Constraining EeV-Scale Dark Matter with Neutrino Observatories Using Tau Regeneration

Jeffrey Lazar

Dark Ghosts Workshop

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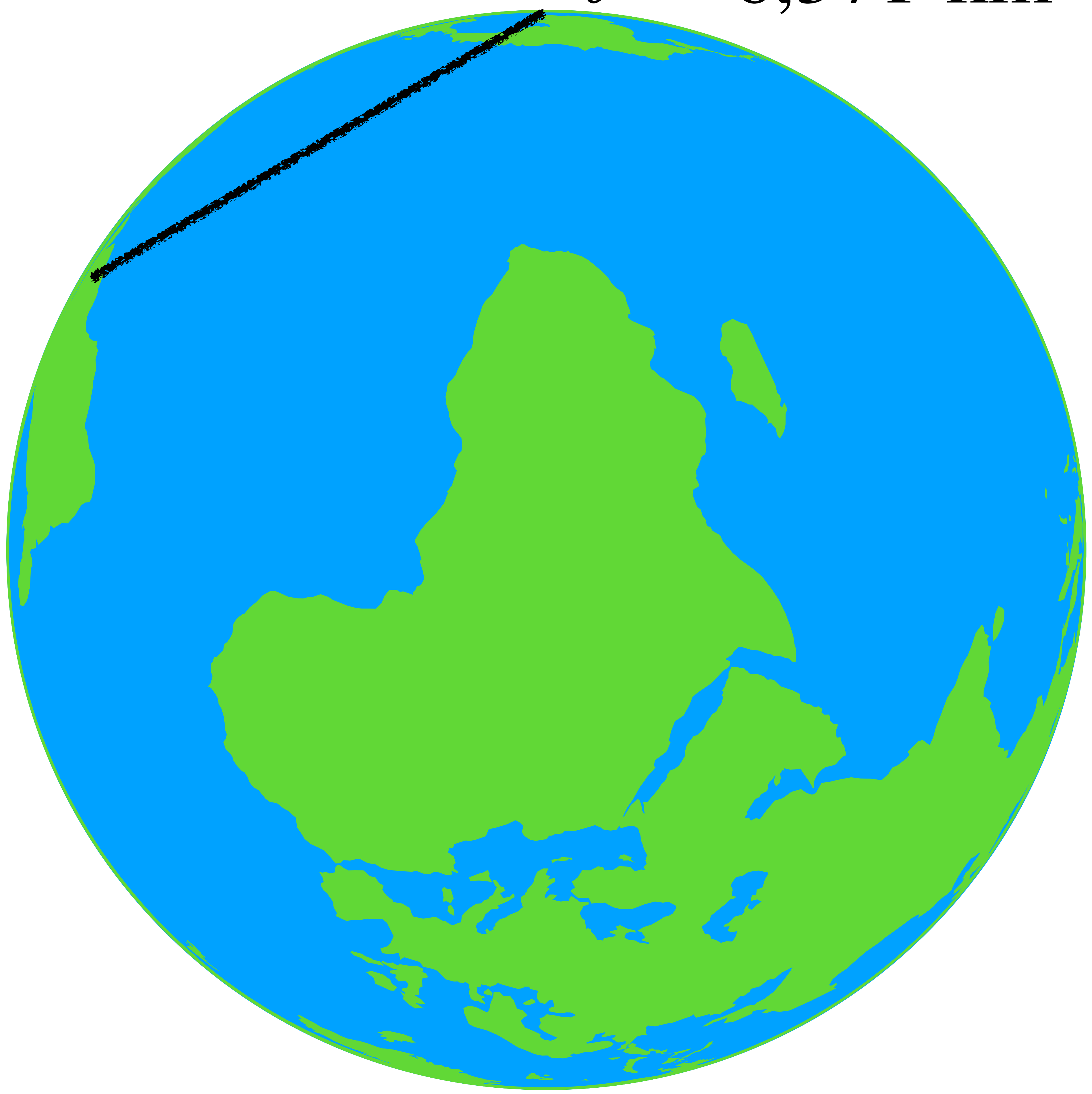
ANITA Anomalous Events

- In 2016 and 2018, ANITA reported observation of two events with ~500 PeV from $30°$ below the horizon
- The chord this would traverse 6,371 km of earth but the interaction length is ~500 km in rock at this energy



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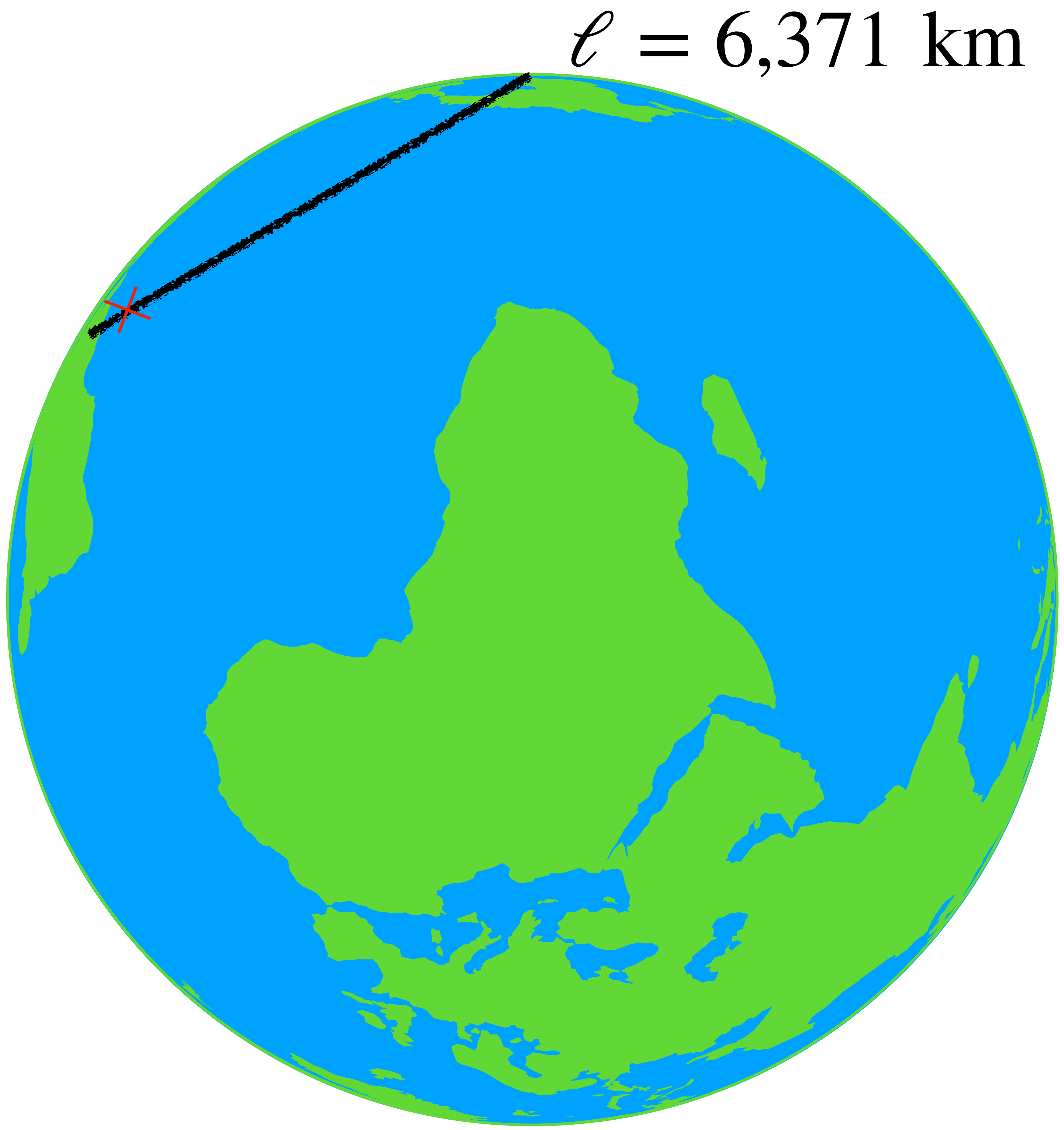
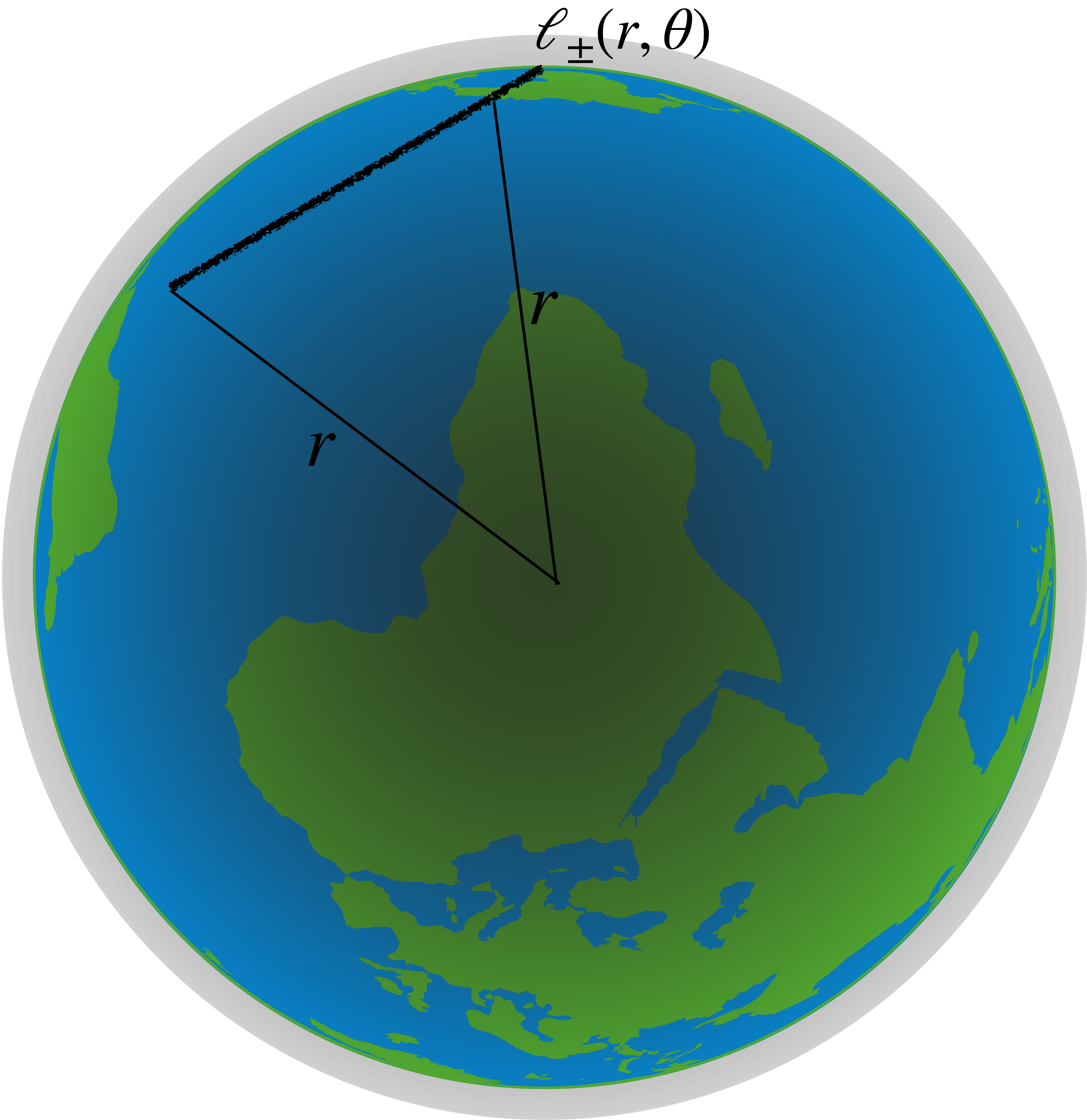


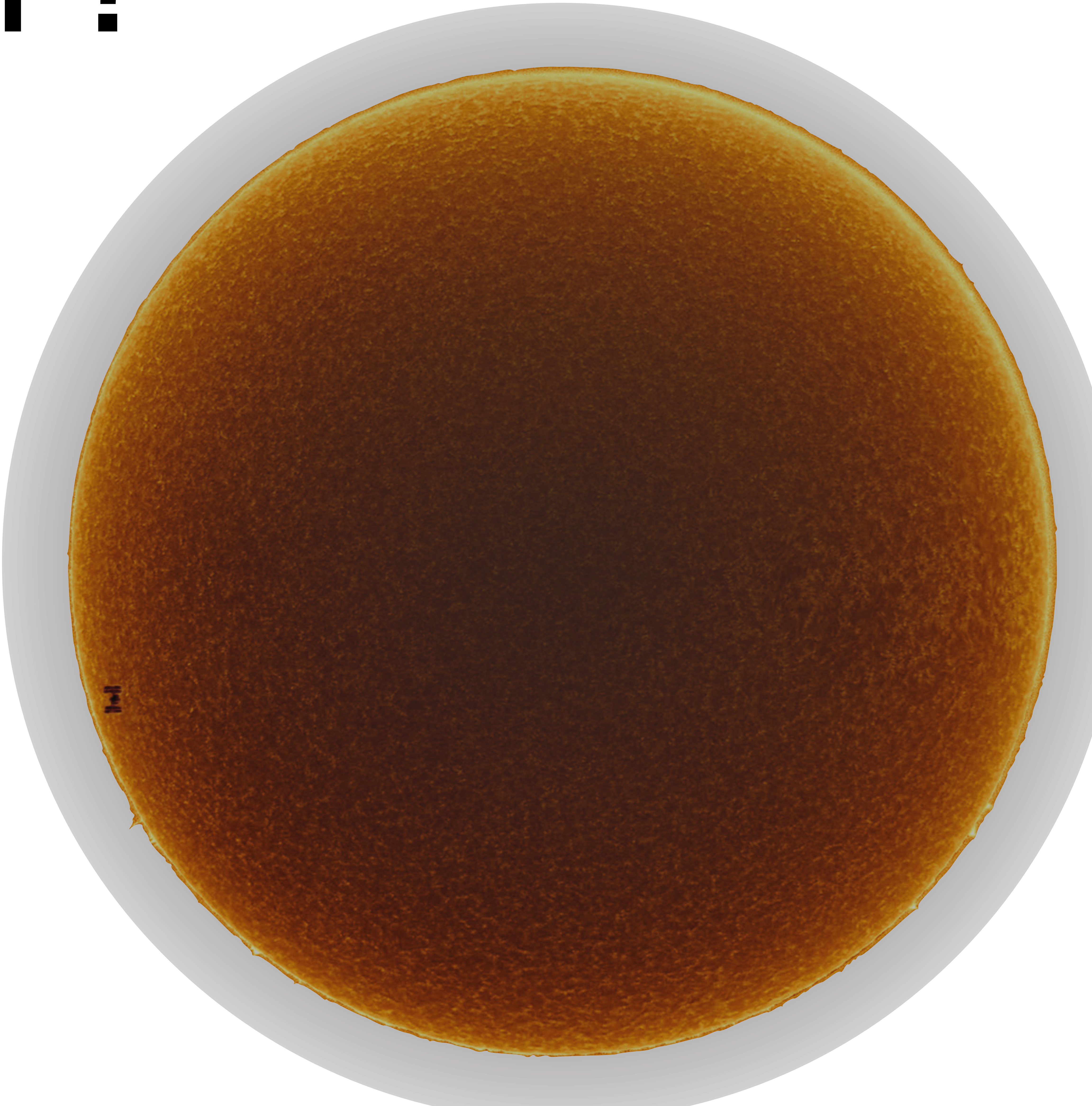
CPT Symmetric Explanation

- L. A. Anchordoqui proposed that this could be due decays of captured heavy right-handed neutrinos
- Model requires a *local modification to dark matter distribution*→we cannot use the Galactic Center as a direct probe of this model



