Searching for dark matter decay to neutrinos with gamma-ray and neutrino telescopes

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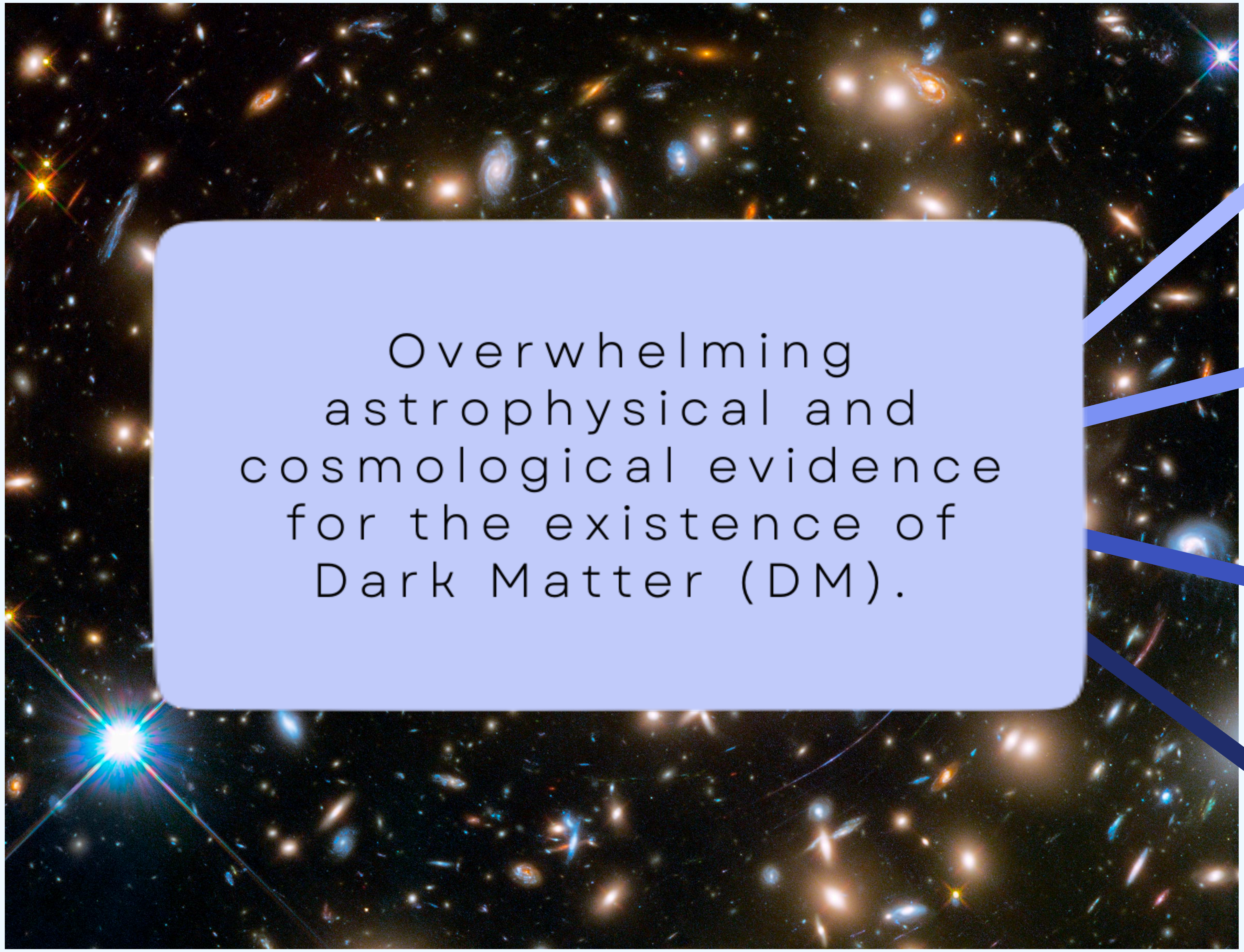
WIMP Origins

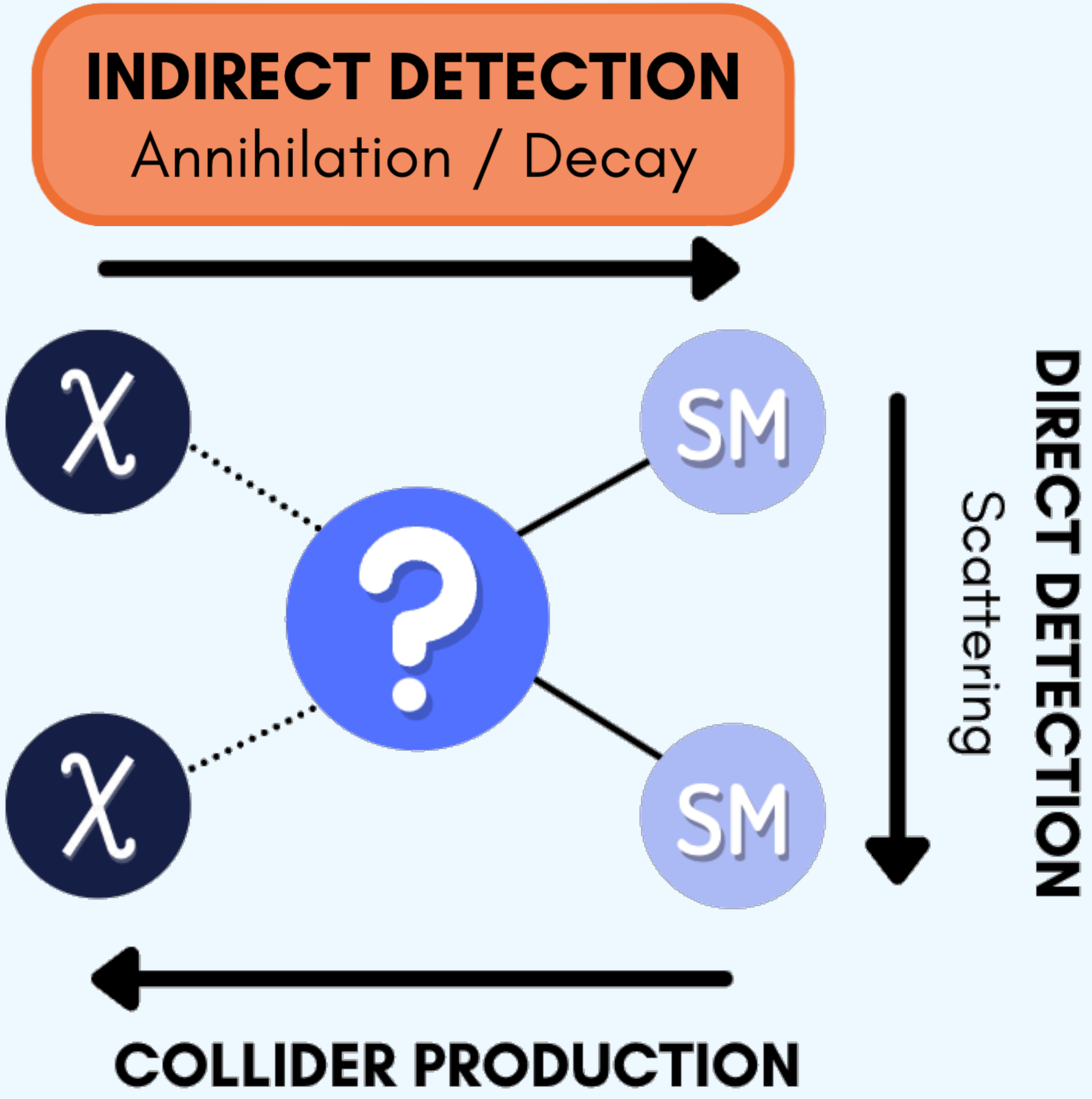


Overwhelming astrophysical and cosmological evidence for the existence of Dark Matter (DM).

- Local Stellar Dynamics
- Galactic Rotation Curves
- Cluster Dynamics
- Gravitational Lensing

We must search for WIMP Dark Matter with a ν perspective!

Neutrino Portal to Dark Matter

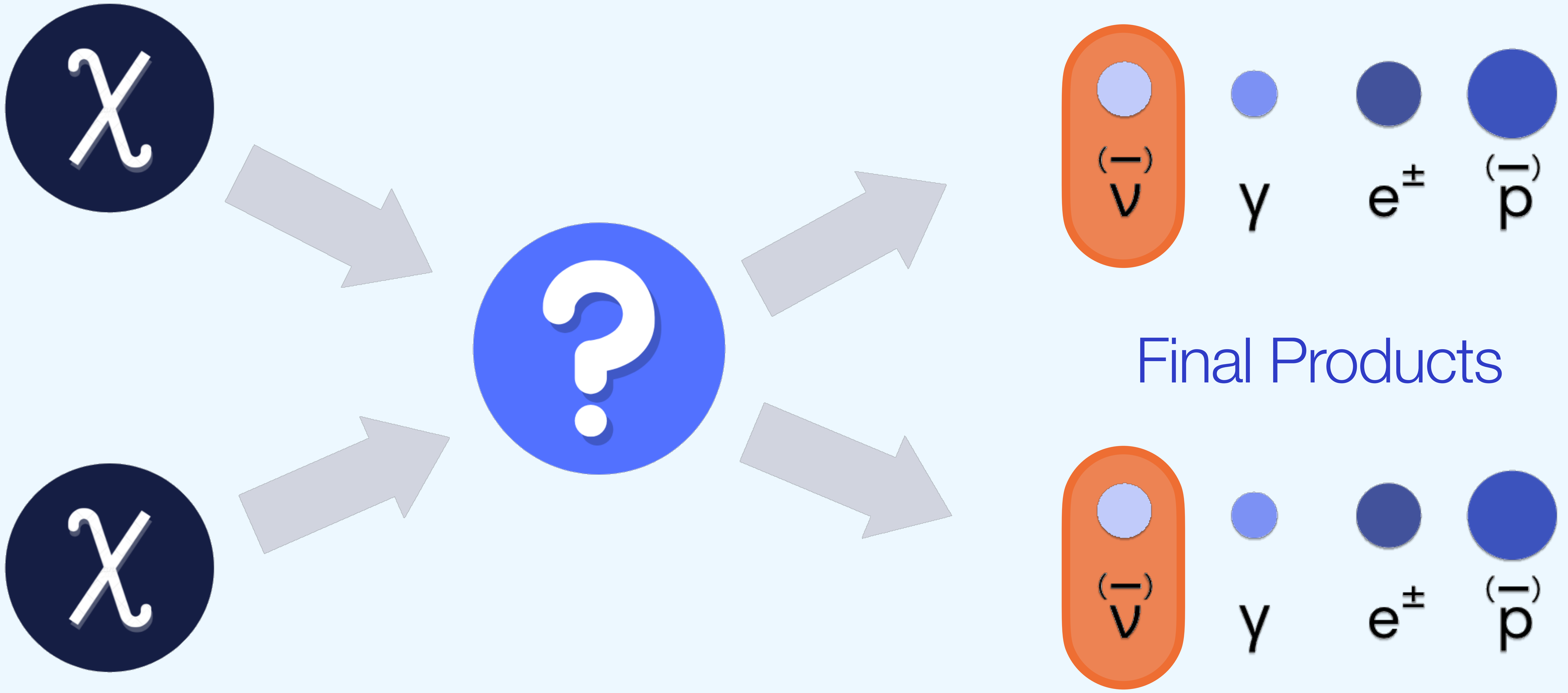


All SM final states eventually lead to gamma rays or neutrinos.

Neutrino portal: the most invisible channel, hardest to detect, difficult to rule out!

Assuming a branching ratio to neutrinos of 100% provides an upper limit on the total DM decay lifetime

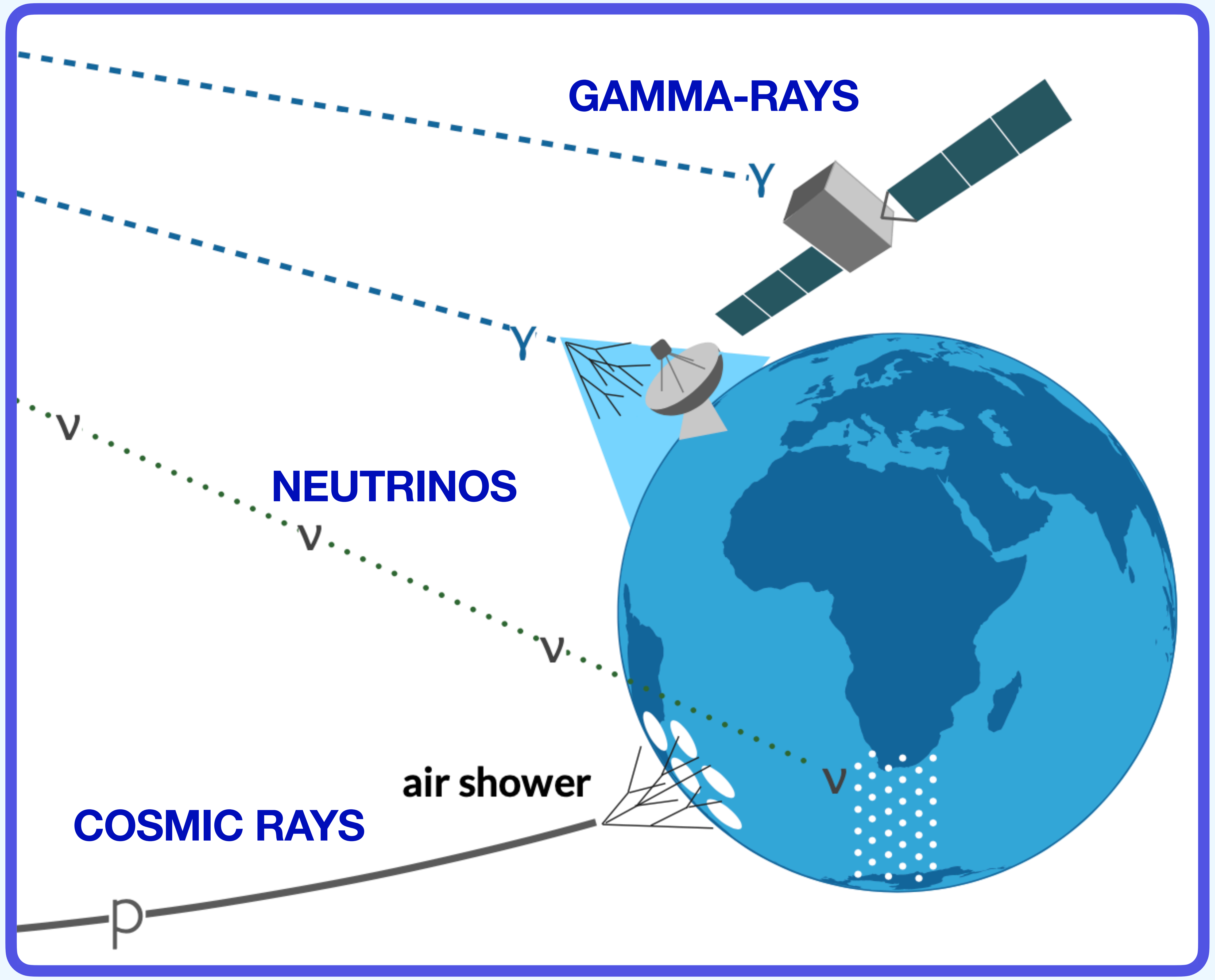
Indirect Detection

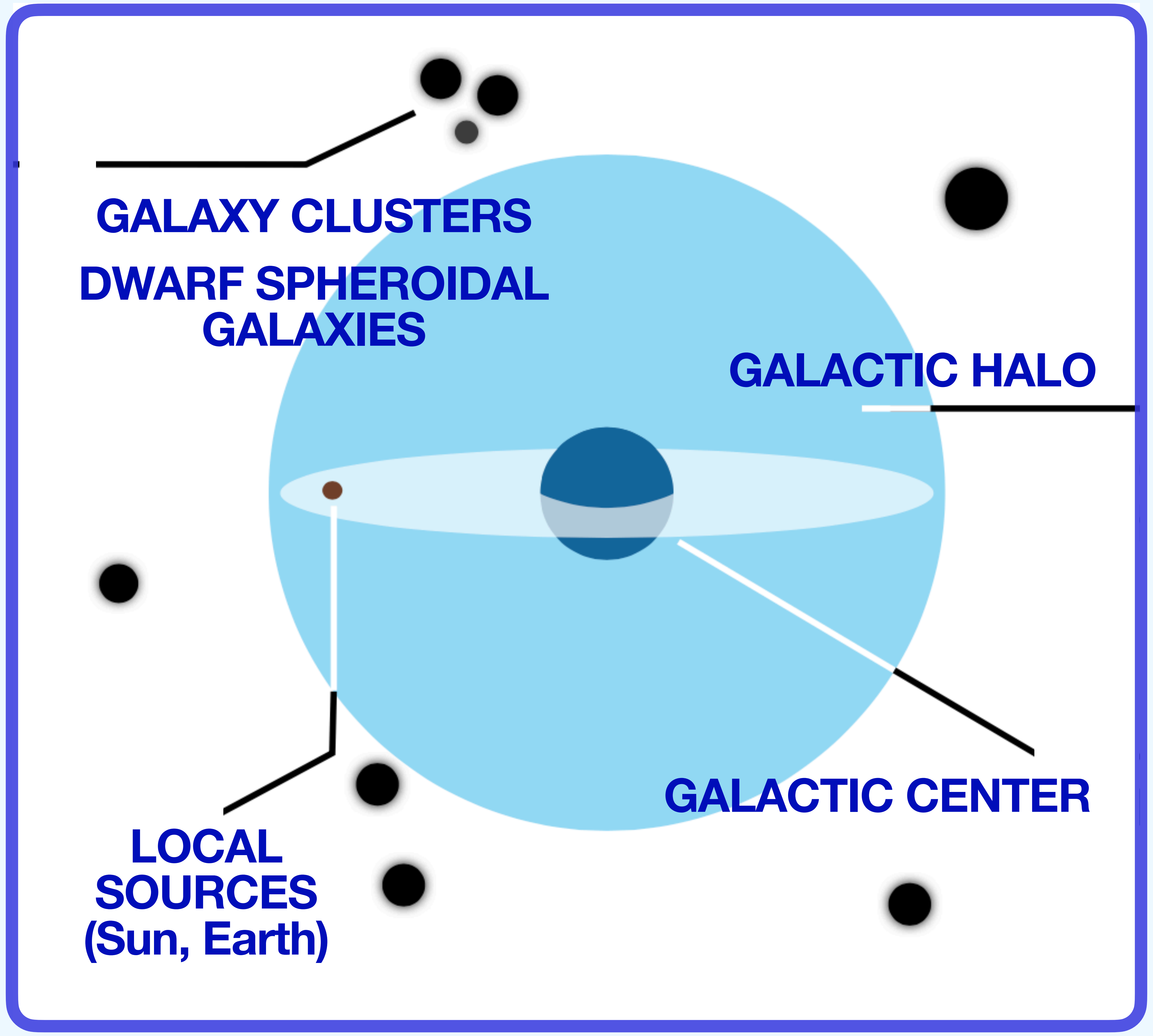


Focus on large reservoirs of DM

Dark Matter Searches

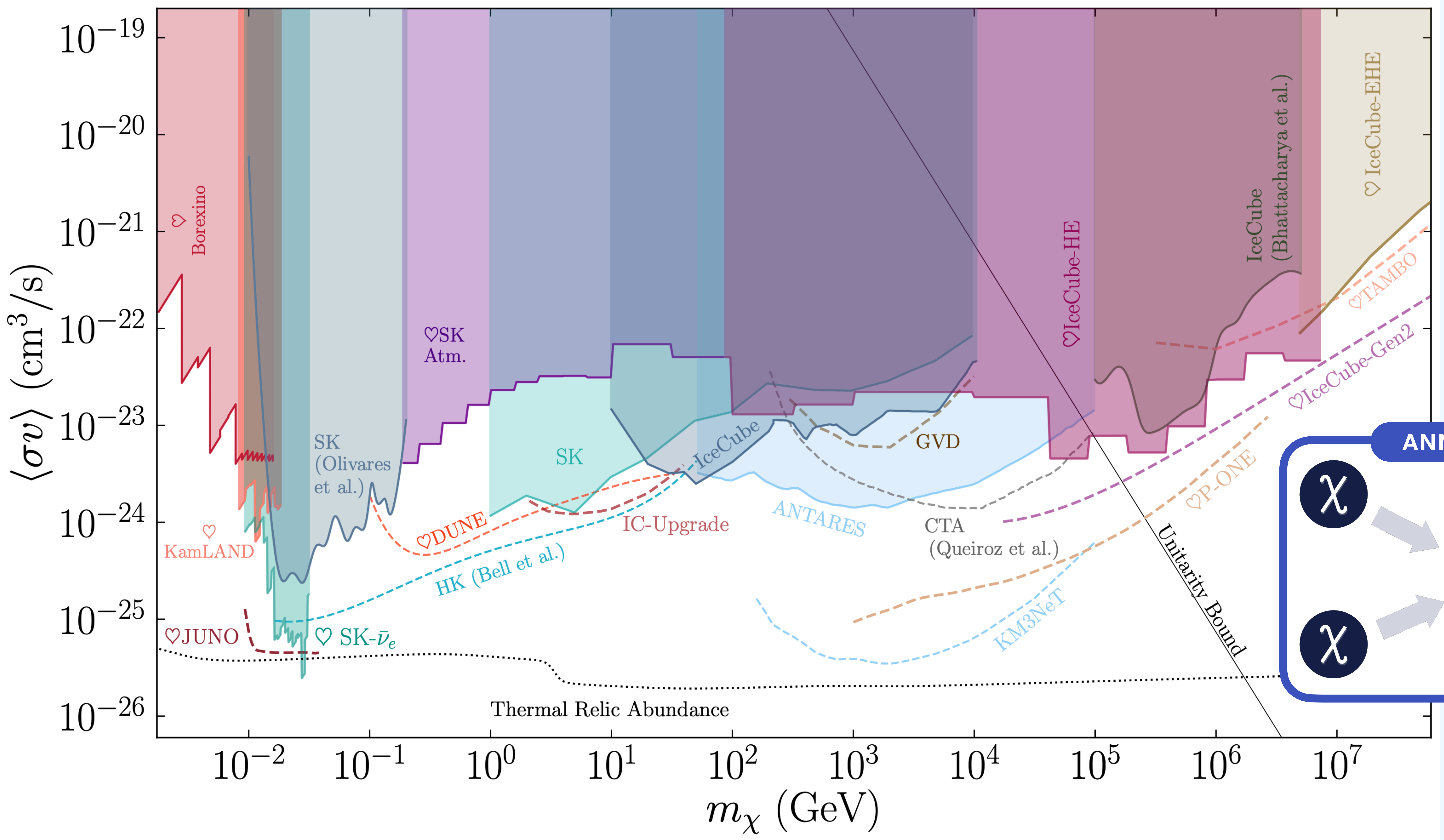
What and where to look?

