Title: QUEST-DMC: Direct Detection of Sub-GeV Dark Matter

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Series: Particle Physics

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Abstract: The QUEST-DMC experiment, aimed at detecting sub-GeV dark matter, utilizes a unique approach by employing superfluid Helium-3 (He-3) in conjunction with quantum sensors. Superfluid He-3 stands out as an ideal target medium for sub-GeV dark matter searches, especially in the context of spin-dependent interactions. This choice aligns seamlessly with a wide array of theoretically motivated dark matter models. The experiment's projected sensitivity to various dark matter models, as well as its potential to set upper limits on dark matter interactions, will be presented.

Zoom link https://pitp.zoom.us/j/99386484623?pwd=dGVQdFJKbEpPMUcrRUNLbHdIR2p3Zz09

QUEST DMC

QUEST-DMC: Direct Detection of Sub-GeV DM

Neda Darvishi

On behalf of the QUEST-DMC collaboration

ROYAL HOLLOWAY UNIVERSITY OF LONDON

October, 2023

QUEST-DMC

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Quantum Enhanced Superfluid Technologies for Dark Matter and Cosmology

- **WP1: Detection of sub GeV dark matter with a quantum amplified 3He calorimeter.**
  - Using superfluid 3He detector as a quantum calorimeter.
  - Reading out energy depositions using quantum sensors.
  - Very low threshold allows low mass dark matter searches.
- WP2: Phase transitions in extreme matter.
  - Simulating the early universe using 3He superfluid.
  - Studying phase transitions between distinct quantum vacua.
  - Searching for gravitational wave.

Core Team

EXPERIMENTAL	Robert Smith
Dr. Samuli Autti	Dr. Michael Thompson
Dr. Andrew Casey	Dr. Viktor Tsepelin
Dr. Paolo Franchini	Dr. Dmitry Zmeev
Prof. Richard Haley	Dr. Vladislav Zavyalov
Dr. Petri Heikkinen	Tineke Salmon
Dr. Sergey Kafanov	Luke Whitehead
Dr. Ashlea Kemp	**THEORY**
Dr. Elizabeth Leason	Prof. Mark Hindmarsh (Leading WP2)
Dr. Lev Levitin	Prof. Stephan Huber
Prof. Jocelyn Monroe (Leading WP1)	Prof. John March-Russell
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Dr. Xavier Rojas	Dr.Neda Darvishi
Prof. John Saunders	Dr. Quang Zhang

Outline

- Dark matter introduction and search strategies
- DM$-^3$He interaction, differential rate and cross-section
  - Setting spin-dependent (SD) limit
  - Setting spin-independent (SI) limit
- QUEST - new technique for sub GeV dark matter search
- The exclusion limit on SD and SI
- The Earth shadowing effect

Evidence for Existence of Dark Matter

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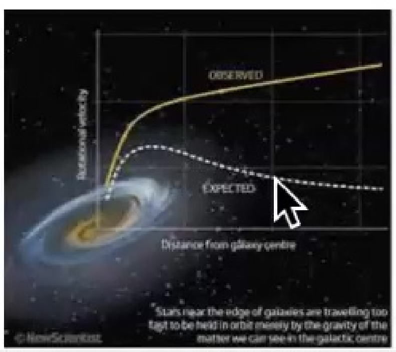
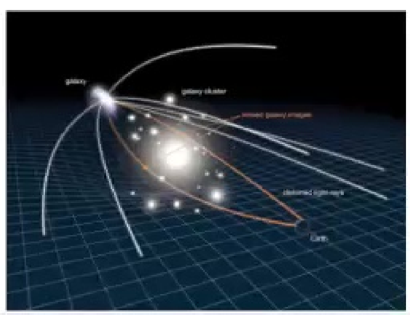
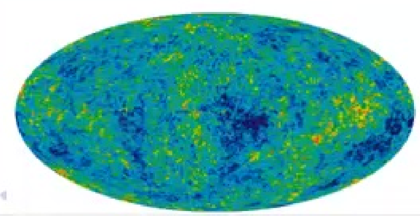
[Rubin et al ’78, Zwicky ’93, N. Aghanim et al ’18]

On a plethora of astrophysical scales:

- Galaxy rotation curves
- Velocity dispersion of galaxies in a cluster
- Gravitational lensing
- X-ray emission from gas in clusters
- CMB power spectra

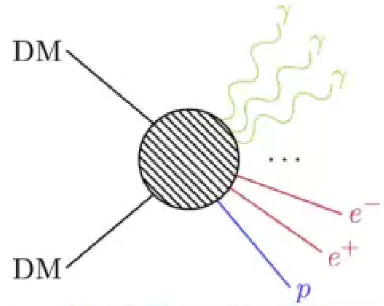


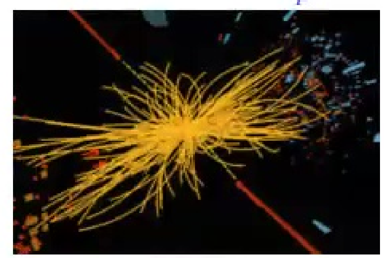


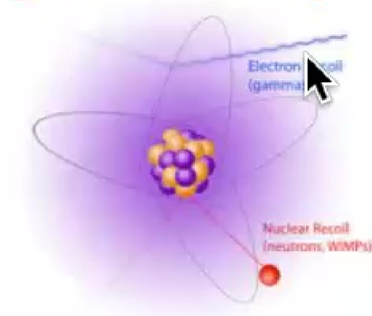


Dark Matter Search Strategies

- Indirect detection
  - Model independent
  - DM relic density $\Omega_{\mathrm{DM}} h^2 = 0.120 \pm 0.001$.
  - Many astrophysical backgrounds
- Collider production
  - DM production from SM particles
  - Search for missing energy/momentum or heavy mediator
  - Model dependent
- **Direct detection**
  - Scattering of DM off nuclei/electron in a detector







Direct Detection Experiment

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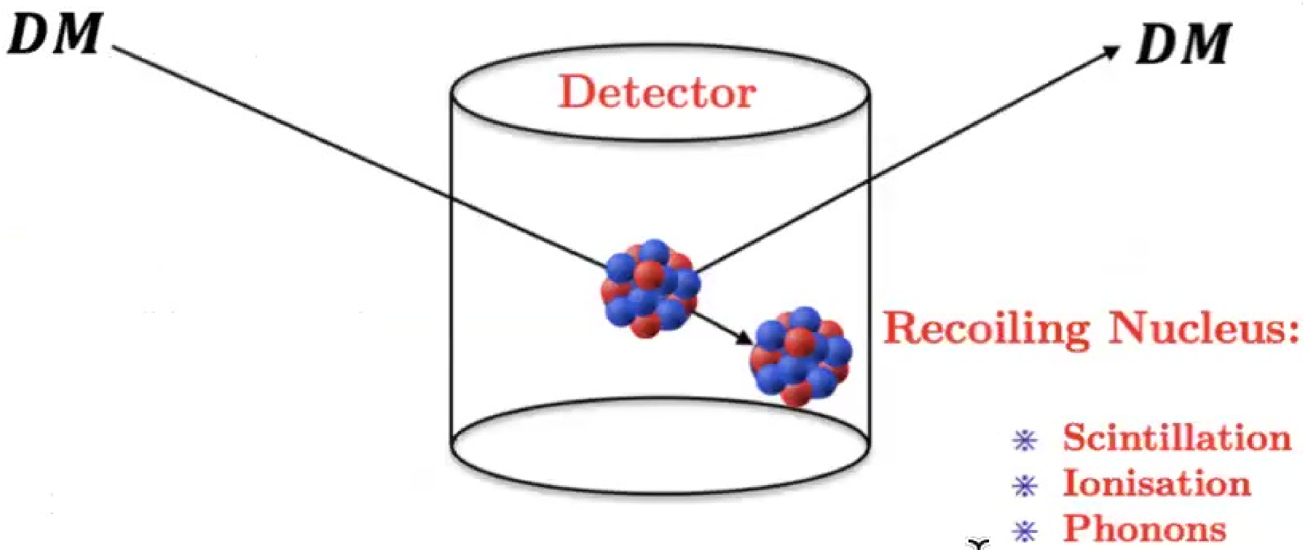
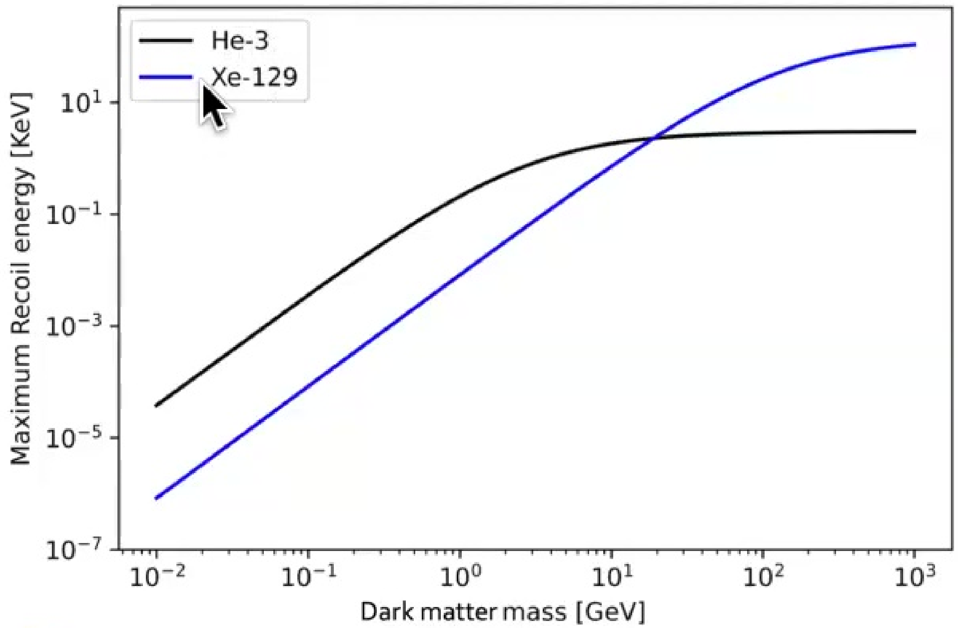
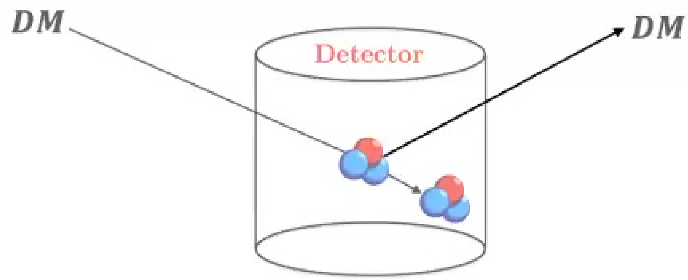


DM nucleon scattering gives recoil energy:

$$E_{\rm recoil} = \frac{\mu_{N\chi}^2 v_\chi^2}{M_N}(1 - \cos\theta)$$





To probe lower DM masses lighter target are more helpful.

Advantages of 3He target:

- Light target
- Low threshold
- Unpaired nucleon – allows SI and SD searches
- Intrinsically radiopure

Models for Sub-GeV dark matter:

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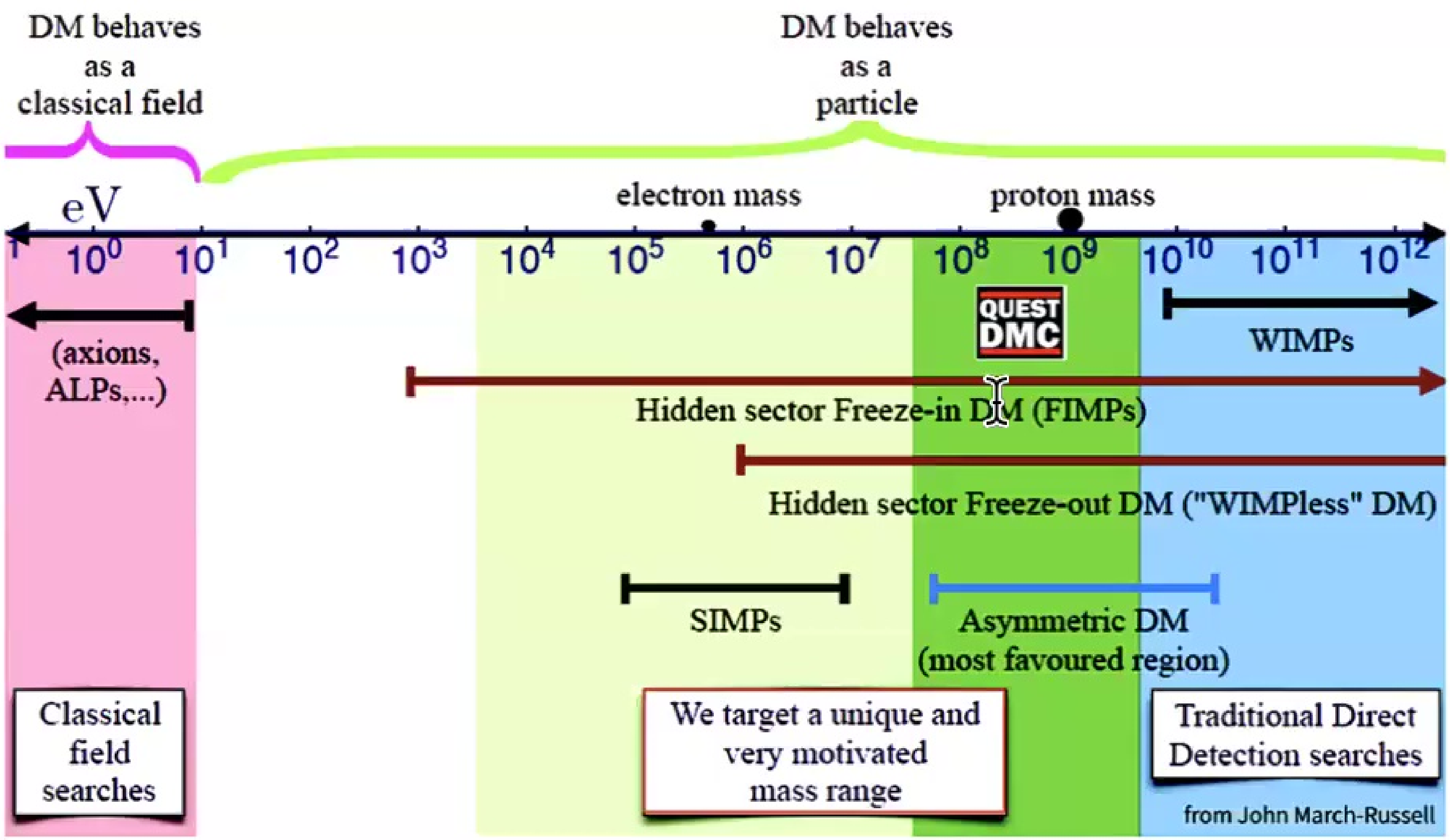
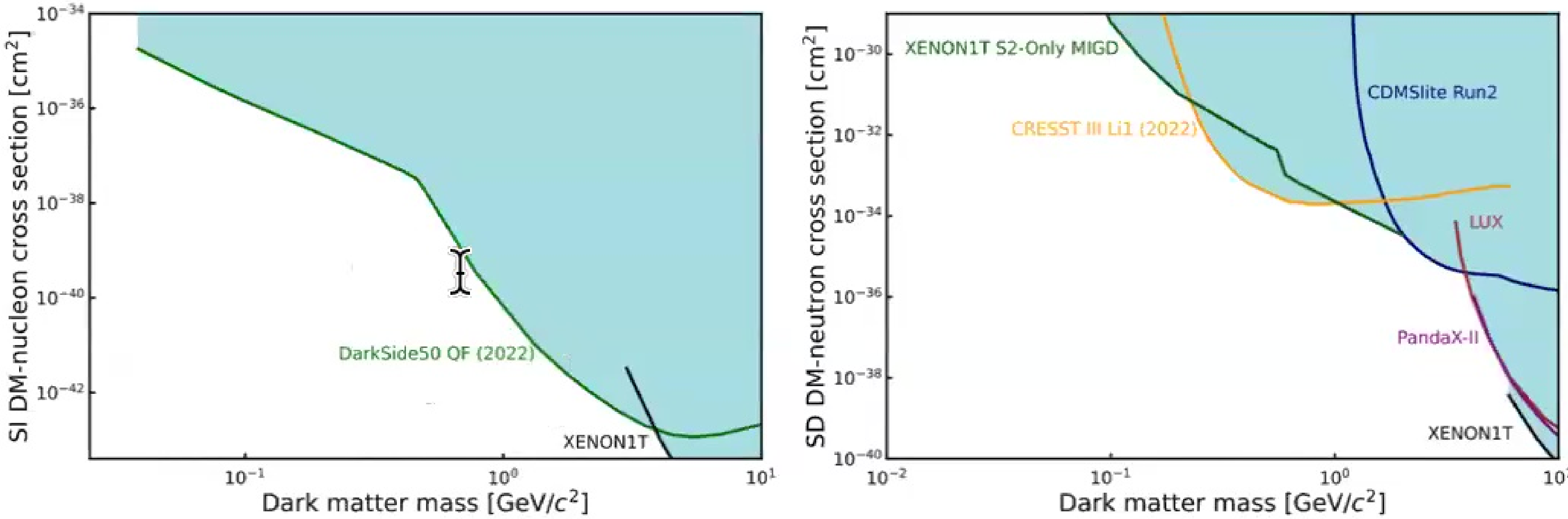


Leading sensitivities in direct detection:



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DM Ints.

$$\bar{\chi}\gamma^5\chi\bar{N}\gamma^5 N$$

$$\frac{P^\mu}{m_{\mathrm{M}}}\bar{\chi}\chi\bar{N}i\sigma_{\mu\alpha}\frac{q^\alpha}{m_{\mathrm{M}}}N$$

$$\frac{P^\mu}{m_{\mathrm{M}}}\bar{\chi}\chi\bar{N}\gamma_\mu\gamma^5 N$$

$$i\frac{P^\mu}{m_{\mathrm{M}}}\bar{\chi}\chi\frac{K_\mu}{m_{\mathrm{M}}}\bar{N}\gamma^5 N$$

$$\bar{\chi}i\sigma^{\mu\nu}\frac{q_\nu}{m_{\mathrm{M}}}\chi\bar{N}\gamma^\mu\gamma^5 N$$

$$\bar{\chi}\gamma^\mu\gamma^5\chi\frac{K_\mu}{m_{\mathrm{M}}}\bar{N}N$$

$$\bar{\chi}\chi\bar{N}N$$

$$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{N}\gamma^\mu\gamma^5 N$$

$$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{N}i\sigma_{\mu\alpha}\frac{q^\alpha}{m_{\mathrm{M}}}N$$

$$i\bar{\chi}\gamma^\mu\gamma^5\chi\frac{K^\mu}{m_{\mathrm{M}}}\bar{N}\gamma^5 N$$

$$i\bar{\chi}\gamma^5\chi\bar{N}N$$

$$i\frac{P^\mu}{m_{\mathrm{M}}}\bar{\chi}\gamma^5\chi\bar{N}\gamma_\mu\gamma^5 N$$

$$\frac{P^\mu}{m_{\mathrm{M}}}\bar{\chi}\gamma^5\chi\frac{K_\mu}{m_{\mathrm{M}}}\bar{N}\gamma^5 N$$

$$i\bar{\chi}\chi\bar{N}\gamma^5 N$$

NR EFT of DM direct detection

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- A general formulation for possible DM-nucleus interactions and a better description of the nuclear response.
- 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 $t^1 = \sigma^3$

$$\sigma^0 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}, \quad \sigma^3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

- Based on three-vectors: $\vec{\mathbf{1}}_\chi, \quad \vec{\mathbf{1}}_N, \quad i\frac{\vec{q}}{m_N}, \quad \vec{v}^\perp, \quad \vec{\mathbf{S}}_\chi, \quad \vec{\mathbf{S}}_N,$

Non-Relativistic operators

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- Hermitian operators are constructed as:

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

Scattering Rate

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- Differential cross section per recoil energy:

$$\frac{d\sigma}{dE_R} = \frac{m_N}{2\pi v^2}\left\{\frac{1}{2j_\chi+1}\frac{1}{2j_N+1}\sum_{\text{spins}}|\mathcal{M}|^2\right\}$$

As was first pointed out by Migdal (1986):

$$P_{\text{tot}} = \frac{1}{2j_\chi+1}\frac{1}{2j_N+1}\sum_{\text{spins}}|\mathcal{M}|^2$$

$$= \frac{4\pi}{2j_N+1}\sum_{k}\sum_{\tau=0,1}\sum_{\tau'=0,1} R_k^{\tau\tau'}\left(\vec{v}_T^{\perp 2}, \frac{\vec{q}^2}{m_N^2}, \left\{c_i^\tau c_j^{\tau'}\right\}\right) S_k^{\tau\tau'}(y)$$

$$k = M,\ \Phi'',\ \Phi'' M,\ \tilde{\Phi}',\ \Sigma'',\ \Sigma',\ \Delta,\ \Delta\Sigma'.$$

R_k relevant to $\vec{S}_N$-SD and -SI operators:

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operator	$R_k^{\tau\tau'}$	operator	$R_k^{\tau\tau'}$
1	$R_M(q^0)$	3	$R_{\Phi''}(q^4)$,$R_{\Sigma'}(q^2)$
4	$R_{\Sigma''}(q^0)$,$R_{\Sigma'}(q^0)$	5	$R_\Delta(q^4)$, $R_M(q^2)$
6	$R_{\Sigma''}(q^4)$	7	$R_{\Sigma'}(q^0)$
8	$R_\Delta(q^2)$, $R_M(q^0)$	9	$R_{\Sigma'}(q^2)$
10	$R_{\Sigma''}(q^2)$	11	$R_M(q^2)$
12	$R_{\Phi''}(q^2)$,$R_{\tilde{\Phi}'}(q^2)$,$R_{\Sigma''}(q^0)$,$R_{\Sigma'}(q^0)$	13	$R_{\tilde{\Phi}'}(q^4)$,$R_{\Sigma''}(q^2)$
14	$R_{\Sigma'}(q^2)$	15	$R_{\Phi''}(q^6)$, $R_{\Sigma'}(q^4)$

R_k relevant to Helium-3

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$$R_{\Sigma''}^{\tau\tau'}\left(v_T^{\perp 2}, \frac{q^2}{m_N^2}\right) = \frac{q^2}{4m_N^2} c_{10}^\tau c_{10}^{\tau'} + \frac{j_\chi(j_\chi+1)}{12}\left[c_4^\tau c_4^{\tau'} + \frac{q^2}{m_N^2}(c_4^\tau c_6^{\tau'} + c_6^\tau c_4^{\tau'}) + \frac{q^4}{m_N^4} c_6^\tau c_6^{\tau'} + v_T^{\perp 2} c_{12}^\tau c_{12}^{\tau'} + \frac{q^2}{m_N^2} v_T^{\perp 2} c_{13}^\tau c_{13}^{\tau'}\right]$$

$$R_{\Sigma'}^{\tau\tau'}\left(v_T^{\perp 2}, \frac{q^2}{m_N^2}\right) = \frac{1}{8}\left[\frac{q^2}{m_N^2} v_T^{\perp 2} c_3^\tau c_3^{\tau'} + v_T^{\perp 2} c_7^\tau c_7^{\tau'}\right] + \frac{j_\chi(j_\chi+1)}{12}\left[c_4^\tau c_4^{\tau'} + \frac{q^2}{m_N^2} c_9^\tau c_9^{\tau'} + \frac{v_T^{\perp 2}}{2}\left(c_{12}^\tau - \frac{q^2}{m_N^2} c_{15}^\tau\right)\left(c_{12}^{\tau'} - \frac{q^2}{m_N^2} c_{15}^{\tau'}\right) + \frac{q^2}{2m_N^2} v_T^{\perp 2} c_{14}^\tau c_{14}^{\tau'}\right]$$

$$R_{M}^{\tau\tau'}\left(v_T^{\perp 2}, \frac{q^2}{m_N^2}\right) = c_1^\tau c_1^{\tau'} + \frac{j_\chi(j_\chi+1)}{3}\left[\frac{q^2}{m_N^2} v_T^{\perp 2} c_5^\tau c_5^{\tau'} + v_T^{\perp 2} c_8^\tau c_8^{\tau'} + \frac{q^2}{m_N^2} c_{11}^\tau c_{11}^{\tau'}\right]$$

Separating SD and SI interactions

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- SD/SI differential scattering rate per recoil energy:

$\hat{\mathcal{O}}_4 = \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{S}}_N \rightarrow$ SD, momentum and velocity independent

$$\frac{d\sigma^{\rm SD}}{dE_R} = \frac{m_N}{v^2}\frac{2}{2j_N+1}\sum_{\tau=0,1}\sum_{\tau'=0,1}\frac{j_\chi(j_\chi+1)}{12}\left[c_4^\tau c_4^{\tau'}\right] S^{\tau\tau'}_{\Sigma'',\Sigma'}(y)$$

$$= \frac{m_N}{2\pi v^2}\frac{32\pi G_F^2}{2j_N+1} S_N^{\rm SD}(q^2)$$

$\hat{\mathcal{O}}_1 = \hat{\mathbf{1}}_\chi \cdot \hat{\mathbf{1}}_N \rightarrow$ SI, momentum and velocity independent:

$$\frac{d\sigma^{\rm SI}}{dE_R} = \frac{m_N}{v^2}\sum_{\tau=0,1}\sum_{\tau'=0,1}\left[c_1^\tau c_1^{\tau'}\right] S_M^{\tau\tau'}(y) = \frac{m_N}{2\pi v^2}P^{\rm SI}_{\rm tot}$$

$$= \frac{8m_N}{v^2}G_F^2\, S_N^{\rm SI}(q^2)$$

Proton and neutron contributions:

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$$|p\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \quad |n\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}, \; c_i^{\mathrm{p}} = \frac{c_i^0 + c_i^1}{2} \quad c_i^{\mathrm{n}} = \frac{c_i^0 - c_i^1}{2}$$

The SD structure function in terms of its isoscalar and isovector parts

$$\begin{aligned} S_N^{\mathrm{SD}}(q^2) &= (a_p^2 + a_n^2 + a_p a_n) S^{00} + 2(a_p^2 - a_n^2) S^{01} + (a_p^2 + a_n^2 - a_p a_n)\, S^{11} \\ &= a_p^2 \left(S^{00} + 2S^{01} + S^{11}\right) + a_n^2 \left(S^{00} + S^{11} - 2S^{01}\right) + a_p a_n \left(S^{00} - S^{11}\right) \\ &= a_p^2 S_p(q) + a_n^2 S_n(q) + a_p a_n S_{np}(q). \end{aligned}$$