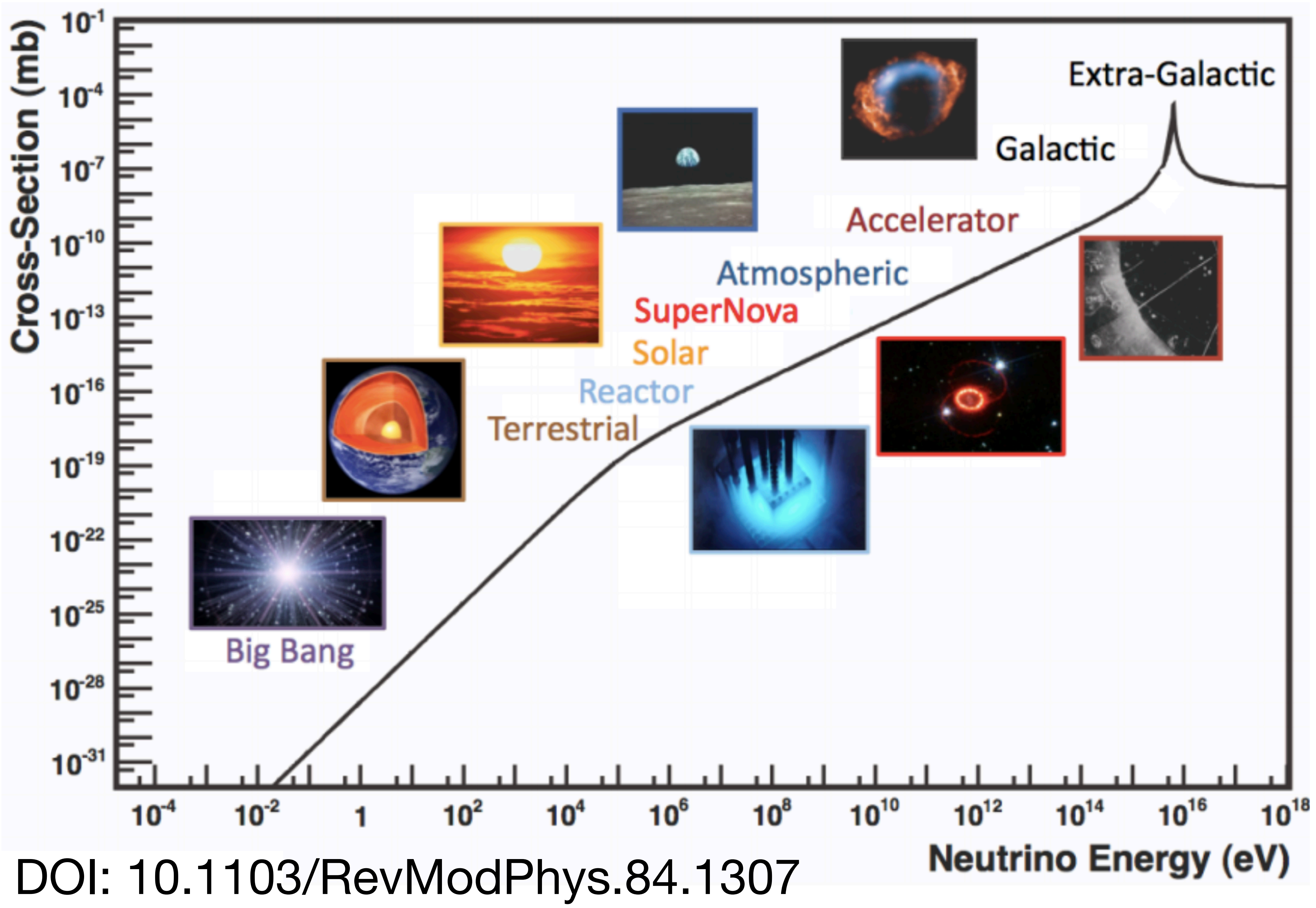
What About the Sun ?

- Sun should capture DM in the same way Earth would
- It is local, and so is subject to the same potential DM overdensity
- Can we test this model using the Sun ?

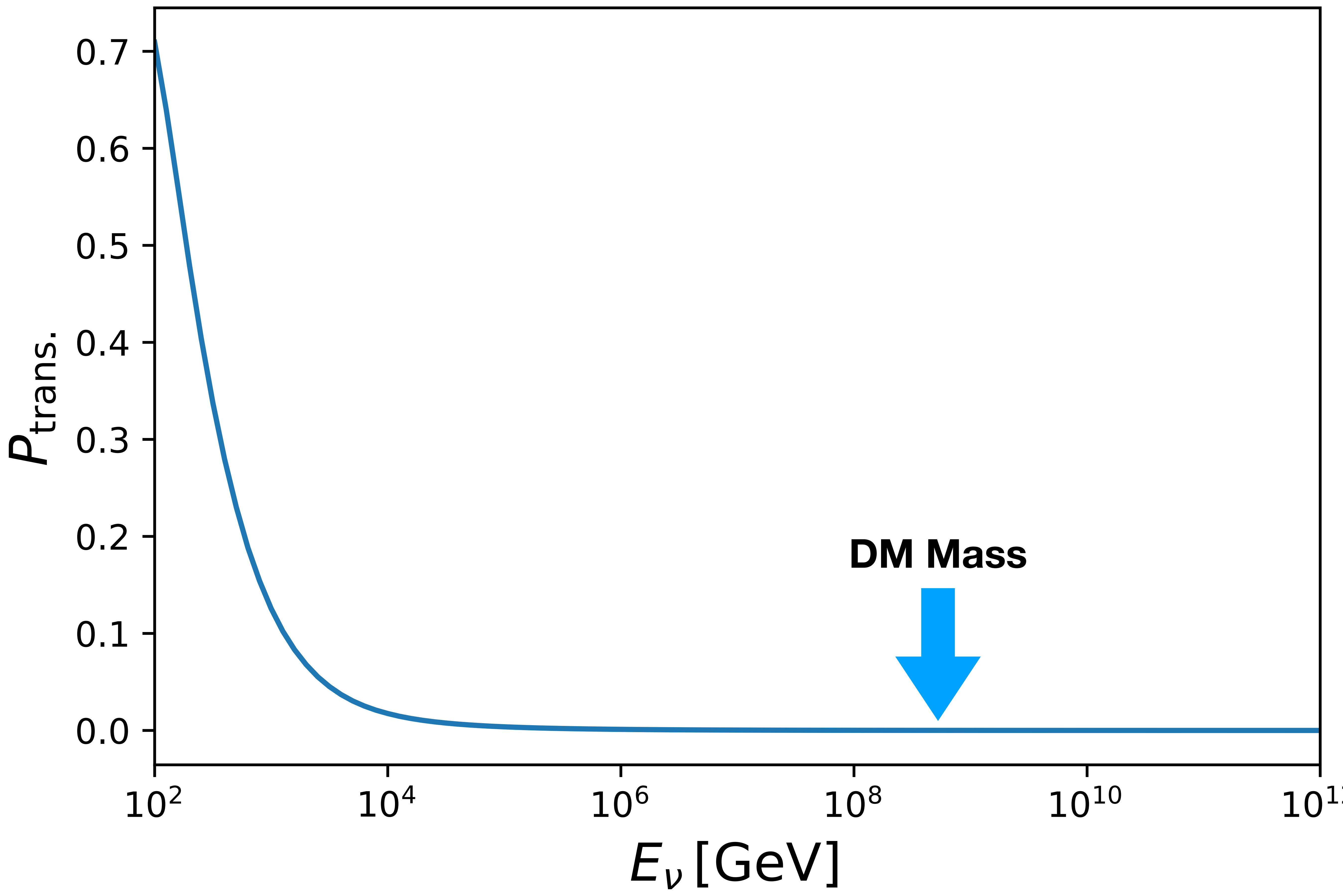


Solar Opacity

- Above ~3 TeV, the solar core becomes opaque to neutrinos
- We run into the same issue as the Earth 😞

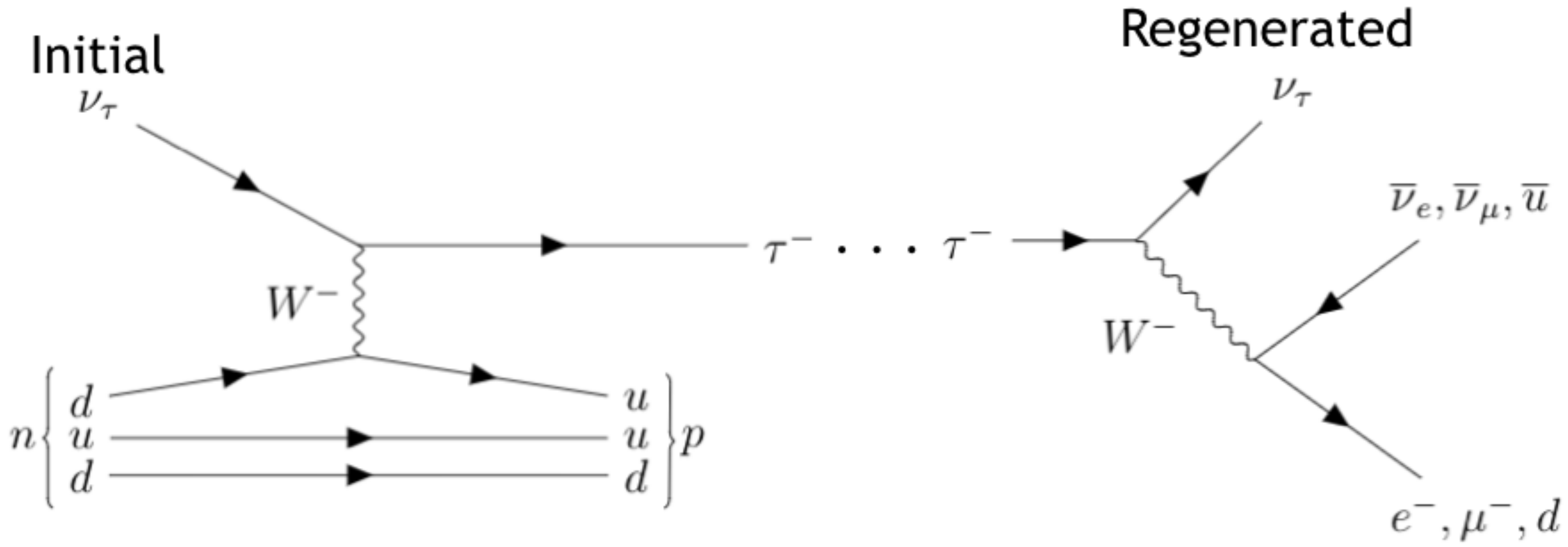


DOI: 10.1103/RevModPhys.84.1307



Tau Neutrino Regeneration

- Since τ decay very quickly secondary ν_τ are created with a significant fraction of the primary energy
- Continues until critical energy where on-spot decay approximation is valid
- Buildup at this energy. ~1 PeV for Earth, *~500 GeV for Sun*
- Use regenerated flux + existing solar WIMP limits to test this model



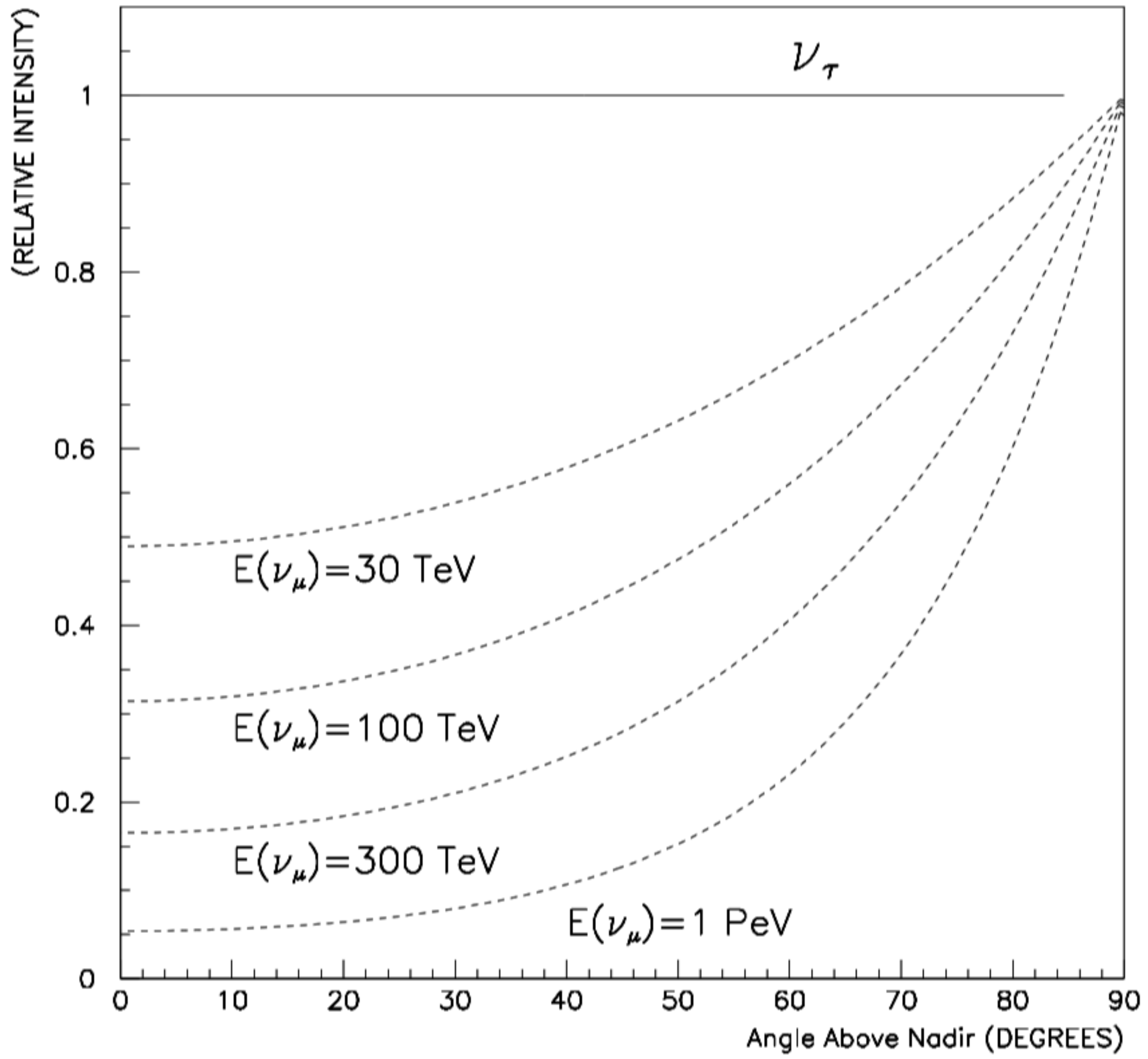


FIG. 2. Plot of the transmission of ν_μ and ν_τ through the Earth's. The transmission of ν_τ is essentially independent of their energy, as described in the text. The event rates are normalized to the maximum.

