Superfluid optomechanics for dark matter direct detection

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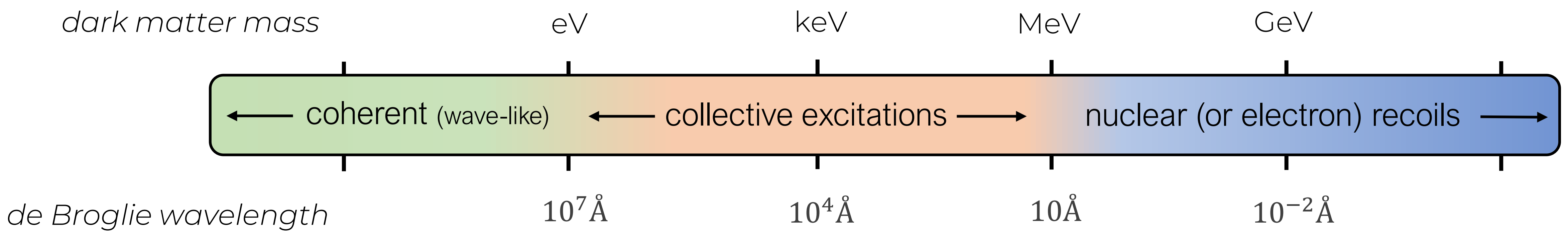
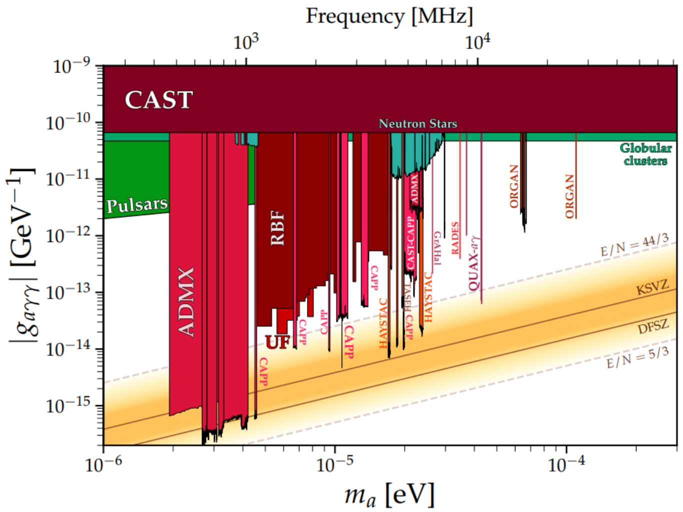
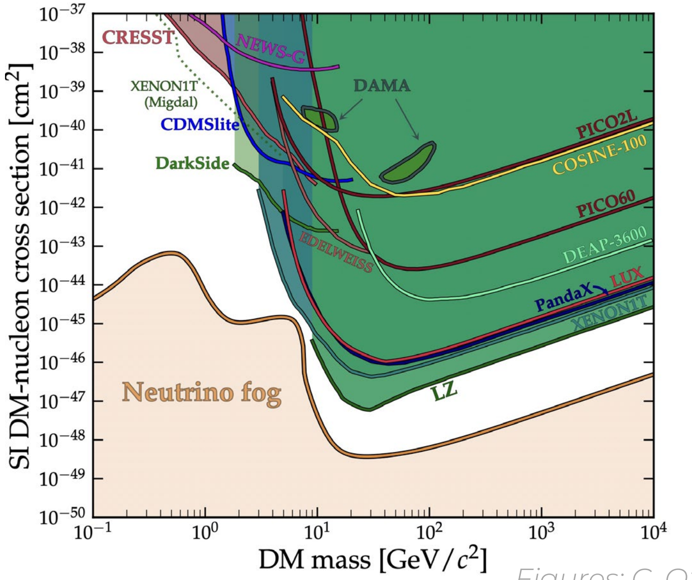
Direct detection regimes

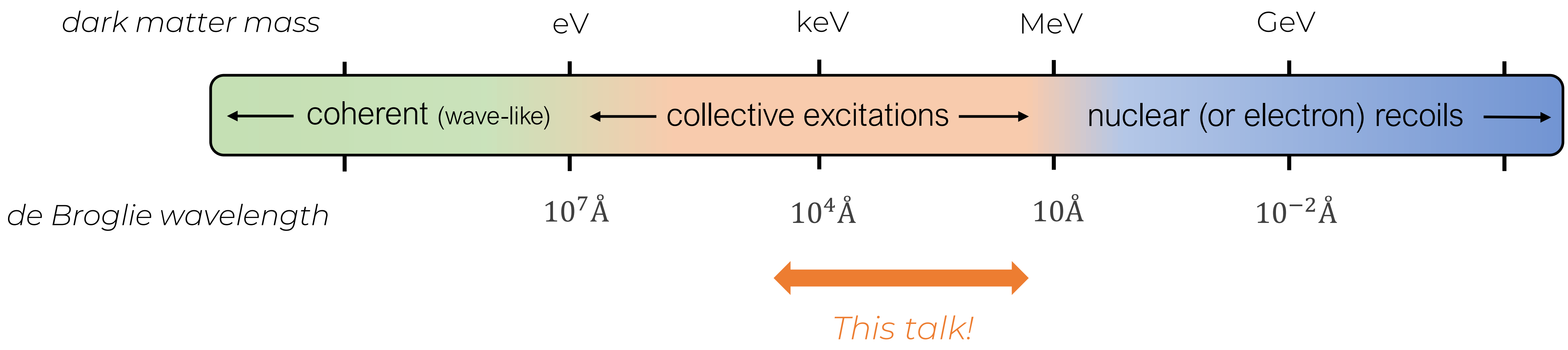






Figures: C. O'Hare

Direct detection regimes



Direct detection in the keV – MeV regime:

- Relevant degrees of freedom are collective modes, not atoms
- Need new detectors with sub-eV thresholds

Superfluid ^{4}He

- Long-lived/stable collective modes (phonons/rotons)

How to detect these low-energy phonons?