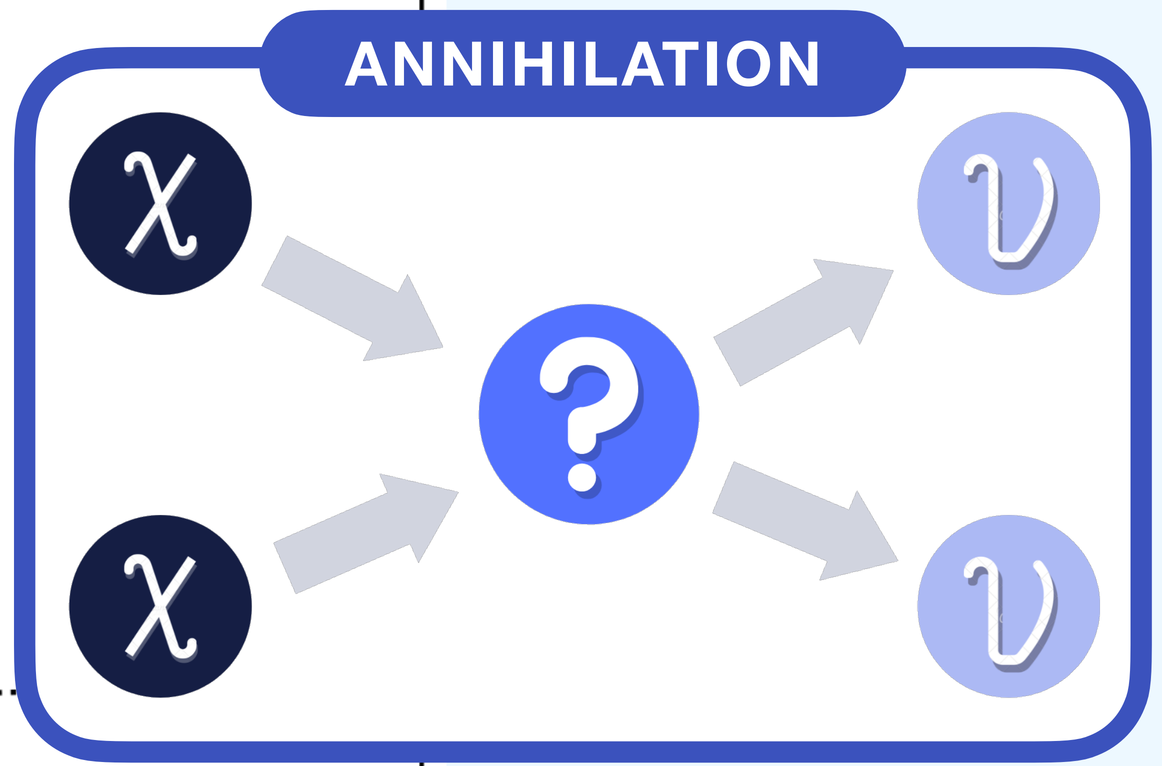




CREDIT: JUAN AGUILAR, ESDU 2018

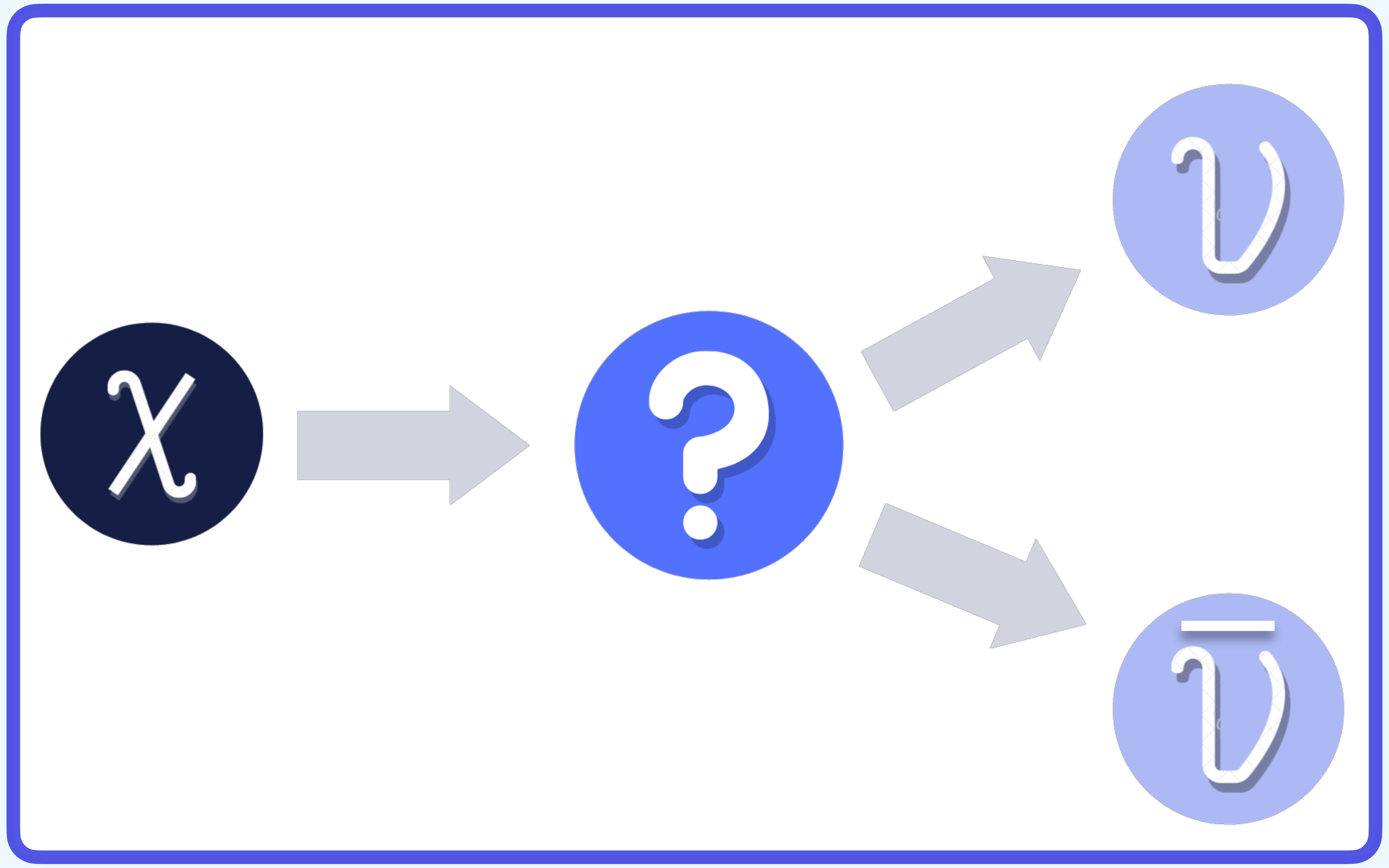
Previous Work: Dark Matter Annihilation to Neutrinos

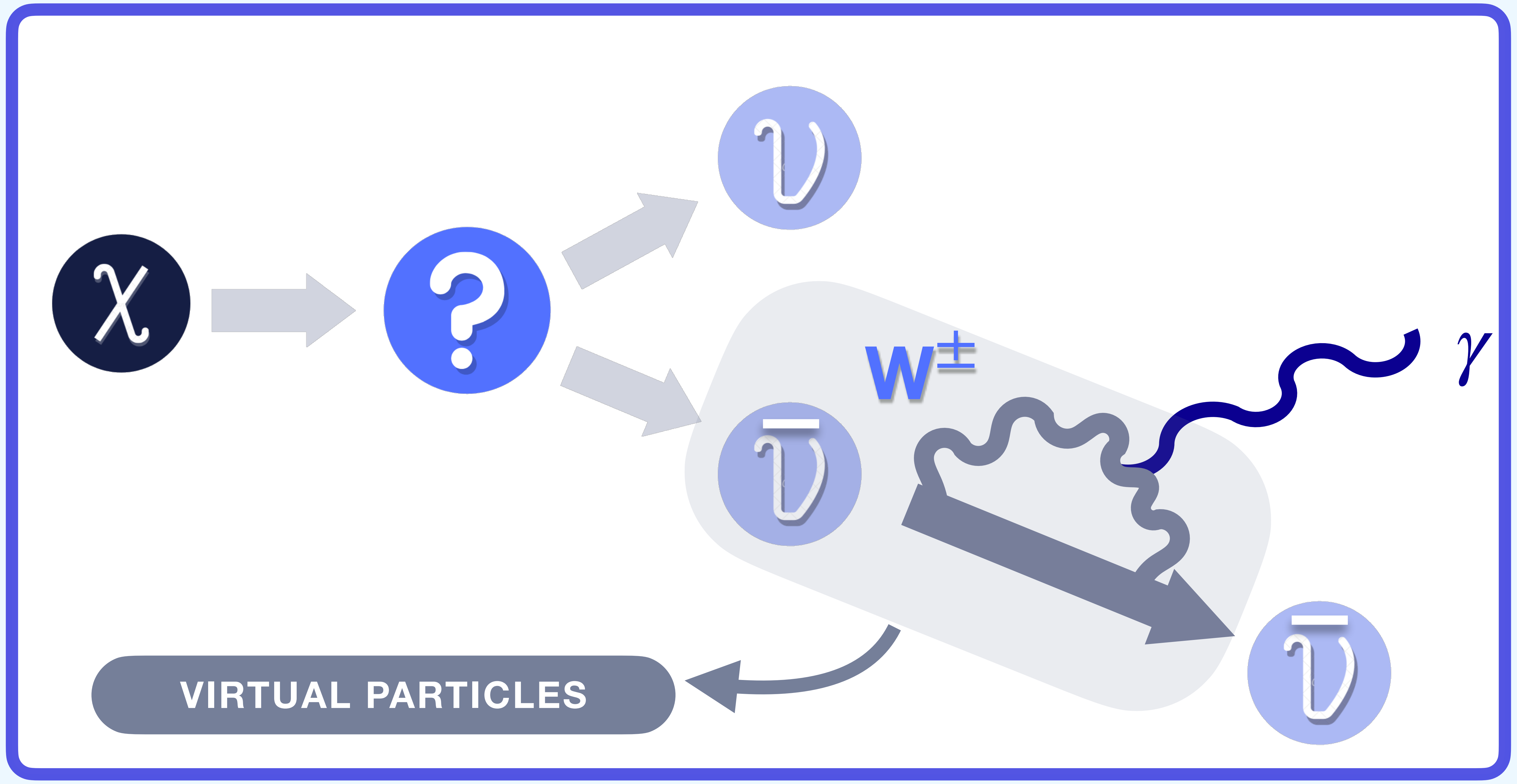




ARGÜELLES, ET AL., REV. MOD. PHYS. 93, ARXIV:1912.09486

Dark Matter Decay to Neutrinos





NEUTRINO SIGNAL

GAMMA-RAY SIGNAL

EXPECTED GAMMA-RAY SIGNAL DUE TO ELECTROWEAK CORRECTIONS

Flux from Dark Matter Decay in our Galaxy

Decay

$$\frac{d\Phi^*_{\nu/\gamma}}{dE} = \frac{1}{4\pi}\frac{1}{m_\chi \tau_\chi}\frac{dN_{\nu/\gamma}}{dE} D(\Omega, x)$$

* Divided by 3 in the case of all neutrino flavors.

Particle Physics | **Astro-physical**

τ_χ DM decay lifetime

$$\frac{dN_\nu}{dE} = \delta\left(\frac{m_\chi}{2} - E_\nu\right)$$

Neutrino Production Spectrum for Direct Decay of DM to neutrinos*

* with gamma-ray production becomes more complicated due to electroweak corrections.

$$D = \int d\Omega \int_{l.o.s.} \rho_\chi(x)\, dx$$

D factor: 3D integral over the sky solid angle and line of sight

Dark Matter density: NFW Profile

$$\rho_\chi = \frac{2^{3-\gamma}\rho_s}{\left(\frac{r}{r_s}\right)^\gamma \left(1 + \frac{r}{r_s}\right)^{3-\gamma}}$$

NAVARRO, ET AL. ASTROPHYS.J. 462, ARXIV:ASTRO-PH/9508025

Extragalactic Flux from Decaying Dark Matter

An isotropic neutrino signal is expected due to the decay of Dark Matter of all other galactic halos of the Universe.

Decay

$$\frac{d\Phi_{\nu/\gamma}}{dE} = \frac{1}{4\pi}\frac{\Omega_{DM}\rho_{crit}}{m_\chi \tau_\chi}\int_0^{z_{up}} \frac{dz}{H(z)}\frac{dN_{\nu/\gamma}(E')}{dE'}$$