DOI:10.1103/PhysRevLett.81.4305

TauRunner

- Complete and versatile Python-based package for simulating UHE neutrinos
- Follows all flavors of neutrinos, and μ and τ leptons
- **Recent rewrite allows for customizable bodies and neutrino trajectories**
- Pip installable !
- Check us out on the [ArXiv]

TauRunner: A Public Python Program to Propagate Neutral and Charged Leptons

Ibrahim Safa[a,b,*], Jeffrey Lazar[a,b,*], Alex Pizzuto[b], Oswaldo Vasquez[a], Carlos A. Argüelles[a,c], Justin Vandenbroucke[b]

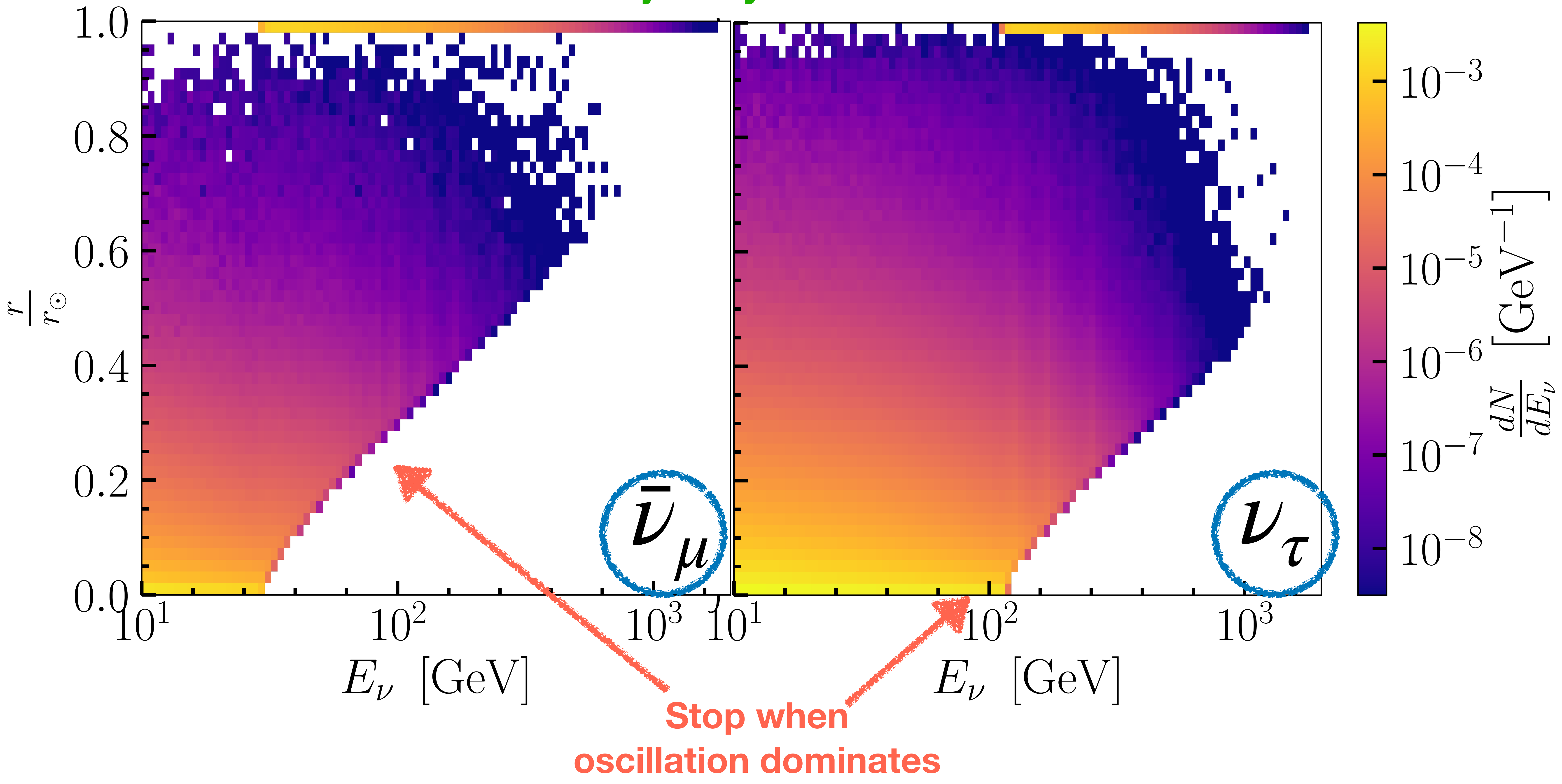
[a] *Department of Physics & Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, MA 02138, USA*
[b] *Department of Physics and Wisconsin IceCube Particle Astrophysics Center, University of Wisconsin-Madison, Madison, WI 53706, USA*
[c] *The NSF AI Institute for Artificial Intelligence and Fundamental Interactions*

https://github.com/icecube/TauRunner

TauRunner Output

- TauRunner allows:
  - Tracking of all leptons
  - Custom bodies, including the Sun
  - Custom trajectories, radial and chord included
  - Custom stopping conditions
  - Example of monochromatic, radially propagated flux from solar center

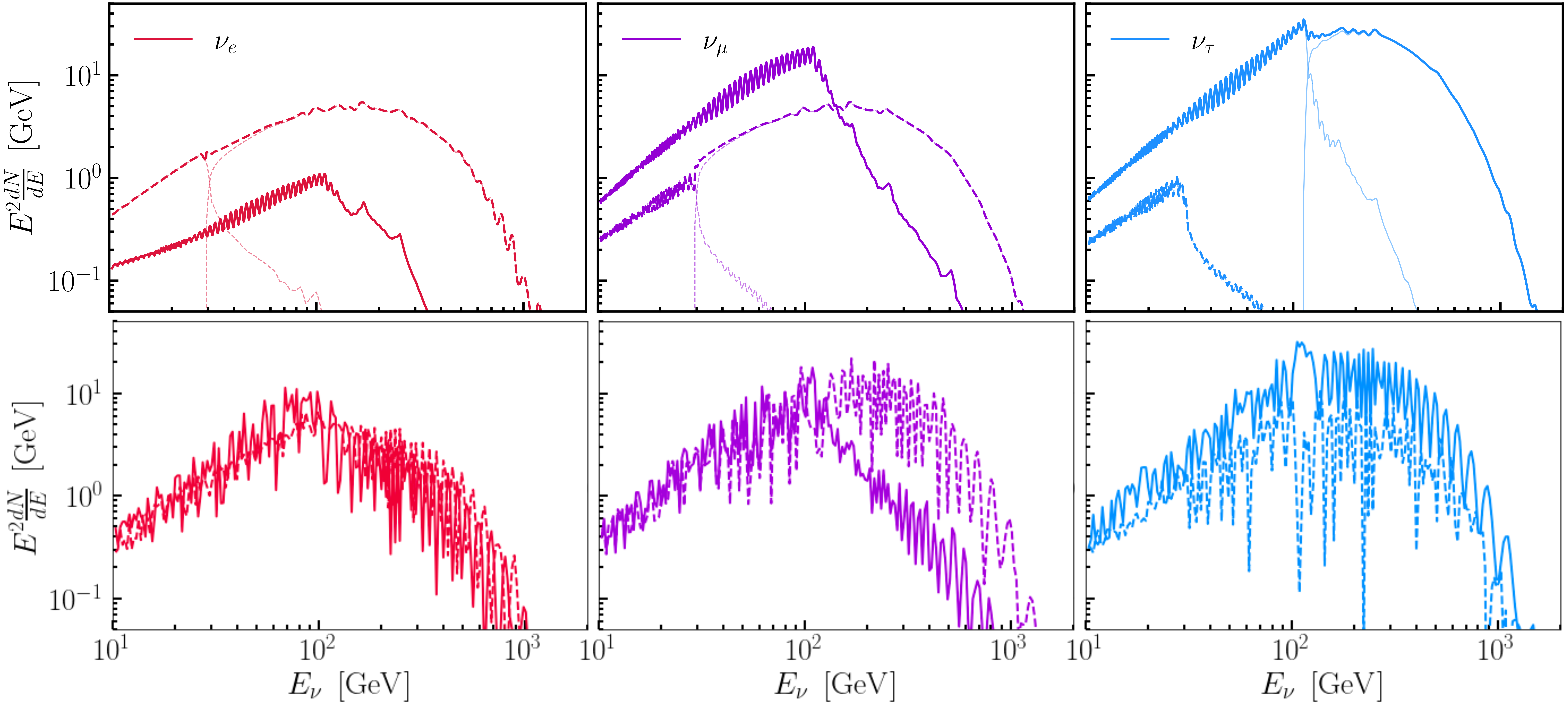
Propagation along a radial trajectory in the Sun



Flux after propagation

$L = 1\ R_\odot$

$L = 1$ A.U.



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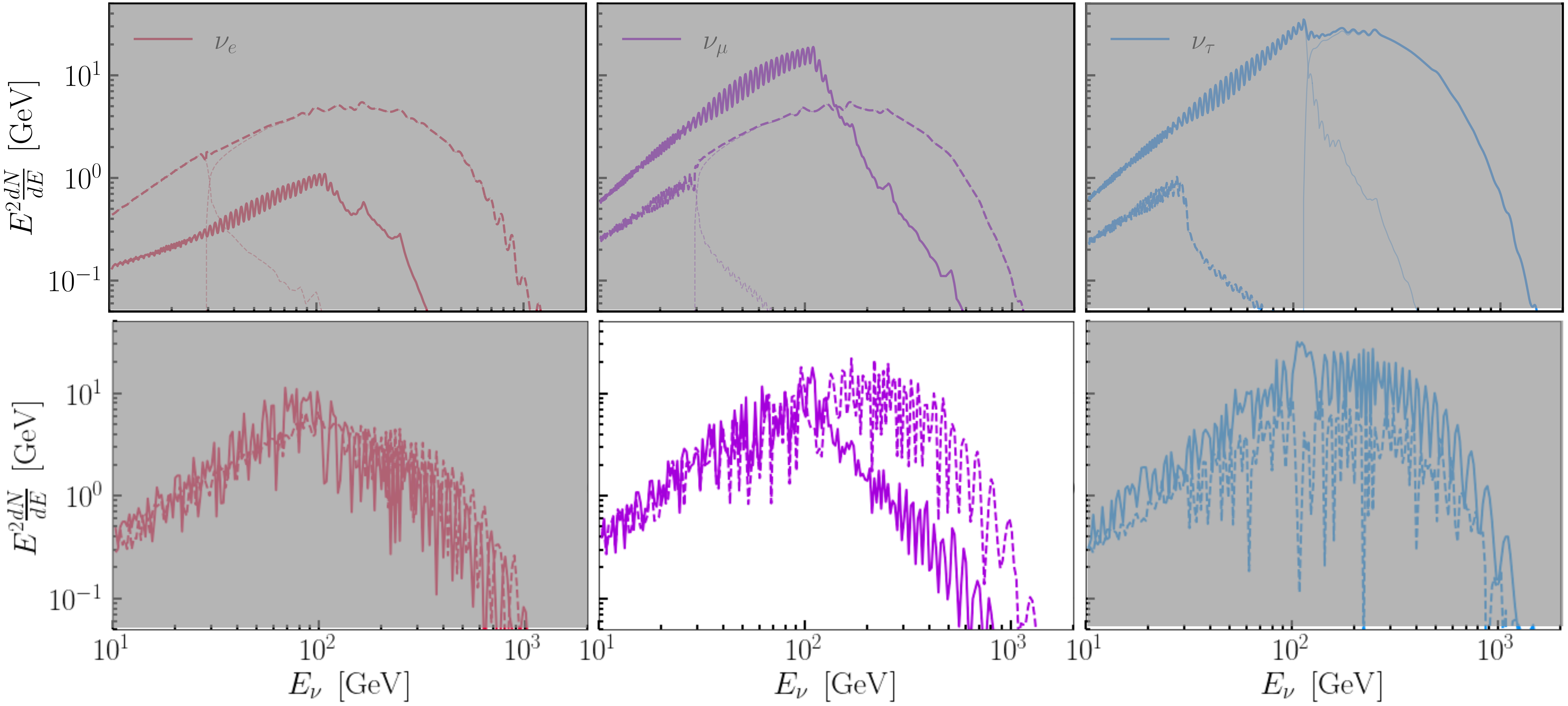
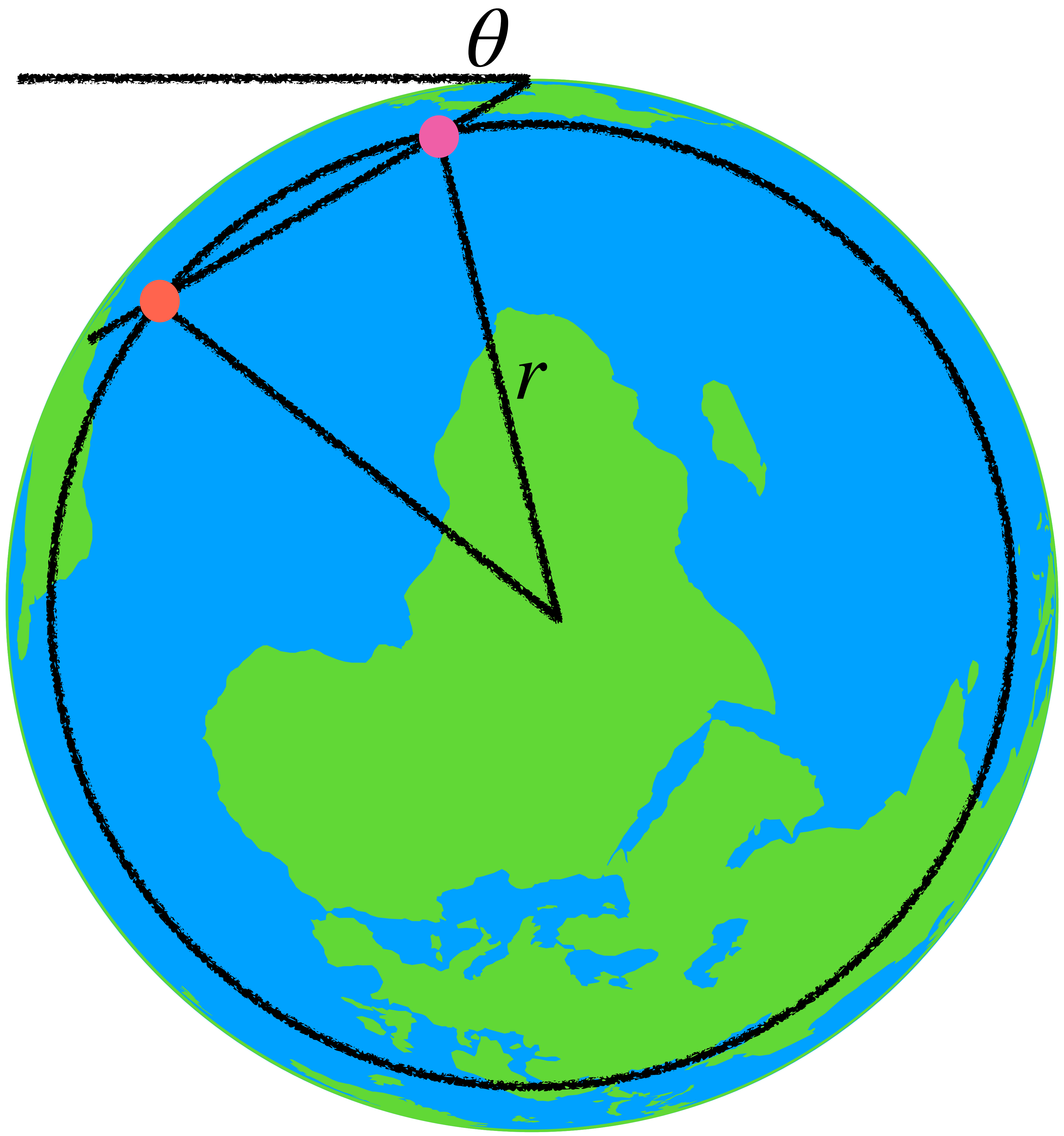


