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

43rd International School of Nuclear Physics - Erice, Sicily
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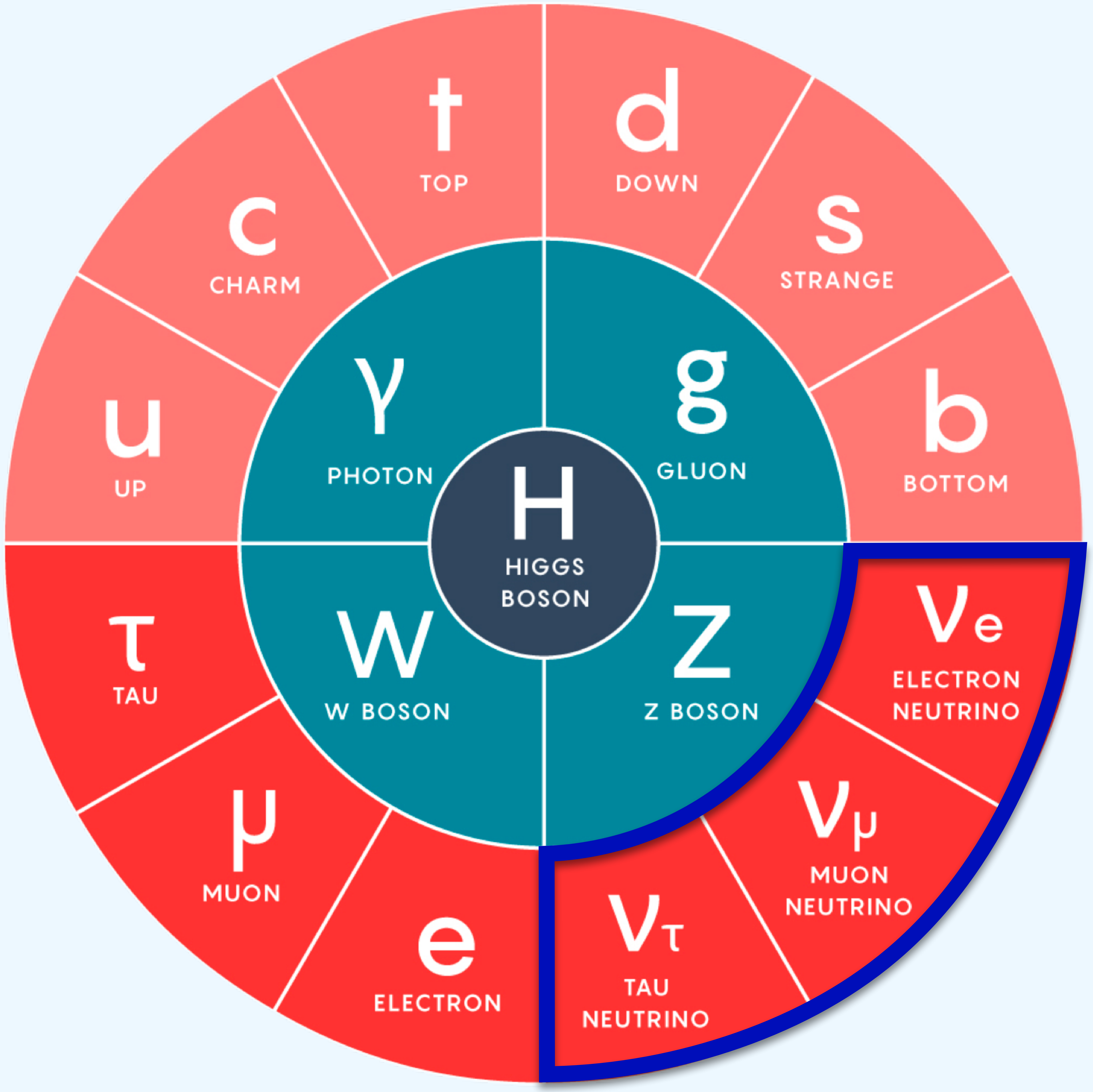
Standard Model is great and all but …

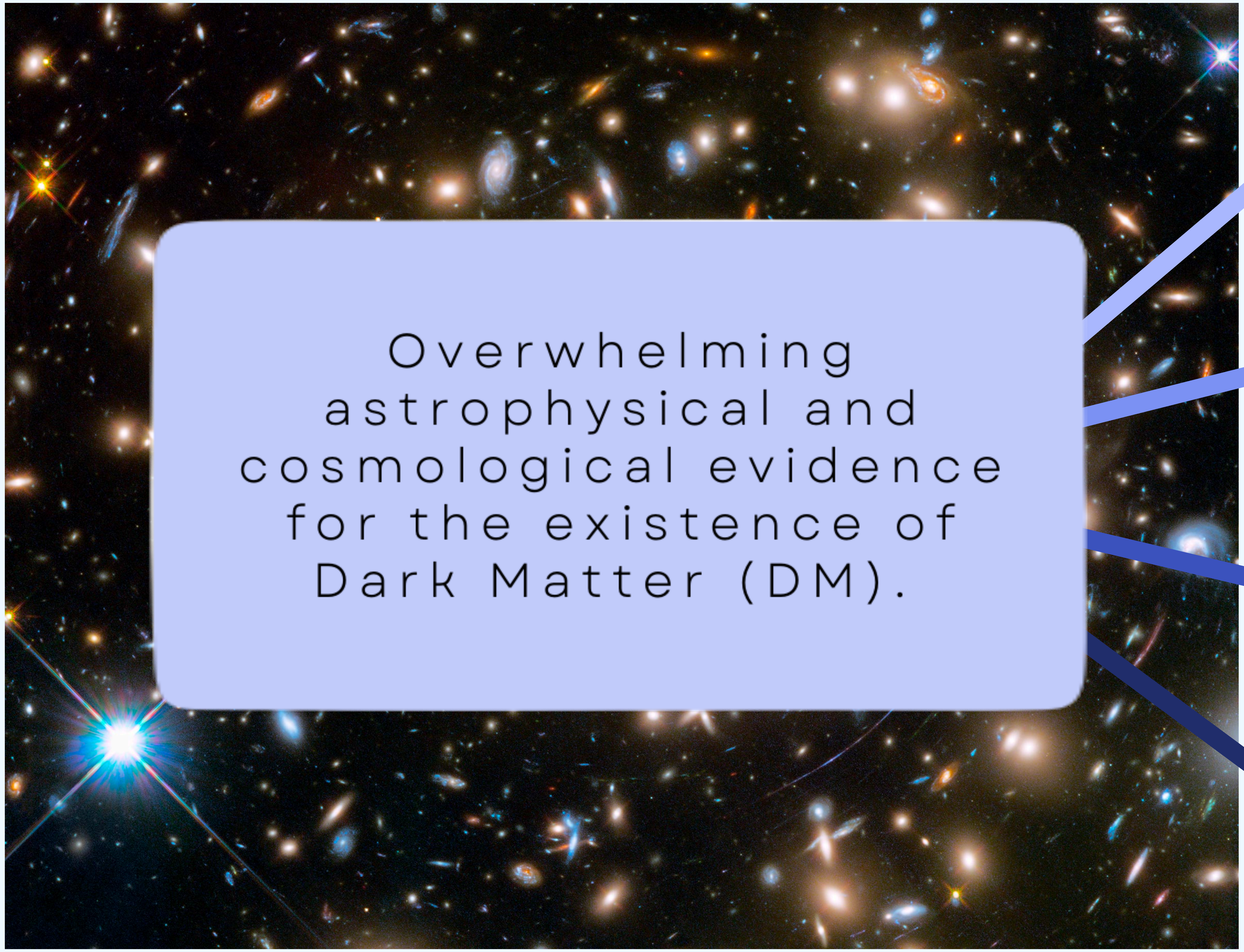


Need SM extension

Looking for a theory that explains observed neutrino masses and the nature of Dark Matter

Weakly-interacting massive particles (WIMPs) are a simple solution.

WIMP Origins

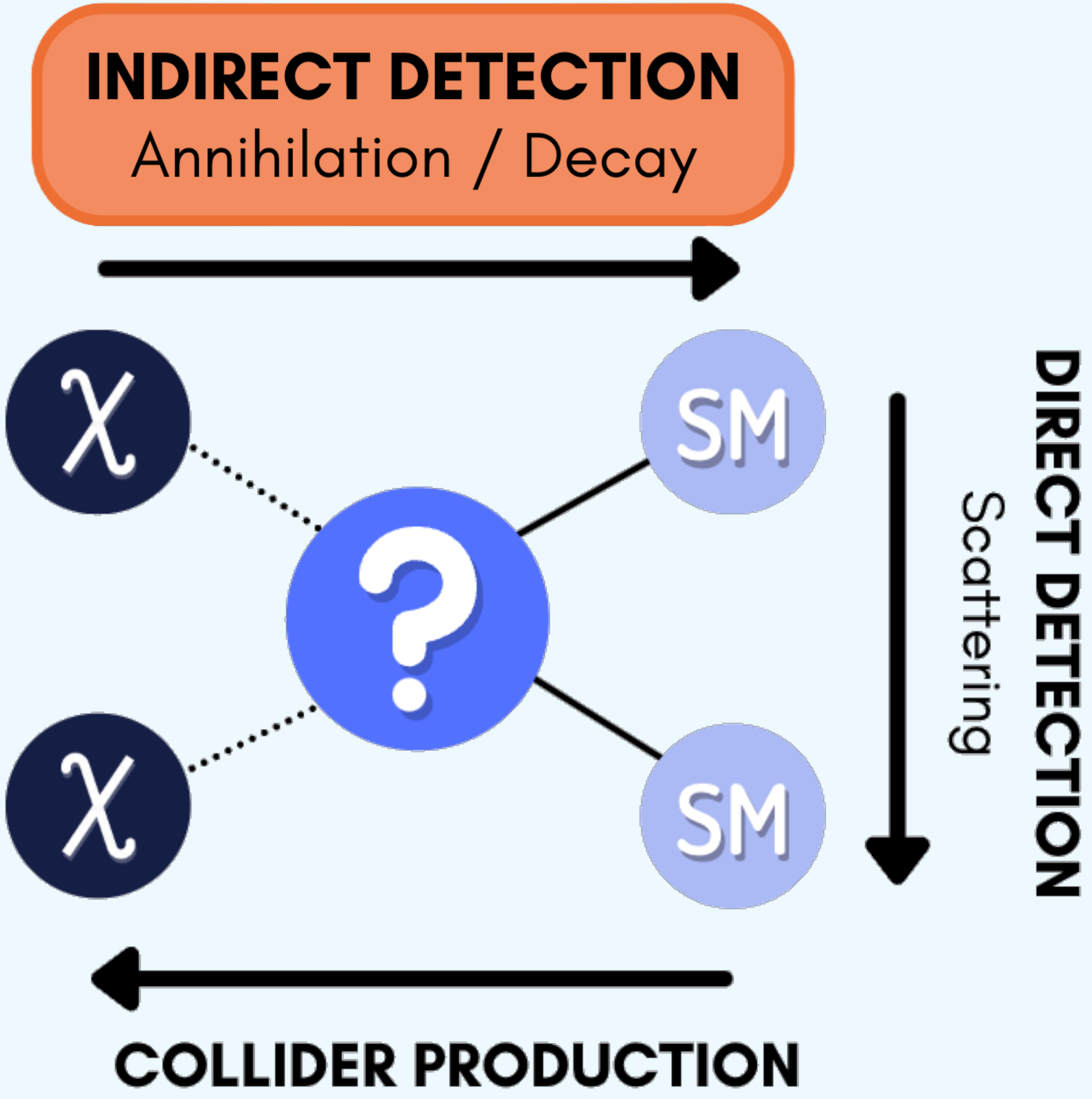


Overwhelming astrophysical and cosmological evidence for the existence of Dark Matter (DM).

- 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

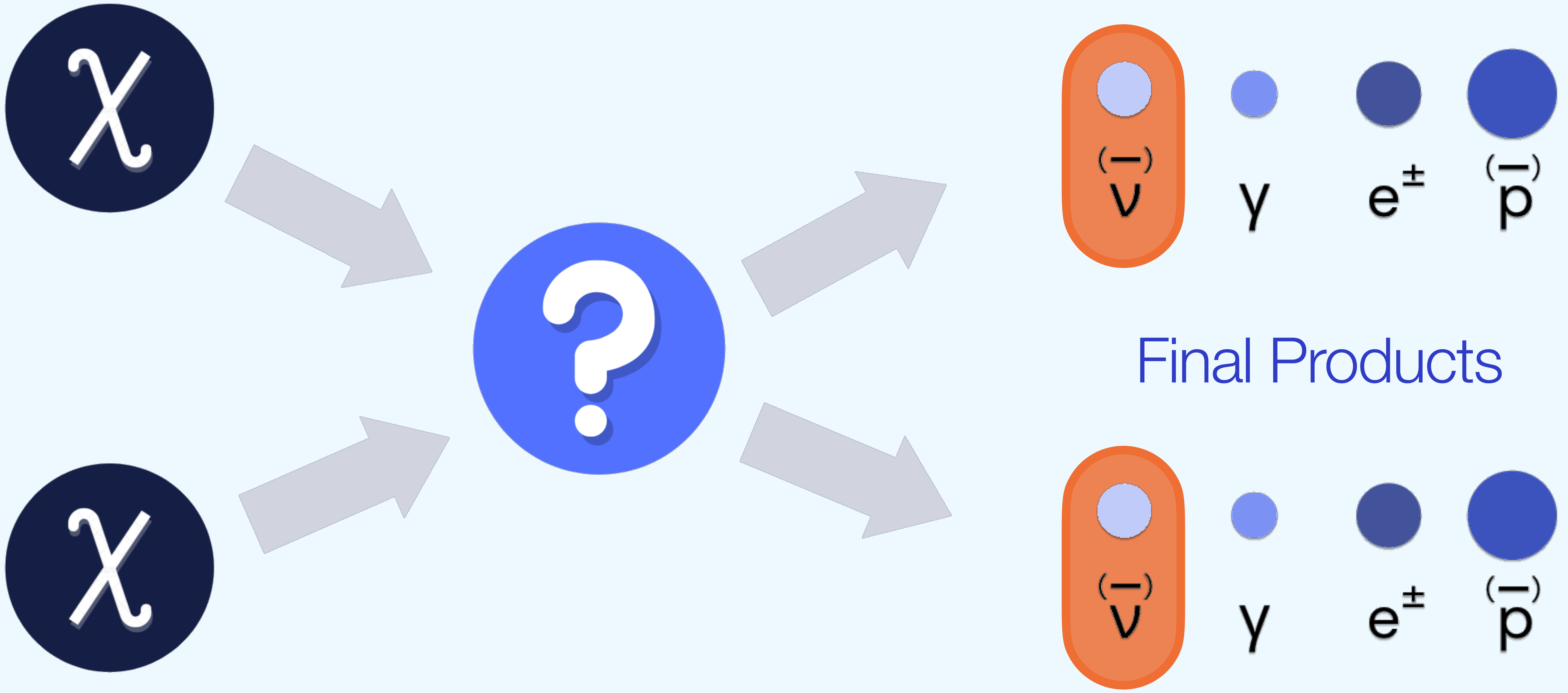


All SM final states eventually lead to gamma rays or neutrinos.

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

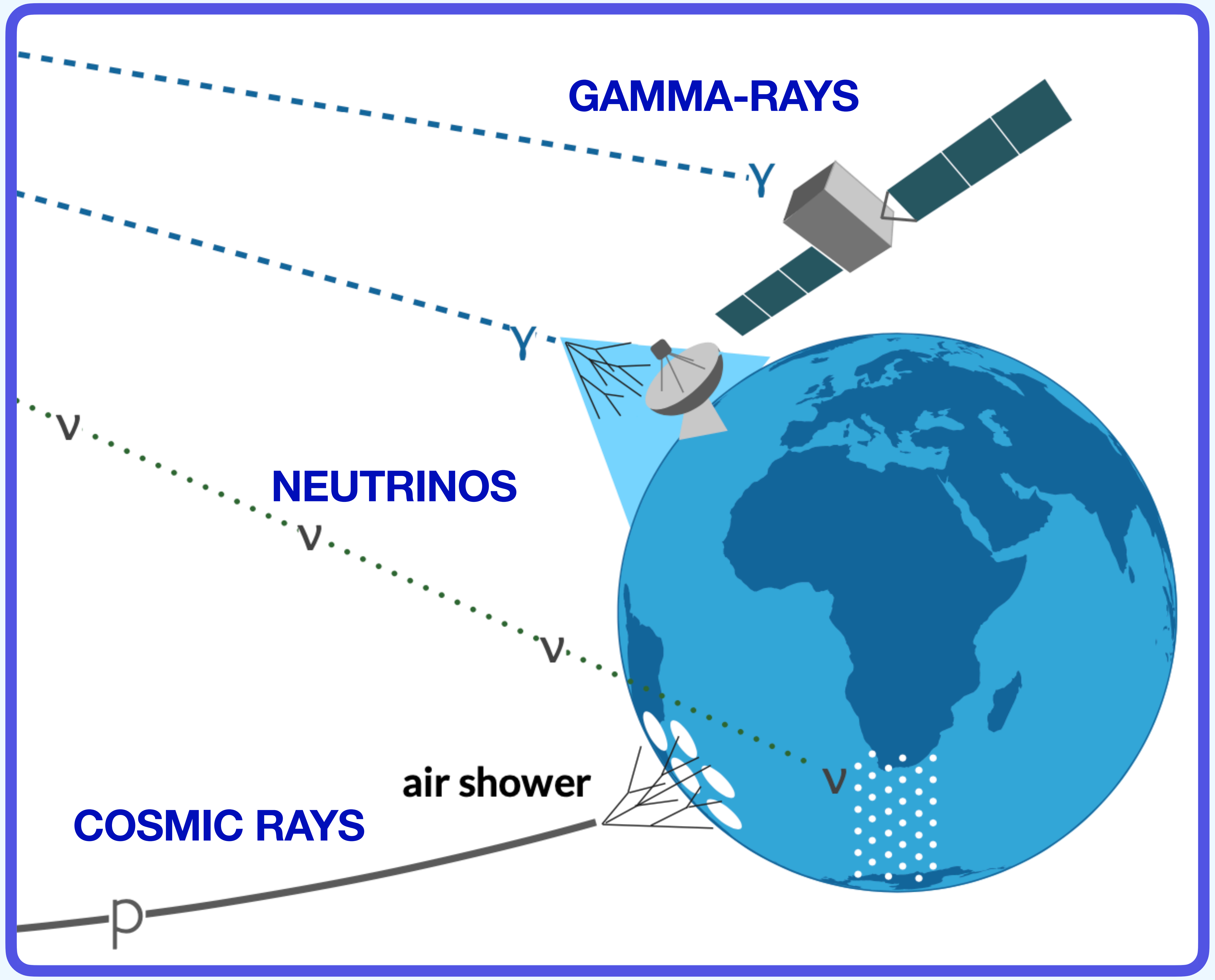


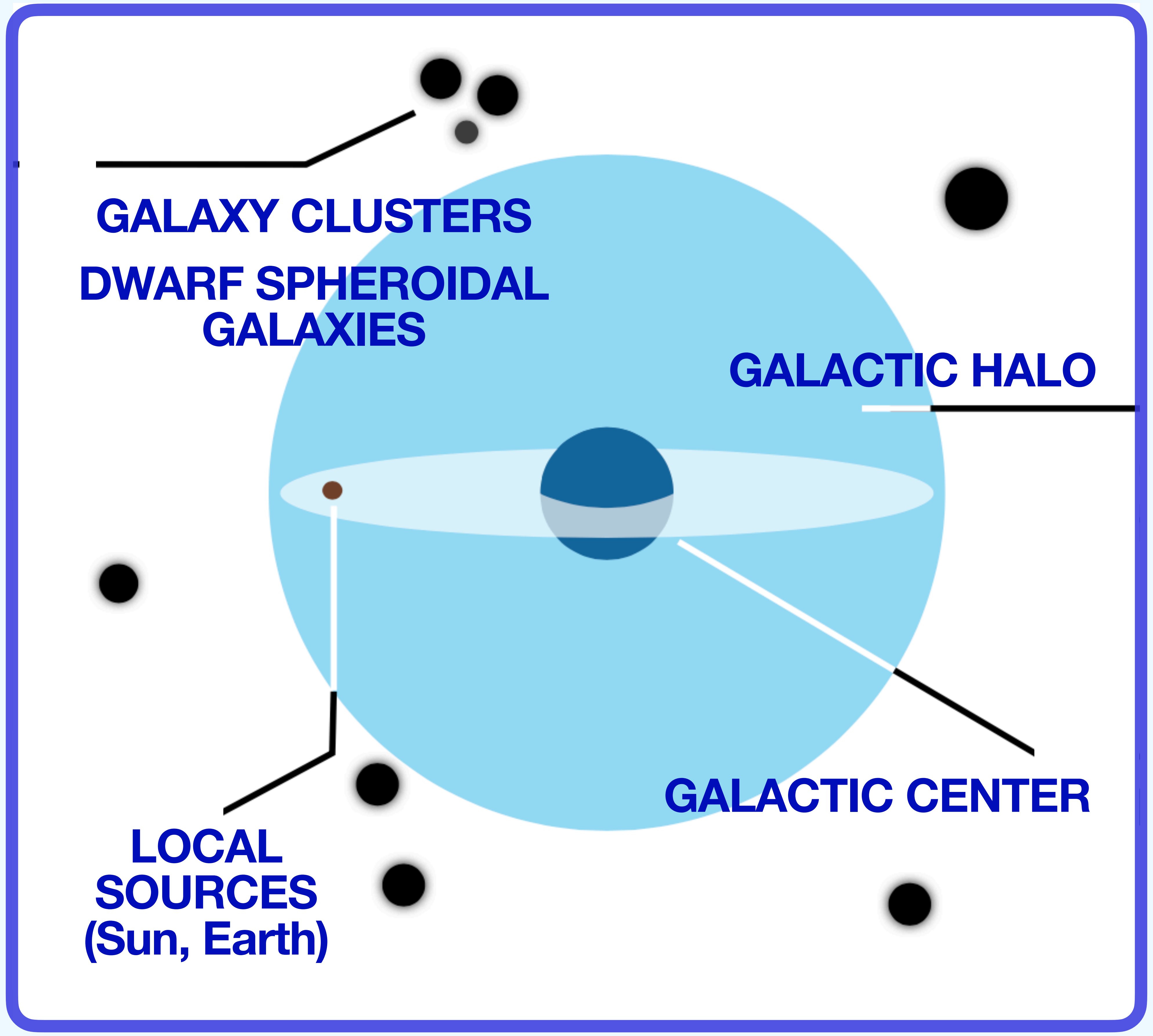
No need of specialized detectors

Focus on large reservoirs of DM

Dark Matter Searches

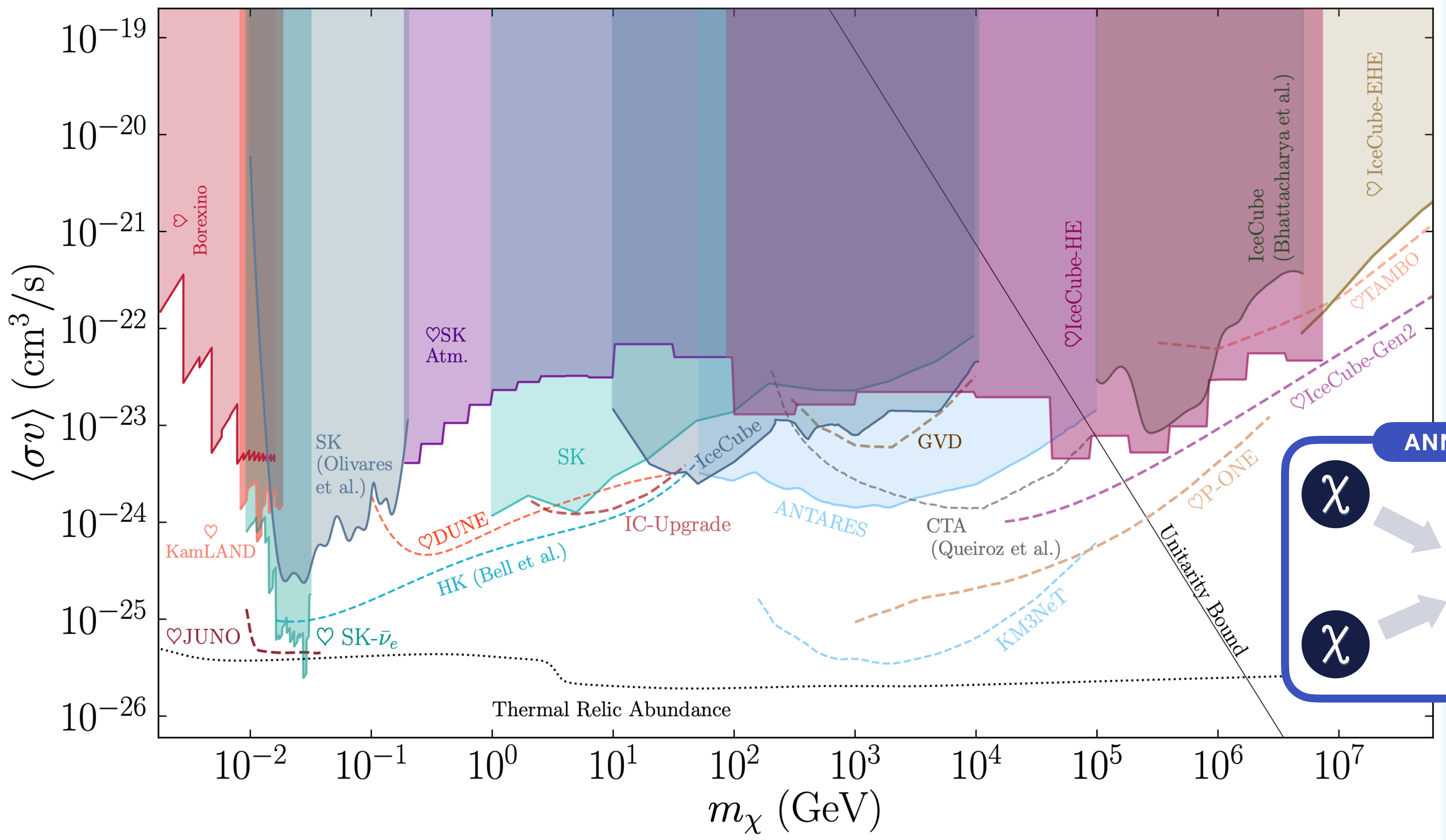
What and where to look?

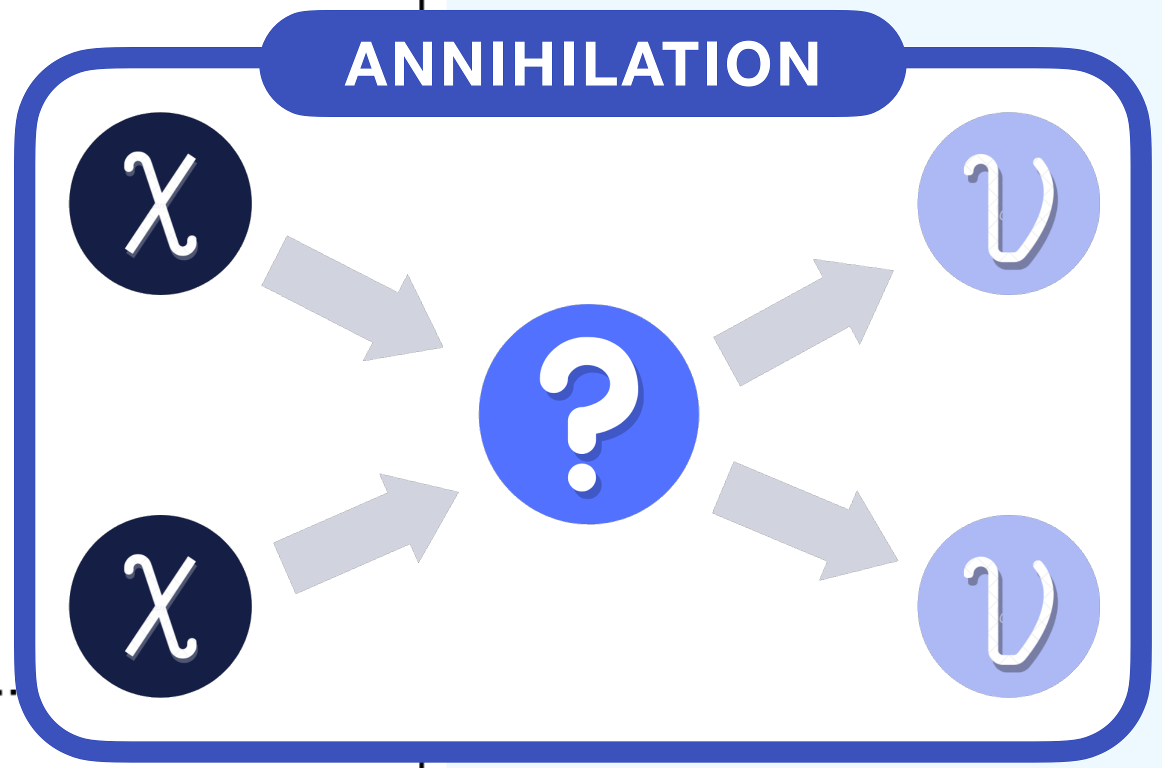




CREDIT: JUAN AGUILAR, ESDU 2018

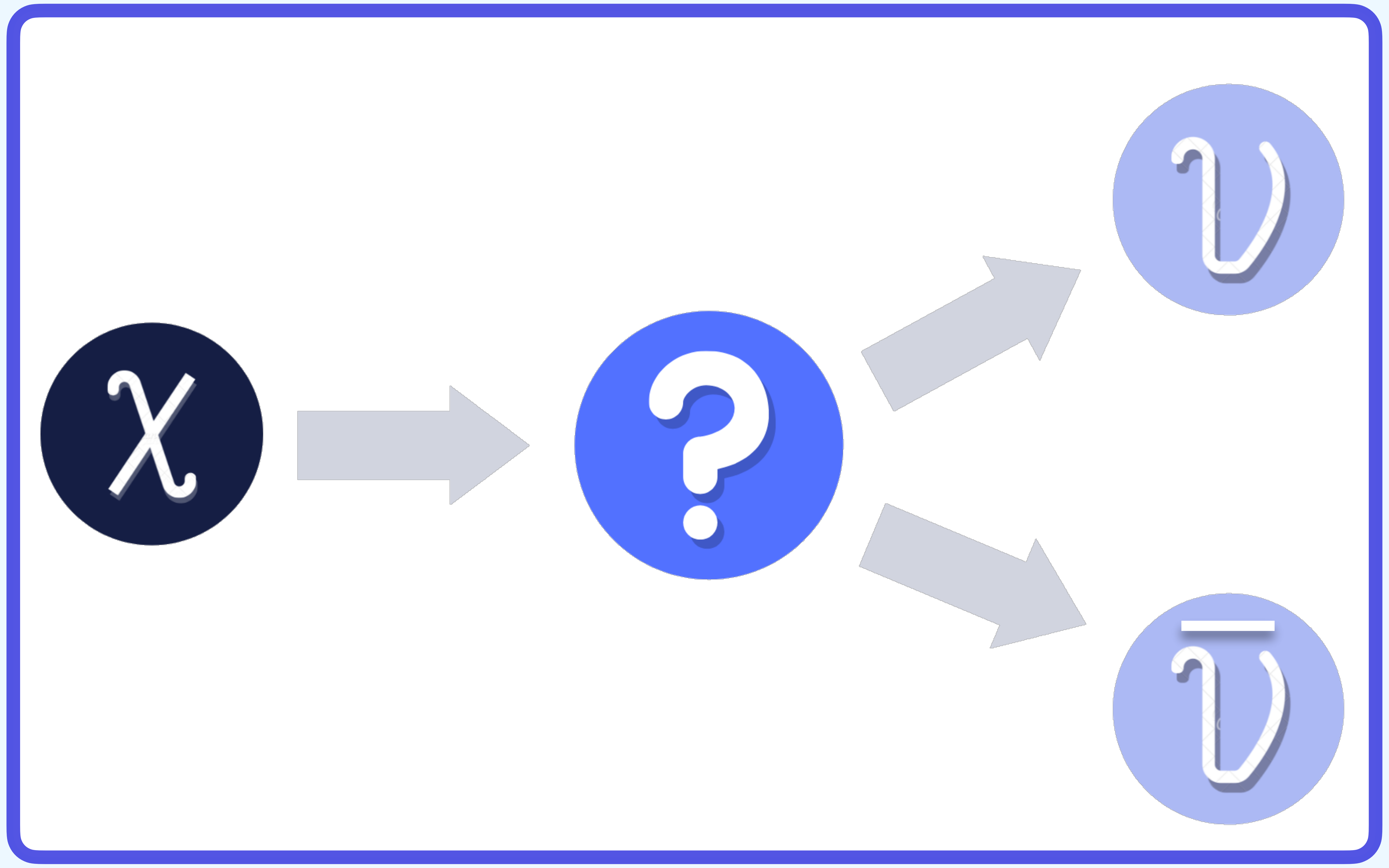
Previous Work: Dark Matter Annihilation to Neutrinos

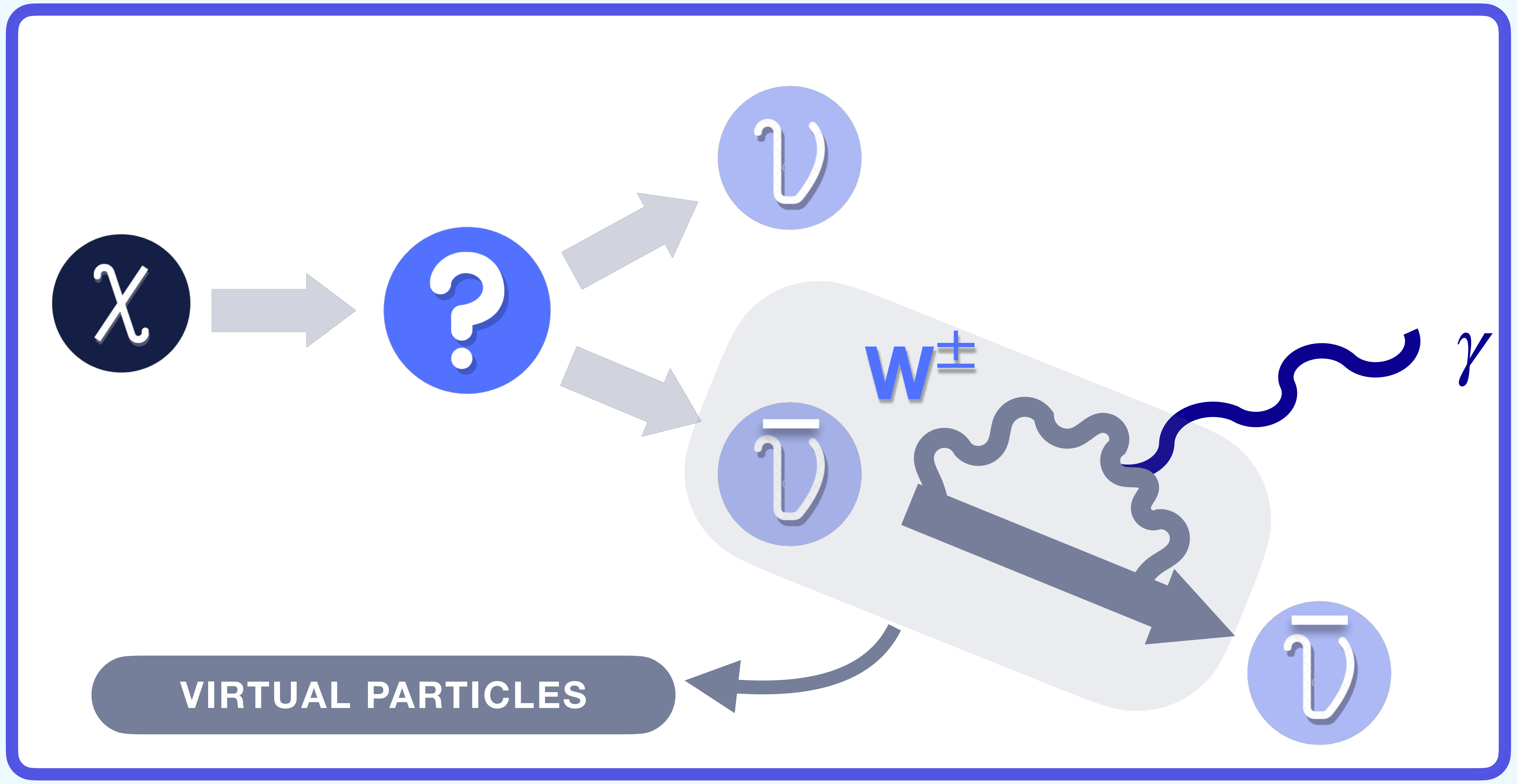




ARGÜELLES, ET AL., REV. MOD. PHYS. 93, ARXIV:1912.09486

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**

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

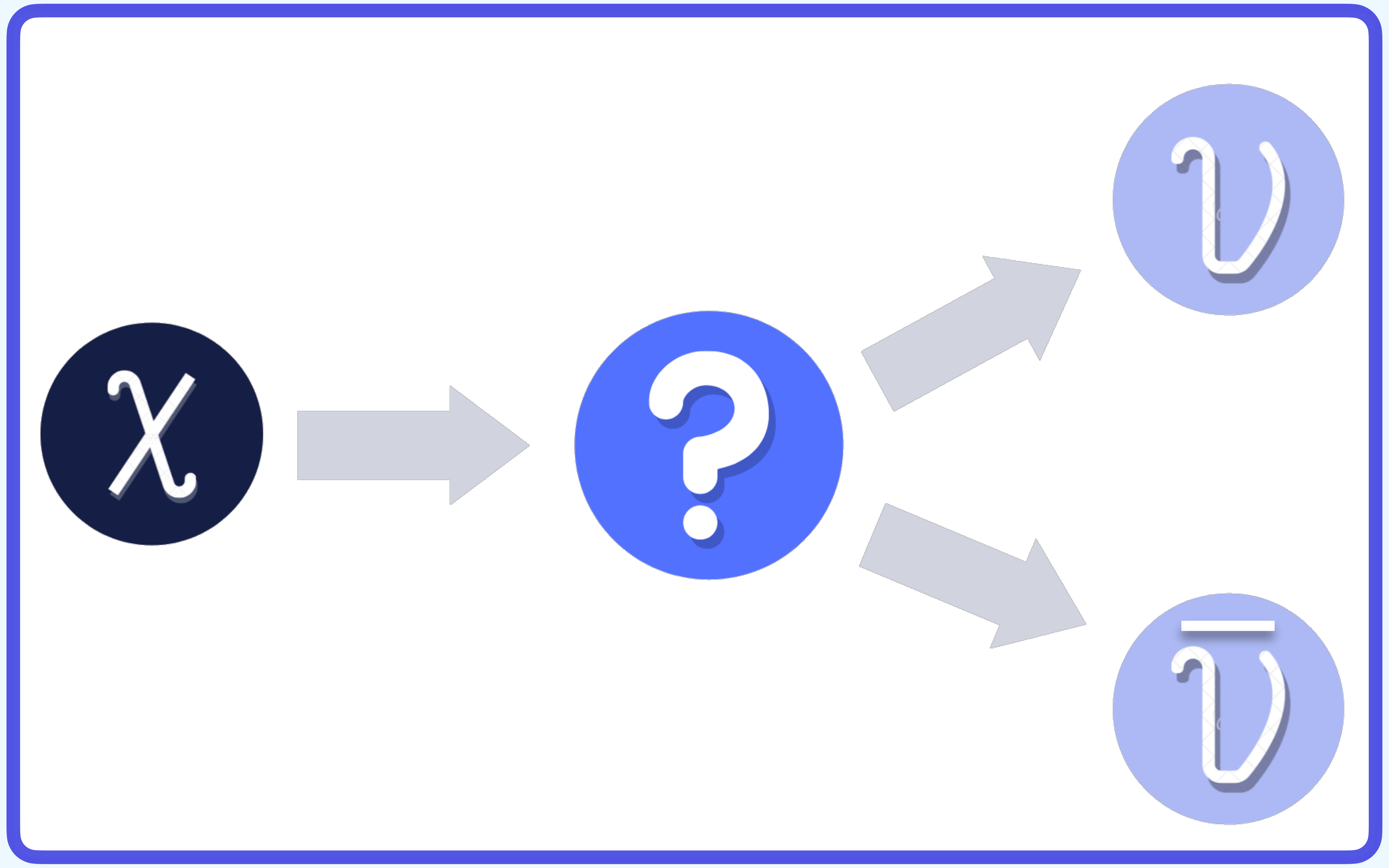
Time-dependent Hubble parameter

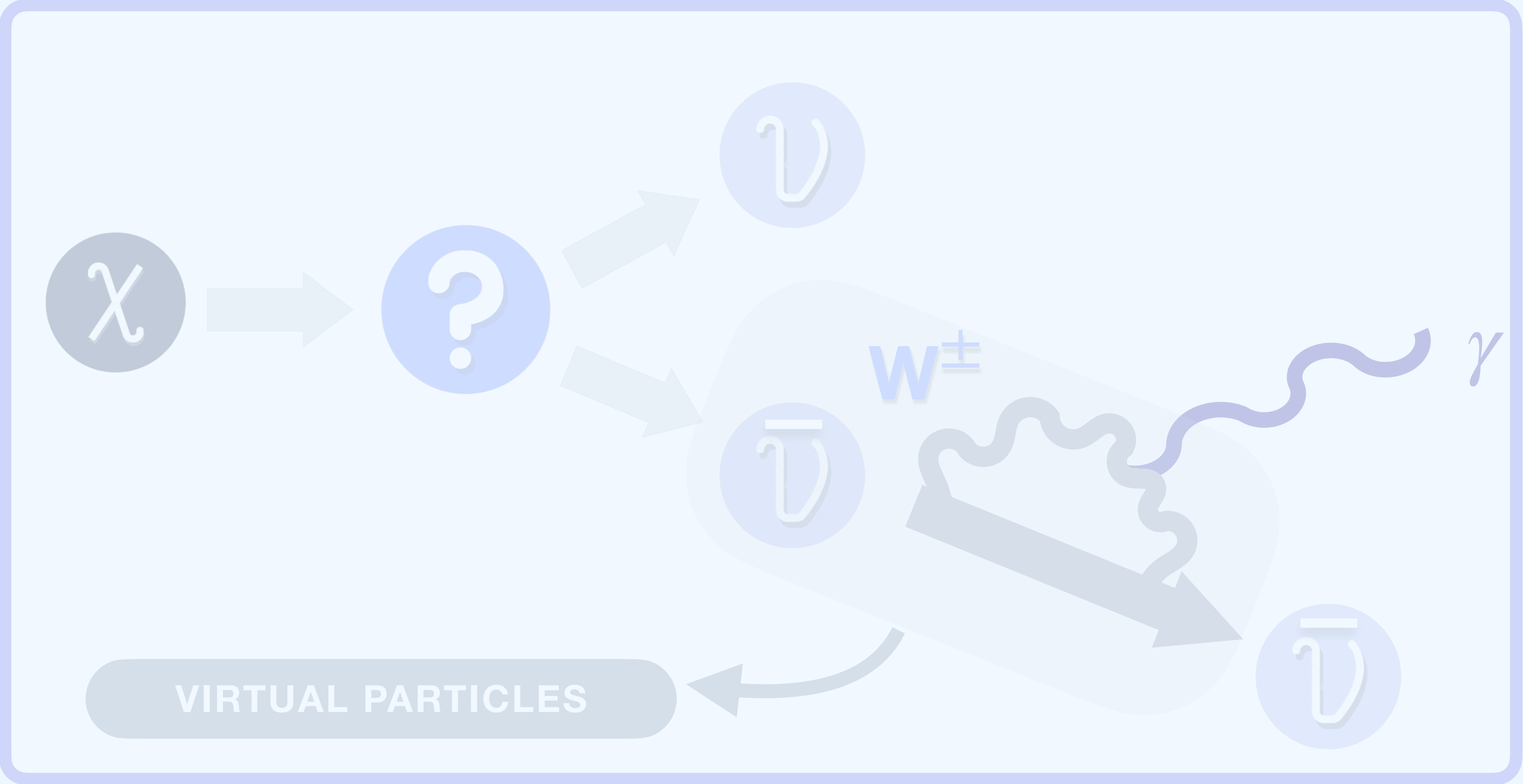
$$E' = (1+z)\, E$$

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





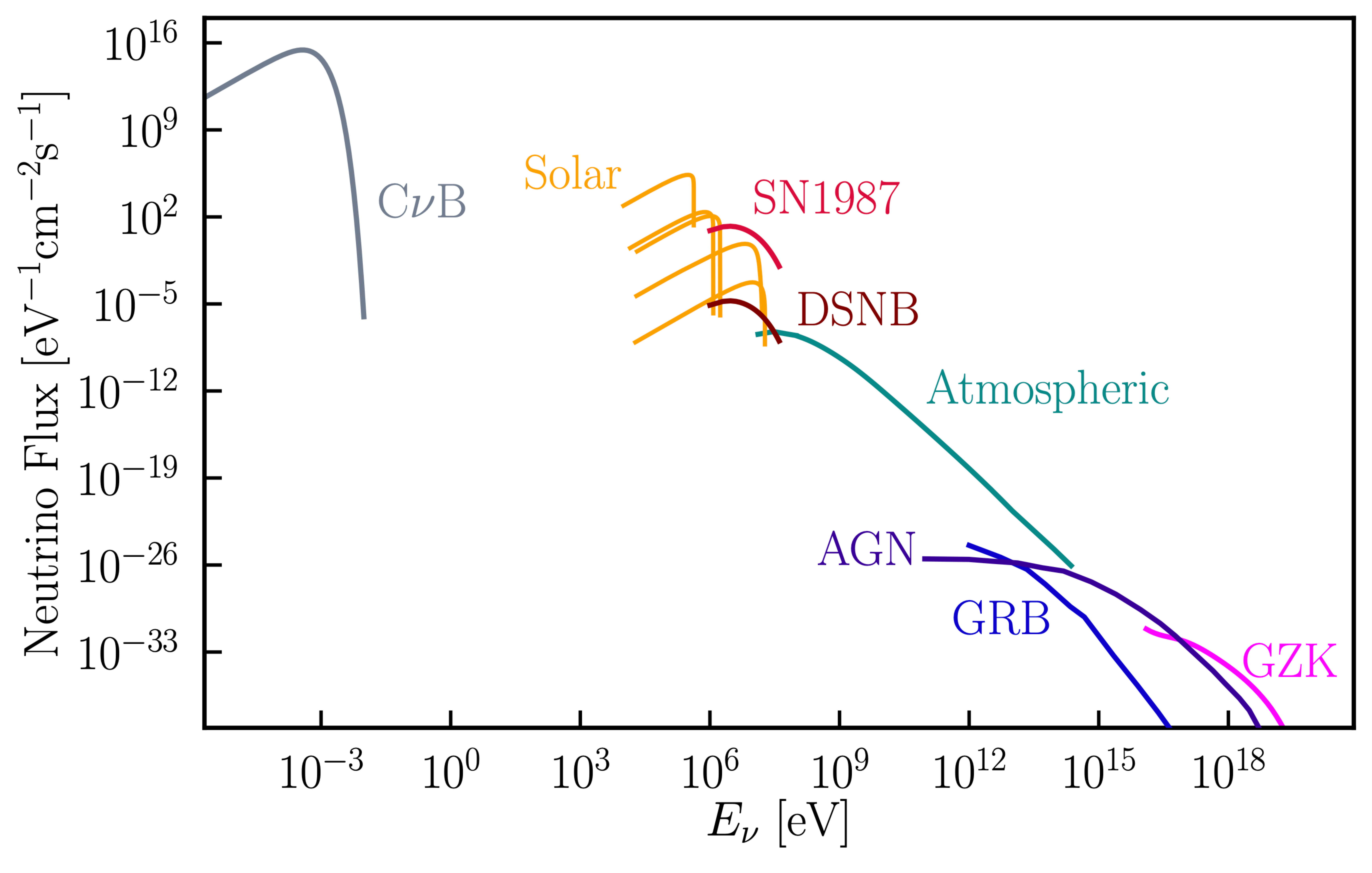
NEUTRINO SIGNAL

GAMMA-RAY SIGNAL

EXPECTED GAMMA-RAY SIGNAL DUE TO ELECTROWEAK CORRECTIONS

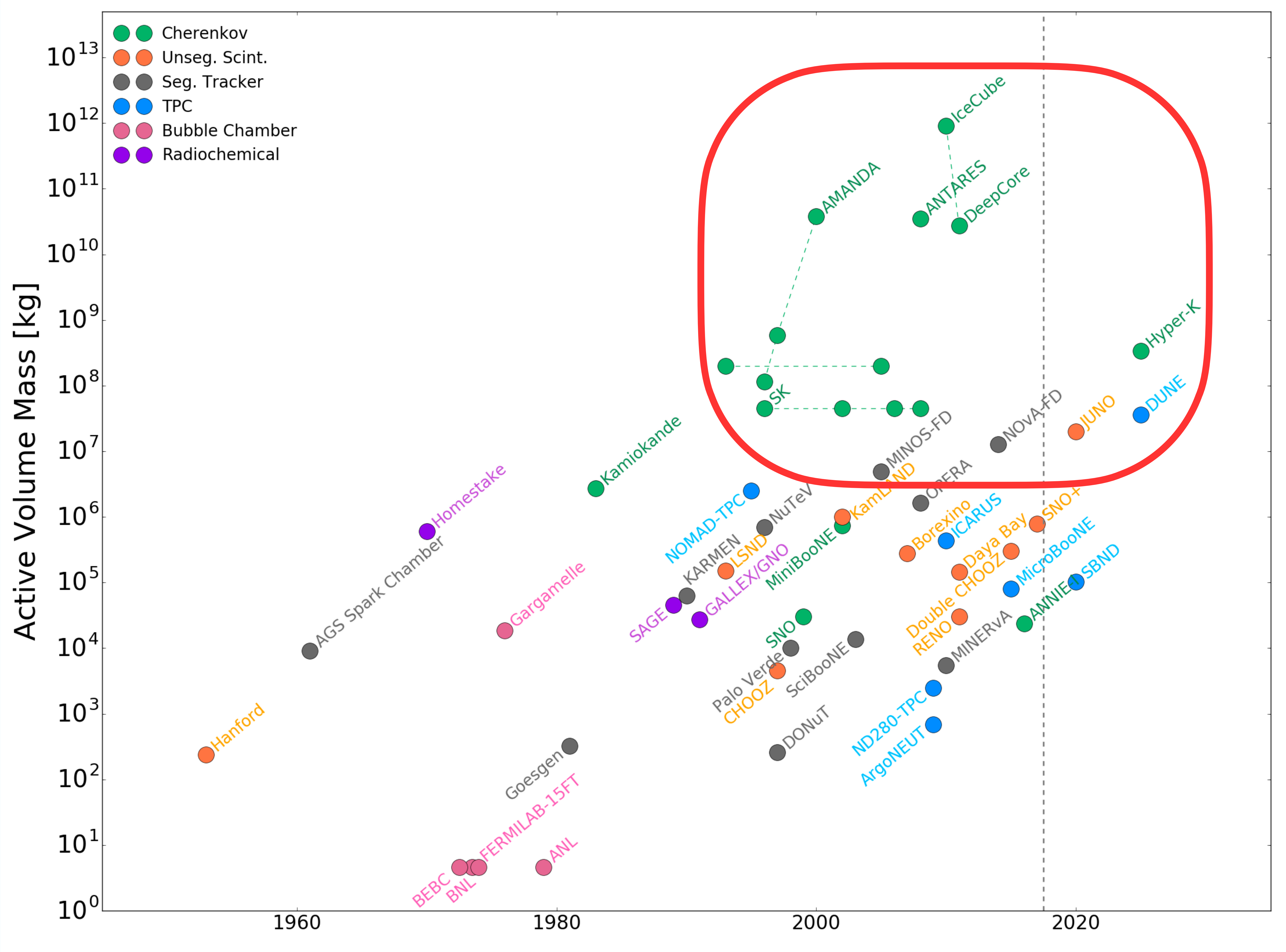
First, we must detect neutrinos!

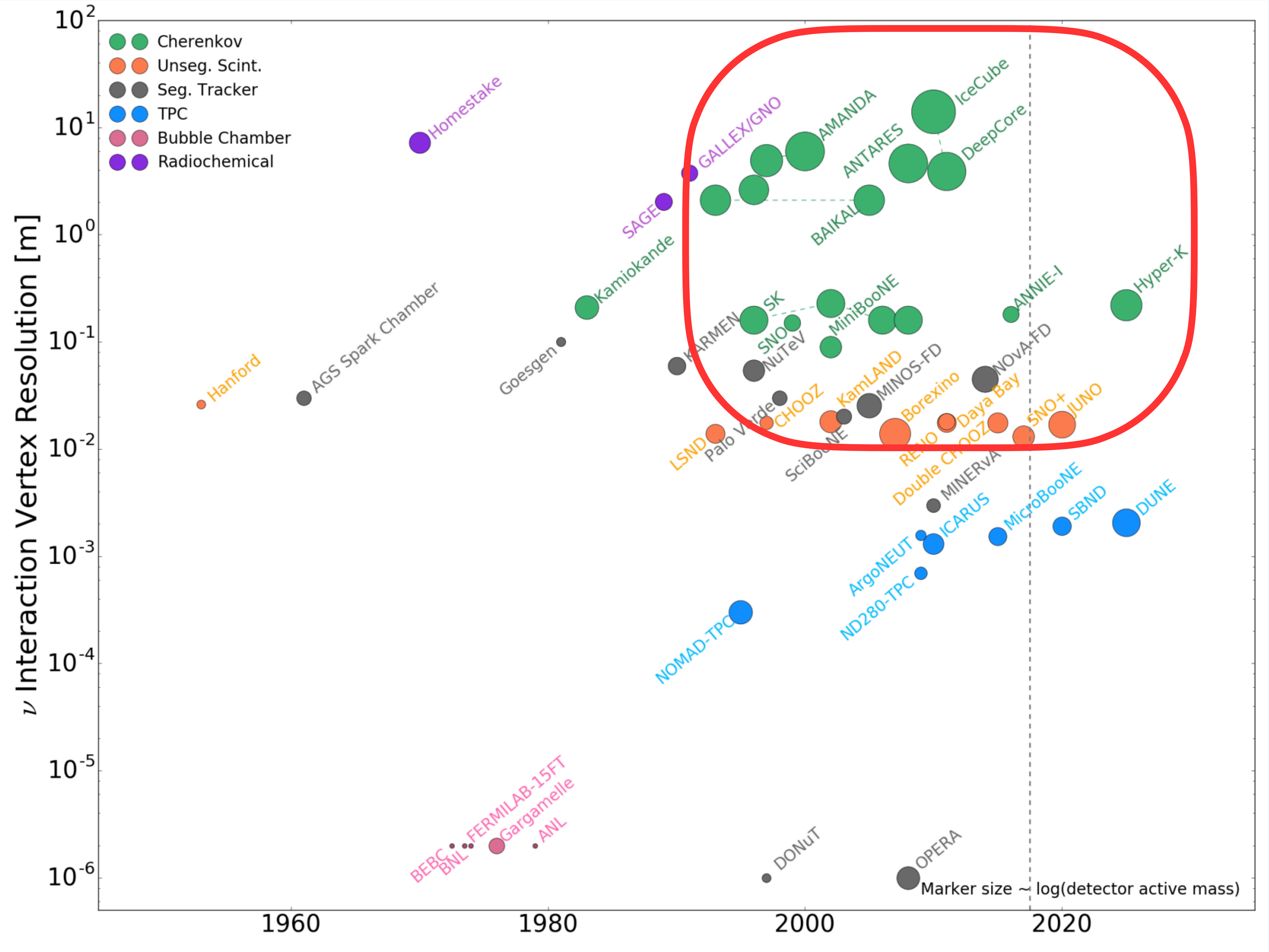
Measured and expected fluxes of natural and reactor neutrinos



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

Neutrino Detection



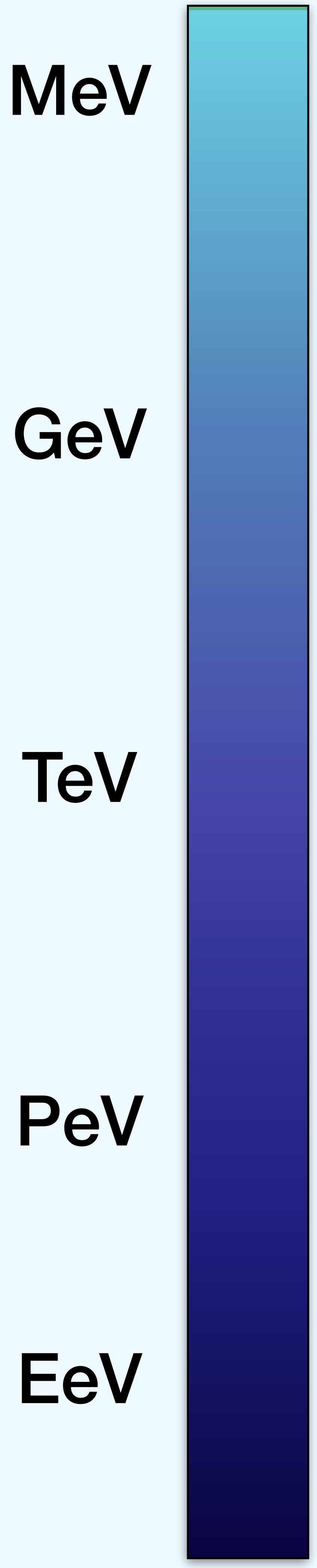


Size (Volume)

Precision

ARGÜELLES ET AL., IOP 23, ARXIV:1907.08311

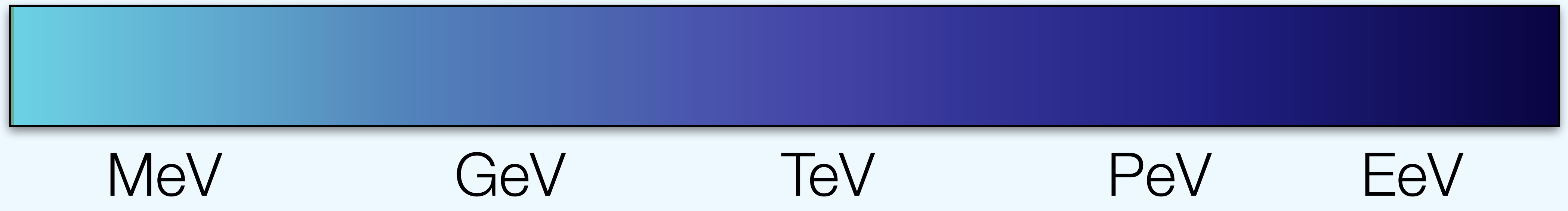
Neutrino Detection



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



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)

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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)

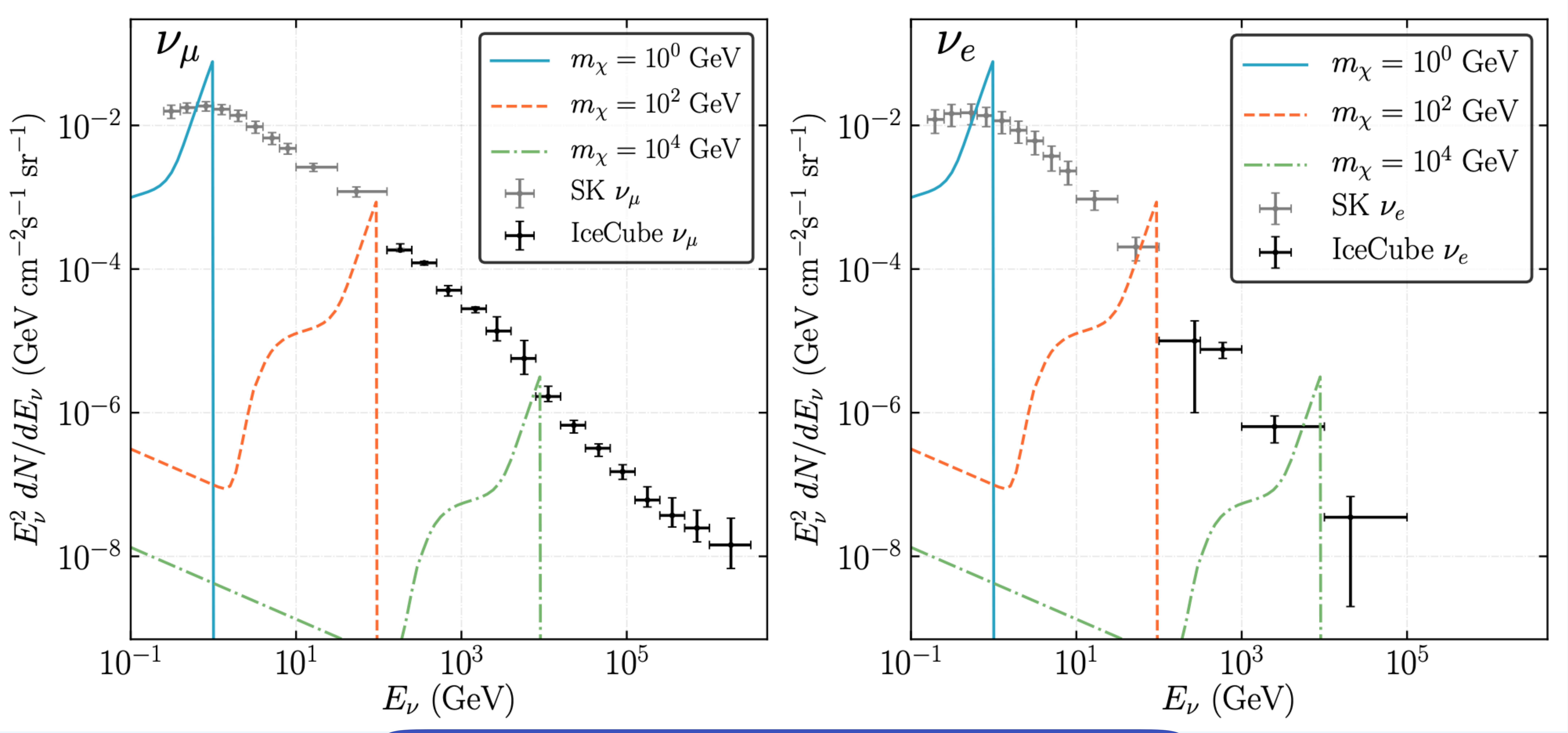
P-ONE: Sea Water Cherenkov Extraterrestrial neutrino fluxes (PeV)

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



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

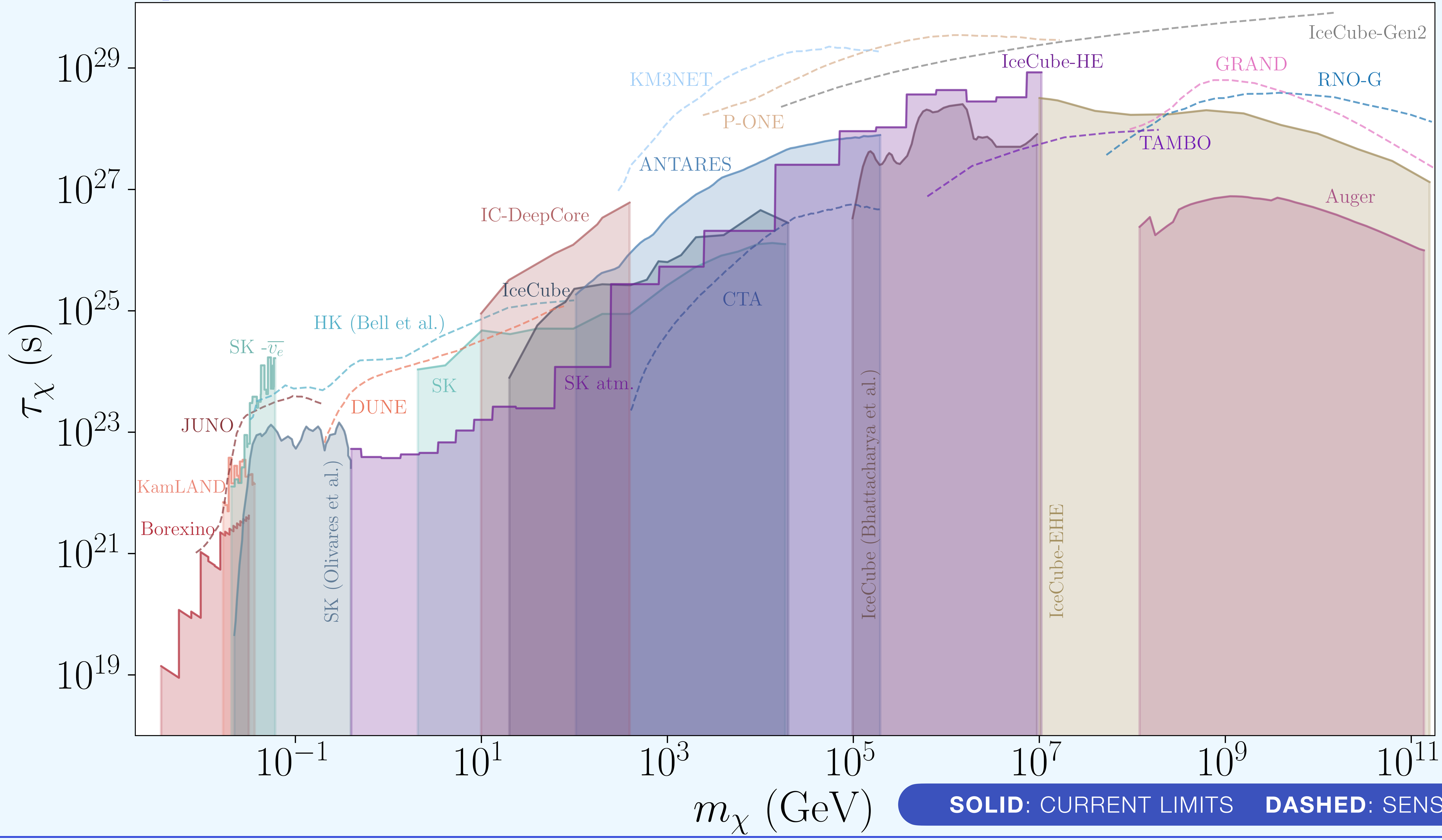
Background Agnostic $\Rightarrow \mathscr{L} = \begin{cases} \mathbb{P}(d\,|\,\mu) & (d < \mu), \\ 1 & (d \geq \mu) \end{cases}$

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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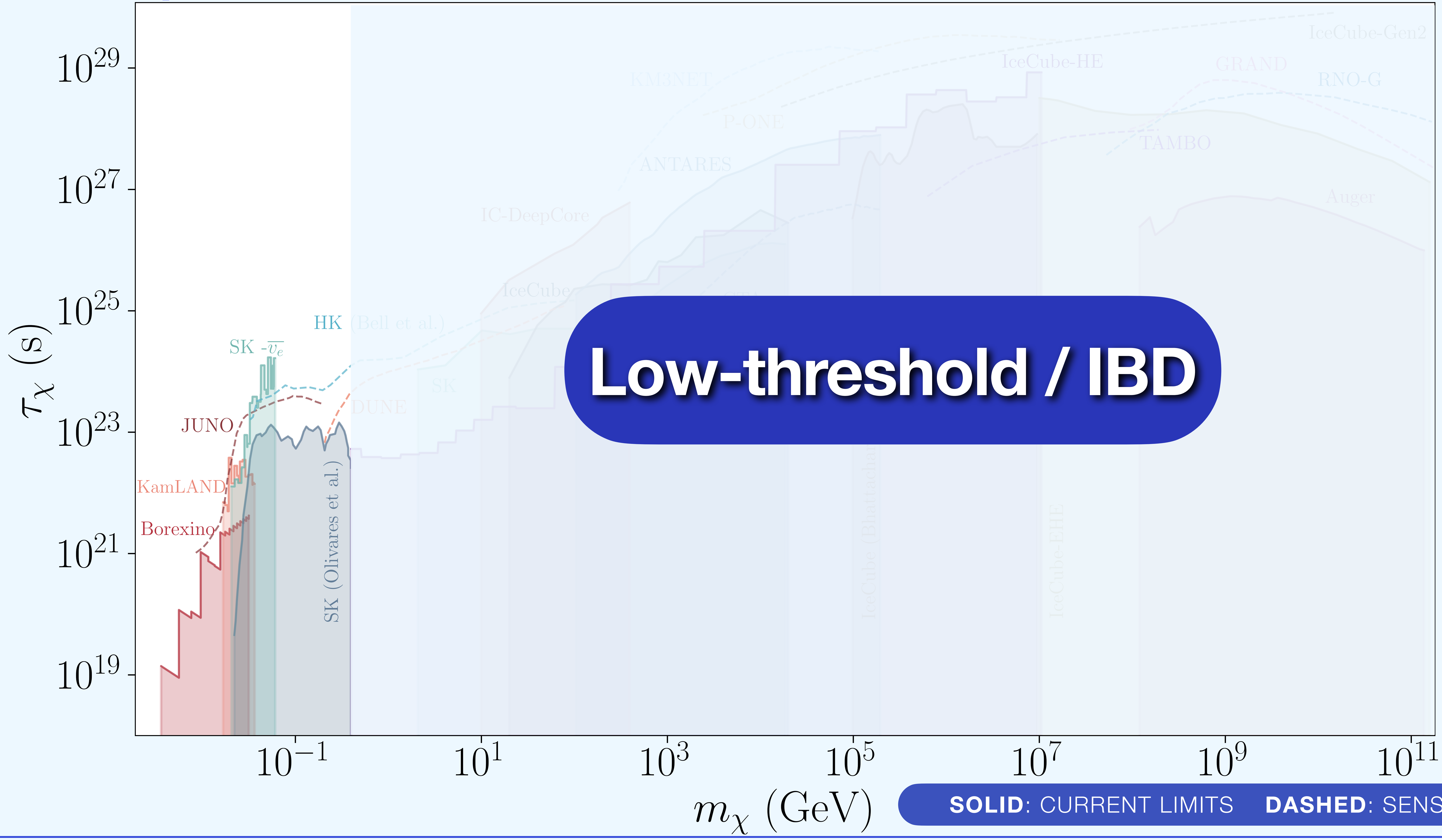

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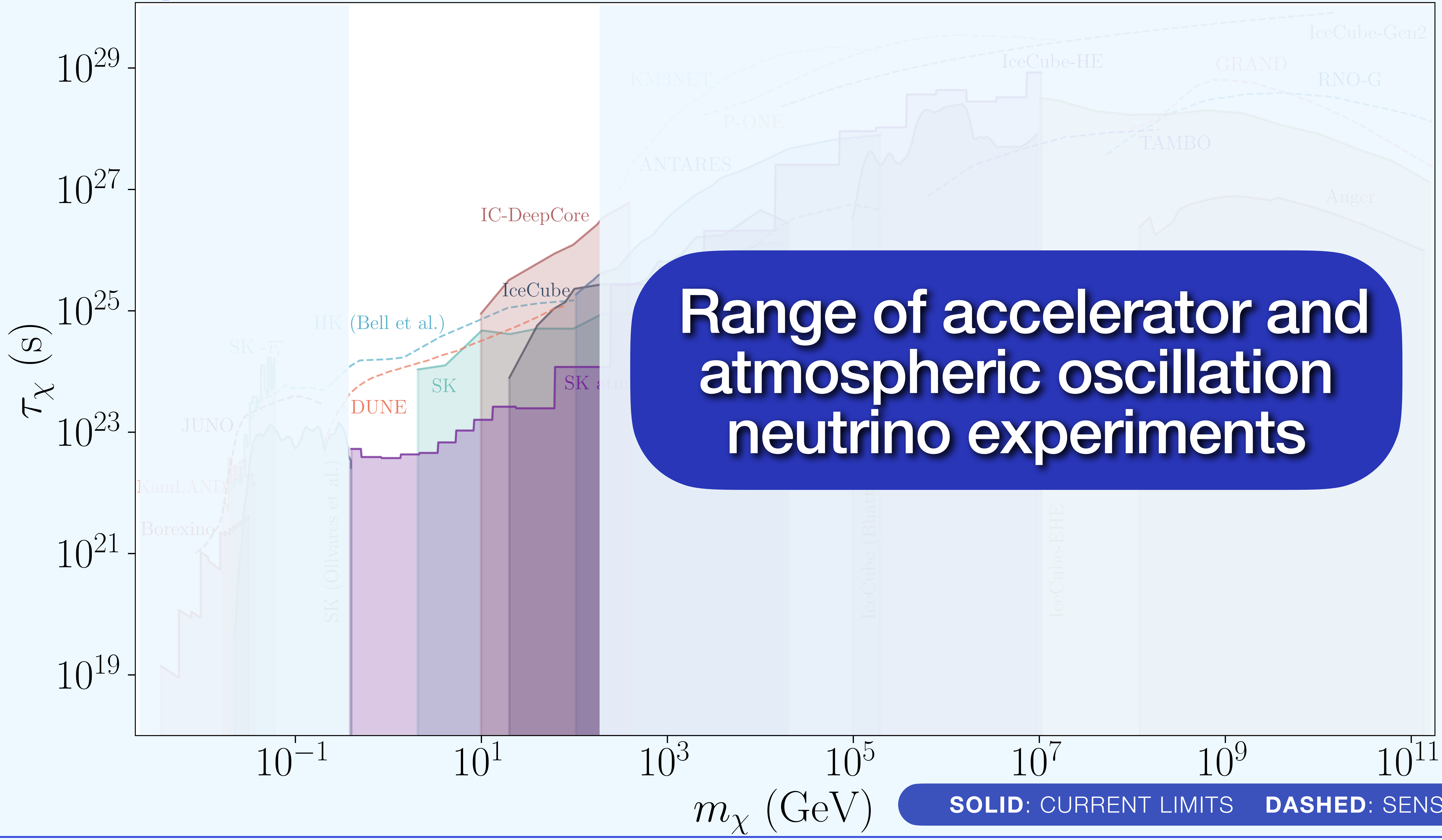
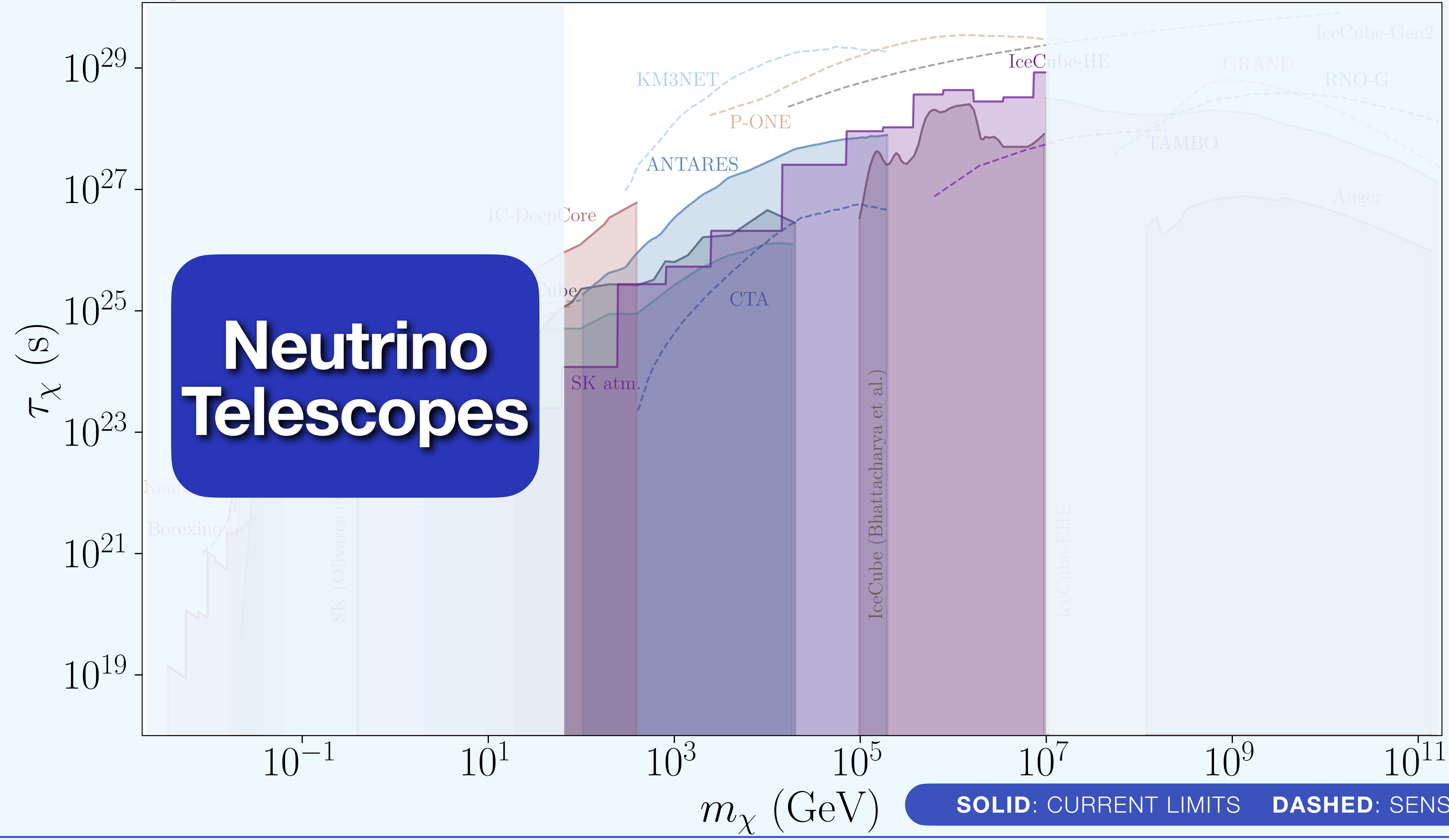


Range of accelerator and atmospheric oscillation neutrino experiments

SOLID: CURRENT LIMITS **DASHED**: SENSITIVITIES

Decay results
Neutrino Experiments

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

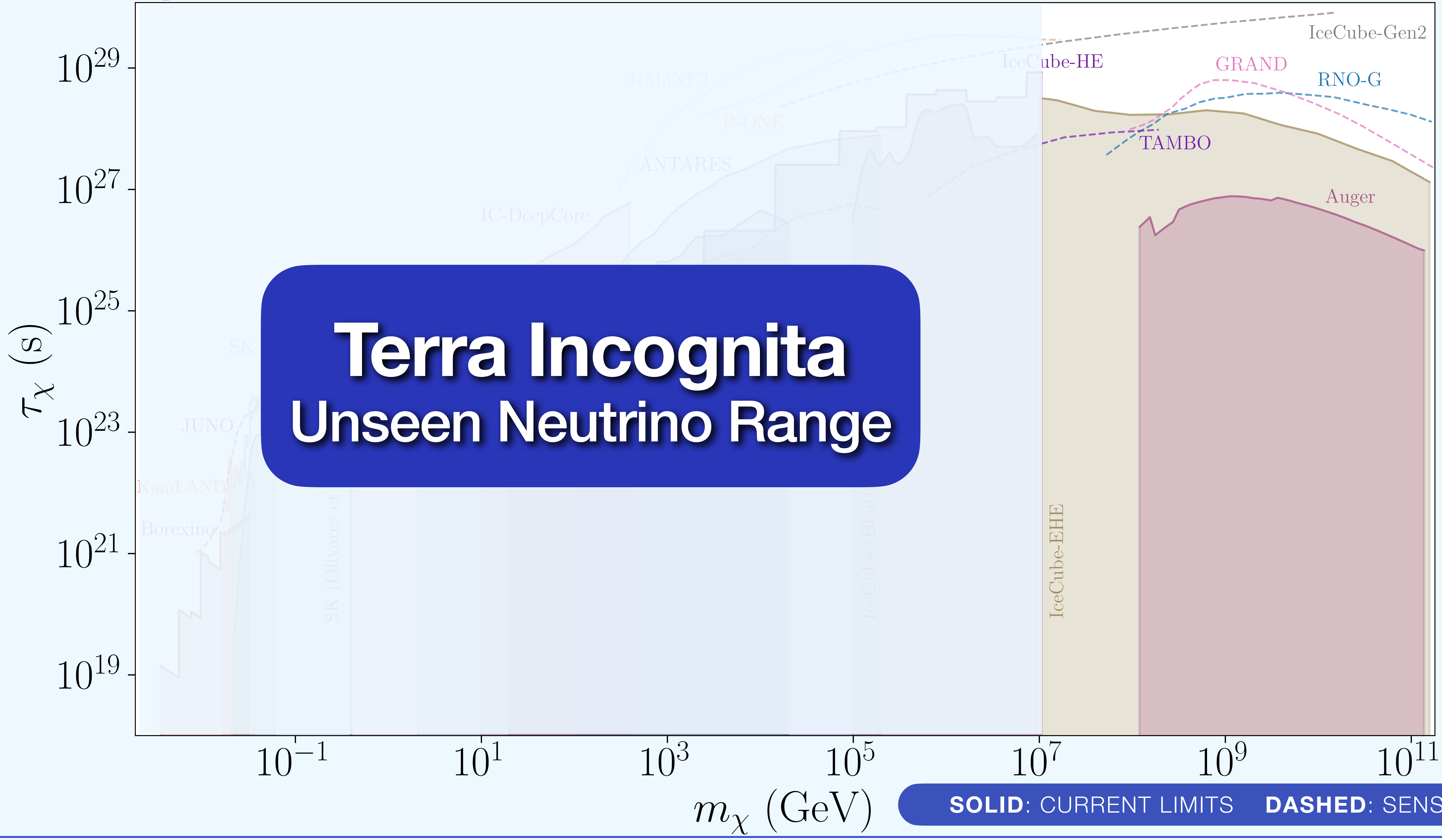


Neutrino Telescopes

SOLID: CURRENT LIMITS **DASHED**: SENSITIVITIES

Decay results
Neutrino Experiments

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



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Decay Results
Neutrino Experiments

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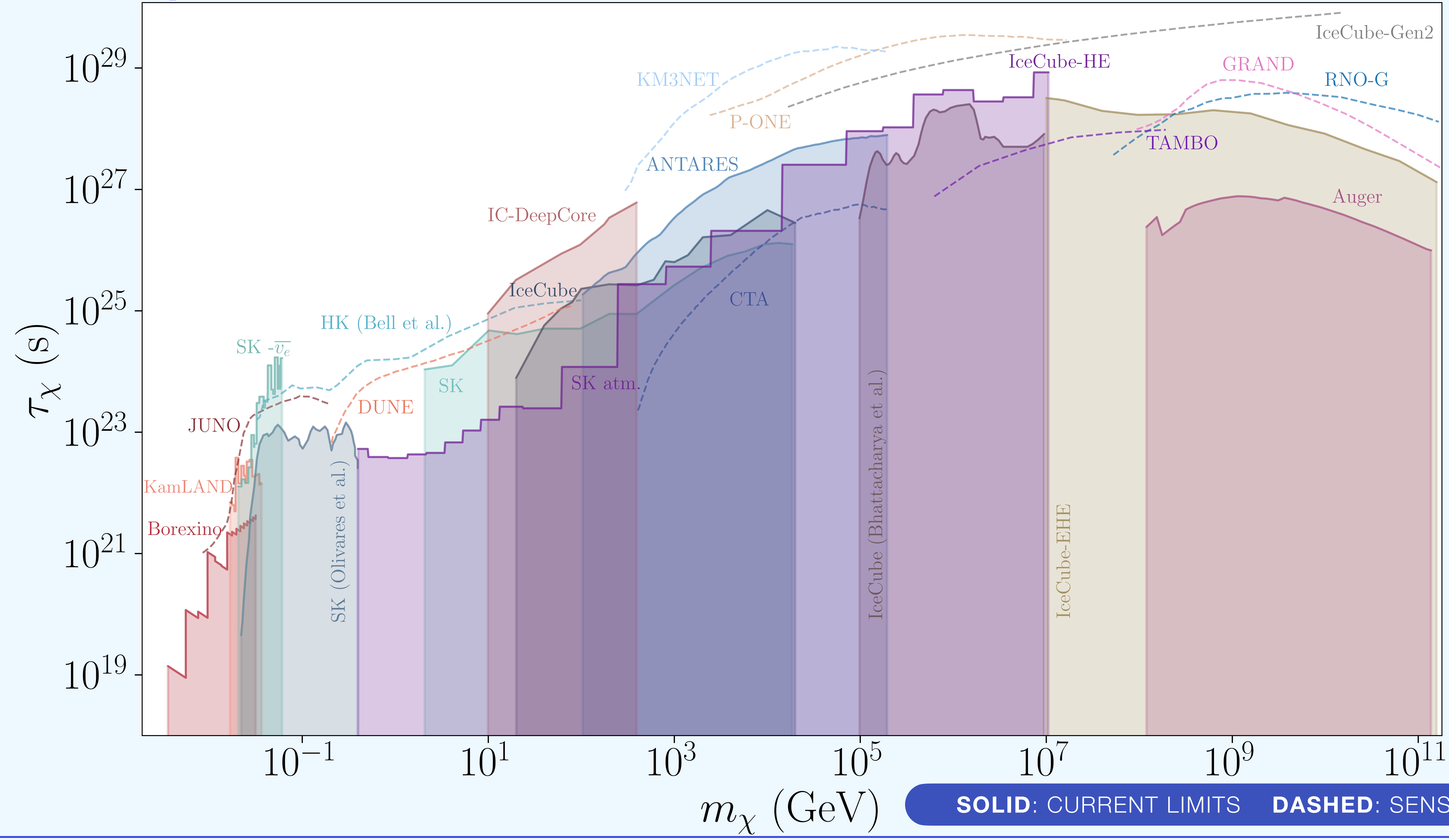
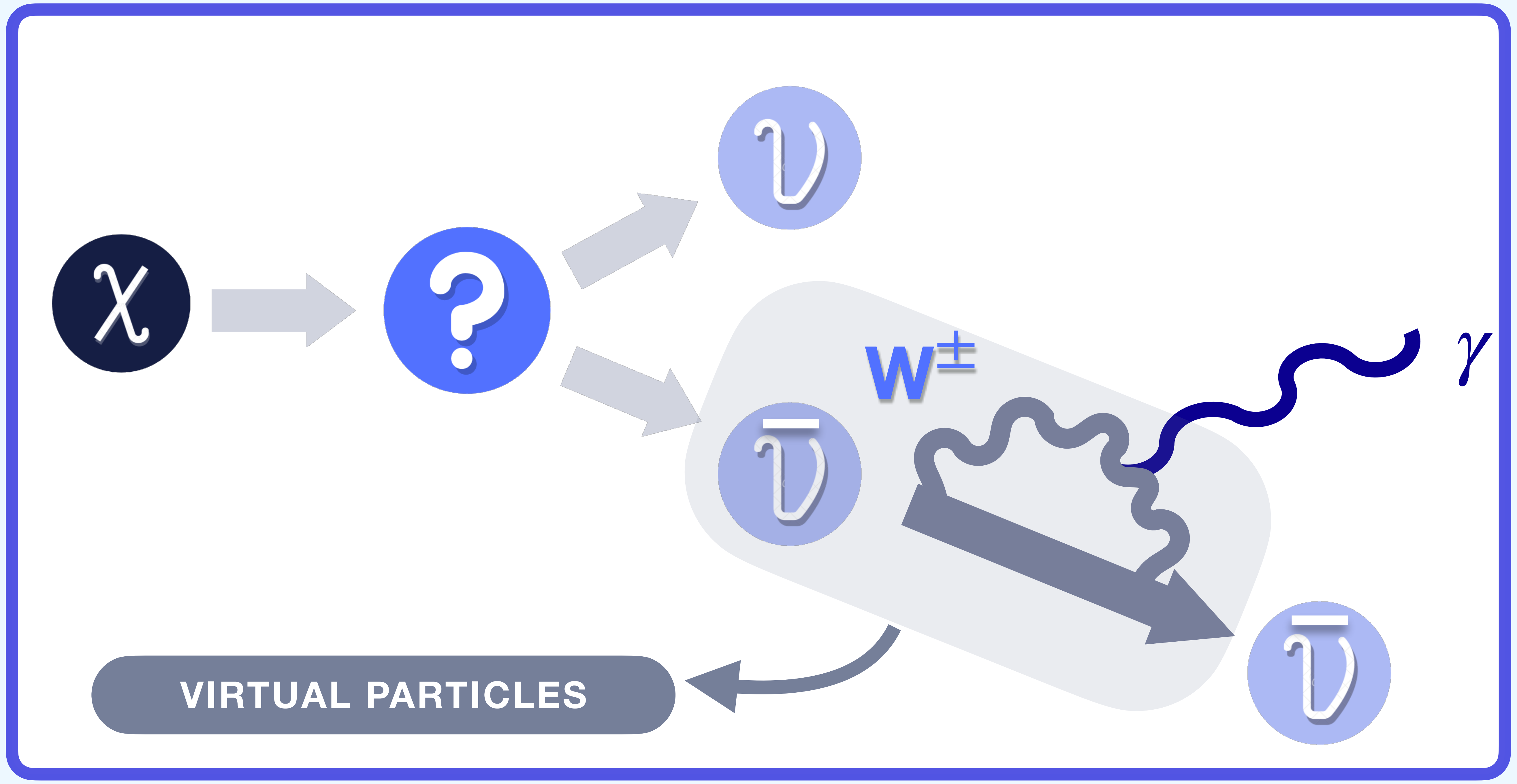


SOLID: CURRENT LIMITS **DASHED**: SENSITIVITIES

Dark Matter Decay to Neutrinos

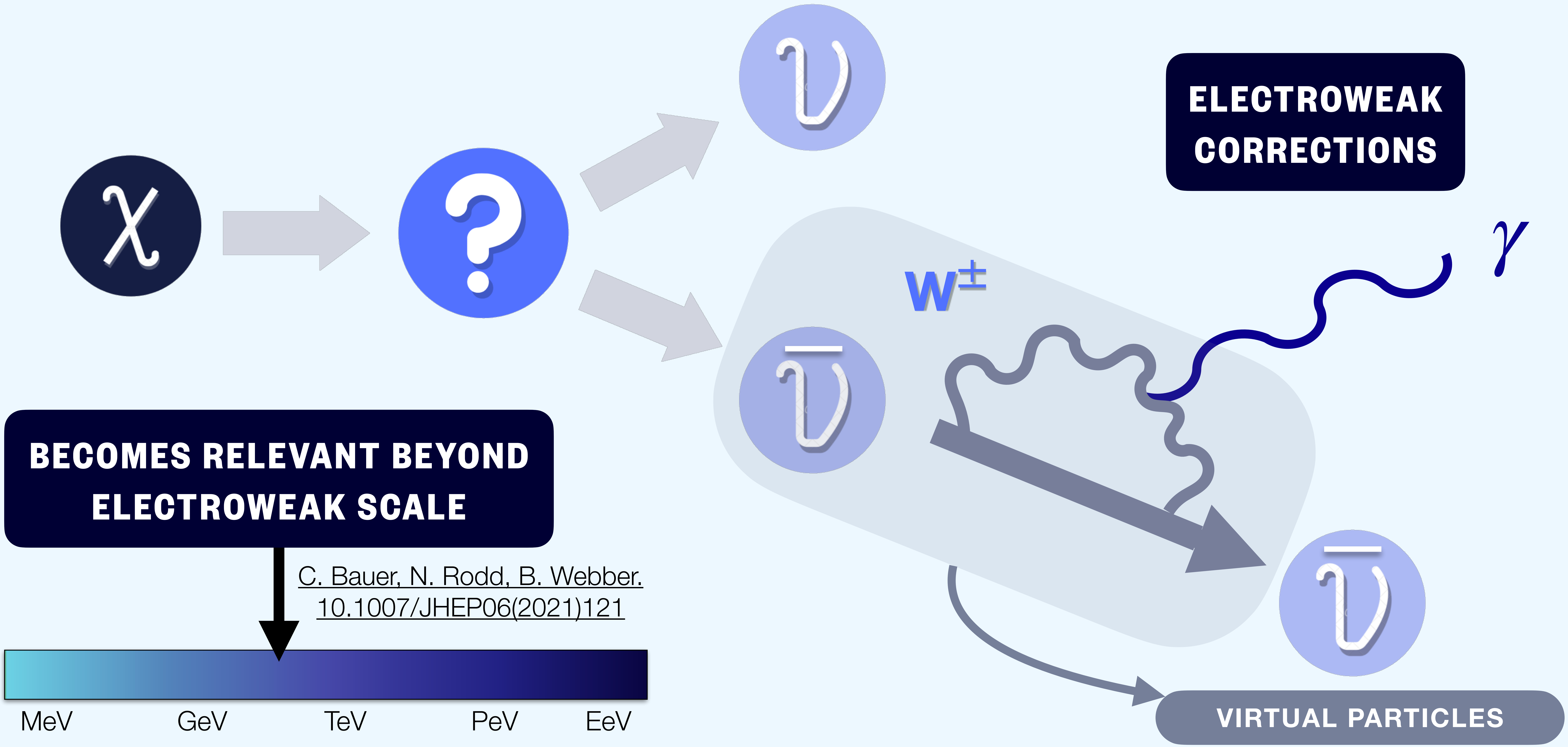


NEUTRINO SIGNAL

GAMMA-RAY SIGNAL

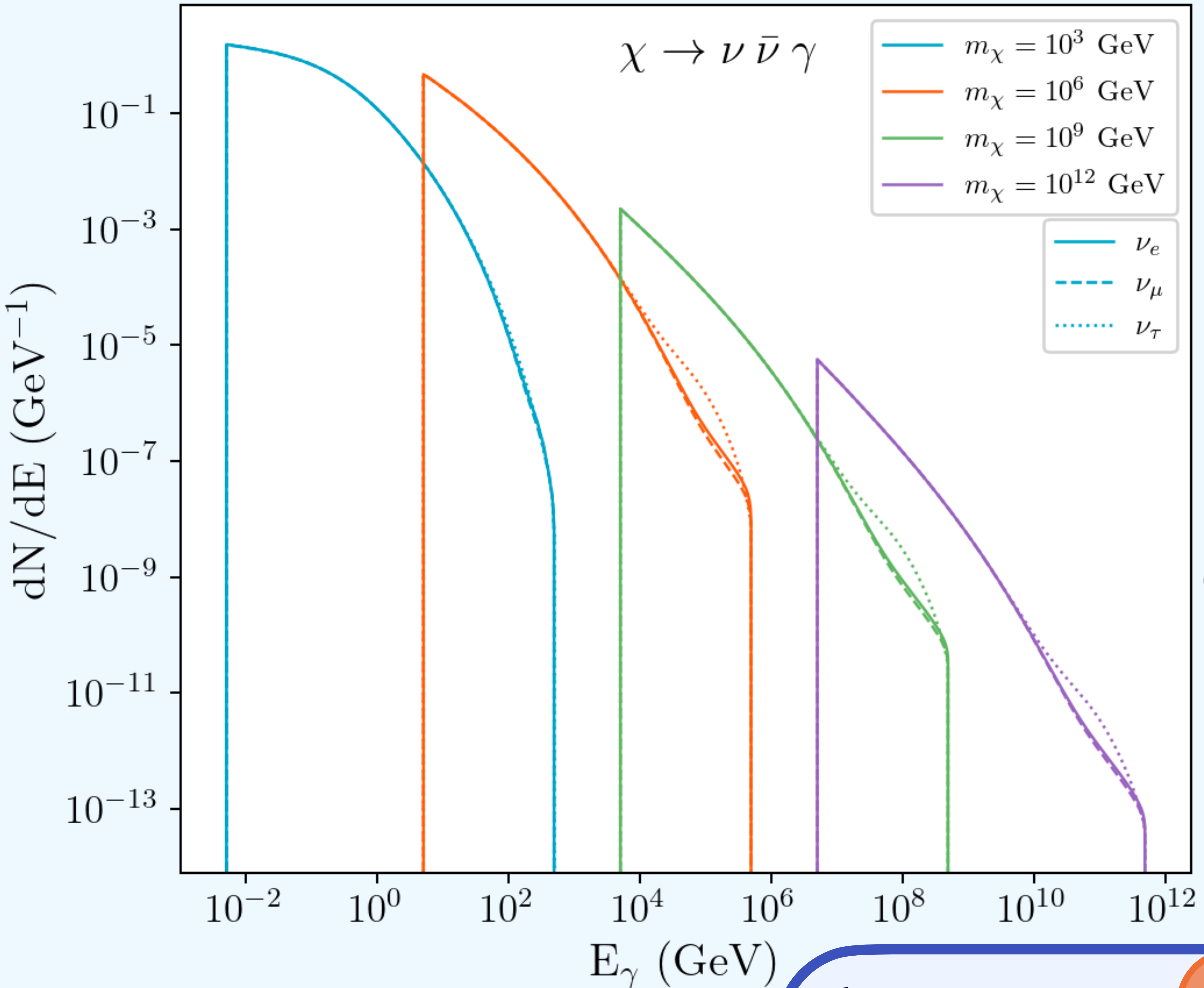
EXPECTED GAMMA-RAY SIGNAL DUE TO ELECTROWEAK CORRECTIONS

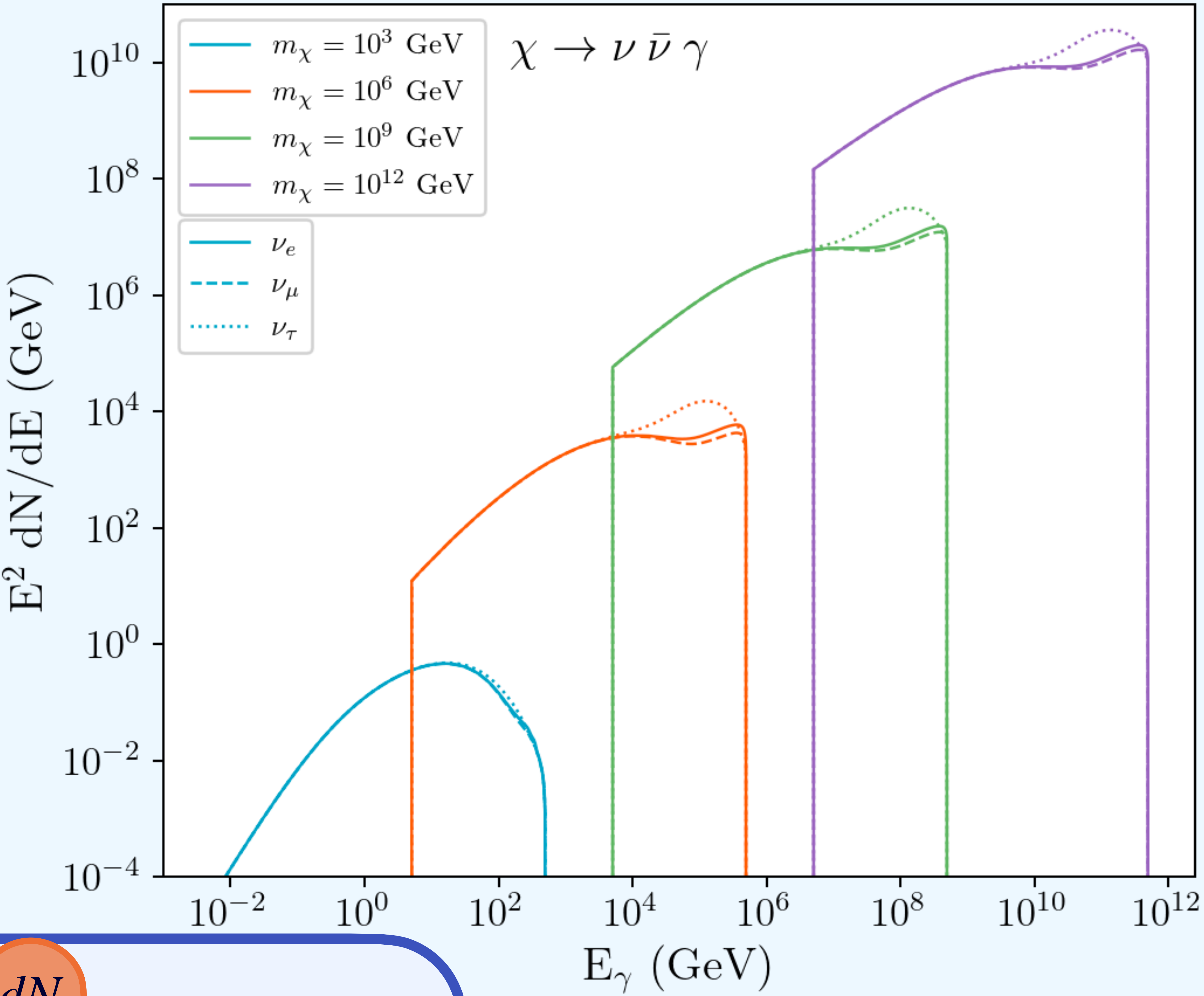
Dark Matter Search Detecting Gammas



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

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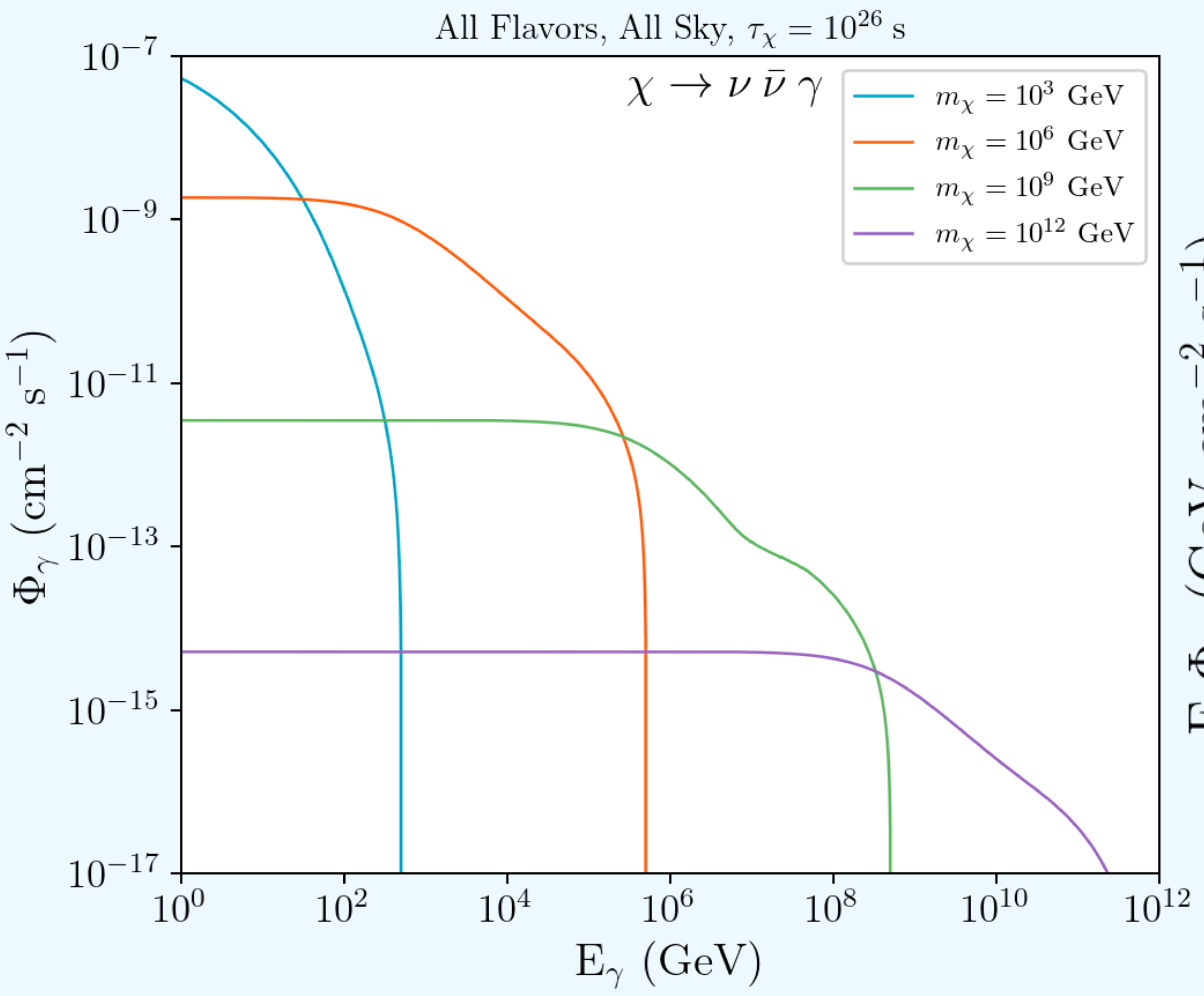
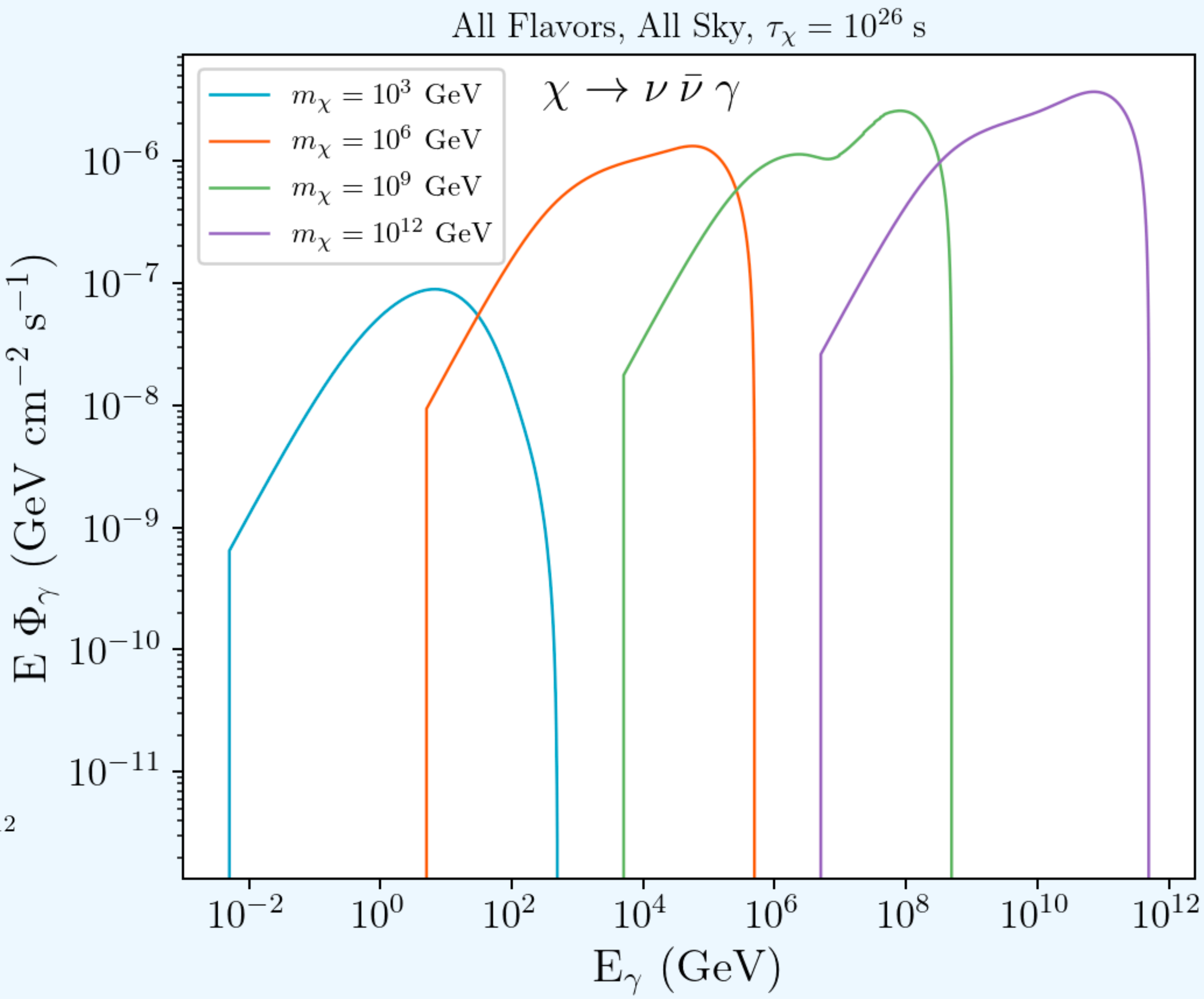
Expected Gamma-Ray Flux for Decaying Dark Matter





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

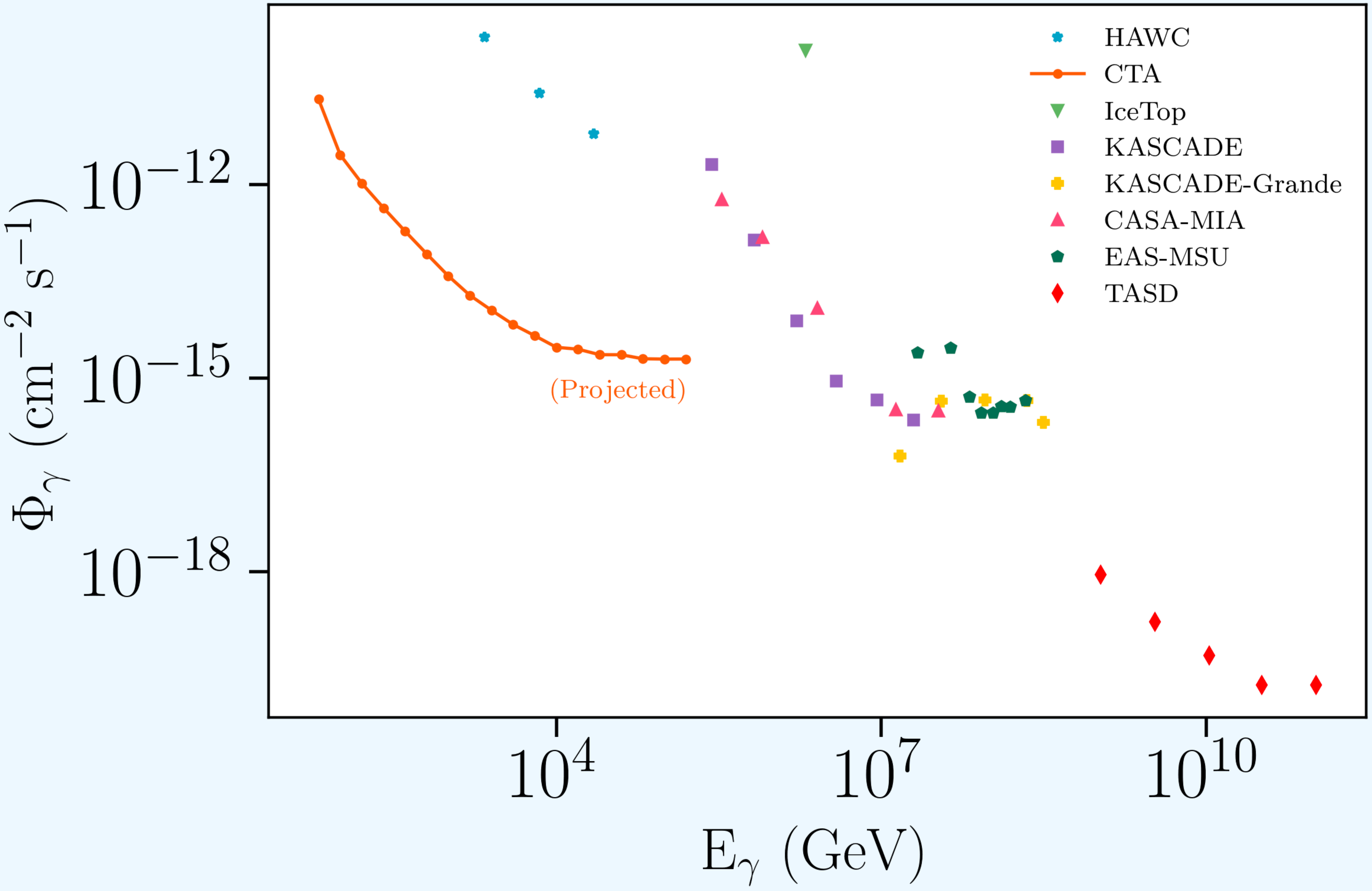
Air Cherenkov. High Energy Gamma Rays (TeV)

IceCube — South Pole Neutrino Observatory — **Ice Top**

Air Showers. Gamma Rays and Cosmic Rays (PeV)

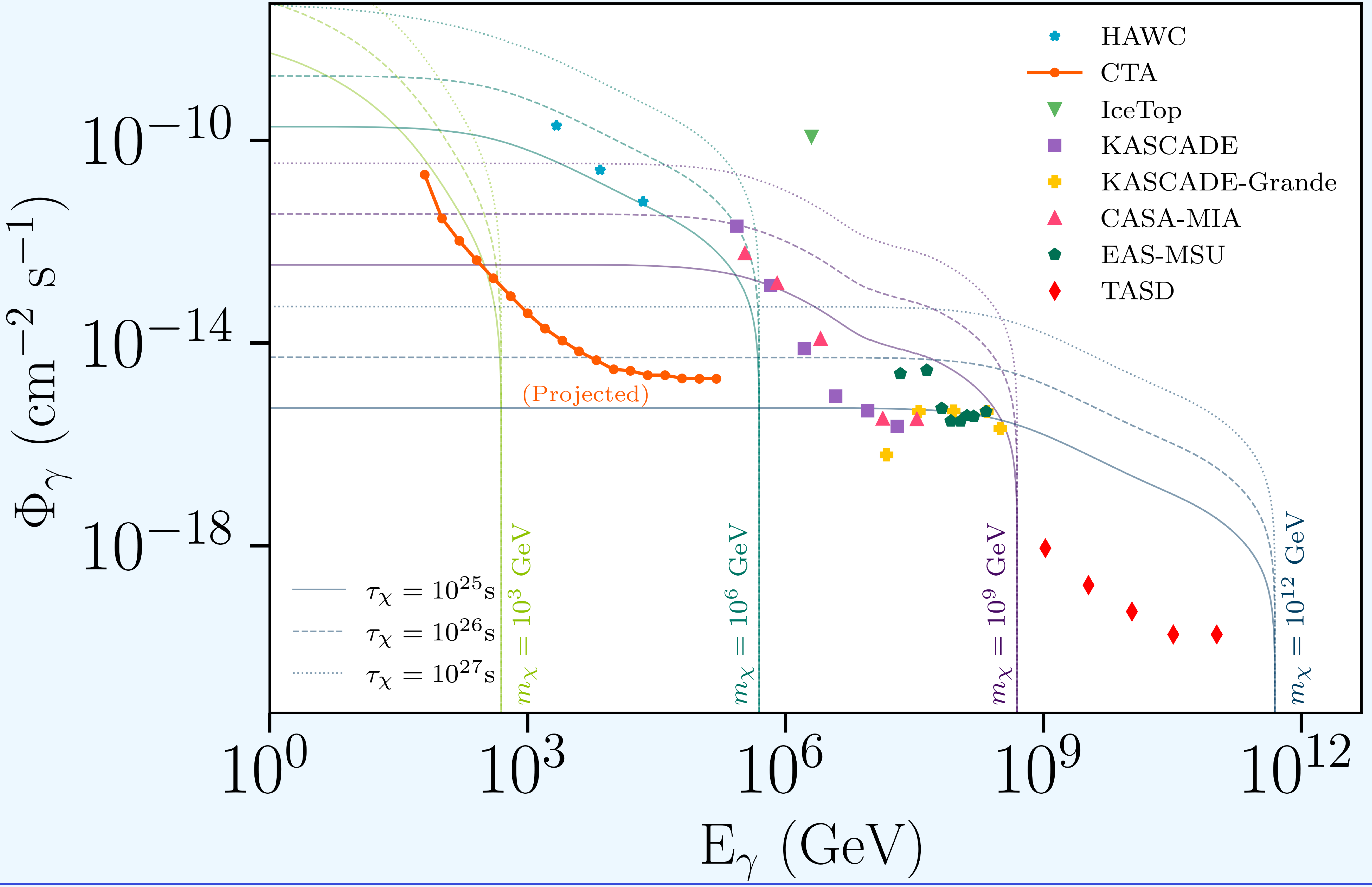
AND OTHER EXPERIMENTS

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	$8.60 \cdot 10^{22}$

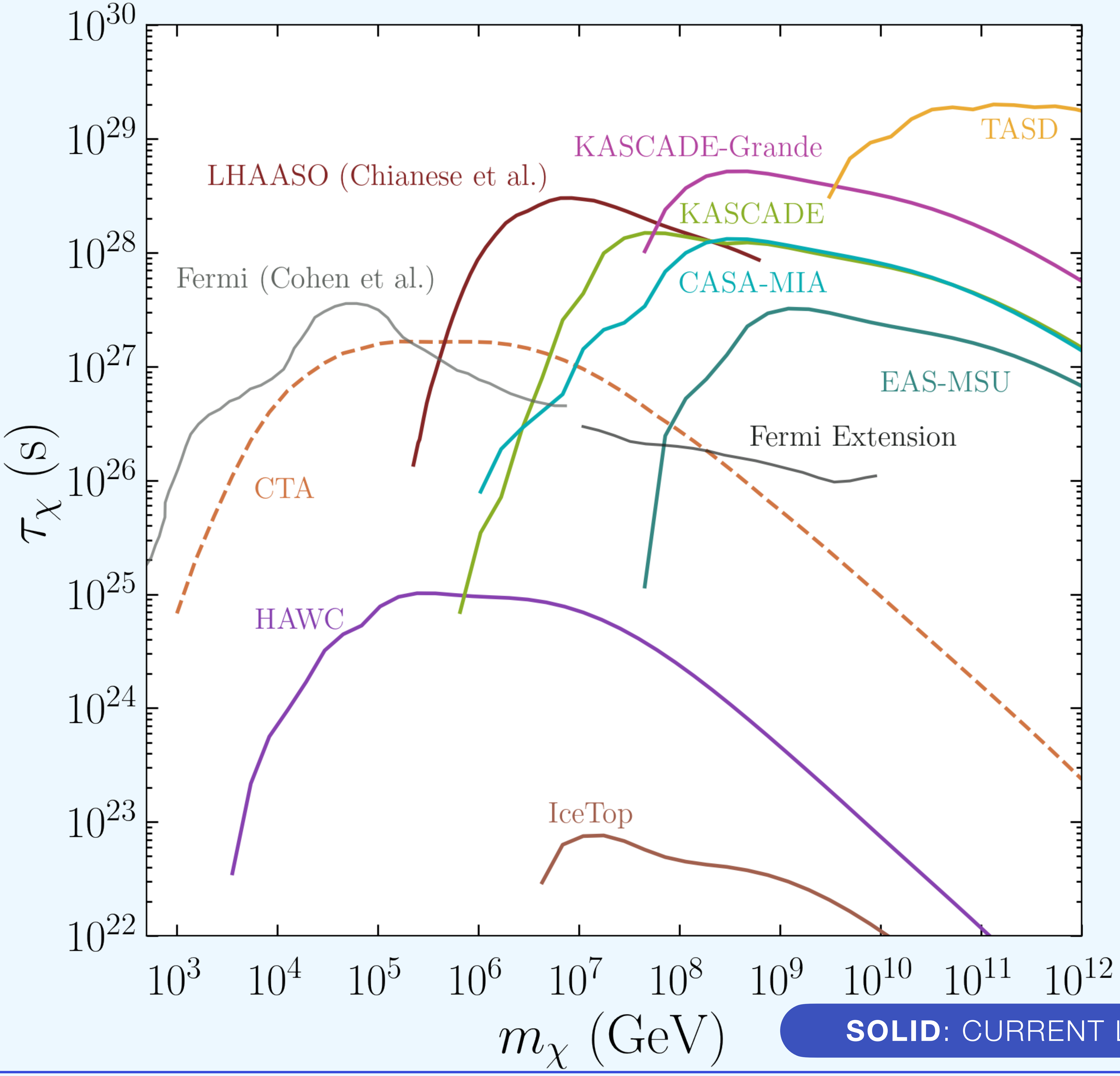
Integral γ Flux from DM and Gamma-Ray Flux Sensitivities



Decay Results

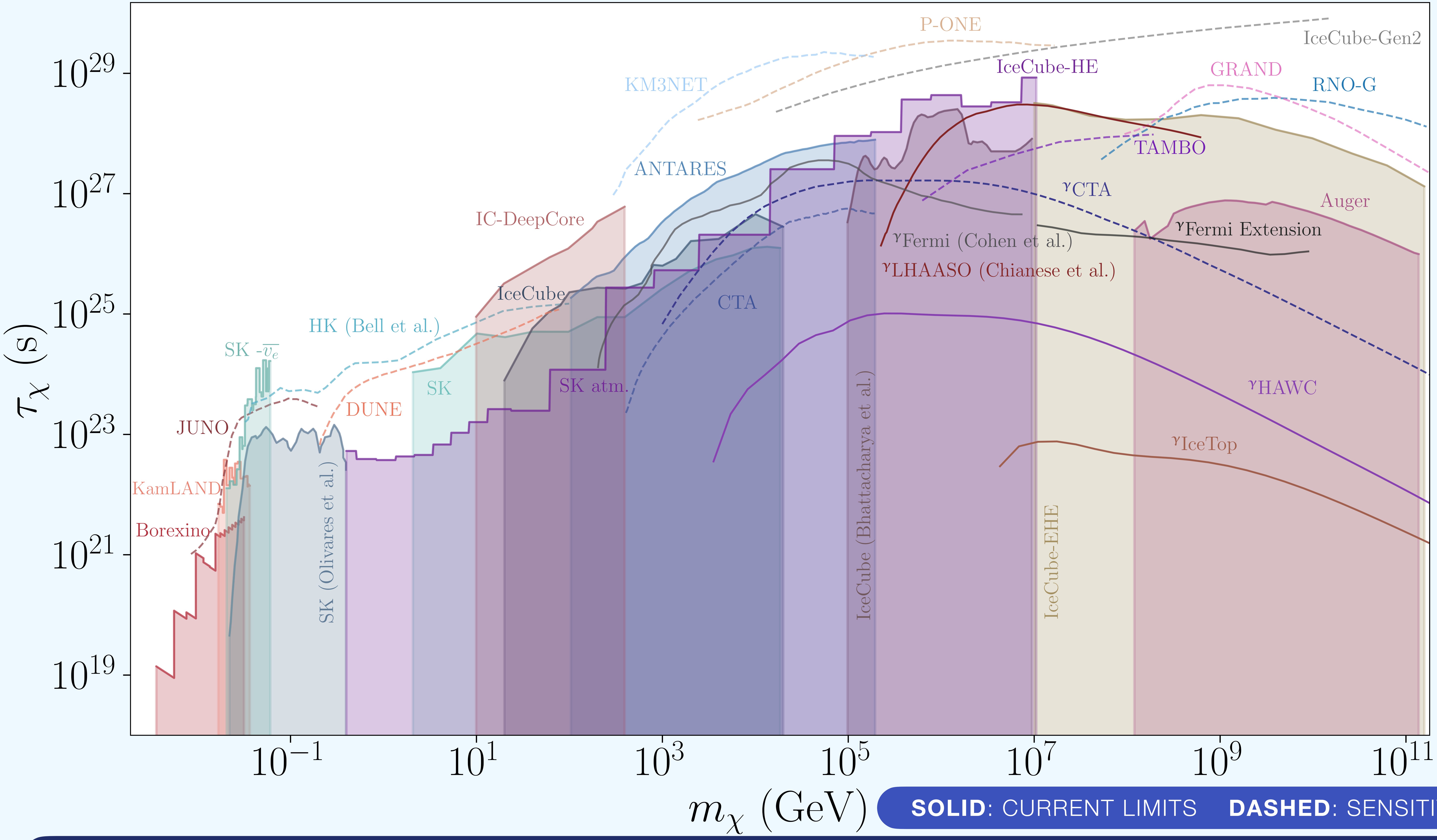
Gamma-Ray Experiments

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 $\rightarrow$ 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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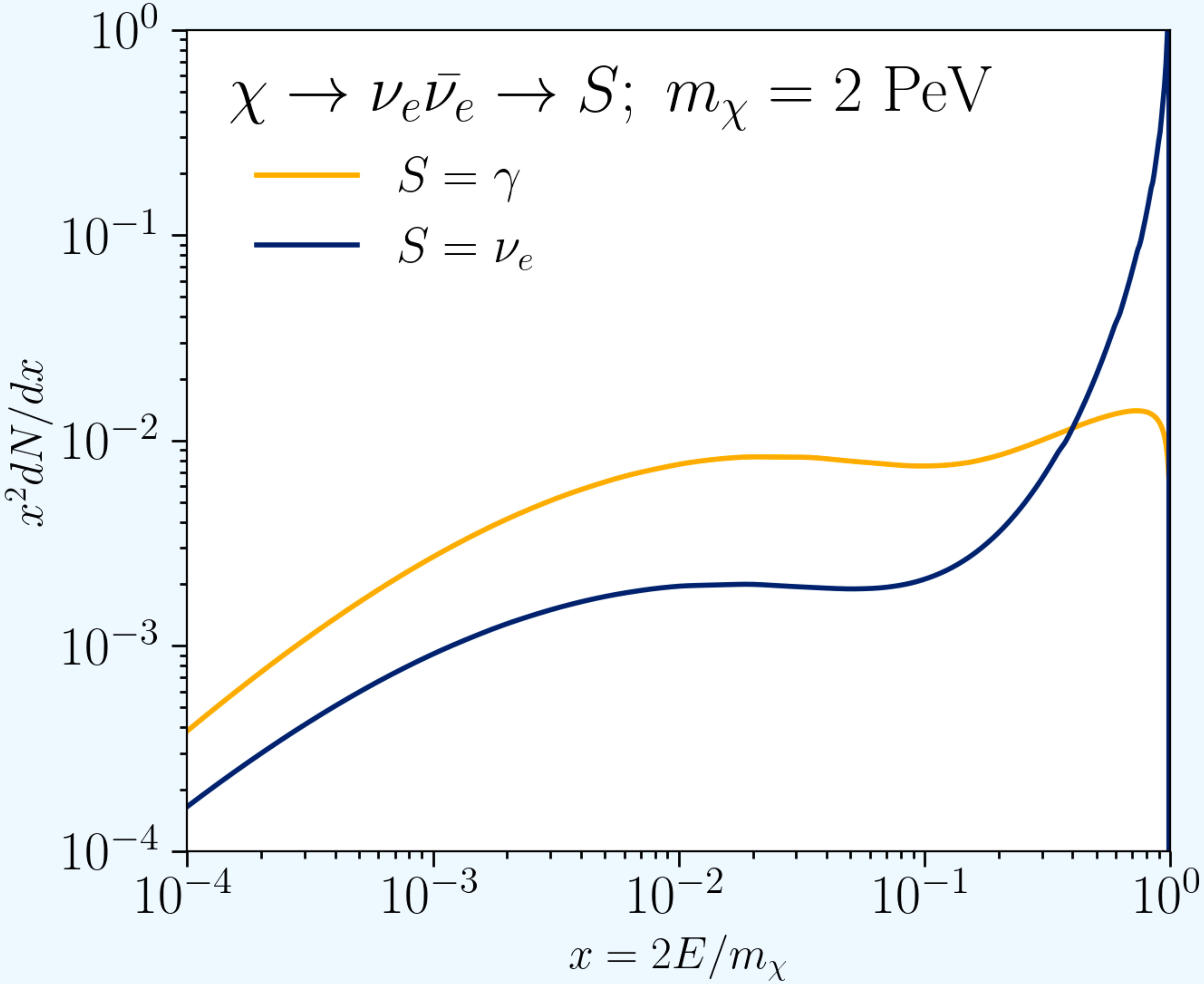
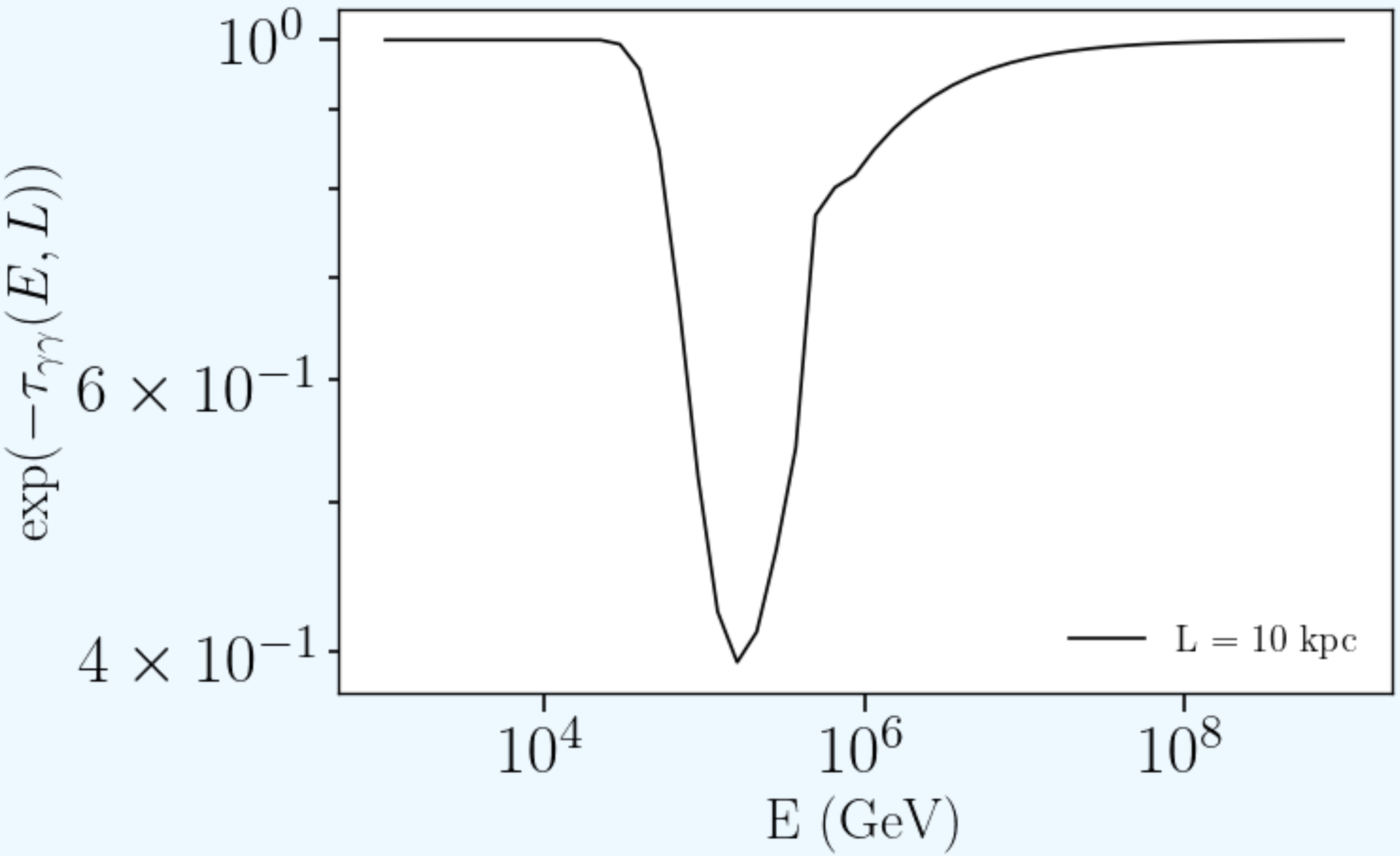
Backup

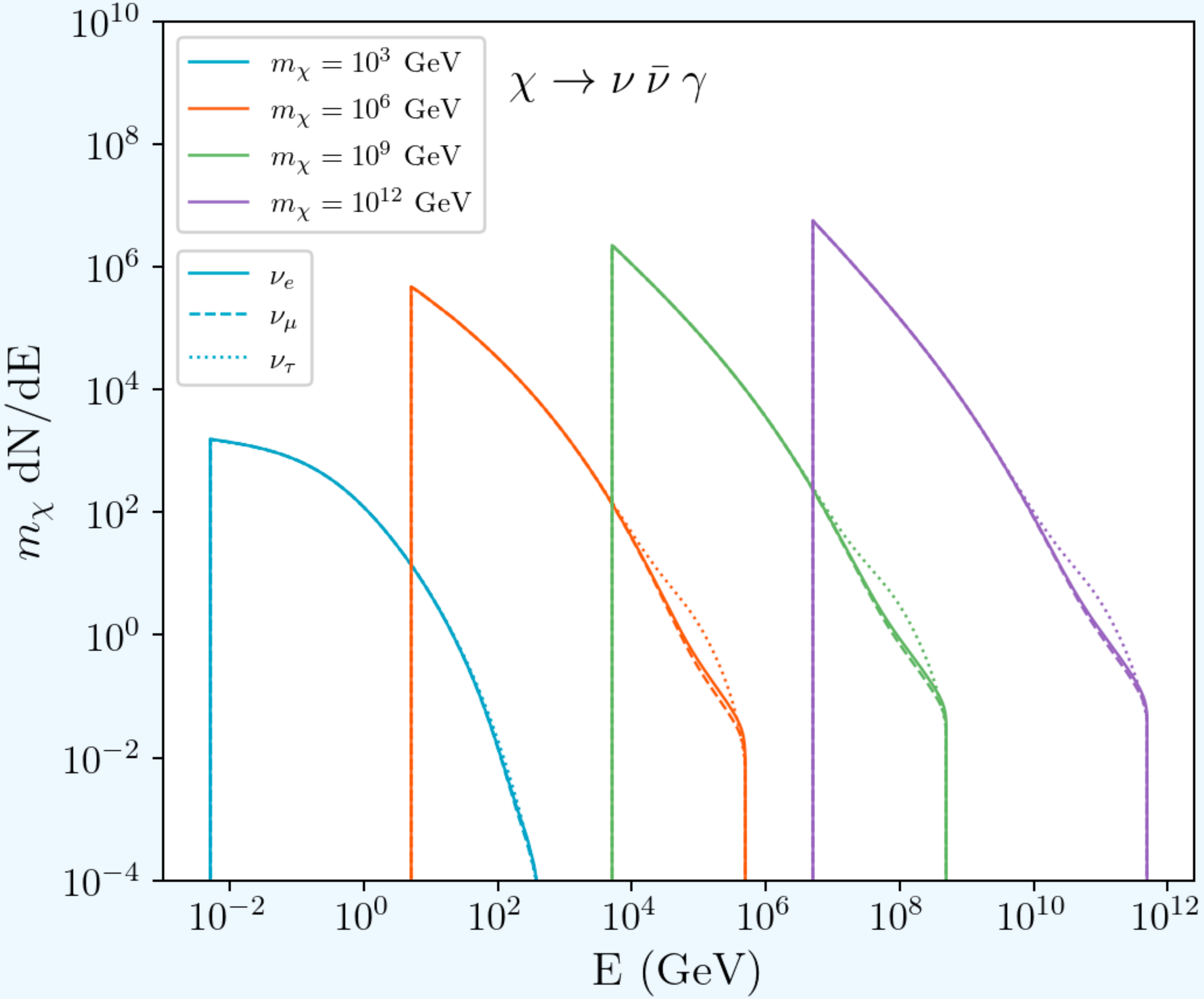
Neutrino Production Spectrum for Direct Decay of DM to Neutrinos



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:

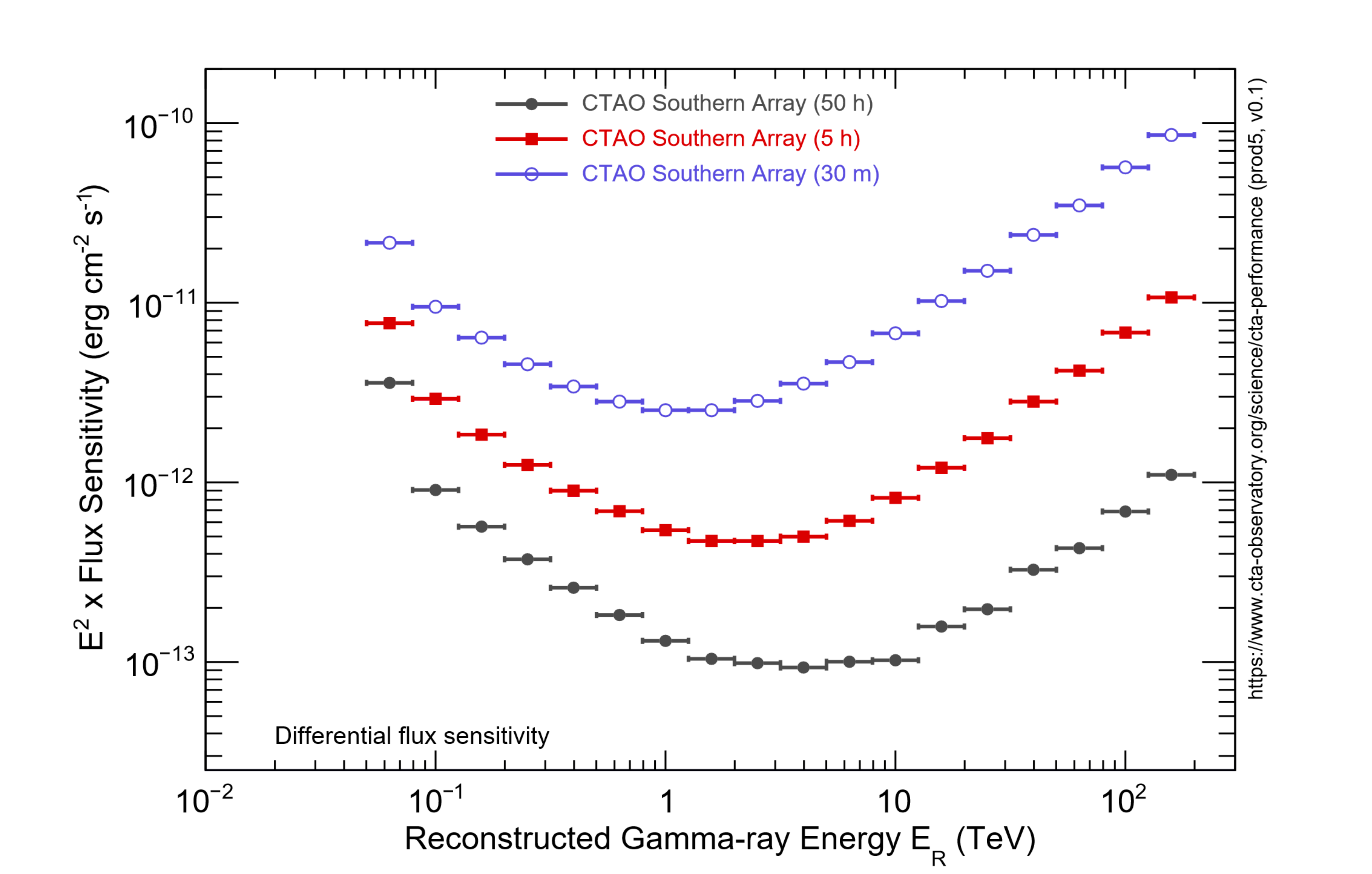
$$\phi_{lim}(\bar{E}) = 4\pi \int_{a_-}^{a^+} f_0 E^{-\alpha} dE \quad \textbf{with} \quad a_\pm \equiv \bar{E}\, 10^{\pm\Delta/2}$$

Δ is the bin width.

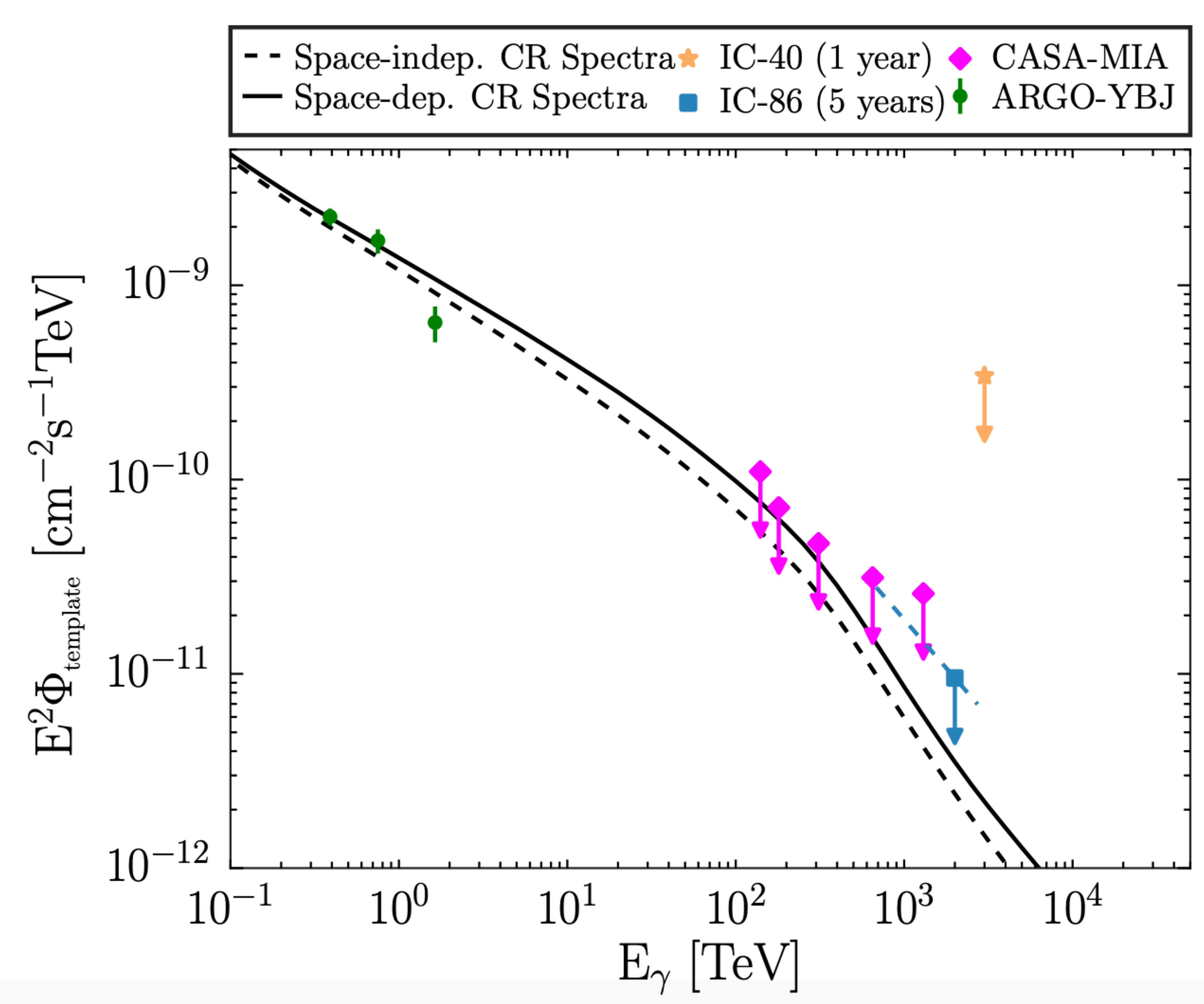
- Dark matter flux is given by:

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

Gamma-Ray Experimental Sensitivities

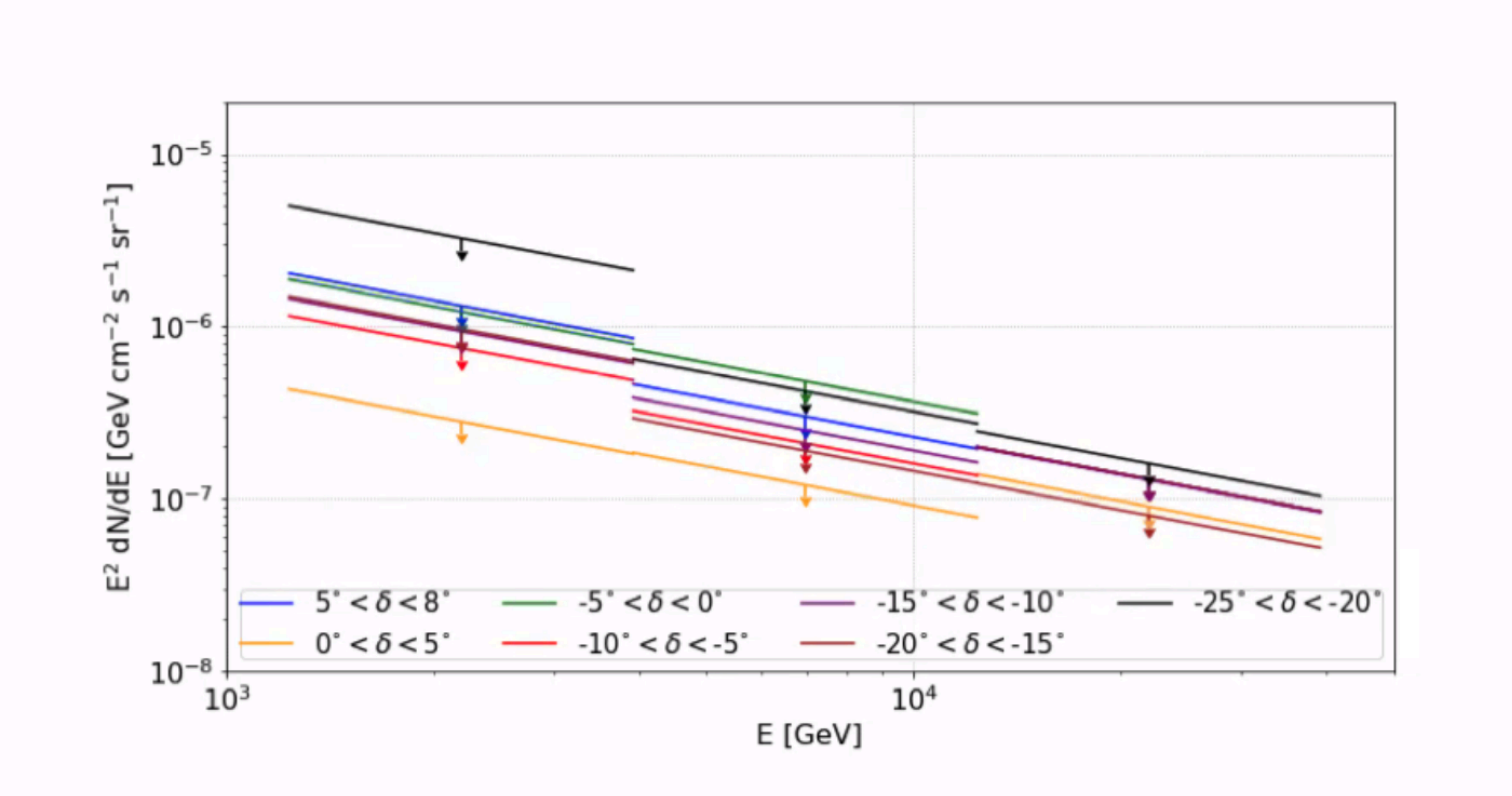


CTA



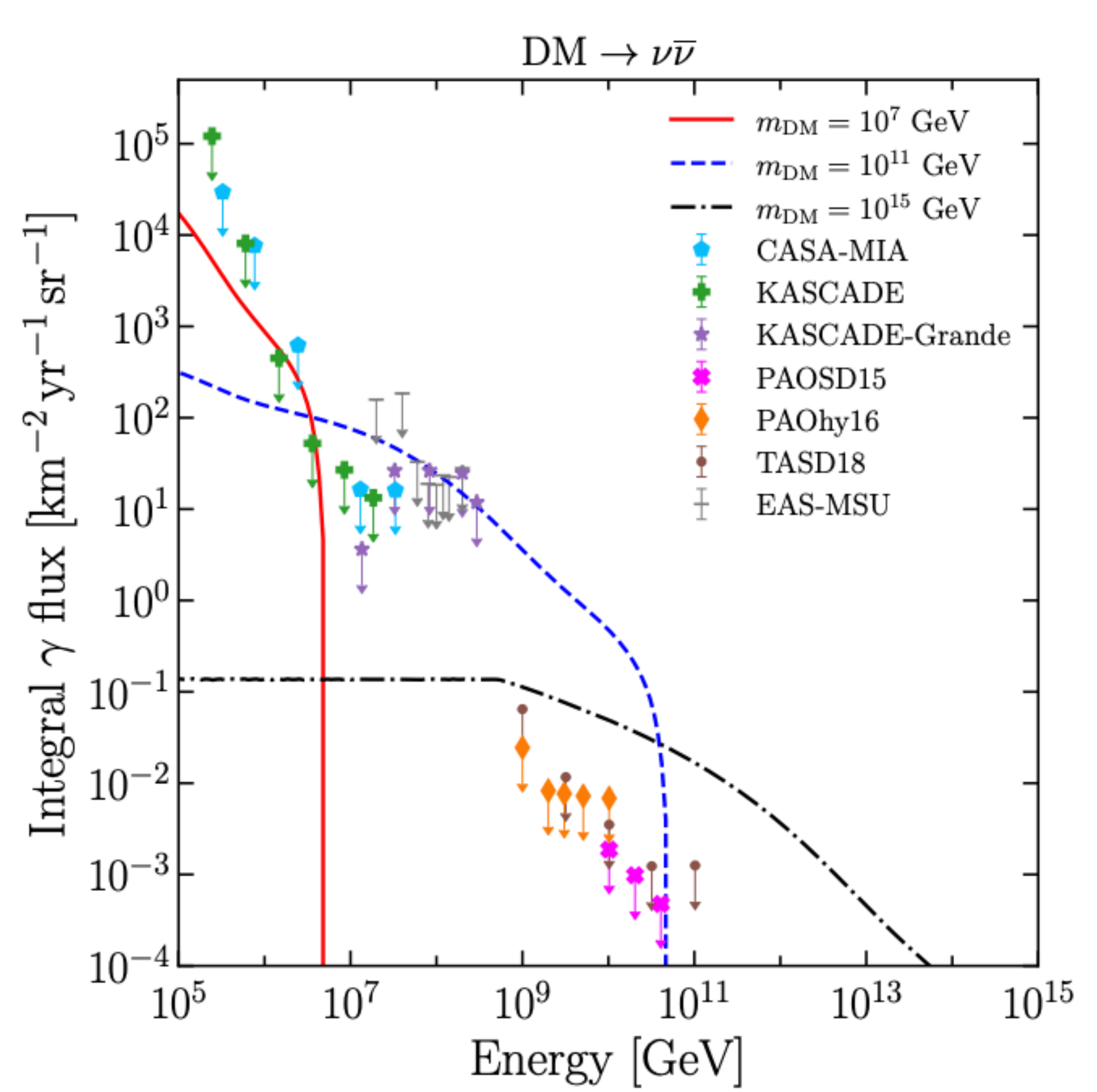
Ice Top

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