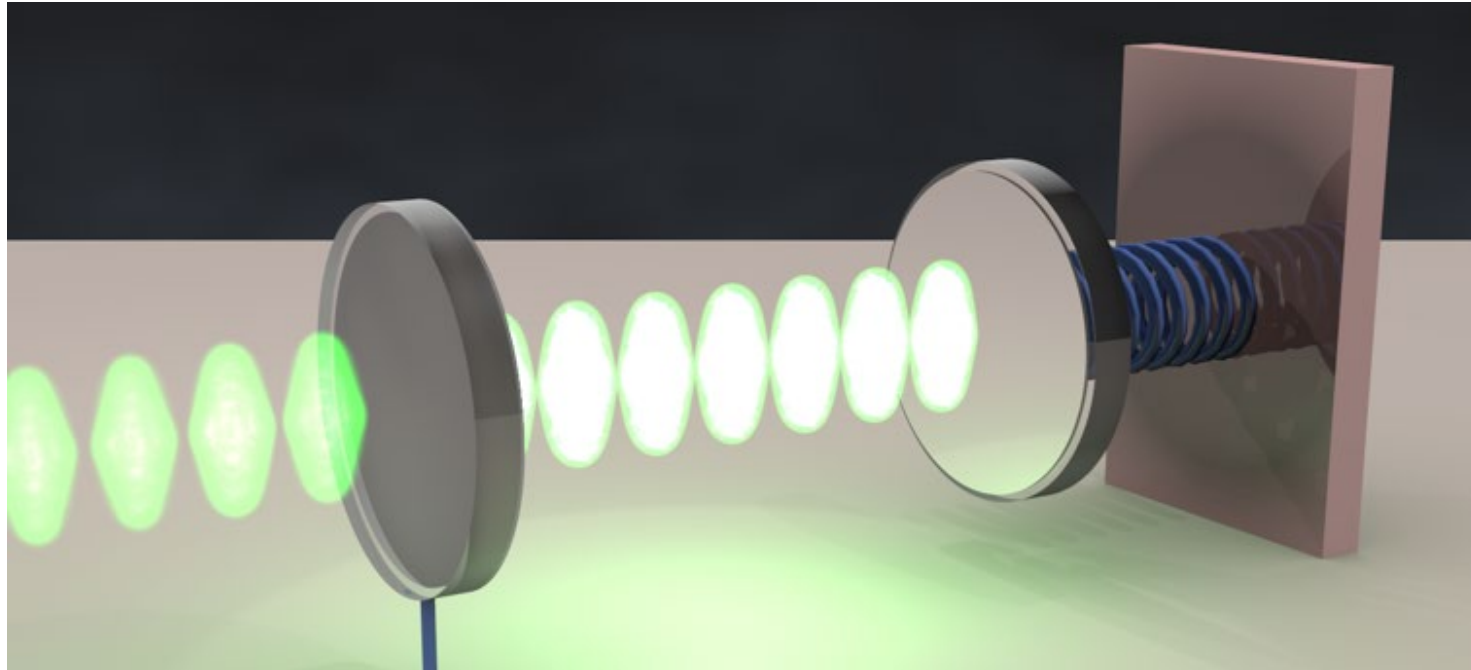
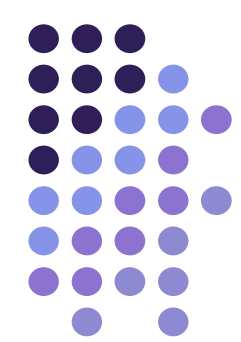




Superfluid Optomechanics for Dark Matter Detection



Glen Harris, Peter Cox, Matthew Dolan, Maxim Goryachev, Christopher Baker, Ben McAllister and Warwick Bowen



Superfluid Helium for Dark Matter Detection



Dr. Ben Brubaker

(PhD in lab of Steve Lamoreaux)

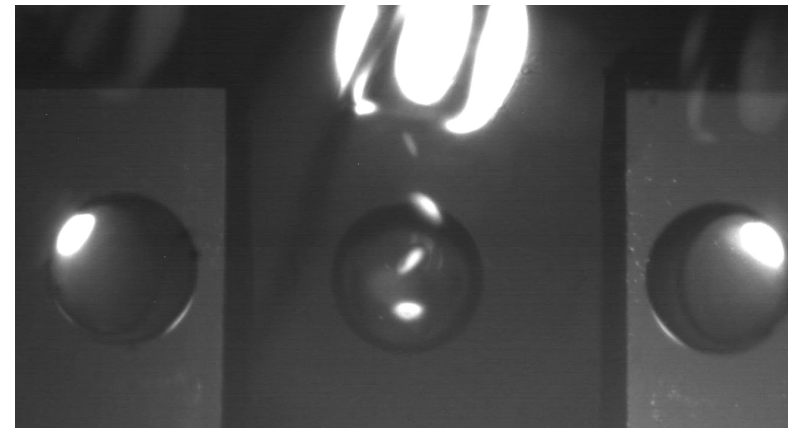
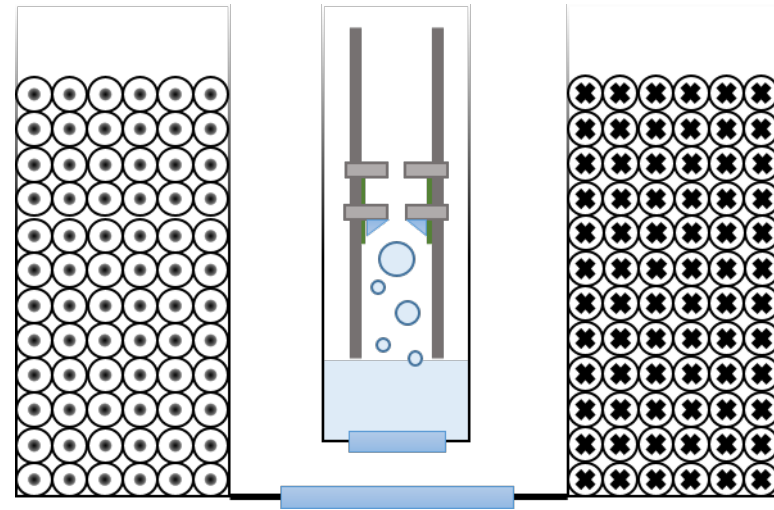
HAYSTAC

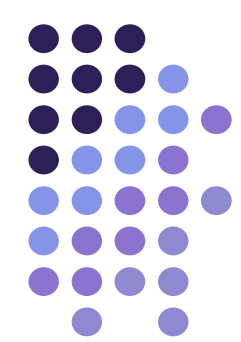


A/Prof Scott Hertel

(Postdoc in lab of Daniel McKinsey)

LUX-ZEPLIN





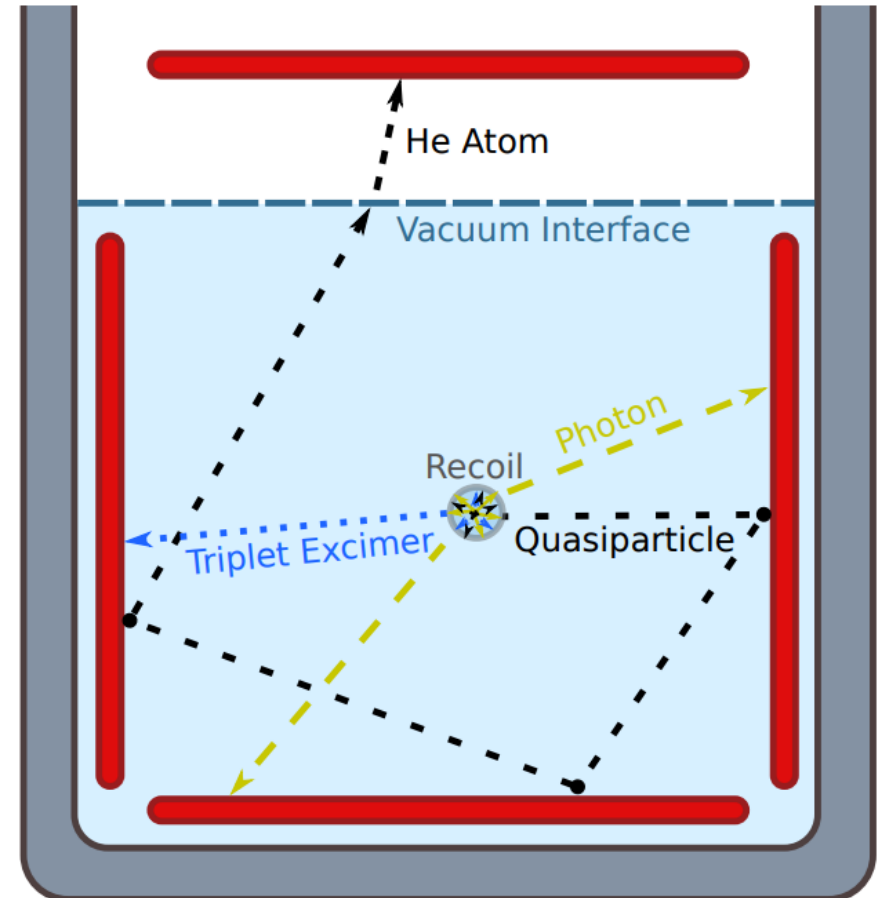
Superfluid Helium for Dark Matter Detection

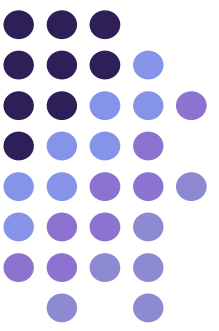


Dr. Ben Brubaker
(PhD in lab of Steve Lamoreaux)
HAYSTAC

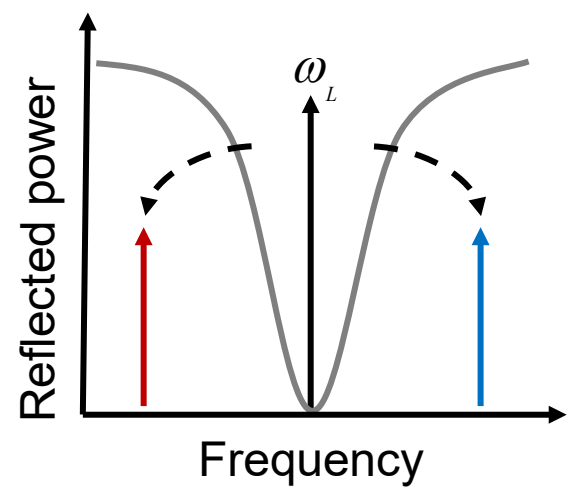
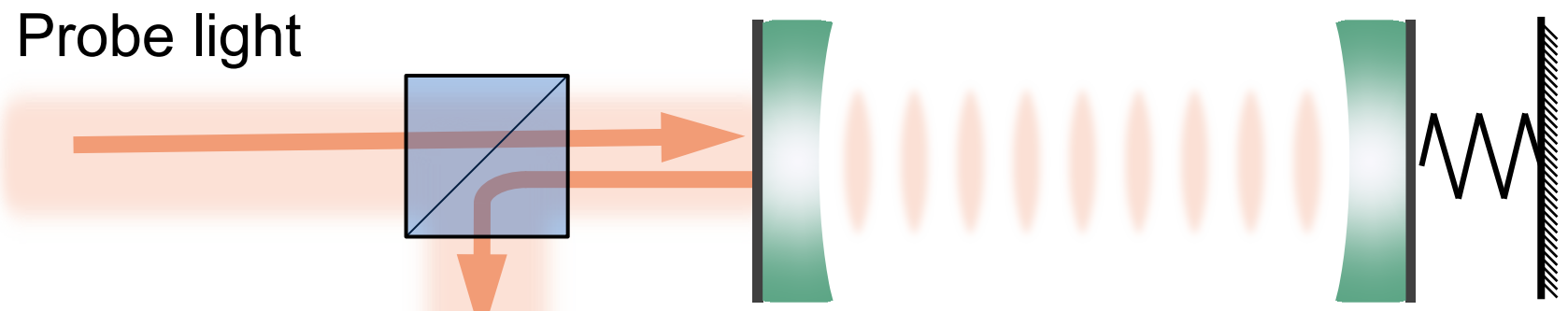


A/Prof Scott Hertel
(Postdoc in lab of Daniel McKinsey)
LUX-ZEPLIN





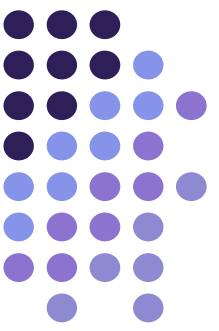
Optomechanics



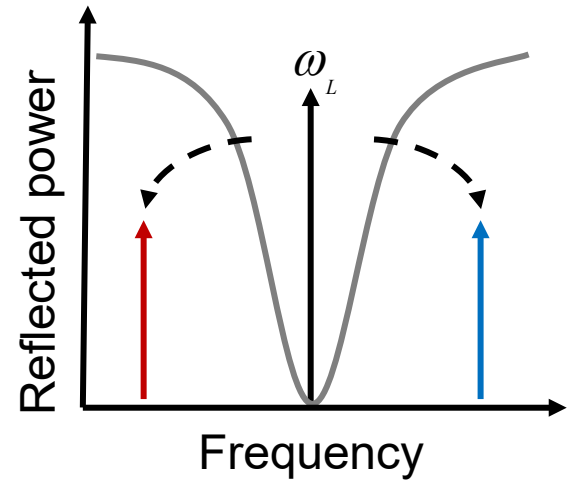
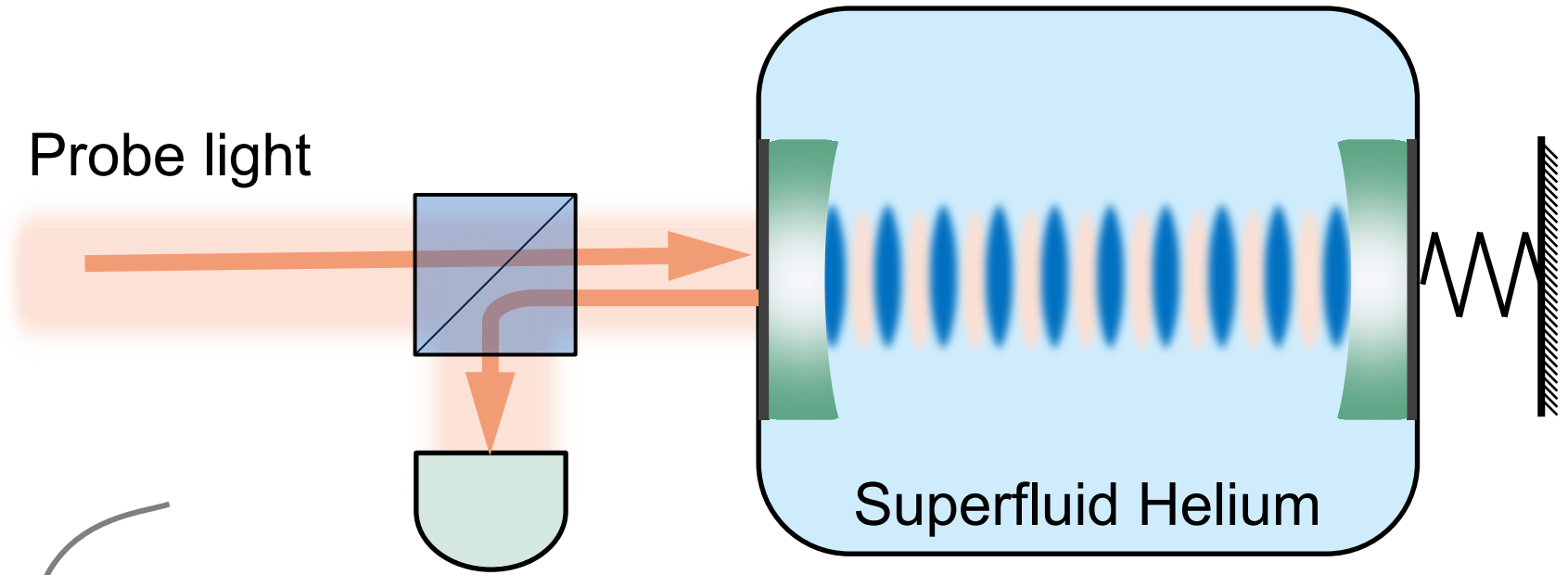
LETTER
<https://doi.org/10.1038/s41586-018-0038-x>
Stabilized oscillator
C. F. Ockeloen-Korppi

nature photonics **LETTERS**
<https://doi.org/10.1038/s41566-021-00866-z>
Check for updates

Optomechanical **RESEARCH**
QUANTUM SYSTEMS
Hanbury Brown and Twiss interferometry of single phonons from an optomechanical resonator
Sungkun Hong,^{1*} Ralf Riedinger,^{1*} Igor Marinković,^{2*} Andreas Wallucks,^{2*} Sebastian G. Hofer,¹ Richard A. Norte,² Markus Aspelmeyer,^{1,†} Simon Gröblacher^{2,†}



Superfluid Optomechanics



Optomechanical interaction
Converts μeV phonons to eV photons



Matthew Dolan



Peter Cox

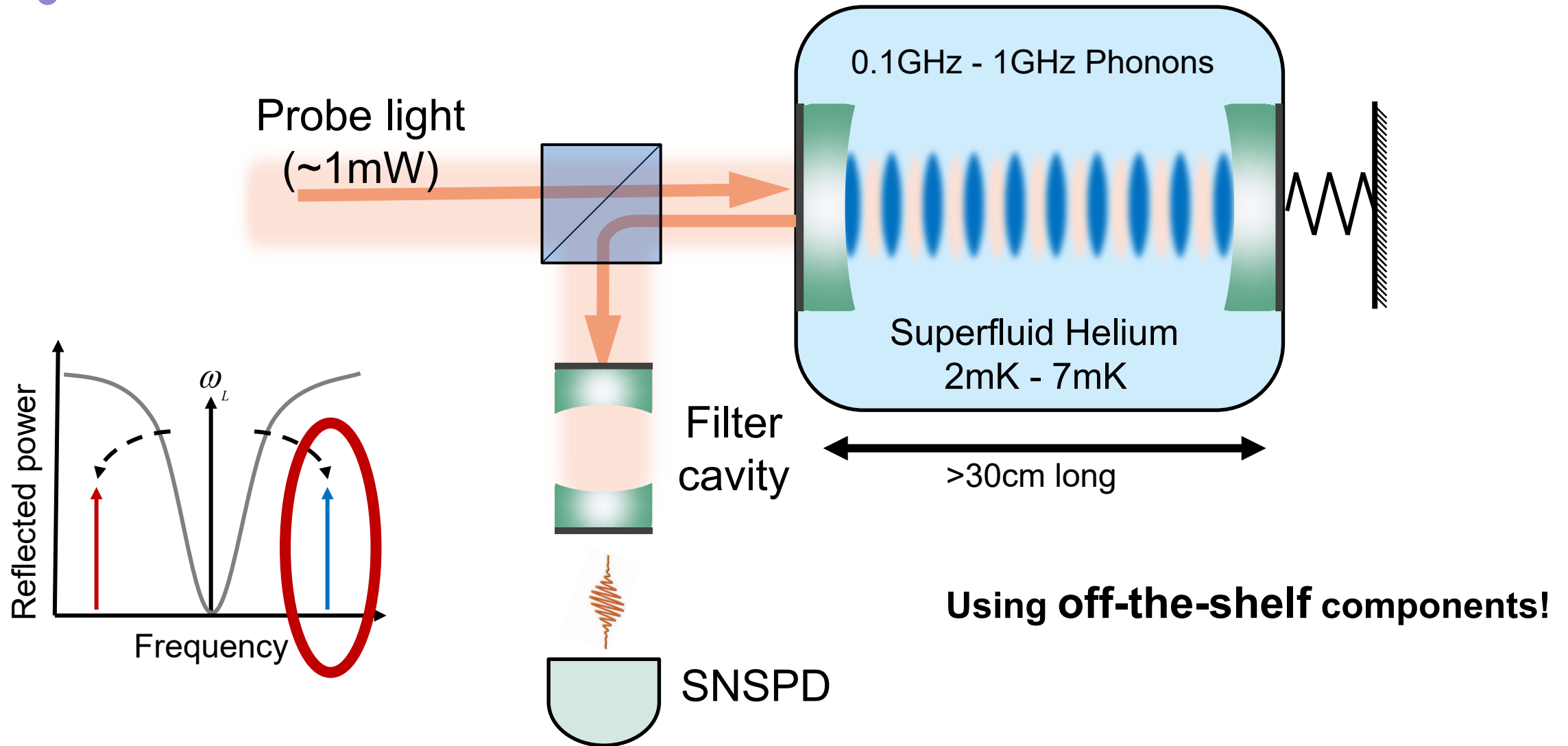


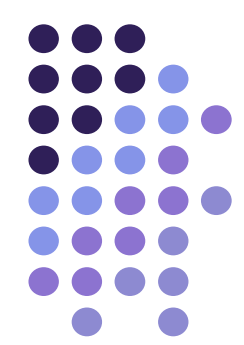
Maxim Goryachev



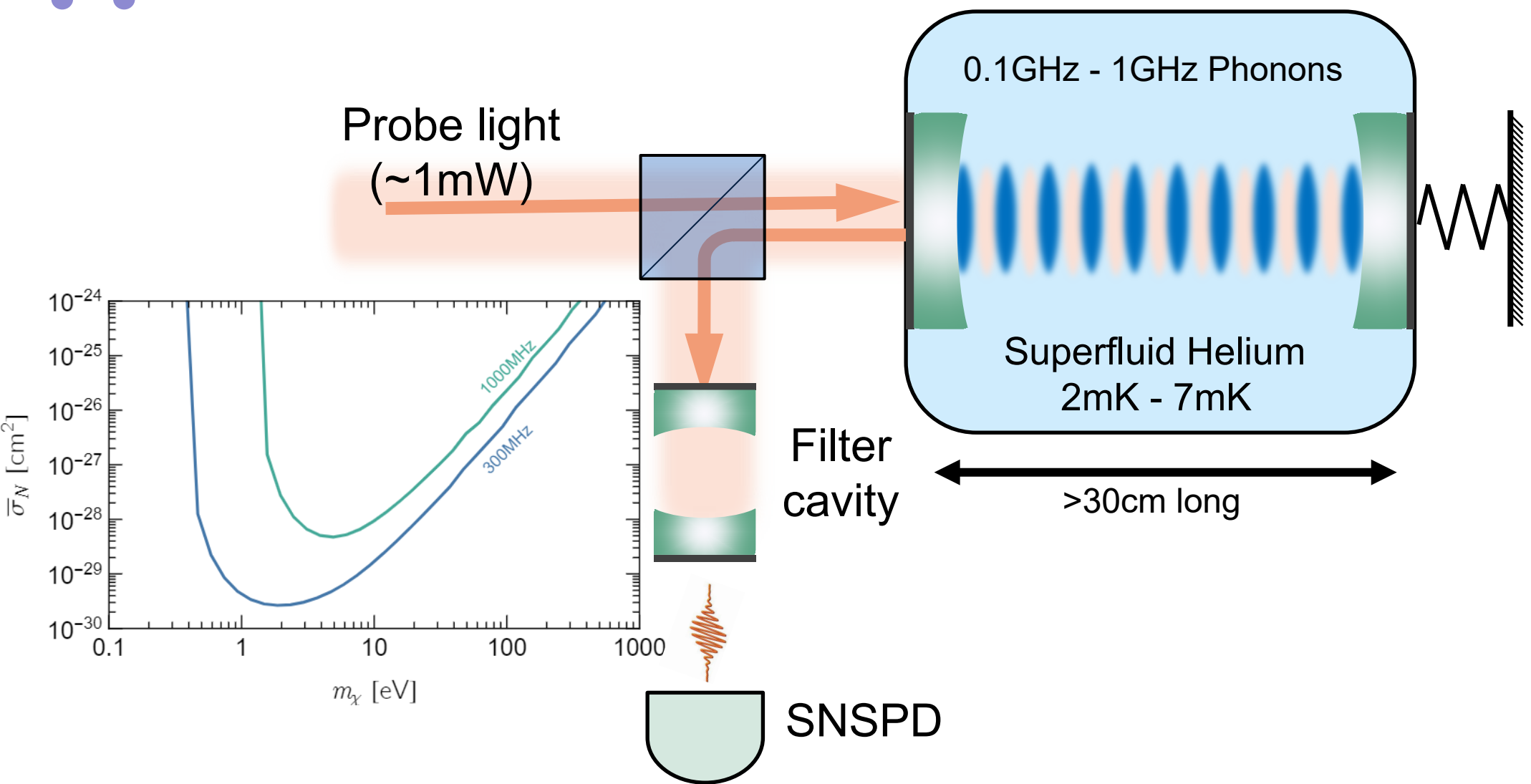
Ben McAllister

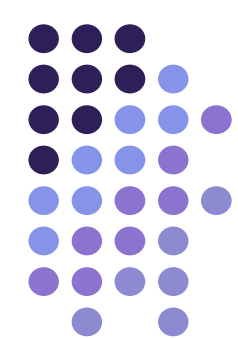
Superfluid Dark Matter Detector





Superfluid Dark Matter Detector





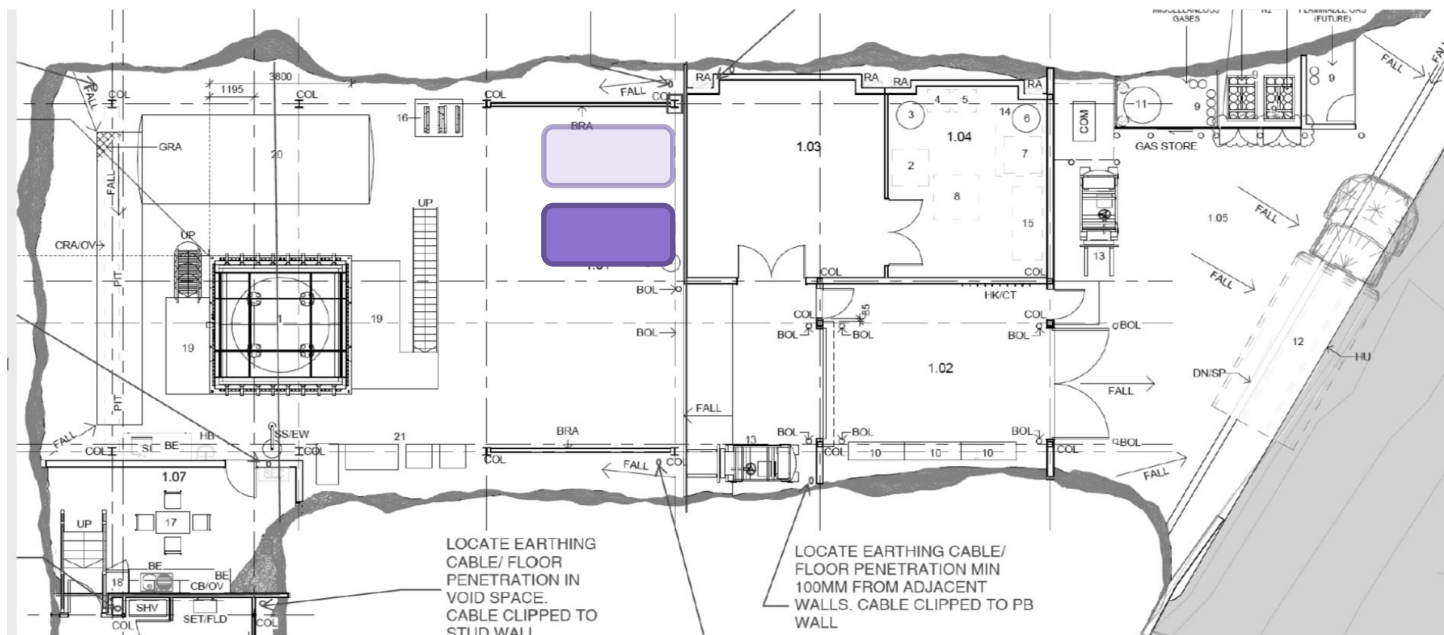
Stawell Underground Physics Laboratory

**Short term goal – Proof of principle demonstration above ground.
Long term goal – LIEF Grant for x1 (ideally x2) cryostat in SUPL.**

Sue Barrell
(Chair)

Renata Polotnianka
(Facilities & Laboratory Manager)

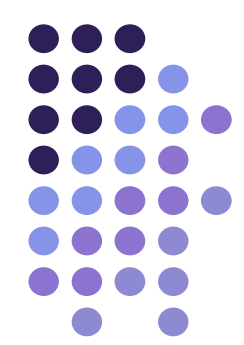
Geoff Taylor
(Research committee)



Other labs installing similar capabilities:

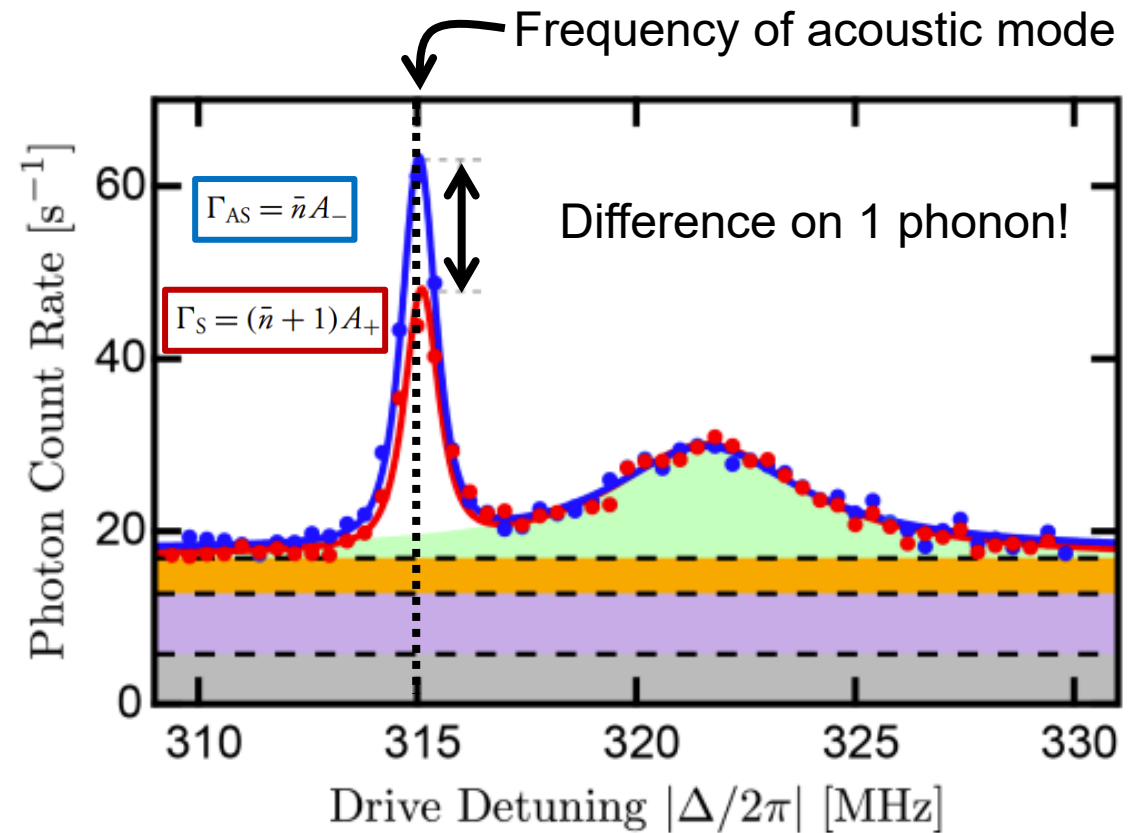
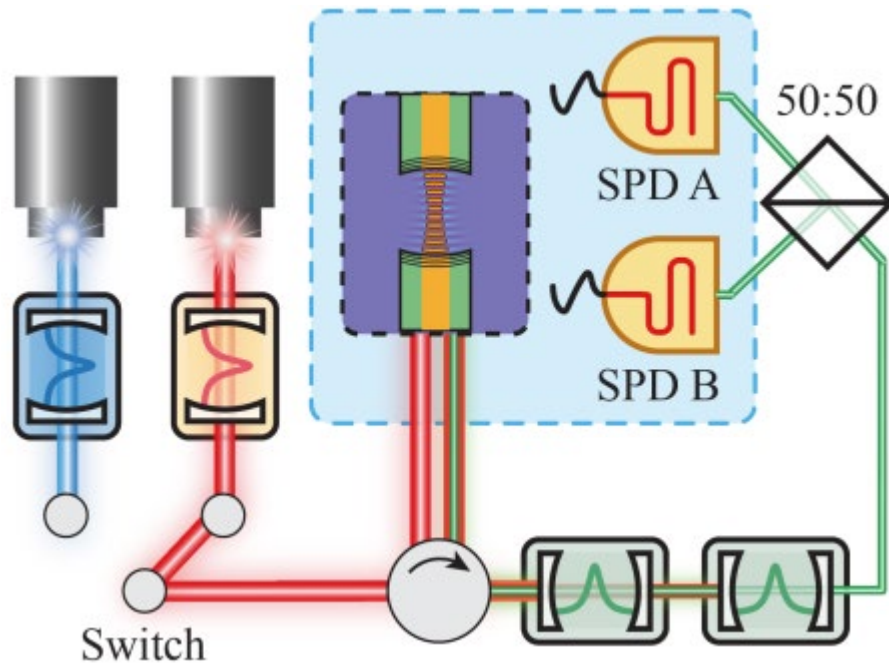
SNOLAB – Cryogenic underground test facility (CUTE)

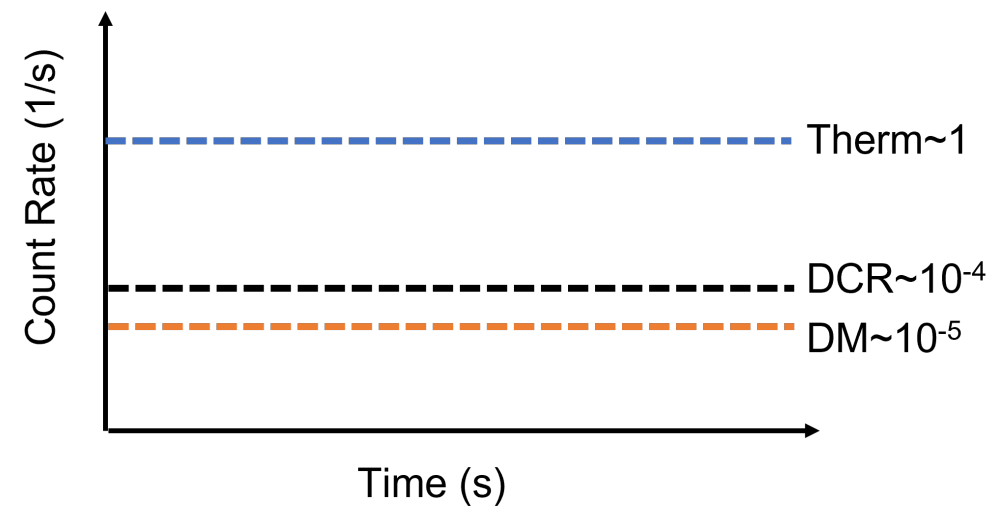
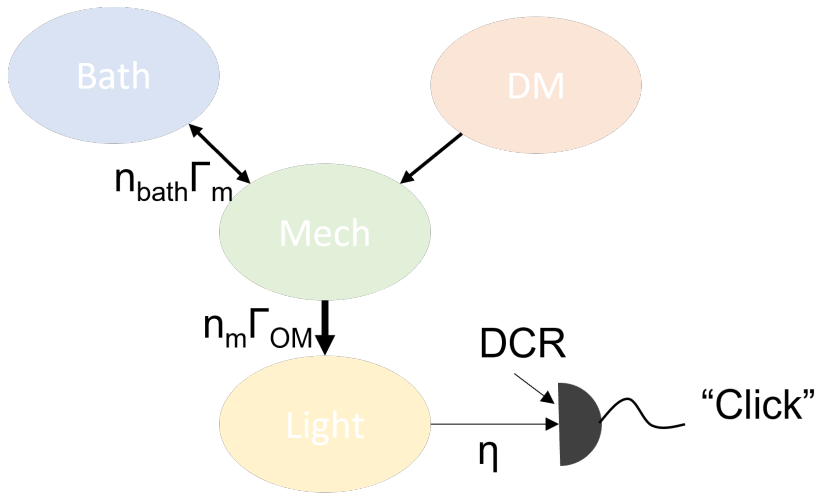
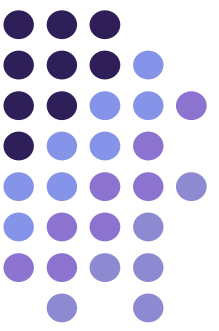
Gran Sasso – Cryogenic Underground Observatory for Rare Events (CUORE)

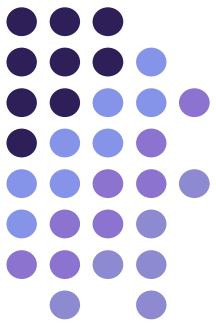


Thankyou!

Superfluid Optomechanics: Phonon Counting







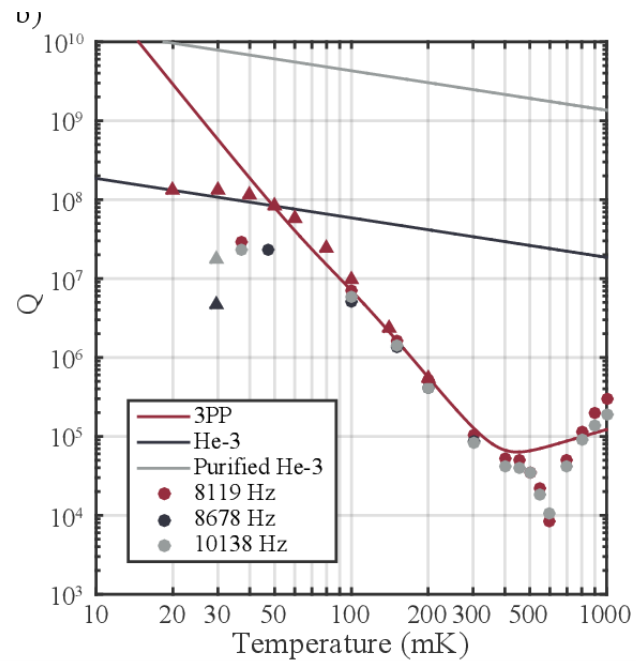
Published: 07 November 2016

Ultra-High Q Acoustic Resonance in Superfluid ^4He

L. A. De Lorenzo & K. C. Schwab

Journal of Low Temperature Physics **186**, 233–240 (2017) | [Cite this article](#)

621 Accesses | 17 Citations | 3 Altmetric | [Metrics](#)



Published: March 1999

An Advanced Dilution Refrigerator Designed for the New Lancaster Microkelvin Facility

D. J. Cousins, S. N. Fisher, A. M. Guénault, R. P. Haley, I. E. Miller, G. R. Pickett, G. N. Plenderleith, P. Skyba, P. Y. A. Thibault & M. G. Ward

Journal of Low Temperature Physics **114**, 547–570 (1999) | [Cite this article](#)

519 Accesses | 31 Citations | [Metrics](#)

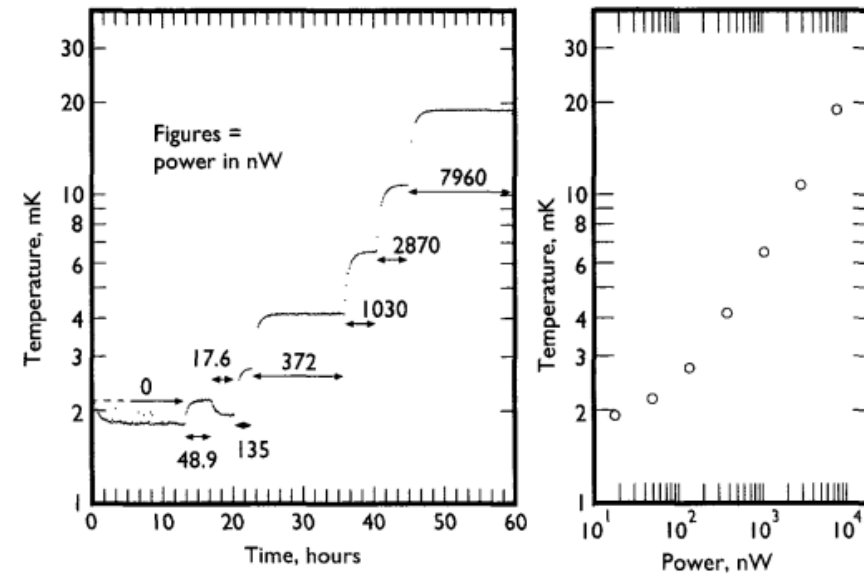
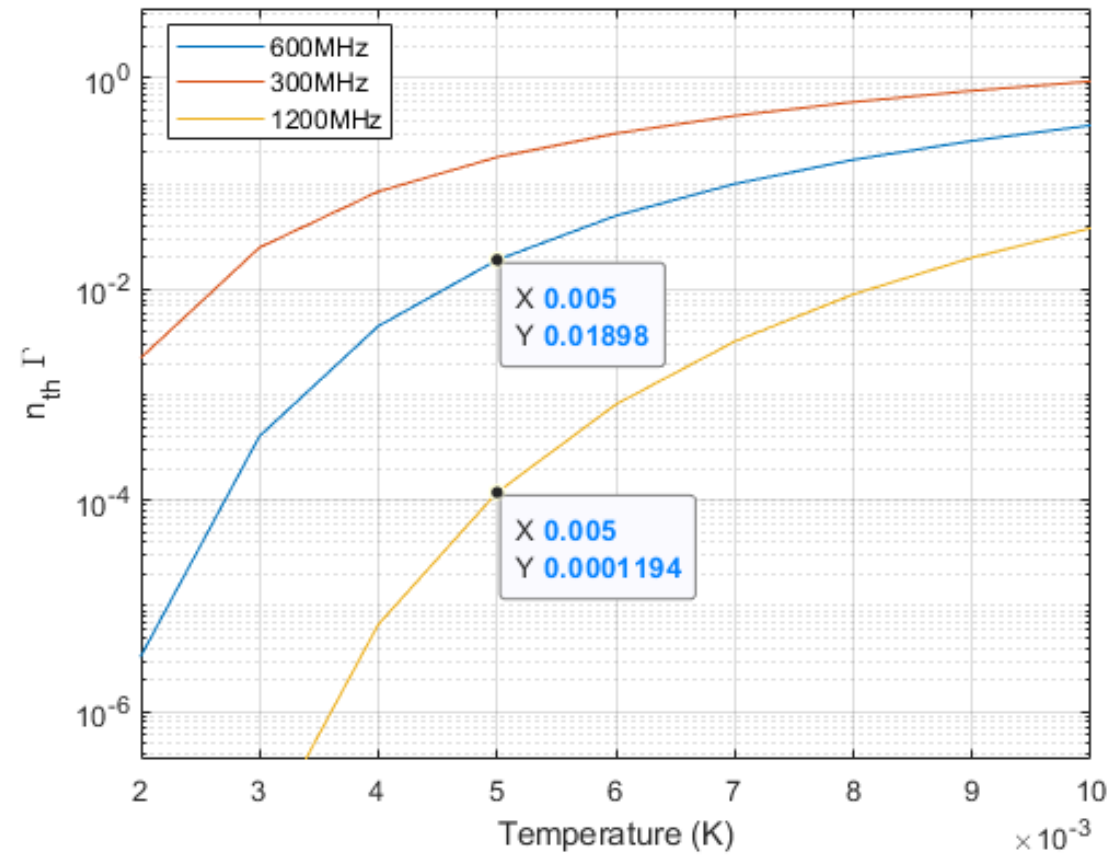
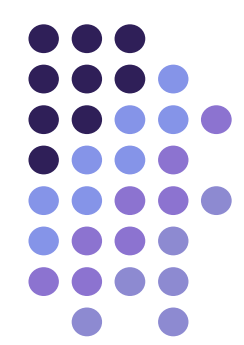
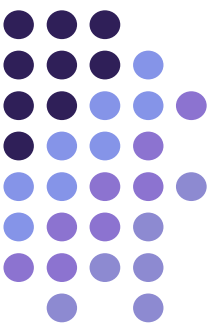


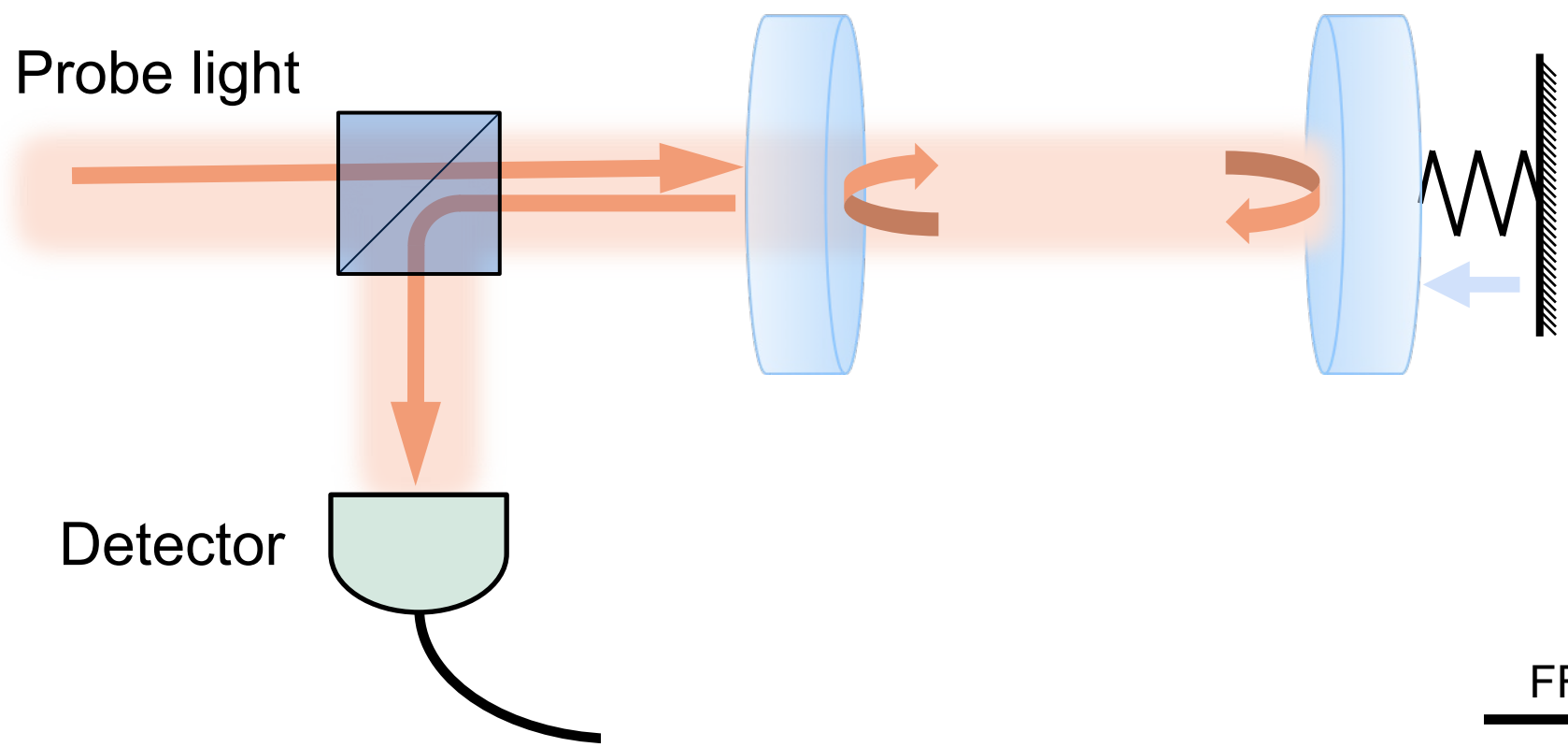
Fig. 11. Measurements of the cooling power of the refrigerator at $265 \mu\text{mol/s}$.



1550nm laser
780nm laser
375nm laser

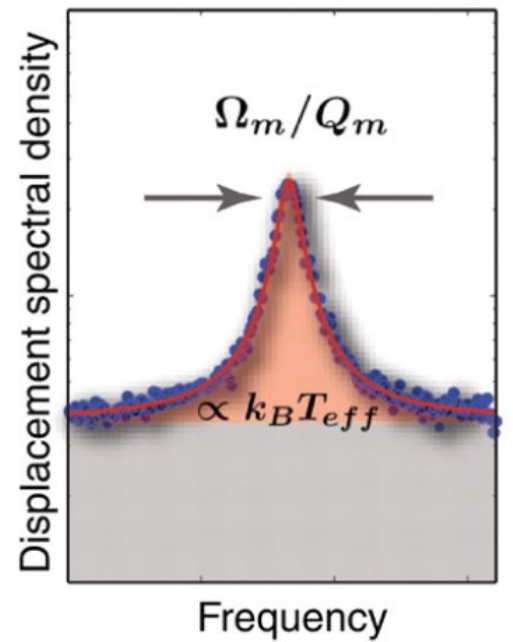


Cavity Optomechanics

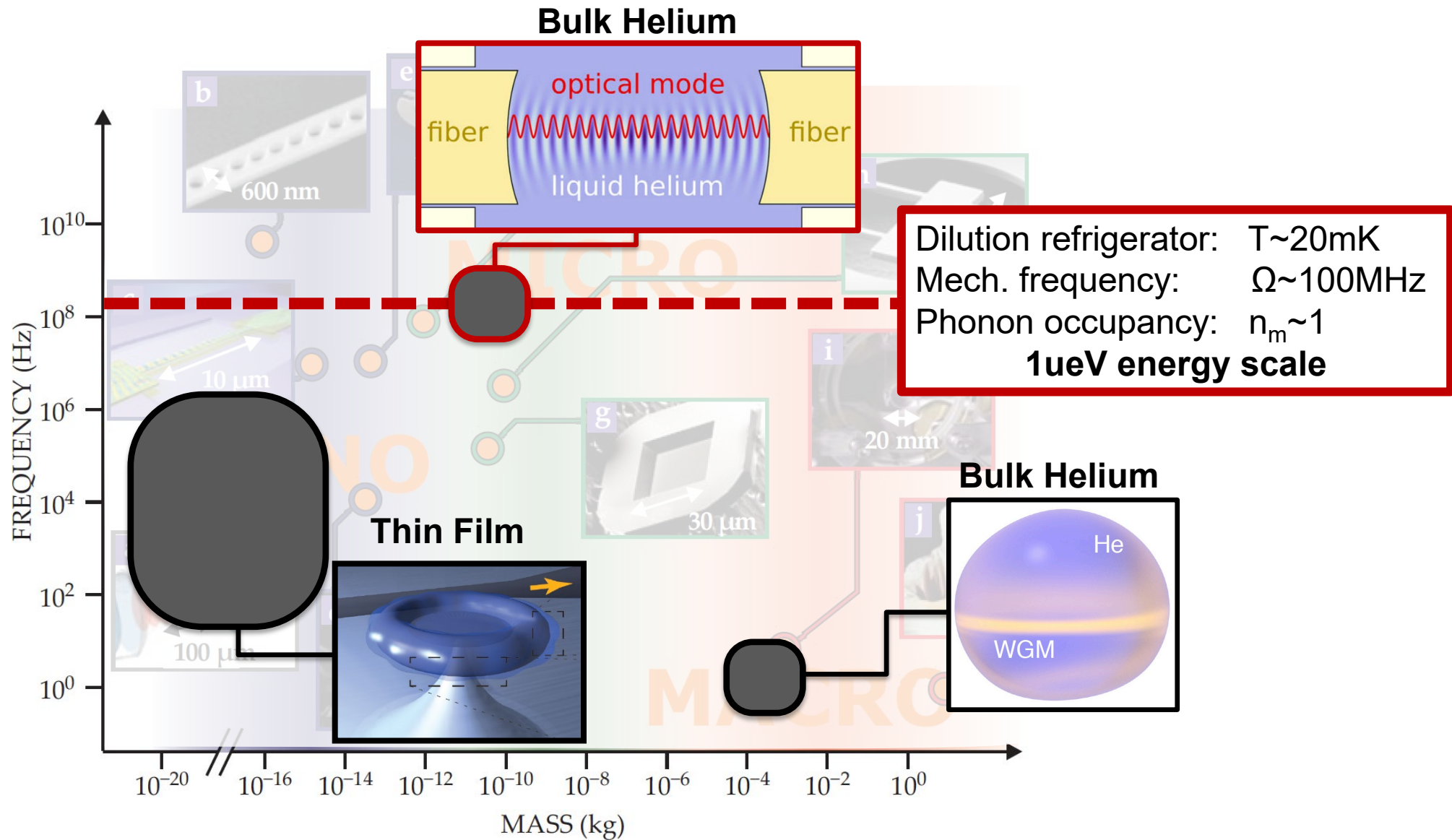


Readout tick

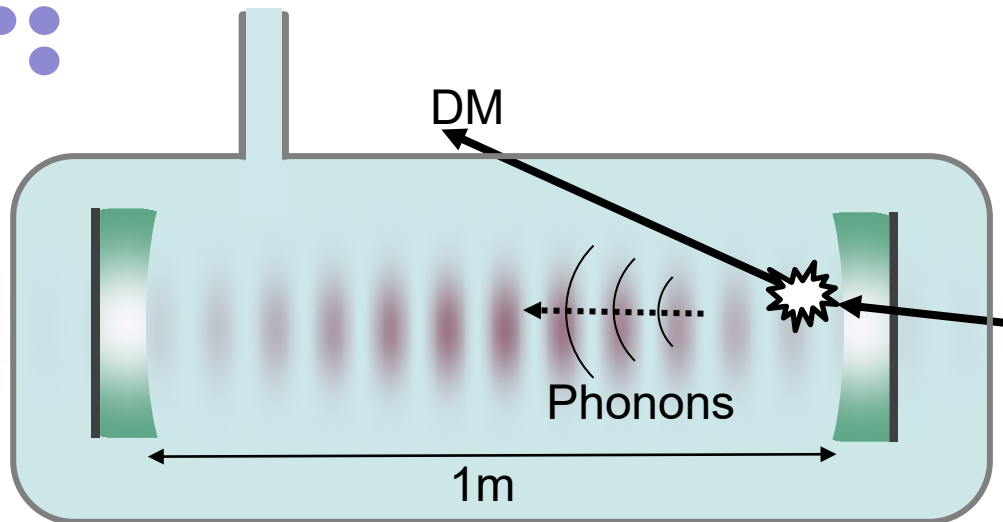
FFT



Superfluid Optomechanics



Optomechanical Detection of Dark Matter



Phonons modes (10^{-6} eV)

- Very different detection scheme.
- Capable of resolving thermal motion ($\sim \mu\text{eV}$).
- Distributed sensing throughout medium (compare to bolometers at the wall).
- Simultaneously measure multiple modes.

Questions/concerns:

- Can only observe specific modes (i.e. narrow energy band).
- What is the rate/cross-section and emission pattern?
- 2-phonon scattering generates non-classical state...!
- Cavity enhanced scattering (i.e. Purcell-like enhancement)?

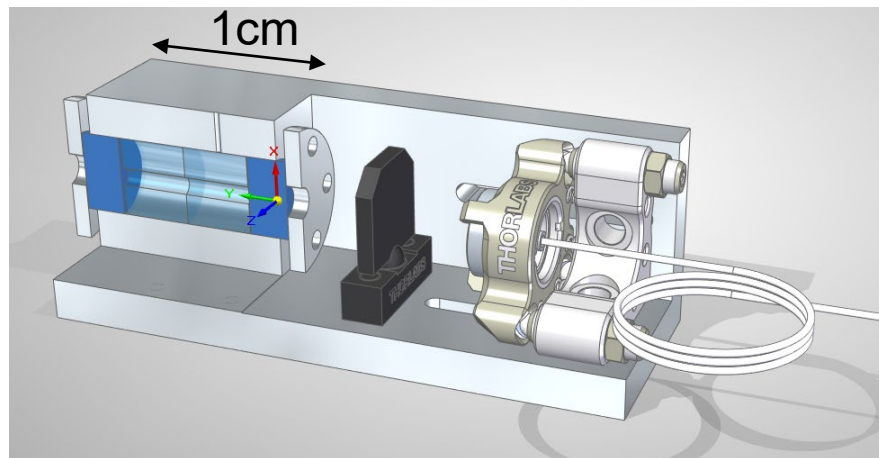
Could also optically detect

Helium Excimers (10eV)

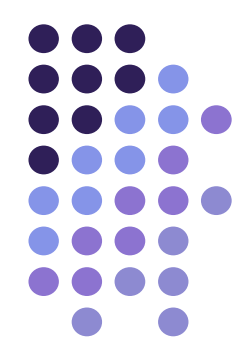
- Detect via fluorescence of long lived triplet state.

Rotons (10^{-3} eV)

- Detected via optical scattering.



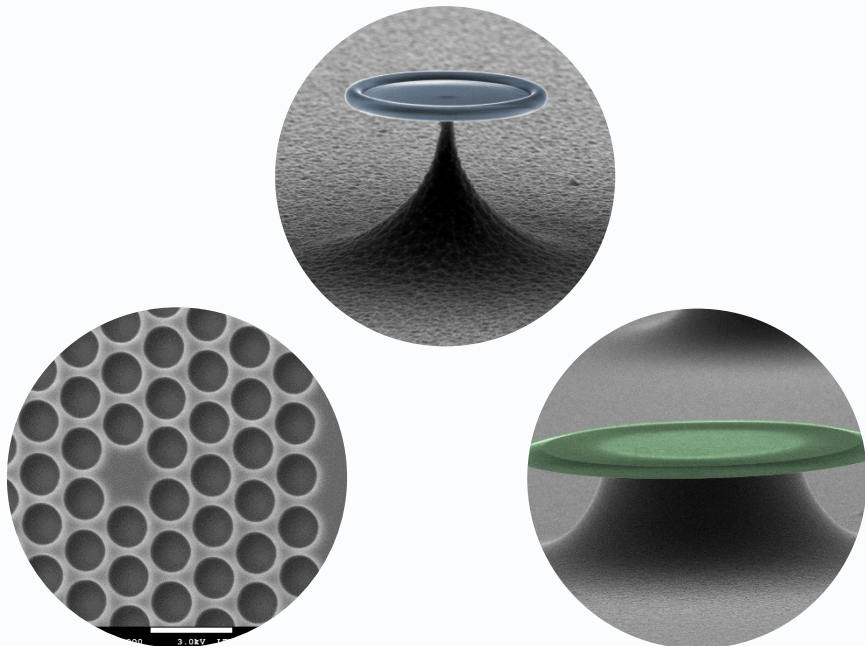
Design for macroscopic cavity filled with LHe



Superfluid Helium Optomechanics

University of Queensland

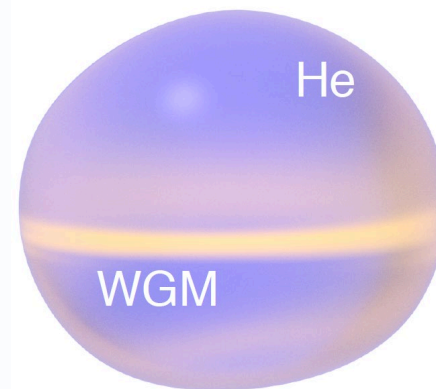
Thin films of superfluid Helium covering optical devices



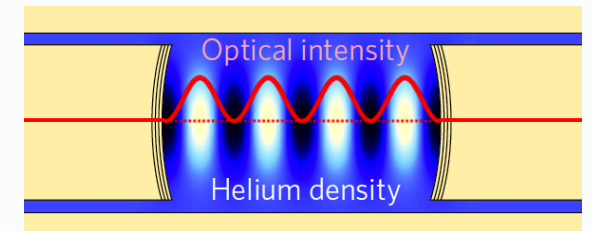
Yale University

Bulk superfluid Helium within optical device

Levitated droplet
~1cm

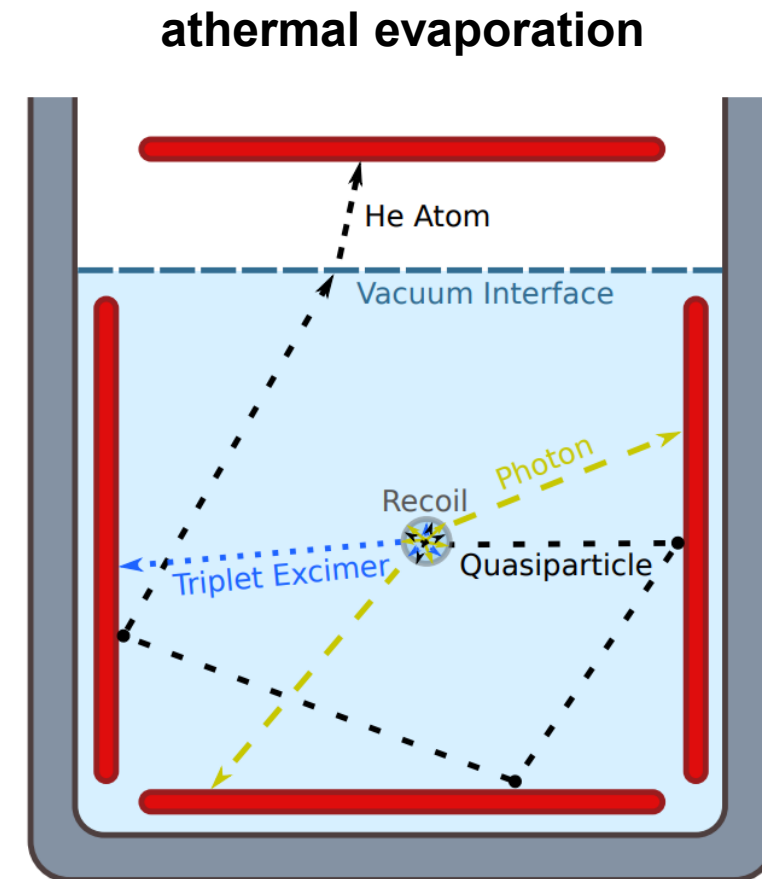


F-P cavity immersed
100um-10cm

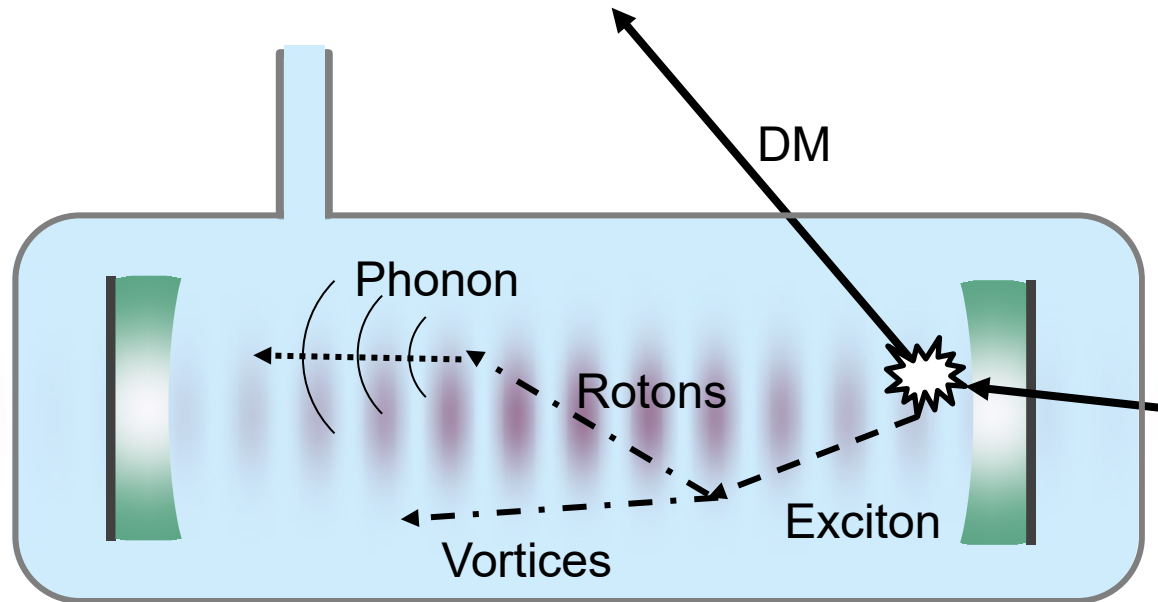
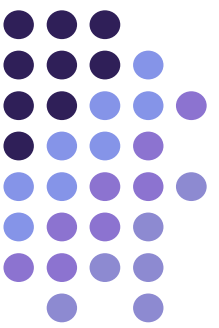


Helium as a target material

- Low nuclear mass → efficient transfer of KE
- Multiple signal channels → allows signal discrimination
- High radiopurity (no isotope) and freeze-out of impurities → low spurious signals
- A large band gap energy of 19eV → low spurious signals
- A liquid state down to 0K → reduce thermal noise
- Cheaper than Xenon by x10!



Optical Readout of DM events



As the energy dissipates it causes a “shower” of particles in the superfluid.

Helium Excimers (10eV)

- Ionizing radiation produces unstable He₂ molecules.
- 1 MeV recoil event creates about >10,000 He₂ molecules
- Detect via fluorescence of long lived triplet state.
- Enables location imaging.

Rotons (10⁻³ eV)

- Long lived quasi-particles.
- Detected via optical scattering.

Phonons modes (10⁻⁶ eV)

- Optomechanical based detection.
- Capable of resolving thermal motion (~ueV)
- Simultaneously measure multiple modes.

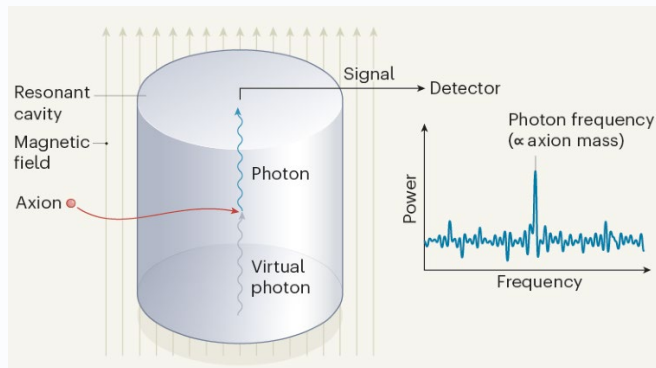
Direct evidence for Dark Matter

Axion

HAYSTACK (USA)

ADMX (USA)

ORGAN (Australia)



WIMP

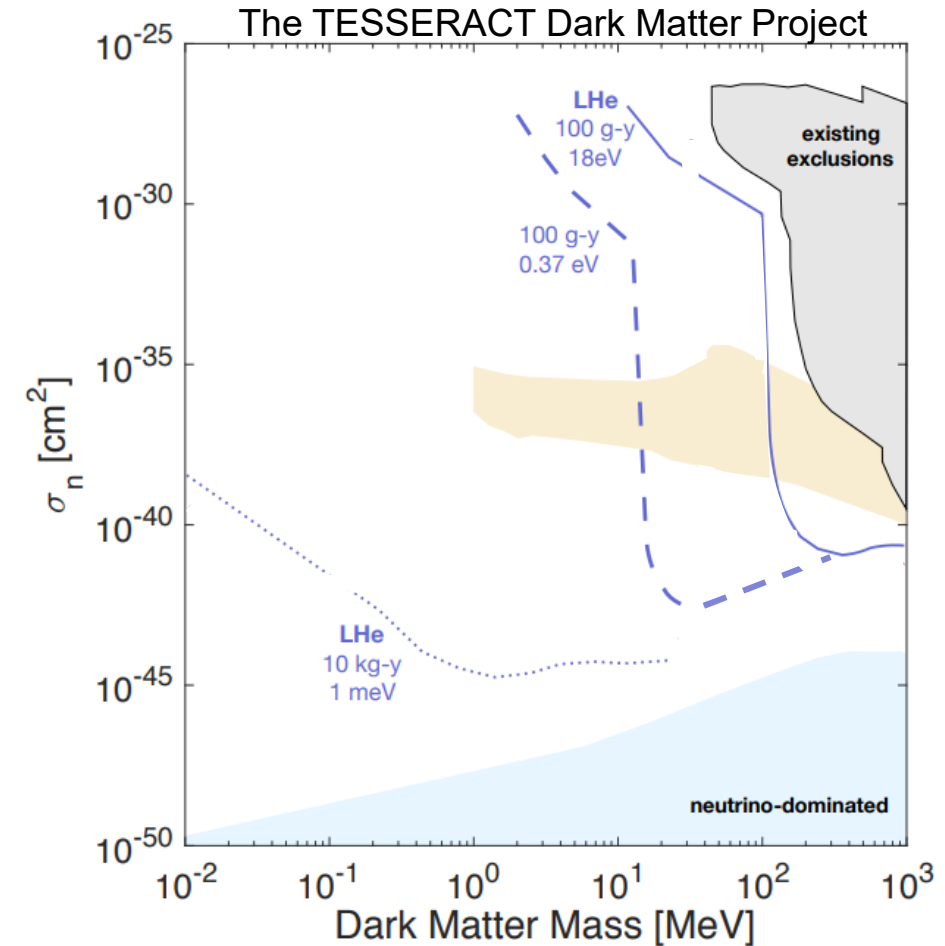
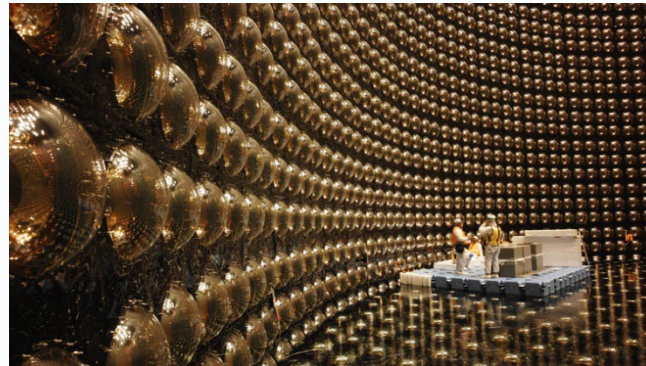
XENONnT (Italy)

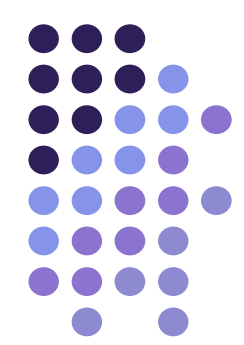
LUX-Zeplin (USA)

PandaX (China)

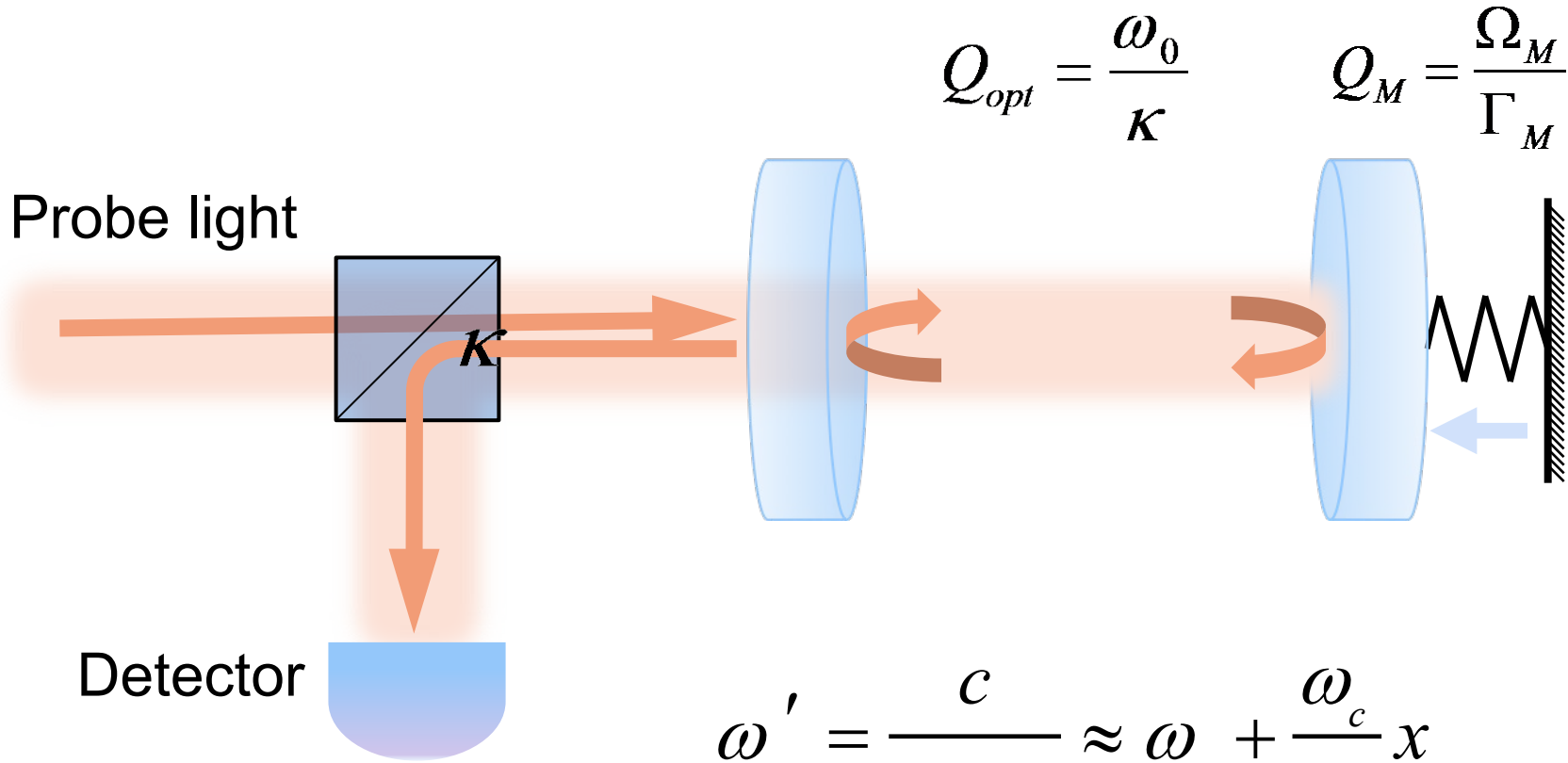
Super-Kamiokande (Japan)

SABRE (Italy/Australia)





Cavity Optomechanics



$$\omega'_c = \frac{c}{L+x} \approx \omega_c + \frac{\omega_c}{L} x$$

$$H_{cav} = \hbar(\omega_c + gx)a^\dagger a$$

$$g_{om} = -\frac{\partial \omega_o}{\partial x}$$

$$g_0 = g_{om} x_{ZPF}$$

Optomechanical Interaction

Linearize by taking $a = \alpha + \delta a$

$$H_{int} = \hbar g \alpha \left(\underbrace{\delta a^\dagger b^\dagger + \delta a b}_{\text{Optomechanical entanglement}} + \underbrace{\delta a^\dagger b + \delta a b^\dagger}_{\text{Optomechanical beam splitter}} \right)$$

Optomechanical entanglement

Optomechanical beam splitter

