

Milky Way White Dwarfs as Sub-GeV to Multi-TeV Dark Matter Detectors

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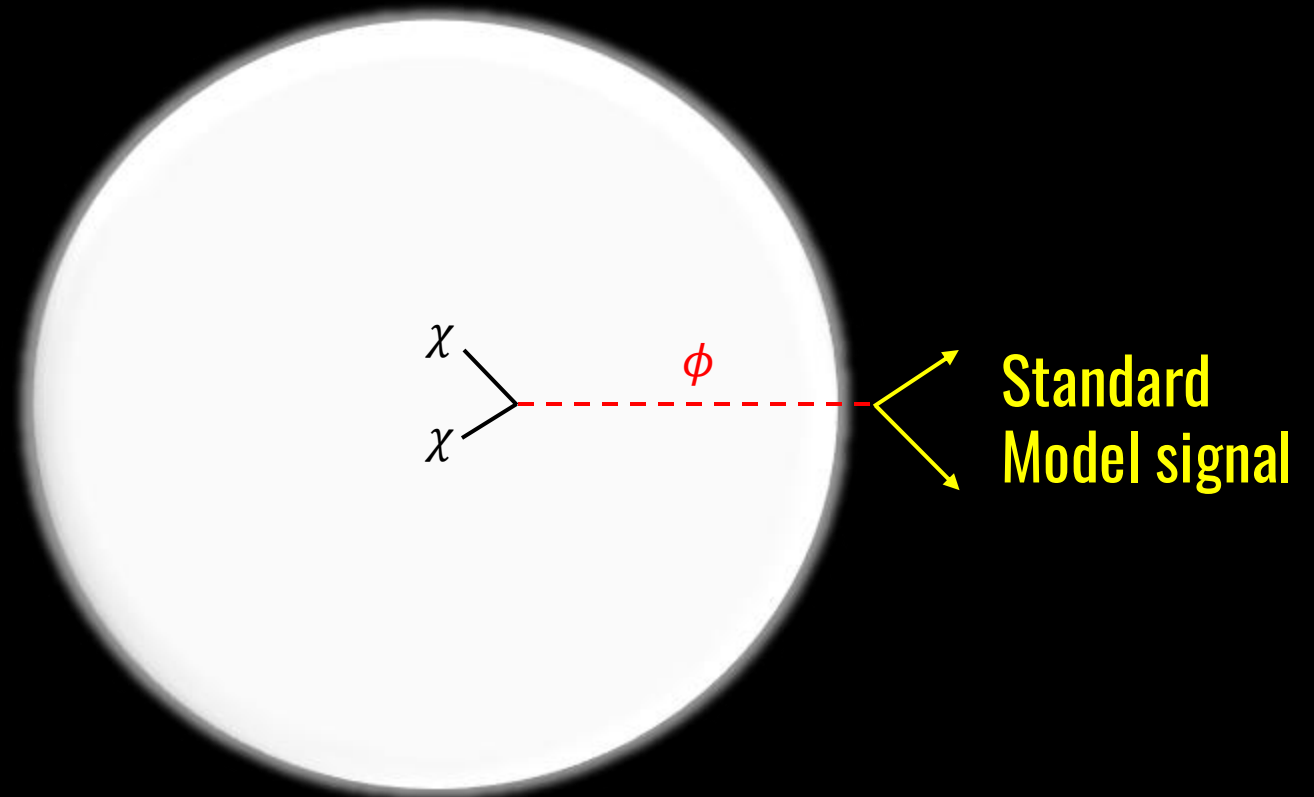
In collaboration with Javier Acevedo and Rebecca Leane

Dark Matter and Stars, July 15, 2025

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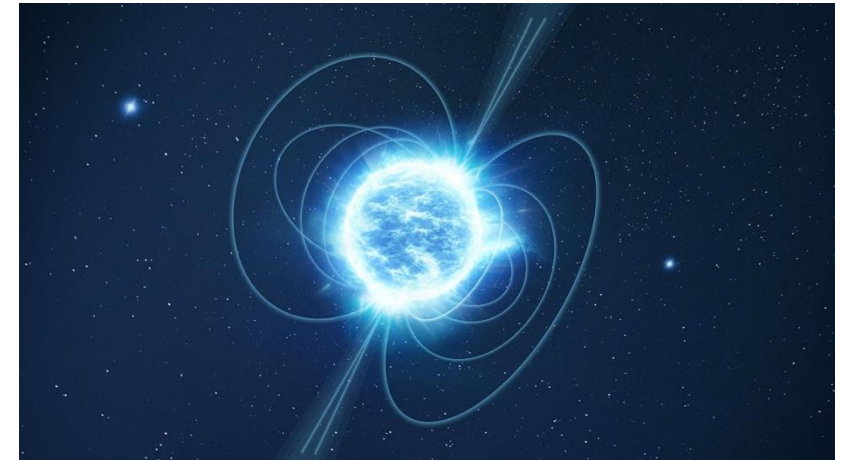
DM capture by celestial objects

- DM scatters off particles inside the object and becomes gravitationally bound
- DM accumulates and annihilates into detectable signature
 - Heating (mediator decays inside object)
 - Standard model flux (mediator decays outside object)



Background and previous work

- Neutron stars and white dwarfs (WDs) are good celestial objects for DM searches
 - Both have high density -> more DM captured
- WDs are larger and more numerous than neutron stars
- WD heating in globular clusters studied in the past
 - Potential high DM density, but with large uncertainty



<https://science.nasa.gov/asset/hubble/illustration-of-magnetar/>



<https://www.space.com/23756-white-dwarf-stars.html>

This work

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 - Why Galactic center? Less uncertainty on DM density

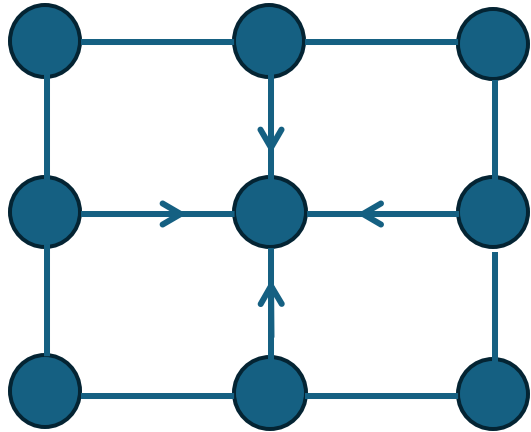
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Two new main ideas:

1. Improve DM capture rate calculation in WDs based on velocity distribution of WD ions
2. Use improved capture framework on WDs in the Galactic center to set new limits on the DM-nucleon cross section
 - Why Galactic center? Less uncertainty on DM density
 - Limits come from Galactic center gamma-ray data

1. Improve DM capture
rate calculation in WDs

Improved capture framework for WDs



The WD ions feel an approximate harmonic oscillator potential with frequency ω_p

Previous treatment:

$$\langle v_N^2 \rangle \sim \frac{T_{WD}}{m_N}$$

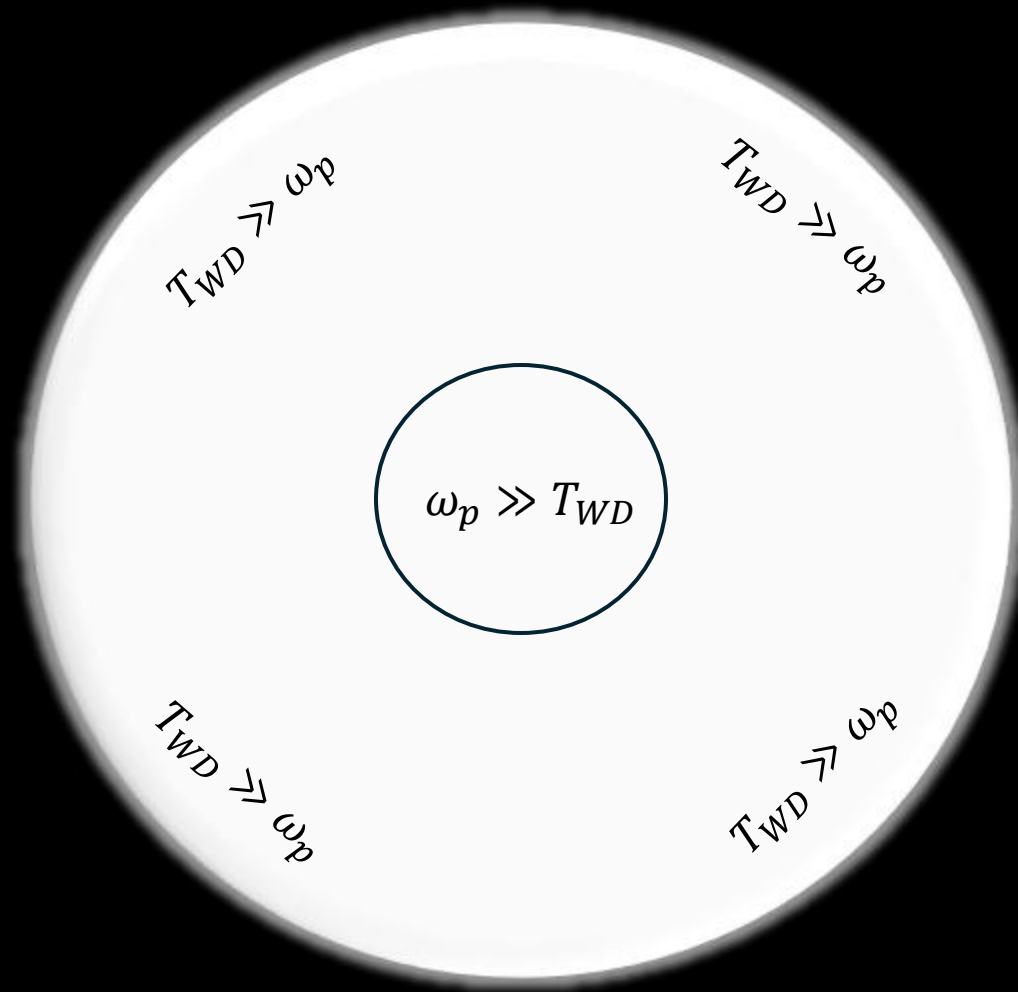
Labels: Ion mean squared velocity (points to $\langle v_N^2 \rangle$), WD temperature (points to T_{WD}), Ion mass (points to m_N)

