Physics Beyond the Standard Model with POEMMA

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Niels Bohr Institute, University of Copenhagen

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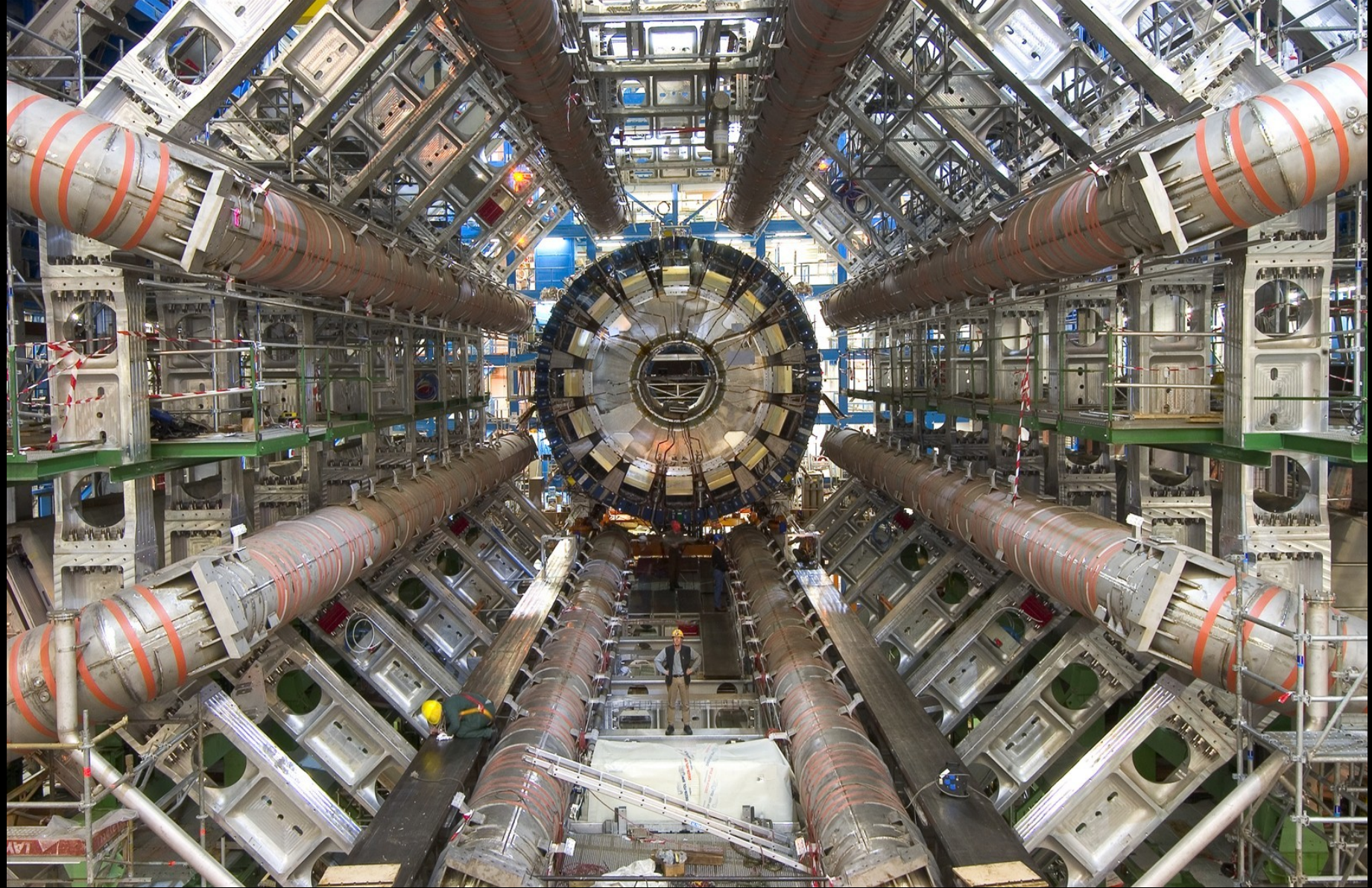
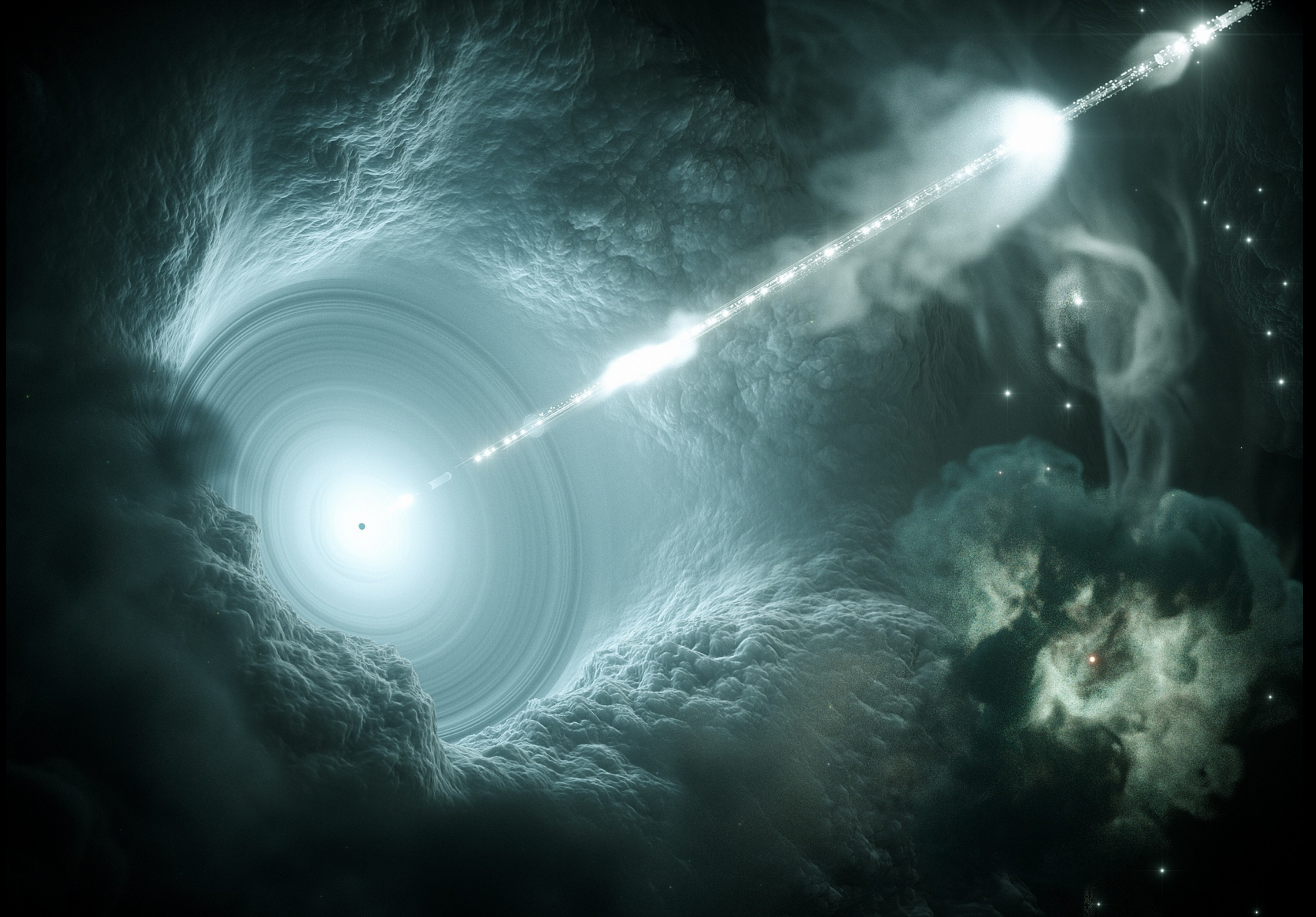
December 03, 2020



ATLAS



DESY

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   Astro: Probe the highest-energy non-thermal astrophysical sources

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4. Neutrinos have a unique quantum number: flavor
   Particle: Versatile probe of flavor-sensitive new physics
   Astro: Can reveal the neutrino production mechanism

Fundamental physics with UHE cosmic neutrinos

- Numerous new-physics effects grow as $\sim \kappa_n \cdot E^n \cdot L$
- So we can probe $\kappa_n \sim 4 \cdot 10^{-47}\ (E/\mathrm{PeV})^{-n}\ (L/\mathrm{Gpc})^{-1}\ \mathrm{PeV}^{1-n}$
- Improvement over limits using atmospheric ν: $\kappa_0 < 10^{-29}$ PeV, $\kappa_1 < 10^{-33}$
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  In spite of
  poor energy, angular, flavor reconstruction
  & astrophysical unknowns

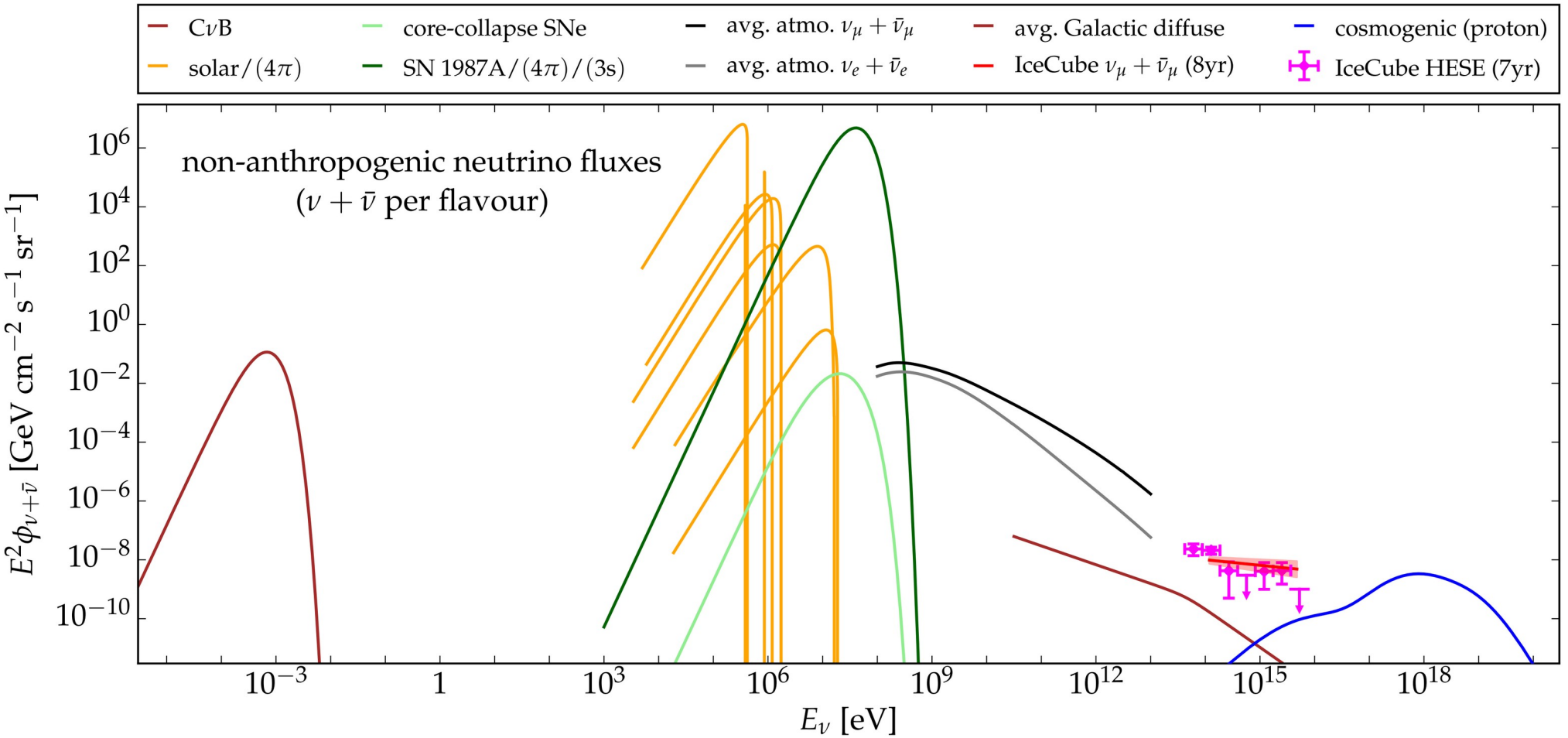
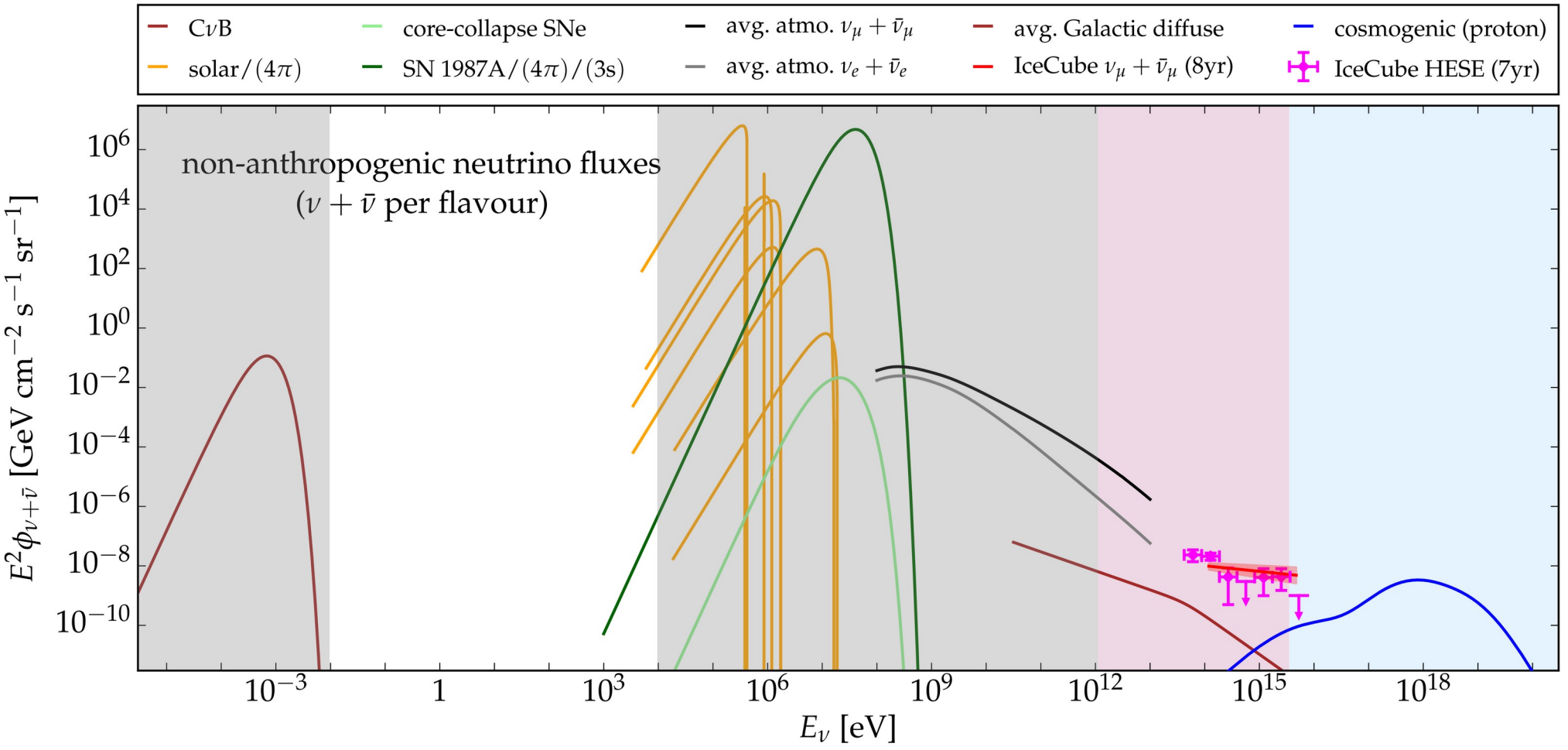


Figure courtesy of Markus Ahlers
Also in: Van Elewyck *et al.*, PoS(ICRC2019), 1023



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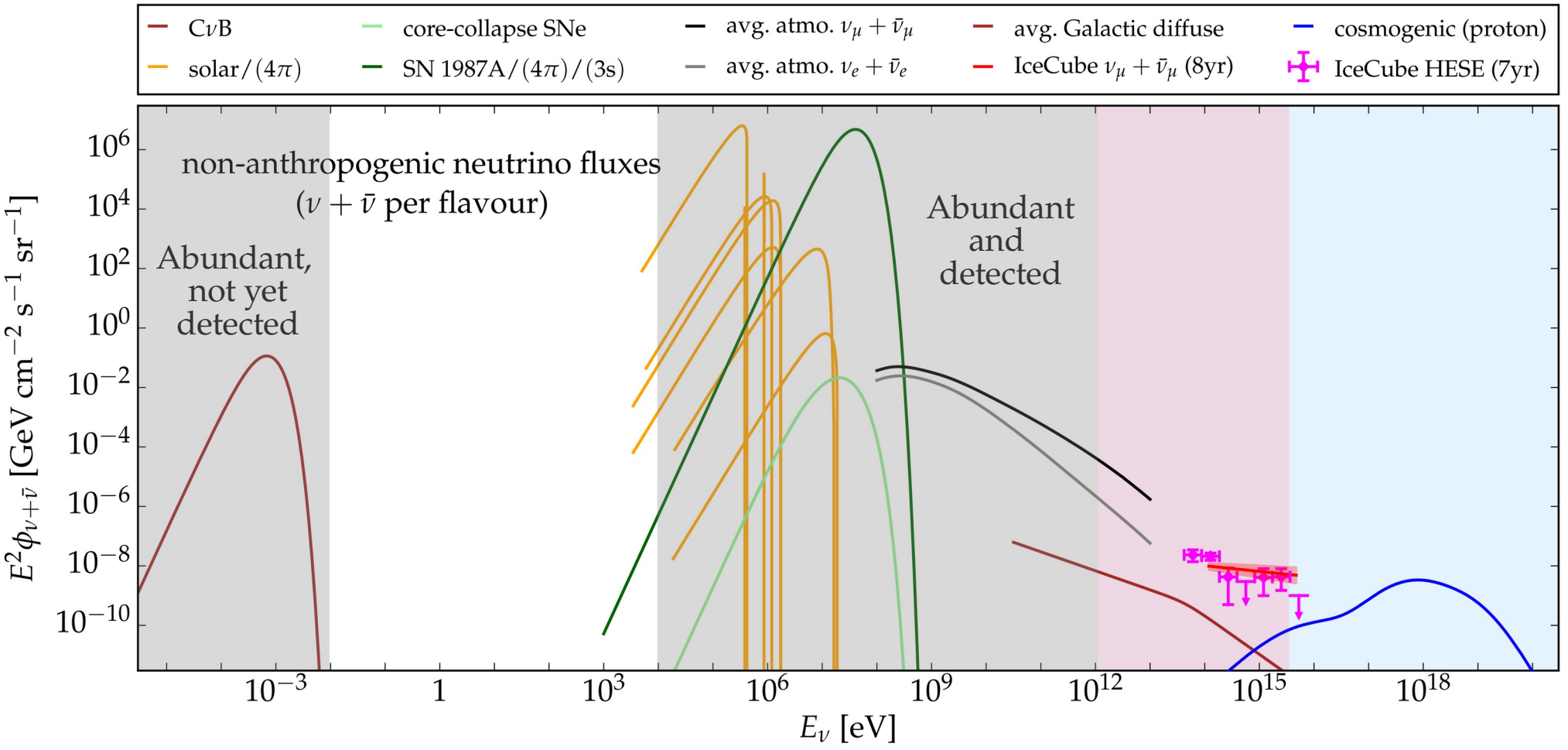

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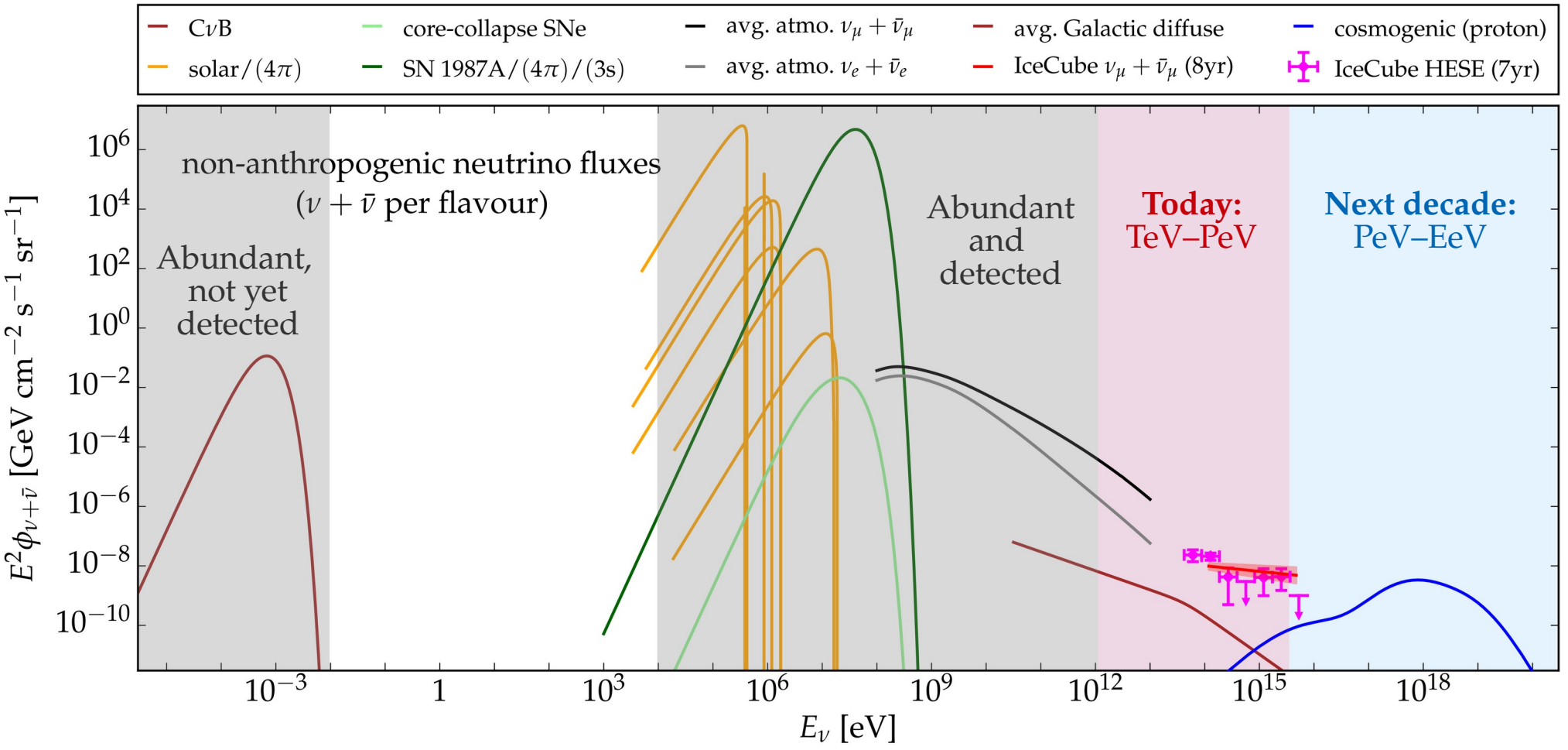

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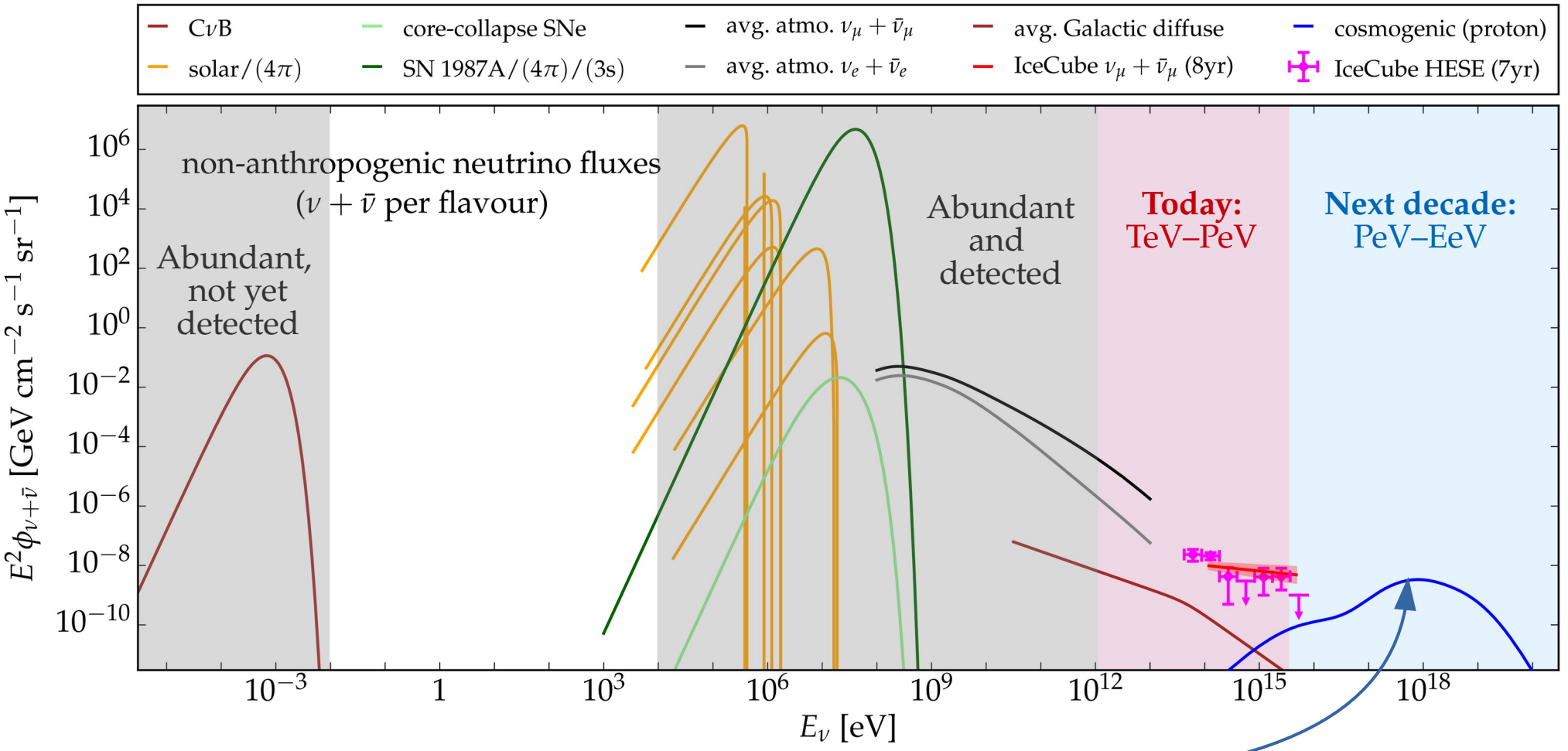

N.B.: POEMMA is *not* sensitive to cosmogenic ν

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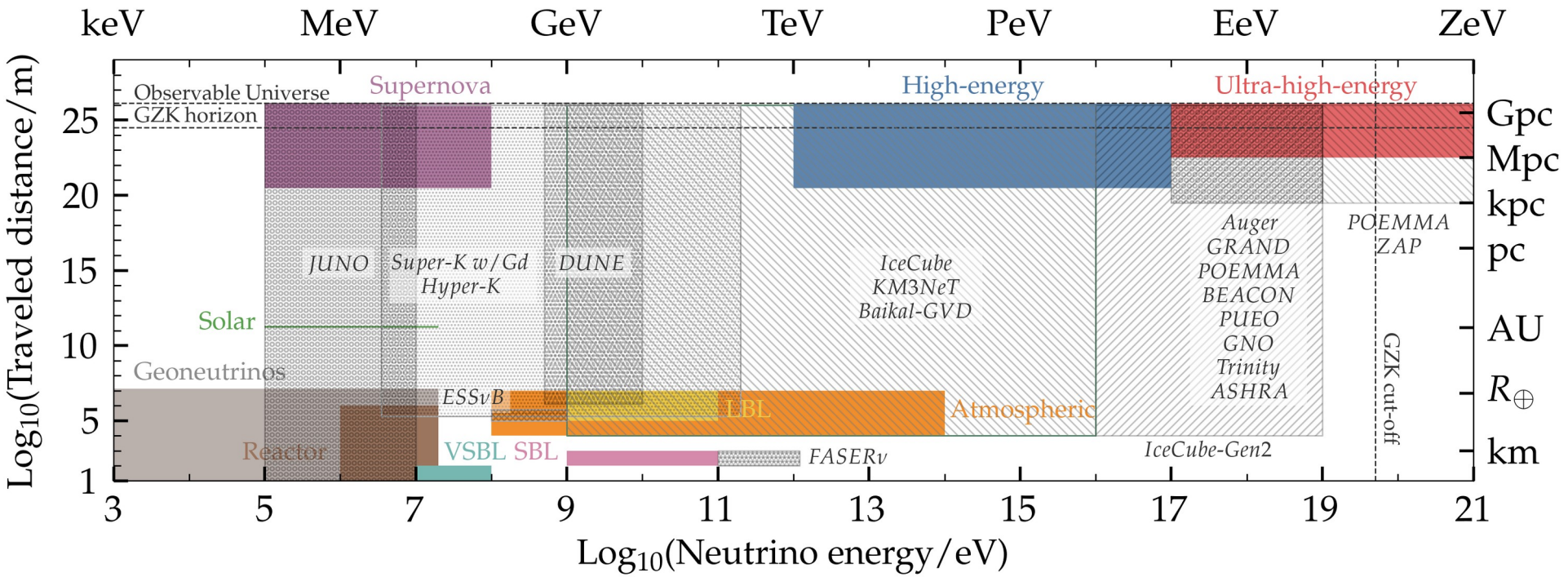
Next decade: a host of planned neutrino detectors



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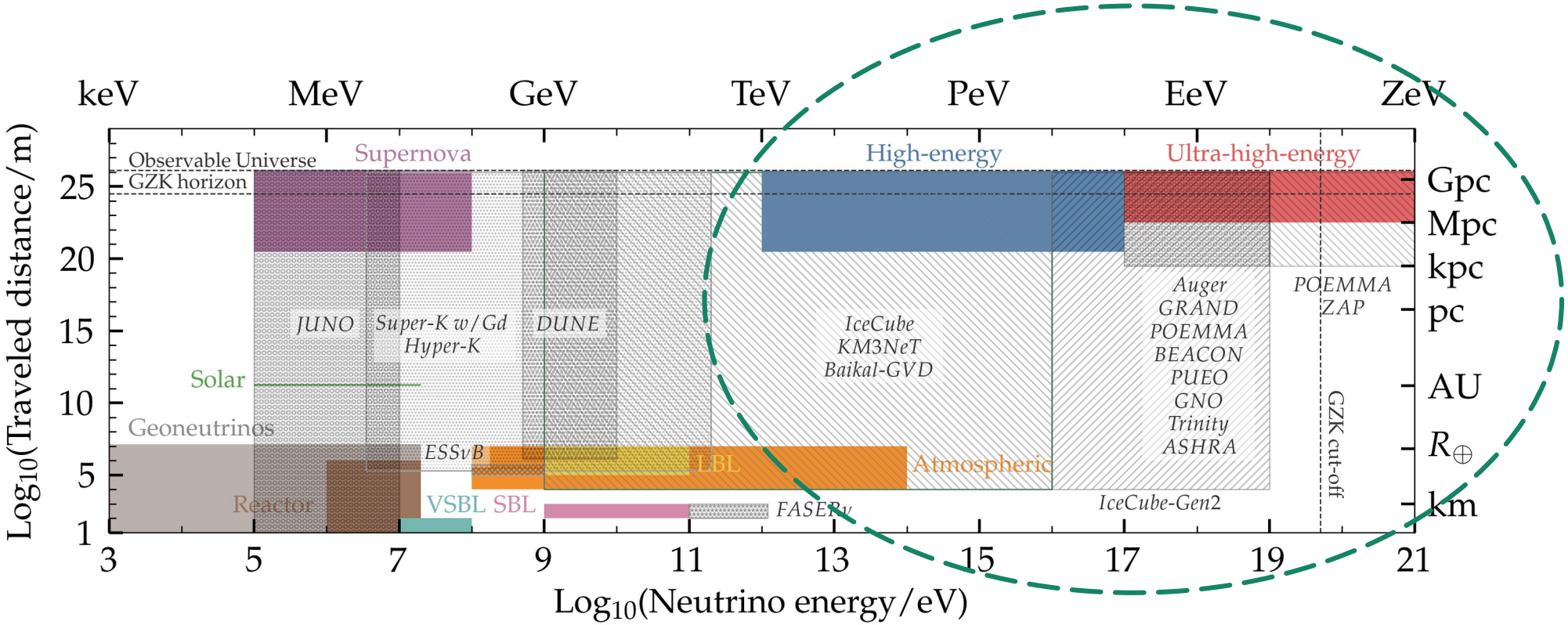

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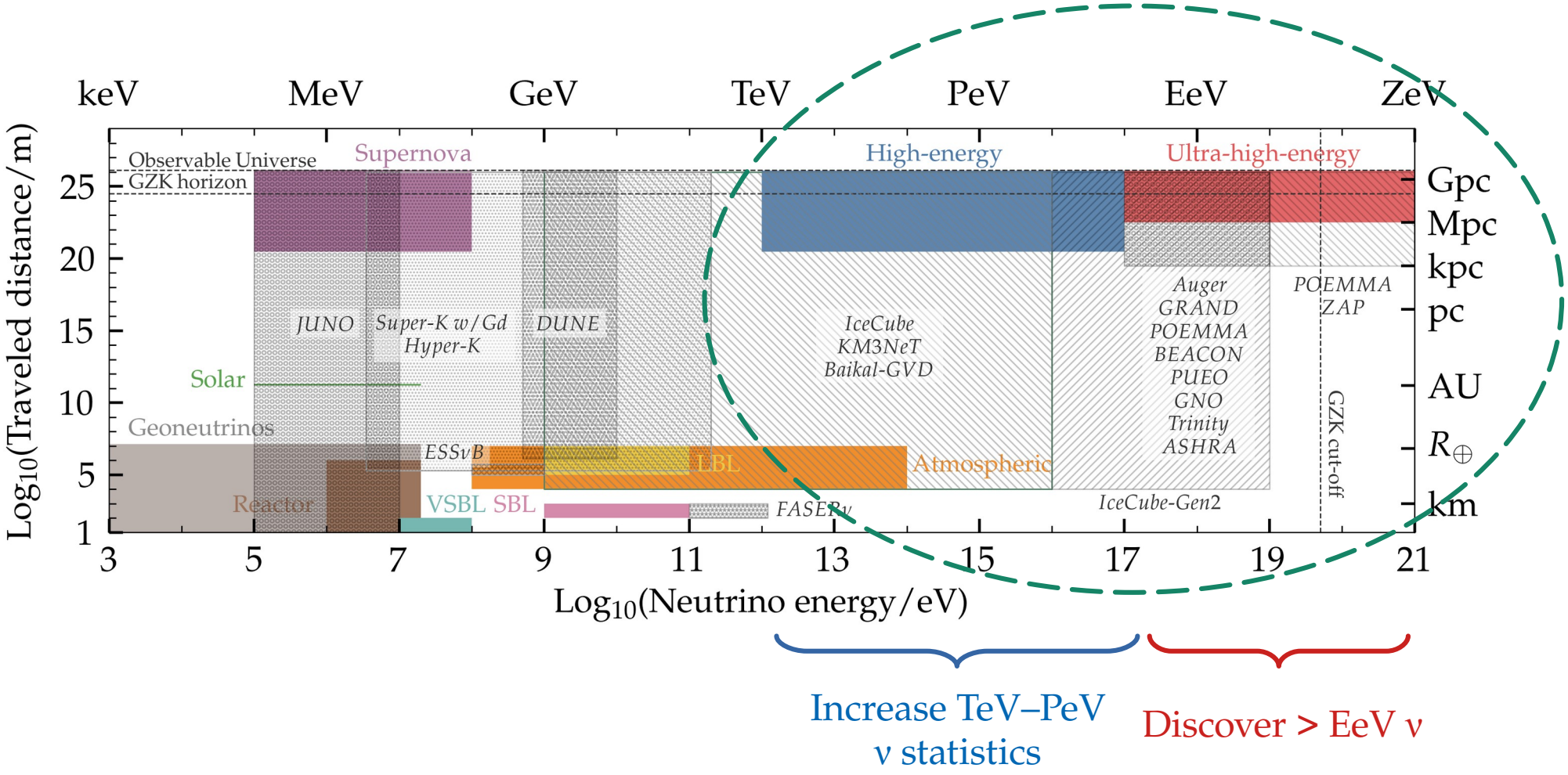

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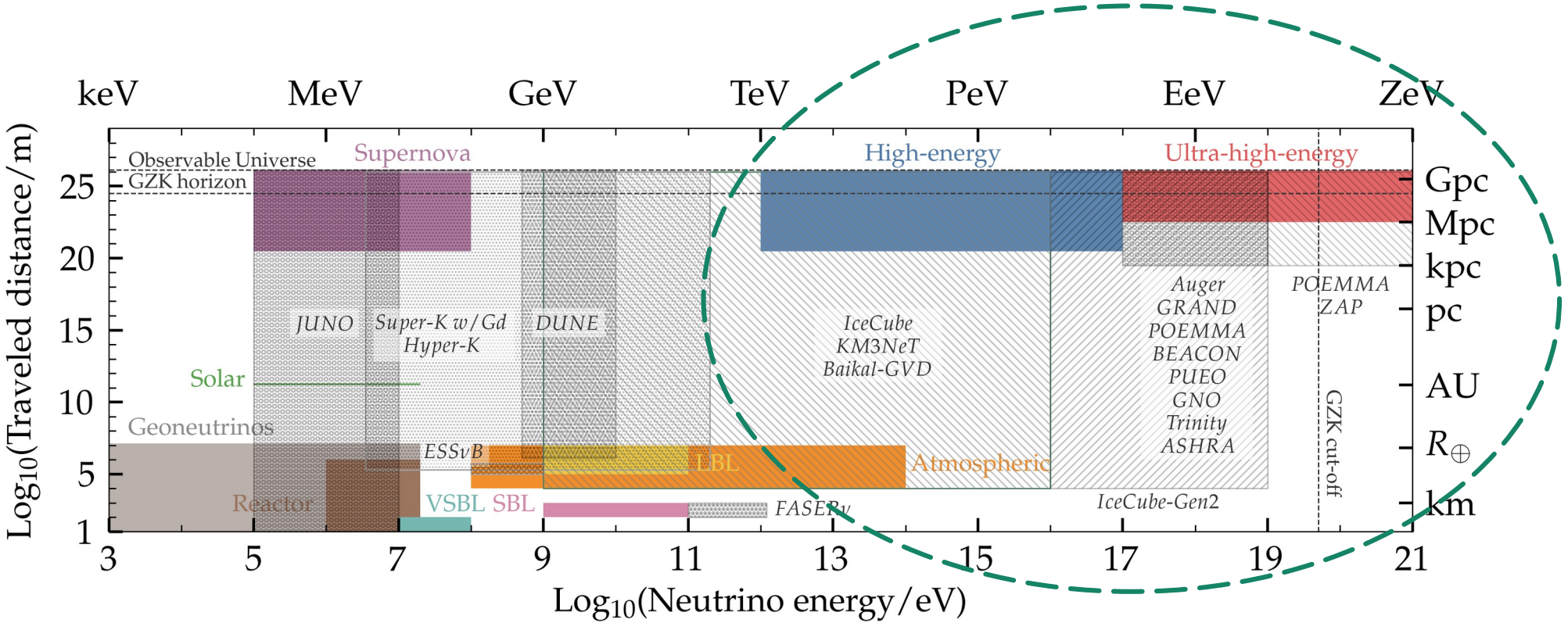

Synergies with lower energies

Increase TeV–PeV ν statistics

Discover > EeV ν

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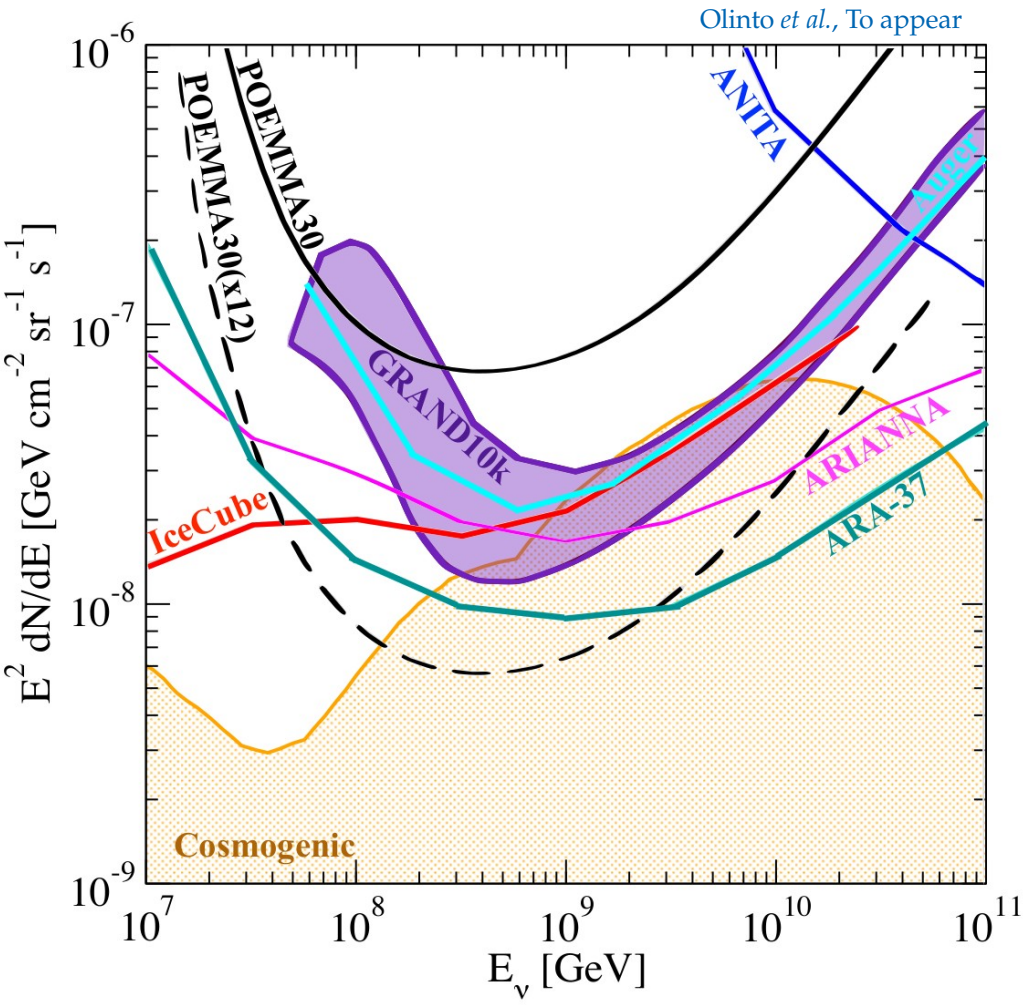
Two disclaimers

(Wait for POEMMA360 for that!)

