

Mysterious Cosmic Rays and Sterile Neutrinos

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USD

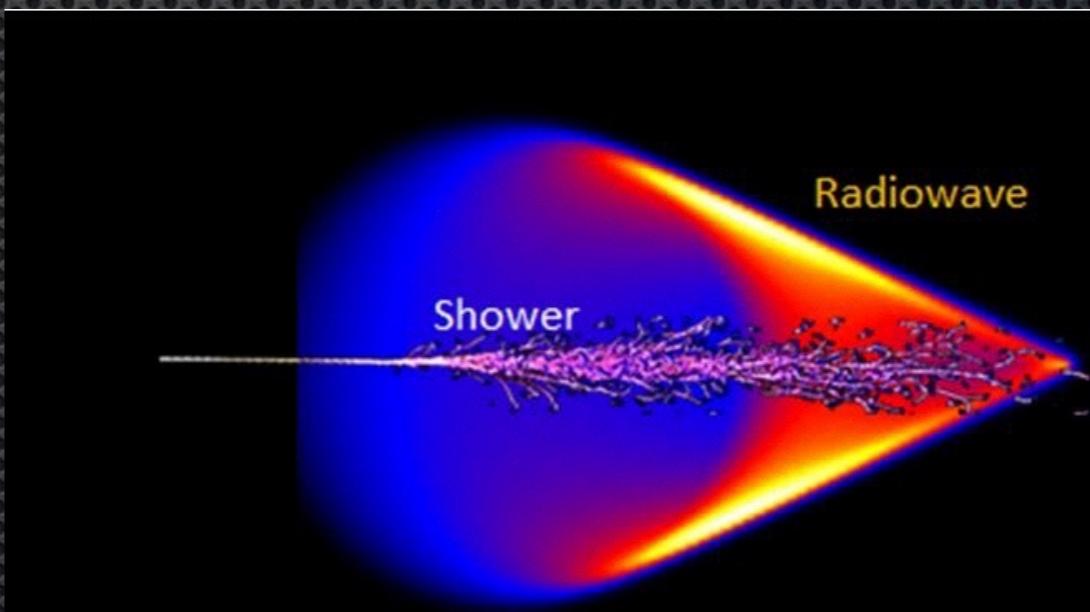


Particle Physics on the Plains, University of Kansas, Sept. 2017

Overview

- The ANITA experiment has observed several cosmic ray air showers in its search for neutrinos.
- One of these showers appears to have emerged from the Earth!
- Trajectory suggests parent particle had less than weak interaction strength.
- Sterile Neutrino?

P. W. Gorham, et al., Physical Review Letters 117, 071101 (2016).





Not to scale,
angles don't
reflect reality

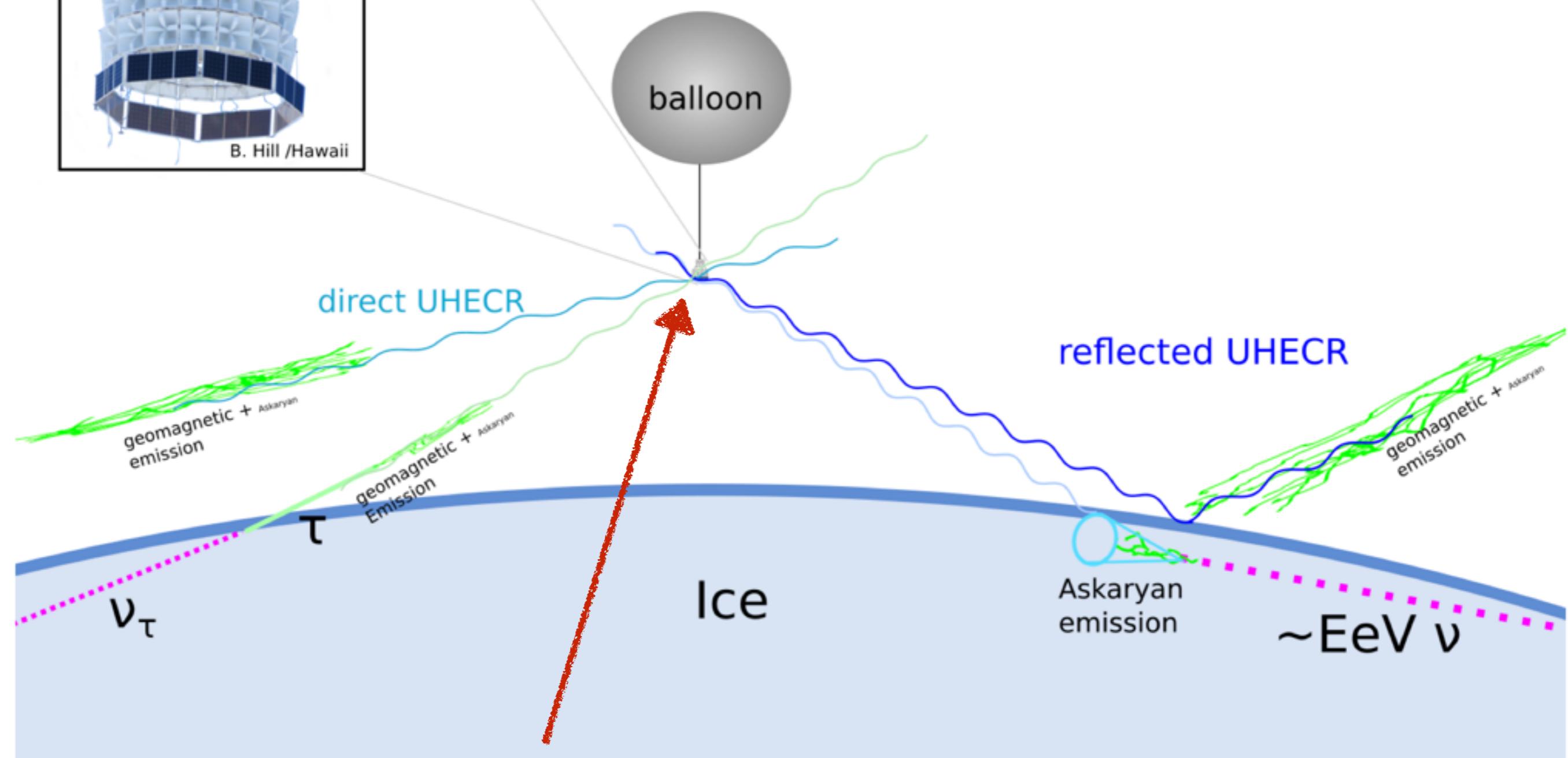


Image Credit: <https://www.hep.ucl.ac.uk/uhen/anita/>

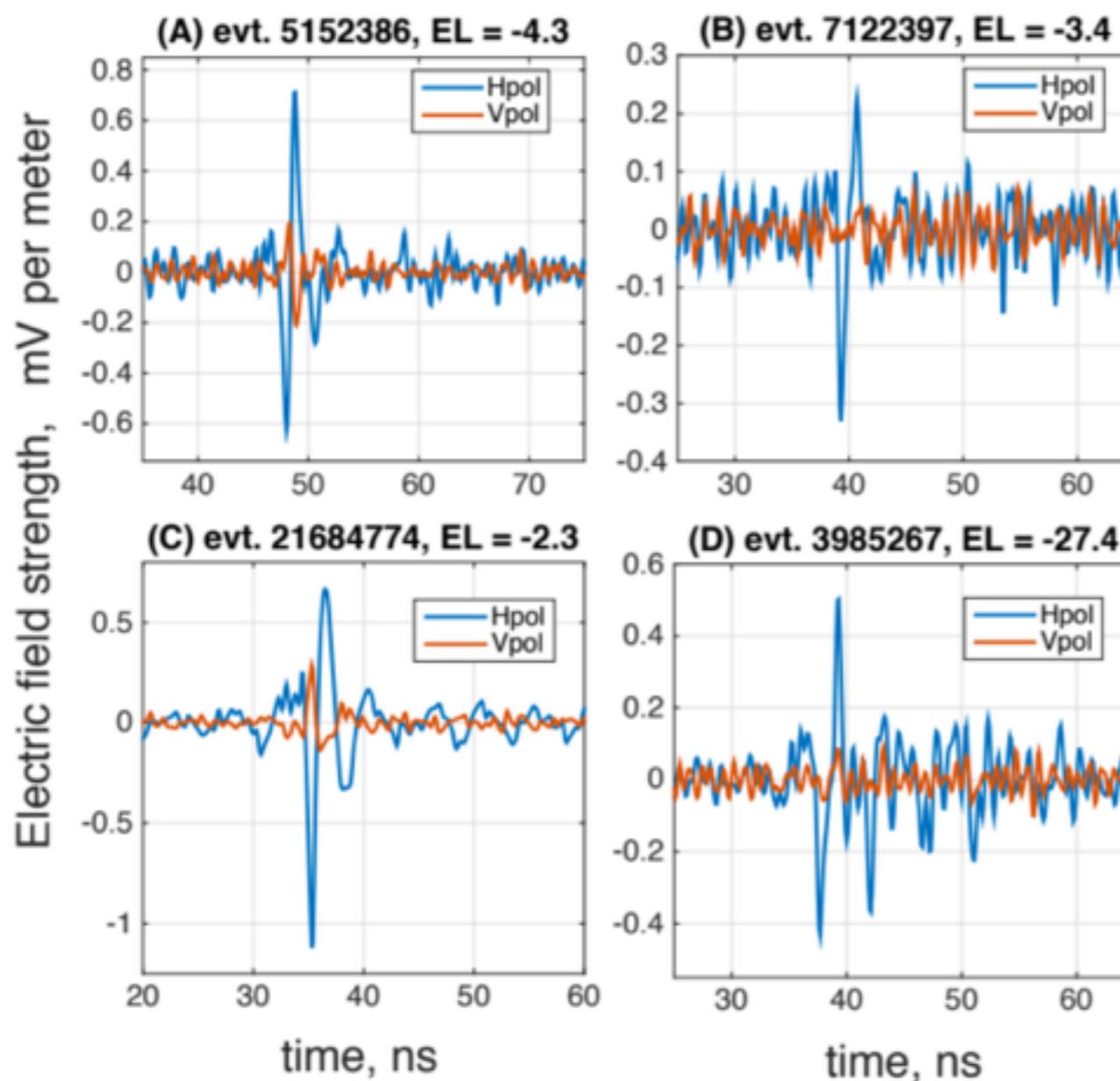
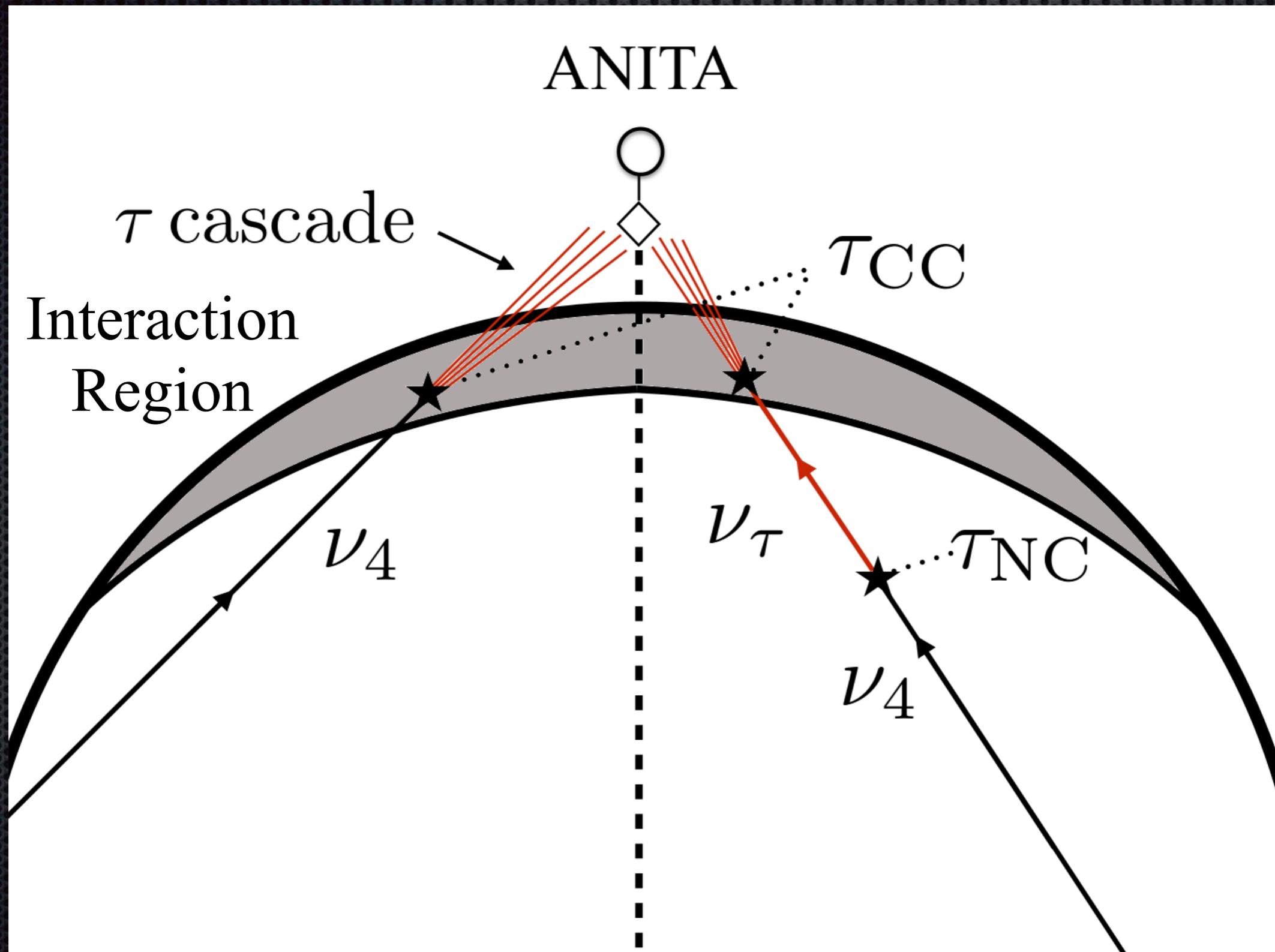


FIG. 1: Waveforms for the four events described here. Events are indexed here and in the text by the letters A,B,C,D.

| event No. | flight | index | Latitude | Longitude [†] | angle |
|-----------|--------|-------|----------|------------------------|------------------------|
| 5152386 | I | A | 80.2S | 49.0W | $-4.25 \pm 0.25^\circ$ |
| 7122397 | I | B | 82.405S | 12.5E | $-3.4 \pm 0.32^\circ$ |
| 21684774 | II | C | 83.24S | 0.87E | $-2.3 \pm 0.3^\circ$ |

| Hypothesis | Latitude | Longitude [†] | angle |
|---------------------------------|----------|------------------------|-----------------------|
| downward CR, reflected | 83.16S | 18.9E | $-27.4 \pm 0.3^\circ$ |
| upward, direct from ice surface | 82.86S | 18.15E | $-27.4 \pm 0.3^\circ$ |
| upward, start 5km above ice | 82.56S | 17.4E | $-27.4 \pm 0.3^\circ$ |

