Secondary Tau Neutrino Probes of Heavy Dark Matter Decay

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Based on: MS, JH, Phys. Rev. D 105, 083025, arXiv:2108.13412

Dark matter can be trapped in Earth (or Sun, etc.)

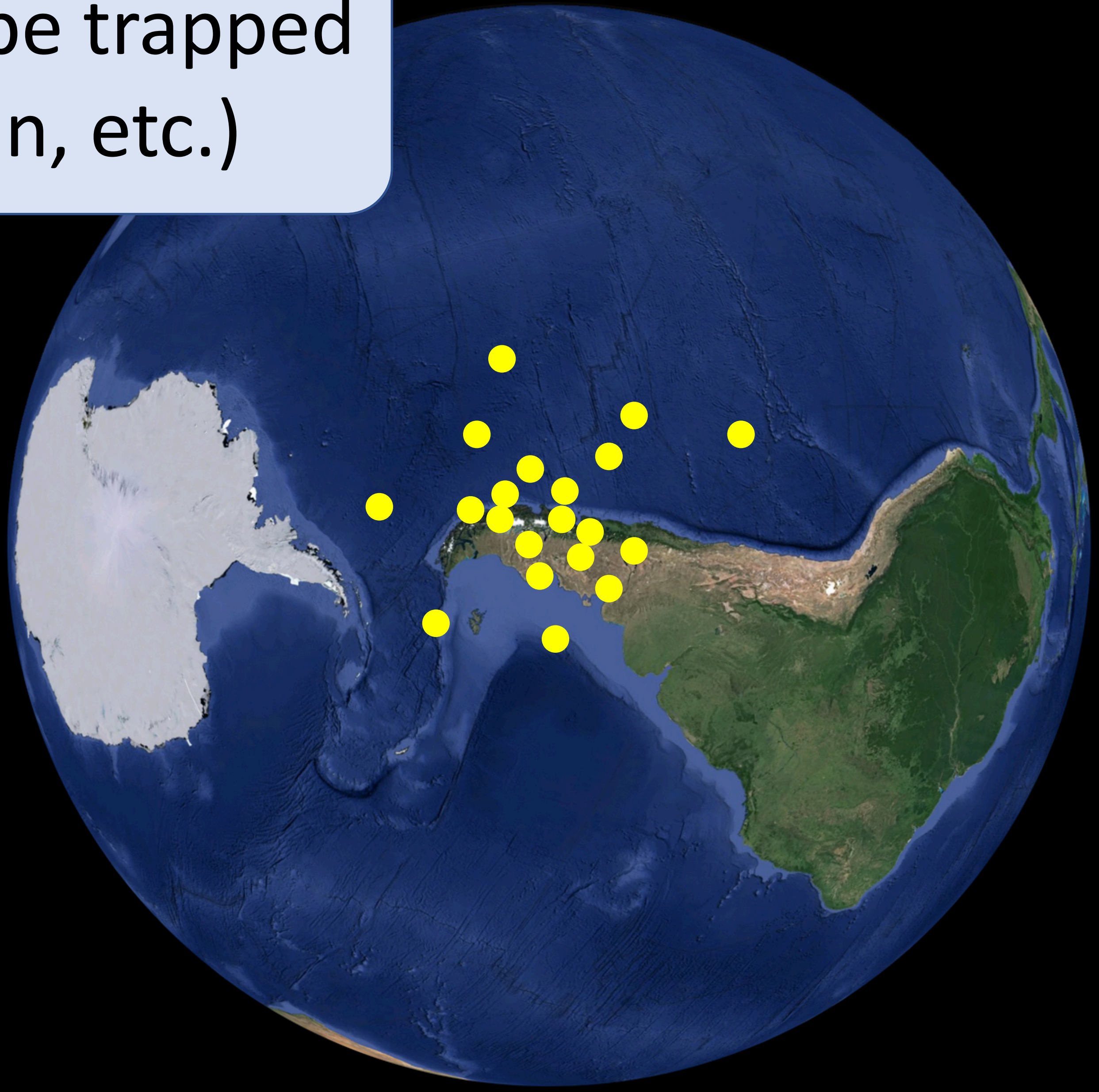

Image Source: NASA

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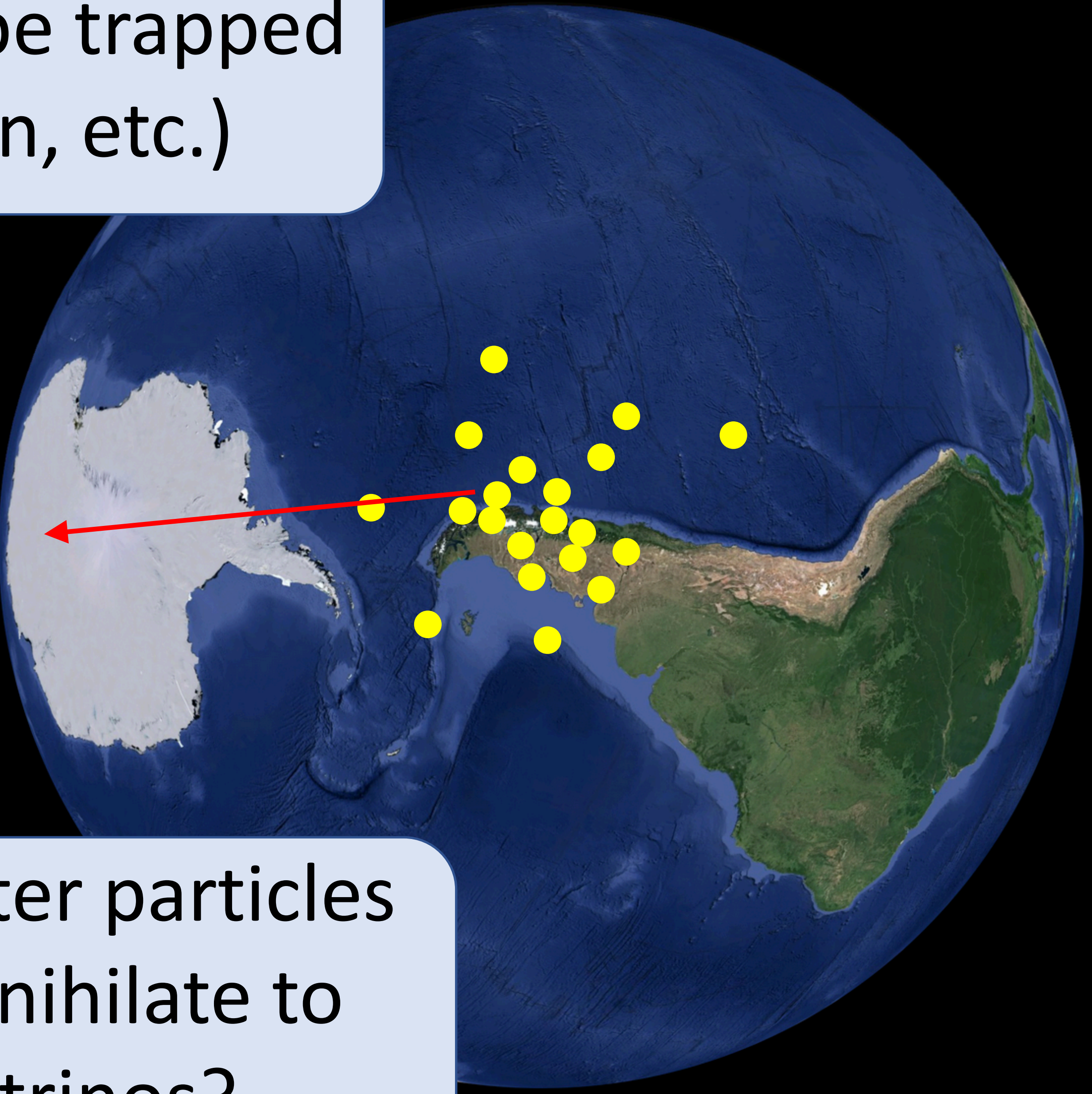