Ω_{DM} **DM density parameter**

ρ_{crit} **Critical density today**

$$H(z) = H_0\left[(1+z)^3\Omega_{DM} + \Omega_\Lambda\right]^{\frac{1}{2}}$$

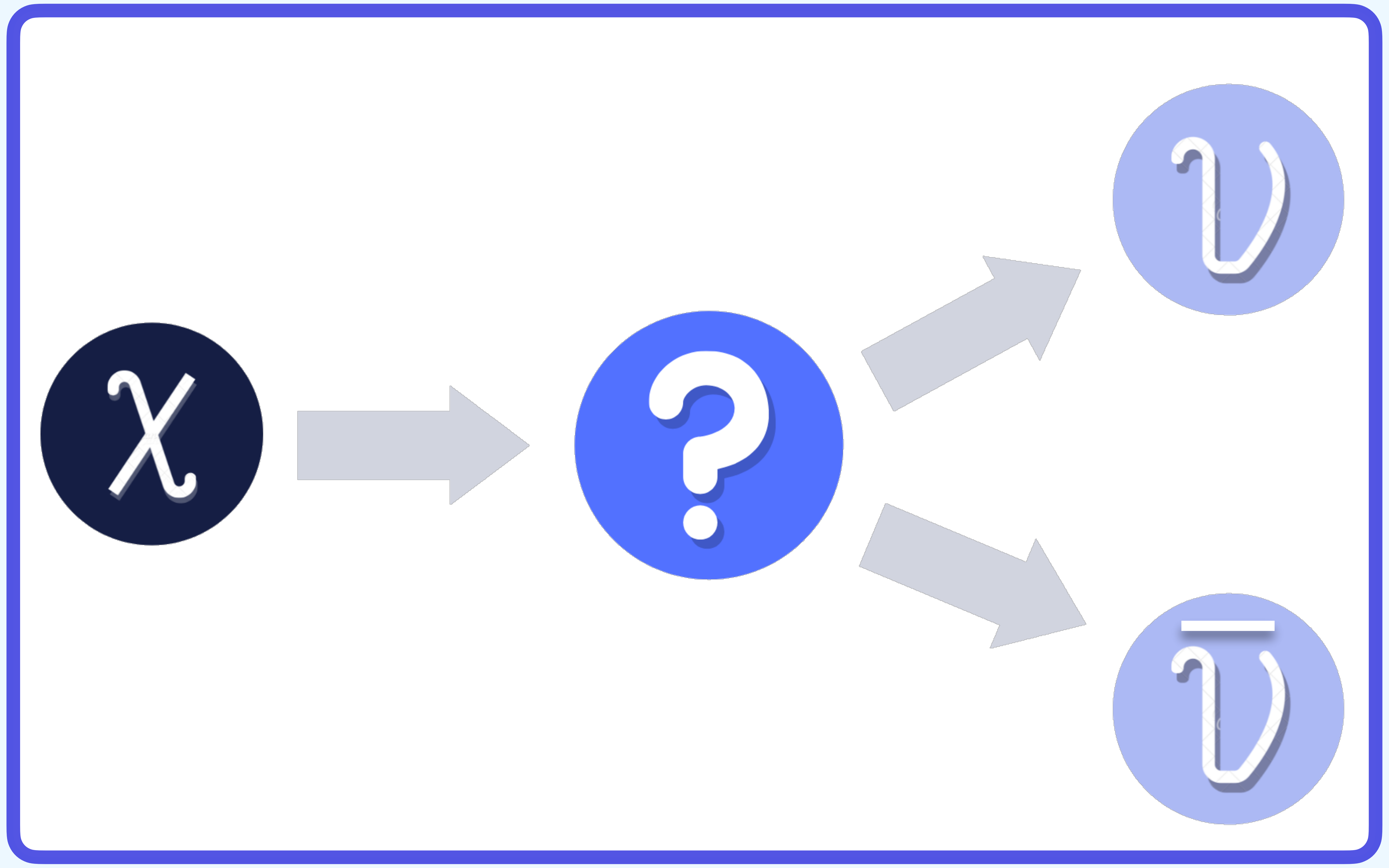
Time-dependent Hubble parameter

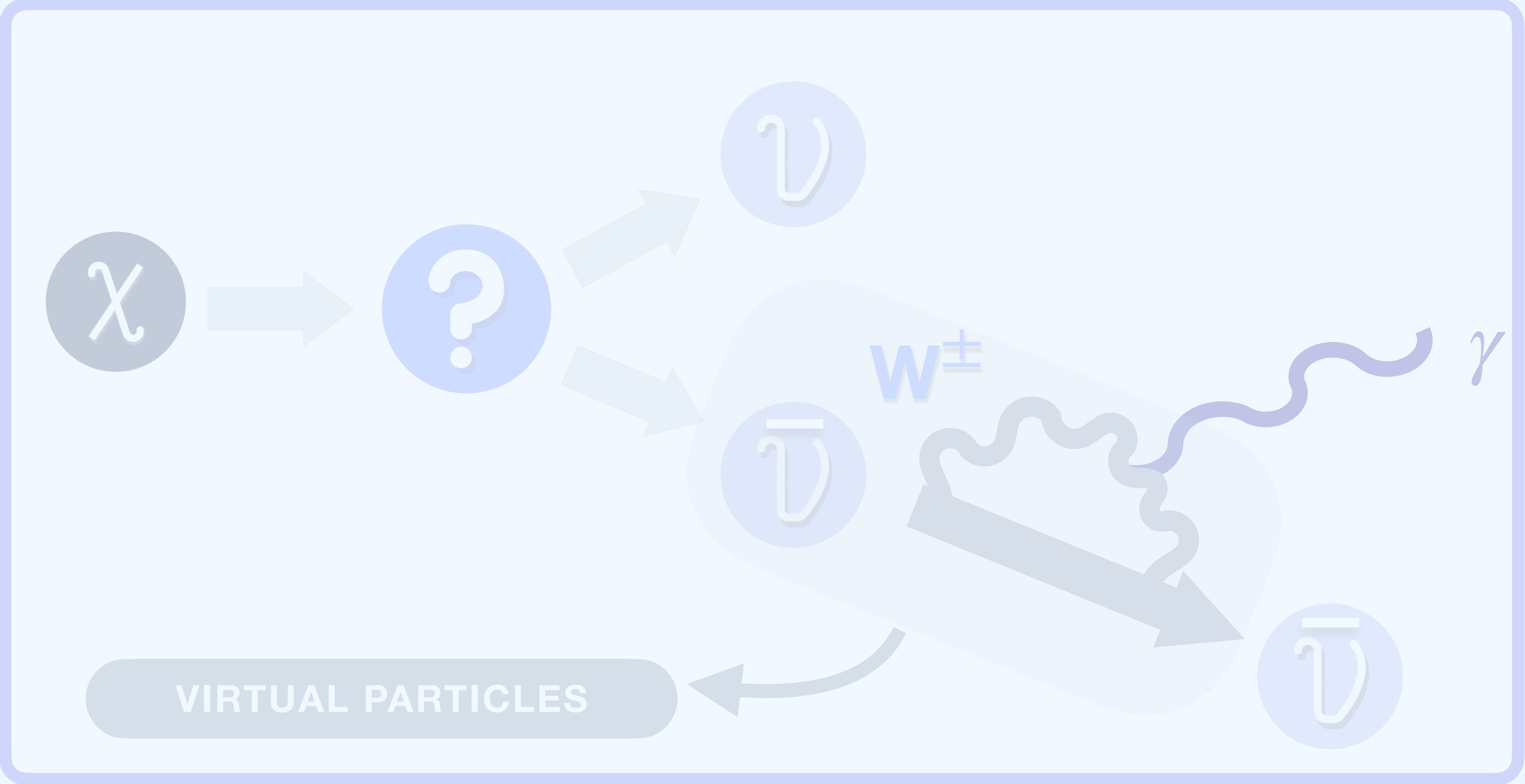
$$E' = (1+z)\,E$$

Starting neutrino energy accounting for the expansion of the Universe

Constants defined in: Beacom. J, et. Al. Phys. Rev. Lett. **99**, 231301

Dark Matter Decay to Neutrinos





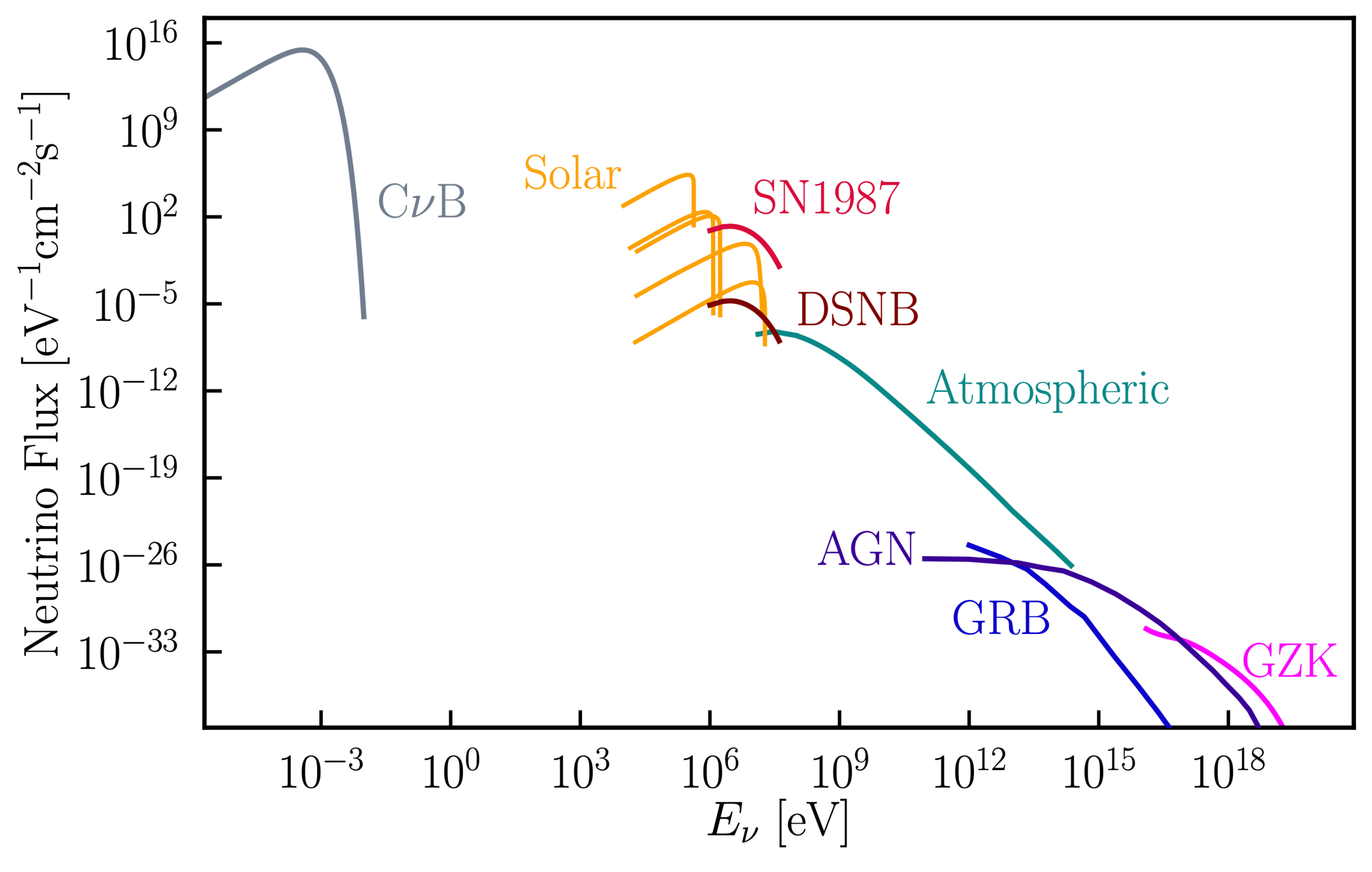
NEUTRINO SIGNAL

GAMMA-RAY SIGNAL

EXPECTED GAMMA-RAY SIGNAL DUE TO ELECTROWEAK CORRECTIONS

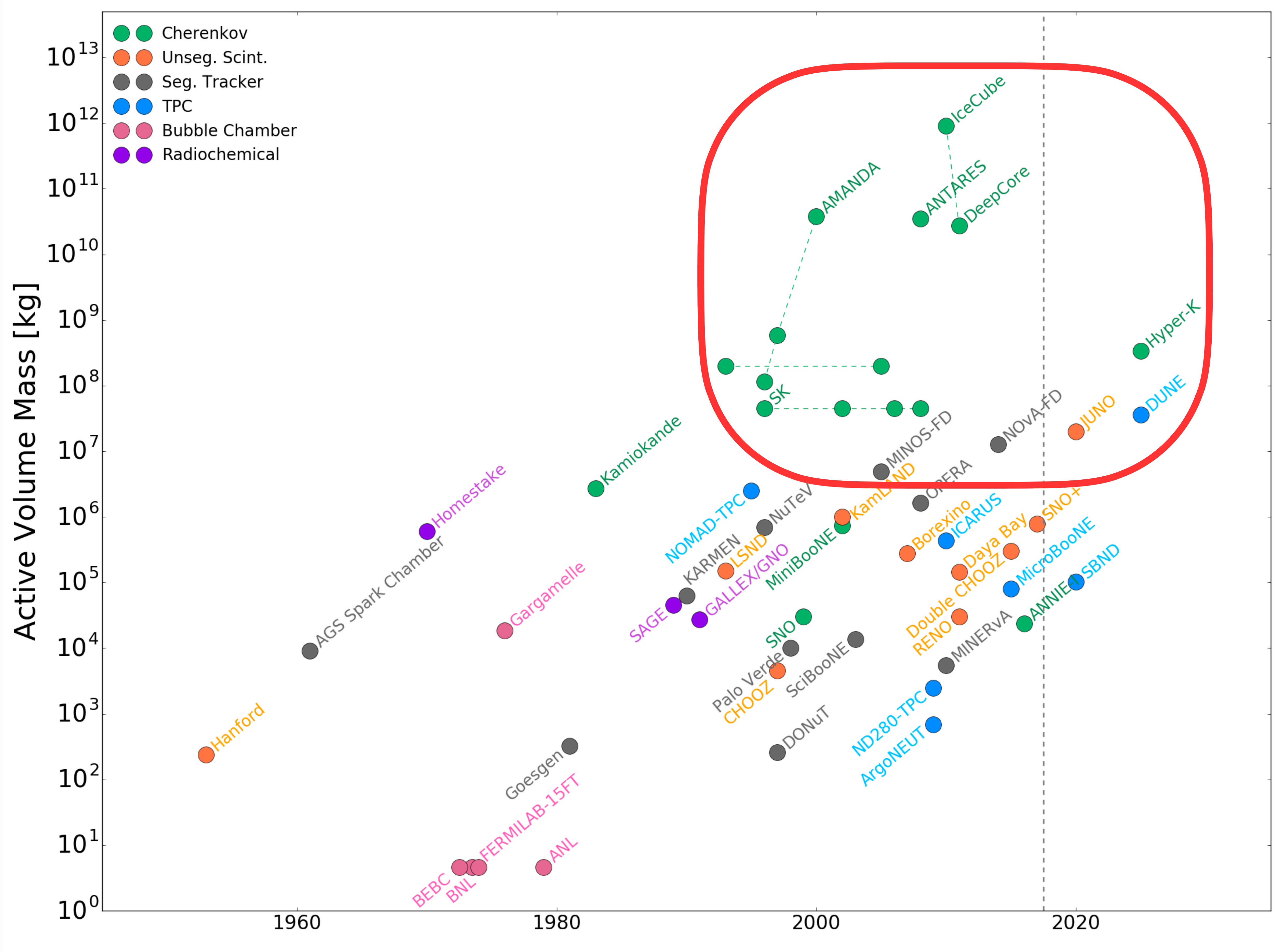
First, we must detect neutrinos!

Measured and expected fluxes of natural and reactor neutrinos

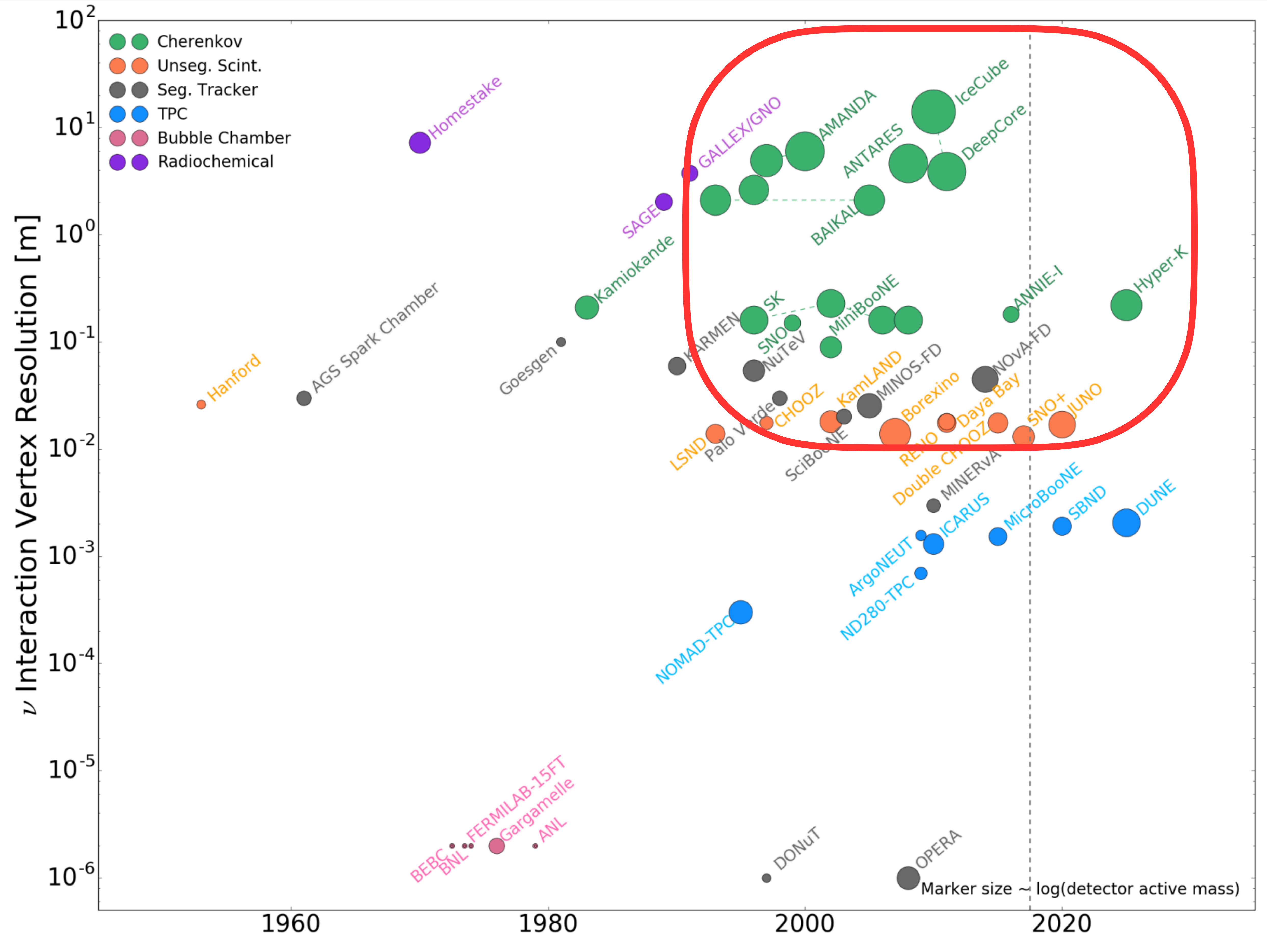


HALZEN, F. AND KHEIRANDISH, A. ARXIV:2202.00694

Neutrino Detection



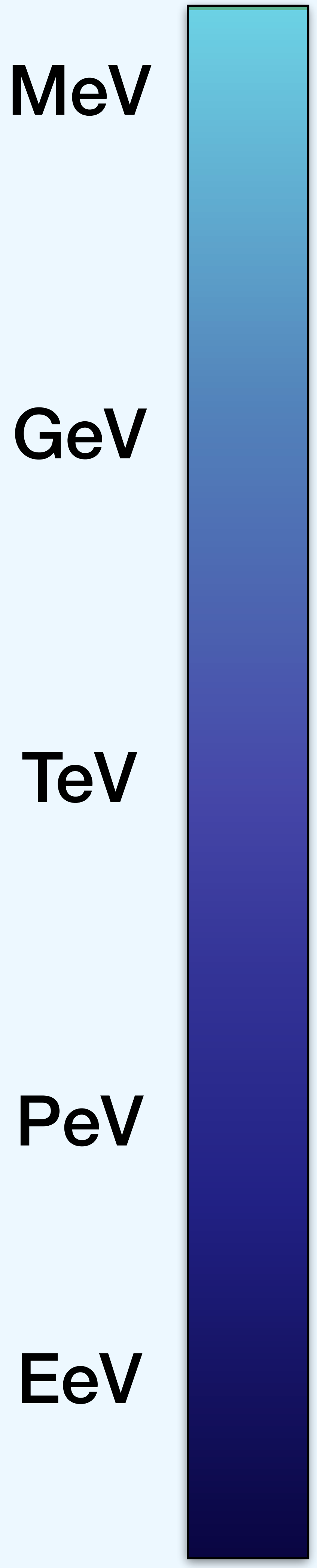
Size (Volume)



Precision

ARGÜELLES ET AL., IOP 23, ARXIV:1907.08311

Neutrino Detection



Energy Range	Experimental Analysis	Directionality	Detected Flavor
2.5 – 15 MeV	Borexino (Bellini *et al.*, 2011)	×	$\bar{\nu}_e$ (IBD)
8.3 – 18.3 MeV	KamLAND (Gando *et al.*, 2012)	✓	$\bar{\nu}_e$ (IBD)
10 – 40 MeV	JUNO (An *et al.*, 2016)	✓	$\bar{\nu}_e$ (IBD)
15 – 10^3 MeV	SK (Olivares-Del Campo *et al.*, 2018a)	×	$\bar{\nu}_e$ (IBD)
	DARWIN (McKeen and Raj, 2018)	×	All Flavors (Coherent)
0.1 – 30 GeV	DUNE (Abi *et al.*, 2020b) HK (Olivares-Del Campo *et al.*, 2018b)	×	$\nu_e, \bar{\nu}_e, \nu_\tau, \bar{\nu}_\tau$ (CC)
1 – 10^4 GeV	SK (Abe *et al.*, 2020; Frankiewicz, 2015)	✓	All Flavors
20 – 10^4 GeV	IceCube (Aartsen *et al.*, 2016a)	✓	All Flavors
50 – 10^5 GeV	ANTARES (Adrian-Martinez *et al.*, 2015)	✓	ν_μ, $\bar{\nu}_\mu$ (CC)
0.2 – 100 TeV	CTA (Queiroz *et al.*, 2016)	✓	All Flavors (Bremsstrahlung)
10 – 10^4 GeV	IC-Upgrade (Baur, 2019)	✓	All Flavors
$>$ 10 PeV	IC Gen-2 (Aartsen *et al.*, 2014b)	✓	All Flavors
10 – 10^4 TeV	KM3Net (Adrian-Martinez *et al.*, 2016)	✓	All Flavors
1 – 100 PeV	TAMBO (Wissel *et al.*, 2019)	✓	ν_τ, $\bar{\nu}_\tau$ (CC)
$>$ 100 PeV	GRAND (Alvarez-Muniz *et al.*, 2018)	✓	ν_τ, $\bar{\nu}_\tau$ (CC)

ARGÜELLES, ET AL., REV. MOD. PHYS. 93, ARXIV:1912.09486

Neutrino Experiments

MeV GeV TeV PeV EeV

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

- Cherenkov detector at the South Pole.
- 1 gigaton of ice target with 5160 PMTs
- IceCube has a measured diffuse astrophysical neutrino flux in the TeV-PeV range.

Neutrino Experiments

MeV GeV TeV PeV EeV

BOREXINO – Liquid scintillator. Solar neutrinos (MeV)

KamLAND – Liquid scintillator (Reactor). Extraterrestrial neutrino fluxes (MeV)

DUNE – Liquid Argon TPC. Atmospheric neutrino fluxes (GeV)

ANTARES – Water Cherenkov. Atmospheric neutrinos (GeV-TeV)

ICECUBE – South Pole Neutrino Observatory

- Cherenkov detector at the South Pole.
- 1 gigaton of ice target with 5160 PMTs
- IceCube has a measured diffuse astrophysical neutrino flux in the TeV-PeV range.

