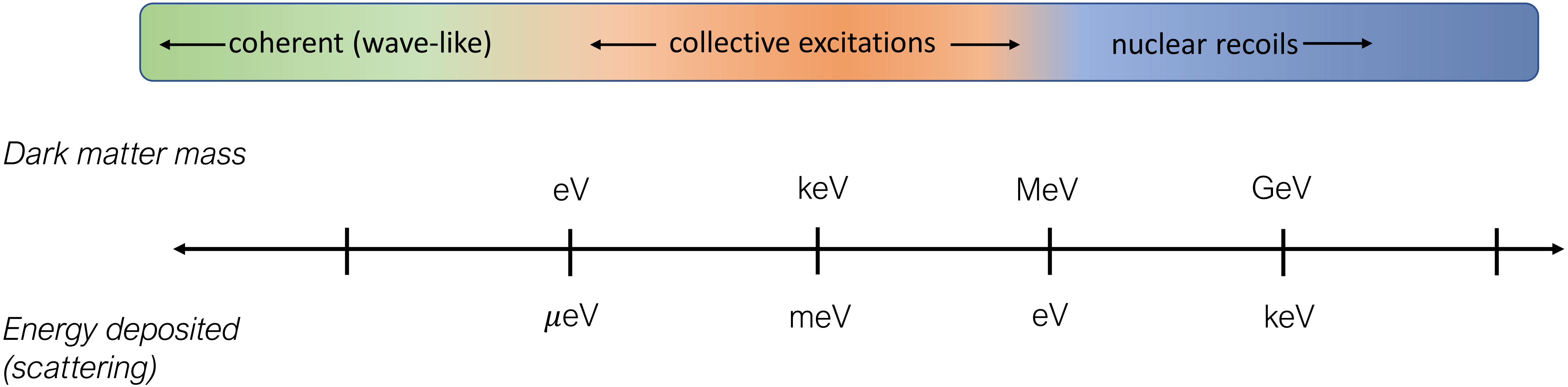
Sub-GeV direct detection with superfluid He

Peter Cox

The University of Melbourne

Detection regimes

Different regimes depending on coherence length of dark matter:



← coherent (wave-like)

← collective excitations →

nuclear recoils →

Dark matter mass

eV

keV

MeV

GeV

Energy deposited (scattering)