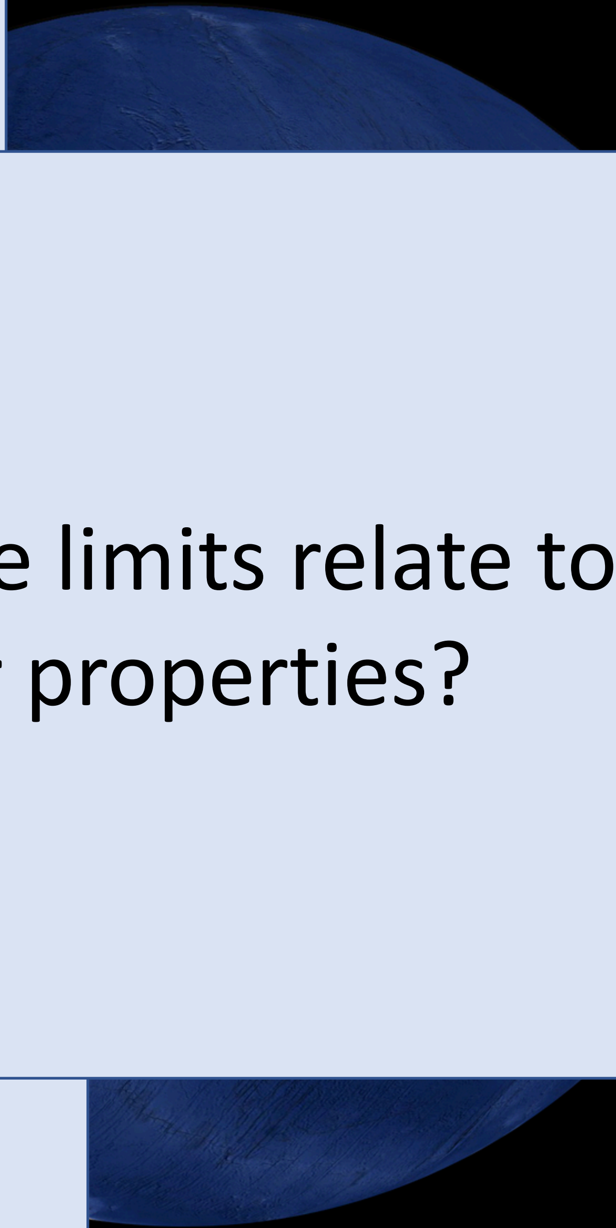


What if dark matter particles can decay or annihilate to produce neutrinos?

Image Source: NASA

Dark matter can be trapped in Earth (or Sun, etc.)



How do IceCube limits relate to dark matter properties?

What if da

can decay or annihilate to produce neutrinos?

Image Source: NASA

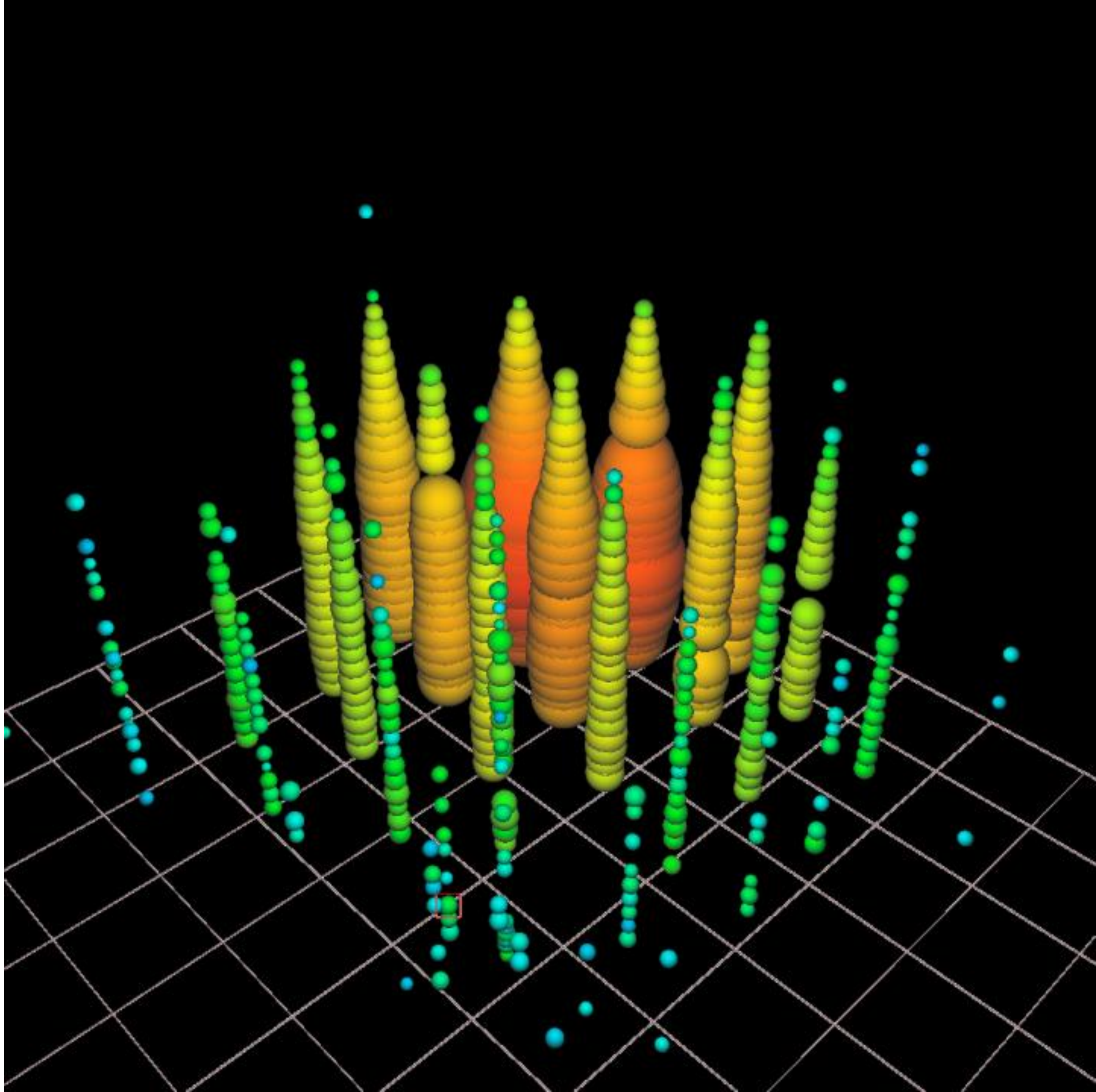
IceCube HESE Data Set

High-Energy Starting Events (HESE), E > 60 TeV

(see arXiv:2011.03545 and 2011.03561)

60 events, 2 double-cascade in 7.5 years

(Image: IceCube)



Earlier work on this topic either…

- Predated IceCube.
- Made unrealistic assumptions about dark matter distribution.
- Unclear connection between observed limits and dark matter properties.
- Effect of propagation through Earth sometimes obscured.
- Focused on anomalous ANITA events.

Our work:

- Based on IceCube data.
- Updated modeling of dark matter capture and distribution in Earth.
- Directly connects observed limits with dark matter properties.
- Gives a useful semianalytic approximation for energy loss.
- Focus not limited to ANITA events.

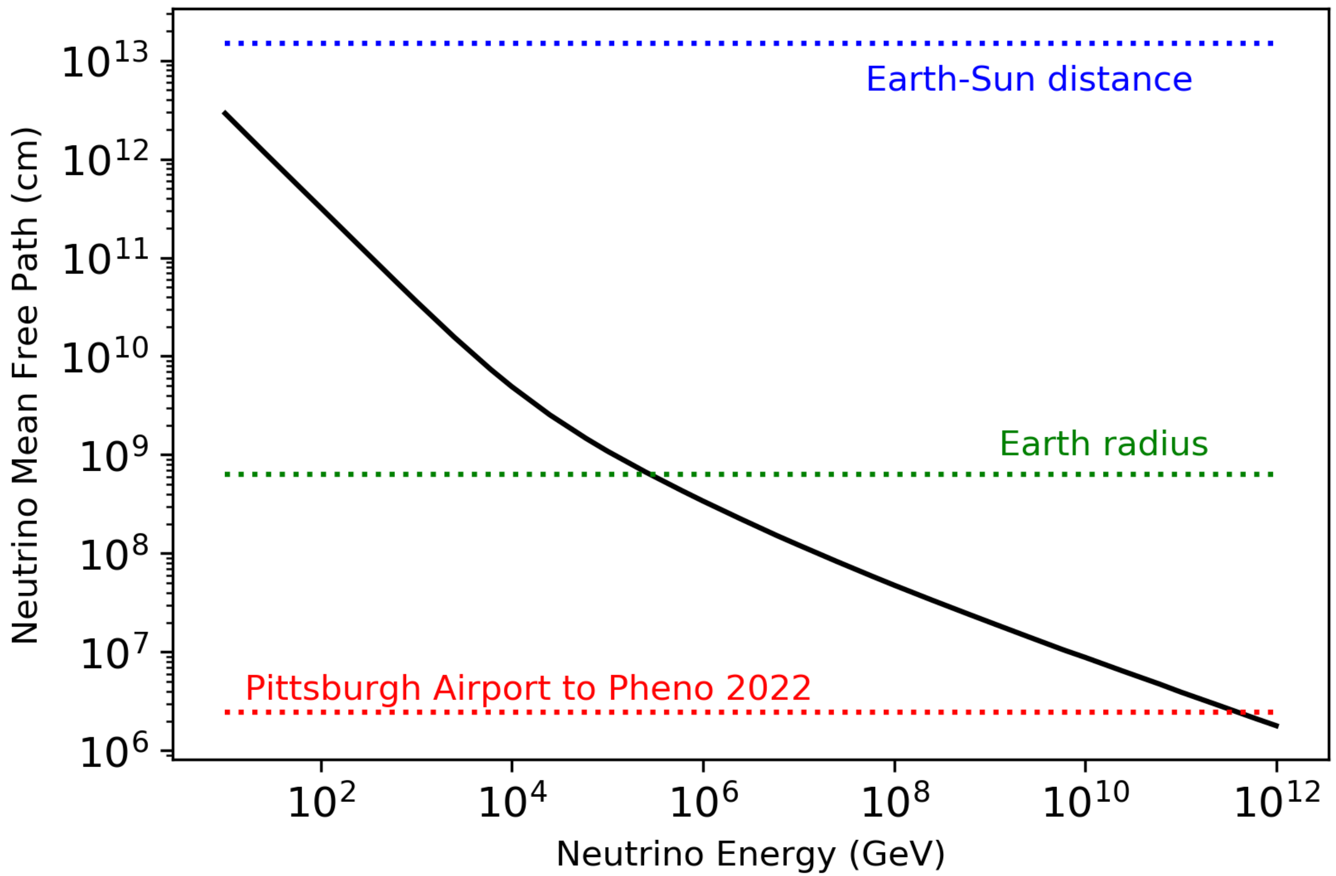
What DM distribution / decay rate do we expect?