The Earth as a detector element



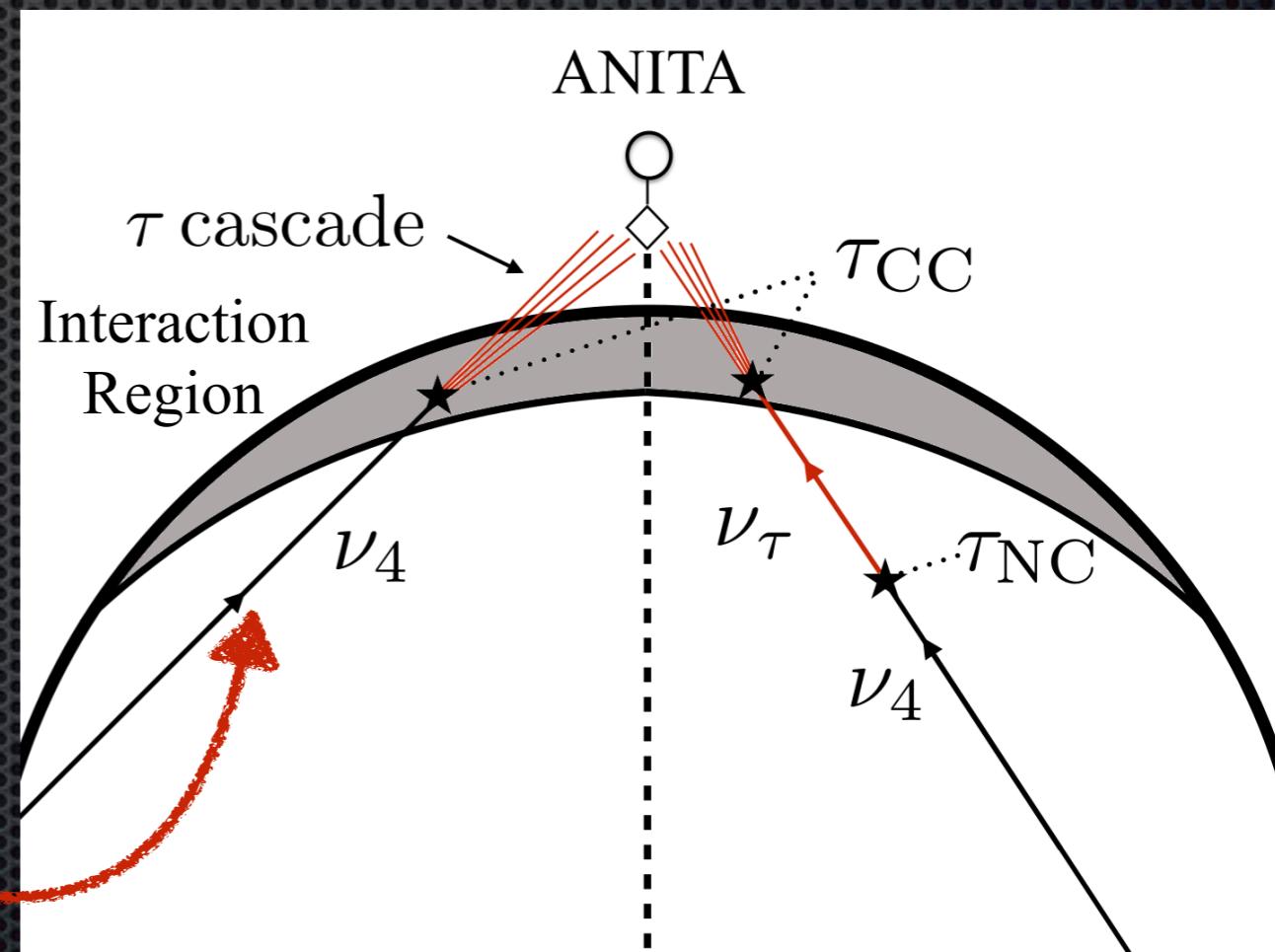
The Interaction Region

$$OD_{int}(\theta_z) = \int_{l_{int}(\theta_z)}^{l_{surf}(\theta_z)} n(l, \theta_z) \sigma_{weak} dl \leq 3$$

Direct CC interaction:

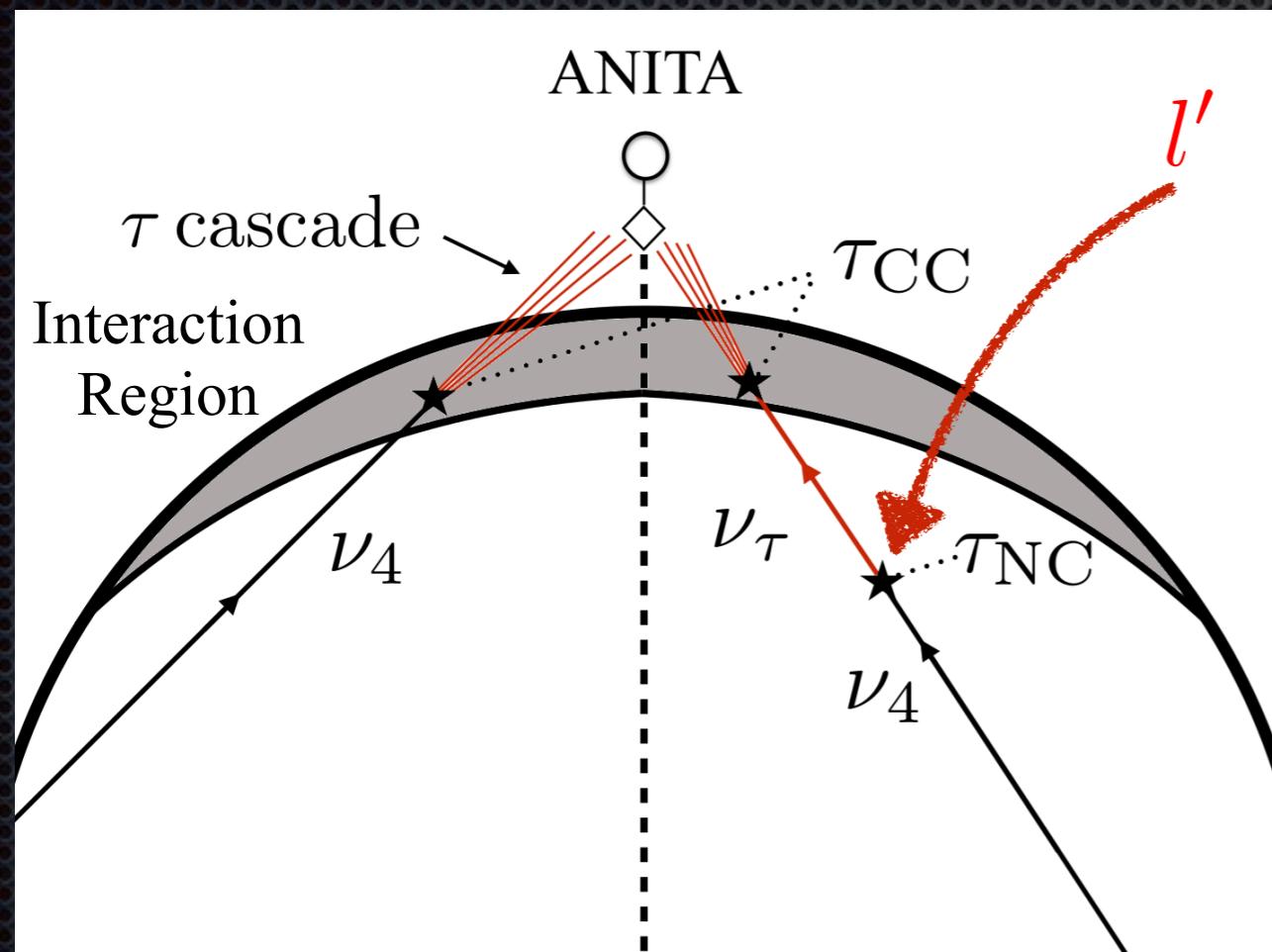
$$OD_{CC}(\theta_z) = \int_0^{l_{int}(\theta_z)} n(l, \theta_z) \sin^2 \theta_{\tau 4} \times \sigma_{weak} dl$$

$$P_{T,CC}(\theta_z) = e^{-OD_{CC}(\theta_z)}$$



Secondary Interaction

$$OD_{NC} (l', \theta_z) = \int_0^{l'} n(l, \theta_z) \sin^2 \theta_{\tau 4} \times \sigma_{weak} dl + \int_{l'}^{l_{int}(\theta_z)} n(l, \theta_z) \times \sigma_{weak} dl$$



