

Sub-GeV direct detection with superfluid He

Peter Cox

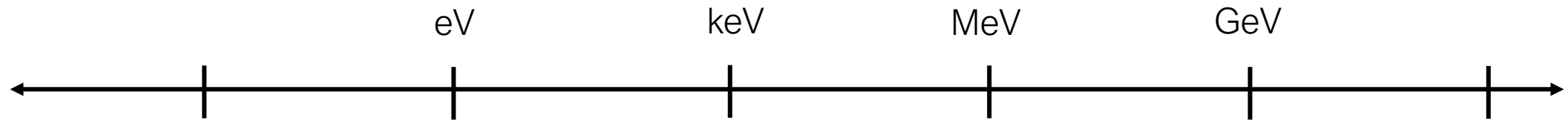
The University of Melbourne

Detection regimes

Different regimes depending on coherence length of dark matter:



Dark matter mass



*Energy deposited
(scattering)*

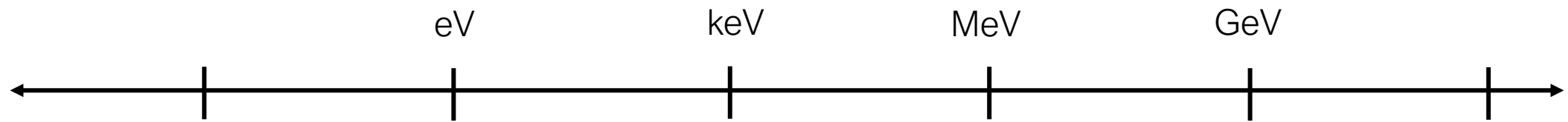


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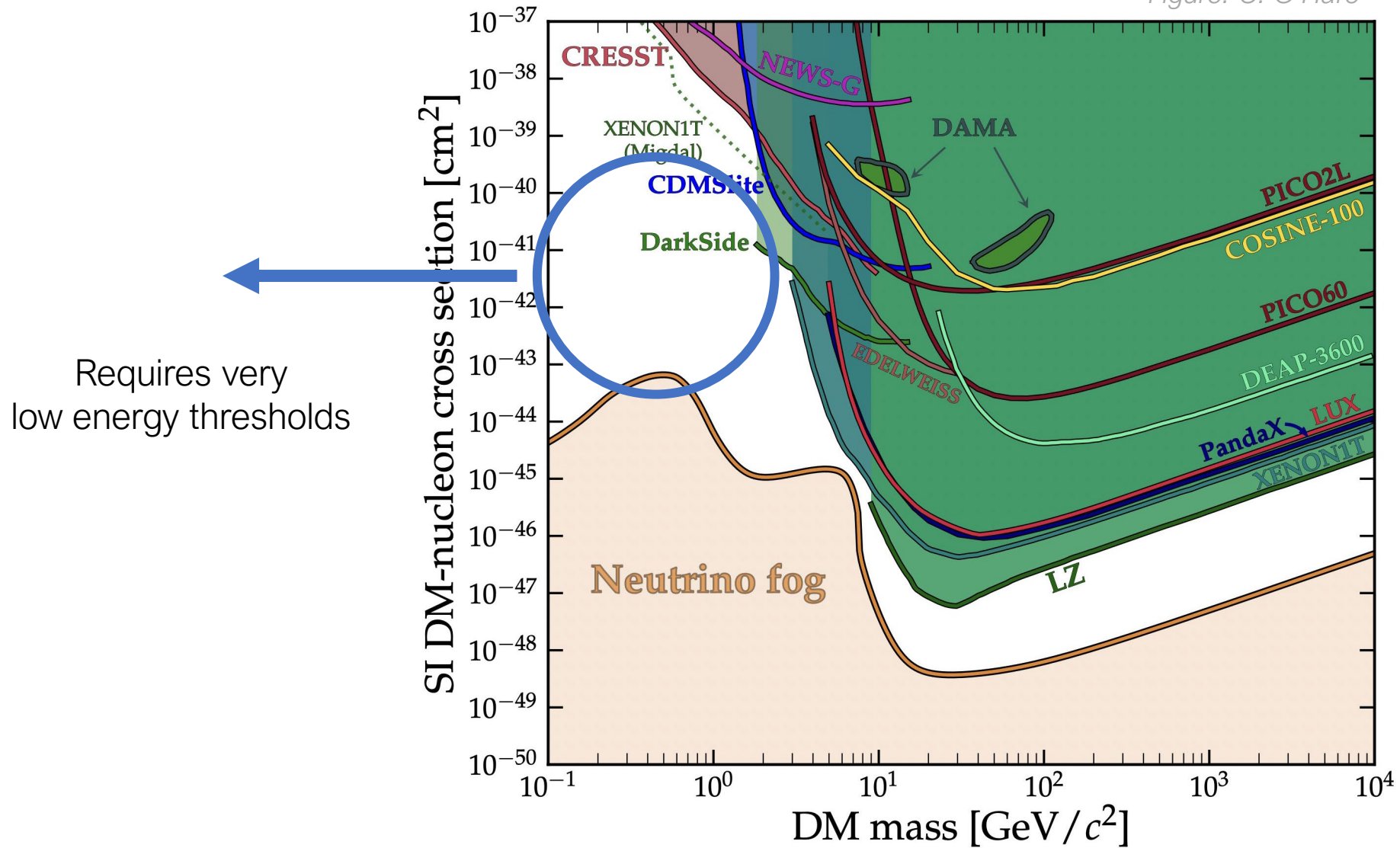
*Energy deposited
(scattering)*



—————
this talk

The sub-GeV frontier

Figure: C. O'Hare



Why Helium?

