Fundamental physics in GRAND

Mauricio Bustamante

Niels Bohr Institute, University of Copenhagen

GRAND White Paper Workshop
IAP, Paris, August 24, 2018

UNIVERSITY OF COPENHAGEN

Can we do EeV particle physics at GRAND?
Yes – but it will be tricky

We will need

1. Enough events

2. Sufficient energy and angular resolution

3. Additional flavor channels

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 can we do?

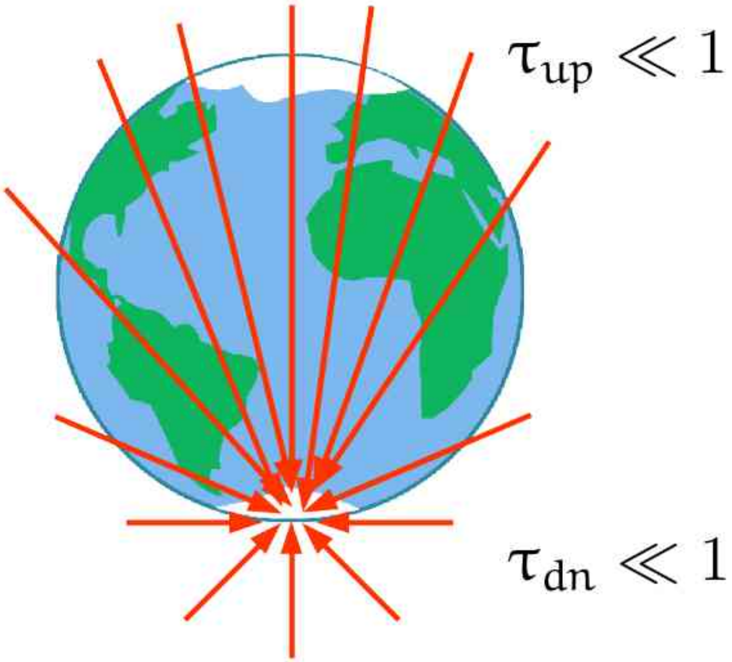
- Measure neutrino-nucleon cross sections at EeV
- Test new neutrino interactions via spectral distortions
- Test new neutrino interactions via angular distortions
- Test new physics via flavor composition?
- ANITA mystery events?
- Test tau physics?
- ?

Cross section

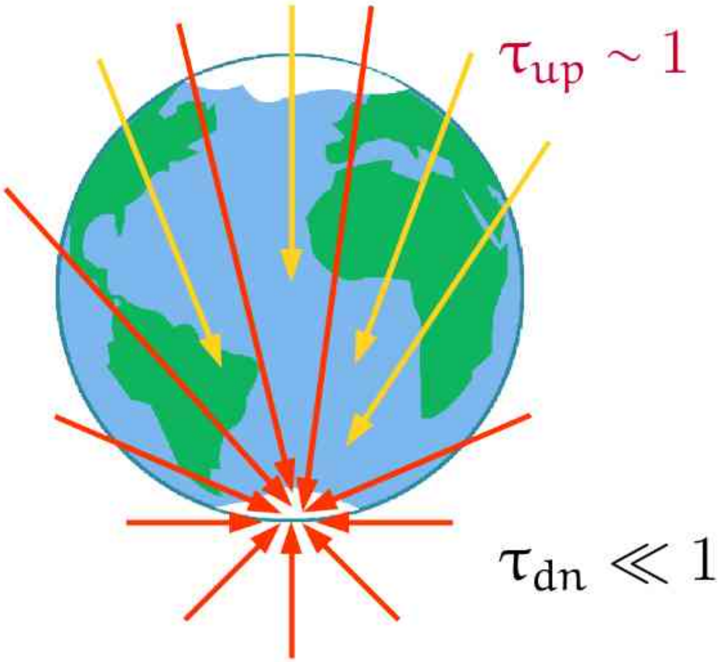
Measuring the high-energy cross section

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

Below ~ 10 TeV: Earth is transparent



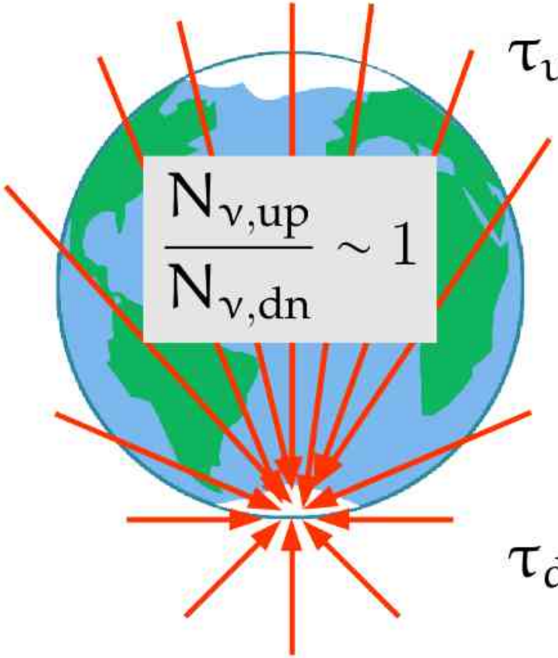
Above ~ 10 TeV: Earth is opaque



Measuring the high-energy cross section

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

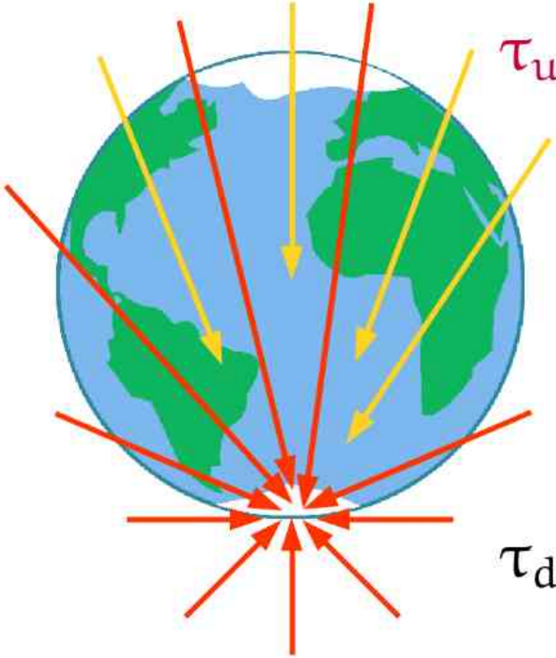
Below ~ 10 TeV: Earth is transparent



$\tau_{\mathrm{up}} \ll 1$

$\tau_{\mathrm{dn}} \ll 1$

Above ~ 10 TeV: Earth is opaque



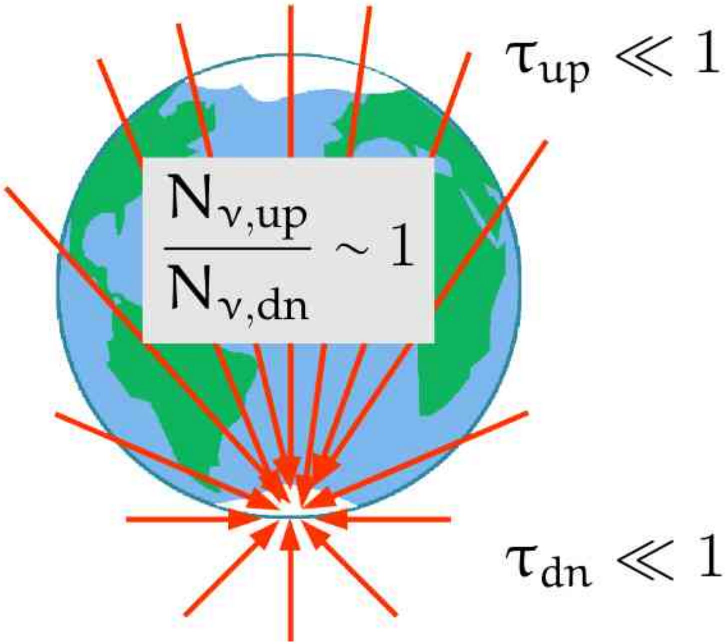
$\tau_{\mathrm{up}} \sim 1$

$\tau_{\mathrm{dn}} \ll 1$

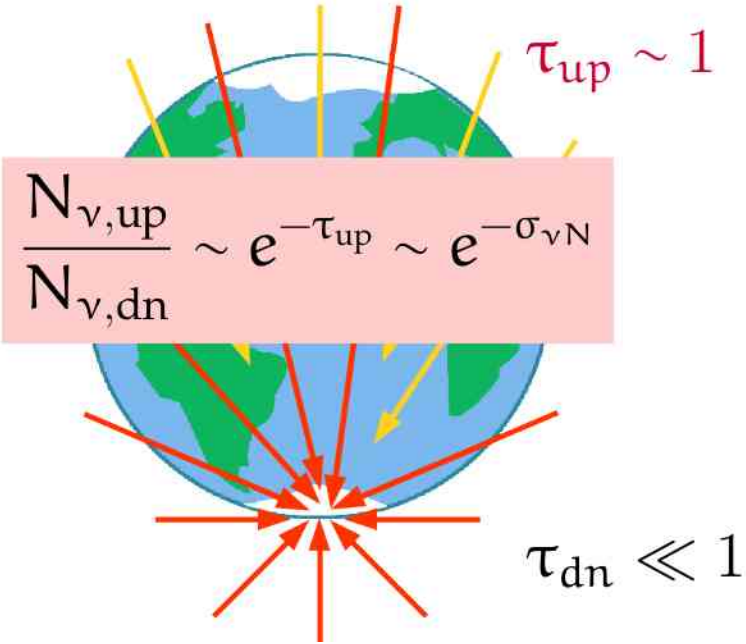
Measuring the high-energy cross section

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

Below ~ 10 TeV: Earth is transparent



Above ~ 10 TeV: Earth is opaque



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)

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

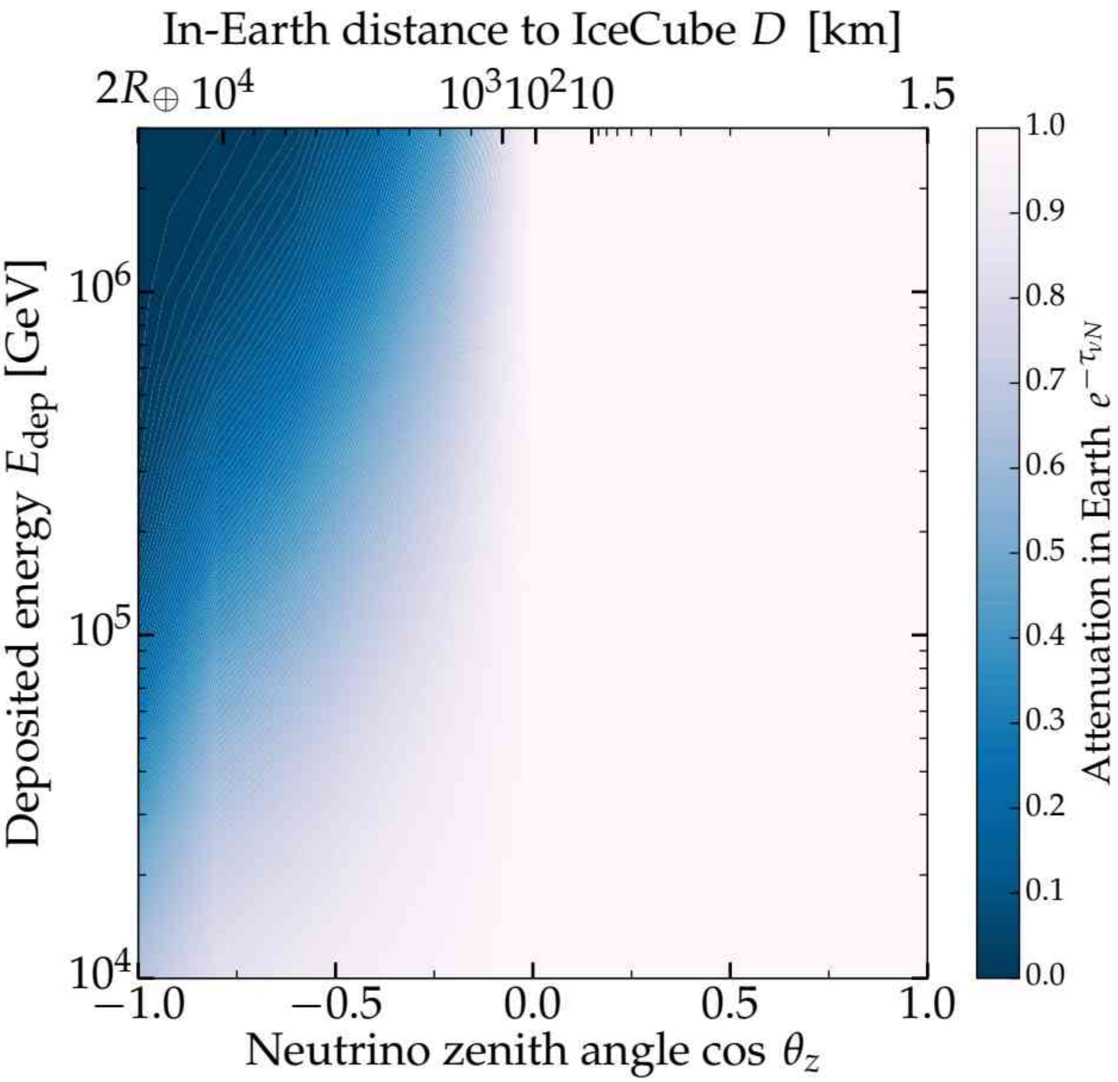
Downgoing events fix the product $\Phi_\nu \cdot \sigma_{\nu N}$

Upgoing (lots of matter)

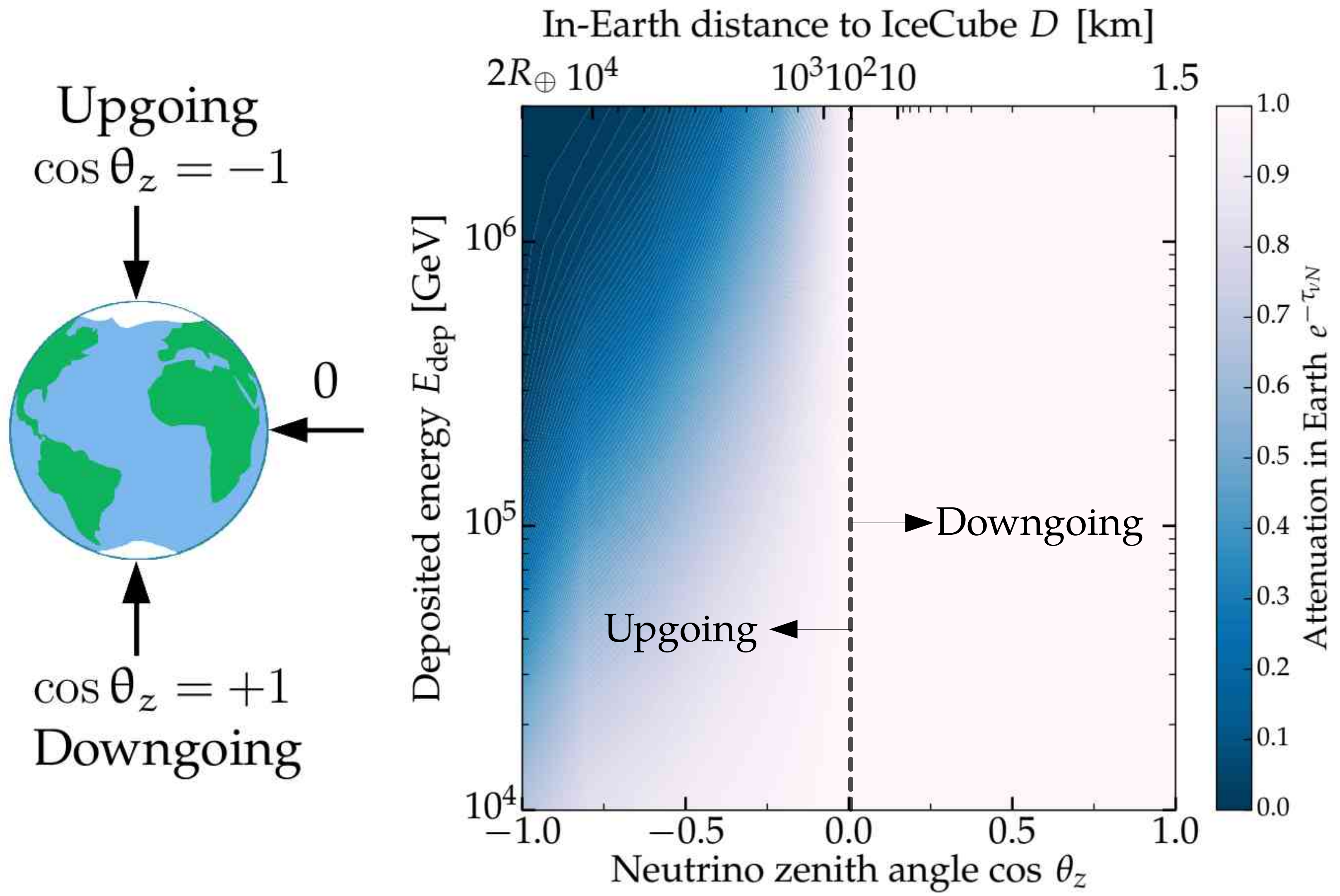
$$N_{\nu,\mathrm{up}} \sim N_{\nu,\mathrm{dn}} \cdot e^{-\tau}$$

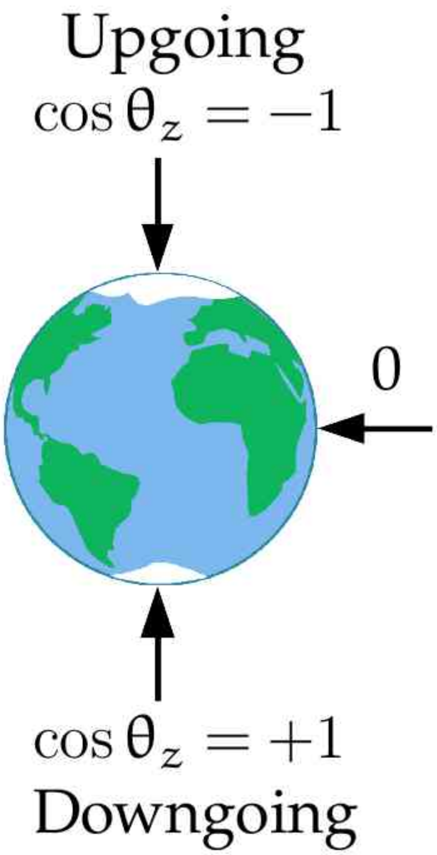
Upgoing events measure $\sigma_{\nu N}$ via τ

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

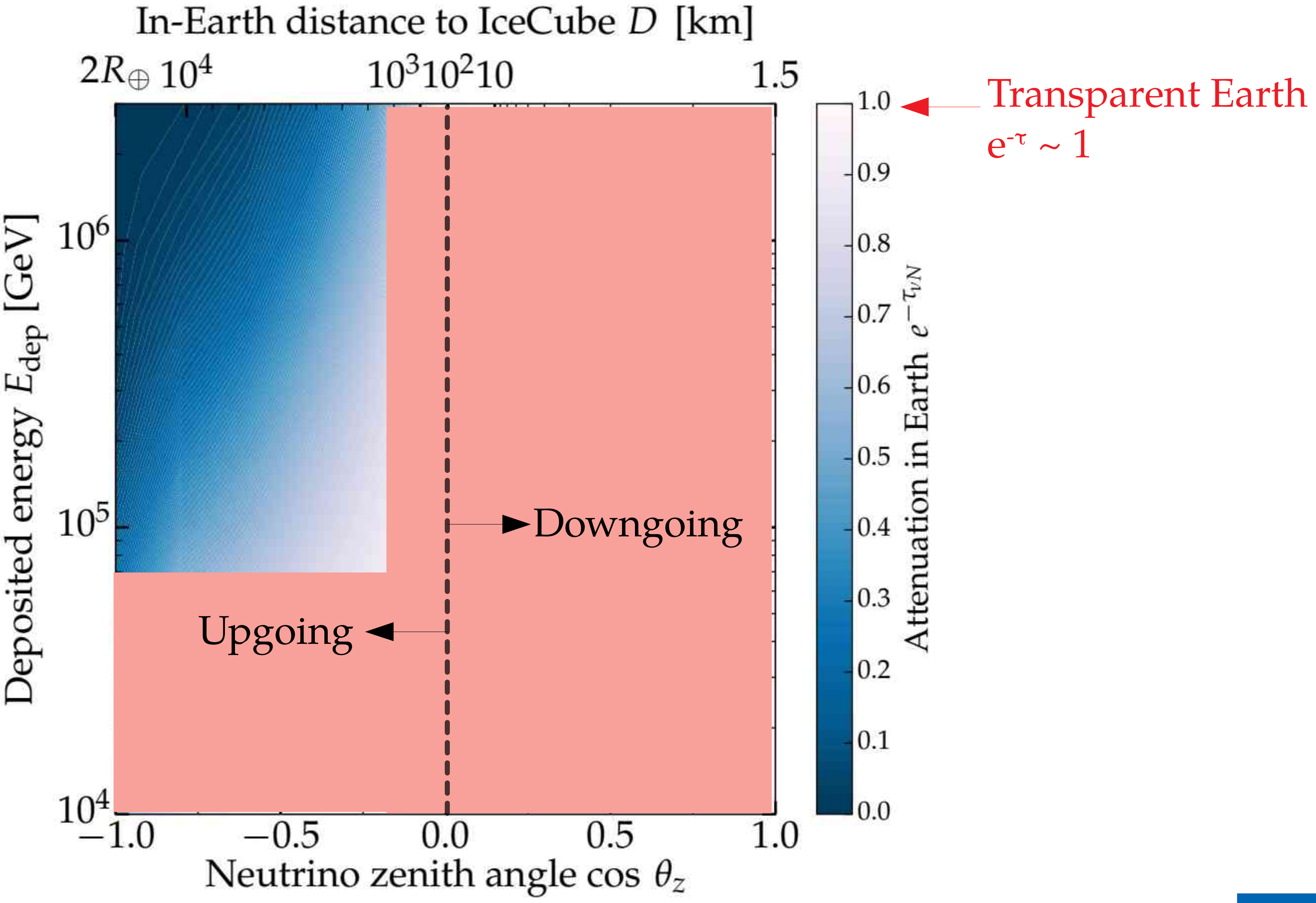


In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4
10^3 10^2 10
1.5
Deposited energy E_{dep} [GeV]
10^6
10^5
10^4
−1.0
−0.5
0.0
0.5
1.0
Neutrino zenith angle cos θ_z
Attenuation in Earth $e^{-\tau_{\nu N}}$
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0

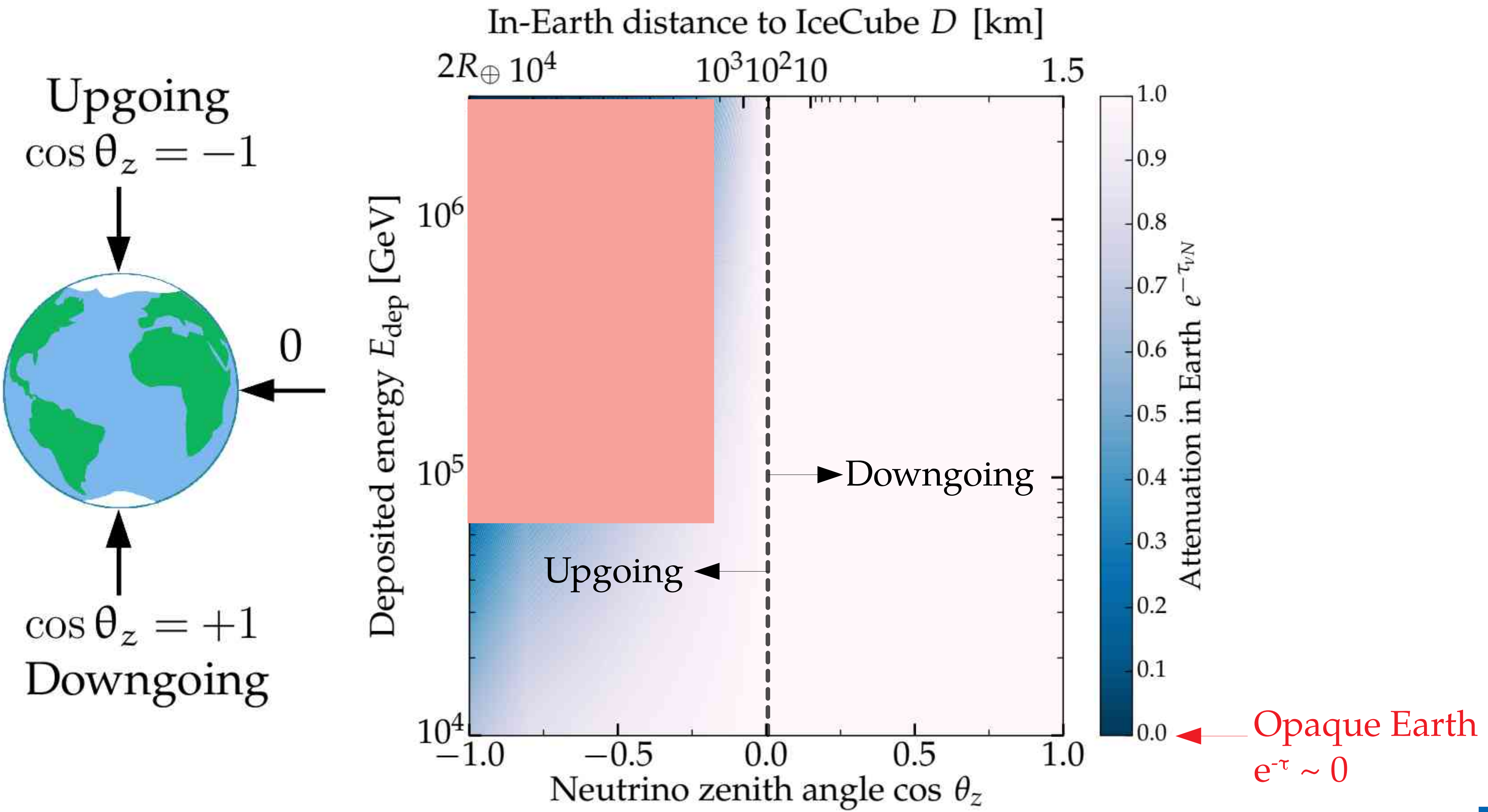

Upgoing
cos θz = −1
0
cos θz = +1
Downgoing
In-Earth distance to IceCube D [km]
2R⊕ 10^4
10^3 10^2 10
1.5
Deposited energy E_dep [GeV]
10^6
10^5
10^4
Downgoing
Upgoing
−1.0
−0.5
0.0
0.5
1.0
Neutrino zenith angle cos θz
Attenuation in Earth e^{−τνN}
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0



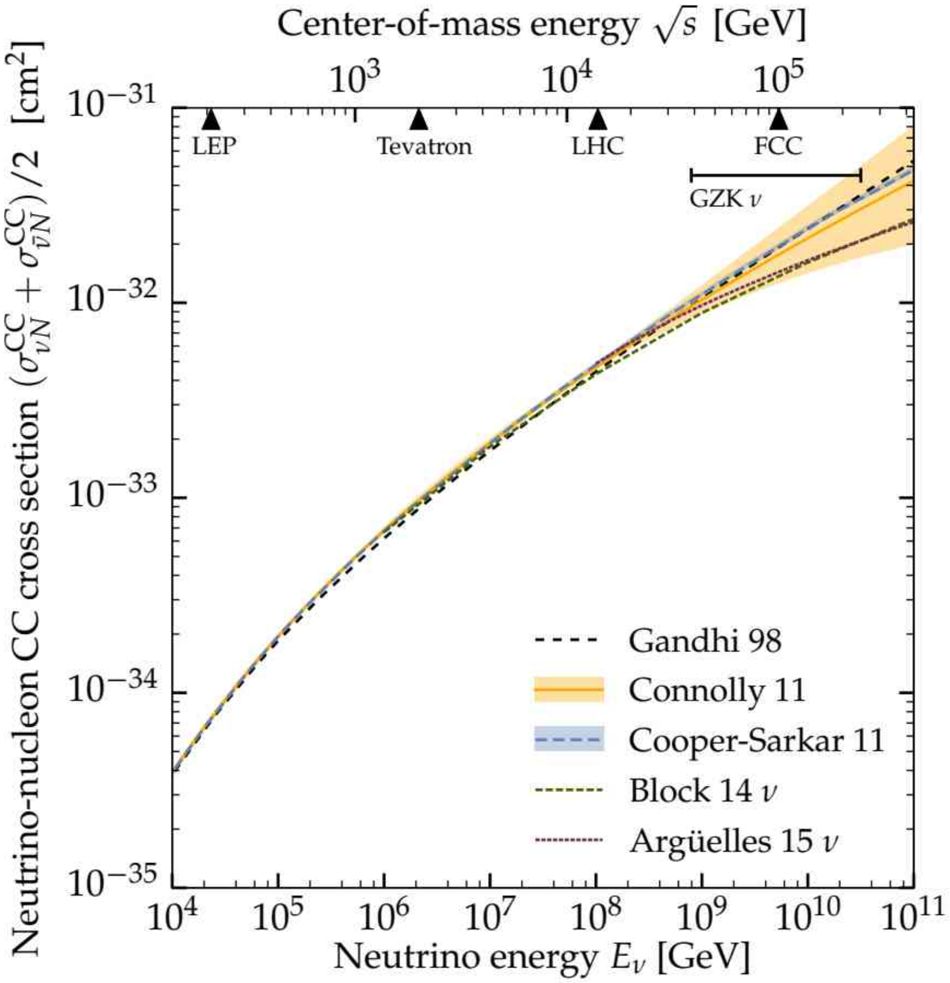
Upgoing
$\cos\theta_z = -1$
0
$\cos\theta_z = +1$
Downgoing



In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4 10^3 10^2 10 1.5
Deposited energy E_{dep} [GeV]
10^6
10^5
10^4
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
Transparent Earth
$e^{-\tau} \sim 1$

