Sub-GeV DM Searches with QUEST-DMC

Neda Darvishi
On behalf of the QUEST-DMC collaboration
ROYAL HOLLOWAY UNIVERSITY OF LONDON

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Cosmology, Astrophysics, Theory and Collider Higgs 2024, Dublin

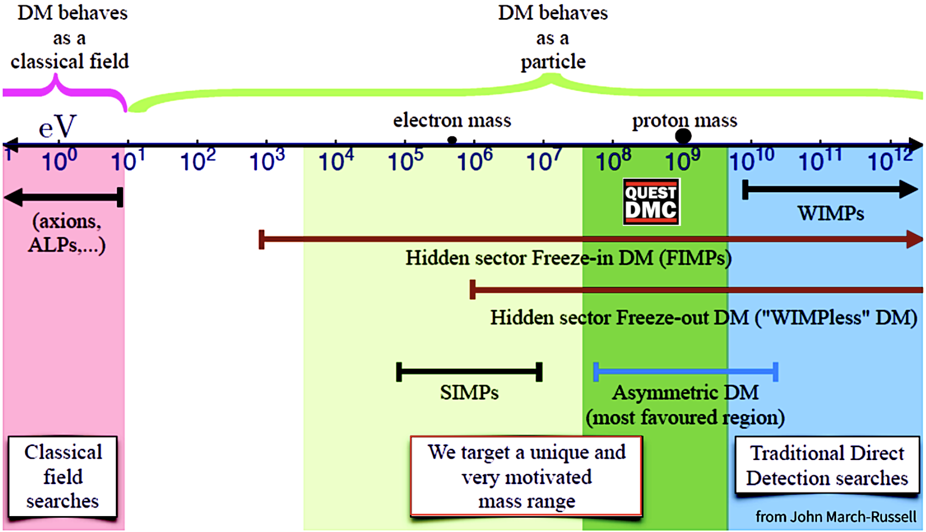
Quantum Enhanced Superfluid Technologies for Dark Matter and Cosmology

- **WP1: Detection of sub-GeV dark matter**
  - 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.

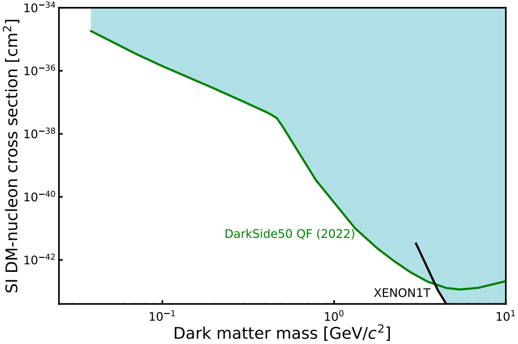
Core Team

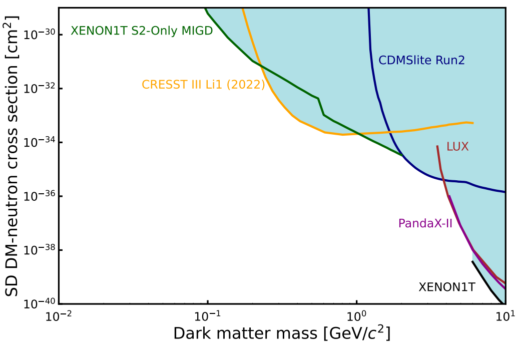
EXPERIMENTAL	
Dr. Samuli Autti	Robert Smith
Dr. Andrew Casey	Dr. Michael Thompson
Dr. Paolo Franchini	Dr. Viktor Tsepelin
Prof. Richard Haley	Dr. Dmitry Zmeev
Dr. Petri Heikkinen	Dr. Vladislav Zavyalov
Dr. Sergey Kafanov	Tineke Salmon
Dr. Ashlea Kemp	Luke Whitehead
Dr. Elizabeth Leason	**THEORY**
Dr.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

Mass Range of Dark Matter



Leading Sensitivities in Direct Detection





DM Ints.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

NR EFT of DM Direct Detection

- 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

- 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

As was first pointed out by Migdal (1986):

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

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

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

- Differential rate per recoil energy:

$$\frac{dR}{dE_{NR}} = \frac{m_N}{2\pi}\frac{\rho_\chi}{m_\chi}\langle\frac{1}{v}P_{\text{tot}}(v^2, q^2)\rangle$$