1. POEMMA is *not* sensitive to the diffuse cosmogenic ν flux
   But there is still BSM physics to test!

2. What I will show next is exploratory, needs more study
   But it already shows great promise!



I. Secret neutrino interactions

Astrophysical neutrino sources

Earth

Galactic (kpc) or extragalactic (Mpc – Gpc) distance

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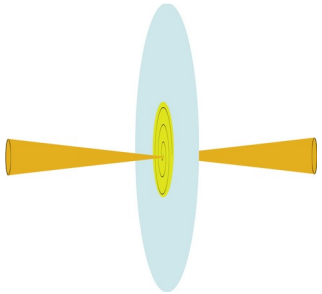

Standard case: ν free-stream

(And oscillate)

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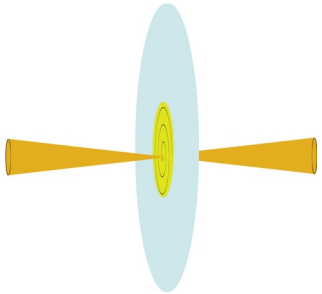

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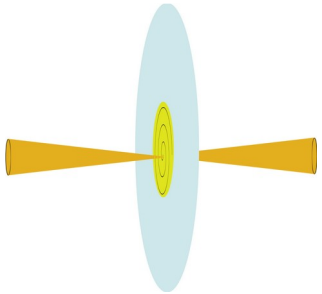

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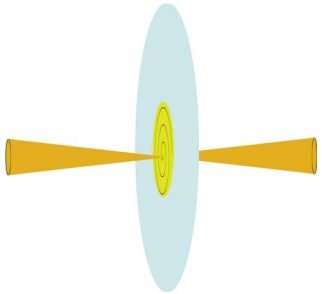

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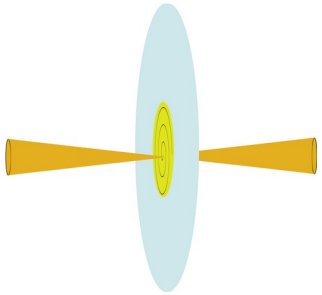

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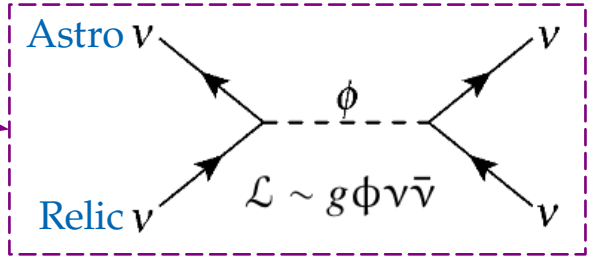

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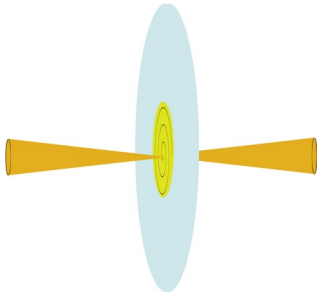

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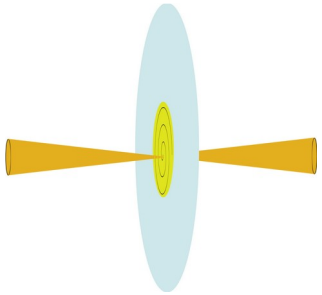

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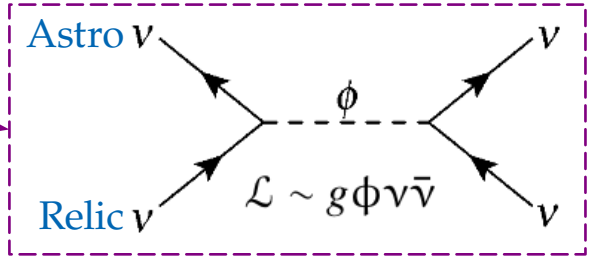

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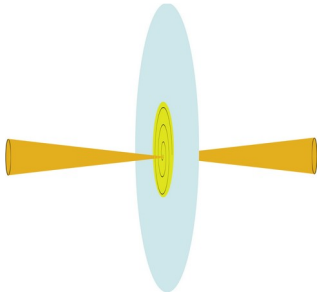

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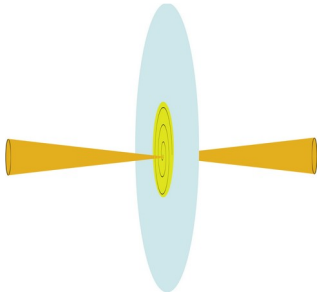

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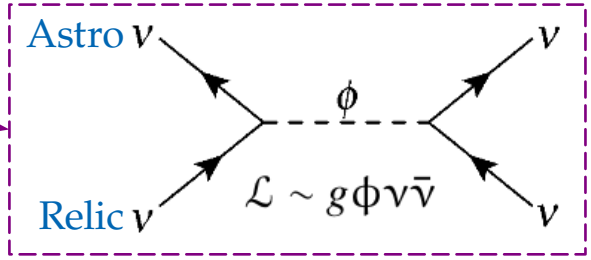

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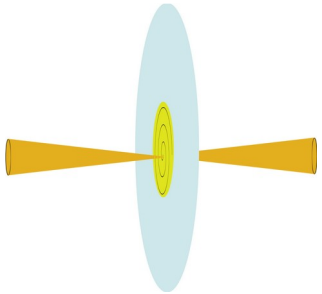

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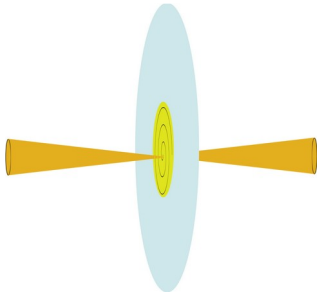

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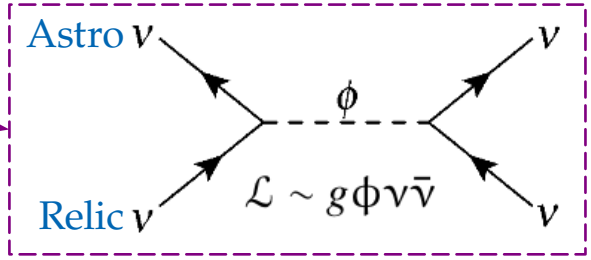

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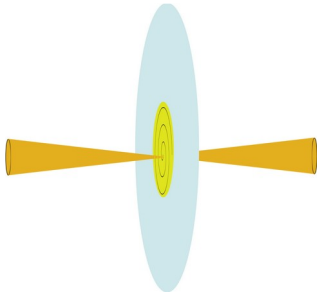

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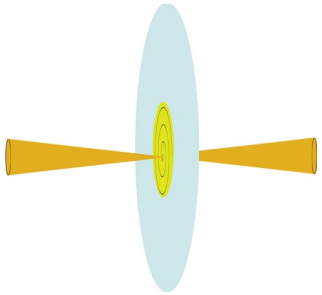

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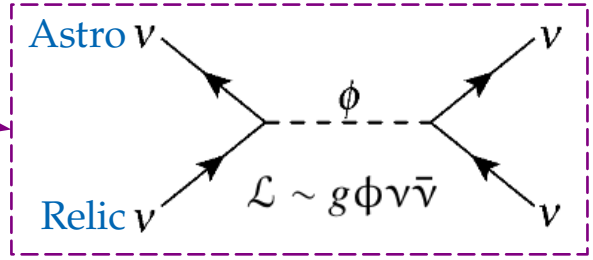

Can change:

- Energy spectrum
- Flavor composition
- Direction

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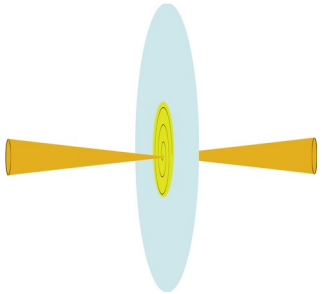

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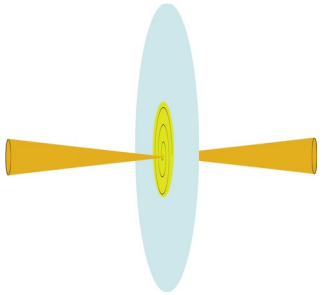

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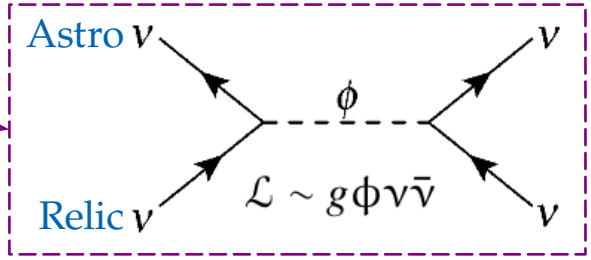

Can change:

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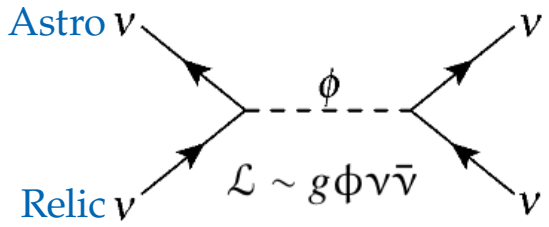
- Flavor composition
- Direction
- Arrival times

Secret interactions of high-energy neutrinos

"Secret" neutrino interactions between UHE ν (EeV) and relic ν (0.1 meV):



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

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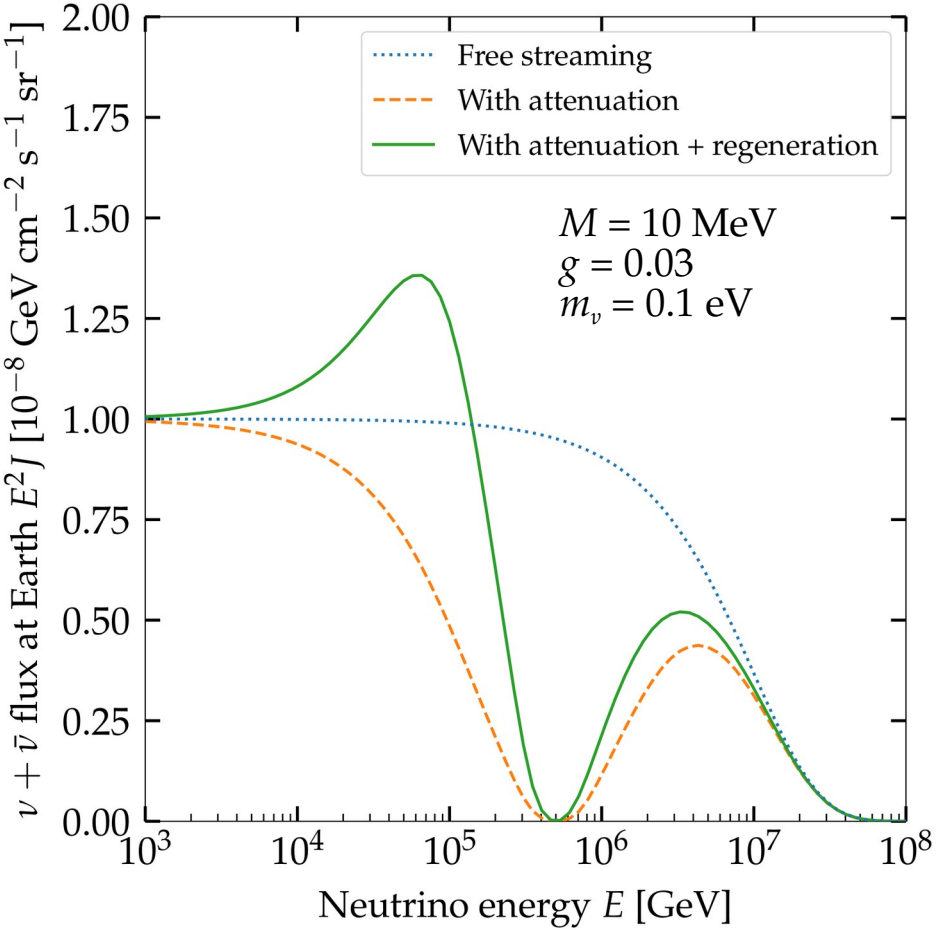

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See also: Ng & Beacom, *PRD* 2014
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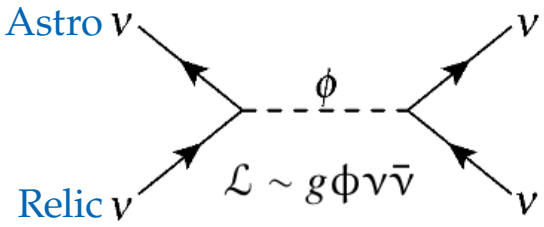

New coupling

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Mediator mass

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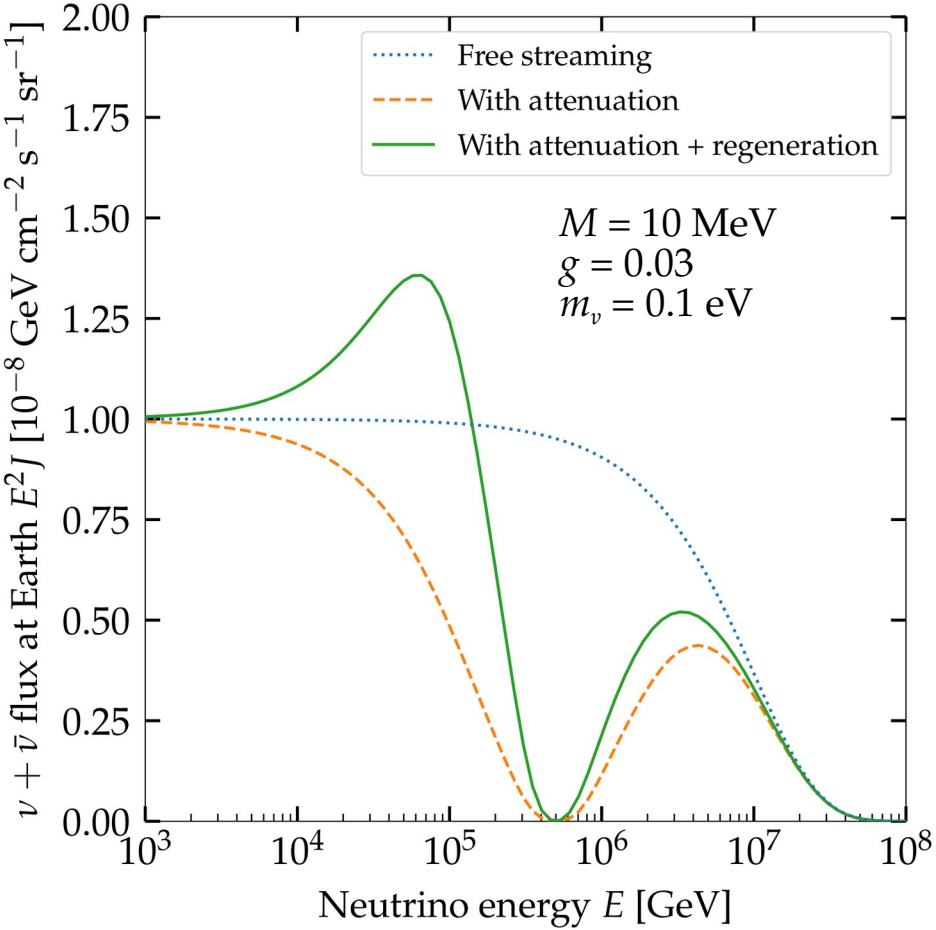

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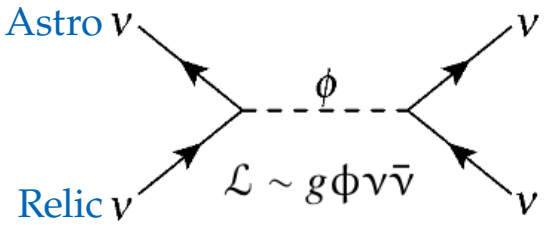

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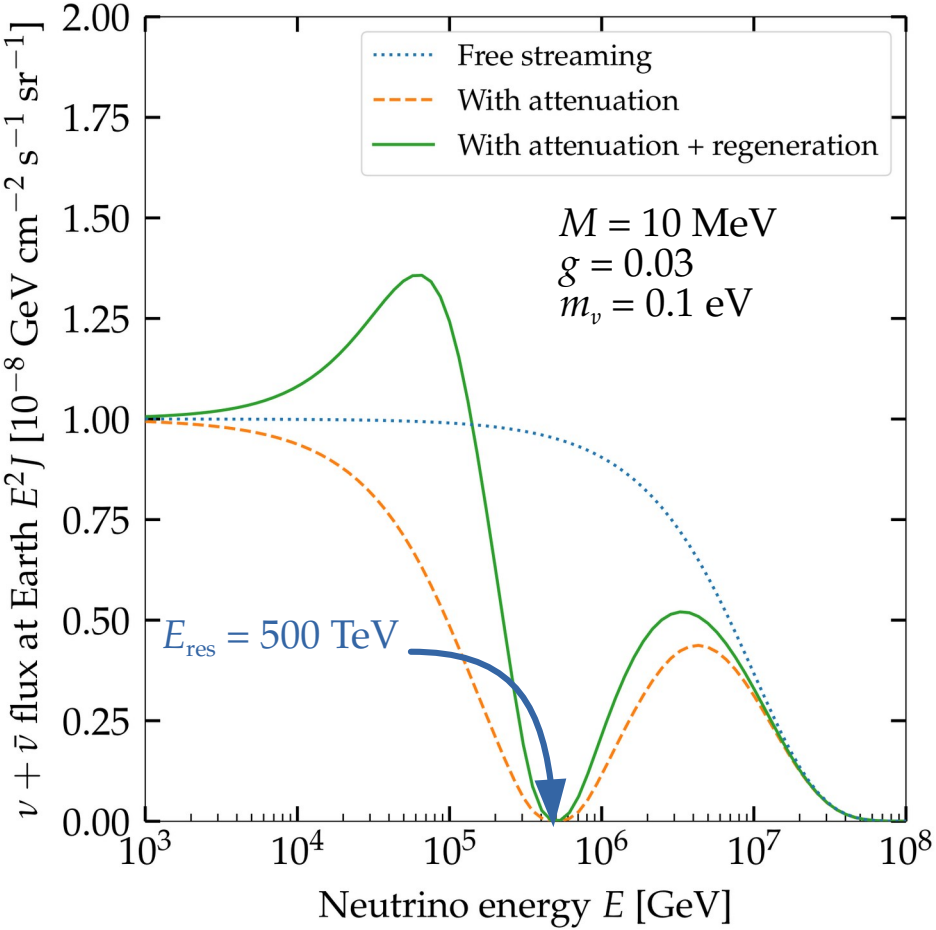

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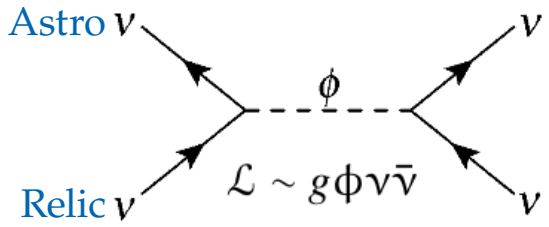

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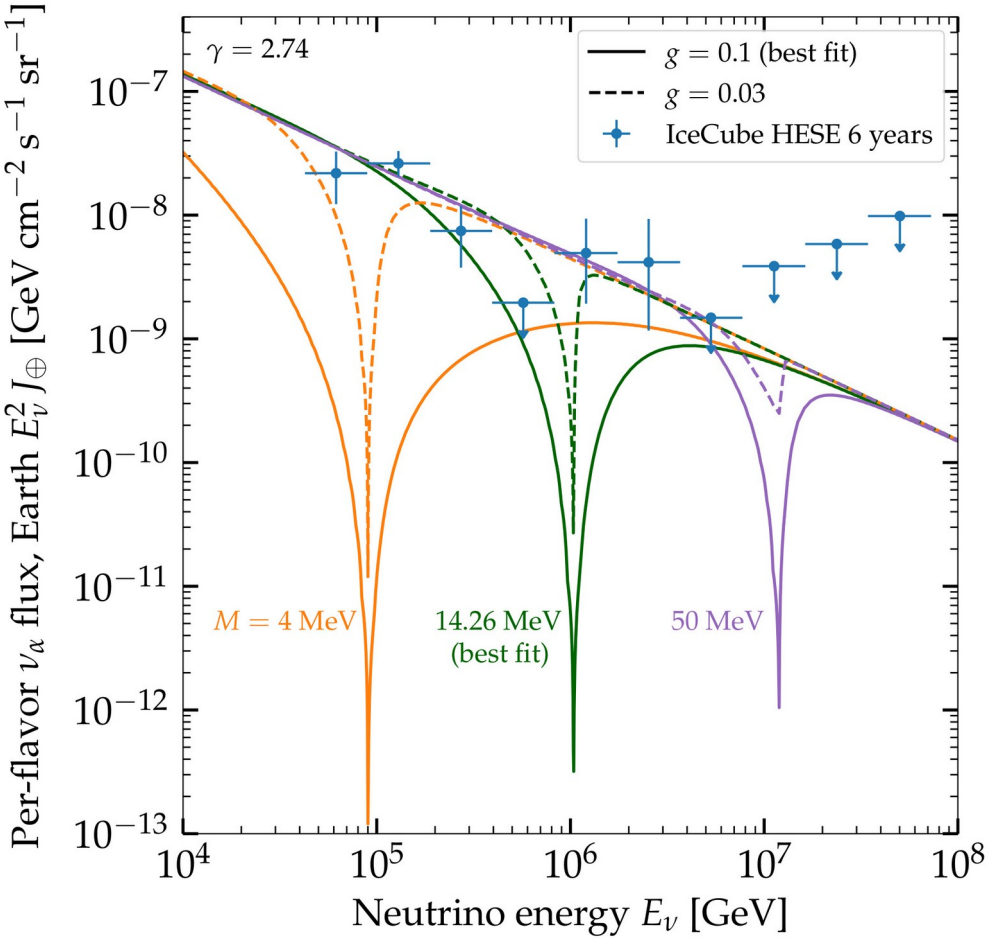
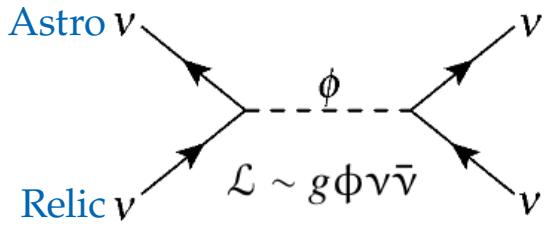


MB, Rosenstroem, Shalgar, Tamborra, *PRD* 2020
See also: Ng & Beacom, *PRD* 2014
Cherry, Friedland, Shoemaker, 1411.1071
Blum, Hook, Murase, 1408.3799

Secret interactions of high-energy neutrinos

"Secret" neutrino interactions between UHE ν (EeV) and relic ν (0.1 meV):



New coupling

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

Mediator mass

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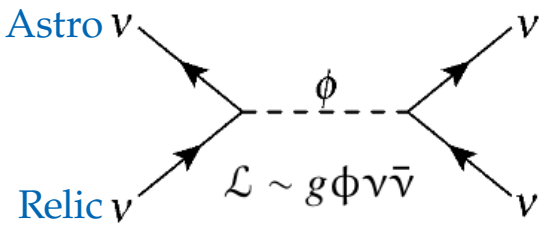
Disappearance of high-energy neutrinos via νSI



If this happens repeatedly, we end up without high-energy neutrinos

So, if we see high-energy neutrinos, we can set an upper limit on the νSI strength

Original idea by Kolb & Turner, using SN1987A (*PRD* 1987)

Mean free path of a ν of energy E: $l_{\rm int}(E) = [n_{\rm C\nu B}\sigma_{\nu\nu}(E)]^{-1}$

Estimated optical depth if emitted by a source at a distance L: $\tau(E) = \dfrac{l_{\rm int}(E)}{L}$

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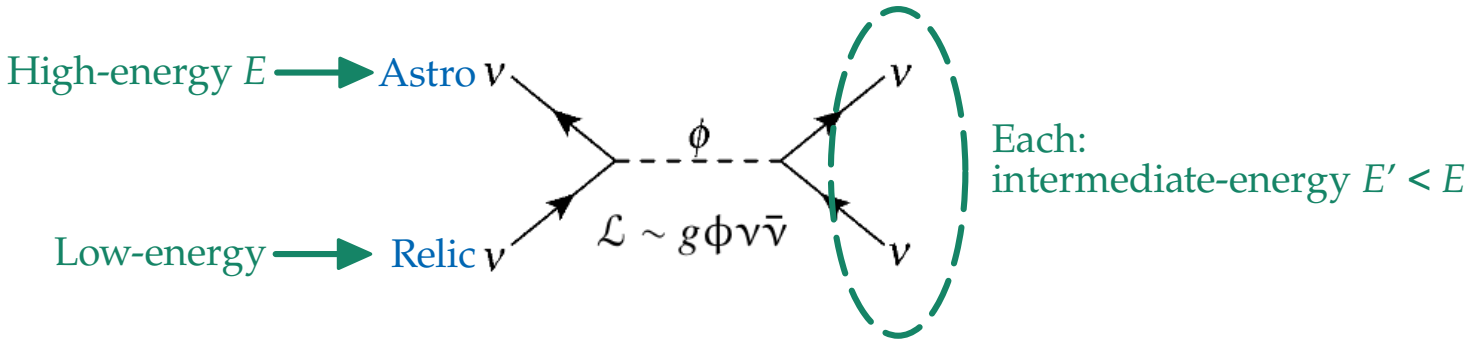

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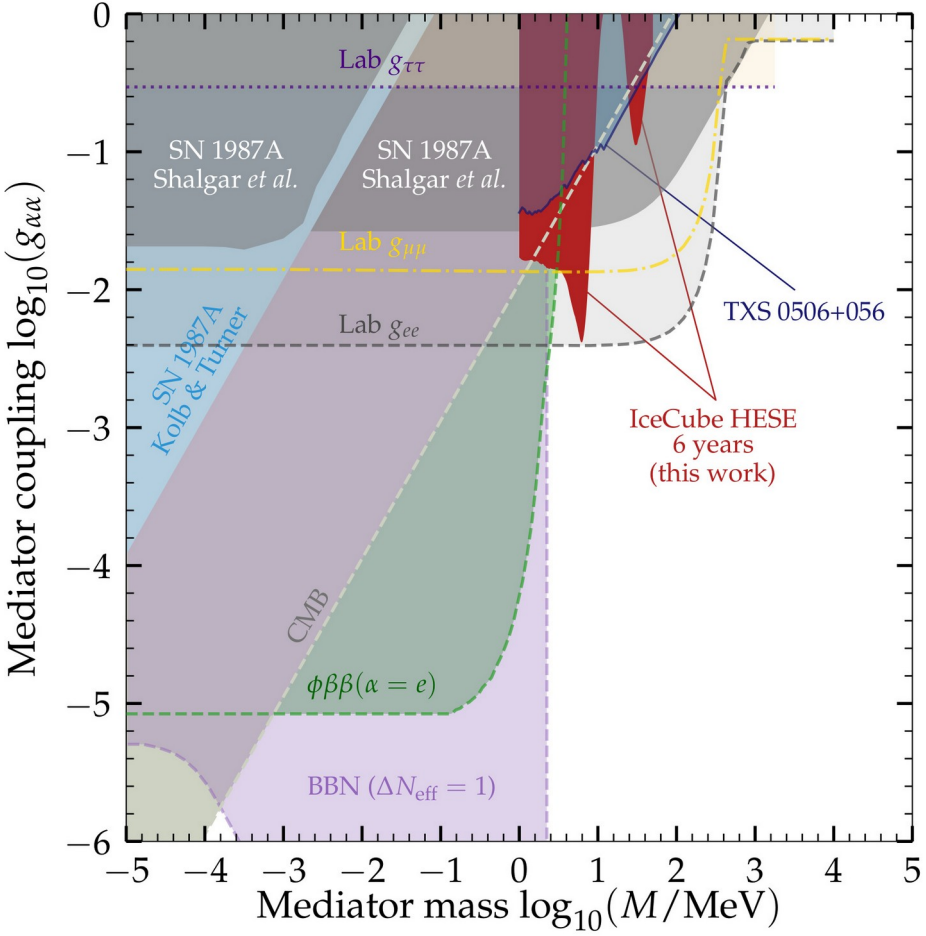
POEMMA can test new parameter space of νSI



MB, Rosenstroem, Shalgar, Tamborra, *PRD* 2020
See also: Shalgar, **MB**, Tamborra, 1912.09115

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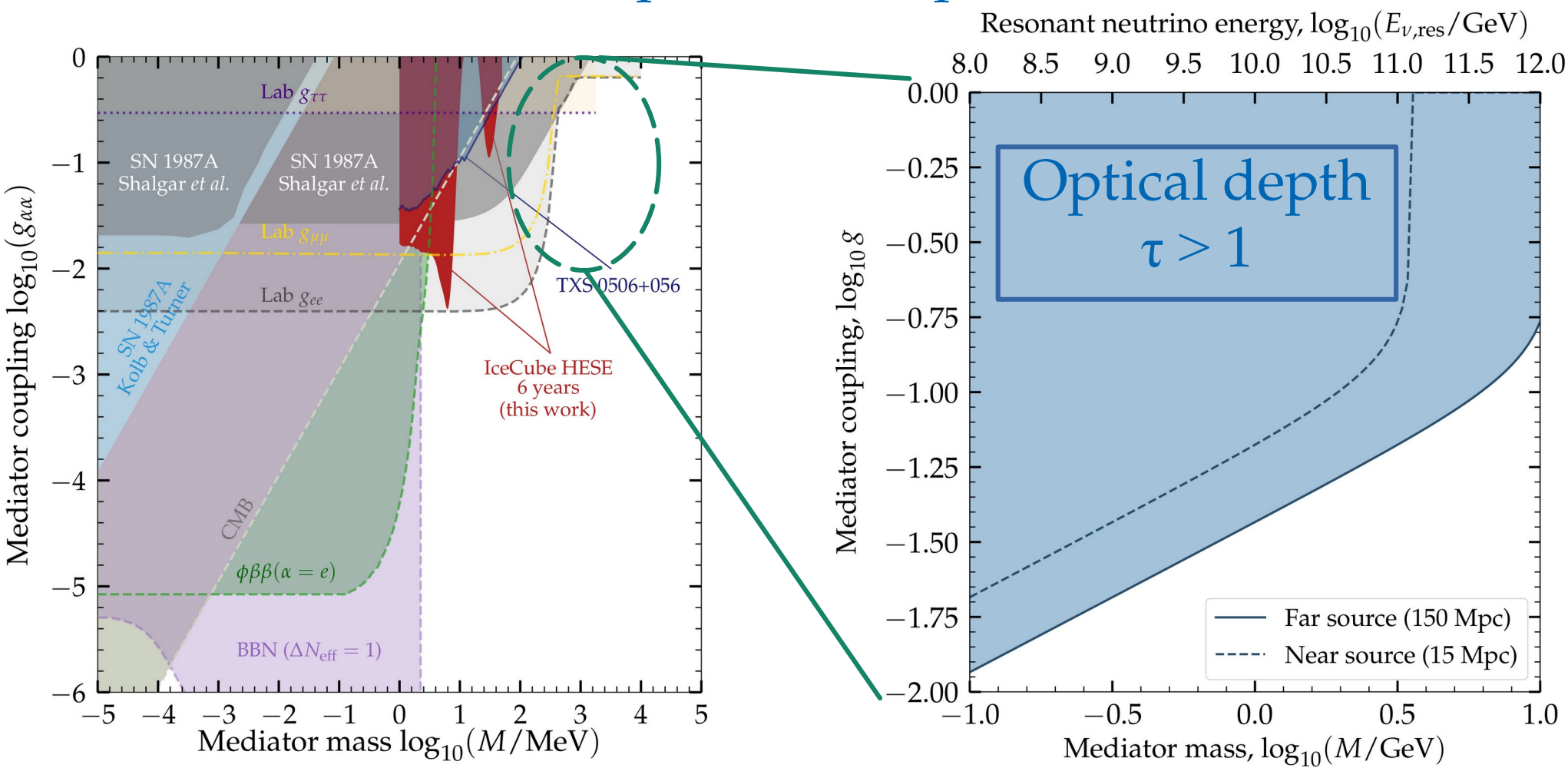

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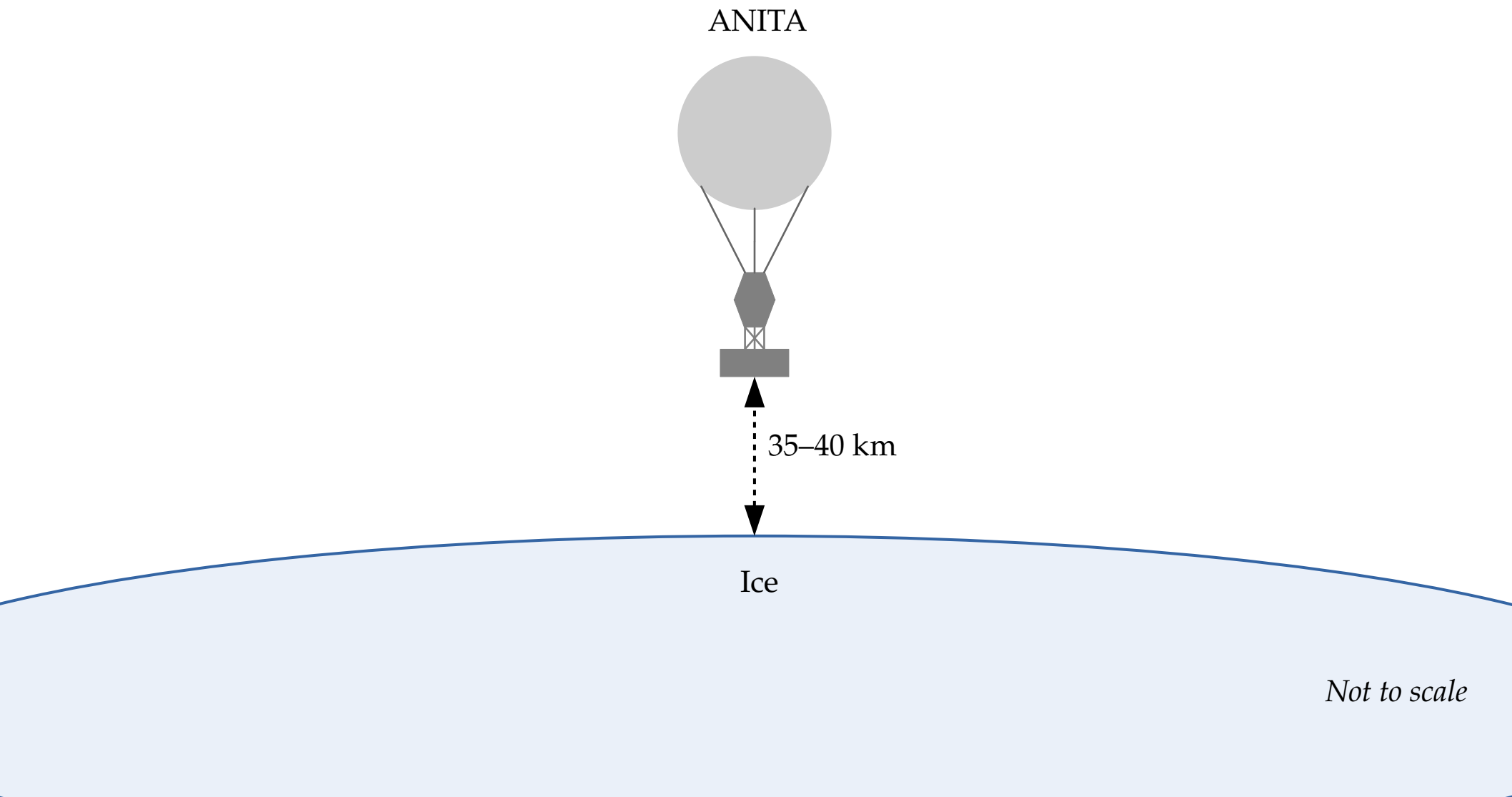
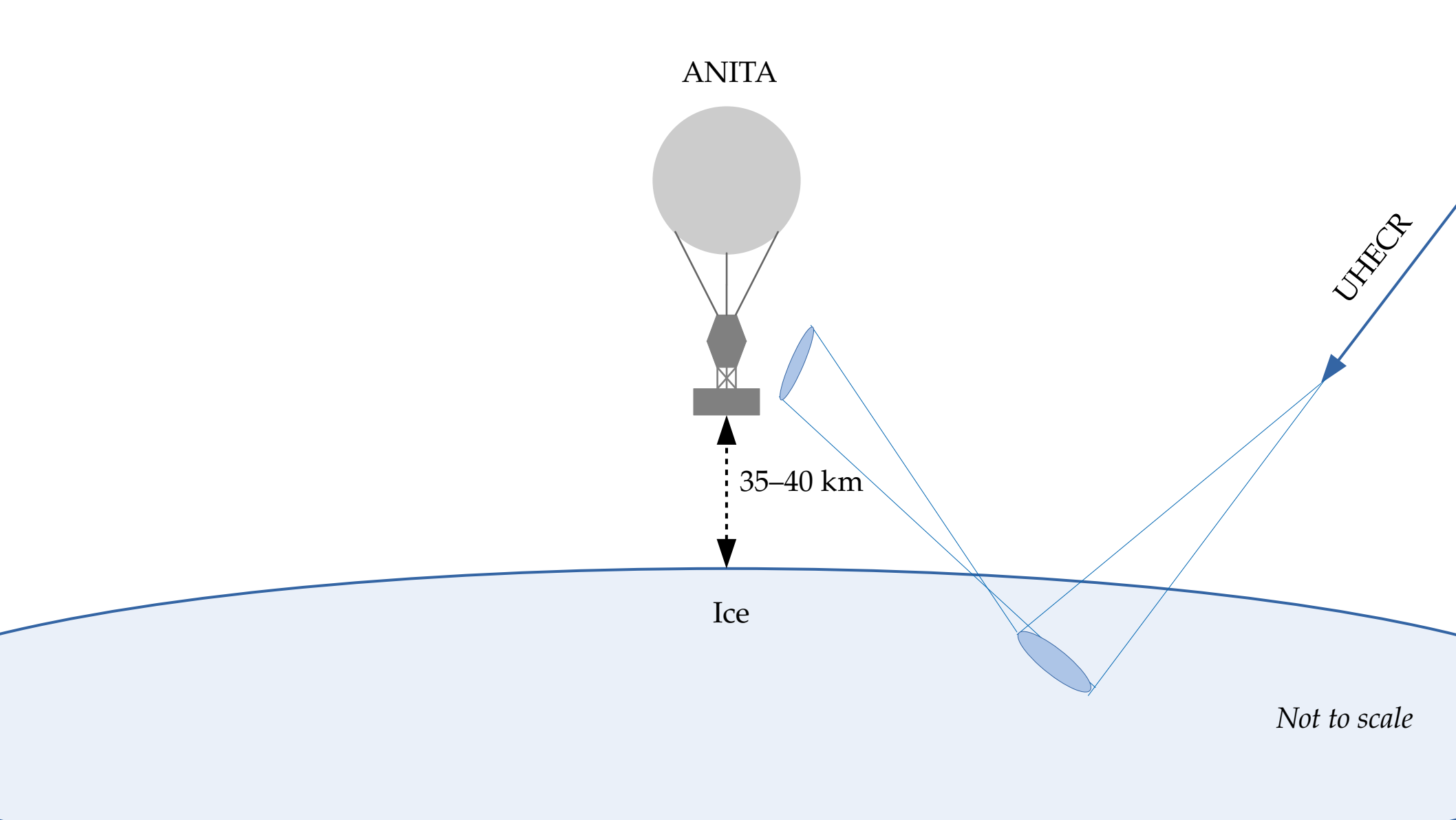
II. ANITA anomalous events