SUPER K – Water Cherenkov. Atmospheric neutrinos (GeV-TeV)

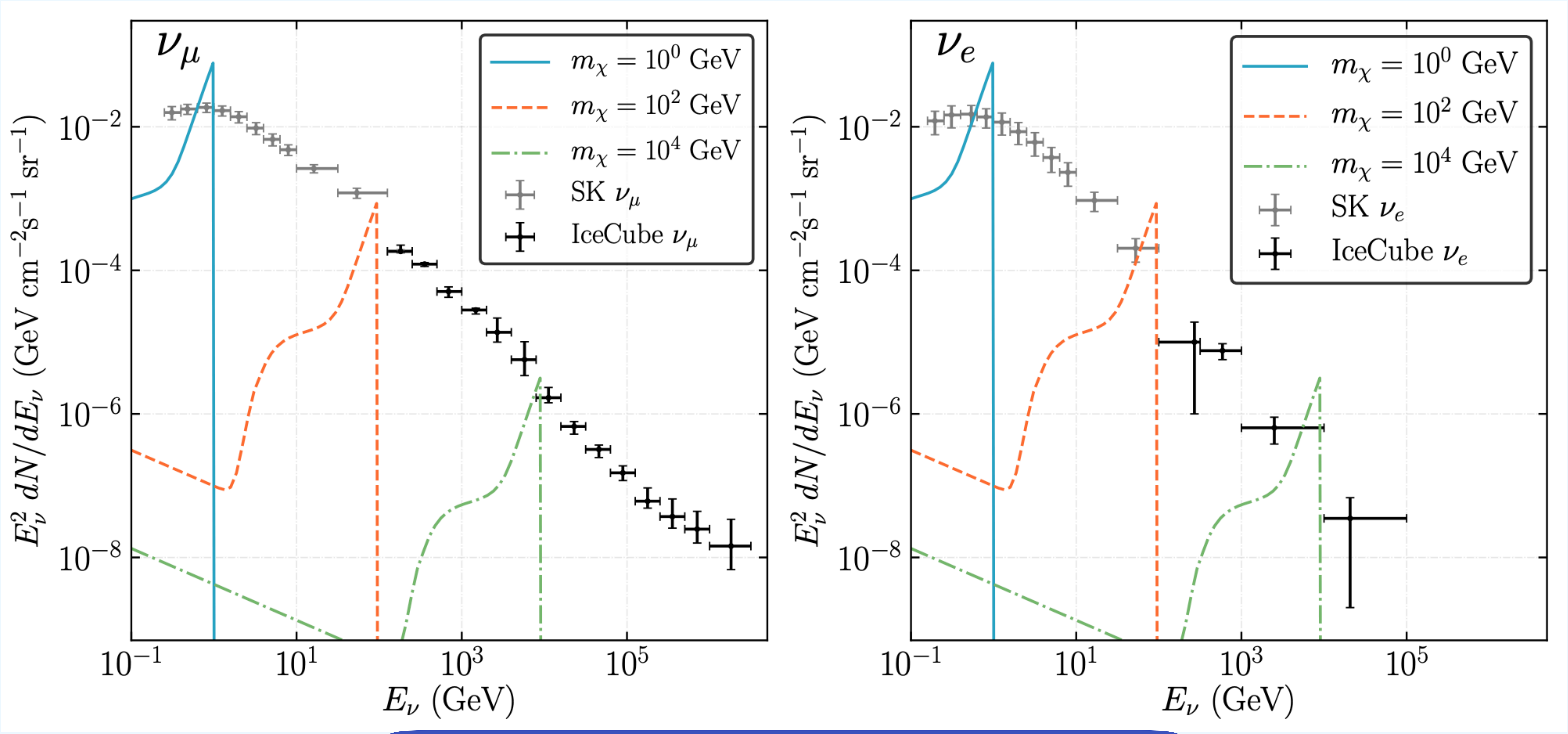
P-ONE – Sea Water Cherenkov Extraterrestrial neutrino fluxes (PeV)

TAMBO – Water Cherenkov. Astrophysical Tau Neutrino (PeV)

PIERRE AUGER OBSERVATORY – Water Cherenkov. Ultra High Energy Cosmic Rays (EeV)

GRAND – Radio Array. Tau Neutrinos (EeV)

Expected Neutrino Flux from Decaying Dark Matter



Background Agnostic $\Rightarrow \mathscr{L} = \begin{cases} \mathbb{P}(d\,|\,\mu) & (d < \mu), \\ 1 & (d \geq \mu) \end{cases}$

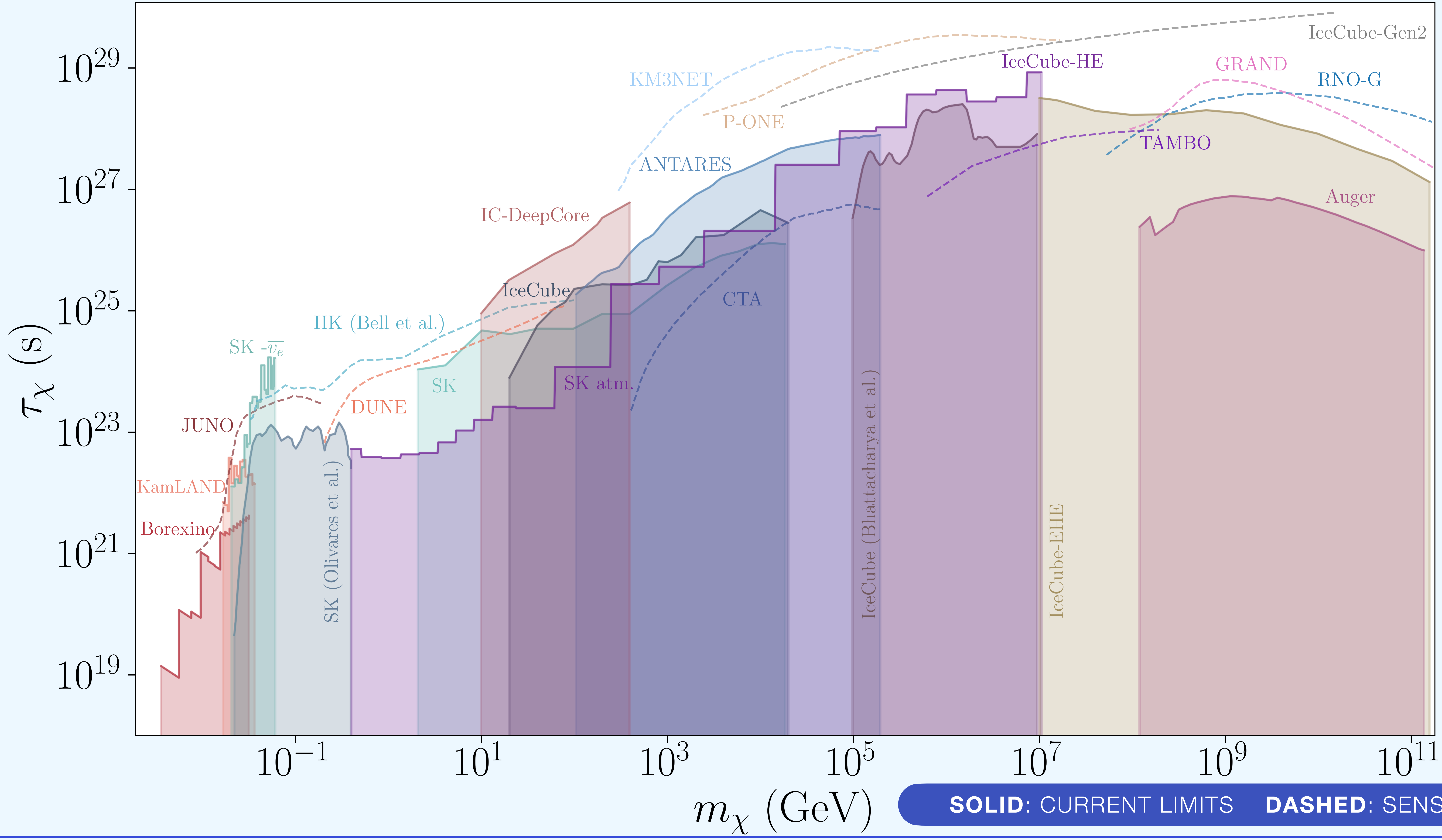
ARGÜELLES, ET AL., REV. MOD. PHYS. 93, ARXIV:1912.09486

RICHARD, E., ET AL. (SUPER-KAMIOKANDE) PHYS. REV. D94 (5), 052001

AARTSEN, M. G., ET AL. (ICECUBE) (2015B), PHYS. REV. D91, 122004

Decay results
Neutrino Experiments

C. Argüelles, **DD**, A. Vincent, A. Friedlander, H. White, A. Kheirandish, I. Safa



SOLID: CURRENT LIMITS **DASHED**: SENSITIVITIES

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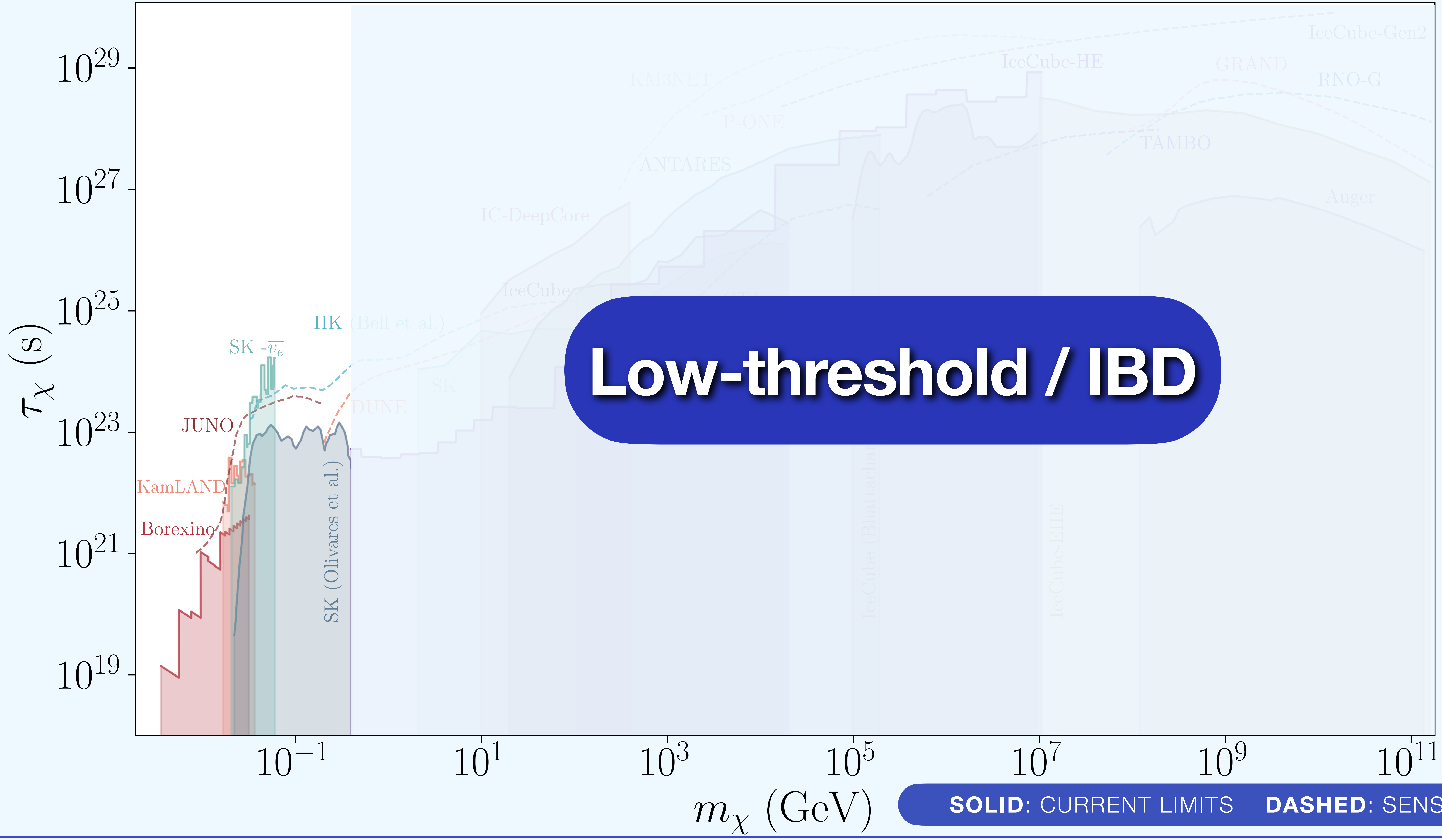

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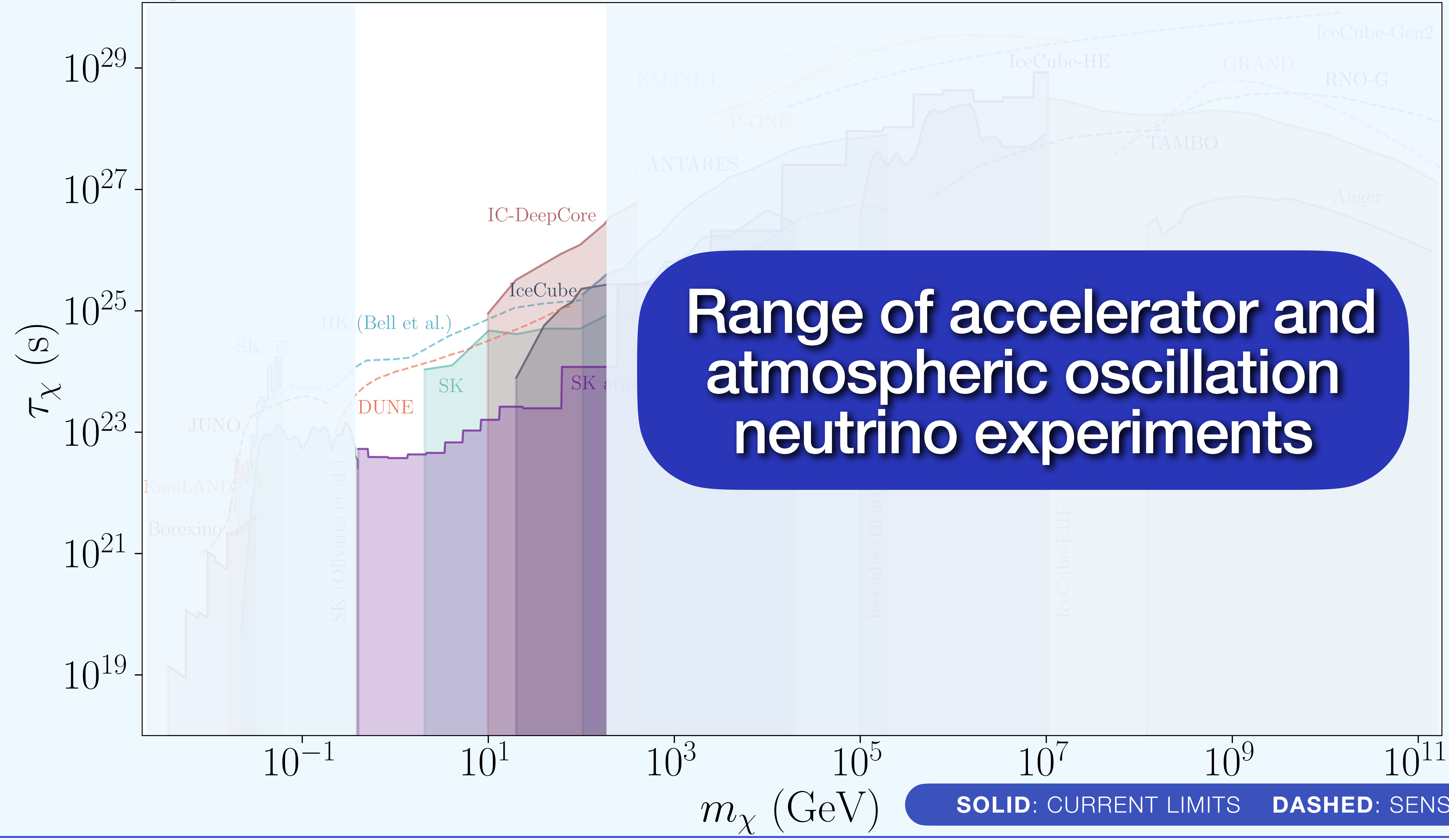

Range of accelerator and atmospheric oscillation neutrino experiments

SOLID: CURRENT LIMITS **DASHED**: SENSITIVITIES

Decay results

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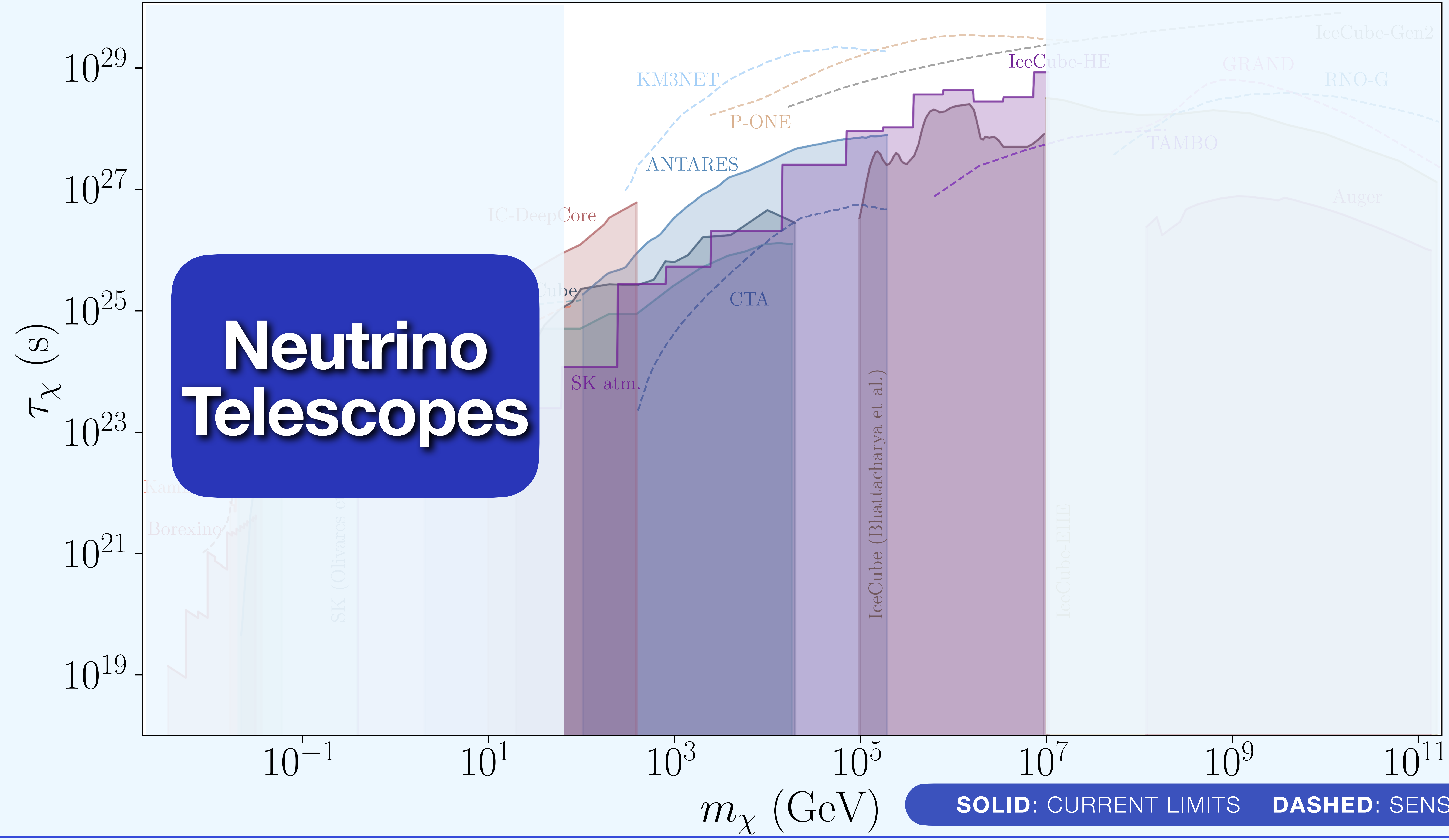

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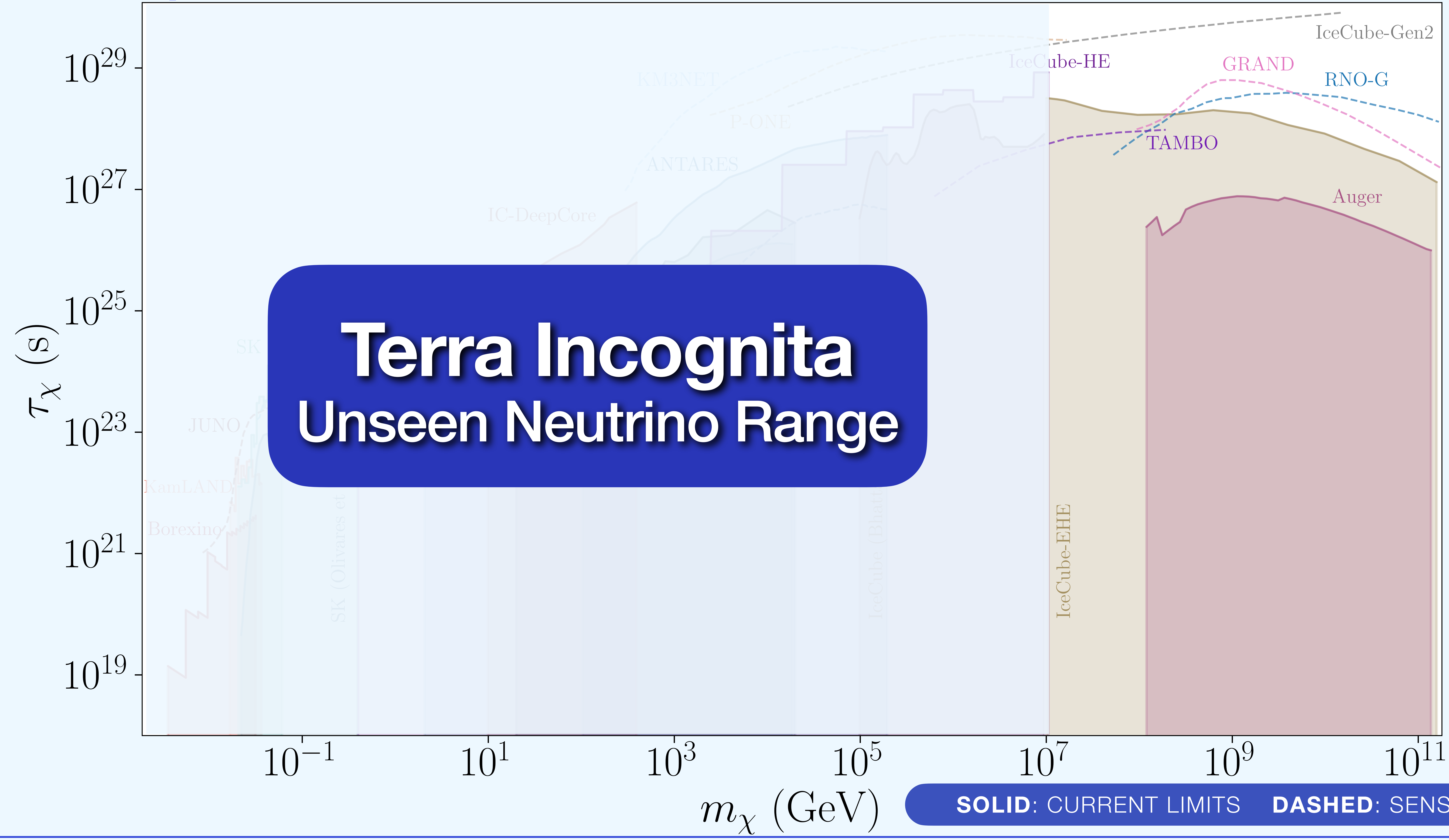

