Dark Matter Interactions in White Dwarfs: A Multi-Energy Approach to Capture Mechanisms

J. Hoefken Zink, S. Hor, and M. E. Ramirez-Quezada. arXiv: 2410.13908 [hep-ph]

Shihwen Hor

The University of Tokyo

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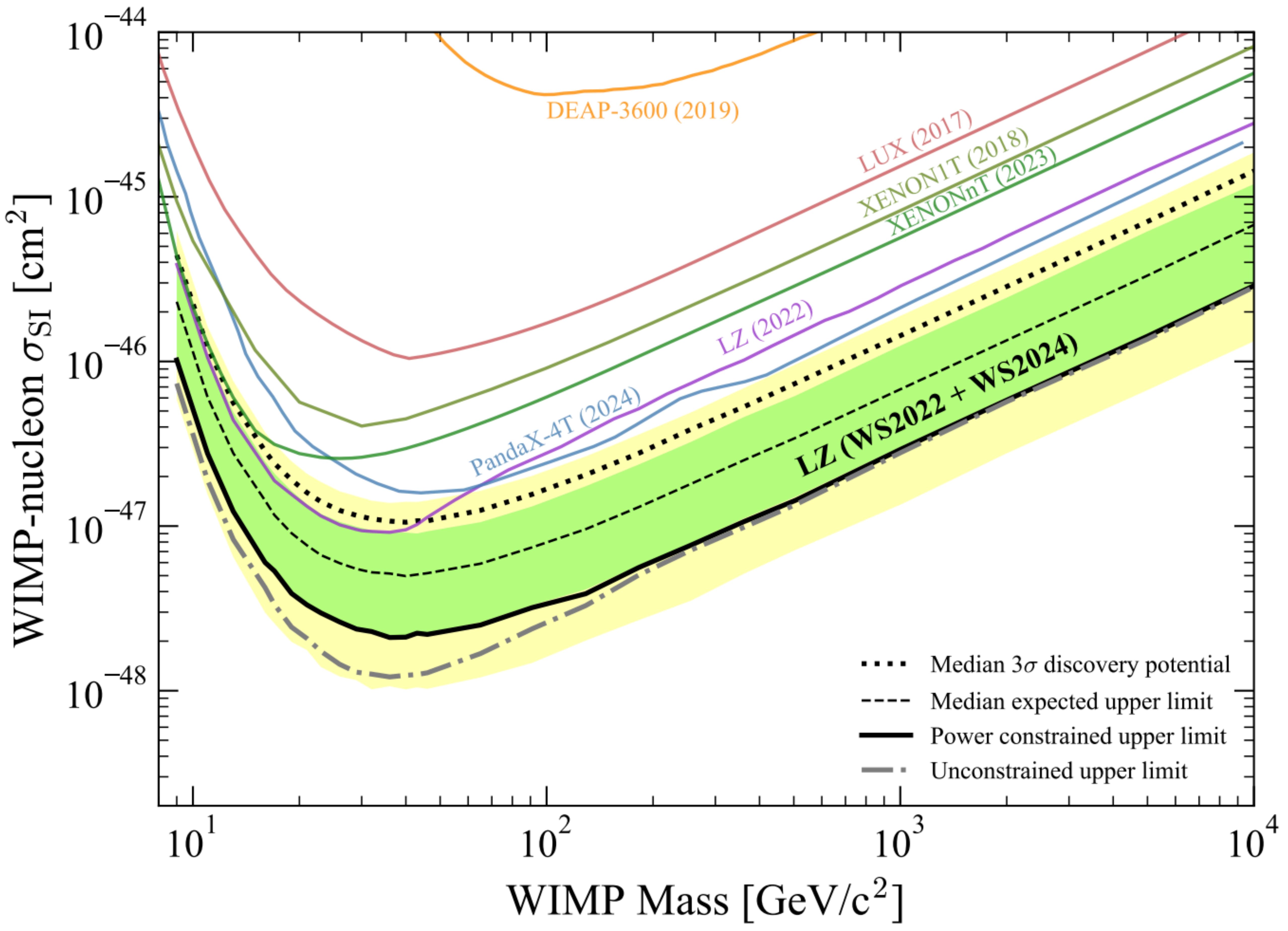
Outlines

* 1. Introduction
* 2. Boosted dark matter capture
* 3. Dark matter scattering-cross sections
* 4. Results: cross sections and capture rates
* 5. Summary

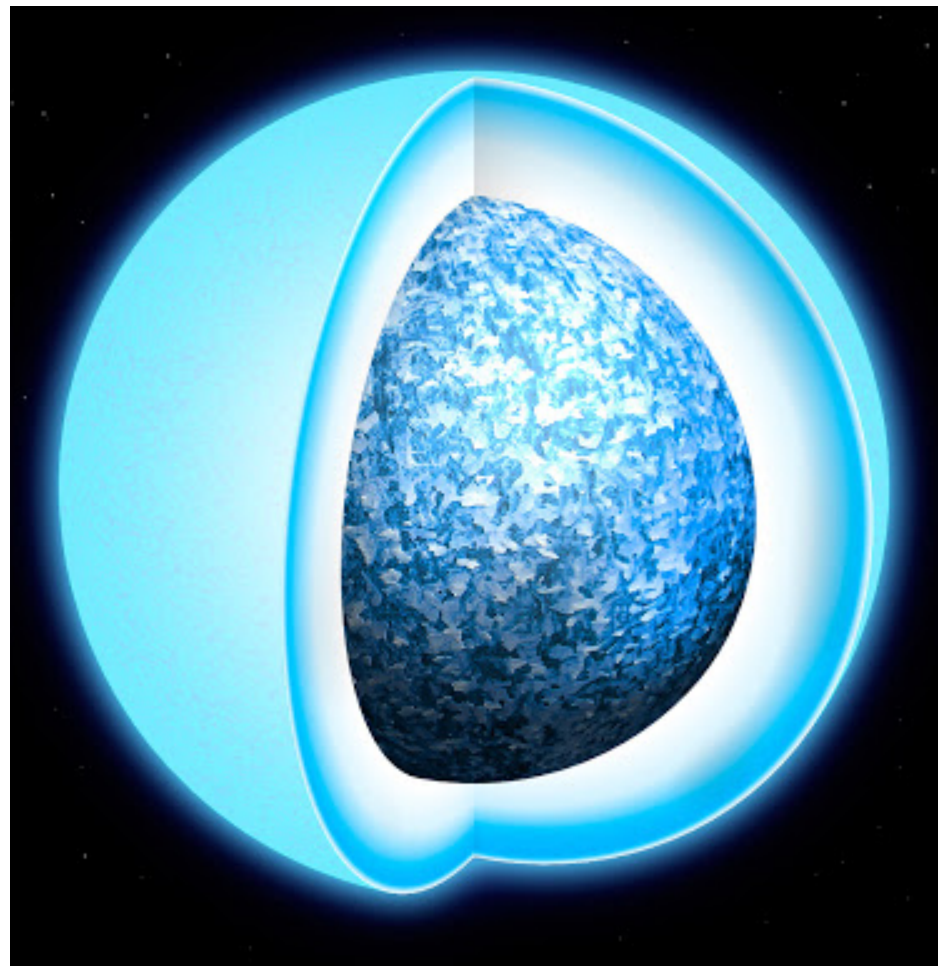
1. Introduction

Dark matter detection



[The LUX-ZEPLIN Collaboration, arXiv: 2410.17036 [hep-ex]]