ANITA
35–40 km
Ice
Not to scale


ANITA
UHECR
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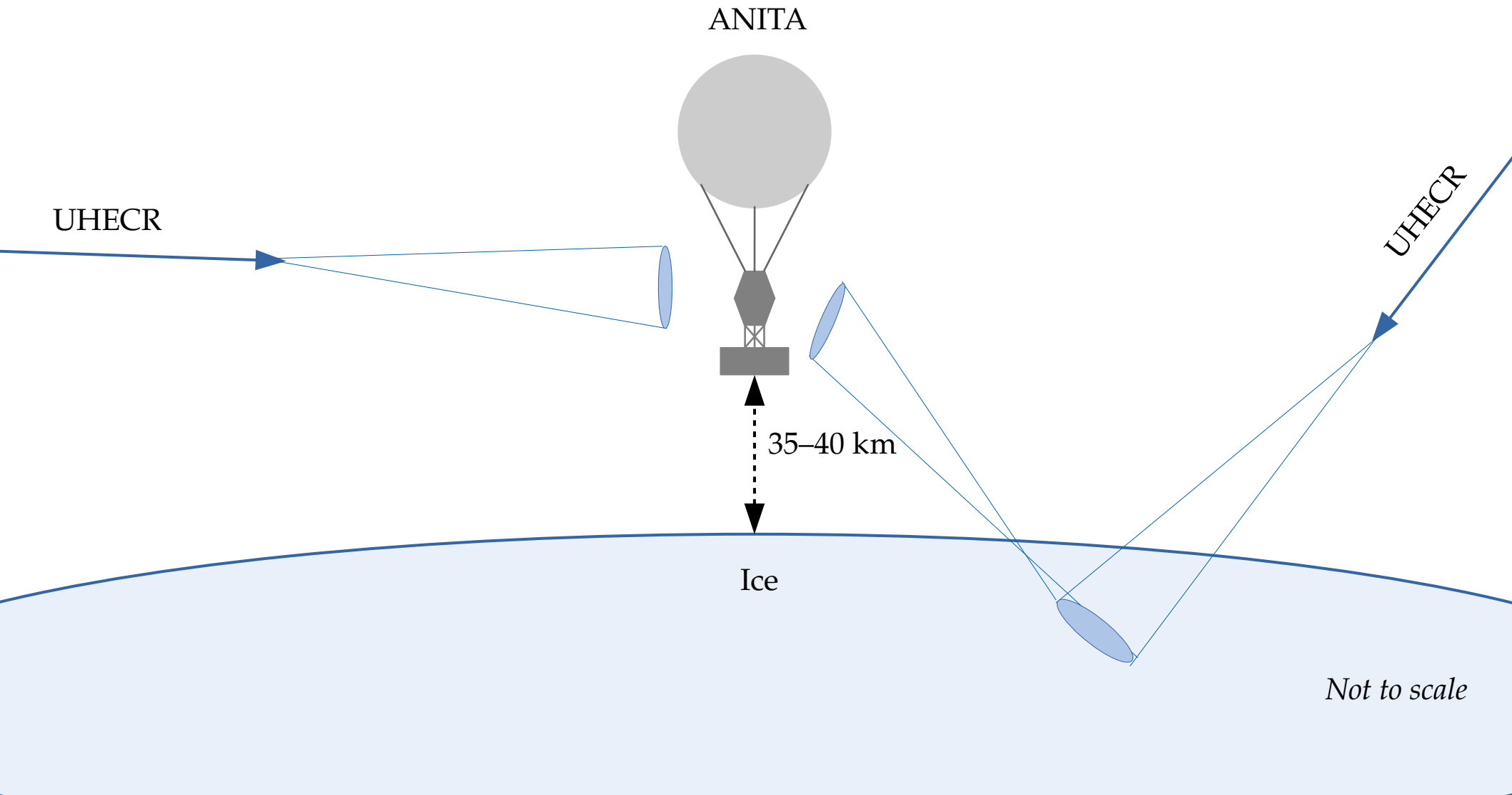
Not to scale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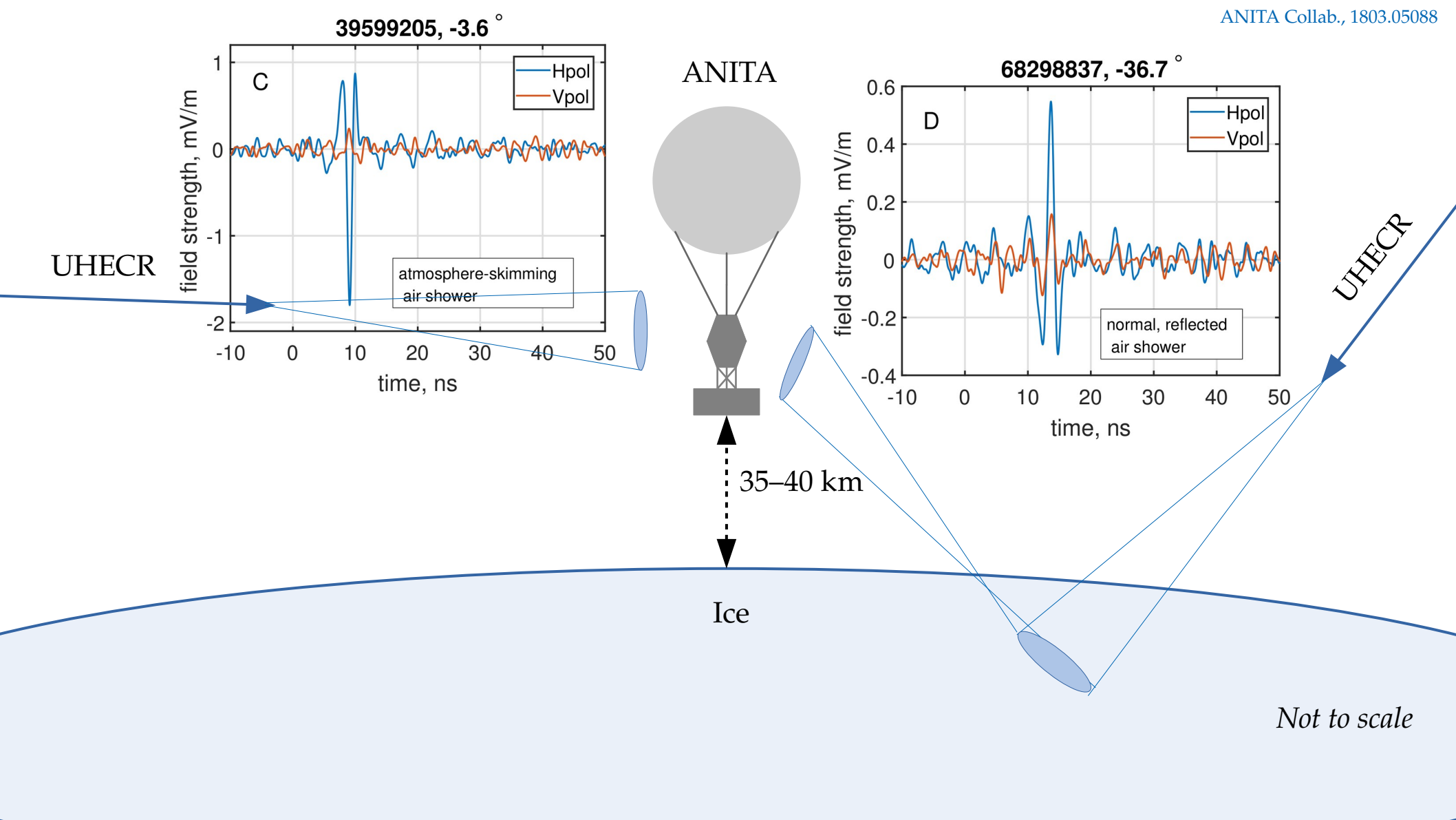
ANITA Collab., 1803.05088



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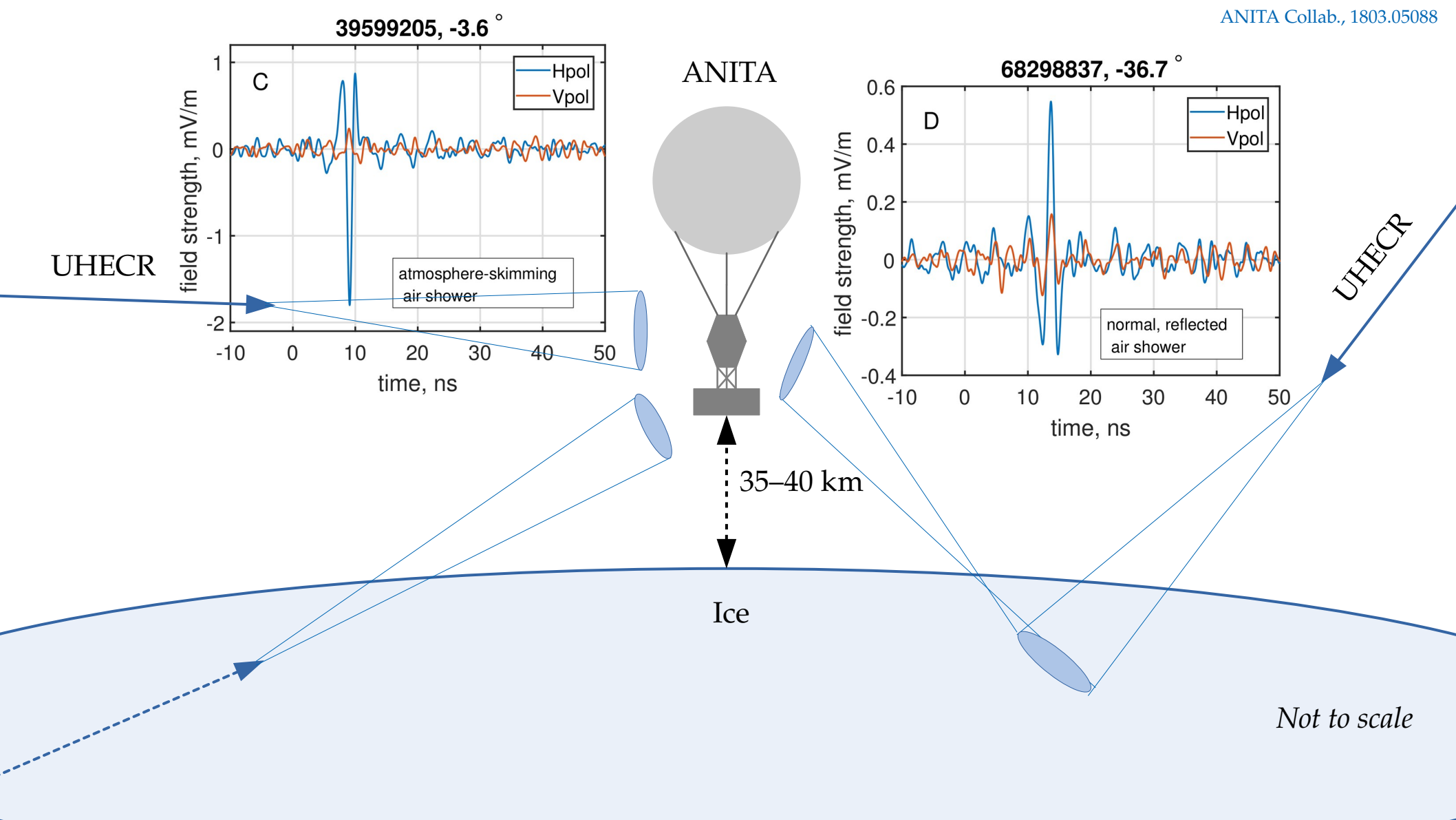

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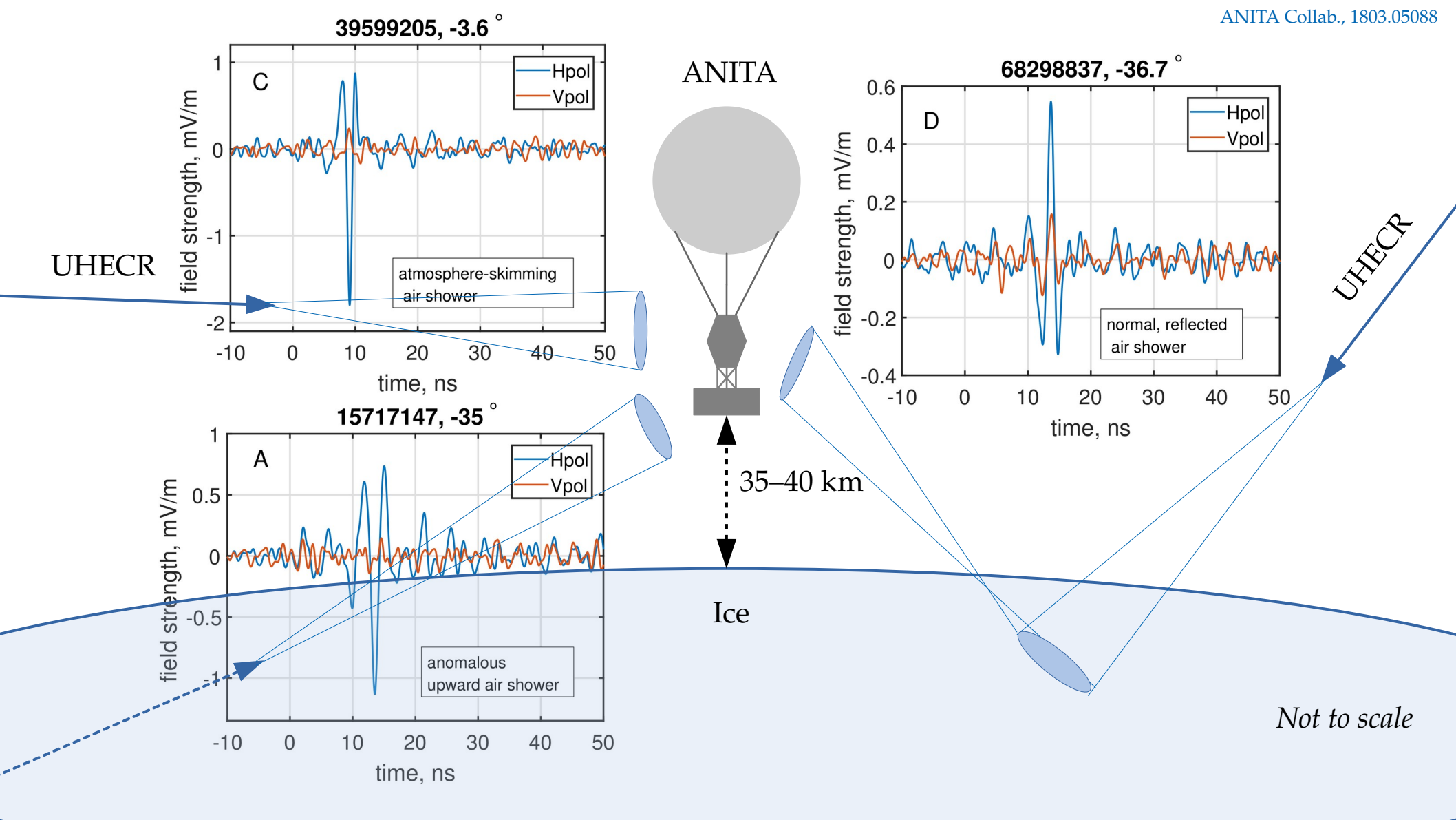

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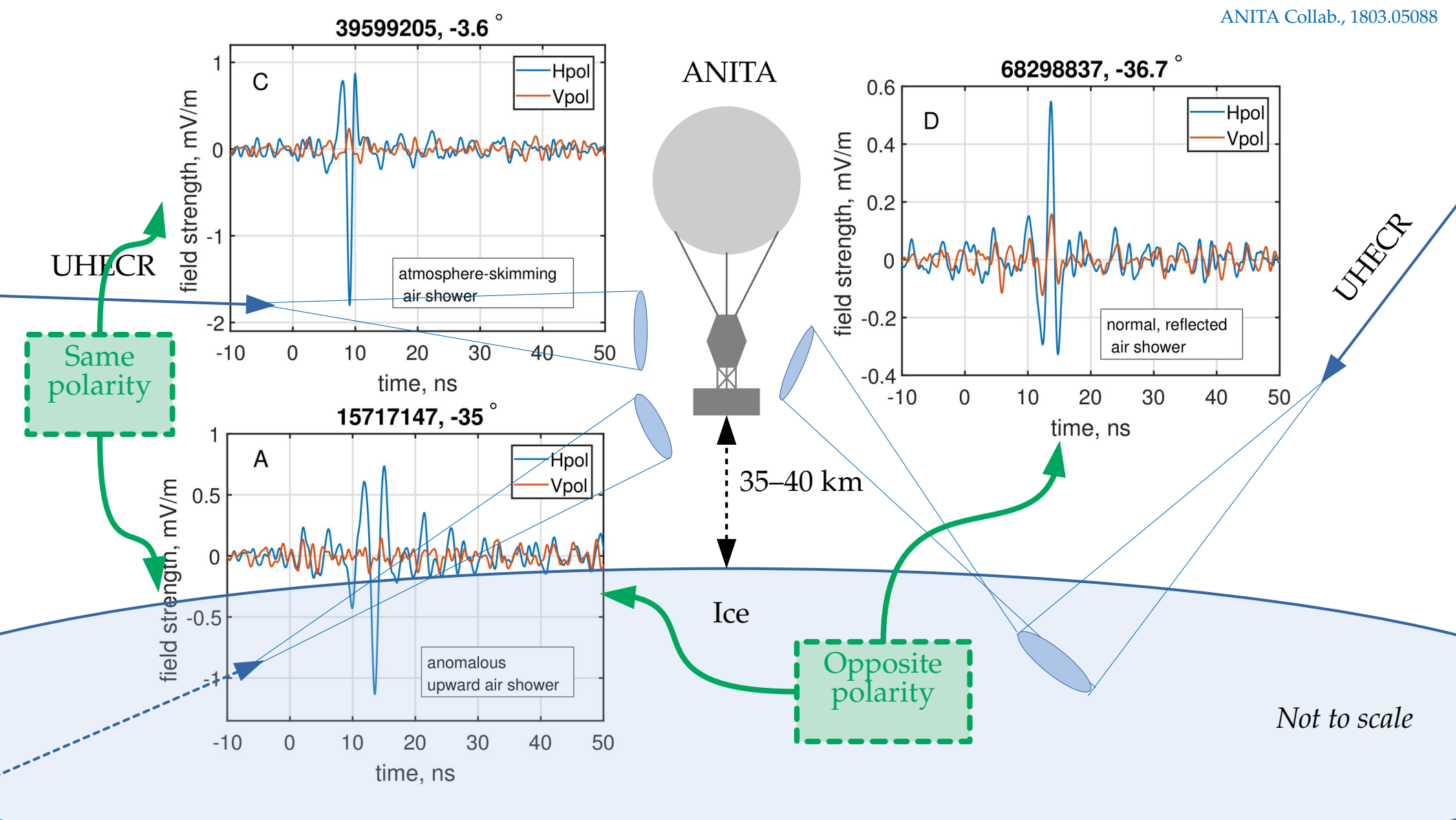

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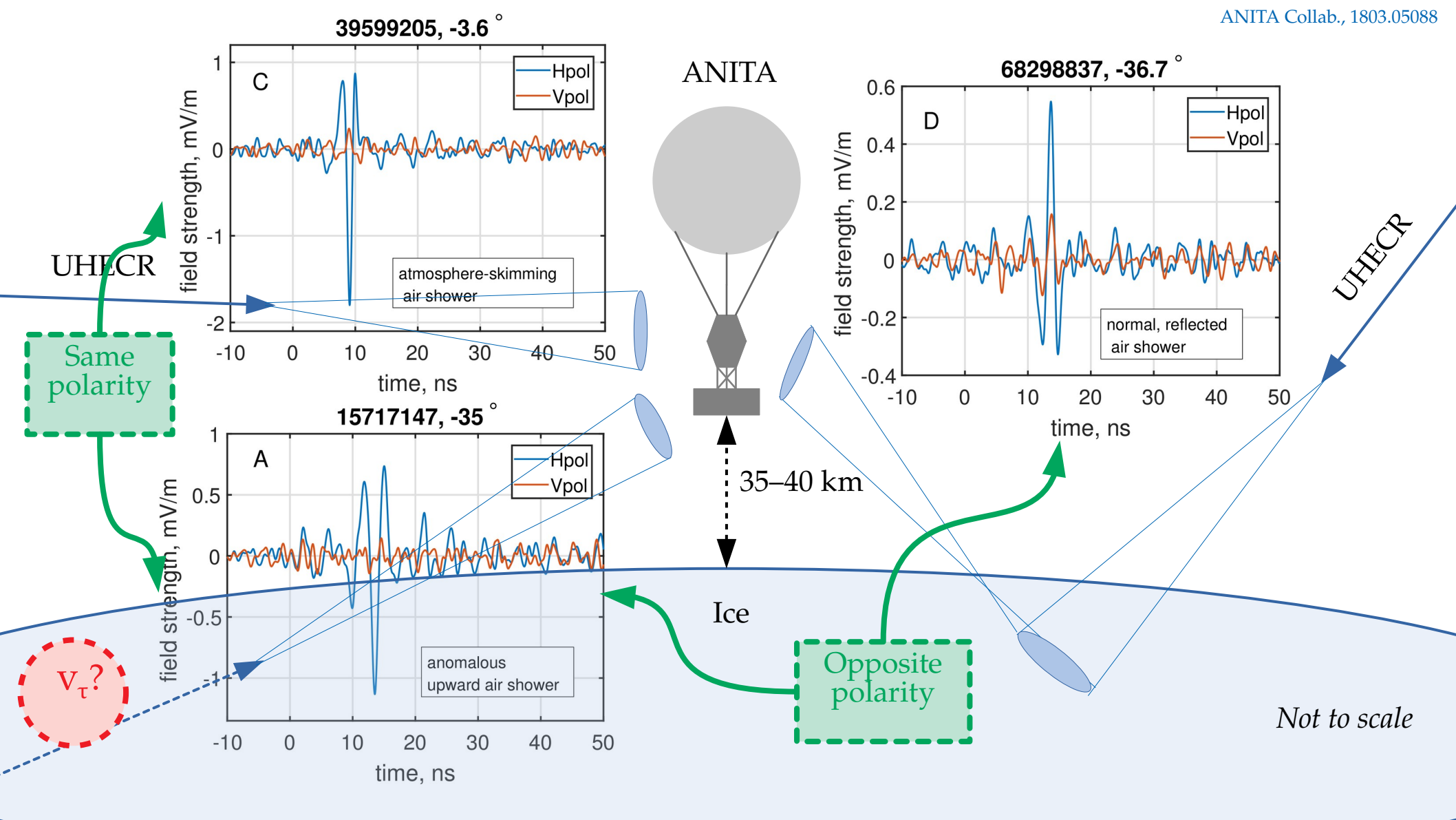

Mystery ANITA events – Are they UHE ν?

- Two upgoing, unflipped-polarity showers:
  - ANITA-1 (2006): -27°±0.3° (rel. hor.), 0.60±0.4 EeV
  - ANITA-3 (2014): -35°±0.3° (rel .hor.), 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-4 (2016): no steeply upgoing anomalous events (only near horizon)

ANITA Collab., *PRL* 2016 + *PRL* 2018 + 2008.05690

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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 + *PRL* 2018 + 2008.05690

So what is ANITA seeing?

- Subsurface reflections in ice [Shoemaker *et al.*, *Annals Glaciol.* 2020; Smith *et al.*, 2009.13010]:
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Mean free path ~ Earth radius Decay length ~ Earth radius

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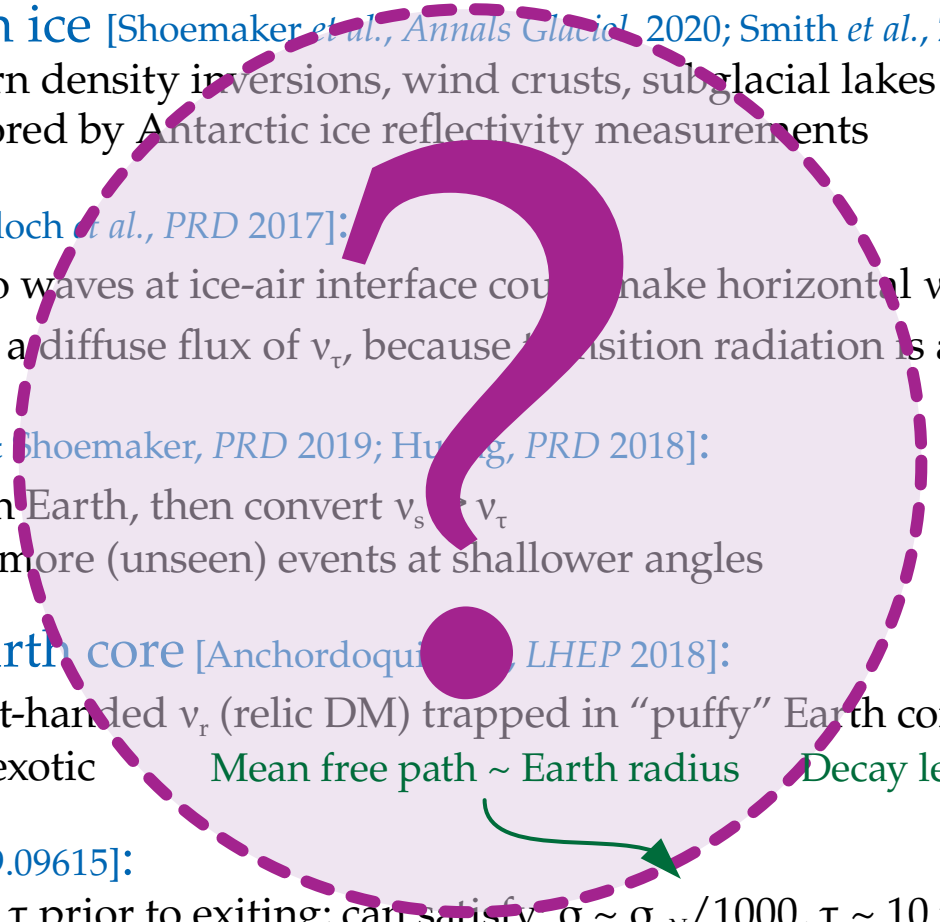
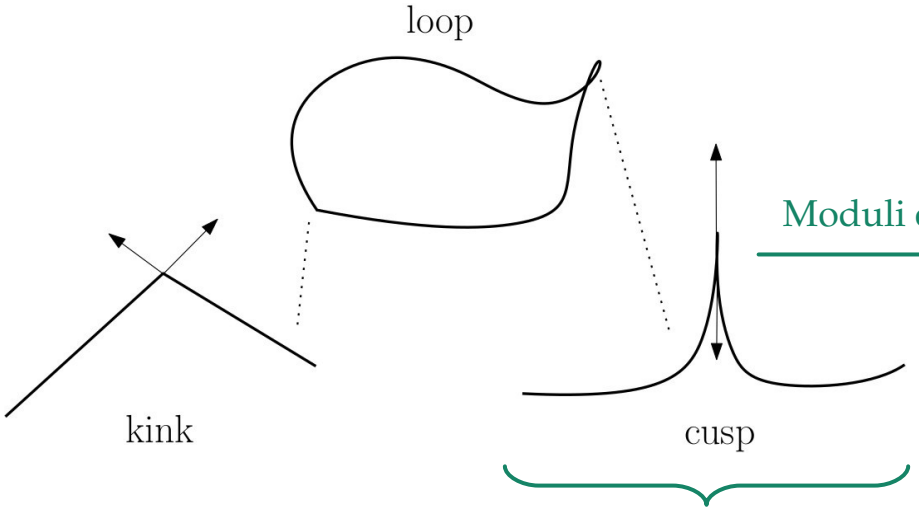


III. Early-Universe relics

Neutrinos from cosmic strings

- Cosmic strings: 1D topological defects formed in an early-Universe phase transition
- Strings form loops – within them, kinks and cusps appear
- Strings may couple strongly to "moduli", relatively light scalar fields
- Moduli have Lorentz boosts of $\Gamma \sim 10^{12}$–10^{13}
- They decay into neutrinos of $> 10^{21}$ eV >> energies from astrophysical acceleration



Moduli emission → Φ ($m \sim 10^5$ GeV, $\Gamma \sim 10^{12}$–10^{13})

Decay to gluons + hadronization → π

Decay → ν ($E > 10^{21}$ eV)

Can oscillate very fast briefly

$$\tau_\Phi \sim 8 \times 10^{-17} \left(\frac{m}{10^5\ \mathrm{GeV}}\right)^{-3} \left(\frac{\alpha}{10^7}\right)^{-2}\ \mathrm{s}$$

Berezinsky, Sabancilar, Vilenkin, *PRD* 2011
Gouttenoire, Servant, Simakachorn, *JCAP* 2020

Neutrino horizon

Neutrino horizon (z_ν):

Maximum redshift from which a neutrino with observed energy E can arrive

CνB number density: $56(1+z)^3$ cm^{-3}

$$\int_0^{z_\nu(E)} dz \frac{dt}{dz} \sigma_{\nu\nu}(E(1+z)) n_\nu(z) = 1$$

$$\nu_i + \bar{\nu}_i \to q_\alpha + \bar{q}_\alpha$$

$$\nu_i + \bar{\nu}_i \to l + \bar{l}$$

$$\nu_i + \bar{\nu}_j \to \nu_i + \bar{\nu}_j$$

$$z_\nu \sim 2.5 \times 10^2 \left(\frac{E}{10^{11}\ \text{GeV}} \right)^{-2/5} \leftarrow \text{Matter-dominated epoch}$$

Berezinsky, Sabancilar, Vilenkin, *PRD* 2011

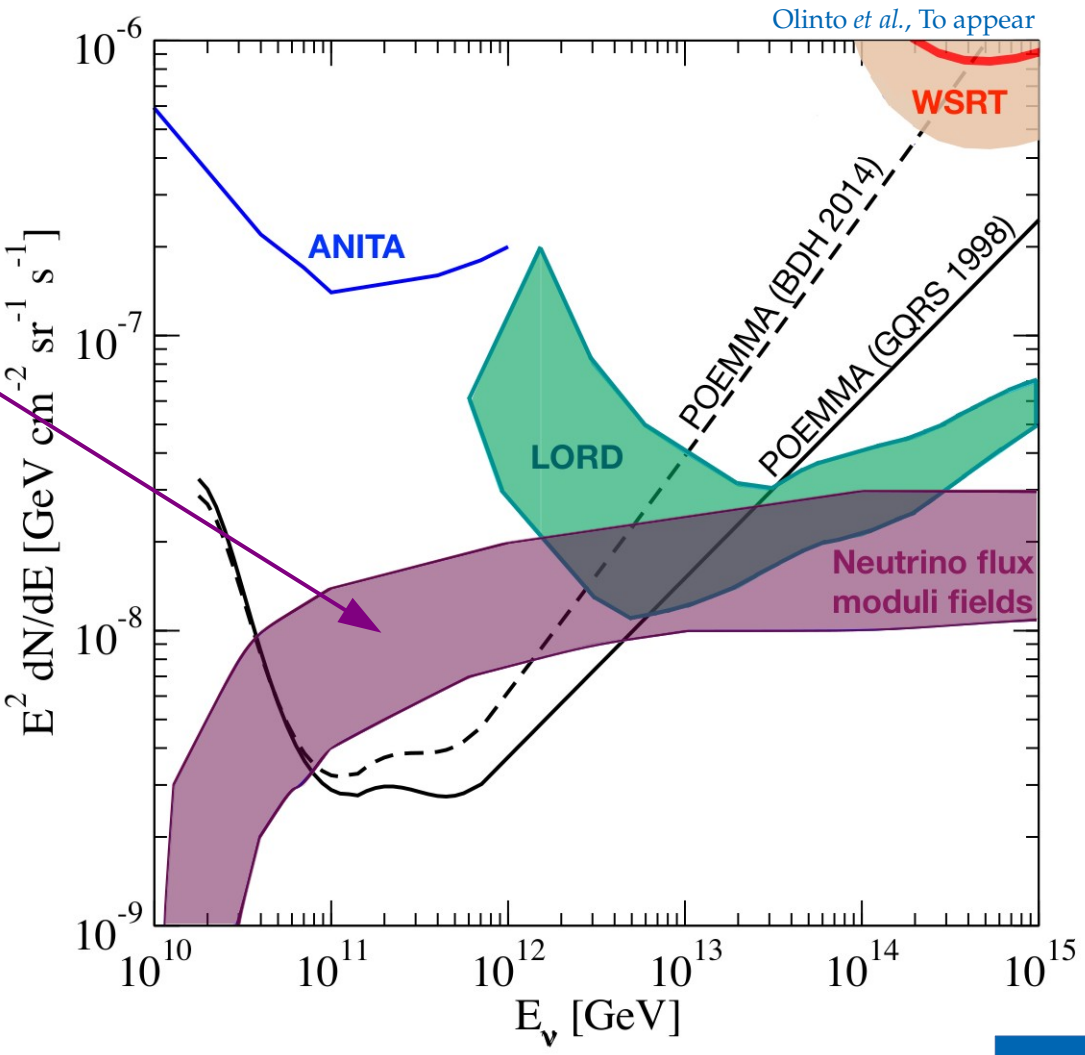
Neutrino flux at Earth

- Diffuse flux depends on:
  - Number density of string loops vs. z
  - Moduli mass, m
  - Moduli coupling strength to SM, α

Gouttenoire, Servant, Simakachorn, *JCAP* 2020

- LORD: Lunar Orbital Radio Detector

Ryabov, Chechin, Gusev, Maung, *Adv. Space Res.* 2016



IV.
The future

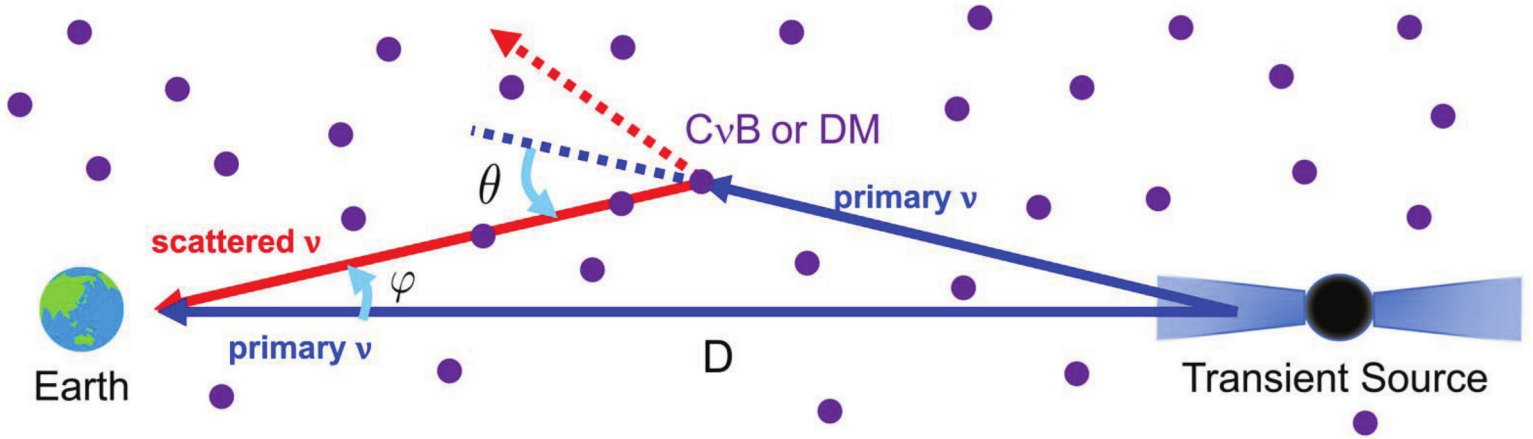
What's next?

- Need detailed studies of POEMMA sensitivity to νSI, ANITA-like events, neutrinos from cosmic strings
- Did not discuss measurement of pp cross section at $s^{1/2} \sim 300$ TeV
- Differences in arrival times between neutrino and gamma-ray flares?
  - Lorentz-invariance violation, νSI delays
- For the future: what can we do with POEMMA360?
  - BSM in the energy spectrum of cosmogenic neutrinos
  - BSM in the arrival directions of cosmogenic neutrinos
  - BSM in neutrino flavor composition?

Backup slides

Delays from secret interactions

Multiple secret νν scatterings may delay the arrival of neutrinos from a transient



Shoemaker & Murase, *PRL* 2019

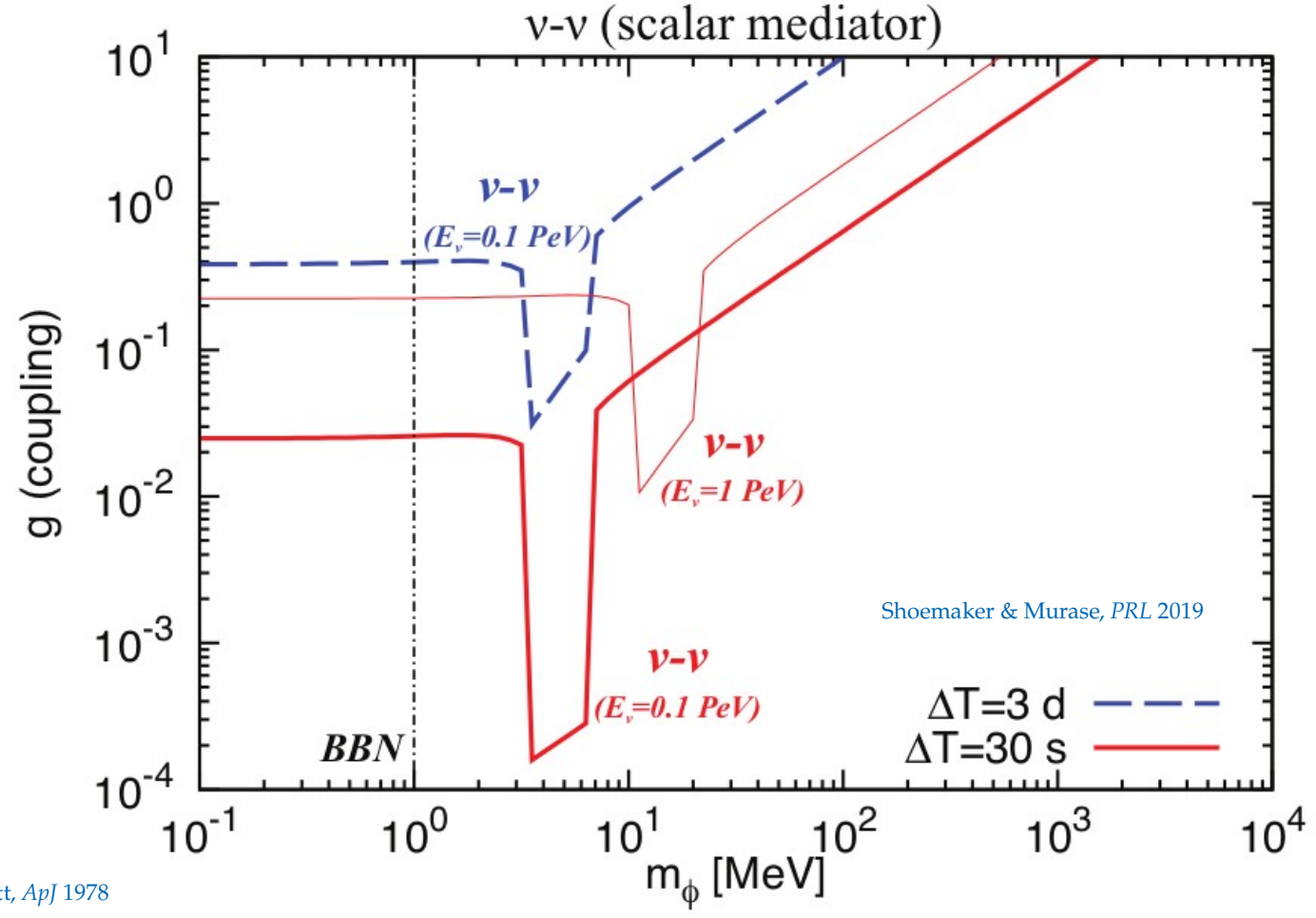
Characteristic time delay —

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

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

See also: Alcock & Hatchett, *ApJ* 1978

Delays from secret interactions



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The multi-messenger connection: a simple picture

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

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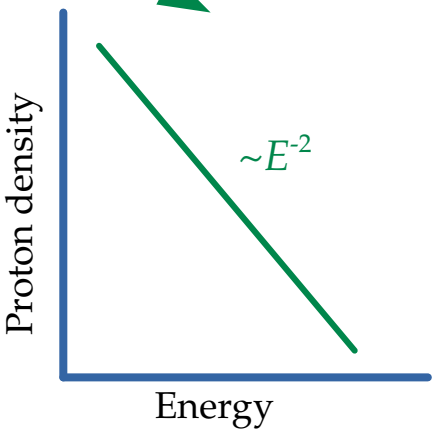

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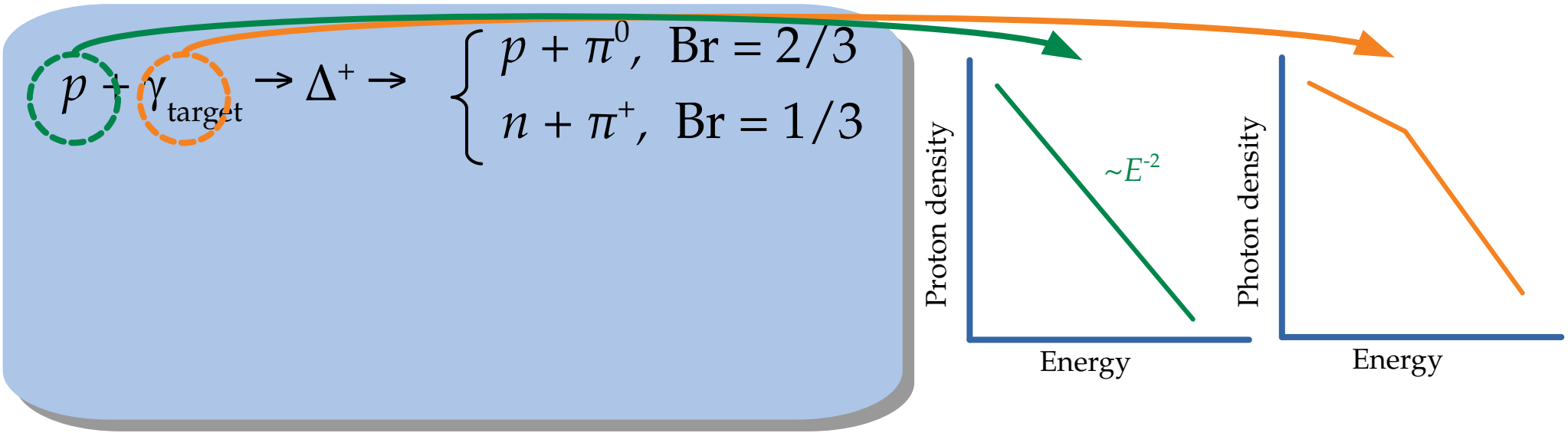

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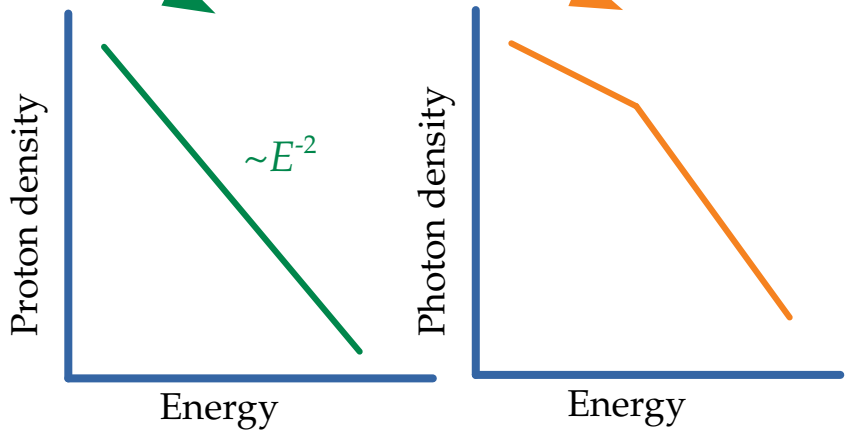
$$\pi^{0} \rightarrow \gamma + \gamma$$

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

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



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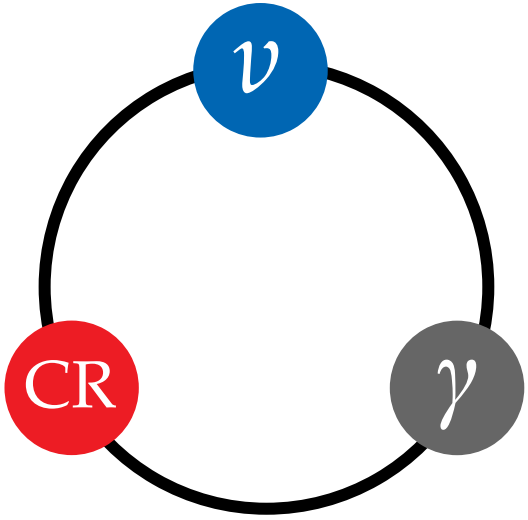


Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 10

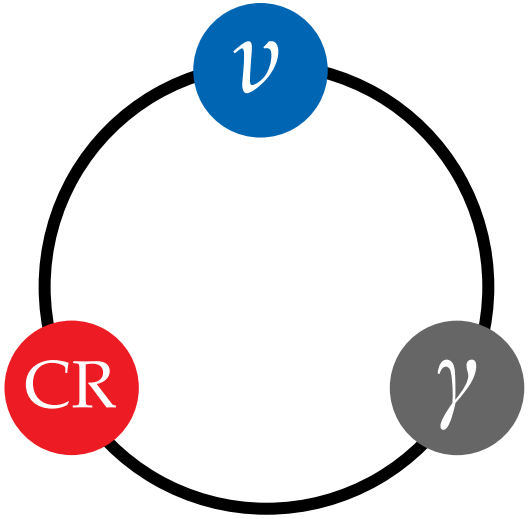
The multi-messenger connection: a simple picture

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

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

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

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

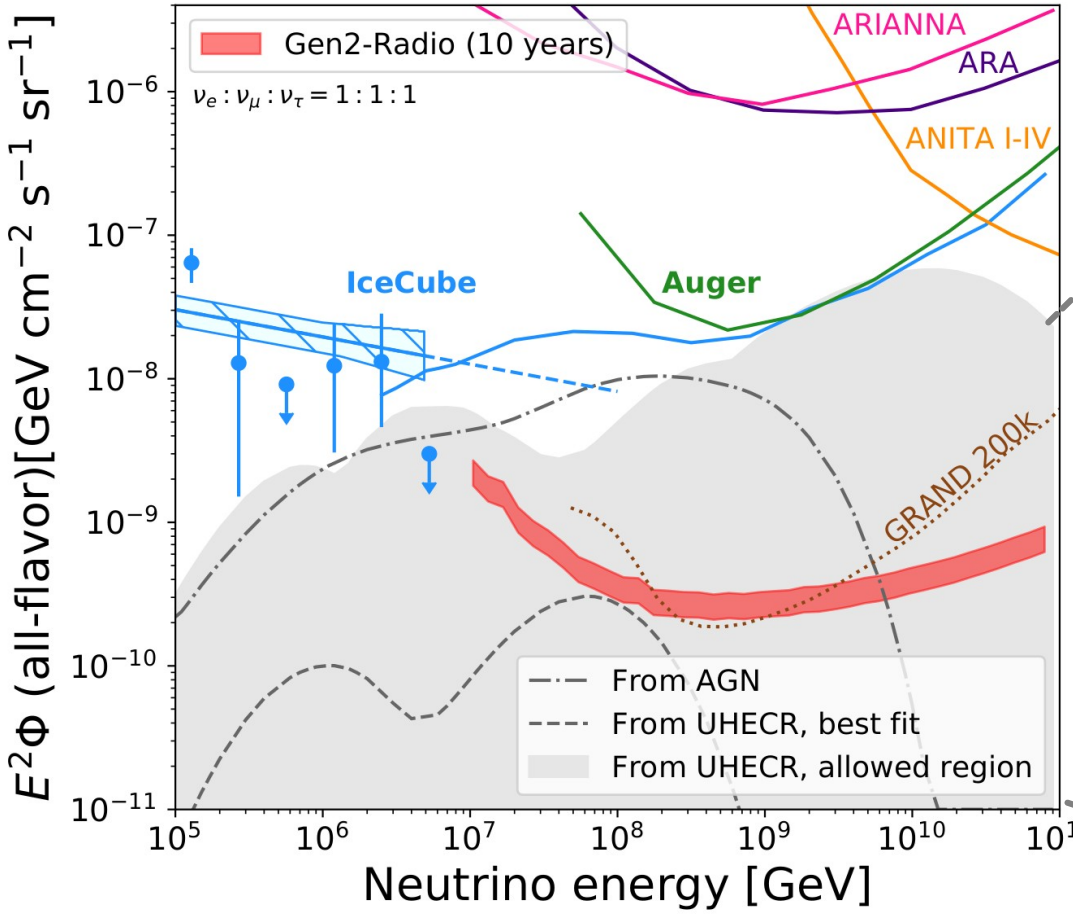


1 PeV 20 PeV

Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 10

Cosmogenic ν flux: how low?



Higher ν flux

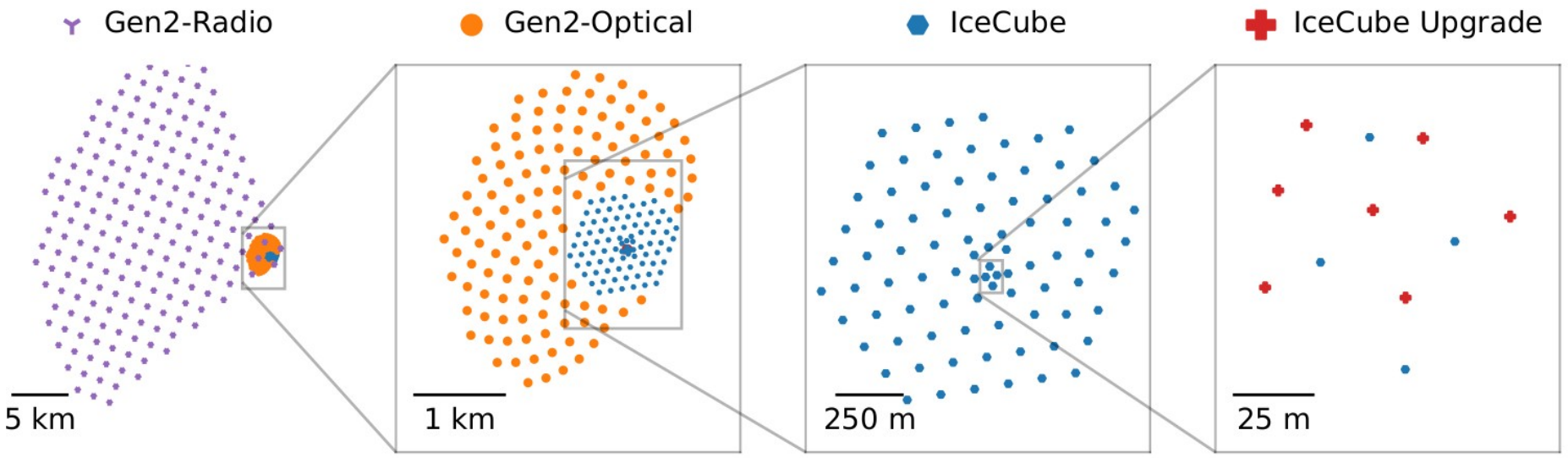
These are all uncertainly known

Lower ν flux

Higher	Harder	Many far	Lighter
Maximum CR energy at sources	UHECR spectral index	Source number density	UHECR mass composition
Lower	Softer	Many near	Heavier

IceCube-Gen2, 2008.04323

IceCube-Gen2



~2040

10s km^3

> 100 PeV ν

~8 km^3

TeV–10 PeV ν

Today

1 km^3

TeV–few PeV ν

2023

7 new strings

GeV–TeV ν

IceCube-Gen2, 2008.04323

The Universe is opaque to UHECRs

Photohadronic processes:

$$p + \gamma \rightarrow \Delta \rightarrow \begin{cases} \nearrow \gamma + \gamma \\ p + \pi^0 \\ n + \pi^+ \\ \searrow \nu_\mu + \bar{\nu}_\mu + \nu_e + e^+ \end{cases}$$

Pair production:

$$p + \gamma \rightarrow p + e^- + e^+$$

Greisen-Zatsepin-Kuzmin (GZK) cut-off:

$$E_p \approx \frac{0.16\ \text{GeV}}{0.66\ \text{meV}} \approx 2 \cdot 10^{11}\ \text{GeV}$$

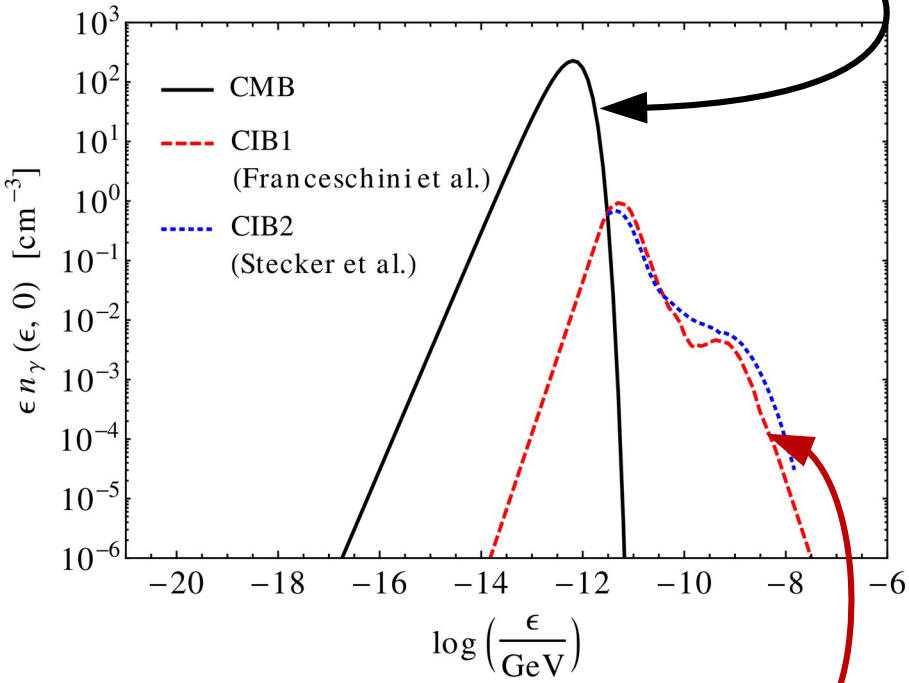
(Assuming only photohadronic interaction)

Accounting also for pair production and CMB width:

$$E_p \approx 5 \cdot 10^{10}\ \text{GeV}$$

Target photon spectra (at $z = 0$):

CMB: Microwave (black body, <ϵ> ~ 0.66 meV)



CIB: optical (stars) + infrared (dust remission)

$n_\gamma(z) = (1+z)^3\, n_\gamma(z=0)$ (exact only for CMB)

Greisen *PRL* 1966; Zatsepin & Kuzmin, *JETP* 1966

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$$p + \gamma \rightarrow \Delta \rightarrow \begin{cases} p + \pi^0 \\ n + \pi^+ \end{cases} \begin{array}{l} \nearrow \gamma + \gamma \\ \searrow \nu_\mu + \bar{\nu}_\mu + \nu_e + e^+ \end{array}$$

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Mean free path:

$$(n_\gamma \langle\sigma\rangle_{p\gamma})^{-1} = (413\ \text{cm}^{-3} \times 200\ \mu\text{barn})^{-1}$$
$$\approx 10^{25}\ \text{cm}$$
$$\approx 4\ \text{Mpc}$$

Energy-loss scale:

$$L = (E/\Delta E)(n_\gamma \langle\sigma\rangle_{p\gamma})^{-1}$$
$$\approx (1/0.2) \times 4\ \text{Mpc}$$
$$\approx 20\ \text{Mpc}$$

A more detailed calculation yields

$$L_{\text{GZK}} = 50\ \text{Mpc}$$

Greisen *PRL* 1966; Zatsepin & Kuzmin, *JETP* 1966

The Universe is opaque to UHECRs

Photohadronic processes:

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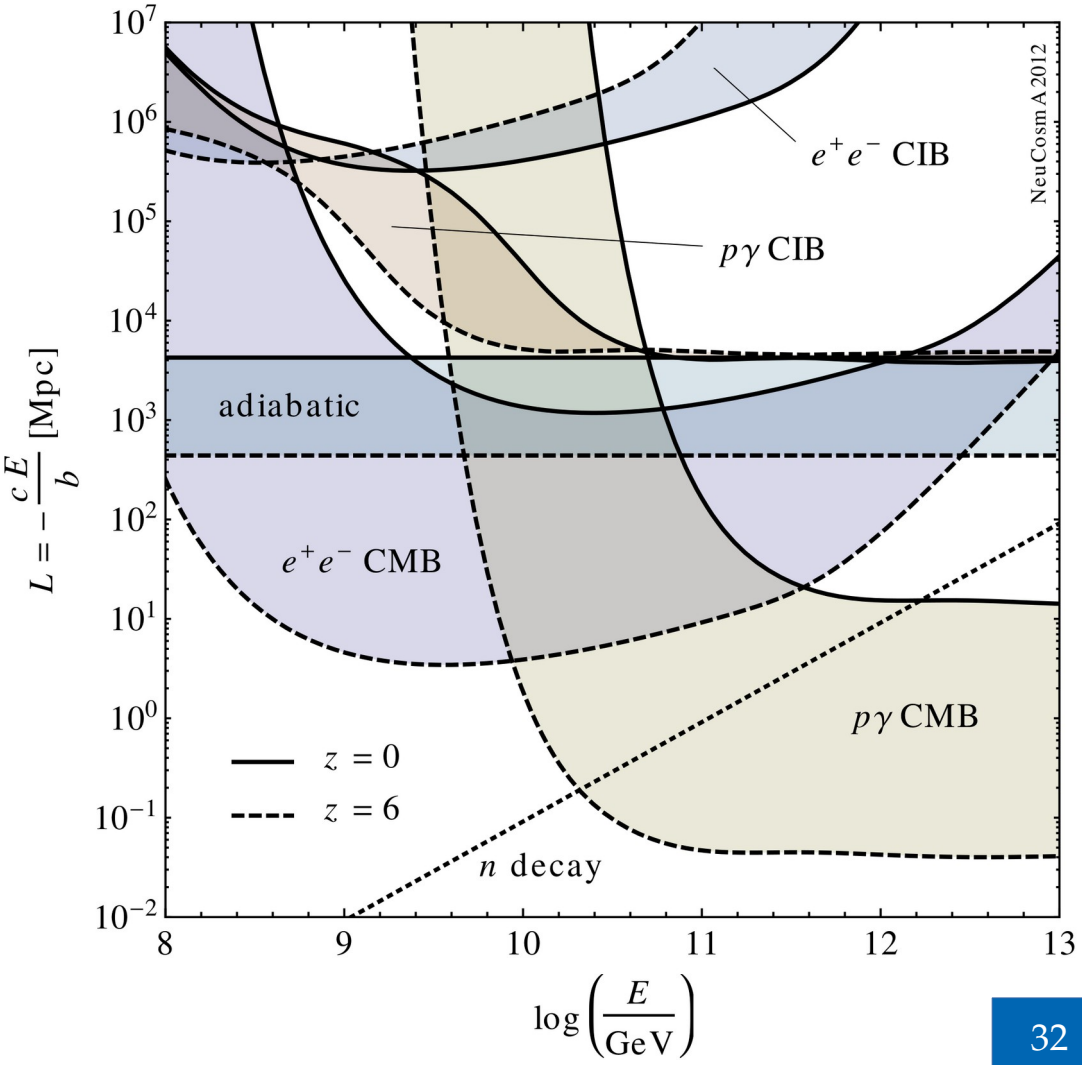


Greisen *PRL* 1966; Zatsepin & Kuzmin, *JETP* 1966

The Universe is *also* opaque to PeV gamma rays

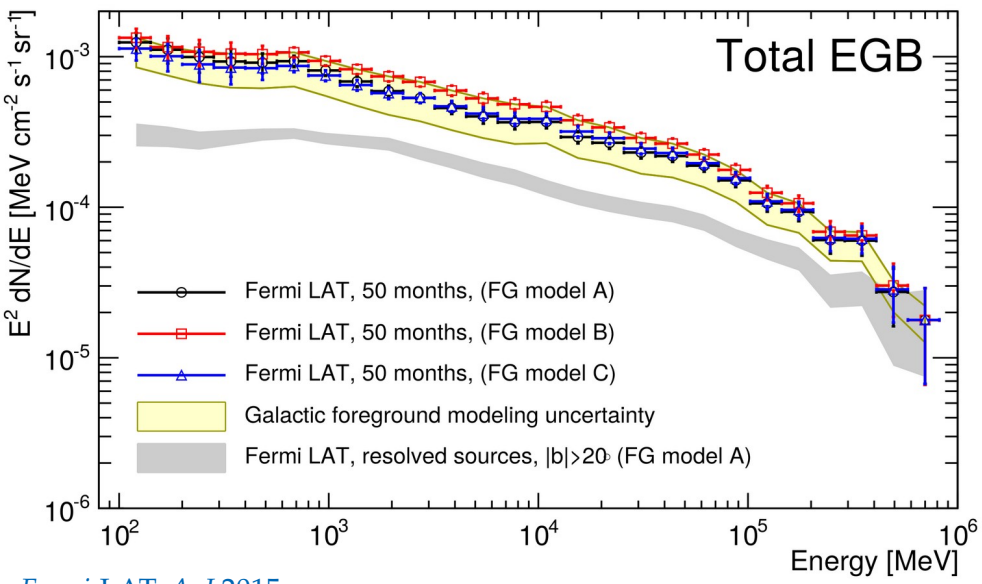
Pair production:

$$\gamma_{astro} + \gamma_{cosmo} \rightarrow e^- + e^+$$

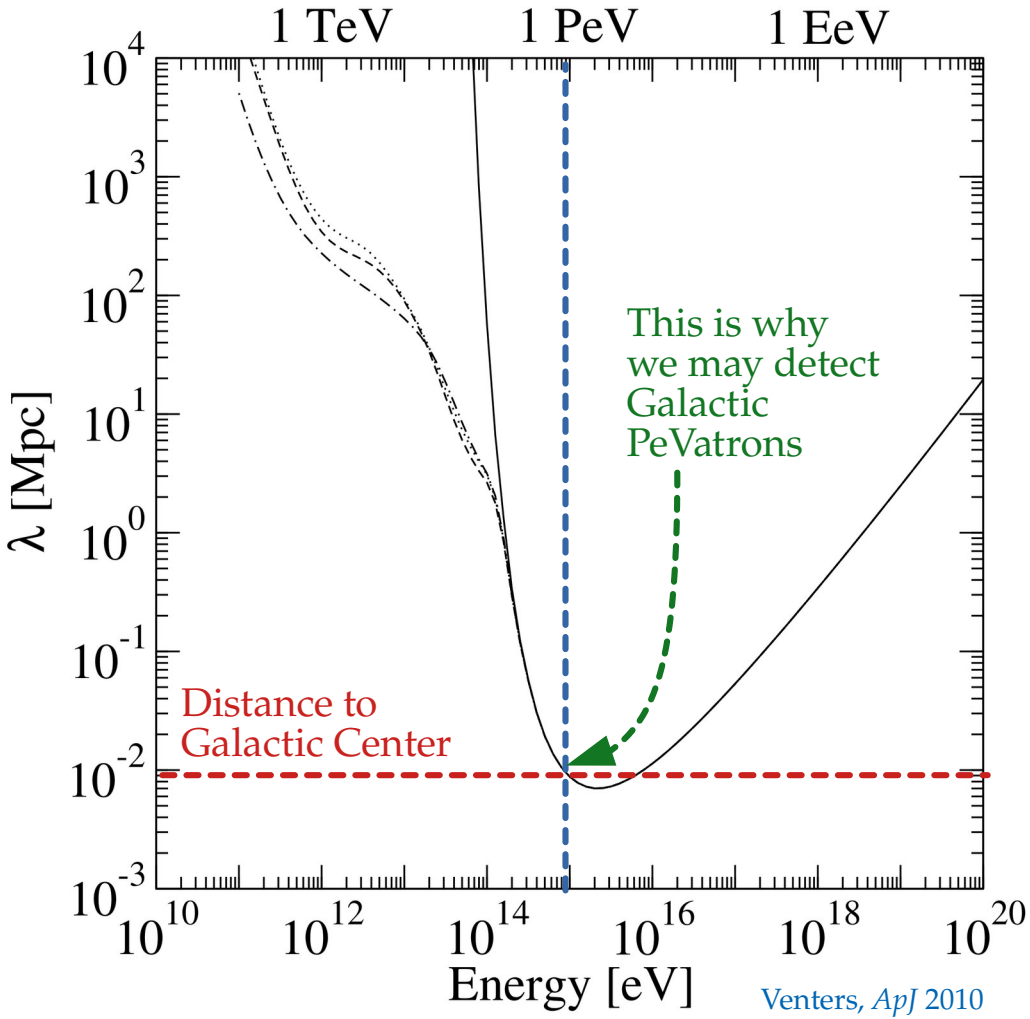
Inverse Compton scattering:

$$e^{\pm} + \gamma_{cosmo} \rightarrow e^{\pm} + \gamma$$

PeV gamma rays cascade down to MeV–GeV:



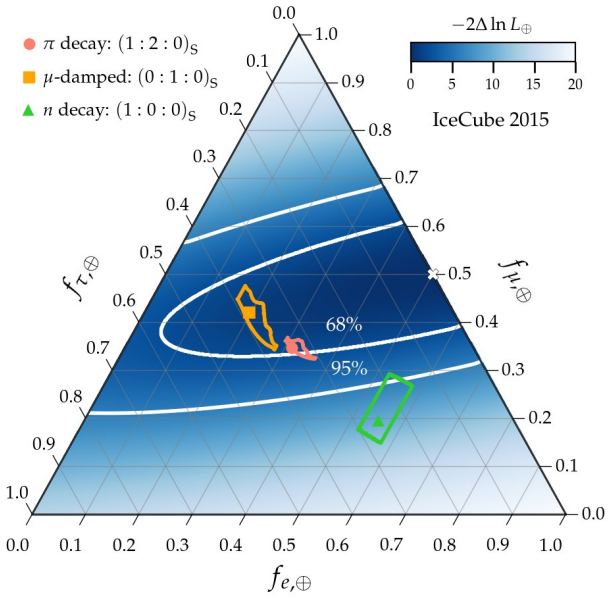
Fermi-LAT, *ApJ* 2015



Venters, *ApJ* 2010

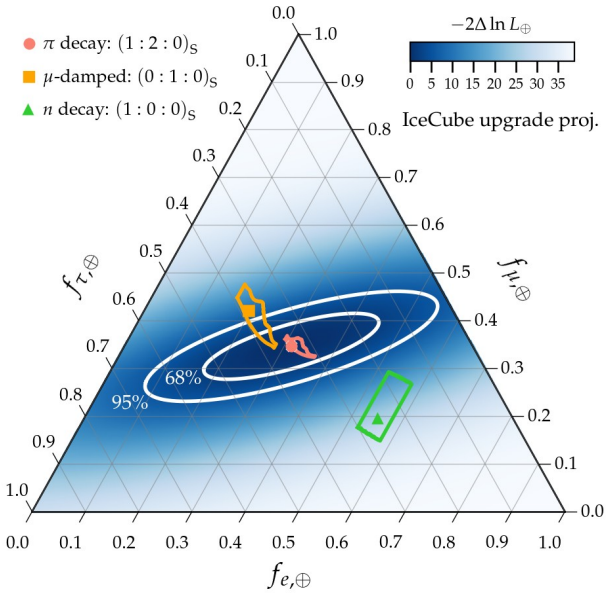
IceCube flavor composition

Today
IceCube

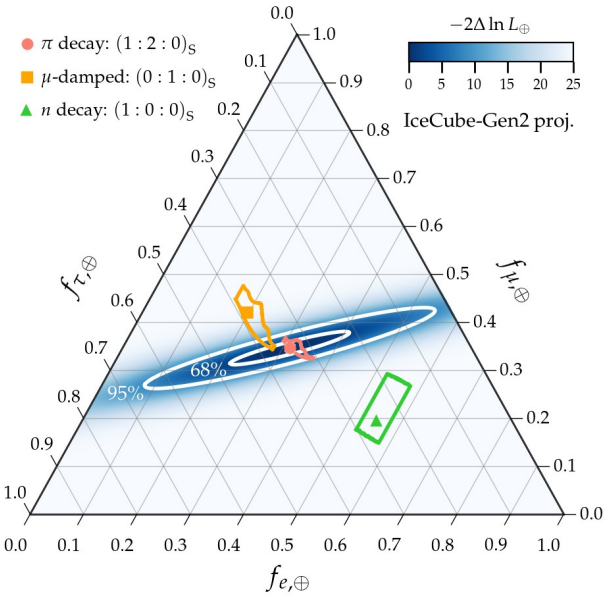


- Best fit:
  $(f_e : f_\mu : f_\tau)_\oplus = (0.49 : 0.51 : 0)_\oplus$
- Compatible with standard source compositions
- Hints of one ν_τ (not shown)

Near future (2022)
IceCube upgrade



In 10 years (2030s)
IceCube-Gen2



Assuming production by the full pion decay chain

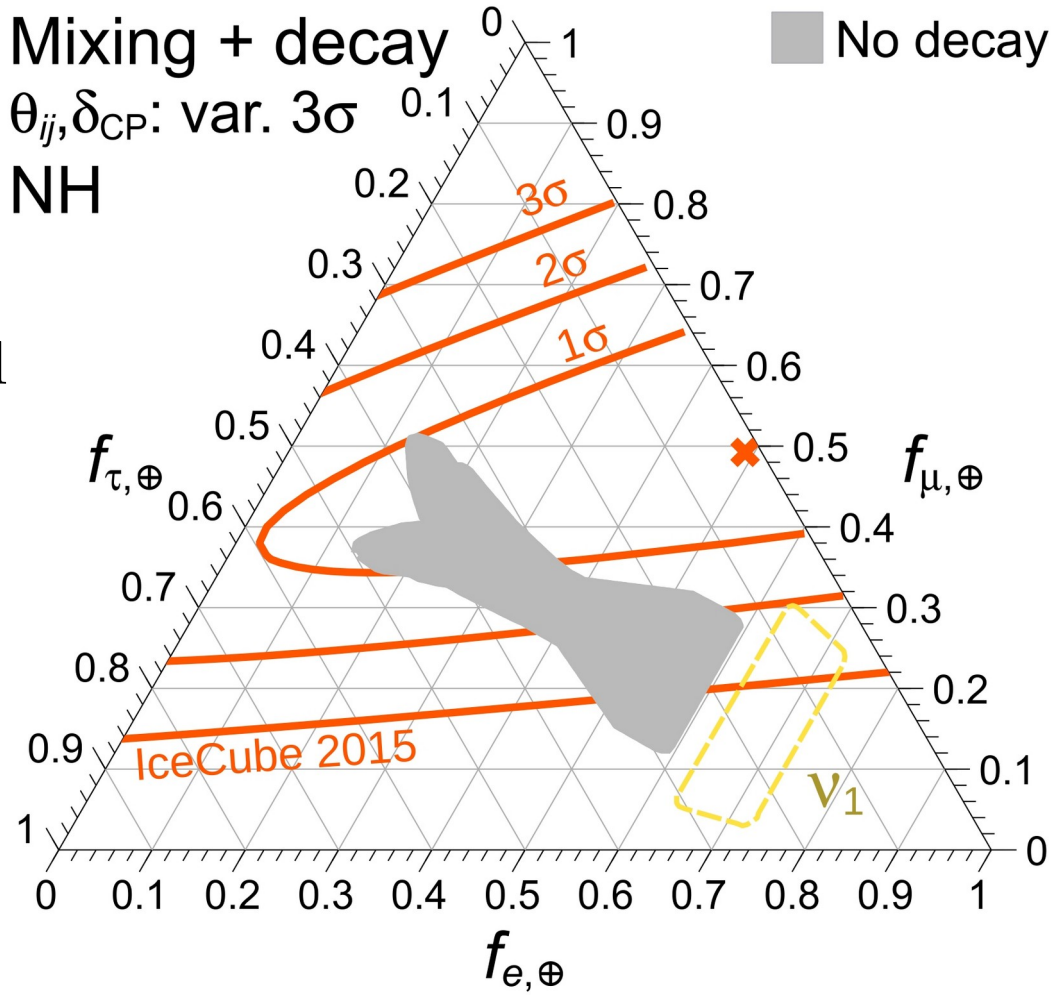
Plus possibly better flavor-tagging, *e.g.*, muon and neutron echoes
[Li, **MB**, Beacom *PRL* 2019]

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

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Fraction of ν_2, ν_3 remaining at Earth

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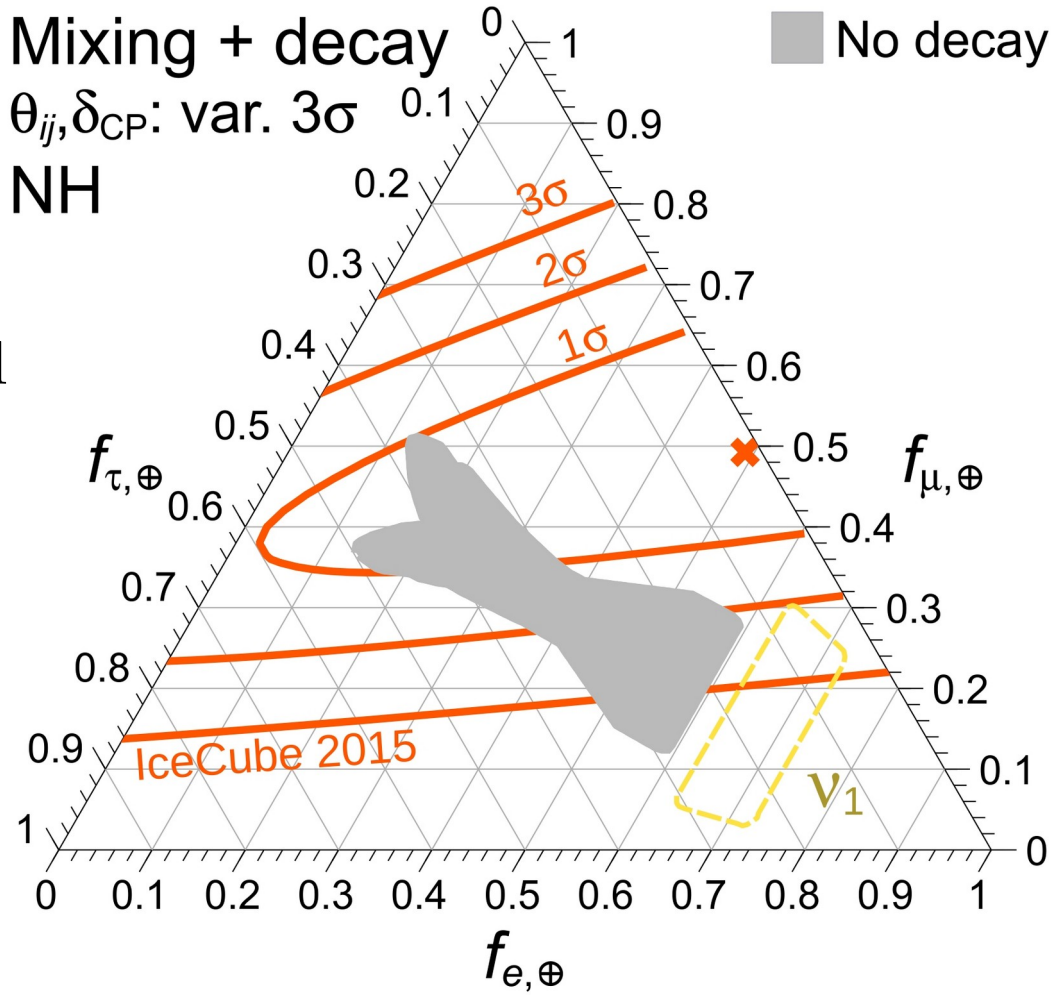

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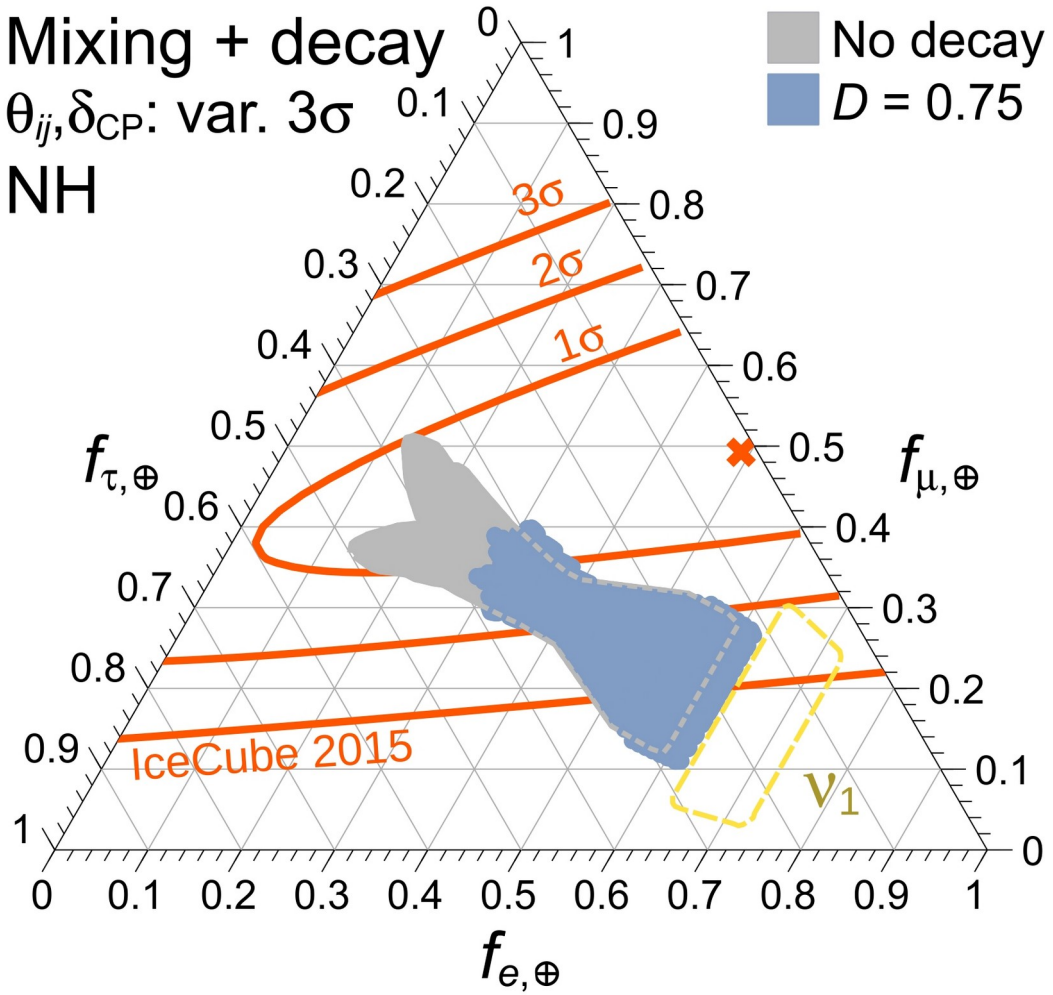

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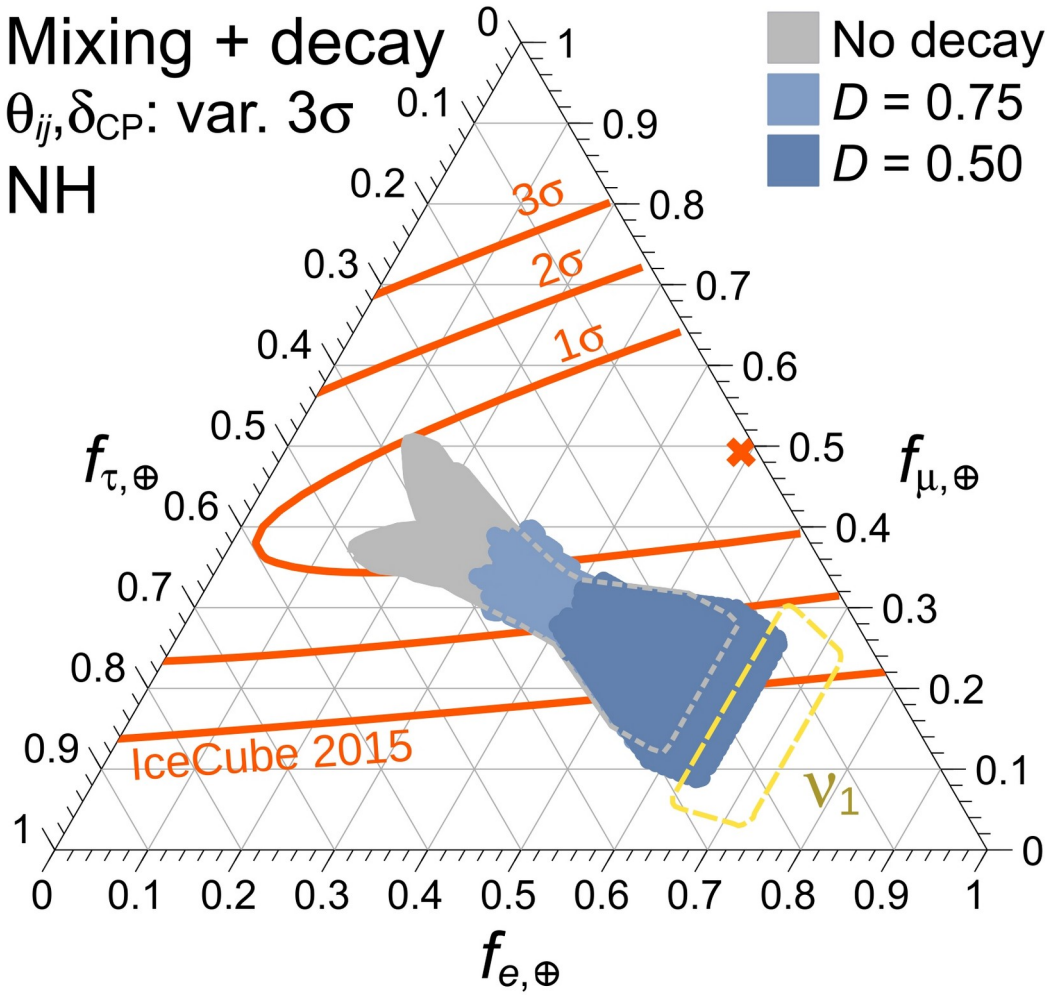

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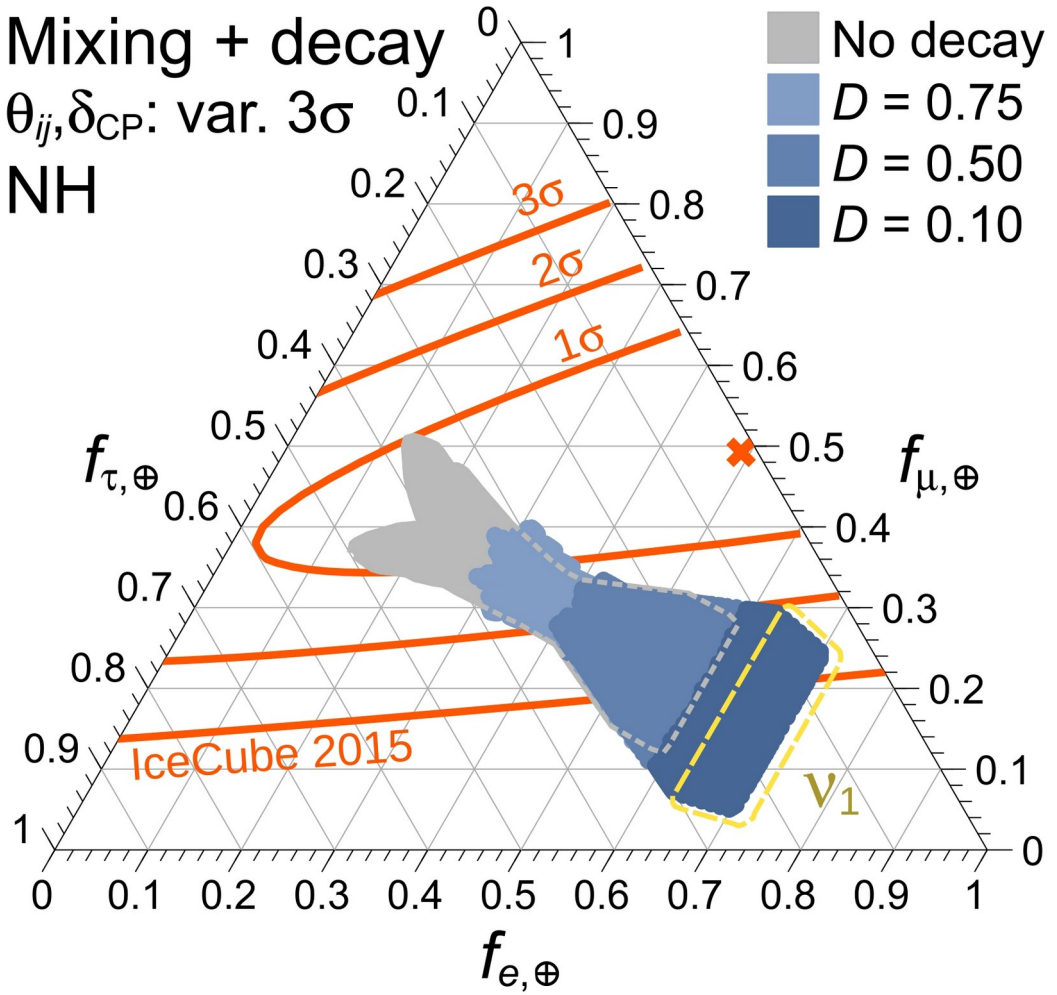

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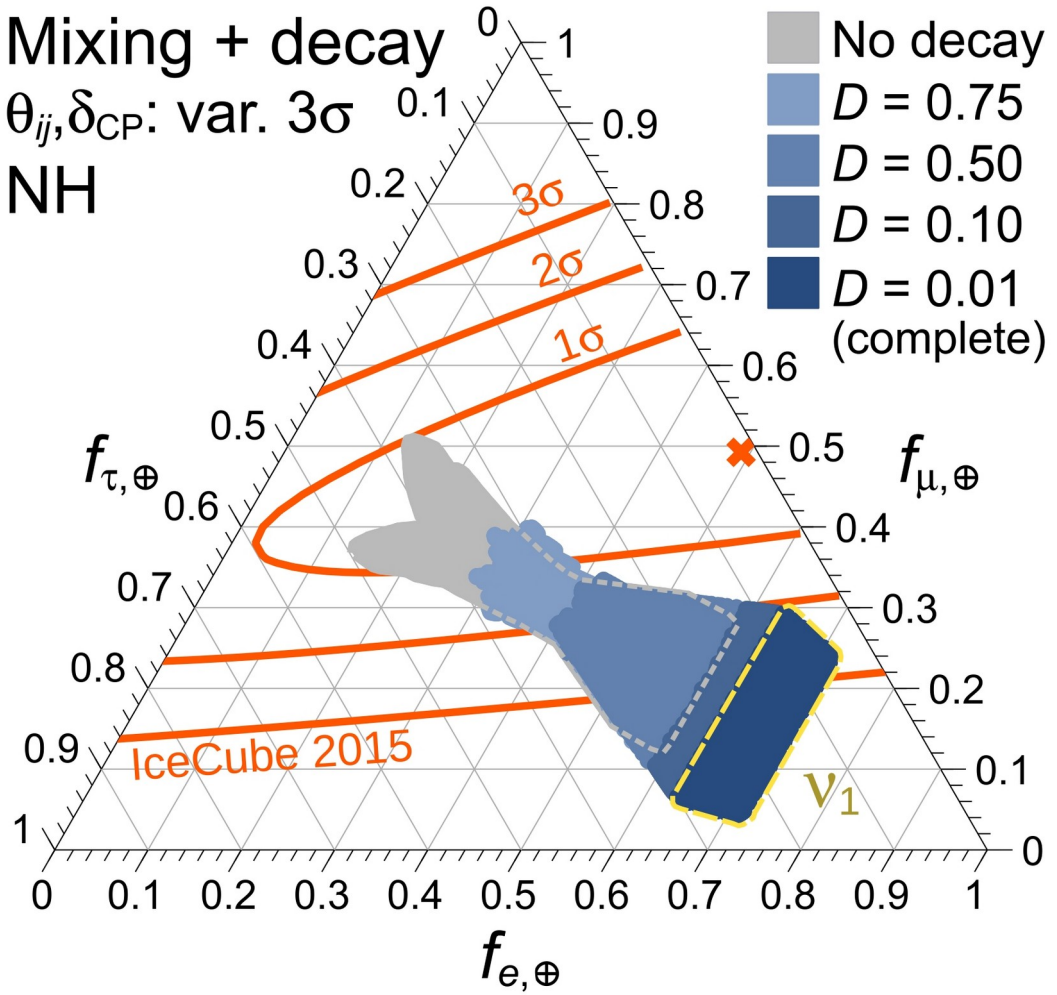

