Indirect Dark Matter Search with Gamma-Ray Telescopes

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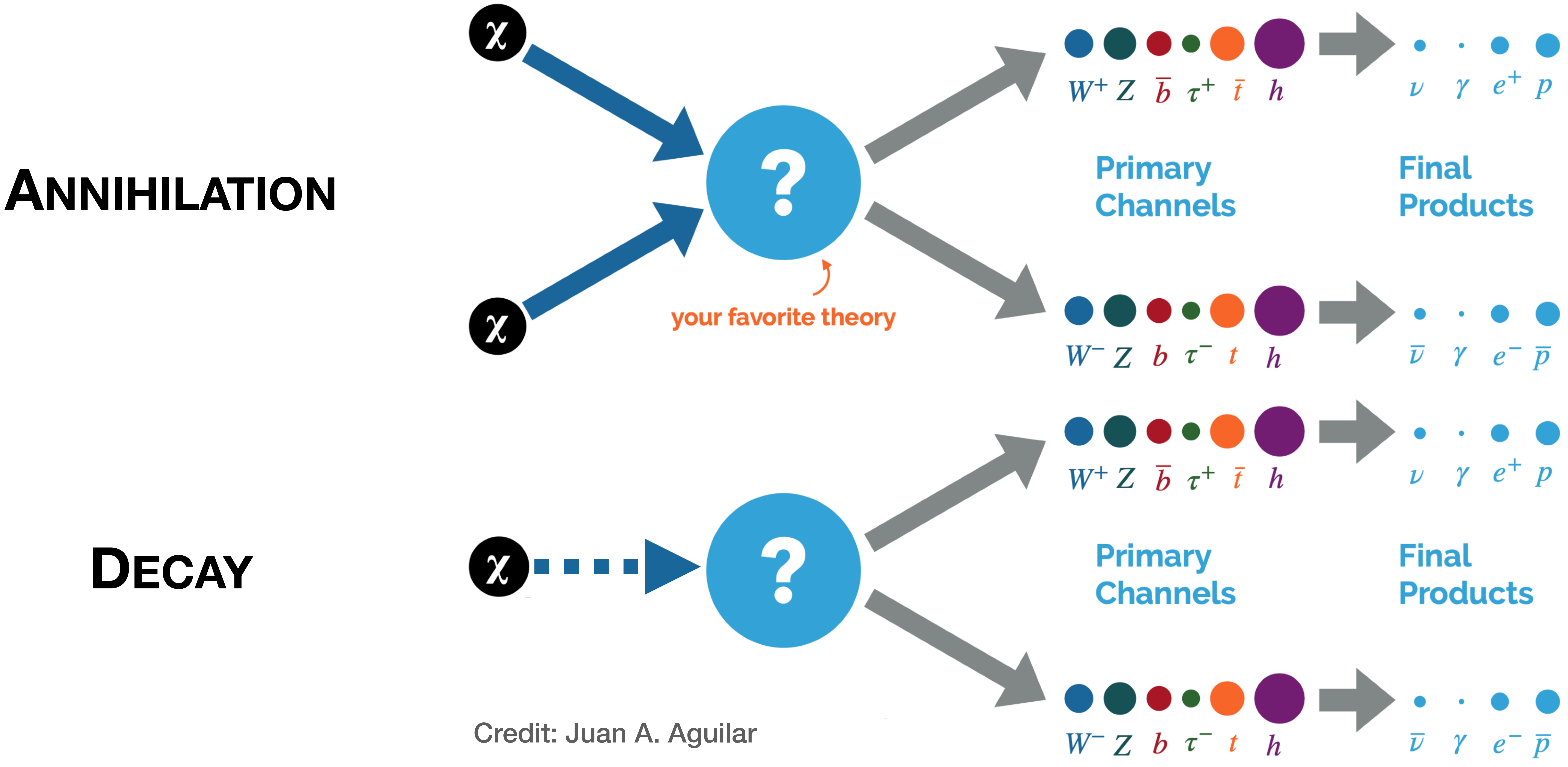
Dark Matter Day @ IJCLab — May 2026

Indirect detection of DM with γ-rays

γ-ray flux is expected from DM annihilation/decay

in a massive astronomical object



Credit: Juan A. Aguilar

Indirect detection of DM with γ-rays

Gamma-ray flux from WIMP DM annihilation and decay

ANNIHILATION

$$\frac{d\Phi_\gamma}{dE_\gamma} = \frac{1}{4\pi}\frac{<\sigma_A v>}{2m_\chi^2}\frac{dN_\gamma}{dE_\gamma}\int_0^{\Delta\Omega} d\Omega \int_{l.o.s.} \rho_\chi^2(r)dr$$

(J-FACTOR)

EXPECTED VS OBSERVED γ-RAY FLUX

PARTICLE PHYSICS

ASTROPHYSICS (DM DISTRIBUTION)

(D-FACTOR)

DECAY

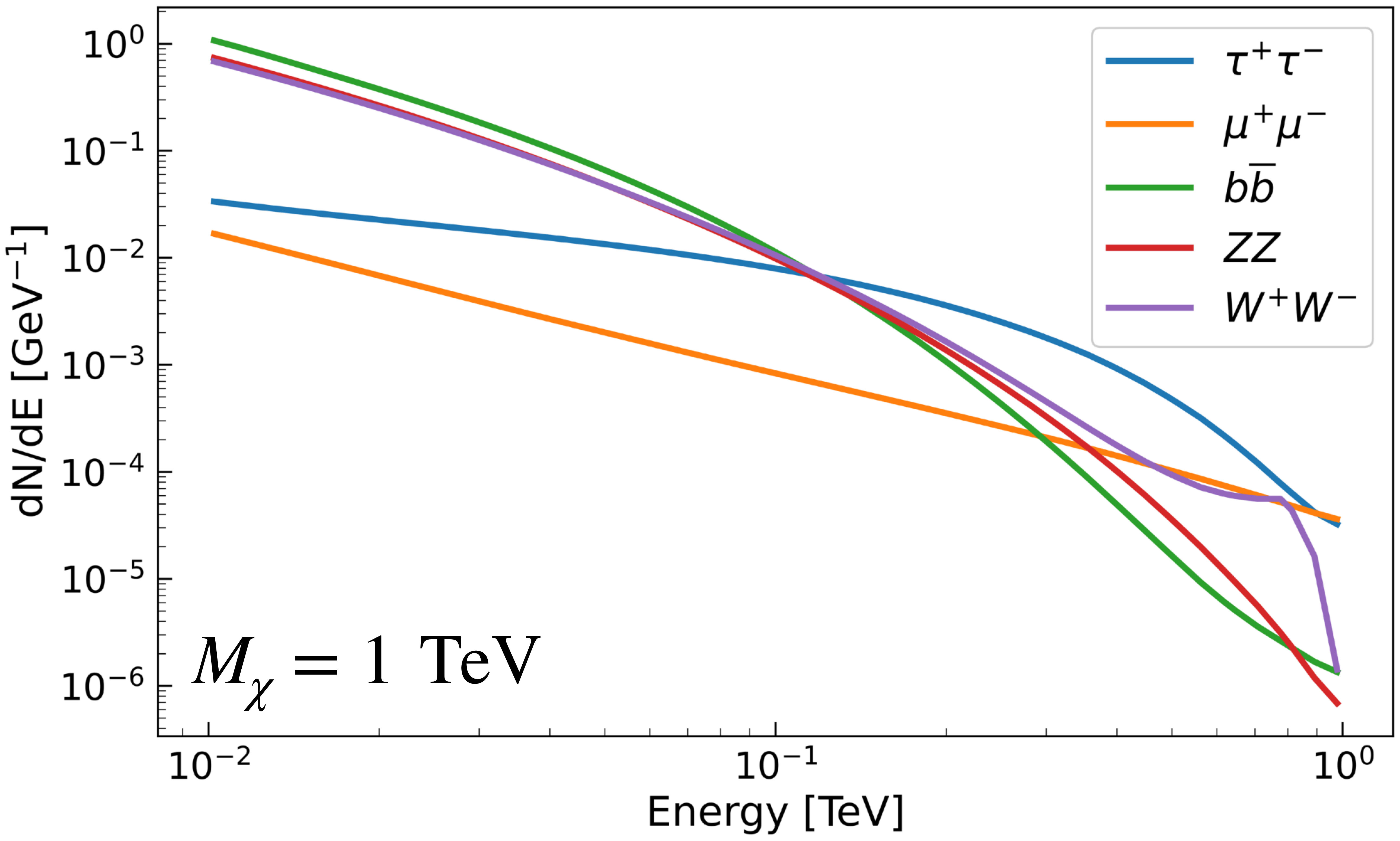
$$\frac{d\Phi_\gamma}{dE_\gamma} = \frac{1}{4\pi}\frac{1}{m_\chi}\frac{1}{\tau_\chi}\frac{dN_\gamma}{dE_\gamma}\int_0^{\Delta\Omega} d\Omega \int_{l.o.s.} \rho_\chi(r)dr$$

Particle physics contribution

$$\frac{d\Phi_\gamma}{dE_\gamma} = \frac{1}{4\pi}\frac{<\sigma_A\nu>}{2m_\chi^2}\frac{dN_\gamma}{dE_\gamma}\int_0^{\Delta\Omega} d\Omega \int_{l.o.s.} \rho_\chi^2(r)dr$$

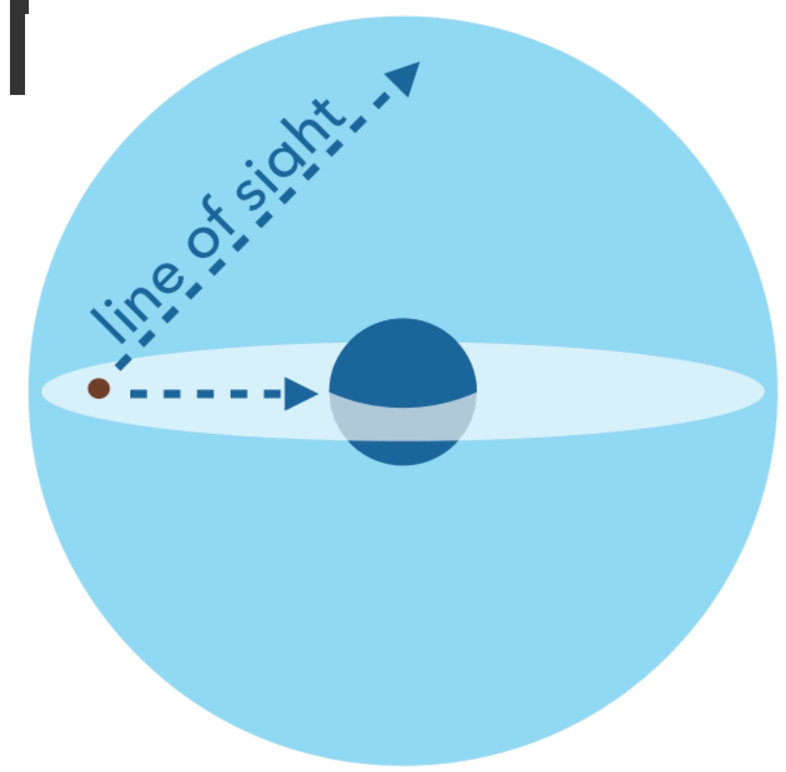
[Cirelli *et al.*, *JCAP* 03(2011)051]

Spectral energy distribution
(spectral features, Sommerfeld enhancement for TeV scale DM, radiative emission for leptonic final states)

