Dark matter detection with superfluid optomechanics

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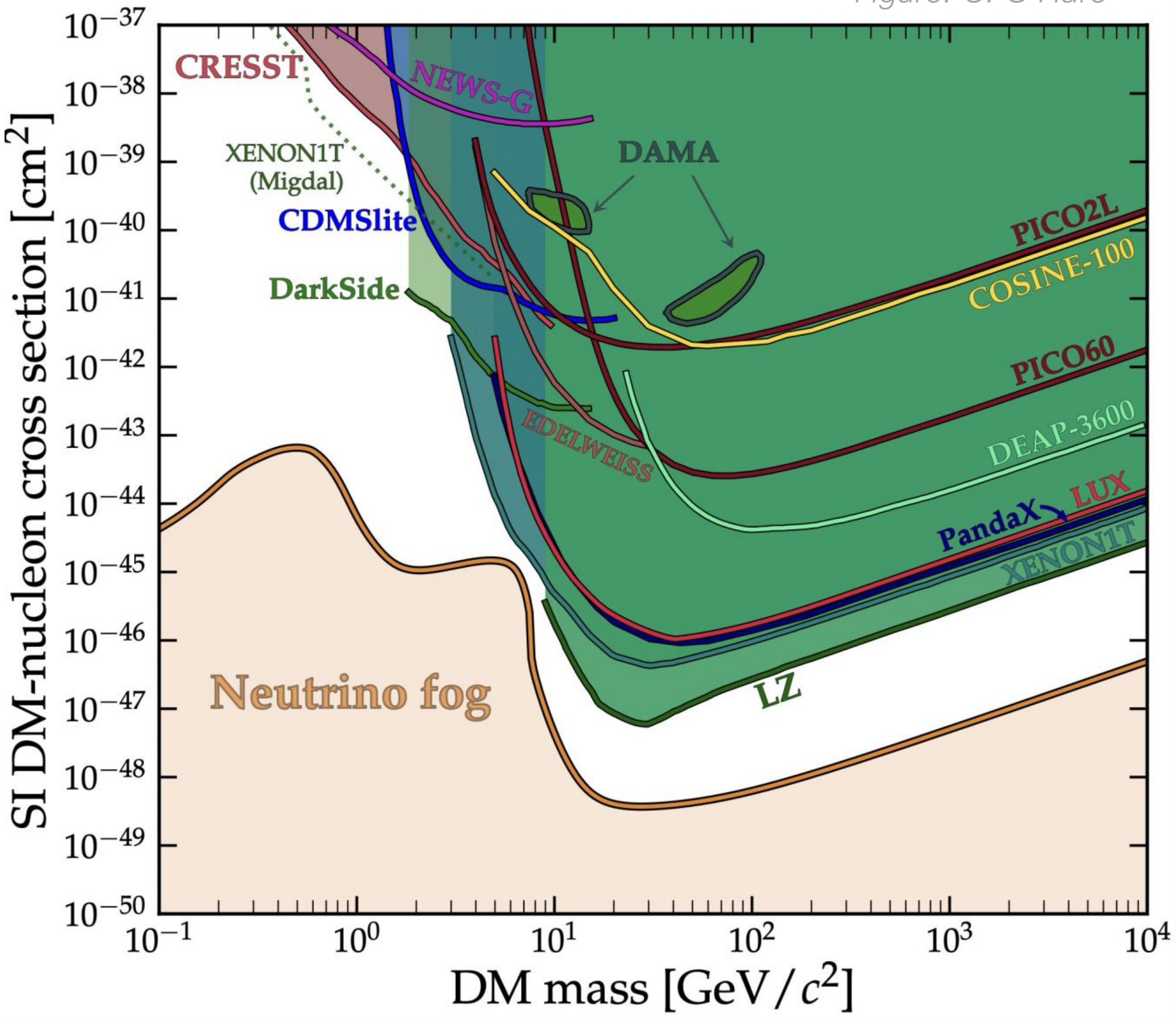
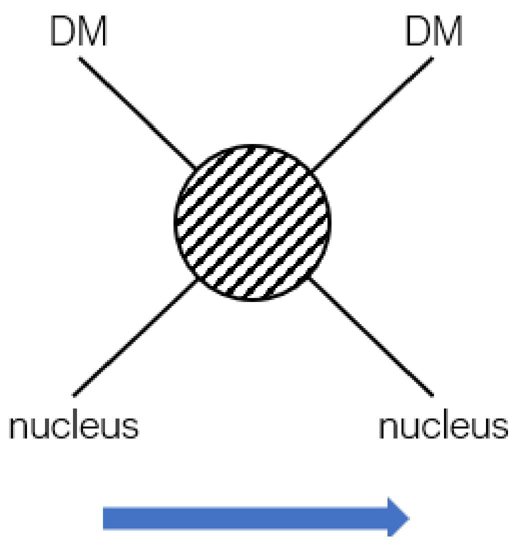
arXiv:2306.09726

THE UNIVERSITY OF MELBOURNE

Direct detection: current status

Figure: C. O'Hare





Direct detection: current status

cryogenic experiments

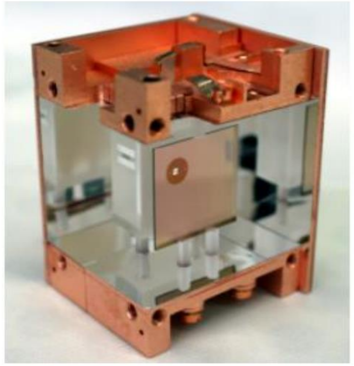


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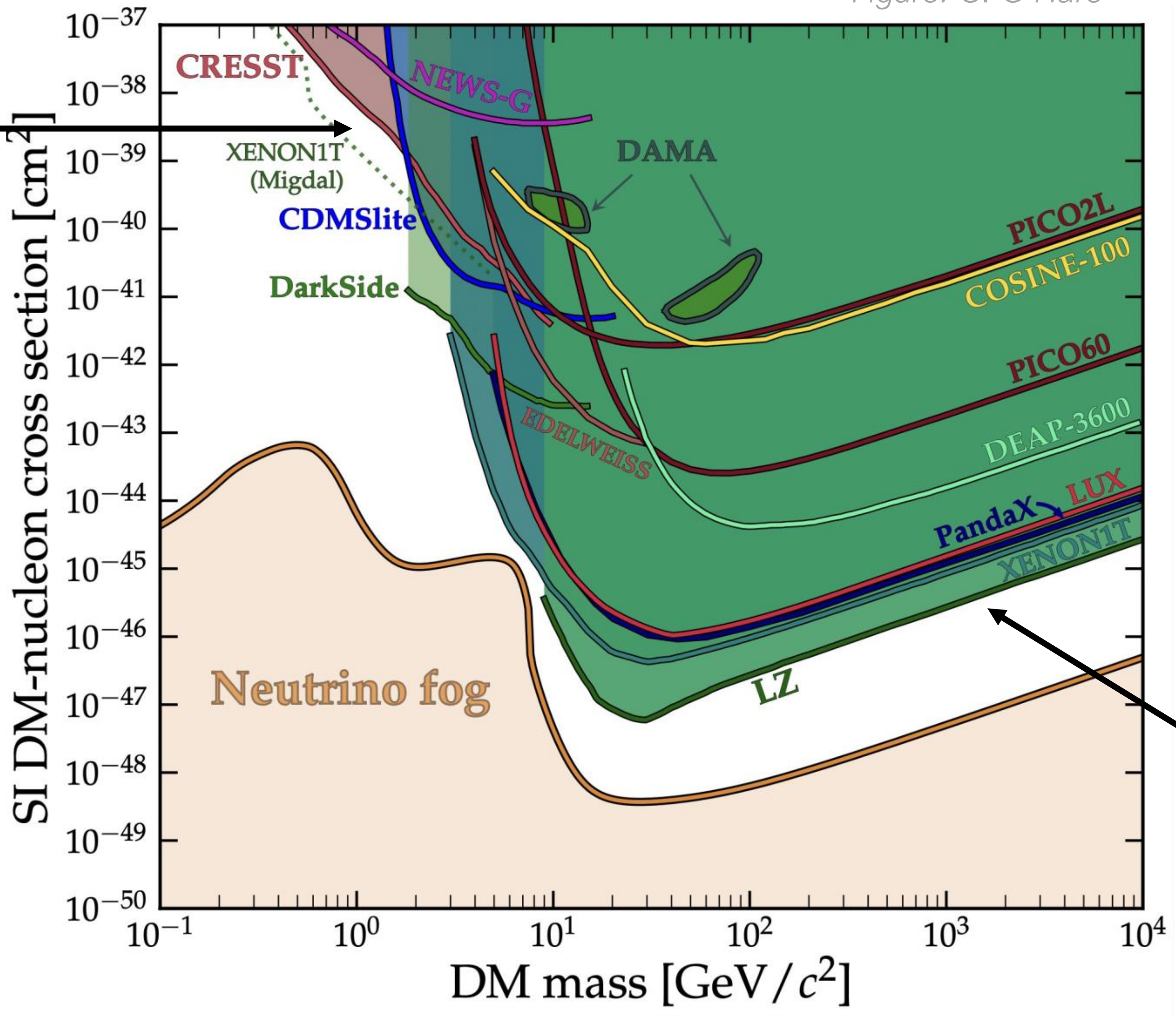
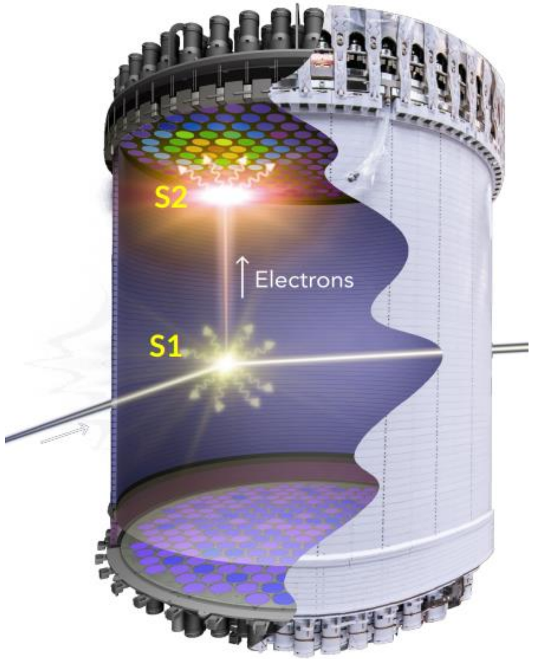
Figure: C. O'Hare