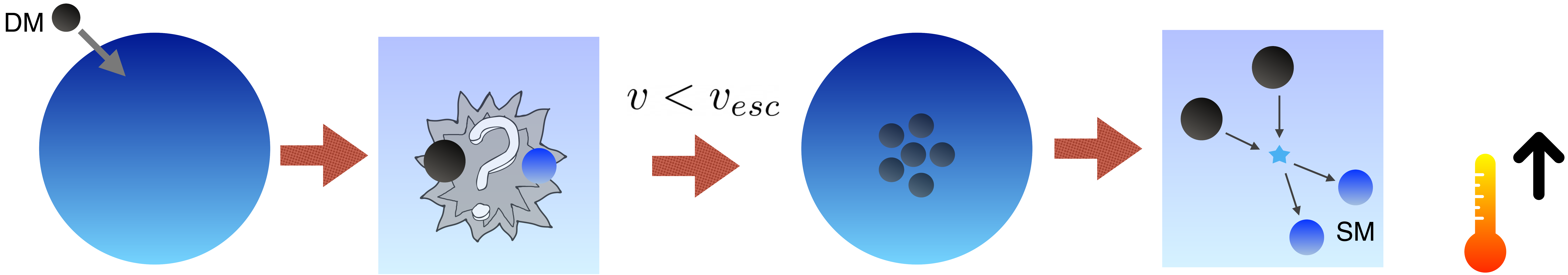
White dwarfs



* White dwarfs: final state of massive stars (below $M_\star \sim 8M_\odot - 10M_\odot$) after collapsing gravitationally
* Composed of carbon (C) and oxygen (O) and possesses an atmosphere either H or He dominated
* No fusion: the only support against gravitational collapse is the electron degeneracy pressure
* DM-nucleon scattering can probe the sub-GeV regime (beyond the reach of the direct detection)

Dark matter capture by compact stars

* Heating of compact objects: DM can accumulate in the core of compact stars, heat them up and hence generate an observable signal



Compact Stars

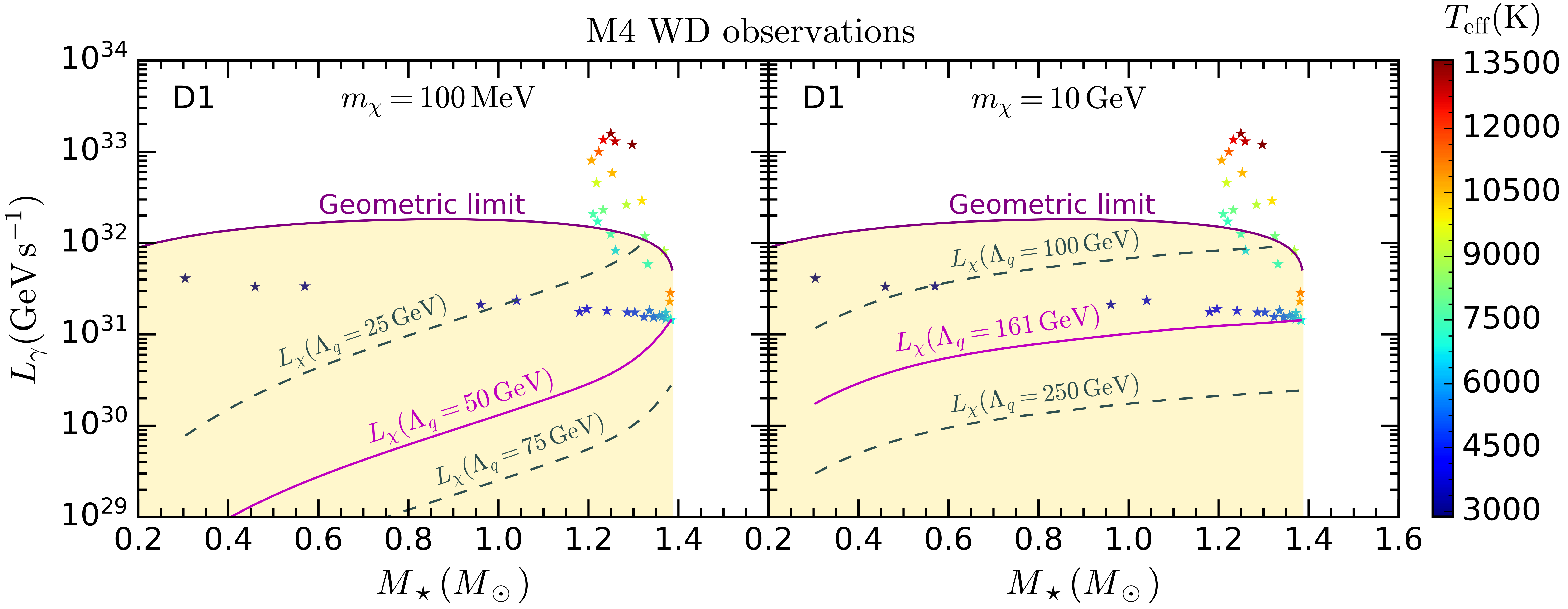
Nucleons & leptons

DM accumulates in the core

DM annihilates to SM particles: Injected heat

White dwarfs capture rate

- Assuming DM capture and annihilation are in equilibrium, the star luminosity due to DM is $L_\chi = m_\chi C(m_\chi)$ ($C(m_\chi)$: capture rate)
- The WD observed luminosity $L_\gamma \geq L_\chi$



[N. Bell, G. Busoni, S. Robles, M. E. Ramirez-Quezada, M. Virgato *JCAP 10 (2021), 083*]

Boosted DM

- Local DM: low DM density —> challenging

[J. W. Wang, A. Graneli, and P. Ulio. Phys. Rev. Lett. 128 (2022) 221104.]