Used recent analytic approximation for capture rates from Acevedo et al. (arXiv:2012.09176) to estimate annihilation and decay rates:

$$\Gamma_{\text{ann.}} \simeq \begin{cases} (1.50 \times 10^{28}\,\text{s}^{-1}) \left(\frac{10^7\,\text{GeV}}{m_\chi}\right)^{1/2} \left(\frac{\langle \sigma v \rangle}{10^{-25}\,\text{cm}^3\text{s}^{-1}}\right) & \text{for } \left(\frac{m_\chi}{1.66\times 10^{12}\,\text{GeV}}\right) < \left(\frac{\sigma_{\chi N}}{10^{-26}\,\text{cm}^2}\right) \\ (1.91 \times 10^{54}\,\text{s}^{-1}) \left(\frac{\langle \sigma v \rangle}{10^{-25}\,\text{cm}^3\text{s}^{-1}}\right) \left(\frac{10^7\,\text{GeV}}{m_\chi}\right)^{11/2} \left(\frac{\sigma_{\chi N}}{10^{-26}\,\text{cm}^2}\right)^5 & \text{for } \left(\frac{m_\chi}{1.66\times 10^{12}\,\text{GeV}}\right) > \left(\frac{\sigma_{\chi N}}{10^{-26}\,\text{cm}^2}\right) \end{cases}$$

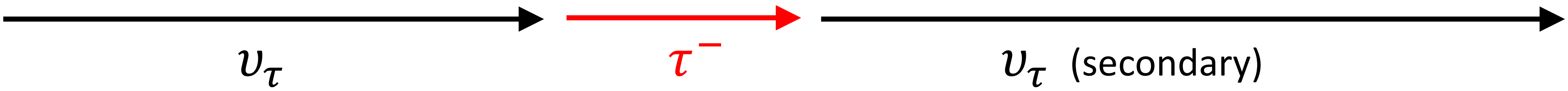
$$\Gamma_{\text{decay}} \simeq \begin{cases} (2.45 \times 10^{22}\,\text{s}^{-1}) \left(\frac{10^3\,\text{GeV}}{m_\chi}\right) \left(\frac{t_{\text{Earth}}}{\tau_\chi}\right) & \text{for } \left(\frac{m_\chi}{1.66\times 10^{12}\,\text{GeV}}\right) < \left(\frac{\sigma_{\chi N}}{10^{-26}\,\text{cm}^2}\right) \\ (8.74 \times 10^{27}\,\text{s}^{-1}) \left(\frac{10^8\,\text{GeV}}{m_\chi}\right)^{7/2} \left(\frac{\sigma_{\chi N}}{10^{-26}\,\text{cm}^2}\right)^{5/2} \left(\frac{t_{\text{Earth}}}{\tau_\chi}\right) & \text{for } \left(\frac{m_\chi}{1.66\times 10^{12}\,\text{GeV}}\right) > \left(\frac{\sigma_{\chi N}}{10^{-26}\,\text{cm}^2}\right) \end{cases}$$

DM Distribution → IceCube Event Rate?



- High-energy neutrinos will interact within Earth.

- Tau neutrino from tau decay (ν_τ regeneration)



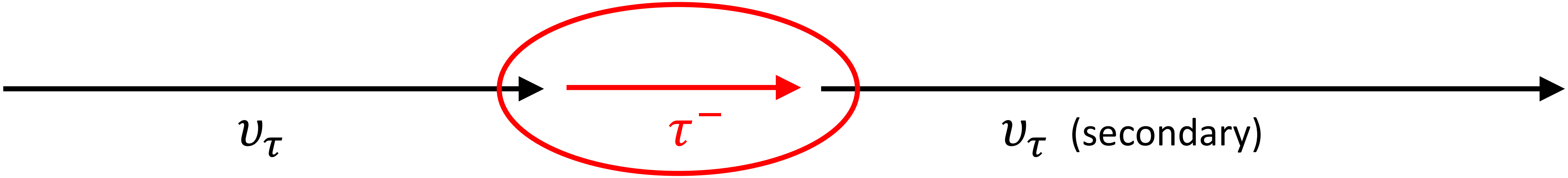
DM Distribution → IceCube Event Rate?