Our treatment:

$$\langle v_N^2 \rangle \sim \frac{T_{WD}}{m_N} \quad (T_{WD} \gg \omega_p)$$

$$\langle v_N^2 \rangle \sim \frac{\omega_p}{m_N} \quad (\omega_p \gg T_{WD})$$

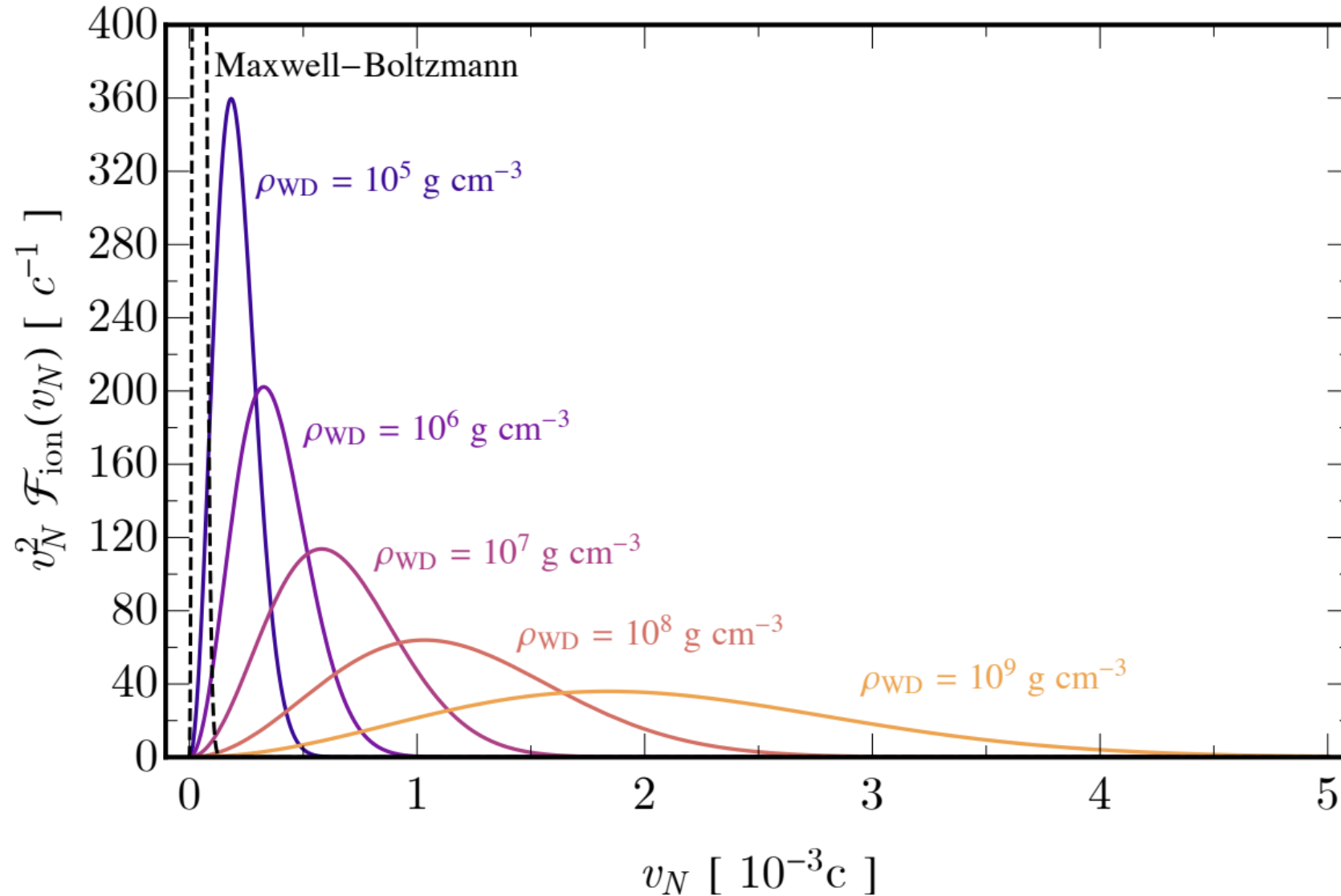
Improved capture framework for WDs



In volume relevant for capture, $\omega_p \gg T_{WD}$ so

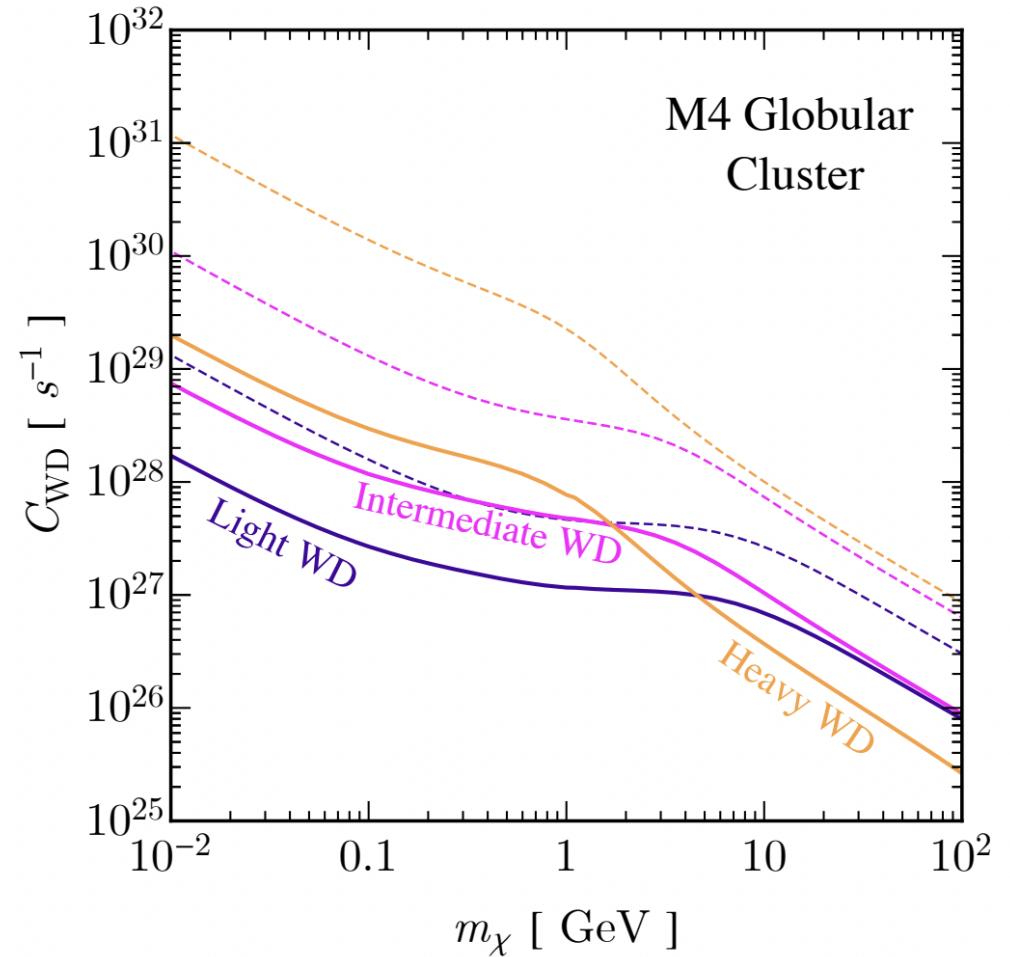
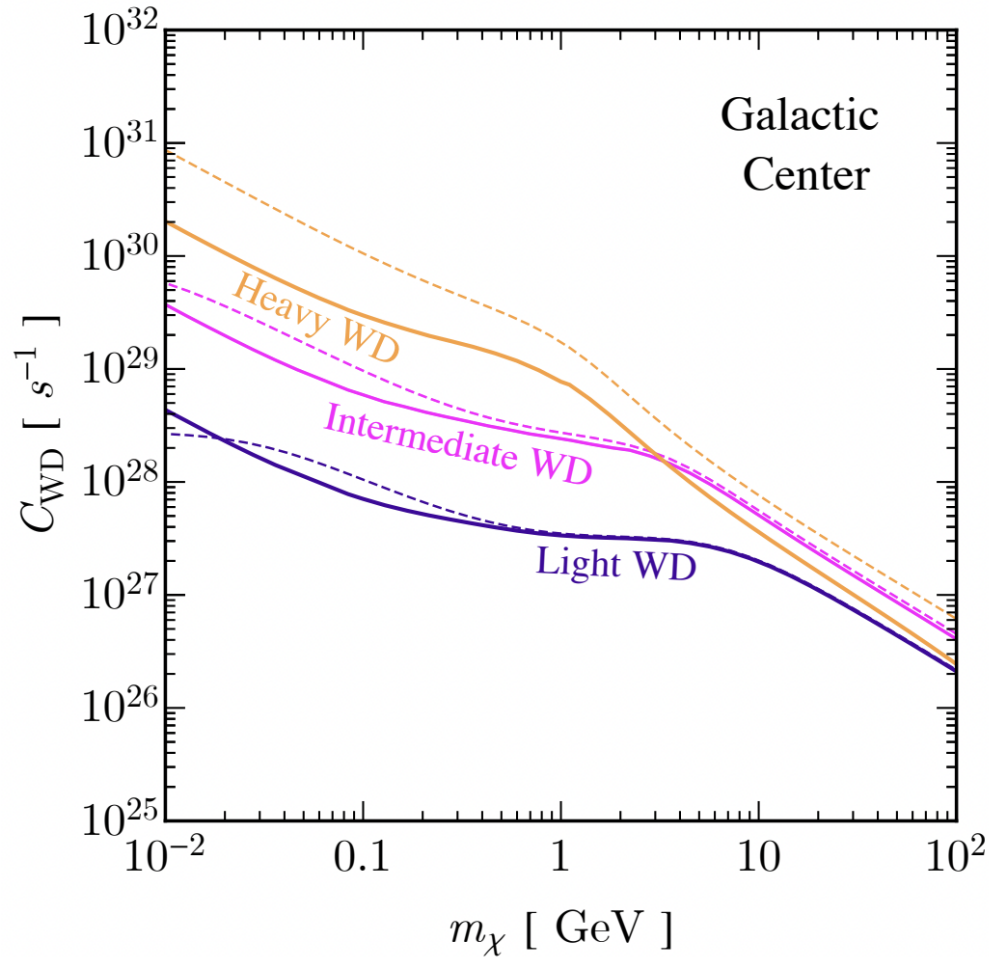
$$\langle v_N^2 \rangle \sim \frac{\omega_p}{m_N} \gg \frac{T_{WD}}{m_N}$$