How much DM do we need ?

$$N = T \int \mathrm{d}E_\nu \, \mathrm{d}\Omega \, A_{\mathrm{eff}}(E_\nu) \, \Phi(E_\nu) = T \int \mathrm{d}E_\nu \, \mathrm{d}\Omega \, \mathrm{d}V \, A_{\mathrm{eff}}(E_\nu) \, \frac{\mathrm{d}\Phi(E_\nu)}{\mathrm{d}V}$$

$$\frac{\mathrm{d}\Phi(E_\nu, r, \theta, t)}{\mathrm{d}V} = \delta\left(E_\nu - \frac{m_\chi}{2}\right) \frac{n(r,t)}{\tau} \left[\frac{p_l^{\mathrm{exit}}}{4\pi\ell_l^2} + \frac{p_s^{\mathrm{exit}}}{4\pi\ell_s^2}\right] \varepsilon(\theta)$$

Monochromatic signal	Dark matter distribution	Probability of neutrino exiting from DM decay at r, θ	Detector angular efficiency



How much DM do we need ?

- Assuming that we have a uniform distribution of DM

$$N = \frac{T\,\Omega\,A_{\text{eff}}\left(\frac{m_\chi}{2}\right)}{2}\,\frac{n_0}{\tau}\int_{R_\oplus \sin\theta}^{R_\oplus}\int_0^{\pi/2} \mathrm{d}r\,\mathrm{d}\theta\, r^2 \sin\theta\, \varepsilon(\theta)\left[\frac{p_+^{\text{exit}}}{\ell_+^2} + \frac{p_-^{\text{exit}}}{\ell_-^2}\right]$$

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$$\frac{N_\oplus}{\tau} = \frac{3\times 10^4}{\rm sec}$$

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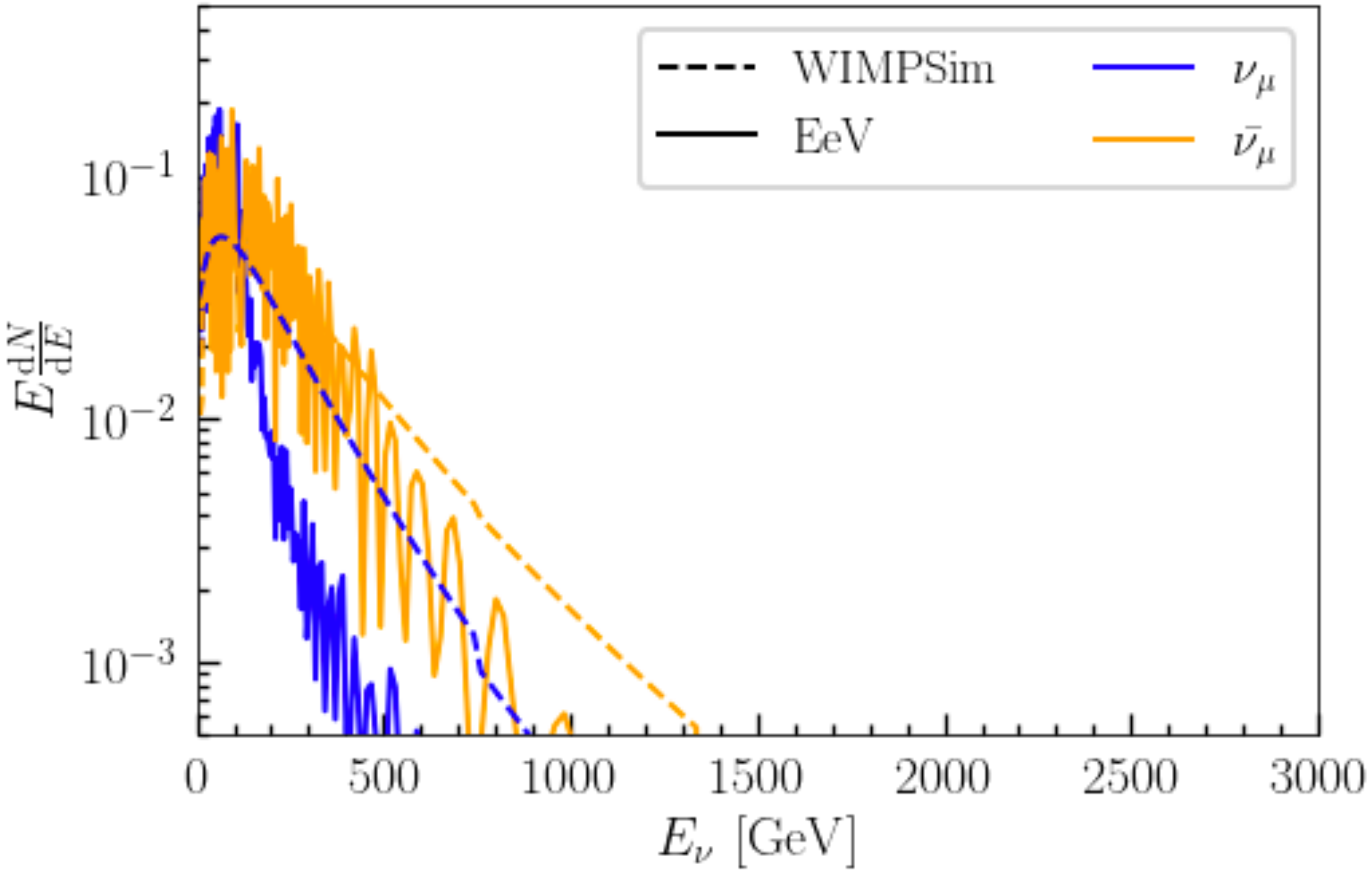
$$\frac{N_\oplus}{\tau} = \frac{3\times 10^4}{\rm sec} \implies \frac{N_\odot}{\tau} = \frac{2.33\times 10^{14}}{\rm sec}$$

How much can we accommodate ?

- Fluxes have different shapes, but are of the same order of magnitude
- Integrated values match within ~30%
- For now, I will call them equal to do a quick calculation

$$\Phi^{\rm IC}_{\rm lim} = \frac{\Gamma_{\rm lim}}{4\pi R^2}\frac{{\rm d}N_{\nu+\bar{\nu}}}{{\rm d}E}$$

$$\Phi^{\rm EeV} = \frac{N_{\odot}^{\rm lim}}{\tau}\frac{1}{4\pi R^2}\frac{{\rm d}N_{\nu+\bar{\nu}}}{{\rm d}E}$$



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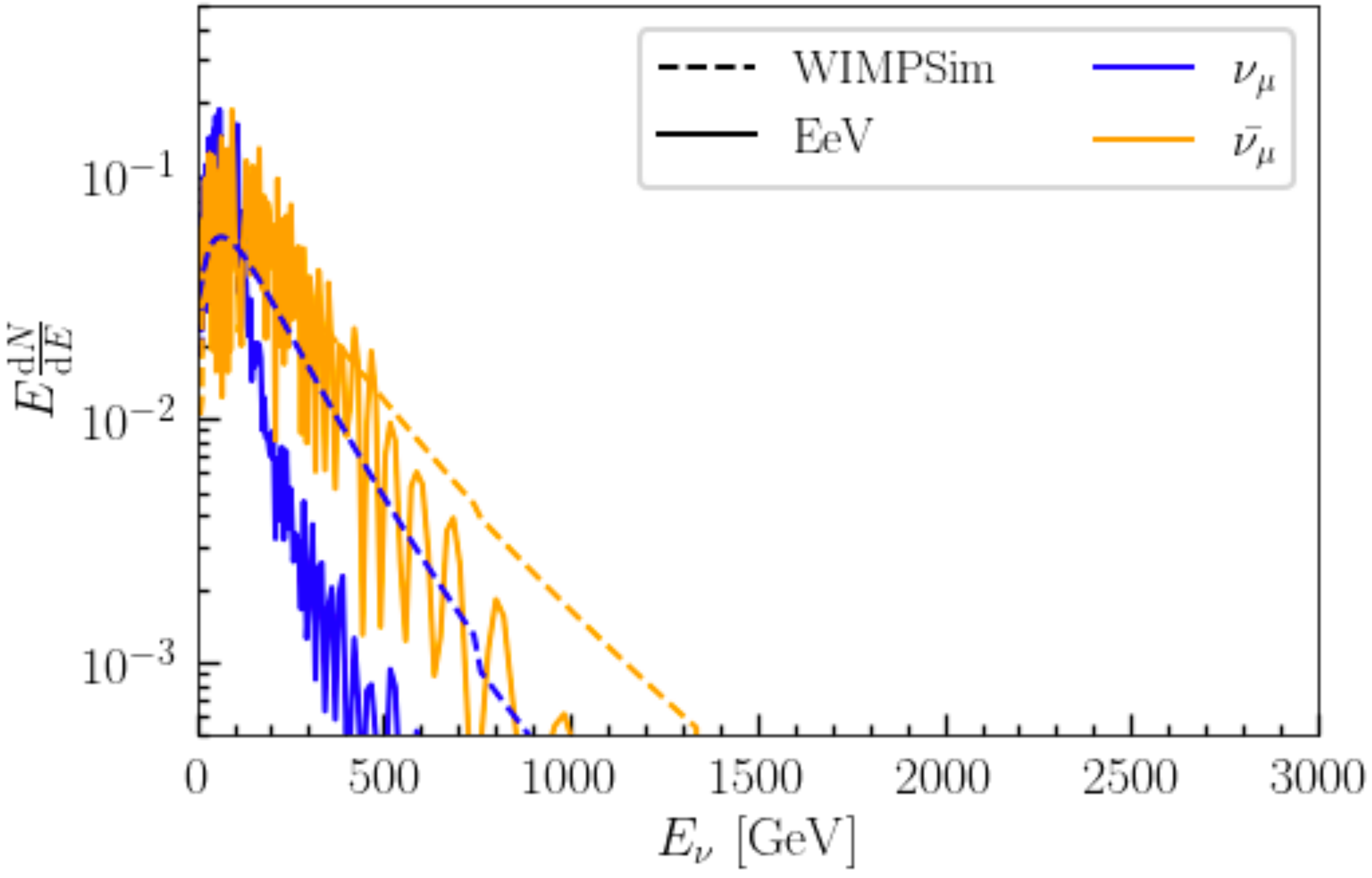


$$\Phi^{IC}_{lim} = \frac{\Gamma_{lim}}{4\pi R^2}\frac{dN_{\nu+\bar{\nu}}}{dE}$$

$$\Phi^{EeV} = \frac{N^{lim}_{\odot}}{\tau}\frac{1}{4\pi R^2}\frac{dN_{\nu+\bar{\nu}}}{dE}$$