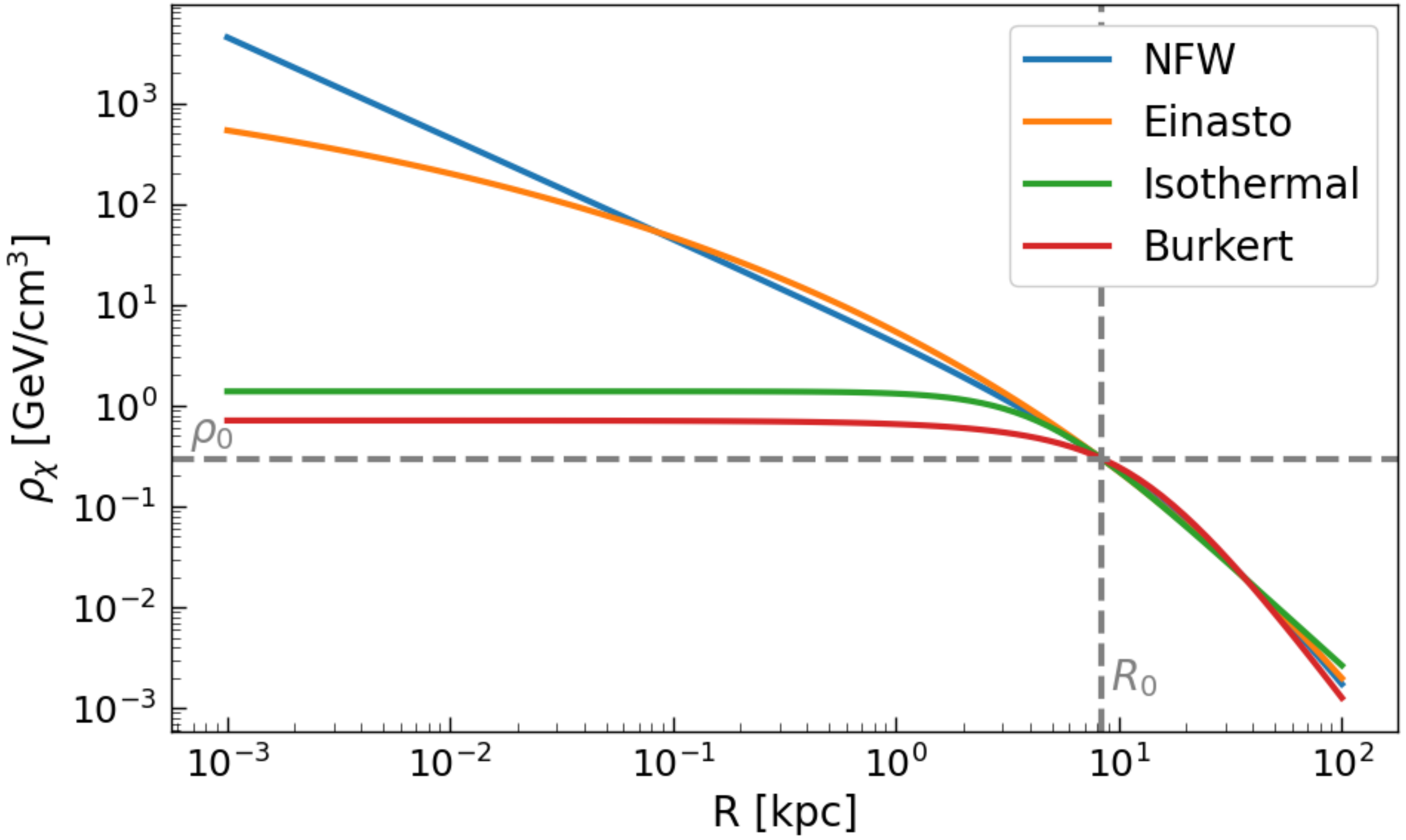


Astrophysics contribution

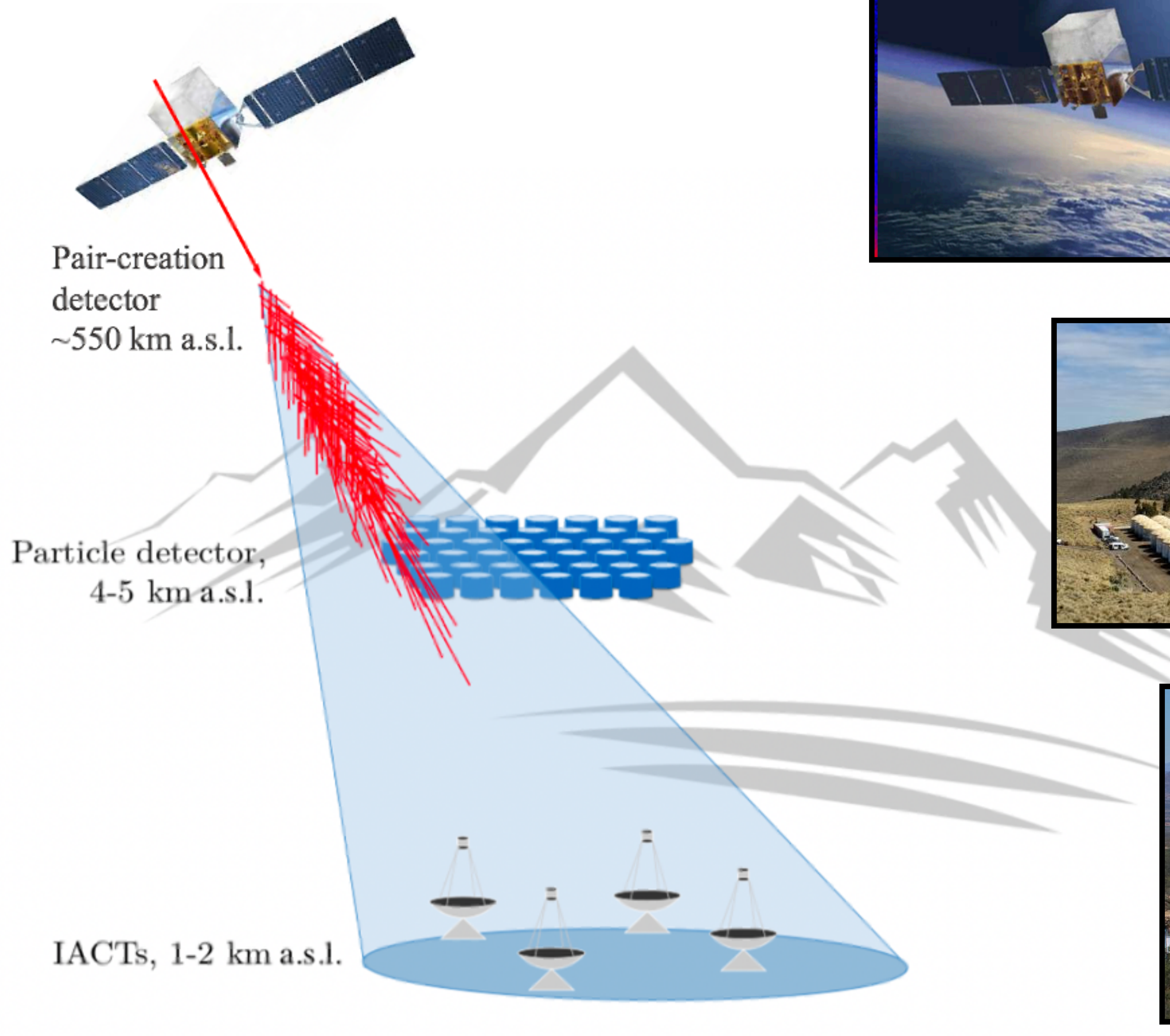
$$\frac{d\Phi_\gamma}{dE_\gamma} = \frac{1}{4\pi}\frac{<\sigma_A v>}{2m_\chi^2}\frac{dN_\gamma}{dE_\gamma}\int_0^{\Delta\Omega} d\Omega \int_{l.o.s.} \rho_\chi^2(r)dr$$



Spatial distribution in astrophysical targets
(asymmetric density profiles, substructures boost factor, local DM density)



Gamma-ray telescopes

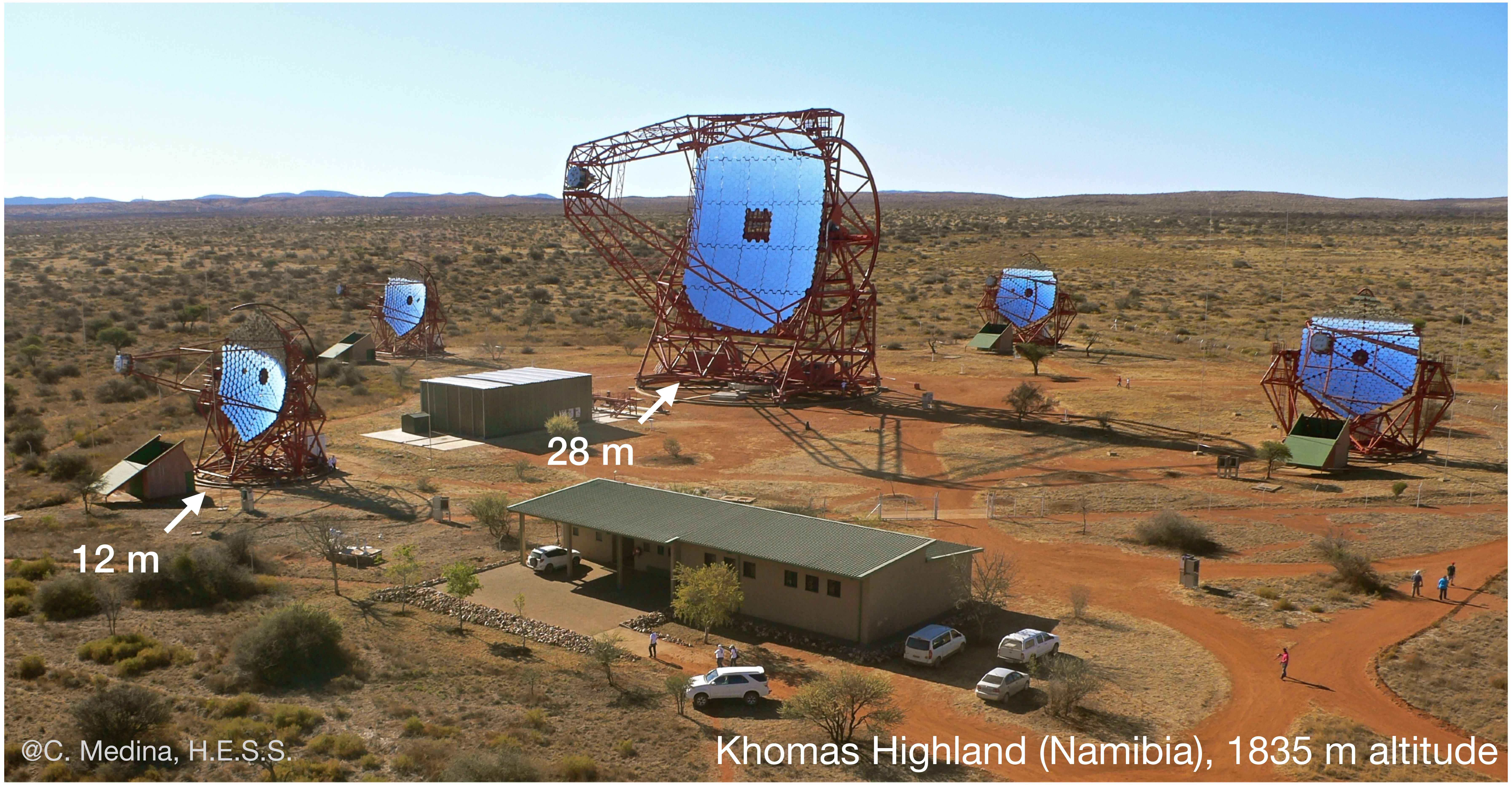


Fermi-LAT

HAWC
LHAASO

VERITAS
H.E.S.S.
MAGIC
LST-1

H.E.S.S.

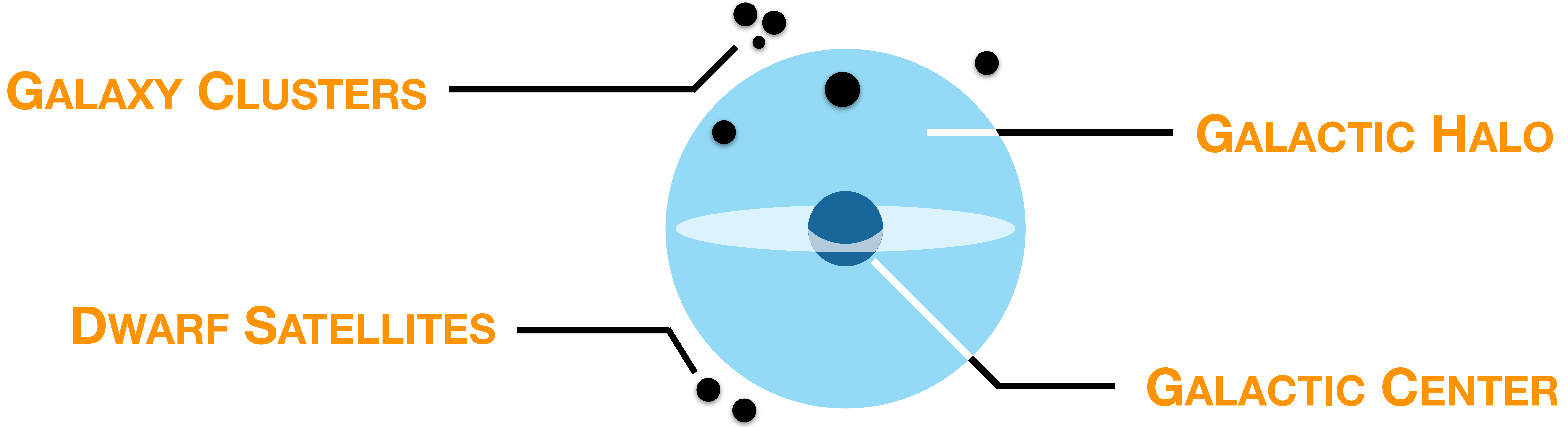


Array of 5 Imaging Atmospheric Cherenkov Telescopes
to detect VHE gamma rays from ~30 GeV to 100 TeV

Where to look?

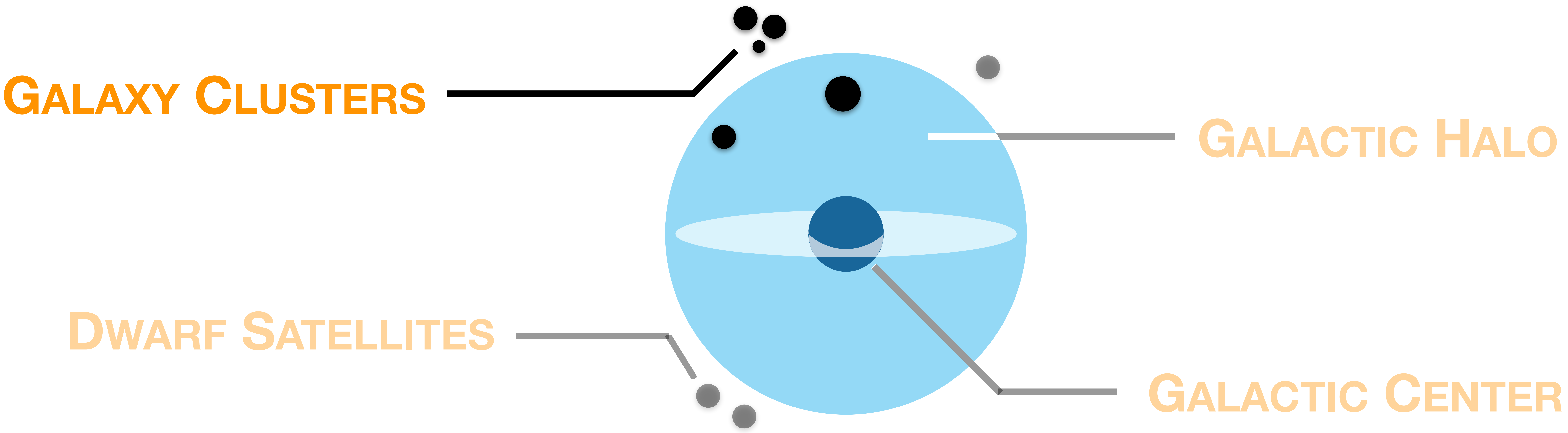
Anywhere there is high concentration!