LUX-ZEPPLIN (LZ)

tonne-scale liquid Ar/Xe experiments

Direct detection: current status

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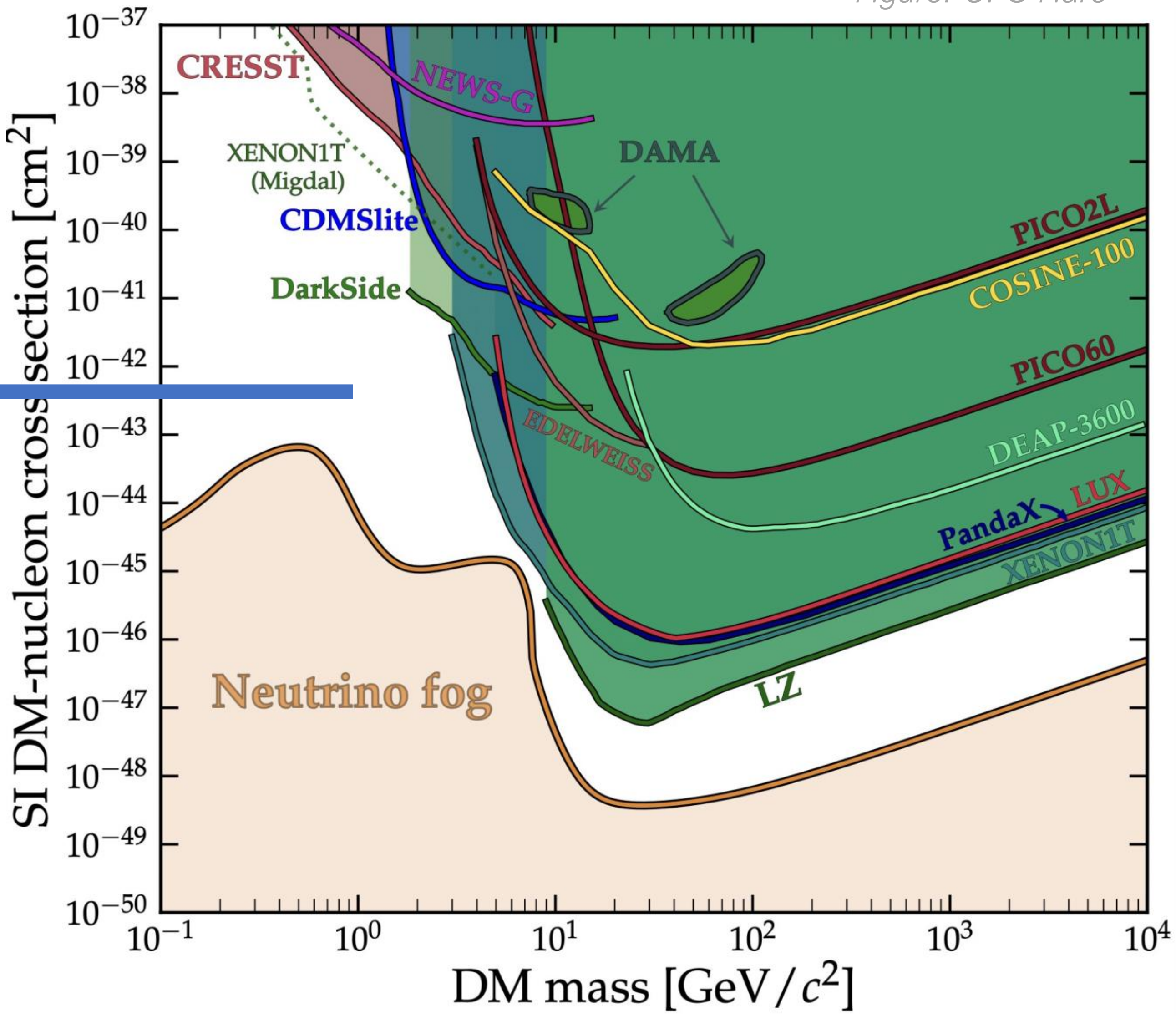


How to extend low mass reach?

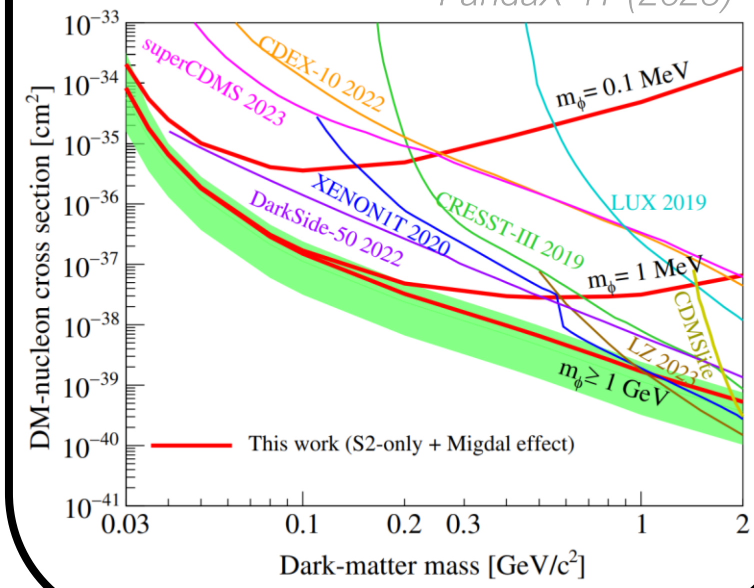
Increased exposure

(bigger detectors)

Sub-GeV direct detection

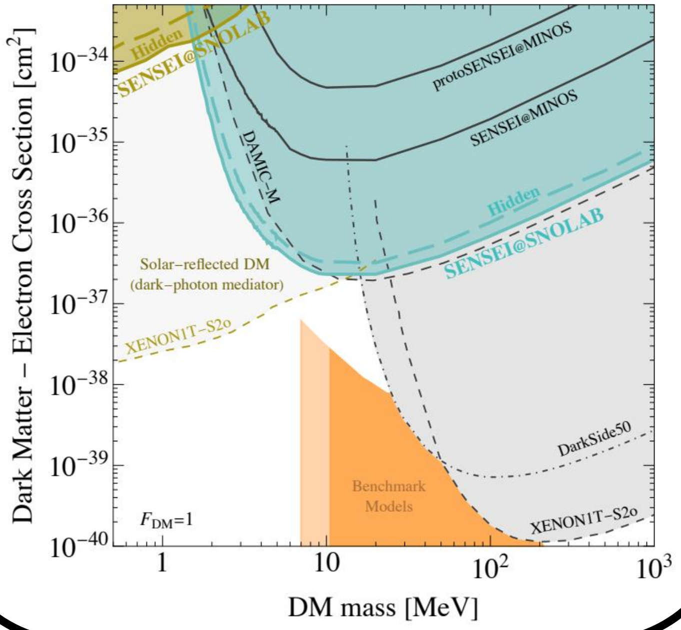
Migdal effect

PandaX-4T (2023)

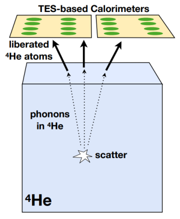


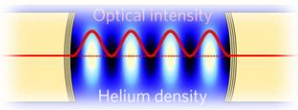
Electron scattering

SENSEI (2023)



Low-threshold detectors





Lots of ideas + R&D

+ DM absorption, boosted DM, ...

Dark matter detection with superfluid ^{4}He

Lanou, Maris & Seidel '87
Guo & McKinsey '13
Ito & Seidel '13
Hertel+ '18

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

Primary signal: *quantum evaporation*

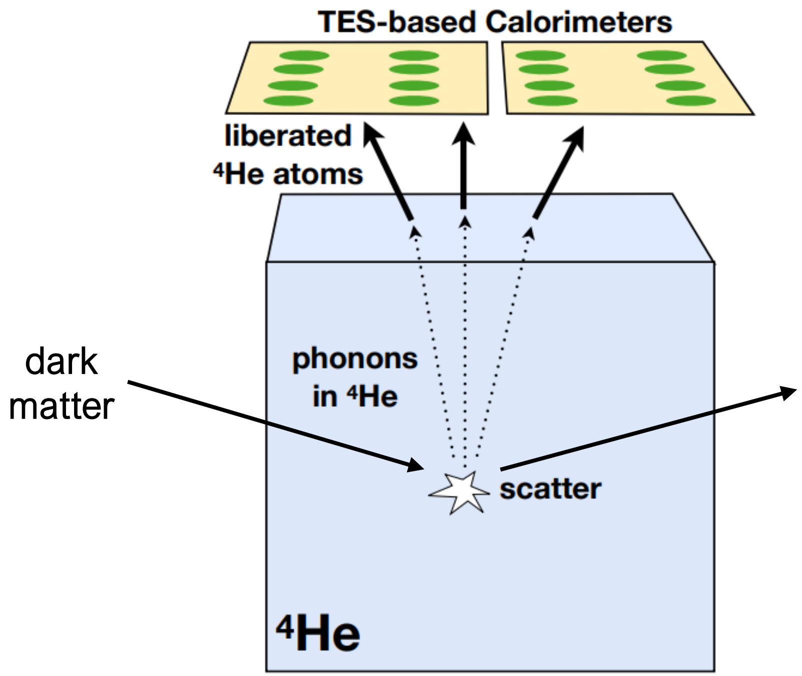


Figure: Herald Collaboration

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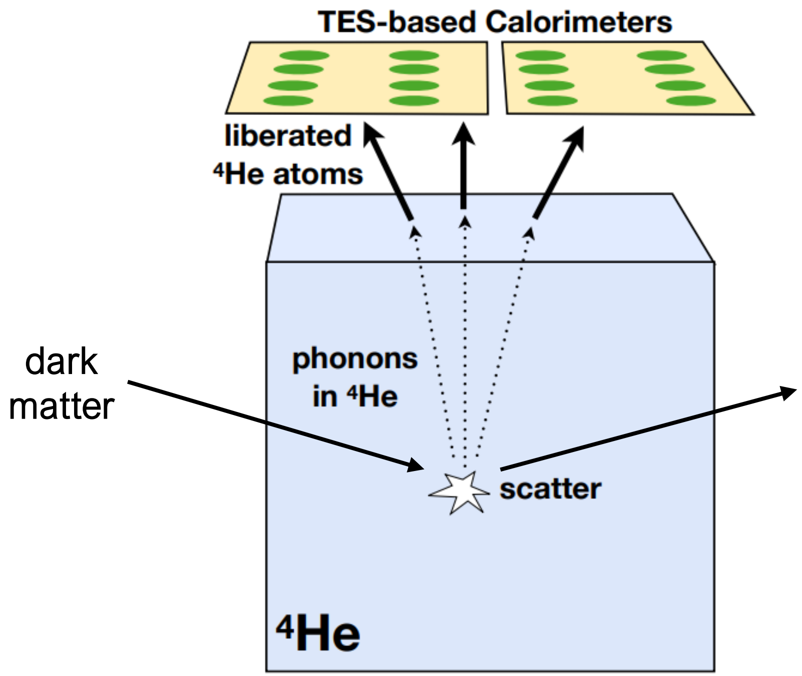

