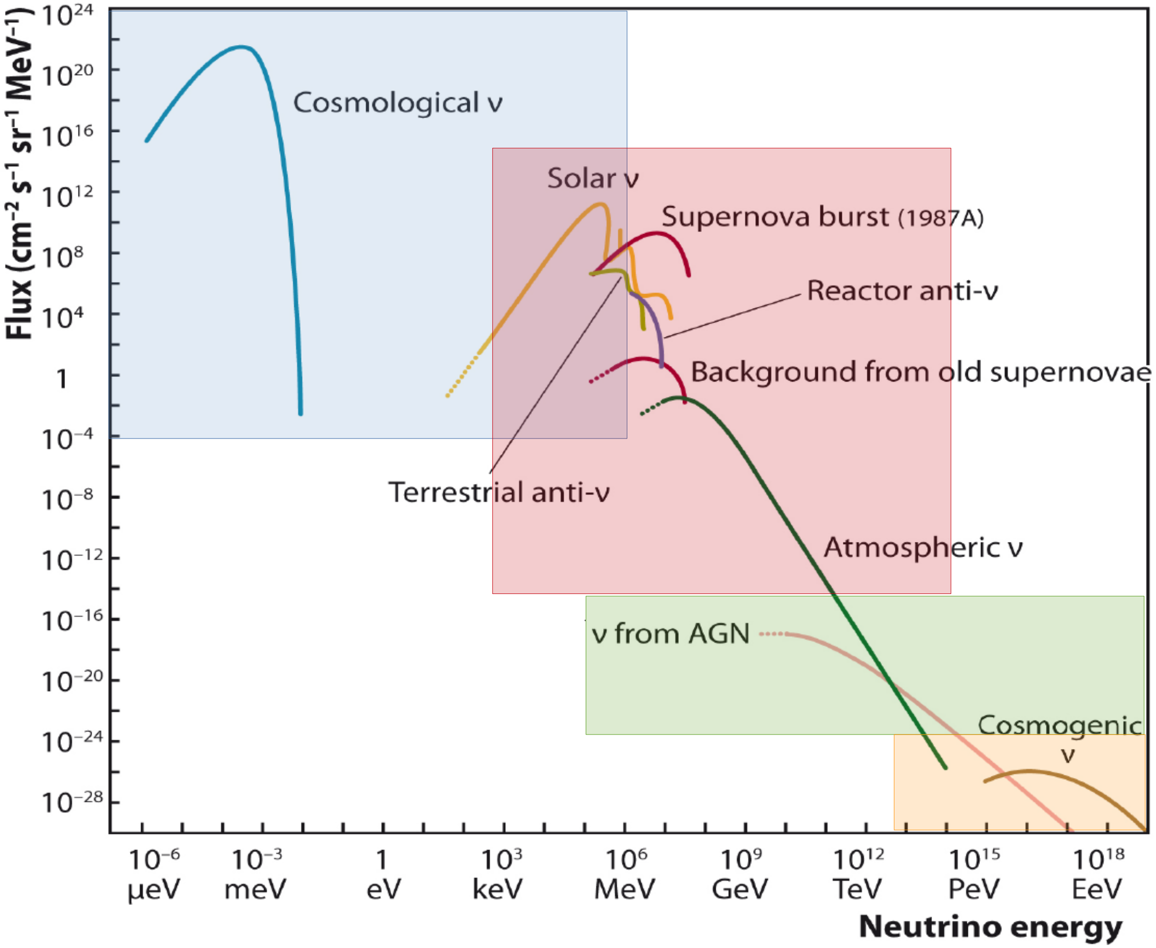
Quo vadis? Ultra-high-energy neutrinos



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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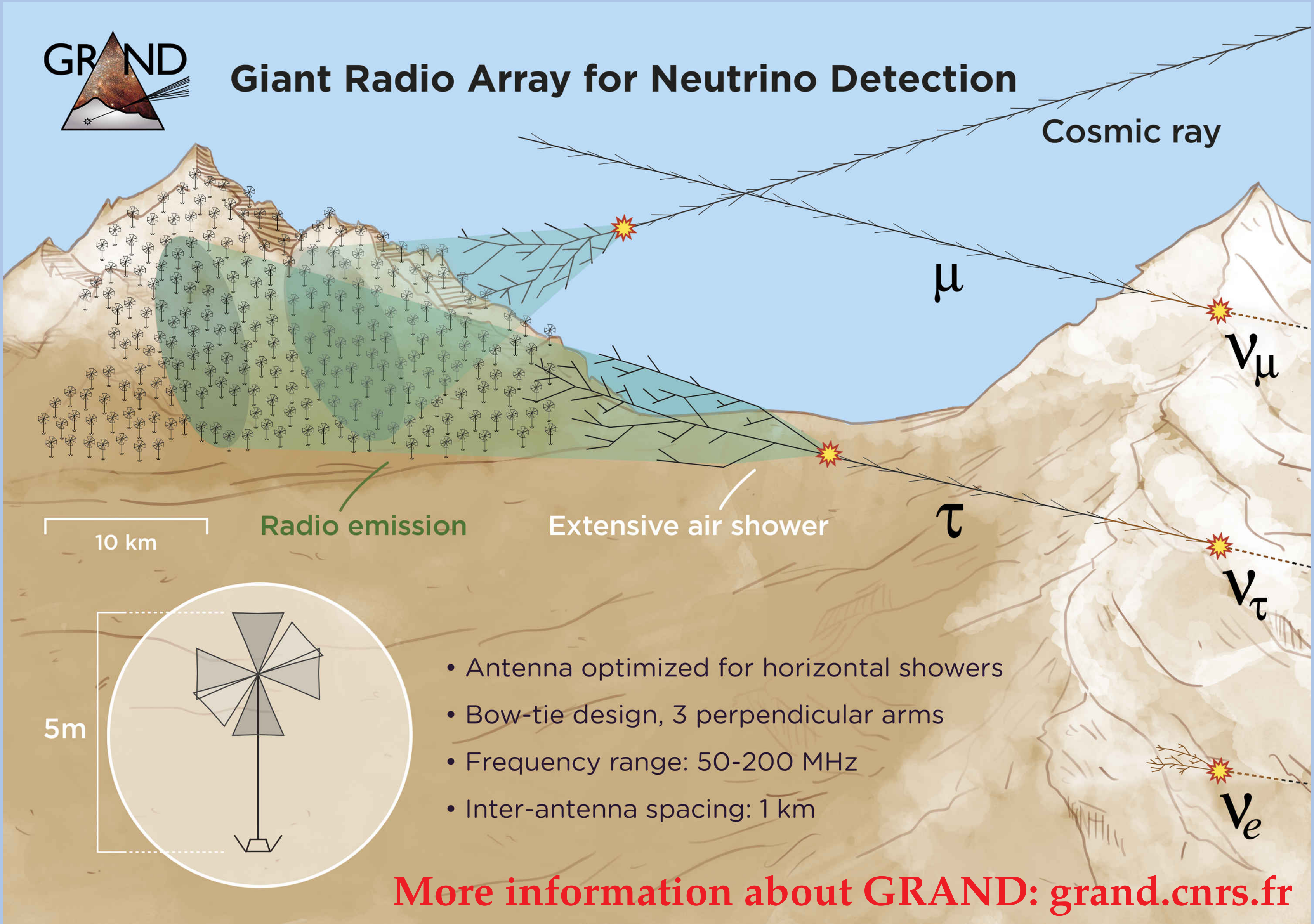
GRAND

Giant Radio Array for Neutrino Detection

White paper: 1810.09994

Web: grand.cnrs.fr


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

What are you taking home?

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

More information in our Astro2020 white papers:

- *Fundamental physics with high-energy cosmic neutrinos*, 1903.04333
- *Astrophysics uniquely enabled by observations of high-energy cosmic neutrinos*, 1903.04334