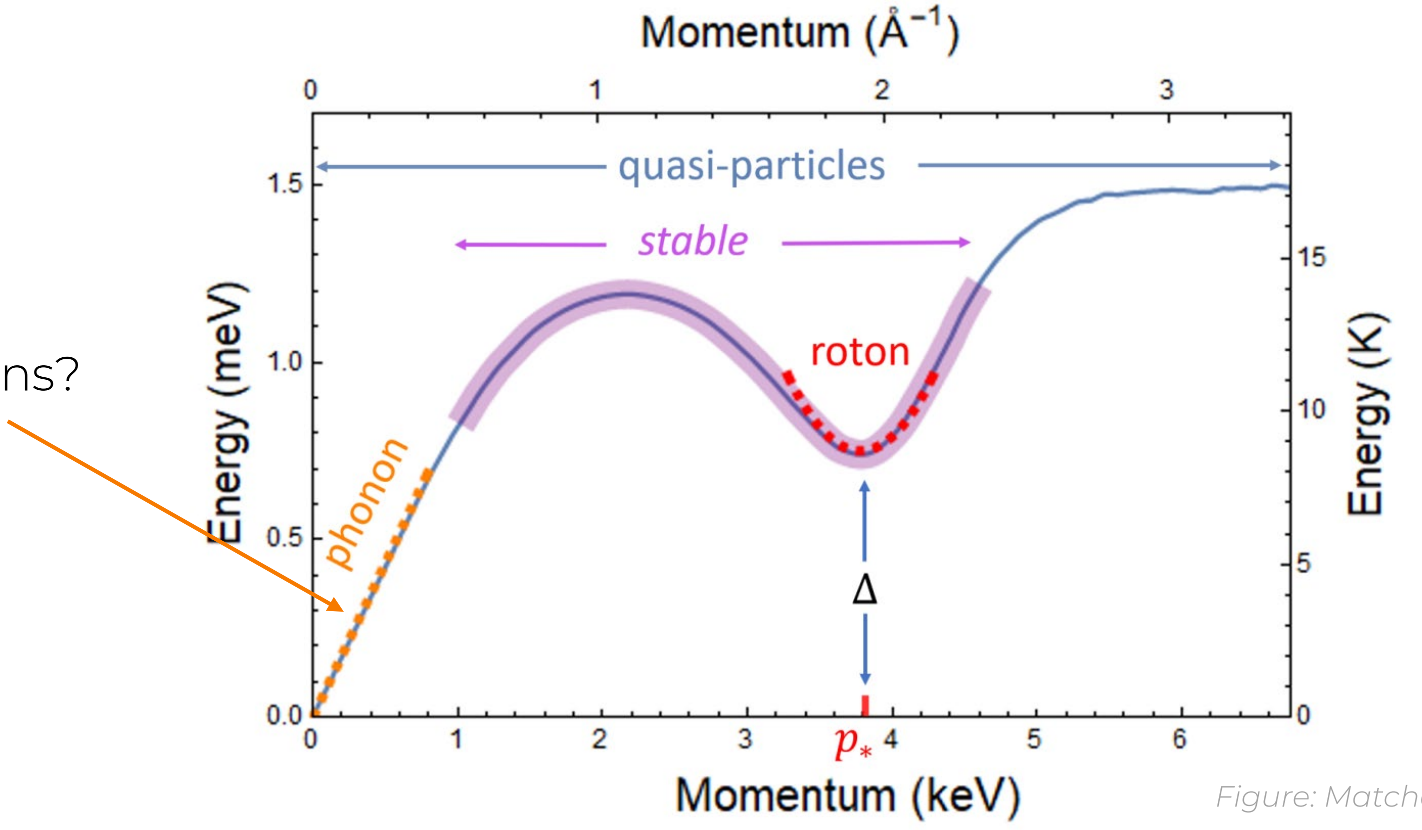


Figure: Matchev+ '21

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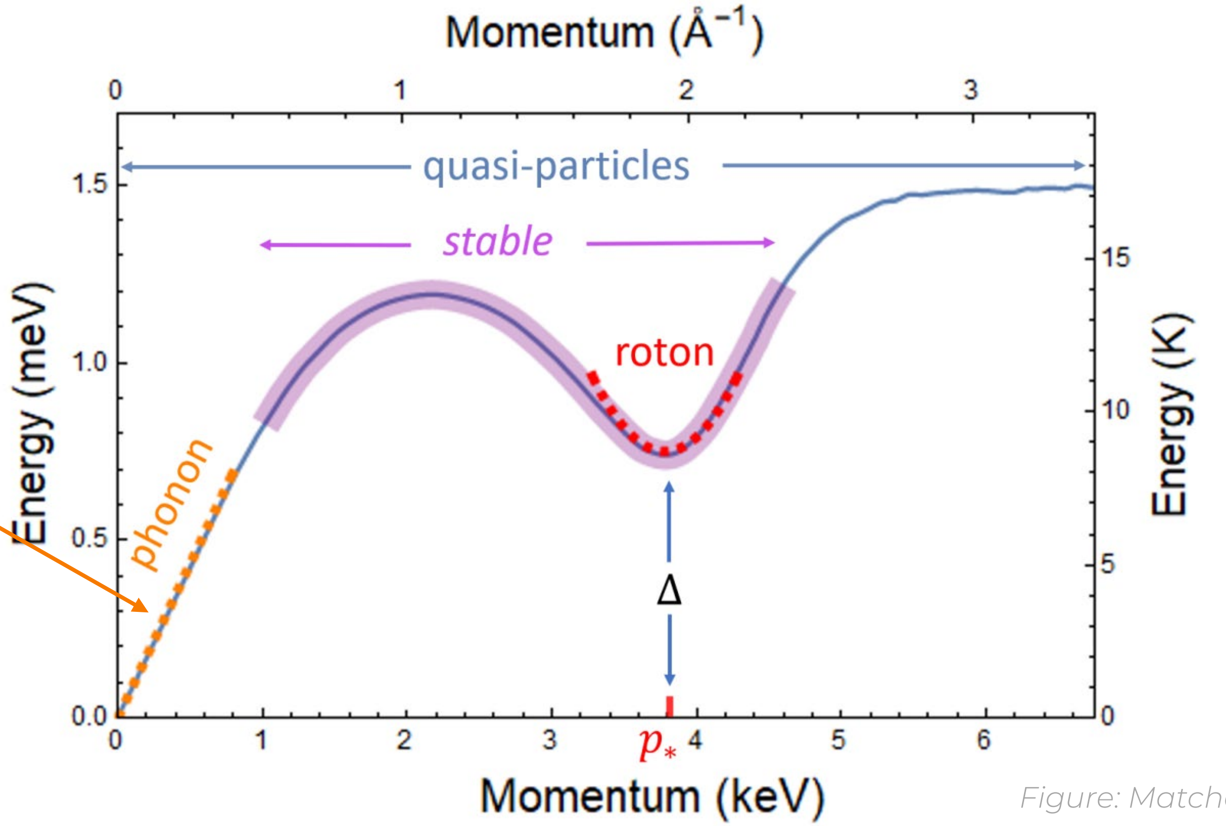