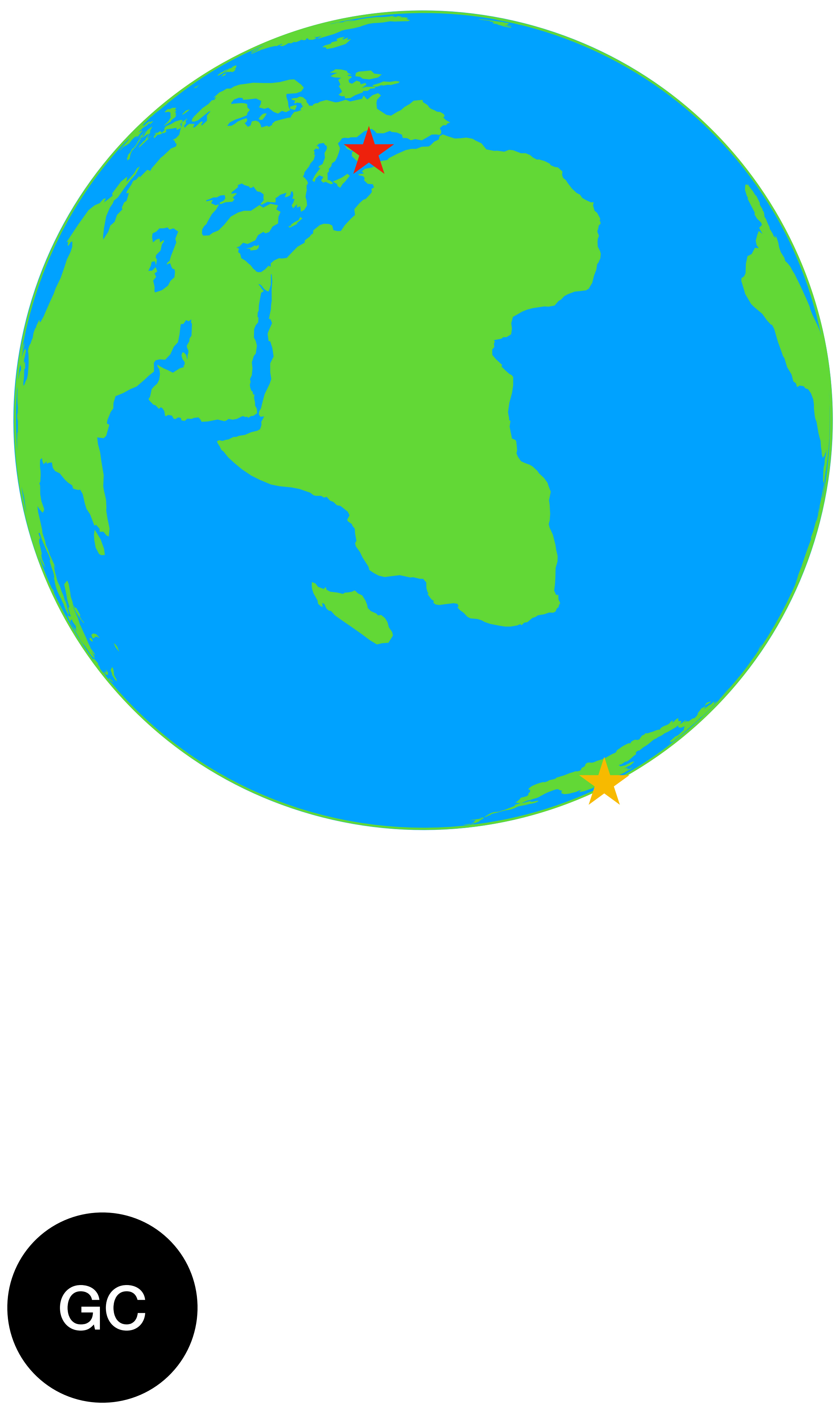
$$\implies \frac{N^{lim}_{\odot}}{\tau} = \Gamma_{lim} = \frac{8.33\times 10^{19}}{\text{sec}} > \frac{2.33\times 10^{14}}{\text{sec}}$$

The Galactic Center

- ANTARES sees GC through the Earth, but these neutrinos cannot traverse the Earth
- Can we use tau regeneration to set limits on the DM lifetime ?
- Looking at ANTARES public muon selection data

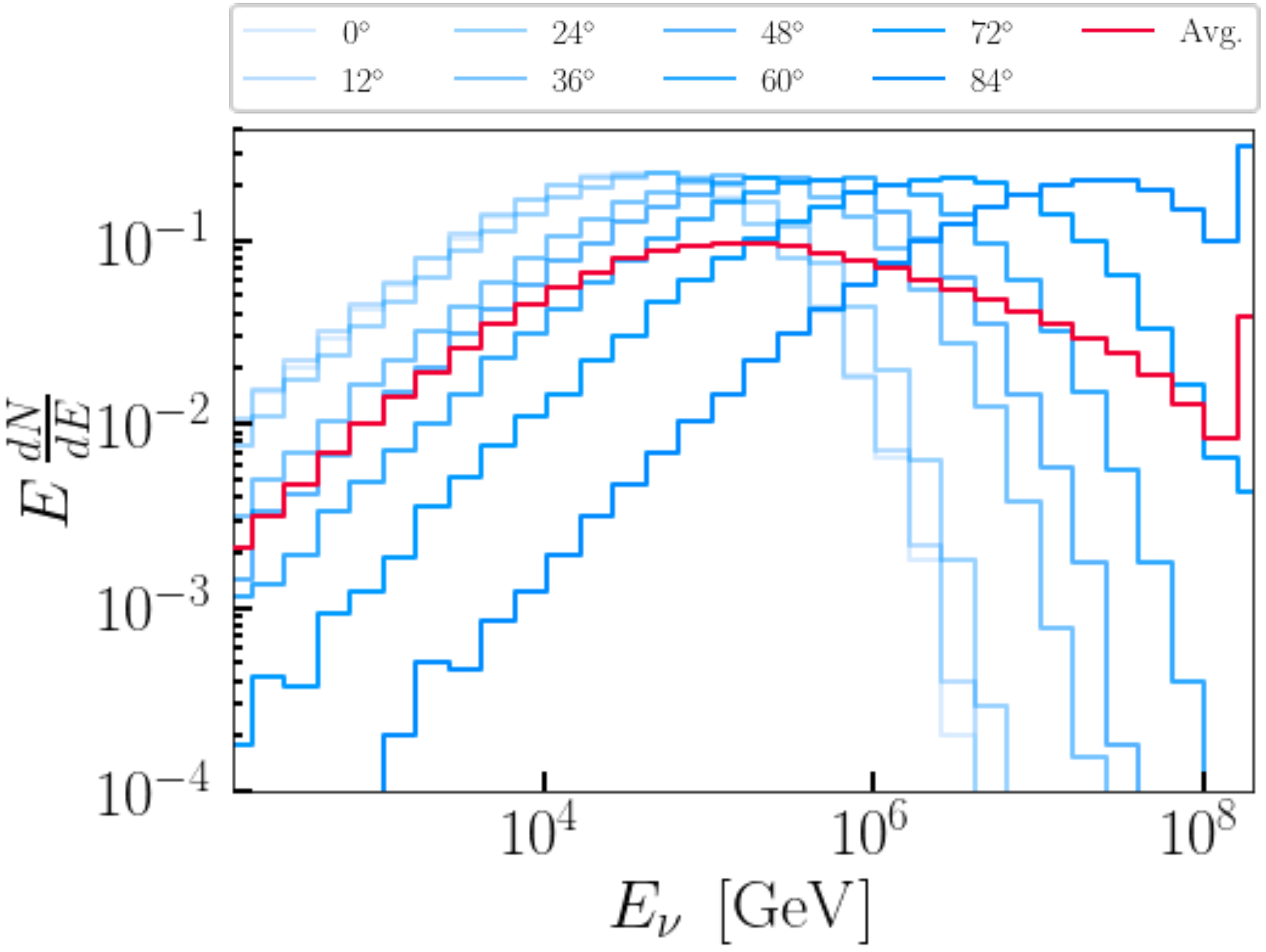
★ IceCube

★ ANTARES



Regenerated Flux

- GC moves with respect to detector coordinates
- We must compute the flux averaged over all angles that ANTARES sees the GC
- Calculate number of muons at the detector

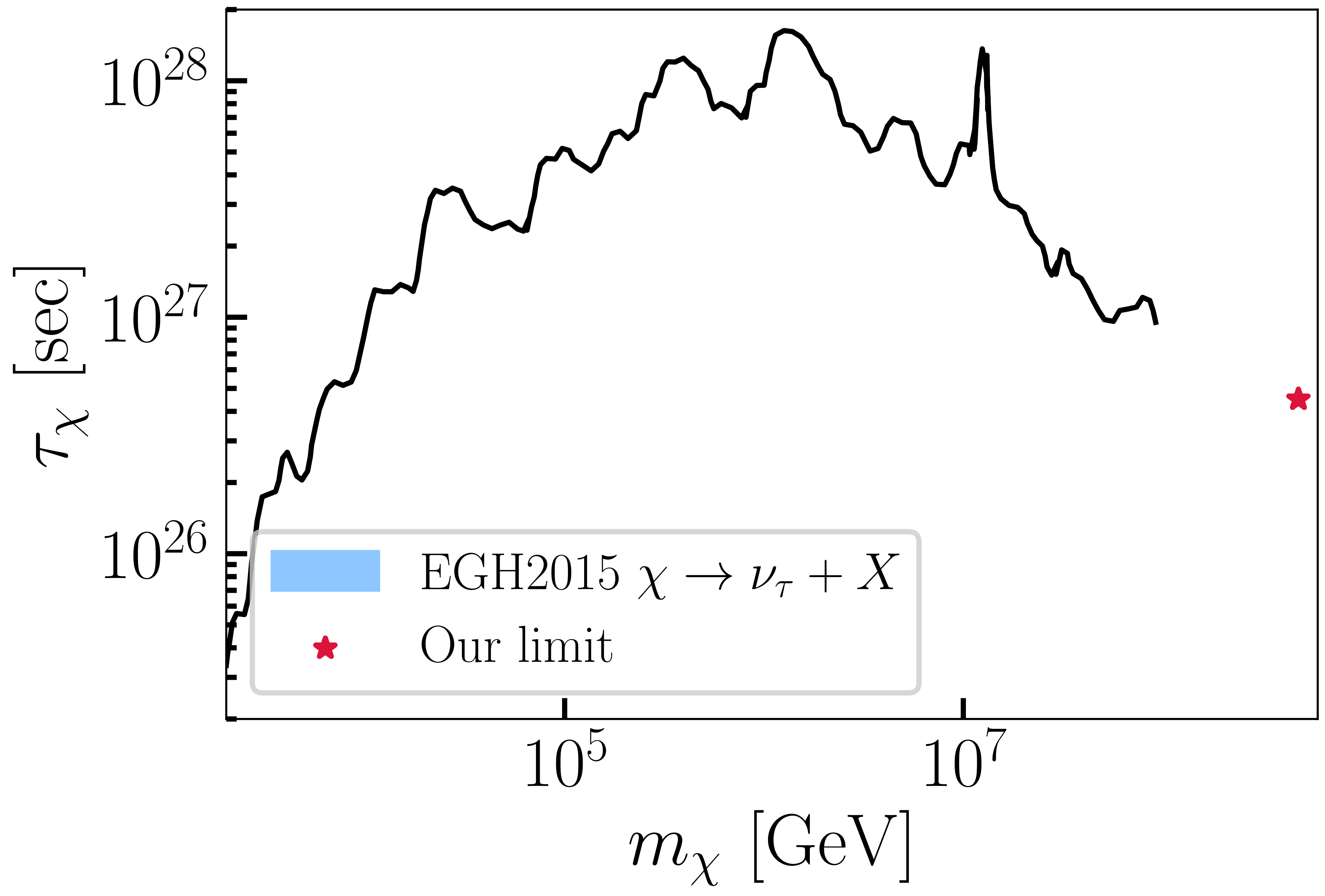


$$N = \Delta T \left[\int \mathrm{dE}_{\nu_\tau}\, \mathrm{d}\Omega\, \bar{\Phi}_{\nu_\tau} \mathrm{Br}_{\tau\to\mu}\, \sigma^{\mathrm{CC}}\left(\mathrm{E}_{\nu_\tau}\right)\, \mathrm{N}_\tau\left(\mathrm{E}_{\nu_\tau}\right) + \int \mathrm{dE}_{\nu_\mu}\, \mathrm{d}\Omega\, \bar{\Phi}_{\nu_\mu}\, \sigma^{\mathrm{CC}}\left(\mathrm{E}_{\nu_\mu}\right)\, \mathrm{N}_\mu\left(\mathrm{E}_{\nu_\mu}\right) \right]$$

$\nu_\tau \to \tau \to \mu$ $\qquad$ $\nu_\mu \to \mu$

Limits

- Assuming the NFW profile, and a region of interest of 6° around the GC, we expect 35.15 events
- 26 events observed in this region
- F-C upper limit of 11.47 events from dark matter
- Upper limit on the lifetime at 4.5×10^{26} sec



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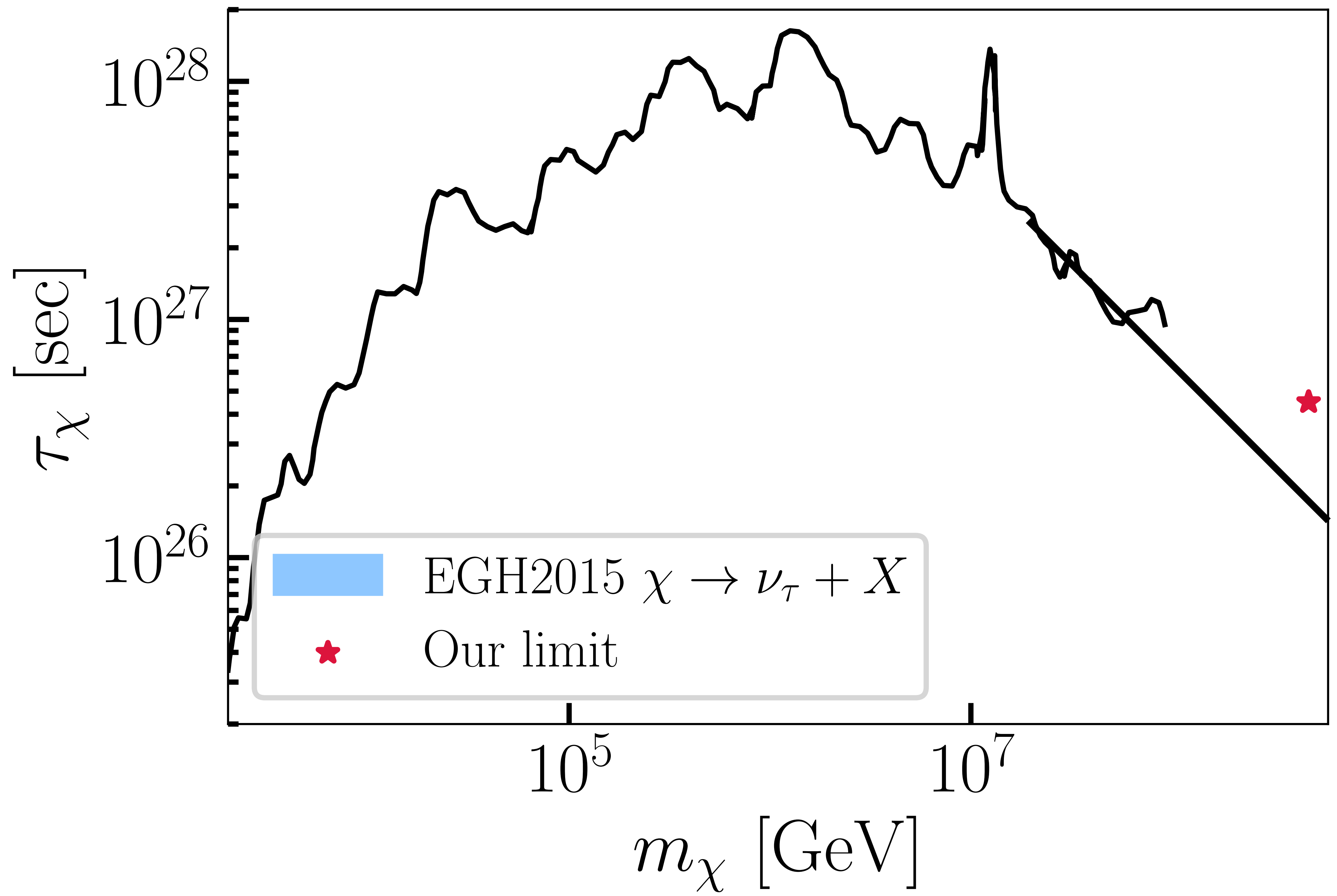


Conclusions

- Tau regeneration in the Sun unable to rule out most conservative heavy RHν proposal for explaining anomalous ANITA events. Can likely rule out SD capture but math is trickier
- Using tau regeneration to probe high-mass dark matter shows promise in Galactic Center
- Tau regeneration in the Sun may offer more power to standard solar WIMP searches. Further studies needed to confirm

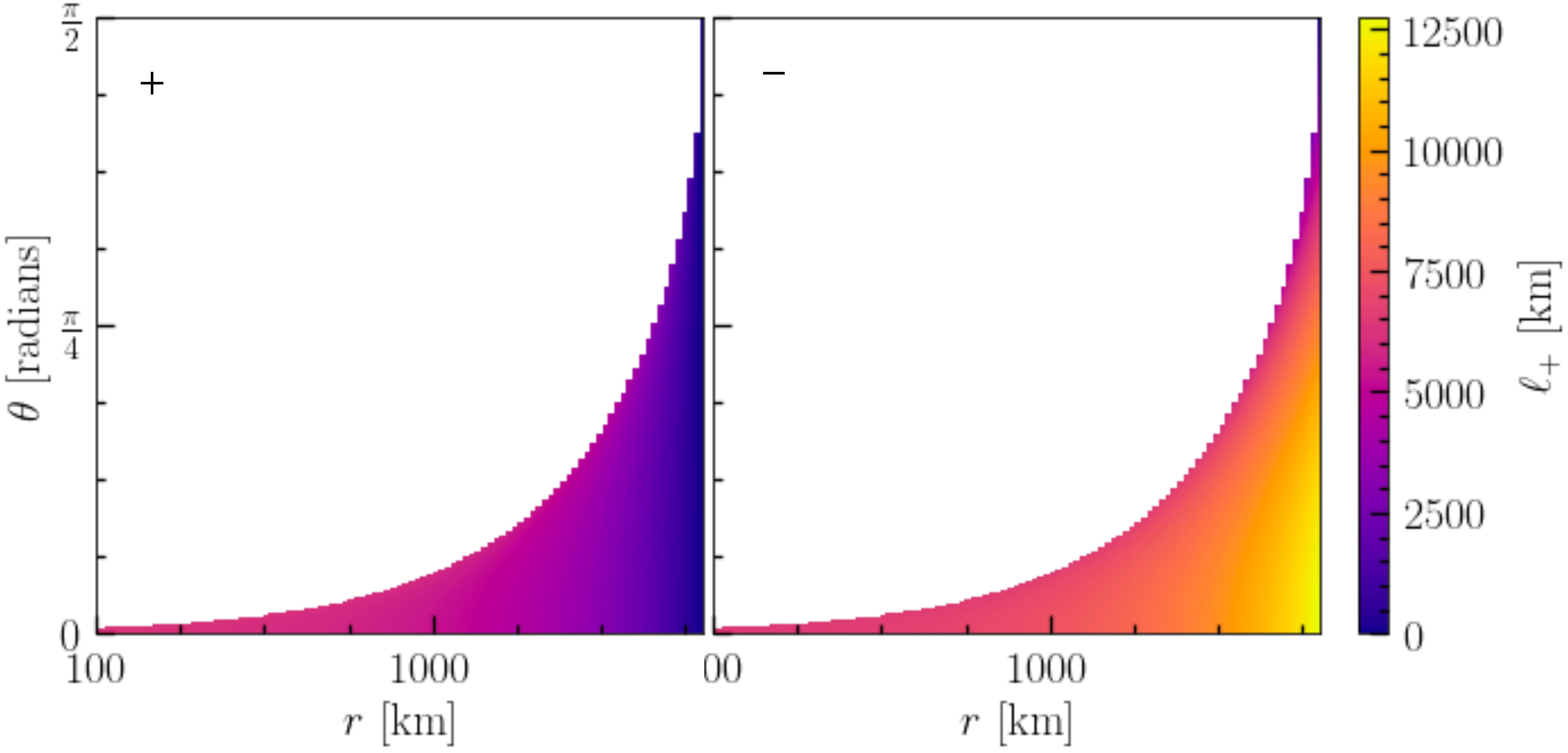
Thank You :-)

For Listening !

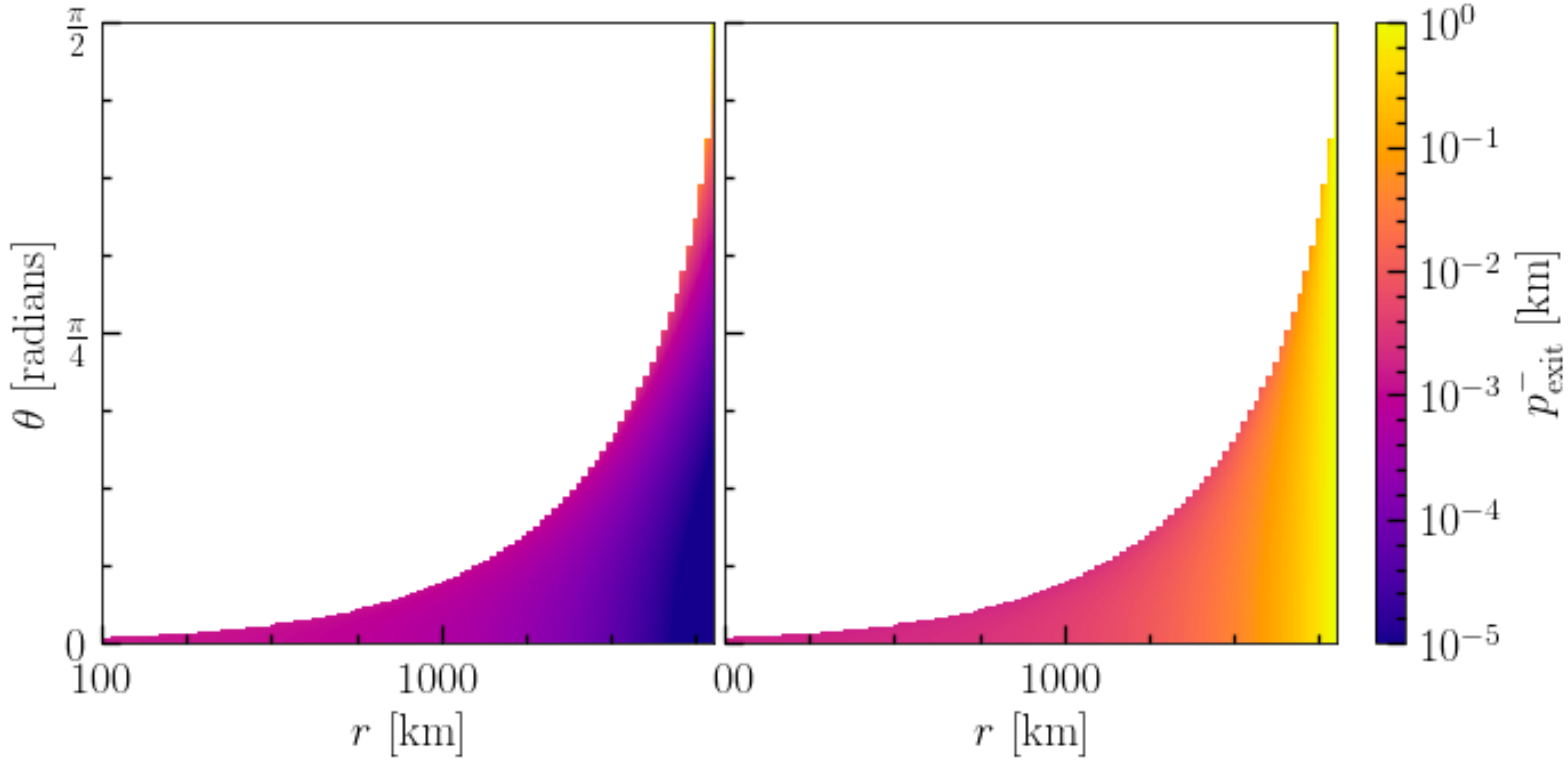
Backups

$\ell_{\pm}$

$$\ell_{\pm} = R_{\oplus}\left[\cos\theta \pm \sqrt{\left(\frac{r}{R_{\oplus}}\right)^2 - \sin^2\theta}\right]$$



$p_{\pm}^{\text{exit}}$

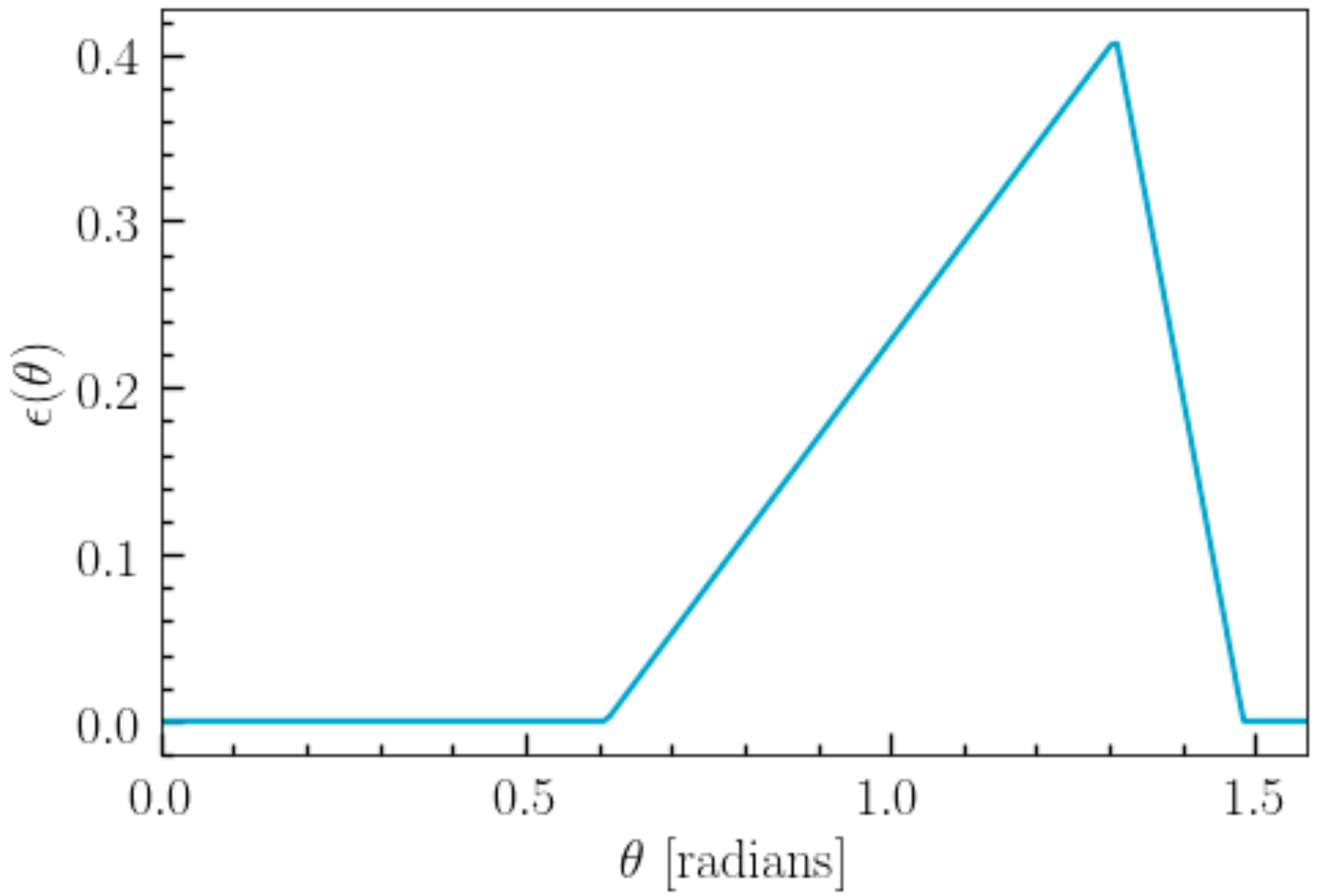


$$p_{\pm}^{\text{exit}} = \exp\left[\frac{-l_{\pm}(r,\theta)}{\lambda_{\text{int}}(E_\nu)}\right]$$

$$\lambda_{\text{int}} = 1.7 \times 10^7 \left(\frac{\sigma_{CC}(E_\nu)}{\text{pb}}\right) \approx 1000\,\text{km}$$

$\varepsilon(\theta)$

- "Note that $\varepsilon(\theta)$ vanishes for $\varepsilon(\theta) < 35°$, peaks at around $75°$, and vanishes above $85°$."