SOLID: CURRENT LIMITS **DASHED**: SENSITIVITIES

Decay Results

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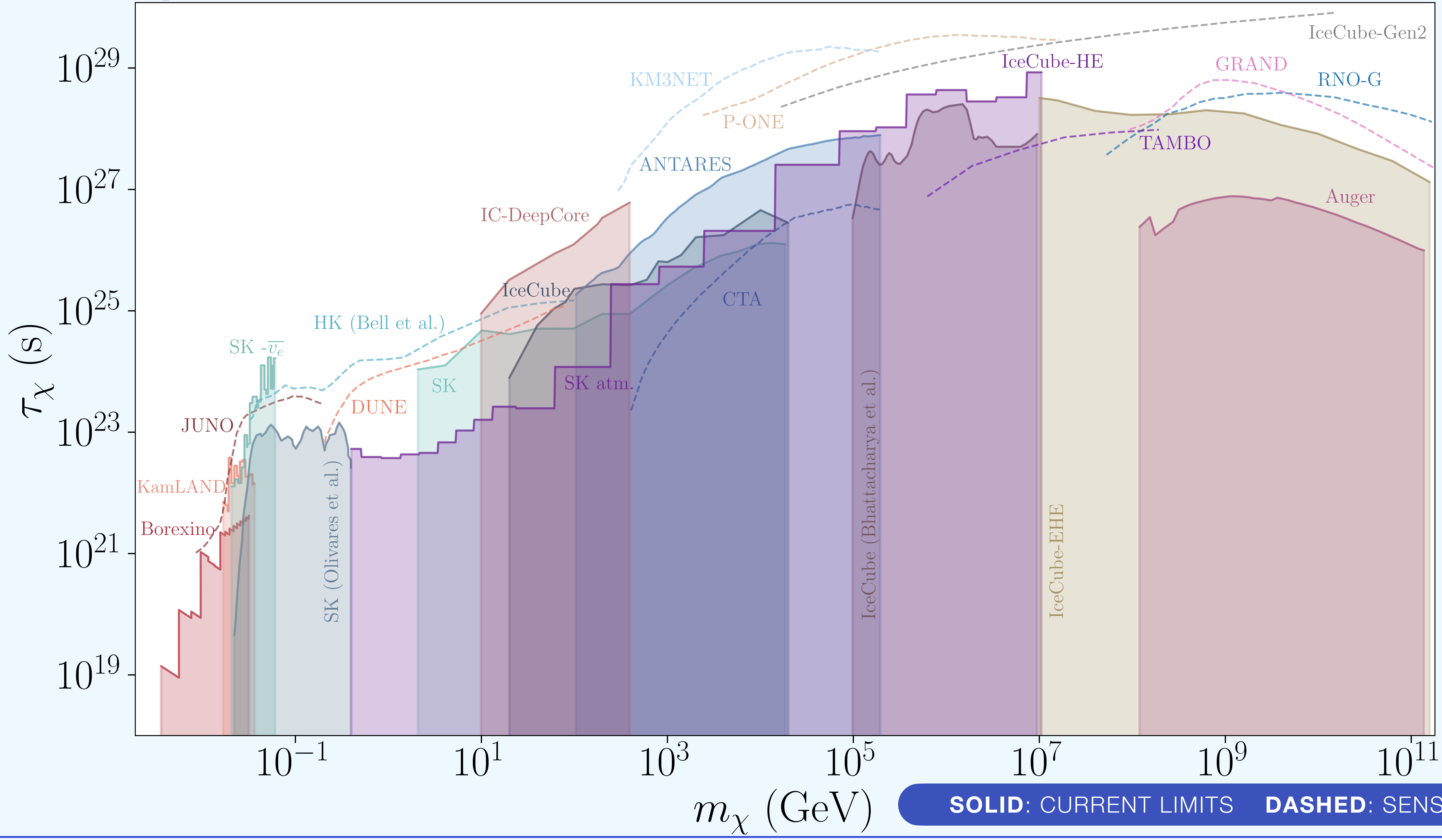
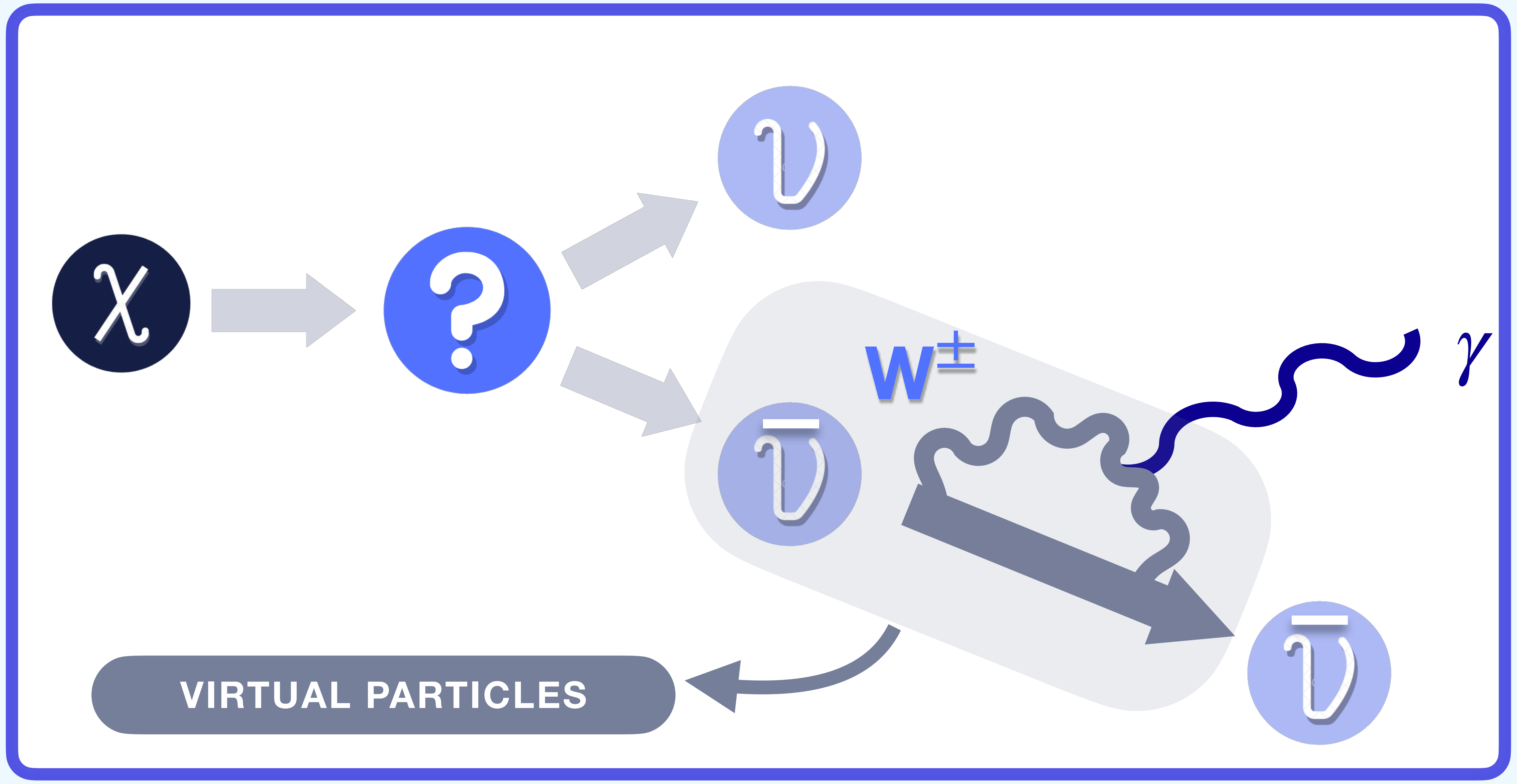