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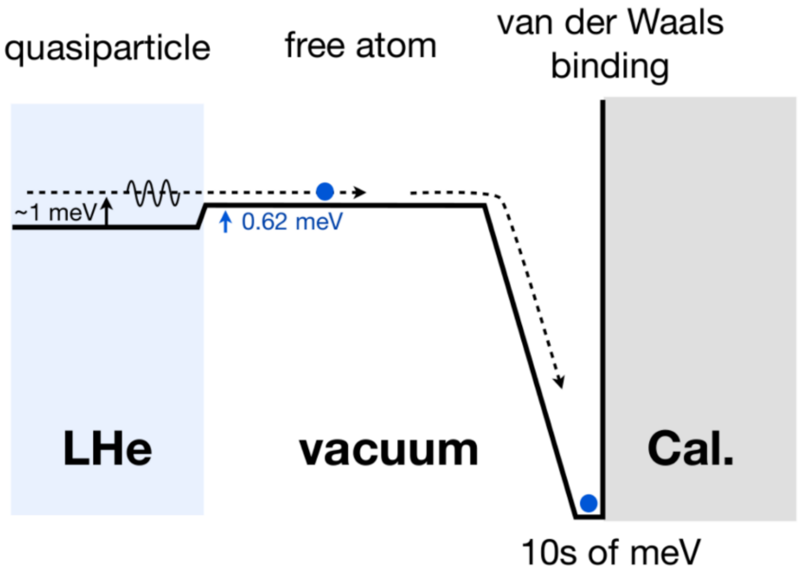


Figure: D. McKinsey

Adsorption onto surface amplifies signal

Dark matter detection with superfluid ^{4}He

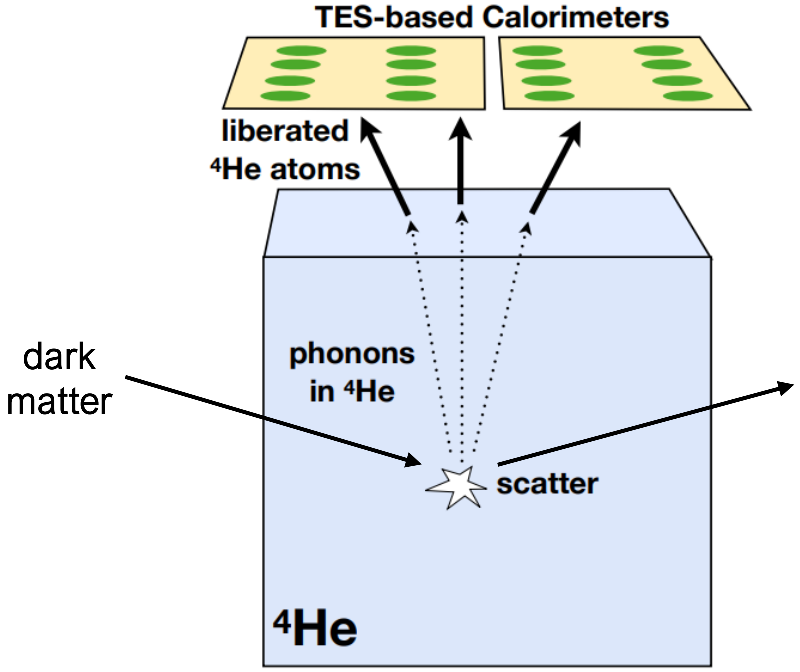
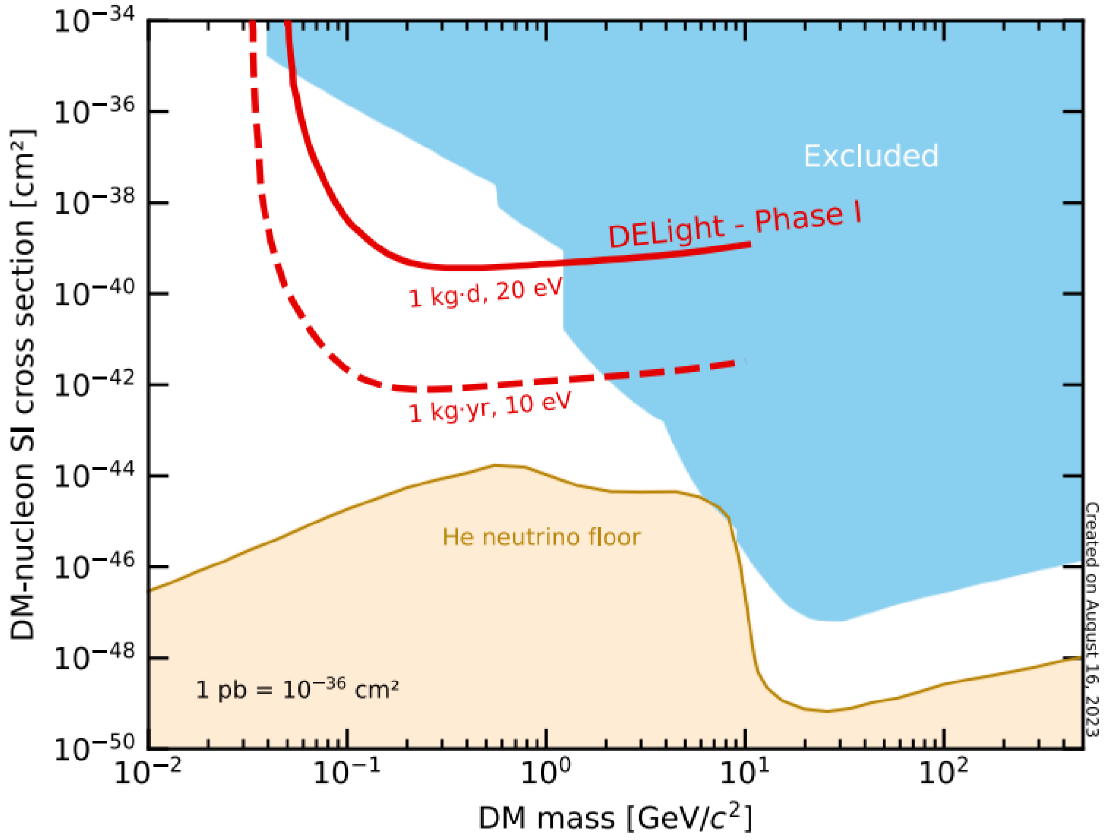


Figure: Herald Collaboration

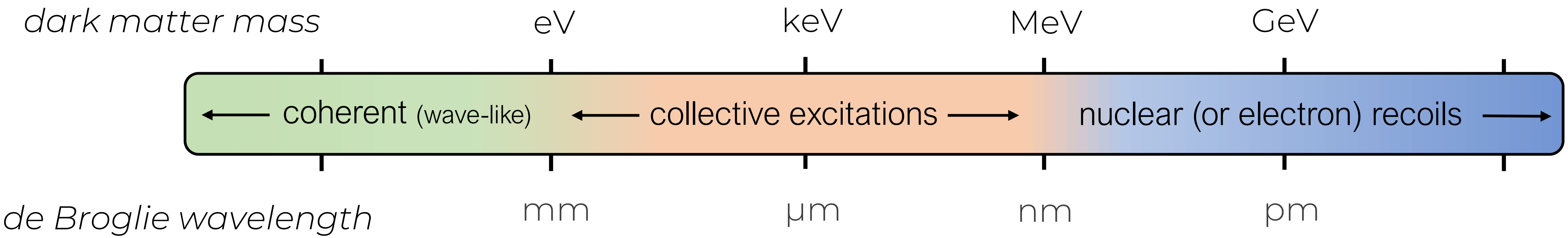
DELight Collaboration



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



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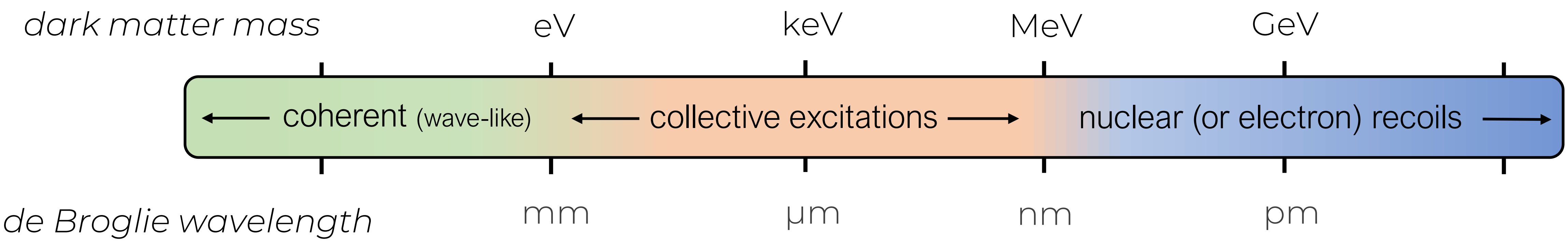
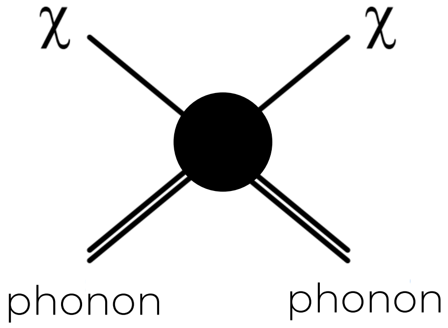