- Boosted DM (high-density flux): improve the bounds for light DM candidates in direct detection experiments
  - Boosting source: blazars, cosmic rays, diffuse supernova neutrino background
  - Relativistic
- **A multi-energy approach to the WD capture**
  - A flux with a particular energy

2. Boosted DM Capture

Capture rate and density

* Capture rate $C = \frac{\rho_\chi}{m_\chi} \int_0^{R\star} dr 4\pi r^2 \int_0^\infty du_\chi \frac{\omega}{u_\chi} f_{\rm MB}(u_\chi) \Omega^-(\omega)$, $\Omega^-(\omega) = \frac{4}{\sqrt{\pi}} \int_0^{v_e} dv \frac{d\sigma}{dv} \omega^2 n_T(r)$.
* Multi-energy approach: **cross section** (different energy regimes) & **flux**
* DM flux: We assume **delta function** of a particular energy from all directions
    * **Capture rate density** (DM density as a free parameter): $\mathscr{C} = \rho_\chi^{-1} C$
        * $\mathscr{C} = \frac{1}{m_\chi} \int_0^{R\star} dr 4\pi r^2 \int_0^\infty du'_\chi \frac{\omega}{u'_\chi} \delta(u'_\chi - u_\chi)\, \Omega^-(\omega)$.
        * Geometric / Optically thick limit (maximum capture probability $\Omega^-(\omega) \to 1$):
$$\mathscr{C}_{\rm geom} = \frac{\pi R_\star^2}{m_\chi} \int_0^\infty du'_\chi \frac{\omega}{u'_\chi} \delta(u'_\chi - u_\chi) .$$

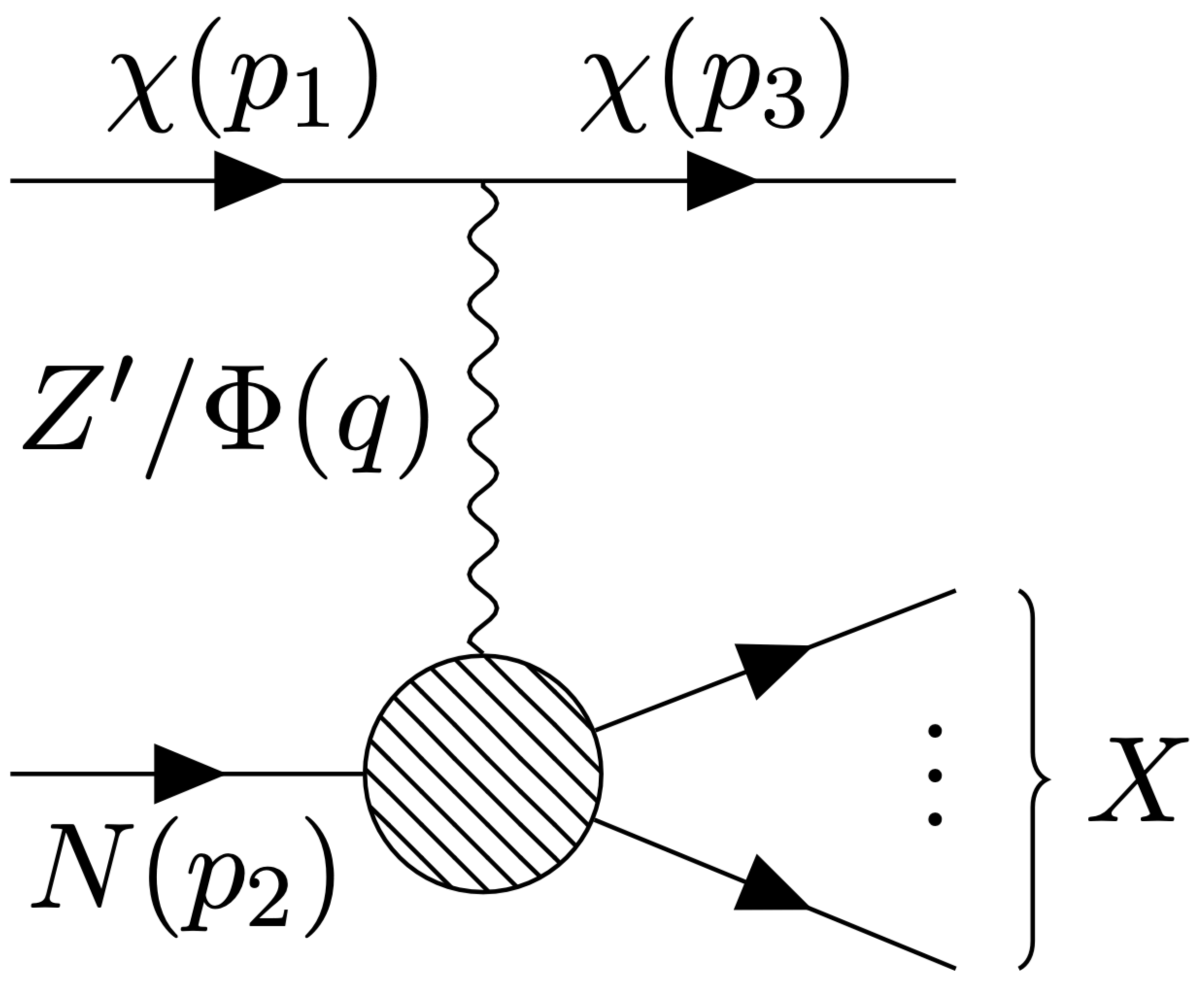
3. DM Scattering-Cross Sections

DM model

* Inspired by **Three-Portal Model** [P. Ballett, M. Hostert, and S. Pascoli. Phys. Rev. D 101 (2020) 115025.]
  * A vectorial, a scalar, and neutrino portal
  * A new U(1)X symmetry: spontaneously broken
  * Fermionic DM interactions with SM fields through a vector or a scalar interaction
  * **A dark photon** Z' : additional broken gauge boson
  * **A complex singlet** Φ : charged under U(1)X, acquires a VEV
* The Lagrangian we consider
  * $\mathscr{L}_{Z'} = -\epsilon e Q_{\mathrm{EM}} J^{\mu}_{\mathrm{EM}} Z'_{\mu} + g_D \bar{\chi}\gamma^{\mu}(g^{\chi}_{V} - g^{\chi}_{A}\gamma^5)\chi Z'_{\mu}$,
  * $\mathscr{L}_{\Phi} = g^{ij}_{\Phi}\overline{\psi}^{i}_{\mathrm{SM}}\psi^{j}_{\mathrm{SM}}\Phi + g_D\bar{\chi}\chi\Phi$.

