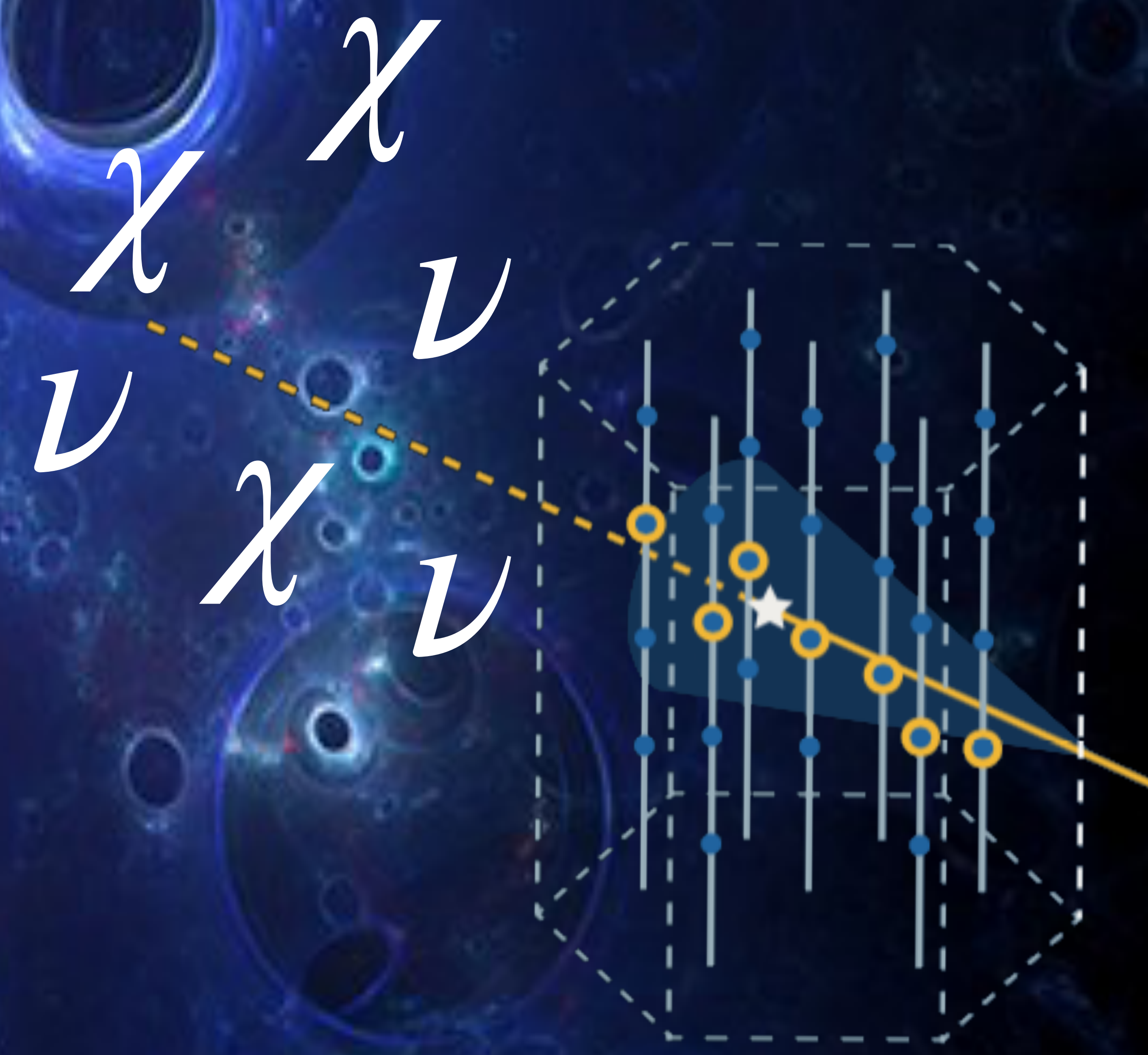
# Illuminating Very Heavy Dark Matter in the Earth with Tau Neutrinos




Qinrui Liu

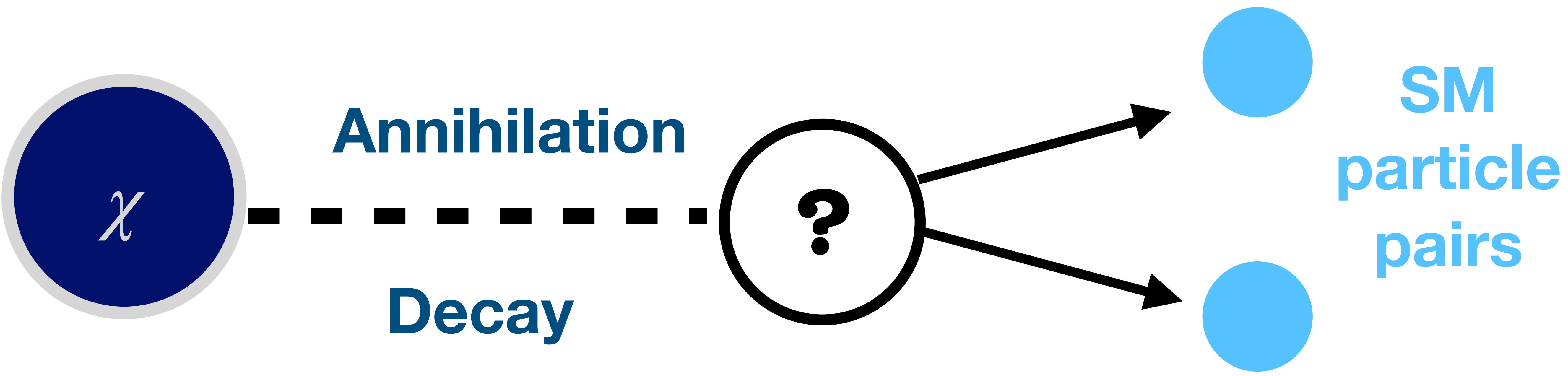
TAUP2025, Xichang, August 25th 2025

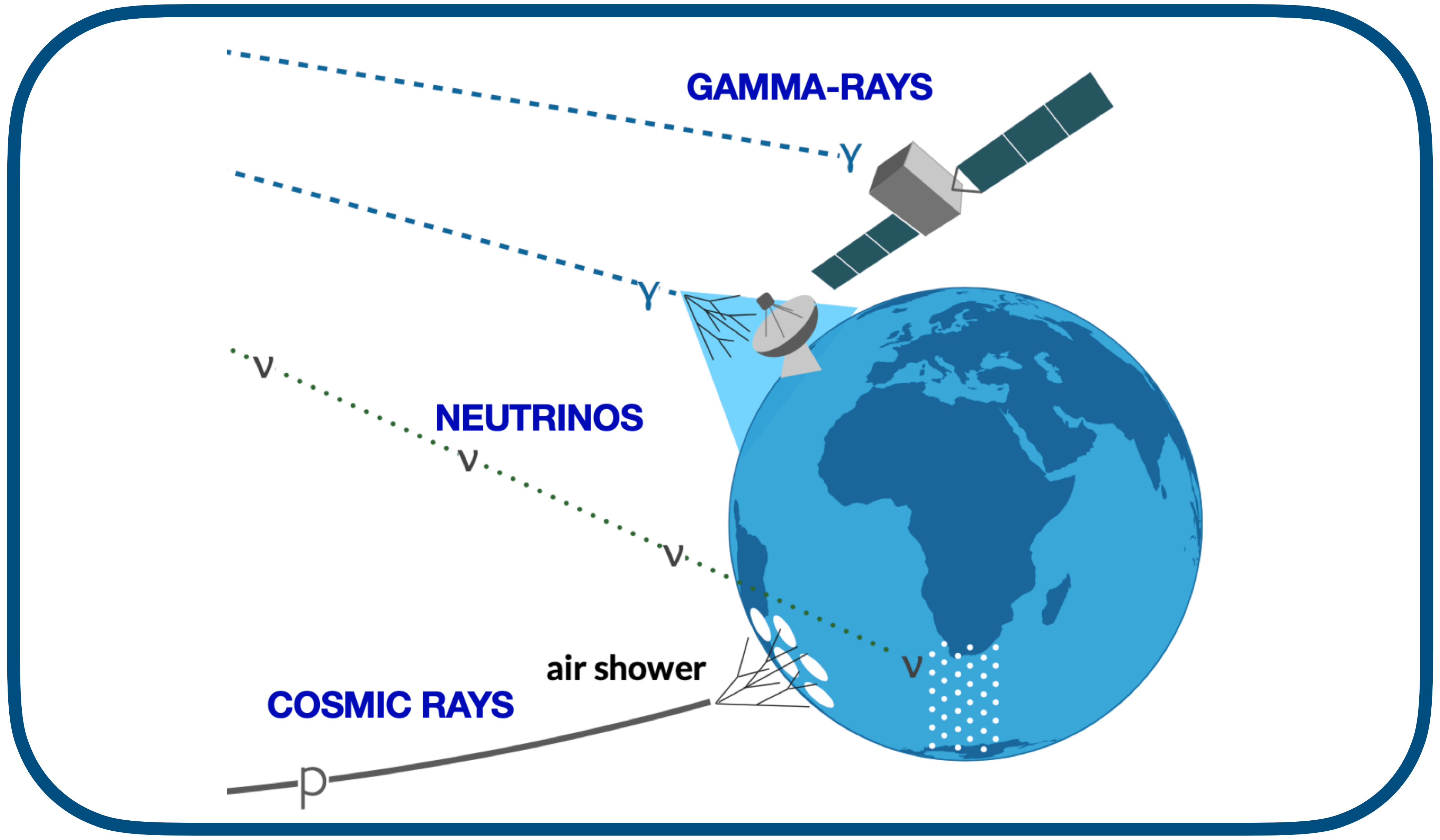
w/ Tianyi Ding & Ali Kheirandish

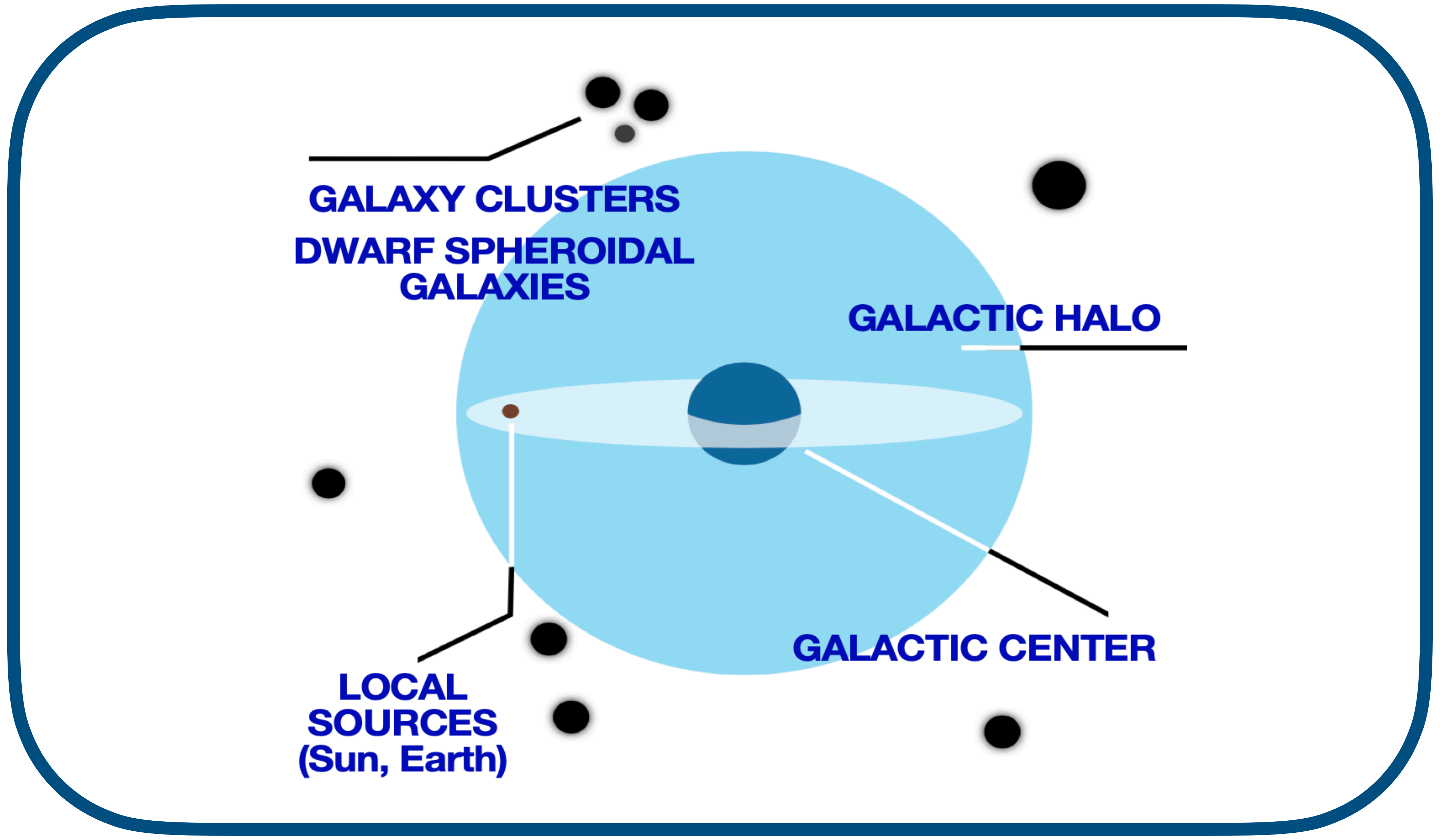
arXiv:2505.09673

McDonald Institute
PERIMETER INSTITUTE
Queen's UNIVERSITY

# Indirect Dark Matter Search



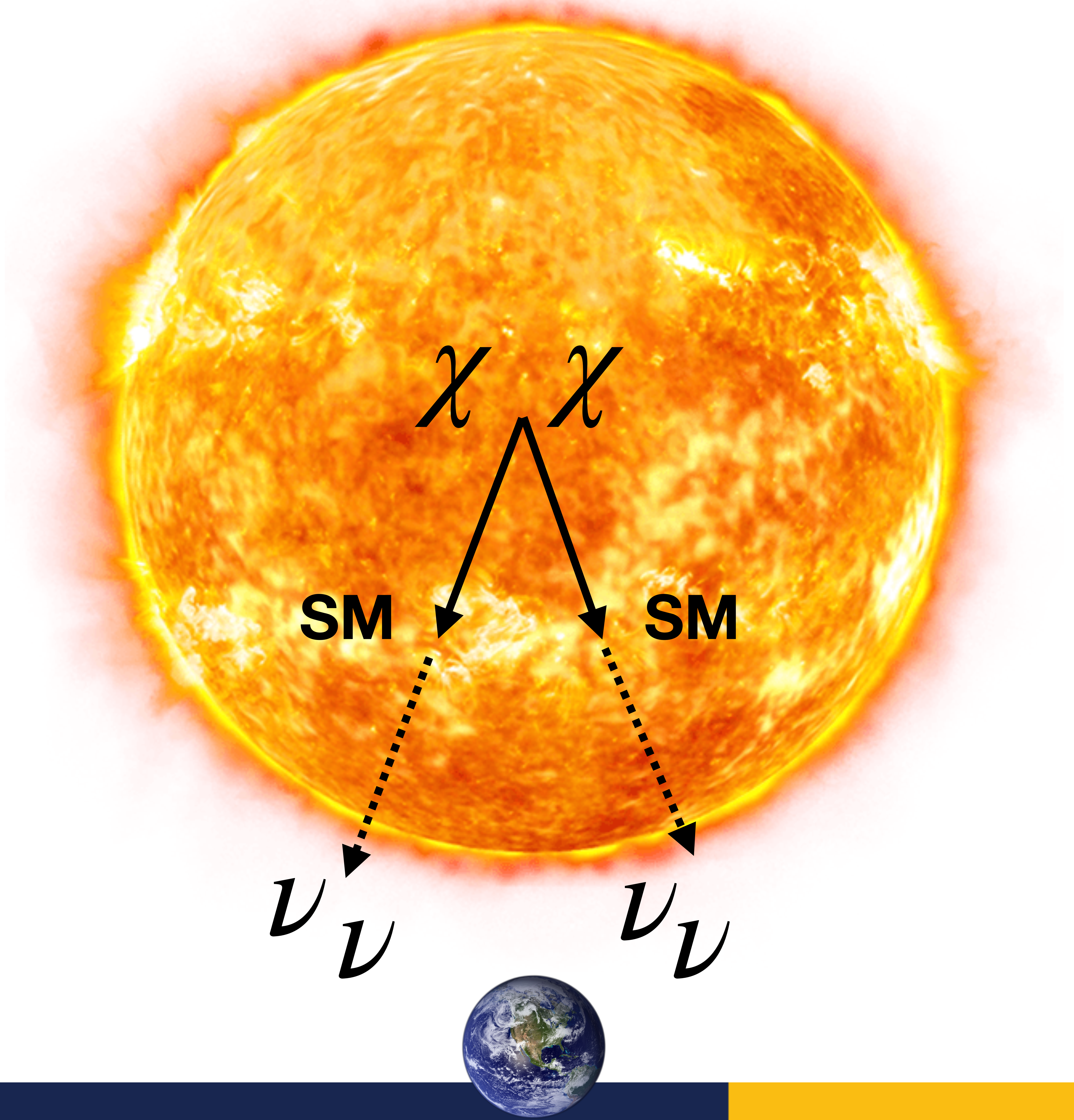




credit: J. A. Aguilar

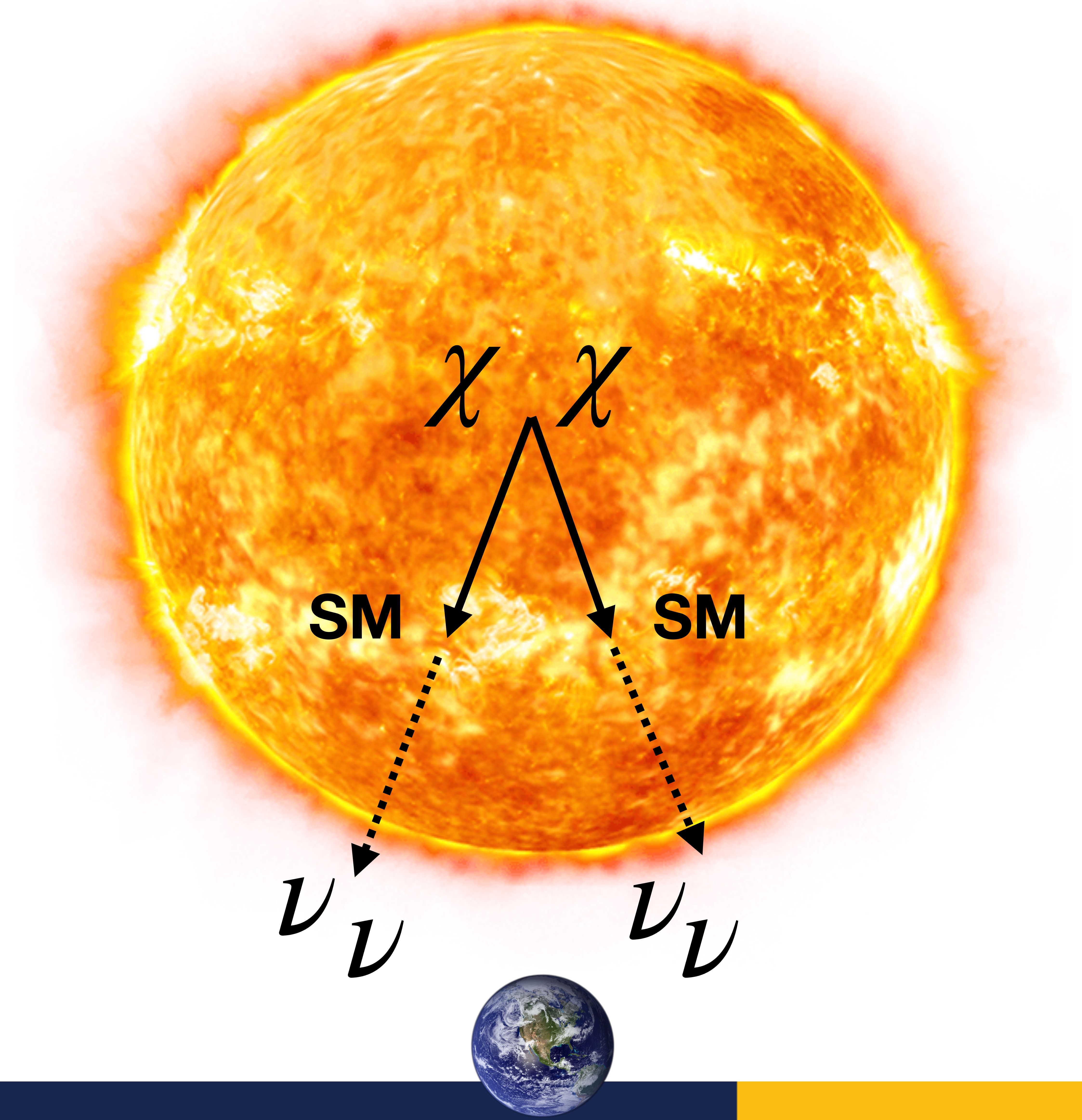
# Indirect Dark Matter Search with Neutrinos

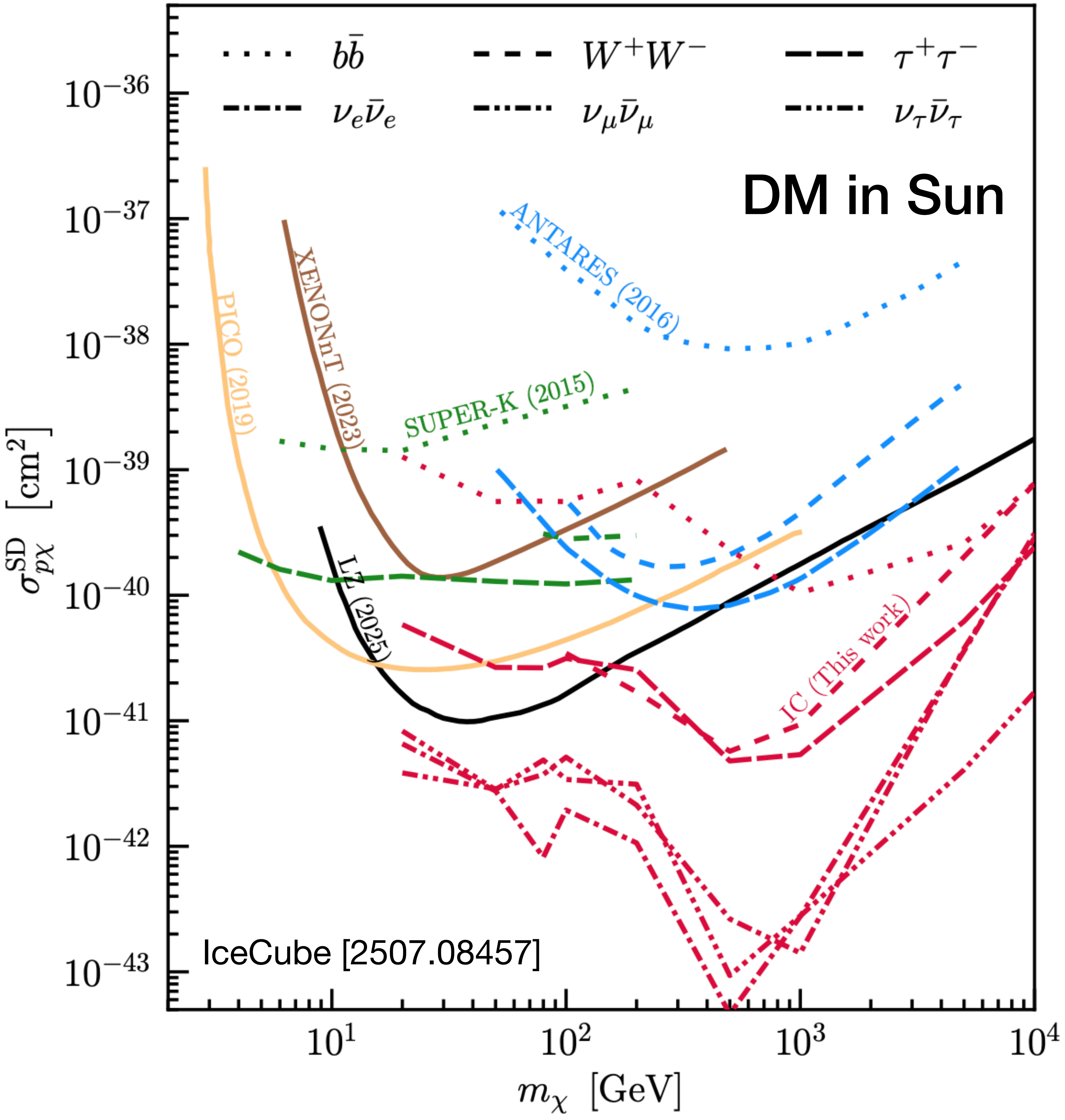
✨ $\nu$: being able to exit dense matter/ radiation environments



# Indirect Dark Matter Search with Neutrinos

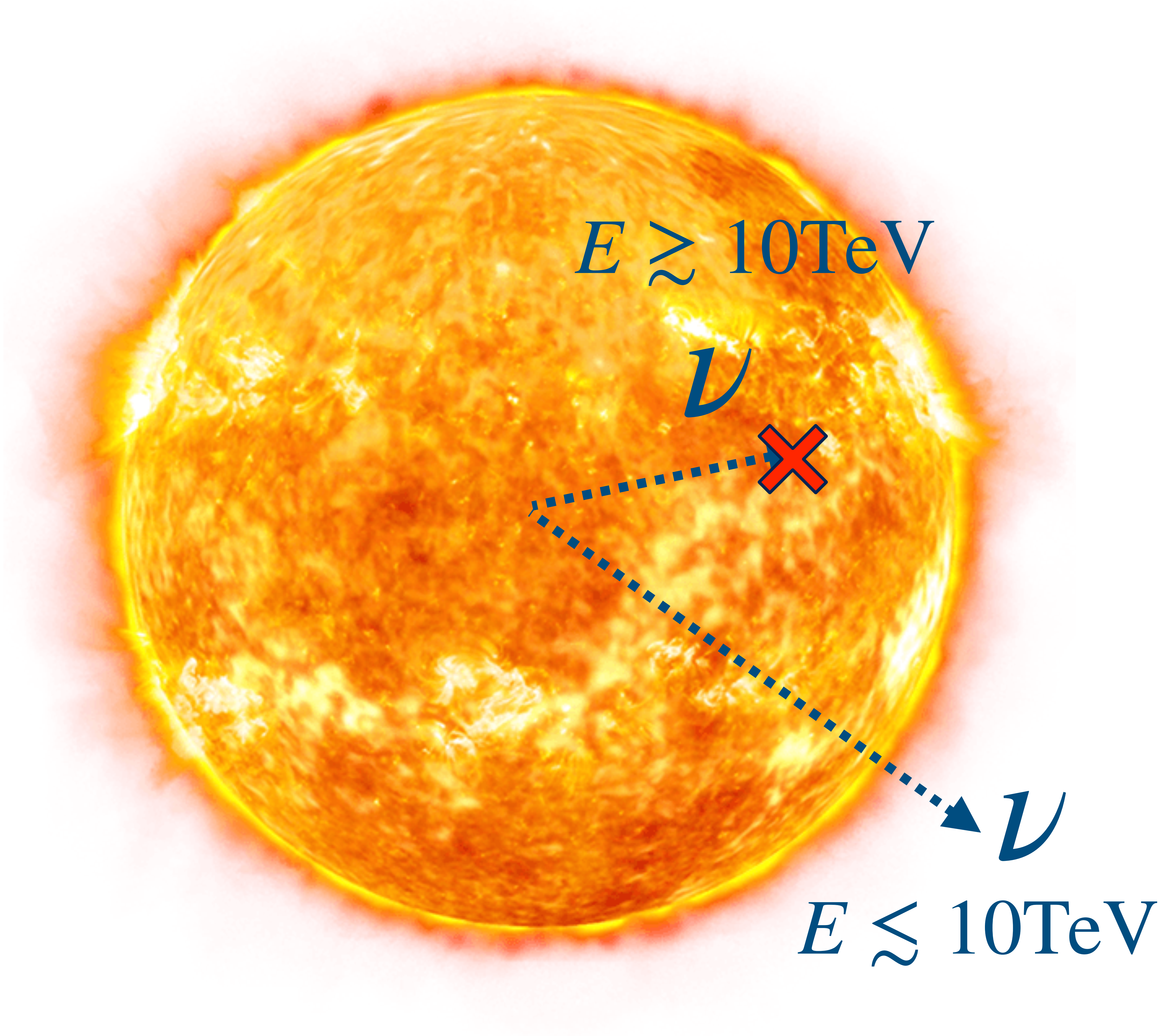
✨ $\nu$: being able to exit dense matter/ radiation environments

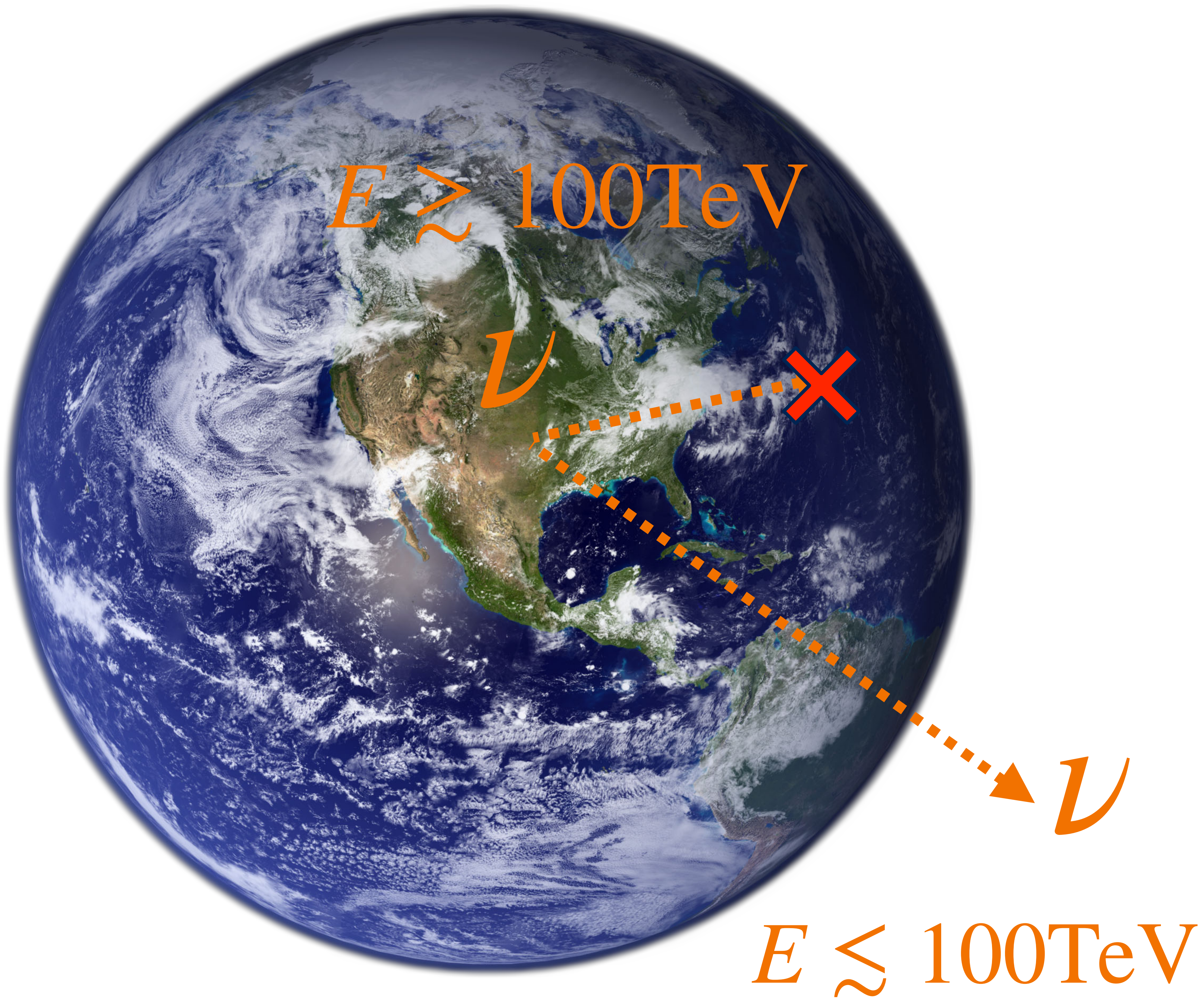



IceCube can obtain world-leading limits for spin-dependent dark matter-nucleon scattering for $m_\chi \gtrsim 100\,\mathrm{GeV}$ by observing the Sun.

Neutrinos have the advantage of being able to escape dense environments compared to other messengers, but the observable energy range is still limited, depending on the celestial body.



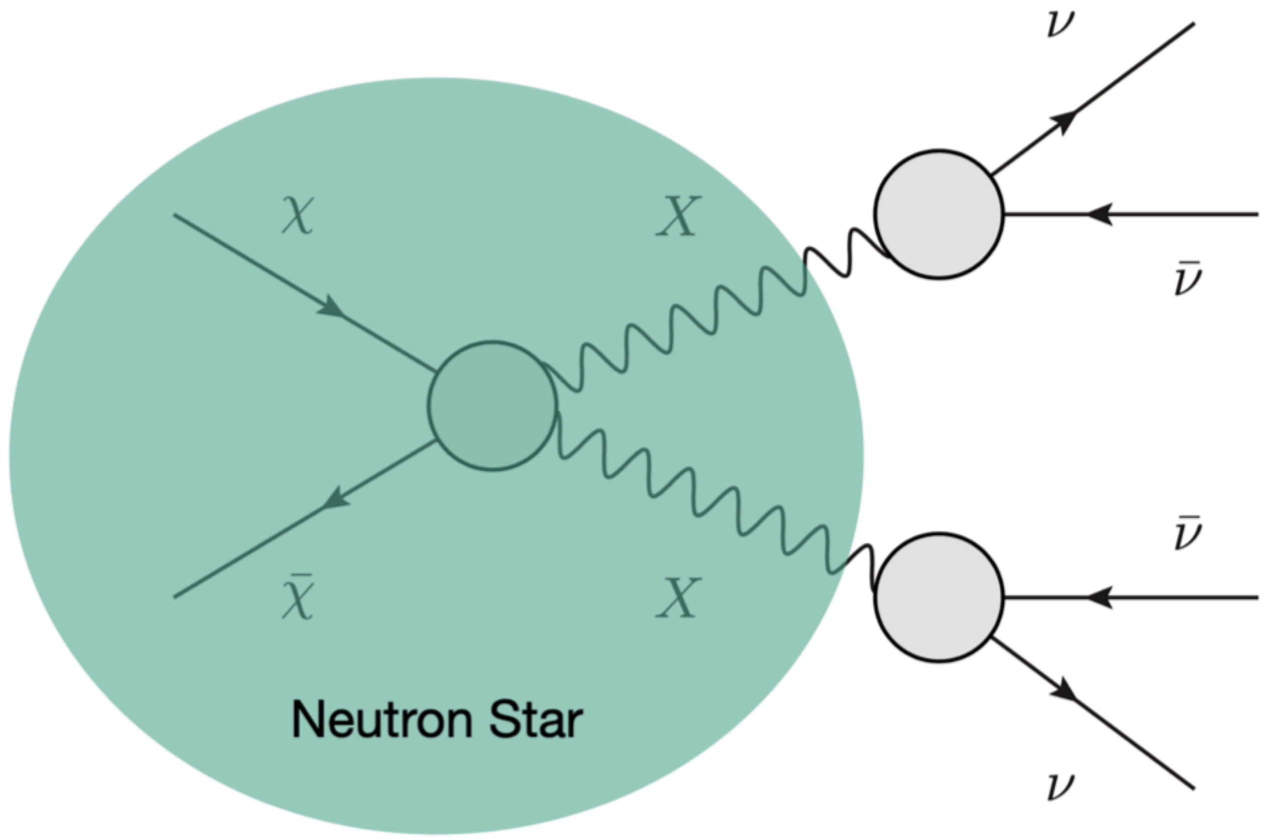



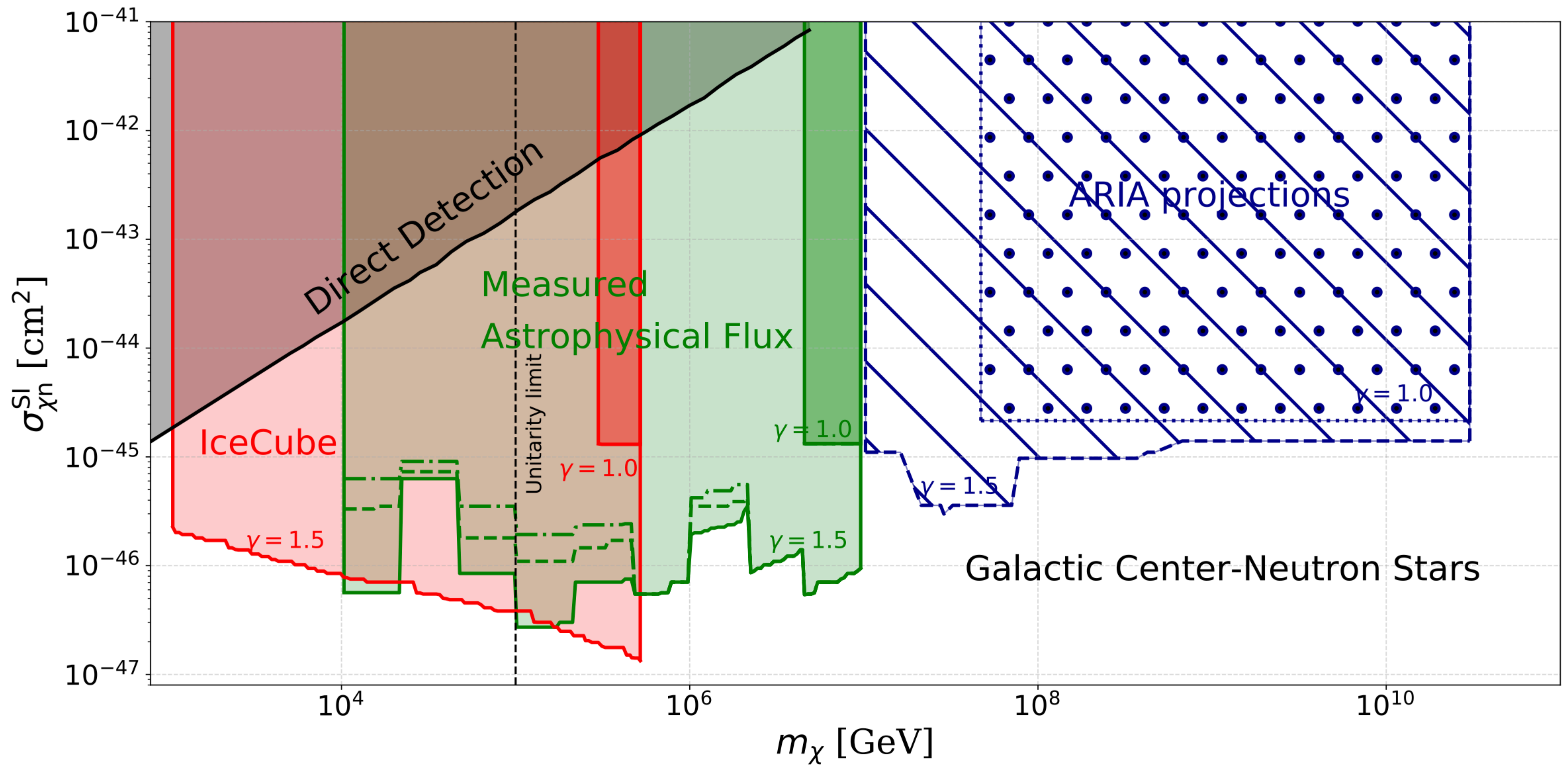

The potential of celestial bodies can be expanded, considering magic✨ from the dark matter models and neutrino interactions!

# If we explore dark matter models…

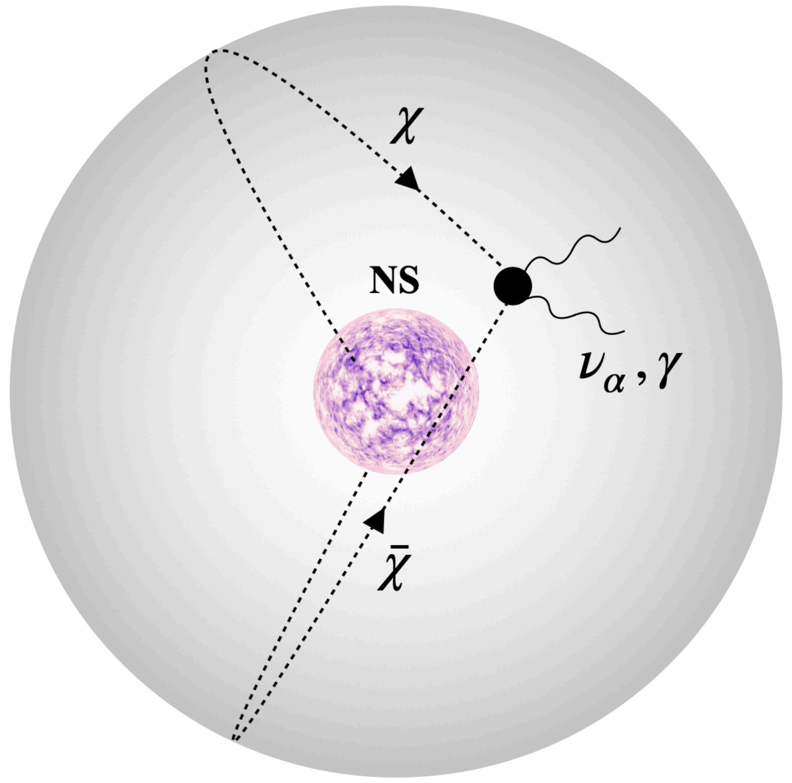
- Annihilations can happen outside celestial bodies or close to the shells.
- Compact objects, such as neutron stars, which capture dark matter efficiently, can be studied.

long-lived mediators

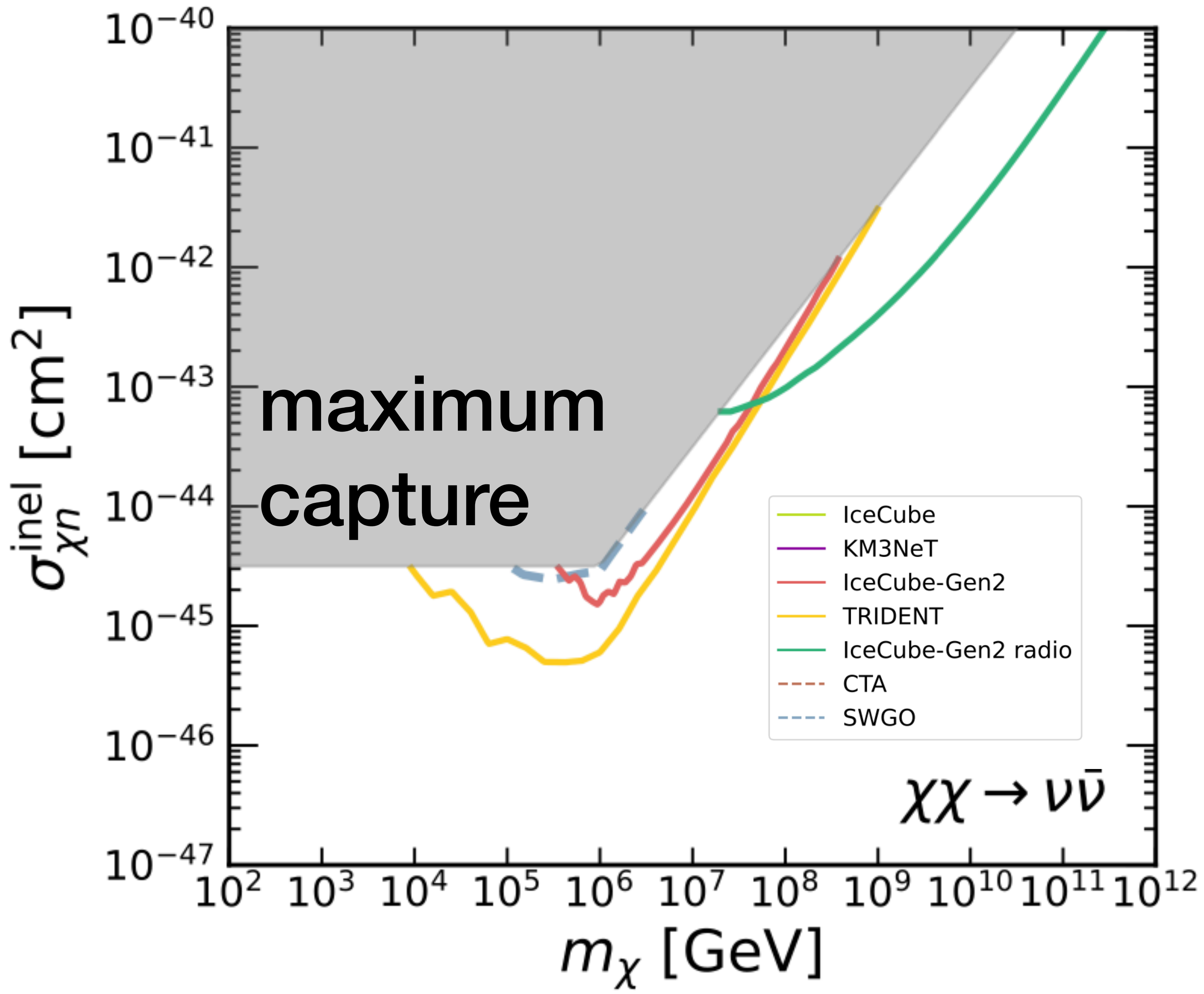



Nguyen & Tait PRD 2023




inelastic dark matter



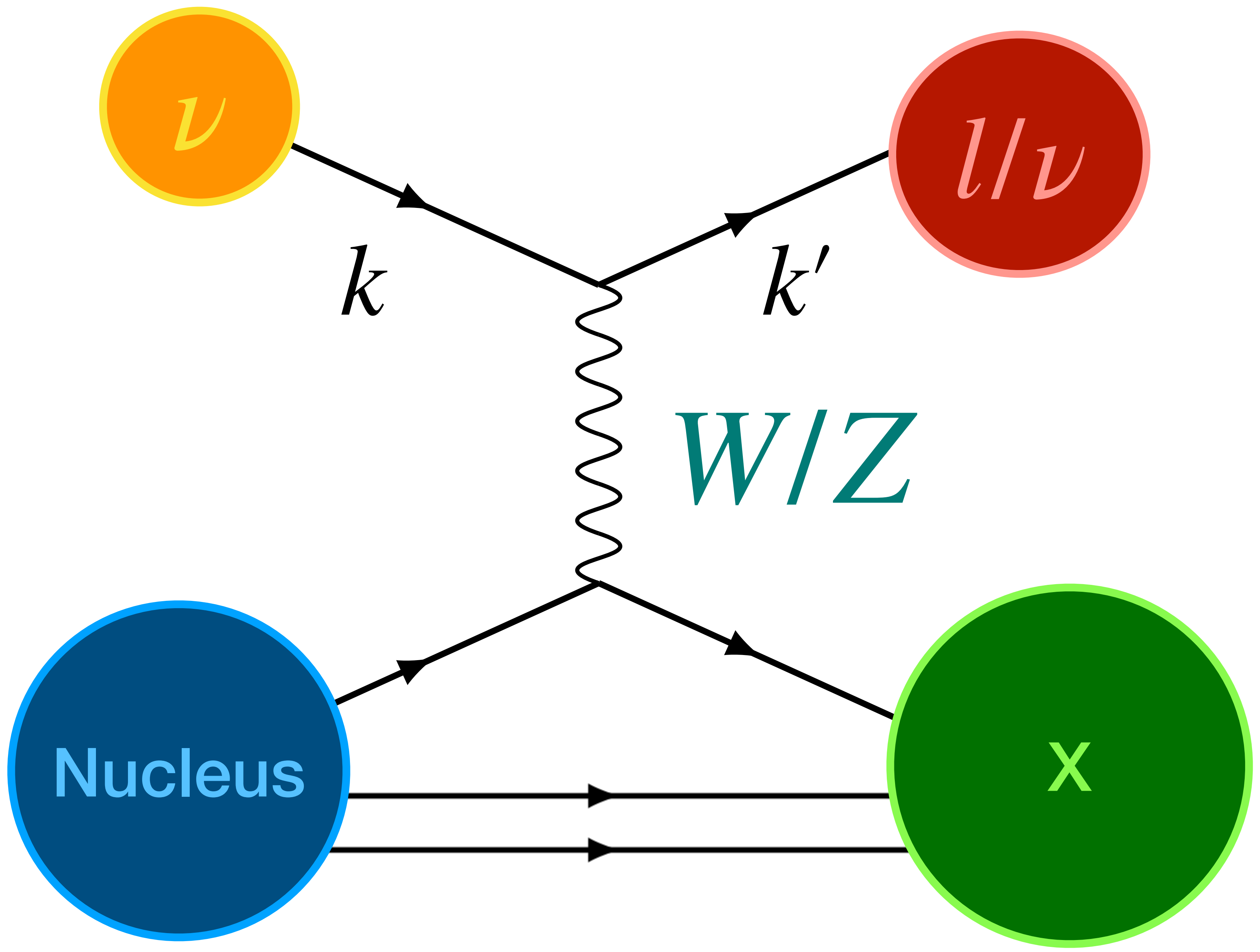

Acevedo, Bramante, **QL**, Tyagi JCAP 2025

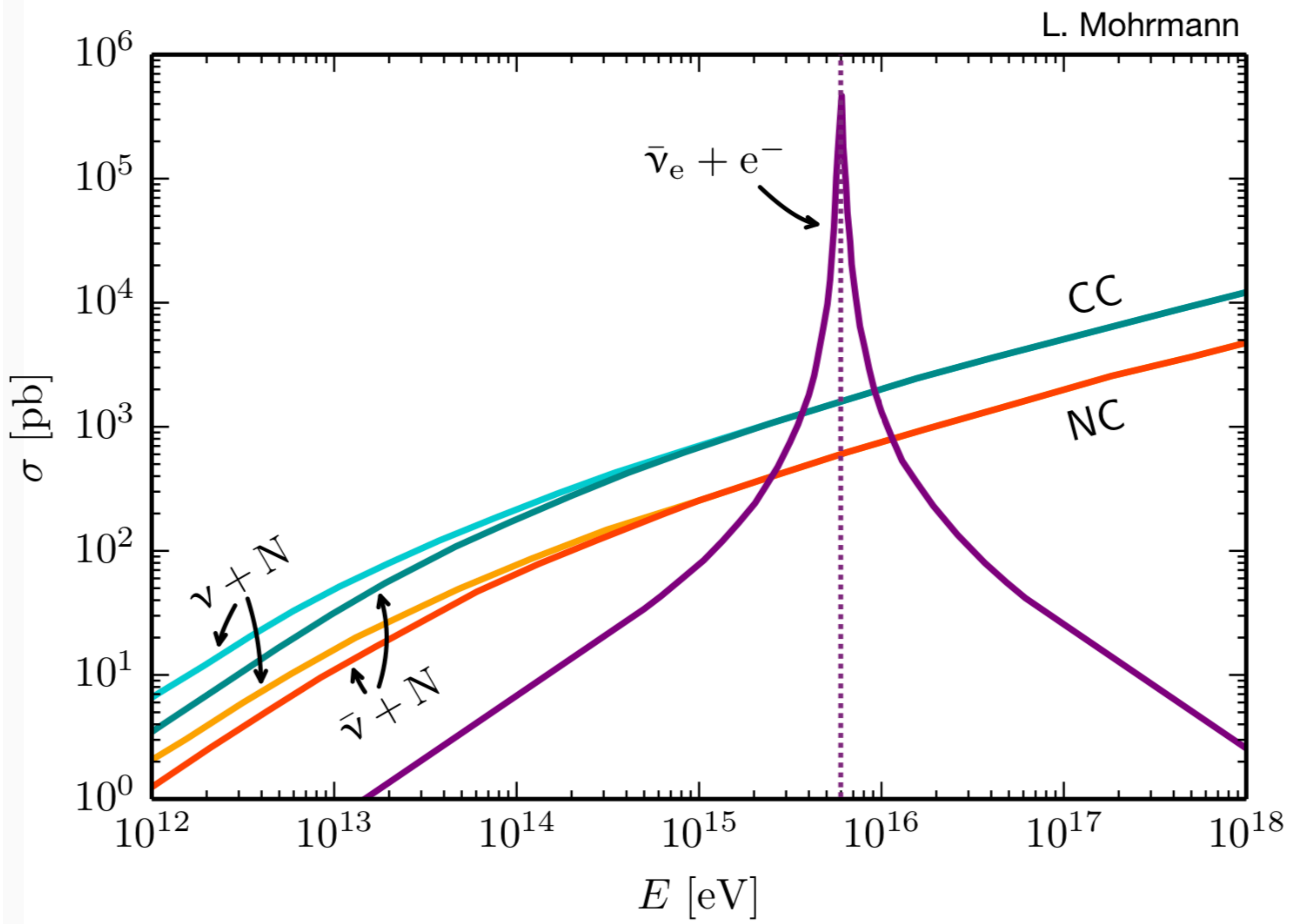
# WHAT ABOUT HEAVY Dark Matter Still ANNIHILATES INSIDE CELESTIAL BODIES?

# WHAT ABOUT HEAVY Dark Matter Still ANNIHILATES INSIDE CELESTIAL BODIES?

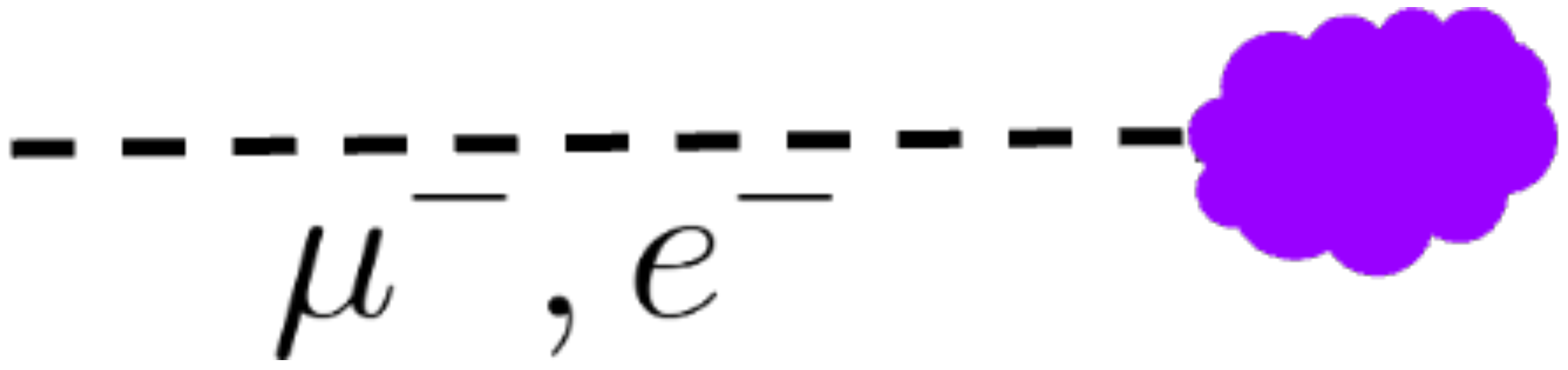

**Let's consider neutrino interactions!**

# High-Energy Neutrino Propagation in Matter



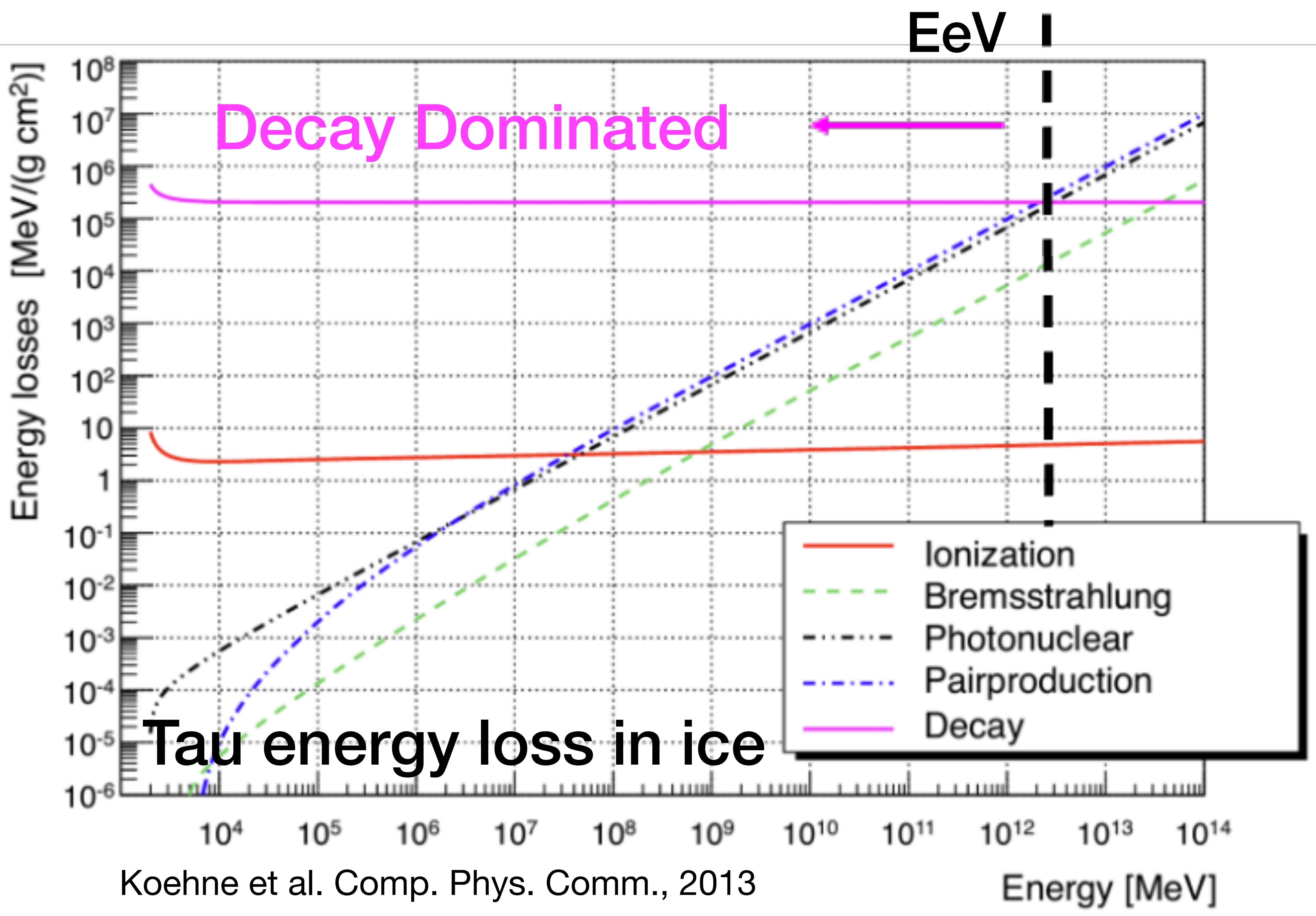




- Neutral Current: sub-dominant, same type of neutrino at a lower energy.
- Charged Current: dominant, $\nu_l \rightarrow l$



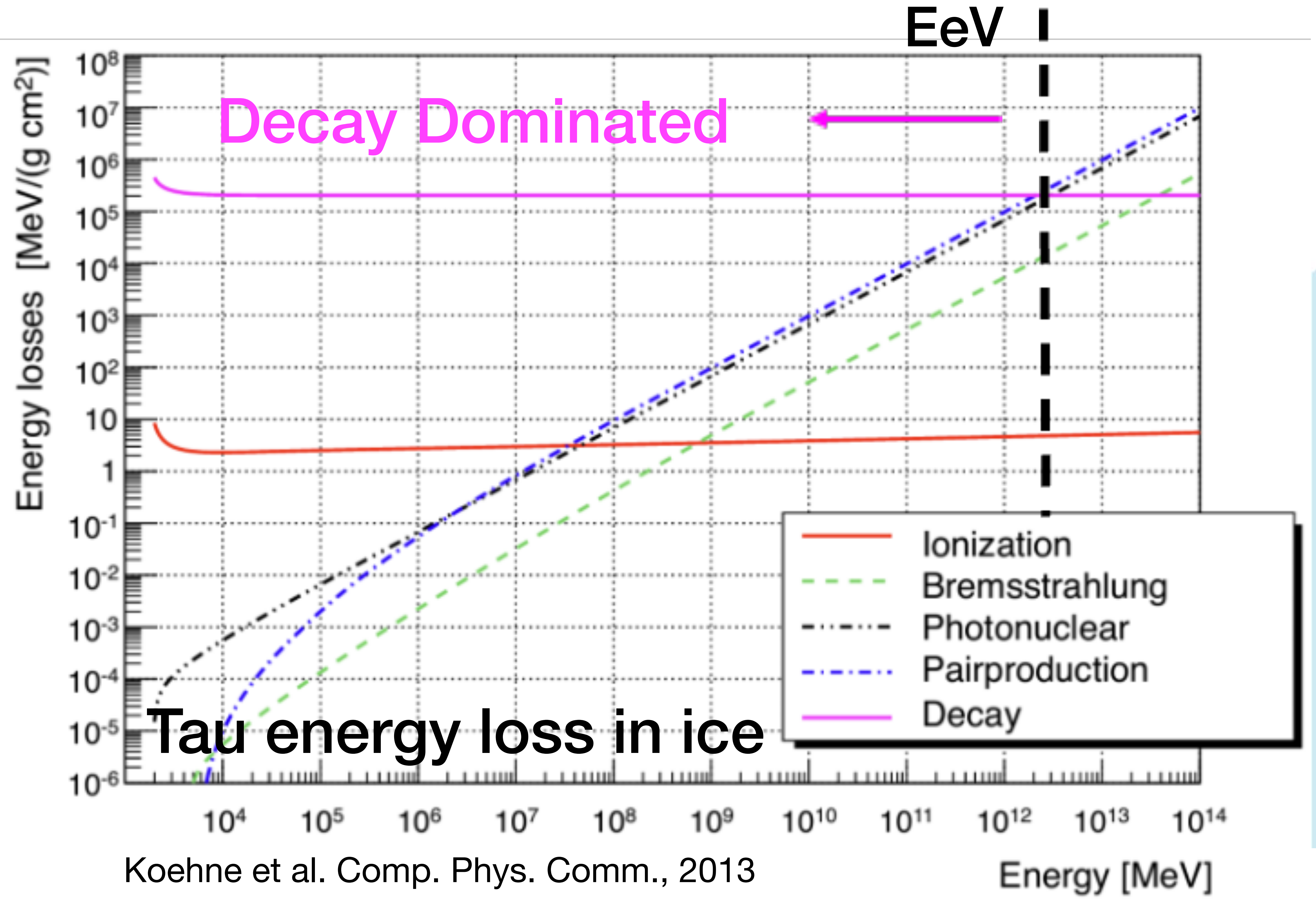

rapid energy loss


very short lifetime $\sim 3 \times 10^{-29}$ s

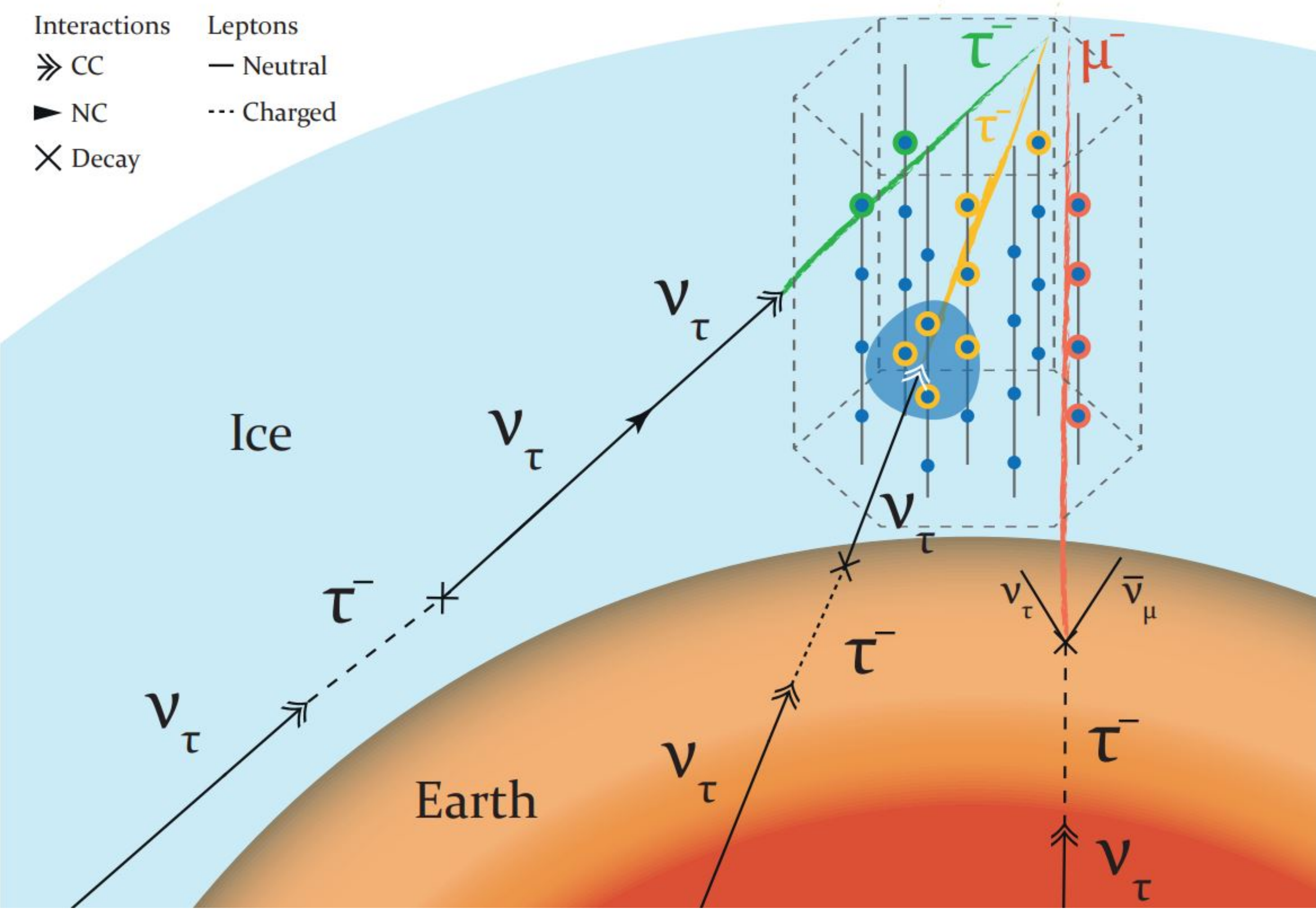



Koehne et al. Comp. Phys. Comm., 2013

# Tau Regeneration Effect

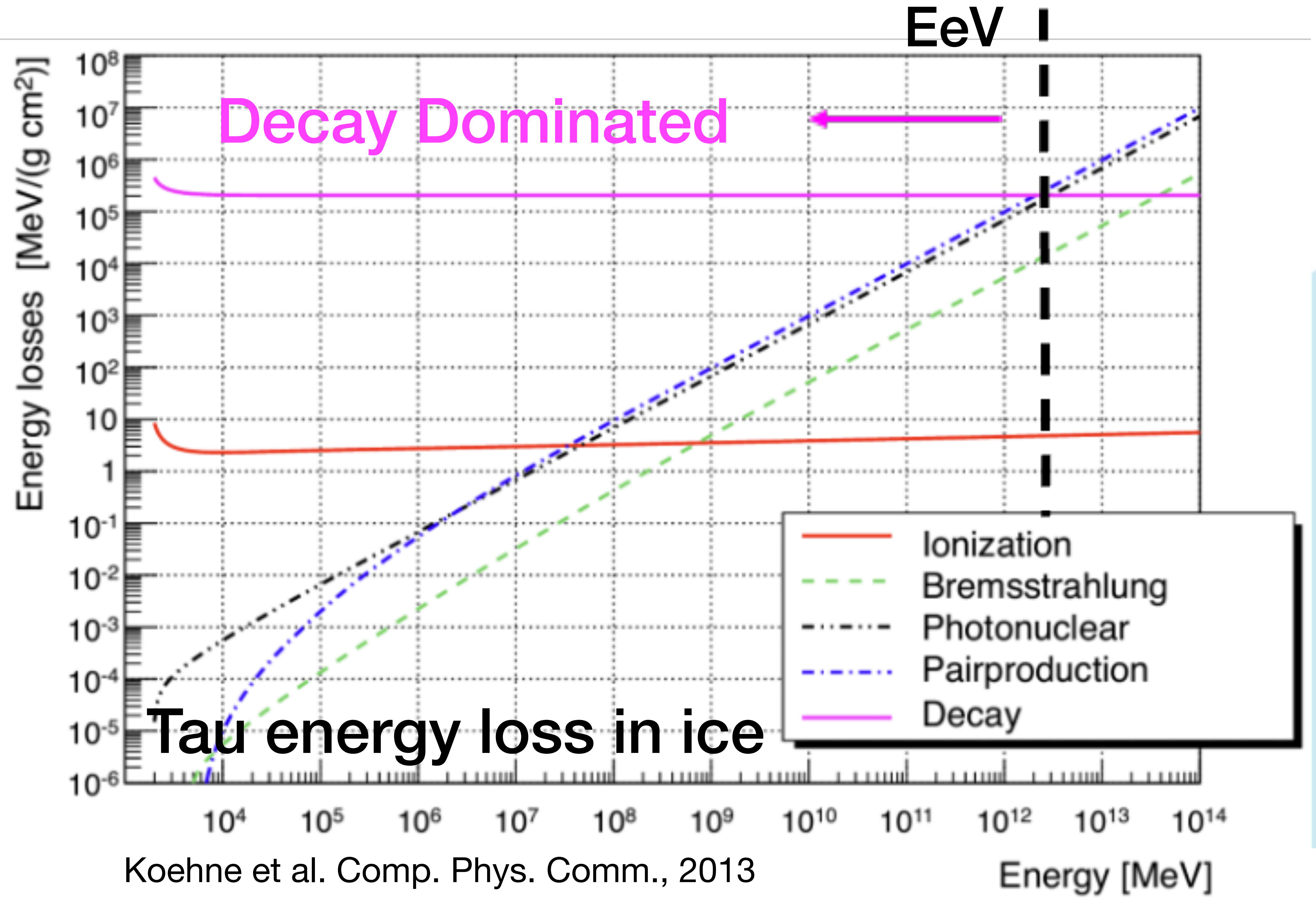



Koehne et al. Comp. Phys. Comm., 2013




High-energy tau neutrinos shift to lower energies

# Tau Regeneration Effect

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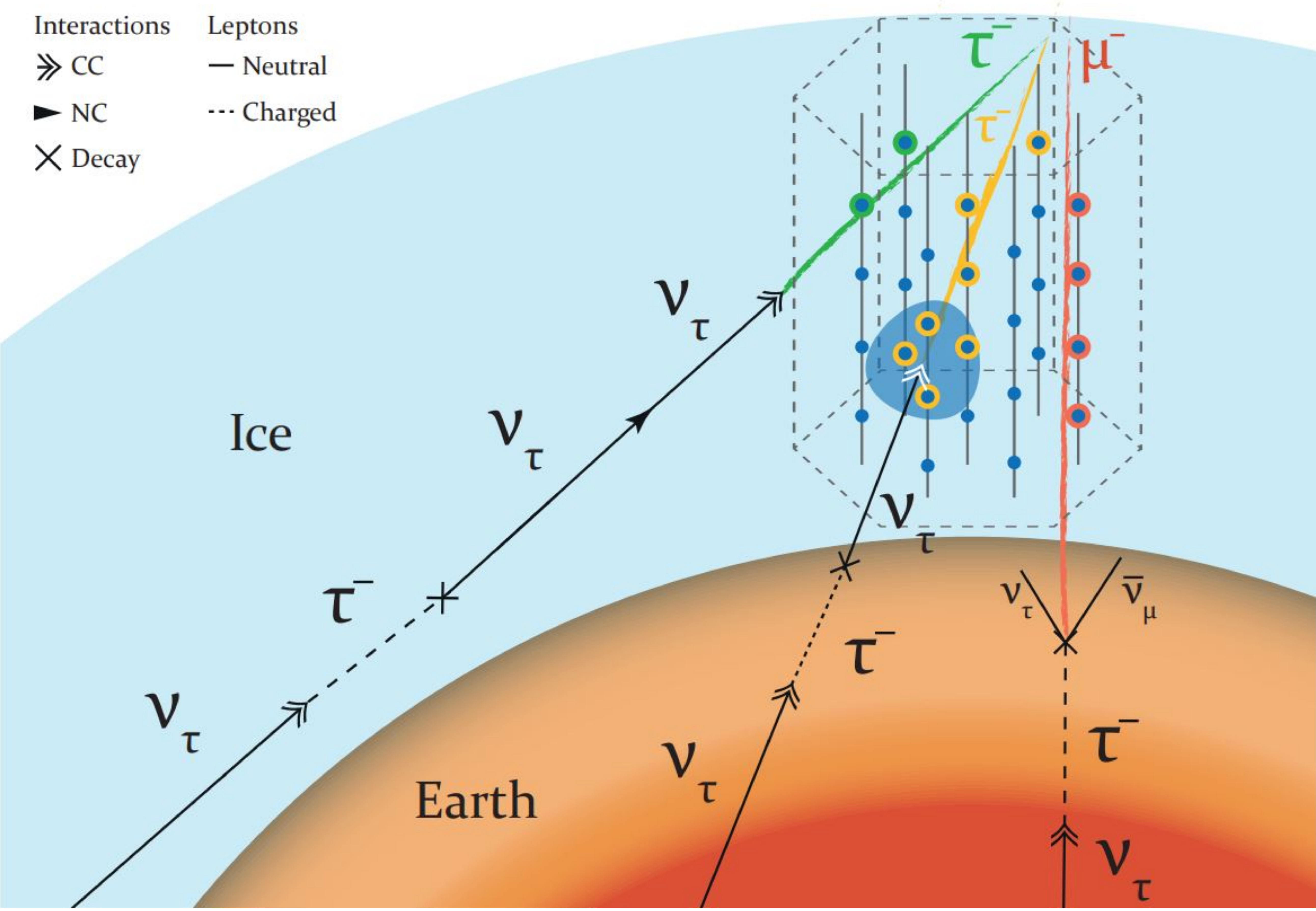
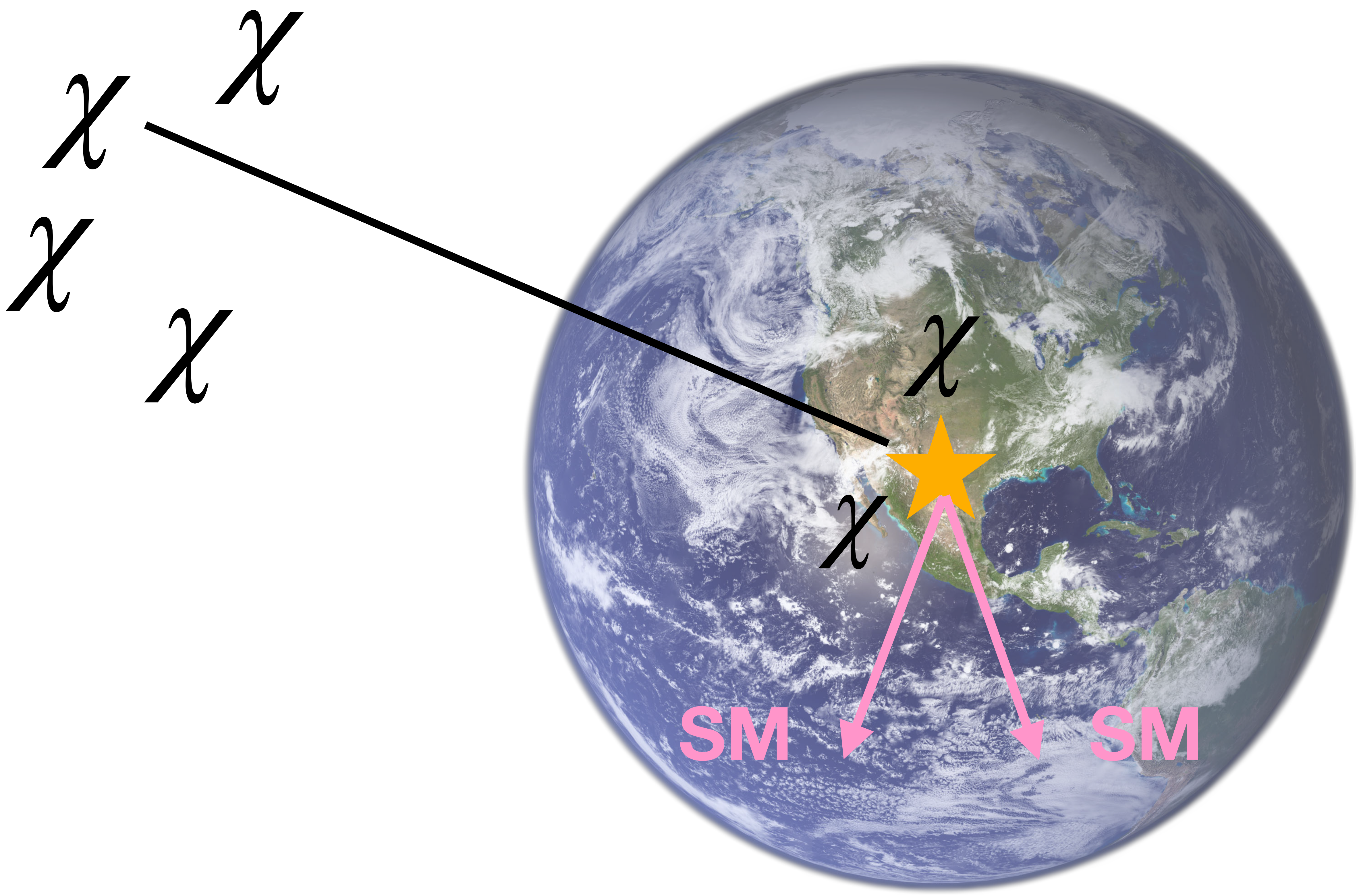



High-energy tau neutrinos shift to lower energies

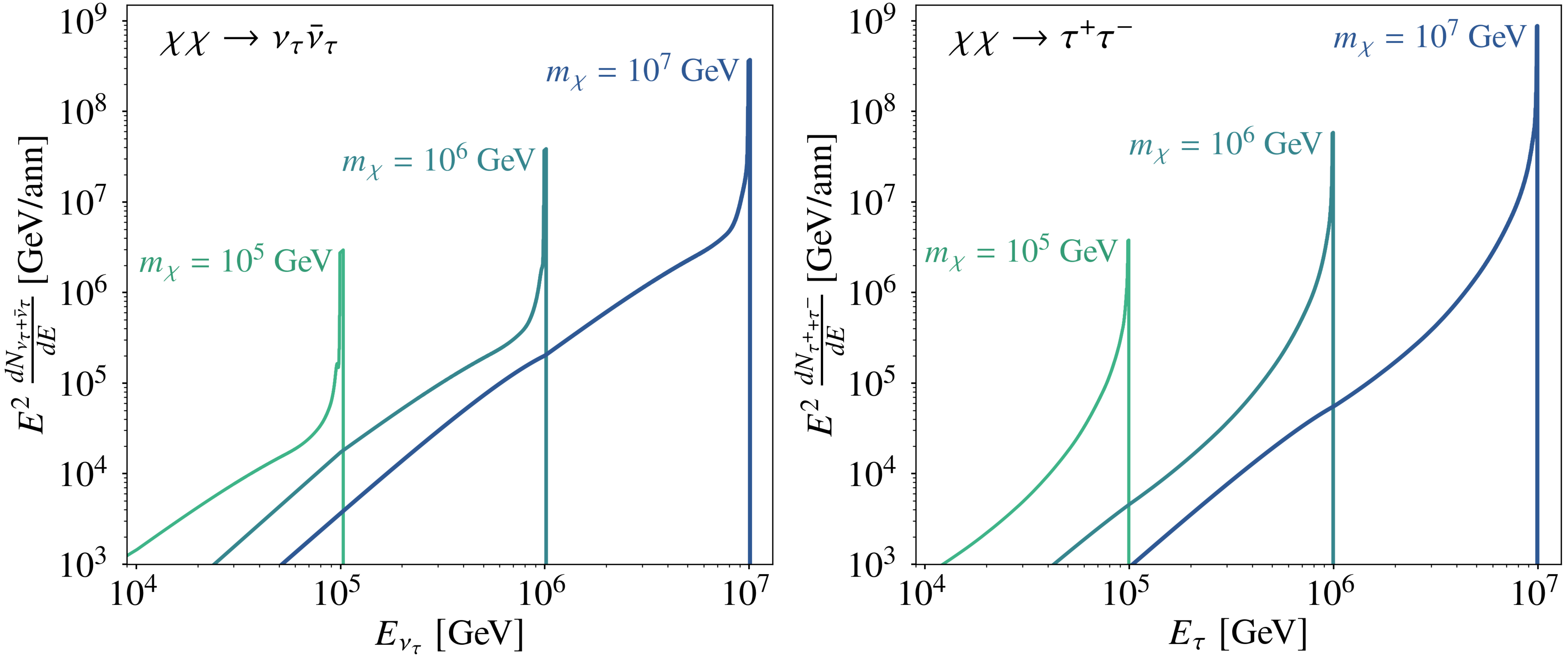
Detectable neutrino flux at lower energies at the detector from very heavy dark matter annihilation in e.g. Earth?

# Step 1: Dark Matter Annihilation at Earth's Center



# Neutrino Spectra of Dark Matter Annihilation

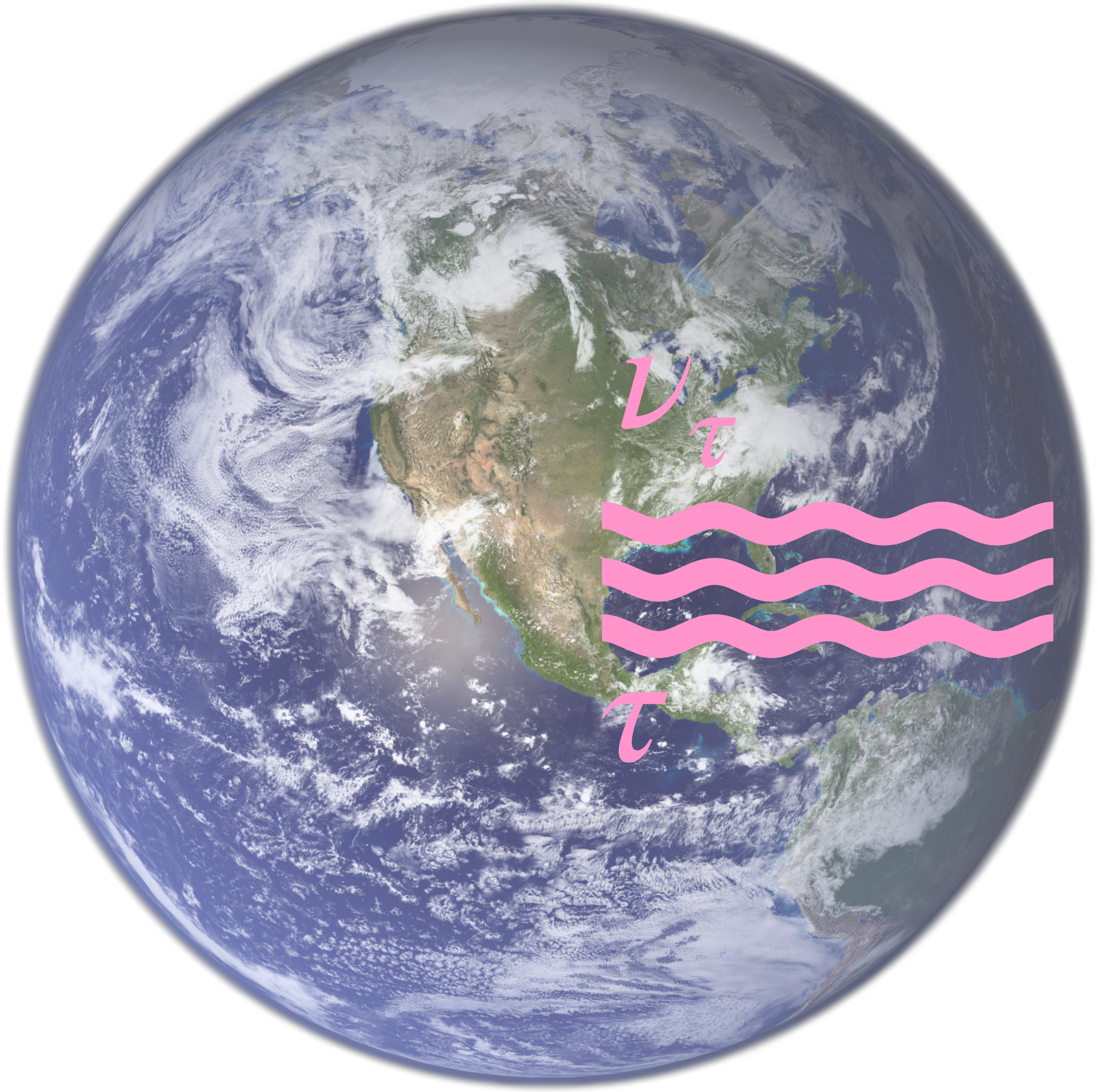
Consider annihilation channels where the main signal is $\nu_\tau$ or $\tau$.




Energies here are well above the electroweak scale;
electroweak radiation is included in the spectrum computation.

**QL**, Lazar, Argüelles, Kheirandish JCAP 2020

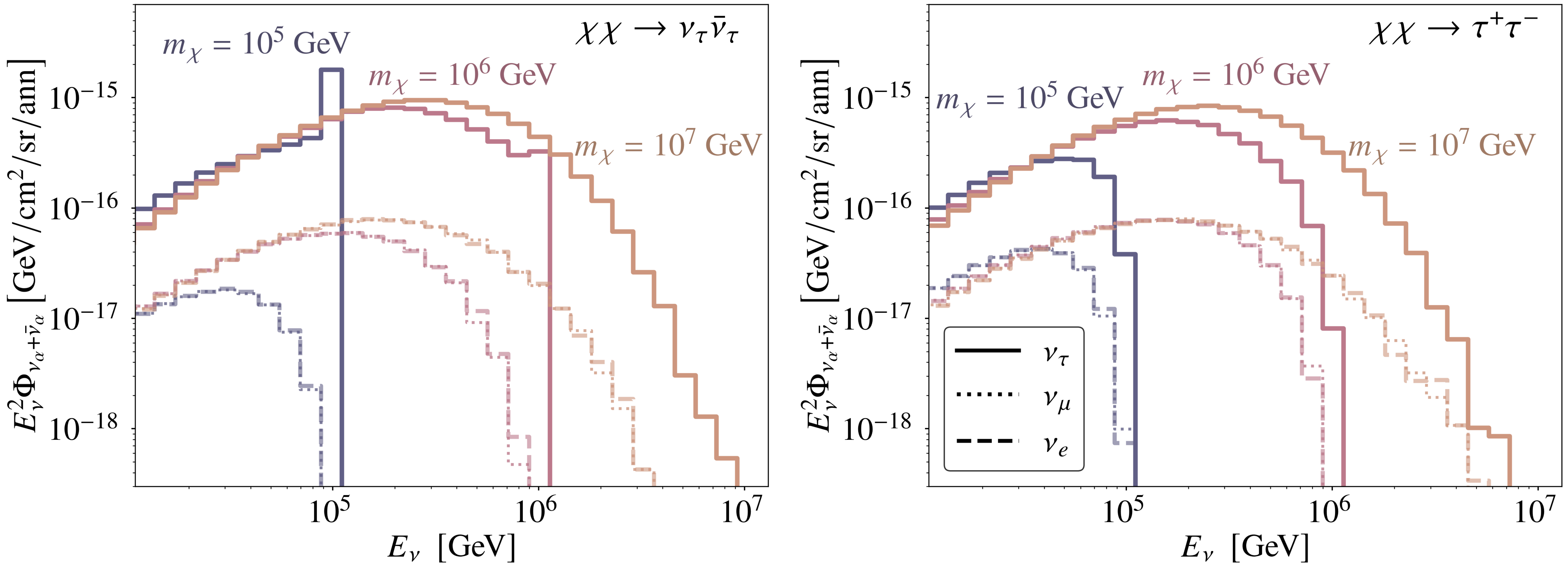
# Step 2: Neutrino Propagation from the Center to the Surface




Incoperating deep-inelastic scatterings of neutrinos, tau interactions and decays.

# Neutrino Spectra at the Surface

neutrino fluxes at the Earth's surface after running propagation simulations




Decays

$$\tau^- \to \nu_\tau + \mu^- + \bar{\nu}_\mu \quad 17.4\%$$

$$\tau^- \to \nu_\tau + e^- + \bar{\nu}_e \quad 17.8\%$$

$$\tau^- \to \nu_\tau + \text{hadrons} \quad 64.8\%$$

$e$, $\mu$ and hadrons get absorbed or stopped before decaying into neutrinos.

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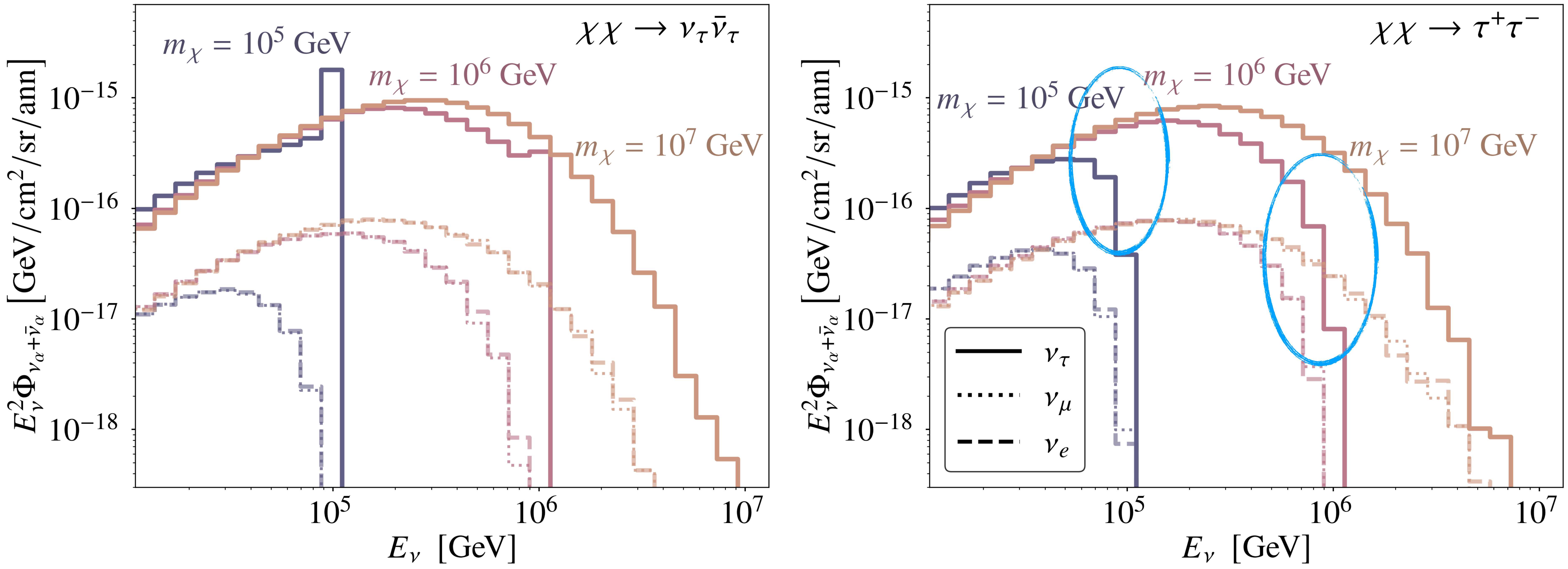
Safa et al. JCAP 2020

# Neutrino Spectra at the Surface

## neutrino fluxes at the Earth's surface after running propagation simulations




- $\tau$ photonuclear interactions with the nucleus near the Earth's center.
- At higher energies, $\nu_\tau \to \tau$ quickly.

Decays

$$\tau^- \to \nu_\tau + \mu^- + \bar{\nu}_\mu \quad 17.4\%$$
$$\tau^- \to \nu_\tau + e^- + \bar{\nu}_e \quad 17.8\%$$
$$\tau^- \to \nu_\tau + \text{hadrons} \quad 64.8\%$$

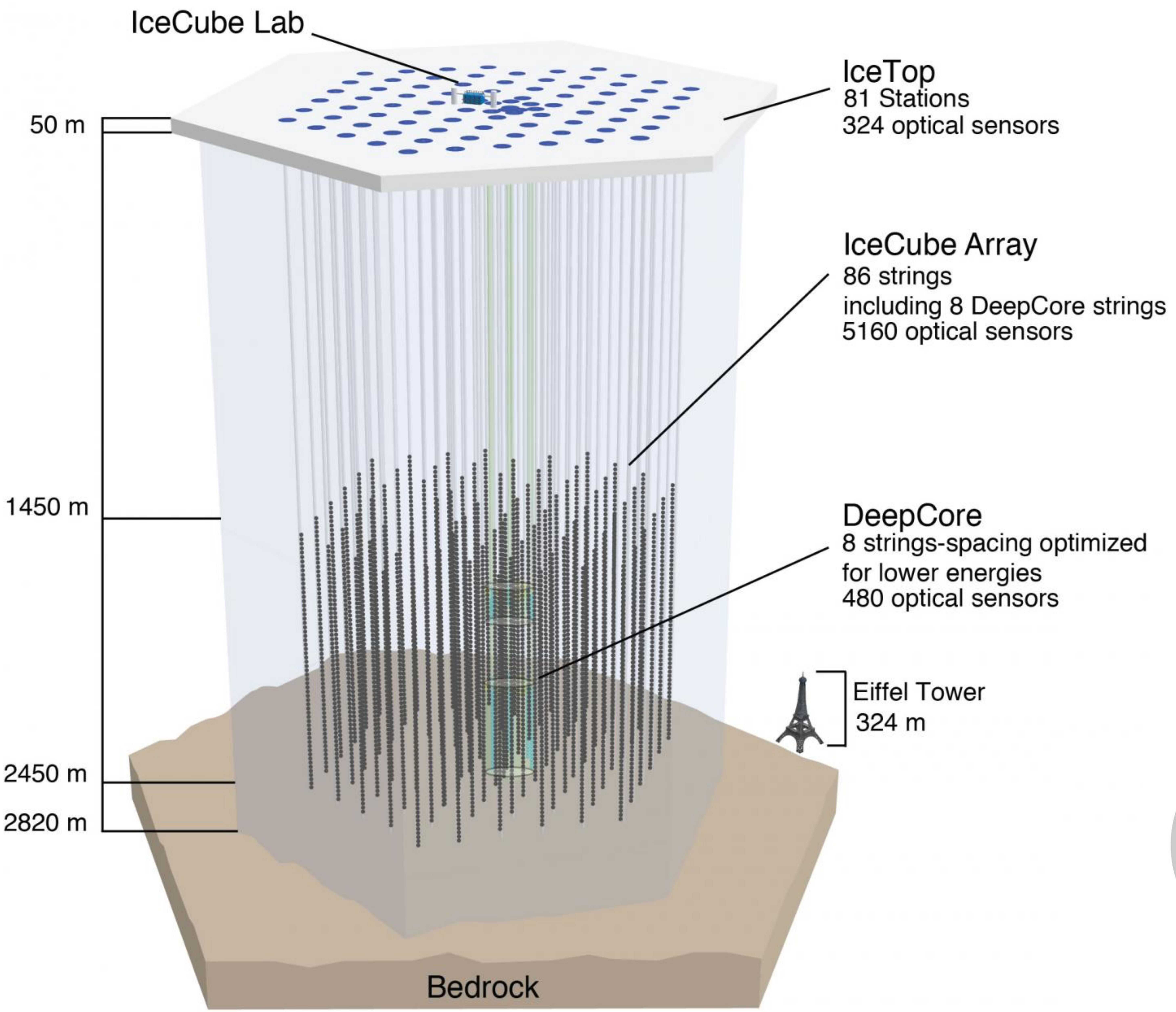
$e$, $\mu$ and hadrons get absorbed or stopped before decaying into neutrinos.

TAURUNNER

Safa et al. JCAP 2020

# Step 3: Neutrino Detection in a Neutrino Telescope

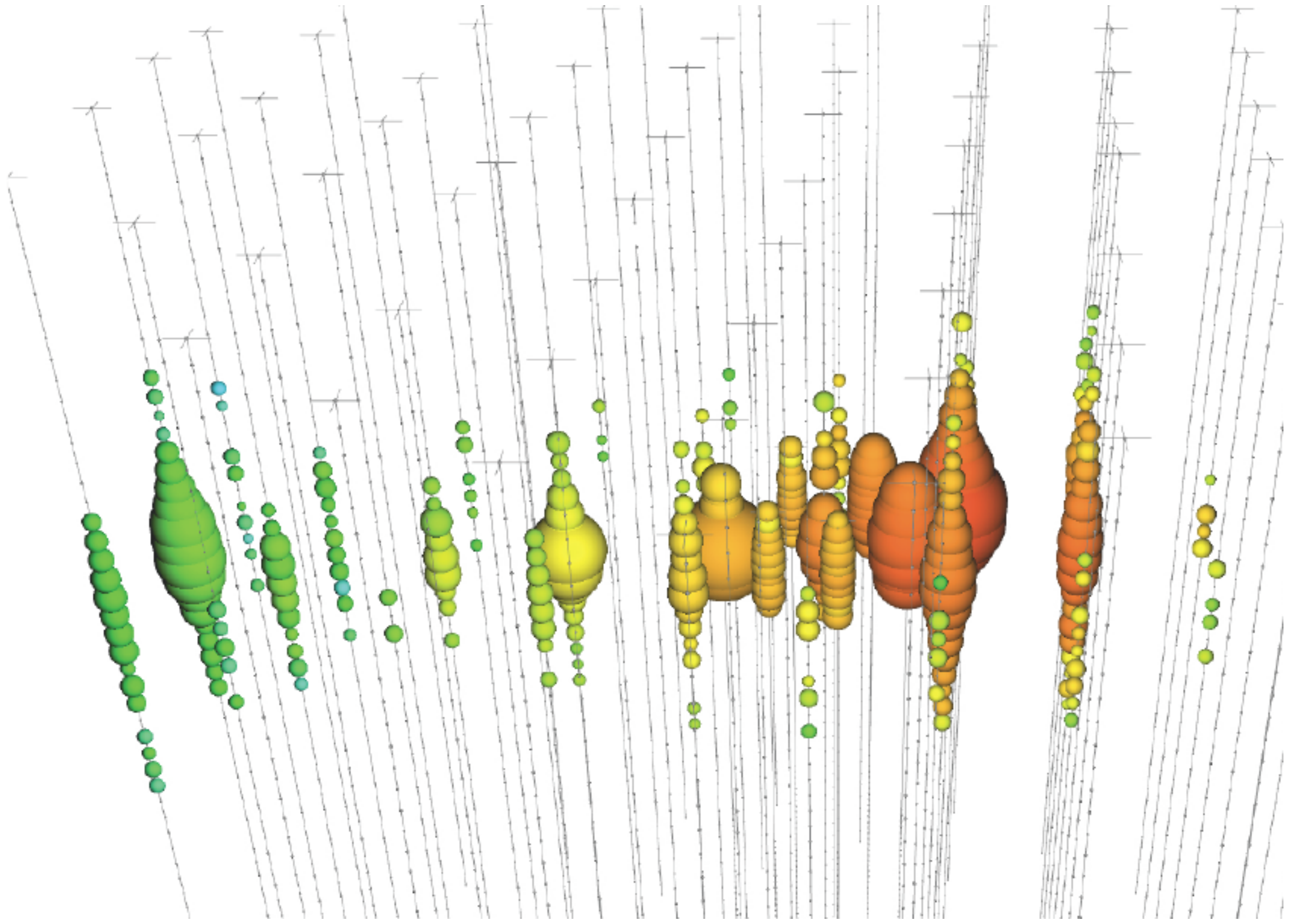
- $1\ \mathrm{km}^3$ Cherenkov detector at the geographic South Pole
- Largest neutrino telescope
- detecting neutrinos from all-sky
- $E_\nu$ : $5\ \mathrm{GeV} \sim 10\ \mathrm{PeV}$




ICECUBE

# Neutrino Events in a Neutrino Telescope

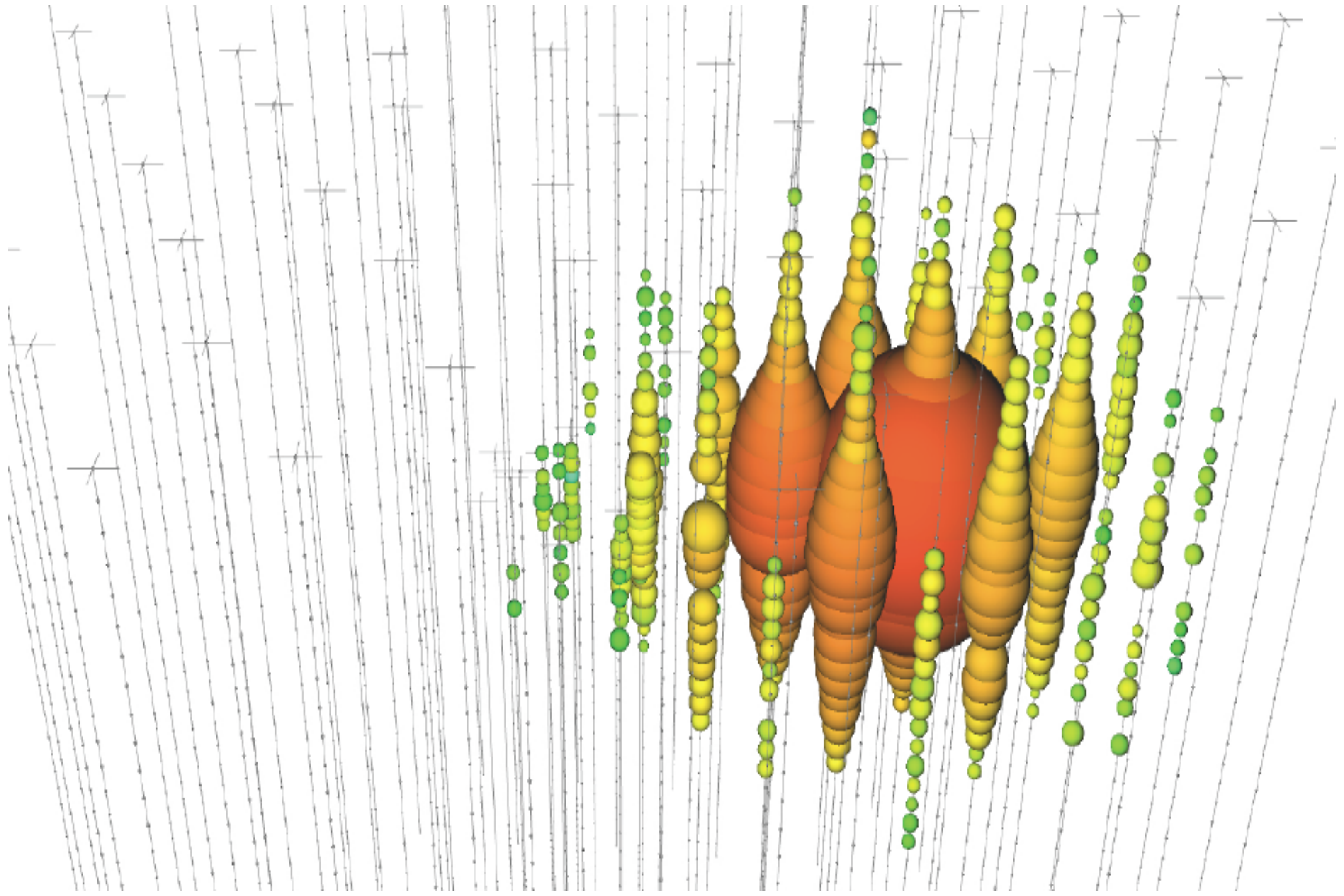
**Charged Current $\nu_\mu$**



$$\nu_\mu + N \rightarrow \mu + X$$

**Track (data)**

**Neutral Current $\nu$ / Charged Current $\nu_e$**

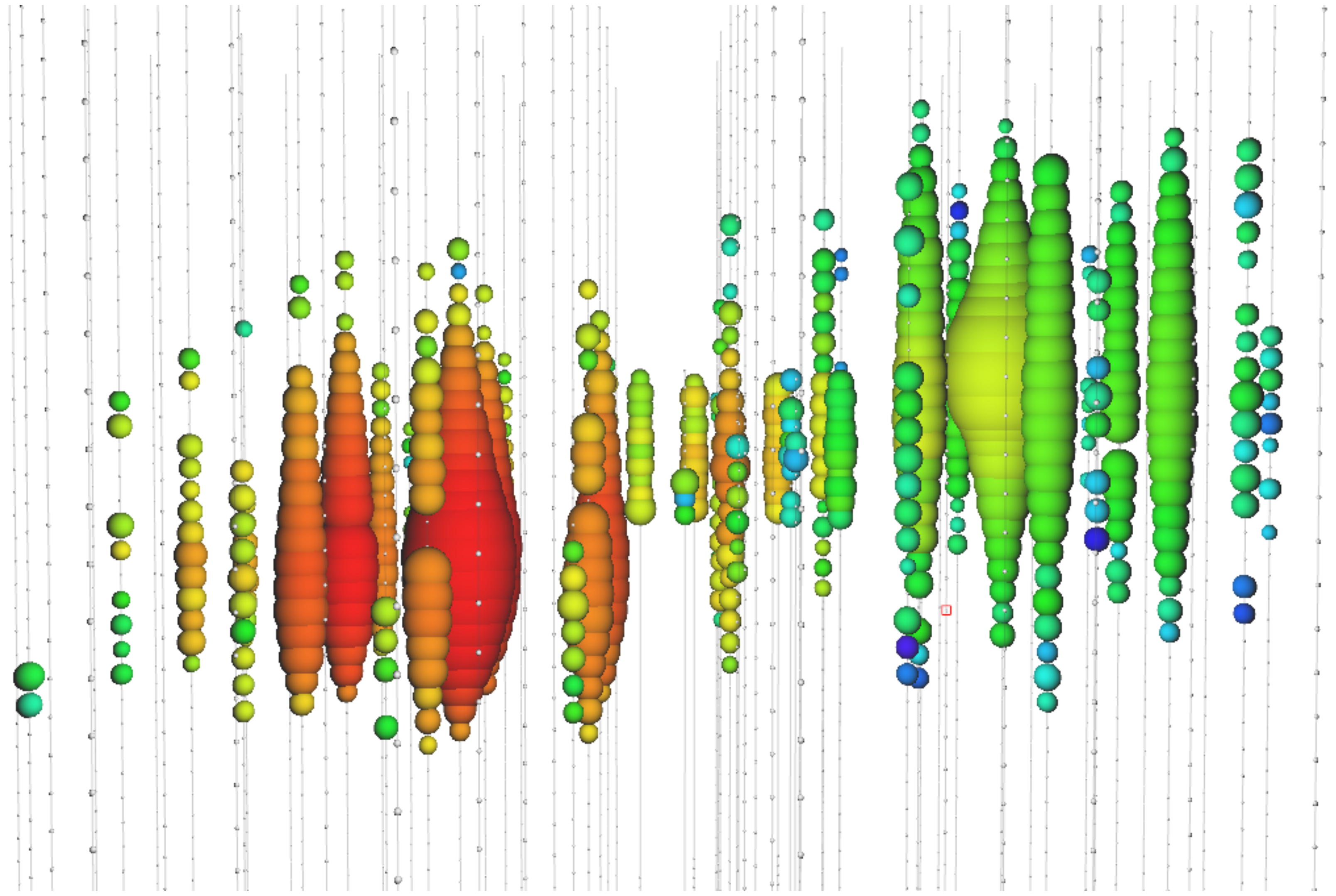


$$\nu_e + N \rightarrow e + X$$

$$\nu_x + N \rightarrow \nu_x + N$$

**Cascade (data)**

**Charged Current $\nu_\tau$**



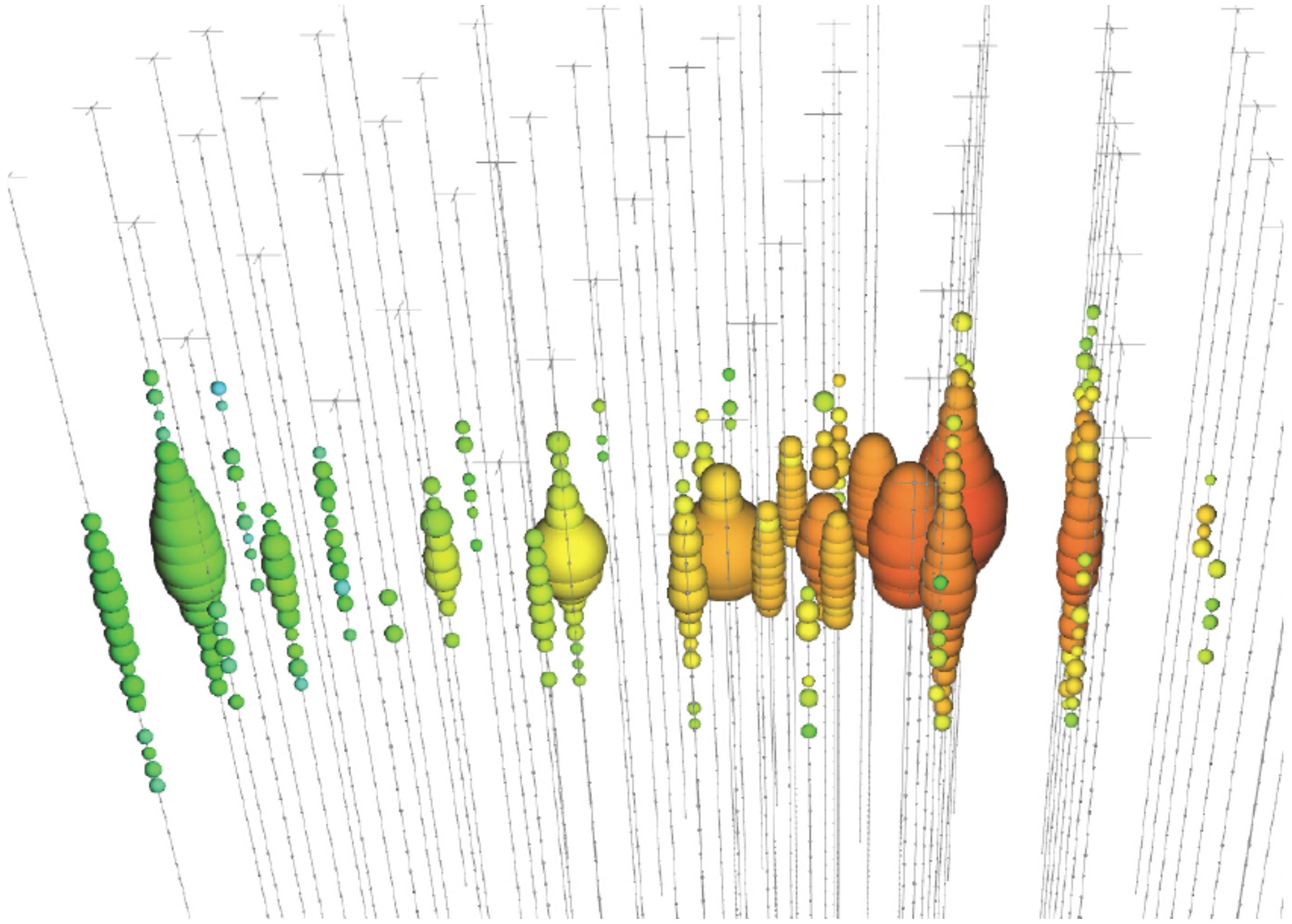
$$\nu_\tau + N \rightarrow \tau + X$$

$$E \gtrsim 1\,\mathrm{PeV}$$

**Double-Cascade (simulation)**

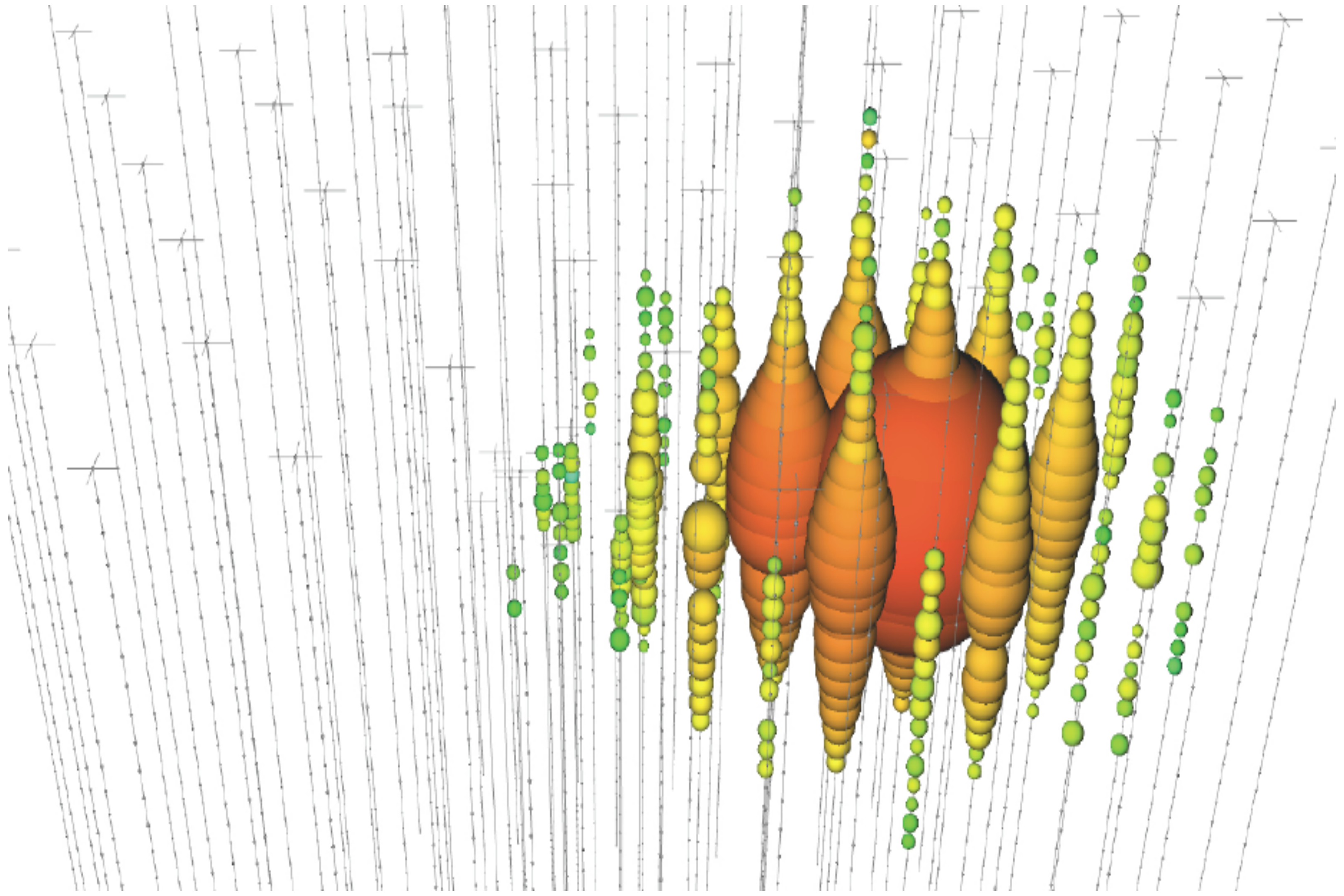
# Neutrino Events in a Neutrino Telescope

| Charged Current $\nu_\mu$ | Neutral Current $\nu$ / Charged Current $\nu_e$ | Charged Current $\nu_\tau$ |
|---|---|---|



$$\nu_\mu + N \to \mu + X$$

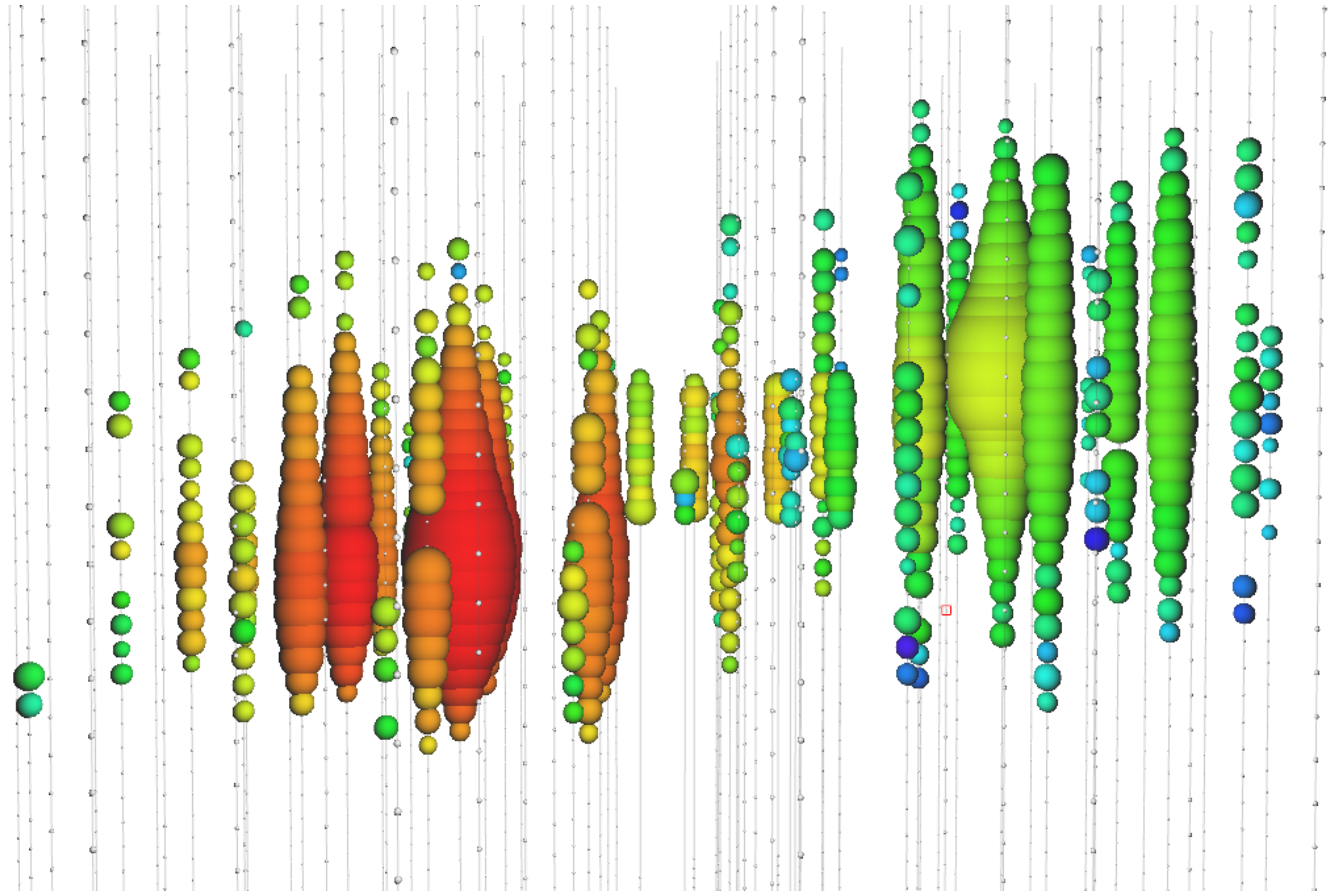
**Track (data)**



$$\nu_e + N \to e + X$$

$$\nu_x + N \to \nu_x + N$$

**Cascade (data)**



$$\nu_\tau + N \to \tau + X$$

$$E \gtrsim 1\,\mathrm{PeV}$$

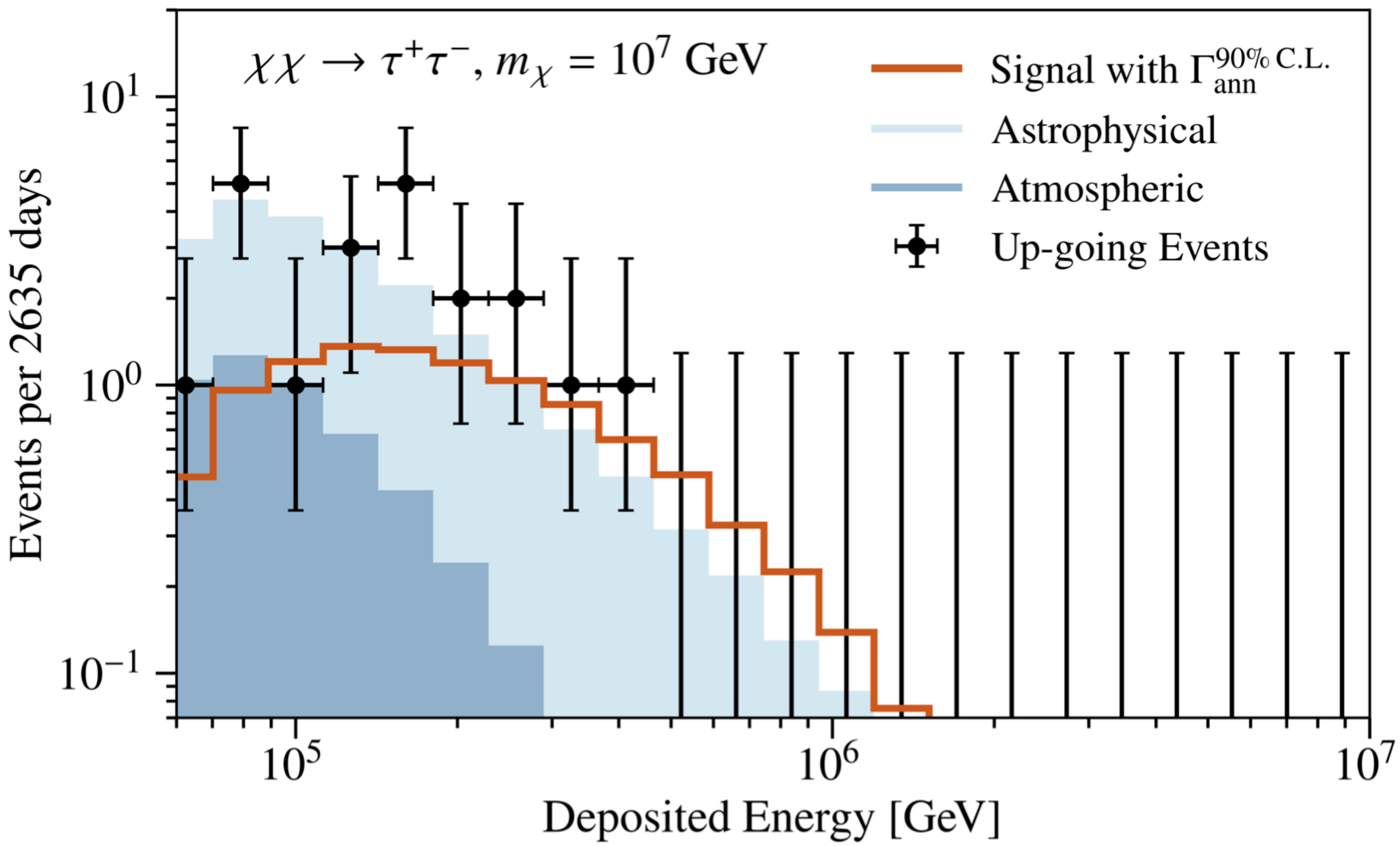
**Double-Cascade (simulation)**

- Double-cascades are difficult to identify. Charged-current events for $\nu_\tau$ below PeV are reconstructed as cascades.
- Tracks are usually well-identified. We do not expect a significant $\nu_\mu$ signal.