Sub-MeV mass DM interacts directly with *collective excitations* (*e.g. phonons*)



Superfluid ^{4}He collective modes (phonons/rotons)

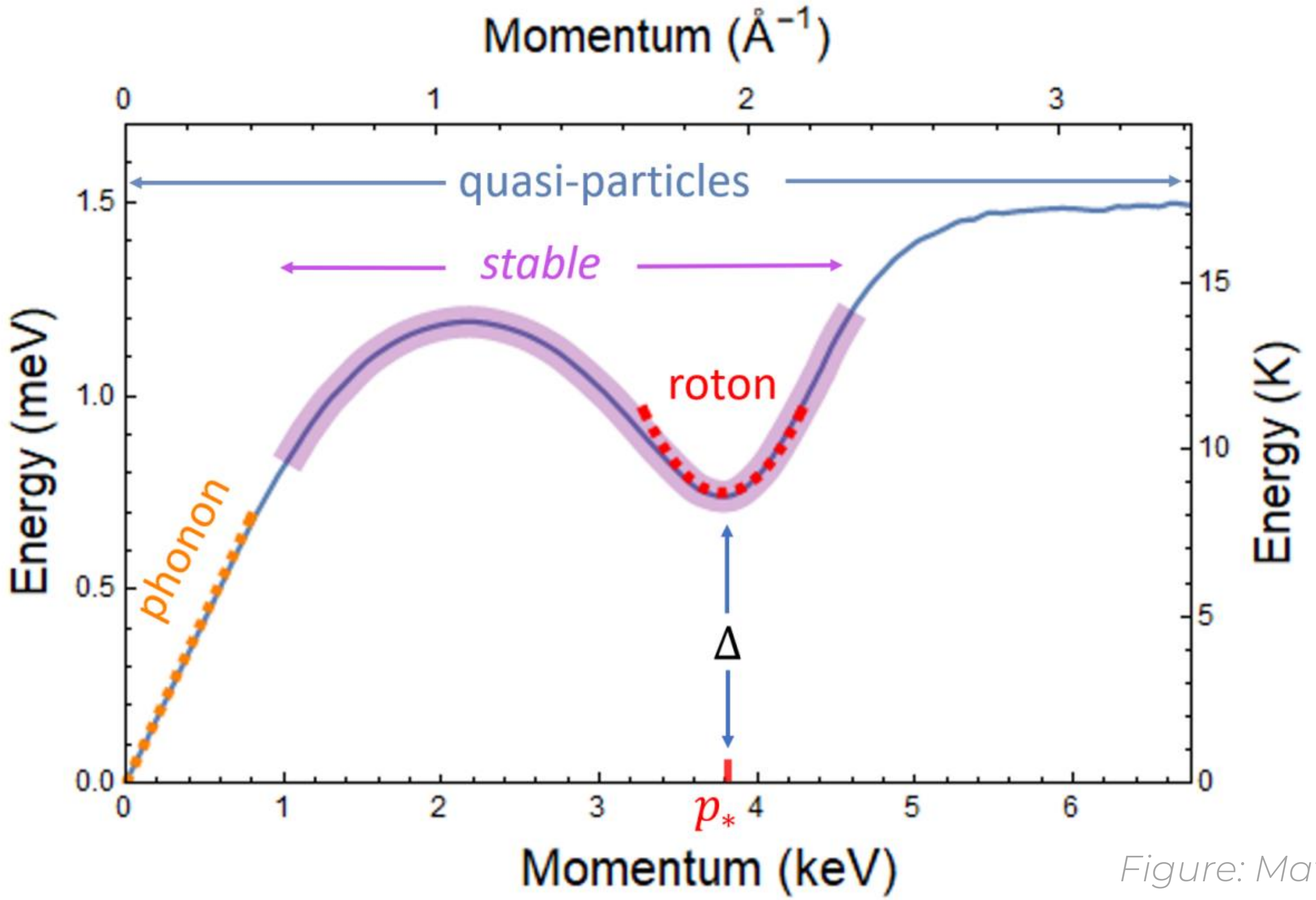


Figure: Matchev et. al '21

Long-lived/stable collective excitations

Superfluid phonon EFT

Son '02
Nicolis '11

Low-energy phonons in superfluid described by effective field theory

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

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

$\mu =$ chemical potential

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

$\mu =$ chemical potential

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

- Preserves linear combination $H - \mu N$

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Most general Lagrangian consistent with shift symmetry:

$$\mathcal{L} = P(X) \qquad X = \sqrt{\partial^\mu \Phi \partial_\mu \Phi}$$

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Most general Lagrangian consistent with shift symmetry:

$$\mathcal{L} = P(X) \qquad X = \sqrt{\partial^\mu \Phi \partial_\mu \Phi} \xrightarrow{\Phi = \mu t} \mu$$

"local chemical potential"

$P(X)$ is identified as the pressure of the superfluid

$$T^{\mu\nu}\big|_{\Phi=\mu t} = \mu n \delta_0^\mu \delta_0^\nu - \eta^{\mu\nu} P(\mu)$$

Superfluid phonon EFT

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Most general Lagrangian consistent with shift symmetry:

$$\mathcal{L} = P(X) \qquad\qquad X = \sqrt{\partial^\mu \Phi \partial_\mu \Phi}$$

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

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

Sound speed, couplings can be expressed in terms of derivatives of $P(\mu)$

Dark matter – phonon interactions

Acanfora, Esposito, Pelosa '19

Consider spin-independent DM-nucleon interaction

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

$$\mathcal{L}_{\text{int}} = g_\chi n \chi^2$$

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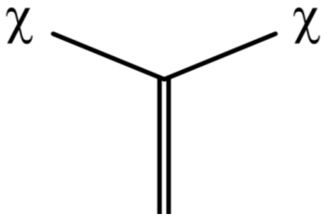
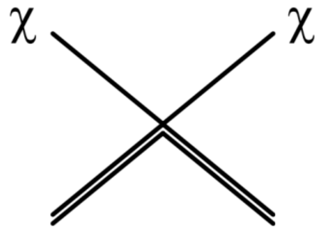
$$\mathcal{L}_{\text{int}} = g_\chi n \chi^2$$
$$= g_\chi \left(\bar{n} + \sqrt{\frac{\bar{n}}{\mu c_s^2}}\dot{\phi} + \lambda_3 \, (\nabla\phi)^2 + \ldots \right) \chi^2$$





Detecting phonons - cavity optomechanics

Basic idea: optomechanical systems can be single phonon detectors

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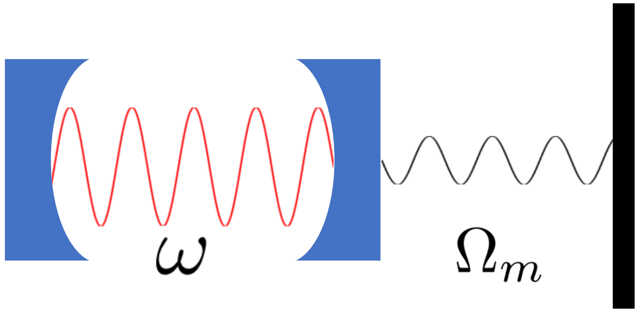
Toy model:



phonon

photon

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

Optical resonance frequency depends on cavity length

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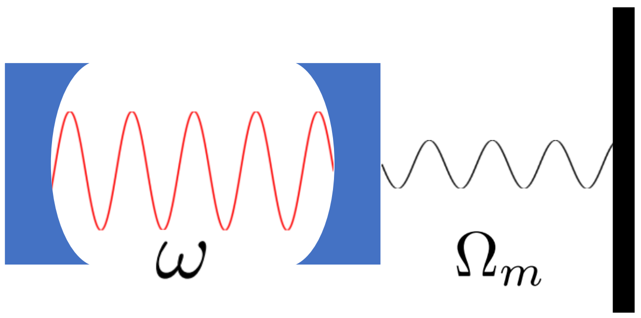

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photon

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

$$= \Omega_m b_m^\dagger b_m + \left(\omega_0 + g_0 (b_m + b_m^\dagger)\right) a^\dagger a$$

optomechanical coupling

Superfluid cavity optomechanics

superfluid ^4He filled optical cavity

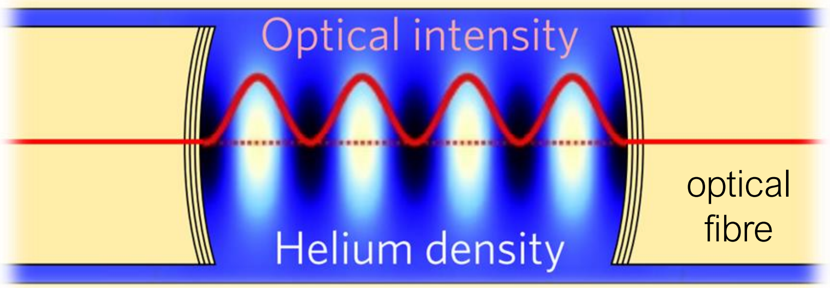


Figure: Kashkanova+ '16

Mechanical mode: phonons in superfluid

Optomechanical interaction due to change in refractive index

Superfluid cavity optomechanics

superfluid ^{4}He filled optical cavity

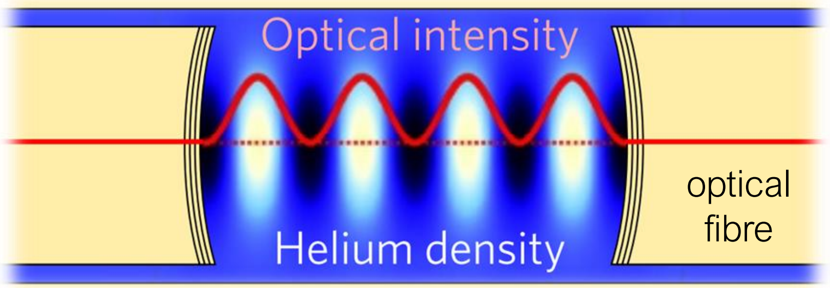
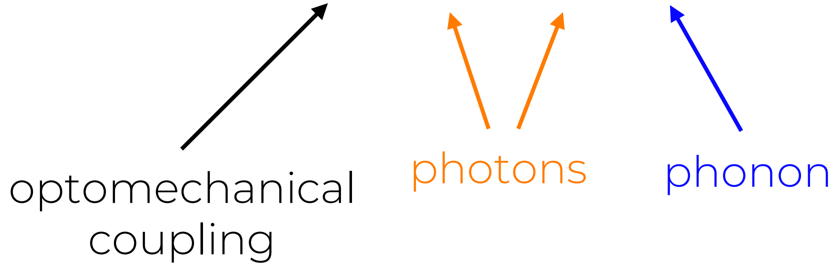


