Dark matter detection with superfluid optomechanics

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Direct detection: current status

Figure: C. O’Hare

[Graph showing the current status of direct detection experiments for dark matter (DM) with coordinates for various experiments and their respective cross sections and masses.]

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Direct detection: current status

- Cryogenic experiments
  - CRESST
  - LUX-ZEPLIN (LZ)
  - Tonne-scale liquid Ar/Xe experiments

Figure: C. O'Hare
Direct detection: current status

How to extend low mass reach?

Increased exposure (bigger detectors)

Figure: C. O’Hare
Sub-GeV direct detection

Migdal effect

Electron scattering

Low-threshold detectors

Lots of ideas + R&D

+ DM absorption, boosted DM, ...
Dark matter detection with superfluid $^4$He

Upcoming experiments using superfluid helium-4 target: HeRALD, DELight

Primary signal: quantum evaporation
Dark matter detection with superfluid $^4$He

Upcoming experiments using superfluid helium-4 target: HeRALD, DELight

Primary signal: *quantum evaporation*

Figure: Herald Collaboration

Adsorption onto surface amplifies signal

Figure: D. McKinsey
Dark matter detection with superfluid $^4$He

Initial sensitivity to DM masses of 10s-100s MeV

Ongoing R&D towards lower threshold calorimeters:
- HeRALD (transition edge sensors)
- DELight (magnetic micro-calorimeter)
Sub-MeV direct detection: collective excitations

- Dark matter mass
- eV
- keV
- MeV
- GeV

- De Broglie wavelength
- mm
- µm
- nm
- pm

- Coherent (wave-like)
- Collective excitations
- Nuclear (or electron) recoils
Sub-MeV direct detection: collective excitations

Sub-MeV mass DM interacts directly with collective excitations (e.g. phonons)
Superfluid $^4$He collective modes (phonons/rotons)

Long-lived/stable collective excitations

Figure: Matchev et. al '21
Superfluid phonon EFT

Low-energy phonons in superfluid described by effective field theory

- Nambu-Goldstone bosons of spontaneously broken $U(1)$ particle number

$$\Phi(x) \to \Phi(x) + \alpha \quad \langle \Phi(x) \rangle = \mu t$$

$\mu =$ chemical potential
Superfluid phonon EFT

Low-energy phonons in superfluid described by effective field theory

- Nambu-Goldstone bosons of spontaneously broken $U(1)$ particle number

\[ \Phi(x) \to \Phi(x) + \alpha \]
\[ \langle \Phi(x) \rangle = \mu t \]
\[ \mu = \text{chemical potential} \]

- VEV breaks internal $U(1)$, Lorentz boosts & time translations

- Preserves linear combination $H - \mu N$
Superfluid phonon EFT

Most general Lagrangian consistent with shift symmetry:

\[ \mathcal{L} = P(X) \quad \text{and} \quad X = \sqrt{\partial_\mu \Phi \partial_\mu \Phi} \]
Superfluid phonon EFT

Most general Lagrangian consistent with shift symmetry:

\[ \mathcal{L} = P(X) \]

\[ X = \sqrt{\partial^\mu \Phi \partial_\mu \Phi} \quad \Phi = \mu t \rightarrow \mu \]

“local chemical potential”

\[ P(X) \] is identified as the pressure of the superfluid

\[ T^{\mu\nu} \bigg|_{\Phi = \mu t} = \mu n \delta^\mu_0 \delta^\nu_0 - \eta^{\mu\nu} P(\mu) \]
Superfluid phonon EFT

Most general Lagrangian consistent with shift symmetry:

\[ \mathcal{L} = P(X) \quad \quad X = \sqrt{\partial^\mu \Phi \partial_\mu \Phi} \]

Nambu-Goldstone phonon: \[ \Phi(x, t) = \mu t + \sqrt{\frac{\mu c_s^2}{n}} \phi(x, t) \]

\[ \mathcal{L} = \frac{1}{2} \phi^2 - \frac{c_s^2}{2} (\nabla \phi)^2 + \lambda_3 \phi (\nabla \phi)^2 + O(\phi^4) \]

Sound speed, couplings can be expressed in terms of derivatives of \( P(\mu) \)
Dark matter – phonon interactions

Consider spin-independent DM-nucleon interaction

$$\Rightarrow \text{DM couples to He number density} \quad n = \frac{P'(X)}{X} \partial^0 \Phi$$

$$\mathcal{L}_{\text{int}} = g_\chi n \chi^2$$
Dark matter – phonon interactions

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\[ L_{\text{int}} = g_\chi n \chi^2 \]

\[ = g_\chi \left( \bar{n} + \sqrt{\frac{\bar{n}}{\mu c_s^2}} \dot{\phi} + \lambda_3 (\nabla \phi)^2 + \ldots \right) \chi^2 \]
Detecting phonons - cavity optomechanics

*Basic idea:* optomechanical systems can be single phonon detectors
Detecting phonons - cavity optomechanics

**Basic idea:** optomechanical systems can be single phonon detectors

**Toy model:**

\[ H = \Omega_m b_m^\dagger b_m + \left( \omega_0 + \frac{\partial \omega}{\partial x} x \right) a^\dagger a \]

Optical resonance frequency depends on cavity length
Detecting phonons - cavity optomechanics