SOLID: CURRENT LIMITS **DASHED**: SENSITIVITIES

Dark Matter Decay to Neutrinos

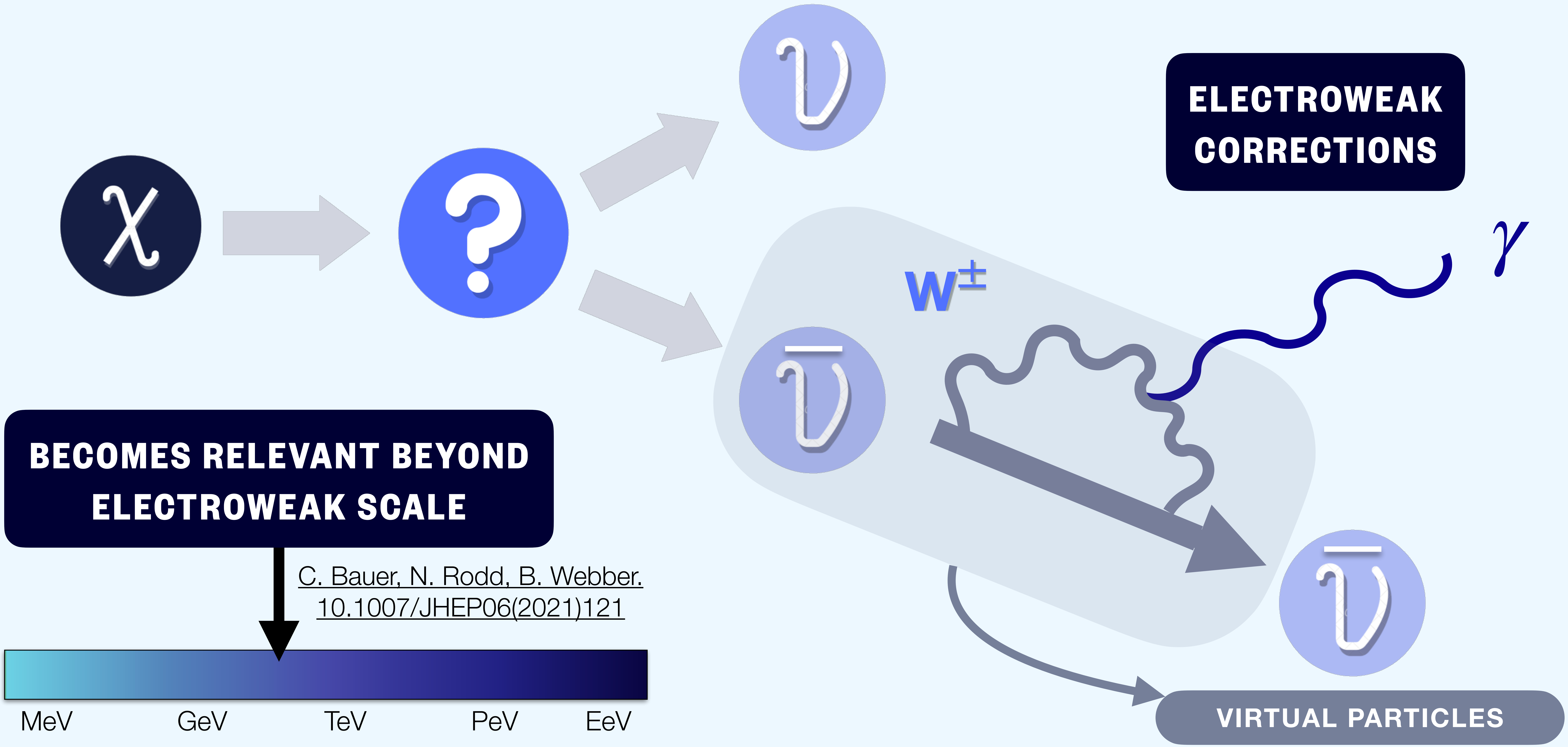


NEUTRINO SIGNAL

GAMMA-RAY SIGNAL

EXPECTED GAMMA-RAY SIGNAL DUE TO ELECTROWEAK CORRECTIONS

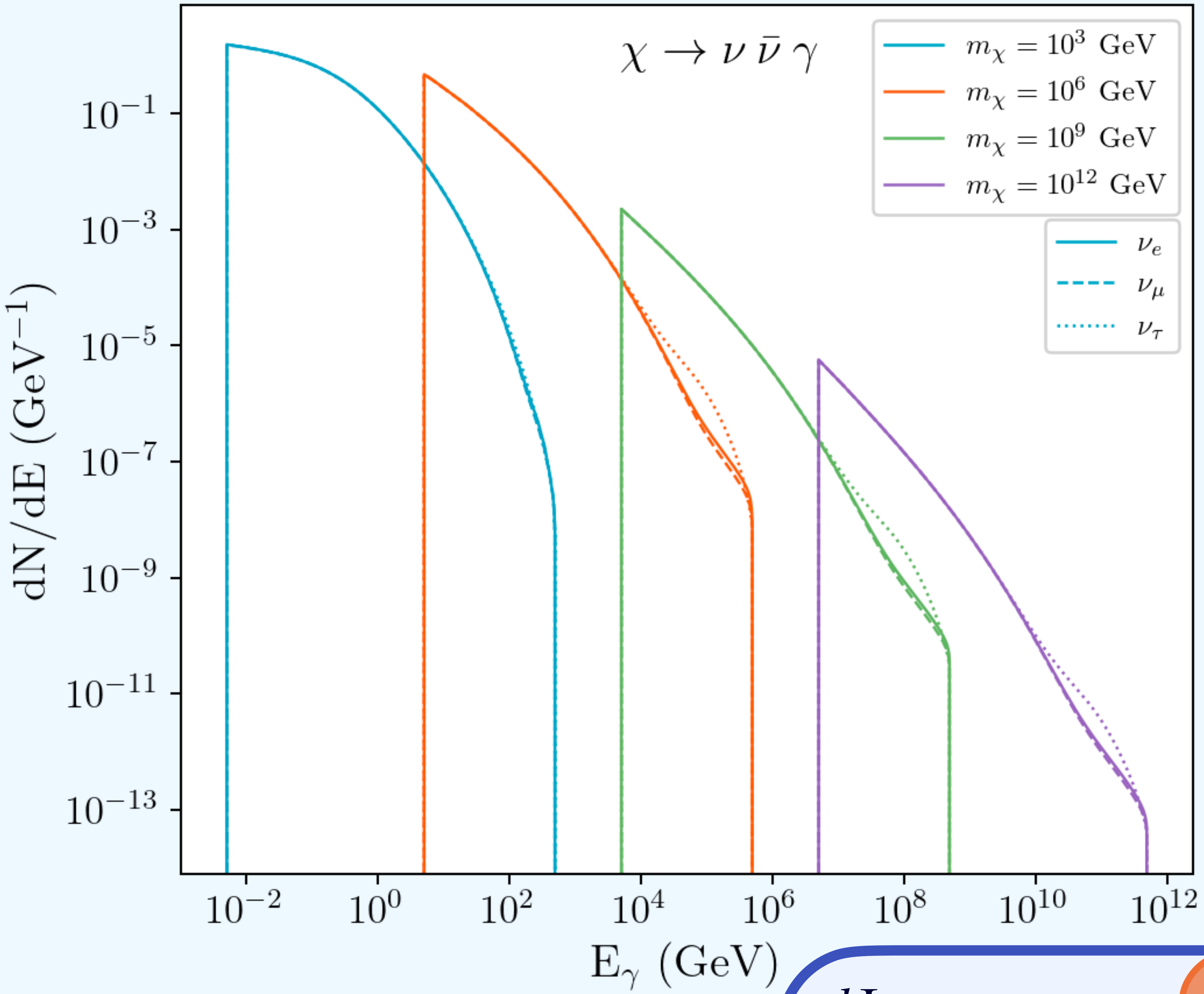
Dark Matter Search Detecting Gammas

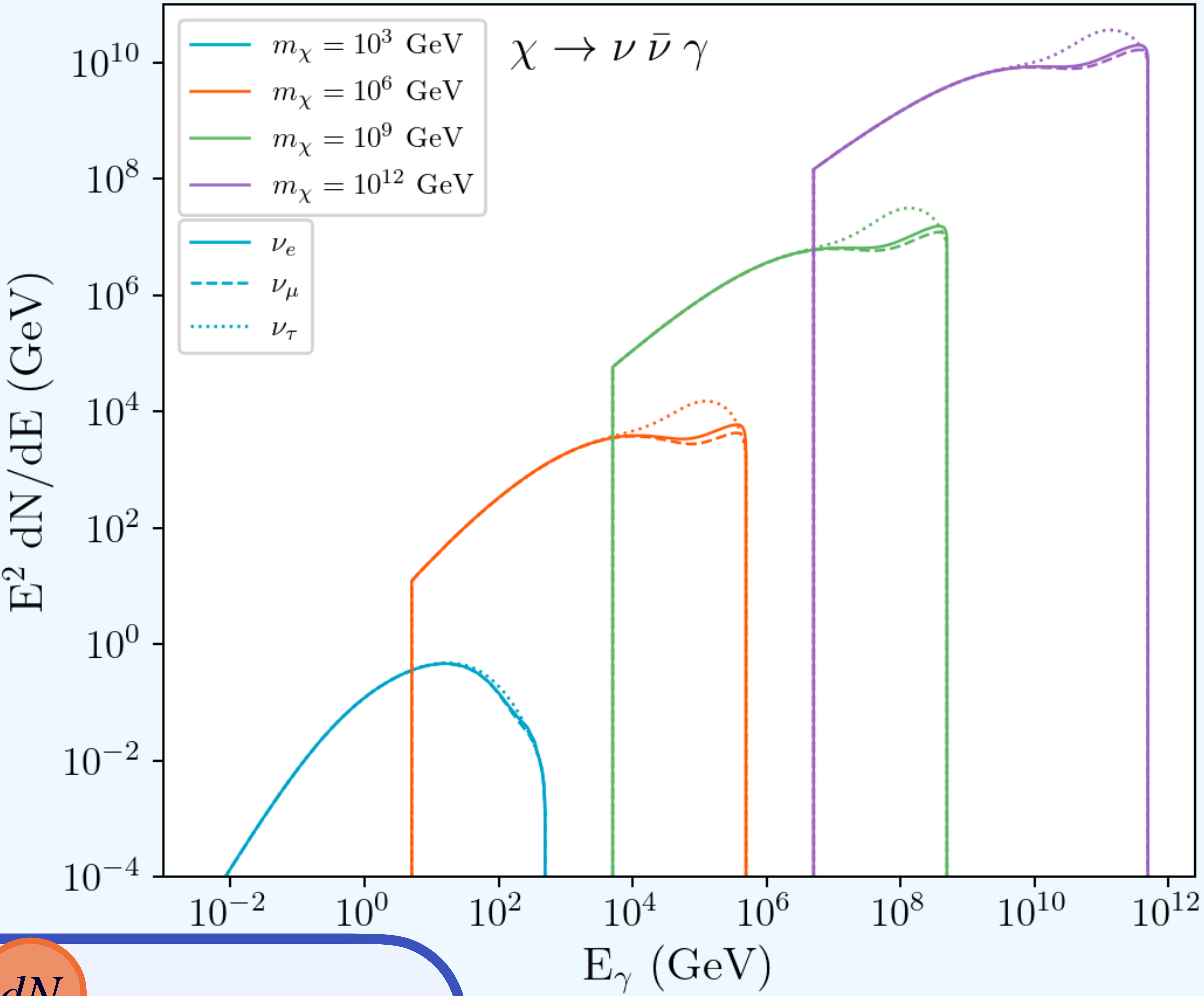


BECOMES RELEVANT BEYOND ELECTROWEAK SCALE

C. Bauer, N. Rodd, B. Webber.
10.1007/JHEP06(2021)121

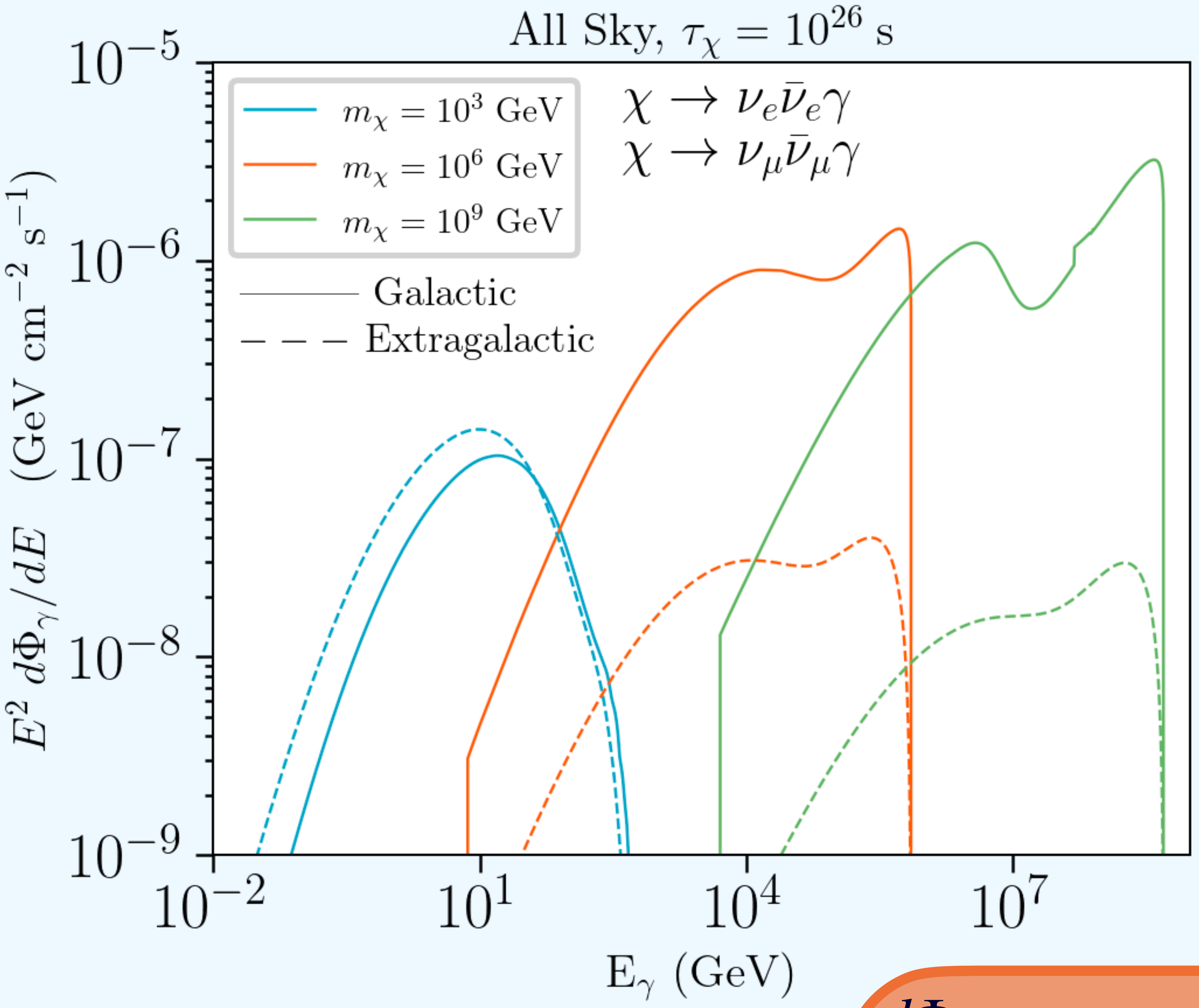
Expected Gamma-Ray Flux for Decaying Dark Matter

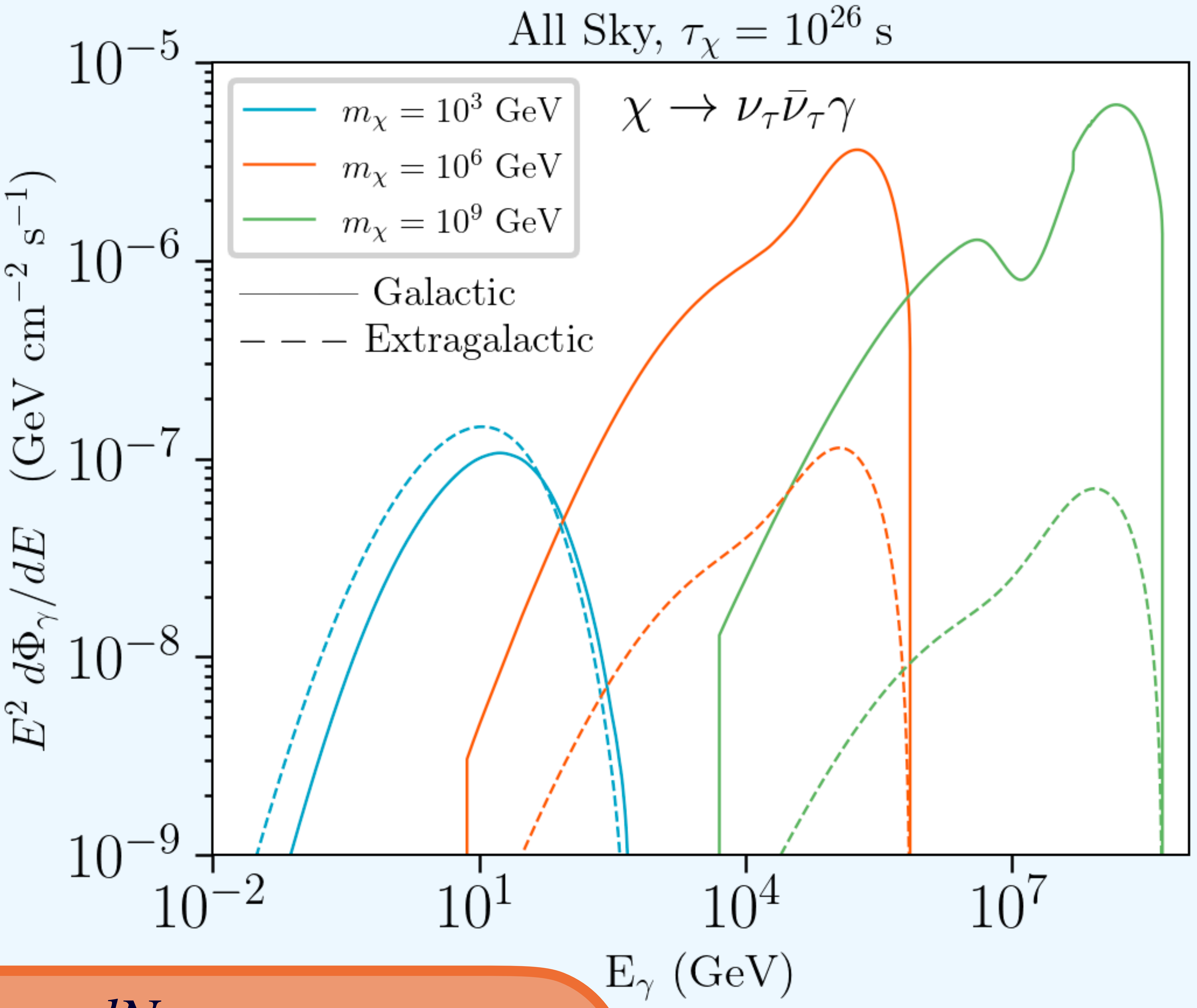




$$\frac{d\Phi_\gamma}{dE} = \frac{1}{4\pi}\,\frac{1}{m_\chi \tau_\chi}\,\frac{dN_\gamma}{dE_\gamma}\, D(\Omega, x)\, e^{-\tau_{\gamma\gamma}(E,L)}$$

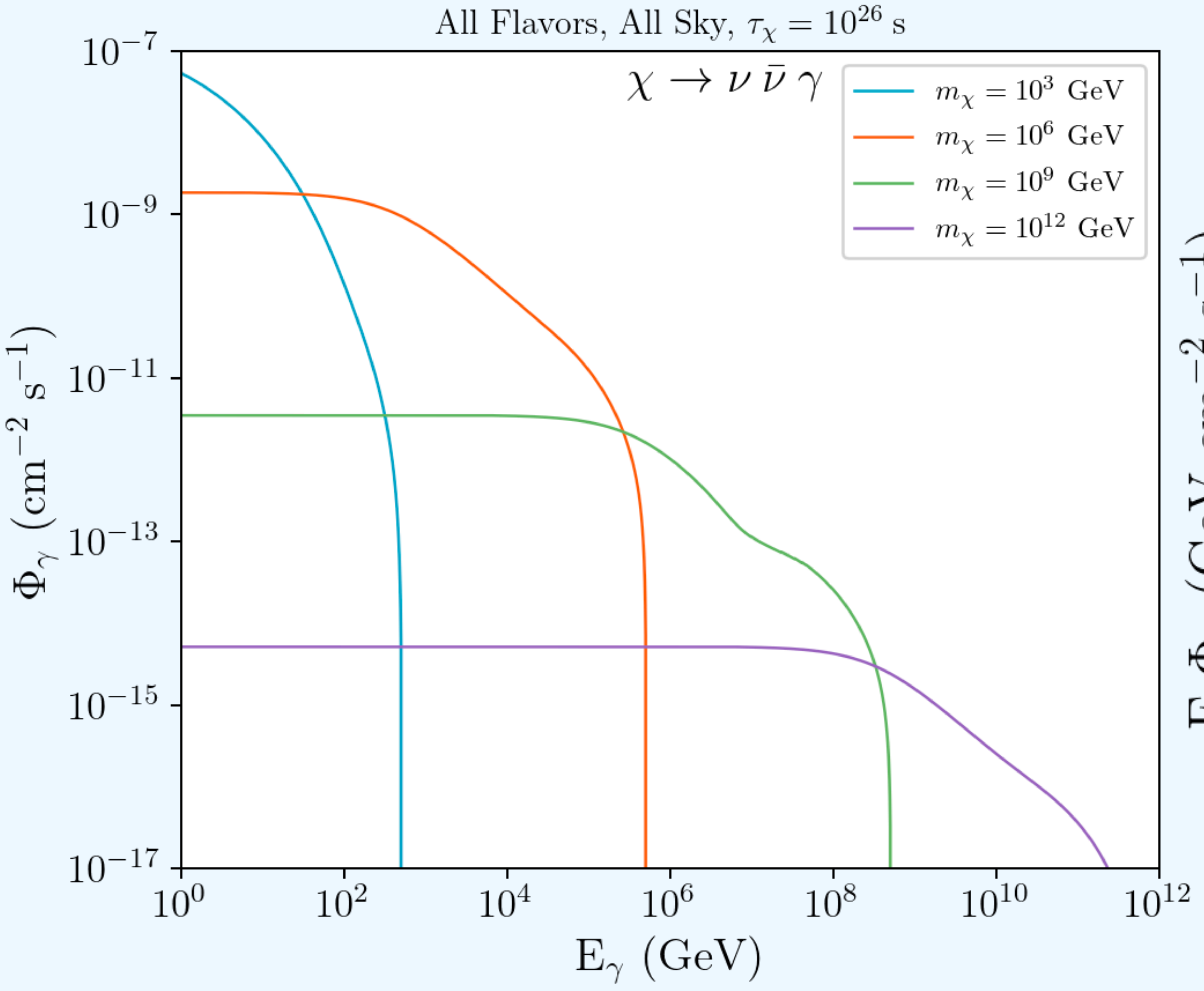
Expected Gamma-Ray Flux for Decaying Dark Matter

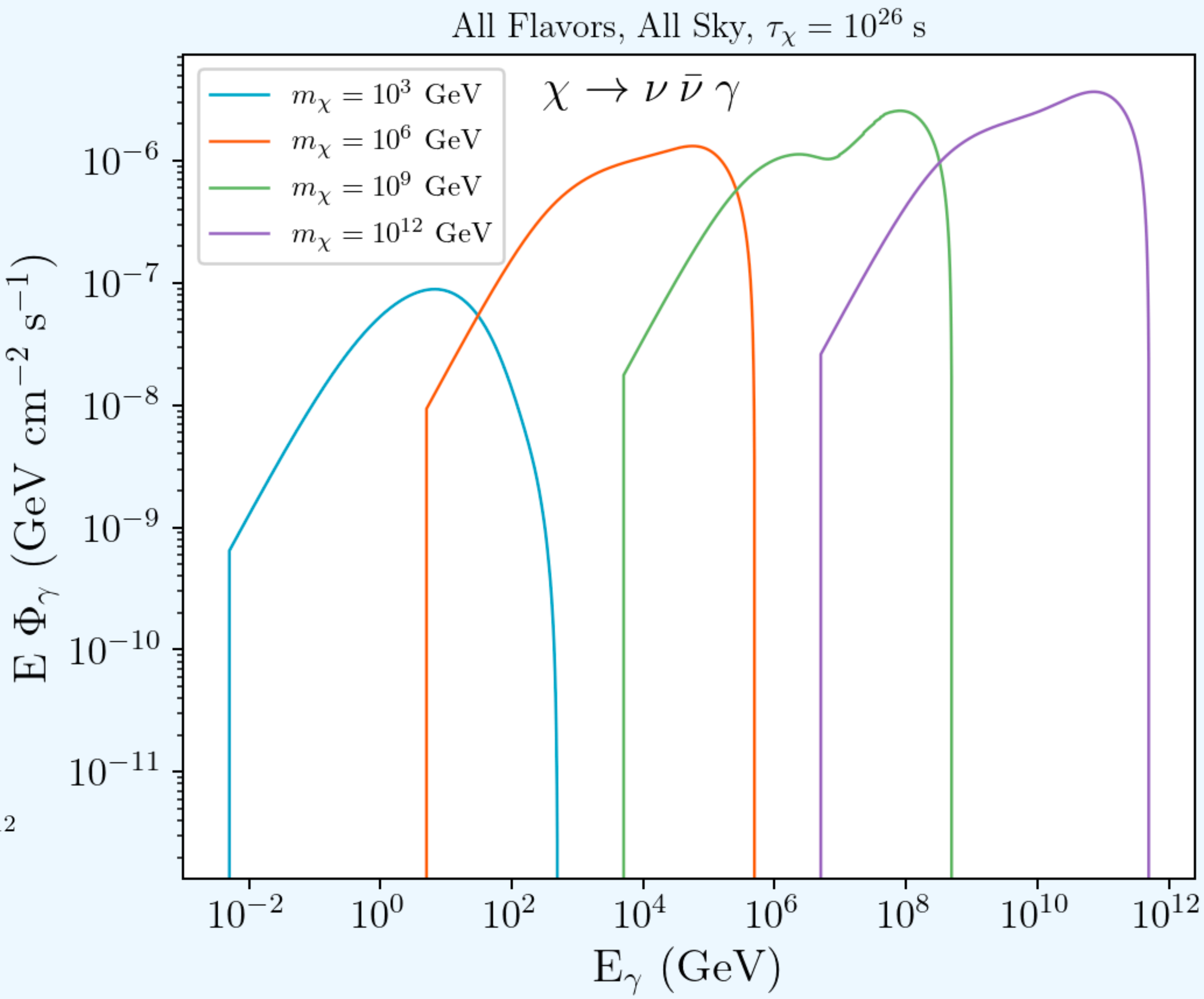




$$\frac{d\Phi_\gamma}{dE} = \frac{1}{4\pi}\,\frac{1}{m_\chi \tau_\chi}\,\frac{dN_\gamma}{dE_\gamma}\; D(\Omega, x)\; e^{-\tau_{\gamma\gamma}(E,L)}$$

Expected Gamma-Ray Flux for Decaying Dark Matter





Gamma-Ray Experiments

MeV GeV TeV PeV EeV

HAWC — High Altitude Water Cherenkov Gamma-Ray Observatory: Water Cherenkov. Gamma Rays and Cosmic Rays (GeV - TeV)

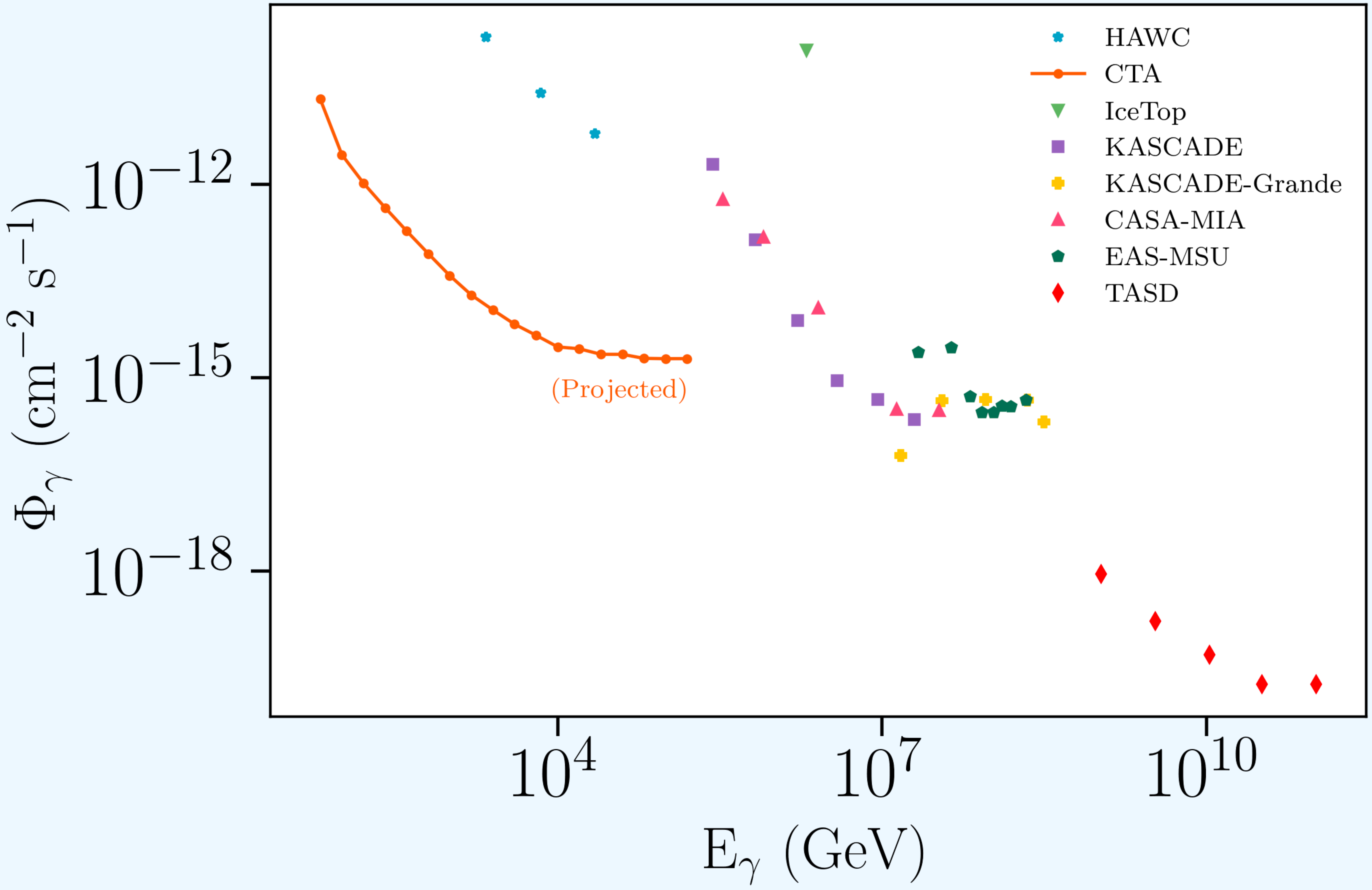
LHAASO: Hybrid Air Shower. Gamma Rays (GeV - PeV)

cta — cherenkov telescope array: Air Cherenkov. High Energy Gamma Rays (TeV)

IceCube — South Pole Neutrino Observatory — **Ice Top**: Air Showers. Gamma Rays and Cosmic Rays (PeV)