Deep inelastic scattering

- DM: **high incoming-energy** beyond the mass of the nucleons
- Deep inelastic scattering (**DIS**)
  - The valence quarks and the sea quarks become visible
  - Partons: carry a fraction of the total momentum of the nucleon
  - A hadronic shower
  - $\chi q \rightarrow \chi X$



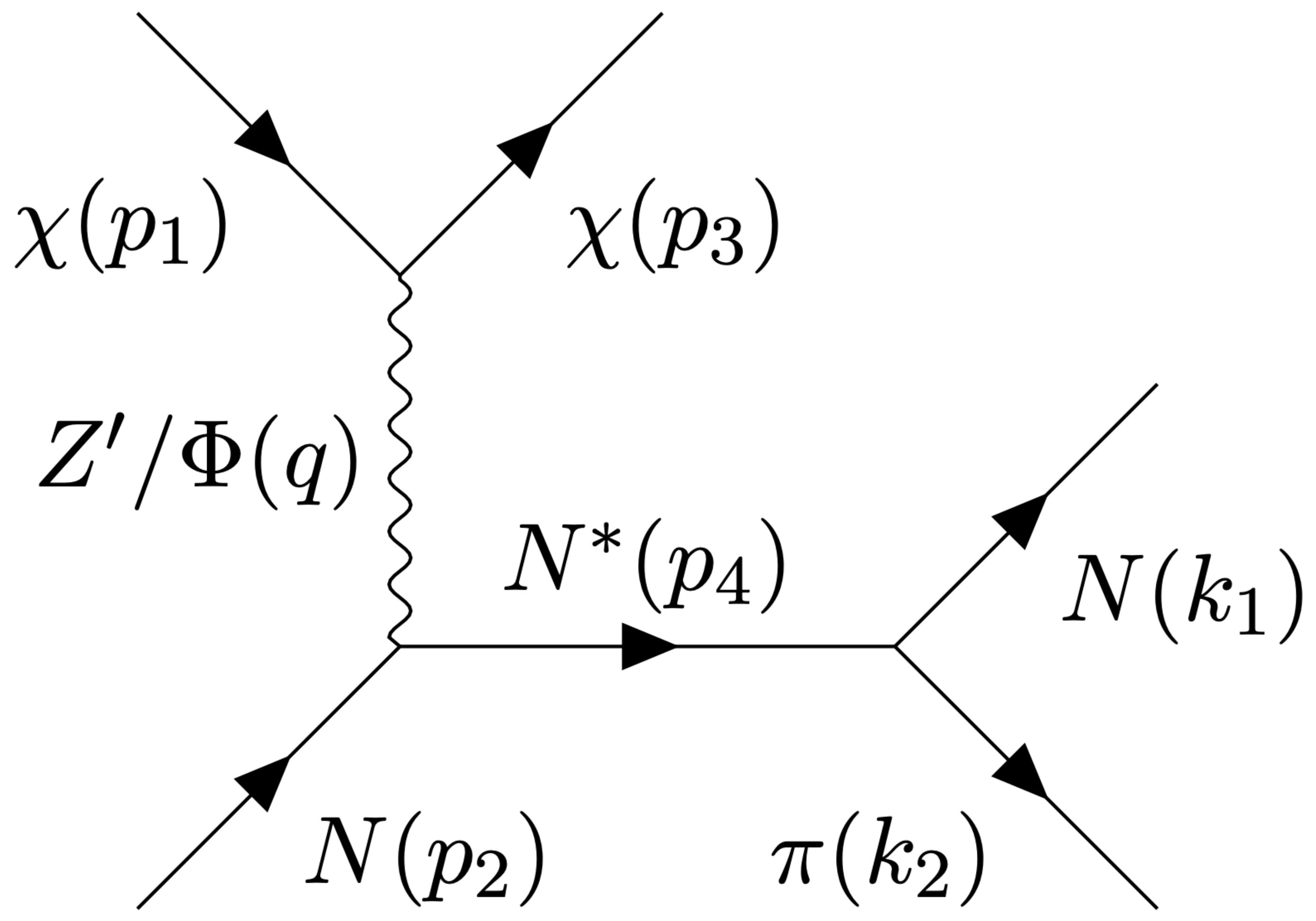
Resonant scattering

* An inelastic interaction with a nucleon that produces a resonance that further decays into a nucleon and a pion

* $\chi + N \to \chi + N^* \to \chi + N + \pi \,.$

* Neutral mediators (dark photon or scalar) have four possible channels:

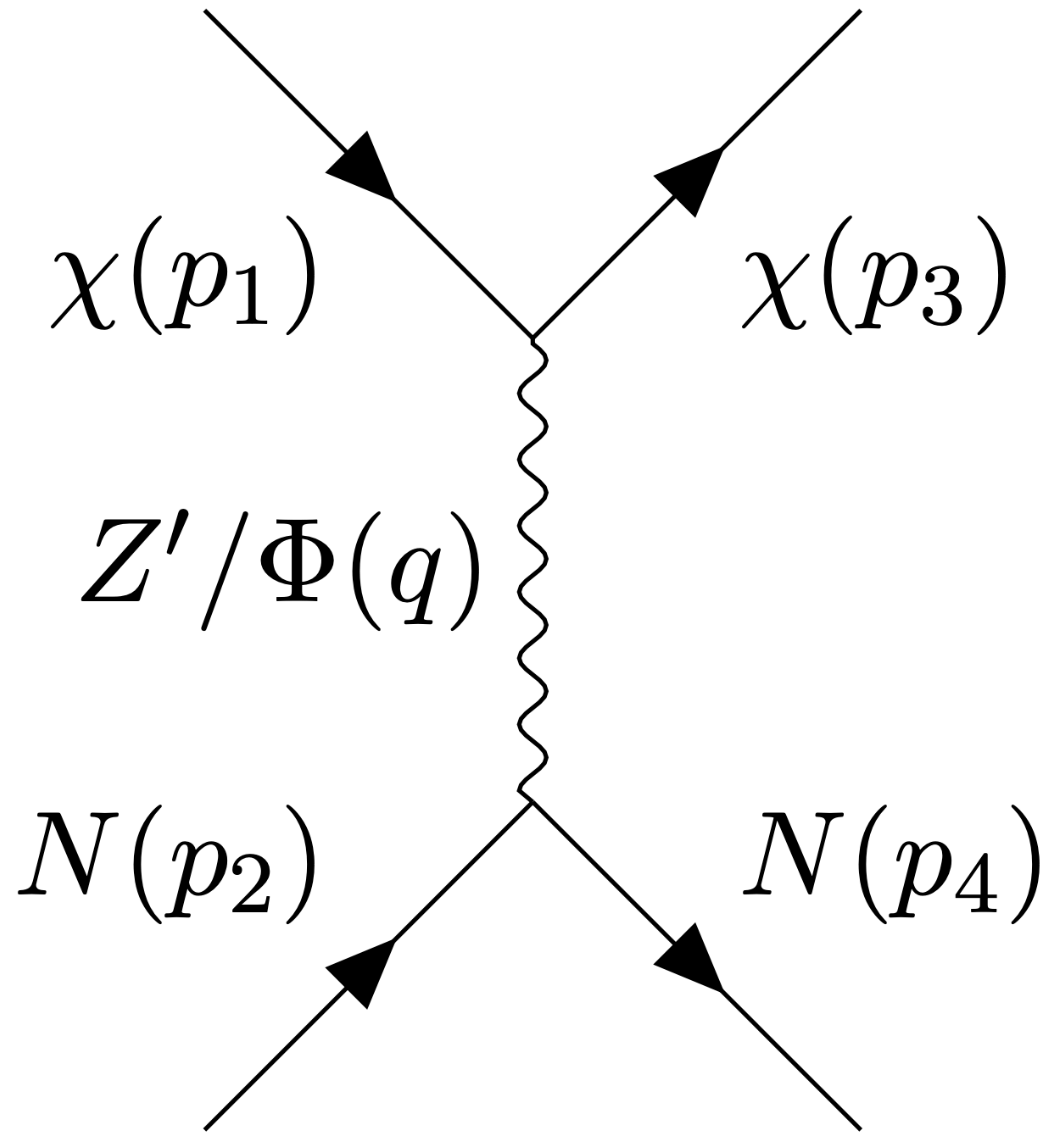
  * $\chi + p \to \chi + p + \pi^0 \;,$
  * $\chi + p \to \chi + n + \pi^+ \;,$
  * $\chi + n \to \chi + n + \pi^0 \;,$
  * $\chi + n \to \chi + p + \pi^- \;.$