Improved capture framework for WDs



$$\omega_p \sim \rho_{\text{WD}}^{1/2}$$

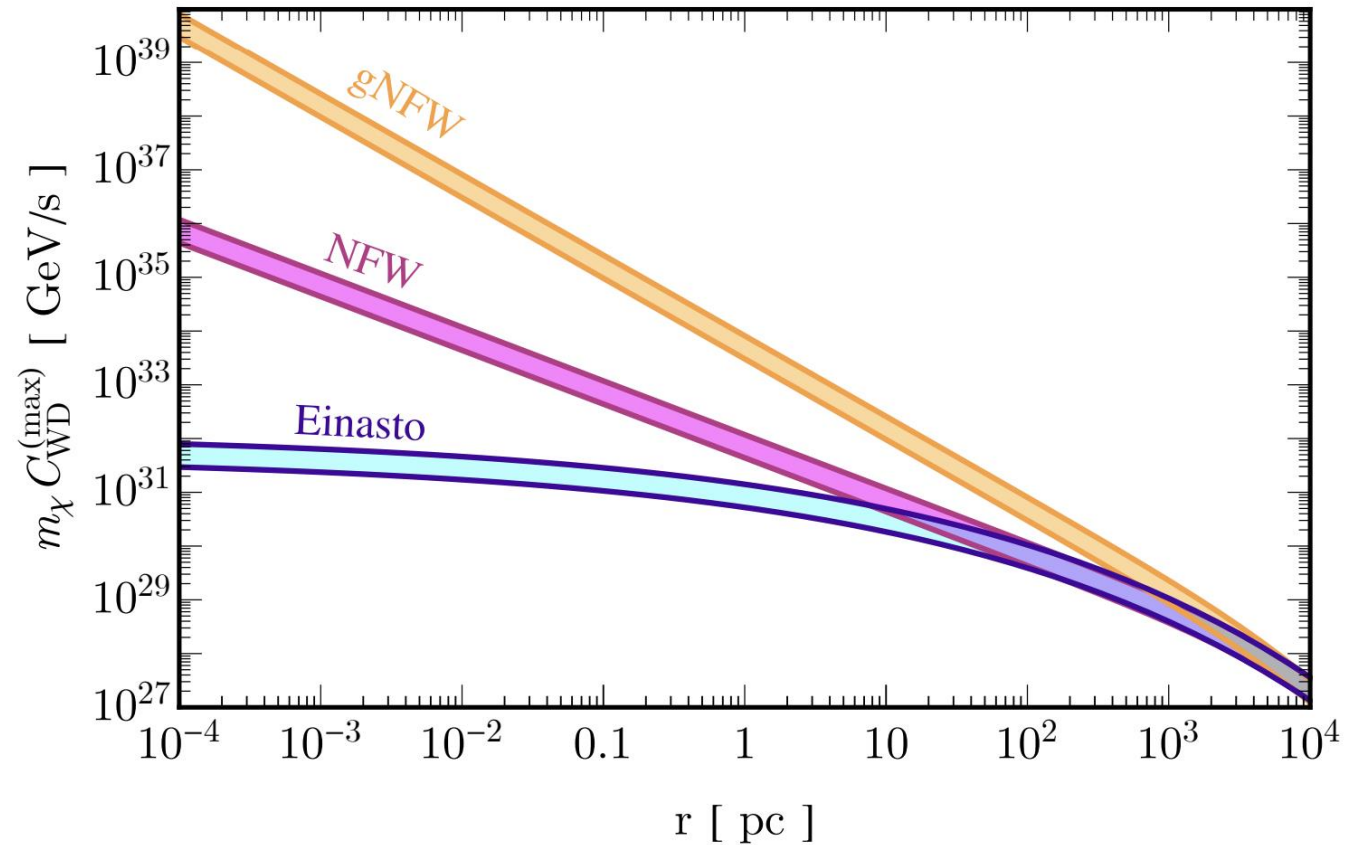
Improved capture framework for WDs



2. Set new limits on the DM-nucleon cross section

Dark matter density profiles

- Conservative (cored):
Einasto
- Intermediate: Navarro-Frenk-White (NFW)
- Optimistic (cuspy):
generalized NFW (gNFW)



Telescopes

Fermi Gamma-Ray Space Telescope (Fermi):