- Optimal conditions for indirect DM searches:
  - High DM density ($\phi_{\rm DM} \propto \rho^2_{\rm DM}$ for annihilation, $\phi_{\rm DM} \propto \rho_{\rm DM}$ for decay)
  - Massive nearby objects ($\phi_{\rm DM} \propto M/d^2_{\oplus}$)
  - Low astrophysical background



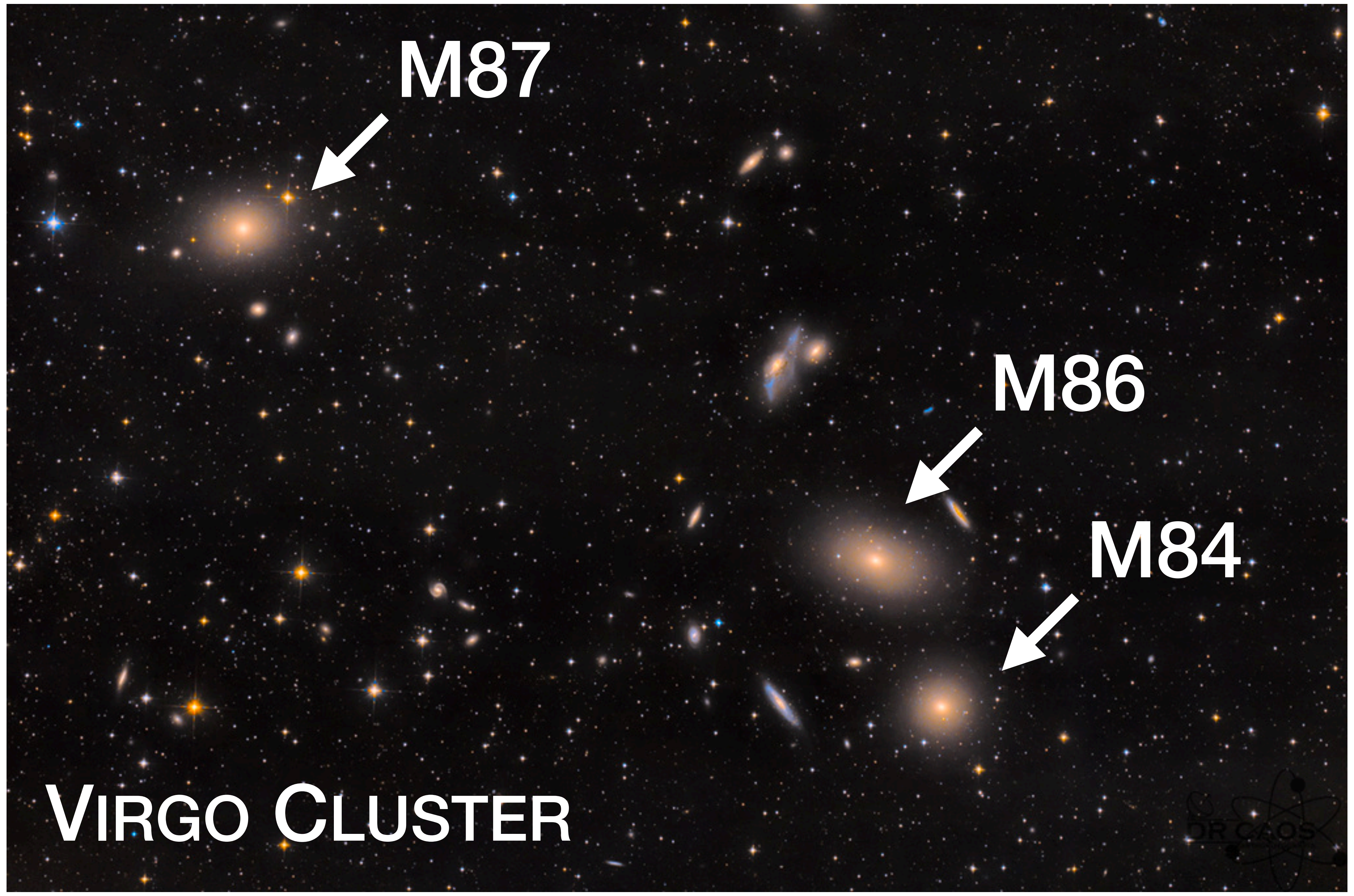
Why DM from Galaxy Clusters?

- Largest gravitationally bound structures formed by gravitational collapse
- Masses in range $10^{14} - 10^{15} M_{\odot}$
- **High dark matter content (80%)** and **mass-to-light ratios** make them prime targets for both decaying and annihilating DM searches, with possible flux boosts from **substructures**
- Well studied dark matter profiles



The Virgo Cluster

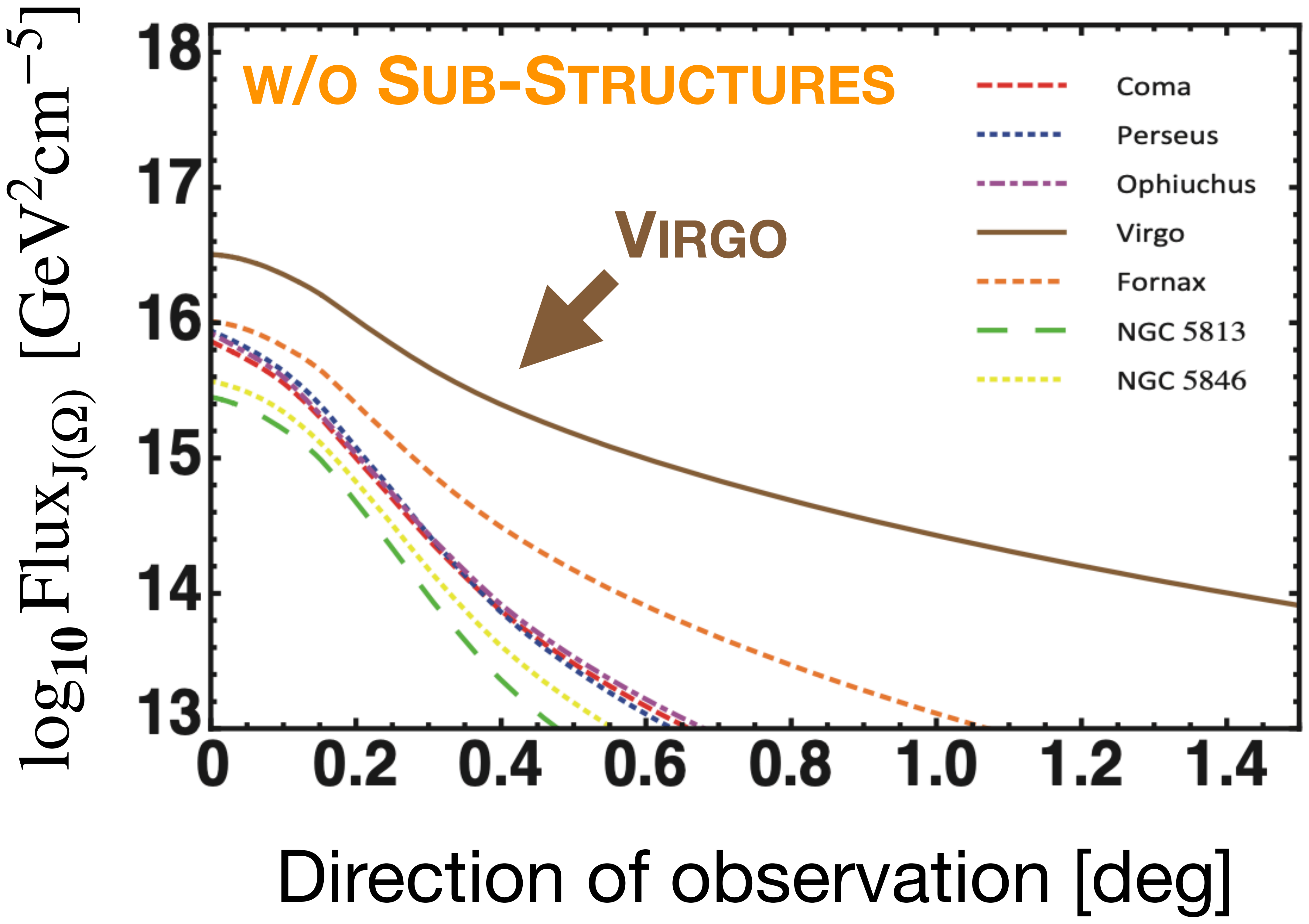
- Virgo is the closest large galaxy cluster to our own local galaxy group
  - $z = 0.0036$
  - $D_L = 15.46$ Mpc
  - $M_{200} = 5.60 \times 10^{14}\ M_\odot$
- Active galaxy M87 in the center of the cluster **monitored actively by IACTs**

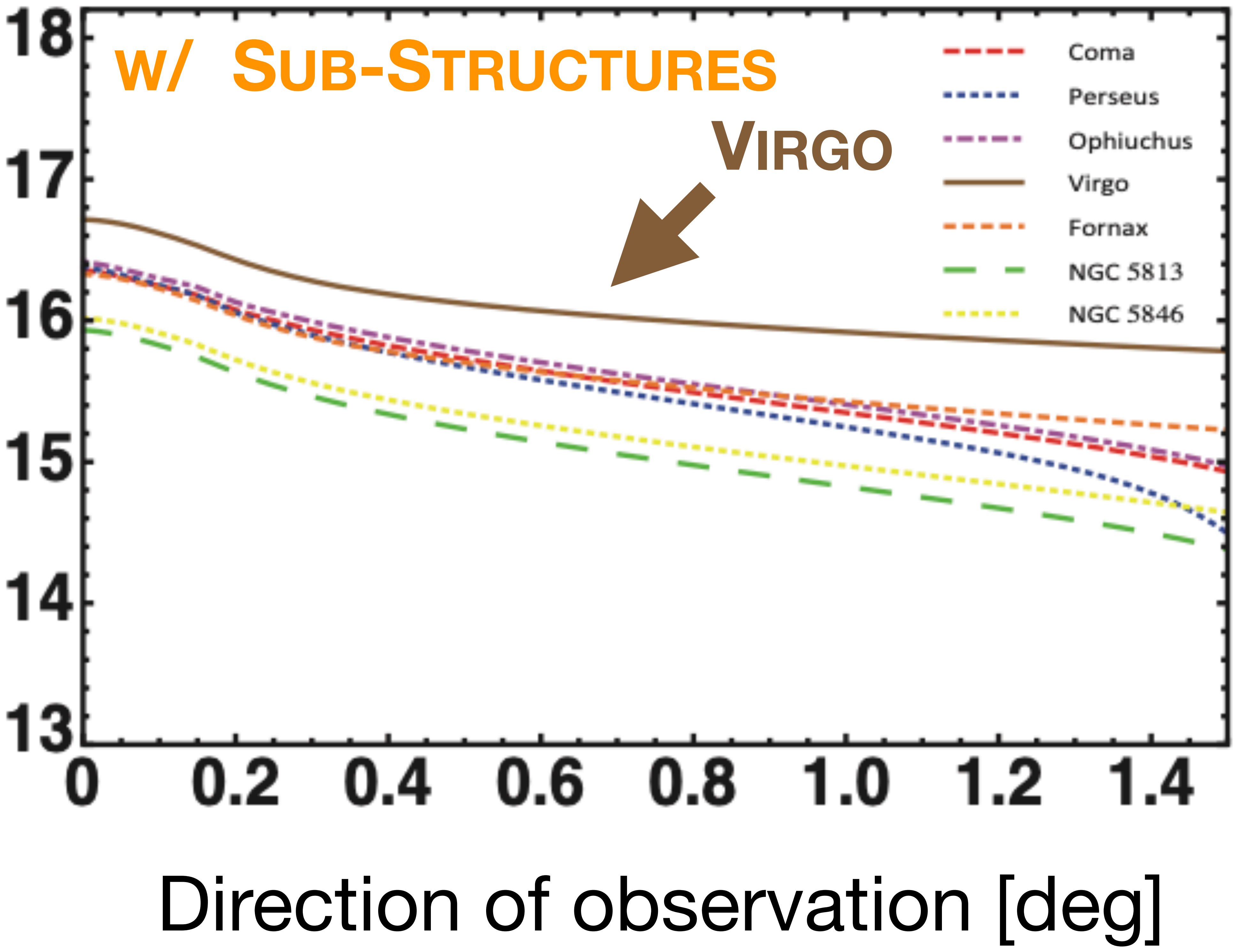


Can provide a strong probe for dark matter decay/annihilation

DM search from the Virgo Cluster

[Sánchez-Conde *et al.*, 2011]





Highest gamma-ray DM annihilation fluxes at all angles among galaxy clusters

Virgo DM density profile

- DM density profile ***$\rho_{tot}(r)$*** describes the DM distribution inside the object
- 2 models used: **Sanchez-Conde et al (2011)** and **Di Mauro et al (2023)**
- Galaxy clusters should host a significant amount of substructure or subhalos
- DM halo mass density has a smooth and a "clumpy" (sub-structure) part ⇒ important consequences for photon flux predictions

$$\rho_{\text{tot}}(r) = \boxed{\rho_{\text{main}}(r)} + < \rho_{\text{halos}} > (r)$$

↓

$$\rho_{\text{NFW}}(r) = \frac{\rho_0}{\left(\frac{r}{r_s}\right)\left(1 + \frac{r}{r_s}\right)^2}$$

