White Dwarfs as Dark Matter Laboratories:

A Multi-Energy Approach to Capture Mechanisms

Jaime Hoefken Zink, **Shihwen Hor** and Maura E. Ramirez-Quezada
The University of Tokyo
arXiv:2410.13908 [hep-ph]

1. Motivations

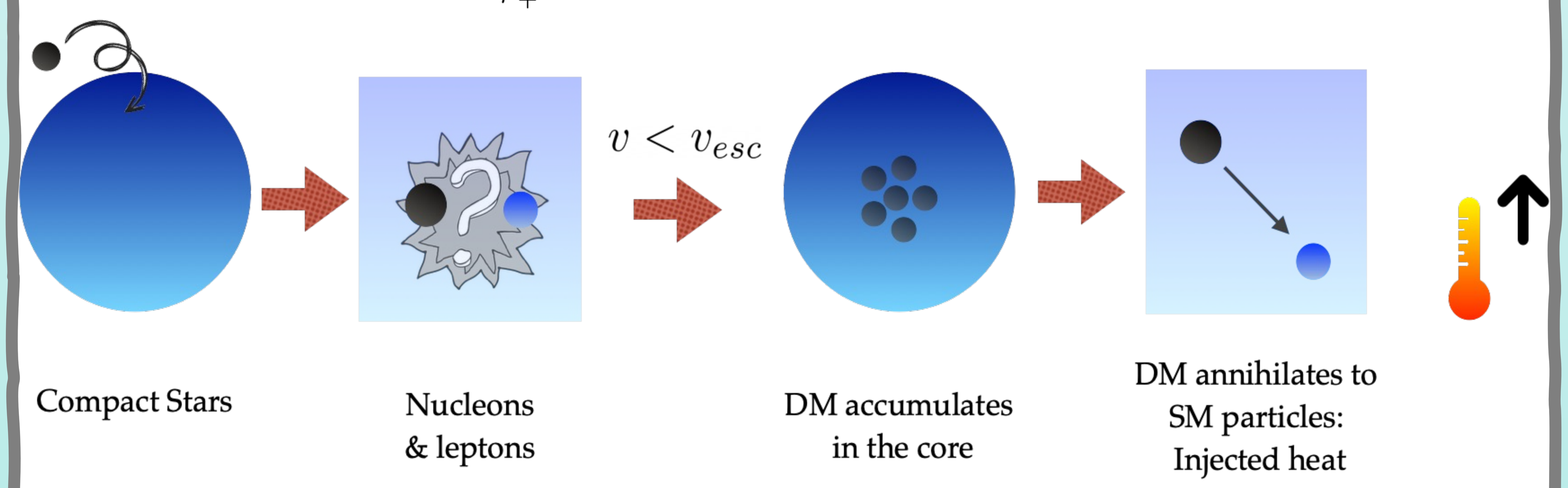
- A big region in the DM interaction parameter space (direct detection experiments are not enough)
- White dwarfs: the interactions of DM in the sub-GeV regime
- Boosted DM (high-density flux): improve the bounds for light DM candidates
- => A multi-energy approach to the white dwarf capture

2. DM Capture in White Dwarfs

○ **Capture rate of DM**

$$C = \frac{\rho_\chi}{m_\chi}\int_0^{R\star} dr 4\pi r^2 \int_0^\infty du_\chi \frac{\omega}{u_\chi} f_{\rm MB}(u_\chi)\Omega^-(\omega),$$

$$\Omega^-(\omega) = \frac{4\mu_+^2}{\mu\omega} n_T(r)\int_{\omega\frac{|\mu_-|}{\mu_+}}^{v_e} dv v \frac{d\sigma}{d\cos\theta}, \quad \mu = m_\chi/m_T,\ \mu_\pm = (\mu\pm 1)/2.$$



○ **Multi-energy approach**: cross section (different energy regimes) & flux

○ **Capture rate density**

- Flux: delta function of a particular energy from all directions
- DM density as a free parameter -> capture rate density $\mathscr{C} = \rho_\chi^{-1} C$

$$\mathscr{C} = \frac{1}{m_\chi}\int_0^{R\star} dr 4\pi r^2 \int_0^\infty du'_\chi \frac{\omega}{u'_\chi}\delta(u'_\chi - u_\chi)\,\Omega^-(\omega).$$

DM velocities near and far from the star $\omega^2 = v_e^2 + (1-v_e^2)u_\chi^2$.

- Maximum capture probability $\Omega^-(\omega) \to 1$

$$\mathscr{C}_{\rm geom} = \frac{\pi R_*^2}{m_\chi}\int_0^\infty du'_\chi \frac{\omega}{u'_\chi}\delta(u'_\chi - u_\chi),$$

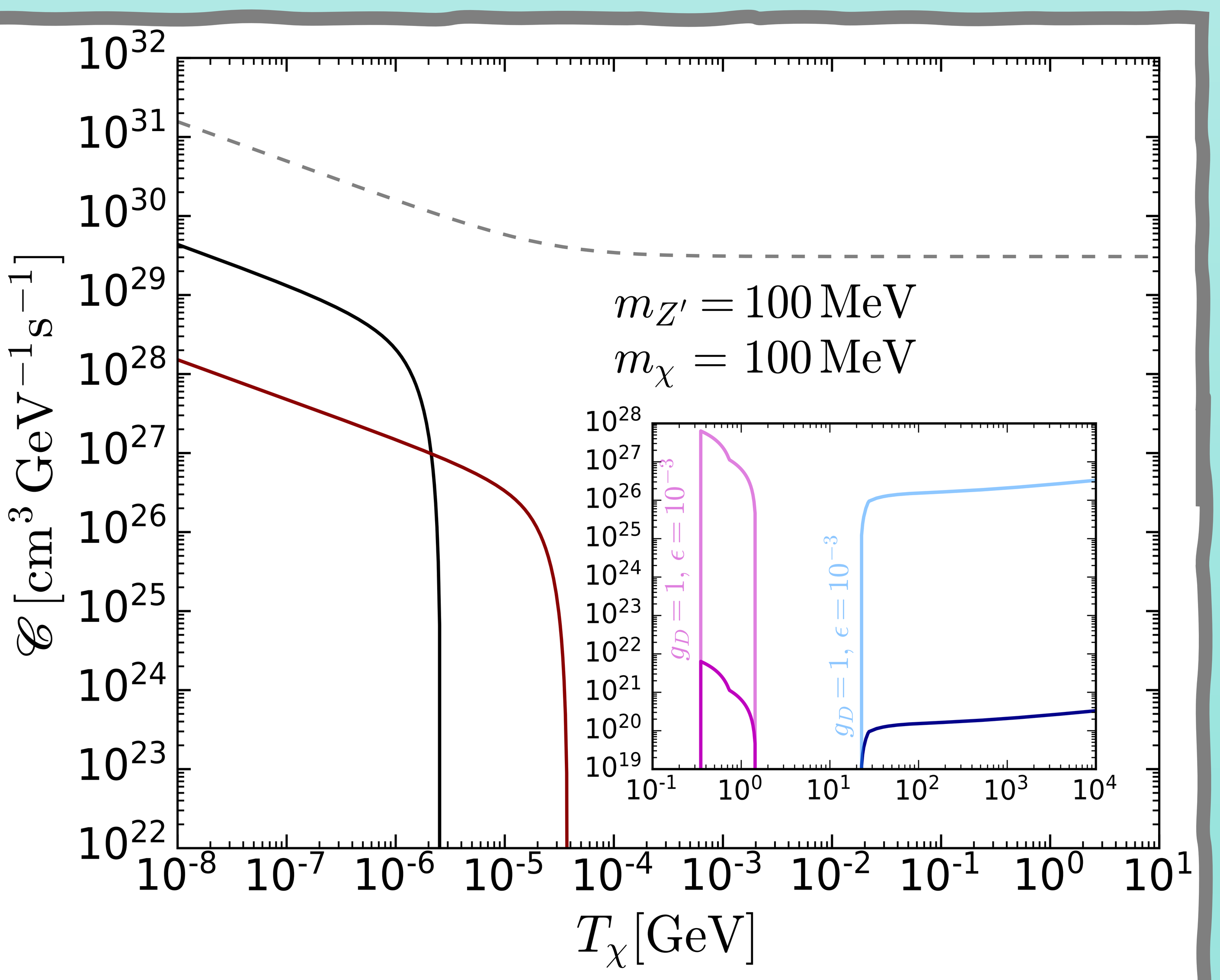
3. Model

- A new U(1)X symmetry: spontaneously broken
- Fermionic DM interacting 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

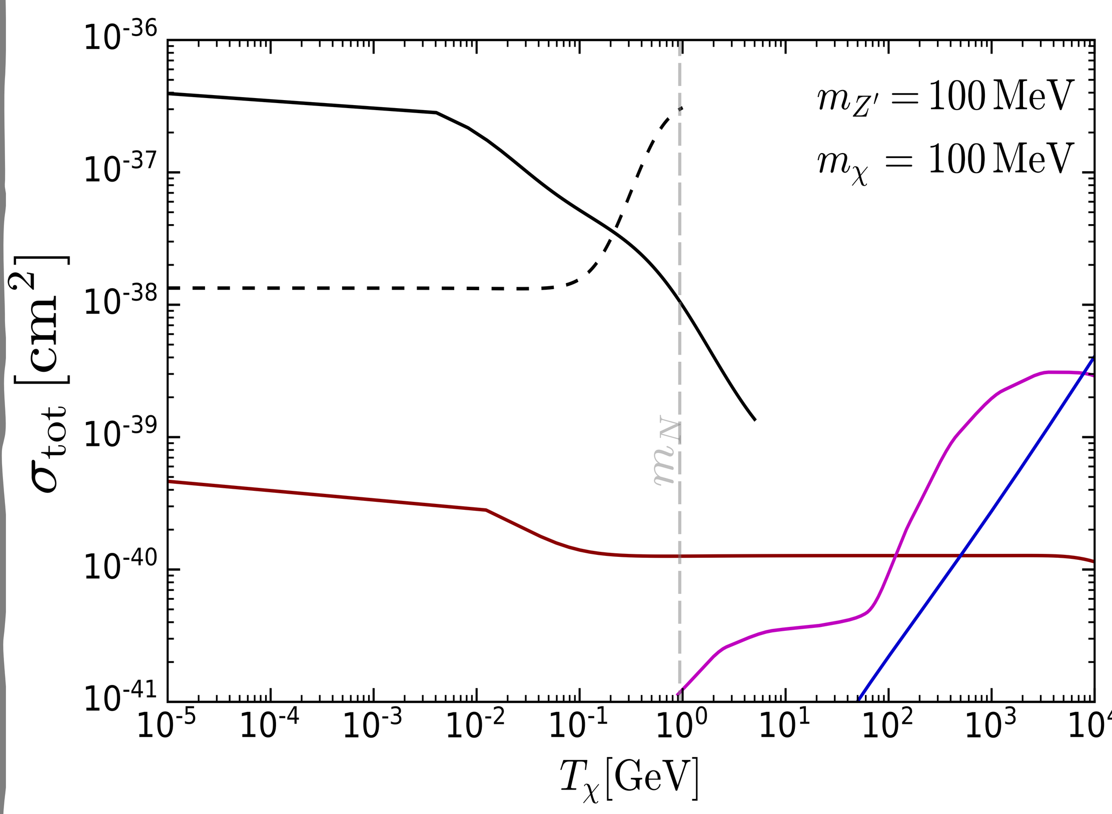
$$\mathcal{L}_{Z'} = -\epsilon e Q_{\rm EM} J^\mu_{\rm EM} Z'_\mu + g_D \bar\chi\gamma^\mu(g_V^\chi - g_A^\chi\gamma^5)\chi Z'_\mu$$
$$\mathcal{L}_\Phi = g_\Phi^{ij}\bar\psi^i_{\rm SM}\psi^j_{\rm SM}\Phi + g_D\bar\chi\chi\Phi.$$

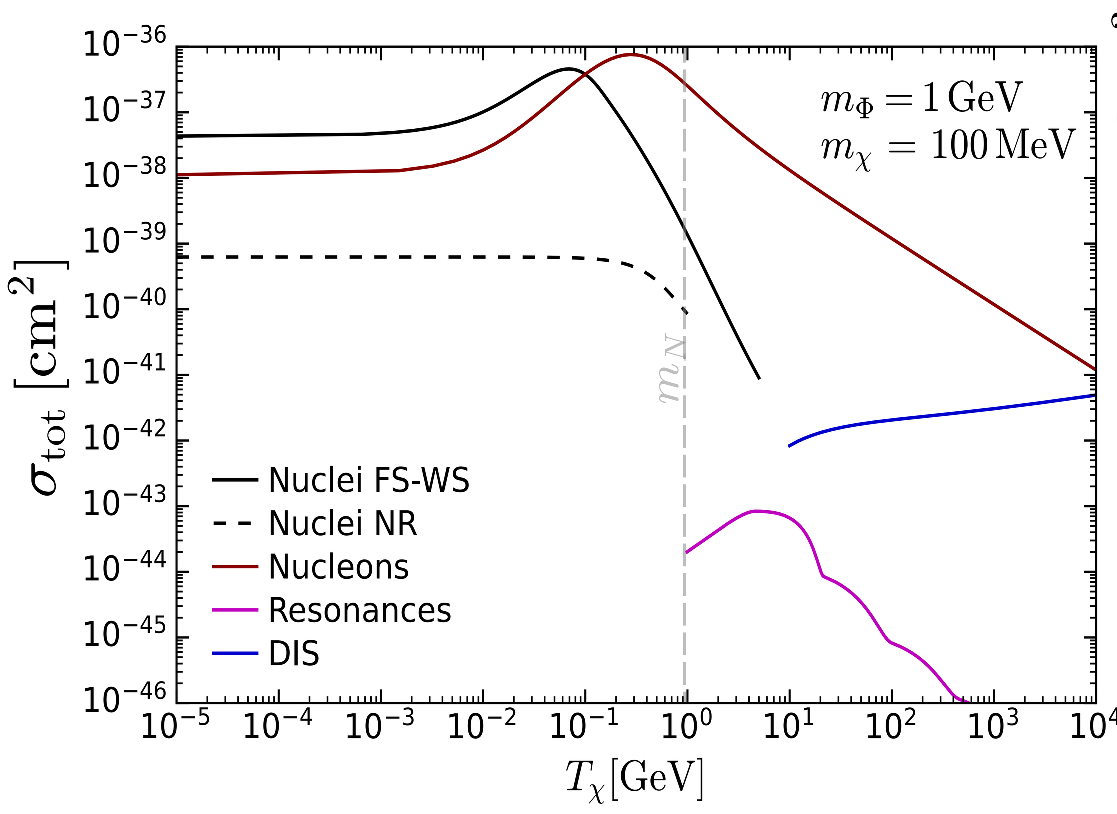
4. DM Scattering Cross Sections

- **Deap inelastic scattering (DIS)**
  At high energy regime, the valence and the sea quarks become visible, leading to the production of a hadronic shower. $\chi q \to \chi X$
- **Resonant scattering**
  $$\chi + N \to \chi + N^* \to \chi + N + \pi$$
  1. $\chi + p \to \chi + p + \pi^0$, 2. $\chi + p \to \chi + n + \pi^+$,
  3. $\chi + n \to \chi + n + \pi^0$, 4. $\chi + n \to \chi + p + \pi^-$.
- **Elastic scattering on nucleons**
- **Elastic scattering on nuclei**
  - Non-relativistic (NR) form factors (at low kinetic energies)
  - Fermi-Symmetrized Woods-Saxon (WS) form factors (do not require non-relativistic)



5. Results: Cross Sections and Density Capture Rates





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

○ Cross sections

- High-energy regime: vector: Resonant scattering dominates for lighter mediators, while DIS becomes the dominant process for heavier mediators.
- High-energy regime: scalar: DIS (suppressed by several orders of magnitude compared to nucleons and nuclei)
- Nucleon: scalar: square of the total energy of the DM (E_1) and the nucleon (E_2) in the denominator

○ Density capture rates