Distilling fundamental high-energy neutrino physics from the sky

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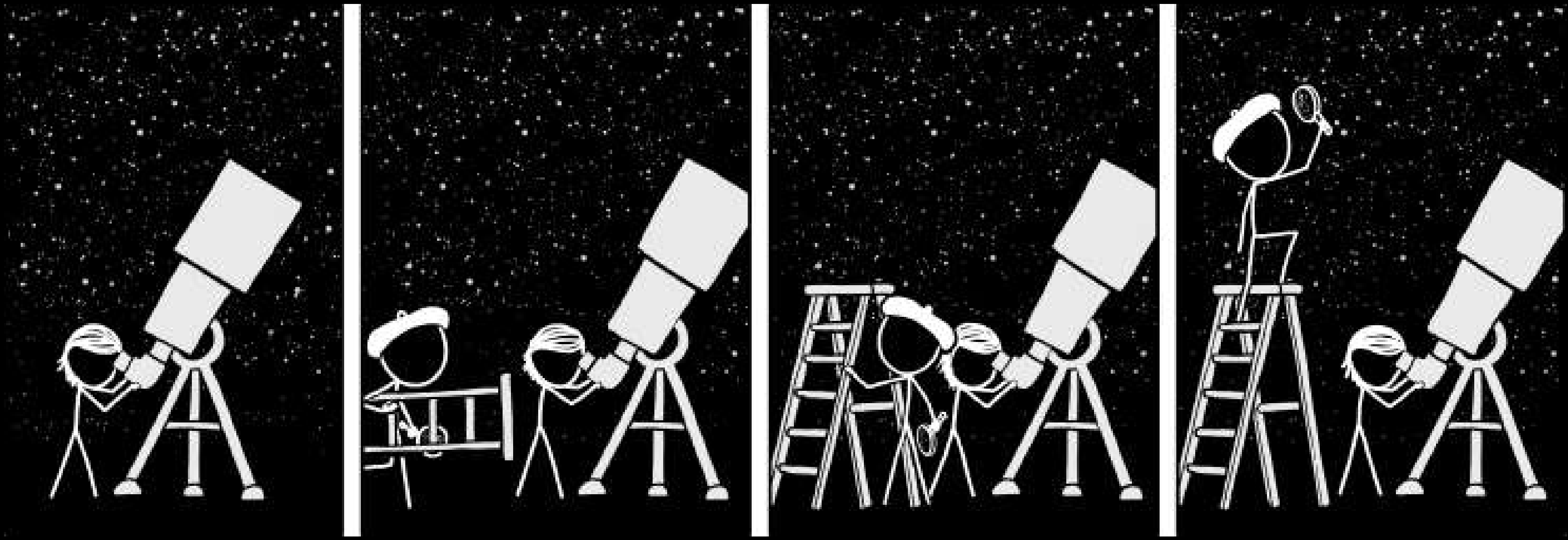
GRAPPA

Amsterdam, May 14, 2018

UNIVERSITY OF COPENHAGEN



xkcd

Symmetry Magazine

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

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

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

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3. It comes *for free*

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.*

What has IceCube found so far (6 years)?

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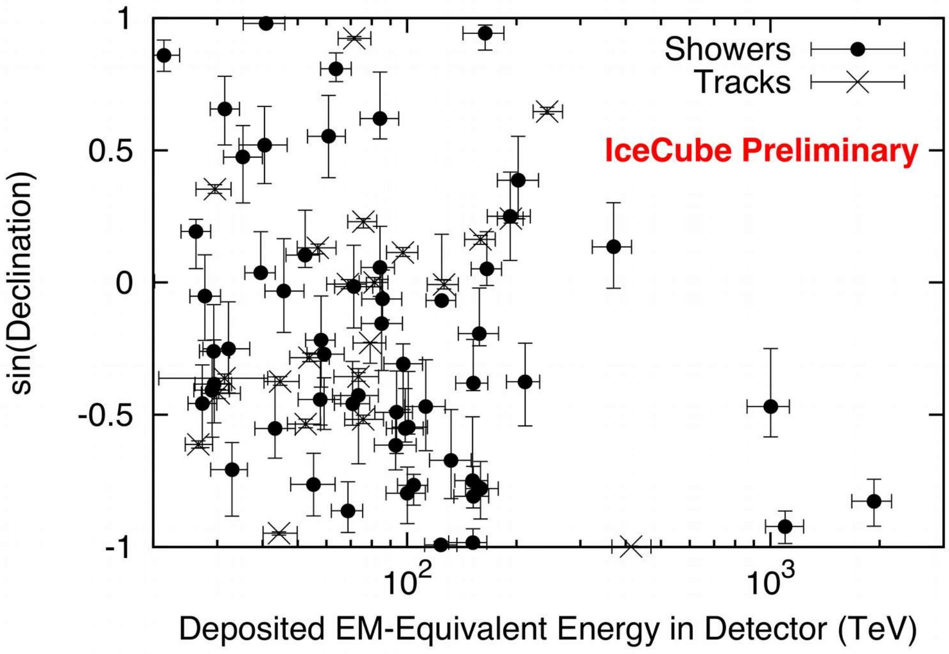
80 contained events between 18 TeV – 2 PeV

(16 atm. neutrinos, 25 atm. muons)



C. Kopper, ICRC 2017

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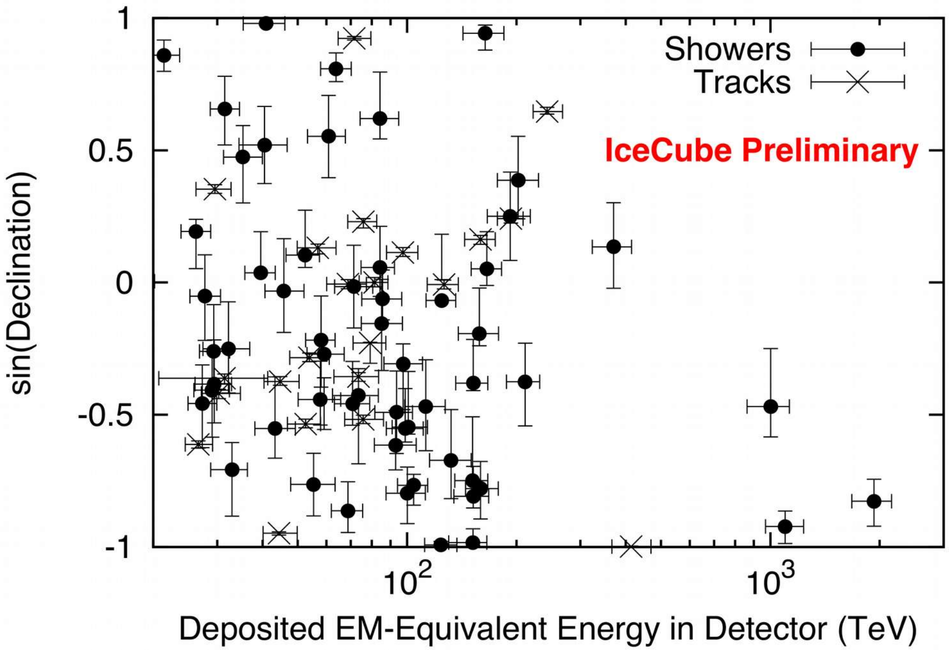
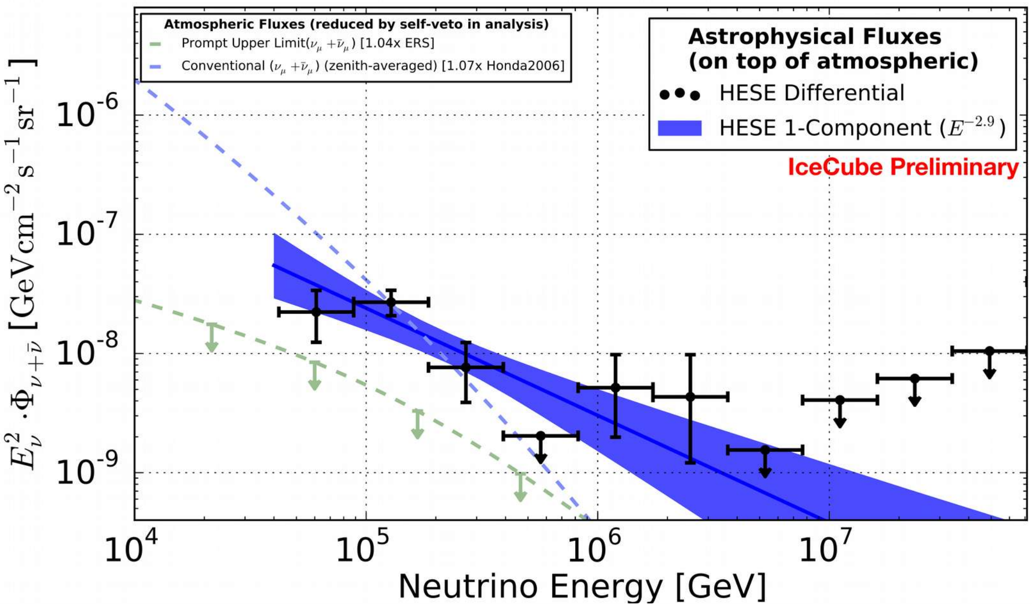


Astrophysical ν flux detected at > 7σ
(Normalization ok, but steep spectrum)



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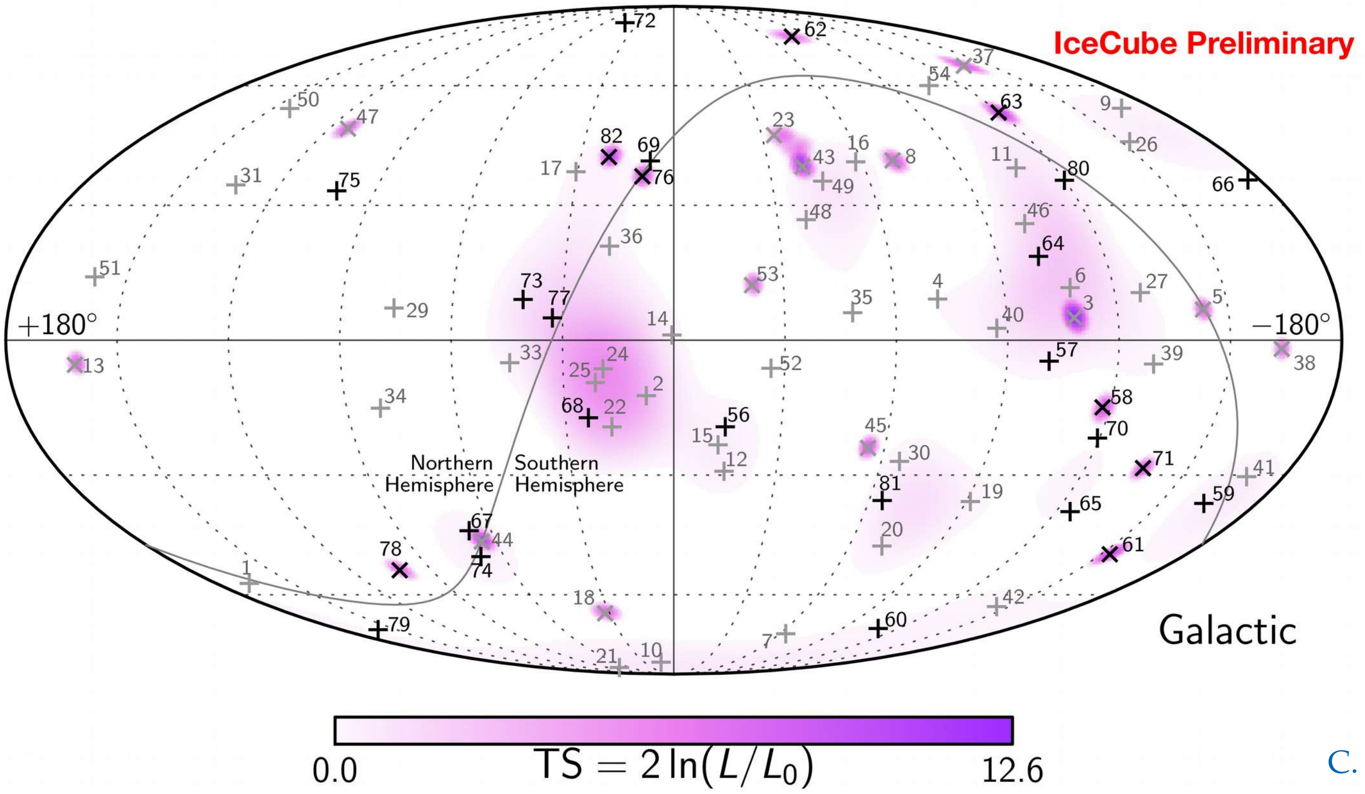
Arrival directions compatible with isotropy



C. Kopper, ICRC 2017

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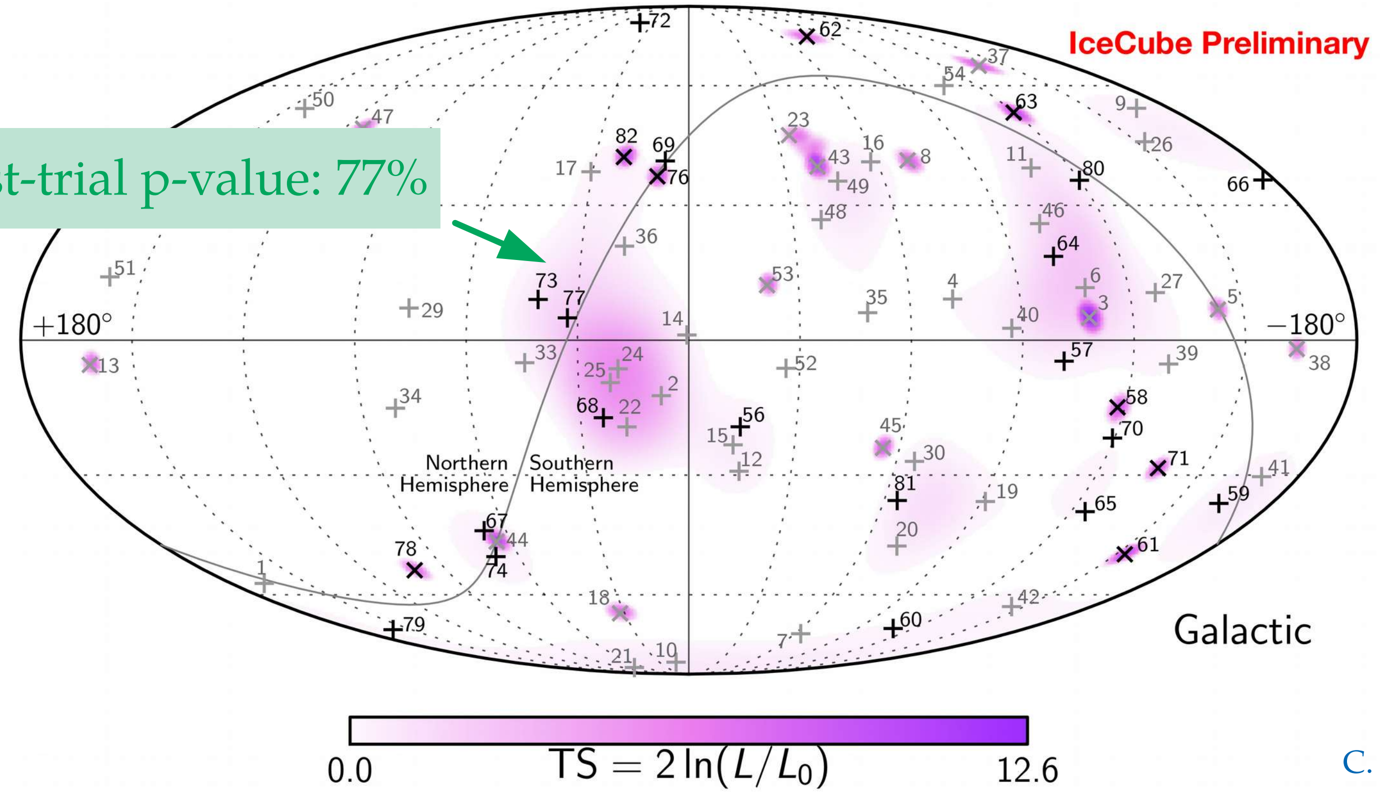
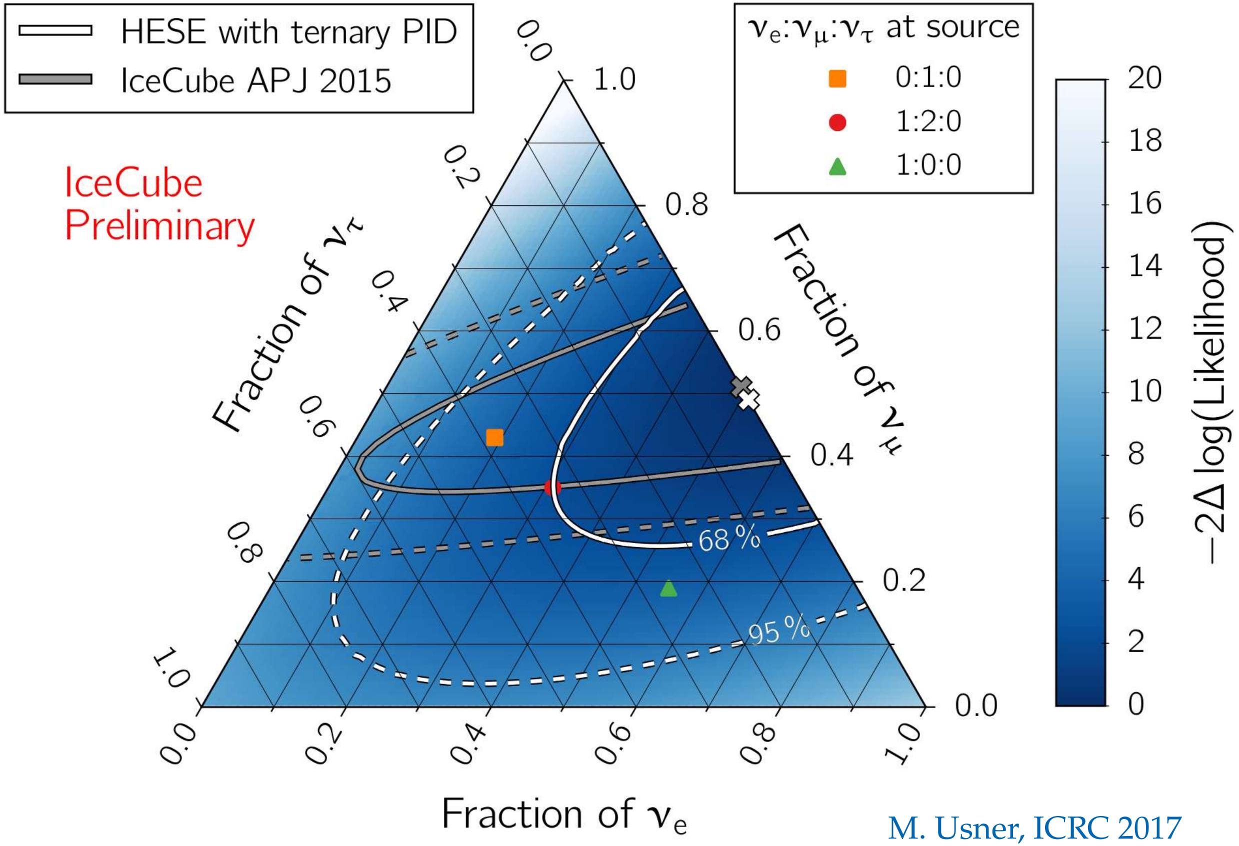
Post-trial p-value: 77%



C. Kopper, ICRC 2017

What has IceCube found so far (6 years)?

Flavor composition compatible with equal proportion of each flavor



M. Usner, ICRC 2017

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

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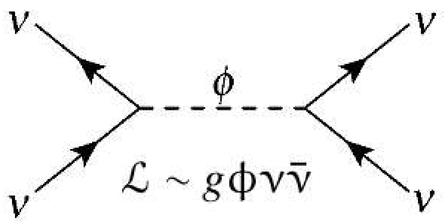
In spite of
poor energy, angular, flavor reconstruction
& astrophysical unknowns

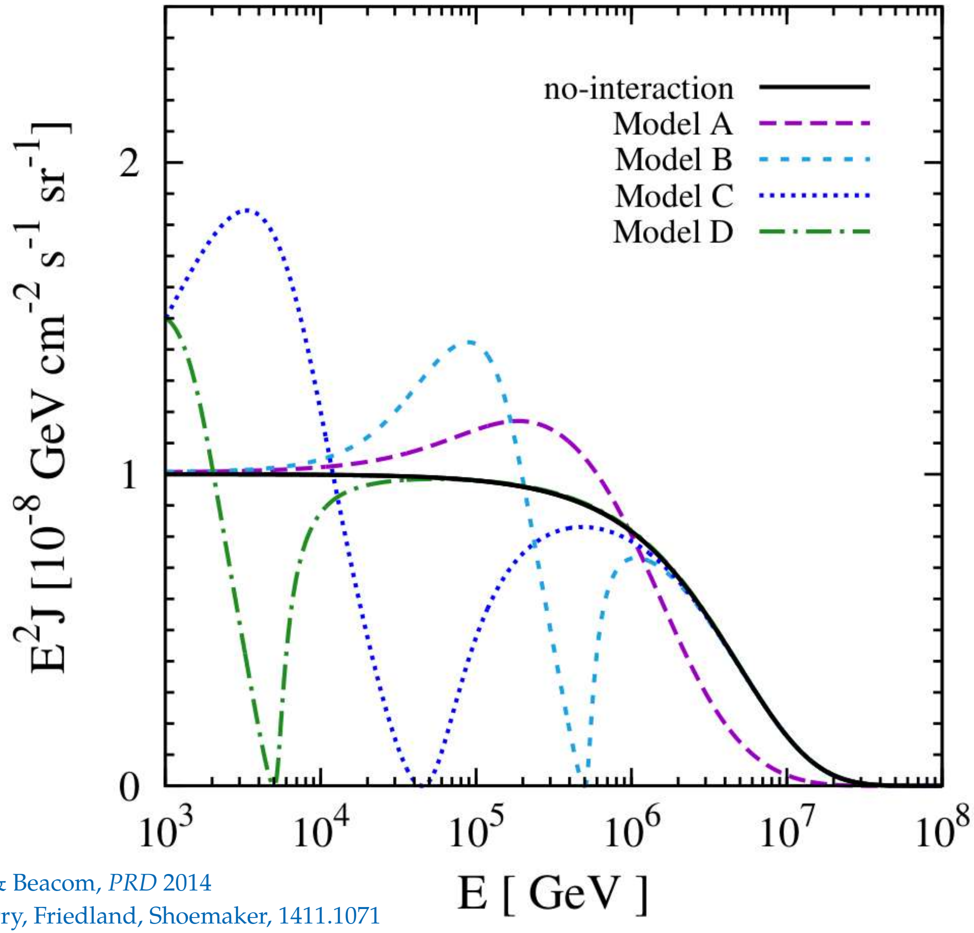
New physics in the spectral shape: $\nu\nu$ interactions

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



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

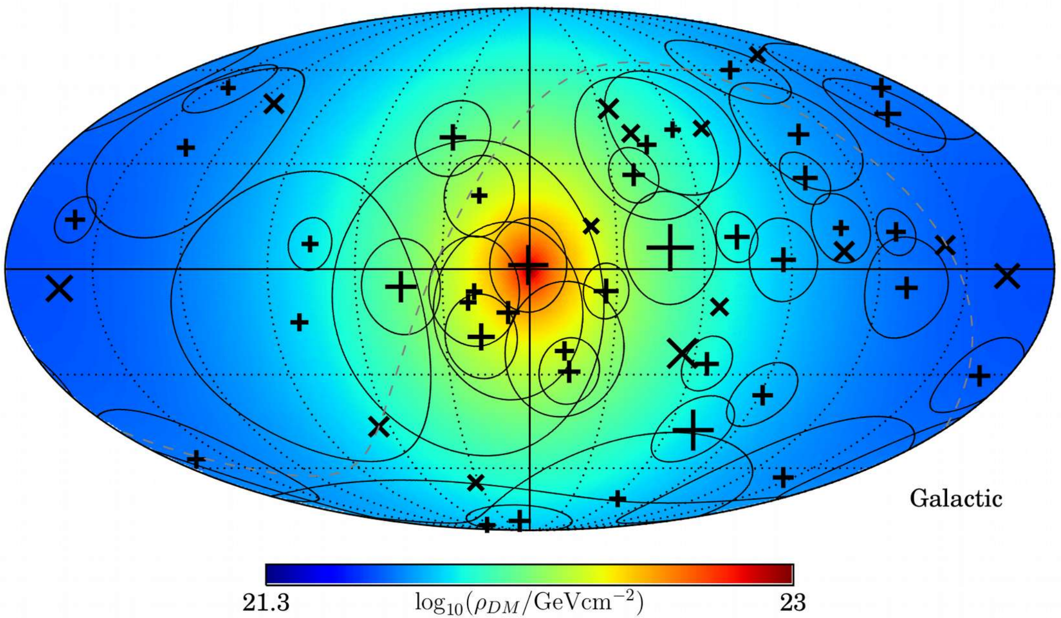
Resonance energy: $$E_{\text{res}} = \frac{M^2}{2m_\nu}$$



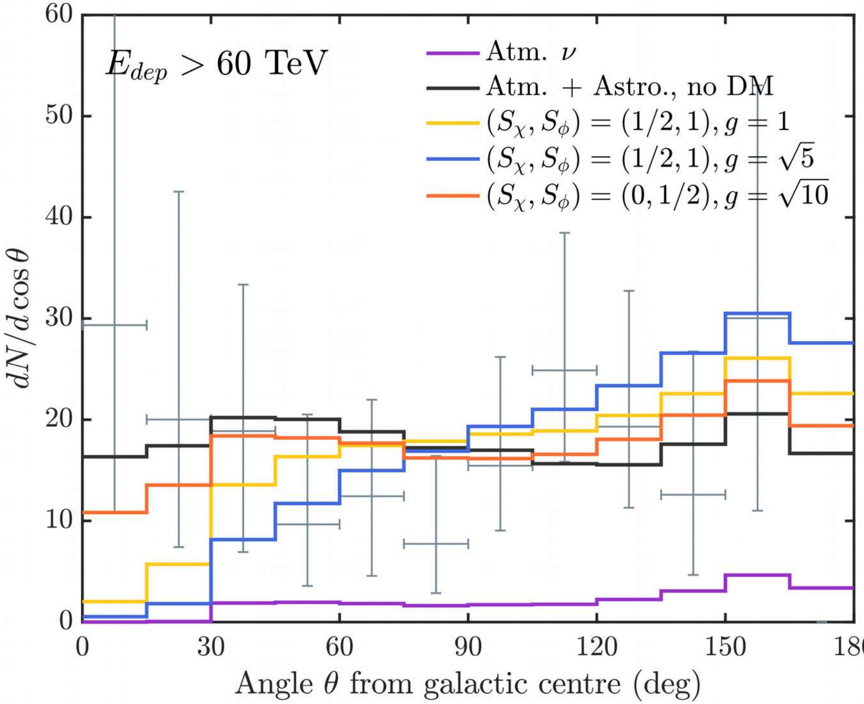
Ng & Beacon, *PRD* 2014
Cherry, Friedland, Shoemaker, 1411.1071
Blum, Hook, Murase, 1408.3799

New physics in the angular distribution: ν-DM interactions

Interaction between astrophysical neutrinos and the Galactic dark matter profile –



Argüelles *et al.*, *PRL* 2017

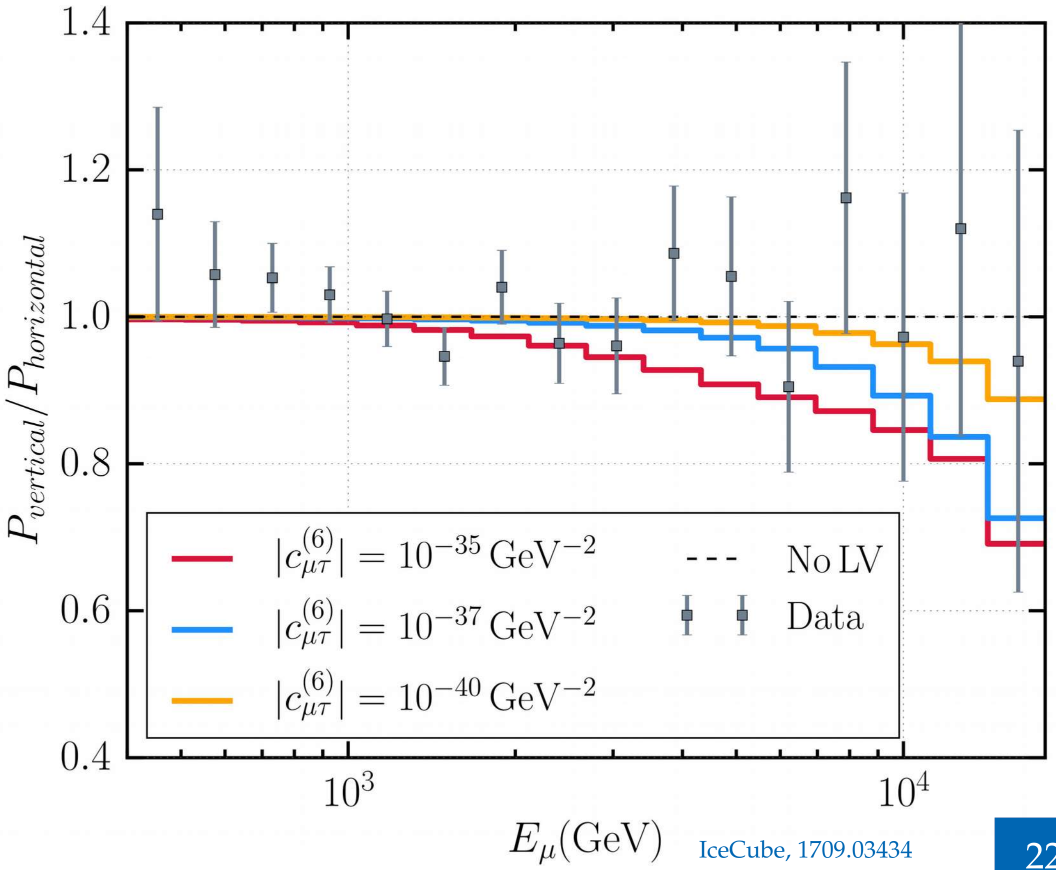


Expected: Fewer neutrinos coming from the Galactic Center

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, 1709.03434

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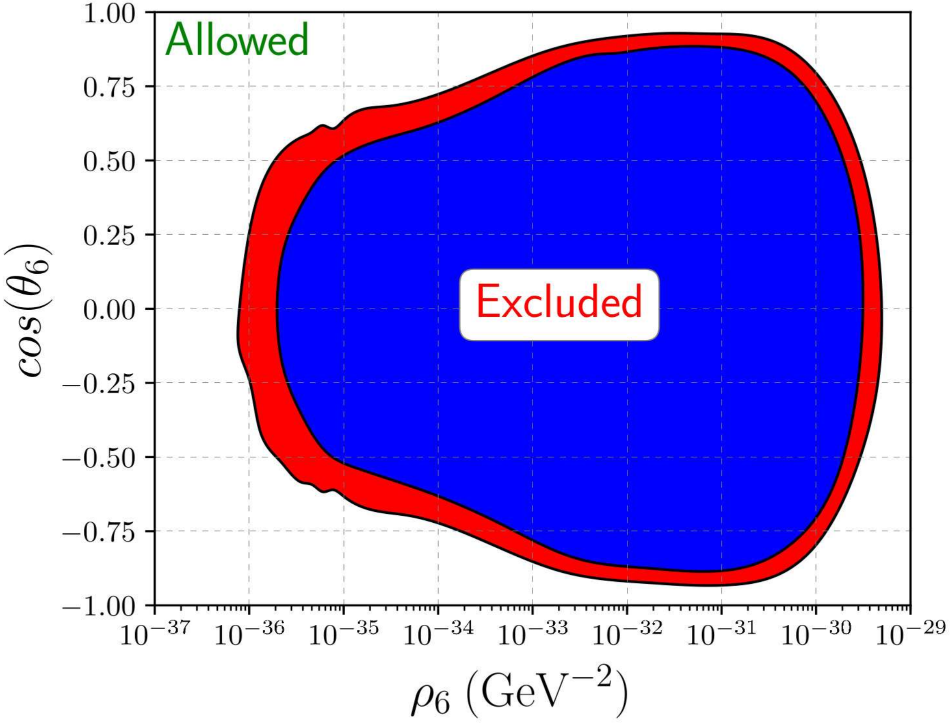
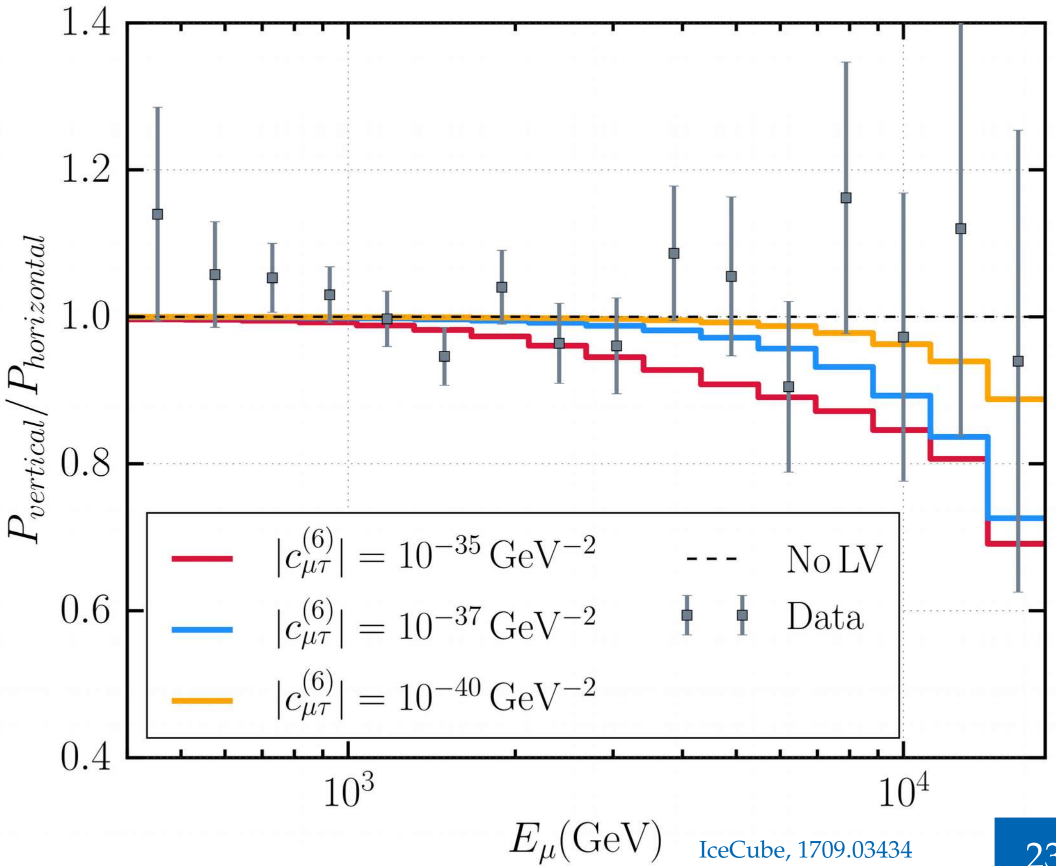
Best bounds come from IceCube





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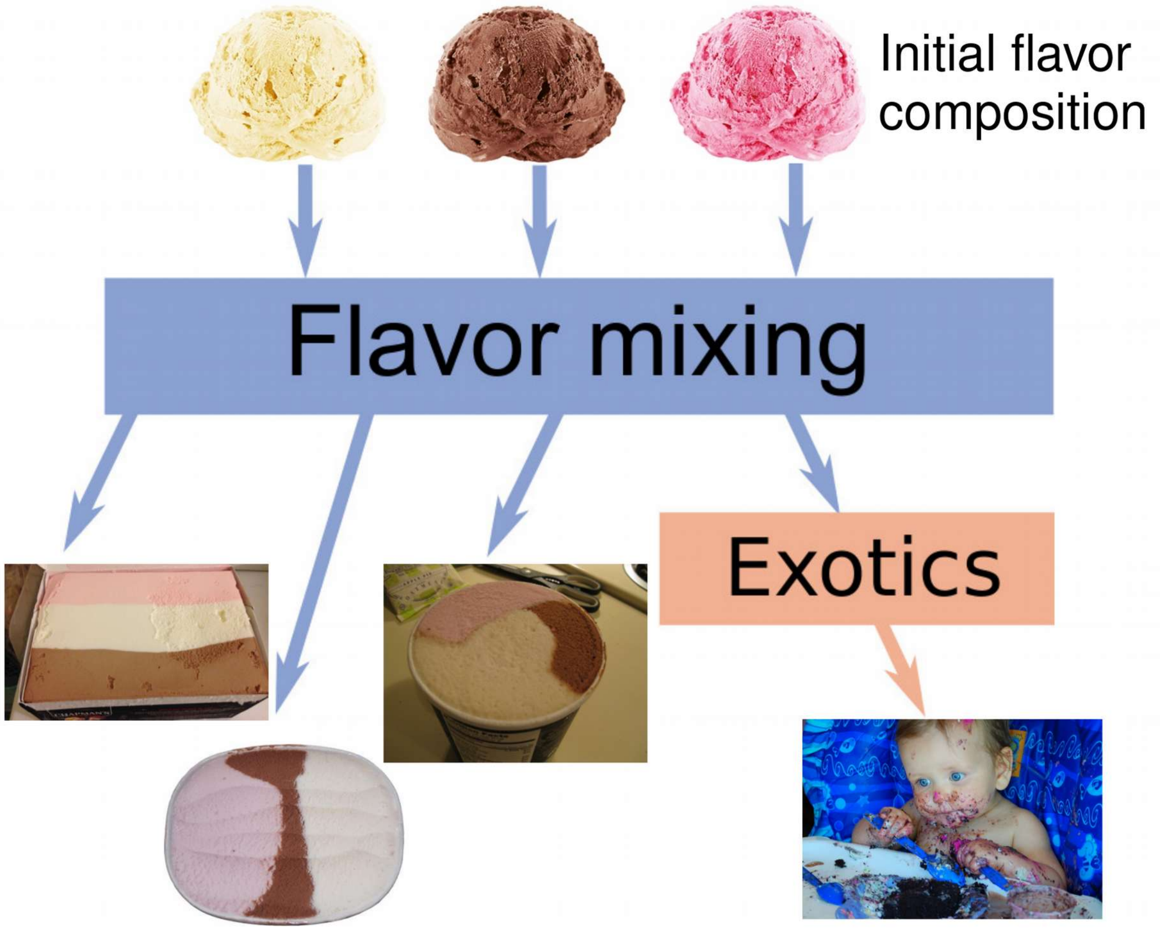
New physics in the flavor composition



Flavor – there and here

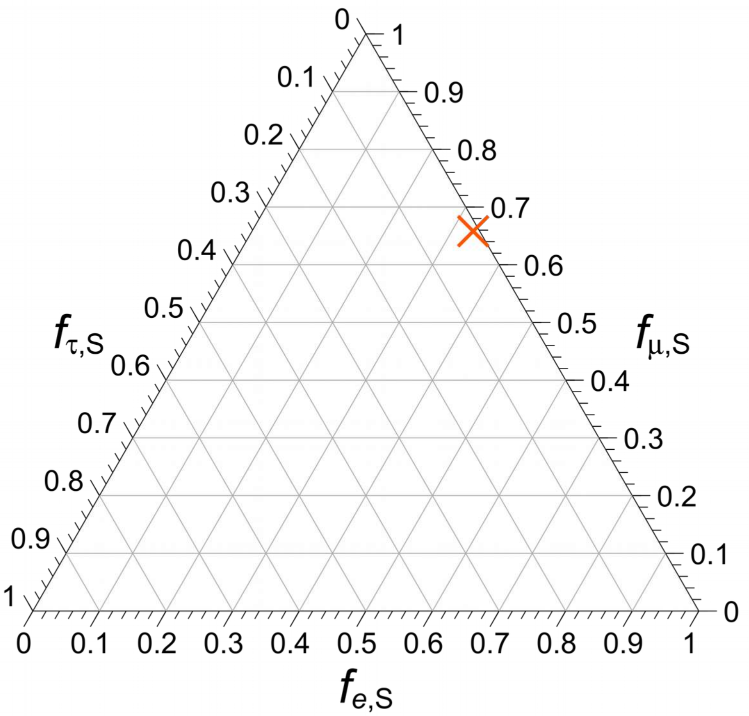
At the sources

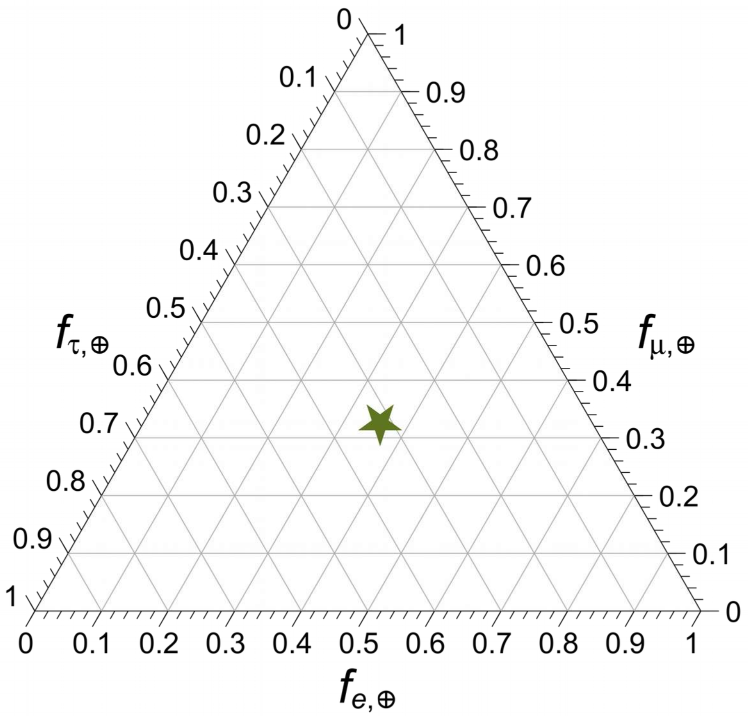
$(f_e:f_\mu:f_\tau)_S = (1/3 : 2/3 : 0)_S$

Neutrino oscillations →

At Earth

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





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

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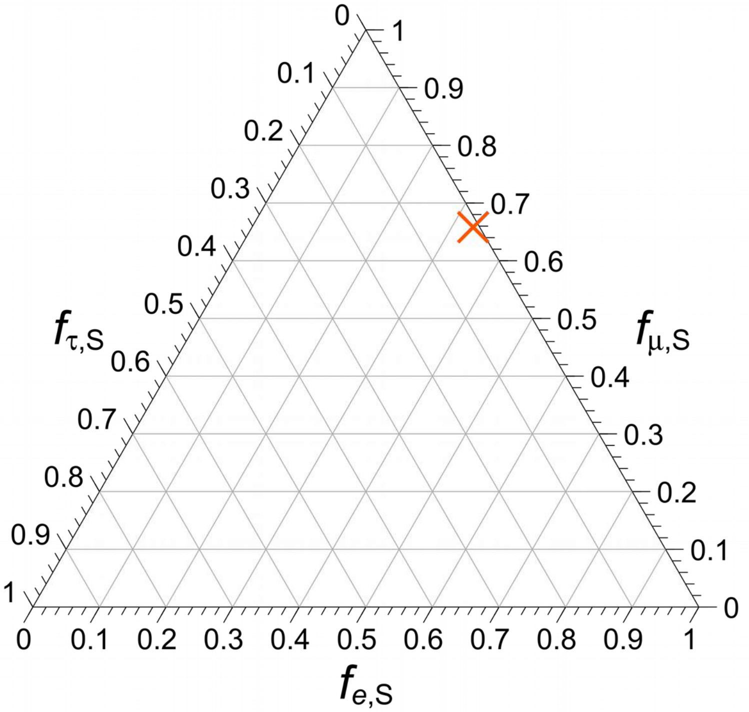

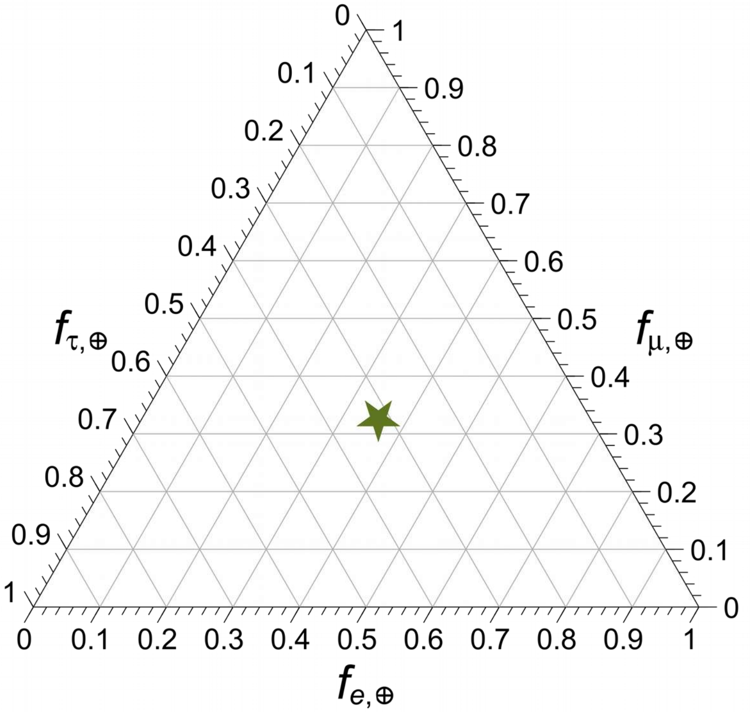

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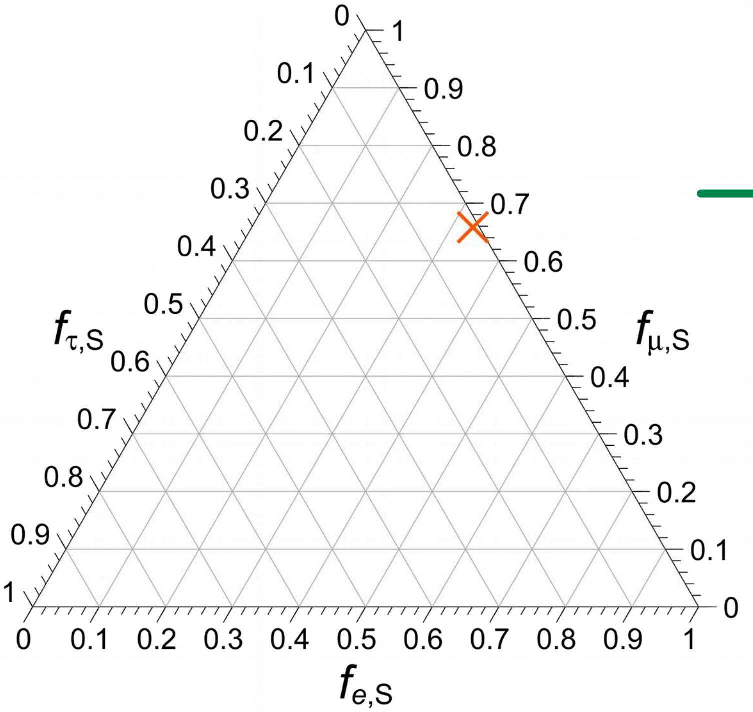
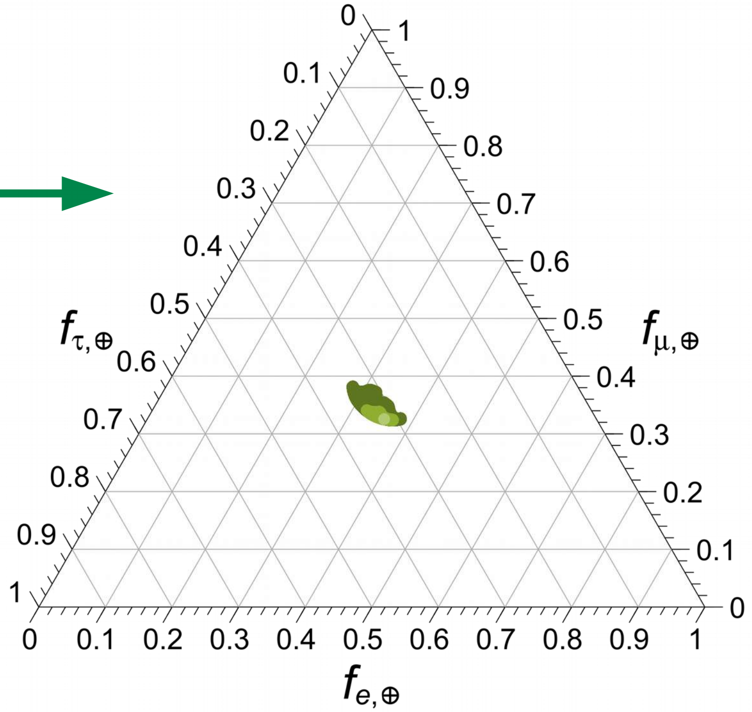
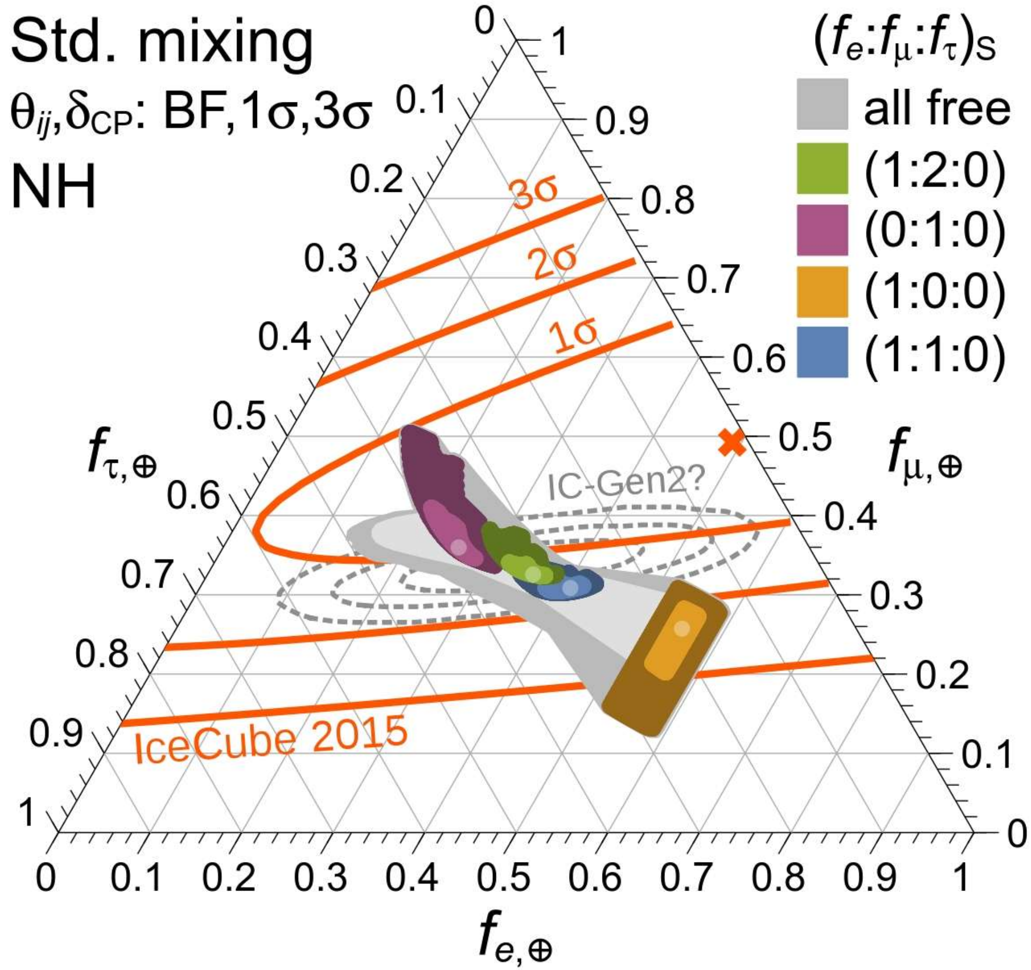


Uncertainties in values of mixing parameter (1σ, 3σ) →



Flavor composition – a few source choices



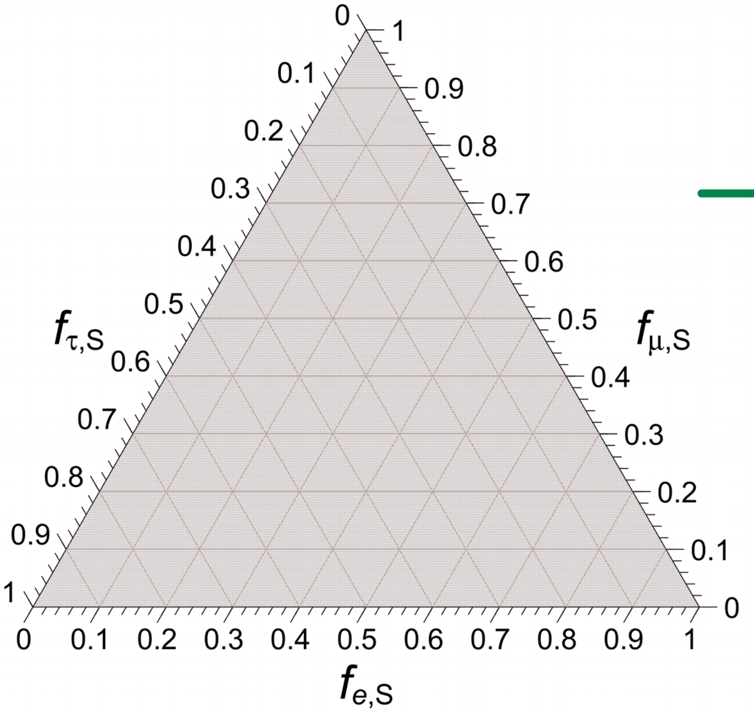
MB, Beacom, Winter *PRL* 2015

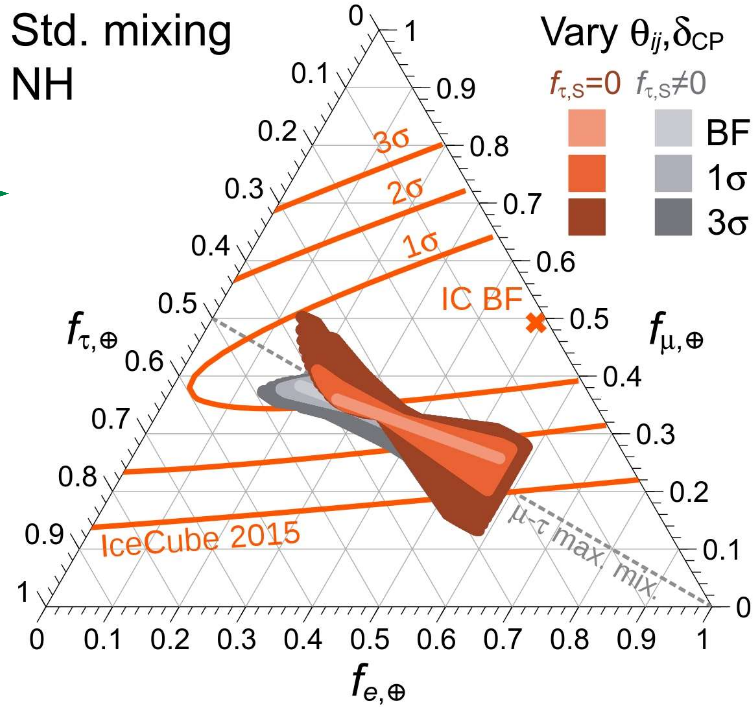
Flavor composition – standard allowed region

At the sources

At Earth

All possible flavor ratios





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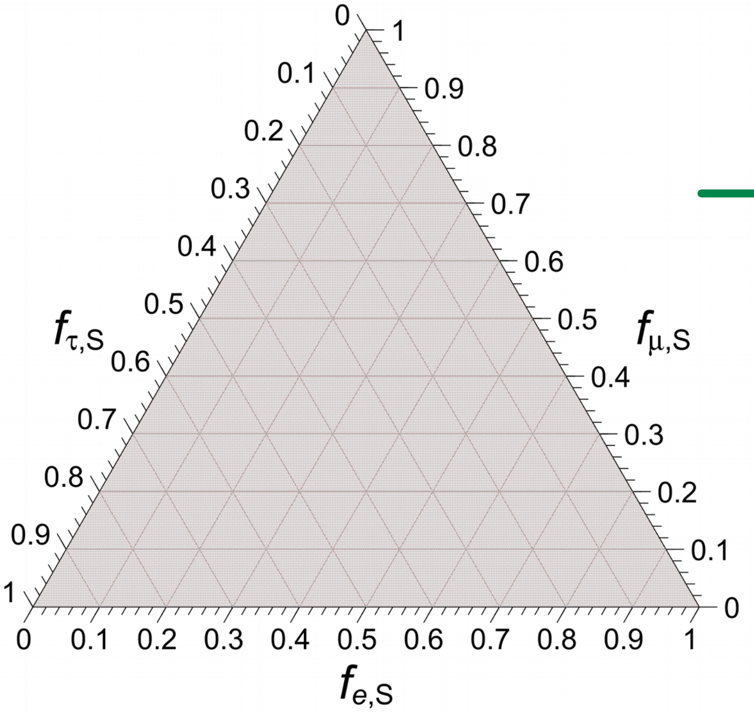
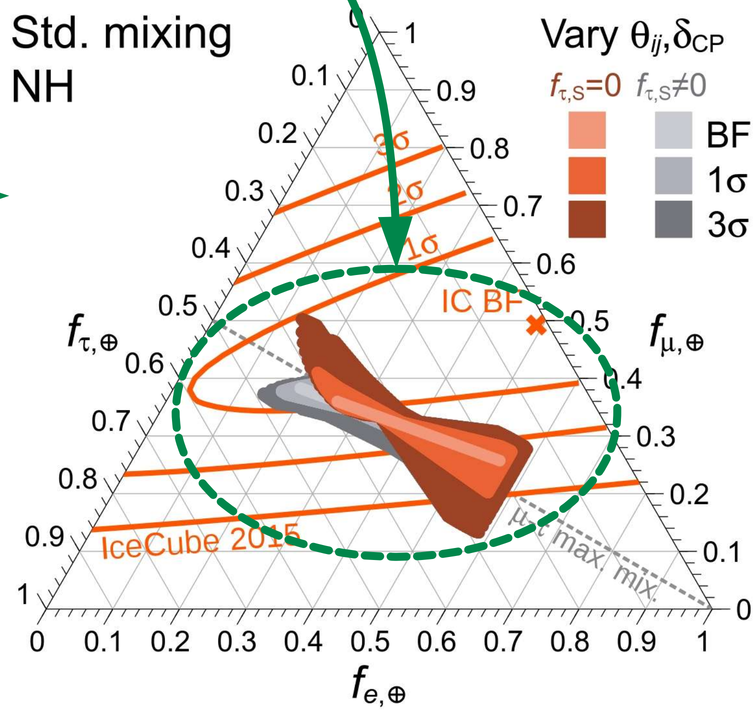


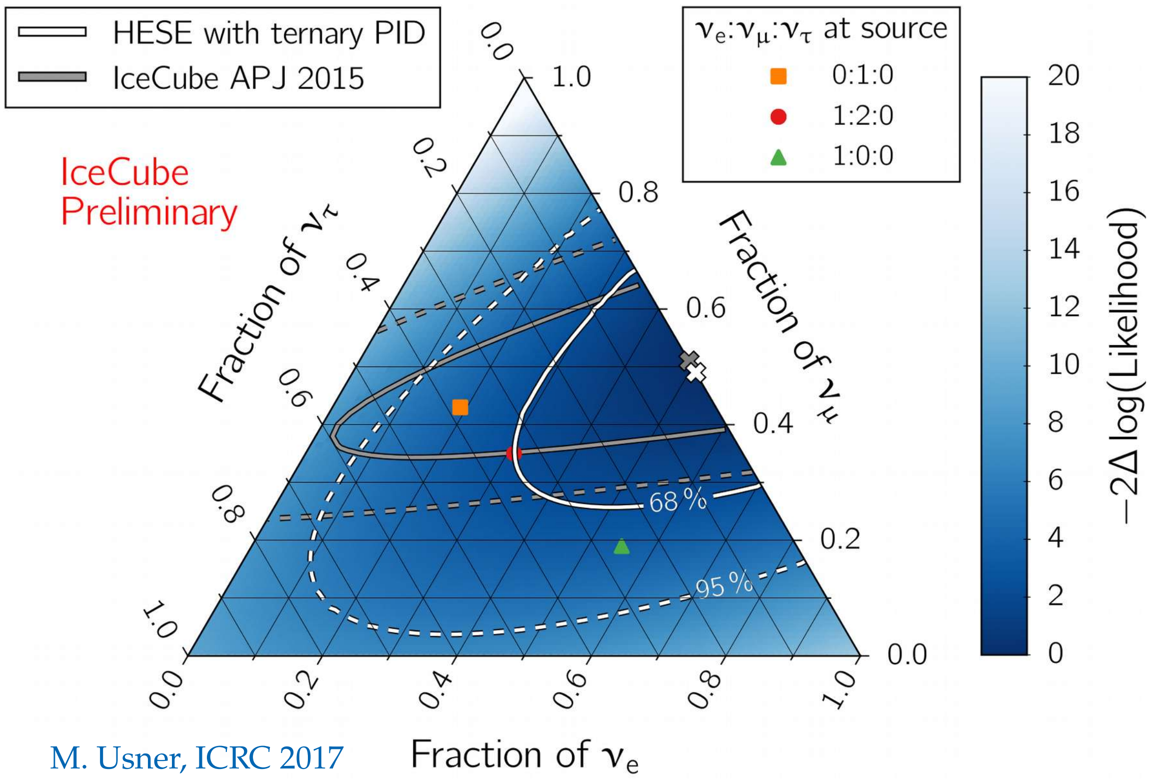
At Earth

Only 10% of parameter space



MB, Beacom, Winter *PRL* 2015

IceCube analysis of flavor composition



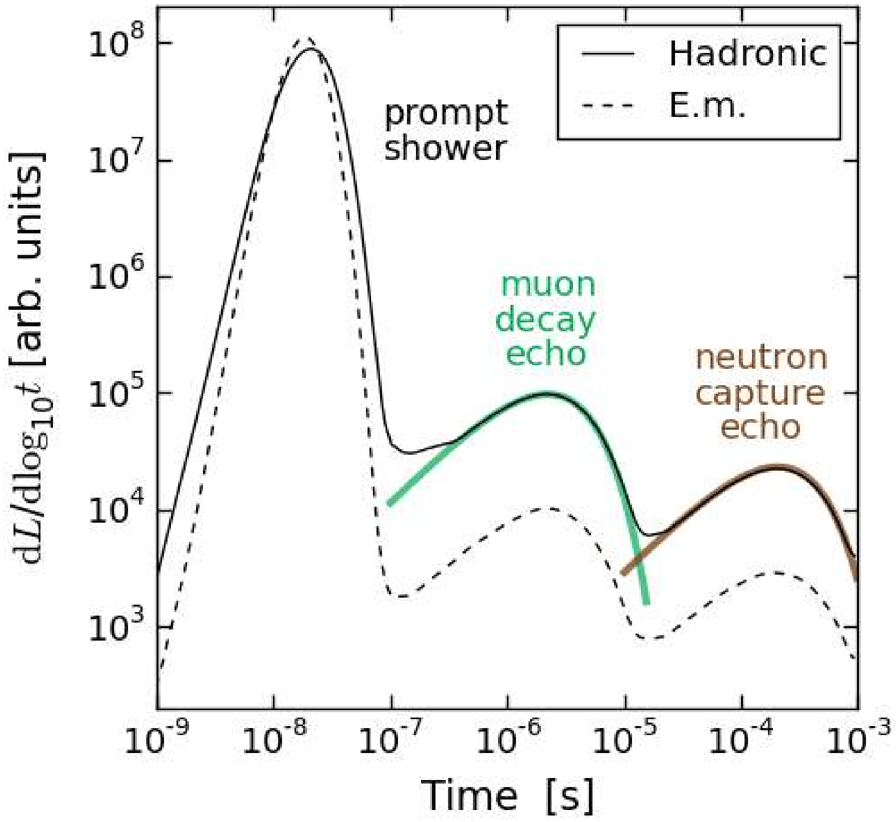
M. Usner, ICRC 2017

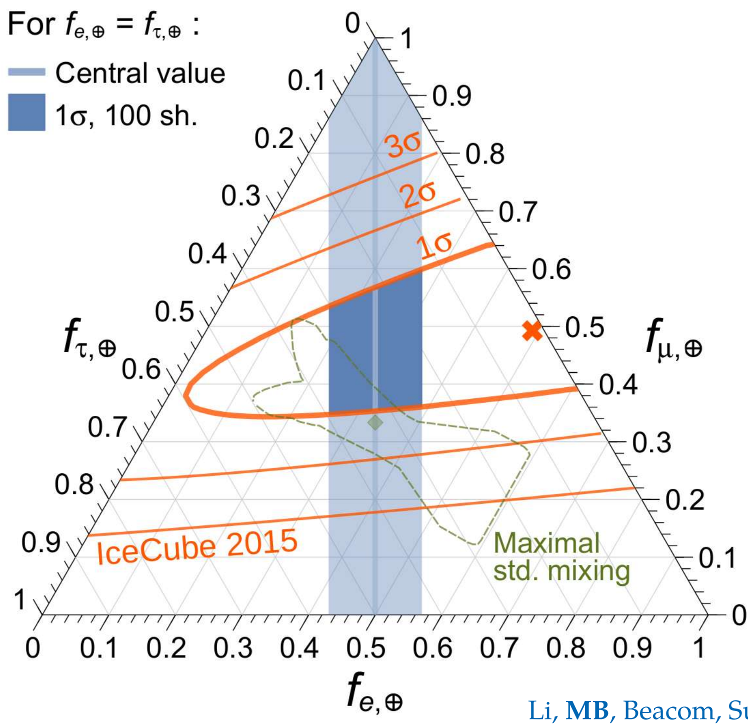
Using contained events plus through-going muons:

- 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

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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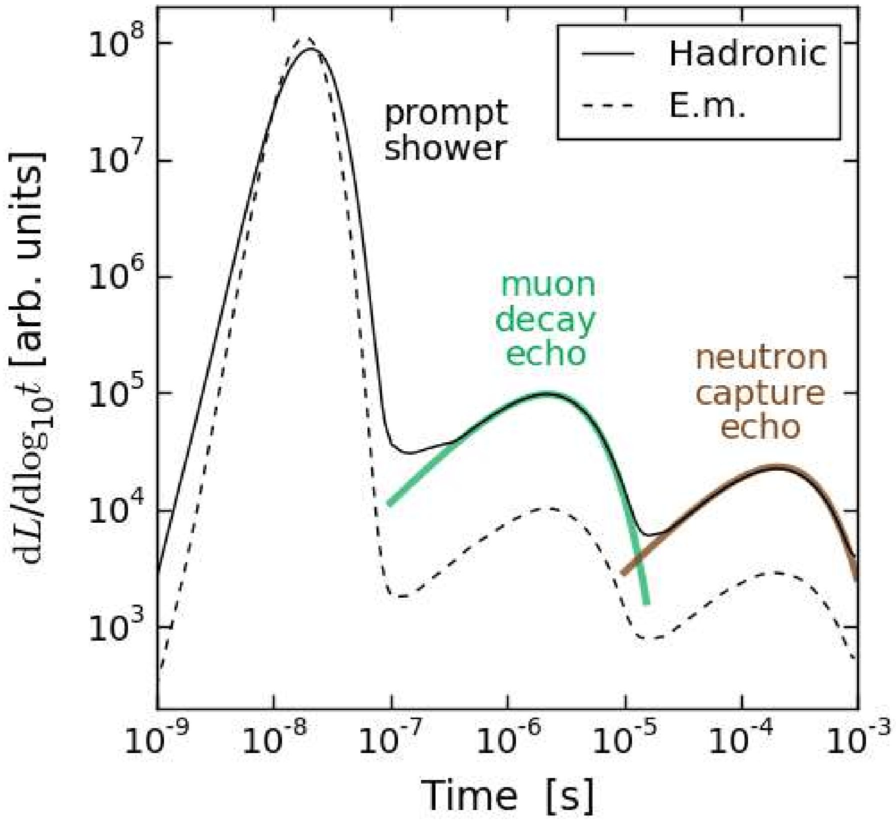
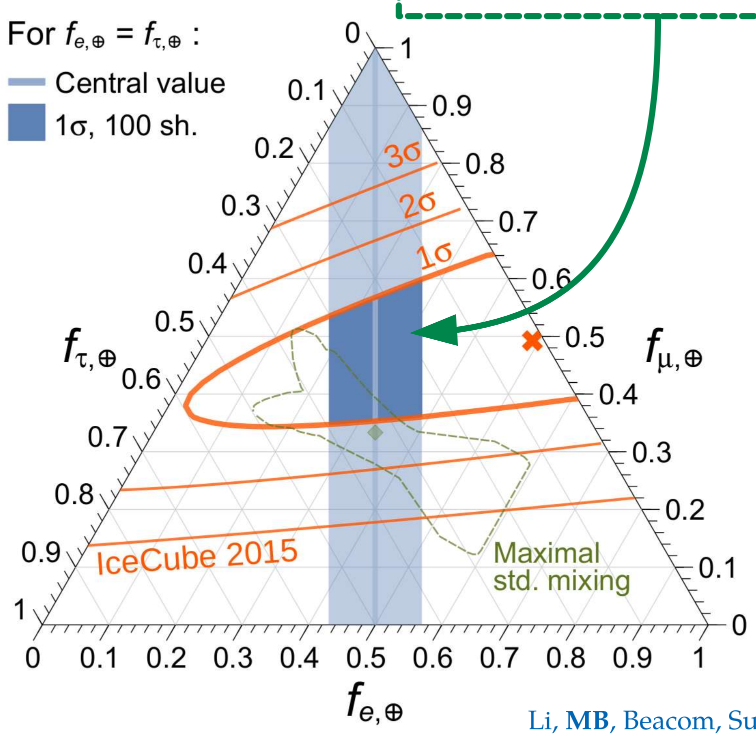


~10 × improvement over current measurement



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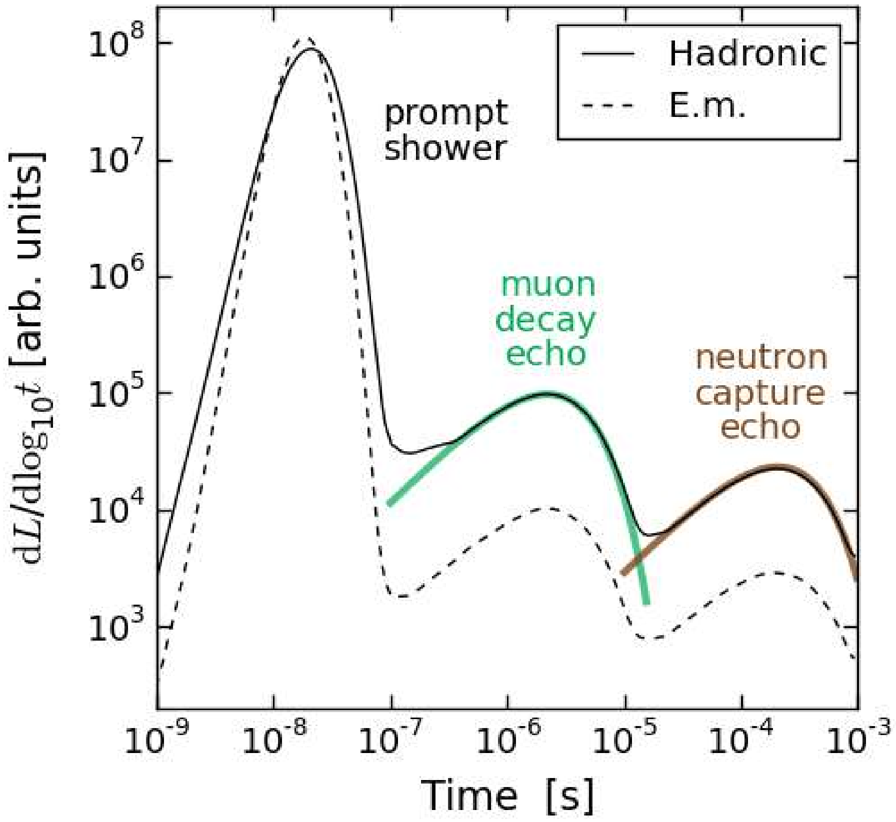

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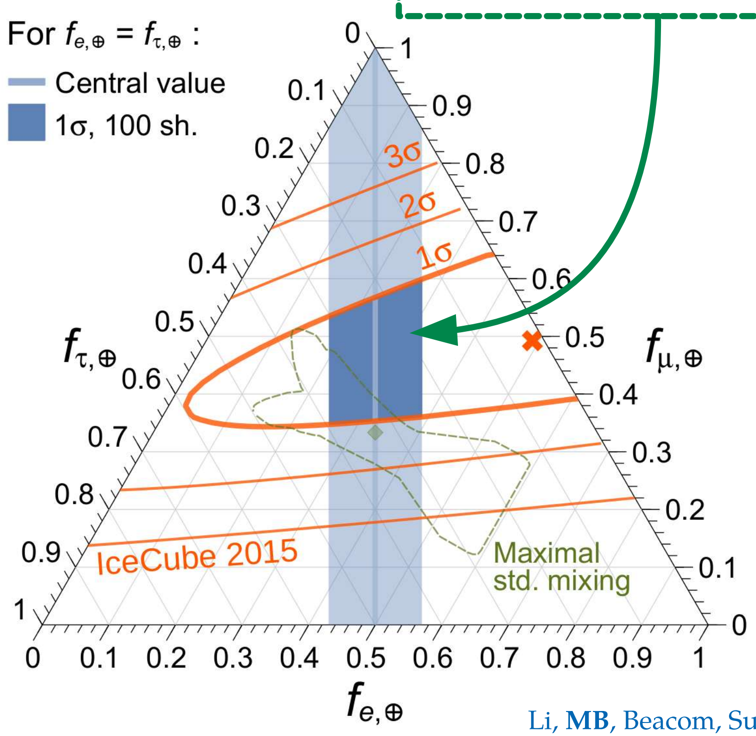

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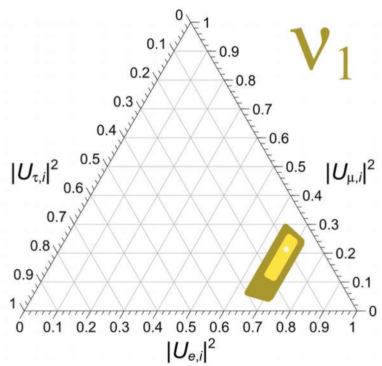
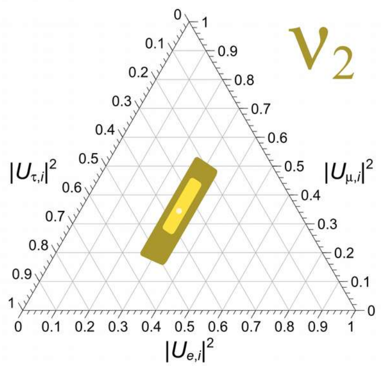
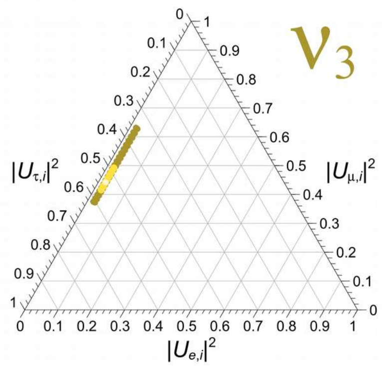
Two classes of new physics

- 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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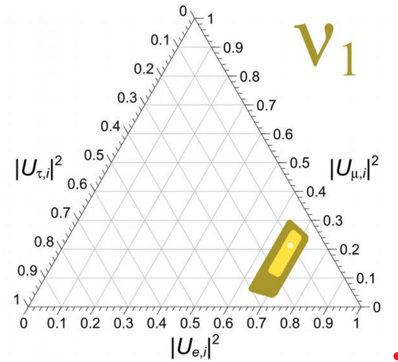
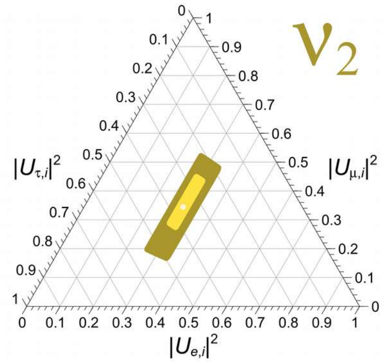
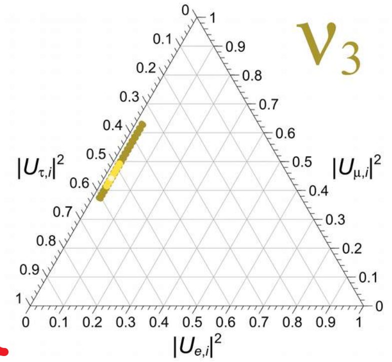
w_1 [

] + w_2 [

] + w_3 [

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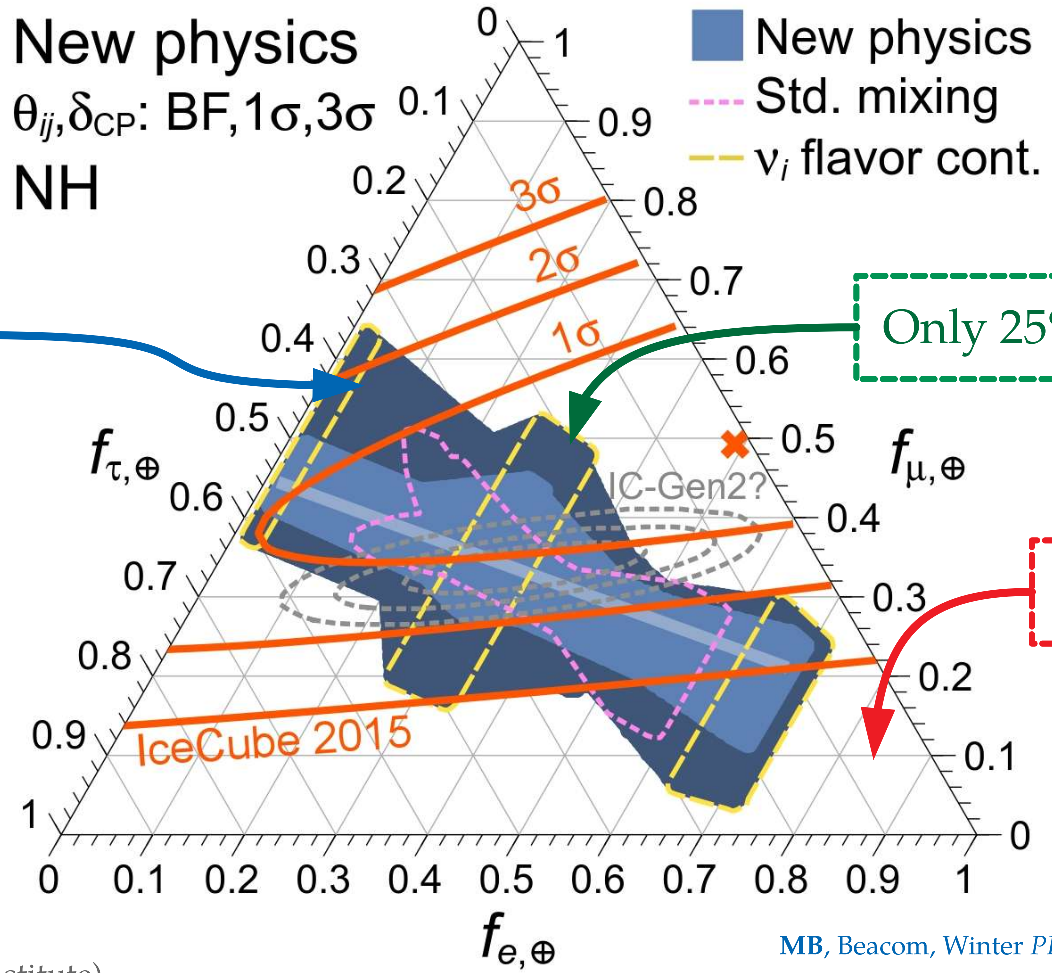
Flavor ratios accessible with decay-like physics

Region of all linear combinations of ν_1, ν_2, ν_3



Only 25% of parameter space

What lives outside?

MB, Beacom, Winter *PRL* 2015

New physics – High-energy effects

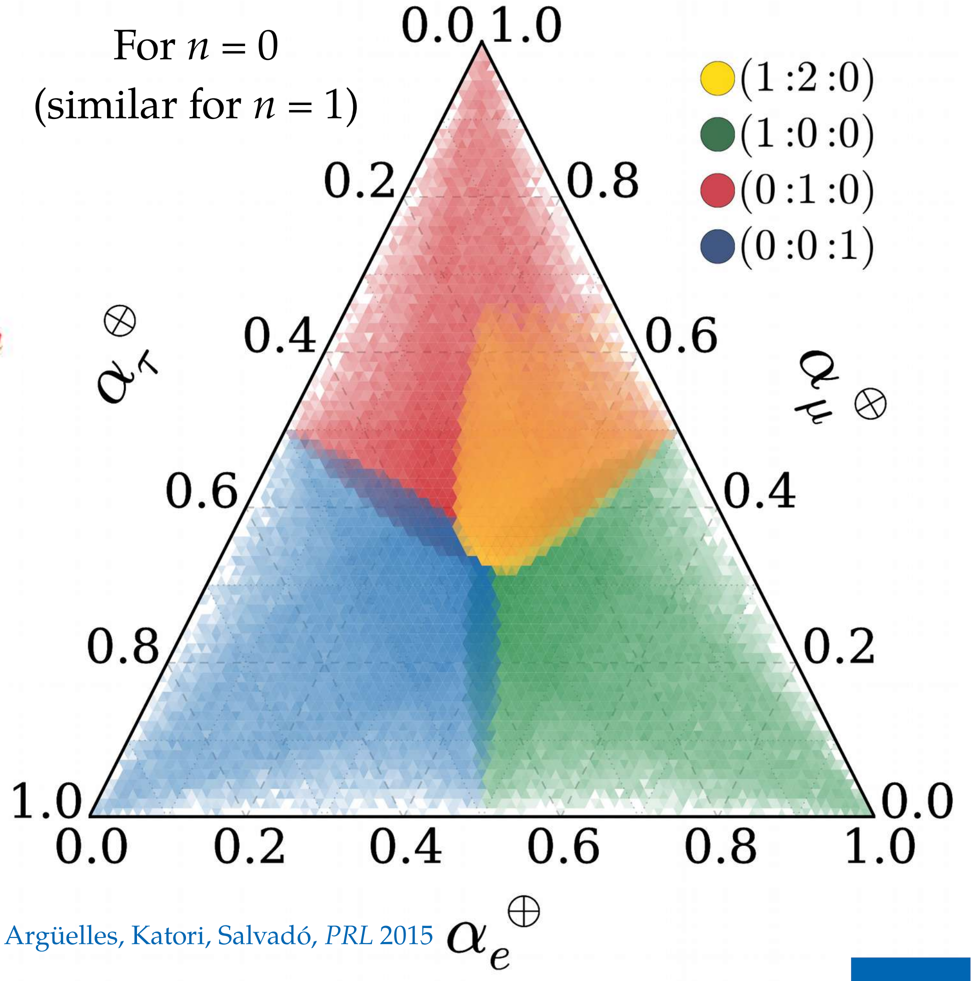
$$H_{\text{tot}} = H_{\text{std}} + H_{\text{NP}}$$

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

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

This can populate *all* of the triangle –

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



Argüelles, Katori, Salvadó, *PRL* 2015

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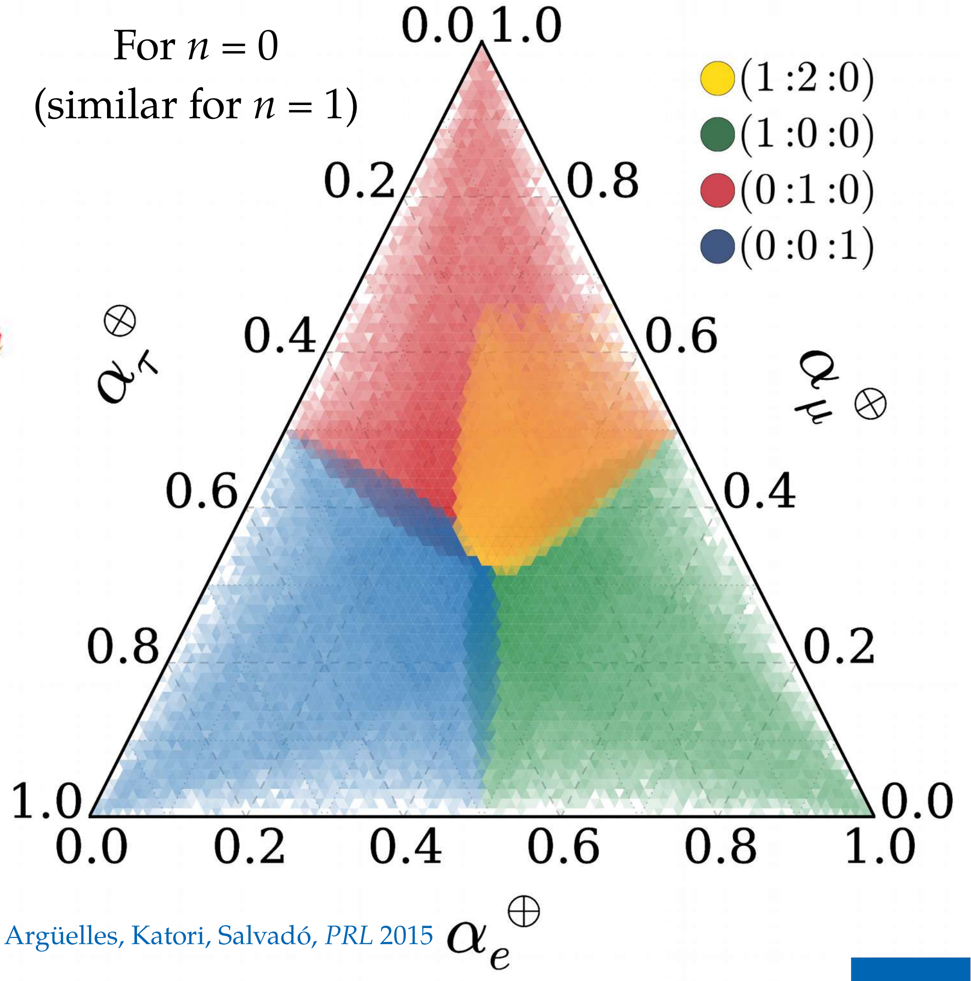
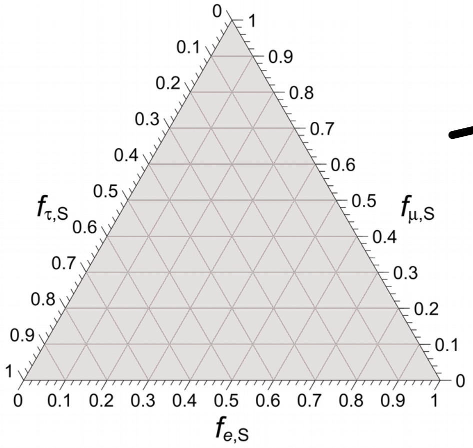
For $n = 0$
(similar for $n = 1$)



Argüelles, Katori, Salvadó, *PRL* 2015

Measuring the neutrino lifetime

Sources



$\nu_2, \nu_3 \to \nu_1$

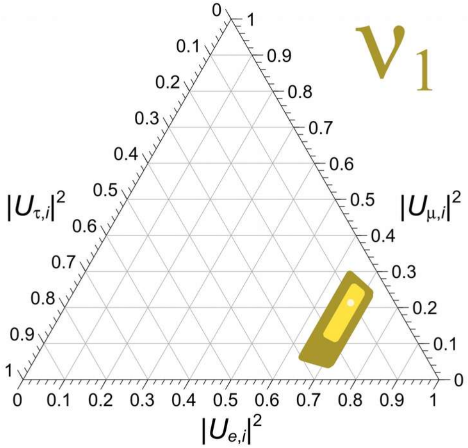
ν_1 lightest and stable

If all unstable neutrinos decay

$\nu_1, \nu_2 \to \nu_3$

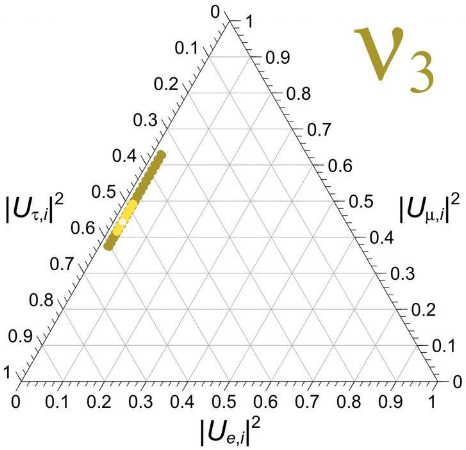
ν_3 lightest and stable

Earth



ν_1

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



ν_3

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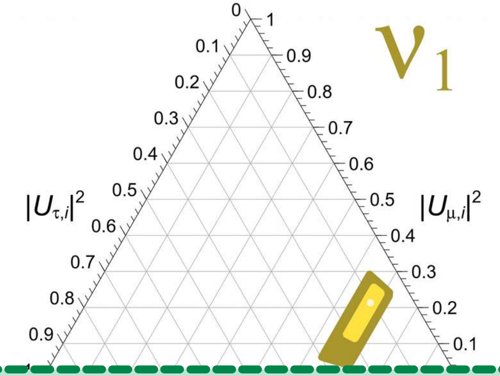

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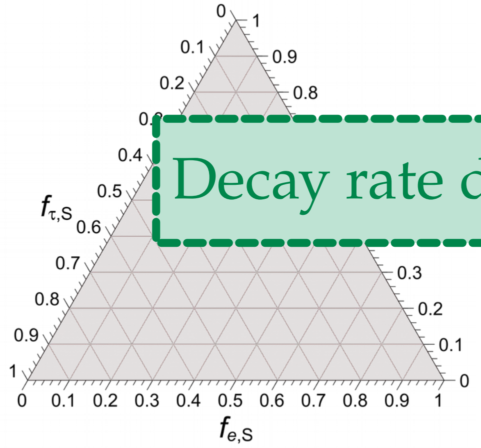
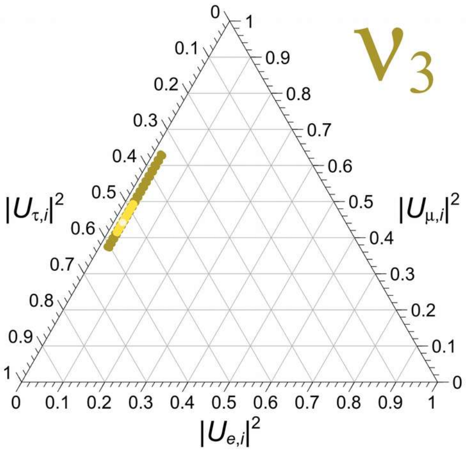
Sources



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

neutrinos decay

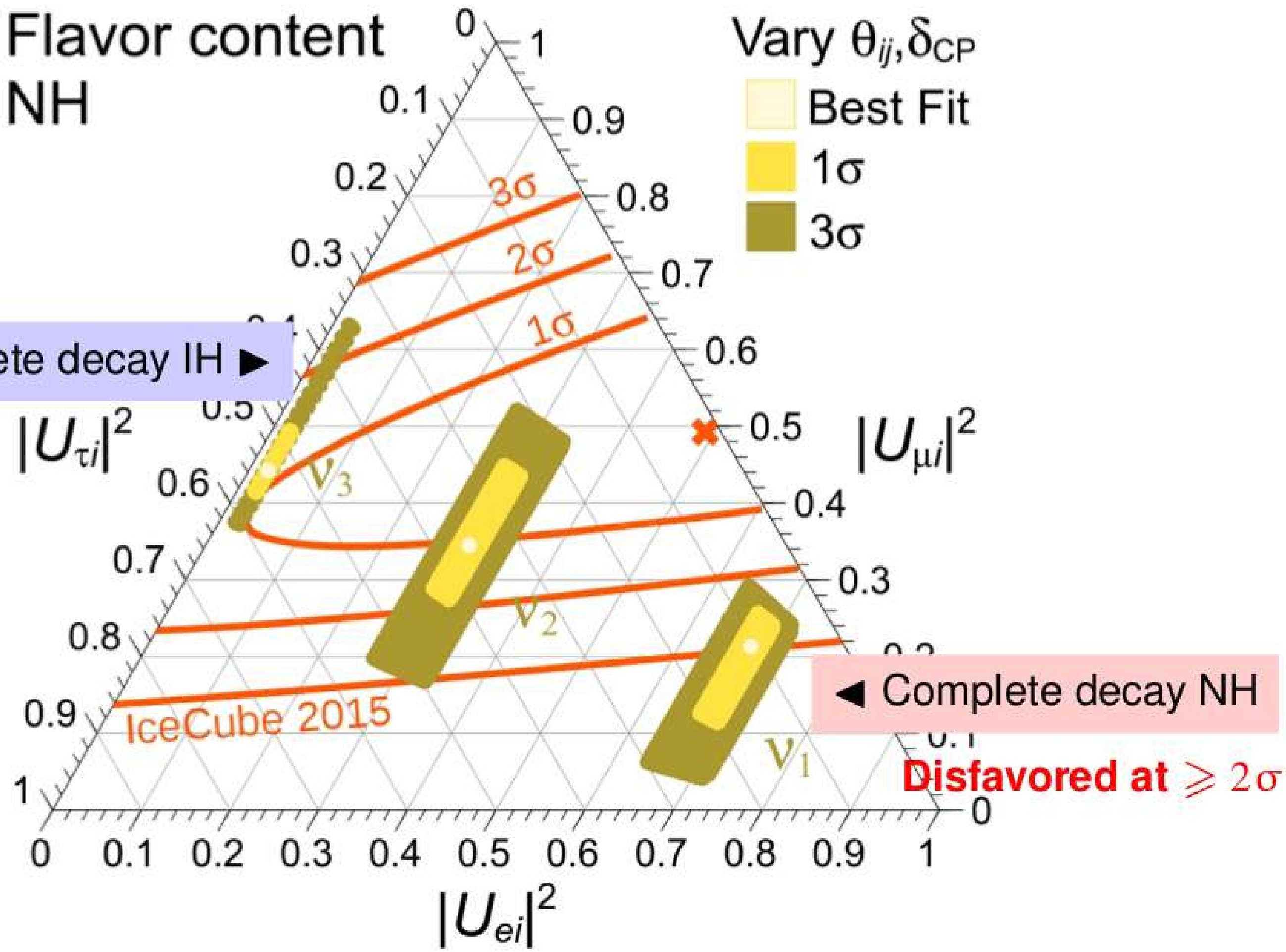


$f_{\alpha,\oplus} = |U_{\alpha 3}|^2$

$\nu_1, \nu_2 \to \nu_3$

ν_3 lightest and stable

Constraining decay from the flavor ratios



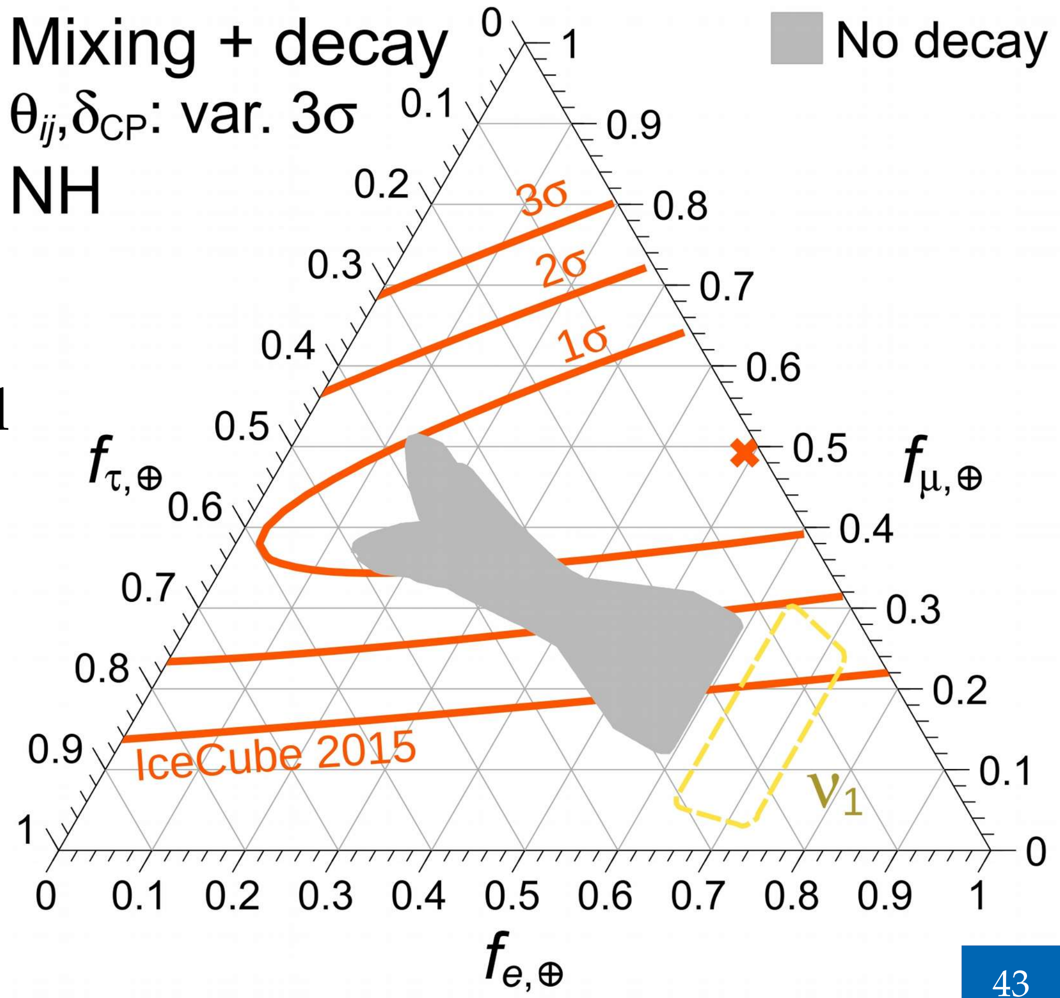
Measuring the neutrino lifetime

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

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
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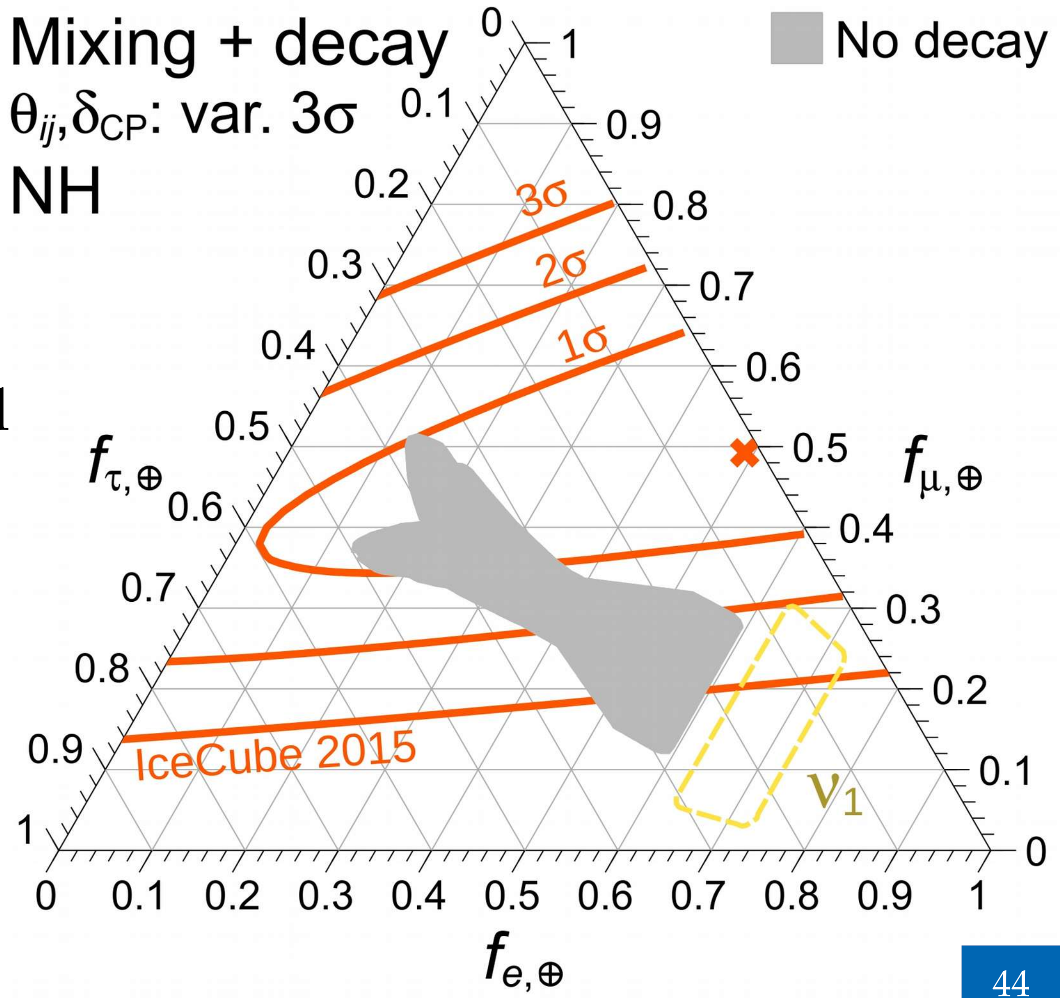