- All-sky exposure
- Sensitive to gamma rays from order 100 MeV to 100 GeV

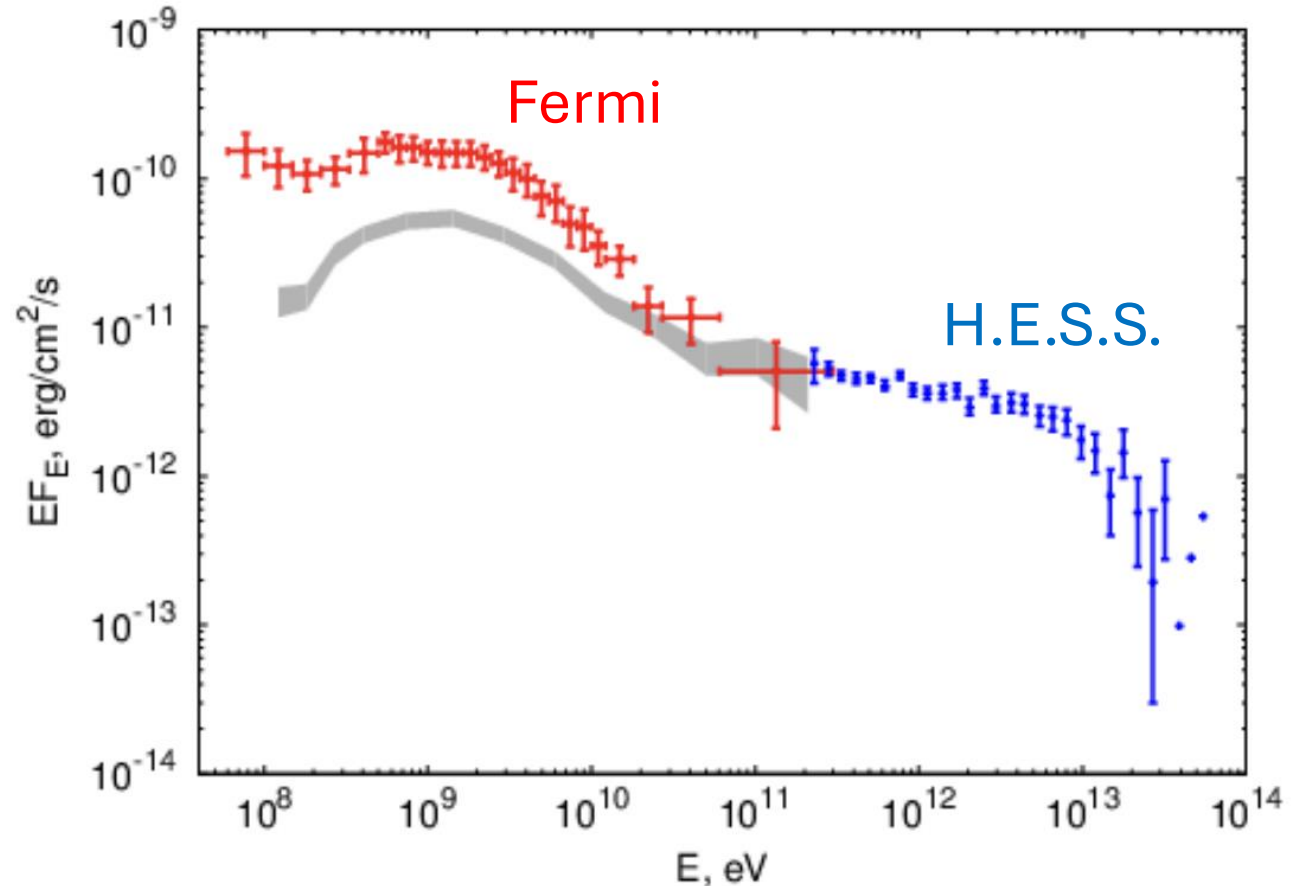
Telescopes

High Energy Stereoscopic System (H.E.S.S.):

- Located in central Namibia
- Good exposure to the Galactic center
- Sensitive to gamma rays of order 10 GeV to 100 TeV

Galactic center gamma-ray data

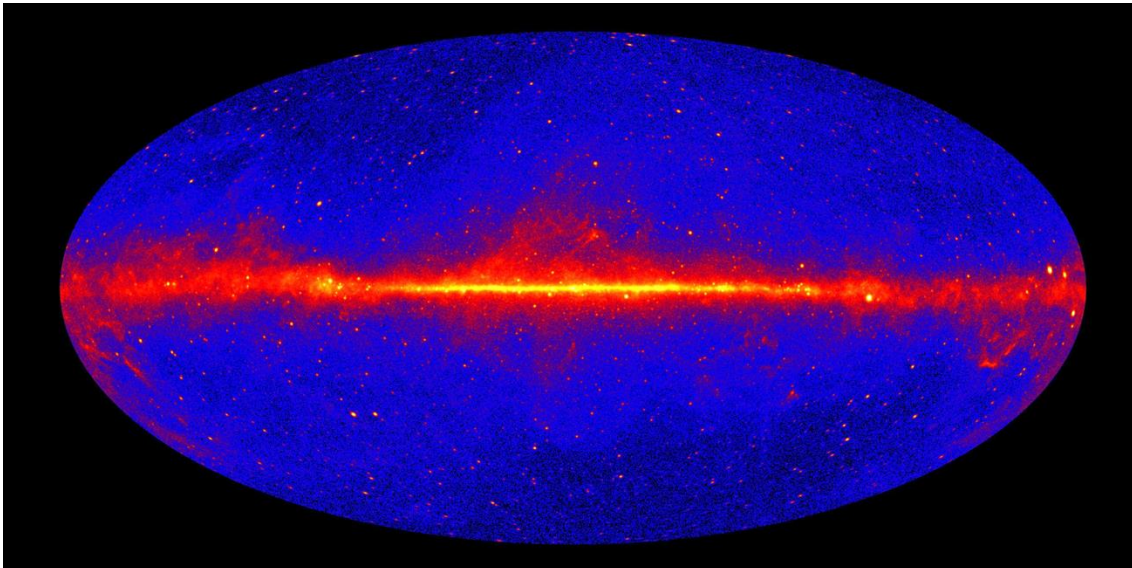
- The sensitivities of both telescopes complement each other well
- Can probe DM masses from 100 MeV to 100 TeV



D. Malyshev, M. Chernyakova, A. Neronov, R. Walter (1503.05120)

Total gamma-ray flux

$$\underbrace{\left(E^2 \frac{d\Phi}{dE} \right)_{\text{tot}}}_{\text{Total gamma-ray flux from Galactic center}} = \int_{r_{\text{min}}}^{r_{\text{max}}} \underbrace{n_{\text{WD}}(r)}_{\text{WD number density}} \underbrace{\left(E^2 \frac{d\Phi}{dE} \right)_{\text{WD}}}_{\text{Gamma-ray flux from individual WD}} 4\pi r^2 dr$$



Individual gamma-ray flux

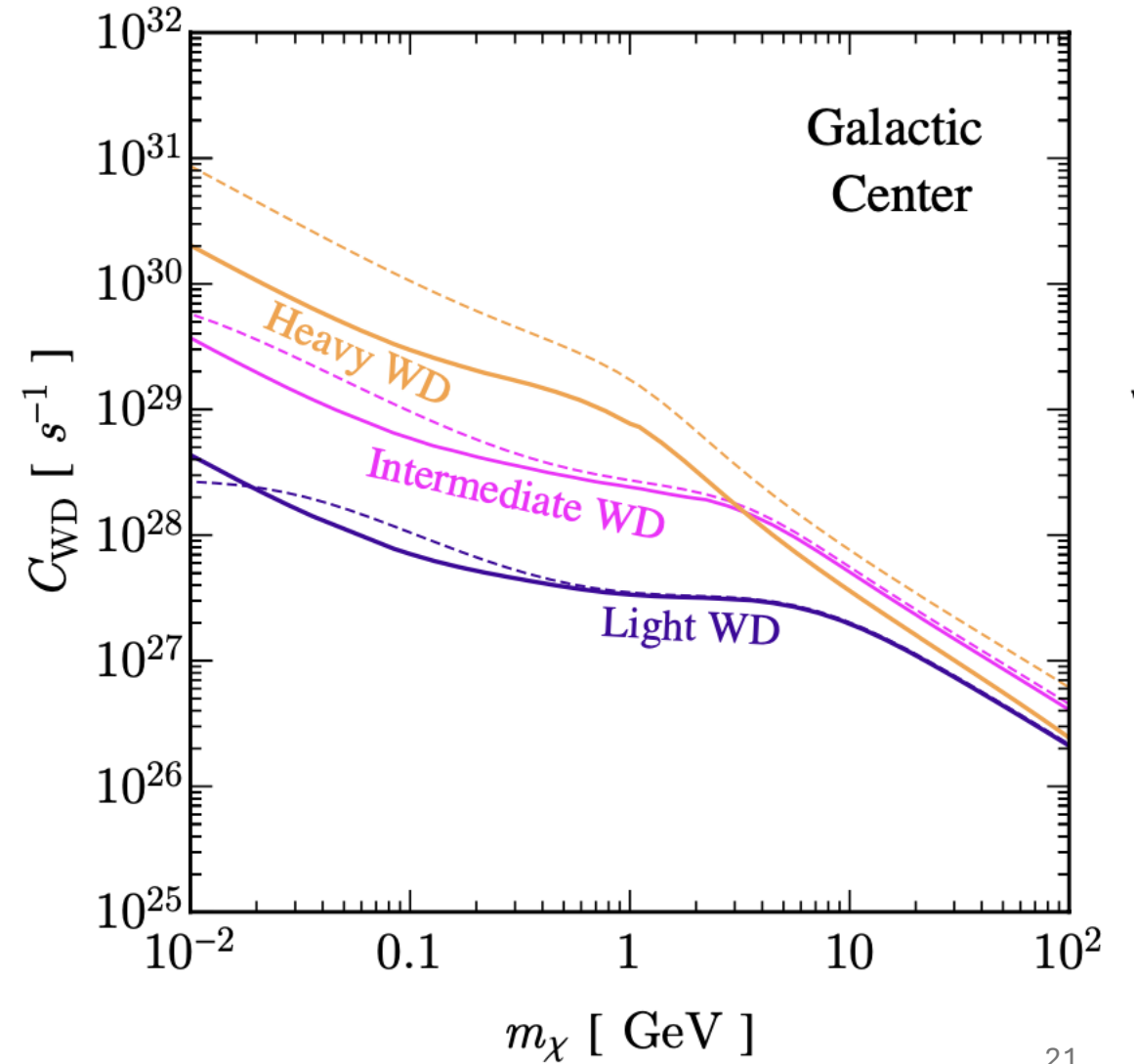
$$\left(E^2 \frac{d\Phi}{dE} \right)_{\text{WD}} \sim \frac{\Gamma_{\text{ann}}}{D^2} \times \underbrace{E^2 \frac{dN}{dE}}_{\text{Gamma-ray spectrum per DM annihilation}} \times \overbrace{\text{Br}(\phi \rightarrow \text{SM})}^{\text{Branching ratio}} \times P_{\text{surv}}$$