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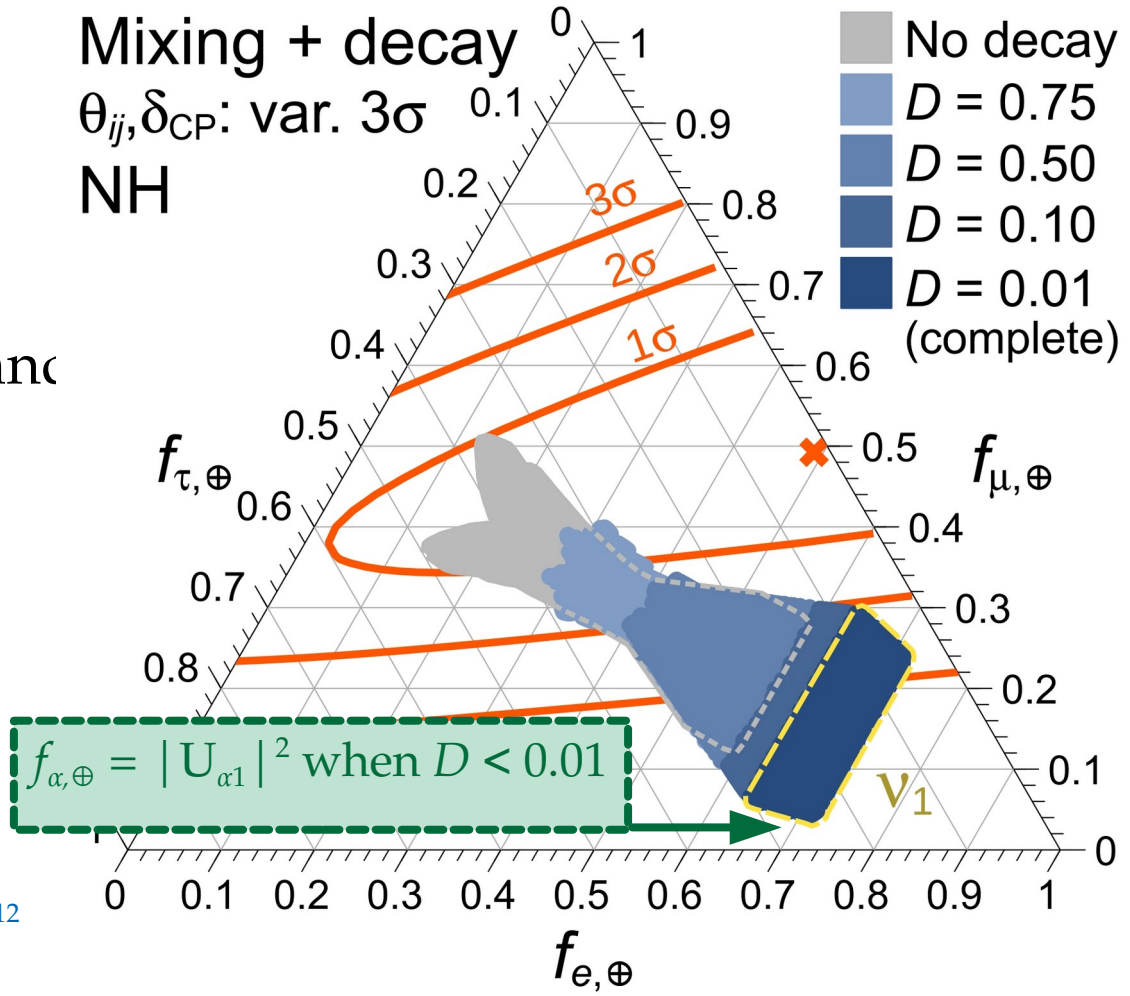

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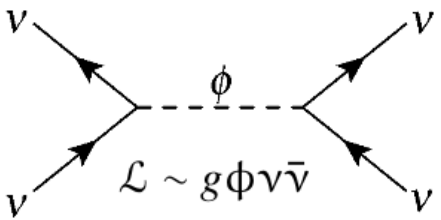
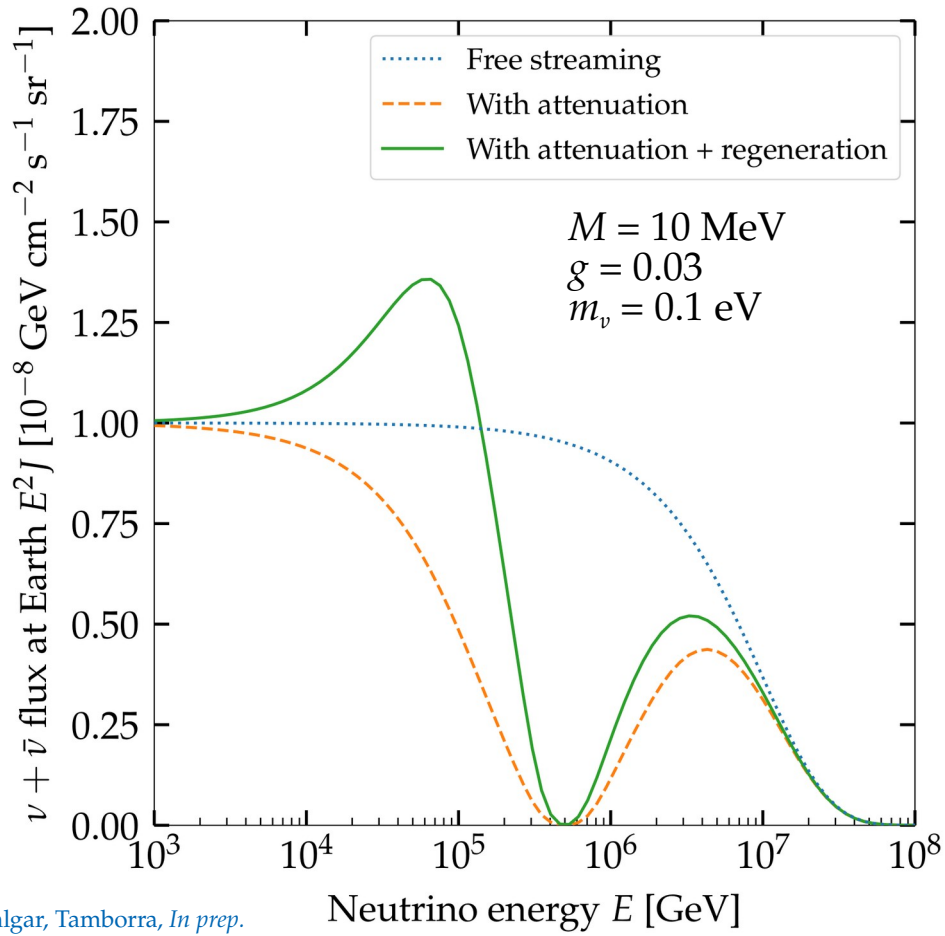
New physics in the spectral shape: νν interactions

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



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

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



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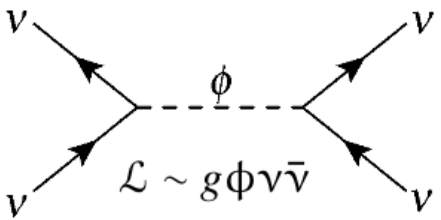

New coupling

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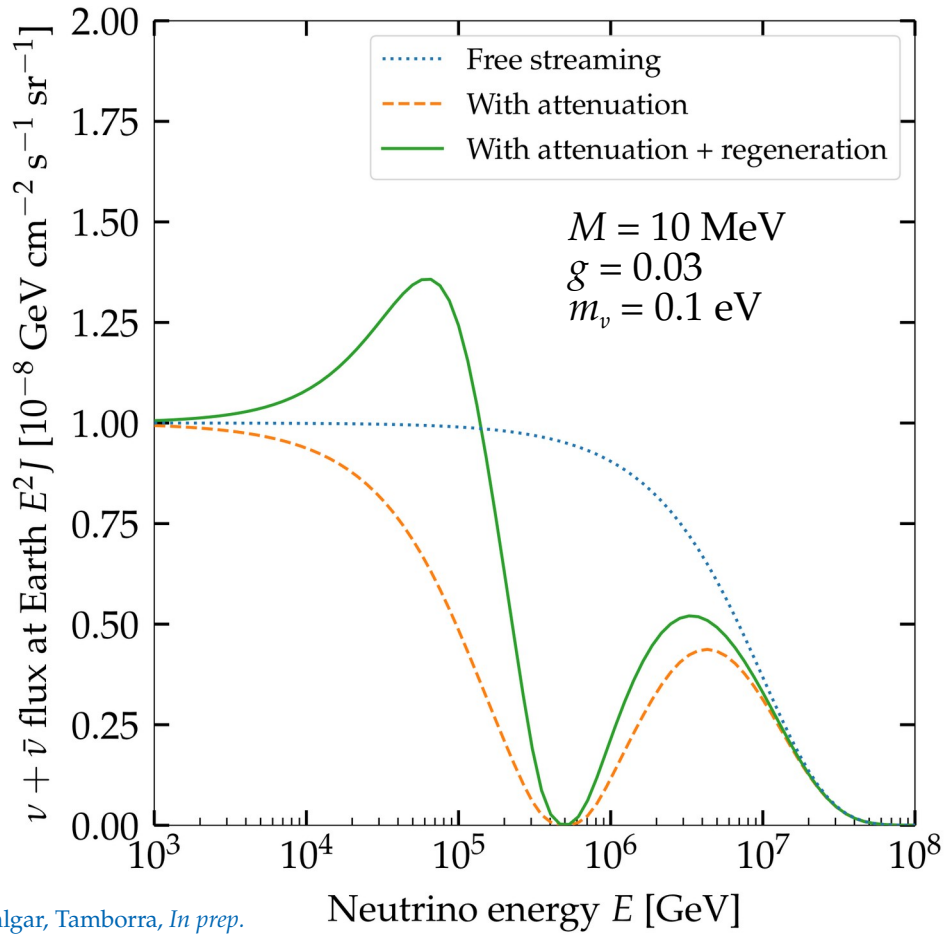
Mediator mass

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



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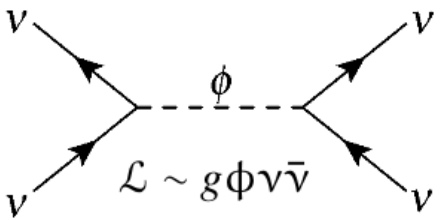

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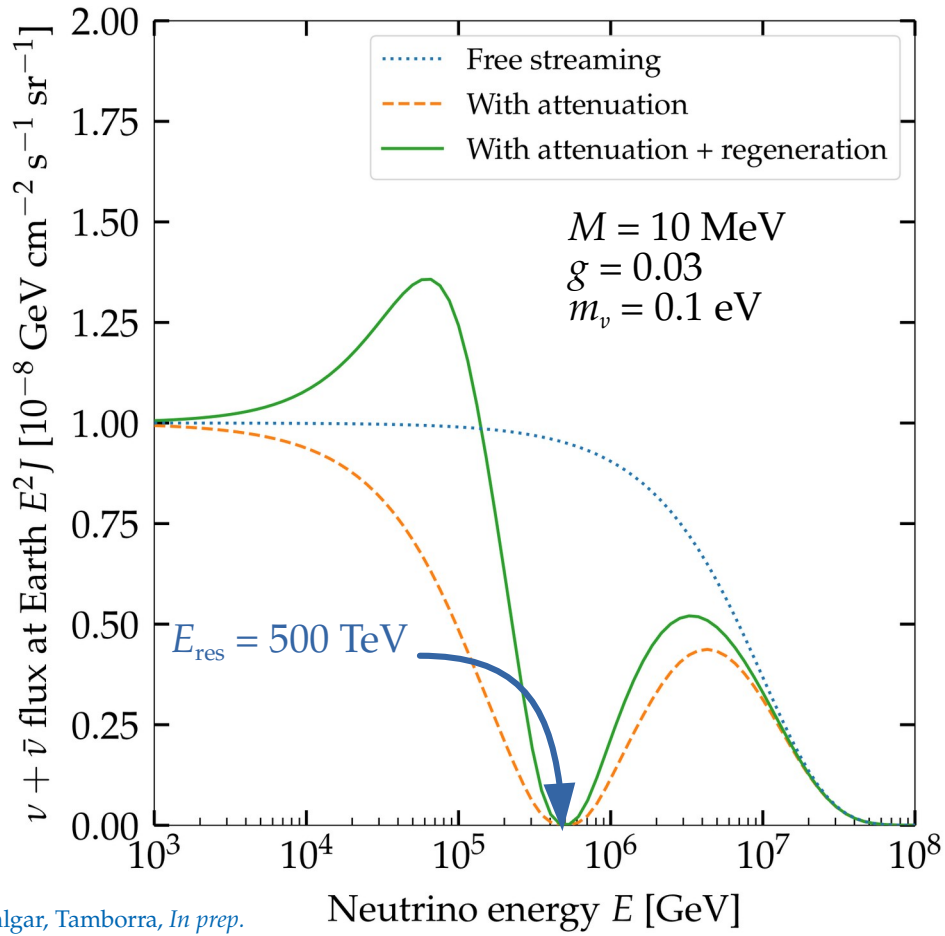

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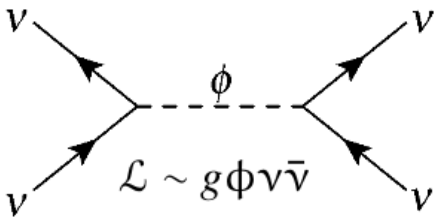

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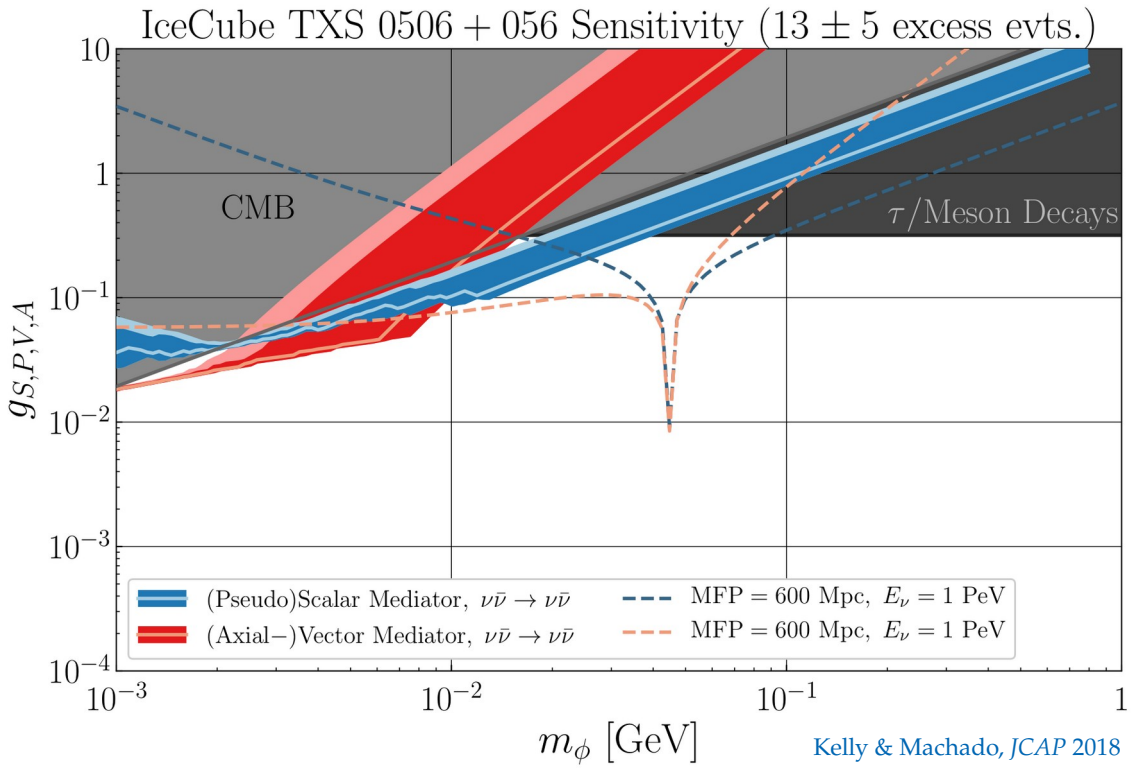
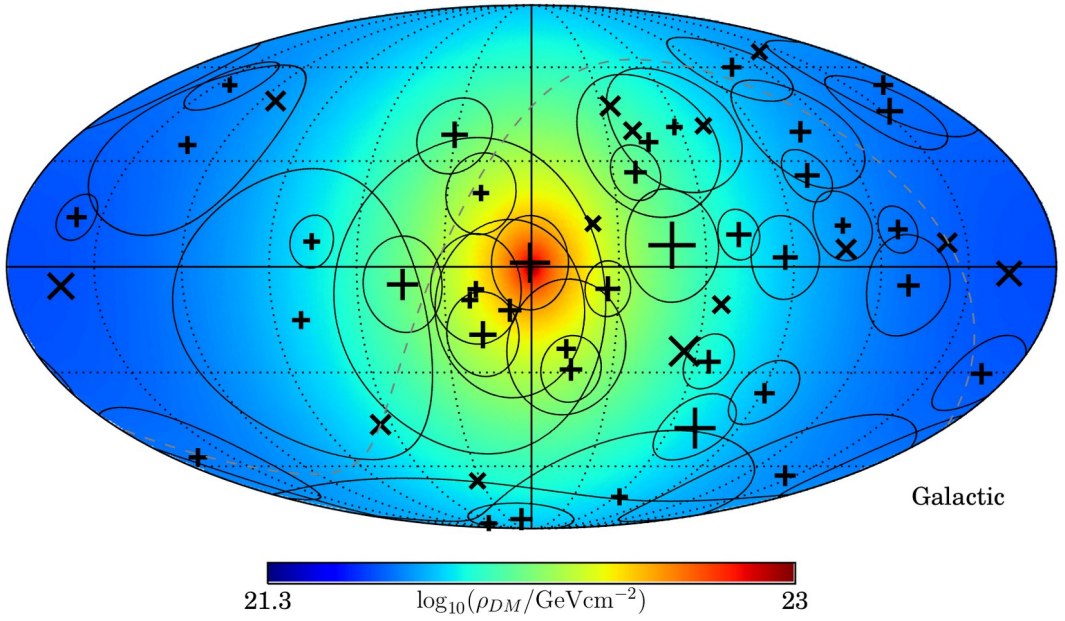
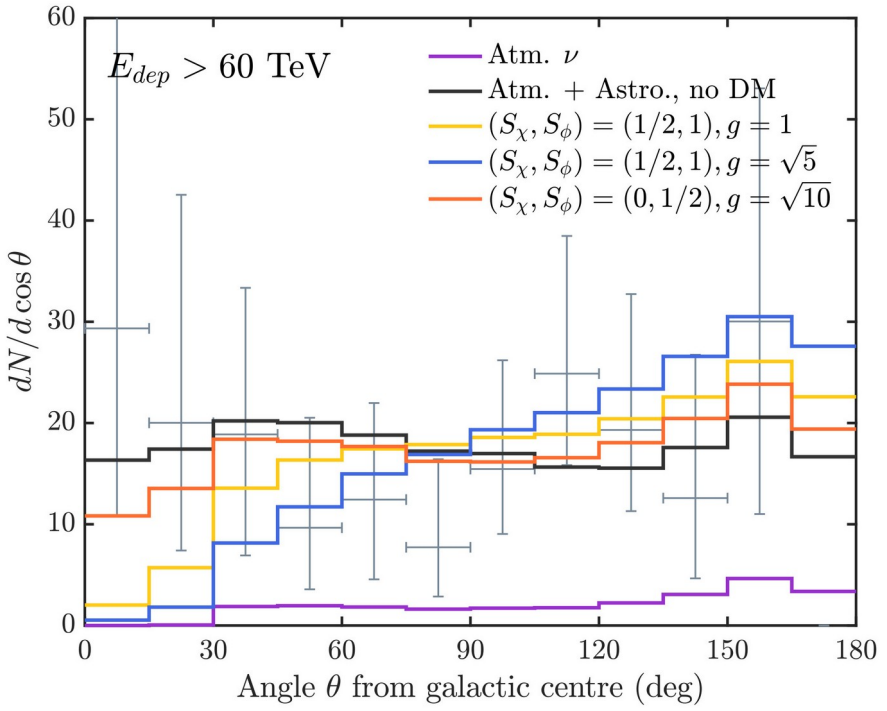


Kelly & Machado, *JCAP* 2018

New physics in the angular distribution: ν-DM interactions

Interaction between astrophysical neutrinos and the Galactic dark matter profile –





Expected: Fewer neutrinos coming from the Galactic Center

Observed: Isotropy

Argüelles, Kheirandish, Vincent, *PRL* 2017

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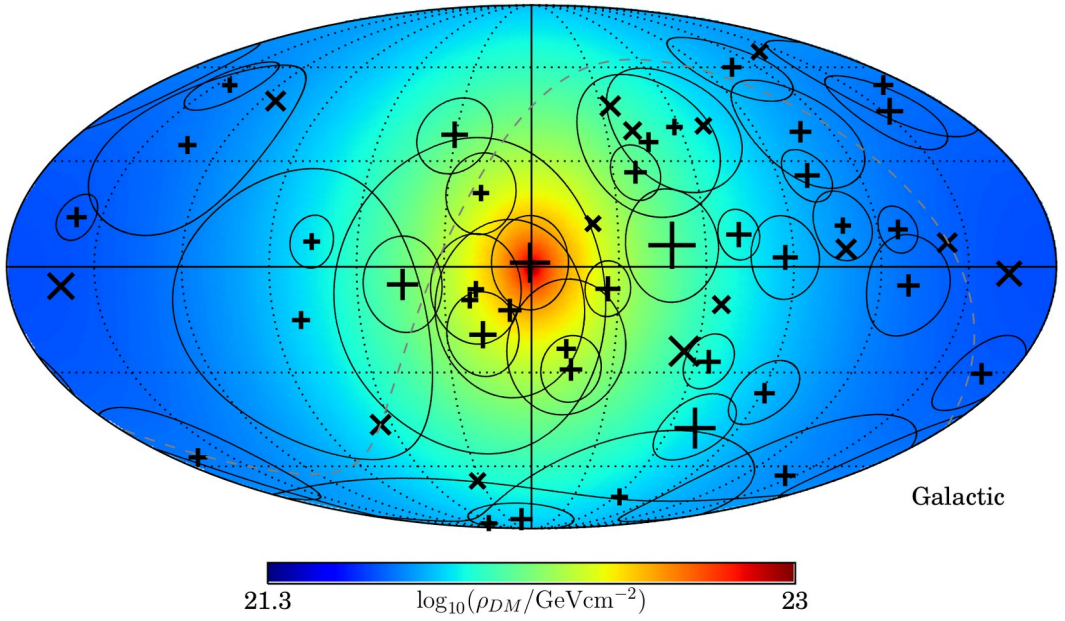

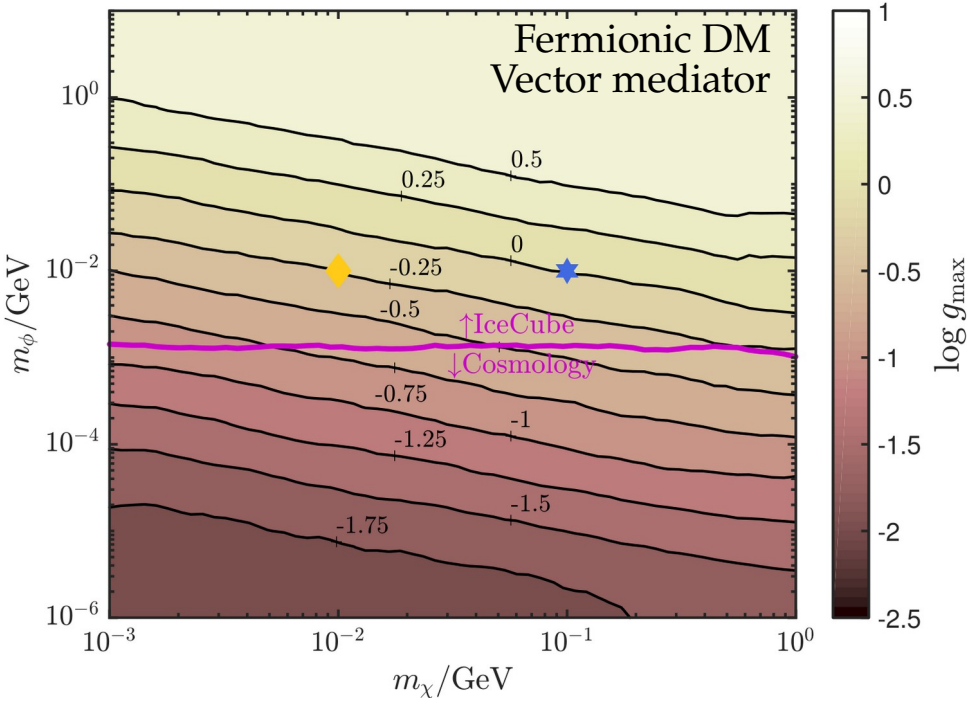

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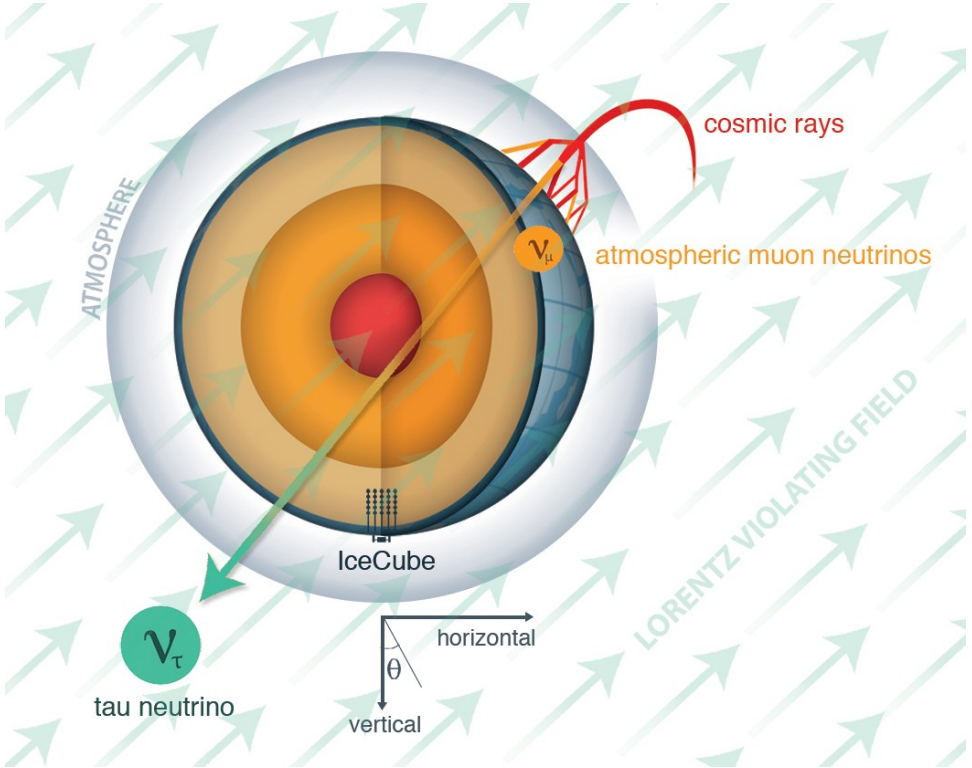
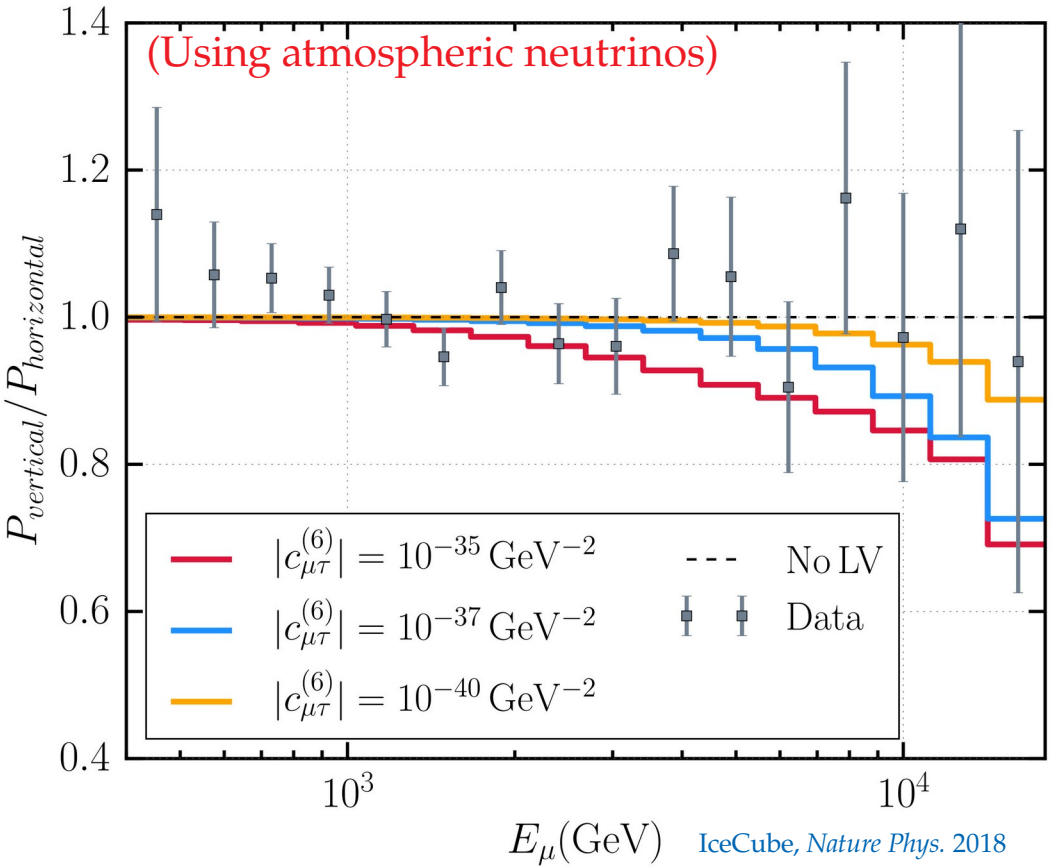
New physics in the energy & angular distribution

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





IceCube, *Nature Phys.* 2018

New physics in the energy & angular distribution

Lorentz violation

Standard oscillations

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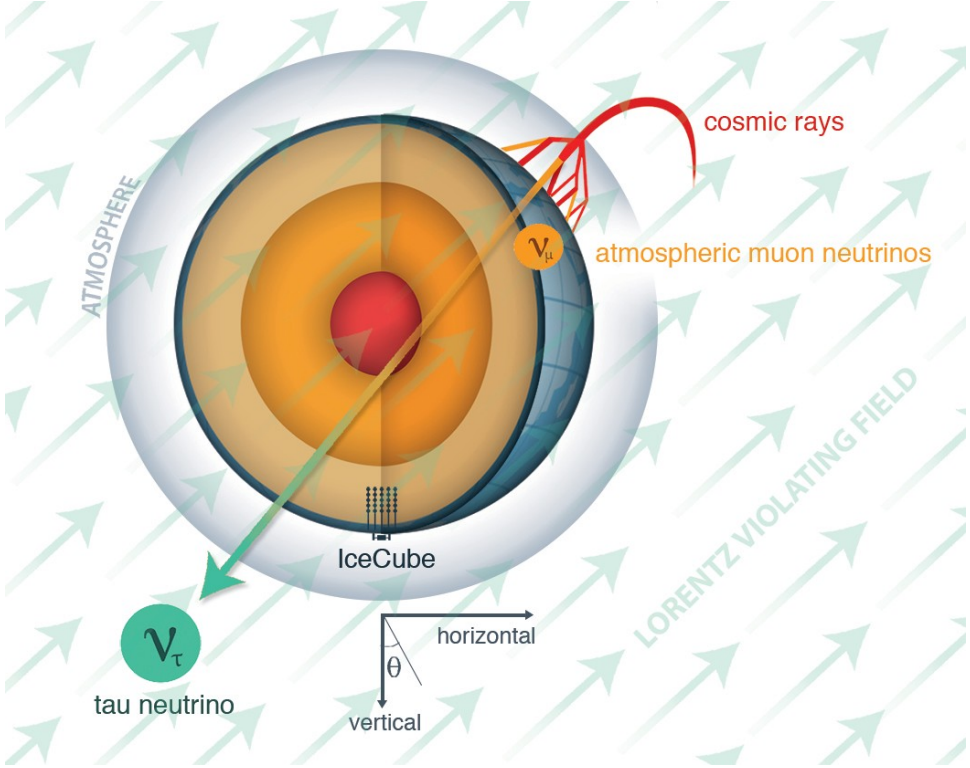

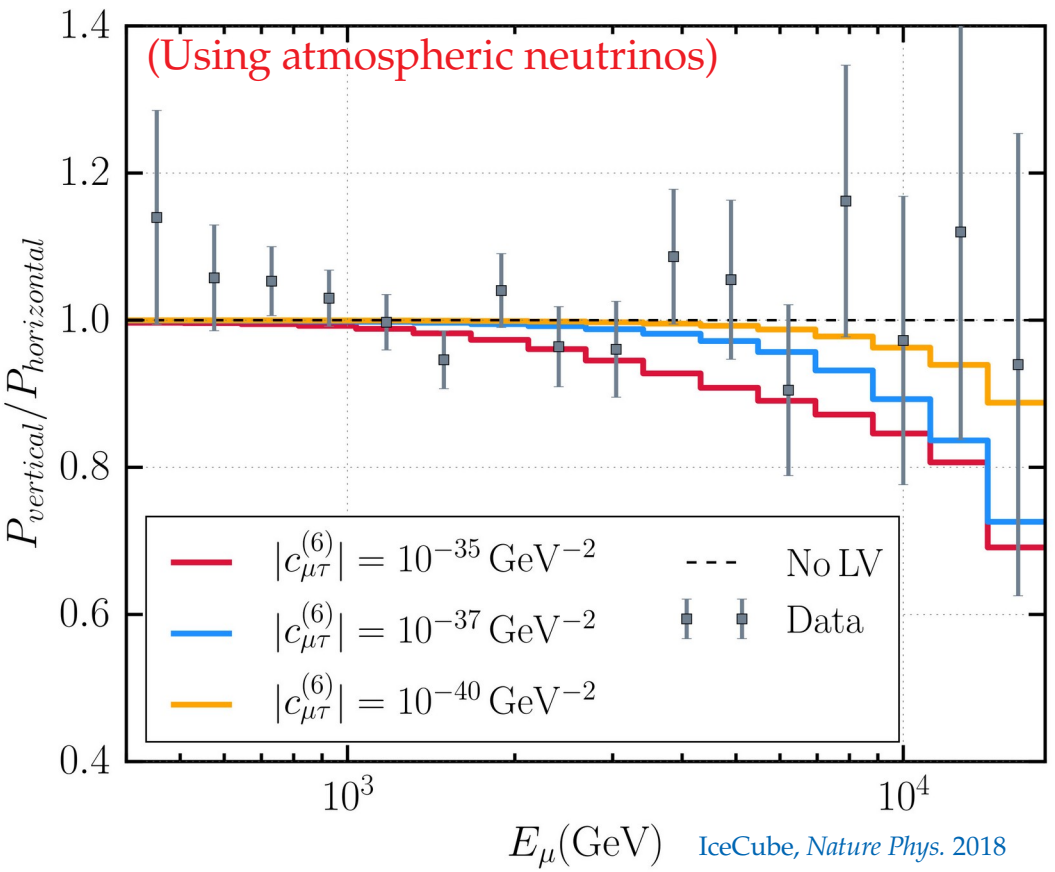

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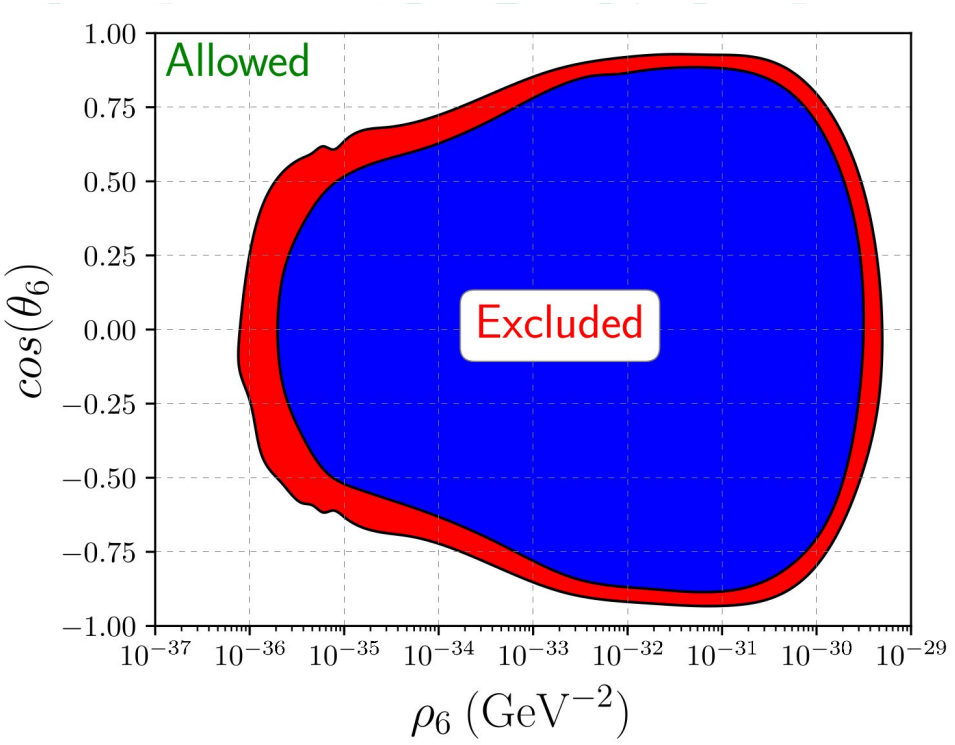
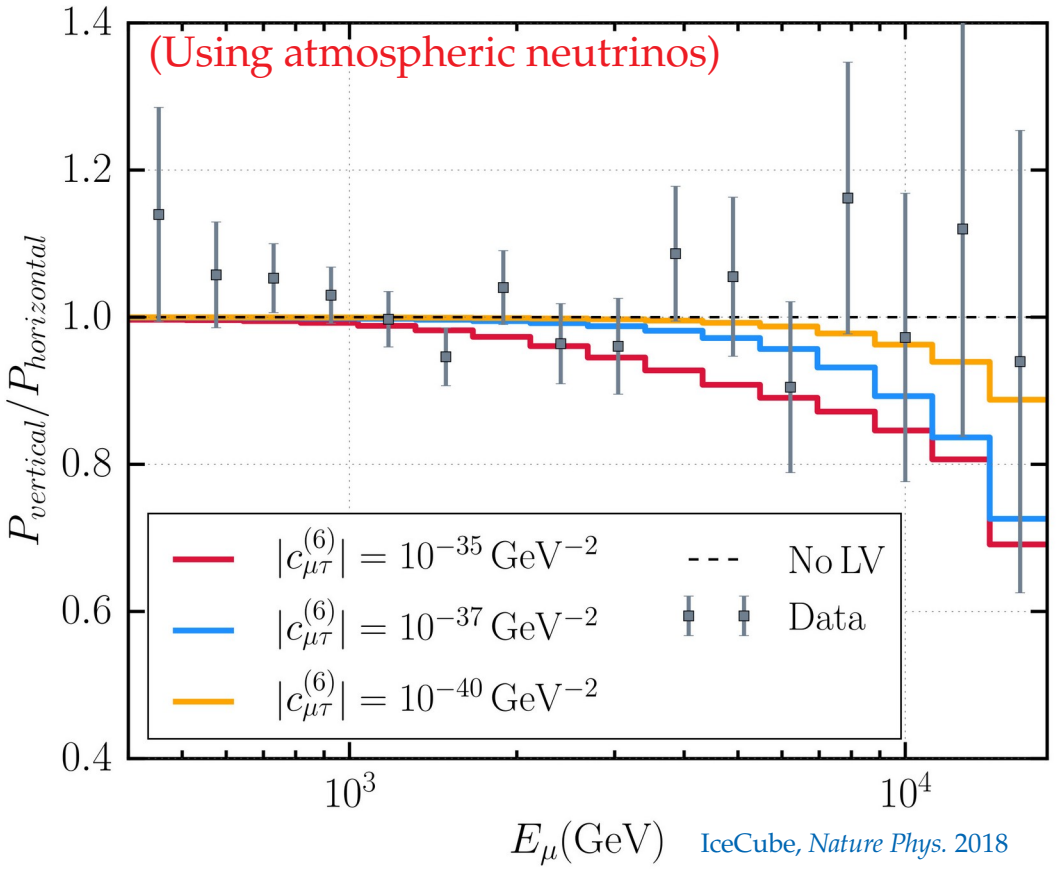
Best bounds come from IceCube





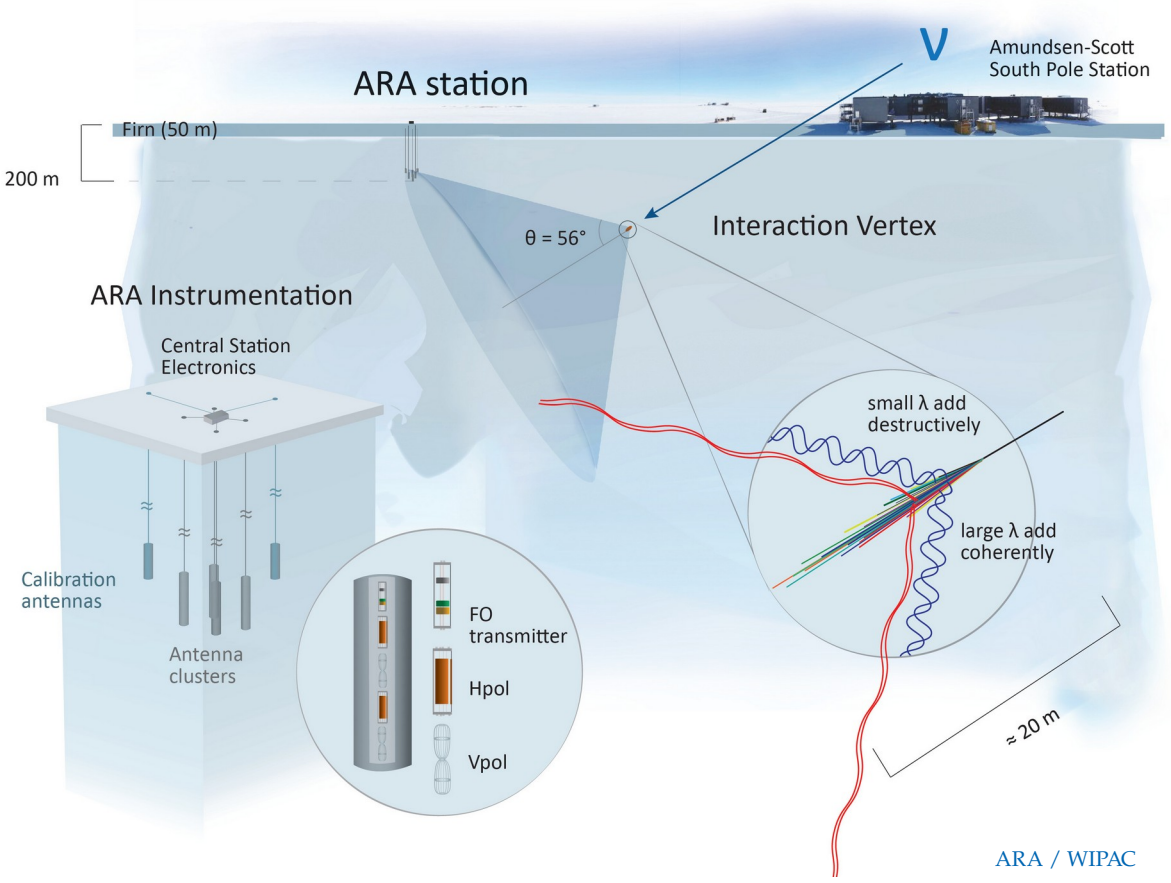
IceCube, *Nature Phys.* 2018

Radio-detection of UHE neutrinos in ice

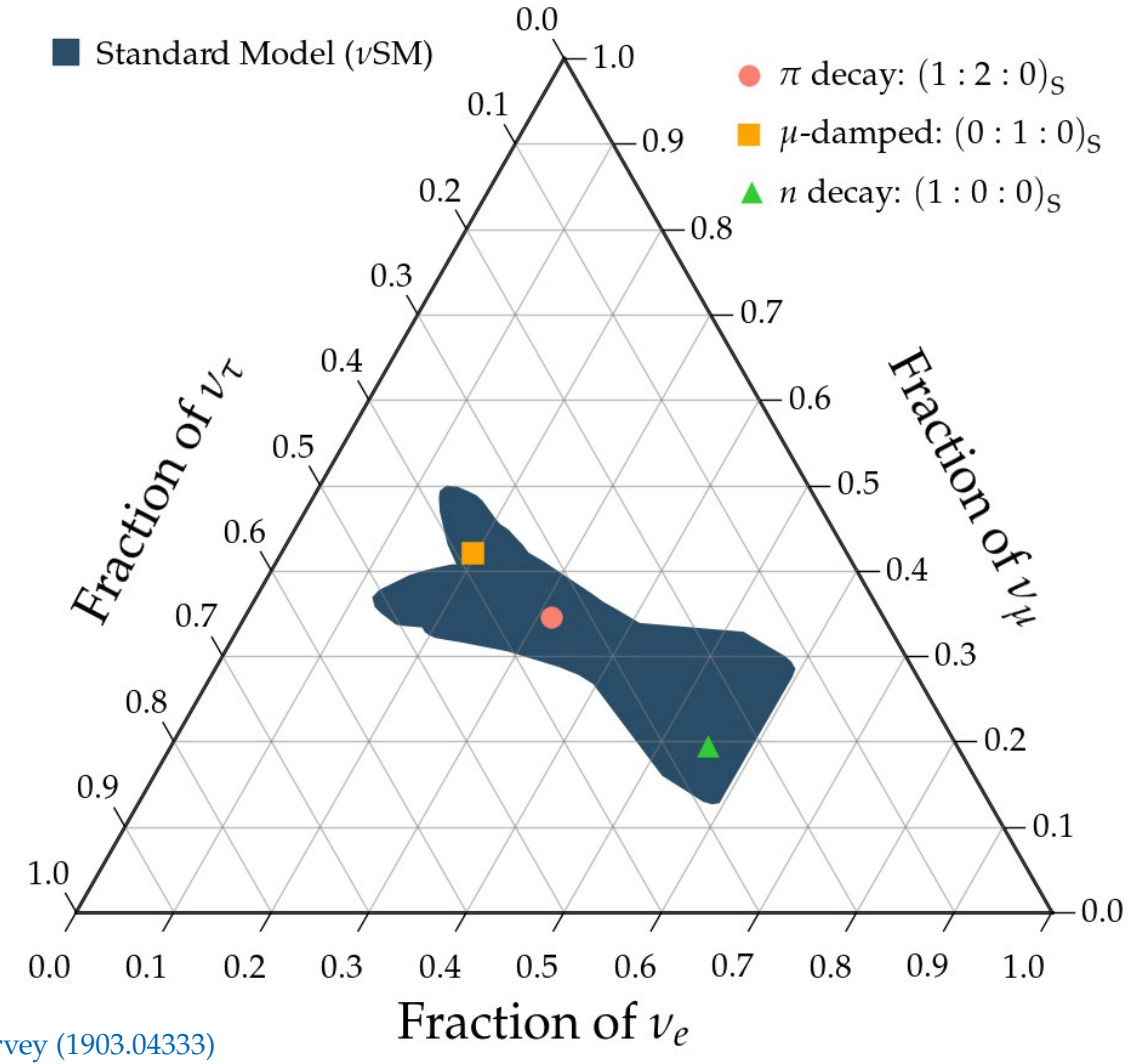
- Radio attenuation length in ice: few km (*vs.* 100 m for light)
- Larger monitored volume than IceCube
- ARA, ARIANNA: antennas buried in ice
- ANITA: antennas mounted on a balloon

No ν detected yet

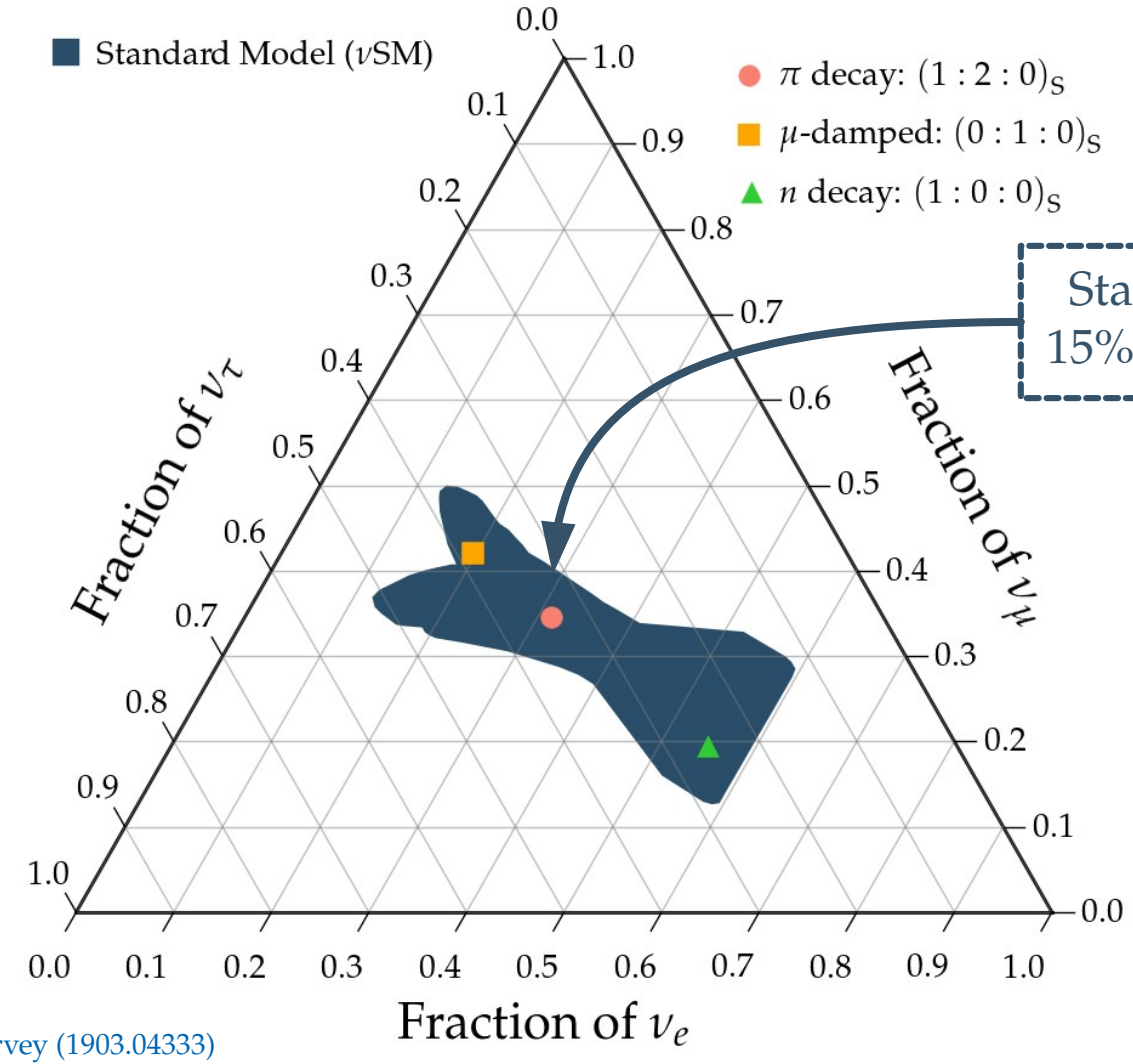
(But UHECRs detected regularly!)



The TeV–PeV ν flavor composition



Ackermann, **MB**, *et al.*, Astro2020 Survey (1903.04333)
Based on: **MB**, Beacom, Winter *PRL* 2015



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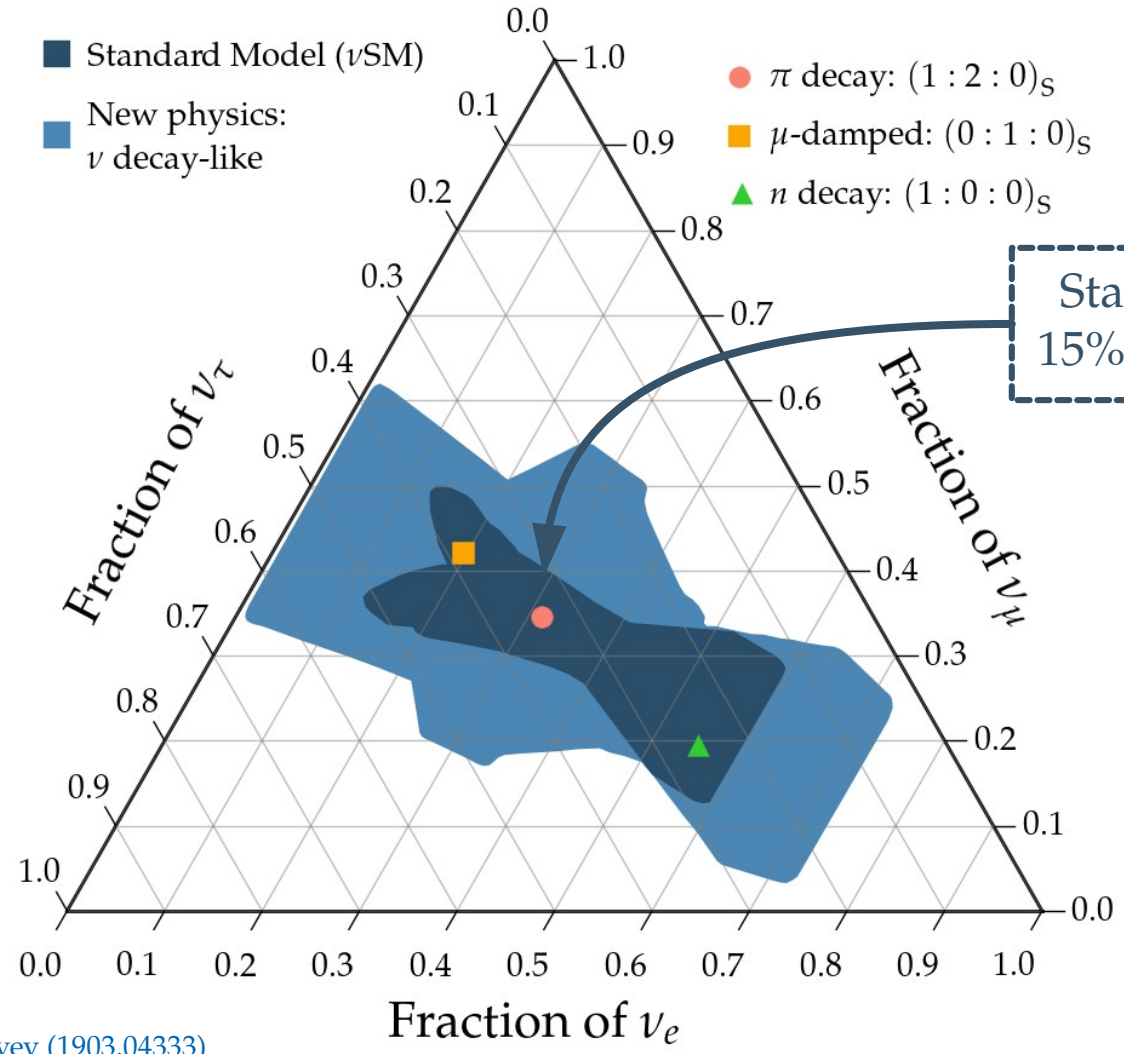

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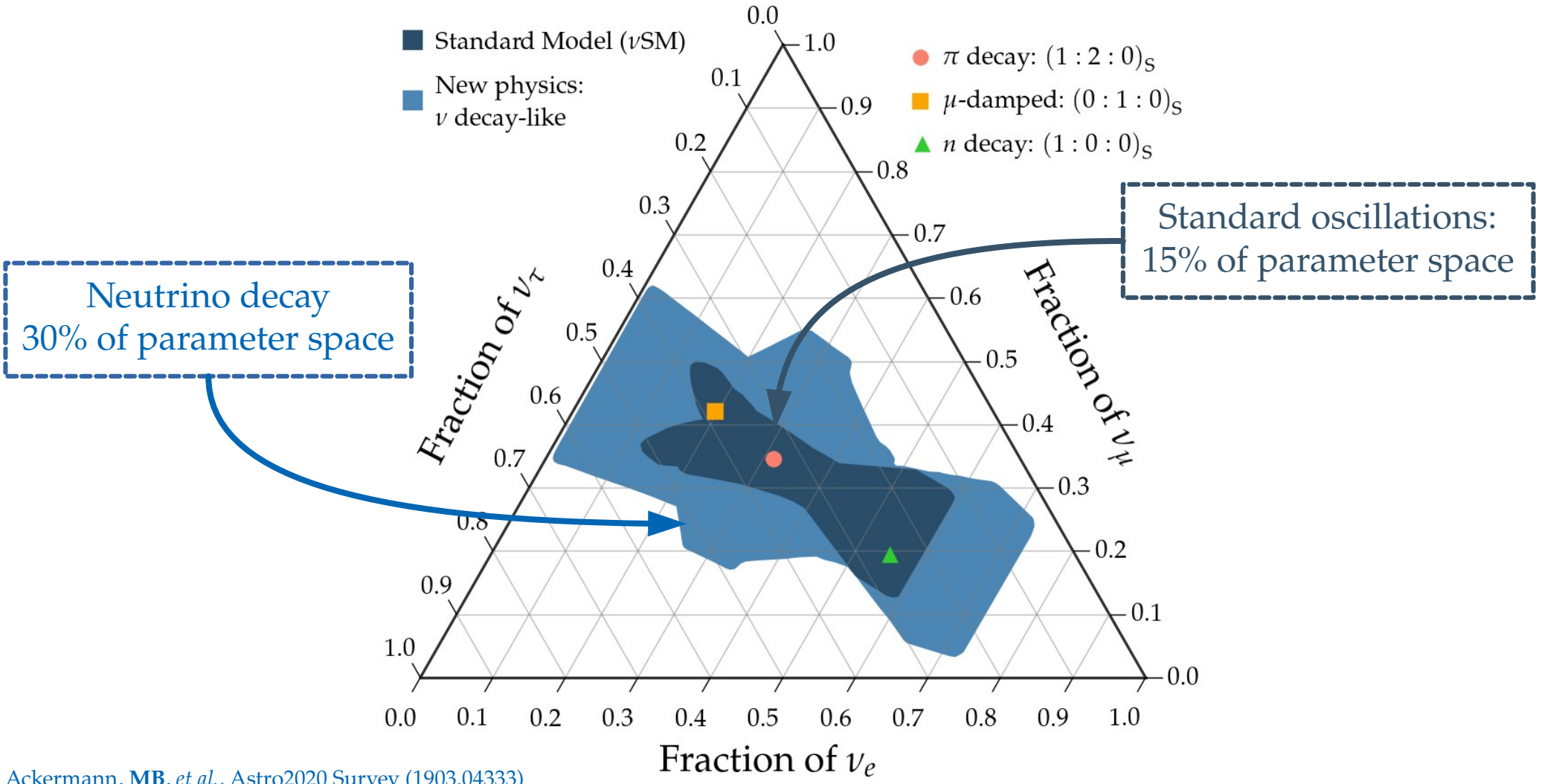

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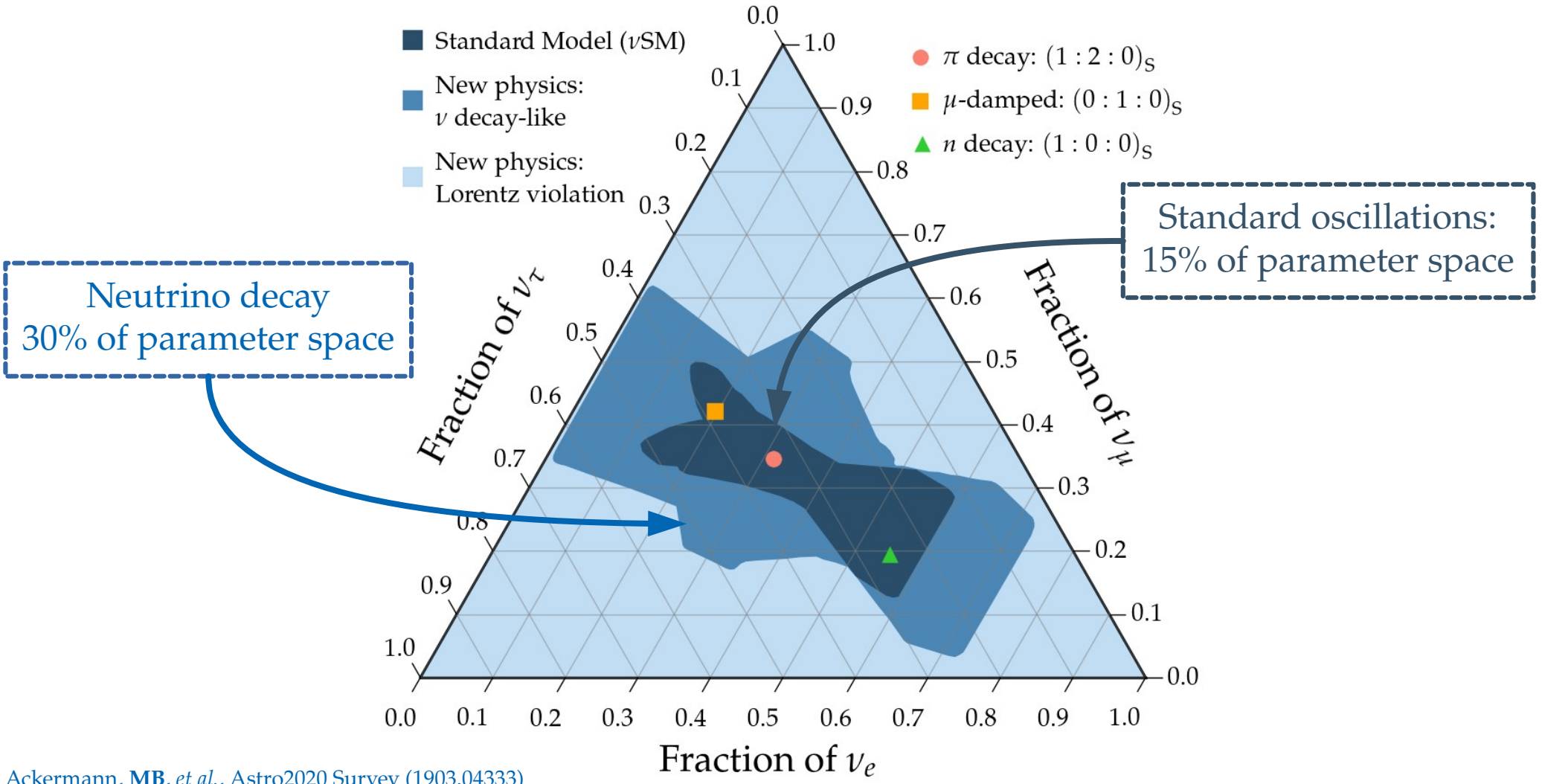

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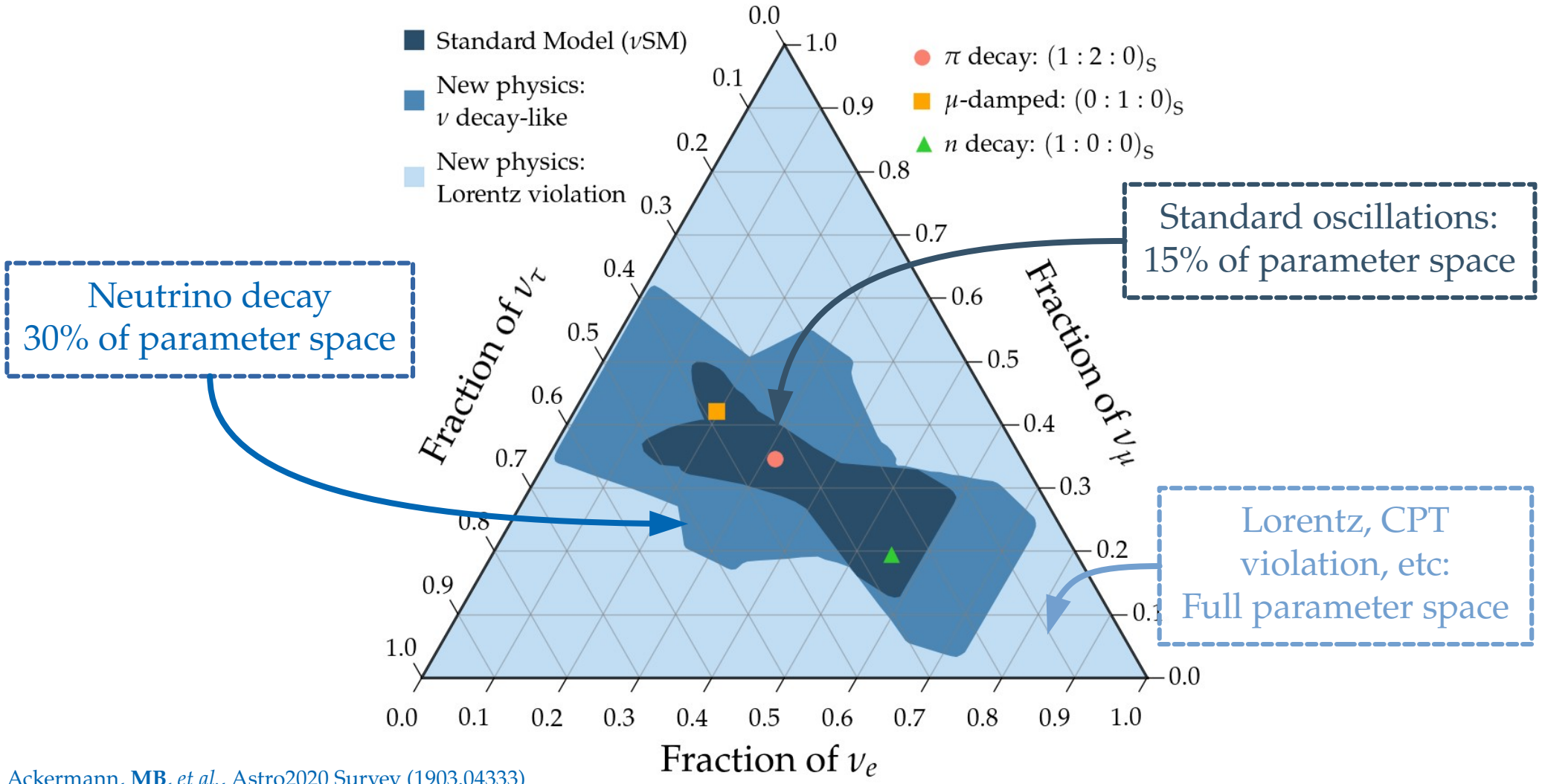

Ackermann, **MB**, *et al.*, Astro2020 Survey (1903.04333)
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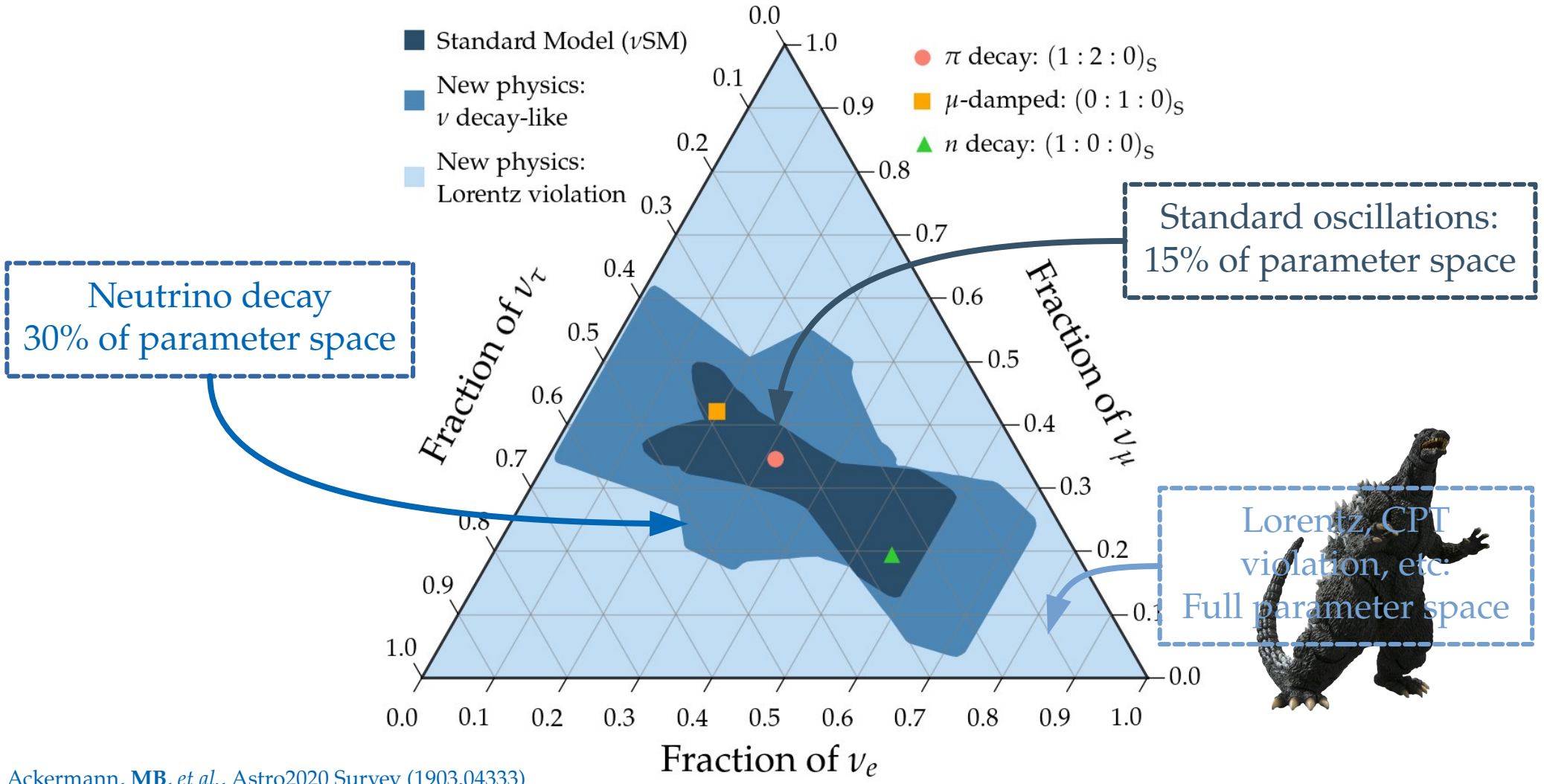


Ackermann, **MB**, *et al.*, Astro2020 Survey (1903.04333)
Based on: **MB**, Beacom, Winter *PRL* 2015

There be dragons

- 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]
  - General non-unitary propagation
    [Ahlers, **MB**, Mu, *PRD* 2018]
- Active-sterile mixing
  [Aeikens *et al.*, *JCAP* 2015; Brdar, *JCAP* 2017]
- Flavor-violating physics
  - New neutrino-electron interactions
    [**MB** & Agarwalla, *PRL* 2019]
  - New νν interactions
    [**MB** *et al.*, *PRD* 2020; Ng & Beacom, *PRD* 2014; Cherry, Friedland, Shoemaker, 1411.1071; Blum, Hook, Murase, 1408.3799]
- …

Toho Company Ltd.

How to fill out the flavor triangle?

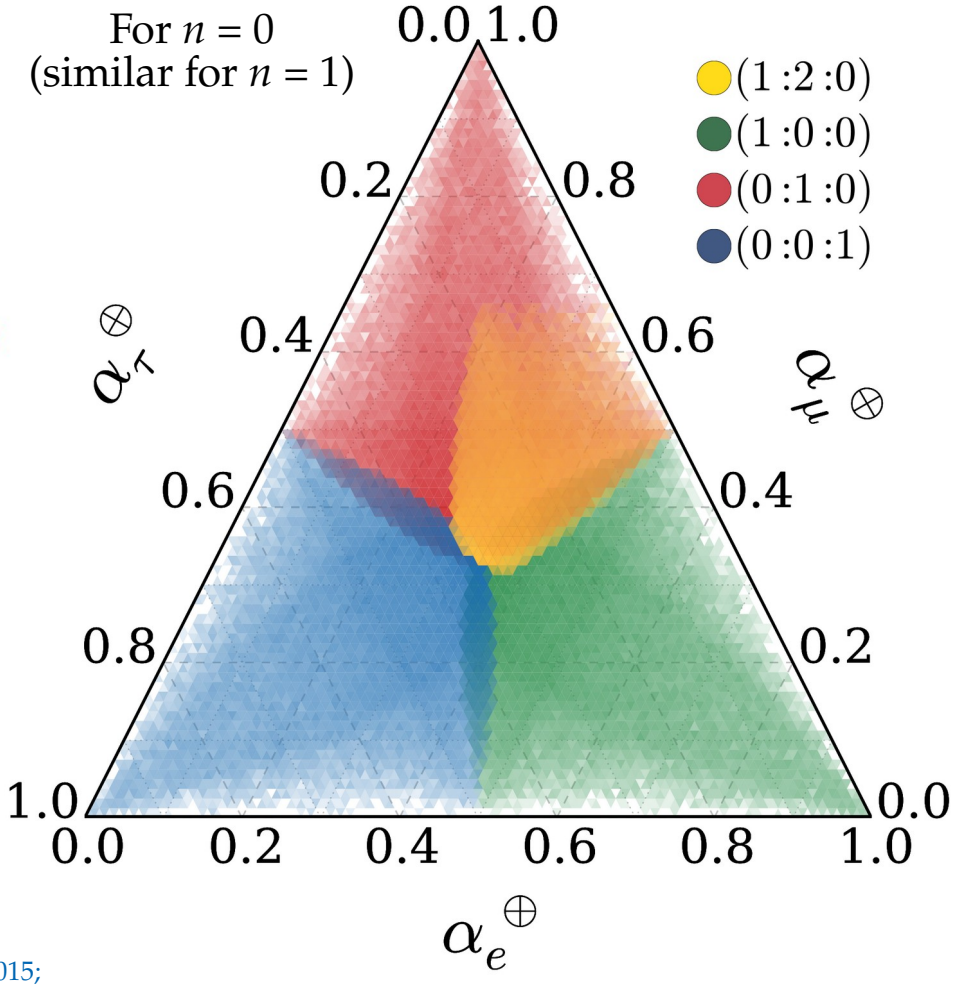
$$H_{\text{tot}} = H_{\text{std}} + H_{\text{NP}}$$

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

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

This can populate *all* of the triangle –

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



Argüelles, Katori, Salvadó, *PRL* 2015

See also: Ahlers, **MB**, Mu, *PRD* 2018; 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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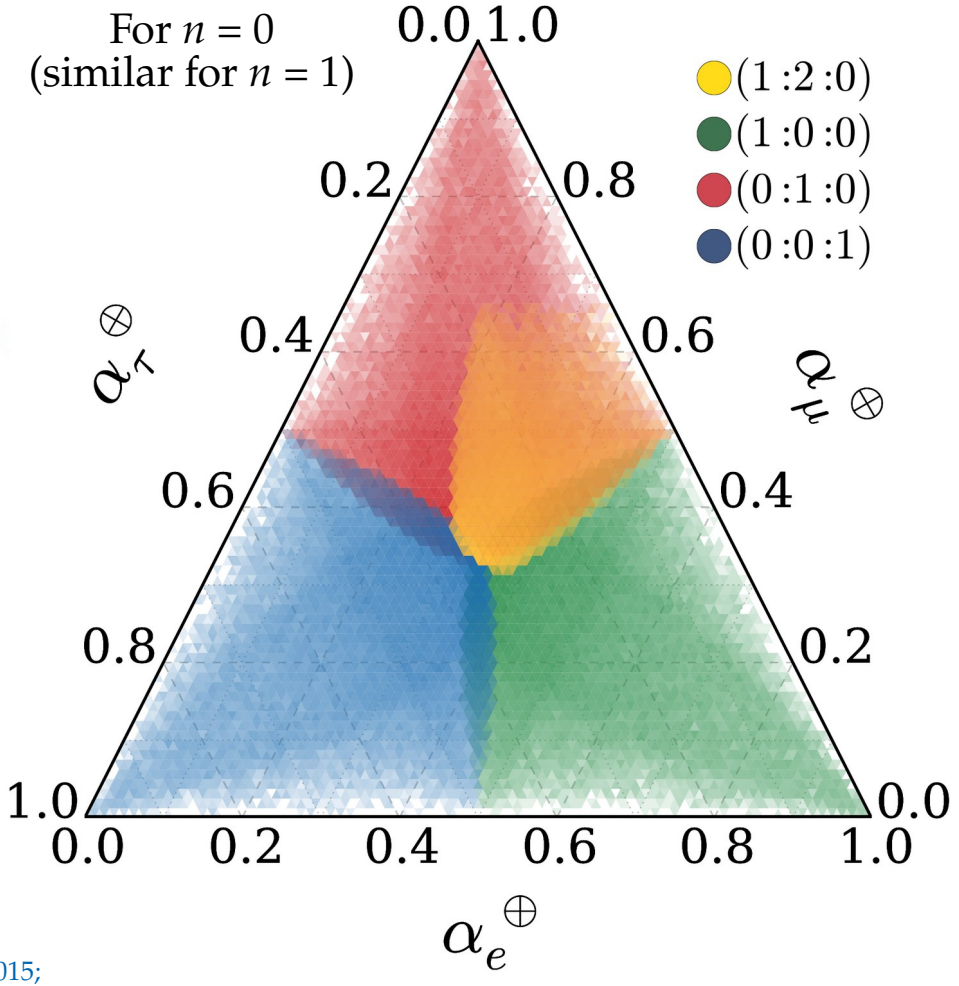

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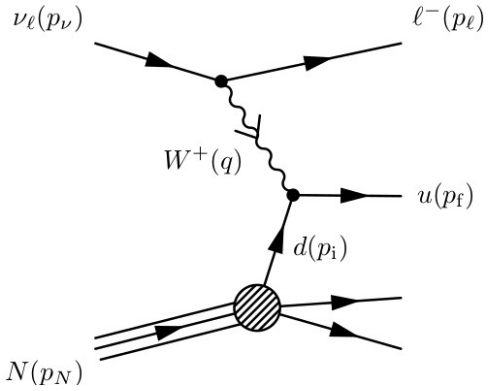
Extrapolating the cross section to high energies

Extrapolating the cross section to high energies

SM



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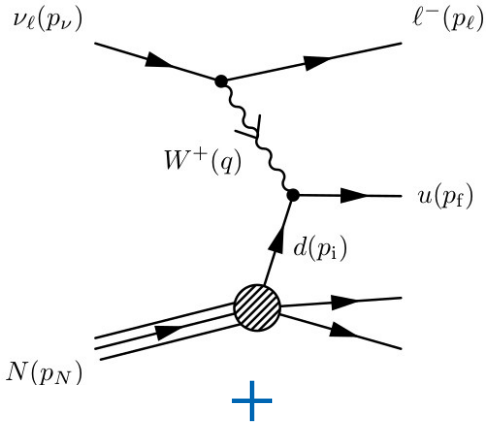

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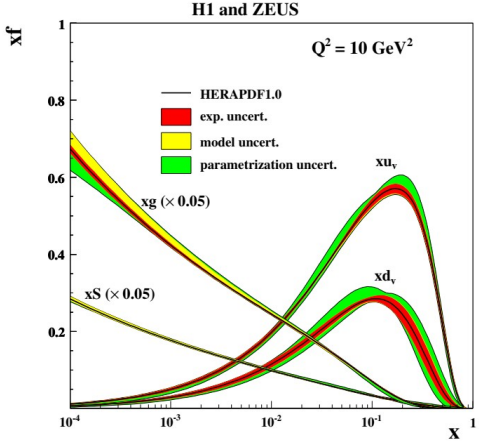
PDFs



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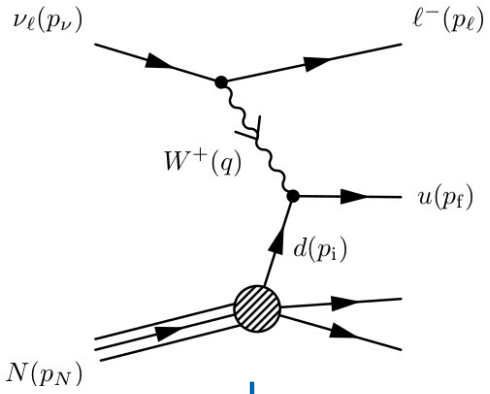
SM



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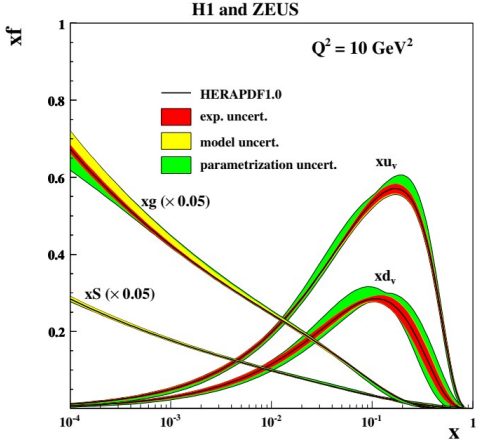
PDFs



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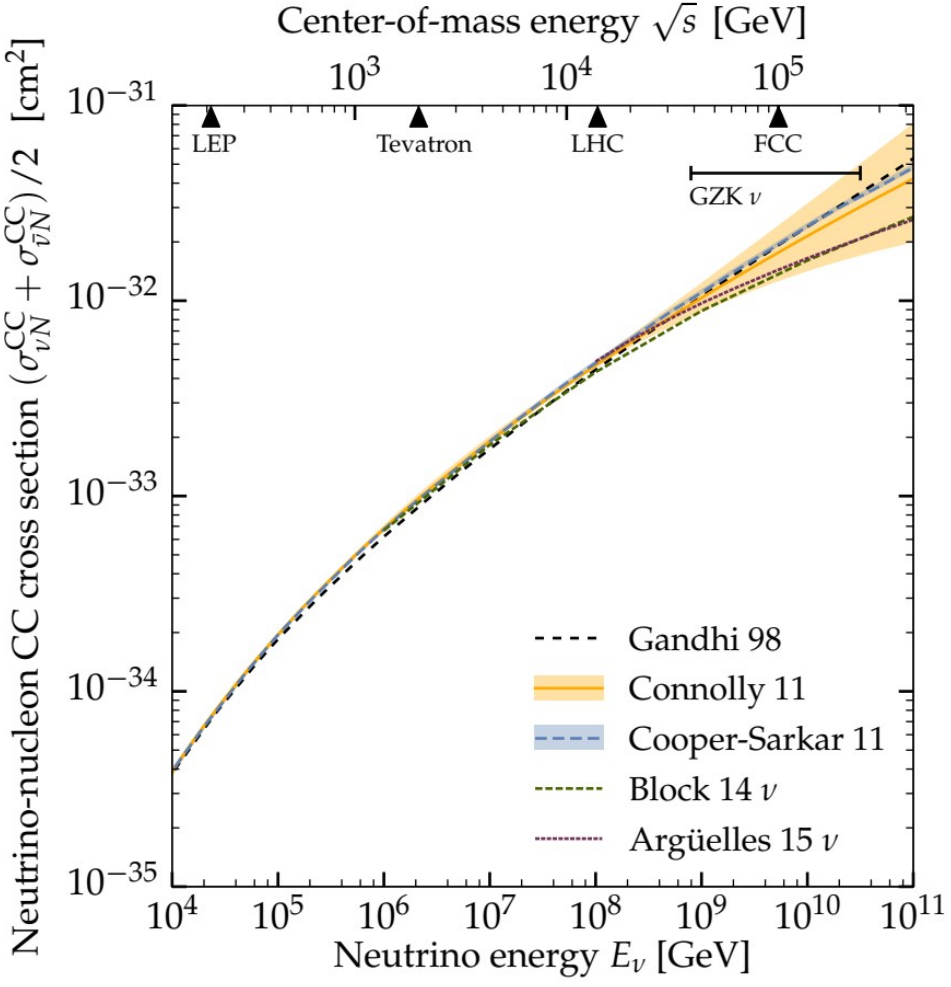

