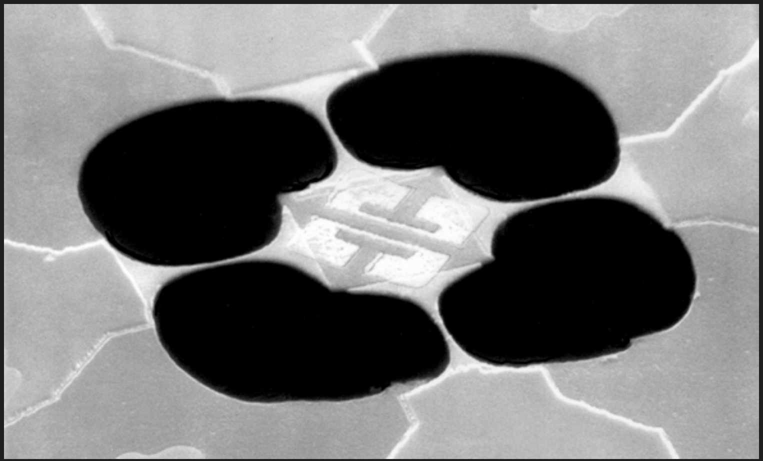
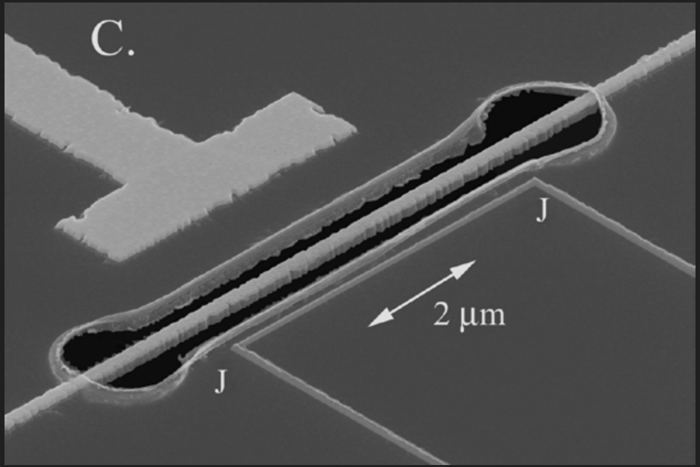
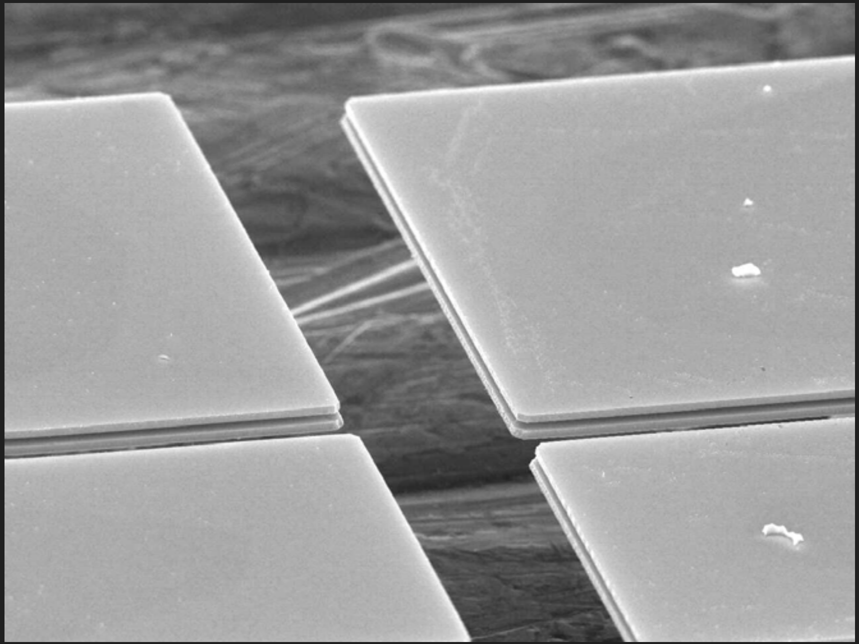
Development of an Ultra-low loss Superfluid He-4 Acoustic Resonator

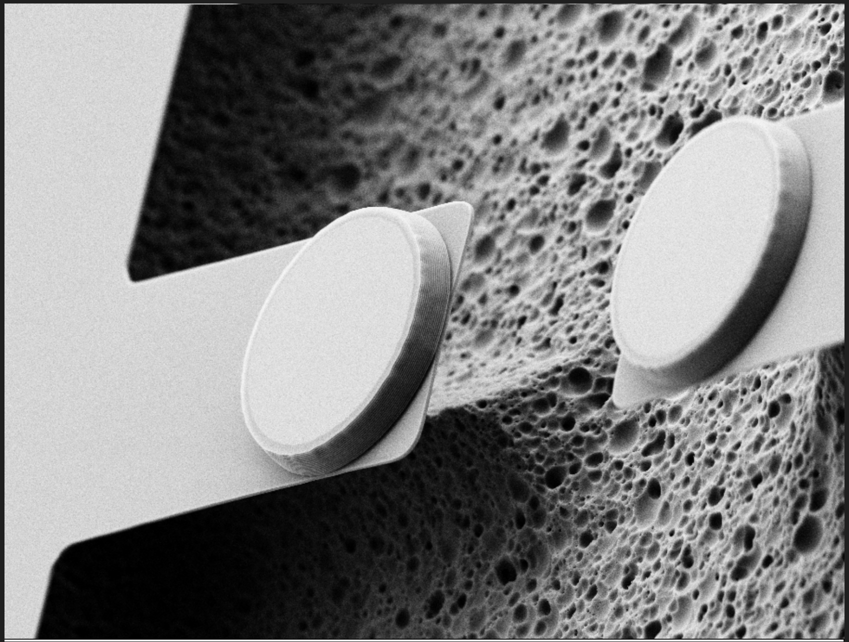


Keith Schwab
and
Laura De Lorenzo

Applied Physics
Caltech
May 2012







Outline

- Motivation
- Properties of superfluid He-4, what is known
- Estimation of the loss mechanisms
  - Intrinsic loss in the fluid - phonon-phonon coupling
  - He-3 impurities
  - Container radiation losses
- Microwave cavity readout near the SQL
- Sensitivity estimates to accelerations, forces, and gravitational waves
- Other possibilities, configurations

Our work in quantum limits of nanomechanics in the past years

REPORTS

Approaching the Quantum Limit of a Nanomechanical Resonator

M. D. LaHaye,[1,2] O. Buu,[1,2] B. Camarota,[1,2] K. C. Schwab[1*]

2004: Approaching the SQL and the ground state with nanomechanics

2006: Observation of the back action forces due to shot noise, and cooling

LETTERS

Cooling a nanomechanical resonator with quantum back-action

A. Naik[1,2], O. Buu[1,3], M. D. LaHaye[1,3], A. D. Armour[4], A. A. Clerk[5], M. P. Blencowe[6] & K. C. Schwab[1]

nature physics

ARTICLES

PUBLISHED ONLINE: 6 DECEMBER 2009 | DOI: 10.1038/NPHYS1479

Back-action-evading measurements of nanomechanical motion

J. B. Hertzberg[1,2], T. Rocheleau[1], T. Ndukum[1], M. Savva[1], A. A. Clerk[3] and K. C. Schwab[4*]

2009: Back action evading measurement:

$$\Delta X_1 = 4 \cdot \Delta x_{zp}$$

2010: Sideband cooling to near the ground state:

<N> = 4

LETTERS

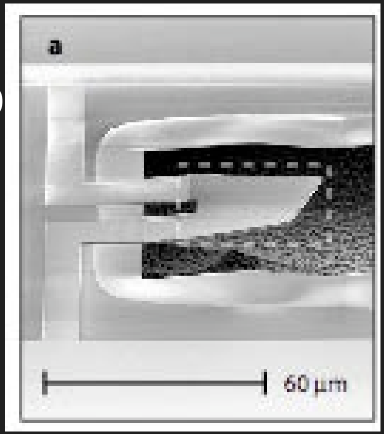
Preparation and detection of a mechanical resonator near the ground state of motion

T. Rocheleau[1*], T. Ndukum[1*], C. Macklin[1], J. B. Hertzberg[2], A. A. Clerk[3] & K. C. Schwab[4]

Studies of motion in the quantum regime – dissipation is key

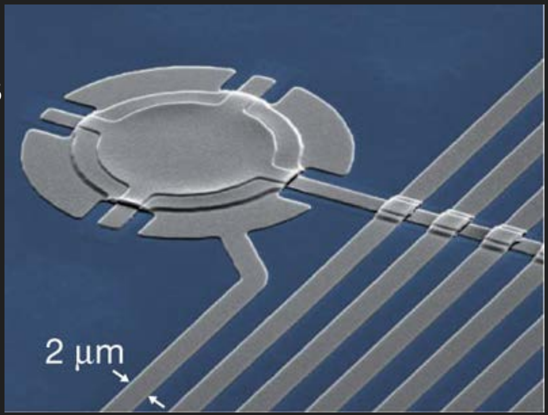
AlN

Q = 900



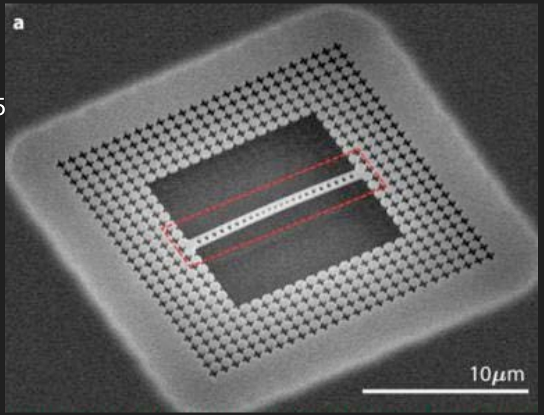
Al

$Q = 3\ 10^5$



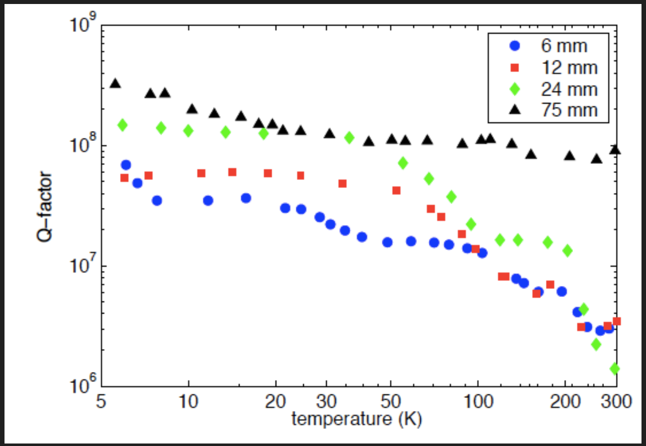
SiO2

$Q = 10^5$



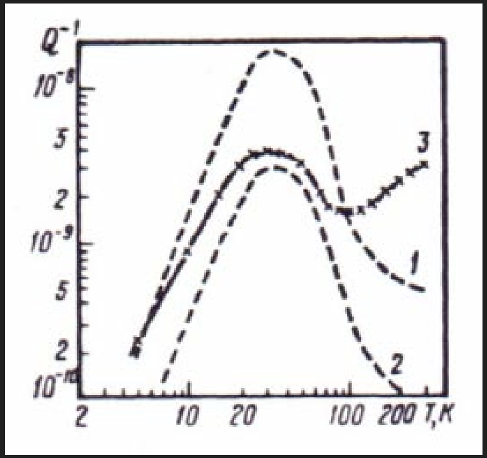
Silicon:

$Q = 4\ 10^8$



Sapphire:

$Q=3\ 10^9$



O'Connel, et al, Nature (2010).

Teufel, Dale, Harlow, Allman, Cicak, Sirois, Whittaker, Lehnert, Simmonds, *Nature* **475**, 359 (2011).

J. Chan, T. Alegre, A. Safavi-Naeini, J. Hill, A. Krause, S. Groblacher, M. Aspelmeyer, O. Painter, *Nature* **478**, 389 (2011).

