Neutrino Properties from Observations in Astroparticle Physics

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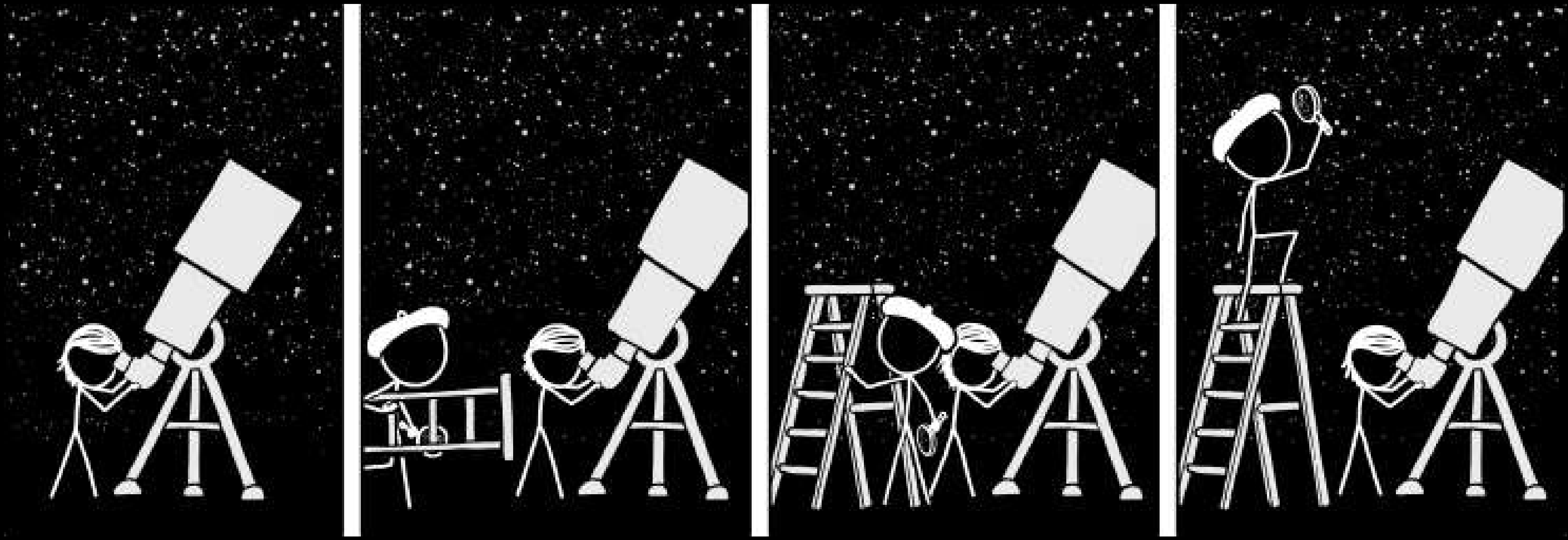
Niels Bohr Institute, University of Copenhagen

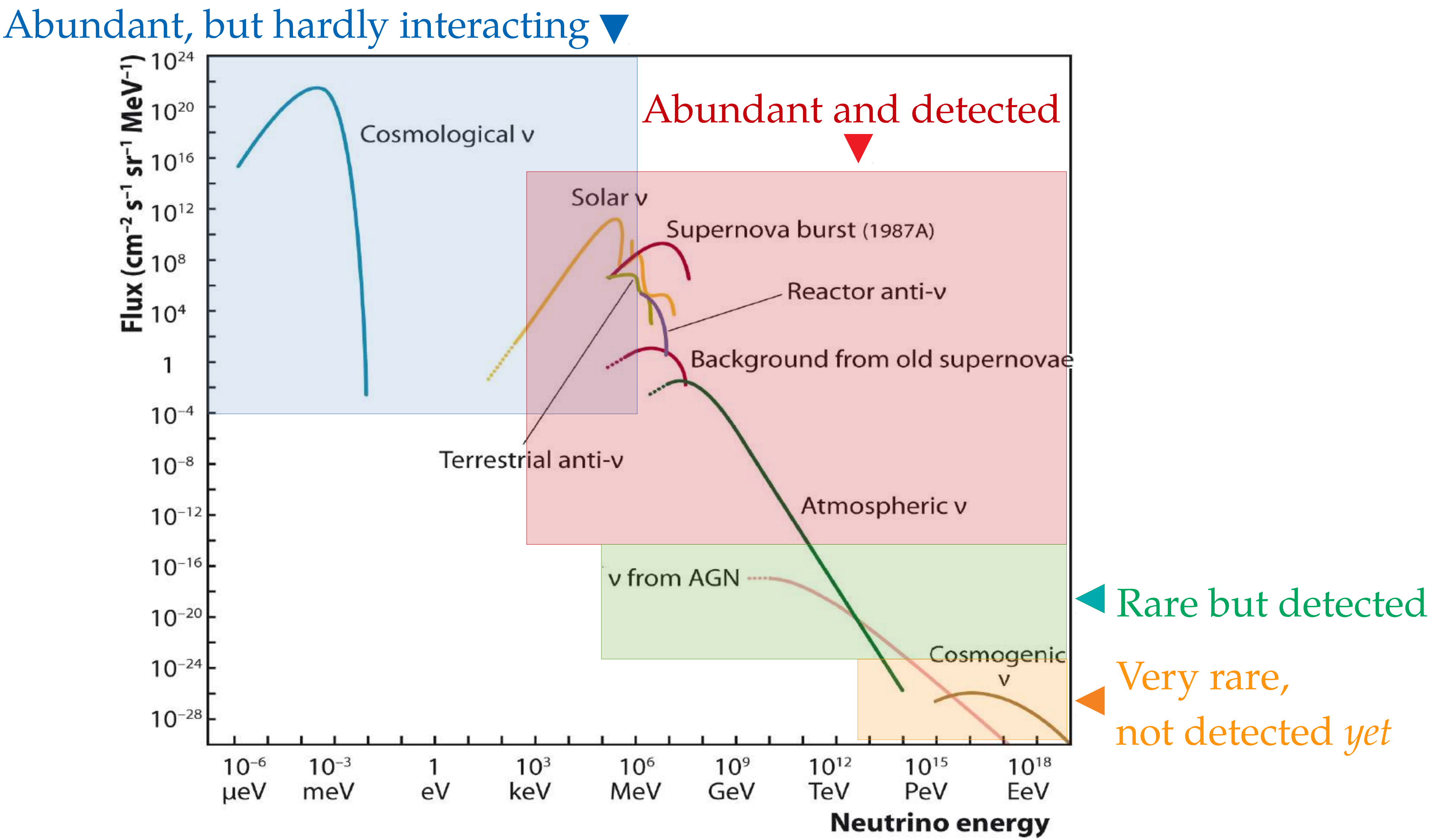
30th Rencontres de Blois
June 07, 2018

UNIVERSITY OF COPENHAGEN



xkcd

Symmetry Magazine



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

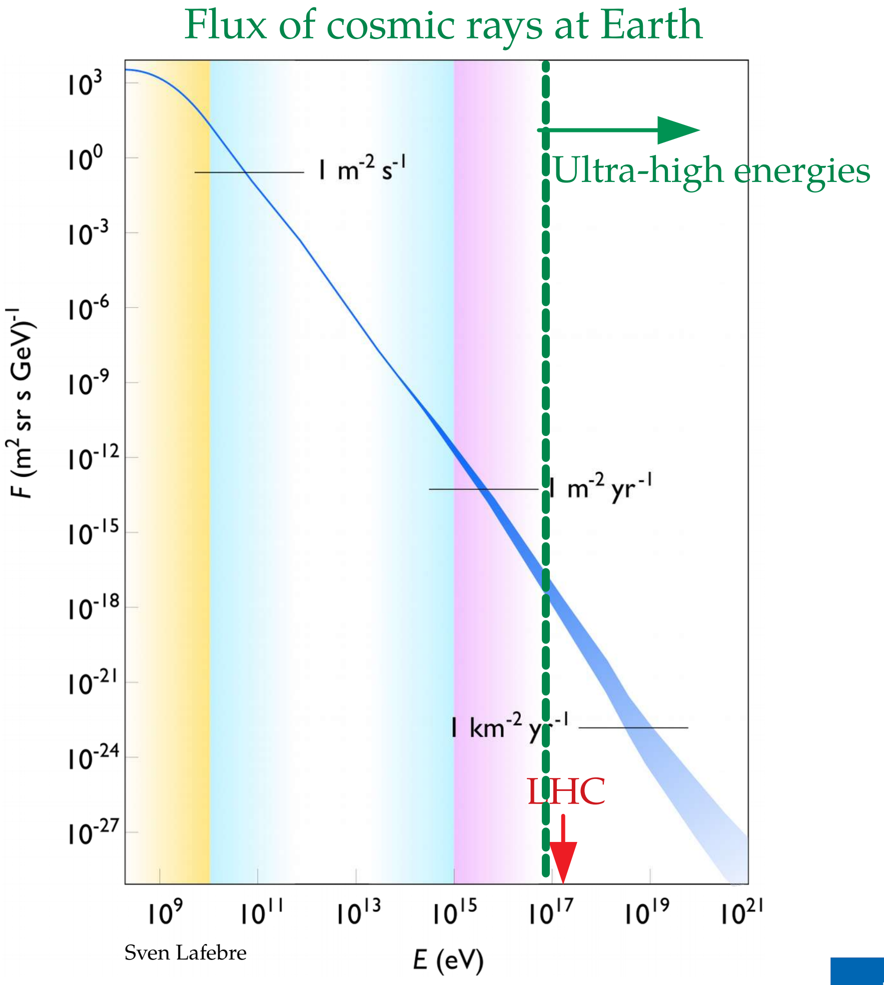
Why study high-energy astrophysical neutrinos?

They are key to answering two major questions –

1. What makes the most energetic particles we detect?

2. How does particle physics look at these energies?

Wed talks: S. Bron, X. Hou, A. Alberti, G. Ferrara, L. Cremonesi, R. Da Silva
Fri talk: K. Satalecka



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

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

1. They have the highest energies (~PeV)
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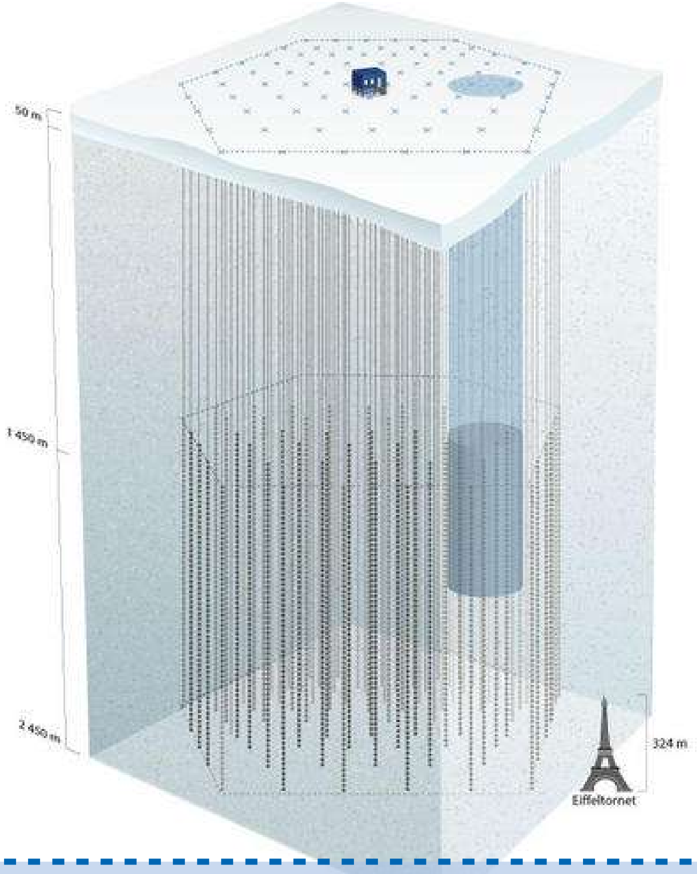
3. It comes *for free*

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

See talk by Konstancja Satalecka, Fri 09:00

How does IceCube see neutrinos?

Two types of fundamental interactions . . .

Charged-current (CC)

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

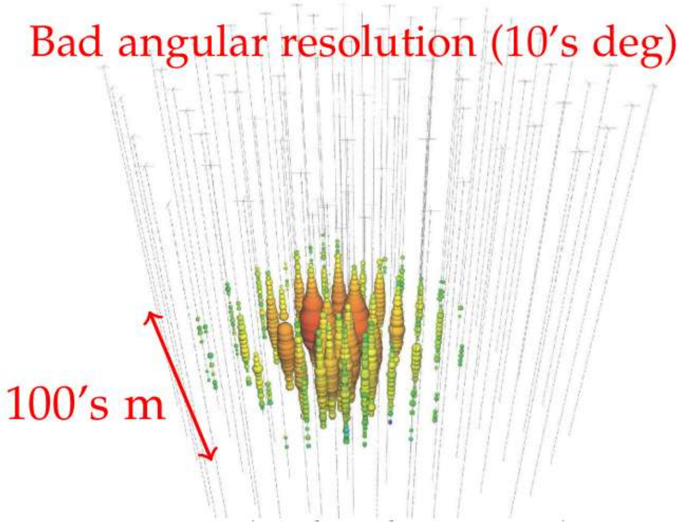
Neutral-current (NC)

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

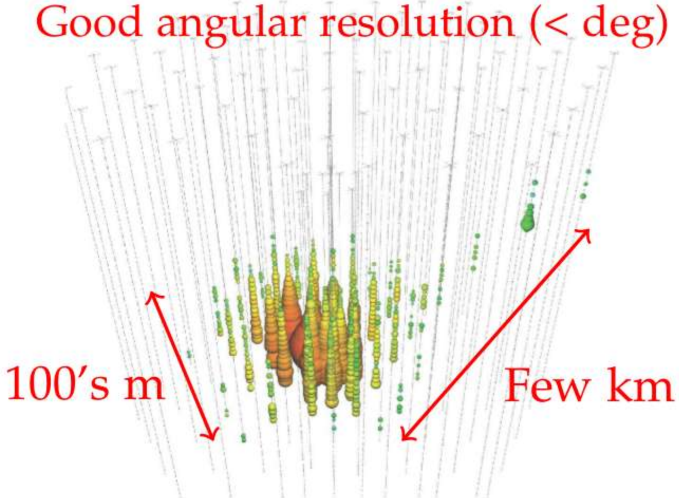
These shower and make light

. . . create two event topologies . . .

Showers — From CC ν_e or ν_τ, or NC ν_x



Tracks — From CC ν_μ mainly



What has IceCube found so far (7.5 years)?

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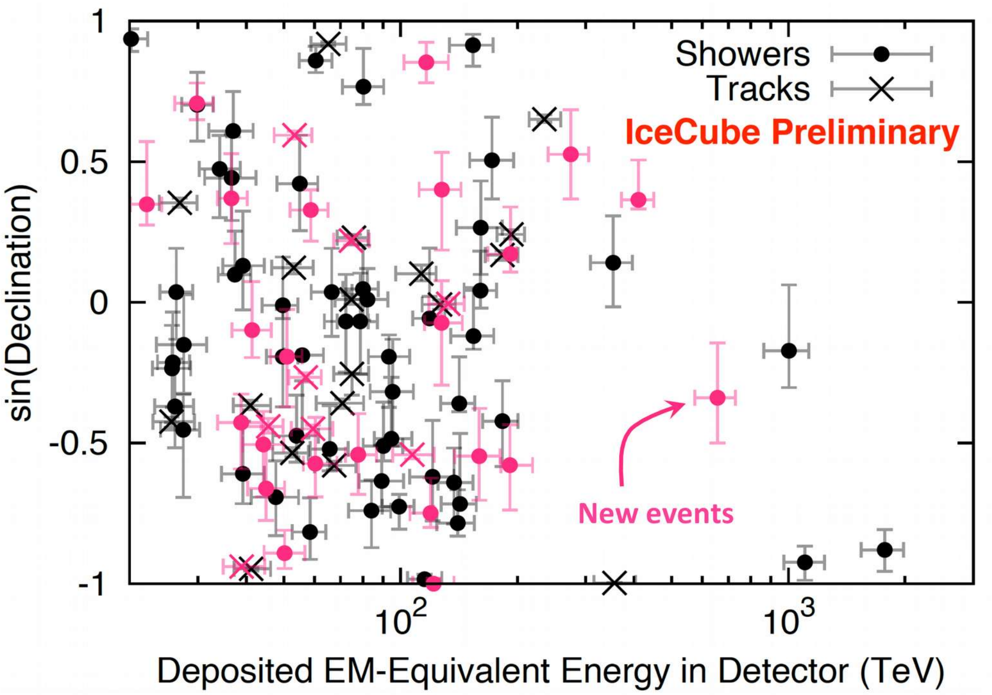
103 contained events between 15 TeV – 2 PeV



I. Taboada, Neutrino 2018

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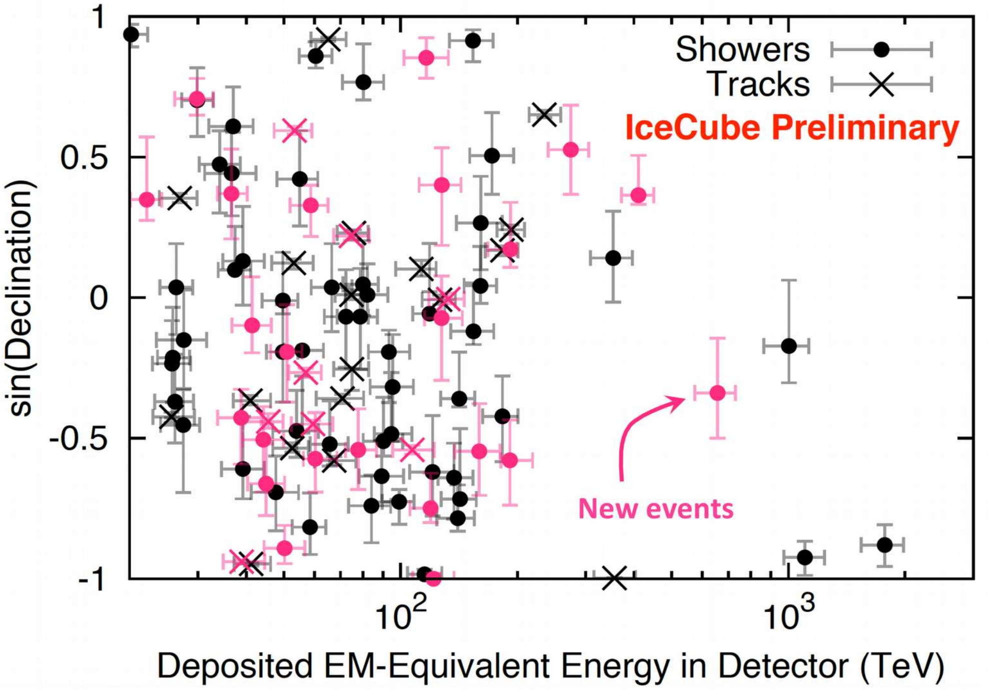
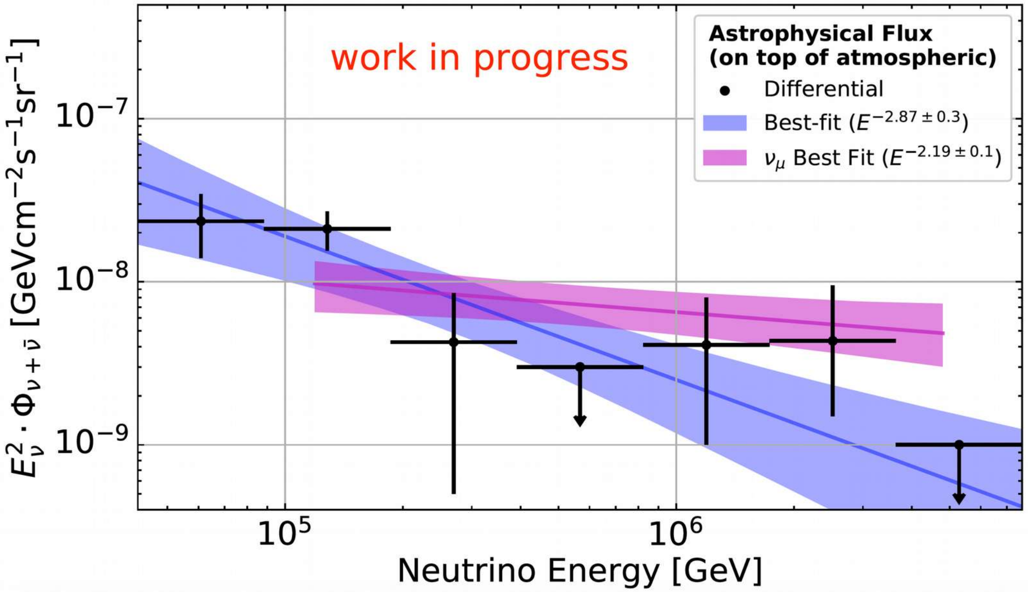


Astrophysical ν flux detected at > 7σ

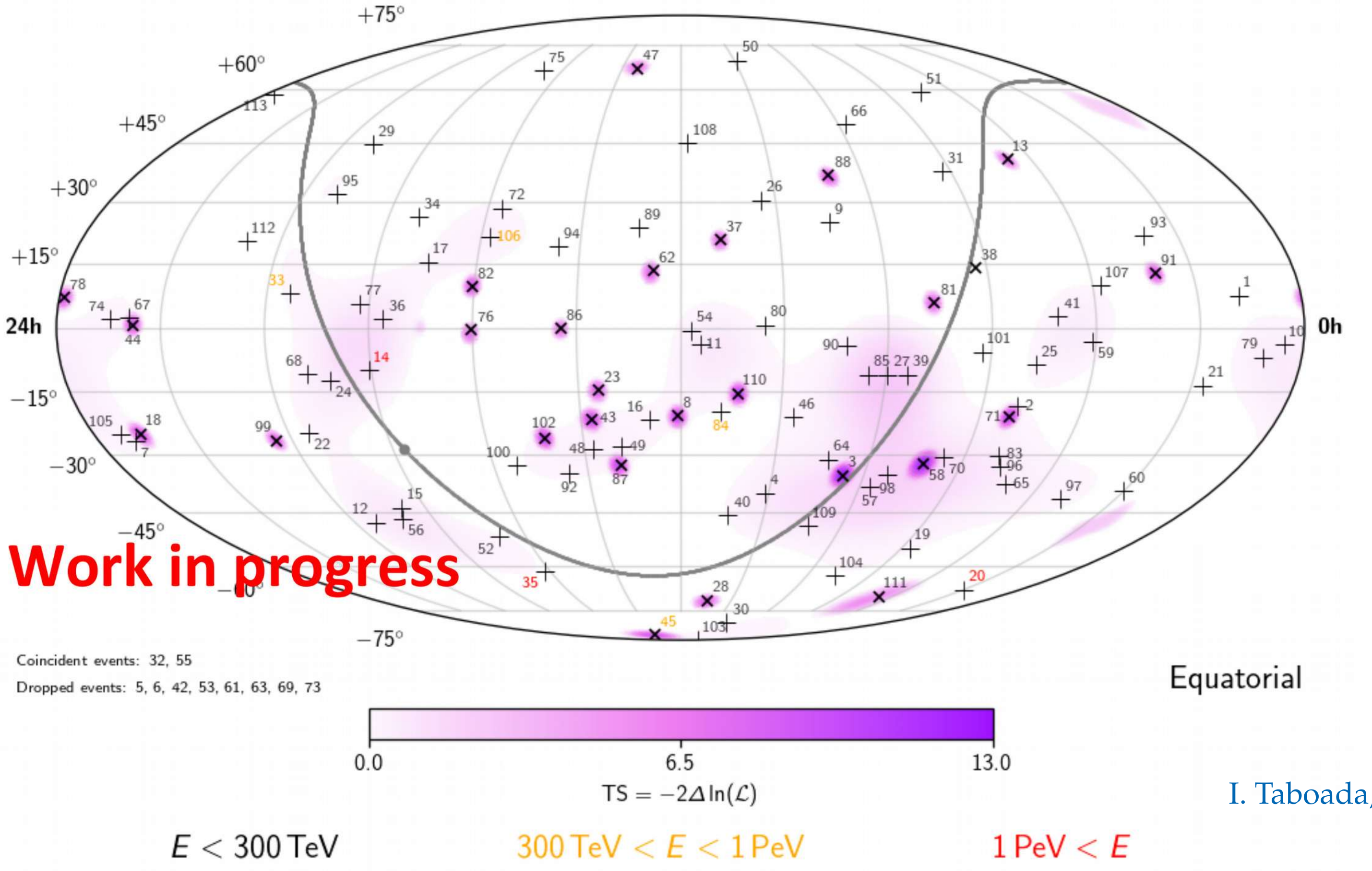
(Normalization ok, but steep spectrum)



I. Taboada, Neutrino 2018

What has IceCube found so far (7.5 years)?

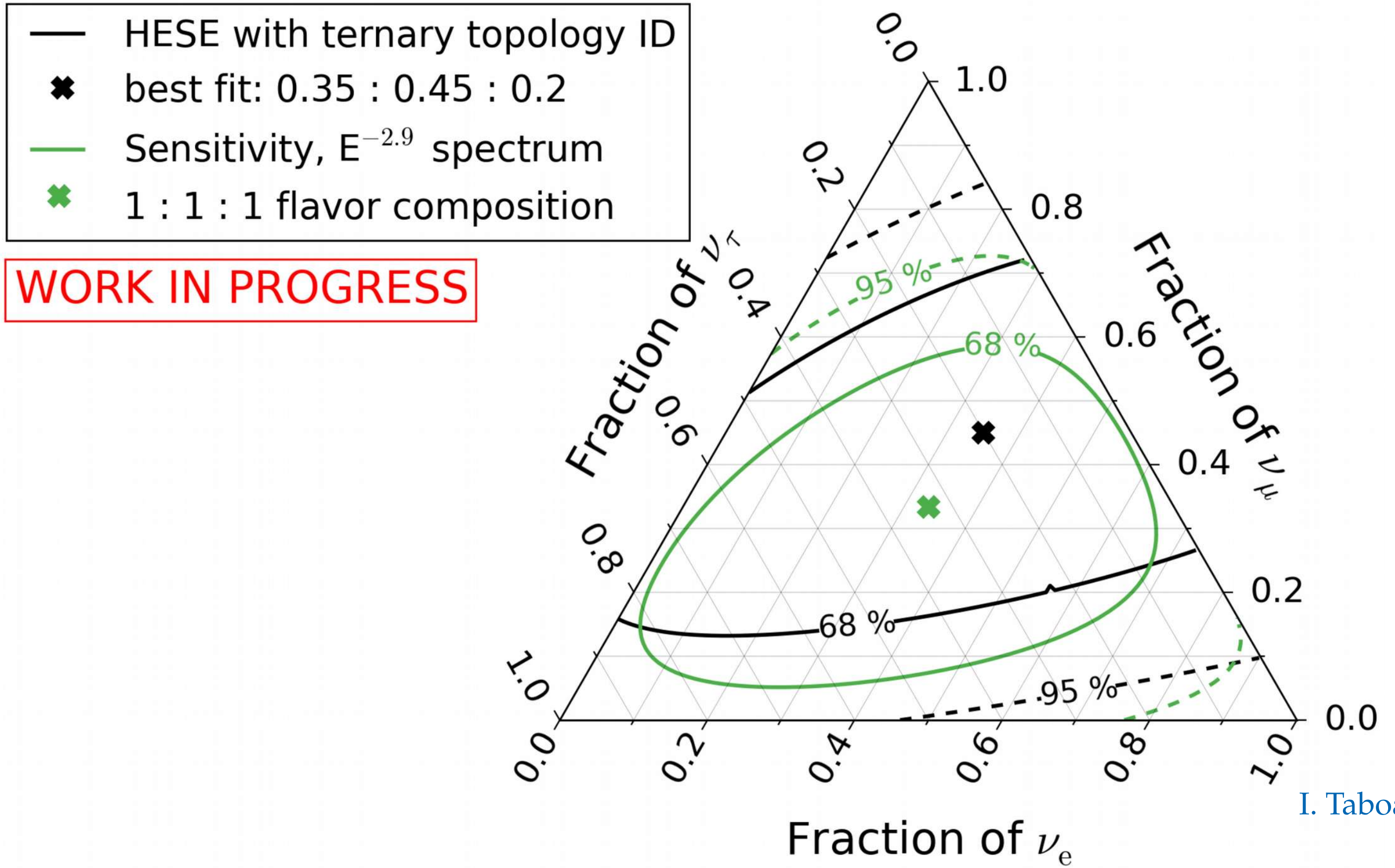
Arrival directions compatible with isotropy



I. Taboada, Neutrino 2018

What has IceCube found so far (7.5 years)?

Flavor composition compatible with equal proportion of each flavor



I. Taboada, Neutrino 2018

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

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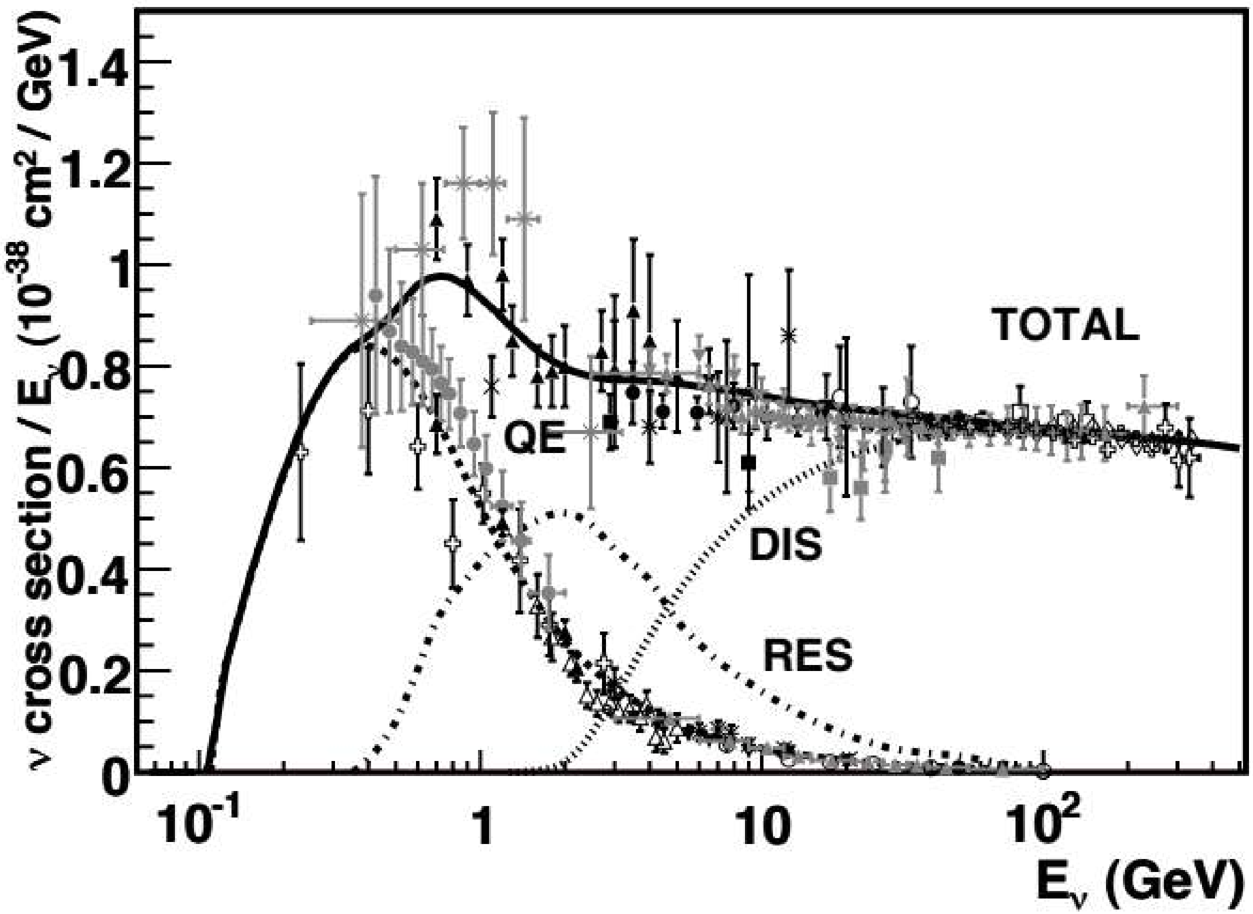
can we extract fundamental TeV–PeV ν physics?

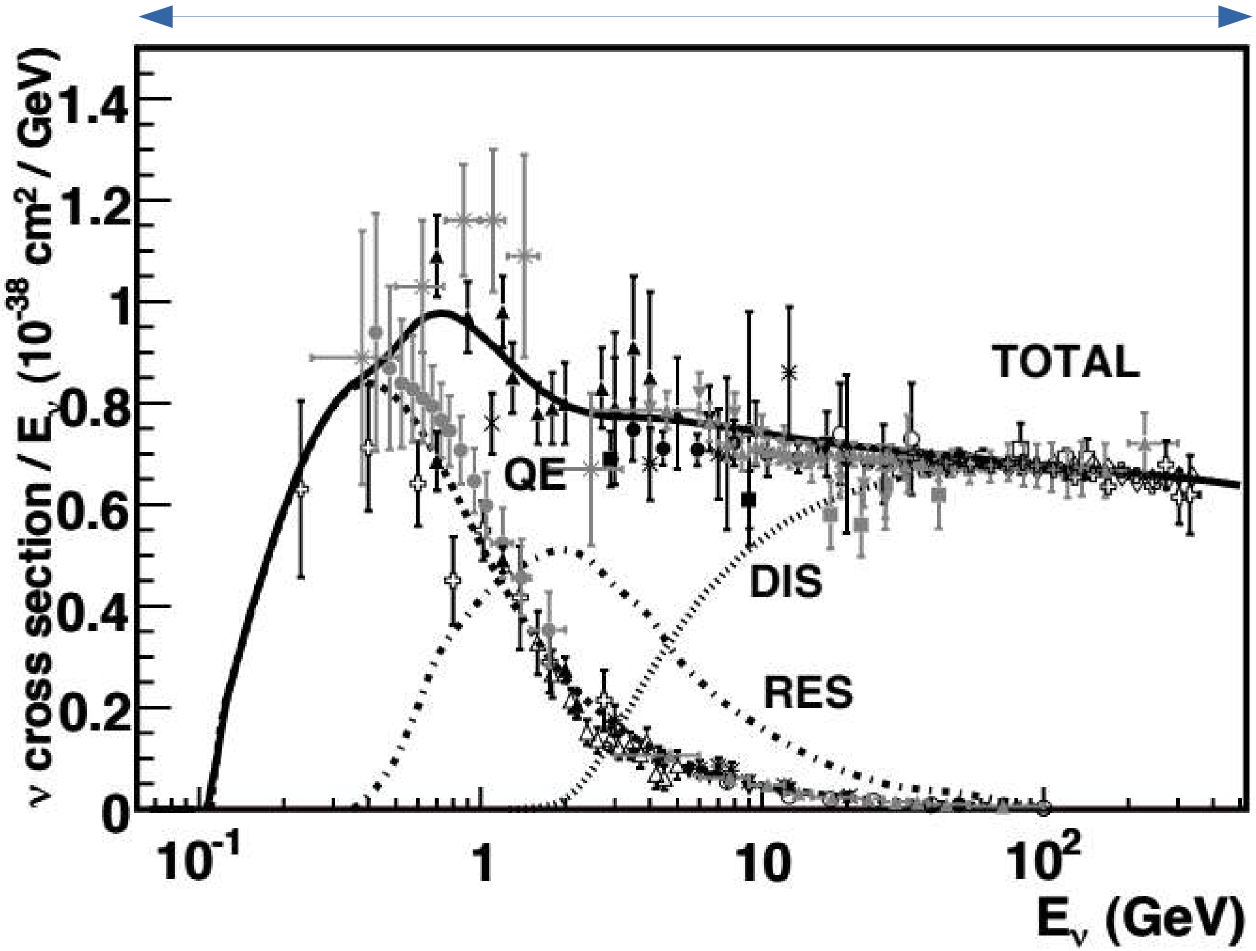
Yes.


Neutrino physicist



Particle Data Group

Accelerator experiments

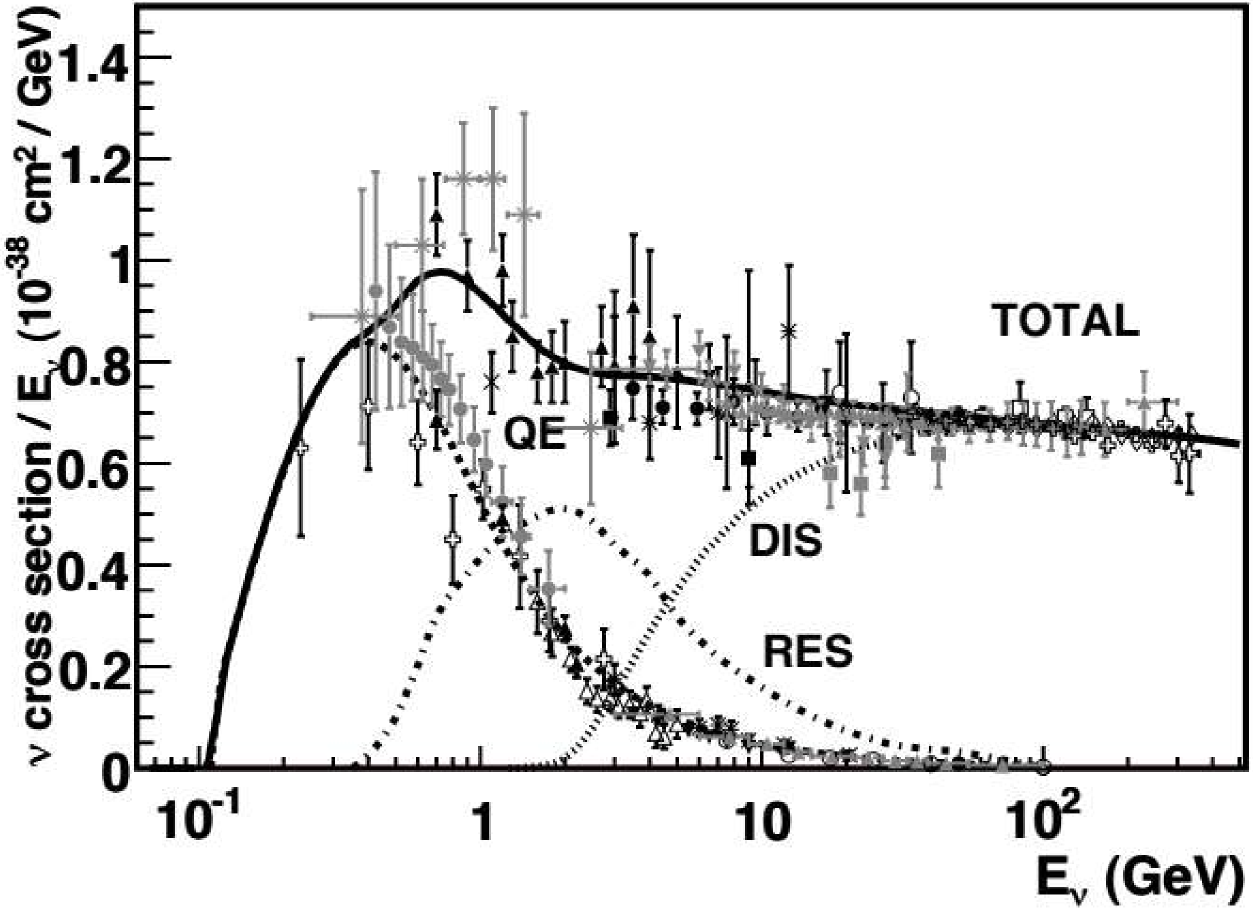


Particle Data Group

Accelerator experiments

One recent measurement (COHERENT)

Talk by Phil Barbeau



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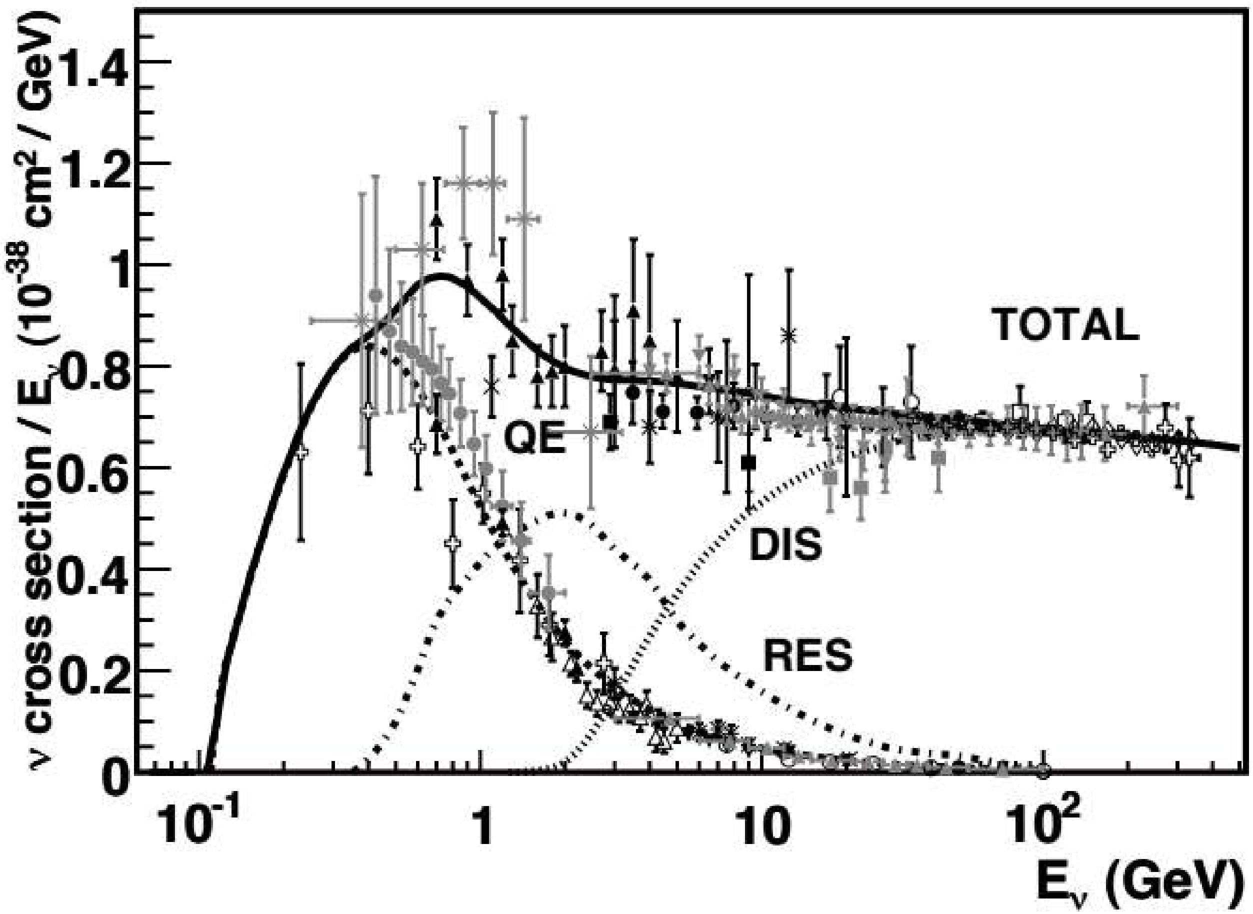


Particle Data Group

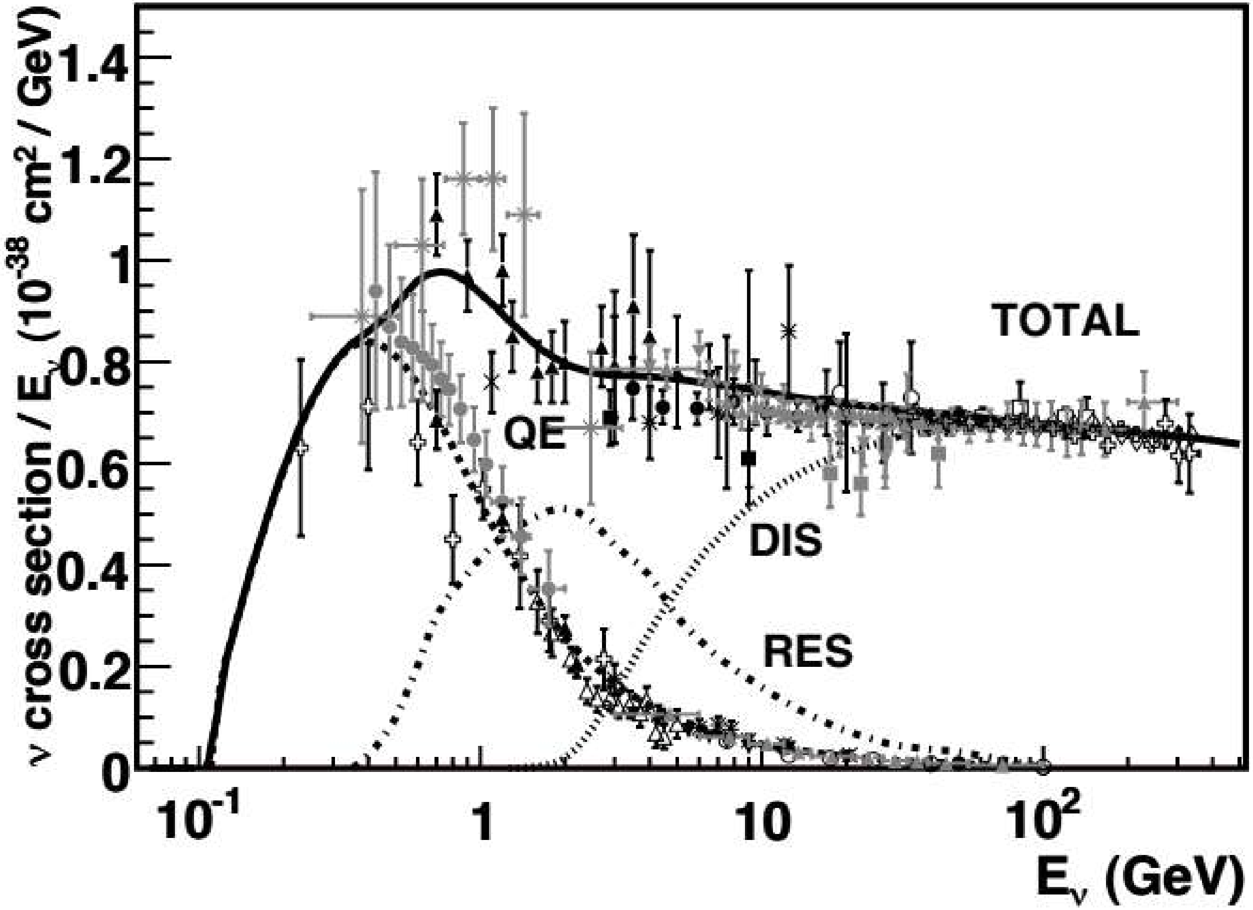
One recent measurement (COHERENT)

Talk by Phil Barbeau

No measurements

… until now!

Accelerator experiments



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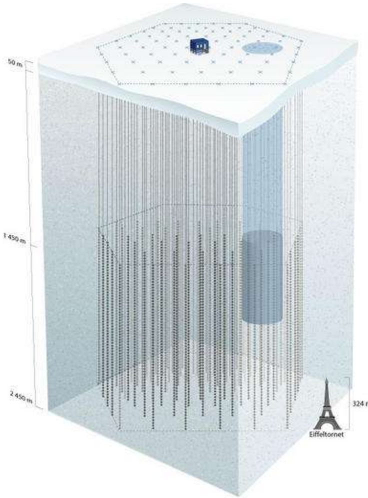
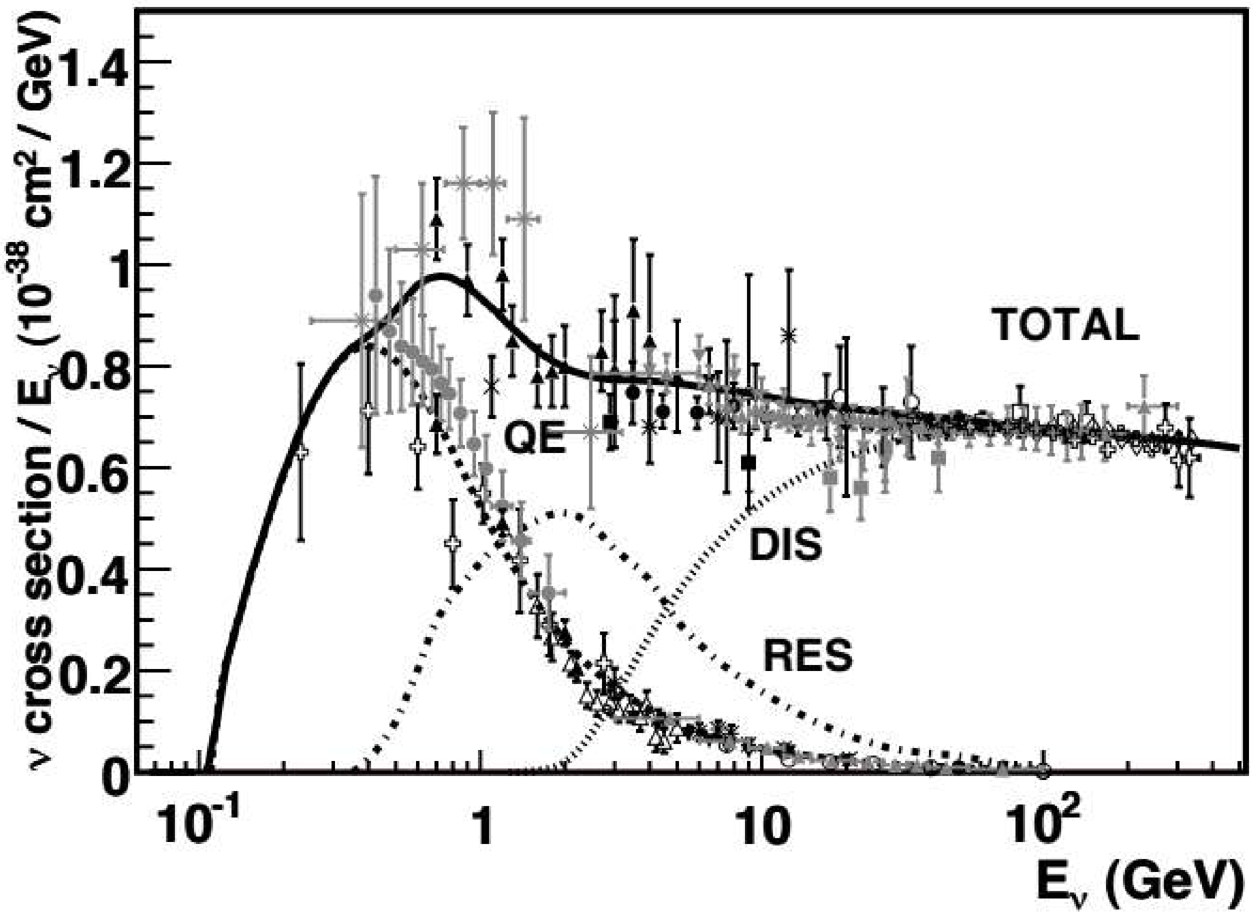


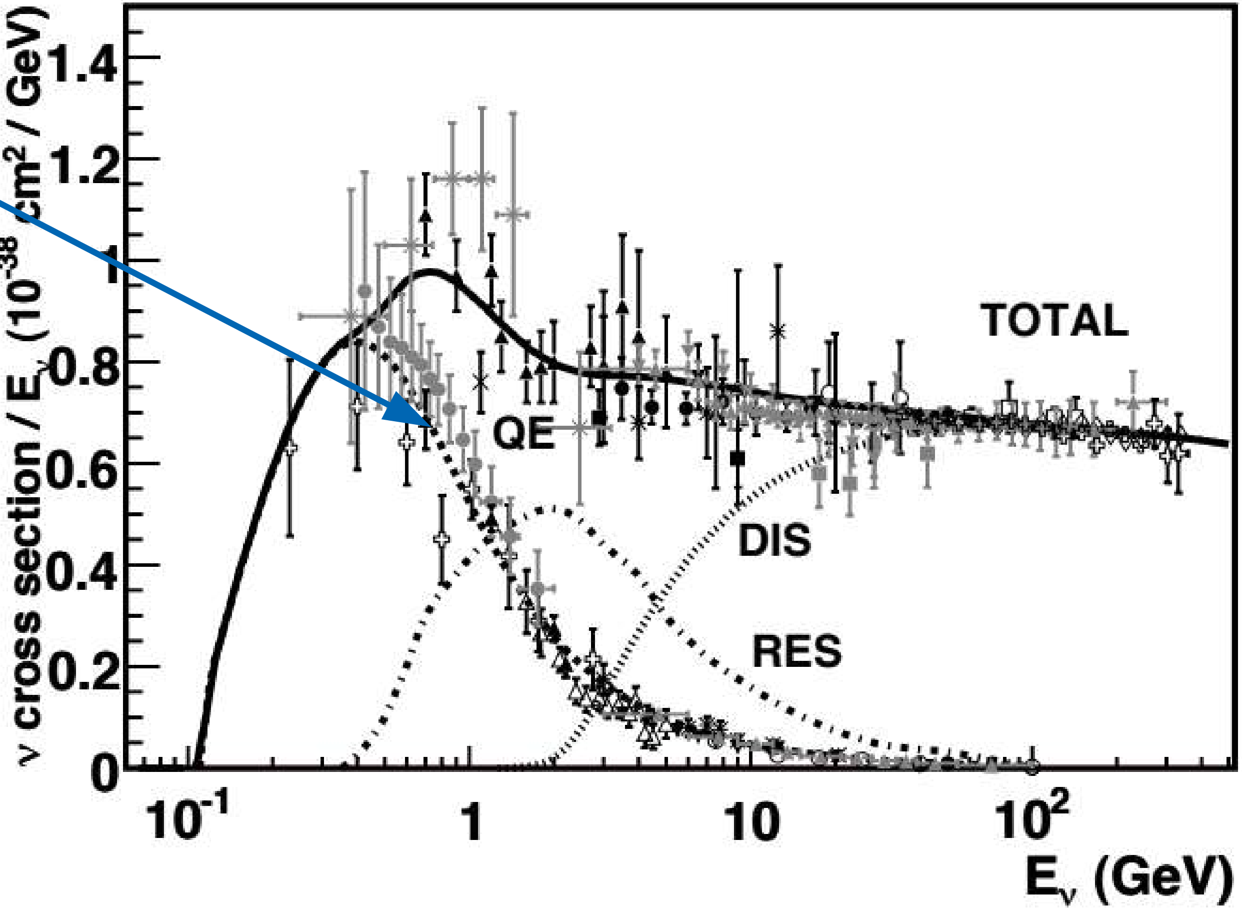


Particle Data Group

Quasi-elastic scattering:

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

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



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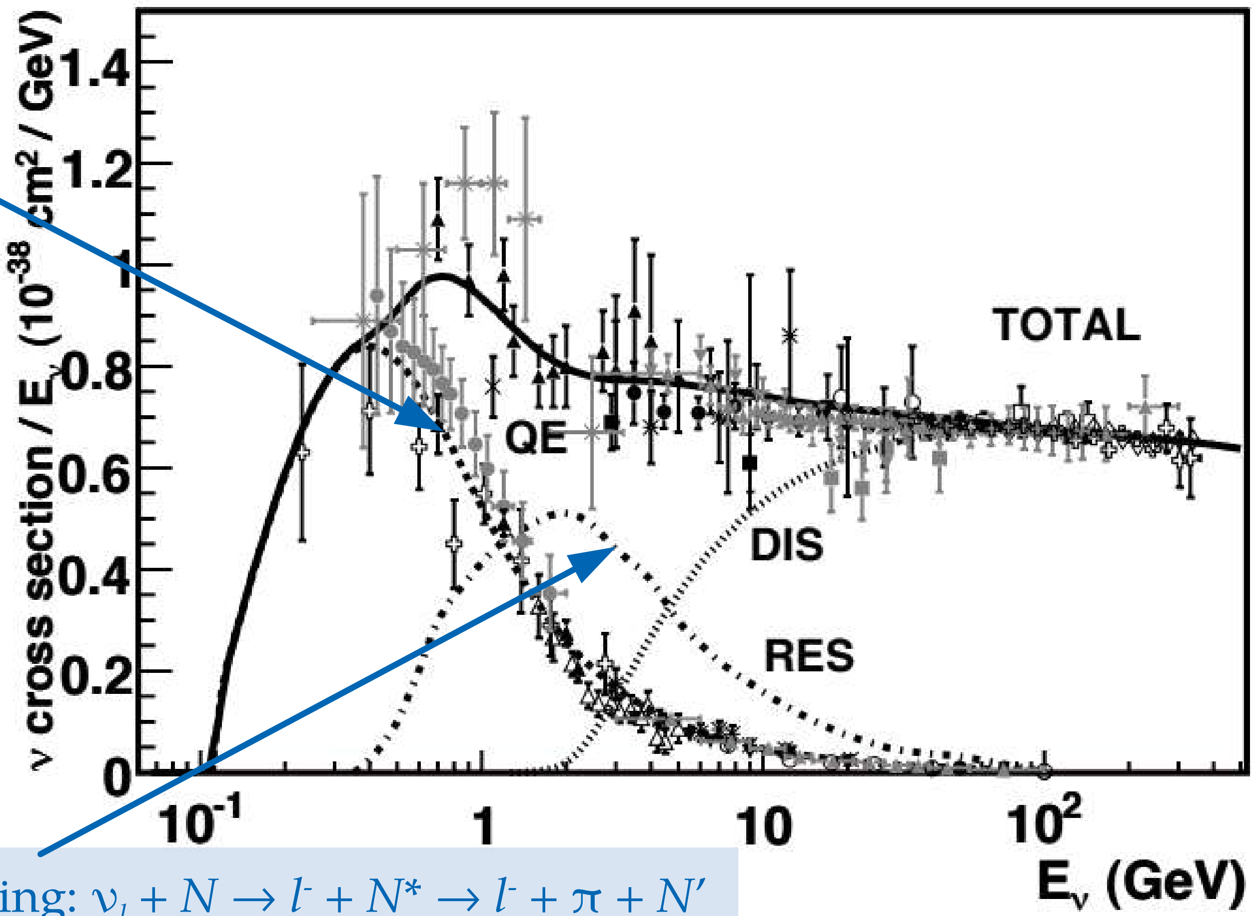

Resonant scattering: $\nu_l + N \to l^- + N^* \to l^- + \pi + N'$

Particle Data Group

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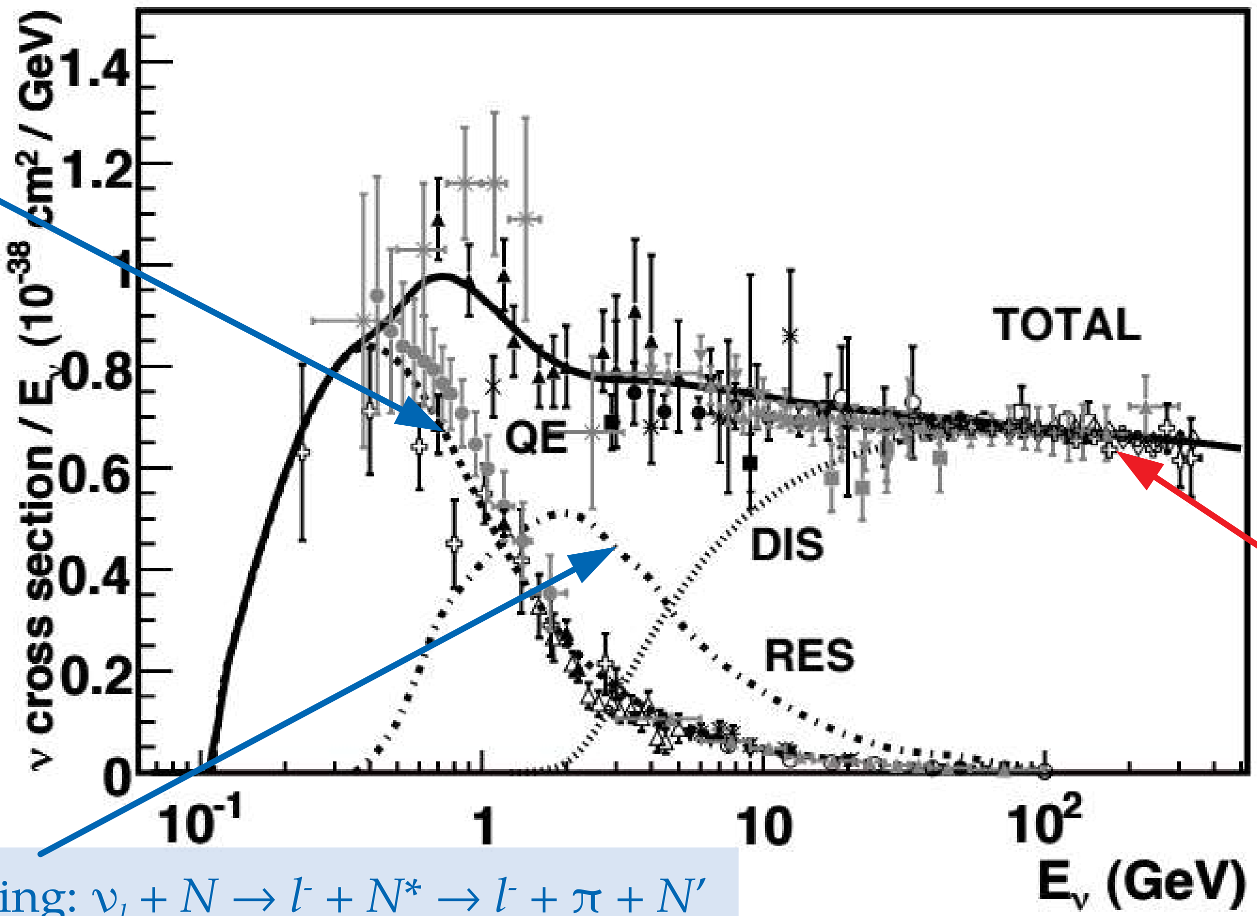
$\nu_l + n \rightarrow l^- + p$

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



Deep inelastic scattering:

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

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

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

Particle Data Group

Extrapolating the cross section to high energies

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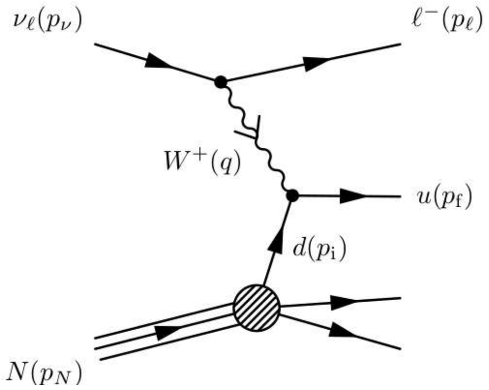
SM



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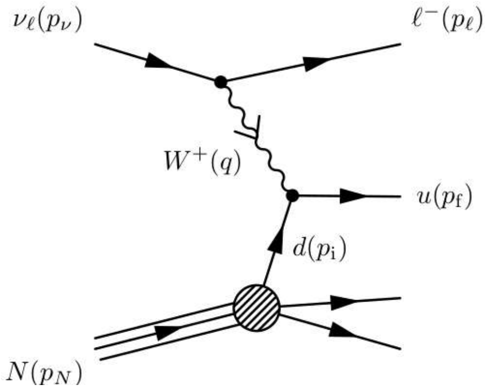

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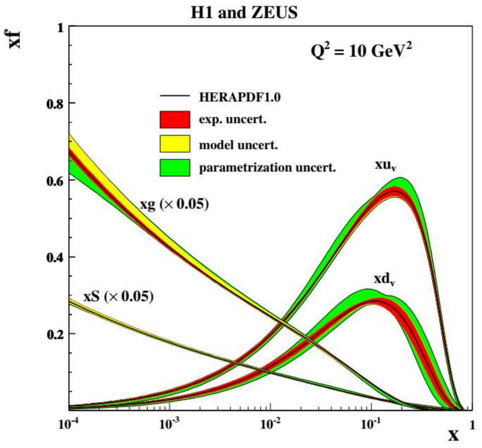
PDFs



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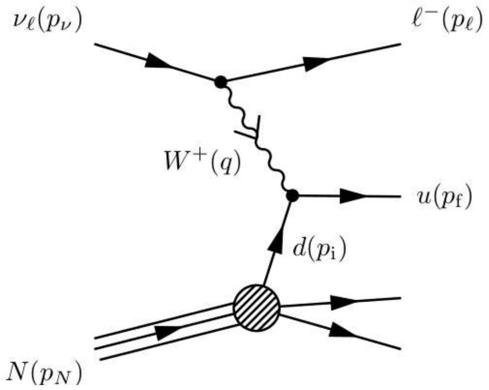

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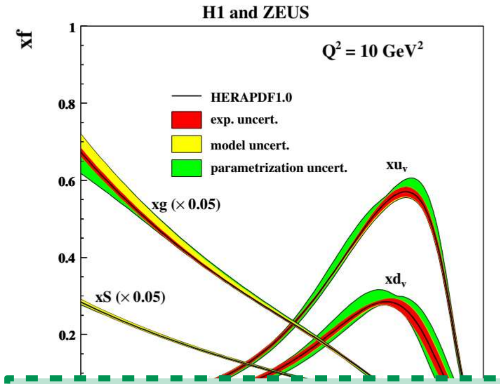

Talk by Francis Petriello

Extrapolating the cross section to high energies

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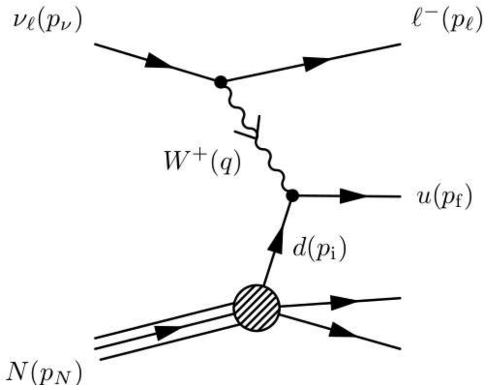

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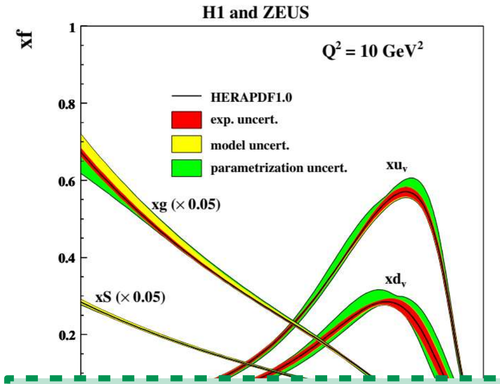

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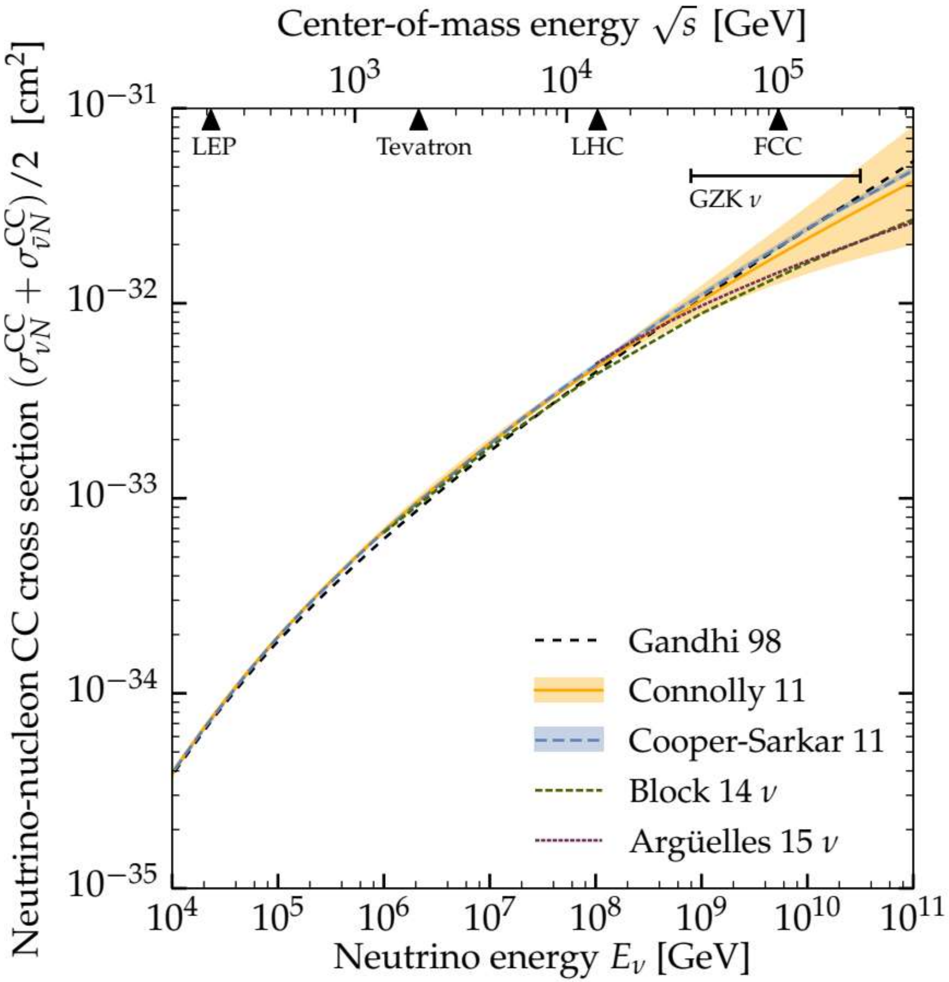
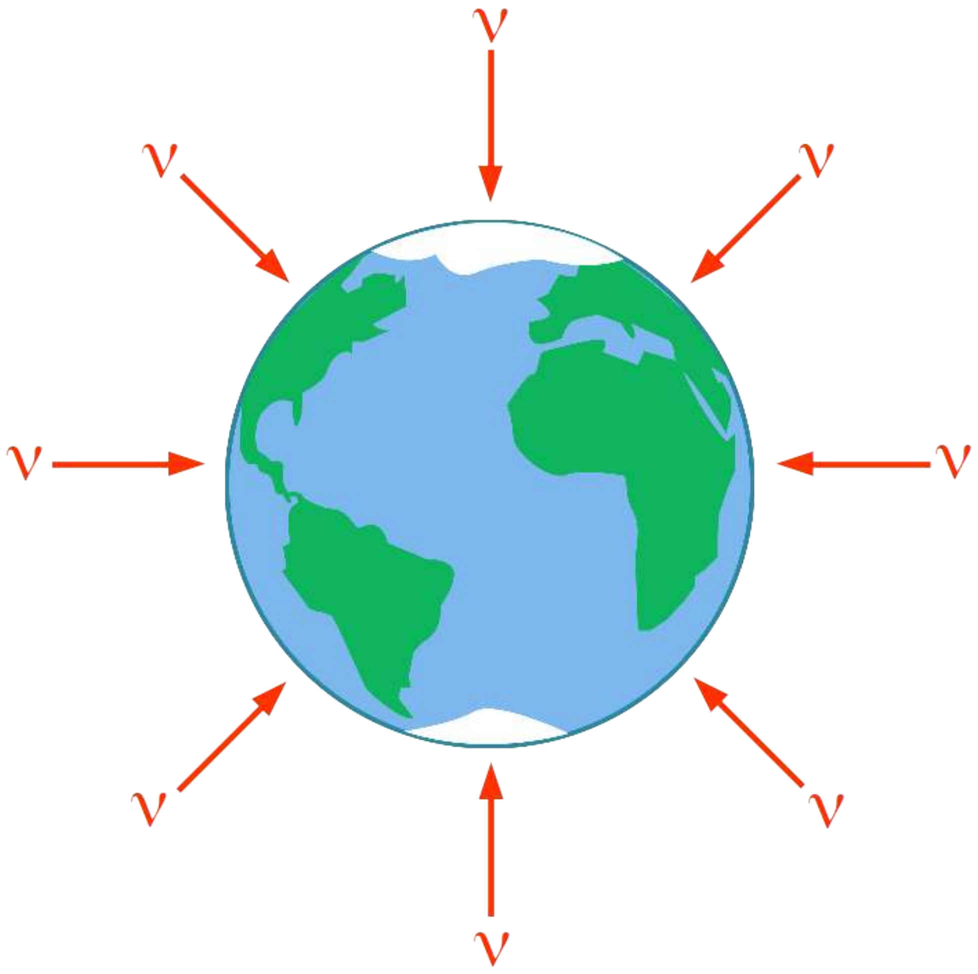


Neutrino, interrupted



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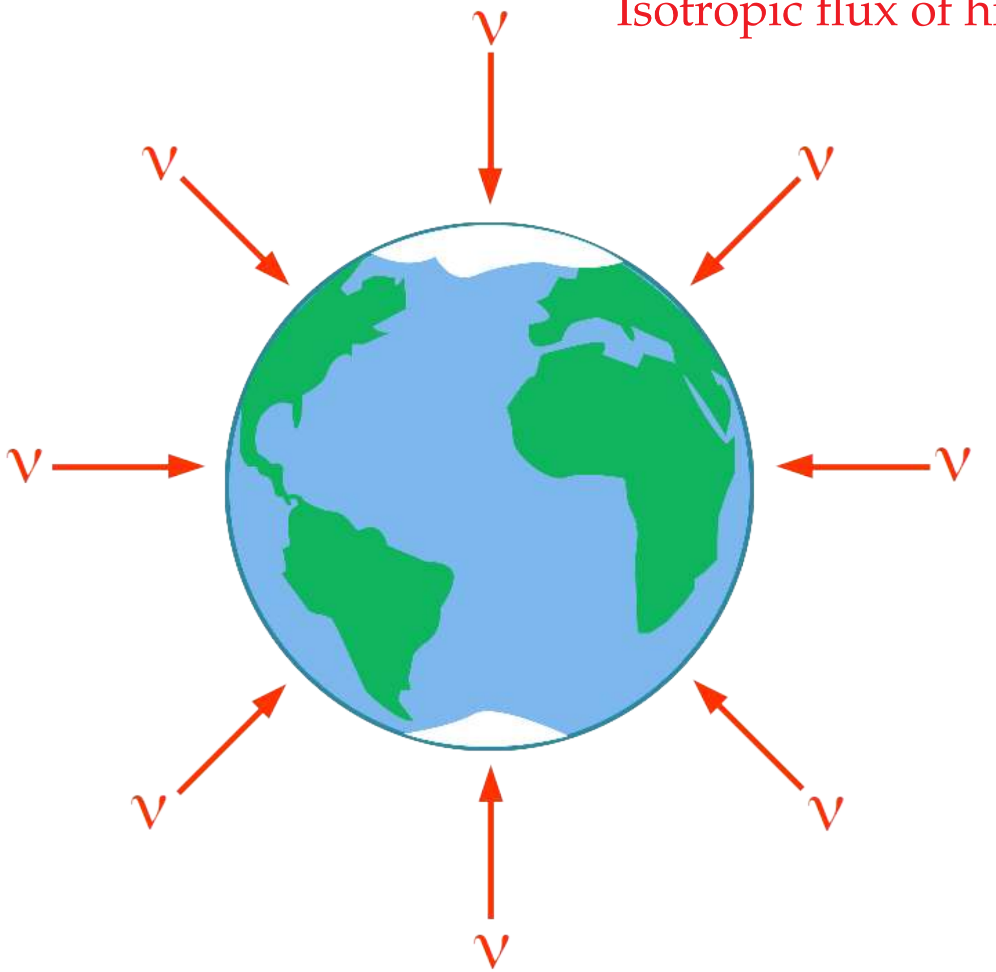
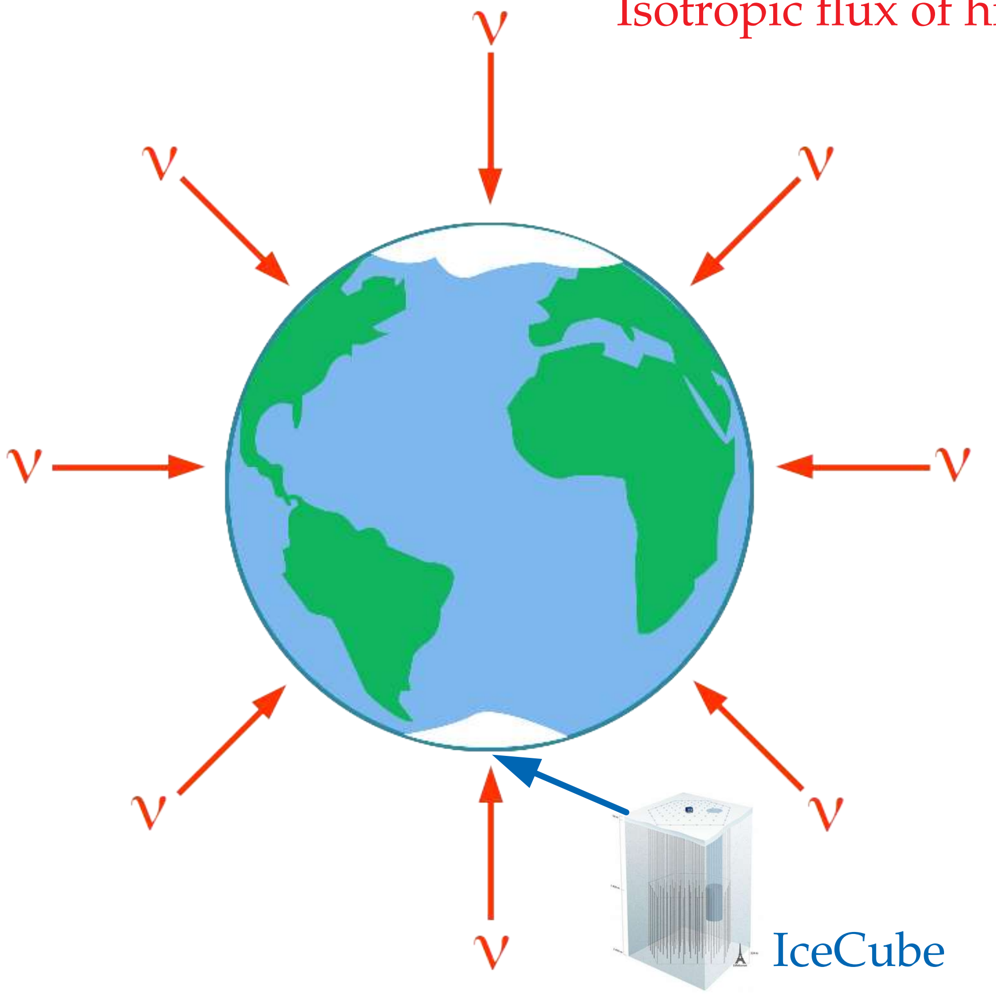
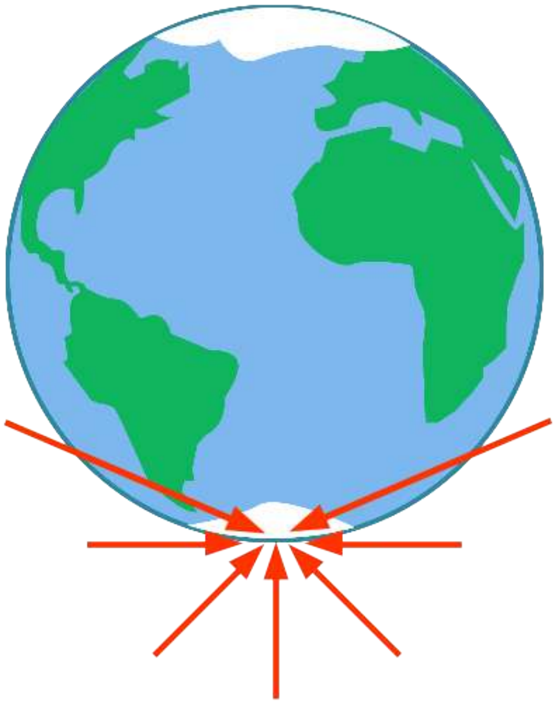


Neutrino, interrupted

Isotropic flux of high-energy neutrinos

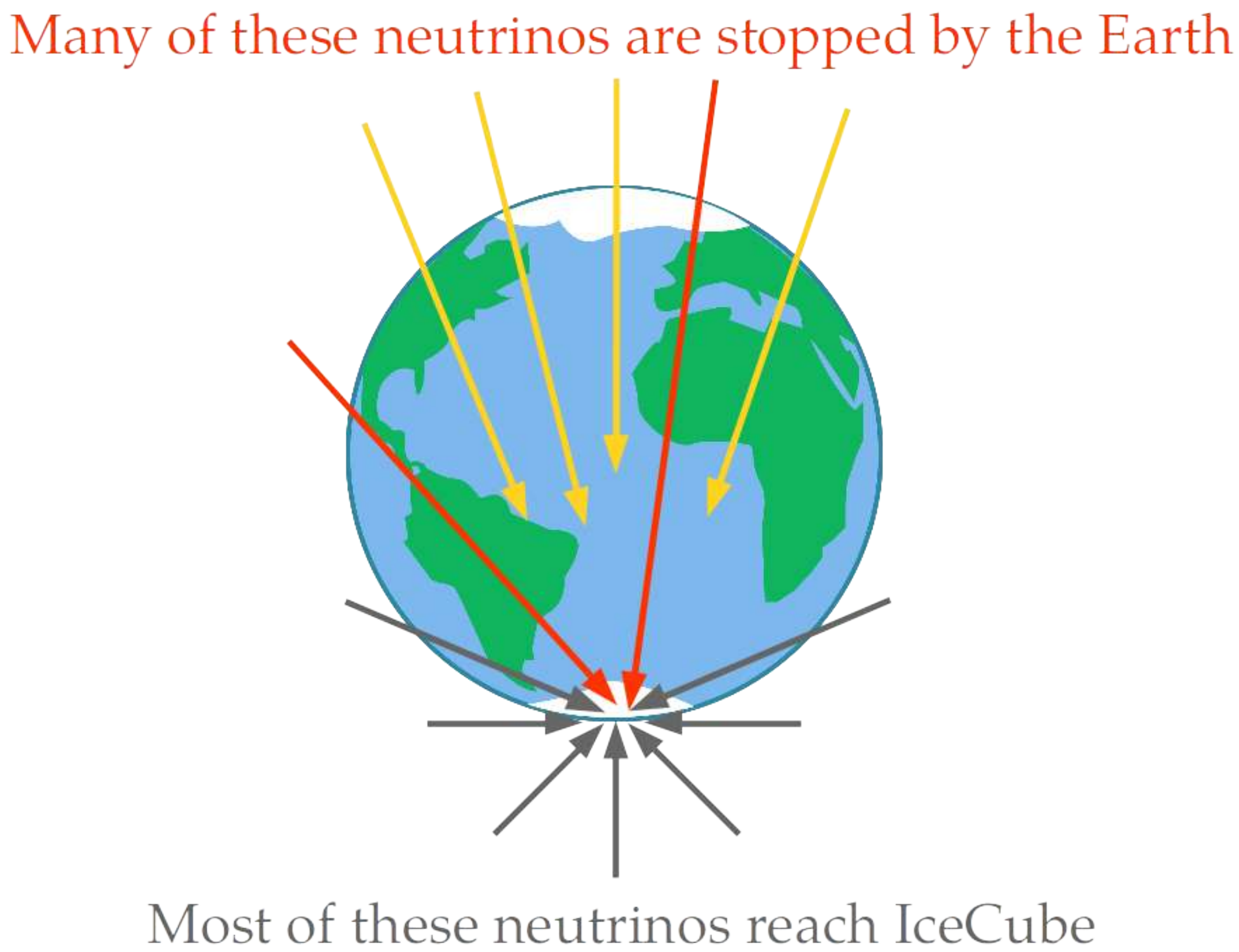


Neutrino, interrupted



Most of these neutrinos reach IceCube

Neutrino, interrupted

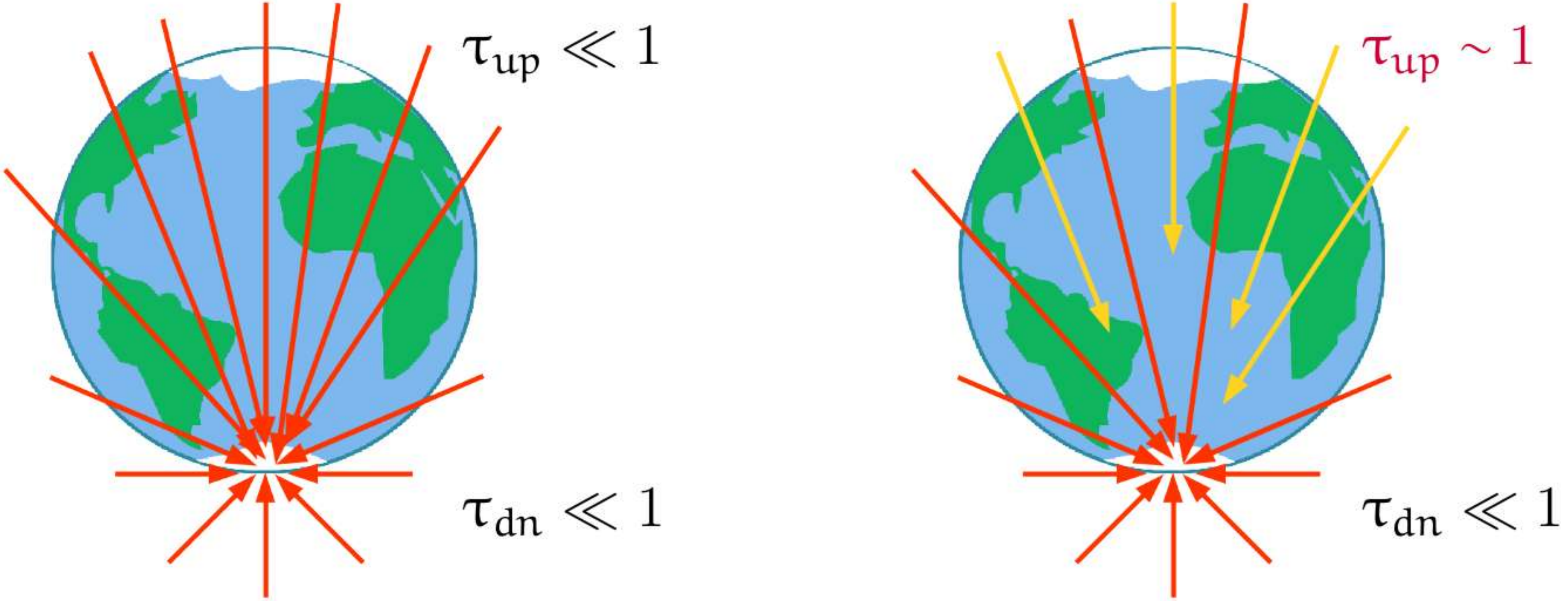


Measuring the high-energy cross section

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

Below ~ 10 TeV: Earth is transparent

Above ~ 10 TeV: Earth is opaque



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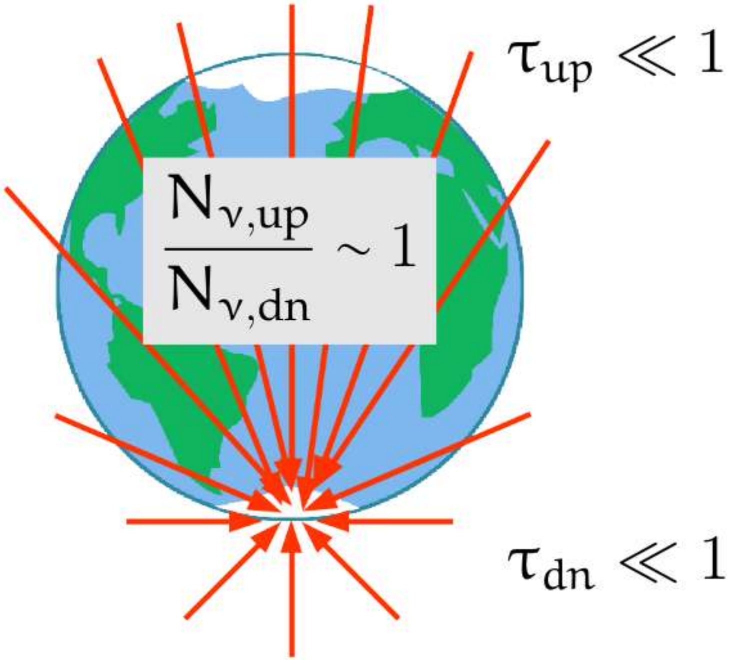

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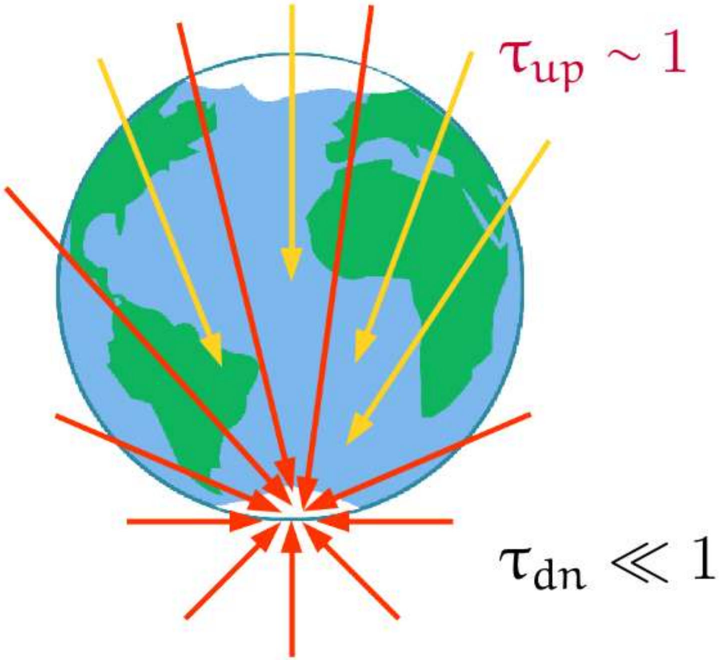

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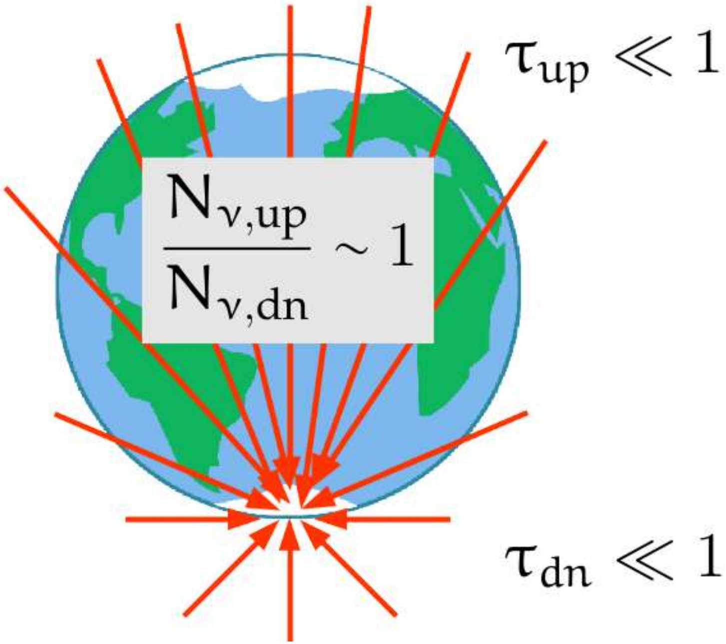

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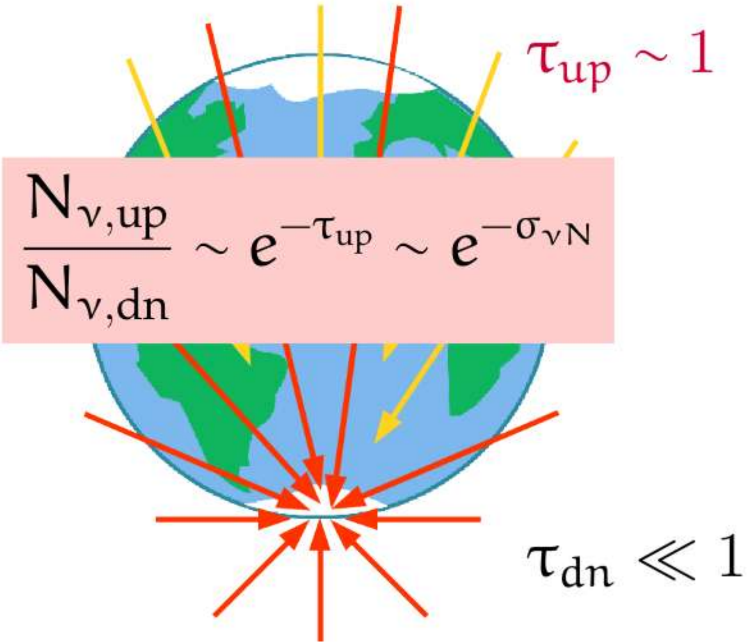
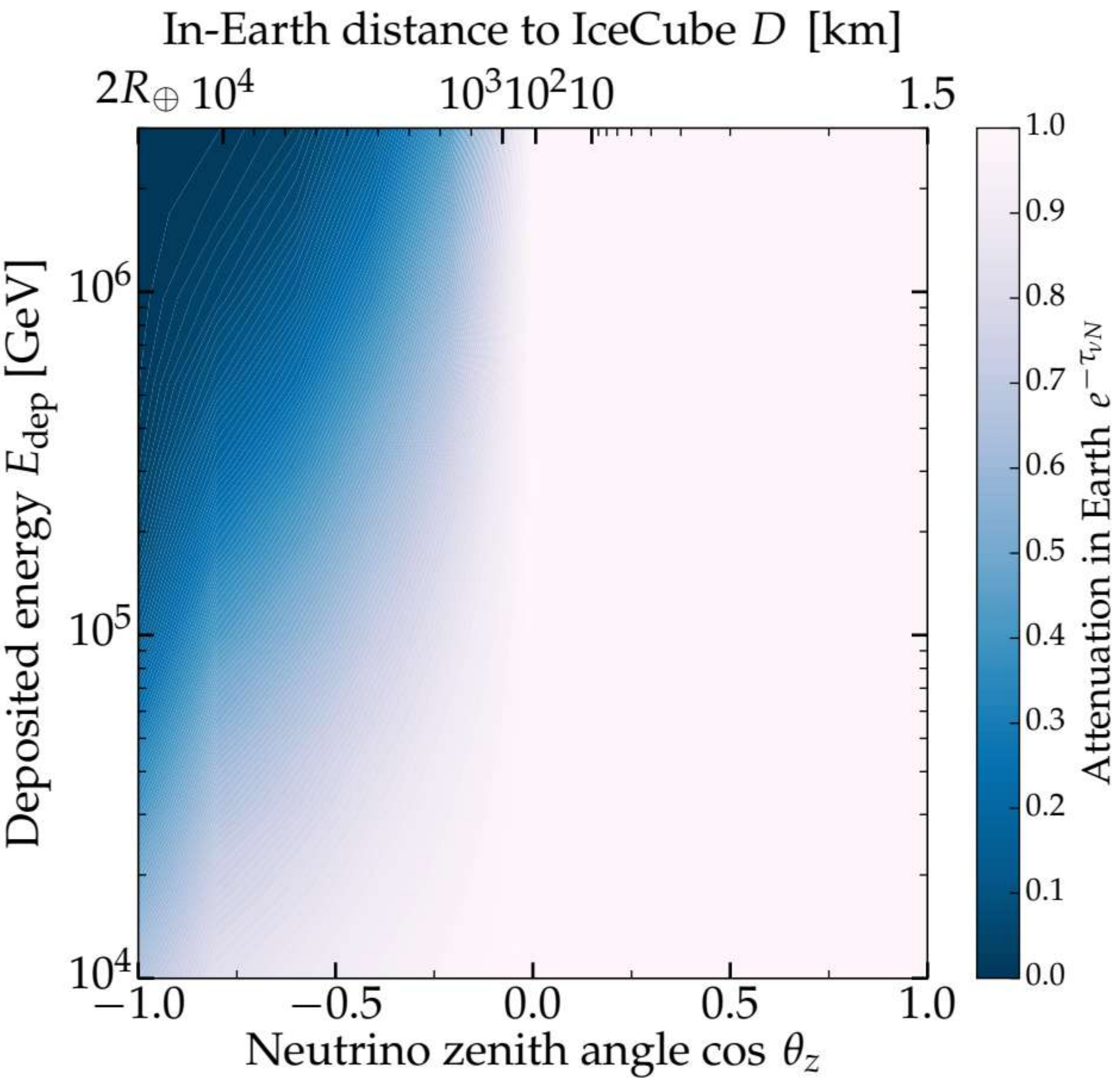
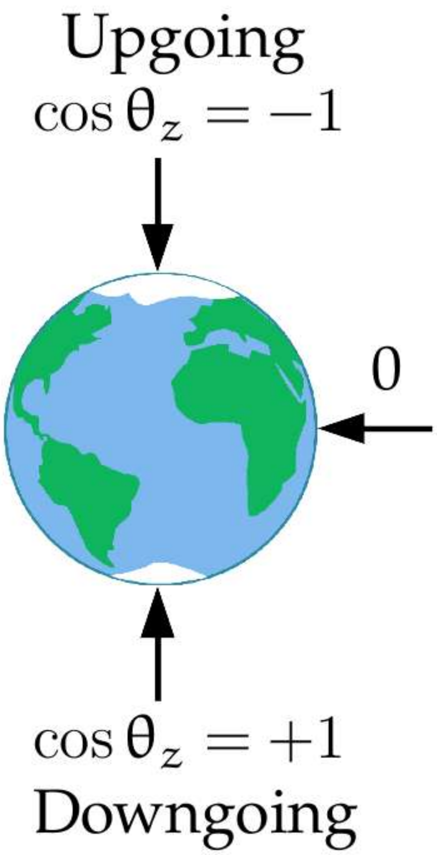
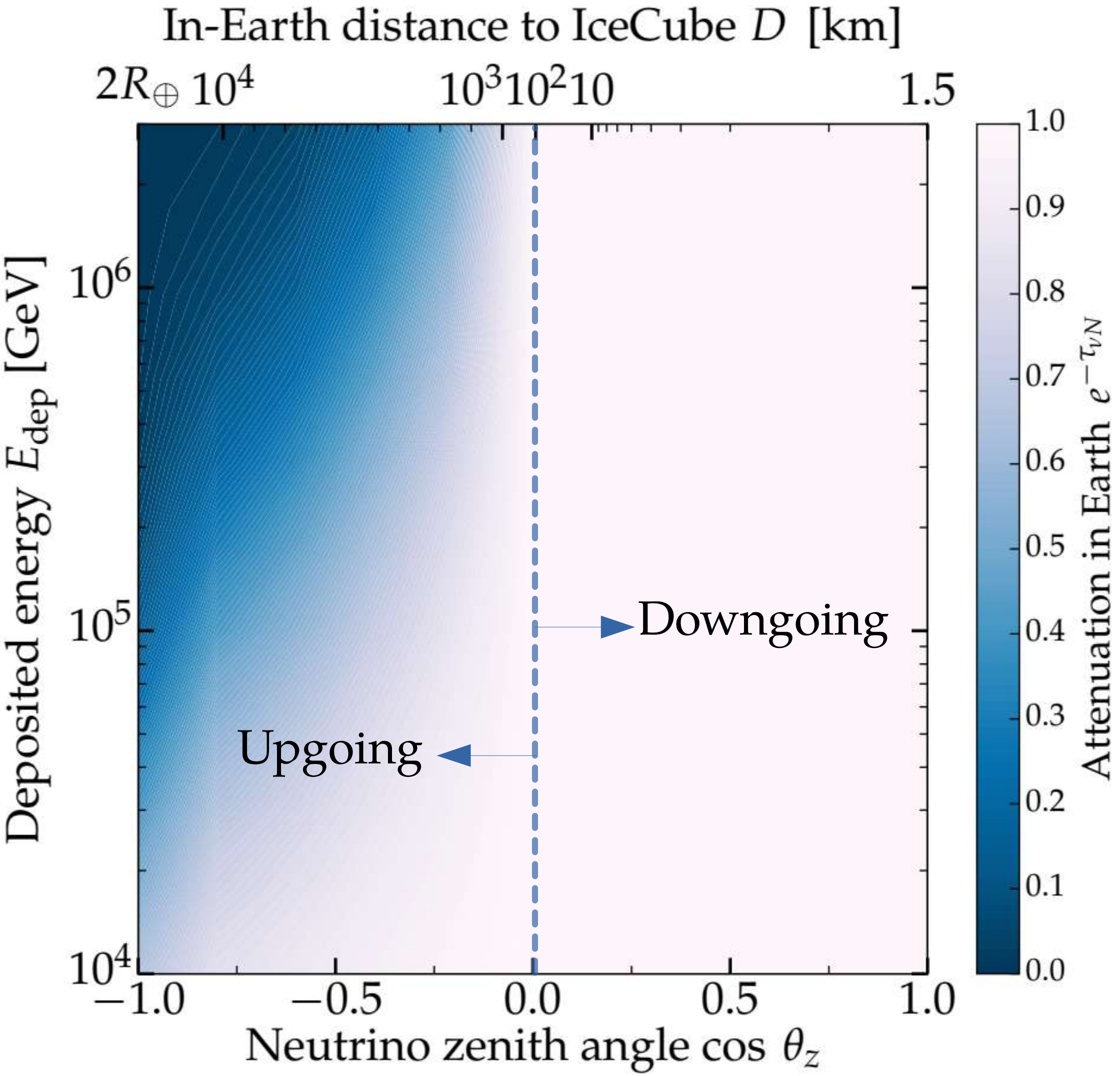




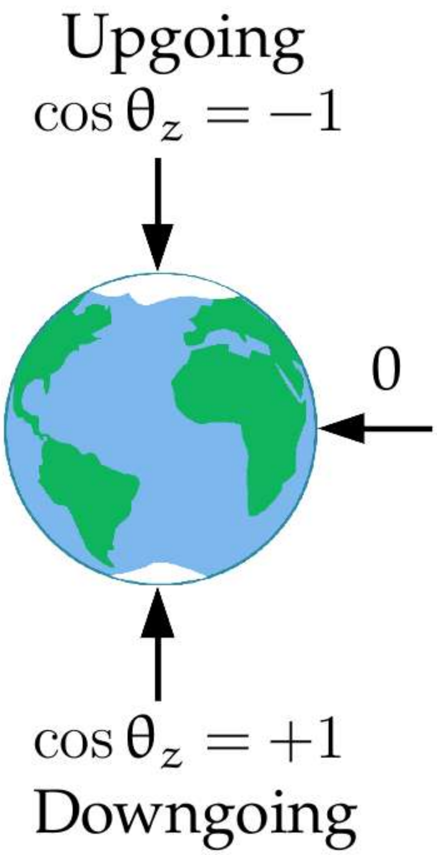
In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4
10^3 10^2 10
1.5
10^6
10^5
10^4
Deposited energy $E_{\rm dep}$ [GeV]
−1.0
−0.5
0.0
0.5
1.0
Neutrino zenith angle cos θ_z
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Attenuation in Earth $e^{-\tau_{\nu N}}$



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


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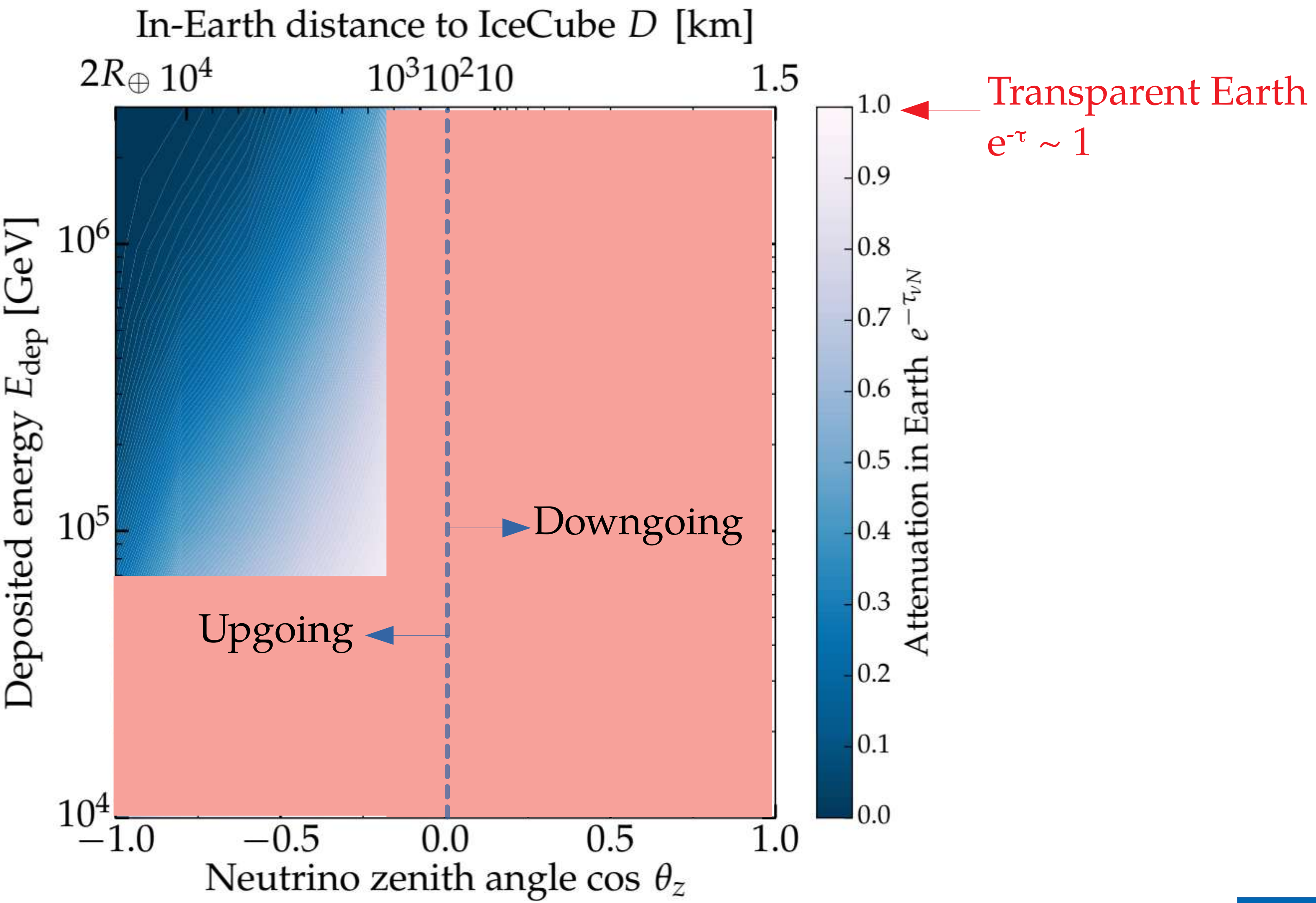
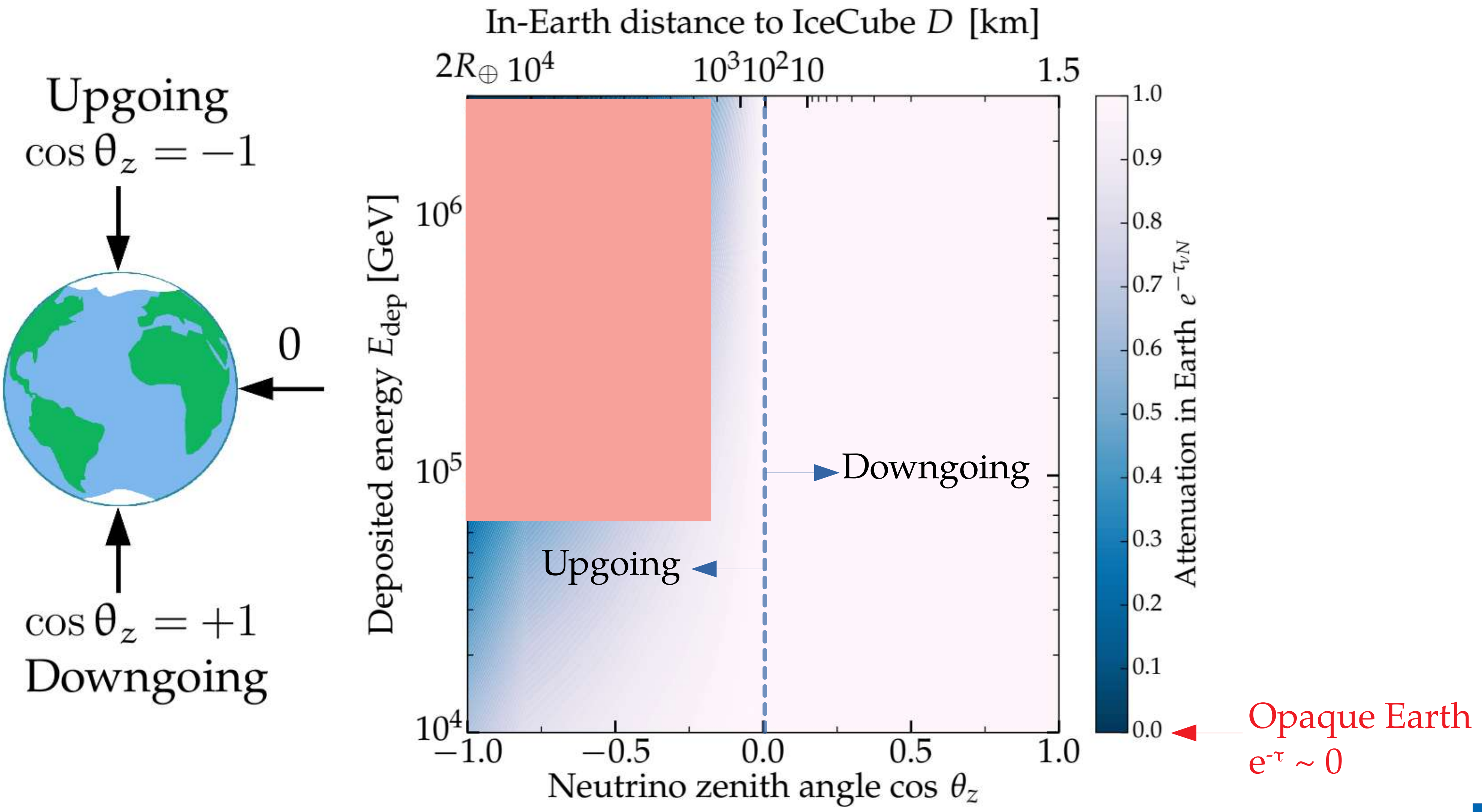
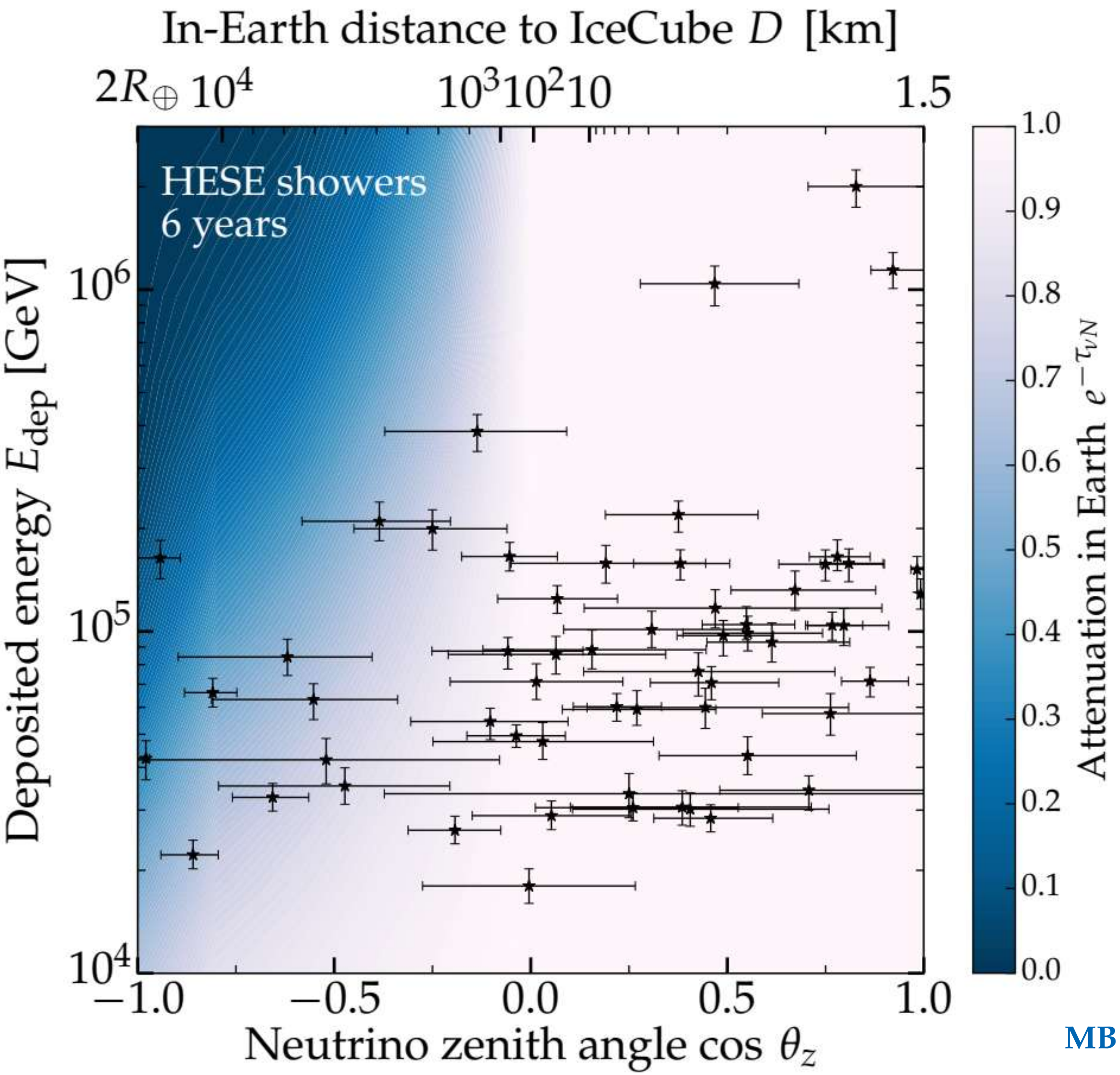
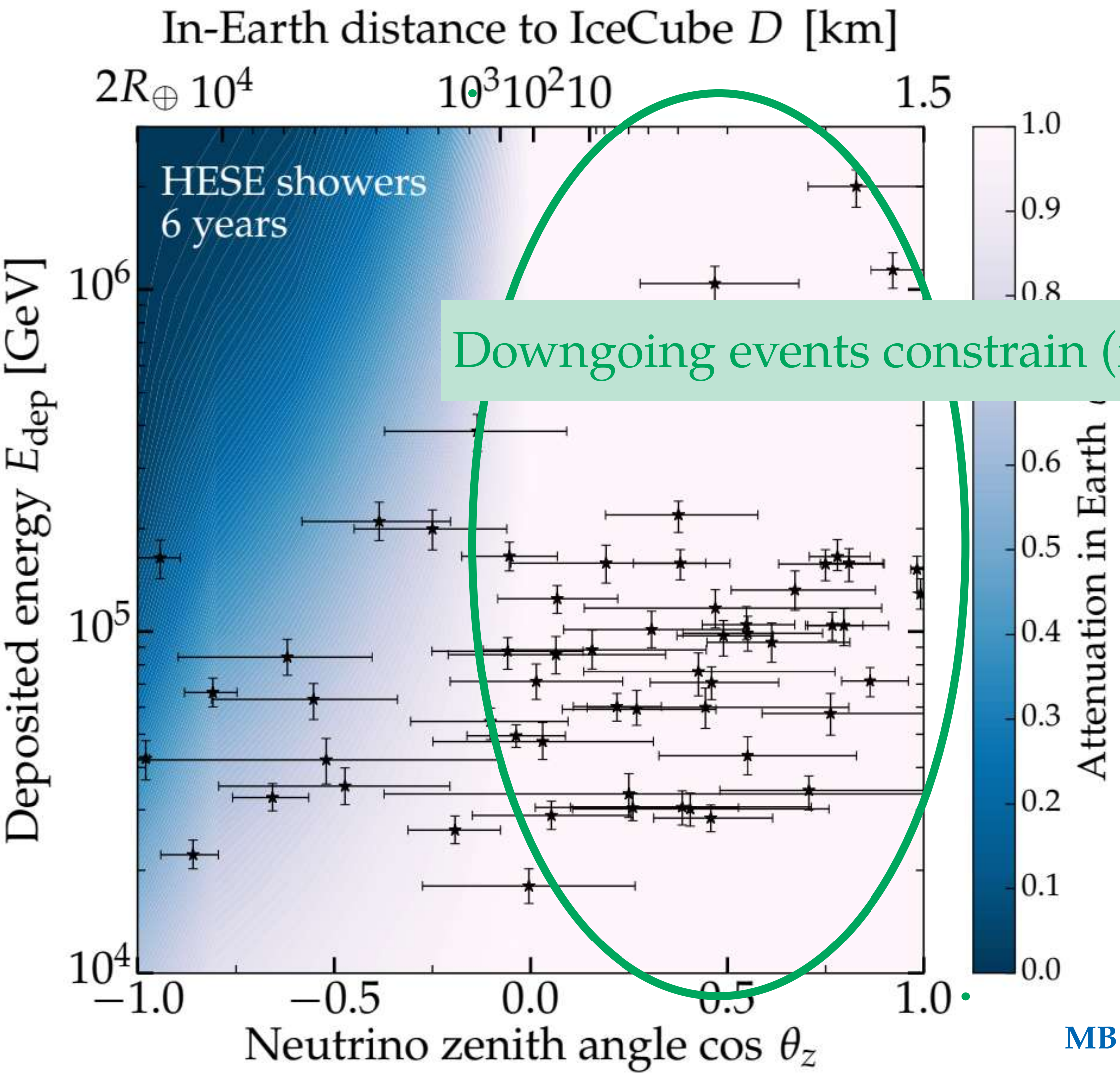
Downgoing


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
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 $e^{-\tau_{\nu N}}$
Transparent Earth
$e^{-\tau} \sim 1$


Upgoing
cos θ_z = −1
0
cos θ_z = +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 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^{−τ_νN}
Opaque Earth
e^{-τ} ~ 0

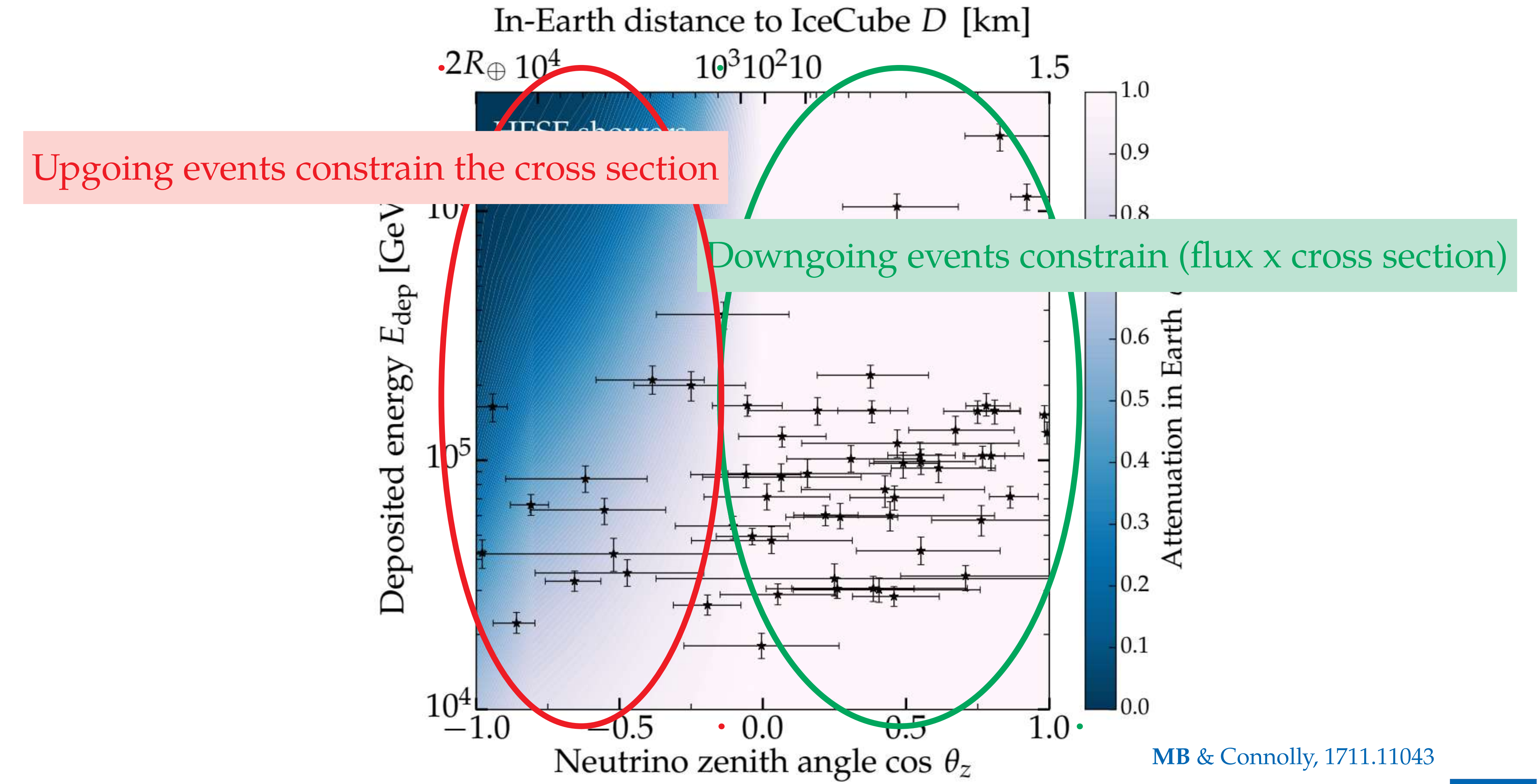


MB & Connolly, 1711.11043



Downgoing events constrain (flux x cross section)

MB & Connolly, 1711.11043



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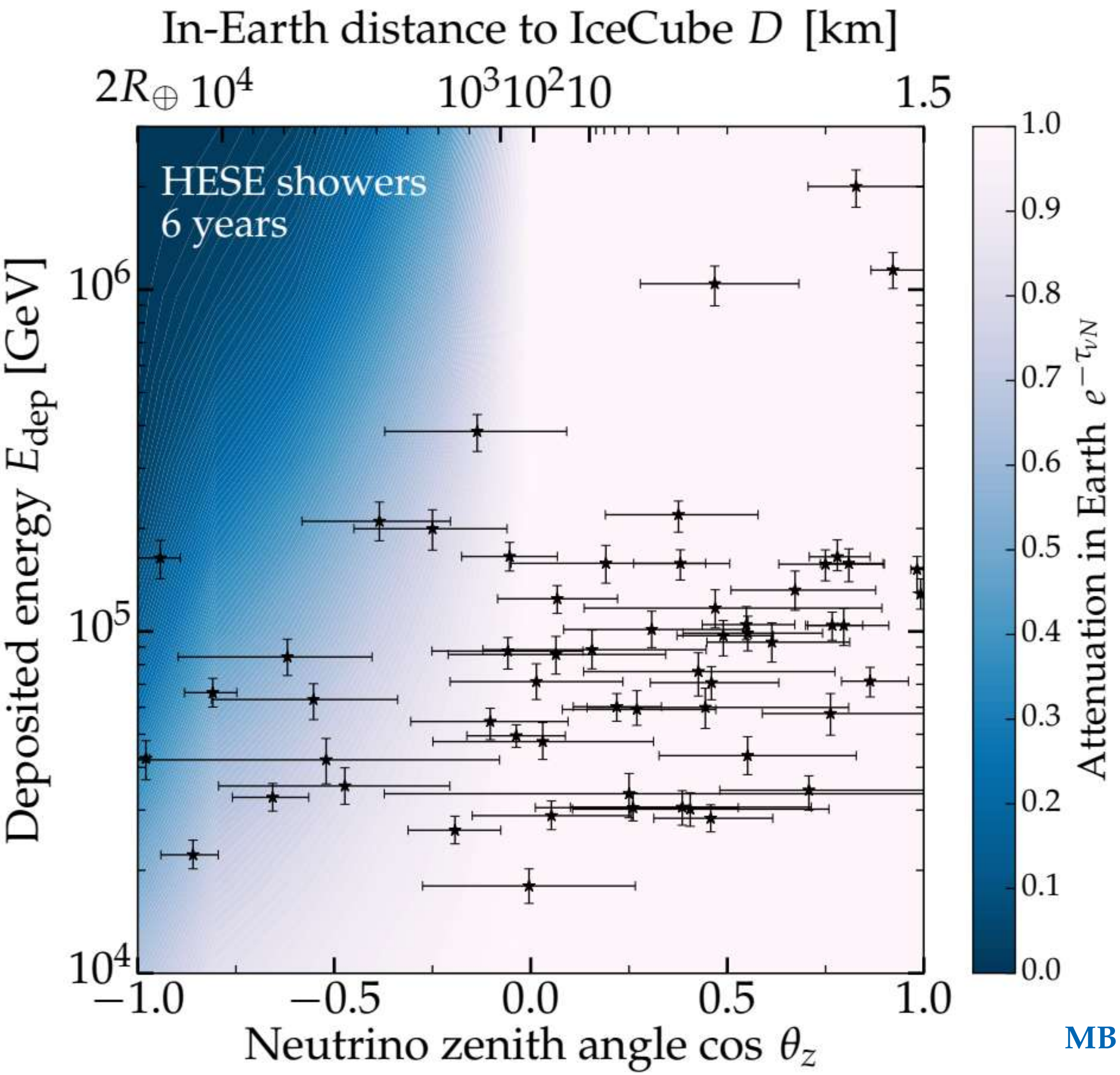

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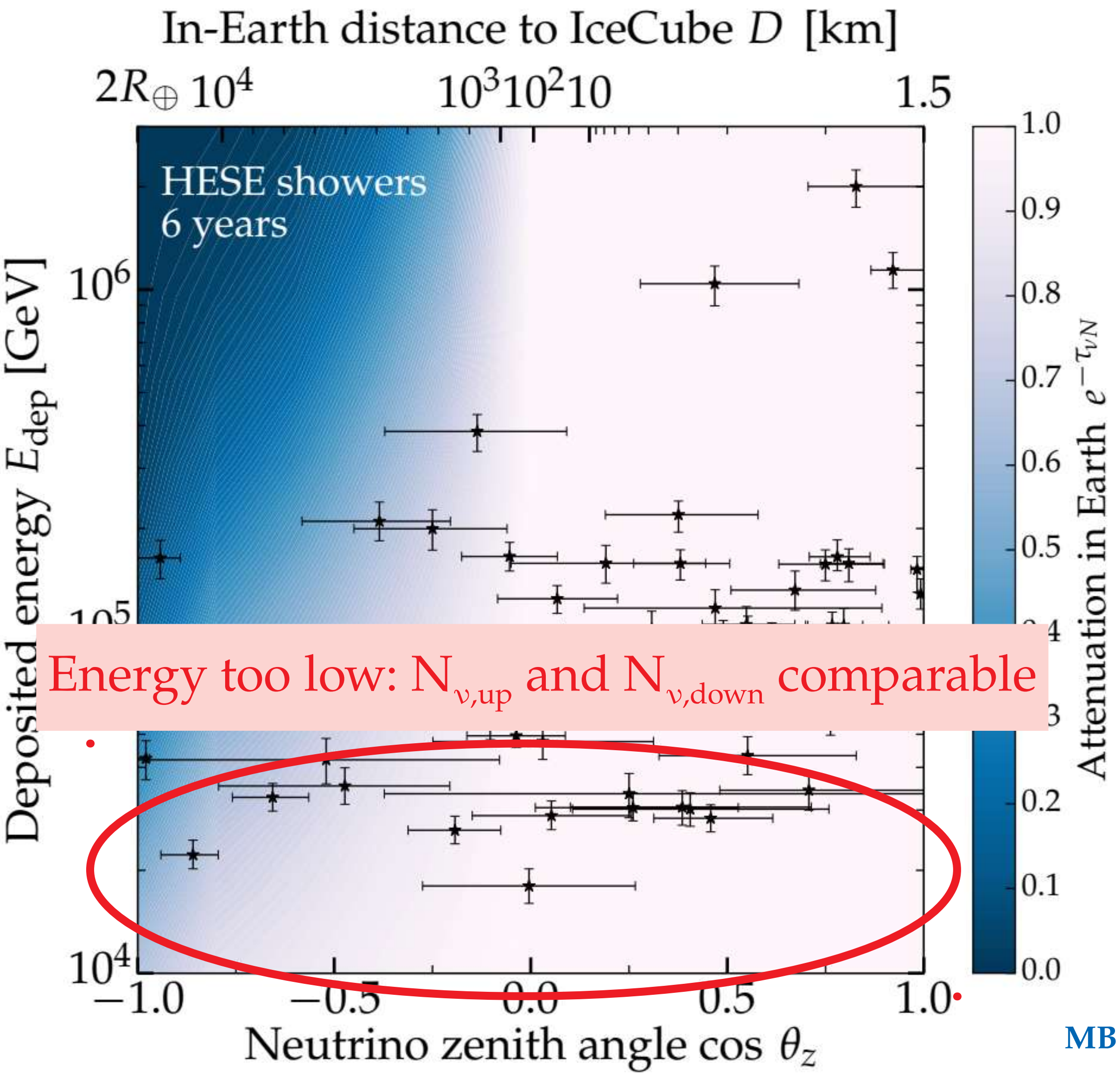

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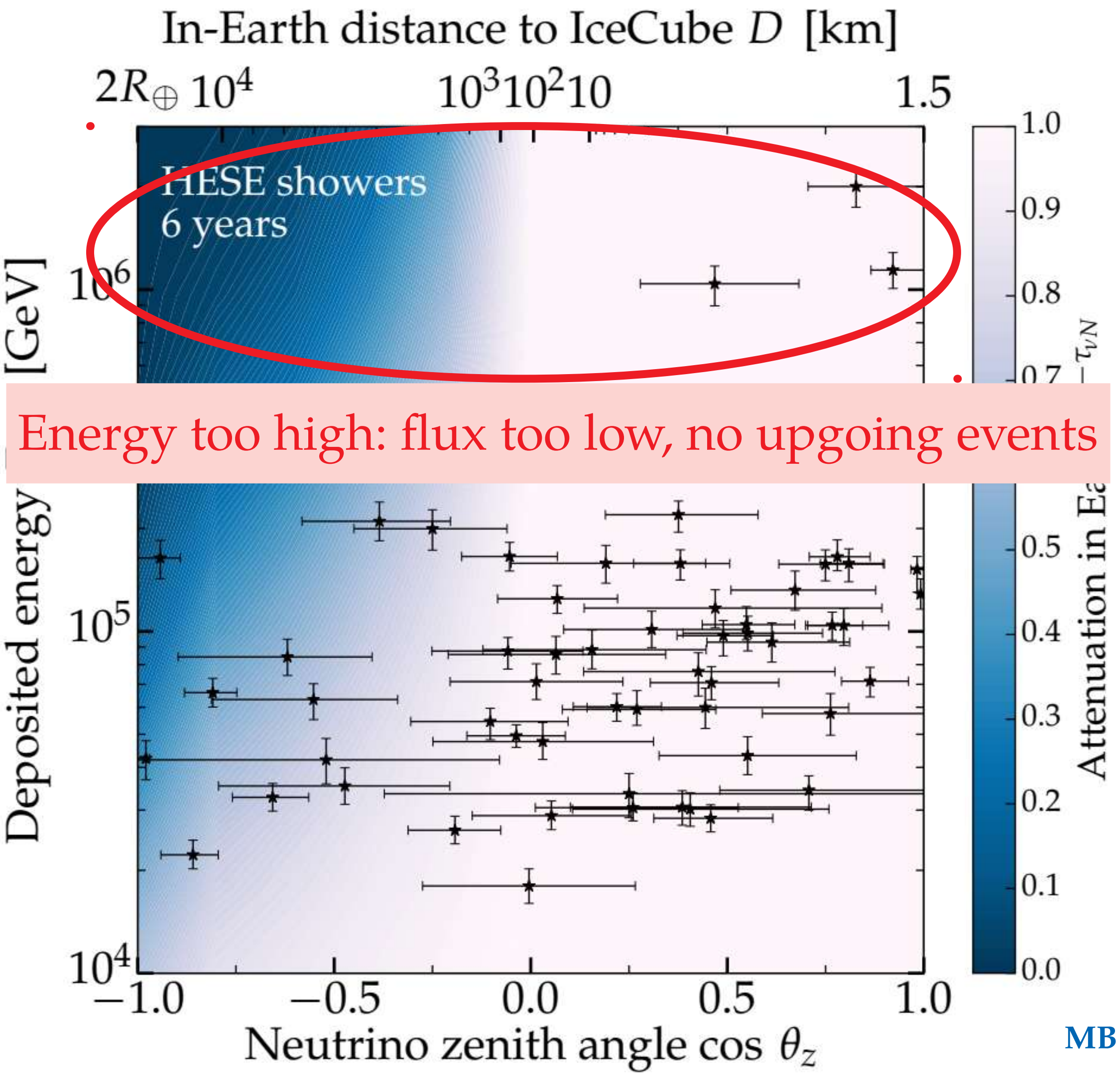
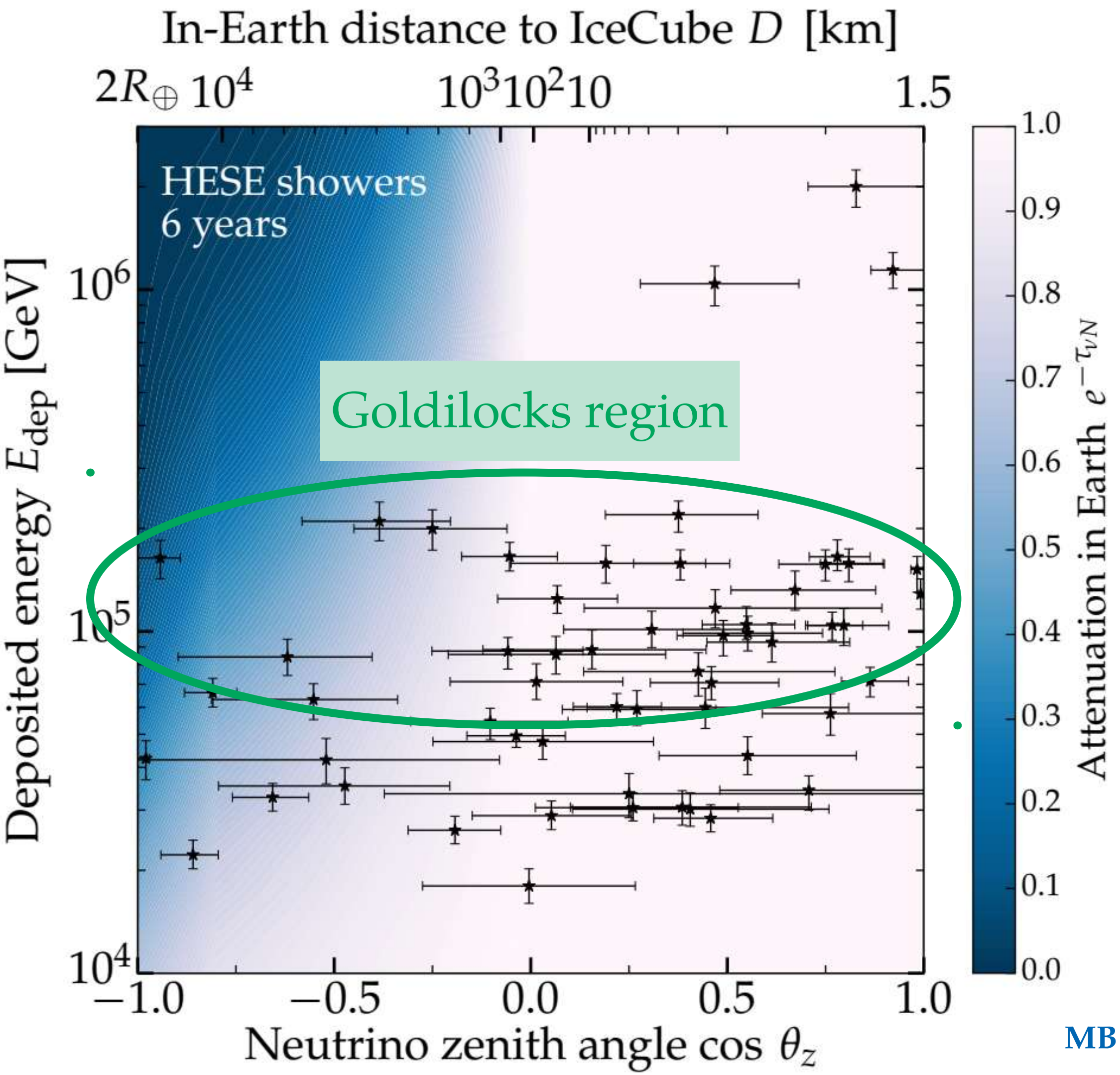


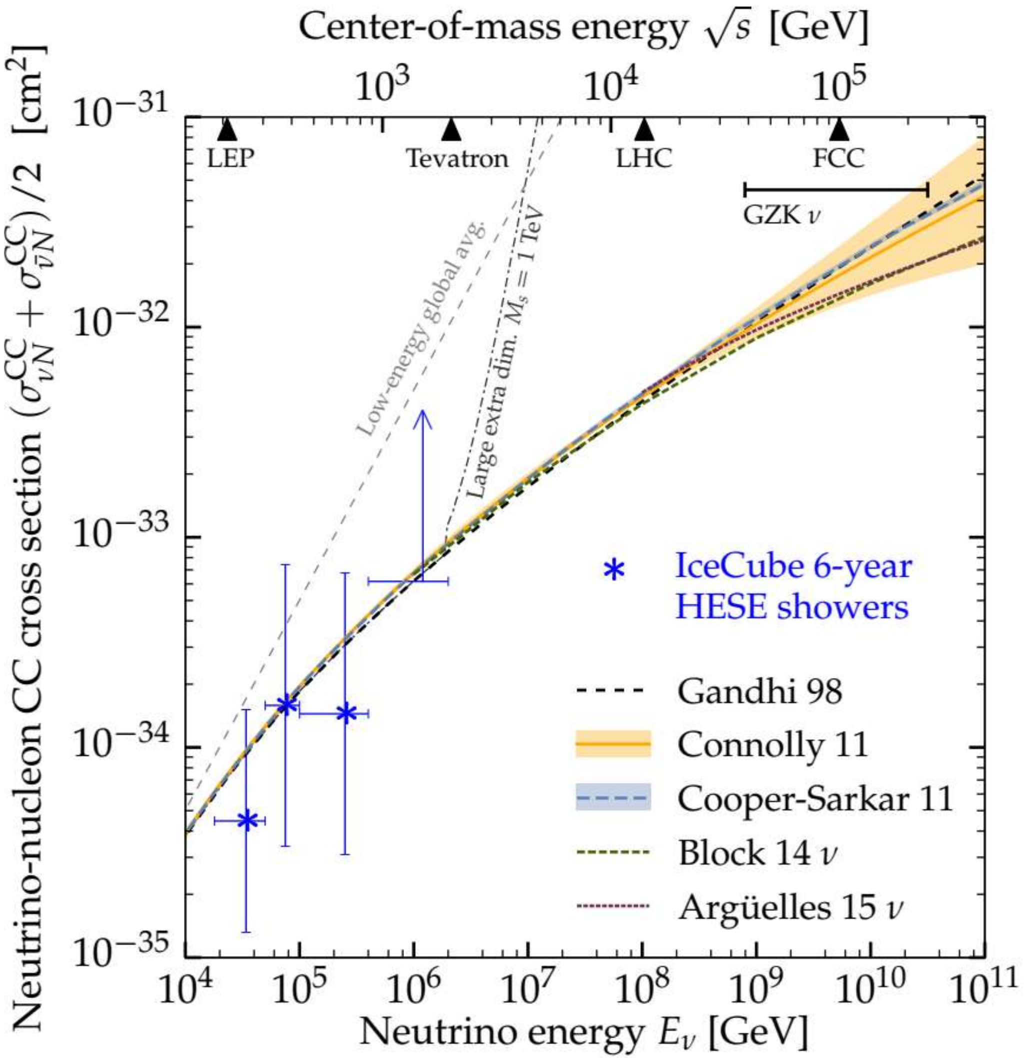
Energy too high: flux too low, no upgoing events

MB & Connolly, 1711.11043



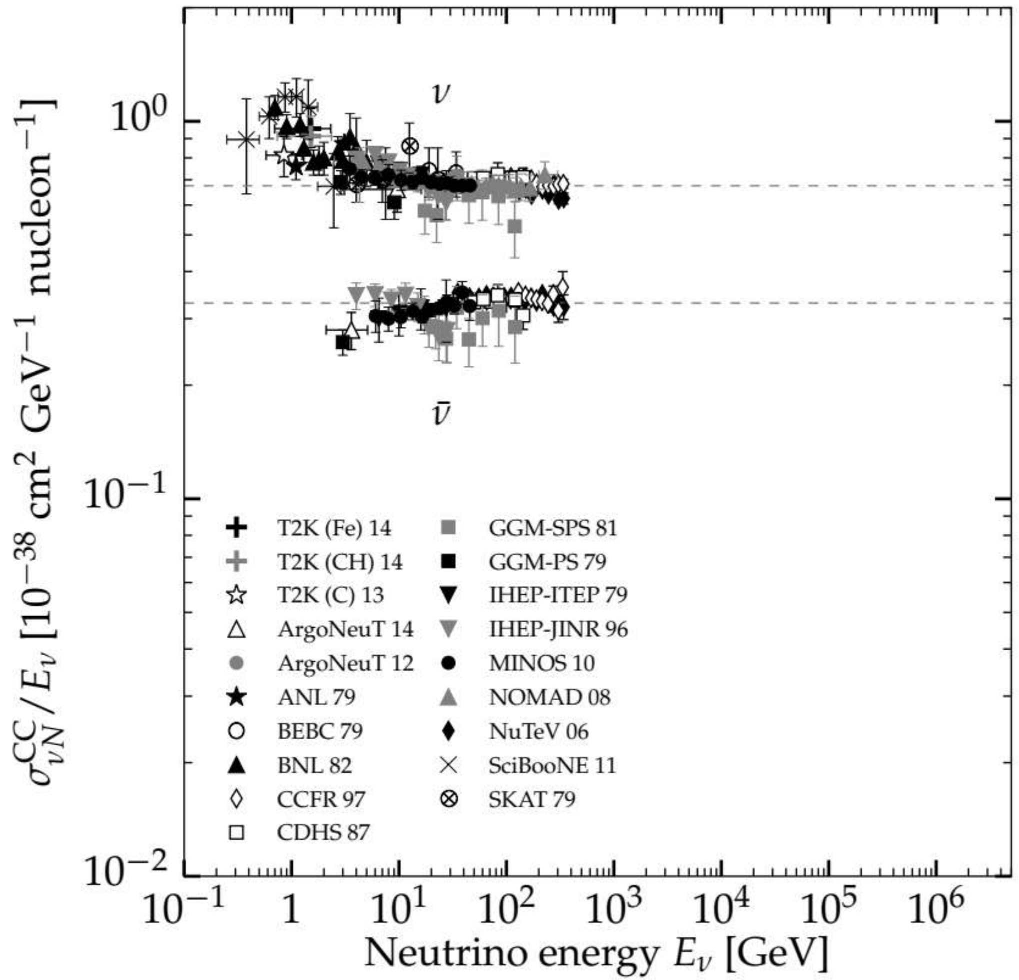
MB & Connolly, 1711.11043

Our result



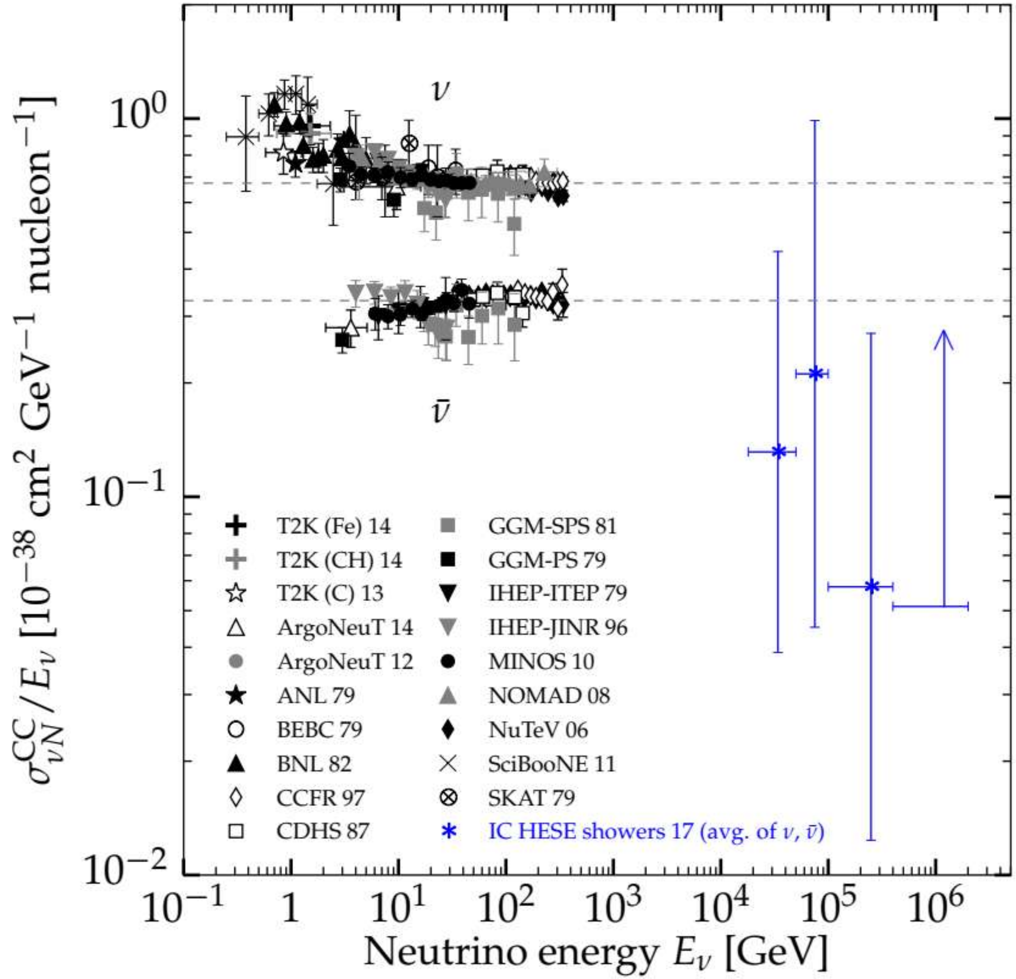
MB & Connolly, 1711.11043

Extending cross section measurements



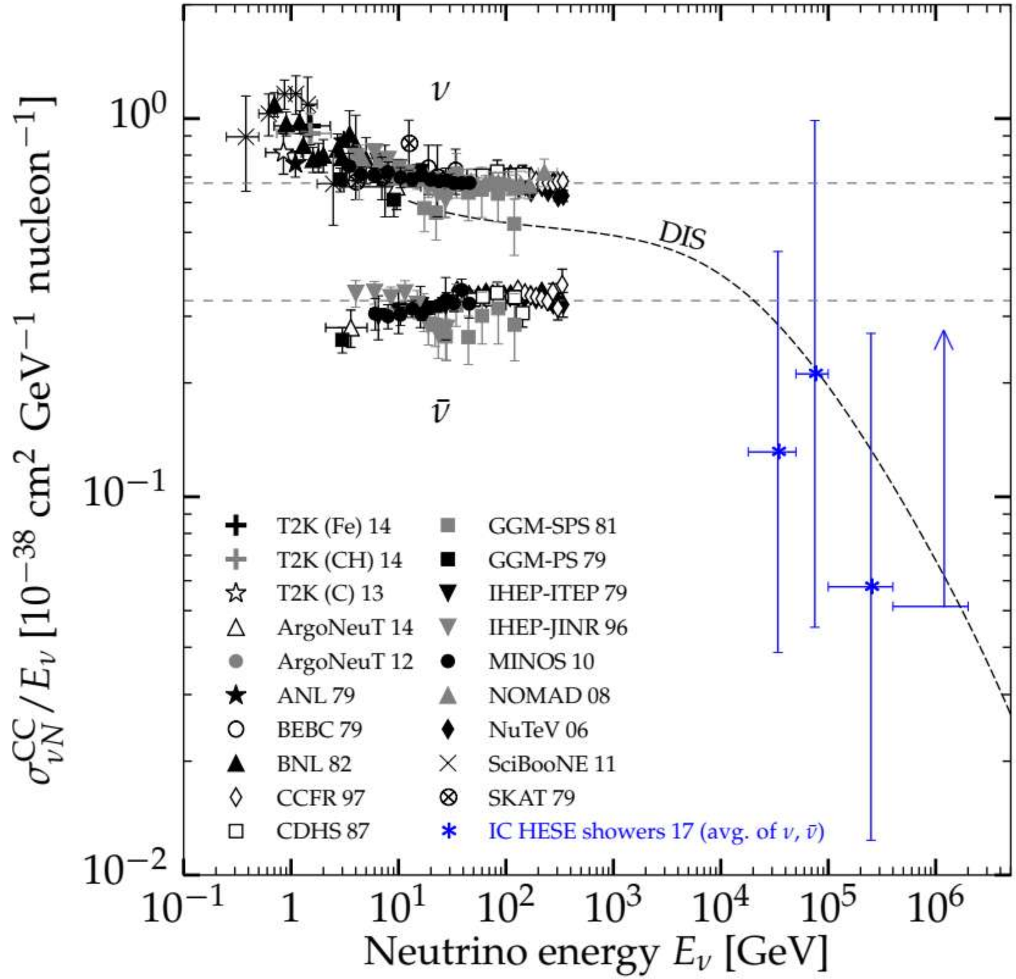
MB & Connolly, 1711.11043

Extending cross section measurements



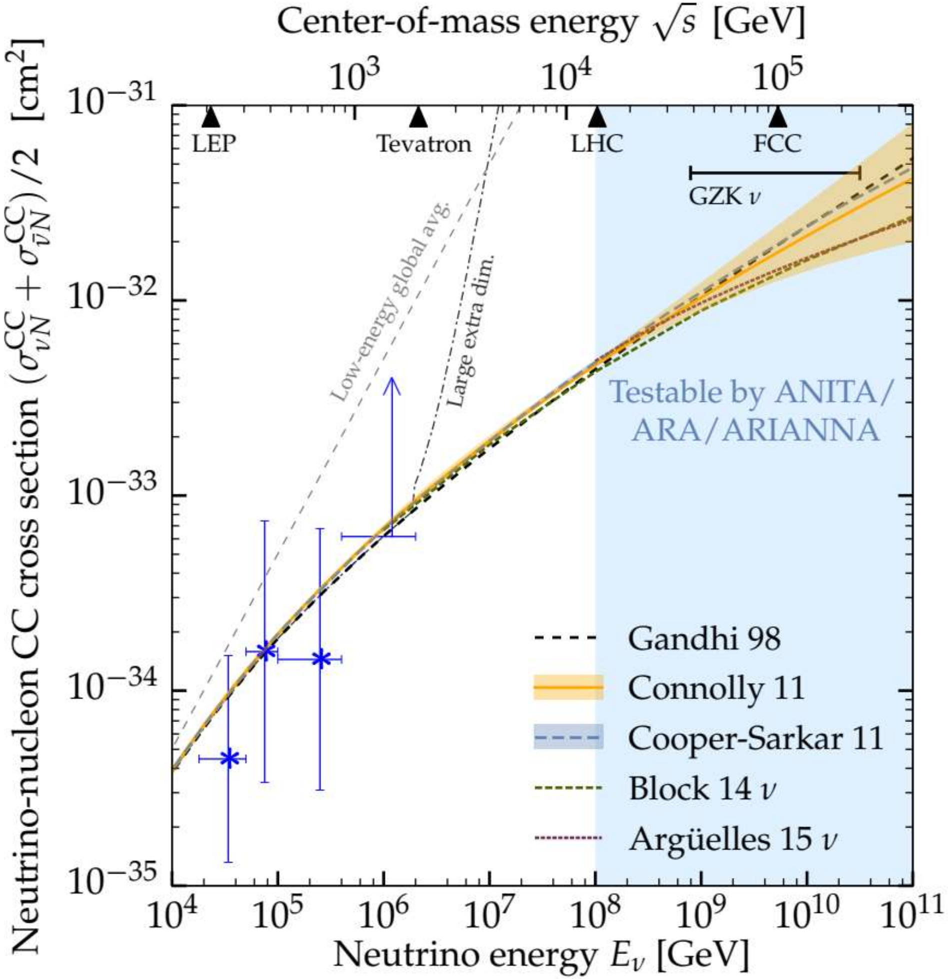
MB & Connolly, 1711.11043

Extending cross section measurements



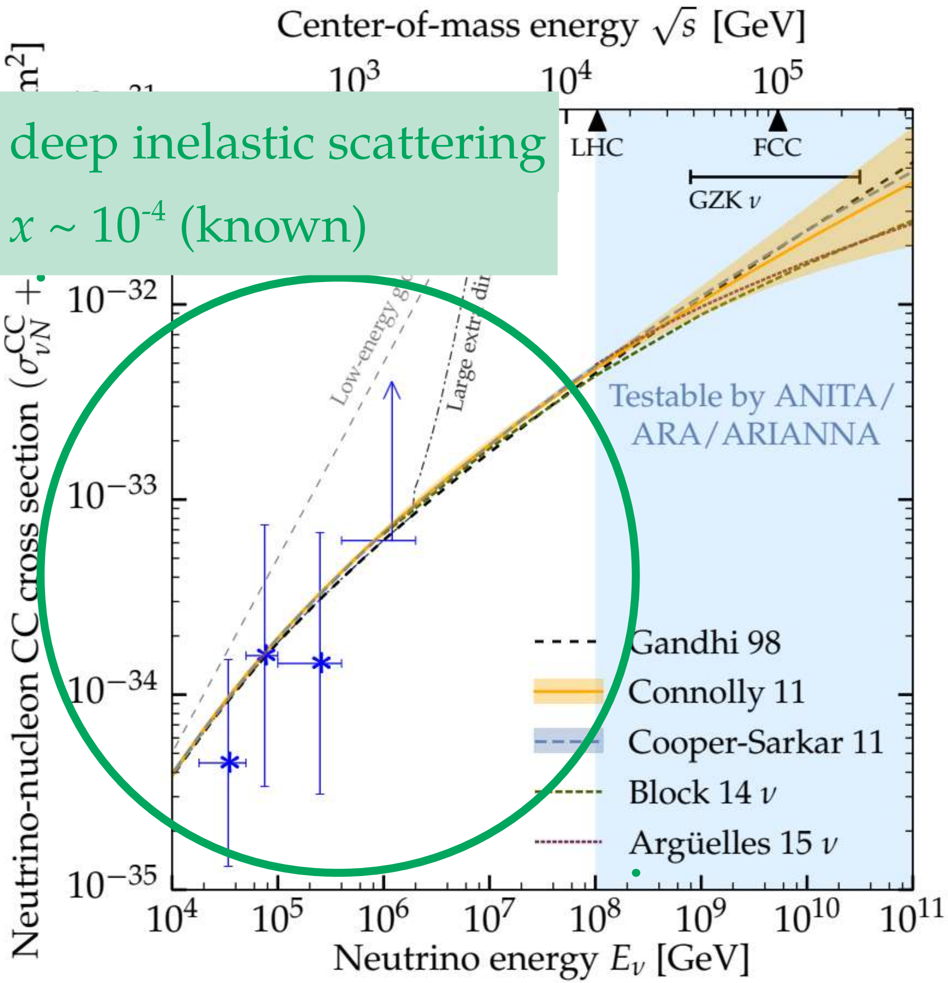
MB & Connolly, 1711.11043

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

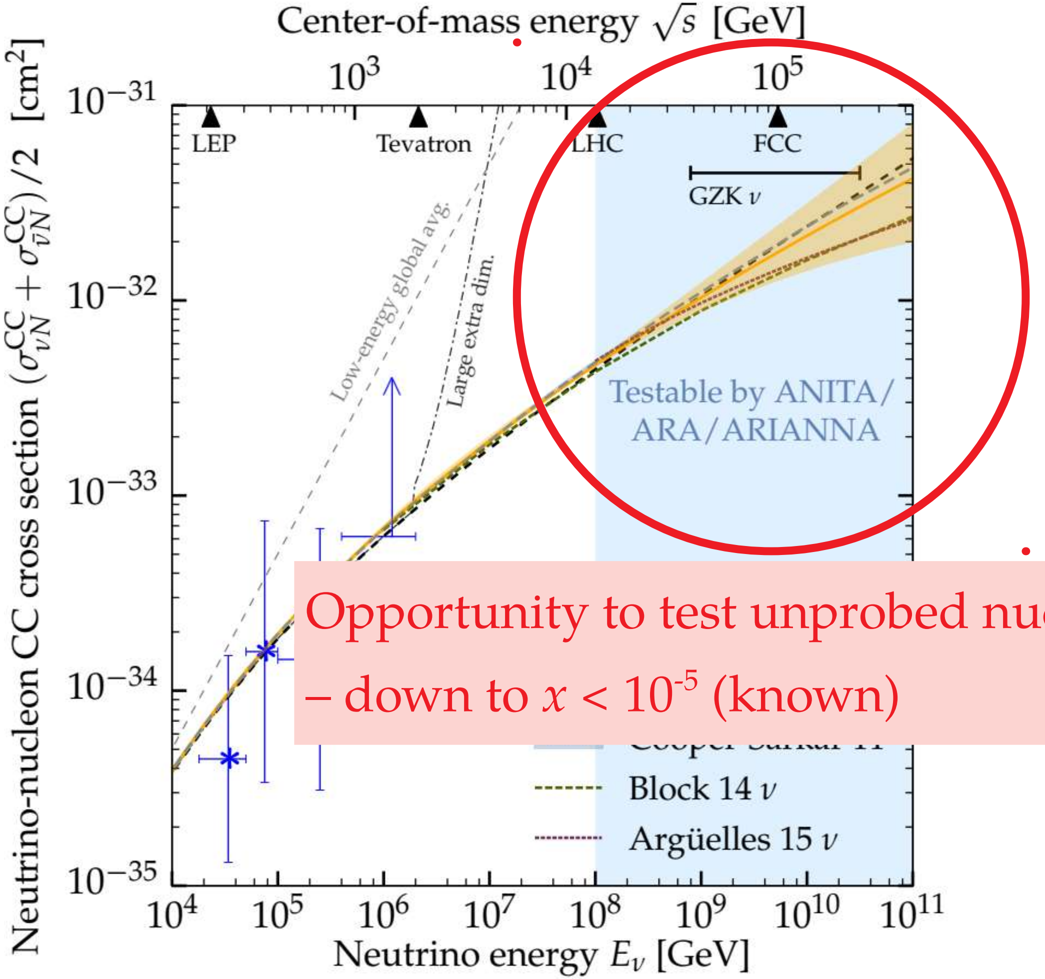


Quo vadis: IceCube vs. ANITA / ARA / ARIANNA / …

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



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



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

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

The new ν physics matrix

Where it happens

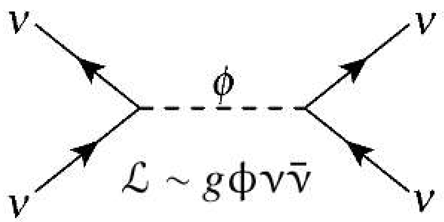
What it changes

	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.*

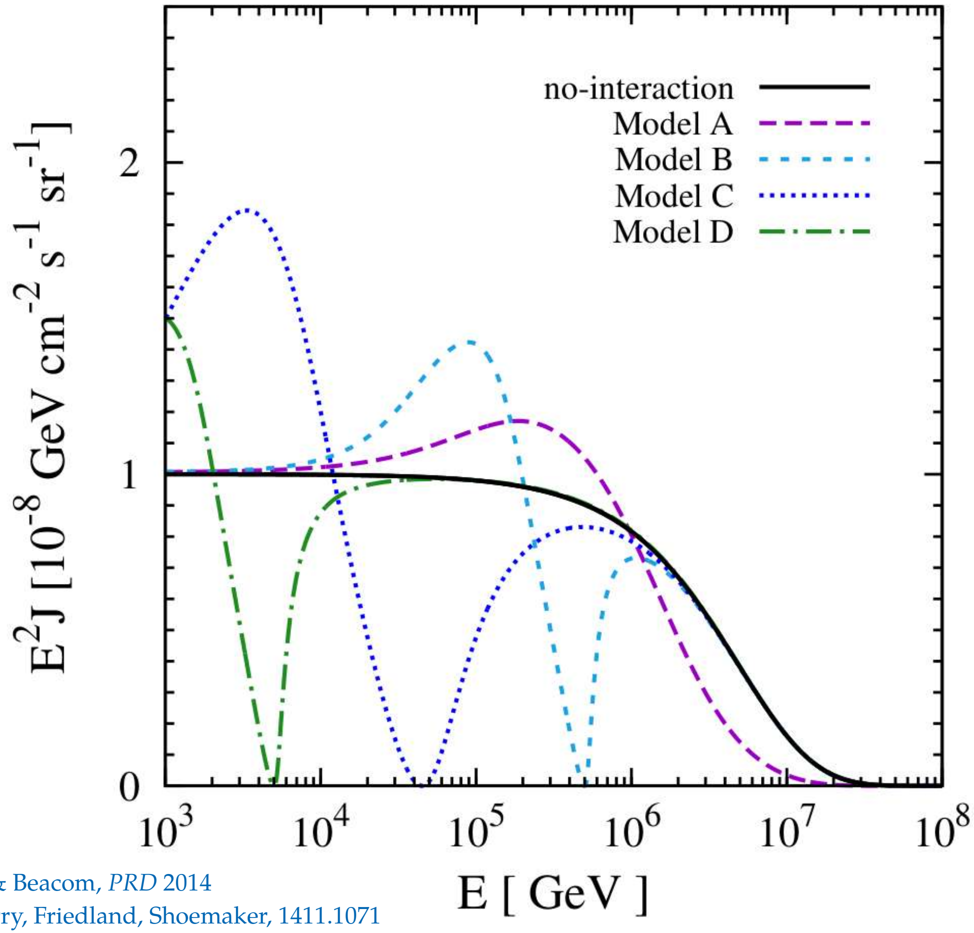
New physics in the spectral shape: $\nu\nu$ interactions

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



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

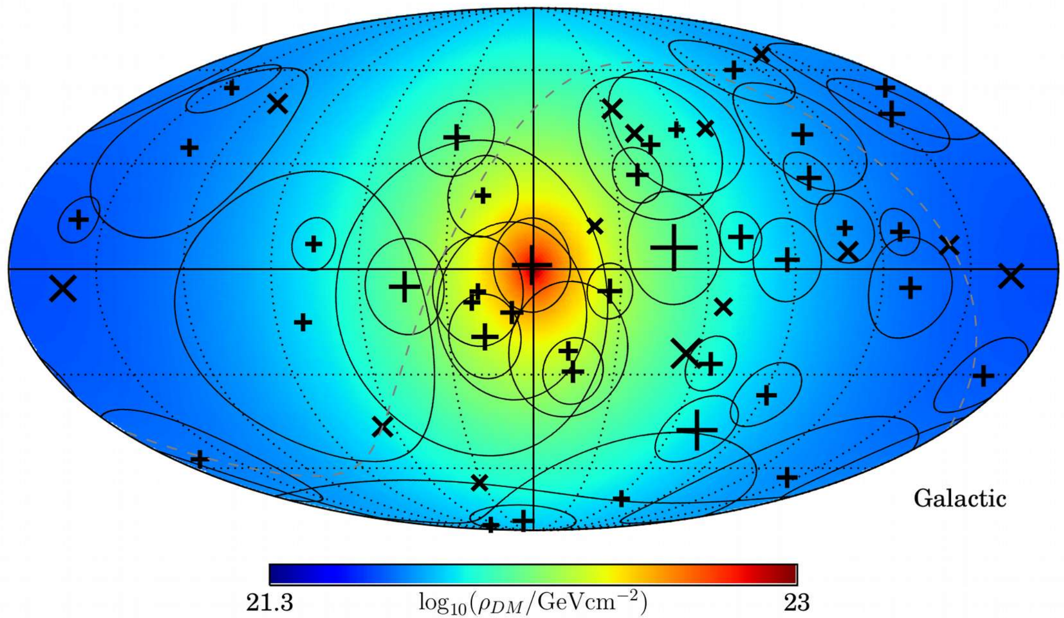
Resonance energy: $E_{\text{res}} = \frac{M^2}{2m_\nu}$



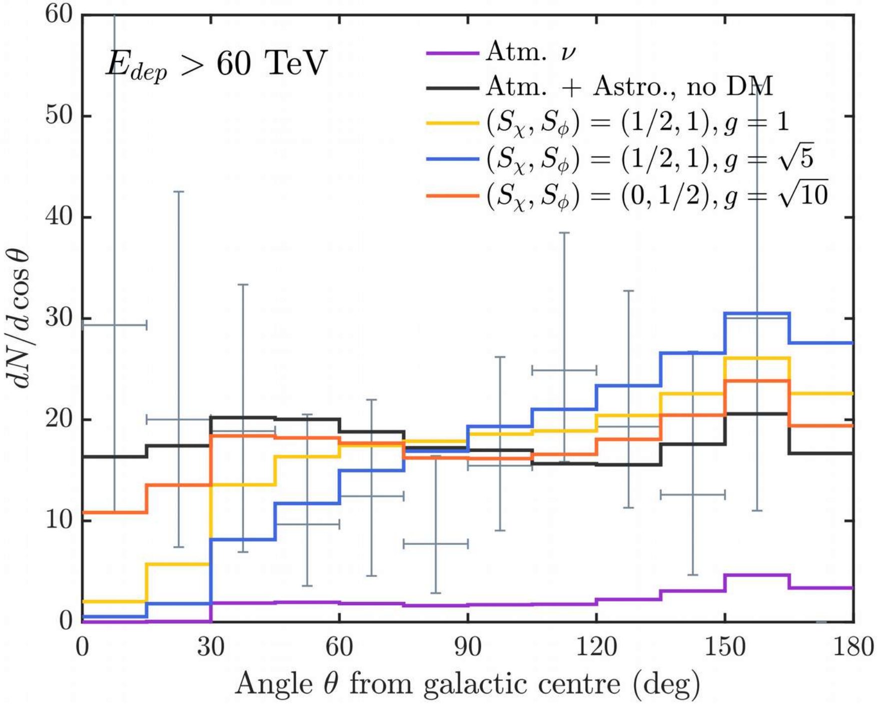
Ng & Beacon, *PRD* 2014
Cherry, Friedland, Shoemaker, 1411.1071
Blum, Hook, Murase, 1408.3799

New physics in the angular distribution: ν-DM interactions

Interaction between astrophysical neutrinos and the Galactic dark matter profile –



Argüelles *et al.*, *PRL* 2017

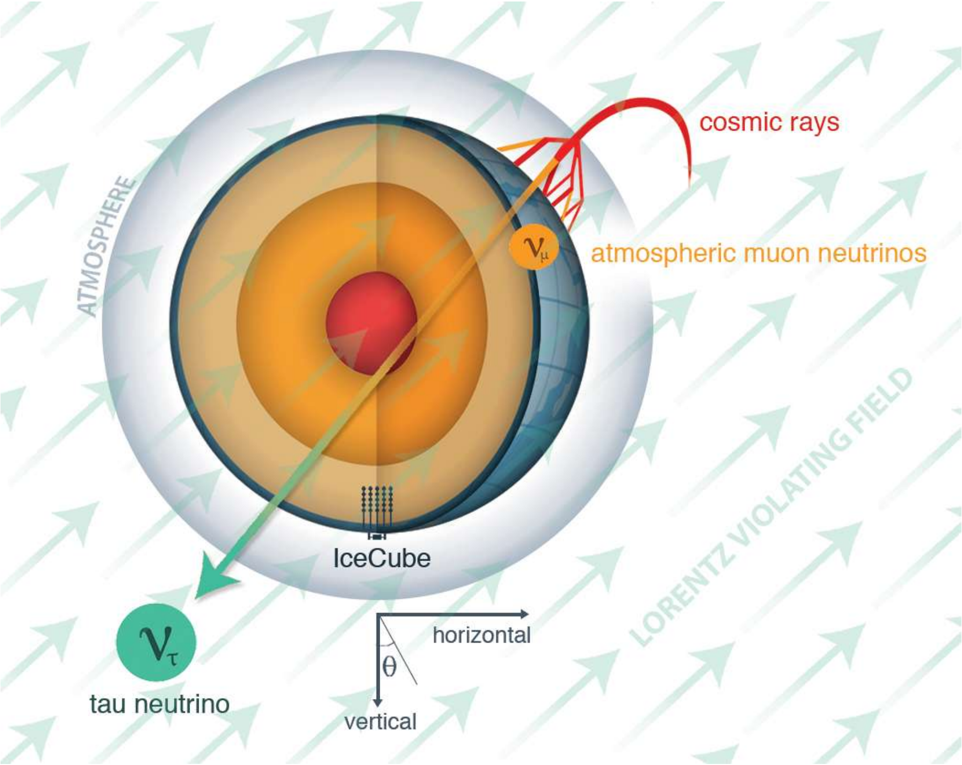


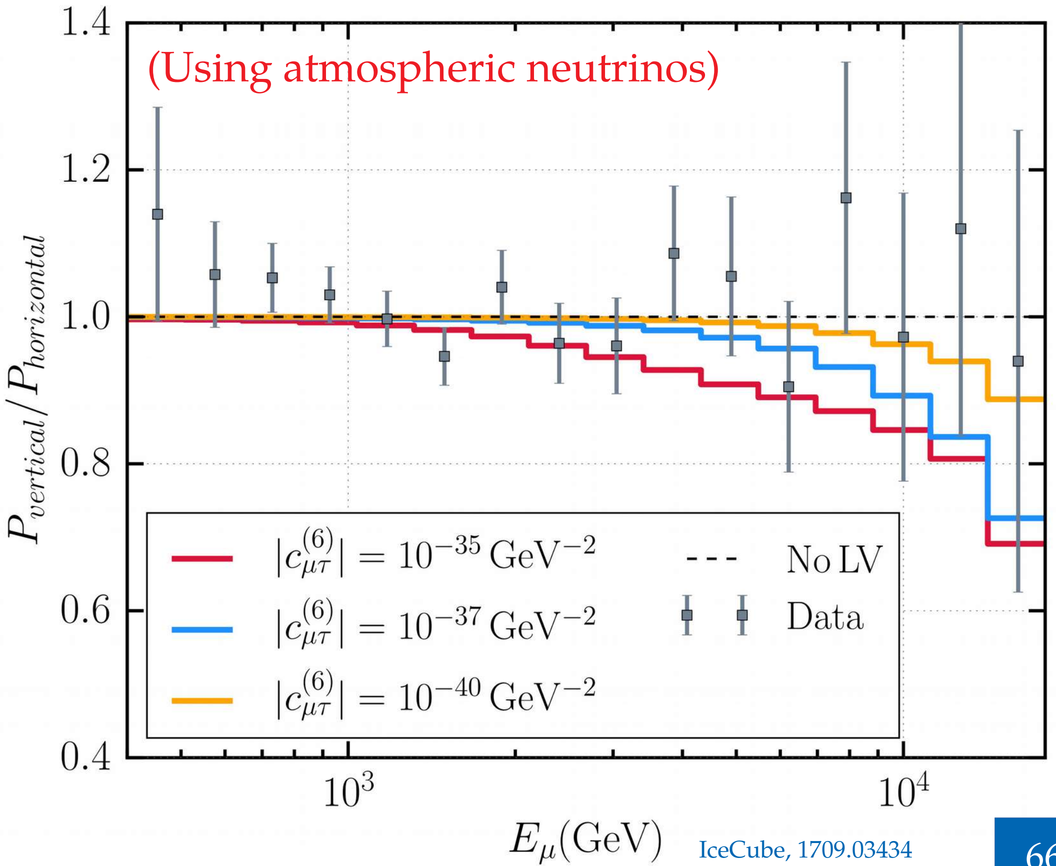
Expected: Fewer neutrinos coming from the Galactic Center

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

New physics in the energy & angular distribution

Lorentz violation

Standard oscillations

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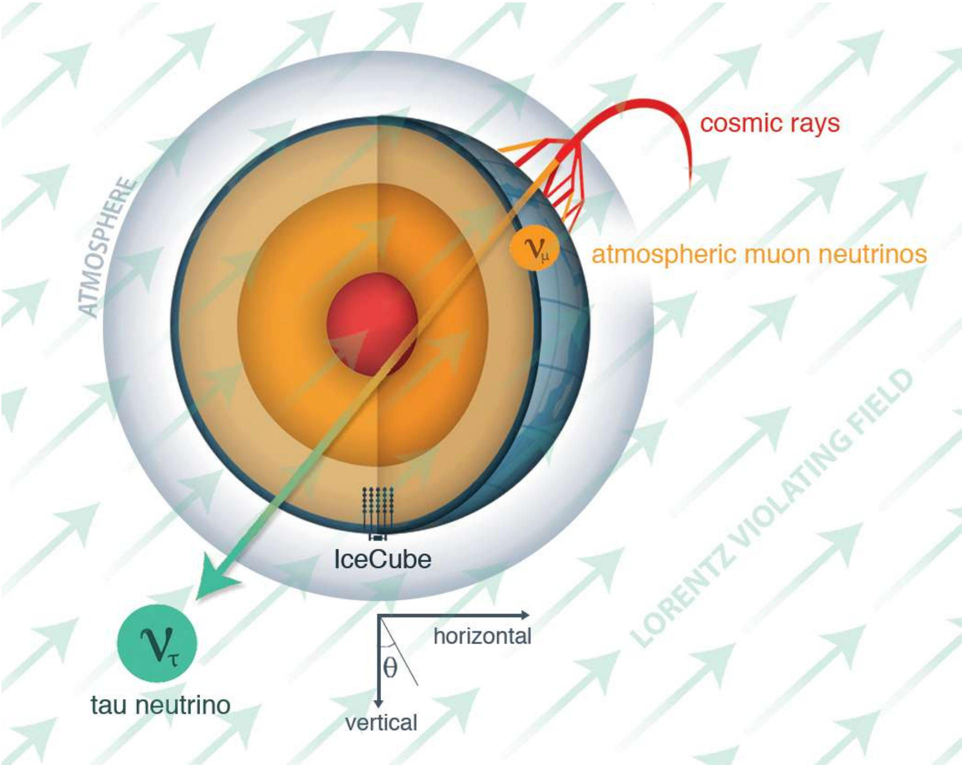

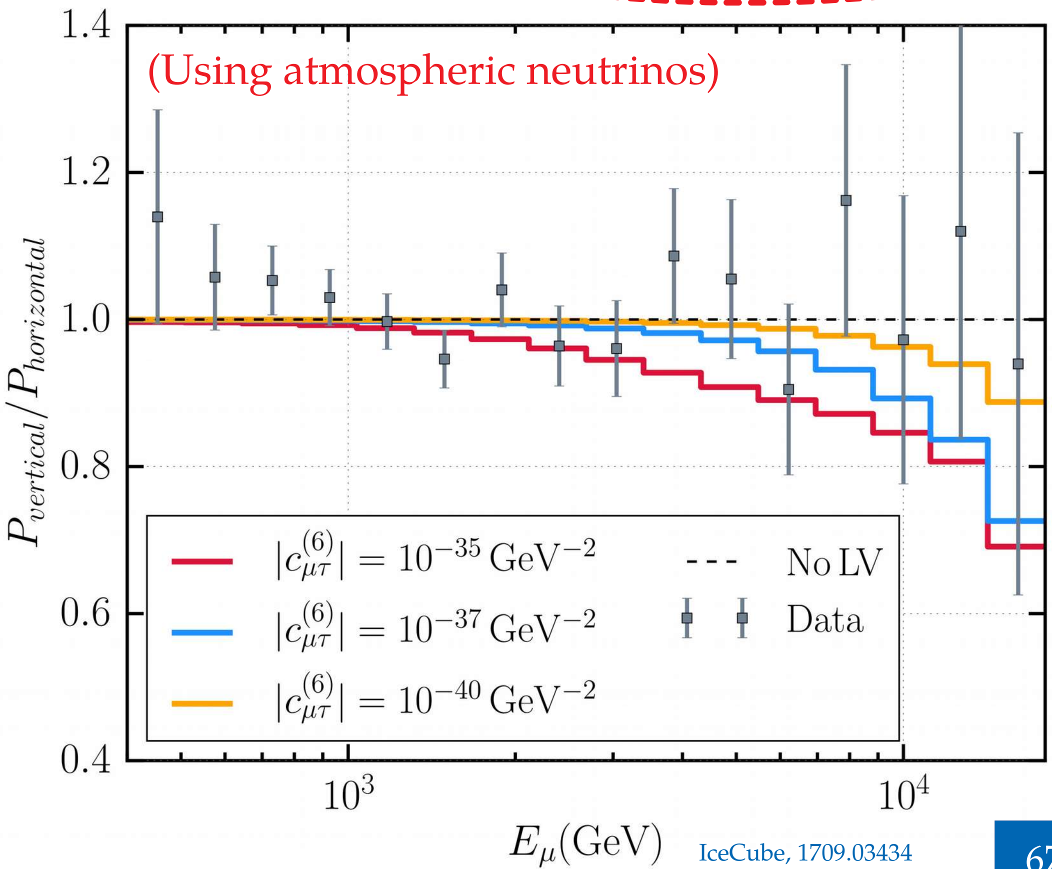

IceCube, 1709.03434

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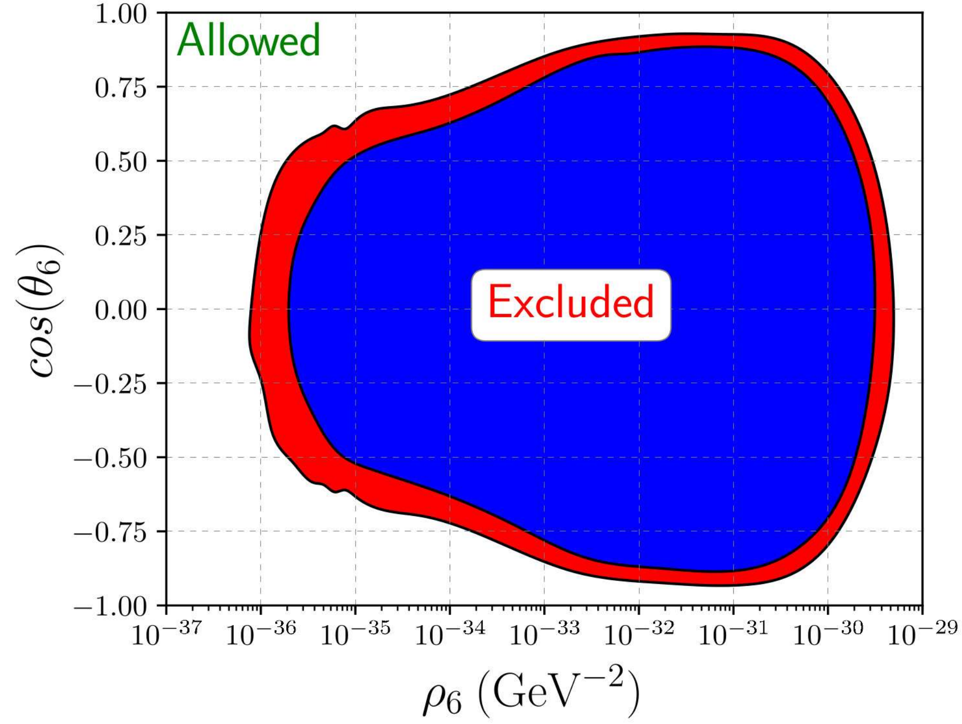
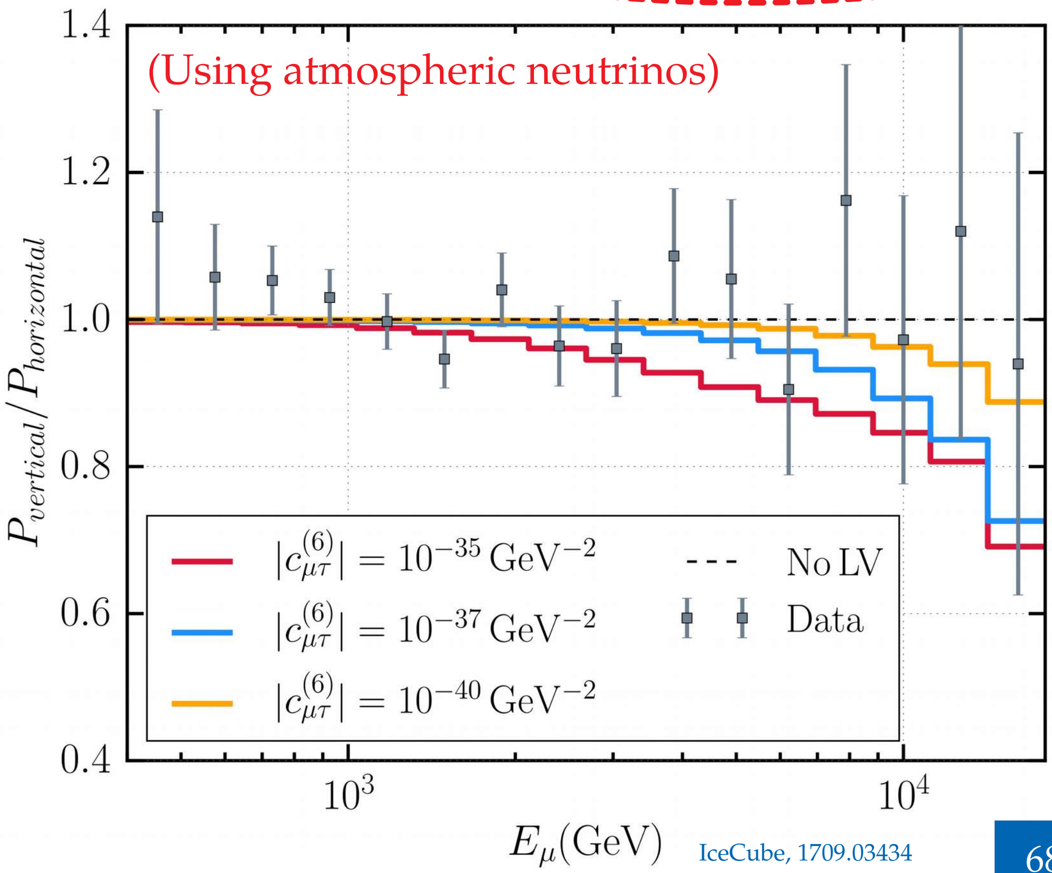
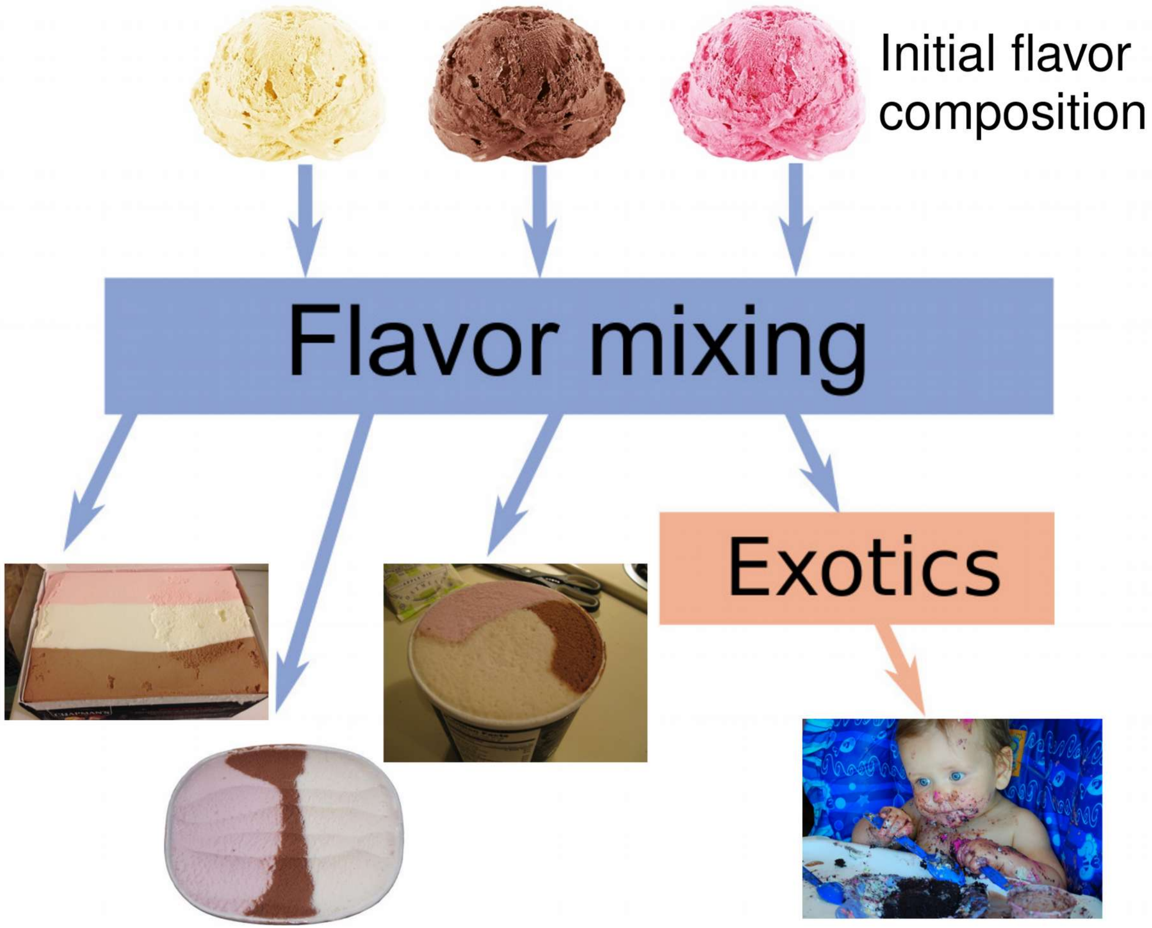
Best bounds come from IceCube





IceCube, 1709.03434

New physics in the flavor composition



Why are flavor ratios useful?

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

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

- Ratios remove systematic uncertainties common to all flavors

- Flavor ratios are useful in astrophysics and particle physics

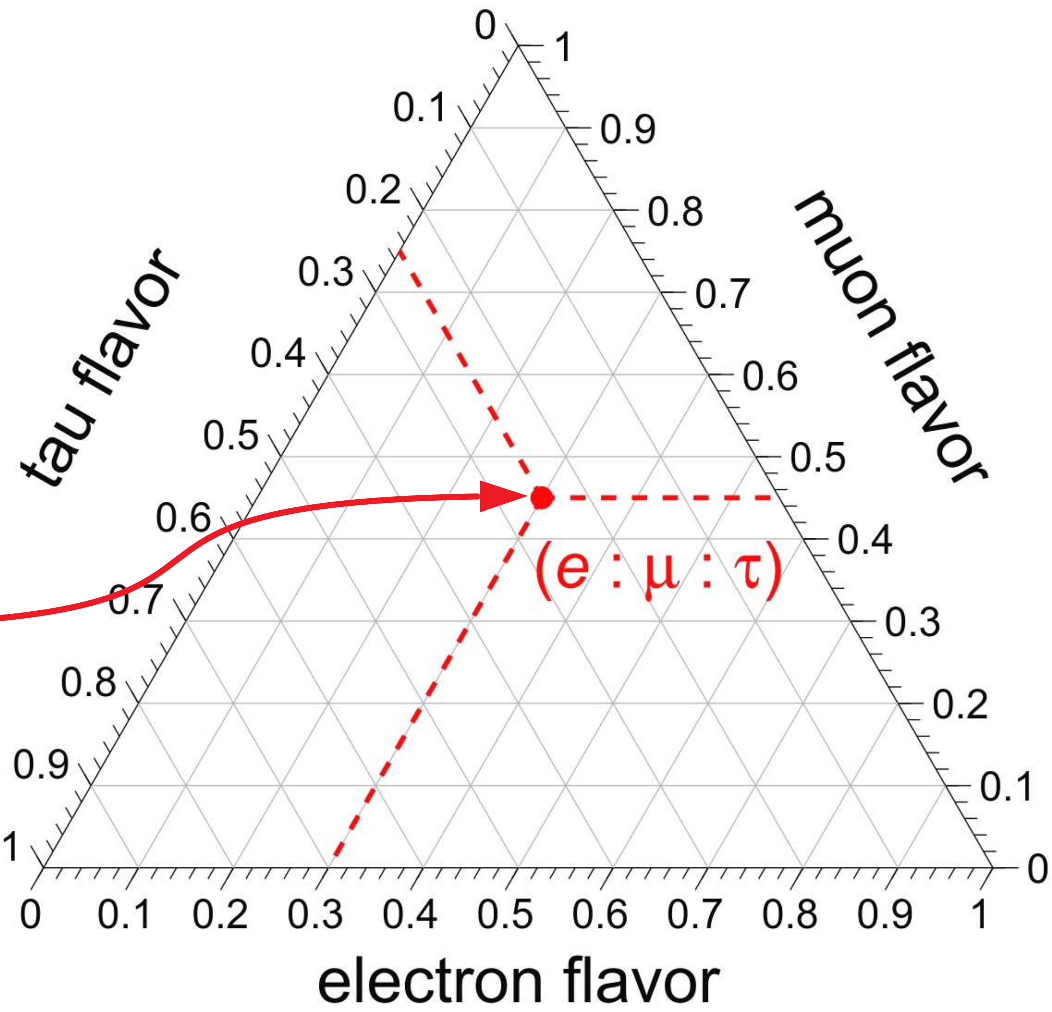
Note: Ratios are for $\nu + \bar{\nu}$, since neutrino telescopes cannot tell them apart

Reading a ternary plot

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

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

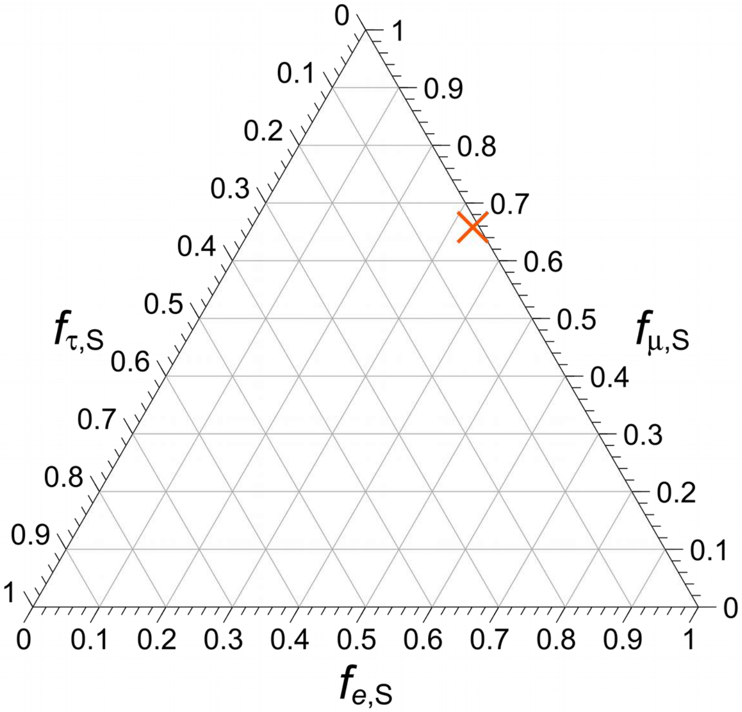
$(e{:}\mu{:}\tau) = (0.30{:}0.45{:}0.25)$



Flavor – there and here

At the sources

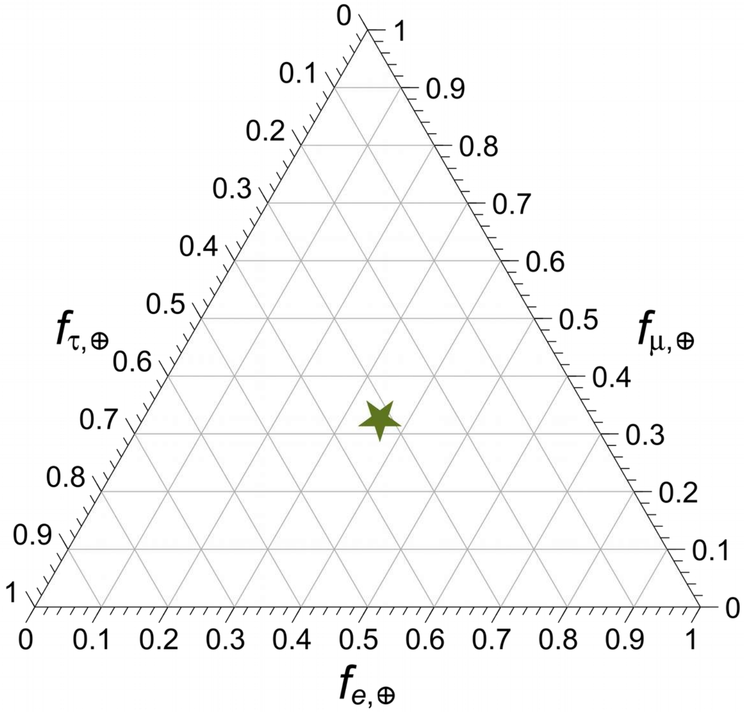
$(f_e:f_\mu:f_\tau)_S = (1/3 : 2/3 : 0)_S$



Neutrino oscillations

At Earth

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



Flavor – there and here

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

At the sources

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

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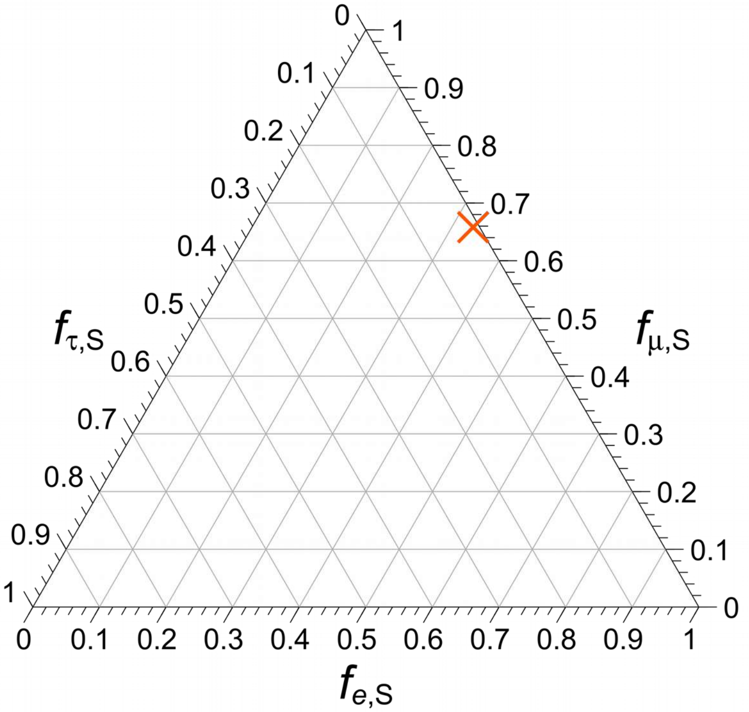

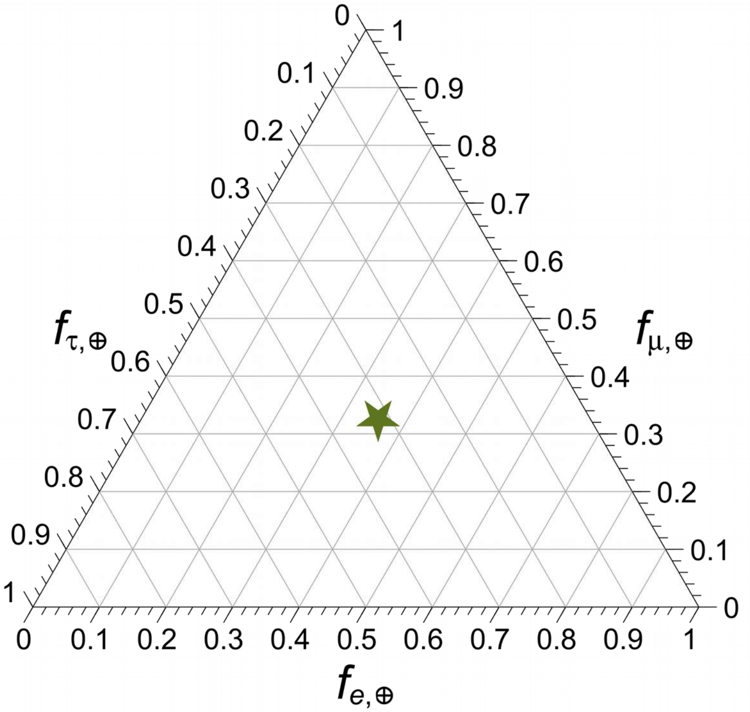

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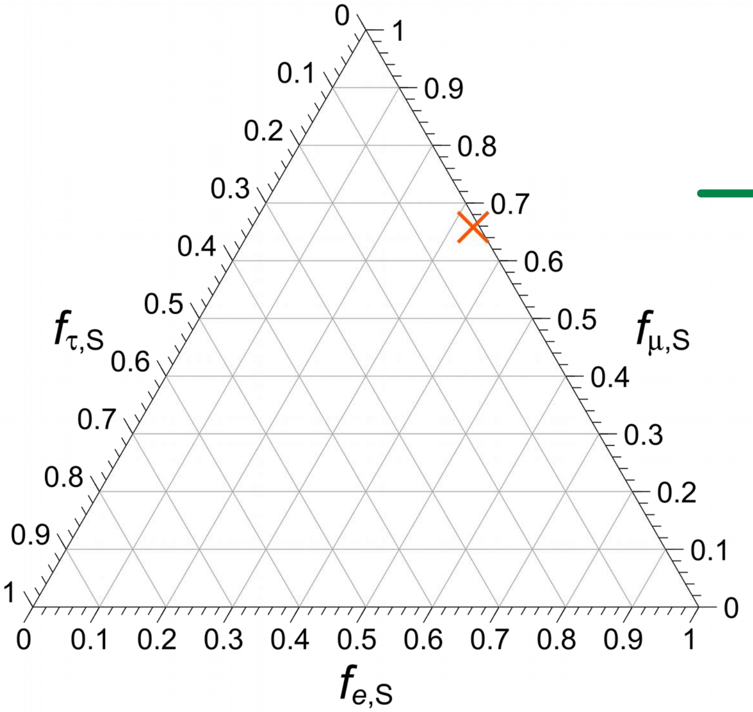
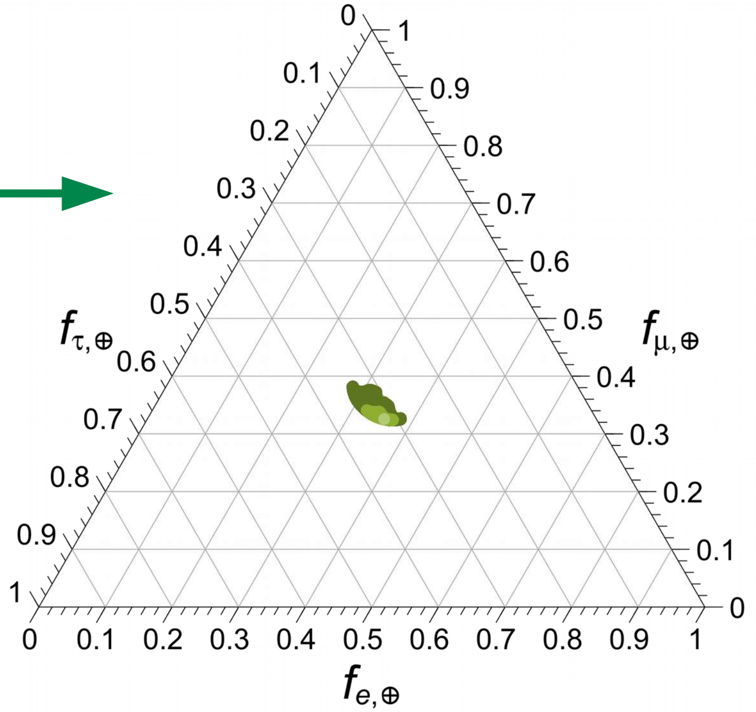


Uncertainties in values of mixing parameter (1σ, 3σ)



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

The ideal world

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

vs.

The <u>real</u> world

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

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

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If you measure *very* precisely the flavor ratios at Earth and...	… you know *very* precisely...	… then you can infer *very* precisely...
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vs.

Talk by Antonio Palazzo

The real world

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	…the neutrino production mechanism... →	… values of the mixing parameters

vs.

But we can thoroughly explore new physics

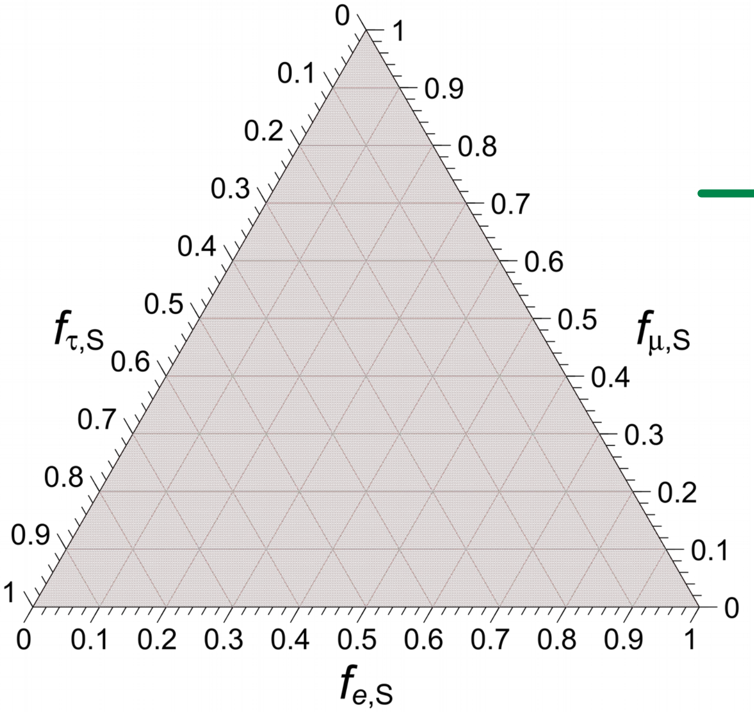
The real world

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

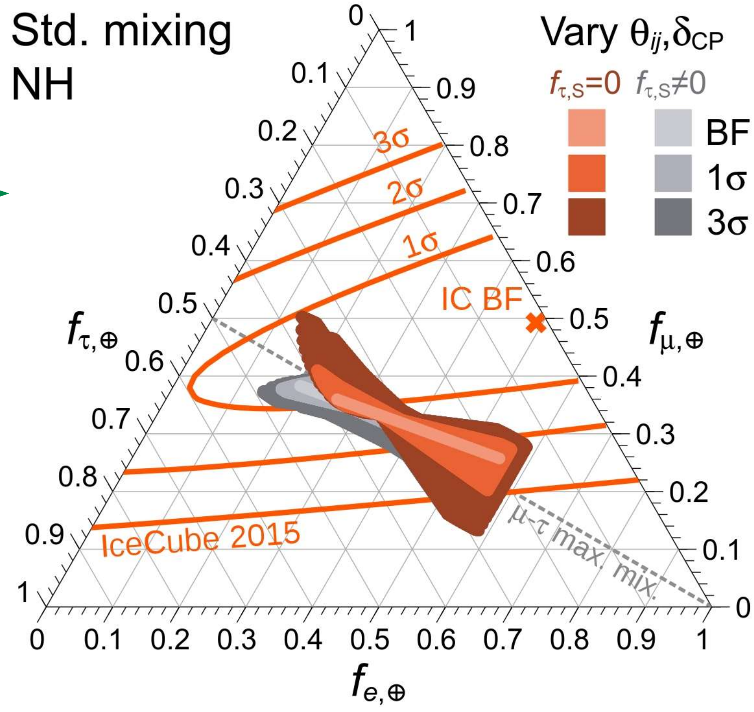
Flavor composition – Standard allowed region

At the sources

All possible flavor ratios



At Earth



MB, Beacom, Winter *PRL* 2015

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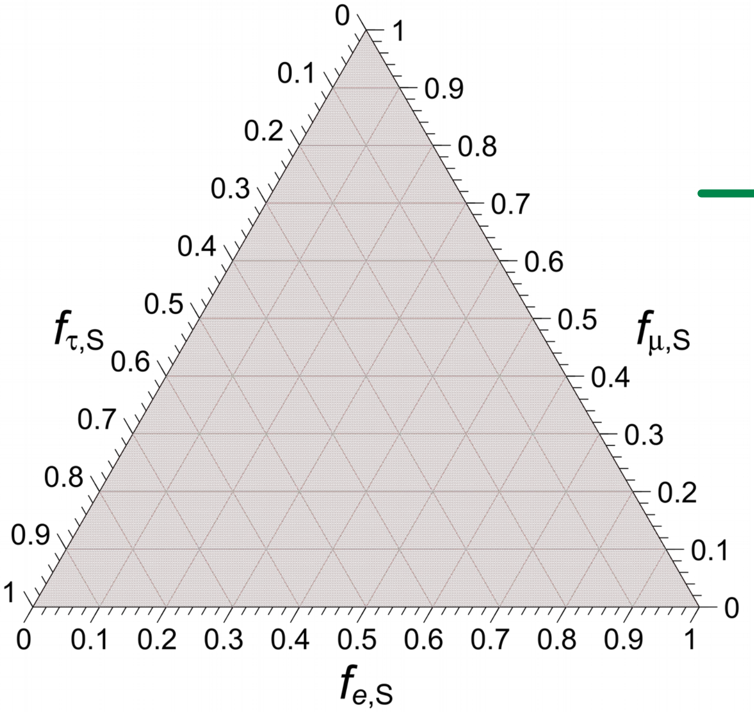
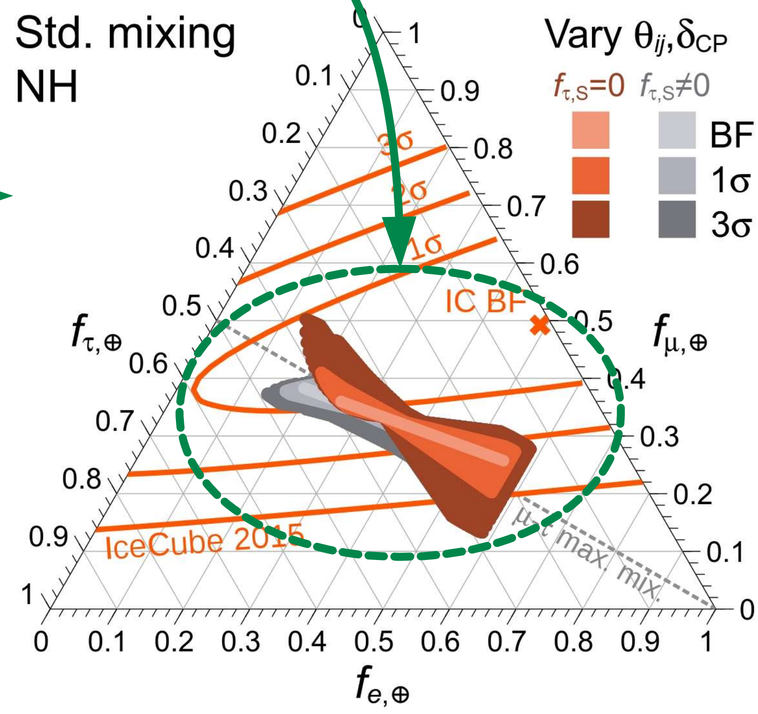


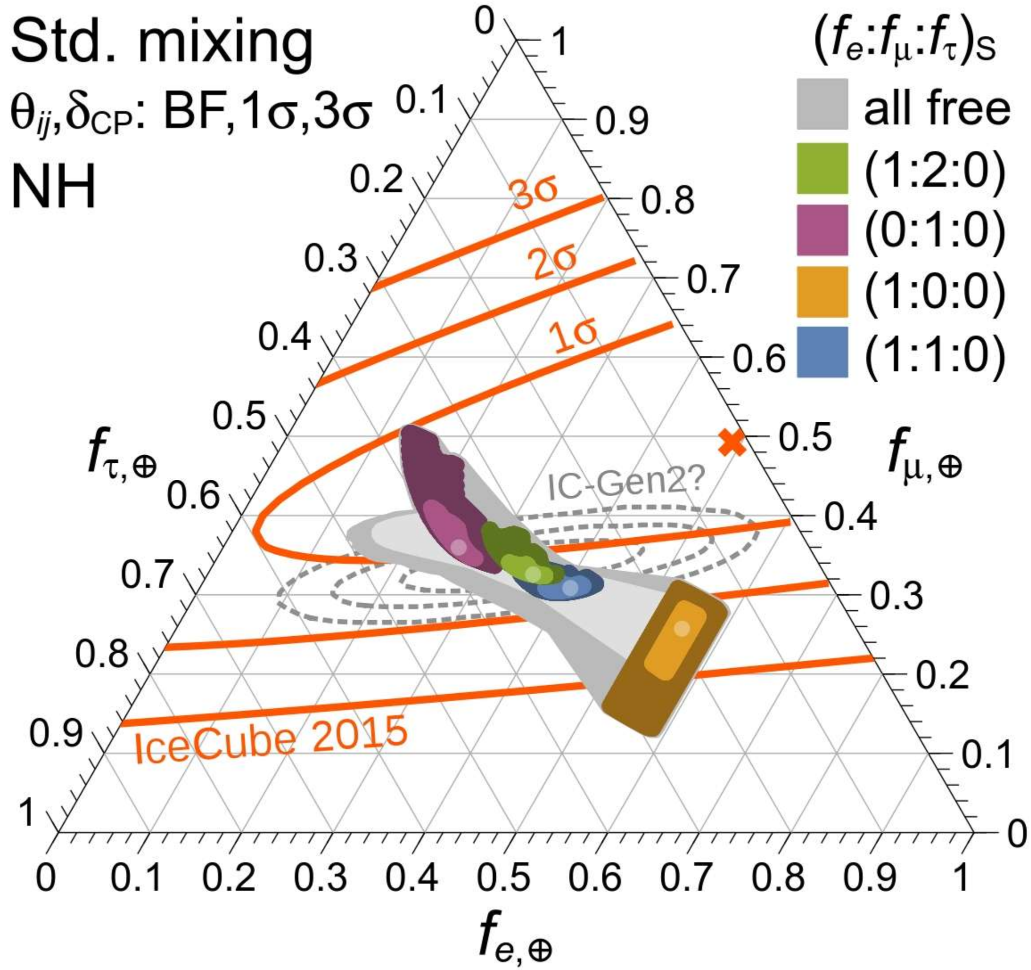
Only 10% of parameter space

At Earth



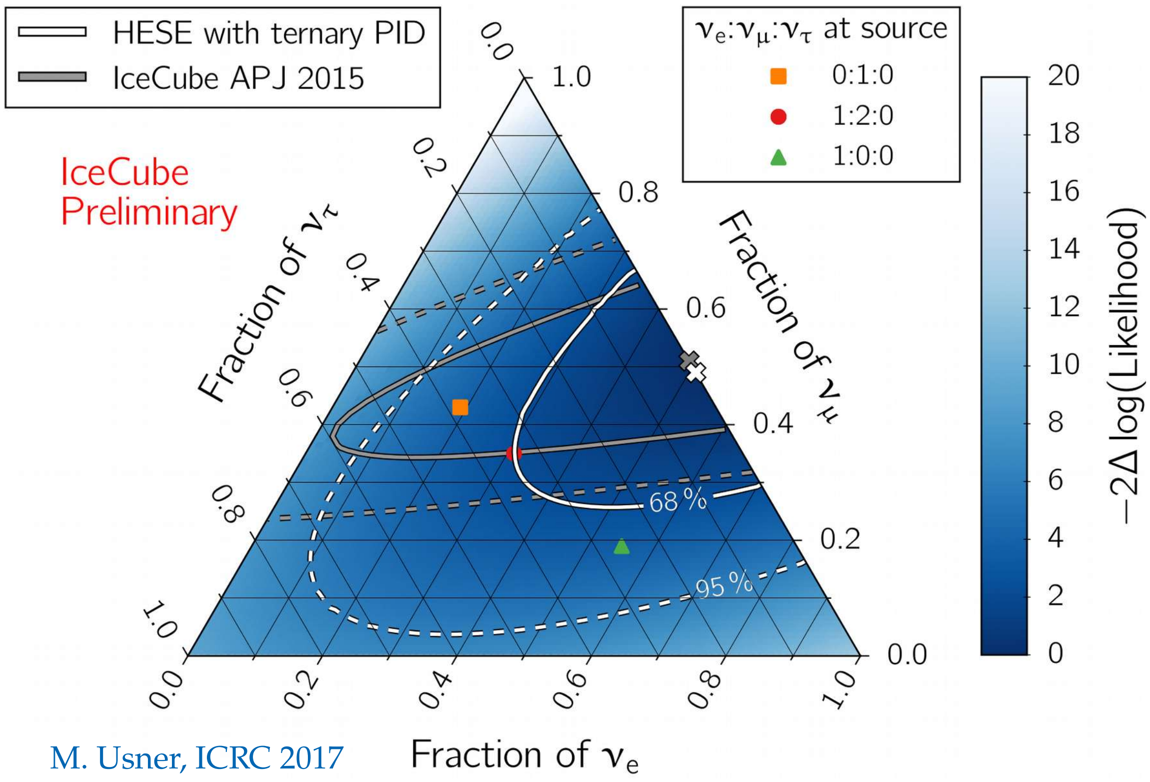
MB, Beacom, Winter *PRL* 2015

Flavor composition – A few source choices



MB, Beacom, Winter *PRL* 2015

IceCube analysis of flavor composition (pre-Neutrino 2018)



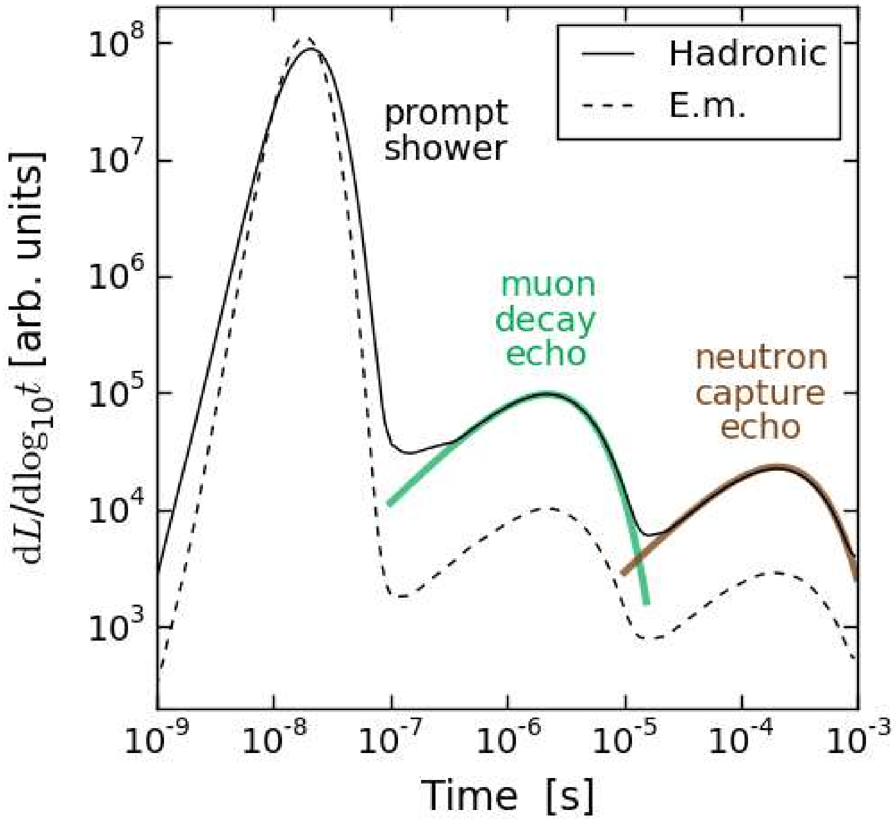
M. Usner, ICRC 2017

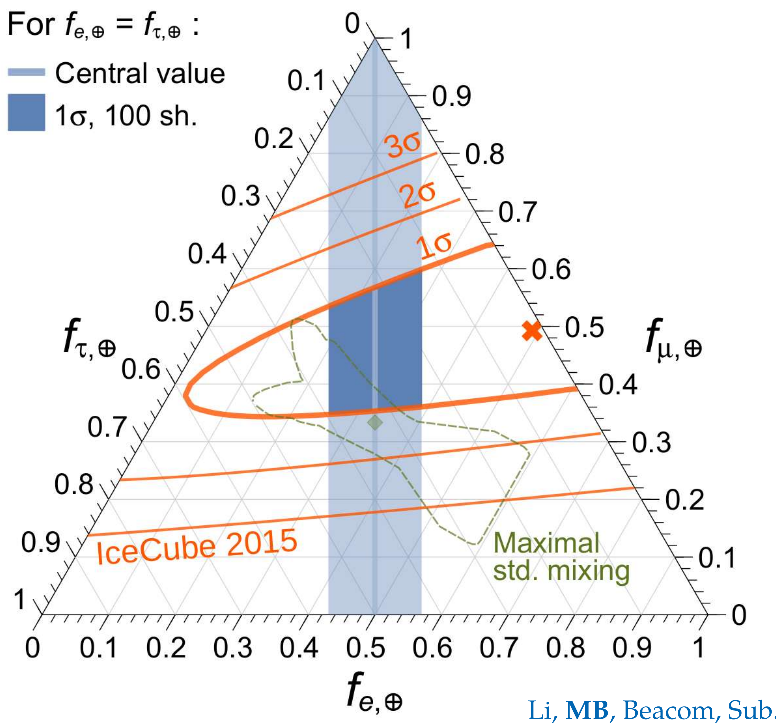
Using contained events plus through-going muons:

- 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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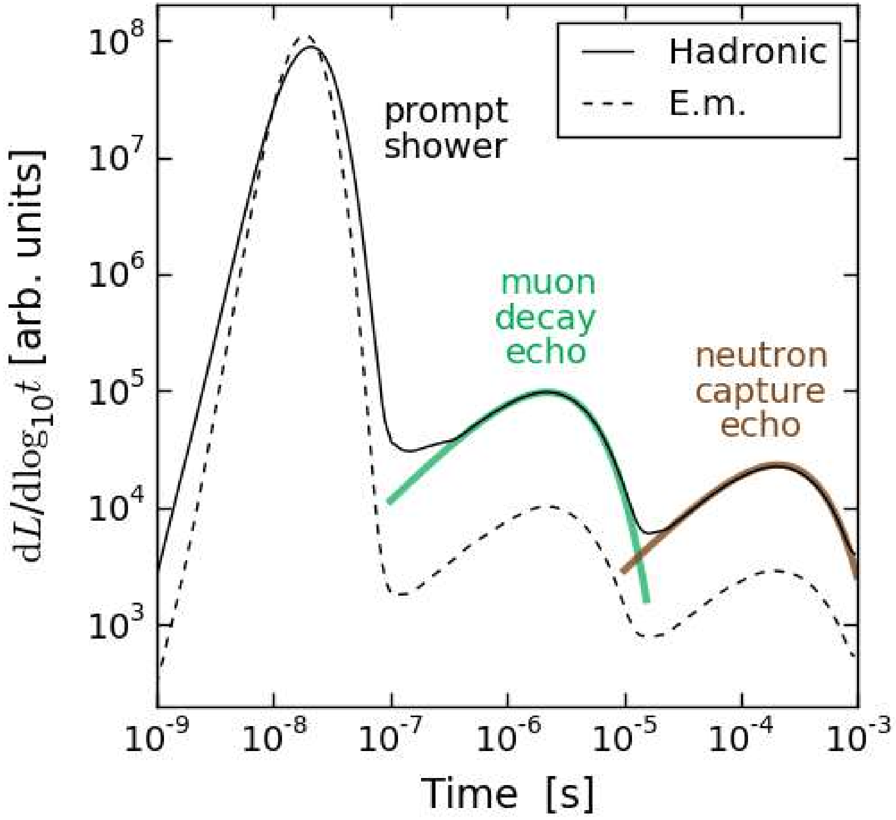
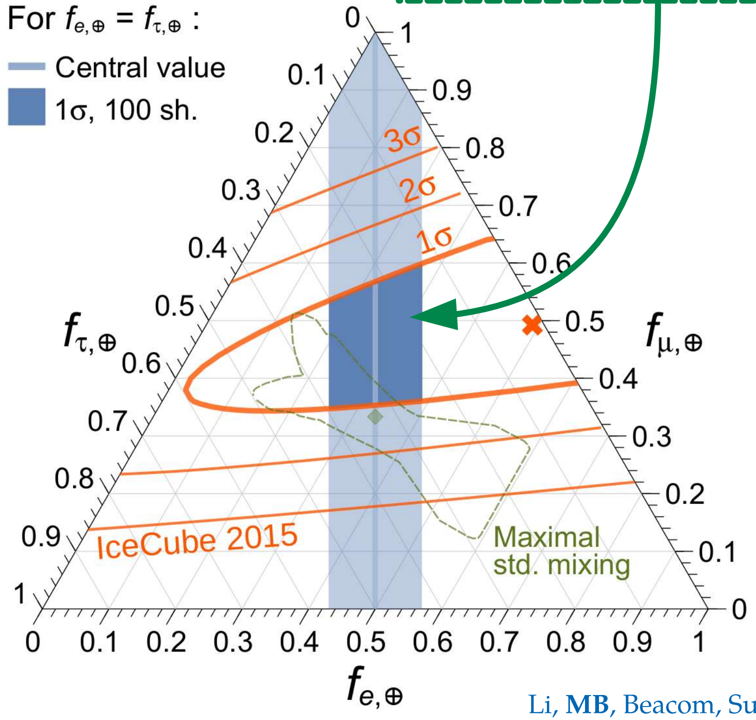


~10 × improvement over current measurement



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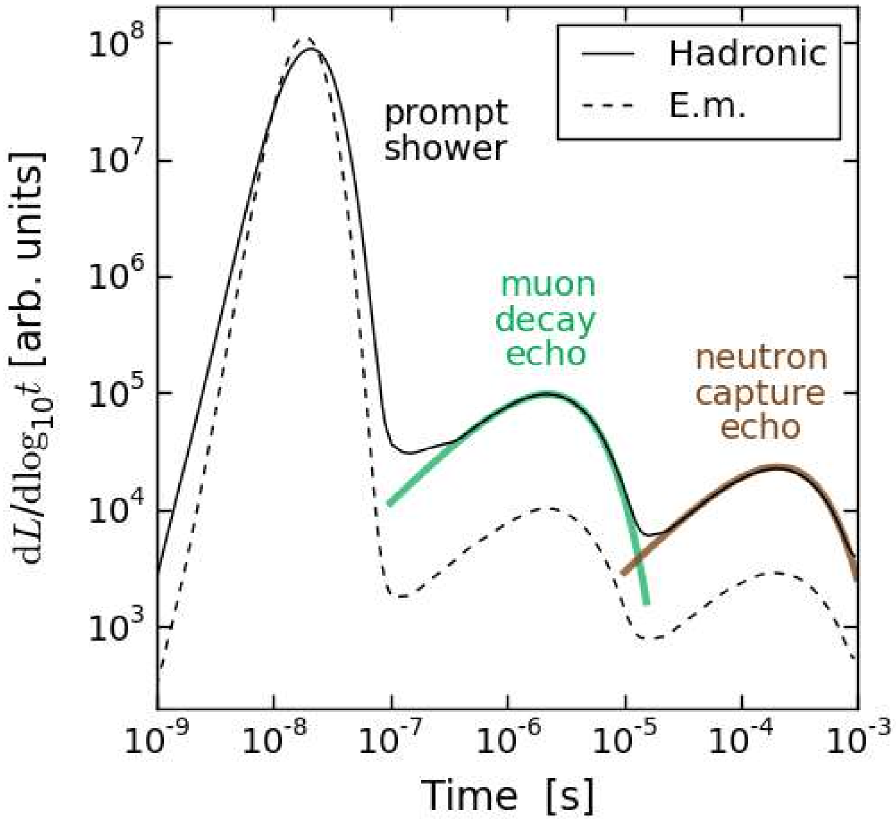

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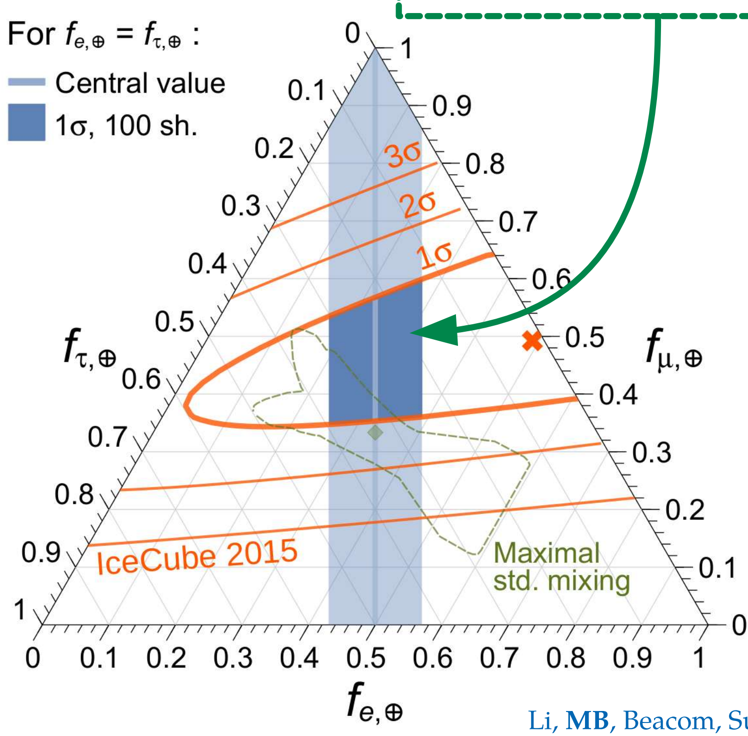
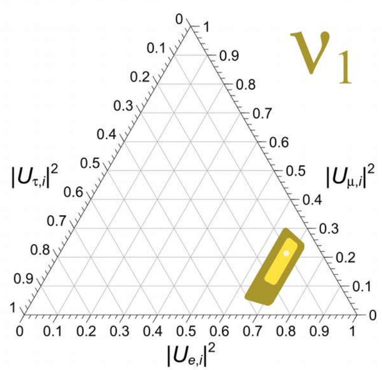
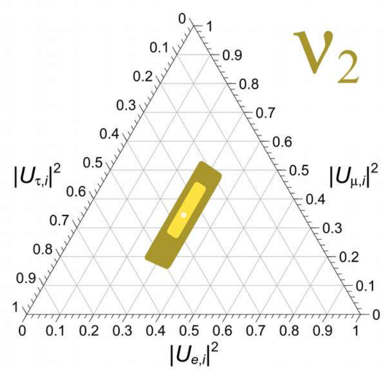


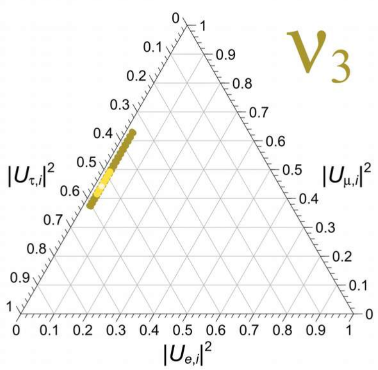
Li, **MB**, Beacom, Sub. to *PRL*

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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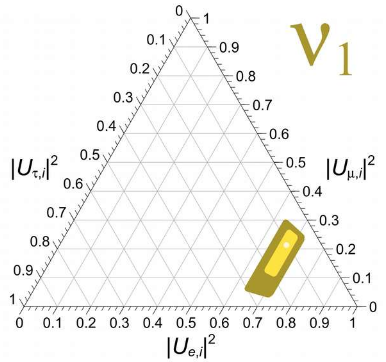
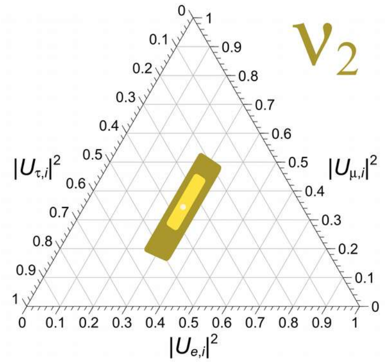
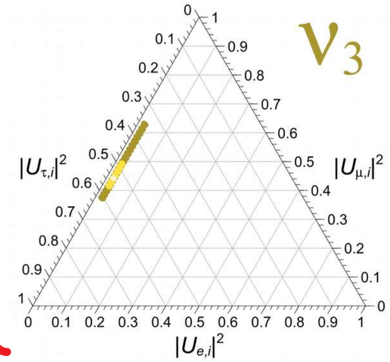
w_1 [

] $+\ w_2$ [

] $+\ w_3$ [

]

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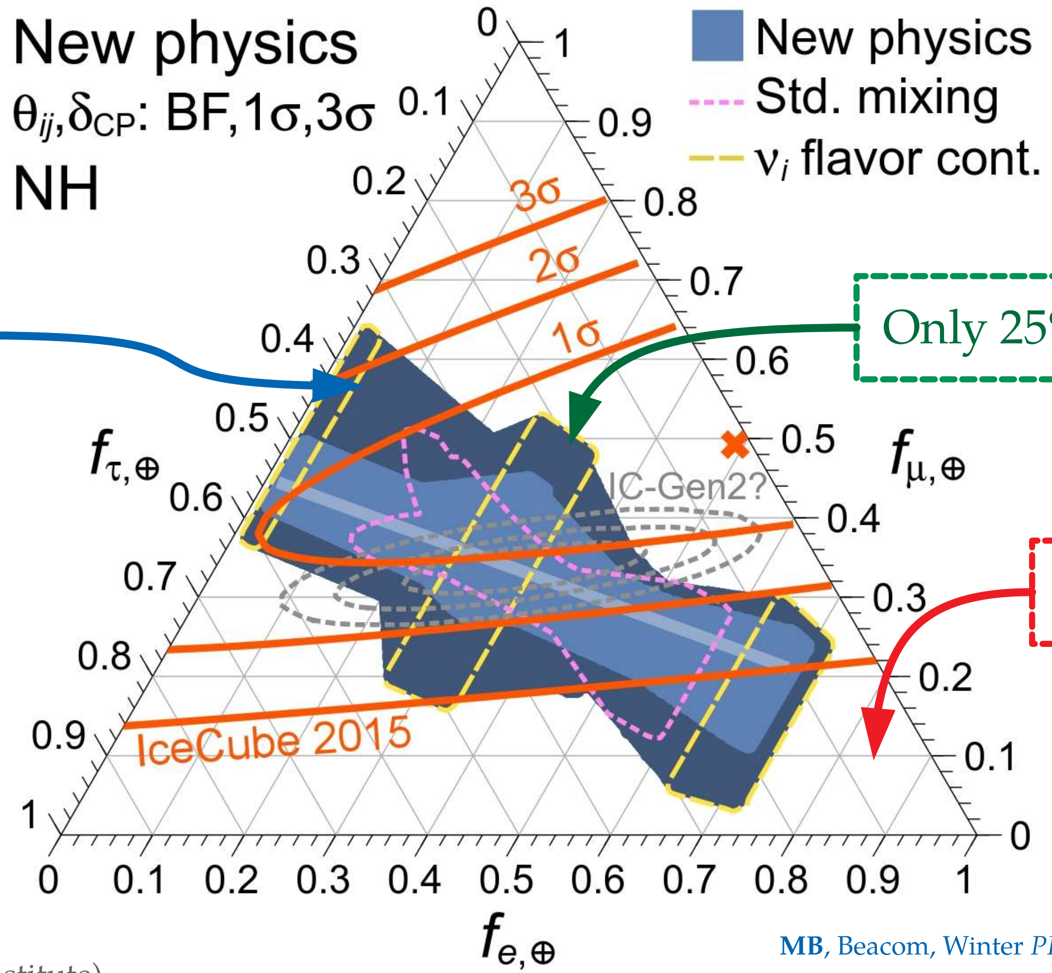
Flavor ratios accessible with decay-like physics

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

What lies beyond? *Take your pick*

- High-energy effective field theories
  - Violation of Lorentz and CPT invariance
    [Barenboim & Quigg, *PRD* 2003; **MB**, Gago, Peña-Garay, *JHEP* 2010; Kostelecky & Mewes 2004]
  - Violation of equivalence principle
    [Gasperini, *PRD* 1989; Glashow *et al.*, *PRD* 1997]
  - Coupling to a gravitational torsion field
    [De Sabbata & Gasperini, *Nuovo Cim.* 1981]
  - Renormalization-group-running of mixing parameters
    [**MB**, Gago, Jones, *JHEP* 2011]

- Active-sterile mixing
  [Aeikens *et al.*, *JCAP* 2015; V. Brdar, *JCAP* 2017]

- Flavor-violating physics
  - New $\nu\nu$ interactions
    [Ng & Beacom, *PRD* 2014; Cherry, Friedland, Shoemaker, 1411.1071; Blum, Hook, Murase, 1408.3799]
  - New neutrino-electron interactions
    [**MB** & Agarwalla, In prep.]

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
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- Active-sterile mixing
  [Aeikens *et al.*, *JCAP* 2015; V. Brdar, *JCAP* 2017]

- Flavor-violating physics
  - New $\nu\nu$ interactions
    [Ng & Beacom, *PRD* 2014; Cherry, Friedland, Shoemaker, 1411.1071; Blum, Hook, Murase, 1408.3799]
  - New neutrino-electron interactions
    [**MB** & Agarwalla, In prep.]

What lies beyond? *Take your pick*

- High-energy effective field theories
  - Violation of Lorentz and CPT invariance
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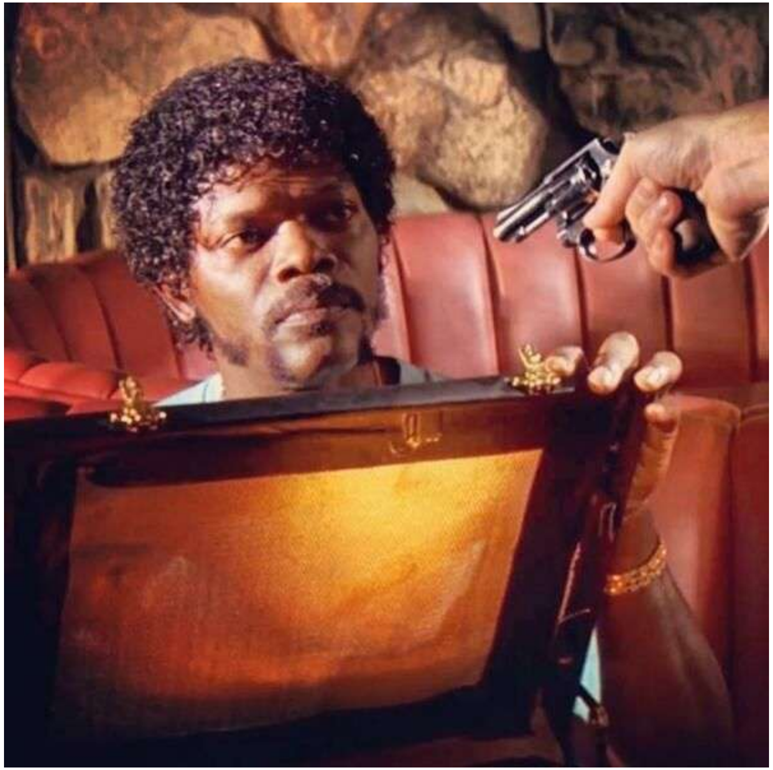


New physics – High-energy effects

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

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

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

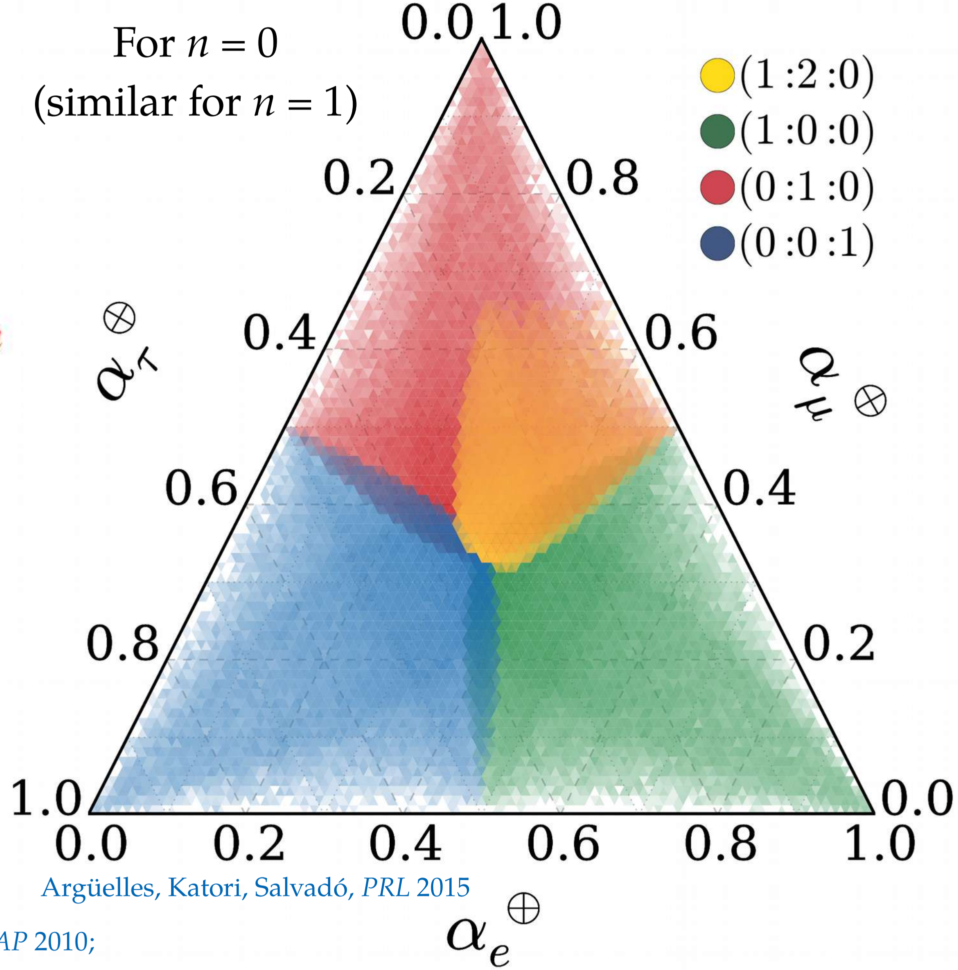
This can populate *all* of the triangle –

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

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

- Sample the unknown new mixing angles

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



Argüelles, Katori, Salvadó, *PRL* 2015

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

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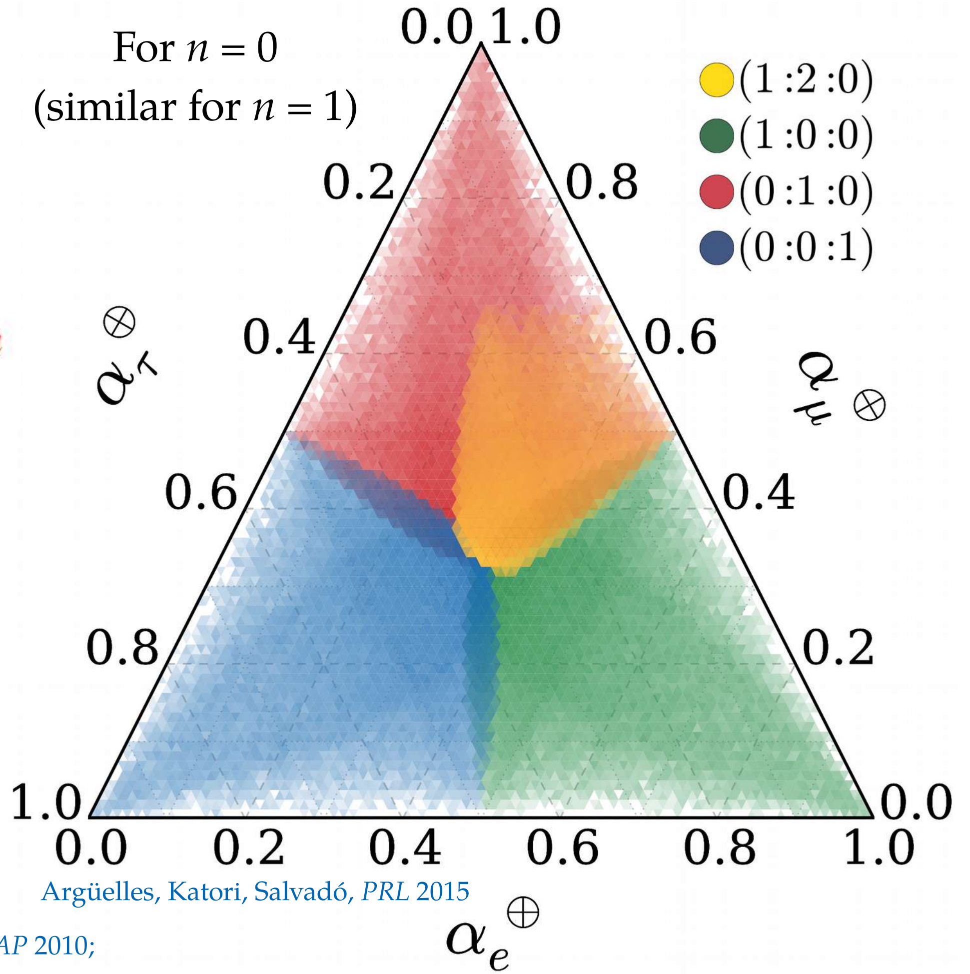

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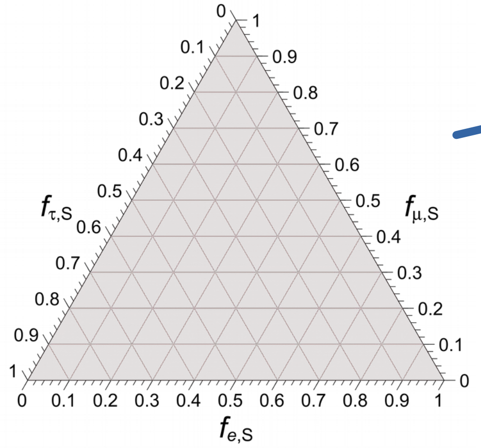
Measuring the neutrino lifetime

Sources



$\nu_2, \nu_3 \rightarrow \nu_1$

ν_1 lightest and stable

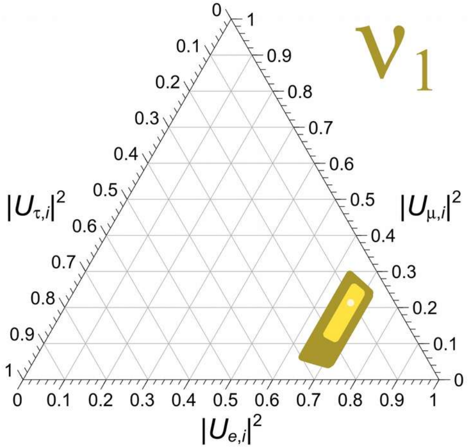
If all unstable neutrinos decay

$\nu_1, \nu_2 \rightarrow \nu_3$

ν_3 lightest and stable

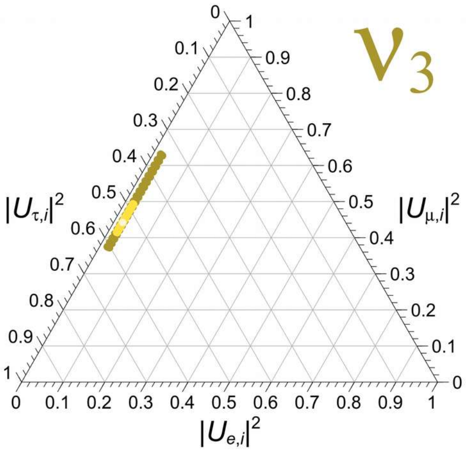
Earth

ν_1



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

ν_3



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Measuring the neutrino lifetime

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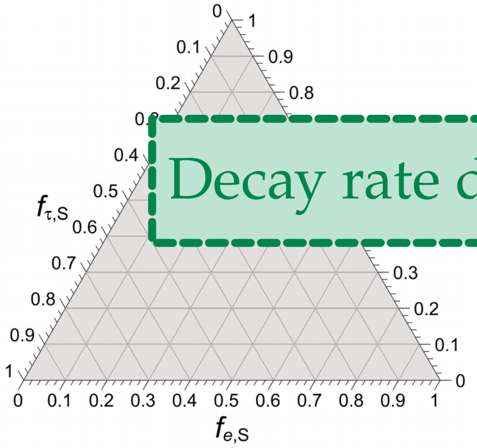


$$\underbrace{\nu_2, \nu_3 \rightarrow \nu_1}_{}$$

ν_1 lightest and stable

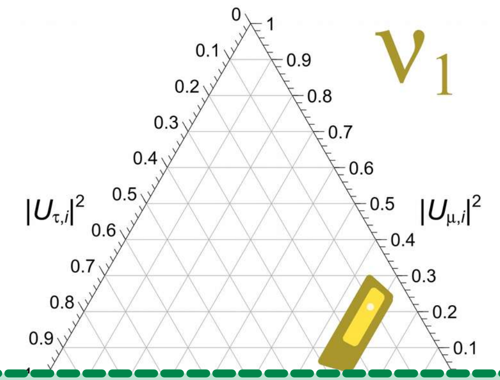
Decay rate depends on $\exp[-\, t \,/\, (\gamma\tau_i)] = \exp[-\, (L/E) \cdot (m_i/\tau_i)]$

neutrinos decay

$$\underbrace{\nu_1, \nu_2 \rightarrow \nu_3}_{}$$

ν_3 lightest and stable

Earth



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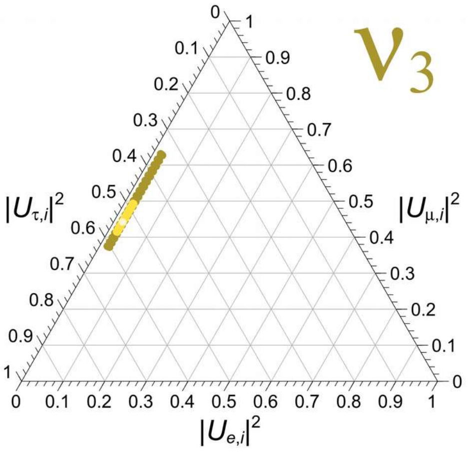
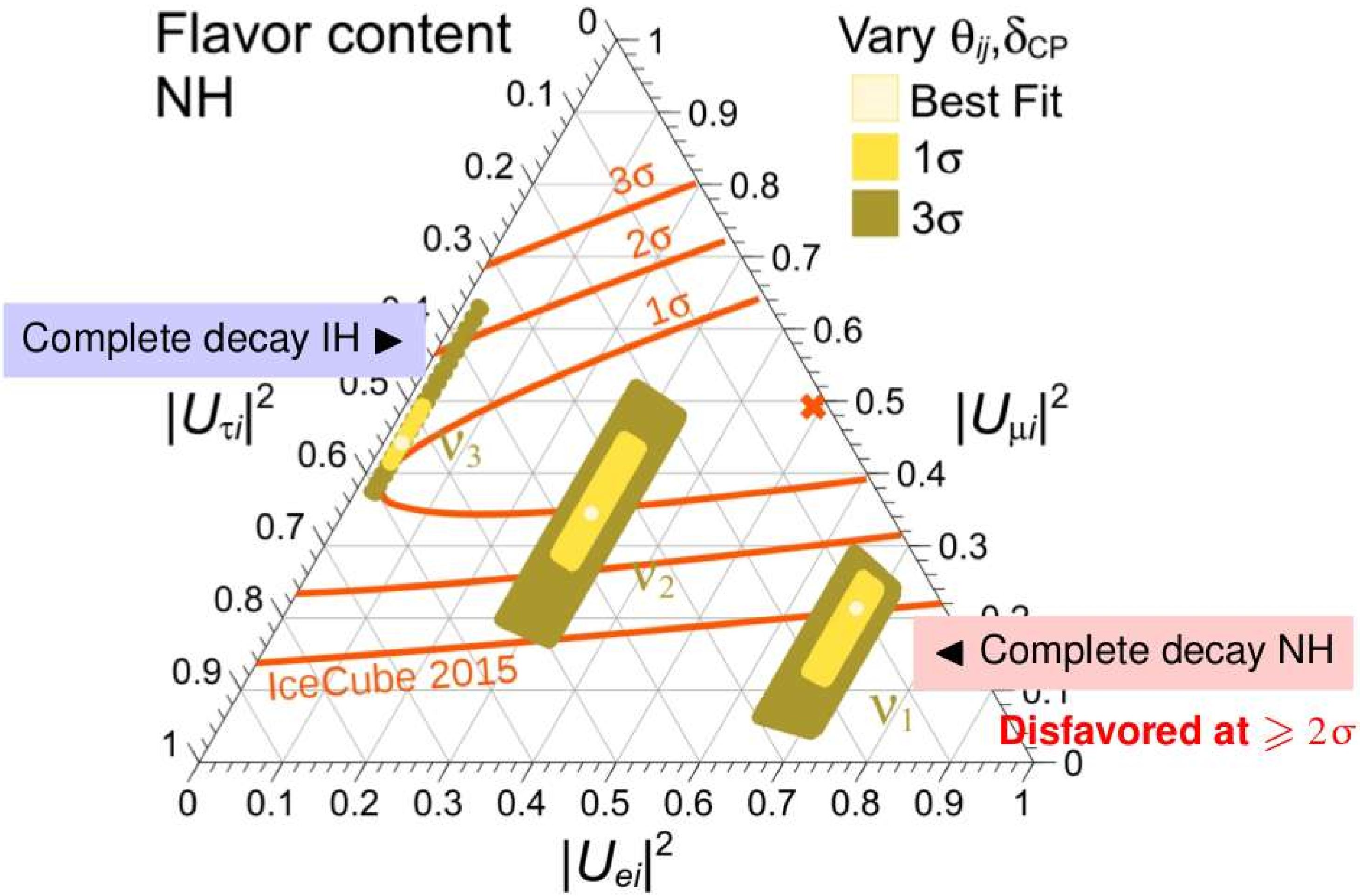
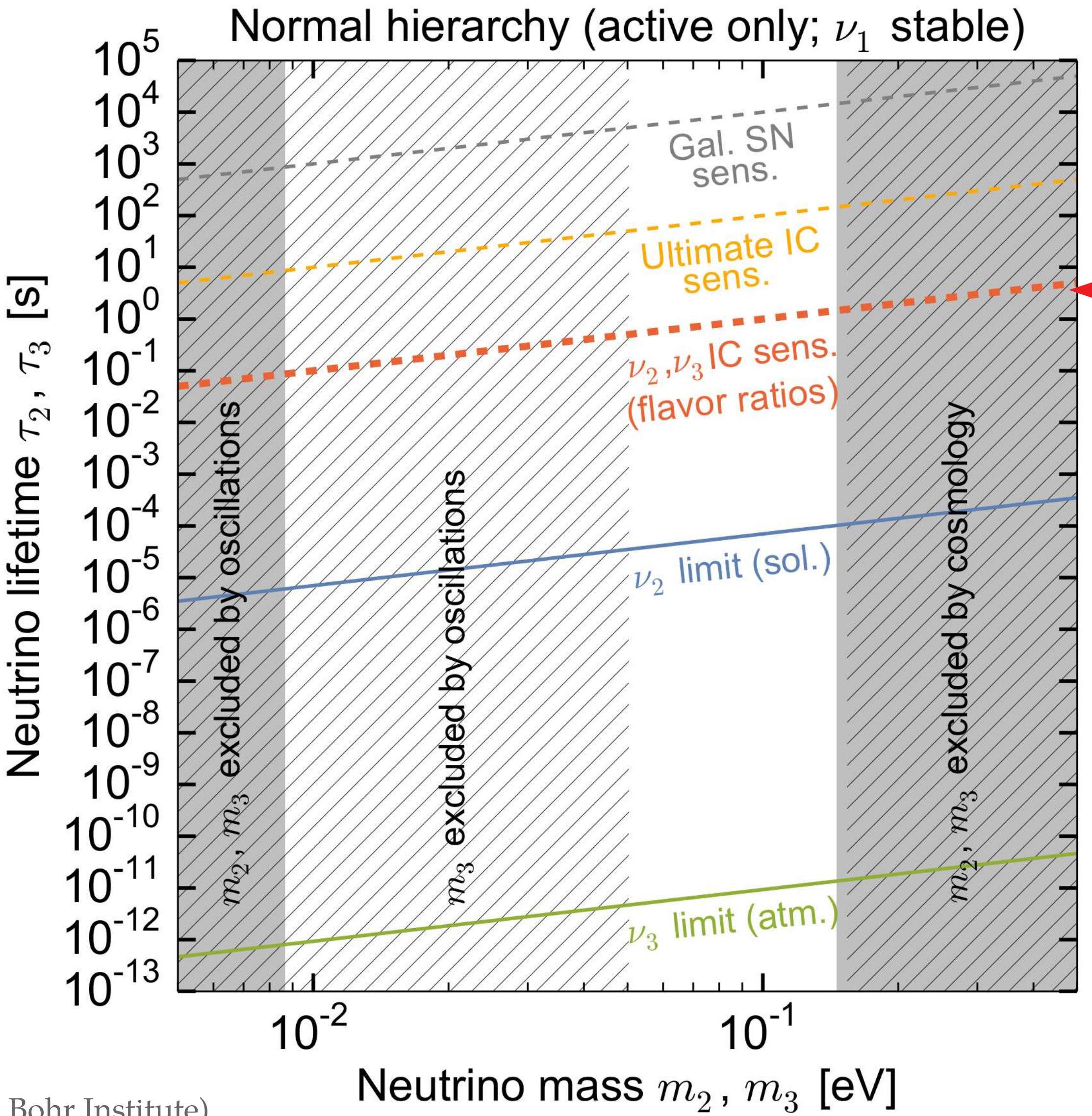


$$f_{\alpha,\oplus} = |U_{\alpha 3}|^2$$

Constraining decay from the flavor ratios





Our result

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

MB, Beacom, Murase, *PRD* 2017

Ultra-long-range flavorful interactions

See talk by Oliviero Cremonesi

- 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
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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 $\sim(1/m')$

The power of many (electrons)

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

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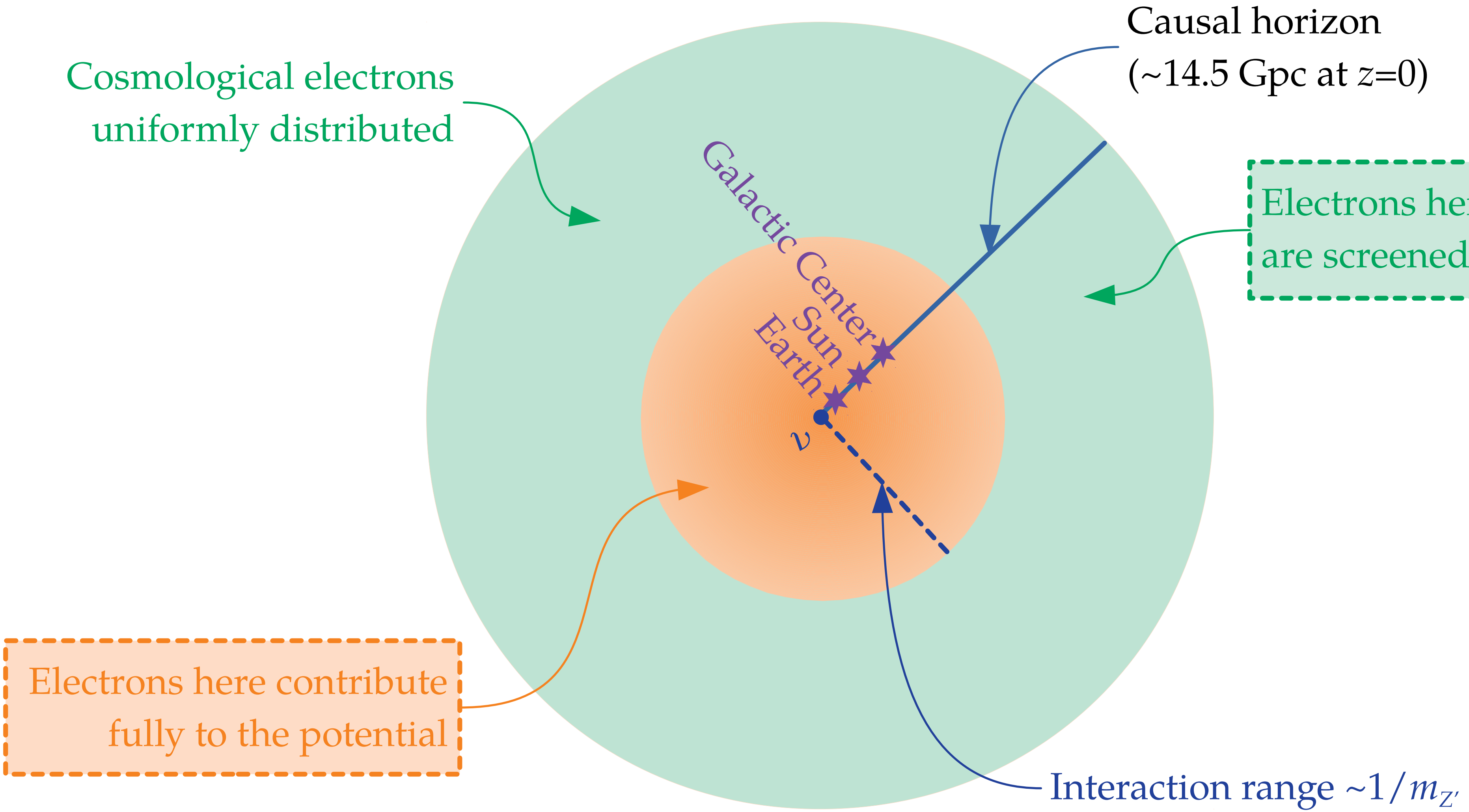
Z′ mass

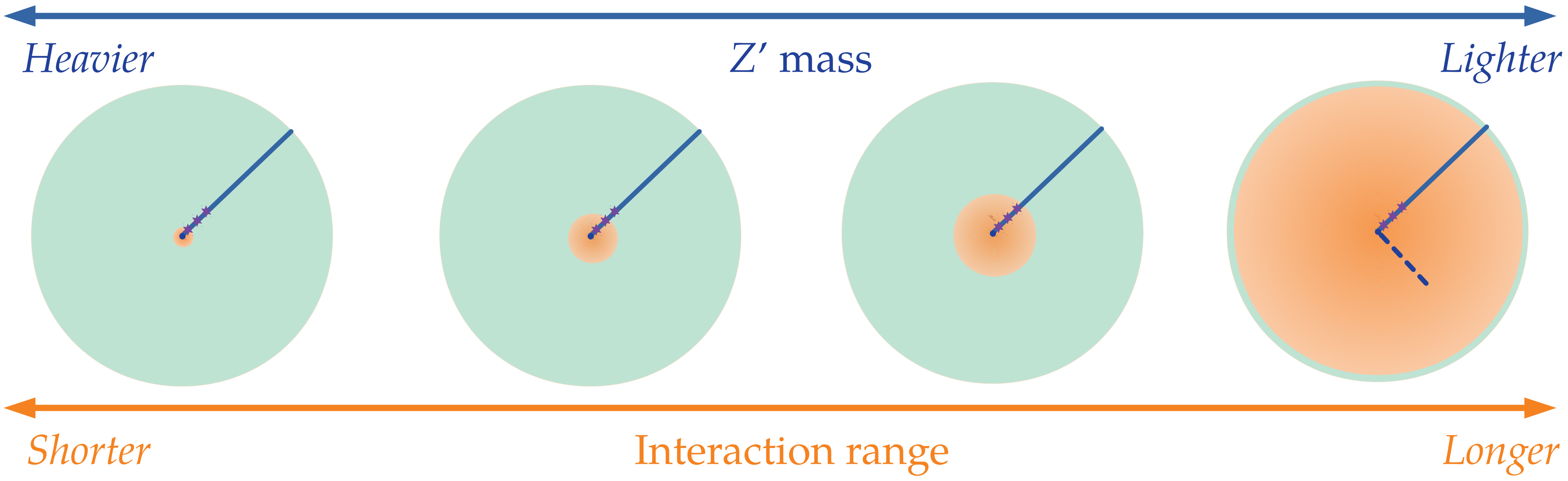
Z′ coupling

Distance to neutrino

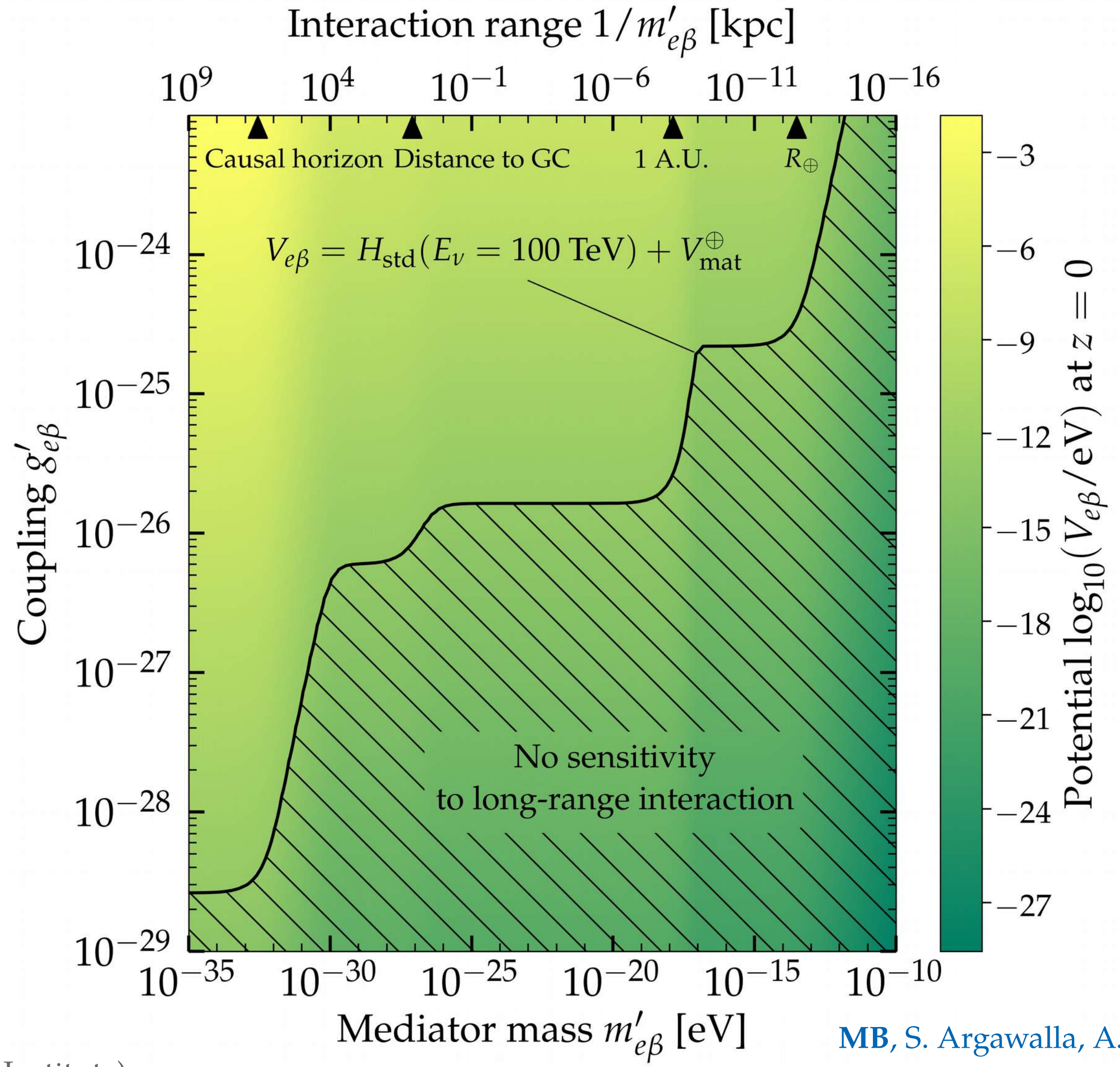
A neutrino "feels" all the electrons within the interaction range $\sim(1/m')$


Causal horizon
(~14.5 Gpc at z=0)
Cosmological electrons
uniformly distributed
Electrons here
are screened
Galactic Center
Sun
Earth
ν
Electrons here contribute
fully to the potential
Interaction range ~$1/m_{Z'}$

Not to scale



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}
10^{-33} eV	Size of the Universe	10^{78}



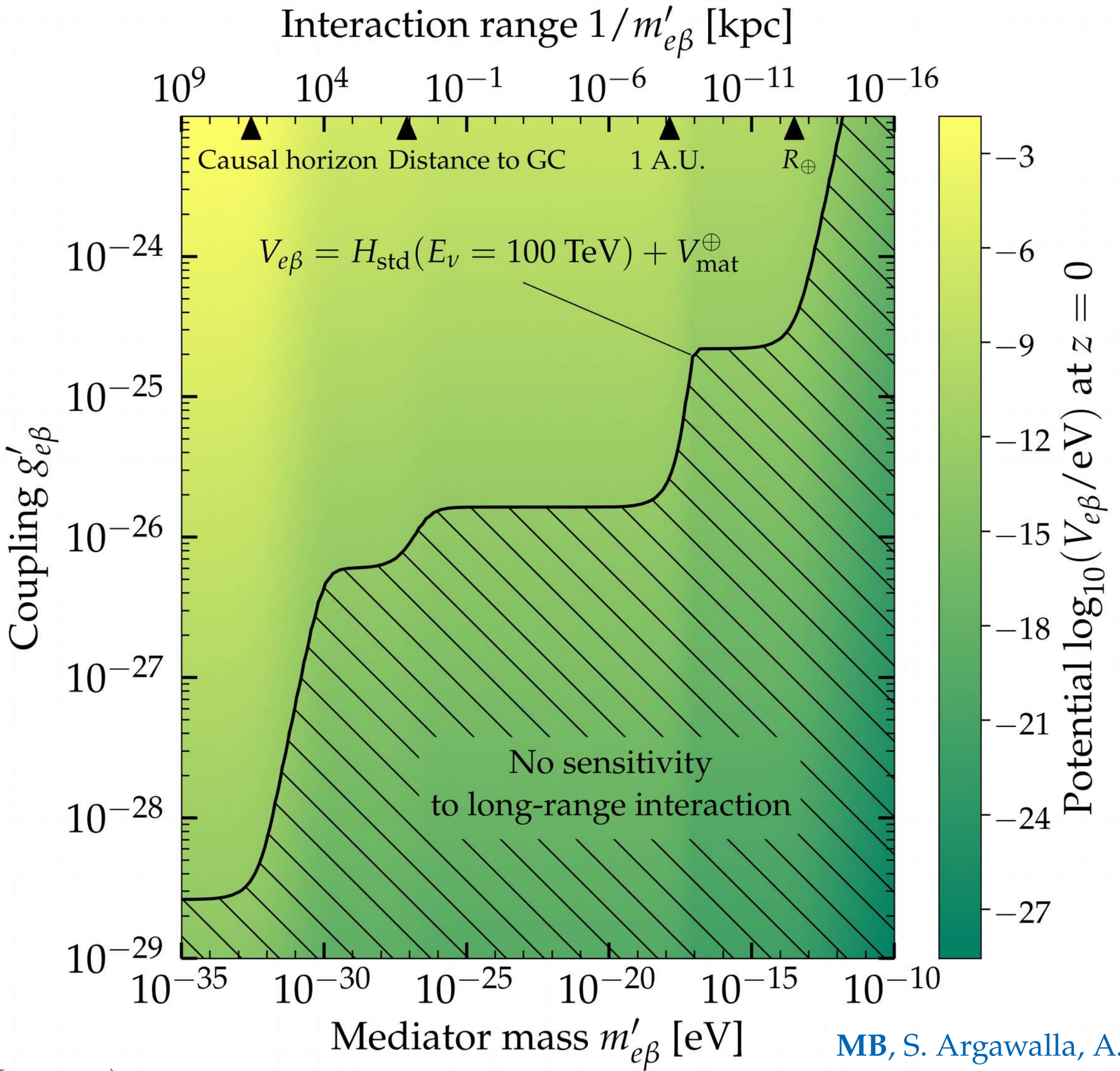
MB, S. Argawalla, A. De Gouvea, *In prep.*

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

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

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

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



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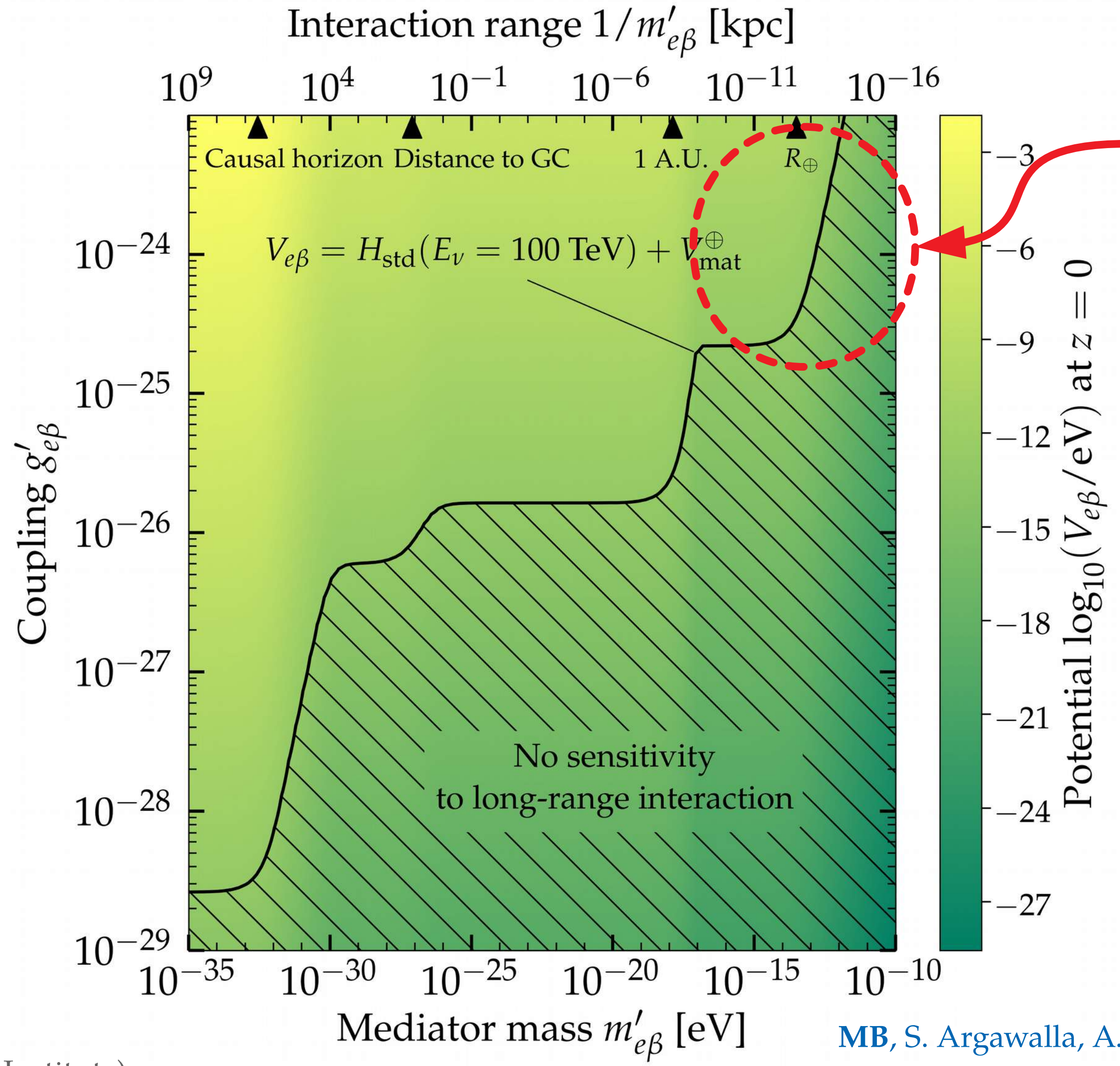

Dominated by electrons in the Earth + Moon

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

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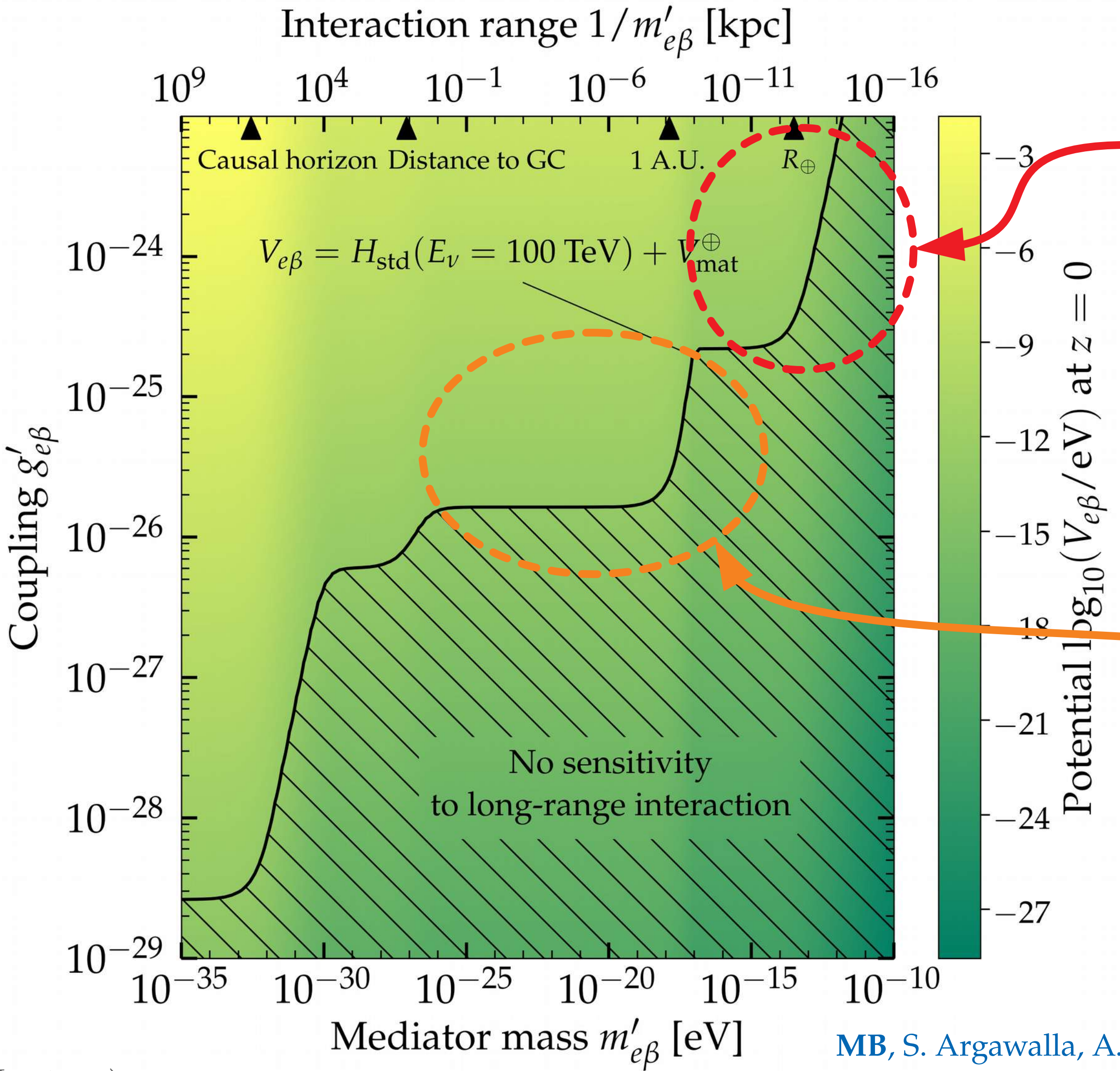

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Dominated by solar electrons (+ Milky-Way *e*)

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

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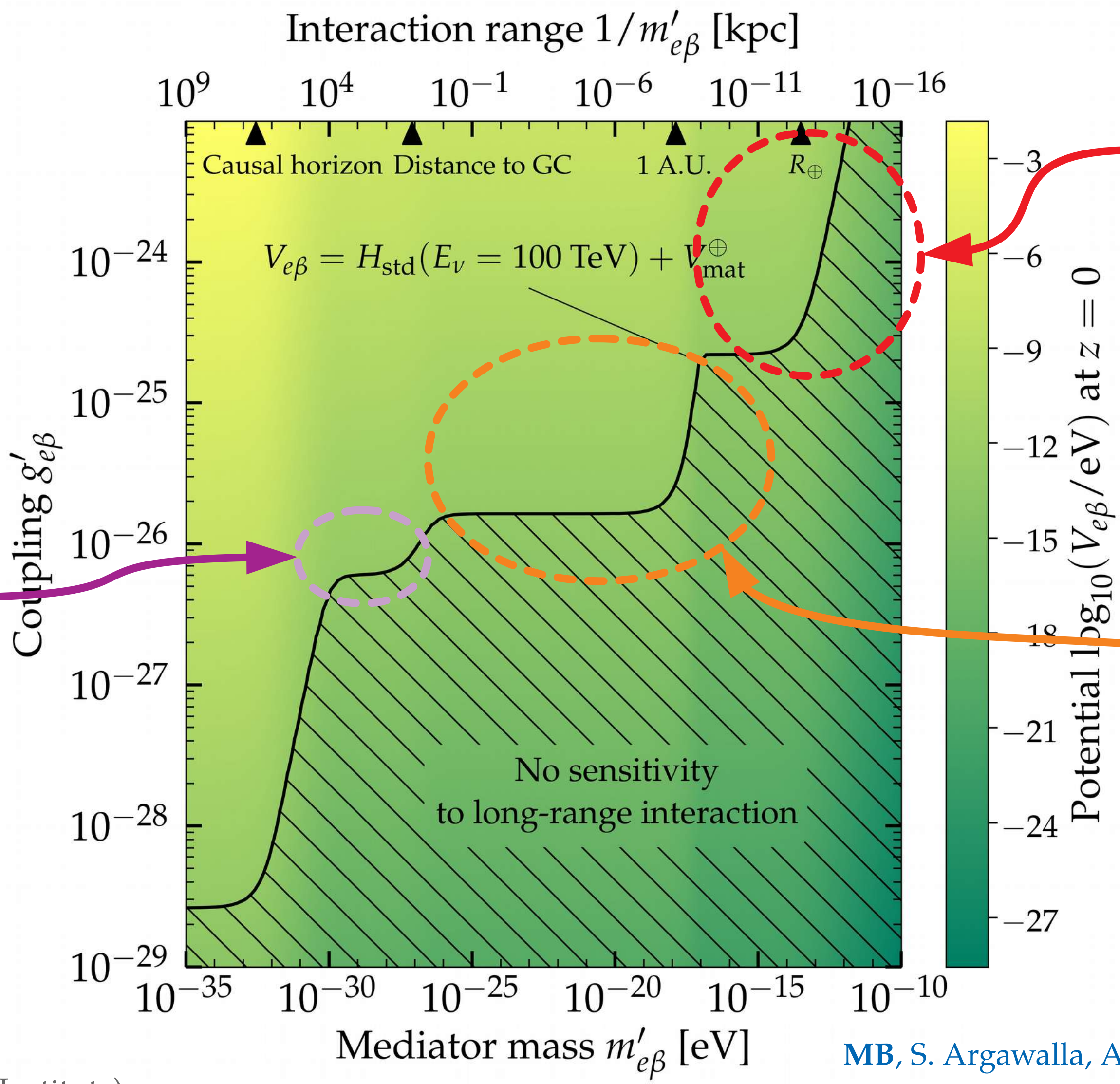

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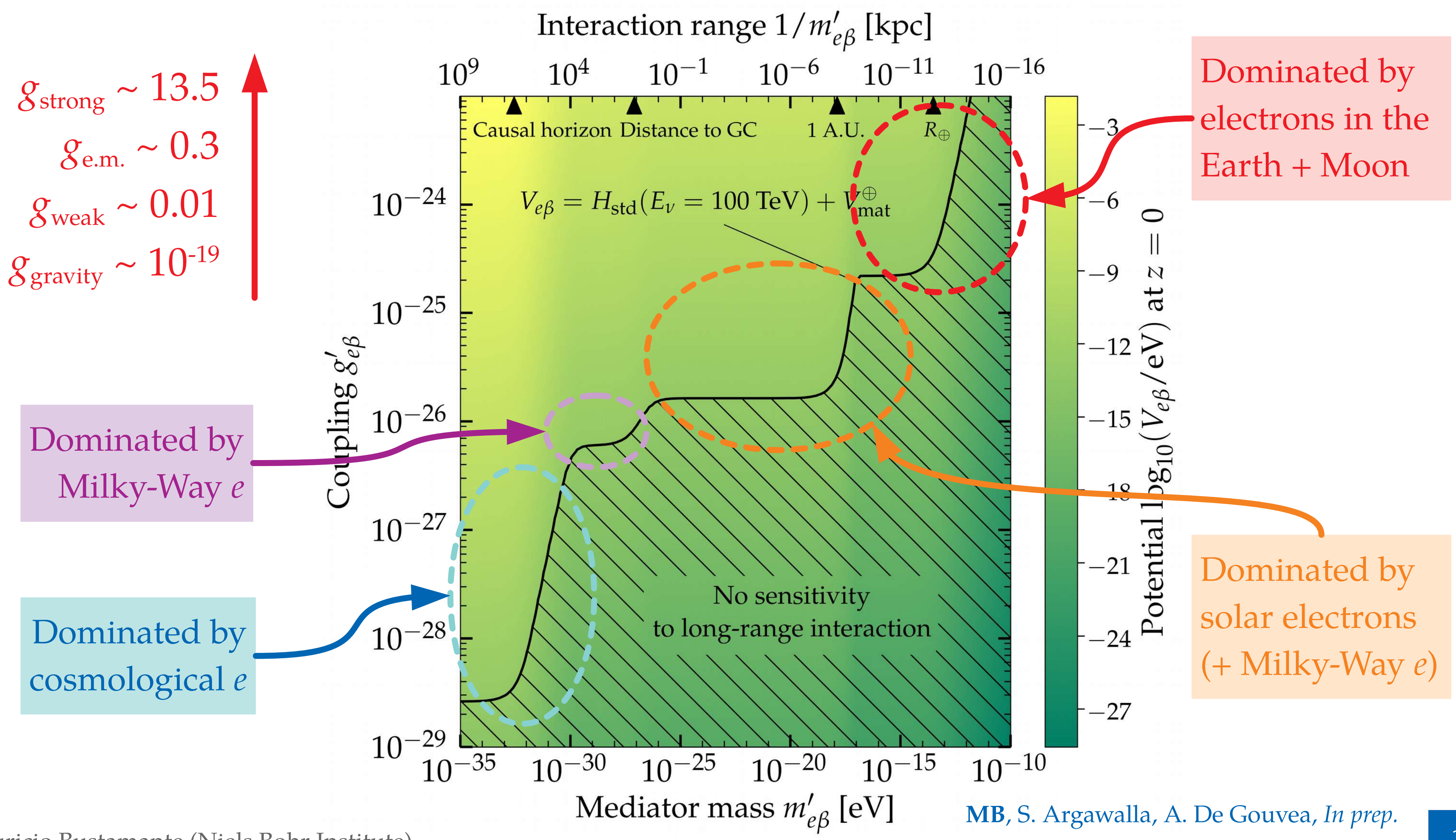
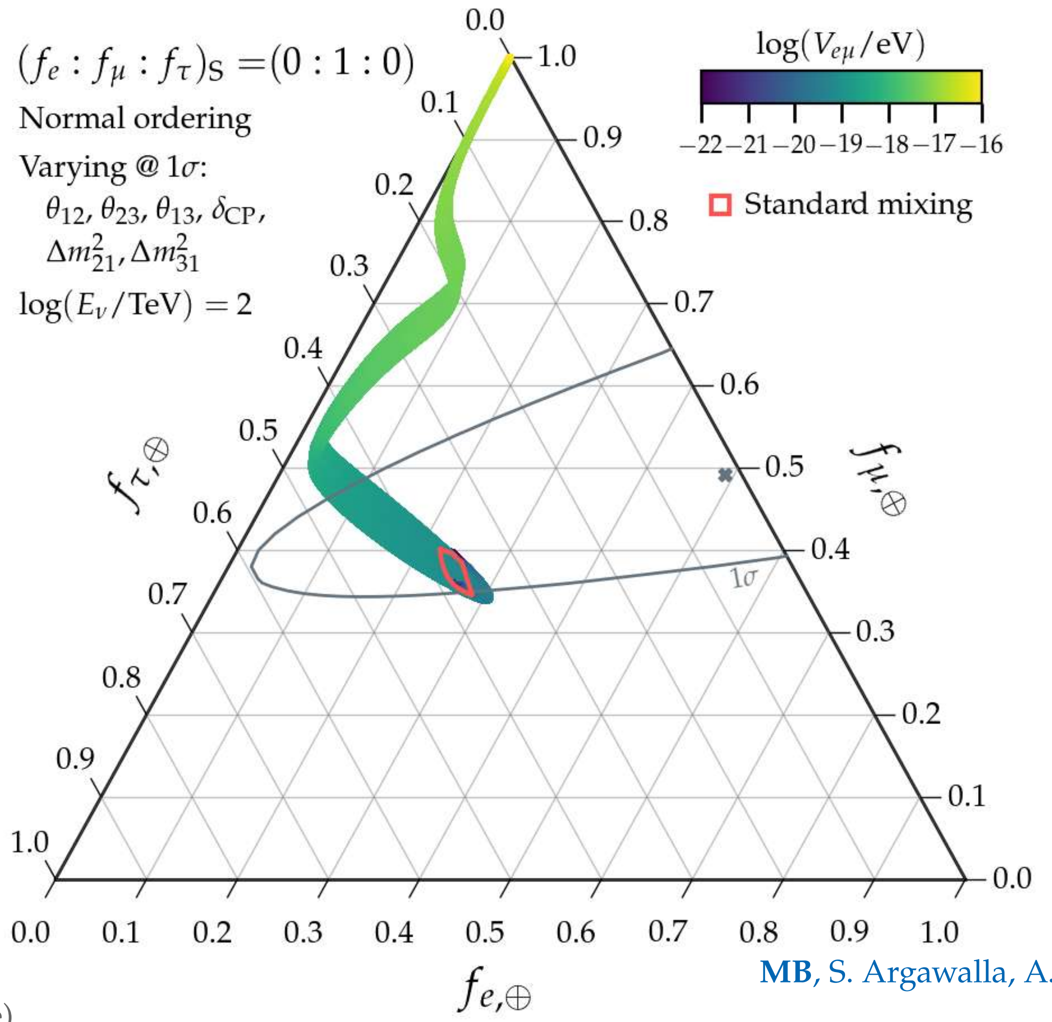


MB, S. Argawalla, A. De Gouvea, *In prep.*

Long-range interactions can turn off flavor mixing



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

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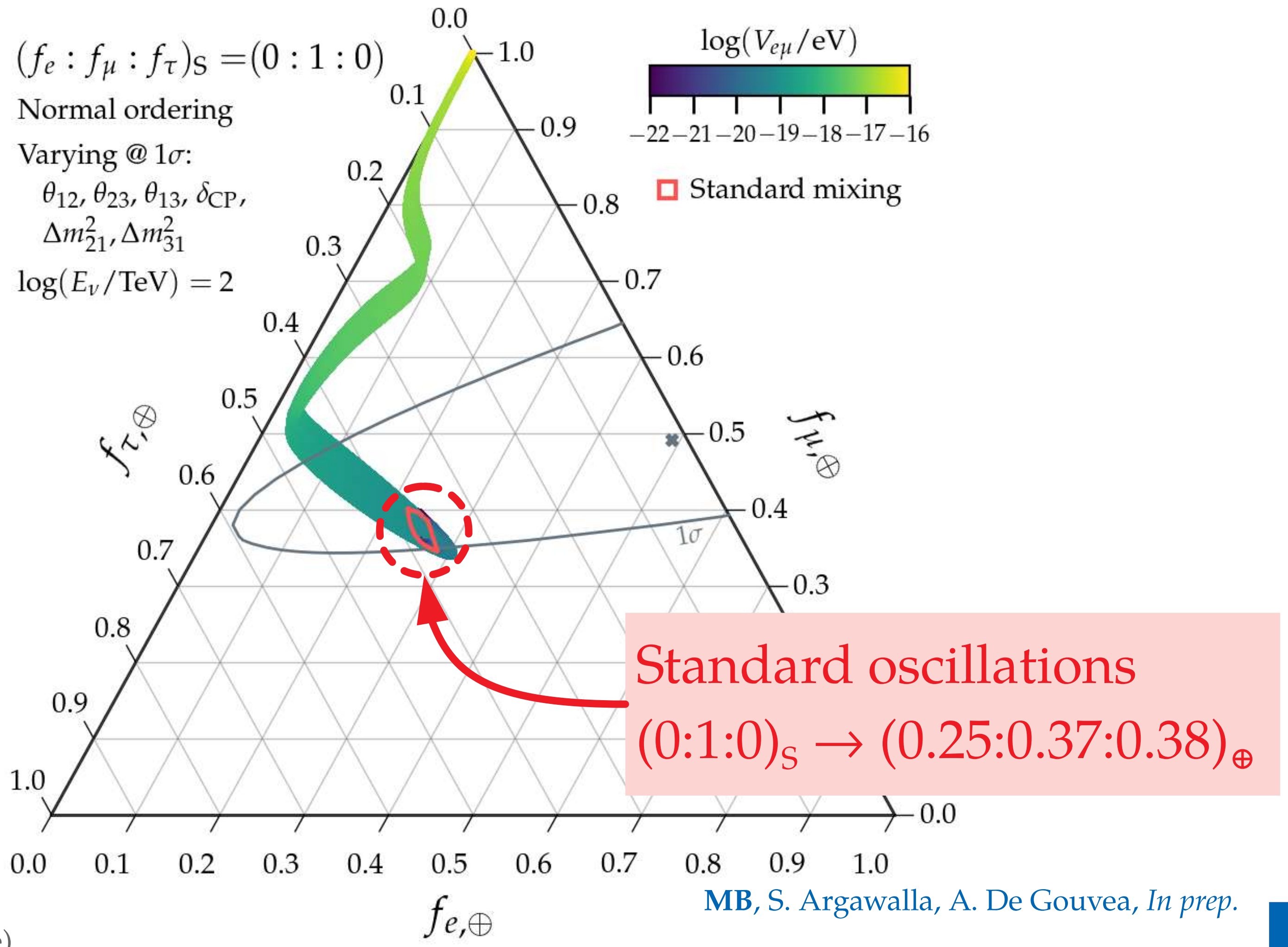

MB, S. Argawalla, A. De Gouvea, *In prep.*

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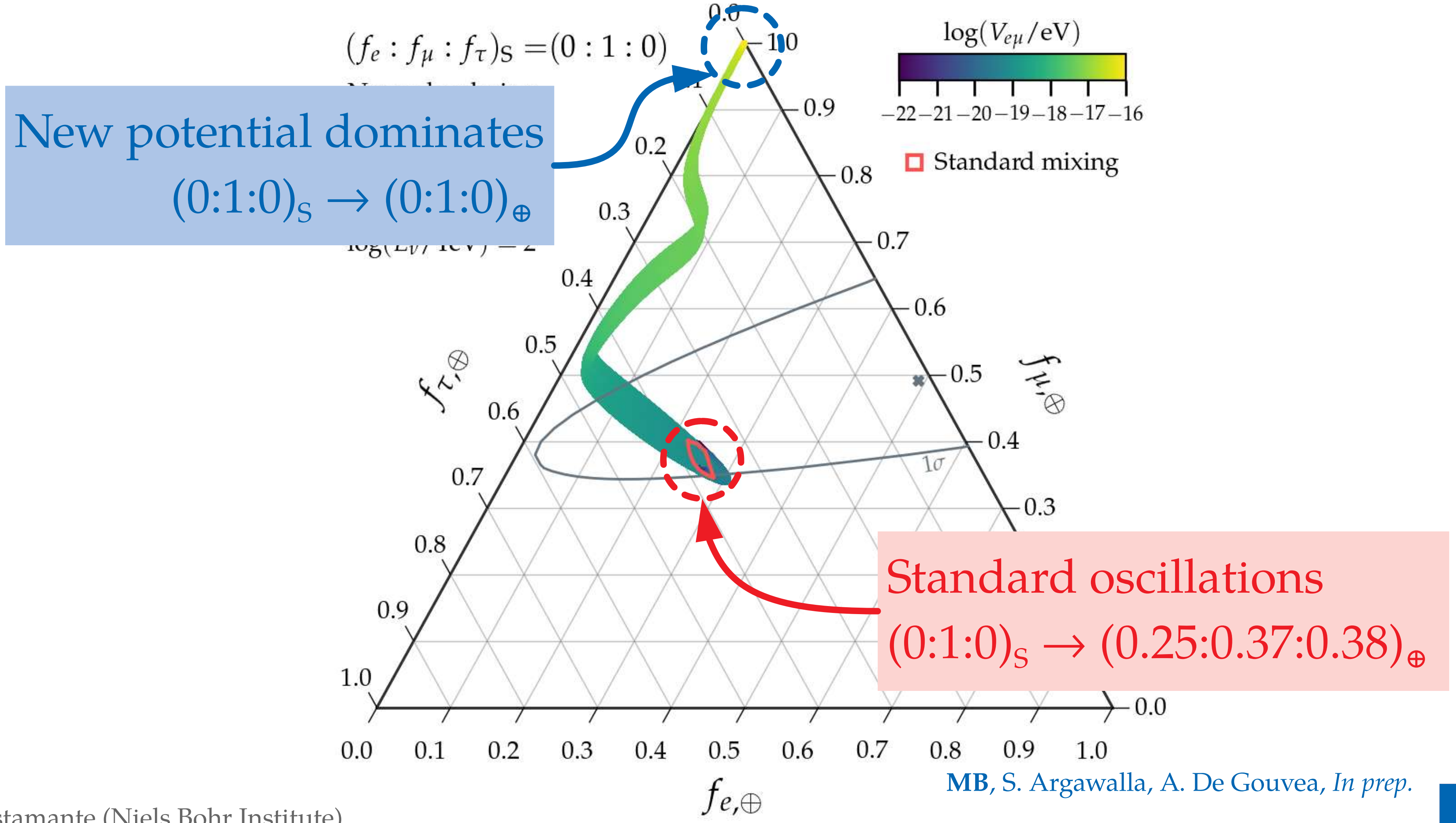

MB, S. Argawalla, A. De Gouvea, *In prep.*

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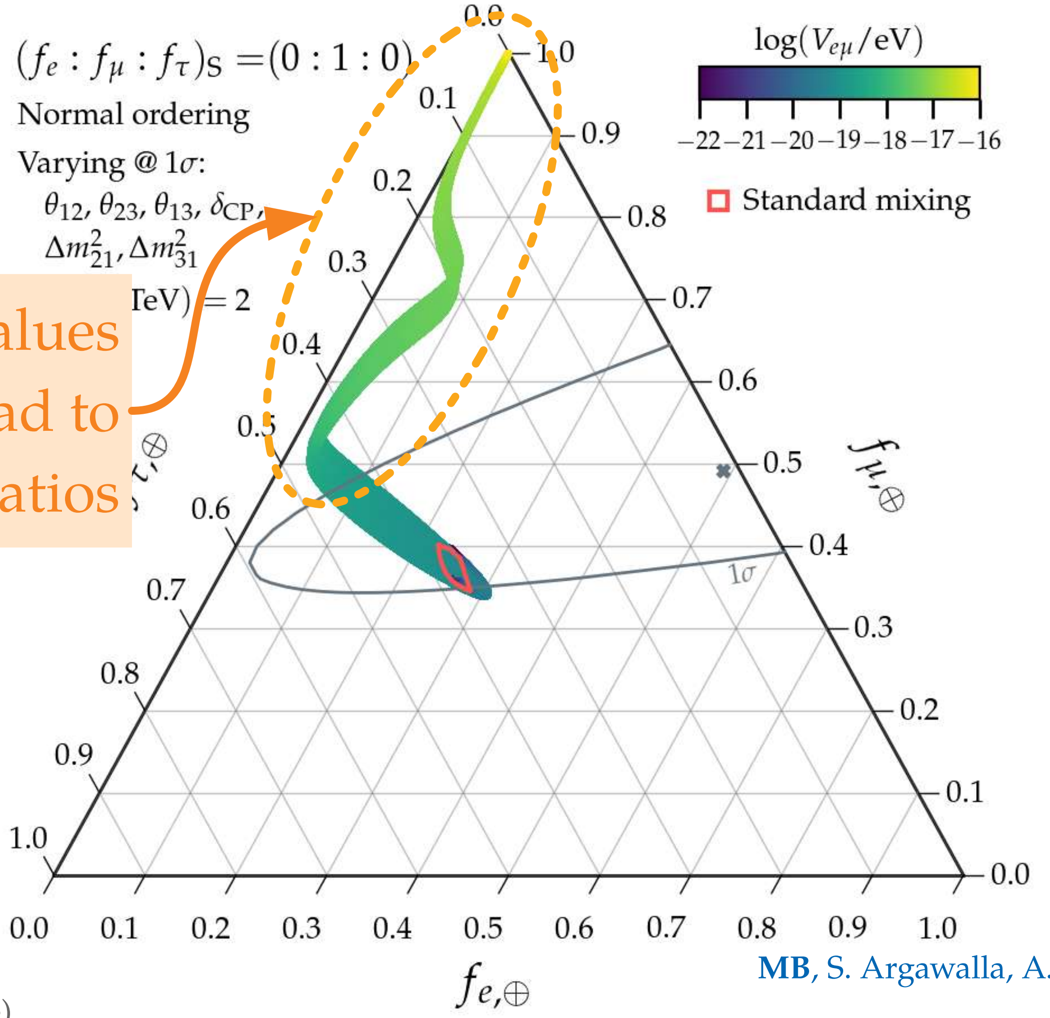
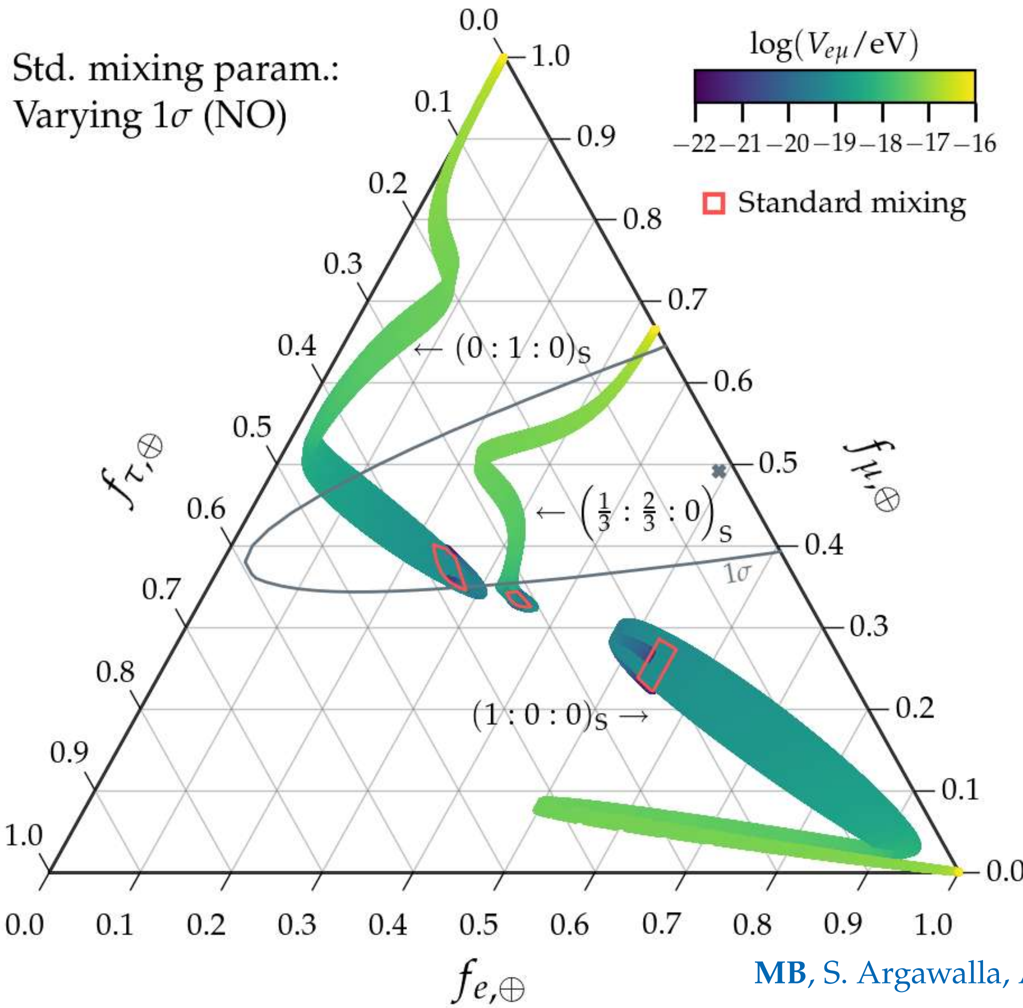


We can disfavor all values of m' and g' that lead to these flavor ratios

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

Long-range interactions can turn off flavor mixing



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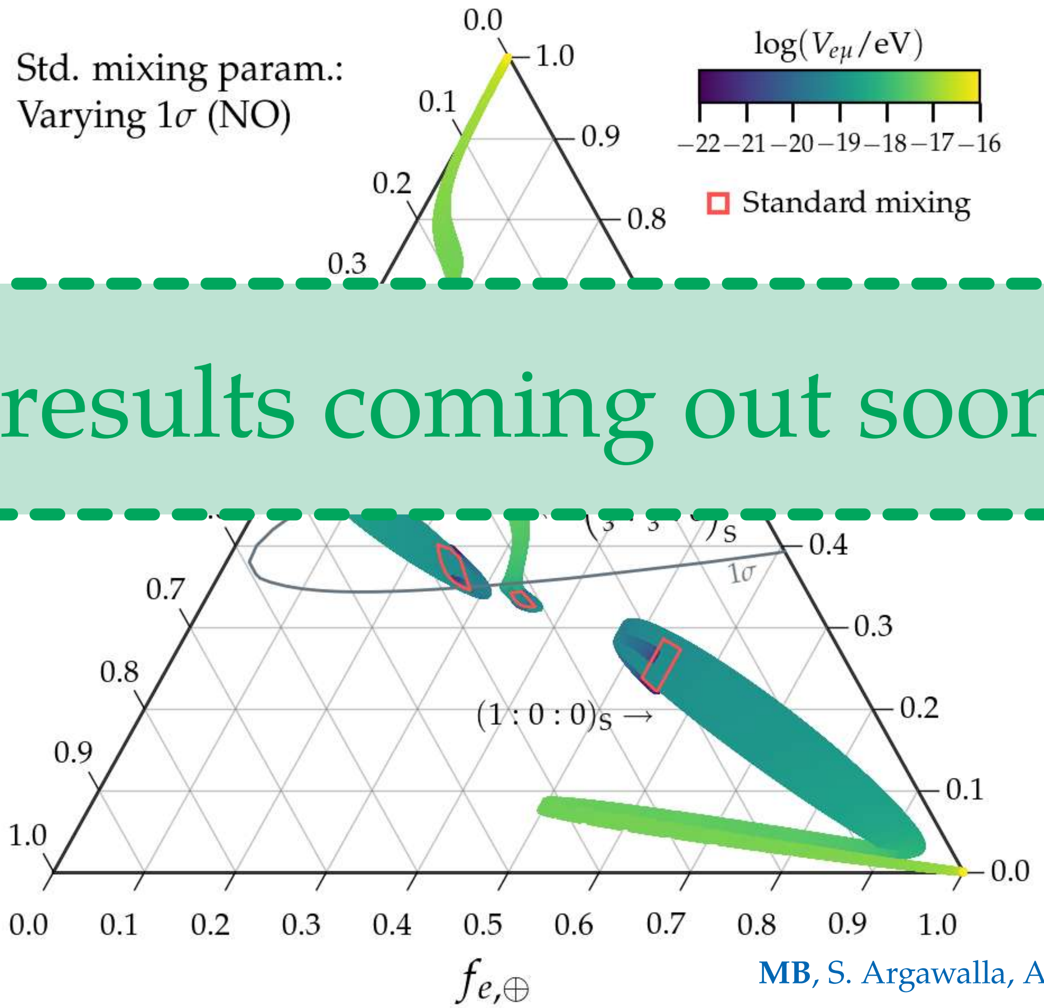


Final results coming out soon!

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

(Ask me about ANITA mystery events)

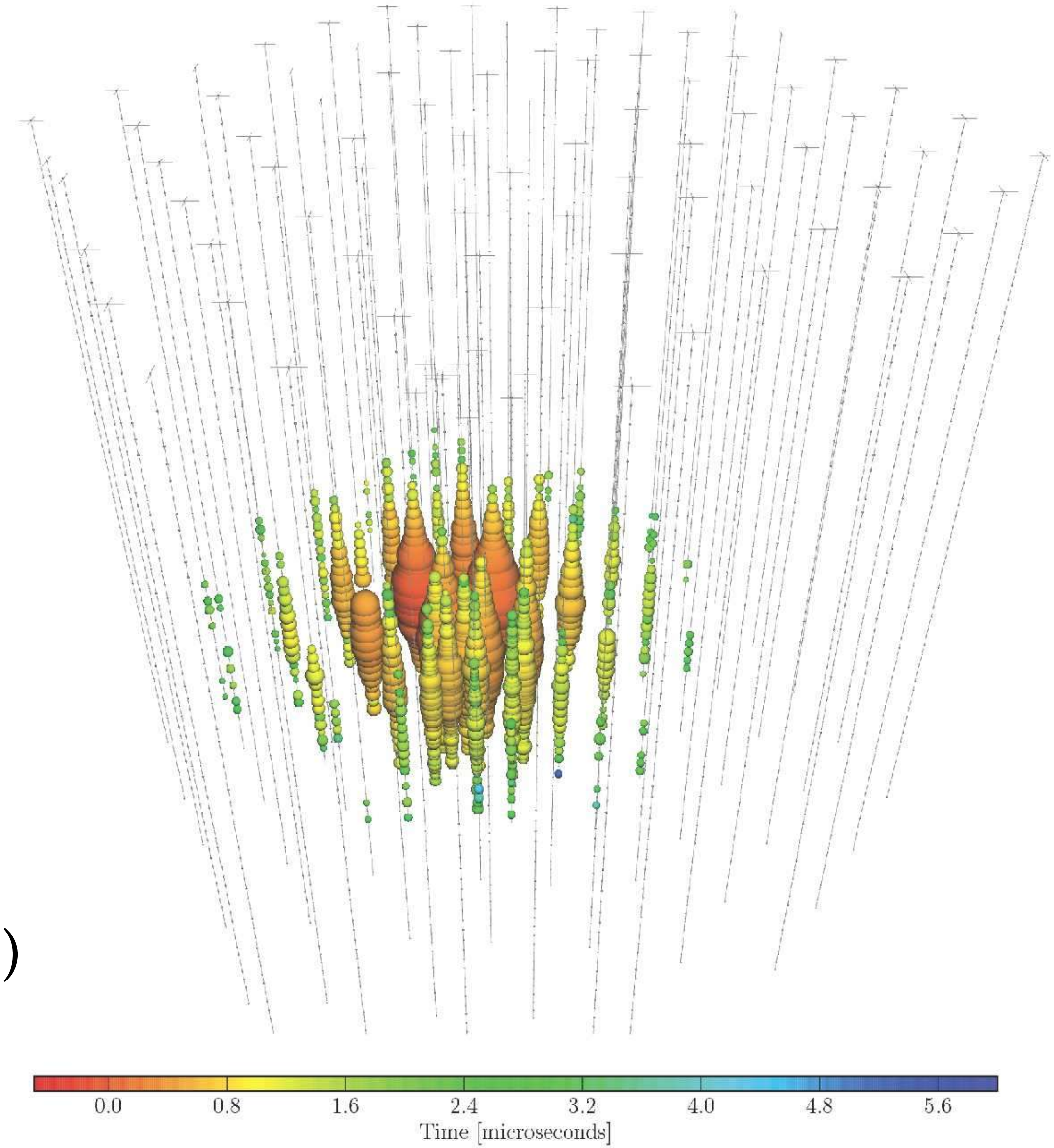
What are you taking home?

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

What do we want? *TeV–PeV neutrino physics*

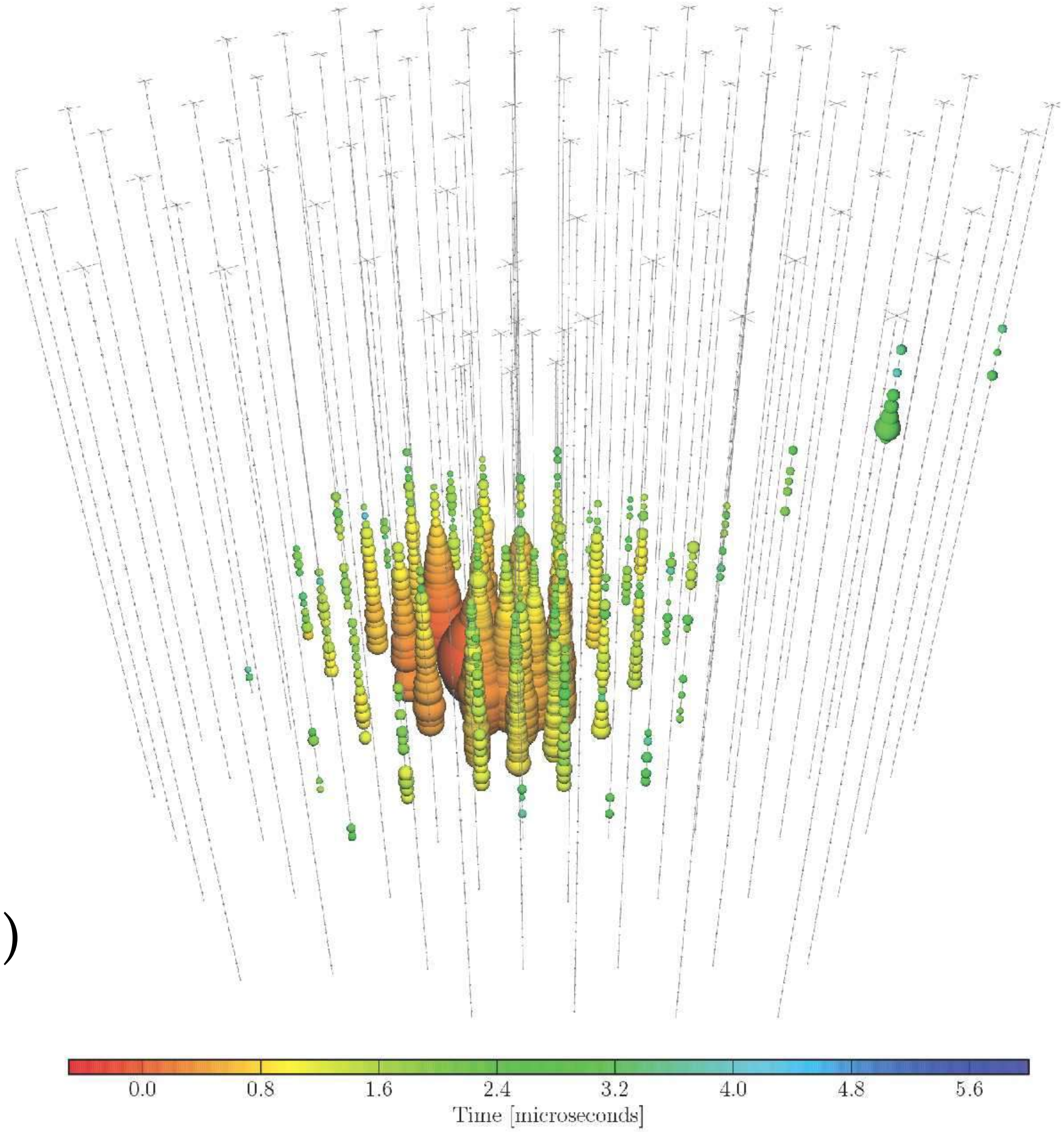
When do we want it? *Today – and we can have it!*

Backup slides



Shower
(IceCube event #22)

Track
(IceCube event #15)



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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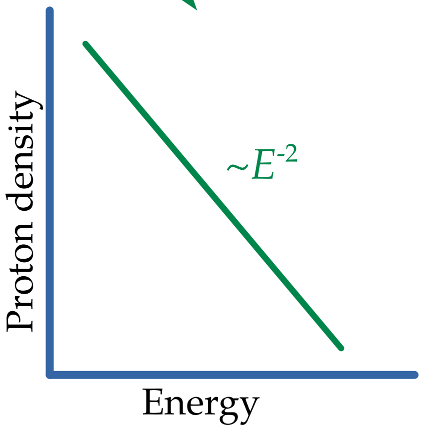

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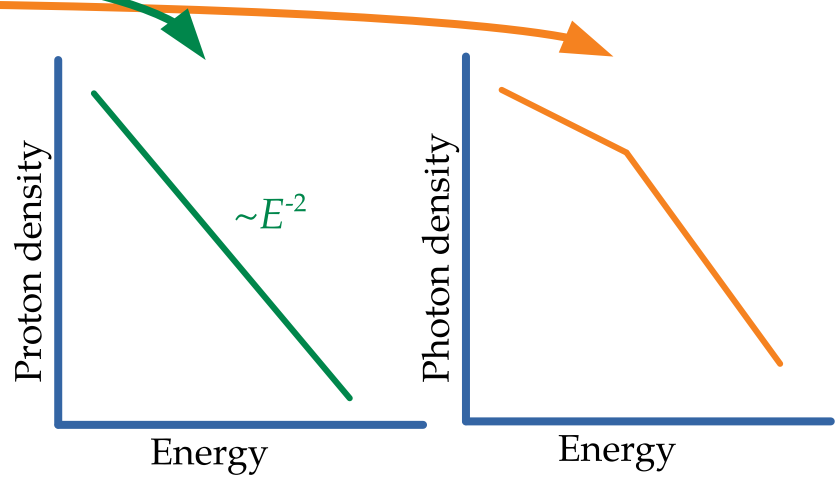

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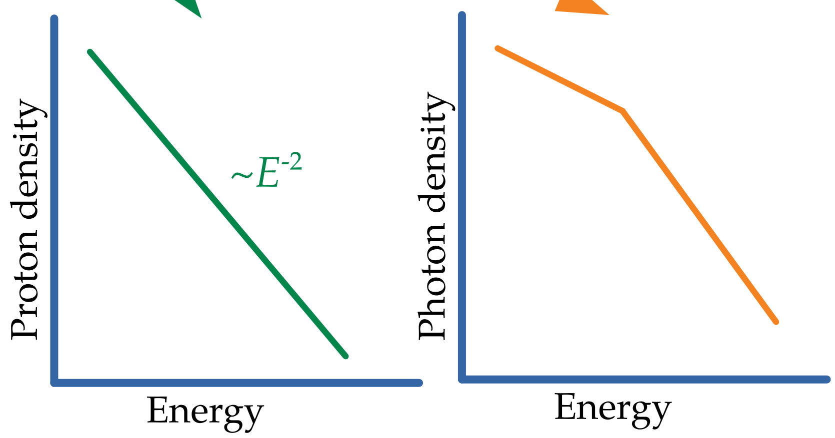
$$\pi^0 \rightarrow \gamma + \gamma$$

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

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



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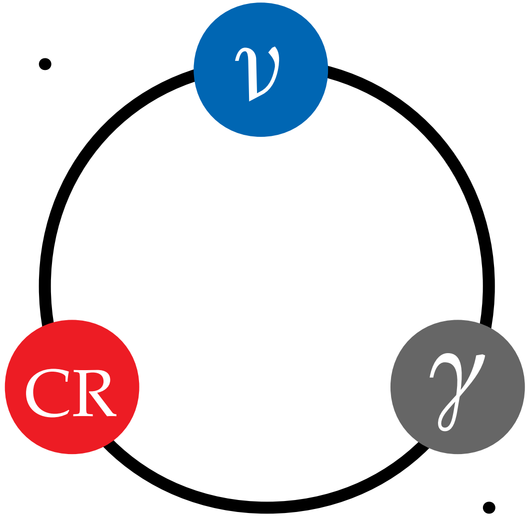

Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 20

The multi-messenger connection

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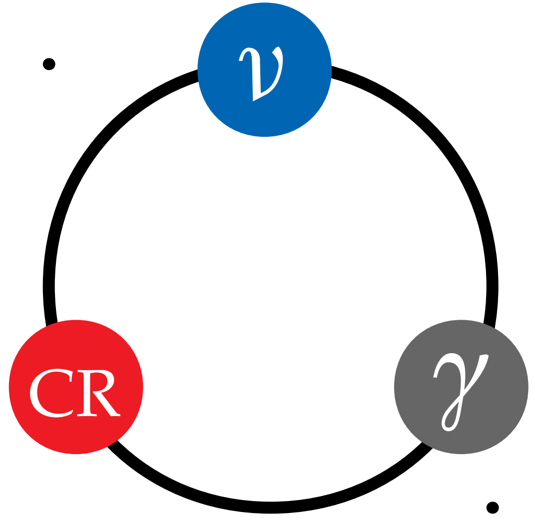

1 PeV 20 PeV

Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 20

The multi-messenger connection

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

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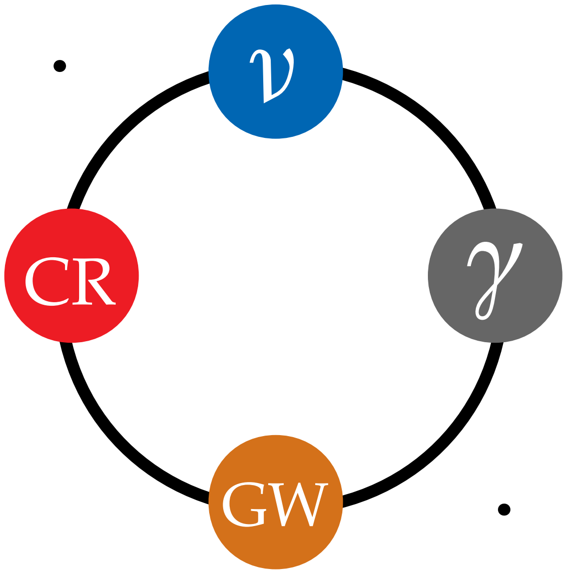
$$\pi^{+} \rightarrow \mu^{+} + \nu_{\mu} \rightarrow \bar{\nu}_{\mu} + e^{+} + \nu_{e} + \nu_{\mu}$$

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



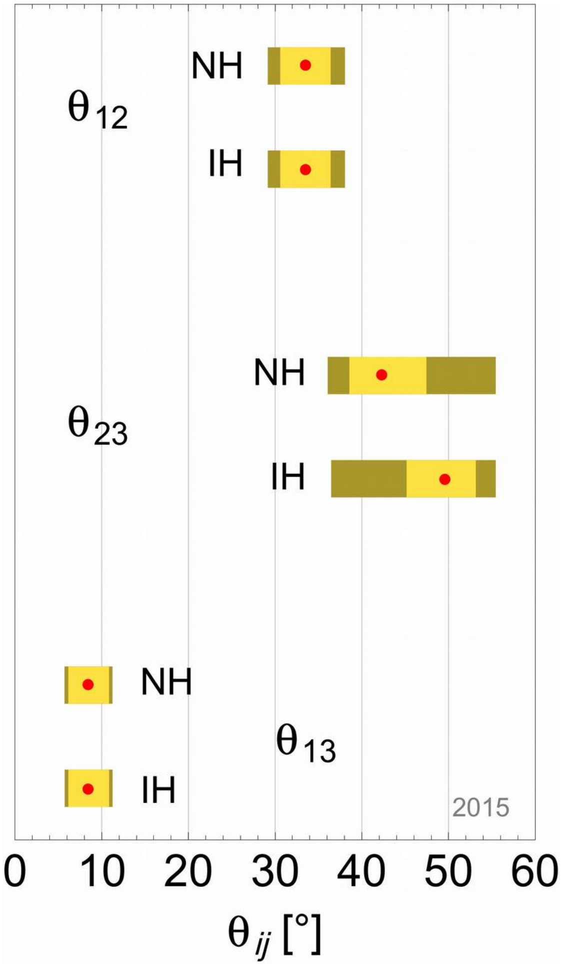
1 PeV 20 PeV

Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 20

Uncertainties in lepton mixing angles

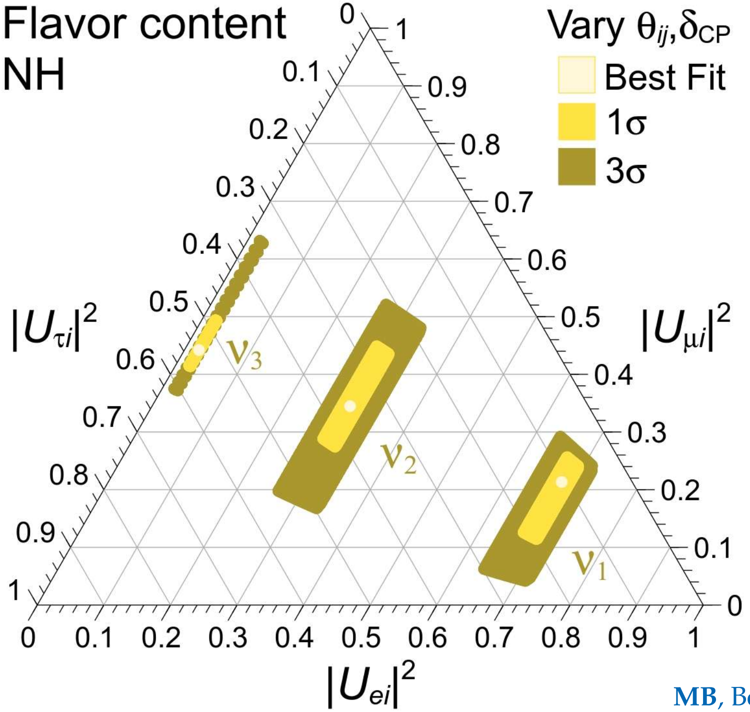
As of 2015 –

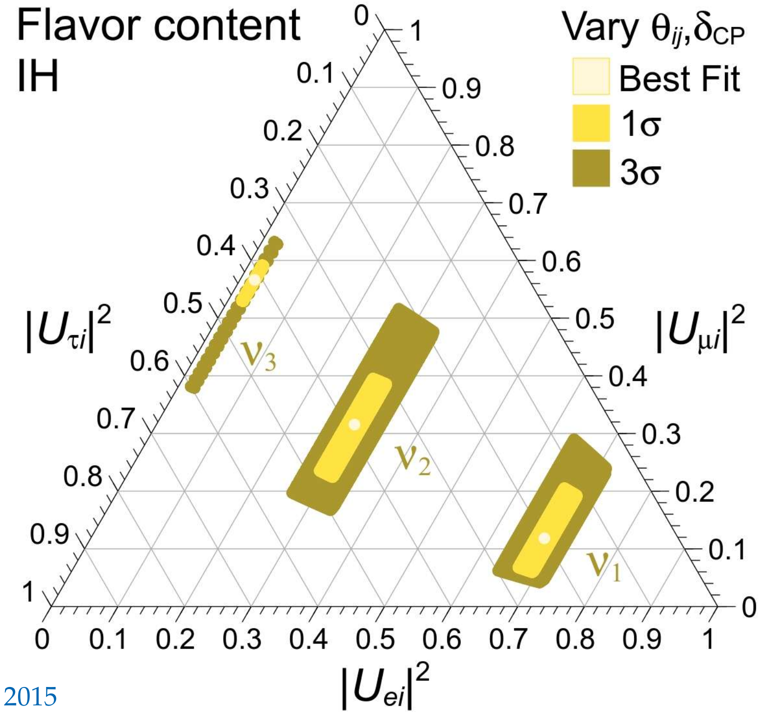


Flavor content of neutrino mass eigenstates

Flavor content for every allowed combination of mixing parameters –

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

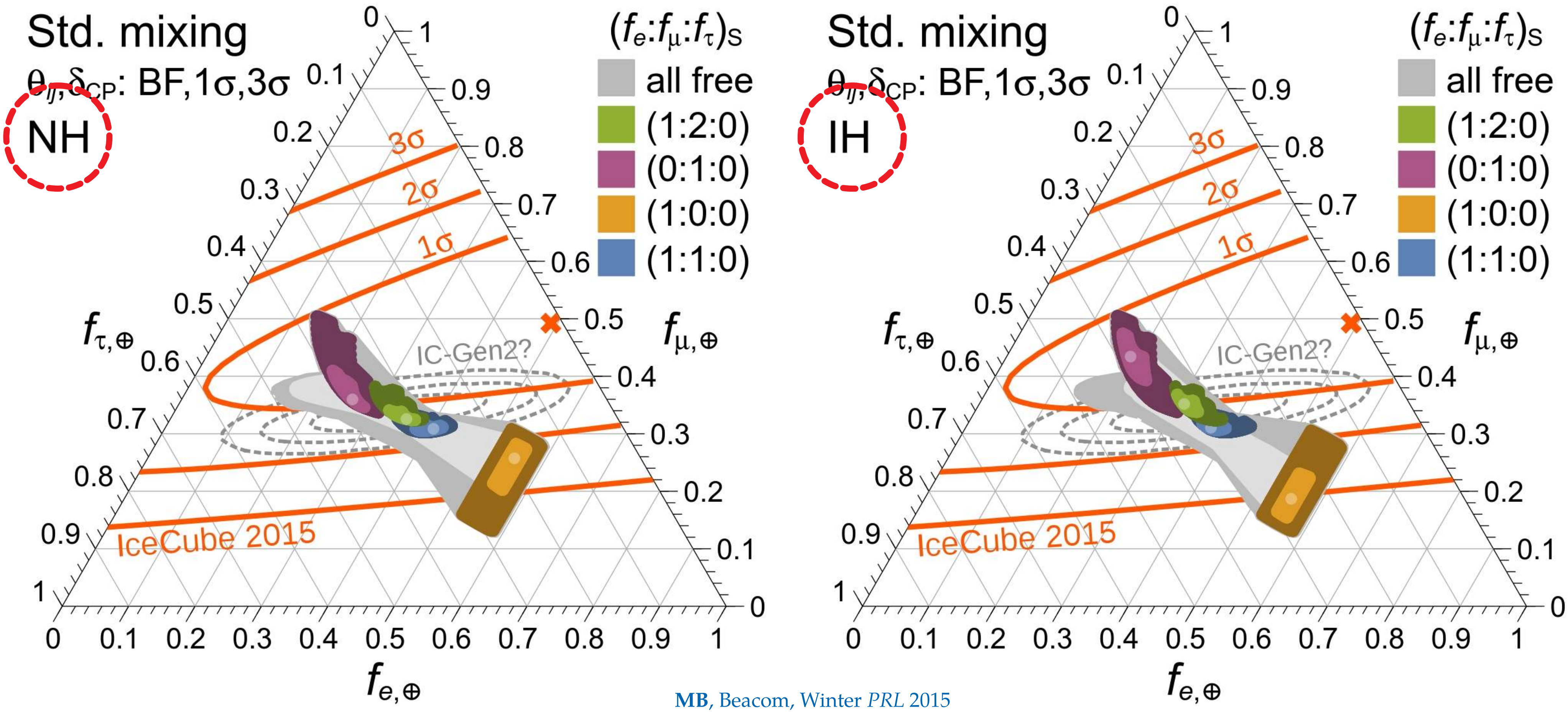




MB, Beacom, Winter *PRL* 2015

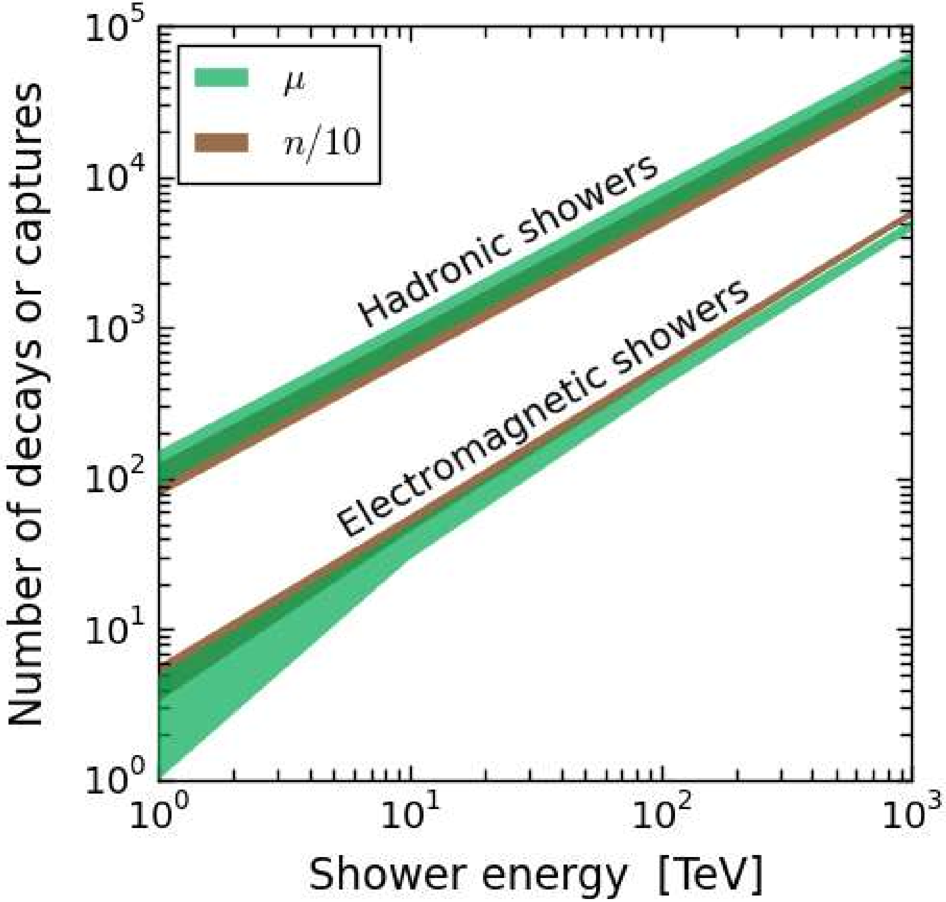
Flavor composition – a few source choices

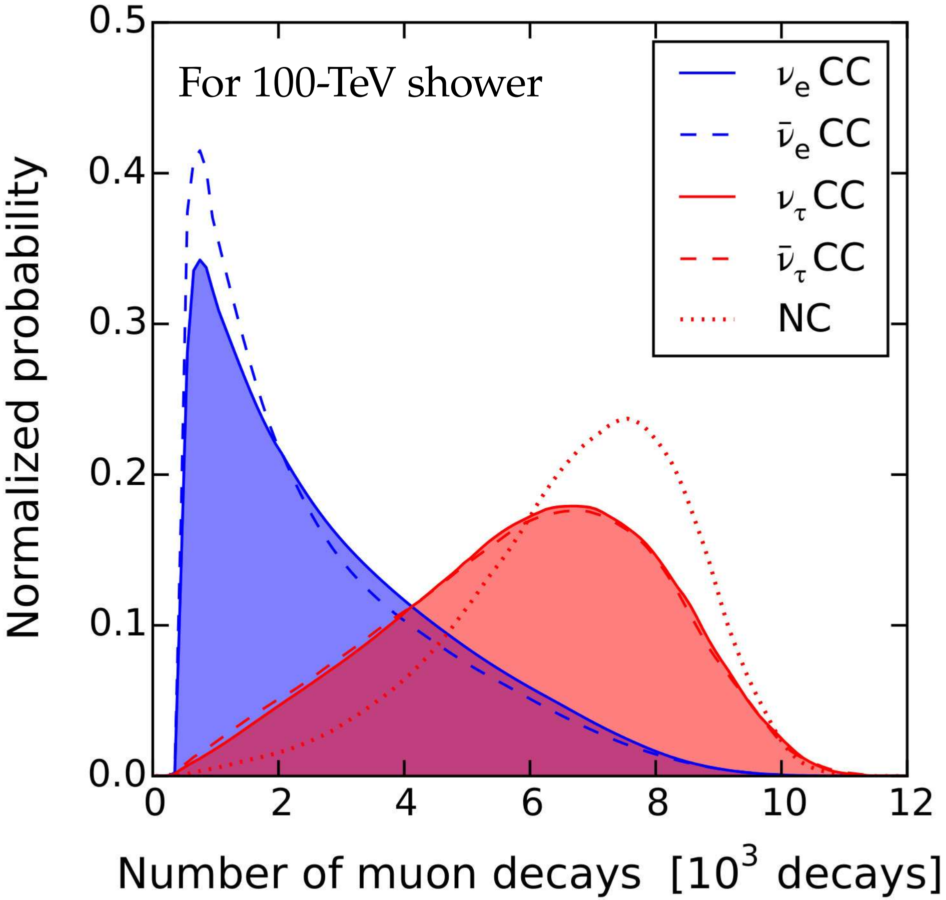
Flavor composition – a few source choices



MB, Beacom, Winter *PRL* 2015

Hadronic *vs.* electromagnetic showers

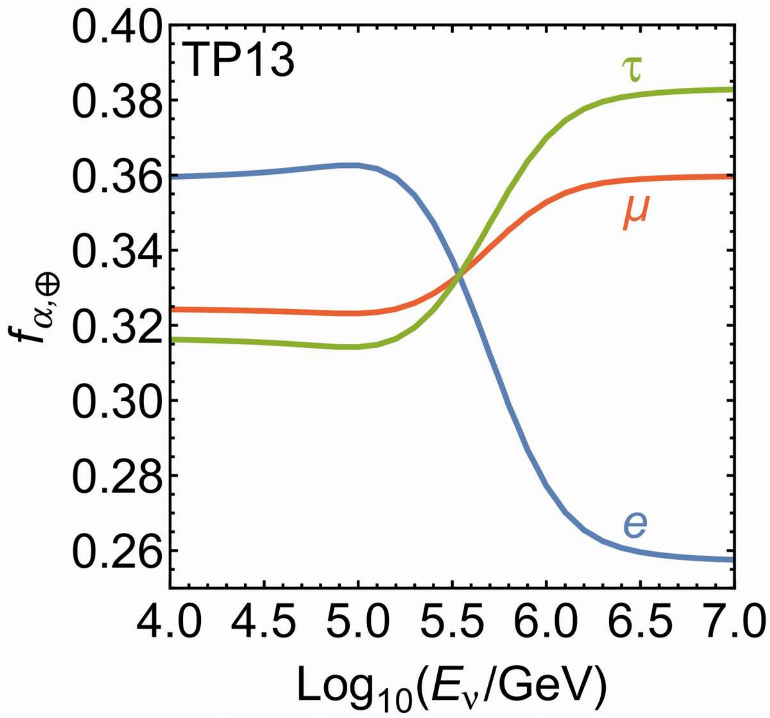


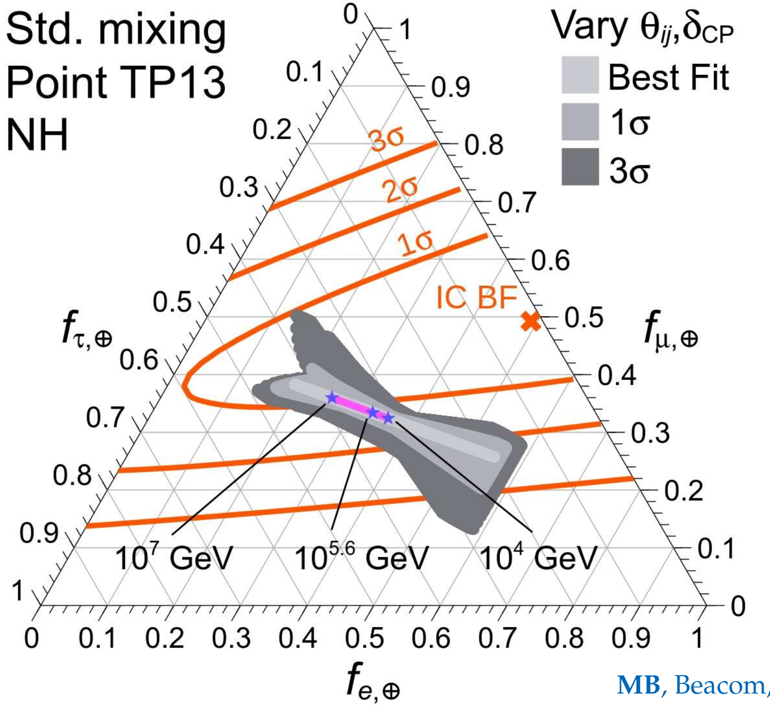


Li, **MB**, Beacom, Sub. to *PRL*

Energy dependence of the flavor composition?

Different neutrino production channels accessible at different energies –

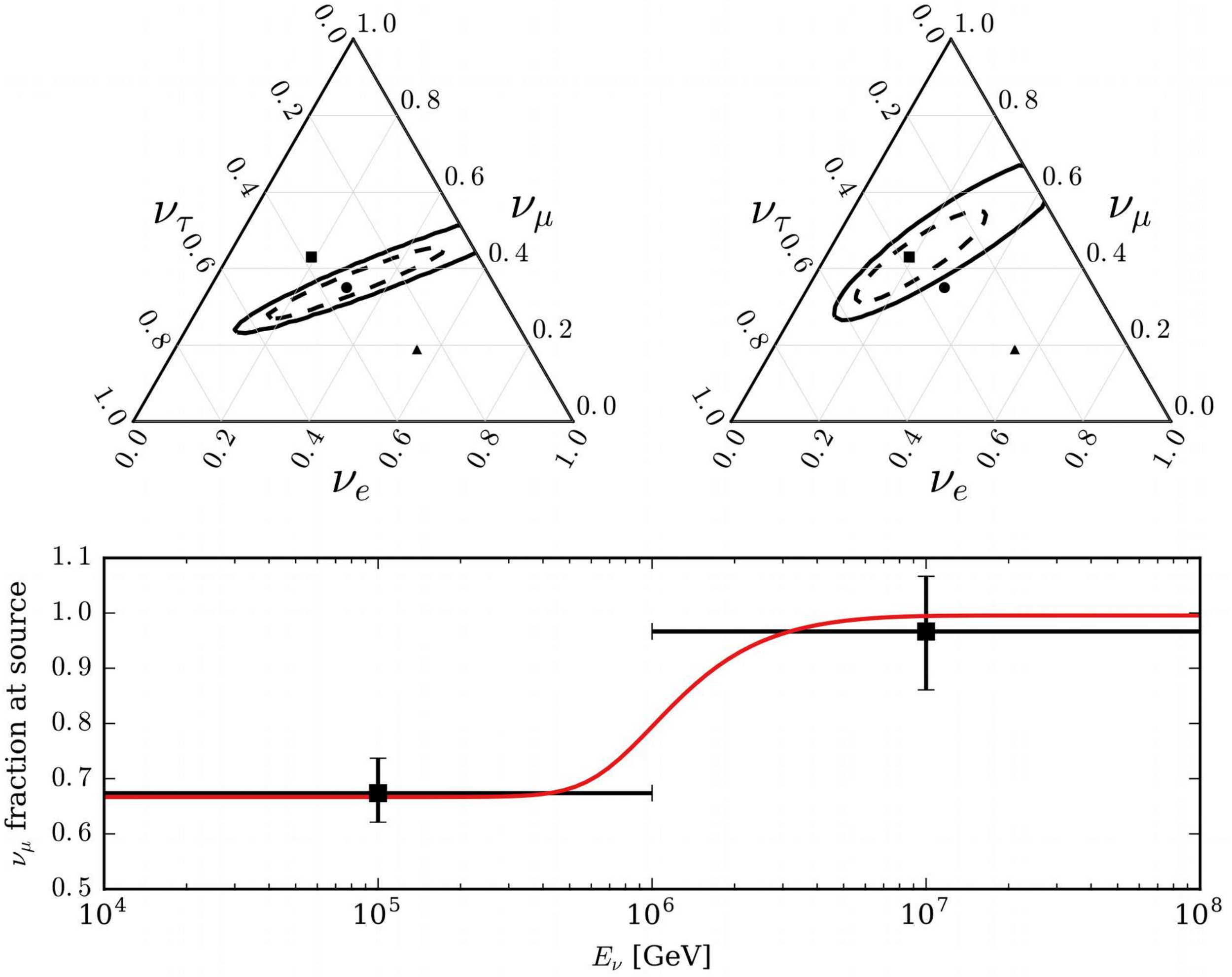




MB, Beacom, Winter *PRL* 2015

- 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]

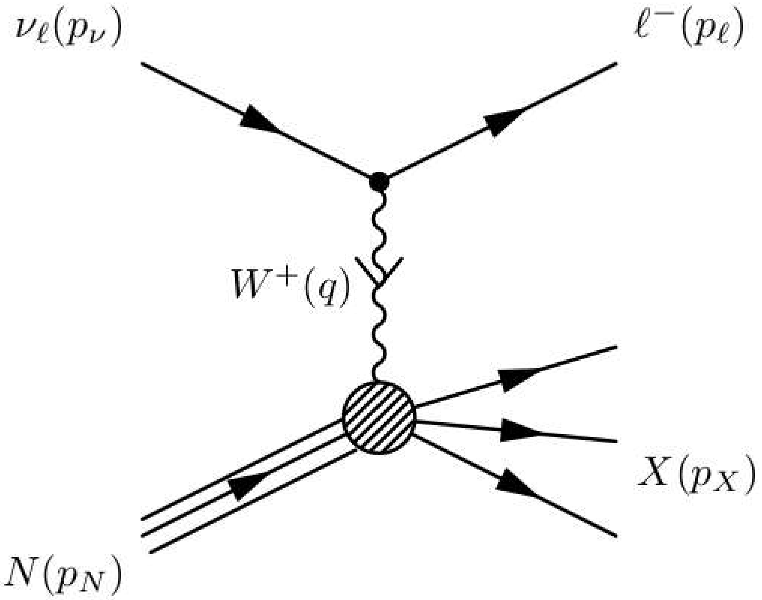
… Observable in IceCube-Gen2?



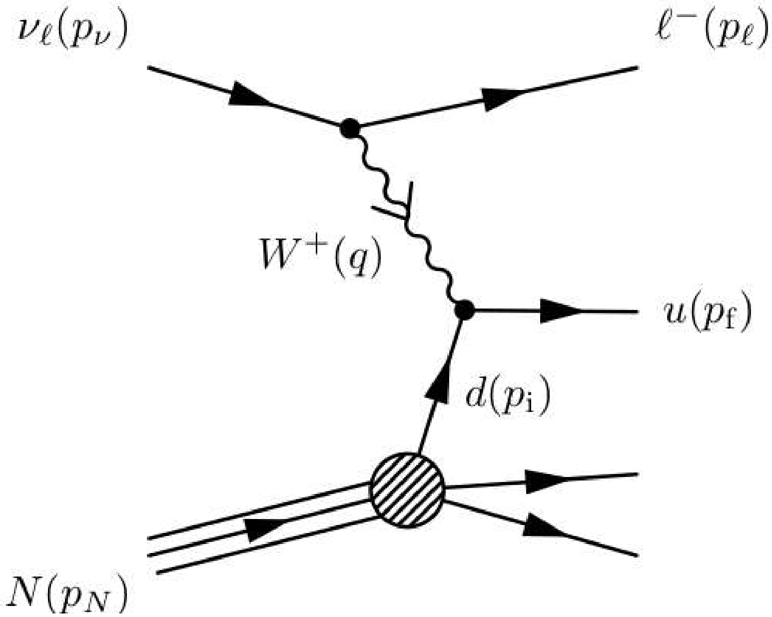
Borrowed from M. Kowalski

How does DIS probe nucleon structure?

What you see



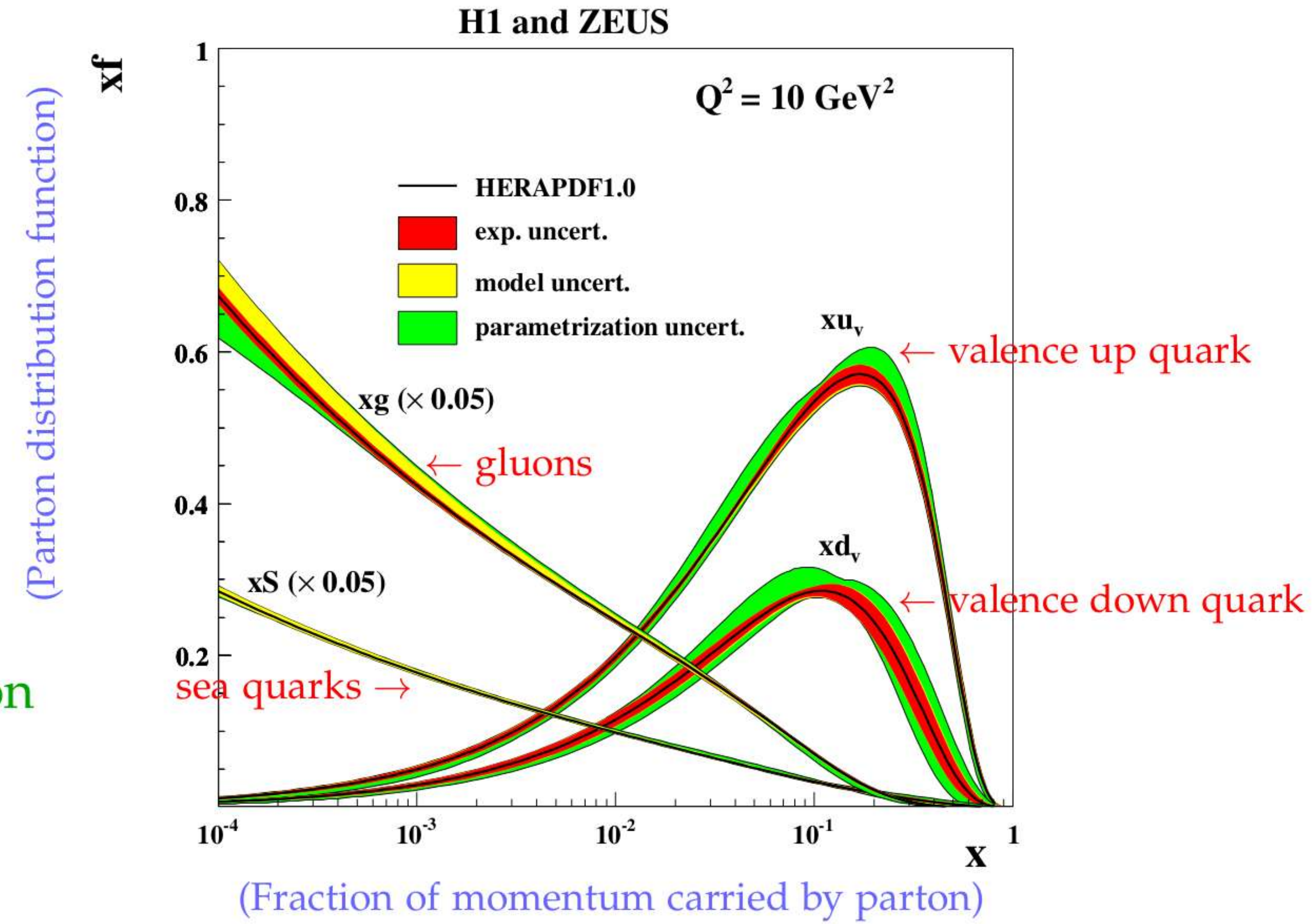
Beneath the hood



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

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

Peeking inside a proton

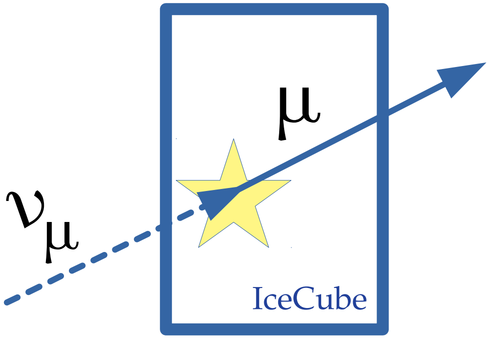


← Extrapolation

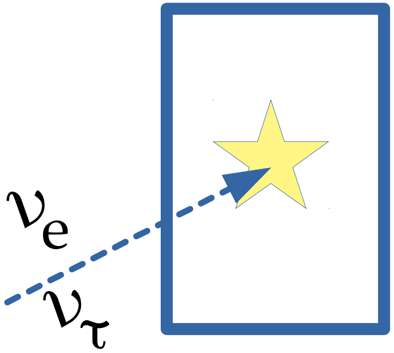
A. Cooper-Sarkar 2012

Contained *vs.* uncontained νN interactions

Contained events



Starting track



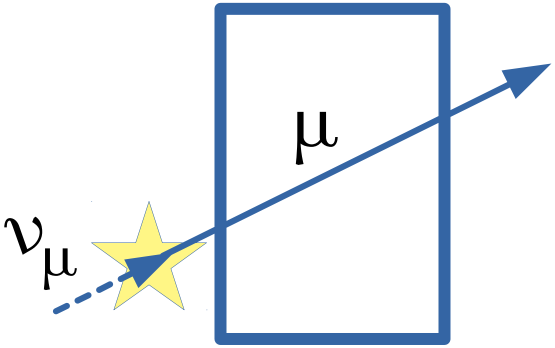
Shower

Pro: Clean determination of E_ν

Con: Few events (<100)

Ref.: MB & A. Connolly, 1711.11043

Uncontained events



Through-going muon

Pro: Lots of events (~10k used)

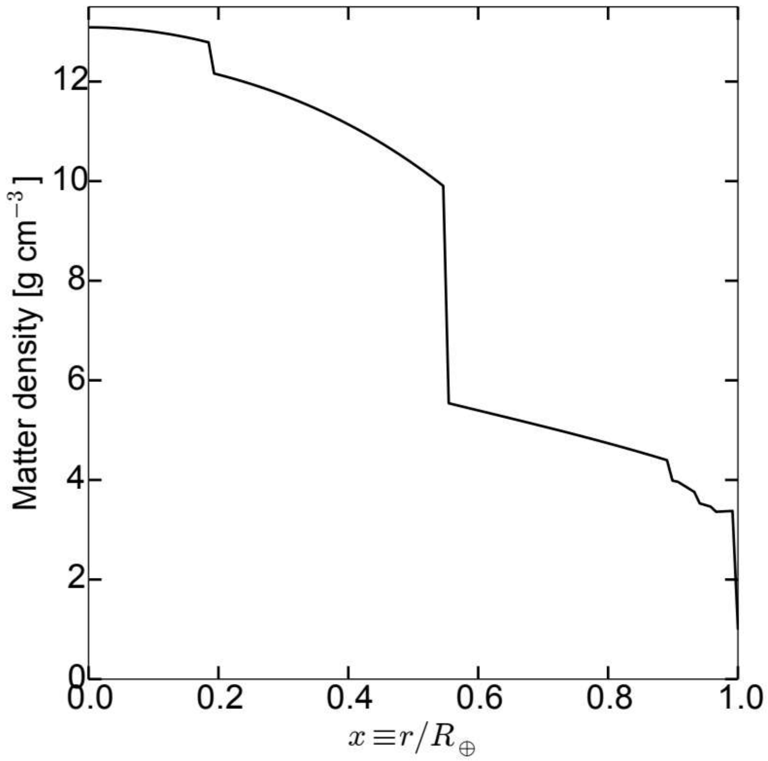
Con: Uncertain estimates of E_ν

Ref.: IceCube, *Nature* 2017, 1711.08119

A feel for the in-Earth attenuation

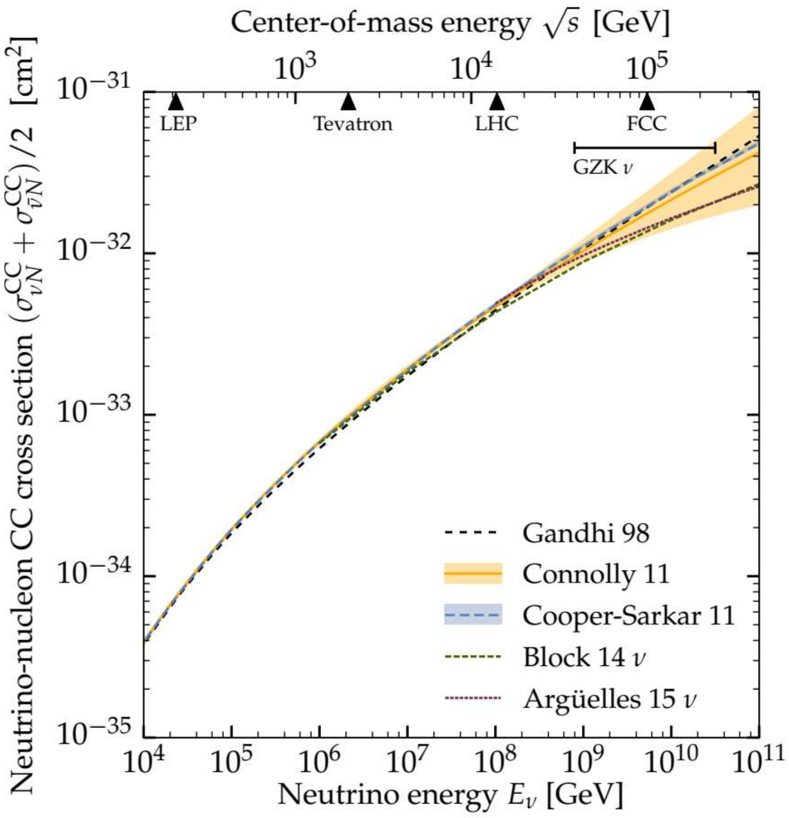
Earth matter density

(Preliminary Reference Earth Model)



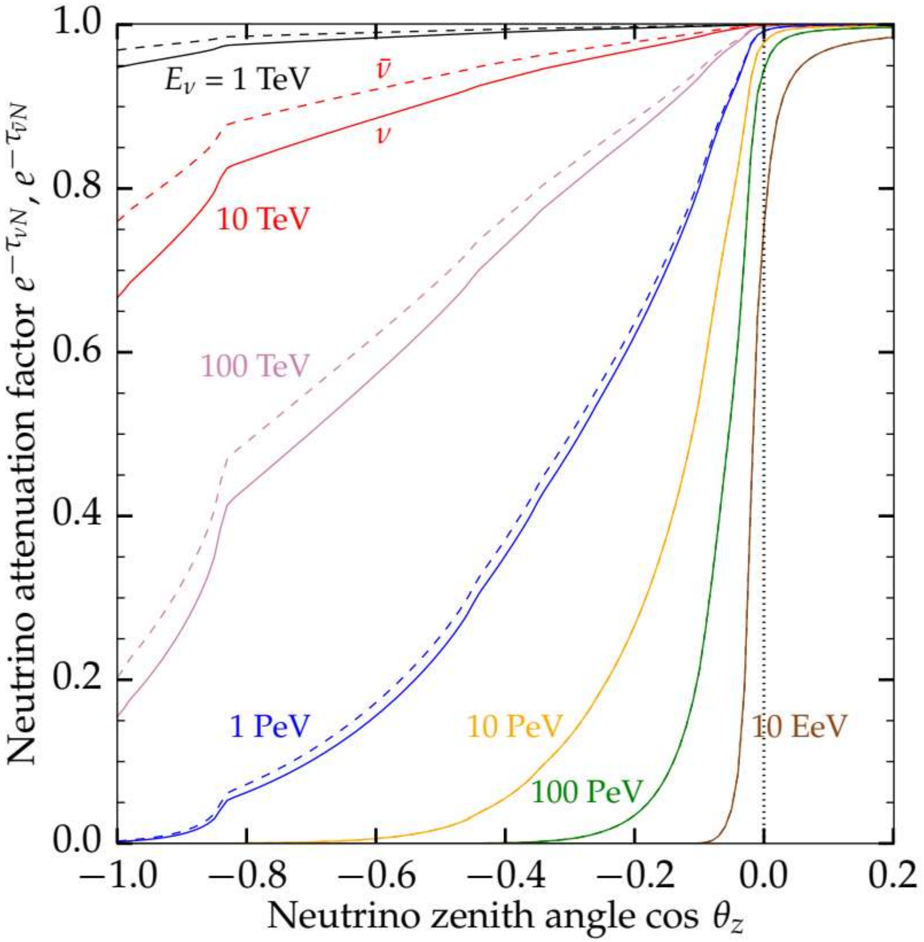
+

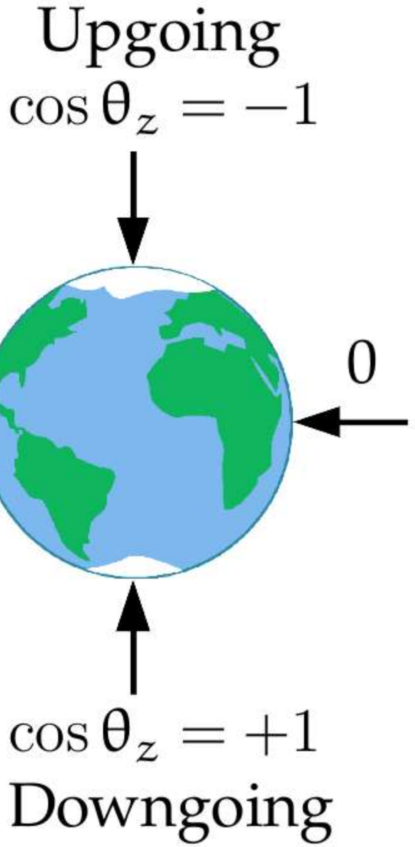
Neutrino-nucleon cross section



A feel for the in-Earth attenuation

=





Cross section from contained events

- $\sigma_{\nu N}$ varies with neutrino energy ⇒ 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 ($E_{\rm dep} \approx E_\nu$)
  - ☒ **Tracks:** partially contained ($E_{\rm dep} < E_\nu$)
- We use the 58 publicly available HESE showers (6-year sample)
- HESE tracks *could* be used
  – but we would need non-public data to reconstruct E_ν without bias

Sensitivity to σ in each bin

Number of contained events in an energy bin:

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

Downgoing (no matter)

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

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

Upgoing (lots of matter)

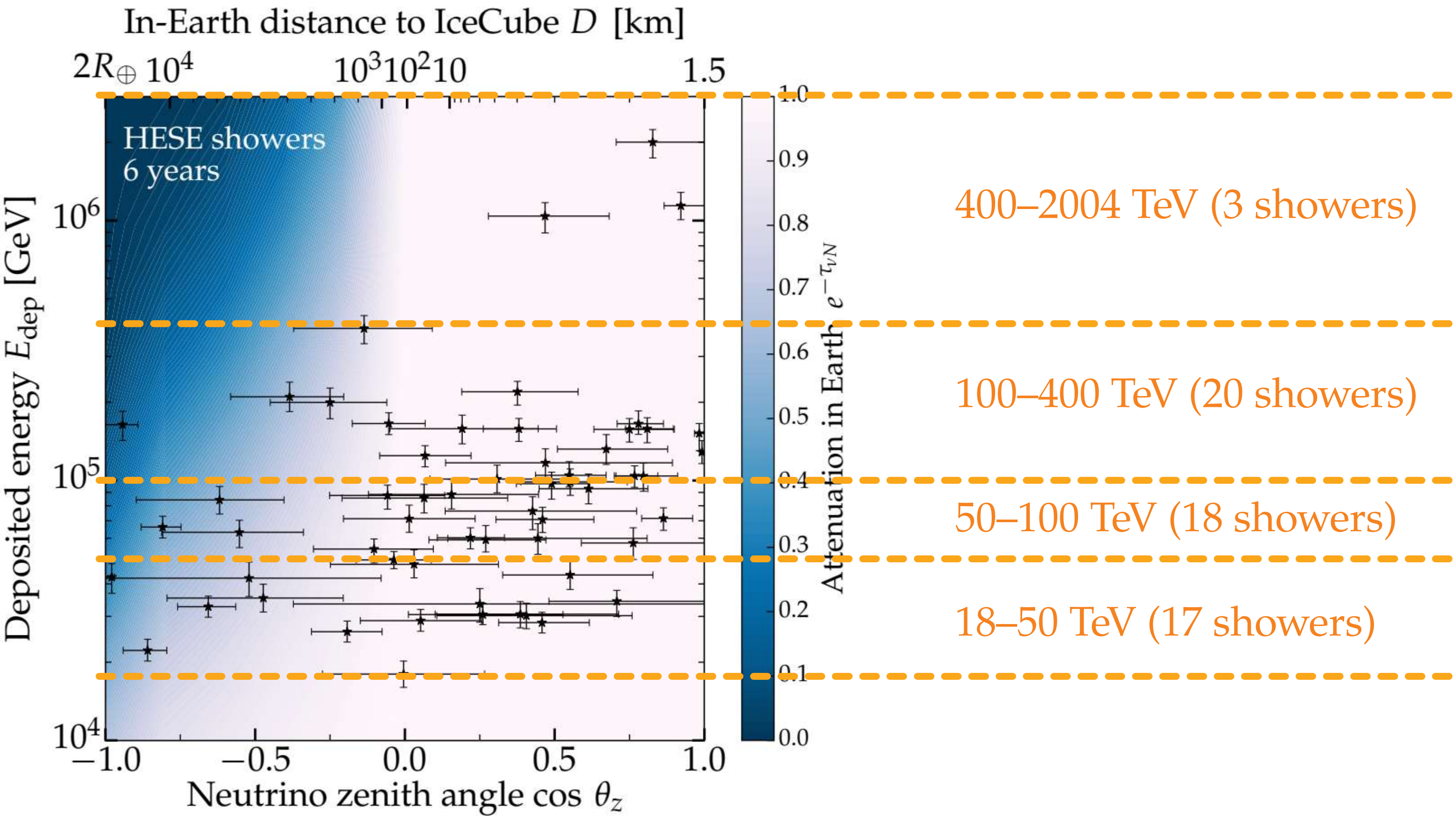
$$N_{\nu,\mathrm{up}} \sim N_{\nu,\mathrm{dn}} \cdot e^{-\tau}$$

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

Reality check:

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

Bin-by-bin analysis



The fine print

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

What goes into the (likelihood) mix?

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

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

- For each combination, we generate the angular and energy shower spectrum…
- … and compare it to the observed HESE spectrum via a likelihood
- Maximum likelihood yields σ_{CC} (marginalized over nuisance parameters)
- Bins are independent of each other – there are no (significant) cross-bin correlations

How to do better / more?

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

Marginalized cross section in each bin

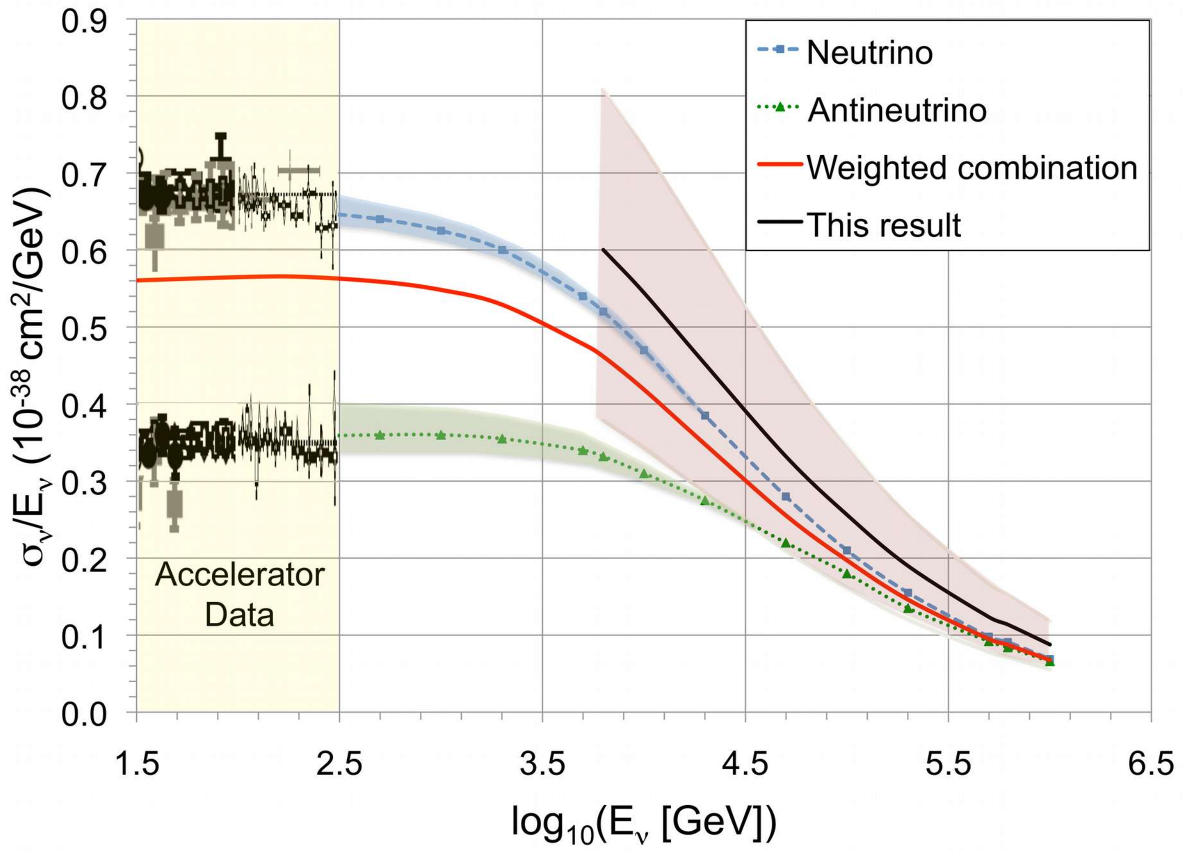
TABLE I. Neutrino-nucleon charged-current inclusive cross sections, averaged between neutrinos ($\sigma_{\nu N}^{\rm CC}$) and anti-neutrinos ($\sigma_{\bar{\nu} N}^{\rm CC}$), extracted from 6 years of IceCube HESE showers. To obtain these results, we fixed $\sigma_{\bar{\nu} N}^{\rm CC} = \langle \sigma_{\bar{\nu}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

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

MB & A. Connolly, 1711.11043

Using through-going muons instead

- Use ~10^4 through-going muons
- Measured: dE_μ/dx
- Inferred: $E_\mu \approx dE_\mu/dx$
- From simulations (uncertain): most likely E_ν given E_μ
- Fit the ratio σ_{obs}/σ_{SM}
  $1.30^{+0.21}_{-0.19}$ (stat.)$^{+0.39}_{-0.43}$ (syst.)
- All events grouped in a single energy bin 6–980 TeV



IceCube, *Nature* 2017

Neutrino zenith angle distribution

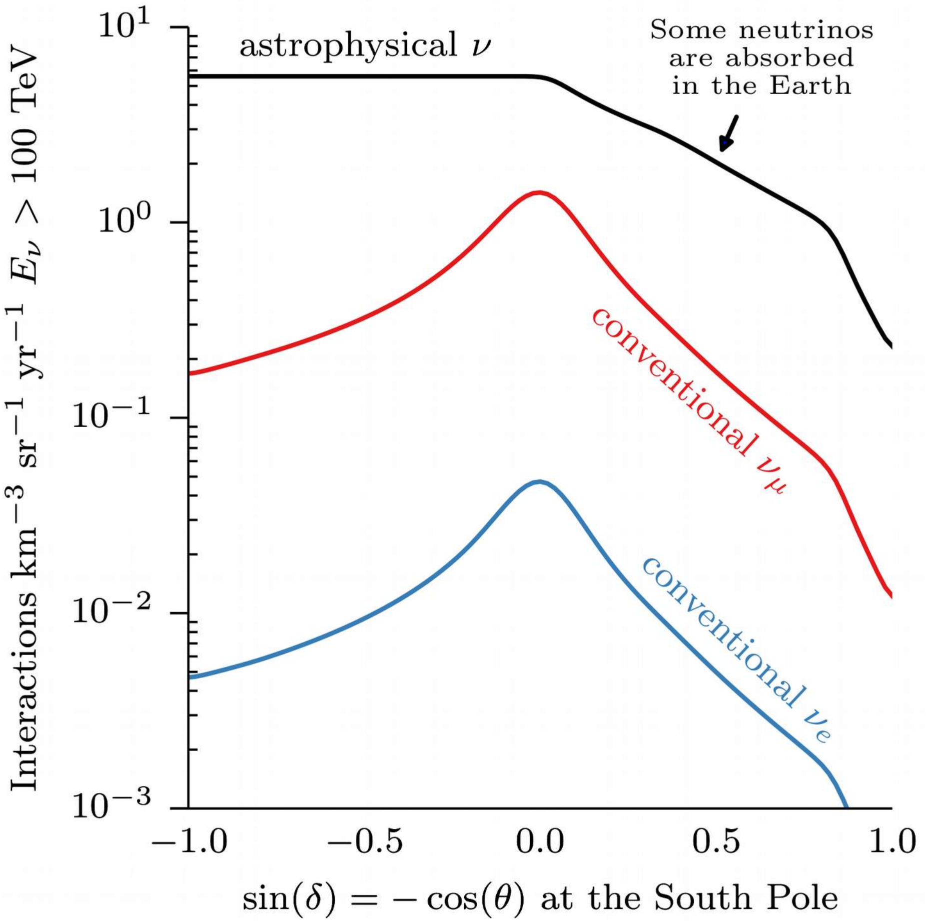
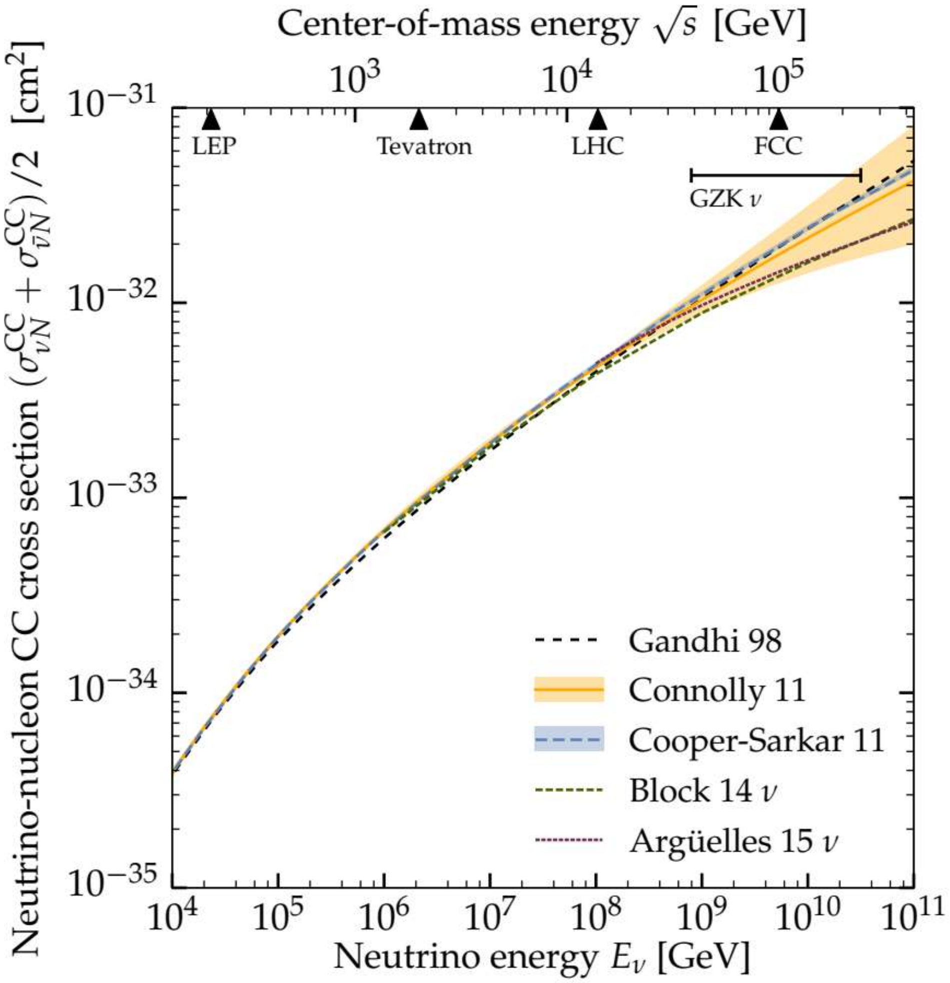


Figure by
Jakob Van Santen
ICRC 2017

What can we measure *now* and later?



MB & Connolly, 1711.11043

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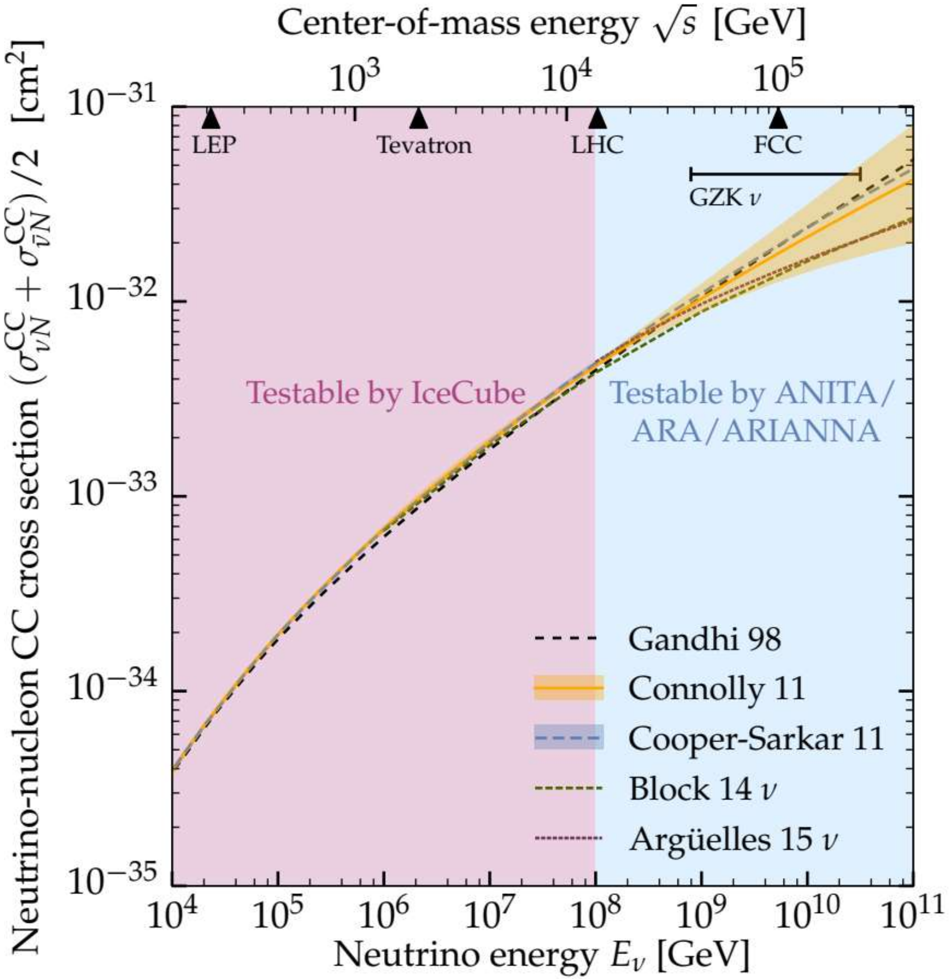
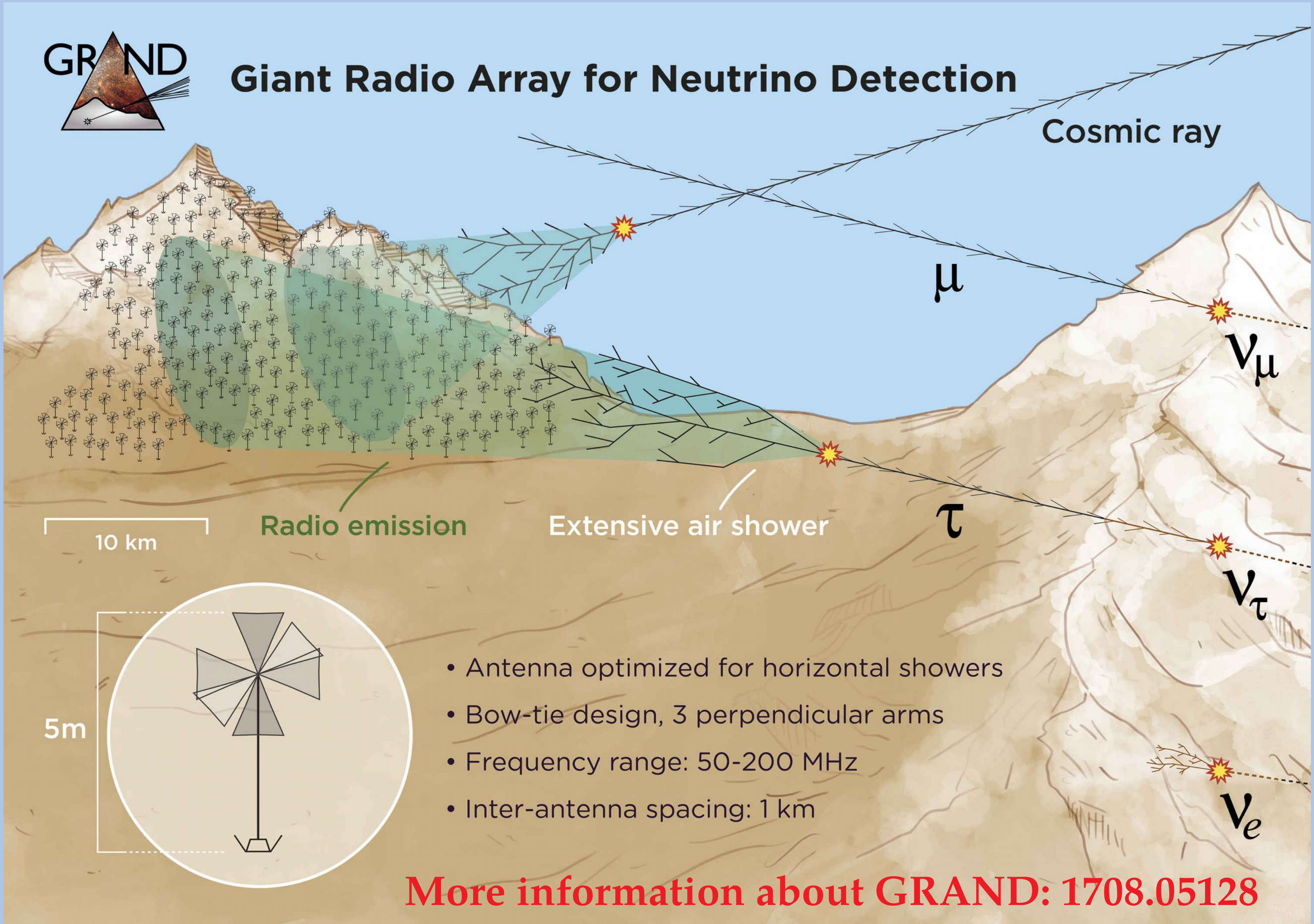


MB & Connolly, 1711.11043



More information about GRAND: 1708.05128


BETPAQDALA DESERT
Lake Balqash
Lake Sasyqköl
Lake Alaköl
MONGOLIAN ALTAI MTS.
BAYTAG BOGD MTS.
MONGOLIA
Dzungarian (Junggar) Gate
Karamay
QARATAU RANGE
Syr Darya
Shū (Chu)
SHŪ-ILE MOUNTAINS
Ile
Karatal
KAZAKHSTAN
ZHONGGHAR ALATAU RA.
Lake Aibi
JUNGGAR BASIN
BOROHORO MTS.
Ürümqi
Ile Depression
Yining
Zhambyl
Almaty
BOGDA MTS.
KARLIK MTS.
EREN HABIRGA MTS.
KETPEN RA.
ILE ALATAU RA.
Bishkek
KYRGYZ ALA RA.
TALAS ALATAU RA.
KUNGOY ALA MTS.
Turfan
154
Turfan Depression
HAMI BASIN
CHATKAL MTS.
Lake Ysyk
SARY-JAZ MTS.
S H A N
HALIK MTS.
Lake Bositeng
Tashkent
KYRGYZSTAN
TESKEY ALA MTS.
Naryn
Victory Peak 7439
Muzat Pass
KURUKTAG MTS.
BEI MTS.
UZBEK.
Namangan
FERGANA RANGE
T I E N
KAKSHAAL RANGE
Khujand
FERGANA VALLEY
ATBASHI RA.
Tarim
Fergana
ALAI RA.
Lop Nor
TURKESTAN MTS.
TRANS-ALAI RA.
FERGANA KYRKA MTS.
Hotan
TARIM BASIN
CHINA
ZERAVSHAN RA.
HISOR RANGE
Lenin Peak 7134
Kashgar
Yarkand
TAKLA MAKAN DESERT
TAJIKISTAN
PAMIRS
Imeni Ismail Samani Peak 7495
Mt. Kongur 7719
Qarqan
ALTUN
Yarkand
Qiemo
Pishan
Karakax
Keriya
Hotan
KUNLUN MTS.
K2 8611
Gasherbrum 8068
Mt. Keriya 7120
45°
40°
70°
75°
80°
85°
90°
95°
Elevation
metres
feet
3,000
9,843
2,000
6,562
1,000
3,281
500
1,640
200
656
0
0
Spot elevations in metres
Spot depth in metres
Intermittent streams
Glaciers
Salt flats
Sand areas
Swamps and marshes
0 100 200 300 mi
0 100 200 300 400 500 km
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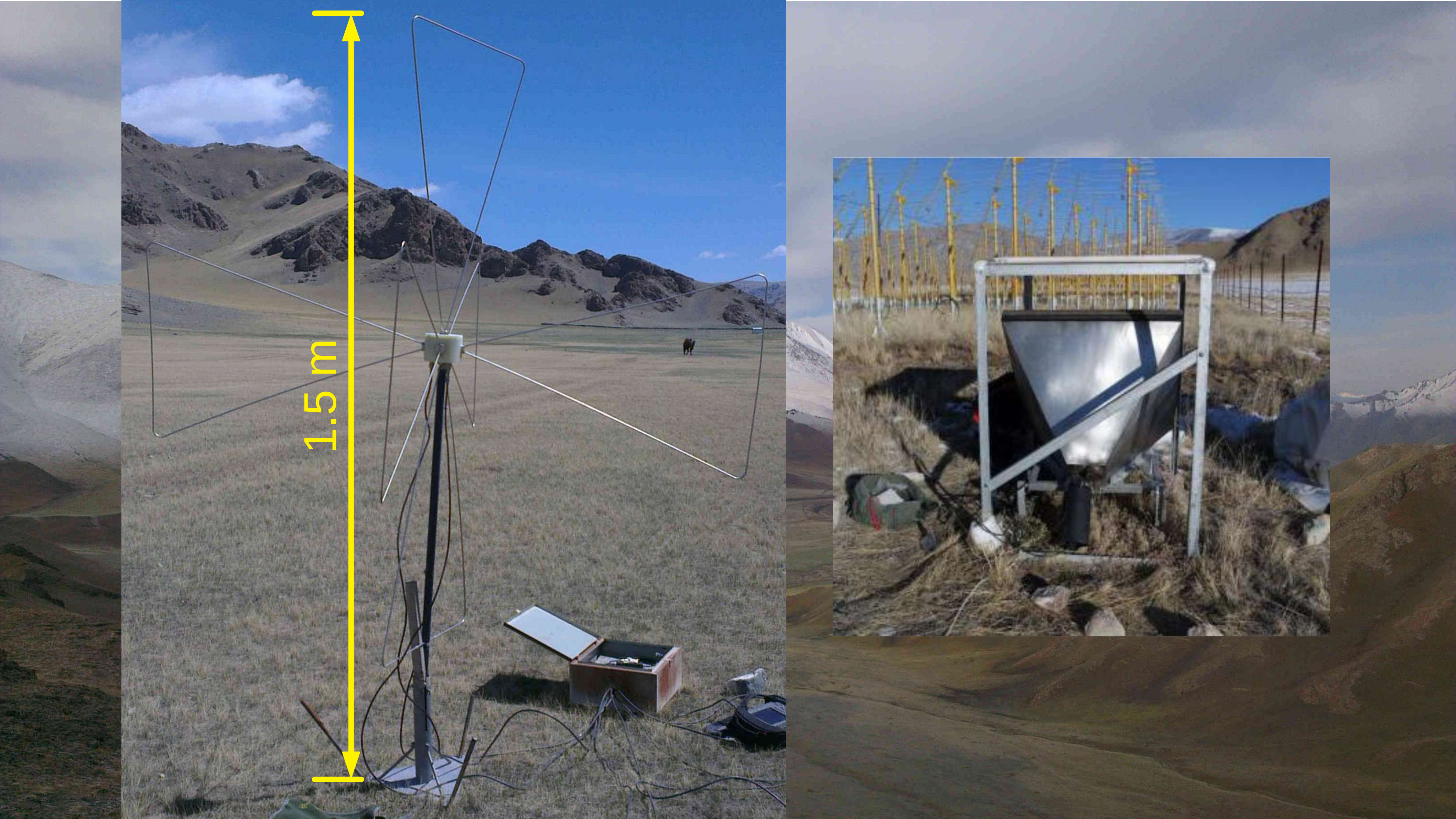
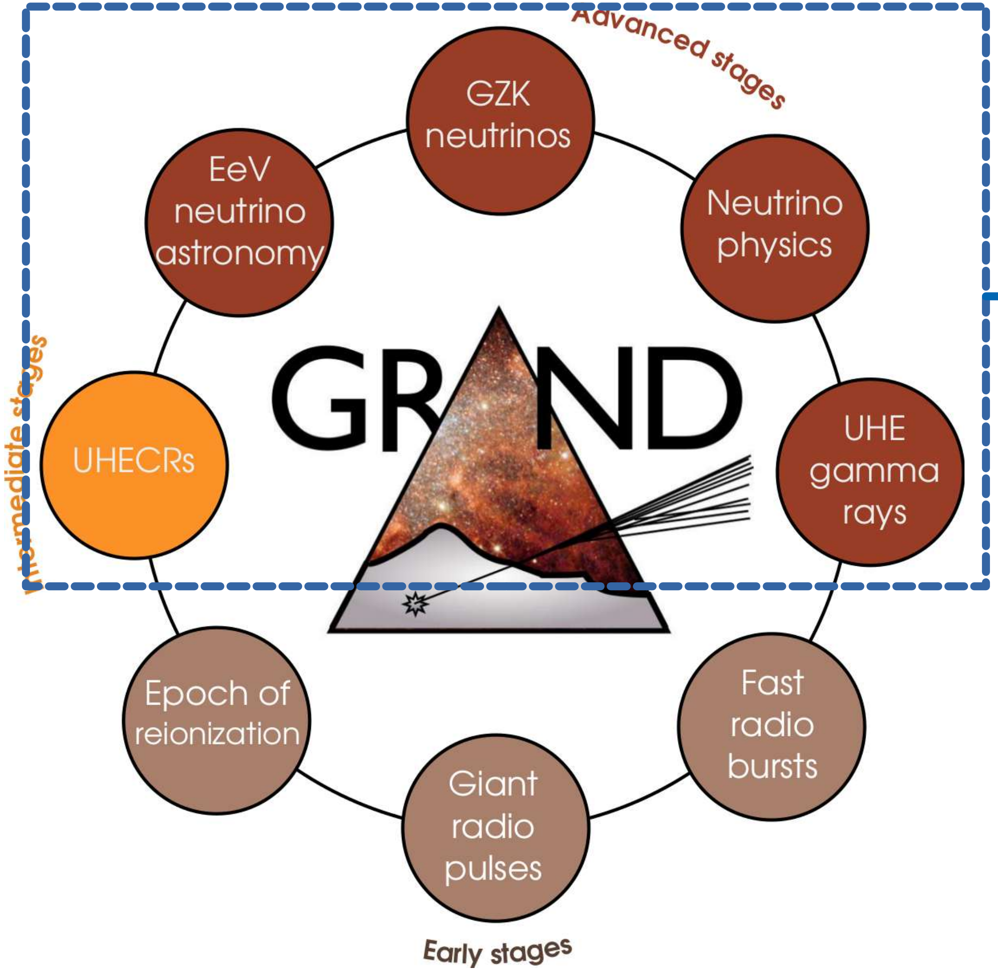
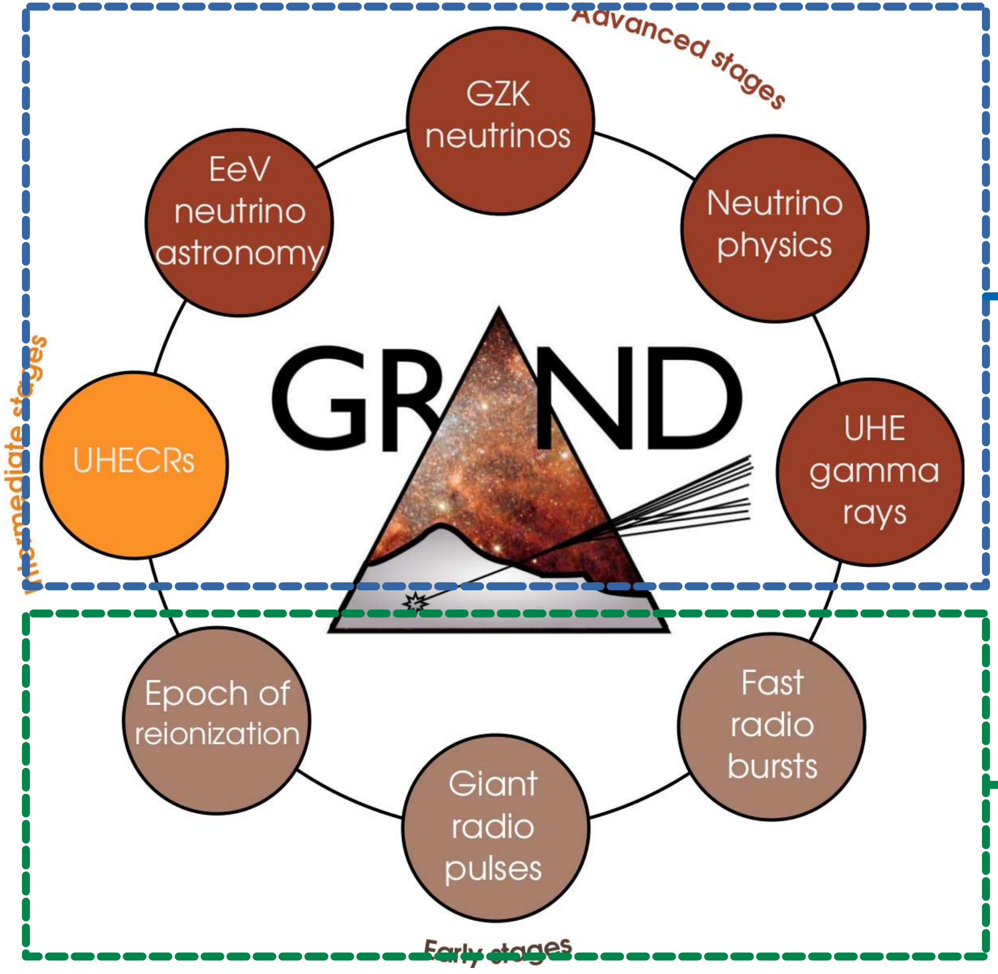

1.5 m


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



Main goal:

Finding the sources of UHECRs above 10^9 GeV



Main goal:

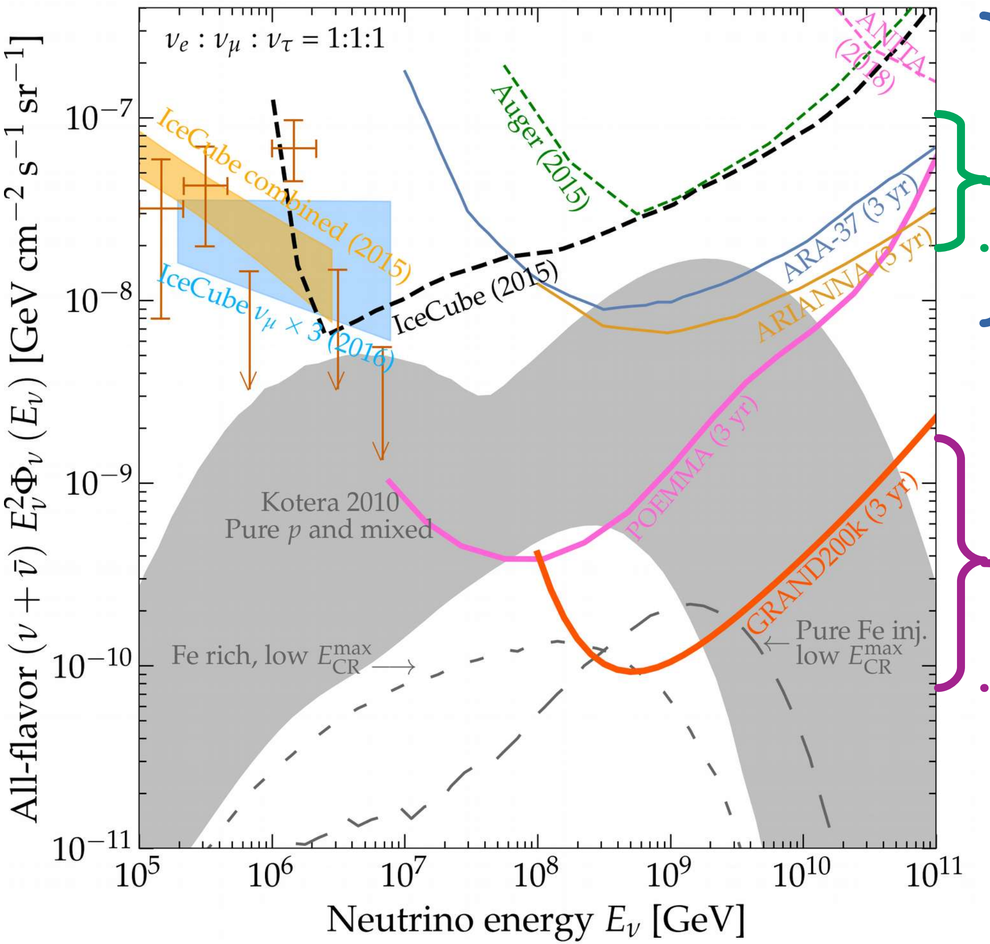
Finding the sources of UHECRs above 10^9 GeV

Secondary goal:

Radioastronomy and cosmology

UHE Neutrinos – Where Do We Go?

Flux predictions (Kotera 2010)

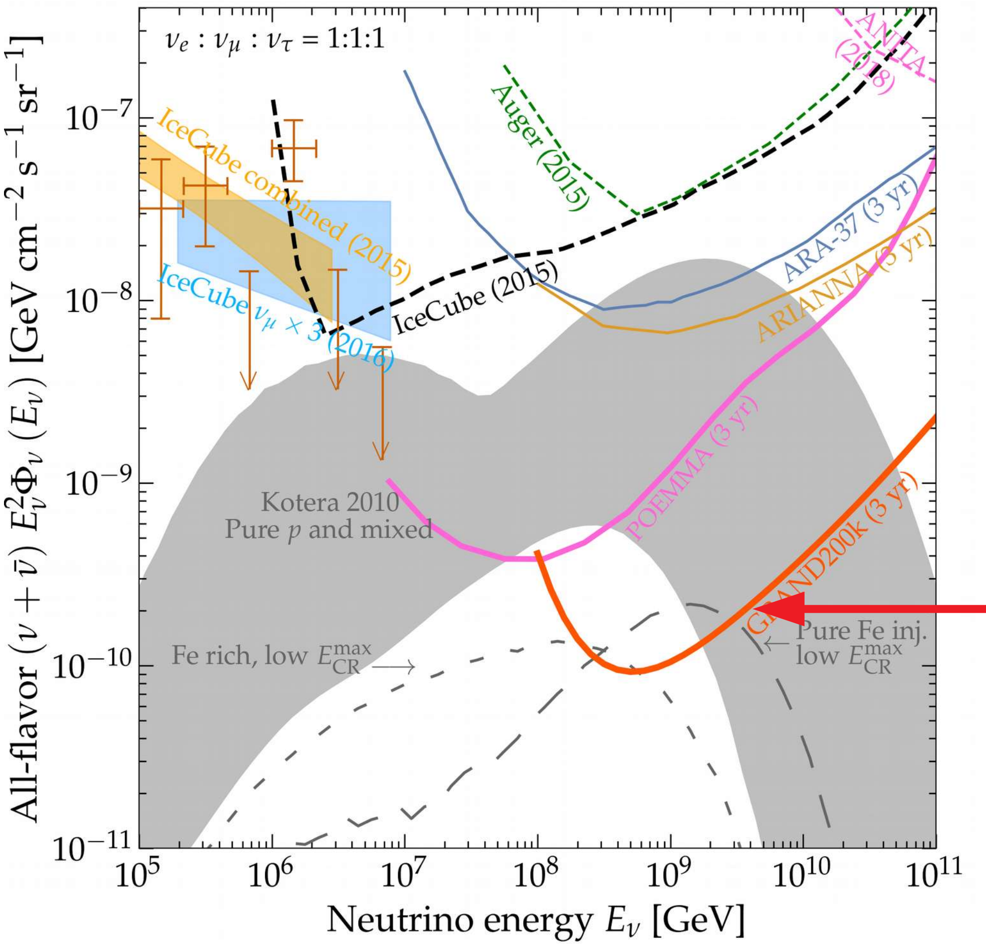


Existing upper limits

Future reach of existing in-ice radio detectors

Next-gen air-radio and space detectors

UHE Neutrinos – Where Do We Go?



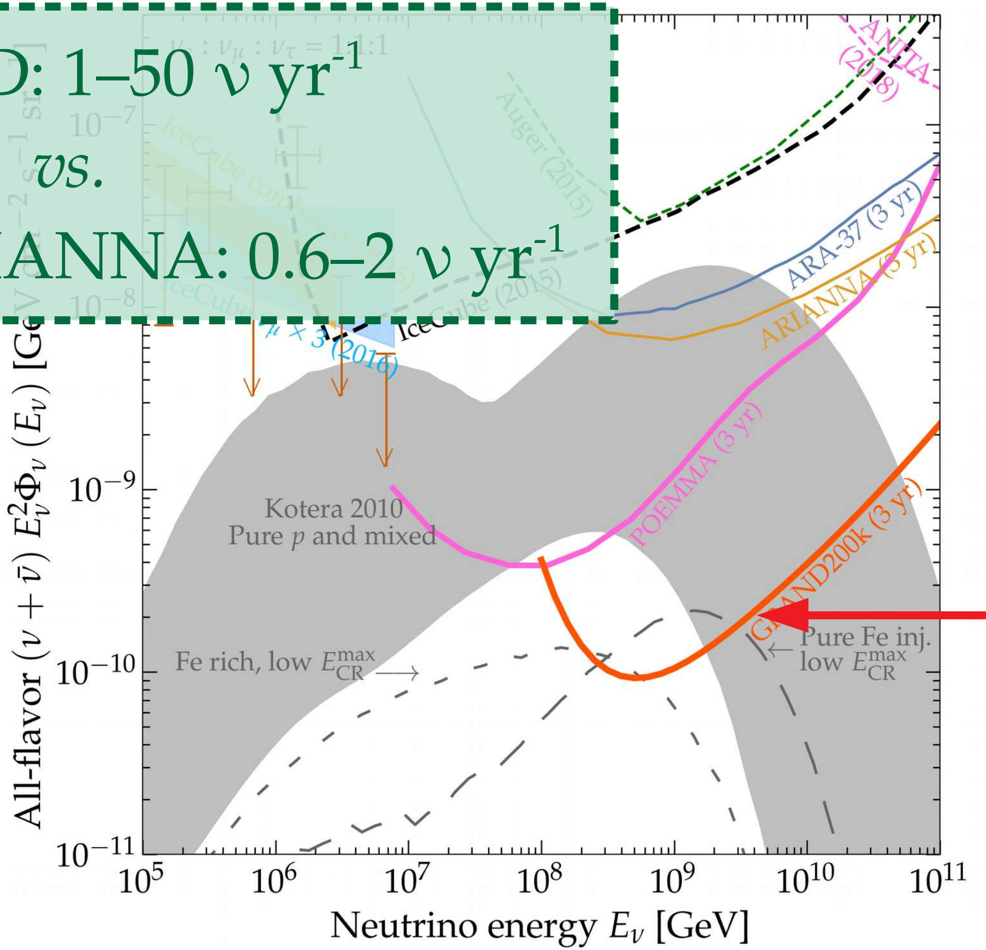
GRAND will probe *very* low fluxes at ~10^9 GeV

UHE Neutrinos – Where Do We Go?

GRAND: 1–50 ν yr^{-1}

vs.

Full ARA, ARIANNA: 0.6–2 ν yr^{-1}



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

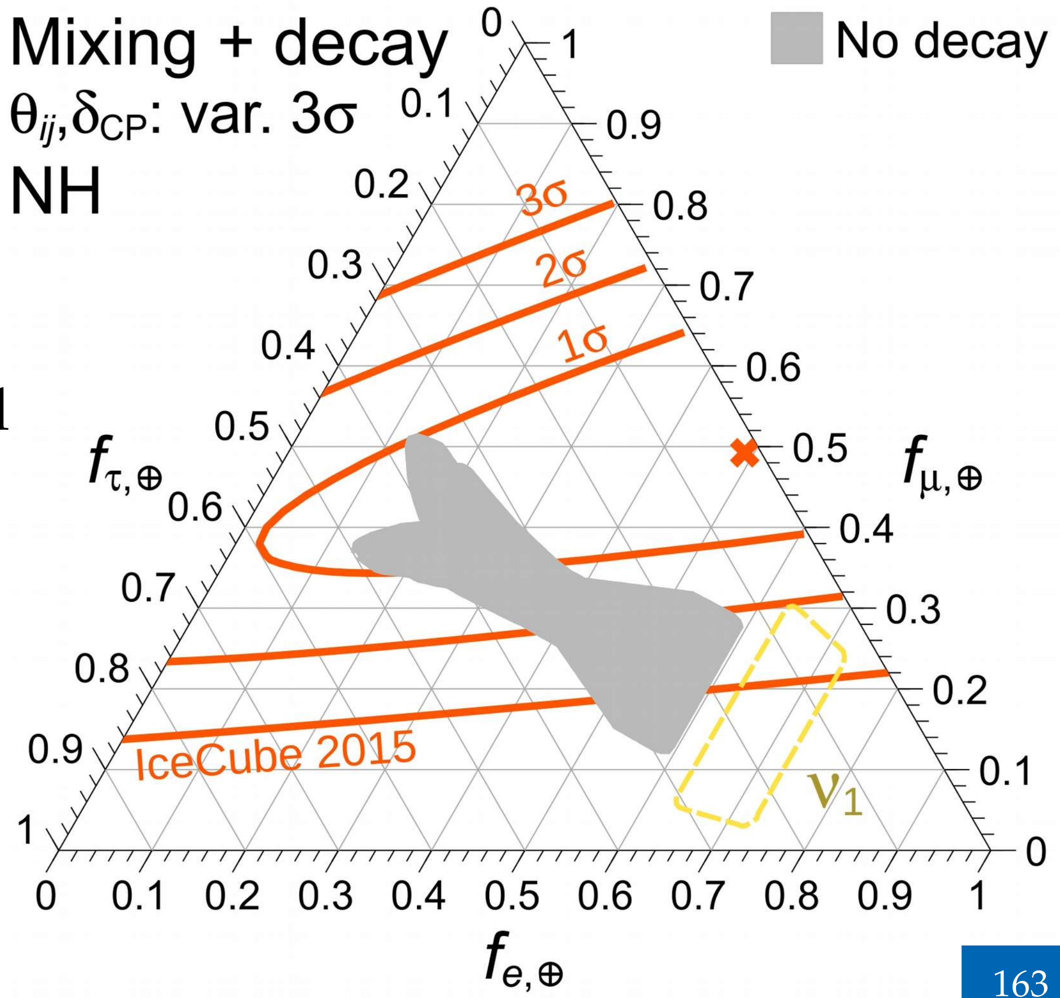
Measuring the neutrino lifetime

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

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

(Assume equal lifetimes of ν_2, ν_3)

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



Measuring the neutrino lifetime

Fraction of ν_2, ν_3 remaining at Earth

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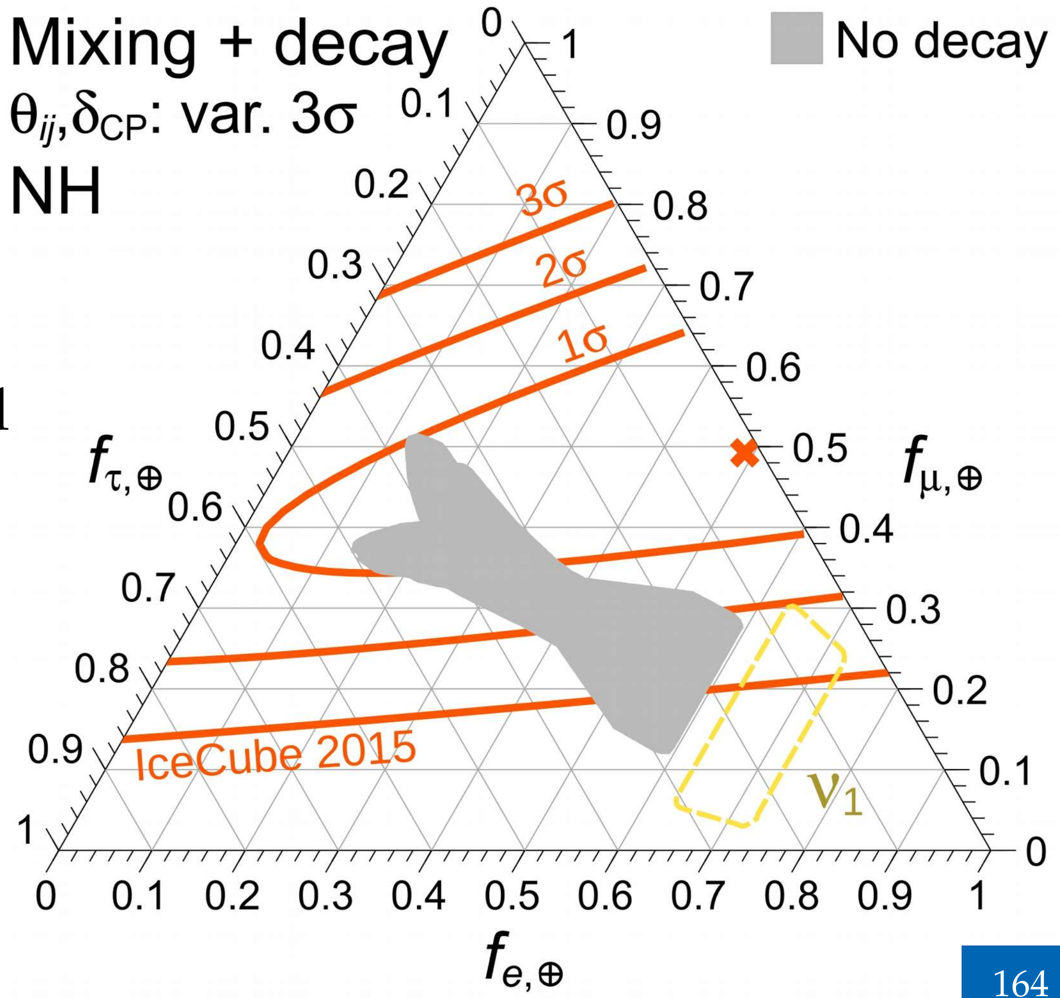

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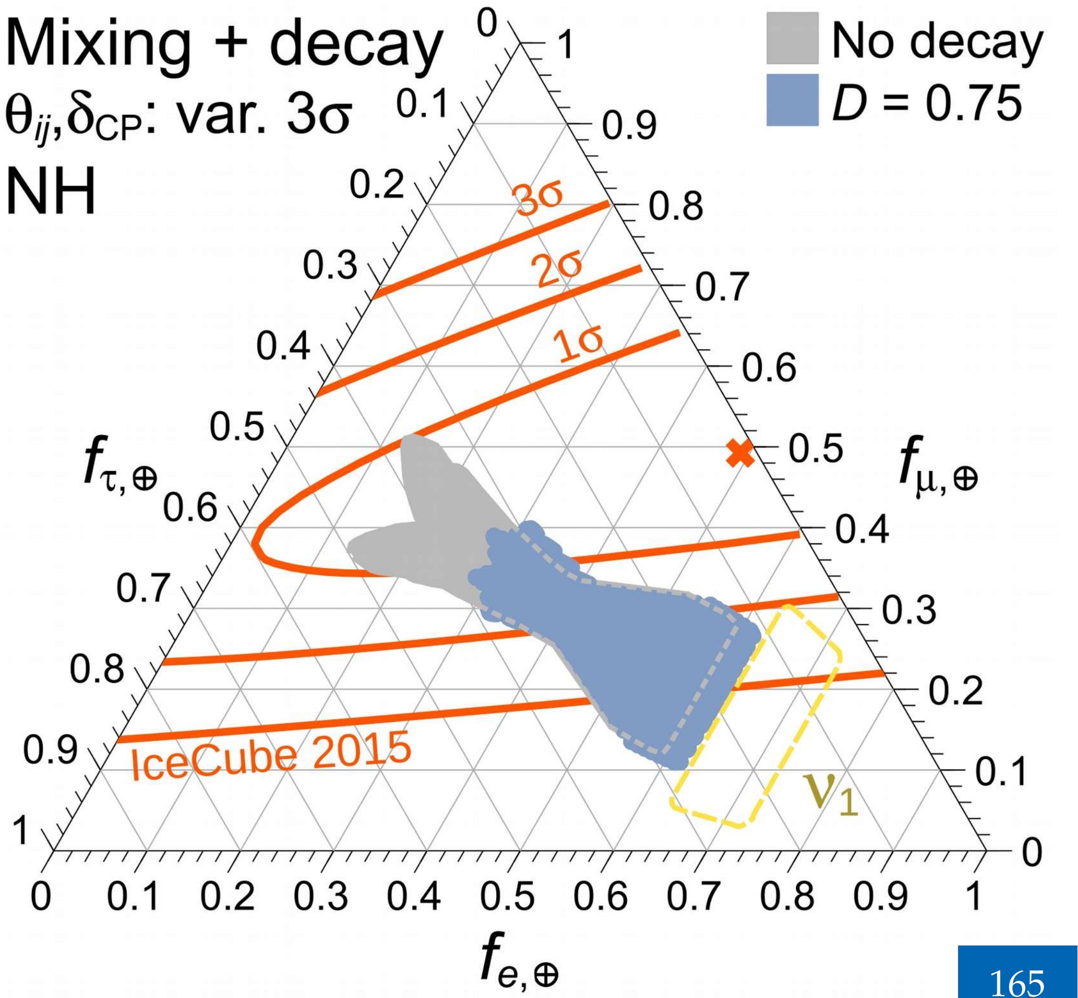

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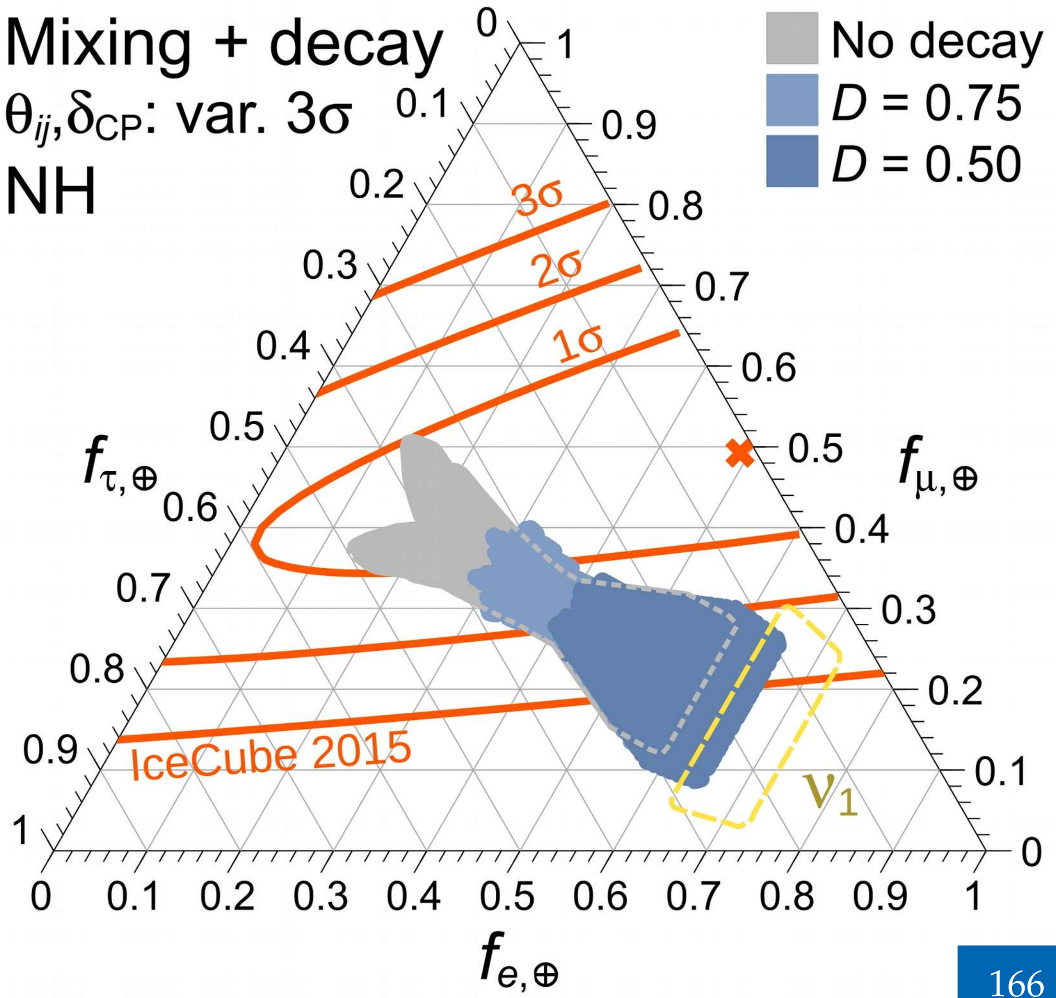

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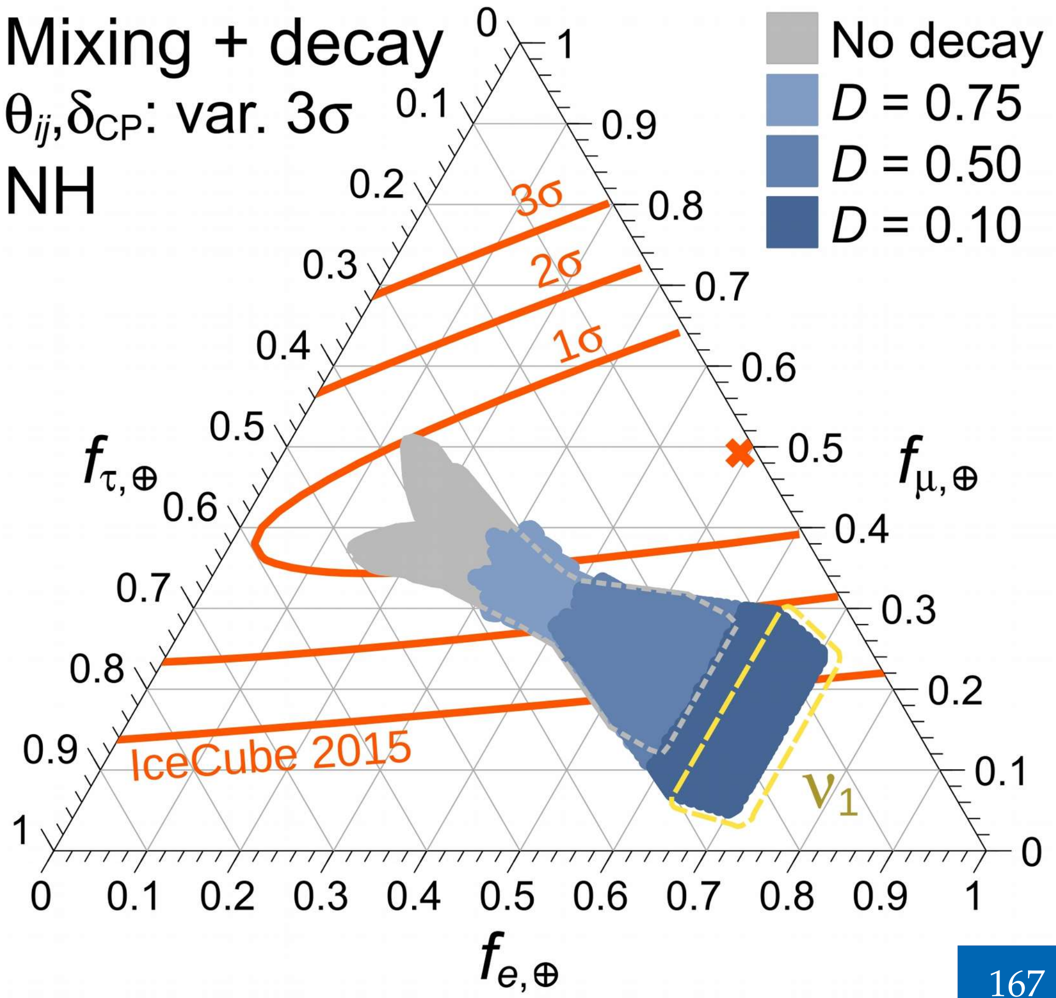

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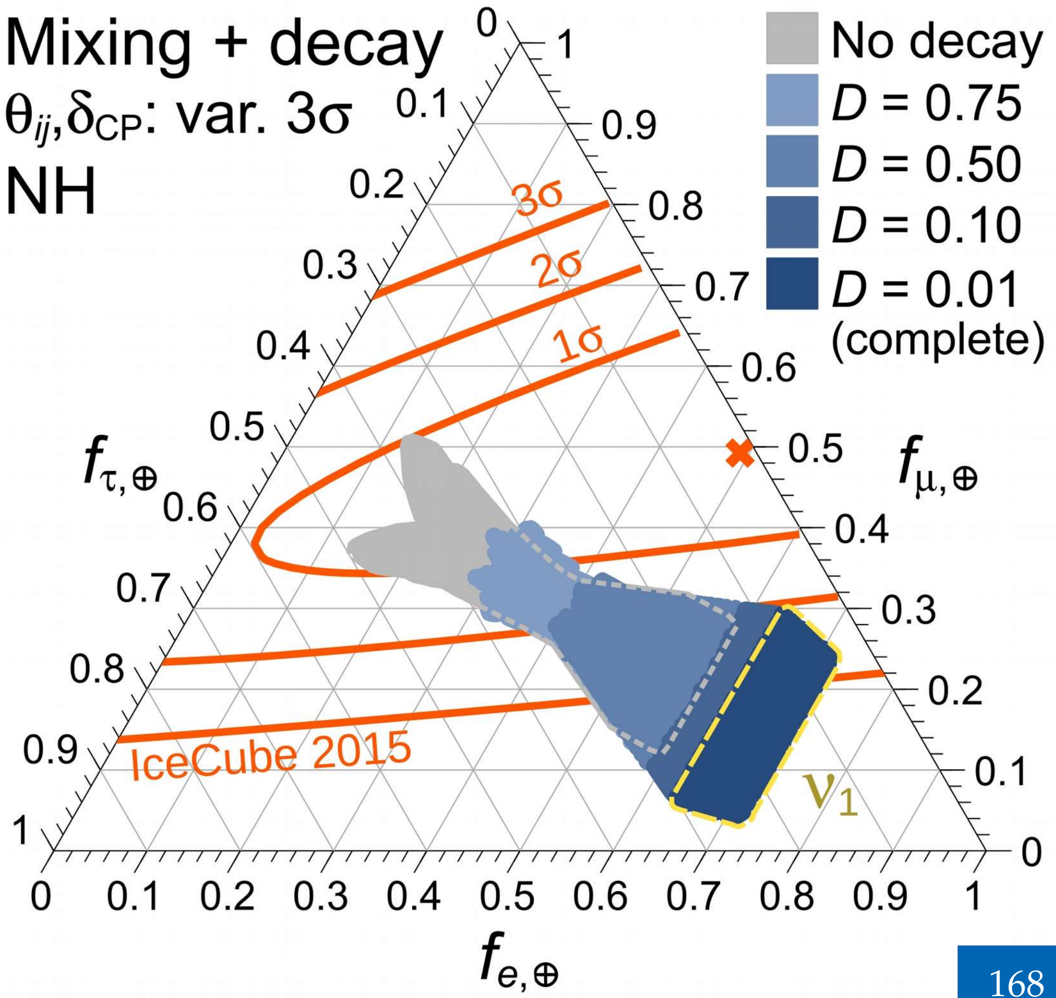

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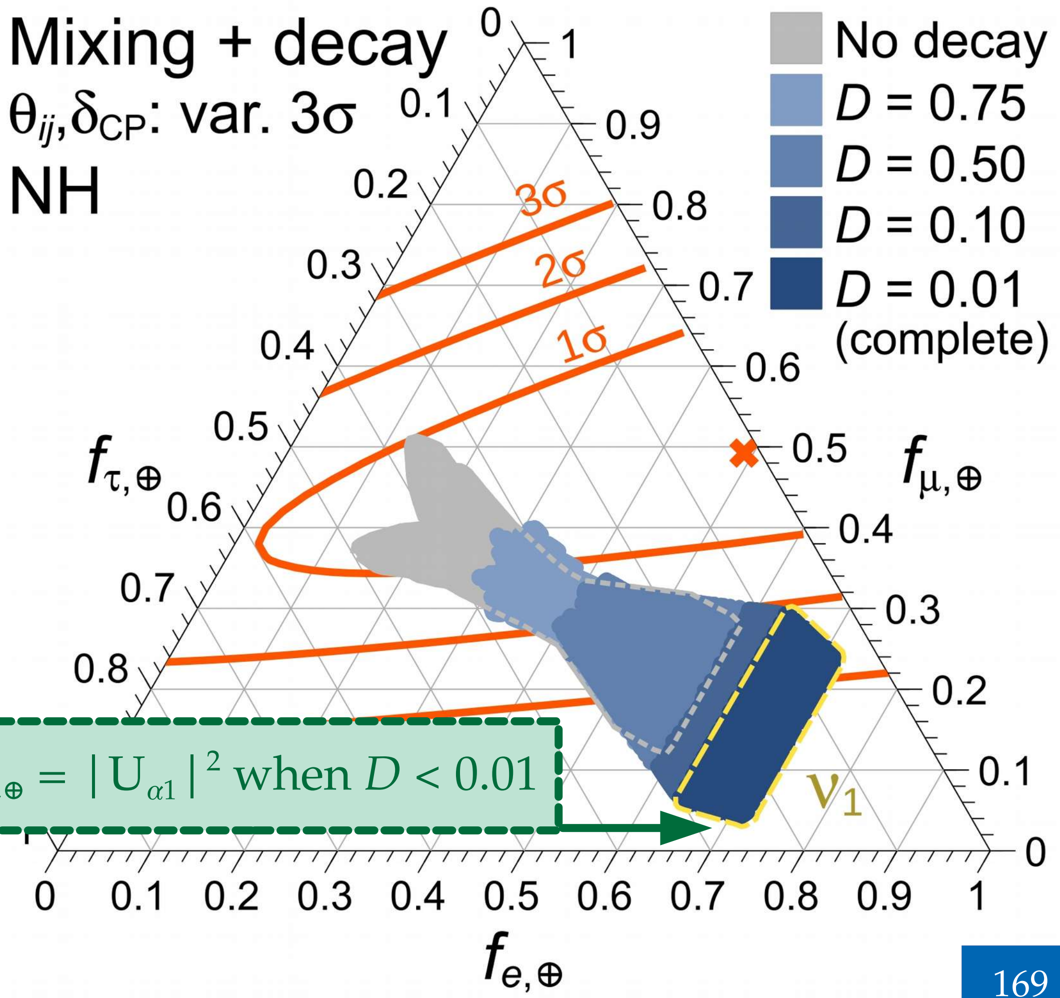
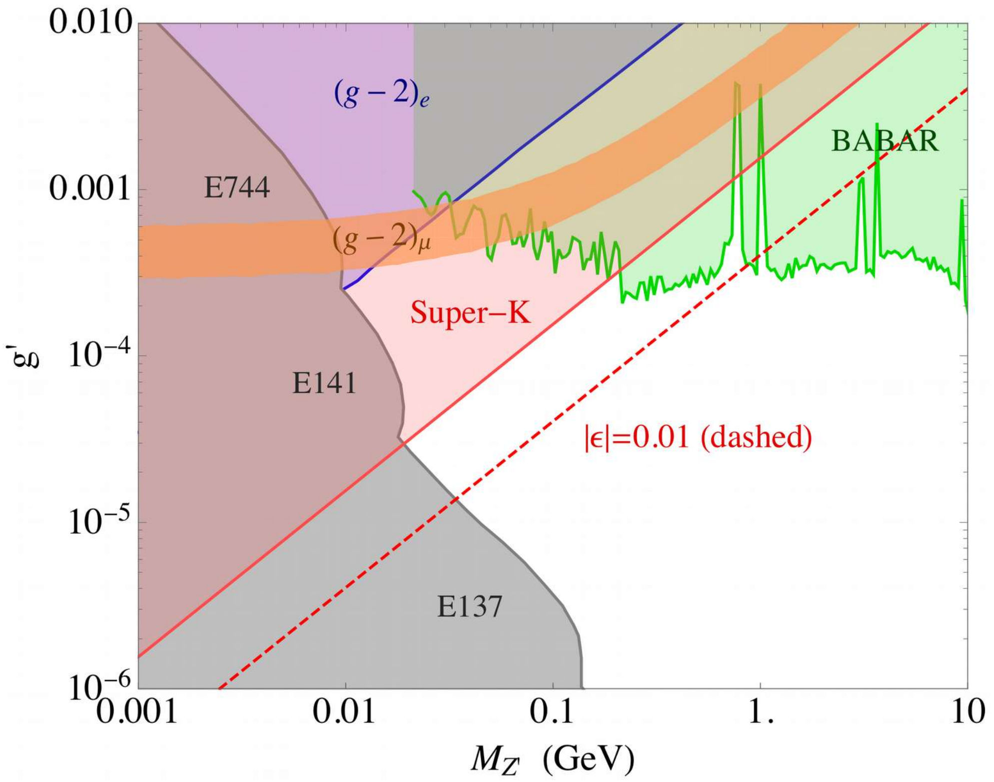


$f_{\alpha,\oplus} = |U_{\alpha 1}|^2$ when $D < 0.01$

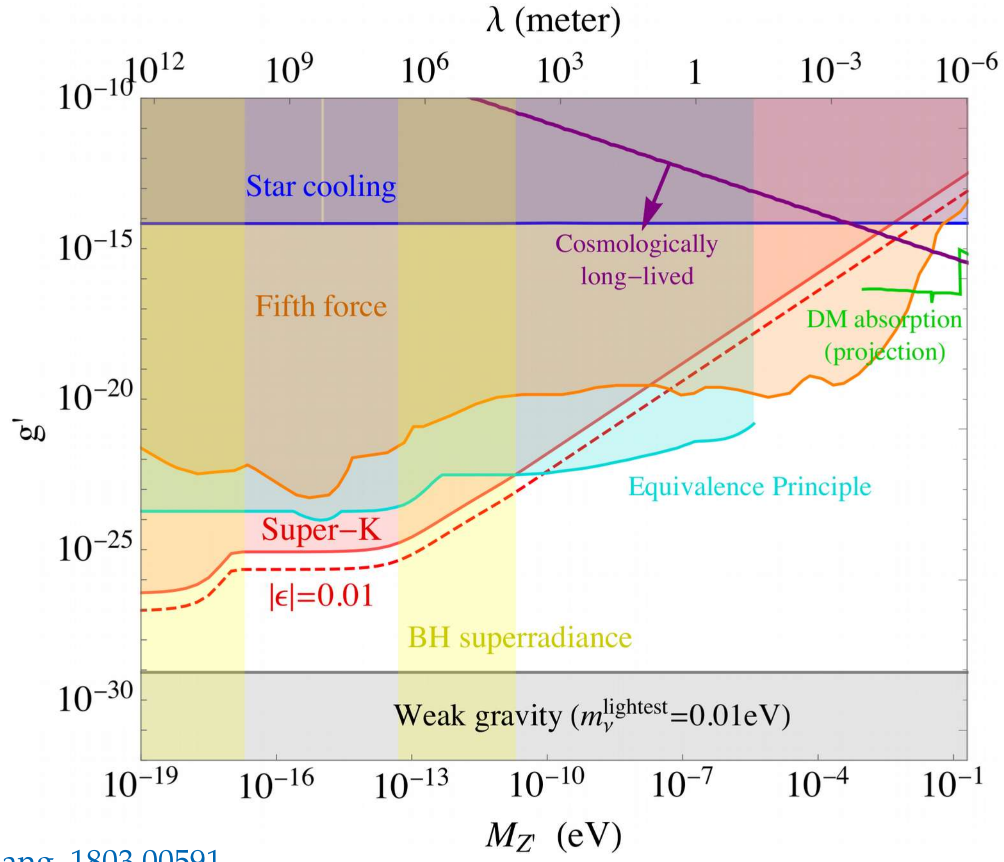
MB, Beacom, Murase, *PRD* 2017
Baerwald, **MB**, Winter, *JCAP* 2012

Current limits on the Z'

MeV–GeV masses

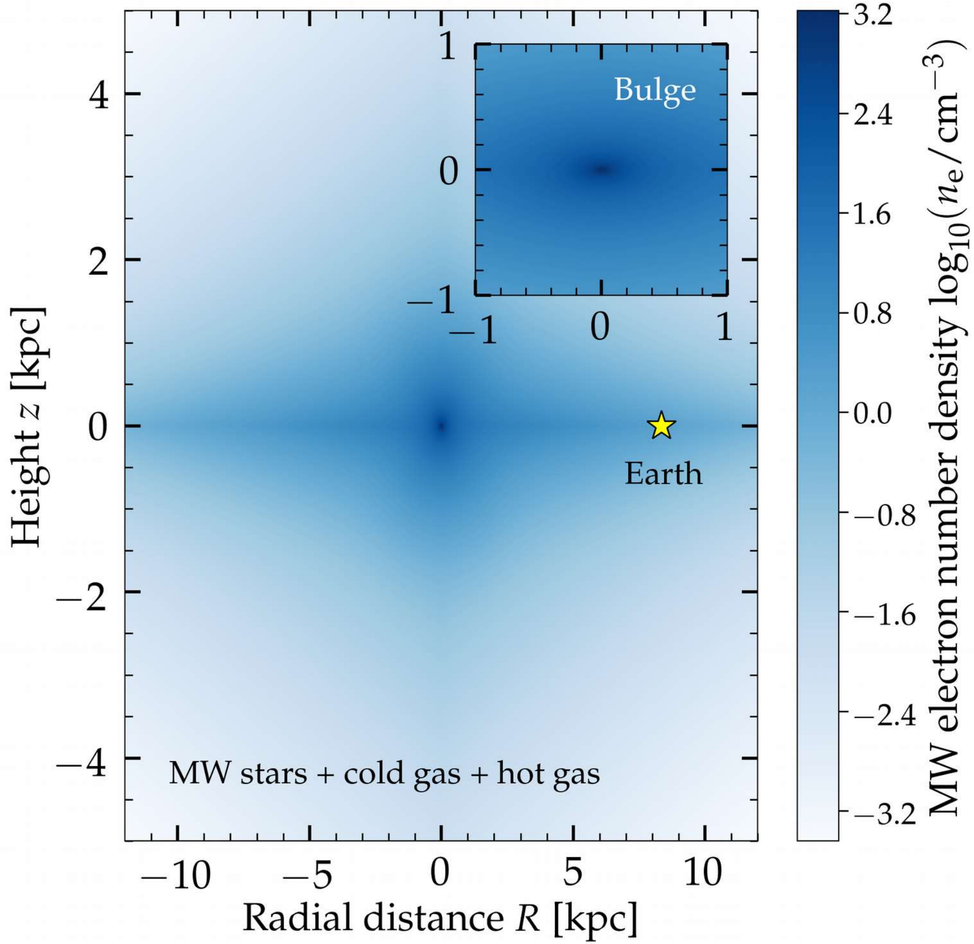


Sub-eV masses

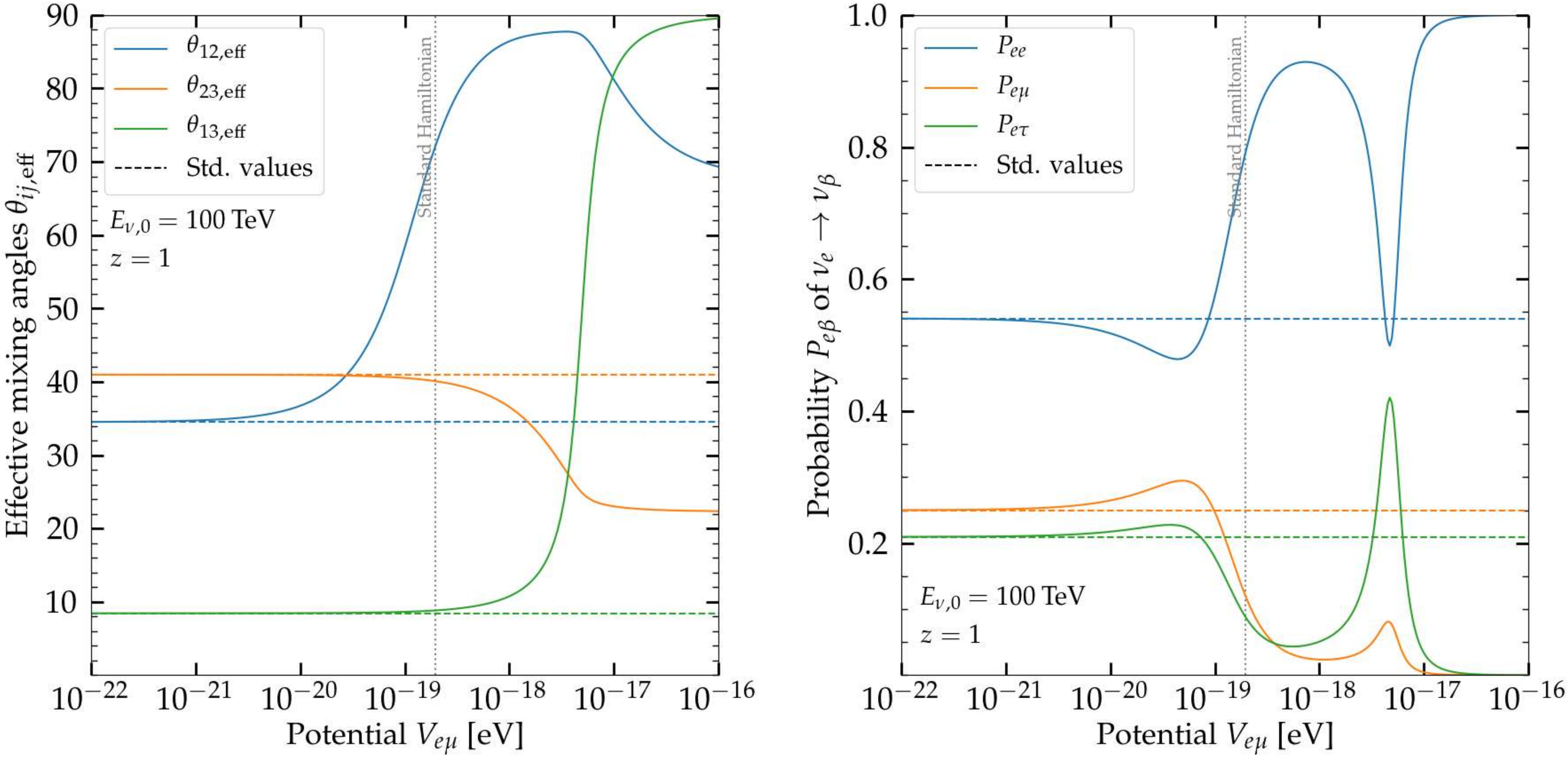


M. Wise & Y. Zhang, 1803.00591

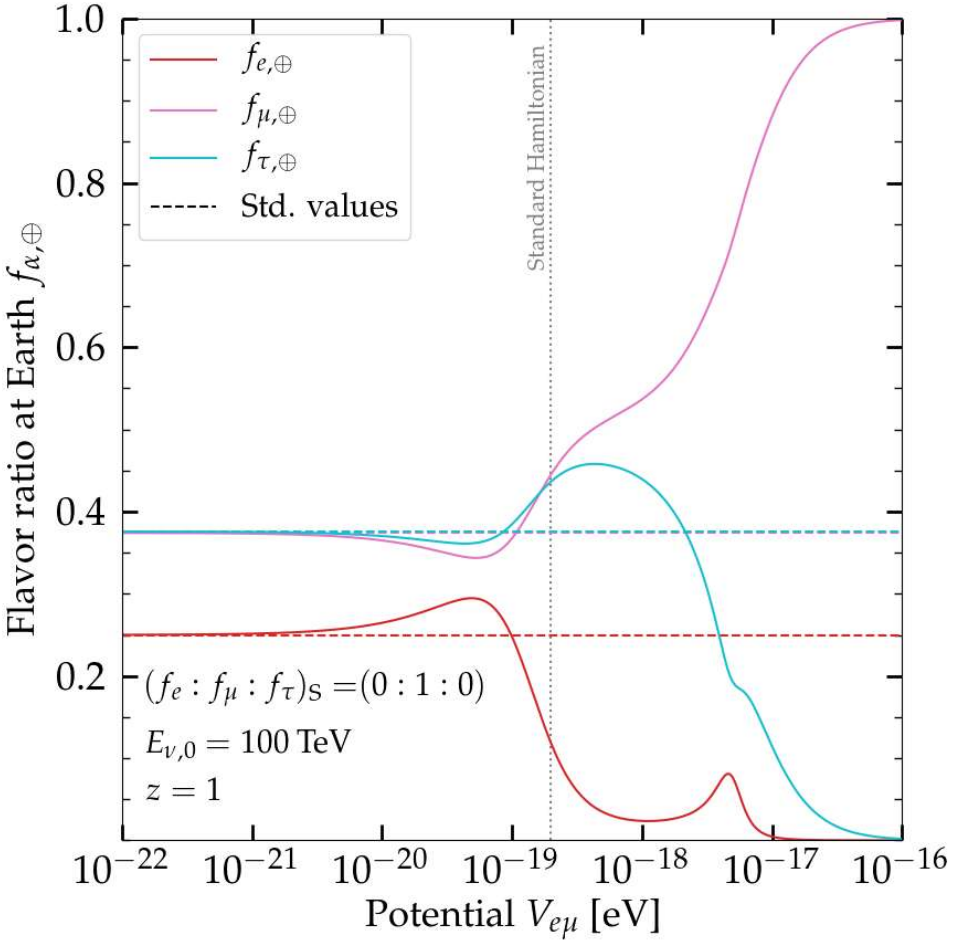
Distribution of electrons in the Milky Way

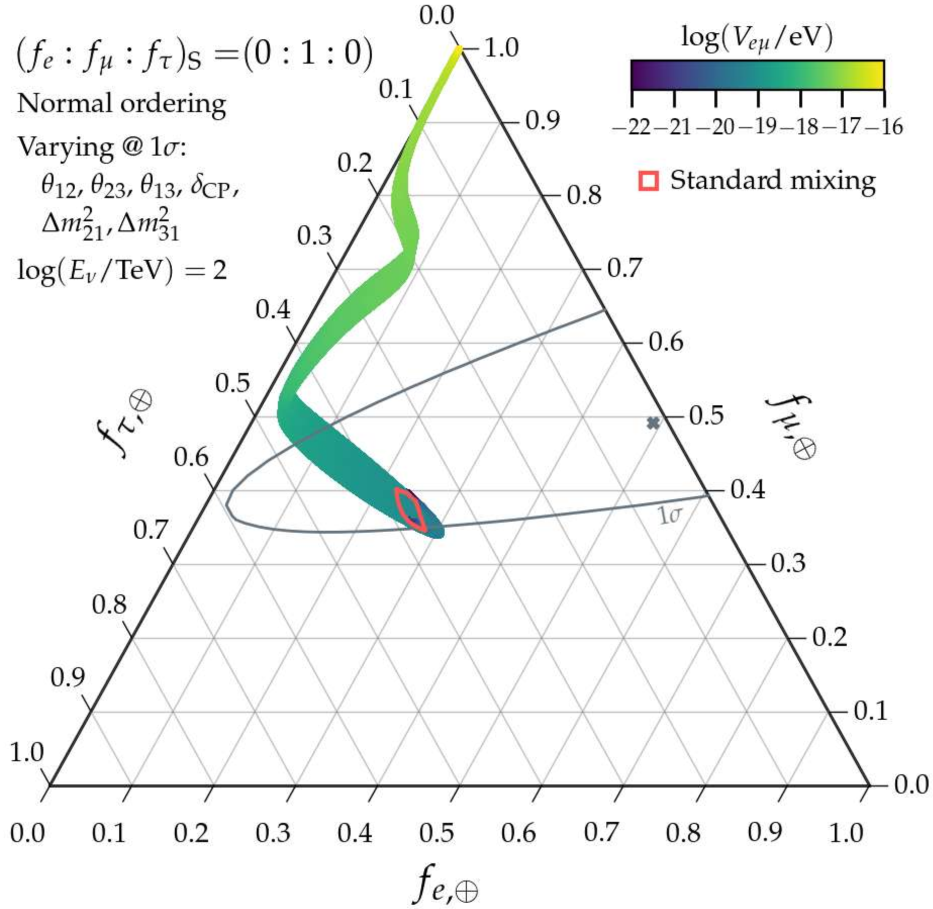


Resonance due to the L_e-L_μ symmetry

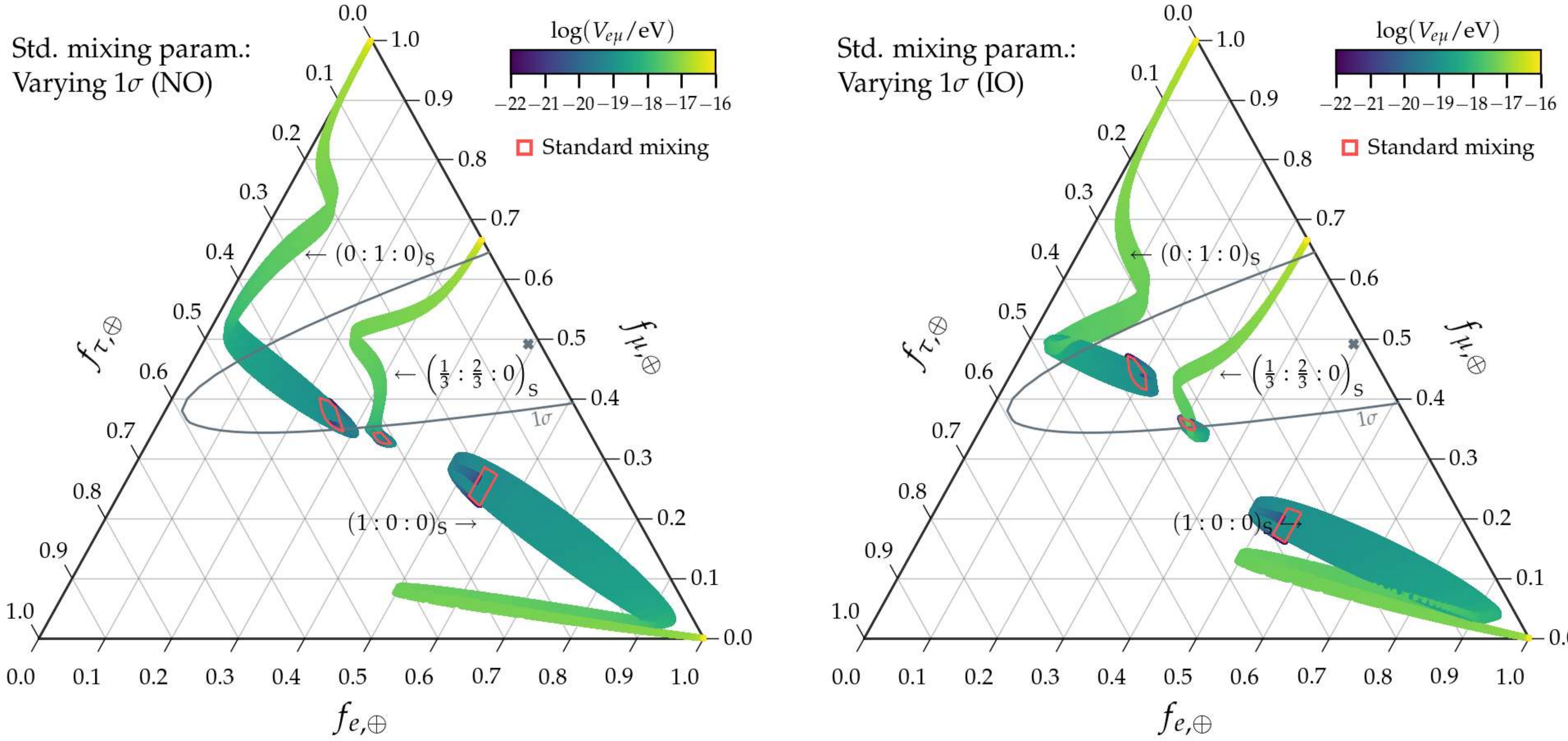


Resonance due to the L_e-L_μ symmetry (*cont.*)

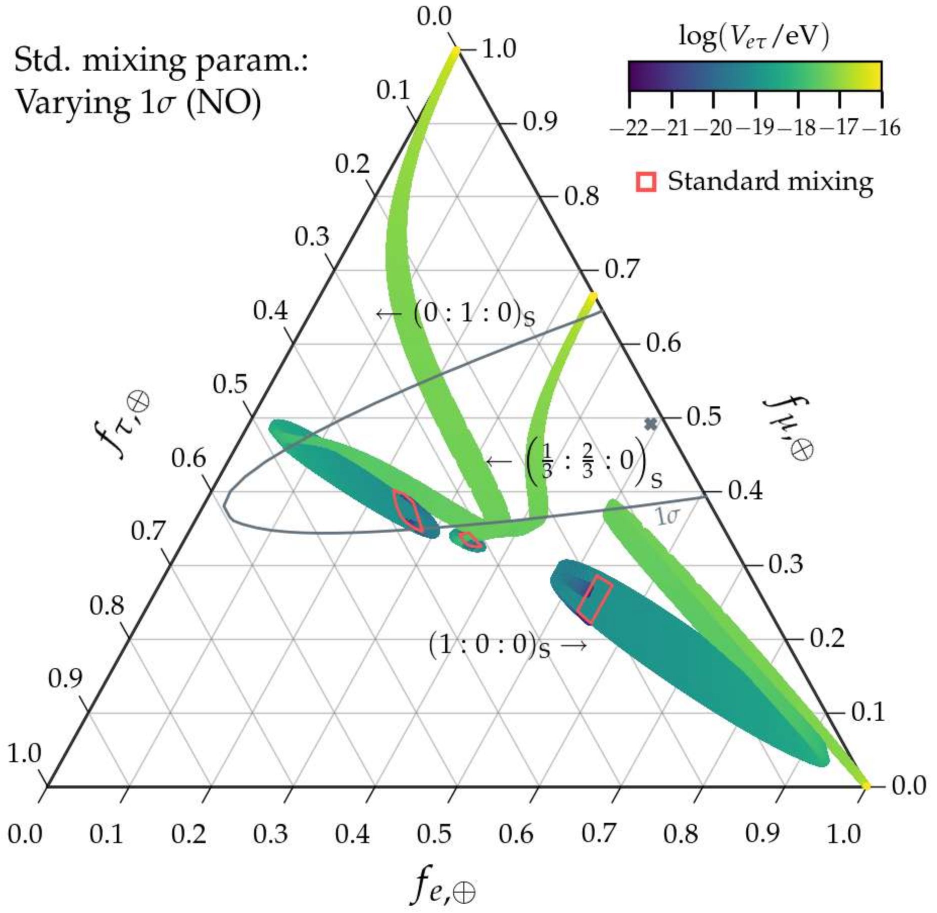


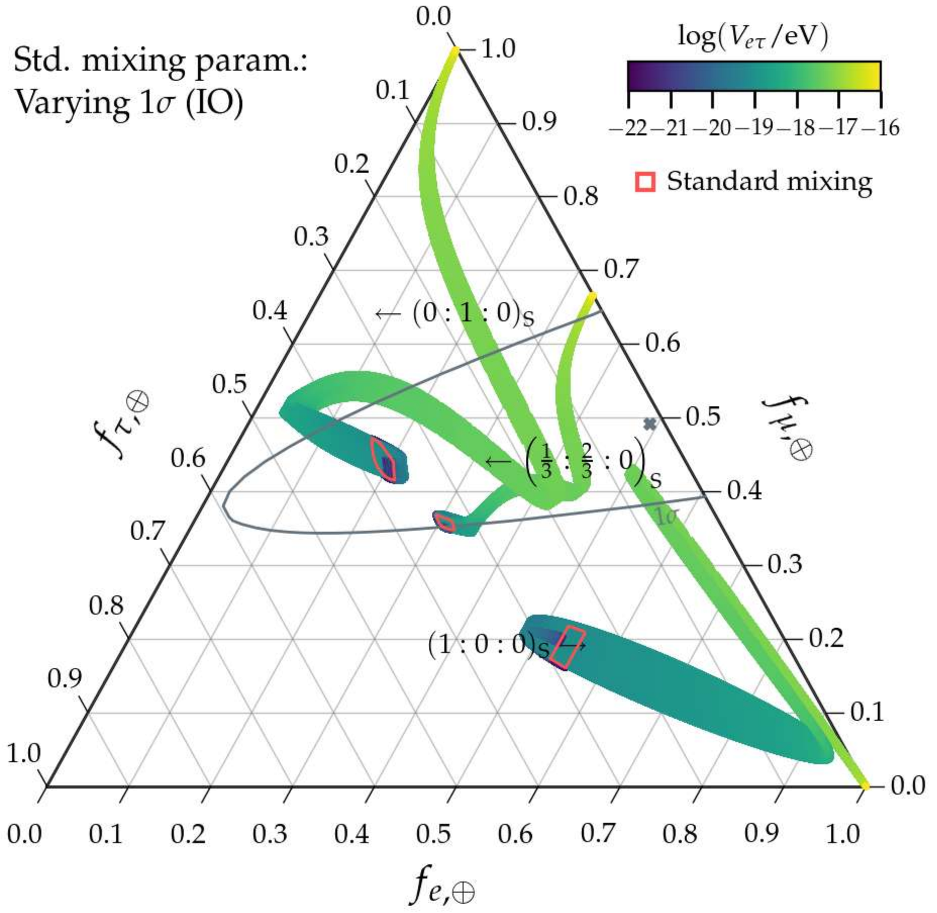


Flavor ratios for the L_e-L_μ symmetry: NO *vs.* IO



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



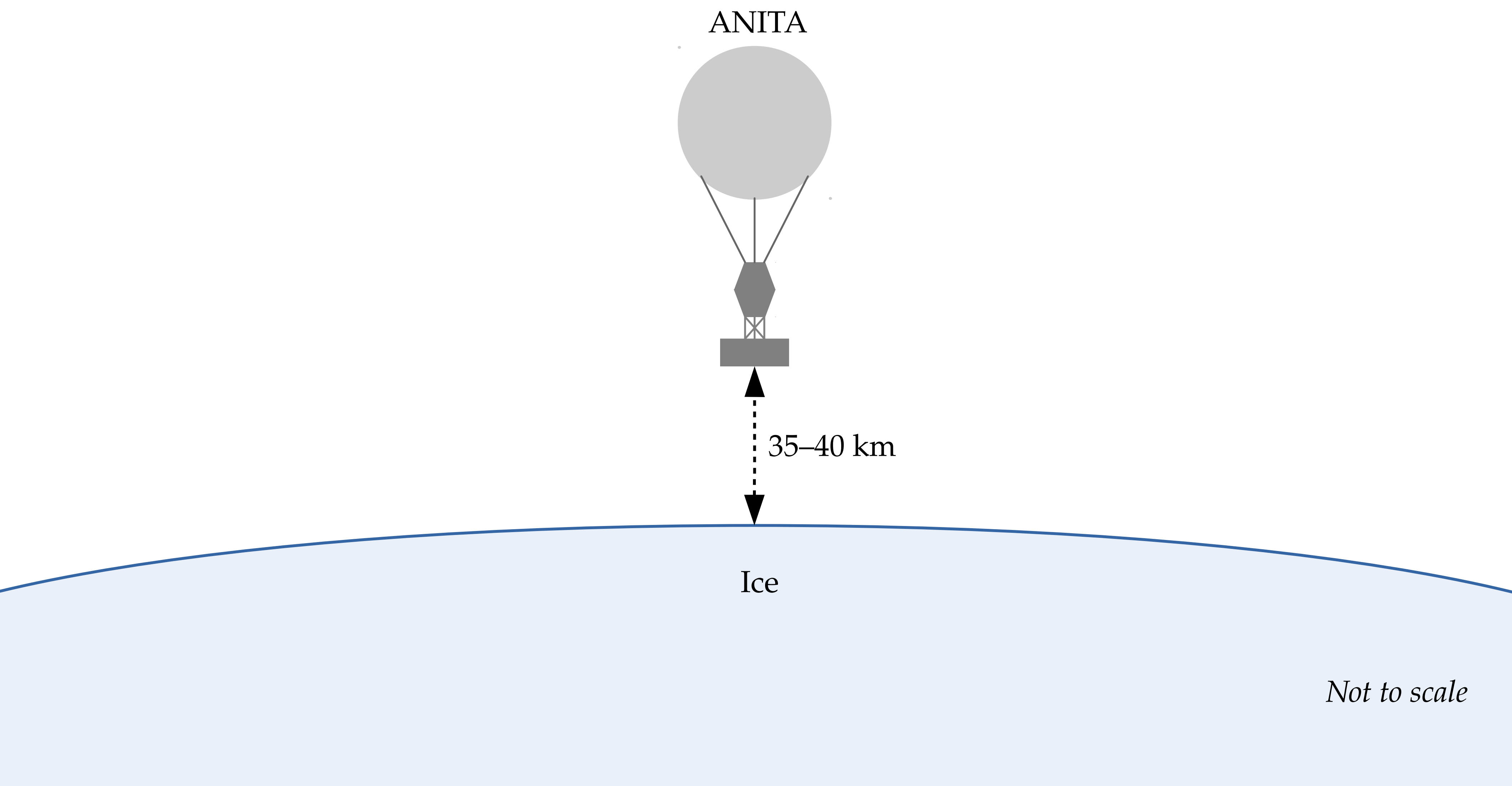


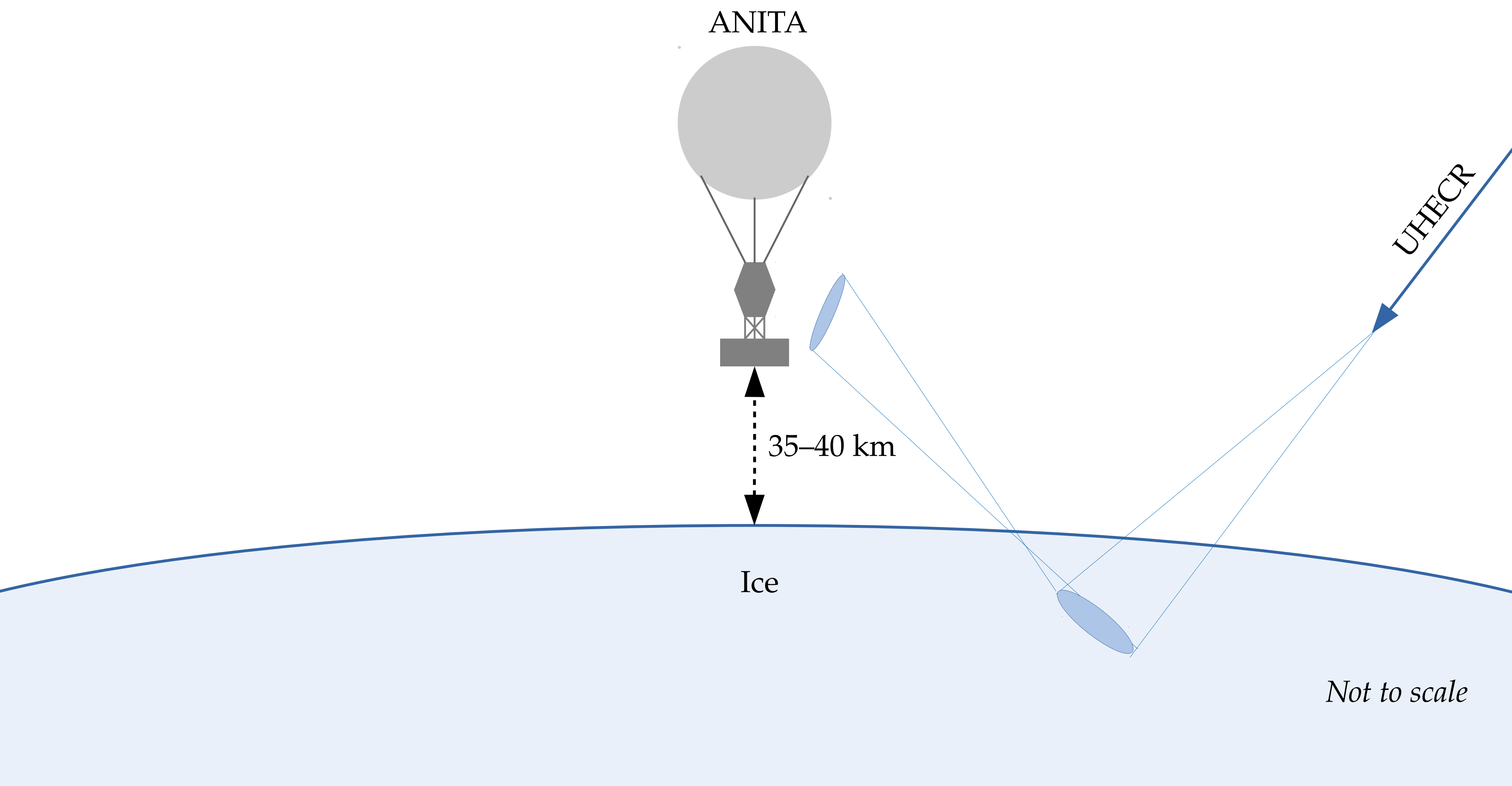
Mystery ANITA events – First UHE ν detected?

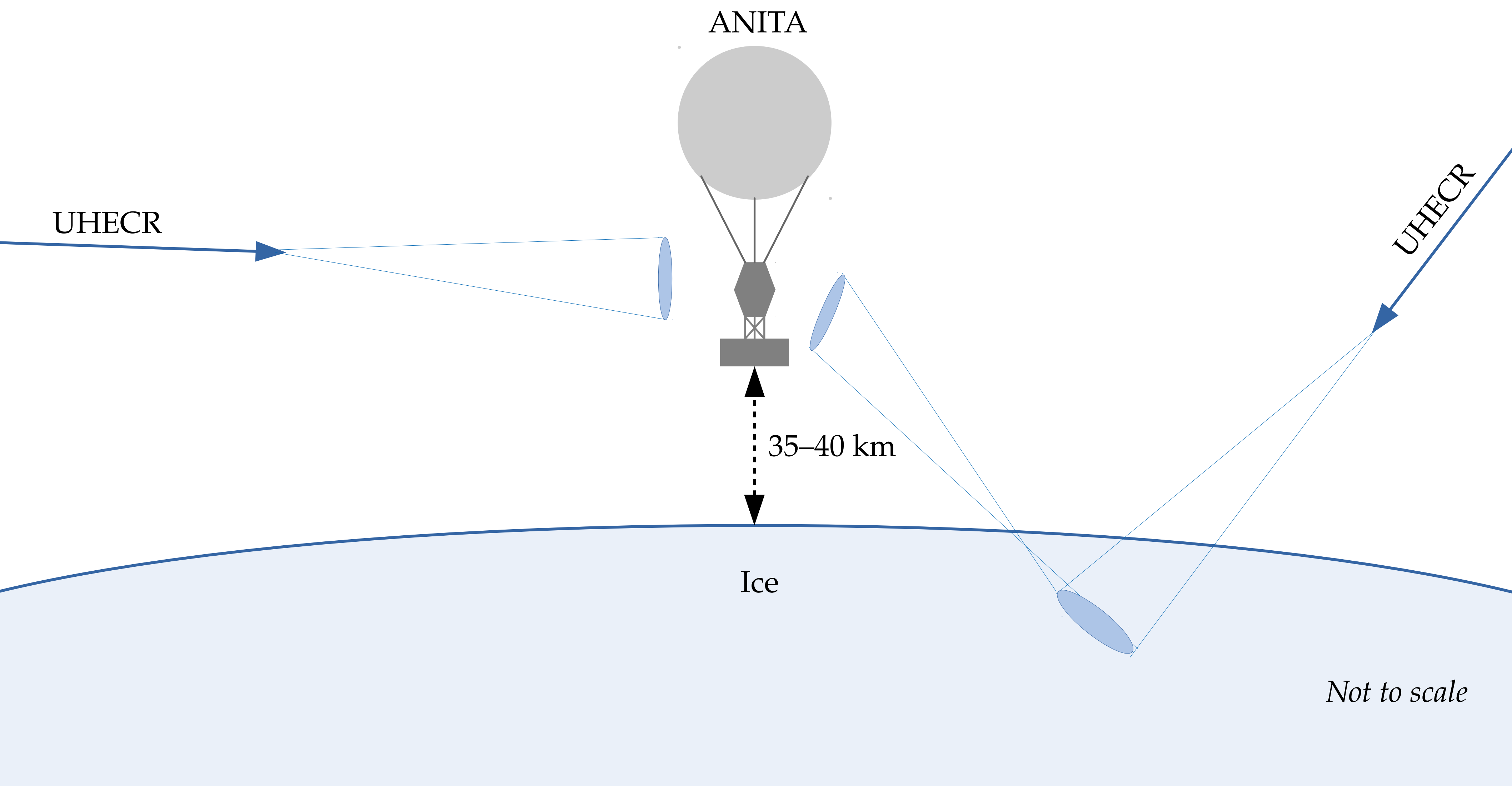
Photo by Spencer Klein

Photo by Brian Hill/U. Hawaii-Manoa

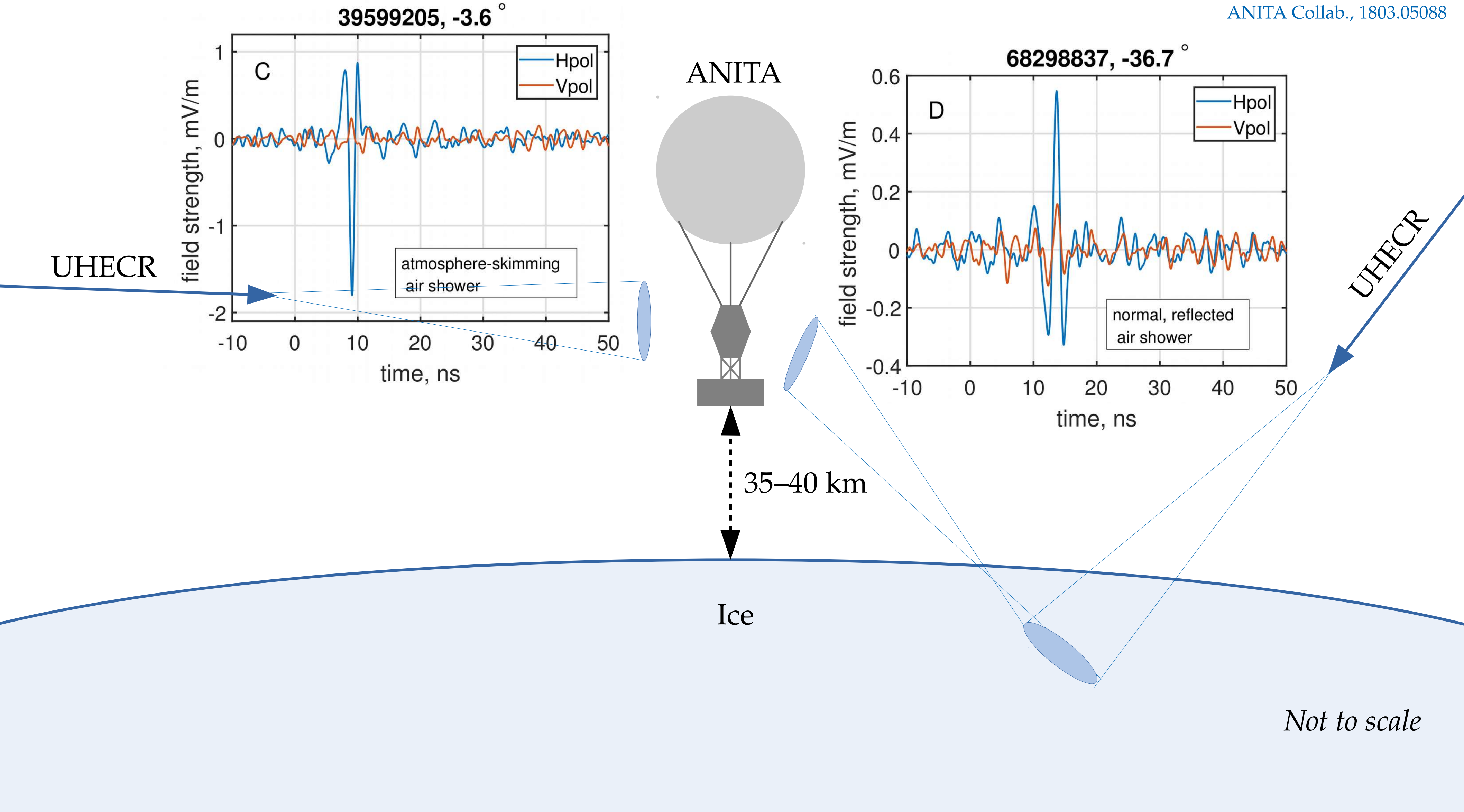
See Wed talk by Linda Cremonesi

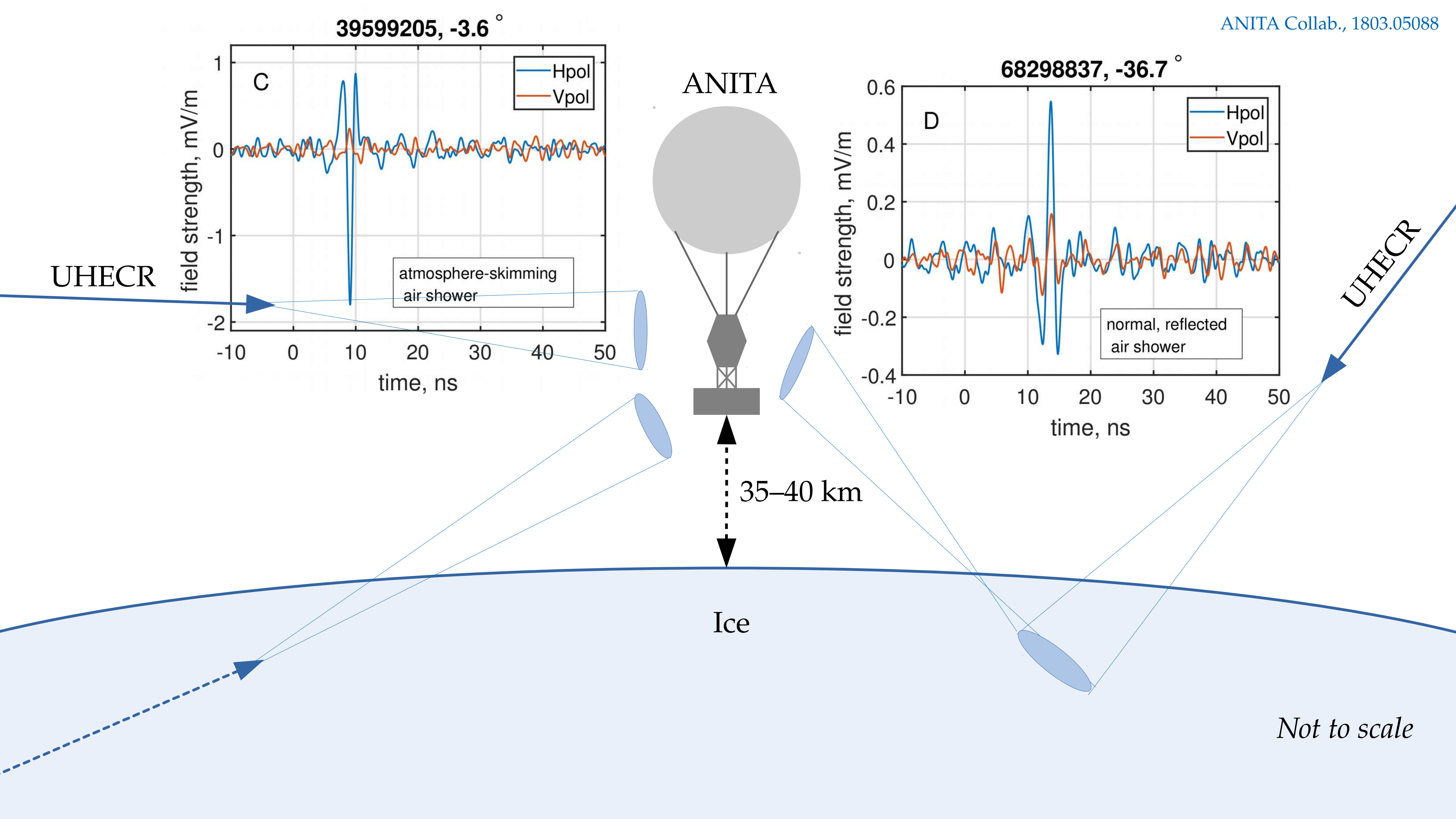

ANITA
35–40 km
Ice
Not to scale

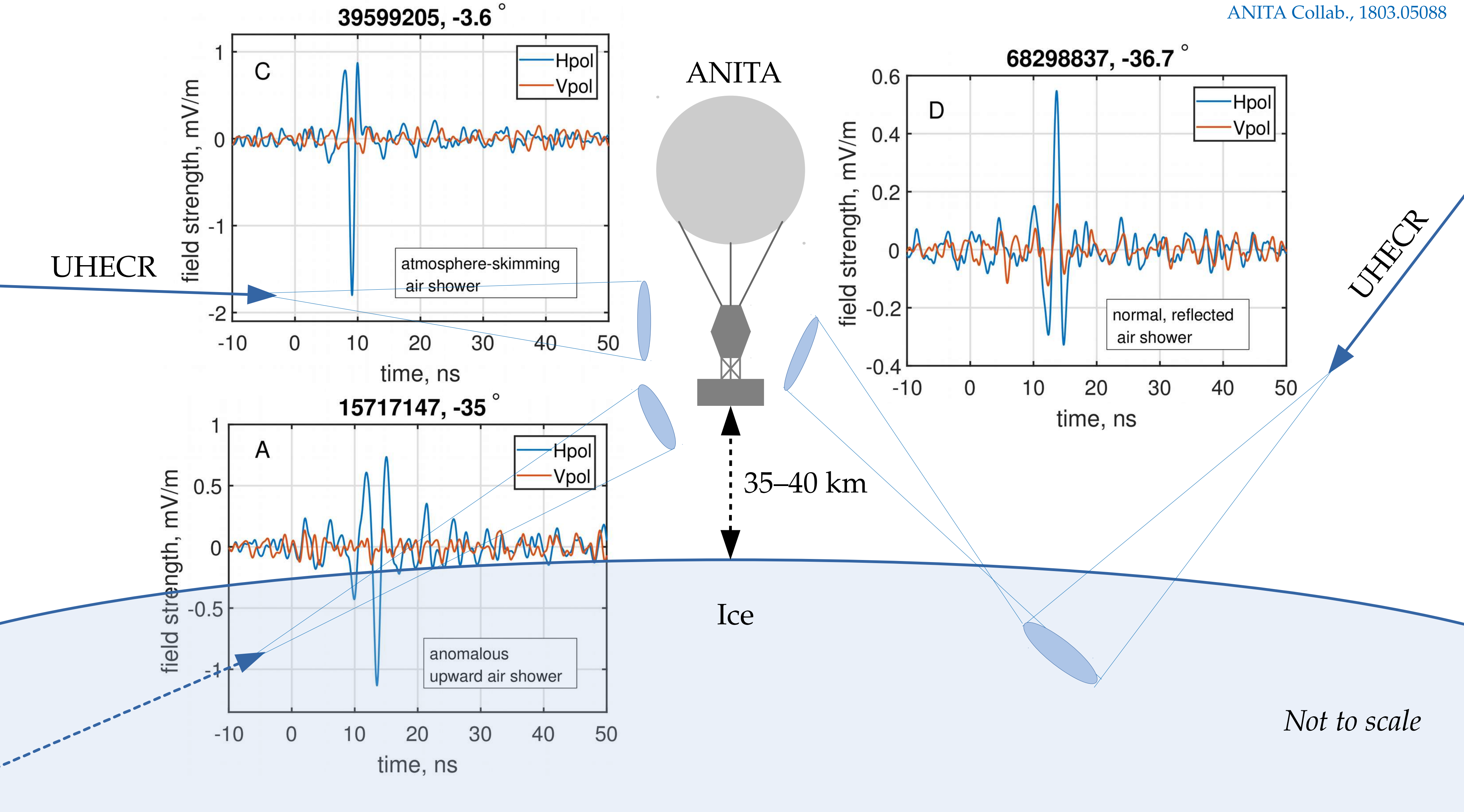

ANITA
UHECR
35–40 km
Ice
Not to scale


ANITA
UHECR
UHECR
35–40 km
Ice
Not to scale

ANITA Collab., 1803.05088




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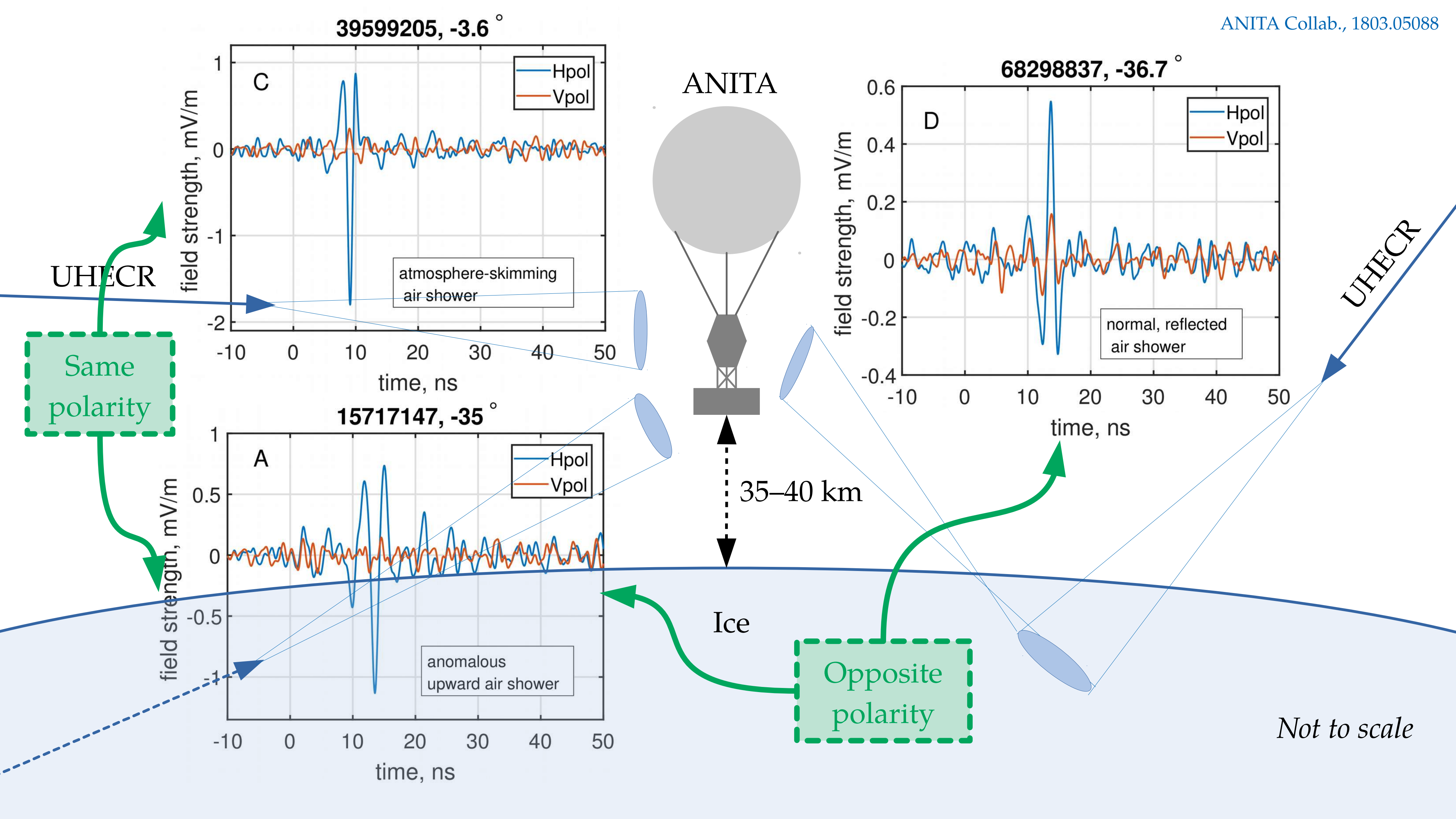

ANITA Collab., 1803.05088
39599205, -3.6 °
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atmosphere-skimming air shower
field strength, mV/m
time, ns
15717147, -35 °
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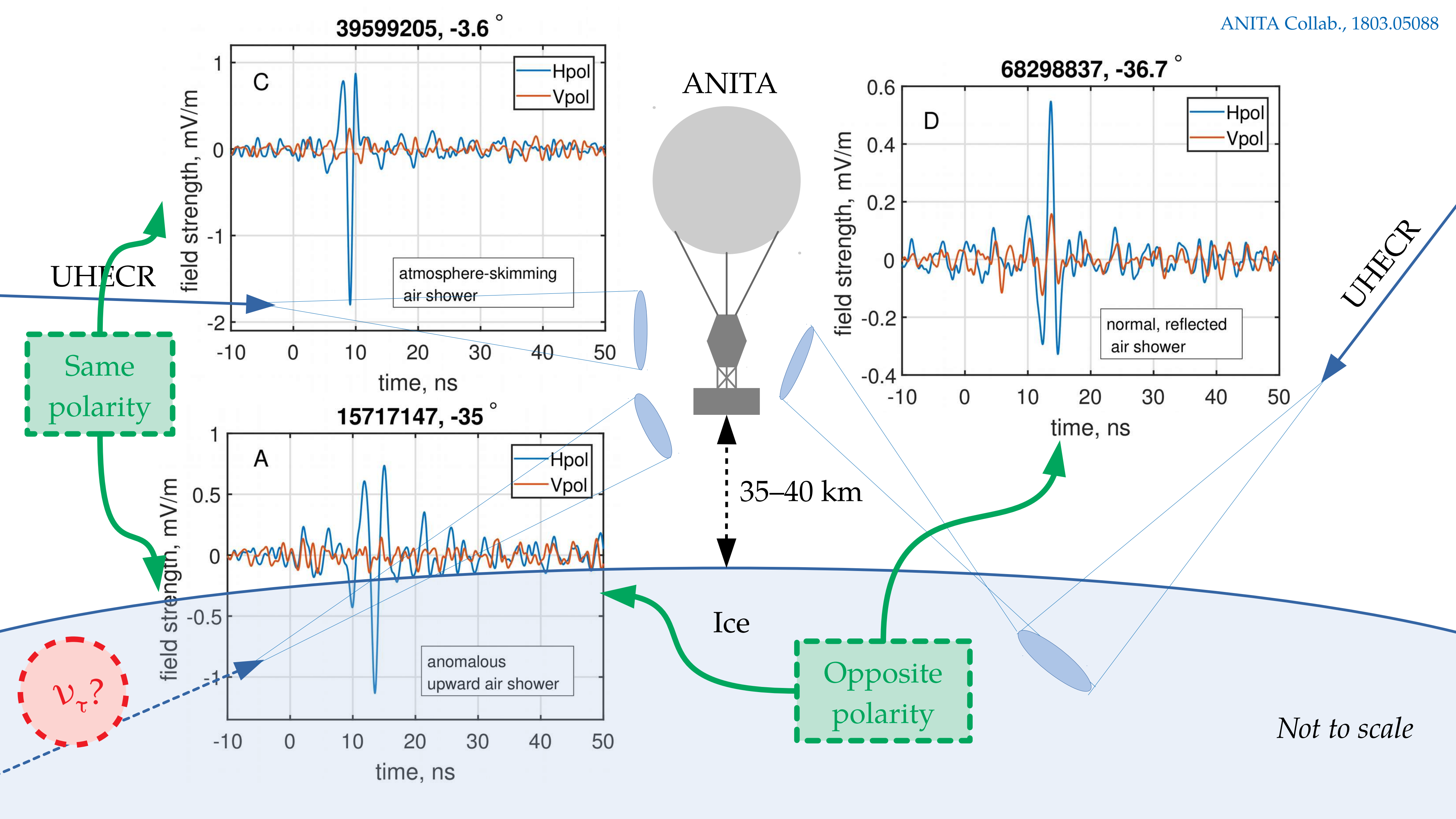
anomalous upward air shower
68298837, -36.7 °
D
normal, reflected air shower
ANITA
UHECR
Same polarity
Opposite polarity
35–40 km
Ice
Not to scale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ANITA
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normal, reflected air shower
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Ice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

Mystery ANITA events – First UHE ν detected?

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

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

- Were these showers due to ν_τ? *Unlikely*

- Optical depth to νN interactions at EeV:

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

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

ANITA Collab., *PRL* 2016 + 1803.05088

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Transient astrophysical event?

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

ANITA Collab., *PRL* 2016 + 1803.05088

Mystery ANITA events – What are they?

- Transition radiation [Motloch *et al.*, *PRD* 2017]:
  - Refraction of radio waves at ice-air interface could make horizontal ν_τ look upgoing
  - Assessment: Needs too large a diffuse flux of ν_τ, because transition radiation is a small effect
- Sterile neutrinos [Cherry & Shoemaker, 1802.01611; Huang, 1804.05362]:
  - Sterile neutrinos propagate in Earth, then convert $\nu_s \to \nu_\tau$
  - Assessment: Model predicts more (unseen) events at shallower angles
- Dark matter decay in Earth core [Anchordoqui *et al.*, 1803.11554]:
  - 480-PeV sterile right-handed ν_r in Earth core decays: $\nu_r \to$ Higgs + ν_τ
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