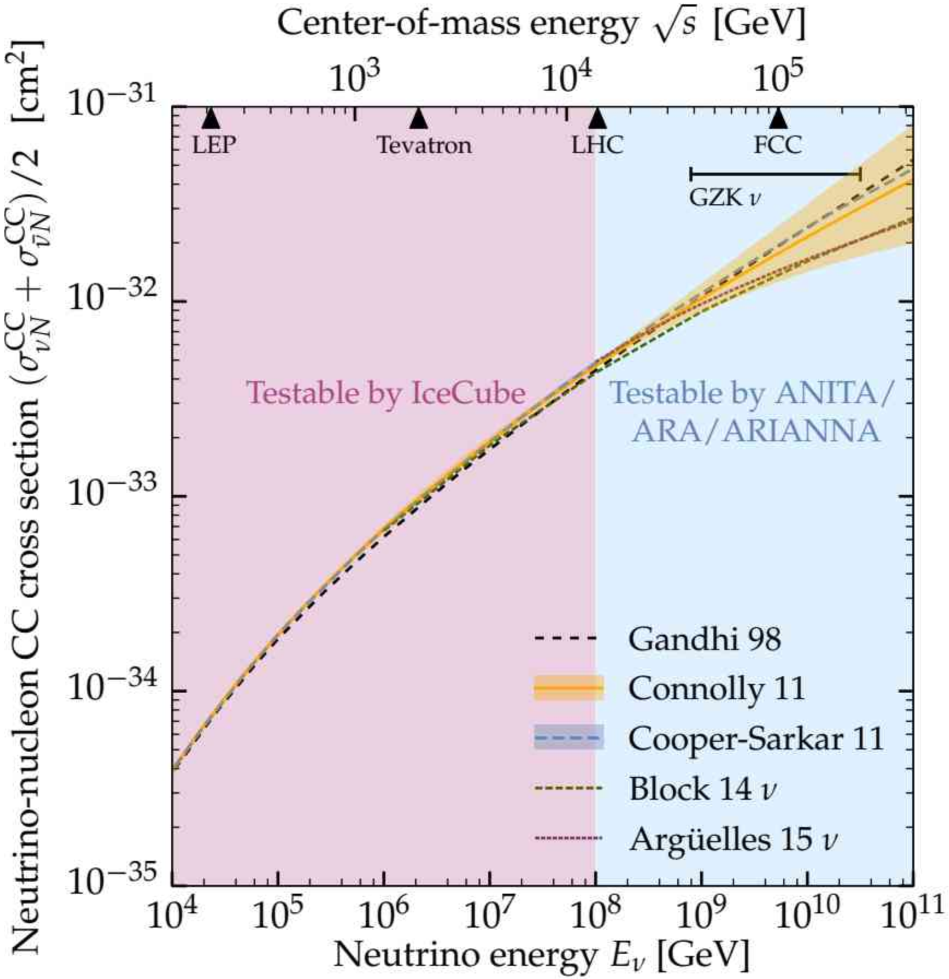

Upgoing
$\cos\theta_z = -1$
0
$\cos\theta_z = +1$
Downgoing
In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4 10^3 10^2 10 1.5
Deposited energy E_{dep} [GeV]
10^6
10^5
10^4
Downgoing
Upgoing
−1.0 −0.5 0.0 0.5 1.0
Neutrino zenith angle $\cos\theta_z$
Attenuation in Earth $e^{-\tau_{\nu N}}$
1.0 0.9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

What can we measure *now* and later?



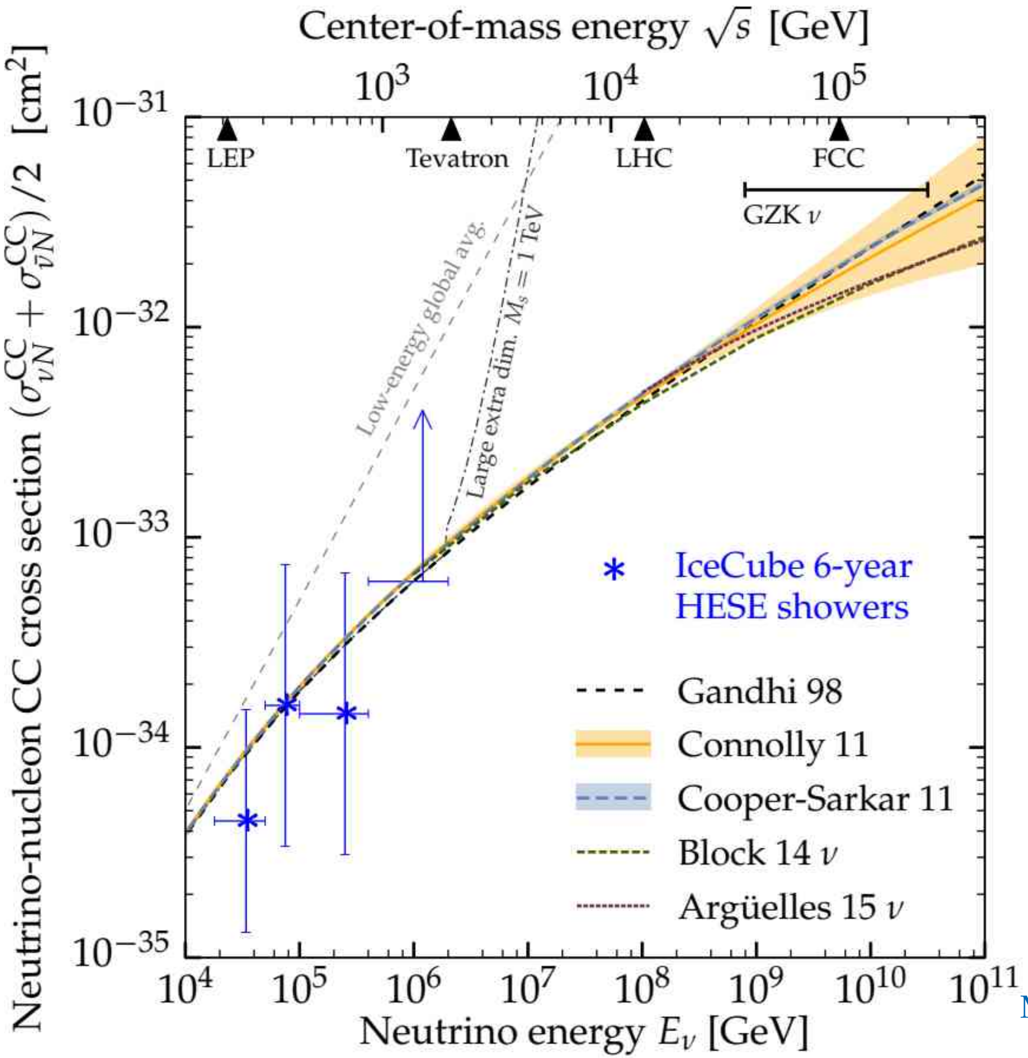
MB & A. Connolly 2017

What can we measure *now* and later?



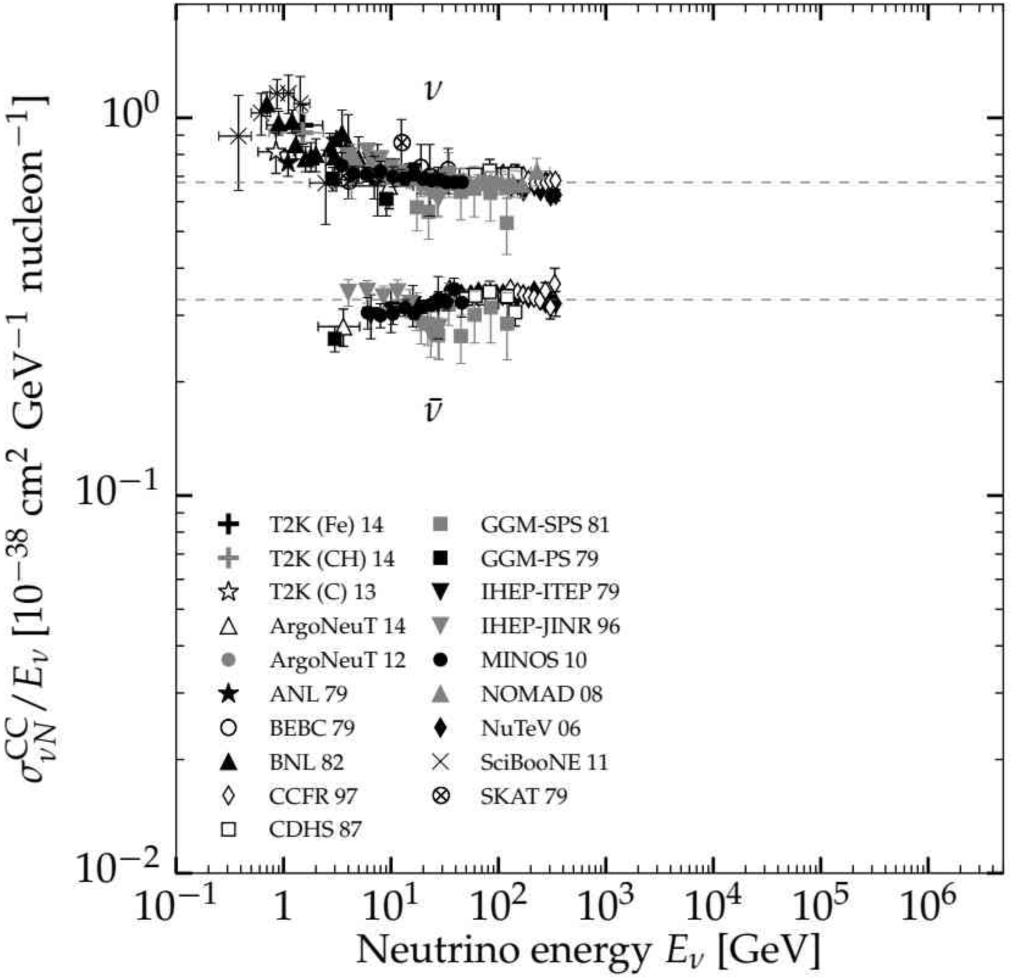
MB & A. Connolly 2017

Our result



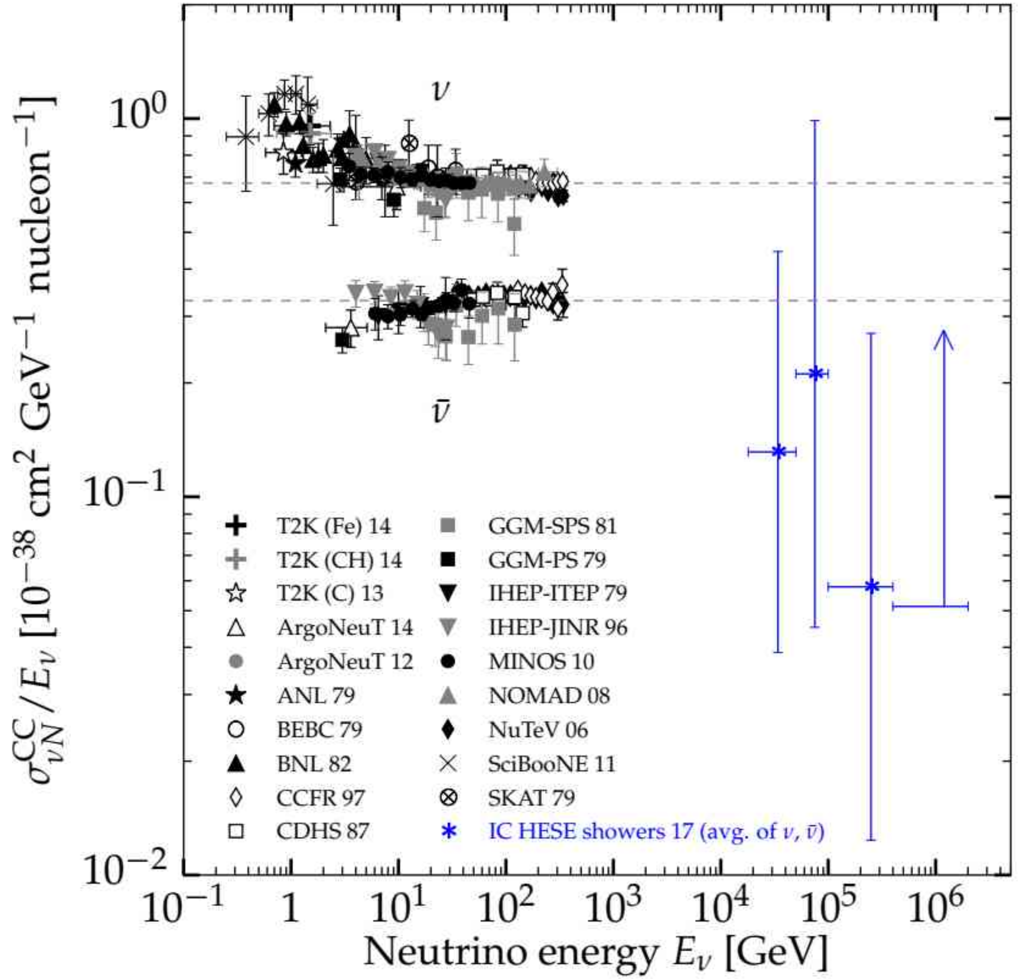
MB & A. Connolly 2017

Extending cross section measurements



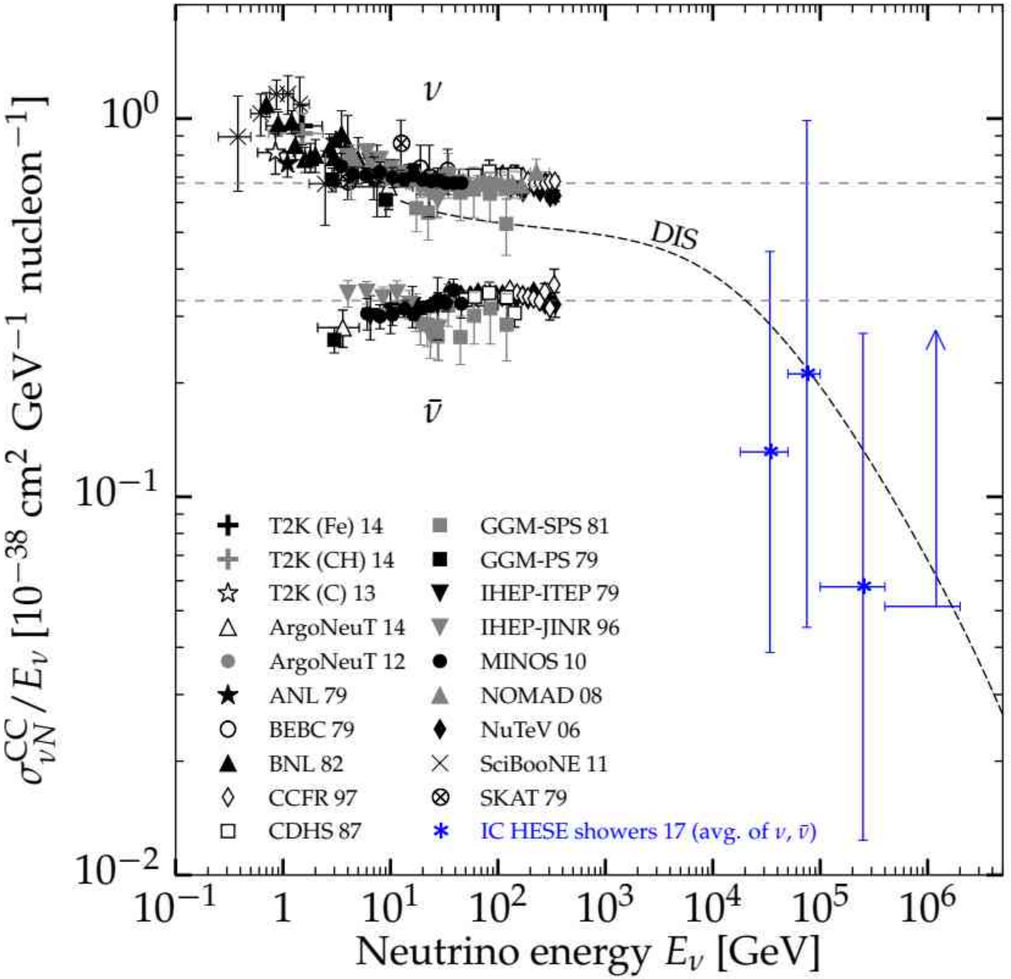
MB & A. Connolly 2017

Extending cross section measurements



MB & A. Connolly 2017

Extending cross section measurements



MB & A. Connolly 2017

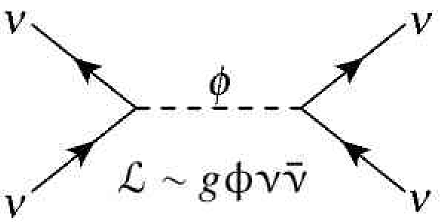
Cross section at GRAND

- We are only sensitive to neutrinos ±5° from the horizon
- So we do not have much range to compare upgoing *vs.* downgoing
- A more complete study is needed
- Worth thinking about: getting more downgoing *atmospheric* events

Spectral distortions

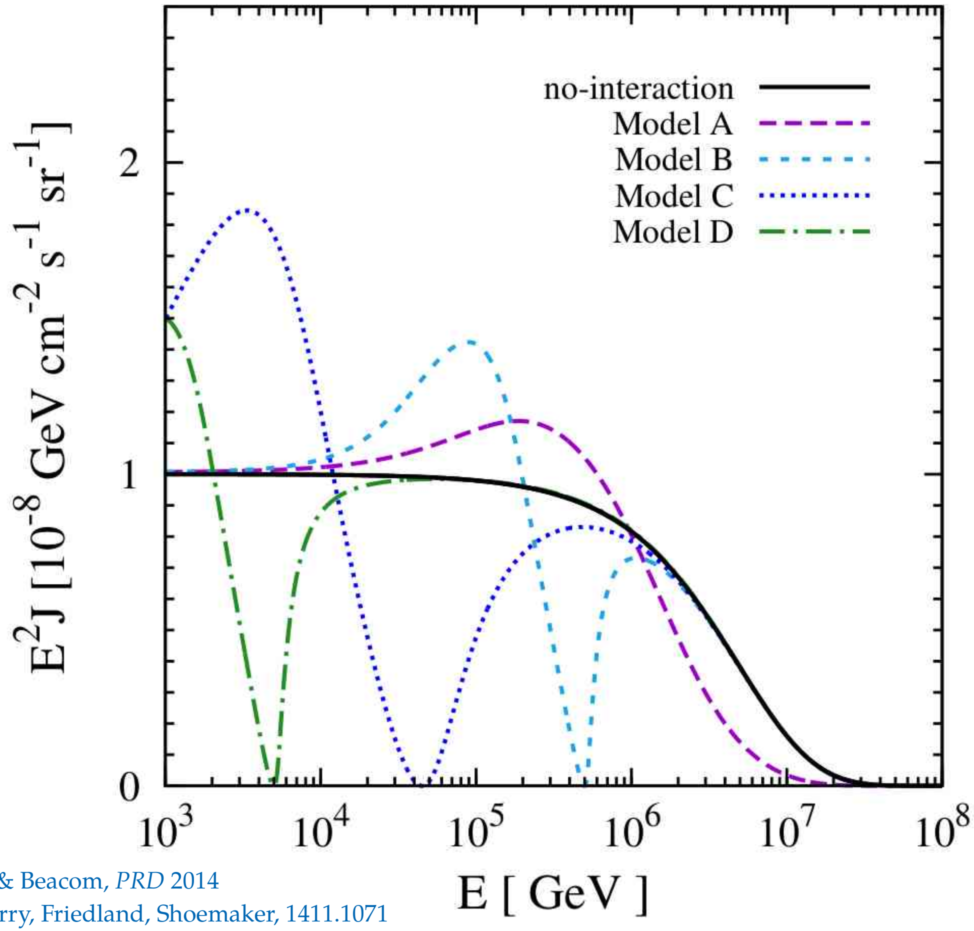
New physics in the spectral shape: $\nu\nu$ interactions

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



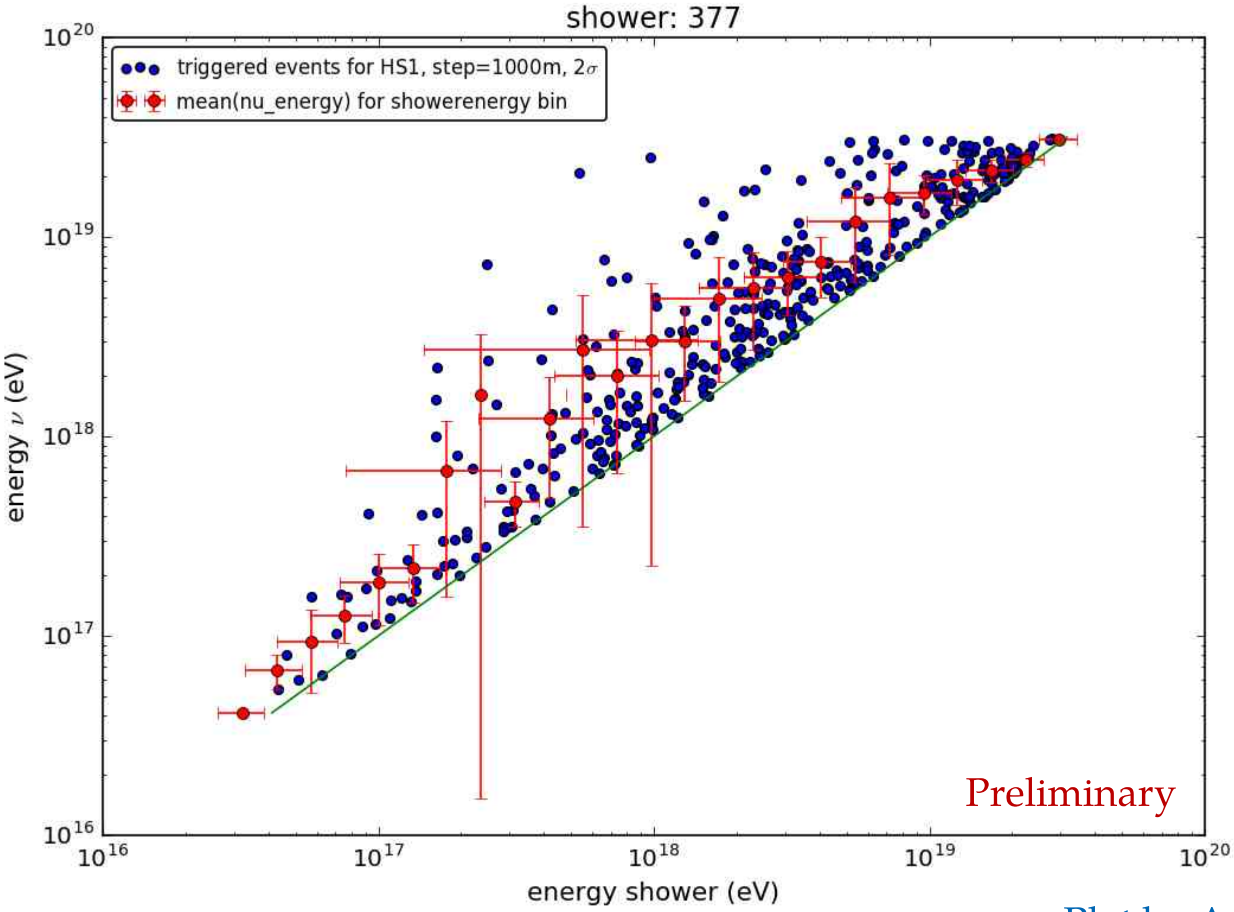
Cross section: $\sigma = \frac{g^4}{4\pi} \frac{s}{(s - M^2)^2 + M^2\Gamma^2}$

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



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

Neutrino energy resolution at GRAND

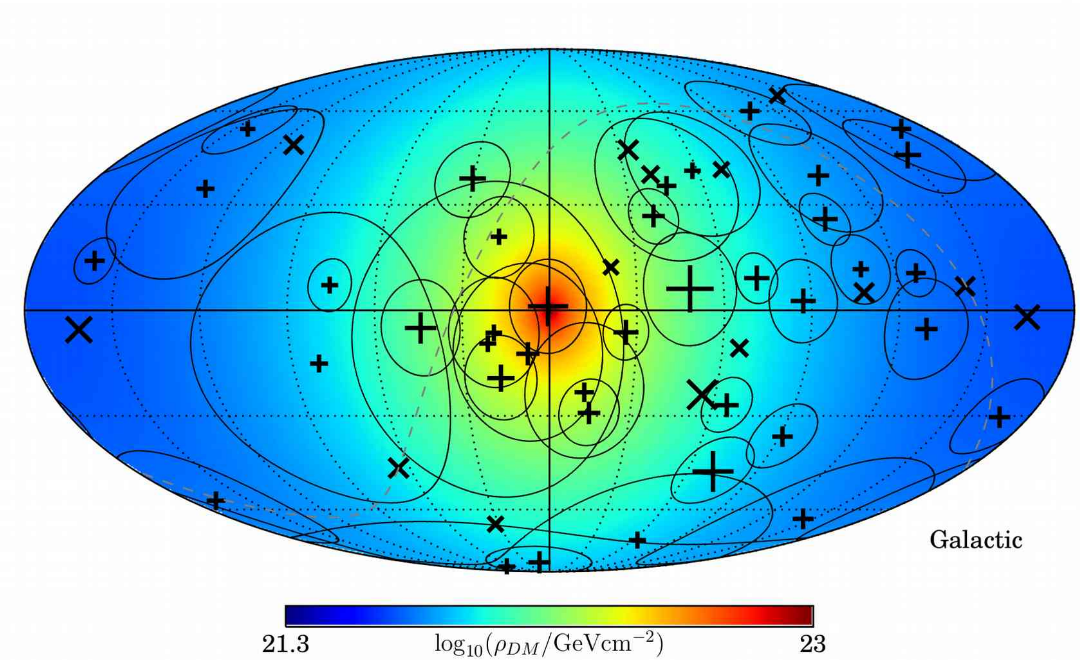


Plot by Anne Zilles

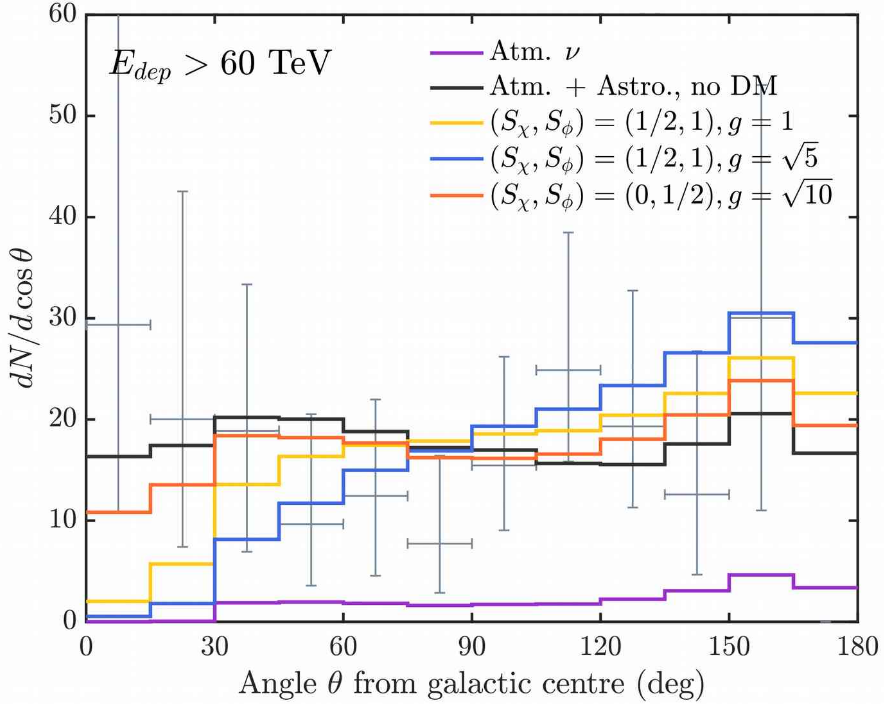
Angular distortions

New physics in the angular distribution: ν-DM interactions

Interaction between astrophysical neutrinos and the Galactic dark matter profile –



Argüelles *et al.*, *PRL* 2017

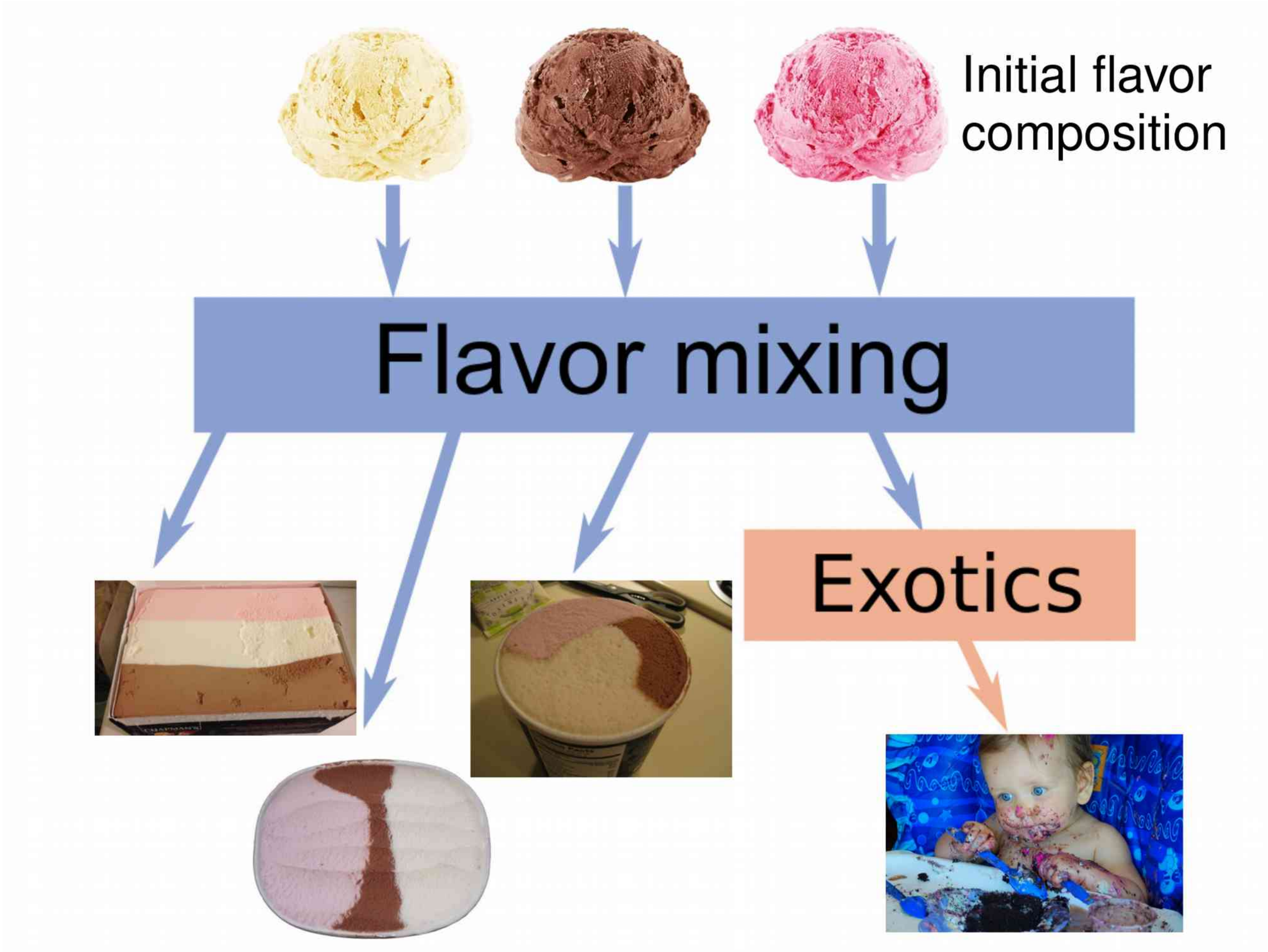


Expected: Fewer neutrinos coming from the Galactic Center

Observed: Isotropy

Flavor

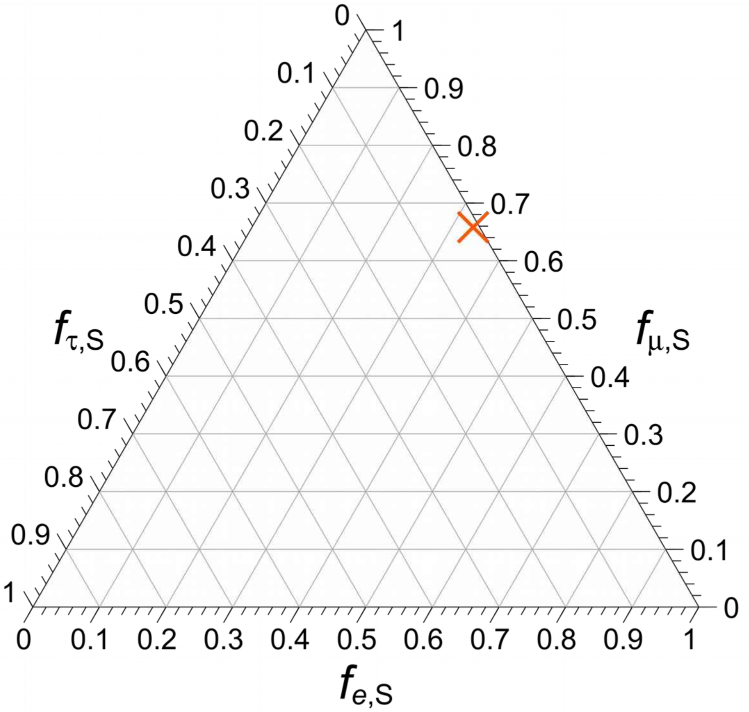
New physics in the flavor composition



Flavor – there and here

At the sources

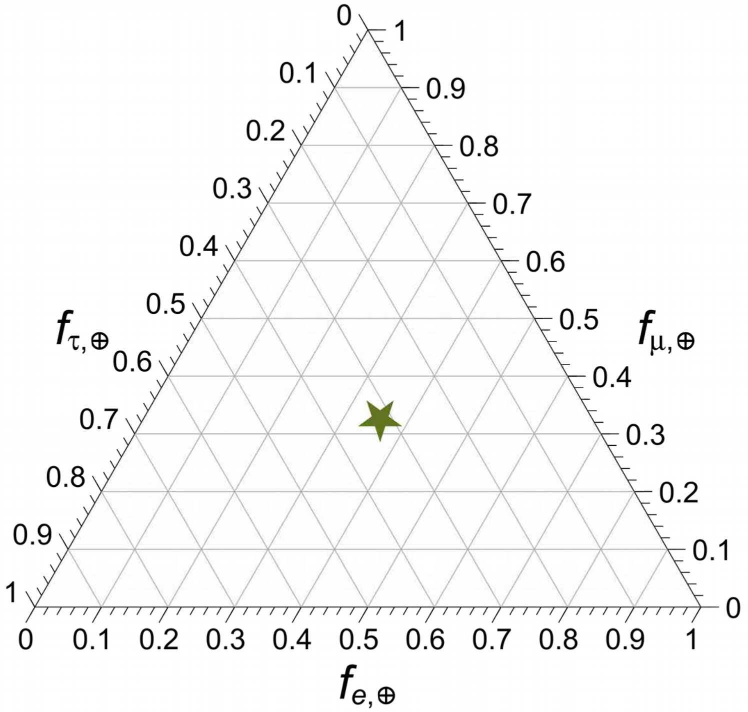
$(f_e{:}f_\mu{:}f_\tau)_S = (1/3 : 2/3 : 0)_S$



Neutrino oscillations

At Earth

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



Flavor – there and here

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

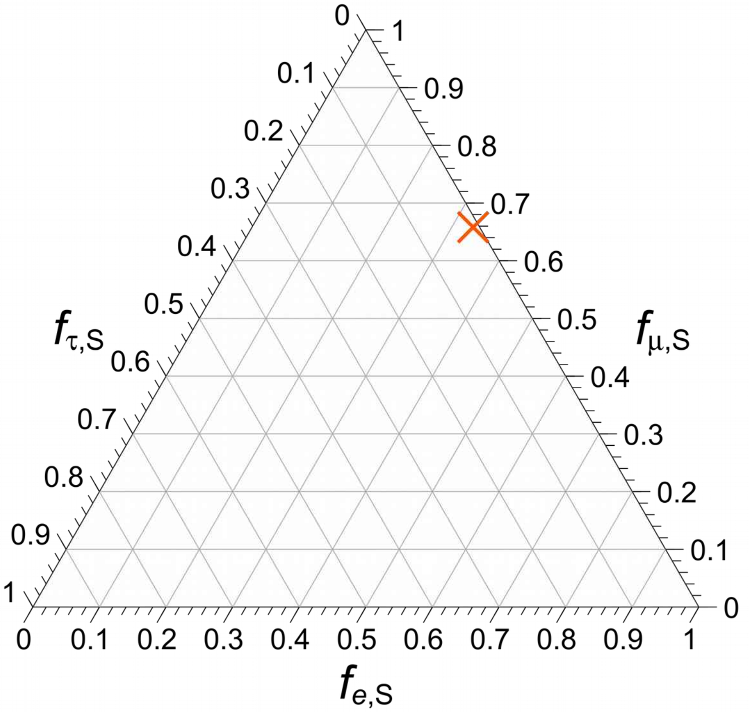
At the sources

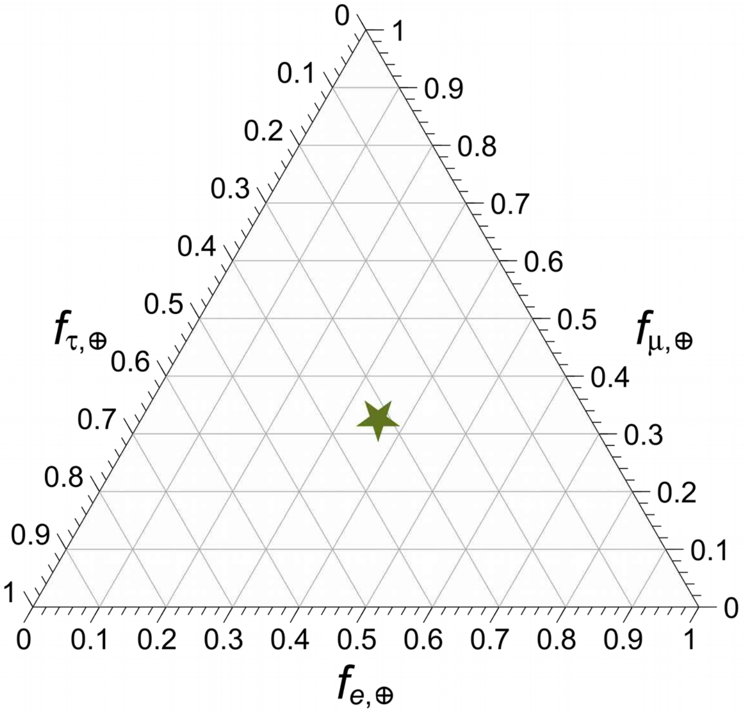
$(f_e{:}f_\mu{:}f_\tau)_S = (1/3 : 2/3 : 0)_S$

Neutrino oscillations

At Earth

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





Flavor – there and here

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

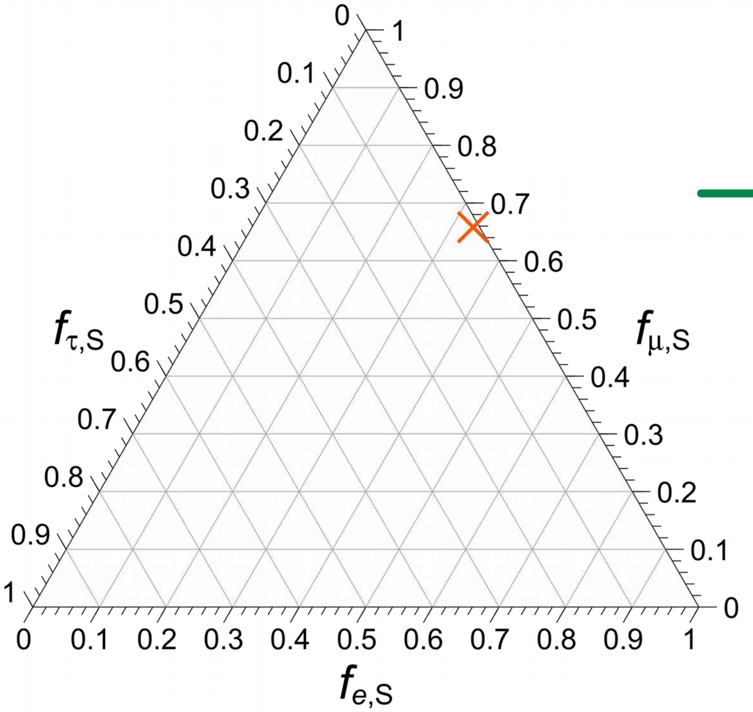
At the sources

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

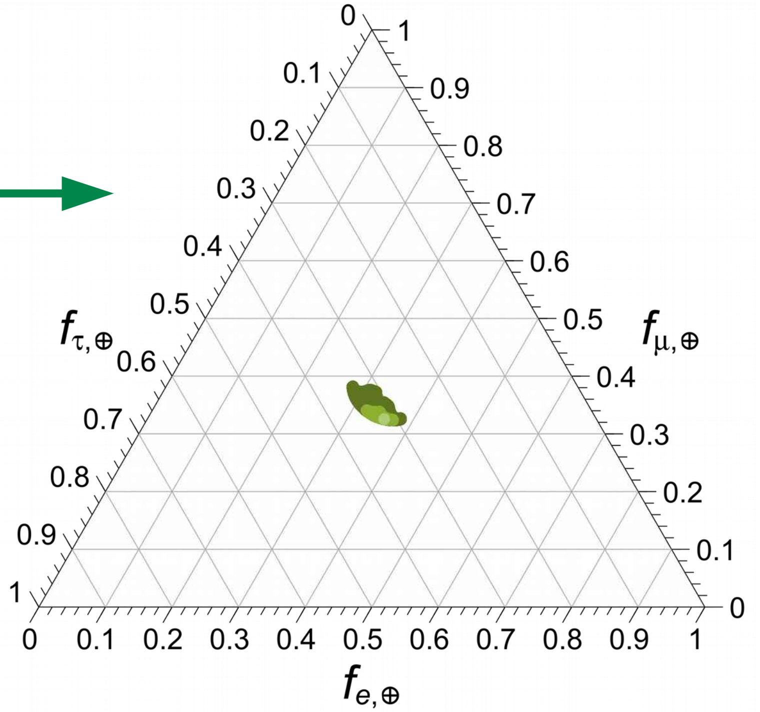
Neutrino oscillations →

At Earth

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



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

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

The ideal world

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

vs.

But we can thoroughly explore new physics

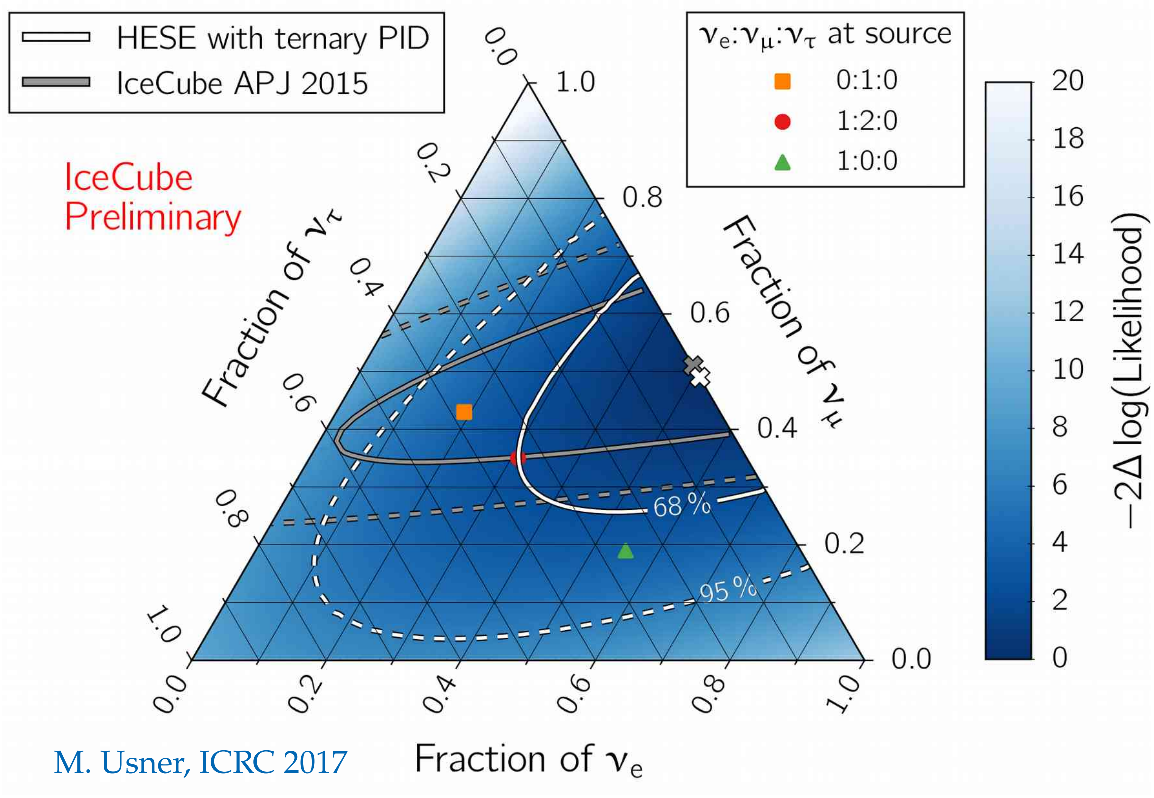
The <u>real</u> world

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 composition – From Earth to sources

Earth (measured)

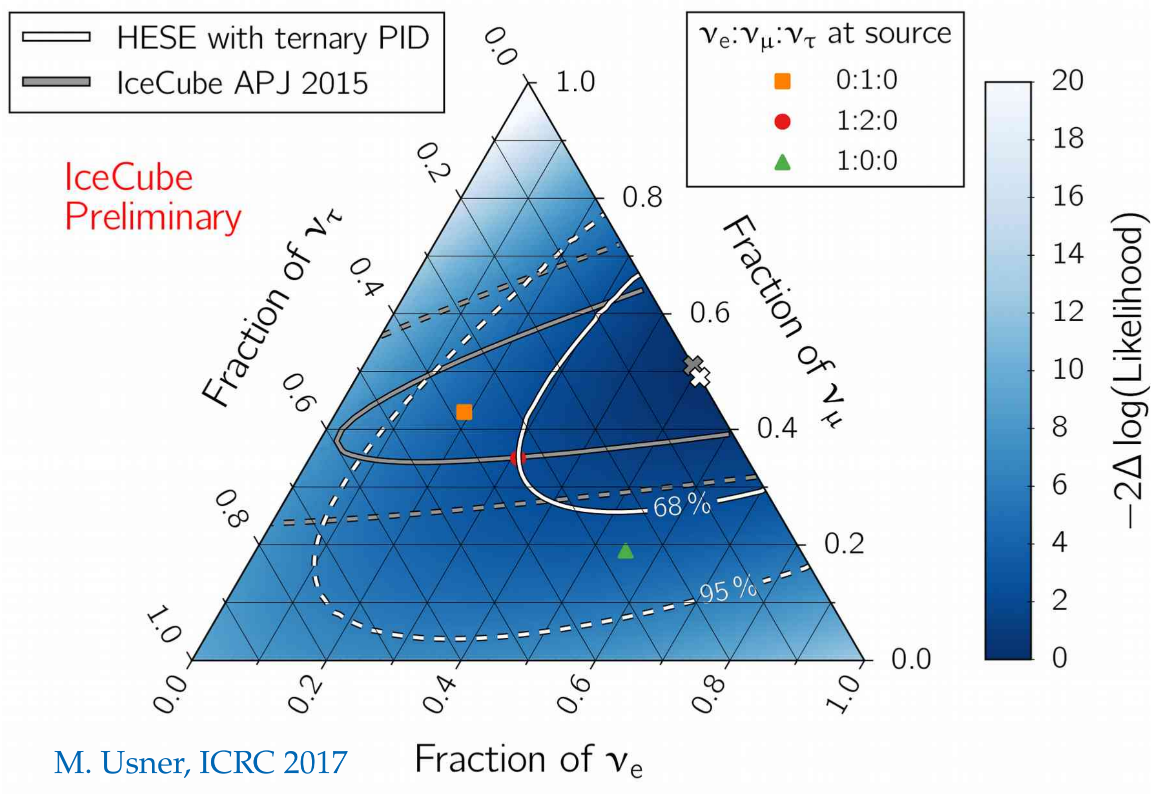
Sources (inferred)



M. Usner, ICRC 2017

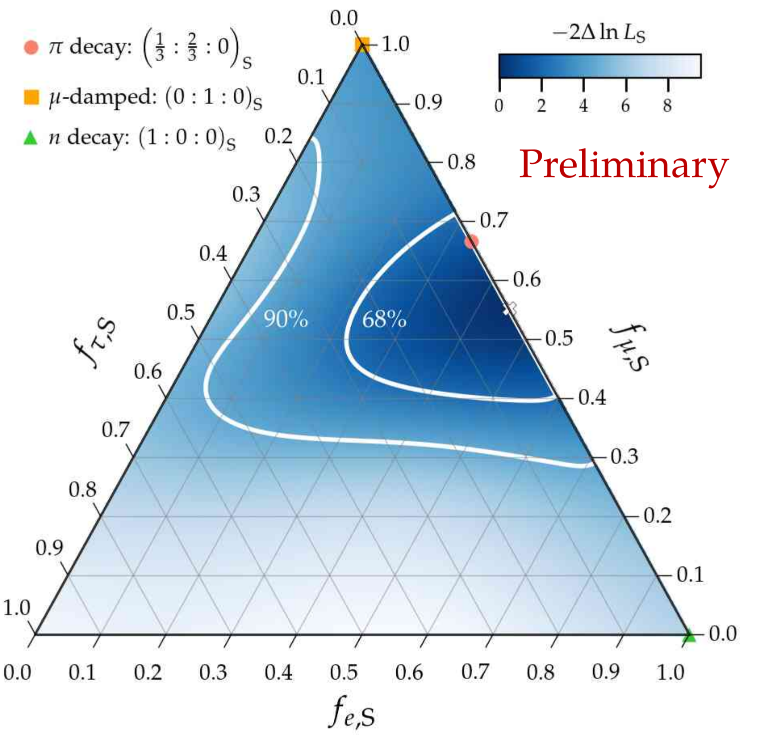
Flavor composition – From Earth to sources

Earth (measured)



M. Usner, ICRC 2017

Sources (inferred)



MB, M. Ahlers, S. Mu, *In preparation*

EeV flavor composition at GRAND

- GRAND is predominantly sensitive to ν_τ only

- So flavor composition studies are not possible unless…
  - A different UHE neutrino experiment measures all flavors
    Little work on the subject – for ARA, perhaps via angular distribution
    S.-H. Wang, P. Chen, J. Nam, M. Huang, 1302.1586

- GRAND measures the all-flavor neutrino interactions in the atmosphere

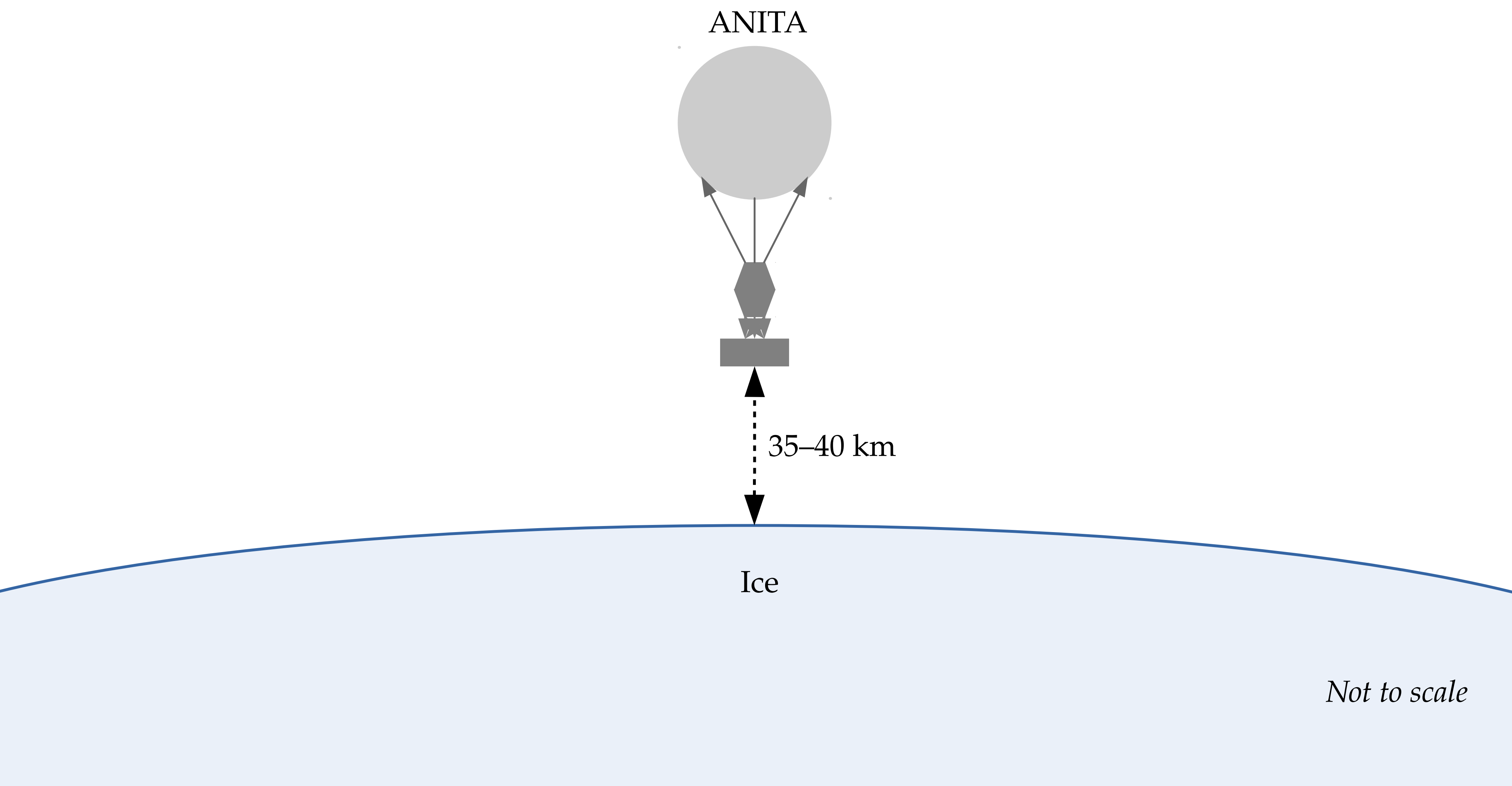
ANITA mystery events

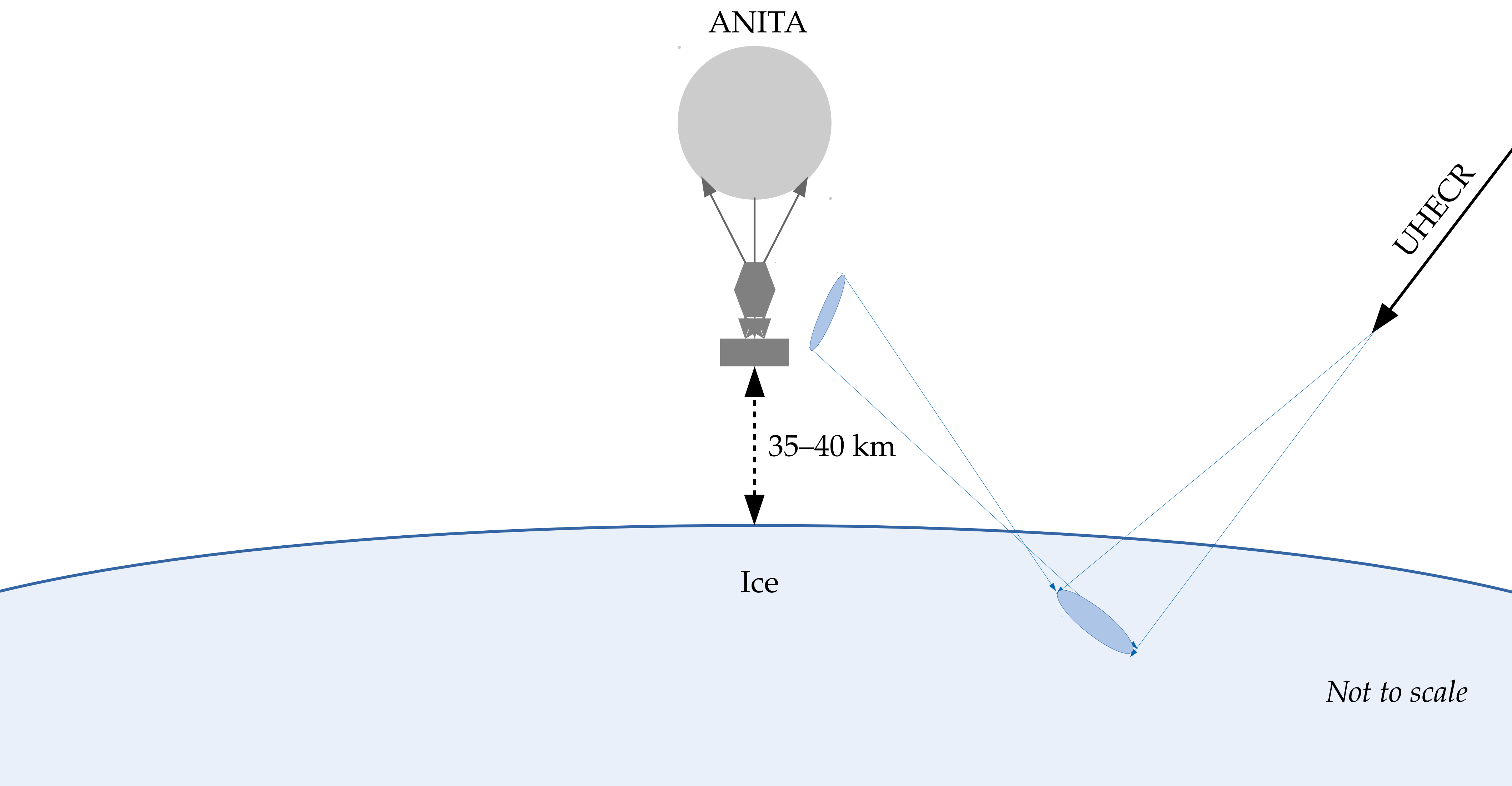
Mystery ANITA events – First UHE ν detected?

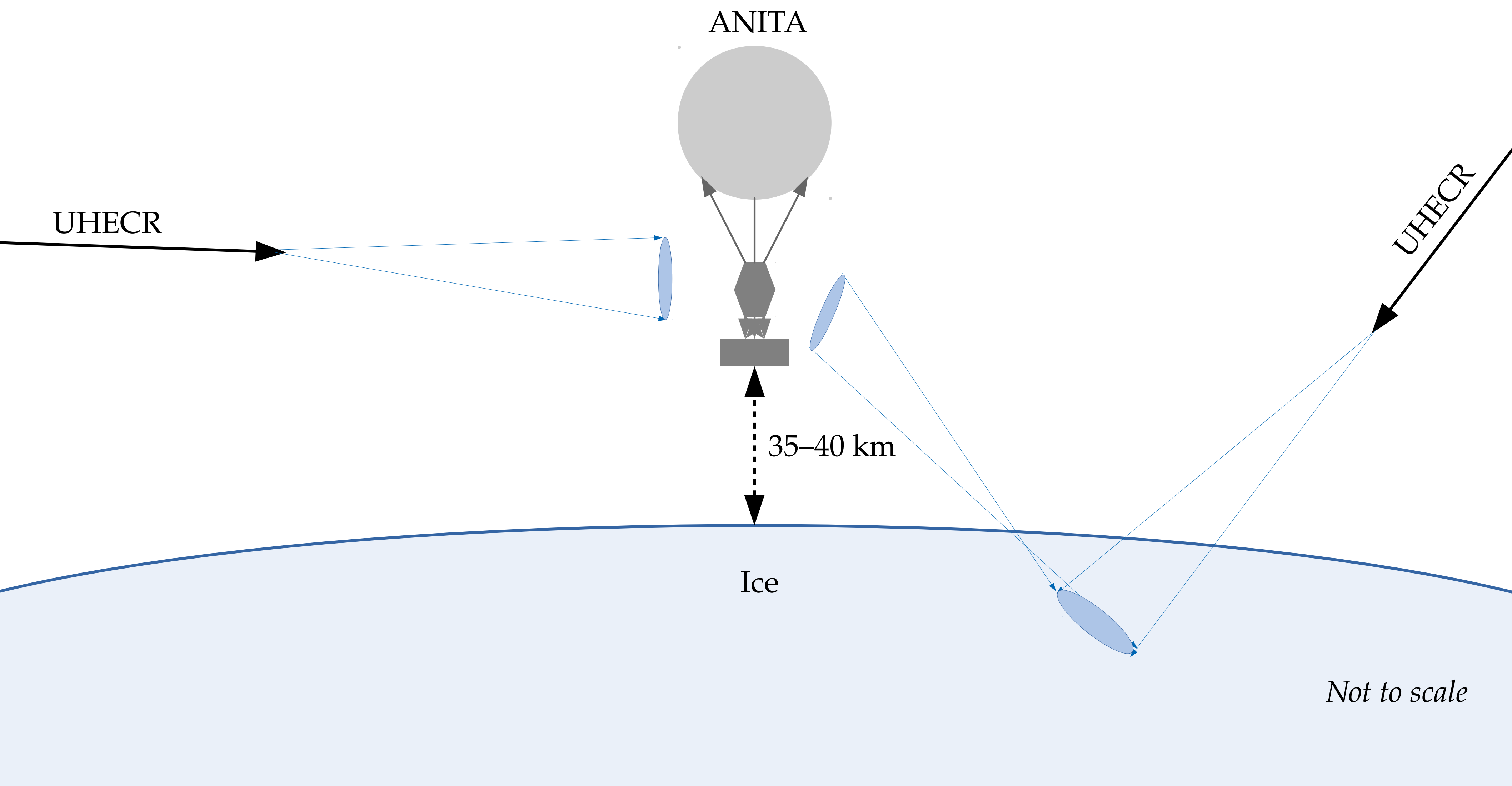
See Wed talk by Linda Cremonesi

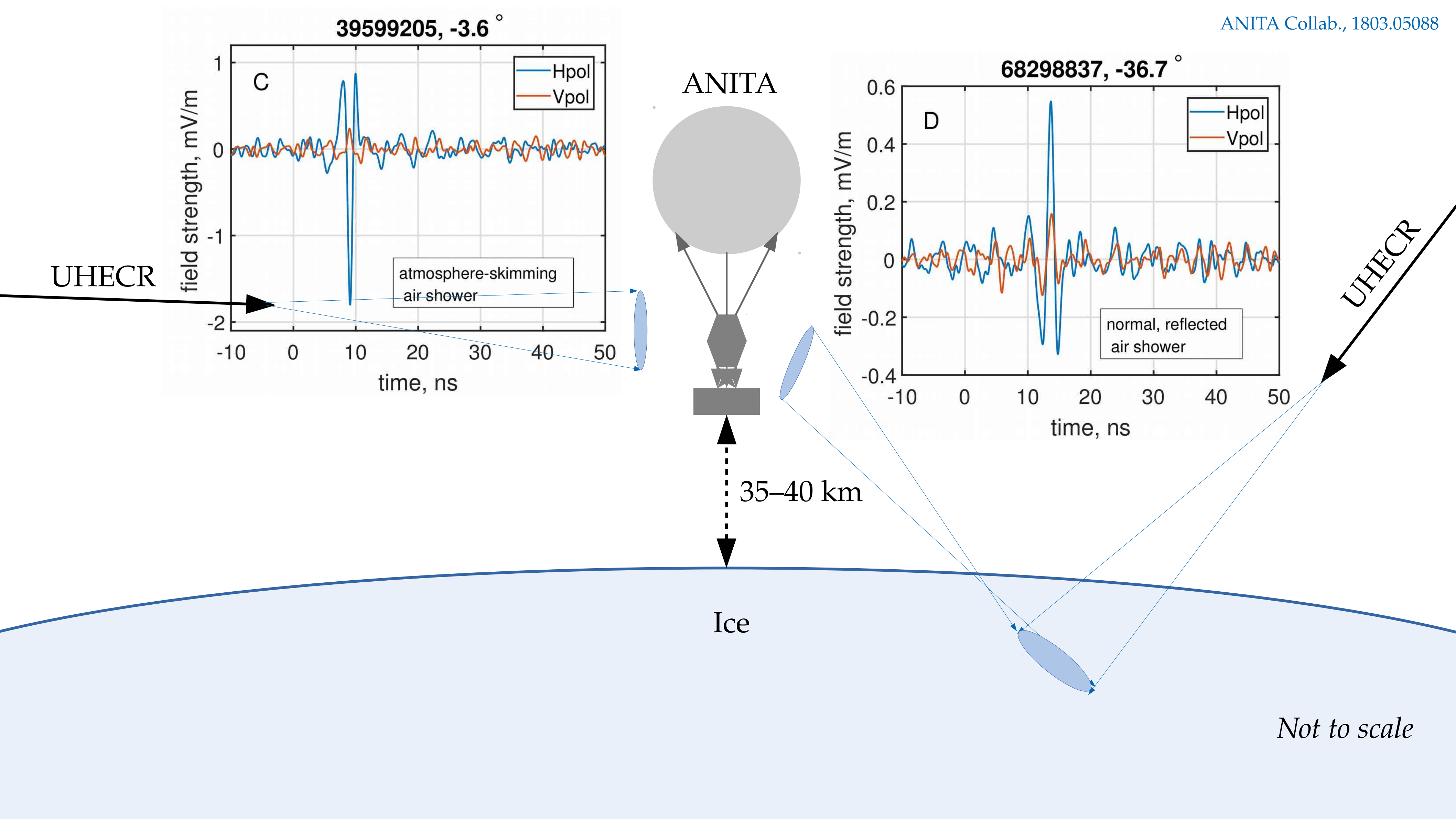
Photo by Spencer Klein

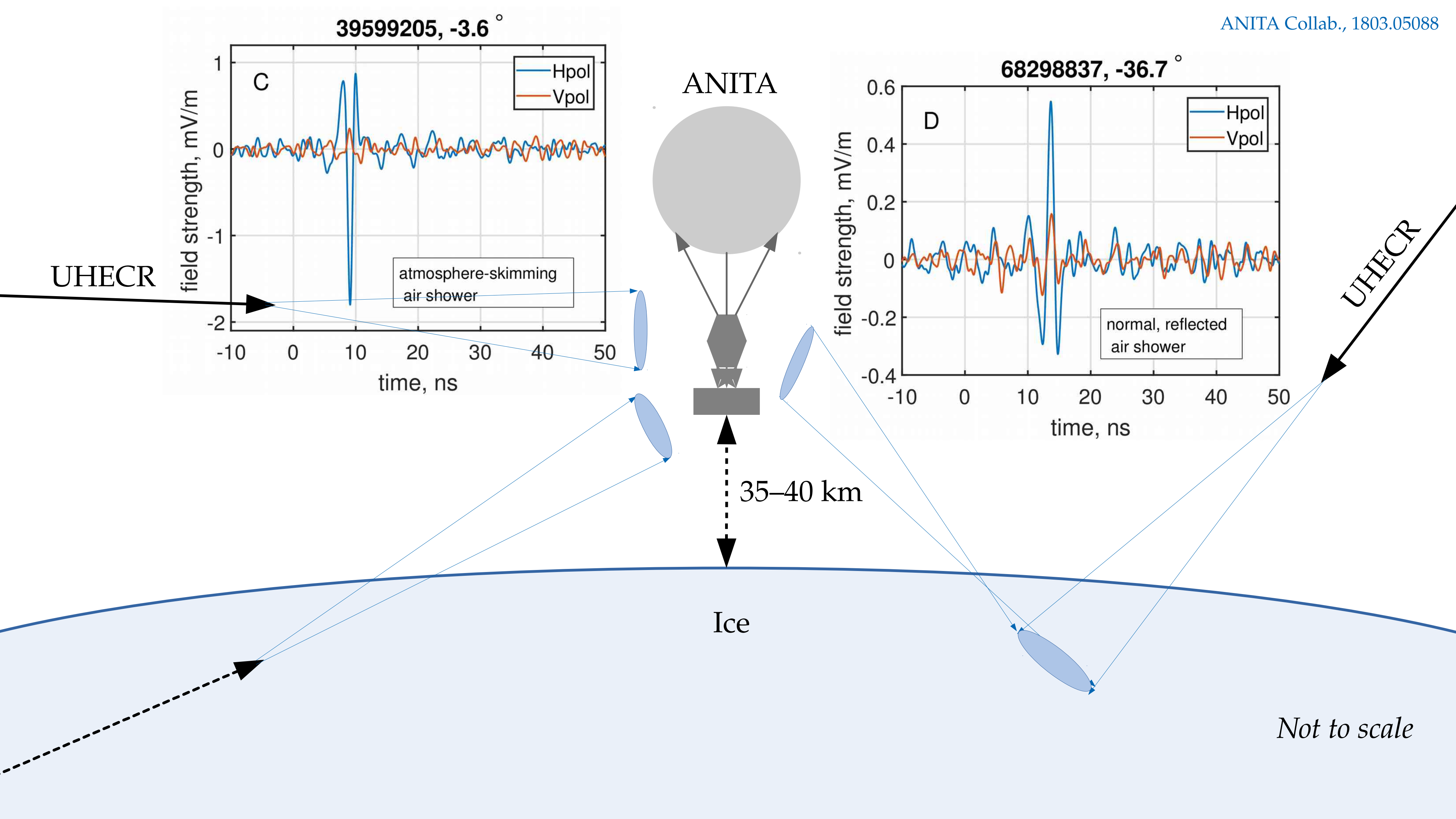
Photo by Brian Hill/U. Hawaii-Manoa


ANITA
35–40 km
Ice
Not to scale

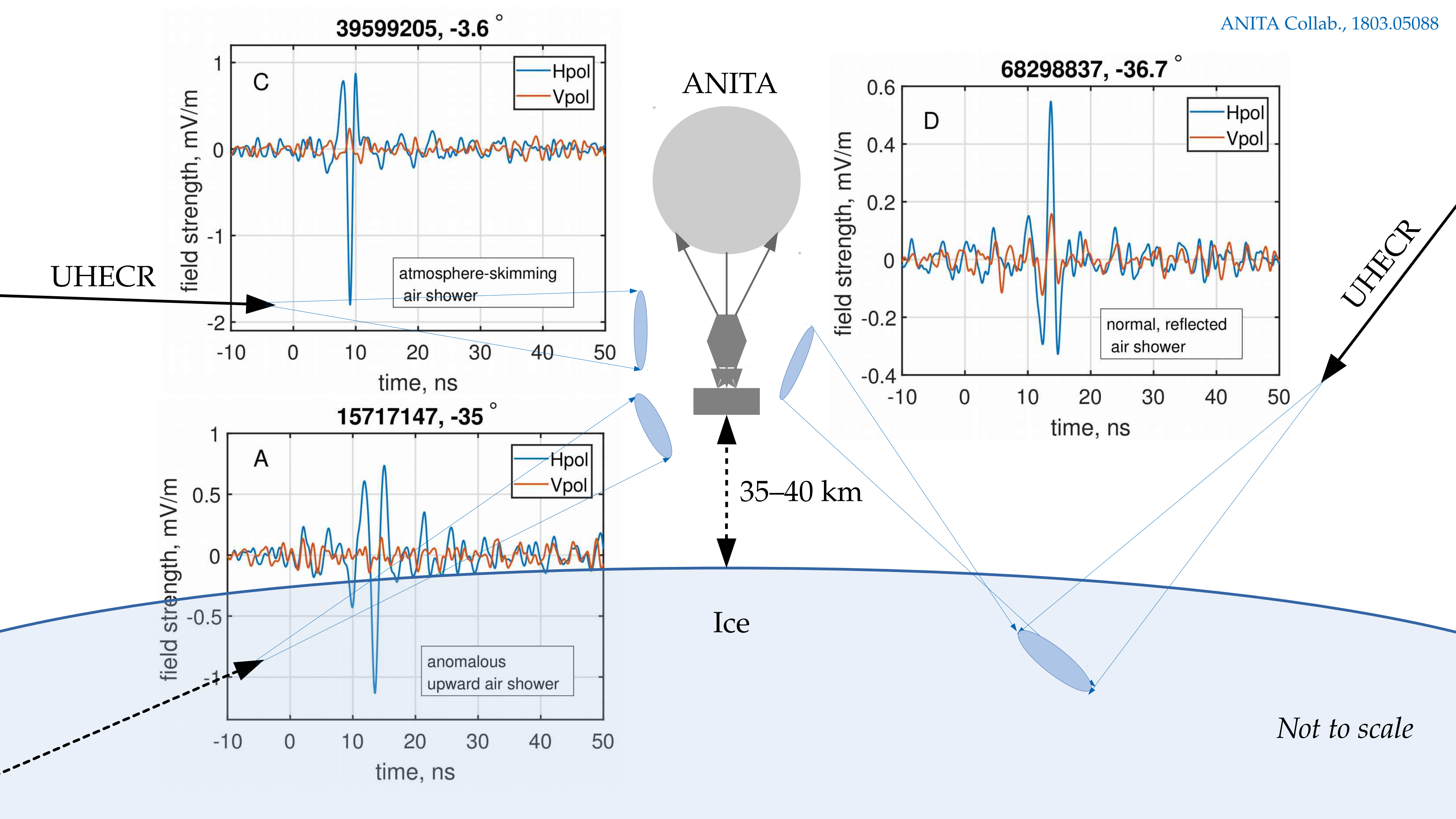

ANITA
UHECR
35–40 km
Ice
Not to scale

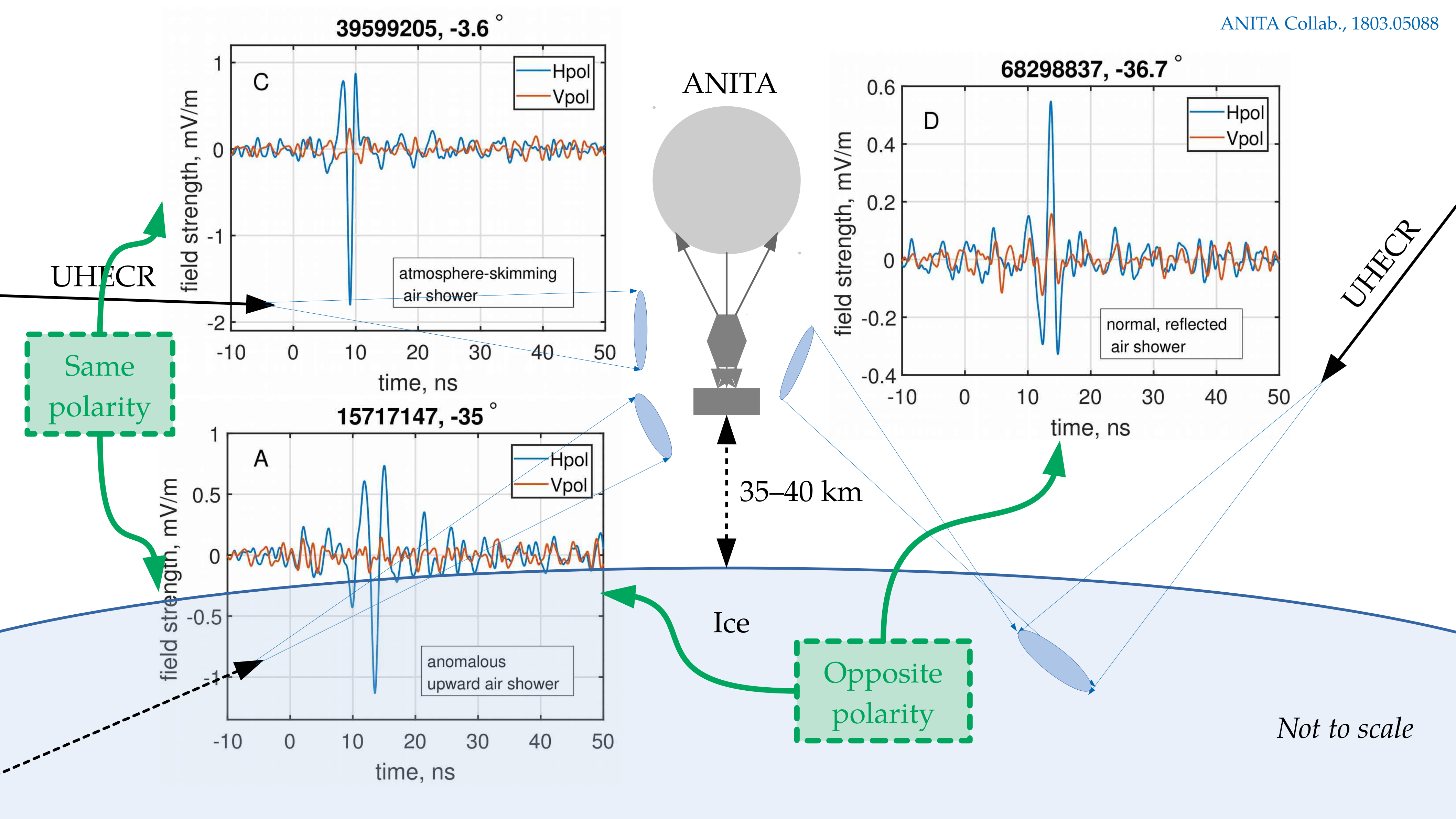

ANITA
UHECR
UHECR
35–40 km
Ice
Not to scale


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

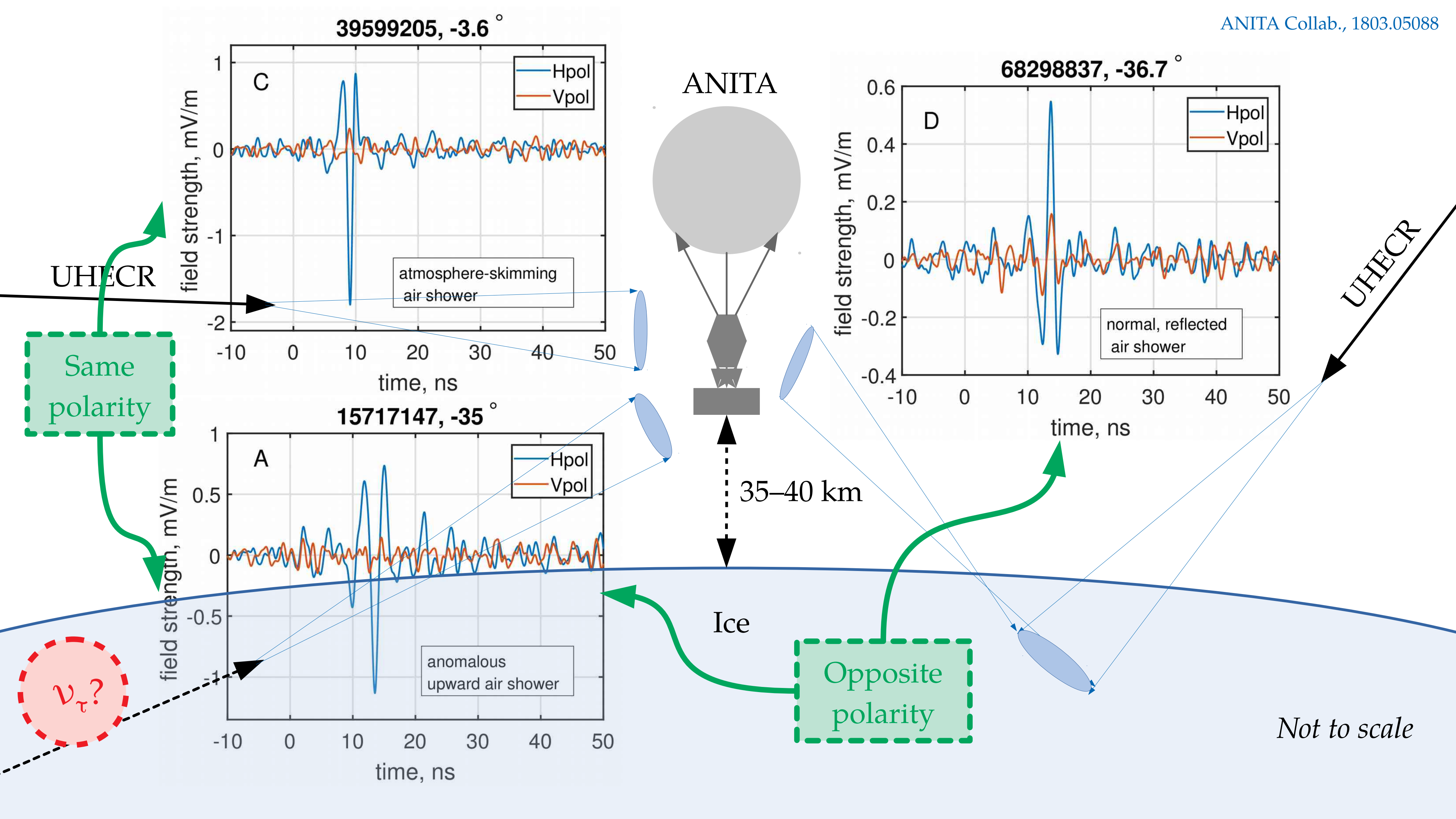


ANITA Collab., 1803.05088
39599205, -3.6 °
C
Hpol
Vpol
field strength, mV/m
time, ns
atmosphere-skimming
air shower
UHECR
ANITA
68298837, -36.7 °
D
normal, reflected
air shower
35–40 km
Ice
Not to scale


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



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



ANITA Collab., 1803.05088
39599205, -3.6 °
C
Hpol
Vpol
atmosphere-skimming air shower
field strength, mV/m
time, ns
UHECR
Same polarity
ANITA
68298837, -36.7 °
D
normal, reflected air shower
UHECR
15717147, -35 °
A
anomalous upward air shower
35–40 km
Ice
Opposite polarity
ν_τ?
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

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 $e^{-18} = 10^{-8}$

Problems with diffuse-flux interp.

- Flux needs to be 10^8 times larger
- No events seen closer to horizon

ANITA Collab., *PRL* 2016 + 1803.05088

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 $e^{-18} = 10^{-8}$

Problems with diffuse-flux interp.

- Flux needs to be 10^8 times larger
- No events seen closer to horizon

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
  - Assessment: Viable, but exotic explanation

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 [illegible]cause transition radiation is a small effect

- Sterile neutrinos [Cherry & Shoemaker, 1802.01611; Huang, [illegible]4.05362]:
  - Sterile neutrinos propagate in Earth, then convert ν [illegible] $\to \nu_\tau$
  - Assessment: Model predicts more (unseen) even[illegible] at shallower angles

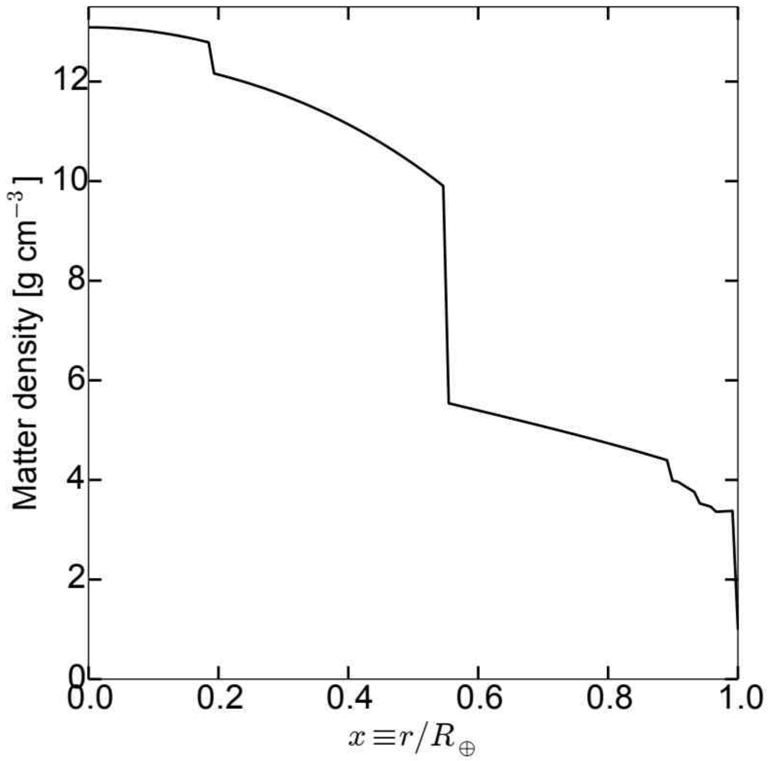
- Dark matter decay in Earth core [Anchordoqui *et al.*, 1803.11554]:
  - 480-PeV sterile right-handed ν_r in Earth core de[illegible]: $\nu_r \to$ Higgs + ν_τ
  - Assessment: Viable, but exotic explanation

Backup slides

A feel for the in-Earth attenuation

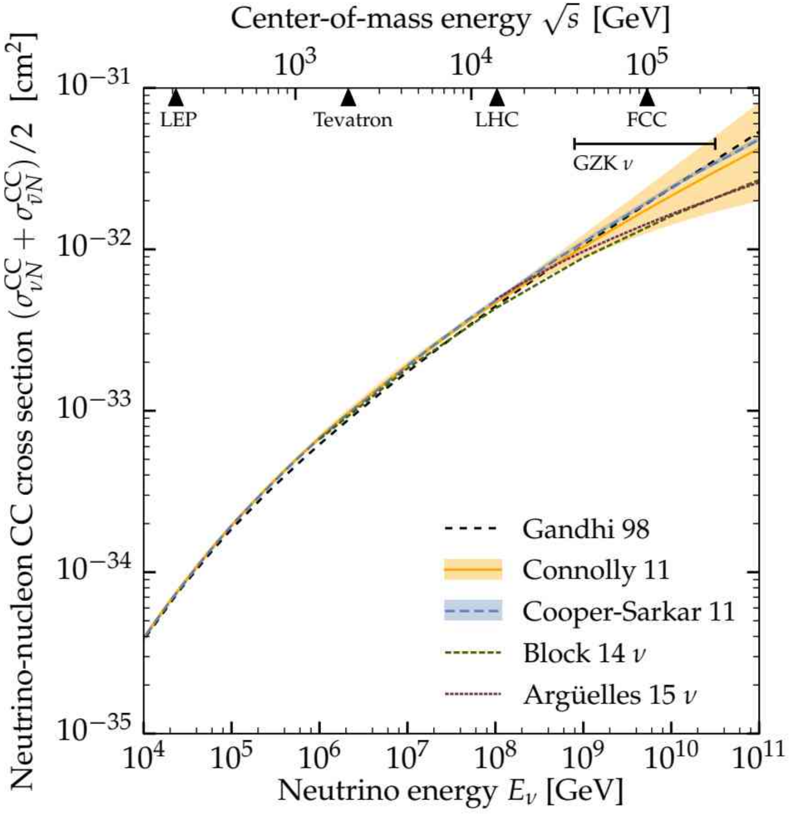
Earth matter density

(Preliminary Reference Earth Model)



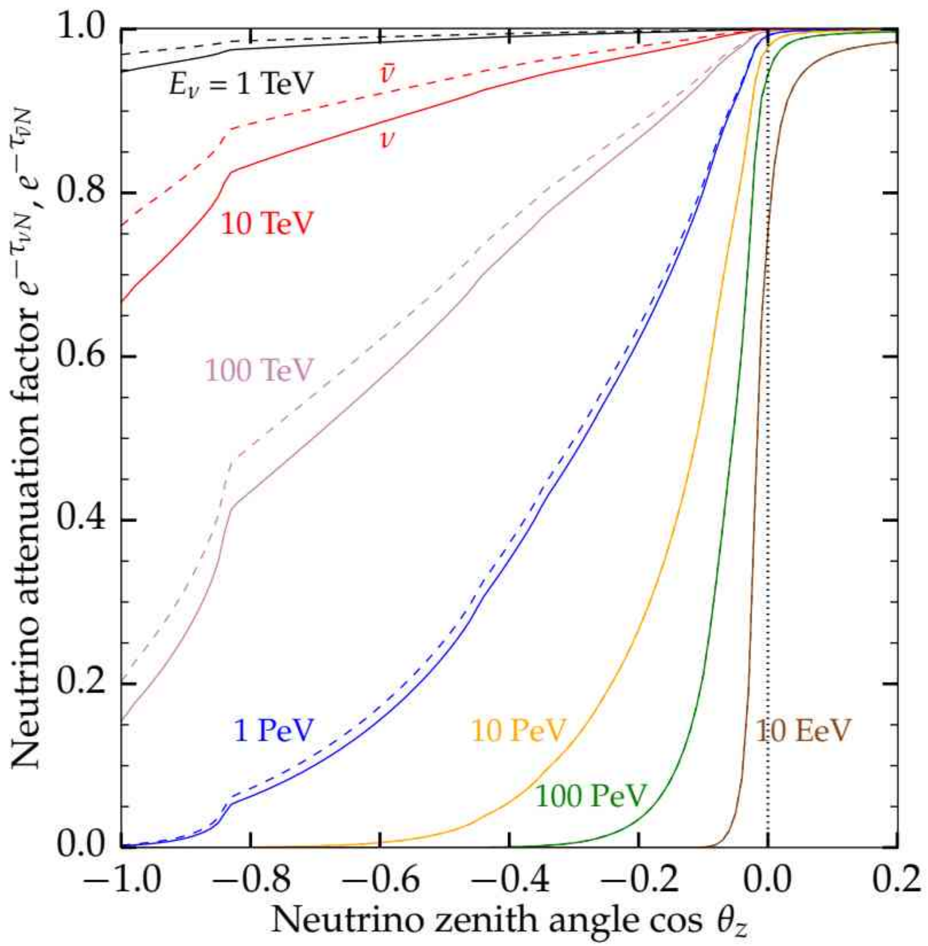
+

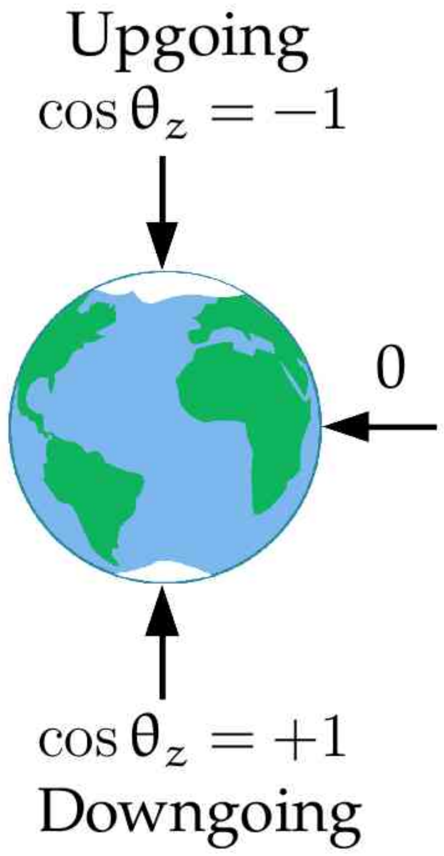
Neutrino-nucleon cross section



A feel for the in-Earth attenuation

=





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.*,

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