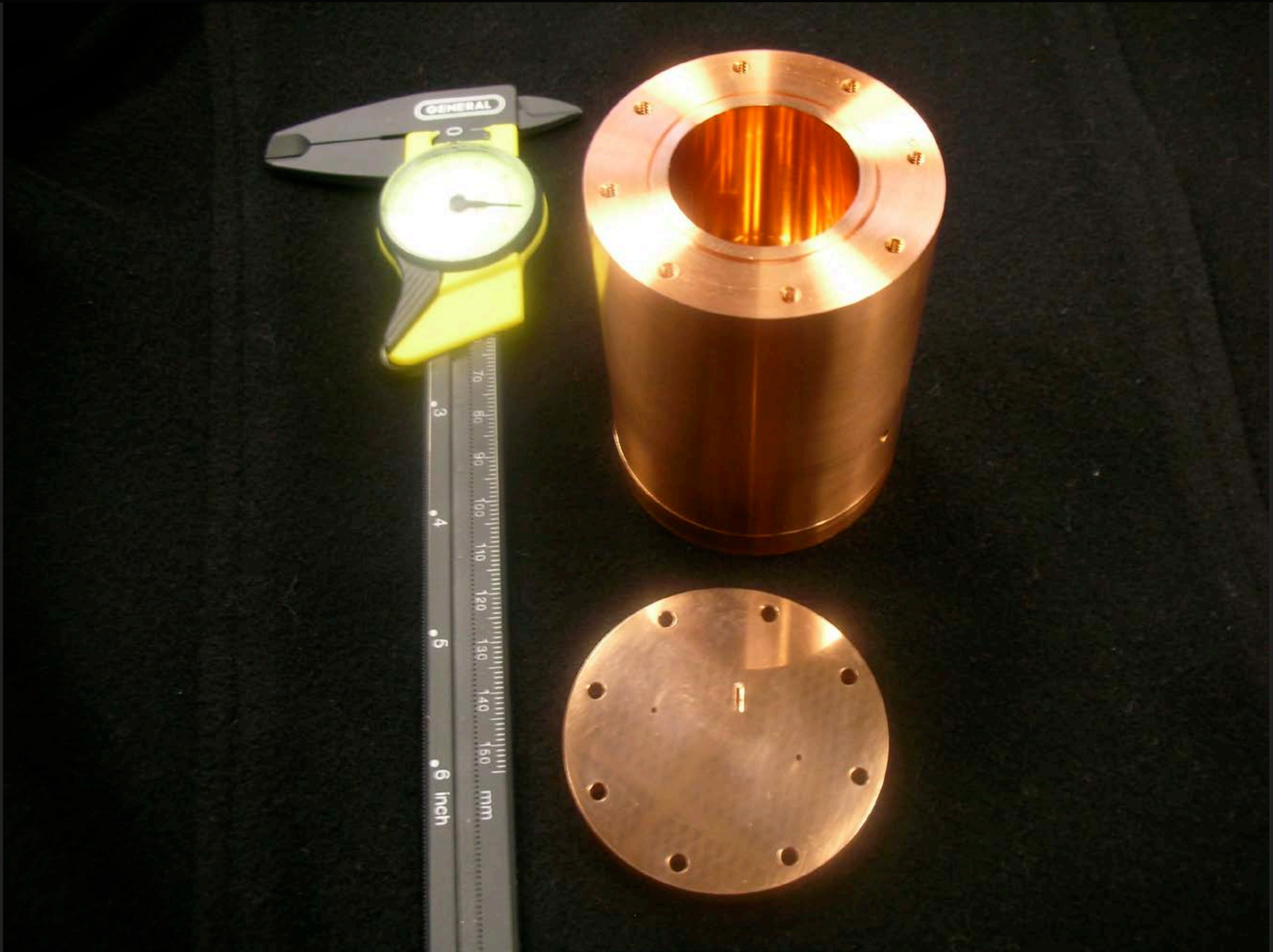
Braginsky, Mitrofanov, Panov, "Systems with Small Dissipation." Univ. of Chicago Press (1985.)

Nawrodt, et al, "High mechanical Q-factor measurements on silicon bulk samples." J. Phys.: Conf. Ser. 112, (2008).

Basic Properties of Superfluid He-4

- Speed of first sound: c=240 m/s (x10 smaller than most metals)
- Density: ρ=145 Kg/m^3 (x10 less than most solids)
- Dielectric constant: 1.05
- Chemically pure (impurities freeze to container walls)
- Isotopic impurities: He-3, concentration of $n=10^{-7}$. Concentration of $n<10^{-14}$ has been achieved
- Transition temperature: T_λ= 2.17K, below this a macroscopic order parameter appears, Ψ
- Entropy resides in normal fluid density composed of rotons (e^{-8K/k_bT}) and phonons (T^4)
- Shows persistent mass currents (frictionless flow) below T_λ, quantized circulation around loops.

Basic concept: superfluid acoustic resonator coupled to microwave resonator



Dissipation of first sound in He-4 – phonon-phonon coupling

•Non-linear acoustic response: $$G = \frac{\rho}{c}\frac{\partial c}{\partial \rho} \cong 2.78$$

•Dispersion relationship for sound: $$e(p) = cp\left(1 - \gamma p^2\right)$$

•For γ<1, three phonon acoustic damping process is possible where phonons scatter off of thermal phonons in fluid

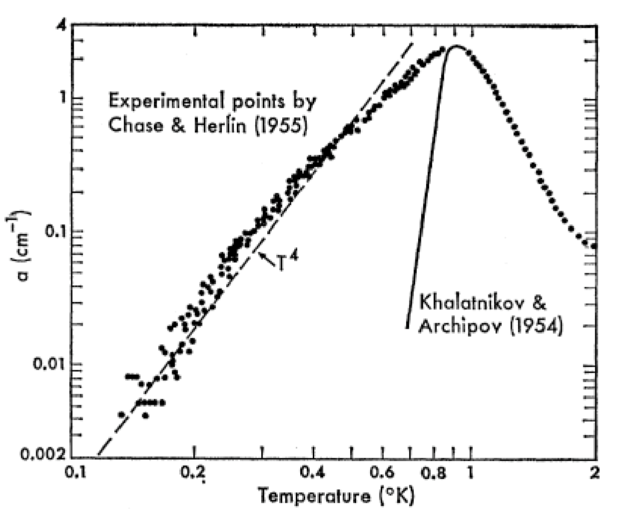


FIG. 1. Absorption of 12 Mc/sec ultrasonic waves in liquid helium. Experimental points by Chase and Herlin,[1] theoretical curve according to calculations by R. B. Archipov [Doklady Akad. Nauk. U.S.S.R. 98, 747 (1954)], based on a relaxation process.

•Acoustic attenuation length:

$$\alpha = \frac{\pi^3}{60}\frac{G+1}{\rho}\frac{k_B^4}{\hbar^3 c^6} T^4 \omega$$

T=10mK, ω=2π 3KHz ⇒ 1/α = 3 10^9 m

T= 1mK, ω=2π 3KHz ⇒ 1/α = 3 10^{13} m

C.E. Chase, Proc. Roy. Soc. (London) A220, 116 (1953).

Humphrey Maris, "Attenuation and Velocity of Sound in Superfluid Helium." *Phys. Rev. Lett.* **28**, 277 (1972).

Dissipation due to He-3 impurities

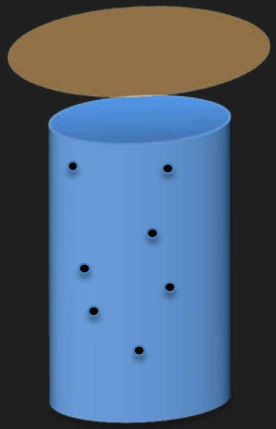
Treat He-3 atoms as dilute, viscous classical gas.

$$\bar{l} = \frac{1}{\sqrt{2}\sigma n_3} \qquad \eta = \frac{1}{3}\bar{l}\rho_3\bar{\upsilon} = \frac{2}{3\sigma}\sqrt{\frac{k_B m_3 T}{\pi}}$$

When mean free path is smaller than container, acoustic attenuation is density independent:

$$\alpha = \frac{2\pi^2\eta}{\rho_4 c_4 \lambda^2}\left(\frac{4}{3} + (\gamma - 1)\frac{1}{\gamma}\right) = \frac{104}{45}\frac{\pi^2\sqrt{k_B T \pi m_3}}{\sigma\rho_4 c_4 \lambda^2}$$

When concentration of He-3 drops to 10^{-8}, mean free path is equal to the size of the container, ~10cm.

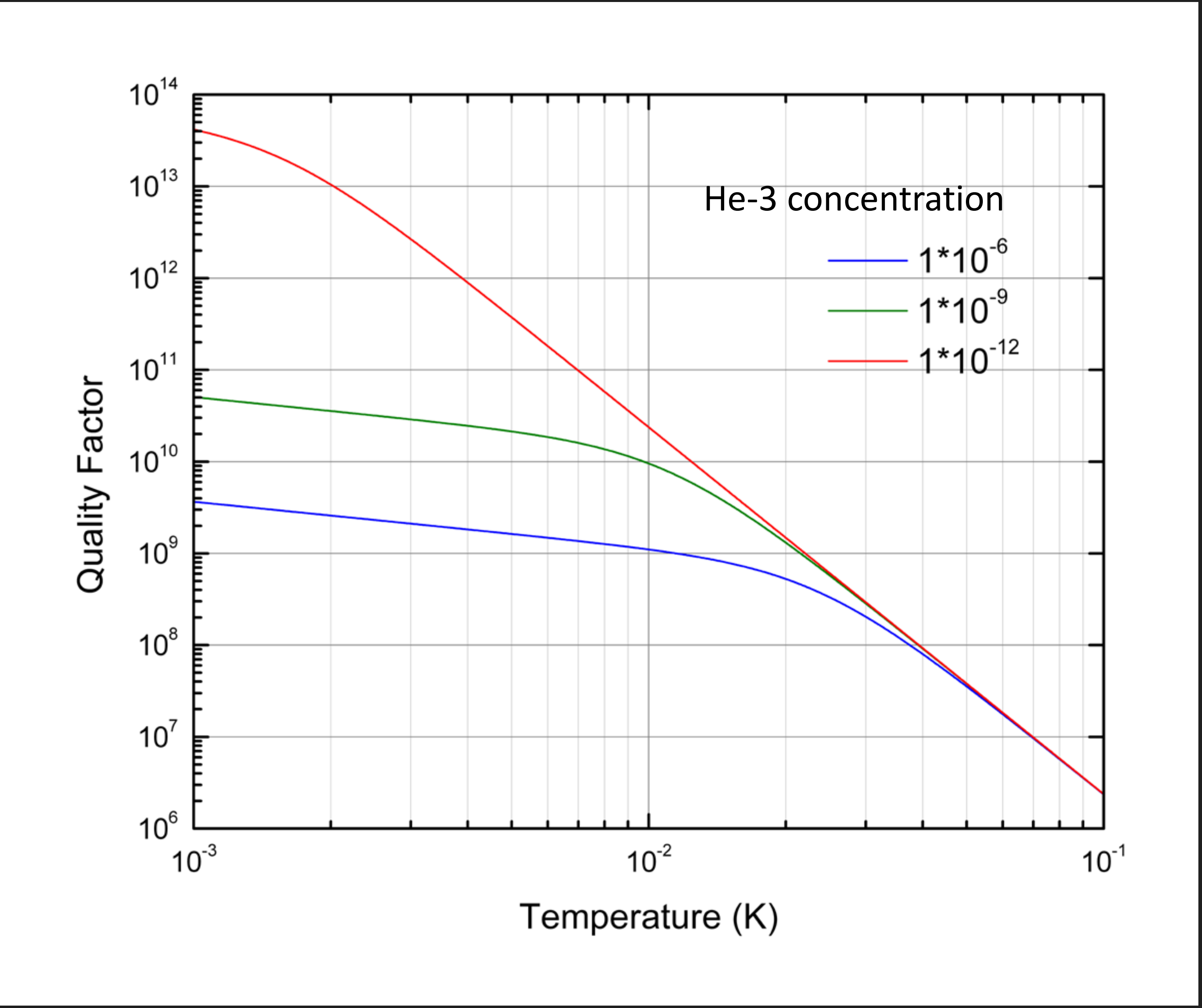


There is some uncertainty about the nature of the scattering of the He-3 atoms on the container walls. We will assume diffuse scattering after N bounces off the walls.

$$\alpha = \frac{104\pi}{45}\sqrt{\frac{2\pi k_B T}{m_3}}\frac{n_3 N}{n_4 c_4 L}$$

Kerscher, Miemetz, Schoepe, “Viscosity and mean Free Path of Very Dilute Solutions of 3He in 4He,” JLTP 124, 163 (2001).

