Title: Analogue gravity with superfluid optomechanics

Speakers:

Collection: Quantum Simulators of Fundamental Physics

Date: June 08, 2023 - 2:00 PM

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QSimFP Workshop - Perimeter Institute for Theoretical Physics

Analogue Gravity with Superfluid Optomechanics

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08 June 2023

Royal Holloway University of London · UKRI Science and Technology Facilities Council · UKRI Engineering and Physical Sciences Research Council · The Royal Society

1. Introduction

2. Analogue gravity experiment

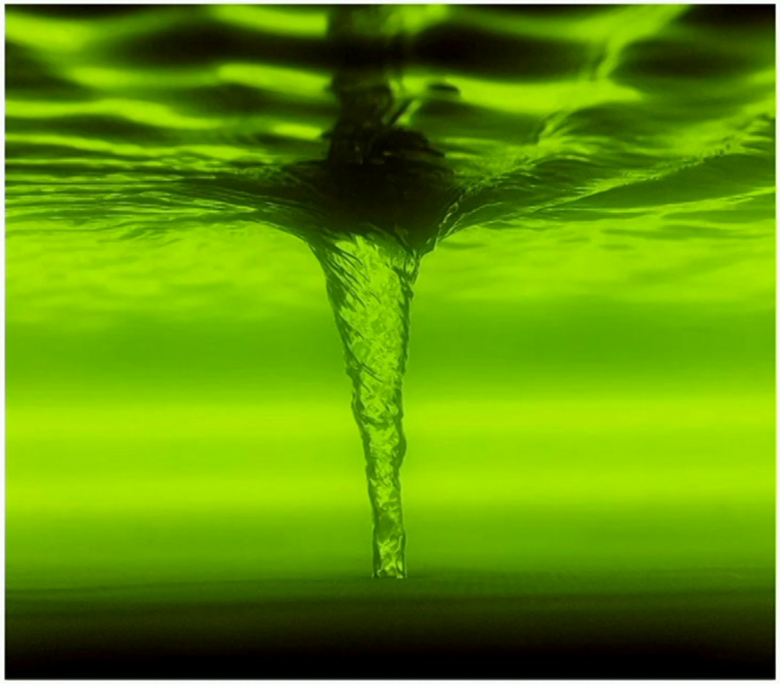
3. Nanofluidic environment

3.1 Superfluid Helmholtz Resonator

3.2 Sonic Crystal Resonator

Analogue gravity

EM fields travelling on the spacetime metric



Sound waves travelling on a background flow

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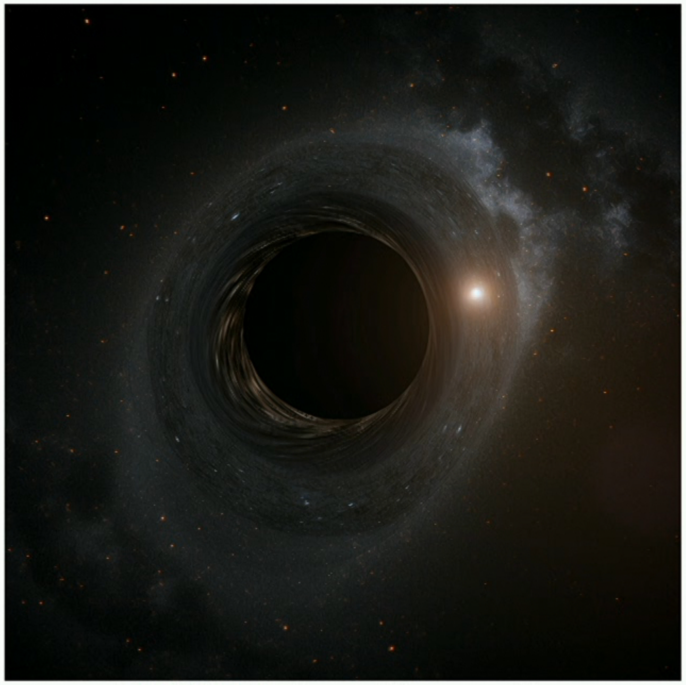
Analogue gravity



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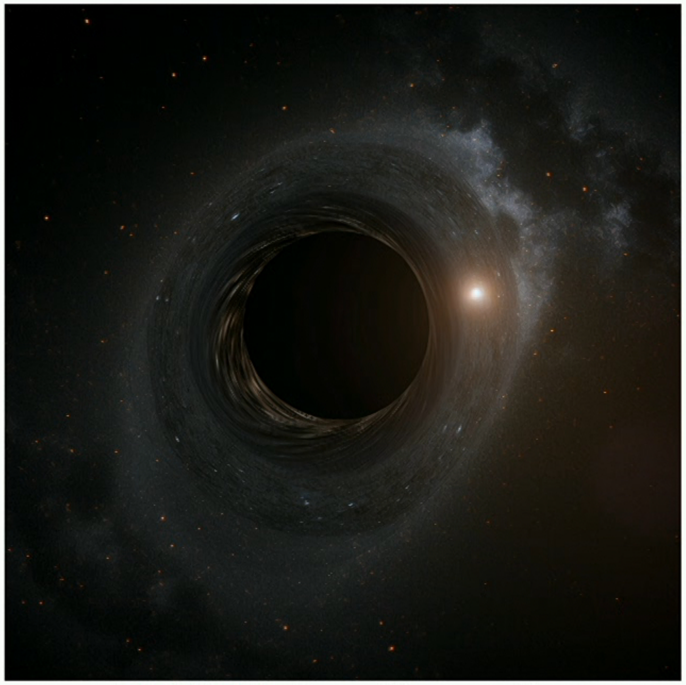

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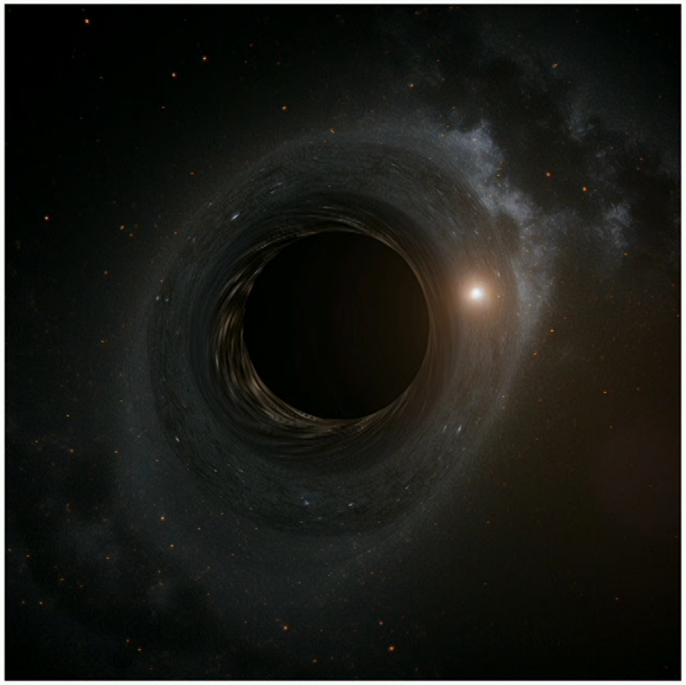

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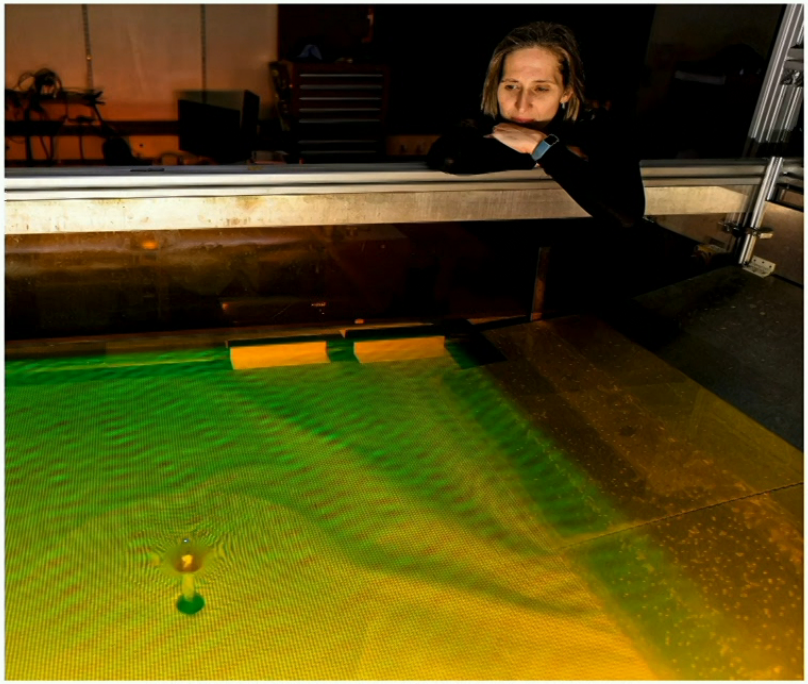

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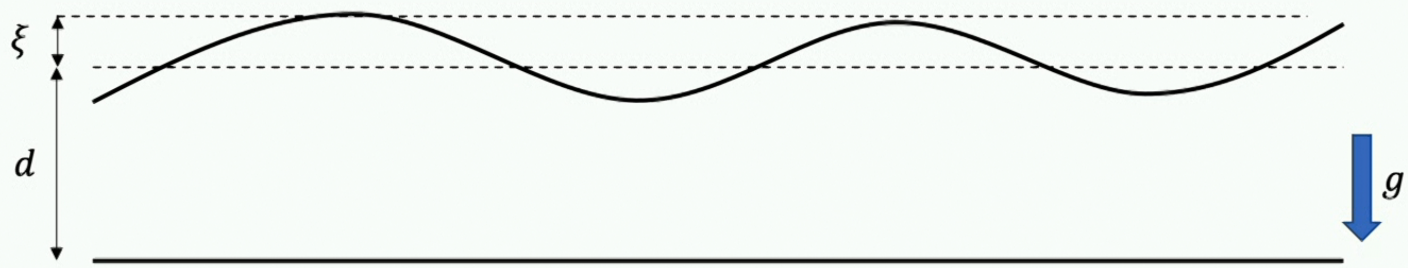

Dispersion relation:

$$\omega^2 = (\rho g + \sigma k^2)\frac{k\tanh(kd)}{\rho}$$

σ: surface tension
ρ: fluid density

- **shallow water wave limit**
  $kd \ll 1 \Rightarrow \tanh(kd) \sim kd$

- **gravity wave limit**
  $\rho g \gg \sigma k^2$
  $\lambda \gg 2\pi\sqrt{\sigma/(\rho g)}$

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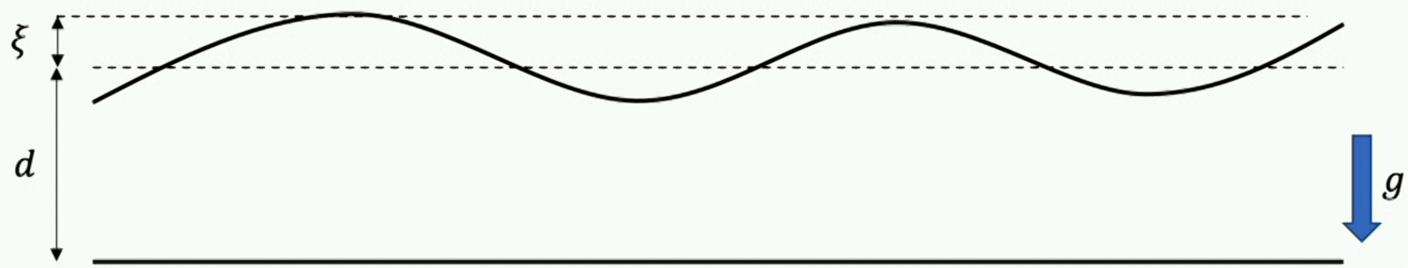

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Linear dispersion:

$\omega \simeq c\,k$, with $c = \sqrt{gd}$

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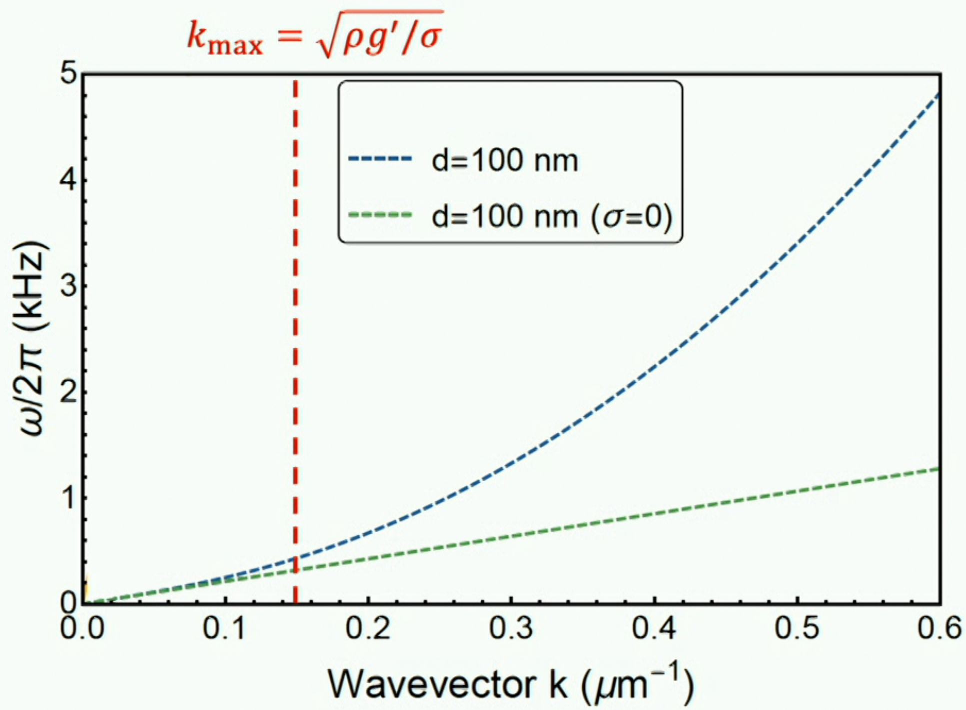
Dispersive regime



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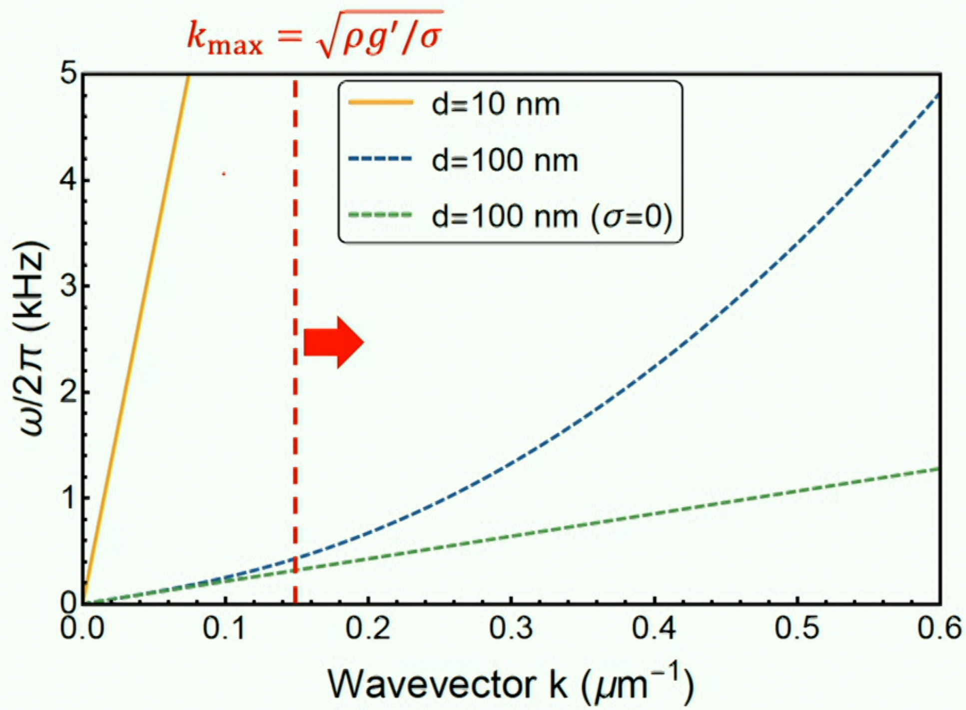

Linear dispersion extends to large wavevectors for small σ and large g'

Effective gravity for surface waves

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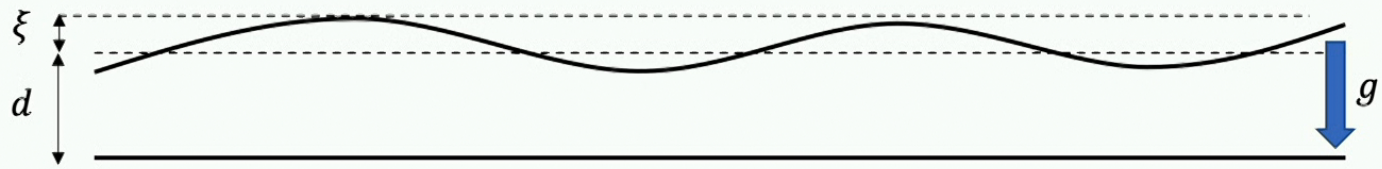

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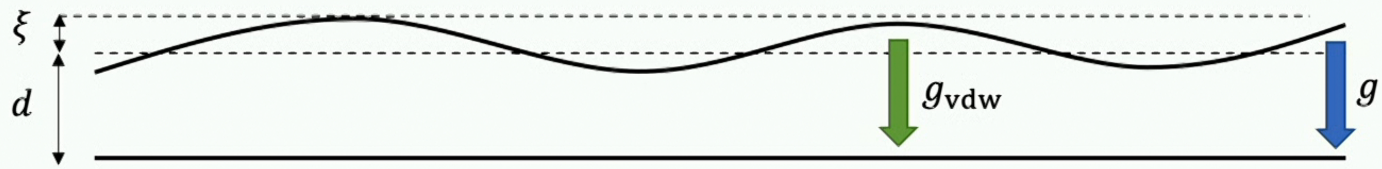

Van der Waals interaction: substrate - fluid

$$g' = g + g_{\rm vdw}$$

$$g_{\rm vdw} = \frac{3\alpha_{\rm vdw}}{d^4}$$

Material	$\alpha_{\rm vdw}$ $[m^5 s^{-2}]$
Silica	2.6×10^{-24}
CaF2	2.2×10^{-24}
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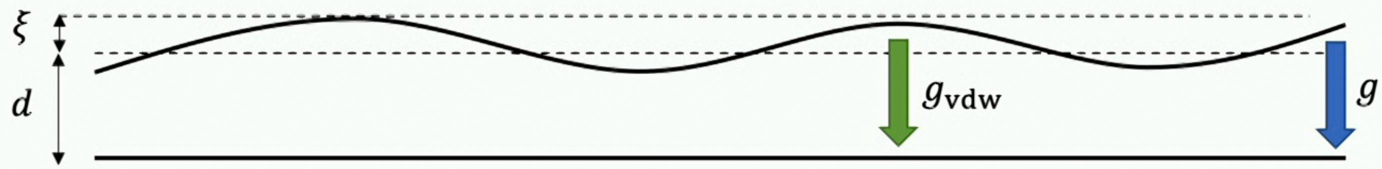

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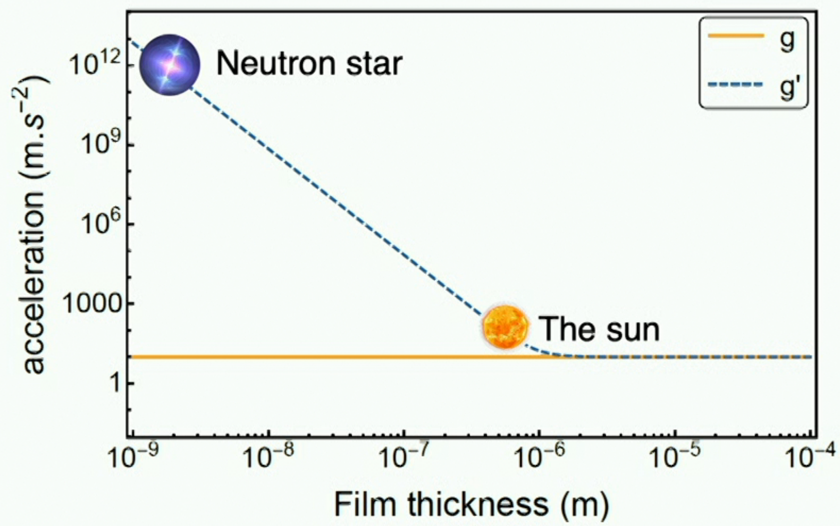

Linear dispersion

$$\boxed{\omega = ck} \quad \text{with } c = \sqrt{g'd} \simeq \sqrt{3\alpha_{\text{vdw}}}\, d^{-\frac{3}{2}}$$

Conditions of validity:

- shallow water wave limit ($kd \ll 1$): easily satisfied for thin films
- gravity wave limit ($\lambda \gg 2\pi\sqrt{\frac{\sigma}{\rho g'}}$):

7

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Orders of magnitude

d	c	$\lambda_{\min}$	$f_{\max}$
1000 nm	0.005 m/s	2.5 mm	0.001 kHz
100 nm	0.1 m/s	50 µm	1 kHz
10 nm	5 m/s	500 µm	10 MHz
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(last two rows:) $T \sim$ 1 mK – 1 K ($T = \hbar\omega/k_b$)

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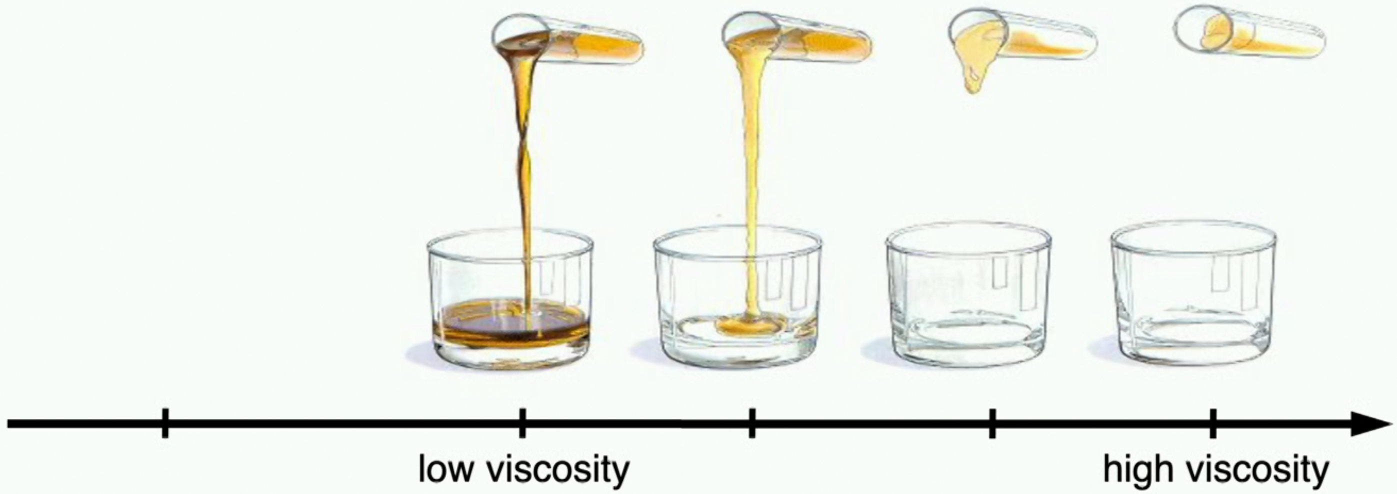
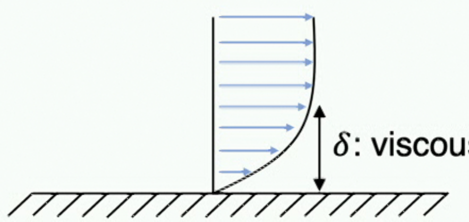
The quantum regime is **only** accessible to **superfluids**

A fluid with zero viscosity!





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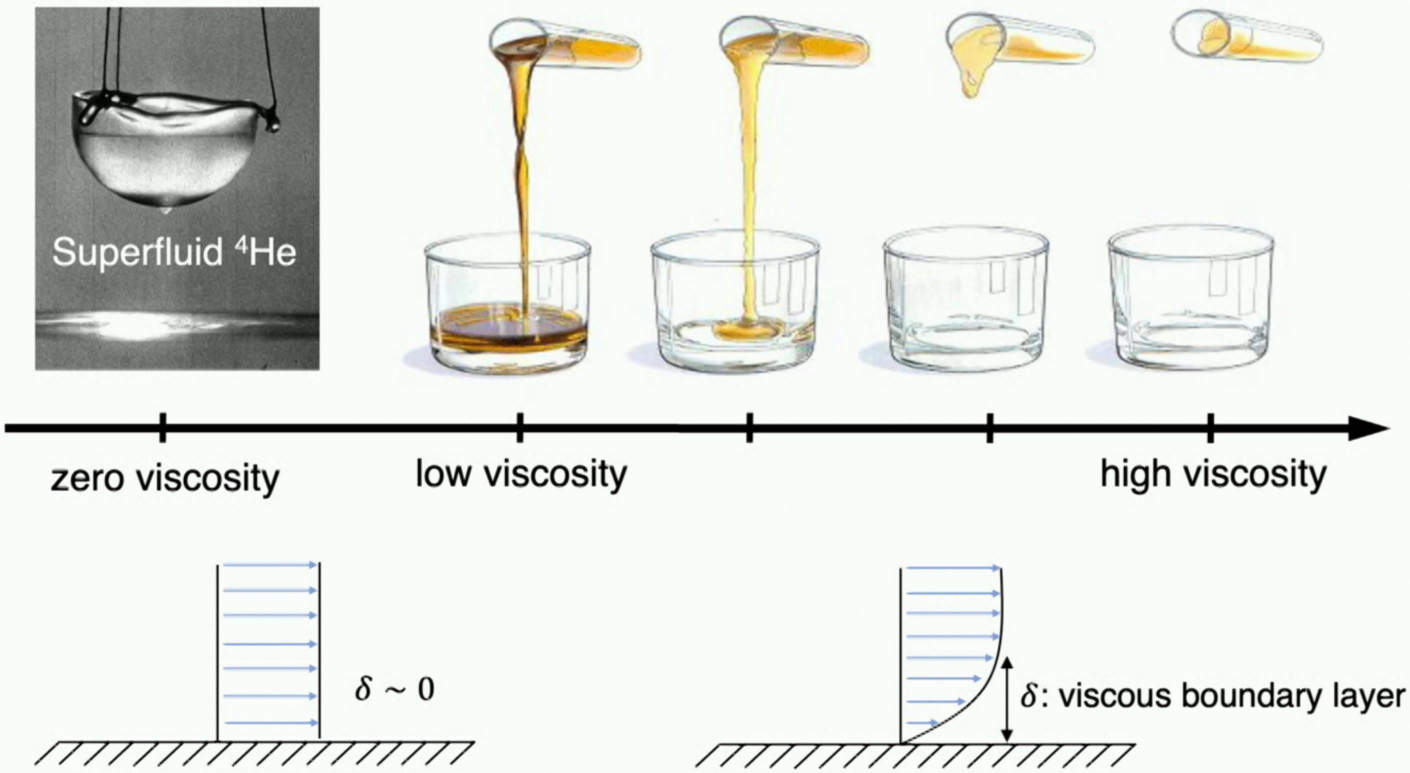

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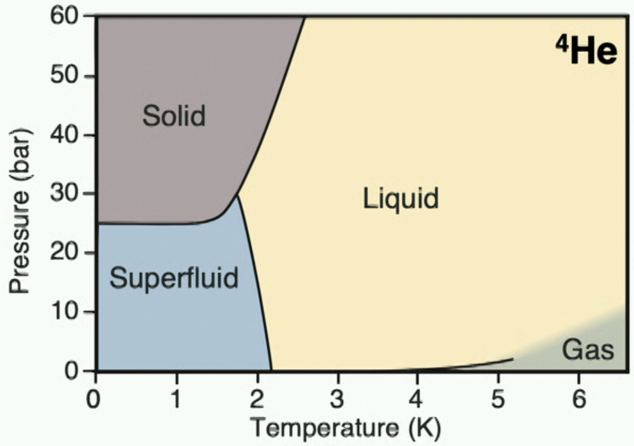
Superfluid ^4He: an exotic phase



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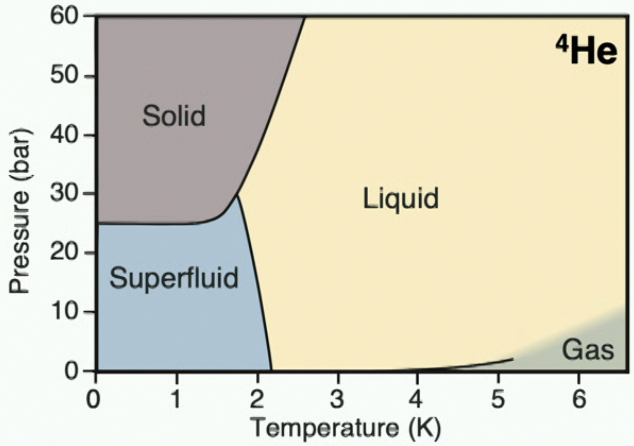

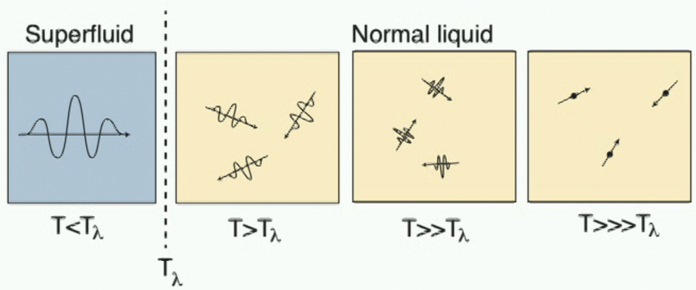

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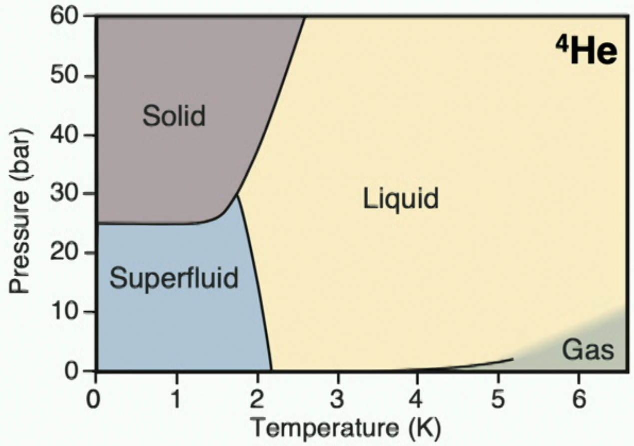
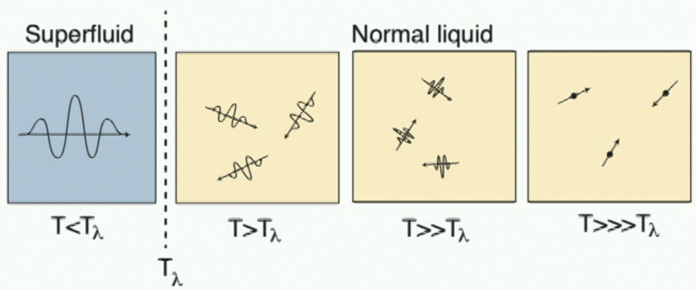


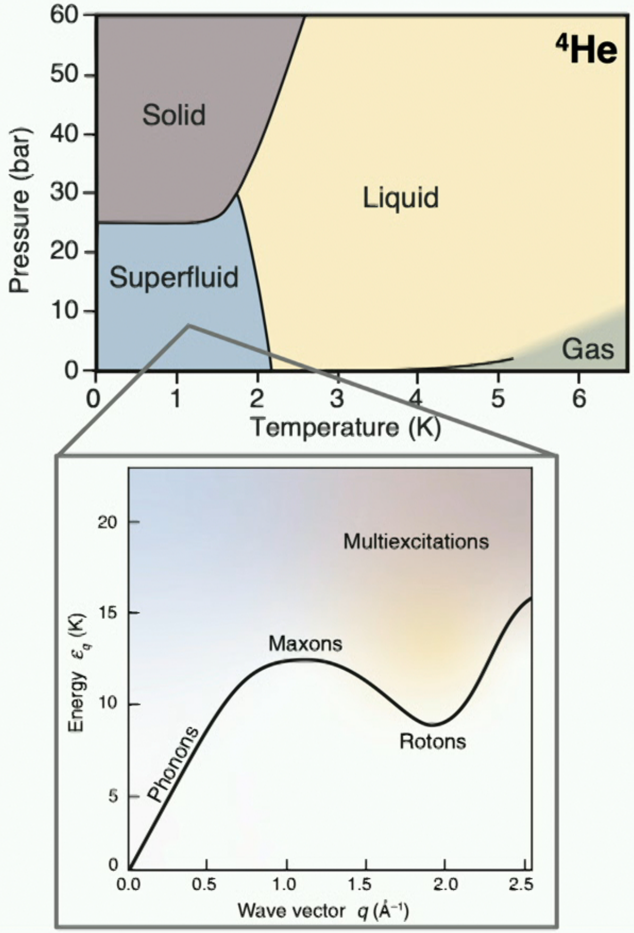
- sound velocity: $c_1 \sim 237\ \mathrm{m/s}$
- density: $\rho \sim 145\ \mathrm{kg/m^3}$
- dielectric constant: $\epsilon \sim 1.056$



Unique properties

- chemically pure: only ^{3}He impurities
- sound velocity is highly tunable:

Superfluid ^{4}He: an exotic phase



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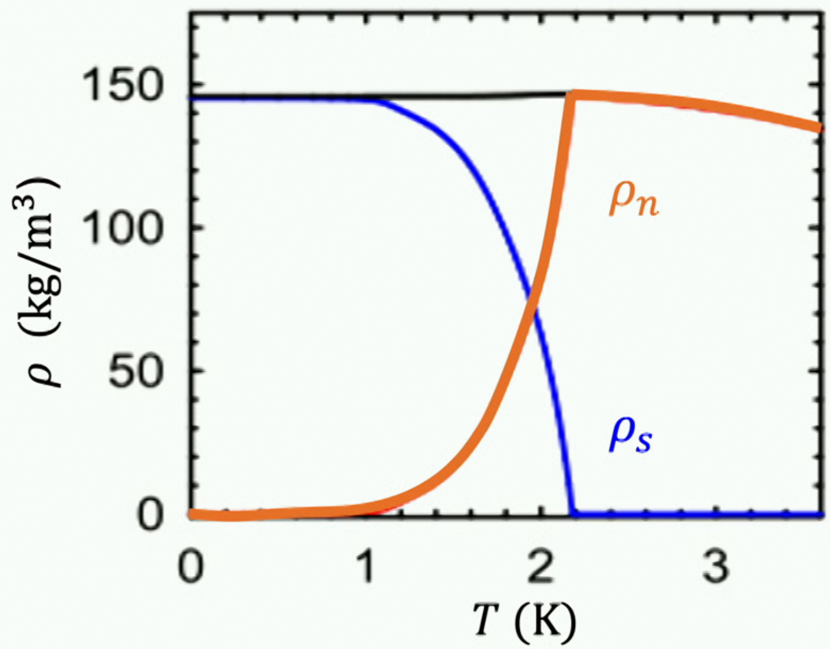
Unique properties

- chemically pure: only ^{3}He impurities
- sound velocity is highly tunable:
- high thermal conductivity
- **ultra-low acoustic loss**
- **ultra-low dielectric loss**
- **quantized vortices**

Two-fluid model of superfluid ^{4}He



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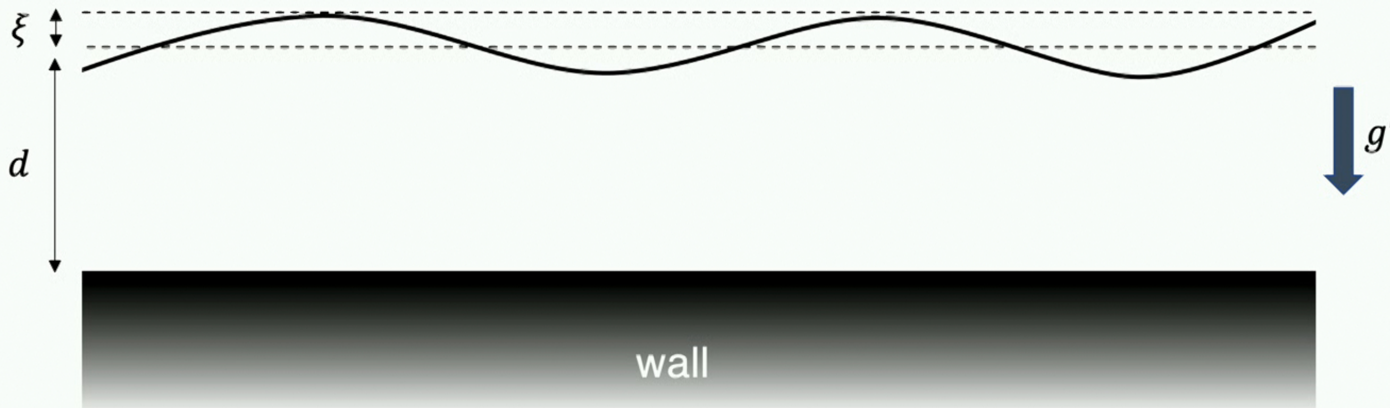
Third-sound



- First-sound: acoustic wave ($\delta\rho$)
- Second-sound: temperature wave (δT)
- **Third-sound:** surface wave on thin films ($\delta\rho_s$, incompressible film)

$$\frac{\partial^2 \xi}{\partial t^2} - c_3 \nabla^2 \xi = 0 \ , \quad c_3 = \sqrt{g' d}$$ (in the low temperature limit)

K. R. Atkins Phys. Rev. **113**, 4 (1959)

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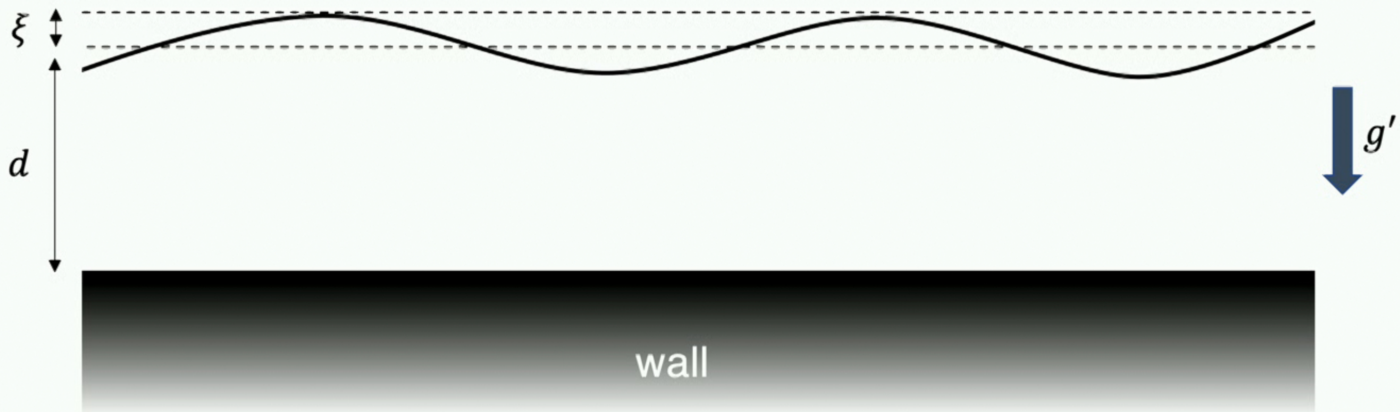

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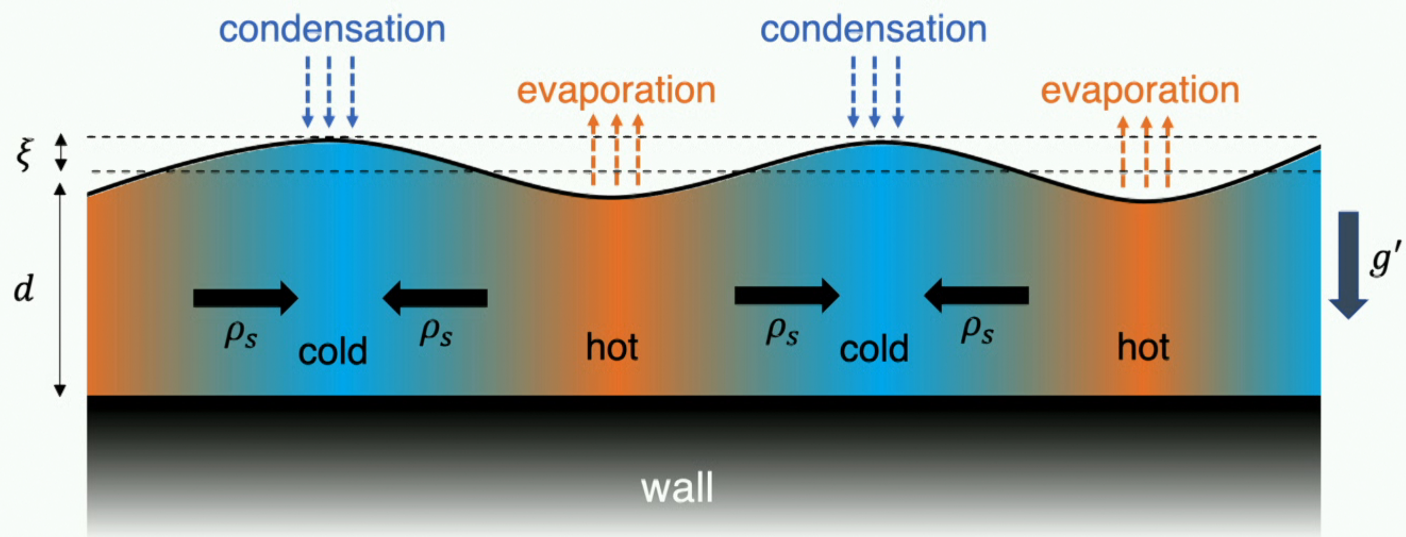

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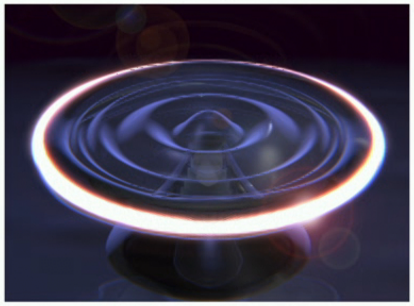
How can we measure these waves?

Optomechanics (Queensland)



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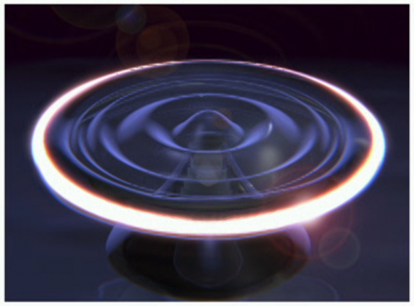

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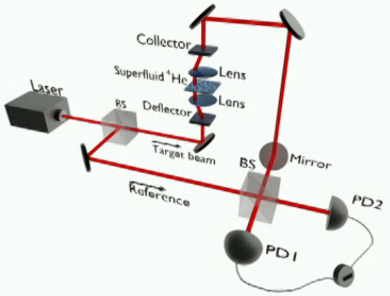

Bunney, arXiv:2302.12023 (2023)

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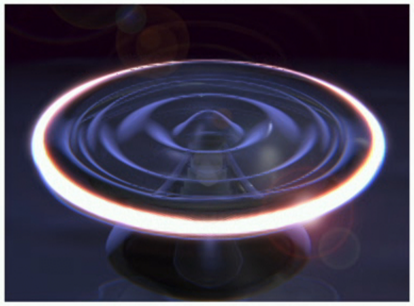

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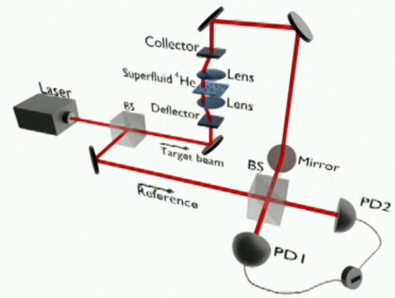

Bunney, arXiv:2302.12023 (2023)

Microwave Optomechanics (RHUL)

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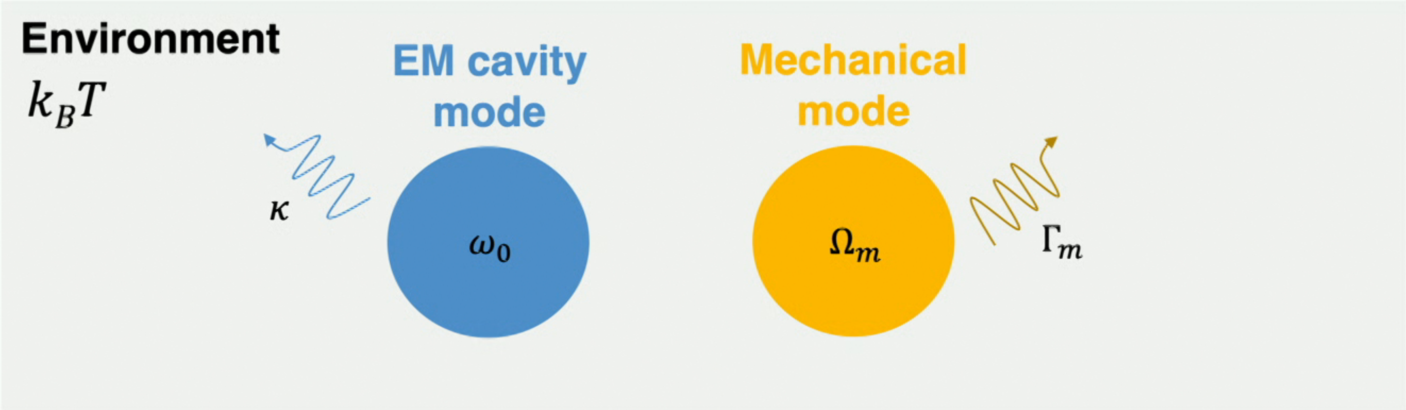
Cavity optomechanics Hamiltonian



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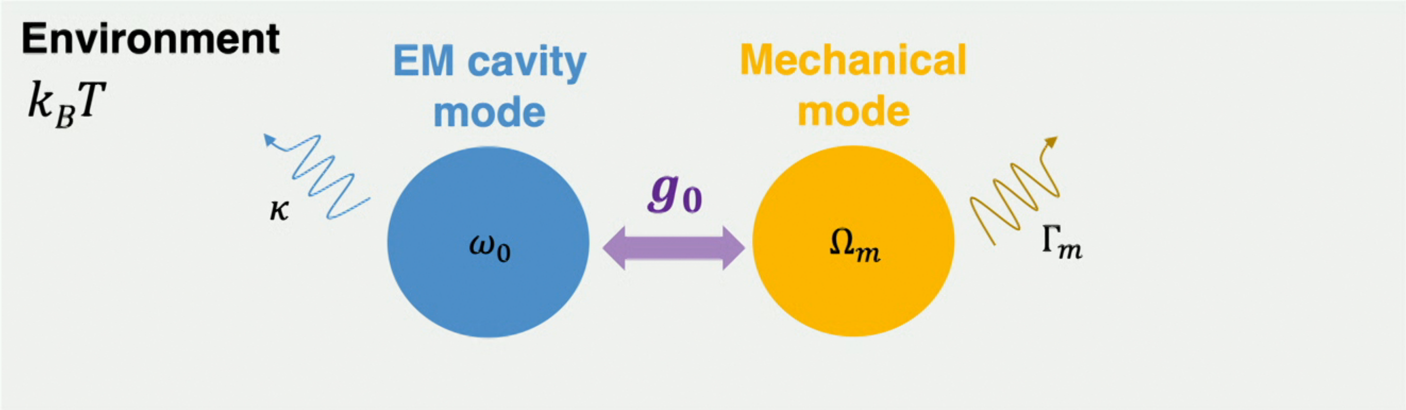


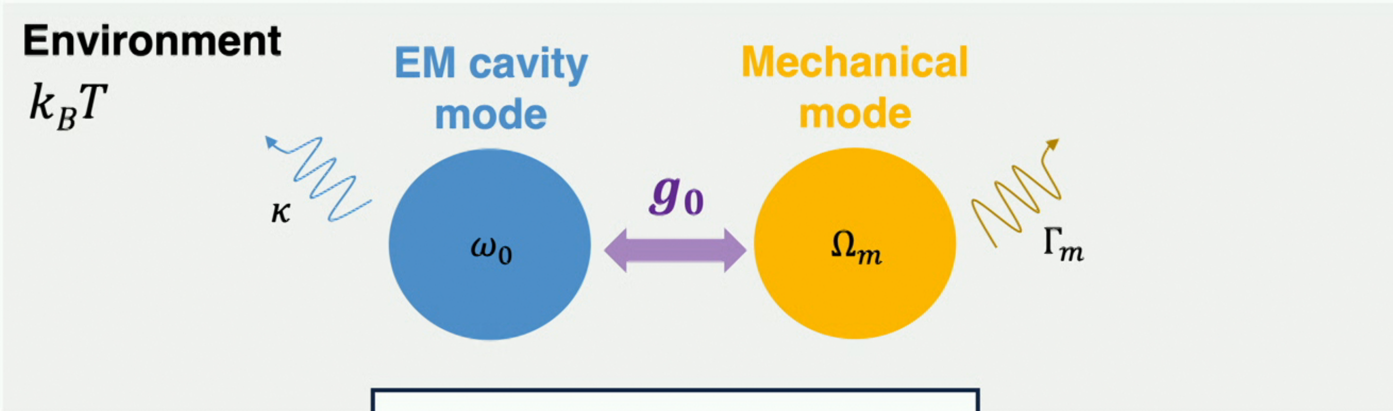
$$H = \hbar\omega_0 a^\dagger a + \hbar\Omega_m b^\dagger b - \hbar g_0 a^\dagger a(b + b^\dagger)$$

$g_0 = G x_{zpf}$ is the optomechanical single photon coupling strength

$G = -\frac{\partial \omega_0}{\partial x}$ is the cavity frequency shift per mechanical displacement

$x_{zpf} = \sqrt{\frac{\hbar}{2 m_{\text{eff}} \Omega_m}}$ is the mechanical zero–point fluctuation amplitude

Cavity optomechanics Hamiltonian



$H = \hbar\omega_0 a^\dagger a + \hbar\Omega$

$$C = \frac{4\, n_{\text{cav}}\, g_0^2}{\kappa\, \Gamma_m}$$

$g_0 = G x_{zpf}$ is t ... upling strength

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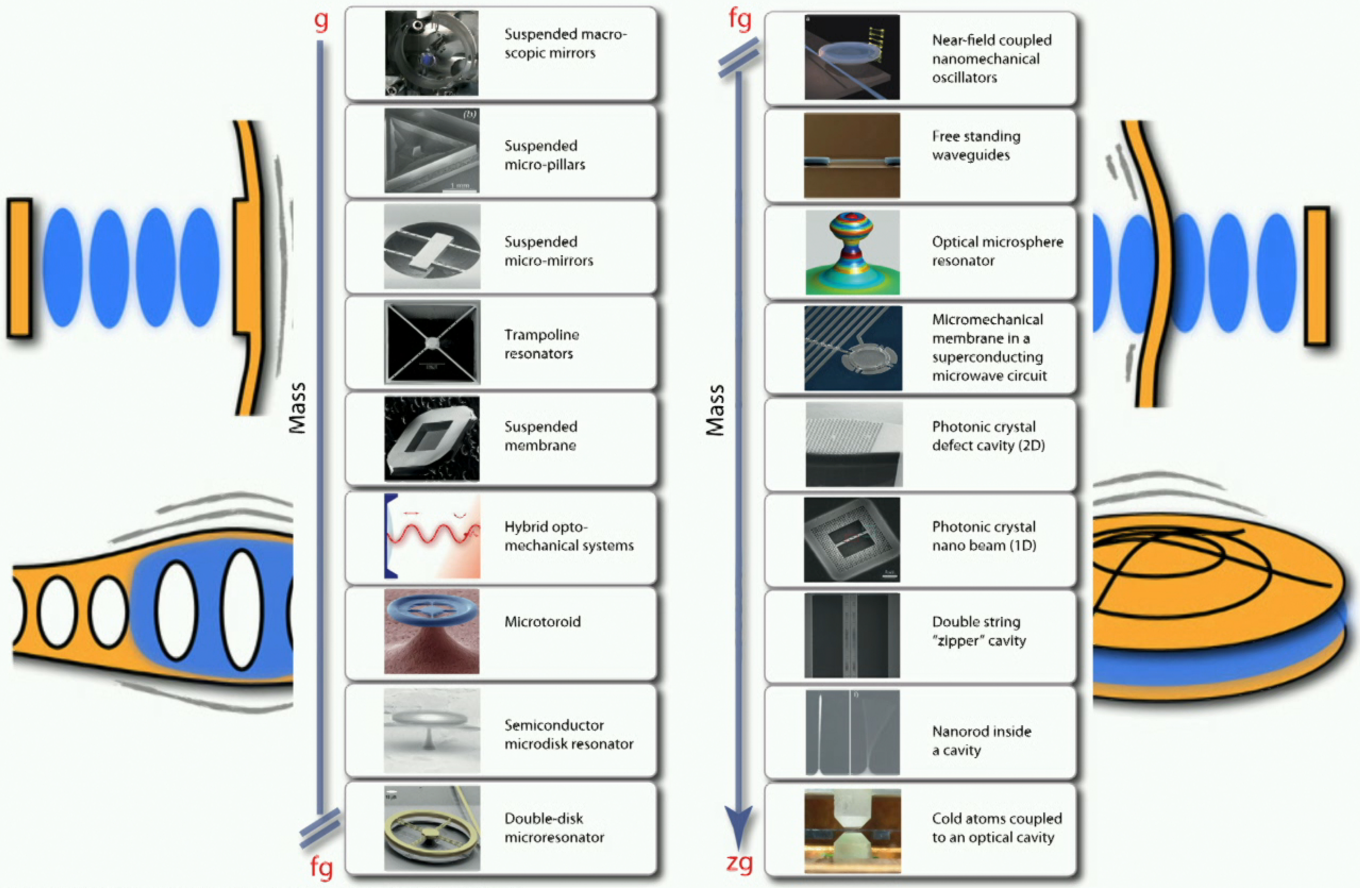
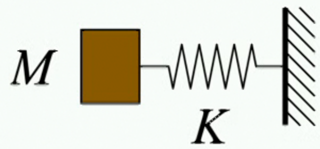
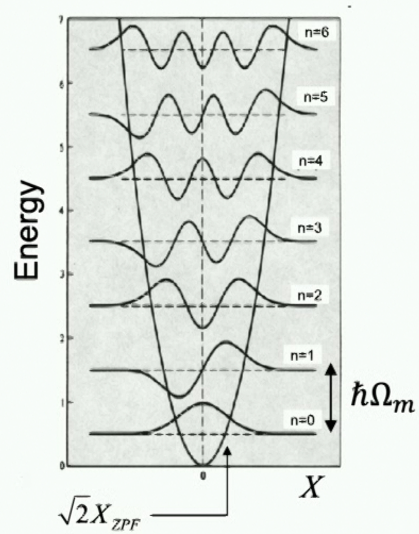
Variety of design