Measuring the neutrino lifetime

Fraction of ν_2, ν_3 remaining at Earth

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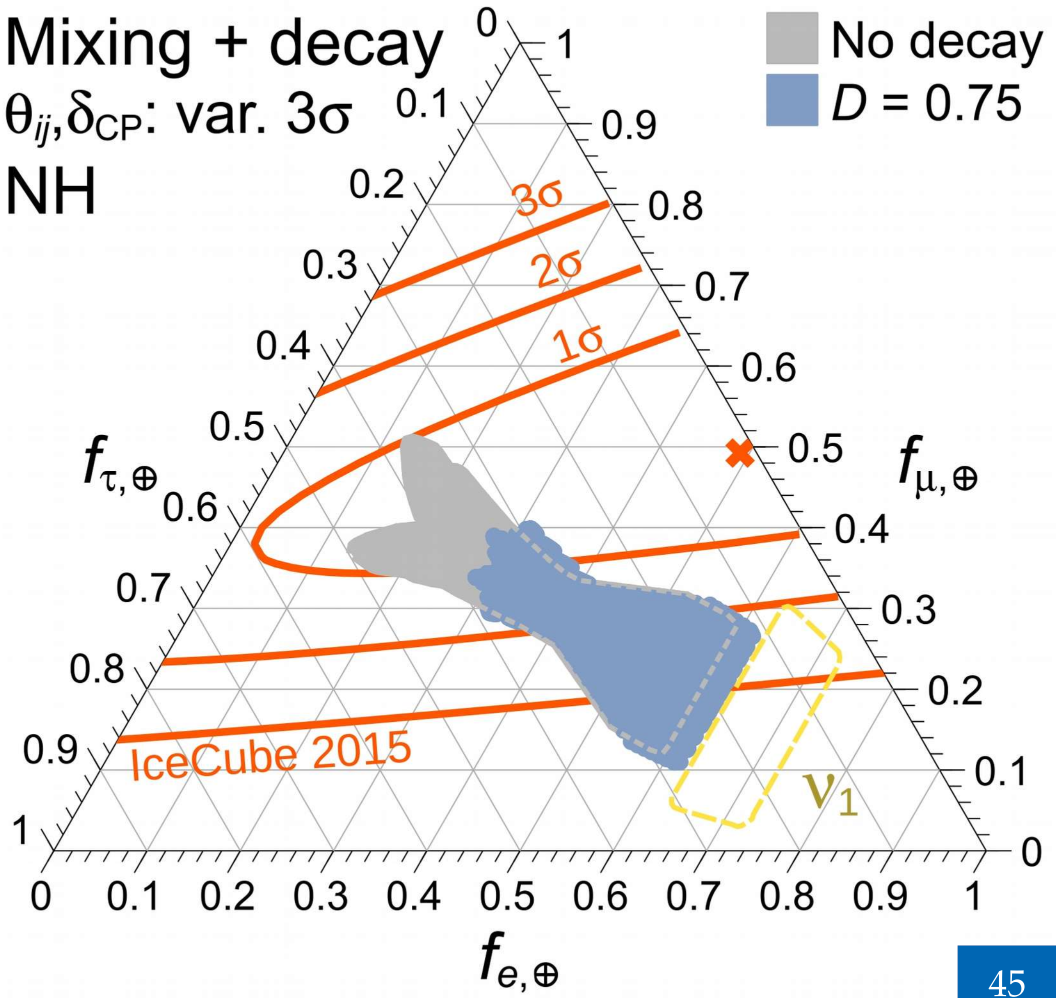

Measuring the neutrino lifetime

Fraction of ν_2, ν_3 remaining at Earth

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

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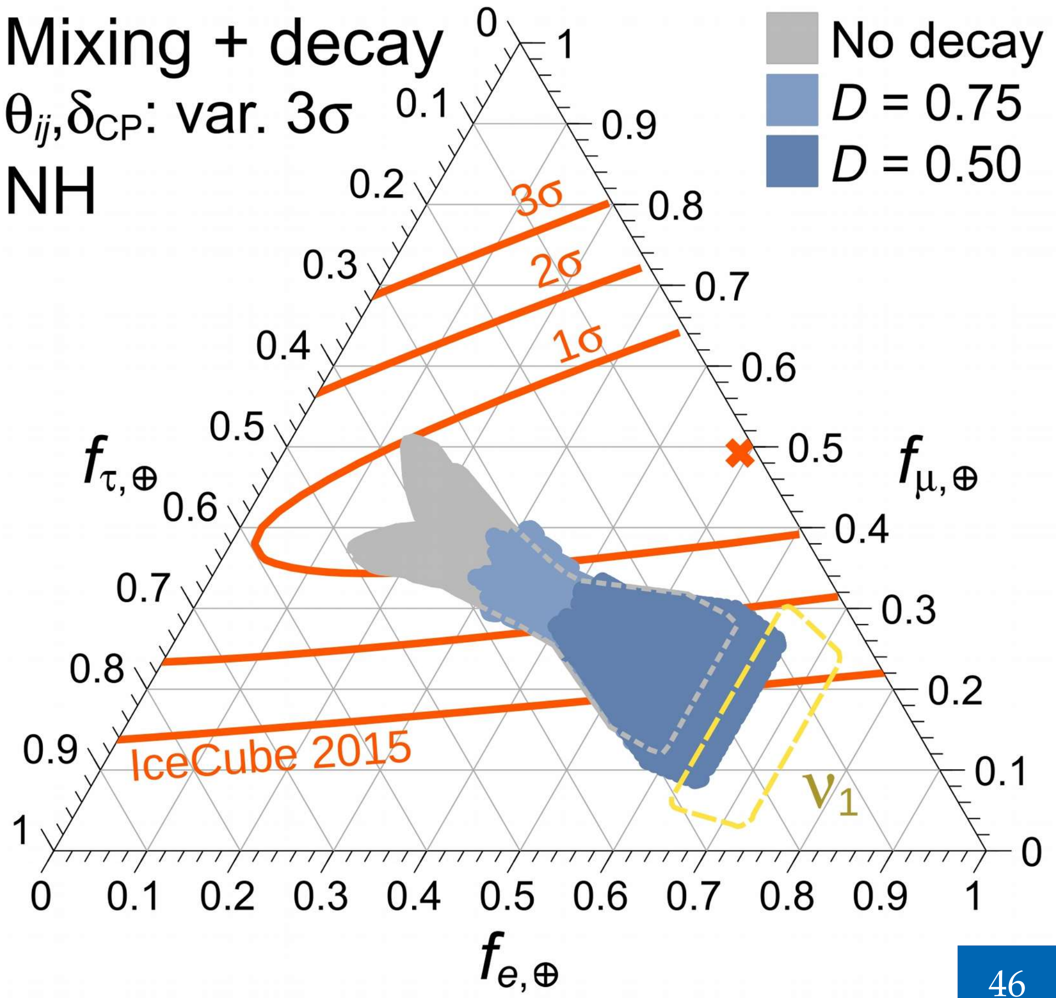

Measuring the neutrino lifetime

Fraction of ν_2, ν_3 remaining at Earth

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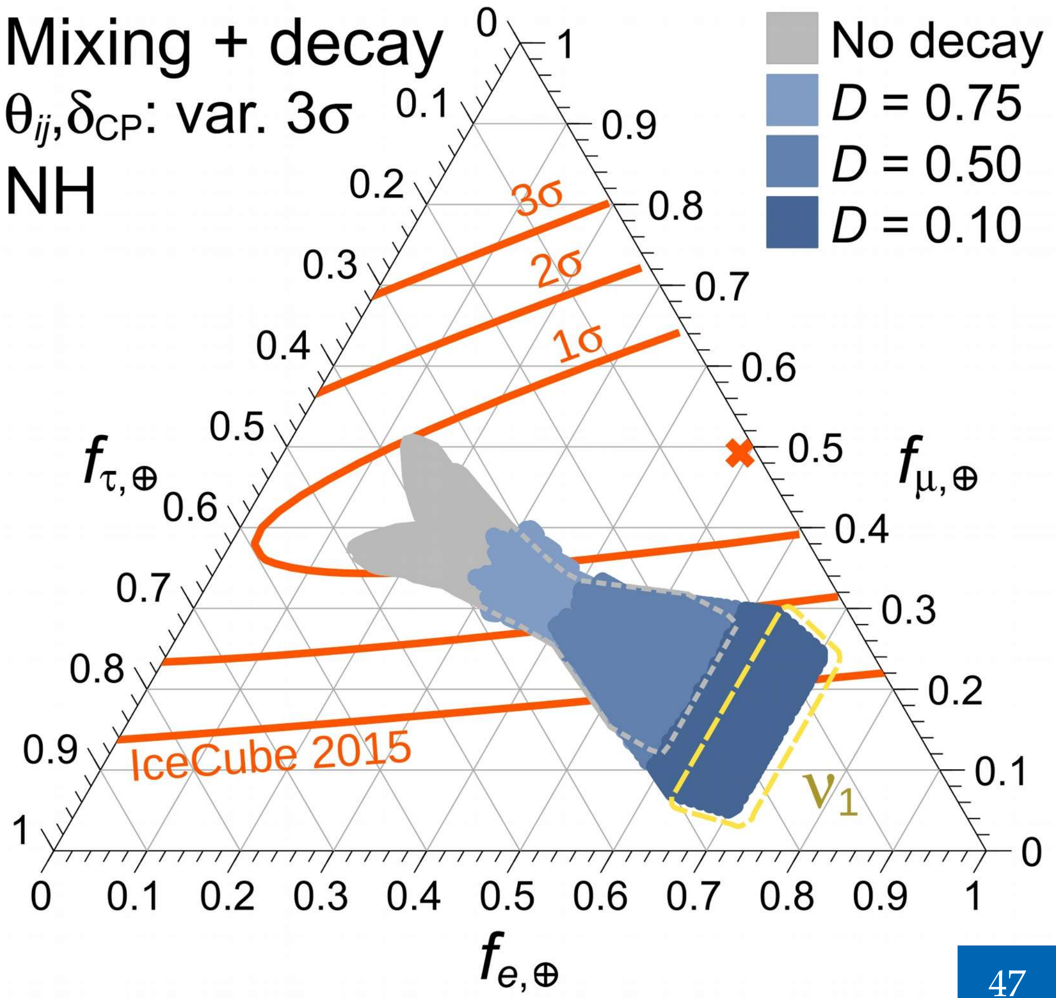

Measuring the neutrino lifetime

Fraction of ν_2, ν_3 remaining at Earth

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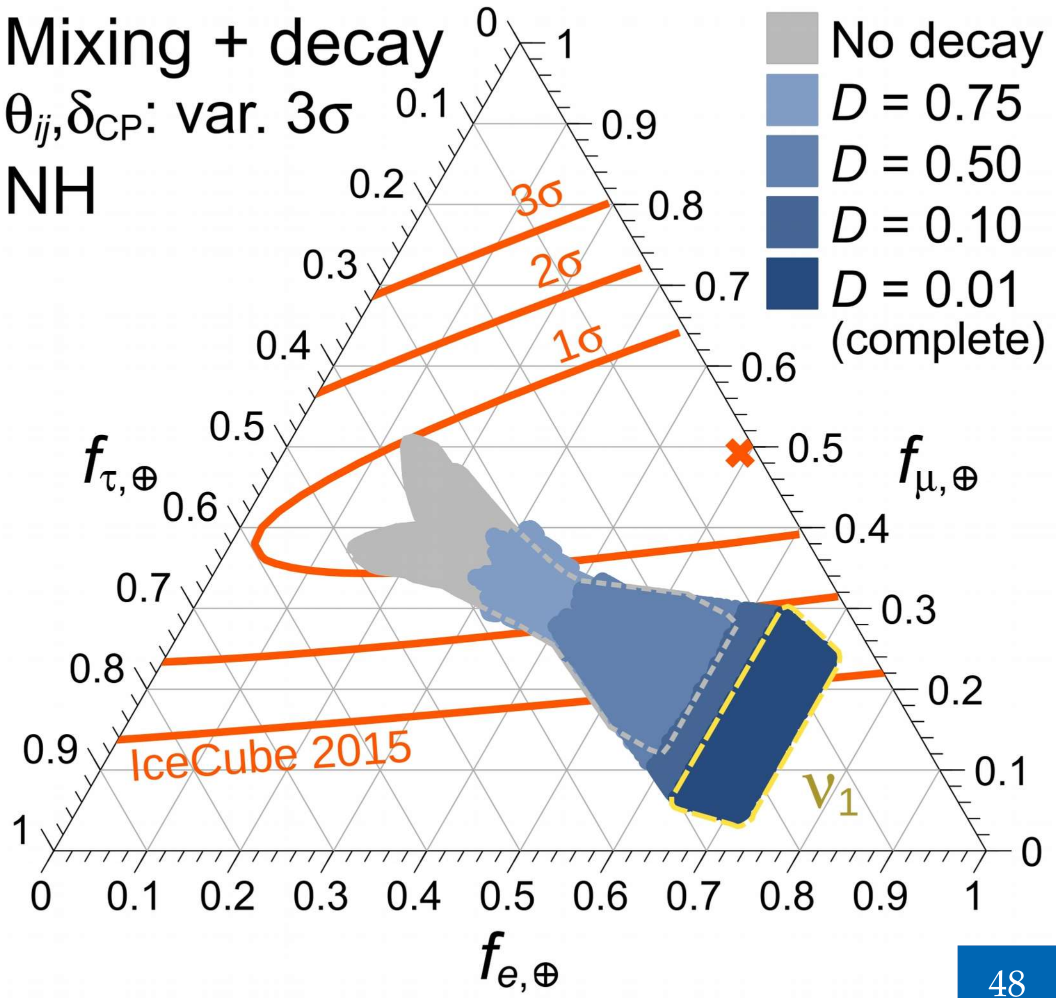

MB, Beacom, Murase, *PRD* 2017
Baerwald, **MB**, Winter, *JCAP* 2012

Measuring the neutrino lifetime

Fraction of ν_2, ν_3 remaining at Earth

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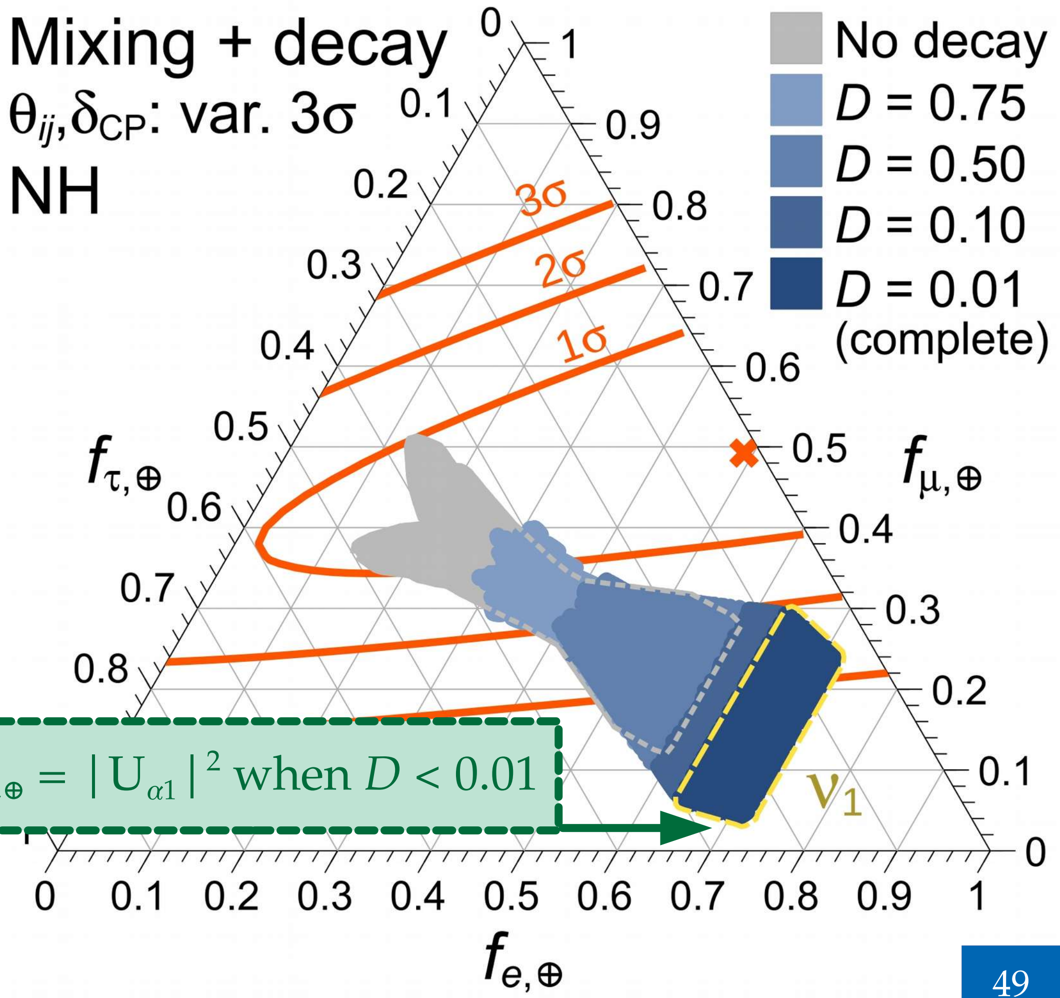
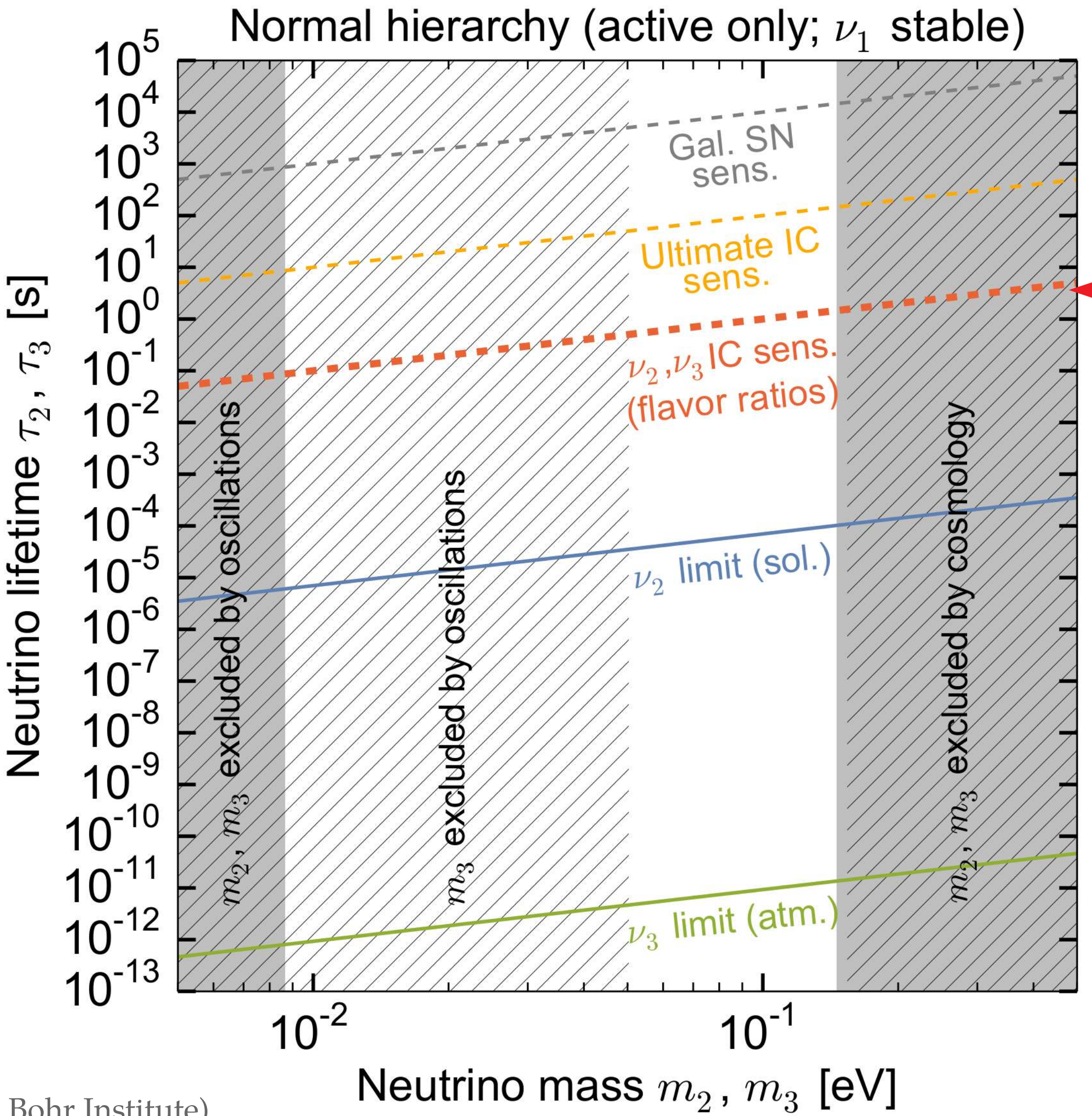


$f_{\alpha,\oplus} = |U_{\alpha 1}|^2$ when $D < 0.01$

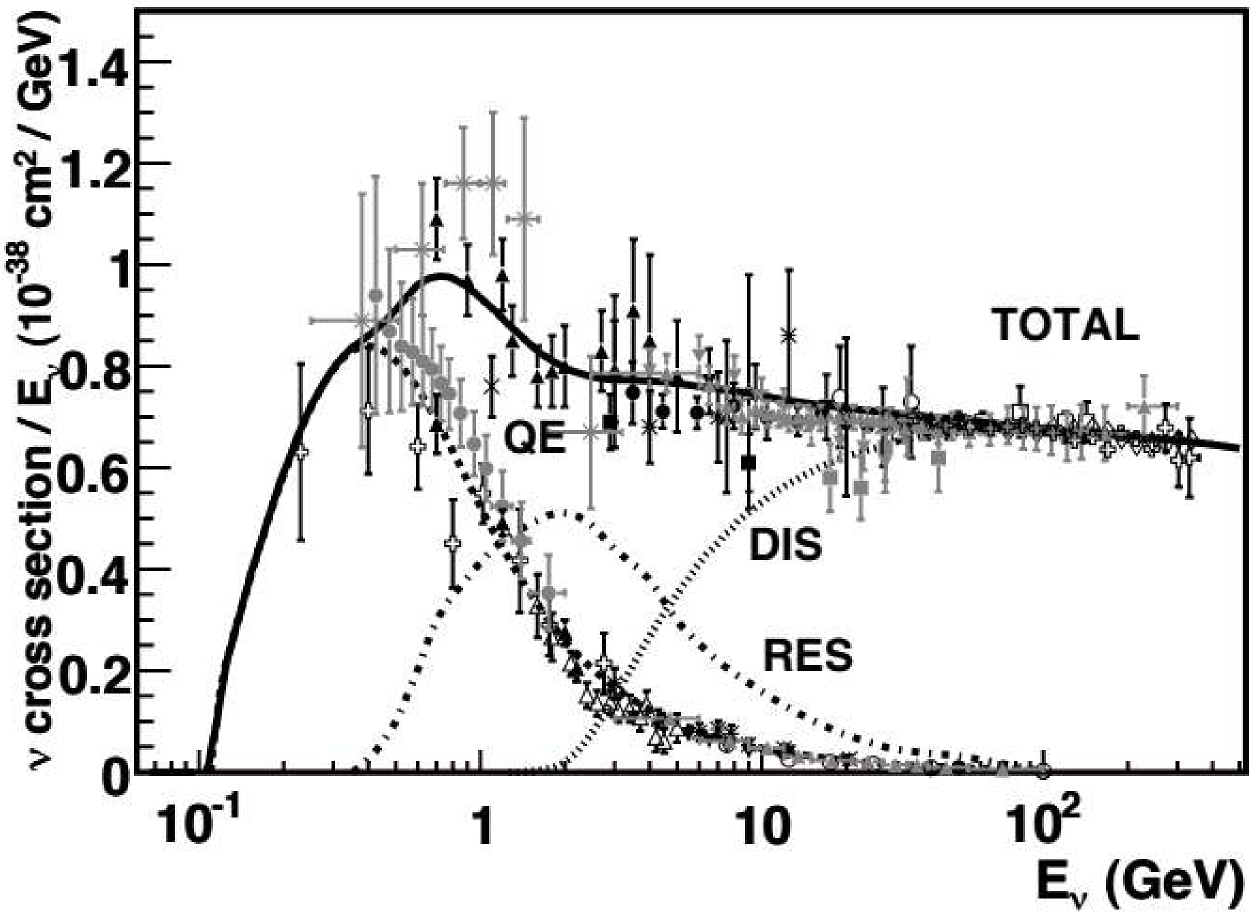
MB, Beacom, Murase, *PRD* 2017
Baerwald, **MB**, Winter, *JCAP* 2012



Our result

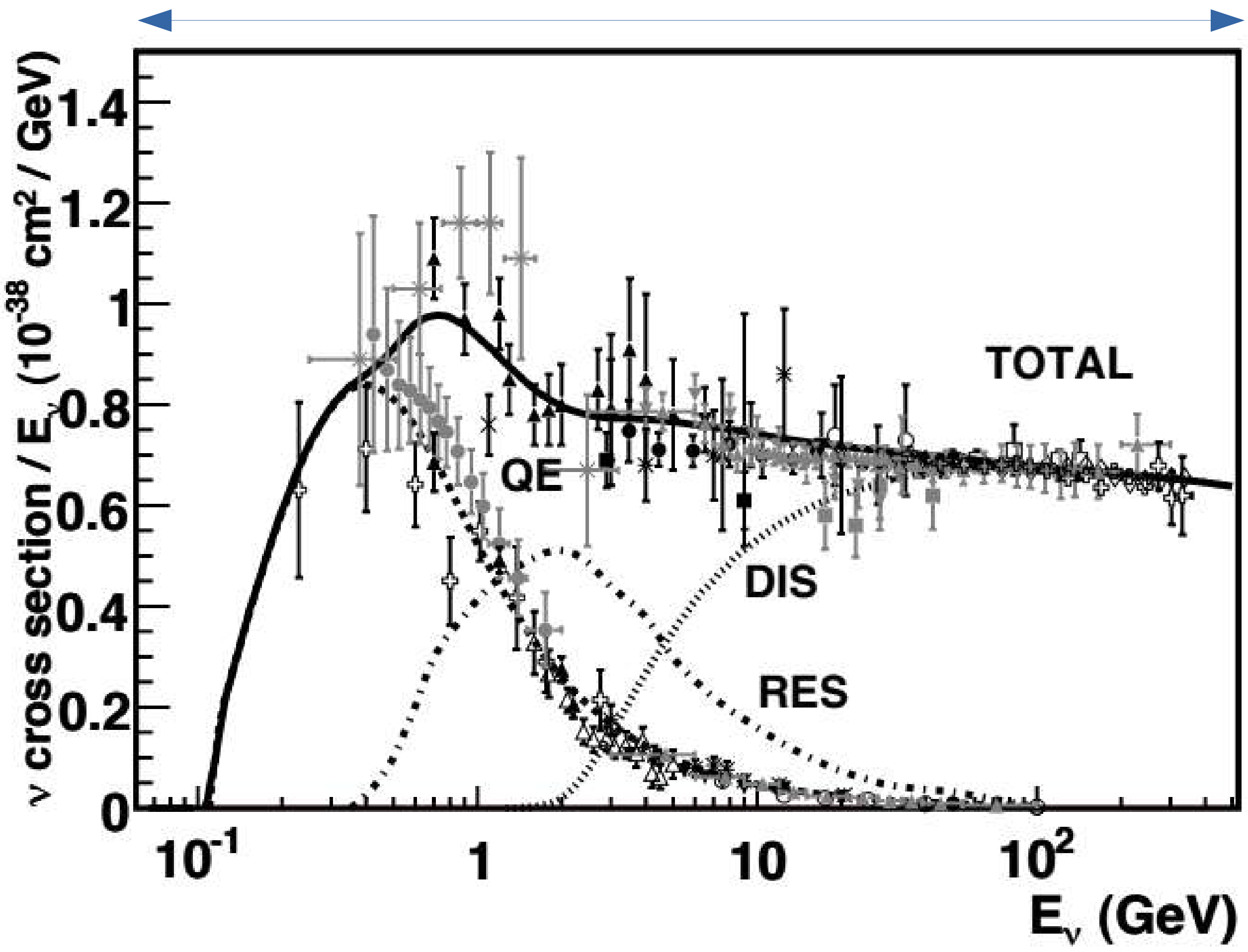
$$\frac{\tau_2}{m_2}, \frac{\tau_3}{m_3} \gtrsim 10 \frac{\text{s}}{\text{eV}}$$

MB, Beacom, Murase, *PRD* 2017



Particle Data Group

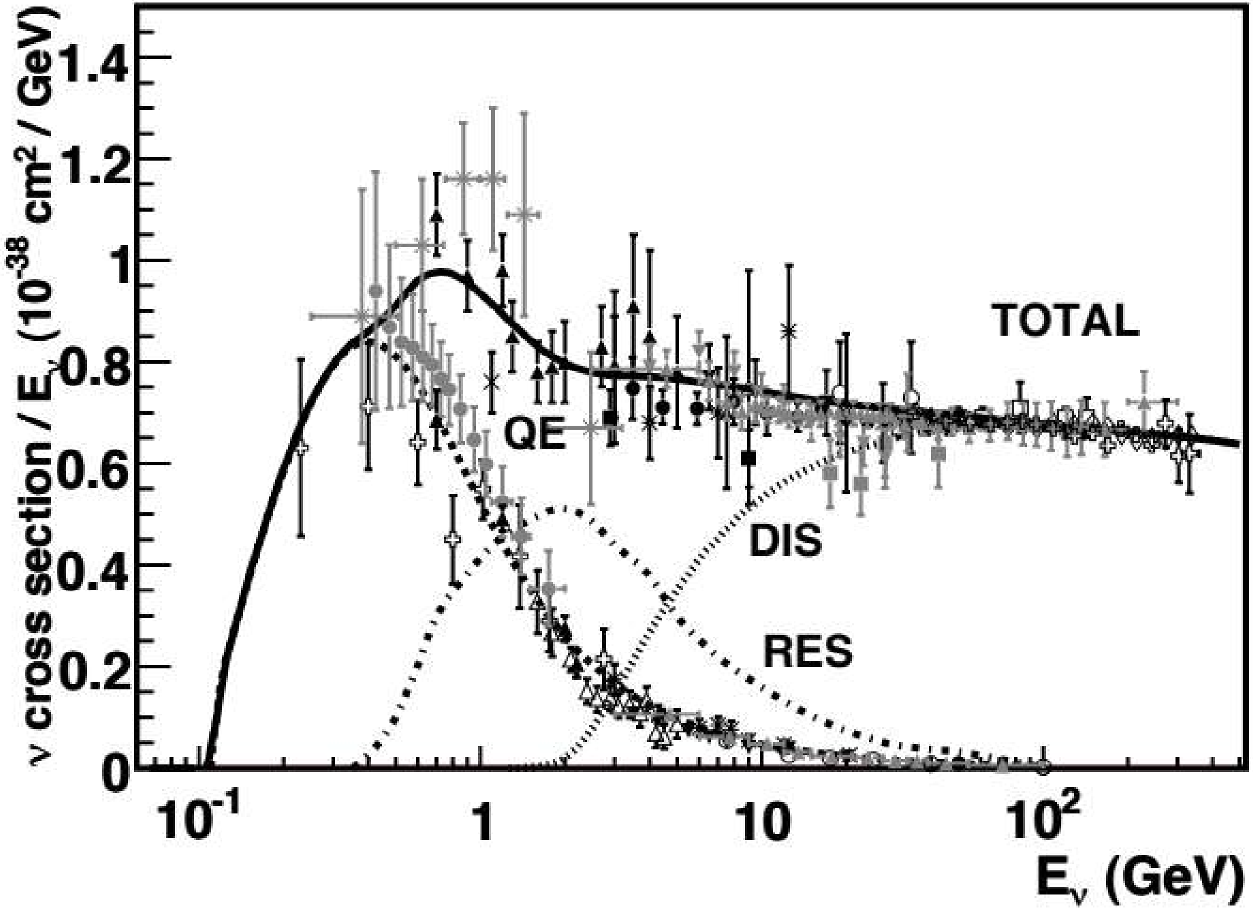
Accelerator experiments



Particle Data Group

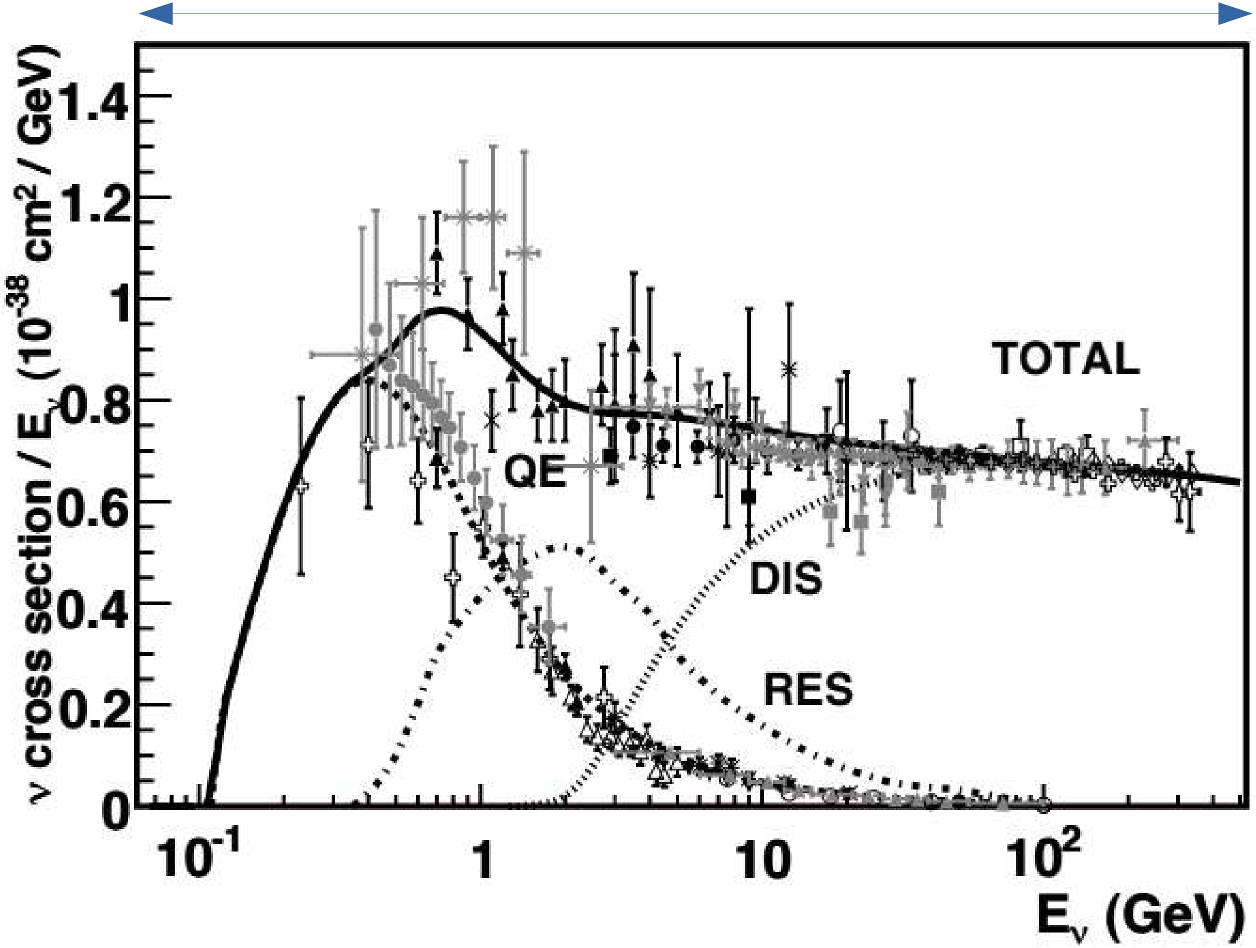
Accelerator experiments

One recent measurement (COHERENT)



Particle Data Group

Accelerator experiments



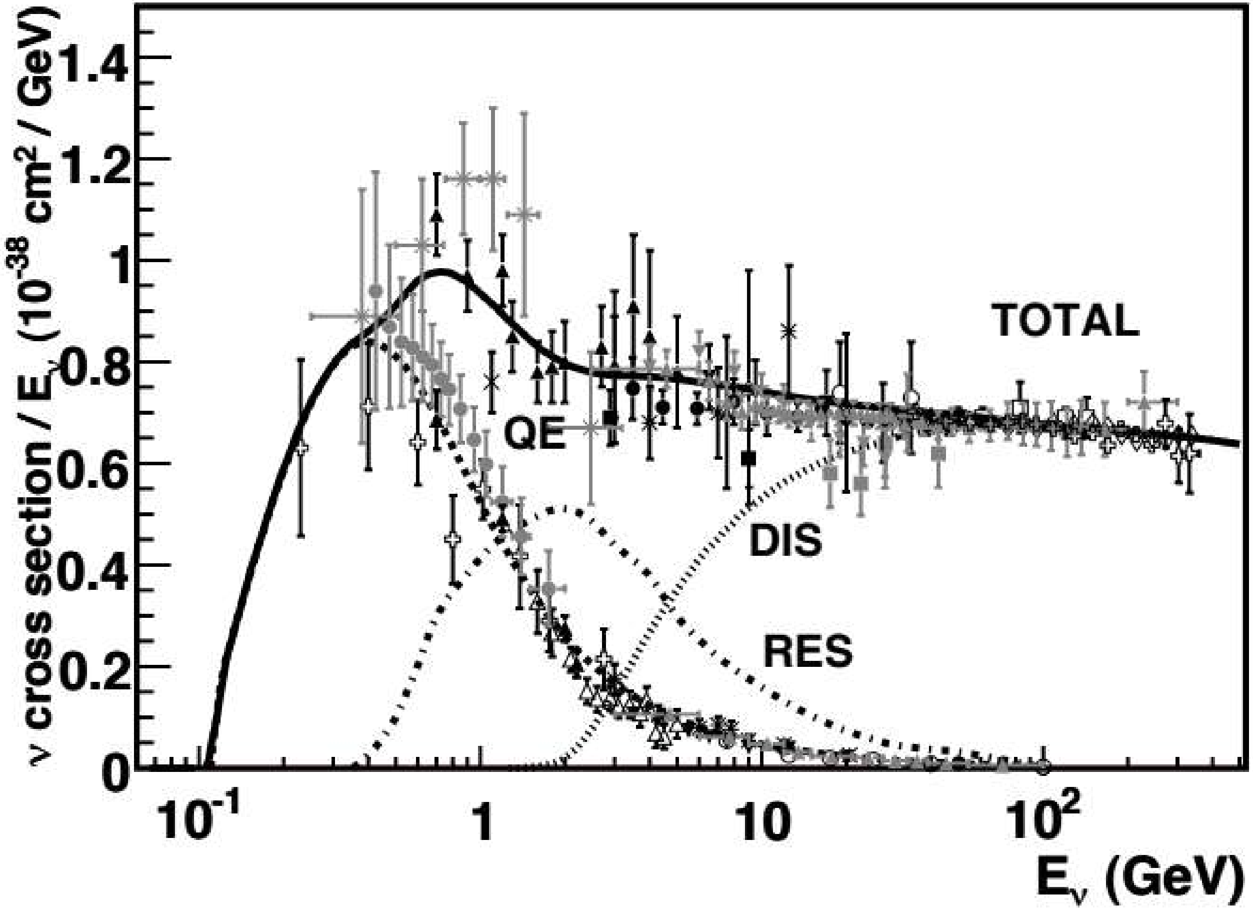
One recent measurement (COHERENT)

No measurements … until now!

