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

NBIA Neutrino Summer School - Copenhagen, DK
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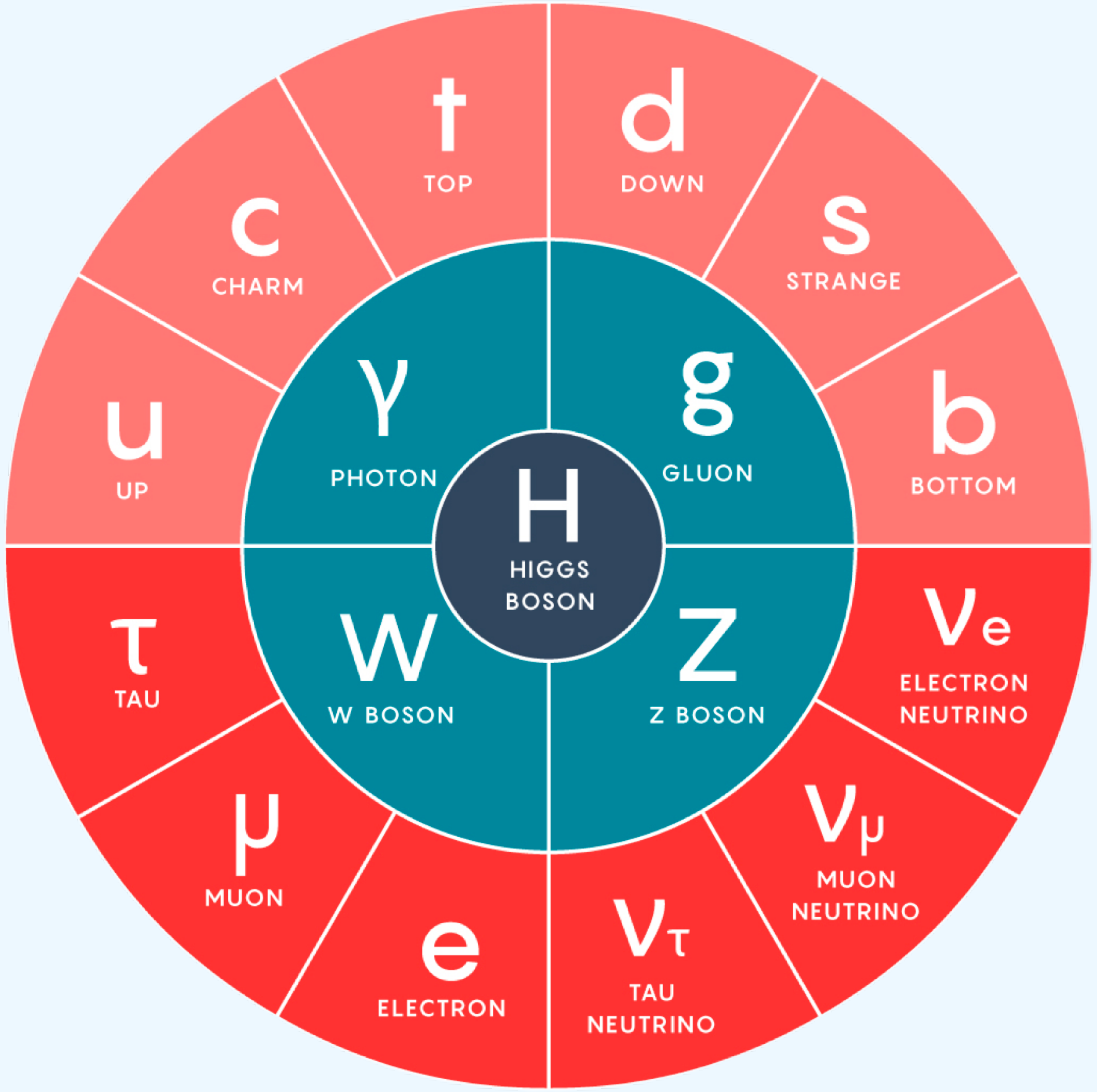
Standard Model is great and all but …



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.

Hunt for the Dark Matter Particle

There's some astrophysical and cosmological evidence that leads to the existence of a new weakly-interacting particle – dark matter (DM).

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

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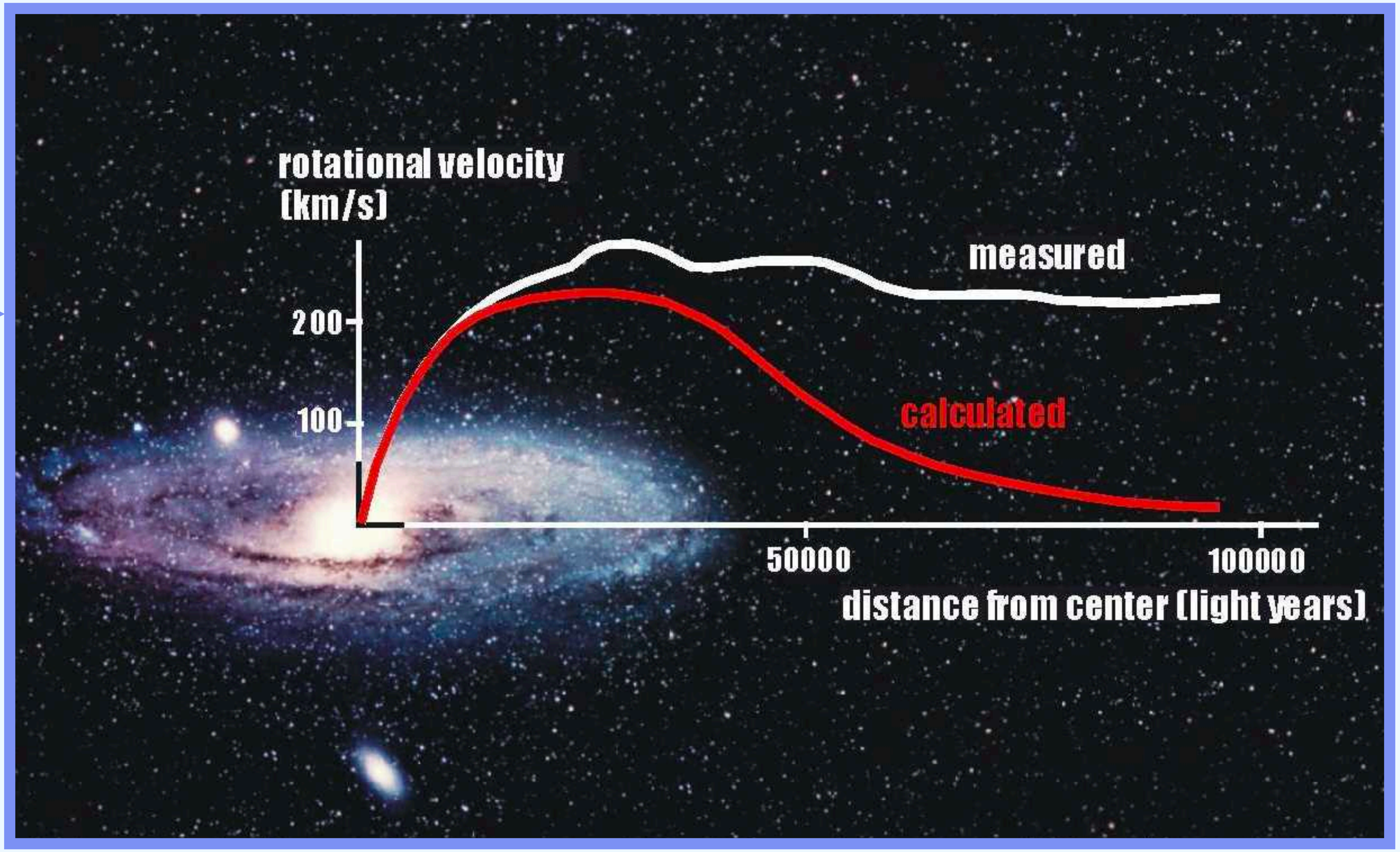

Hunt for the Dark Matter Particle

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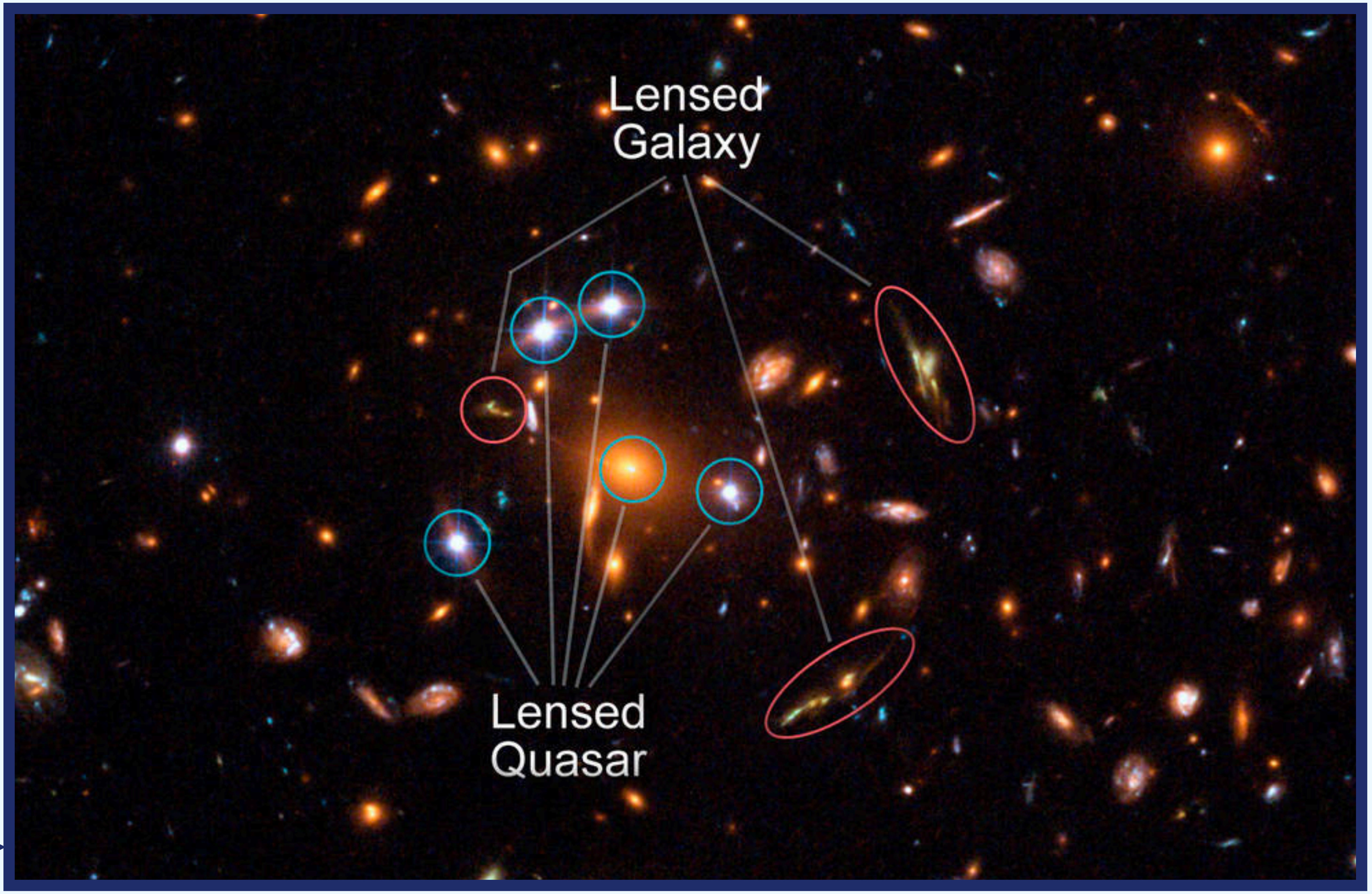
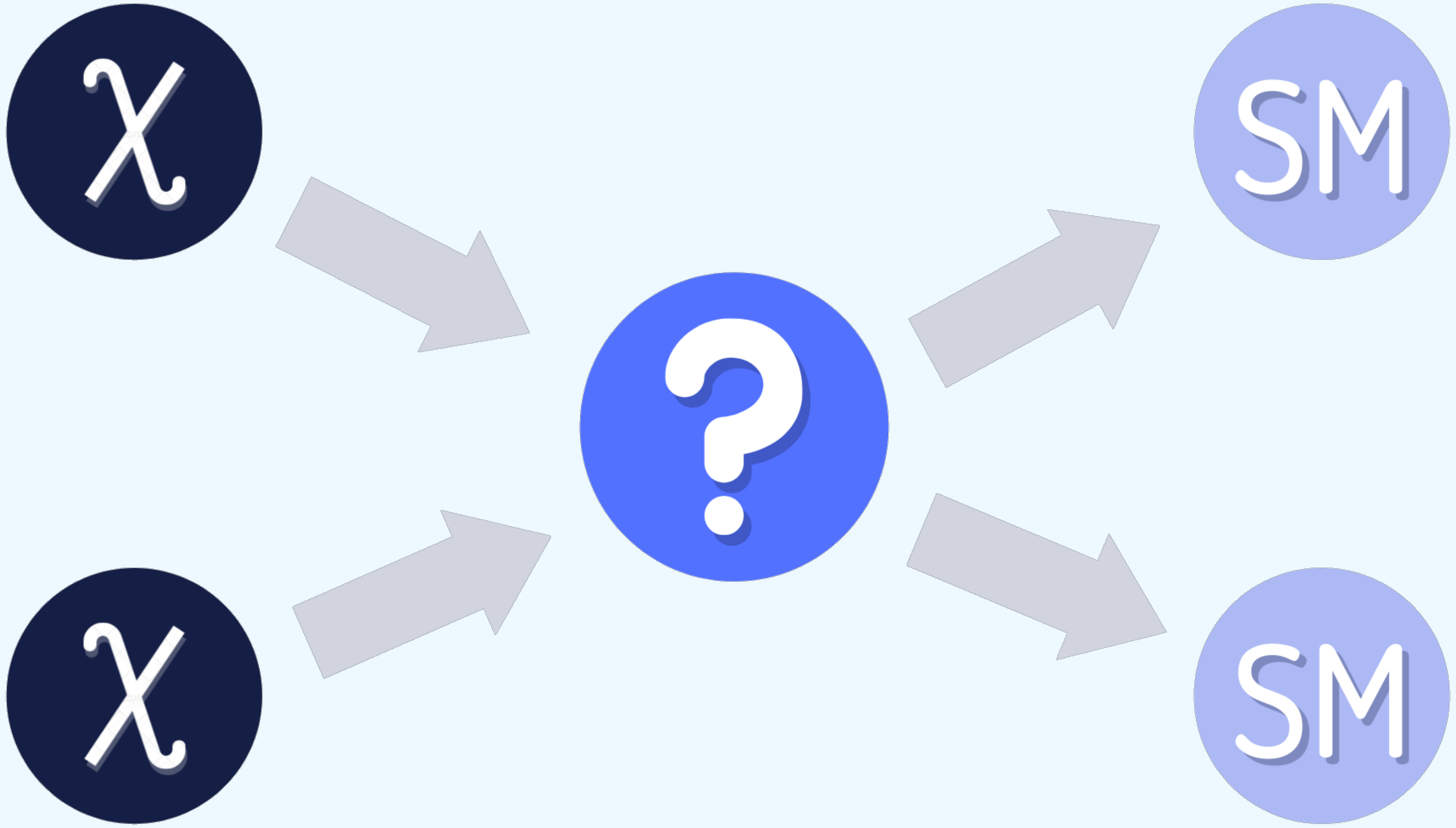
- Galactic Rotation Curves
- Cluster Dynamics
- **Gravitational Lensing**



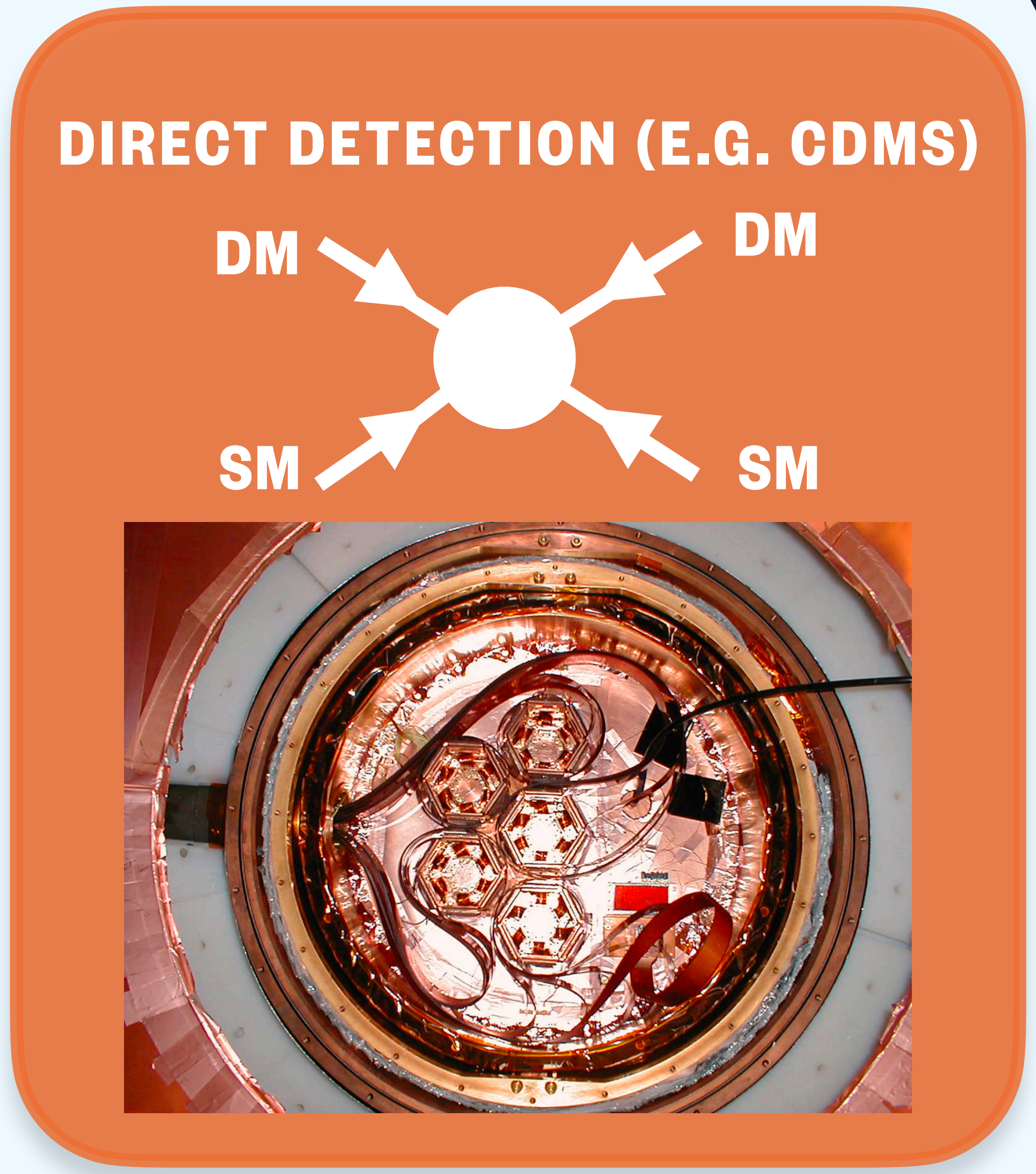
CREDIT: ESA, NASA, K. SHARON (TEL AVIV UNIVERSITY) AND E. OFEK (CALTECH)