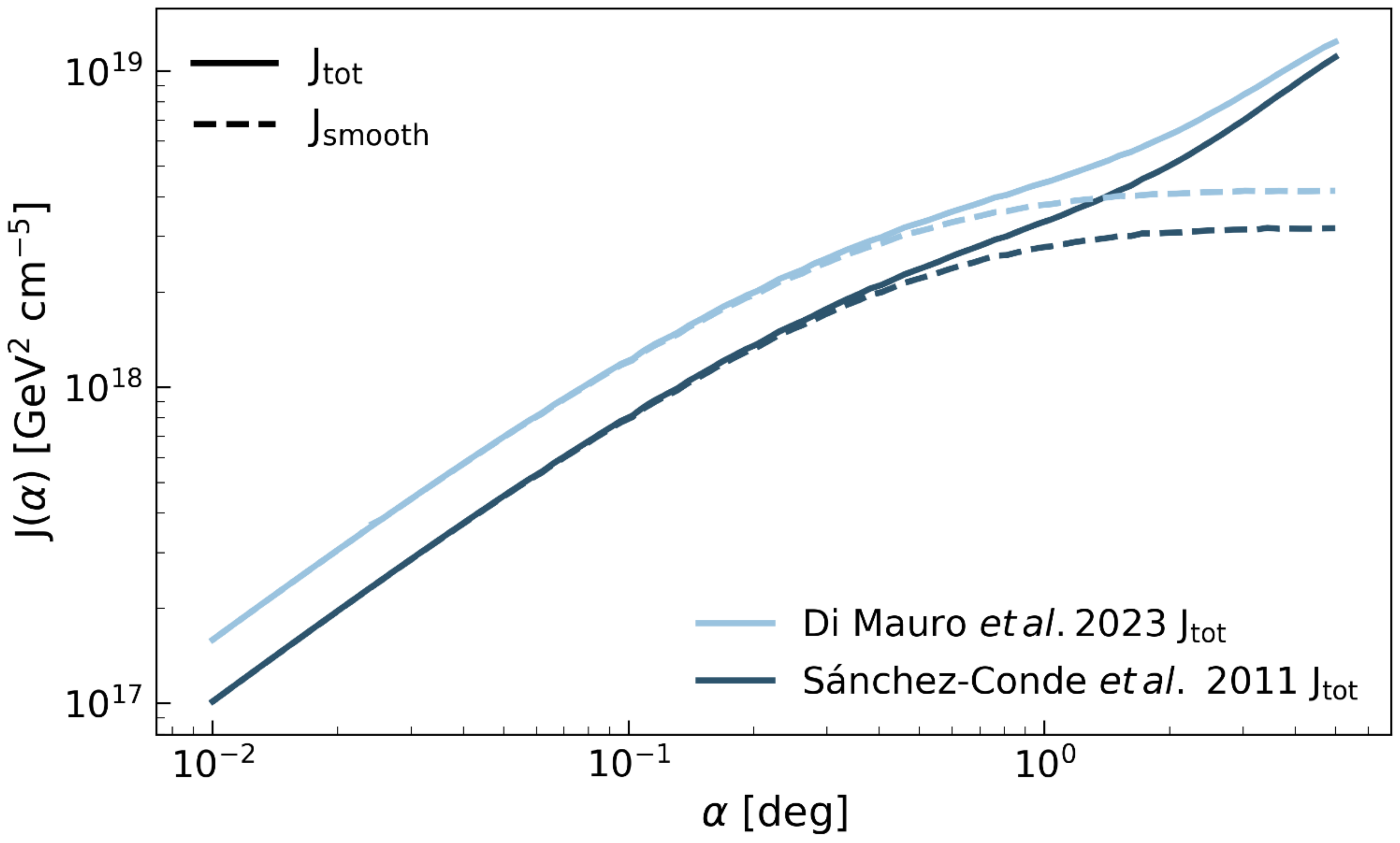
Virgo Clump model

- The mass into clumps was assumed to be 20% of total cluster mass, minimum mass $10^{-6} M_\odot$
- The mass distribution of clumps is a power-law:

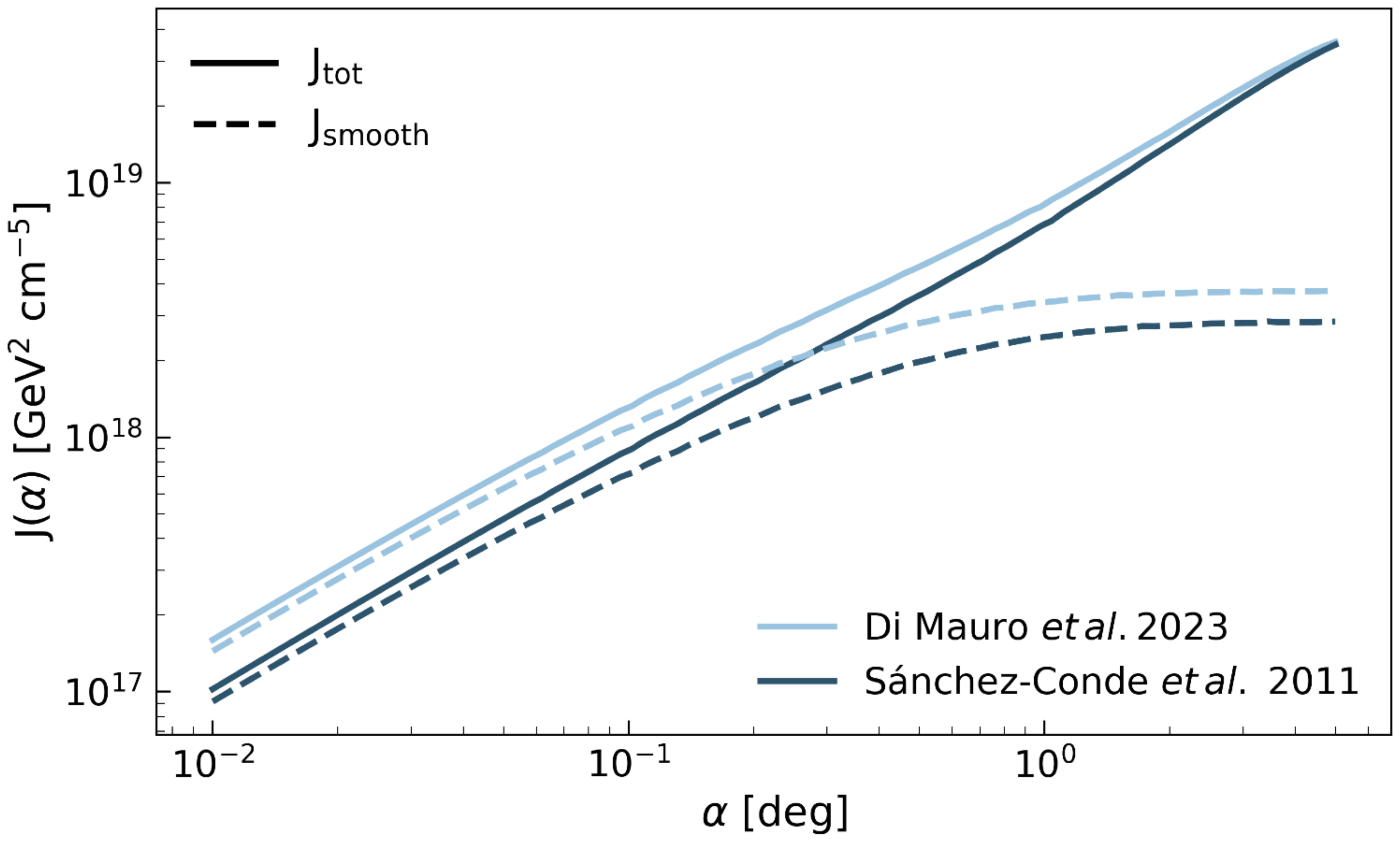
$$\frac{dN_{\rm clumps}}{dm} = N_0 m^{-\kappa}$$

- Clumps dominate the contribution to J at distances $> 1°$ from the center of Virgo

κ = 1.9

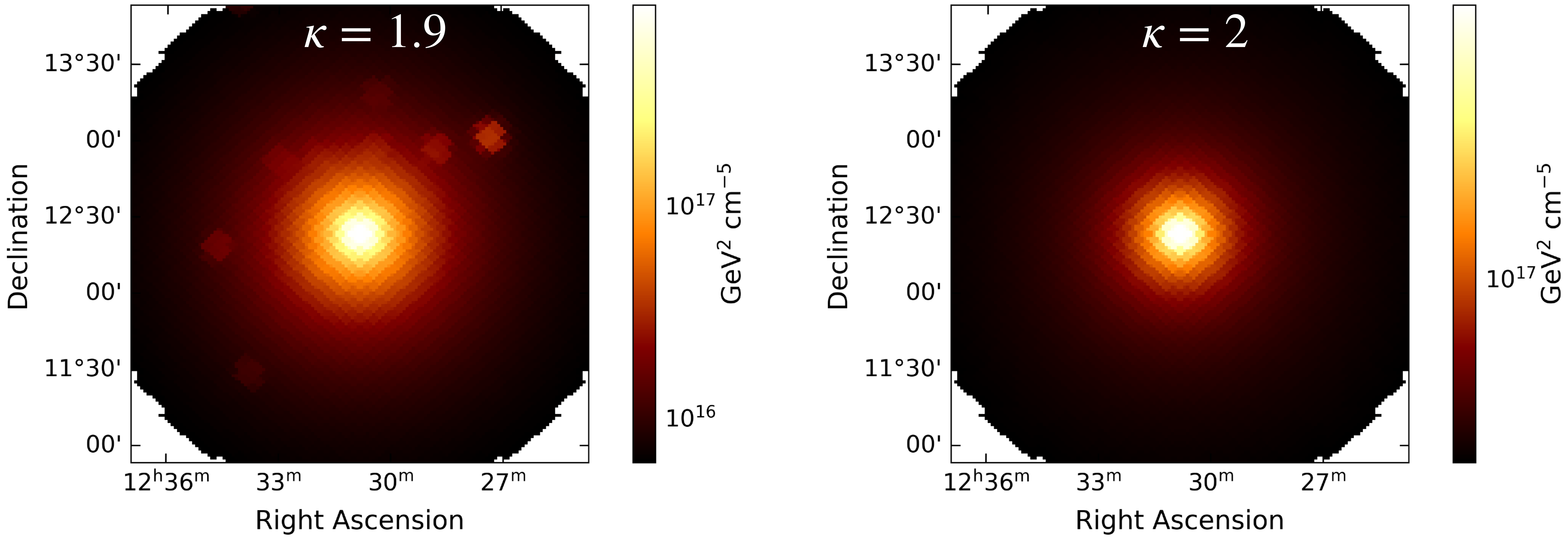


κ = 2



Virgo J-factor maps

DM spatial distribution simulated with public program CLUMPY



J-Factor model: Sánchez-Conde et al. 2011

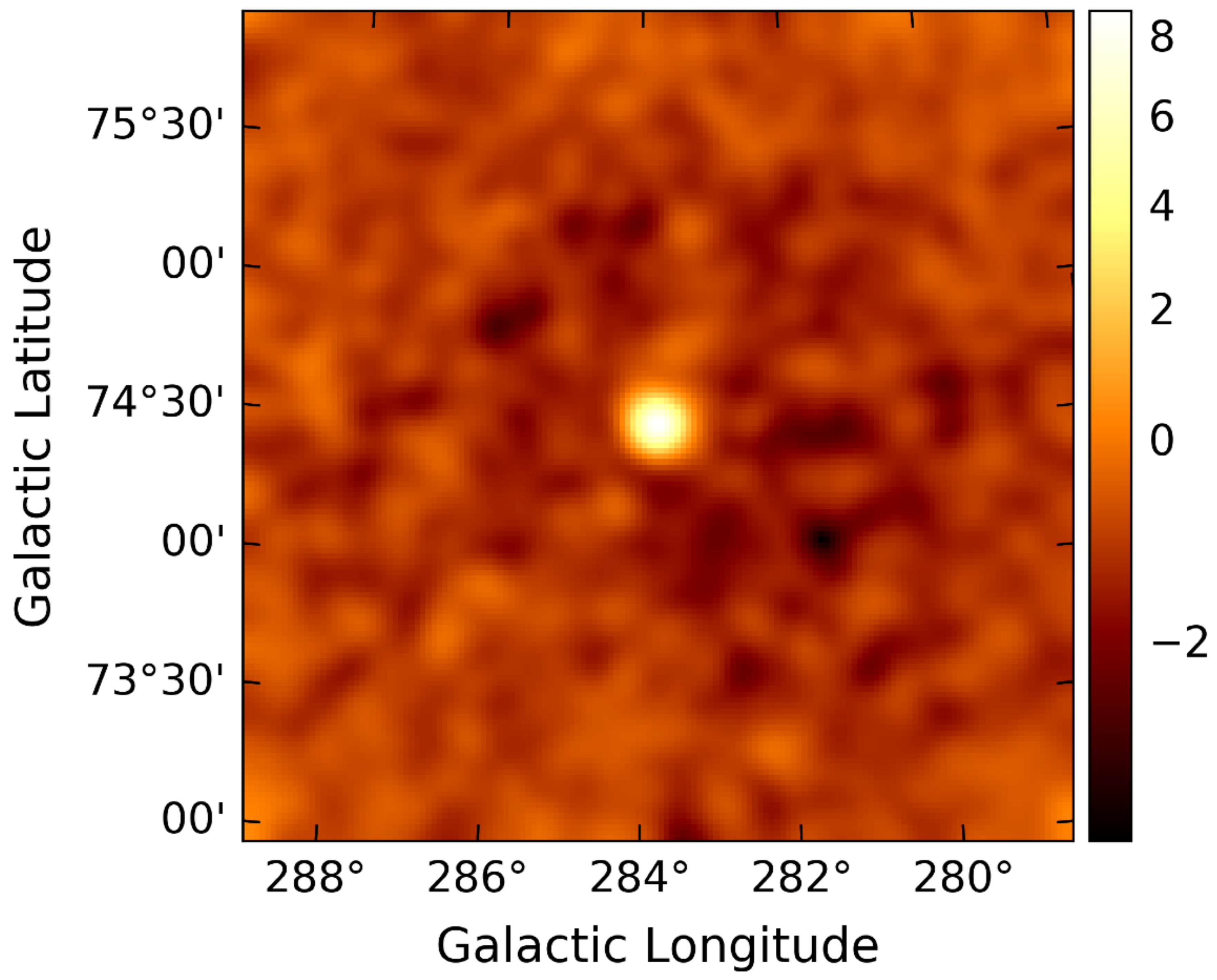
Data Analysis

First step: central source (M87) + hadronic background modelization

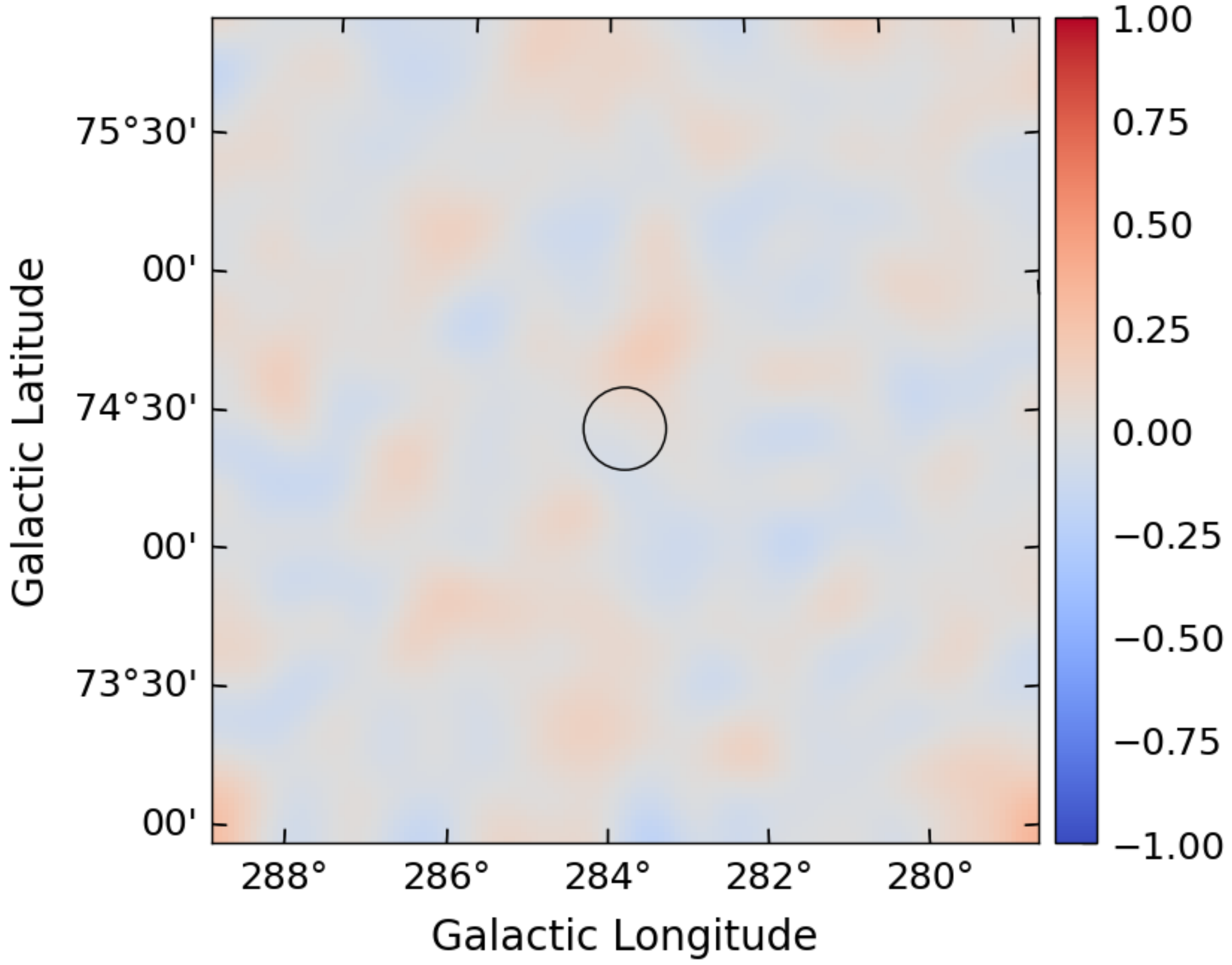
Central Source Model
- PointSpatialModel
- $$\frac{dN}{dE} = N_0 \left(\frac{E}{E_0}\right)^{-\Gamma} e^{-\alpha \times \tau(E,z)}$$

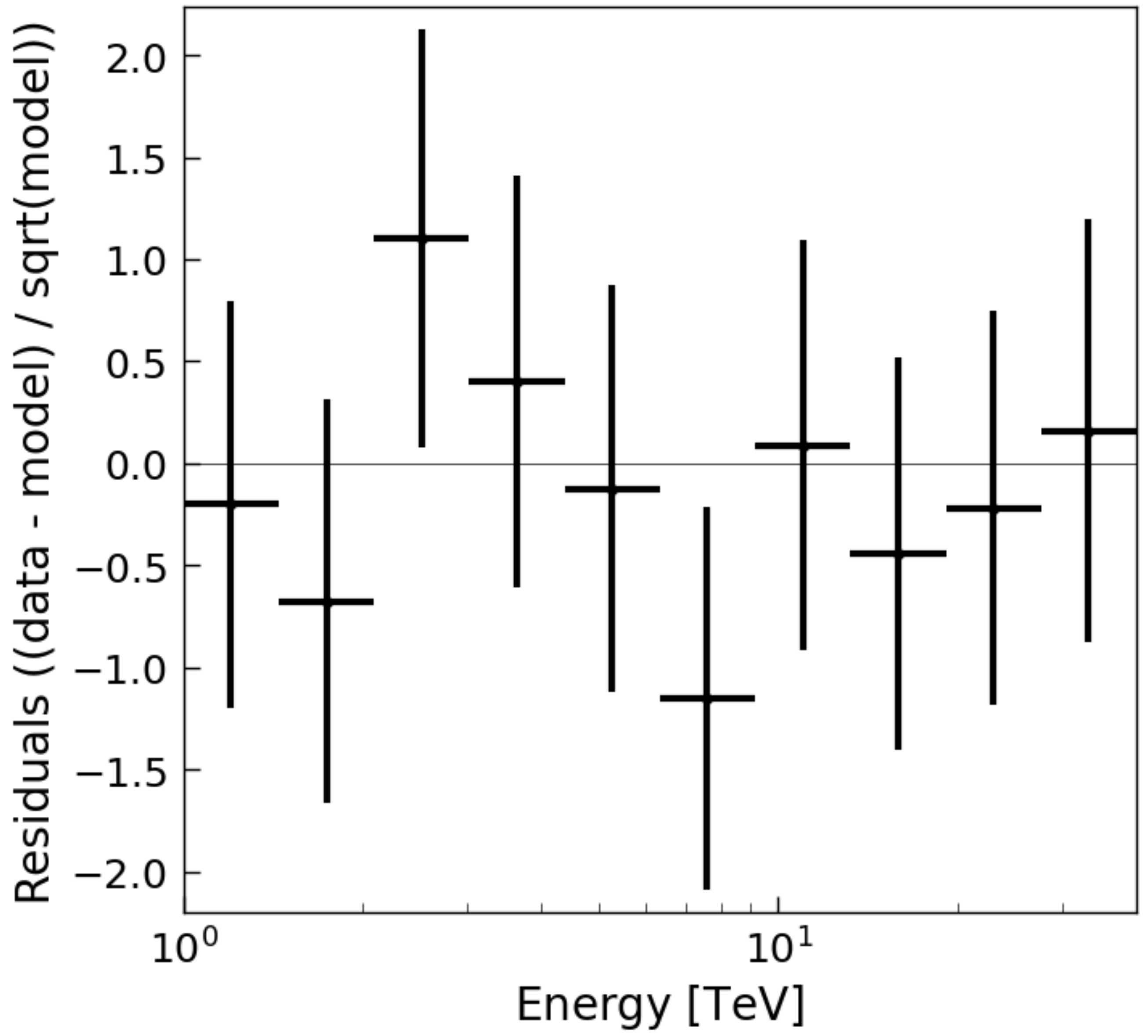
⊗ **FoVBackgroundModel**

Excess Map before Fit



Residuals from fit





Data Analysis

Second step: annihilation/decaying DM fit

CENTRAL SOURCE MODEL

- PointSpatialModel
- $$\frac{dN}{dE} = N_0 \left(\frac{E}{E_0}\right)^{-\Gamma} e^{-\alpha \times \tau(E,z)}$$

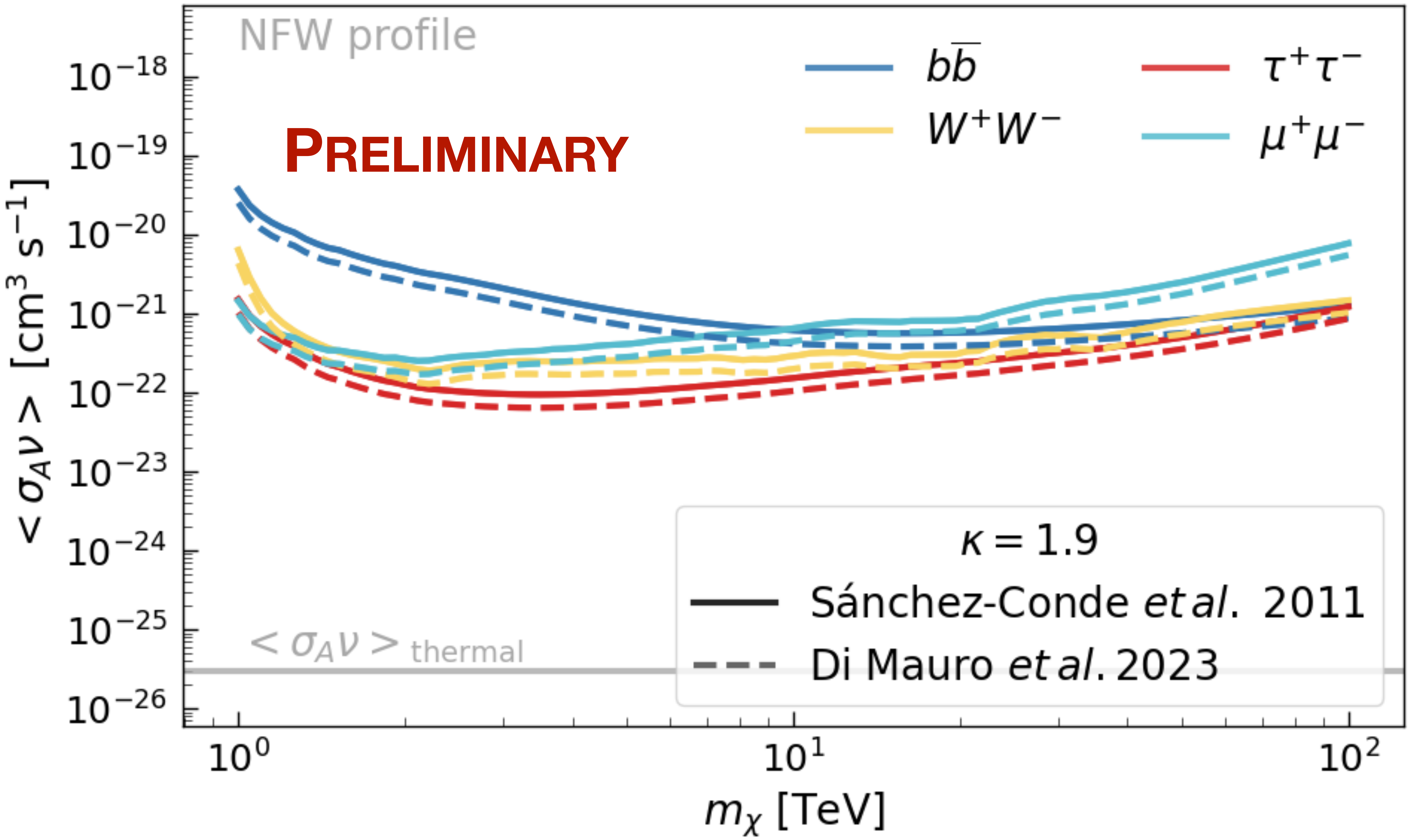
⊗ **FoVBackgroundModel**

⊗ **DARK MATTER MODEL**

- J-Factor/D-Factor Map
- $$\frac{d\phi_\gamma}{dE}(E) = \frac{1}{4\pi m_\chi} \frac{dN_\gamma}{dE}(E) \times \begin{cases} \frac{\langle \sigma v \rangle}{2m_\chi} \\ \frac{1}{\tau} \end{cases}$$

DM annihilation: limits

[J.F. Glicenstein, FB (H.E.S.S.) PoS(ICRC2025)659]

