

Constraining Super-Heavy Dark Matter with High-Energy Multi-Messenger Astronomy

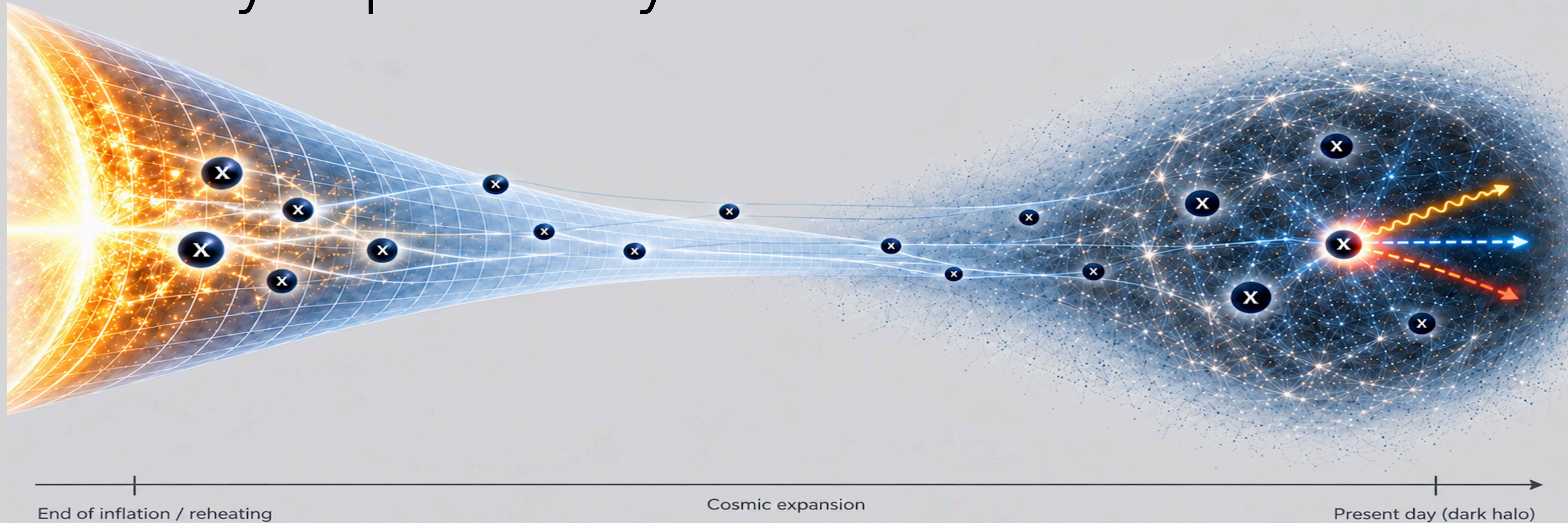
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Based on ArXiv: [2508.08779](#) [astro-ph.HE], *Phys.Rev.D* 113 (2026) 4, 043024

GDR DUPhy meeting, Paris, 19-21 October 2026



Why Super Heavy Dark Matter Candidates?



Theoretical Motivation

SHDM can be produced out of equilibrium during inflation or reheating

Experimental Motivation

No conclusive WIMP signal so far

Testing physics at energies inaccessible on Earth with multi messenger astronomy

Phenomenological Opportunity

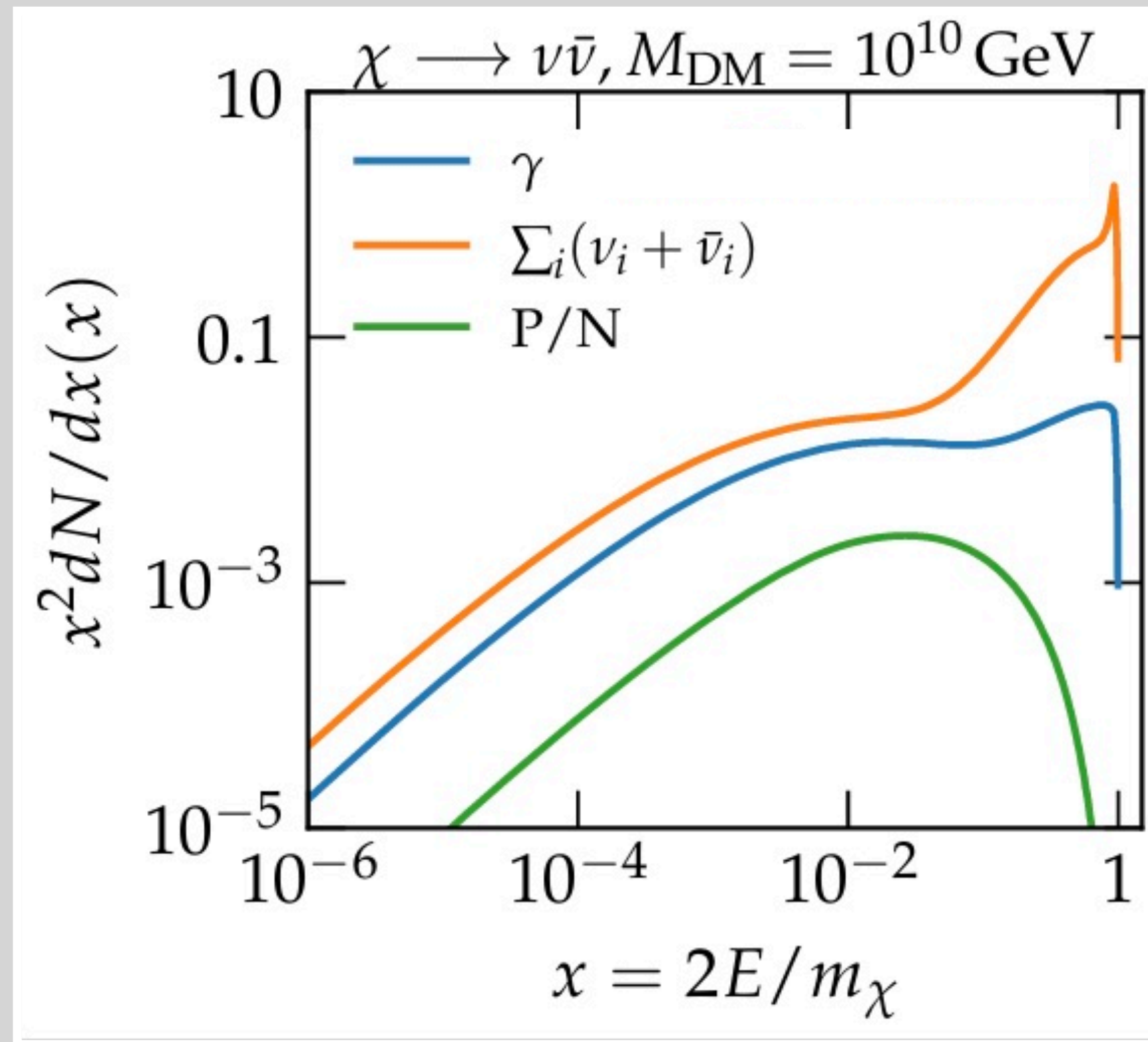
Metastable particles

$$\tau_U \ll \tau_X < +\infty$$

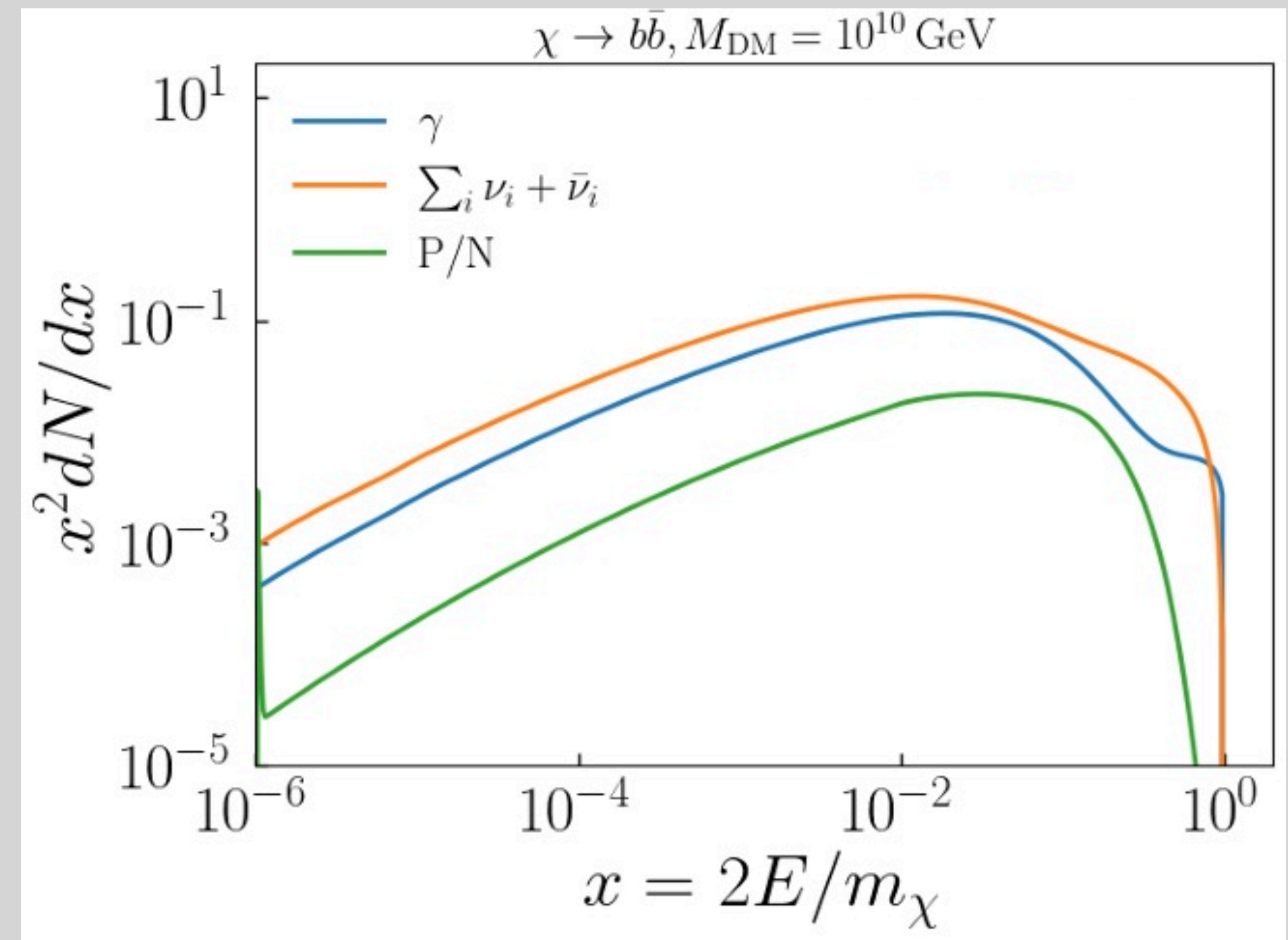
Rare decays might produce observable particles