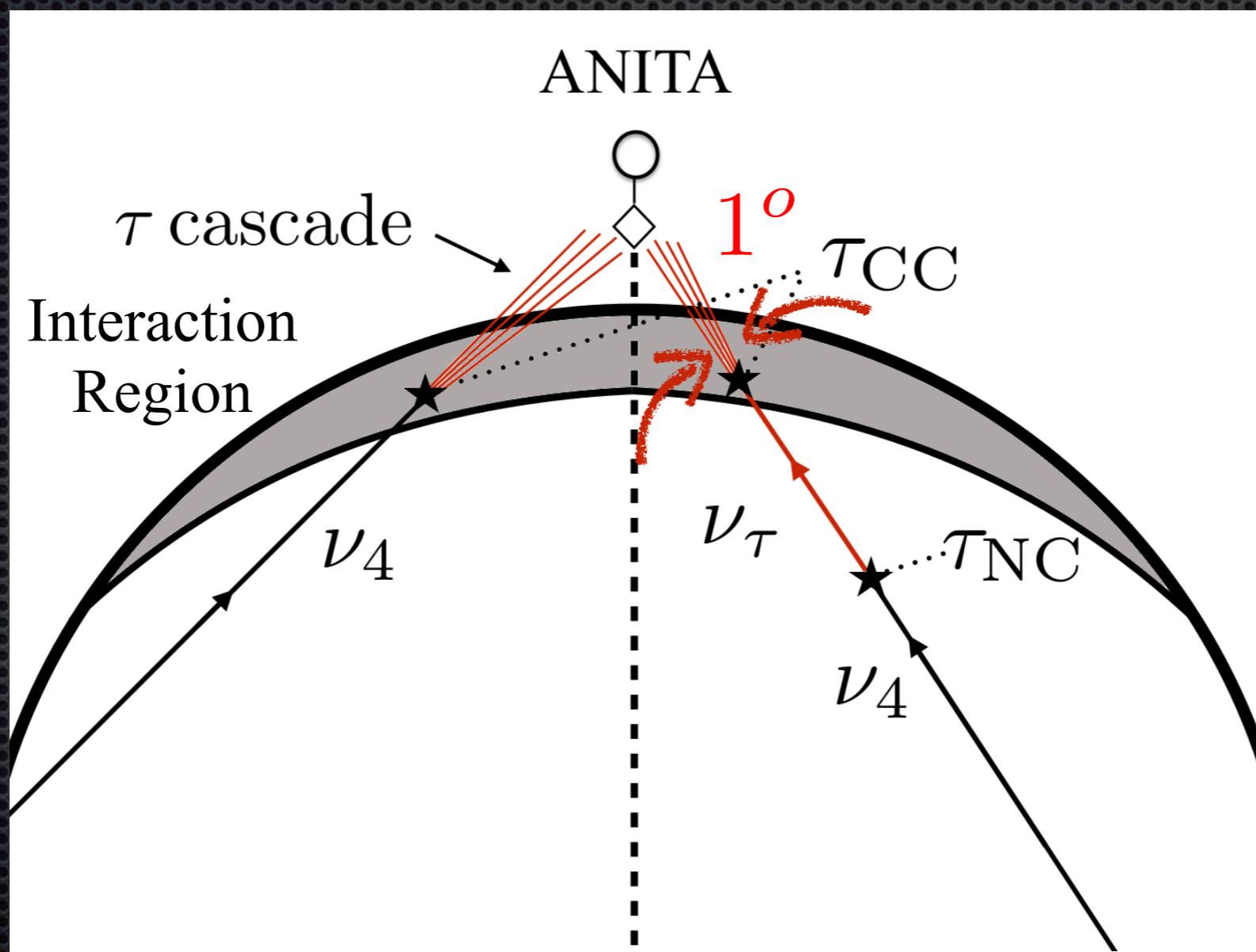
Average over midpoints

$$\frac{dP_{NC}}{dl'} \approx n(l', \theta_z) \sin^2 \theta_{\tau 4} \times \sigma_{NC}$$

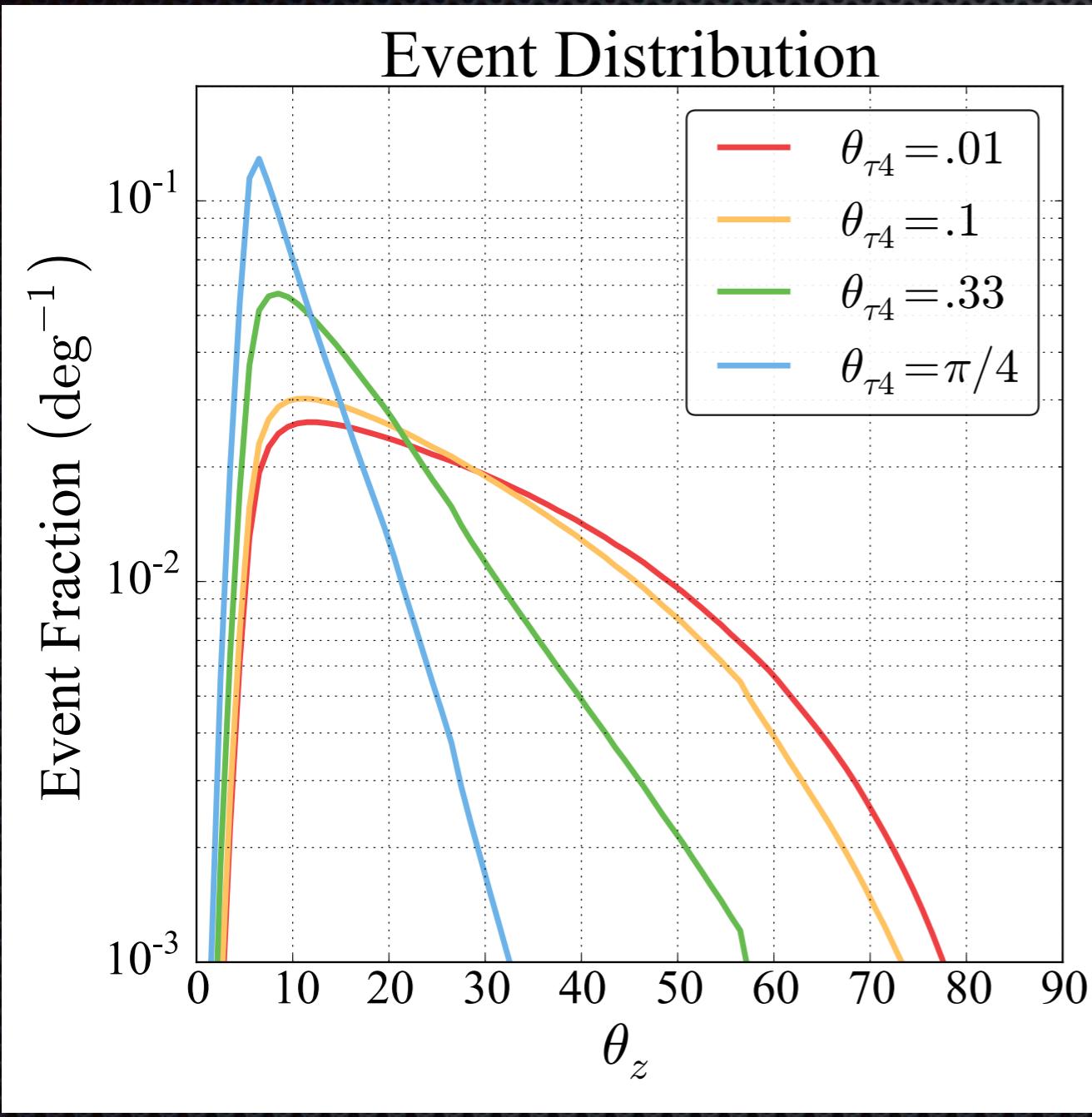
$$P_{T, NC} (\theta_z) = \int_0^{l_{int}(\theta_z)} e^{-OD_{NC}(l', \theta_z)} \frac{dP_{NC}}{dl'} dl'$$