Basic idea: optomechanical systems can be single phonon detectors

Toy model:

\[ H = \Omega_m b_m^\dagger b_m + \left( \omega_0 + \frac{\partial \omega}{\partial x} x \right) a^\dagger a \]

\[ = \Omega_m b_m^\dagger b_m + \left( \omega_0 + g_0 (b_m + b_m^\dagger) \right) a^\dagger a \]
Superfluid cavity optomechanics

*superfluid $^4$He filled optical cavity*

Mechanical mode: phonons in superfluid

Optomechanical interaction due to change in refractive index

*Figure: Kashkanova+ '16*
Superfluid cavity optomechanics

\[ H_{OM} = -g_0(a_1^\dagger a_2 b_m^\dagger + h.c.) \]

Energy-momentum conservation:
\[ \Omega_m = \omega_2 - \omega_1 \ll \omega_{1,2} \]
\[ \lambda_m \approx \lambda_\gamma / 2 \]
Superfluid cavity optomechanics

Optomechanical interaction converts ~μeV phonons into detectable ~eV photons

\[ H_{OM} = -g_0 (a_{\gamma_1}^\dagger a_{\gamma_2} b_m^\dagger + h.c.) \]
\[ \rightarrow -g_0 \sqrt{N_1} (a_{\gamma_2} b_m^\dagger + h.c.) \]

pump laser enhances small \( g_0 \)

Energy-momentum conservation:
\[ \Omega_m = \omega_{\gamma_2} - \omega_{\gamma_1} \ll \omega_{\gamma_1,2} \]
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Superfluid cavity optomechanics

Optomechanical interaction converts \( \sim \mu eV \) phonons into detectable \( \sim eV \) photons

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Energy-momentum conservation:

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\[ \lambda_m \approx \lambda_\gamma / 2 \]

Optomechanical systems have demonstrated \( \mu eV \) phonon counting

(e.g. Patil et. al. '22)
Narrow-band detection

Superfluid optomechanical systems as dark matter detectors:

- exceptional low-energy sensitivity (~μeV)
- narrow-band detector (single phonon energy)

→ Very low dark matter scattering rate due to restricted phase space
Narrow-band detection & phonon lasing

Superfluid optomechanical systems as dark matter detectors:

✓ exceptional low-energy sensitivity (~µeV)
× narrow-band detector (single phonon energy)

→ Very low dark matter scattering rate due to restricted phase space

Solution: Phonon lasing

- Stimulated scattering rate (proportional to phonon occupation number)
- Achieved via optomechanical interaction
Scattering rate

Initial state phonon number density

Acoustic quality factor: $Q = \frac{\Omega_m}{\Gamma_m}$

3-phonon coupling

Resonantly enhanced
Scattering rate

Initial state phonon number density

Acoustic quality factor: \( Q = \Omega_m / \Gamma_m \)

3-phonon coupling

\[
R \propto \frac{\rho \chi \sigma \chi n}{m_\chi^3} n_s Q^2 \frac{\Omega_r \Omega_s}{m_{\text{He}} c_s^4} (1 + \gamma_G)^2
\]

Scattering is between specific initial and final phonon states:

I. Scattering is at fixed momentum transfer: \( q = (\Omega_r - \Omega_m) / c_s \sim \text{eV} \)

II. Event rate doesn't scale with detector volume (resolved mode regime)
Optomechanical detection

Dark matter detector requires optomechanical control of two acoustic modes.
Optomechanical detection

1. **Phonon lasing**
   Lower-energy phonon mode $\Omega_s$, populated via optomechanical interaction.
Optomechanical detection

2 Scattering
Stimulated dark matter scattering excites higher energy phonon mode

![Graph showing acoustic and optical modes with dark matter scattering](image)
Optomechanical detection

3: **Conversion & amplification**
Optomechanical conversion of $\Omega_r$ phonon to higher energy photon
Optomechanical detection

4 Detection
Photon detected by single photon detector (SNSPD)
ODIN: Optomechanical Dark-matter INstrument

cavity dimensions ~ 30cm x 0.7mm
ODIN: Optomechanical Dark-matter INstrument

Main detector backgrounds:

- **Thermal phonons**
  \((10^{-5} \text{ Hz at } T = 4\text{mK and } Q = 10^{10})\)

- **SNSPD dark counts**
  \((\sim 6 \times 10^{-6} \text{ Hz})\)

- **Incomplete filtering of pump lasers**
  (especially 532nm, suppressed with filter cavities)

Expected background rate ~1 event/day

cavity dimensions ~ 30cm x 0.7mm
ODIN: Projected Sensitivity

Sensitivity determined by:

- Phonon occupation
- Acoustic Q-factor (phonon width)
- Intrinsic background rate

Sensitive to keV-scale dark matter
Summary

• Superfluid He is a promising target for light dark matter searches

• Optomechanical detection uses conversion of ~μeV phonons to ~eV photons

• ODIN will be sensitive to ~keV mass dark matter

• Currently exploring improvements to sensitivity – signal modulation?

• Potential application to high frequency gravitational waves

• Proposals to also use optomechanical detectors for ultralight DM [Manley+ ’19, Manley+ ’22, Brady+ ’22, Murgui+’22].
Backup
Optical asymmetry

Optical mode spacing (FSR) can be engineered to select amplification/cooling of acoustic modes: