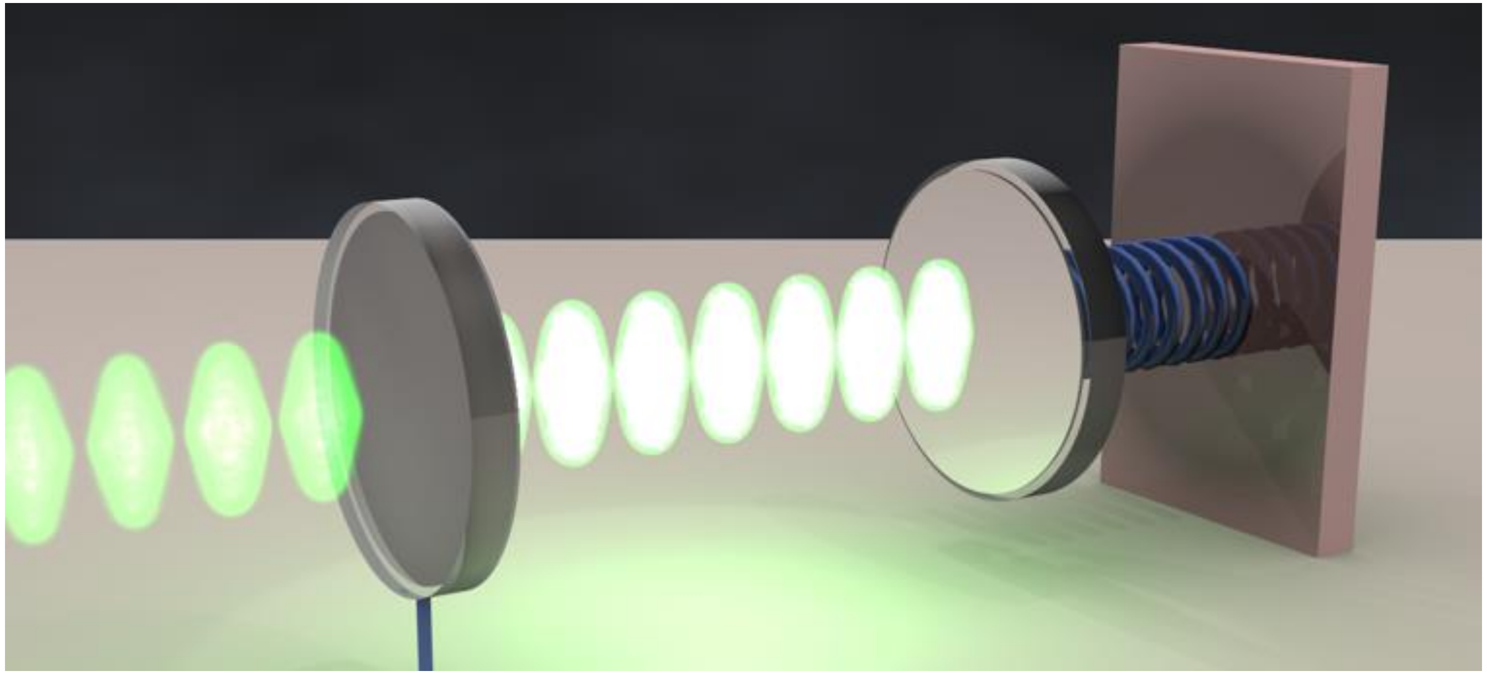
Superfluid Optomechanics for Dark Matter Detection



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

EQUS · Australian Government Australian Research Council · BQI · The University of Queensland Australia

Superfluid Helium for Dark Matter Detection

Dr. Ben Brubaker

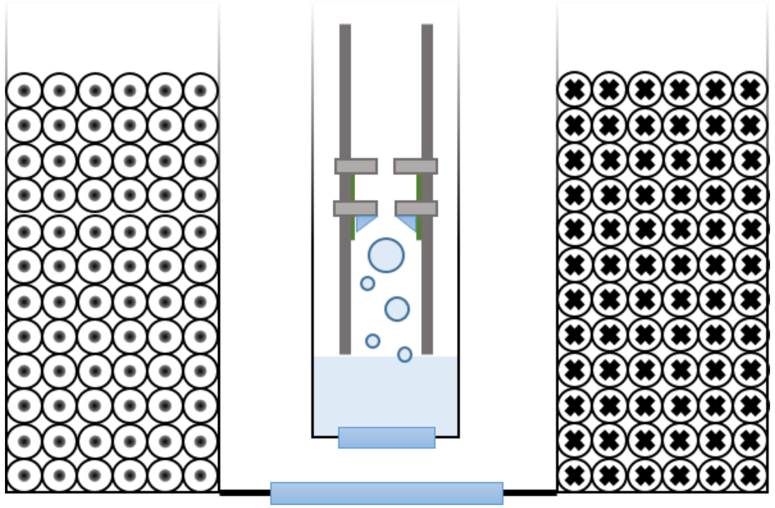
(PhD in lab of Steve Lamoreaux)

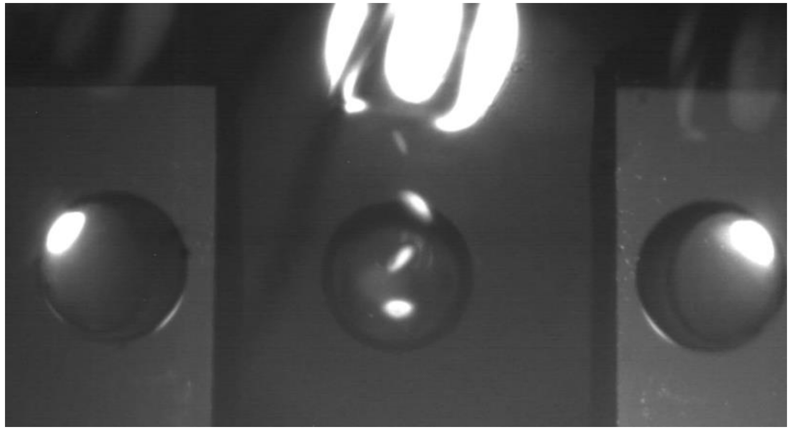
HAYSTAC

A/Prof Scott Hertel

(Postdoc in lab of Daniel McKinsey)

LUX-ZEPLIN





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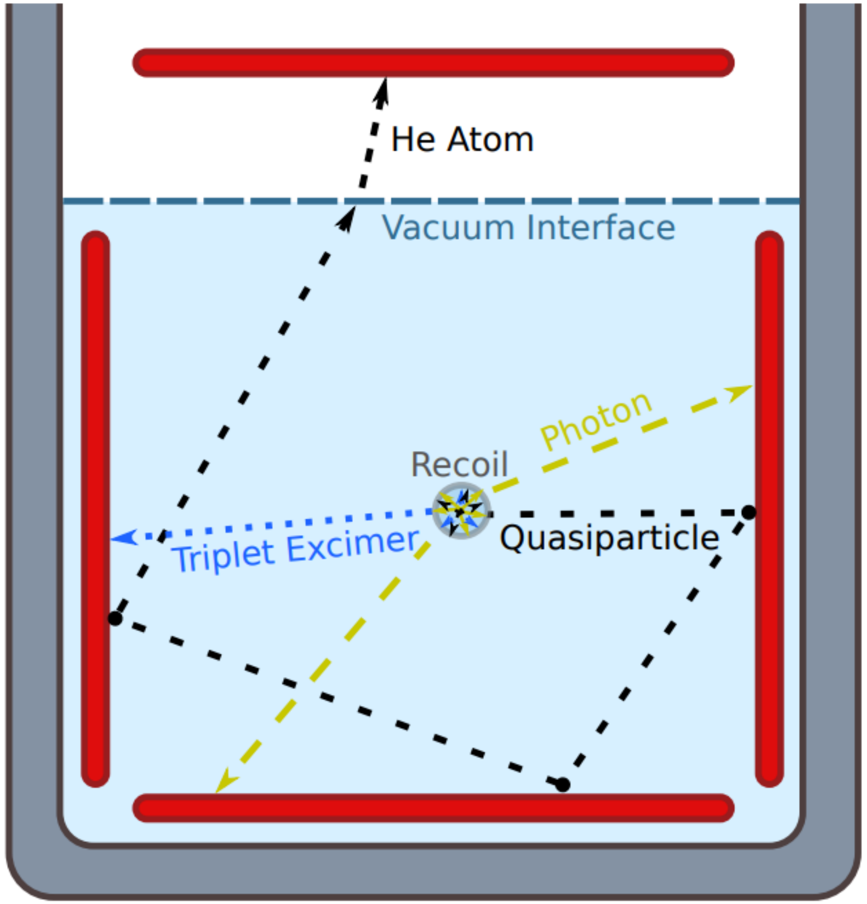
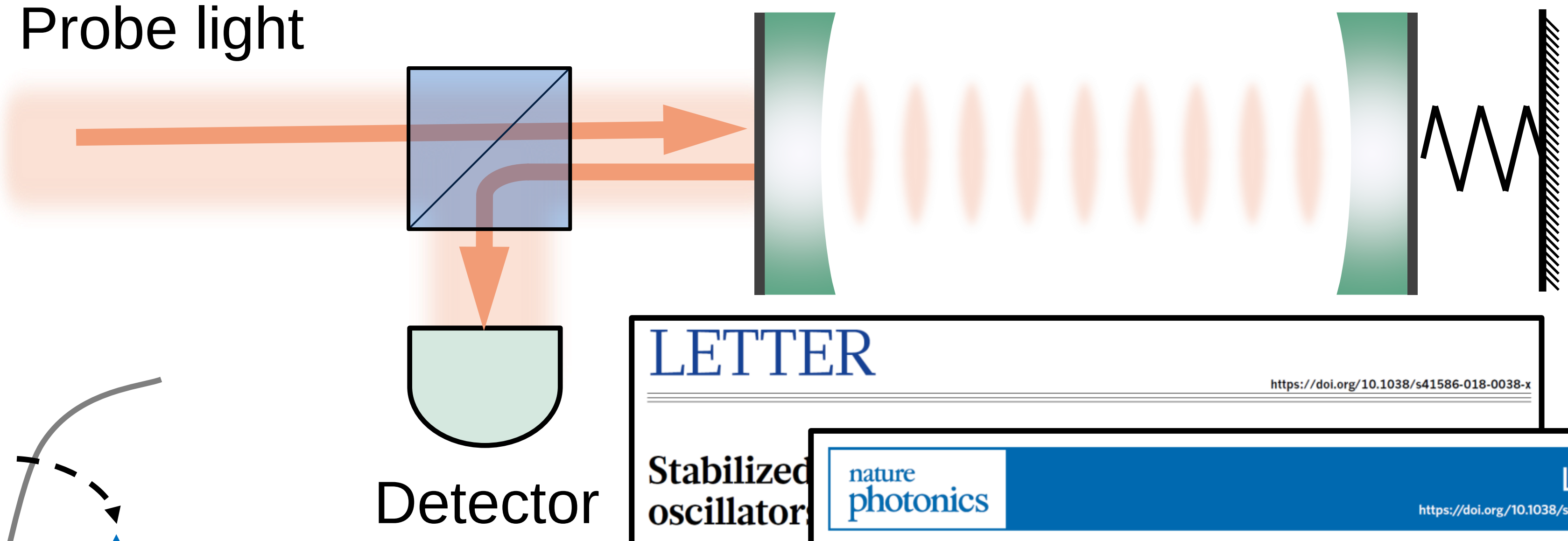
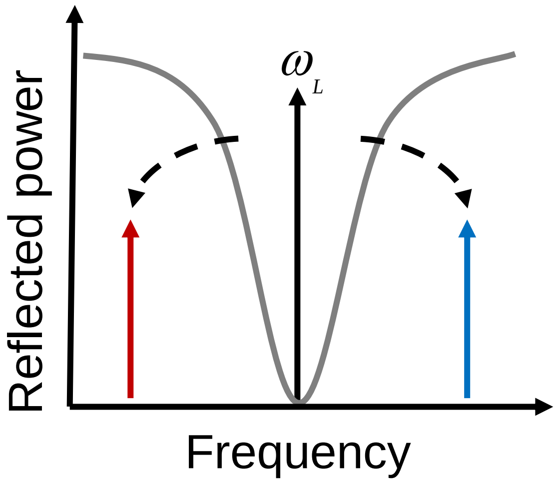
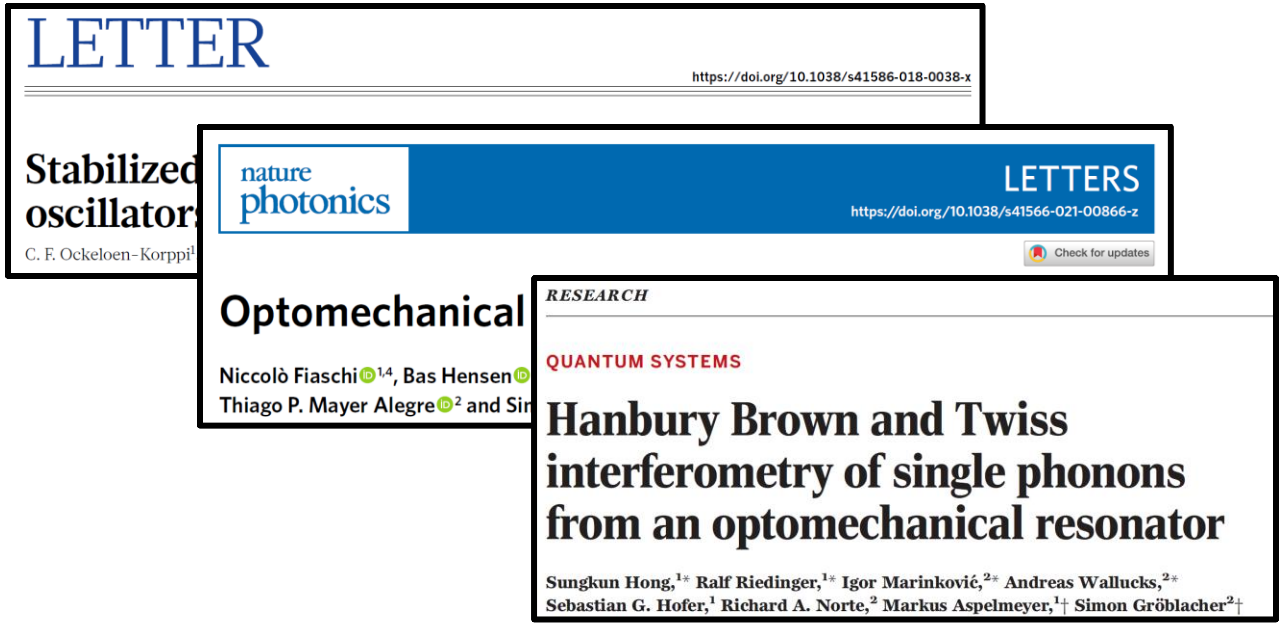


Optomechanics







LETTER
https://doi.org/10.1038/s41586-018-0038-x

Stabilized
oscillator
C. F. Ockeloen-Korppi[1]

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

Optomechanical
Niccolò Fiaschi[1,4], Bas Hensen
Thiago P. Mayer Alegre[2] and Si

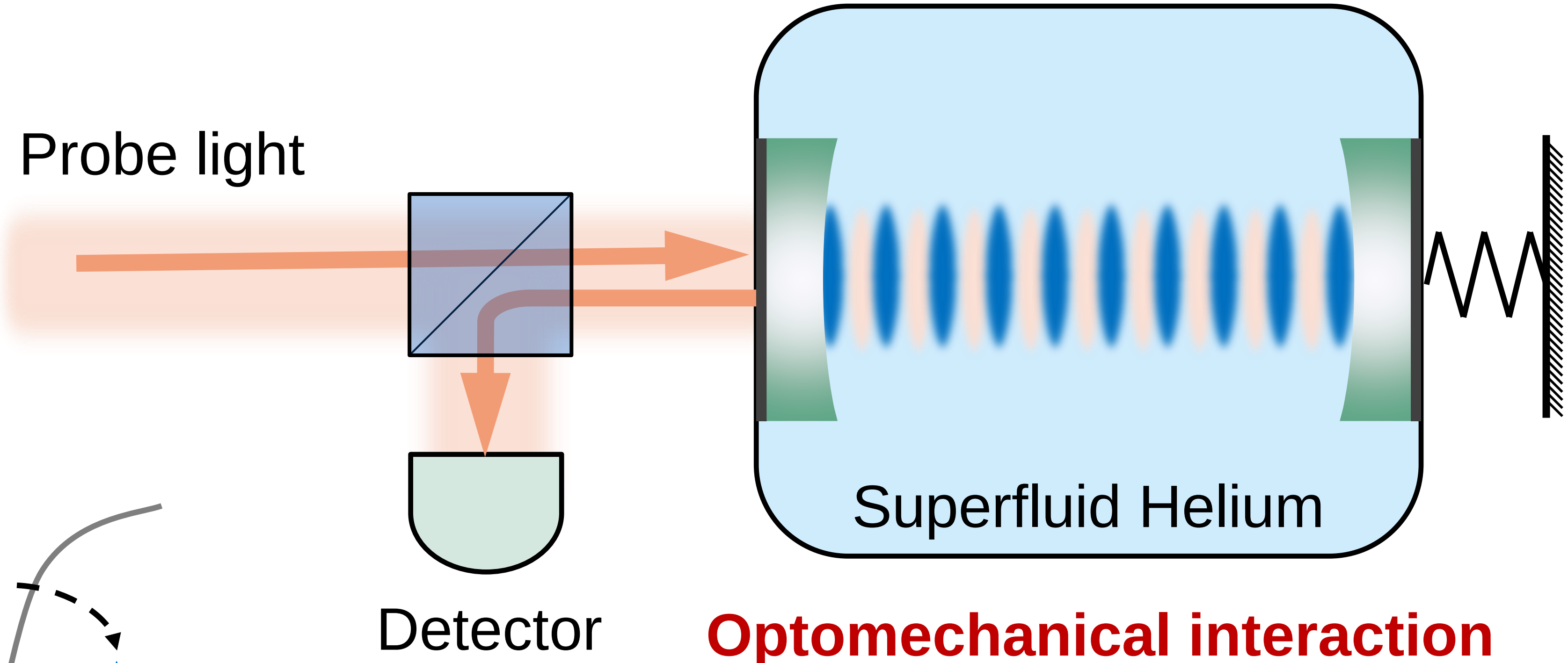
RESEARCH

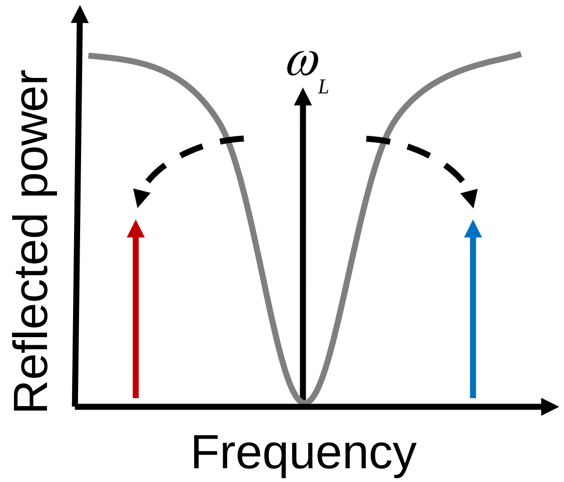
QUANTUM SYSTEMS

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†]

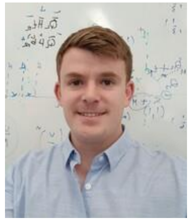
Superfluid Optomechanics

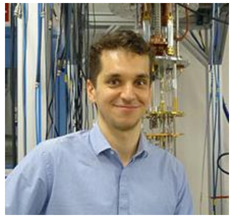




Optomechanical interaction
Converts μeV phonons to eV photons

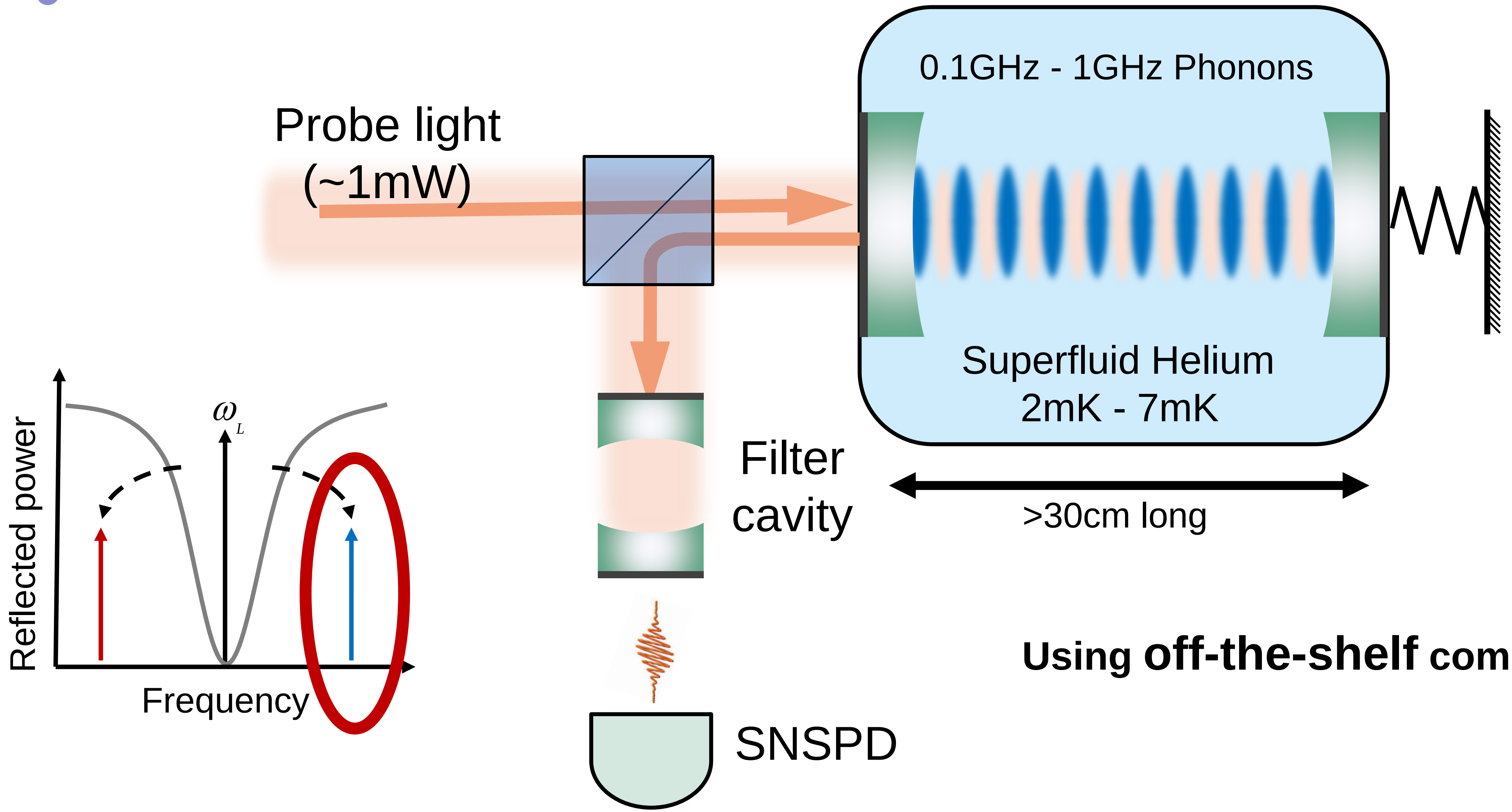

Matthew Dolan


Peter Cox


Maxim Goryachev

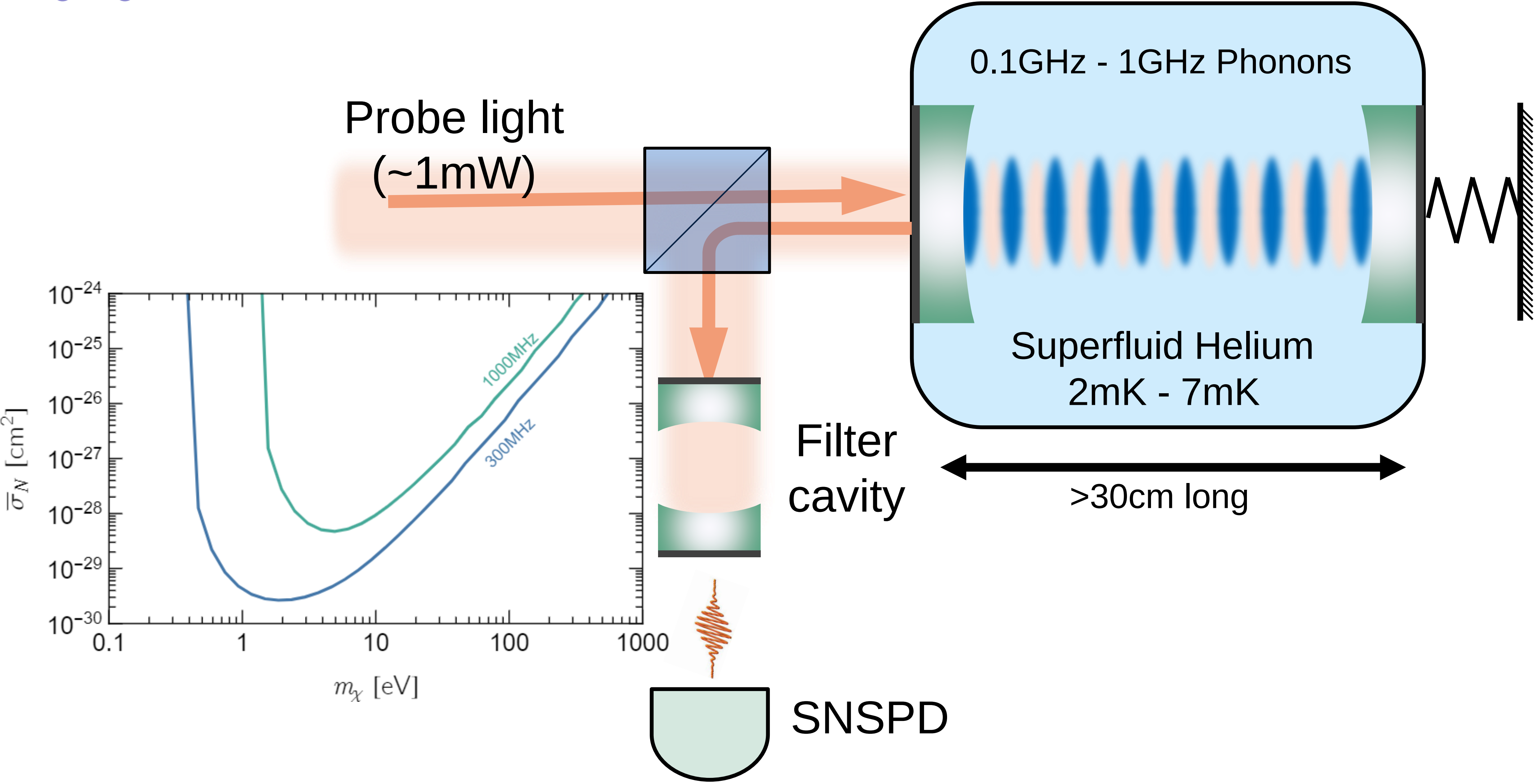

Ben McAllister

Superfluid Dark Matter Detector



Using off-the-shelf components!

Superfluid Dark Matter Detector



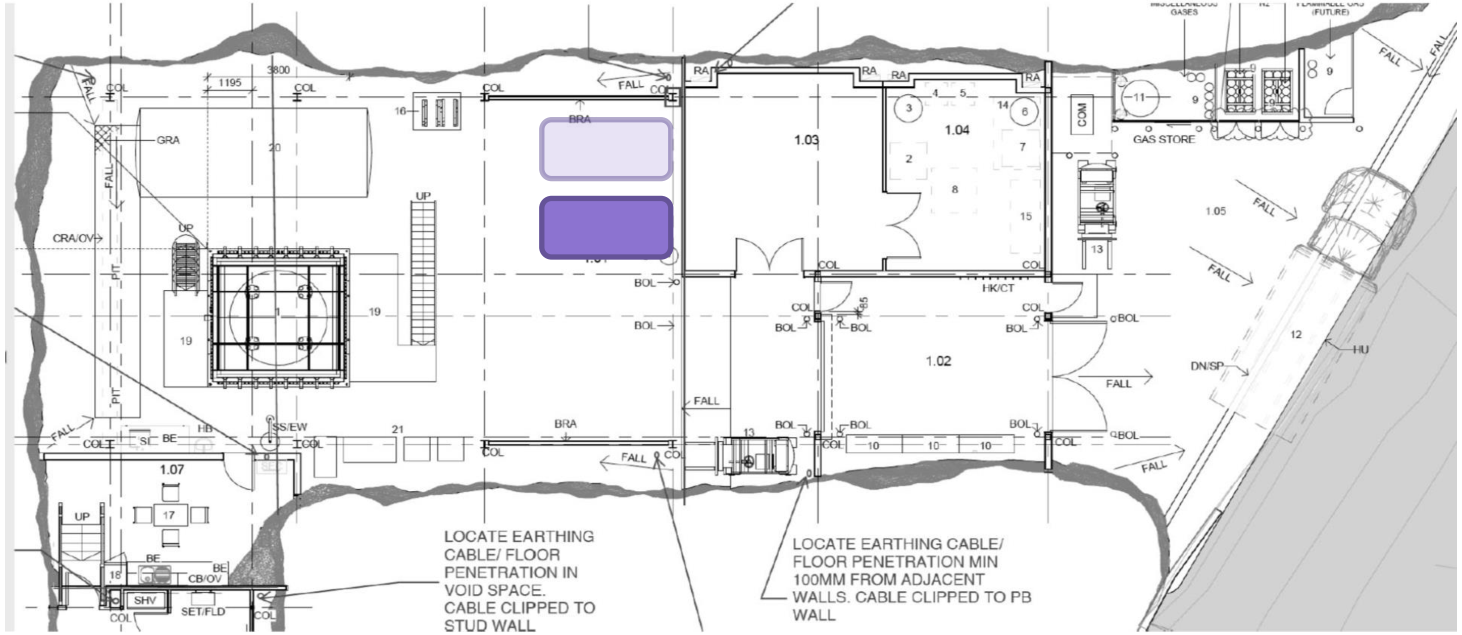
Stawell Underground Physics Laboratory

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)

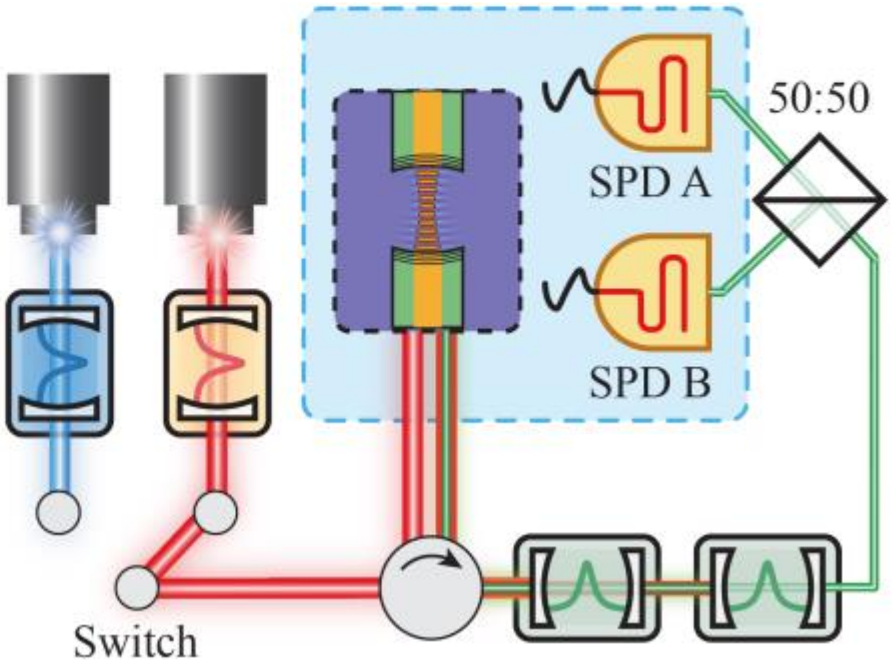
Geoff Taylor
(Research committee)

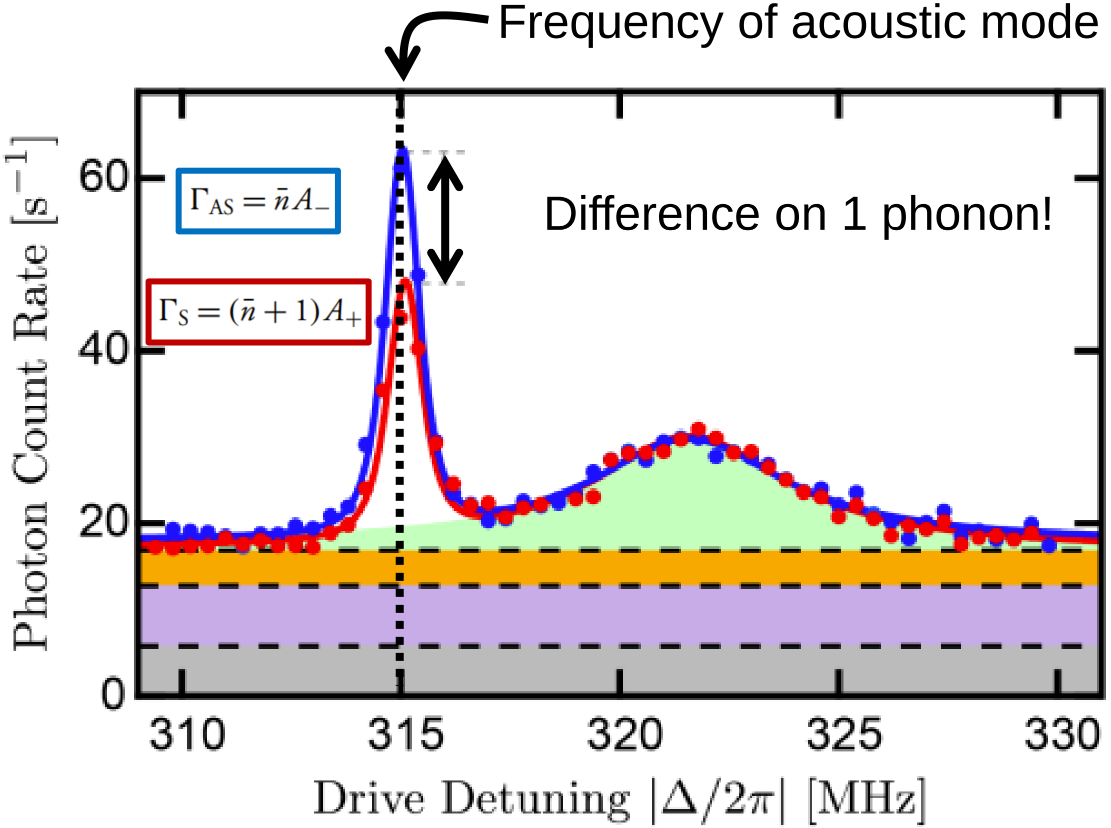


Other labs installing similar capabilities:
SNOLAB – Cryogenic underground test facility (CUTE)
Gran Sasso – Cryogenic Underground Observatory for Rare Events (CUORE)

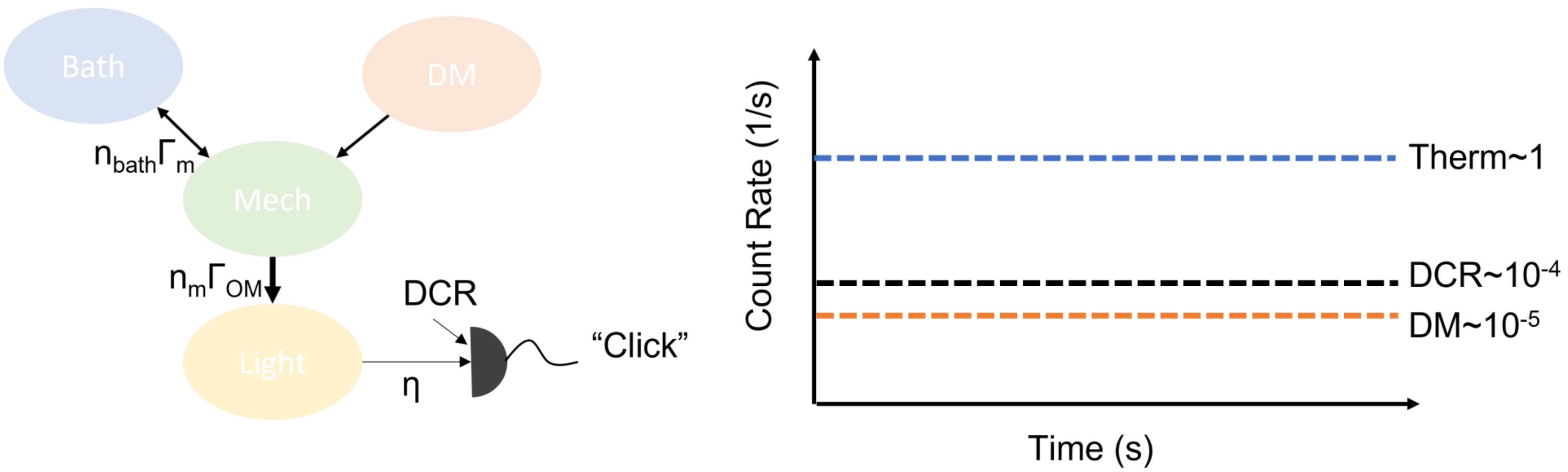
Thankyou!

Superfluid Optomechanics: Phonon Counting





Y. S. S. Patel, et. al., "Measuring High-Order Phonon Correlations in an Optomechanical Resonator", arXiv:2201.07340v1



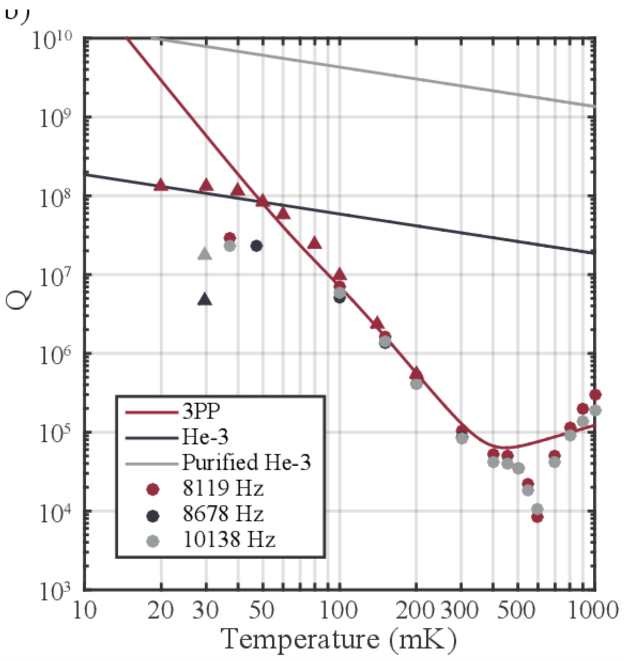
Bath
DM
$n_{bath}\Gamma_m$
Mech
$n_m\Gamma_{OM}$
DCR
Light
η
"Click"
Count Rate (1/s)
Therm~1
DCR~10-4
DM~10-5
Time (s)

Published: 07 November 2016

Ultra-High *Q* Acoustic Resonance in Superfluid ^{4}He

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

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



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

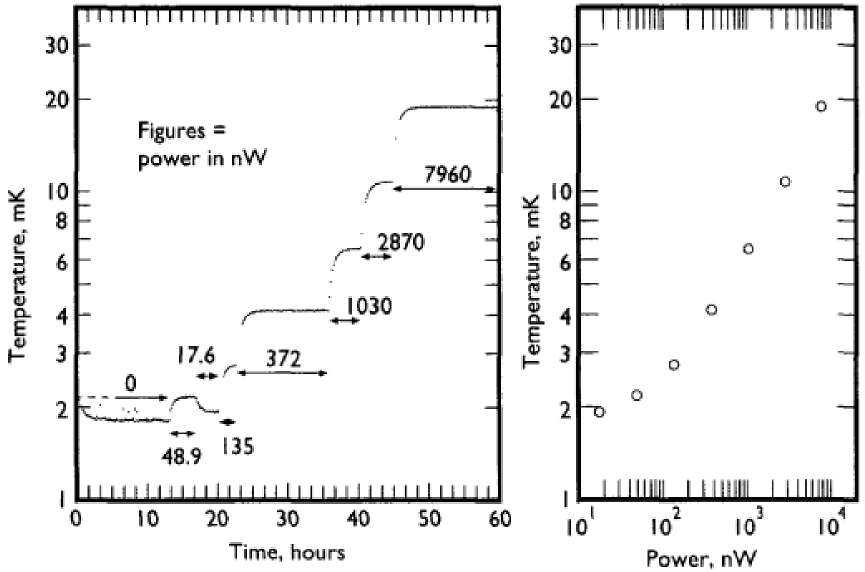
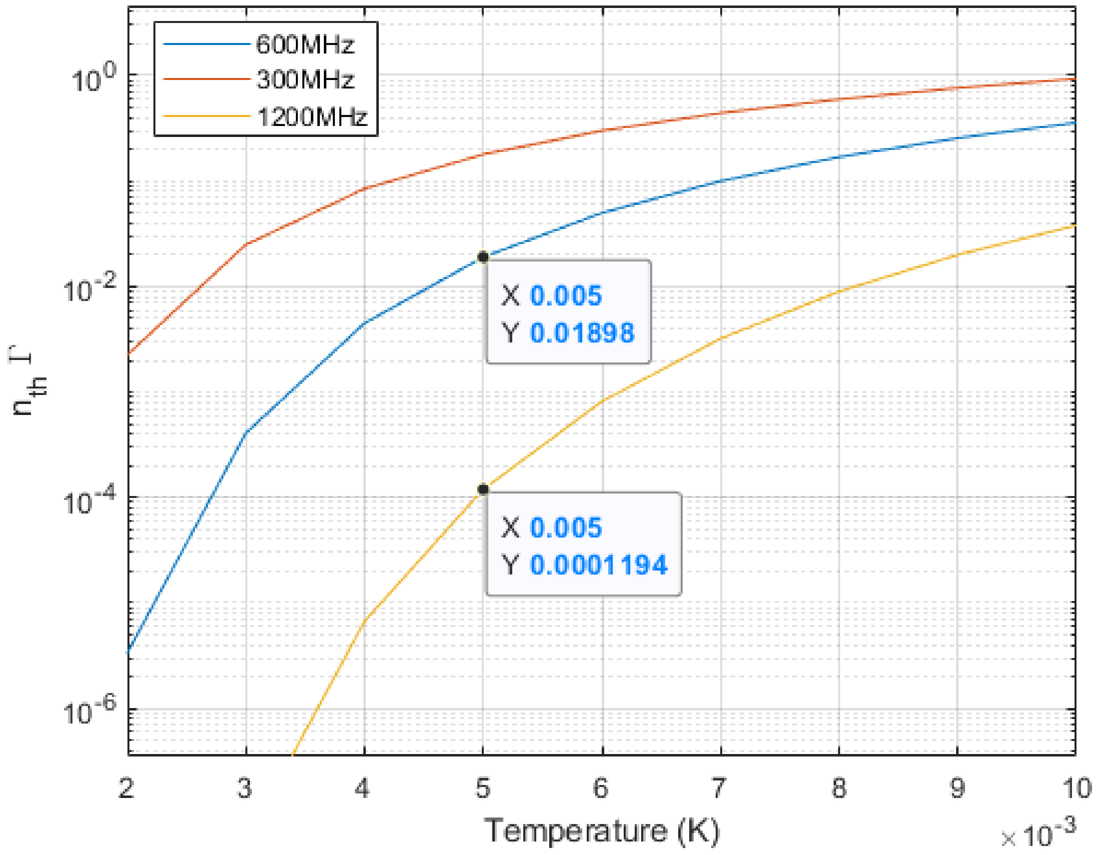


Fig. 11. Measurements of the cooling power of the refrigerator at 265 μmol/s.



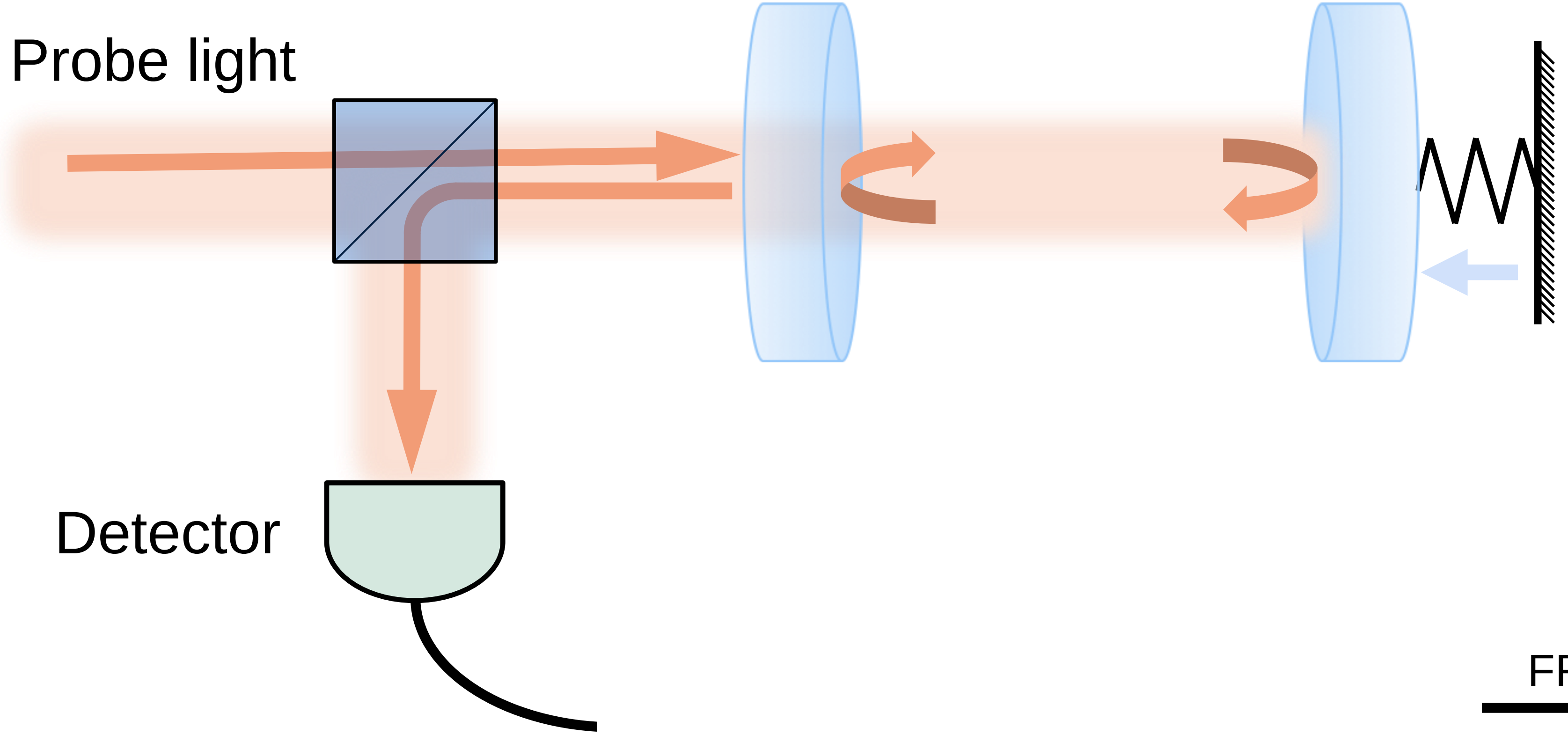
1550nm laser

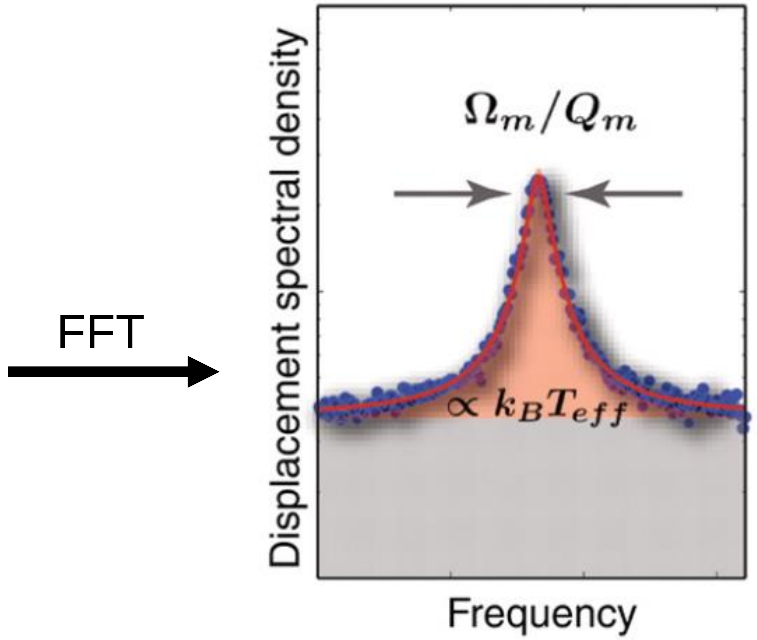
780nm laser

375nm laser

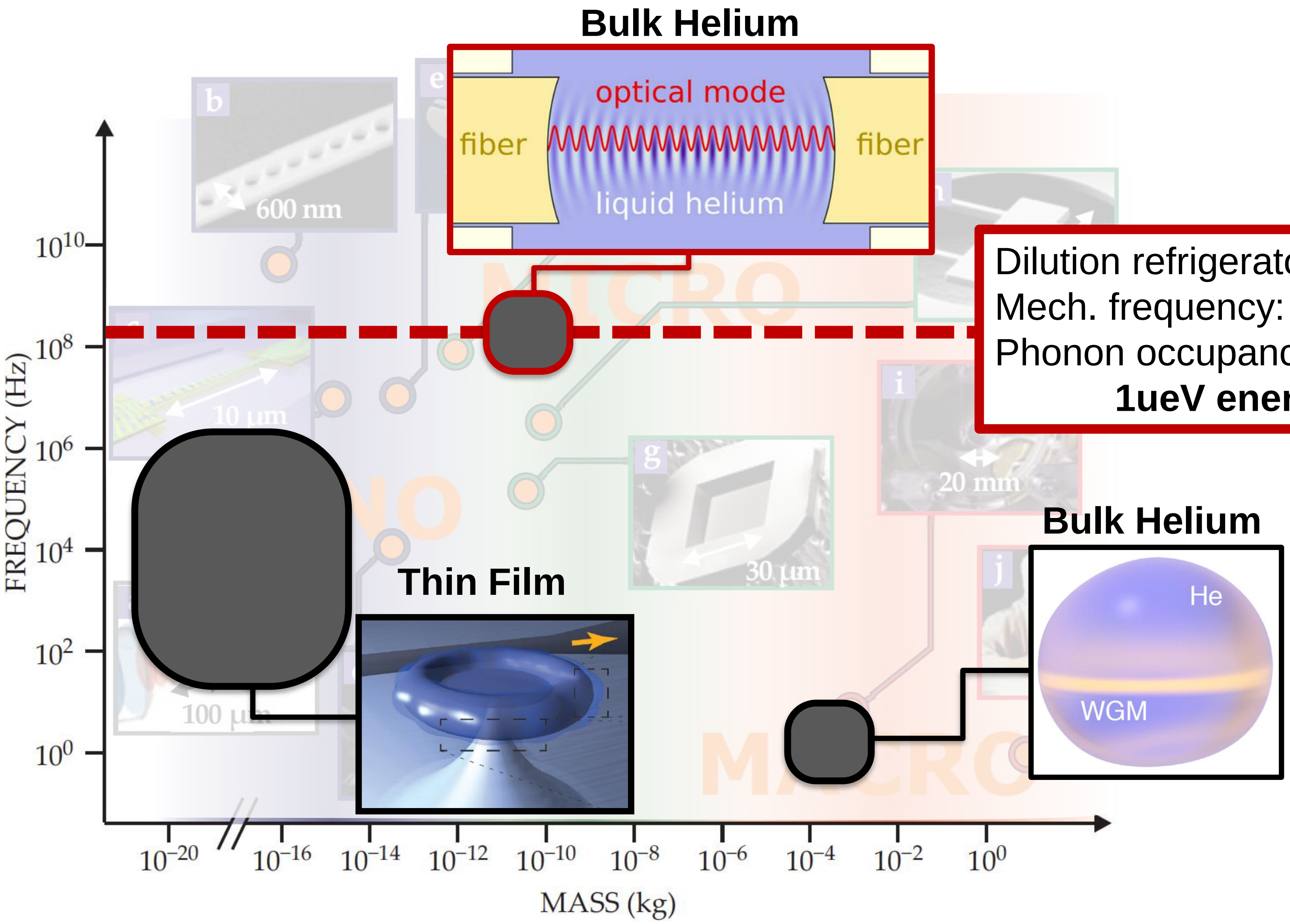
Cavity Optomechanics

Readout tick



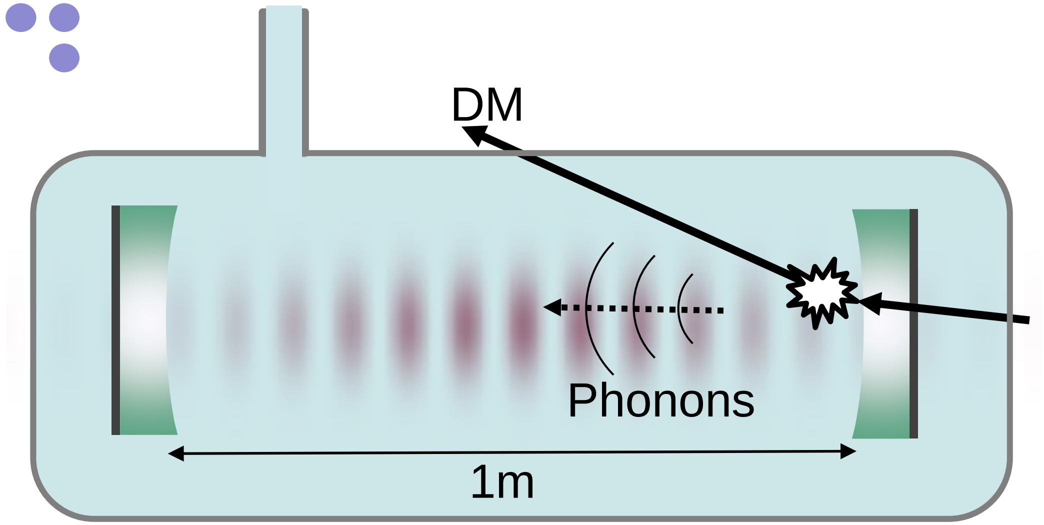


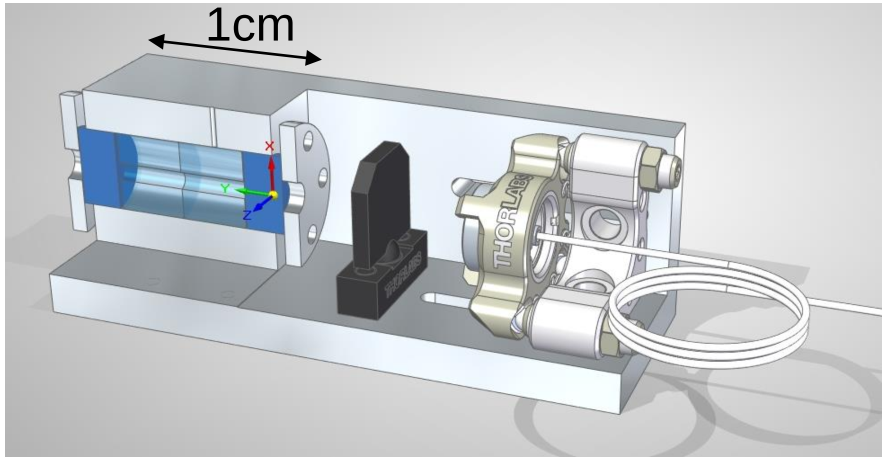
Superfluid Optomechanics



Dilution refrigerator: T~20mK
Mech. frequency: Ω~100MHz
Phonon occupancy: n_m~1
1ueV energy scale

Optomechanical Detection of Dark Matter





Design for macroscopic cavity filled with LHe

<u>Phonons modes (10^{-6} eV)</u>

- Very different detection scheme.
- Capable of resolving thermal motion (~ueV).
- 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

<u>Helium Excimers (10eV)</u>

- Detect via fluorescence of long lived triplet state.

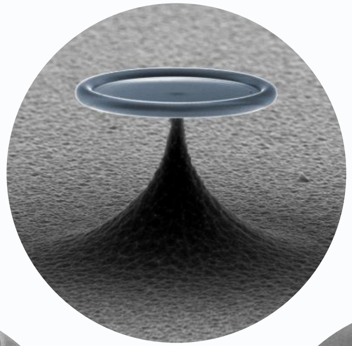
<u>Rotons (10^{-3} eV)</u>

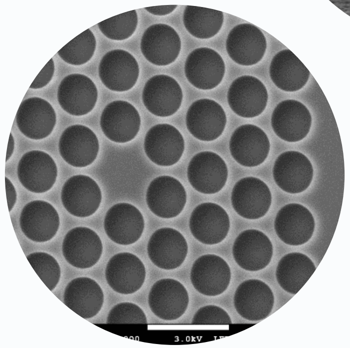
- Detected via optical scattering.

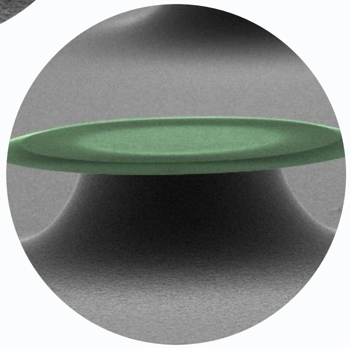
Superfluid Helium Optomechanics

University of Queensland

Thin films of superfluid Helium covering optical devices



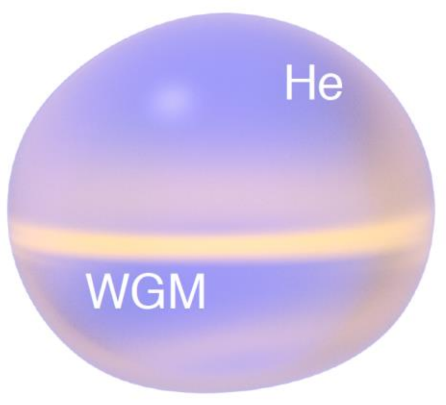




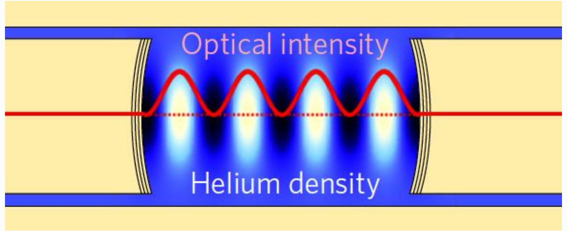
Yale University

Bulk superfluid Helium within optical device

Levitated droplet ~1cm



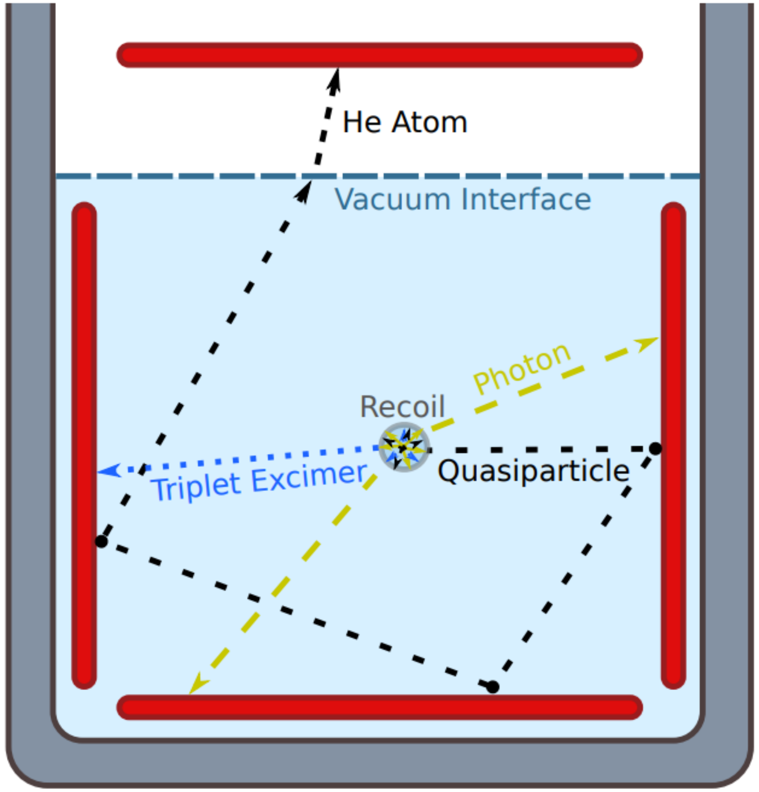
F-P cavity immersed 100um-10cm



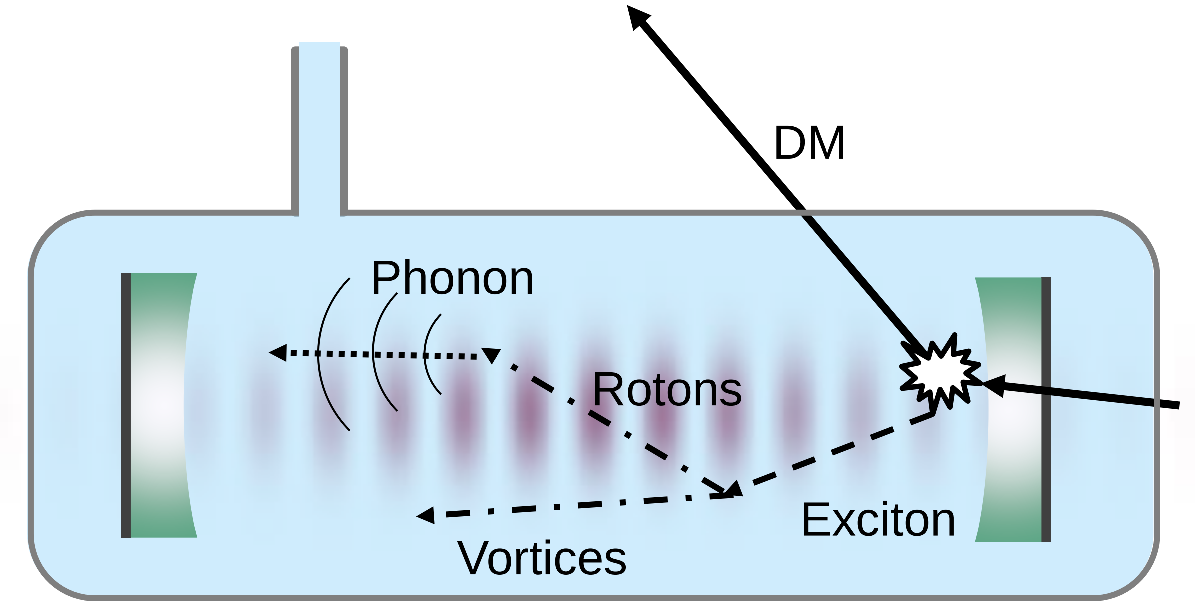
Helium as a target material

- 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!

athermal evaporation



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.

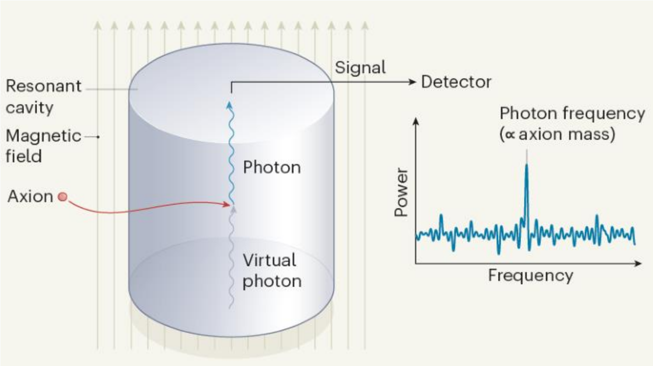
Direct evidence for Dark Matter

Axion

HAYSTACK (USA)

ADMX (USA)

ORGAN (Australia)



WIMP

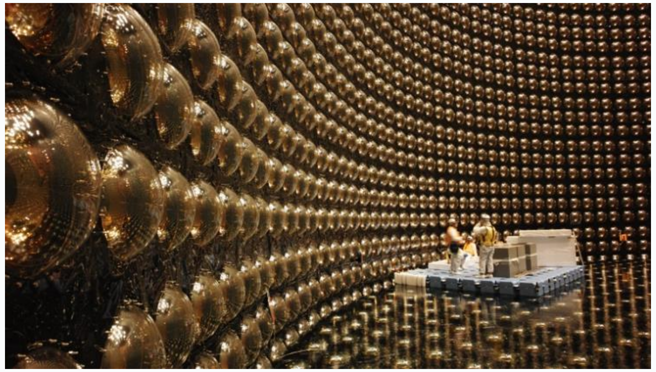
XENONnT (Italy)

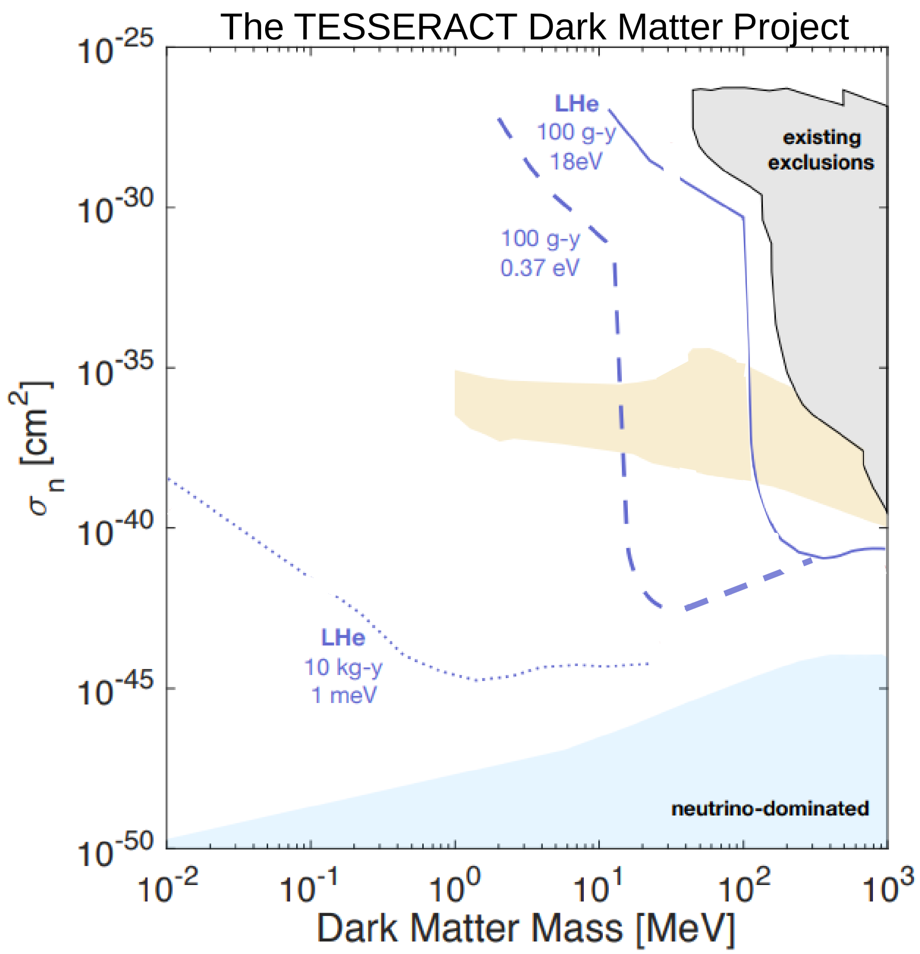
LUX-Zeplin (USA)

PandaX (China)

Super-Kamiokande (Japan)

SABRE (Italy/Australia)

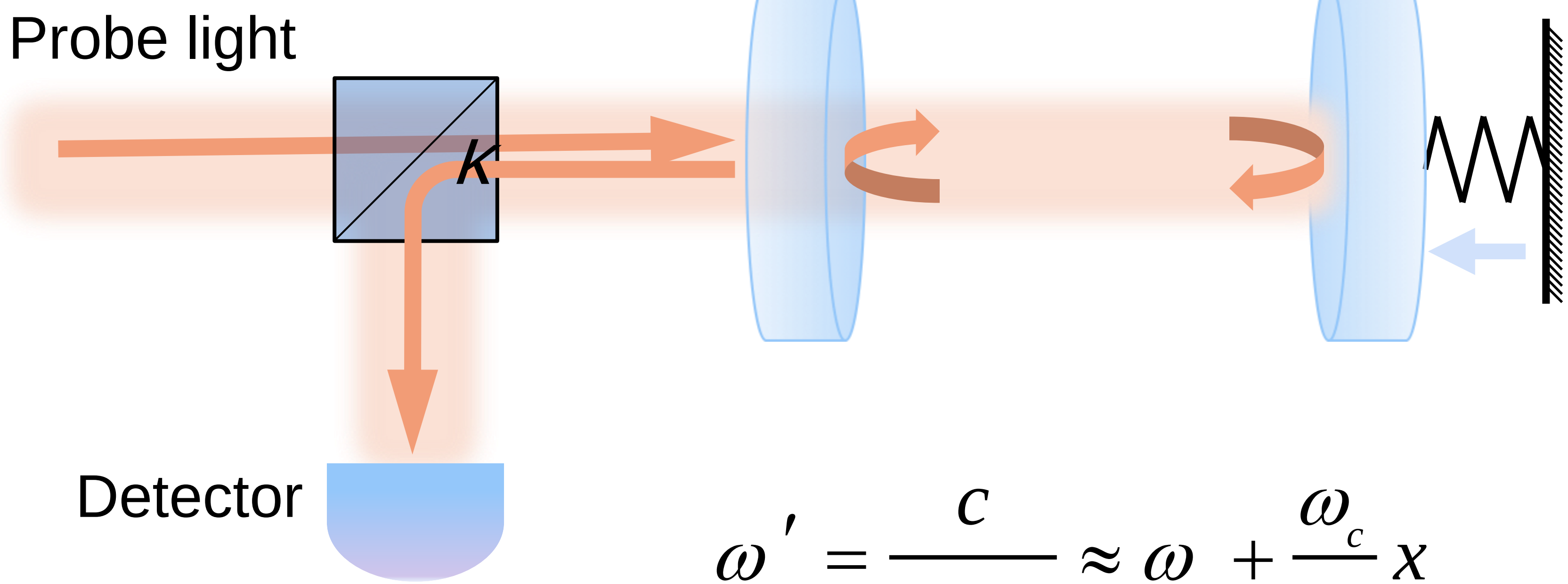




EQUS · Australian Government Australian Research Council · NASA · Precision Sensing Initiative, The University of Queensland · DST Group · ORICA

Cavity Optomechanics

$$Q_{opt} = \frac{\omega_0}{\kappa} \qquad Q_M = \frac{\Omega_M}{\Gamma_M}$$



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

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

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

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

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