

QUantum Enhanced Superfluid Technologies for Dark Matter and Cosmology

Sensitivity Ceilings for the QUEST-DMC Detector

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On behalf of QUEST-DMC Collaboration

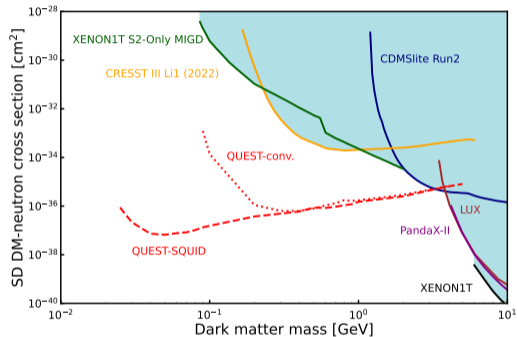
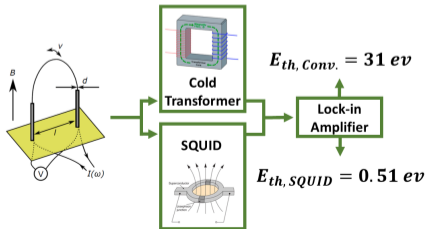
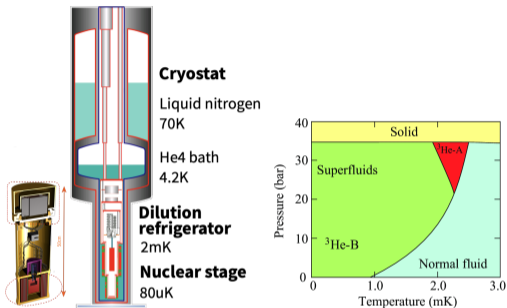


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QUEST-DMC and Its Sensitivity

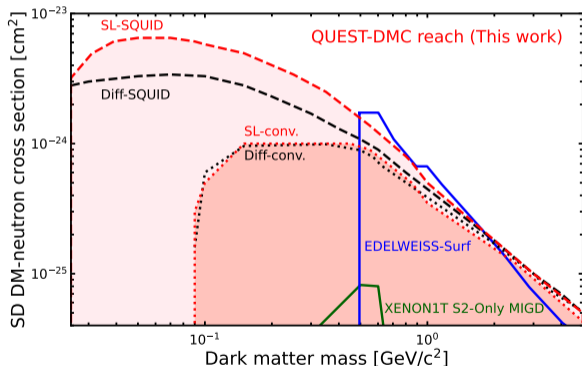


World-leading sensitivity to SD and SI interactions.

An upper limit in the cross-section sensitivity region is present due to DM scattering in the Earth and atmosphere and would never reach the detector.

We evaluate the cross-section sensitivity ceiling via two primary trajectories:

- ◇ Straight-line (SL) path approximation
- ◇ Diffusion framework (Diff)

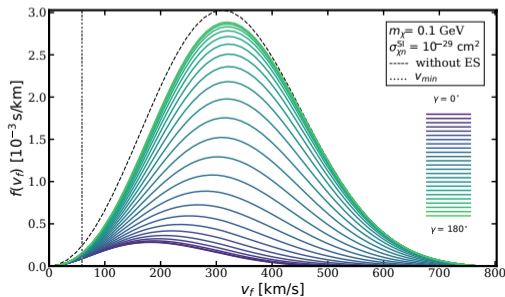
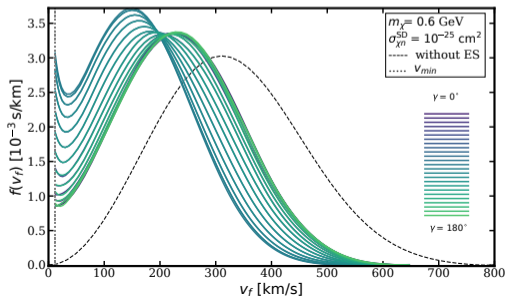
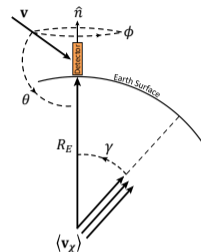


Straight-line Path Approx.



$$f(\mathbf{v}_i, \gamma) \propto \exp\left(-\frac{|\mathbf{v}_i - \langle \mathbf{v}_\chi \rangle|^2}{v_{\text{dis}}^2}\right) \Theta(v_{\text{esc}} - |\mathbf{v}_i - \langle \mathbf{v}_\chi \rangle|)$$

$$f(v_f^{\text{int}}, \gamma) = \oint v_i^2 f(\mathbf{v}_i, \gamma) \frac{dv_i}{dv_f^{\text{int}}} d^2\hat{\mathbf{v}}$$



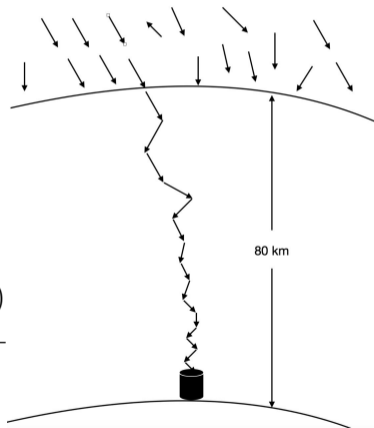
Simulates a random walk of DM particle interactions through the atmosphere as a series of n isotropic scatterings.

- ▶ The energy spectrum:

$$\frac{dN}{dE}_{\text{total}}(z, E) = \sum_{n=0}^{\infty} \int_z^{\infty} P_n(z') dz' \frac{dN}{dE}_n(E)$$

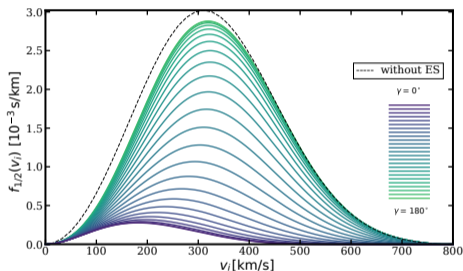
- ▶ The probability of scatterings:

$$P^{\text{int}}(\Delta E) = \frac{\sum_N (n_N \sigma_0^{\text{int}} / E_{\text{max},N}) \theta(E_{\text{max},N} - \Delta E)}{\sum_N n_N \sigma_0^{\text{int}}}$$



The initial DM velocity distribution is calculated under the assumption of the Earth being fully opaque to DM.

$$\begin{aligned} f_{1/2}(v_i, \gamma) &= \int_{\text{half-sphere}} v_i^2 f(\mathbf{v}_i, \gamma) d^2\hat{\mathbf{v}} \\ &= \int_{-1}^0 v_i^2 f(v_i, \gamma, \cos \theta) d(\cos \theta) \end{aligned}$$

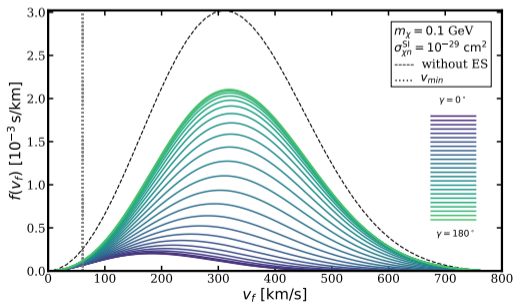
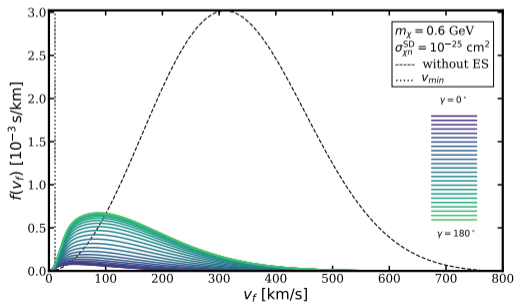


Converted and plugged into the iterative process:

$$\frac{dN}{dE}_{\text{total}}(z, E) = \sum_{n=0}^{\infty} \int_z^{\infty} P_n(z') dz' \frac{dN}{dE}_n(E)$$

Converting the energy spectrum to the velocity distribution:

$$f(v_f, \gamma) \propto \frac{dN}{dE_{\text{total}}} (z, E)$$

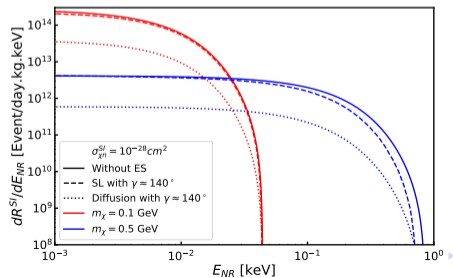
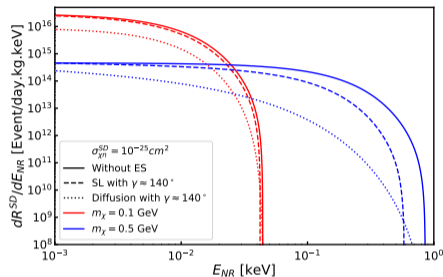
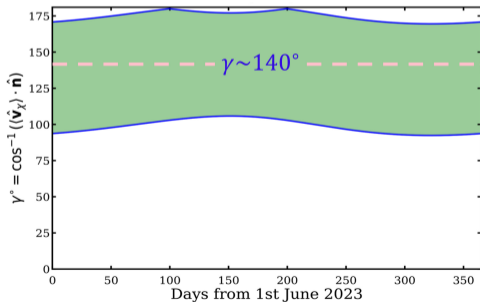


The Event Rates

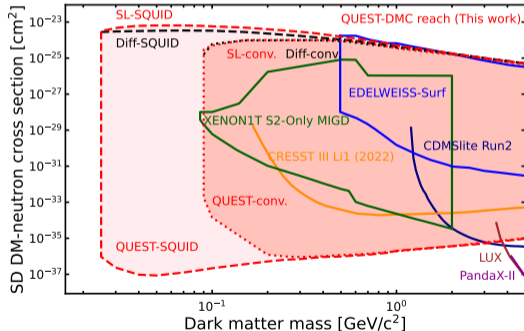
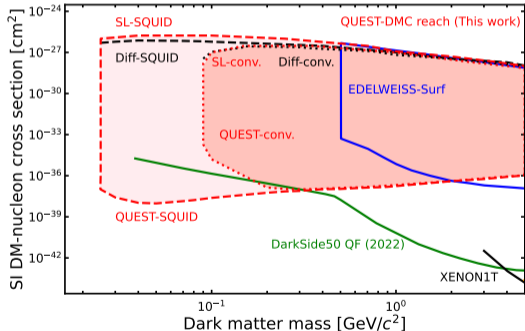


$$\frac{dR}{dE_{NR}} = \frac{\rho_\chi}{m_\chi m_N} \int_{v_{\min}}^{\infty} \frac{d\sigma}{dE_{NR}} v f(\mathbf{v}) d^3\mathbf{v},$$

where $v_{\min} = (m_N E_{NR} / 2\mu_{\chi N}^2)^{1/2}$



SI and SD Projection Sensitivities



◇ The *small* and *large* cross-sections for \mathcal{O}_1 and \mathcal{O}_4 interactions.



◇ The interaction Hamiltonian: $\hat{\mathcal{H}} = \sum_{\tau=0,1} \sum_{i=1}^{15} c_i^\tau \mathcal{O}_i t^\tau$ (the isospin operators $t^0 = \sigma^0$ and $t^1 = \sigma^3$).

$\mathcal{O}_1 = 1_\chi 1_N$	$\mathcal{O}_9 = i\vec{S}_\chi \cdot (\vec{S}_N \times \frac{\vec{q}}{m_N})$
$\mathcal{O}_2 = (v^\perp)^2$	$\mathcal{O}_{10} = i\vec{S}_N \cdot \frac{\vec{q}}{m_N}$
$\mathcal{O}_3 = i\vec{S}_N \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp)$	$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$
$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$	$\mathcal{O}_{12} = \vec{S}_\chi \cdot (\vec{S}_N \times \vec{v}^\perp)$
$\mathcal{O}_5 = i\vec{S}_\chi \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp)$	$\mathcal{O}_{13} = i(\vec{S}_\chi \cdot \vec{v}^\perp)(\vec{S}_N \cdot \frac{\vec{q}}{m_N})$
$\mathcal{O}_6 = (\vec{S}_\chi \cdot \frac{\vec{q}}{m_N})(\vec{S}_N \cdot \frac{\vec{q}}{m_N})$	$\mathcal{O}_{14} = i(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N})(\vec{S}_N \cdot \vec{v}^\perp)$
$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp$	$\mathcal{O}_{15} = -(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N})((\vec{S}_N \times \vec{v}^\perp) \cdot \frac{\vec{q}}{m_N})$
$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp$	

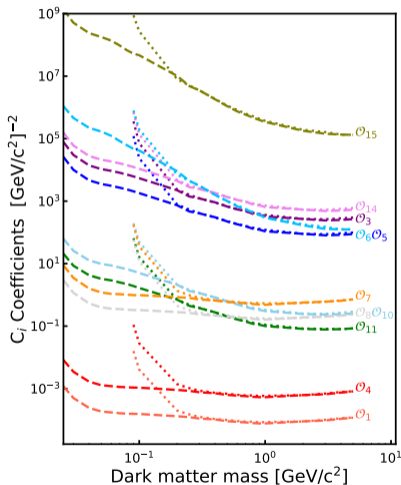


As was first pointed out by Migdal (1986):

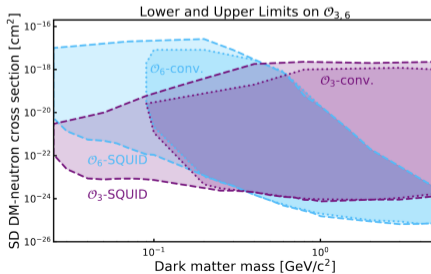
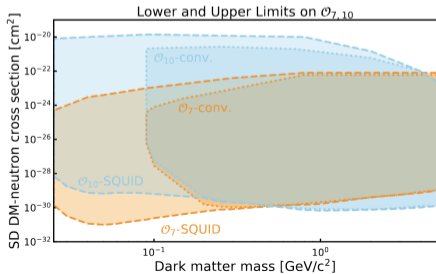
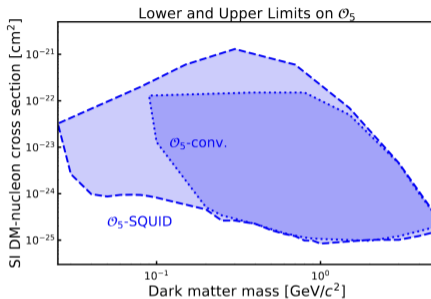
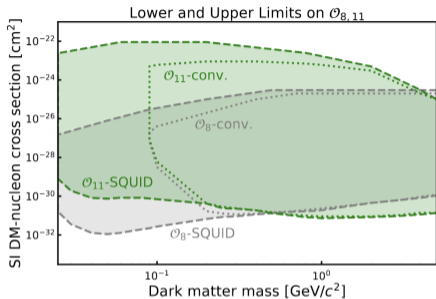
$$P_{\text{tot}} = \frac{1}{2j_\chi + 1} \frac{1}{2j_N + 1} \times \sum_{\text{spins}} |\mathcal{M}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^2}{m_N^2}, \{c_i^\tau c_j^{\tau'}\})|^2$$

◇ Differential rate per recoil energy:

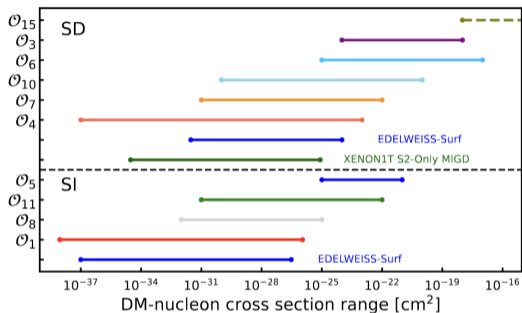
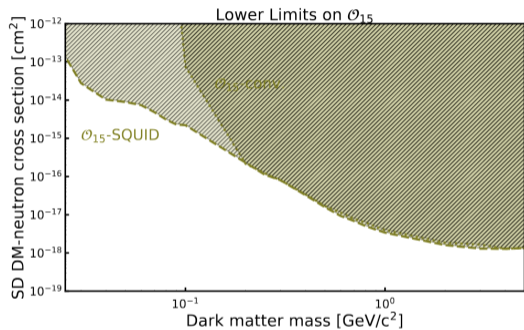
$$\frac{dR}{dE_{\text{NR}}} = \frac{\rho_\chi}{m_\chi m_N} \int_{v_{\text{min}}}^{\infty} \frac{1}{v} P_{\text{tot}}(v^2, q^2) f(\mathbf{v}) d^3\mathbf{v}.$$



Non Relativistic EFT Operators of DM



Non Relativistic EFT Operator 15



- ▶ Among all non-relativistic EFT operators, operator 15 has the highest lower limit.
- ▶ No upper-limit is assigned to operator 15.



- ▶ The **QUEST-DMC** collaboration is currently operating He-3 bolometers at RHUL and Lancaster. These are instrumented with vibrating nanowires and readout with SQUID. (See E. Leason's talk)
- ▶ Our SD sensitivity reaches $\sim 7 \times 10^{-37} \text{ cm}^2$ at $\sim 500 \text{ MeV}/c^2$ with a 0.51 eV threshold (SQUID readout).
- ▶ The SD ceiling limit for QUEST-DMC is $\sim 3 \times 10^{-24} \text{ cm}^2$ using the diffusive propagation model, increasing by roughly a factor of two with the straight-line approximation.
- ▶ The SI ceiling limit is $\sim 7.5 \times 10^{-27} \text{ cm}^2$ under the diffusive model and also increases by about a factor of two in the straight-line path model.

[1] QUEST-DMC collaboration, **Dark Matter Attenuation Effects: Sensitivity Ceilings for Spin-Dependent and Spin-Independent Interactions**, arXiv:2502.10251[hep-ph], accepted for publication in JCAP (2025).

[2] QUEST-DMC collaboration, **QUEST-DMC superfluid ^3He detector for sub-GeV dark matter**, Eur. Phys. J. C 84, 248 (2024).

[3] QUEST-DMC collaboration, **QUEST-DMC: Background Modelling and Resulting Heat Deposit for a Superfluid Helium-3 Bolometer**, J Low Temp Phys 215, 465–476 (2024).