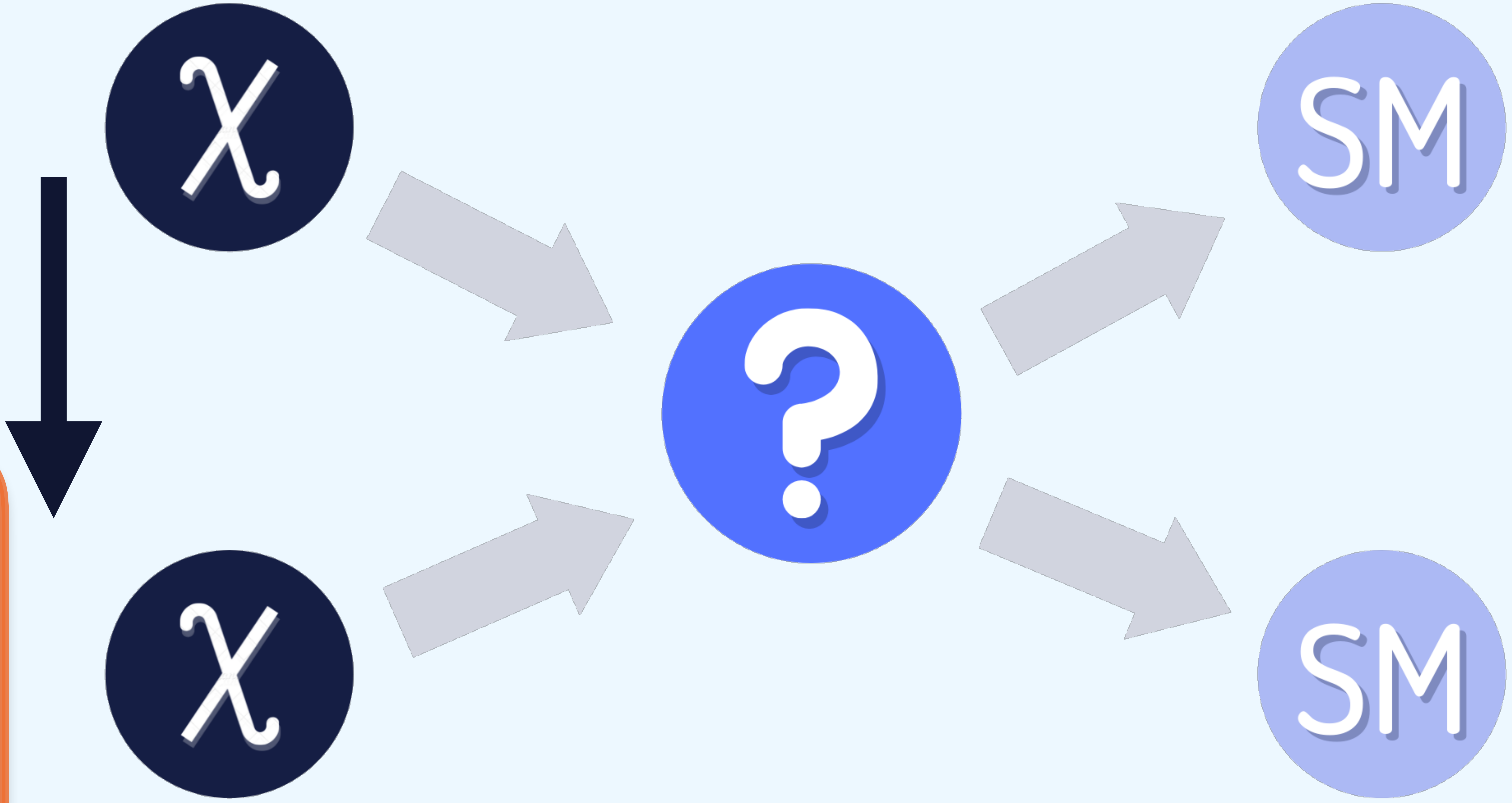
Hunt for the Dark Matter Particle



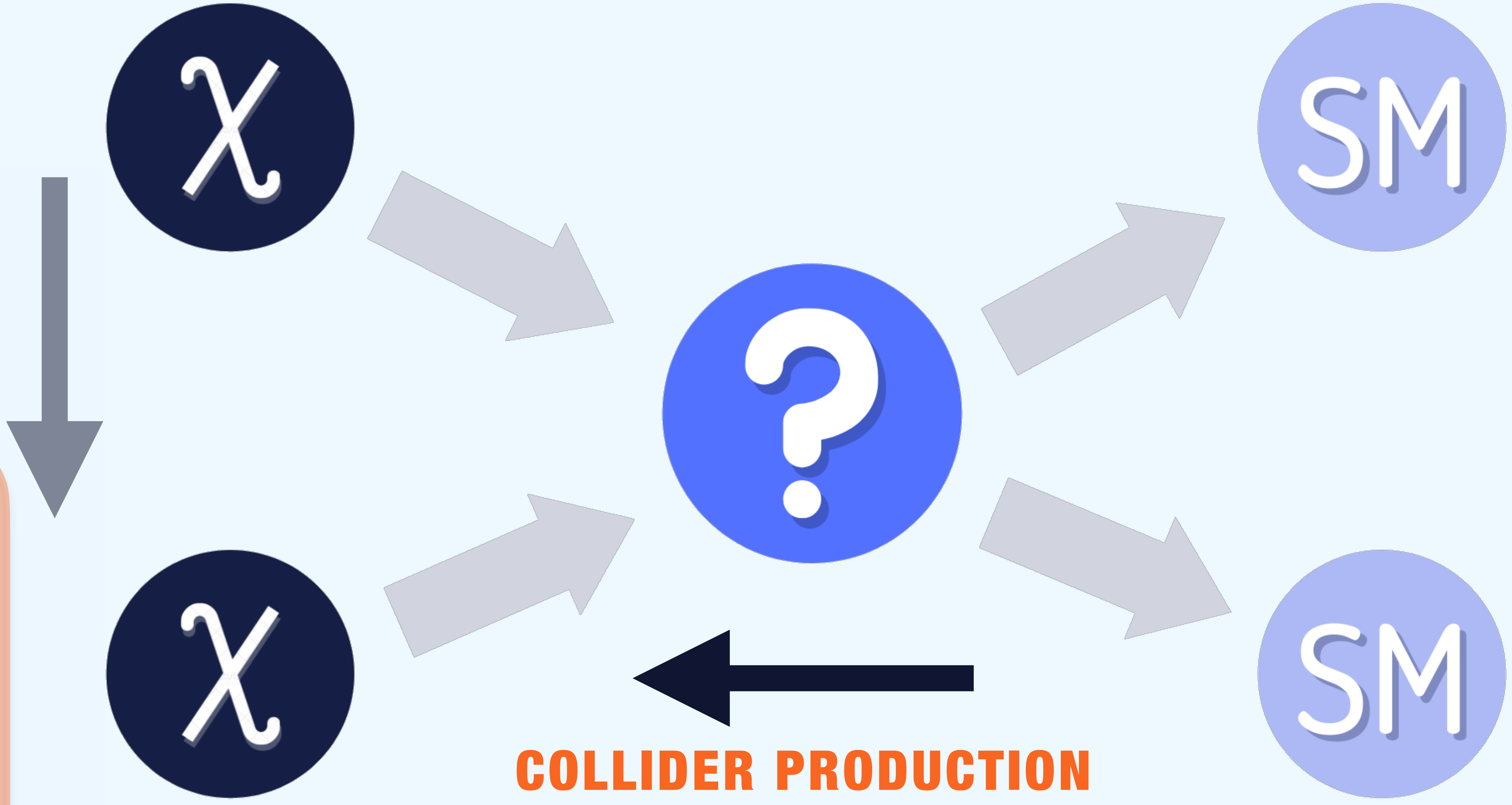
Hunt for the Dark Matter Particle

DIRECT
DETECTION
(SCATTERING)



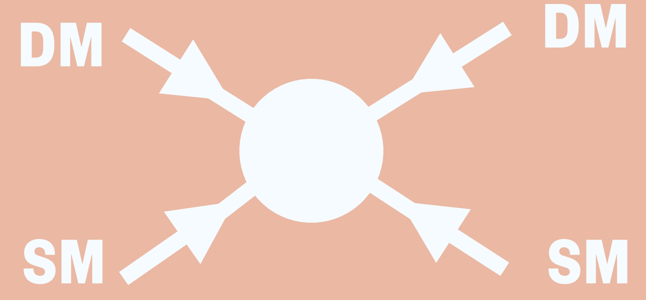


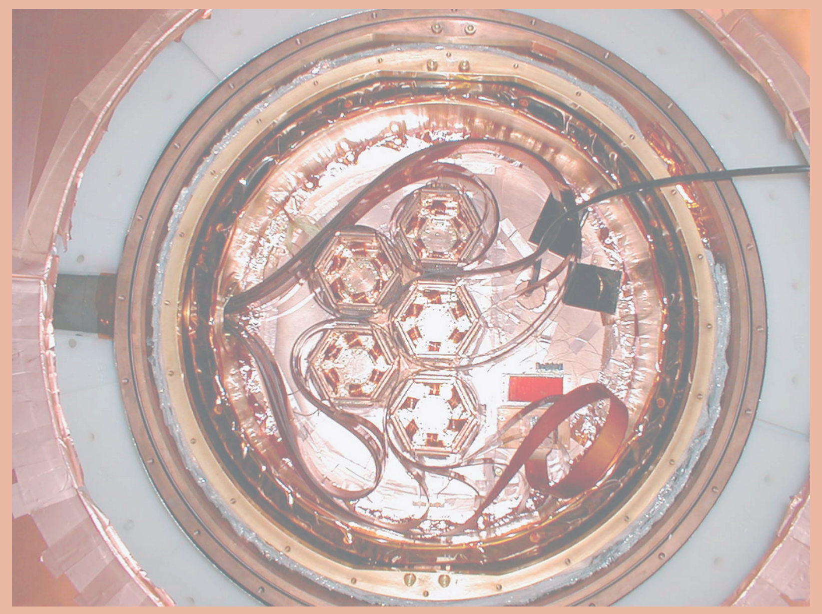
Hunt for the Dark Matter Particle



DIRECT DETECTION (SCATTERING)

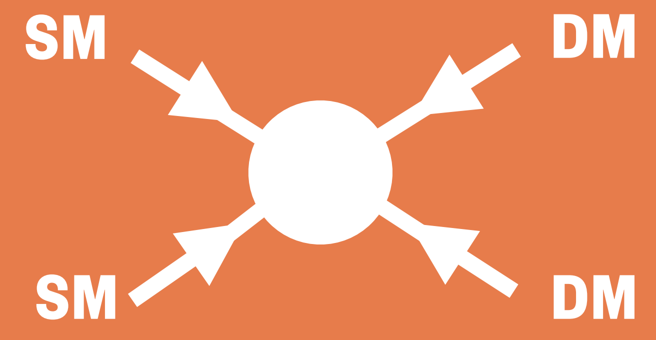
DIRECT DETECTION (E.G. CDMS)

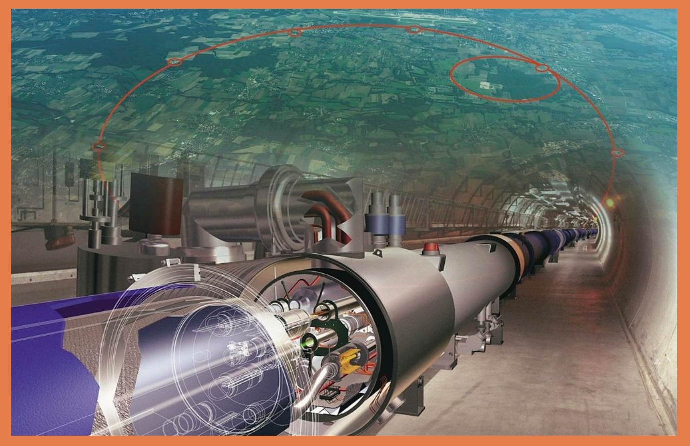




COLLIDER PRODUCTION

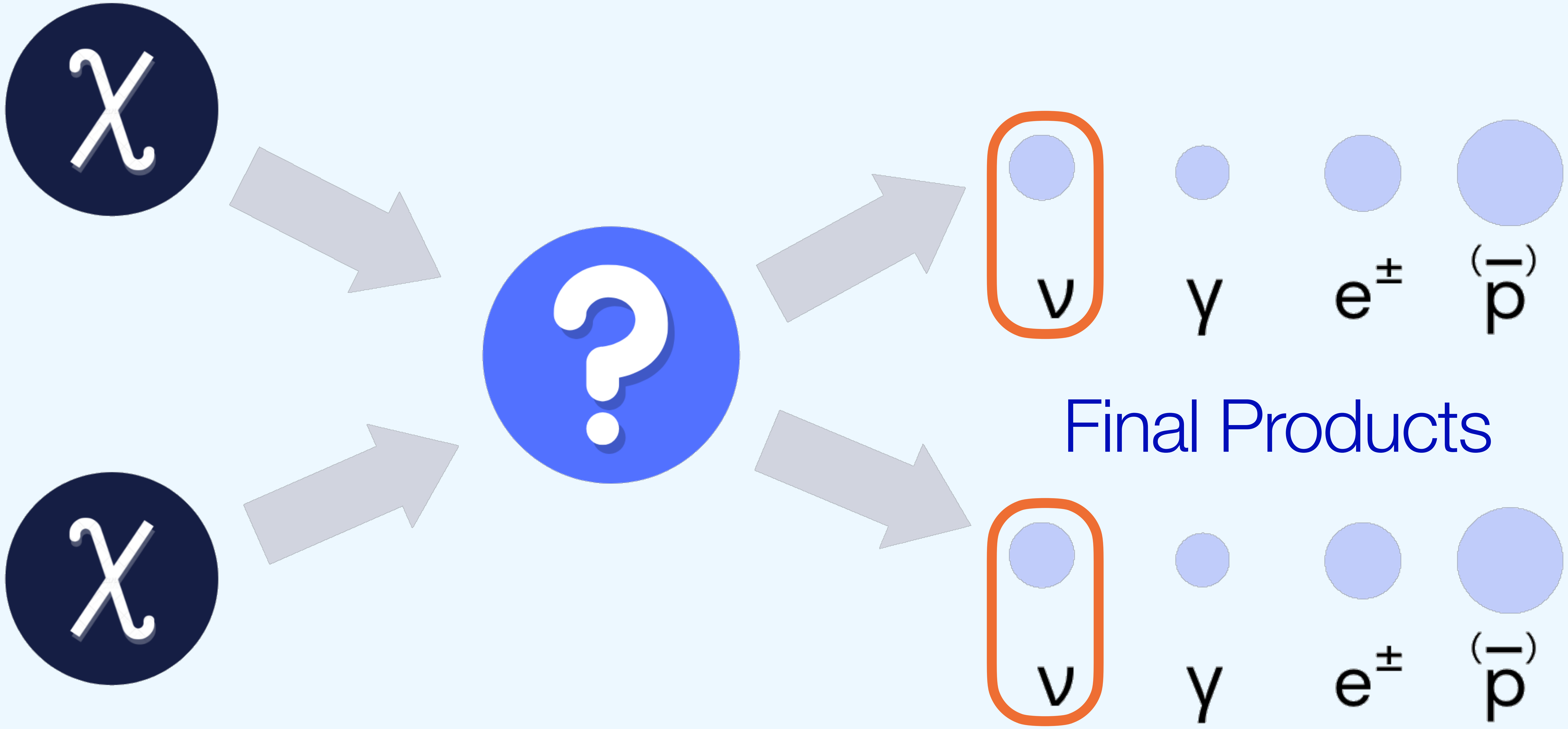
PARTICLE COLLIDERS (E.G. LHC)





Hunt for the Dark Matter Particle

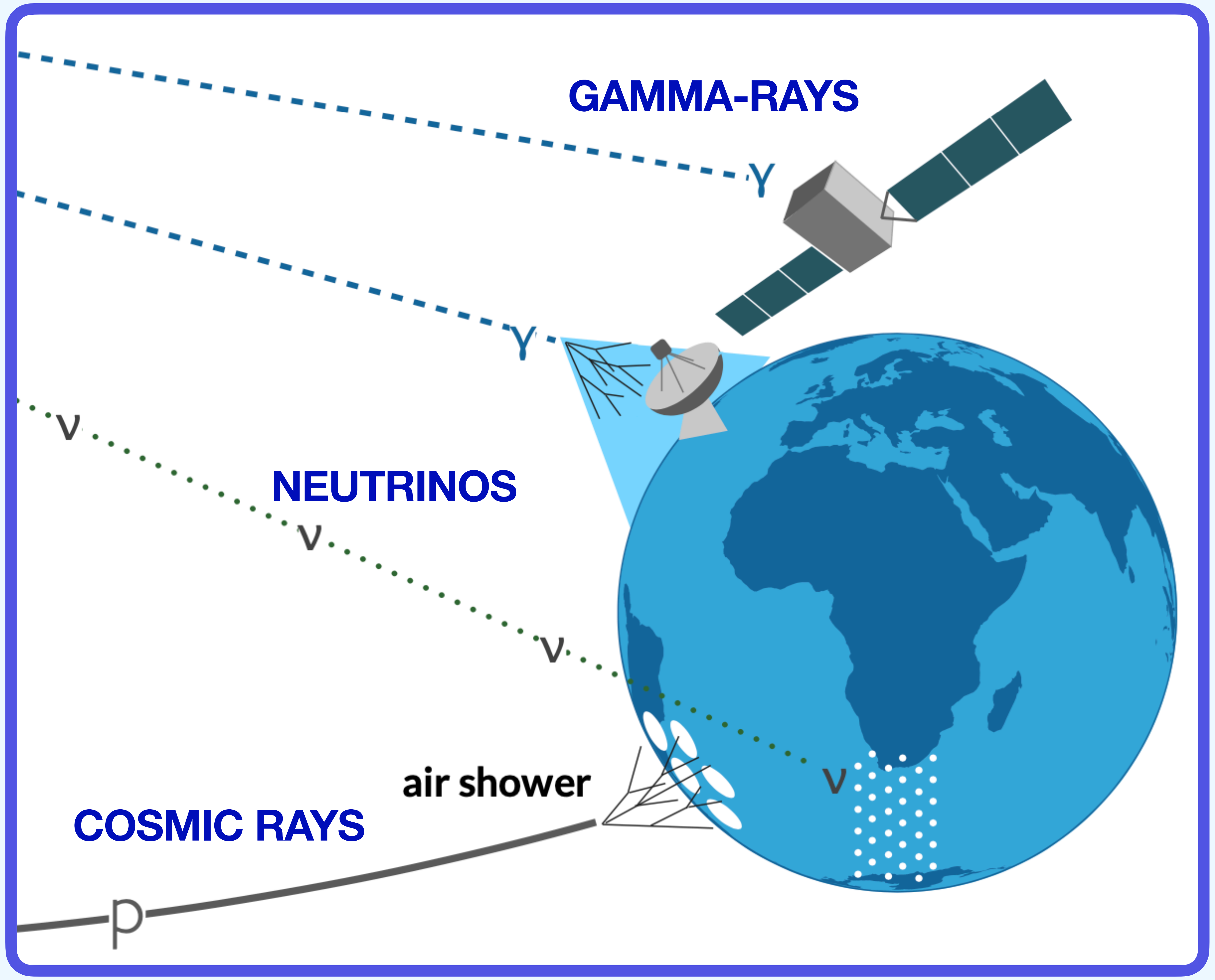
Indirect Detection

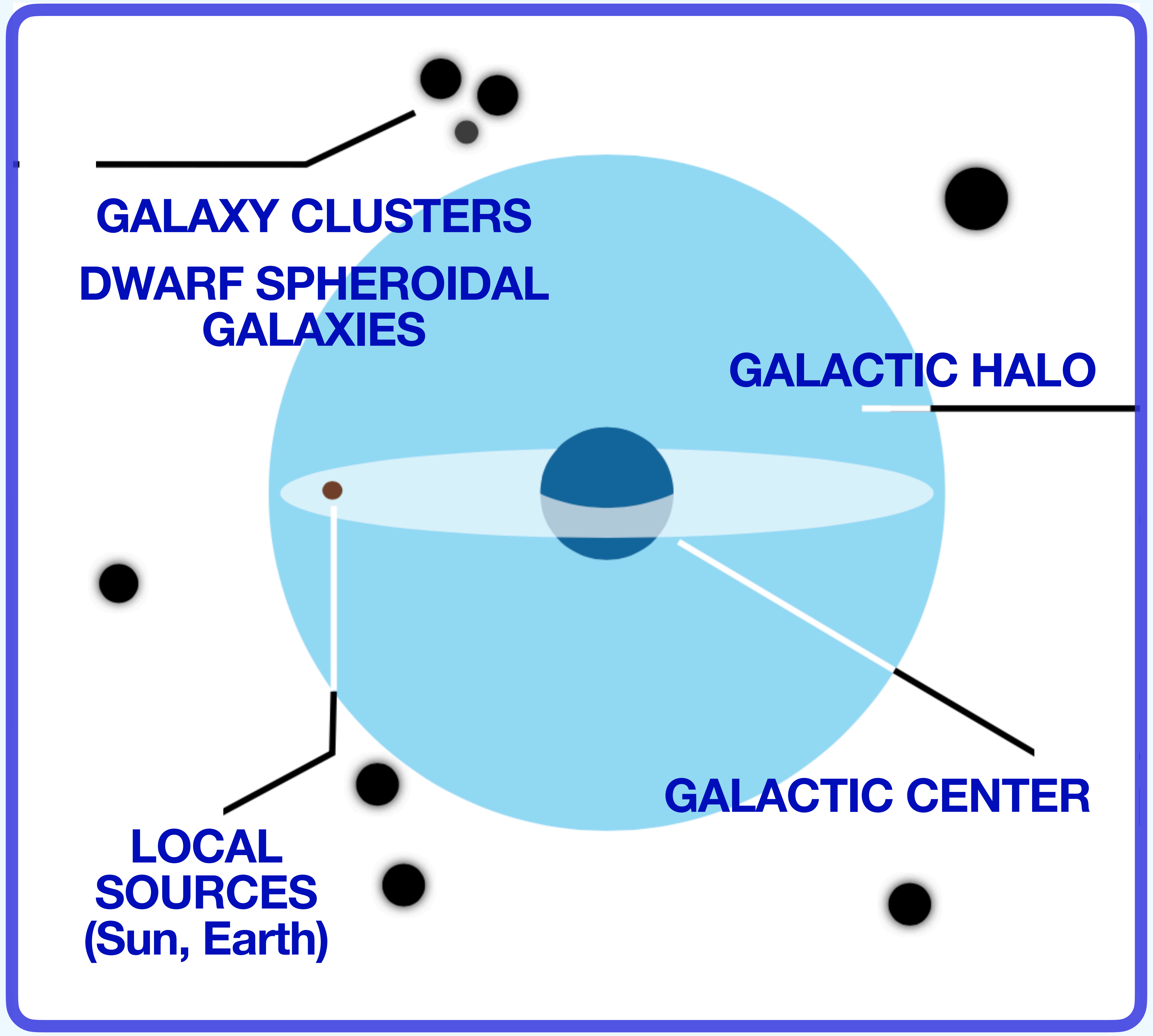


No need of specialized detectors: **Gamma-ray telescopes, neutrino detectors, CR-experiments**
Search for products of dark matter decay processes: **Focus on large reservoirs of dark matter**

Dark Matter Searches

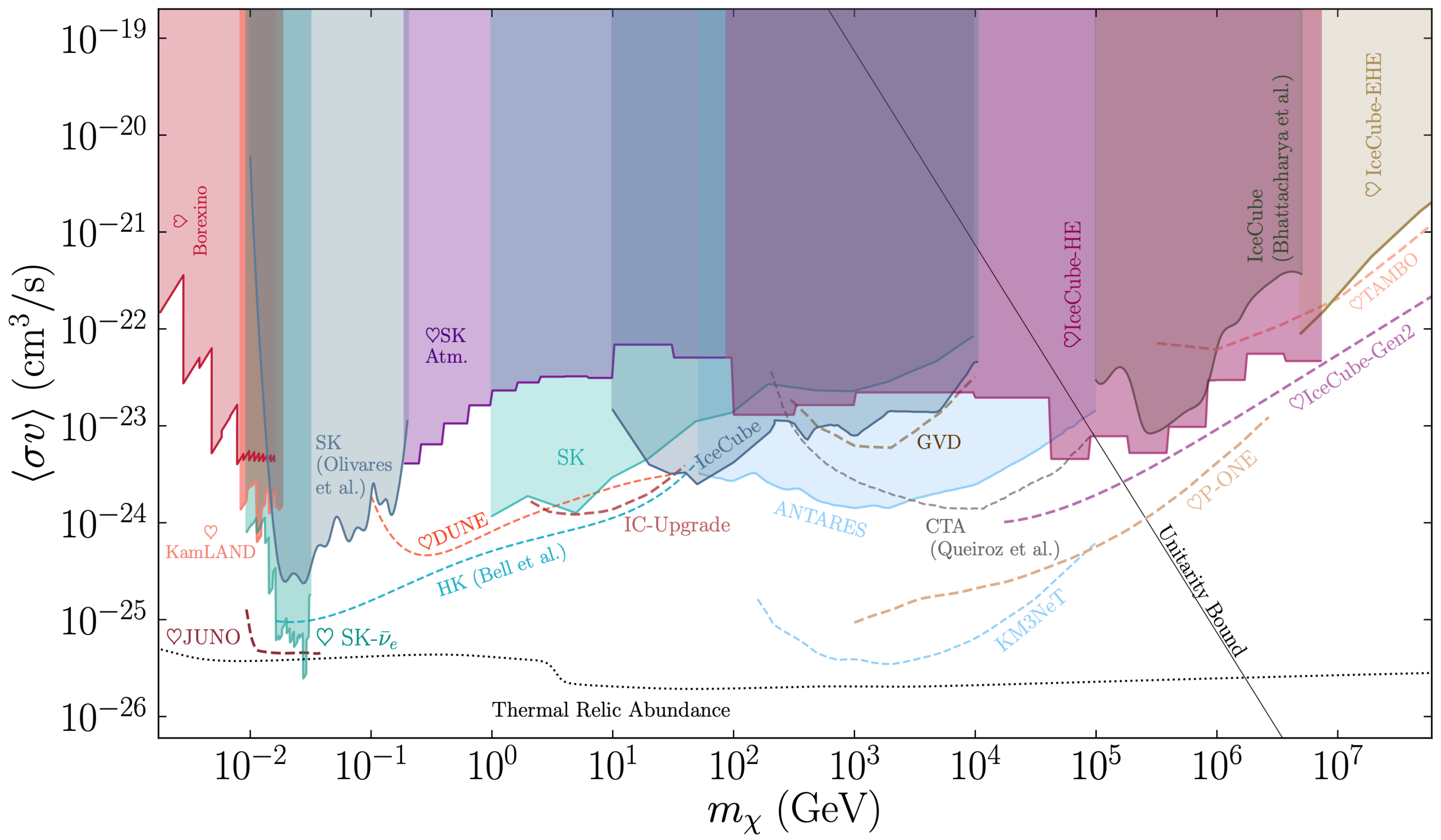
What and where to look?





CREDIT: JUAN AGUILAR, ESDU 2018

Previous Work: Dark Matter Annihilation to neutrinos



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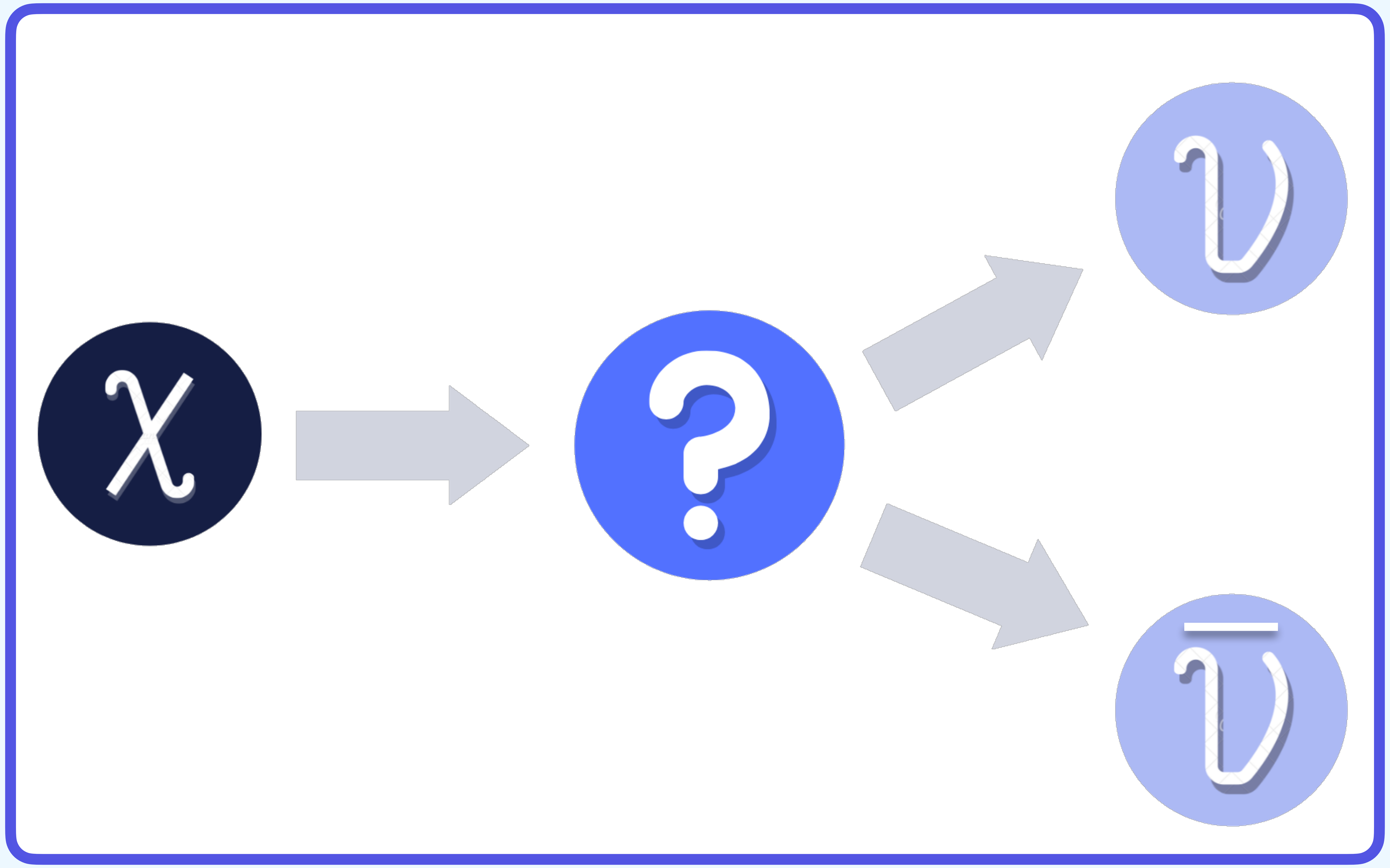
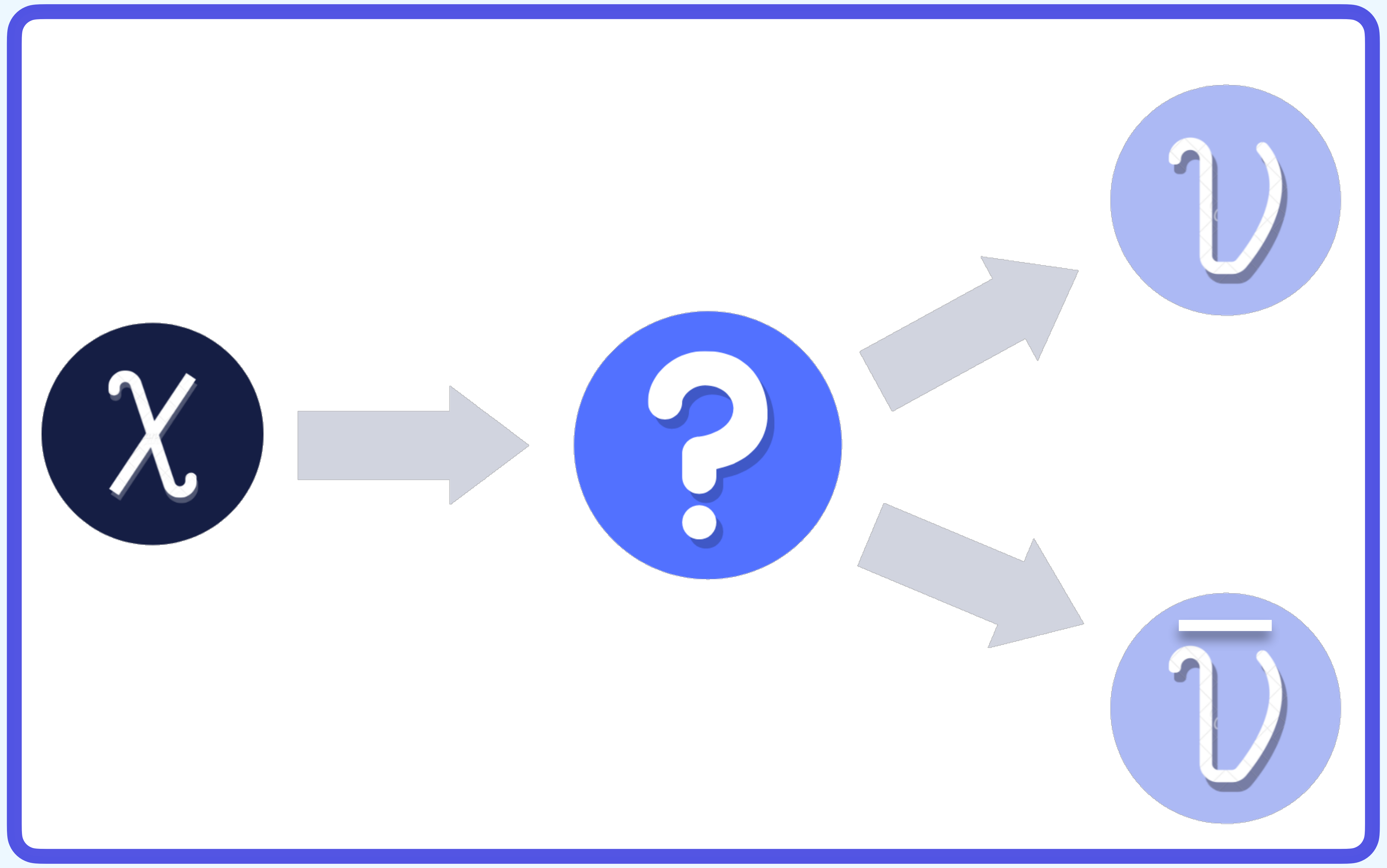
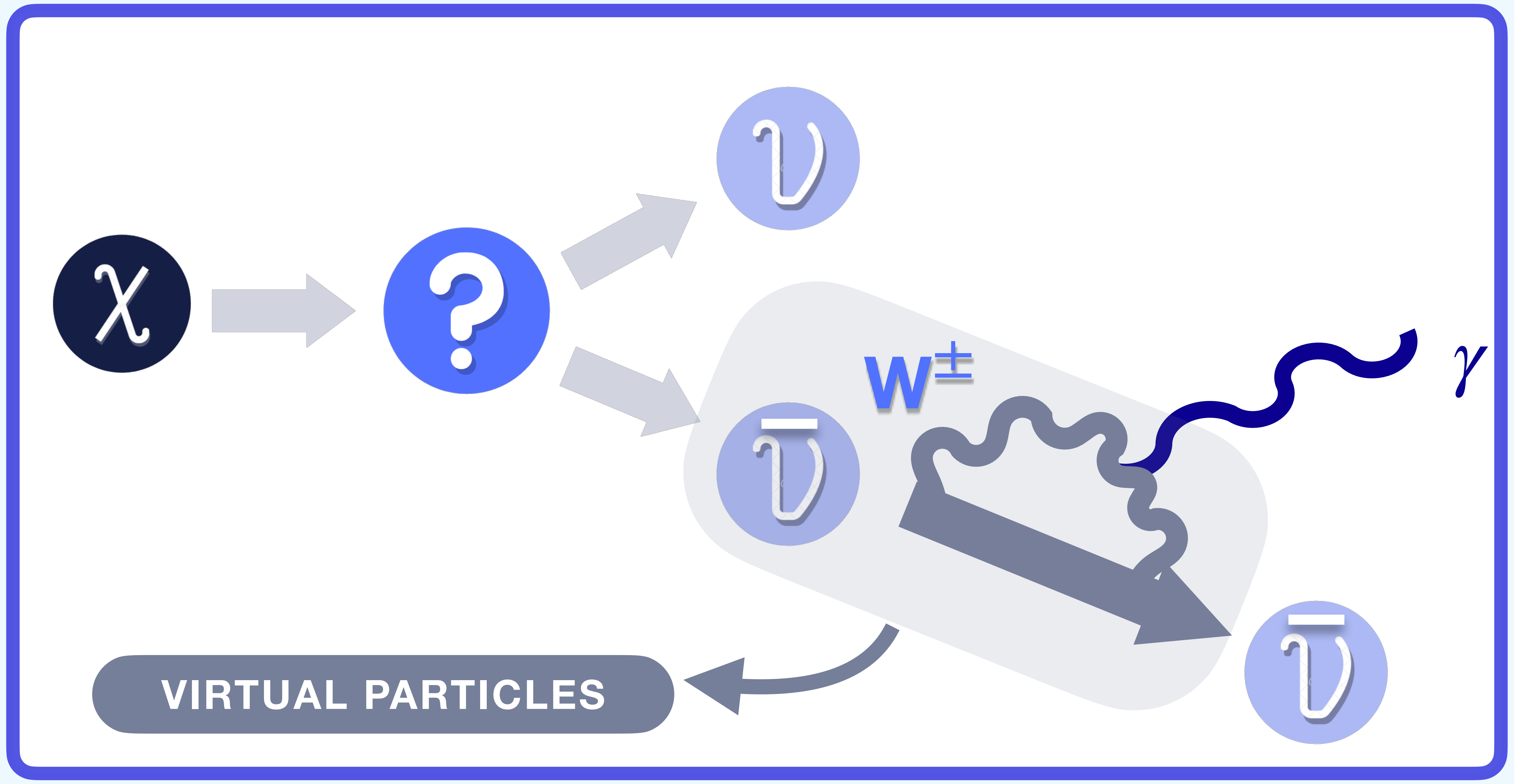
Focus on Dark Matter decay to neutrinos



