Fermionic Dark Matter Conversion to Neutrinos with Nucleon Fermi Motion

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Dark Matter

Energy density of the universe

- Baryonic matter $\sim 5\%$
- Dark matter $\sim 25\%$
- Dark energy $\sim 70\%$

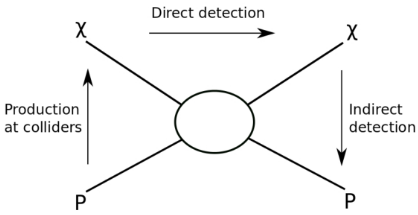
Kinematic types of DM

- Hot
- Cold
- Warm

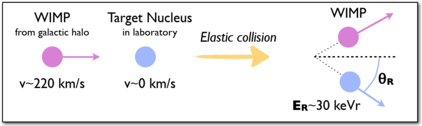
Possible particle DM

- Neutrinos ($\leq 2\%$)
- Weakly interacting massive particles (WIMPs)
- Axions & axion-like particles
- Sterile neutrinos
- Dark photons
- Dark sectors
- ...

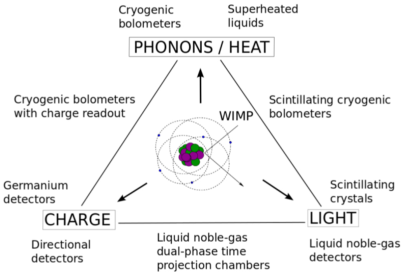
Signals from Particle Dark Matter



DM signal types.
Source: Undagoitia+, 2015 (1509.08767)



WIMP elastic scattering.
Source: Cooley, 2022 (2110.02359)

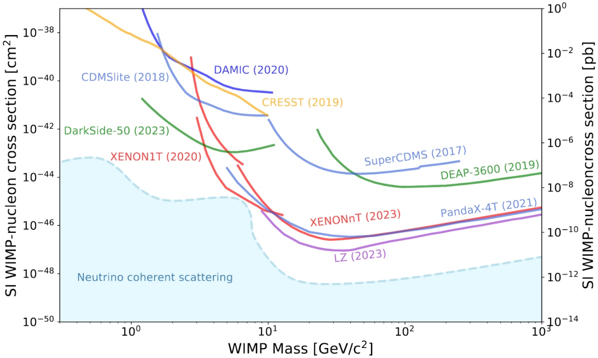


Direct detection signals.
Source: Undagoitia+, 2015 (1509.08767)

DM Direct Detection

Common approach

- Elastic scattering on nuclei
- Energy deposit due to DM kinetic energy $\sim (\mu_\chi v_\chi)^2/2m_A$
- Strong limits on $m_\chi \gtrsim 1$ GeV



Upper limits on SI DM-nucleon cross section. *Source:* PDG

Problem

Energy deposits for sub-GeV DM are too small, $\lesssim 1$ keV
$\Rightarrow$ need new experimental strategies & theoretical ideas

Fermionic DM Absorption: Idea

Interaction & signal

1. **Scattering**
   Energy deposit $\sim (\mu_\chi v_\chi)^2/2m_A$
2. **Absorption**
   Energy deposit $\sim m_\chi$

Absorption of *fermionic DM*
Proposed in

- J. A. Dror, G. Elor, R. McGehee 1905.12635

Further development in

- J. A. Dror, G. Elor, R. McGehee, 1908.10861
- J. A. Dror, G. Elor, R. McGehee, T. T. Yu 2011.01940
- S.-F. Ge, X.-G. He, X.-D. Ma, J. Sheng 2201.11497

Fermionic DM absorption on nucleus

- Charged current

$$\chi + (A, Z) \to e^{\mp} + (A, Z \pm 1)^*$$

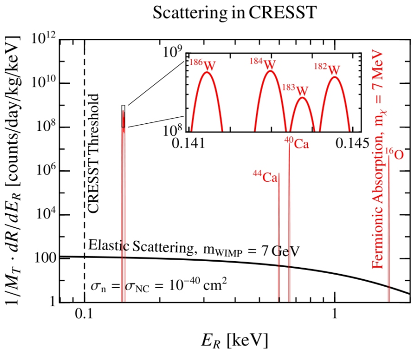
  - Dim-6 operators: $(\bar{\chi}\mathcal{O}_i e)(\bar{n}\mathcal{O}_i p)$
  - Signal: prompt e + delayed de-excitation γ
  - Alternative: endpoint shift in β-unstable isotopes

- Neutral current

$$\chi + (A, Z) \to \nu + (A, Z)$$

  - Dim-6 operators: $(\bar{\chi}\mathcal{O}_i \nu)(\bar{N}\mathcal{O}_i N)$
  - Signal: sharp peak in nuclear recoil at $E_R = \frac{m_\chi^2}{2m_A}$
  - Coherent enhancement $\propto A^2$

DM Absorption: NC Signal

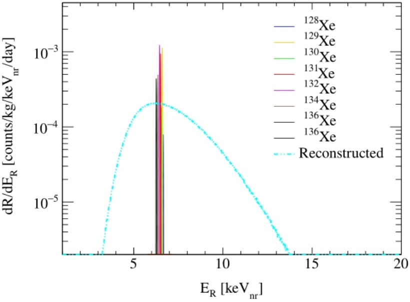


Expected differential event rate from NC ($m_\chi = 7$ MeV, $\sigma_{\text{NC}} = \frac{m_\chi^2}{4\pi\Lambda^4} = 10^{-40}$ cm^2).
Source: Dror+, 2019 (1908.10861)

$$\frac{dR}{dE_R} = N_T \frac{\rho}{m_\chi} \sigma_{\text{NC}} A^2 F^2(q^2) \delta(E_R - E_R^0)$$

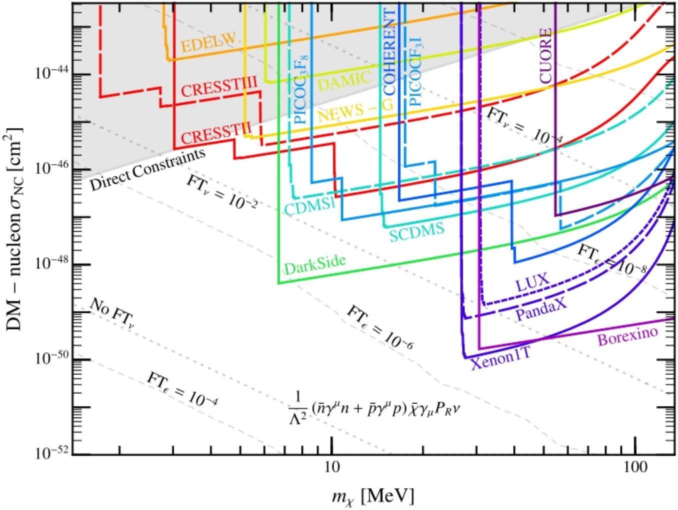
Advantages compared to elastic scattering

- Energy deposit $\sim 1/v_\chi^2 = 10^6$ larger $\Rightarrow m_\chi \sim 1$ MeV is accessible
- Spectrum: peak at $E_R = \frac{m_\chi^2}{2m_A}$ (or multiple peaks, if resolvable)



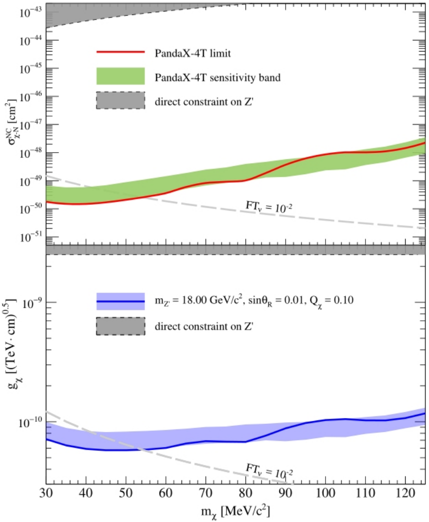
Expected differential rate from NC in Xe ($m_\chi = 40$ MeV, $\sigma_{\text{NC}} = 10^{-49}$ cm^2).
Source: Gu+, 2022 (2205.15771)

DM Absorption: Current Constraints on NC

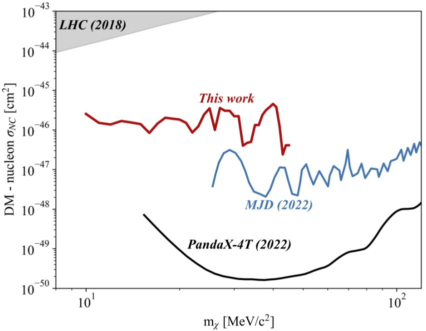


Limits on σ_{NC} as a function of m_χ.
Source: Dror+, 2019 (1908.10861)

DM Absorption: Current Constraints on NC



PandaX-4T limits on σ_{NC} as a function of m_χ. *Source:* Gu+, 2022 (2205.15771)



CDEX-10 limits on σ_{NC} as a function of m_χ. *Source:* Dai+, 2022 (2209.00861)

DM Absorption on Nuclei: Coherency

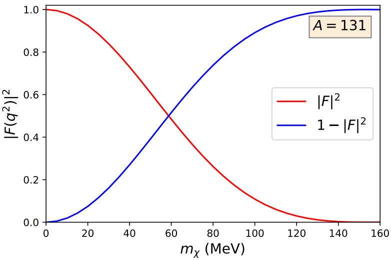
Momentum transfer

$q \approx p_\nu \approx m_\chi \Rightarrow$ for $m_\chi \sim 100$ MeV
$\Rightarrow 1/q \sim 1$ fm $\sim R_{\text{nucleus}}$
$\Rightarrow$ resolve individual nucleons

Coherent vs incoherent scattering regimes
(see, e.g., Bednyakov+, 2018 1806.08768)

$$\frac{d\sigma_{\text{coh}}}{dq^2} \propto A^2 |F(\boldsymbol{q}^2)|^2$$
$$\frac{d\sigma_{\text{incoh}}}{dq^2} \propto A(1 - |F(\boldsymbol{q}^2)|^2)$$

"incoherent" $\Leftrightarrow$ "inelastic"
$\Rightarrow$ excited nucleus
$\Rightarrow$ can expect extra experimental signatures from de-excitation



Helm form factor as a function of $q = m_\chi$ for $A = 131$.

Shao-Feng Ge & OT, 2405.05728

Q: how significant is the contribution of incoherent regime for NC channel?

Relativistic Fermi Gas

Impulse approximation

- Large momentum transfer $\Rightarrow$"nucleus" $=$ "individual nucleons"
- One-body nuclear current operators $J \to \sum_{i=1}^{A} j_i$
- Interaction with single nucleon N

$$\chi + N \to \nu + N',$$

other $(A-1)$ nucleons are spectators

Fermi Gas

- Momentum distribution

$$f(\boldsymbol{p}_N) = \frac{3}{4\pi p_F^3}\theta(p_F - |\boldsymbol{p}_N|)$$

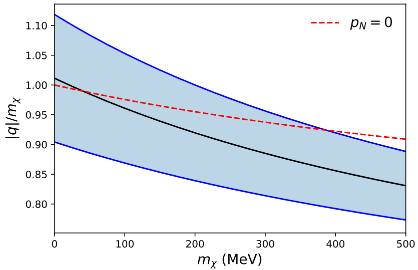
- Fermi momentum

$$p_F = \frac{1}{R}\sqrt[3]{\frac{9\pi}{4}}\sqrt[3]{\frac{Z}{A}} \approx 250 \text{ MeV}$$

- Different p_F for protons/neutrons

Fermi Motion

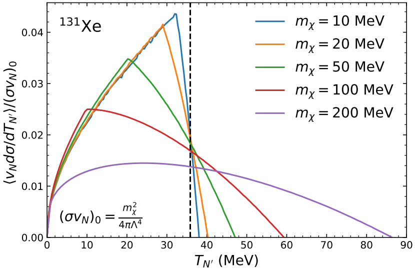
- Lab frame (= nucleus rest frame): $v_N \sim 0.1 \gg v_\chi \sim 10^{-3} \Rightarrow \chi$ at rest
- Final nucleon kinetic energy smearing: $T_{N'} \approx T \pm \Delta T'$
  Width: $\Delta T' \sim \frac{|\boldsymbol{p}_N| m_\chi}{m_N} \sim 10$ MeV
- Momentum transfer smearing: $|\boldsymbol{q}| \sim m_\chi(1 \pm 0.1)$



Momentum transfer smearing for $p_N = 100\,\mathrm{MeV}$

Event rate $\propto \langle \sigma v_N \rangle$

$$= \int \frac{\overline{|\mathcal{M}|^2}}{4 m_\chi E_N} \frac{dT_{N'}}{8\pi |\boldsymbol{p}_N|} f(\boldsymbol{p}_N) d^3\boldsymbol{p}_N$$



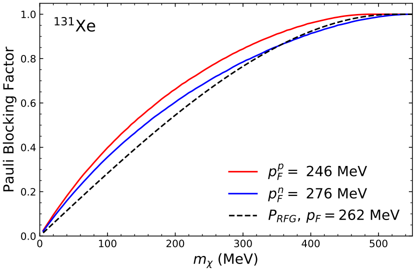
Differential cross section for incoherent DM absorption

Pauli Blocking

- Fermions ⇒ Pauli exclusion principle applies
- Require $|\boldsymbol{p}'| = |\boldsymbol{p} + \boldsymbol{q}| > p_F$ in final state
- Rate suppression at $m_\chi \approx |\boldsymbol{q}| < 2p_F \approx 500$ MeV
- Higher p_F for neutrons ⇒ stronger suppression

Geometric estimate for Pauli suppression (Bodek, 2021, 2111.03631):

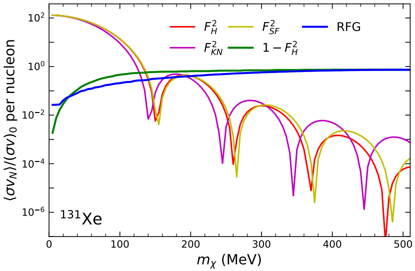
$$P_{\mathrm{RFG}} = \frac{3}{4}\frac{|\boldsymbol{q}|}{p_F} - \frac{1}{16}\left(\frac{|\boldsymbol{q}|}{p_F}\right)^3, \qquad |\boldsymbol{q}| \leq 2p_F,$$
$$P_{\mathrm{RFG}} = 1, \qquad |\boldsymbol{q}| > 2p_F.$$



Pauli blocking factor as function of DM mass

Form Factors

- Coherent regime:
  - Spin-Independent interaction $\sigma \propto A^2 |F|^2$
  - Spin-Dependent interaction $\sigma \propto |F|^2$
- Incoherent regime: $\sigma \propto A(1 - |F|^2)$



Comparison of cross sections for different form factor parametrizations.

Form factor parametrizations suggested in the literature:

- Helm

$$F_{\mathrm{H}}(\boldsymbol{q}^2) \equiv 3 \frac{j_1(|\boldsymbol{q}| r_n)}{|\boldsymbol{q}| r_n} e^{-(|\boldsymbol{q}| s)^2/2}$$

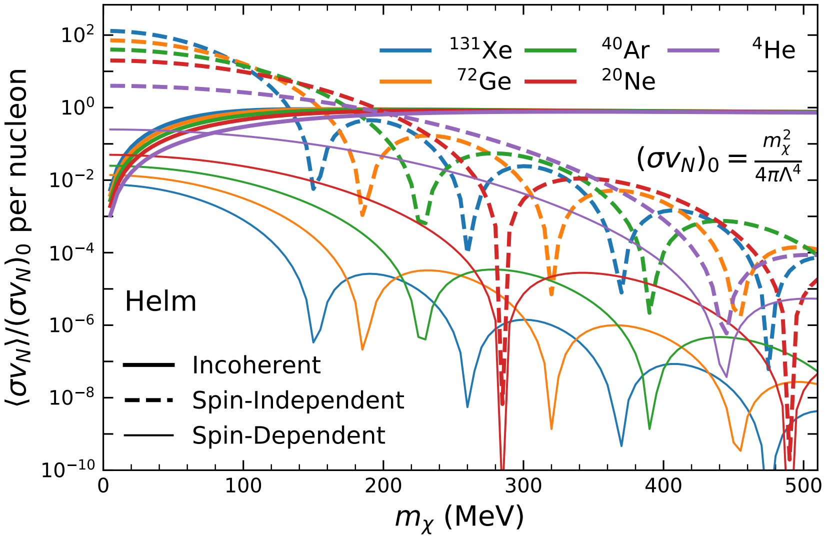
- Klein-Nystrand

$$F_{\mathrm{KN}}(\boldsymbol{q}^2) \equiv 3 \frac{j_1(|\boldsymbol{q}| r_n)}{|\boldsymbol{q}| r_n} \frac{1}{1 + |\boldsymbol{q}|^2 a_k^2}$$

- Symmetrized Fermi distribution

$$F_{\mathrm{SF}}(\boldsymbol{q}^2) \equiv \frac{3}{|\boldsymbol{q}| c} \left[\frac{\sin(|\boldsymbol{q}| c)}{(|\boldsymbol{q}| c)^2} \frac{\pi |\boldsymbol{q}| a}{\tanh(\pi |\boldsymbol{q}| a)} - \frac{\cos(|\boldsymbol{q}| c)}{|\boldsymbol{q}| c} \right] \times \frac{\pi |\boldsymbol{q}| a}{\sinh(\pi |\boldsymbol{q}| a)} \frac{1}{1 + (\pi a / c)^2}$$

Comparison of Different Targets



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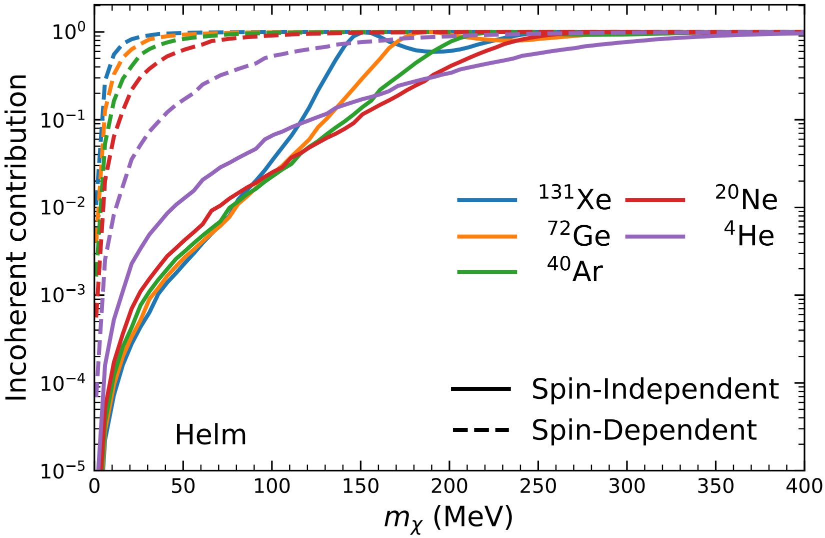
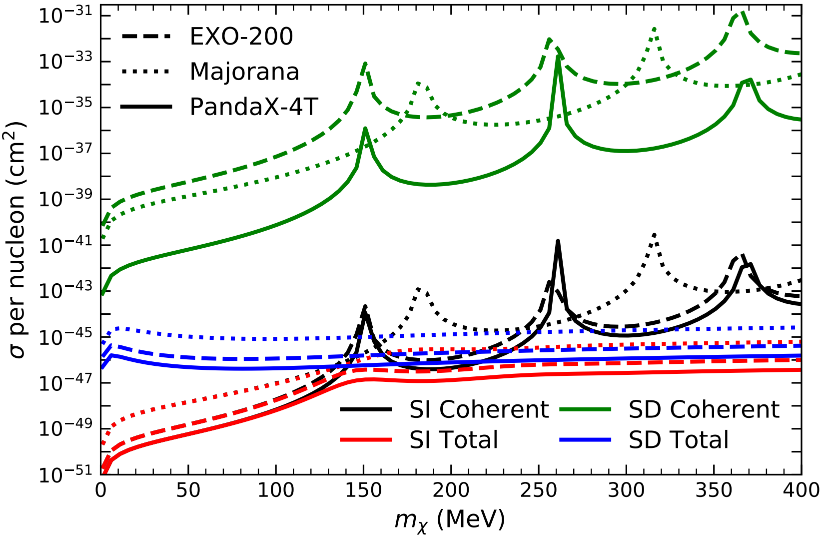


Projected Sensitivities



Summary

- Models with fermionic DM absorption allow direct detection of sub-GeV DM
- Incoherent absorption regime is significant for $m_\chi \gtrsim 100$ MeV (and even lower m_χ for SD interactions)
- Heavier targets are affected at lower m_χ
- Can expand the range for current experiments & improve sensitivity

Thank you!