# Neutrino Events in IceCube

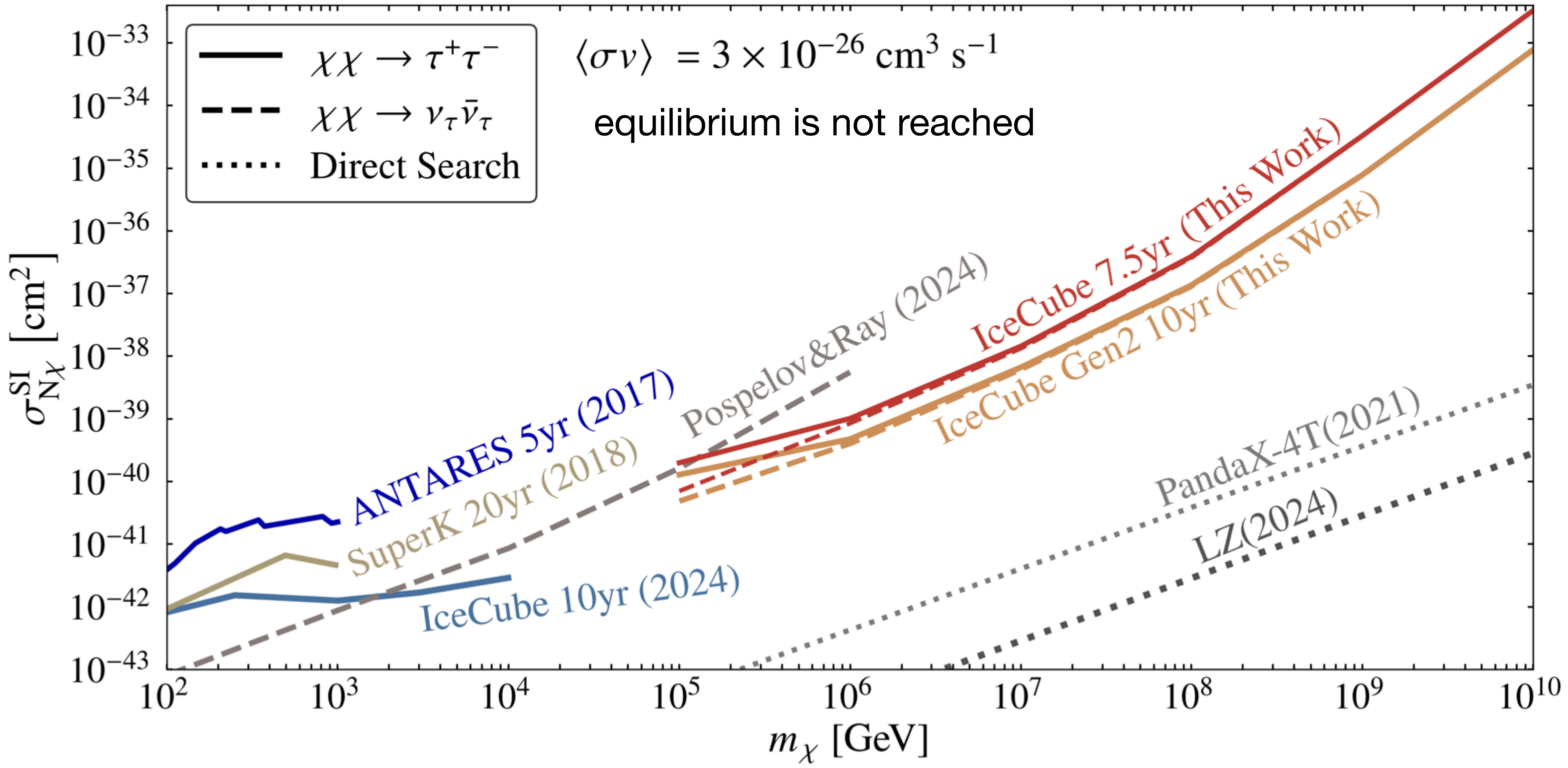
7.5yr IceCube high-energy starting events (all sky, all flavor, $E_{\text{deposit}} > 60\,\text{TeV}$)

cascades + double cascades



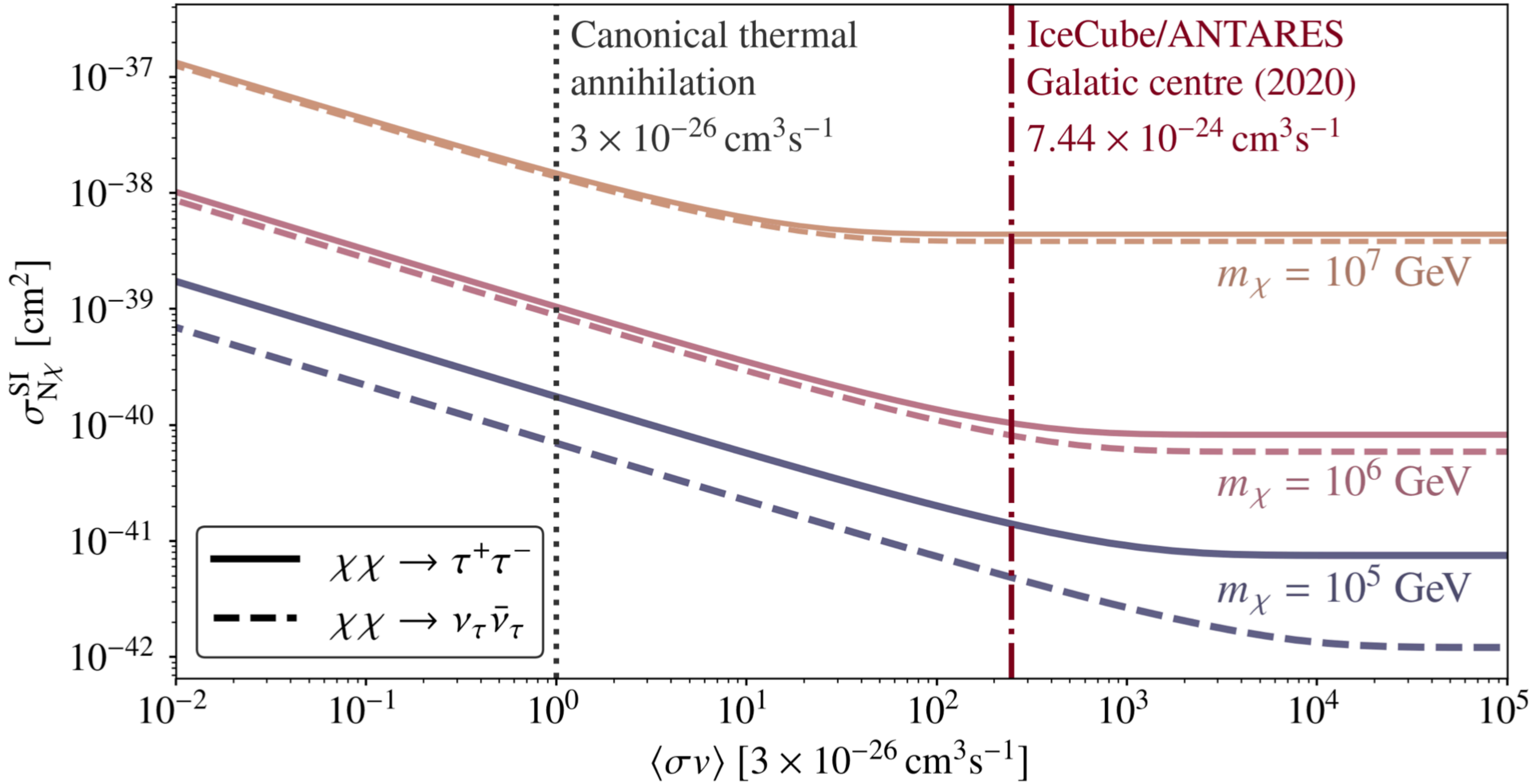

Compared to using all morphologies or double cascades only, it provides the best sensitivity.

# Constraints




The sensitivity of a neutrino telescope towards celestial body-bounded DM can be extended to heavier dark matter, expanding the potential of neutrino telescopes.

# Constraints vs Annihilation Cross Section




larger $<\sigma v>$ ⟶ equilibrium can be reached

# Summary

- Indirect search by detecting cosmic messengers produced by the annihilation/decay of dark matter has been a major focus for dark matter searches. Neutrino telescopes have great potential to explore dark matter models and dark matter in multiple astrophysical sources.

- The tau regeneration effect makes it possible to expand the detectable signal from heavier dark matter captured in celestial bodies.

- Using IceCube data, we set upper limits on the spin-independent dark matter-nucleon scattering cross section for heavy dark matter in Earth with PeV-EeV masses.

- The work can be extended to other celestial bodies as well as to test specific dark matter models.

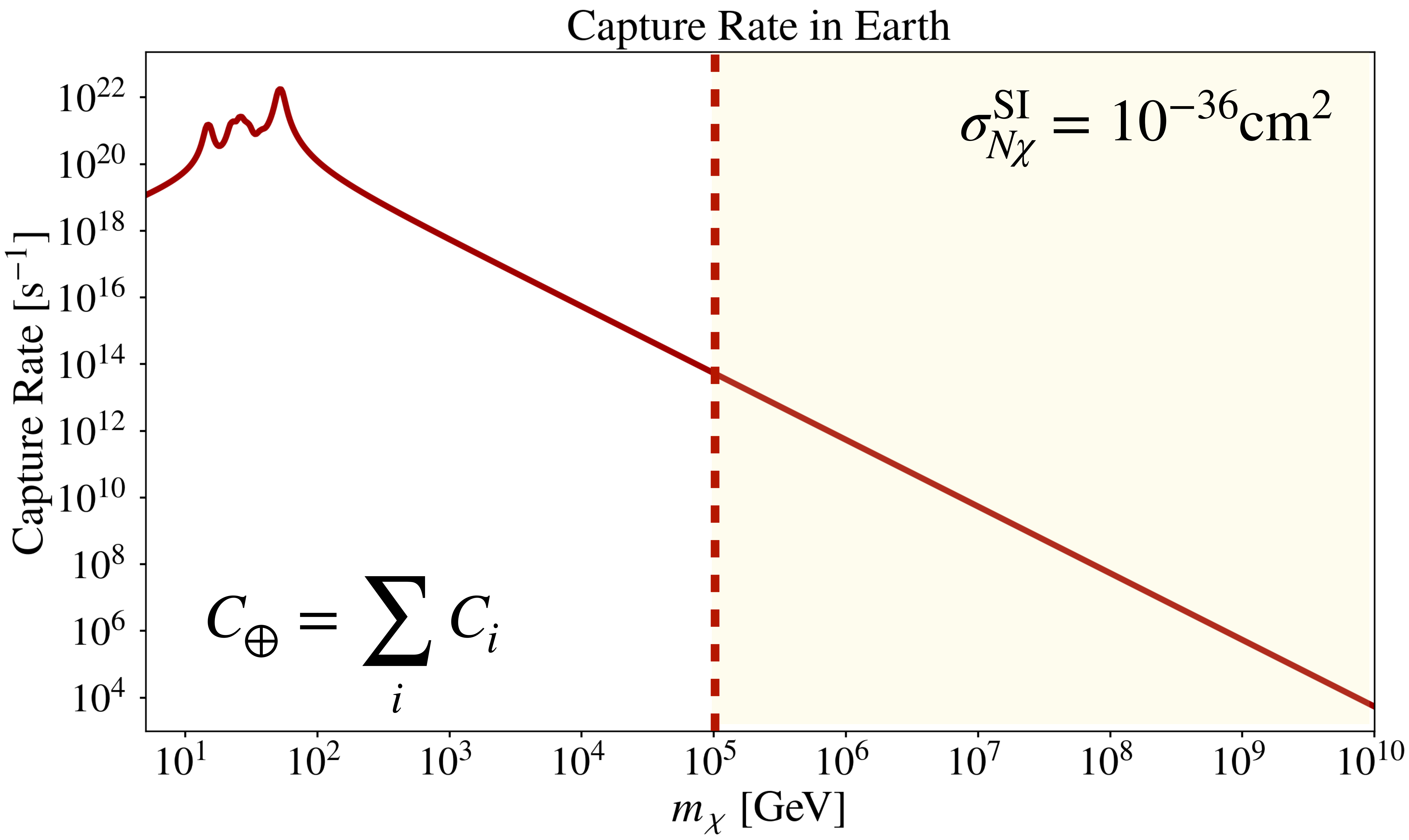
- Upcoming next-generation neutrino telescopes are expected to improve sensitivities for dark matter studies.

Thank you!

# Bonus Slides

# Dark Matter Capture by Earth

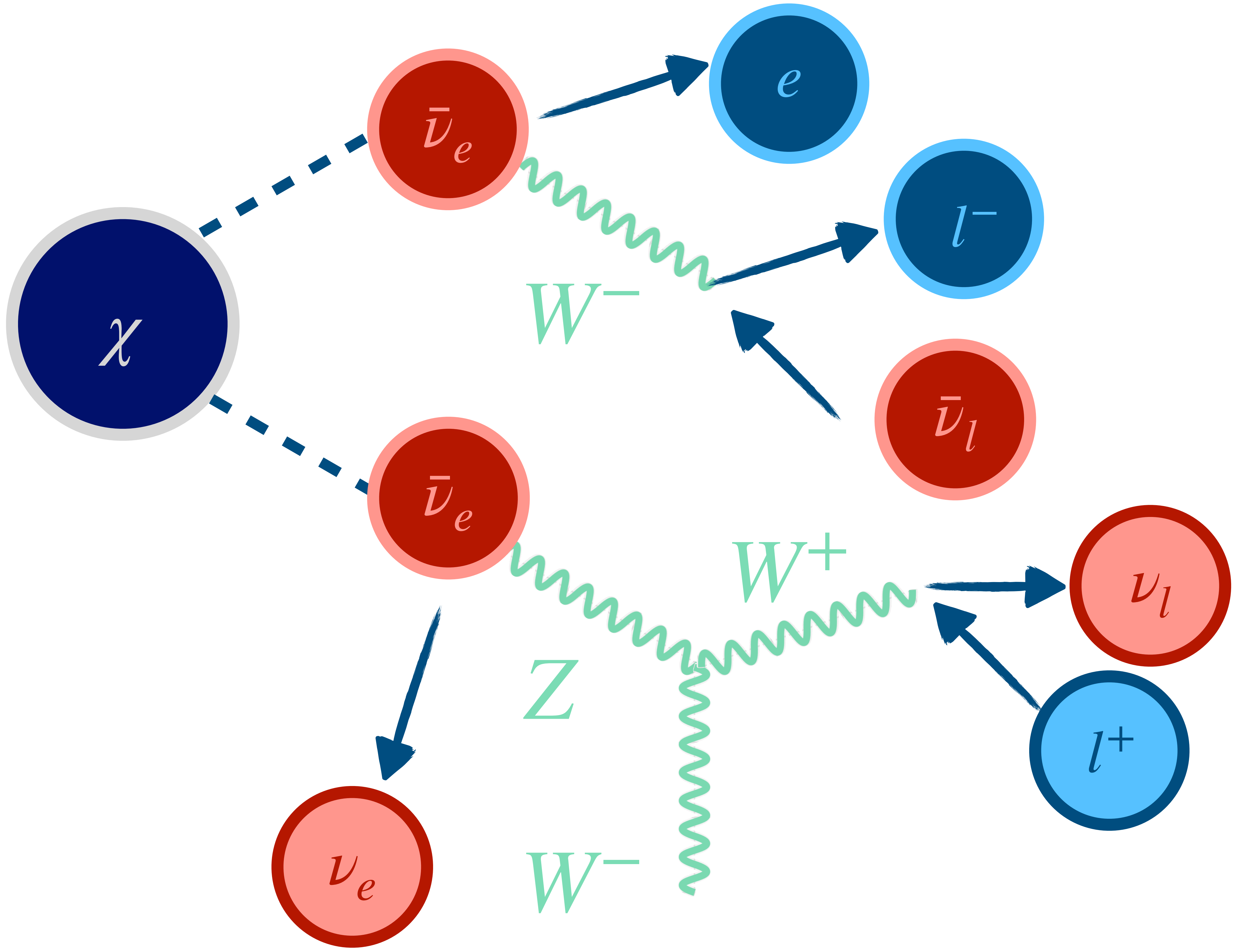
Very heavy DM $m_\chi$ > 100 TeV



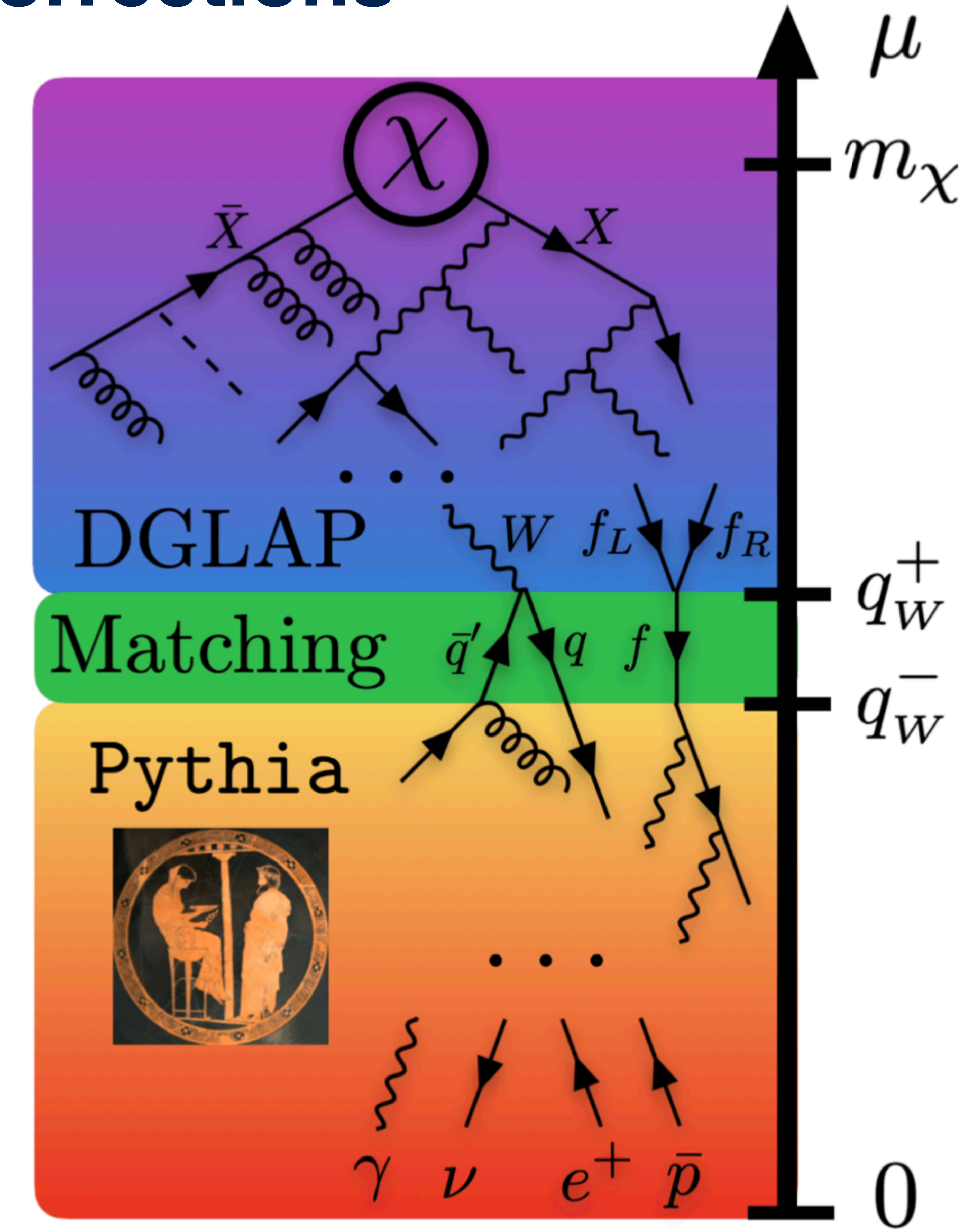

Capture is well below the geometric capture limit

single scatter regime [Gould 1987]