Geometric flux sensitivity

$$\Delta(\theta_z) = \sin(\theta_z + 1^\circ) - \sin(\theta_z - 1^\circ) = \cos \theta_z \times \sin(1^\circ)$$



Angular Distribution



$$A_{eff}^{CC}(\theta_z) = \int_{d_{surf}(\theta_z)}^{d_{surf}(\theta_z) + d_{int}(\theta_z)} n(r, \theta_z) \sin^2 \theta_{\tau 4} \times \sigma_{CC}$$

$$\times P_{T,CC}(\theta_z) \times \Delta(\theta_z) \times 2\pi r^2 dr$$

$$A_{eff}^{NC}(\theta_z) = \int_{d_{surf}(\theta_z)}^{d_{surf}(\theta_z) + d_{int}(\theta_z)} n(r, \theta_z) \times \sigma_{NC}$$

$$\times P_{T,NC}(\theta_z) \times \Delta(\theta_z) \times 2\pi r^2 dr$$

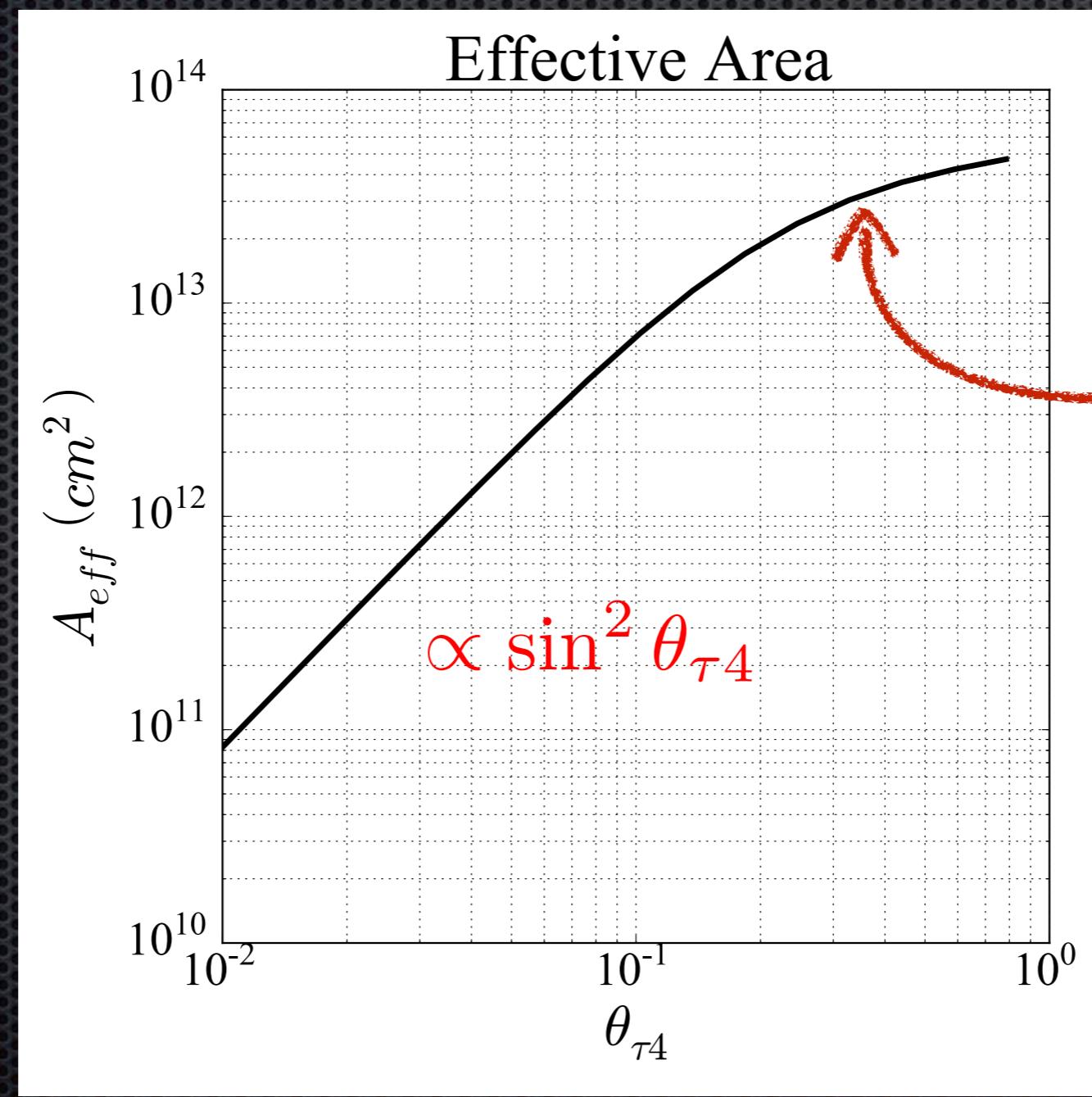
TABLE I: Angular Event Distributions

| $\theta_{\tau 4}$ | 67% flux range |
|-------------------|----------------------------------|
| $\pi/4$ | $5^\circ < \theta_z < 14^\circ$ |
| .33 | $7^\circ < \theta_z < 26^\circ$ |
| .1 | $10^\circ < \theta_z < 42^\circ$ |
| .01 | $11^\circ < \theta_z < 47^\circ$ |

$$\theta_z = 27.4^\circ$$

Total Effective Area

$$A_{eff} = \int_{0^\circ}^{90^\circ} [A_{eff}^{CC}(\theta_z) + A_{eff}^{NC}(\theta_z)] d\cos(\theta_z + 90^\circ)$$



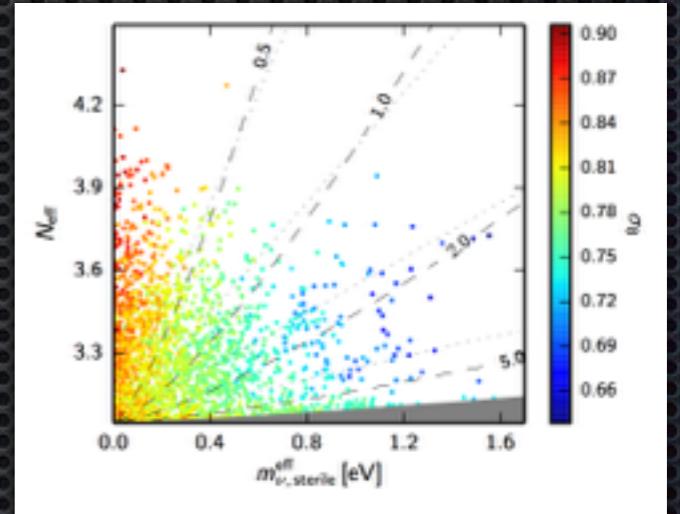
ν_4
Opacity
suppressed

LSND/MiniBooNE sterile ν

- The Planck 2015 data places strong constraints the relic abundance of new neutrinos.

$$\left. \begin{array}{l} N_{\text{eff}} < 3.7 \\ m_{\nu, \text{sterile}}^{\text{eff}} < 0.52 \text{ eV} \end{array} \right\} 95\% \text{ CI}$$

Planck Collaboration, arXiv:1502.01589v2



- Hamann, J. and Hasenkamp, J., JCAP **10**, 044 (2013) : These limits rule out plain vanilla sterile neutrino models which have large mixing angles and \sim eV masses.

$$\Delta N_{\text{eff}} = 1$$

$$m_{\nu, \text{sterile}}^{\text{eff}} = \Delta N_{\text{eff}} \times m_{\nu, \text{sterile}} \sim 1 \text{ eV}$$