An arrow labeled "Annihilation rate" points to Γ_{ann} .
 An arrow labeled "Distance between WD and Earth" points to D^2 .
 An arrow labeled "Survival probability of mediator" points to P_{surv} .

Annihilation rate

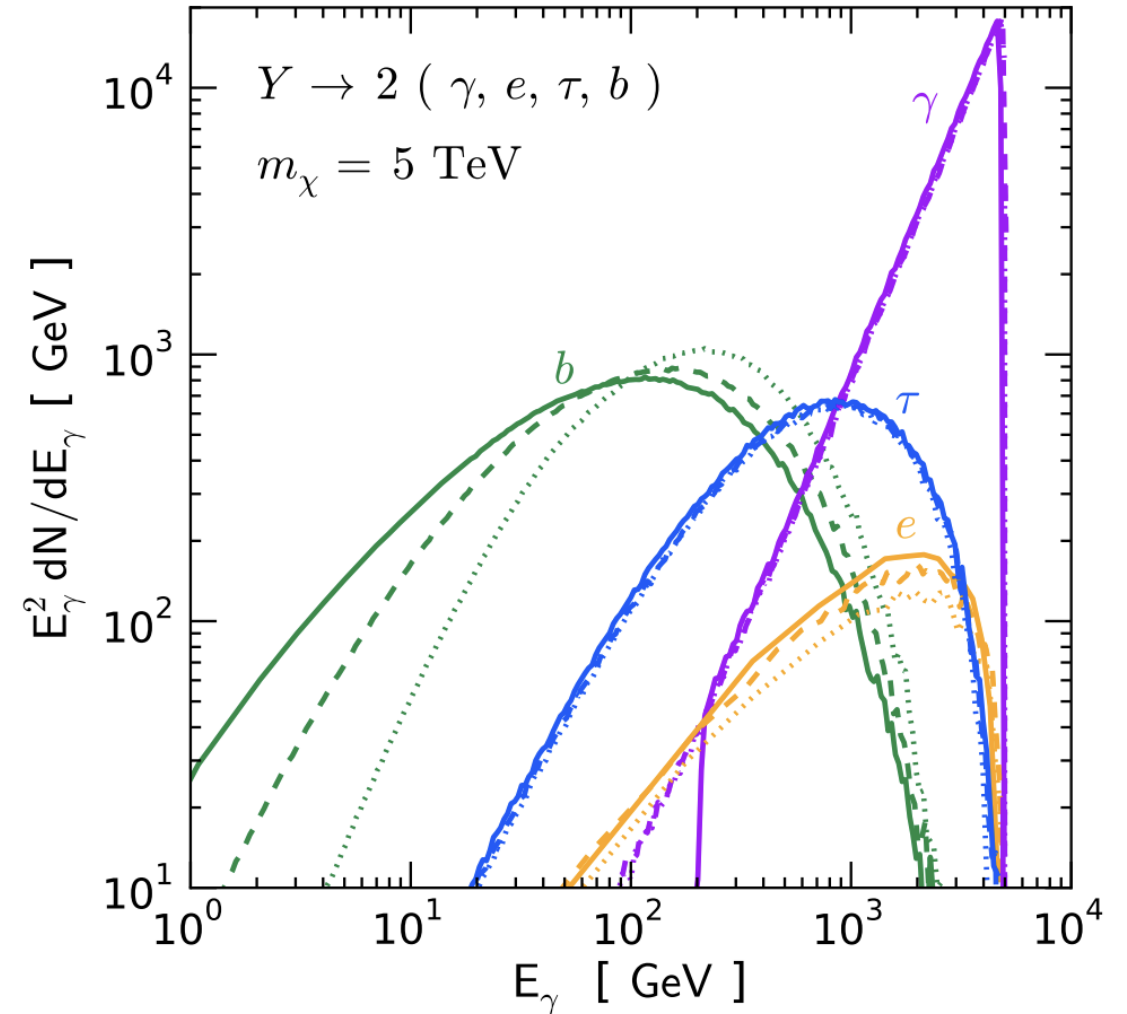
$$\left(E^2 \frac{d\Phi}{dE}\right)_{\text{WD}} \sim \frac{\Gamma_{\text{ann}}}{D^2} \times E^2 \frac{dN}{dE} \times \text{Br}(\phi \rightarrow \text{SM}) \times P_{\text{surv}}$$

$$\Gamma_{\text{ann}} = C_{\text{WD}}/2$$



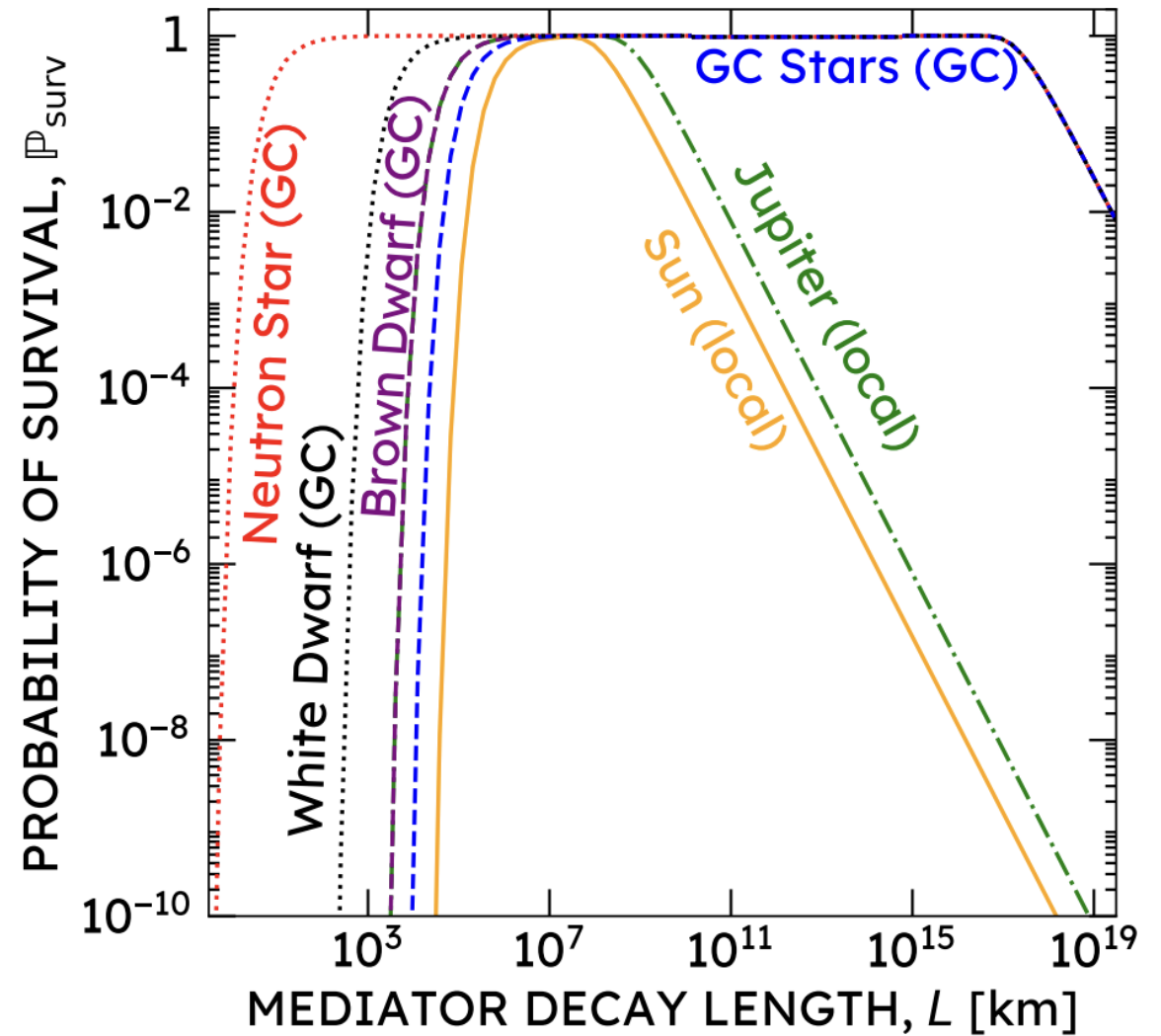
Spectrum per annihilation and branching ratio