R_k relevant to Helium-3

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

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

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

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:

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

SD Helium-3

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

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

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

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

with $j_N = 1/2$ leading to

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

Limits on c_i coefficients for Helium-3

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

$$\mathcal{O}_3 \Rightarrow (c_3)^2 = \frac{4}{S_{\Sigma'}(0)} \frac{\sigma^{\rm SI}_{\chi n}}{\mu^2_{\chi n}}$$

$$\mathcal{O}_4 \Rightarrow (c_4)^2 = \frac{4\pi}{j_\chi(j_\chi+1)} \frac{\sigma^{\rm SD}_{\chi n}}{\mu^2_{\chi n}}$$

$$\mathcal{O}_5 \Rightarrow (c_5)^2 = \frac{3\pi}{j_\chi(j_\chi+1)} \frac{\sigma^{\rm SI}_{\chi n}}{\mu^2_{\chi n}}$$

$$\mathcal{O}_6 \Rightarrow (c_6)^2 = \frac{6}{j_\chi(j_\chi+1)} \frac{1}{S_{\Sigma''}(0)} \frac{\sigma^{\rm SD}_{\chi n}}{\mu^2_{\chi n}}$$

$$\mathcal{O}_7 \Rightarrow (c_7)^2 = \frac{4}{S_{\Sigma'}(0)} \frac{\sigma^{\rm SI}_{\chi n}}{\mu^2_{\chi n}}$$

$$\mathcal{O}_8 \Rightarrow (c_8)^2 = \frac{3\pi}{j_\chi(j_\chi+1)} \frac{\sigma^{\rm SD}_{\chi n}}{\mu^2_{\chi n}}$$

$$\mathcal{O}_9 \Rightarrow (c_9)^2 = \frac{6}{j_\chi(j_\chi+1)} \frac{1}{S_{\Sigma'}(0)} \frac{\sigma^{\rm SD}_{\chi n}}{\mu^2_{\chi n}}$$

$$\mathcal{O}_{10} \Rightarrow (c_{10})^2 = \frac{2}{S_{\Sigma''}(0)} \frac{\sigma^{\rm SI}_{\chi n}}{\mu^2_{\chi n}}$$

$$\mathcal{O}_{11} \Rightarrow (c_{11})^2 = \frac{3\pi}{j_\chi(j_\chi+1)} \frac{\sigma^{\rm SD}_{\chi n}}{\mu^2_{\chi n}}$$

$$\mathcal{O}_{12} \Rightarrow (c_{12})^2 = \frac{12}{j_\chi(j_\chi+1)} \frac{\sigma^{\rm SD}_{\chi n}}{\mu^2_{\chi n}} \left(\frac{\pi}{3-\pi S_{\Sigma'}(0)}\right)$$

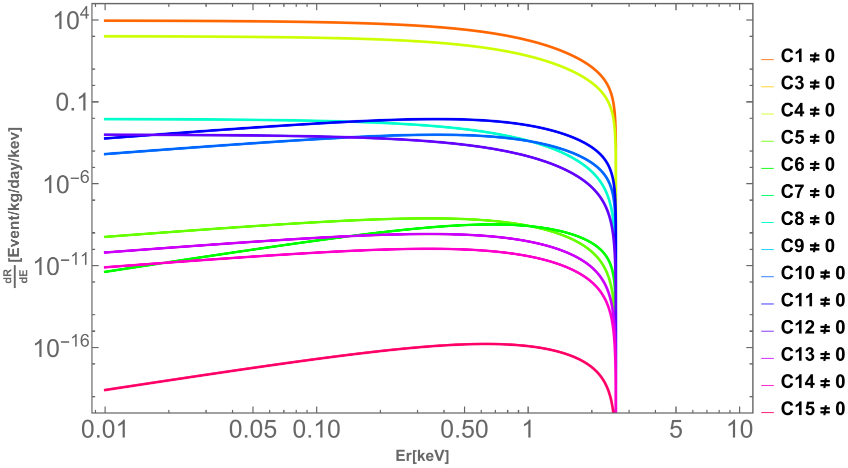
$$\mathcal{O}_{13} \Rightarrow (c_{13})^2 = \frac{6}{j_\chi(j_\chi+1)} \frac{1}{S_{\Sigma''}(0)} \frac{\sigma^{\rm SD}_{\chi n}}{\mu^2_{\chi n}}$$

$$\mathcal{O}_{14} \Rightarrow (c_{14})^2 = \frac{12}{j_\chi(j_\chi+1)} \frac{1}{S_{\Sigma'}(0)} \frac{\sigma^{\rm SD}_{\chi n}}{\mu^2_{\chi n}}$$