Note: Normalization chose so that it integrates to one when integrated over solid angle

Total Number of Events

$$N = T\int \mathrm{d}E_\nu\, \mathrm{d}\Omega\, A_{\mathrm{eff}}(E_\nu)\, \Phi(E_\nu) = T\int \mathrm{d}E_\nu\, \mathrm{d}\Omega\, \mathrm{d}V\, A_{\mathrm{eff}}(E_\nu)\, \frac{\mathrm{d}\Phi(E_\nu)}{\mathrm{d}V}$$

$$= T\,\Omega\, A_{\mathrm{eff}}(E_0) \int \mathrm{d}V\, \frac{\mathrm{d}\Phi(E_0)}{\mathrm{d}V} \quad \text{where} \quad E_0 = \frac{m_\chi}{2}$$

$$= T\,\Omega\, A_{\mathrm{eff}}(E_0) \int \mathrm{d}V\, \frac{n(r,t)}{\tau} \left[\frac{p_+^{\mathrm{exit}}}{4\pi\ell_+^2} + \frac{p_-^{\mathrm{exit}}}{4\pi\ell_-^2}\right] \varepsilon(\theta)$$

$$= \frac{T\,\Omega\, A_{\mathrm{eff}}(E_0)}{4\pi\tau} \int \mathrm{d}r\, \mathrm{d}\theta\, \mathrm{d}\phi\, r^2 \sin\theta\, \varepsilon(\theta)\, n(r,t) \left[\frac{p_+^{\mathrm{exit}}}{\ell_+^2} + \frac{p_-^{\mathrm{exit}}}{\ell_-^2}\right]$$

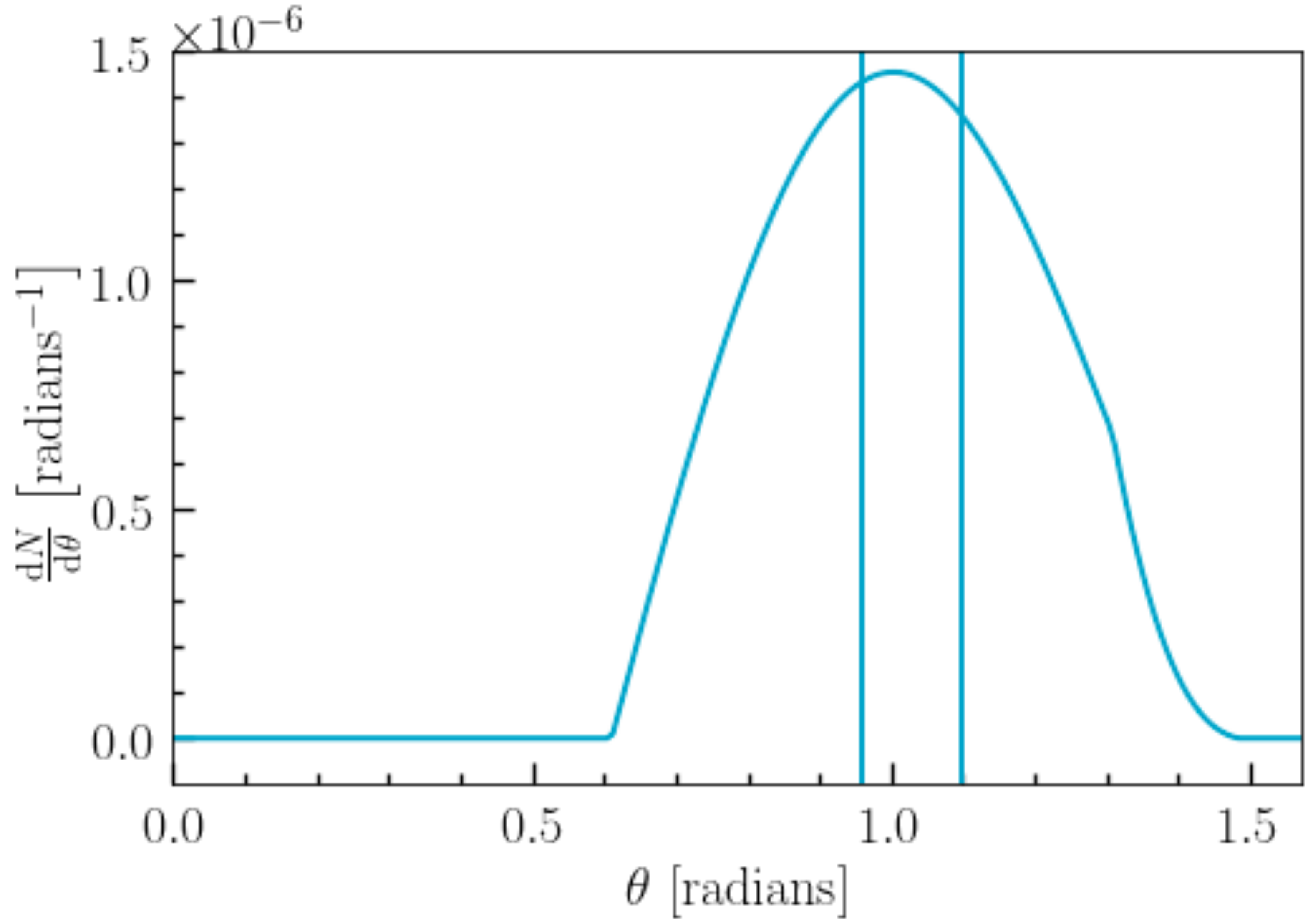
$$= \frac{T\,\Omega\, A_{\mathrm{eff}}(E_0)}{2\tau} \int \mathrm{d}r\, \mathrm{d}\theta\, r^2 \sin\theta\, \varepsilon(\theta)\, n(r,t) \left[\frac{p_+^{\mathrm{exit}}}{\ell_+^2} + \frac{p_-^{\mathrm{exit}}}{\ell_-^2}\right]$$

Total Number of Events

- Assuming that we have a uniform distribution of DM

$$= \frac{T\,\Omega\,A_{\rm eff}(E_0)}{2\tau}\, n_0 \int_{R_\oplus \sin\theta}^{R_\oplus} \int_0^{\pi/2} \mathrm{d}r\,\mathrm{d}\theta\, r^2 \sin\theta\, \varepsilon(\theta) \left[\frac{p_+^{\rm exit}}{\ell_+^2} + \frac{p_-^{\rm exit}}{\ell_-^2} \right]$$

- If we integrate this over radius we get the following distribution



Note: The vertical lines are the positions of the events so this uniform distribution recreates the expected distribution

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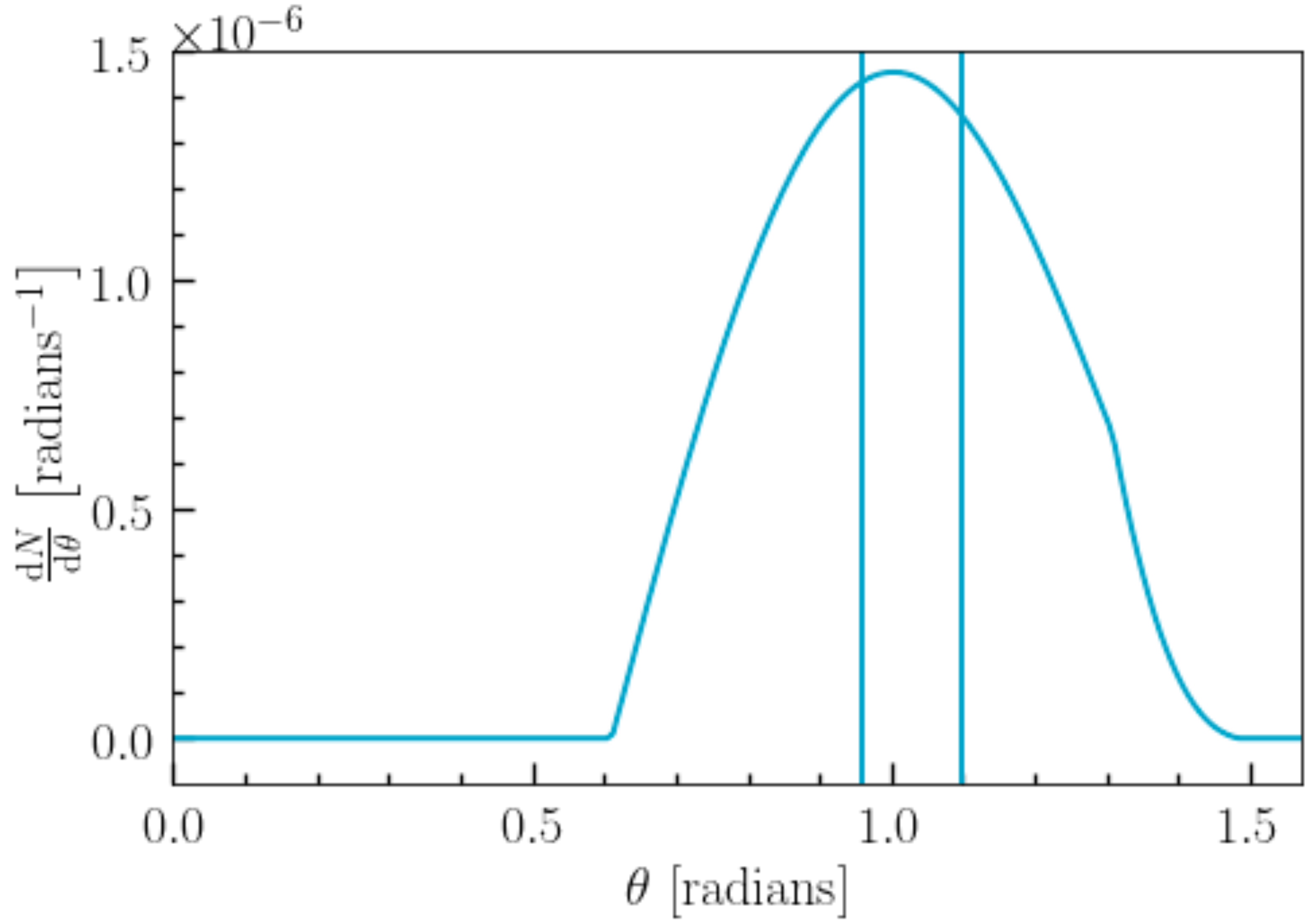

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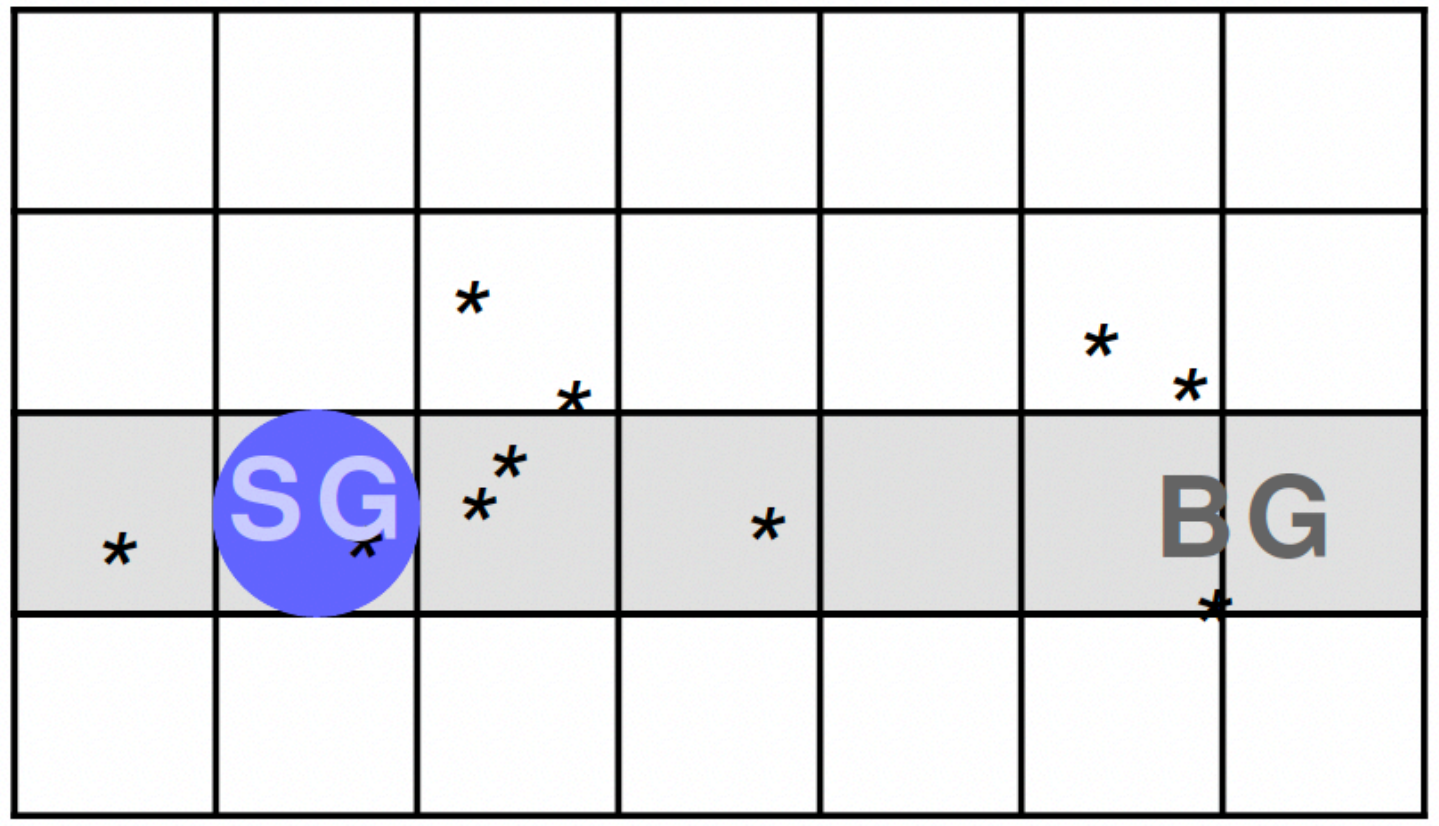
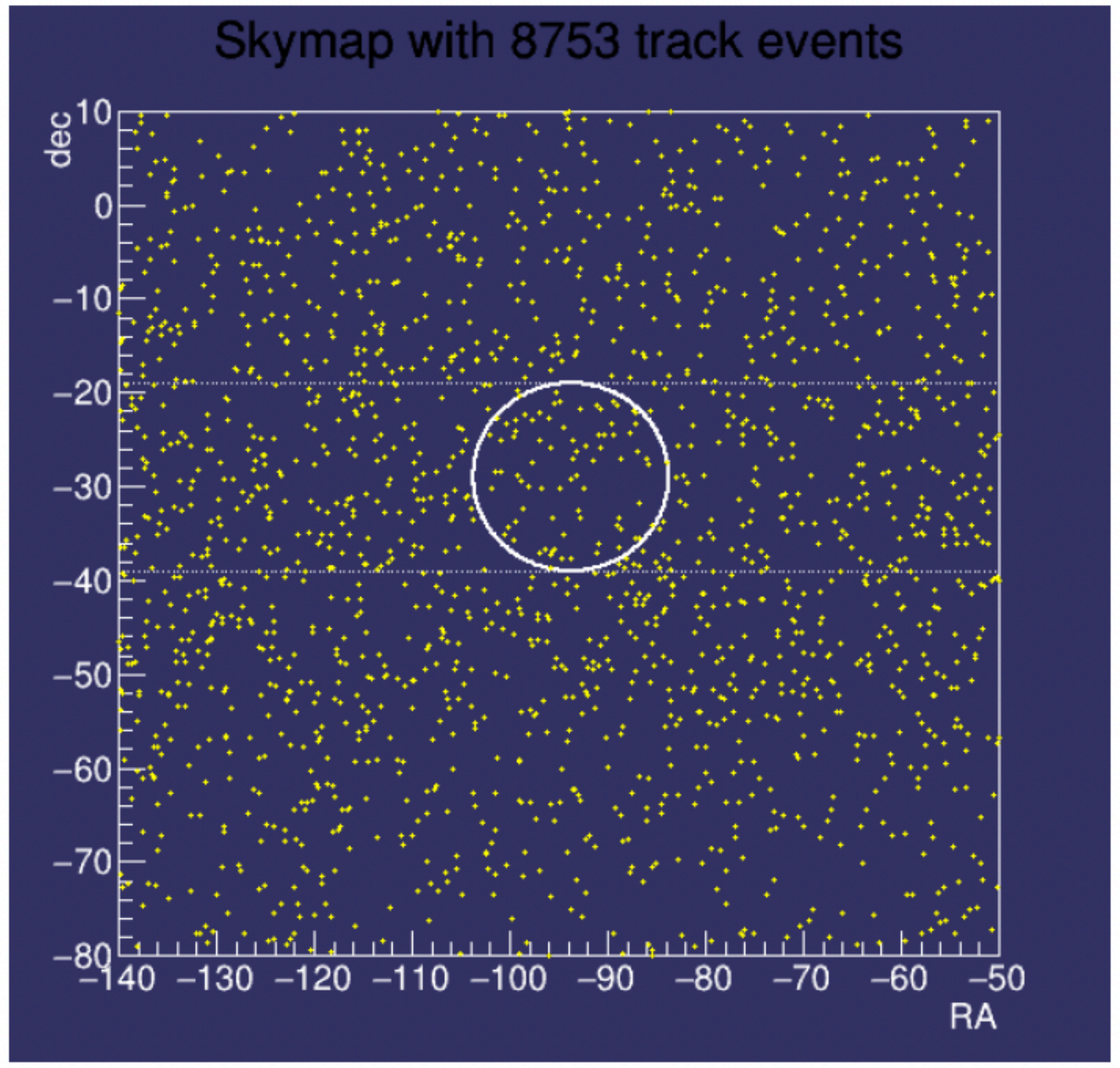
$$\frac{N_\oplus}{\tau} = \frac{3\times 10^4}{\rm sec} \qquad \frac{N_\odot}{N_\oplus} = \frac{C_\odot}{C_\oplus}$$

First estimate: with Feldman-Cousins tables, evaluate U.L. and L.L. from the observation of n_{obs} events in RoI, expecting n_{bg}. The (average) background number is obtained from a band at the declination of the source, scaled to the angular size of the RoI.