- Low atomic mass $E_{\text{recoil}} = \frac{2m_{\chi}^2 v^2}{m_T} \quad (m_{\chi} < m_T)$
- Superfluid at cryogenic temperatures
- Readily obtainable and naturally radiopure
- Multiple detectable signals
- Scalable

Nuclear recoil signals

Nuclear recoils in liquid Helium can produce a variety of signals:

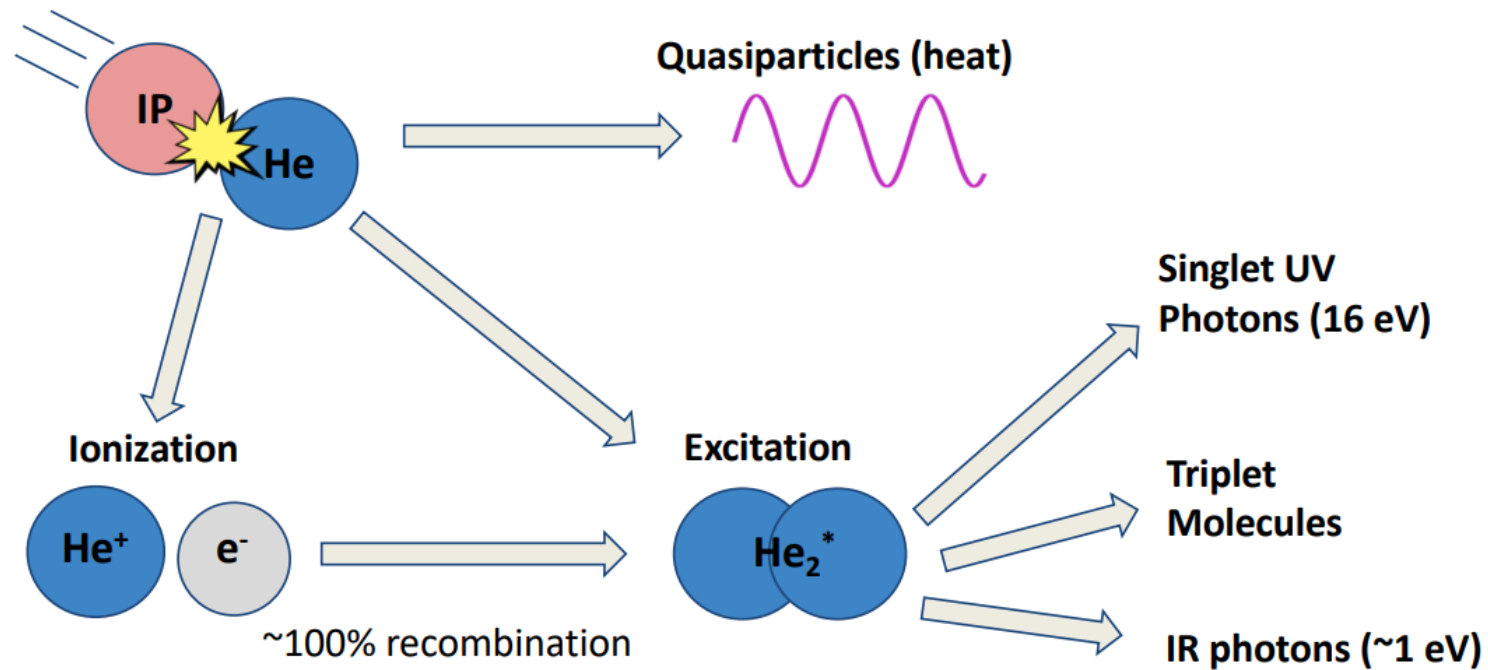


Figure: D. McKinsey

Schematic experiment

Proposed experiments have multiple detection channels

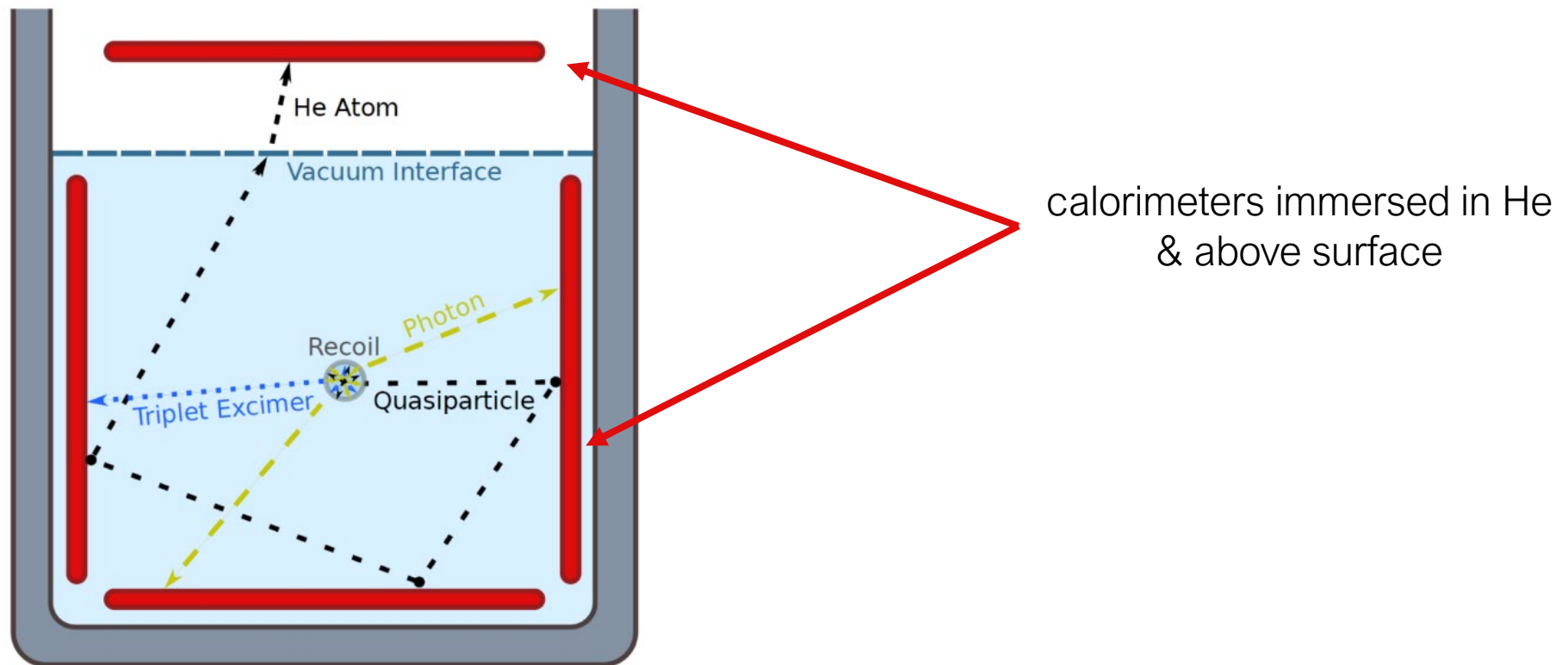


Figure: TESSERACT collaboration

Schematic experiment

Proposed experiments have multiple detection channels

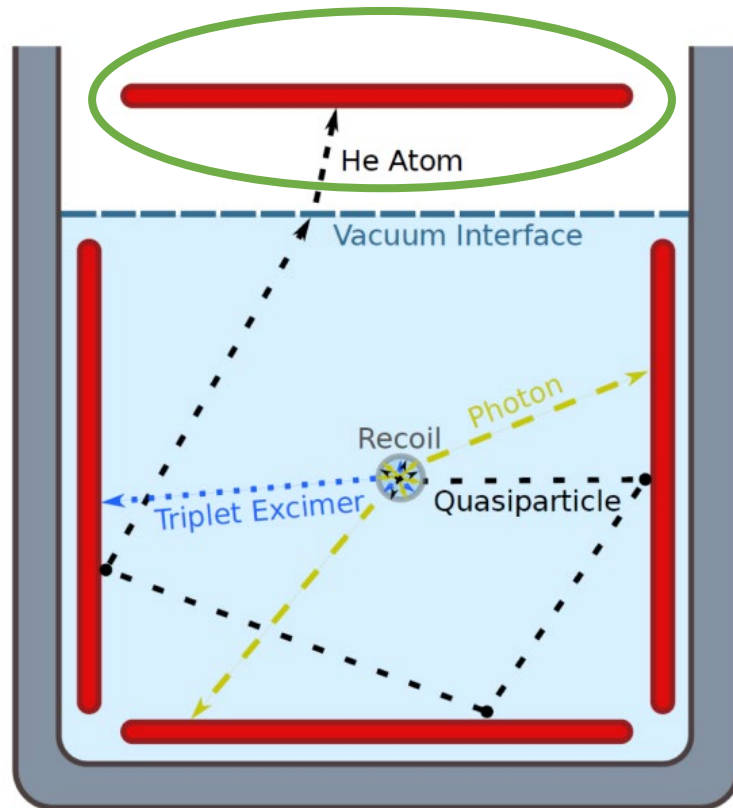


Figure: TESSERACT collaboration

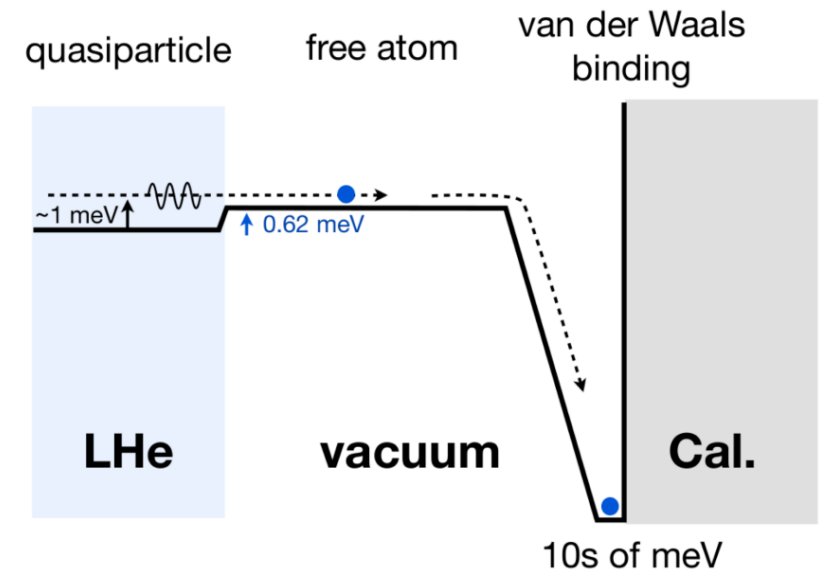


Figure: D. McKinsey

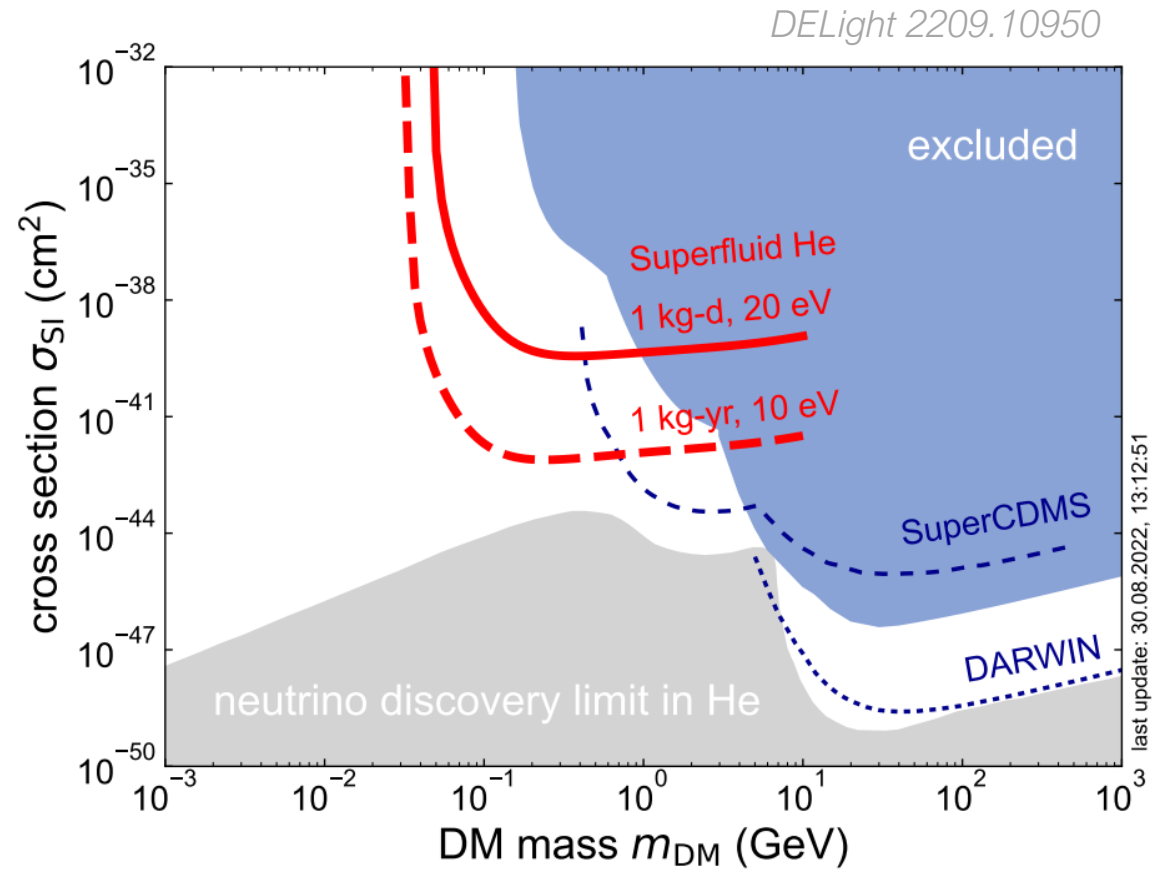
Adsorption onto surface amplifies signal

Sensitivity

Proposed experiments:

- HeRALD/TESSERACT
(*transition edge sensors*)
- DELight
(*micro magnetic calorimeters/SQUID*)

Realistic, near-term sensitivity competitive with other cryogenic experiments



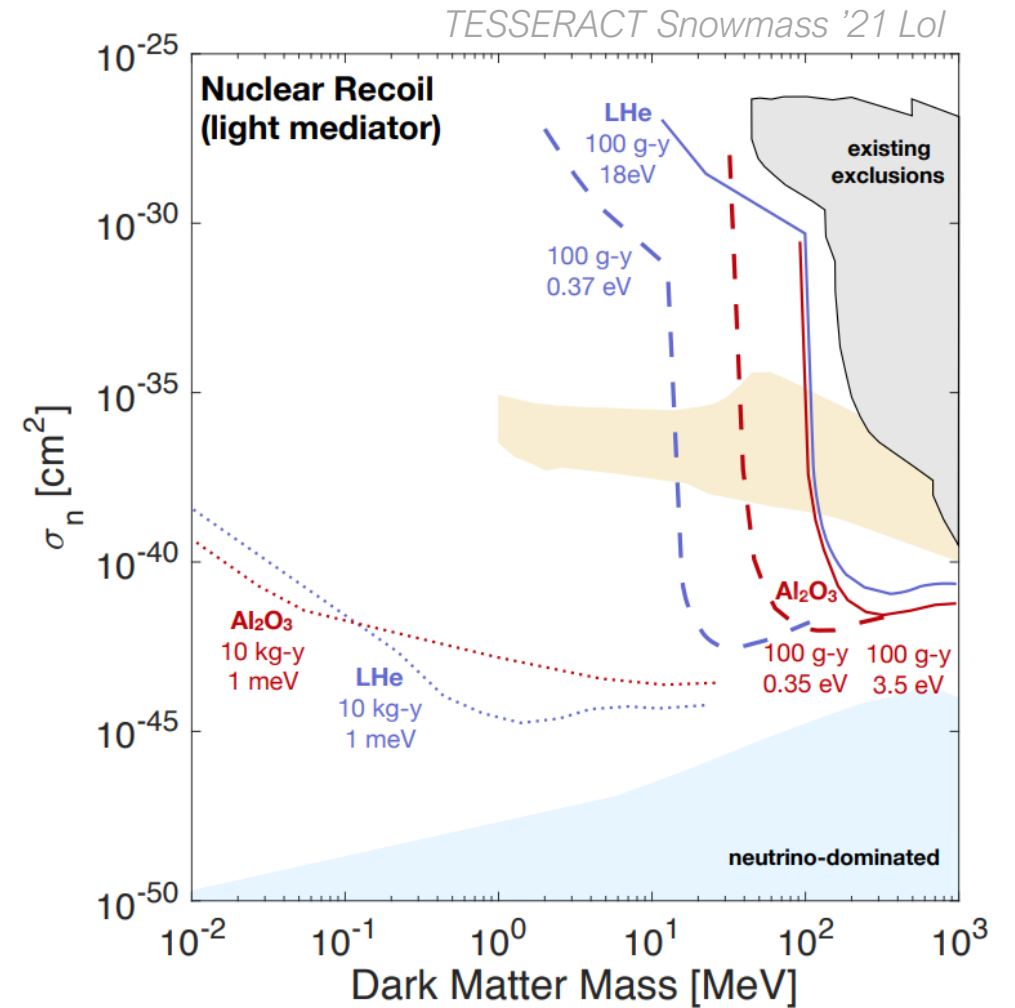
Sensitivity

Proposed experiments:

- HeRALD/TESSERACT (transition edge sensors)
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Realistic, near-term sensitivity competitive with other cryogenic experiments

Ambitious goals to achieve very low thresholds



Collective excitations

Sub-MeV dark matter can only excite collective modes
(phonons/rotons)

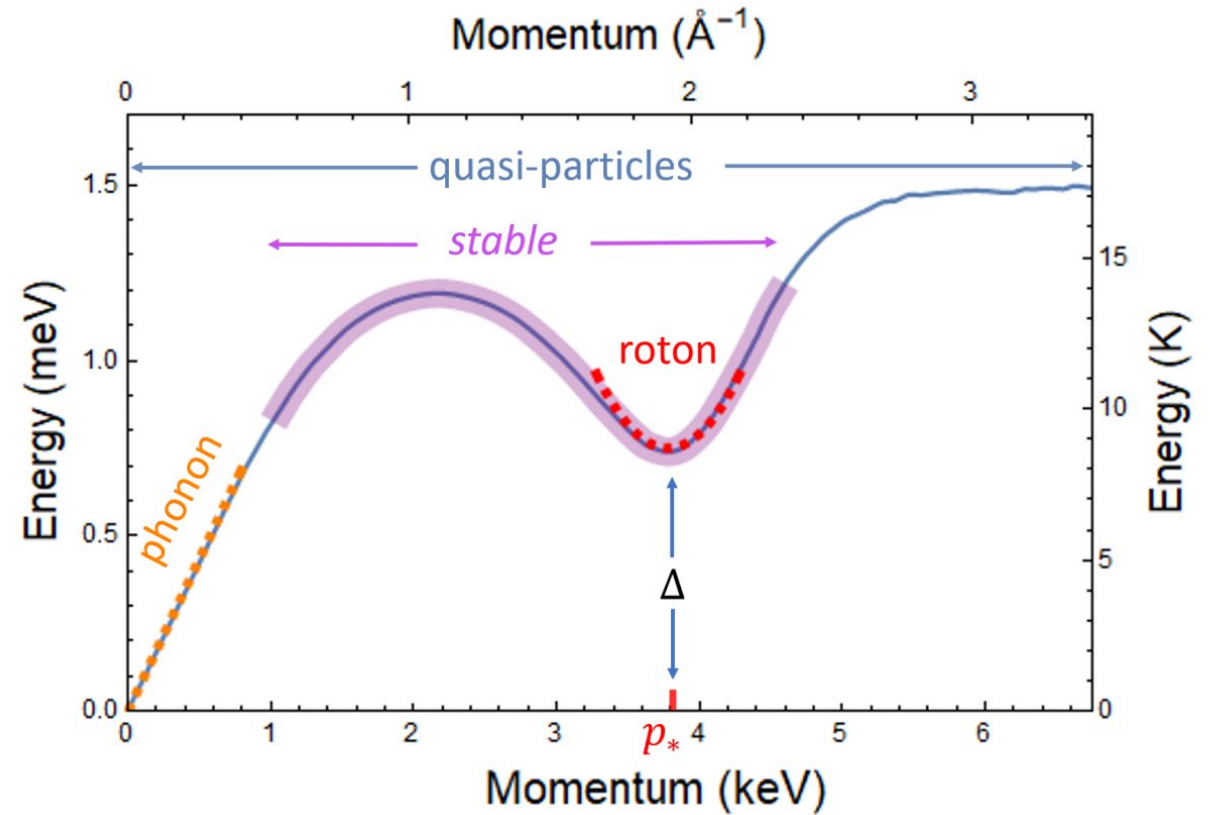


Figure: arXiv:2108.07275

Collective excitations

'Anomalous' dispersion:

$$\omega(q) \simeq sq(1 + \zeta_A q^2 + \dots)$$

Cascade decay into lower energy phonons:

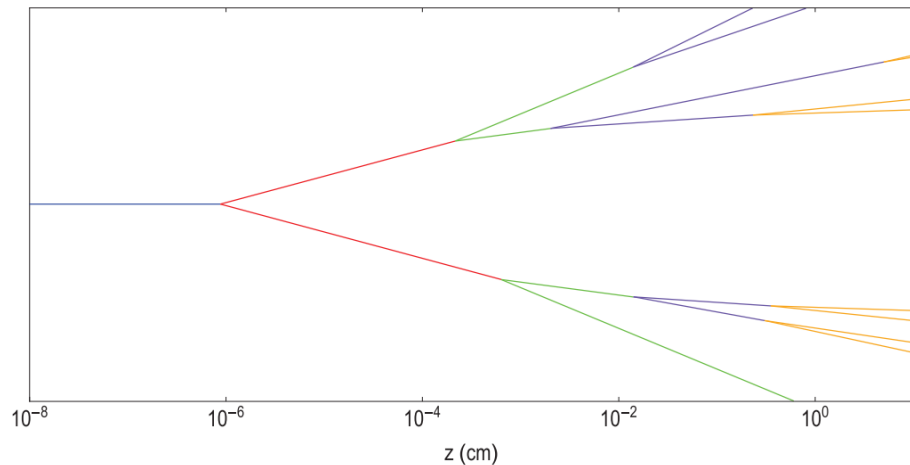


Figure: arXiv:2005.08824

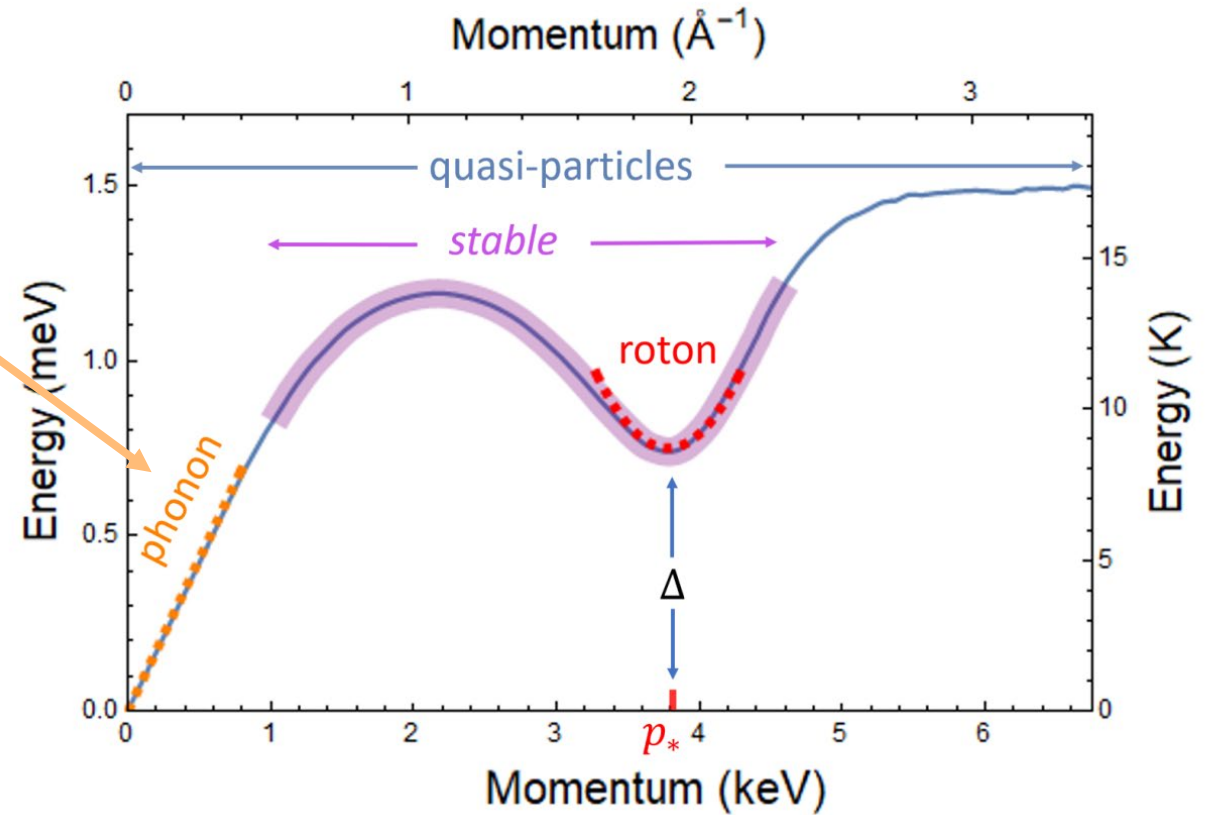


Figure: arXiv:2108.07275

Scattering rates

Rate for inelastic scattering that excites collective modes:

$$\frac{dR}{d^3q d\omega} = \frac{\rho_\chi V}{(2\pi)^3 m_\chi} \int d^3v f_\chi(\mathbf{v}) \frac{A^2 \pi \sigma_{\chi n}}{m_{\chi n}^2} F(q) \delta(\omega + E'_{DM} - E_{DM}) S(\mathbf{q}, \omega)$$

DM halo distribution

DM model

energy conservation

target

Scattering rates

Rate for inelastic scattering that excites collective modes:

$$\frac{dR}{d^3q d\omega} = \underbrace{\frac{\rho_\chi V}{(2\pi)^3 m_\chi} \int d^3v f_\chi(\mathbf{v})}_{\text{DM halo distribution}} \underbrace{\frac{A^2 \pi \sigma_{\chi n}}{m_{\chi n}^2} F(q)}_{\text{DM model}} \underbrace{\delta(\omega + E'_{DM} - E_{DM})}_{\text{energy conservation}} \underbrace{S(\mathbf{q}, \omega)}_{\text{target}}$$

Details of target encoded in *dynamic structure factor*

$$S(\mathbf{q}, \omega) = \frac{2\pi}{V} \sum_f \left| \langle \Psi_f | \int d^3x e^{i\mathbf{q}\cdot\mathbf{x}} n_4(\mathbf{x}) | \Psi_i \rangle \right|^2 \delta(E_f - E_i - \omega)$$

Calculated using tools from condensed matter physics or *measured* in neutron scattering

Superfluid Effective Field Theory

Real scalar with U(1) particle number symmetry: $\psi(x) \rightarrow \psi(x) + a$

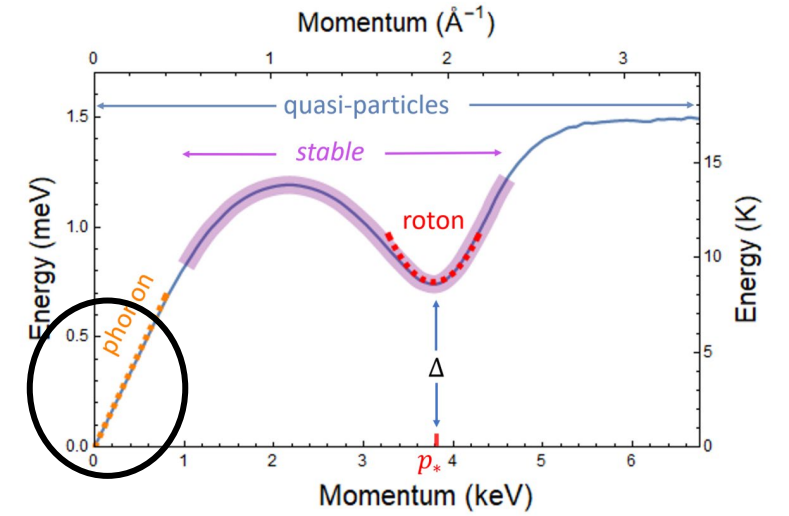


Figure: arXiv:2108.07275

Superfluid Effective Field Theory

Real scalar with U(1) particle number symmetry: $\psi(x) \rightarrow \psi(x) + a$

Finite density VEV: $\langle \psi(x) \rangle = \mu t$

Spontaneously breaks U(1), time translations & boosts (but preserves $H - \mu N$)

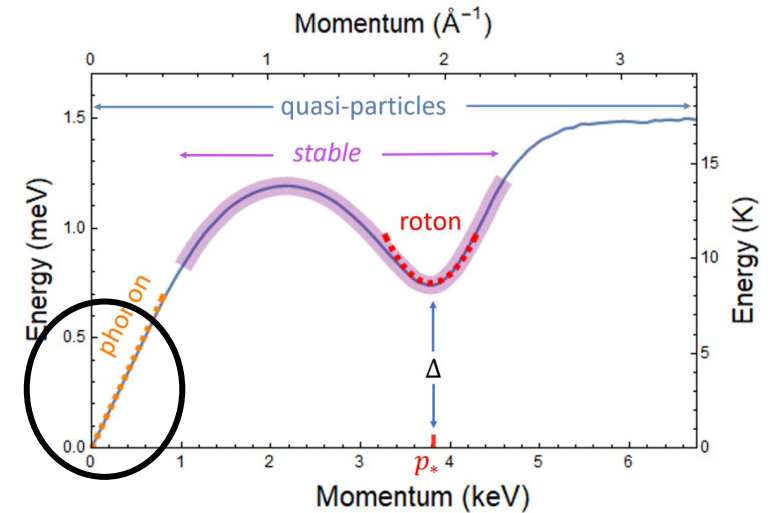


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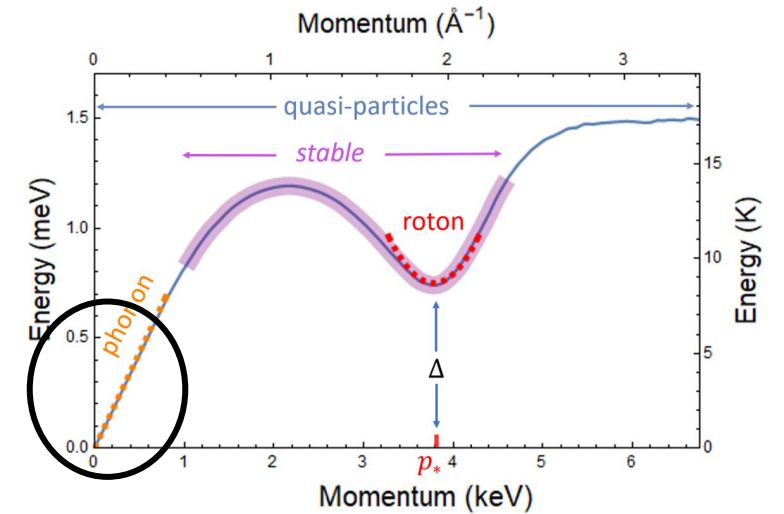


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Non-relativistic Goldstone mode:

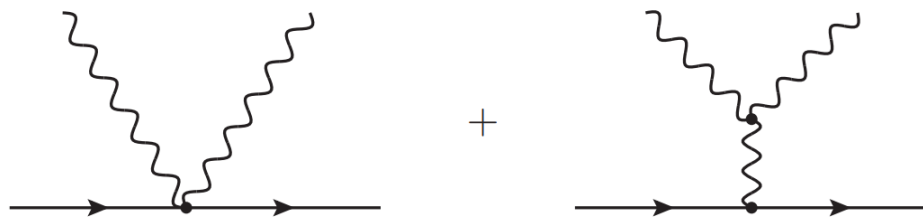
$$S = \int d^4x \left(\frac{1}{2} \dot{\pi}^2 - \frac{c_s^2}{2} (\nabla \pi)^2 \right) + \mathcal{O}(\pi^3)$$

sound speed

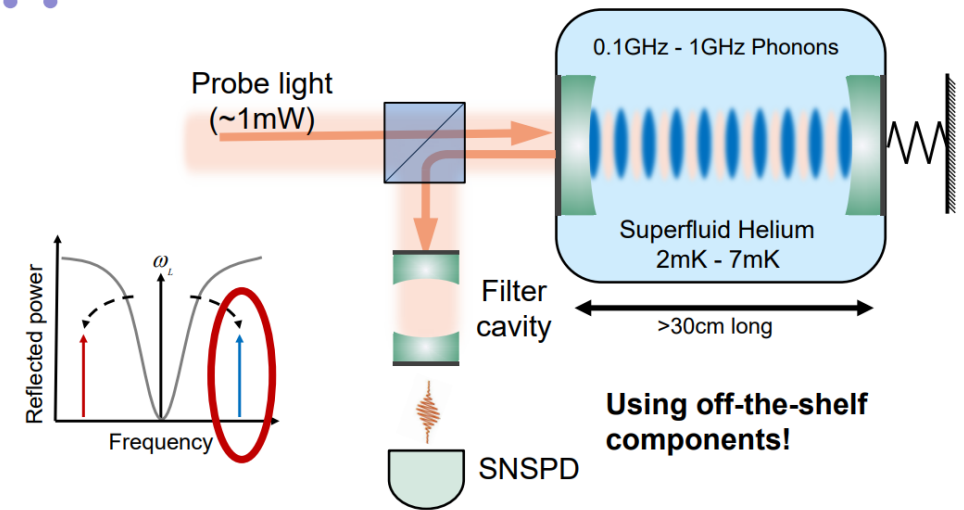
Superfluid optomechanics for DM

- Sensitive to keV - MeV dark matter masses
- Challenge: low rate due to single mode sensitivity

Ongoing work: optimise DM sensitivity, take advantage of 2-phonon processes?



Superfluid Dark Matter Detector



see Glen's talk

Outlook

- Sub-GeV regime still relatively unexplored
- Superfluid He is a promising target, still at R&D stage
- New parameter space can be probed with small scale experiments
- Space for new ideas!