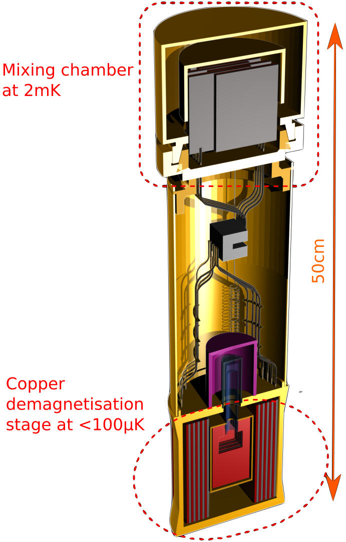
$$\mathcal{O}_{15} \Rightarrow (c_{15})^2 = \frac{12}{j_\chi(j_\chi+1)} \frac{1}{S_{\Sigma'}(0)} \frac{\sigma^{\rm SD}_{\chi n}}{\mu^2_{\chi n}},$$

All Operators

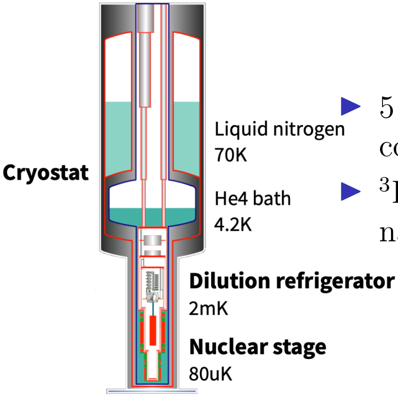
- $m_\chi = 1\ \mathrm{GeV},\ \sigma_{\chi n} = 10^{-36}\ \mathrm{cm}^2$



QUEST-DMC Detector

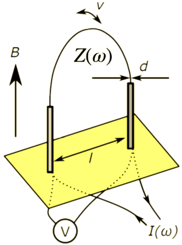


QUEST-DMC Detector



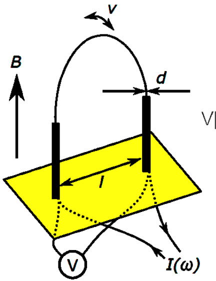
Credit: P. Franchini

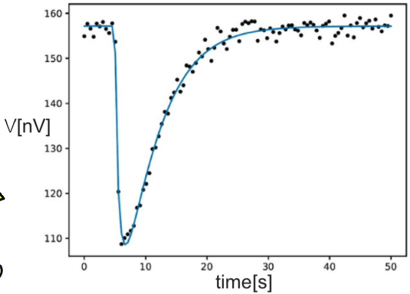
- Cool-down system consists of three stages:
  - Liquid nitrogen and 4He bath
  - ^{3}He/^{4}He dilution refrigerator
  - Nuclear demagnetisation
- $5 \times 1\text{cm}^3$ bolometer targets, each 0.1g ^{3}He cooled to $<100\ \mu K$.
- ^{3}He bolometer instrumented with vibrating nanowire resonators.