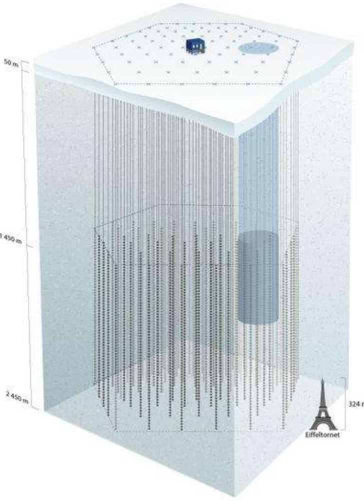
Particle Data Group

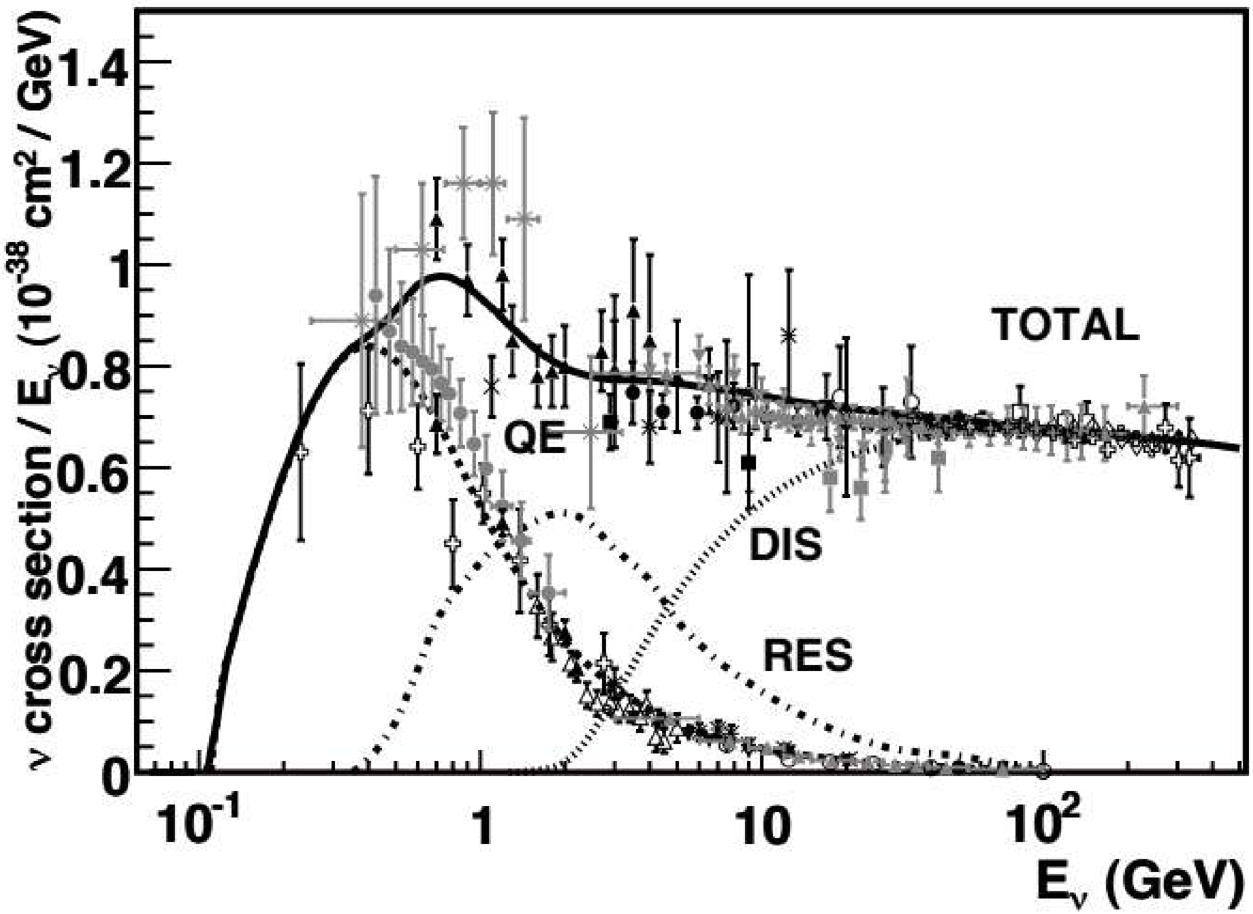
Accelerator experiments

One recent measurement (COHERENT)



Particle Data Group



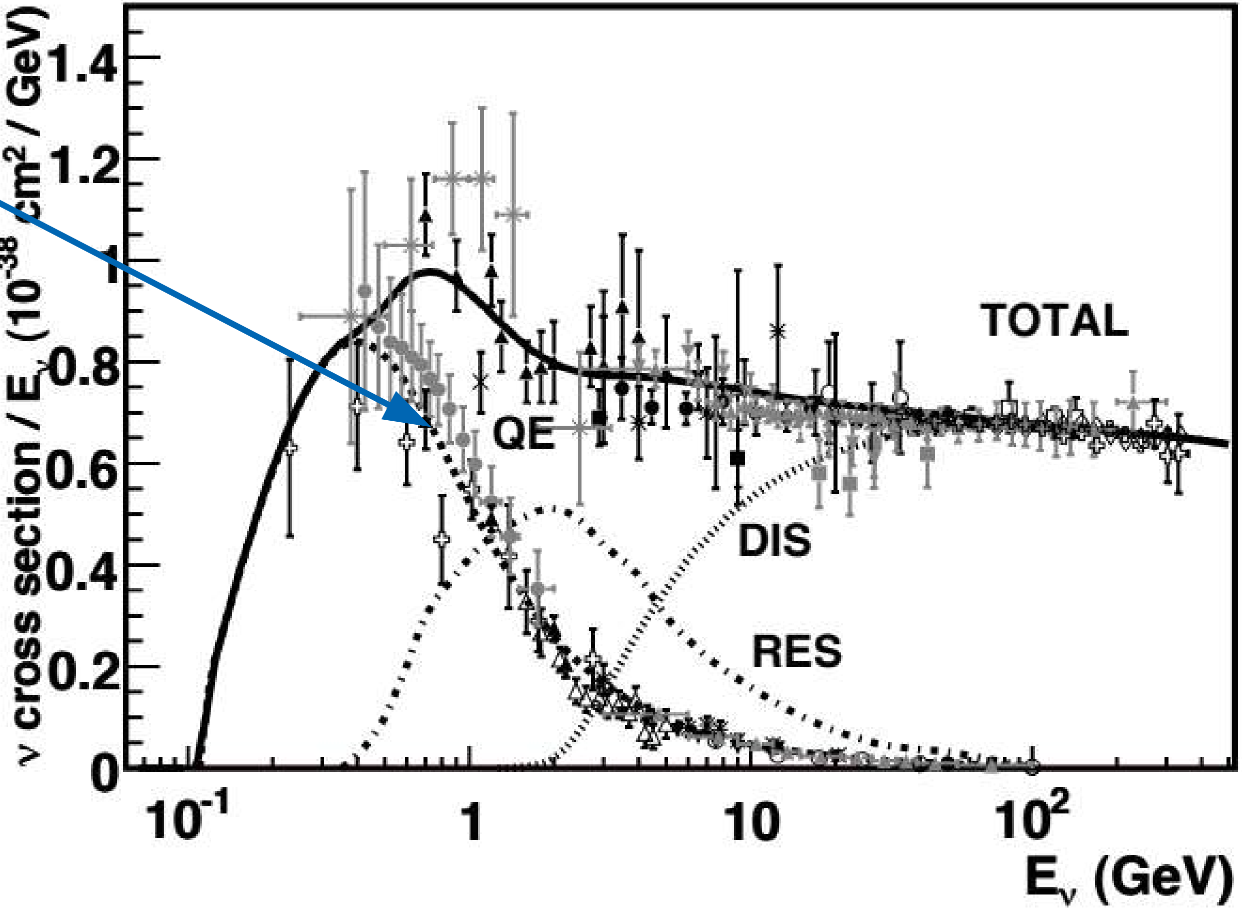


Particle Data Group

Quasi-elastic scattering:

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

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

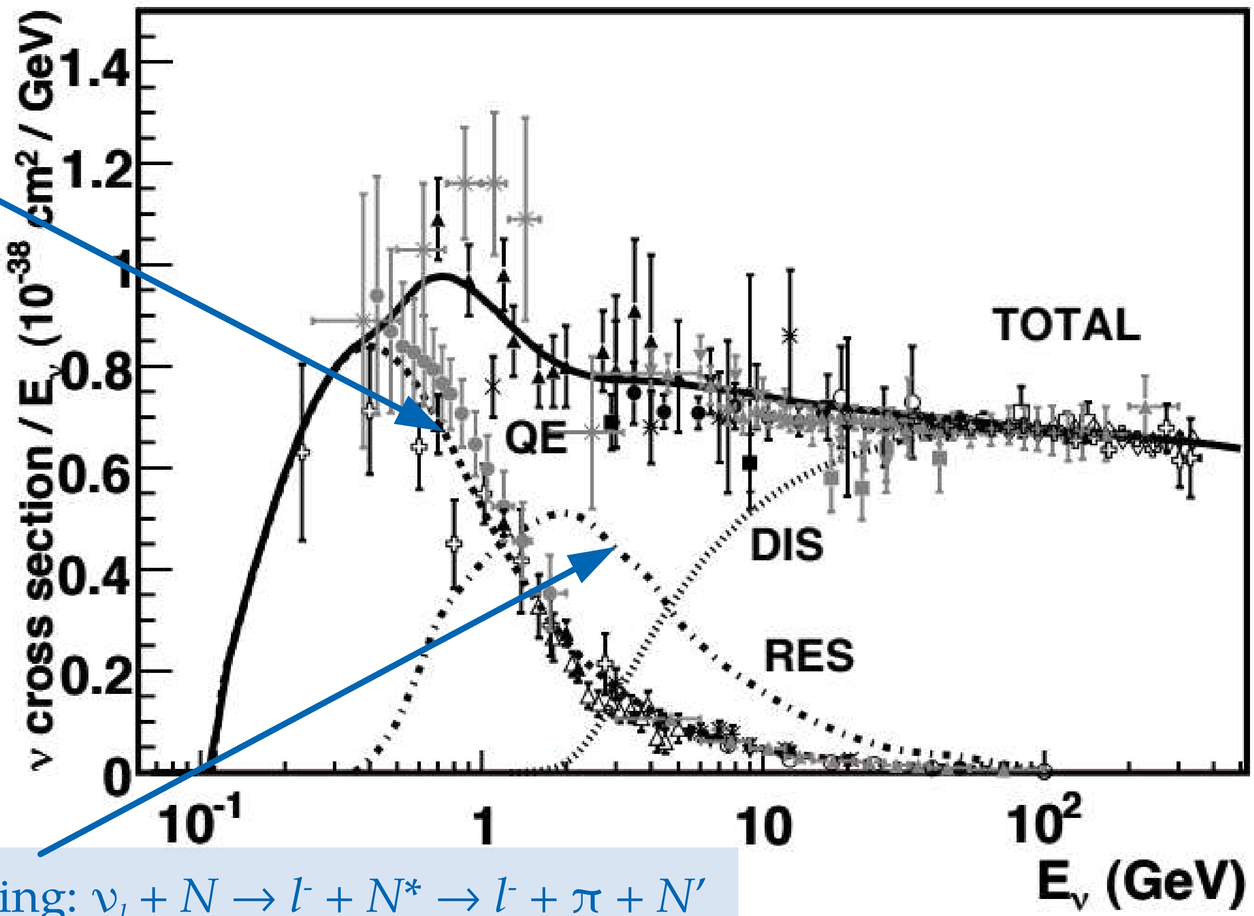


Particle Data Group

Quasi-elastic scattering:

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

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



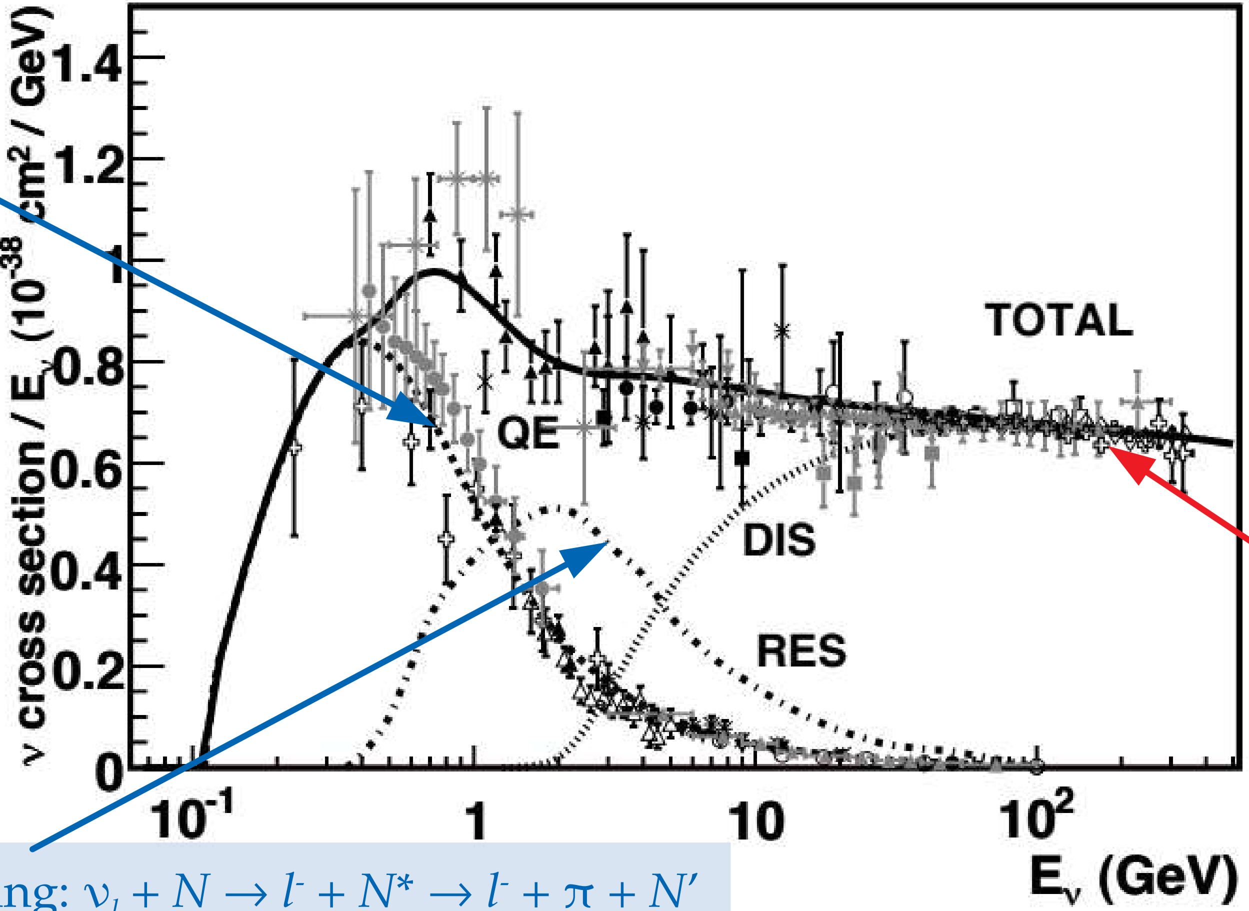
Resonant scattering: $\nu_l + N \rightarrow l^- + N^* \rightarrow l^- + \pi + N'$

Particle Data Group

Quasi-elastic scattering:

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

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



Particle Data Group

Deep inelastic scattering:

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

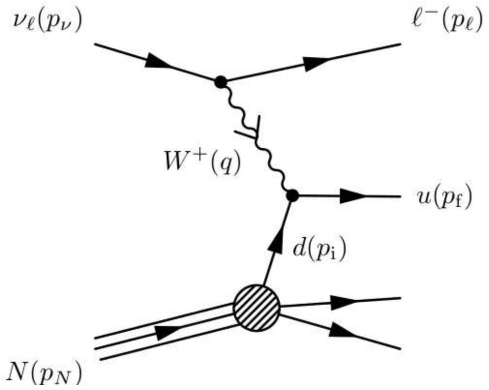
$\bar{\nu}_l + N \rightarrow l^+ + X$

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

Extrapolating the cross section to high energies

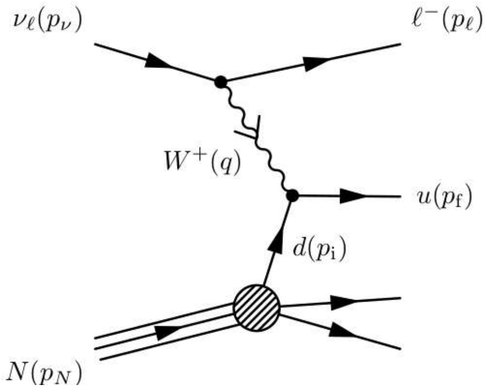
Extrapolating the cross section to high energies

SM



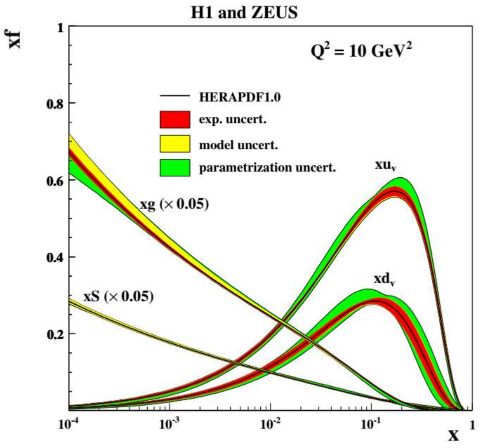
Extrapolating the cross section to high energies

SM



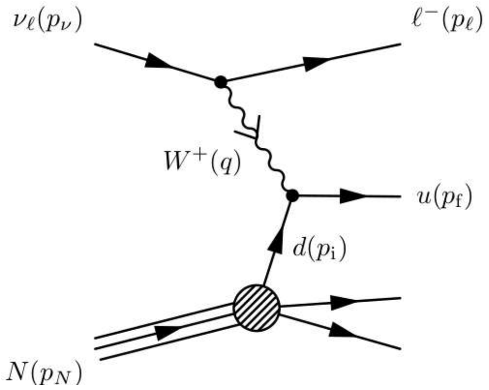
+

PDFs



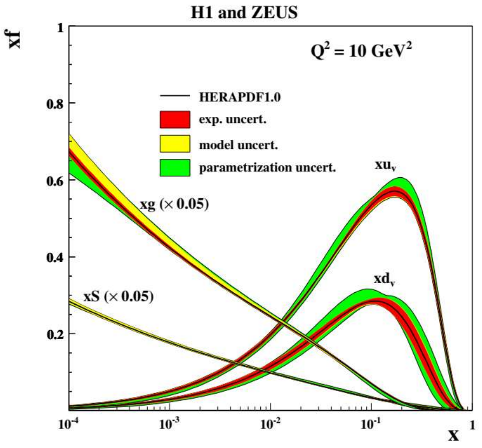
Extrapolating the cross section to high energies

SM

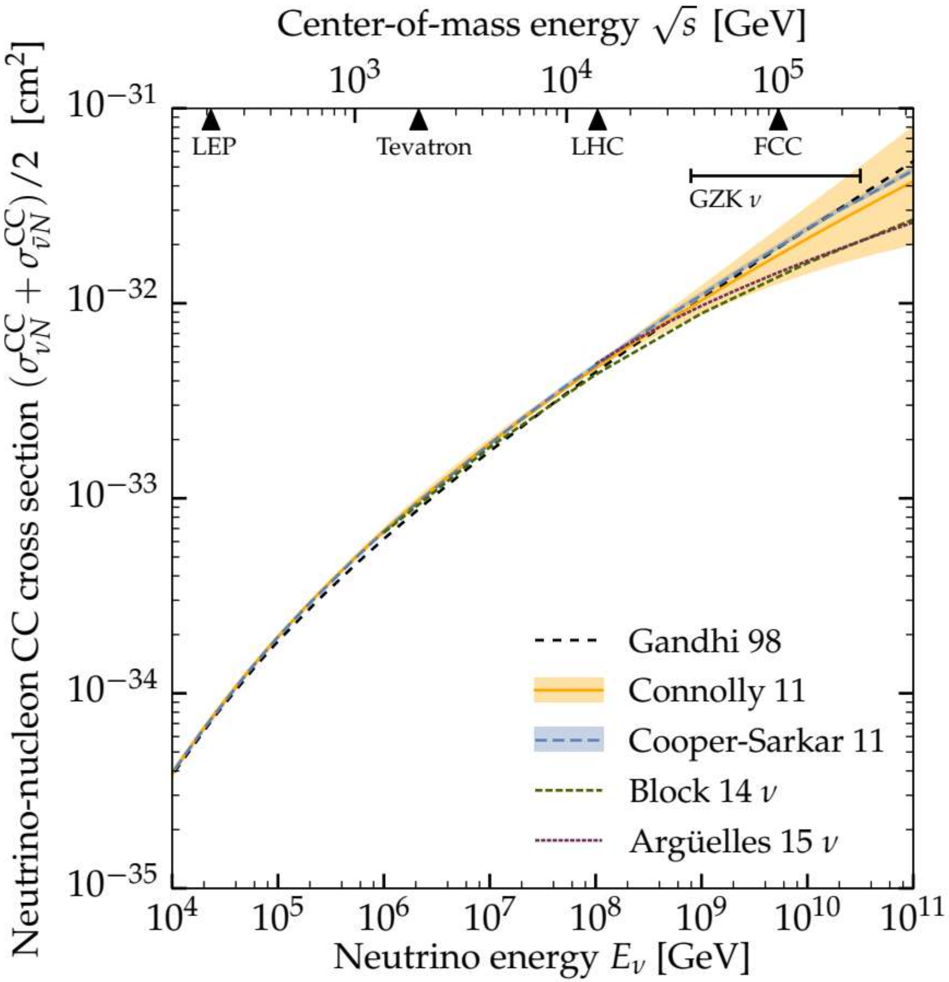


+

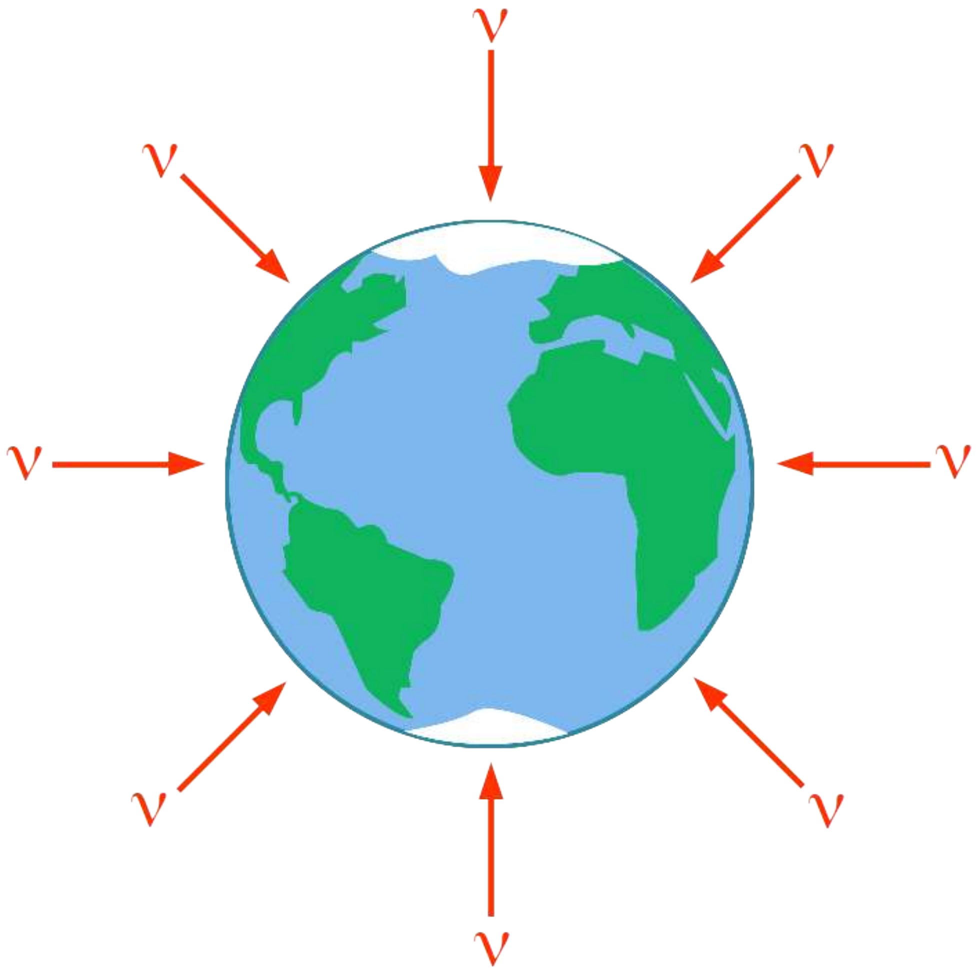
PDFs



=

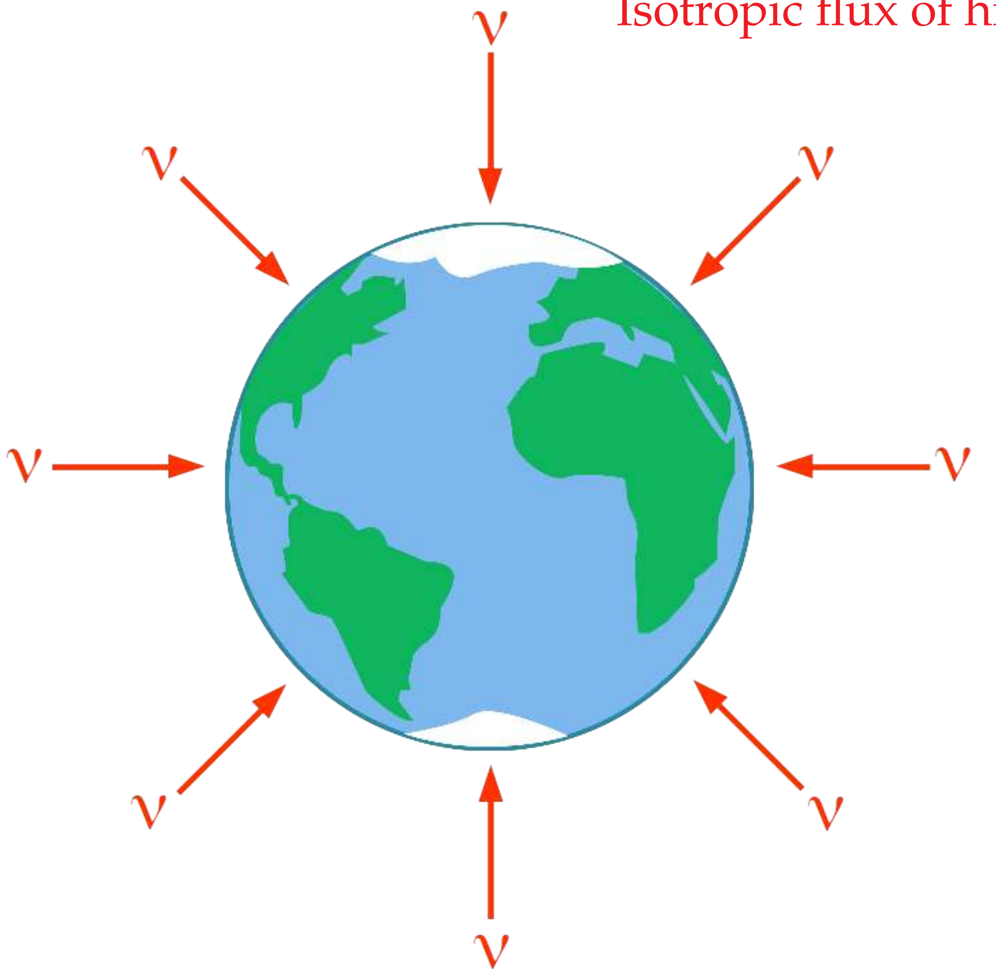


Neutrino, interrupted



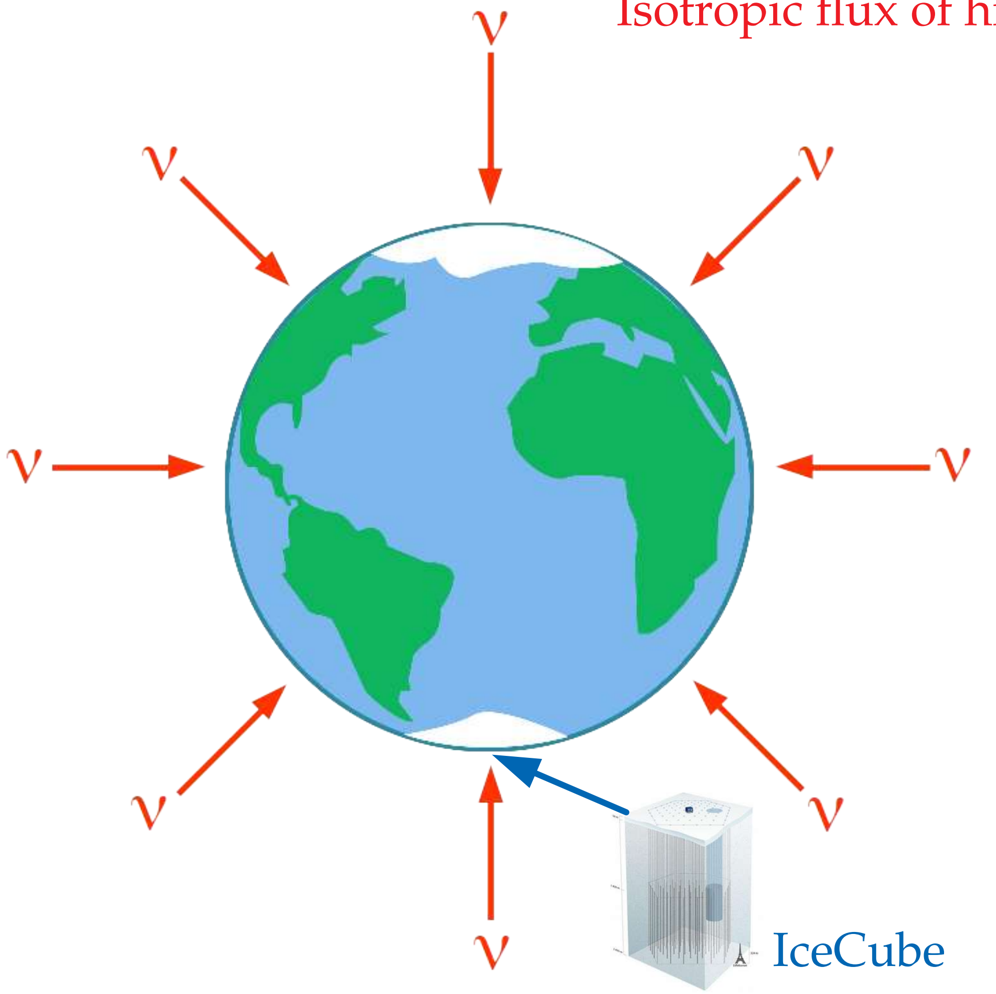
Neutrino, interrupted

Isotropic flux of high-energy neutrinos

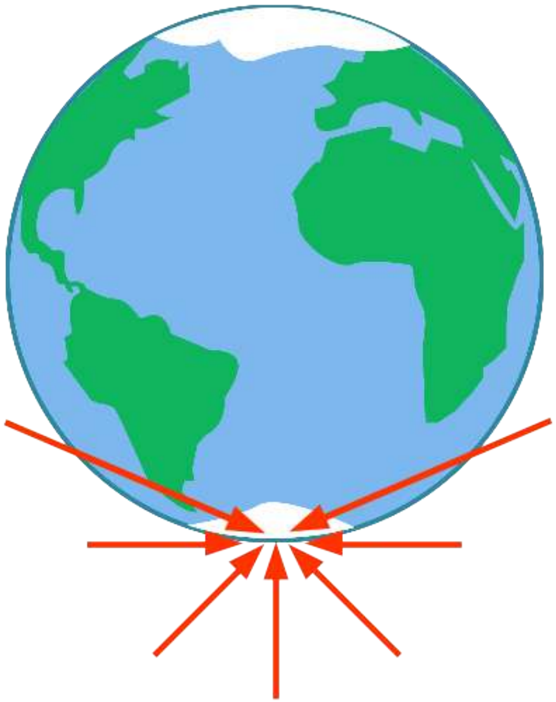


Neutrino, interrupted

Isotropic flux of high-energy neutrinos

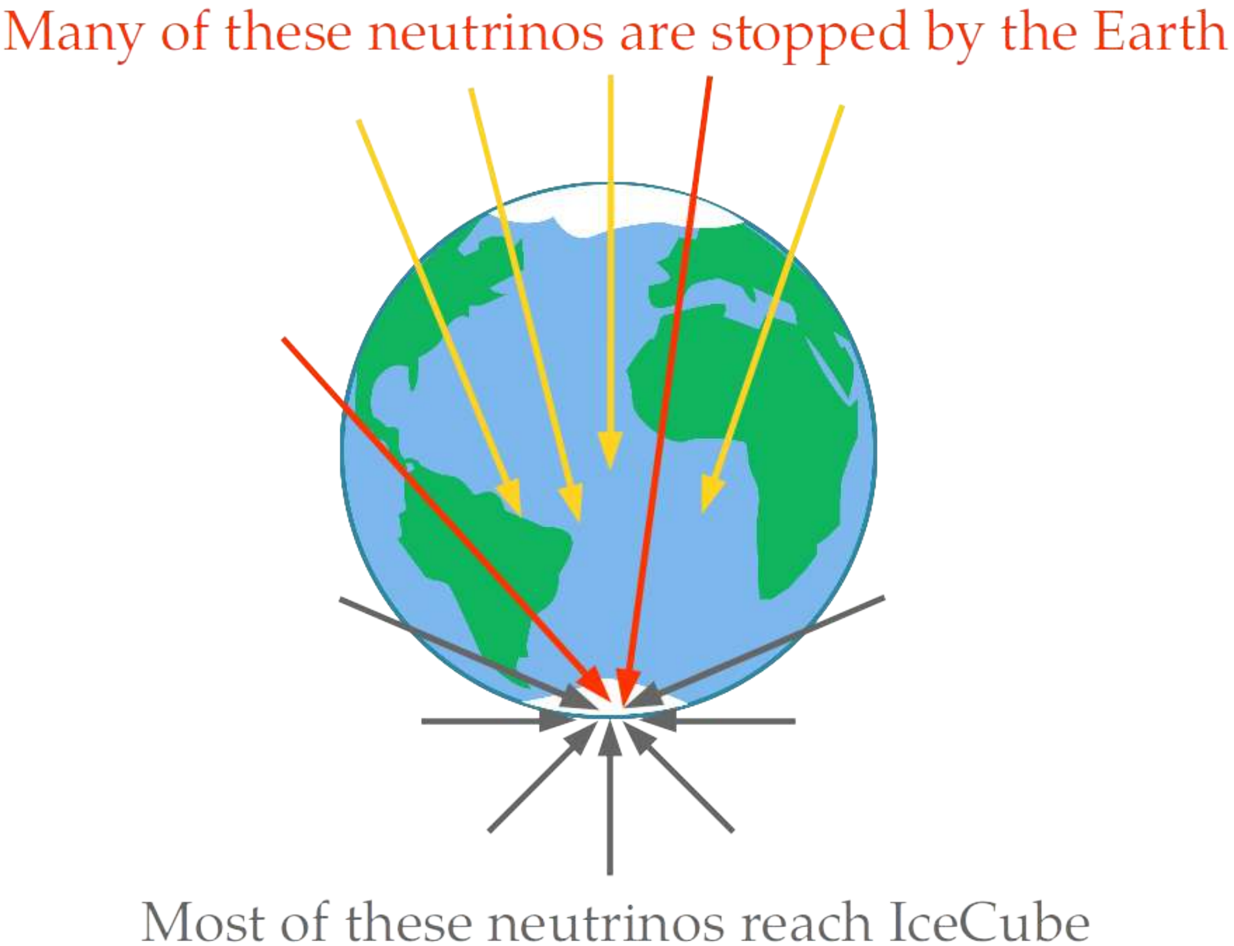


Neutrino, interrupted



Most of these neutrinos reach IceCube

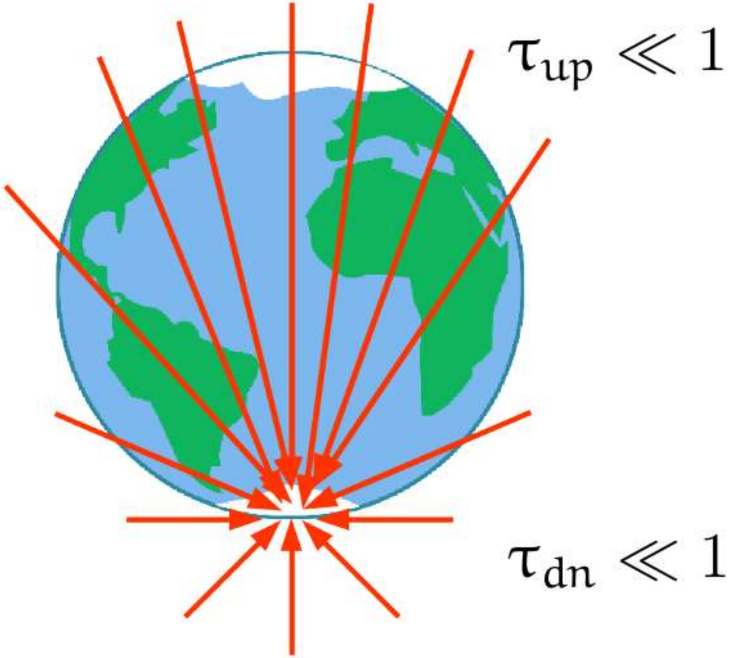
Neutrino, interrupted



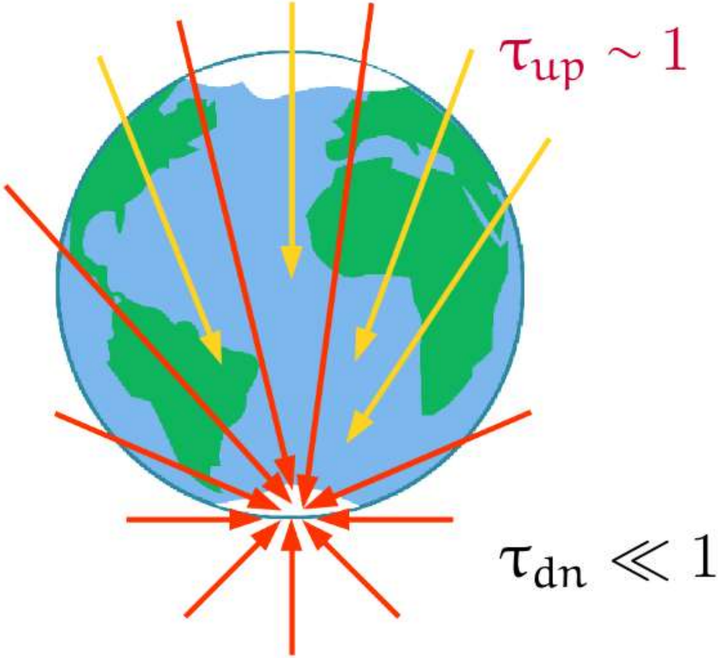
Measuring the high-energy cross section

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

Below ~ 10 TeV: Earth is transparent



Above ~ 10 TeV: Earth is opaque



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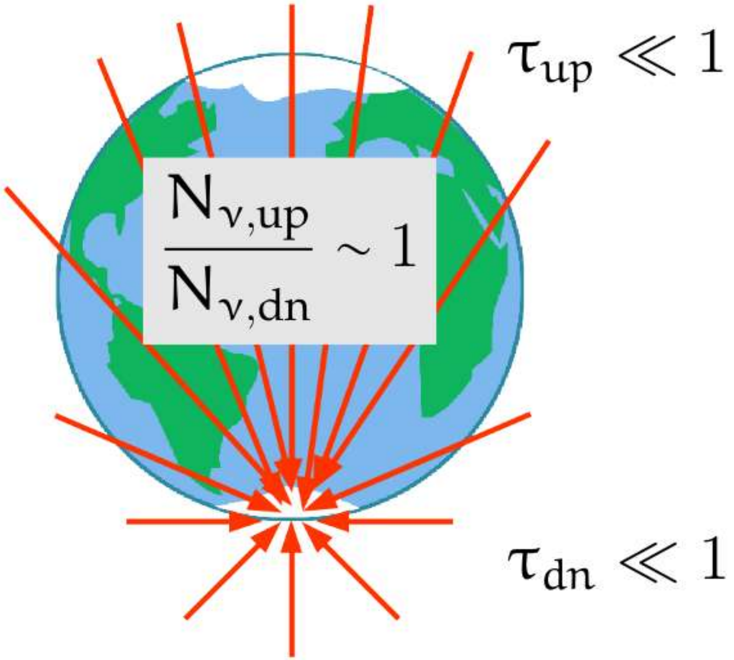

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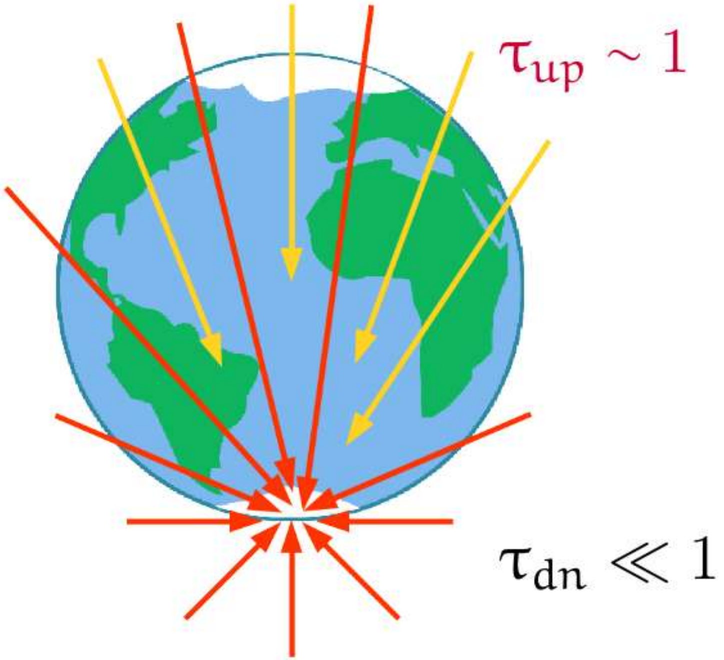

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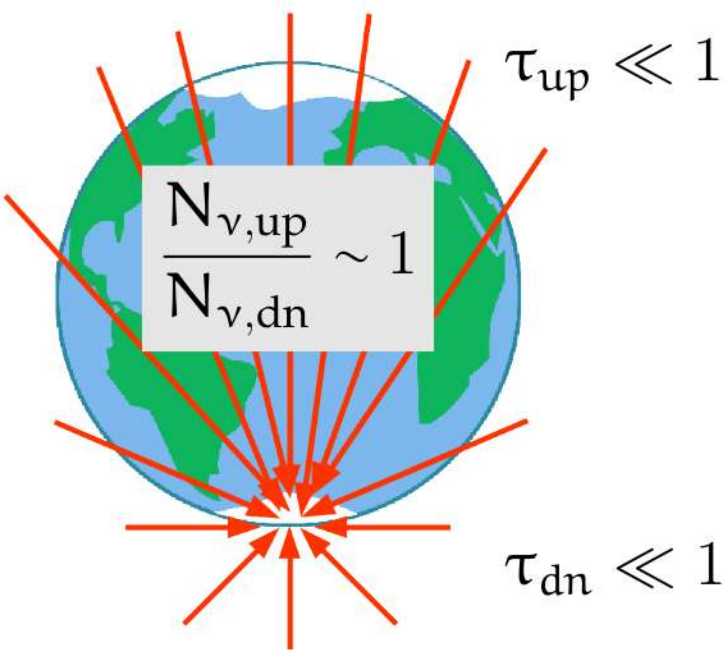

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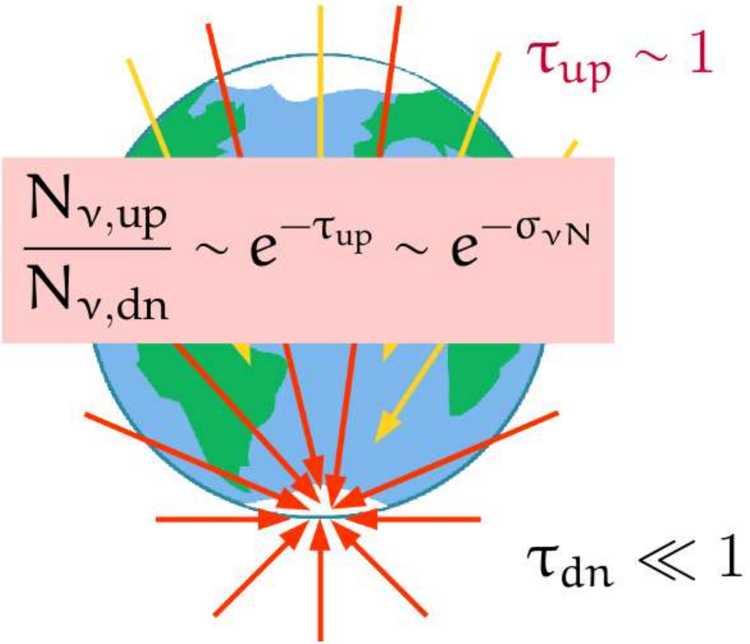
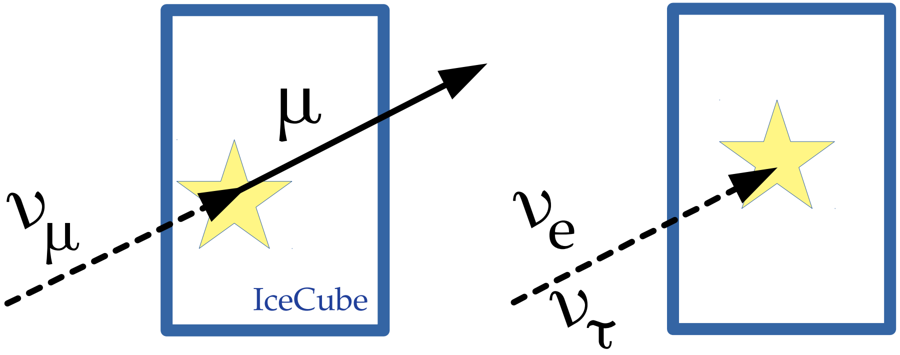


Contained *vs.* uncontained νN interactions

Contained events



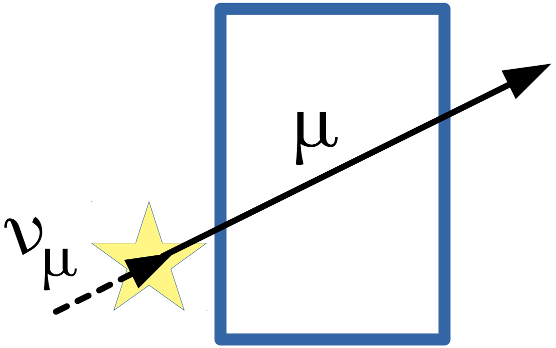
Starting track Shower

Pro: Clean determination of E_ν

Con: Few events (<100)

Ref.: MB & A. Connolly, 1711.11043

Uncontained events

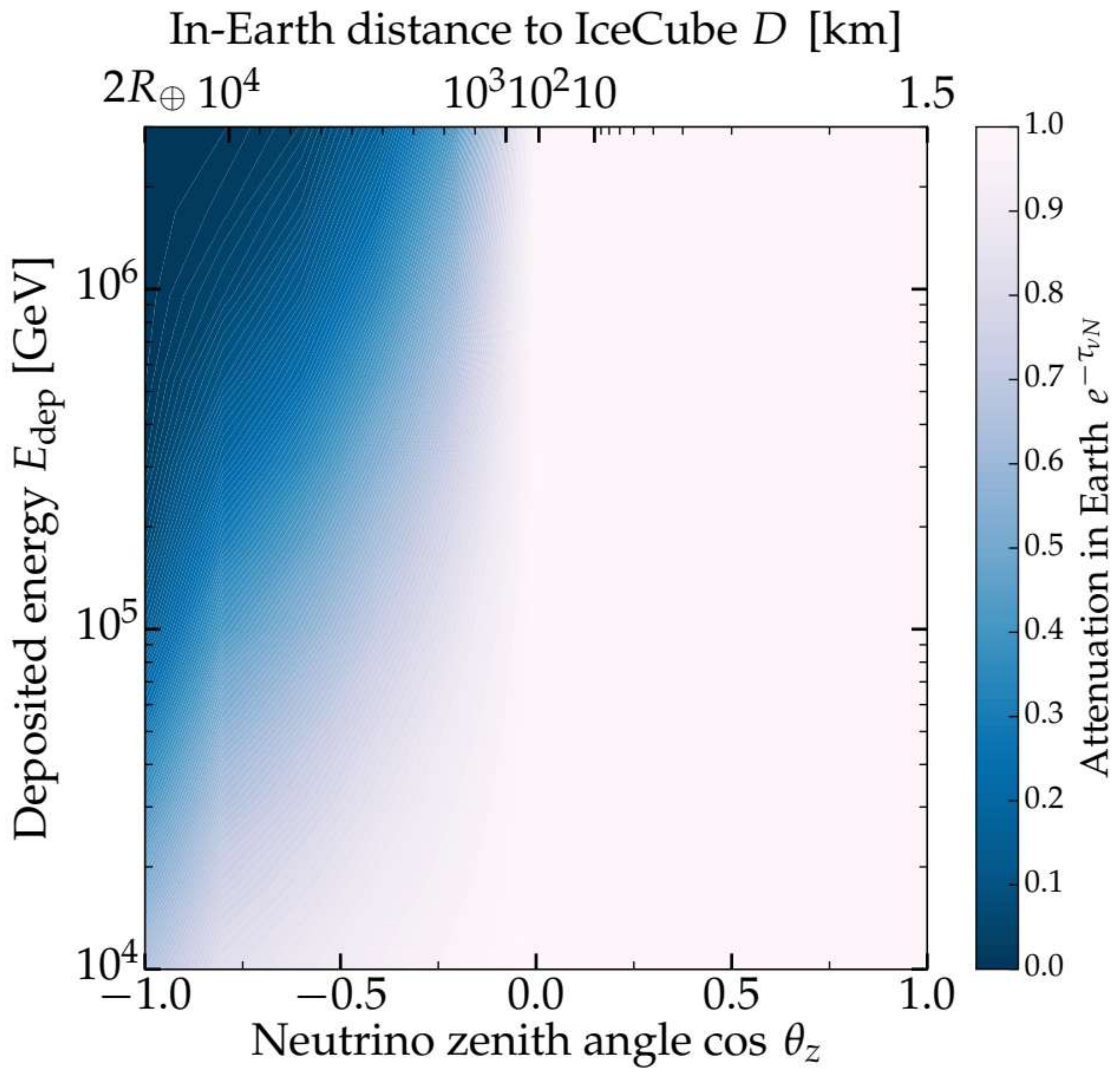


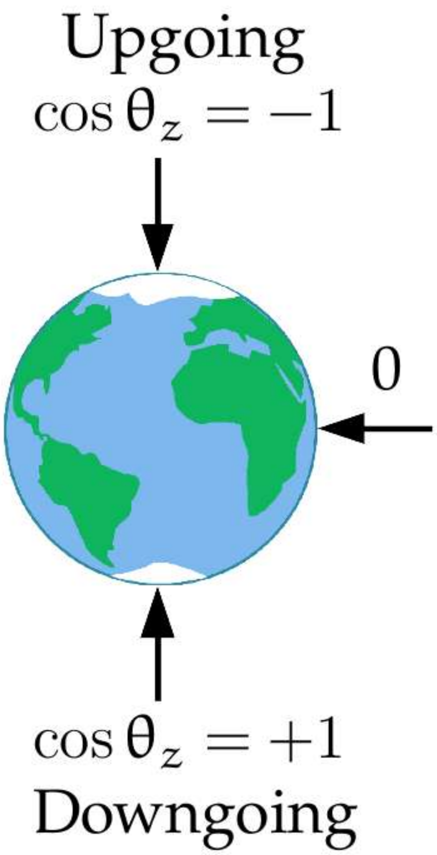
Through-going muon

Pro: Lots of events (~10k used)

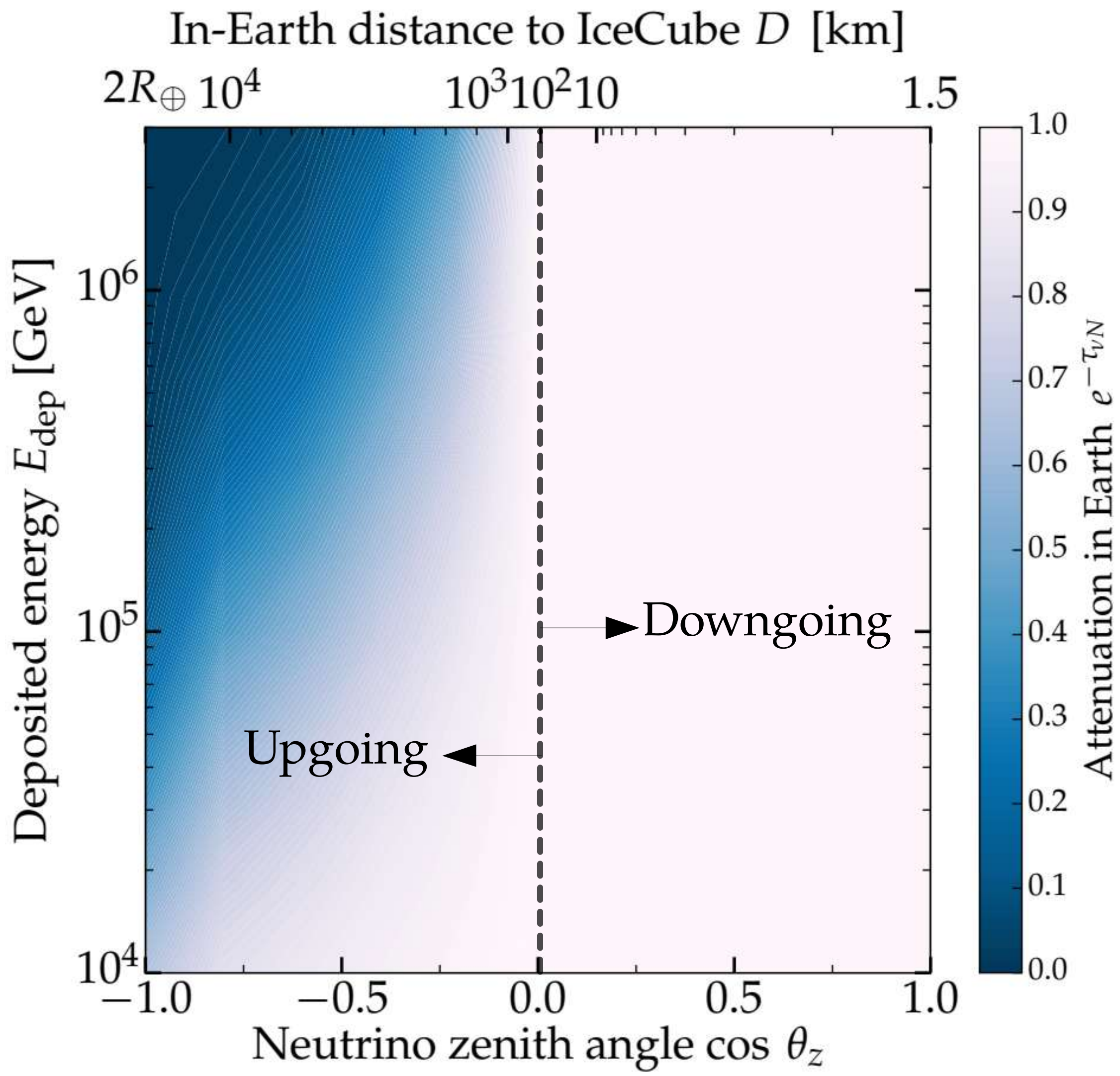
Con: Uncertain estimates of E_ν

Ref.: IceCube, *Nature* 2017, 1711.08119

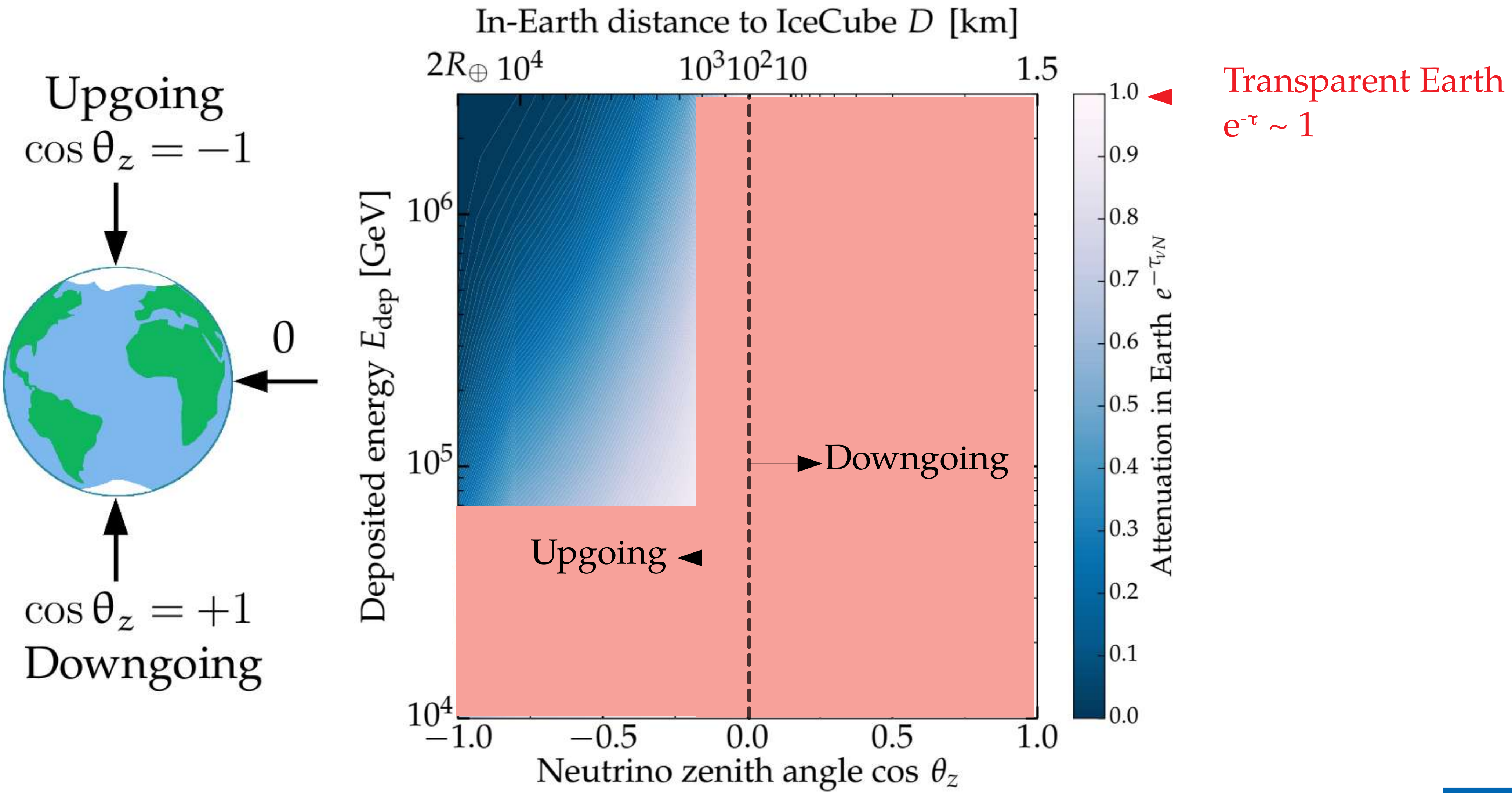

In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4 10^3 10^2 10 1.5
Deposited energy $E_{\rm dep}$ [GeV]
10^6
10^5
10^4
−1.0 −0.5 0.0 0.5 1.0
Neutrino zenith angle cos θ_z
Attenuation in Earth $e^{-\tau_{\nu N}}$
1.0 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0.0

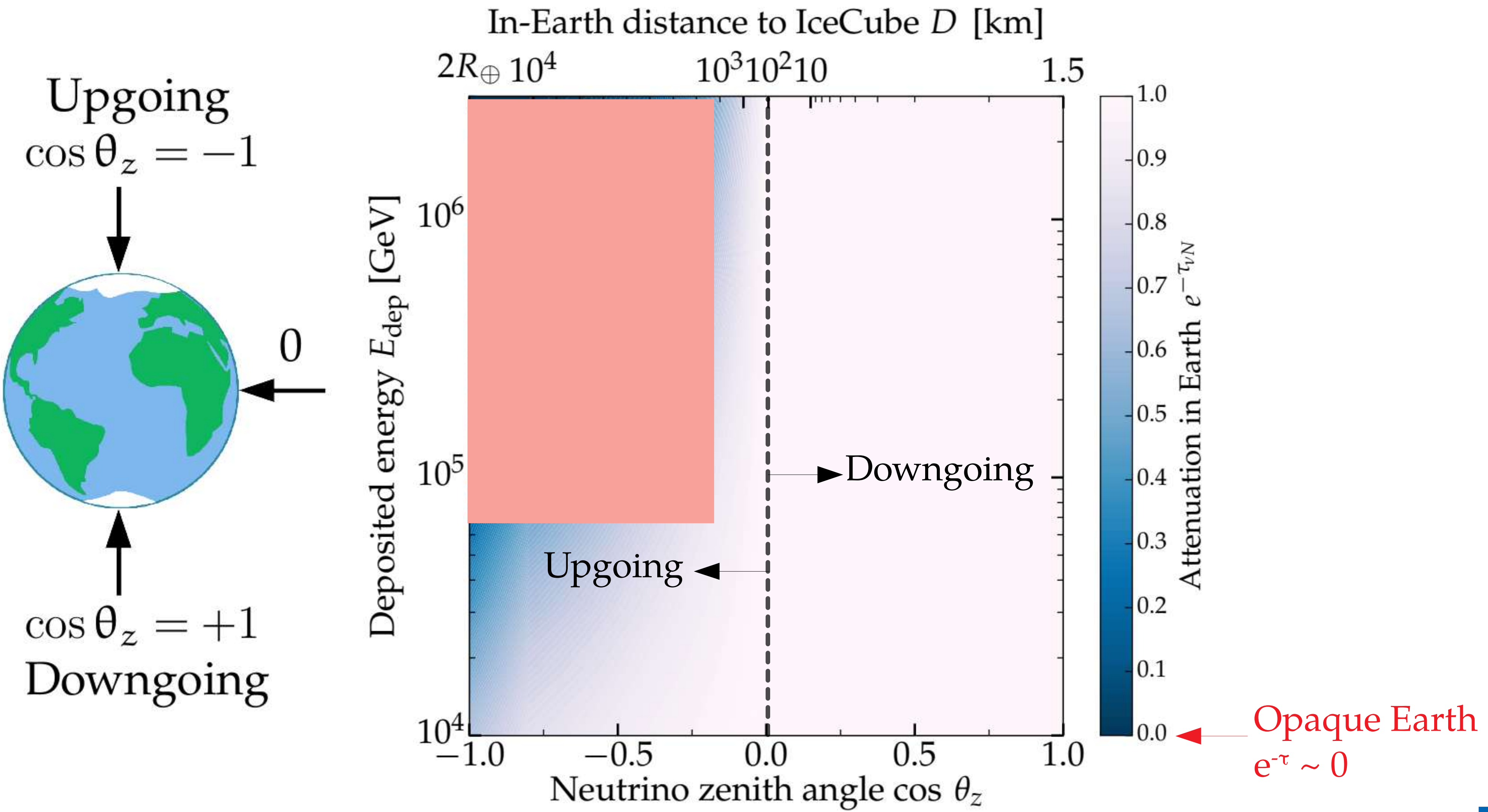


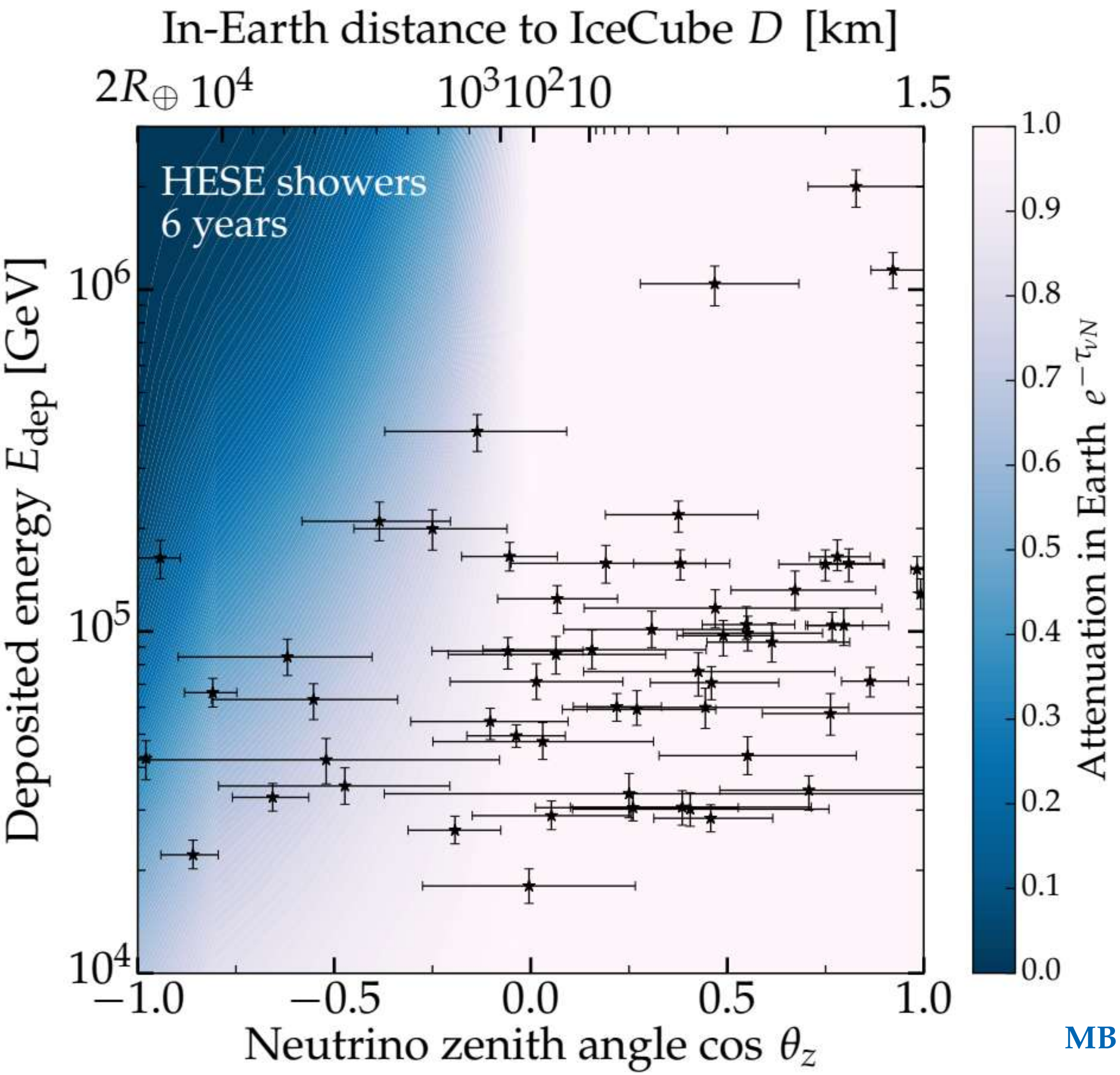
Upgoing
$\cos\theta_z = -1$
0
$\cos\theta_z = +1$
Downgoing



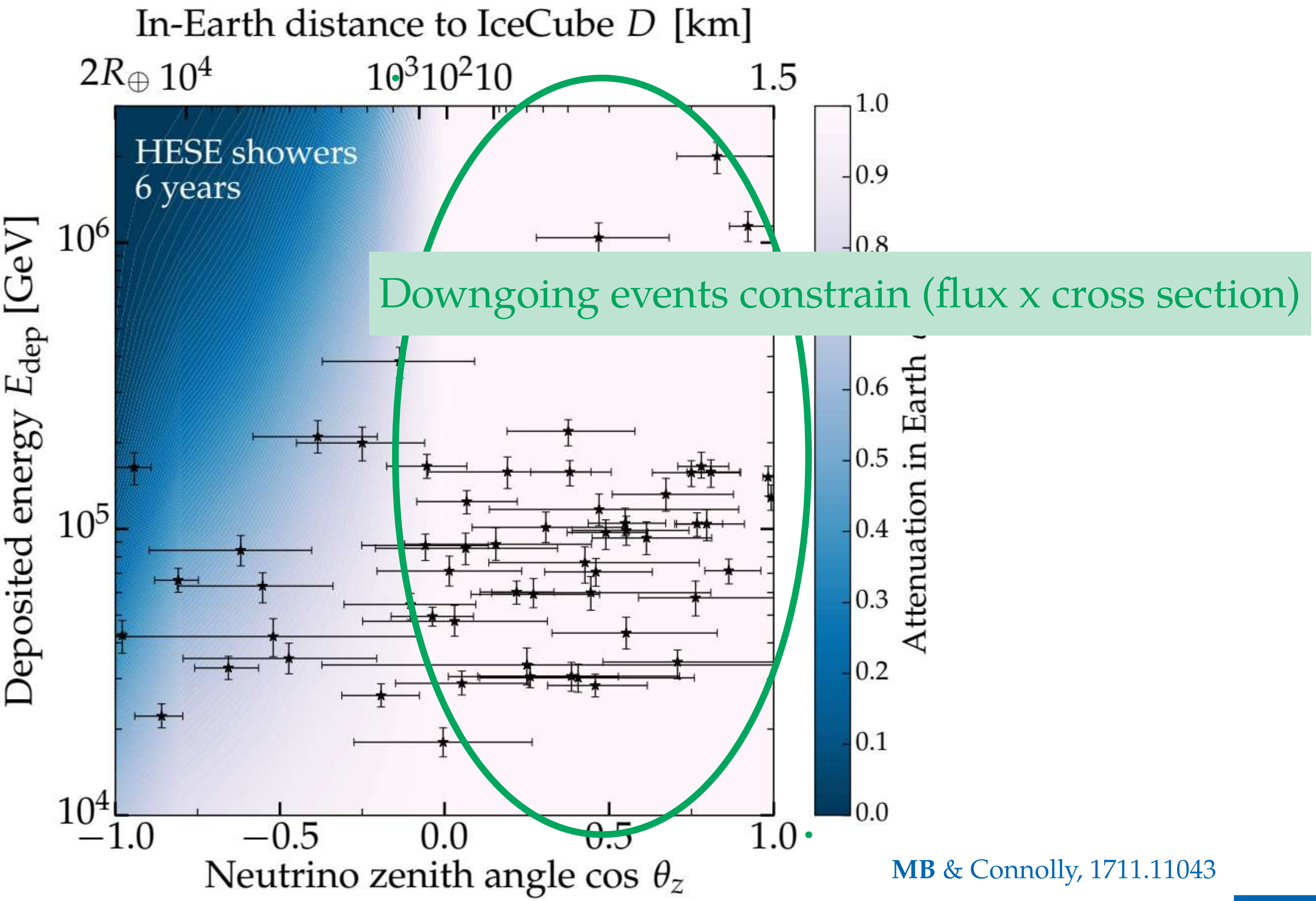
In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4
10^3 10^2 10
1.5
Deposited energy $E_{\rm dep}$ [GeV]
10^6
10^5
10^4
Downgoing
Upgoing
−1.0
−0.5
0.0
0.5
1.0
Neutrino zenith angle $\cos\theta_z$
Attenuation in Earth $e^{-\tau_{\nu N}}$
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0


Upgoing
cos 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 Edep [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
$e^{-\tau} \sim 0$



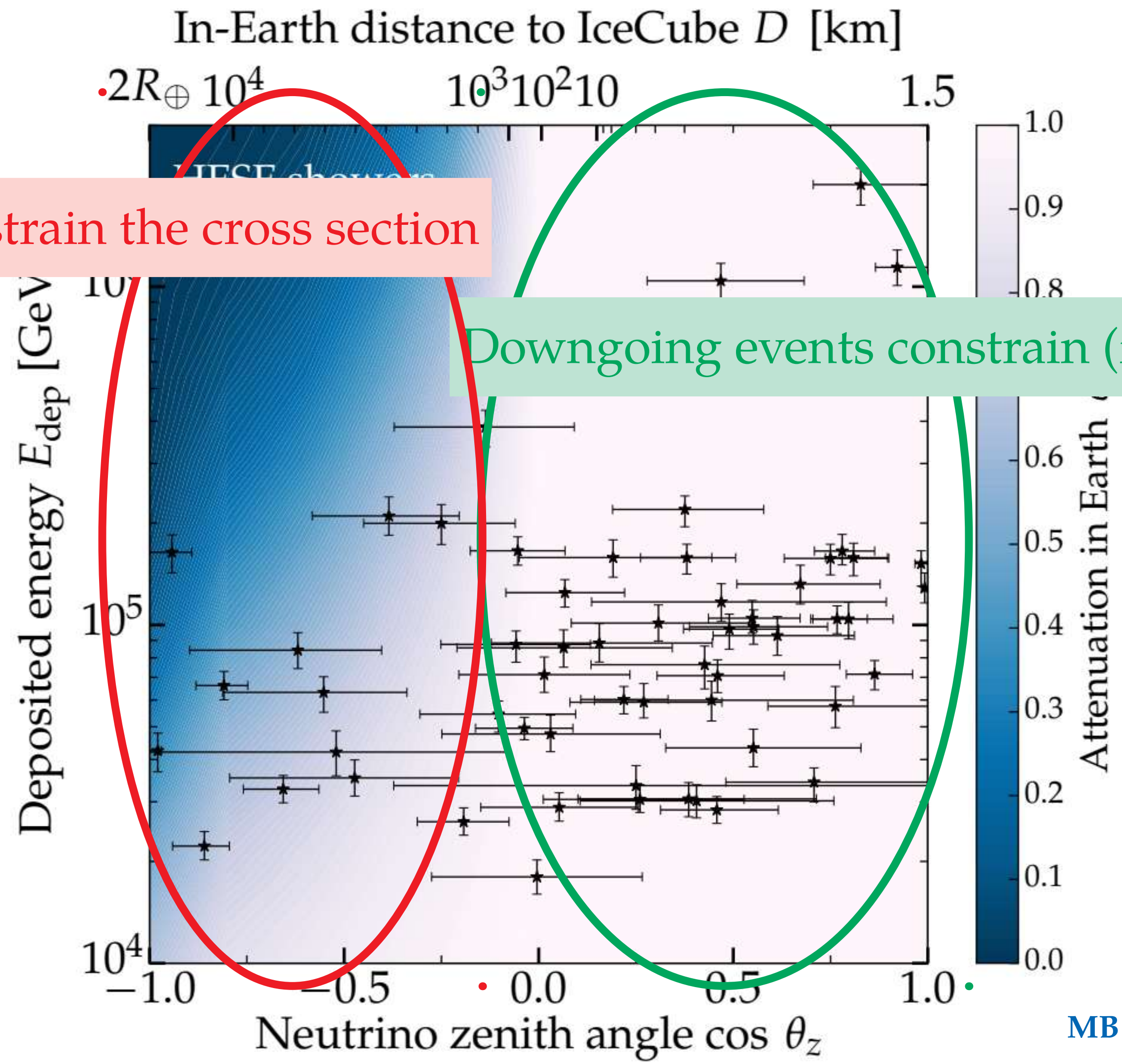
MB & Connolly, 1711.11043



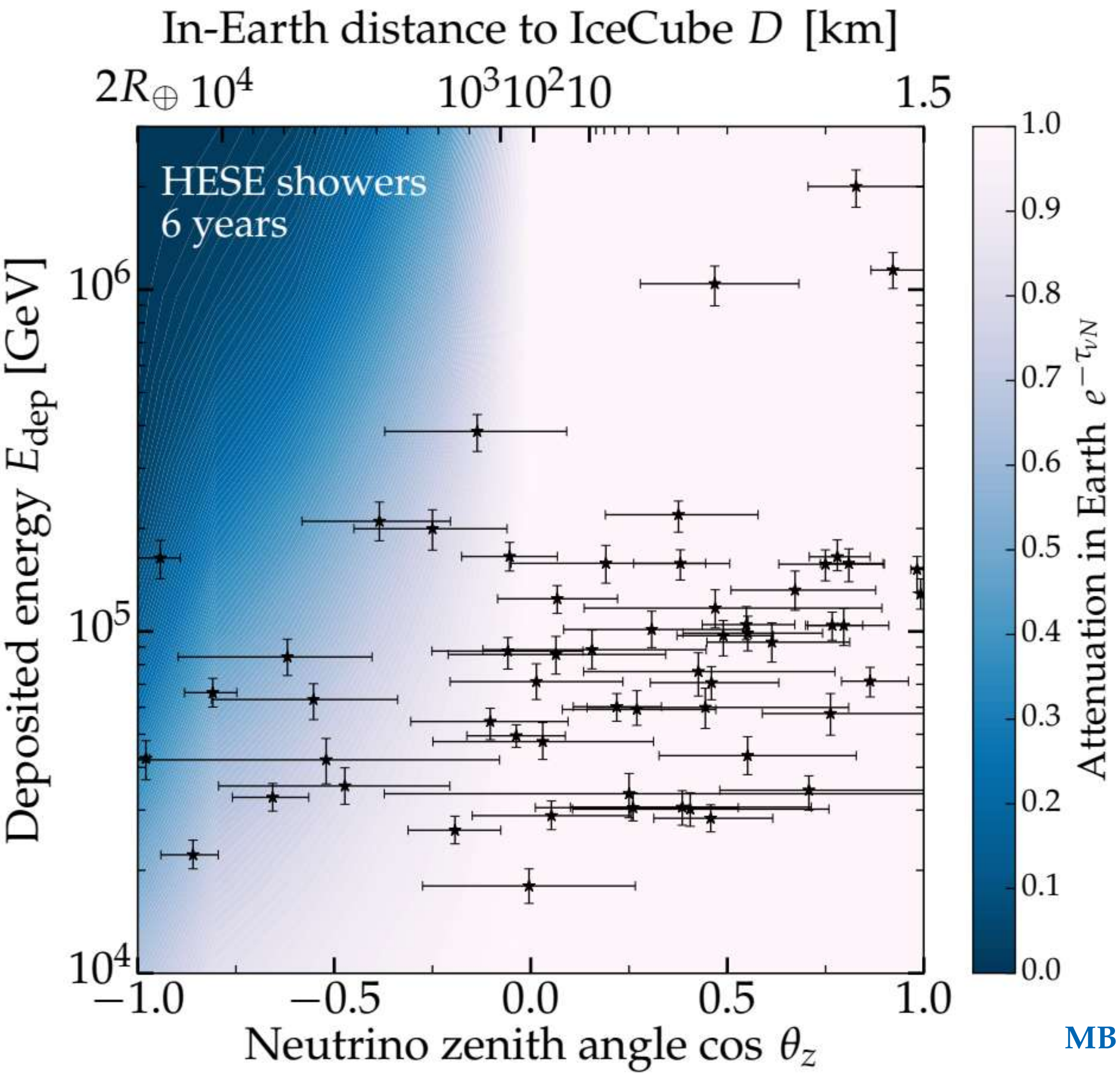
MB & Connolly, 1711.11043

Upgoing events constrain the cross section

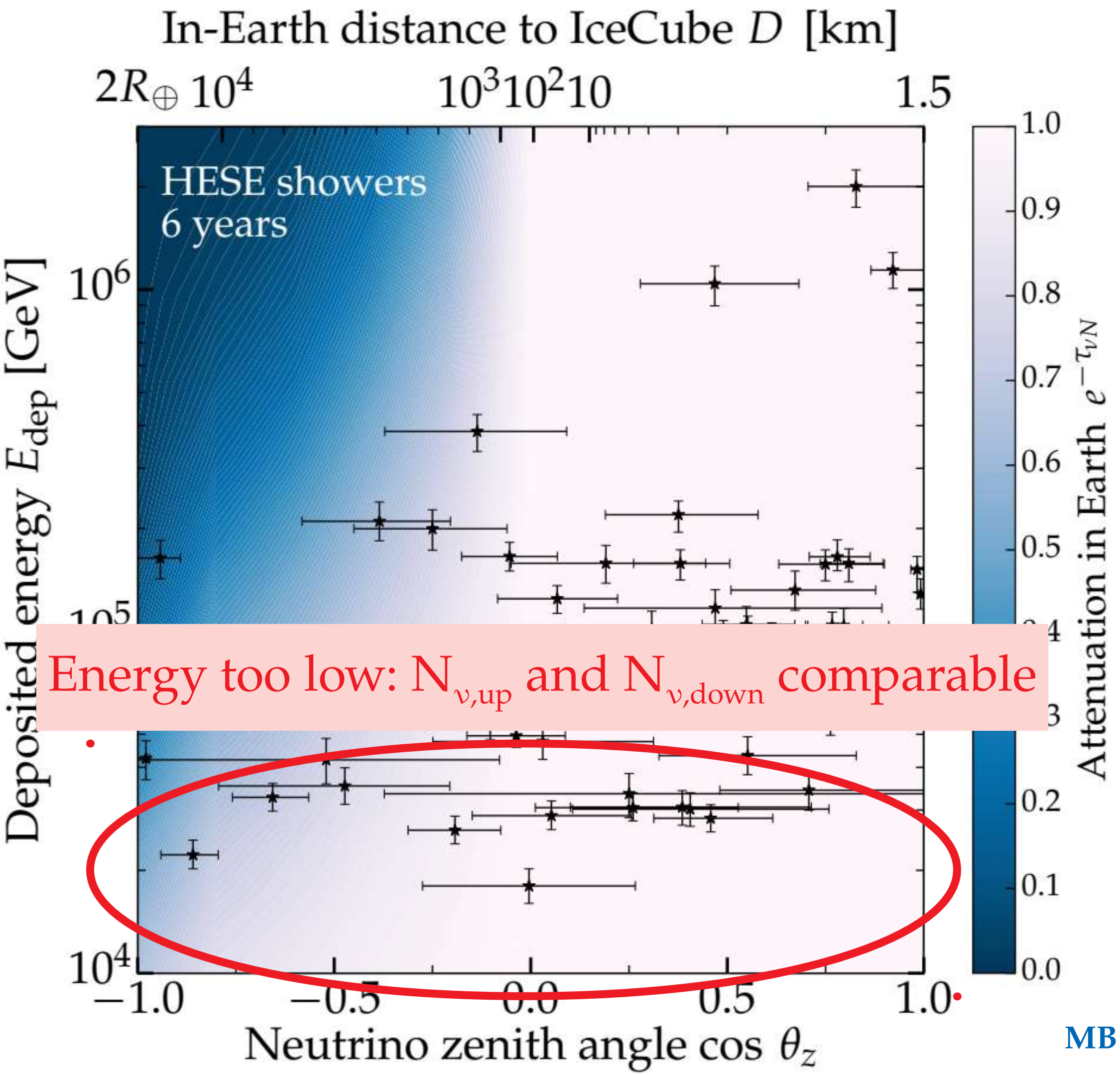
Downgoing events constrain (flux x cross section)



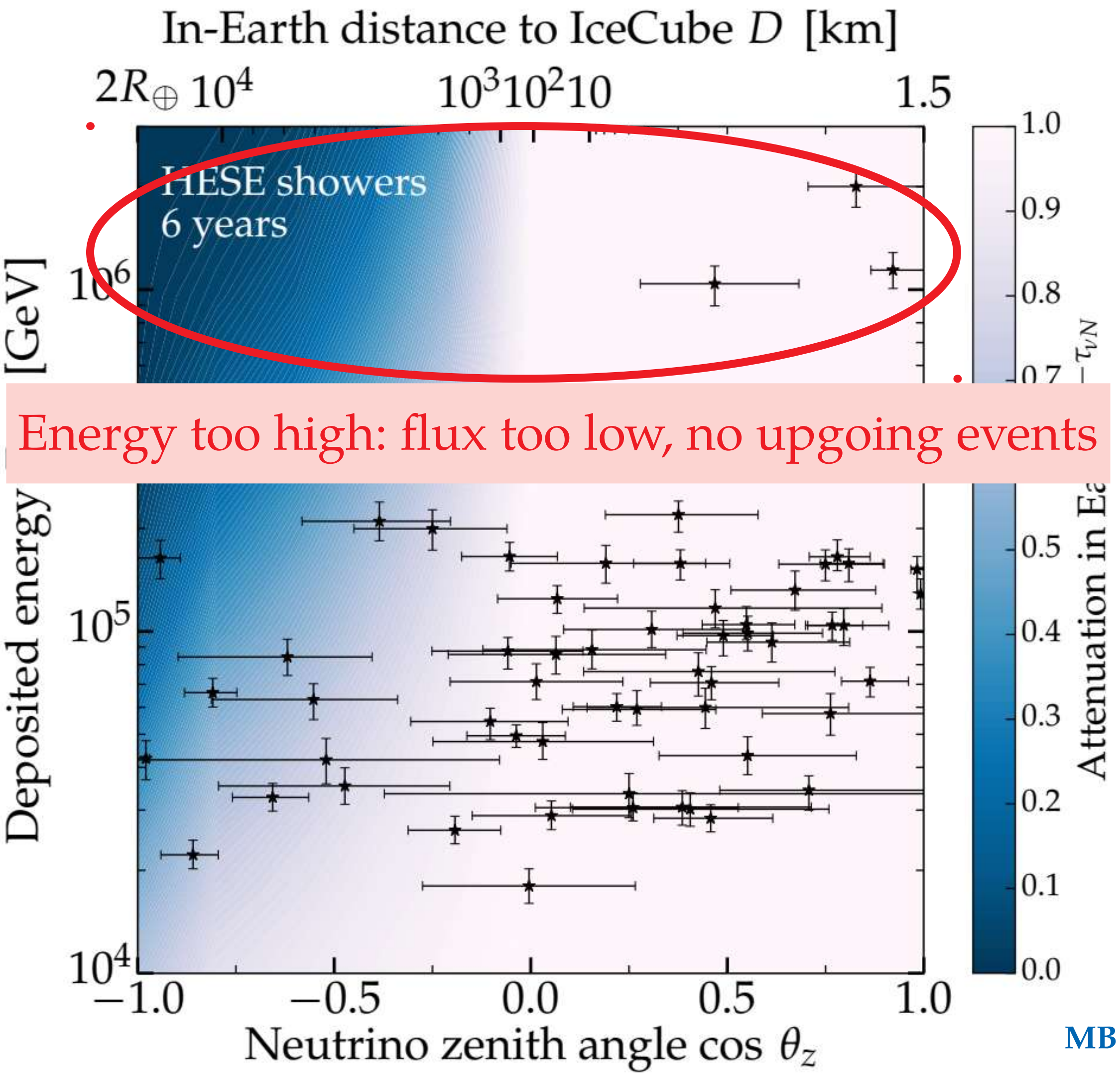
MB & Connolly, 1711.11043



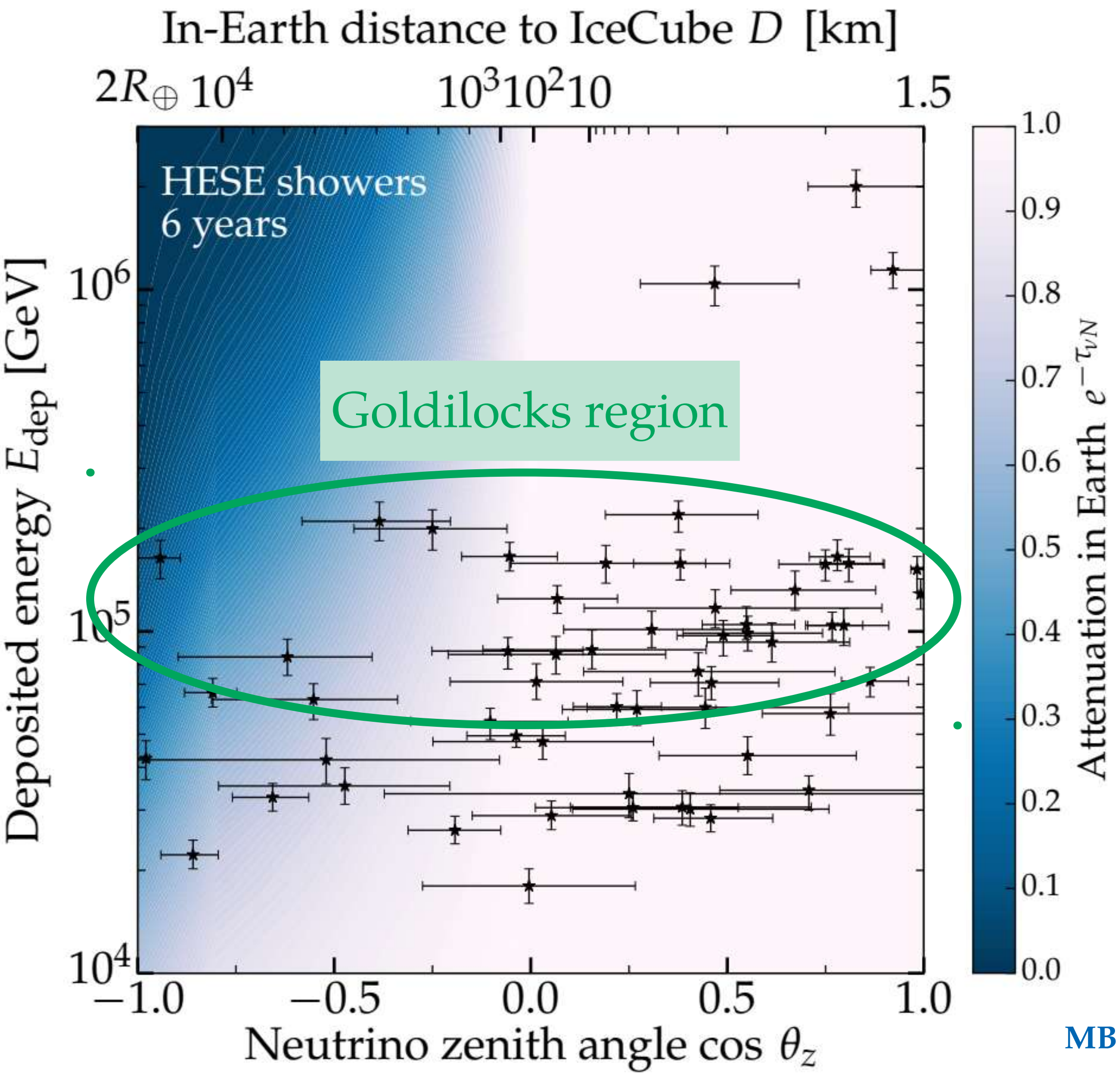
MB & Connolly, 1711.11043



MB & Connolly, 1711.11043

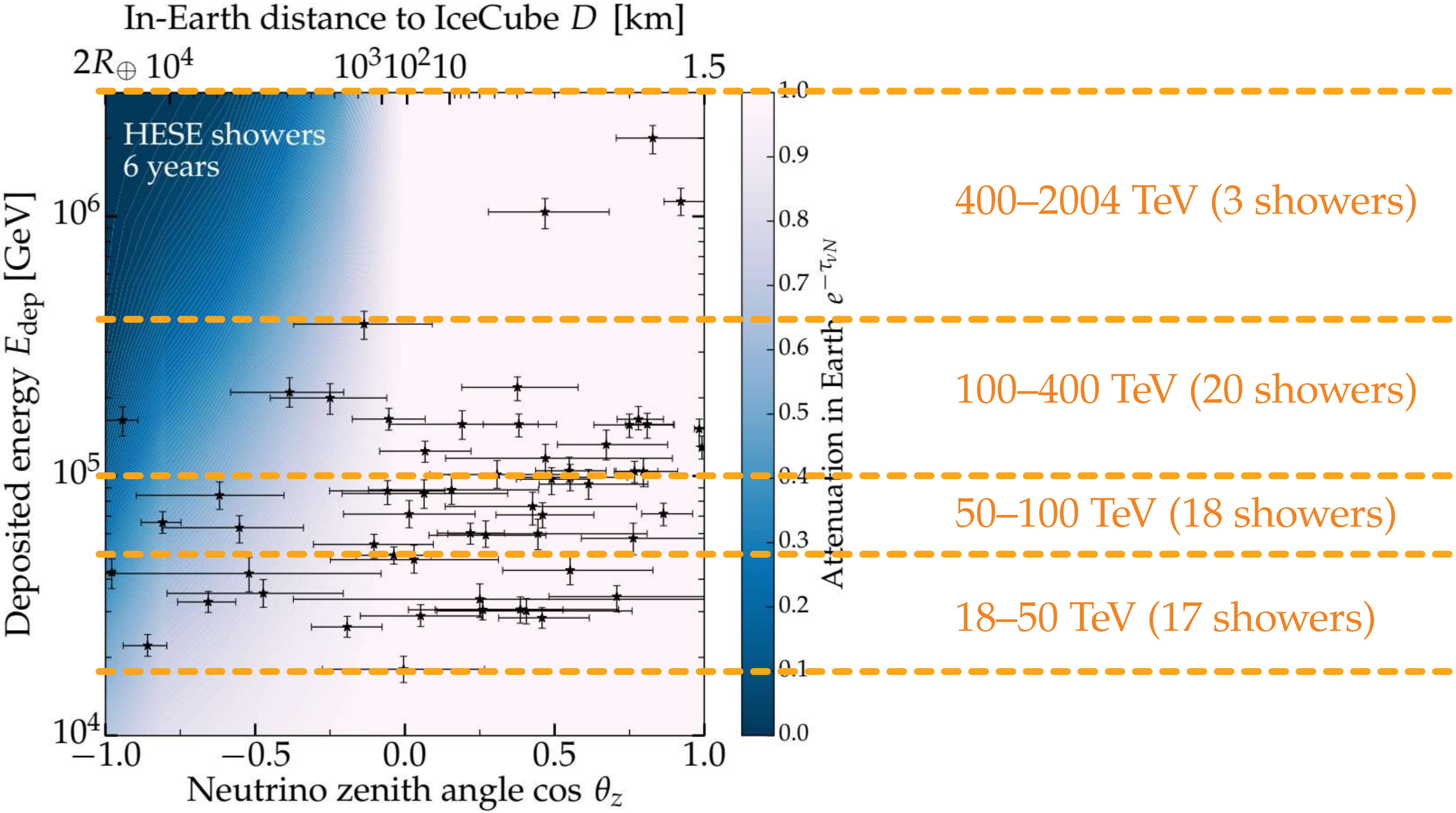


MB & Connolly, 1711.11043



MB & Connolly, 1711.11043

Bin-by-bin analysis



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)

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- … and compare it to the observed HESE spectrum via a likelihood
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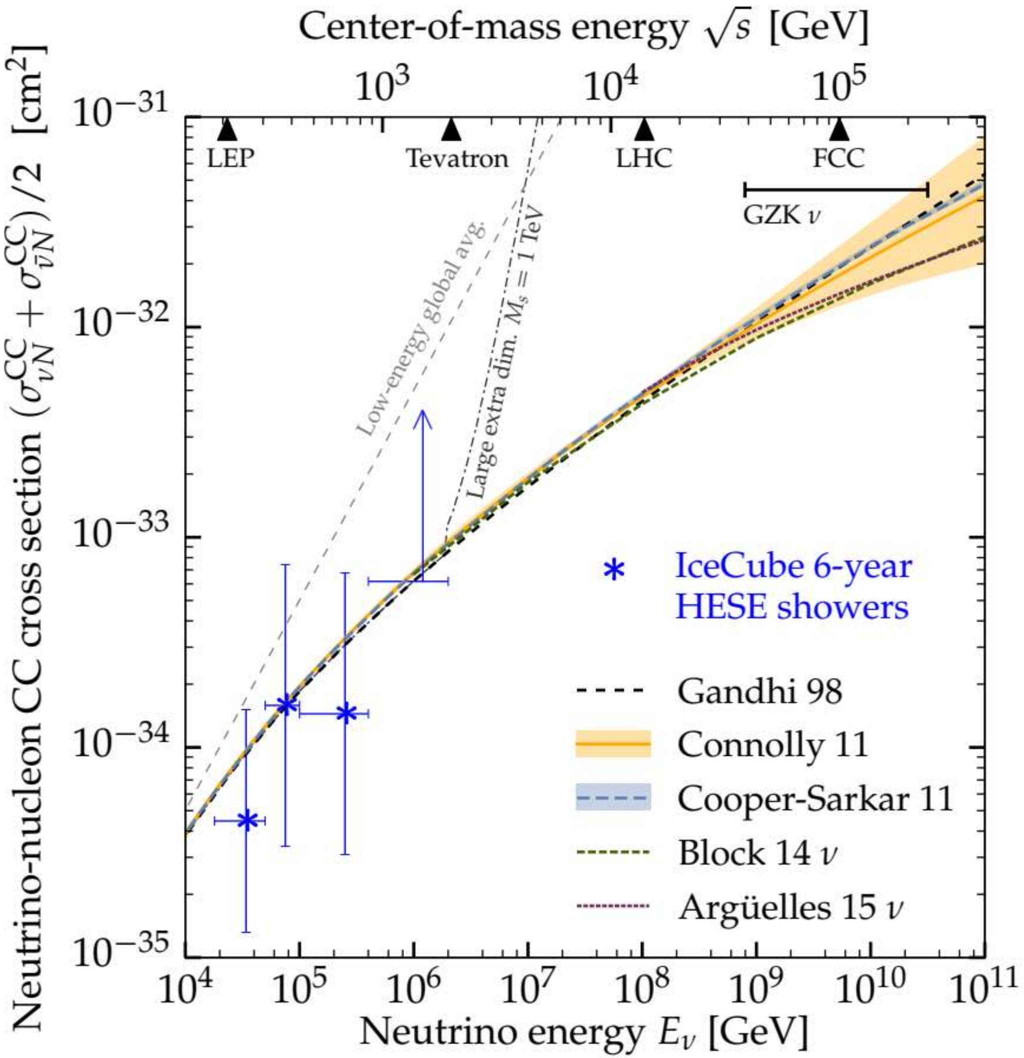
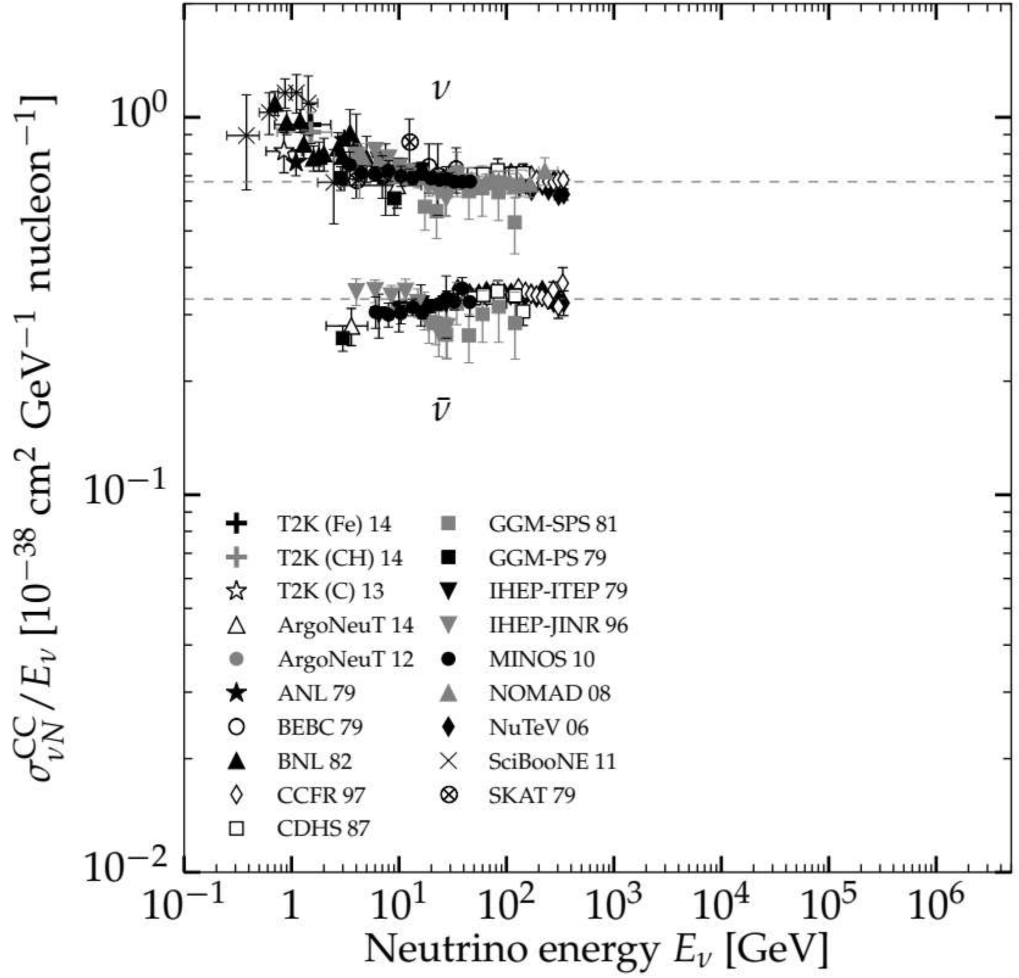
Our result



MB & Connolly, 1711.11043

Extending cross section measurements



MB & Connolly, 1711.11043

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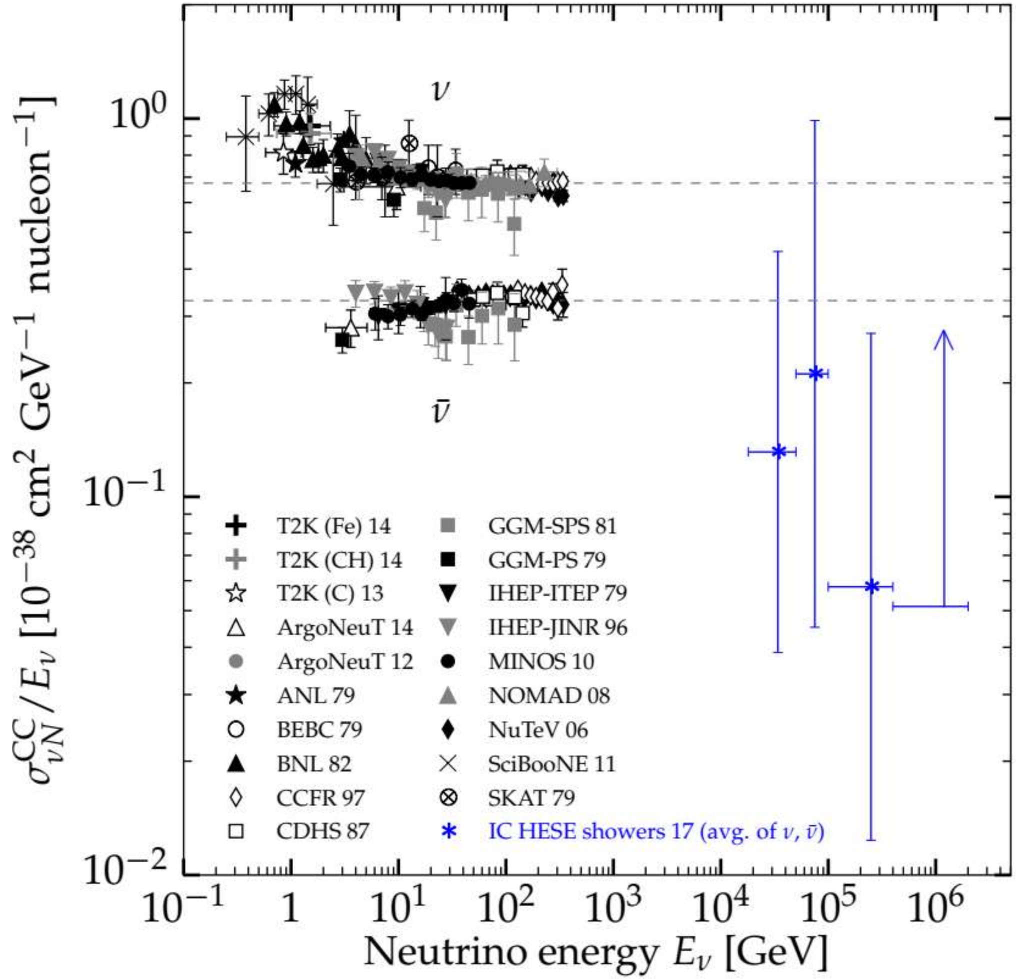

MB & Connolly, 1711.11043

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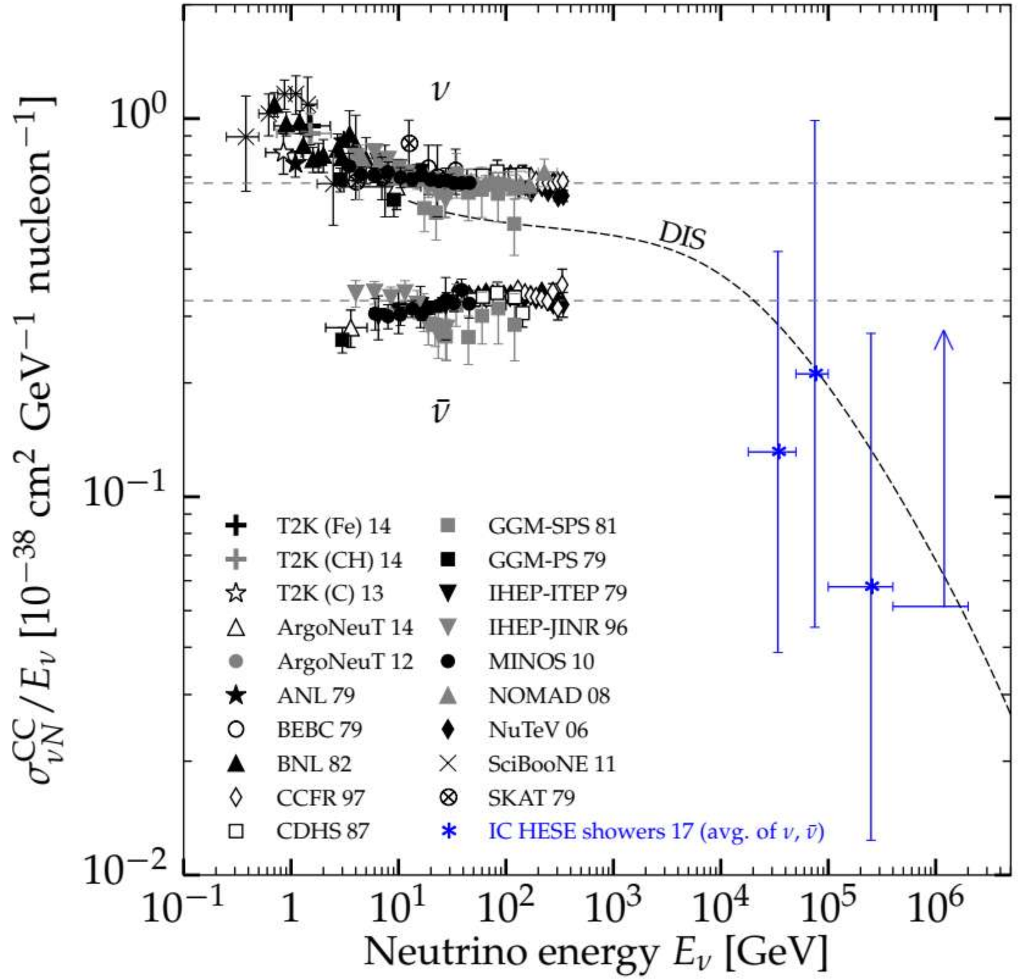
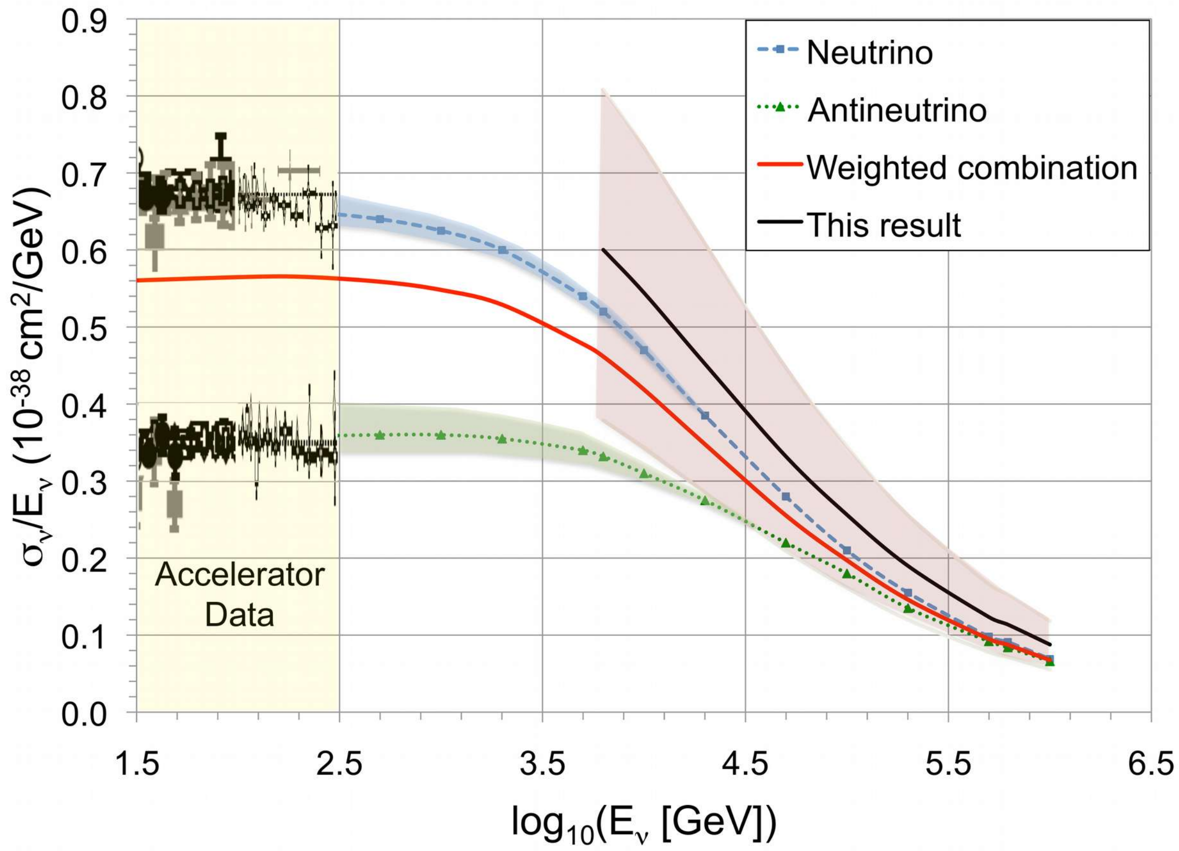


MB & Connolly, 1711.11043

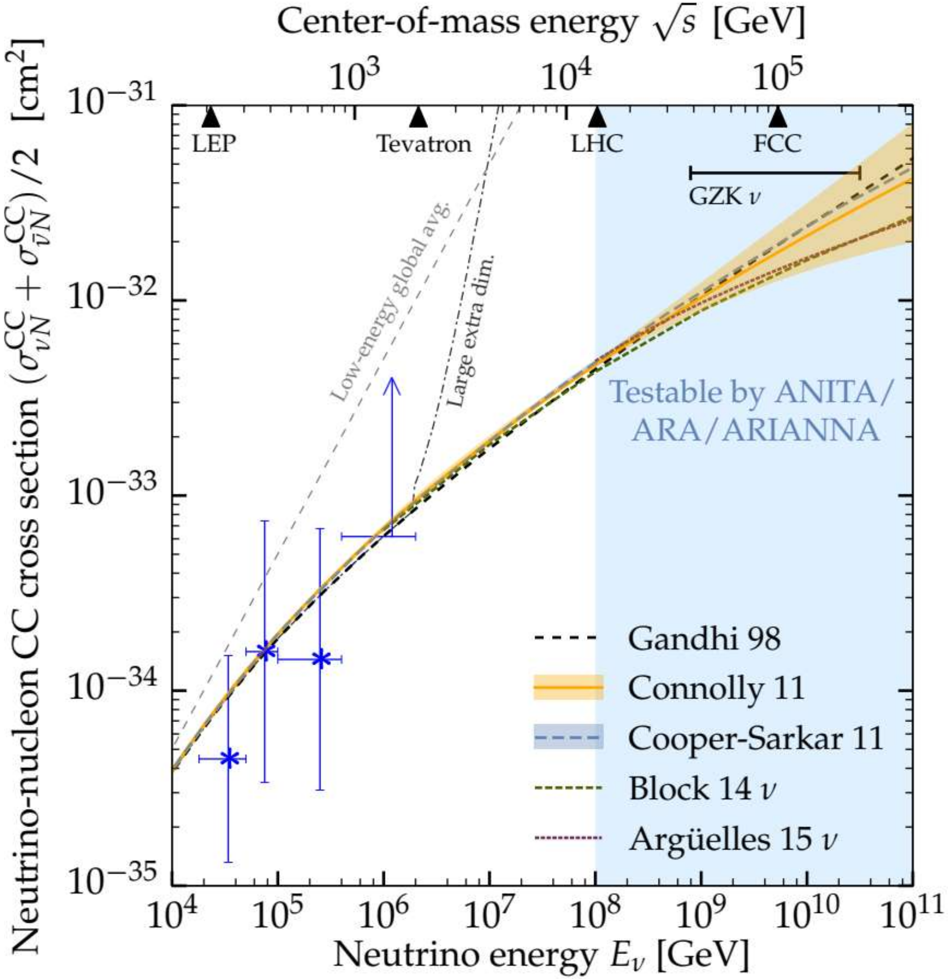
Using through-going muons instead

- 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



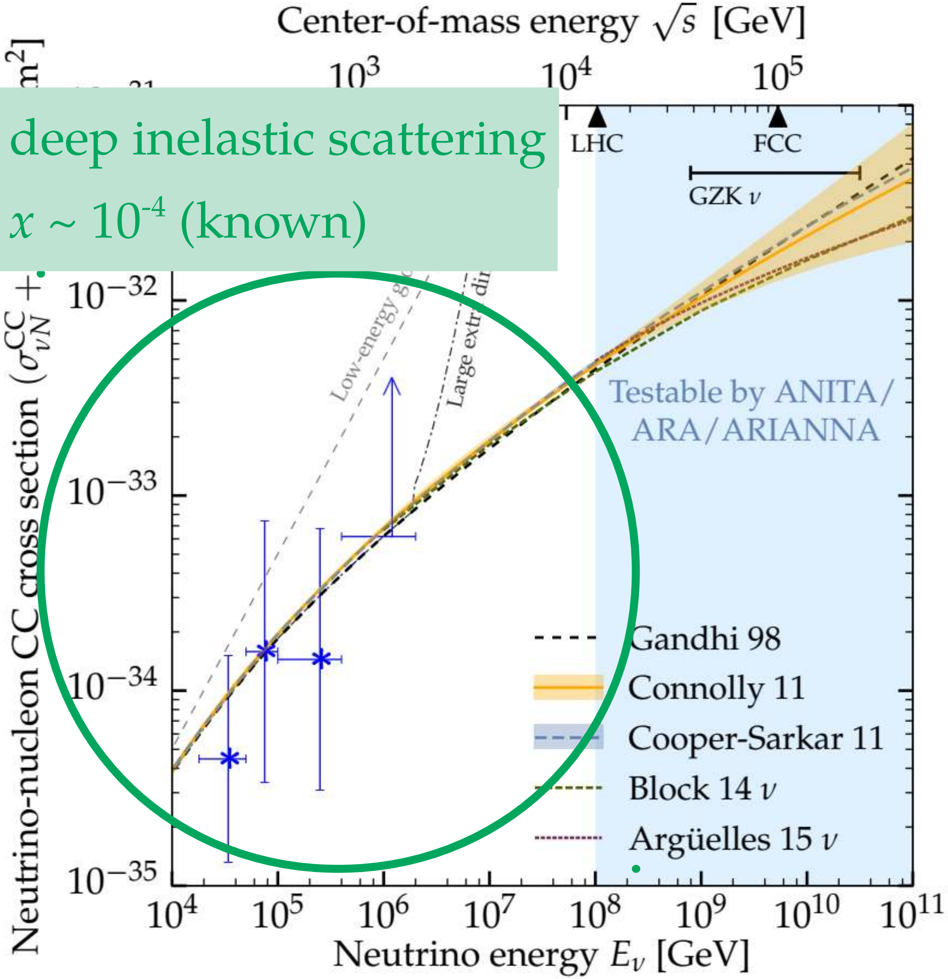
IceCube, *Nature* 2017

Quo vadis: IceCube vs. ANITA / ARA / ARIANNA / ...



Quo vadis: IceCube vs. ANITA / ARA / ARIANNA / …

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



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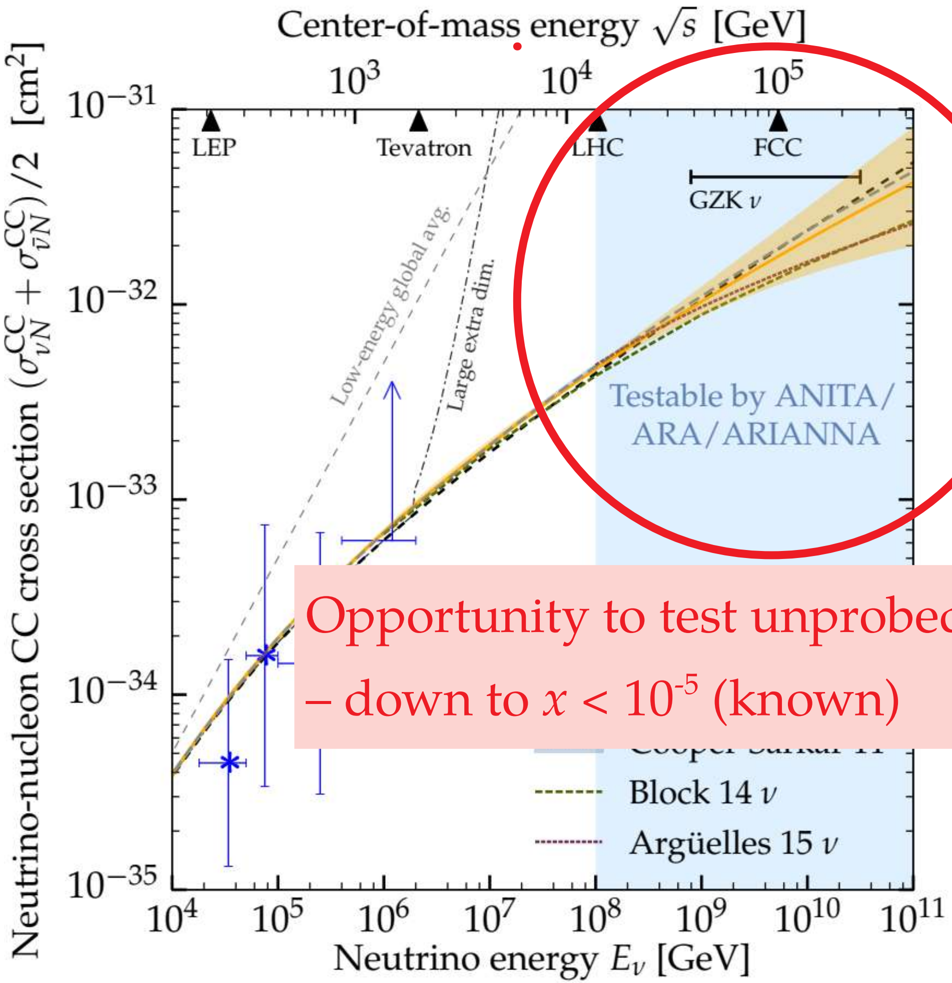

Opportunity to test unprobed nucleon structure – down to $x < 10^{-5}$ (known)

Ultra-long-range flavorful interactions

- The SM *must* be extended
- Simple extension: promote global symmetries of the SM to local symmetries
- Economical option: anomaly-free lepton-number symmetries L_μ-L_τ, L_e-L_μ, L_e-L_τ
- Gauging any of them introduces a new neutral vector boson (Z')
- (Caveat: less economical in the SM with neutrino masses and mixing)
- L_μ-L_τ: studied for ability to generate maximal $\mu\tau$ mixing
- L_e-L_μ, L_e-L_τ: introduce new interaction between electrons and ν_e and ν_μ or ν_τ

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

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Ok, but *why* is this interesting?

- Detectable through effects on neutrino 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
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The power of many (electrons)

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

$$V \sim (g'^2/d)\, e^{-m'd}$$

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

Z′ mass	Interaction range	Number of electrons
10^{-12} eV	Earth radius	10^{51}
10^{-18} eV	1 A.U.	10^{56}
10^{-28} eV	Size of the Milky Way	10^{67}
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Z′ mass

Z′ coupling

Distance to neutrino

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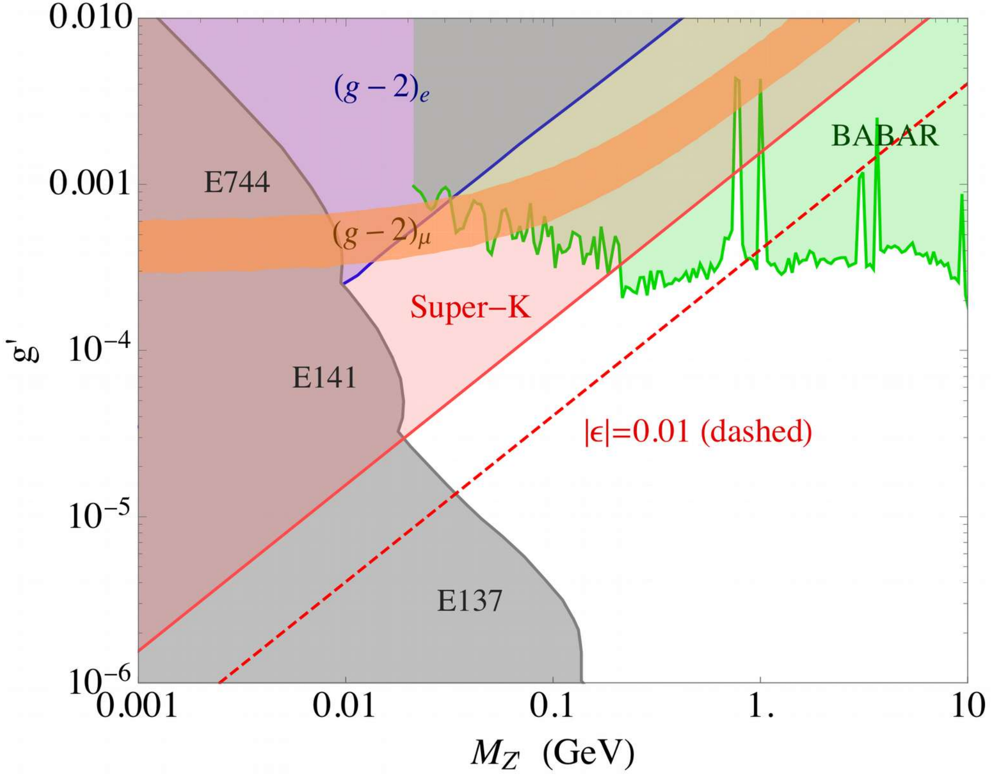
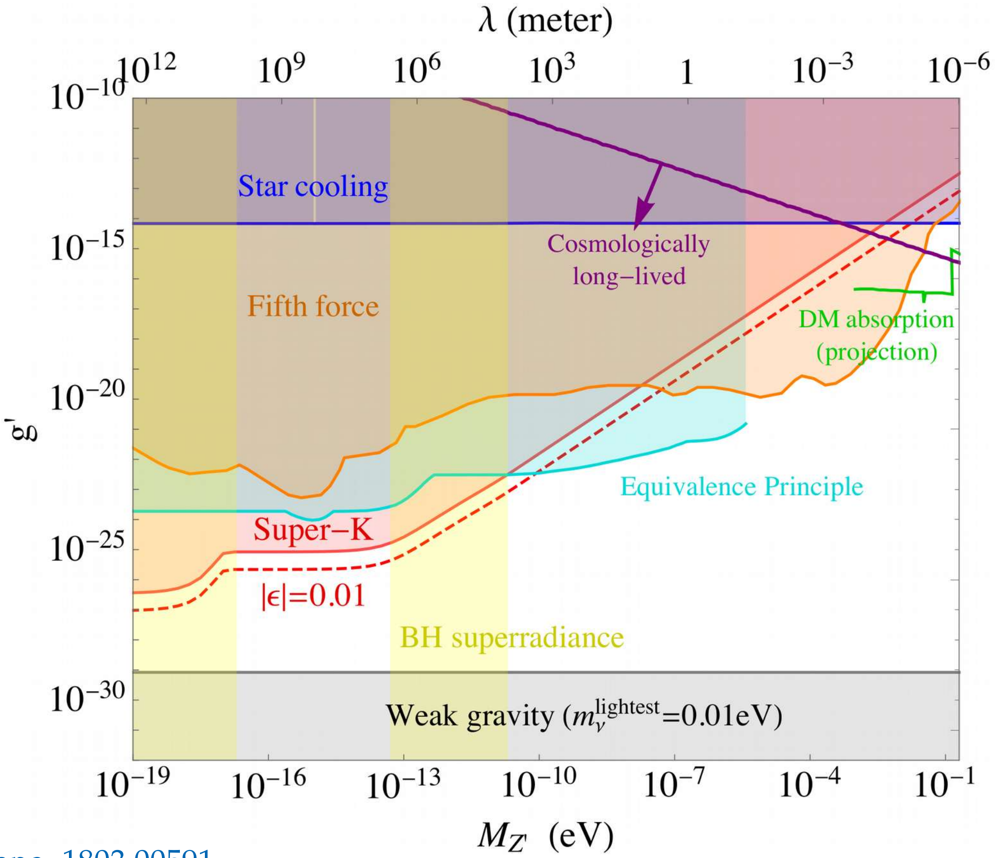
Current limits on the Z'

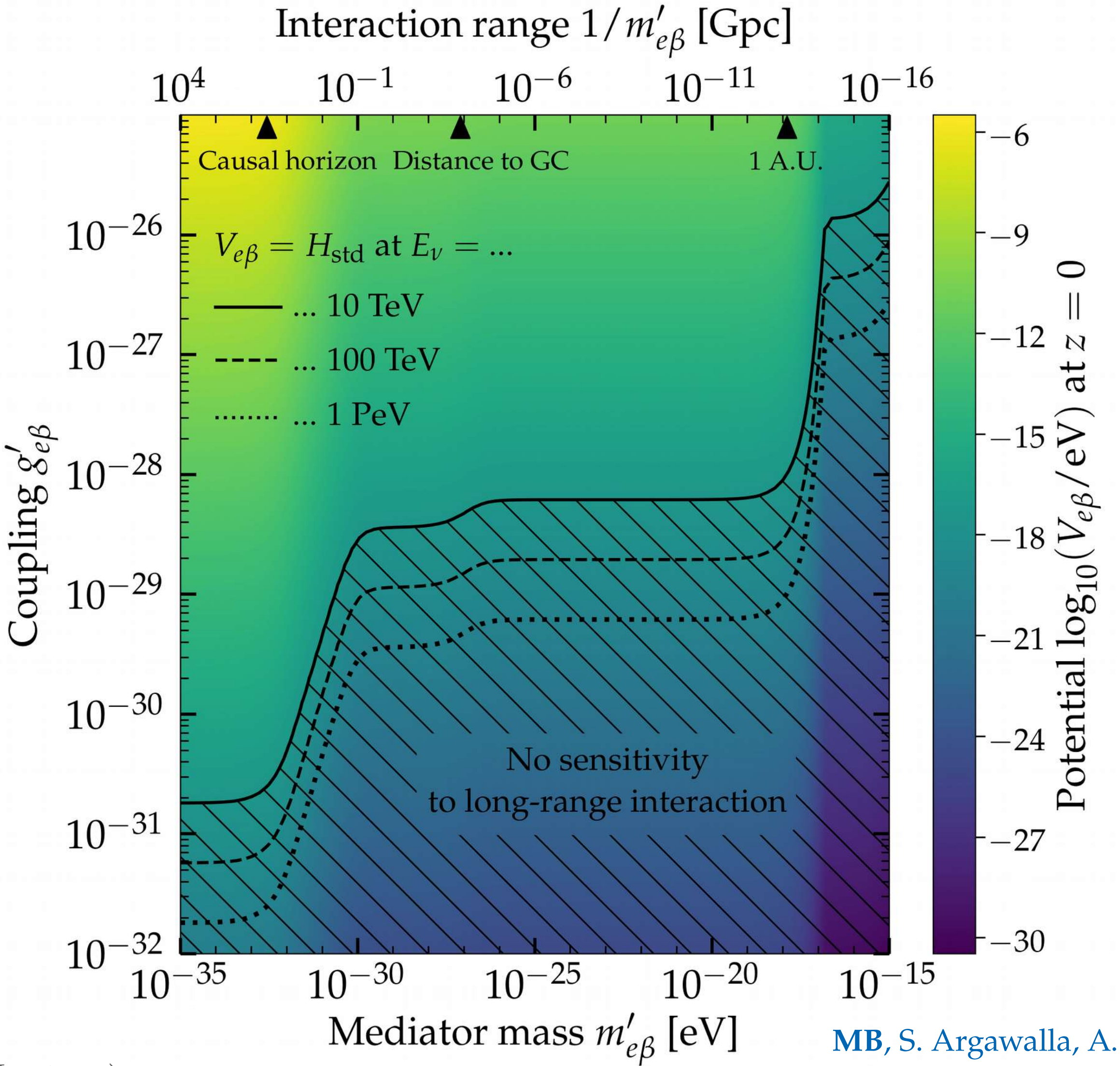
MeV–GeV masses



Sub-eV masses



M. Wise & Y. Zhang, 1803.00591



MB, S. Argawalla, A. De Gouvea, *In prep.*

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

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

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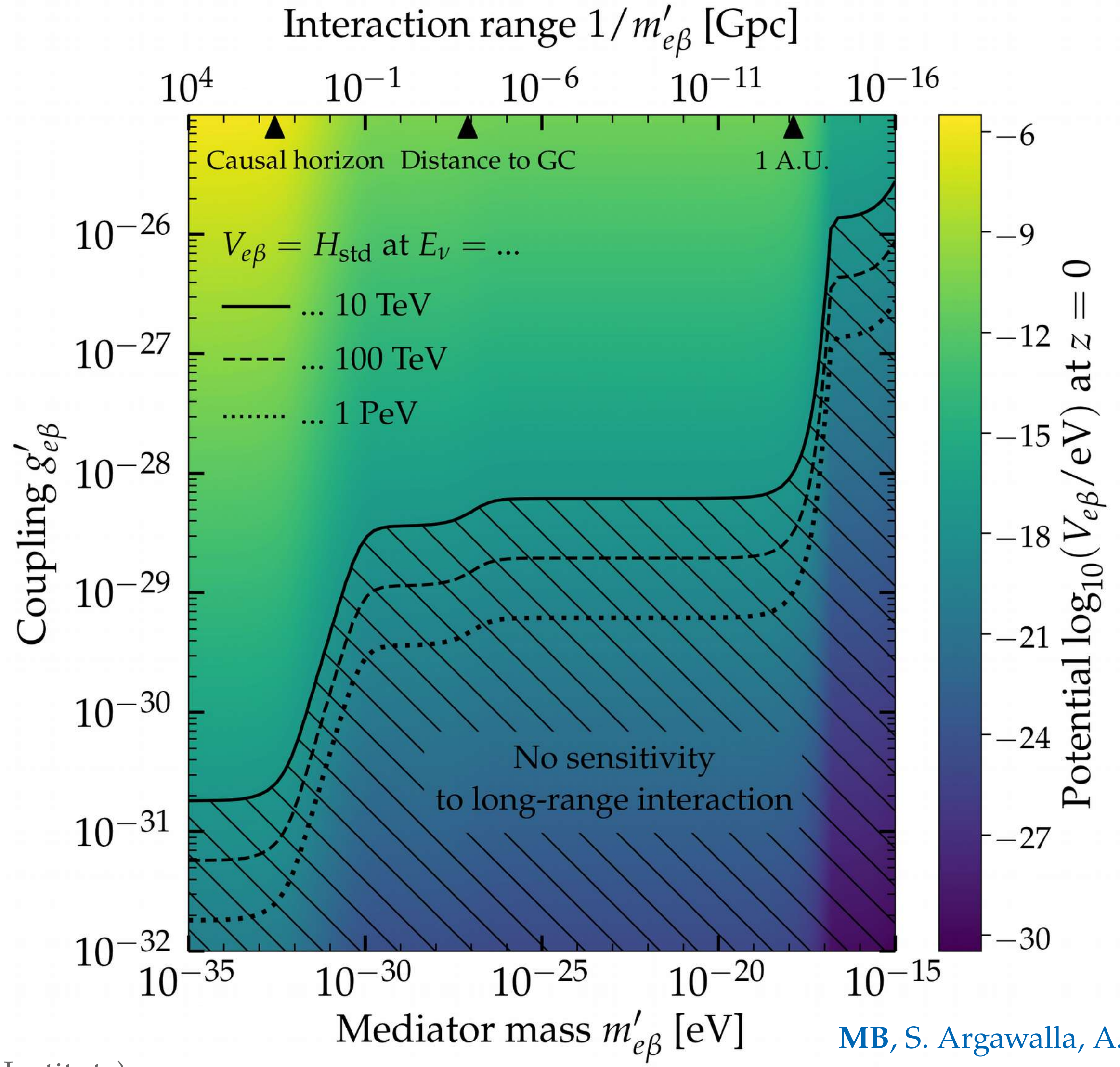
$g_{\text{gravity}} \sim 10^{-19}$



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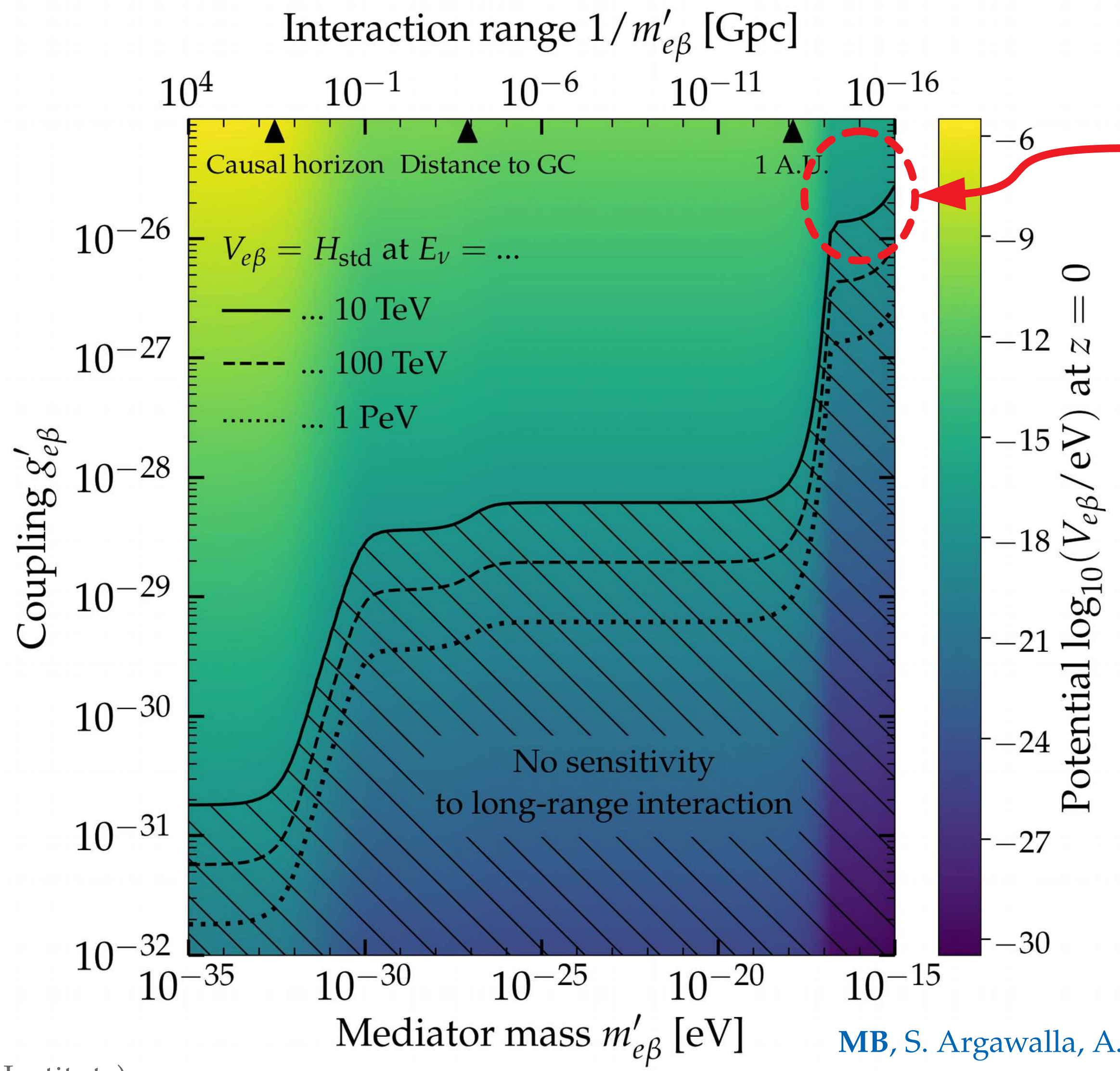

Dominated by electrons in the Earth + Moon

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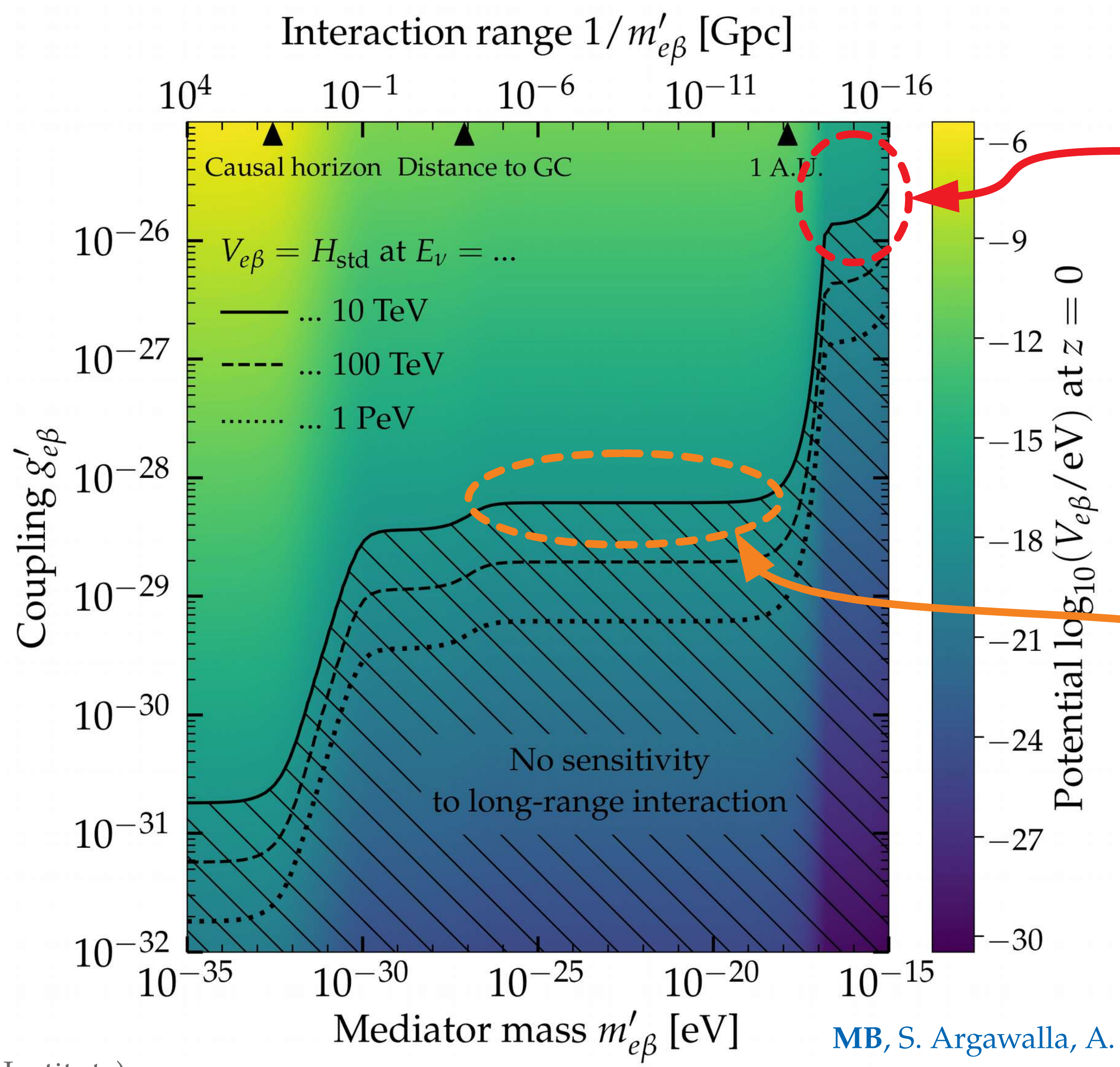

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Dominated by solar electrons (+ Milky-Way *e*)

MB, S. Argawalla, A. De Gouvea, *In prep.*

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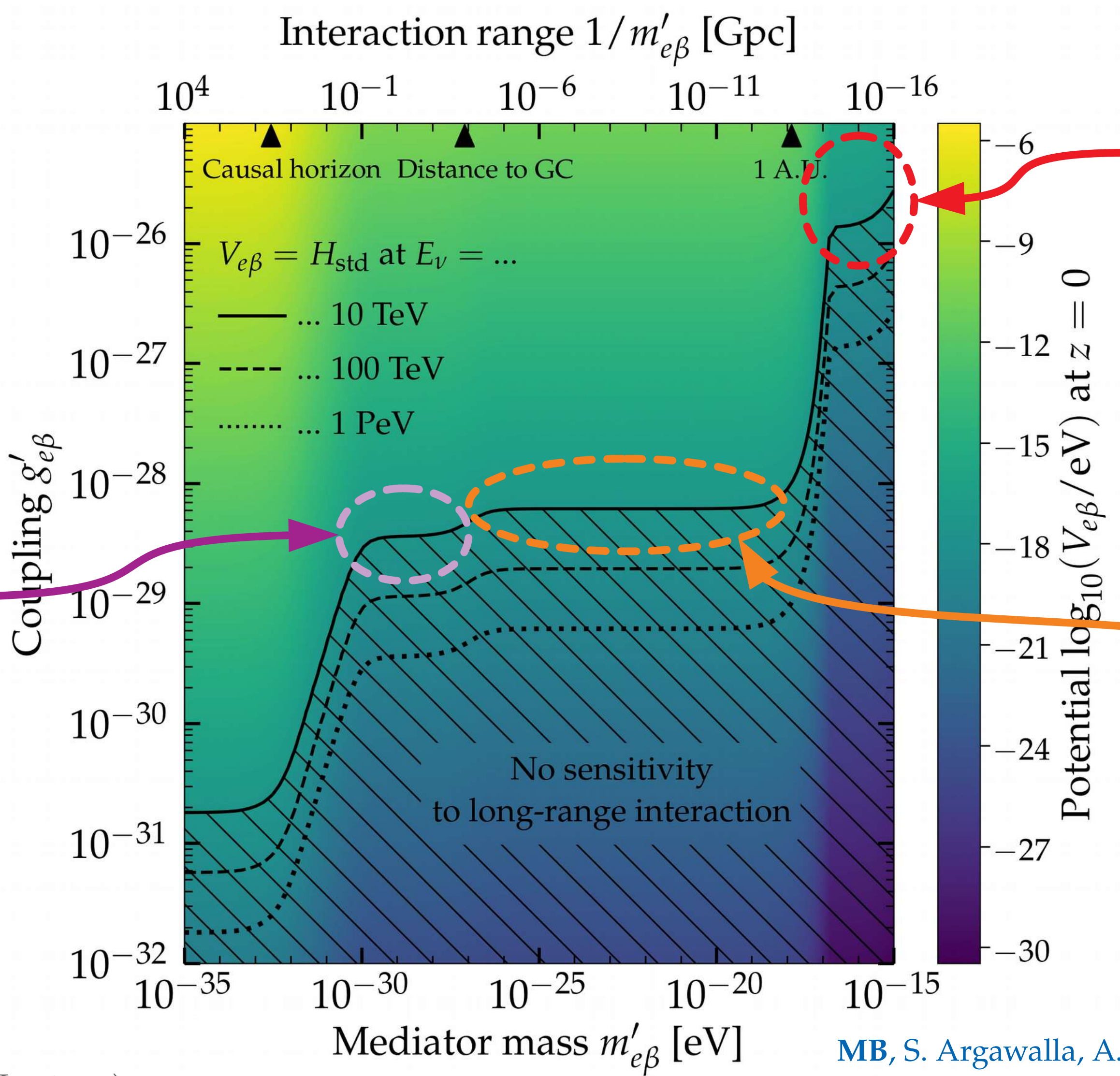

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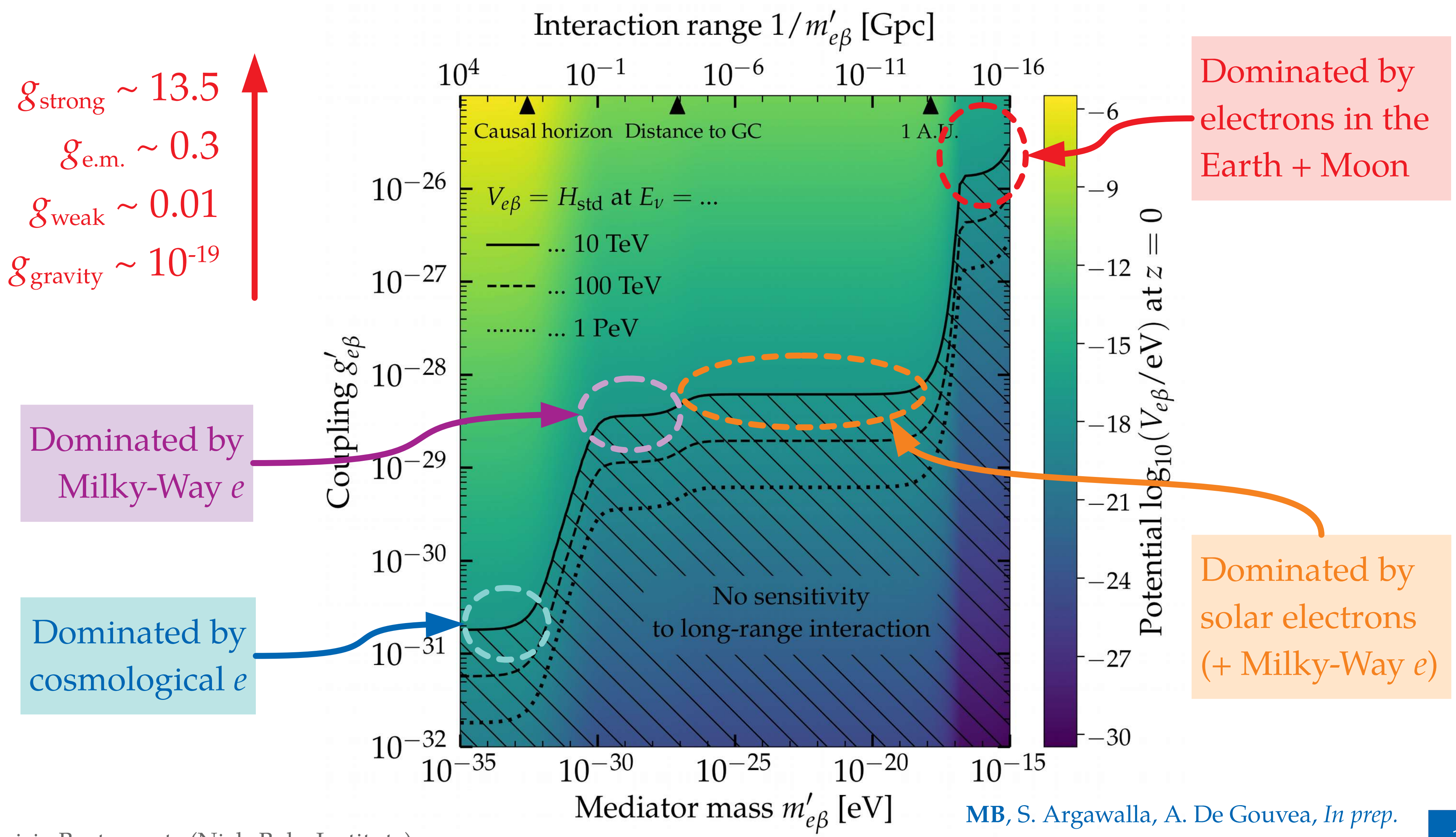
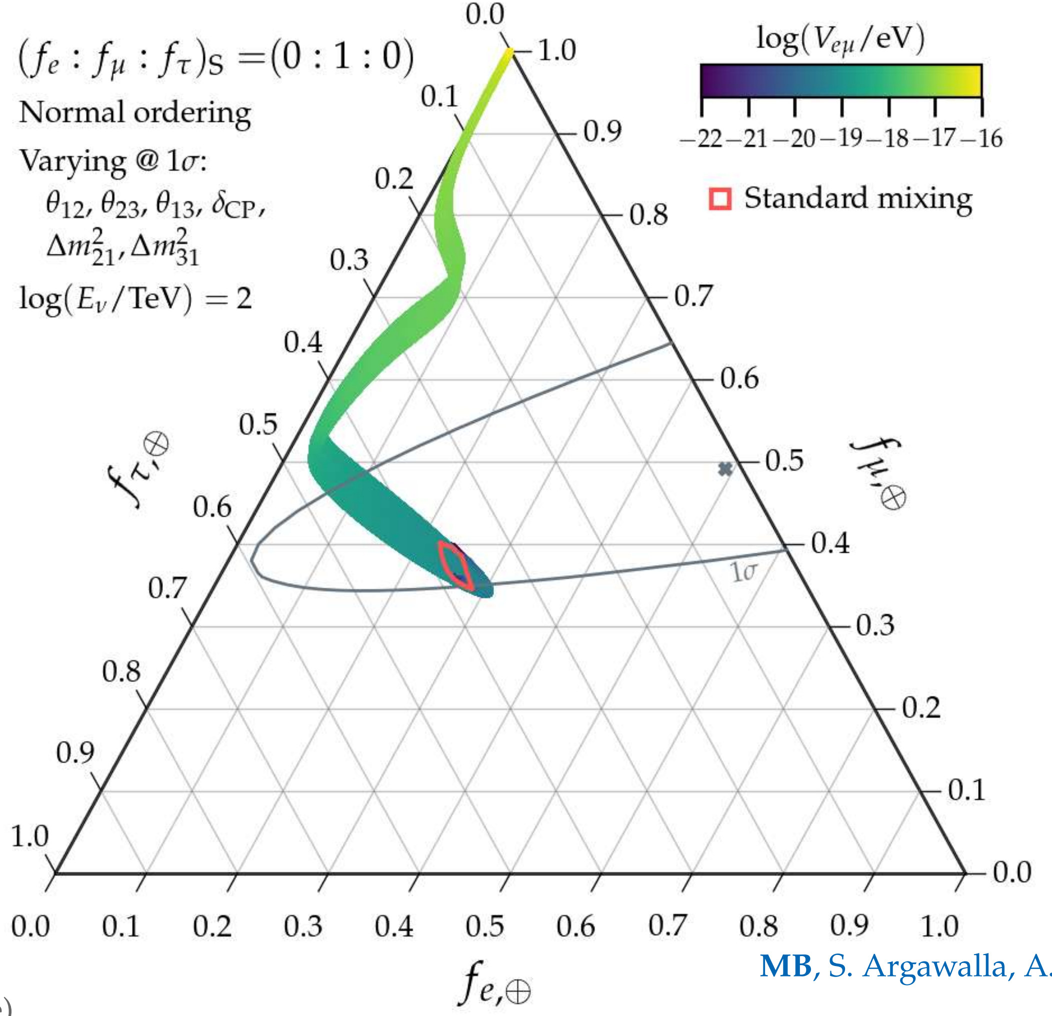


MB, S. Argawalla, A. De Gouvea, *In prep.*

Long-range interactions can turn off flavor mixing



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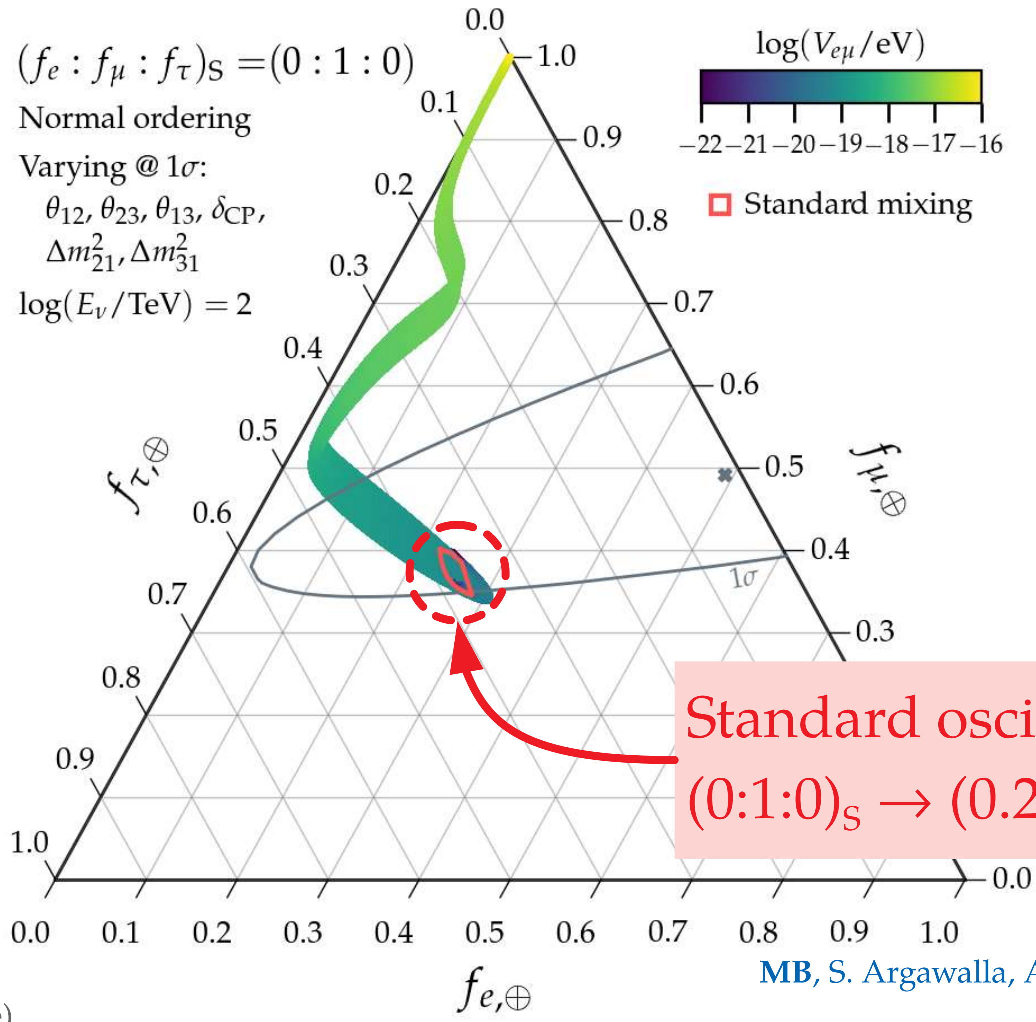
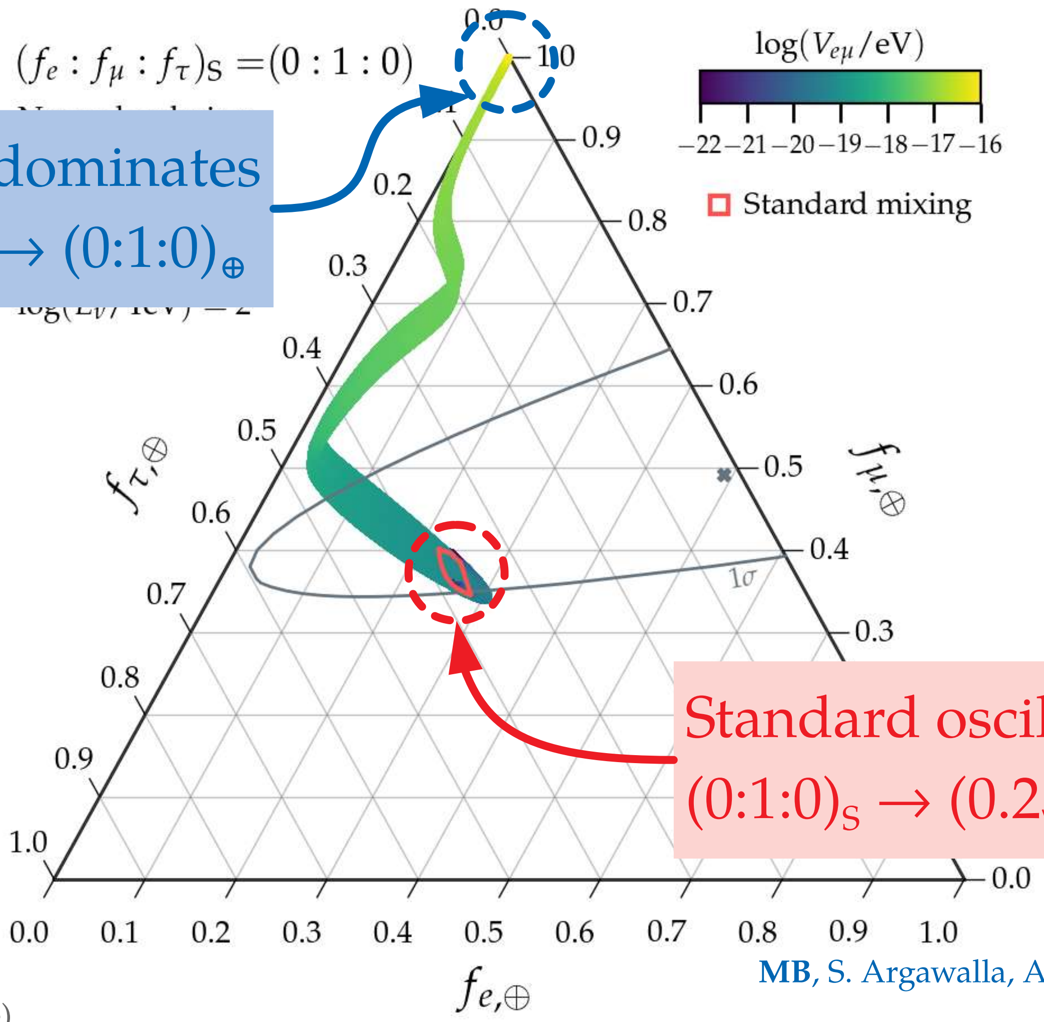


Standard oscillations
$(0{:}1{:}0)_S \rightarrow (0.25{:}0.37{:}0.38)_\oplus$

MB, S. Argawalla, A. De Gouvea, *In prep.*

Long-range interactions can turn off flavor mixing

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



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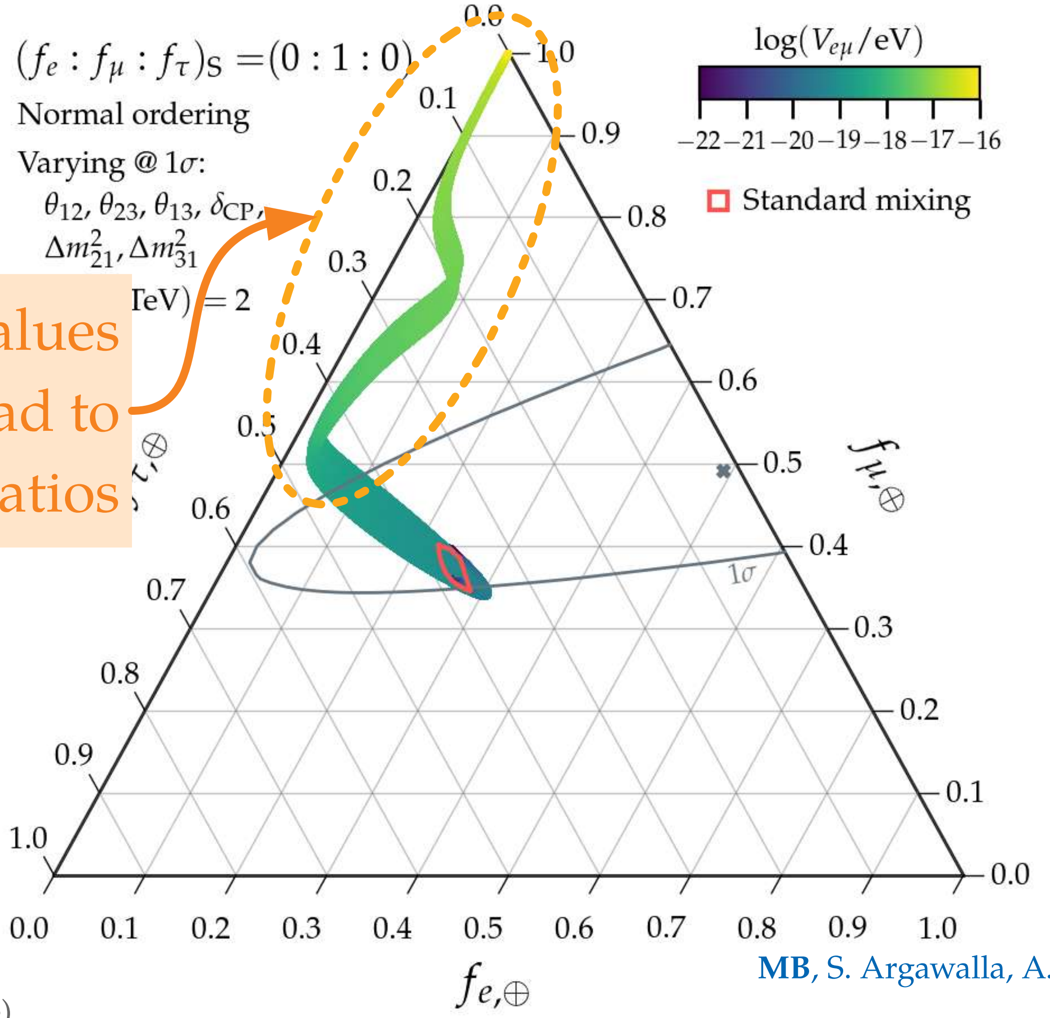
MB, S. Argawalla, A. De Gouvea, *In prep.*

Long-range interactions can turn off flavor mixing

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



MB, S. Argawalla, A. De Gouvea, *In prep.*

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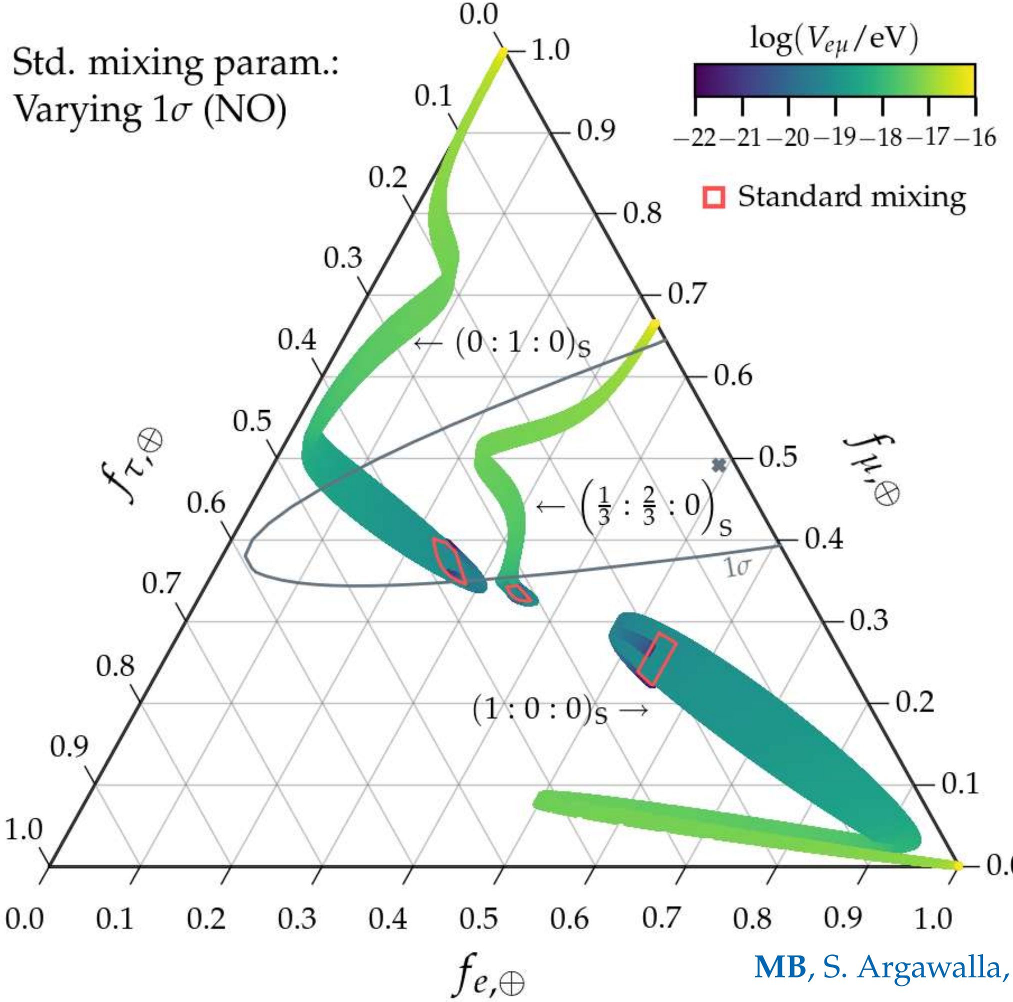

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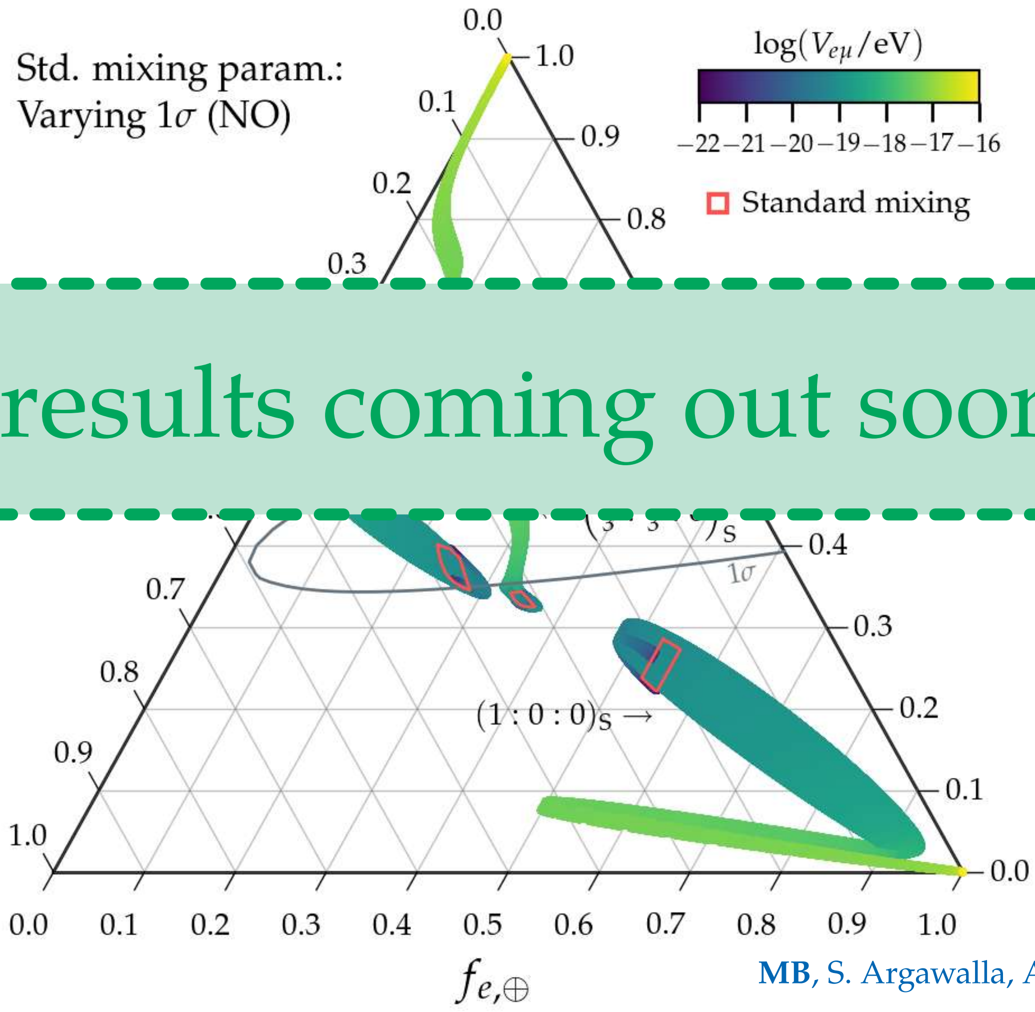
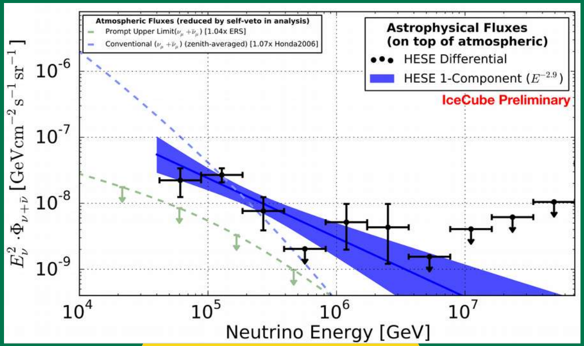
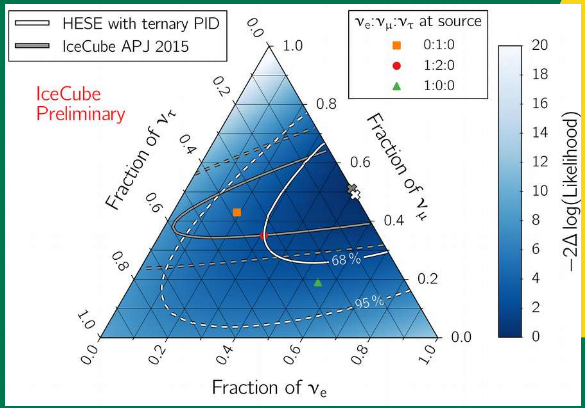
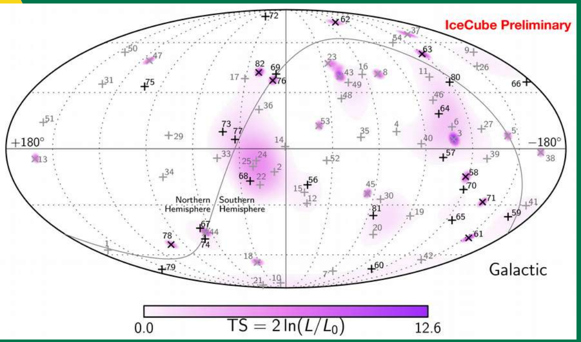


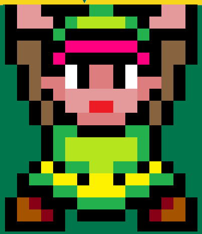
Final results coming out soon!

MB, S. Argawalla, A. De Gouvea, *In prep.*


Atmospheric Fluxes (reduced by self-veto in analysis)
Astrophysical Fluxes
(on top of atmospheric)
HESE Differential
HESE 1-Component ($E^{-2.9}$)
IceCube Preliminary
$E_\nu^2 \cdot \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino Energy [GeV]


HESE with ternary PID
IceCube APJ 2015
$\nu_e:\nu_\mu:\nu_\tau$ at source
0:1:0
1:2:0
1:0:0
IceCube
Preliminary
Fraction of ν_τ
Fraction of ν_μ
Fraction of ν_e
68 %
95 %
-2Δ log(Likelihood)


IceCube Preliminary
Northern Hemisphere
Southern Hemisphere
Galactic
TS = $2\ln(L/L_0)$



What are you taking home?

- Astrophysical neutrinos are the only feasible way to probe TeV–PeV physics
- New physics is likely sub-dominant – so we need to be thorough
- When? *Already today*
- Future improvements: statistics, better reconstruction, higher energies

Neutrino telescopes can probe fundamental particle physics (cross section, flavor composition, anisotropies)

Backup slides

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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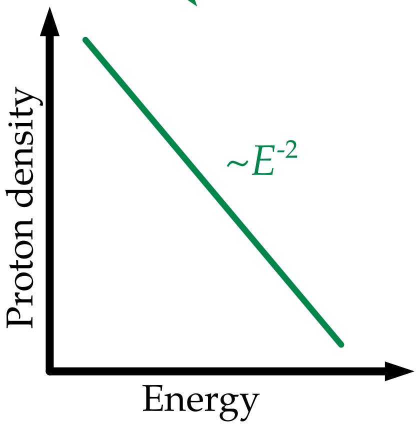

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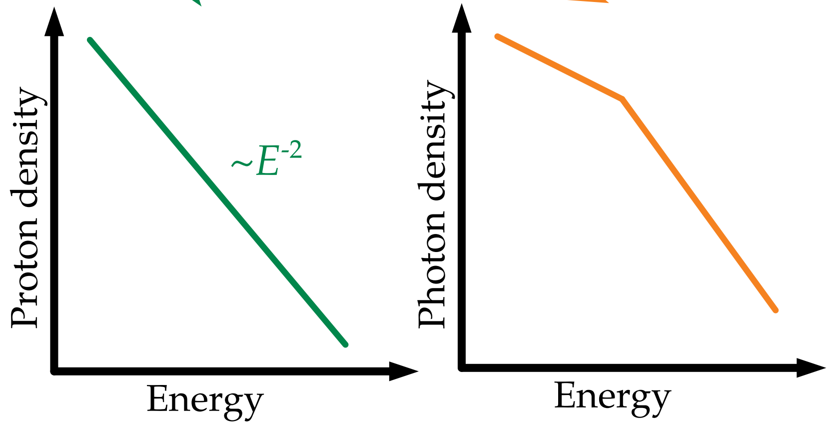

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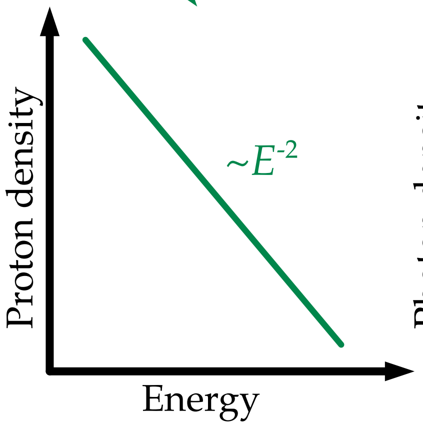
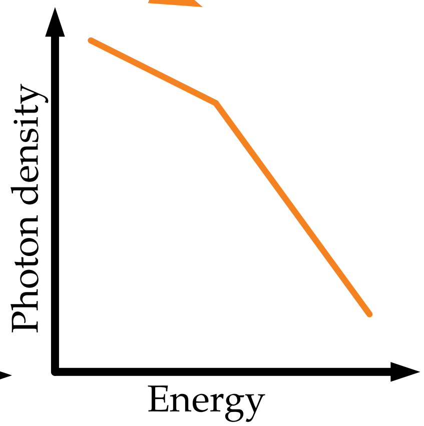
$$\pi^0 \rightarrow \gamma + \gamma$$

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

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





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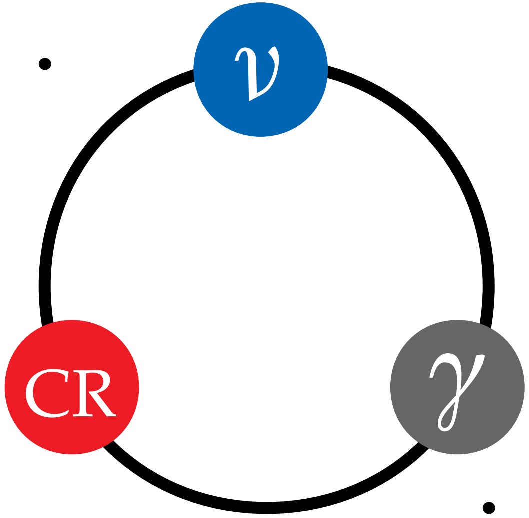

Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 20

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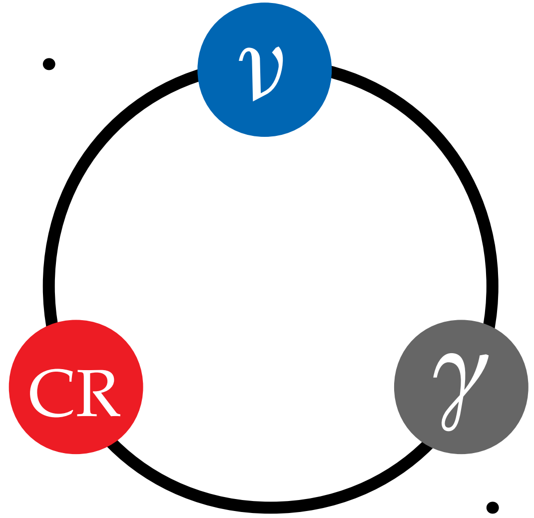

1 PeV 20 PeV

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The multi-messenger connection

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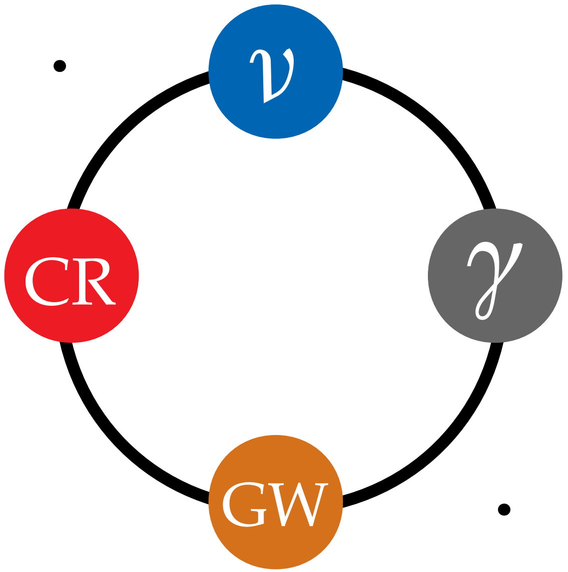


1 PeV 20 PeV

Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 20

How does IceCube see neutrinos?

Two types of fundamental interactions ...

Charged-current (CC)

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

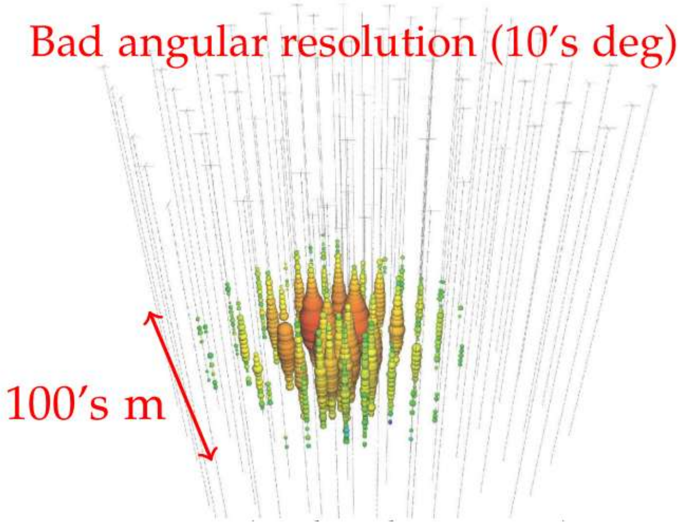
Neutral-current (NC)

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

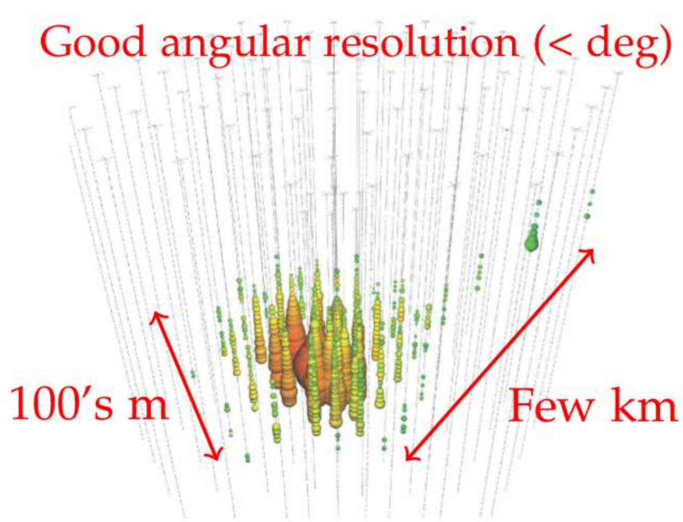
These shower and make light

... create two event topologies ...

Showers — From CC ν_e or ν_τ, or NC ν_x

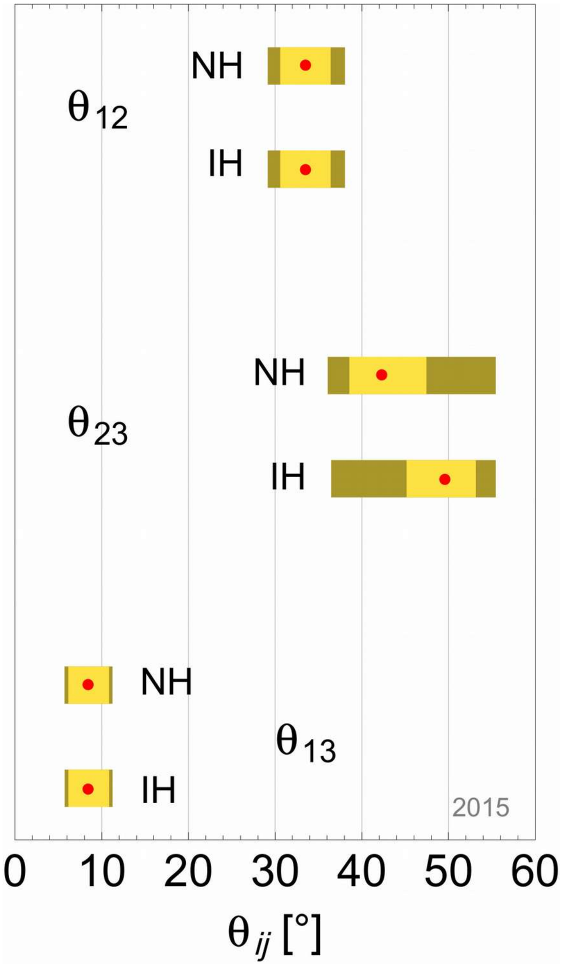


Tracks — From CC ν_μ mainly



Uncertainties in lepton mixing angles

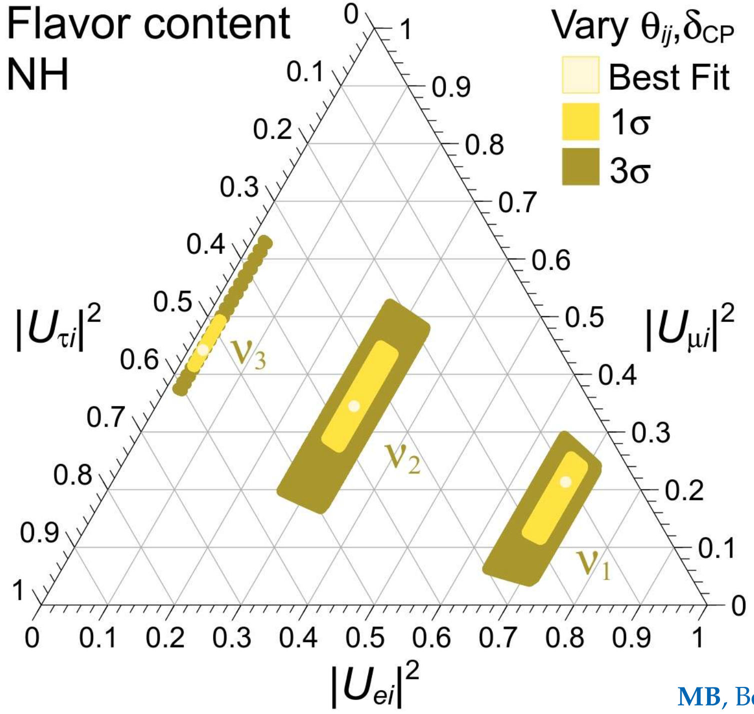
As of 2015 –

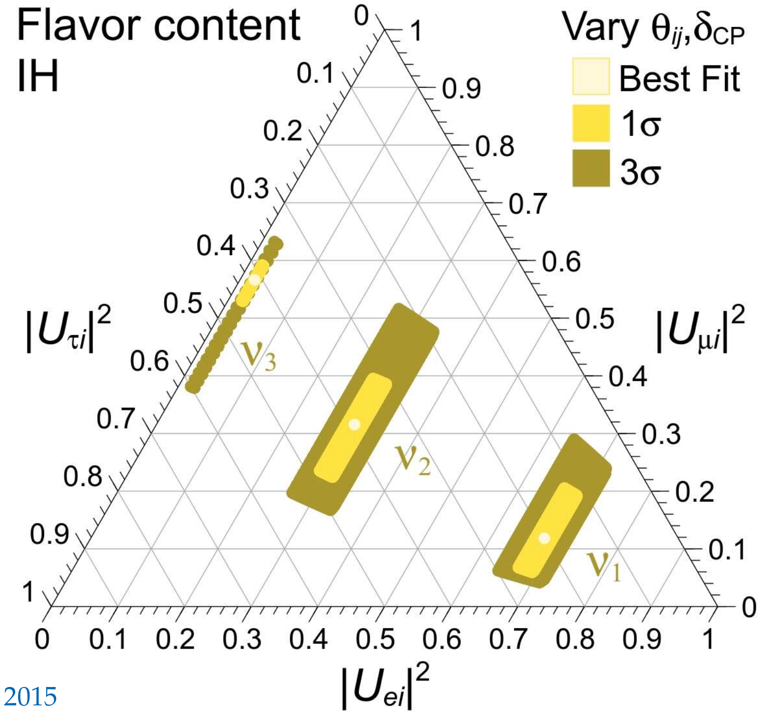


Flavor content of neutrino mass eigenstates

Flavor content for every allowed combination of mixing parameters –

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





MB, Beacom, Winter *PRL* 2015

Flavor composition – a few source choices

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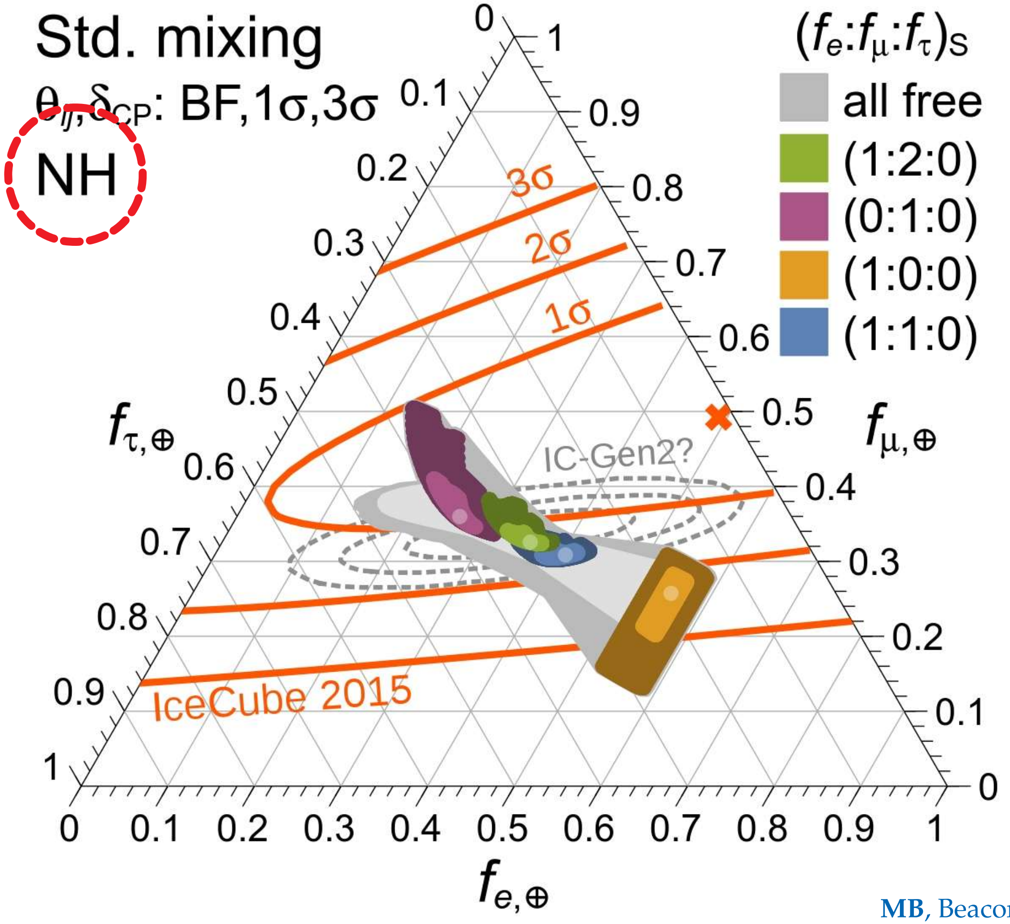
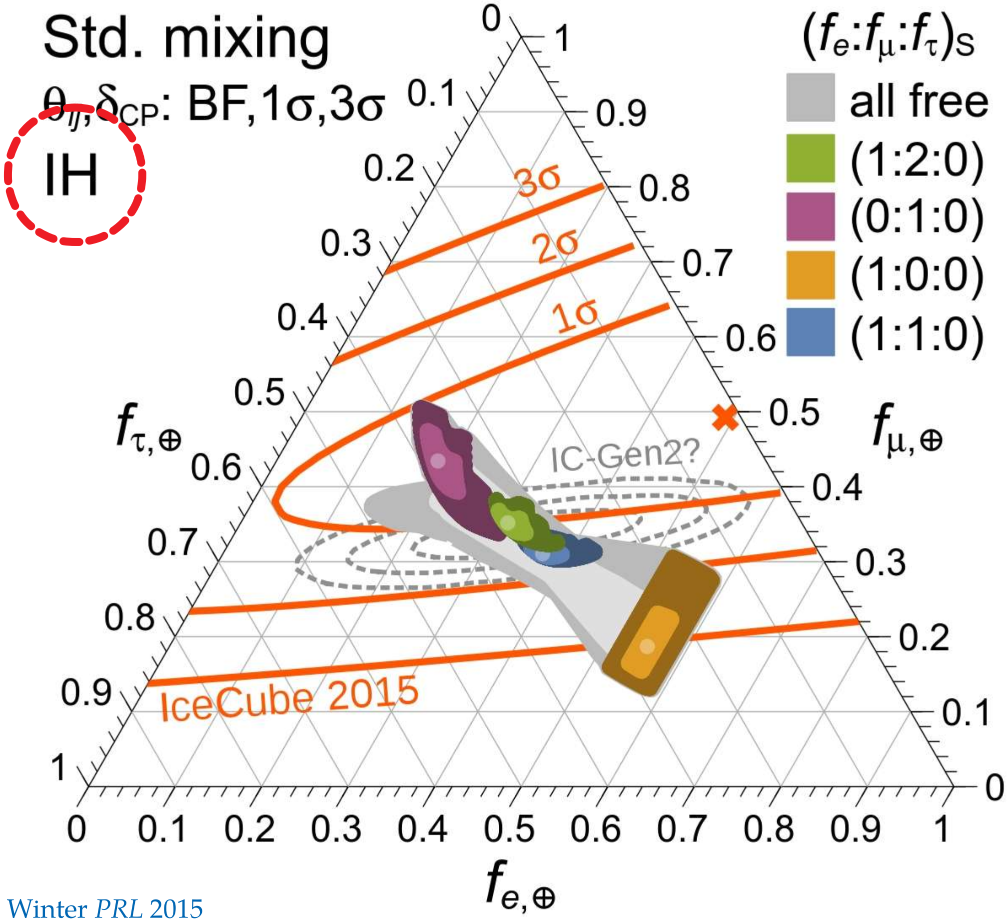
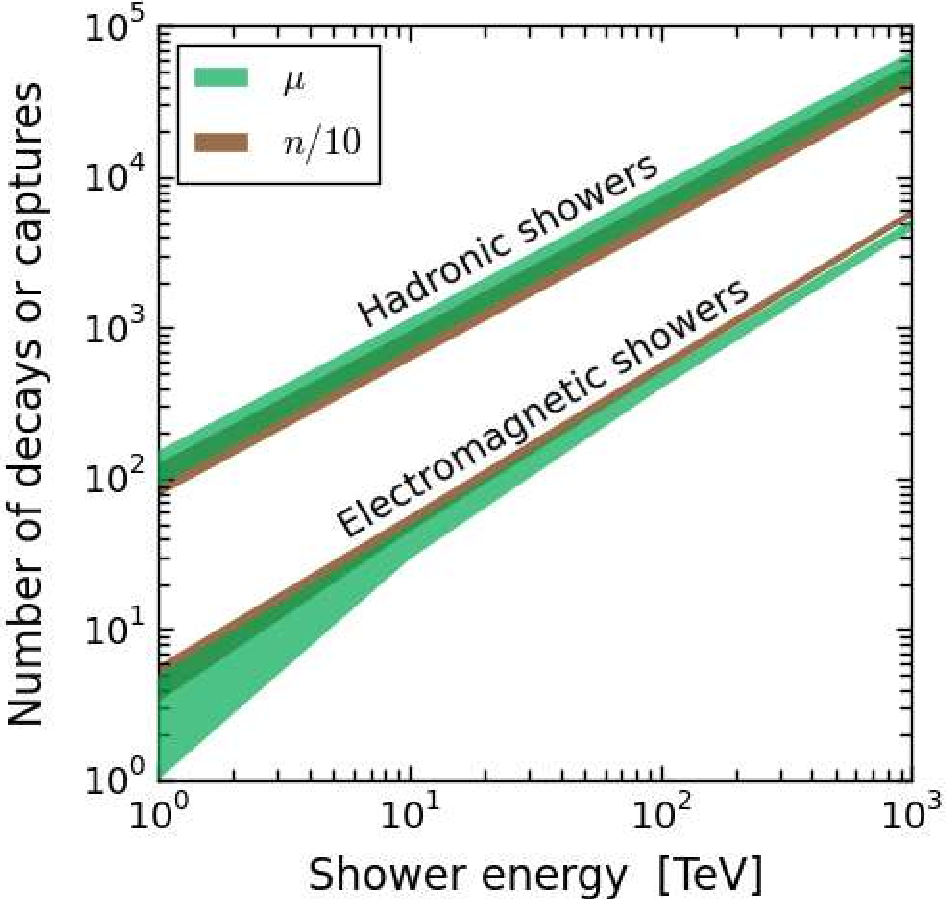
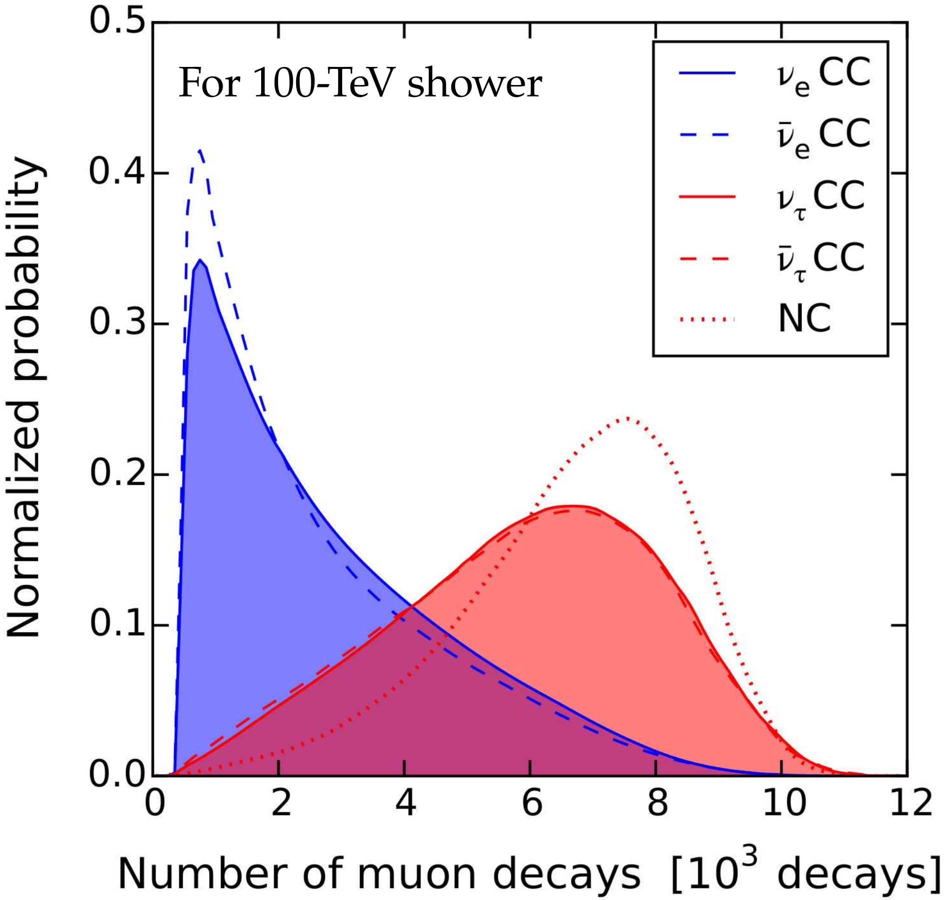




MB, Beacom, Winter *PRL* 2015

Hadronic *vs.* electromagnetic showers

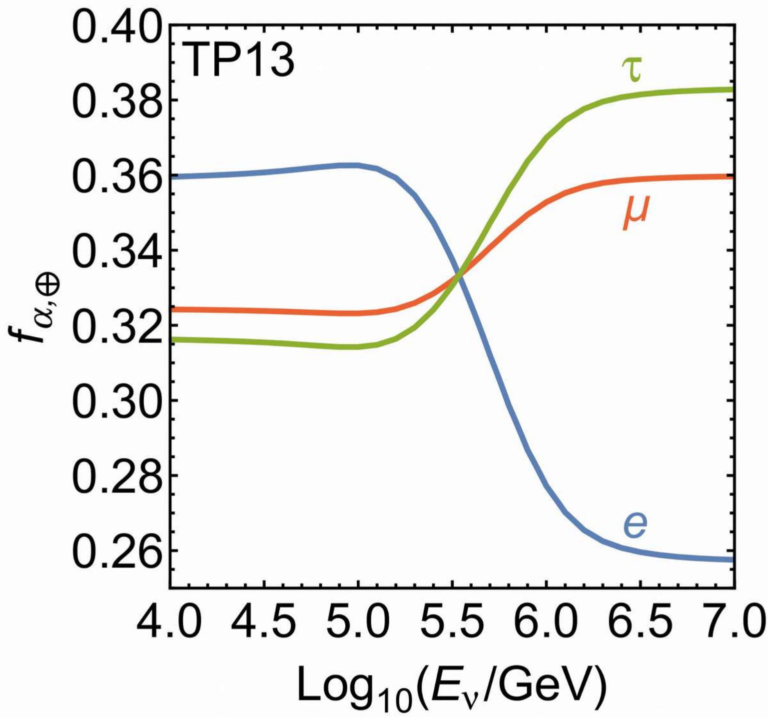


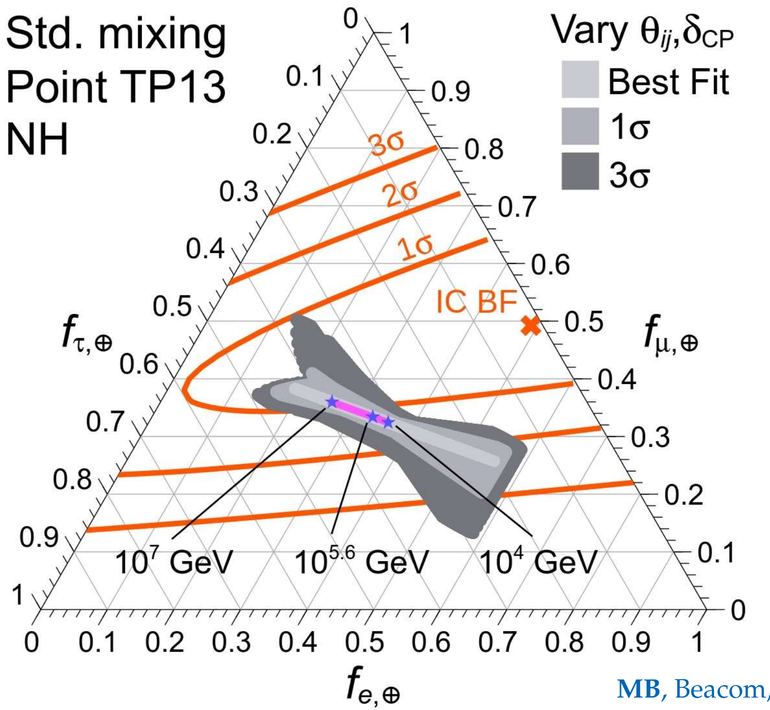


Li, **MB**, Beacom, Sub. to *PRL*

Energy dependence of the flavor composition?

Different neutrino production channels accessible at different energies –

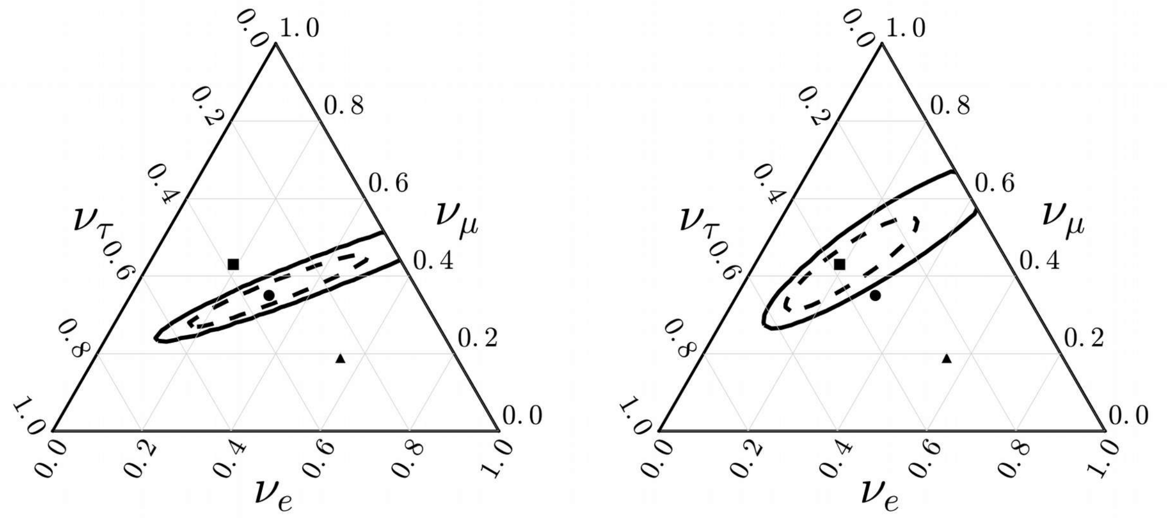


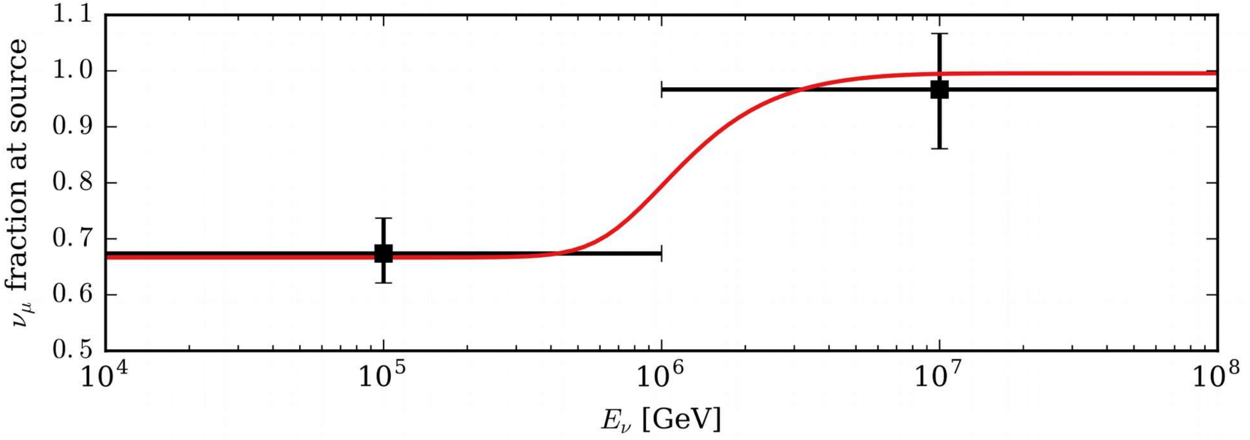


MB, Beacom, Winter *PRL* 2015

- 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?

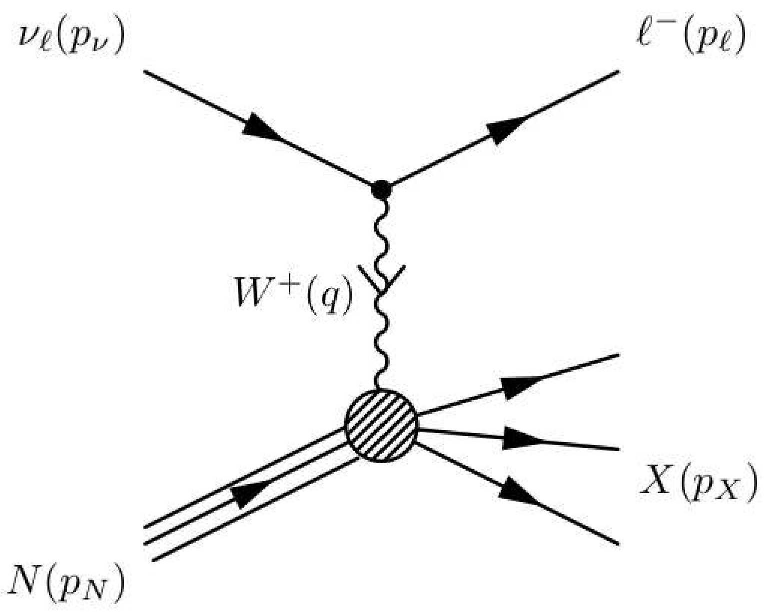




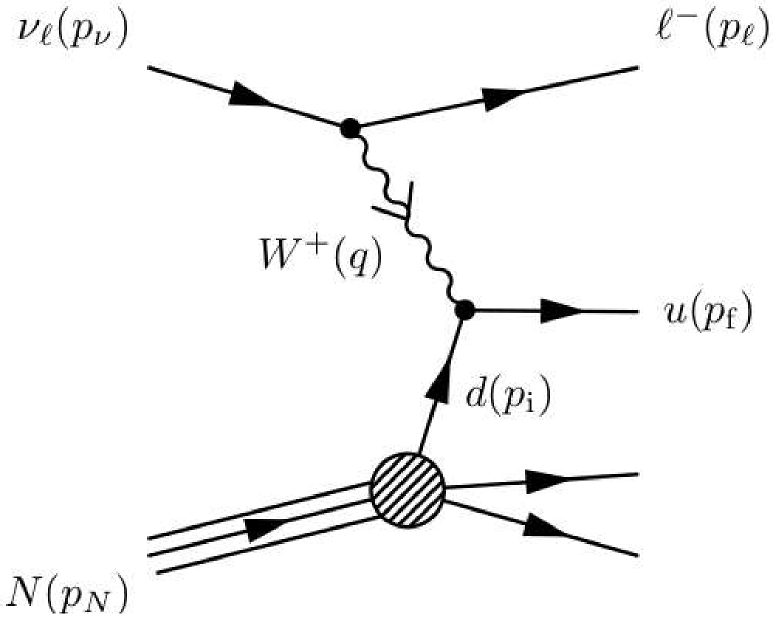
Borrowed from M. Kowalski

How does DIS probe nucleon structure?

What you see



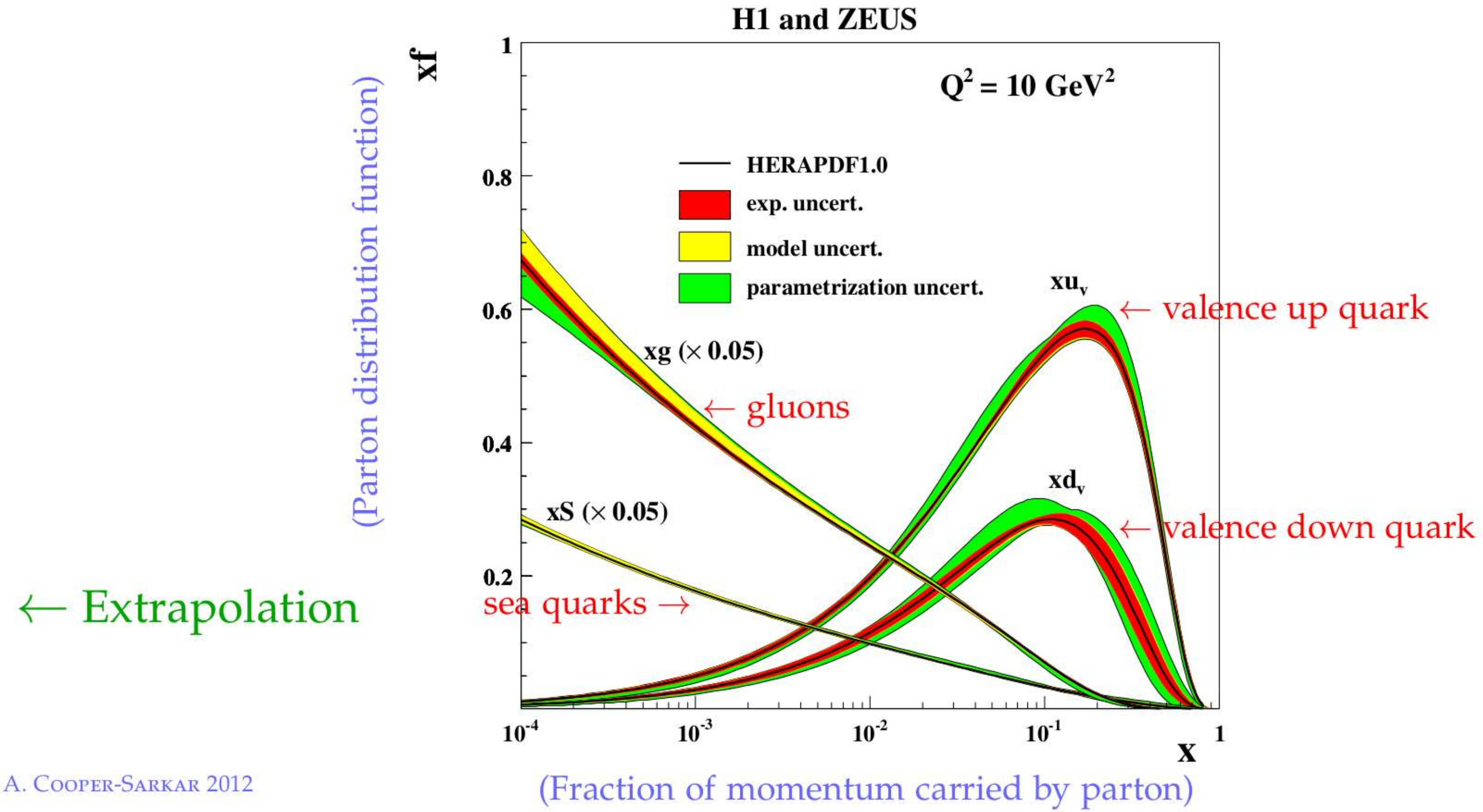
Beneath the hood



(Plus the equivalent neutral-current process (Z-exchange))

Giunti & Kim, *Fundamentals of Neutrino Physics & Astrophysics*

Peeking inside a proton

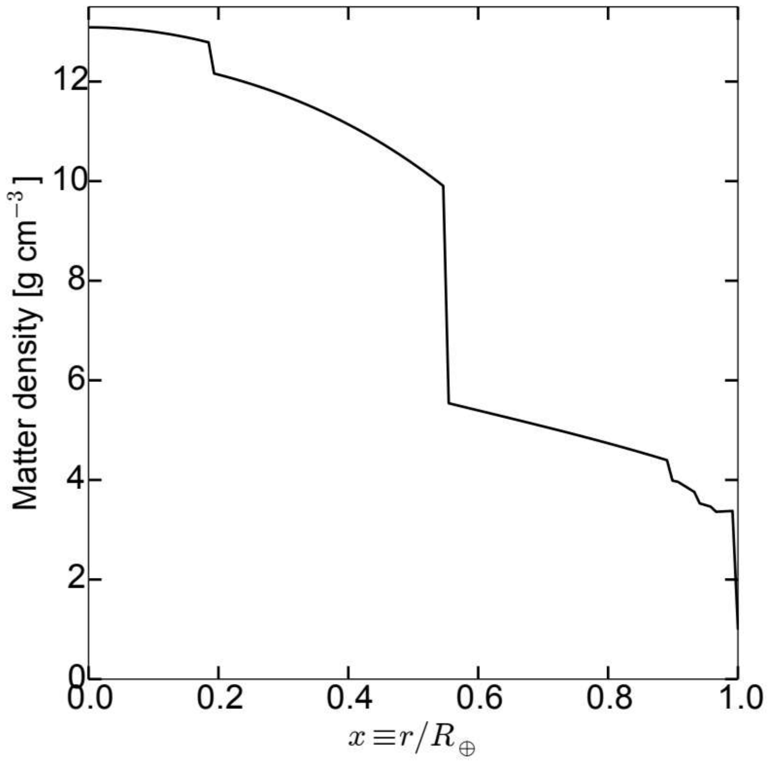


A. Cooper-Sarkar 2012

A feel for the in-Earth attenuation

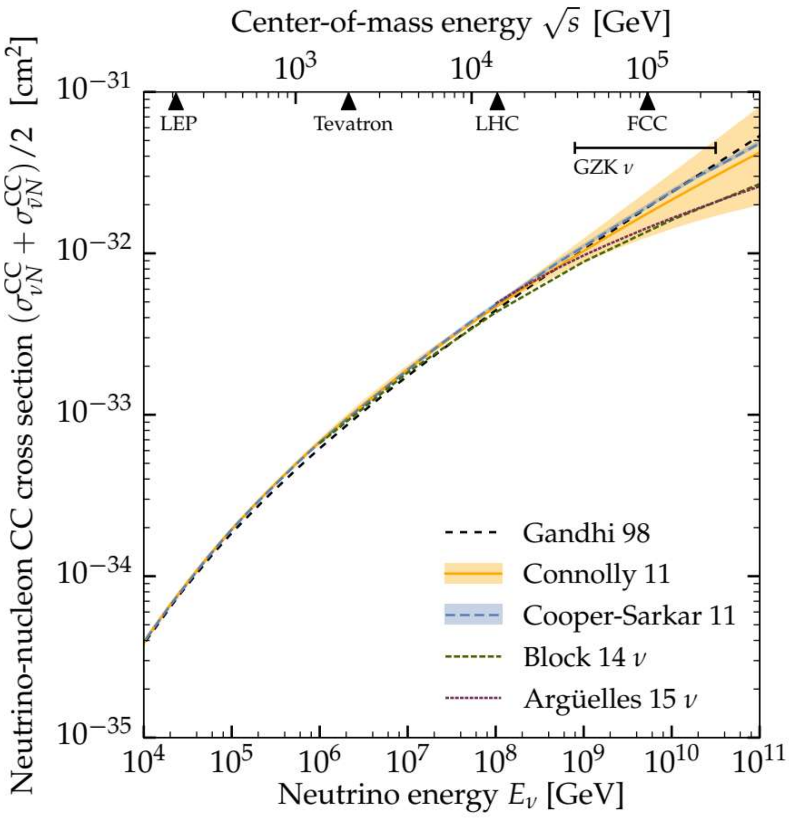
Earth matter density

(Preliminary Reference Earth Model)



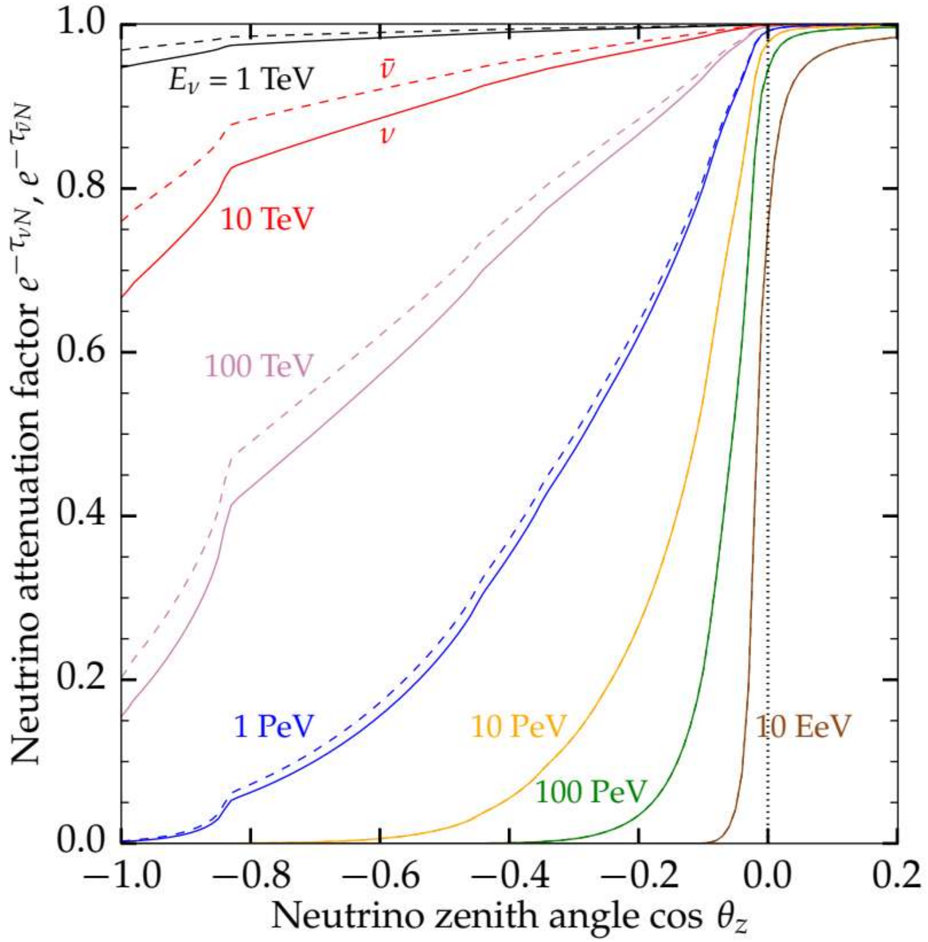
+

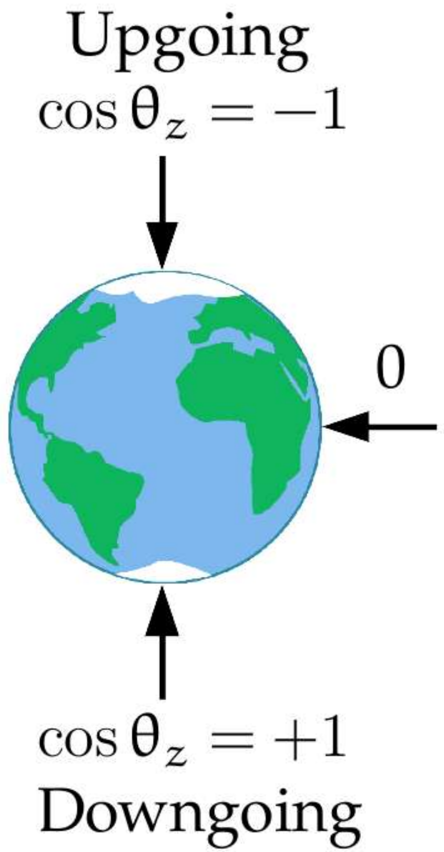
Neutrino-nucleon cross section



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

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

How to do better / more?

- Currently, we are statistics-limited
  $\mapsto$ Solvable with more data from IceCube, IceCube-Gen2, KM3NeT

- Large errors in arrival direction (~10°) give errors in attenuation
  $\mapsto$ Solvable with ongoing IceCube improvements + KM3NeT

- Charged-current + neutral-current cross sections are indistinguishable
  $\mapsto$ Solvable (?) with muon and neutron echoes (Li, MB, Beacom 16)

- Cannot separate ν from $\bar{\nu}$
  $\mapsto$ Wait to detect Glashow resonance (~6.3 PeV), sensitive only to $\bar{\nu}_e$

- Use starting tracks / through-going muons
  $\mapsto$ Doable / done by IceCube (more next)

Marginalized cross section in each bin

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

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

MB & A. Connolly, 1711.11043

Neutrino zenith angle distribution

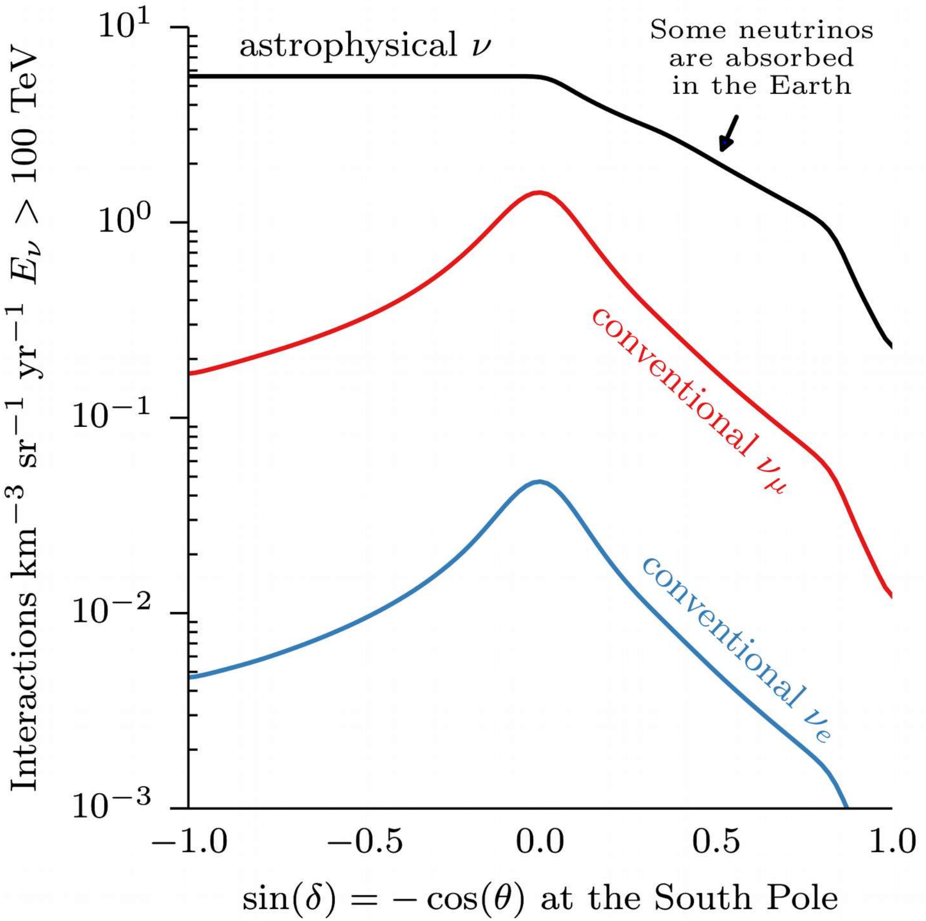
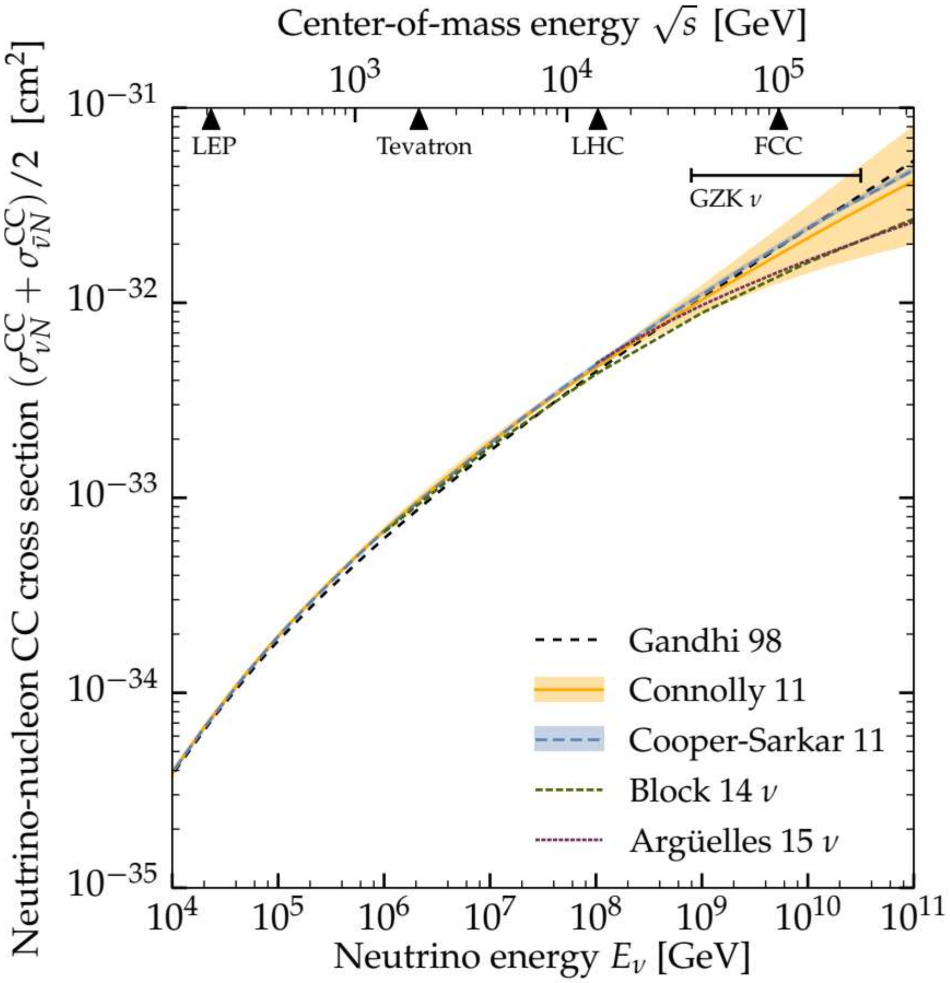


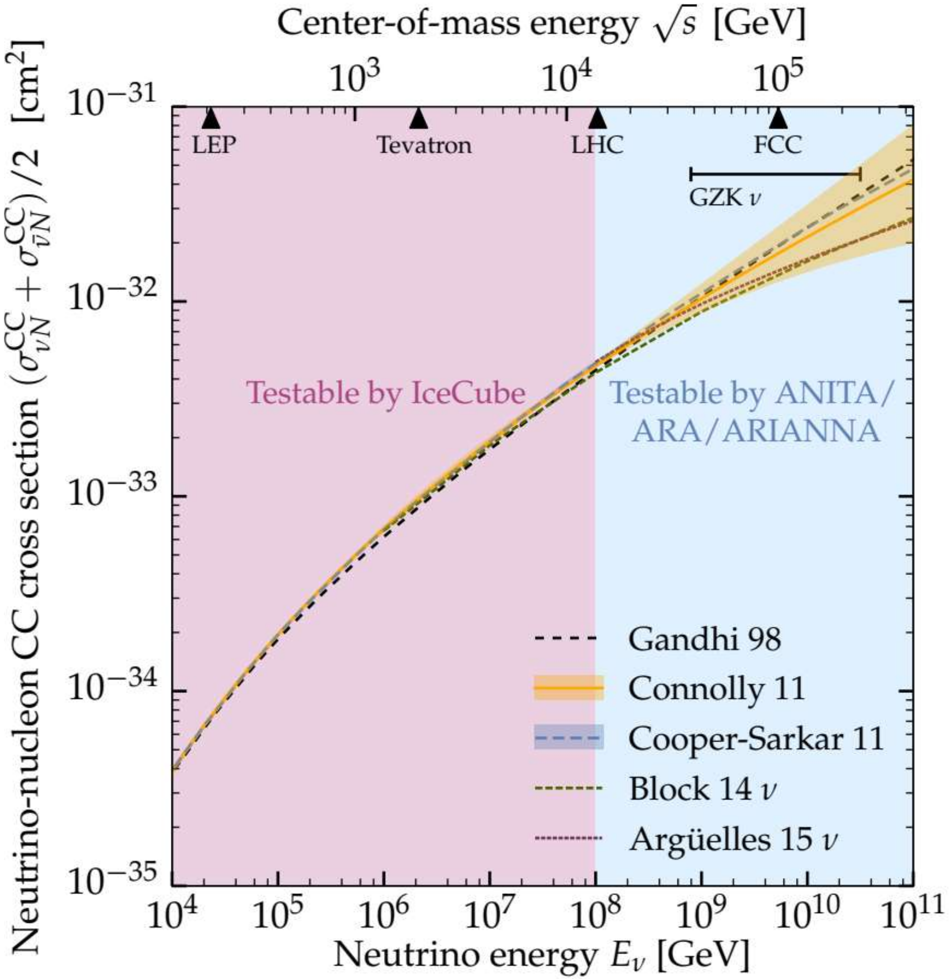
Figure by
Jakob Van Santen
ICRC 2017

What can we measure *now* and later?



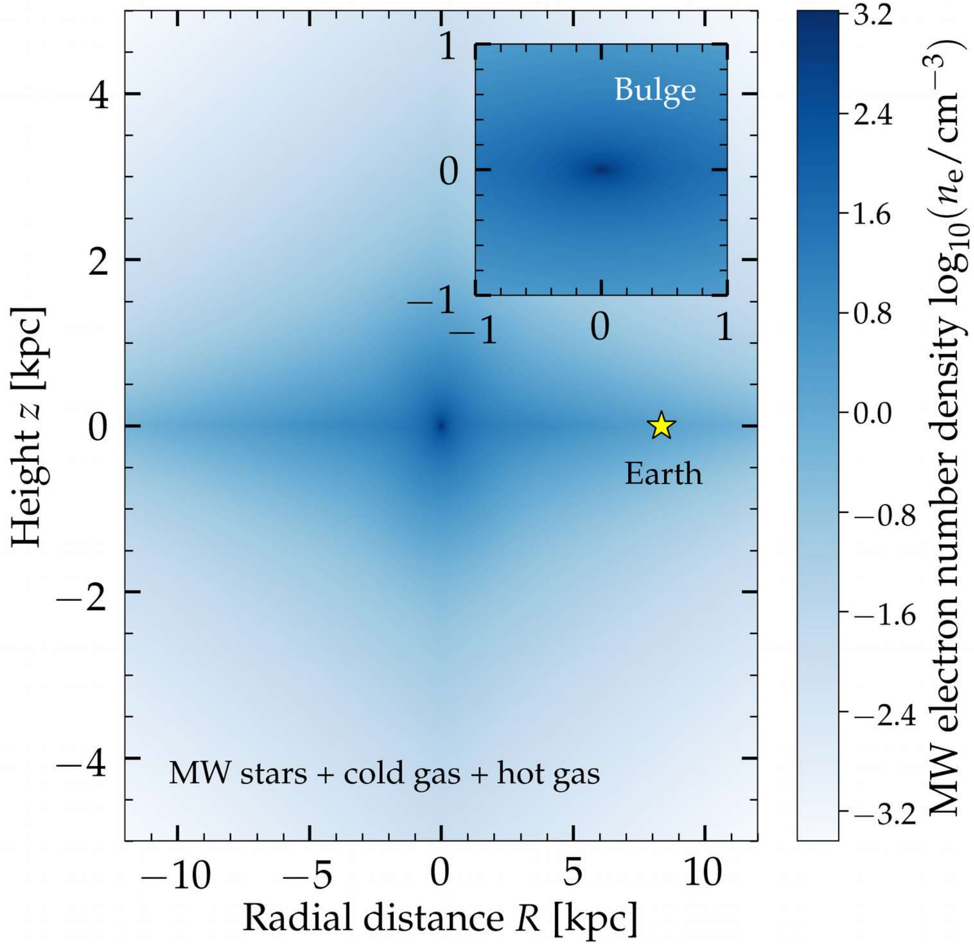
MB & Connolly, 1711.11043

What can we measure *now* and later?

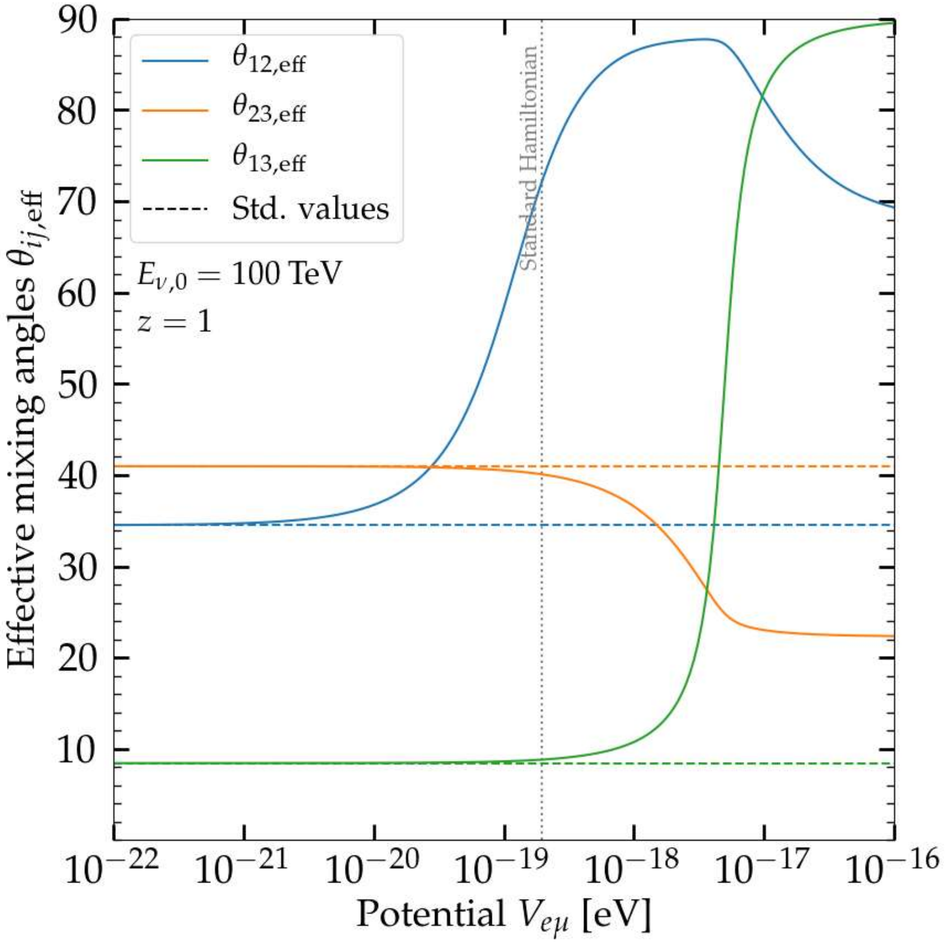


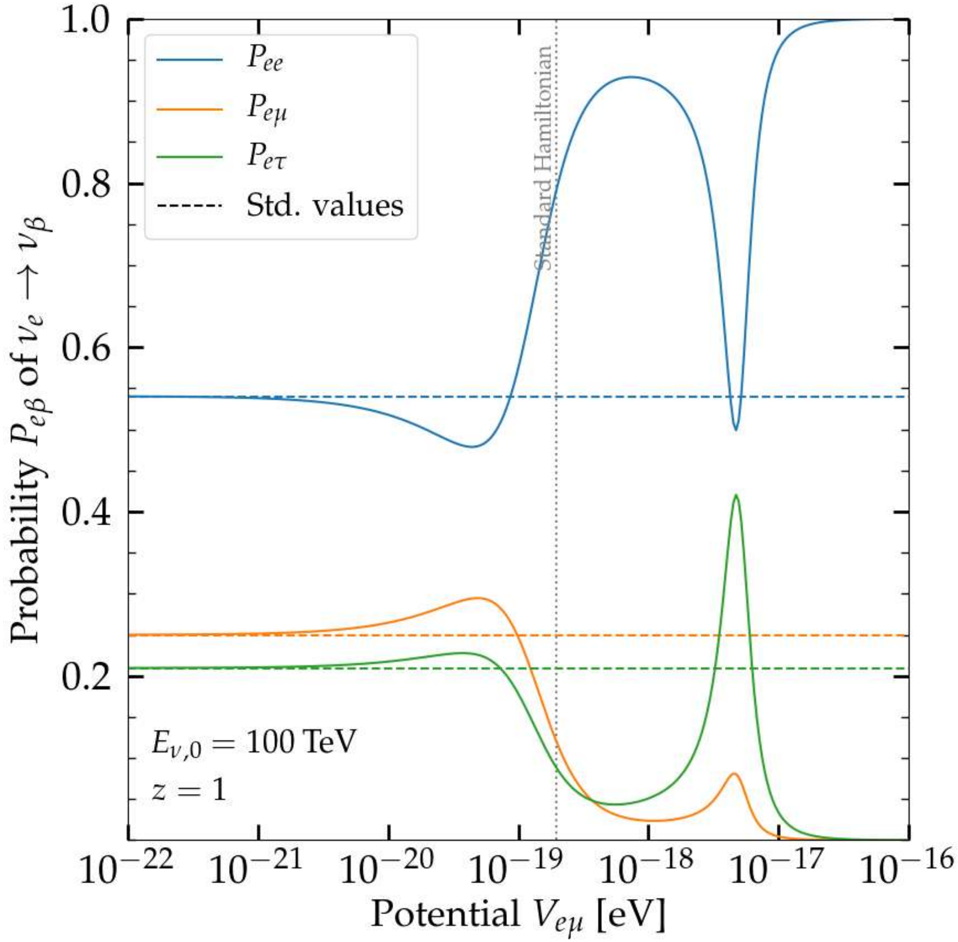
MB & Connolly, 1711.11043

Distribution of electrons in the Milky Way

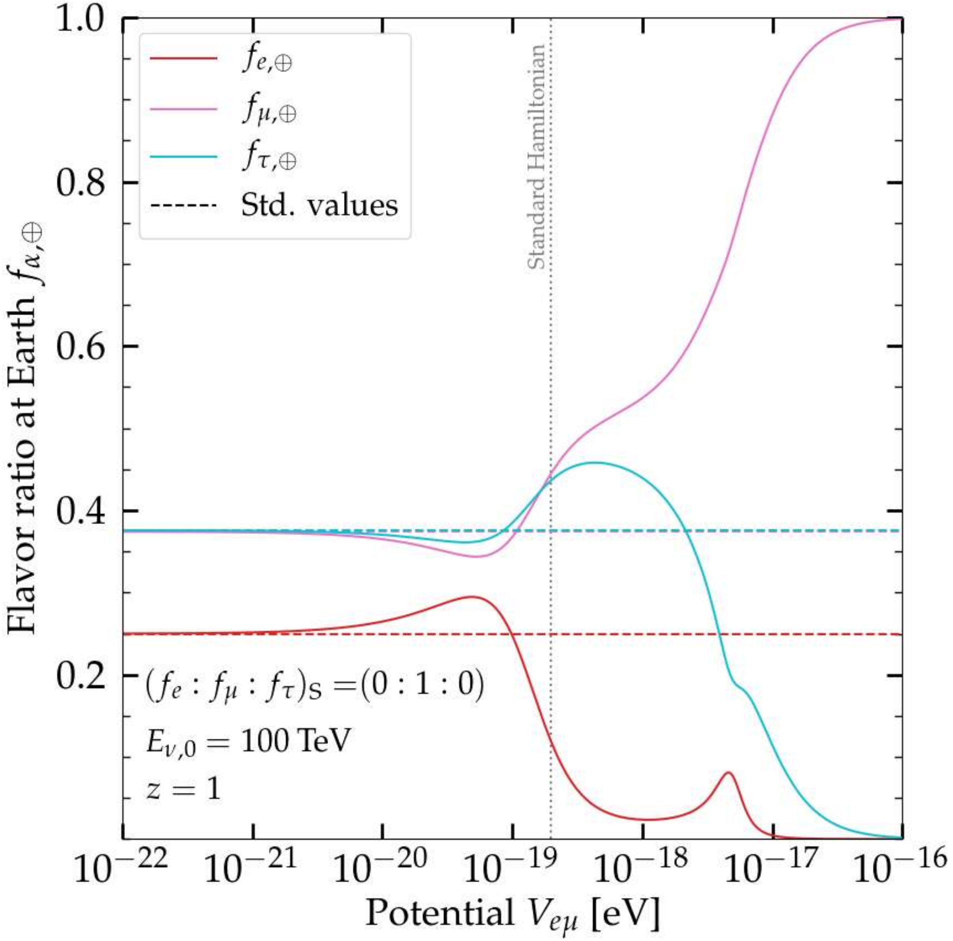


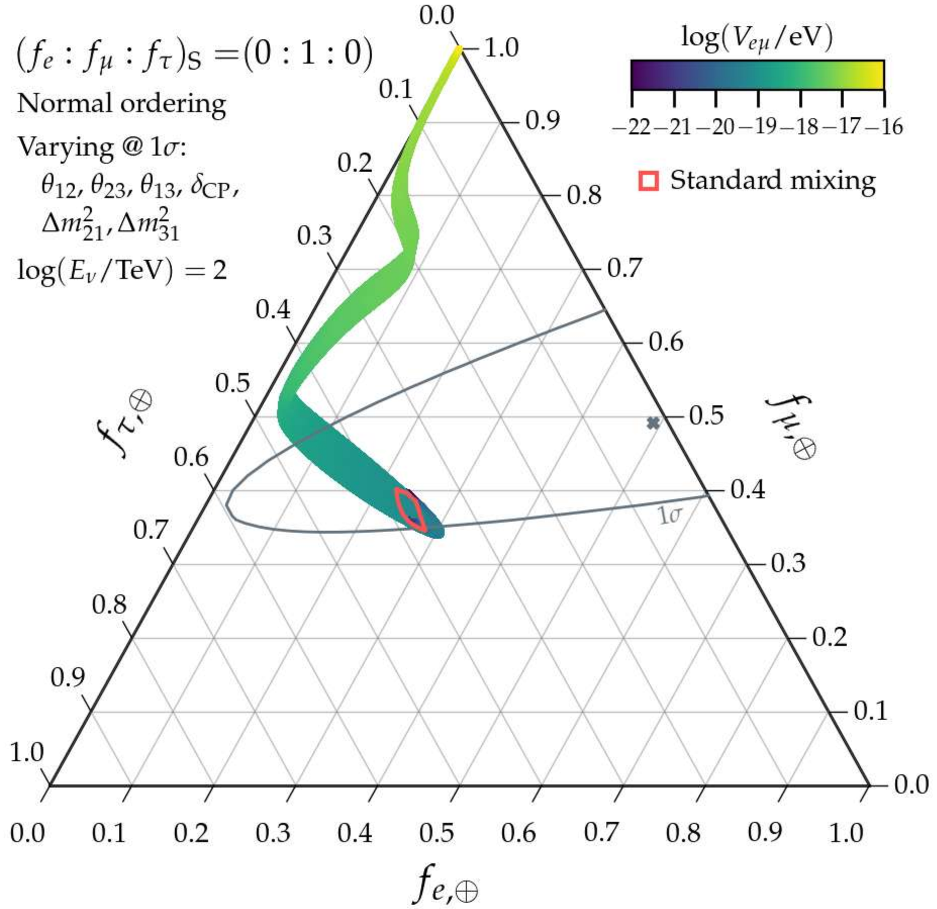
Resonance due to the L_e-L_μ symmetry



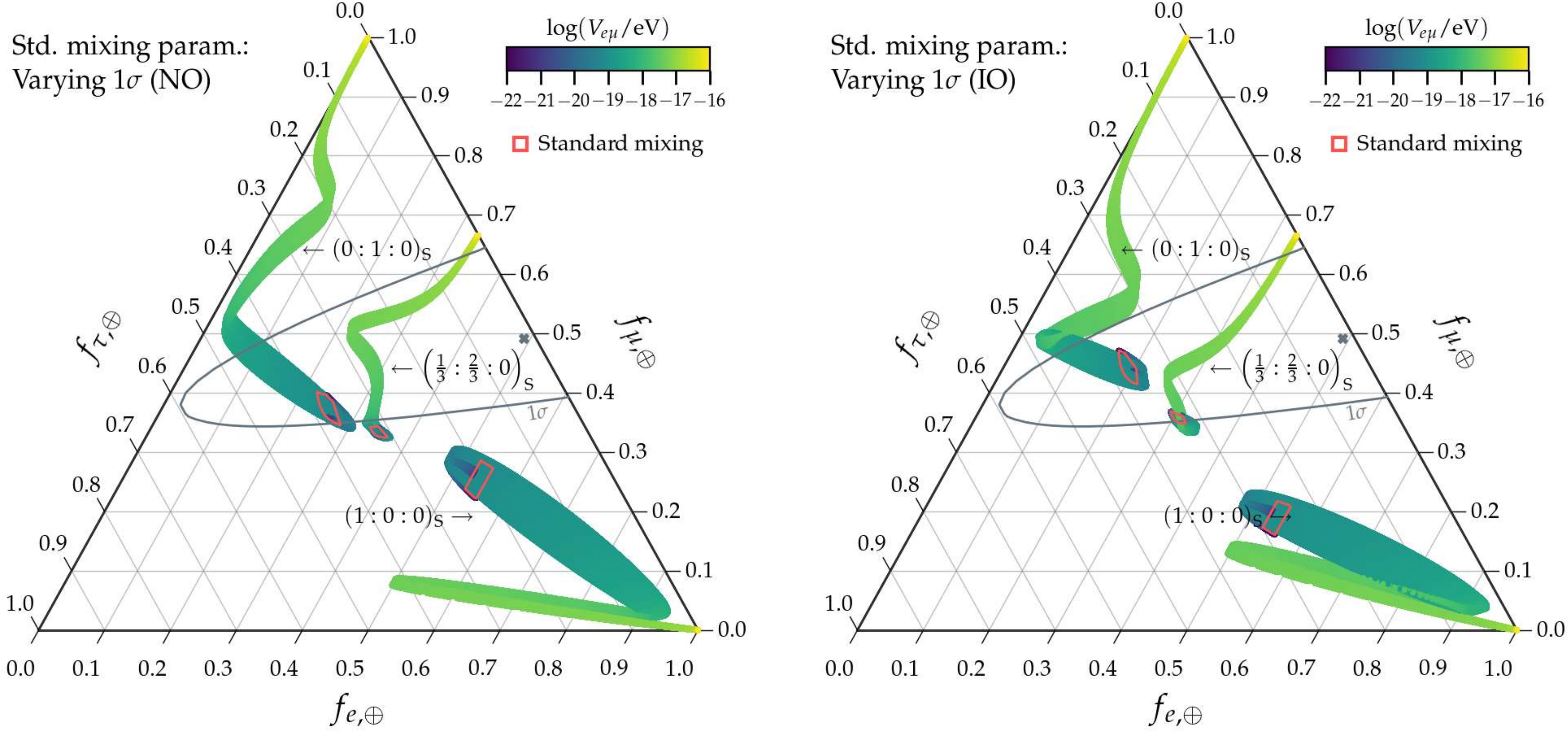


Resonance due to the L_e-L_μ symmetry (*cont.*)





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



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