Figure: Matchev+ '21

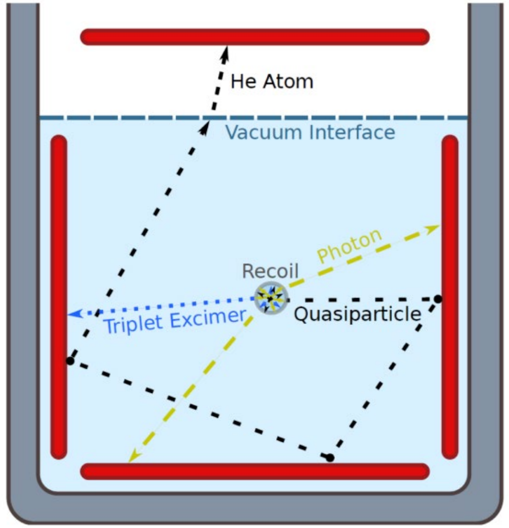


Figure: Hertel+ '18

- Existing proposals use quantum evaporation signal in bulk superfluid *(HeRALD, DELight)*

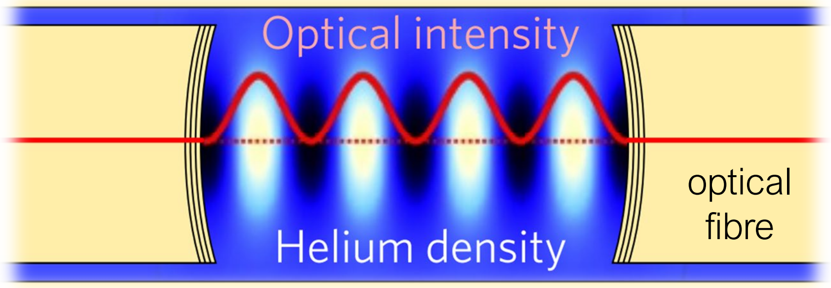
Single phonon detection

Basic idea: Superfluid optomechanical systems are *single phonon detectors*

Coupling between acoustic (density) modes and optical modes:

➡ convert ~μeV phonons into detectable ~eV photons

Figure: Kashkanova+ '16



superfluid filled optical cavity

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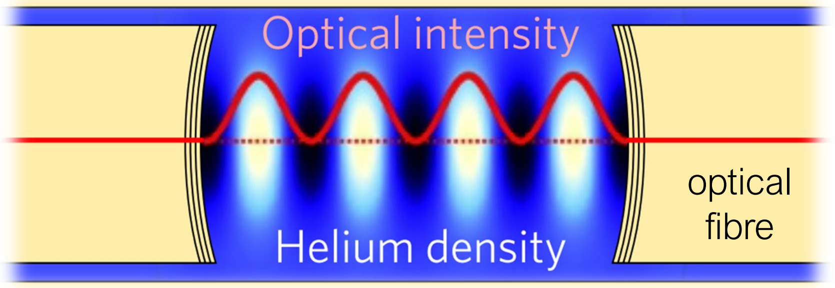


superfluid filled optical cavity

Optomechanical systems have demonstrated μeV phonon counting (e.g. Patil et. al. '22)

Superfluid optomechanics

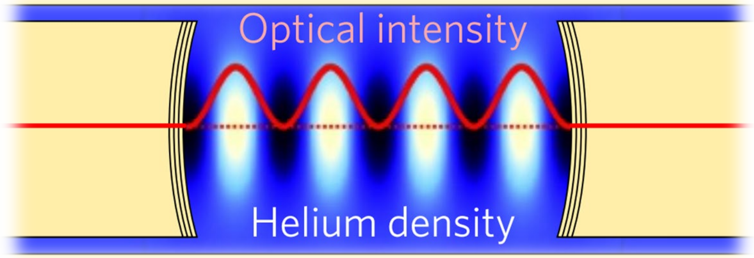
At quantum level described by the Hamiltonian:

photons phonon

$$H_{\rm OM} = -g_0(a_{\gamma_1} a^\dagger_{\gamma_2} b_m + a^\dagger_{\gamma_1} a_{\gamma_2} b^\dagger_m)$$

optomechanical coupling

Figure: Kashkanova+ '16



Superfluid optomechanics

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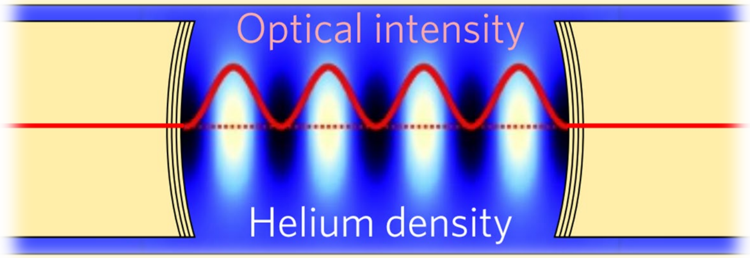
$$H_{\rm OM} = -g_0(a_{\gamma_1} a^\dagger_{\gamma_2} b_m + a^\dagger_{\gamma_1} a_{\gamma_2} b^\dagger_m)$$
$$\to -g_0\sqrt{N_1}(a^\dagger_{\gamma_2} b_m + a_{\gamma_2} b^\dagger_m)$$

pump laser enhances small g_0

Figure: Kashkanova+ '16



Acoustic mode energy/wavelength related to optical modes:

$$\Omega_m = \pm(\omega_{\gamma_1} - \omega_{\gamma_2})$$
$$\lambda_m \approx \lambda_\gamma/2$$

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

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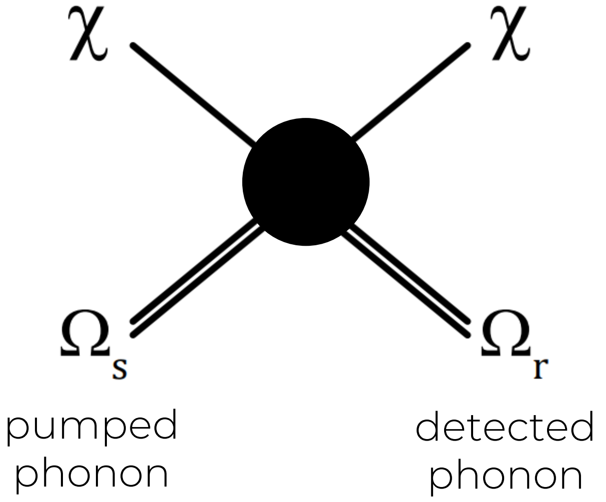


