keV dark matter detection with superfluids

Peter Cox
The University of Melbourne

with C. Baker, W. Bowen, M. Dolan, M. Goryachev, G. Harris

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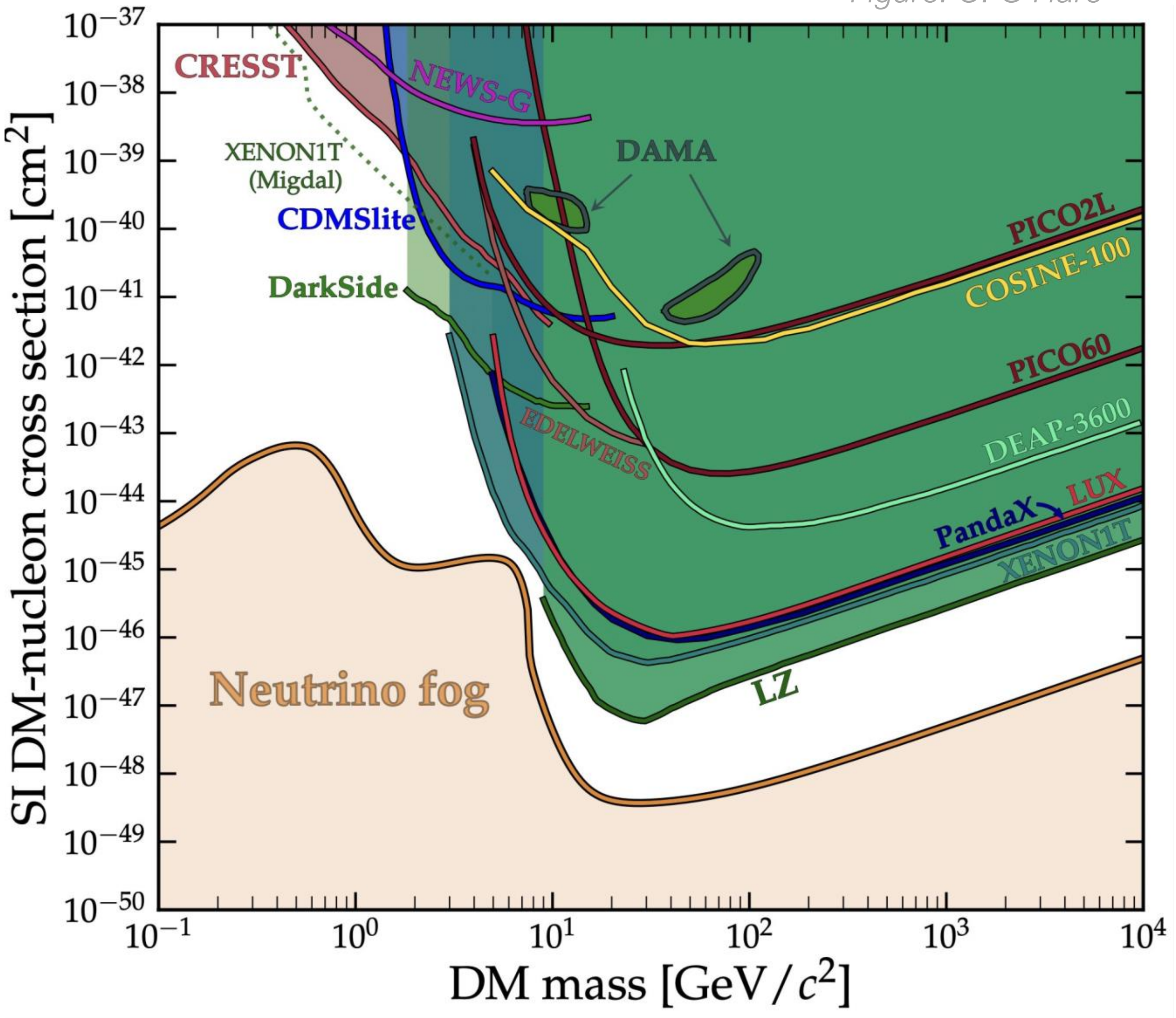
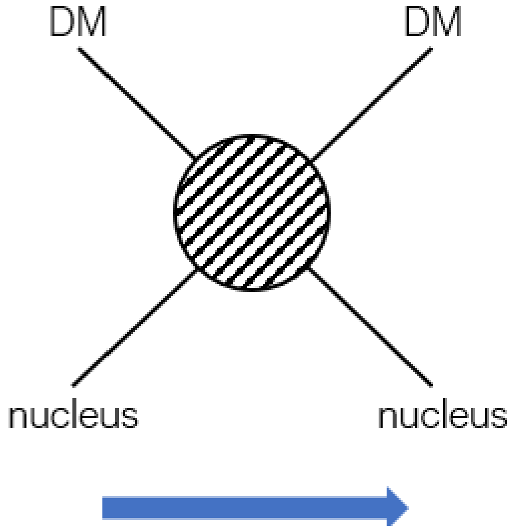
Direct detection: DM-nucleus scattering