Properties of the Super Heavy Relic Decays

$$X \longrightarrow \text{SM particle/antiparticle} \longrightarrow \text{P, N, } \nu, \gamma$$



◆ γ -ray signature suppressed

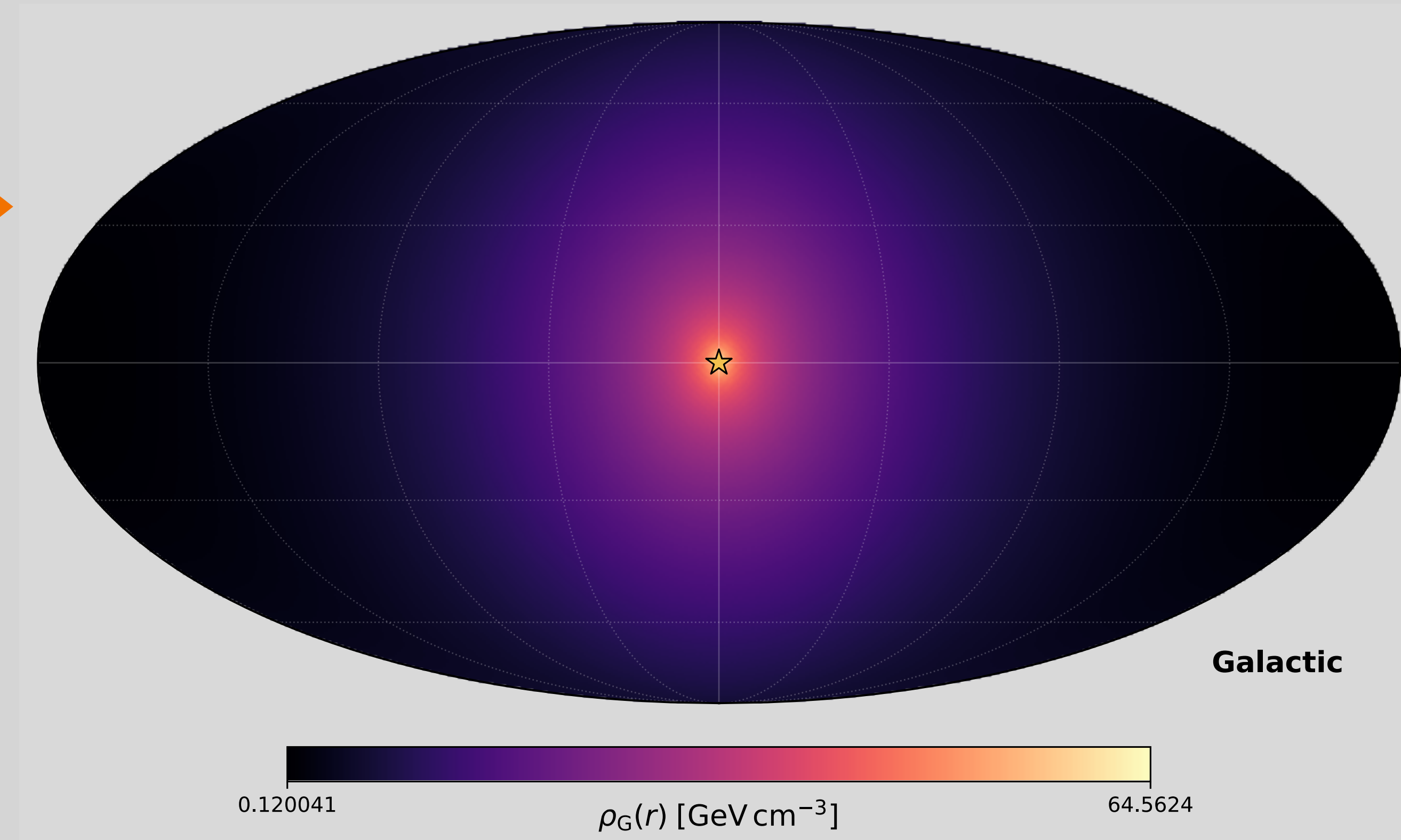
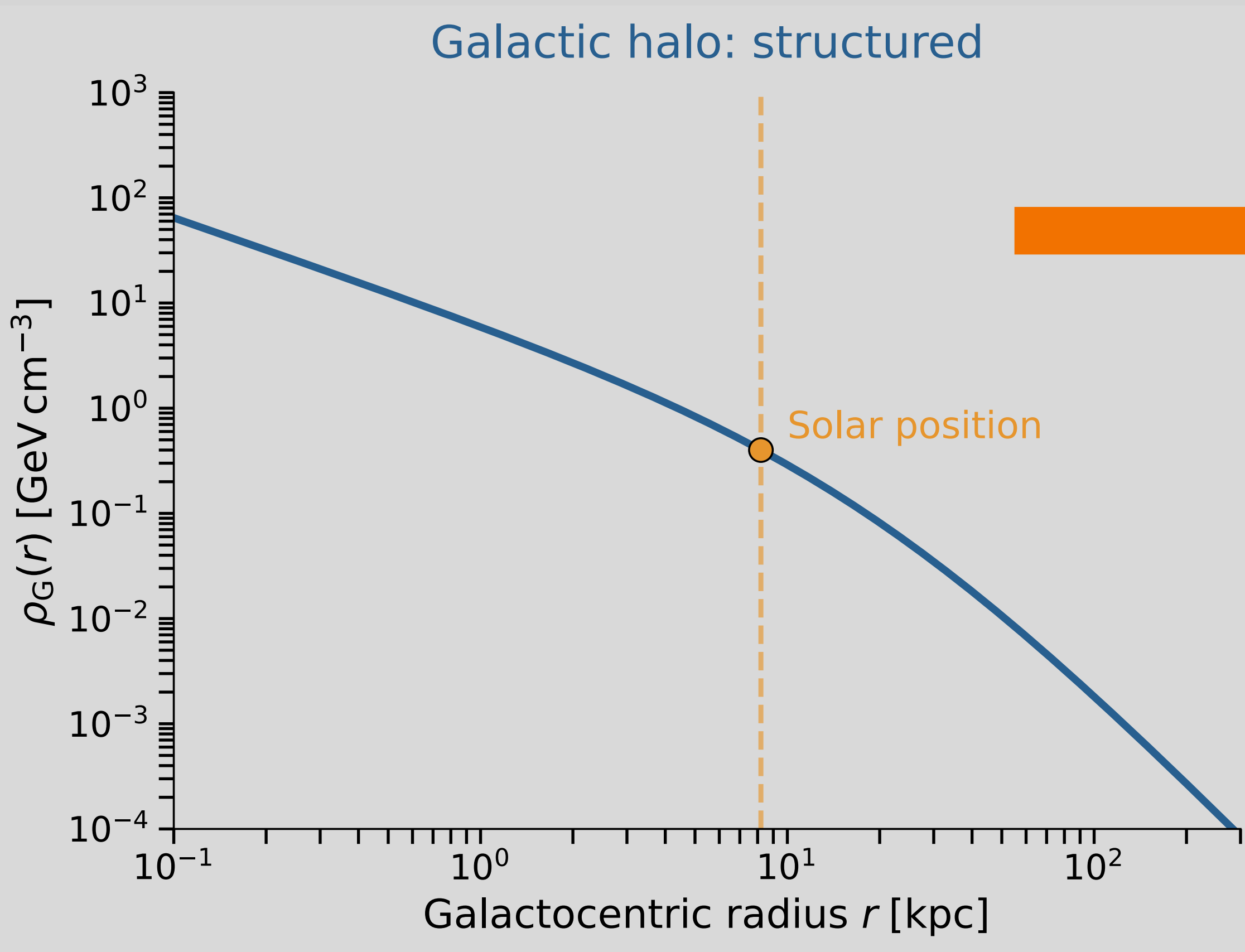


◆ γ -ray enhanced due to hadronization

Fluxes obtained with the public **HDMspectra** code (<https://arxiv.org/abs/2007.15001>)

Distribution of DM in the Universe

DM distribution peaks at the Galactic centre (*Astrophys.J.* 462 (1996) 563-575)