The SI structure function:

$$S_N^{\mathrm{SI}}(q^2) = (Z f_p + (A - Z) f_n)^2\, S(q^2).$$

Defining

$$c_4^n c_4^n = 8\; G_F^2 a_n^2 \left\{\frac{12}{j_\chi(j_\chi + 1)}\right\} \quad c_4^p c_4^p = 8\; G_F^2 a_p^2 \left\{\frac{12}{j_\chi(j_\chi + 1)}\right\}$$

$$c_1^n c_1^n = c_1^p c_1^p = 8\; G_F^2 \left((A - Z) f_n + Z f_p\right)^2$$

SD Helium-3

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SD Helium-3	$y = (bq/2)^2$
$S^{00}_{\Sigma''}(y) = \ 0.0397887e^{-2y}$	$S^{00}_{\Sigma'}(y) = \ 0.0795775e^{-2y}$
$S^{11}_{\Sigma''}(y) = \ 0.0397887e^{-2y}$	$S^{11}_{\Sigma'}(y) = \ 0.0795775e^{-2y}$
$S^{10}_{\Sigma''}(y) = -0.0397887e^{-2y}$	$S^{10}_{\Sigma'}(y) = -0.0795775e^{-2y}$
$S^{01}_{\Sigma''}(y) = -0.0397887e^{-2y}$	$S^{01}_{\Sigma'}(y) = -0.0795775e^{-2y}$

$$S_N(0) \equiv a_n^2(S^{00} + S^{11} - 2S^{01}) = 0.47746\ a_n^2$$

The mean spin of the neutron and proton in Helium-3

$$\langle \mathbf{S_N} \rangle^{\mathbf{2}} \equiv \frac{\mathbf{4\pi}}{\mathbf{2j_N + 1}} \frac{\mathbf{j_N}}{\mathbf{4(j_N + 1)}}\ \mathbf{S_n(0)}$$

with $j_N = 1/2$ leading to

$$\langle \mathbf{S_N} \rangle = \sqrt{\frac{\pi S_n(0)}{6}} = \mathbf{0.5}$$

SD Helium-3

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$$P_{\rm tot}^{\rm SD} \equiv \frac{32(j_N+1)}{j_N}\, G_F^2 a_n^2\, \langle \mathbf{S_N}\rangle^2 \frac{S_n(q^2)}{S_n(0)} = 24\, G_F^2\, a_n^2 \frac{S_n(q^2)}{S_n(0)}$$

$$c_4^n c_4^n = 8\, G_F^2 a_n^2 \left\{ \frac{12}{j_\chi(j_\chi+1)} \right\}$$

$$\sigma_{\chi \rm n}^{\rm SD} = \frac{\mu_{\chi \rm n}^2}{\pi} P_{\rm tot}^{\rm SD} \qquad \longrightarrow \qquad (\mathbf{c_4^n})^2 \equiv \frac{\mathbf{16}\pi}{\mathbf{3}} \frac{\sigma_{\chi \rm n}^{\rm SD}}{\mu_{\chi \rm n}^{\mathbf{2}}}$$

A differential cross section and event rate for SD:

$$\frac{d\sigma^{\rm SD}}{dE_R} = \frac{2m_N \sigma_{\chi \rm n}^{\rm SD}}{3\mu_{\chi n}^2 v^2} \frac{(J+1)}{J} \langle S_n \rangle^2 \frac{S_n(q^2)}{S_n(0)} = \frac{m_N \sigma_{\chi \rm n}^{\rm SD}}{2\mu_{\chi n}^2 v^2} \frac{S_n(q^2)}{S_n(0)},$$

$$\frac{dR^{\rm SD}}{dE_R} = \frac{\rho_\chi \sigma_{\chi n}^{\rm SD}}{2\, m_\chi \mu_{\chi n}^2} \frac{S_n(q^2)}{S_n(0)} \int \frac{1}{v}\, f(\mathbf{v})\, d^3\mathbf{v}.$$

SI Helium-3

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SI Helium-3	$y = (bq/2)^2$
$S_M^{00}(y) = \ 0.358099e^{-2y}$	$S_M^{11}(y) = \ 0.0397887e^{-2y}$
$S_M^{01}(y) = \ 0.119366e^{-2y}$	$S_M^{10}(y) = \ 0.119366e^{-2y}$

$$P_{\rm tot}^{\rm SI} \equiv \ 8\, G_F^2 \, (Z f_p + (A-Z) f_n)^2 S(q^2)$$

$$c_1^n c_1^n = 8 \, G_F^2 (Z f_p + (A-Z) f_n)^2$$

$$\sigma_{\chi \rm n}^{\rm SI} = \frac{\mu_{\chi \rm n}^2}{\pi} P_{\rm tot}^{\rm SI} \qquad \longrightarrow \qquad (c_1)^2 \equiv \pi \frac{\sigma_{\chi \rm n}^{\rm SI}}{\mu_{\chi \rm n}^2}$$

A differential cross section and event rate for SI Helium-3:

$$\frac{d\sigma^{\rm SI}}{dE_R} = \frac{m_N \sigma_{\chi \rm n}^{\rm SI}}{2\mu_{\chi n}^2 v^2} S(q^2),$$

$$\frac{dR^{\rm SI}}{dE_R} = \frac{\rho_\chi \sigma_{\chi n}^{\rm SI}}{2\, m_\chi \mu_{\chi n}^2} S(q^2) \int \frac{1}{v} \, f(\mathbf{v}) \, d^3\mathbf{v}.$$

Limits on c_i coefficients for Helium-3

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$$\mathcal{O}_1 \Rightarrow (c_1)^2 \equiv \pi \frac{\sigma^{\rm SI}_{\chi \rm n}}{\mu^2_{\chi \rm n}}$$

$$\mathcal{O}_3 \Rightarrow (c_3)^2 \equiv \frac{2\pi}{3\langle S_N\rangle^2_{\Sigma'}} \frac{m_N^2}{q^2} \frac{\sigma^{\rm SD}_{\chi \rm n}}{\mu^2_{\chi \rm n} v_T^{\perp 2}}$$

$$\mathcal{O}_4 \Rightarrow (c_4)^2 \equiv \frac{16\pi}{3} \frac{\sigma^{\rm SD}_{\chi \rm n}}{\mu^2_{\chi \rm n}}$$

$$\mathcal{O}_5 \Rightarrow (c_5)^2 \equiv \pi \frac{m_N^2}{q^2} \frac{\sigma^{\rm SI}_{\chi \rm n}}{\mu^2_{\chi \rm n} v_T^{\perp 2}}$$

$$\mathcal{O}_6 \Rightarrow (c_6)^2 \equiv \frac{4\pi}{3\langle S_N\rangle^2_{\Sigma''}} \frac{m_N^4}{q^4} \frac{\sigma^{\rm SD}_{\chi \rm n}}{\mu^2_{\chi \rm n}}$$

$$\mathcal{O}_7 \Rightarrow (c_7)^2 \equiv \frac{2\pi}{3\langle S_N\rangle^2_{\Sigma'}} \frac{\sigma^{\rm SD}_{\chi \rm n}}{\mu^2_{\chi \rm n} v_T^{\perp 2}}$$

$$\mathcal{O}_8 \Rightarrow (c_8)^2 \equiv \pi \frac{\sigma^{\rm SI}_{\chi \rm n}}{\mu^2_{\chi \rm n} v_T^{\perp 2}}$$

$$\mathcal{O}_9 \Rightarrow (c_9)^2 \equiv \frac{4\pi}{3\langle S_N\rangle^2_{\Sigma'}} \frac{m_N^2}{q^2} \frac{\sigma^{\rm SD}_{\chi \rm n}}{\mu^2_{\chi \rm n}}$$

$$\mathcal{O}_{10} \Rightarrow (c_{10})^2 \equiv \frac{\pi}{3\langle S_N\rangle^2_{\Sigma''}} \frac{m_N^2}{q^2} \frac{\sigma^{\rm SD}_{\chi \rm n}}{\mu^2_{\chi \rm n}}$$

$$\mathcal{O}_{11} \Rightarrow (c_{11})^2 \equiv \pi \frac{m_N^2}{q^2} \frac{\sigma^{\rm SI}_{\chi \rm n}}{\mu^2_{\chi \rm n}}$$

$$\mathcal{O}_{12} \Rightarrow (c_{12})^2 \equiv \frac{16\pi}{3} \frac{\sigma^{\rm SD}_{\chi \rm n}}{\mu^2_{\chi \rm n} v_T^{\perp 2}} \left[1 + \frac{1}{4\langle S_N\rangle^2_{\Sigma'}}\right]$$

$$\mathcal{O}_{13} \Rightarrow (c_{13})^2 \equiv \frac{4\pi}{3\langle S_N\rangle^2_{\Sigma''}} \frac{m_N^2}{q^2} \frac{\sigma^{\rm SD}_{\chi \rm n}}{\mu^2_{\chi \rm n} v_T^{\perp 2}}$$

$$\mathcal{O}_{14} \Rightarrow (c_{14})^2 \equiv \frac{8\pi}{3\langle S_N\rangle^2_{\Sigma''}} \frac{m_N^2}{q^2} \frac{\sigma^{\rm SD}_{\chi \rm n}}{\mu^2_{\chi \rm n} v_T^{\perp 2}}$$

$$\mathcal{O}_{15} \Rightarrow (c_{15})^2 \equiv \frac{8\pi}{3\langle S_N\rangle^2_{\Sigma'}} \frac{m_N^4}{q^4} \frac{\sigma^{\rm SD}_{\chi \rm n}}{\mu^2_{\chi \rm n} v_T^{\perp 2}}$$

The differential rate per recoil energy

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$$\frac{dR^{\rm SD}}{dE_R} = \frac{\rho_\chi m_N}{2\pi m_\chi}\langle\frac{1}{v}P_{\rm tot}(v^2, q^2)\rangle \equiv \frac{\rho_\chi \sigma^{\rm SD}_{\chi n}}{2\, m_\chi \mu^2_{\chi n}}\int_{v_{\rm min}}^{\infty}\frac{1}{v}\, f(\mathbf{v})\, d^3\mathbf{v}$$

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

- $\mathbf{v} = (v_x, v_y, v_z)$ and $v = |\mathbf{v}|$
- The mean DM velocity $\langle\mathbf{v}_\chi\rangle = -\mathbf{v}_{\rm lab}(t)$
- $v > v_{\rm min} = \sqrt{m_N E_R/(2\mu^2_{\chi N})}$

All Operators

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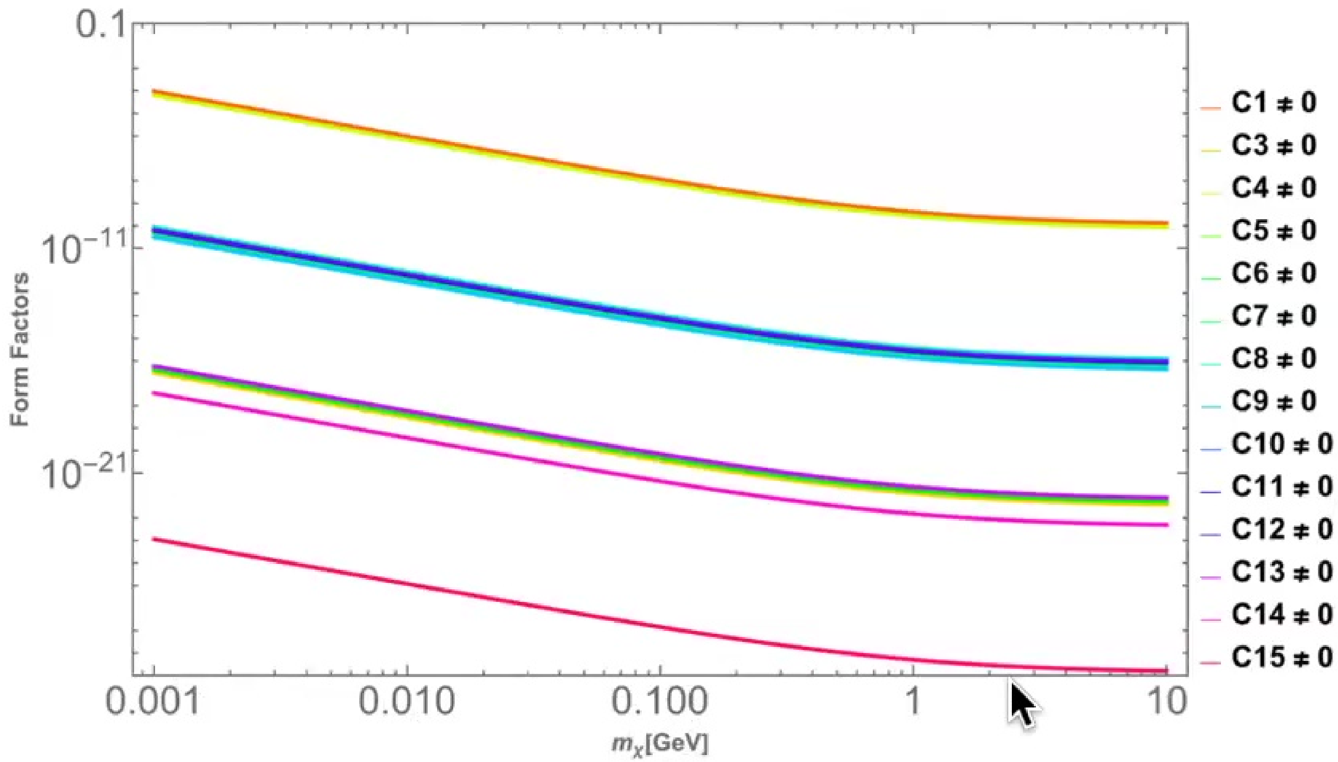
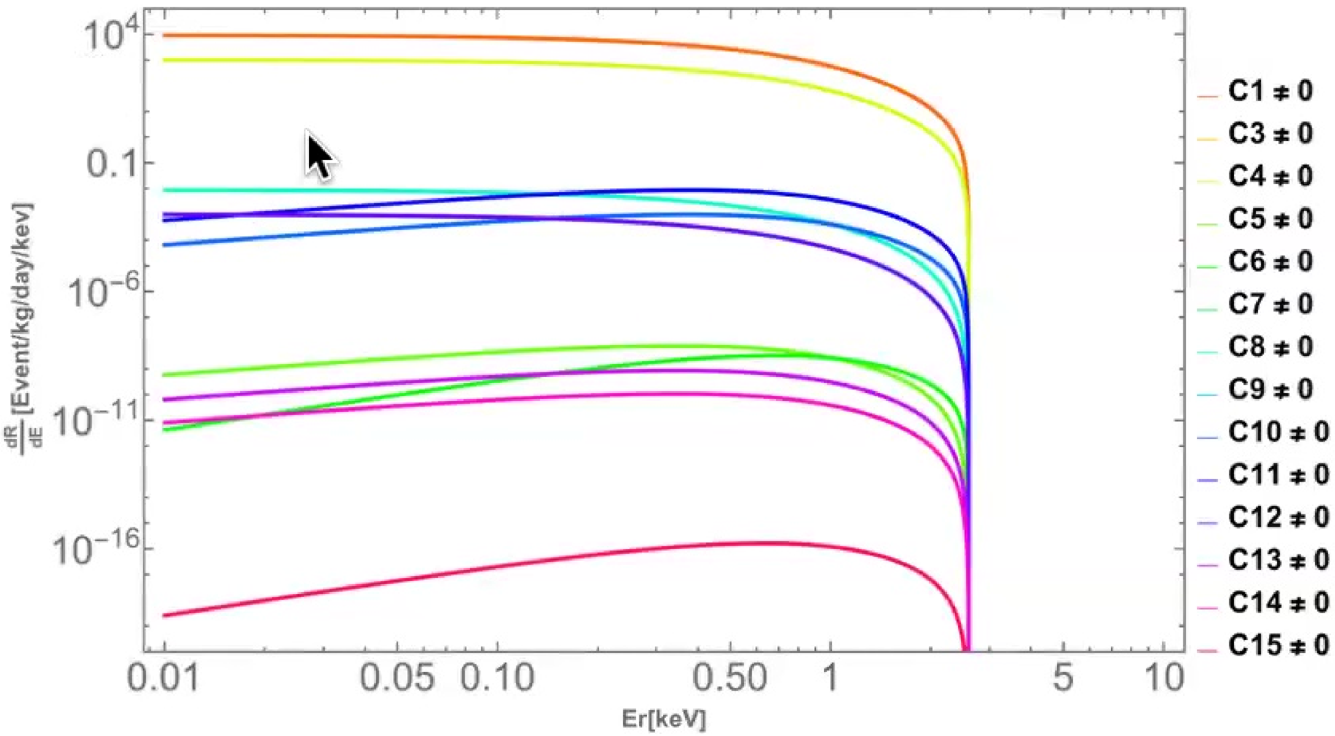


All Operators

- $m_\chi = 1$ GeV



The SD differential rate per recoil energy

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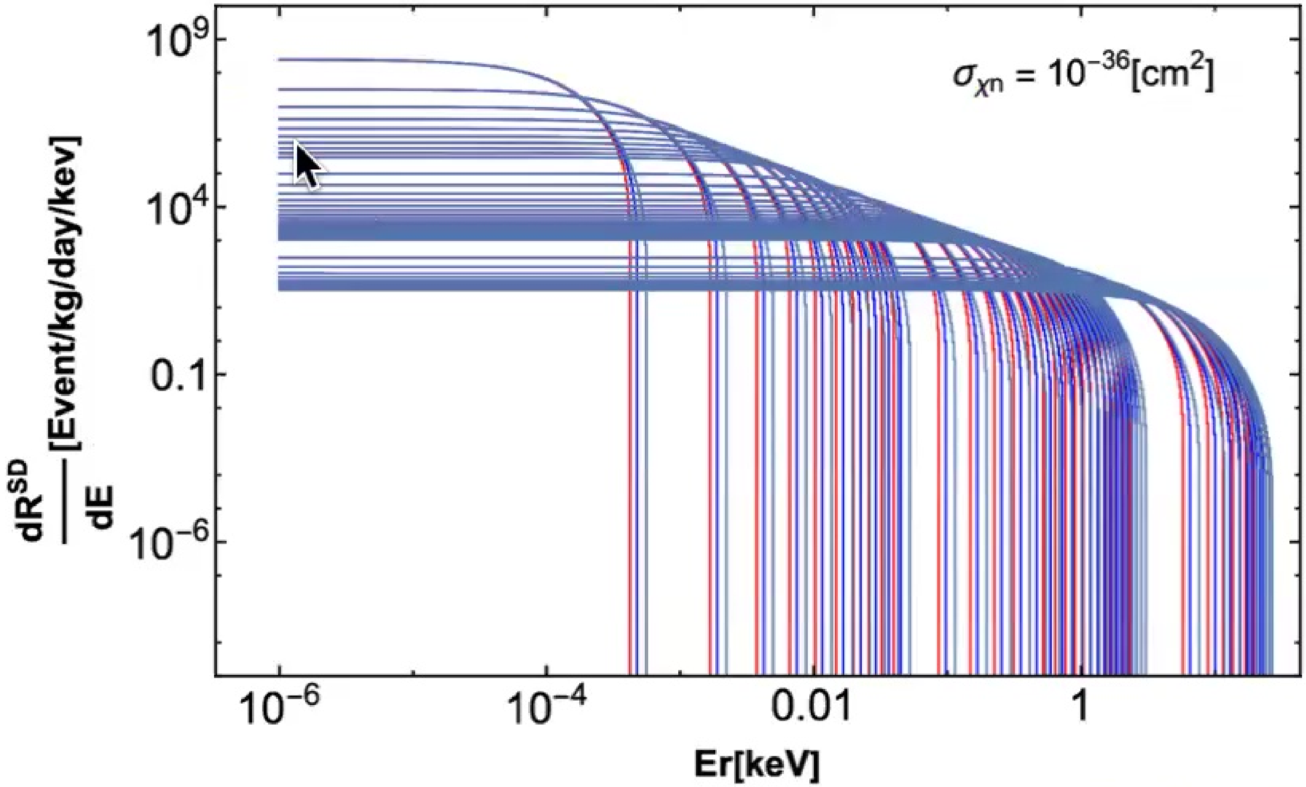
- $m_\chi = \{0.01, 0.02, 0.03, \cdots, 9.0, 10.0 \text{ GeV}\}$



The SI differential rate per recoil energy

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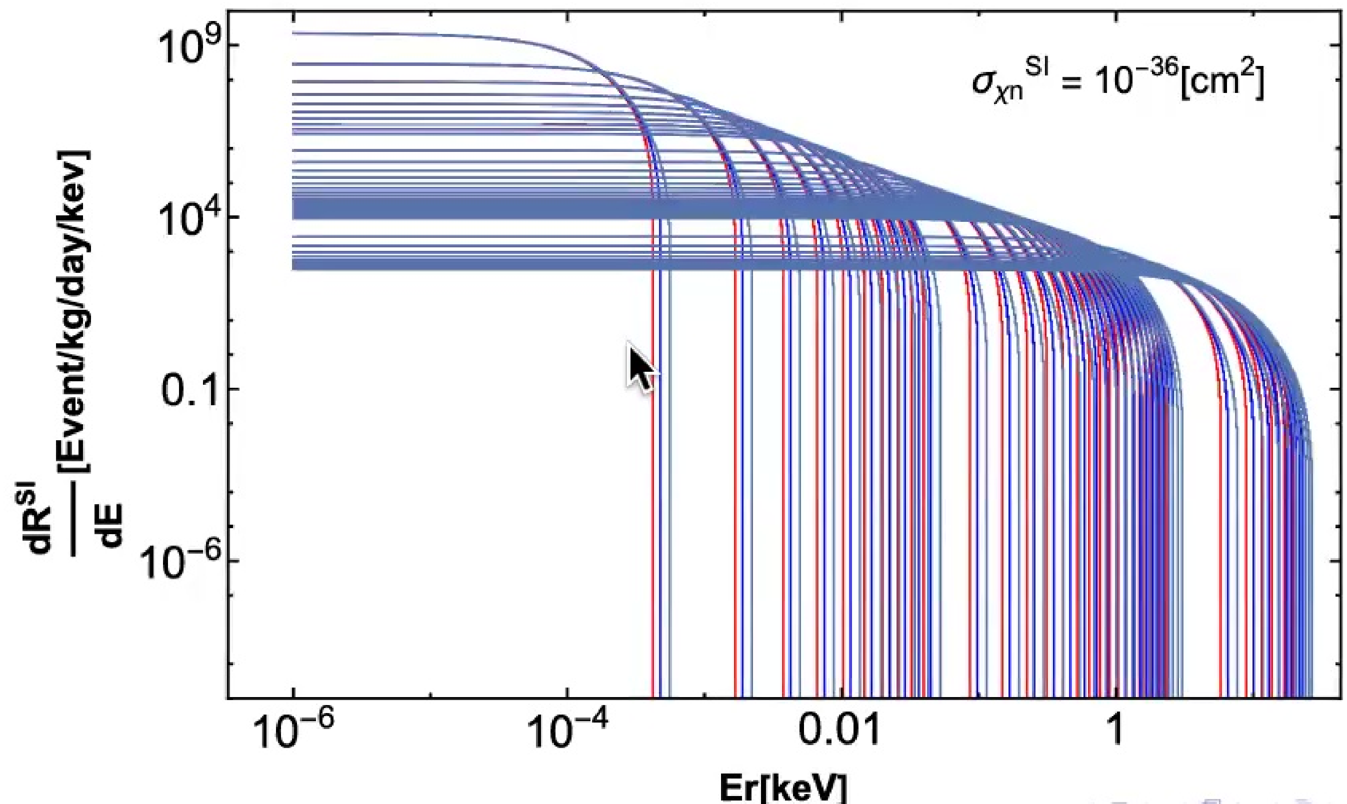
- $m_\chi = \{0.01, 0.02, 0.03 \cdots, 9.0, 10.0 \text{ GeV}\}$



QUEST-DMC Detector

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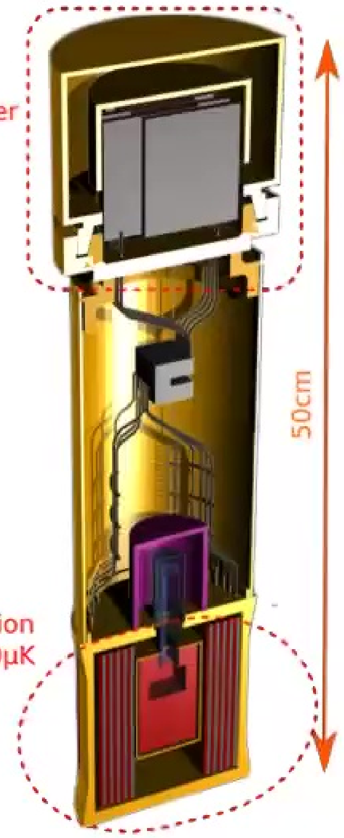

QUEST-DMC Detector

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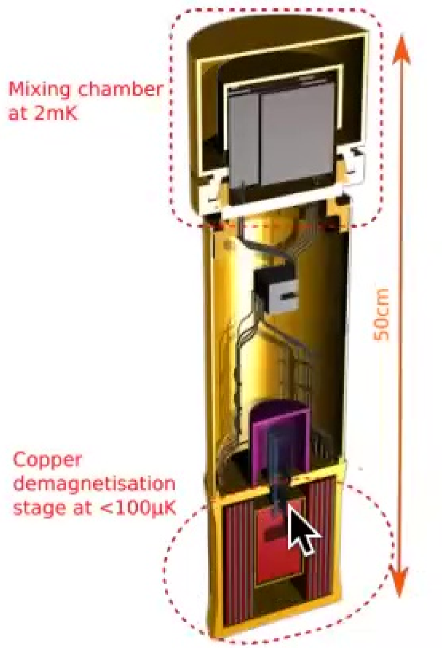
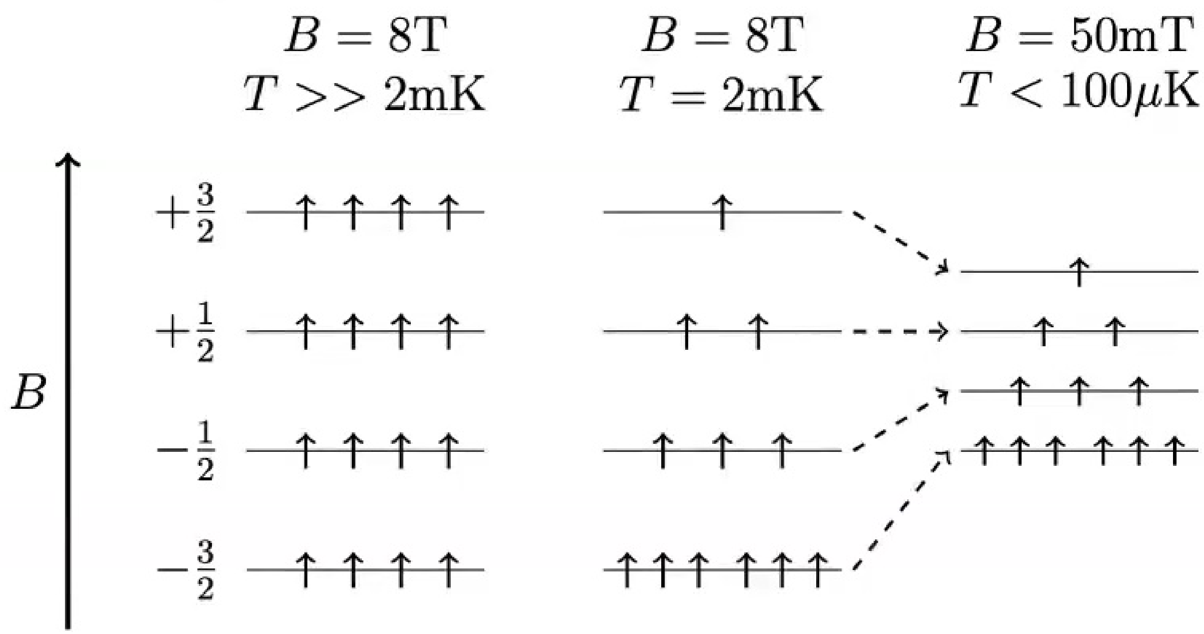
Credit: P. Franchini

- $5 \times 1\text{cm}^3$ bolometer targets, each 0.1g ^{3}He cooled to $<100\ \mu K$
- Cool-down system consists of three stages:
  - Liquid nitrogen and 4He bath.
  - ^{3}He/^{4}He dilution refrigerator.
  - Nuclear demagnetisation refrigerator.

QUEST-DMC Detector

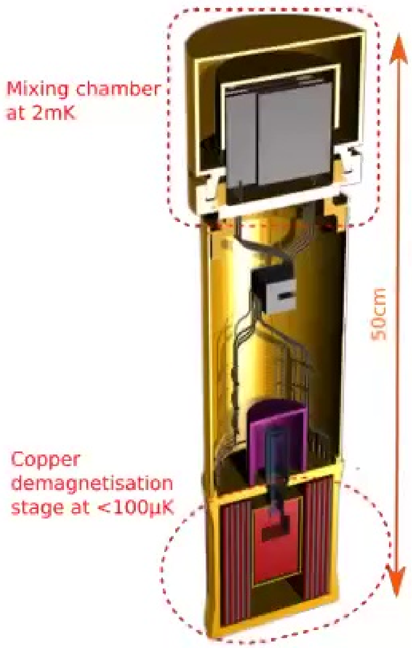


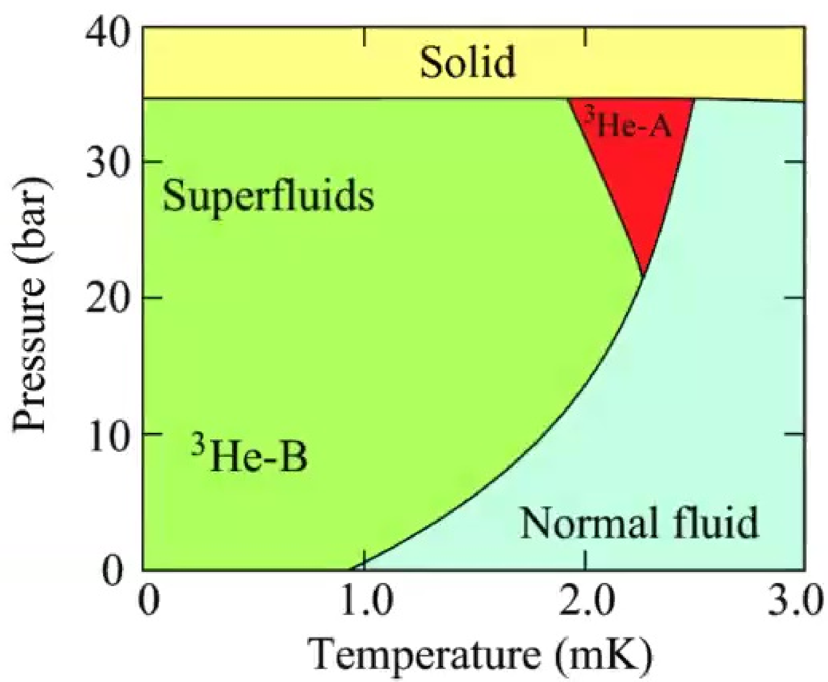
- In presence of B field, nuclear energy levels split into four via the Zeeman effect.



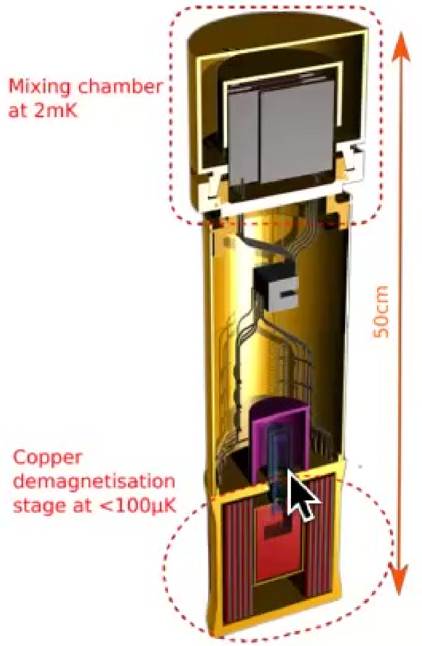
QUEST-DMC Detector

- Gaining superfluid ^{3}He





QUEST-DMC Detector



- Dark matter ^{3}He scattering energy generates heat and photons
- Photon detection using Silicon Photomultiplier (SiPM) technology. Photon detectors to be located above the ^{3}He target.
- Heat (quasiparticles) detects using bolometer. Bolometer measures temperature changes. These temperature changes can hint at dark matter's presence.

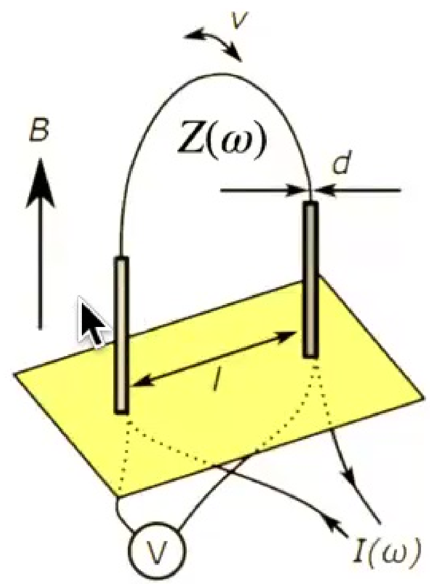
3He Bolometer

- ^{3}He bolometer instrumented with vibrating nanowire resonators.
- Nanowire in ^{3}He box is subjected to B field and driven by AC current and oscillates at frequency, ω.
- Wire loop is moving with velocity v, and force and voltage on an element of wire

$$dF = I|dl \times B| \qquad dV = v \cdot |dl \times B|$$

- By integrating along the length of wire, the total force and voltage:

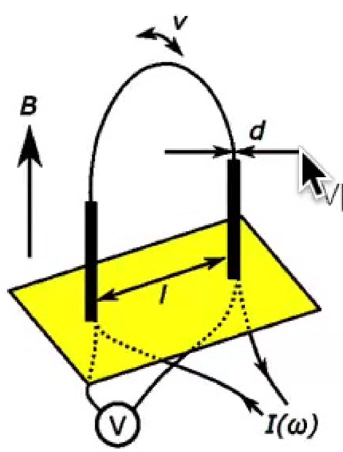
$$F = ILB \qquad V = vLB$$

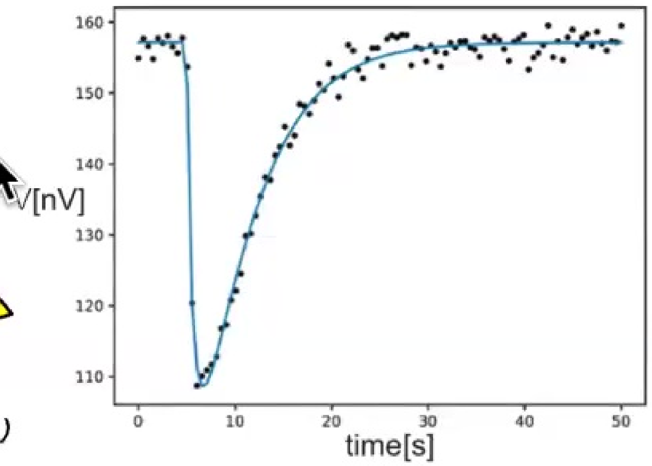


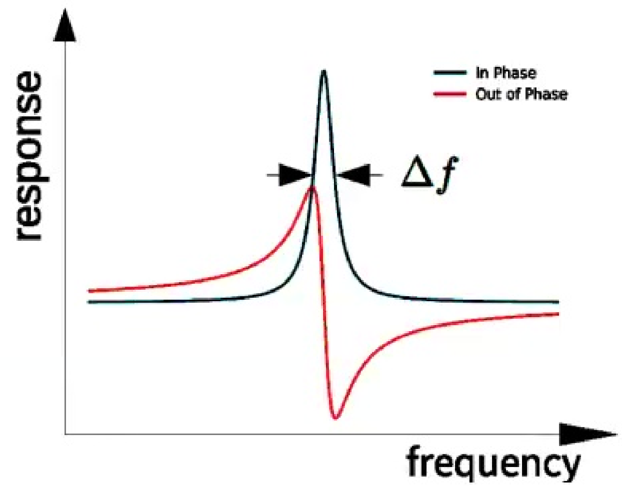
Credit: P. Franchini

3He Bolometer

- Nanowire experiences a damping force due to interactions with quasiparticles.
- Observe a pulse that is induced in the voltage $V(t)$.
- The wire response is measured as a function of frequency.







3He Bolometer

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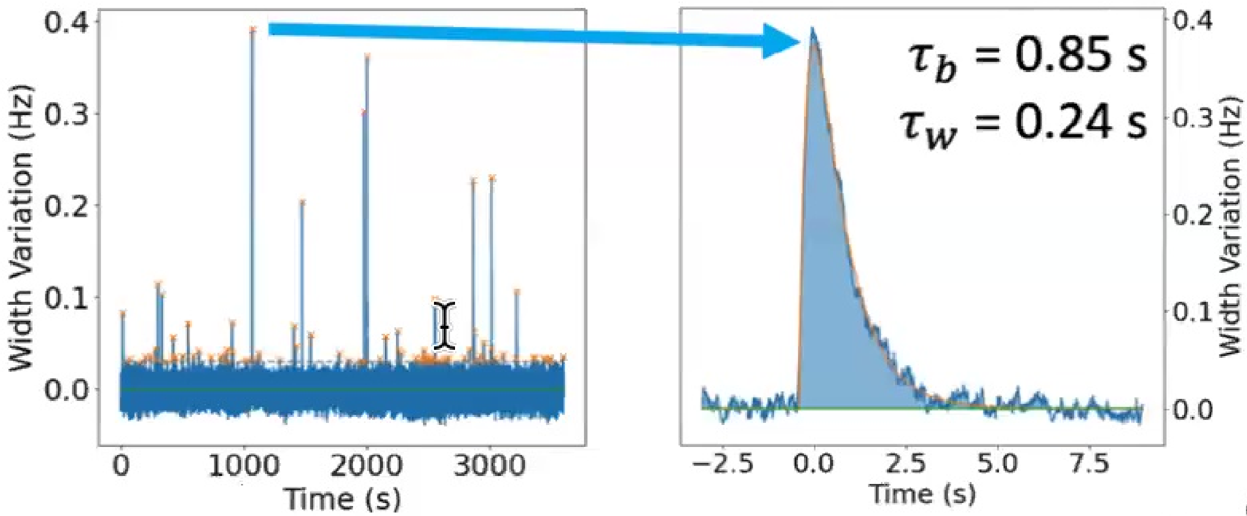
- The wire response is parametrised by resonance width Δf and an amplitude.



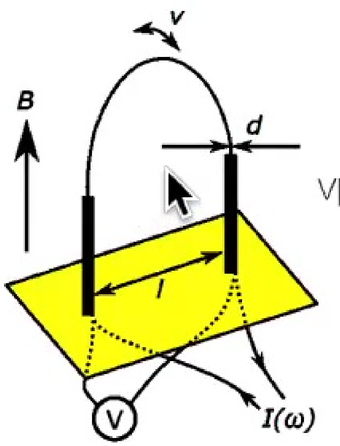
Credit: T. Salmon

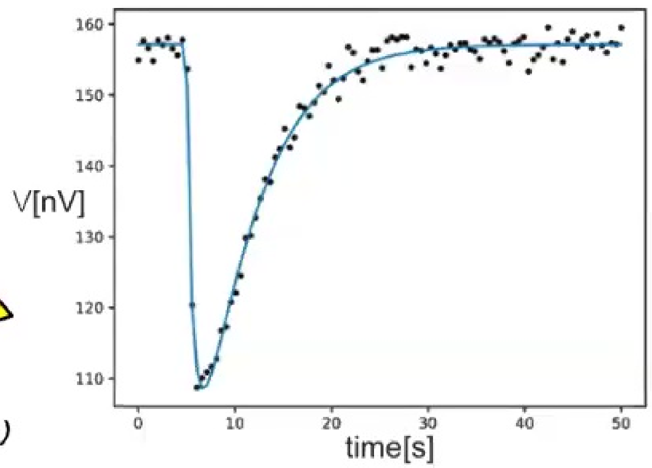
$$\Delta f(t) = \Delta f_{\text{base}} + \Delta(\Delta f)\left(\tau_{\text{b}}\tau_{\text{w}}^{-1}\right)^{\tau_{\text{w}}(\tau_{\text{b}}-\tau_{\text{w}})^{-1}} \tau_{\text{b}}(\tau_{\text{b}} - \tau_{\text{w}})^{-1}\left(e^{-t/\tau_{\text{b}}} - e^{-t/\tau_{\text{w}}}\right)$$

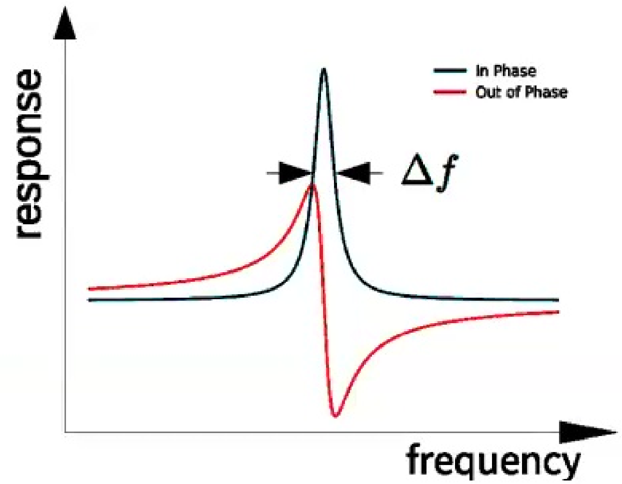
$$E_{dep} = KT\Delta(\Delta f)$$

3He Bolometer

- Nanowire experiences a damping force due to interactions with quasiparticles.
- Observe a pulse that is induced in the voltage $V(t)$.
- The wire response is measured as a function of frequency.







3He Bolometer

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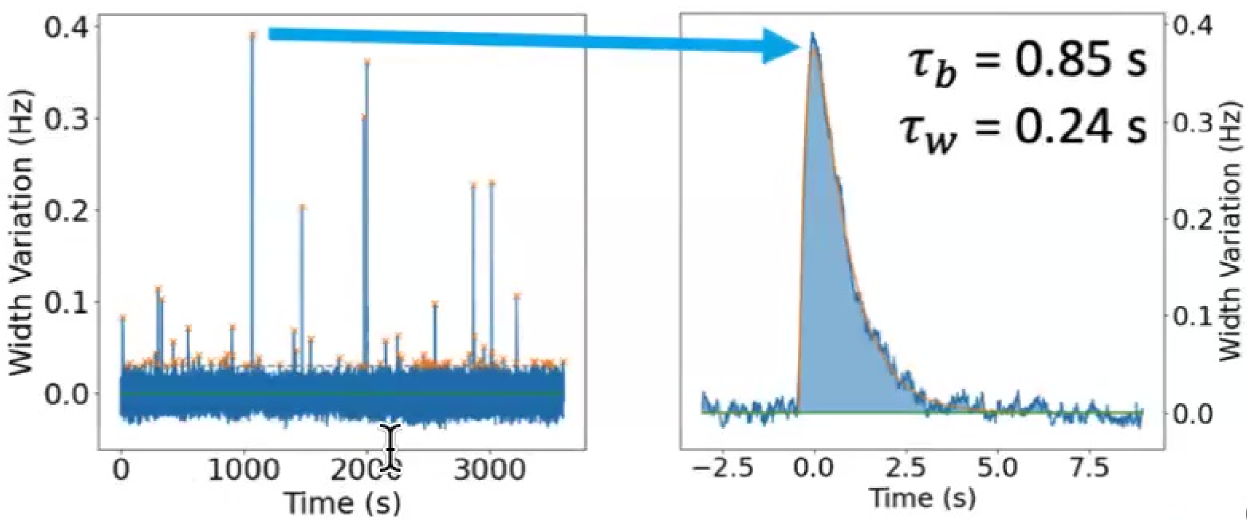
- The wire response is parametrised by resonance width Δf and an amplitude.



Credit: T. Salmon

$$\Delta f(t) = \Delta f_{\mathrm{base}} + \Delta(\Delta f)\left(\tau_{\mathrm{b}}\tau_{\mathrm{w}}^{-1}\right)^{\tau_{\mathrm{w}}(\tau_{\mathrm{b}}-\tau_{\mathrm{w}})^{-1}}\tau_{\mathrm{b}}(\tau_{\mathrm{b}}-\tau_{\mathrm{w}})^{-1}\left(e^{-t/\tau_{\mathrm{b}}}-e^{-t/\tau_{\mathrm{w}}}\right)$$

$$E_{dep} = KT\Delta(\Delta f)$$

^{3}He Bolometer

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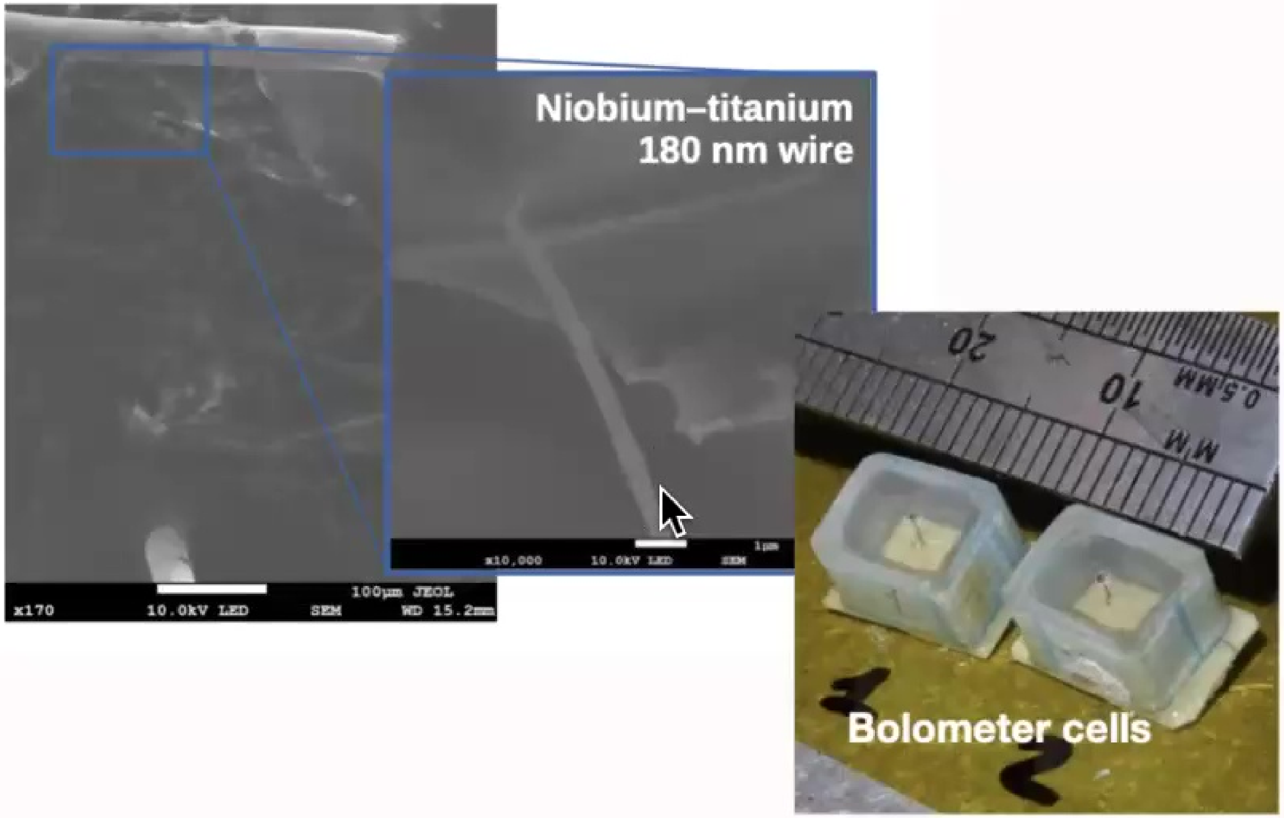
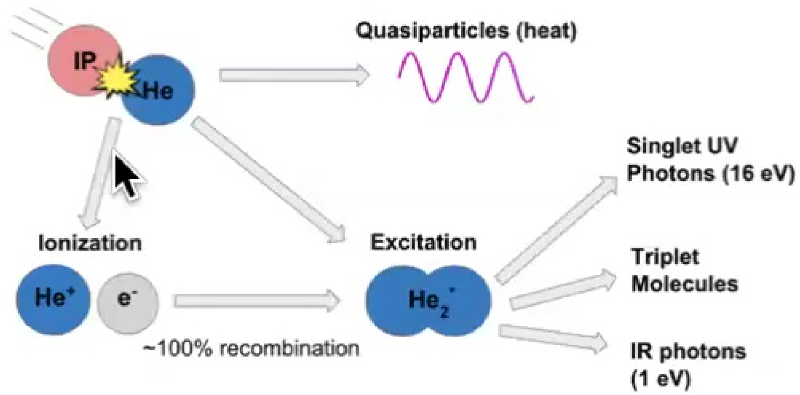
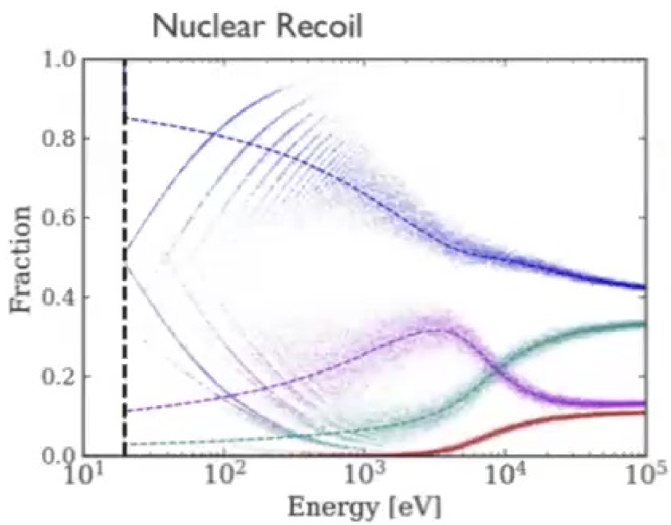


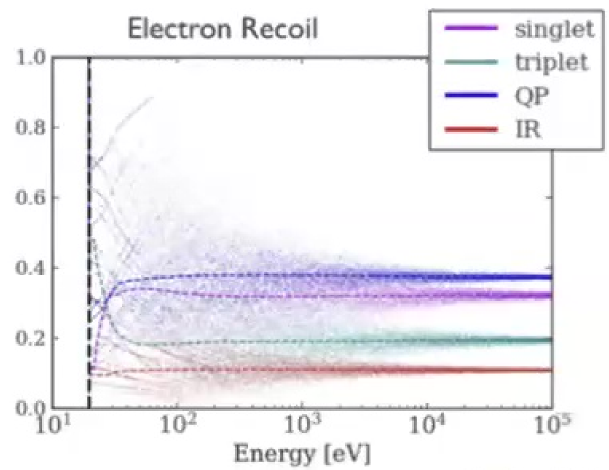
Credit: D. Zmeev, R. Smith

Energy Deposition in Superfluid ^{3}He

- Fraction of energy deposited:







Credit: A. Kemp, E. Leason

Nanowire Readout Techniques

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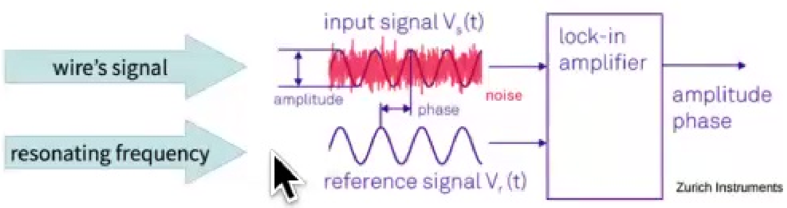
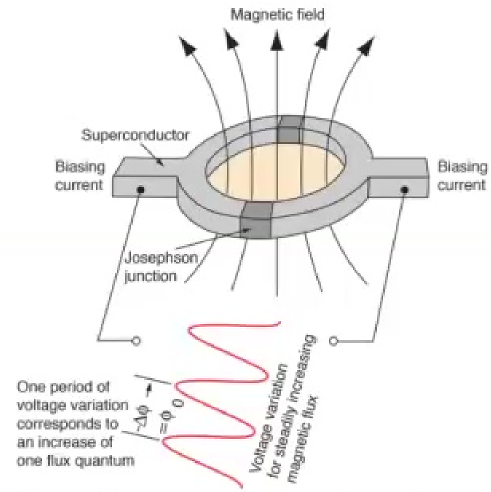
Vibrating nanowire can be read out via Lock-in amplifier and SQUID:



Credit: P. Franchini



Lock-in amplifier compares input signal $V_s(t)$ (amplitude, phase) to a reference signal $V_r(t)$ and extract signal from noisy background.

SQUID: Superconducing QUantum Interference Device is a magnetometer sensitive to $\sim 10^{-14}$ T and converts magnetic flux into voltage.

Detector Response Model

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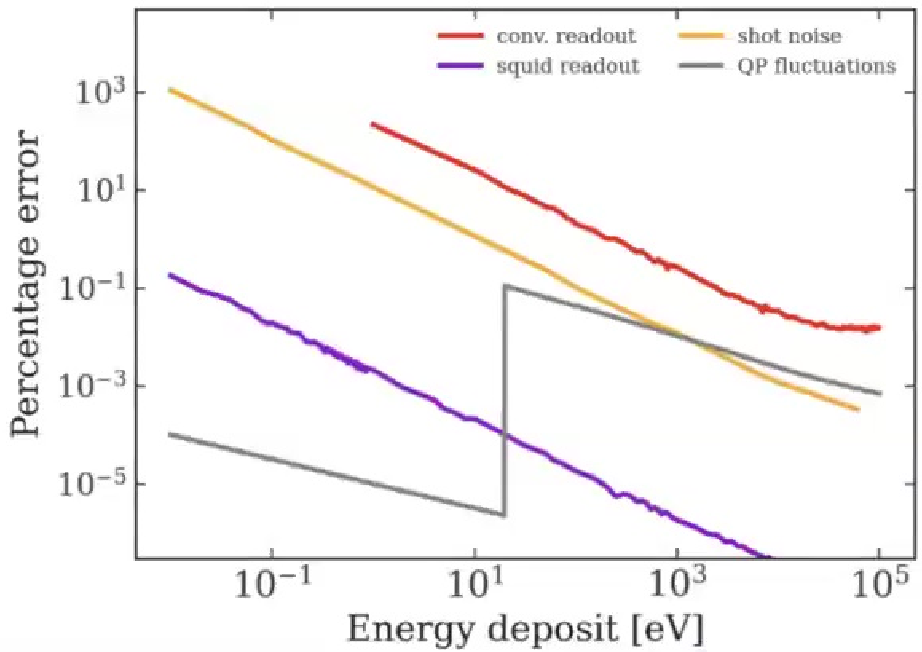
Conventional readout $E_{th,conv} = 39$ eV

SQUID readout $E_{th,SQUID} = 0.71$ eV

- Uncertainties on the energy measurement has a direct impact on the threshold scale.

- SQUID could reduce readout noise, reducing the energy threshold and enhancing the DM sensitivity.

Credit: E. Leason, R. Smith



Background Model

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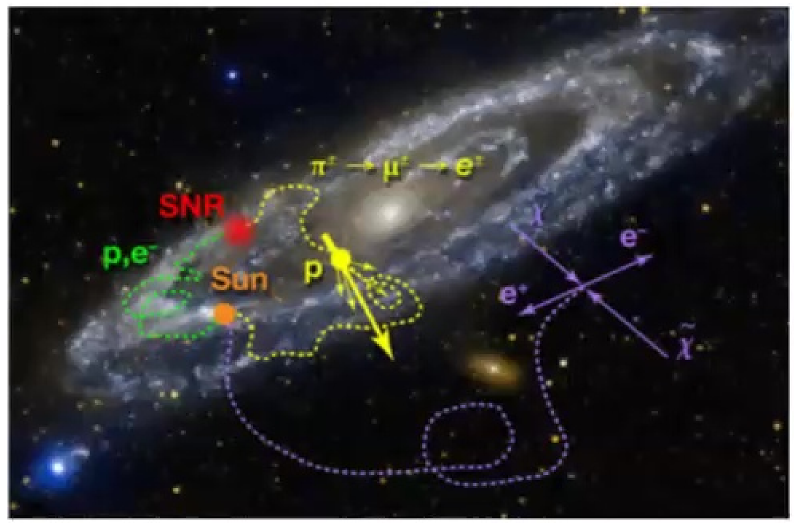
The 3He itself is super pure. But the materials that make up the detector, or even particles from outer space, might interfere.

Backgrounds:

- Cosmic rays
- Radiogenics
- Neutrinos



Background Model

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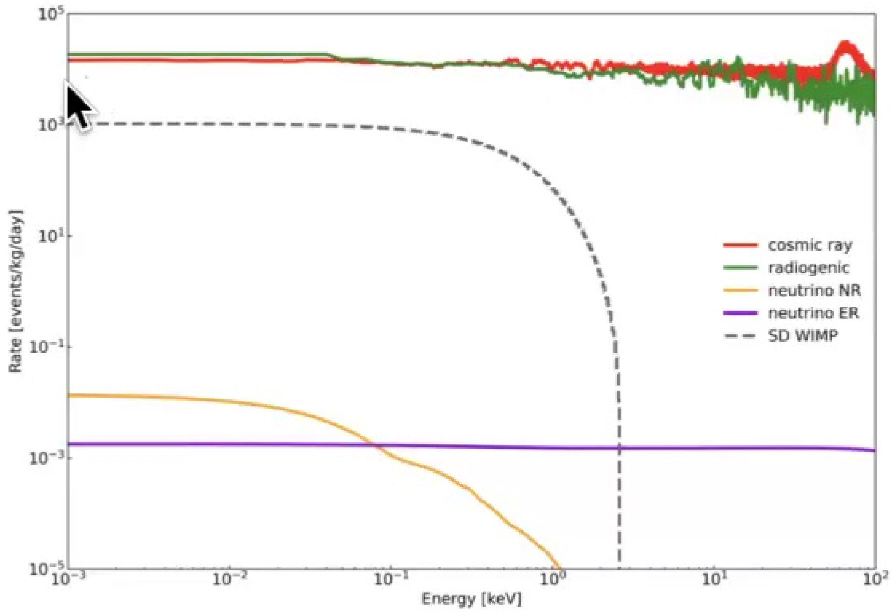
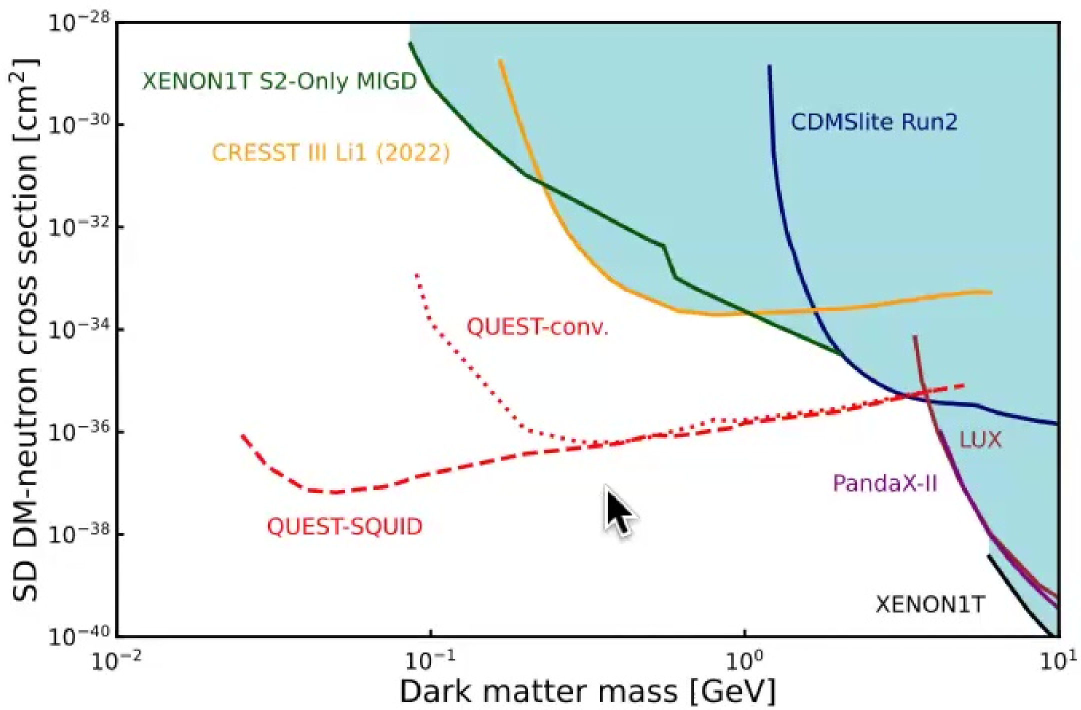
- Cosmic rays estimated using CRY and Geant4, assuming 90% veto efficiency and no shielding.
- Radiogenics estimated using material screening results and Geant4.

Credit: R. Smith, E. Leason



The exclusion limit on SD

SD sensitivity projection for: 6 months run; $5 \times 1\ \mathrm{cm}^3$ ^{3}He cells ($0.1\ \mathrm{g/cm}^3$).



The exclusion limit on SI

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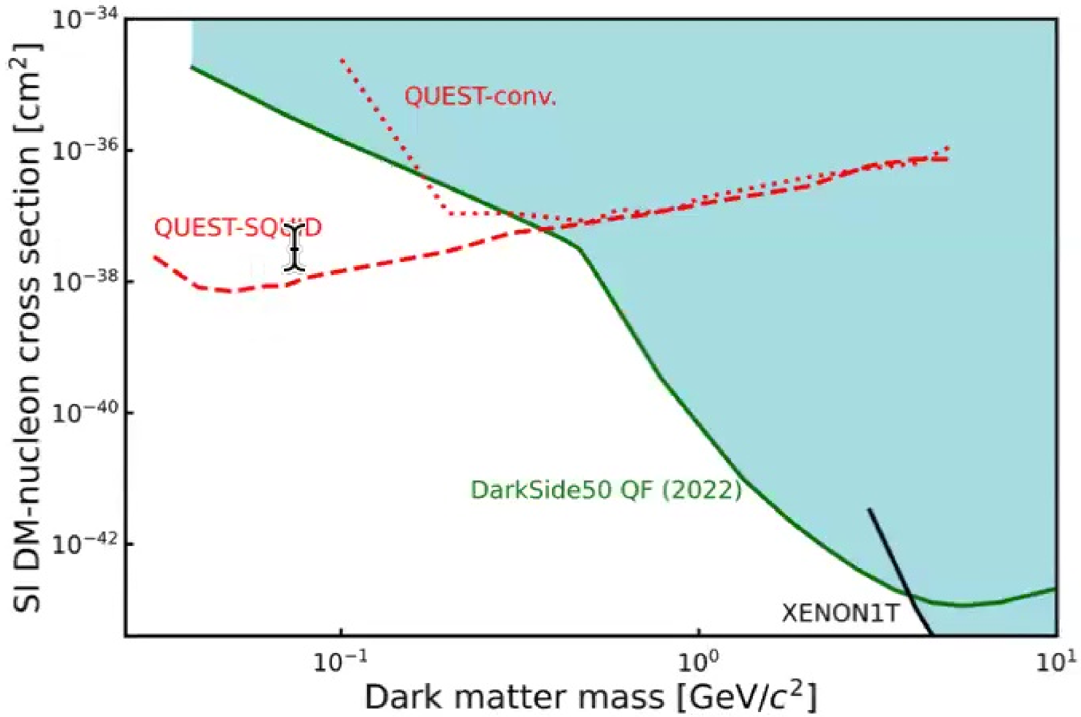
SI sensitivity projection for: 6 months run; $5 \times 1\ \mathrm{cm}^3$ ^{3}He cells (0.1 g/cm3).



The Earth shadowing

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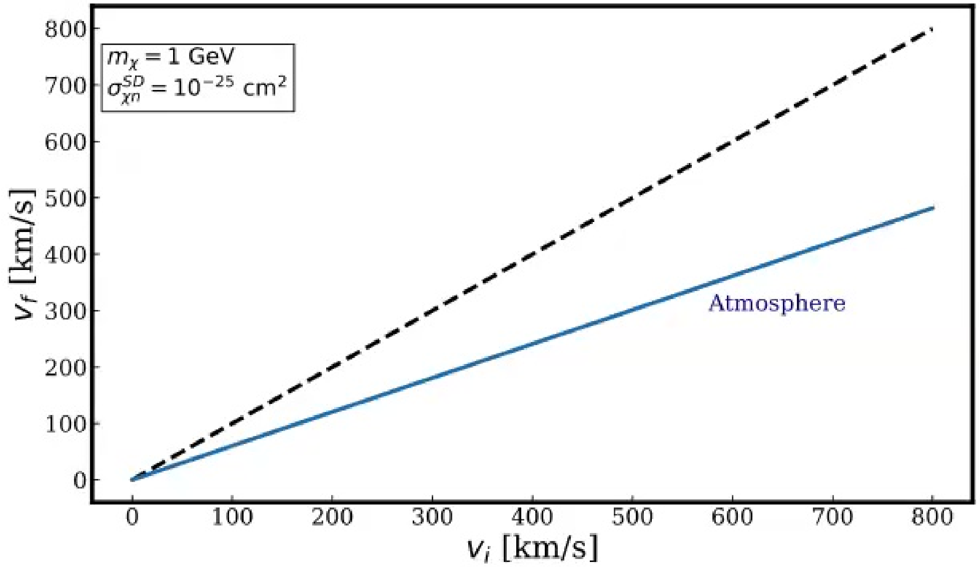
Each DM particle is propagated through three regions:

- Atmosphere - stopping by Oxygen and Nitrogen.
- Earth - stopping by different Earth elements - In our case detector is in the surface.
- Shielding - the particles propagate through any shielding which surrounds the detector.

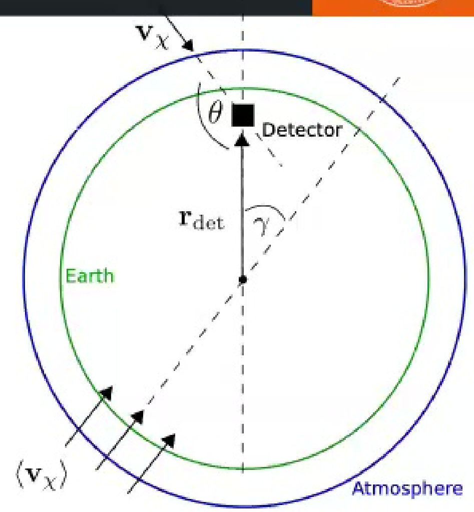


$$v_f = v_i + \int_0^{\ell} \frac{\mathrm{d}v}{\mathrm{d}D}(v, r)\,\mathrm{d}D$$

The Earth shadowing

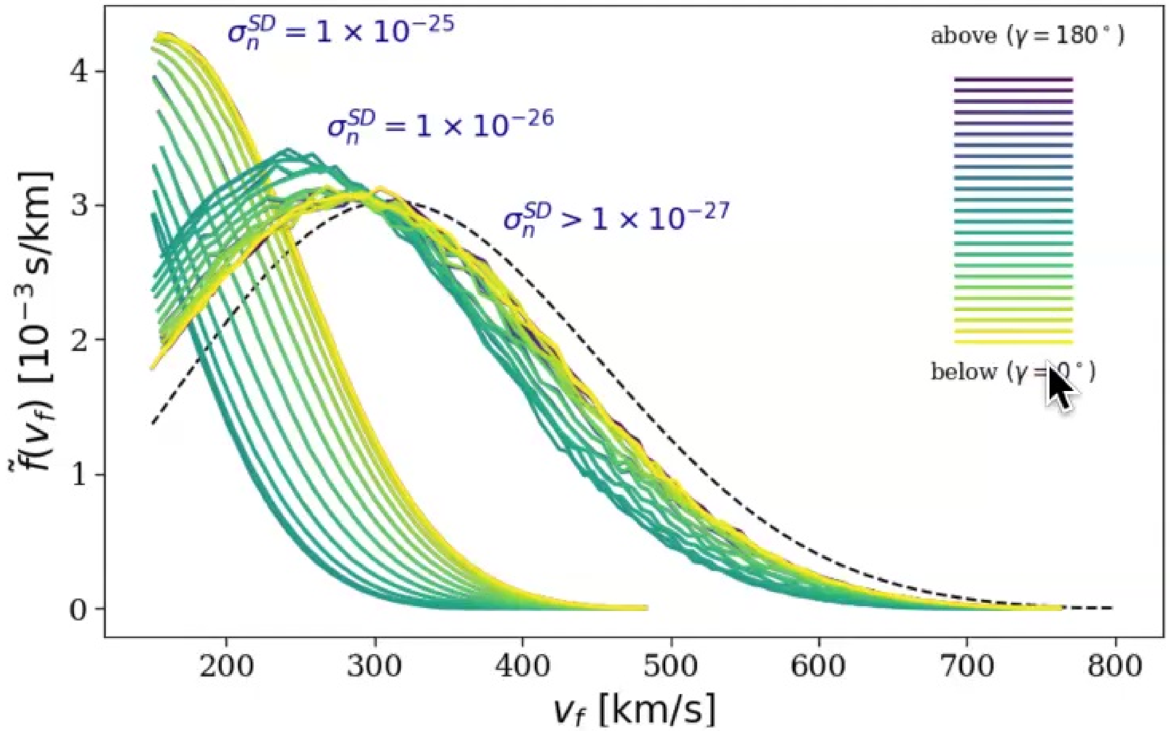
$$\frac{\mathrm{d}R_D}{\mathrm{d}E_R} = \frac{\rho_\chi}{m_\chi}\int_{v_{\min}}^{\infty} v f(\mathbf{v},\gamma)\frac{\mathrm{d}\sigma_{\chi N}}{\mathrm{d}E_R}\,\mathrm{d}^3\mathbf{v}$$

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



- $|\mathbf{v}-\langle\mathbf{v}_\chi\rangle|^2 = v^2 - 2vv_{\mathrm{lab}}\cos\delta + v_{\mathrm{lab}}^2$
- $\cos\delta = \sin\gamma\sin\theta\cos\phi + \cos\gamma\cos\theta$
- $\gamma = \cos^{-1}\left(\langle\hat{\mathbf{v}}_\chi\rangle\cdot\hat{\mathbf{r}}_{\mathrm{det}}\right)$
- The detector radius: $|\mathbf{r}_{\mathrm{det}}| = R_E - d =$ Earth Radius - Depth

The Earth shadowing: MB velocity distribution



The Earth shadowing: Rate

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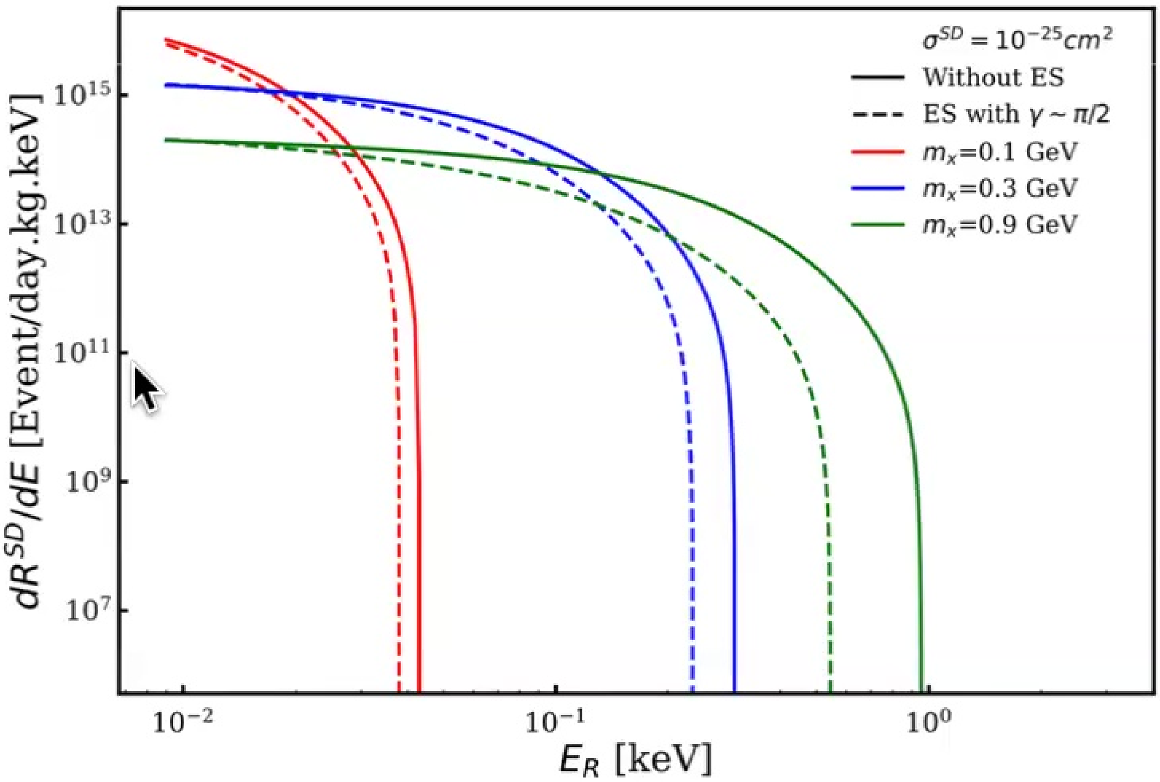
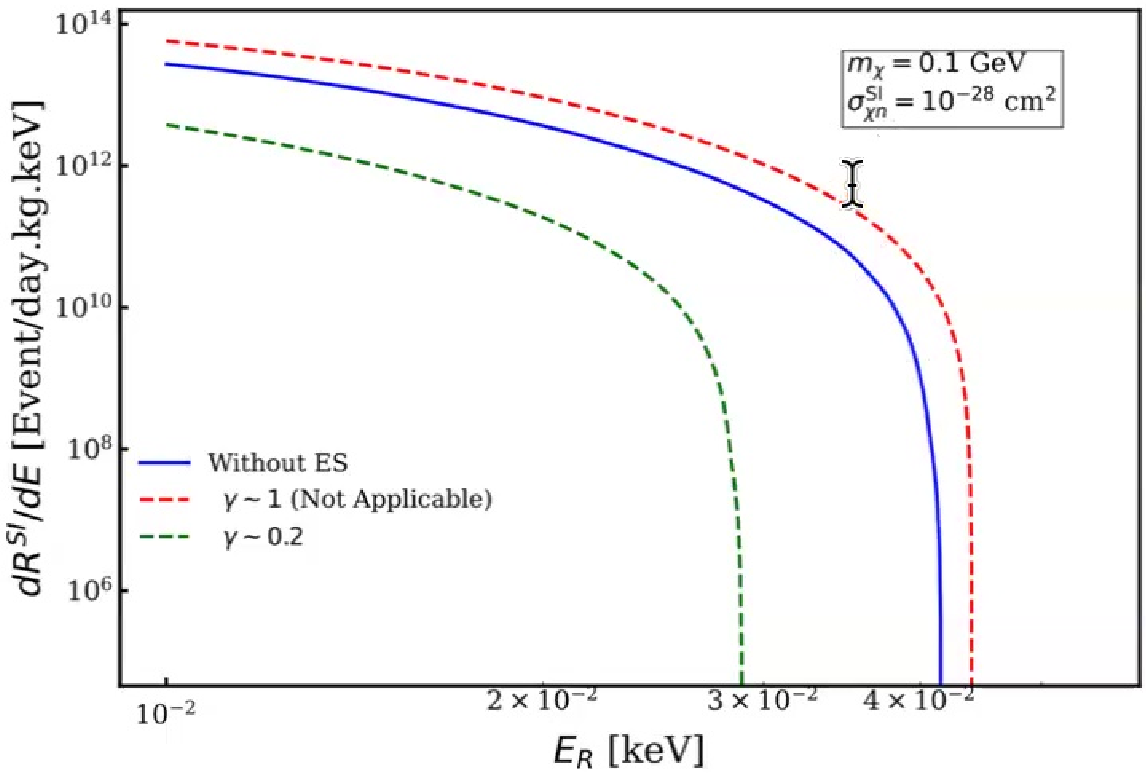
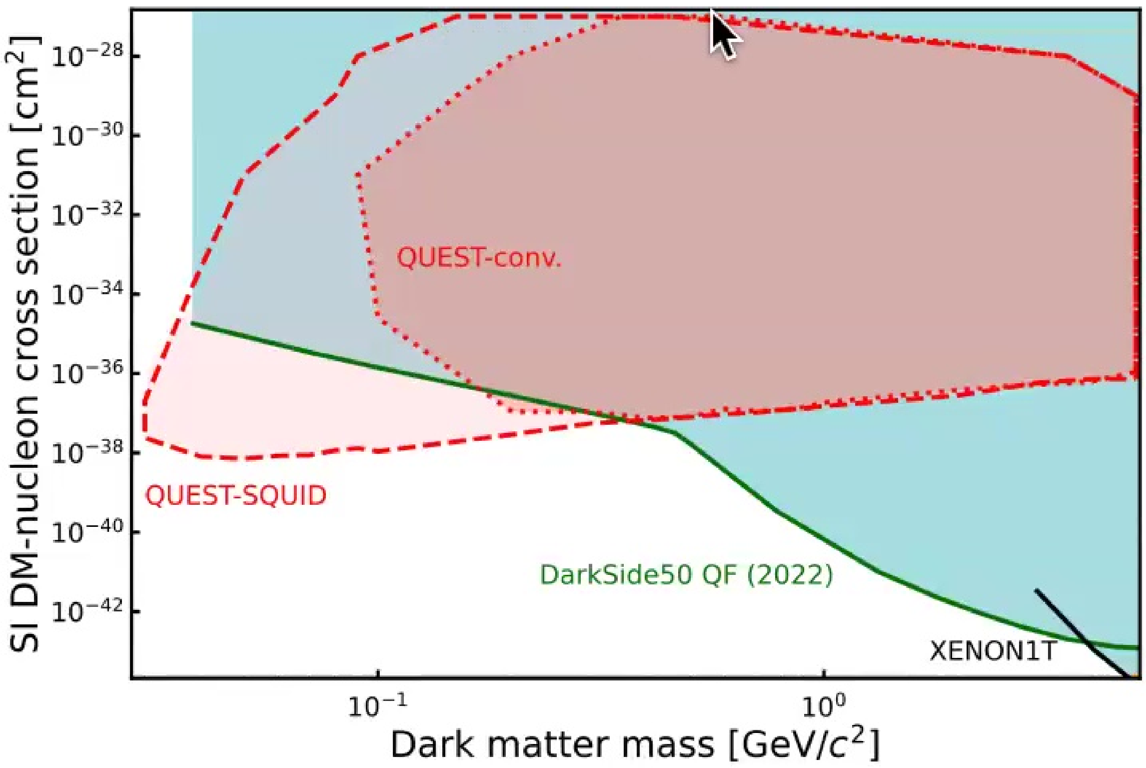


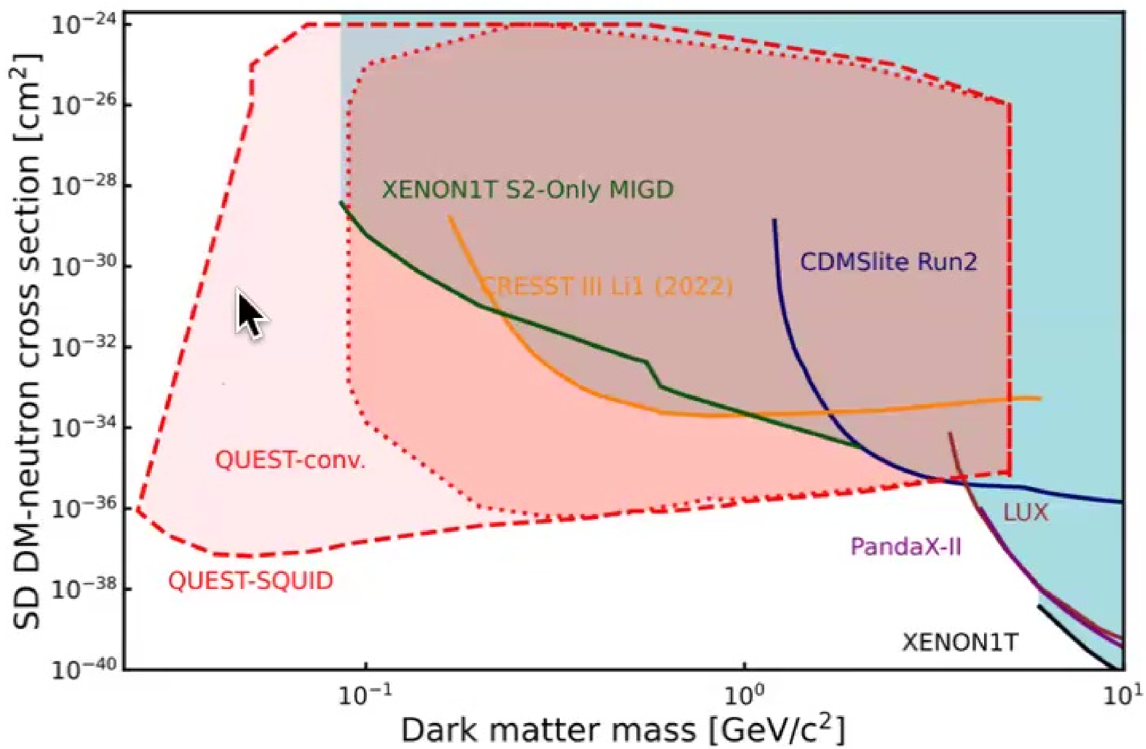
The Earth shadowing: Rate



The Earth shadowing: SI Cross-Section Limits



The Earth shadowing: SD Cross-Section Limit



Summary

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- QUEST-DMC is a superfluid ^{3}He bolometer instrumented with vibrating nanowire detectors that aims to set world-leading sensitivity to GeV and sub-GeV mass dark matter with eV scale energy threshold.
- We have set limit of SD and SI cross section and event rate. Our score on SD sensitivity 7×10^{-37} cm^2 at ~ 500 MeV/c2 with a 0.71 eV threshold (SQUID readout).
- The Earth shadowing effect has been shown.
- "*QUEST-DMC superfluid 3He detector for sub-GeV dark matter*" arXiv:2310.11304v1