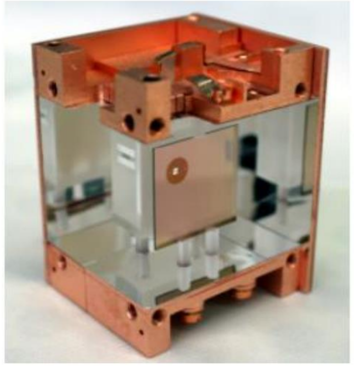
Figure: C. O'Hare





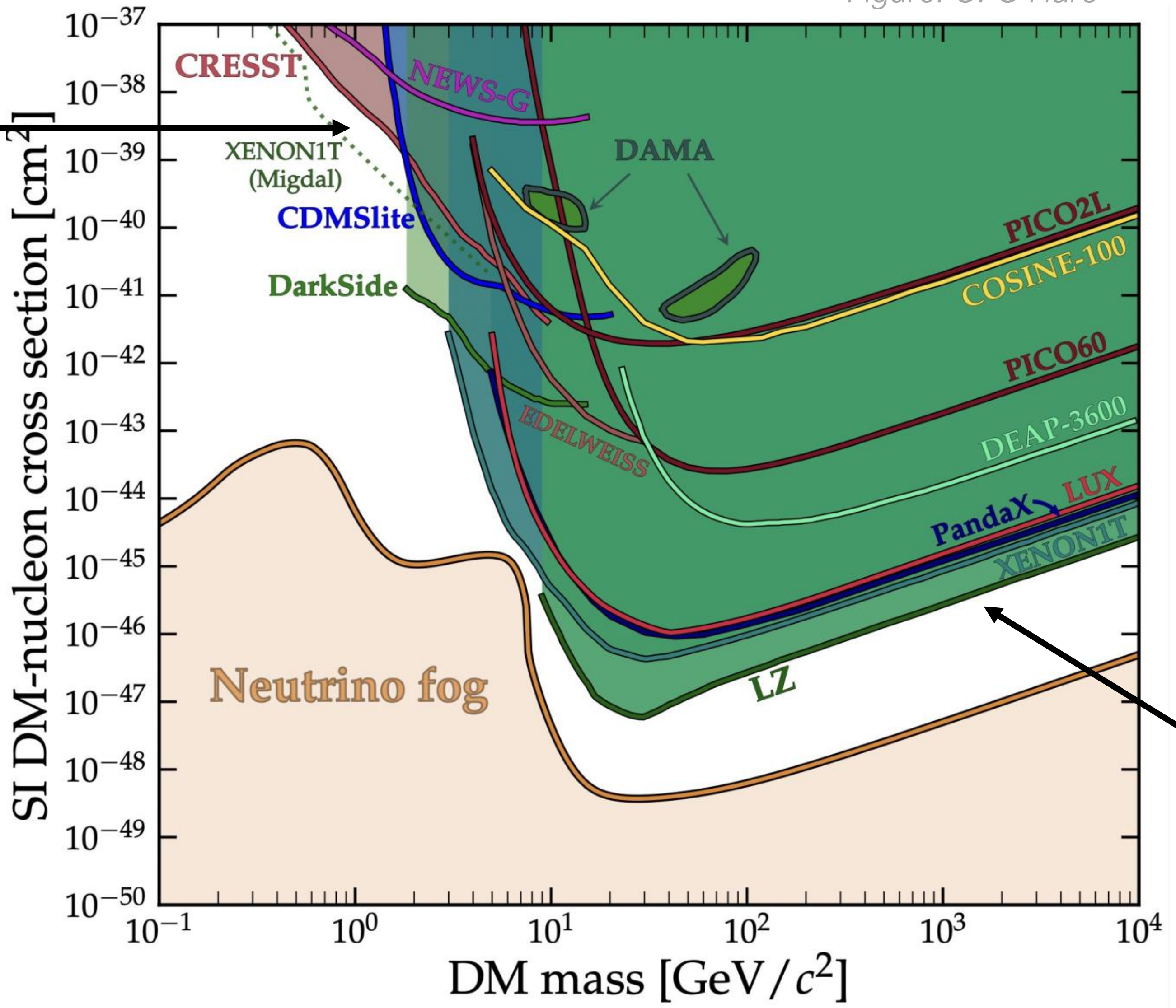
Direct detection: DM-nucleus scattering

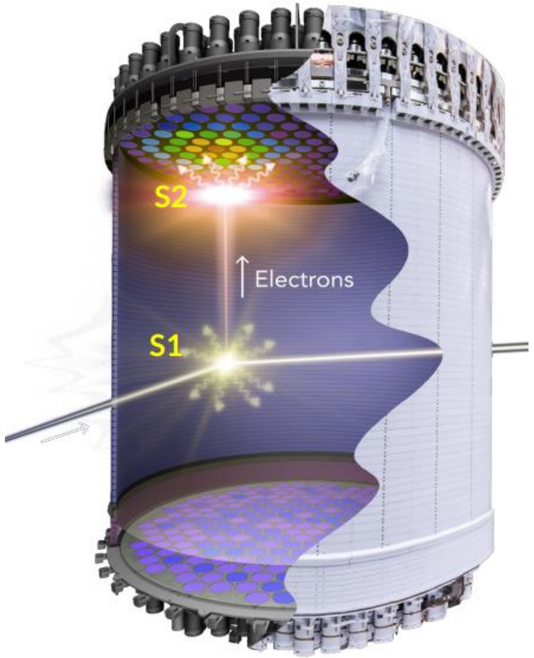
cryogenic experiments



CRESST

Figure: C. O'Hare



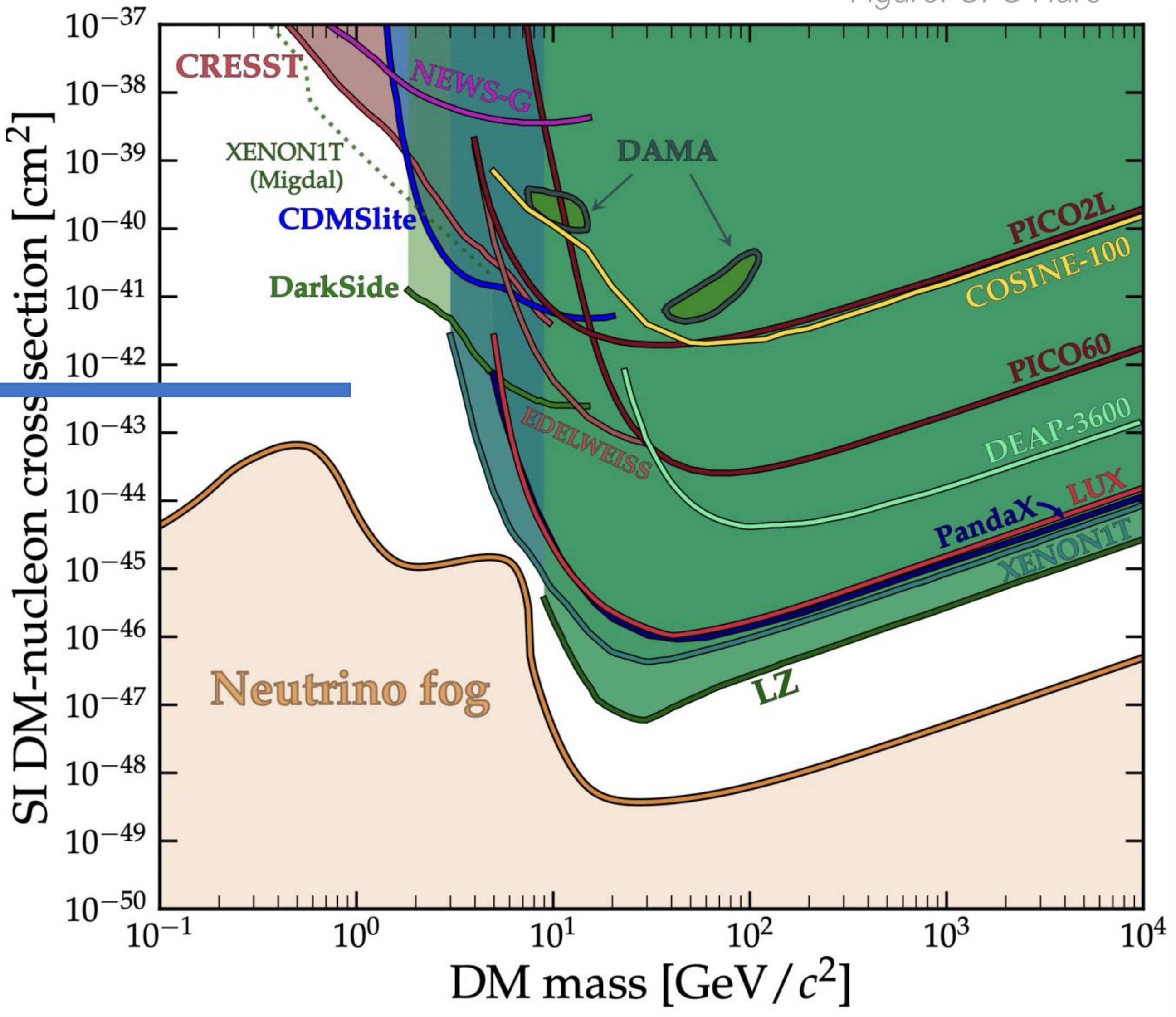


LUX-ZEPPLIN (LZ)

tonne-scale liquid Ar/Xe experiments

Direct detection: DM-nucleus scattering

Figure: C. O'Hare



How to extend low mass reach?

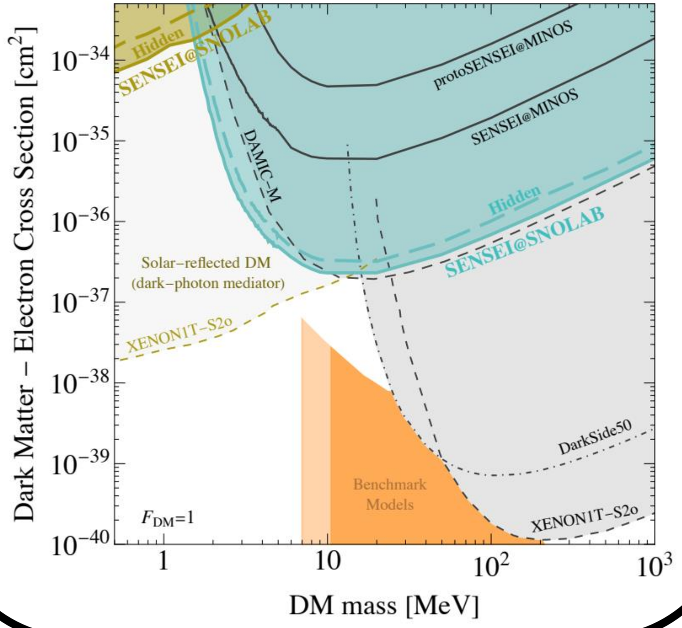
Increased exposure

(bigger detectors)

Sub-GeV direct detection

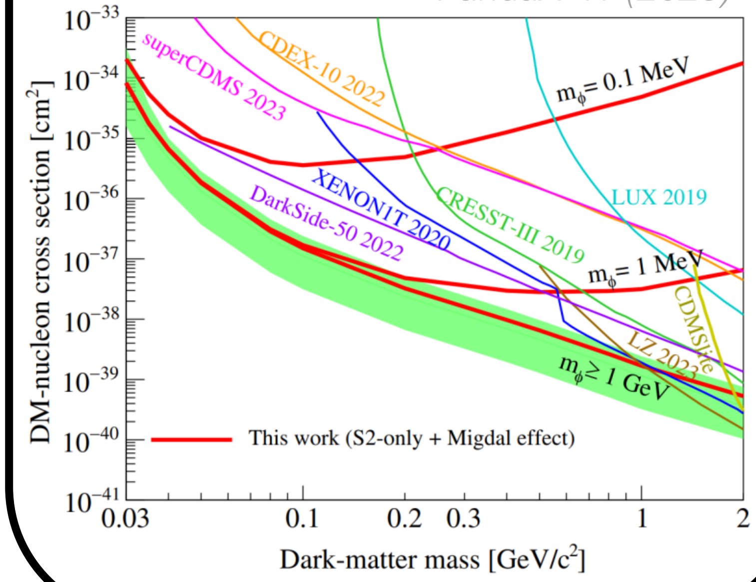
Electron scattering

SENSEI (2023)

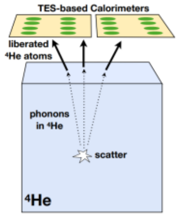


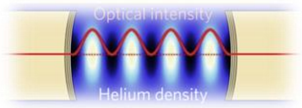
Migdal effect

PandaX-4T (2023)



Low-threshold detectors



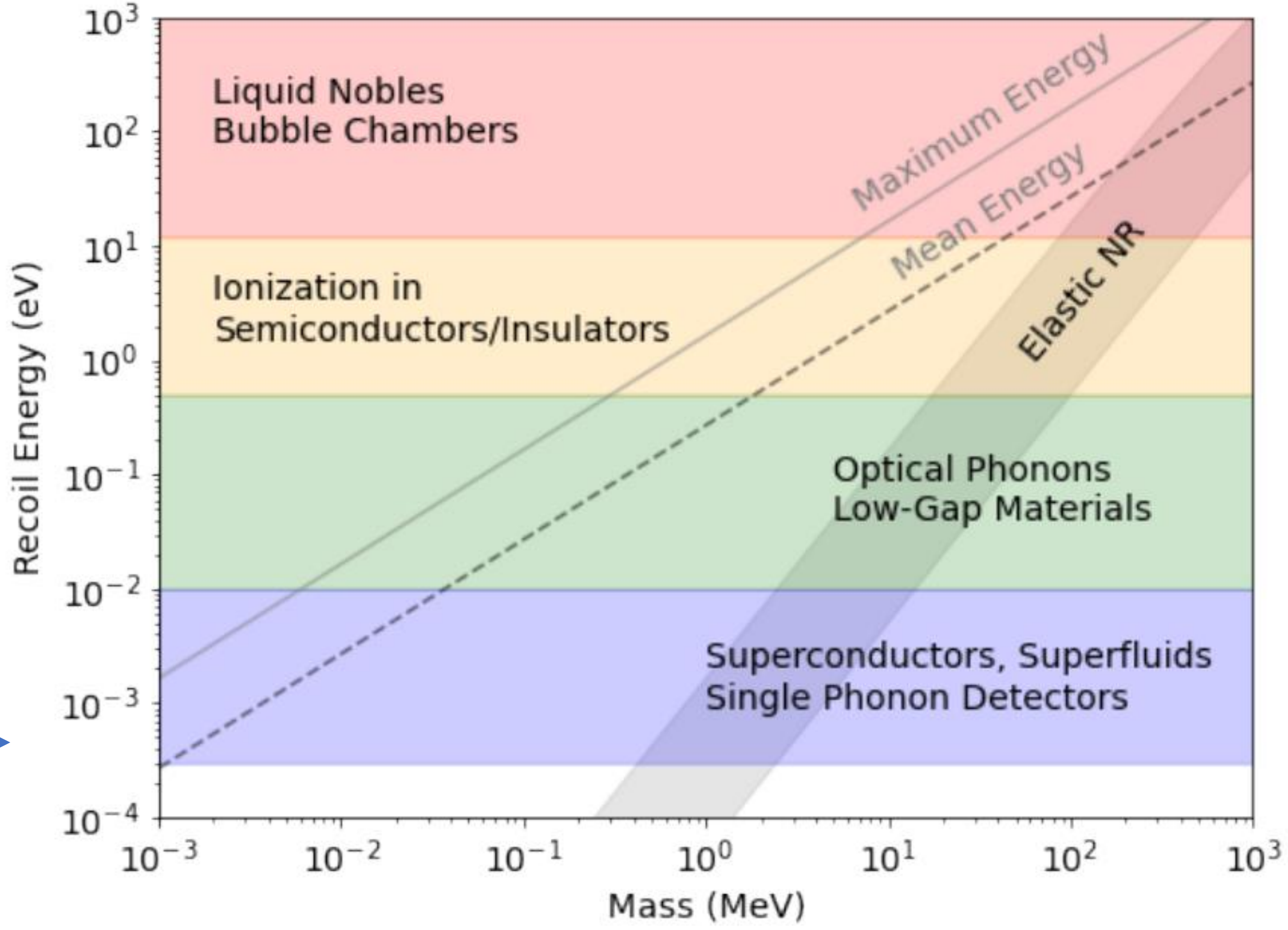


Lots of ideas + R&D

+ DM absorption, boosted DM, …

Sub-GeV direct detection

Figure: 2203.08297 (Snowmass 21)



This talk →

Sub-GeV DM with superfluid ^{4}He

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

Upcoming experiments: *HeRALD, DELight*

Primary signal: *quantum evaporation*

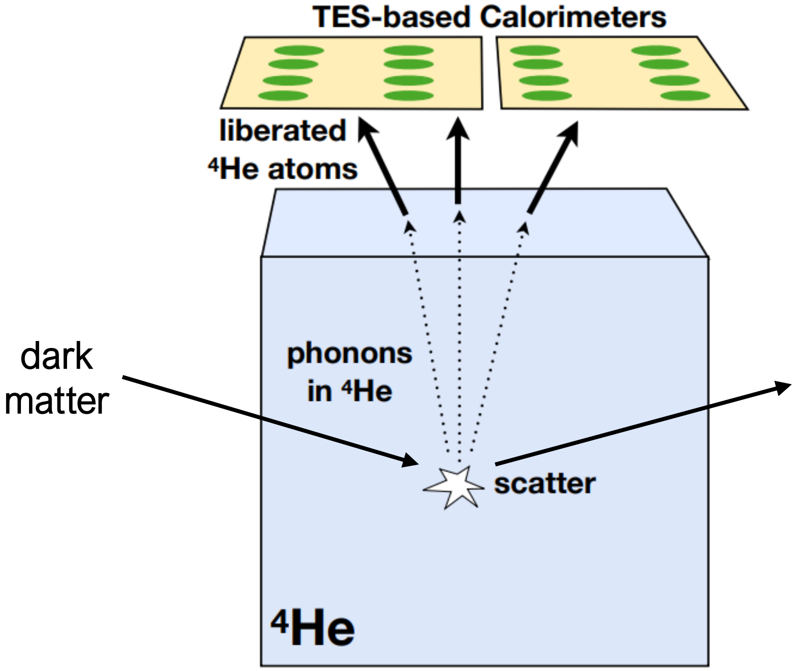


Figure: Herald Collaboration

Sub-GeV DM with superfluid ^{4}He

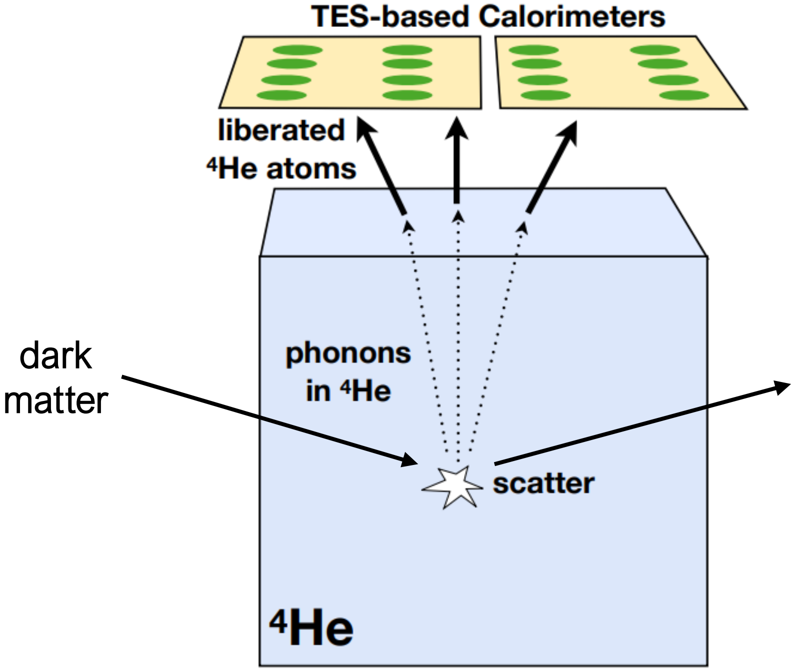
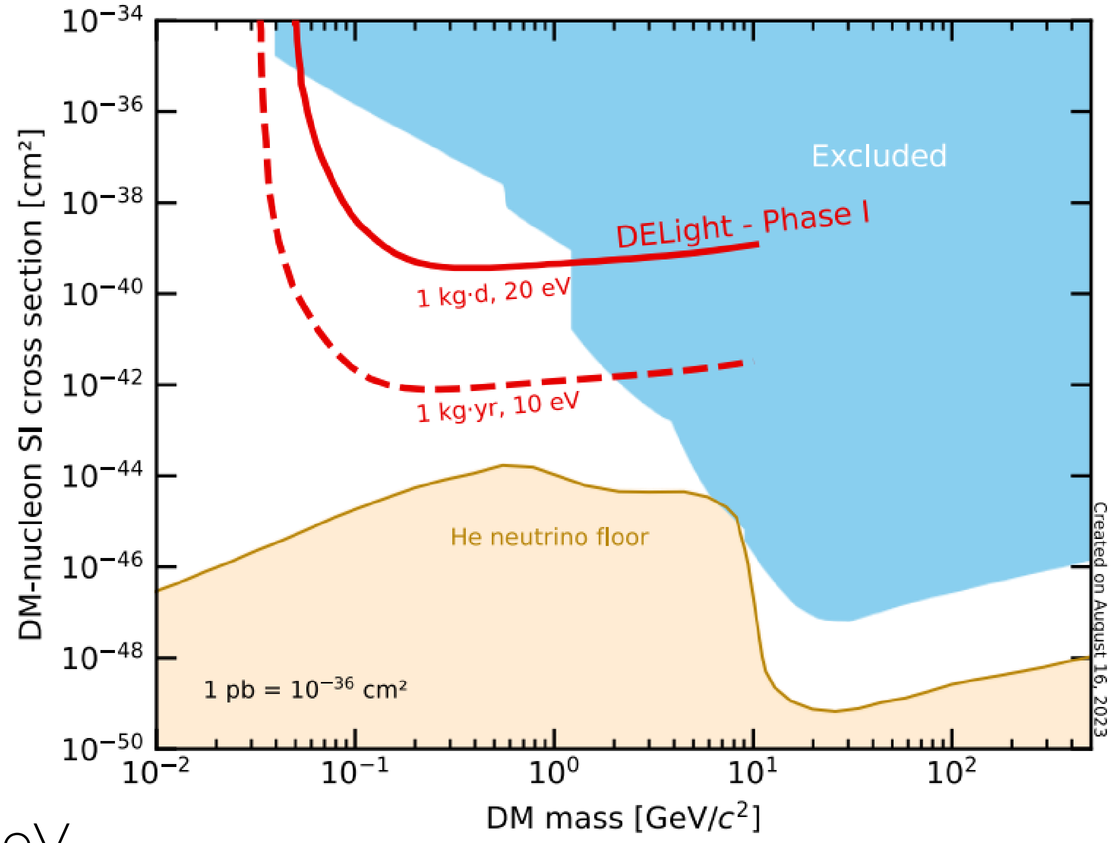


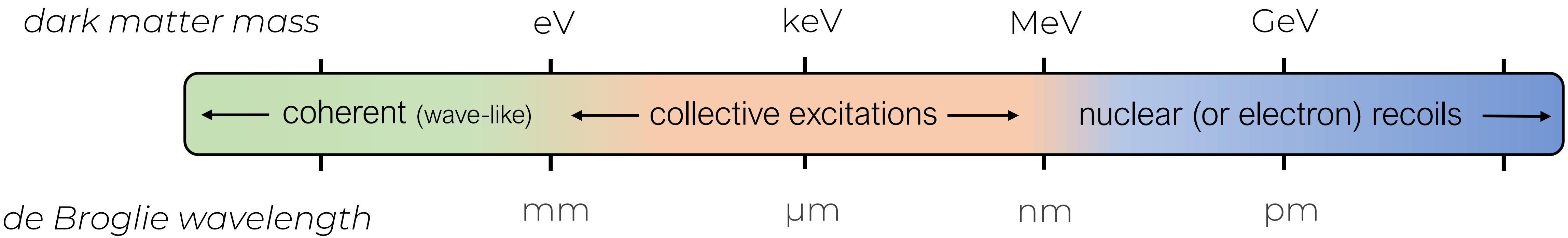
Figure: Herald Collaboration

DELight Collaboration

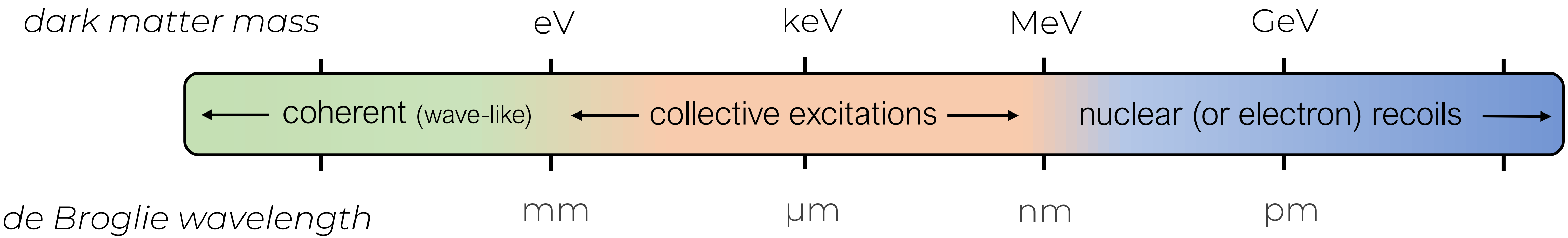


- Initial sensitivity to DM masses of 10s-100s MeV
- Ongoing R&D towards lower threshold calorimeters: HeRALD (transition edge sensors)
  DELight (magnetic micro-calorimeter)

Sub-MeV direct detection: collective excitations



Sub-MeV direct detection: collective excitations

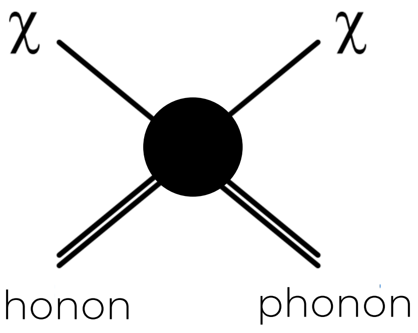


dark matter mass eV keV MeV GeV

← coherent (wave-like) ← collective excitations → nuclear (or electron) recoils →