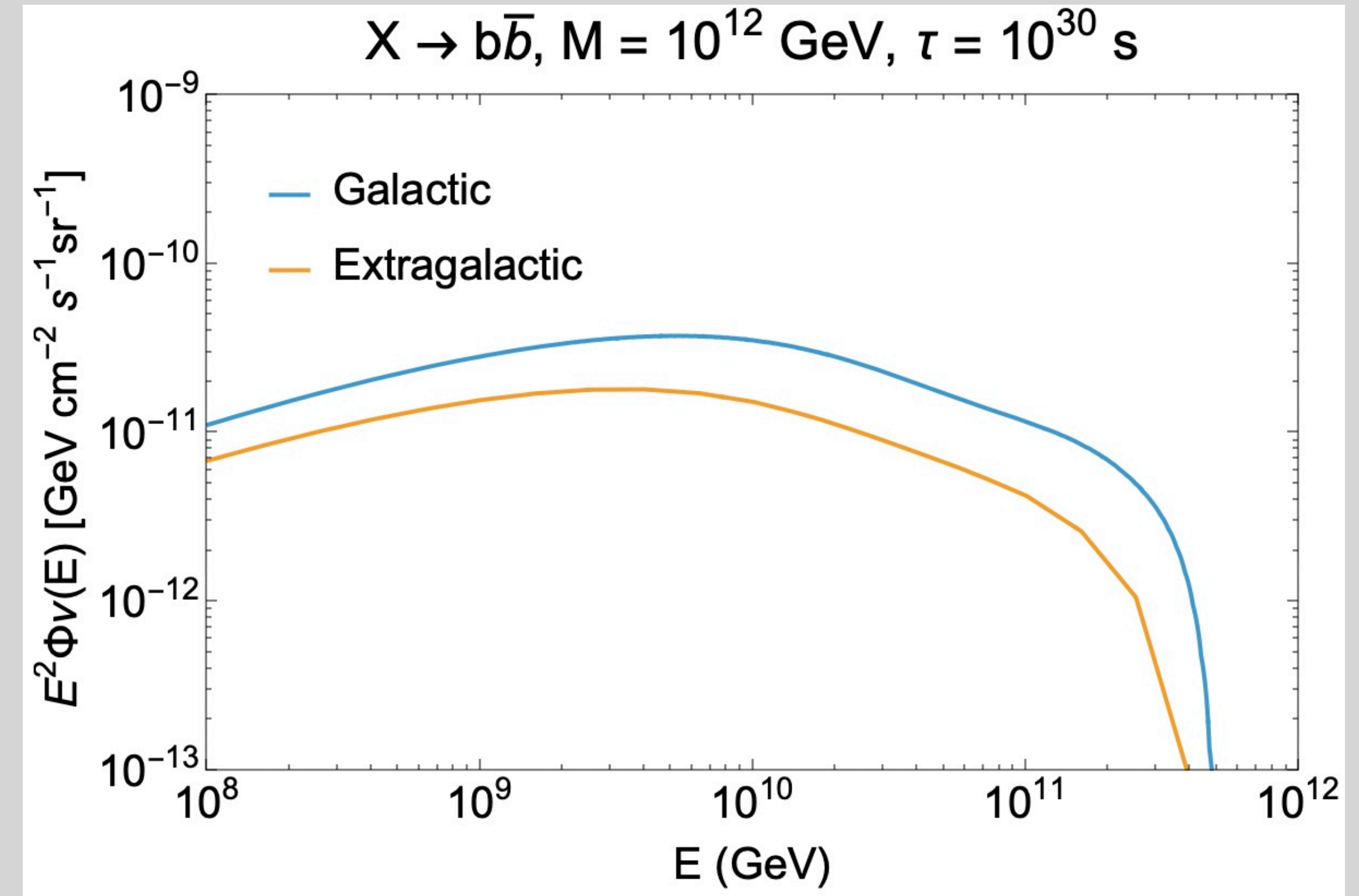
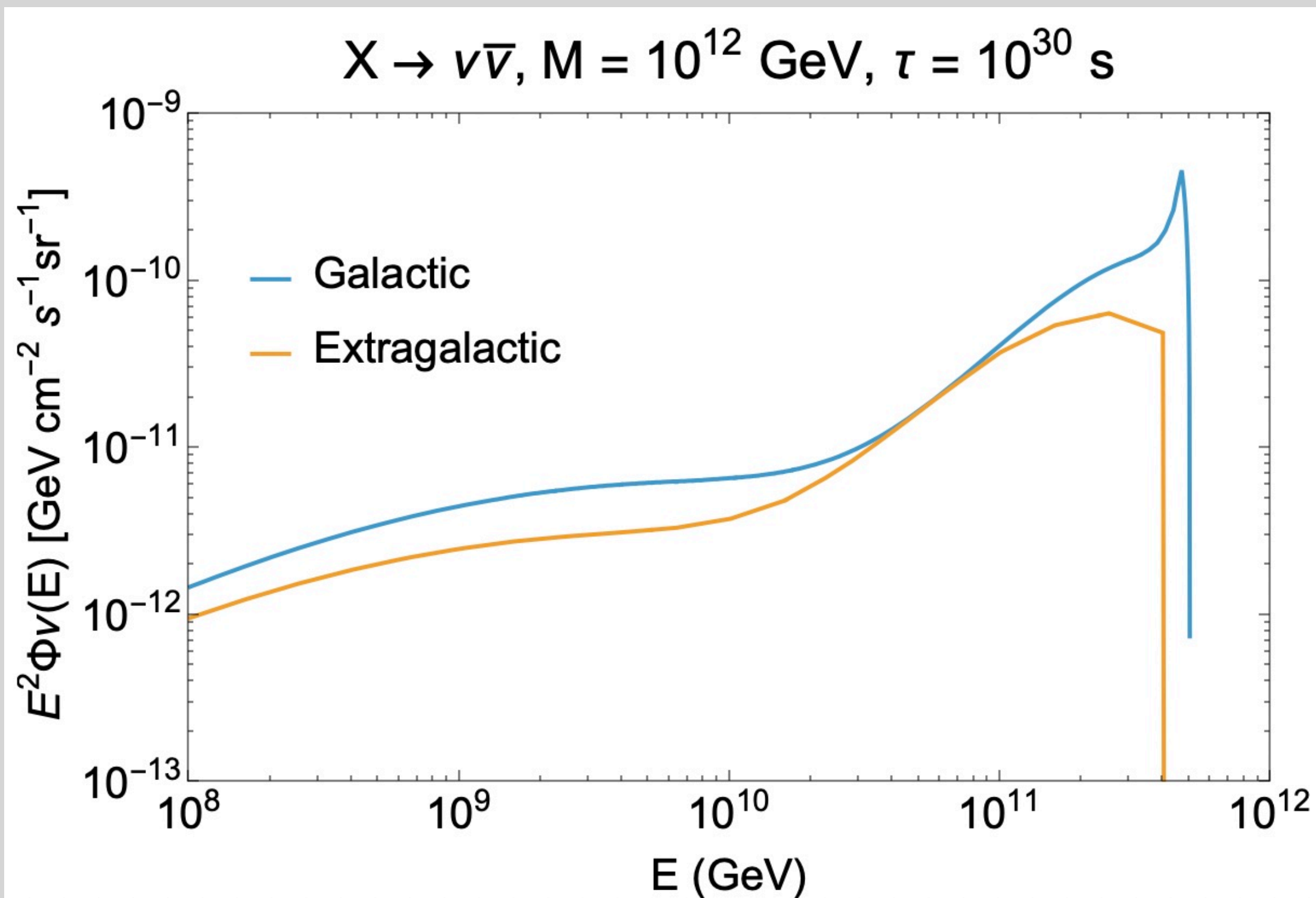


SHDM Signatures: Galactic vs Extragalactic Fluxes

$$\frac{d\phi_{G,i}}{dE d\Omega} \left(E, M_\chi, \tau_\chi \right) = \frac{1}{4\pi M_\chi \tau_\chi} \frac{dN_i}{dE}(E) \int ds \rho(s, l, b) e^{-s/\lambda_i(l,b)}$$

$$\frac{d^2\phi_{EG,i}}{dE d\Omega}(E) = \frac{\Omega_\chi \rho_{\text{cr}} c}{4\pi M_\chi \tau_\chi H_0} \int_0^{z_{\text{max}}} \frac{dz}{E(z)} \frac{dN_i}{dE}(E(1+z))$$

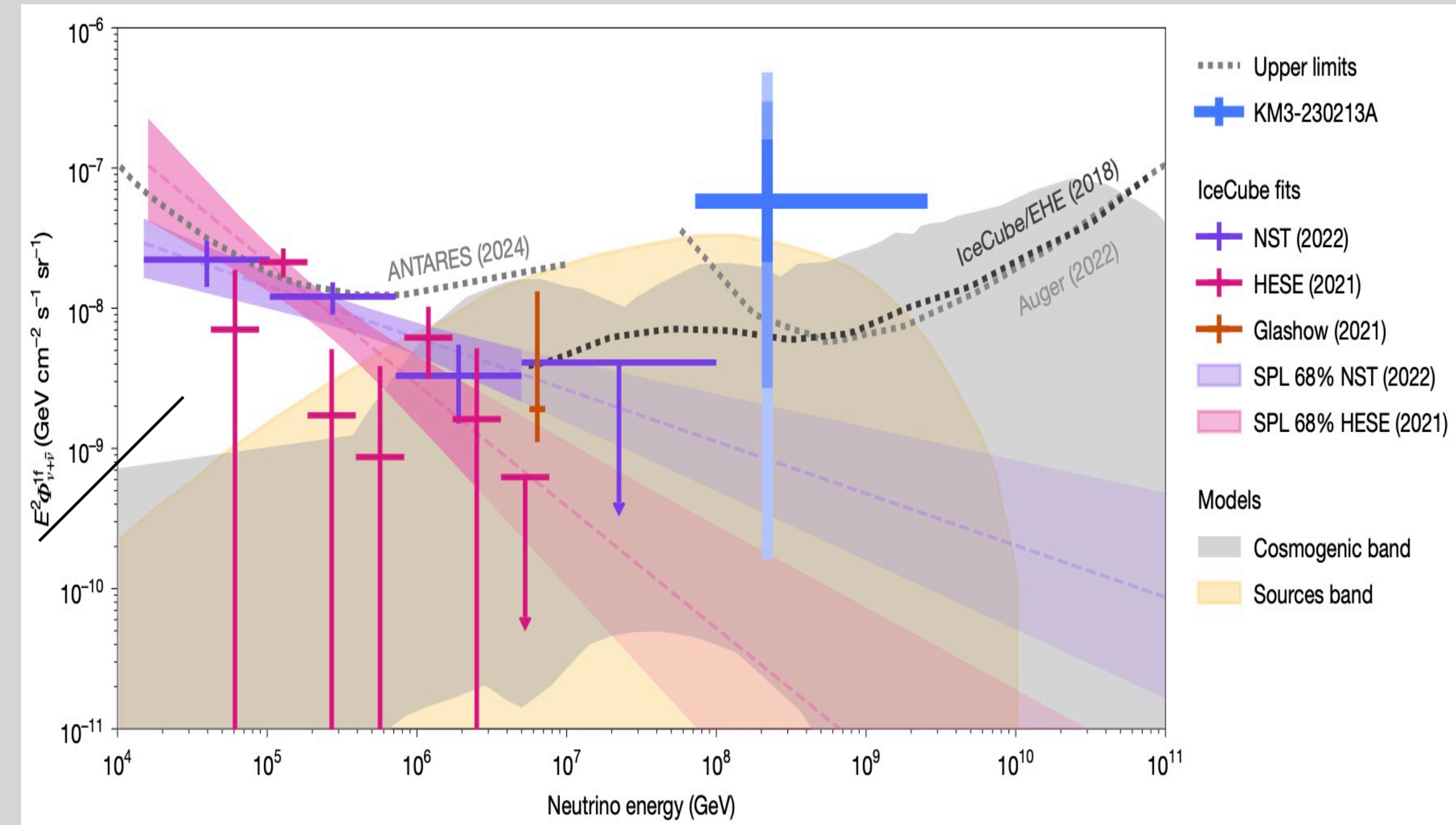
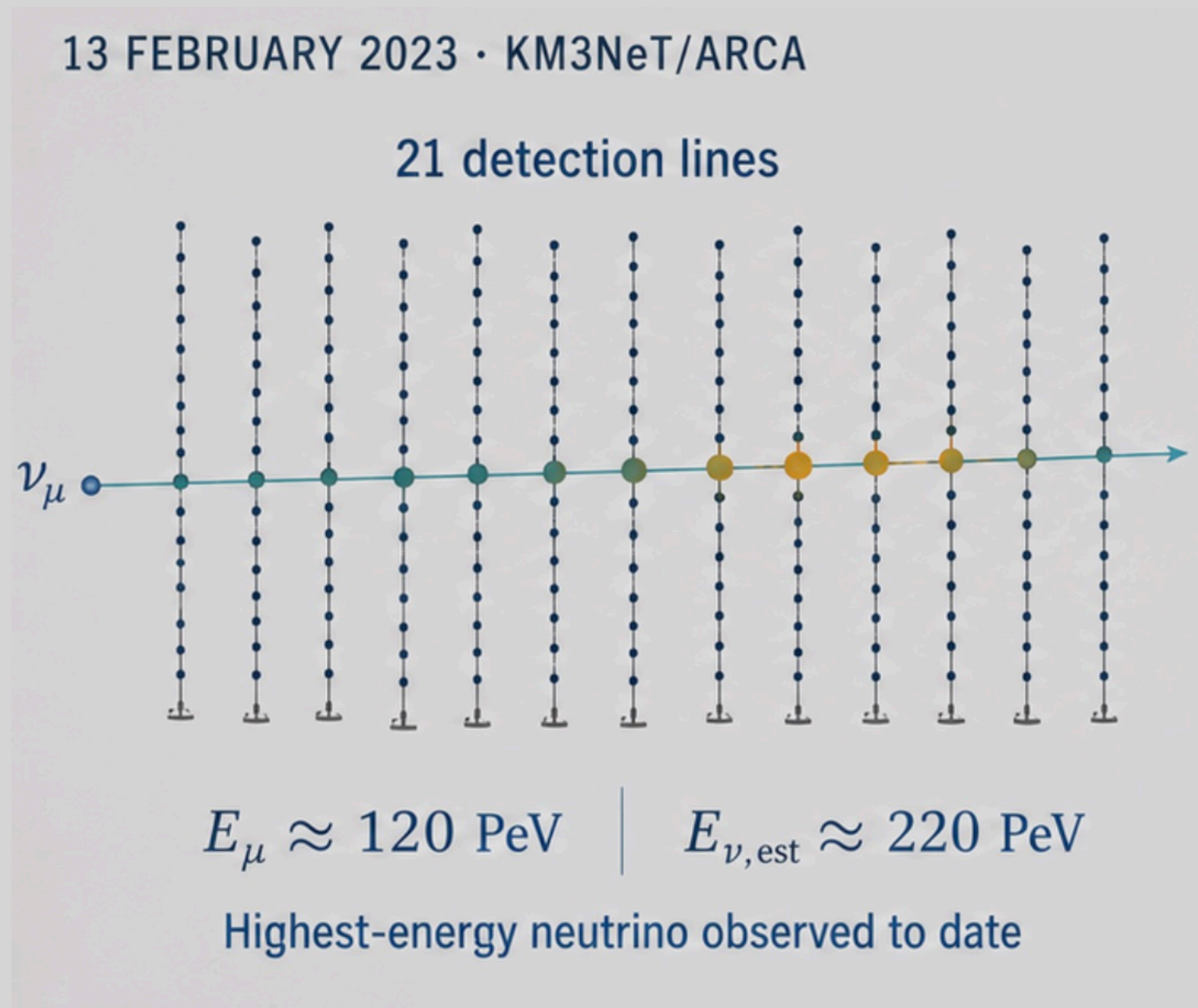
The Galactic flux is averaged over the entire sky



The dark matter lifetime (τ) is a key parameter to constrain

High-Energy Neutrino Astronomy as a Probe for New Physics

Nature 638 (2025) 8050, 376-382

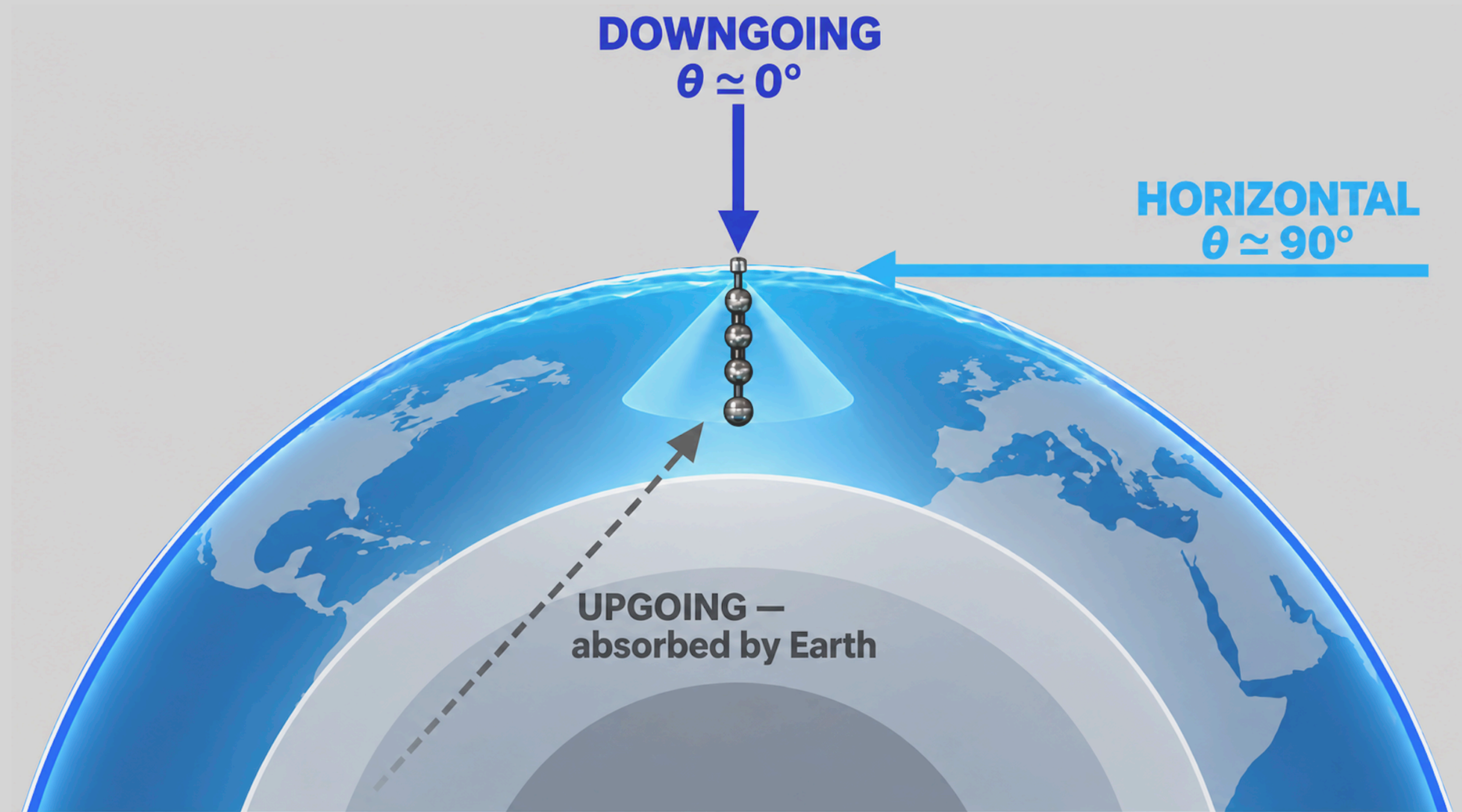
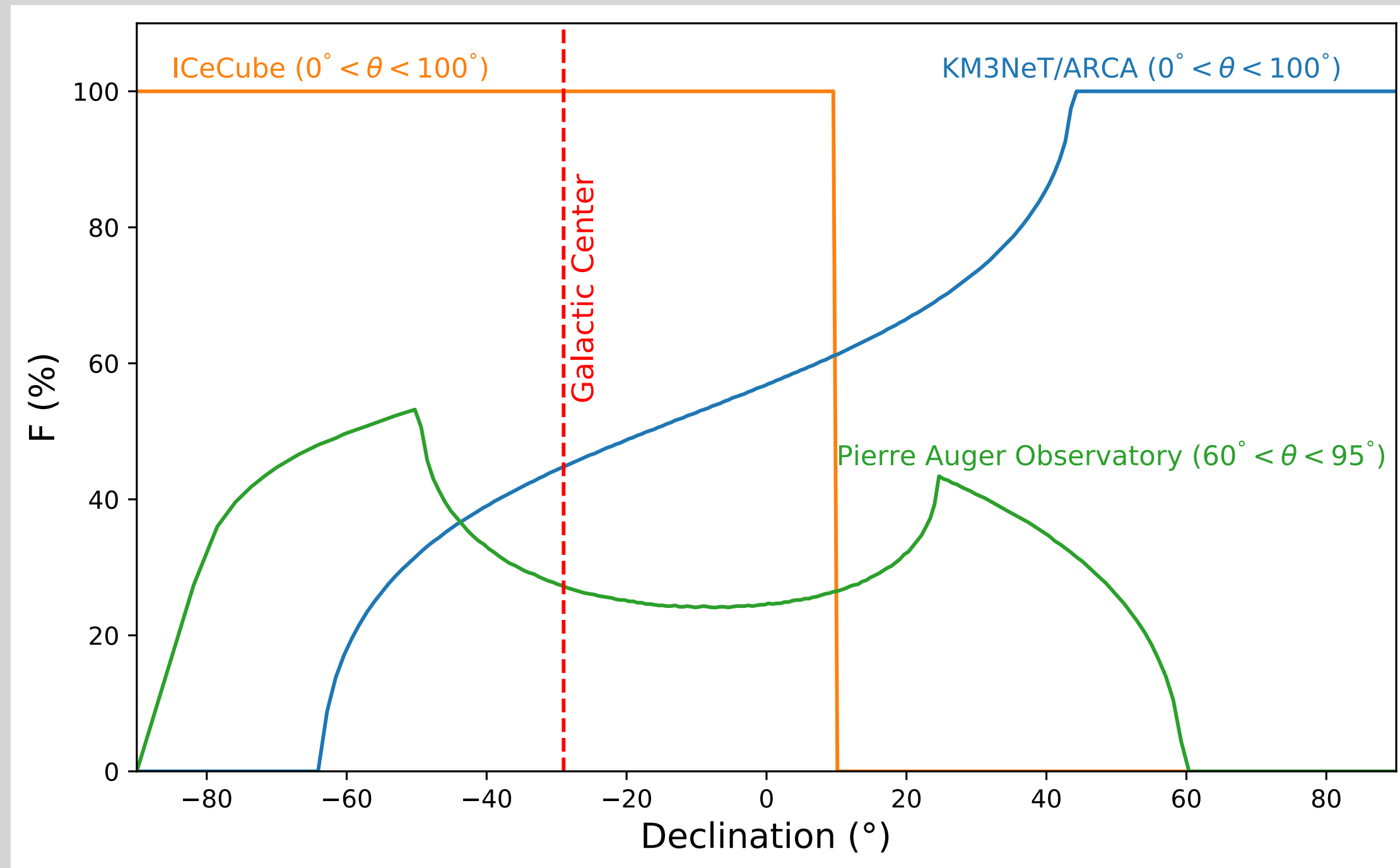


The High Energy Sky becomes a detector to constrain BSM physics

The visibility of Neutrino Telescope at the highest energies

For $E_\nu \gtrsim 10 \text{ PeV}$, the Earth becomes opaque to neutrinos

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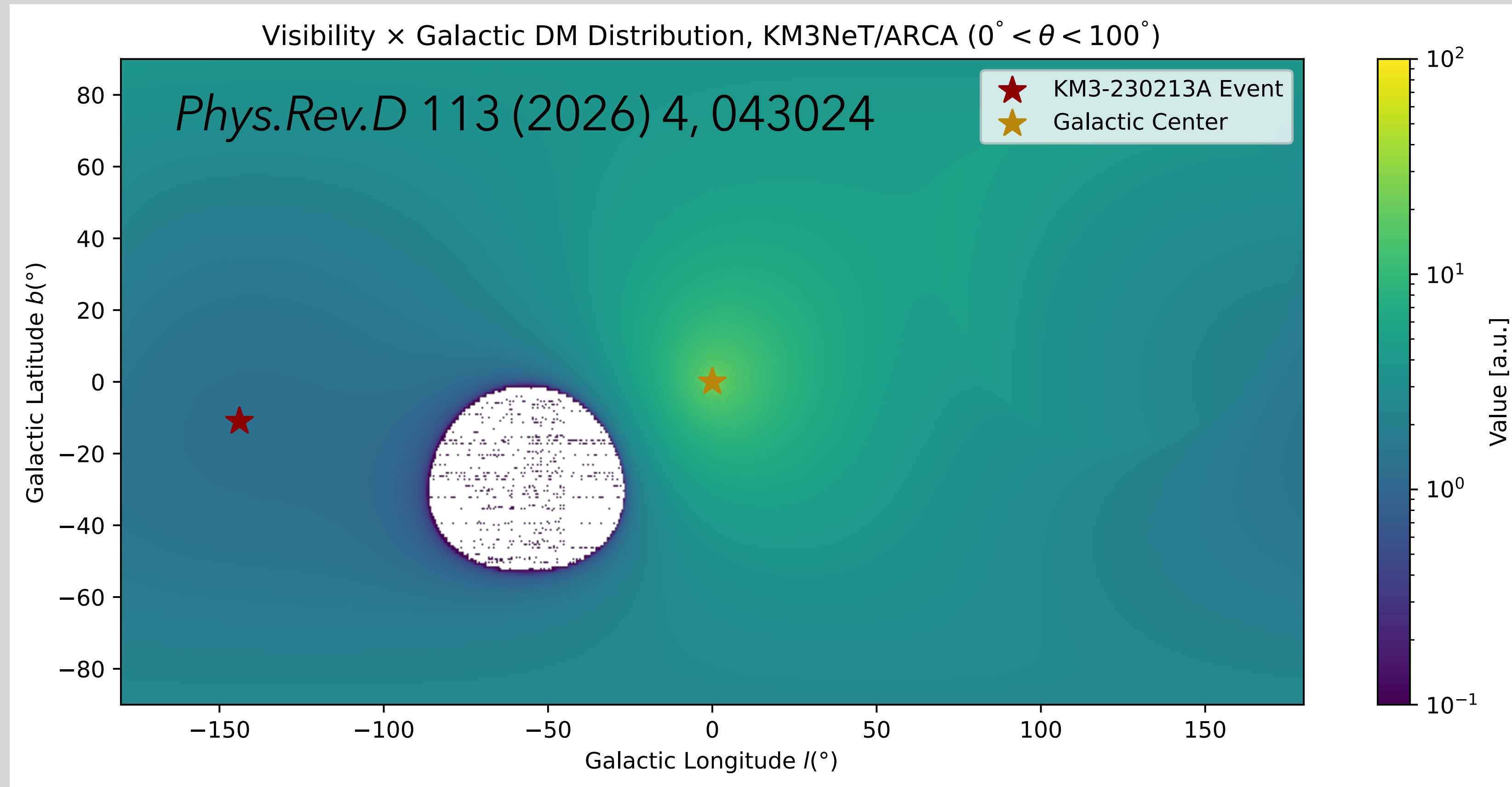


UHE neutrino searches shift from the upgoing sky to the horizon and above.

Can the KM3-230213A Event be DM signature?

◆ The KM3-230213A event direction ($l_{\text{event}} = 216.1^\circ, b_{\text{event}} = -11^\circ$) strongly disfavors a DM origin

The flux should be dominated by the Galactic Center



CAVEAT: this is proof of concept, the result does not take into account the full pipeline of the KM3NeT collaboration

A Multi-Messenger Likelihood Analysis

1

EVENT COUNTS

2

γ -RAY LIMITS

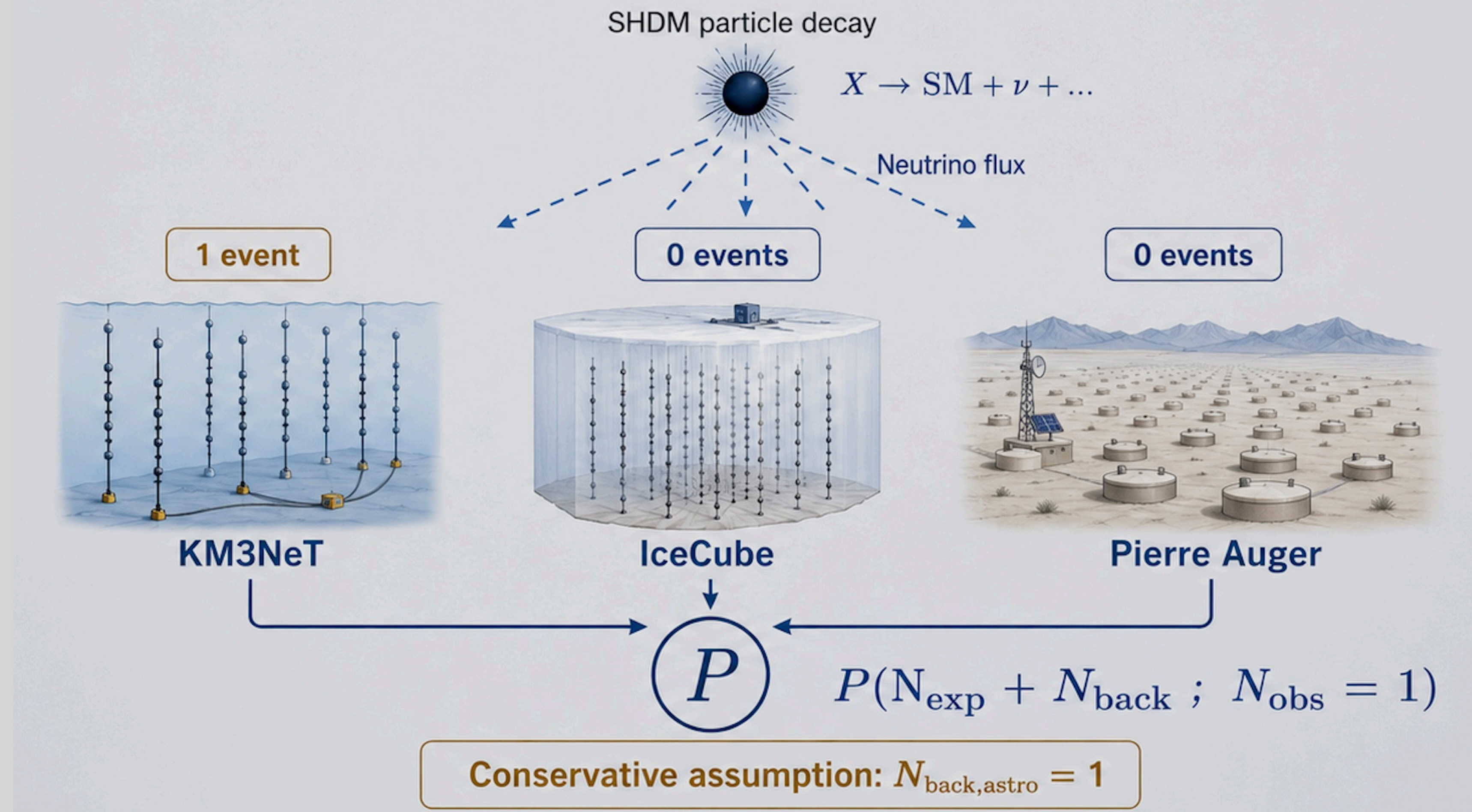
3

GALACTIC ν

4

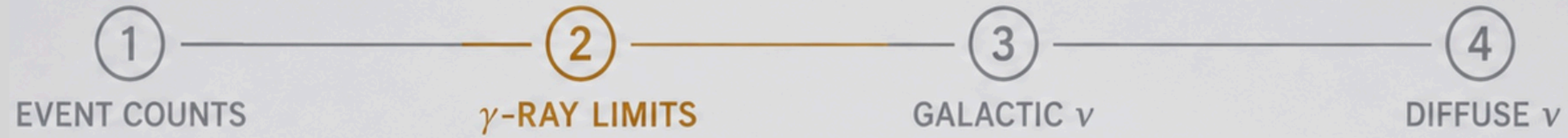
DIFFUSE ν

- Using all Neutrino Telescopes as one, in order to maximize constraining power
- Poissonian probability for SHDM to add events above a global neutrino background



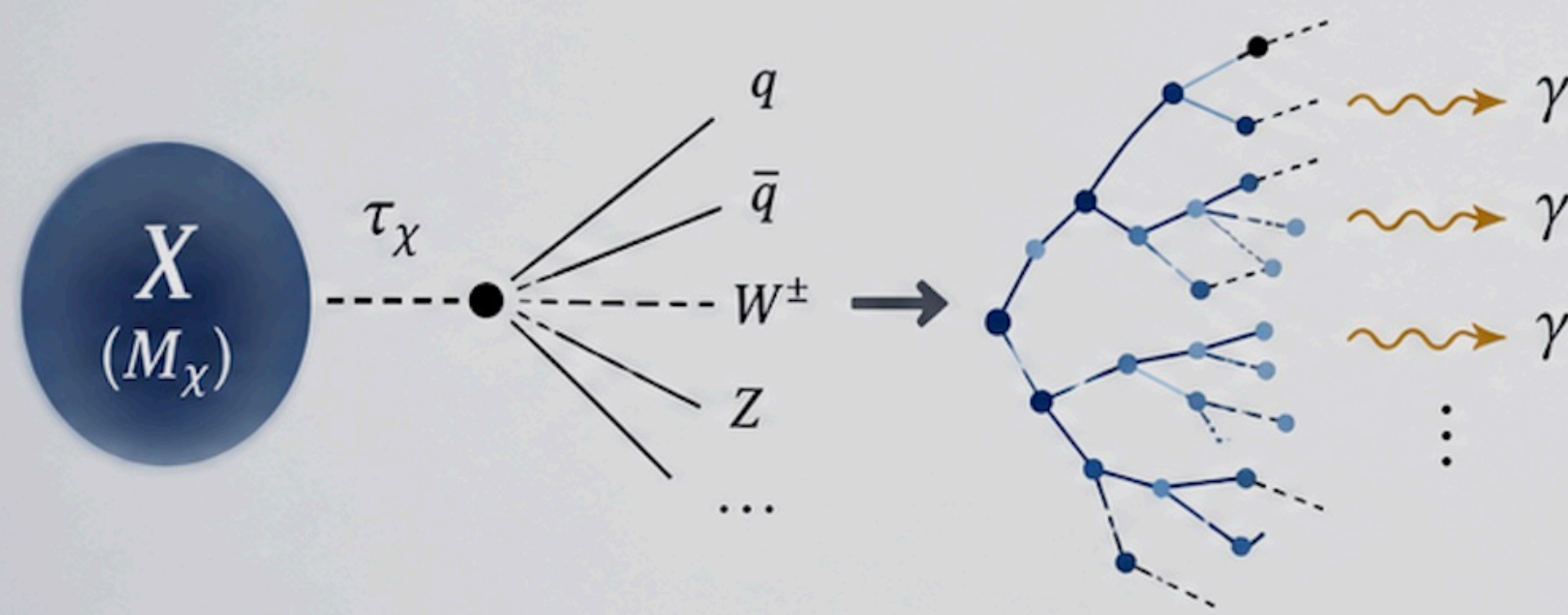
A Multi-Messenger Likelihood Analysis

2 · γ -RAY CONSISTENCY

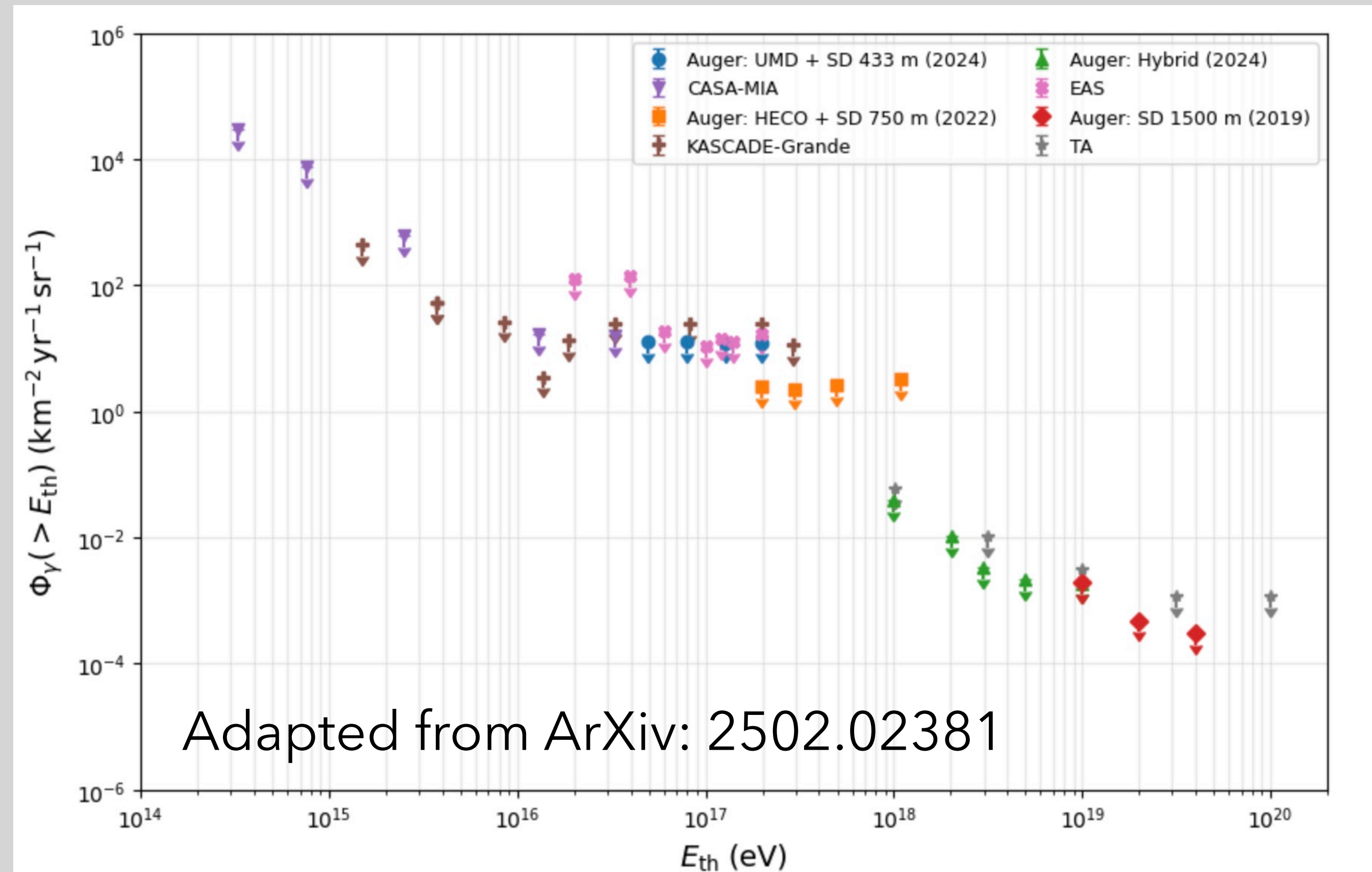


SHDM decay

Electroweak shower & hadronization

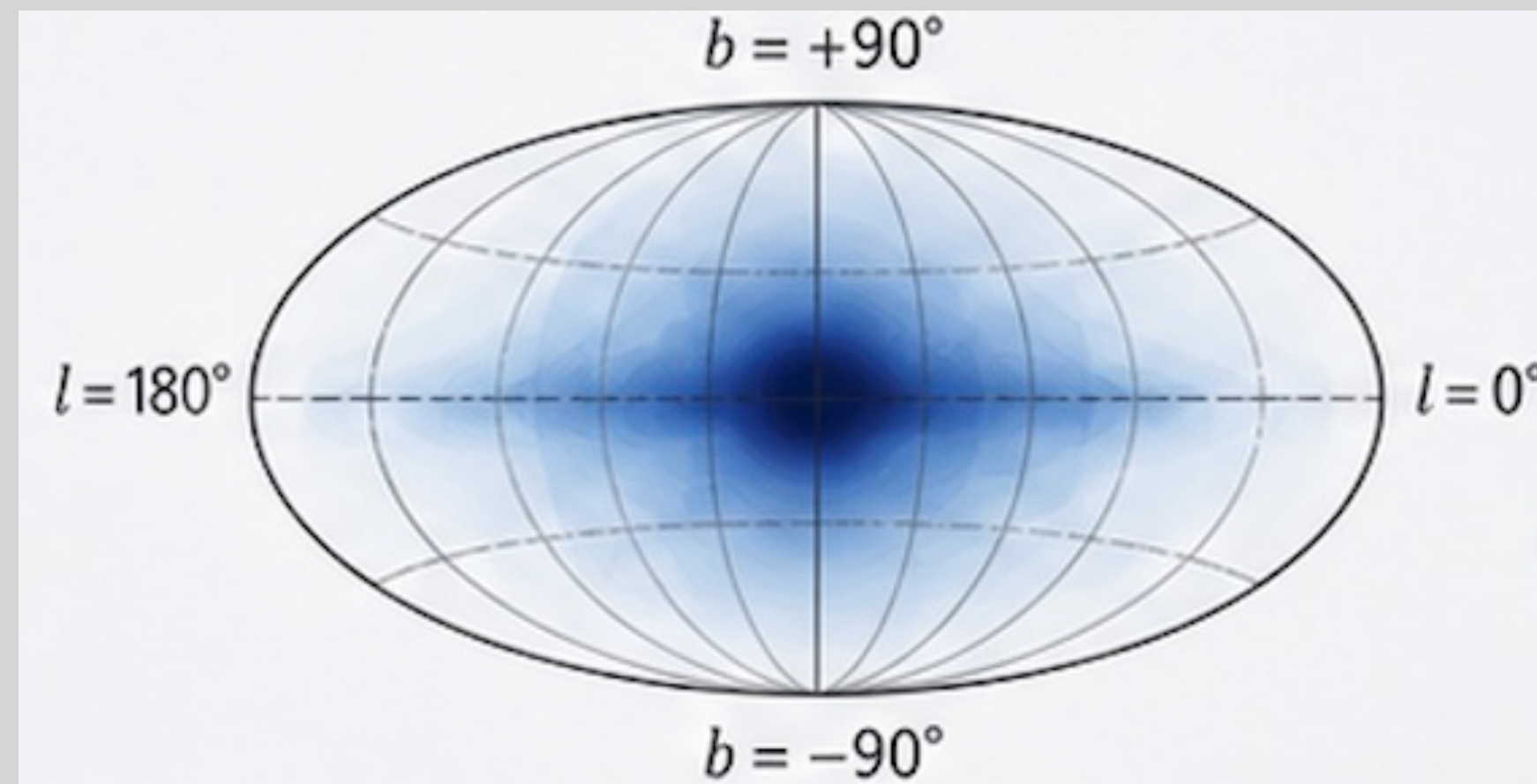
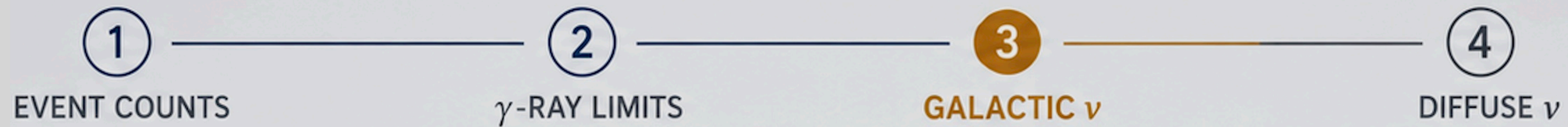


The associated γ -ray flux must remain below the existing limits (Pierre Auger, Telescope Array, Kascade-Grande etc...)

$$\exp \left[-\frac{\chi_{\gamma}^2(M_{\chi}, \tau_{\chi})}{2} \right]$$


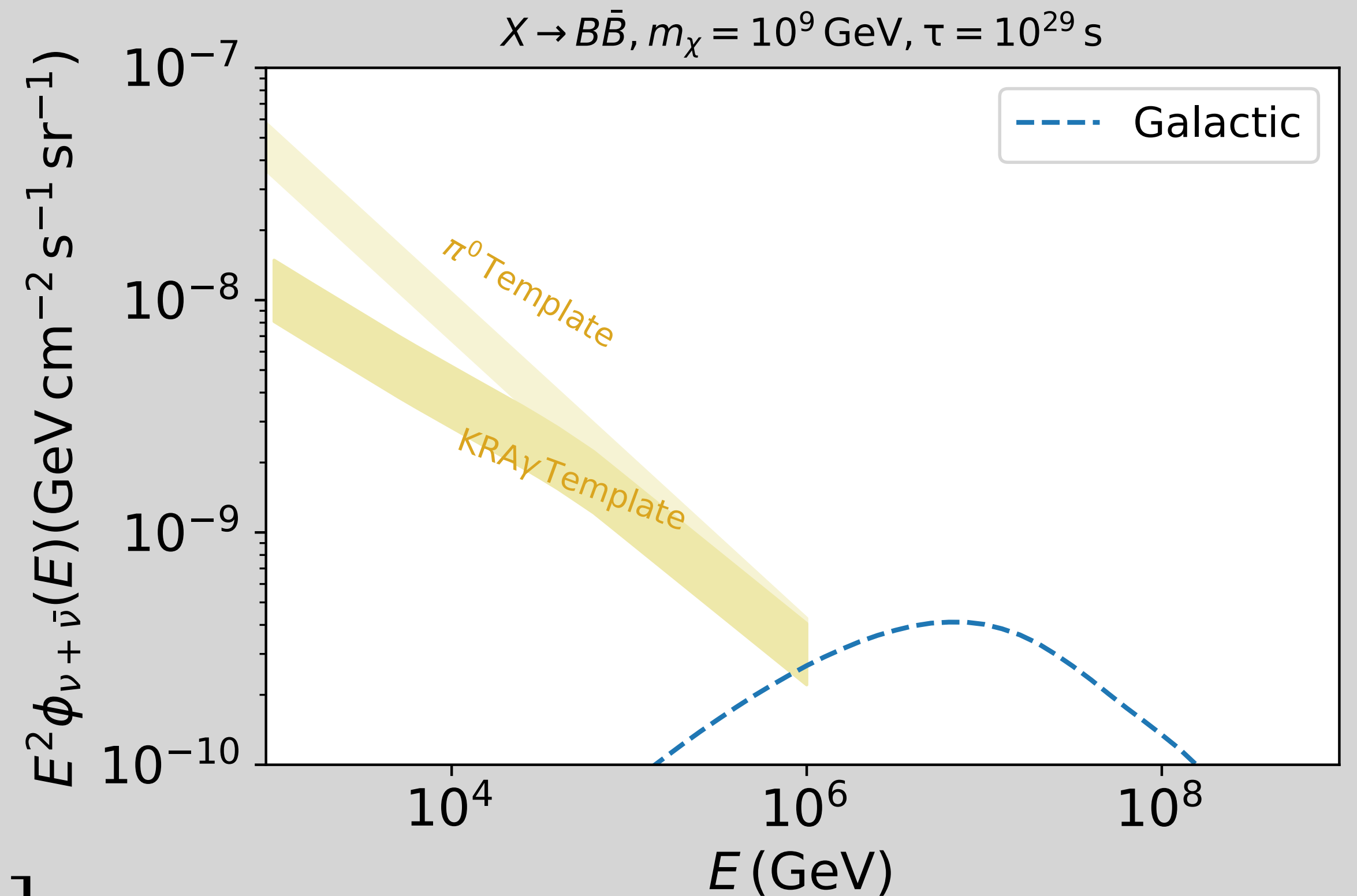
A Multi-Messenger Likelihood Analysis

3 · THE GALACTIC NEUTRINO FLUX



- The tail of the Galactic neutrino flux must remain below the flux constrained by the IceCube collaboration below $\lesssim 1$ PeV

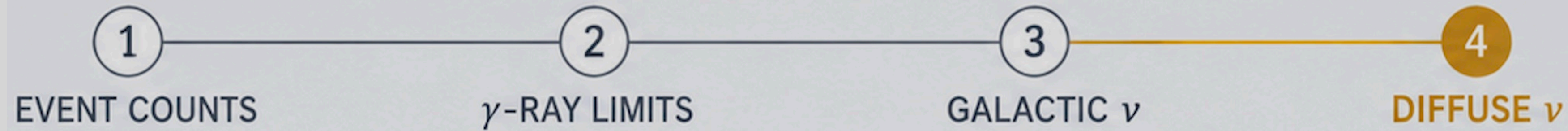
$$\exp \left[-\frac{f_G^2(M_\chi, \tau_\chi)}{2\sigma_F^2} \right]$$



Galactic neutrino flux from *Science* 380 (2023) 6652, adc9818

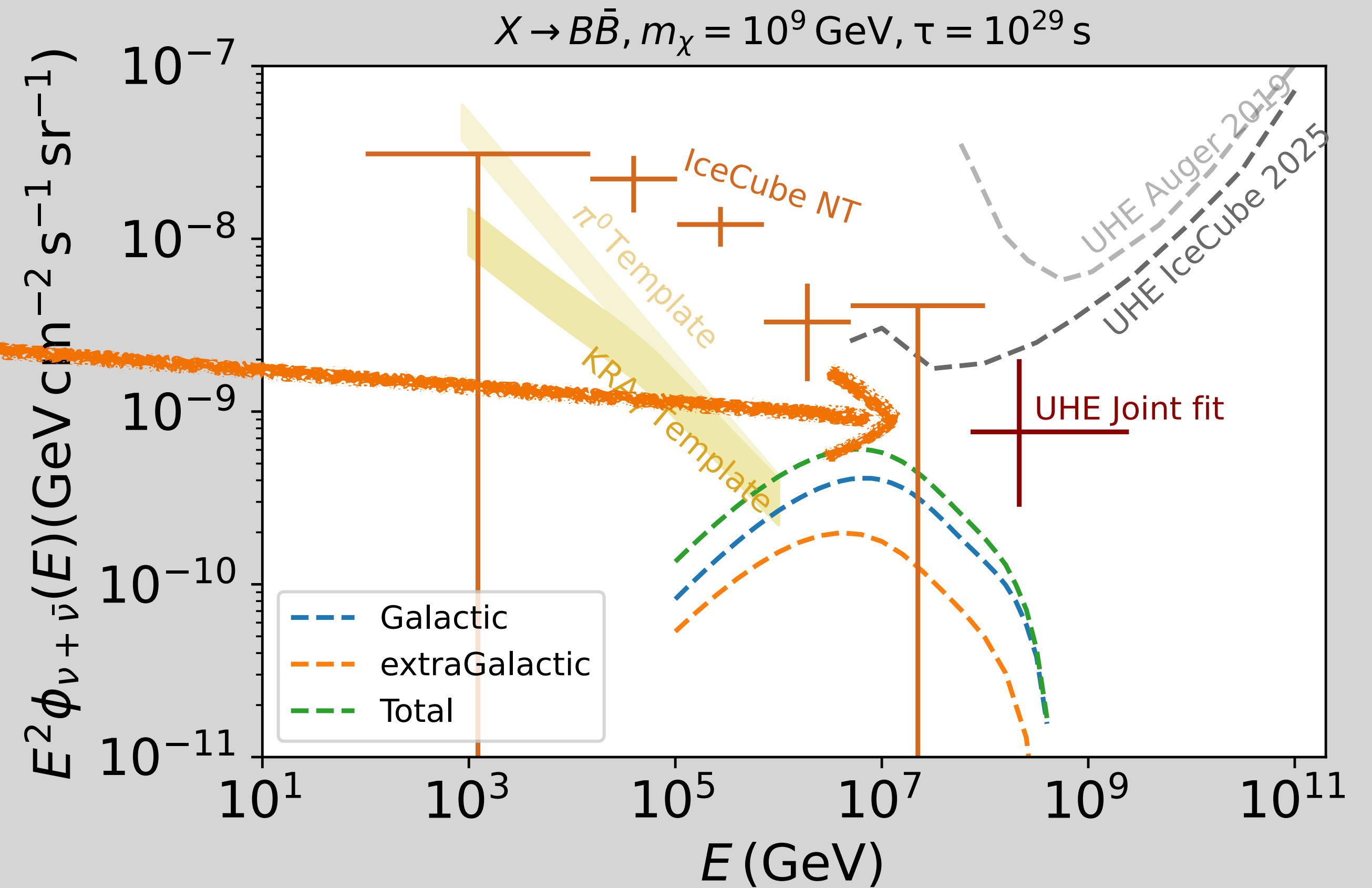
A Multi-Messenger Likelihood Analysis

4 · THE DIFFUSE UHE NEUTRINO LIMIT



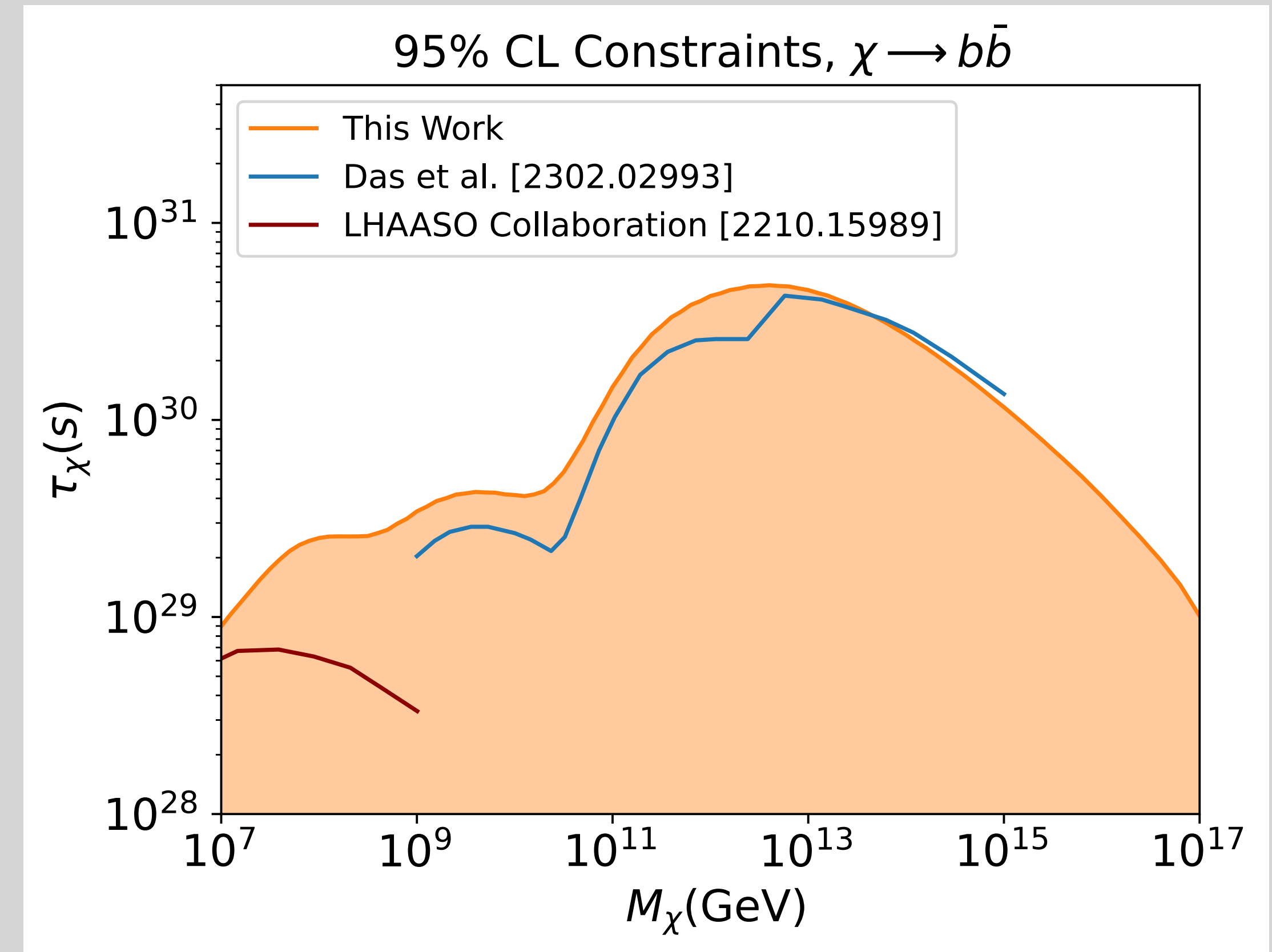
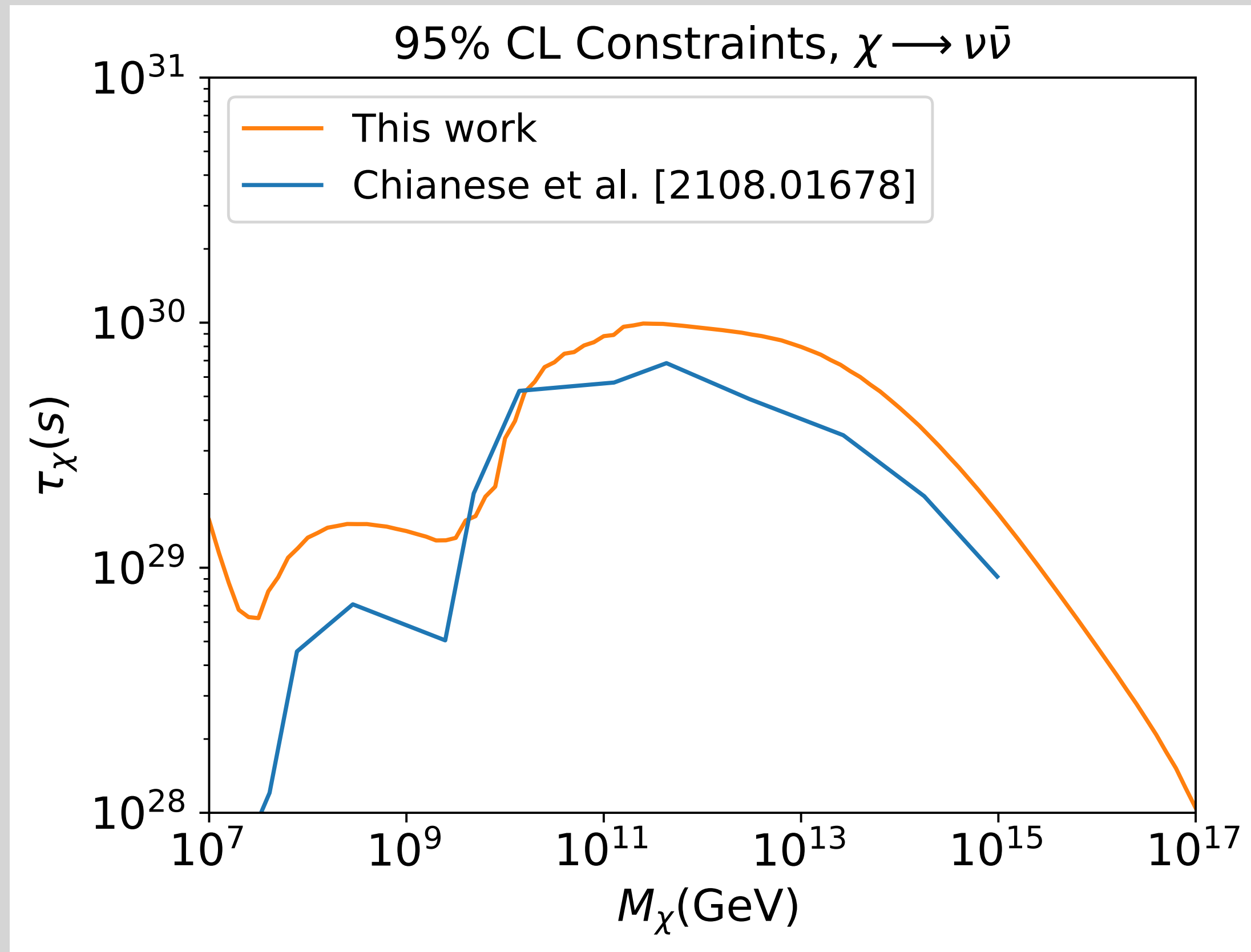
- The total Neutrino Flux (Galactic + ExtraGalactic) must be below the IceCube upper limit measured between 5-100 PeV (Astrophys.J. 928 (2022) 1, 50)

$$\exp[-\chi_D^2(M_\chi, \tau_\chi)/(2\sigma_D^2)]$$



SHDM Lifetime Bounds

The New constraints improve previous bounds on DM lifetime



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The bounds have improved more for the $X \rightarrow \nu\bar{\nu}$ channel, because of a higher neutrino yield

Conclusions

- Multi-Messenger Astronomy is a powerful tool to test fundamental interactions at energies way beyond any accelerators on Earth
- The KM3-230213A event paves the way for UHE neutrino astronomy, but its direction strongly constraints SHDM decay physics
- The implemented multi-messenger likelihood analysis puts the strongest bounds on the SHDM lifetime up to today
- Future analyses might exploit spatial distribution of datasets across several experiment to impose even stronger constraints