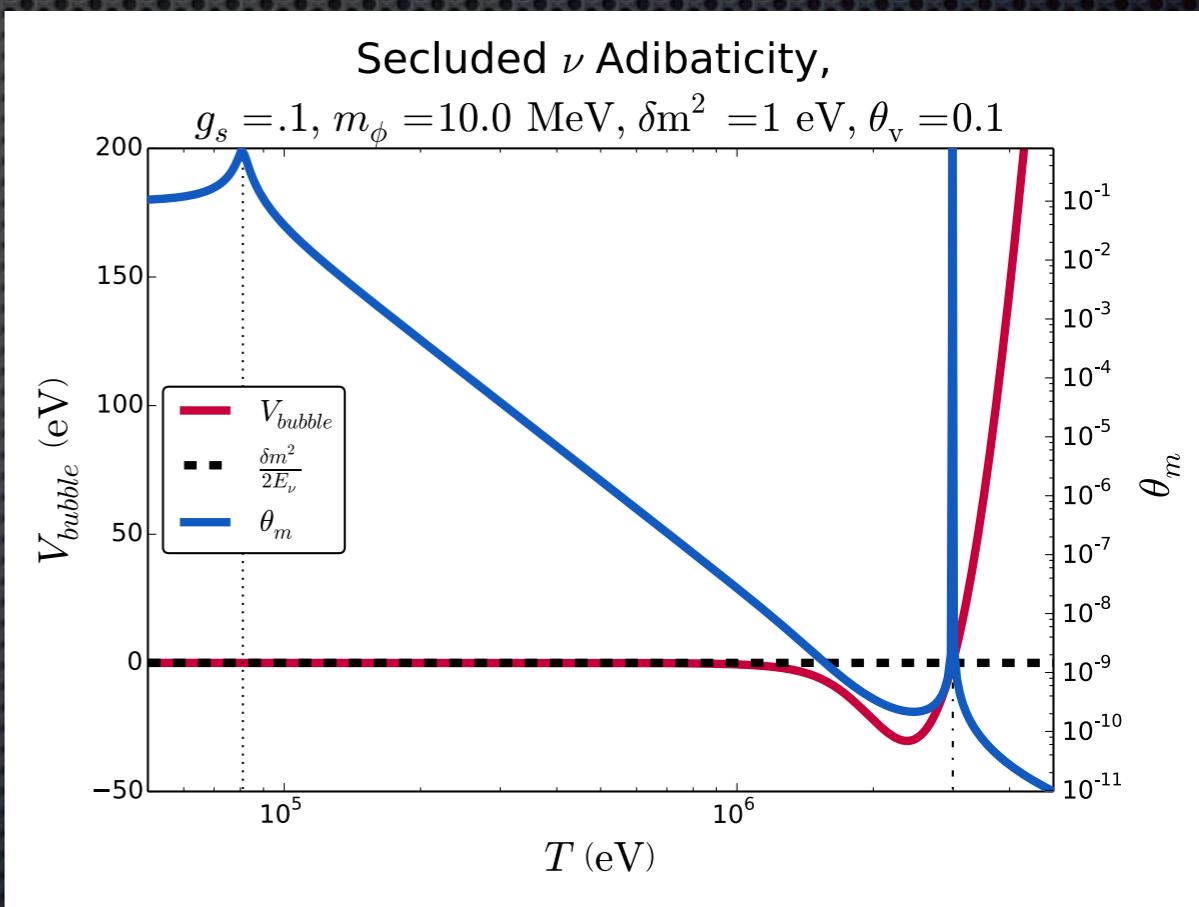
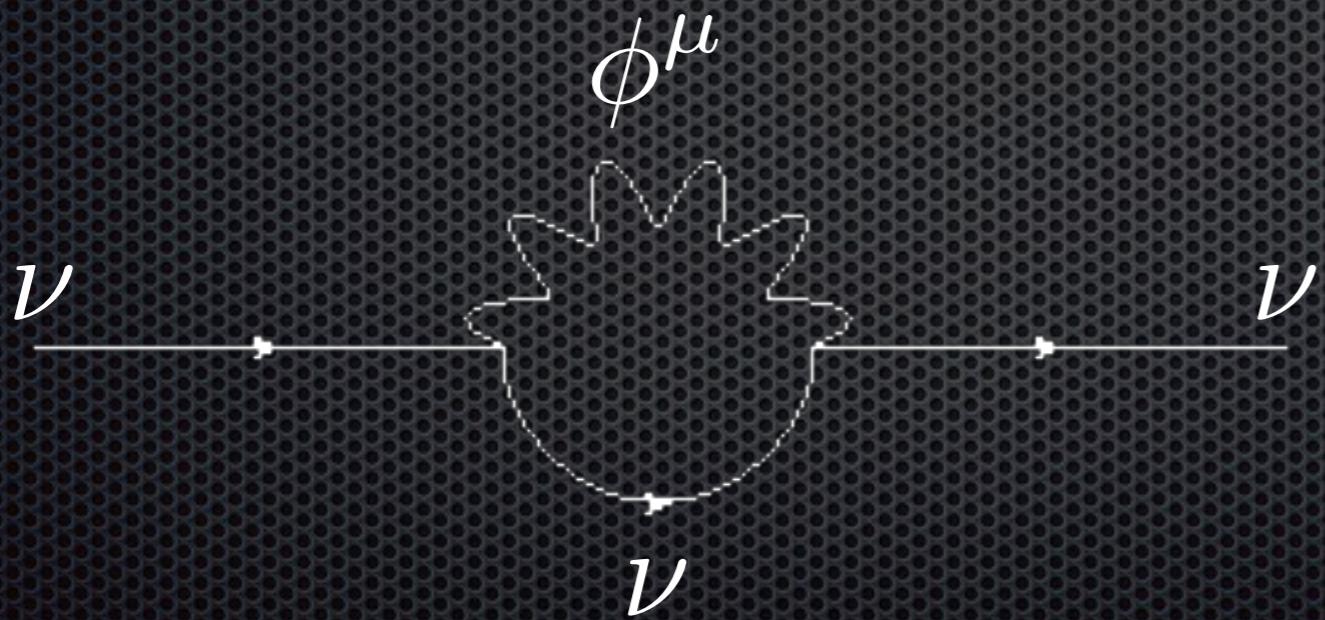
Sterile Interactions Suppress Mixing

B. Dasgupta and J. Kopp, PRL **112**, 031803 (2014)

S. Hannestad, R. S. Hansen, and T. Tram, PRL **112**, 031802 (2014)

$$\sin 2\theta_{\text{eff}} = - \frac{\frac{\delta m_V^2}{2E_\nu} \sin 2\theta_V}{\sqrt{\left(\frac{\delta m_V^2}{2E_\nu} \cos 2\theta_V + A\right)^2 + \left(\frac{\delta m_V^2}{2E_\nu} \sin 2\theta_V\right)^2}}$$