Expected intrinsic dissipation of He-4: phonons and impurities



Acoustic coupling and losses in container

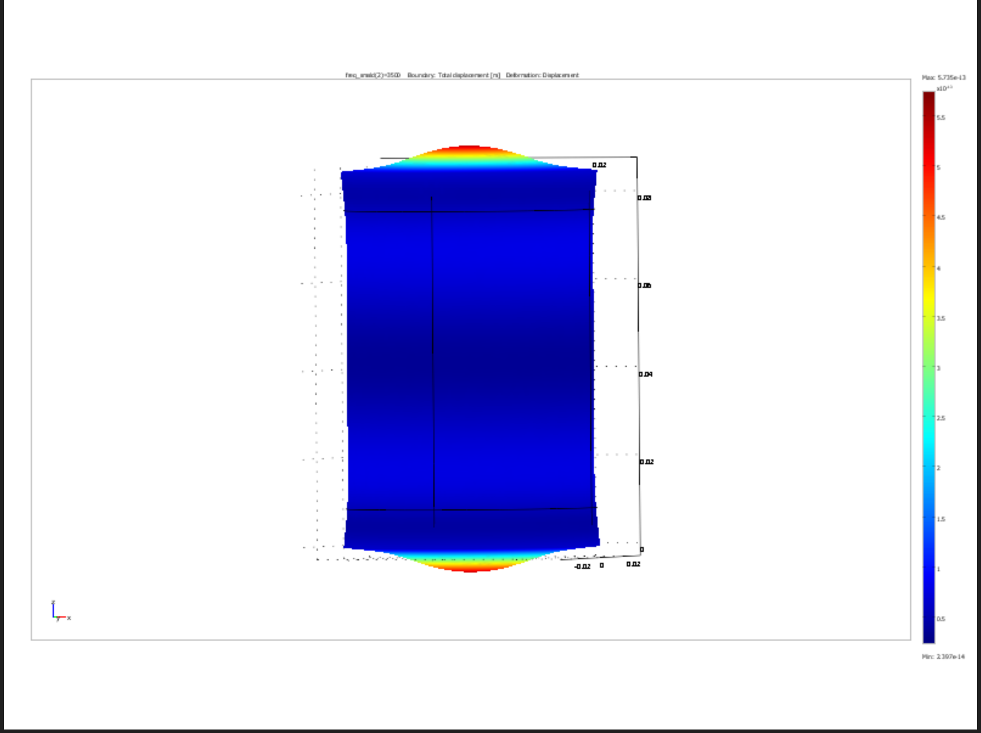
Copper: c_{Cu}=3900 m/s

Niobium: c_{Nb}=3500 m/s

First normal modes of container is at:

12.5KHz, 13.2KHz, 13.6KHz

Superfluid resonance is at 3.5KHz



$$\dot{E} = E_{He}\gamma_{He} + E_C\gamma_C$$

Energy stored in Cu or Nb container for design shown in photo:

$$\frac{E_C}{E_{He}} = 10^{-6}$$

Quality factor at 50mK:

Cu Q =10^5

BeCu Q = 8 10^6

Nb Q = 40 10^6

This will limit Q of superfluid resonance to

Cu: Q = 10^{11}

BeCu: Q = 10^{13}

Nb: Q = 10^{14}

Duffy, W. “Acoustic quality factor of copper, brass, and beryllium copper from 50mK to 300K.” Cryogenics 32, 1121 (1992).

Acoustic resonator coupled to a microwave resonance

L=6.8 cm

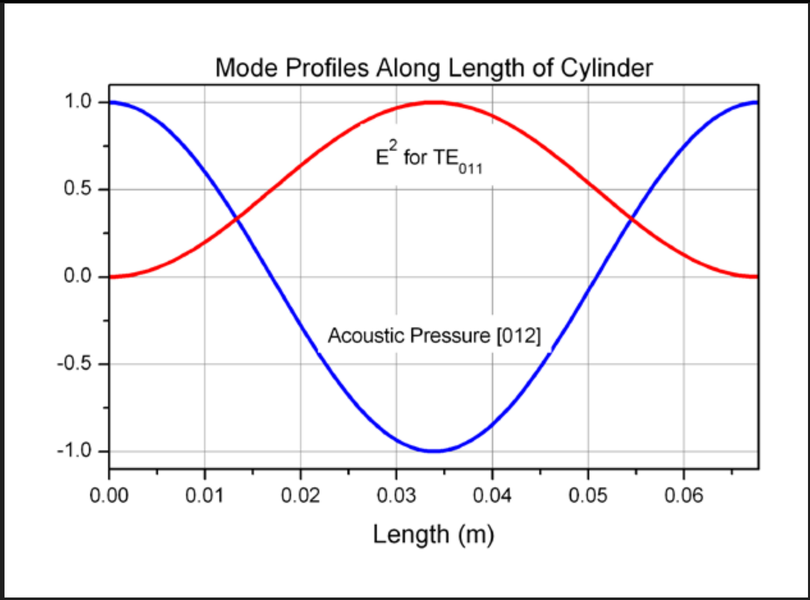
D = 3 cm

M= 7g

ω = 3.5 kHz

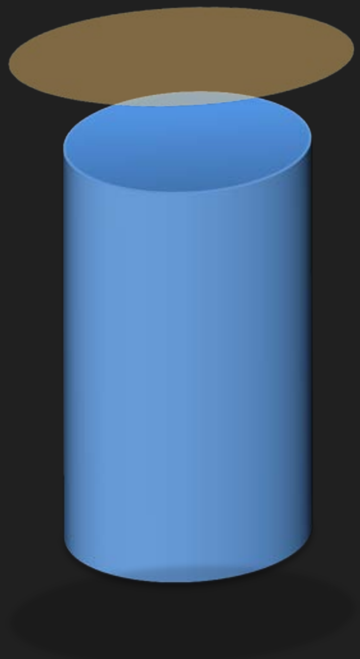
ω = 12 GHz

$$\frac{\Delta\omega_c}{\omega_c} = \frac{\int \Delta\mu |H|^2 + \Delta\varepsilon |E|^2 \, dV}{\int \mu |H|^2 + \varepsilon |E|^2 \, dV}$$



Opto-mechanical Hamiltonian

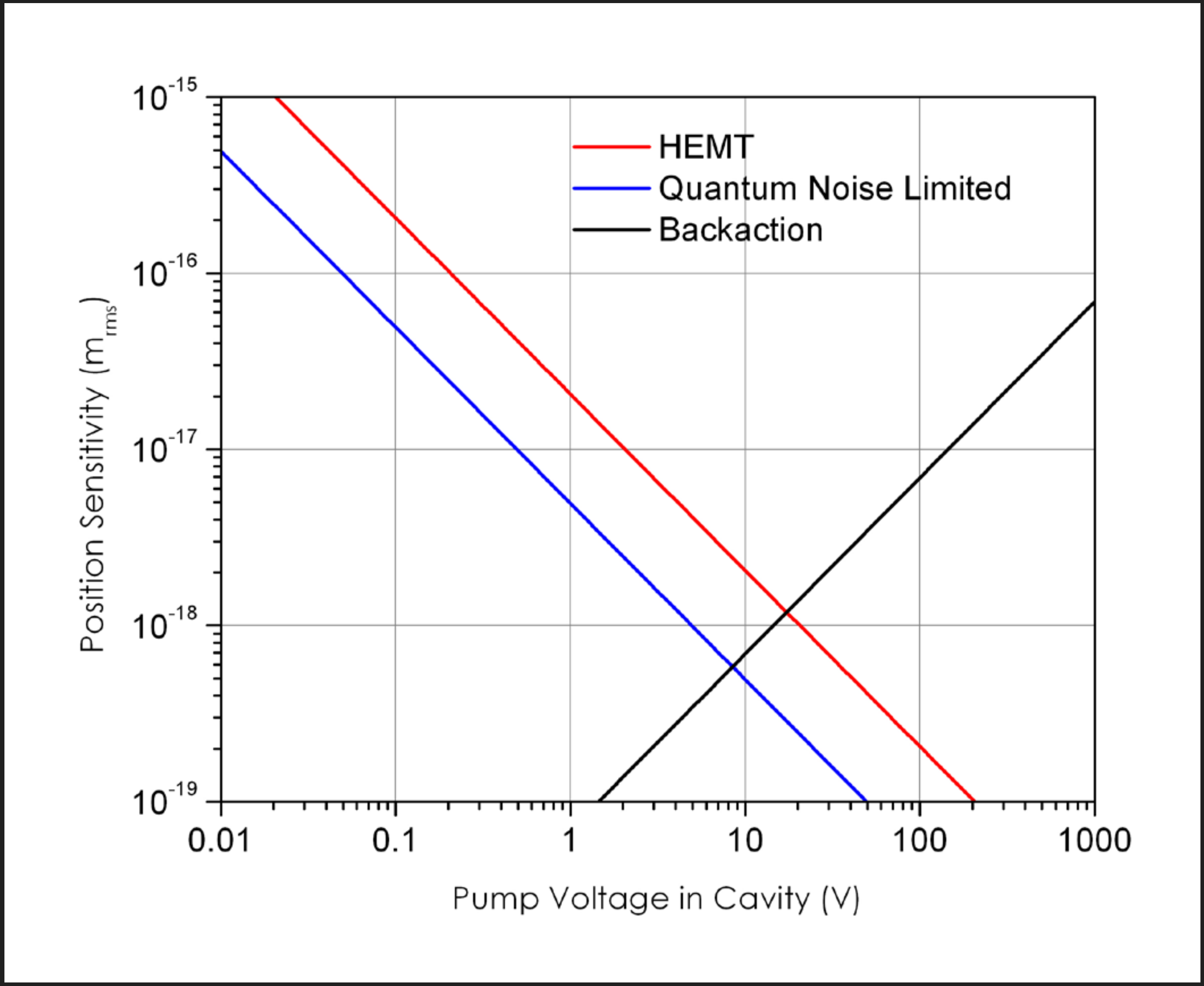
$$H = \hbar\omega_c\left(a^\dagger a + \frac{1}{2}\right) + \hbar\omega_m\left(b^\dagger b + \frac{1}{2}\right) + \hbar\frac{\partial\omega_c}{\partial x}\Delta x_{zp}\left(b^\dagger + b\right)\left(a^\dagger a + \frac{1}{2}\right)$$



Coupling per quanta…very weak

$$\frac{\partial\omega_c}{\partial x}\Delta x_{zp} = 10^{-6}$$

"Position" sensitivity



Sensitivity to sudden gravitational wave pulse

Imagine sudden pulse, of duration $\tau_i \sim 1 ms$

Pulse energy density: $F(\omega) \sim \frac{c^3 h^2}{4\pi G}$

Energy deposited into resonant bar detector: $U_s \sim F(\omega)\frac{8MGV^2}{\pi c^2}$

Energy sensitivity: $U_s = 2k_B T \frac{\tau_i}{\tau_a} + \frac{|Z_{12}|^2}{2M} S_i(\omega)\tau_i + \frac{2M}{|Z_{21}|^2}\frac{S_e(\omega)}{\tau_i}$

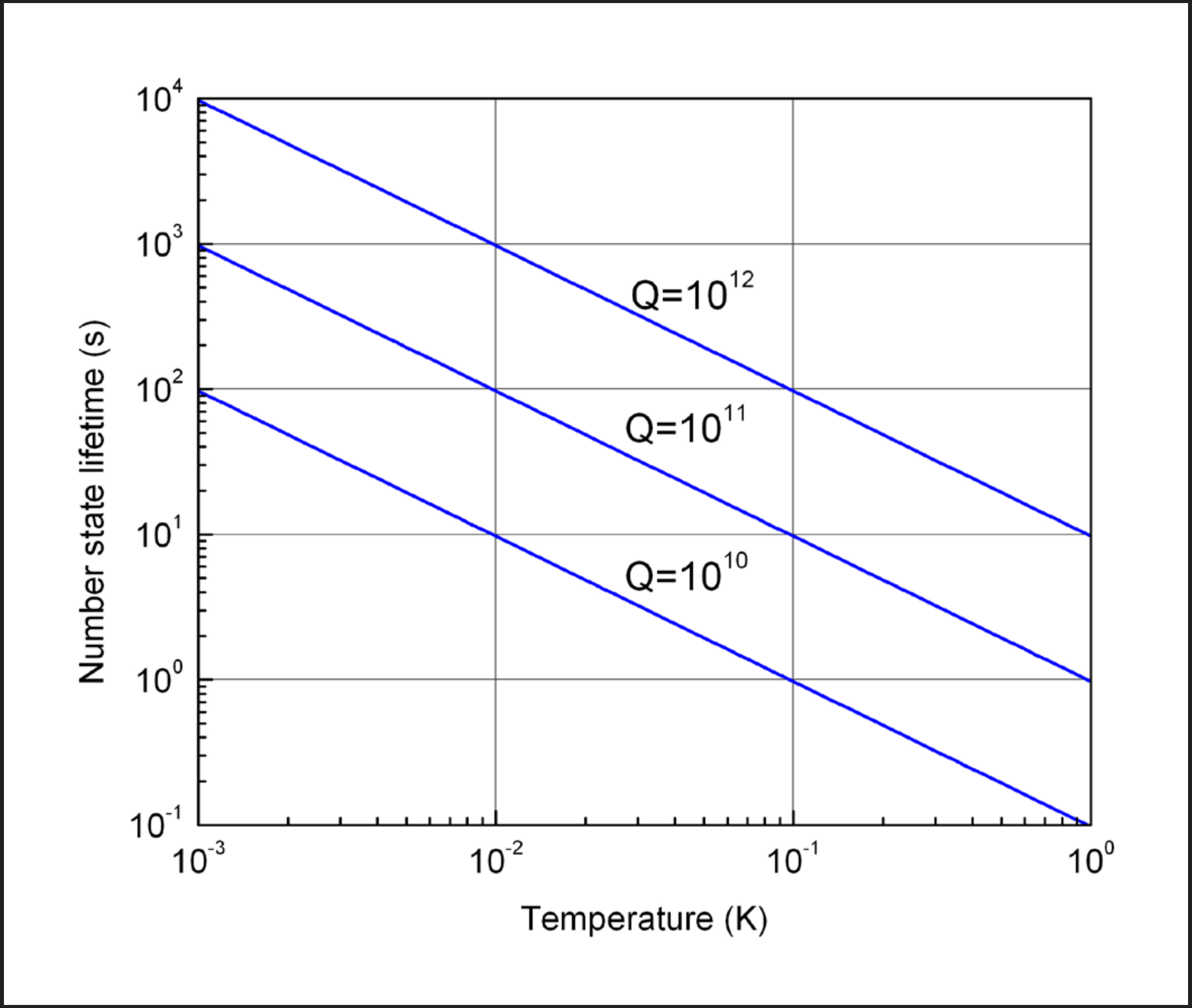
$\sim 10^{-4}\hbar\omega$ $\quad\quad$ $\sim \hbar\omega$

Strain sensitivity:

Vol (m³)	F (Hz)	h
1	120	10^{-21}
0.1	250	10^{-18}
0.01	500	10^{-15}
0.001	1000	10^{-12}

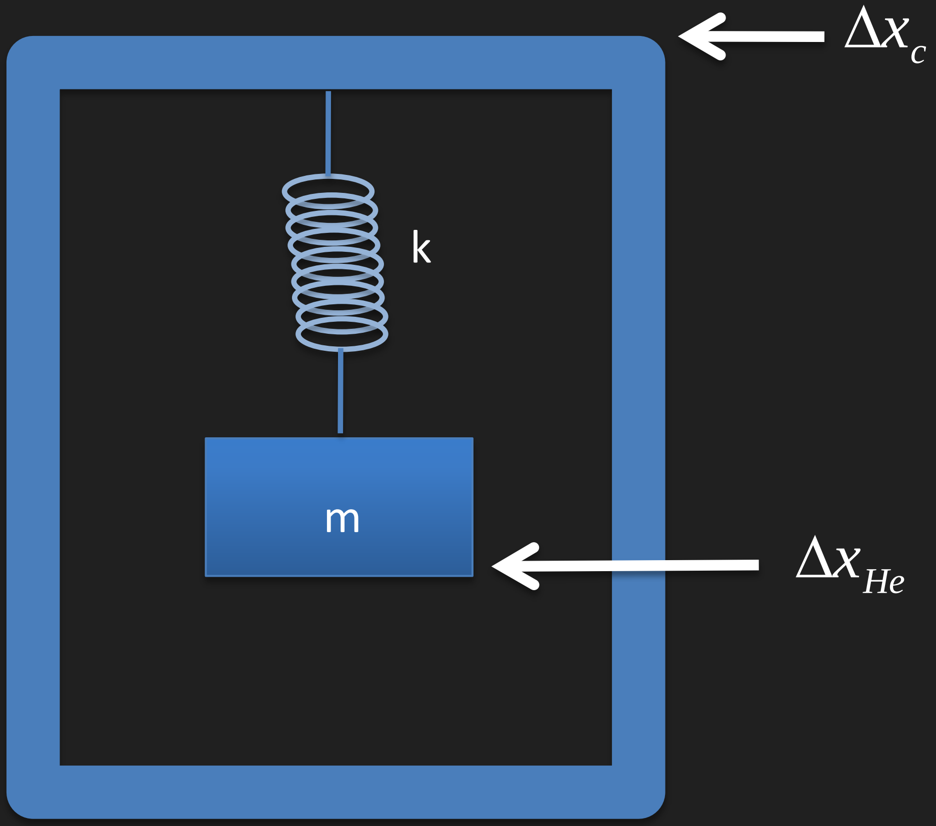
Blair, “The Detection of Gravitational Waves.” Cambridge University Press, Cambridge (1991).

Time for one phonon to enter acoustic resonator



$$\tau = \frac{\hbar Q}{k_B T}$$

Sensitivity to linear displacements and gravitational gradient forces



M=10g

F = 3.5KHz

K = 10^6 N/m

T = 10mK

Q=10^{10}

$$\Delta x_{He} = Q \Delta x_c$$

$$\Delta x_{He} = \sqrt{\frac{k_B T}{m\omega^2}} = 10^{-16}\, m$$

$$\Delta x_c = 10^{-26}\, m$$

$$\Delta x_c / L = 10^{-25}$$

$$\omega^2 \Delta x_c = 10^{-18}\, g$$

This is the gravitational force of 10g at 10m, oscillating 1 cm

Further challenges....

Phase noise of microwave source will require superconducting cavity filter to achieve SQL.

Nb cell will be required to avoid ohmic heating to achieve less than 10mK.

Coupling the microwave circuit without spoiling the mechanical Q: antenna coupling?

Holding onto the cell and providing strong thermal link, without spoiling mechanical Q.

Filling the cell: pre-filling at 300K at 1K bar will avoid a fill line

Conclusions

~~This will never work.~~

~~Life is a dark and bitter place.~~

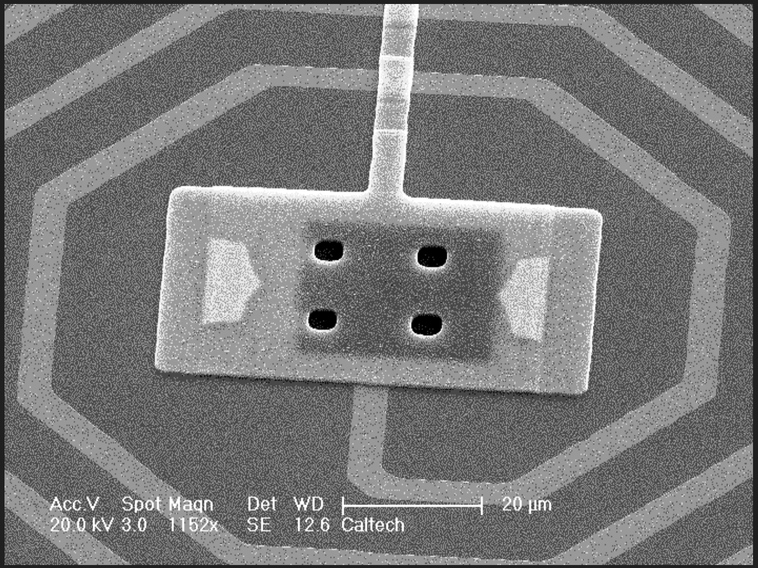
~~I should spend a lot more time in Hawaii and stop worrying so much about low temperature physics.~~

Superfluid resonators offer an extremely low dissipation material for mechanical resonators with very long coherence times and extreme sensitivity to accelerations.

This could be an excellent system to manipulate the quantum state of motion of a gram sized object.

schwab@caltech.edu

Meanwhile, at the other end of parameter space....



Acceleration of nanomechanical resonator

$$\omega = 2\pi \cdot 1GHz$$

$$x = 10nm$$

$$a = \omega^2 x = 4 \cdot 10^{10} g$$

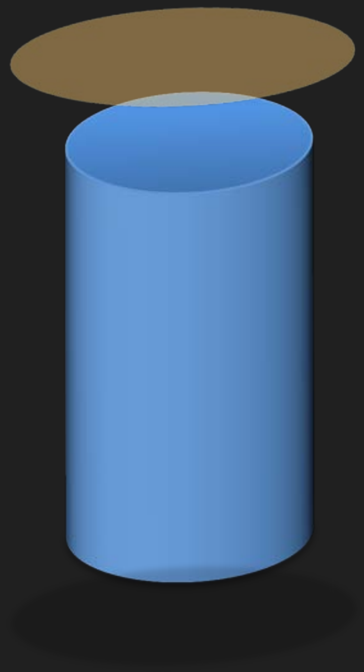
Neutron star accelerations in the laboratory

What physics can be probed with this extreme parameter?

Acoustic resonator coupled to a microwave resonance

Treat He-3 atoms as dilute, viscous classical gas.

When the mean free path is smaller than the container size:



Gravitational wave antenna – Weber bars

Auriga

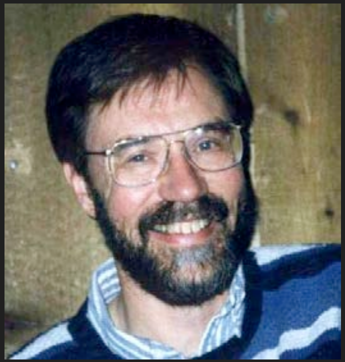
2 Ton Acoustic Resonators

$$\Delta x \approx 167 \Delta x_{QL}$$

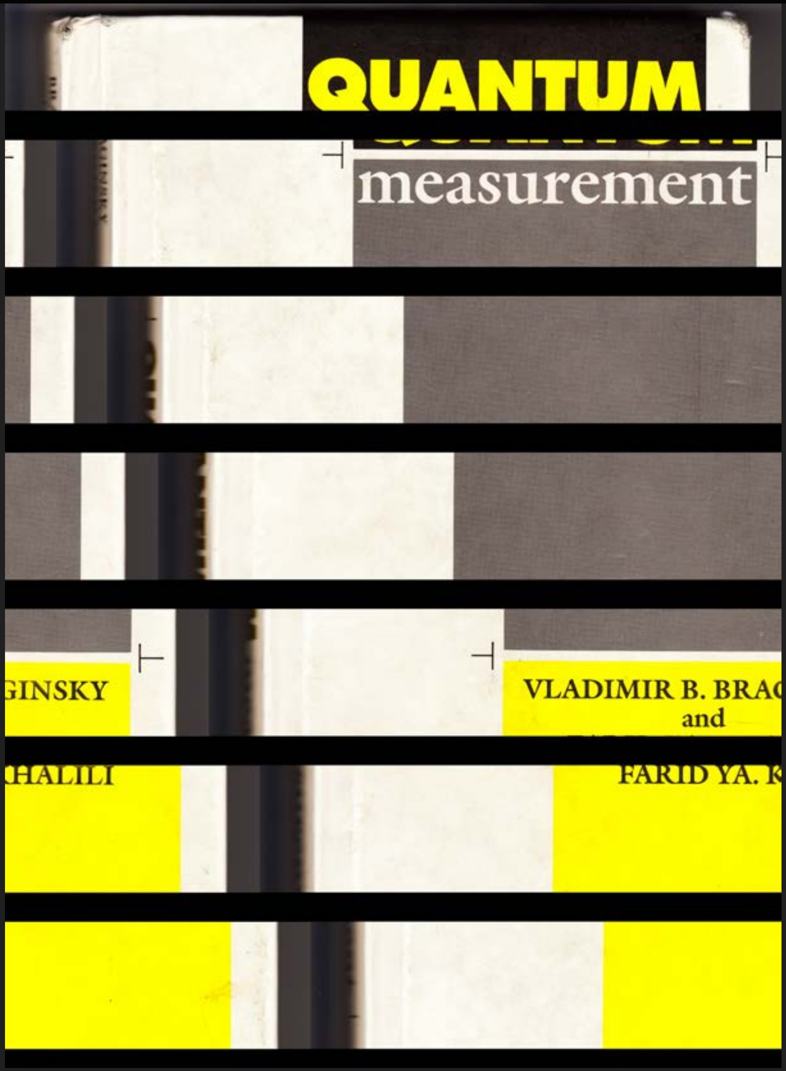
Gravitational wave antenna – Interferometers

Gravitational wave antenna – Early literature starting in the 1970's

V. Braginsky



Carlton Caves



On the measurement of a weak classical force coupled to a quantum-mechanical oscillator. I. Issues of principle*

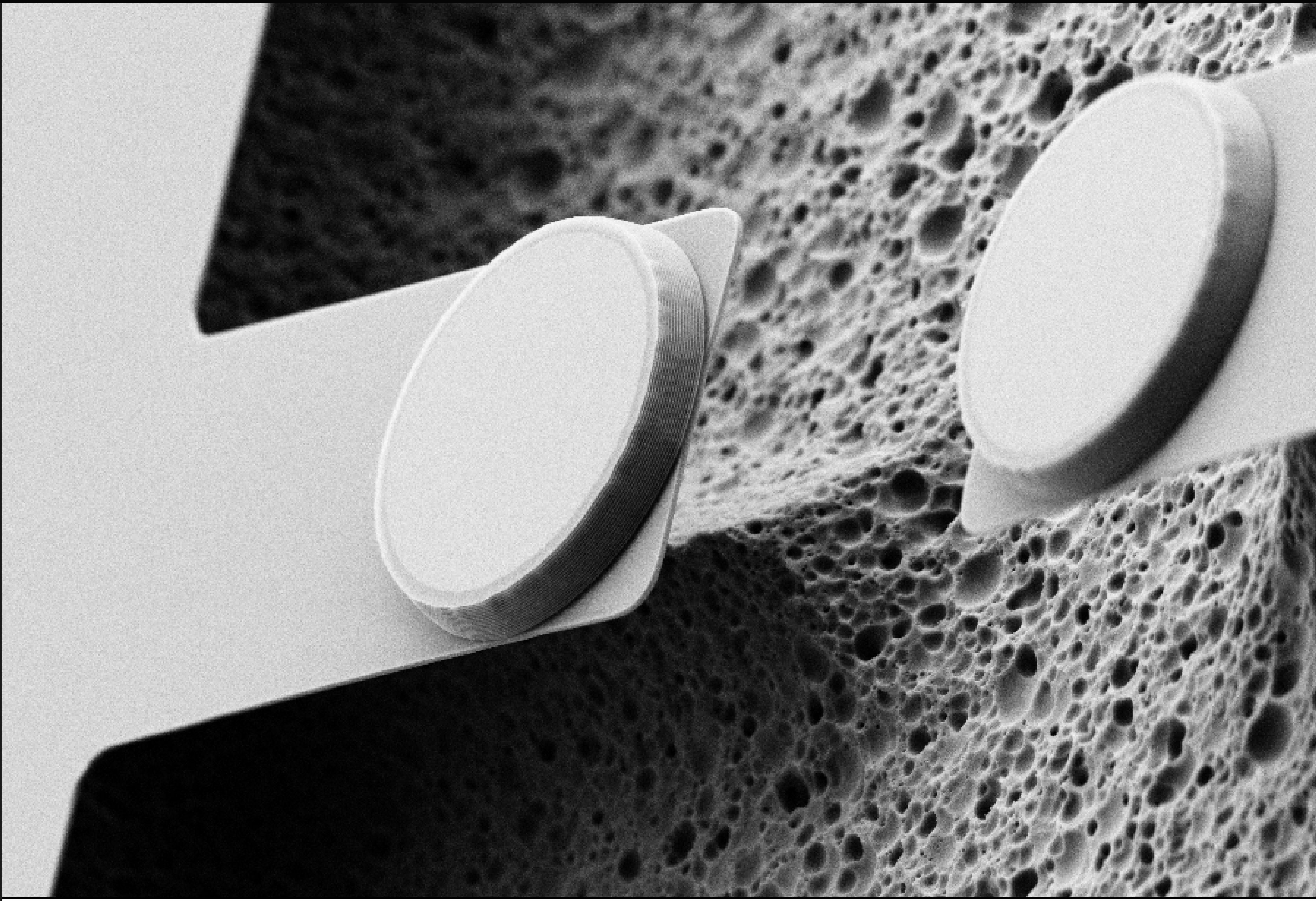
Carlton M. Caves, Kip S. Thorne, Ronald W. P. Drever,[†] Vernon D. Sandberg,[‡] and Mark Zimmermann[§]

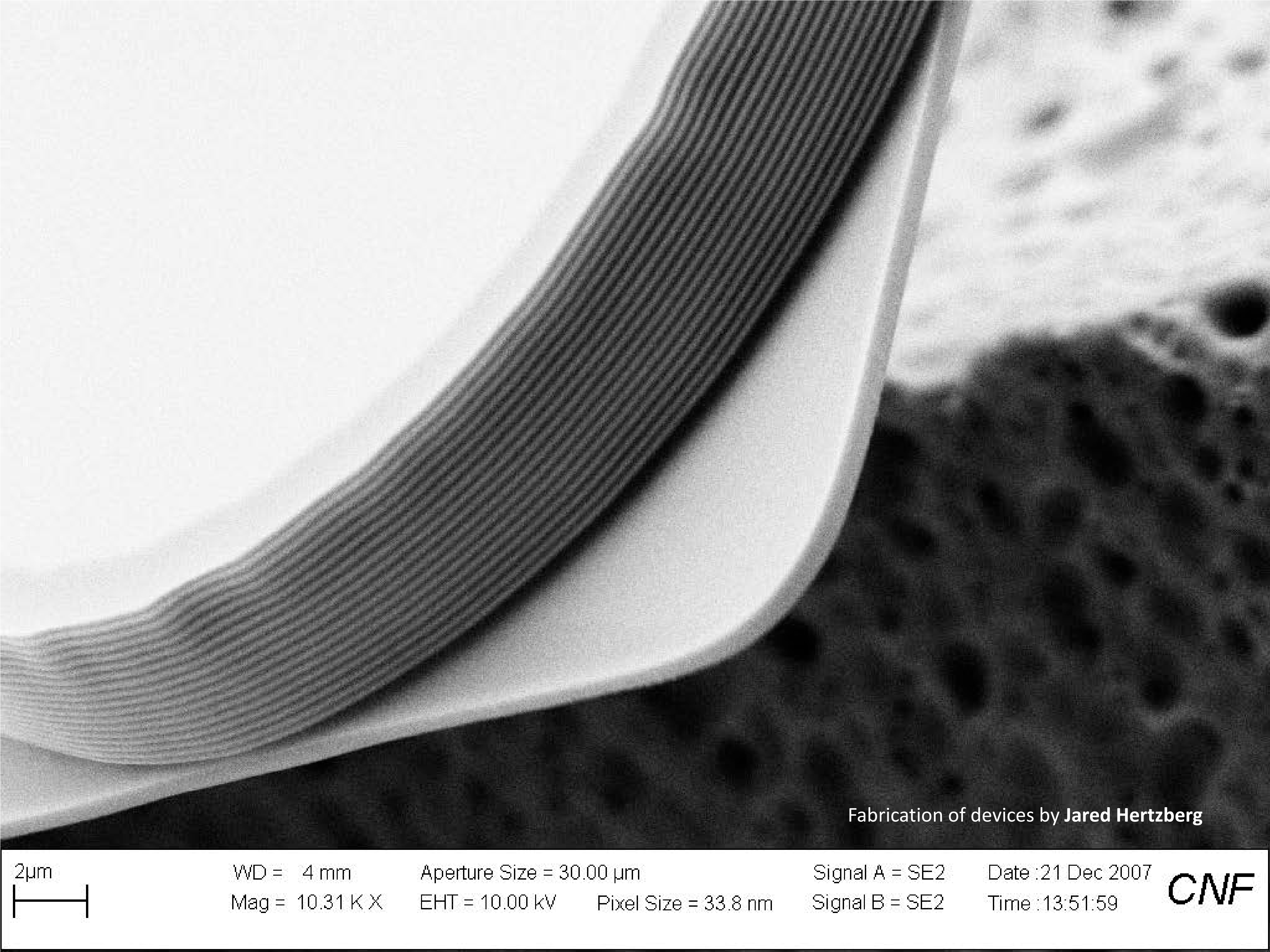
W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125

Kip Thorne

Ron Dreaver

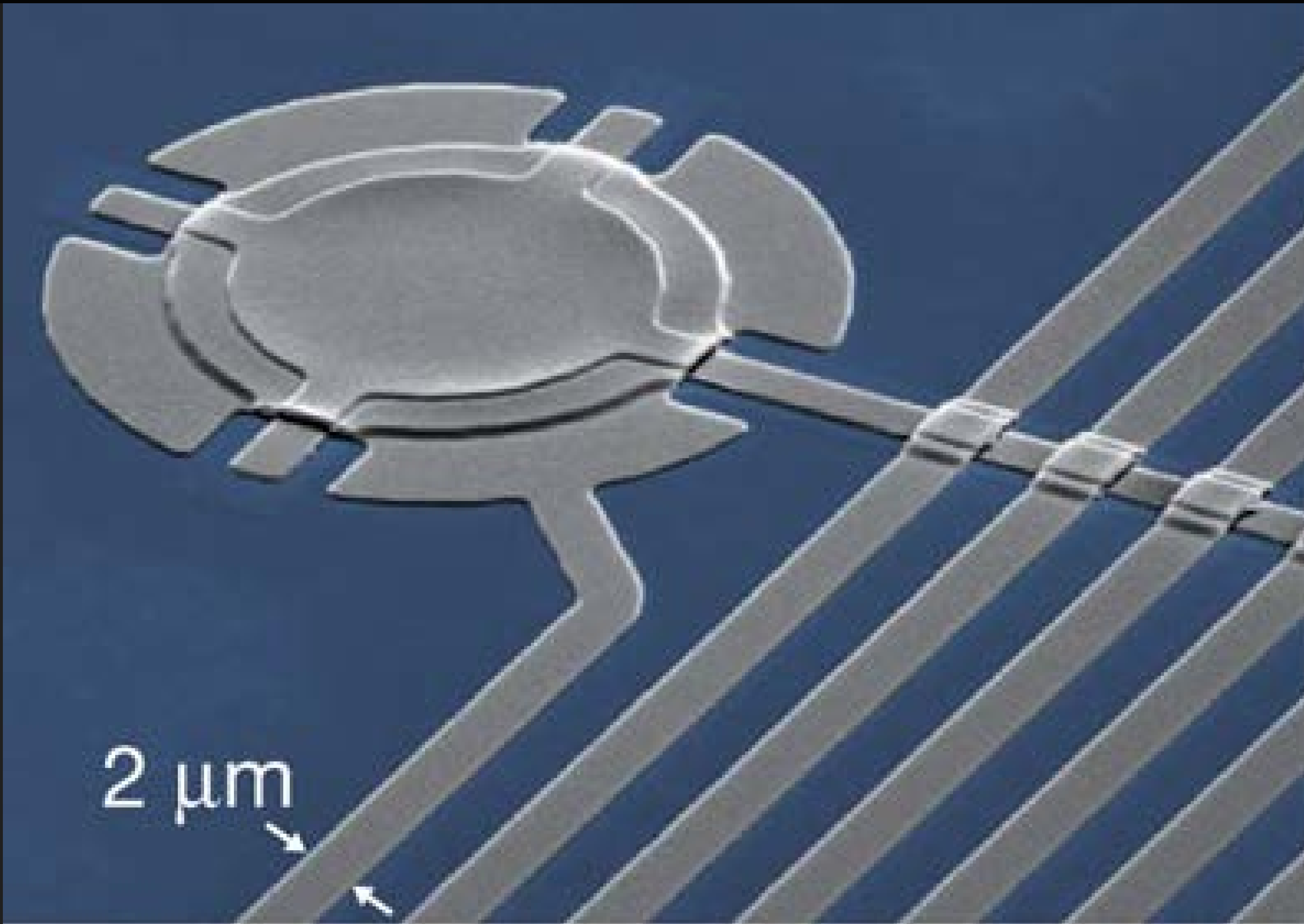
Opto-mechanical structures



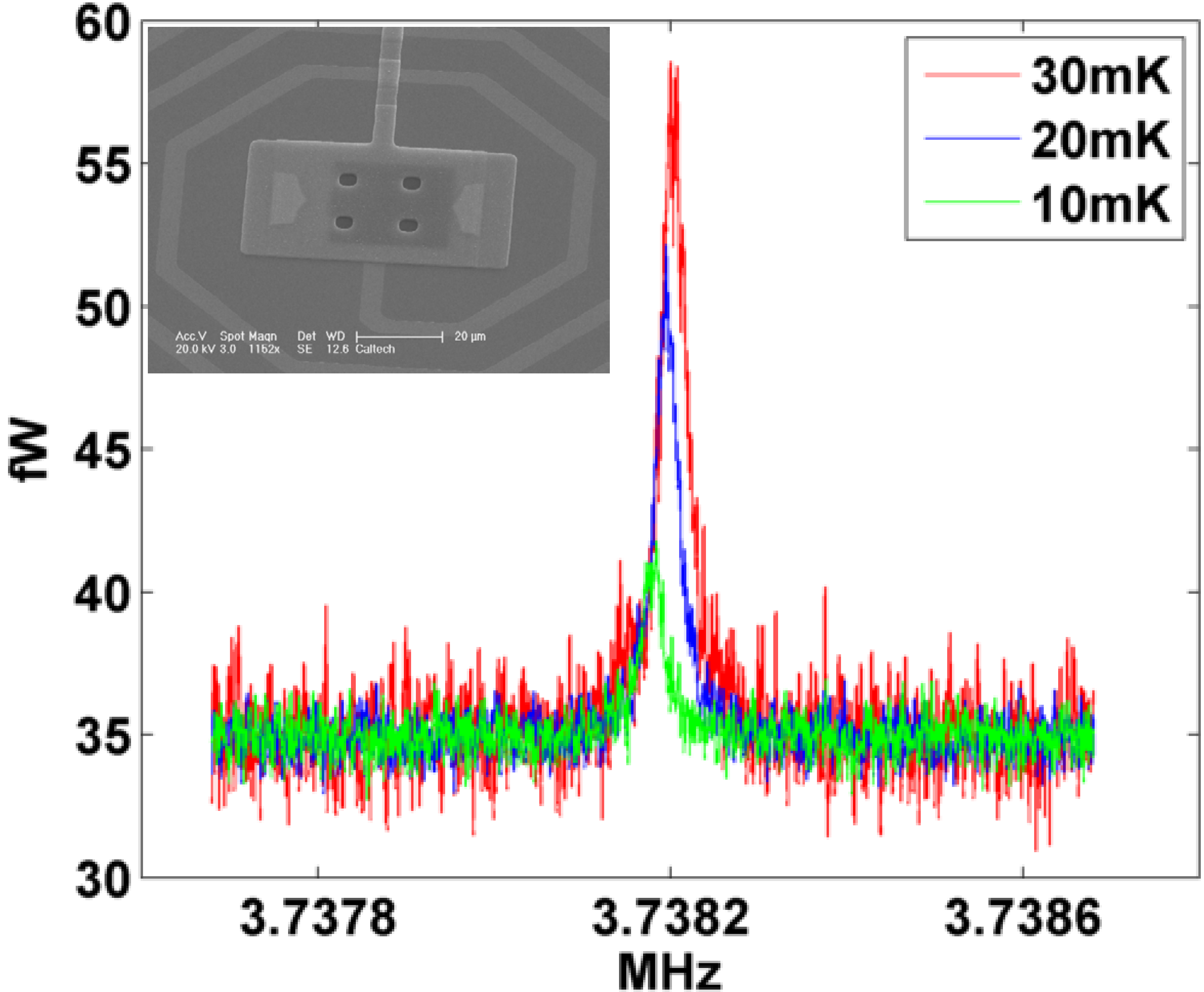


Fabrication of devices by **Jared Hertzberg**
2µm
WD = 4 mm
Mag = 10.31 K X
Aperture Size = 30.00 µm
EHT = 10.00 kV
Pixel Size = 33.8 nm
Signal A = SE2
Signal B = SE2
Date :21 Dec 2007
Time :13:51:59
CNF

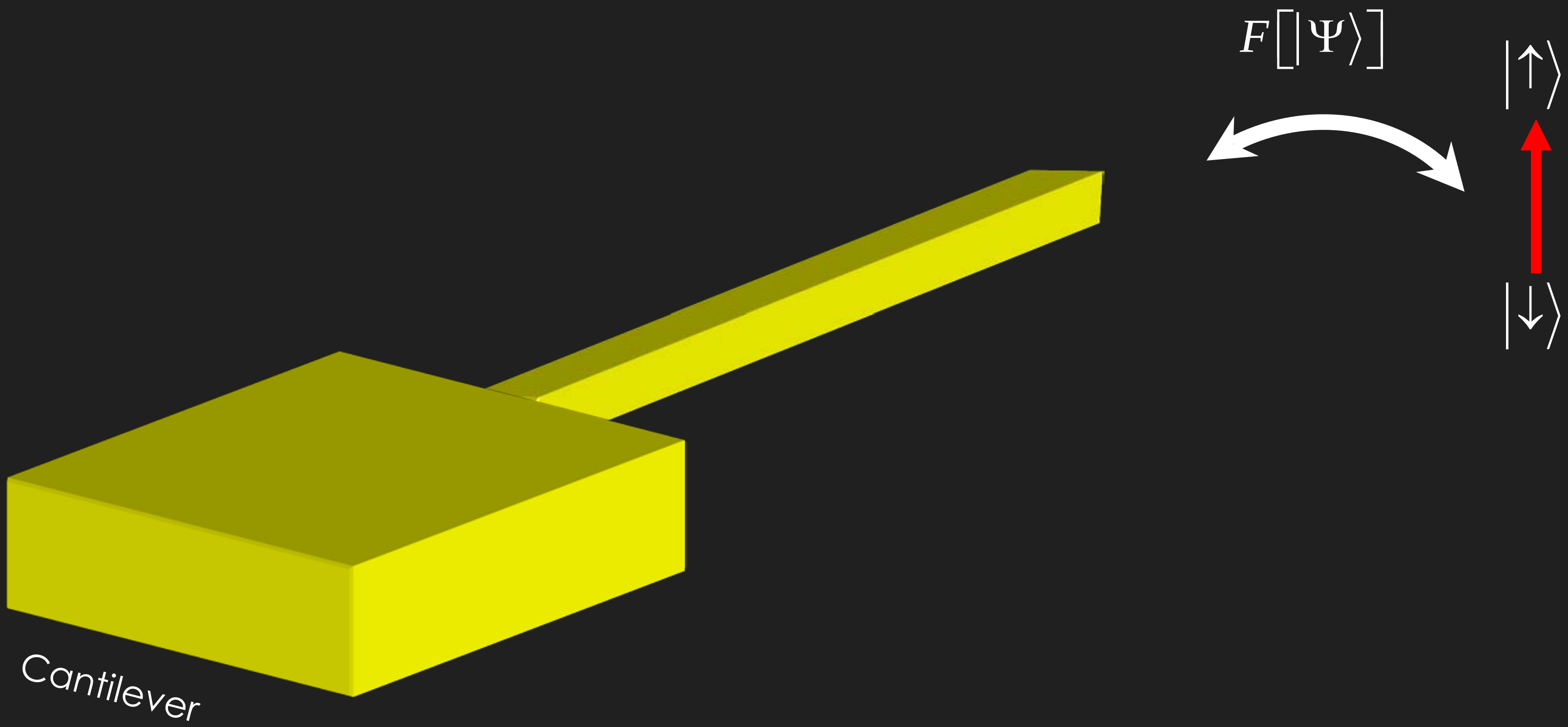
Electro-mechanical structures



Membrane thermalizes down to 10mK

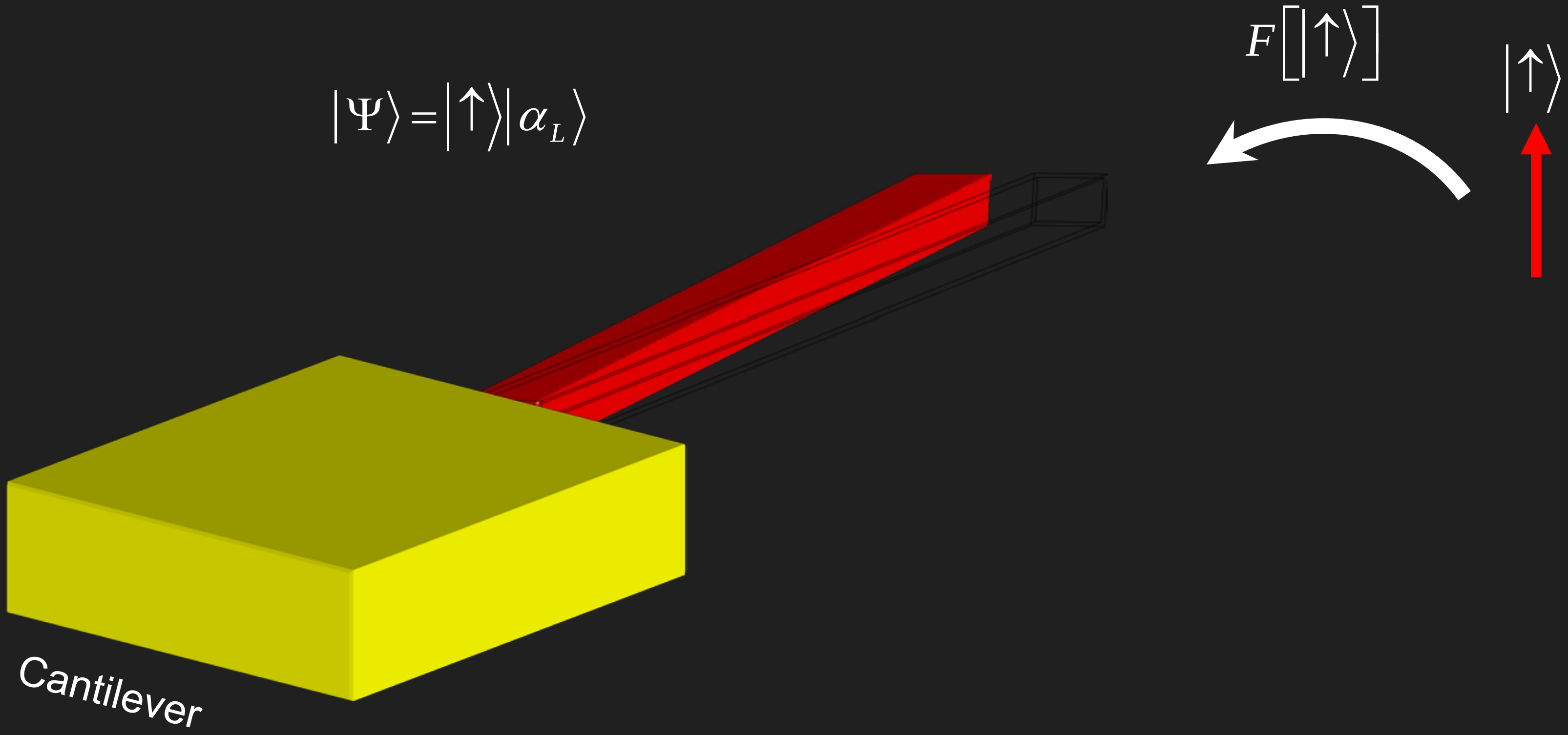


Schrödinger's Whisker

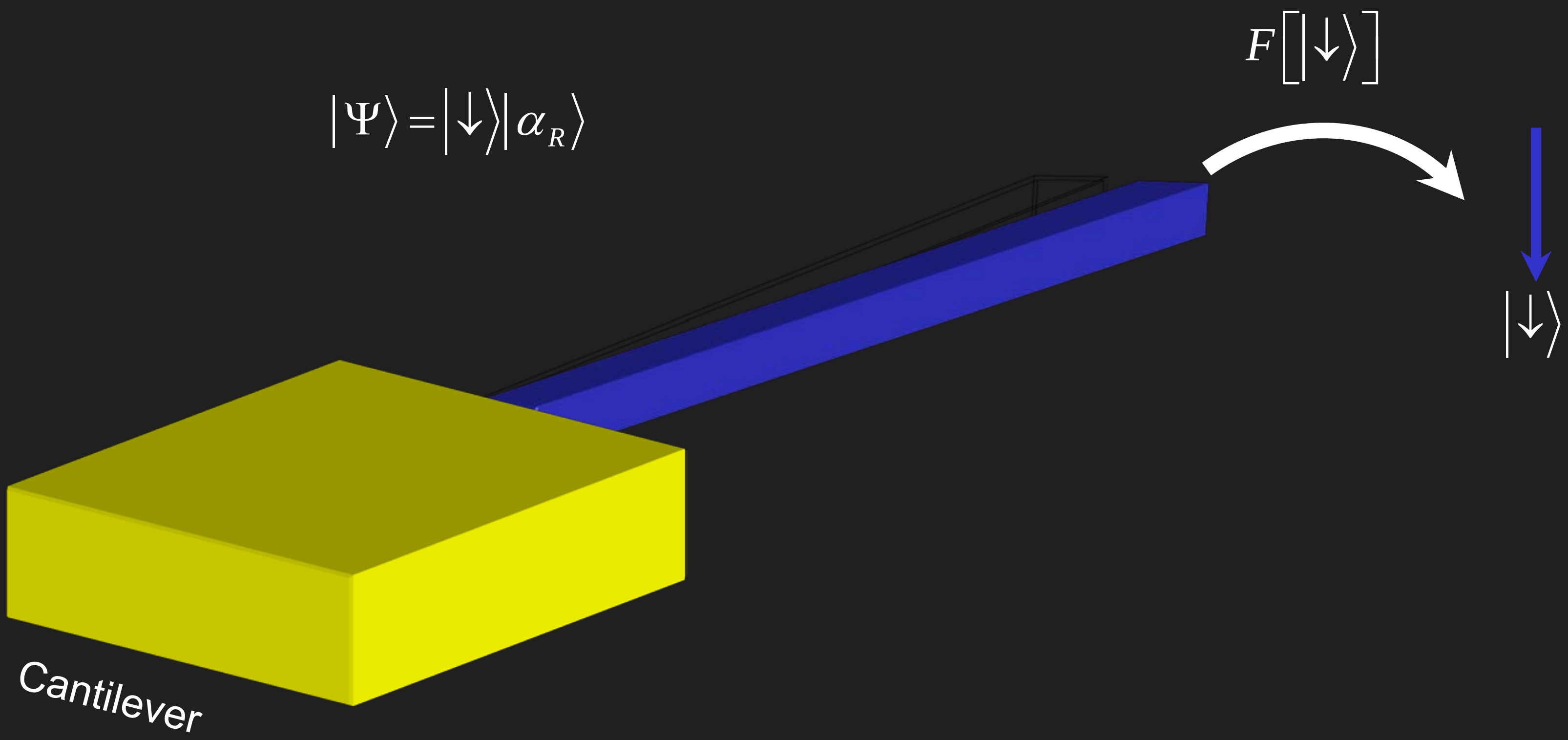


Armour, Blencowe, and Schwab, Phys. Rev. Lett. **88,** 148301 (2002).

Schrödinger's Whisker

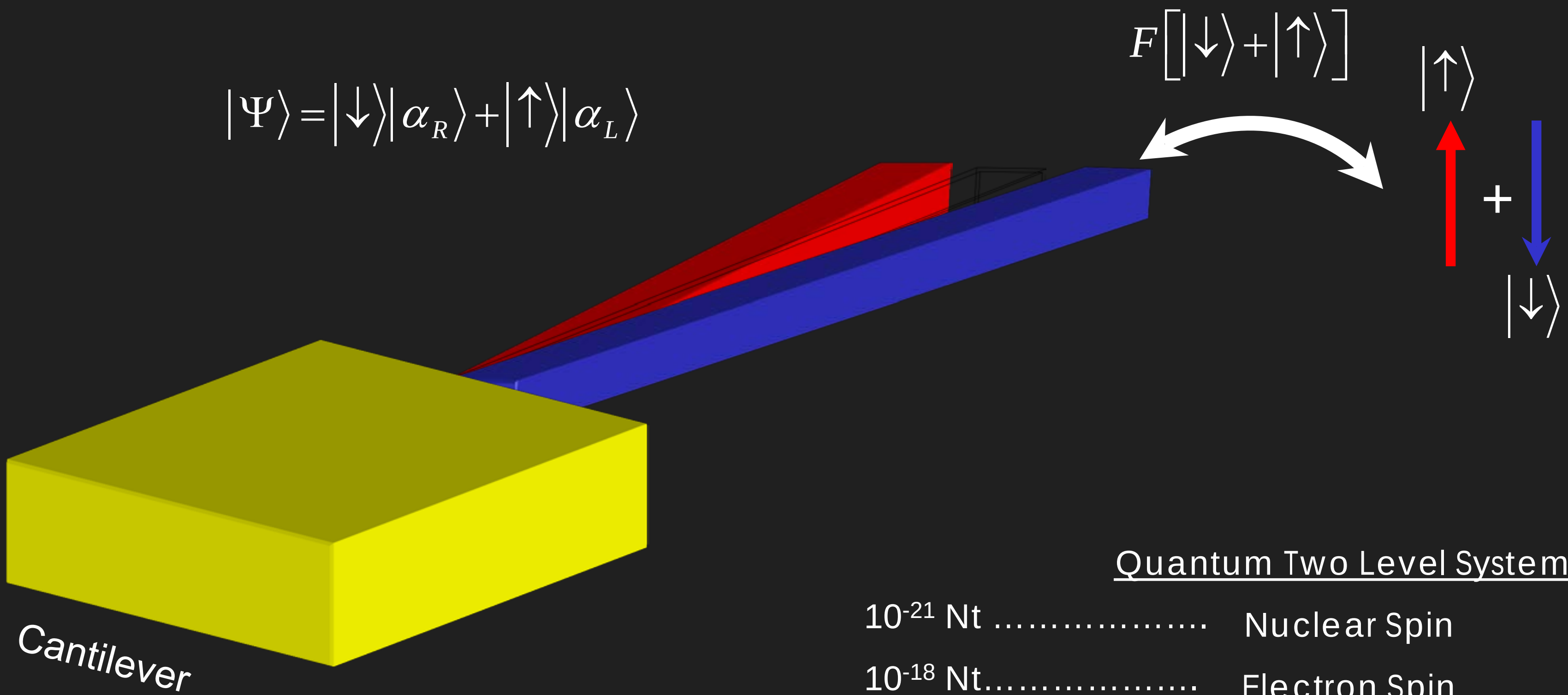


Schrödinger's Whisker



Armour, Blencowe, and Schwab, Phys. Rev. Lett. **88,** 148301 (2002).