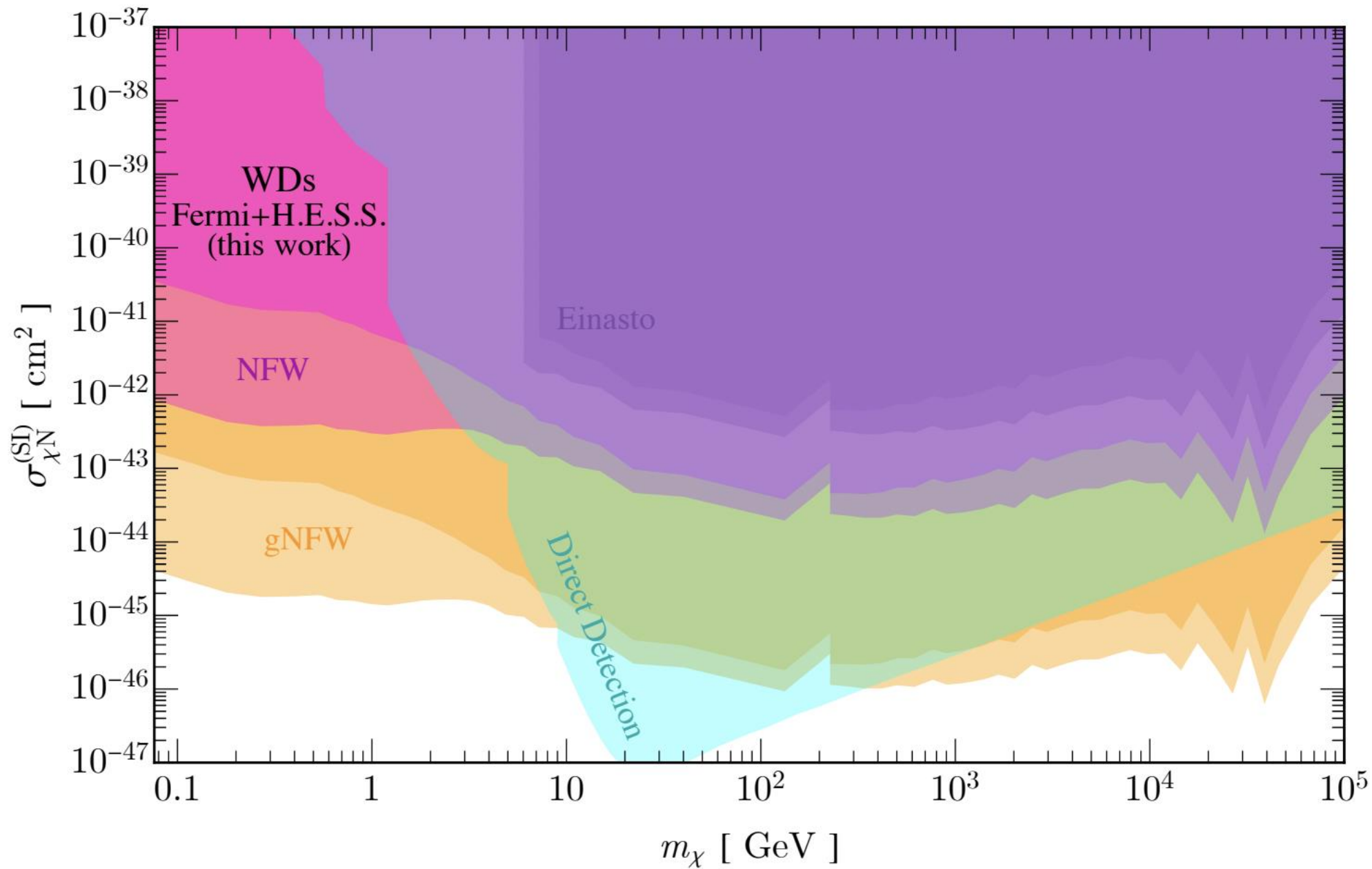
$$\left(E^2 \frac{d\Phi}{dE} \right)_{\text{WD}} \sim \frac{\Gamma_{\text{ann}}}{D^2} \times E^2 \frac{dN}{dE} \times \text{Br}(\phi \rightarrow \text{SM}) \times P_{\text{surv}}$$

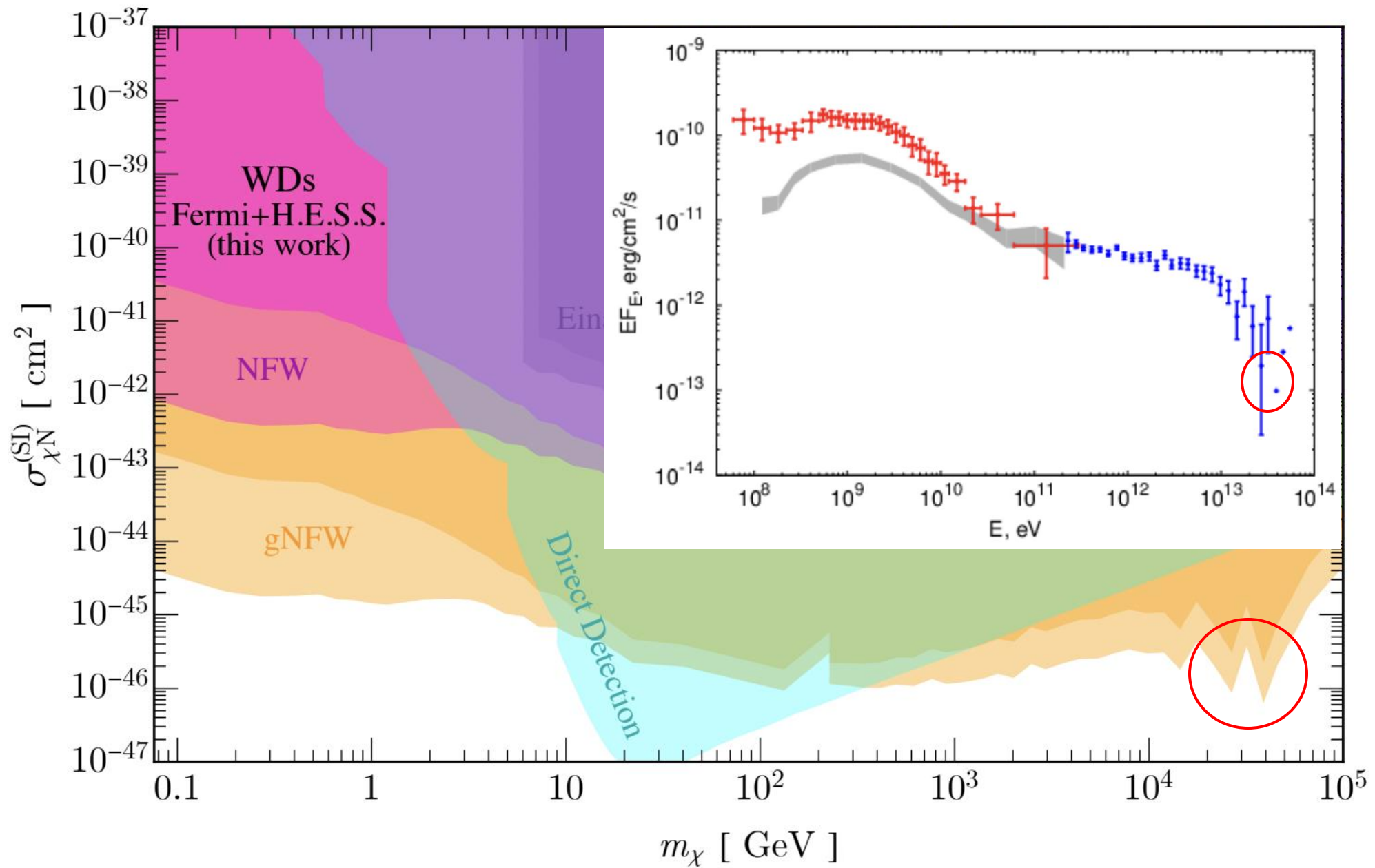


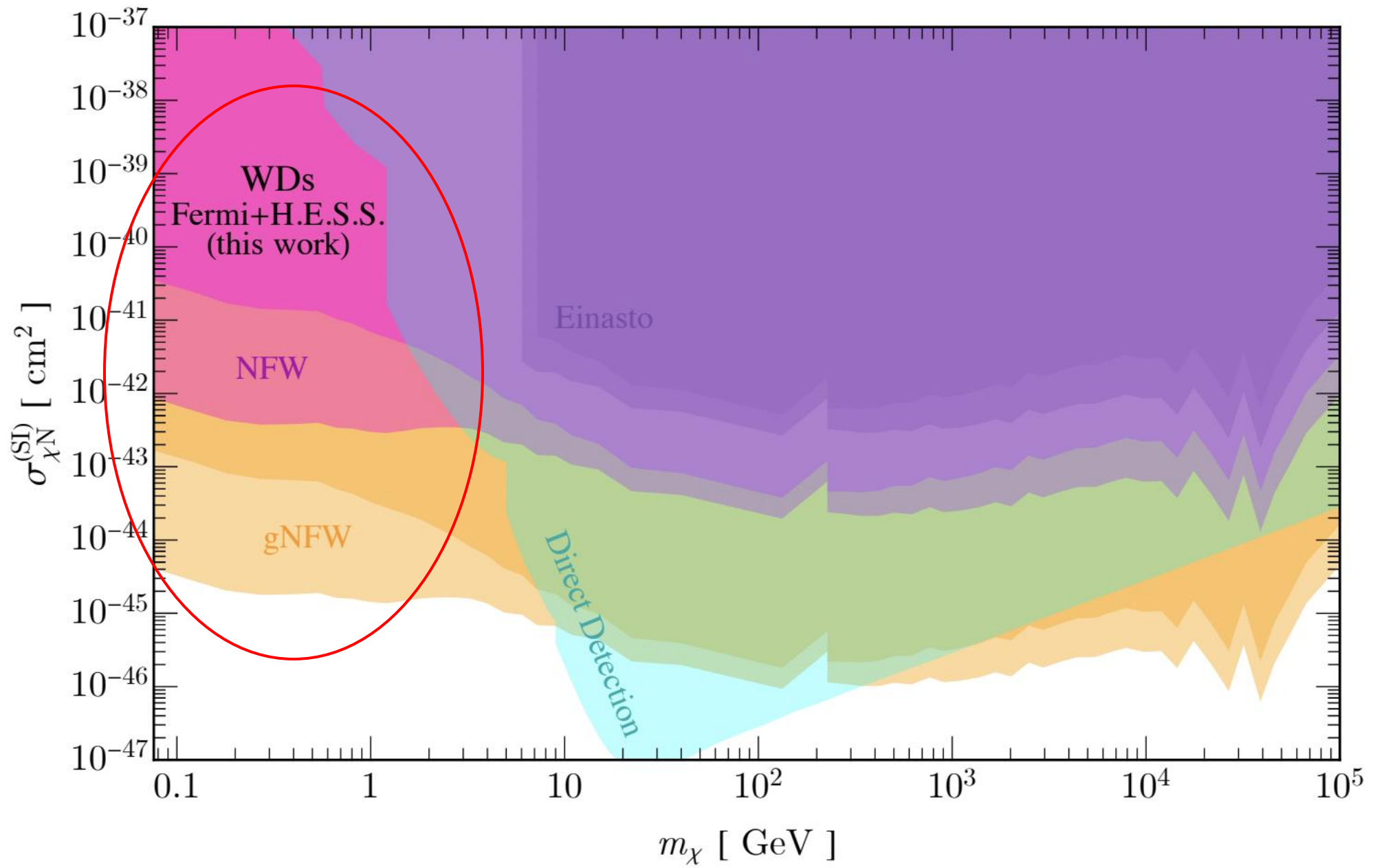
Survival probability

$$\left(E^2 \frac{d\Phi}{dE}\right)_{\text{WD}} \sim \frac{\Gamma_{\text{ann}}}{D^2} \times E^2 \frac{dN}{dE} \times \text{Br}(\phi \rightarrow \text{SM}) \times P_{\text{surv}}$$









Summary

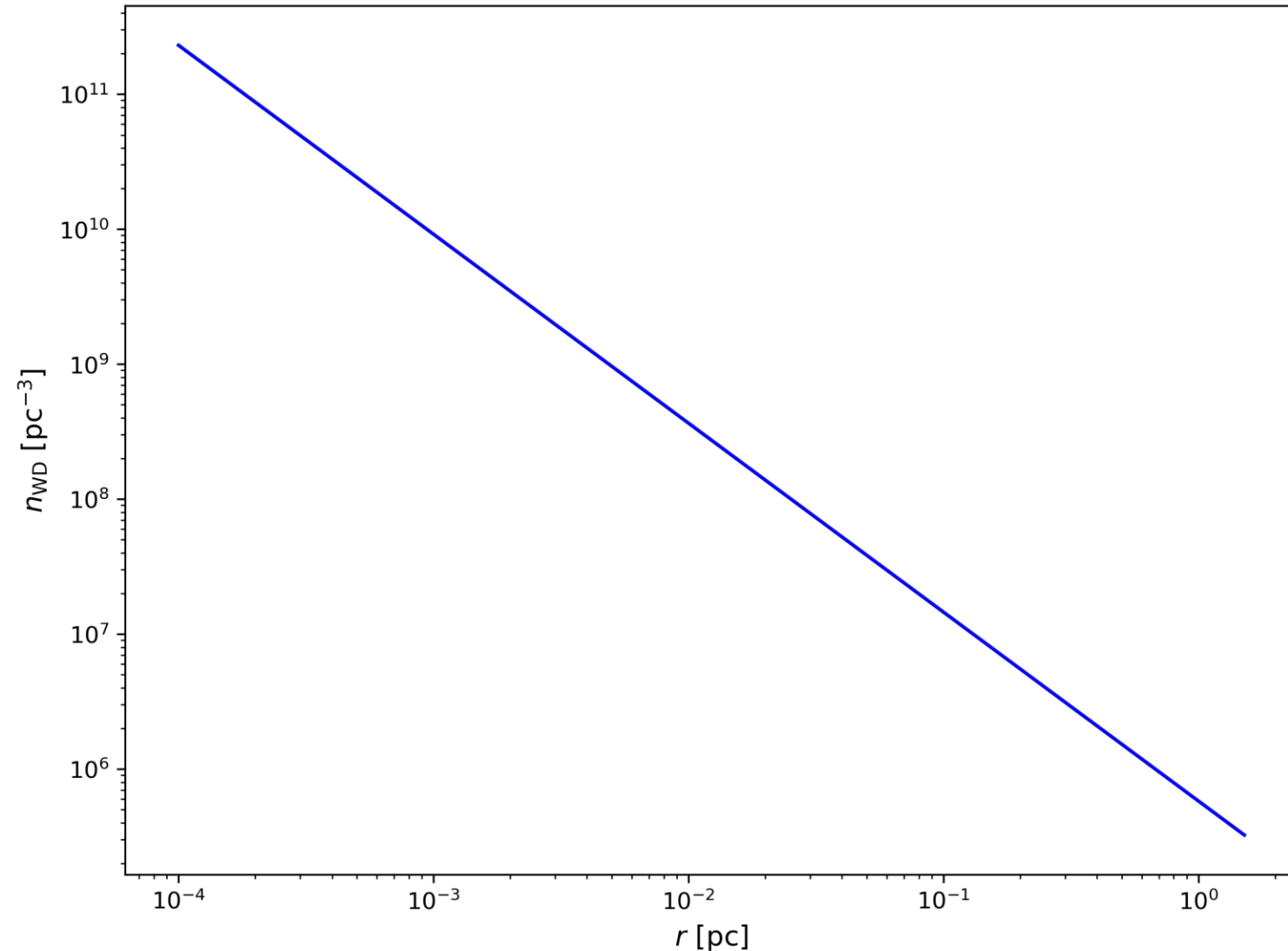
- White dwarfs are good celestial objects for DM searches because of their density and size, so they can capture a lot of DM
- We develop a new DM capture framework in WDs with an improved calculation of the ion velocity distribution
- We use this new framework and gamma-ray data from the Galactic center to constrain the DM-nucleon cross section
- Constraints from Galactic center WDs are stronger than existing limits by several orders of magnitude in the sub-GeV mass range



Backup



WD number density



- Power-law distribution, according to N-body simulations and mass segregation solutions
- Cuspy distributions favored by recent spectroscopic and photometric surveys
- Slope depends on star formation history, initial mass function, and initial-to-final mass relation for stellar remnants (we use 1.4)
- Normalization comes from analysis of different star formation scenarios in the Galactic center (including metallicity measurements from spectroscopic surveys)
- $\sim 10^6$ WDs predicted in central 1.5 pc