Tau propagation → rapid energy loss, $\left\langle \frac{dE}{dx} \right\rangle = -\beta E$, where

$$\beta(E) = \; p_0 + p_1 (E/GeV)^{p_2}$$

with p_0 = 2.06 x 10^{-7} cm^2/g, p_1 = 4.93 x 10^{-9} cm^2/g, p_2 = 0.228.

(ALLM parametrization, see arXiv:hep-ph/9712415 and 1707.00334)



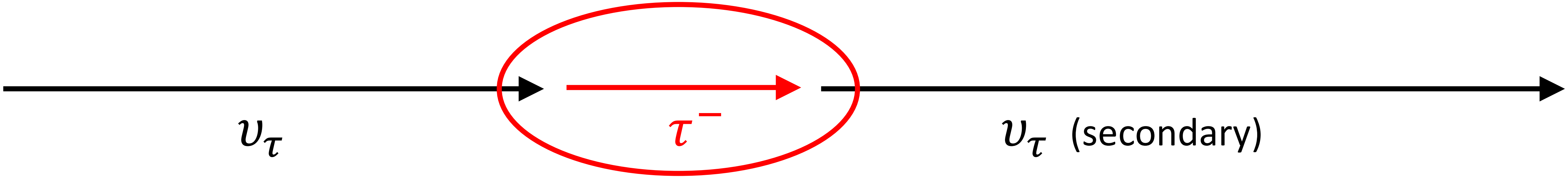
DM Distribution → IceCube Event Rate?

To see *qualitative* effect, approximate (for now) $\beta \approx 5 \times 10^{-7}$ cm^2/g (value at 10^8 GeV)

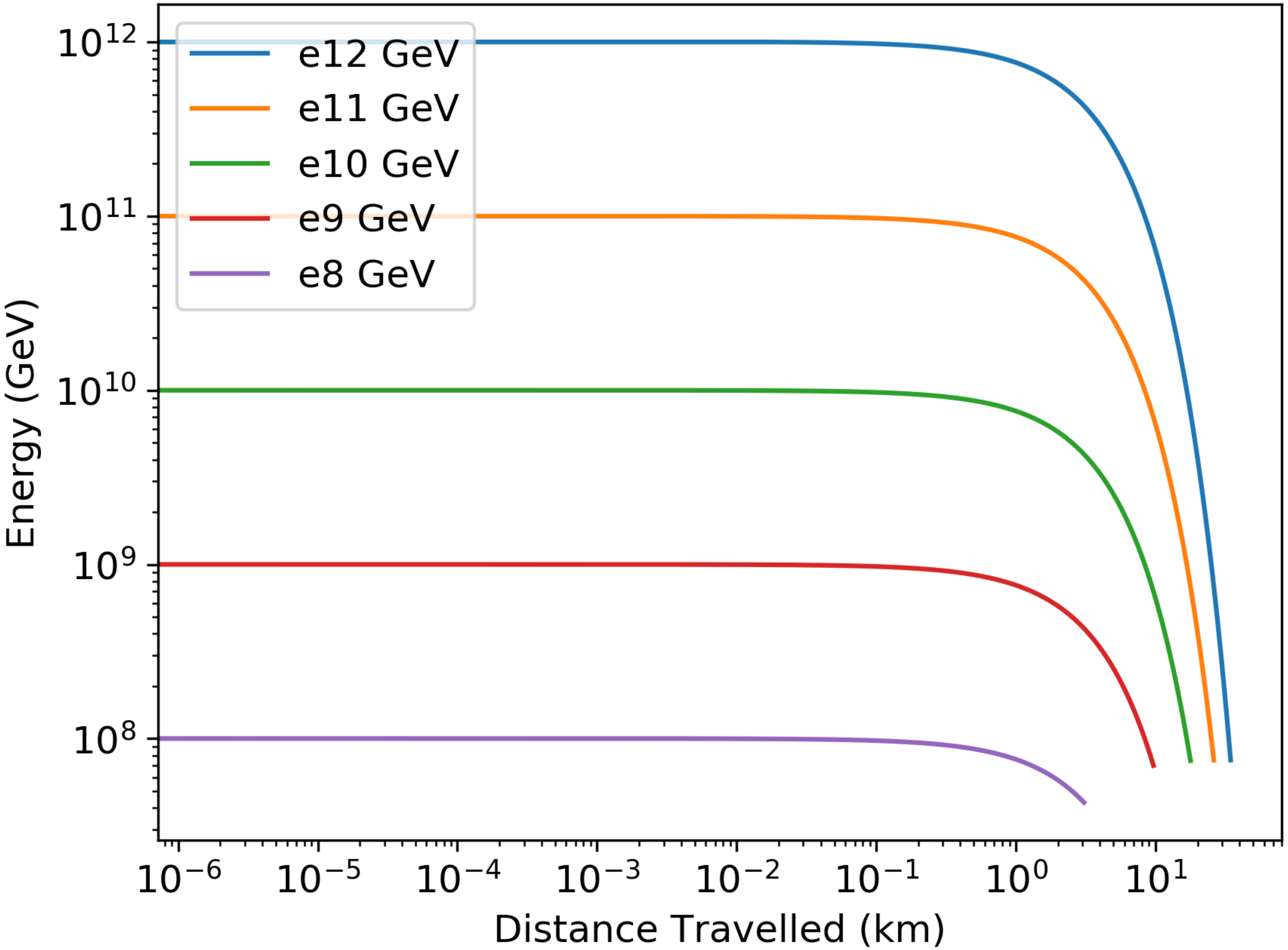
$$E = E_0 \exp(-\beta x) = E_0 \exp(-\beta\rho z)\,,$$

and distance travelled during one lifetime is

$$z_{decay} \approx \frac{1}{\beta\rho} log\left(\frac{\beta\rho c t_0 E_0}{mc^2} + 1\right)$$



DM Distribution → IceCube Event Rate?