Schrödinger's Whisker



<u>Quantum Two Level Systems</u>

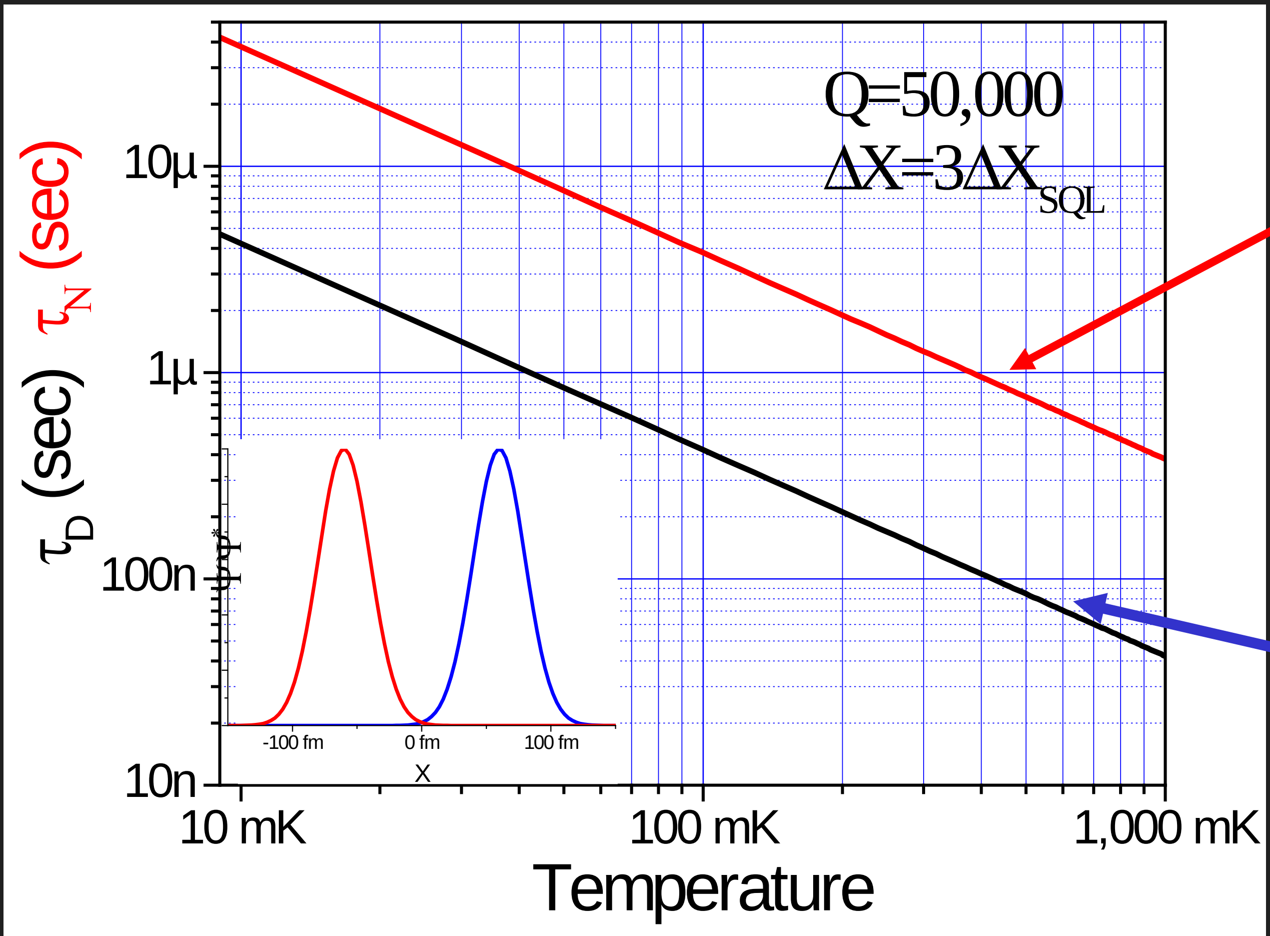
10^{-21} Nt	Nuclear Spin
10^{-18} Nt....................	Electron Spin
10^{-13} Nt........	Artificial Atoms - Qubits

Best qubits to date

t_1, t_2 ~ 10-100 μsec

Armour, Blencowe, and Schwab, Phys. Rev. Lett. **88,** 148301 (2002).

Coherence time and Fock state lifetime



Lifetime for number state:

$$\tau_N = Q\frac{\hbar}{k_B T}$$

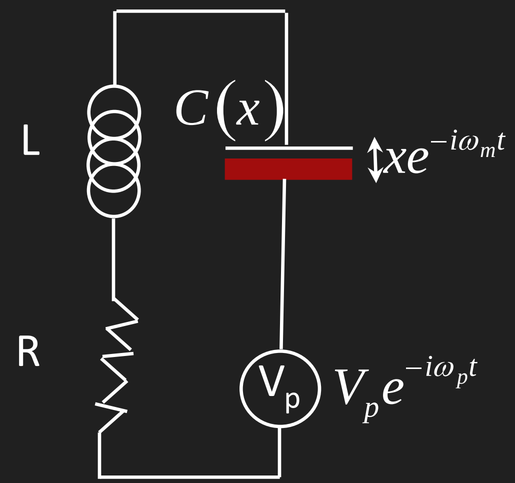
Decoherence time for superposition of coherent states:

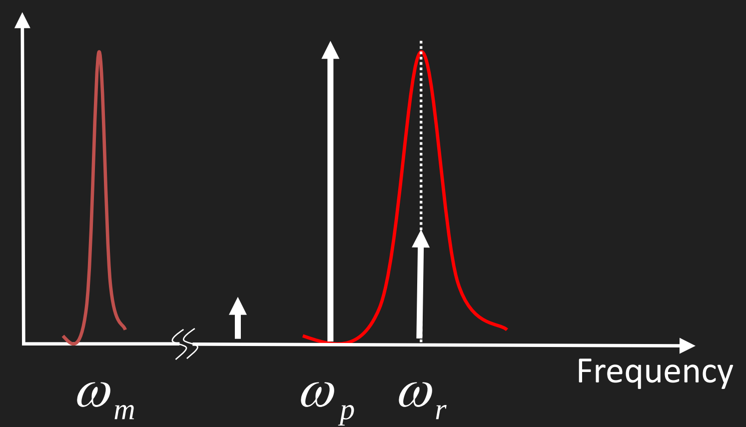
$$\tau_D = \frac{\hbar^2}{2m\gamma_m k_B T(\Delta x)^2}$$

$$= Q\frac{\hbar}{k_B T}\left[\frac{\Delta x_{SQL}}{\Delta x}\right]^2$$

Zurek, Habib, Paz, Phys. Rev. Lett. ***70****, 1187 (1993).*

Parametric Transducer





$$\delta Q(t) = \delta C e^{-i\omega_m t} \cdot V_P e^{-i\omega_p t}$$

$$\omega_{sideband} = \omega_p \pm \omega_m$$

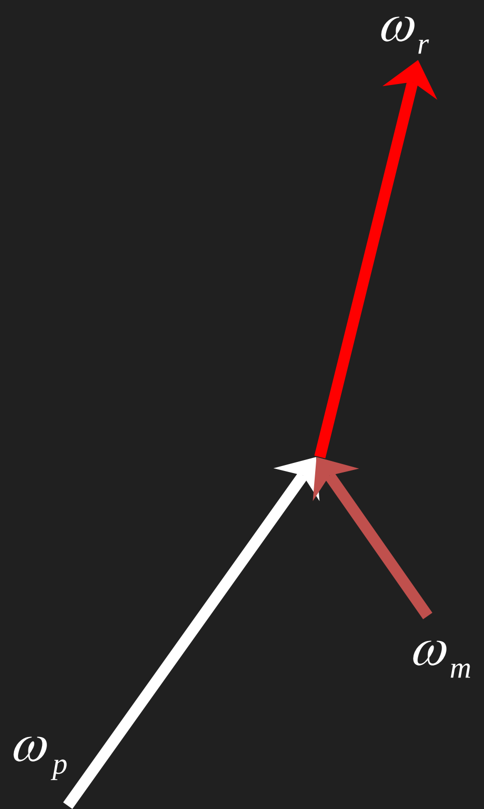
Johnson, Warren W., Bocko, Mark, Approaching the Quantum "Limit" for Force Detection. *Phys. Rev. Lett.* **47**, 1184-1187 (1981).

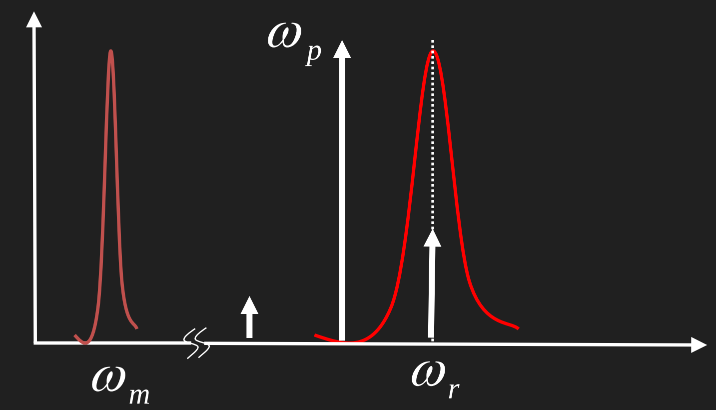
Braginsky, V. B., Khalili, F. Ya., *Quantum Measurement* (Cambridge Univ. Press, Cambridge, 1995).

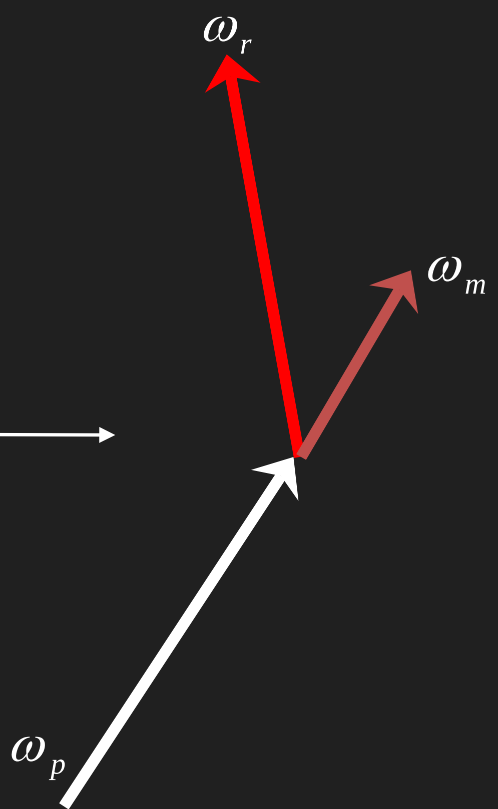
Blair, Ivanov, Tobar, Turner, Kann, Heng, High Sensitivity Gravitational Wave Antenna with Parametric Transducer Readout. *Phys. Rev. Lett*. **74**, 1908 (1995).

Bocko, Mark F., Onofrio, Roberto, On the measurement of a weak classical force coupled to a harmonic oscillator: experimental progress. *Rev. Mod. Phys.* **68**, 755-799 (1996).