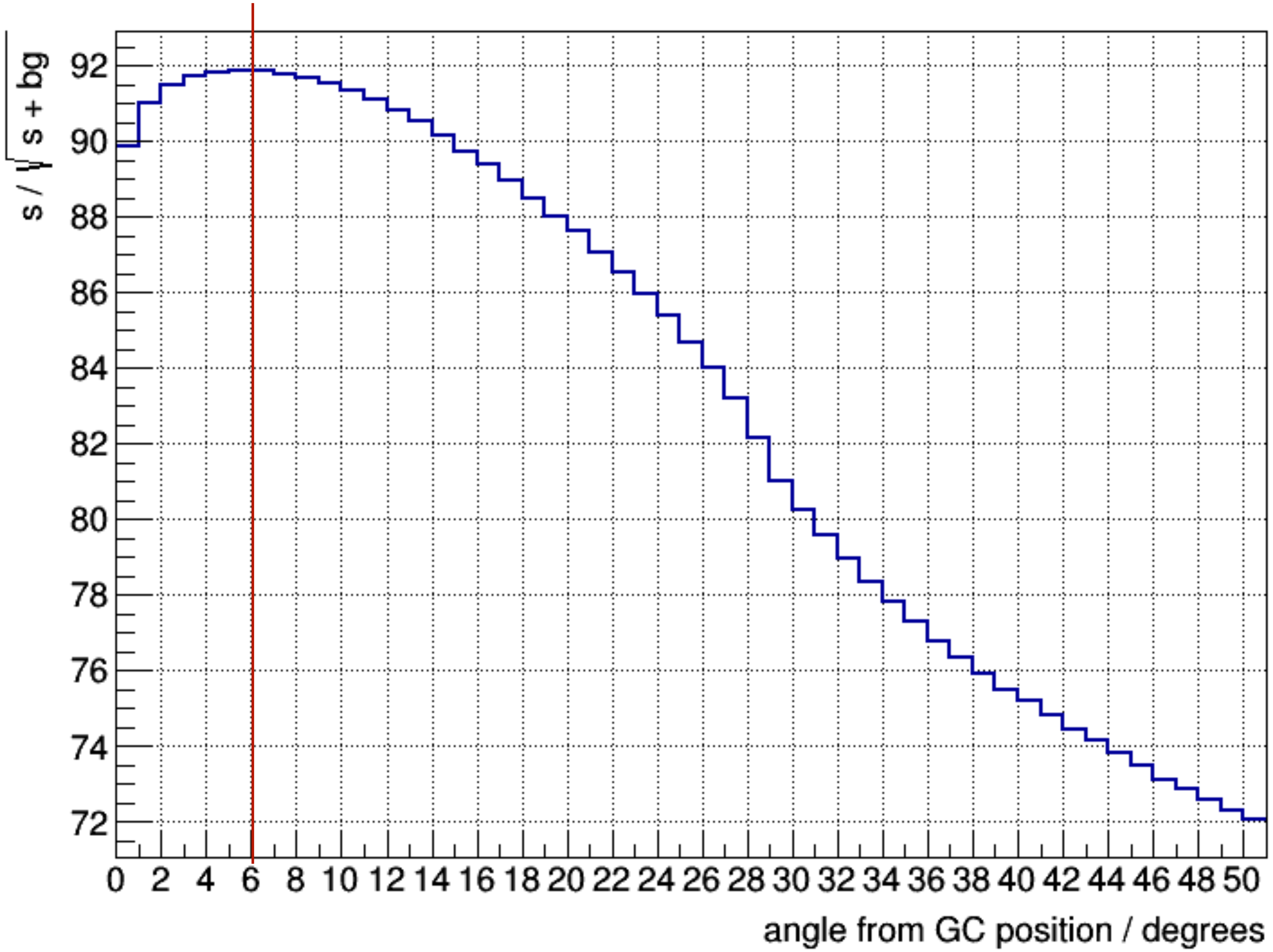


Example considering RoI $= 10^{\circ}$, 8753 tracks:

`estimated background: 97.3868, (384.87 for RoI = 20°)`

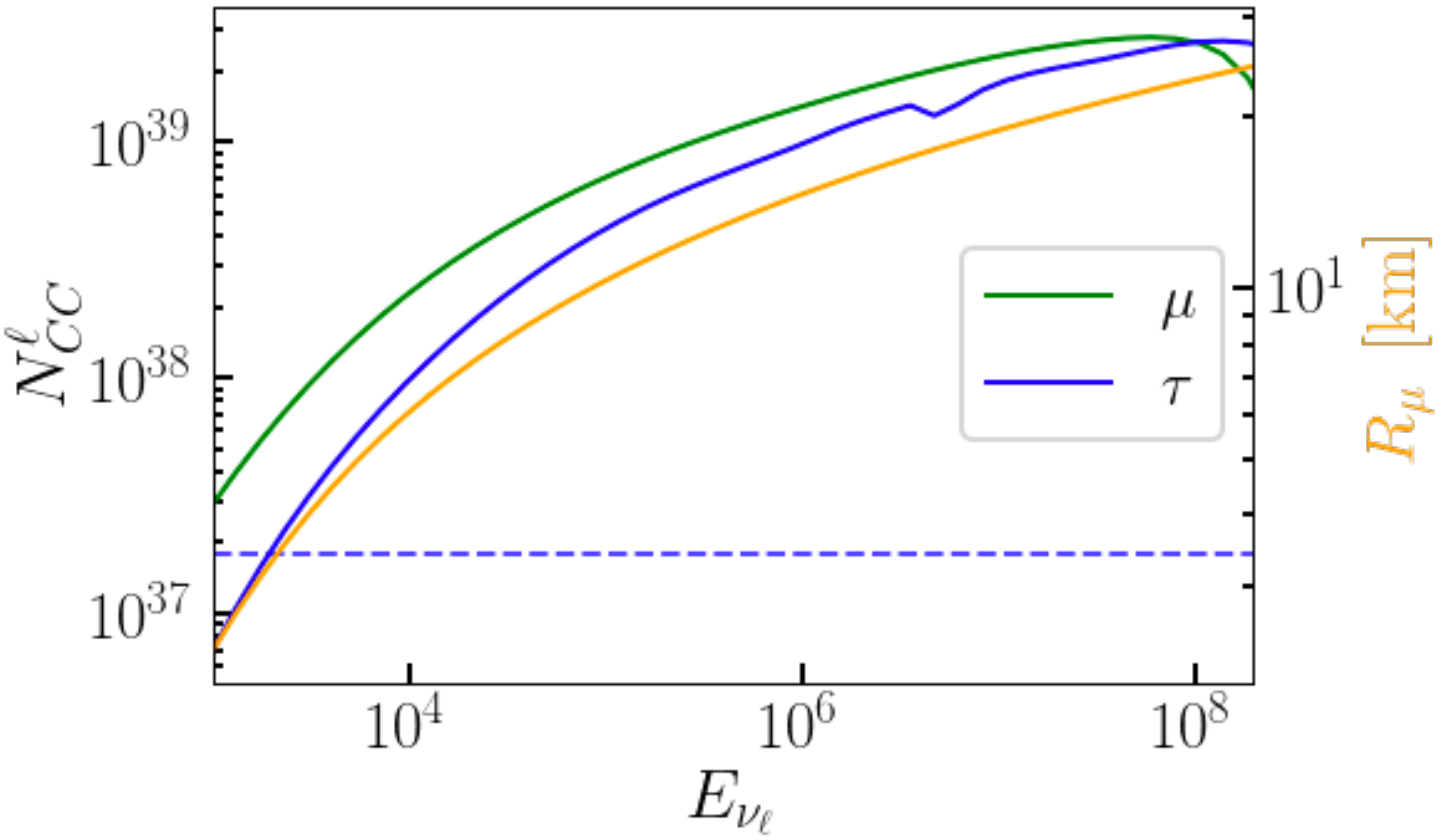
`number of observed events: 91 (379 for RoI = 20°)`

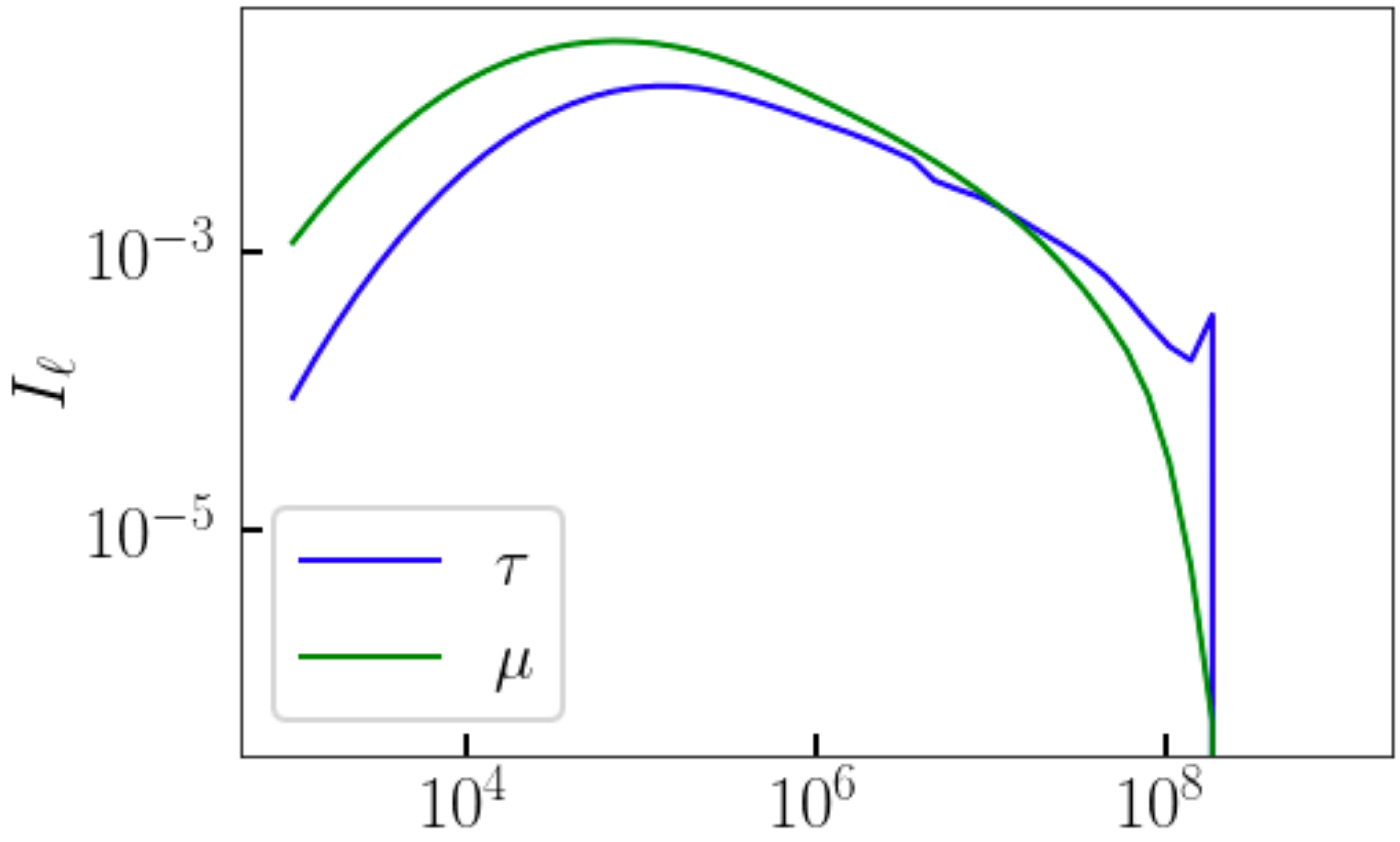
`UL = 18.3 (35.2 for RoI = 20°), LL = 0`



- $s/\sqrt{s+bg}$ peaks at $6°$
- Expectation of 11 events
- J-factor of 4.5e21GeV cm^{-2}
- →limit on lifetime of 1.04e24 seconds
- Limit from IceCube is ~1e27 seconds

Compute number of targets





10^{-3}
10^{-5}
I_ℓ
τ
μ
10^4
10^6
10^8

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$$N^{\tau}_{\mathrm{CC}} = \int dE_\mu \, dE_\tau \, \frac{dP_\mu}{dE_\mu}(E_\mu; E_\tau) \, \frac{dP_\tau}{dE_\tau}(E_\tau; E_{\nu_\tau}) \, R_\mu(E_\mu) \, A_{\mathrm{eff}}(E_\mu) \frac{\rho_{\mathrm{iso}}}{M_{\mathrm{iso}}}$$

$$N^{\mu}_{\mathrm{CC}} = \int dE_\mu \frac{dP_\mu}{dE_\mu}(E_\mu; E_{\nu_\mu}) \, R_\mu(E_\mu) \, A_{\mathrm{eff}}(E_\mu) \frac{\rho_{\mathrm{iso}}}{M_{\mathrm{iso}}}$$