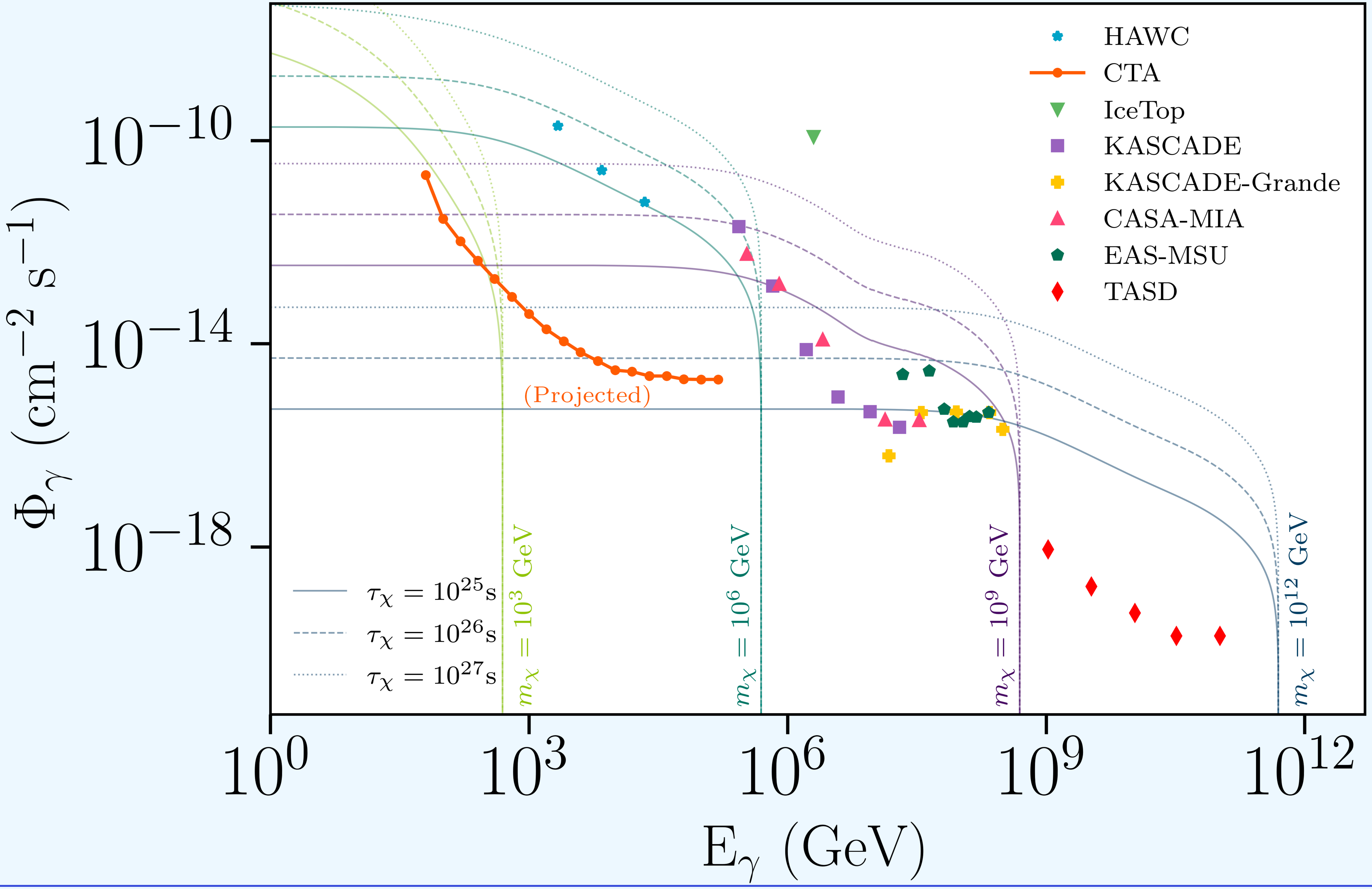
AND OTHER EXPERIMENTS

Integral γ Flux Sensitivities



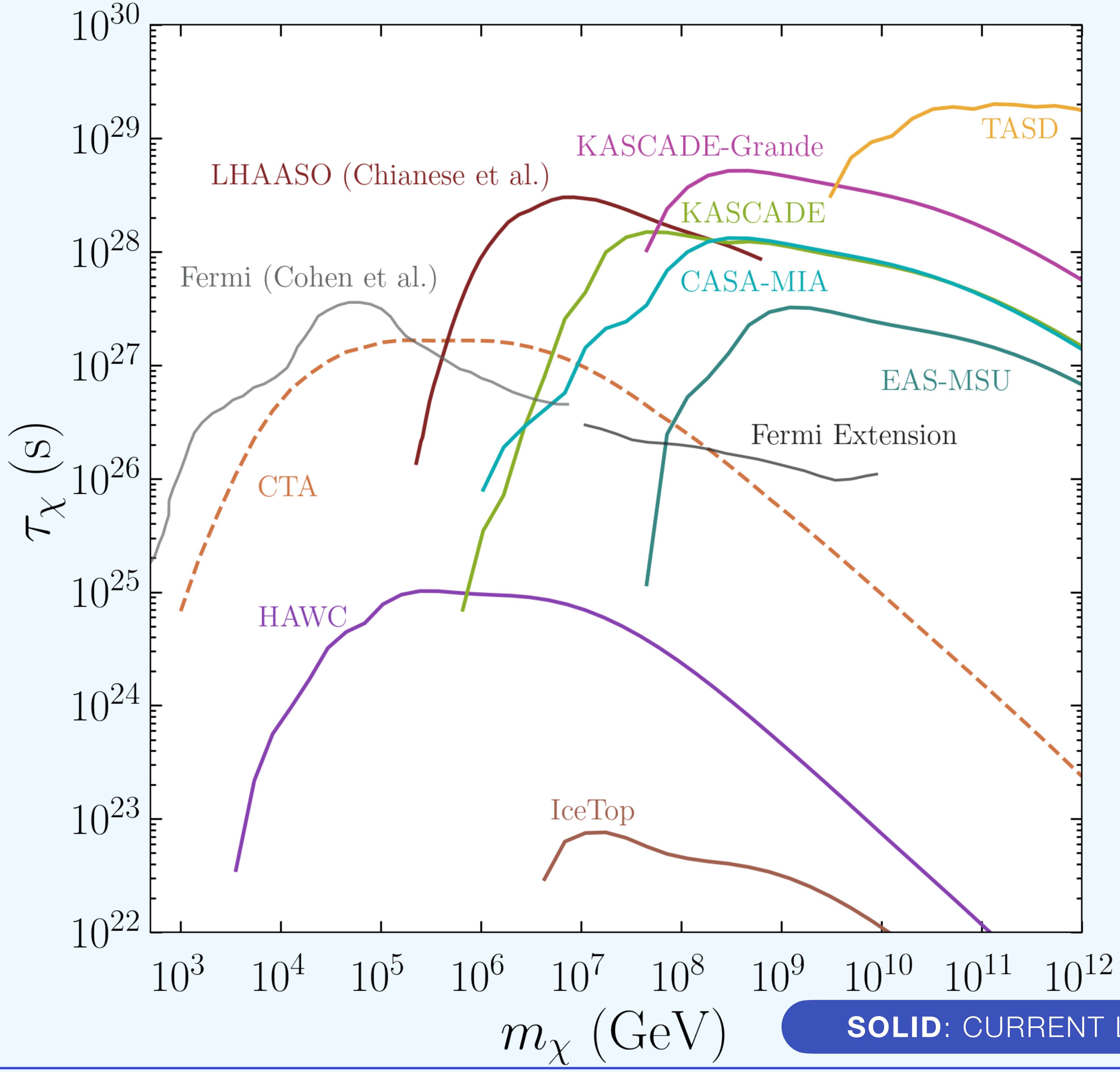
Experiment	D (GeV cm^{-2}sr^{-1})
CTA	$3.29 \cdot 10^{20}$
HAWC	$2.95 \cdot 10^{21}$
IceTop	$8.74 \cdot 10^{22}$
KASCADE	$9.18 \cdot 10^{22}$
KASCADE-Grande	$9.18 \cdot 10^{22}$
CASA-MIA	$1.13 \cdot 10^{23}$
EAS-MSU	$8.35 \cdot 10^{22}$
TASD	$8.60 \cdot 10^{22}$

Integral γ Flux from DM and Gamma-Ray Flux Sensitivities



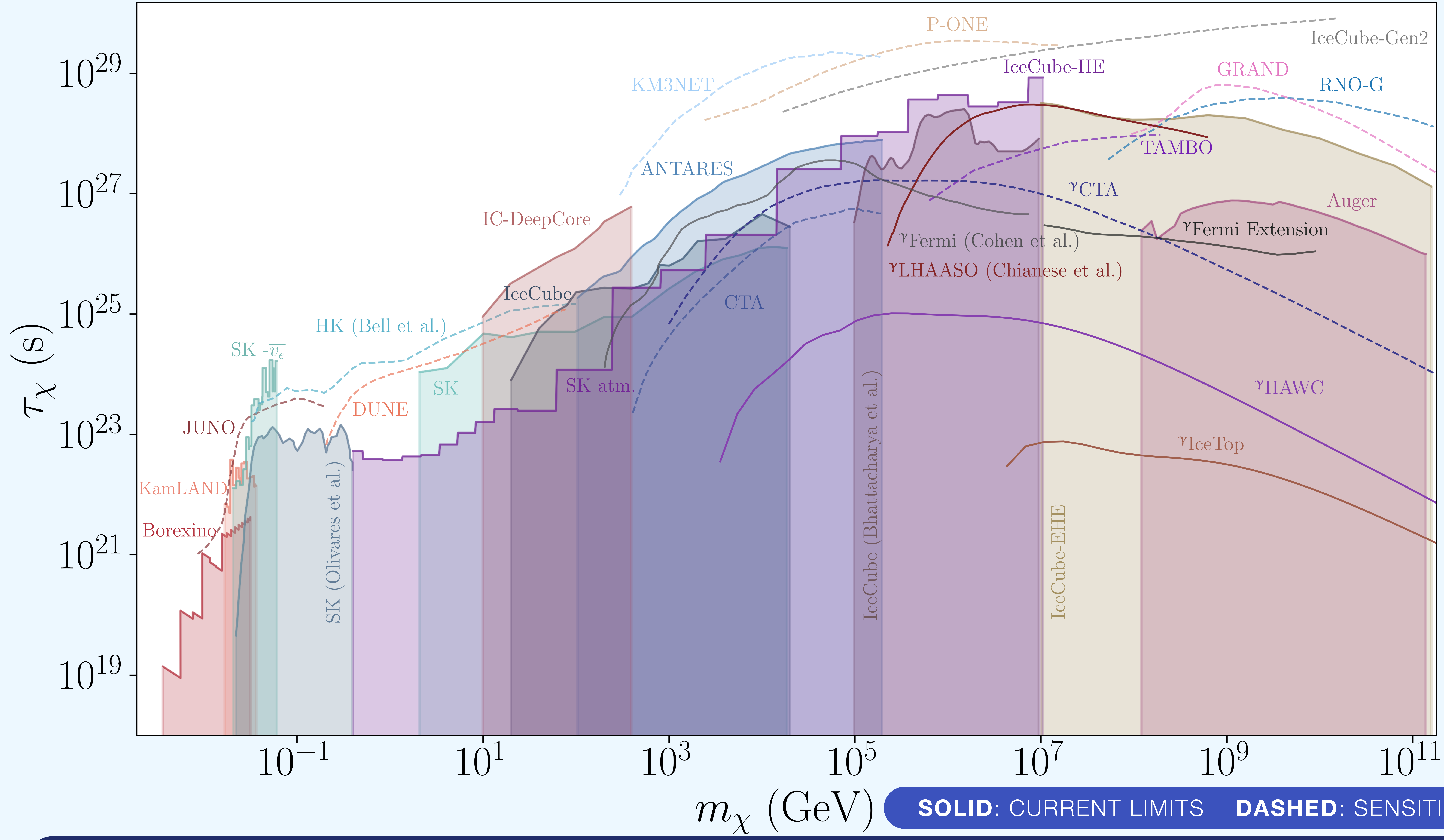
Decay Results
Gamma-Ray Experiments

C. Argüelles, **DD**, A. Vincent, A. Friedlander, H. White, A. Kheirandish, I. Safa



SOLID: CURRENT LIMITS **DASHED**: SENSITIVITIES

Dark Matter Decay to Neutrinos: Comprehensive Results



SOLID: CURRENT LIMITS **DASHED**: SENSITIVITIES

C. ARGÜELLES, **D. DELGADO**, A. VINCENT, A. FRIEDLANDER, H. WHITE, A. KHEIRANDISH, I. SAFA **[IN PREPARATION (2022)]**

Summary

- **Dark Matter (DM) neutrino connections** offer solutions to the mysteries of the nature of Dark Matter and origin of neutrino mass.
- We can look for both neutrinos and gamma-rays as final products of Dark matter decay to neutrinos → Correlated signal.
- We present new comprehensive constrains for the Dark Matter decay lifetime in the **wide mass range** of m_χ = [MeV - EeV], thanks to major experimental advances.
- New constraints for gamma rays contribution to the lifetime limits will be reported on an upcoming paper. Stay tuned!

THANK YOU!

ANY QUESTIONS?

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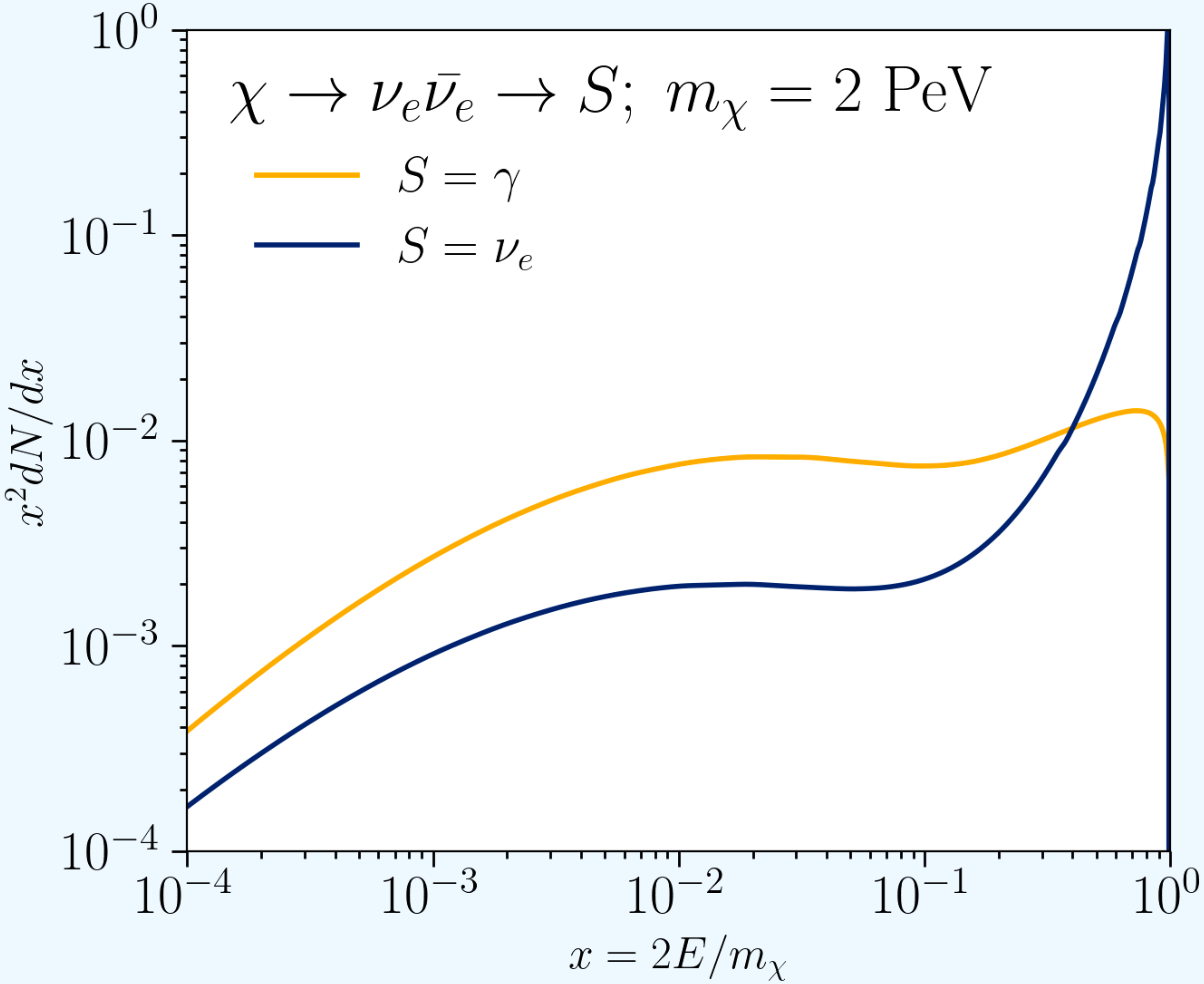
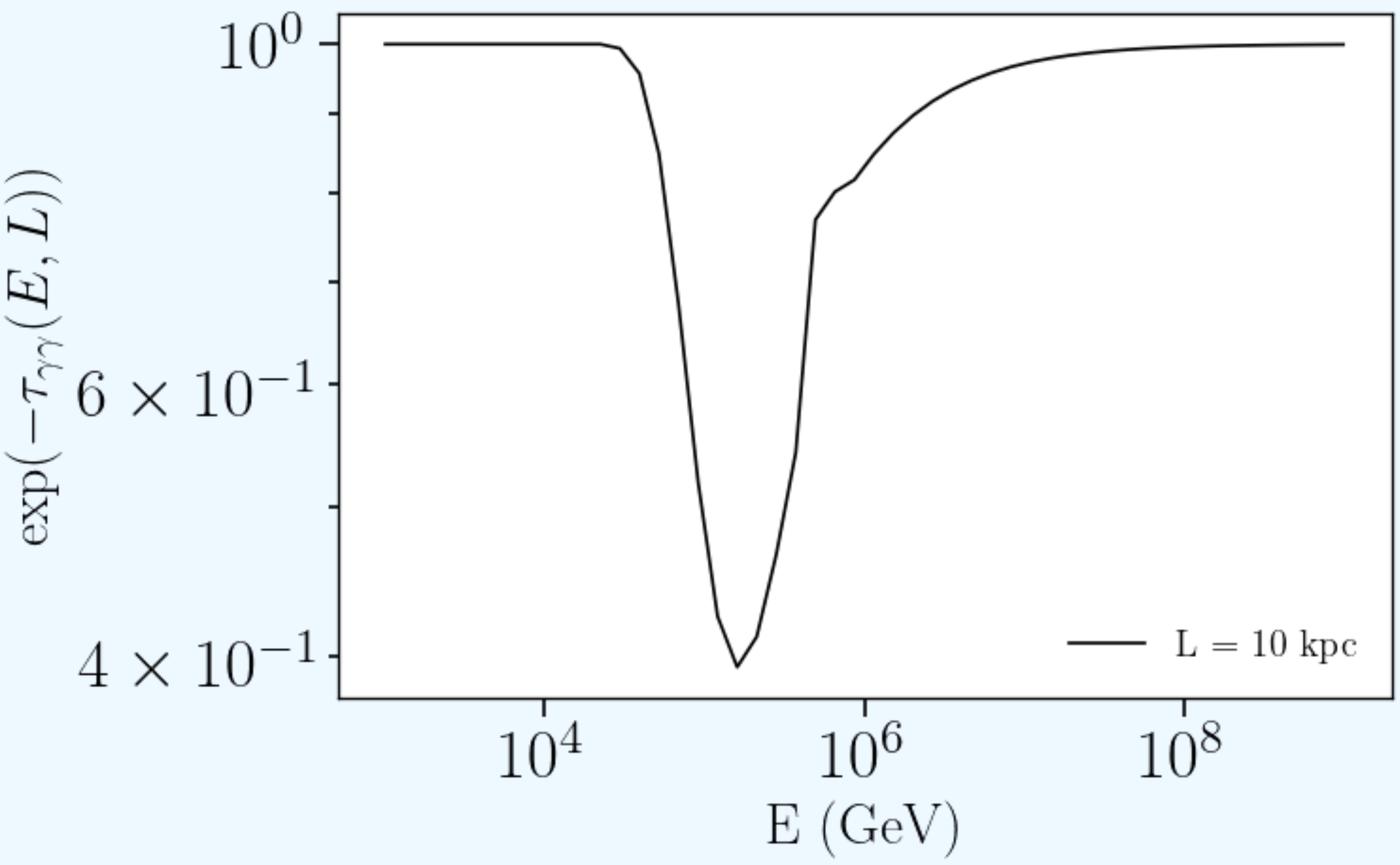
Backup

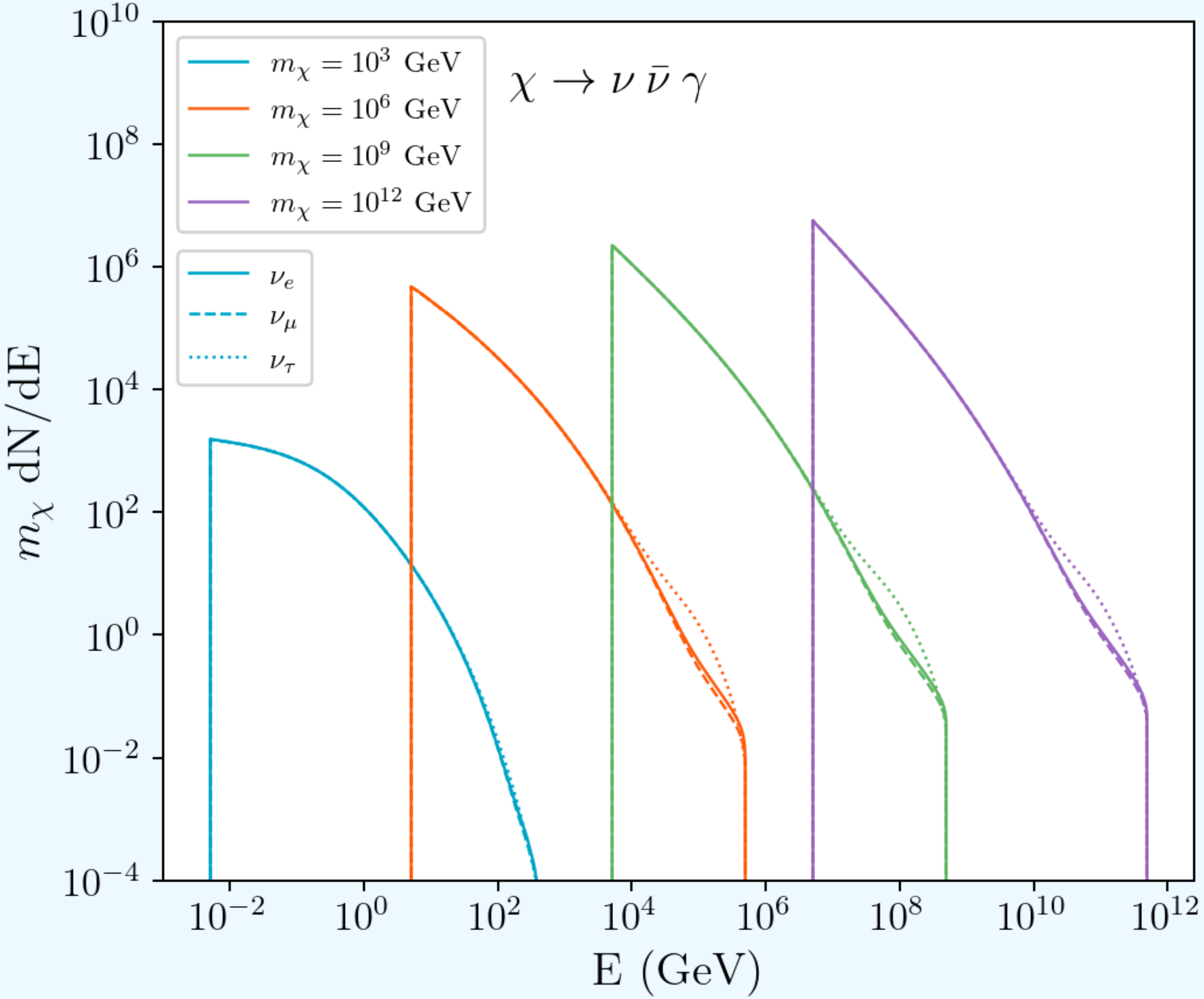
Neutrino Production Spectrum for Direct Decay of DM to Neutrinos



Absorption Factor for Gamma-Ray Flux



Expected Gamma-Ray Flux for Decaying Dark Matter



Converting Differential or Diffuse Flux Limits to Lifetimes

1

Diffuse Fluxes

$$\tau_\chi = \frac{1}{4\pi}\frac{1}{m_\chi \Phi_\nu}\frac{1}{3}\frac{dN_\nu}{dE} D$$

2

Differential Fluxes

$$\tau = \frac{2D(\alpha - 1)}{3m_\chi^2(4\pi)^2}\left(\left(10^{\Delta/2} - 10^{-\Delta/2}\right)\frac{d\phi}{dE}\bigg|_{lim}\right)^{-1}$$

Differential Fluxes ($\alpha = 1$)

$$\tau = \frac{2D}{3m_\chi^2(4\pi)^2}\left(\Delta\ln(10)\frac{d\phi}{dE}\bigg|_{lim}\right)^{-1}$$

3

Rescaled Annihilation Limits

Converting Gamma-Ray Diffuse Flux Limits to Limits on the Dark Matter Differential Spectrum

- The reported gamma-ray flux limit, $\left.\frac{d\phi}{dE}\right|_{lim} \equiv f_0\, E^{-\alpha}$, for which the actual limit at the bin center $E = \bar{E}$ is:

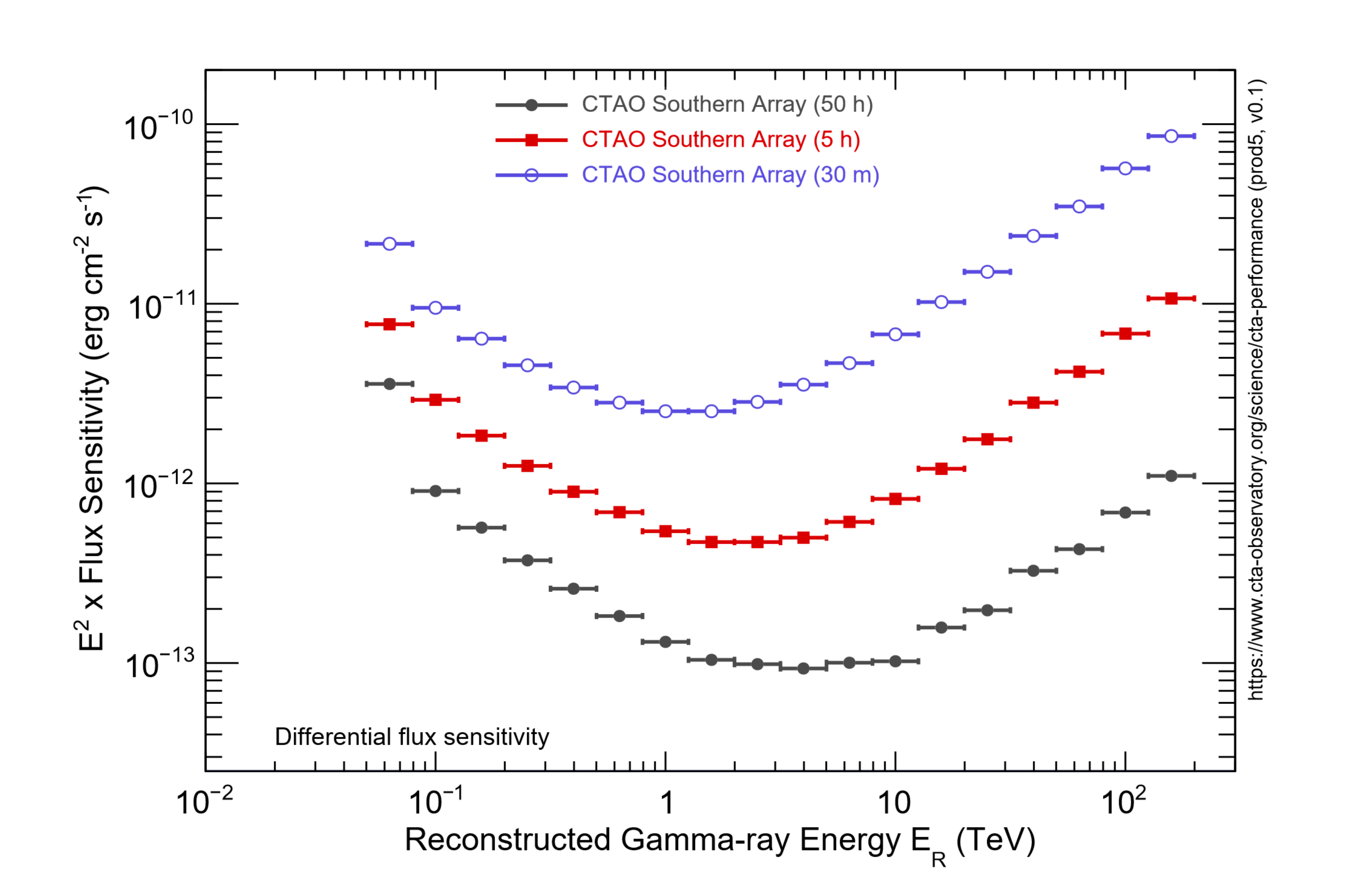
$$\phi_{lim}(\bar{E}) = 4\pi \int_{a_-}^{a^+} f_0 E^{-\alpha} dE \quad \textbf{with} \;\; a_\pm \equiv \bar{E}\, 10^{\pm\Delta/2}$$

Δ is the bin width.

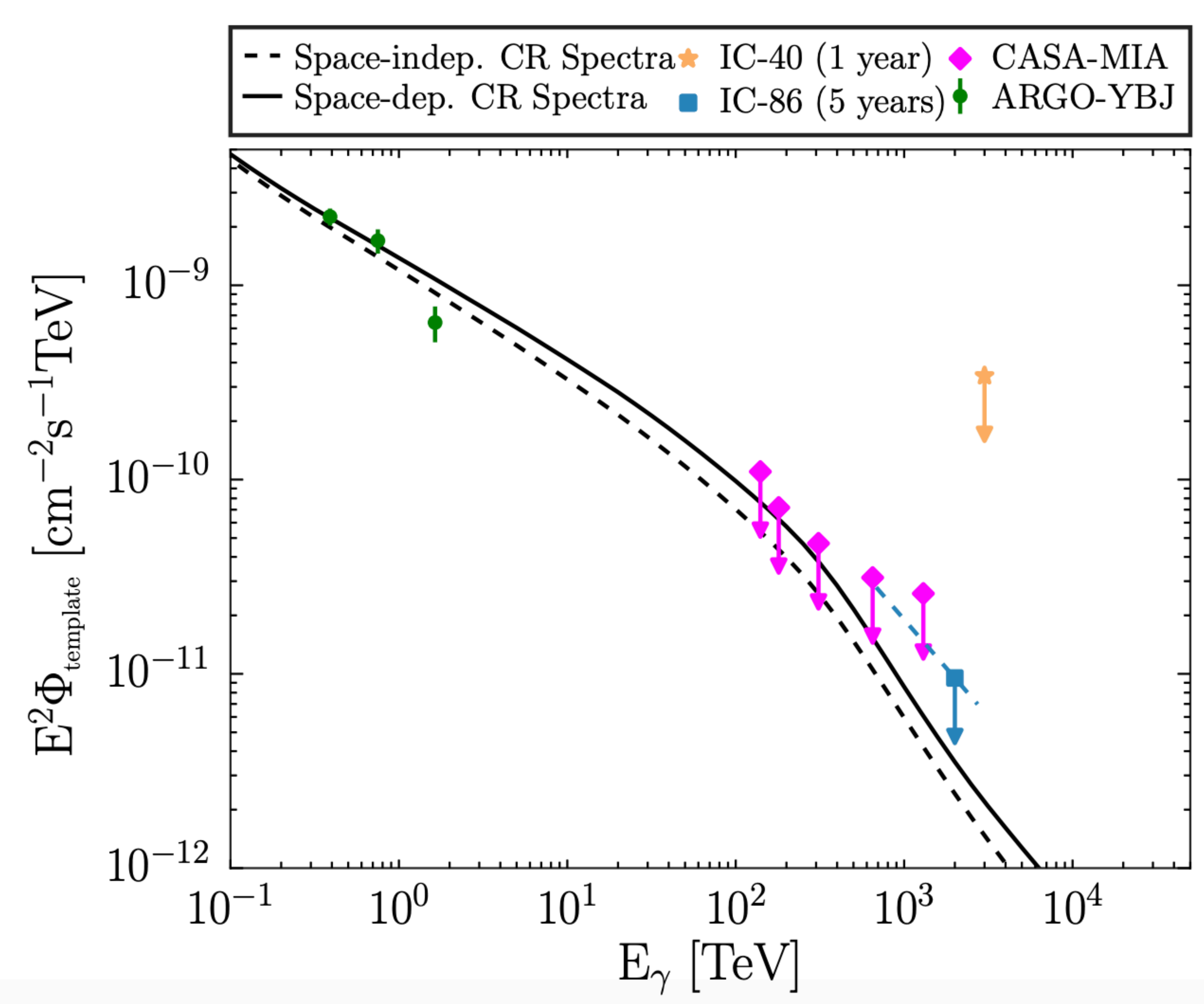
- Dark matter flux is given by:

$$\phi = \int dE\, \frac{1}{4\pi} \frac{1}{m_\chi \tau_\chi} \frac{dN_\gamma}{dE} D(\Omega, x)$$

Gamma-Ray Experimental Sensitivities

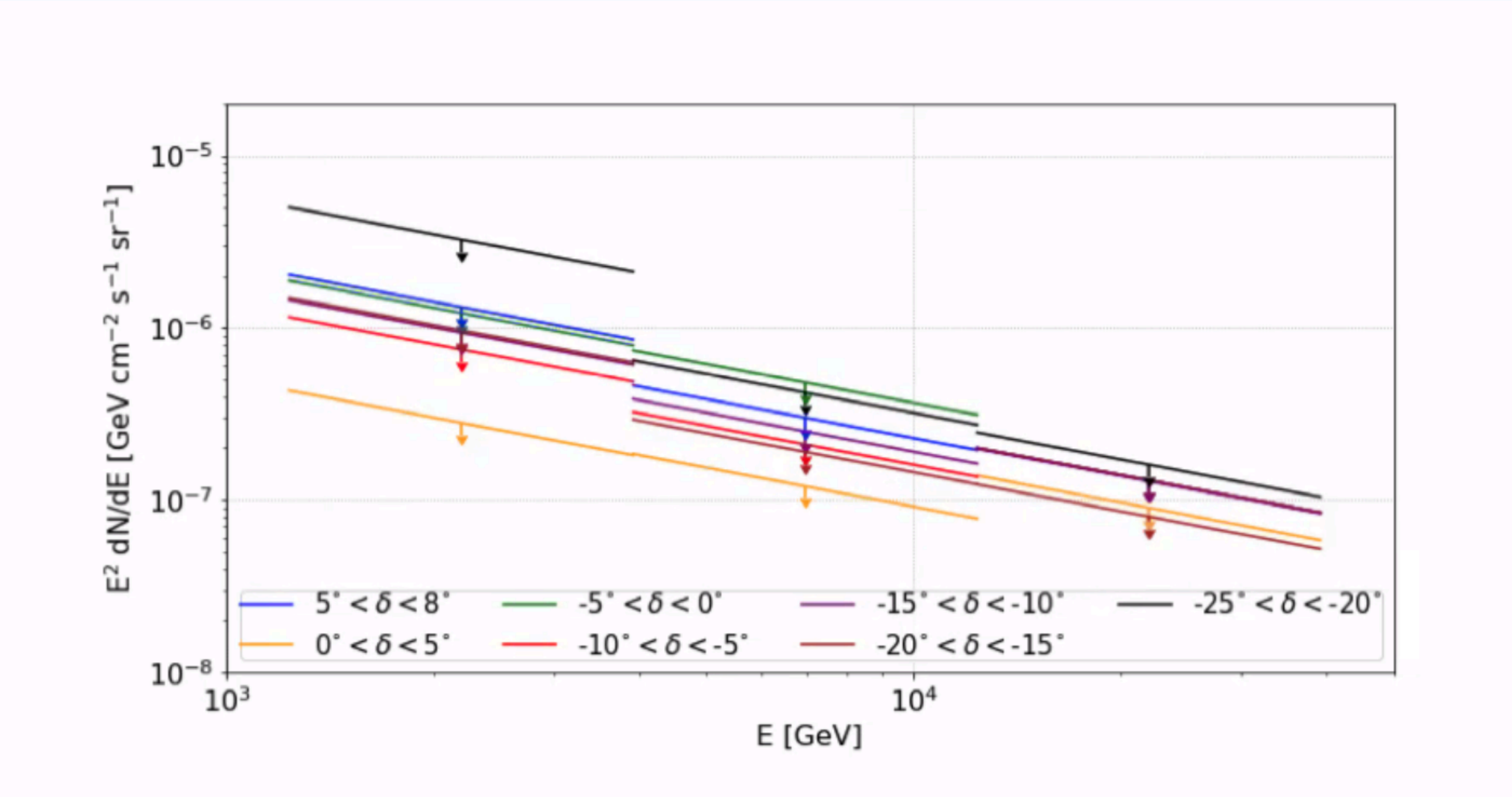


CTA



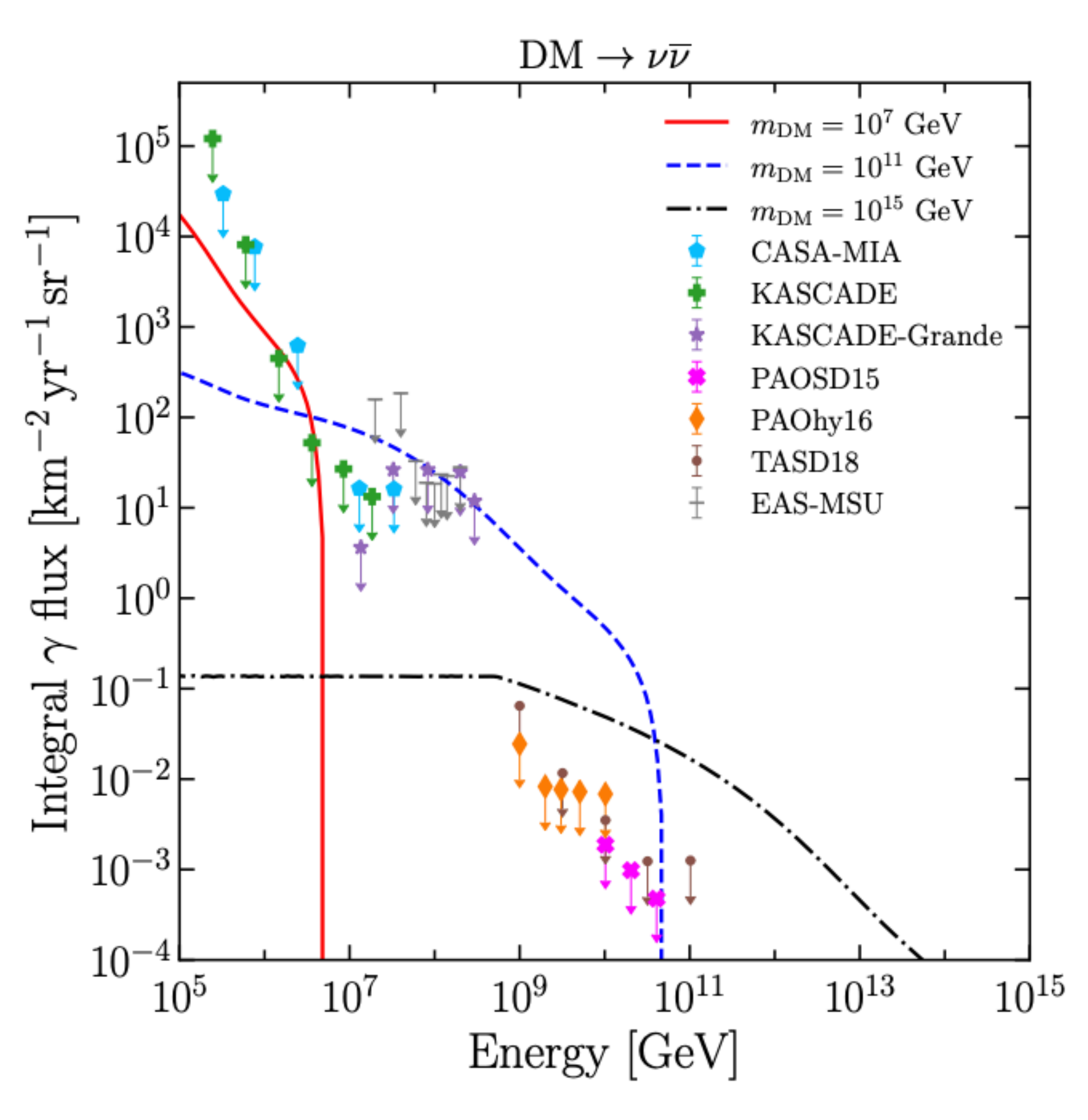
Ice Top

Gamma-Ray Experimental Sensitivities



HAWC

Gamma-Ray Experimental Sensitivities



CHIANESE ET. AL. (2021)

Gamma-Ray Electroweak Corrections

- The standard 1 → 2 decay process is $\chi \to \bar{\nu}\nu$.
- Higher orders involve the bremsstrahlung of an electroweak gauge boson.
- The branching ratio $R = \sigma(\chi \to \bar{\nu}\nu W)$ / $\sigma(\chi \to \bar{\nu}\nu)$ only depends generally only on the details of the underlying 1 → 2 process for $Q^2 \sim m_\chi^2$.
- We have three cases:

1. Fermi regime $m_\chi \lesssim m_W$
2. Perturbative electroweak regime $m_\chi \lesssim m_W \lesssim 10^6$ GeV
3. Non-perturbative regime where large logarithms over-compensate the small electroweak coupling α_2

KACHELRIEß, ET AL.,PHYS. REV. D 76, ARXIV:0707.0209