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

Dark Ghost 3rd GNN Workshop (Univ. Granda, Spain)
March 31, 2022

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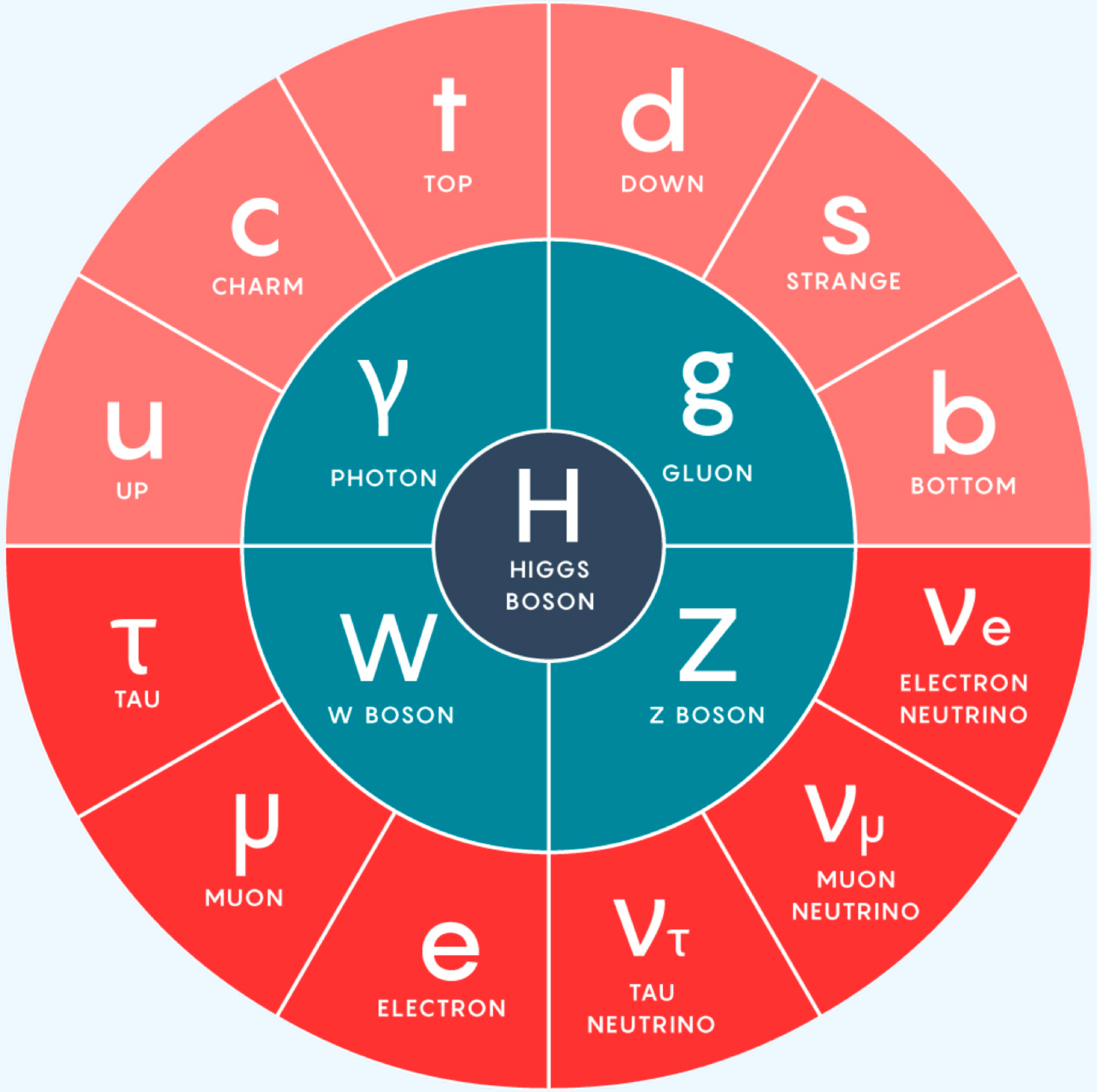
Standard Model is great and all but ...

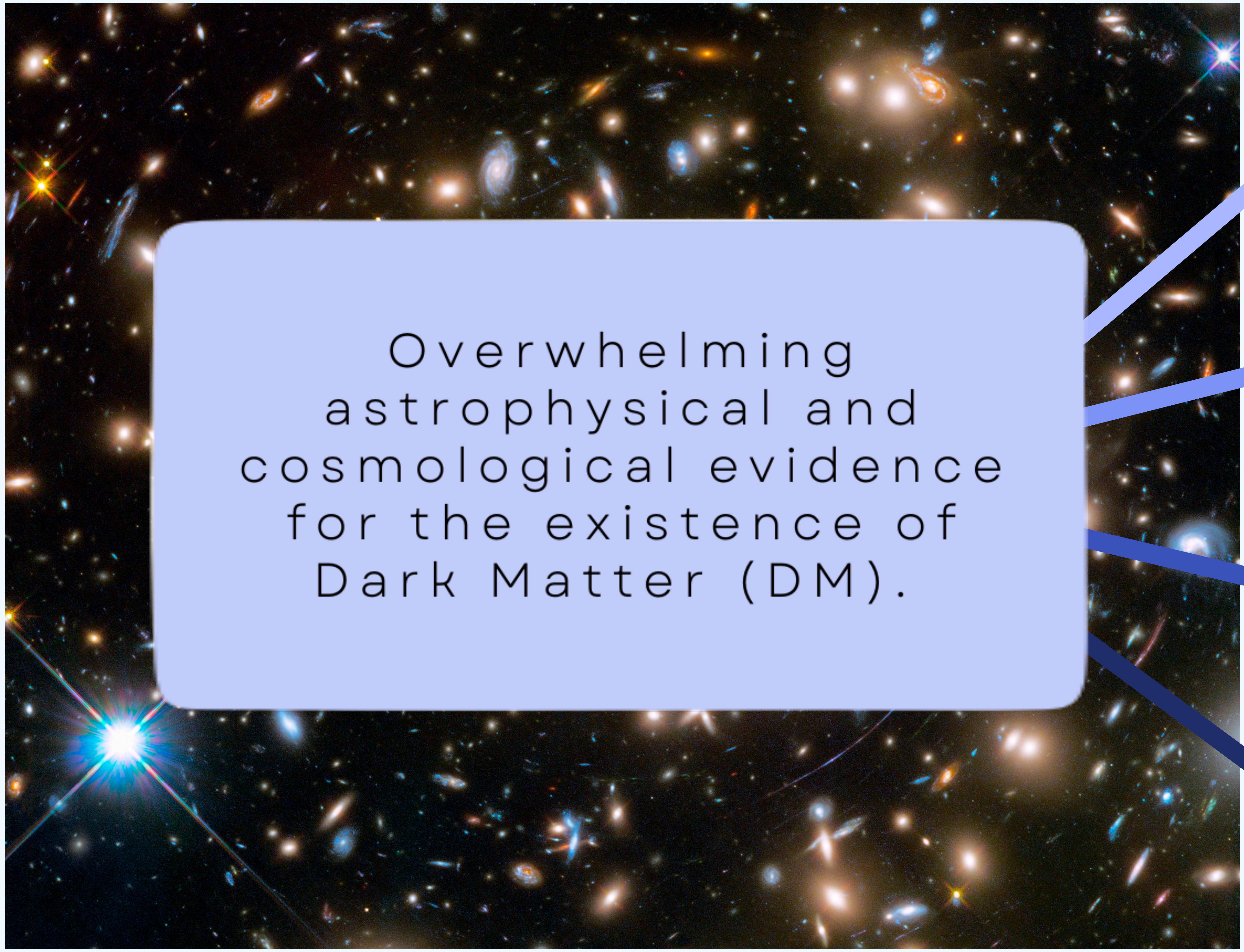


Need SM extension

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

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

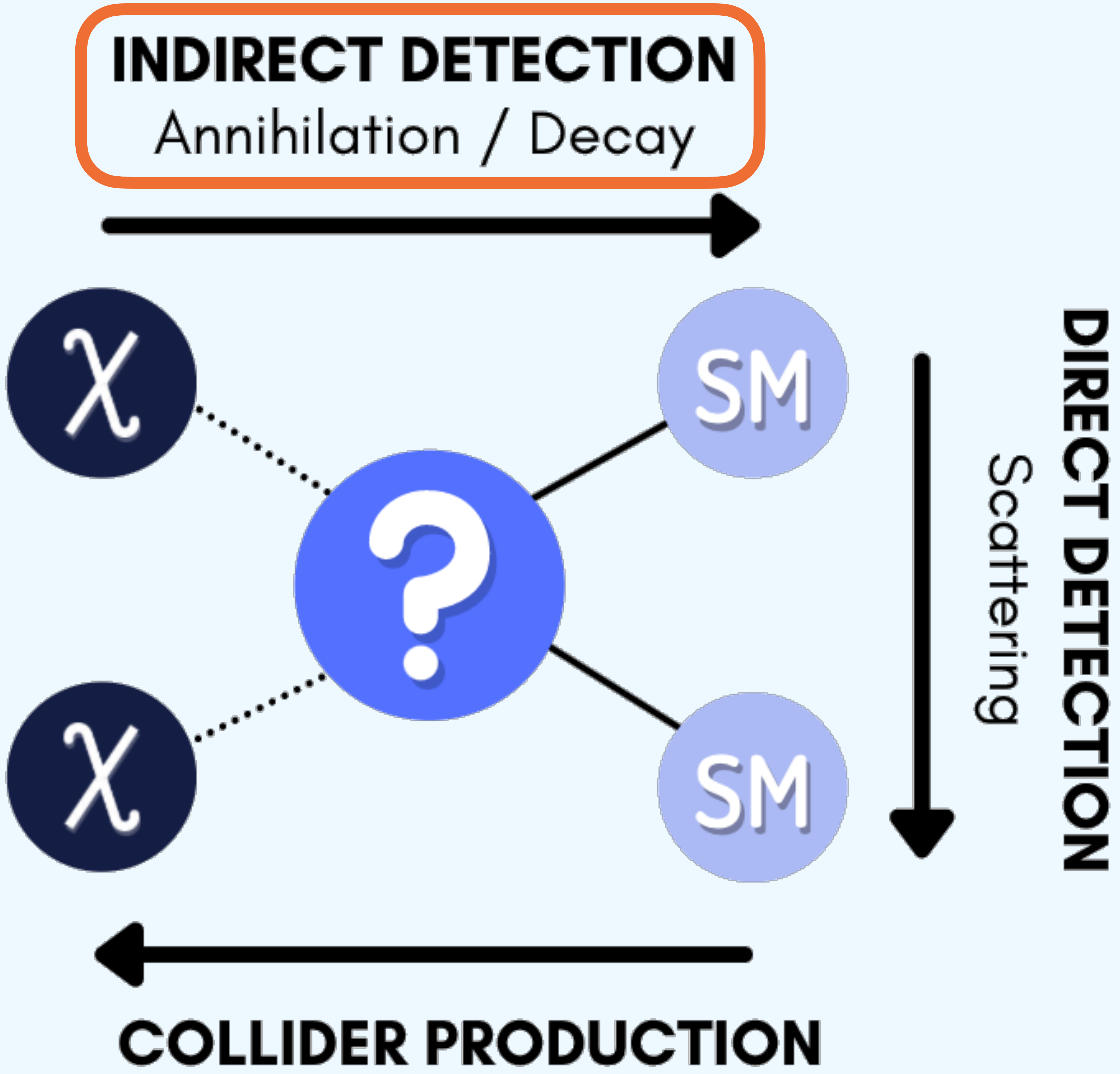
WIMP Origins



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

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

Neutrino Portal to Dark Matter

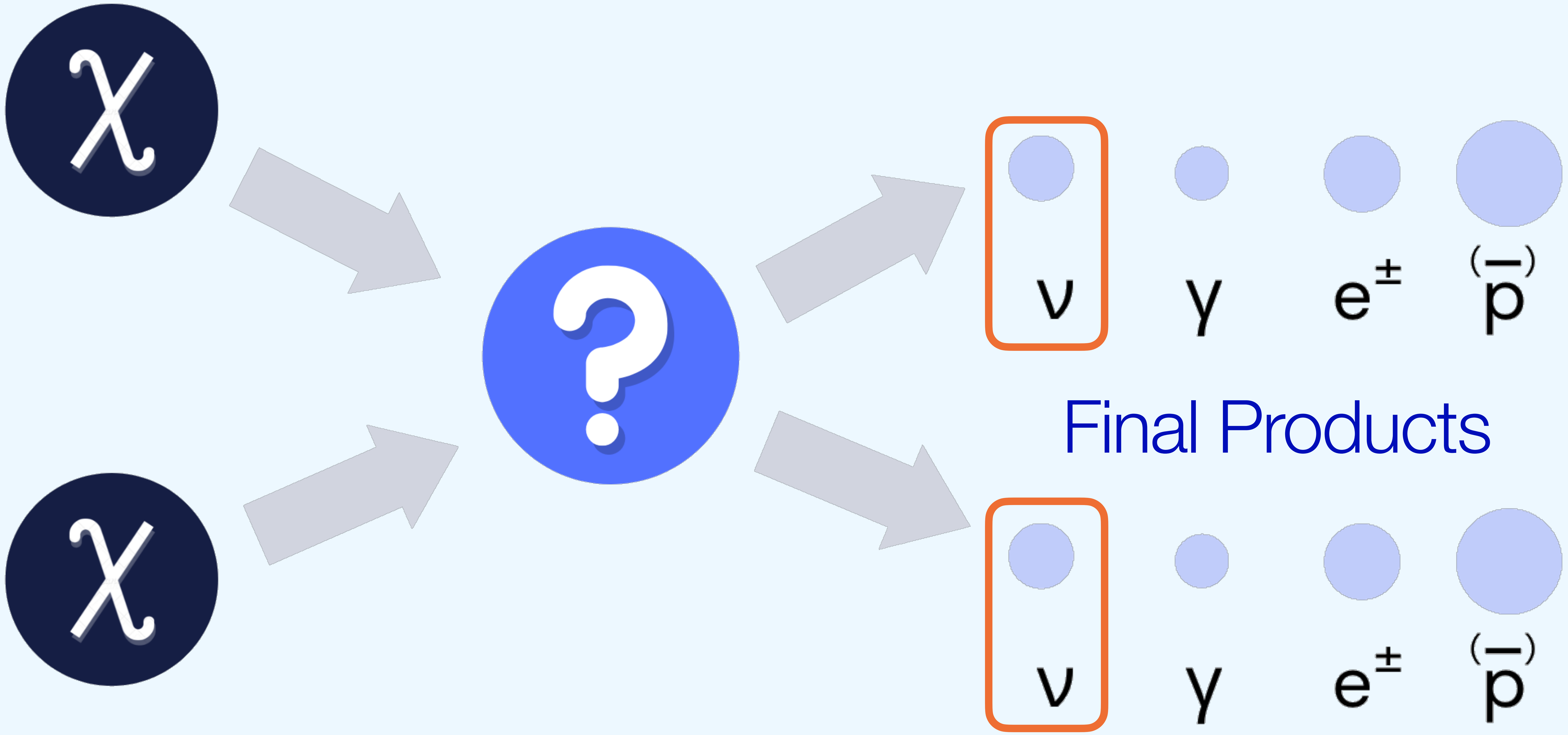


All SM final states eventually lead to gamma rays or neutrinos.

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

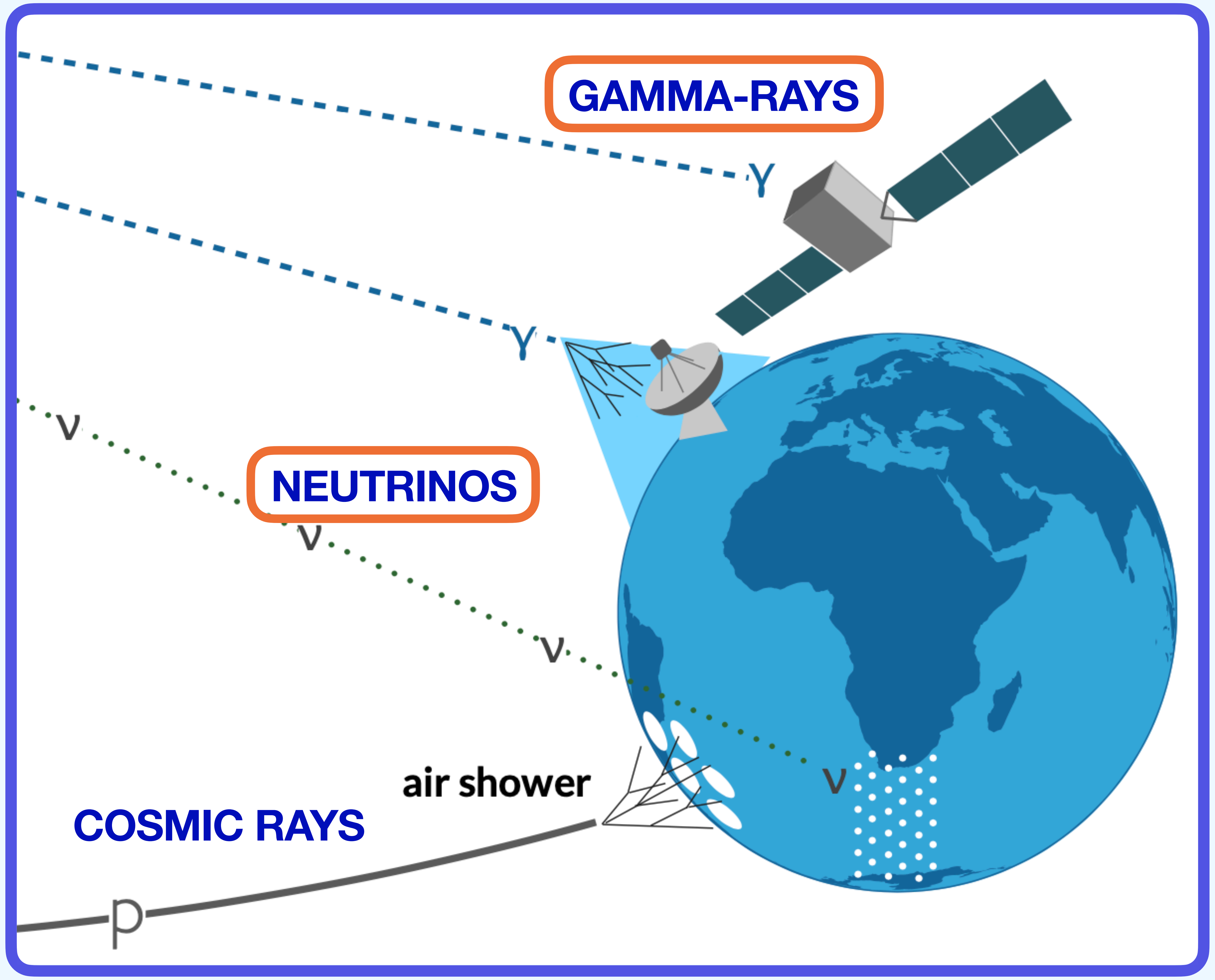


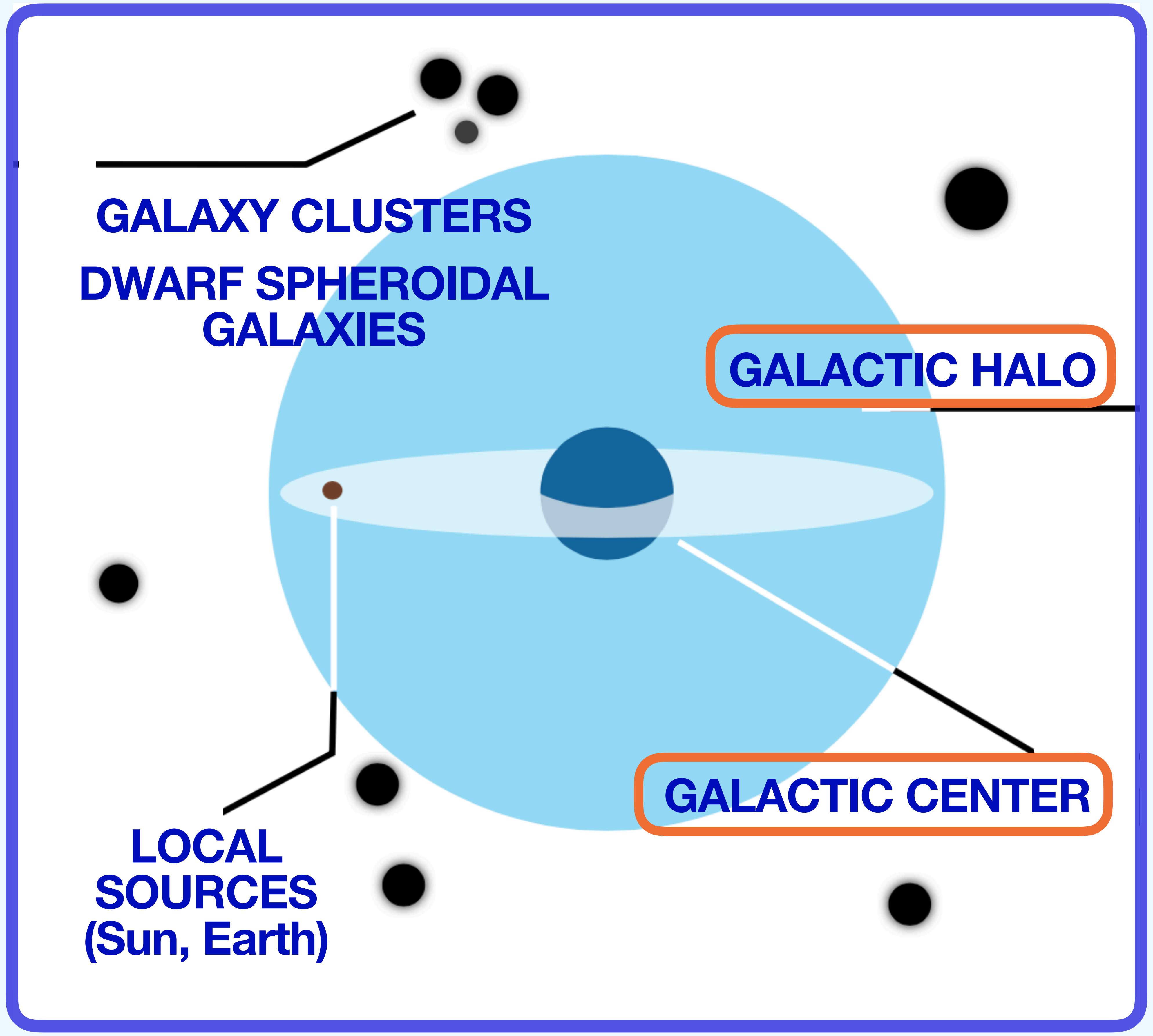
No need of specialized detectors

Focus on large reservoirs of DM

Dark Matter Searches

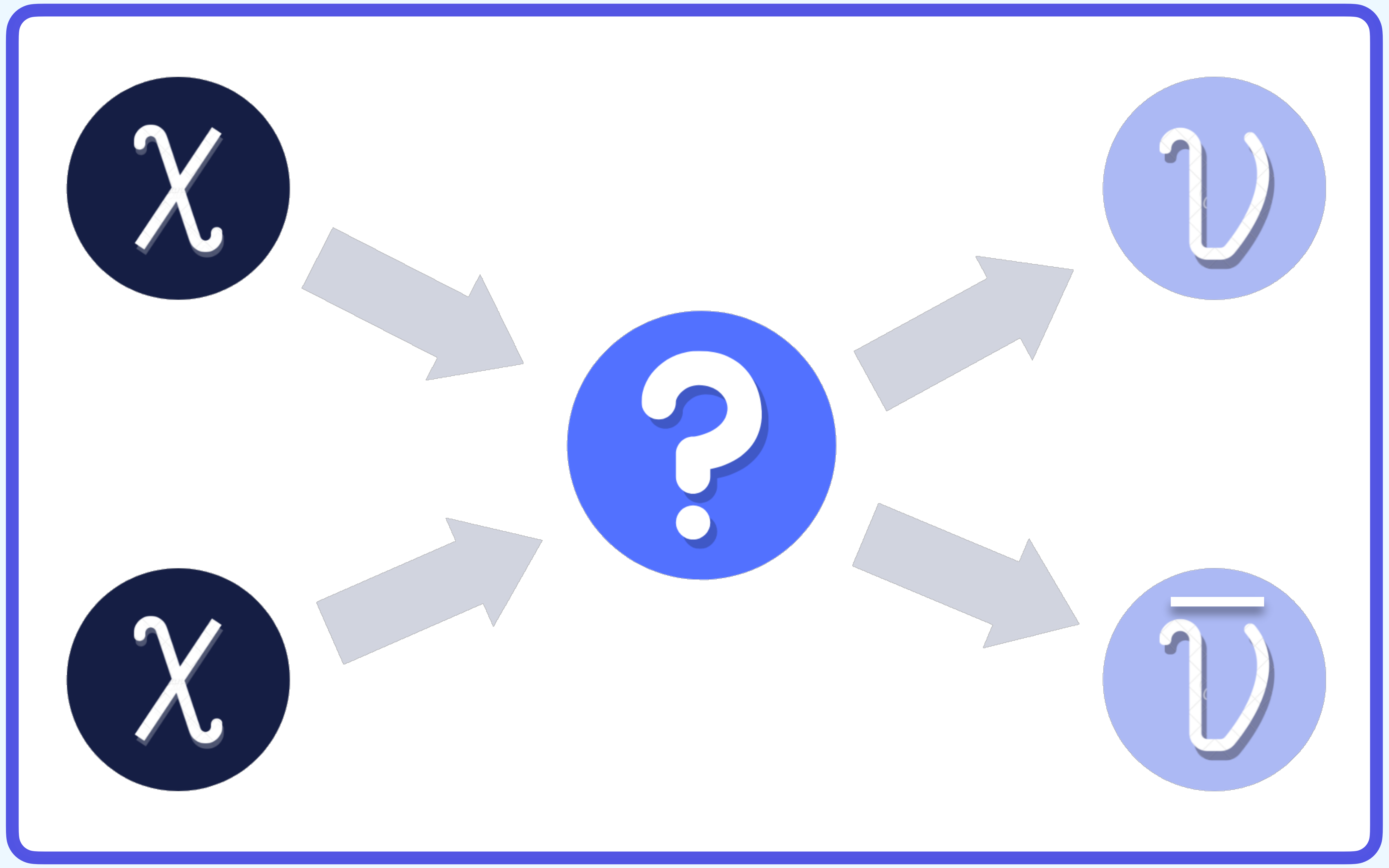
What and where to look?



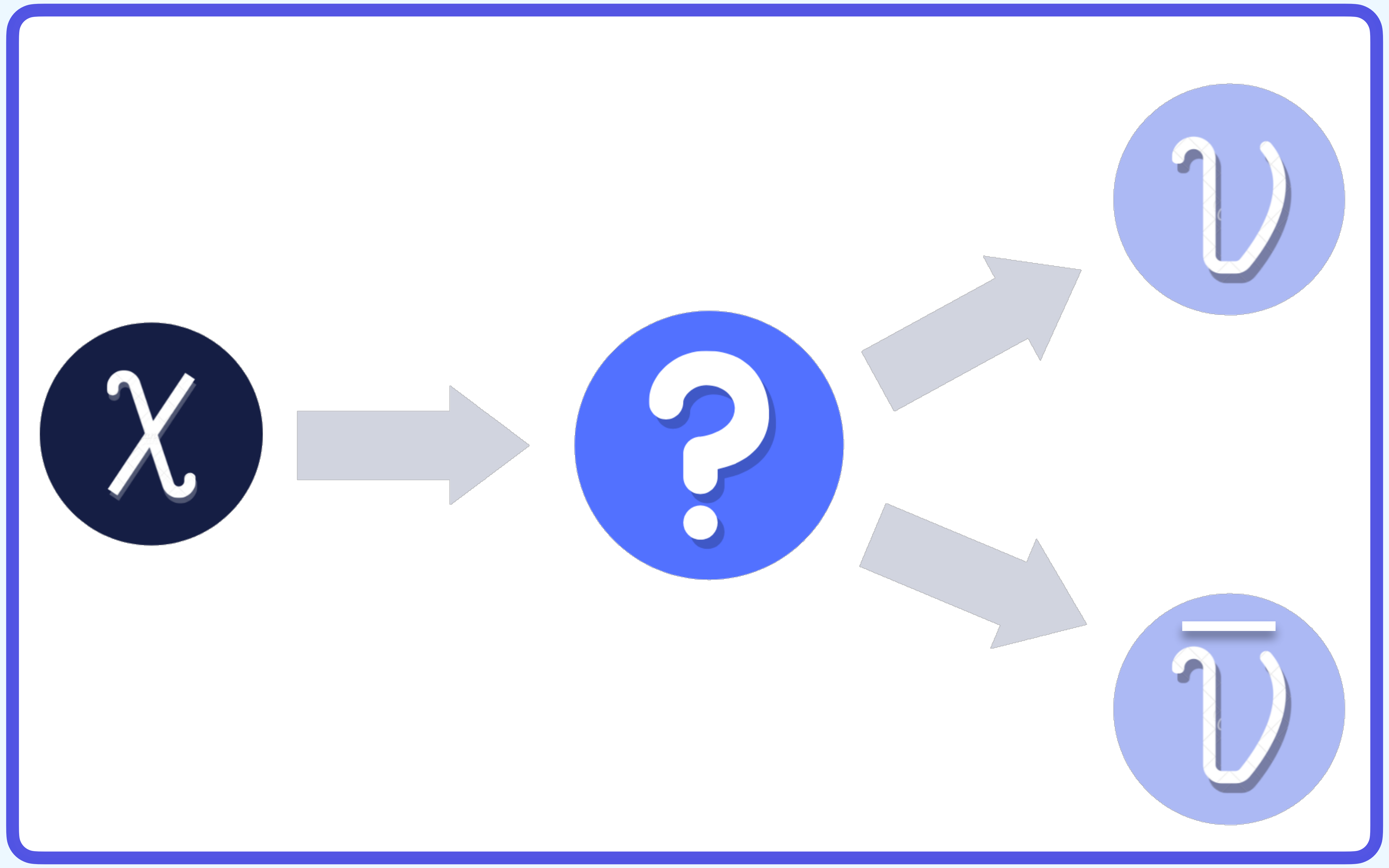


CREDIT: JUAN AGUILAR, ESDU 2018

Dark Matter Annihilation and Decay to neutrinos



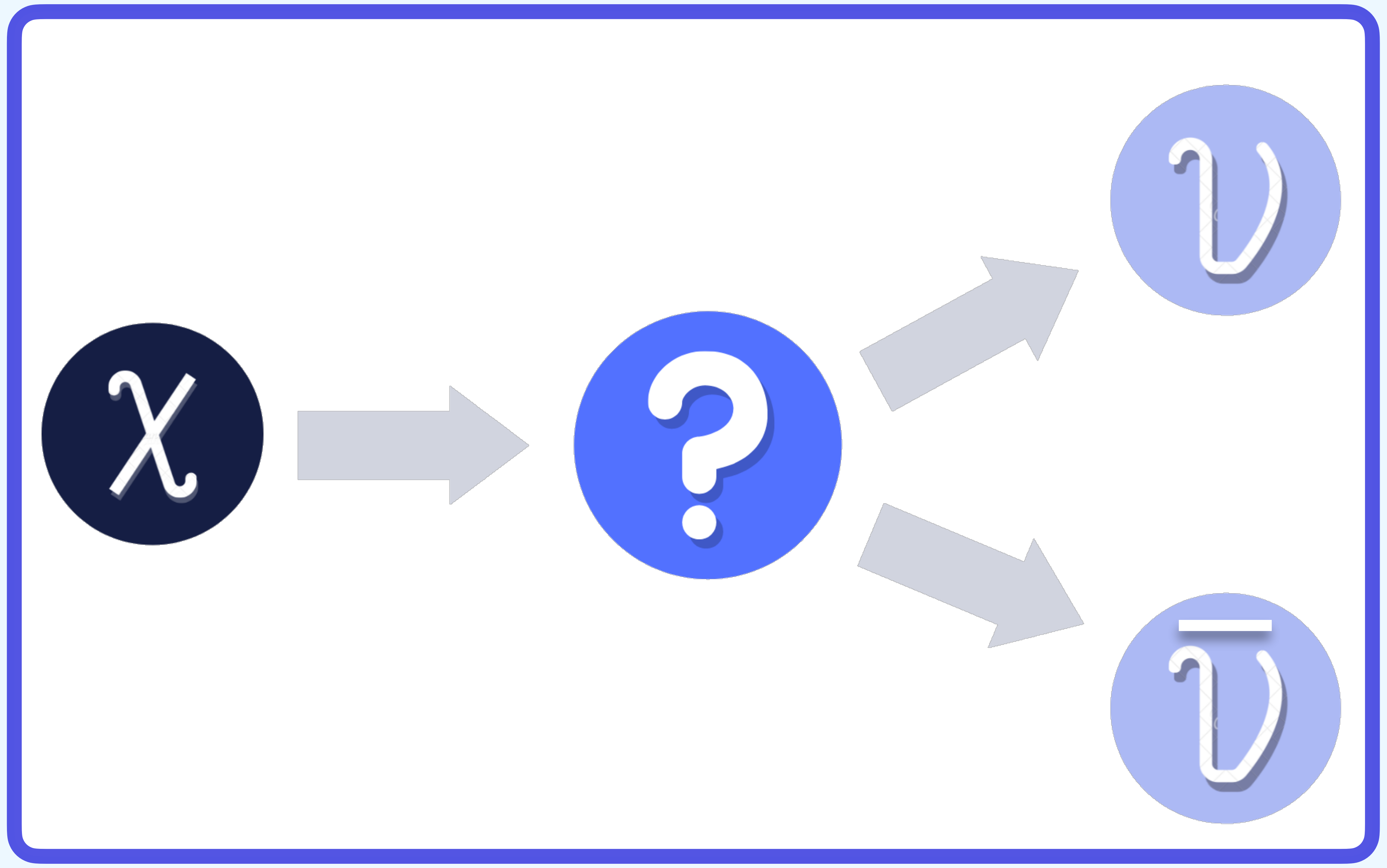
ANNIHILATION



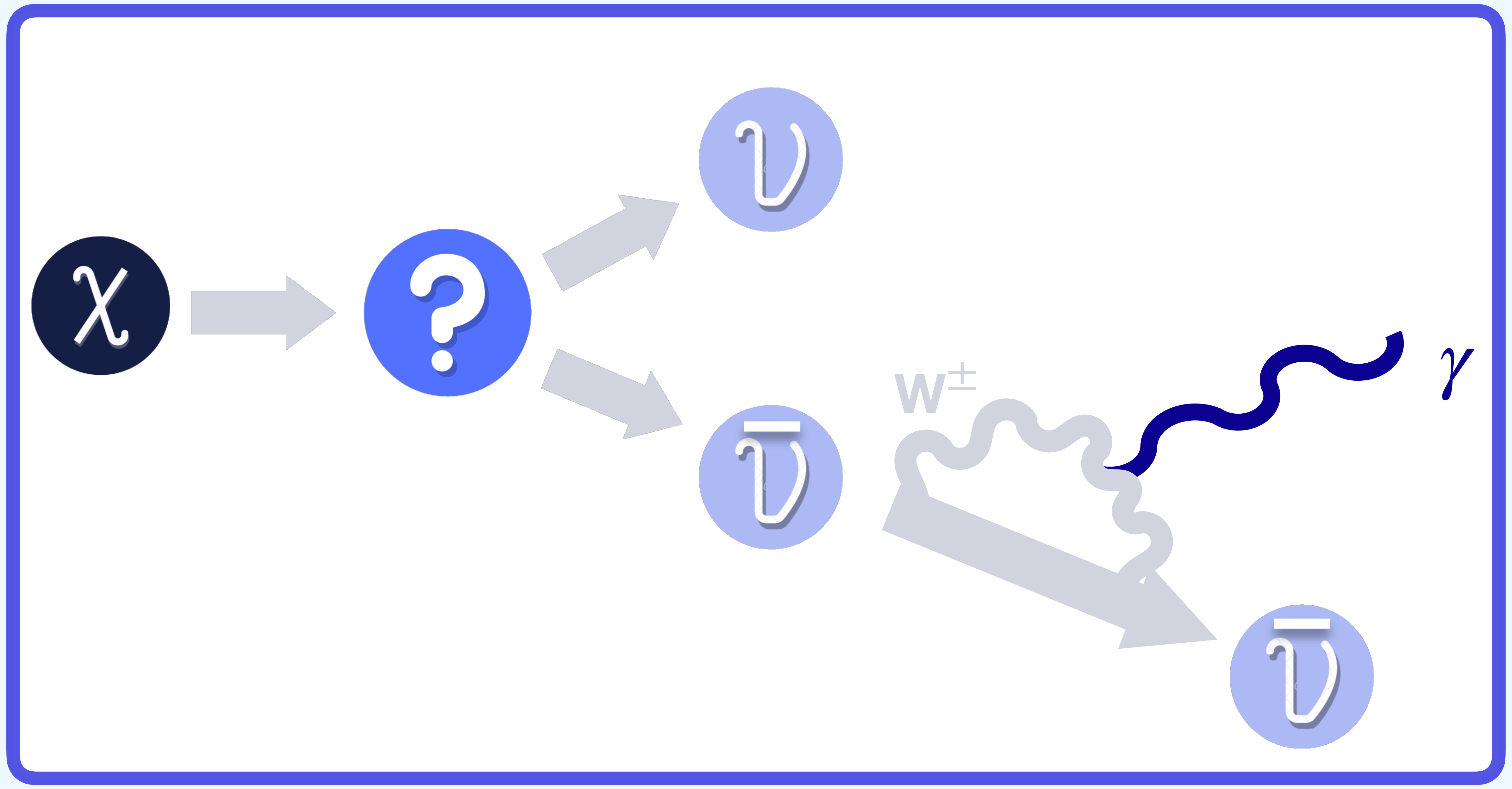
DECAY

EXPECTED GAMMA-RAY SIGNAL DUE TO ELECTROWEAK CORRECTIONS

Dark Matter Decay to neutrinos



NEUTRINO SIGNAL



GAMMA-RAY SIGNAL

Annihilation

Galactic contribution

FLUX FROM DARK MATTER IN OUR GALAXY

$$\frac{d\Phi_\nu}{dE} = \frac{1}{4\pi} \frac{\langle \sigma v \rangle}{2m_\chi^2} \frac{1}{3} \frac{dN_\nu}{dE} J(\Omega, x)$$

Annihilation

Galactic contribution

FLUX FROM DARK MATTER IN OUR GALAXY

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NEUTRINO PRODUCTION SPECTRUM FOR DIRECT ANNIHILATION OF DM TO NEUTRINOS

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

Annihilation

Galactic contribution

FLUX FROM DARK MATTER IN OUR GALAXY

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

$$J = \int d\Omega \int_{l.o.s.} \rho_\chi^2(x)\, dx$$

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

Annihilation

Galactic contribution

FLUX FROM DARK MATTER IN OUR GALAXY

$$\frac{d\Phi_\nu}{dE} = \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_\chi^2}\frac{1}{3}\frac{dN_\nu}{dE}J(\Omega, x)$$

THERMALLY AVERAGED DM ANNIHILATION CROSS SECTION

NEUTRINO PRODUCTION SPECTRUM FOR DIRECT ANNIHILATION OF DM TO NEUTRINOS

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

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

Decay

Galactic contribution

FLUX FROM DARK MATTER IN OUR GALAXY

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

Decay

Galactic contribution

FLUX FROM DARK MATTER IN OUR GALAXY

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

NEUTRINO PRODUCTION SPECTRUM FOR DIRECT DECAY OF DM TO NEUTRINOS *

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

* WITH GAMMA-RAY PRODUCTION BECOMES MORE COMPLICATED DUE TO ELECTROWEAK CORRECTIONS

Decay
Galactic contribution

FLUX FROM DARK MATTER IN OUR GALAXY

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

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

Decay

Galactic contribution

FLUX FROM DARK MATTER IN OUR GALAXY

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

DM DECAY LIFETIME

NEUTRINO PRODUCTION SPECTRUM FOR DIRECT DECAY OF DM TO NEUTRINOS *

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

*** WITH GAMMA-RAY PRODUCTION BECOMES MORE COMPLICATED DUE TO ELECTROWEAK CORRECTIONS**

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

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

Annihilation and Decay

Extragalactic contribution*

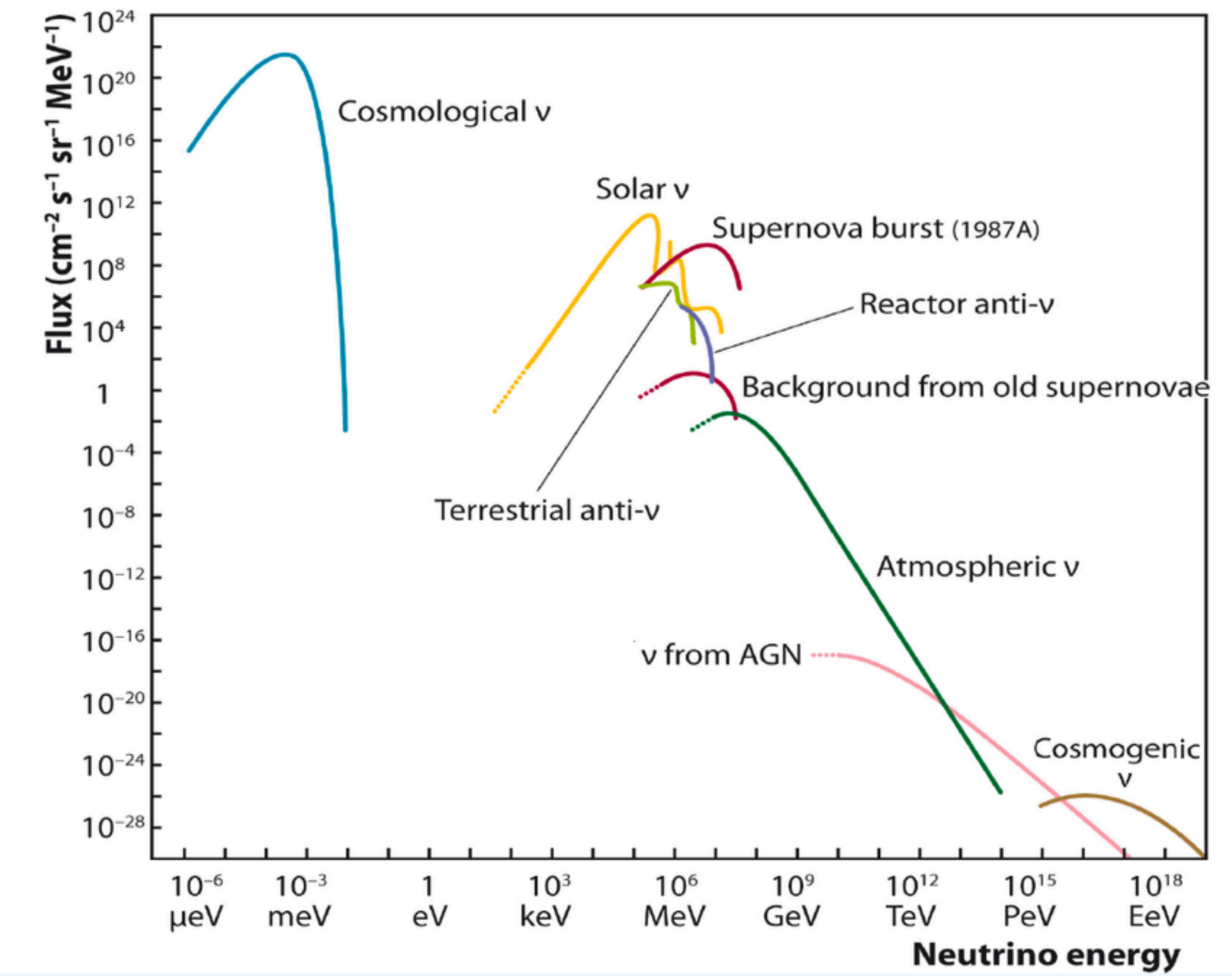
Extragalactic contribution also plays an important role!

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

* SEE ARGÜELLES, ET AL., REV. MOD. PHYS. 93, ARXIV:1912.09486 AND UPCOMING PAPER FOR A MORE DETAILED REVIEW.

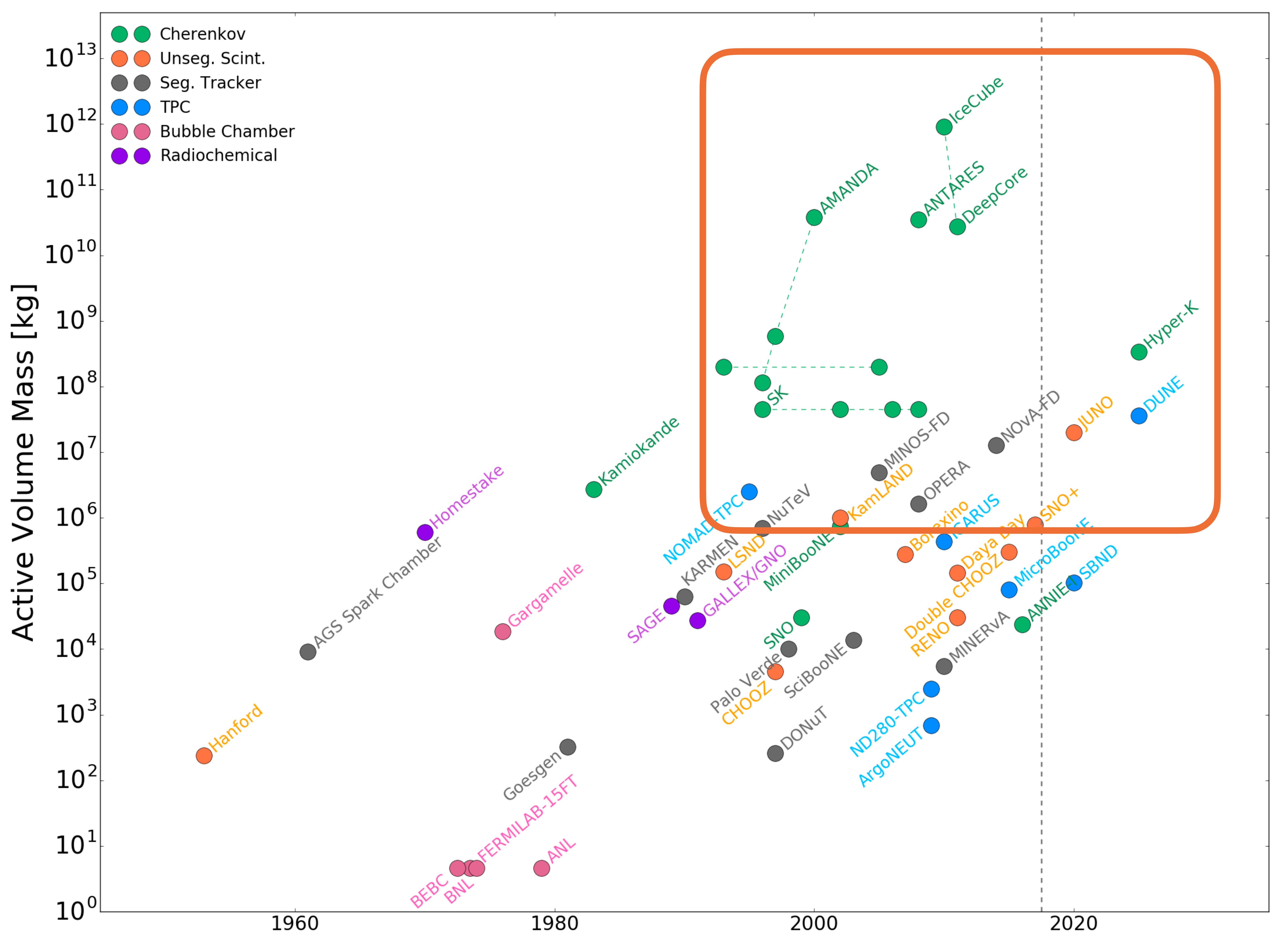
First we must detect neutrinos

Measured and expected fluxes of natural and reactor neutrinos



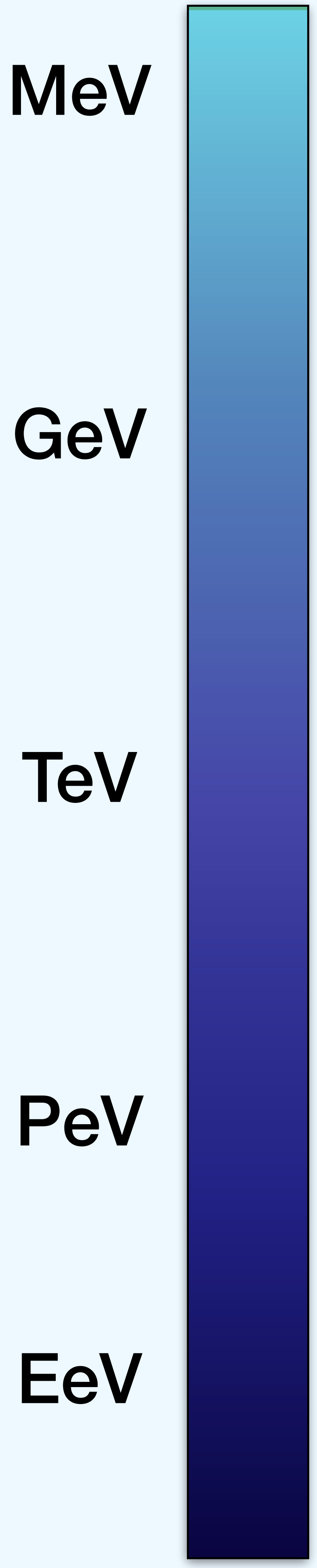
SPIERING,EPJ H 37, ARXIV:1207.4952

First we must detect neutrinos



ARGÜELLES ET AL., IOP 23, ARXIV:1907.08311

Detecting neutrinos



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)

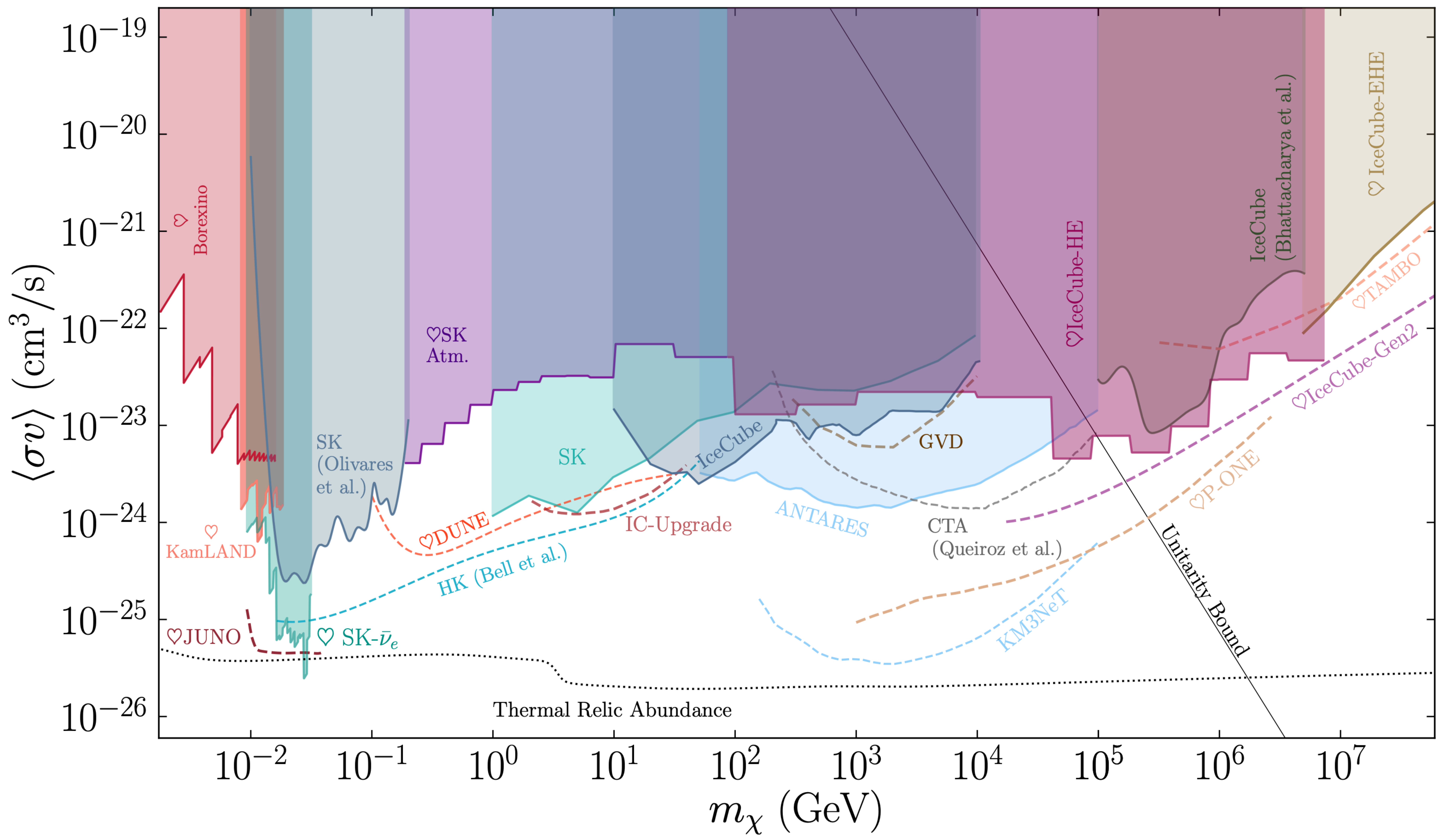
P-ONE — Sea Water Cherenkov Extraterrestrial neutrino fluxes (PeV)

TAMBO — Water Cherenkov. Astrophysical Tau Neutrino (PeV)

Pierre Auger Observatory — Water Cherenkov. Ultra High Energy Cosmic Rays (EeV)

GRAND — Radio Array. Tau Neutrinos (EeV)

Annihilation results: s-wave



p-wave ($\langle \sigma v \rangle = b(v/c)^2$) and d-wave ($\langle \sigma v \rangle = d(v/c)^4$) also computed.

Converting Differential or Diffuse Flux Limits to Lifetimes

DIFFUSE FLUXES

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

DIFFERENTIAL FLUXES

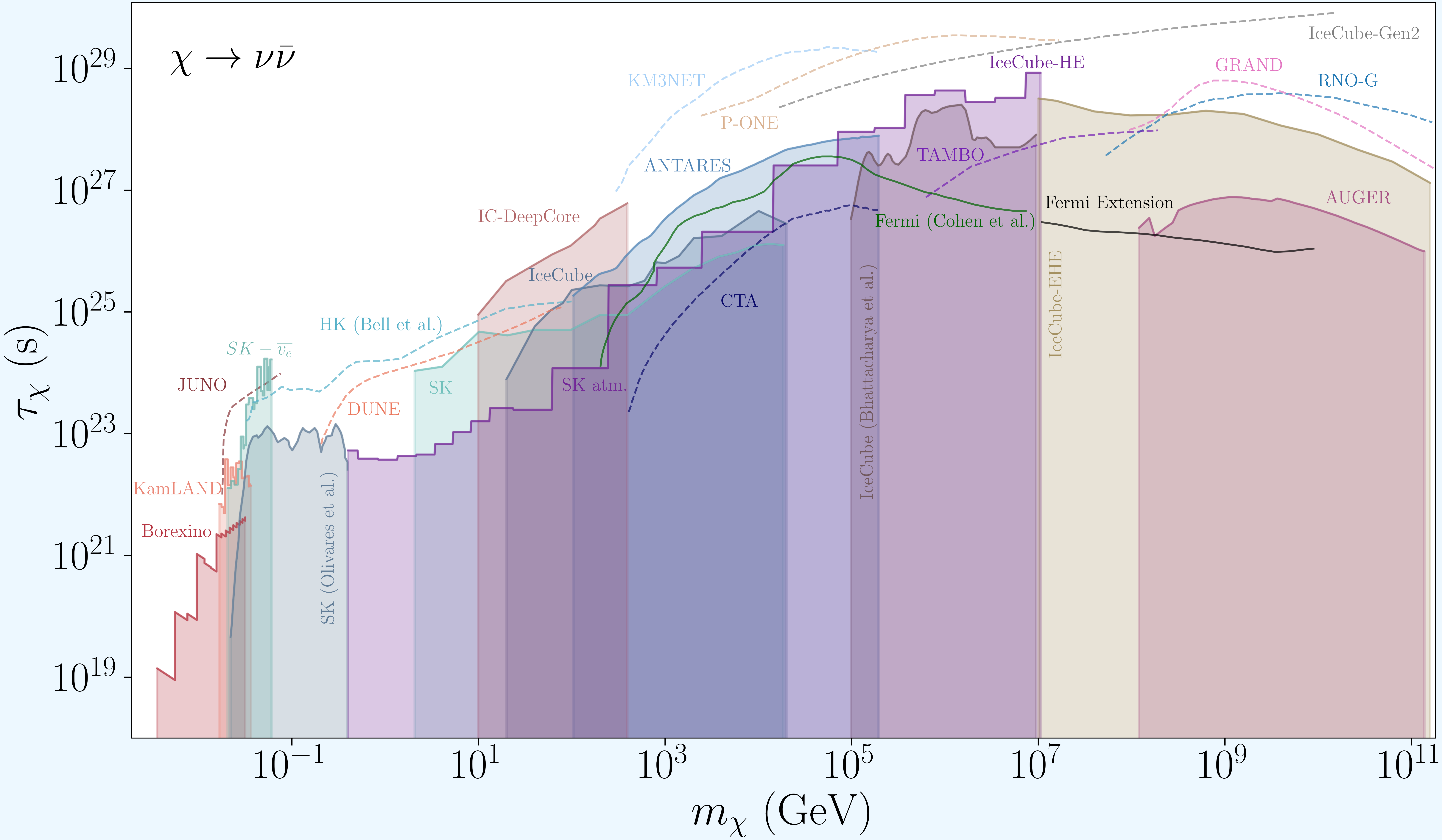
$$\tau = \frac{2D(\alpha-1)}{3m_\chi^2(4\pi)^2}\left(\left(10^{\Delta/2} - 10^{-\Delta/2}\right)\frac{d\phi}{dE}\bigg|_{lim}\right)^{-1}$$

DIFFERENTIAL FLUXES ($\alpha = 1$)

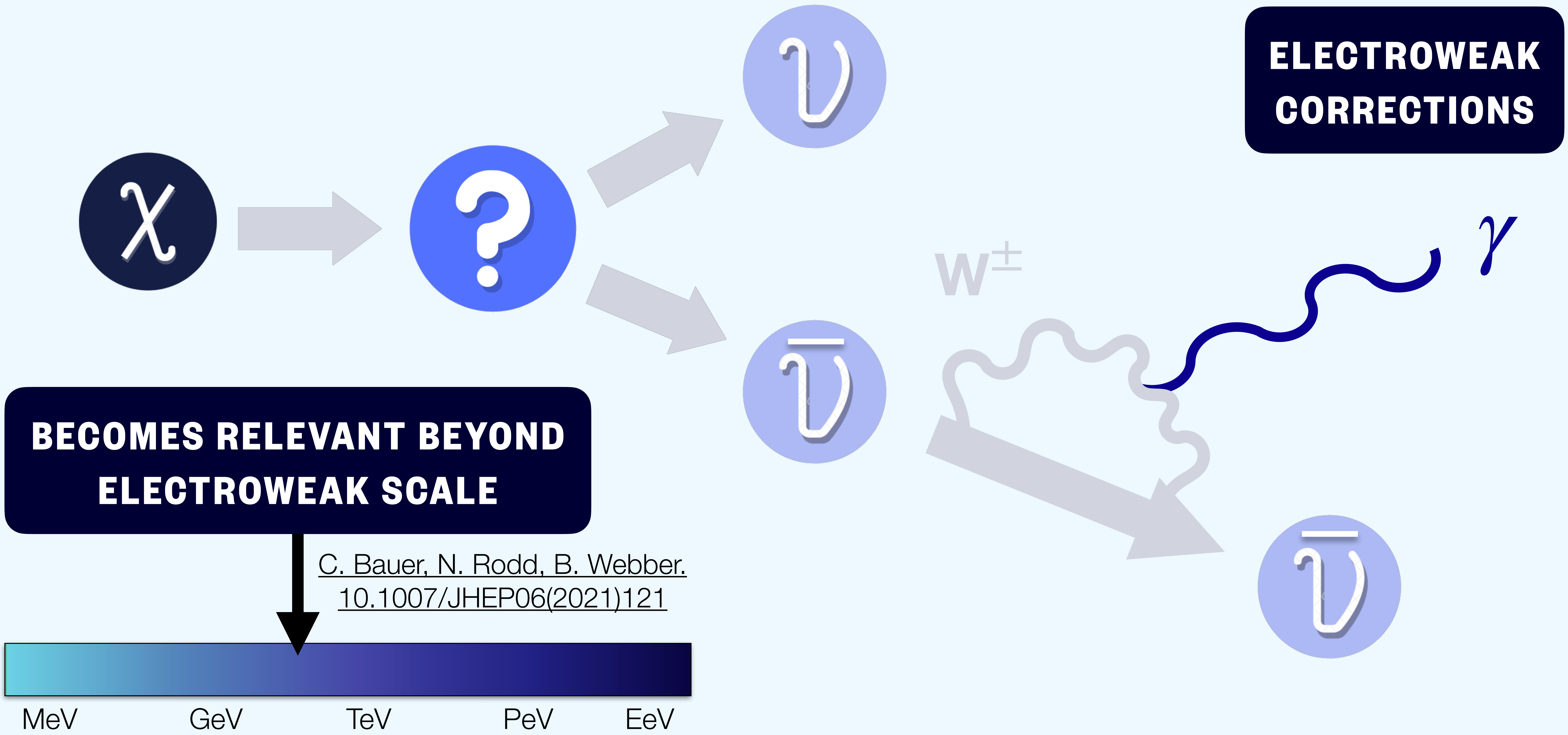
$$\tau = \frac{2D}{3m_\chi^2(4\pi)^2}\left(\Delta\ln(10)\frac{d\phi}{dE}\bigg|_{lim}\right)^{-1}$$

RESCALED ANNIHILATION LIMITS

Decay results
Neutrino Experiments



Dark Matter Search detecting gammas



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

Gamma-Ray Experiments

MeV GeV TeV PeV EeV

LHAASO

Hybrid Air Shower. Gamma Rays (GeV - PeV)

HAWC High Altitude Water Cherenkov Gamma-Ray Observatory

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

IceCube South Pole Neutrino Observatory Ice Top

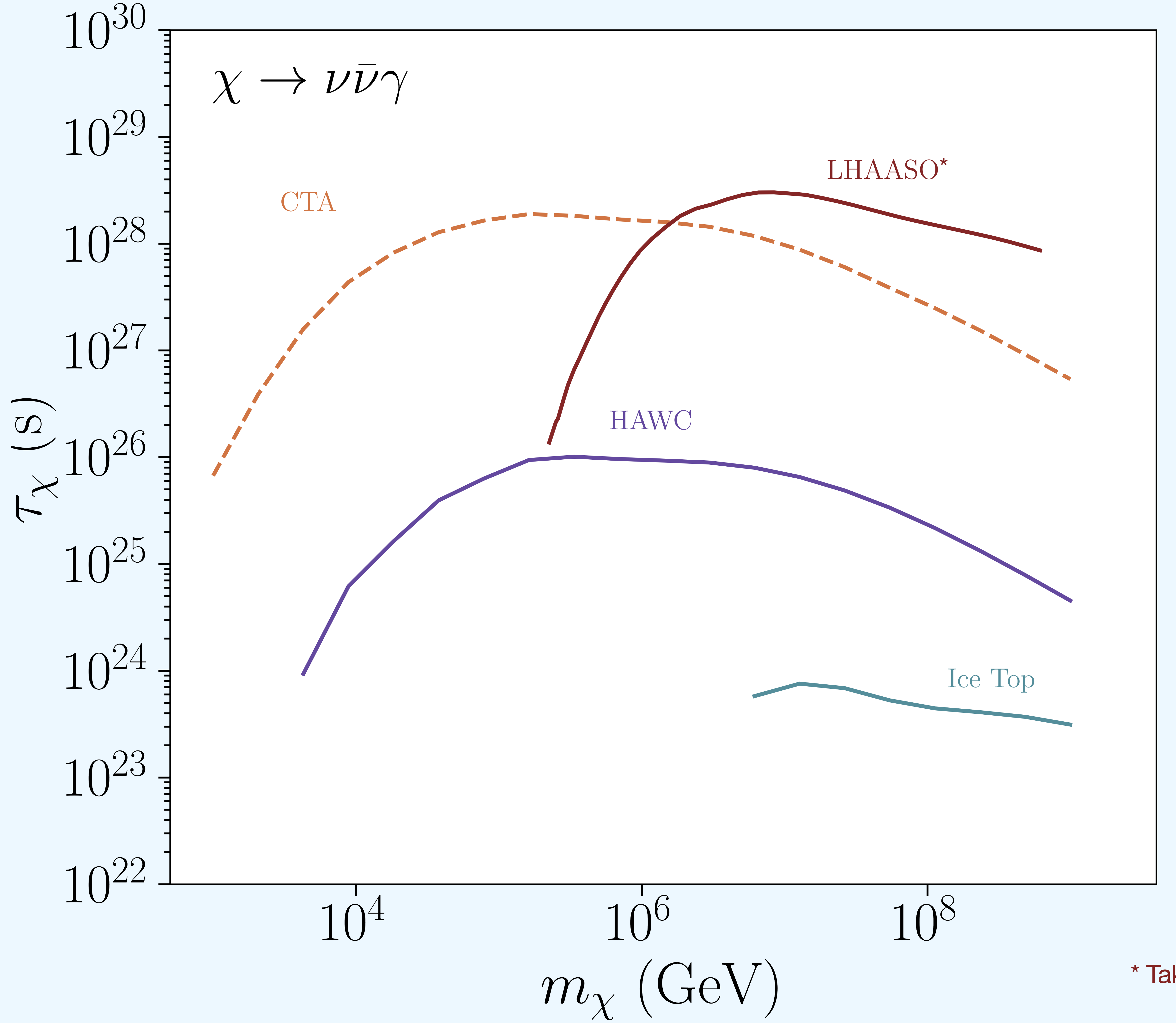
Air Showers. Gamma Rays and Cosmic Rays (TeV)

cta cherenkov telescope array

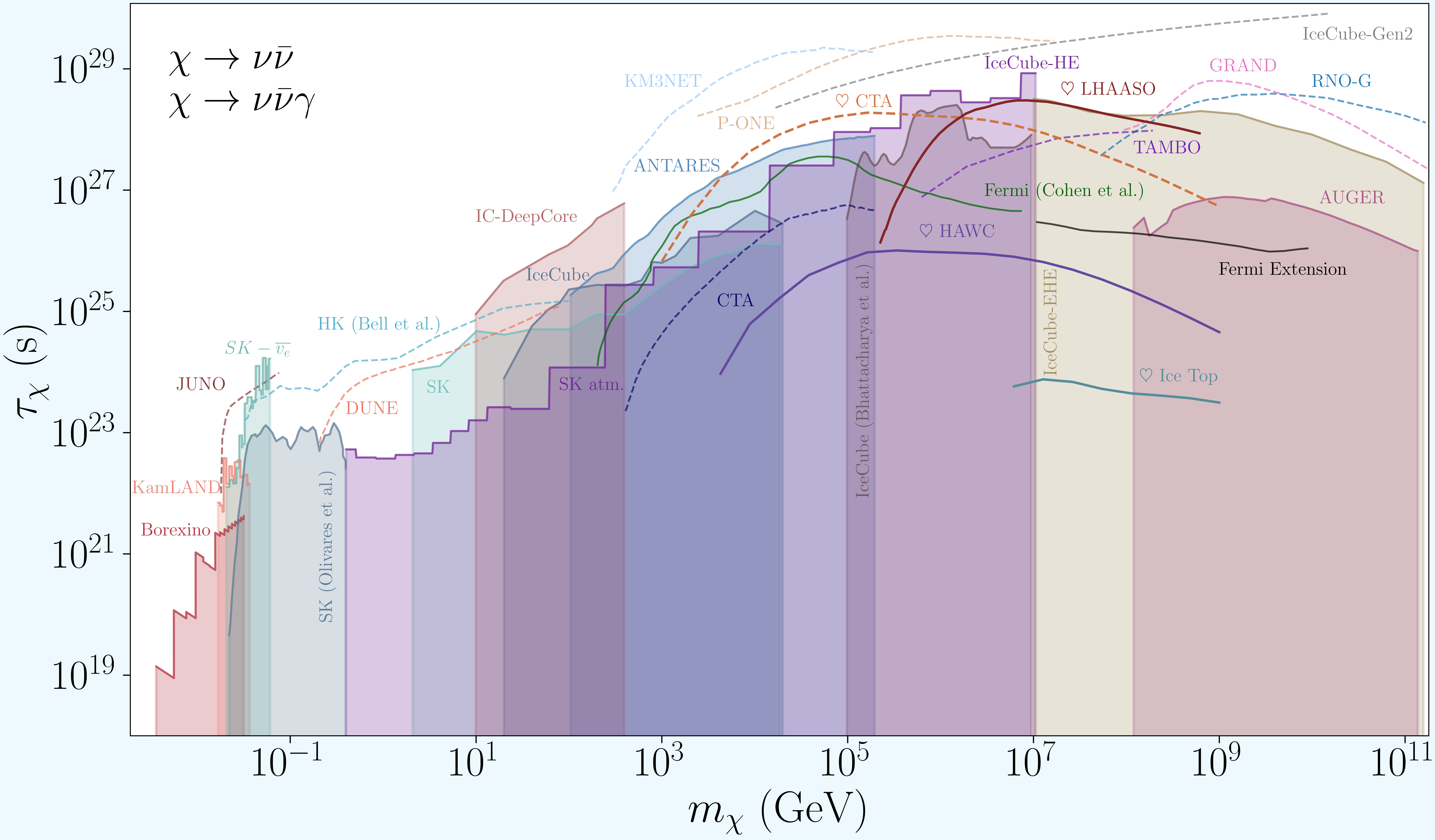
Air Cherenkov. High Energy Gamma Rays (TeV)

Decay Results

Gamma-Ray Experiments



* Taken from Marco Chianese (ICRC21)



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

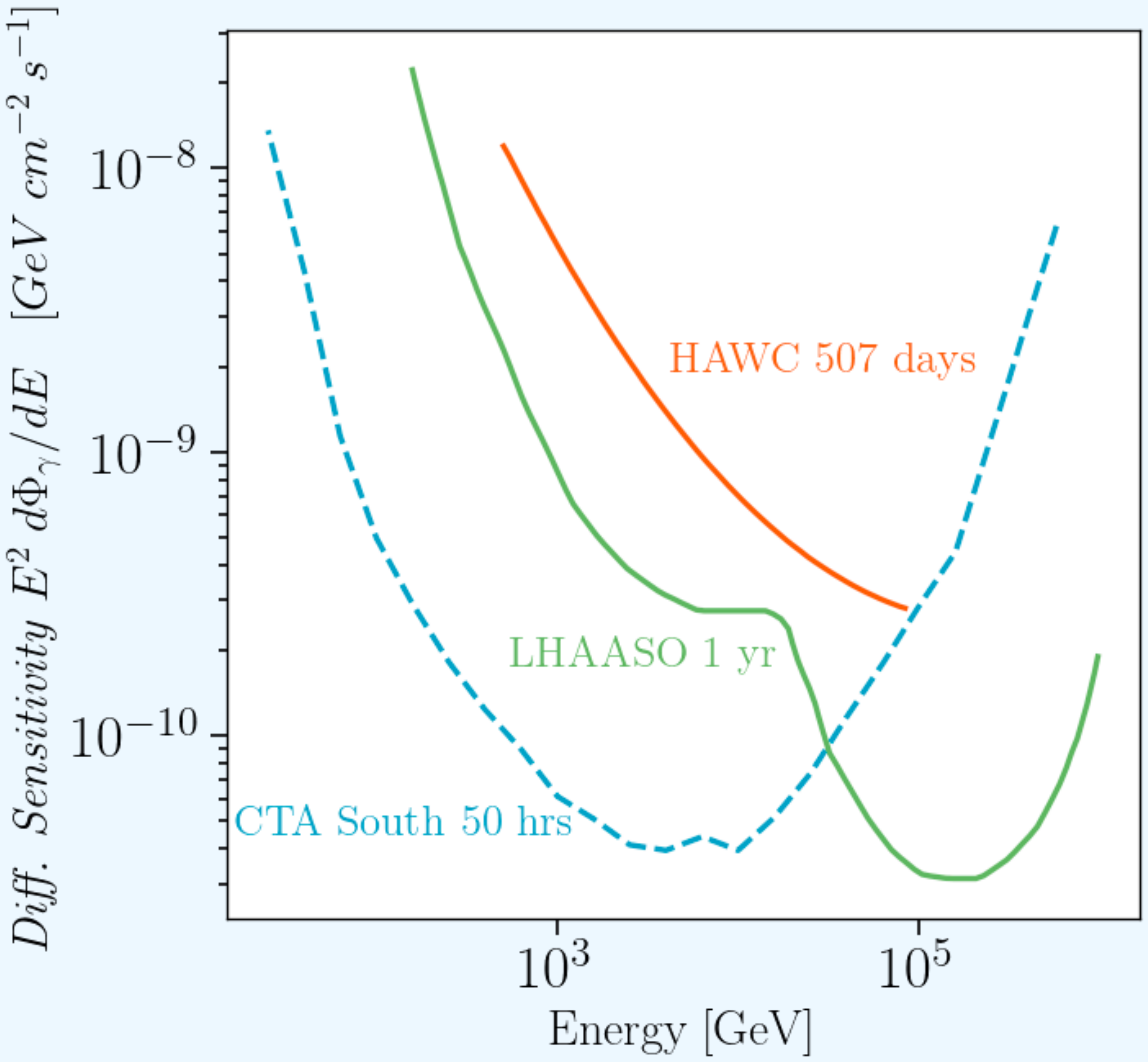
In preparation (2022)

Summary

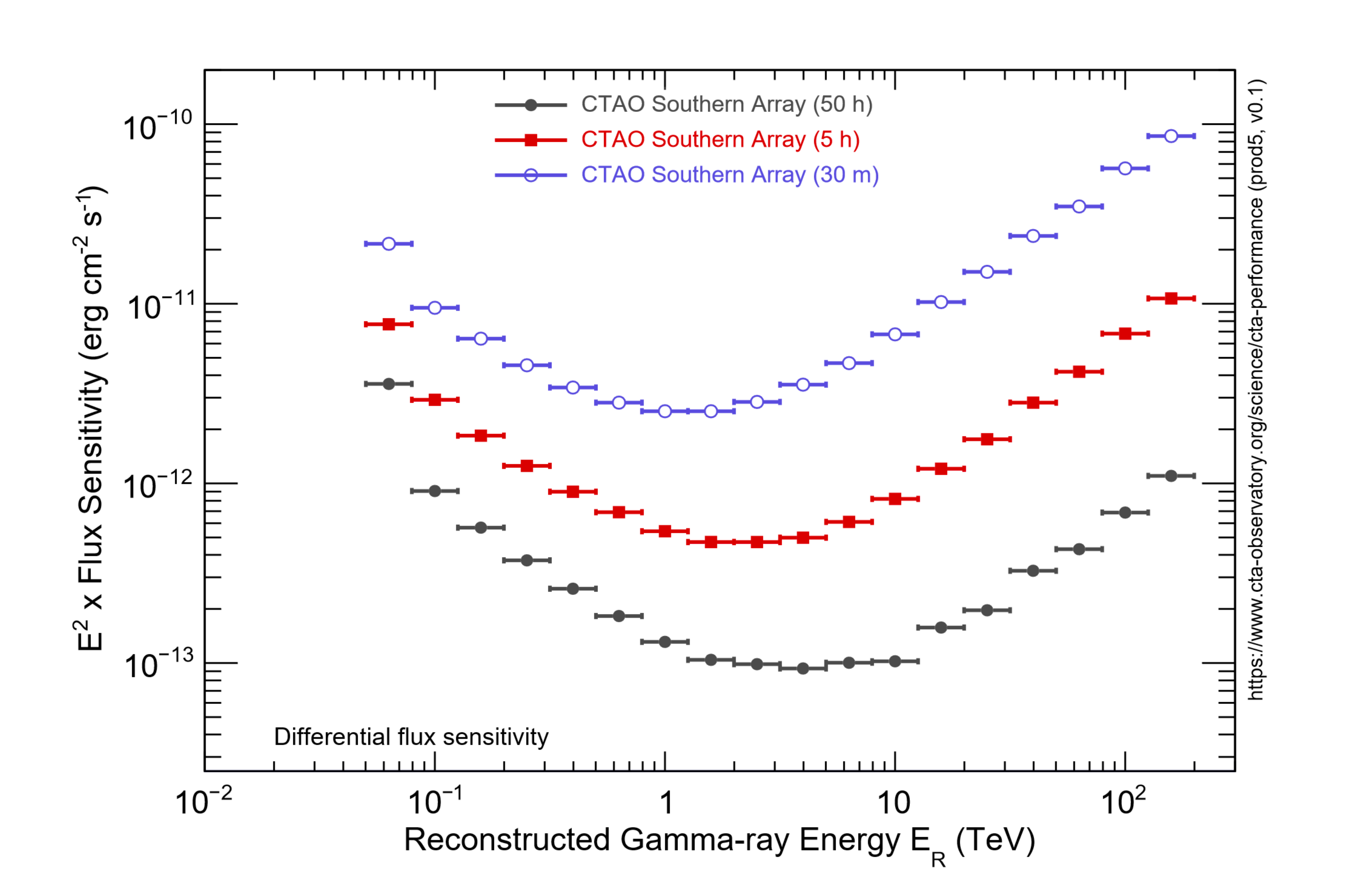
- The nature of Dark Matter and origin of neutrino mass remain a mystery.
- Dark Matter neutrino connections offer solutions to both problems.
- We can measure both neutrinos and gamma-rays as final products of Dark matter decay to neutrinos $\rightarrow$ Correlated signal.
- Major experimental advances 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

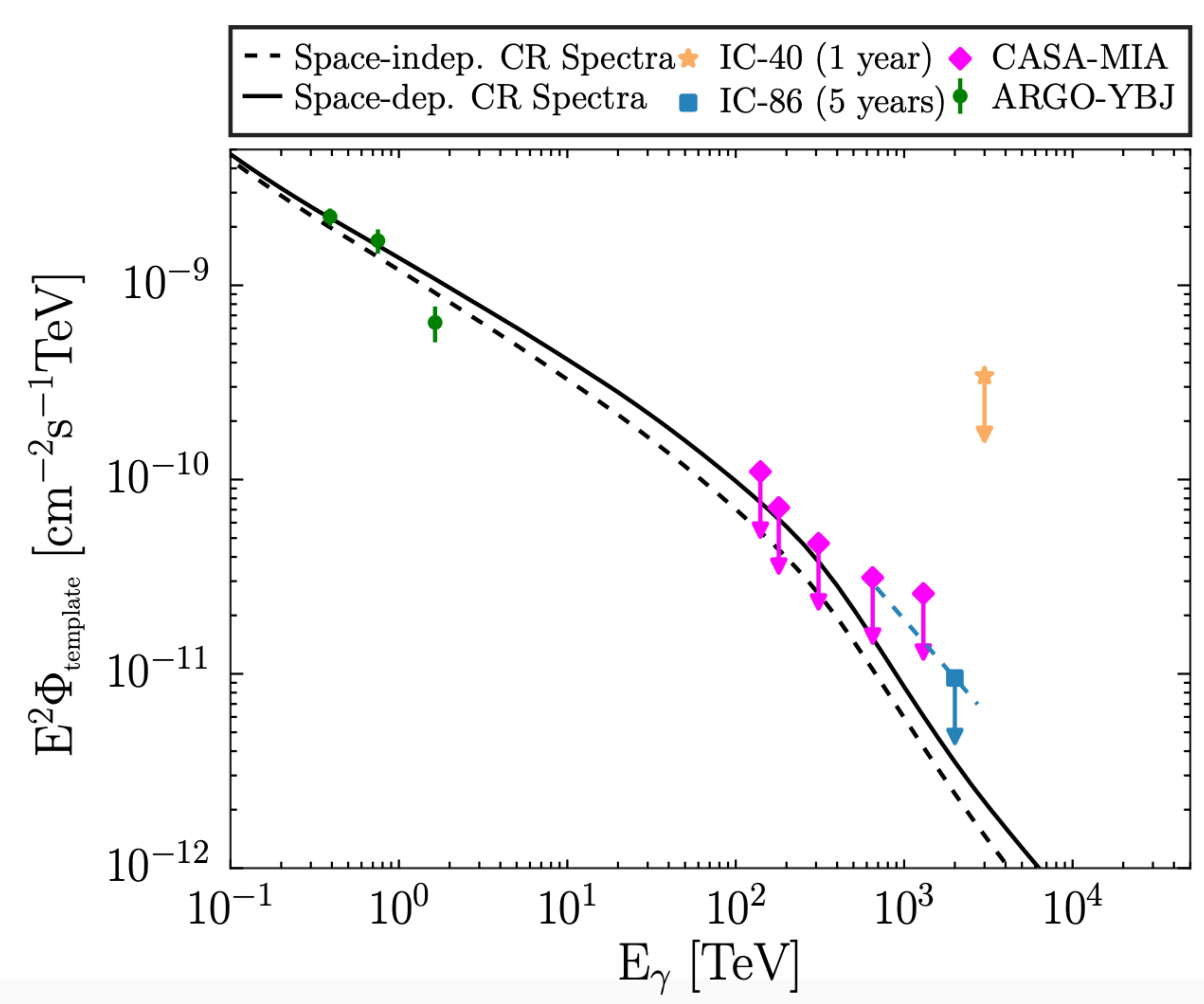
Gamma-Ray Experimental Sensitivities



Gamma-Ray Experimental Sensitivities

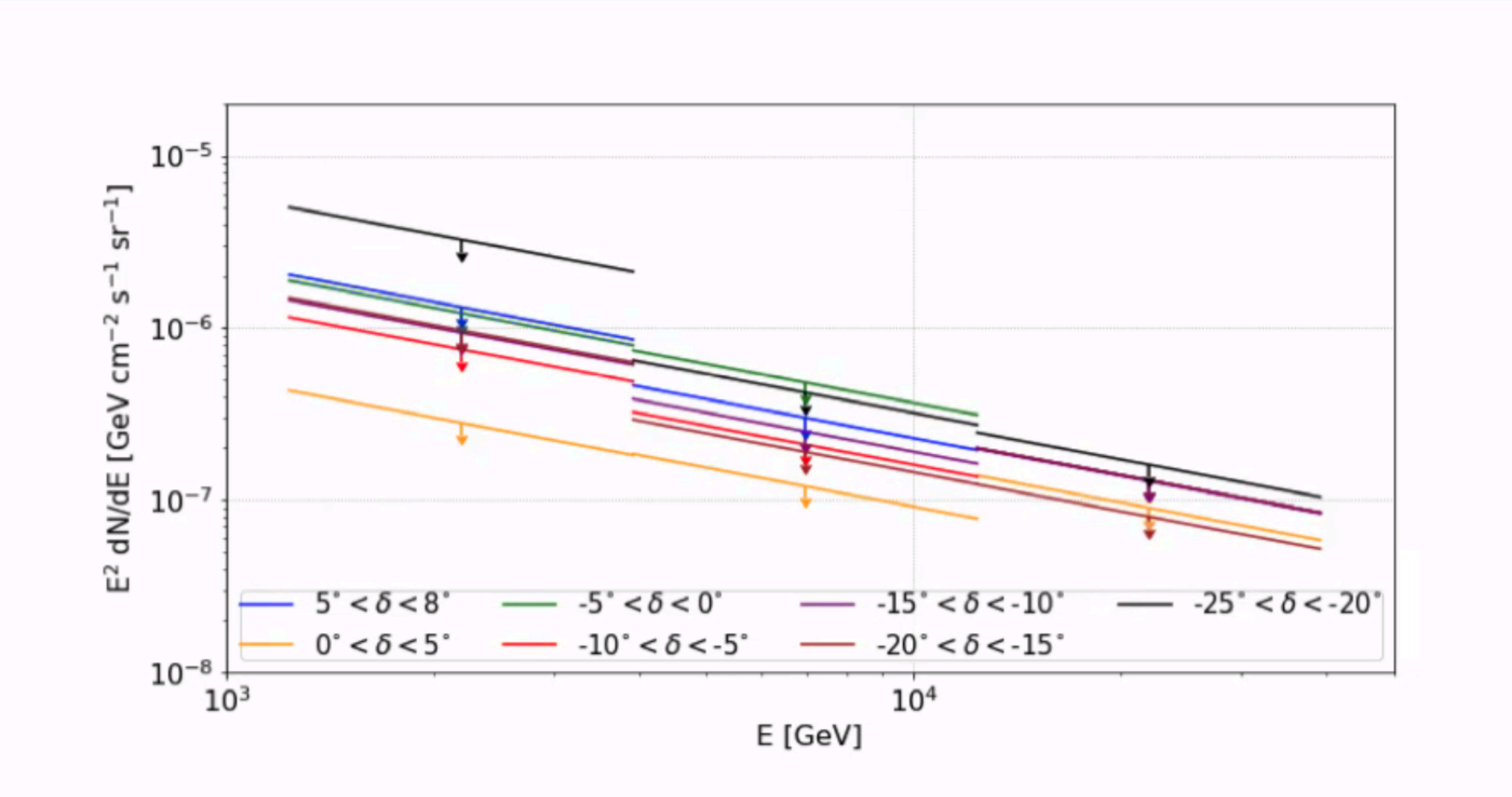


CTA



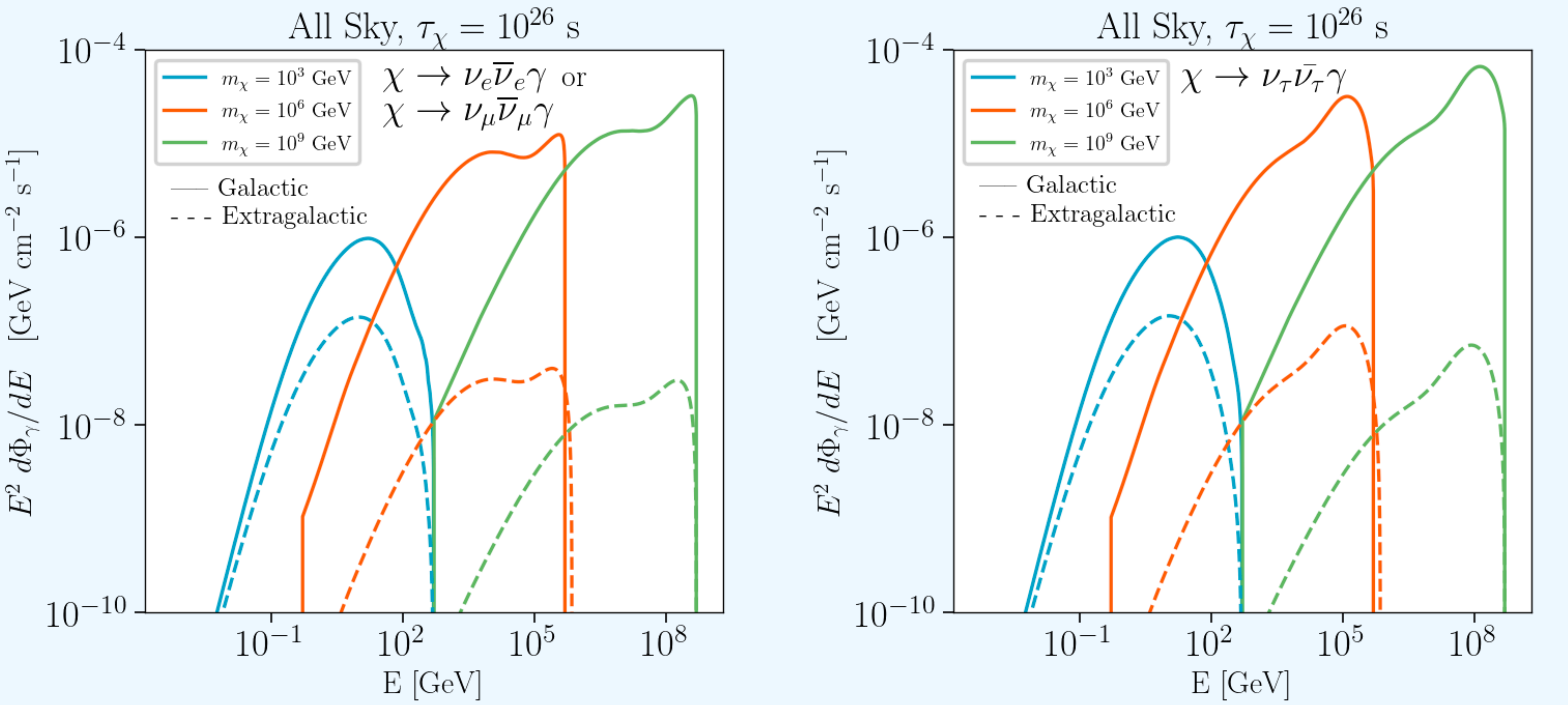
Ice Top

Gamma-Ray Experimental Sensitivities



HAWC

Expected Gamma-Ray DM Flux



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

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:

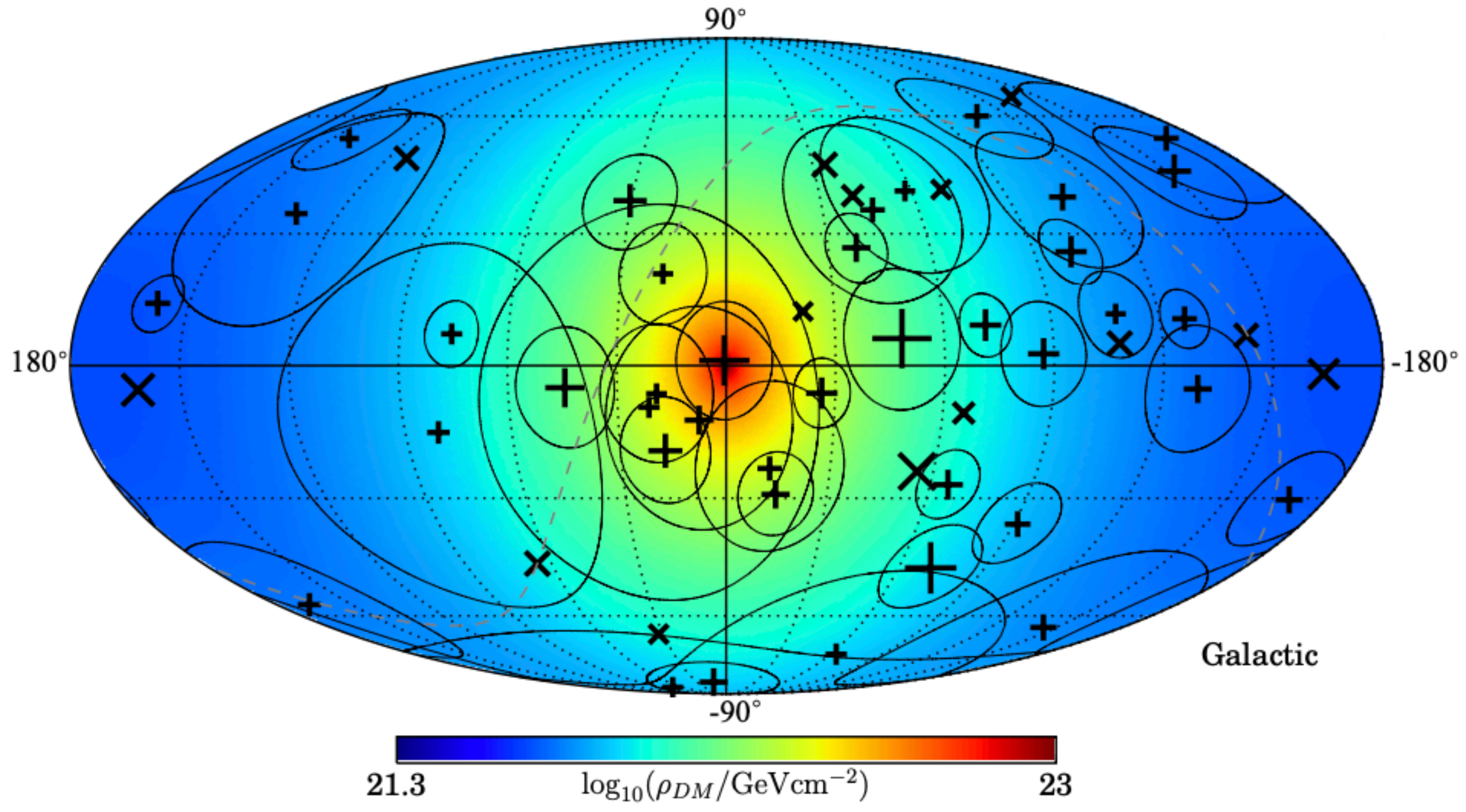
$$\phi_{lim}(\bar{E}) = 4\pi \int_{a_-}^{a^+} f_0 E^{-\alpha} dE \quad \textbf{with} \;\; a_\pm \equiv \bar{E}\, 10^{\pm\Delta/2}$$

Δ is the bin width.

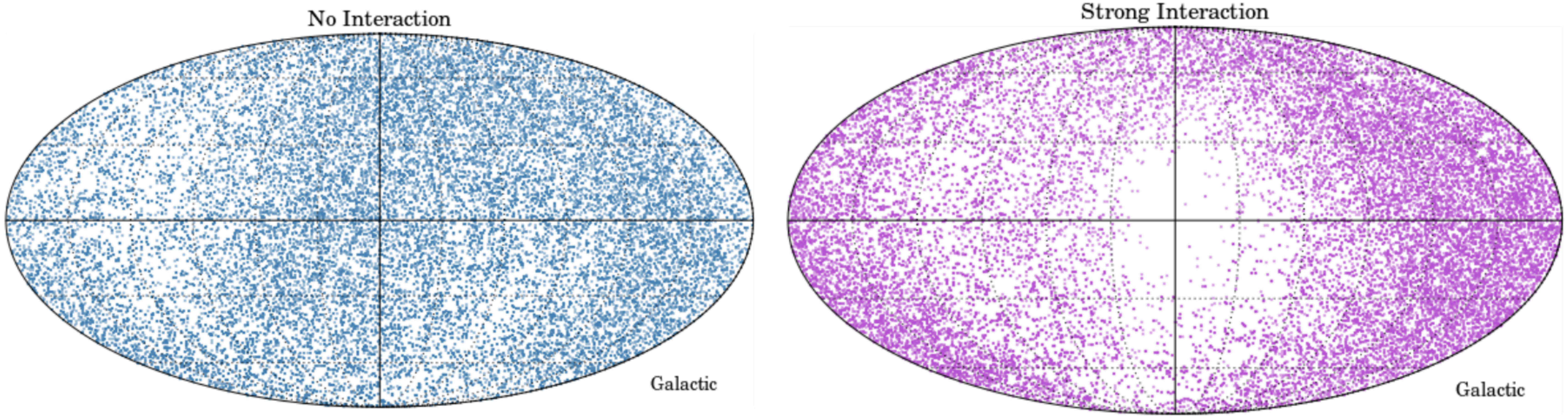
- Dark matter flux is given by:

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

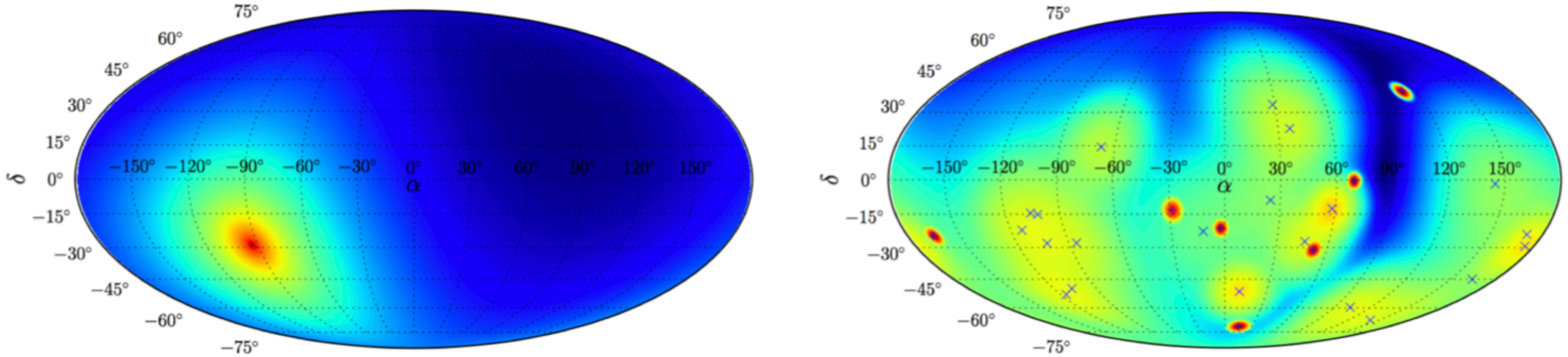
Dark matter column density seen from Earth



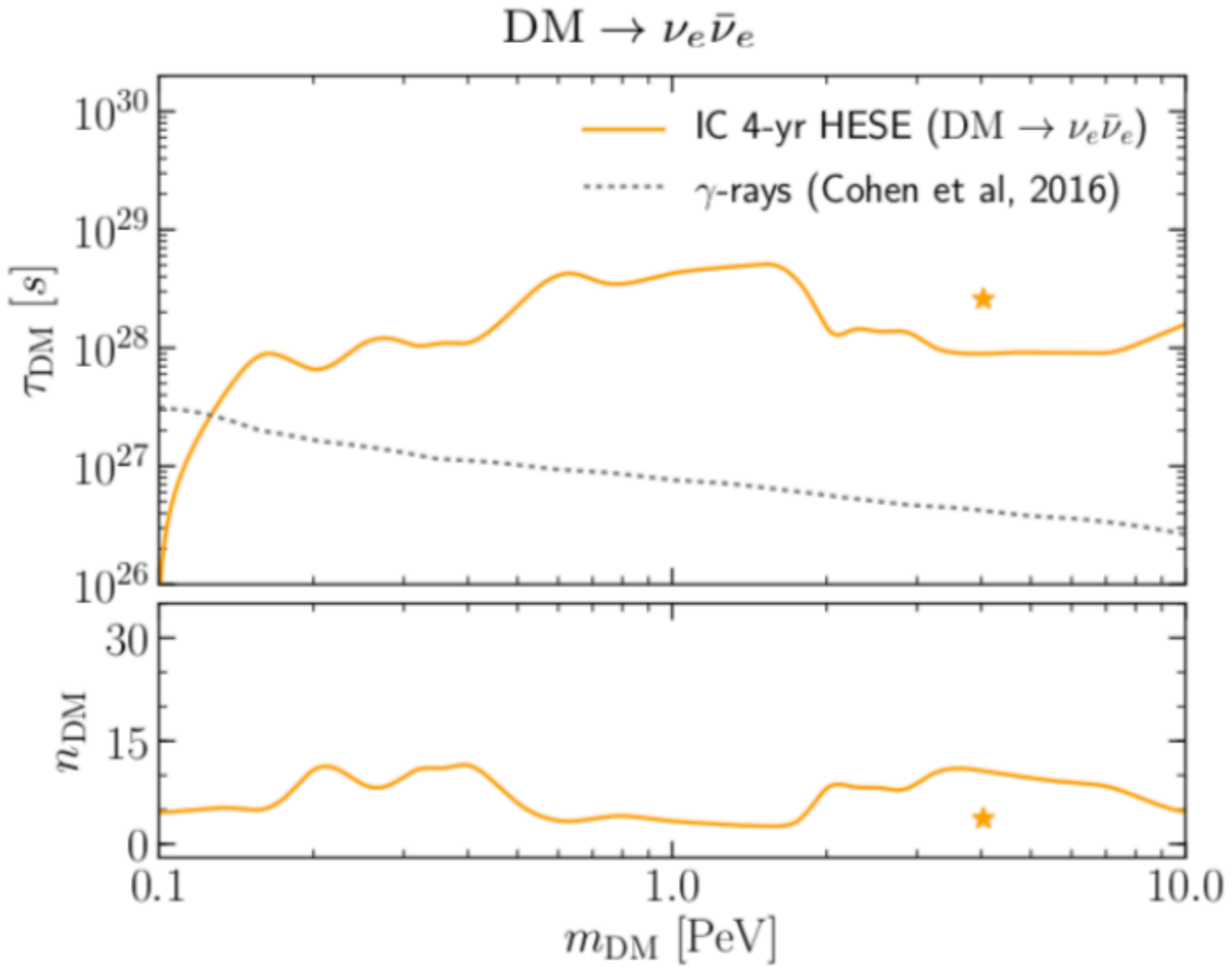
Simulation including effects of detector, Earth



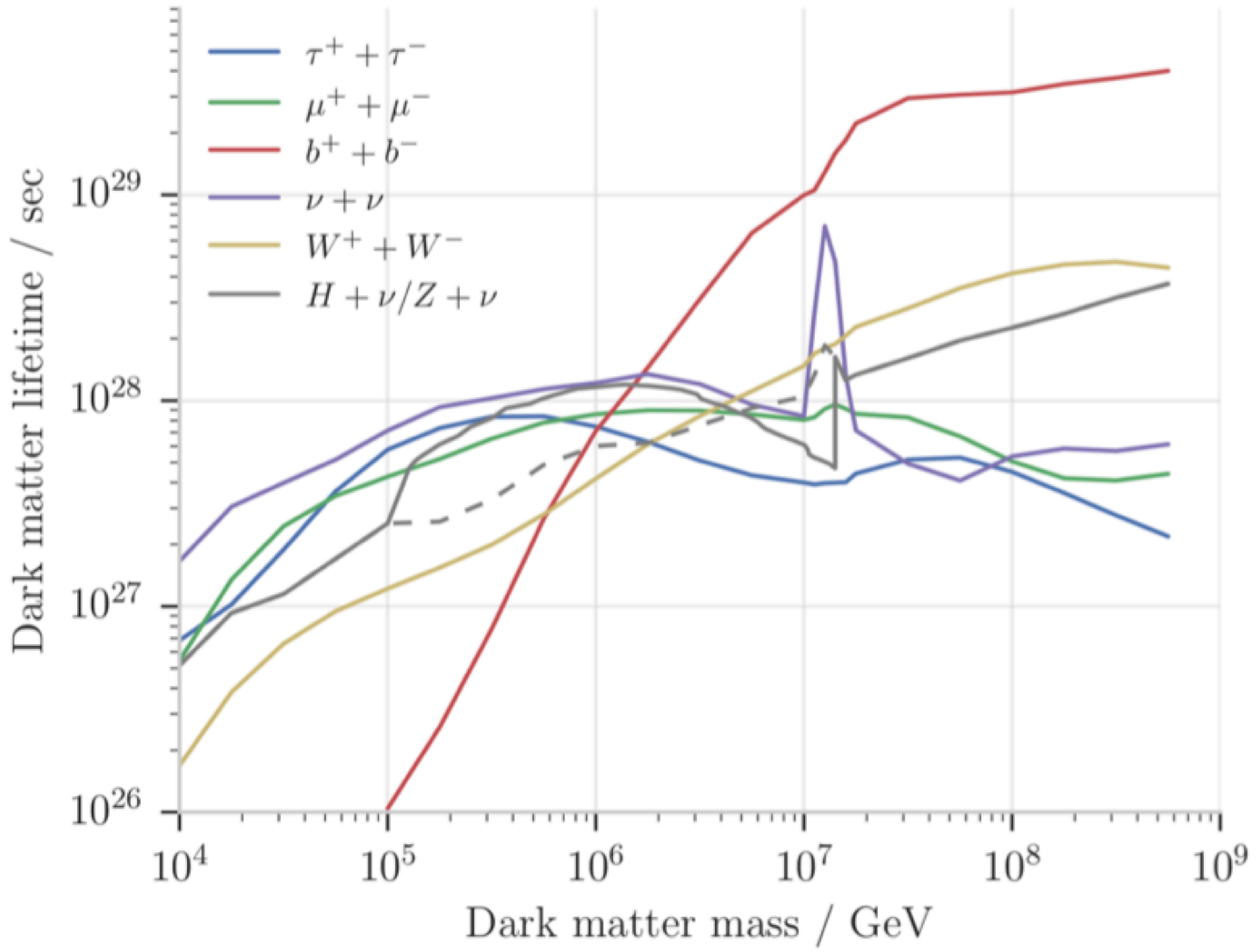
Decay



Yang Bai et al 2016



Atri Bhattacharya et al JCAP07(2017)027



IceCube Collaboration DOI: [10.1140/epjc/s10052-018-6273-3](https://doi.org/10.1140/epjc/s10052-018-6273-3)