Figure: Kashkanova+ '16

$$H_{\mathrm{OM}} = -g_0 (a^\dagger_{\gamma_1} a_{\gamma_2} b^\dagger_m + \mathrm{h.c.})$$



Energy-momentum conservation:

$$\Omega_m = \omega_{\gamma_2} - \omega_{\gamma_1} \ll \omega_{\gamma_{1,2}}$$

$$\lambda_m \approx \lambda_\gamma / 2$$

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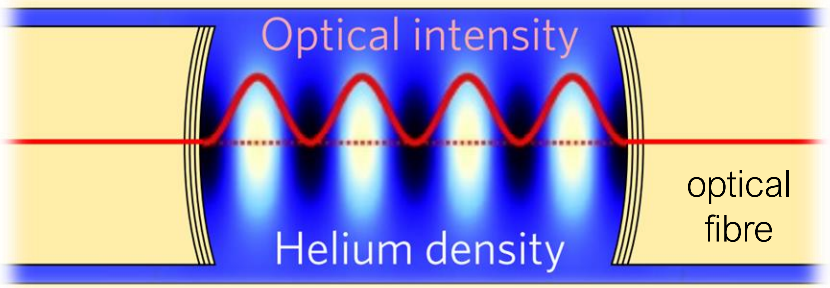

Figure: Kashkanova+ '16

Optomechanical interaction converts ~μeV phonons into detectable ~eV photons

$$H_{\rm OM} = -g_0(a^\dagger_{\gamma_1} a_{\gamma_2} b^\dagger_m + \text{h.c.})$$
$$\to -g_0\sqrt{N_1}(a_{\gamma_2} b^\dagger_m + \text{h.c.})$$

pump laser enhances small g_0

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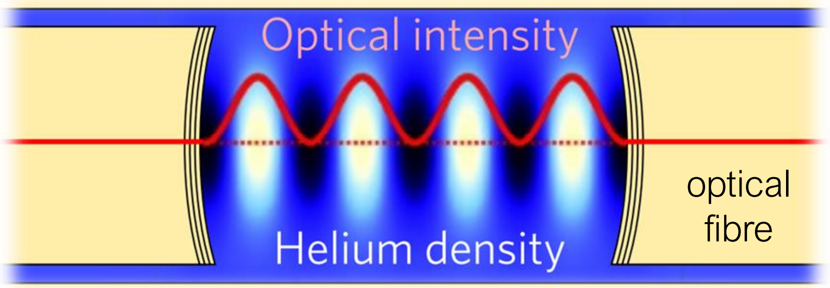

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Optomechanical systems have demonstrated μeV phonon counting

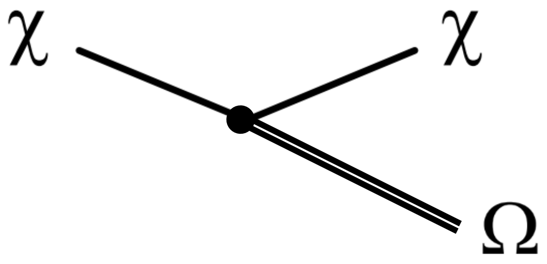
(e.g. Patil et. al. '22)

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

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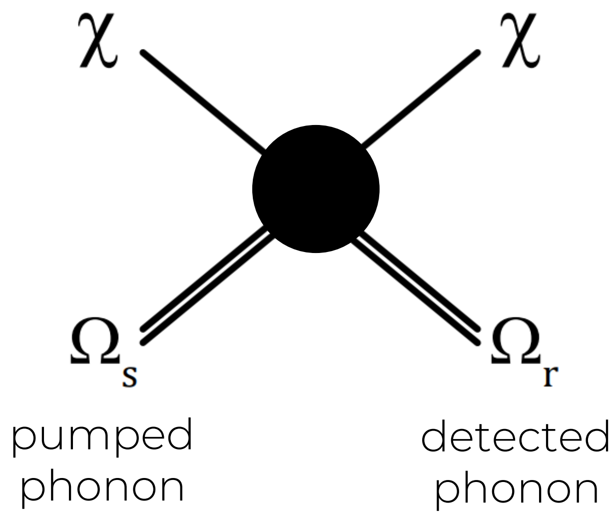
Solution: *Phonon lasing*

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



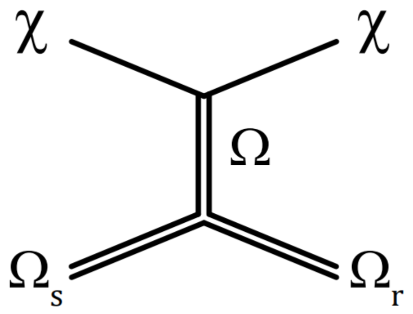
Scattering rate

Initial state phonon number density

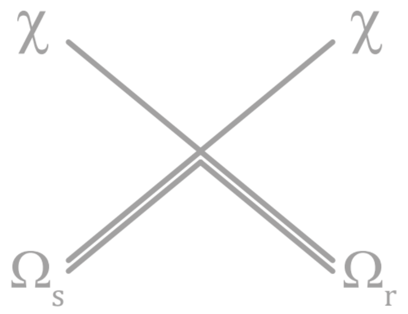
$$R \propto \frac{\rho_\chi \sigma_{\chi n}}{m_\chi^3} n_s Q^2 \frac{\Omega_r \Omega_s}{m_{\text{He}}^2 c_s^4} (1+\gamma_G)^2$$

Acoustic quality factor: $Q = \Omega_m / \Gamma_m$

3-phonon coupling



resonantly enhanced



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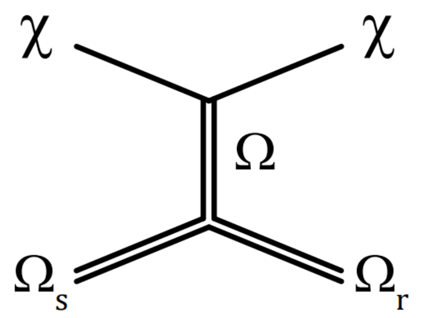
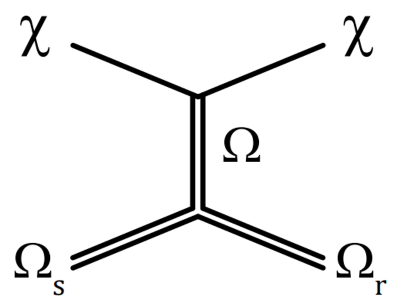


Scattering is between specific initial *and final* phonon states:

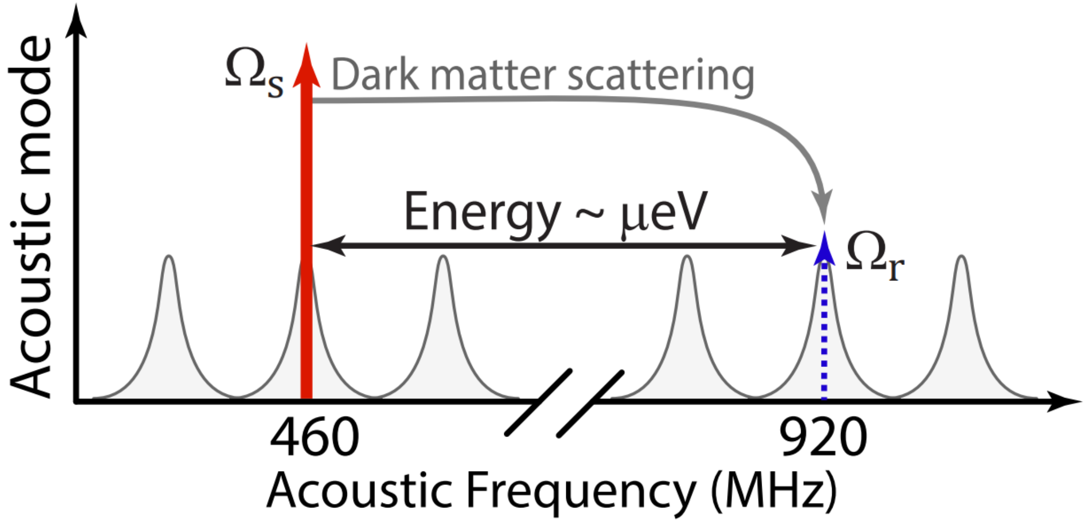
I. Scattering is at fixed momentum transfer: $q = (\Omega_r - \Omega_m)/c_s \sim \mathrm{eV}$

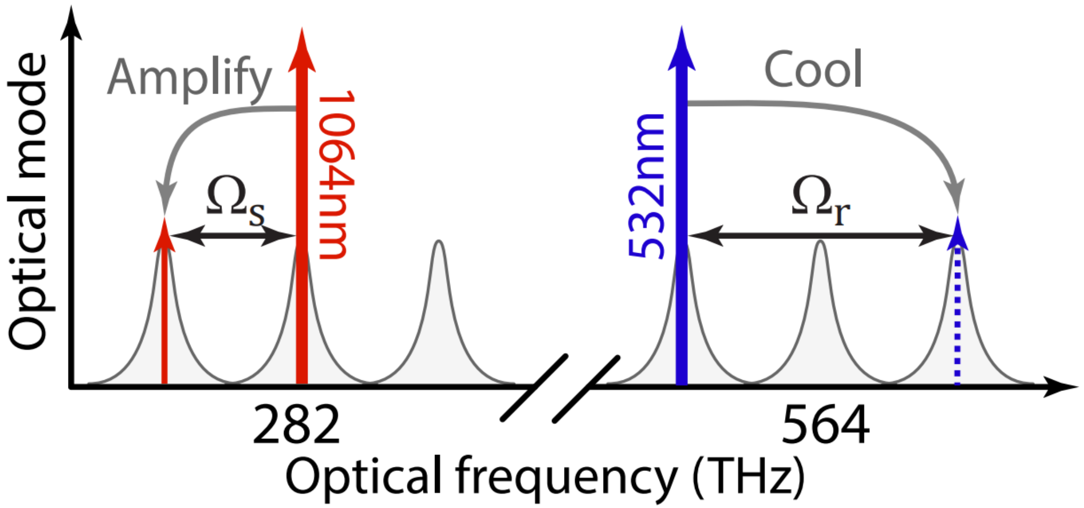
II. Event rate *doesn't* scale with detector volume (resolved mode regime)

Optomechanical detection



Dark matter detector requires optomechanical control of *two* acoustic modes





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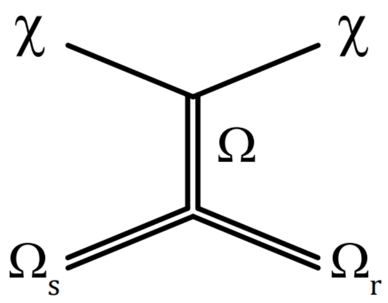
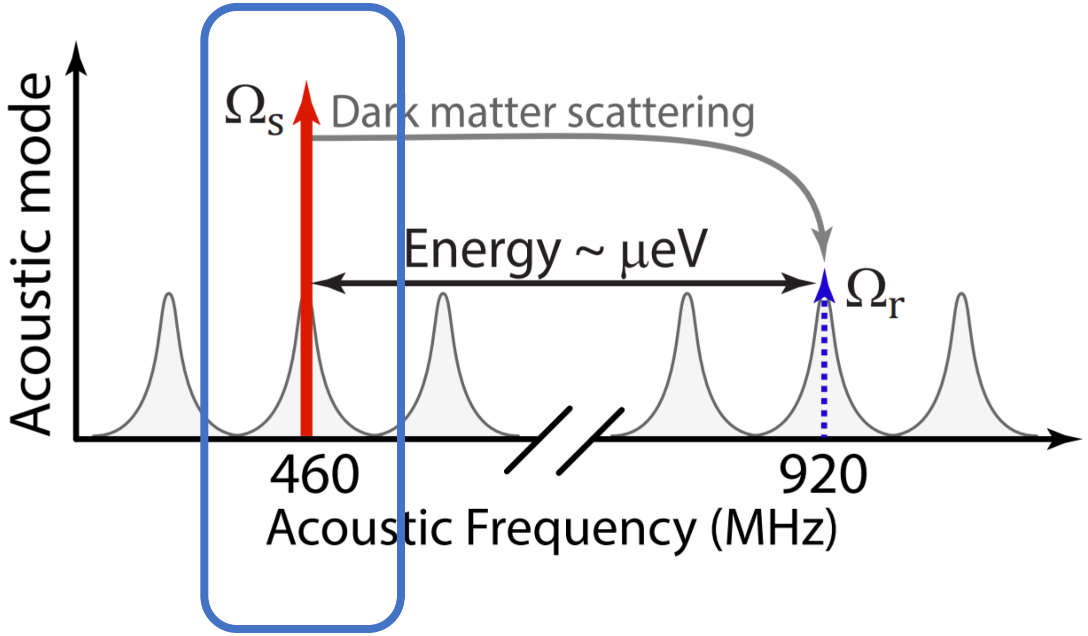
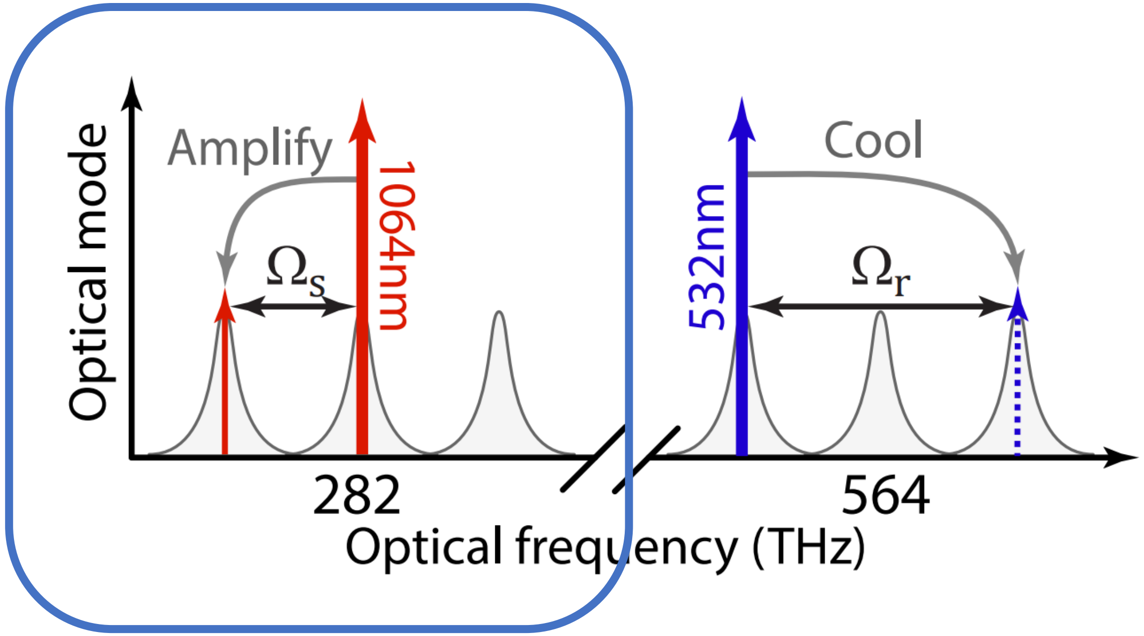


1 *Phonon lasing*

Lower-energy phonon mode Ω_s populated via optomechanical interaction





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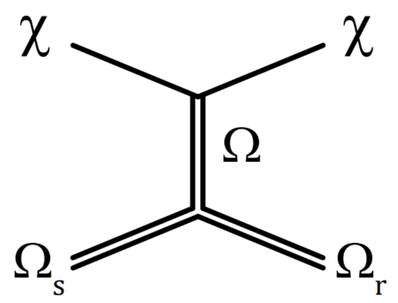
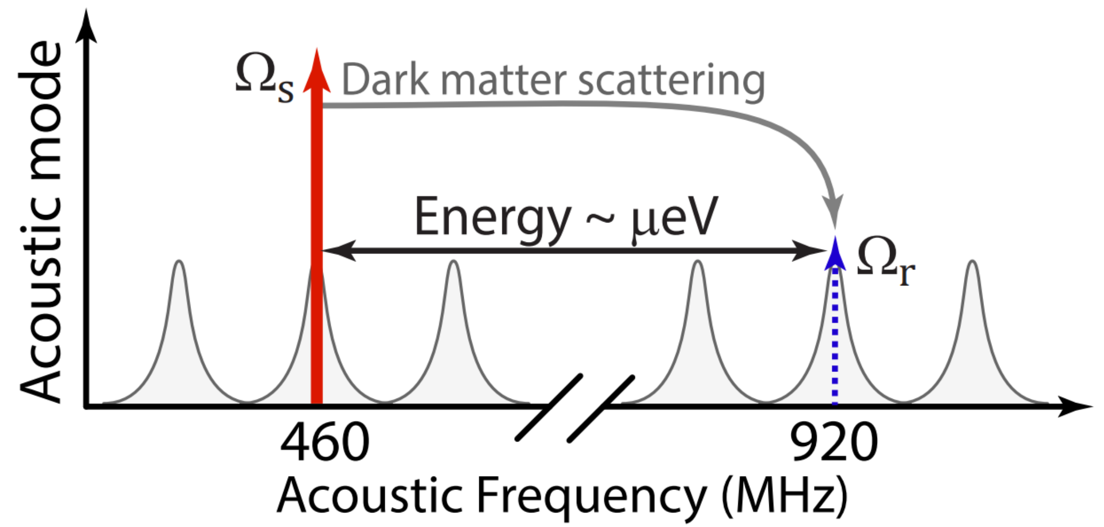
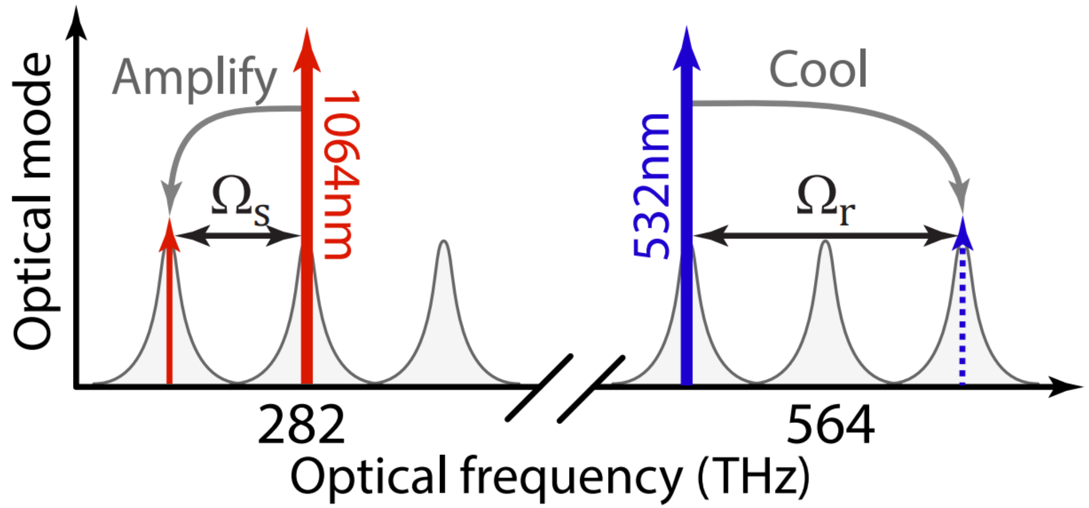