Aspelmeyer *et al.* Rev. Mod. Phys. **86**, 1391 (2014)

Mechanics towards the quantum regime





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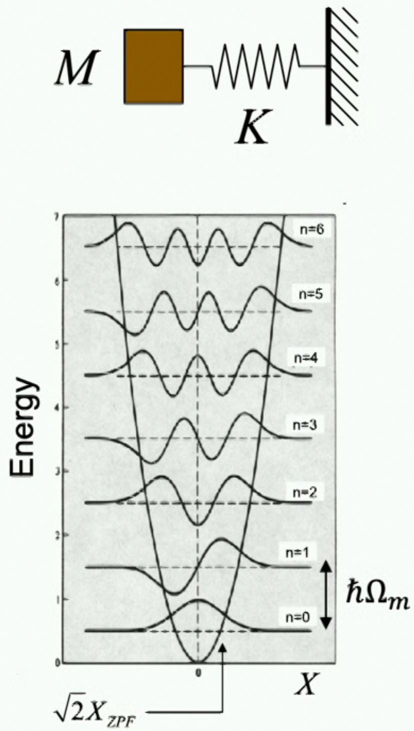

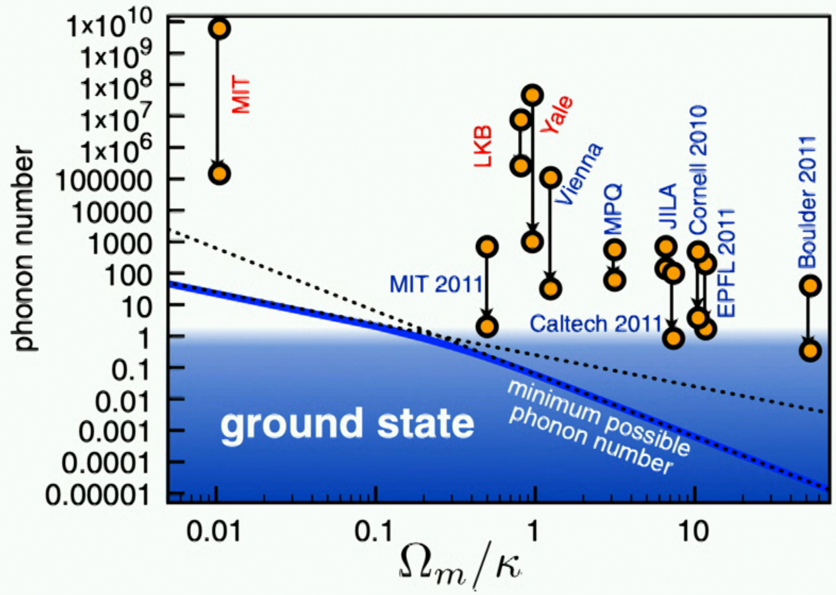

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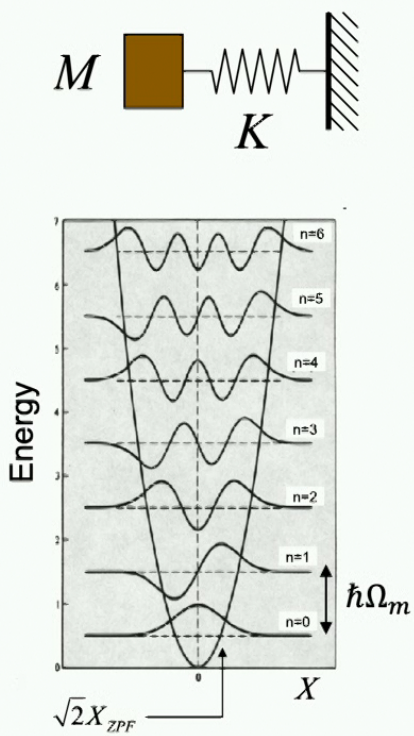

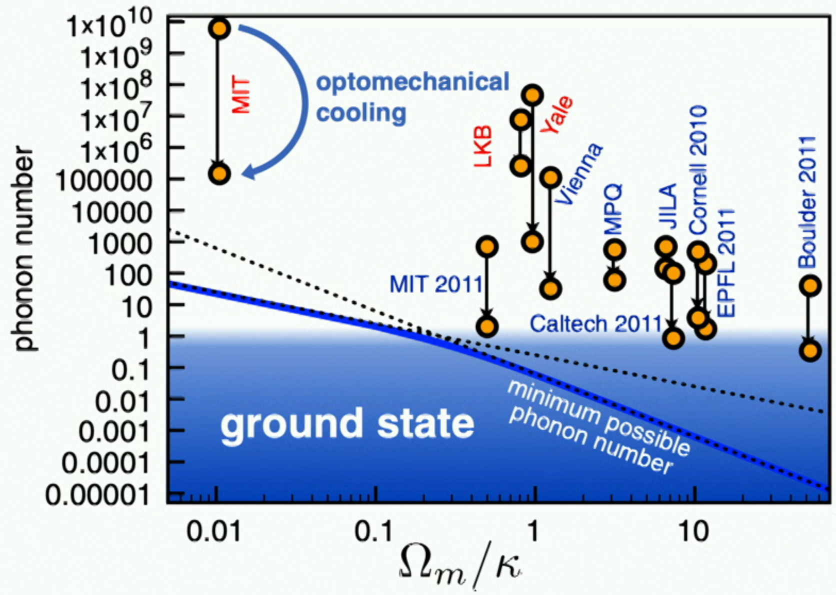

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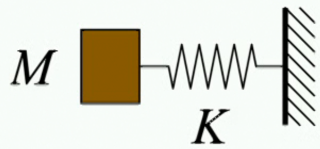

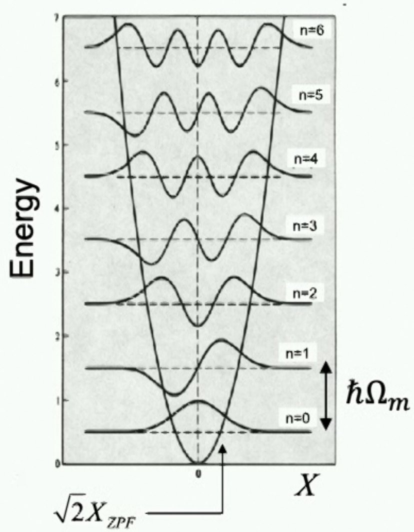

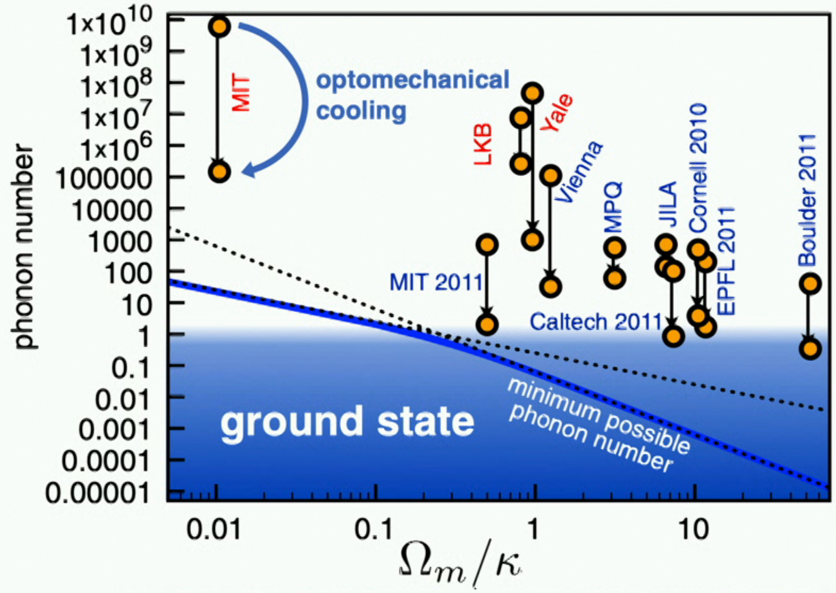

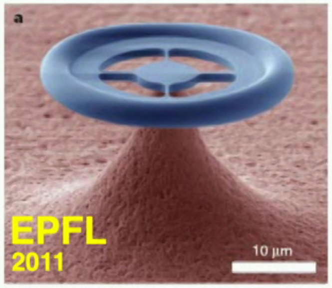

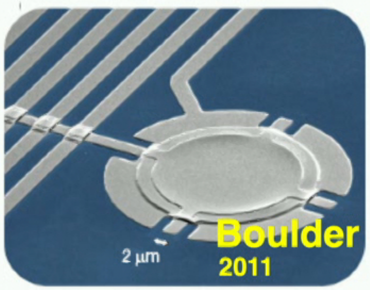

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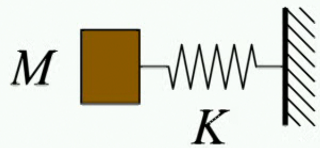
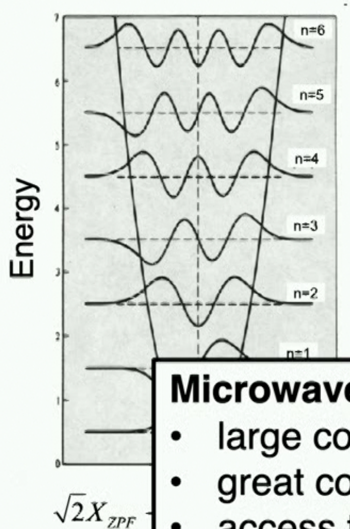
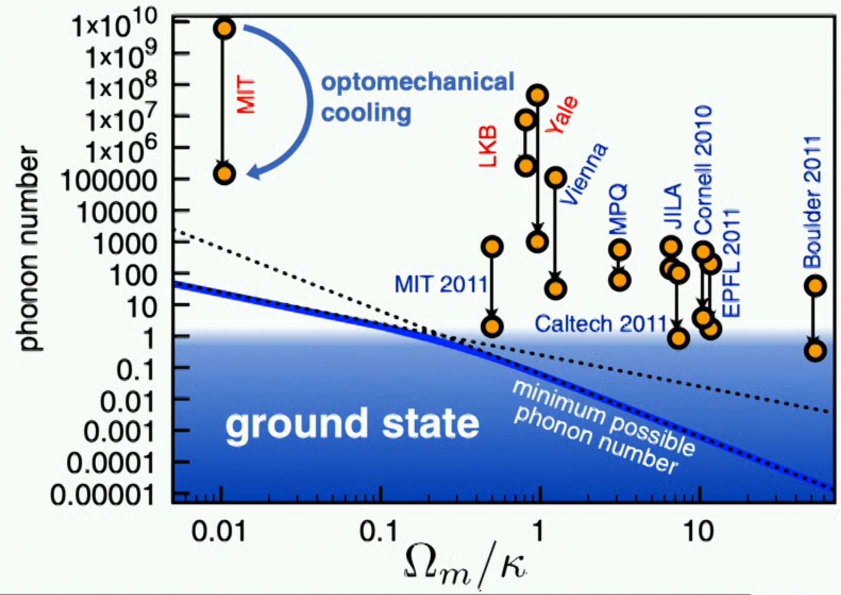
Mechanics towards the quantum regime

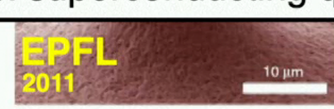


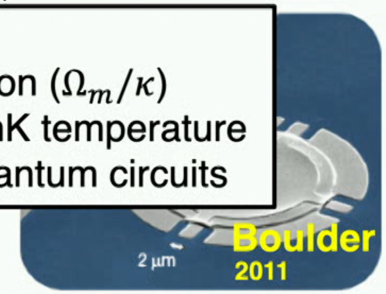




Microwave optomechanics offers:

- large cooperativities (C) and high sideband resolution (Ω_m/κ)
- great compatibility with cryogenic environment at mK temperature
- access to quantum resources: superconducting quantum circuits





Aspelmeyer *et al.* Rev. Mod. Phys. **86**, 1391 (2014)

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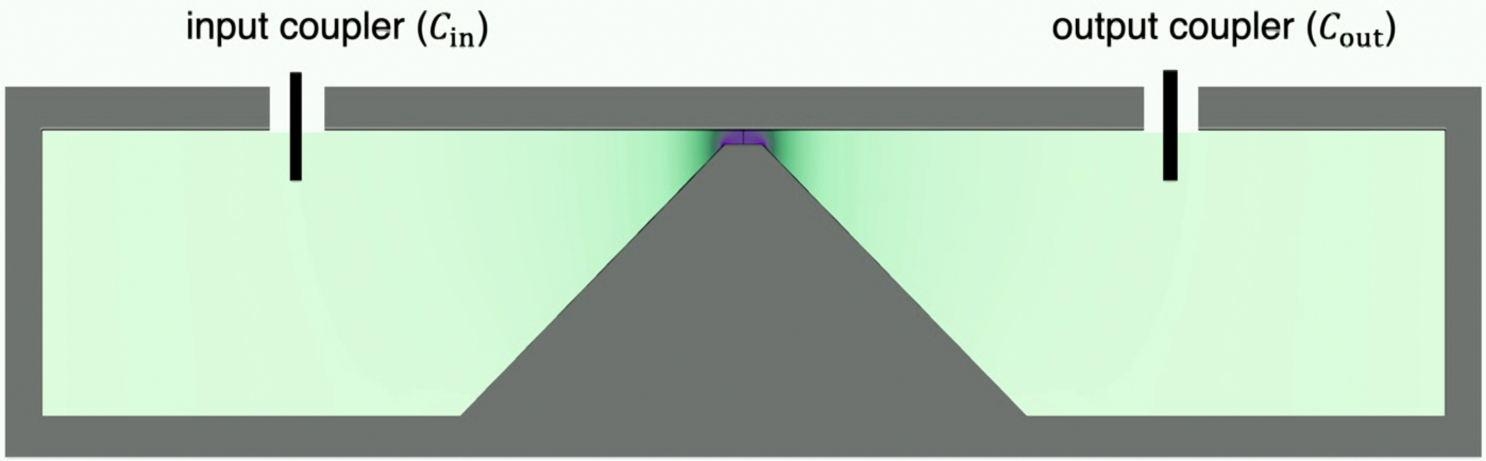
2. Analogue gravity experiment

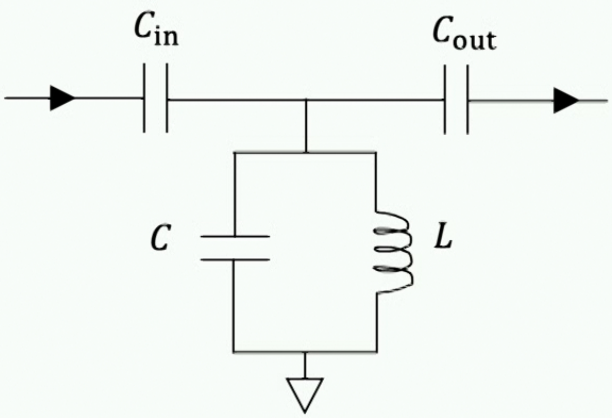
3. Nanofluidic environment

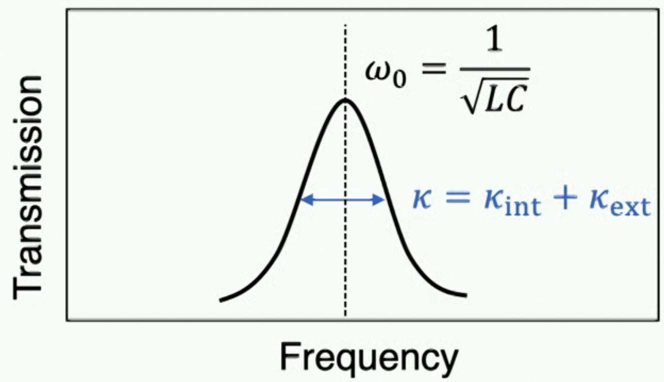
3.1 Superfluid Helmholtz Resonator

3.2 Sonic Crystal Resonator

Microwave re-entrant cavity – circuit







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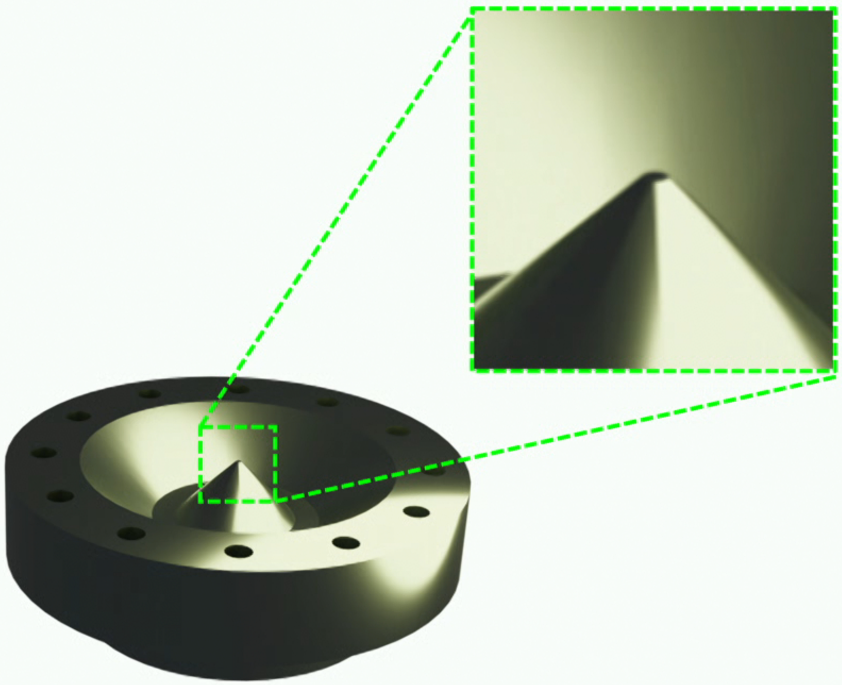
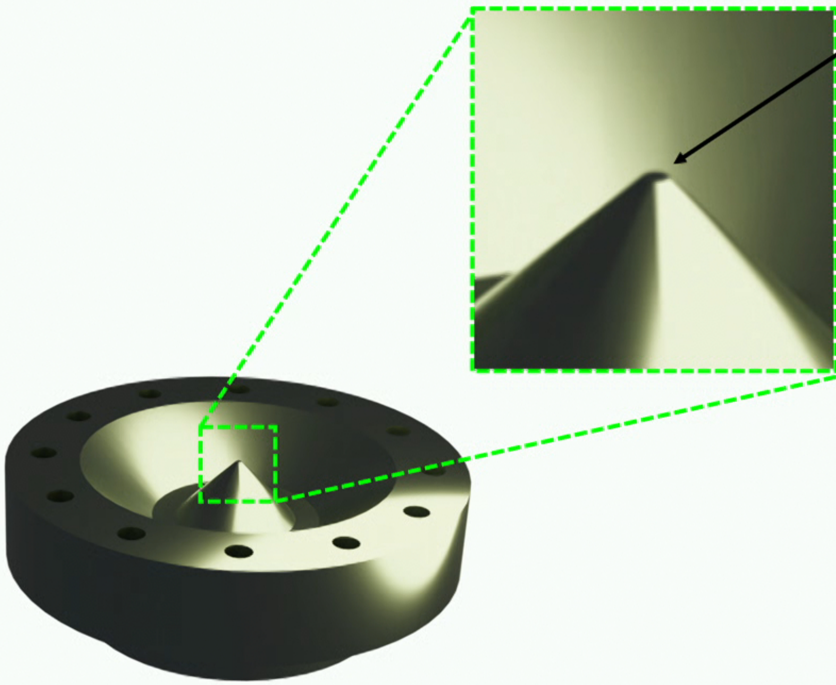
Microwave re-entrant cavity - coupling



Cavity resonance frequency:

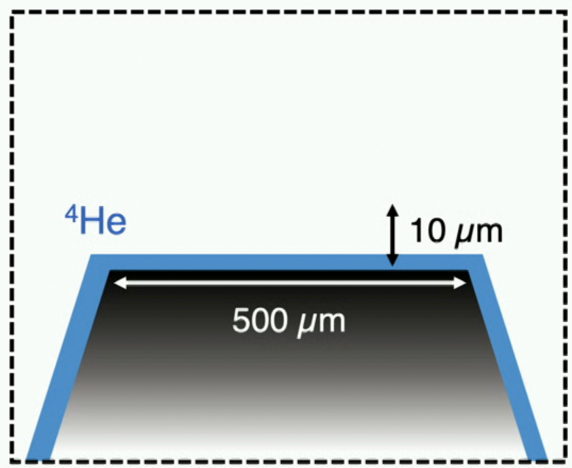
$$\omega_0/2\pi = \frac{1}{\sqrt{LC}}$$

Microwave re-entrant cavity - coupling



Pillar's tip:
disk's diameter ~ 500 μm

Defines the geometry of our **surface wave resonator**



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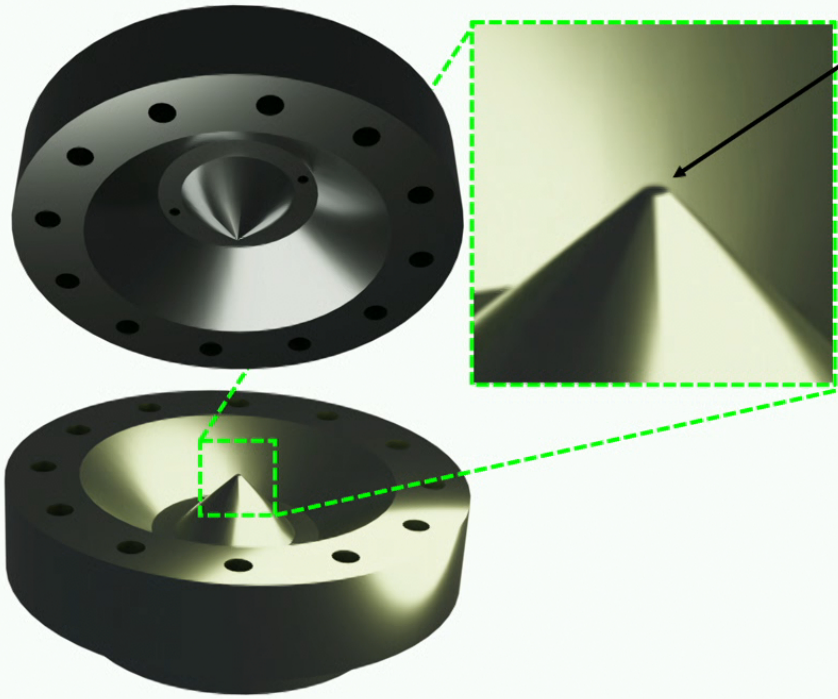

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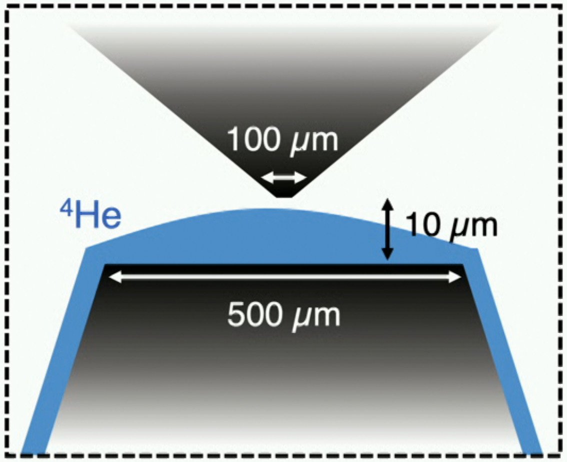

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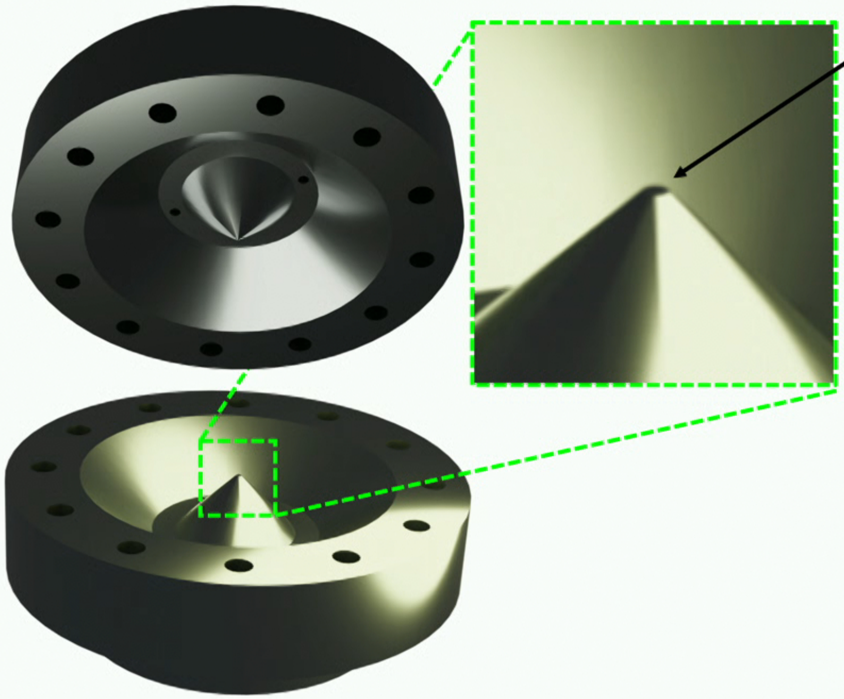

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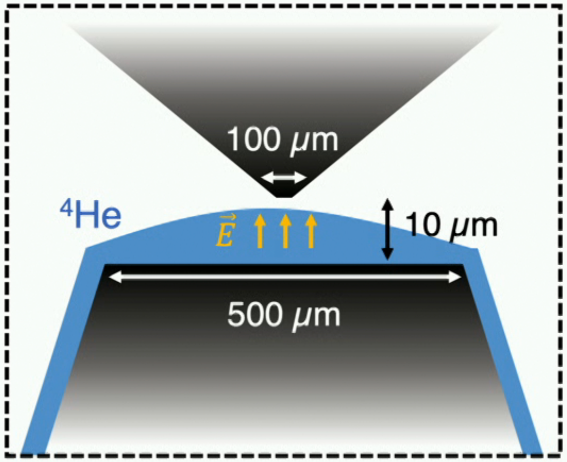

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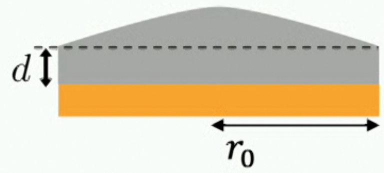
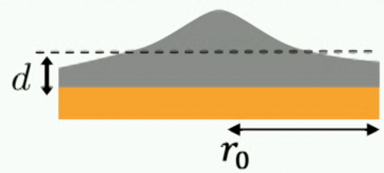
Surface Wave Resonator (SWR)

Fixed boundary condition ($\zeta_{0,1} = 2.4$)



Free boundary condition ($\zeta_{0,1} = 3.8$)



Mode shape:

$$\xi_{\mu,\nu}(r,\theta) = A_{\mu,\nu}\cos(\mu\theta)\,J_\mu\left(\frac{\zeta_{\mu,\nu} r}{r_0}\right)$$

Resonant frequency:

$$\Omega_m = \frac{\zeta_{\mu,\nu}\, c}{r_0}$$

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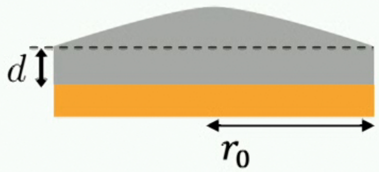

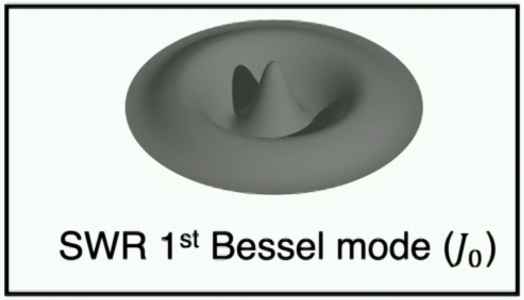

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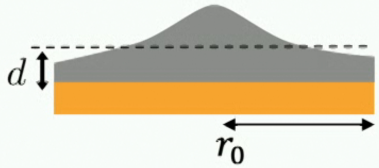

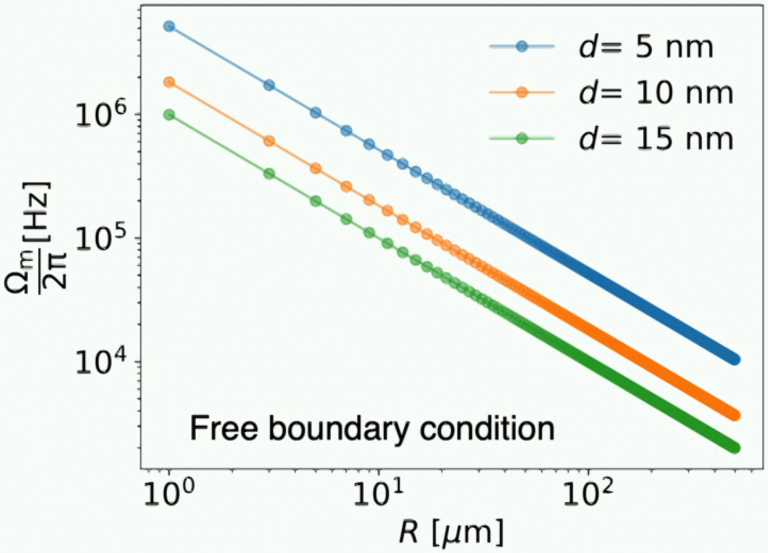

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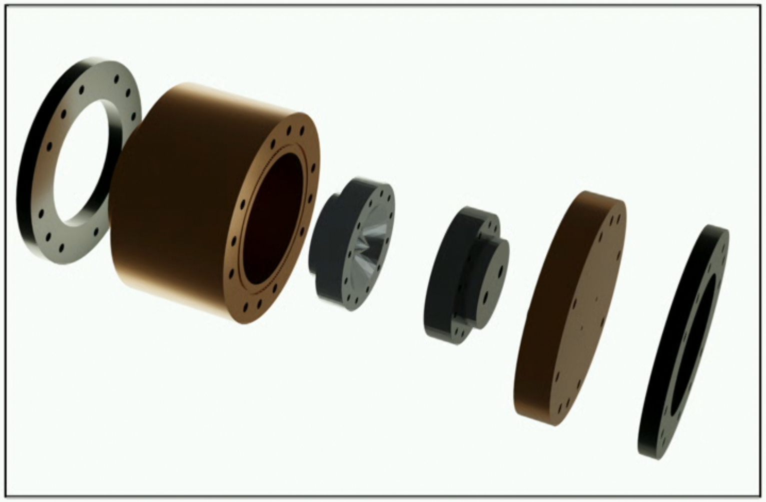
Where are we now?

Microwave cavity

Copper immersion cell



Experimental progress:

- Development of reliable superfluid leak tight microwave feedthroughs
- Design, fabrication, testing of microwave re-entrant cavities with ***μ*m size gaps**
- Surface wave resonators with **RMS surface roughness ~ 5 nm**

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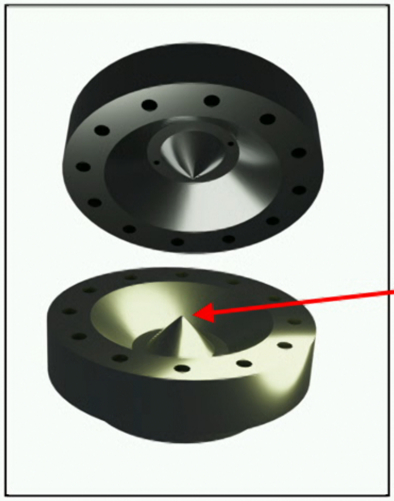
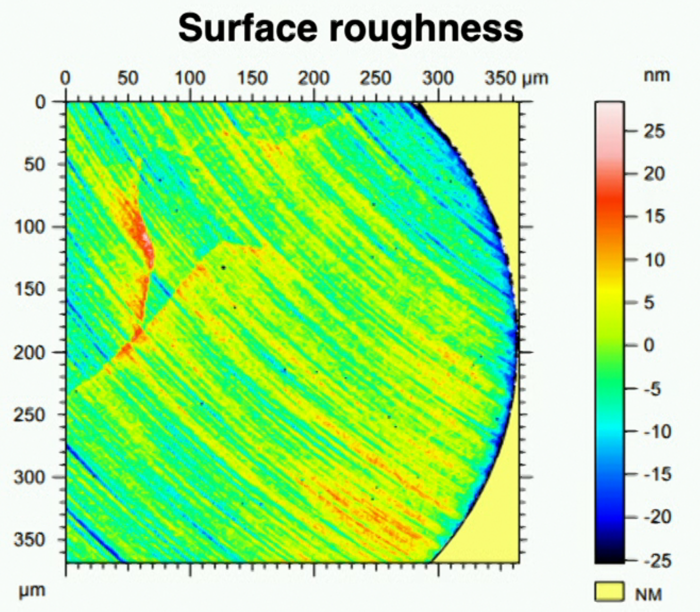
Microwave cavity





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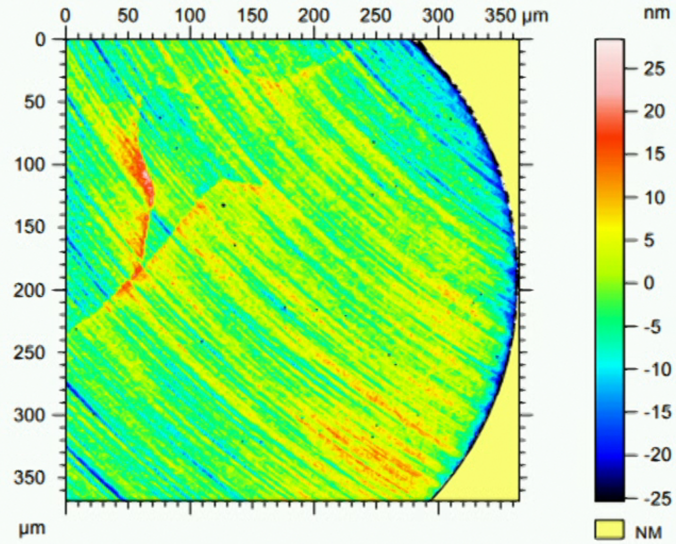

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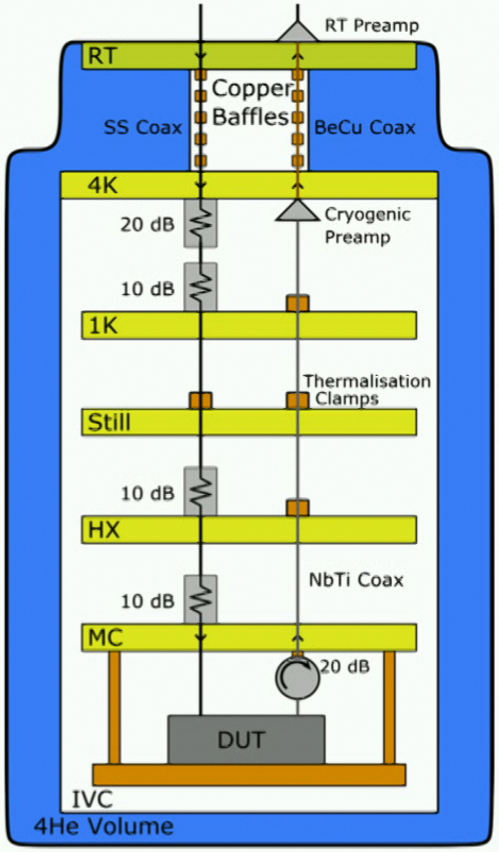
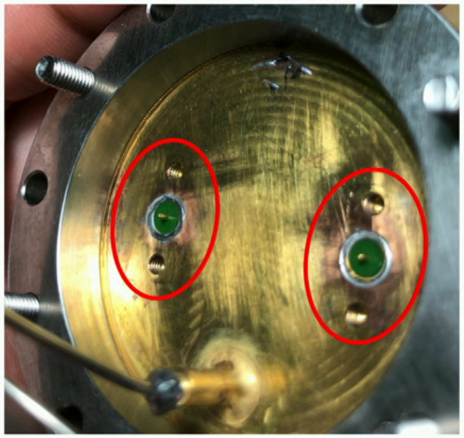
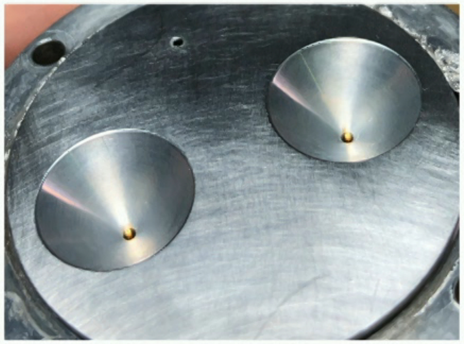
Cryogenic microwave setup

Cryostat



Microwave feedthroughs





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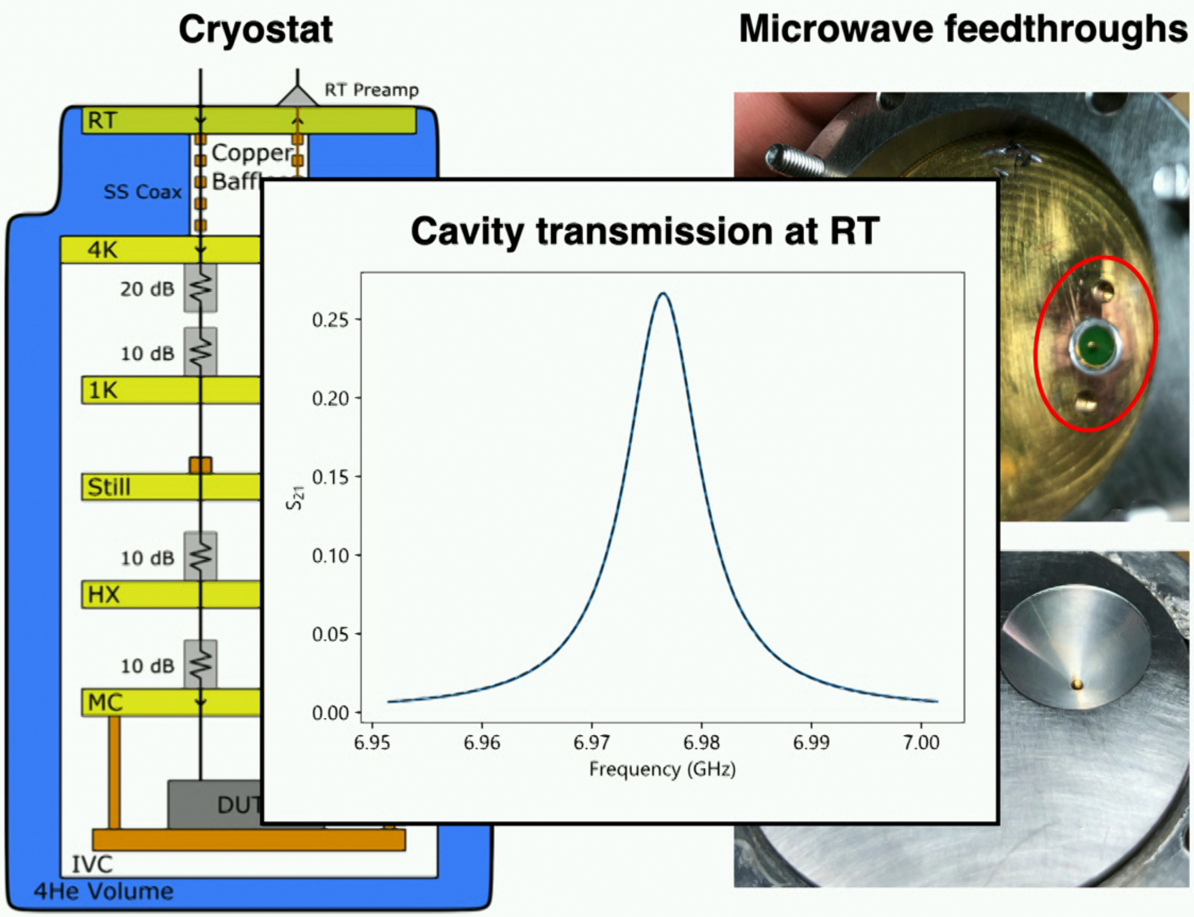

What's next?

Microwave re-entrant cavity

- smaller re-entrant gaps: $g_0(d)$
  μm ⟶ nm
- higher resonance frequency: $g_0(\omega_0)$
  up to 12 GHz max
- higher quality factor: κ
  values of $\kappa \sim 1\ \mathrm{Hz}$ are achievable

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Surface wave resonator

- higher order modes (e.g. whispering gallery modes)
  smaller effective mass: $m_{\mathrm{eff}} \propto R^4/d$
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- thinner films: $g_{\mathrm{vdw}}(d)$, $\Omega_m(d)$
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How do we make improvements?

Nanofabrication:

- dimensions (μm ⟶ nm)
- surface roughness

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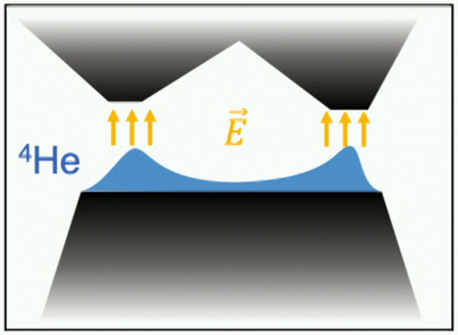
Nanostructured probe



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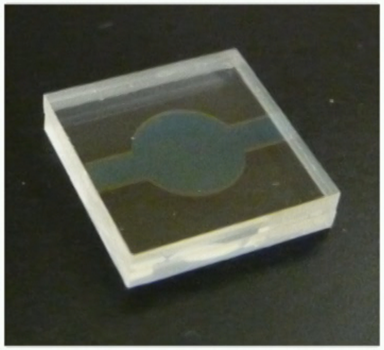
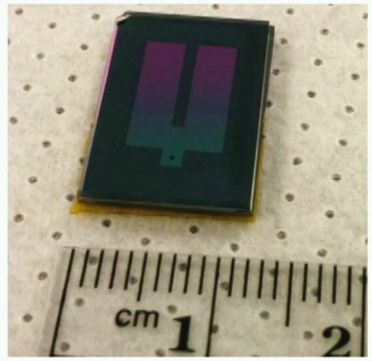
Nanofluidic confinement

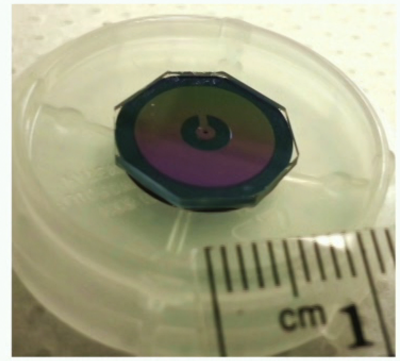
University of Alberta



glass - glass

Royal Holloway & Cornell University

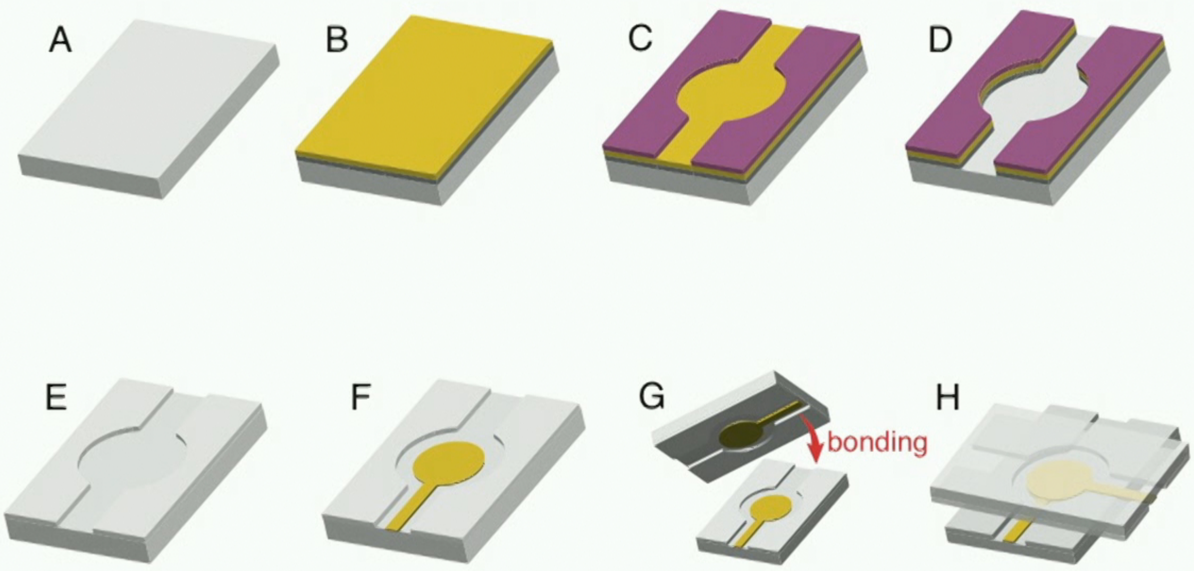




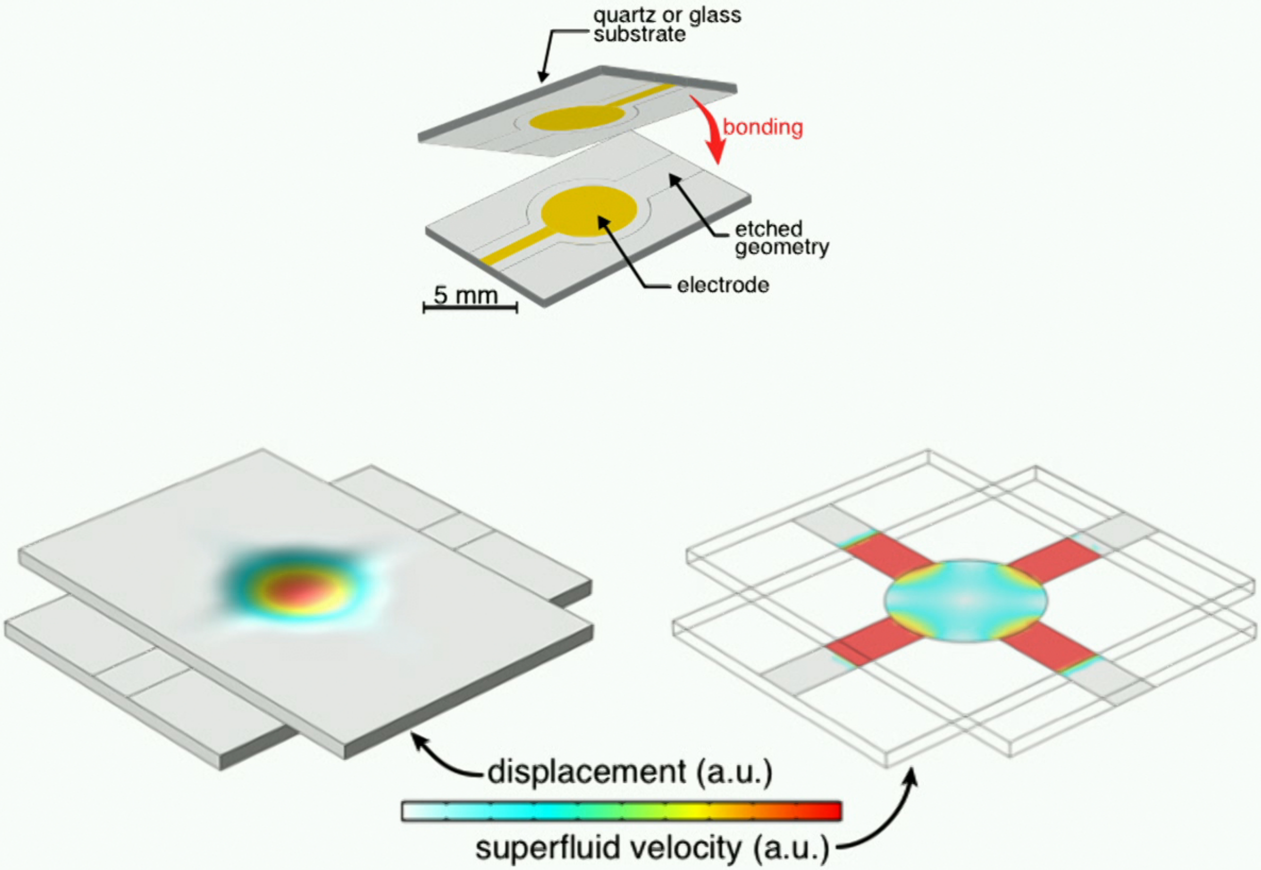
silicon - glass

$$g_0 \propto x_{zpf} \propto \sqrt{\hbar / \left(2 m_{eff} \Omega_m\right)}$$

Nanofabrication process



Superfluid Helmholtz resonator



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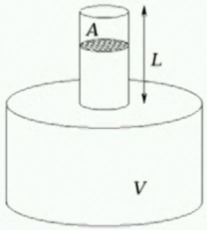
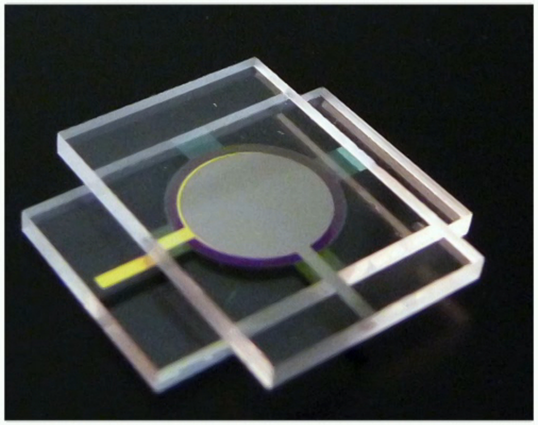
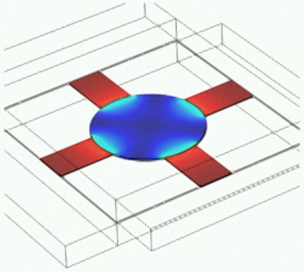
Superfluid Helmholtz resonator

Helmholtz resonator



Superfluid Helmholtz resonator



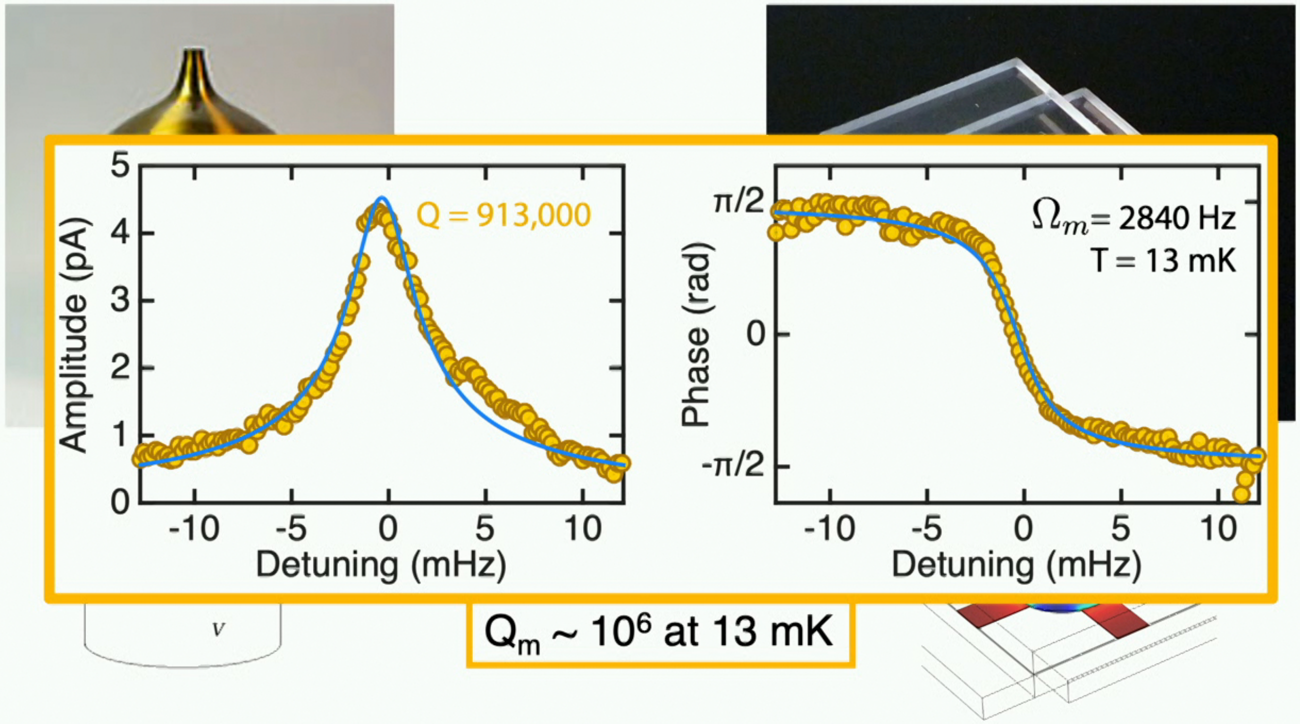


Rojas *et al.* PRB **91**, 024503 (2015)

Souris *et al.* Phys. Rev. App. **7**, 044008 (2017)

Superfluid Helmholtz resonator

Helmholtz resonator | **Superfluid Helmholtz resonator**



$Q_m \sim 10^6$ at 13 mK

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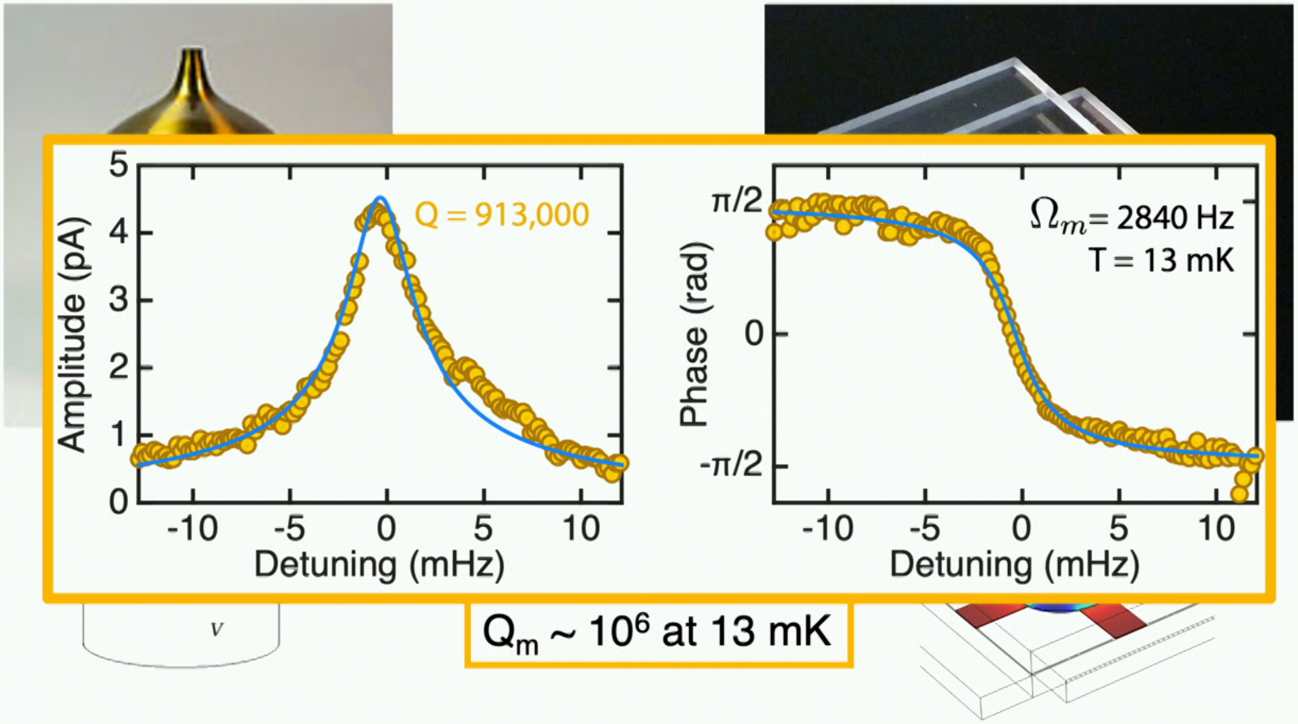
Superfluid Helmholtz resonator

Helmholtz resonator

Superfluid Helmholtz resonator



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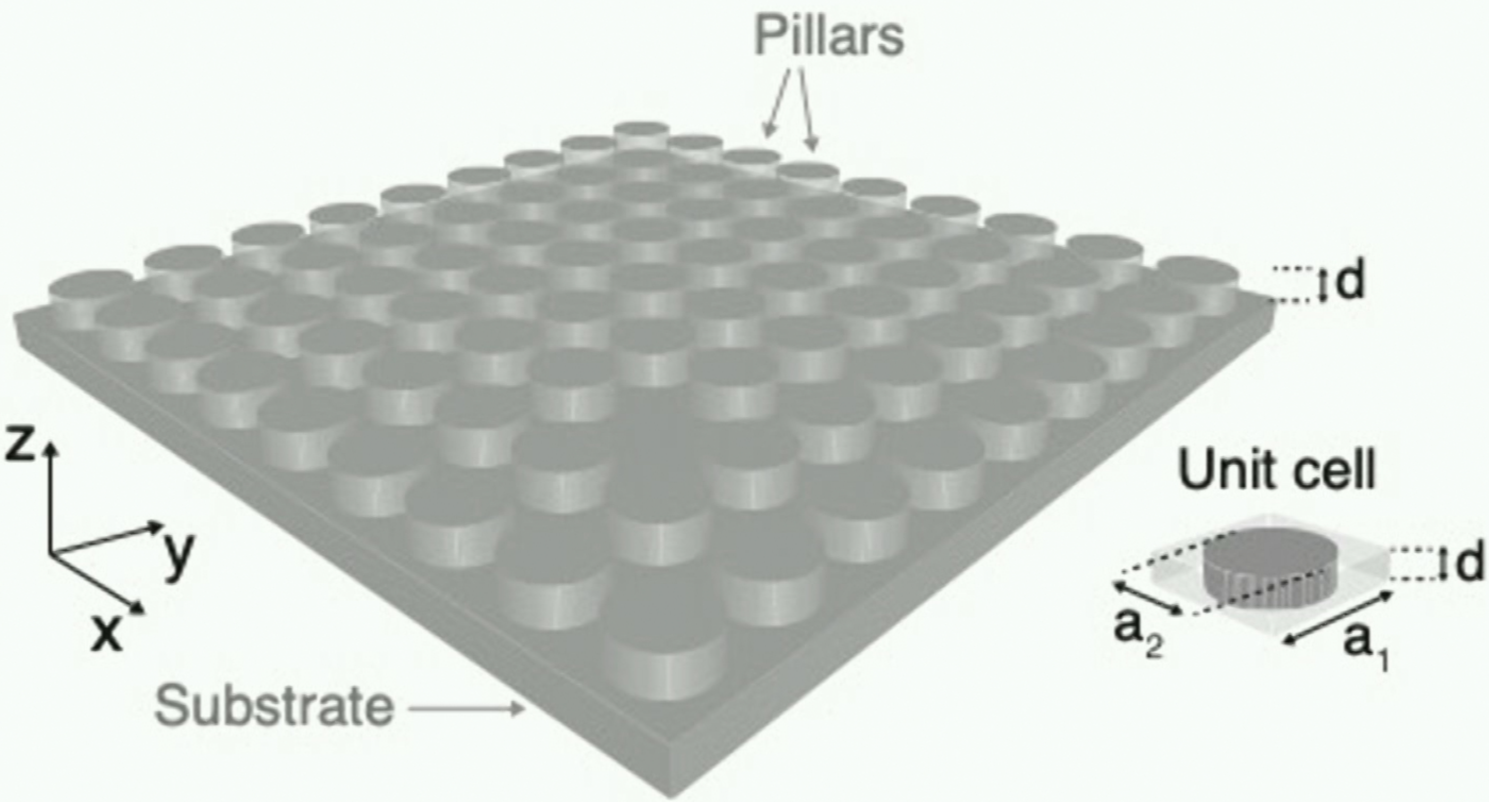
2D Sonic crystal



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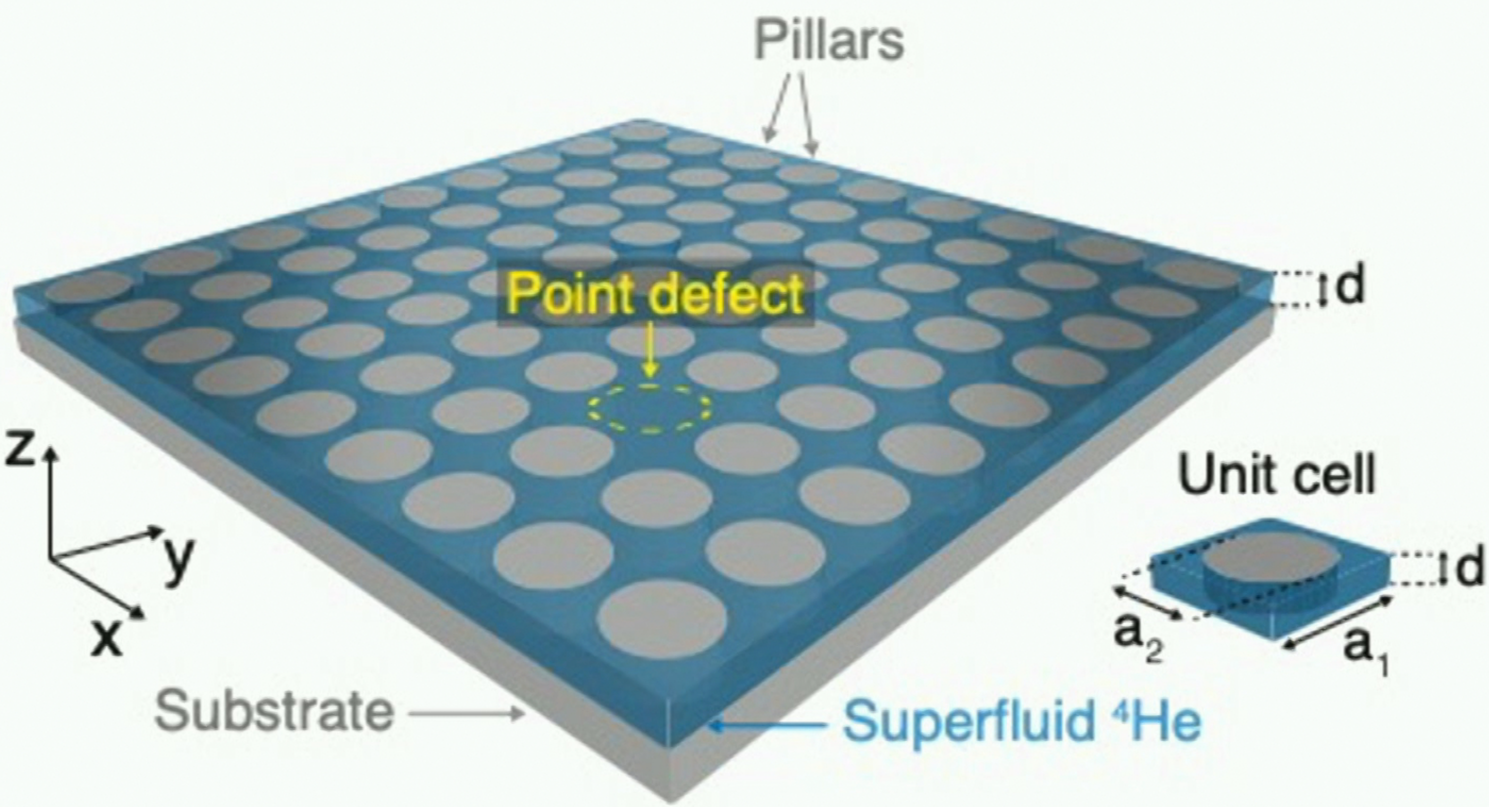

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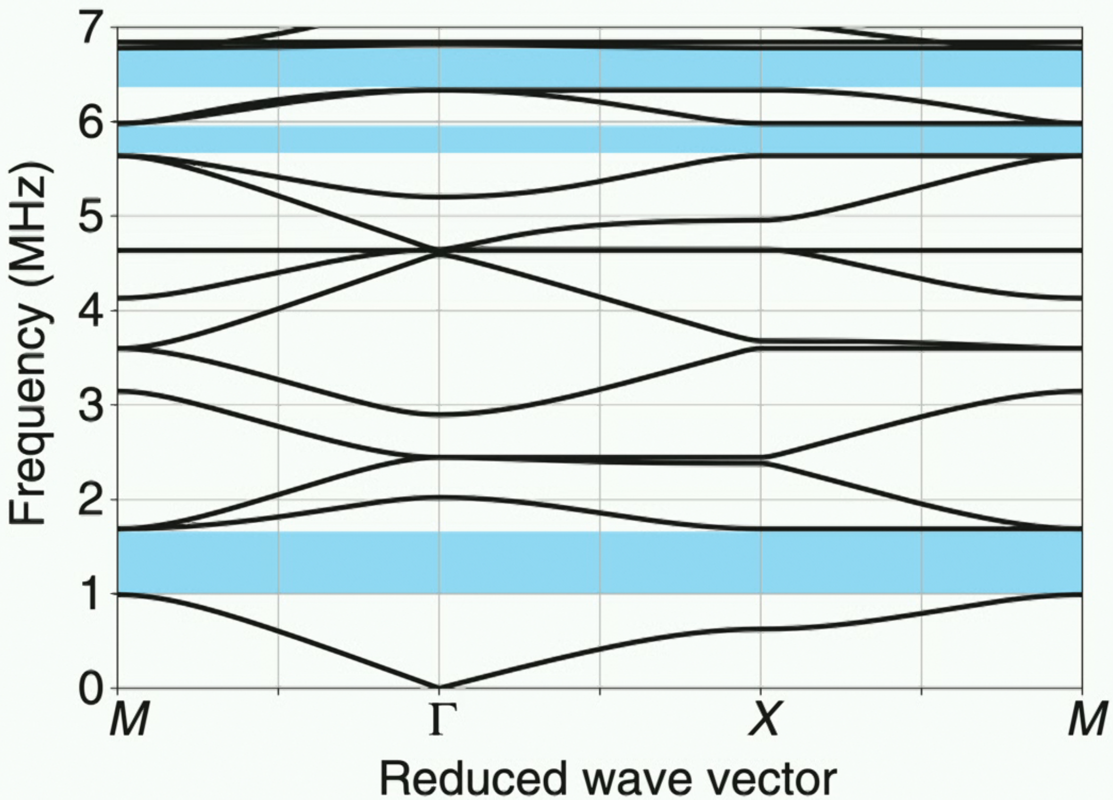
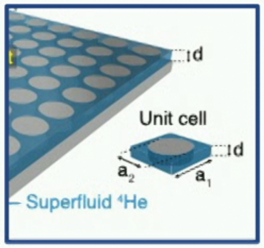
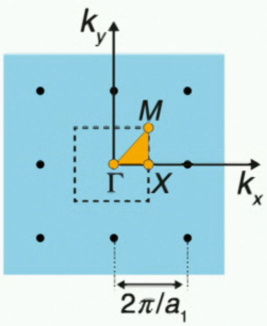
Phononic band structure

Simulation: $a_1 = 100\ \mu m$; $a_2 = 80\ \mu m$; $d = 200$ nm







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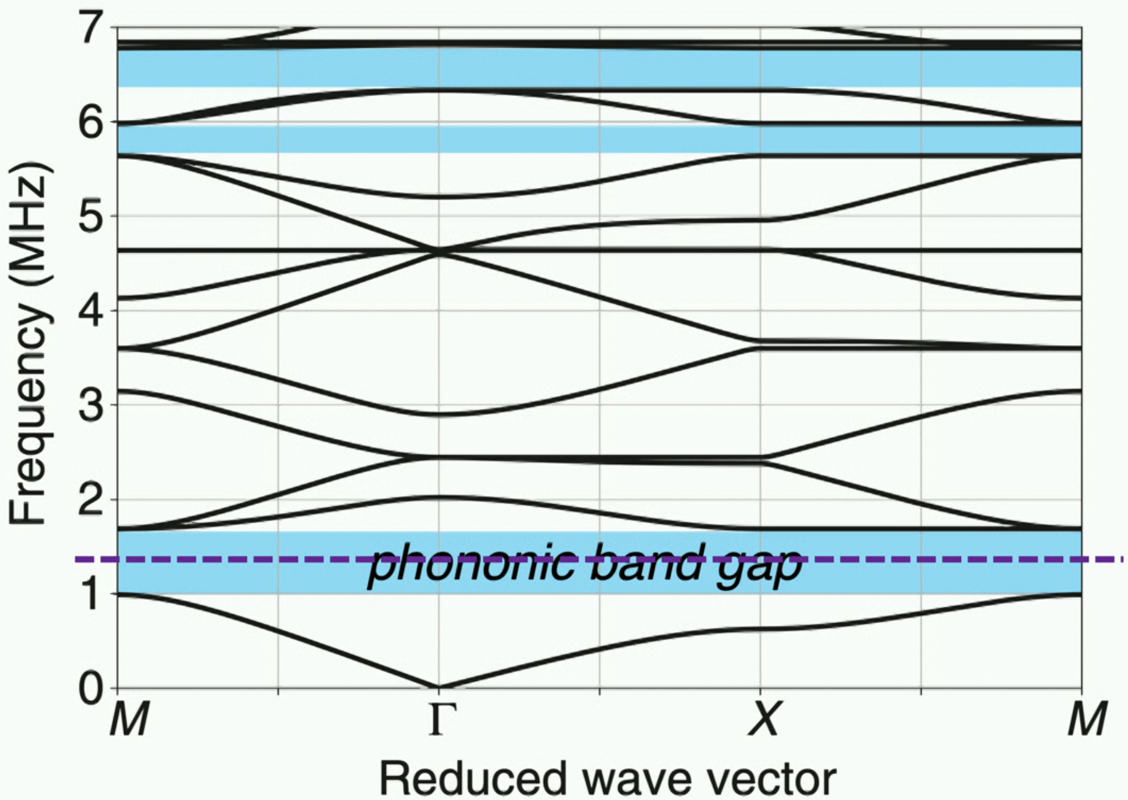
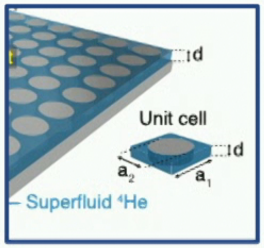
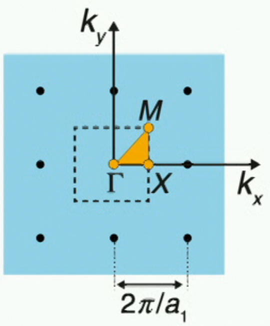
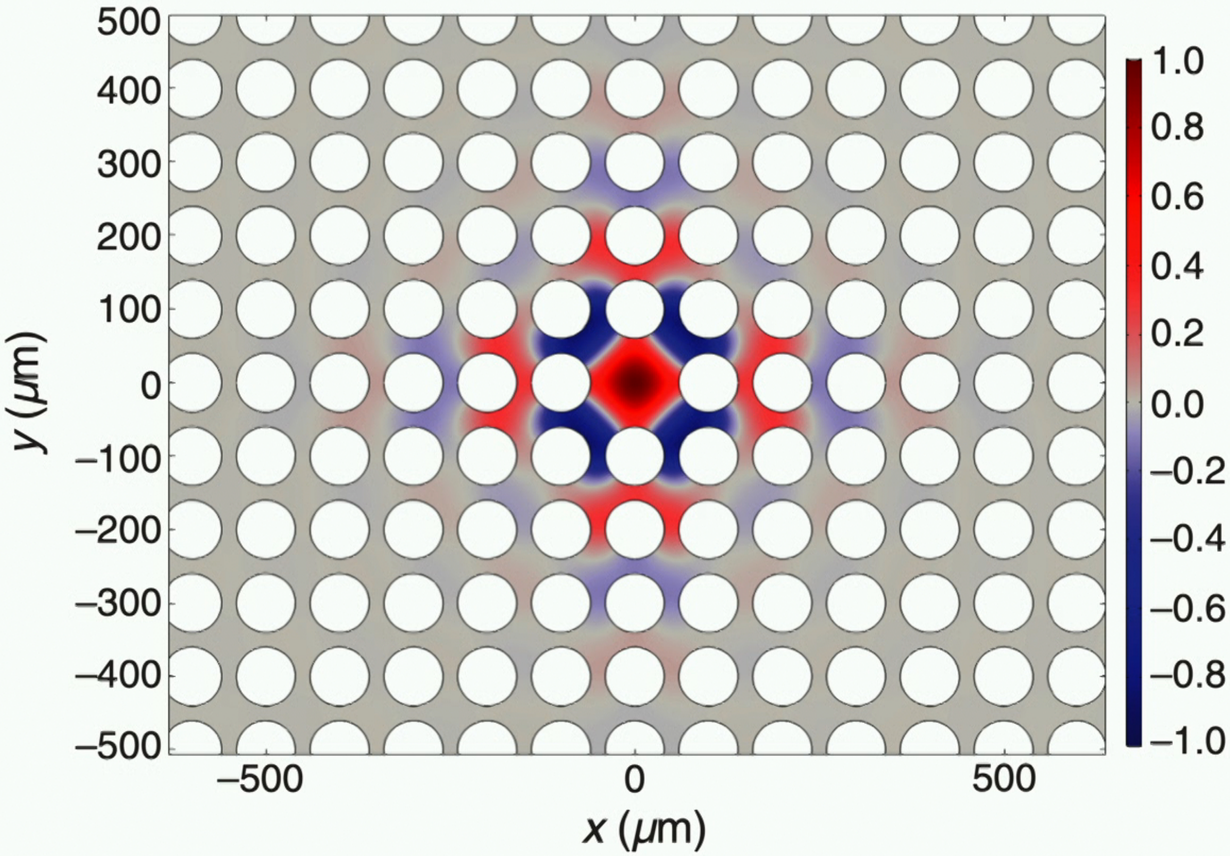


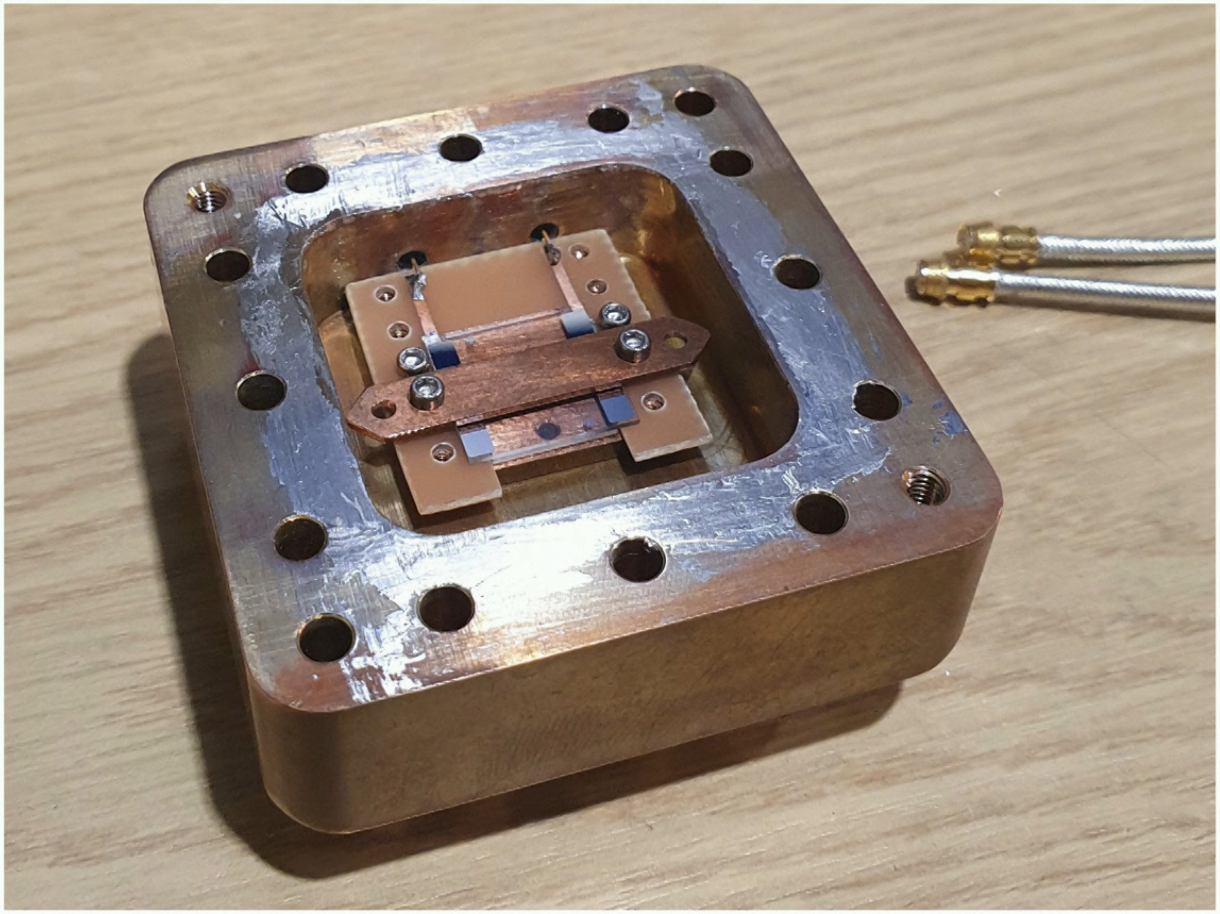




Point defect mode shape: pressure field



Direct capacitive measurement



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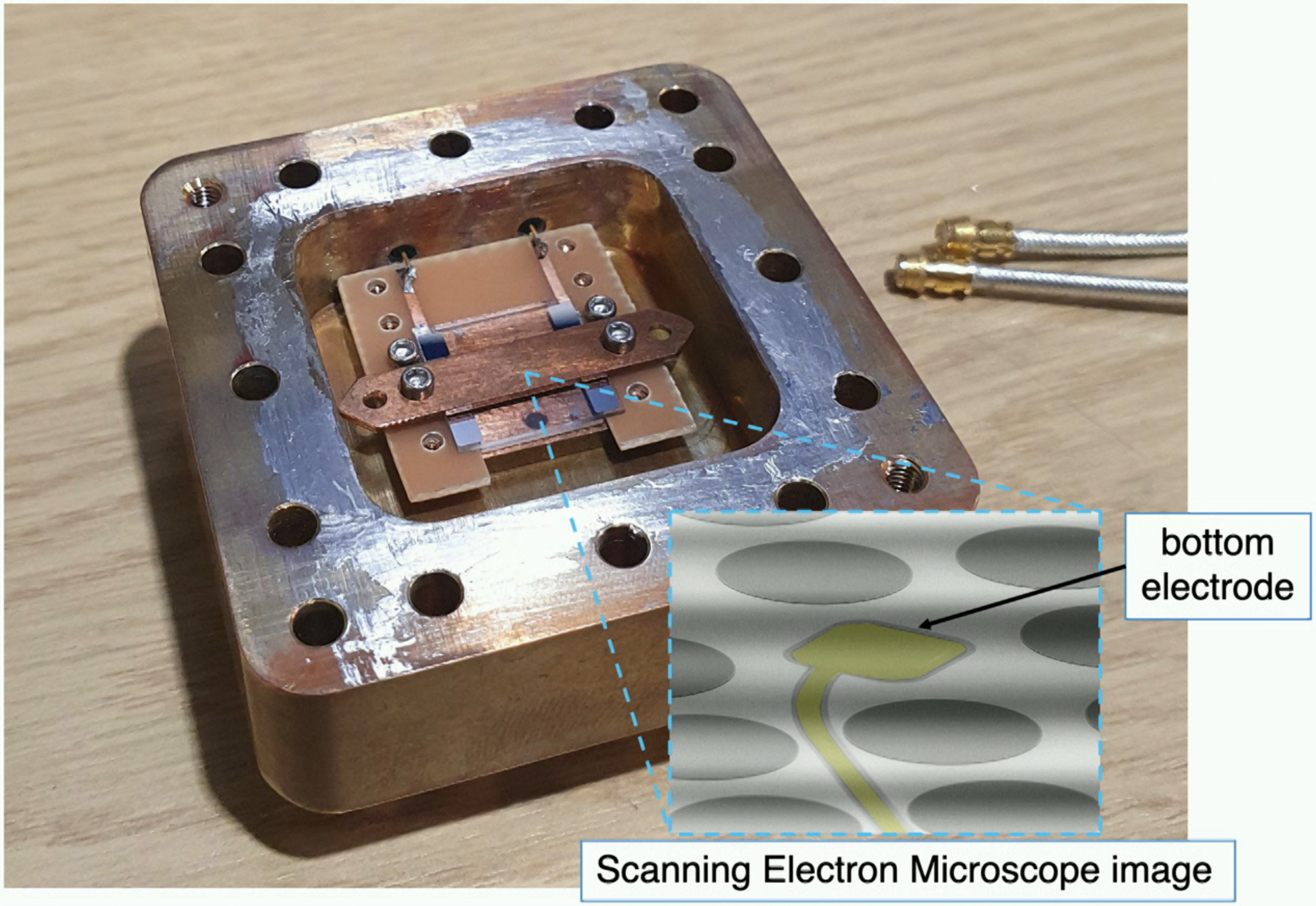
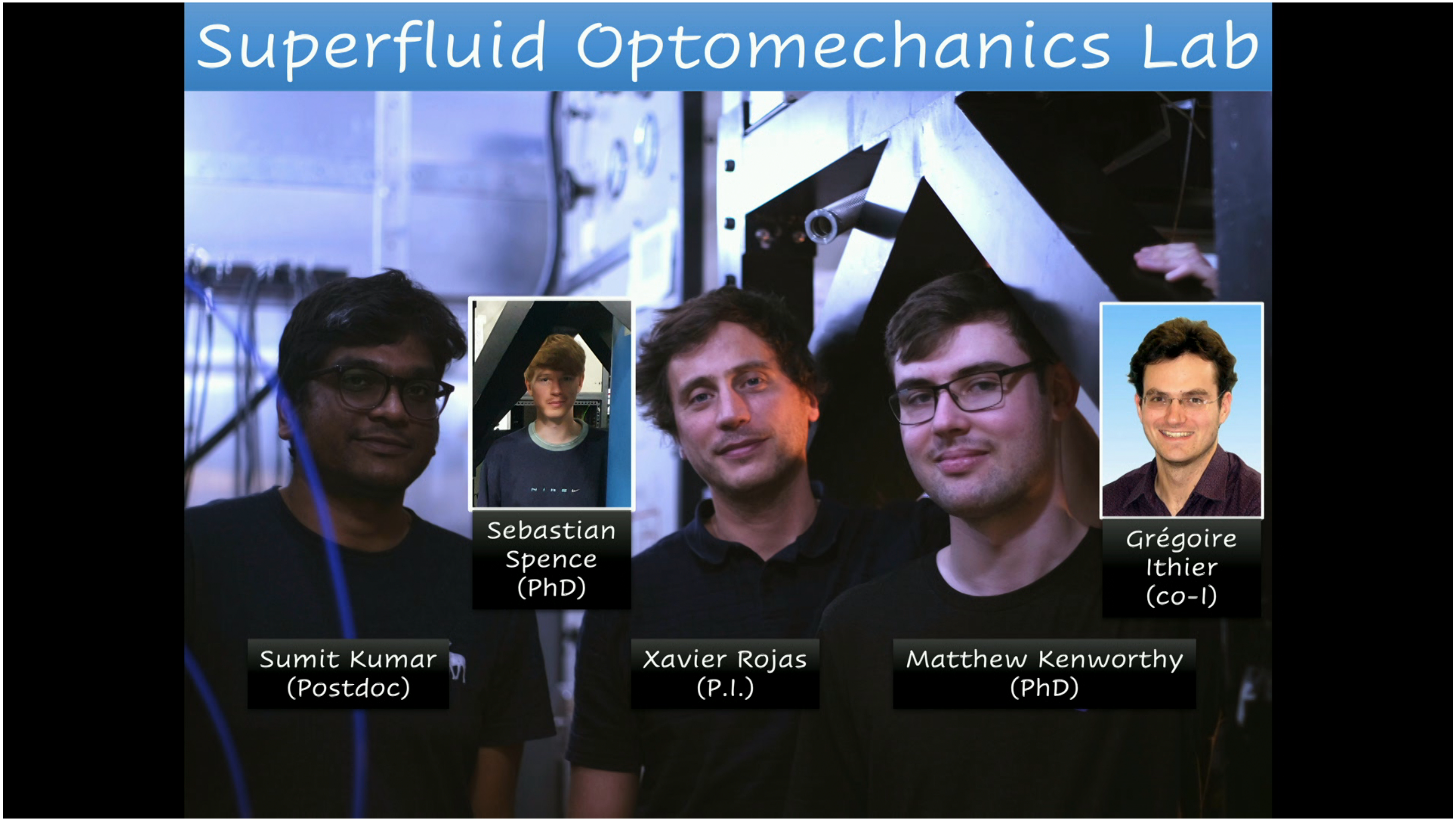
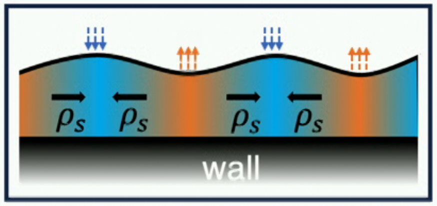



Superfluid Optomechanics Lab
Sebastian Spence (PhD)
Grégoire Ithier (co-I)
Sumit Kumar (Postdoc)
Xavier Rojas (P.I.)
Matthew Kenworthy (PhD)

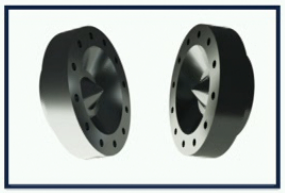
Conclusion

Analogue gravity experiment with superfluid ^{4}He



- large effective gravity, large speed of wave
- zero viscosity, low loss
- quantum fluid, quantized vortices

Microwave superfluid optomechanics



- compatible with low temperature environment
- detection/control of excitations at the quantum level
- enable active cooling techniques to reduce phonon occupancies

…. experiment in progress

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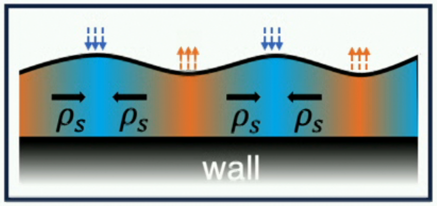

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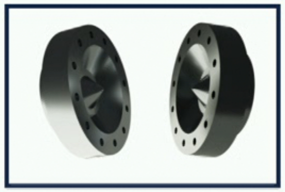
- quantum fluid, quantized vortices

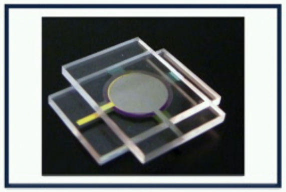
Microwave superfluid optomechanics



- compatible with low temperature environment
- detection/control of excitations at the quantum level
- enable active cooling techniques to reduce phonon occupancies

…. experiment in progress

Nanofluidic environment



- higher frequency and coupling
- control over boundary conditions
- atomic scale surface roughness

… experiment in progress

Thanks for your attention!