μeV

meV

eV

keV

Detection regimes

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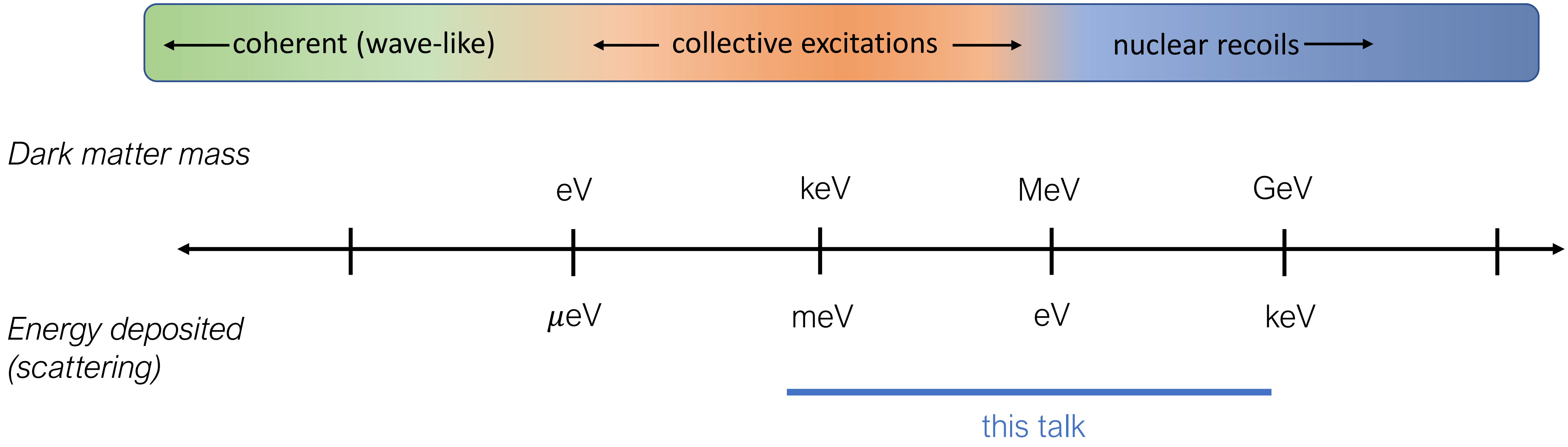
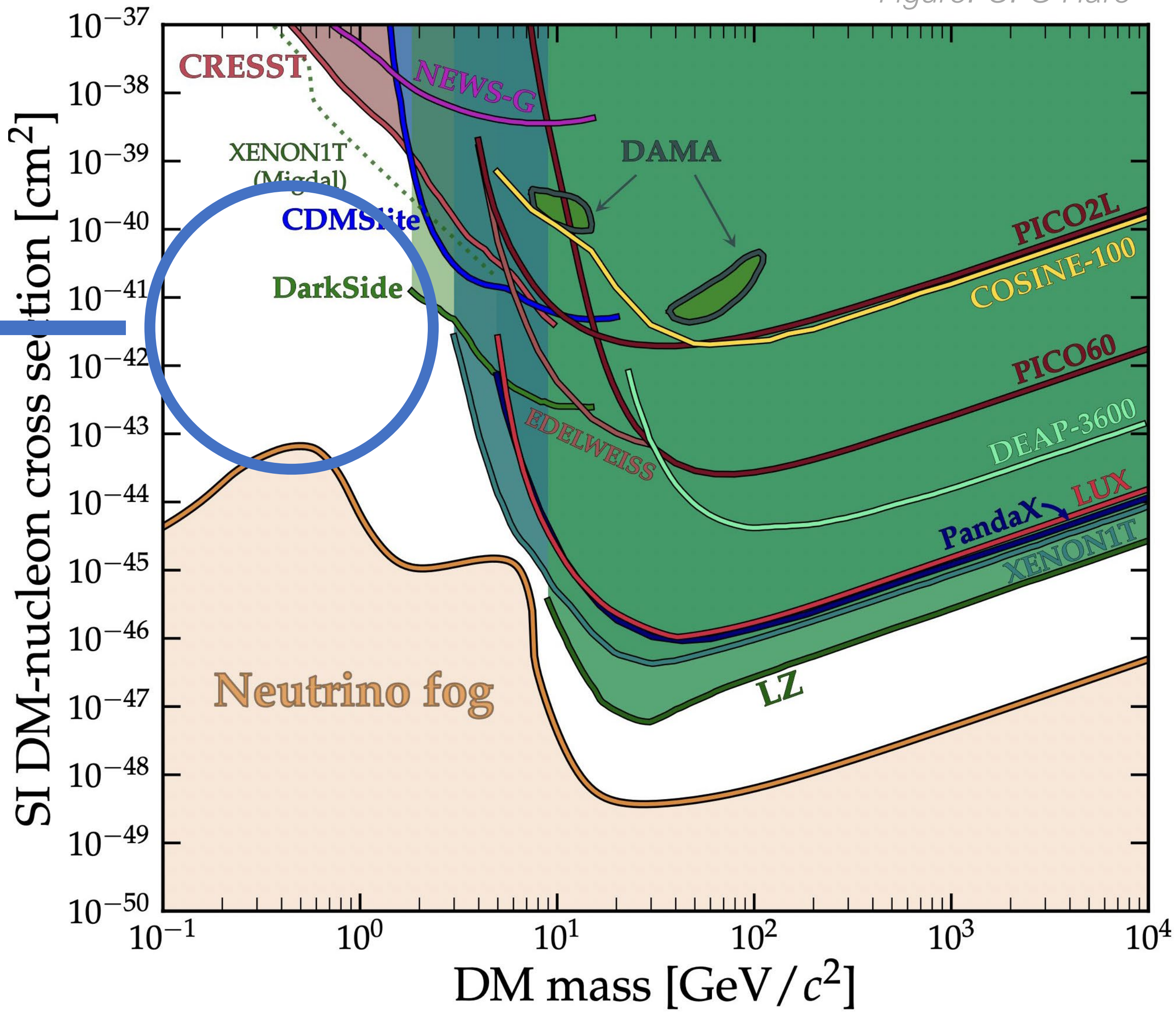


The sub-GeV frontier

Figure: C. O'Hare



Requires very
low energy thresholds

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:

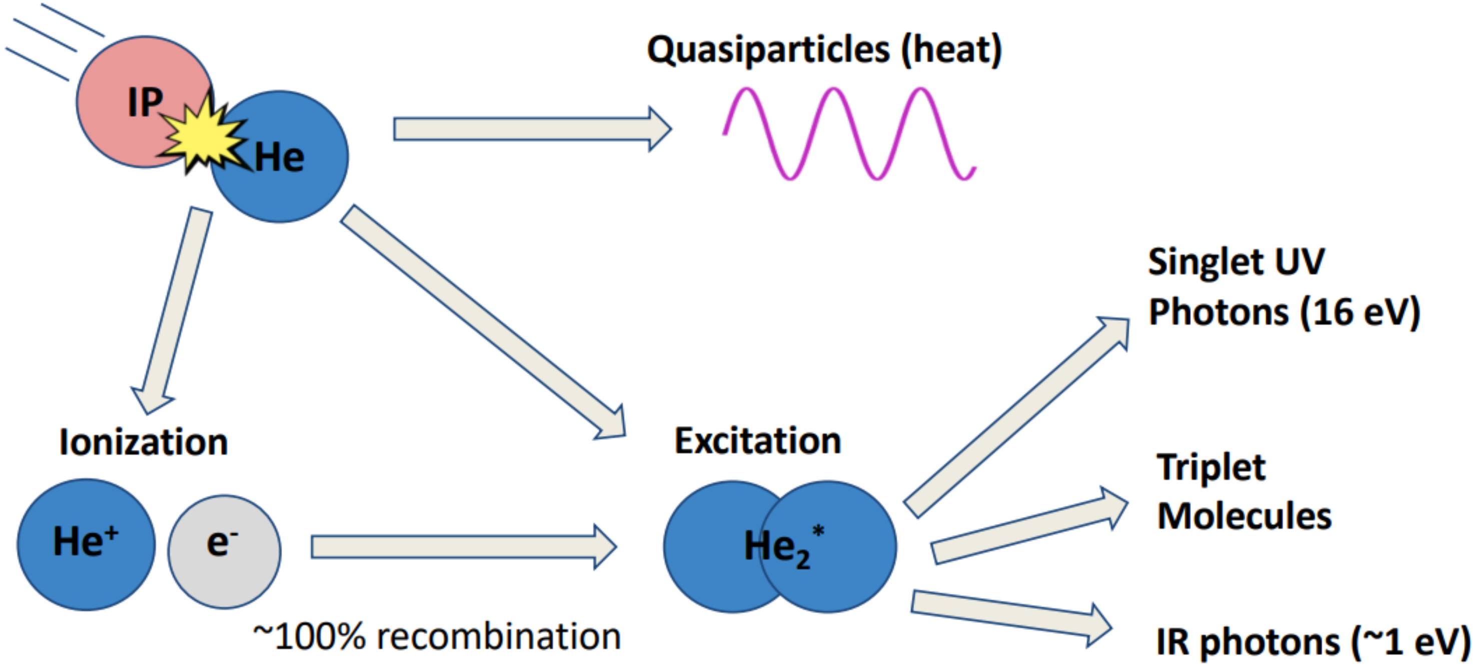
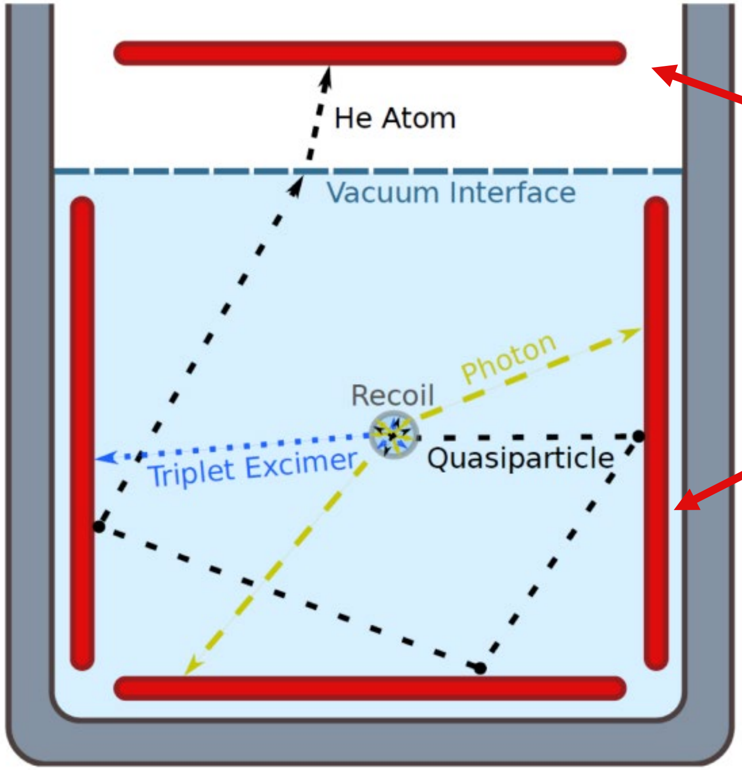


Figure: D. McKinsey

Schematic experiment

Proposed experiments have multiple detection channels



calorimeters immersed in He
& above surface

Figure: TESSERACT collaboration

Schematic experiment

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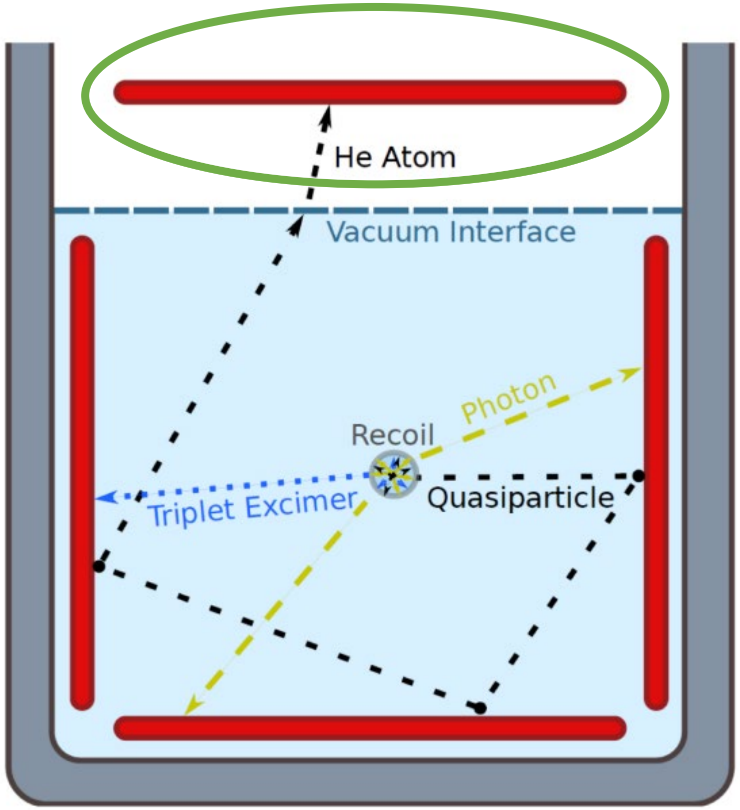


Figure: TESSERACT collaboration

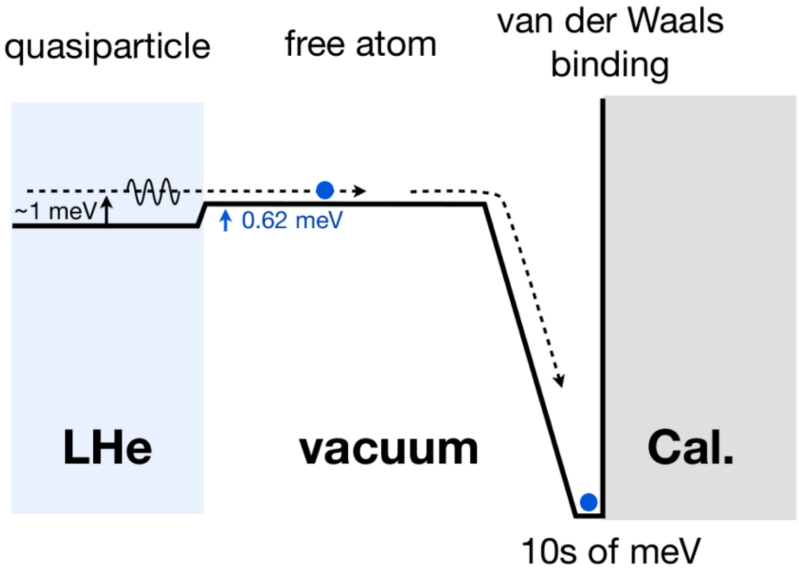


Figure: D. McKinsey

Adsorption onto surface amplifies signal

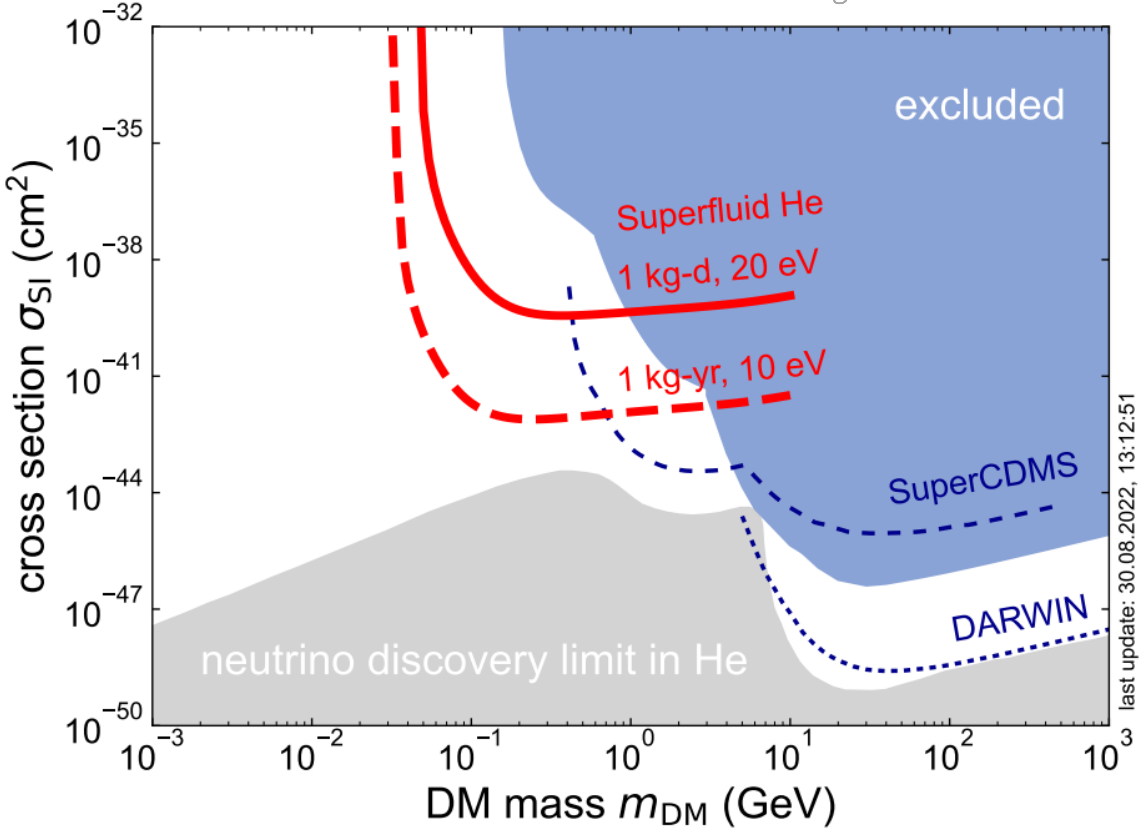
Sensitivity

Proposed experiments:

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

Realistic, near-term sensitivity competitive with other cryogenic experiments

DELight 2209.10950



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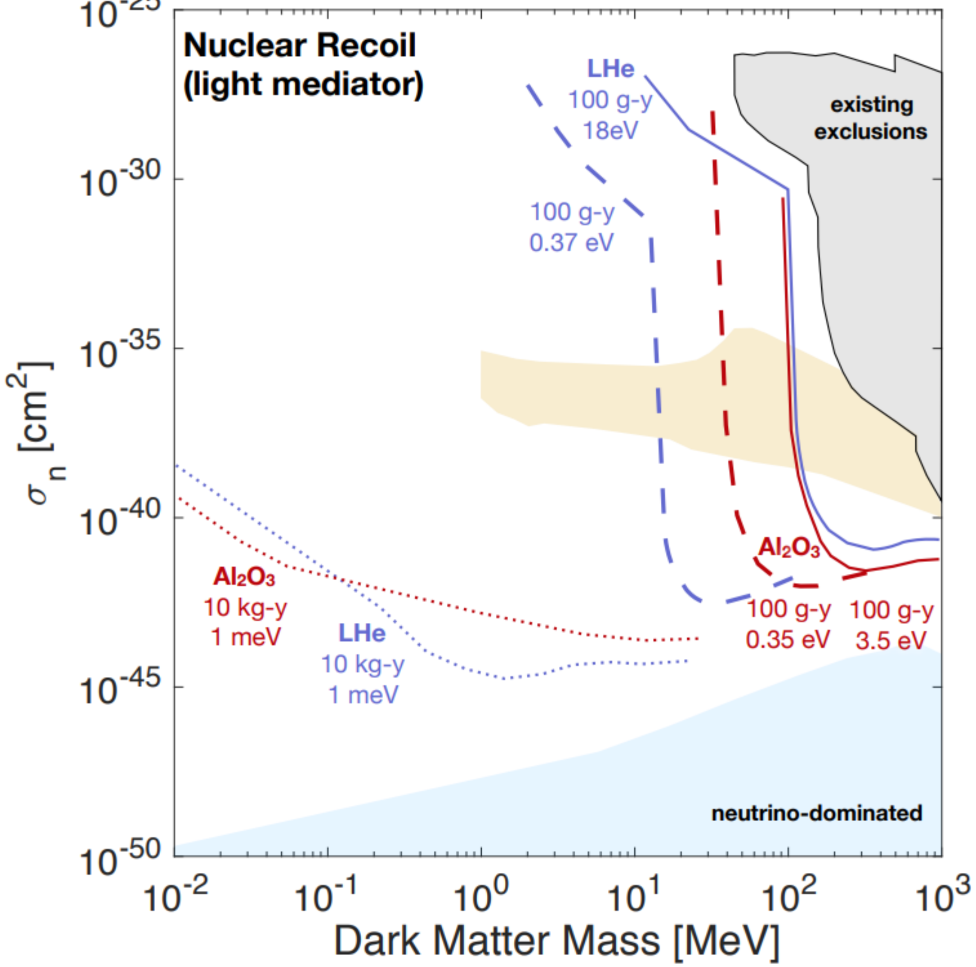
Ambitious goals to achieve very low thresholds



TESSERACT Snowmass '21 LoI

Collective excitations

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

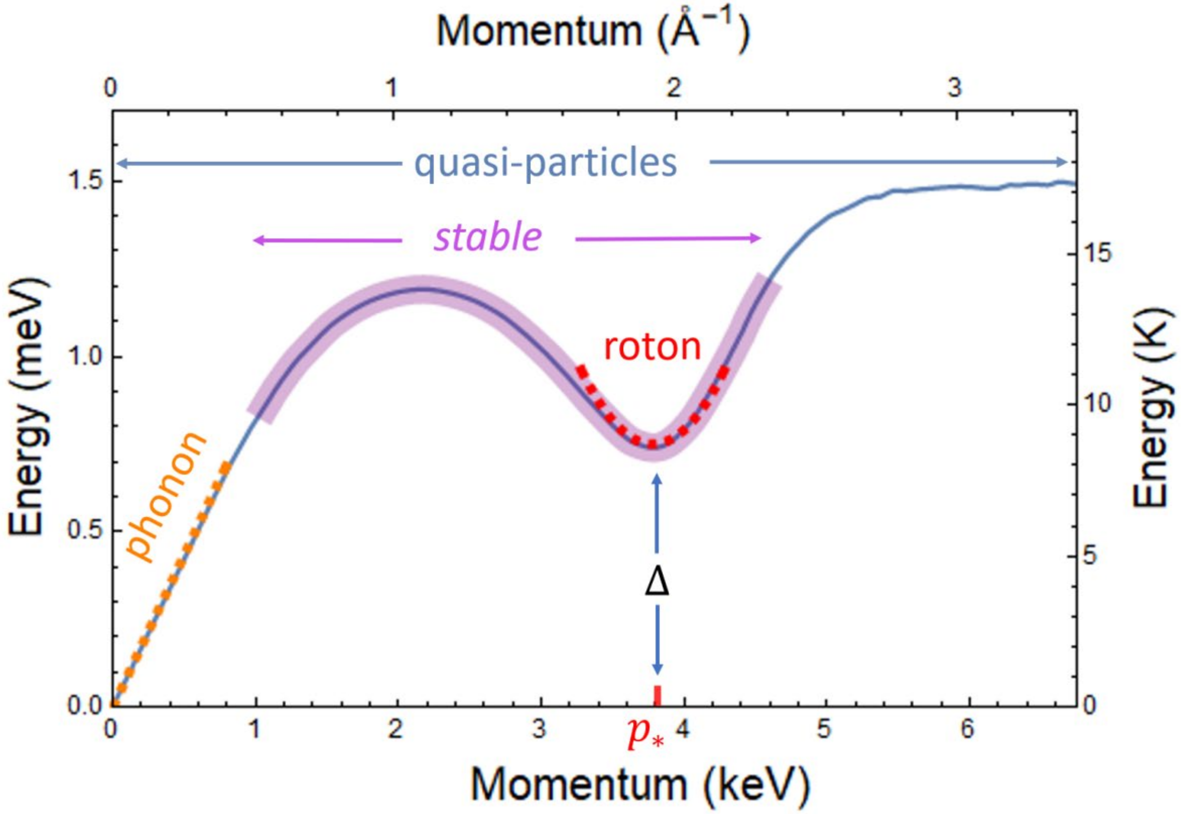


Figure: arXiv:2108.07275

Collective excitations

‘Anomalous’ dispersion:

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

Cascade decay into lower energy phonons:

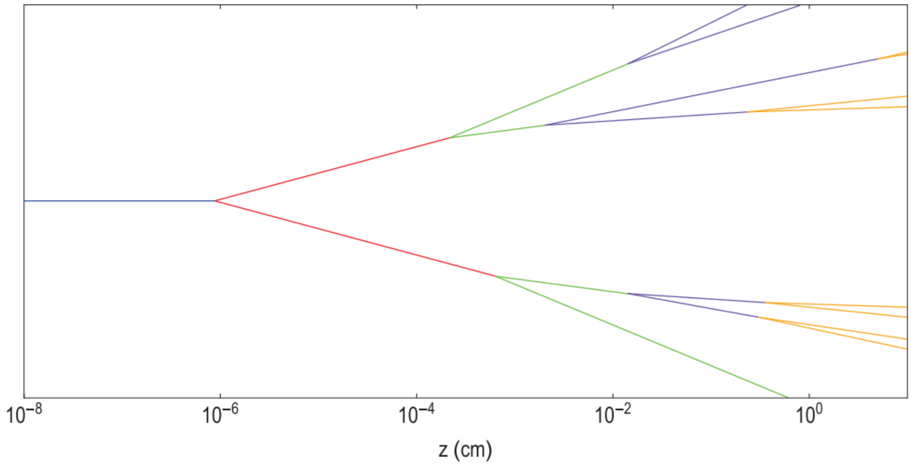
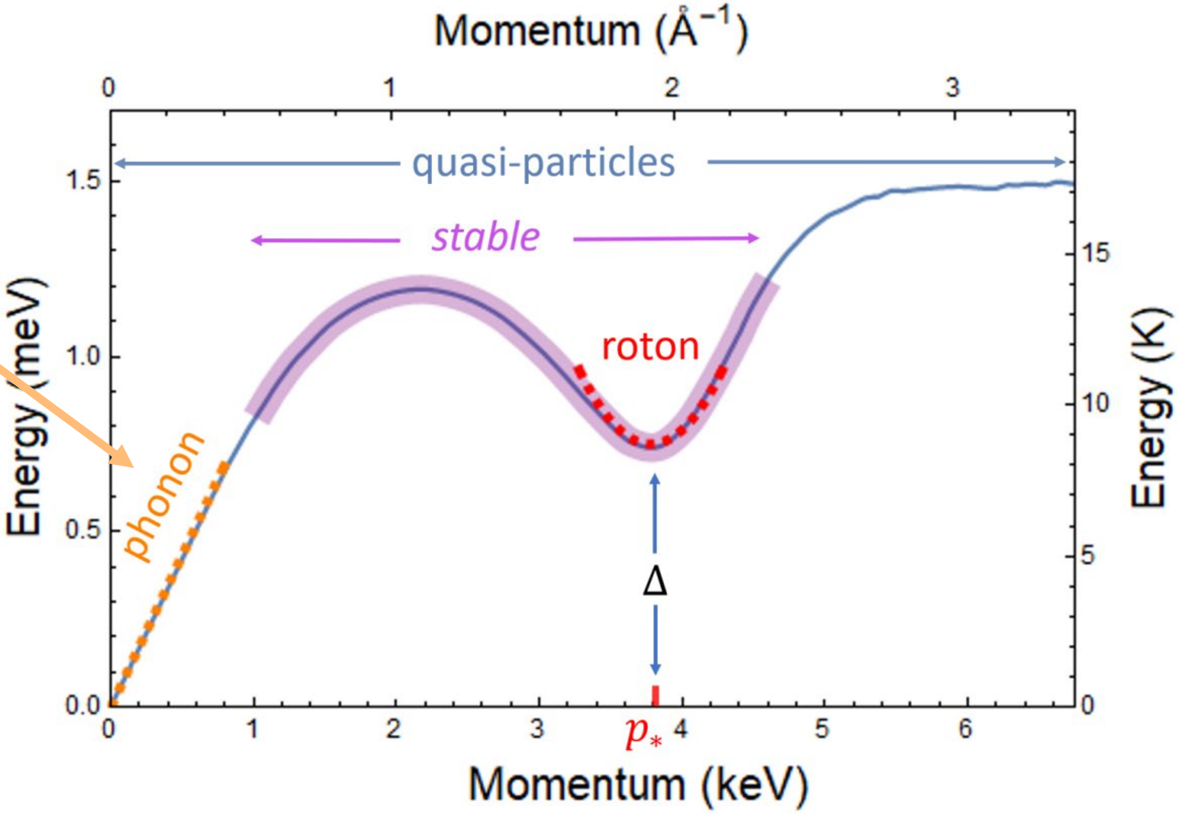


Figure: arXiv:2005.08824



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Scattering rates

Rate for inelastic scattering that excites collective modes:

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

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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: $\psi(x) \rightarrow \psi(x) + a$

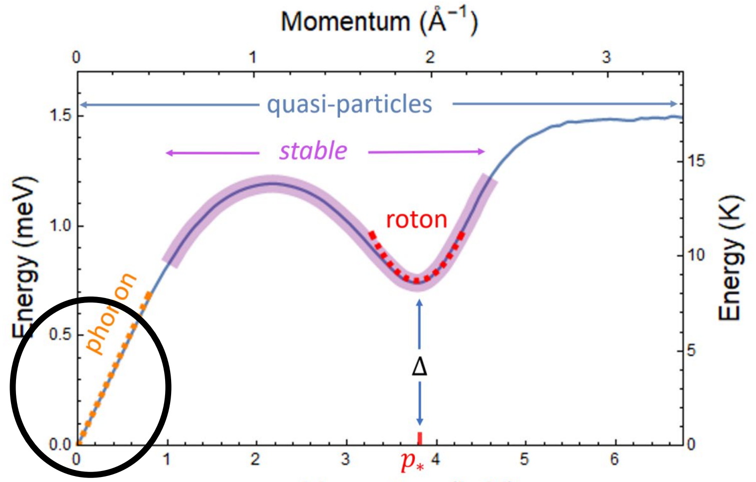


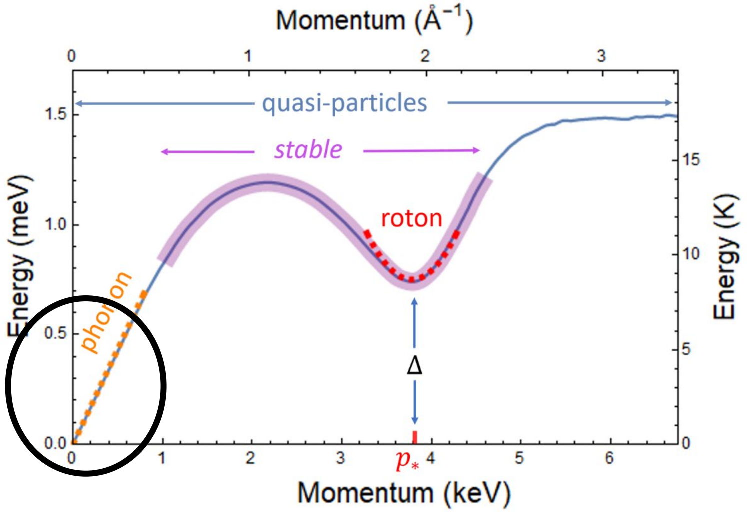
Figure: arXiv:2108.07275

Superfluid Effective Field Theory

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

Finite density VEV: $\langle \psi(x) \rangle = \underbrace{\mu}_{\text{chemical potential}} t$

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



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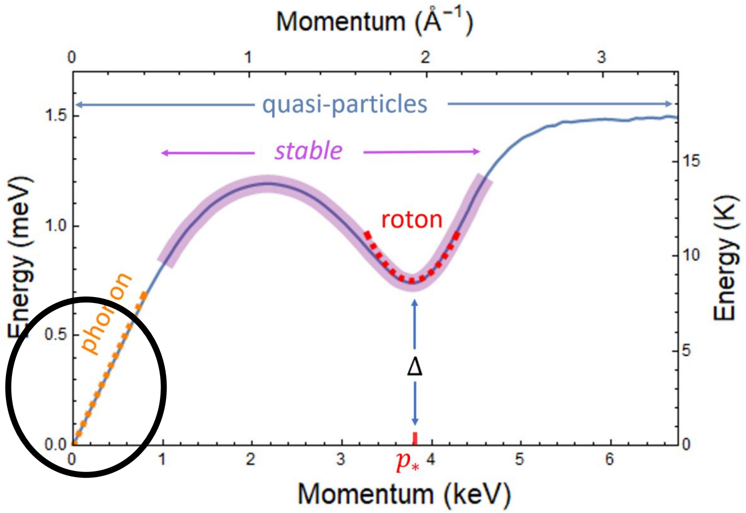


Figure: arXiv:2108.07275

Non-relativistic Goldstone mode:

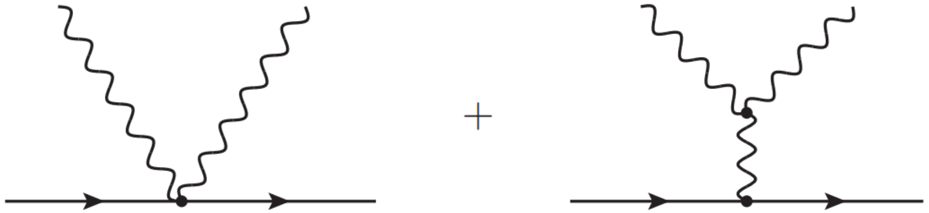
sound speed

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

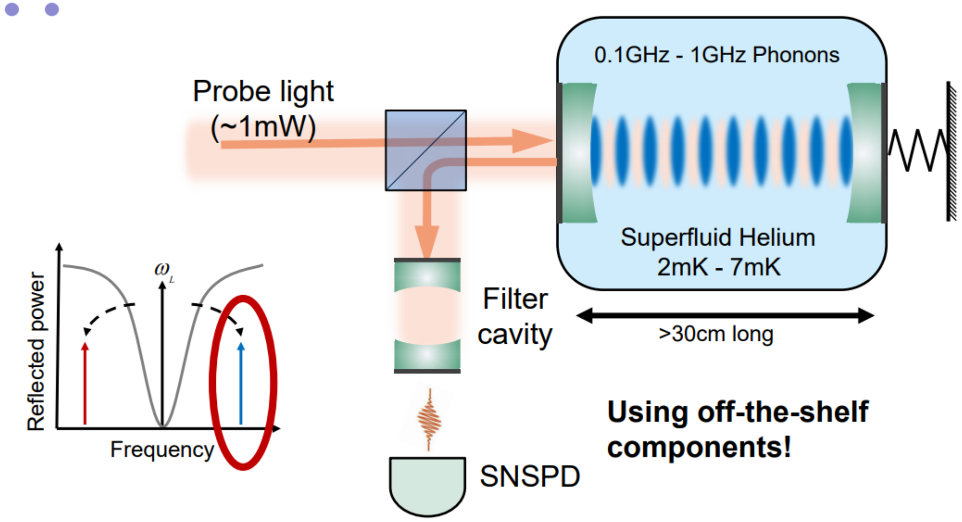
Superfluid optomechanics for DM

- 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



Using off-the-shelf components!

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!