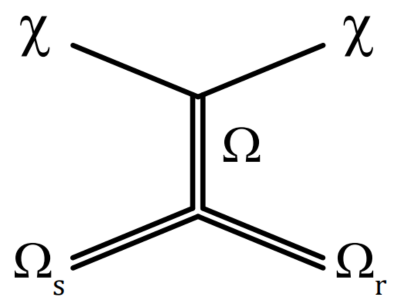
2 *Scattering*

Stimulated dark matter scattering excites higher energy phonon mode



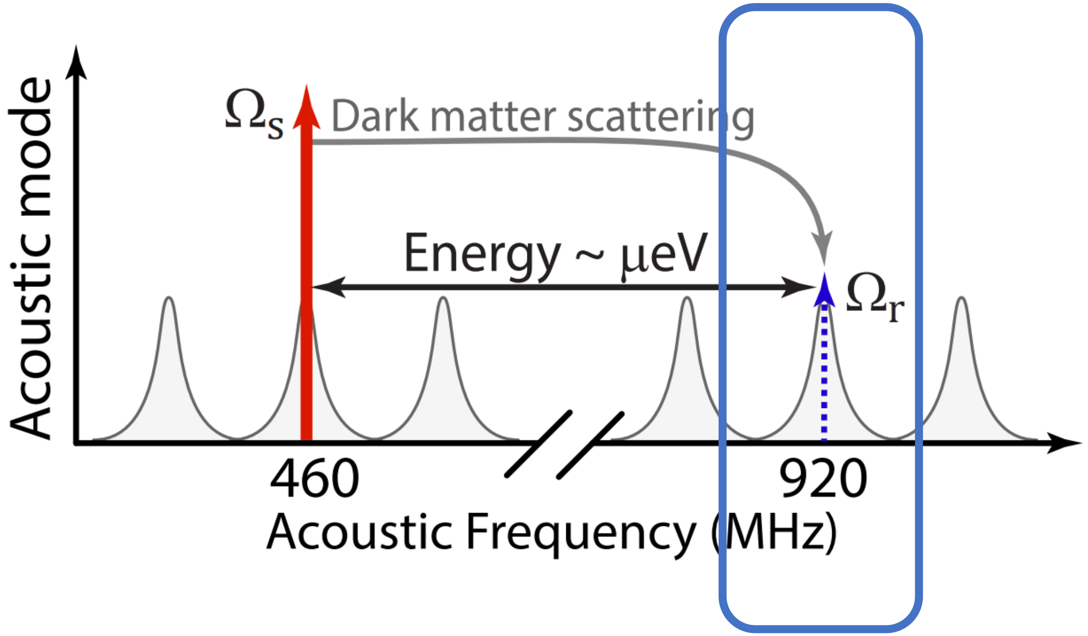


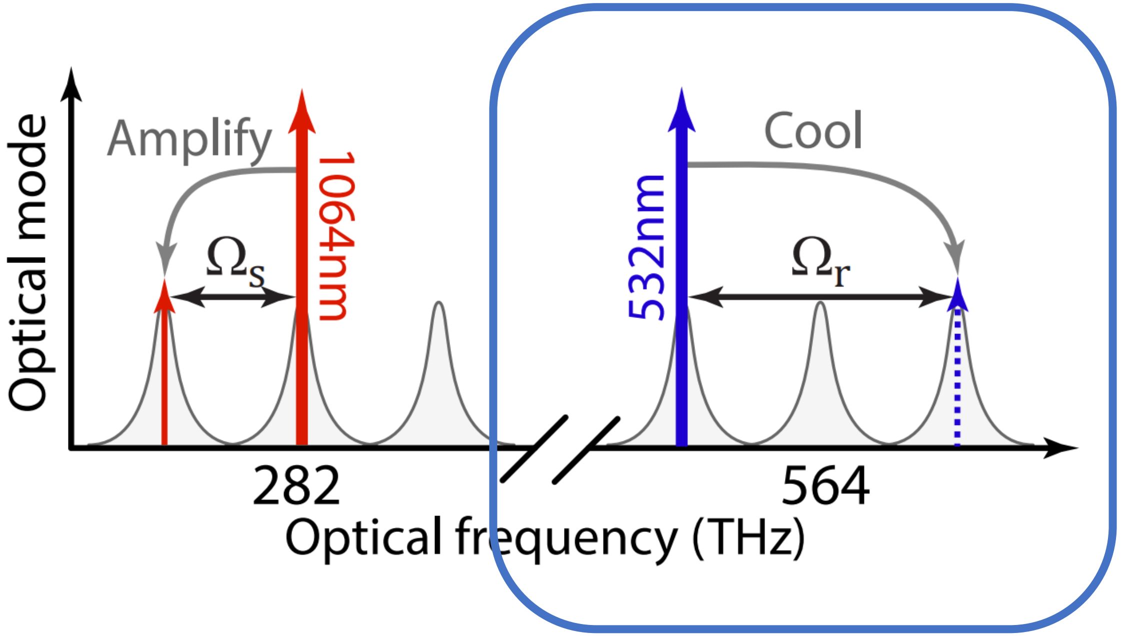
Optomechanical detection



3 *Conversion & amplification*

Optomechanical conversion of Ω_r phonon to higher energy photon





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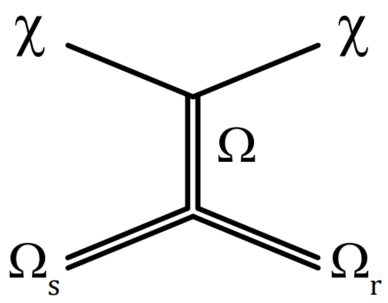
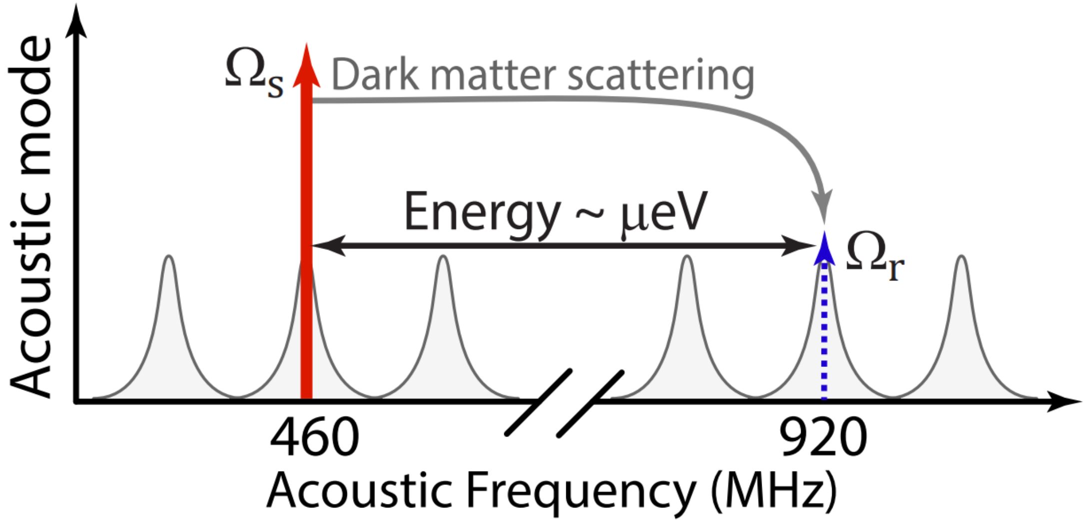
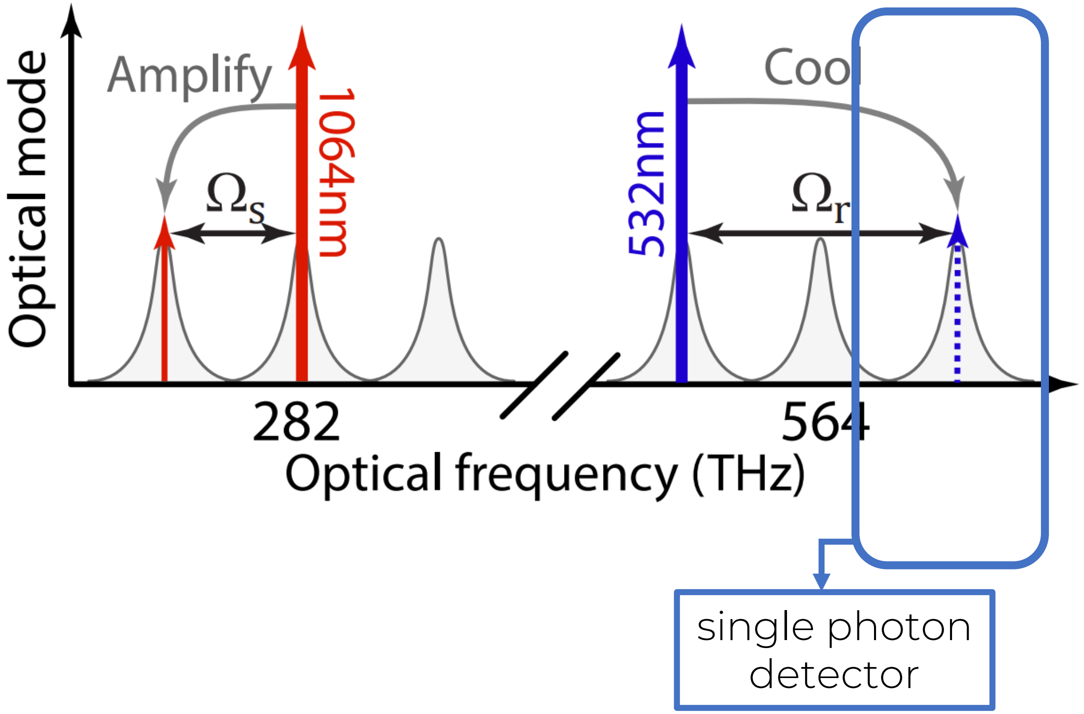


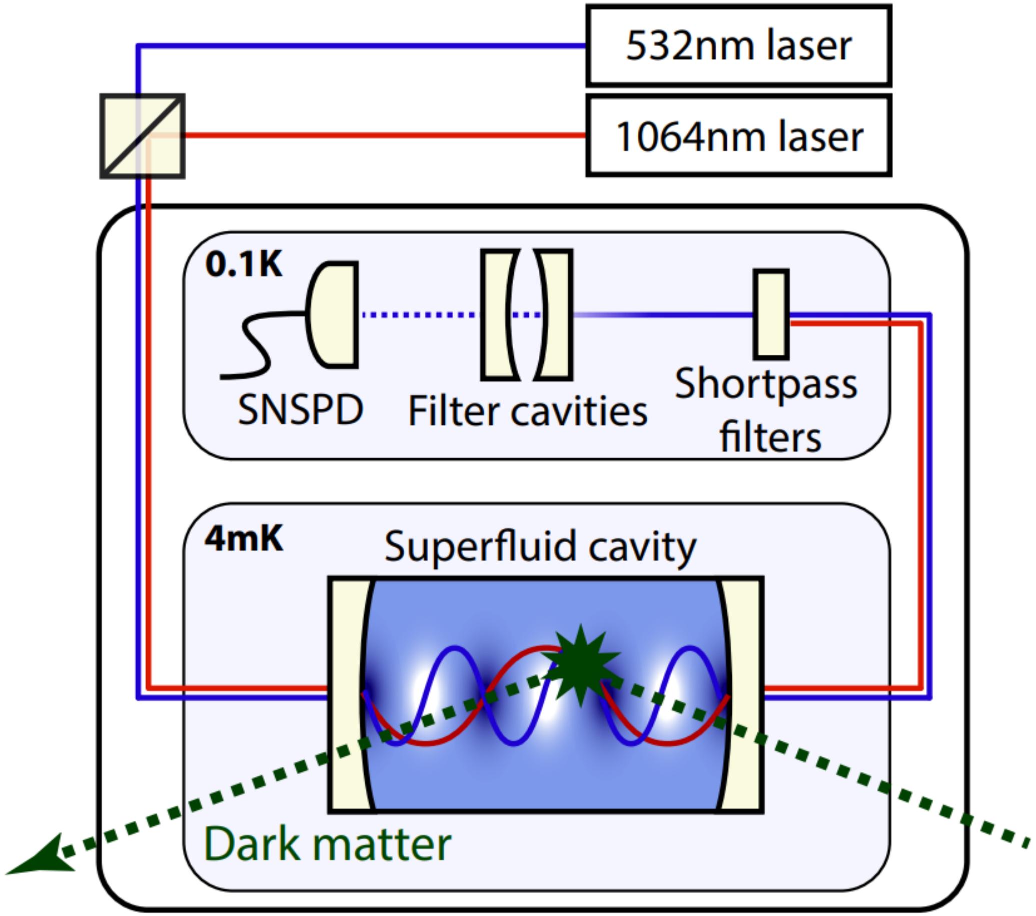
4 *Detection*

Photon detected by single photon detector (SNSPD)





ODIN: Optomechanical Dark-matter INstrument



cavity dimensions ~ 30cm x 0.7mm

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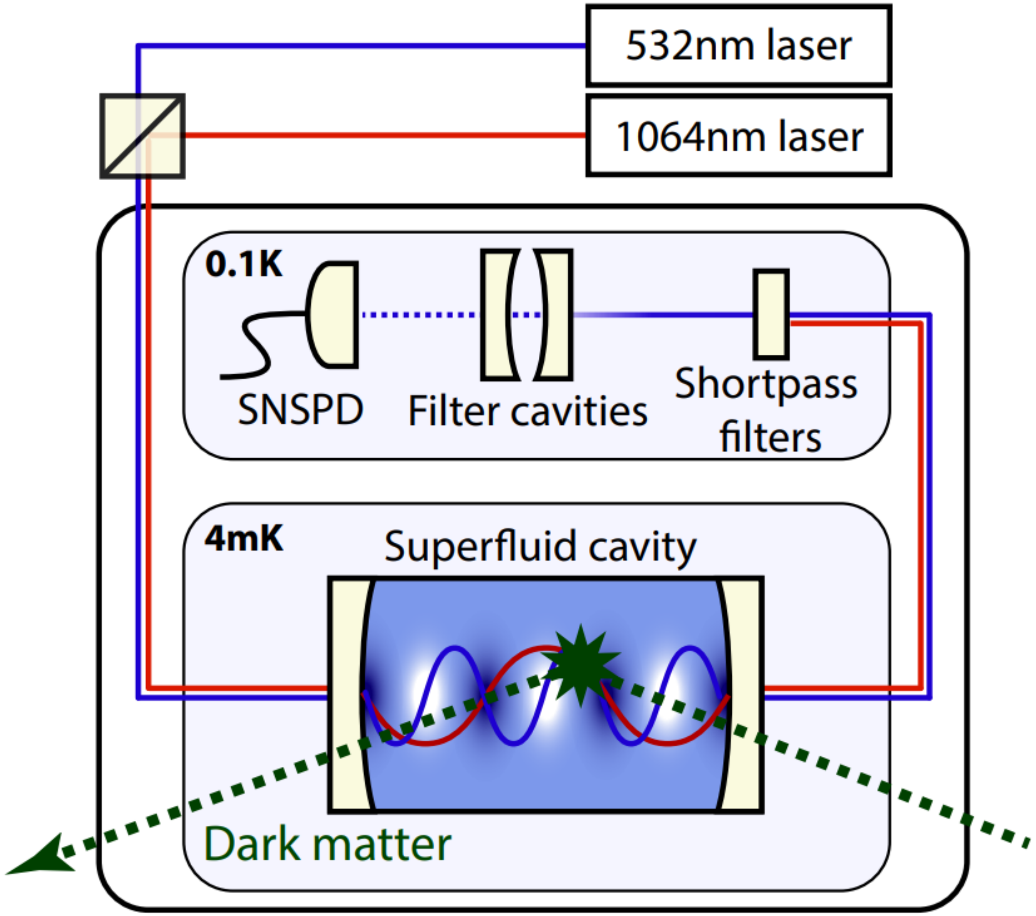


cavity dimensions ~ 30cm x 0.7mm

Main detector backgrounds:

- *Thermal phonons*

  (10^{-5} Hz at T = 4mK and Q = 10^{10})

- *SNSPD dark counts*

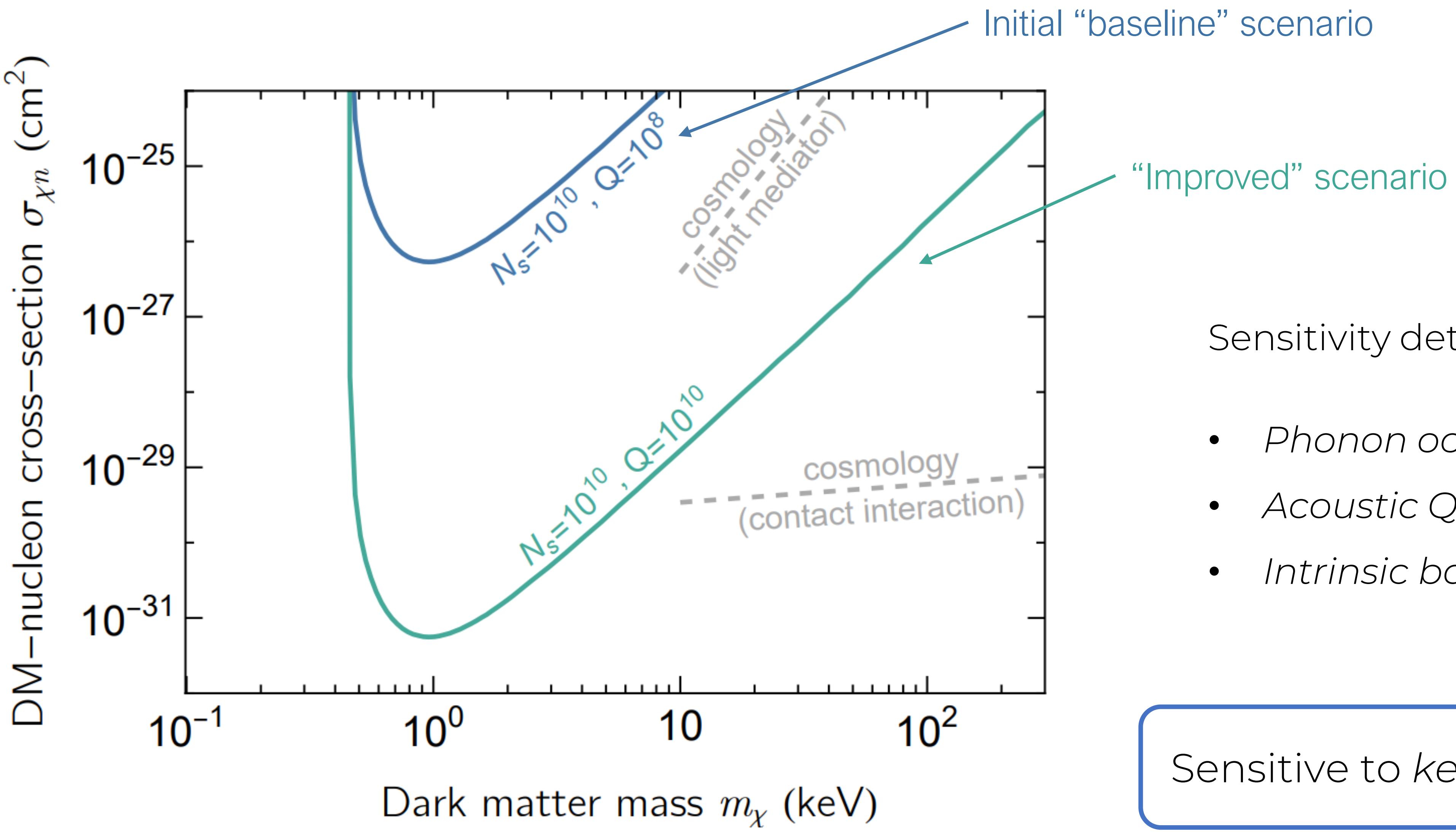
  (~6×10^{-6} Hz)

- *Incomplete filtering of pump lasers*

  (especially 532nm, supressed with filter cavities)

Expected background rate ~1 event/day

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: