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

DIYASELIS M. DELGADO LÓPEZ

EMAIL: ddelgado@g.harvard.edu

TEVPA (CHENGDU, CHINA) - PARALLEL TALK

OCT 27, 2021

Standard Model is great and all but...

Standard Model is great and all but...

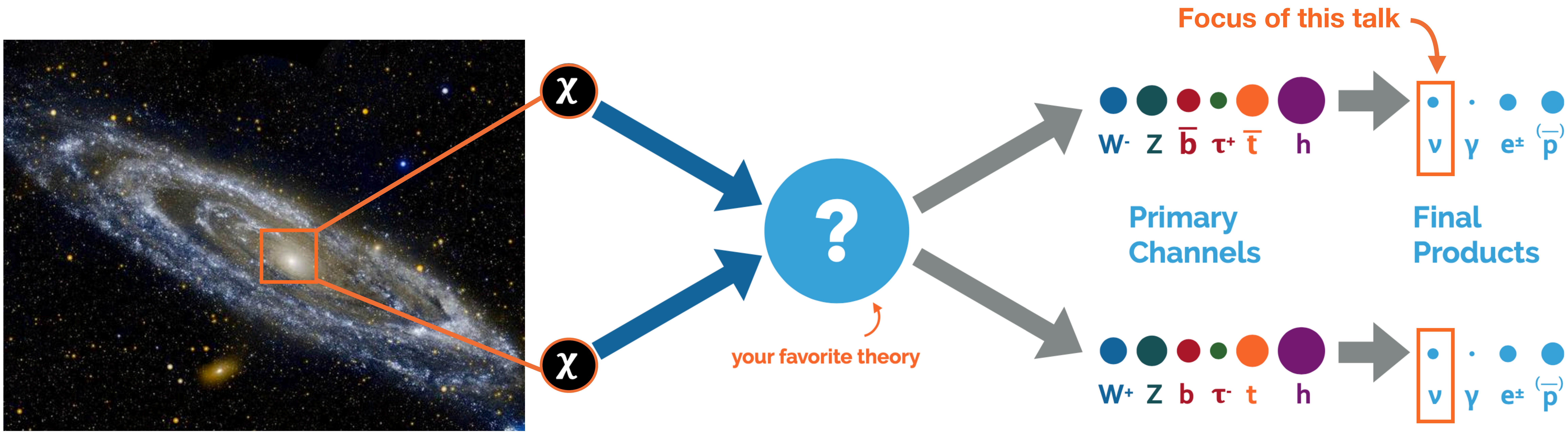
Need SM extension

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

Weakly-interacting massive particles (WIMPs) are a simple solution. A new particle connected to the Standard Model by a new force.

Overwhelming astrophysical and cosmological evidence for the existence of Dark Matter (DM).
Hints from bullet cluster and dwarf galaxies pointing to corpuscular nature of DM

Indirect detection

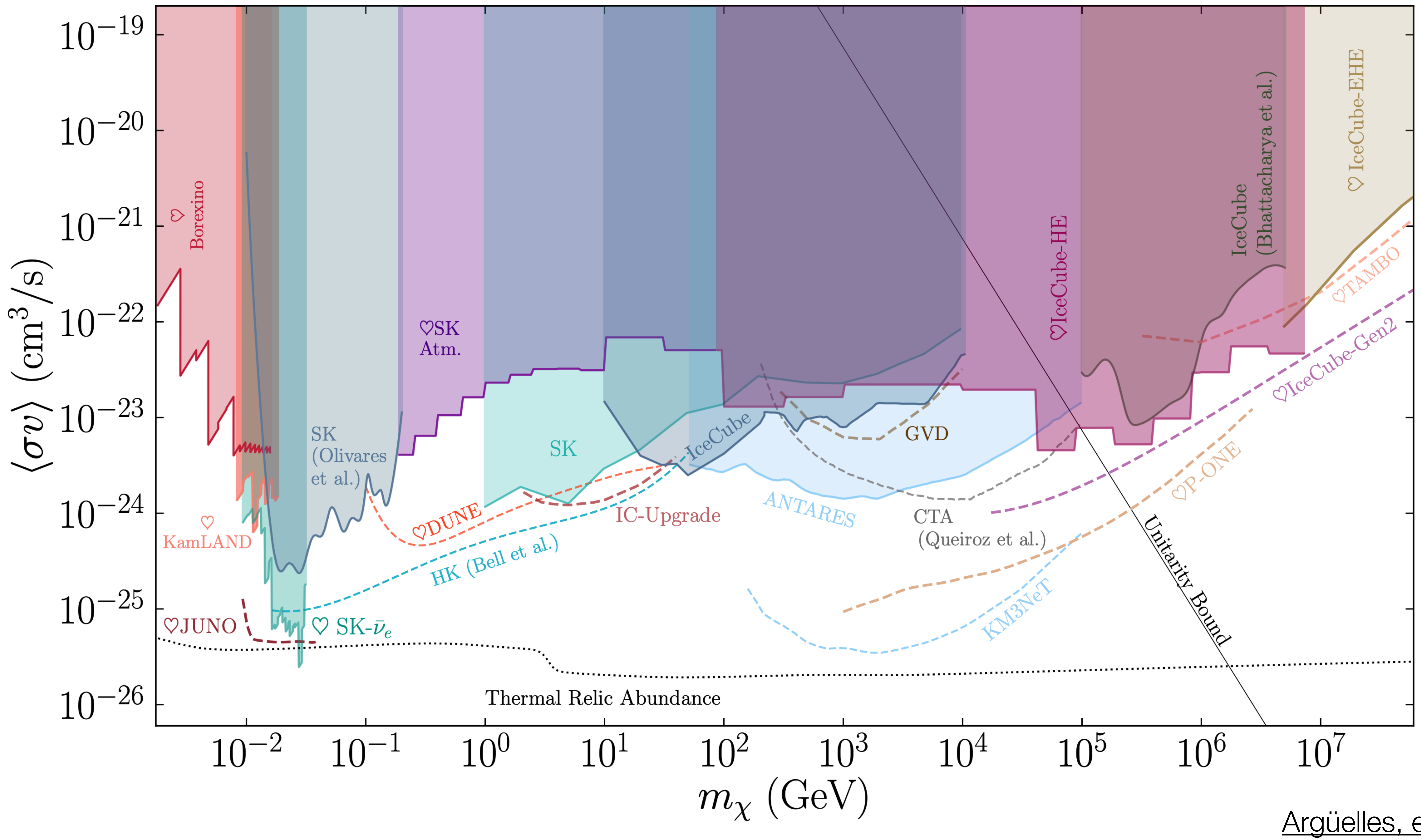


No need for specialized detectors: **Neutrino detectors, Gamma-ray telescopes, CR-experiments**

Search for products of dark matter decay processes: **Focus on large reservoirs of dark matter**

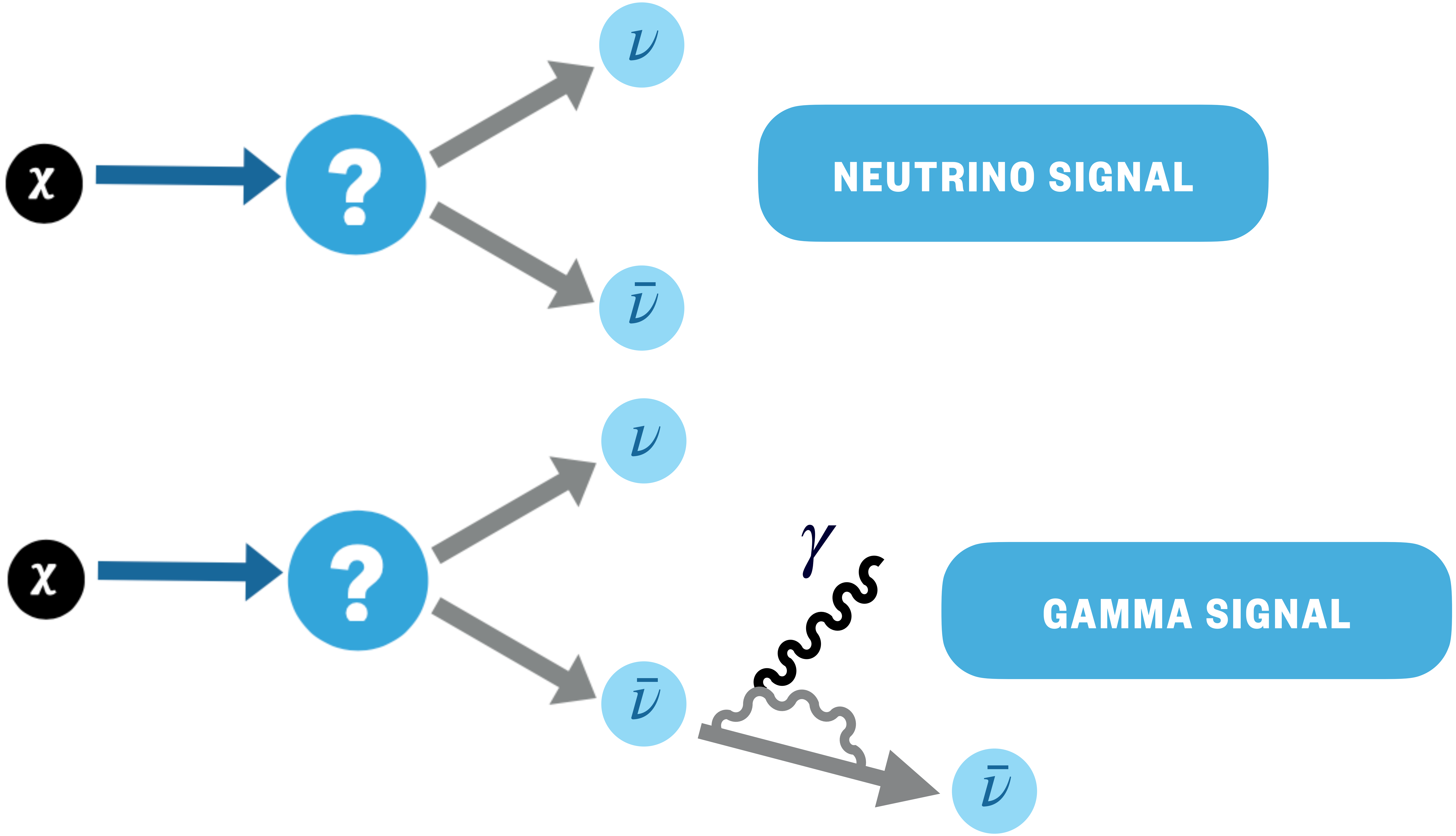
Figure from Juan Aguilar

Motivation: Dark Matter Annihilation to Neutrinos

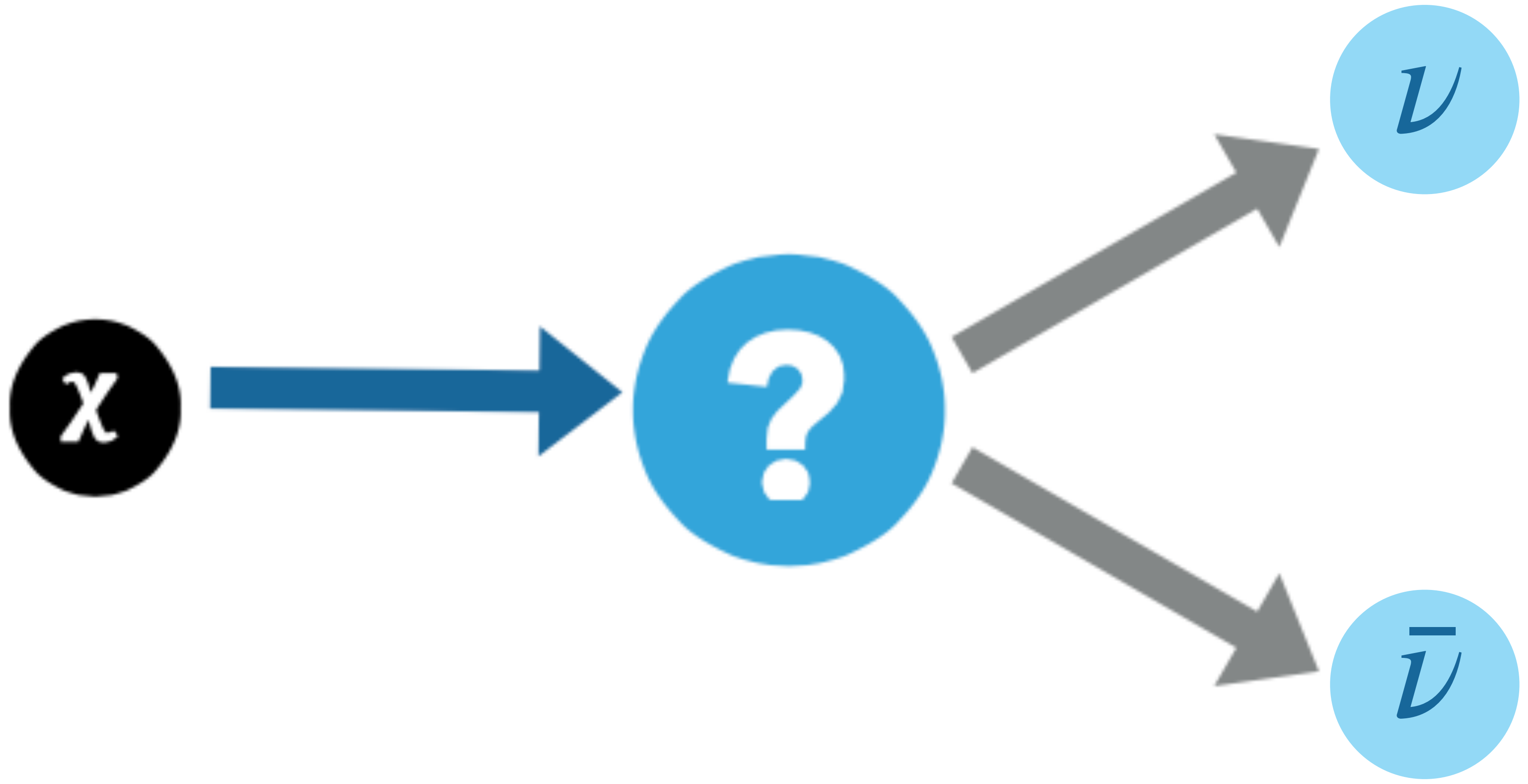


Argüelles, et al.,10.1103

Dark Matter Decay to neutrinos



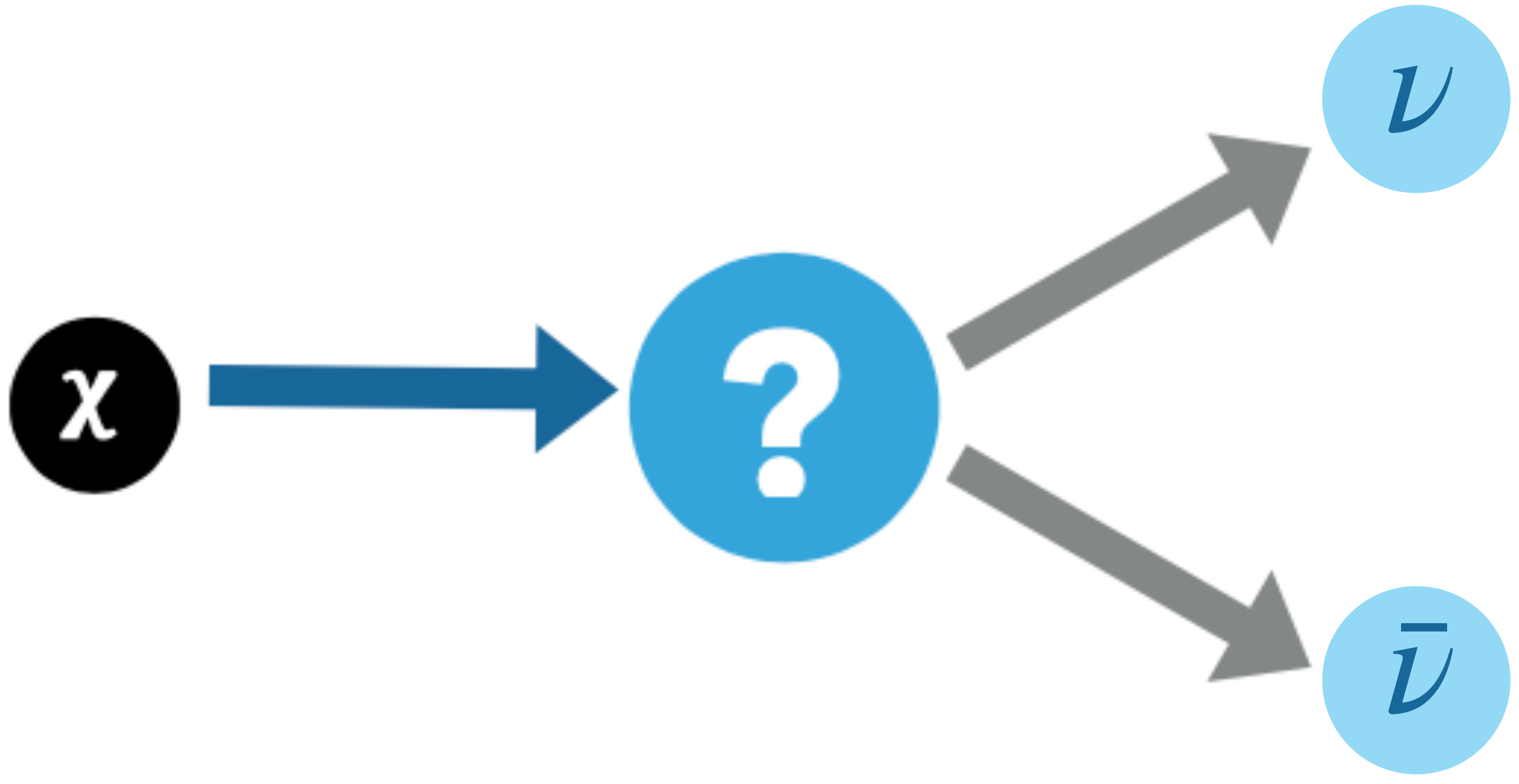
Dark Matter Decay to neutrinos



FLUX FROM DARK MATTER IN OUR GALAXY (GALACTIC CONTRIBUTION)

$$\frac{d\Phi}{dE} = \frac{1}{4\pi}\frac{dN}{dE}D(\Omega, x)\frac{\Gamma_\chi}{m_\chi}$$

Dark Matter Decay to neutrinos



FLUX FROM DARK MATTER IN OUR GALAXY (GALACTIC CONTRIBUTION)

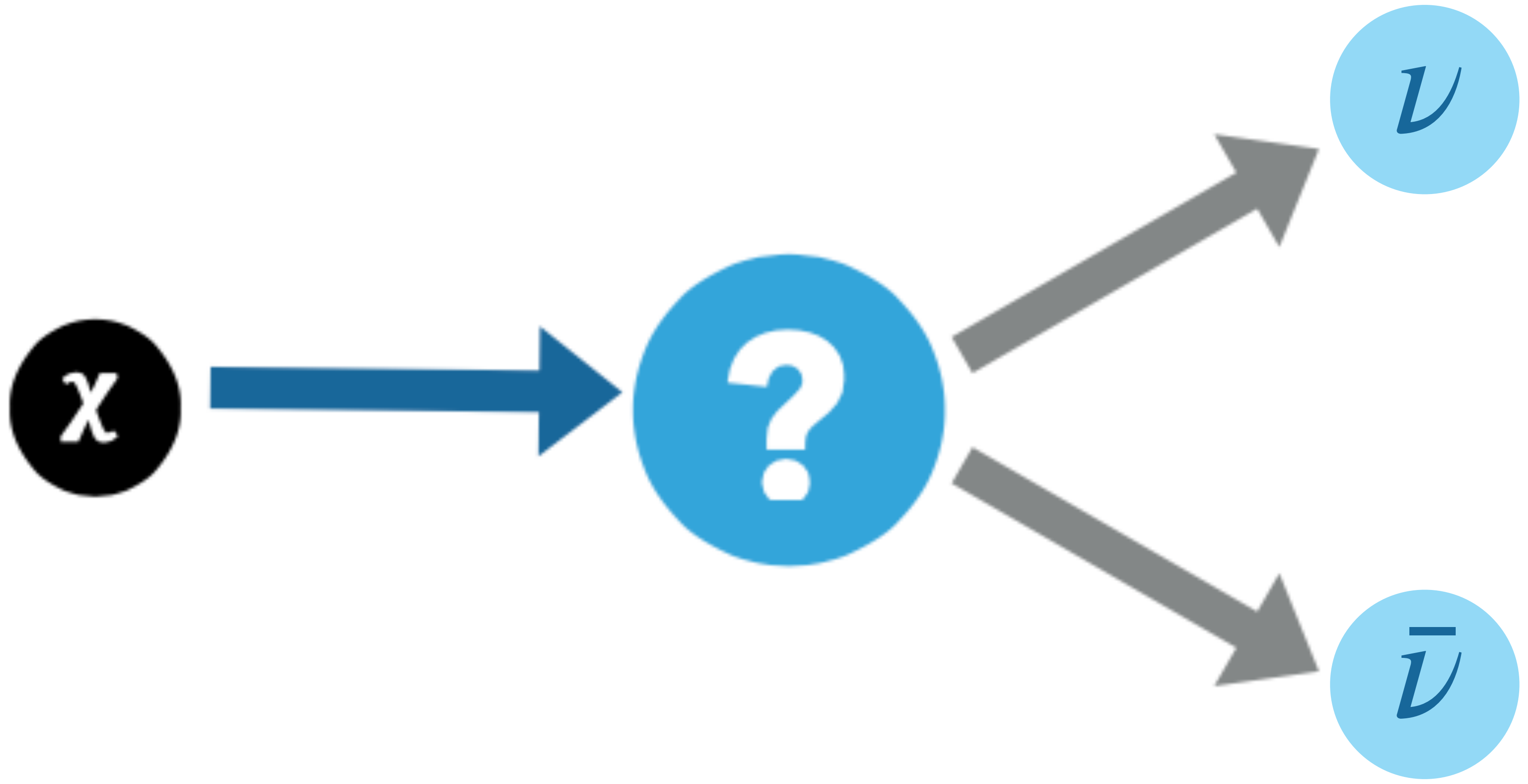
$$\frac{d\Phi}{dE} = \frac{1}{4\pi} \frac{dN}{dE} D(\Omega, x) \frac{\Gamma_\chi}{m_\chi}$$

NEUTRINO PRODUCTION SPECTRUM FOR DECAY OF DM TO NEUTRINOS *

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

*** TRUE FOR NEUTRINOS BUT FOR GAMMAS BECOMES MORE COMPLICATED WITH ELECTROWEAK CORRECTIONS**

Dark Matter Decay to neutrinos



FLUX FROM DARK MATTER IN OUR GALAXY (GALACTIC CONTRIBUTION)

$$\frac{d\Phi}{dE} = \frac{1}{4\pi} \frac{dN}{dE} D(\Omega, x) \frac{\Gamma_\chi}{m_\chi}$$

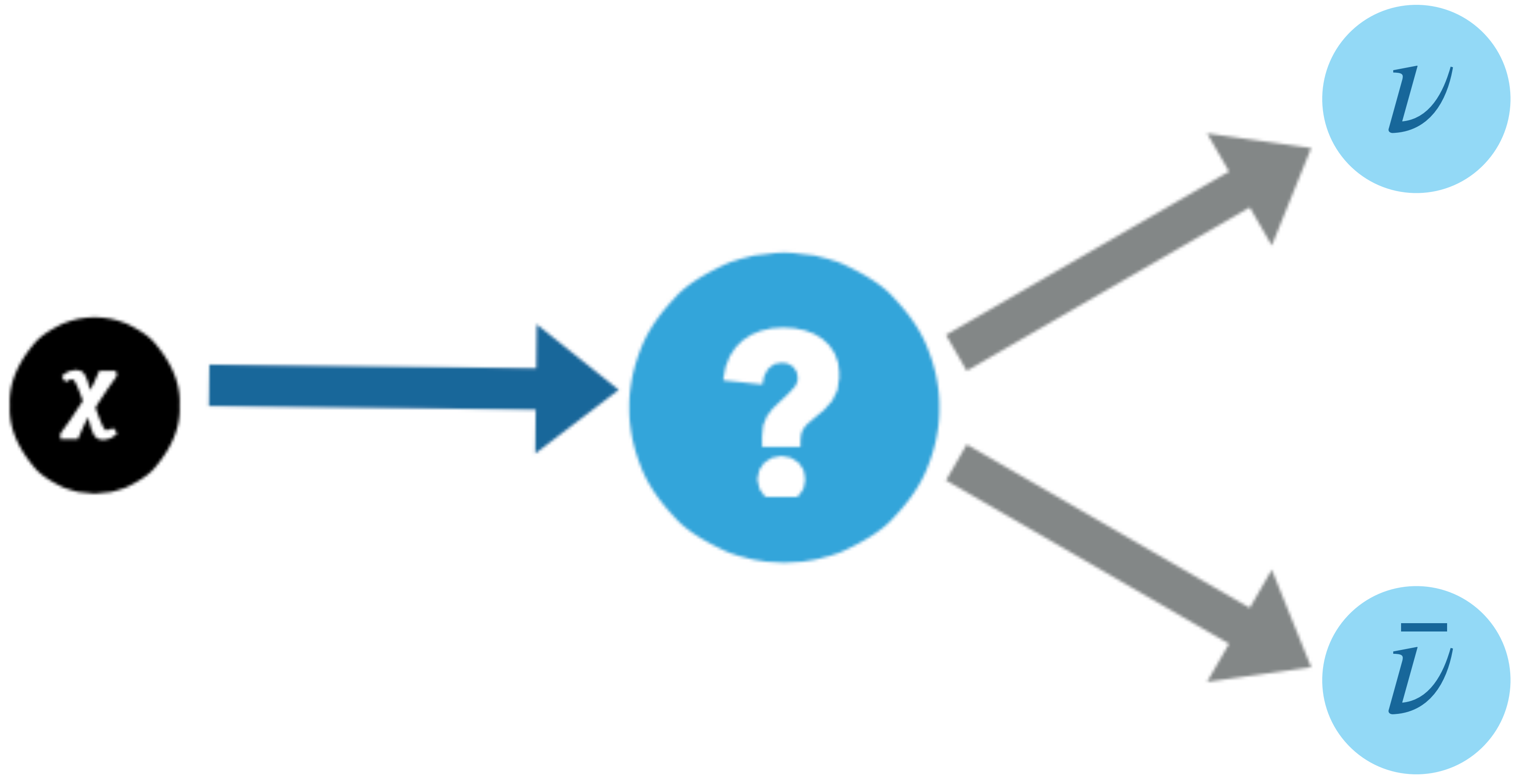
NEUTRINO PRODUCTION SPECTRUM FOR DECAY OF DM TO NEUTRINOS *

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

D FACTOR: 3D INTEGRAL OVER THE SKY SOLID ANGLE AND LINE OF SIGHT

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

Dark Matter Decay to neutrinos



FLUX FROM DARK MATTER IN OUR GALAXY (GALACTIC CONTRIBUTION)

$$\frac{d\Phi}{dE} = \frac{1}{4\pi}\frac{dN}{dE}\, D(\Omega, x)\, \frac{\Gamma_\chi}{m_\chi}$$

NEUTRINO PRODUCTION SPECTRUM FOR DECAY OF DM TO NEUTRINOS *

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

D FACTOR: 3D INTEGRAL OVER THE SKY SOLID ANGLE AND LINE OF SIGHT

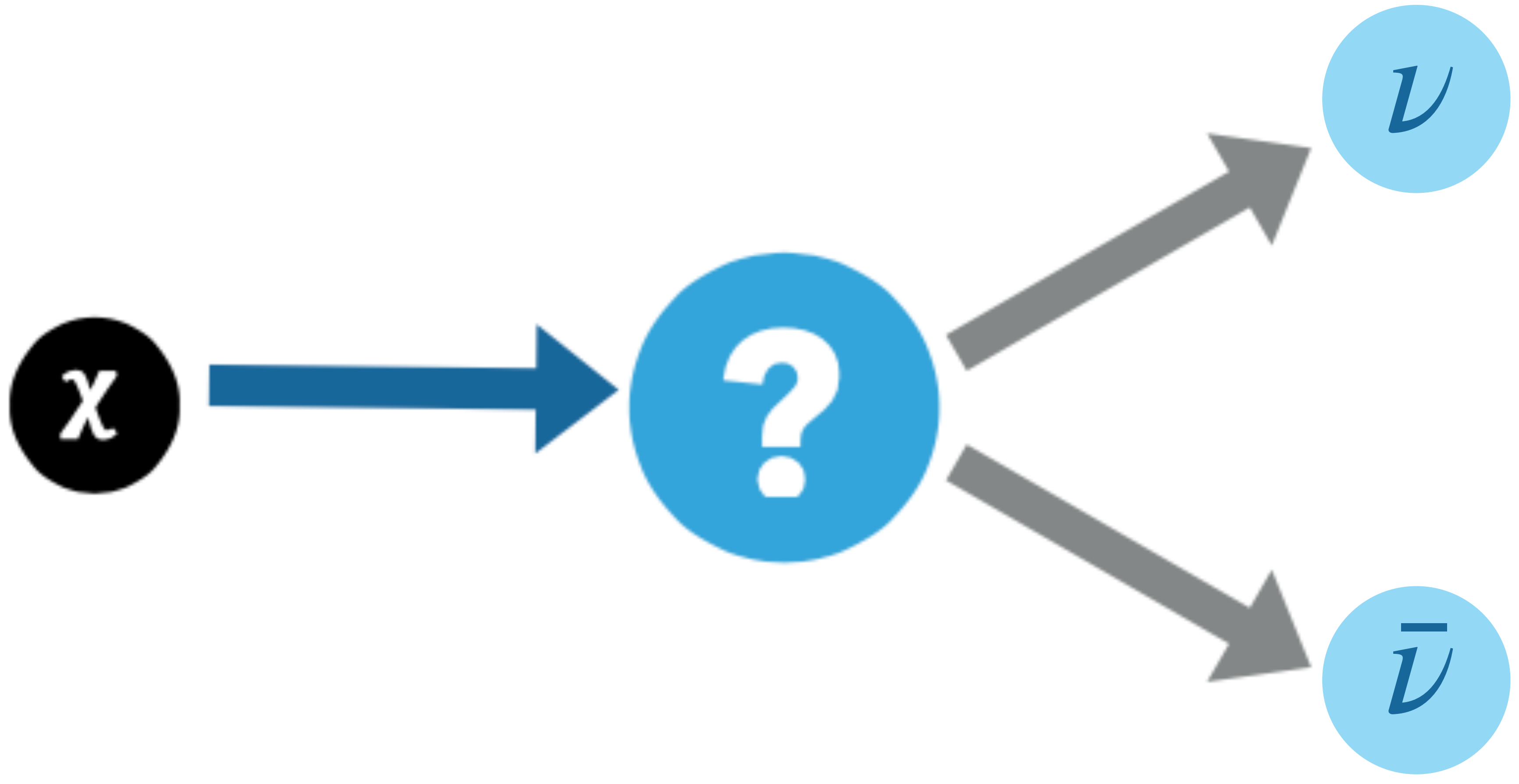
$$D = \int d\Omega \int_{l.o.s.} \rho_\chi(x)\, dx$$

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.,9508025

Dark Matter Decay to neutrinos



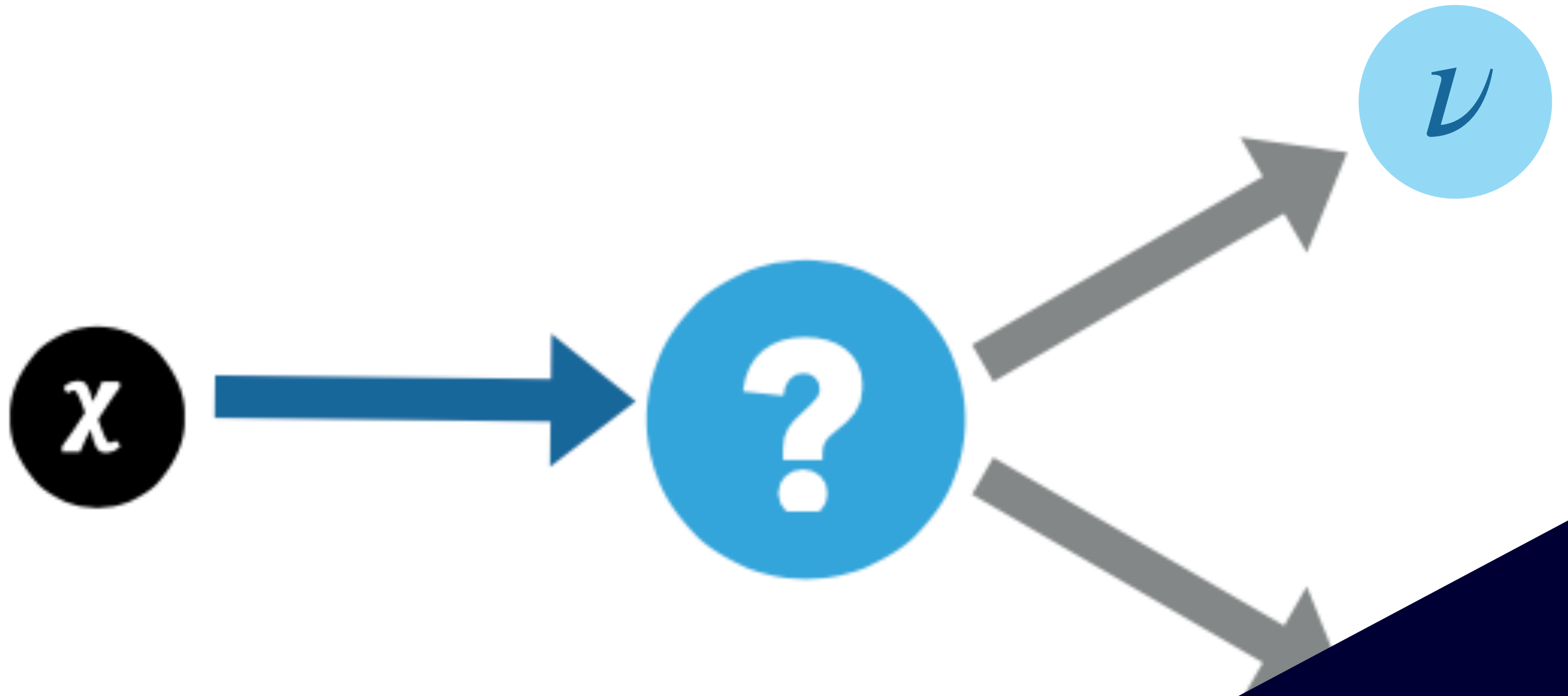
FLUX FROM DARK MATTER IN OUR GALAXY (GALACTIC CONTRIBUTION)

$$\frac{d\Phi}{dE} = \frac{1}{4\pi}\frac{dN}{dE}D(\Omega, x)\frac{\Gamma_\chi}{m_\chi}$$

WE WANT TO DETERMINE THE LIMIT ON THE LIFETIME

$$\Gamma_\chi = \frac{1}{\tau_\chi}$$

Dark Matter Decay to neutri



FLU

m_χ

NE

PRO

Extragalactic contribution also plays an important role!

Depends on the dark matter distribution.

GRAL
SOLID ANGLE
LINE OF SIGHT

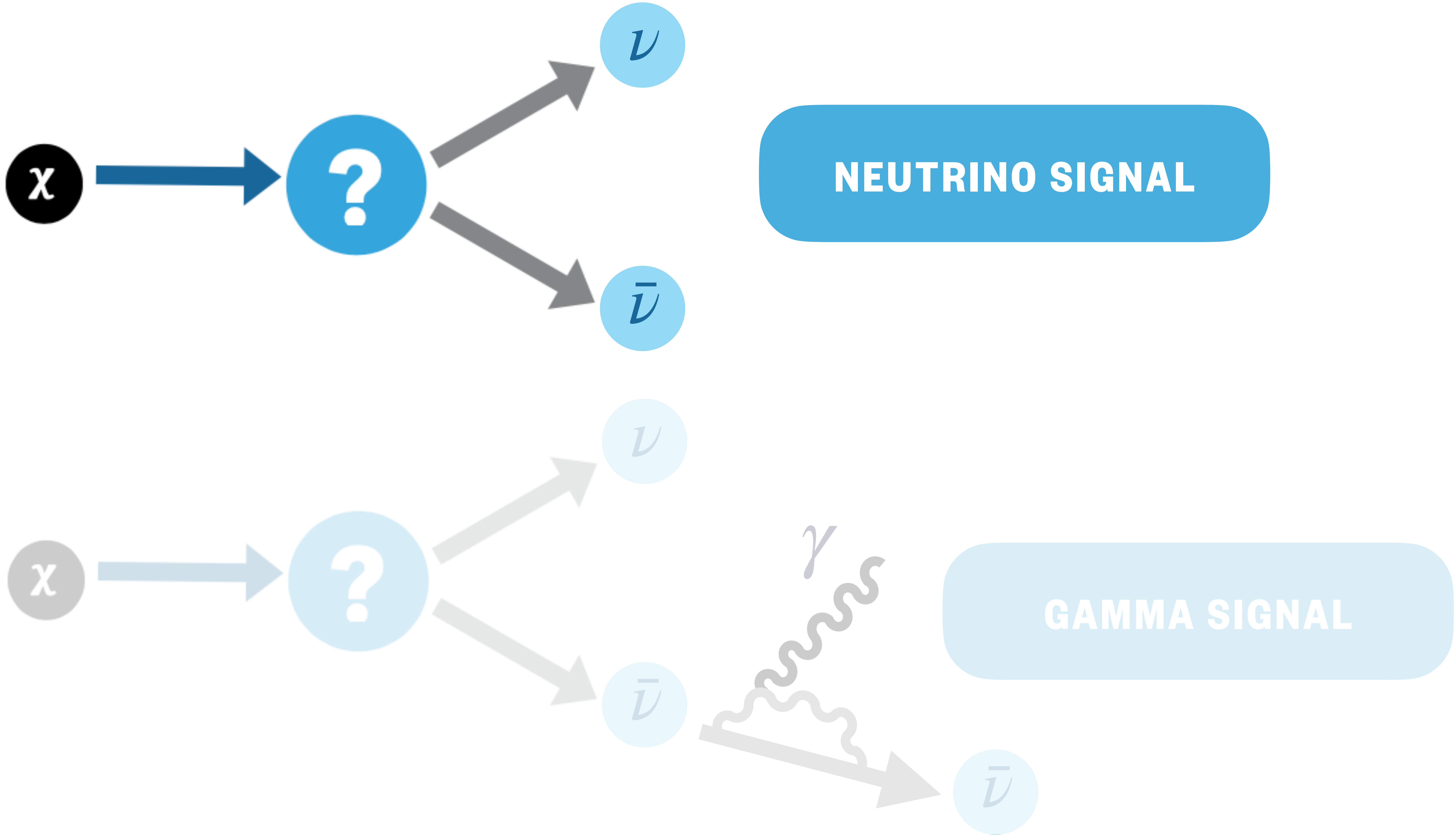
$$D = \int d\Omega \int_{l.o.s.} \rho_\chi(x)\, dx$$

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.,9508025

Dark Matter Decay to neutrinos



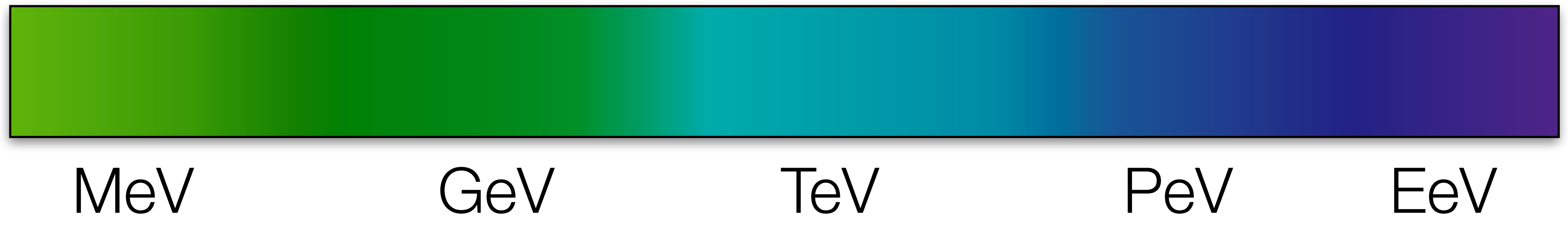
Dark Matter Search using neutrinos

MeV
GeV
TeV
PeV
EeV

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.,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

Liquid scintillator. Solar neutrinos (MeV)

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

Liquid Argon TPC. Atmospheric neutrino fluxes (GeV)

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.

Water Cherenkov. Atmospheric neutrinos (GeV-TeV)

Sea Water Cherenkov Extraterrestrial neutrino fluxes (PeV)

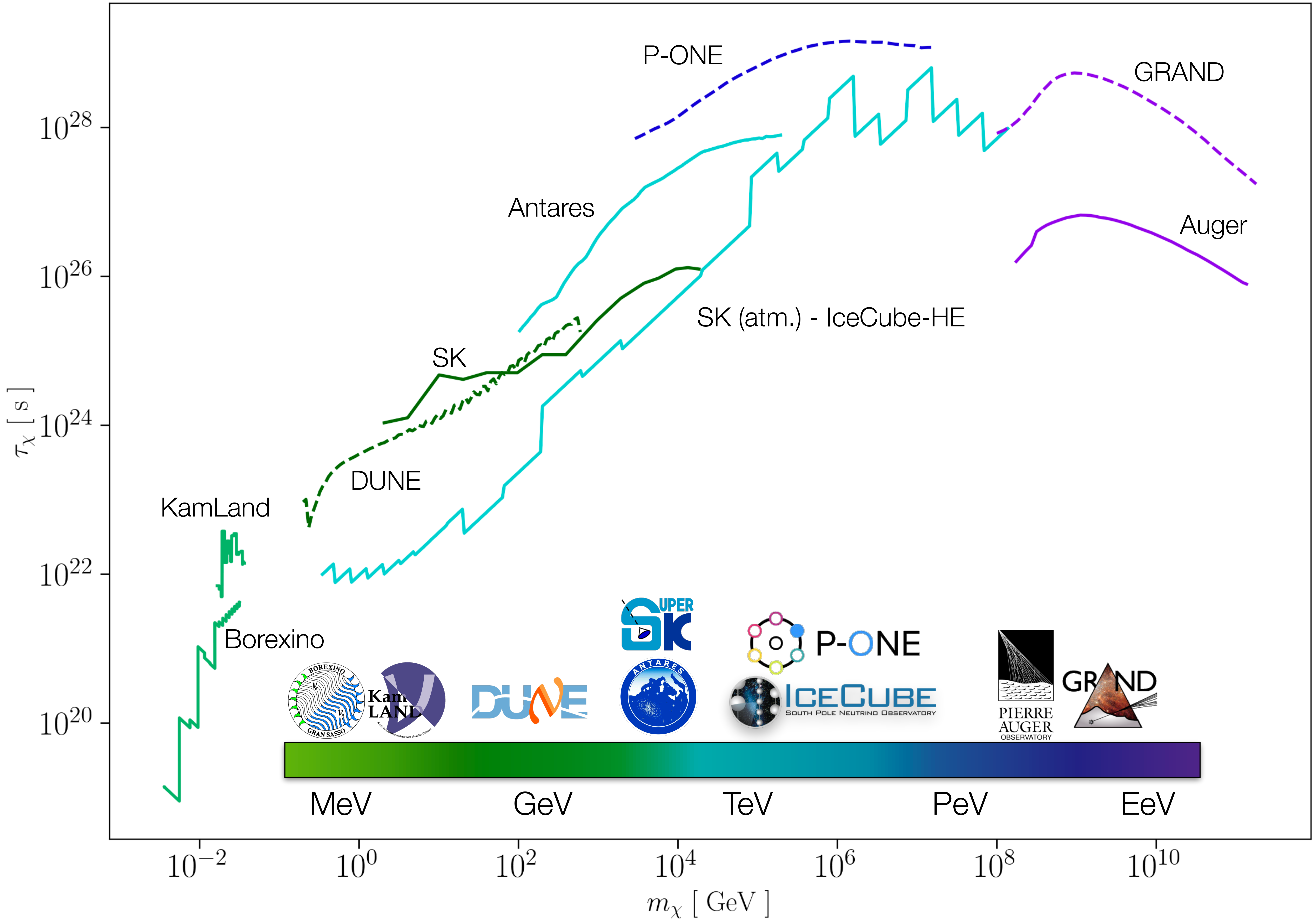
Water Cherenkov. Astrophysical Tau Neutrino (PeV)

Water Cherenkov. Ultra High Energy Cosmic Rays (EeV)

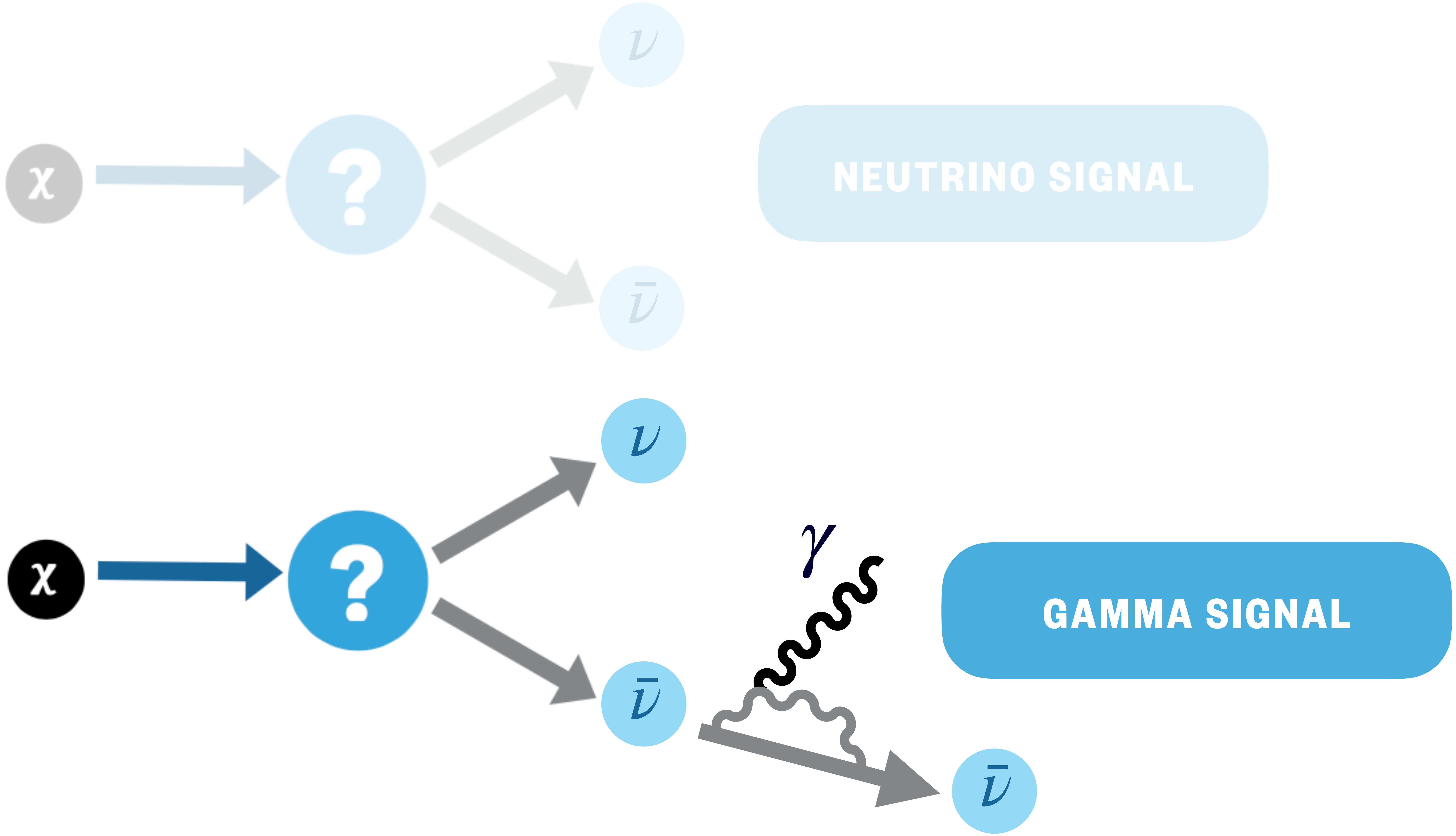
Radio Array. Tau Neutrinos (EeV)

Lifetime Limits

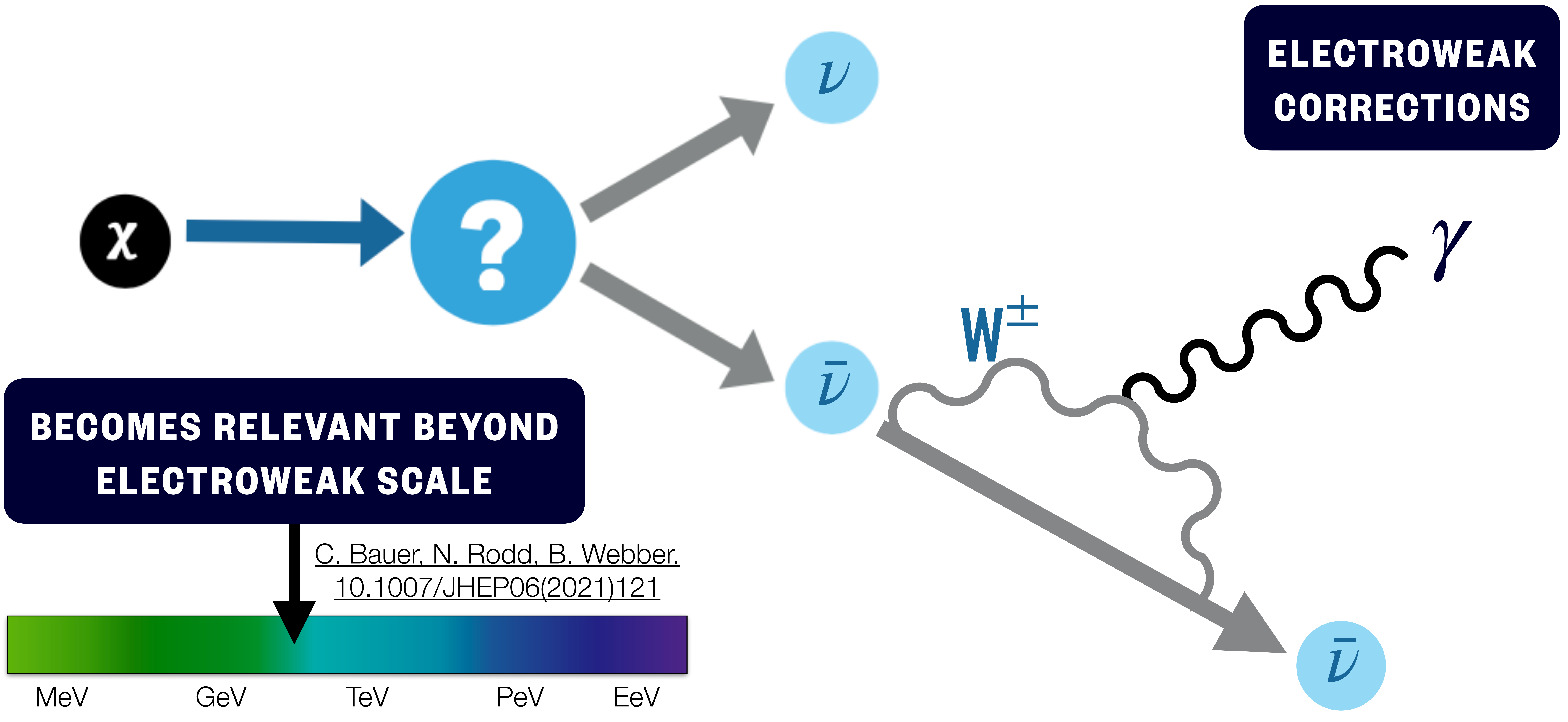
C. Argüelles, **D. Delgado**, A. Vincent, A. Friedlander,
H. White, A. Kheirandish, I. Safa



Dark Matter Decay to neutrinos



Dark Matter Search detecting gammas

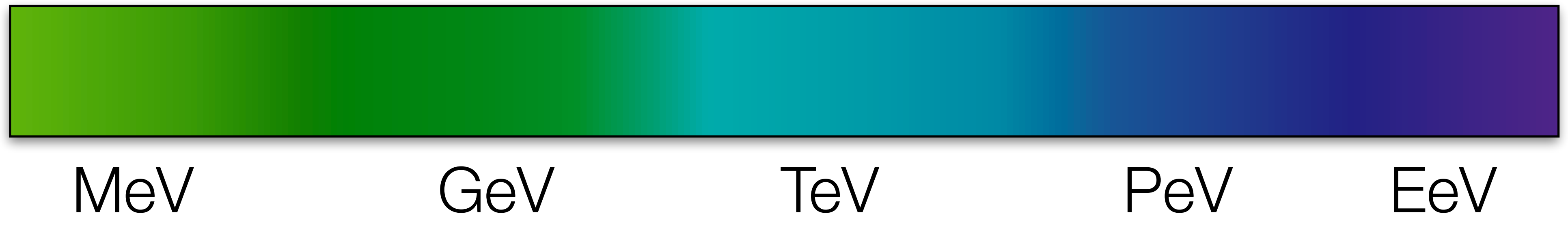


Gamma-Ray Experiments

Hybrid Air Shower. Gamma Rays (GeV - PeV)

Water Cherenkov. Gamma Rays and Cosmic Rays (GeV - TeV)

Air Cherenkov. High Energy Gamma Rays (TeV)



Recipe for Lifetime Limits

EXPECTED BACKGROUND (GAMMA-RAYS)

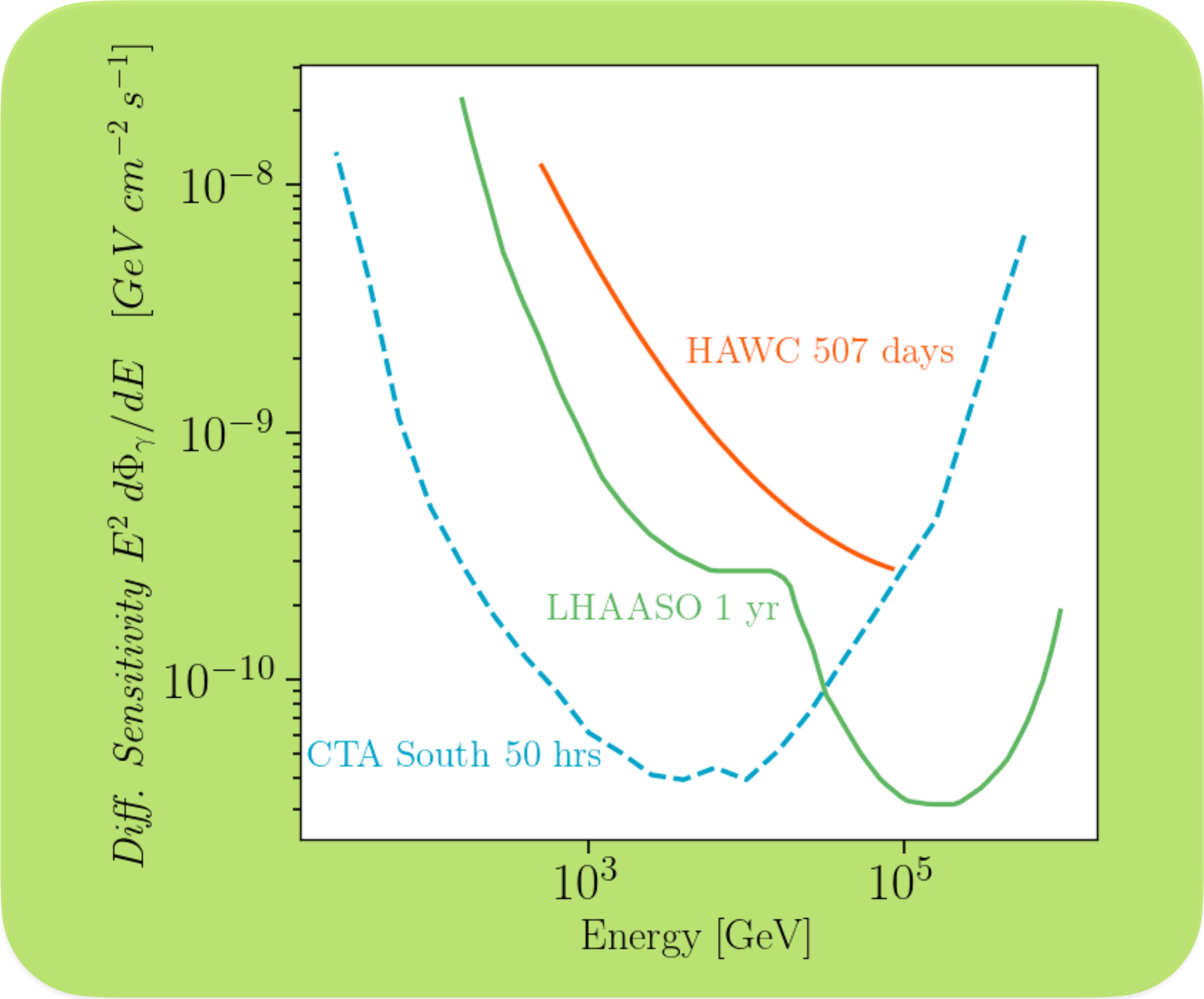
- Gamma-Ray Sensitivities from the experiments
- Effective Areas and Observation Time
- Expected Number of Events

EXPECTED SIGNAL (DARK MATTER)

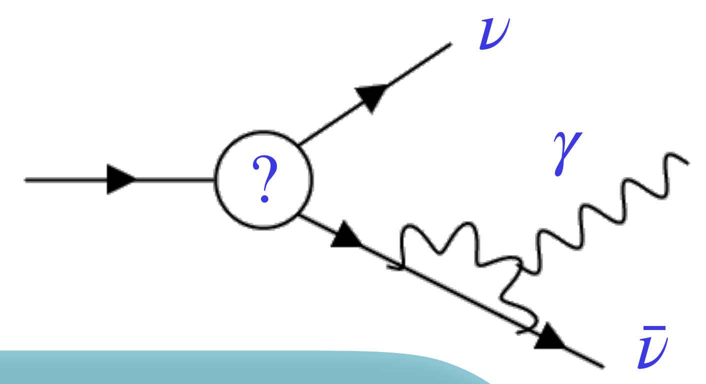
- Neutrino Production Spectrum for Decay of DM to neutrinos
- Dark Matter Expected Flux (Galactic & Extragalactic)
- Expected Number of Events

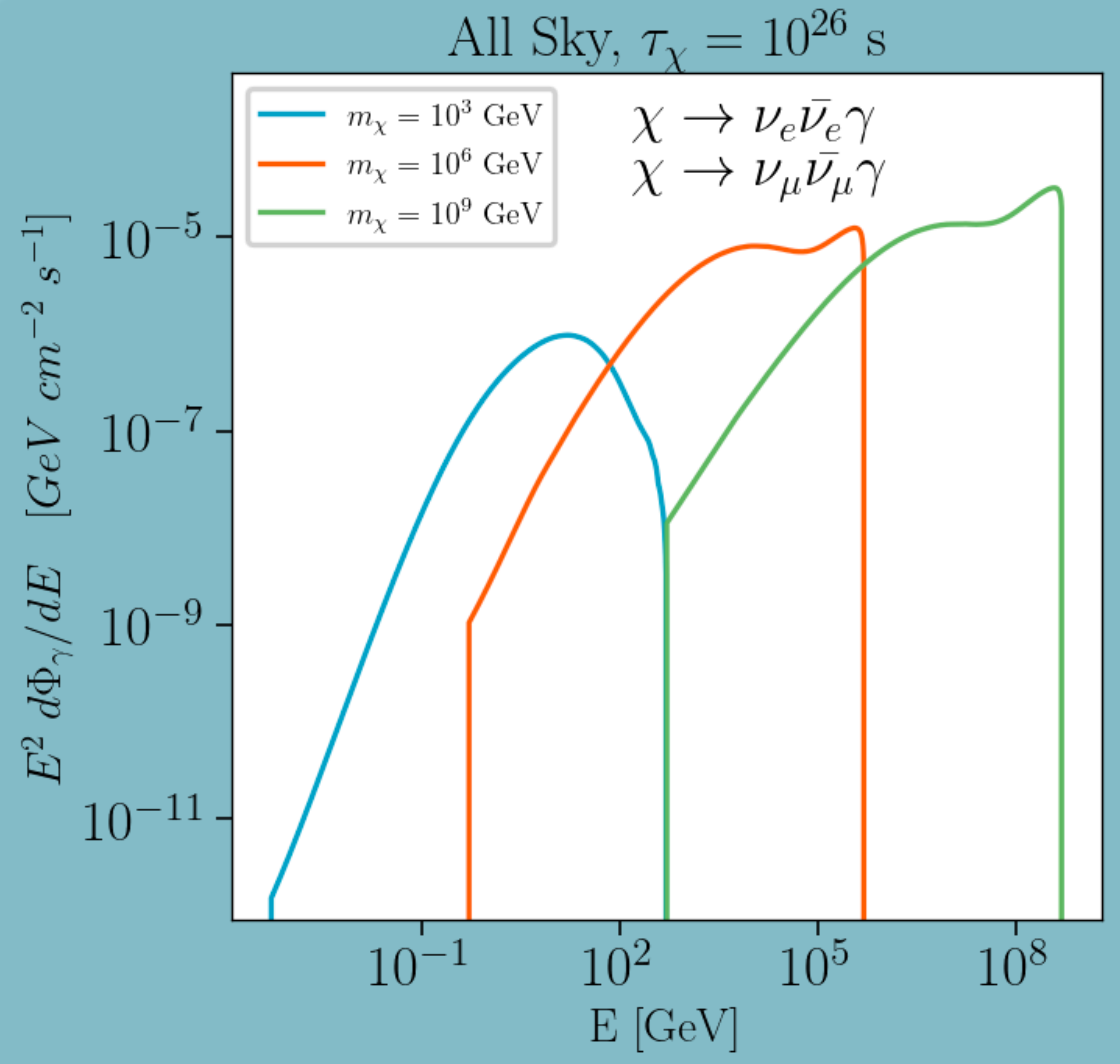
$$N_{evt} = \int dE\, A_{eff} \frac{d\Phi}{dE} T_{obs}$$

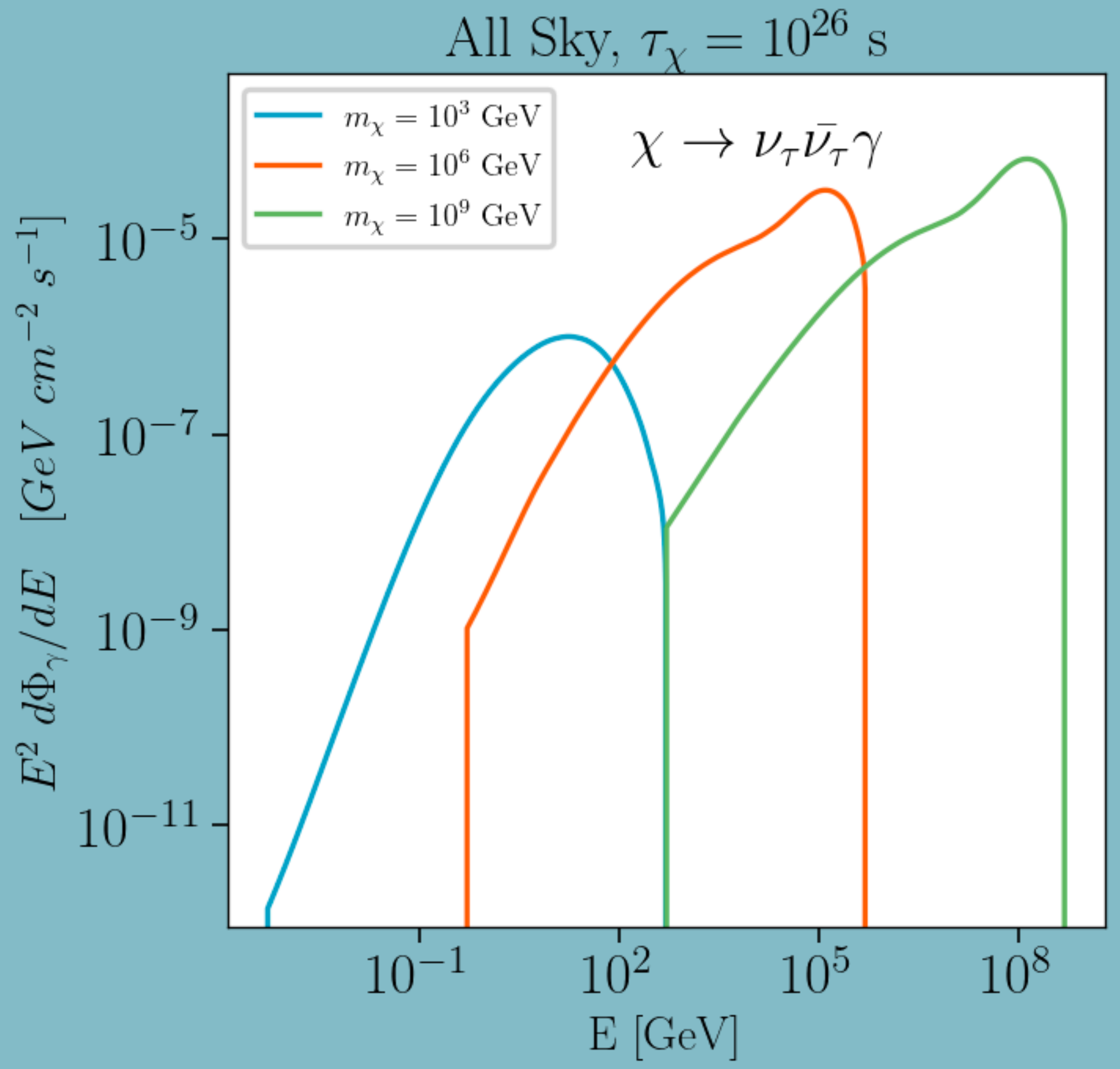
Gamma-Ray Experimental Sensitivities



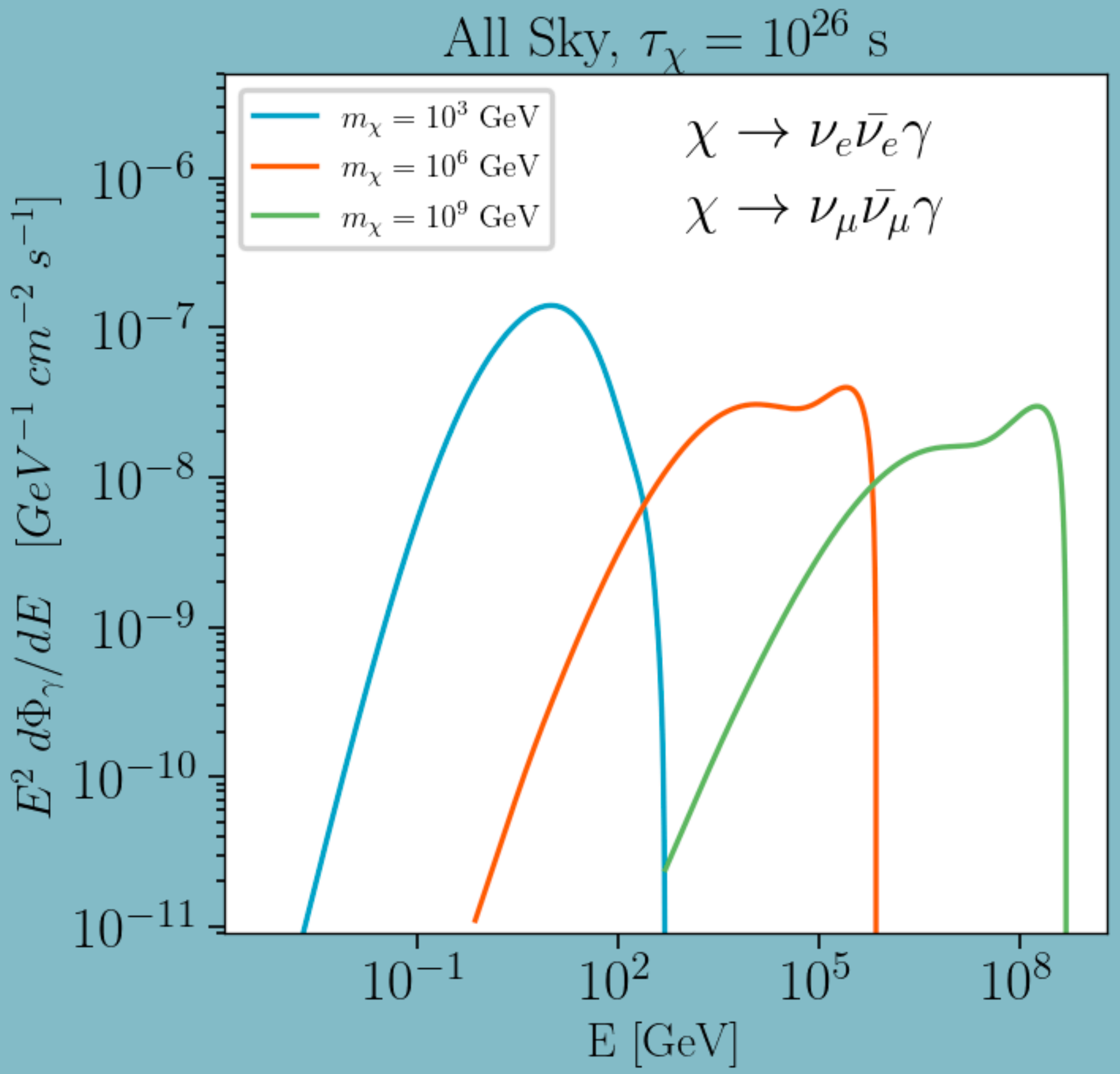
Expected gamma flux (Galactic)

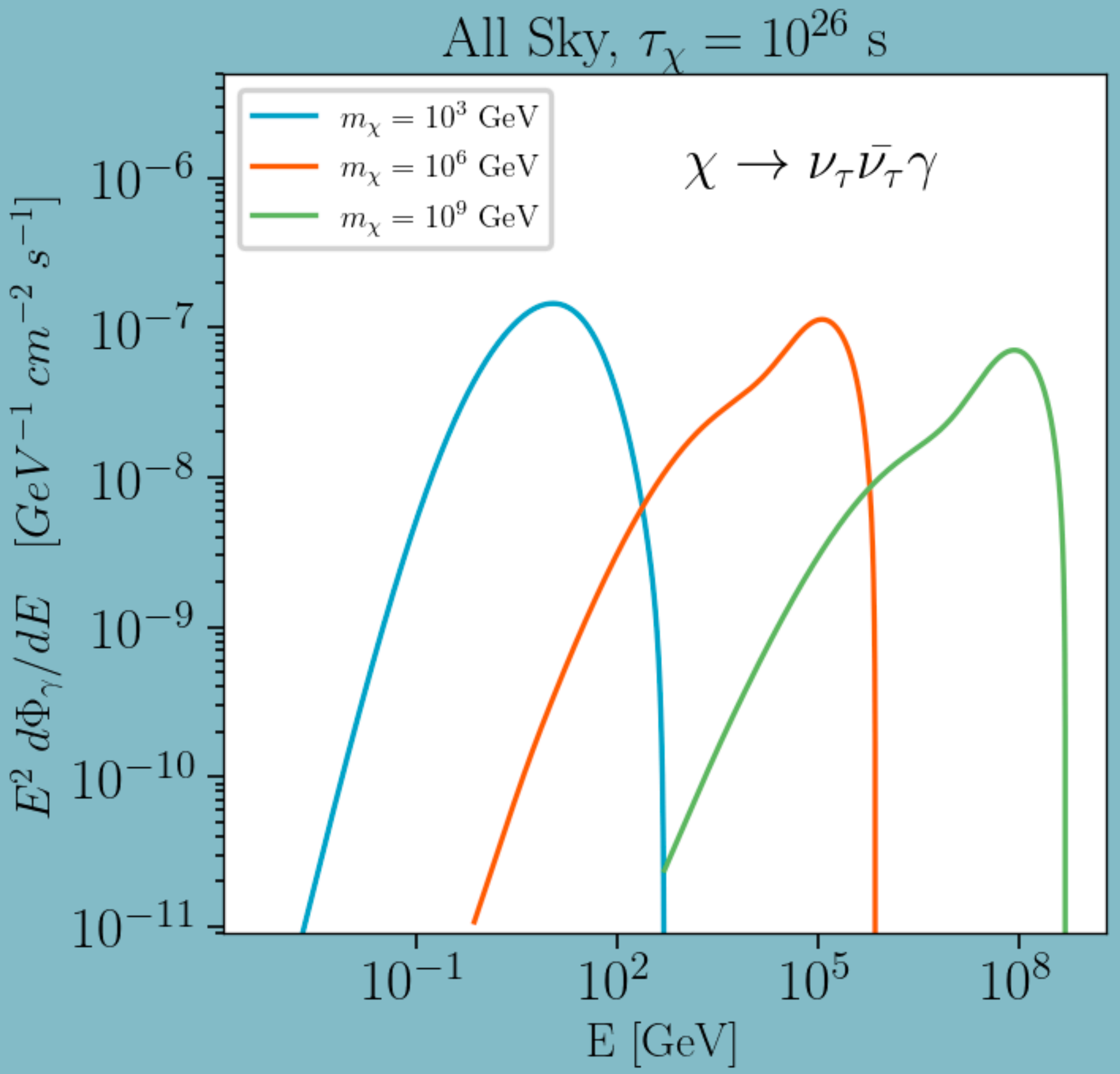






Expected gamma flux (Extragalactic)





Summary

- The nature of Dark Matter and origin of neutrino mass remain a mystery.
- Dark Matter neutrino connections offer solutions to both problems.
- We can measure both neutrinos and gamma-rays as final products of Dark matter decay to neutrinos → Correlated signal.
- Major experimental advances in neutrino and gamma-ray detection allows us to explore a wide mass range (MeV - ZeV).
- New constraints for gamma rays contribution lifetime limits will be reported on an upcoming paper. Stay tuned!

Backup

Electro weak corrections: why gamma-rays?

- 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.,0707.0209

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.

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:

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

Calculating lifetime limits

- We determine the number of events from the following equation:

$$N_{evt} = \int dE \, A_{eff} \, \Phi \, T_{obs}$$

Calculating lifetime limits

- We determine the number of events from the following equation:

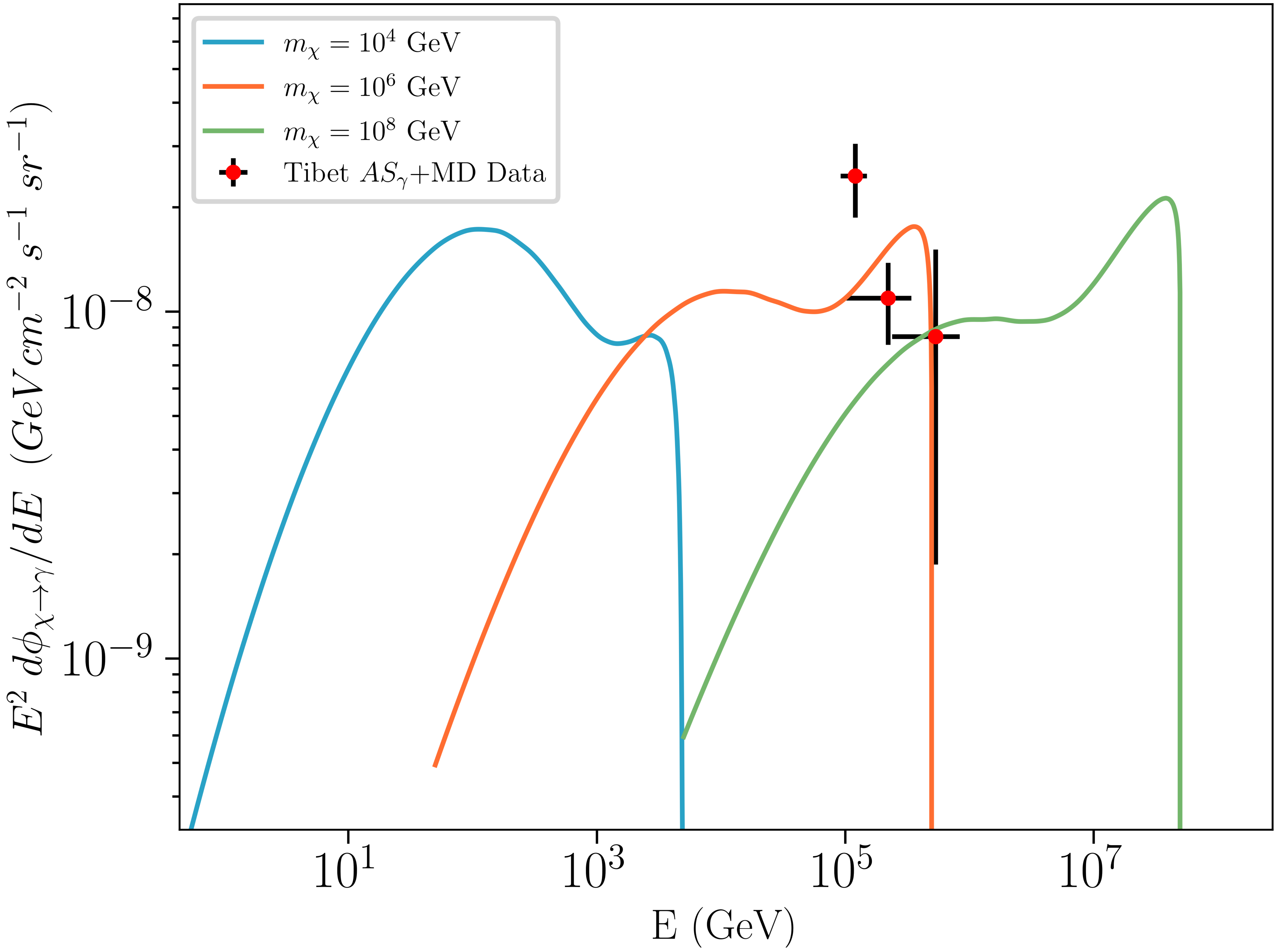
$$N_{evt} = \int dE\, A_{eff}\, \Phi\, T_{obs}$$

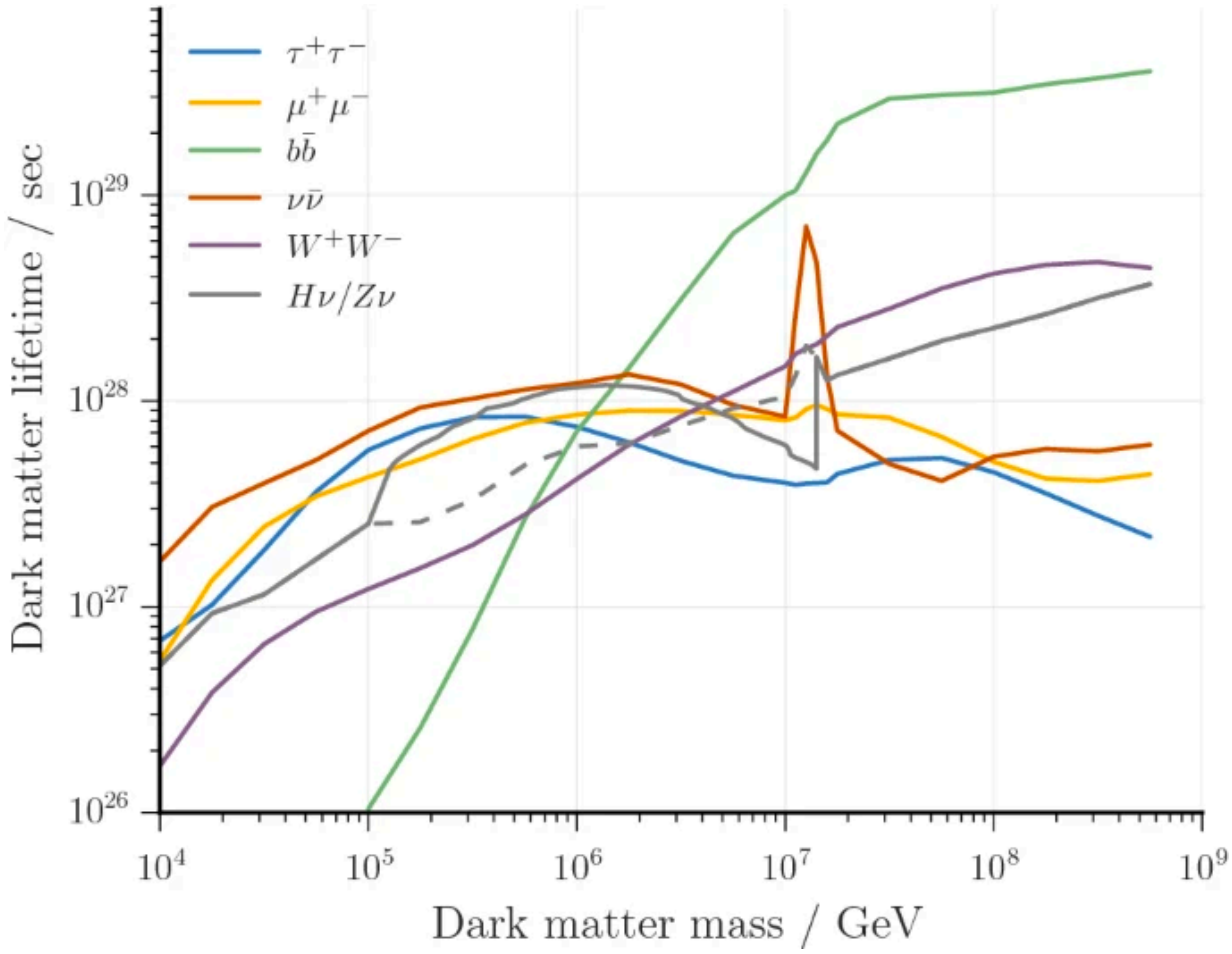
- Equate using both Gamma-ray flux and Expected Dark Matter Flux:

$$N_{evt} = \int dE\, A_{eff}\, \underline{\frac{1}{4\pi}\frac{1}{m_\chi \tau_\chi}\frac{dN_\gamma}{dE} D(\Omega, x)}\, T_{obs} = \int_{a_-}^{a^+} dE\, A_{eff}\, \underline{f_0\, E^{-\alpha}}\, T_{obs}$$

- We are interested in the limit of τ_χ that makes the equation true.

Expected neutrino flux





IceCube Collaboration: 10.1140/epjc/s10052-018-6273-3