Solution: Phonon lasing

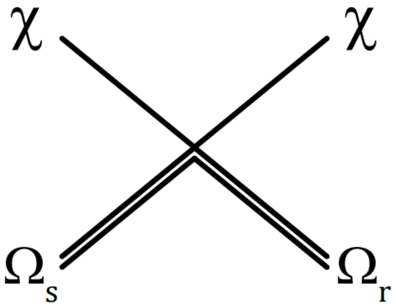
➡ Stimulated scattering rate proportional to phonon occupation number

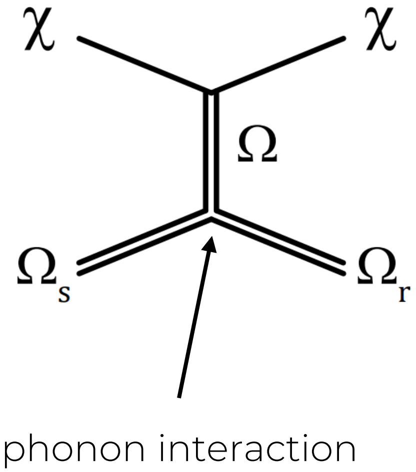
Dark matter – phonon scattering

Low-energy phonons in superfluid described by effective field theory (EFT)

- Phonons are Nambu-Goldstone bosons of U(1) symmetry breaking

Two contributions to stimulated scattering process:





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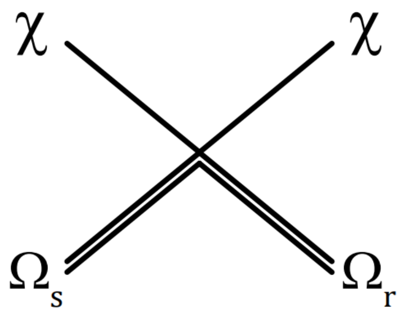
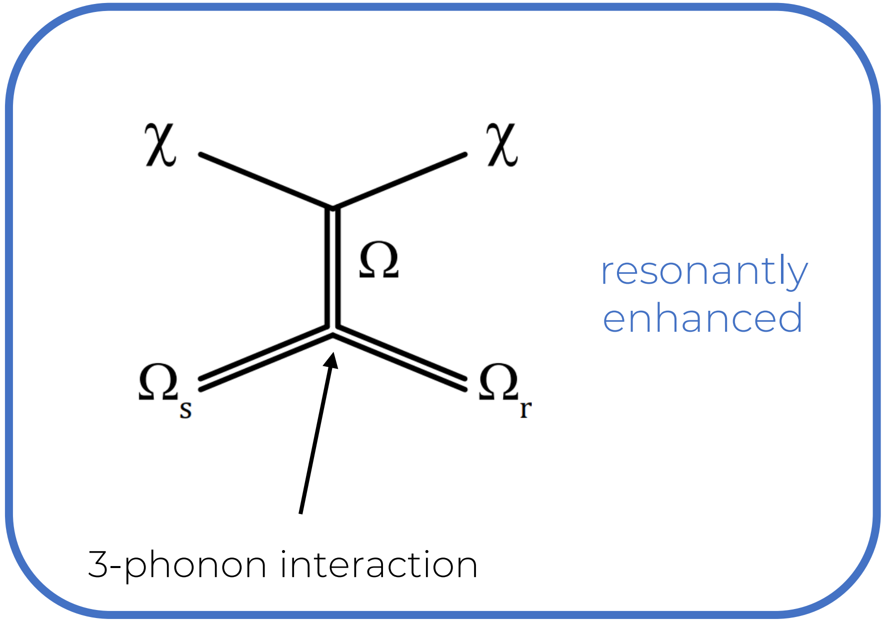




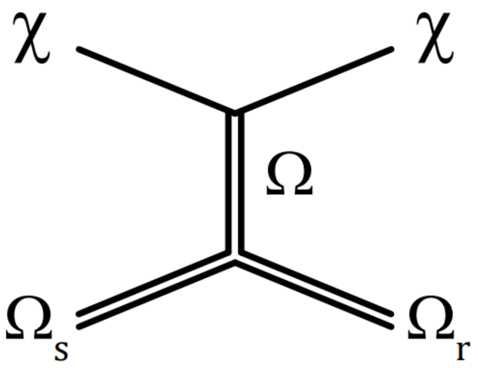
Scattering rate

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 interaction
(Grüneisen parameter)



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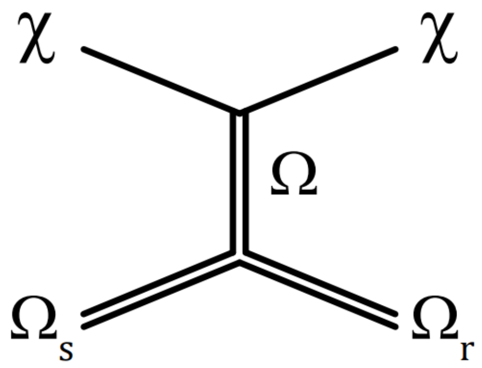
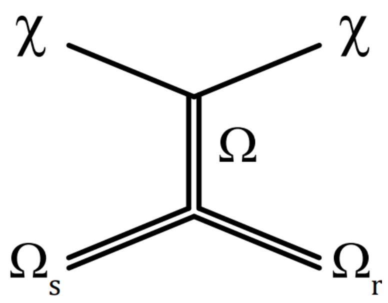


Scattering is between specific initial *and final* phonon states:

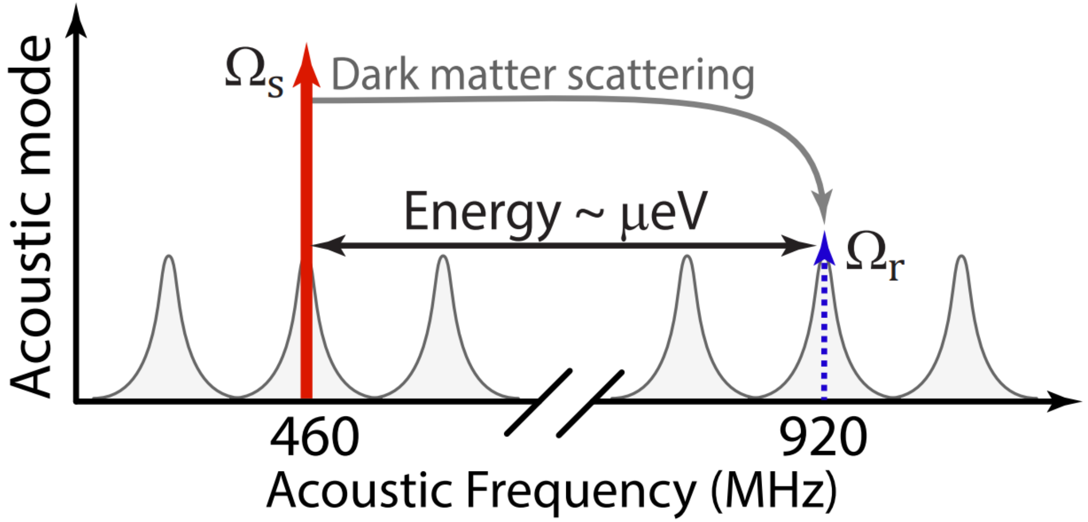
I. Scattering is at fixed momentum transfer: $q = (\Omega_r - \Omega_m)/c_s$

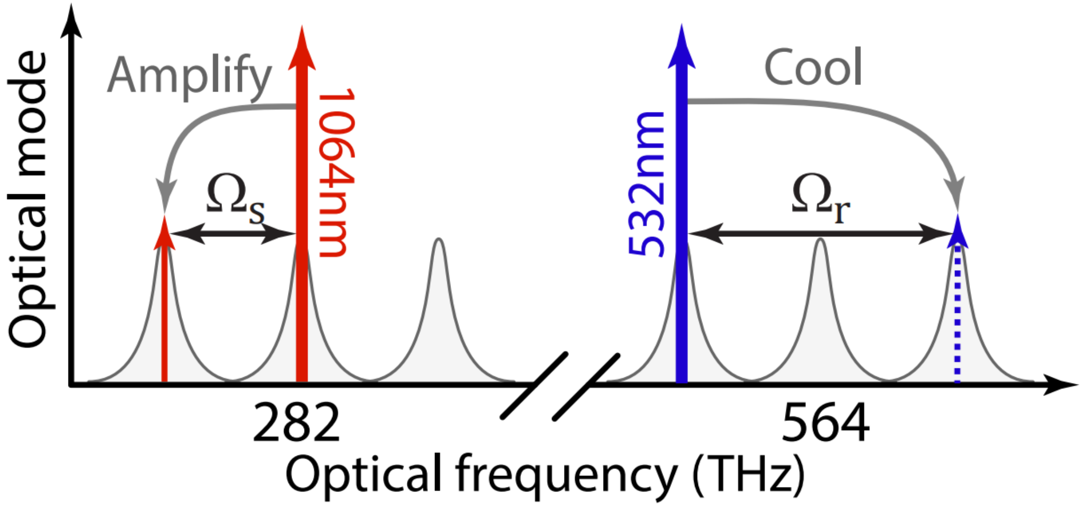
II. Event rate is *independent* of detector volume!

Optomechanical detection

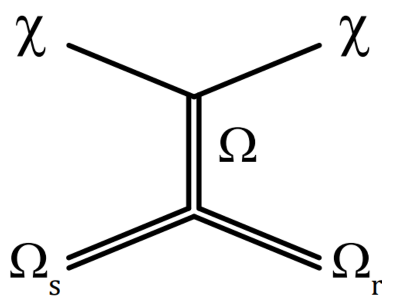


Dark matter detector requires optomechanical control of *two* acoustic modes

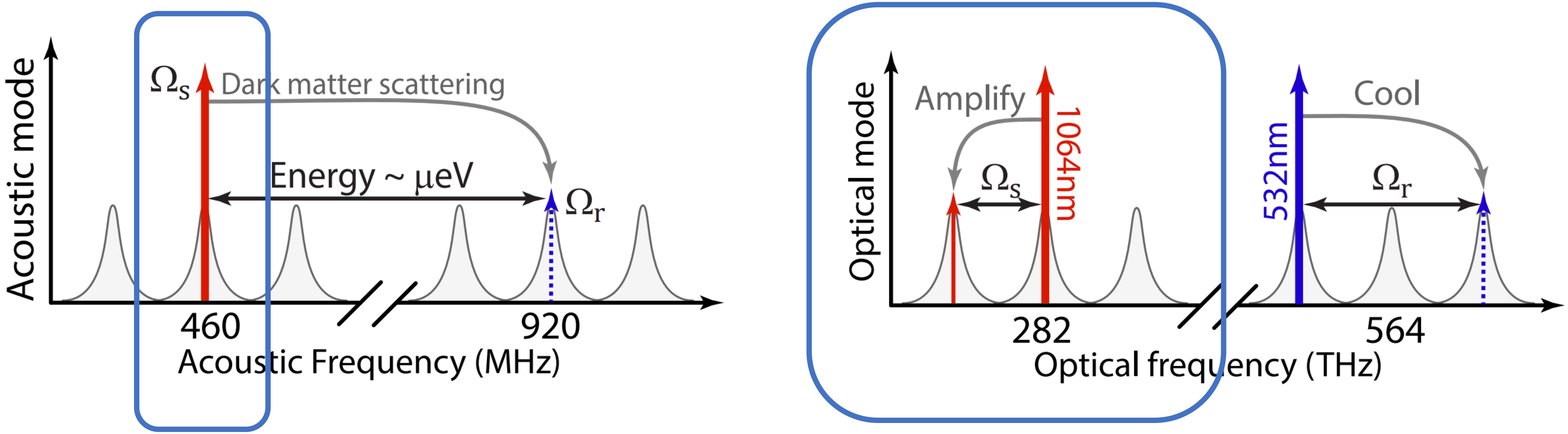




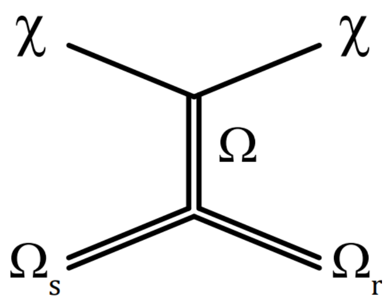
Optomechanical detection



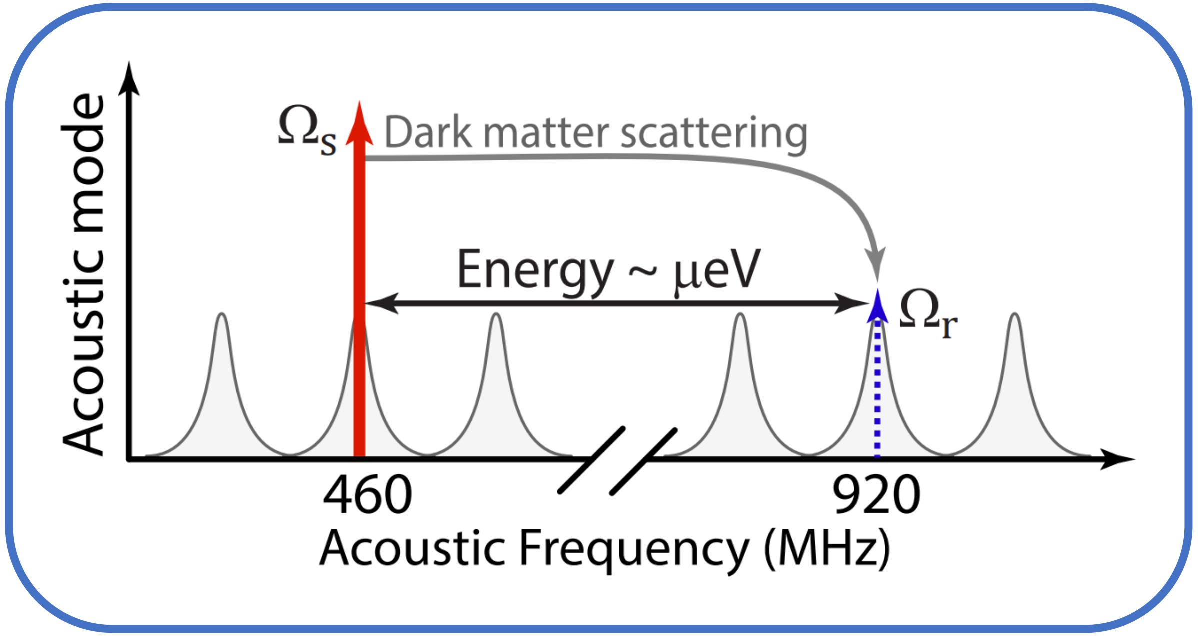
1 Lower-energy phonon mode Ω_s populated via optomechanical interaction

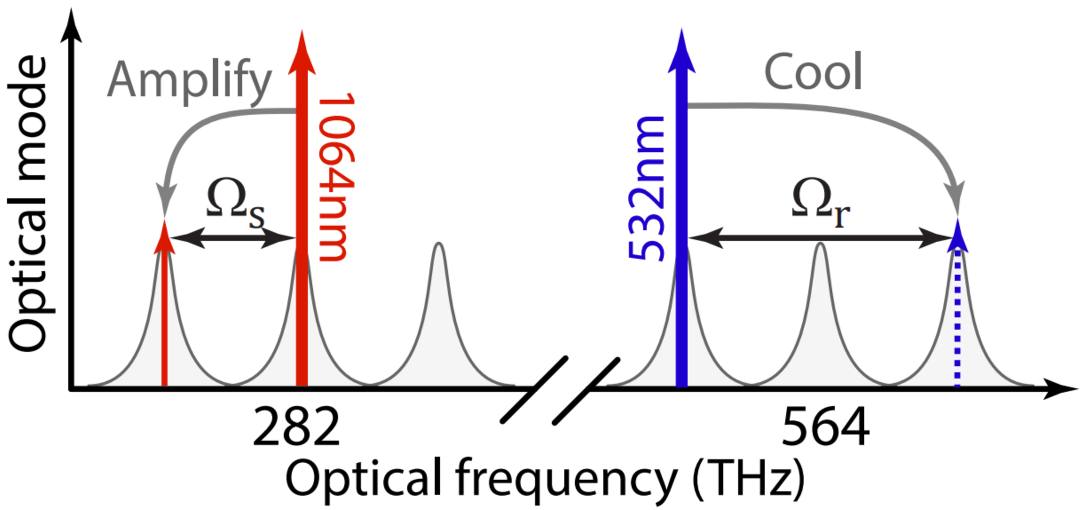


Optomechanical detection

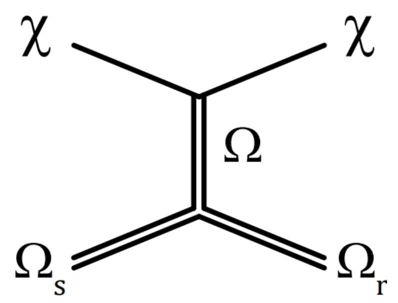


(2) Stimulated dark matter scattering excites higher energy phonon mode $\Omega_s \to \Omega_r$

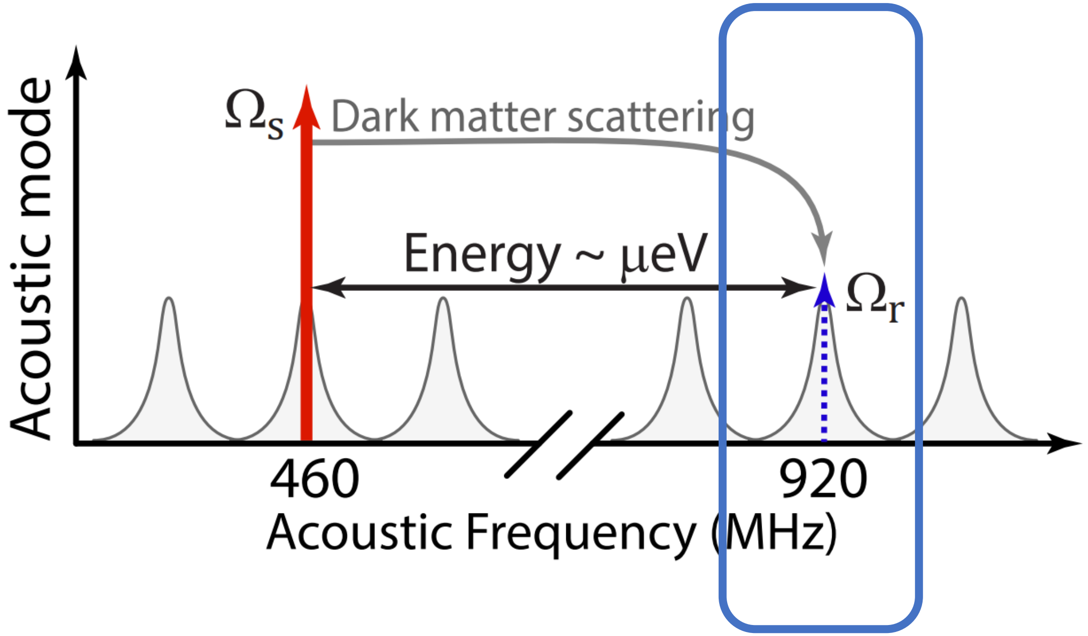


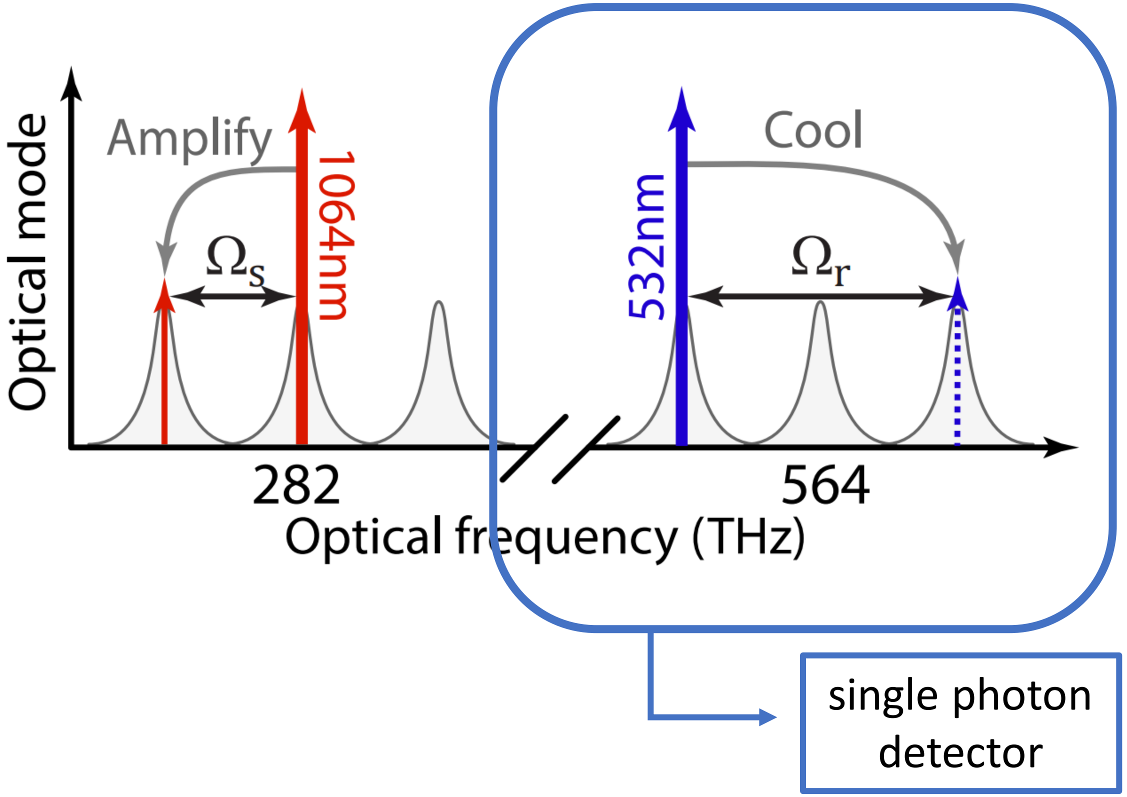


Optomechanical detection

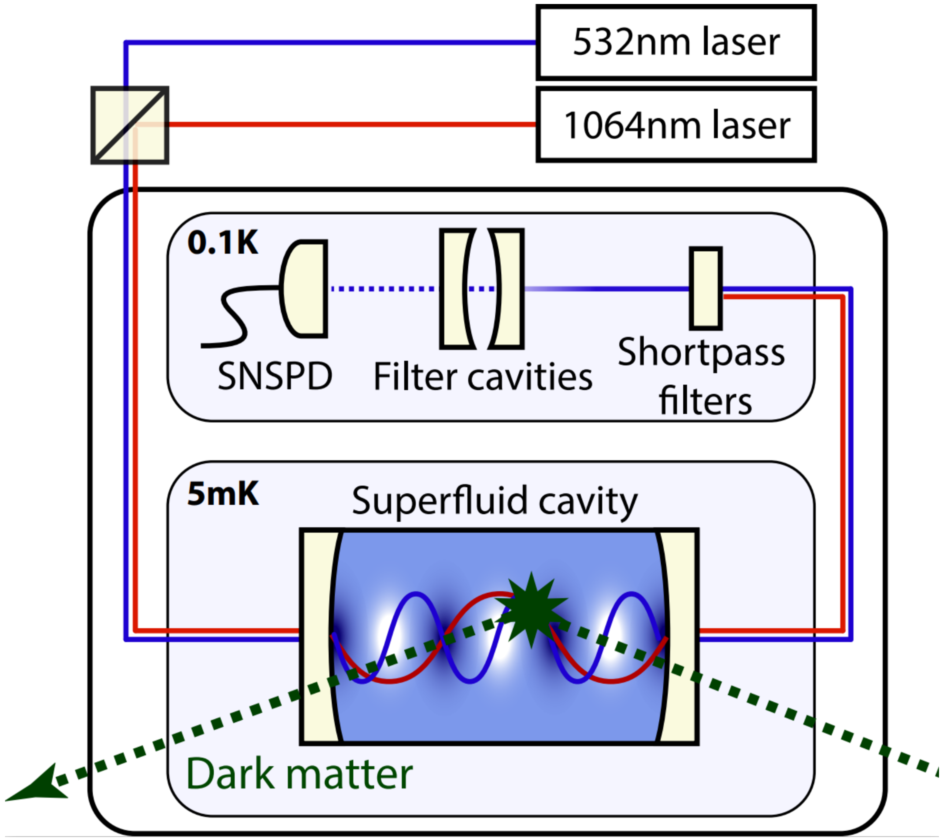


3. Optomechanical conversion of Ω_r phonon to photon that is detected with SNSPD





Schematic experiment



Important detector backgrounds:

- *Thermal phonons*

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

- *Dark counts in SNSPD*

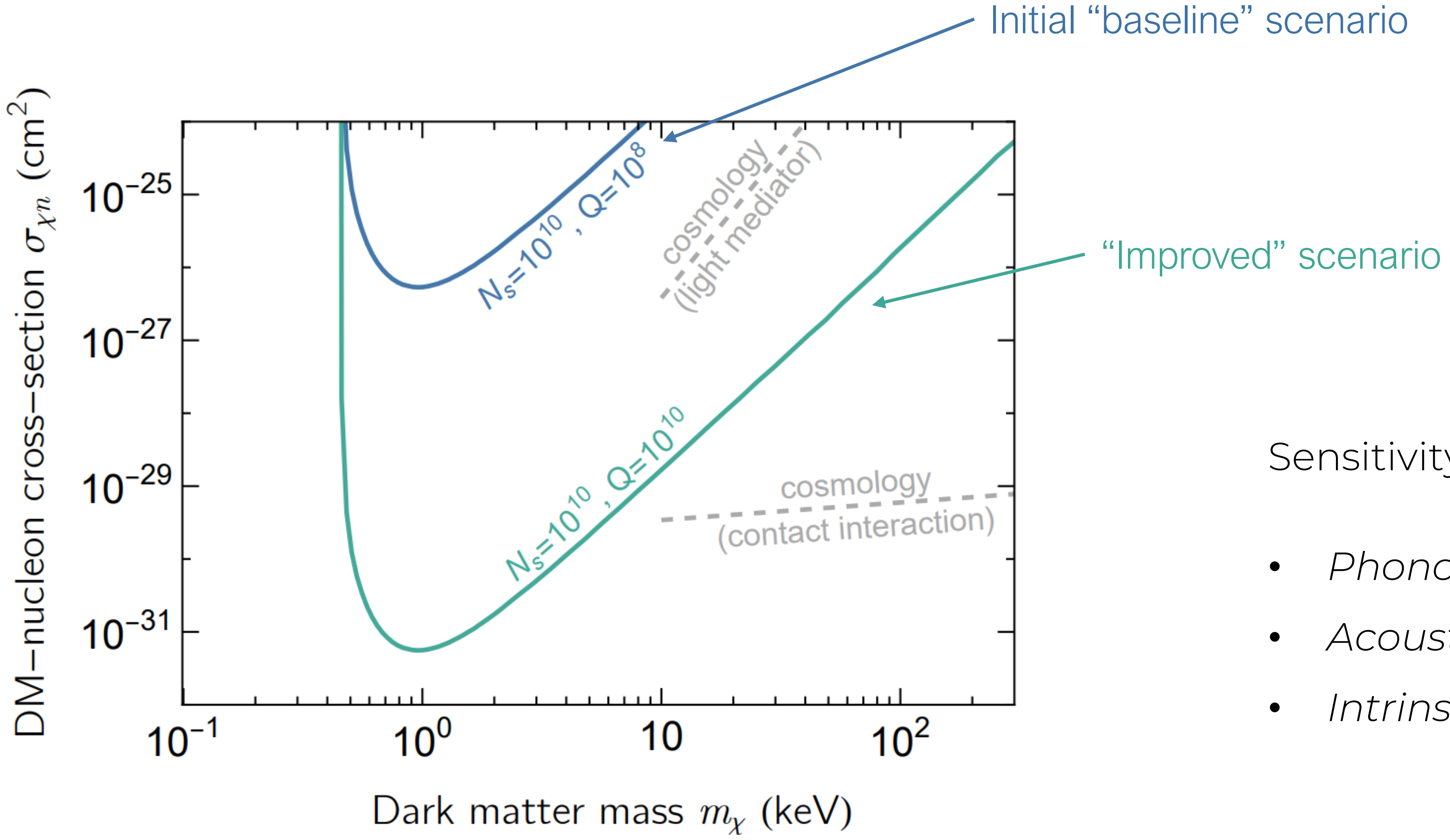
  ($\sim 6 \times 10^{-6}$ Hz)

- *Photons from pump lasers*

  (especially 532nm, supressed with filter cavities)

Expected background rate ~1 event/day

Projected Sensitivity

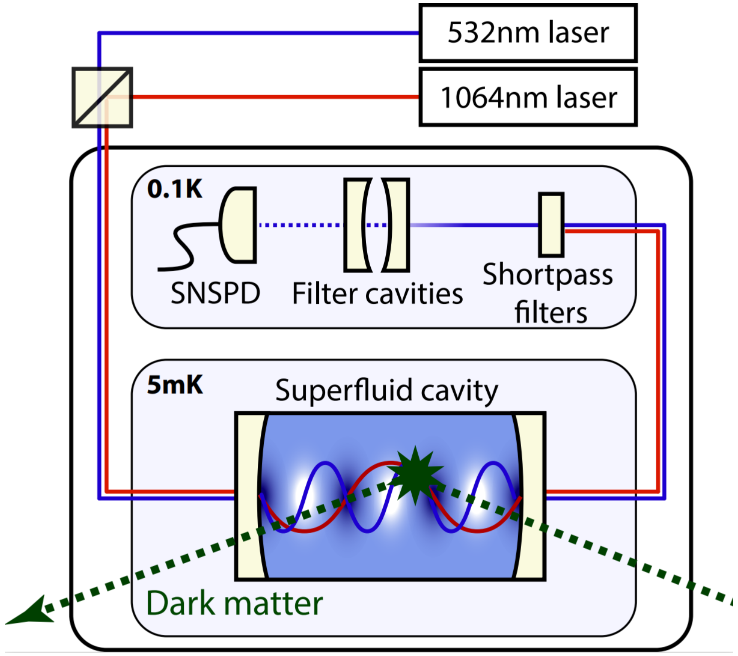


Sensitivity primarily determined by:

- *Phonon occupation* N_s
- *Acoustic Q-factor* (Ω_m/Γ_m)
- *Intrinsic background rate*

Outlook

- Superfluid optomechanical systems are *single phonon detectors*
- Conversion of ~μeV phonons to ~eV photons
- Phonon lasing enhances dark matter event rate
- Sensitive to dark matter in the keV mass range with cross-sections as low as O(10^{-32}) cm^2



Backup

Optical asymmetry

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