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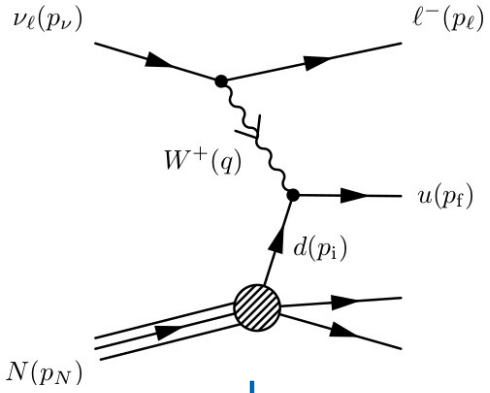
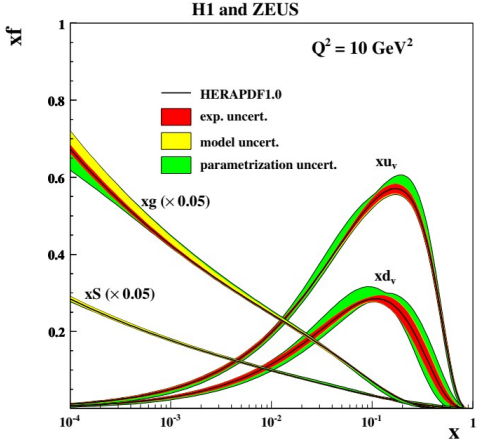


+

PDFs



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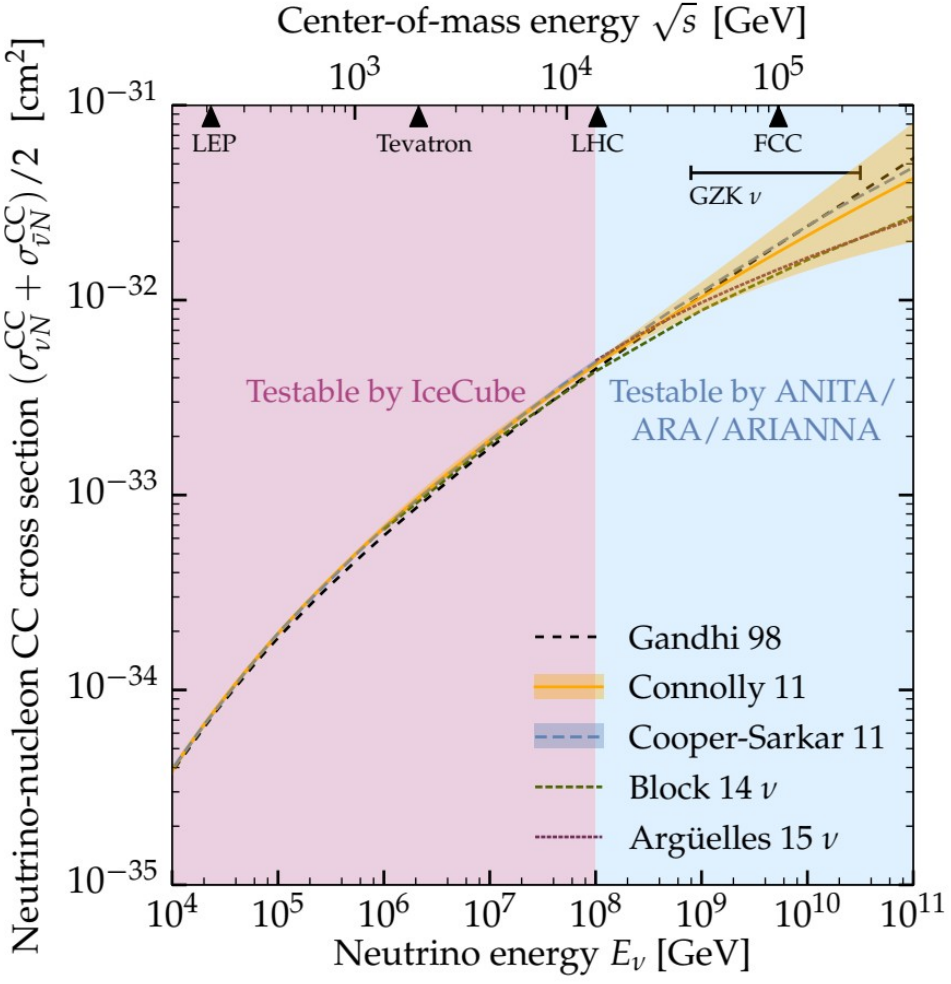


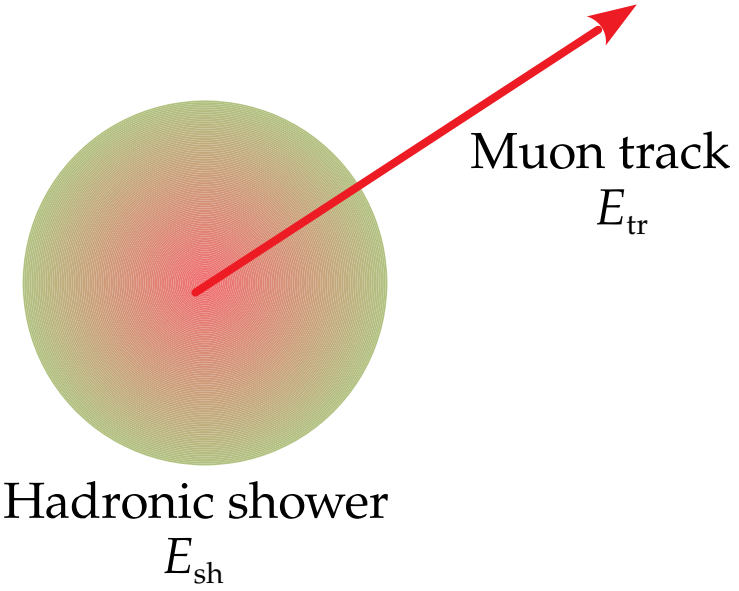
Bonus: Measuring the inelasticity $\langle y \rangle$

- Inelasticity in CC ν_μ interaction $\nu_\mu + N \rightarrow \mu + X$:
  $E_X = y\,E_\nu$ and $E_\mu = (1\text{-}y)\,E_\nu \Rightarrow y = (1 + E_\mu/E_X)^{-1}$

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

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

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



IceCube, *PRD* 2019

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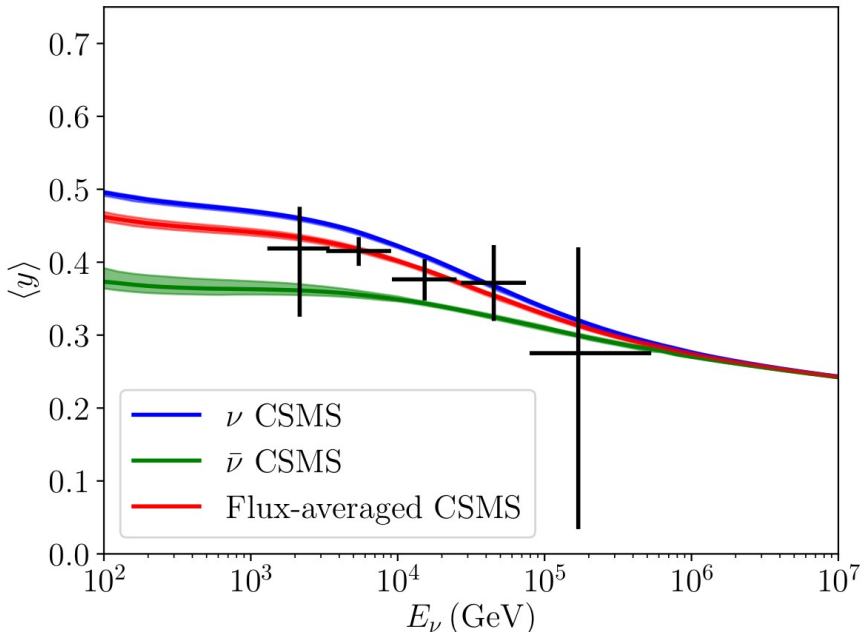
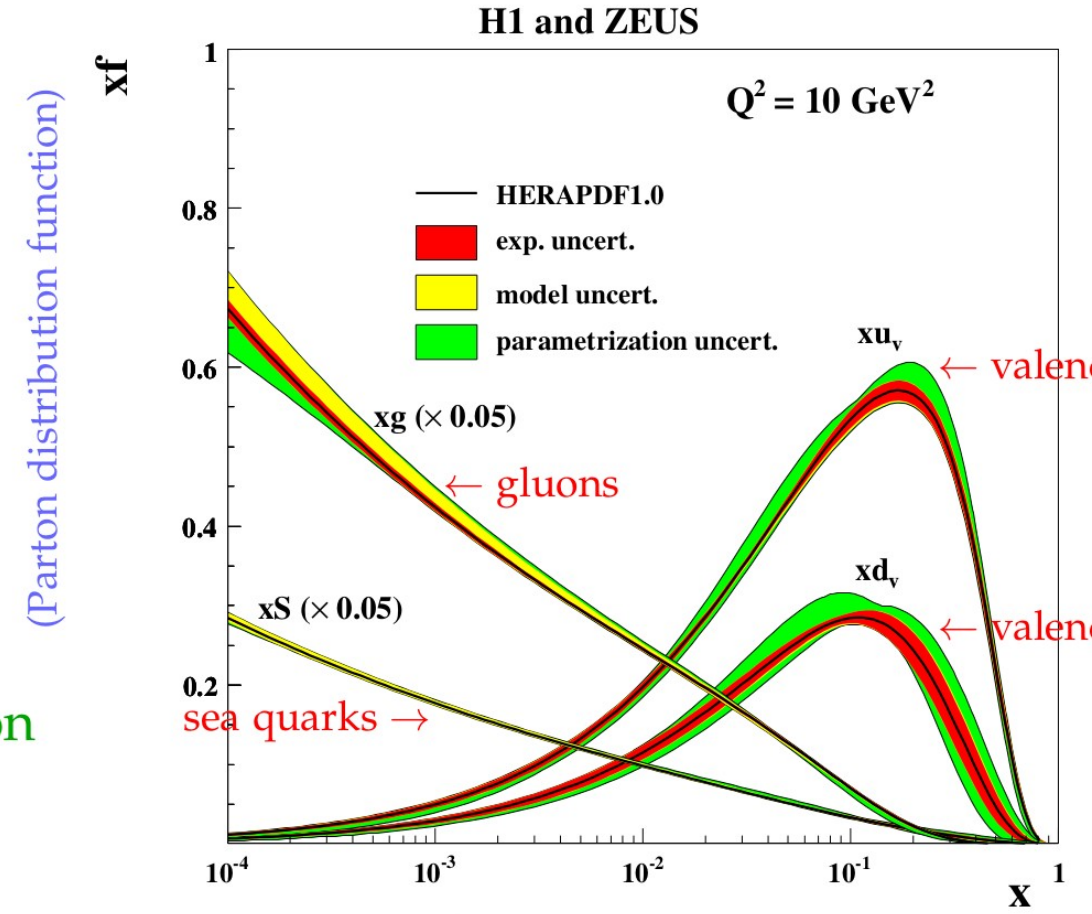


IceCube, *PRD* 2019

Peeking inside a proton



(Parton distribution function)

← valence up quark

← gluons

← valence down quark

← Extrapolation

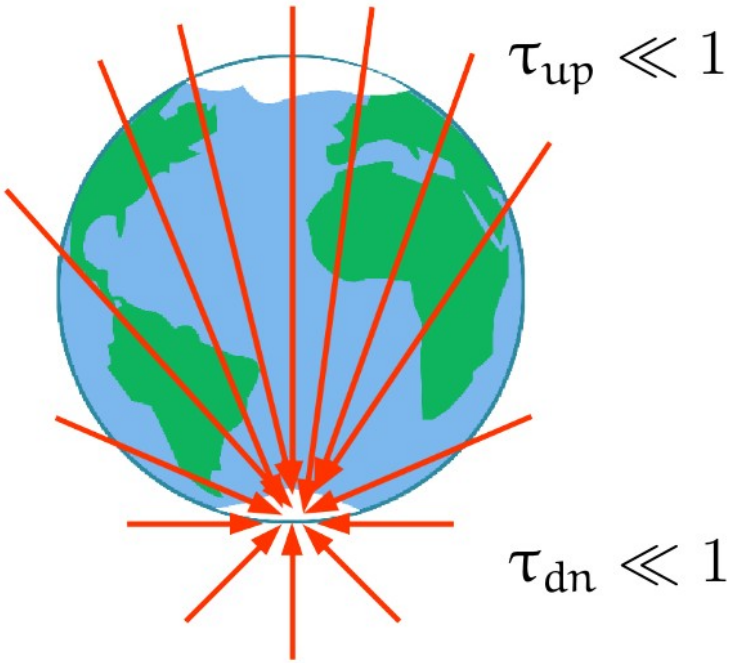
sea quarks →

(Fraction of momentum carried by parton)

Measuring the high-energy cross section

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

Below ~ 10 TeV: Earth is transparent



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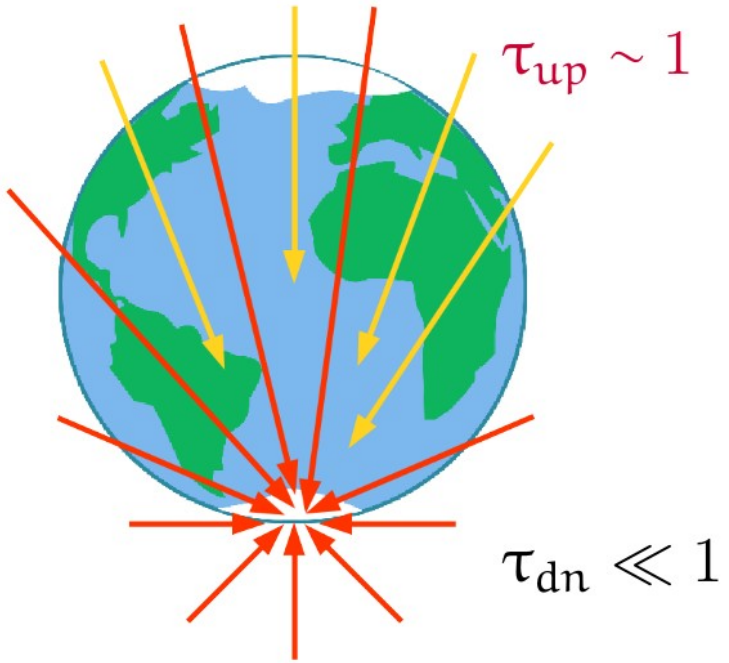

Hooper, *PRD* 2002; Hussain *et al.*, *PRL* 2006; Borriello *et al.*, *PRD* 2008
Hussain, Mafatia, McKay, *PRD* 2008 Connolly, Thorne, Waters, *PRD* 2011; Marfatia, McKay, Weiler, *PLB* 2015

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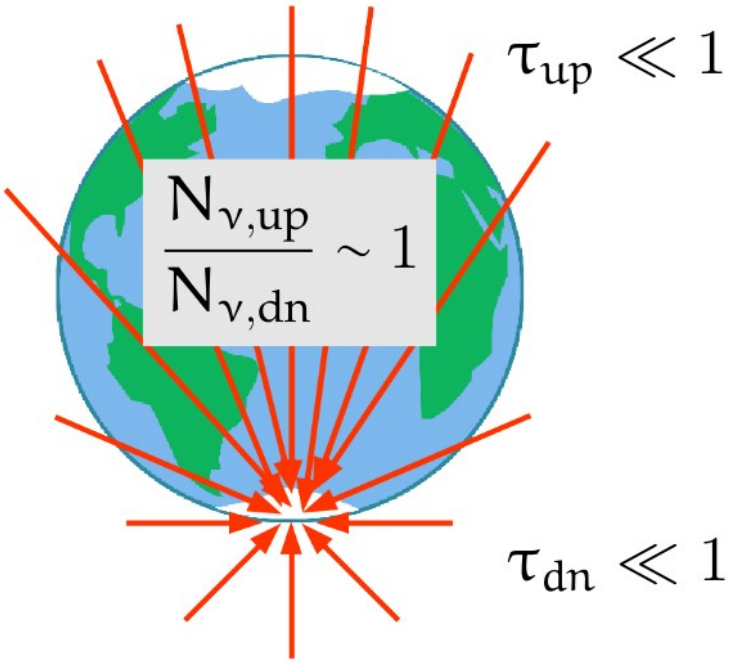

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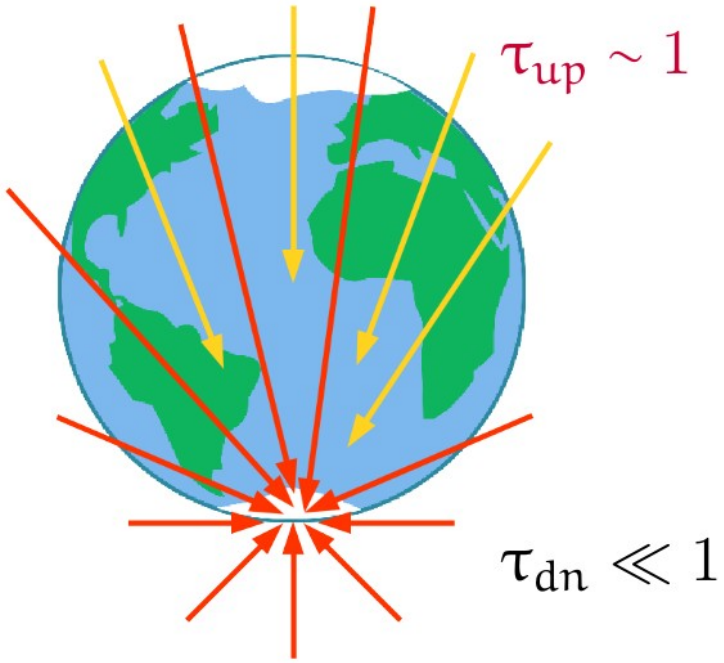

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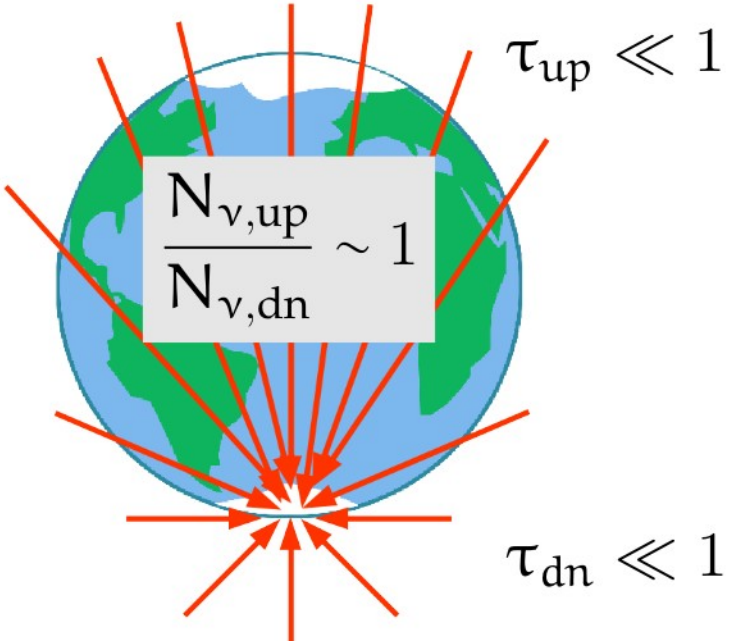

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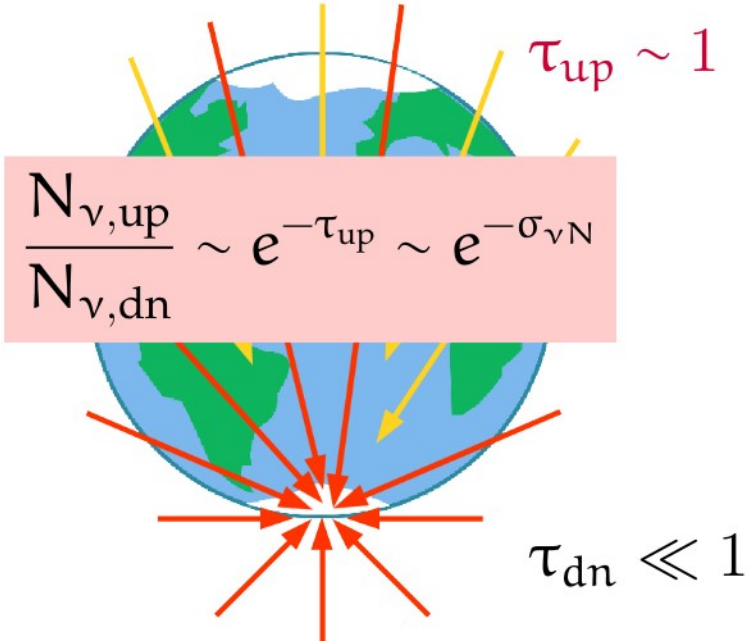

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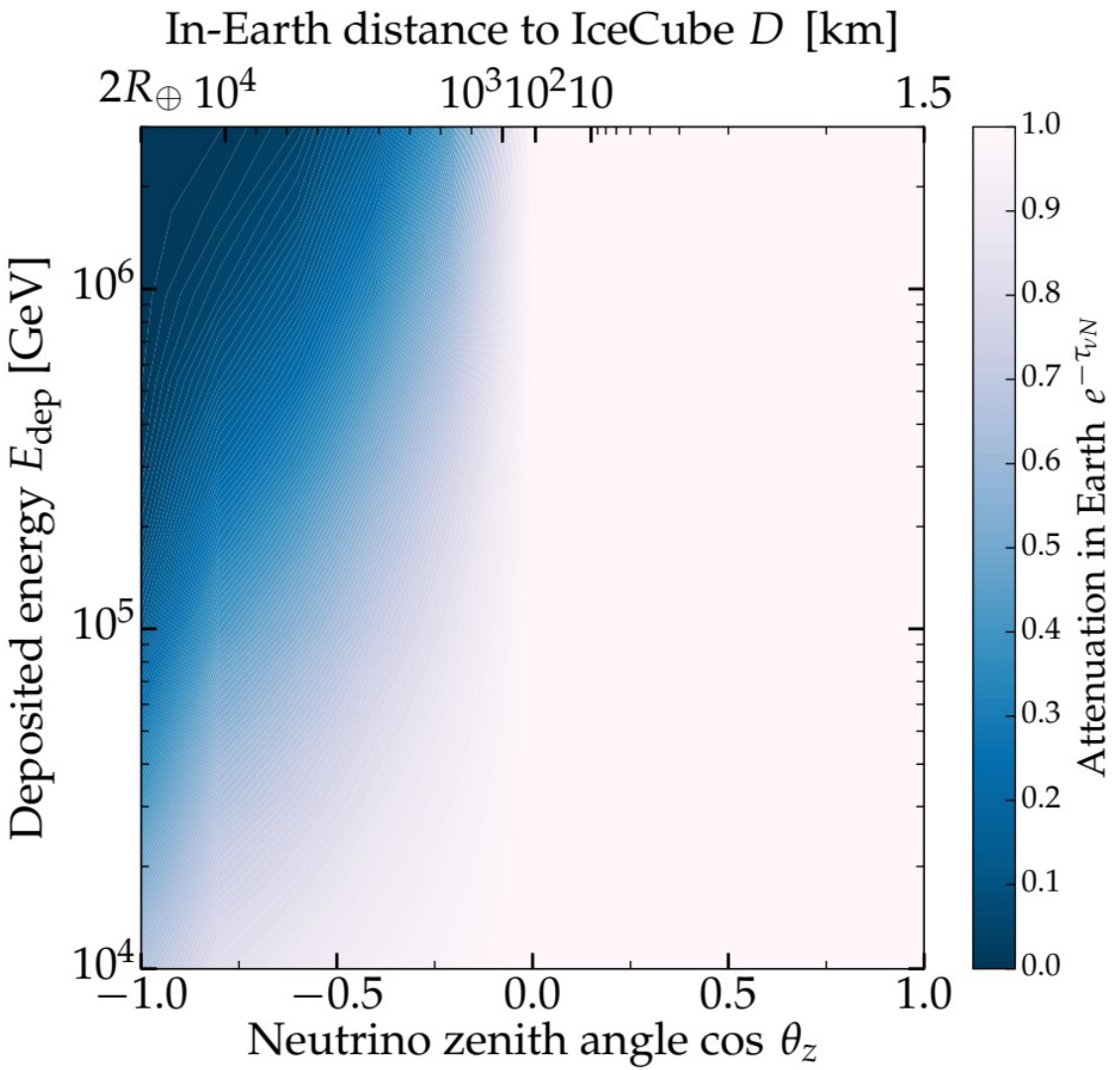
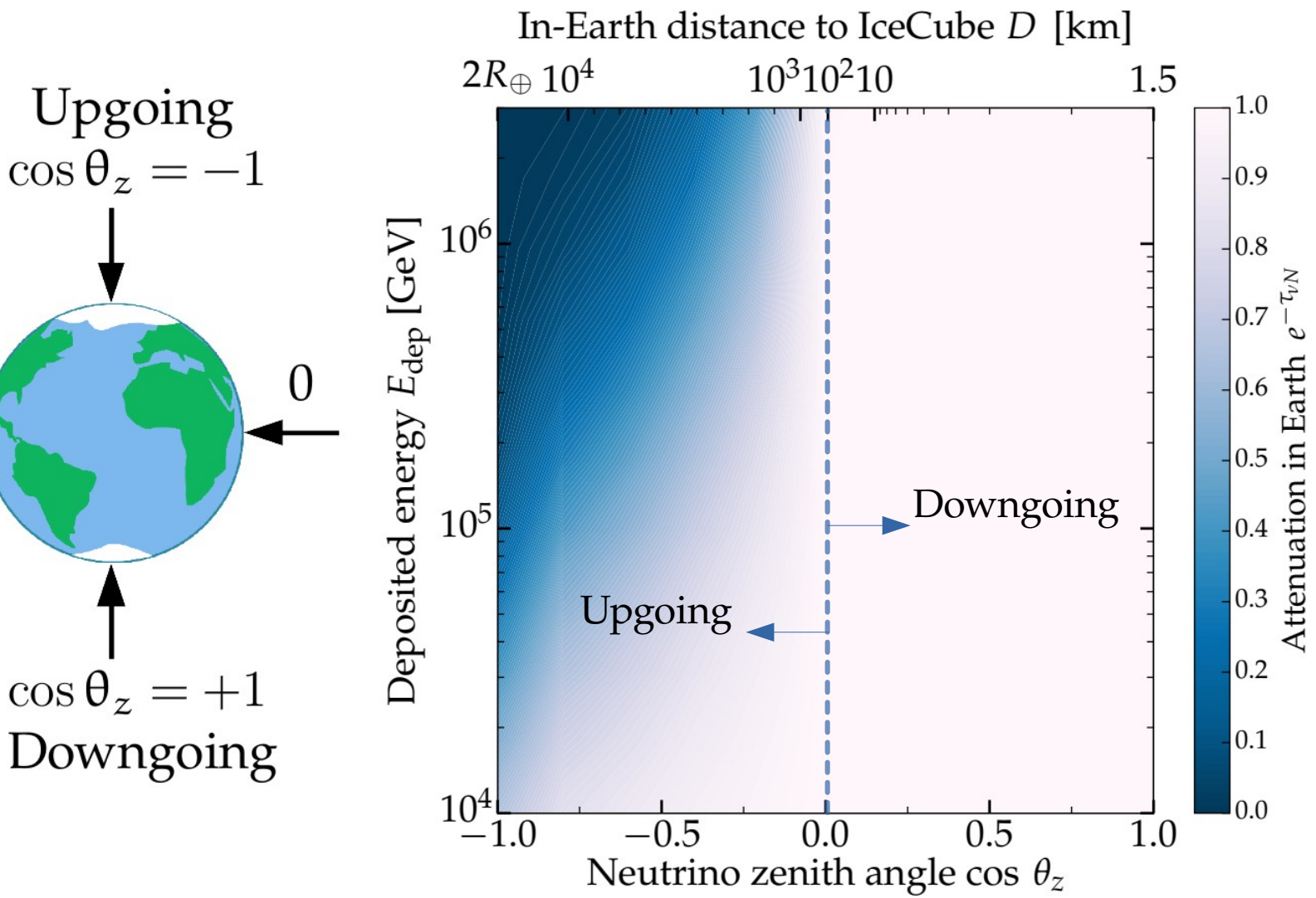

In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4
10^3 10^2 10
1.5
Deposited energy $E_{\rm dep}$ [GeV]
10^6
10^5
10^4
−1.0
−0.5
0.0
0.5
1.0
Neutrino zenith angle cos θ_z
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Attenuation in Earth $e^{-\tau_{\nu N}}$


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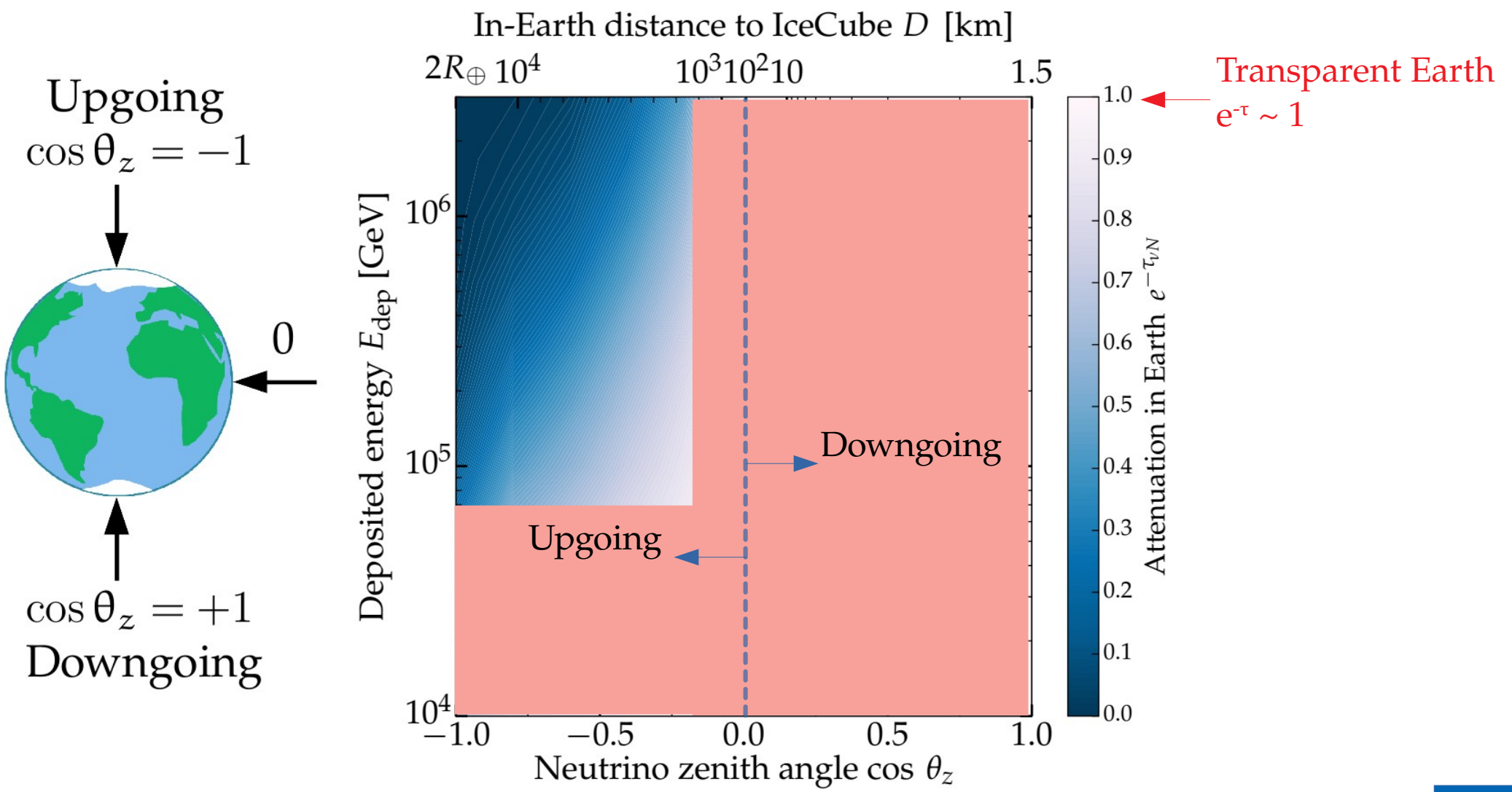
0.1
0.0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0
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Downgoing
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$2R_\oplus$ 10^4
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1.5
Deposited energy $E_{\rm dep}$ [GeV]
10^6
10^5
10^4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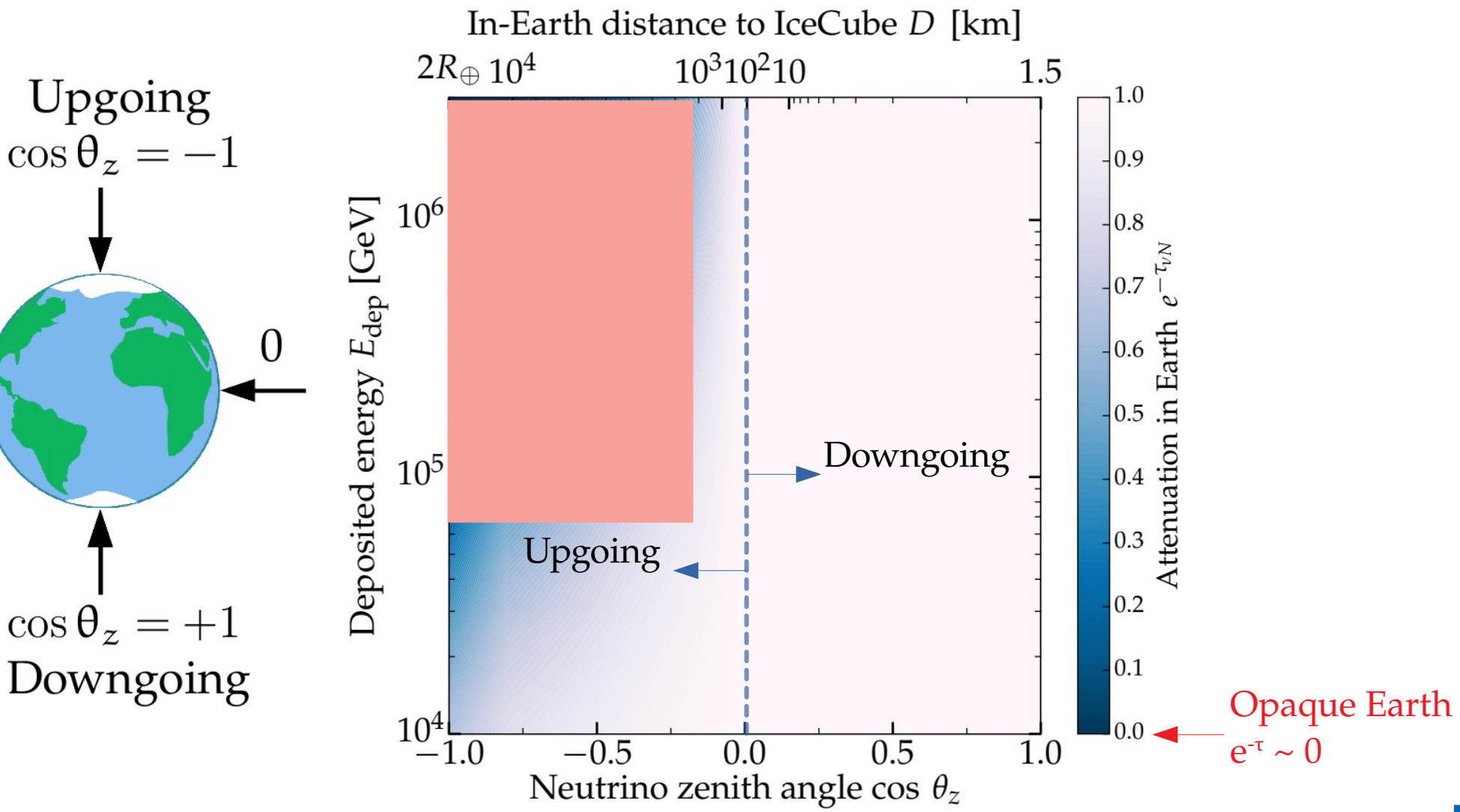
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Transparent Earth
$e^{-\tau} \sim 1$


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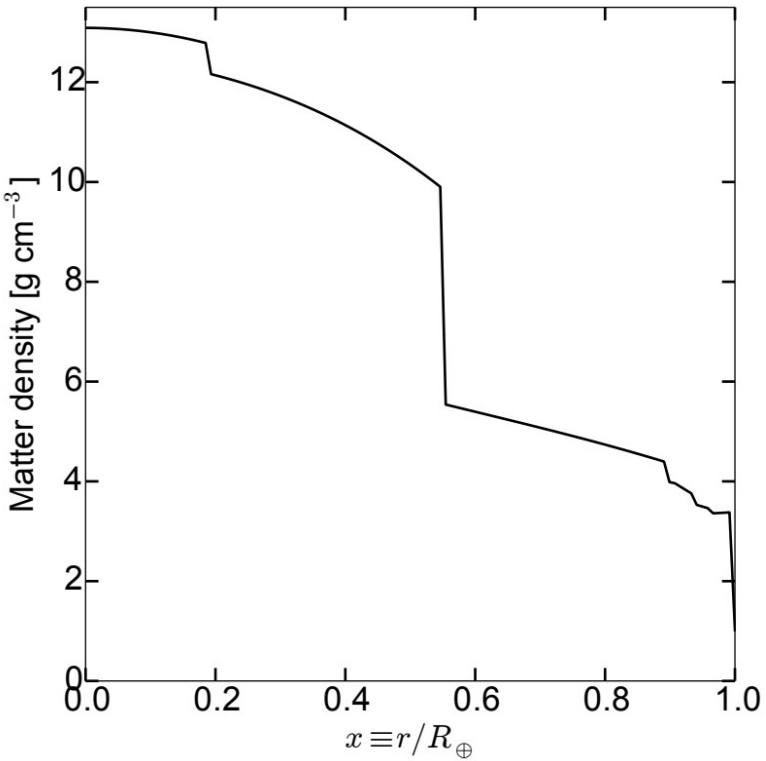
Downgoing
In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4
10^3 10^2 10
1.5
Deposited energy $E_{\rm dep}$ [GeV]
10^6
10^5
10^4
Downgoing
Upgoing
−1.0
−0.5
0.0
0.5
1.0
Neutrino zenith angle cos θ_z
Attenuation in Earth $e^{-\tau_{\nu N}}$
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Opaque Earth
$e^{-\tau}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

A feel for the in-Earth attenuation

Earth matter density

(Preliminary Reference Earth Model)



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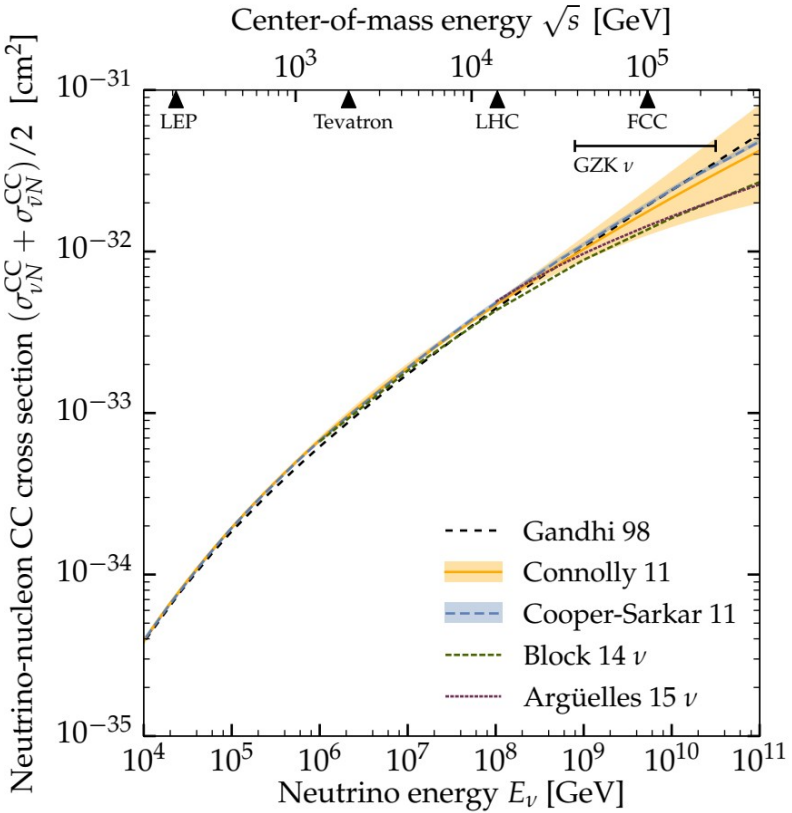
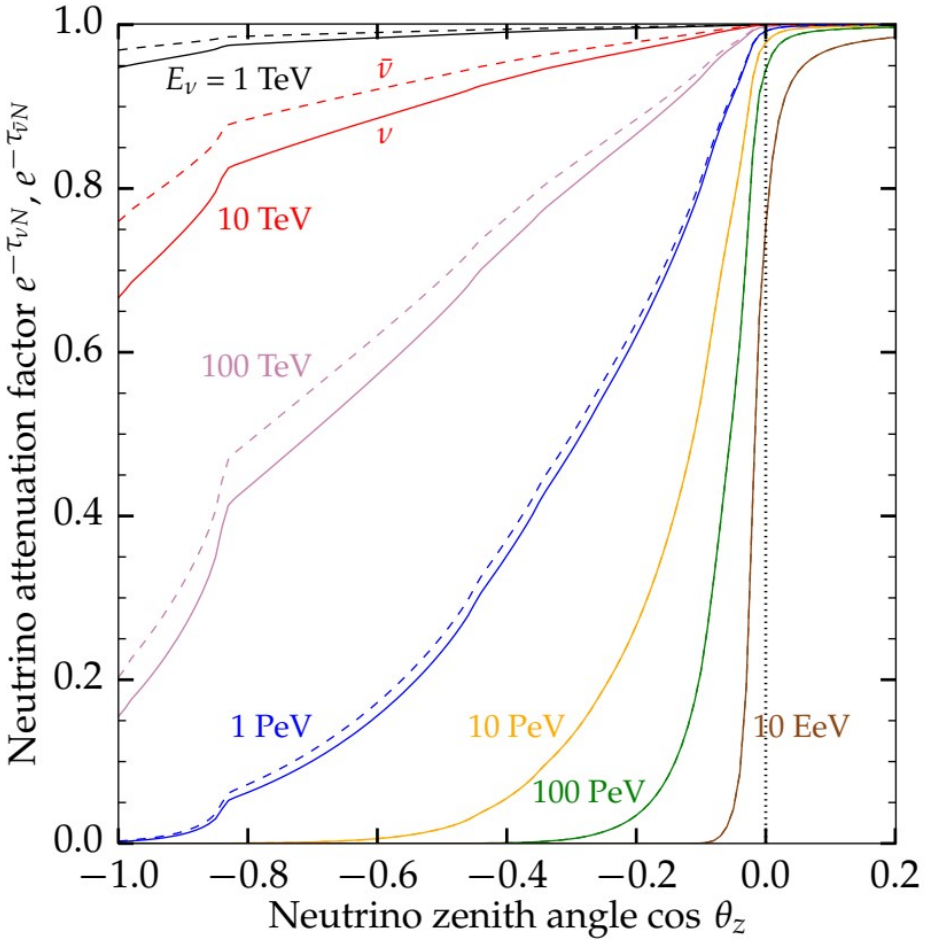
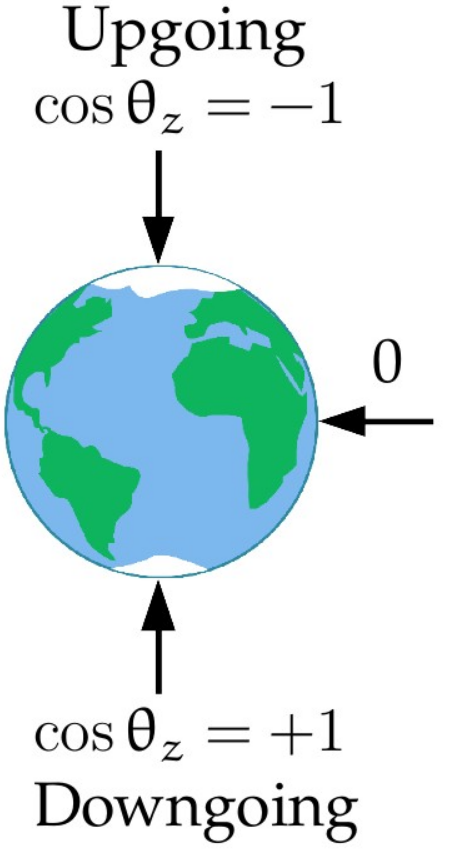
Neutrino-nucleon cross section

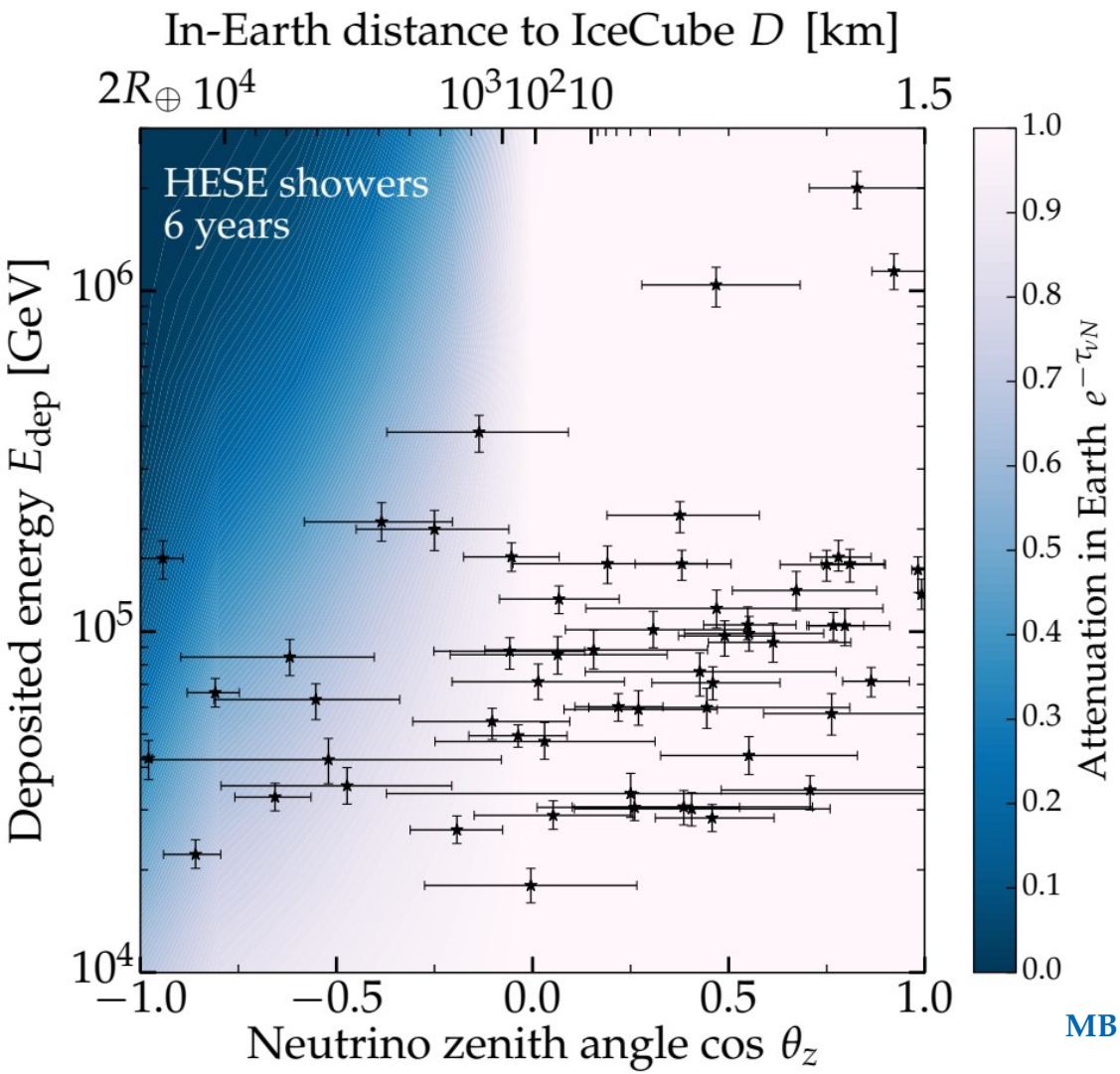


A feel for the in-Earth attenuation

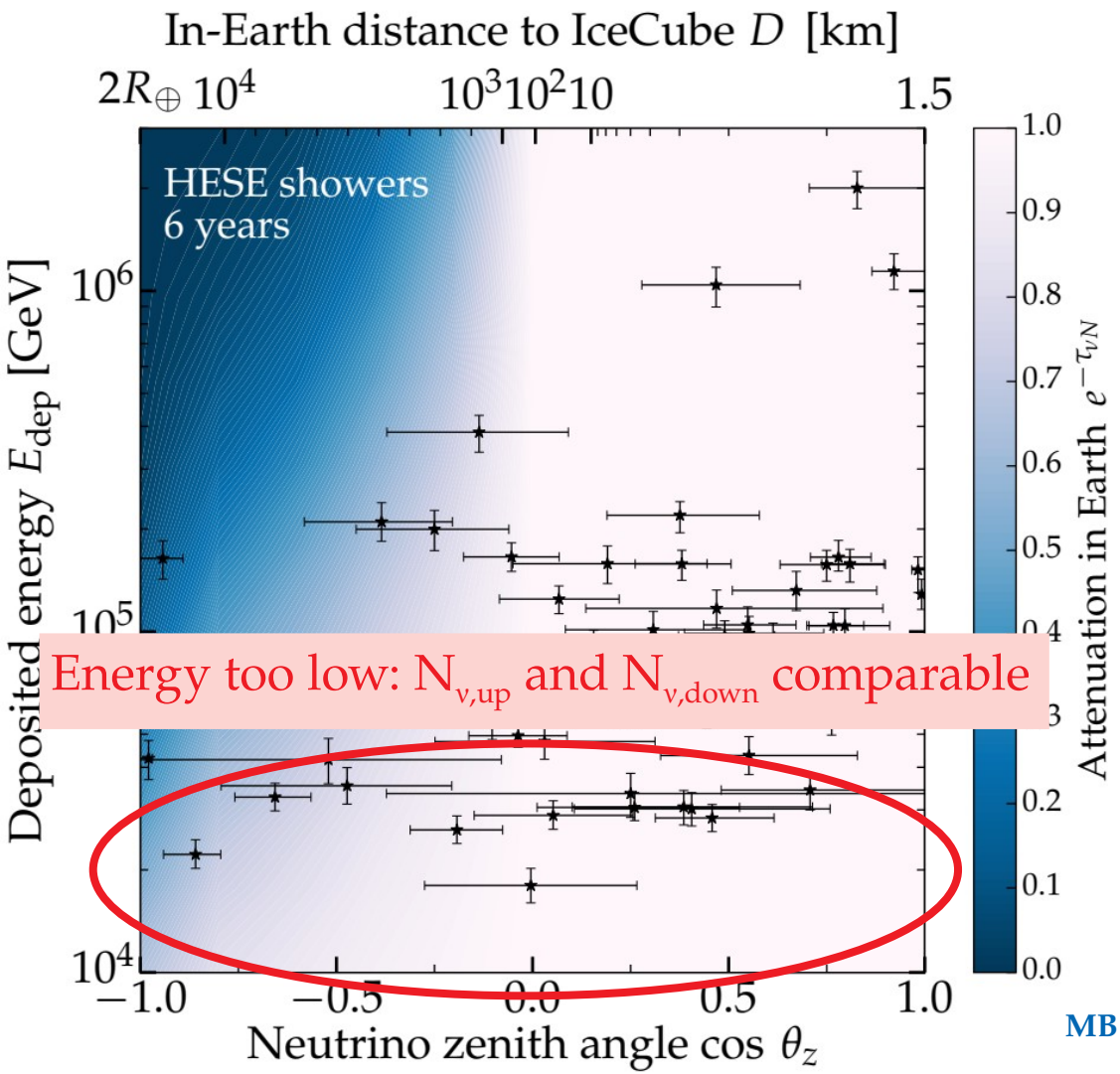
=





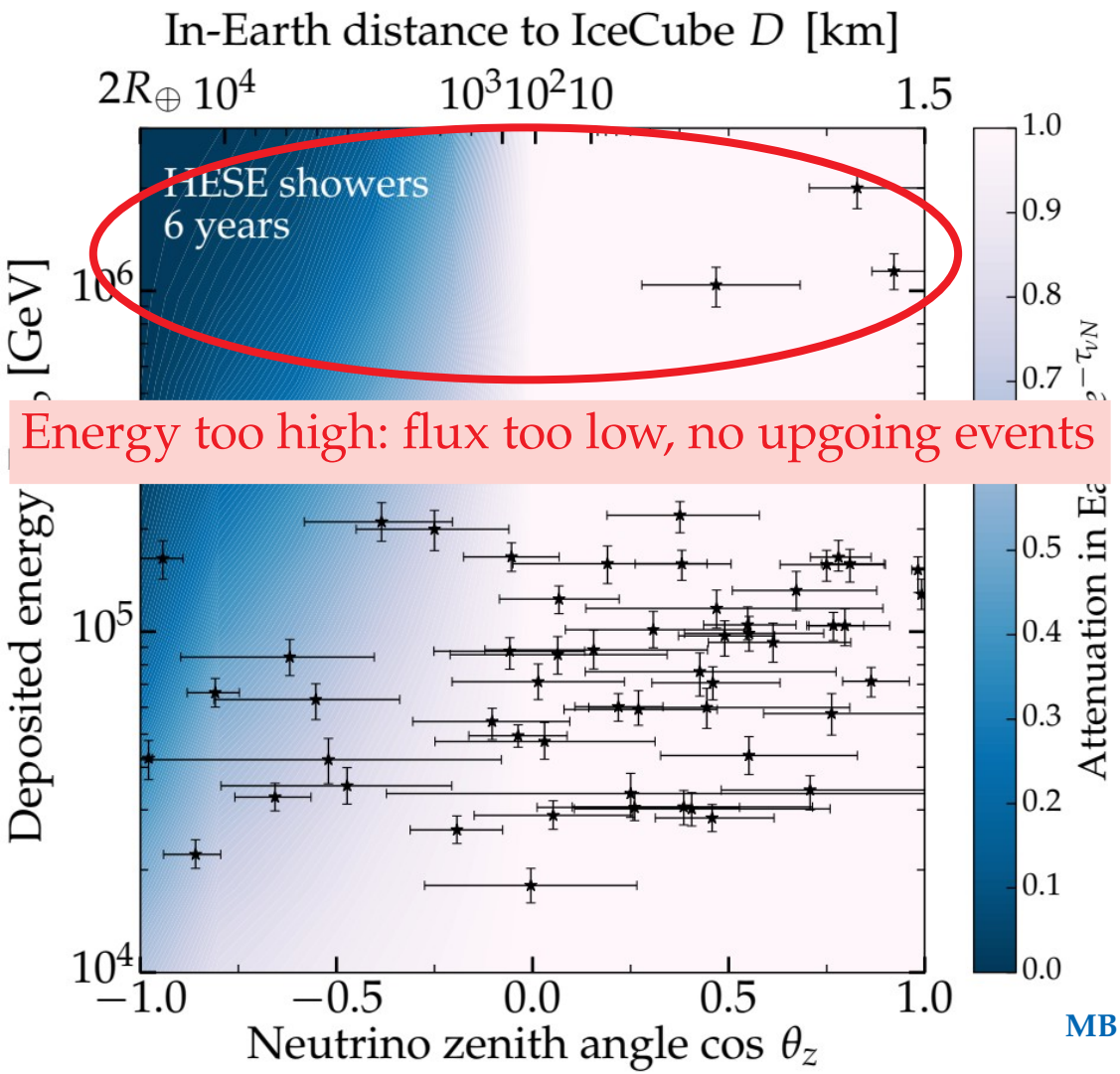


MB & Connolly, *PRL* 2019

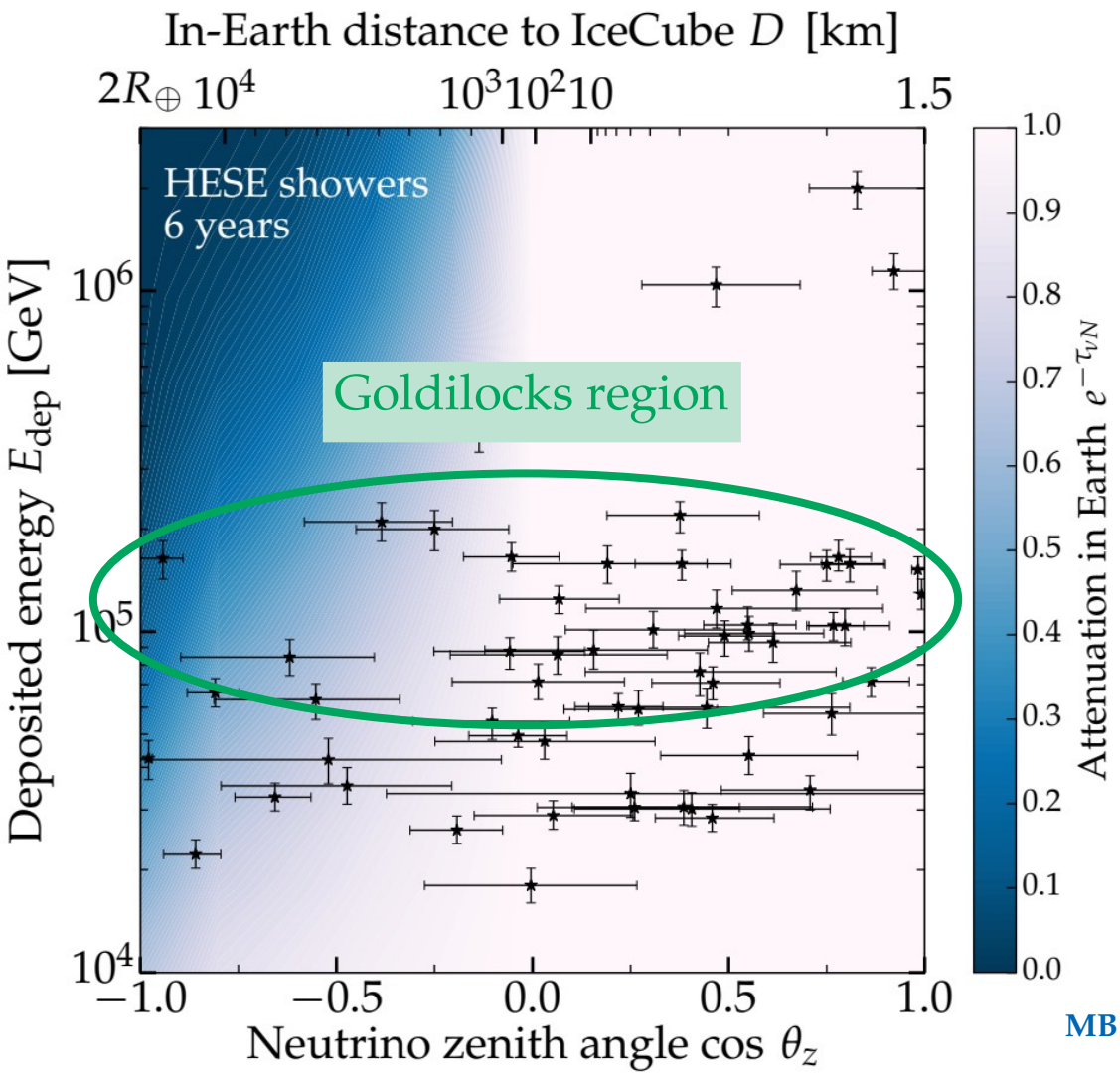


Energy too low: $N_{\nu,up}$ and $N_{\nu,down}$ comparable

MB & Connolly, *PRL* 2019

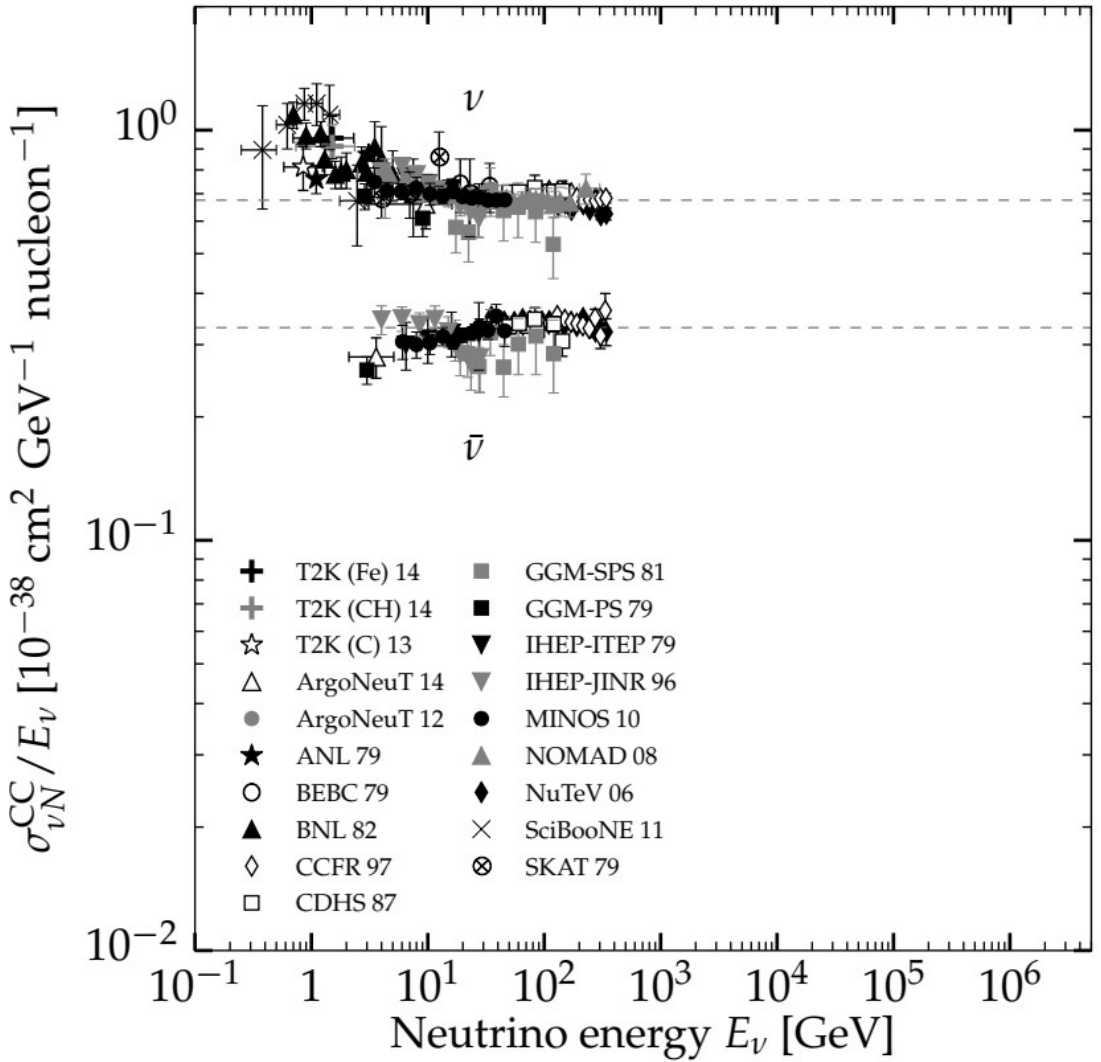


MB & Connolly, *PRL* 2019

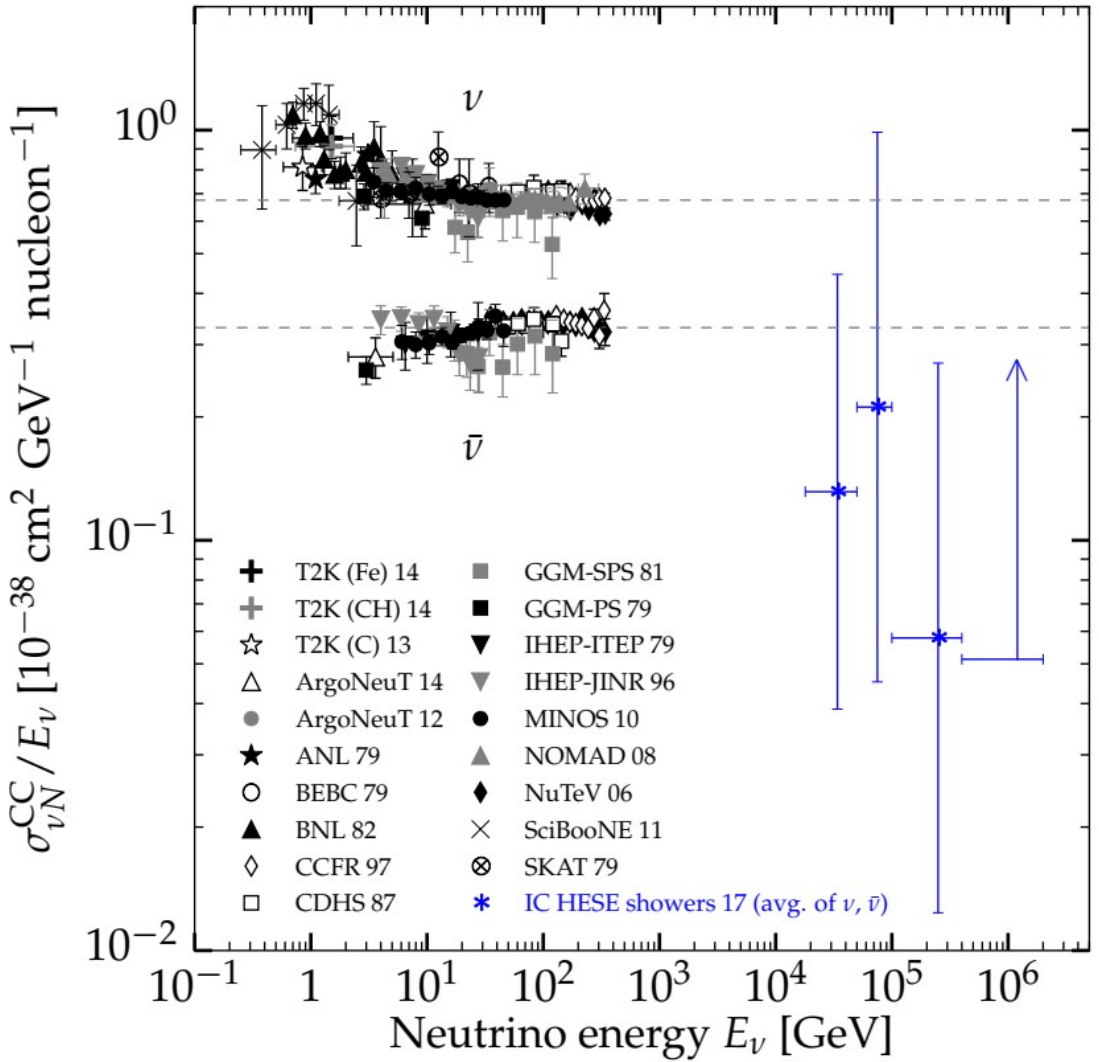


MB & Connolly, *PRL* 2019

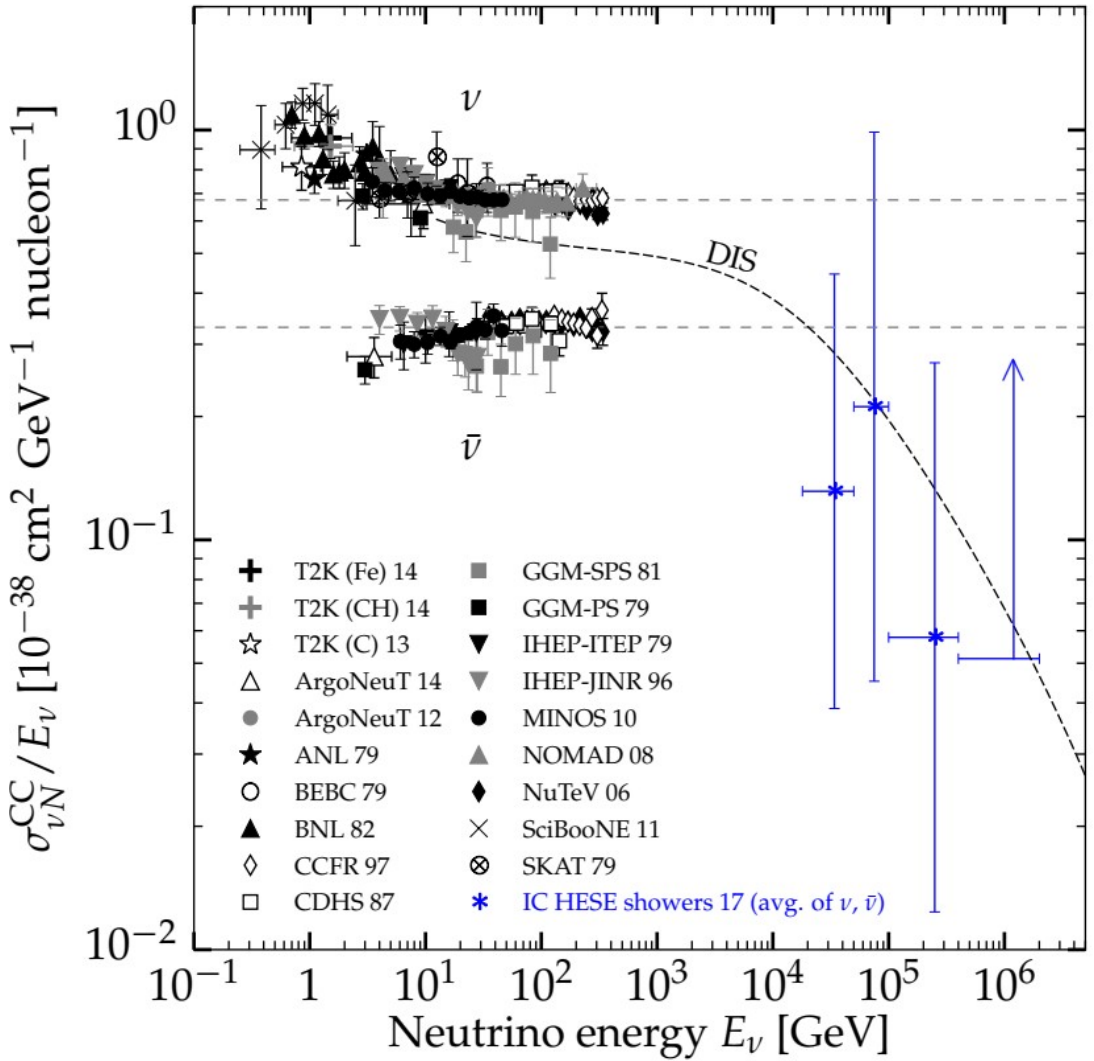
MB & Connolly *PRL* 2019
See also: IceCube, *Nature* 2017



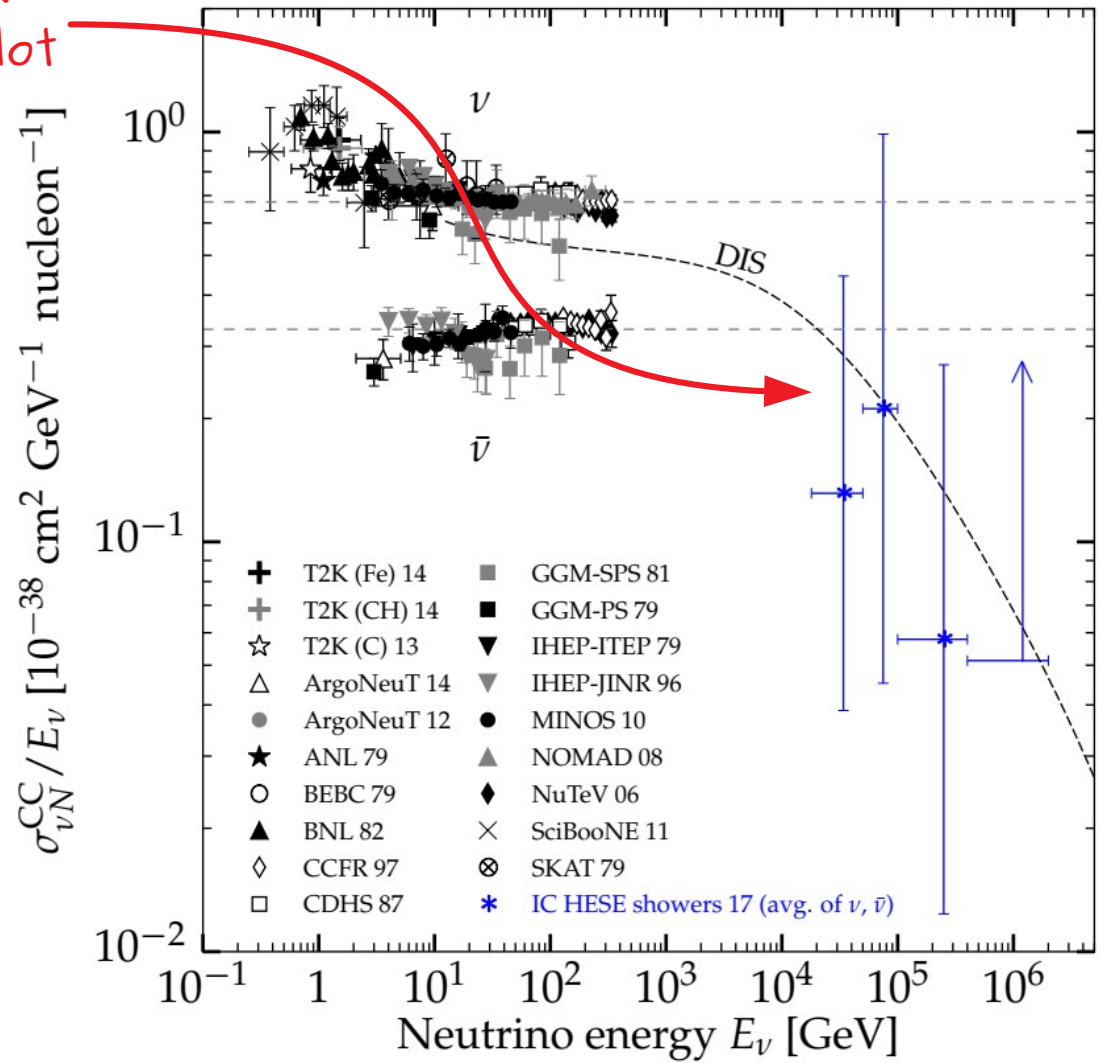
MB & Connolly *PRL* 2019
See also: IceCube, *Nature* 2017



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



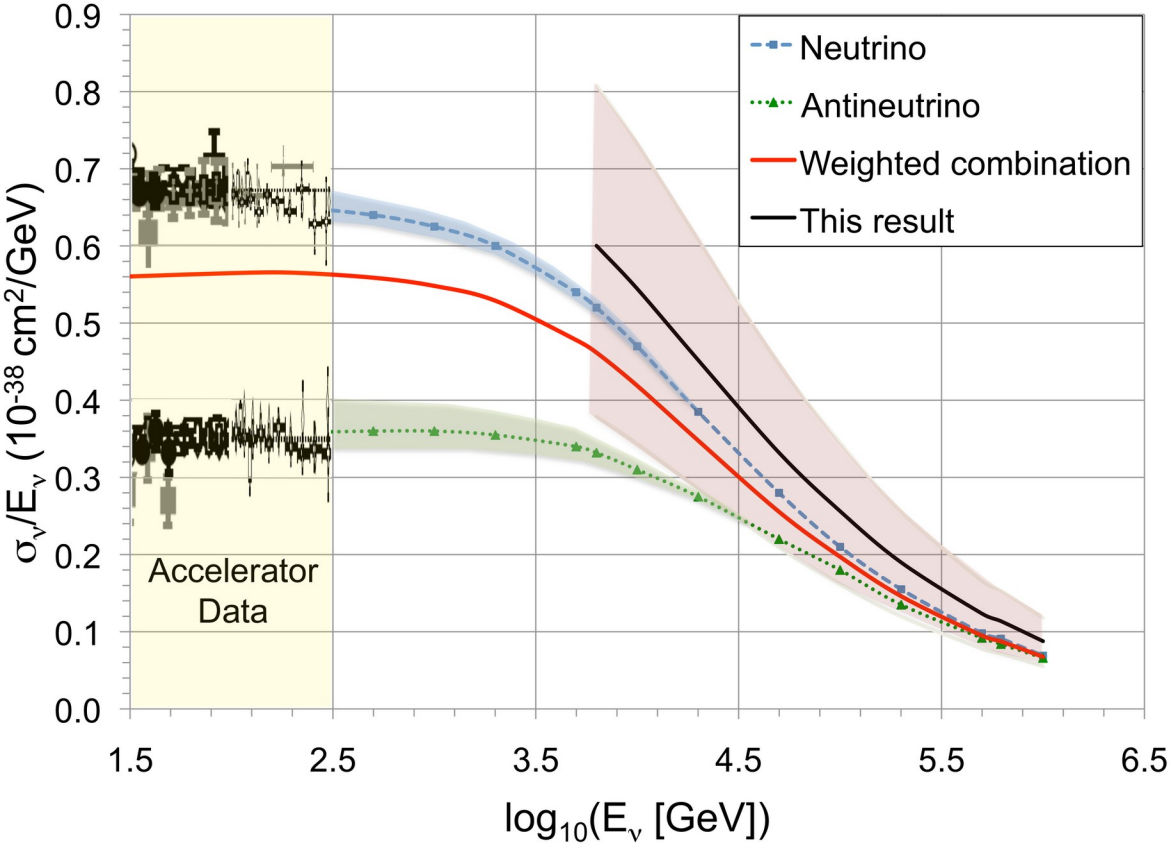
Extending the PDG cross-section plot



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

Using through-going muons instead

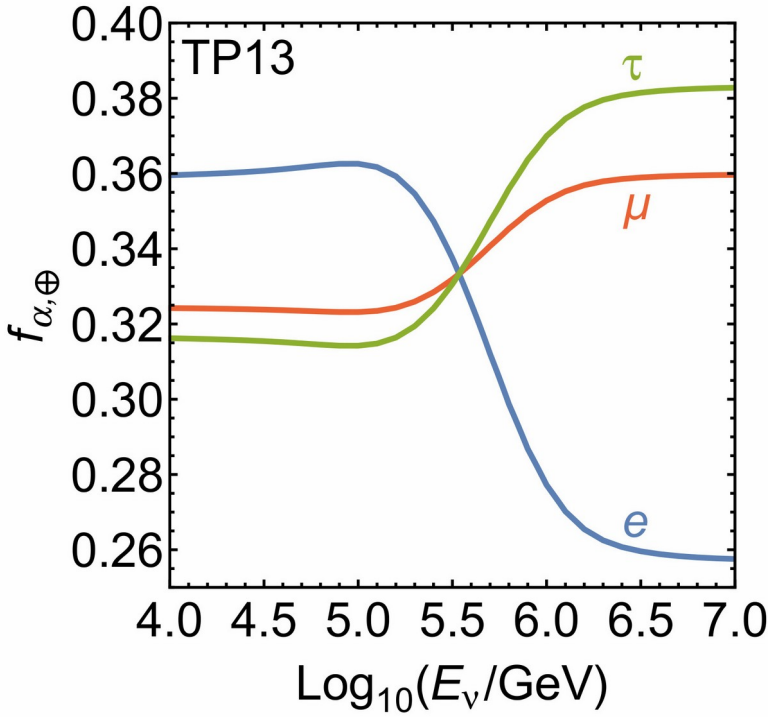
- Use ~10^4 through-going muons
- Measured: dE_μ/dx
- Inferred: $E_\mu \approx dE_\mu/dx$
- From simulations (uncertain): most likely E_ν given E_μ
- Fit the ratio σ_{obs}/σ_{SM}
  $1.30\ ^{+0.21}_{-0.19}(\text{stat.})\ ^{+0.39}_{-0.43}(\text{syst.})$
- All events grouped in a single energy bin 6–980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

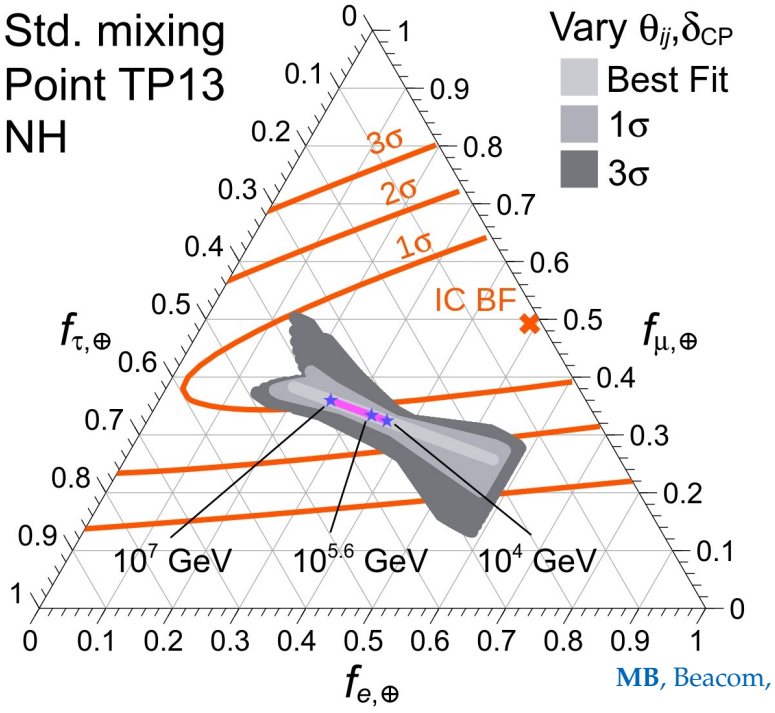


IceCube, *Nature* 2017

Energy dependence of the flavor composition?

Different neutrino production channels accessible at different energies –

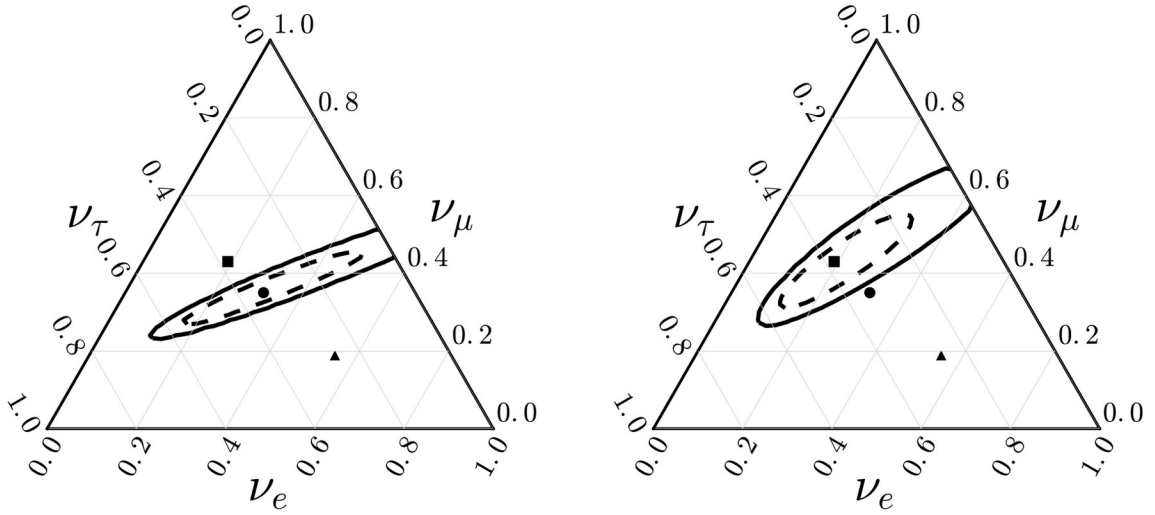


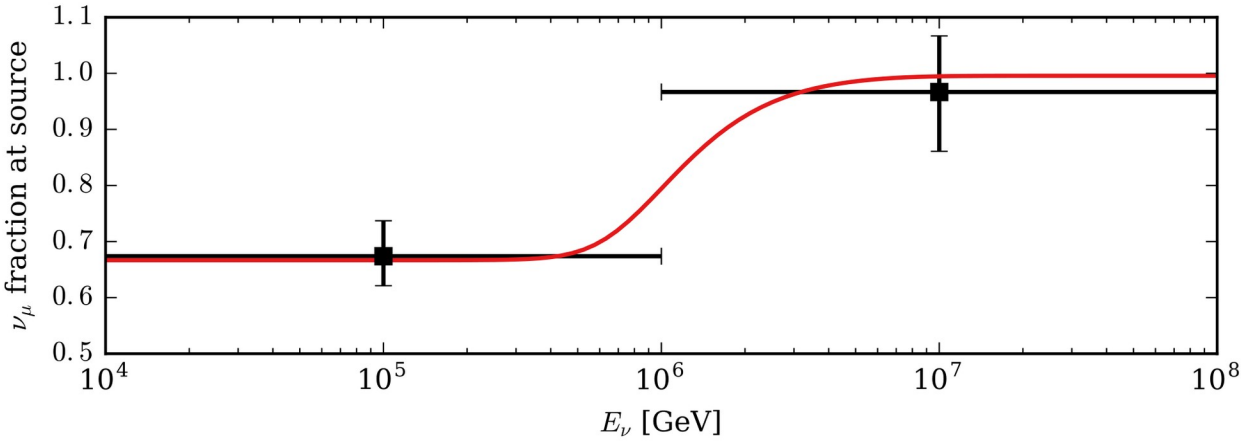


MB, Beacom, Winter *PRL* 2015

- TP13: *p*γ 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