de Broglie wavelength mm μm nm pm

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



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

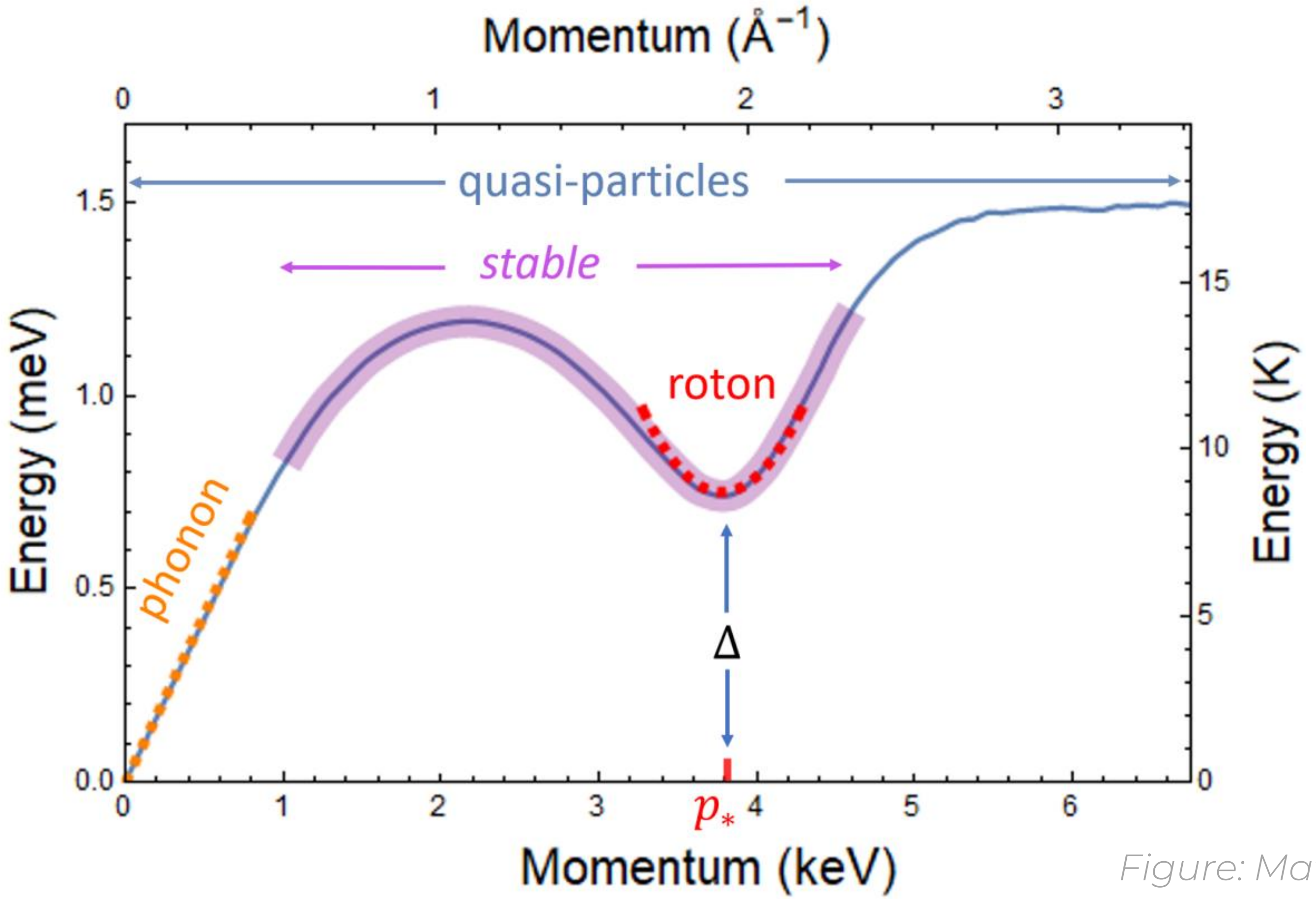


Figure: Matchev et. al '21

Long-lived/stable collective excitations

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

Linear dispersion relation (NGB)

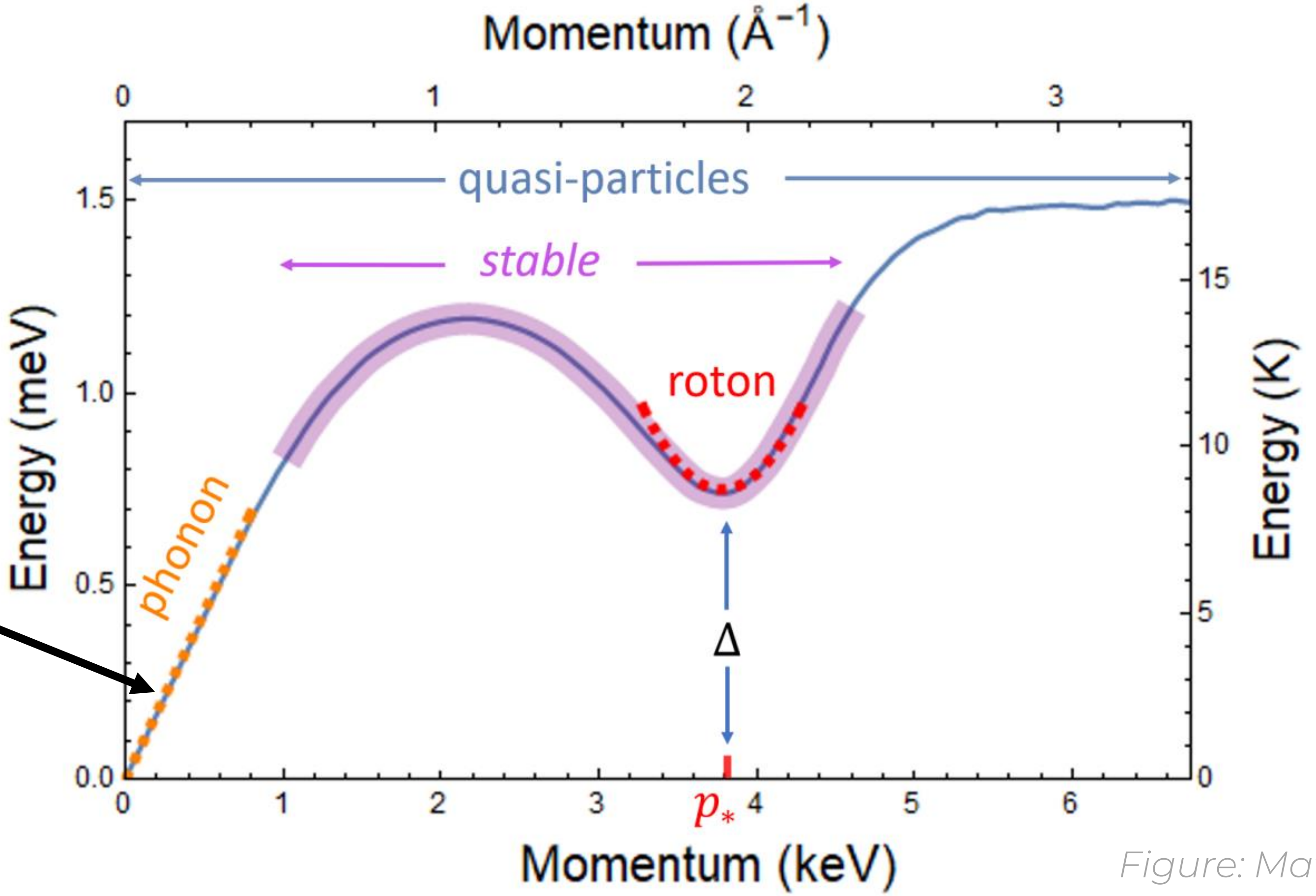


Figure: Matchev et. al '21

Long-lived/stable collective excitations

Superfluid phonon EFT

Son '02
Nicolis '11
Nicolis & Piazza '11

- Spontaneously broken $U(1)$ symmetry (*particle number*)
- Finite density

$$\Phi(x) \to \Phi(x) + \alpha$$

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Noether current: $j^\mu \propto \partial^\mu \Phi \quad \longrightarrow \quad \langle \partial_t \Phi \rangle = \mu$

$$(\langle \Phi \rangle = \mu t)$$

$\mu =$ chemical potential

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$\mu =$ chemical potential

VEV spontaneously breaks boosts & time translations

Preserves linear combination $\langle H - \mu N \rangle = 0$

Superfluid phonon EFT

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Most general Lagrangian consistent with shift symmetry:

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

Superfluid phonon EFT

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Most general Lagrangian consistent with shift symmetry:

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

P = pressure

"local chemical potential"

Superfluid phonon EFT

Son '02
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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: $\Phi(x,t) = \mu t + \sqrt{\frac{\mu c_s^2}{\bar{n}}}\, \underline{\phi(x,t)}$

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

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

Dark matter–phonon EFT

Consider spin-independent DM-nucleon interaction

$\Longrightarrow$ DM couples to He number density

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

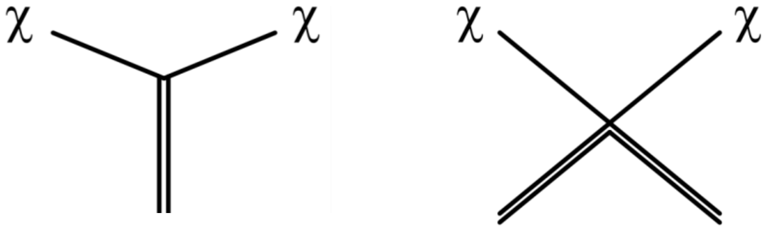
Dark matter–phonon EFT

Acanfora, Esposito, Pelosa '19

Consider spin-independent DM-nucleon interaction

$\Longrightarrow$ DM couples to He number density

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



Detecting phonons - cavity optomechanics

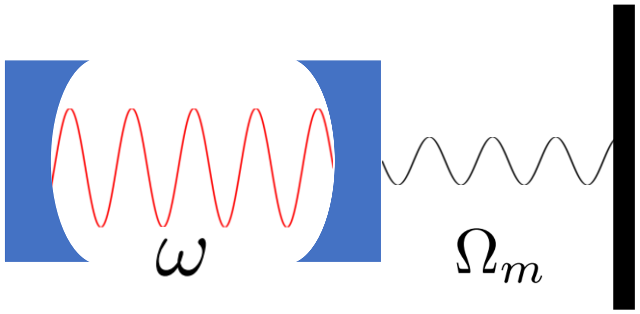
Basic idea: optomechanical systems can be single phonon detectors

Optomechanical systems already used to search for ultralight DM, e.g. HeLIOS

Detecting phonons - cavity optomechanics

Basic idea: optomechanical systems can be single phonon detectors

Toy model:



Detecting phonons - cavity optomechanics

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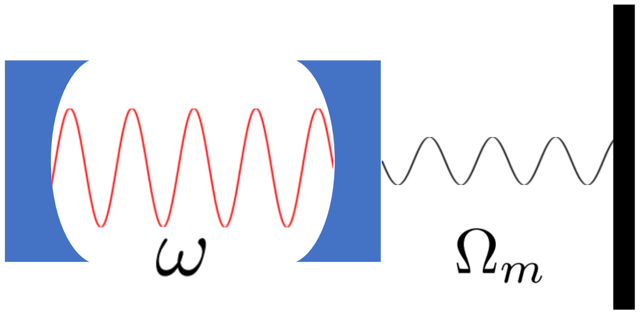

$$H \supset \left(\omega_0 + \frac{\partial\omega}{\partial x}x\right) a^\dagger a$$

Optical resonance frequency depends on cavity length

Detecting phonons - cavity optomechanics

Basic idea: optomechanical systems can be single phonon detectors

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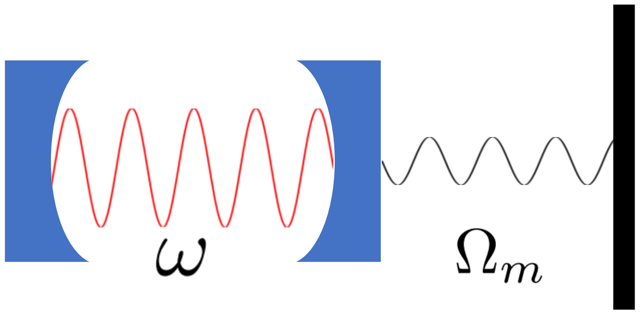


$$\begin{aligned} H &\supset \left(\omega_0 + \frac{\partial \omega}{\partial x} x\right) a^\dagger a \\ &\rightarrow \left(\omega_0 + g_0 (b_m + b_m^\dagger)\right) a^\dagger a + \Omega_m b_m^\dagger b_m \end{aligned}$$

photon

phonon

optomechanical coupling

Superfluid cavity optomechanics

superfluid ^{4}He filled optical cavity

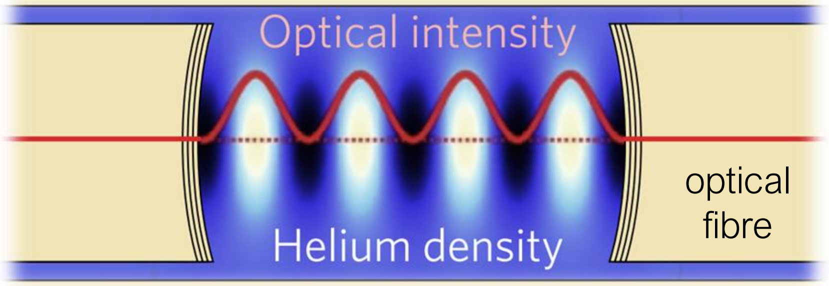
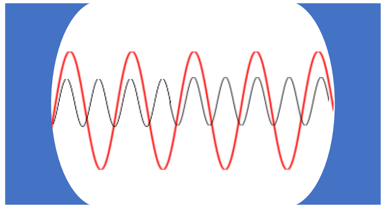


Figure: Kashkanova+ '16

Mechanical mode: phonons in superfluid



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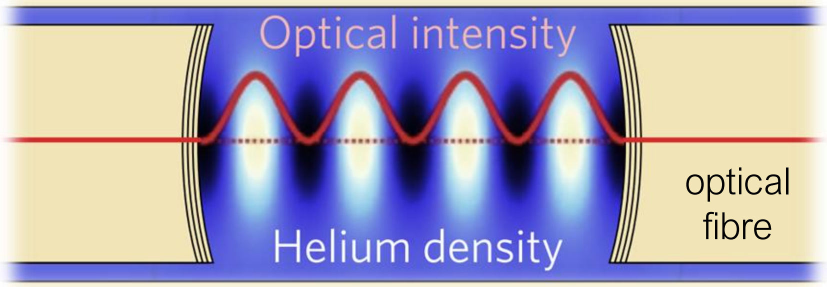

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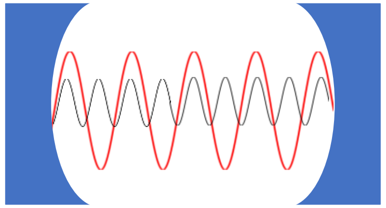

Optomechanical interaction due to change in refractive index

$$\mathcal{H}_{\mathcal{OM}} = \frac{1}{2} g_1 \epsilon_0 \frac{\delta\rho}{\rho} E^2$$

Agarwal & Jha '14

Superfluid cavity optomechanics

$$\Omega_m = \omega_{\gamma_2} - \omega_{\gamma_1}$$

superfluid ^{4}He filled optical cavity

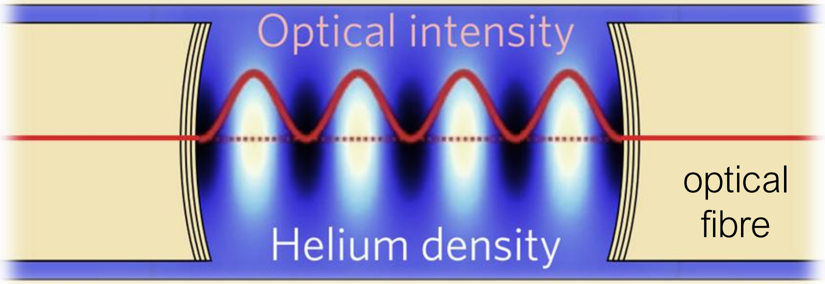

Figure: Kashkanova+ '16

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

optomechanical coupling

photons

phonon

Superfluid cavity optomechanics

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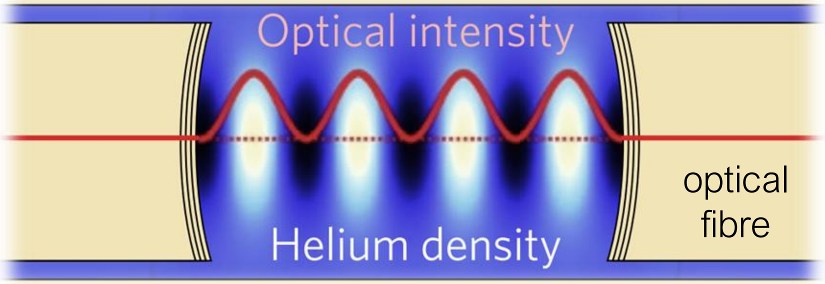
superfluid ⁴He filled optical cavity



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coupling to a *single* phonon mode

$$\lambda_1 \approx \lambda_2 \approx 2\lambda_m$$

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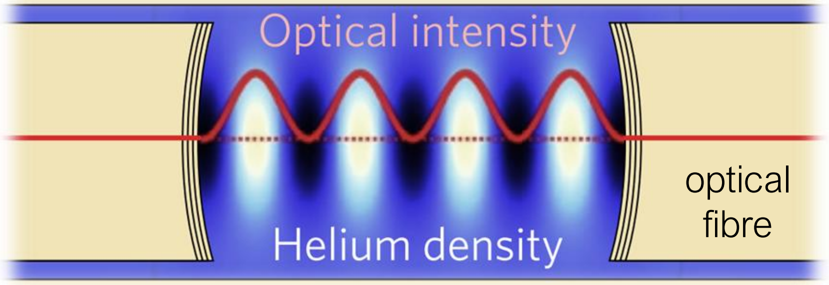

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$$\to -g_0\sqrt{N_1}(a^\dagger_{\gamma_2} b_m + b^\dagger_m a_{\gamma_2})$$

pump laser enhances small g_0

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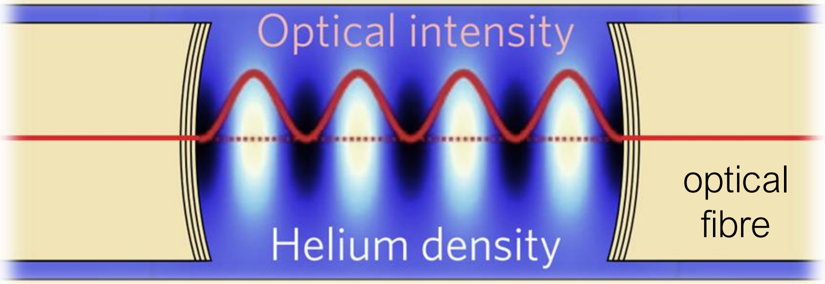

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Optomechanical conversion of ~μeV phonons to ~eV photons

e.g. $\gamma_1 + \Omega_m \rightarrow \gamma_2$ $\Omega_m = \omega_{\gamma_2} - \omega_{\gamma_1} \ll \omega_{\gamma_{1,2}}$

Superfluid cavity optomechanics

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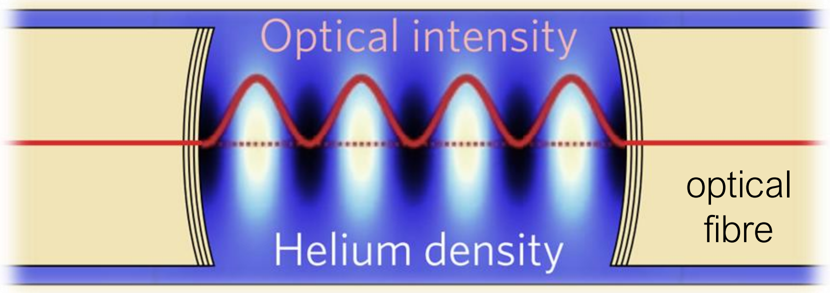
superfluid ^{4}He filled optical cavity



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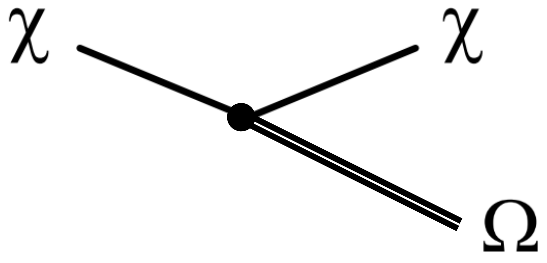
Optomechanical systems have demonstrated μeV phonon counting (e.g. Patil et. al. '22)

Narrow-band detection

Superfluid optomechanical systems as dark matter detectors:

- ✓ exceptional low-energy sensitivity (~μeV)
- × narrow-band detector (single phonon energy set by pump laser frequency)

⟶ *Very low dark matter scattering rate due to restricted phase space*



Narrow-band detection & phonon lasing

Superfluid optomechanical systems as dark matter detectors:

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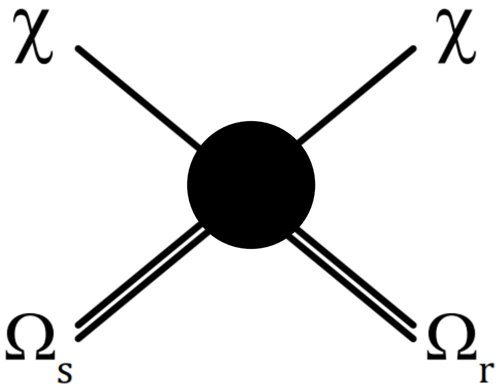
Solution: *Phonon lasing*

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



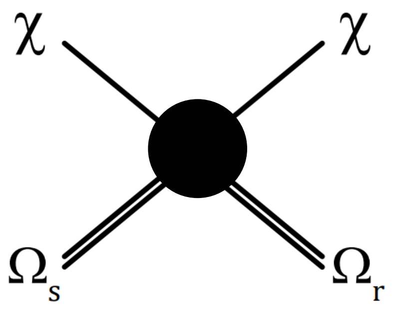
pumped phonon

detected phonon

Optomechanical detection

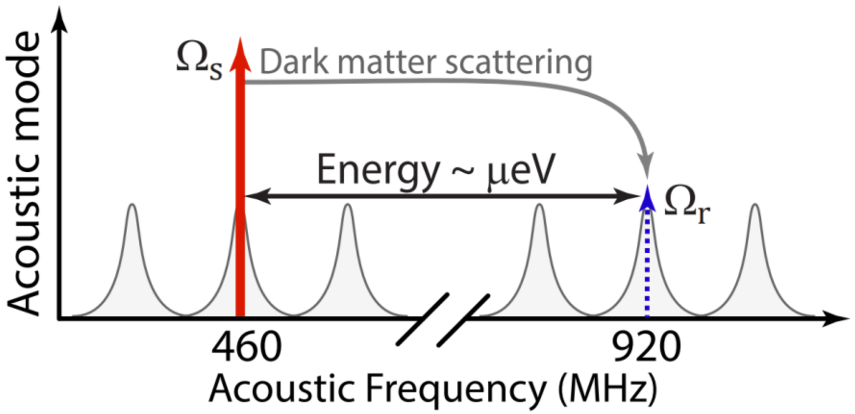
1 *Scattering*

DM excites ~μeV phonon in superfluid



pumped phonon
(lower-energy, high occupation)

excited phonon
(higher energy)



Optomechanical detection

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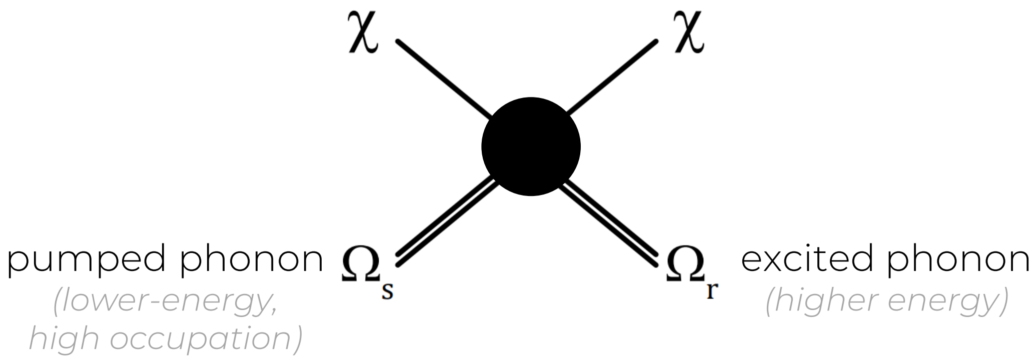
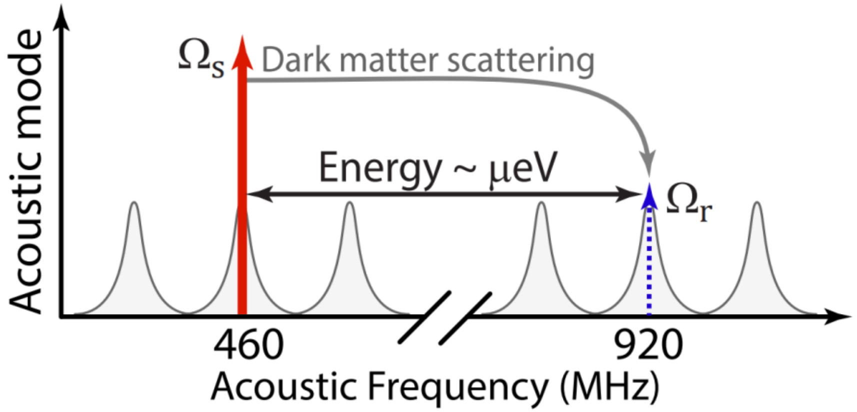
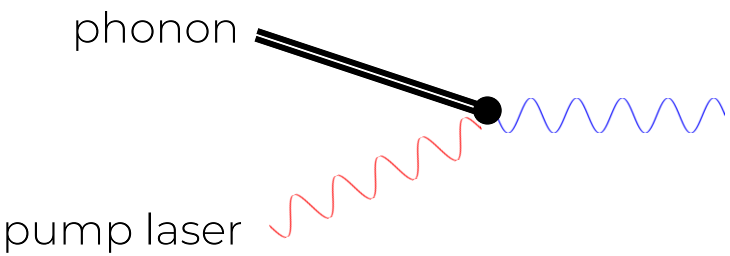
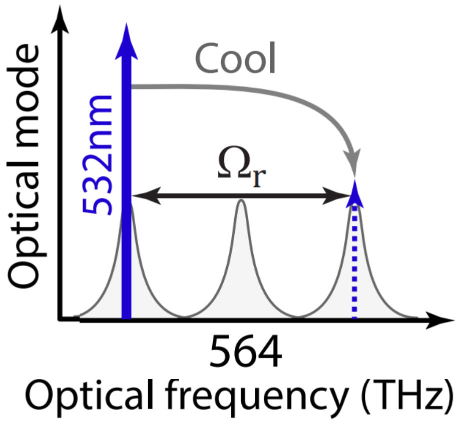




② *Conversion & amplification*

phonon interacts with pump laser, producing higher energy photon





Optomechanical detection

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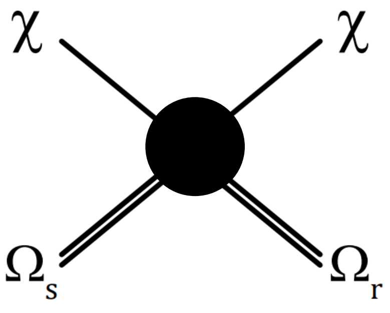
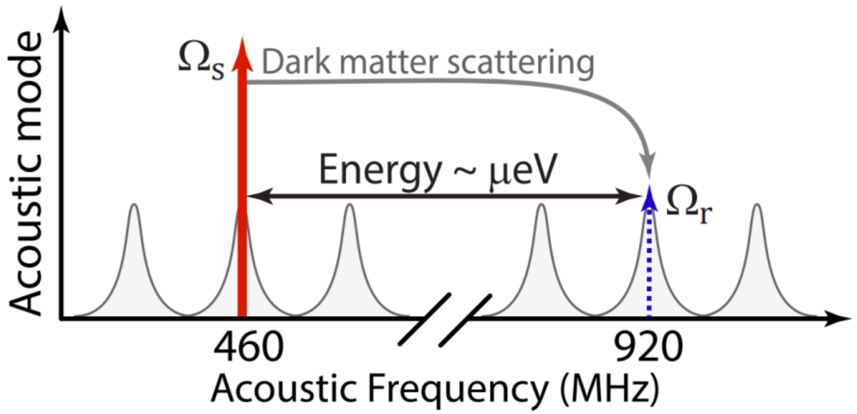


pumped phonon
(lower-energy, high occupation)

excited phonon
(higher energy)



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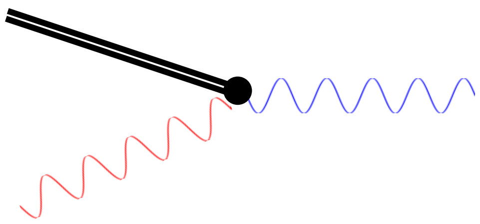
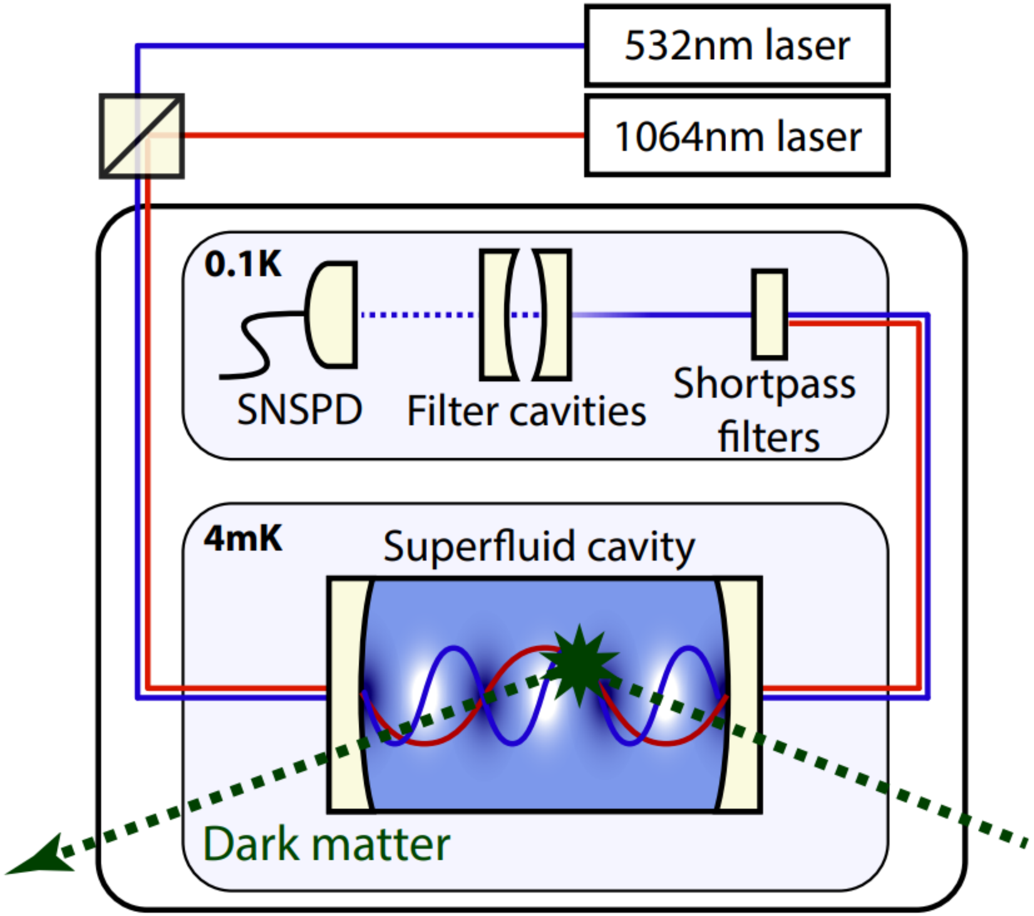


phonon

pump laser

③ *Detection*
photon detected by single photon detector (SNSPD)

ODIN: Optomechanical Dark-matter INstrument



cavity dimensions ~ 32cm x 0.7mm

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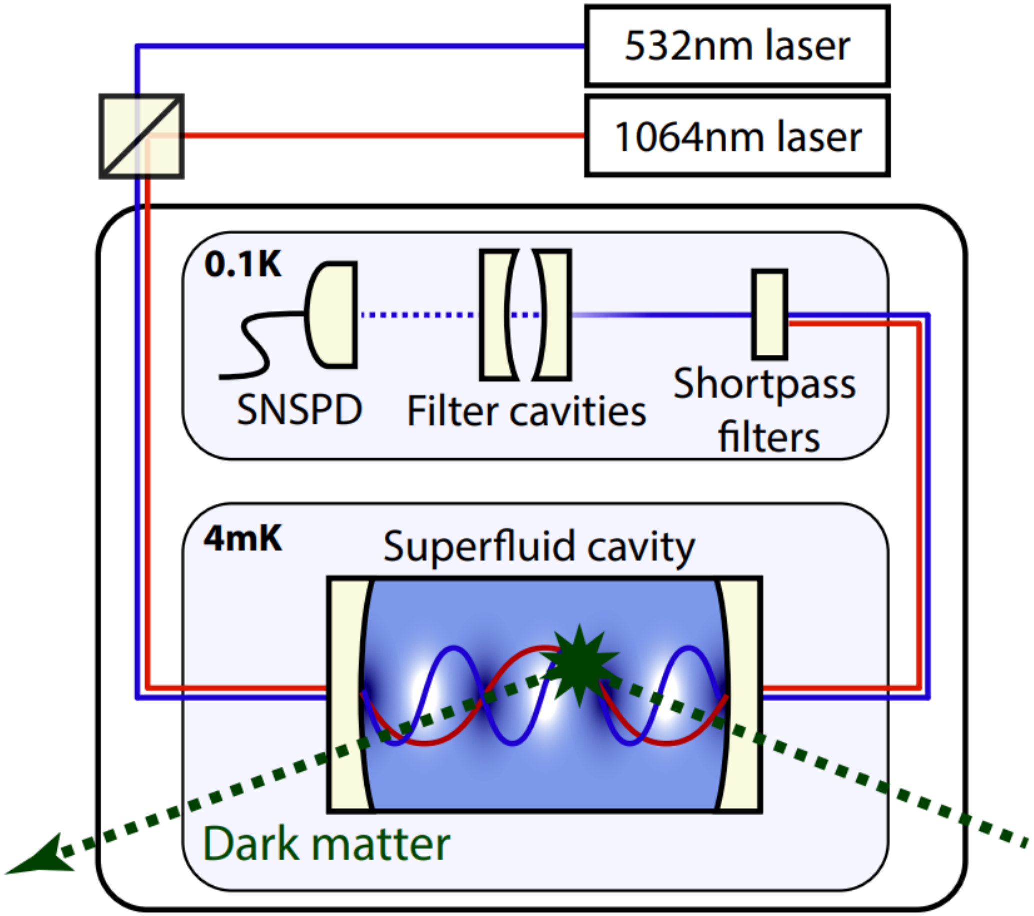

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Main detector backgrounds:

- *Thermal phonons*

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

- *SNSPD dark counts*

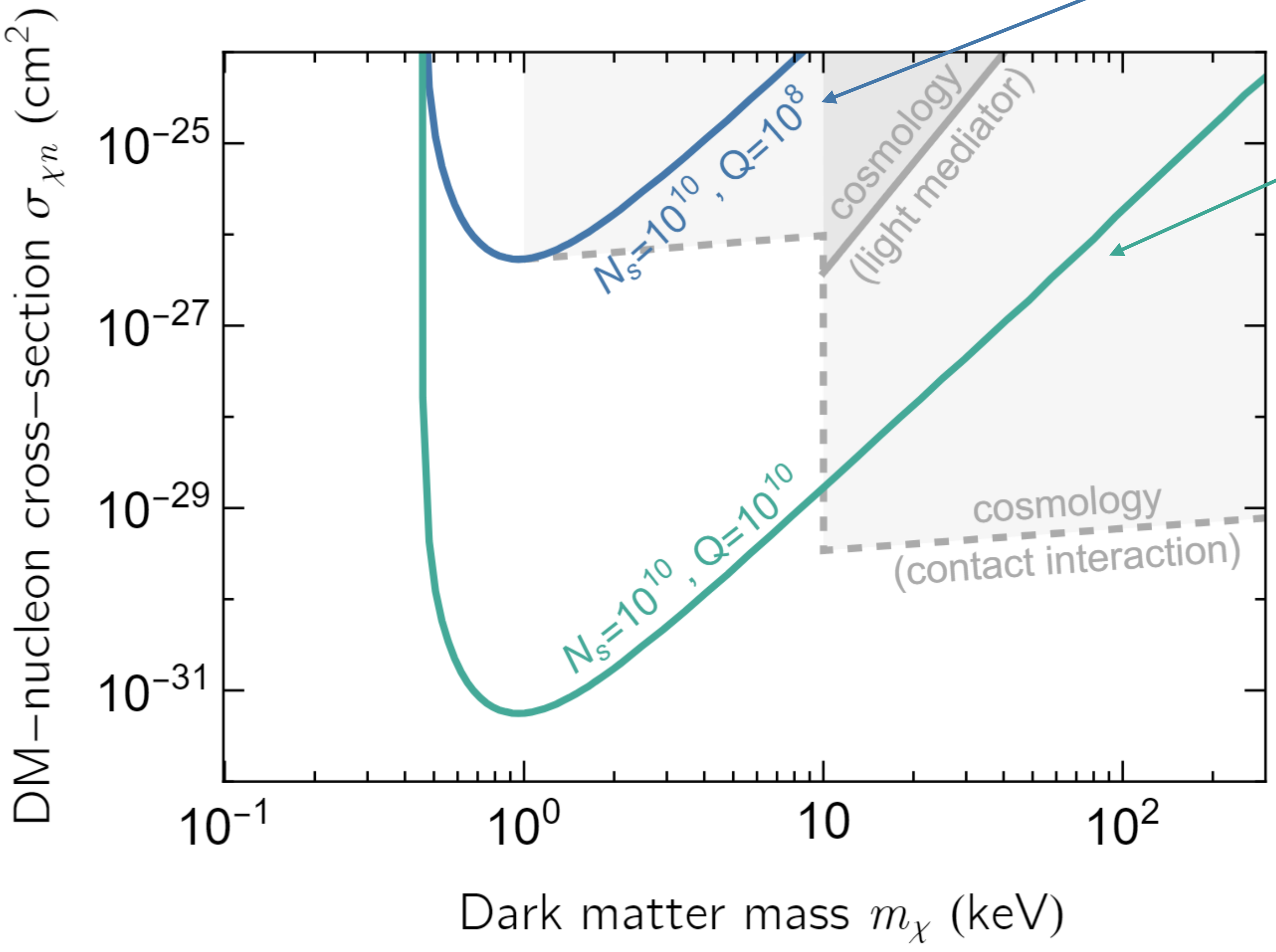
  (~6×10^{-6} Hz)

- *Incomplete filtering of pump lasers*

  (especially 532nm, supressed with filter cavities)

Expected background rate ~1 event/day

ODIN: Projected Sensitivity



Initial “baseline” scenario

“Improved” scenario

Sensitivity determined by:

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

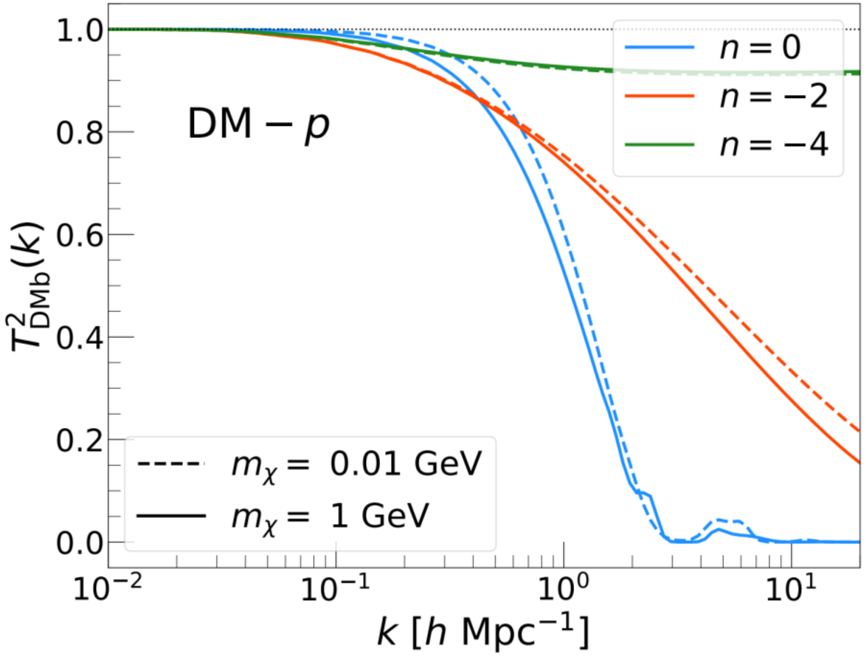
Existing constraints on keV-MeV DM

Leading “model-independent” bounds from cosmology

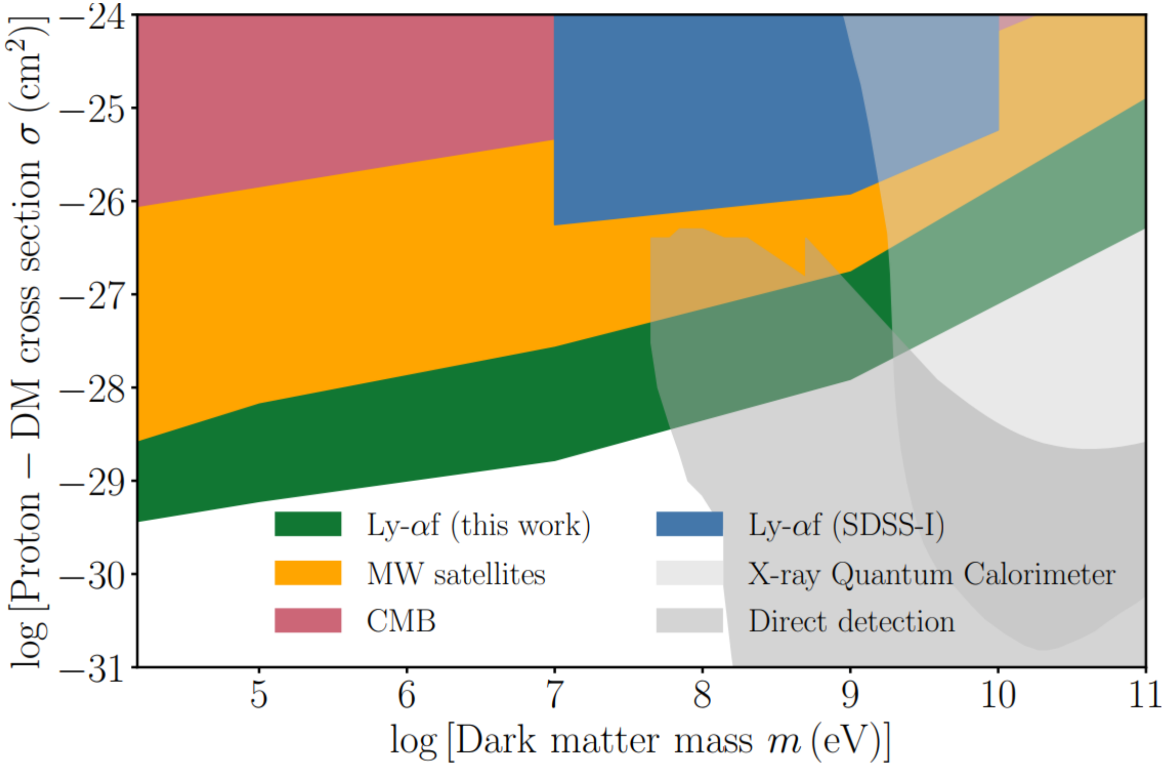
- *DM-baryon interactions modify matter power spectrum*

  suppress structure on smaller scales - probed by Lyman-α, CMB, MW satellites

Buen-Abad el. al. (2021)



Rogers, Dvorkin, Peiris (2021)



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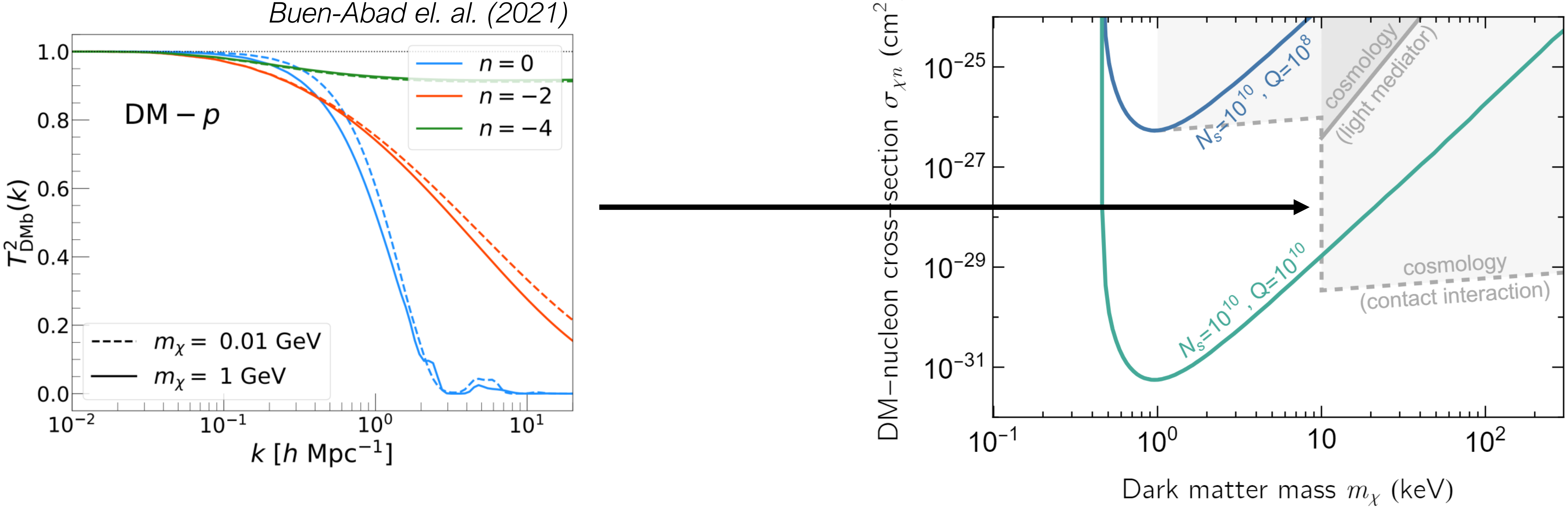


Buen-Abad el. al. (2021)

Also expect warm dark matter bounds

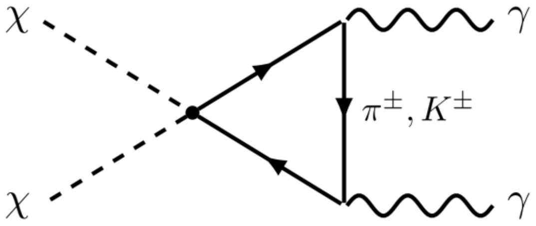
Realistic models are more constrained

Example: gluon-coupled DM $\frac{\alpha_s}{8\pi}G^{a,\mu\nu}G_{a,\mu\nu}$

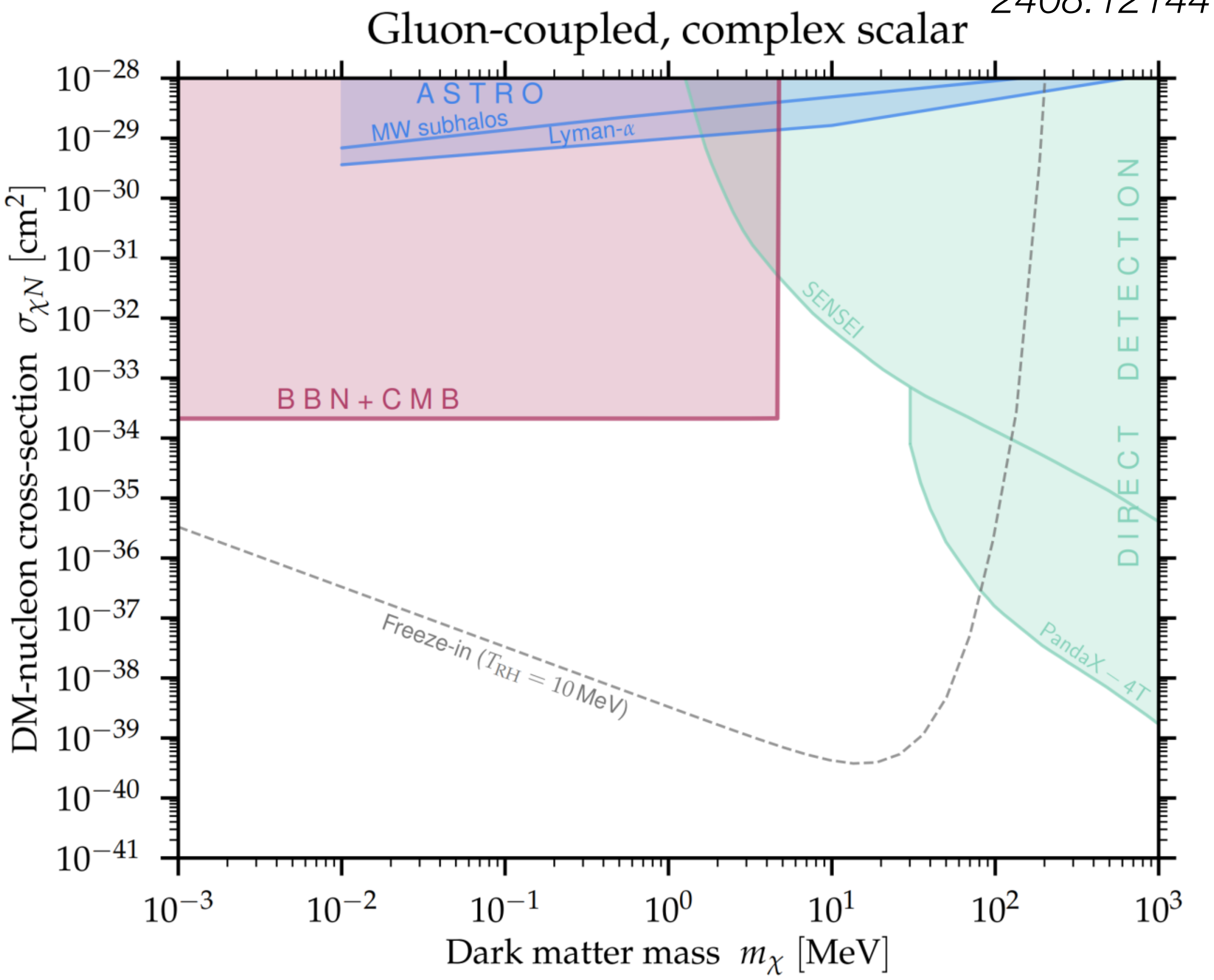
Contact interaction between DM and mesons

Conservative BBN/CMB bound:

$\gamma\gamma \to \chi\chi$ *out-of-equilibrium at T = 10 MeV*



PC, Matthew Dolan, Josh Wood
2408.12144



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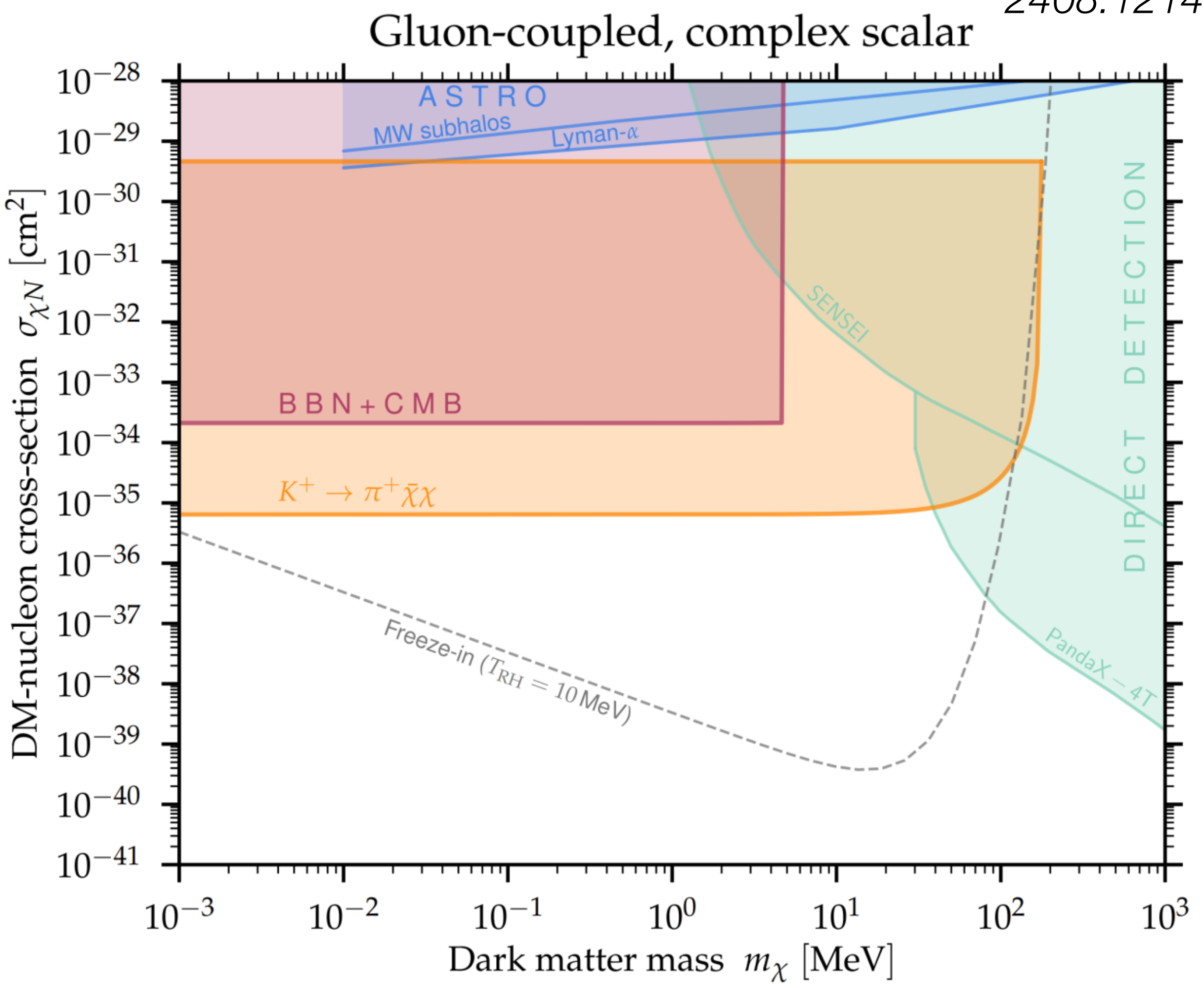
$\gamma\gamma \to \chi\chi$ *out-of-equilibrium at T = 10 MeV*

Kaon decays lead to stronger bound:

$$\mathrm{BR}(K^+ \to \pi^+ \chi\chi) \lesssim 10^{-10}$$

(NA62)



Summary

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

- Optomechanical detection uses conversion of *μeV phonons to eV photons*

- ODIN would be sensitive to keV mass DM

- Other applications?