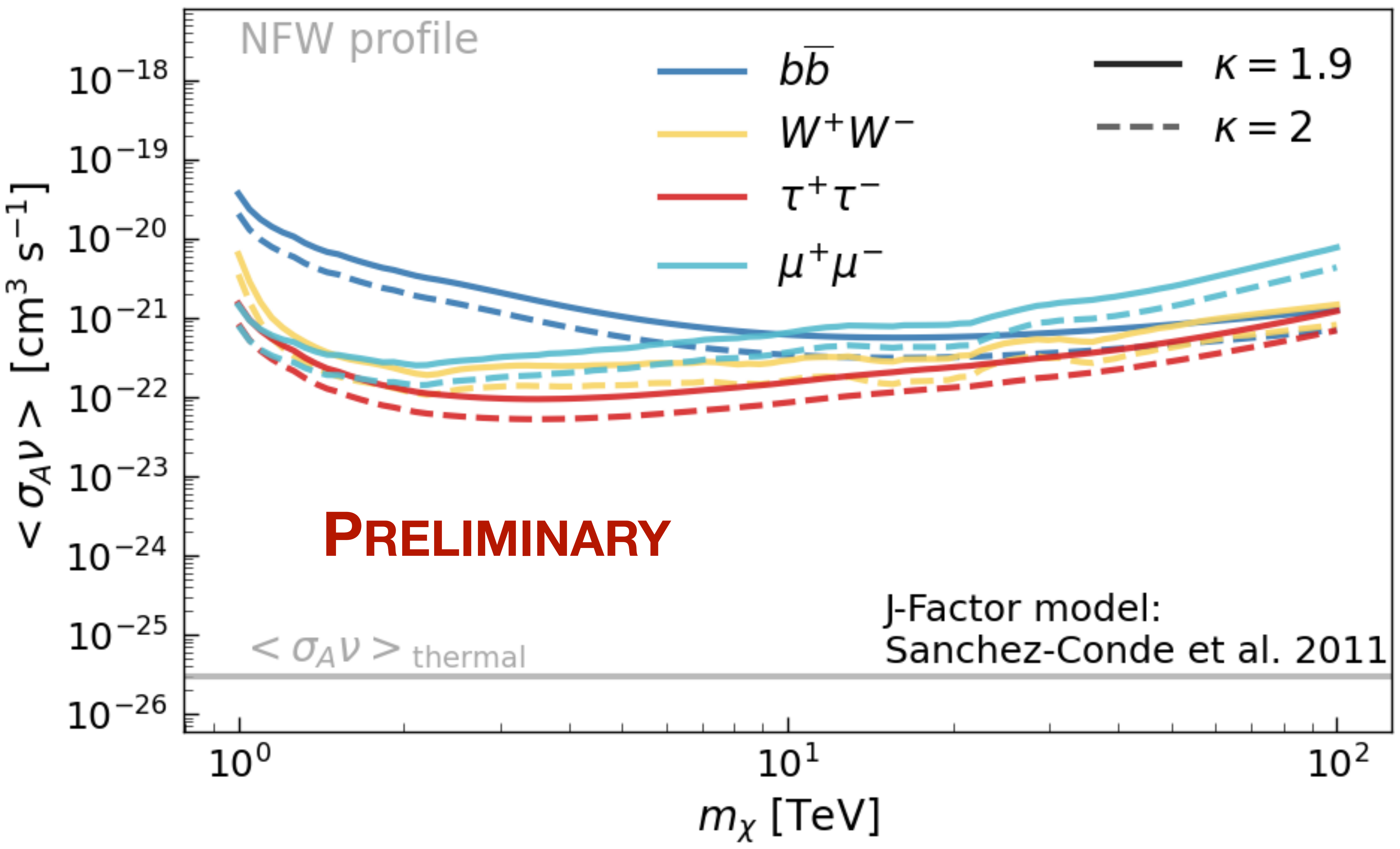


- No evidence for a DM halo ⇒ 95% C.L. UL on $< \sigma_A v >$ in the $10^{-22} - 10^{-23}$ cm^3/s range
- Sanchez-Conde et al (2011) model more conservative than di Mauro et al (2023)

DM annihilation: limits

J-factor slope index comparison (sub-halos effect)

[J.F. Glicenstein, FB (H.E.S.S.) PoS(ICRC2025)659]



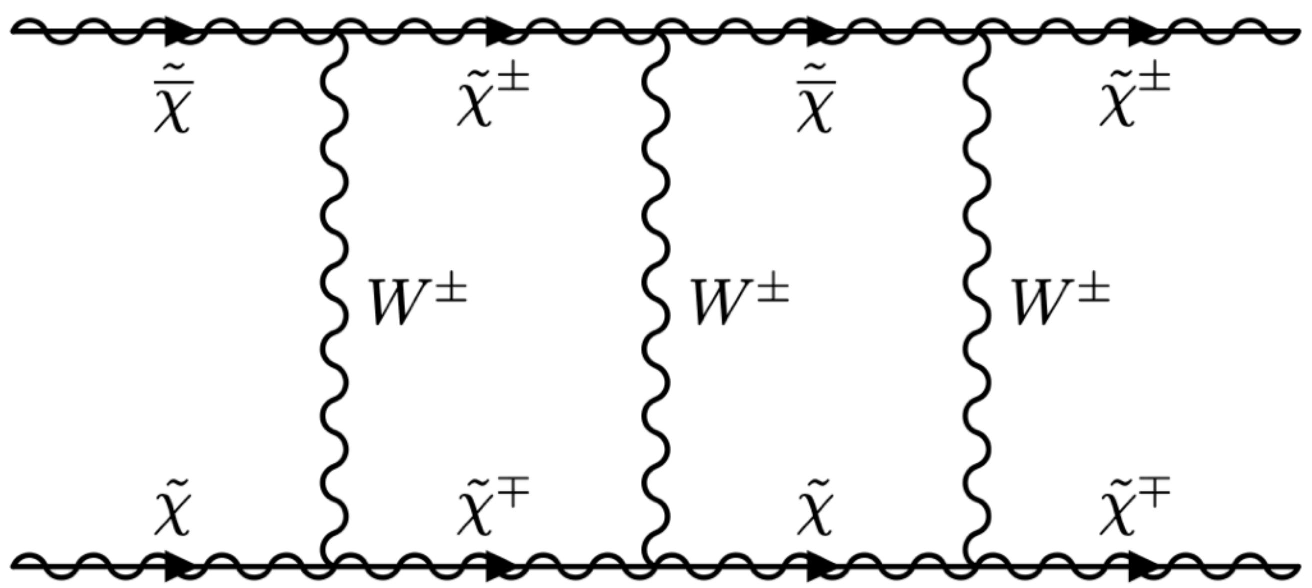
- Model with index $\kappa = 1.9$ systematically more conservative than model with $\kappa = 2$

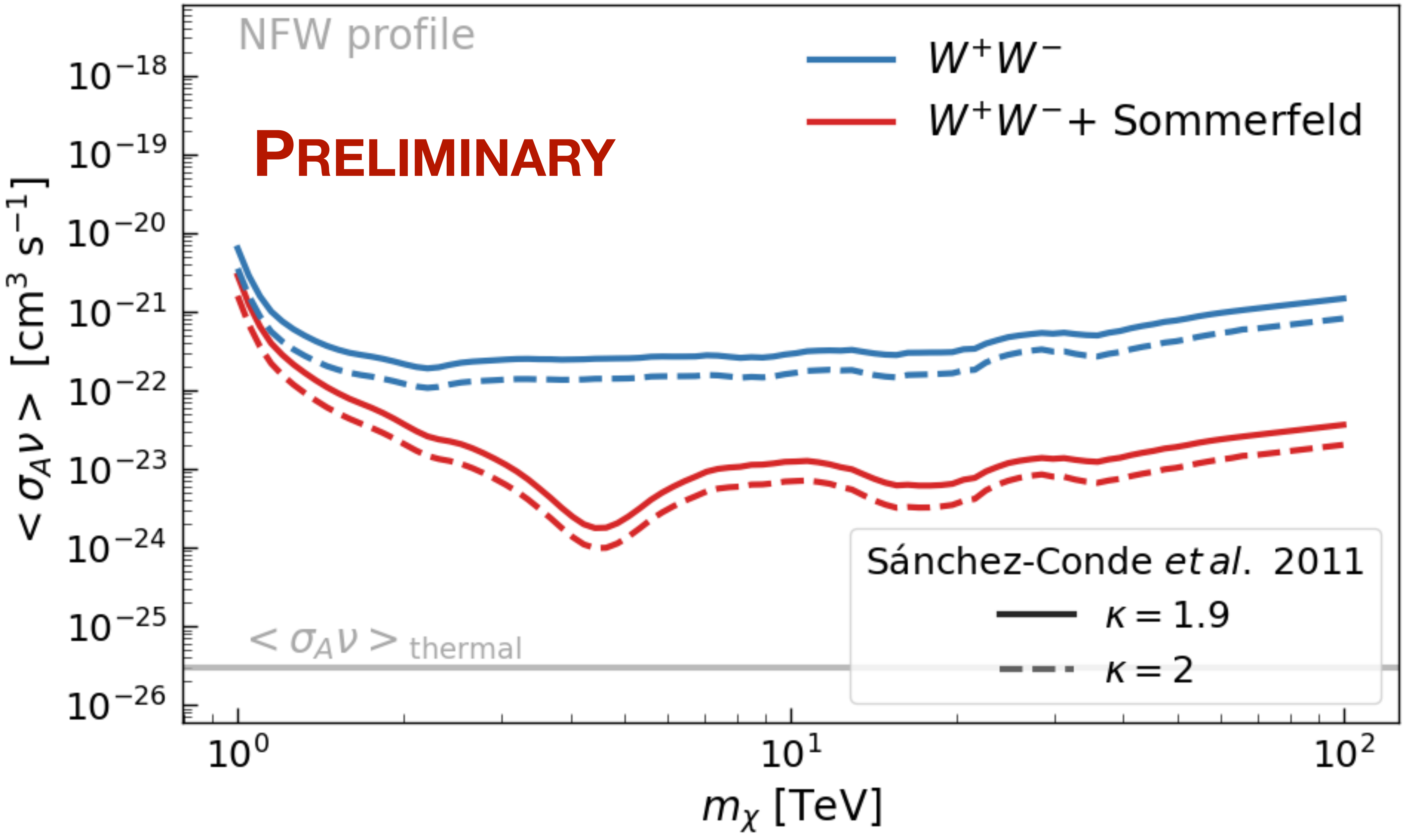
DM annihilation: limits

Sommerfeld effect

[J.F. Glicenstein, FB (H.E.S.S.) PoS(ICRC2025)659]

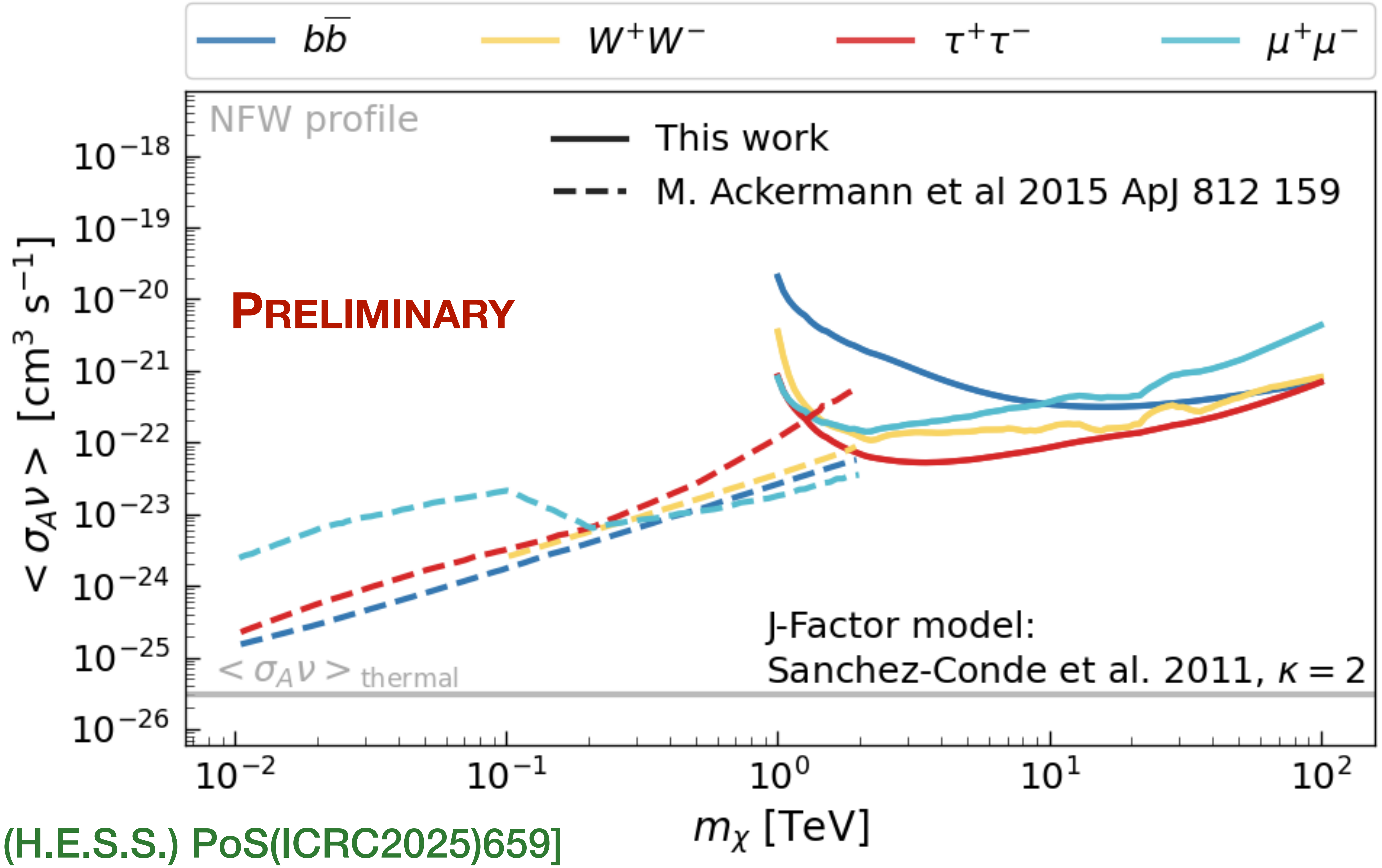
- Exchange of electroweak gauge bosons enhances annihilation for today slow DM
- Very important for low velocity dispersion
- Velocity dispersion assumed for Virgo: $\Delta v = 5 \cdot 10^{-3}$ c





DM annihilation: limits

Comparison with Fermi-LAT's results

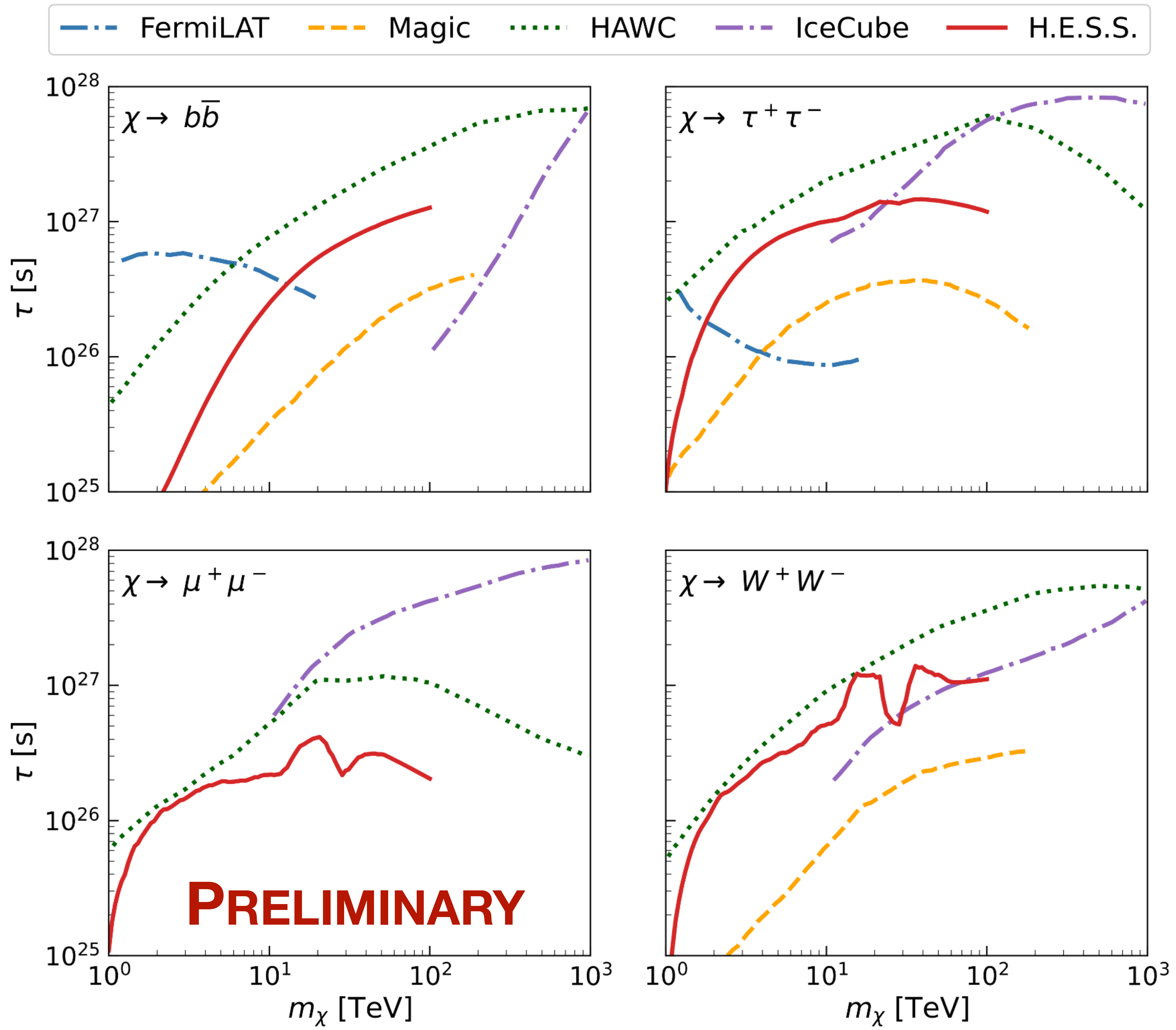


[J.F. Glicenstein, FB (H.E.S.S.) PoS(ICRC2025)659]

DM decay: limits

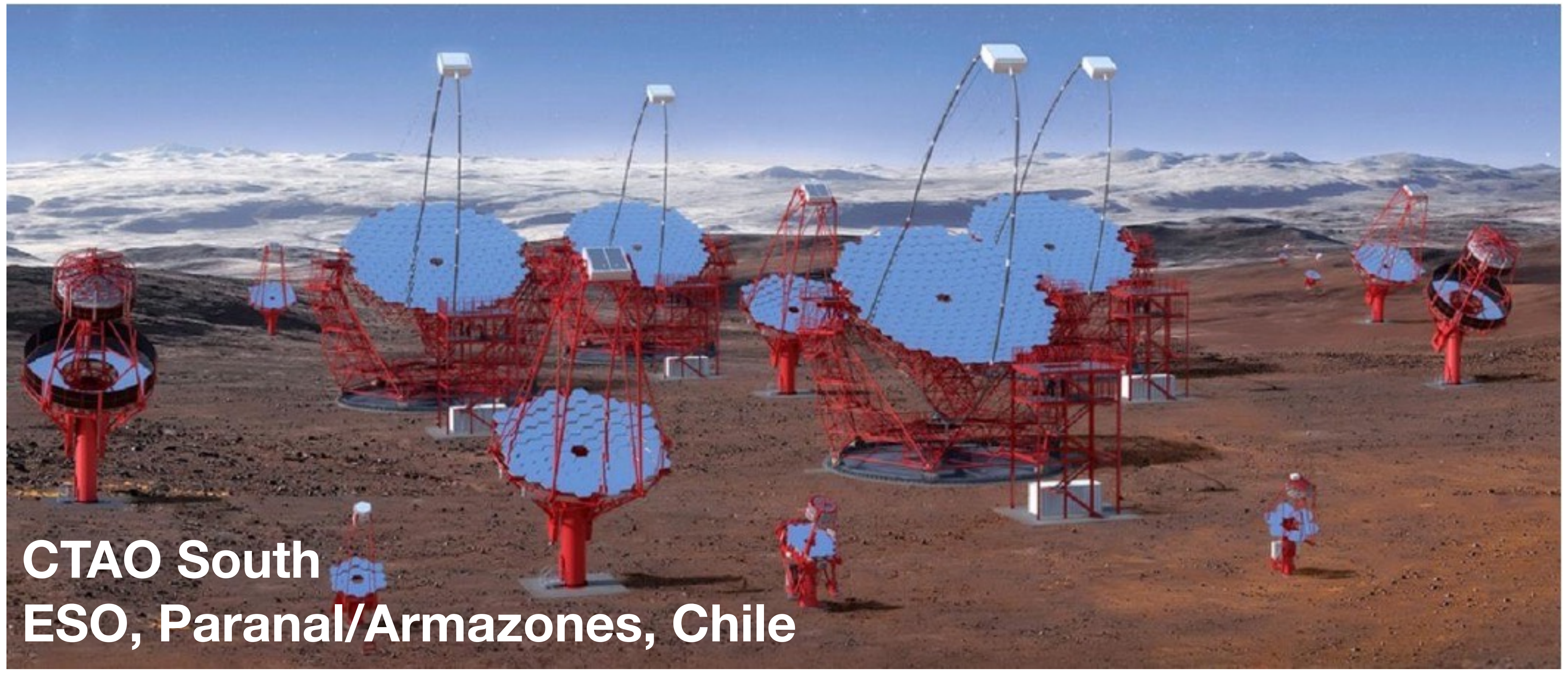
Comparison with FermiLAT, Magic, HAWC and IC

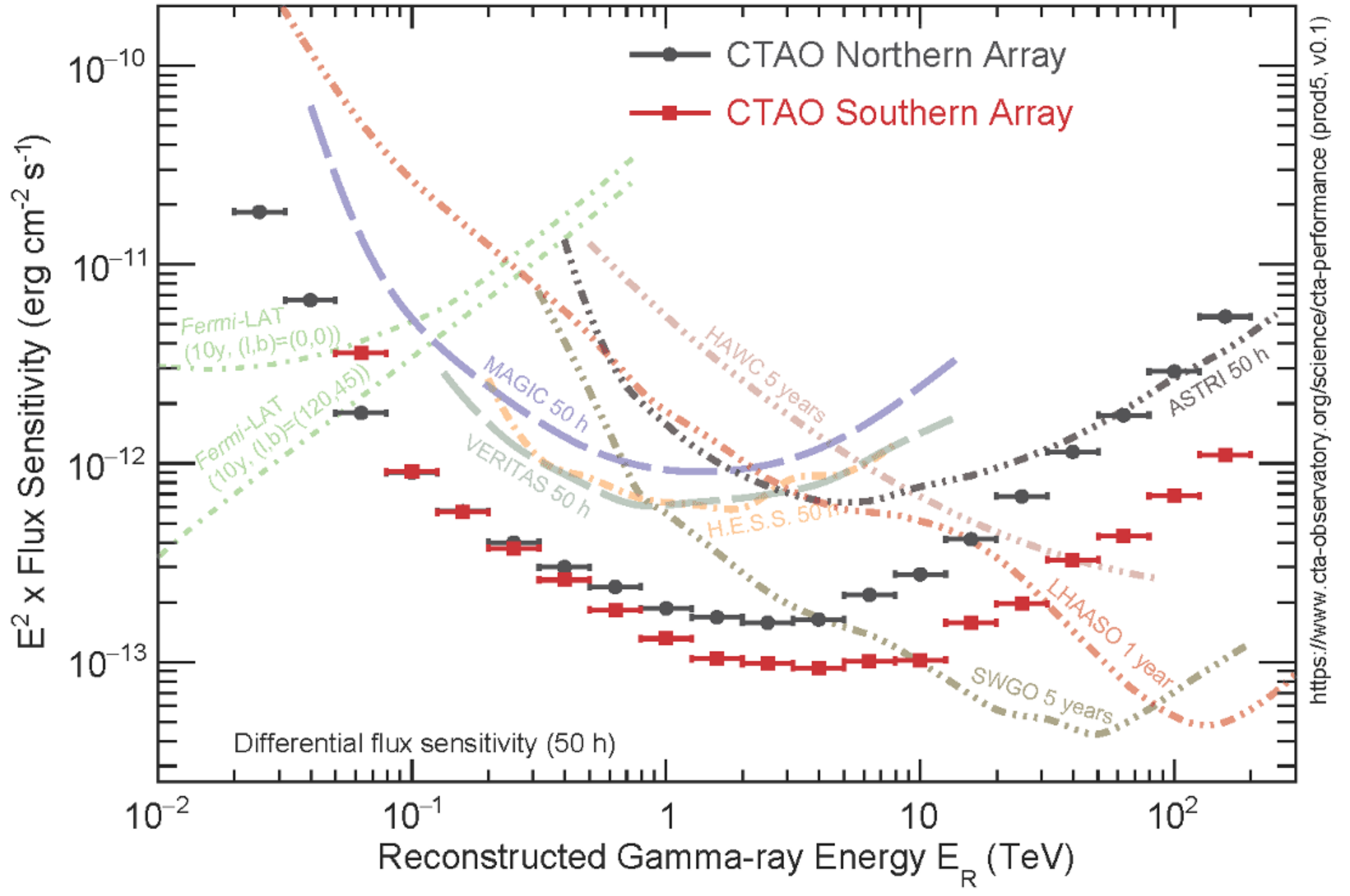
- Data analysis similar as for annihilation, with **D-map** replacing J-map
- 95% C.L. on τ in the $10^{25} - 10^{26}$ s range.
- 95% C.L. on τ comparable to limits from other instruments (HAWC somewhat more constraining).



[J.F. Glicenstein, FB (H.E.S.S.) PoS(ICRC2025)659]

What is next? CTAO!