Effective mass term



Mixing Portal Prescription

Cherry, Friedland, Shoemaker, arXiv:1411.1071

$$\mathcal{L} \supset LH\nu_R + \nu_s H'\nu_R + \Lambda\nu_R\nu_R$$

$$\mathcal{L} \supset \frac{(LH)(\nu_s H')}{\Lambda}$$



Basic seesaw type operator

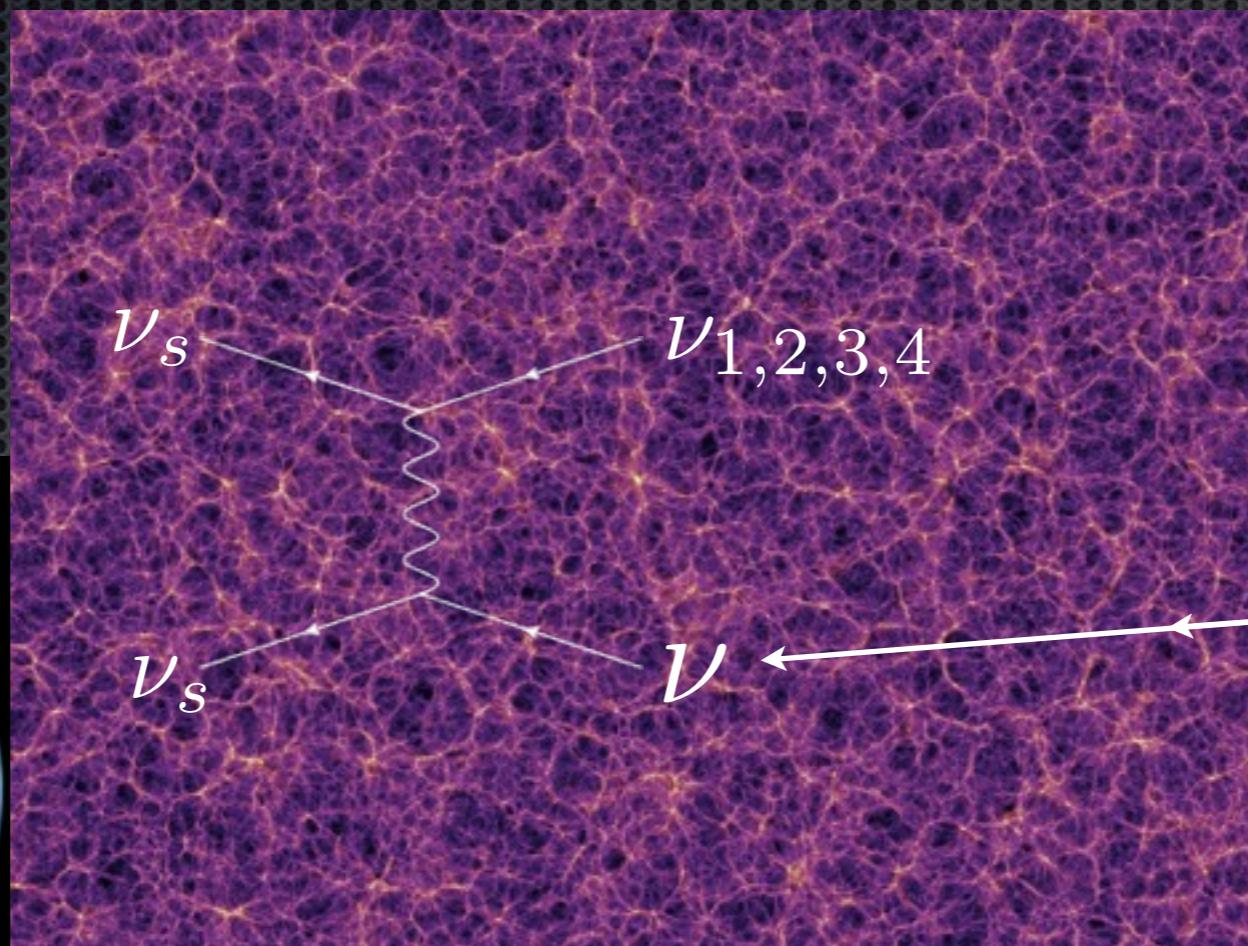
Similar to M. Pospelov, Phys. Rev. D **84**, 085008 (2011)

$$\nu_s, \theta_s \quad \langle \nu_s | \nu_{e,\mu,\tau} \rangle \equiv 0$$

Goldstone Boson associated
with ν_s acquires mass when
 H' symmetry is broken

$$\mathcal{L} \supset g_s \phi^\mu \bar{\nu}_s \gamma_\mu \nu_s$$

Scattering = Measurement

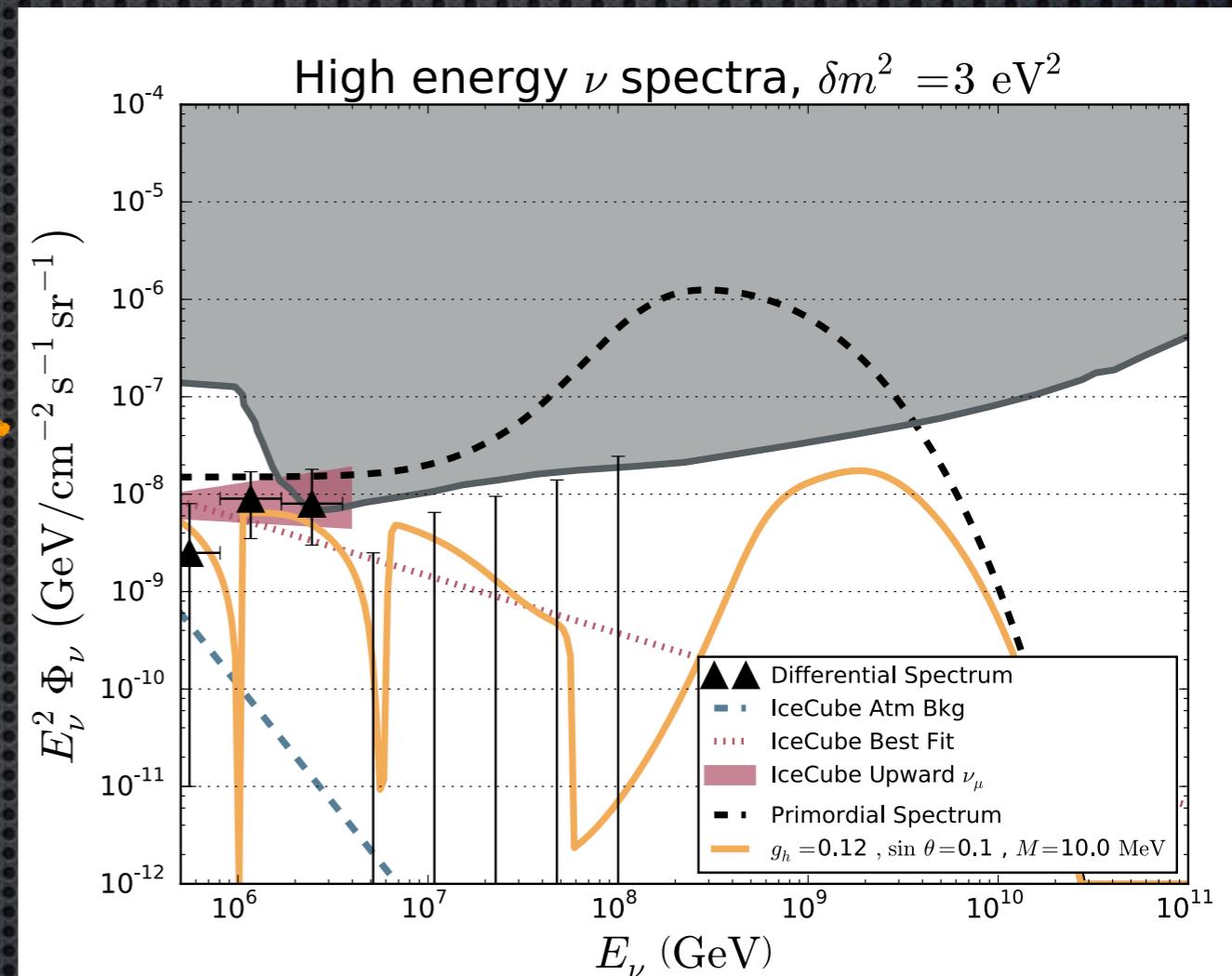
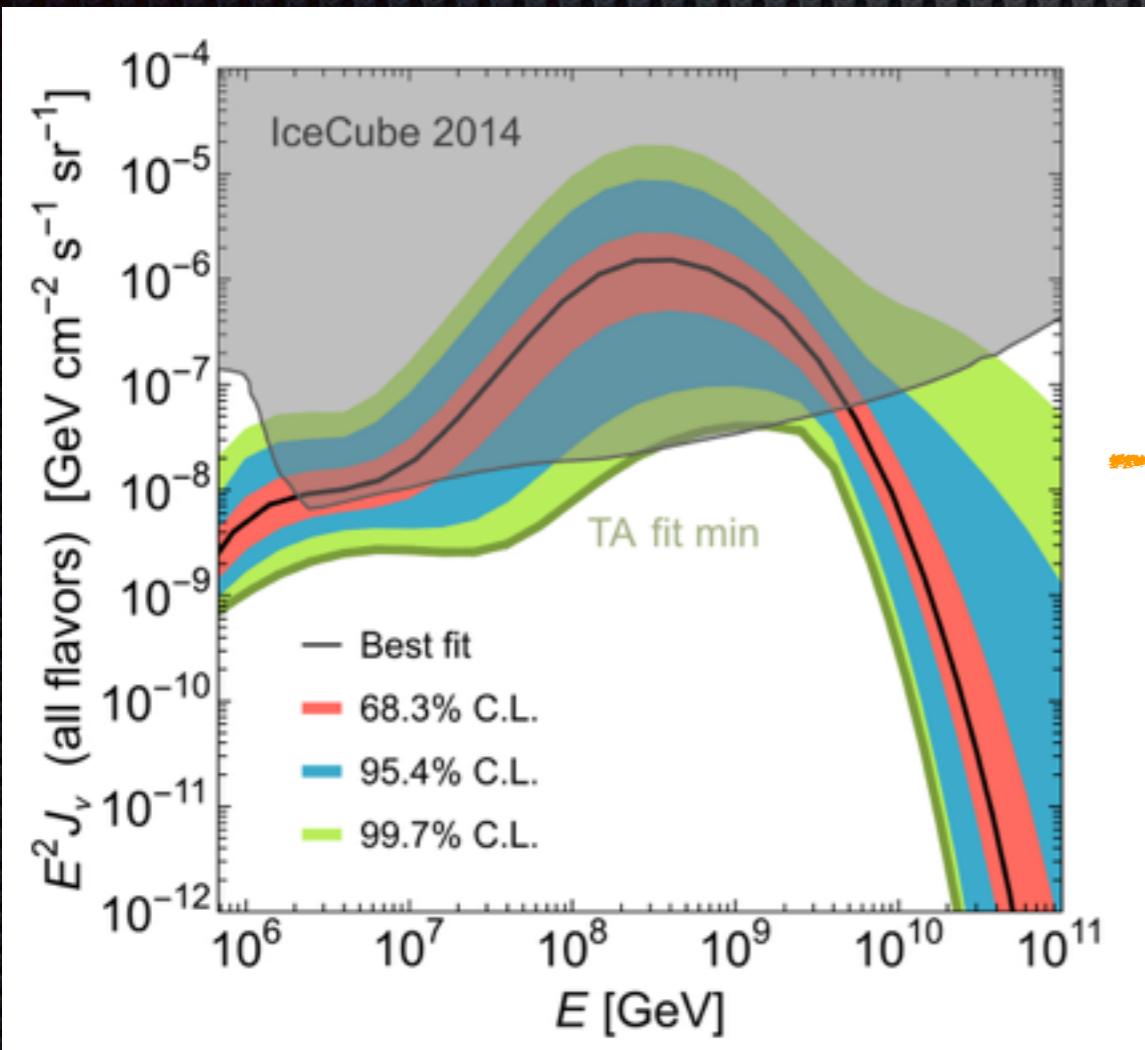


$$\langle \nu_s | \nu_{e, \mu, \tau} \rangle \equiv 0$$

We can put our differences behind us. For Science.
You monster.



Neutrino horizon and UHECR fits



$C_V B$ Scattering

For SM neutrinos:

$$-(1+z)H(z)\frac{df_i}{dz} = J_i(E', z) - f_i(E') \sum_j \langle n_{\nu_j} \sigma_{ij}(E', z) \rangle$$

For Sterile neutrinos:

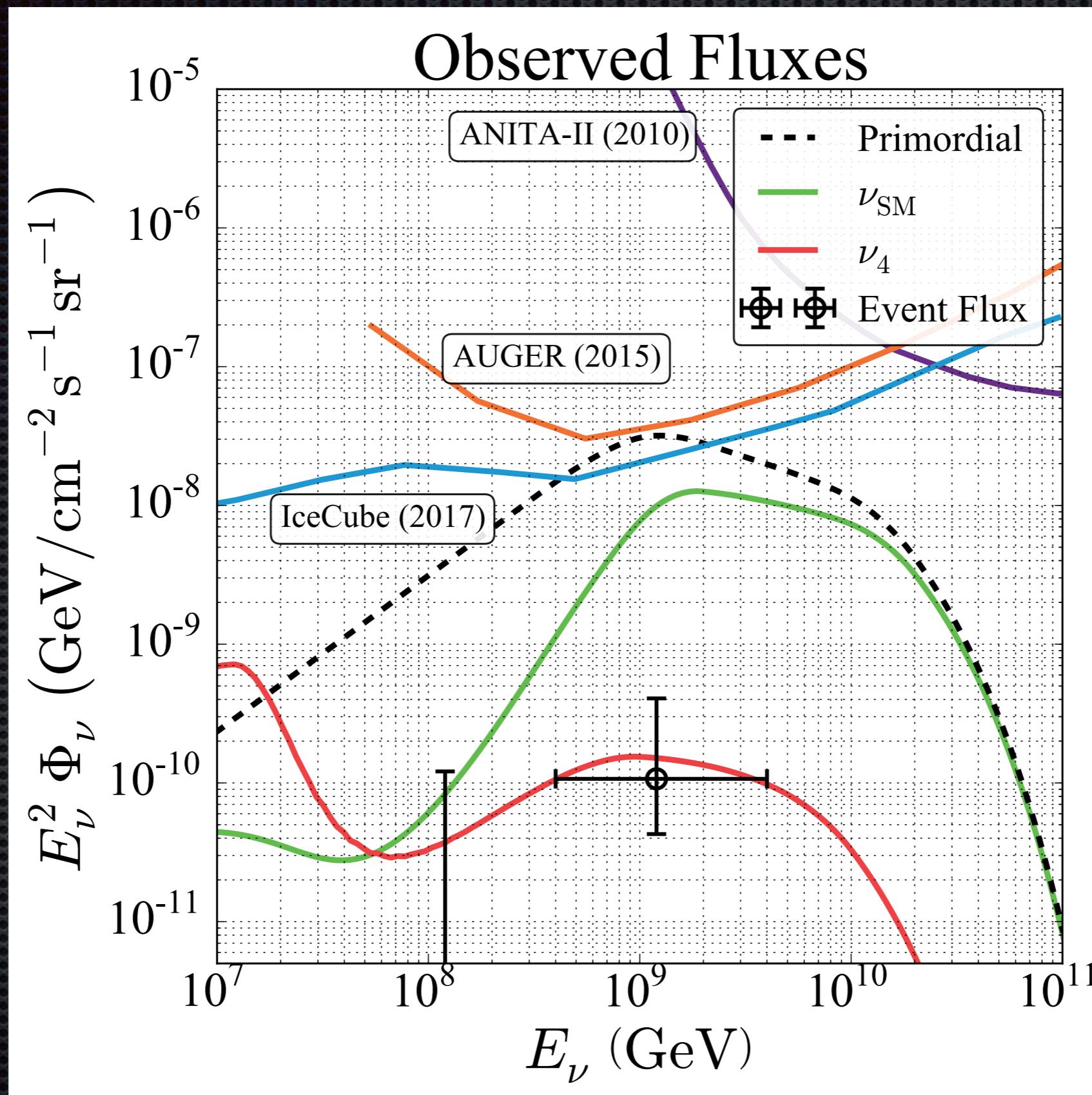
$$-(1+z)H(z)\frac{df_4}{dz} = \sum_i 2f_i(2E') \sum_j \langle n_{\nu_j} \sigma_{ij}(2E', z) \rangle - f_4(E') \sum_j \langle n_{\nu_j} \sigma_{4j}(E', z) \rangle$$

$$\sigma_{44} \sim g^4/m_\phi^2$$

$$\sigma_{i4} \sim \sin^2 \theta_{i4} \times g^4/m_\phi^2$$

$$\sigma_{ij} \sim \sin^2 \theta_{i4} \times \sin^2 \theta_{j4} \times g^4/m_\phi^2$$

Cascade Result



Conclusions:

- Hidden neutrino interactions can reprocess UHECR neutrinos to create EeV energy ν_s .
- Angular distribution favors tau mixing close to existing bounds on e and mu flavor limits.
- Only suggested alternative for this event (transition radiation) is unlikely, with 2.5×10^{-3} events expected with ANITA's current exposure.
G. H. Collin, et al., Physical Review Letters 117,
221801 (2016), 1607.00011.
- If this model is true, ARA and ANITA will collect many such events with increased exposure!

Thank you very much!