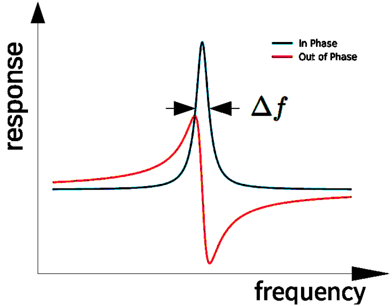


3He Bolometer

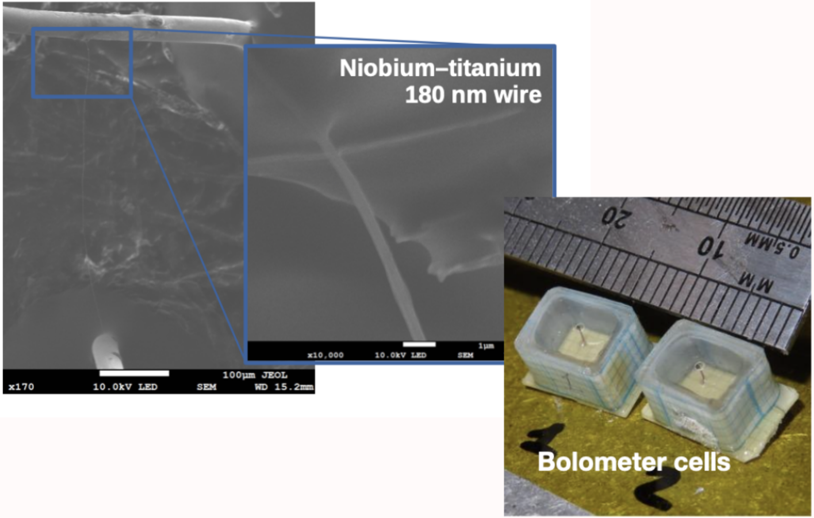
- Nanowire experiences a damping force due to interactions with quasiparticles.
- Observe a pulse that is induced in the voltage $V(t)$.
- The wire response is measured as a function of frequency.







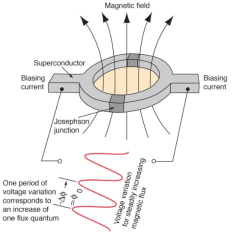
^{3}He Bolometer



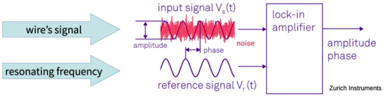
Credit: D. Zmeev, R. Smith

Nanowire Readout Techniques

Vibrating nanowire can be read out via **S**uperconducing **QU**antum **I**nterference **D**evice (SQUID) and Lock-in amplifier:



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



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.

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

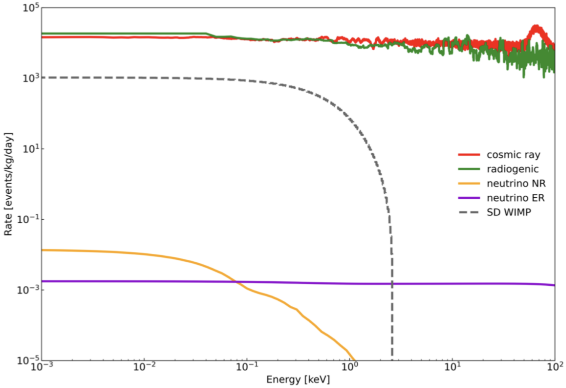
SQUID readout $E_{th,SQUID} = 0.71$ eV

Background Model

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

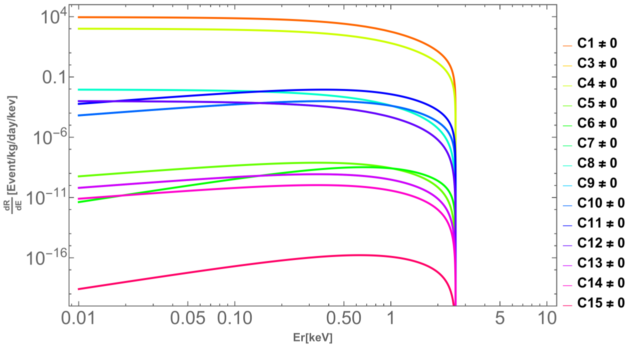
- Radiogenics estimated using material screening results and Geant4.

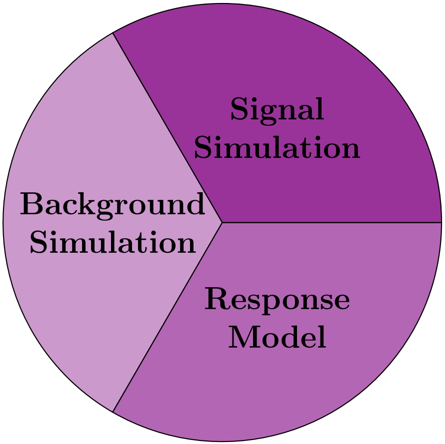
Credit: R. Smith, E. Leason



All SI & SD Operators

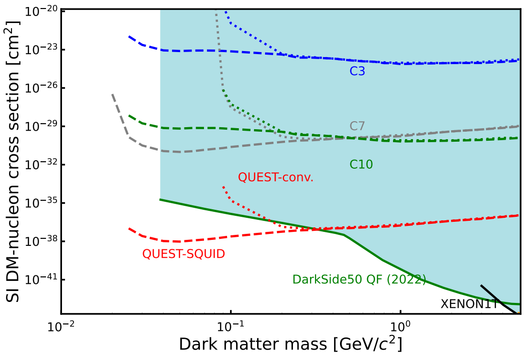
- $m_\chi = 1\ \mathrm{GeV},\ \sigma_{\chi n} = 10^{-36}\ \mathrm{cm}^2$

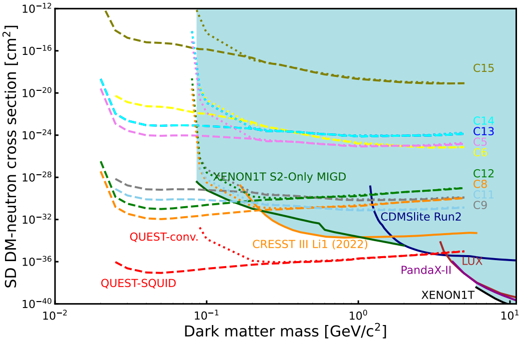




SI and SD Operators

SI and SD sensitivity projection for: 6 months run; 5 × 1 cm^3 ^3He cells ($0.1\ g/cm^3$).

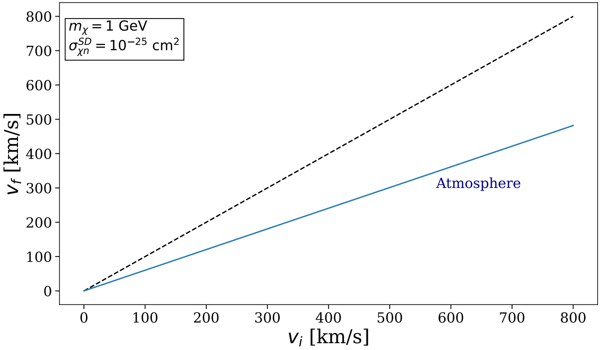




The Stopping Effect

Each DM particle is propagated through three regions:

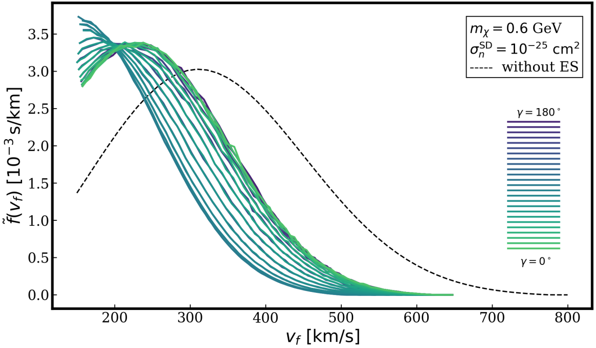
- Atmosphere - stopping by Oxygen and Nitrogen.
- Earth - stopping by different Earth elements - In our case detector is in the surface.
- Shielding - the particles propagate through any shielding which surrounds the detector.

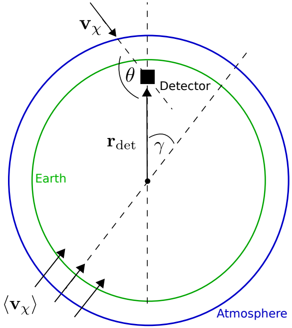


$$v_f = v_i + \int_0^\ell \frac{\mathrm{d}v}{\mathrm{d}D}(v, r)\,\mathrm{d}D$$

The Stopping Effect: Velocity Distribution

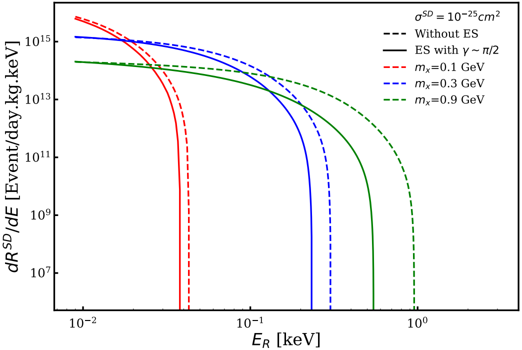
$$f(\mathbf{v},\gamma) \propto \exp\left(-\frac{\left|\mathbf{v}-\langle\mathbf{v}_\chi\rangle\right|^2}{v_{\rm dis}^2}\right)\Theta\left(v_{\rm esc}-\left|\mathbf{v}-\langle\mathbf{v}_\chi\rangle\right|\right)$$

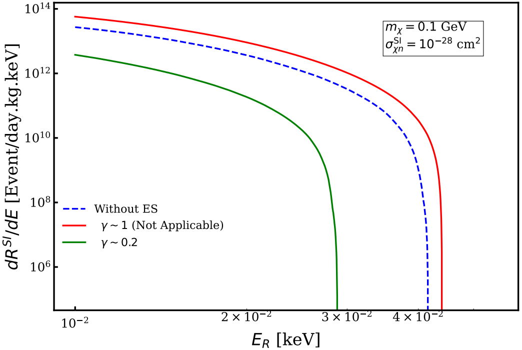




The Stopping Effect: Rate

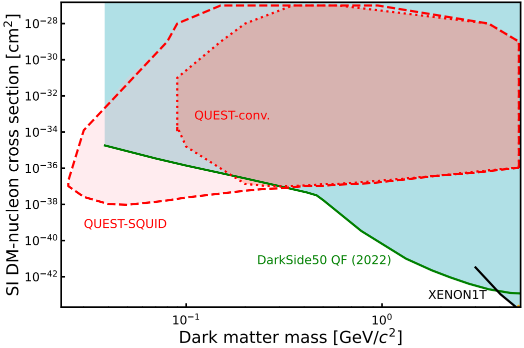
$$\frac{dR}{dE_R} = \frac{\rho_\chi}{m_\chi} \int_{v_{\min}}^{\infty} v f(\mathbf{v}, \gamma) \frac{d\sigma_{\chi N}}{dE_R} \, d^3\mathbf{v}$$

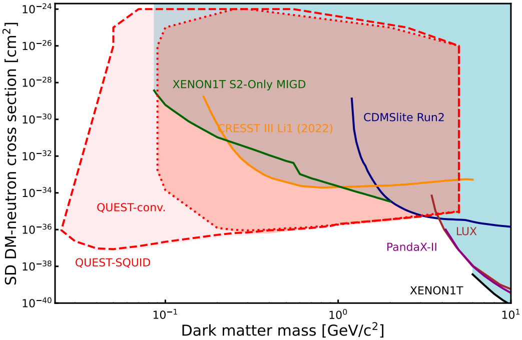




The Stopping Effect: SI and SD Limit

SI and SD sensitivity projection for: 6 months run; 5×1 cm^3 ^{3}He cells (0.1 g/cm^3).





Summary

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- QUEST-DMC is a superfluid ^{3}He bolometer instrumented with vibrating nanowire detectors 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 discussed.
- "*QUEST-DMC superfluid 3He detector for sub-GeV dark matter*", Eur.Phys.J.C 84 (2024) 3, 248.
- "*Long nanomechanical resonators with circular cross-section*", arXiv: 2311.02452.
- "*QUEST-DMC: Background Modelling and Resulting Heat Deposit for a Superfluid Helium-3 Bolometer*", arXiv:2402.00181.

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Check 1:

- Non-zero amplitude in the $p \to 0$:

$$i\mathcal{A} \propto \left[\text{coupling}_{\text{Med}-\text{DM}} \left(\frac{i}{p^2 - M^2_{\text{Med}}}\right) \text{coupling}_{\text{Med}-\text{target}}\right] \overset{p\to 0}{\neq} 0$$

- For example the DM amplitude in 2HDM + Complex Singlet:

$$i\mathcal{A} = -\, i\frac{m_{f_k}}{2v}\bar{f}_k(p_2)\left(\kappa_1 v_1, \quad \kappa_2 v_2, \quad 0, \quad \lambda_s v_s\right)\left(M^2\right)^{-1}\begin{pmatrix} c^{(1)}_{f_k} + i\gamma_5 \tilde{c}^{(1)}_{f_k} \\ c^{(2)}_{f_k} + i\gamma_5 \tilde{c}^{(2)}_{f_k} \\ c^{(3)}_{f_k} + i\gamma_5 \tilde{c}^{(3)}_{f_k} \\ 0 \end{pmatrix} f_k(p_1)$$

Sec. III of [Grzadkowski, ND, JHEP 06 (2022) 092]

Models with CPV and Phase Transition

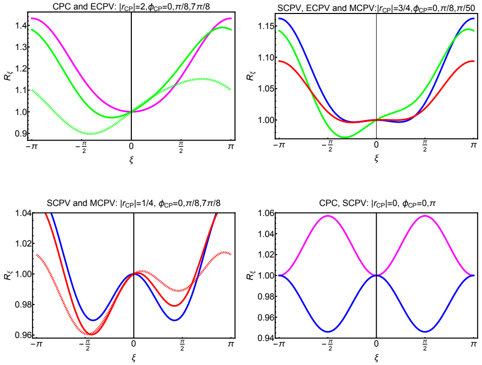
Check 2:

- Take the boundary conditions of your model and change all complex parameters into phases:

$$2\,|r_{\rm CP}|\,\sin(\xi+\varphi_{12})\;-\;\sin(2\xi+\varphi_5)\;=\;0$$

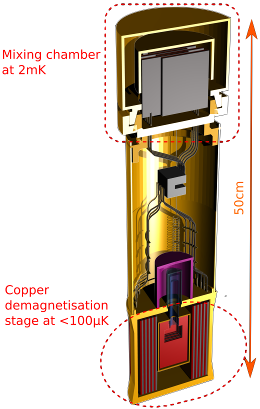
Define the ratio of scalar potentials:

$$R_\xi\;\equiv\;\frac{\mathcal{V}_\xi}{|\mathcal{V}_{\xi=0}|}$$

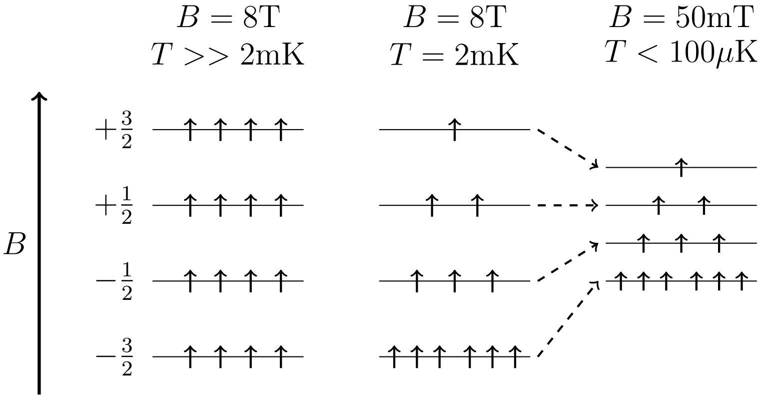


Sec. II of [Pilaftsis, Yu, ND, arXiv:2312.00882]

QUEST-DMC Detector

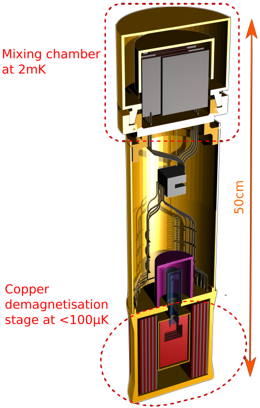


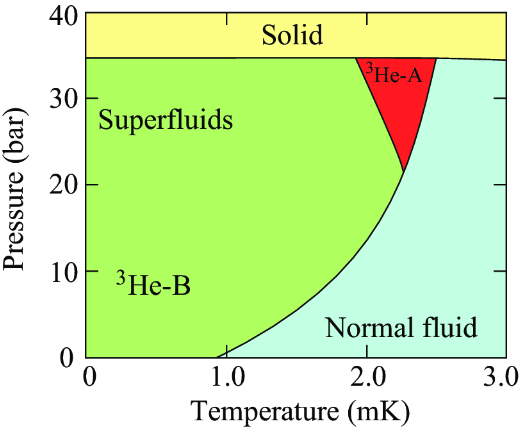
- In presence of B field, nuclear energy levels split into four via the Zeeman effect.



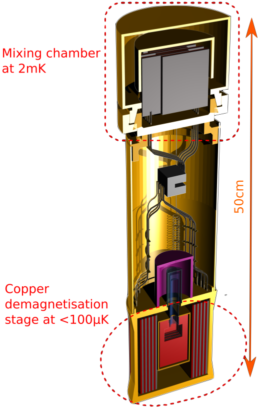
QUEST-DMC Detector

- 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.

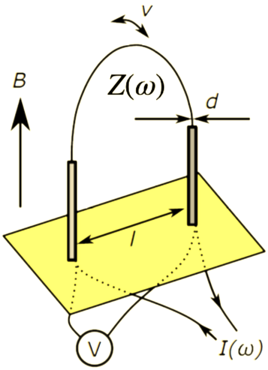
3He Bolometer

- ^{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:

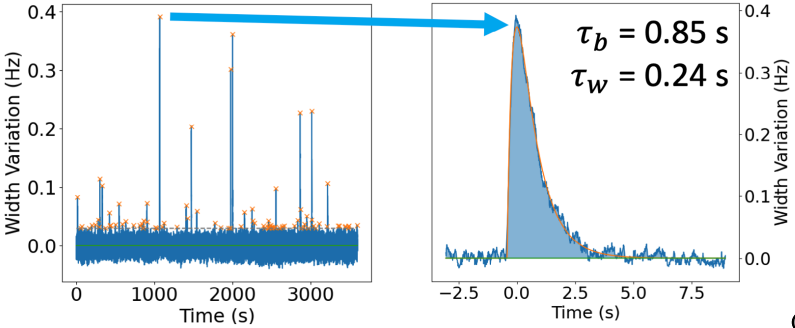
$$F = ILB \qquad V = vLB$$



Credit: P. Franchini

3He Bolometer

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



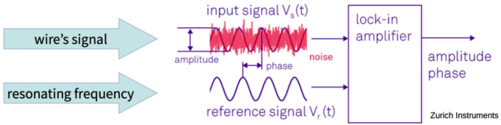
Credit: T. Salmon

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

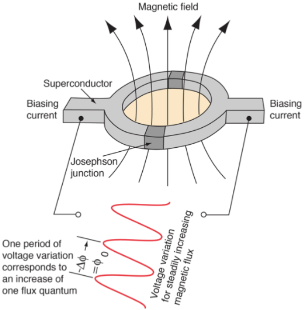
$$E_{dep} = KT\Delta(\Delta f)$$

Nanowire Readout Techniques

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

Detector Response Model

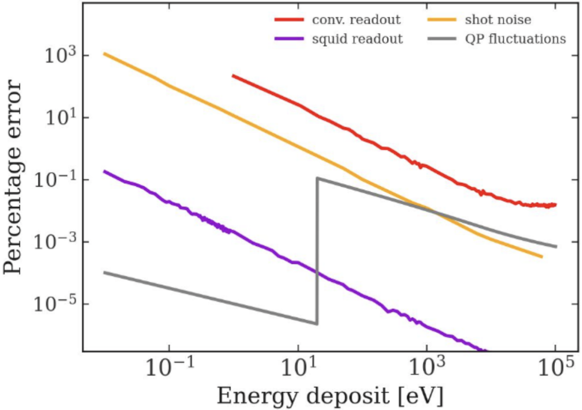
- Uncertainties on the energy measurement has a direct impact on the threshold scale.

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

Credit: E. Leason, R. Smith

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

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



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 $\langle\mathbf{v}_\chi\rangle = -\mathbf{v}_{\rm lab}(t)$
- $v > v_{\rm min} = \sqrt{m_N E_R/(2\mu^2_{\chi N})}$

Separating SD and SI Interactions

- 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

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

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

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

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

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

Proton and Neutron contributions:

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

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:

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

Defining

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

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

SD Helium-3

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

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

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

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

A differential cross section and event rate for SD:

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

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

SI Helium-3

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

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

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

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

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

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

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

Models for Sub-GeV dark matter:

- Asymmetric DM. [Nussinov, 1985; Kaplani et al, 2009;Falkowski et al, 2011]
- Freeze-in [Hall et al, 2009]
- SIMP. [Y Hochberg, 2014]
- Hidden sectors. [P Barnes, 2020]
- WIMPless DM. [Feng Kumar, 2008;Feng, Shadmi, 2011]
- Axions [Rajagropal et al, 1991;Covi et al 1999;Ellis et al, 1984]
- Sterile neutrino DM. [Kusenko 2006 (review)]
- . . .