WD properties

BENCHMARK	MASS [M_{\odot}]	RADIUS [km]	CENTRAL DENSITY [g/cm^3]
Light Mass	0.49	9390	1.98×10^6
Intermediate Mass	1.00	5380	3.46×10^7
Heavy Mass	1.38	1250	1.14×10^{10}

EOS: Feynman-Metropolis-Teller (commonly used for DM capture by WDs)

Get resulting WD configuration using EOS and the Tolman-Volkoff-Oppenheimer equation

Assume WD ages greater than about 3 Gyr

WD properties

- Composition:
 - Carbon-12
 - Oxygen-16
 - For heavier WDs, can include heavier elements
- Carbon-Oxygen WDs more prevalent in Galactic center according to N-body simulations
- We assume WDs made solely of carbon to remain conservative (lower nucleon number means smaller coherent enhancement to cross section)

Ion velocity distribution

$$\mathcal{F}_{\text{ion}}(v_N) = \left(\frac{m_N}{\pi \omega_p \coth(\omega_p/2T_{\text{WD}})} \right)^{3/2} \exp \left[-\frac{m_N v_N^2}{\omega_p \coth(\omega_p/2T_{\text{WD}})} \right]$$

$$\langle v_N^2 \rangle = 4\pi \int_0^\infty dv_N v_N^4 \mathcal{F}_{\text{ion}}(v_N) = \left(\frac{3\omega_p}{2m_N} \right) \coth \left(\frac{\omega_p}{2T_{\text{WD}}} \right)$$

$$\omega_p = \left(\frac{4\pi Z^2 e^2 n_N}{m_N} \right)^{1/2}$$

Capture rate

$$\mathcal{F}_{\text{rel}}(u_\chi) = \frac{u_\chi}{v_{\text{WD}}} \left(\frac{3}{2\pi(v_d^2 + \langle v_N^2 \rangle)} \right)^{1/2} \left[\exp\left(-\frac{3(u_\chi - v_{\text{WD}})^2}{2(v_d^2 + \langle v_N^2 \rangle)}\right) - \exp\left(-\frac{3(u_\chi + v_{\text{WD}})^2}{2(v_d^2 + \langle v_N^2 \rangle)}\right) \right]$$

$$C_{\text{WD}} = \frac{\rho_\chi}{m_\chi} \int_0^{R_{\text{WD}}} dr 4\pi r^2 \int_0^\infty du_\chi \frac{w(r)}{u_\chi} \mathcal{F}_{\text{rel}}(u_\chi) \Omega^-(w)$$

$$\Omega^-(w) = \int_0^{v_{\text{esc}}(r)} dv R^-(w \rightarrow v)$$

$$R^-(w \rightarrow v) = \int_0^\infty ds \int_0^\infty dt 32\pi\mu_+^4 \frac{vt}{w} \frac{d\sigma_{N\chi}}{d\cos\theta} n_N(r) \mathcal{F}_{\text{ion}}(v_N) \Theta(t + s - w) \Theta(v - |t - s|)$$

$$\frac{d\sigma_{N\chi}}{d\cos\theta} = A^4 \left(\frac{m_\chi + m_n}{m_\chi + Am_n} \right)^2 |F_{\text{helm}}(E_R)|^2 \sigma_{n\chi}$$

Maximum capture rate

$$C_{\text{WD}}^{(\text{max})} = \frac{\pi R_{\text{WD}}^2 \rho_{\chi}}{3v_{\text{WD}} m_{\chi}} \left[(3v_{\text{esc}}^2(R_{\text{WD}}) + 3v_{\text{WD}}^2 + v_d^2) \operatorname{erf} \left(\sqrt{\frac{3}{2}} \frac{v_{\text{WD}}}{v_d} \right) + \sqrt{\frac{6}{\pi}} v_{\text{WD}} v_d \exp \left(-\frac{3v_{\text{WD}}^2}{2v_d^2} \right) \right]$$

Equilibrium timescales

$$t_{\text{eq}} = \sqrt{\frac{V}{\langle \sigma_{\text{ann}} v_{\text{rel}} \rangle C_{\text{WD}}}}$$

V = full volume of our light white dwarf, to be conservative

$$t_{\text{eq}} \simeq \begin{cases} 6 \times 10^{-3} \text{ Gyr} & s\text{-wave} \\ 0.6 \text{ Gyr} \left(\frac{10^{-2} c}{v_{\text{rel}}} \right) & p\text{-wave} \end{cases}$$

Values for $\sigma \sim 10^{-47} \text{ cm}^2$ and DM mass of 40 TeV, assuming $r = 1.5 \text{ pc}$ and gNFW (conservative because it's the lowest value for which we get observable gamma-ray signal)

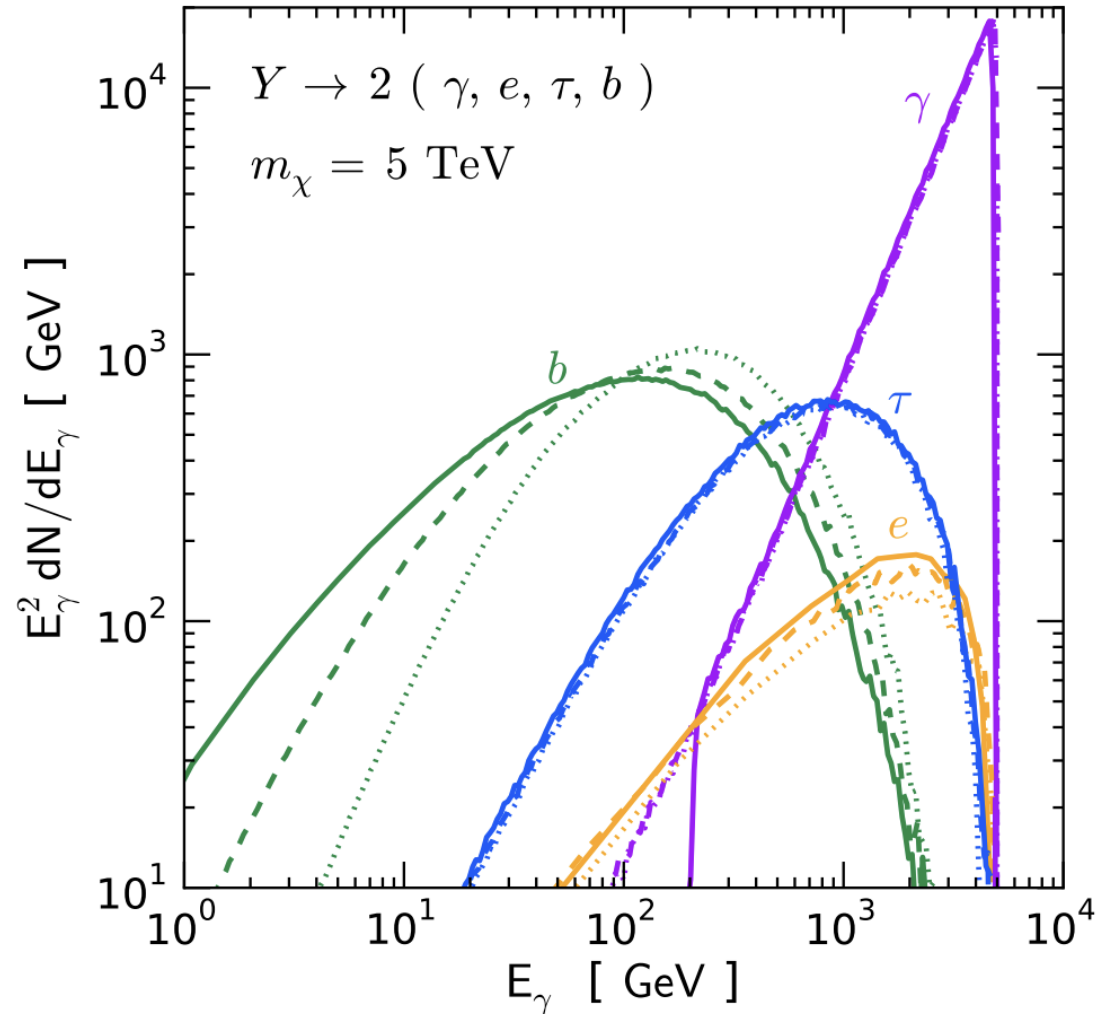
Gamma-ray spectrum per DM annihilation

$$\frac{dN}{dE} = \frac{4}{\Delta E} \Theta(E - E_-) \Theta(E_+ - E)$$

$$\Delta E = E_+ - E_- = \sqrt{m_\chi^2 - m_\phi^2}$$

$$E_\pm = \frac{m_\chi}{2} \left(1 \pm \sqrt{1 - \frac{m_\phi^2}{m_\chi^2}} \right)$$

$$m_\phi = 10^{-3} m_\chi$$



Survival probability

$$P_{\text{surv}} = \exp\left(-\frac{R_{\text{WD}}}{L}\right) - \exp\left(-\frac{D}{L}\right)$$