EXPECTED GAMMA-RAY SIGNAL DUE TO ELECTROWEAK CORRECTIONS

Dark Matter Decay to neutrinos





NEUTRINO SIGNAL

GAMMA-RAY SIGNAL

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

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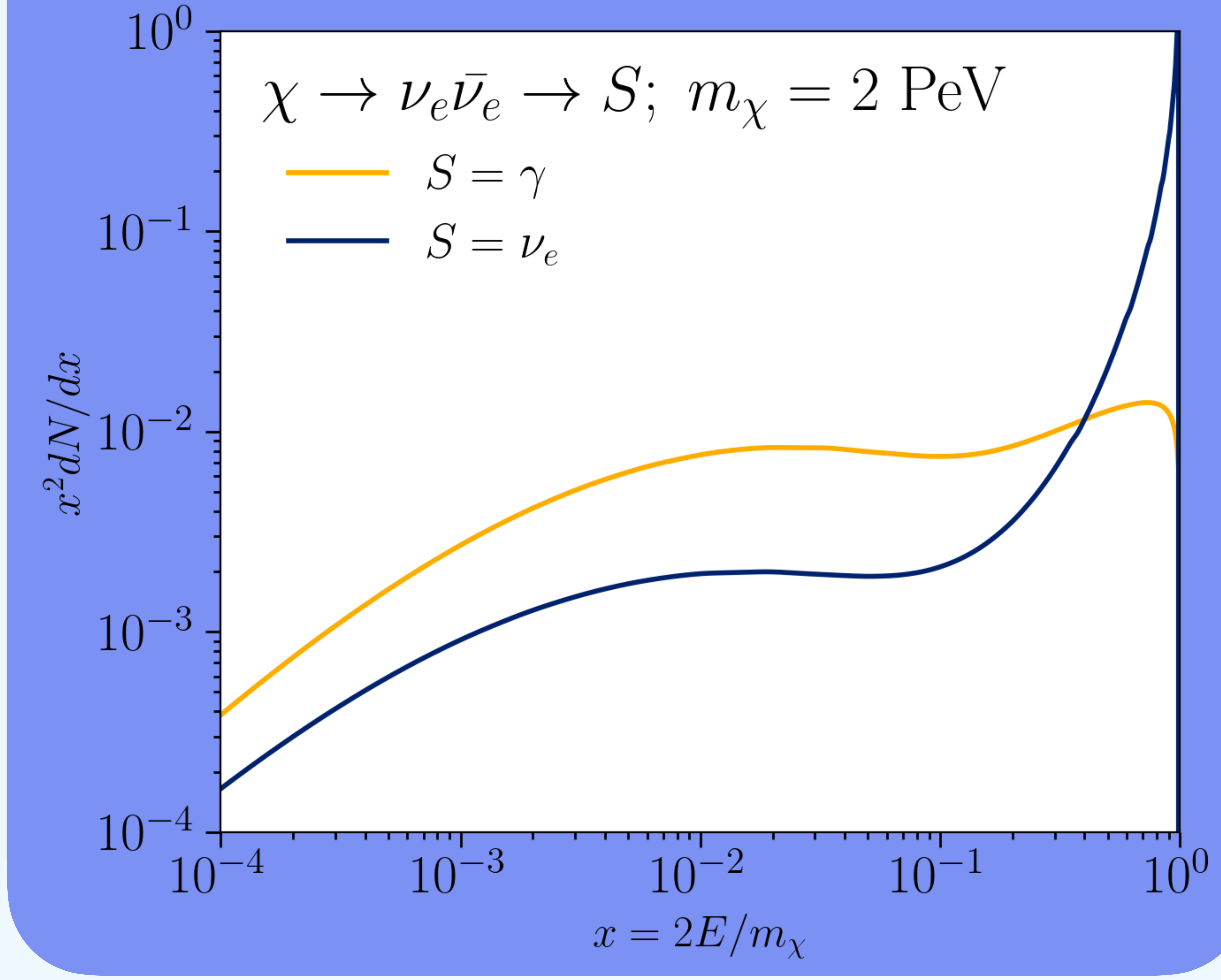
$$\frac{d\Phi_\nu}{dE} = \frac{1}{4\pi}\frac{1}{m_\chi \tau_\chi}\frac{dN_\nu}{dE_\nu}D(\Omega, x)$$

**** ABOVE ELECTROWEAK SCALE**



NEUTRINO PRODUCTION SPECTRUM FOR DIRECT DECAY OF DM TO NEUTRINOS

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

**** MORE COMPLICATED WITH ELECTROWEAK CORRECTIONS**

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** MORE COMPLICATED WITH ELECTROWEAK CORRECTIONS

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

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

DM DECAY LIFETIME

NEUTRINO PRODUCTION SPECTRUM FOR DIRECT DECAY OF DM TO NEUTRINOS

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

Decay

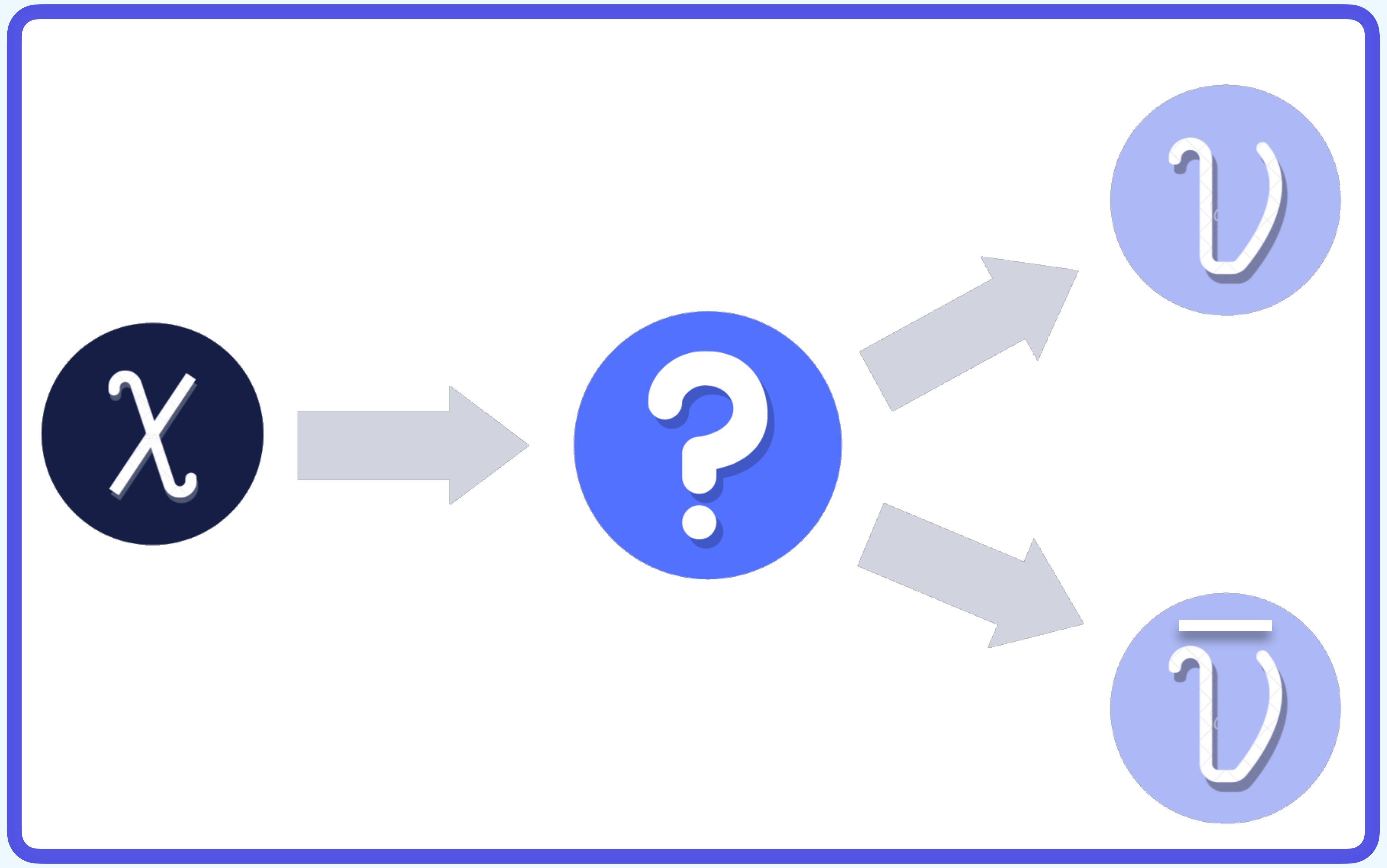
Extragalactic contribution*

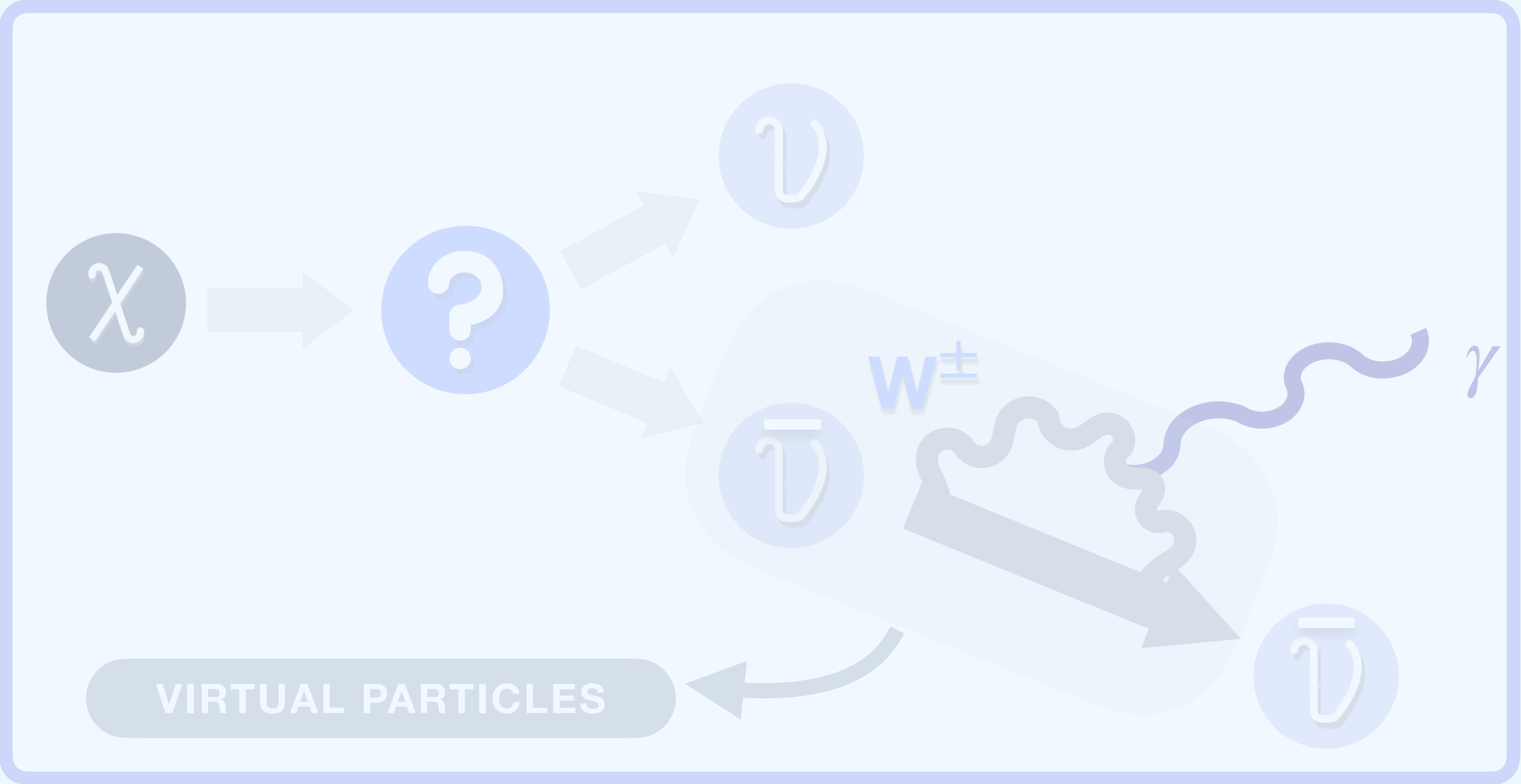
Extragalactic contribution also plays an important role!

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

* SEE UPCOMING PAPER FOR A MORE DETAILED REVIEW.

Dark Matter Decay to neutrinos



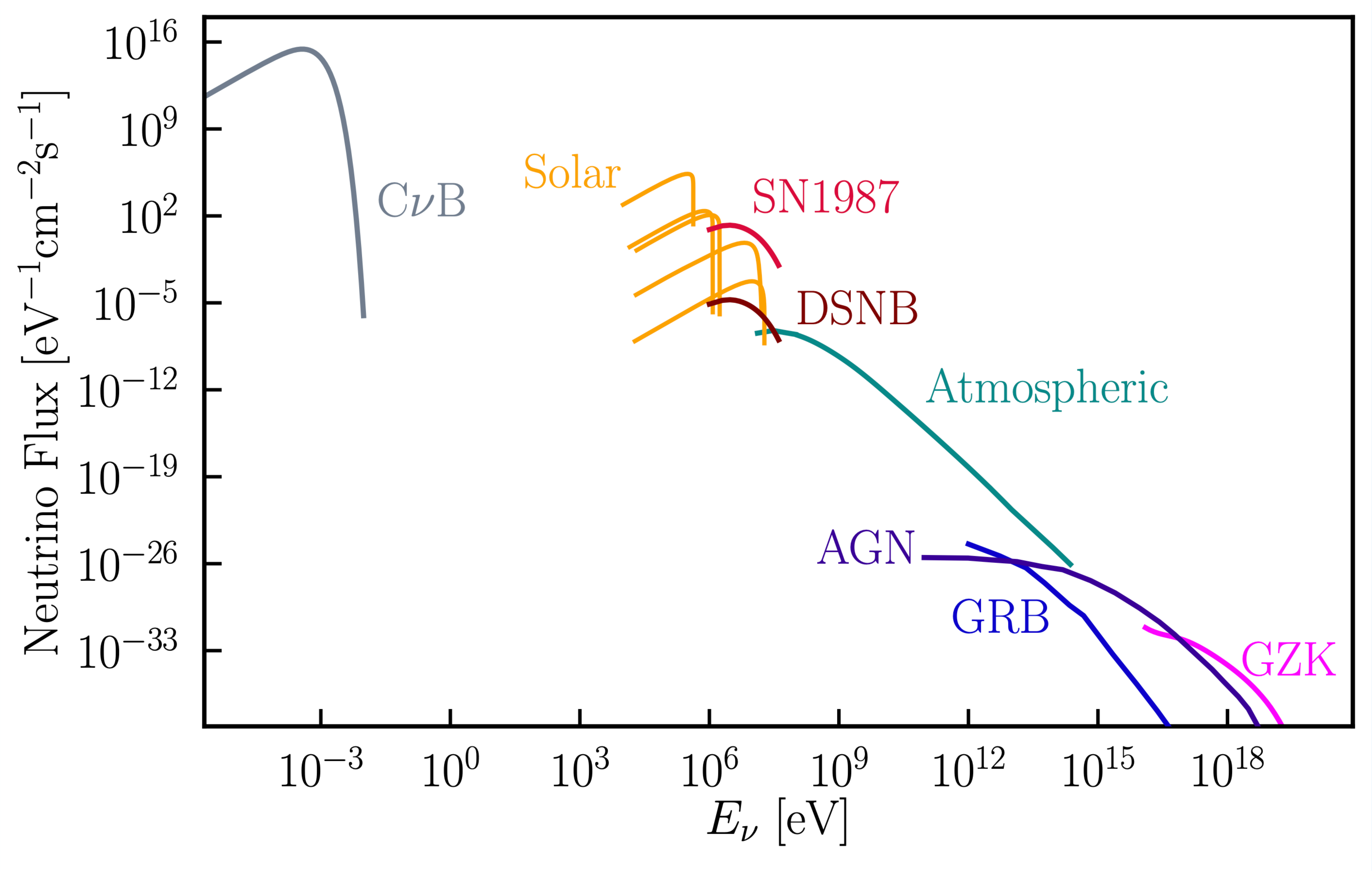


NEUTRINO SIGNAL

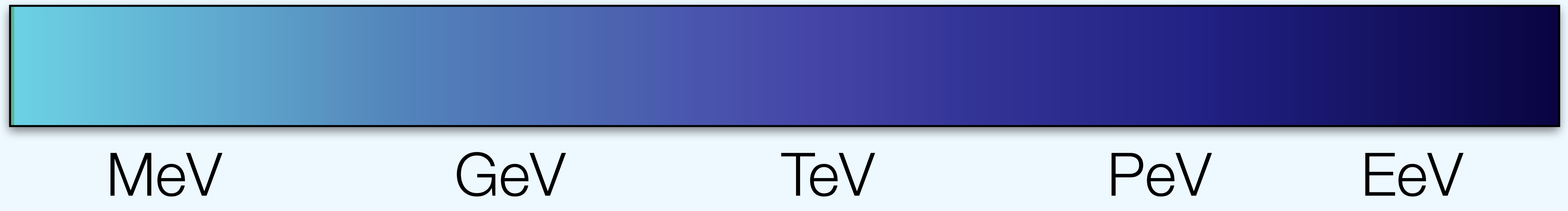
GAMMA-RAY SIGNAL

First we must detect neutrinos

Measured and expected fluxes of natural and reactor neutrinos



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)

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

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

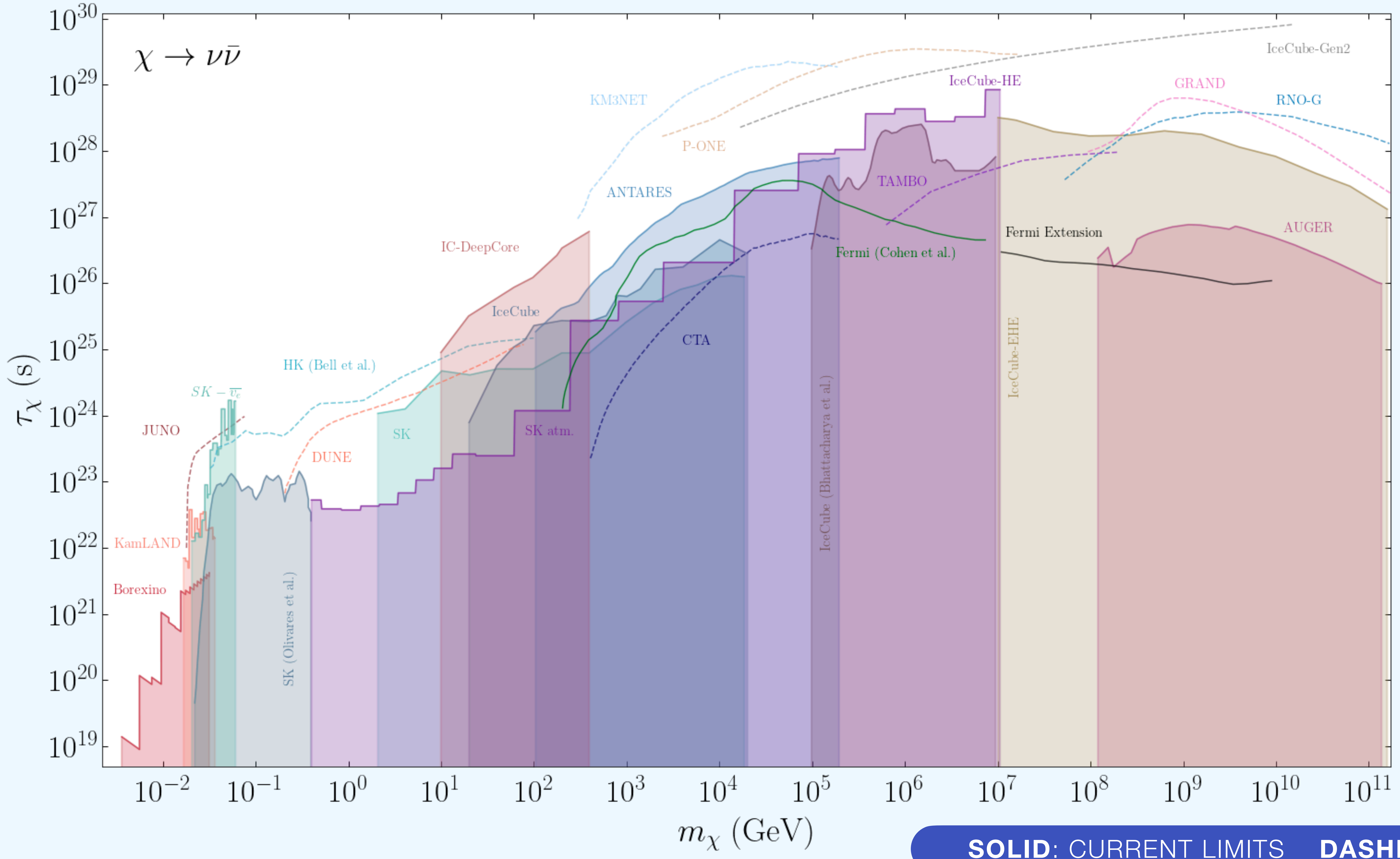
TAMBO
Water Cherenkov.
Astrophysical Tau Neutrino (PeV)

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

GRAND
Radio Array. Tau Neutrinos (EeV)

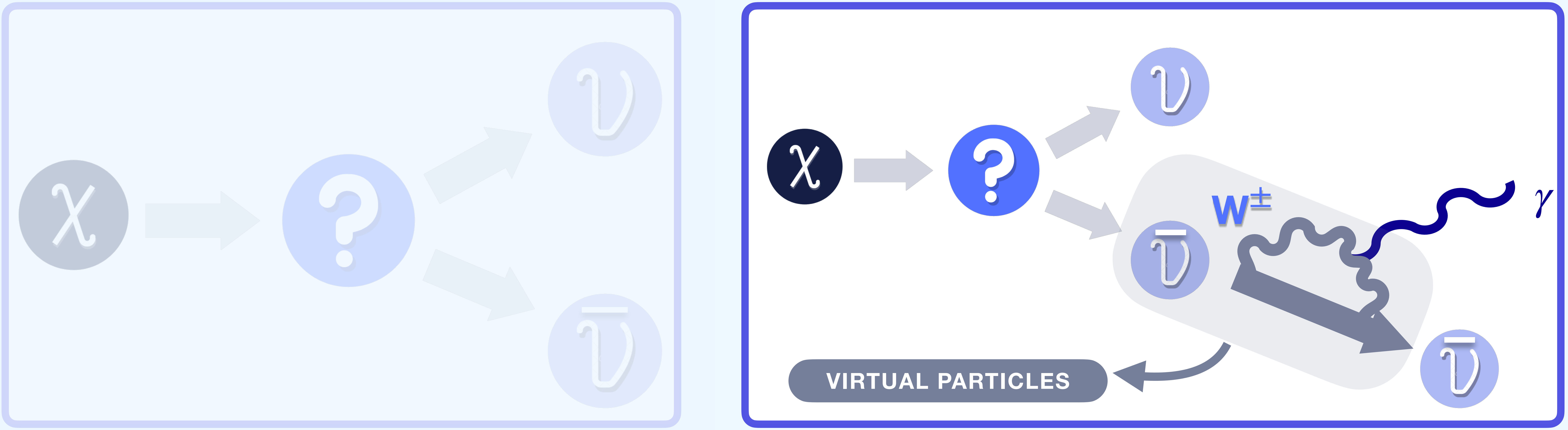
Decay results
Neutrino Experiments

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



SOLID: CURRENT LIMITS **DASHED**: SENSITIVITIES

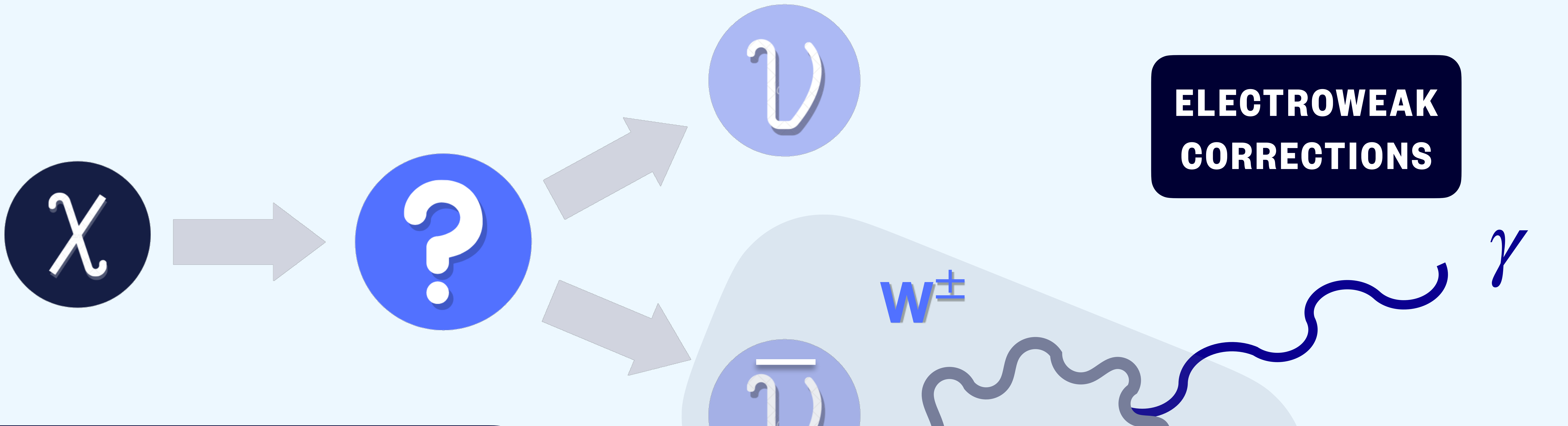
Dark Matter Decay to neutrinos



NEUTRINO SIGNAL

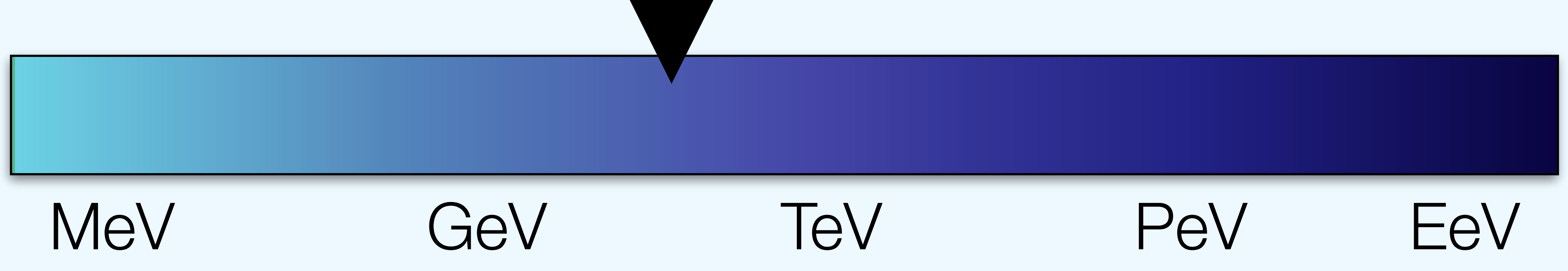
GAMMA-RAY SIGNAL

Dark Matter Search detecting gammas



BECOMES RELEVANT BEYOND ELECTROWEAK SCALE

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



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

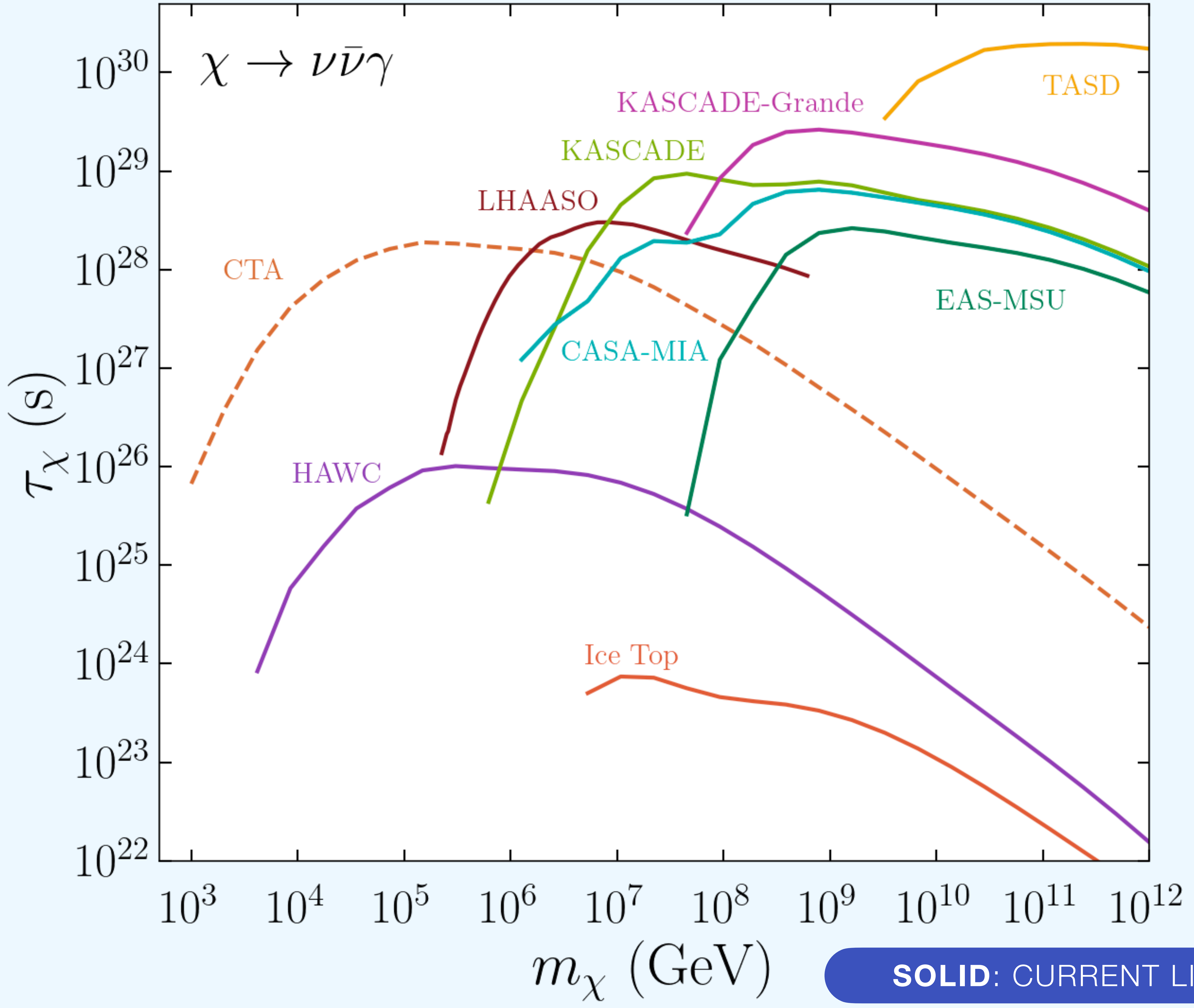
Air Showers. Gamma Rays and Cosmic Rays (PeV)

AND OTHER EXPERIMENTS

Decay Results

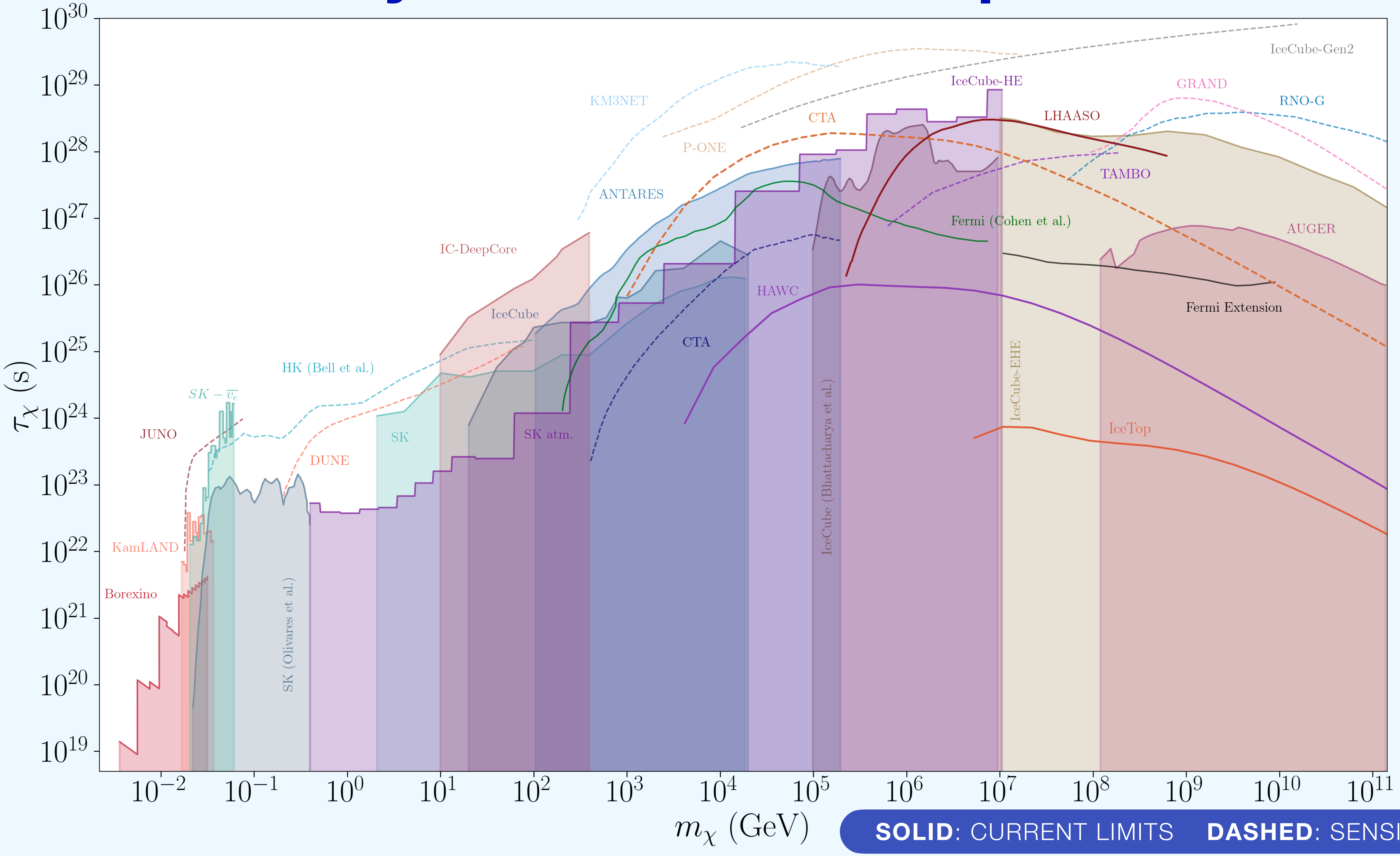
Gamma-Ray Experiments

C. Argüelles, **D. Delgado**, 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!

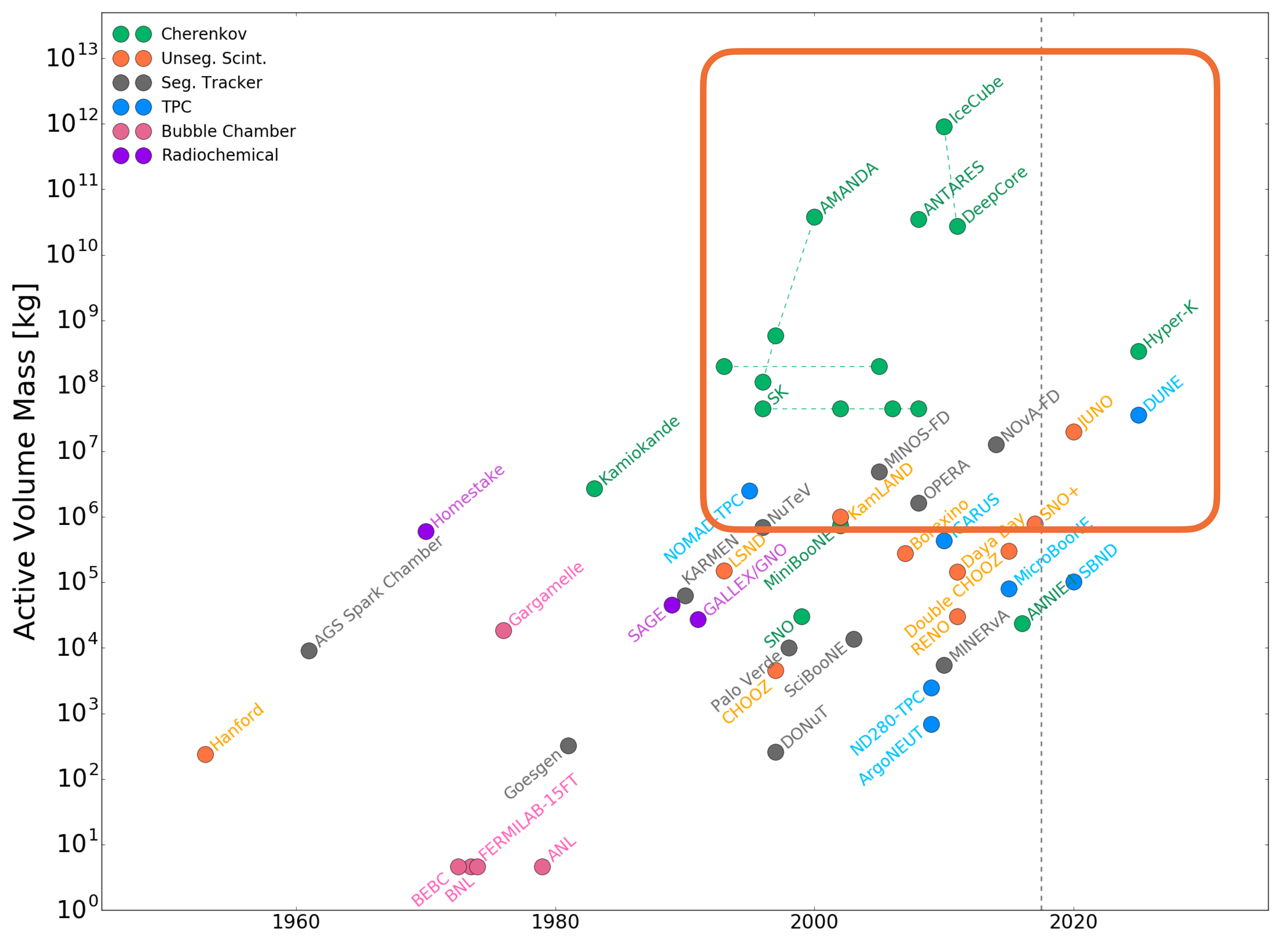
THANK YOU!

ANY QUESTIONS?

ddelgado@g.harvard.edu

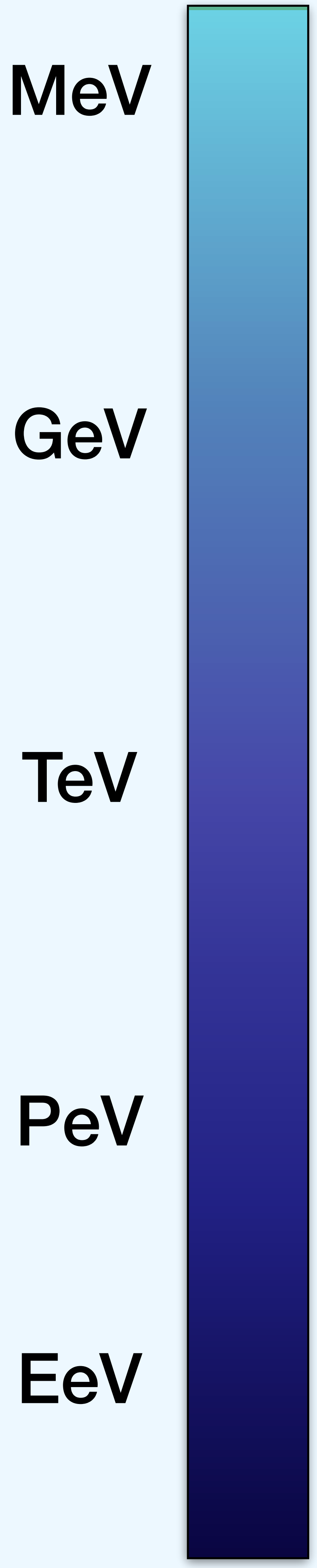
Backup

First we must detect neutrinos



ARGÜELLES ET AL., IOP 23, ARXIV:1907.08311

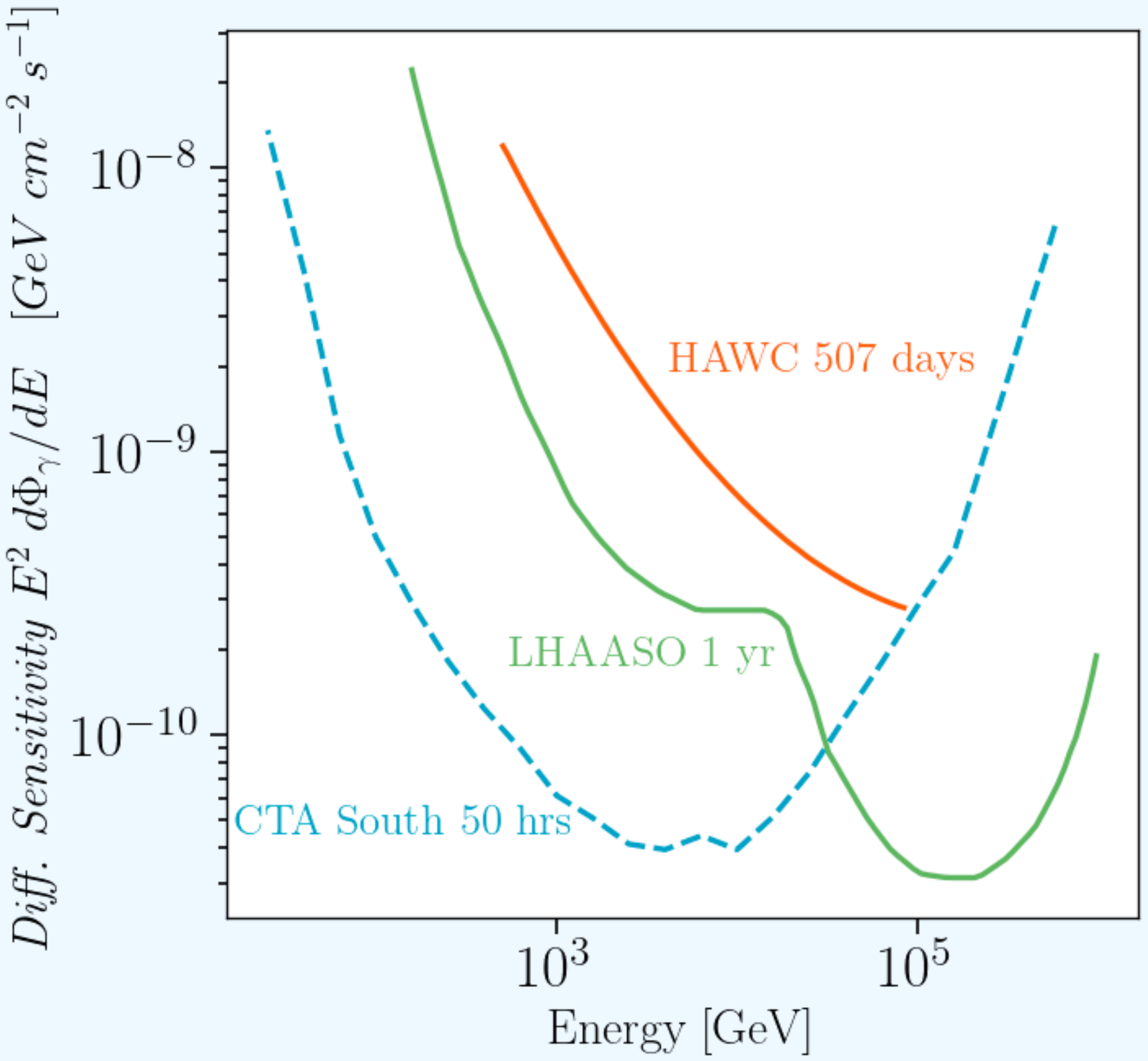
Detecting neutrinos



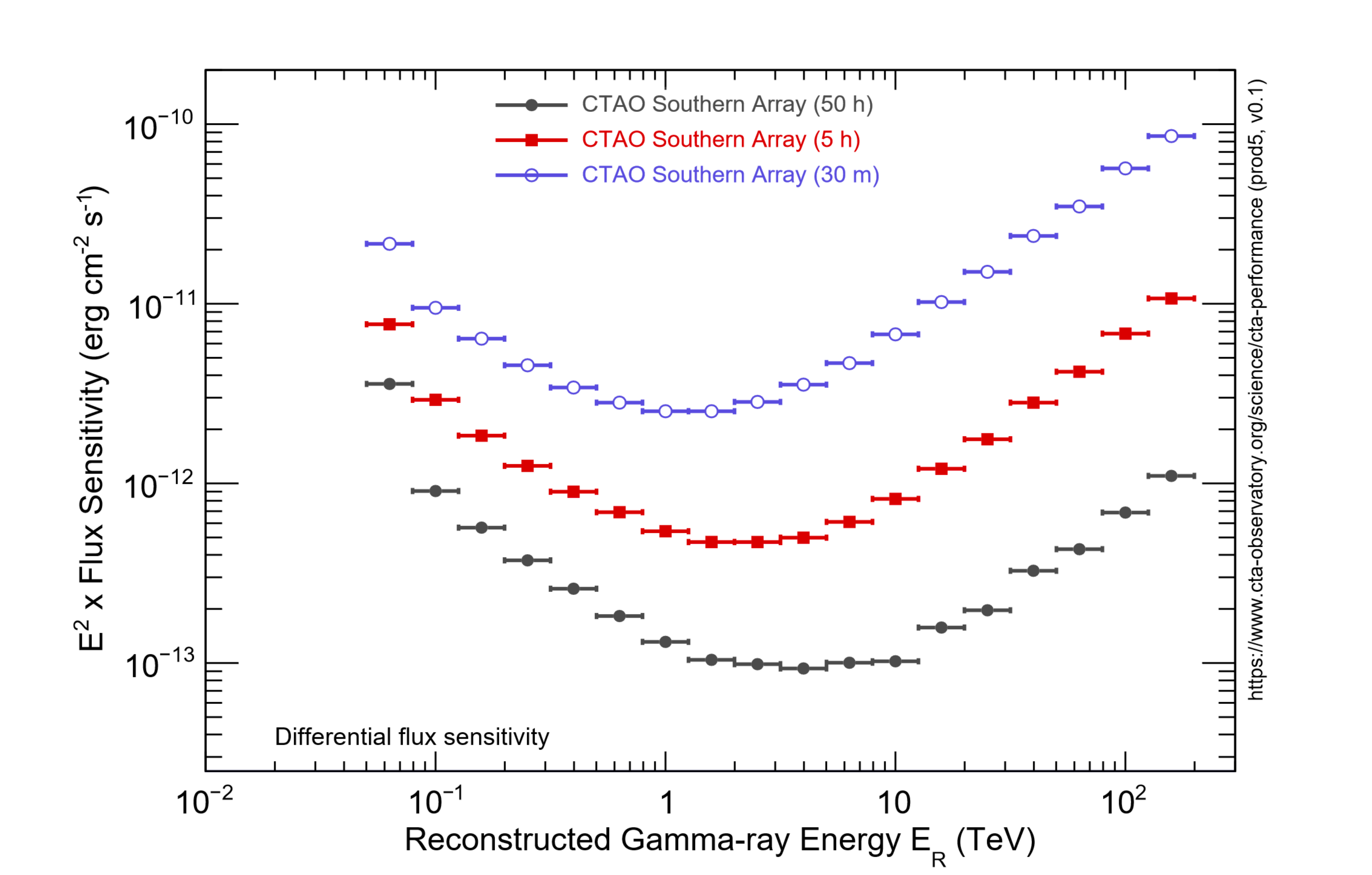
Energy Range	Experimental Analysis	Directionality	Detected Flavor
2.5 – 15 MeV	Borexino (Bellini *et al.*, 2011)	×	$\bar{\nu}_e$ (IBD)
8.3 – 18.3 MeV	KamLAND (Gando *et al.*, 2012)	✓	$\bar{\nu}_e$ (IBD)
10 – 40 MeV	JUNO (An *et al.*, 2016)	✓	$\bar{\nu}_e$ (IBD)
$15 - 10^3$ MeV	SK (Olivares-Del Campo *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

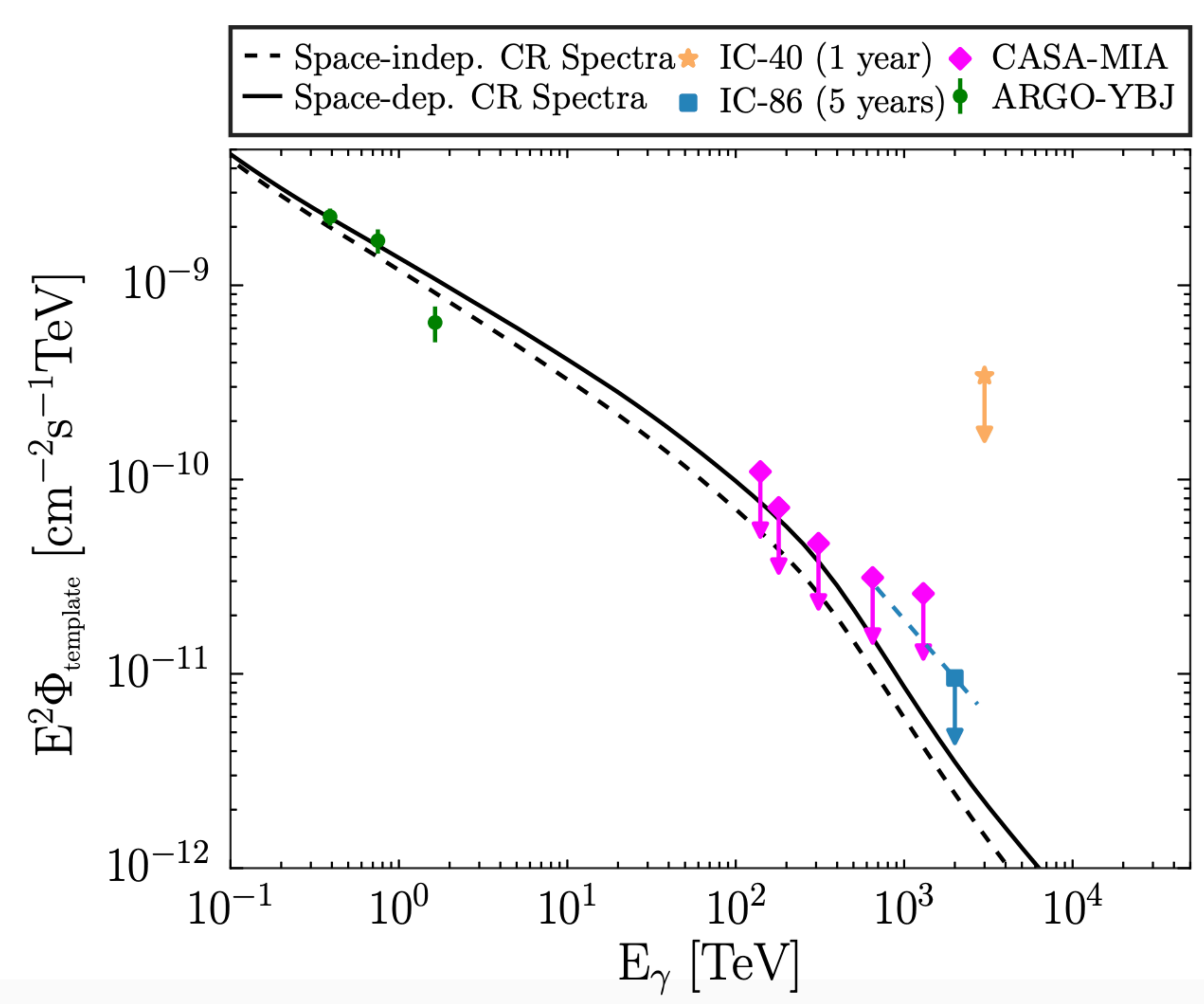
Gamma-Ray Experimental Sensitivities



Gamma-Ray Experimental Sensitivities

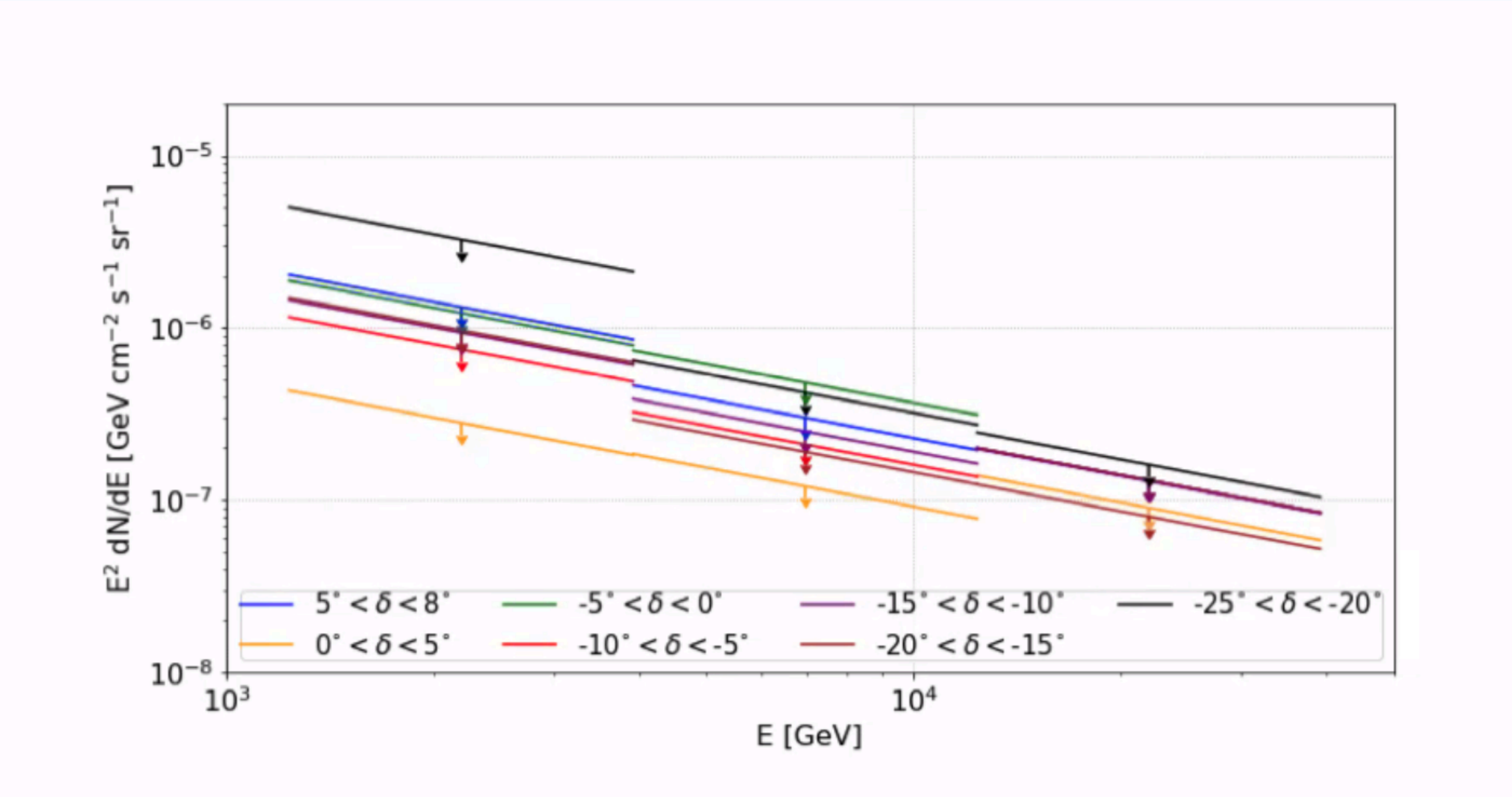


CTA



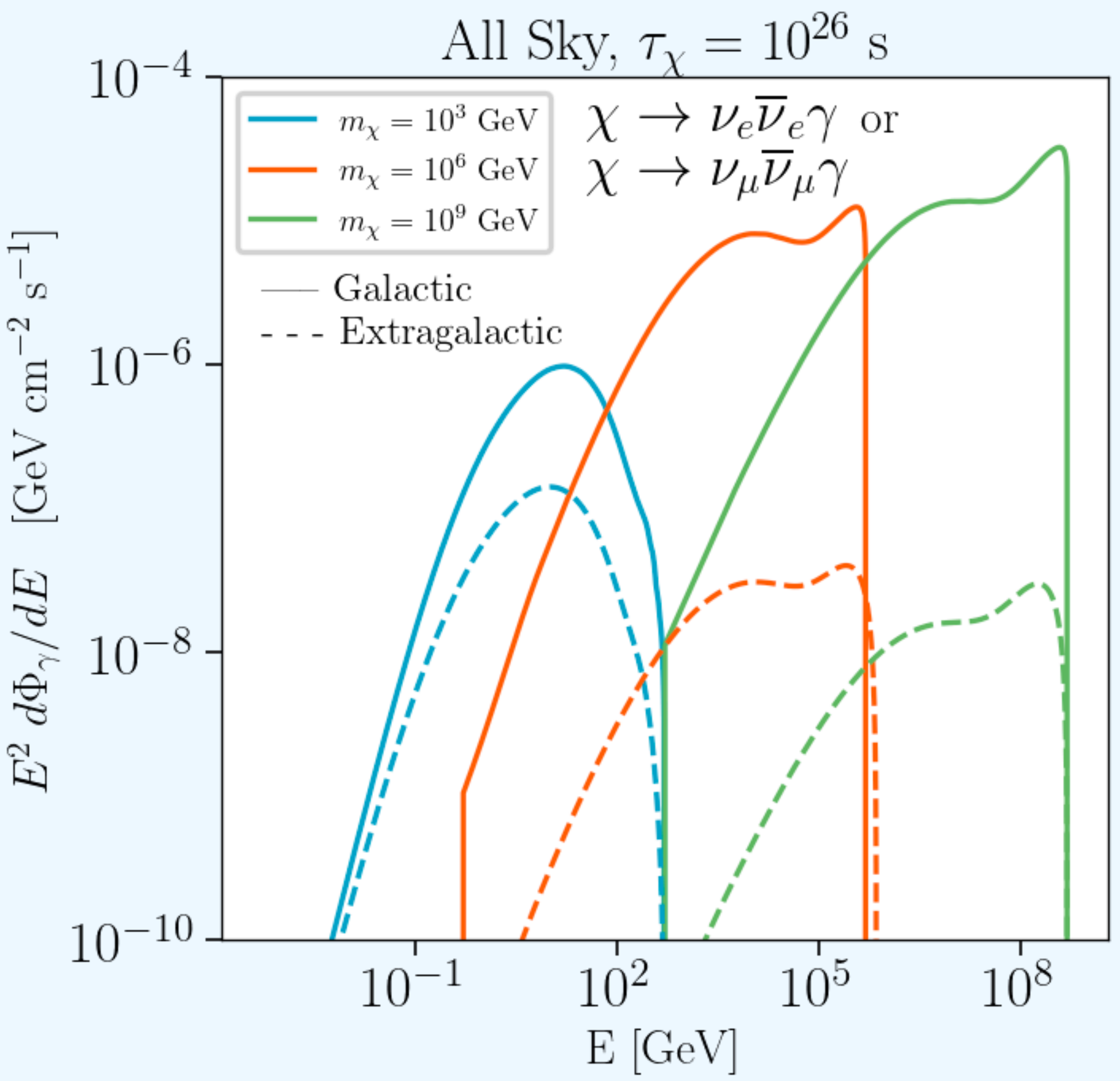
Ice Top

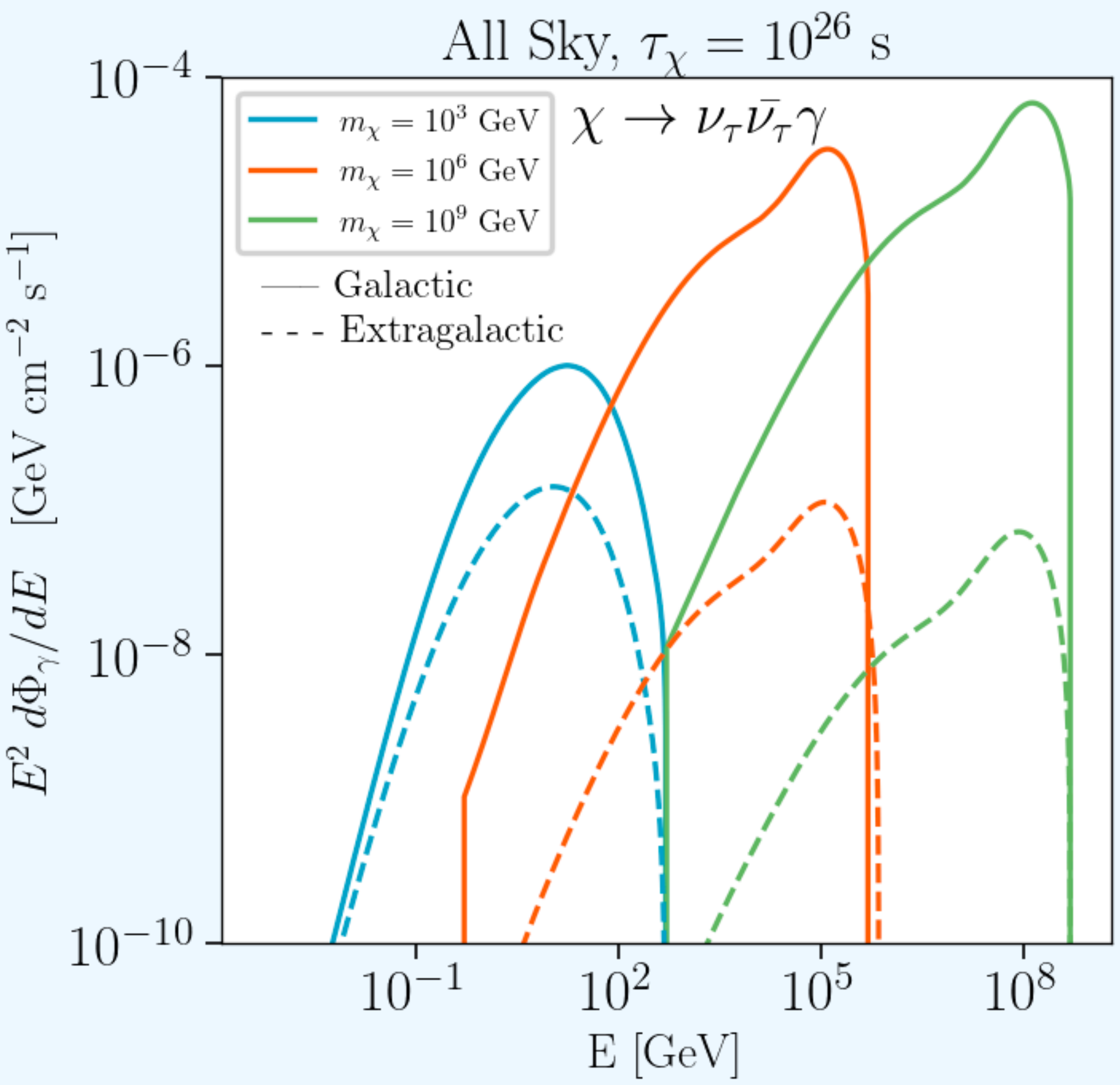
Gamma-Ray Experimental Sensitivities



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

An isotropic neutrino signal is also expected due to annihilation of dark matter in every other galactic halo in the universe,

$$\frac{d\Phi_\nu}{dE} = \frac{c}{4\pi}\frac{\Omega_{DM}^2\rho_{crit}^2\langle\sigma v\rangle}{2m_x^2}\int_0^{z_{up}} dz \frac{(1+G(z))(1+z)^3}{H(z)}\frac{dN_\nu(E')}{dE},$$

Time-dependent Hubble parameter

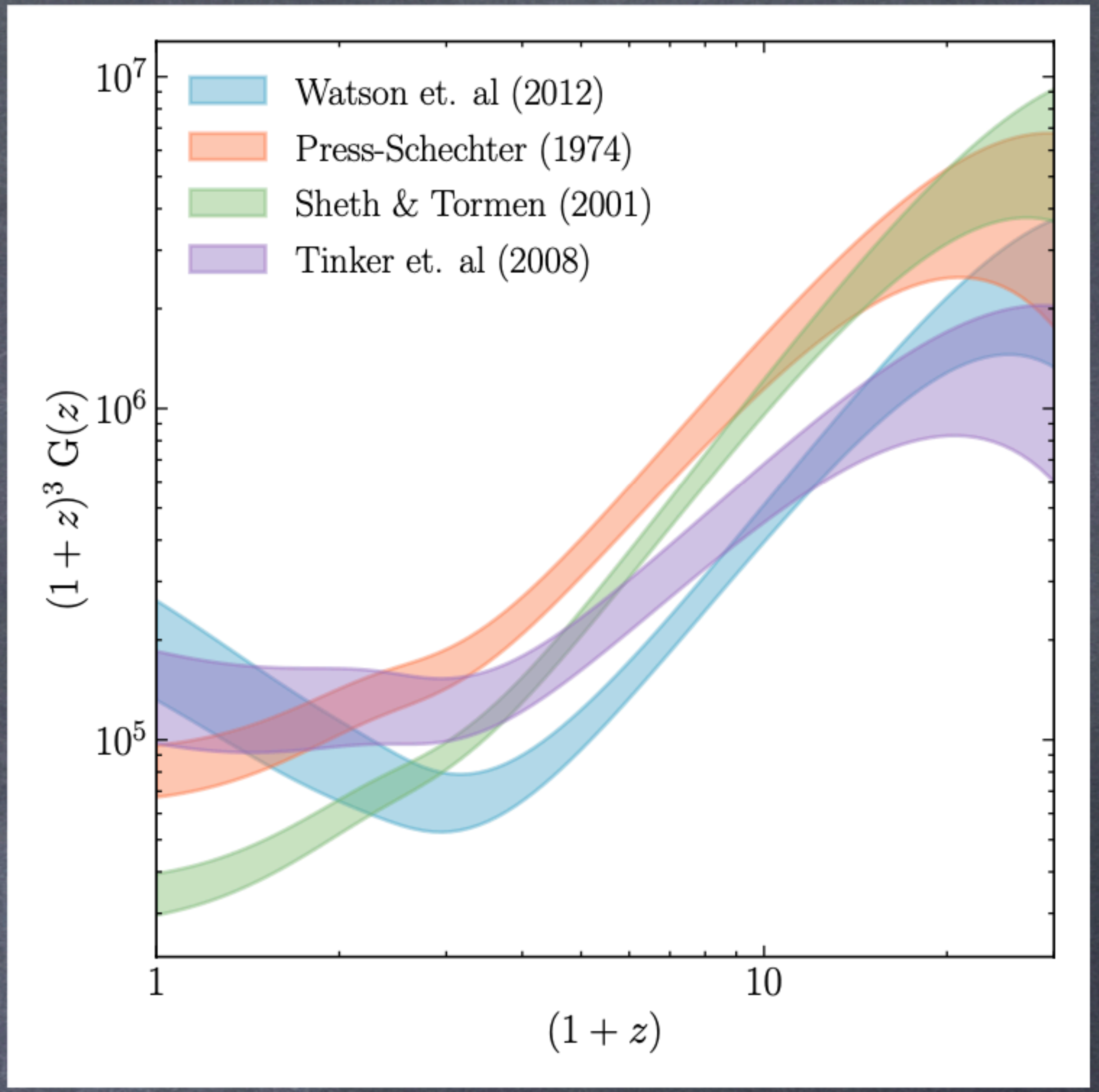
$$H(z) = H_0\left[(1+z)^3\Omega_{DM} + \Omega_\Lambda\right]^{1/2}$$

Production spectrum

$$\frac{2}{3E}\delta\left[z - \left(\frac{m_\chi}{E} - 1\right)\right]$$

Halo boost

$$G(z) = \frac{1}{\Omega_{DM,0}^2\rho_c^2}\frac{1}{(1+z)^6}\int dM \frac{dn(M,z)}{dM}\int dr\, 4\pi r^2\, \rho_{\text{halo}}^2(r)\,.$$

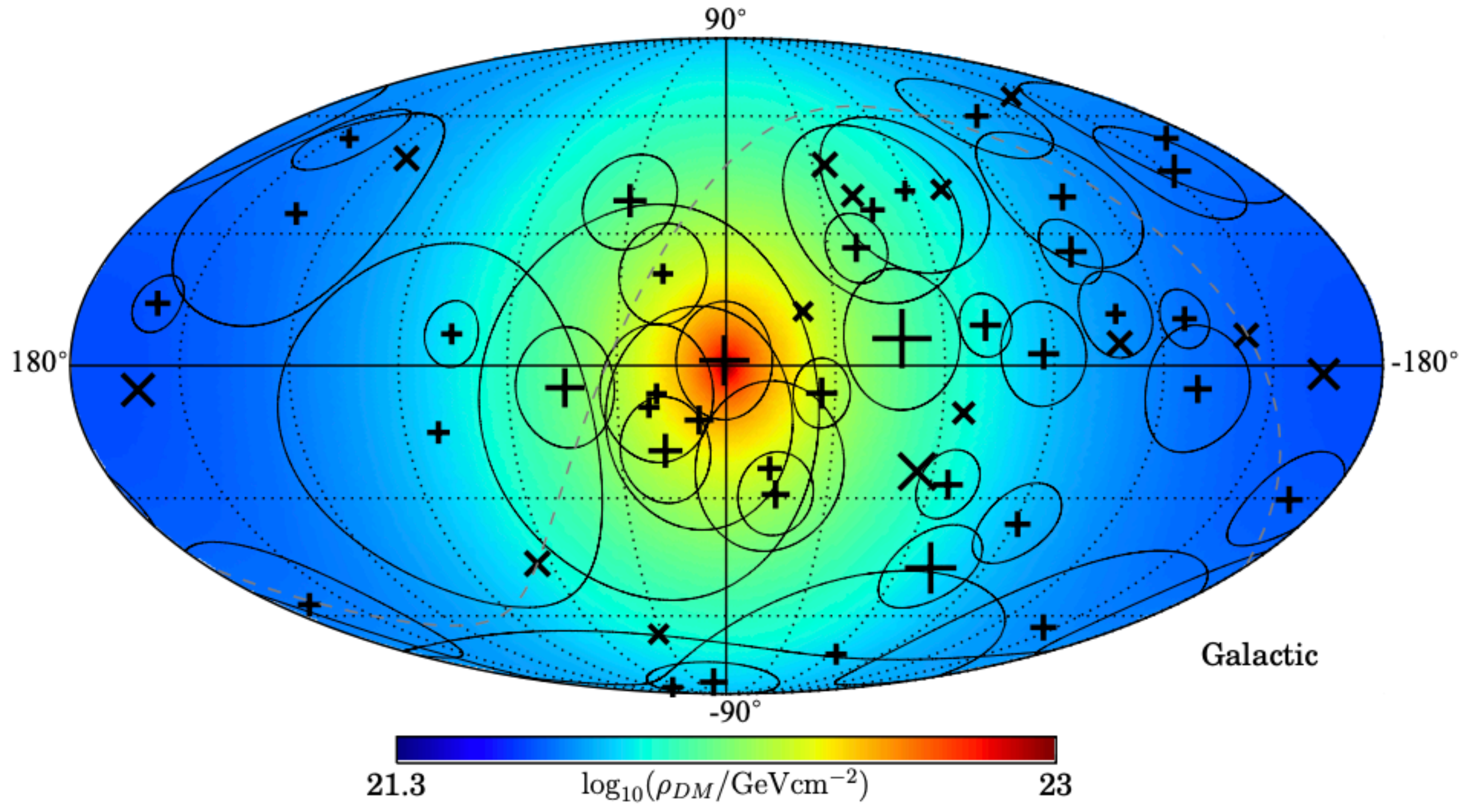


The band shows the uncertainty from the choice of minimum halo mass from 10^{-9} to 10^{-3} M_{sun}

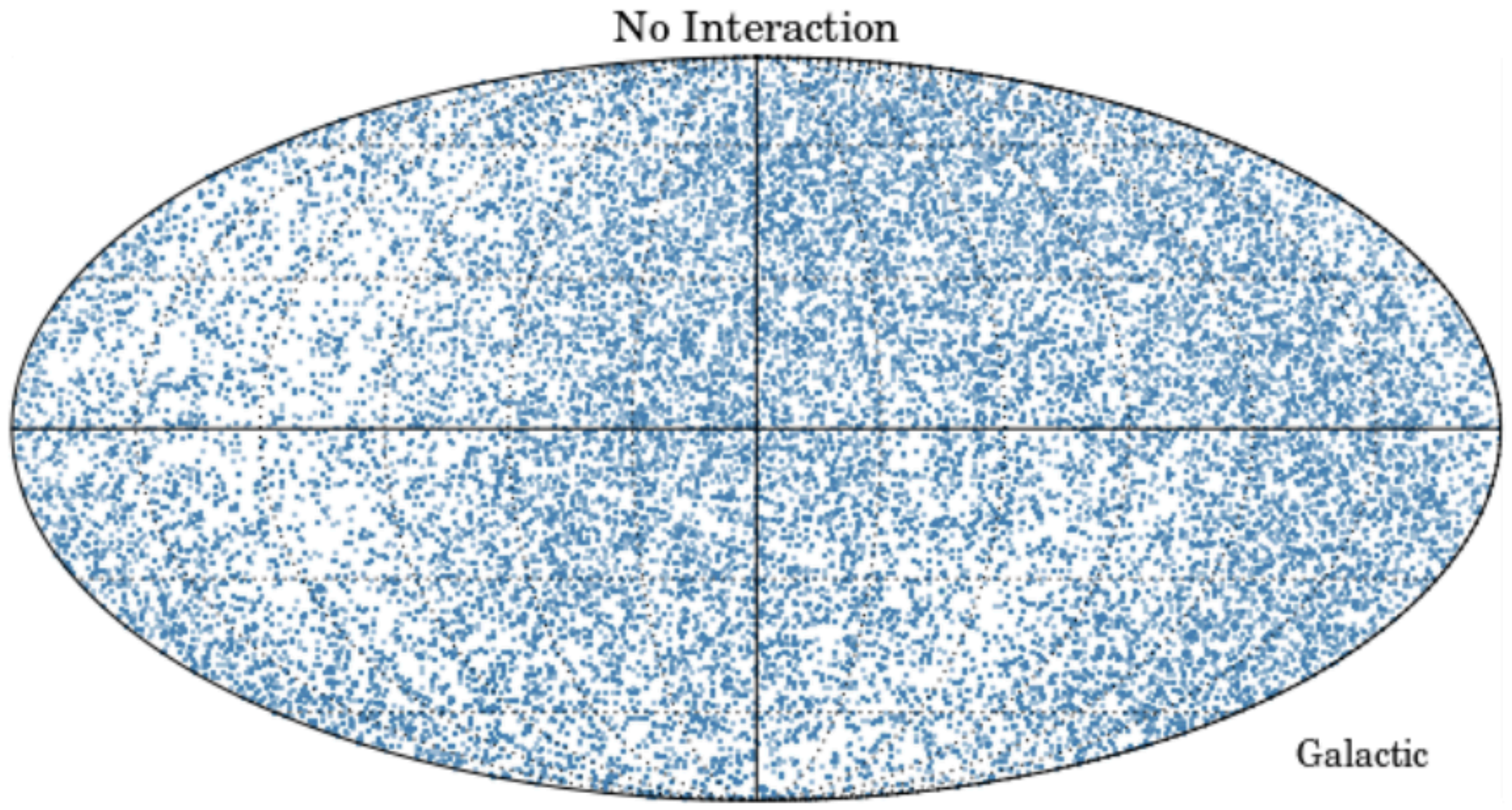
Limits shown in this work use Watson et. al and a conservative choice of minimum mass ($M_{min} = 10^{-3}$ M_{sun}).

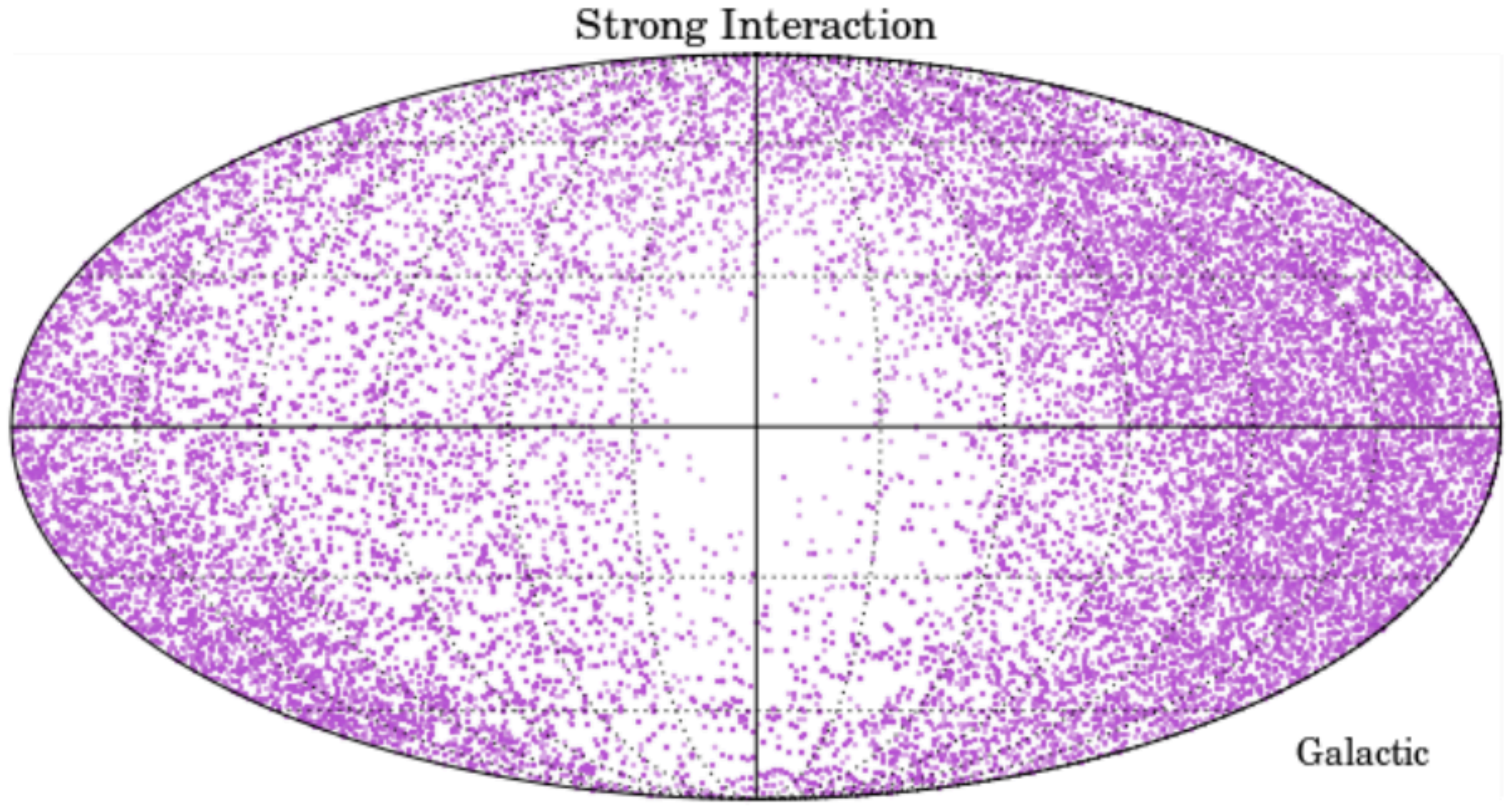
CREDIT: I. SAFA

Dark matter column density seen from Earth

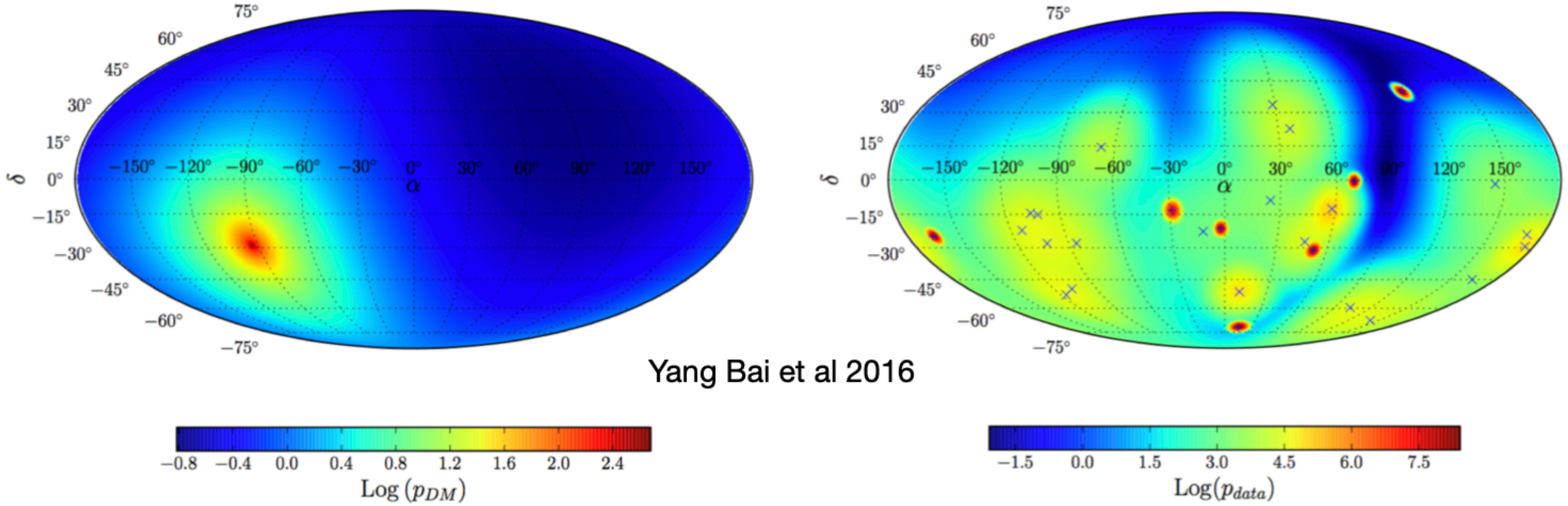


Simulation including effects of detector, Earth





Decay



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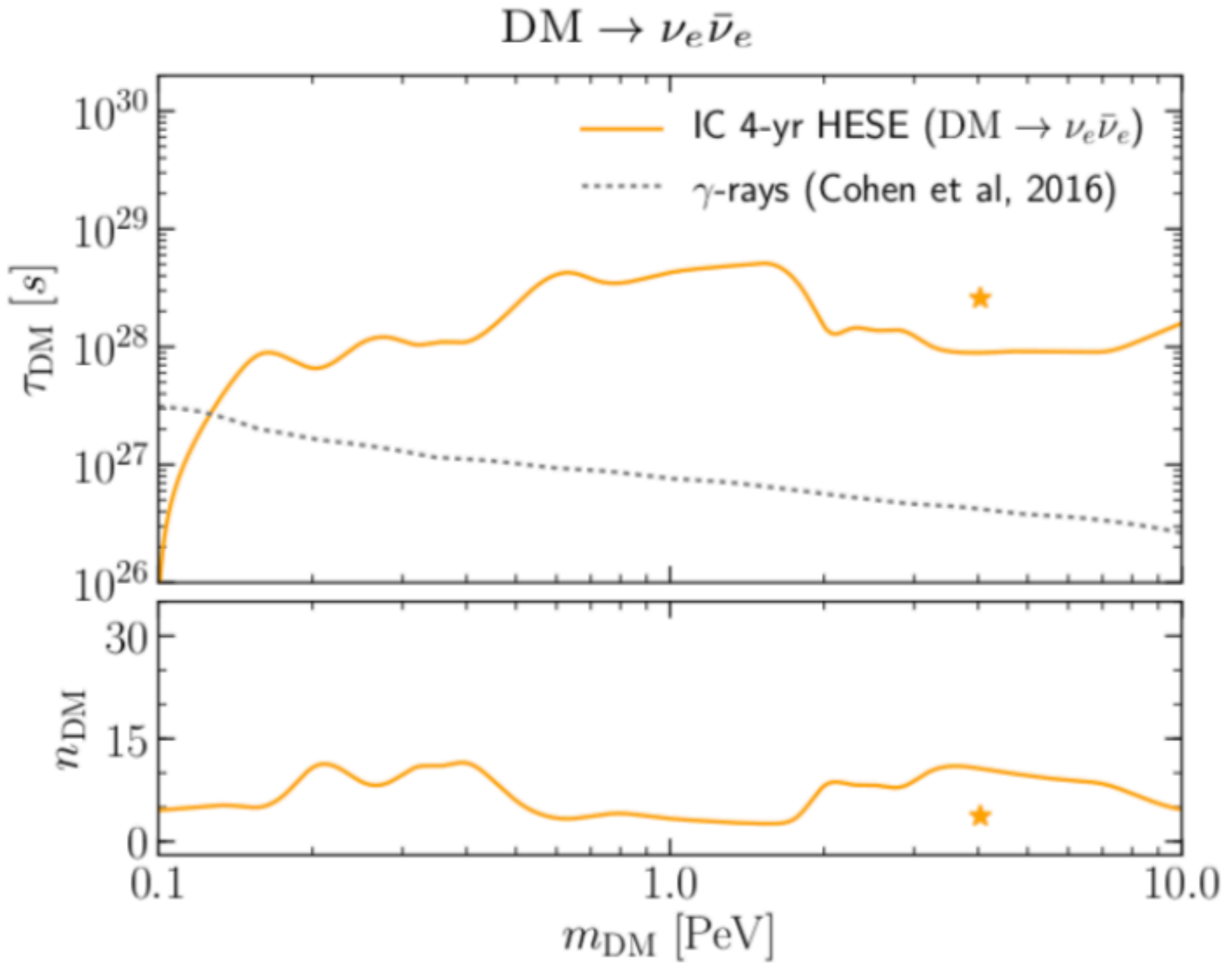

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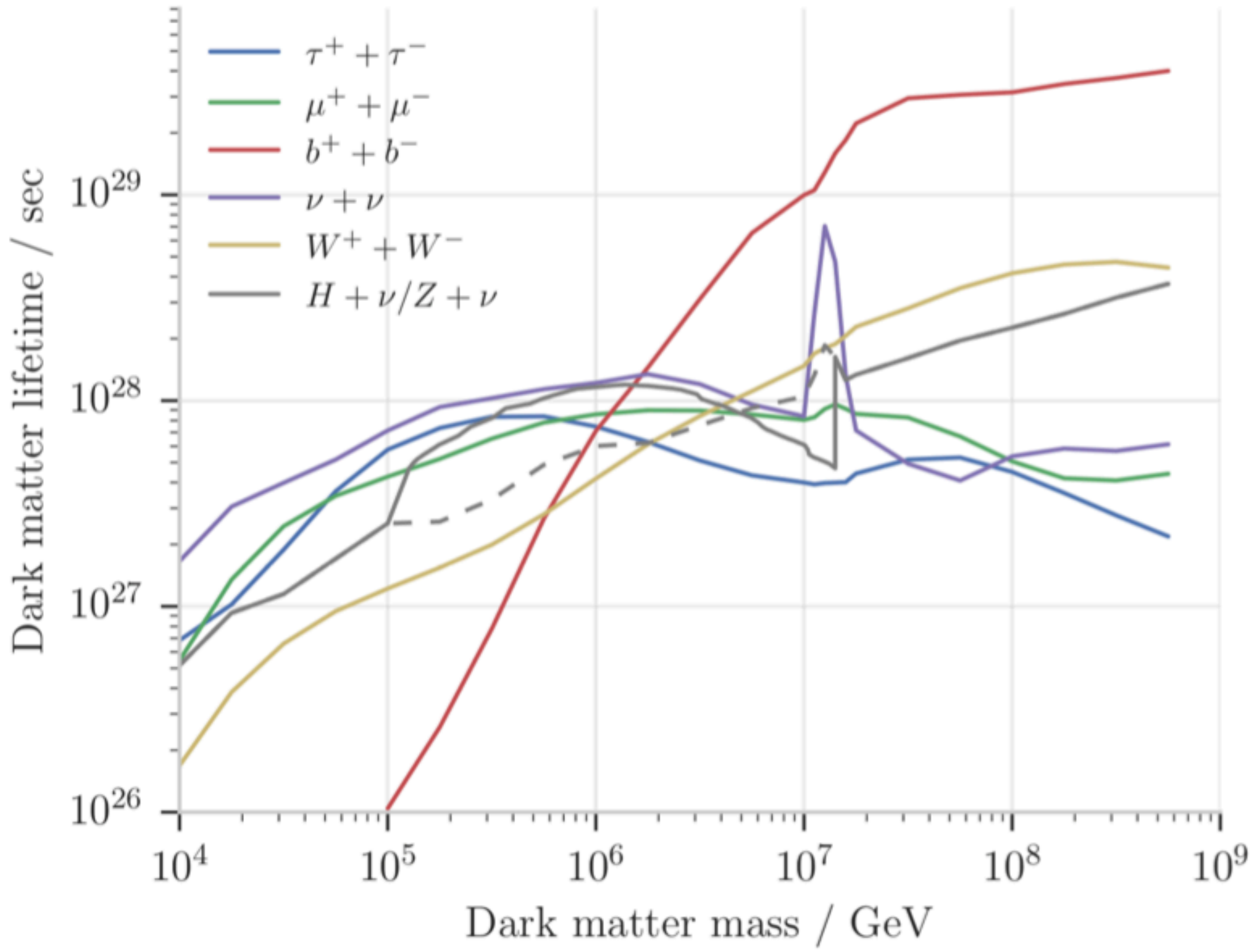

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