# Spectrum Generation with Electroweak Corrections

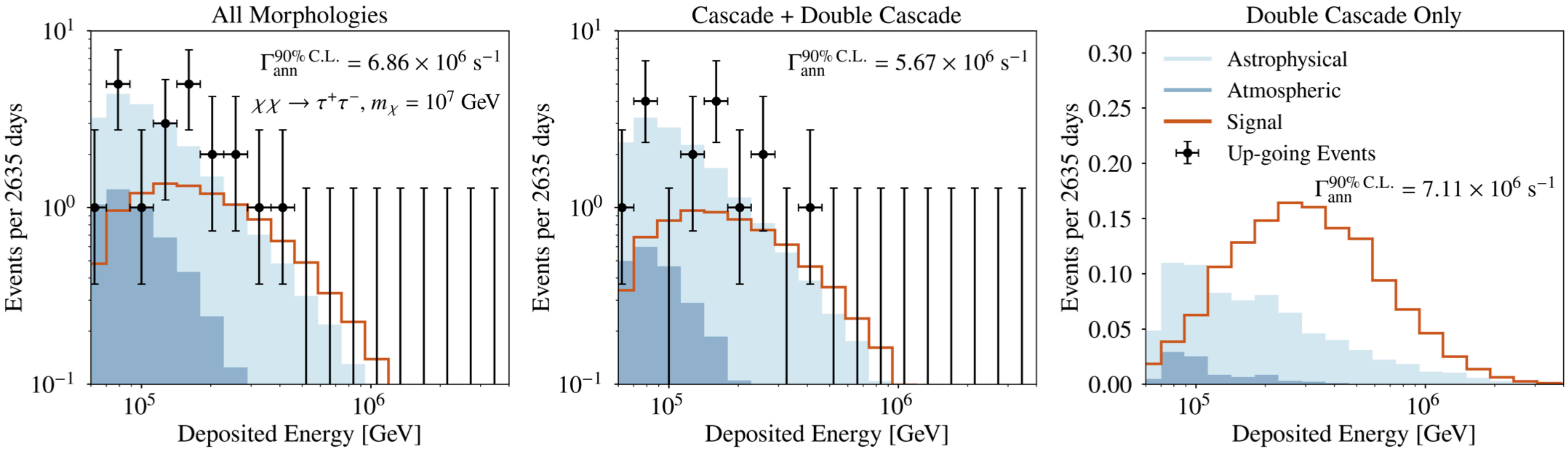



$\bar{\nu}$ flux is not 0 even $\bar{\nu}$ is not produced initially

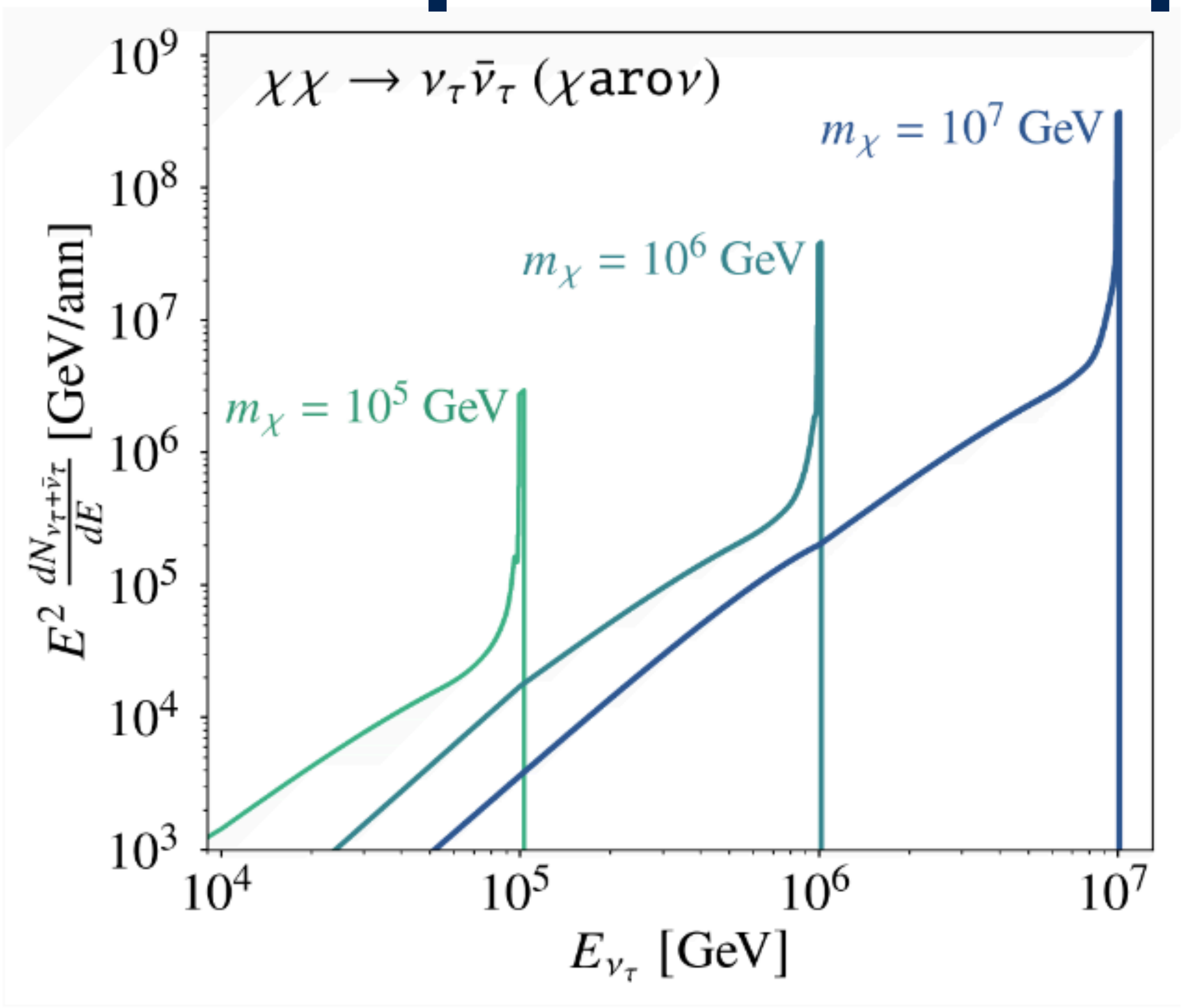


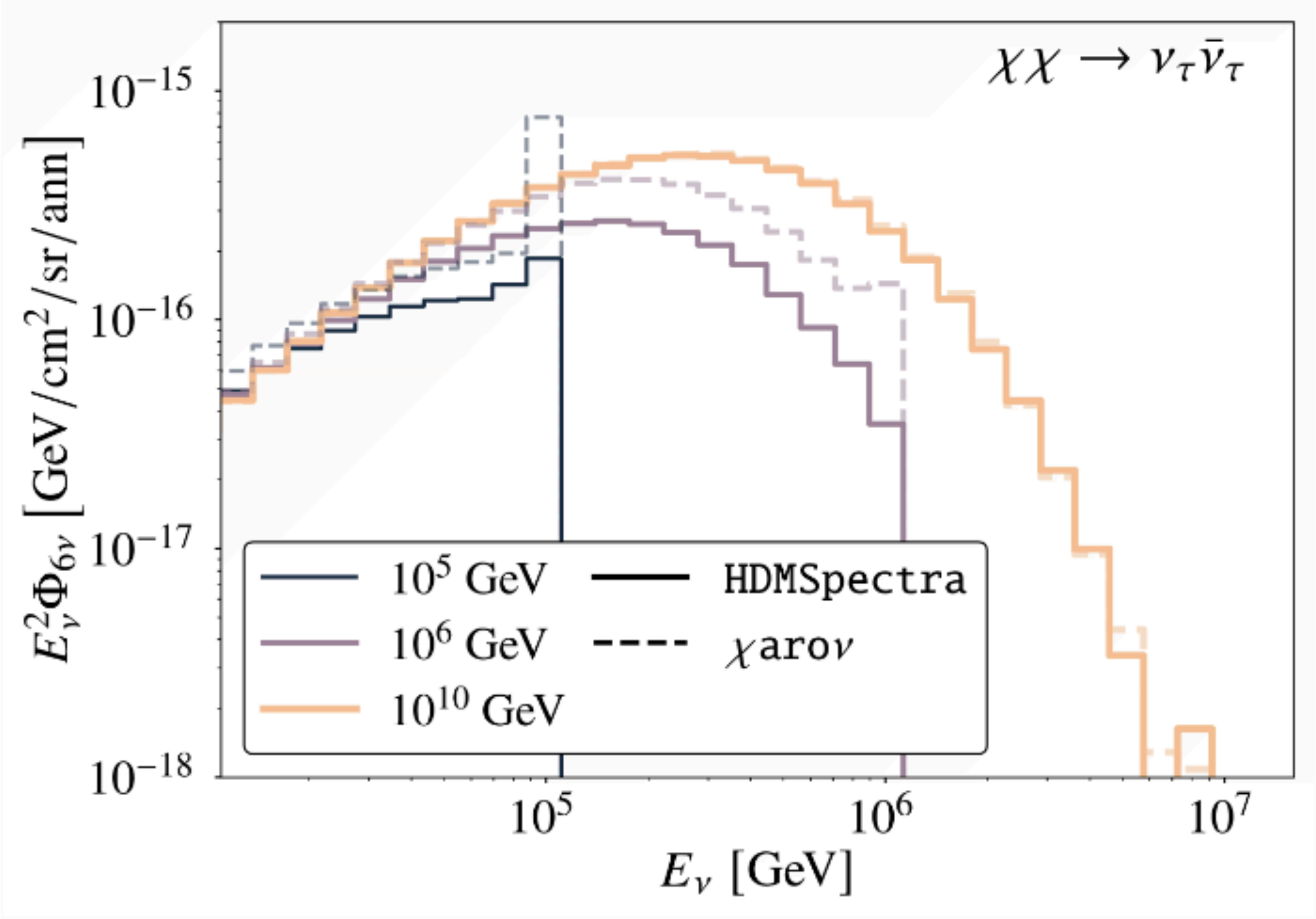

Bauer, Rodd, Webber JHEP 06 (2021) 121

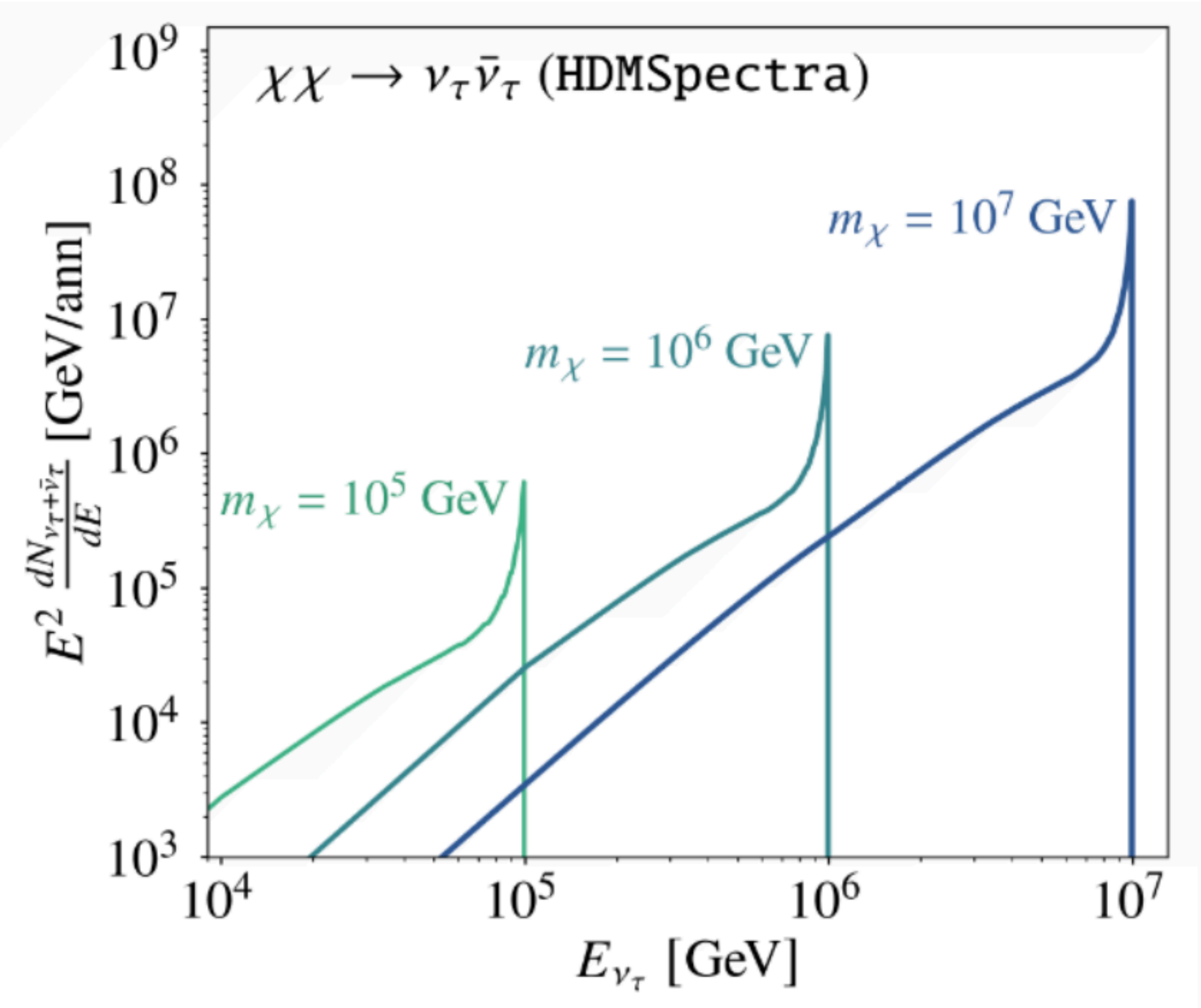
# Event Numbers of Different Morphologies

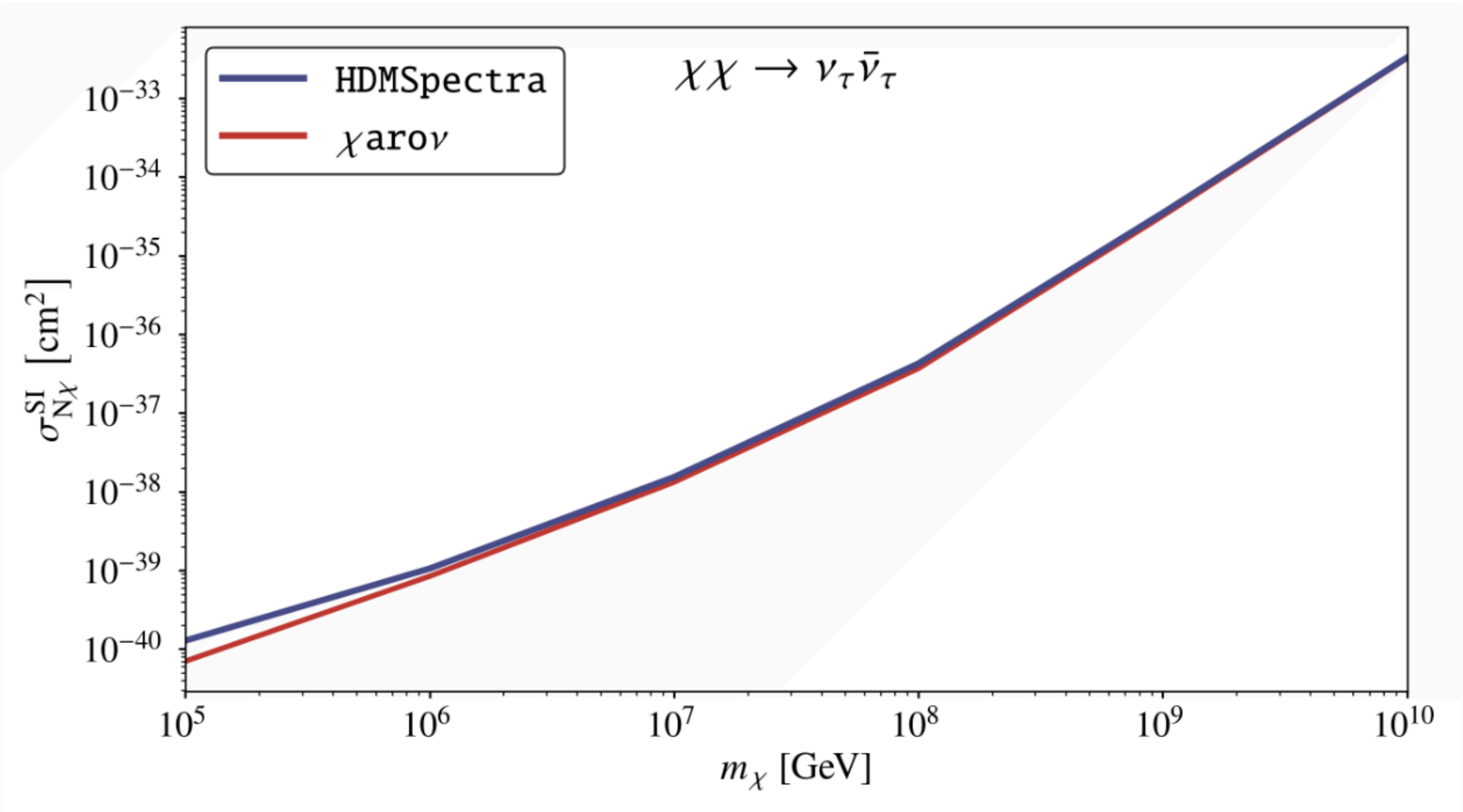


# Neutrino Spectra Comparison



# DM Annihilation

$$\frac{dN(t)}{dt} = C_{\oplus} - AN(t)^2$$

evaporation is negligible

$$A \propto < \sigma v >$$

Annihilation rate

$$\Gamma_{\text{ann}} = \frac{1}{2}AN(t)^2 = \frac{C}{2}\tanh^2(\frac{t}{\sqrt{CA}})$$

Equilibrium is not reached inside Earth.