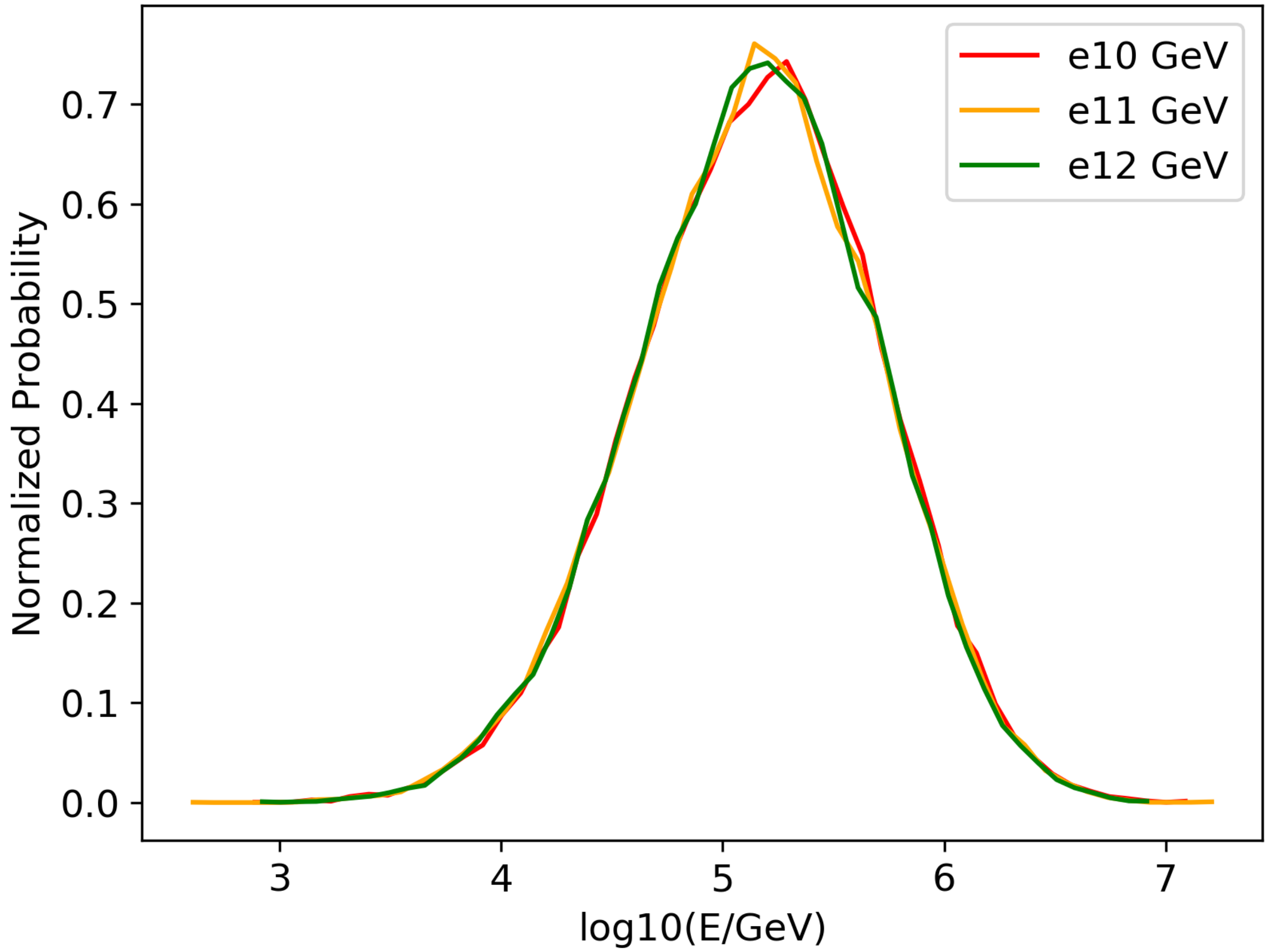


DM Distribution → IceCube Event Rate?

Full numerical simulation (modified NuTauSim):

$$f(\epsilon) = \exp\left(-\frac{(\mu-\epsilon)^2}{2\sigma^2}\right)/(2\pi\sigma^2)$$

with $\sigma = 0.54, \ \mu = 5.15,$
$\epsilon \equiv$ E / GeV.



DM Distribution → IceCube Event Rate?

Expected number of events in IceCube HESE data set:

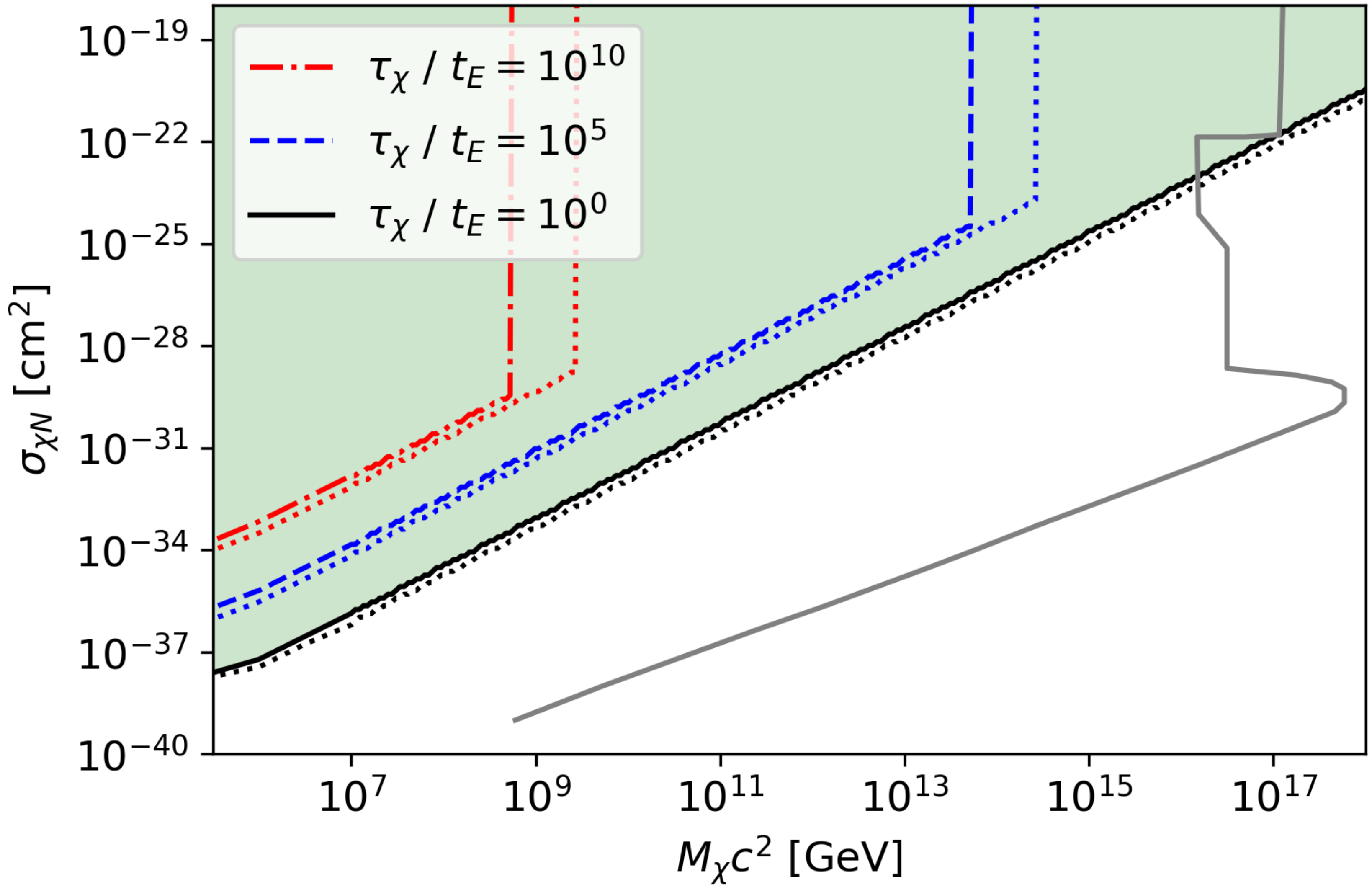
$$N = T\frac{\Gamma}{4\pi R^2}\int_{60\ TeV} dE\ f(E_{obs}, E_{initial})A_{eff}(E_{obs})$$