DM searches with CTAO

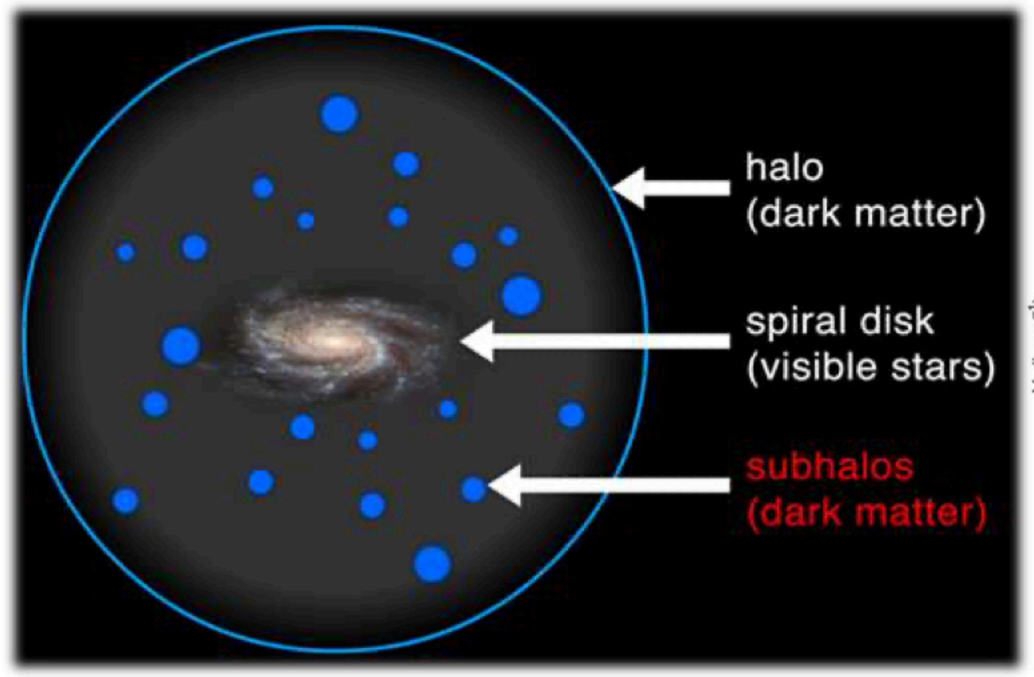
One of the main Key Science Projects

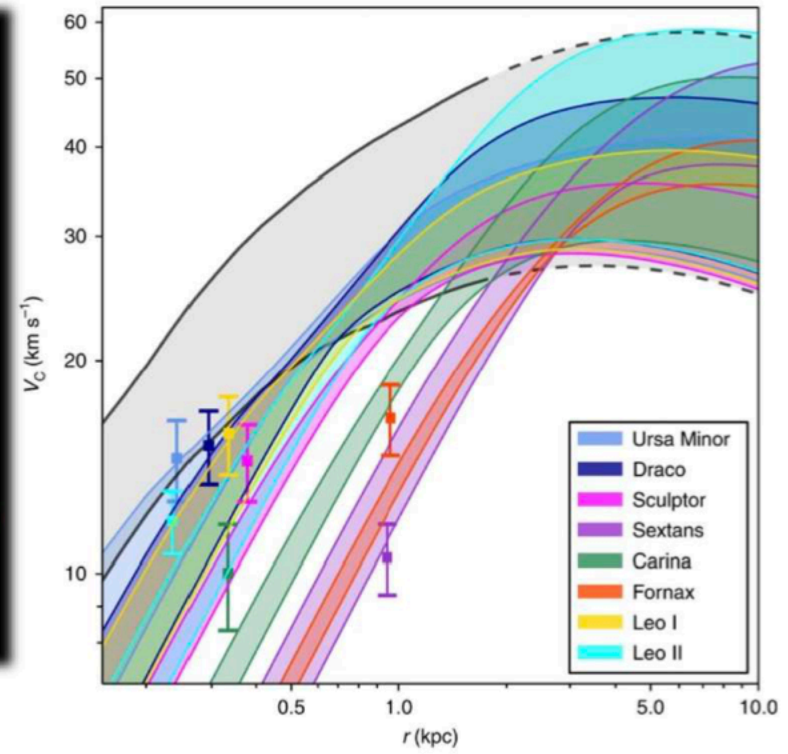
Milky Way : **Galactic Center**

Galaxy clusters

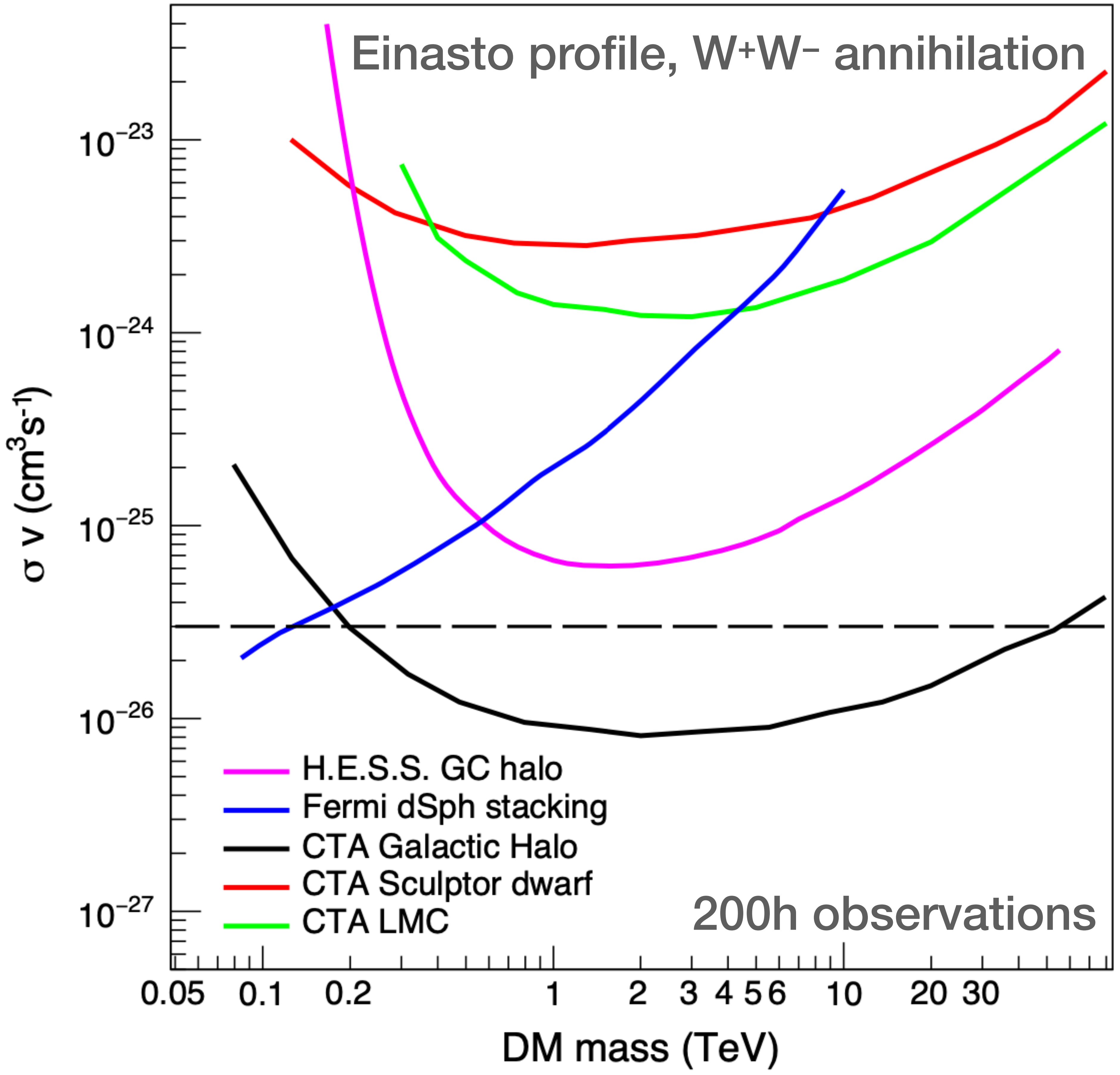
E.g., Perseus

Dwarf **spheroidal (dSph)** galaxies





M.Valli, H. Yu, Nature Astronomy (2018)

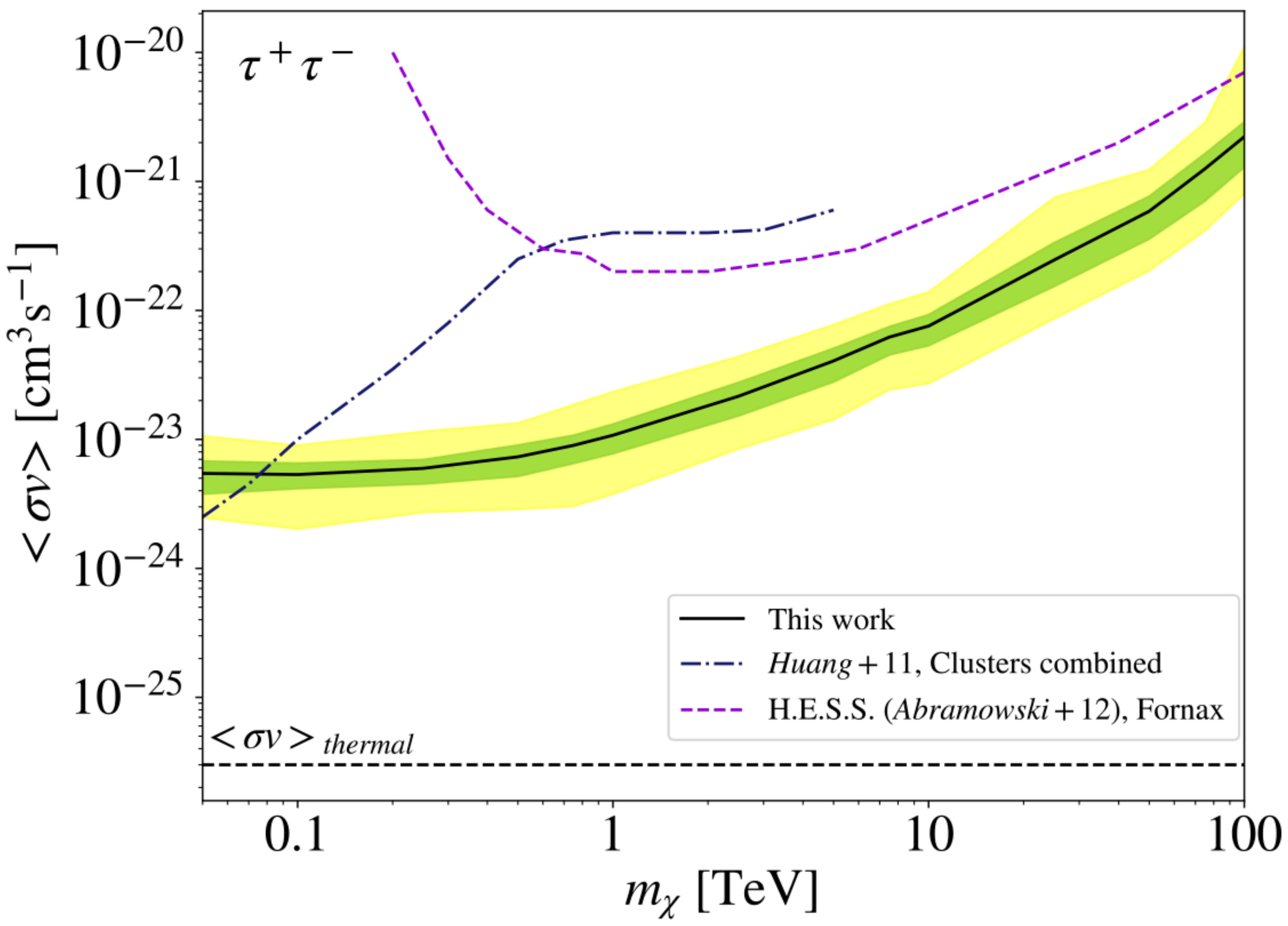


[Science with the Cherenkov Telescope Array (arXiv:1709.07997)]

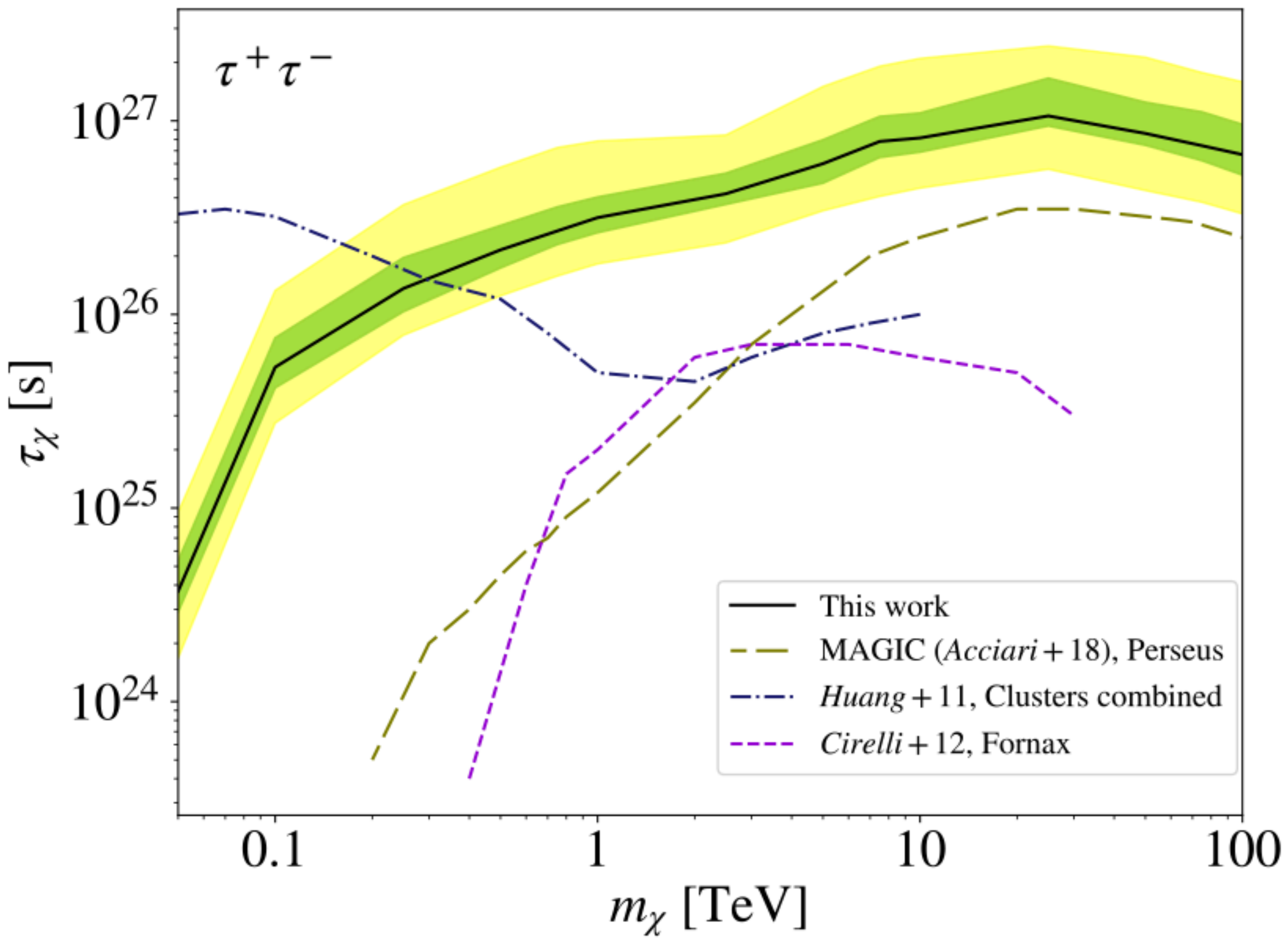
DM searches with CTAO

Sensitivity of CTA to a DM signal from the Perseus cluster

ANNIHILATION



DECAY



[CTAO, JCAP10(2024)004]

Conclusions

- **Galaxy clusters** are great targets for DM searches:
  - Most massive bound structures in the Universe
  - Large dark matter content + substructure boost
  - Extended targets → complementary to dwarfs & Galactic Center
- No yet evidence for a dark matter signal ⇒ Constraints: $\langle \sigma v \rangle \geq 10^{-23}\ \mathrm{cm^3/s}$ and $\tau \geq 10^{25}\ \mathrm{s}$
- Key limitations:
  - Extended emission + complex morphology
  - Astrophysical contamination (e.g. central AGN)
  - J-factor and substructure uncertainties
- Outlook with **CTAO**
  - $\times$10 sensitivity improvement
  - Access to multi-TeV DM
  - Strong potential for extended emission