[D. Rein and L. M. Sehgal. Annals Phys. 133, 79 (1981).]
[C. Berger and L. M. Sehgal, Phys. Rev. D 76, 113004 (2007).]
[K. S. Kuzmin, V. V. Lyubushkin, and V. A. Naumov, Mod. Phys. Lett. A 19, 2815 (2004).]

Elastic scattering on nucleons and nuclei

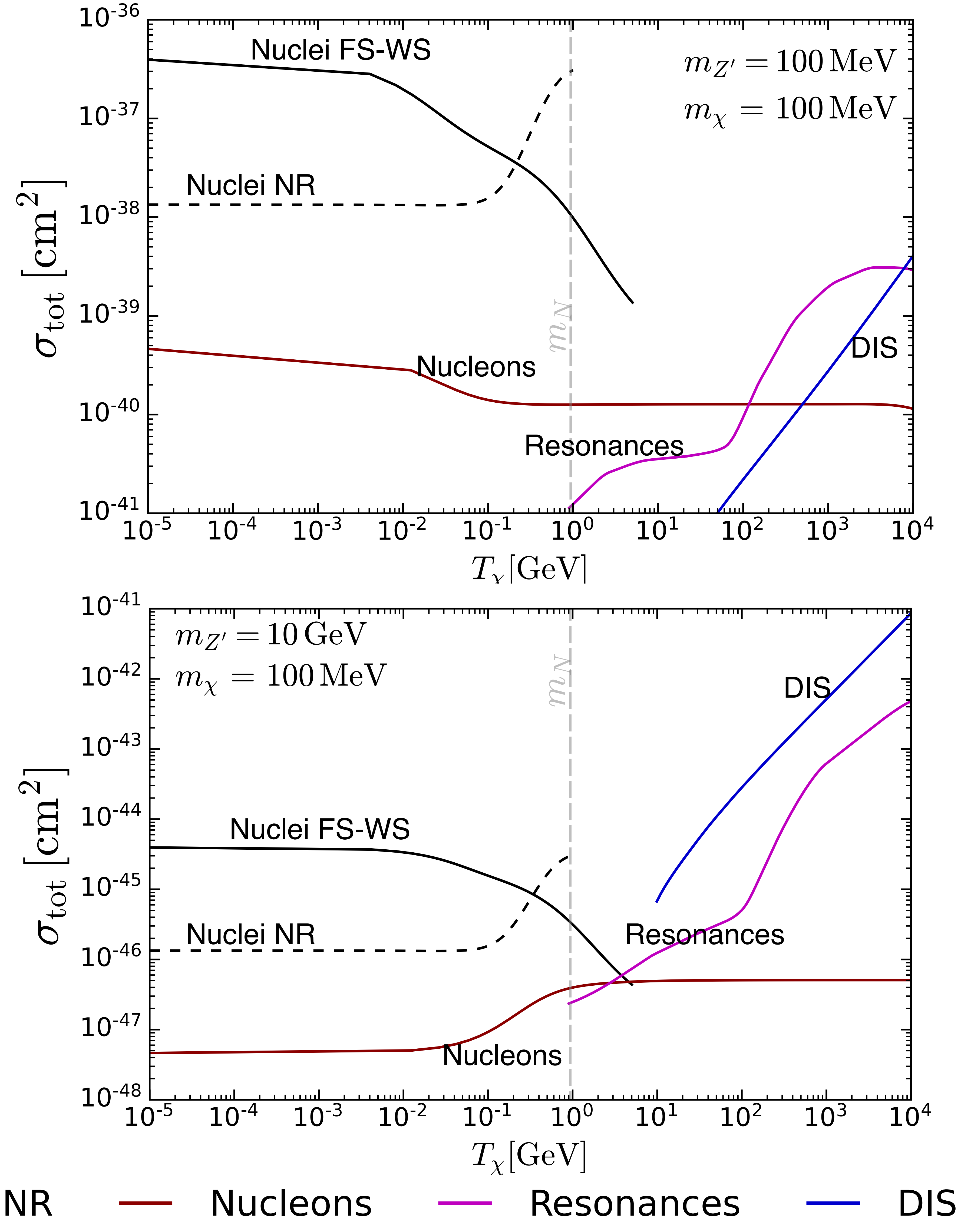
* Elastic interactions with nucleons
  * The DM incoming-energies are lower than those required for DIS
  * Form factor approach
    [J. D. Walecka, Vol. 16 (Cambridge University Press, 2001)]
* Elastic interactions with nuclei
  * Low-energy regime
  * Fermi-Symmetrized Woods-Saxon (**FS-WS**) form factor
    [M. Grypeos, G. Lalazissis, S. Massen, and C. Panos, Journal of Physics G: Nuclear and Particle Physics 17, 1093 (1991).]
  * A comprehensive treatment of 15 types of **non-relativistic (NR) operators** [R. Catena and B. Schwabe, JCAP 04, 042 (2015).]



4. Results: Cross Sections and Capture Rates

Vector cross sections

- High-energy regime
  - Resonant scattering dominates for lighter mediators
  - DIS dominates for heavier mediators
- Low-energy regime
  - Nuclei FS-WS or nuclei NR dominates
  - Cross sections do not depend on the kinetic energy on the limit $T_\chi \to 0$



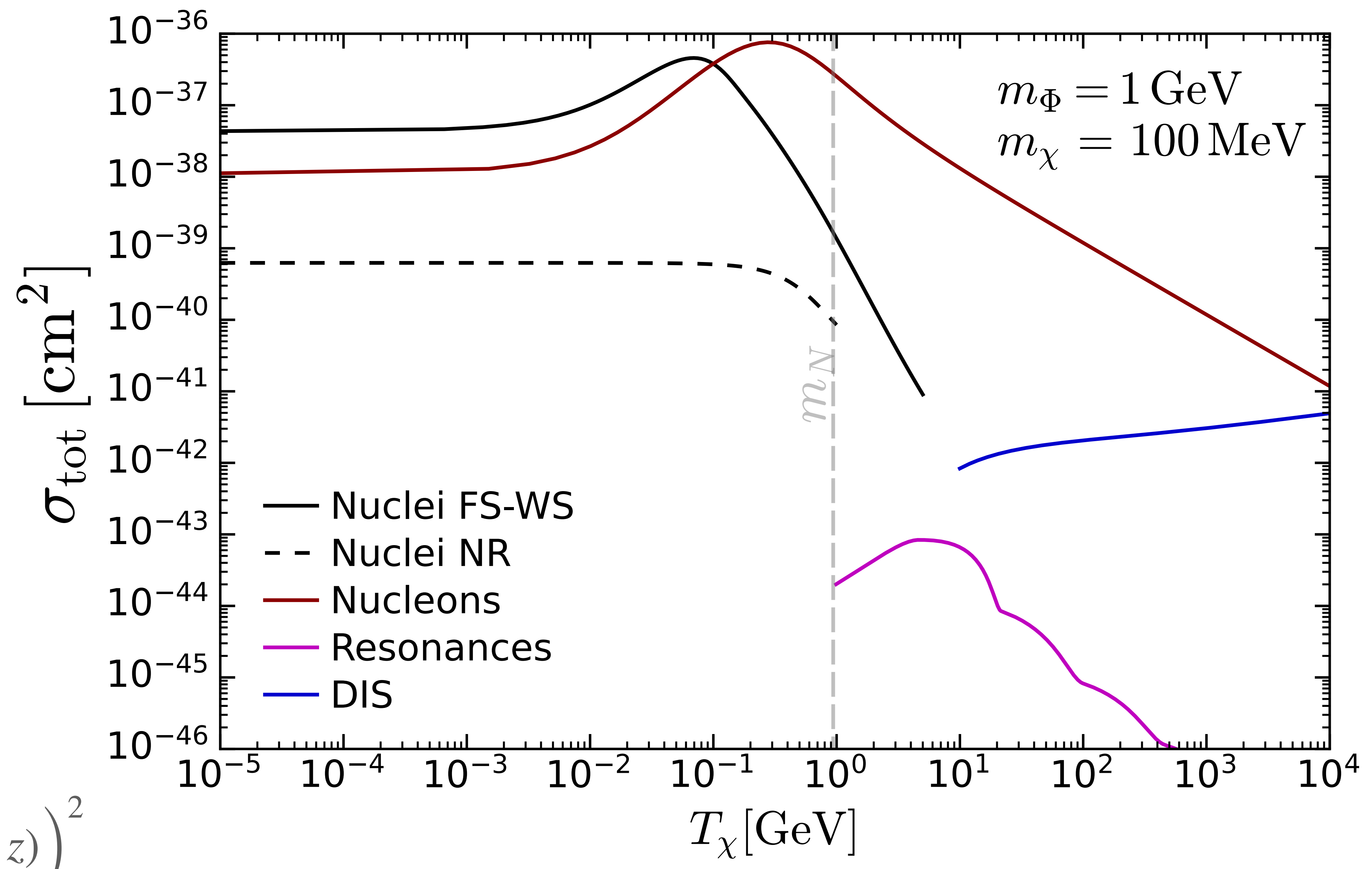
White dwarf: $M_* = M_\odot$, $R_* = 5.7\times10^3 km$
$\epsilon = 10^{-5}$, $g_{N\Phi} = 10^{-5}$, $g_D = 0.1$, $g_q^S = 1$

Scalar cross sections

* High-energy regime
  * **Dominated by DIS**
  * **Suppressed** by several orders of magnitude compared to nucleons and nuclei
* Nucleon: square of the total energy of the DM (E_1) and the nucleon (E_2) in the denominator

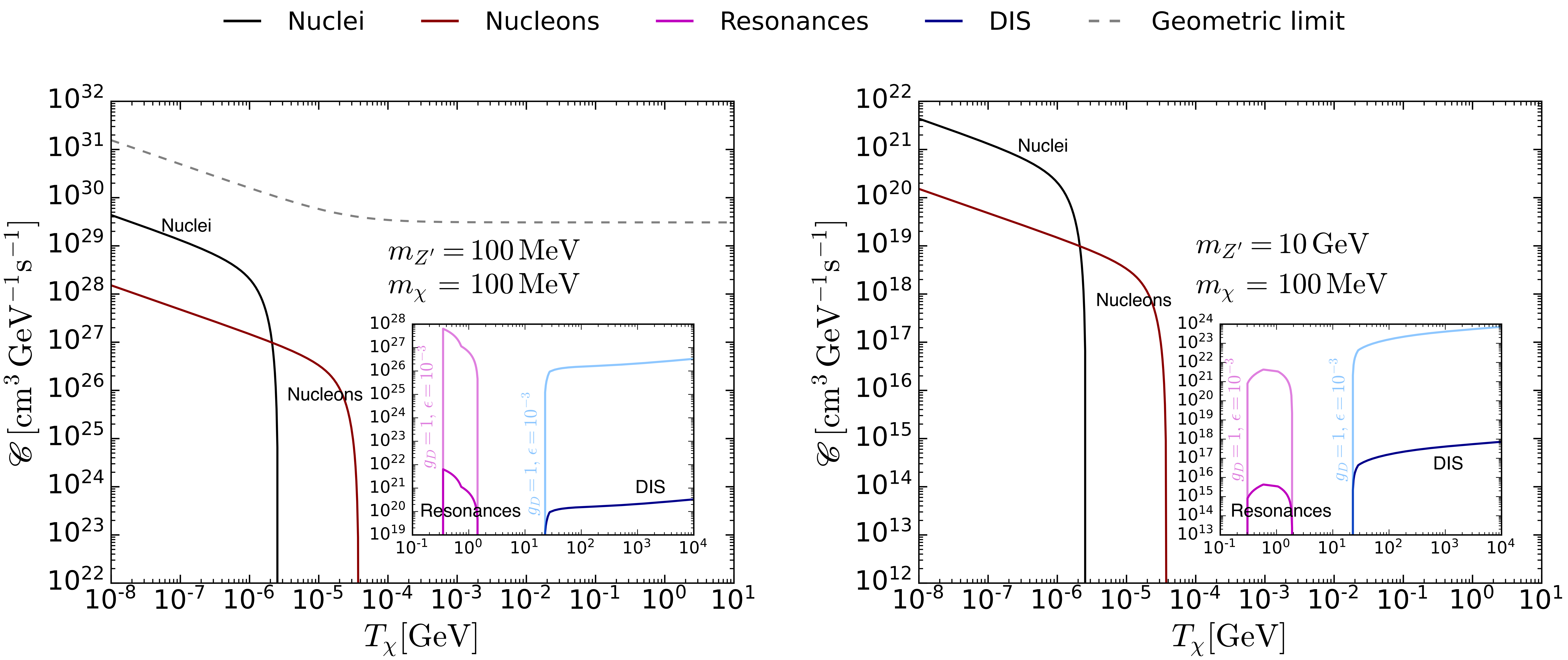
$$\frac{d\sigma^N}{dz} = \frac{g_D^2 g_{\Phi N}^2}{8\pi m_N^2 \left(E_1+E_2\right)^2} \frac{\left(E_1^2+m_\chi^2-p_1^2 z\right)\left(p_1^2(1+z)+2m_N^2\right)\left(2F_1^{\rm SN} m_N^2 - p_1^2 F_2^{\rm SN}(1-z)\right)^2}{\left(2p_1^2(1-z)+m_\Phi^2\right)^2}$$

* Low-energy regime: nuclei

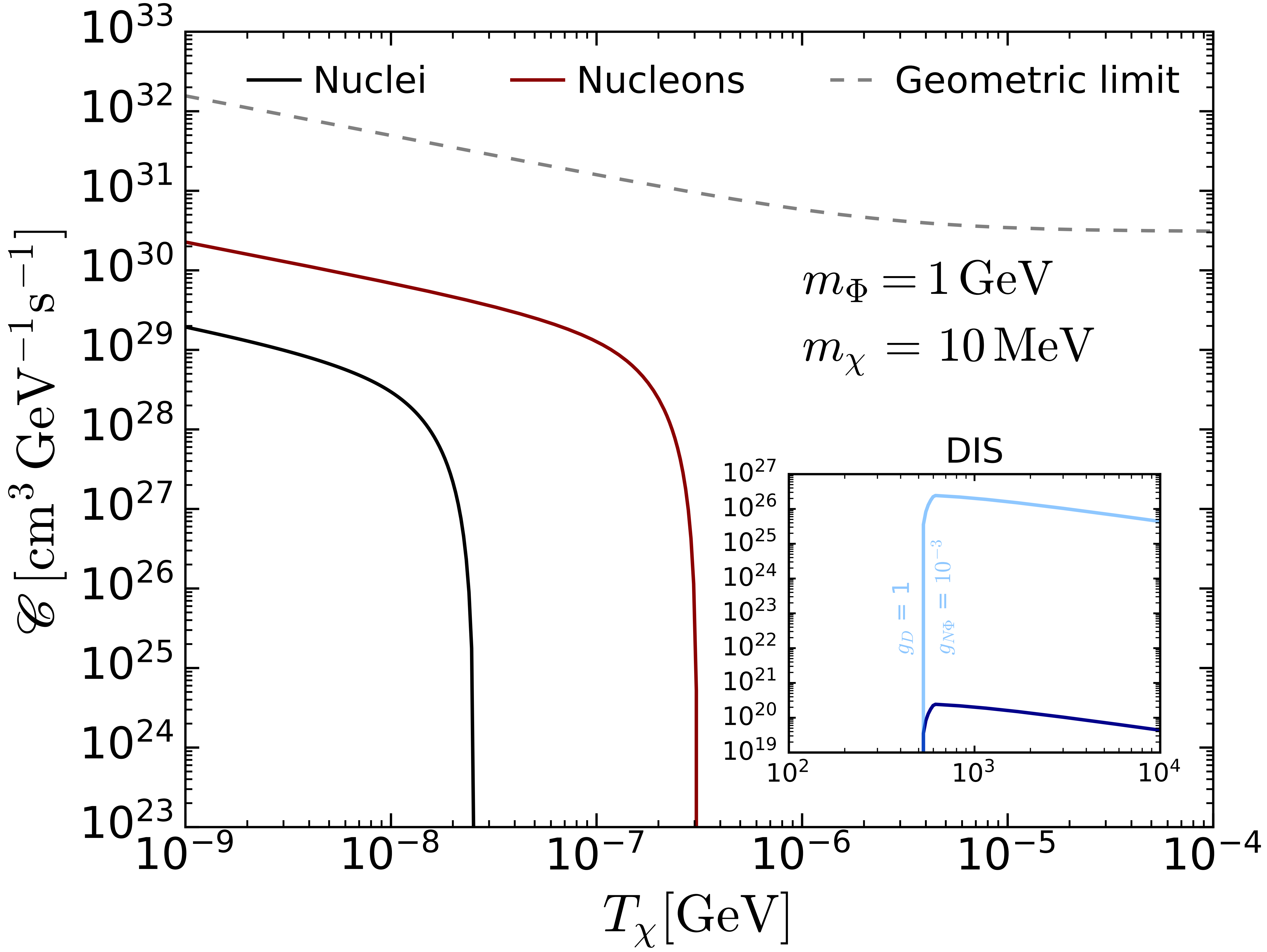


White dwarf: $M_* = M_\odot$, $R_* = 5.7\times10^3 km$
$\epsilon = 10^{-5}$, $g_{N\Phi} = 10^{-5}$, $g_D = 0.1$, $g_q^S = 1$

Vector DM capture rate density



Scalar DM capture rate density



5. Summary

Summary

- DM captured in WDs across a full energy regime
  - Flux: a delta function of a specific energy
  - Interaction: DIS, resonance scattering, elastic scattering on nucleons, elastic scattering on nuclei
- Fermionic DM interacting with stellar matter through a dark photon or a dark scalar
- Results: cross section & capture rate densities
  - Vector mediator: DIS and resonant interactions can also mediate the capture of DM for high energy incoming particles (a gap in energies $T_\chi \sim \mathcal{O}(10^{-4} - 10^{-1})\,\mathrm{GeV}$)
  - Scalar mediator: capture of high energy incoming particle is very suppressed and possible for only DIS.

Backup Slides

Three Portal Model

$$\mathscr{L} \supset (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi, H) - \frac{1}{4} X^{\mu\nu} X_{\mu\nu} + \overline{N} i \partial\!\!\!/ N + \overline{\nu_D} i D\!\!\!\!/ \nu_D - \left[y_\nu^\alpha (\overline{L_\alpha} \cdot \widetilde{H}) N^c + \frac{\mu'}{2} \overline{N} N^c + y_N \overline{N} \nu_D^c \Phi + \text{h.c.} \right],$$

Nucleon Form Factors

$$\mathcal{M}_N = i\frac{g_D g_{\rm Had}}{q^2 - m_{Z'}^2}[\overline{u}(p_3)\gamma^\mu(g_V^\chi - g_A^\chi\gamma^5)u(p_1)]\left(g_{\mu\nu} - \frac{q_\mu q_\nu}{m_{Z'}^2}\right)\langle N(p_4)|\, j^\nu_{Z'Q}(0)\,|N(p_2)\rangle$$

$$j^\nu_{Z'Q} = \sum_q g_V^q \bar{q}\gamma^\nu q - \sum_q g_A^q \bar{q}\gamma^\nu\gamma^5 q.$$

$$j^\nu_{Z'Q} \equiv v^\nu_{Z'Q} - a^\nu_{Z'Q},$$

$$v^\nu_{Z'Q} = -2(g_V^u + 2g_V^d)v_3^\nu + 3(g_V^u + g_V^d)j^\nu_{AQ} + (g_V^u + g_V^d + g_V^s)v_s^\nu - [g_V^s\bar{b}\gamma^\nu b + (3g_V^u + 3g_V^d + g_V^s)(\bar{c}\gamma^\nu c + \bar{t}\gamma^\nu t)]$$

$$a^\nu_{Z'Q} = (g_A^u - g_A^d)a_3^\nu + (g_A^u + g_A^d)a_0^\nu + g_A^s a_s^\nu - \sum_{q=c,b,t}(g_A^s - g_A^q)\bar{q}\gamma^\nu\gamma^5 q.$$

$$\langle N(p_4)|\, v^\mu_{Z'Q}(0)\,|N(p_2)\rangle = \overline{u}_N(p_4)\left[\gamma^\mu F_1^{Z'N}(Q^2) + i\frac{q_\nu}{2m_N}\sigma^{\mu\nu}F_2^{Z'N}(Q^2)\right]u_N(p_2),$$

$$\langle N(p_4)|\, a^\mu_{Z'Q}(0)\,|N(p_2)\rangle = \overline{u}_N(p_4)\left[\gamma^\mu\gamma^5 G_A^{Z'N}(Q^2) + \frac{q_\mu}{m_N}\gamma^5 G_P^{Z'N}(Q^2)\right]u_N(p_2).$$

$$F_i^{Z'N} \simeq \mp(g_V^u + 2g_V^d)(F_i^p - F_i^n) + 3(g_V^u + g_V^d)F_i^N + (g_V^u + g_V^d + g_V^s)F_i^{sN}$$

$$G_k^{Z'N} \simeq \pm\frac{1}{2}(g_A^u - g_A^d)G_k + (g_A^u + g_A^d)G_k^{0N} + g_A^s G_k^{sN},$$

Nuclei NR operators

$$\langle\Psi_f|\, H_T\, |\Psi_i\rangle = (2\pi)^3\delta^{(3)}(\vec{p}_1+\vec{p}_2-\vec{p}_3-\vec{p}_4)i\mathcal{M}_T^{NR}.$$

$$\mathcal{H}_T(\vec{r}) = \sum_{i=1}^{A}\sum_{j=0,1}\sum_{k=1}^{15} c_k^j \mathcal{O}_k^{(i)}(\vec{r})t^j(i),$$

$$\frac{1}{N_i}\sum_{i,j}|\mathcal{M}_T^{NR}|^2 = \frac{m_T^2}{m_N^2}\sum_{i,j}^{15}\sum_{\alpha,\beta=0,1} c_i^\alpha c_j^\beta F_{ij}^{\alpha\beta}(v^2,q^2,y).$$

$$\frac{d\sigma_T^{NR}}{d\cos\theta} = \frac{1}{32\pi(m_\chi+m_T)^2}\frac{1}{N_i}\sum_{i,j}|\mathcal{M}_T^{NR}|^2.$$

$\hat{\mathcal{O}}_1 = \mathbb{1}_{\chi N}$	$\hat{\mathcal{O}}_9 = i\hat{\mathbf{S}}_\chi \cdot \left(\hat{\mathbf{S}}_N \times \frac{\hat{\mathbf{q}}}{m_N}\right)$
$\hat{\mathcal{O}}_3 = i\hat{\mathbf{S}}_N \cdot \left(\frac{\hat{\mathbf{q}}}{m_N} \times \hat{\mathbf{v}}^\perp\right)$	$\hat{\mathcal{O}}_{10} = i\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}$
$\hat{\mathcal{O}}_4 = \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{S}}_N$	$\hat{\mathcal{O}}_{11} = i\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}$
$\hat{\mathcal{O}}_5 = i\hat{\mathbf{S}}_\chi \cdot \left(\frac{\hat{\mathbf{q}}}{m_N} \times \hat{\mathbf{v}}^\perp\right)$	$\hat{\mathcal{O}}_{12} = \hat{\mathbf{S}}_\chi \cdot \left(\hat{\mathbf{S}}_N \times \hat{\mathbf{v}}^\perp\right)$
$\hat{\mathcal{O}}_6 = \left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left(\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)$	$\hat{\mathcal{O}}_{13} = i\left(\hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{v}}^\perp\right)\left(\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)$
$\hat{\mathcal{O}}_7 = \hat{\mathbf{S}}_N \cdot \hat{\mathbf{v}}^\perp$	$\hat{\mathcal{O}}_{14} = i\left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left(\hat{\mathbf{S}}_N \cdot \hat{\mathbf{v}}^\perp\right)$
$\hat{\mathcal{O}}_8 = \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{v}}^\perp$	$\hat{\mathcal{O}}_{15} = -\left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left[\left(\hat{\mathbf{S}}_N \times \hat{\mathbf{v}}^\perp\right) \cdot \frac{\hat{\mathbf{q}}}{m_N}\right]$

Fermi-Symmetrized Woods-Saxon Form Factors

$$\frac{d\sigma^N}{dQ^2} = \frac{\sigma_0 E_\chi^2}{4\mu_N(E_\chi^2 - m_\chi^2)} F_H^2(Q^2),$$

$$F^{FS-WS}(Q) = \frac{3\pi a}{r_0^2 + \pi^2 a^2} \frac{a\pi \coth(\pi Q a)\sin(Q r_0) - r_0 \cos(Q r_0)}{Q r_0 \sinh(\pi Q a)},$$

$s \simeq 0.9$ fm, $a \simeq 0.523$ fm and $c \simeq 1.23 A^{1/3} - 0.60$ fm, for an atomic mass number A.