which evaluates to

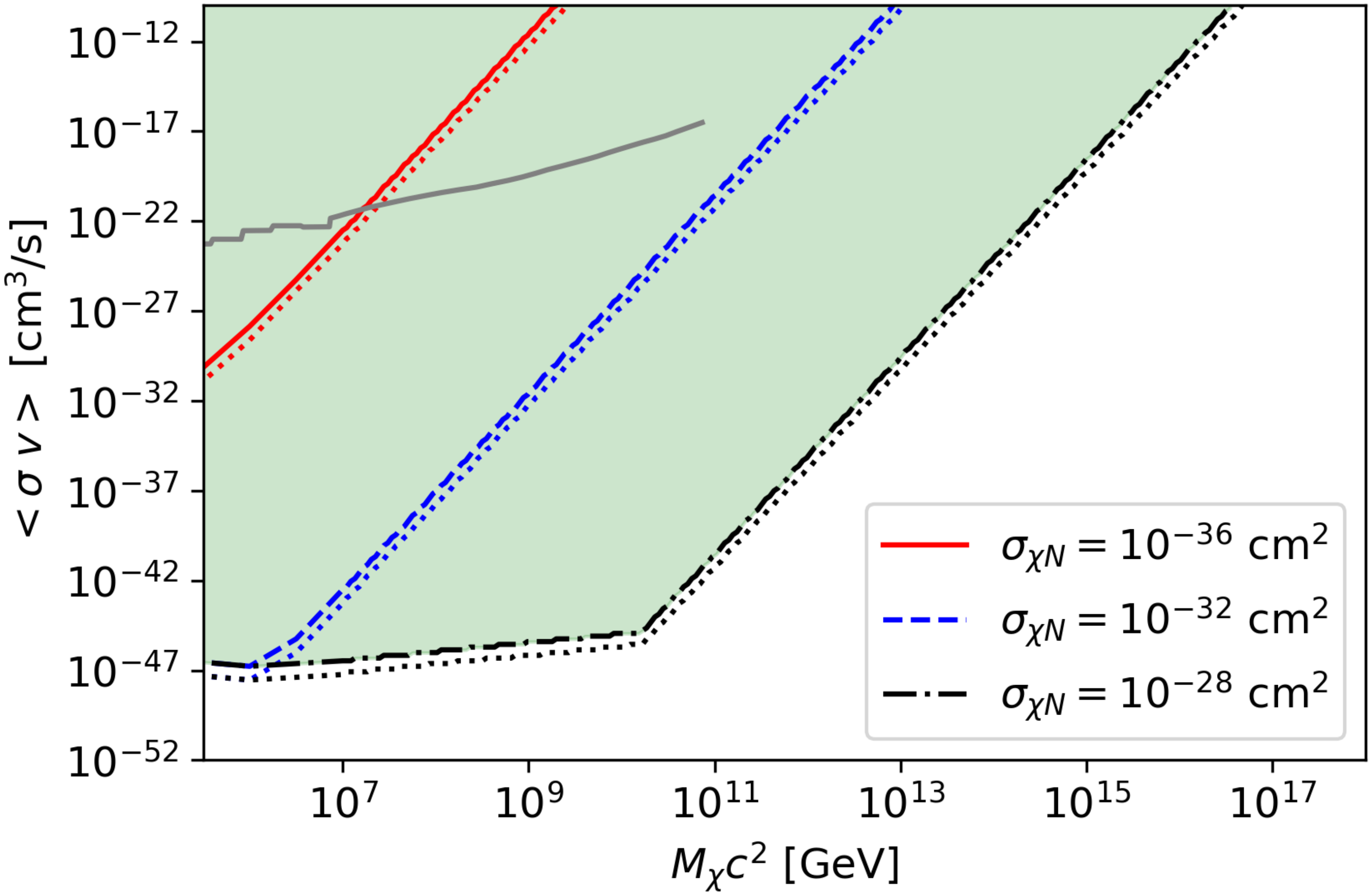
$$N \cong 10^{-14} T\Gamma$$

We said N > 10 predicted events in HESE data set excluded.

Parameter Space Reach – Decays



Parameter Space Reach – Annihilations

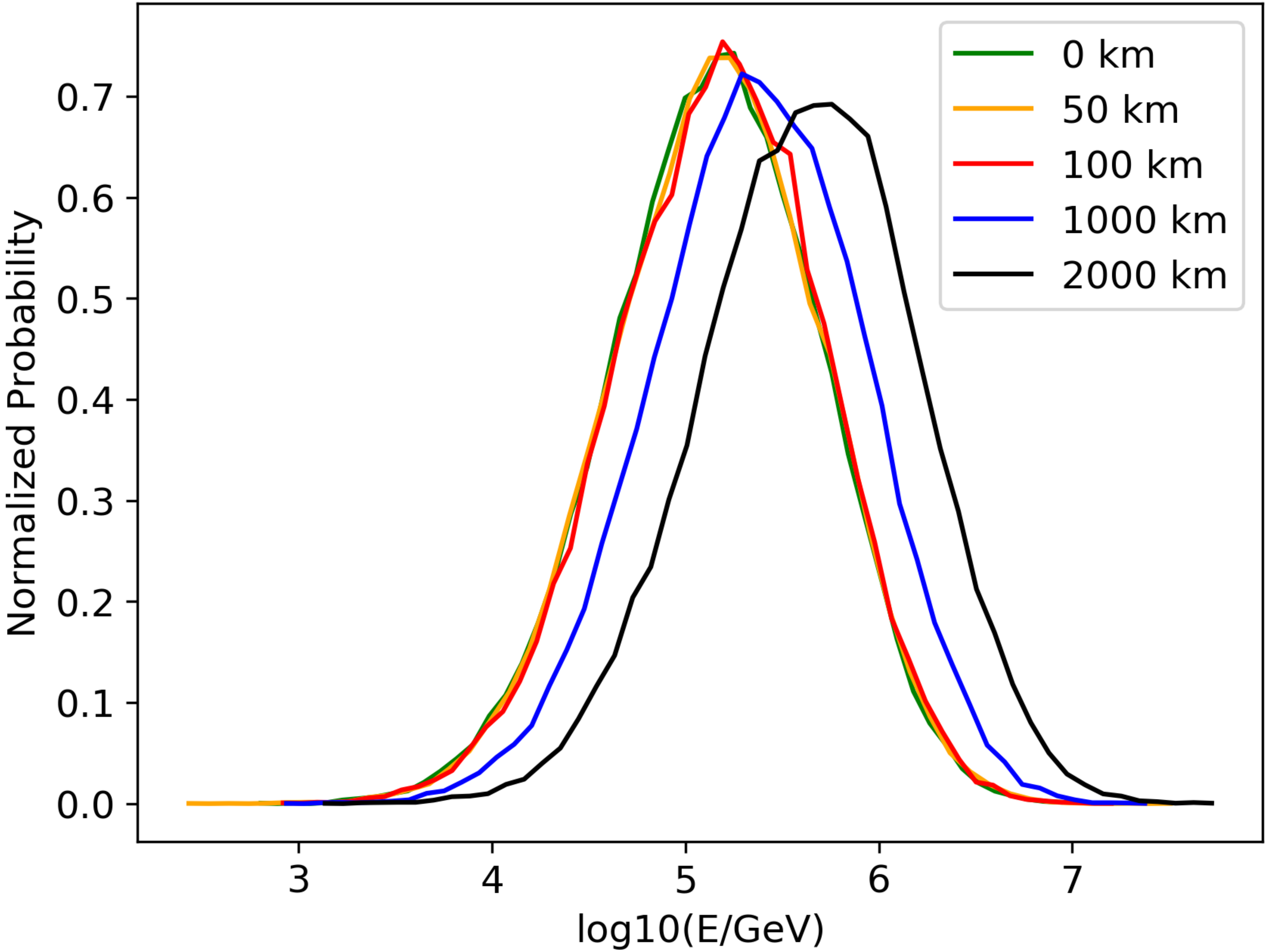


Summary

- Tau neutrino regeneration allows very heavy dark matter decays to be probed at IceCube.

- Modeling capture / thermalization along with tau neutrino propagation and detection shows that the parameter space probed by IceCube is in tension with direct detection bounds.

- Unless an assumption about capture / thermalization is wrong! Can use our result to look at alternatives w/o doing full neutrino simulation.


0 km
50 km
100 km
1000 km
2000 km
Normalized Probability
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
3
4
5
6
7
log10(E/GeV)