Up and down conversion -- Raman process







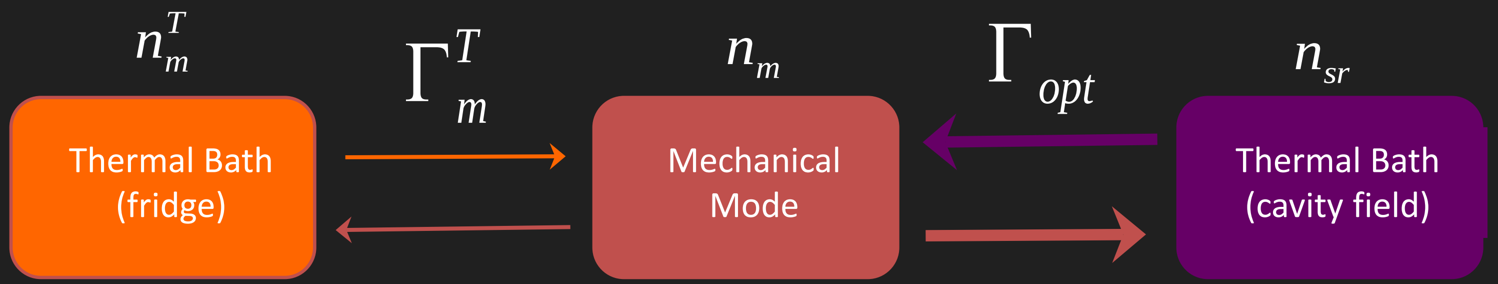
Up-conversion from pump
→ Cooling, positive damping of mechanics

$$\Gamma_{-} \propto n_m$$

Down-conversion from cavity
→ Heating of mechanics

$$\Gamma_{+} \propto n_m + 1$$

Detailed Balance

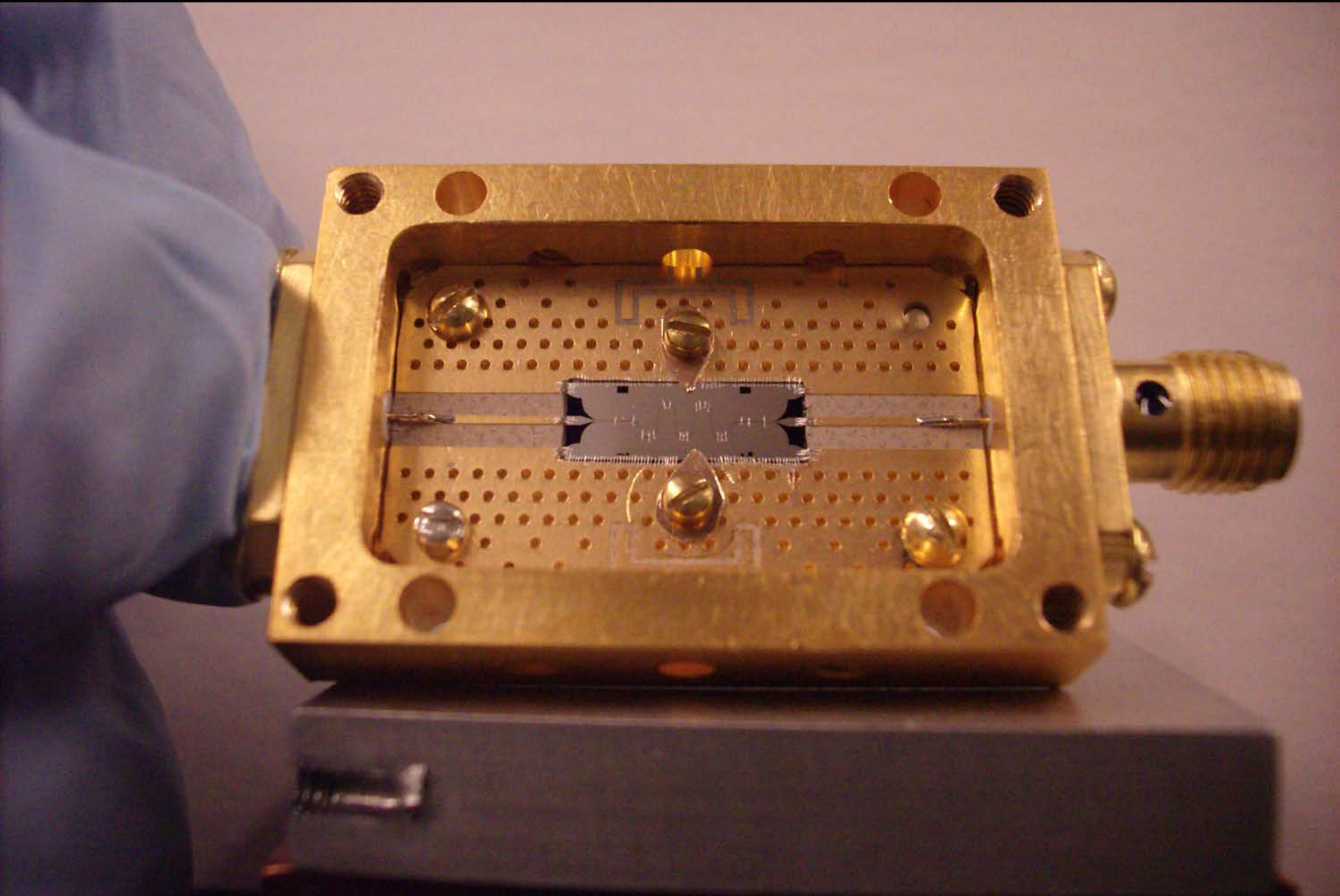


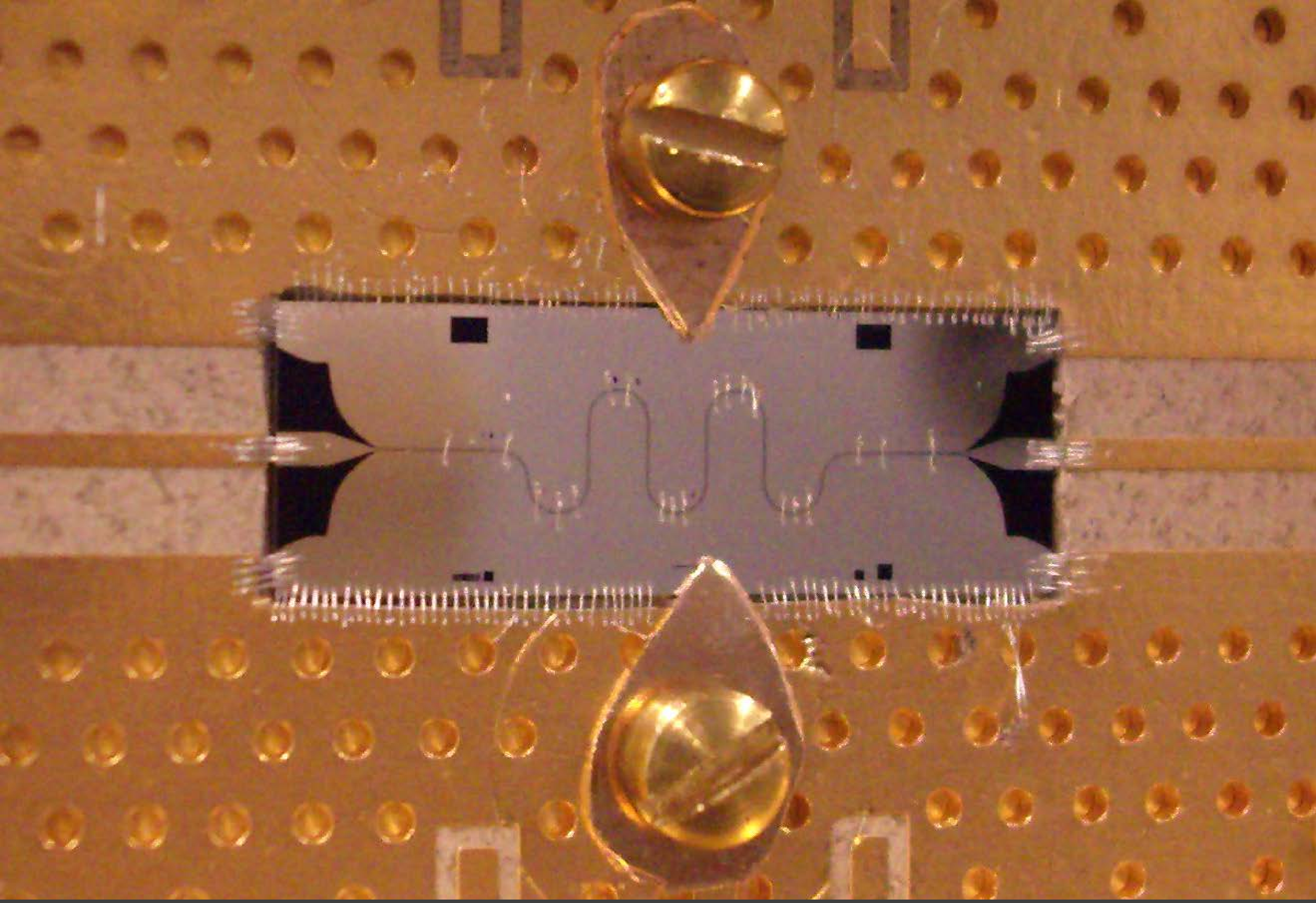
$$n_m = \frac{\Gamma_m^T n_m^T + \Gamma_{opt} n_{sr}}{\Gamma_m^T + \Gamma_{opt}}$$

$$\Gamma_{opt} = 4 x_{zp}^2 \left(\frac{\partial \omega_{sr}}{\partial x} \right)^2 \frac{n_p}{\kappa}$$

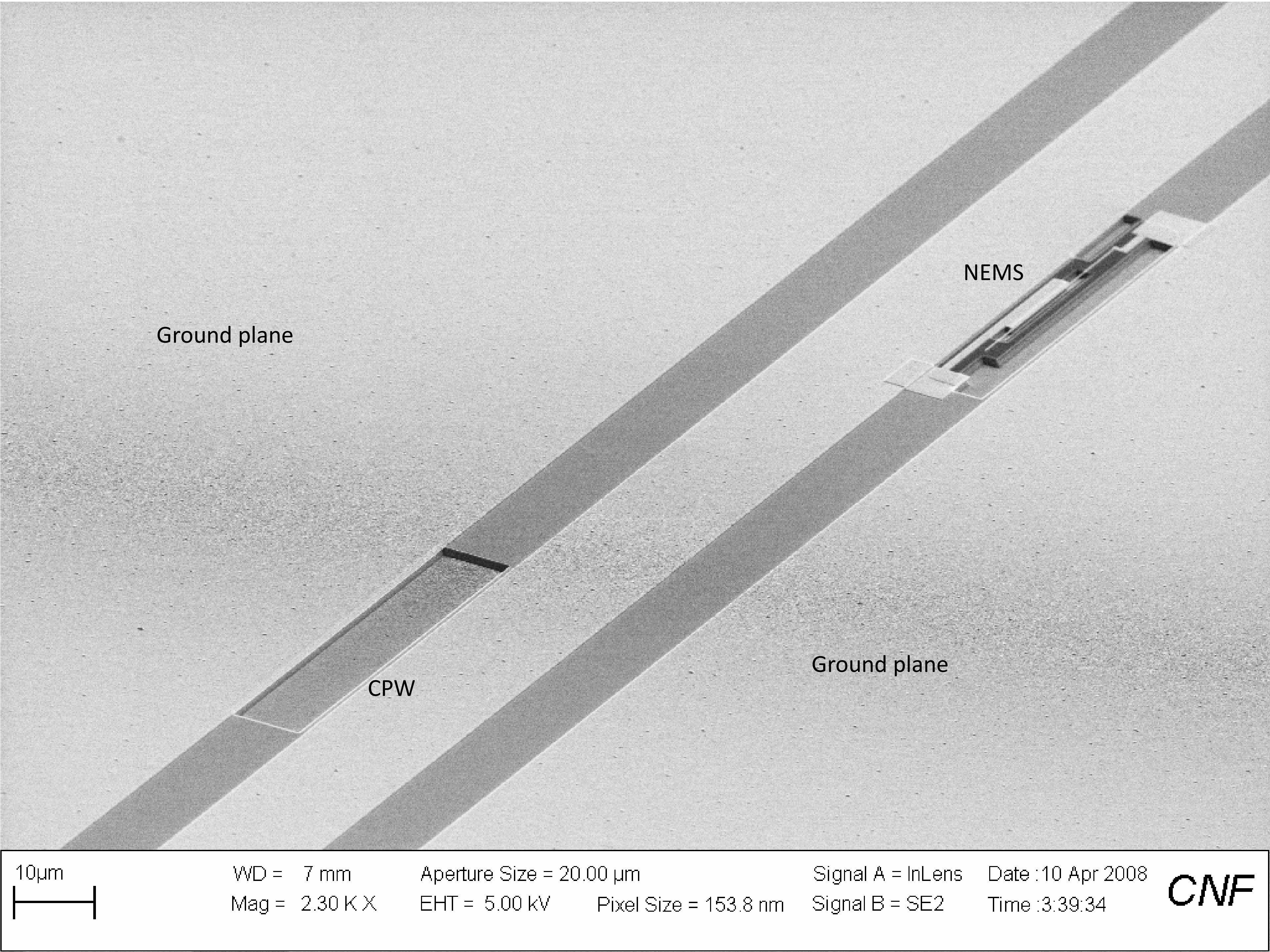
$$n_{sr} = \left(\frac{\kappa}{4\omega_m} \right)^2 + n_{sr}^T \left[1 + 2 \left(\frac{\kappa}{4\omega_m} \right)^2 \right]$$

Devices

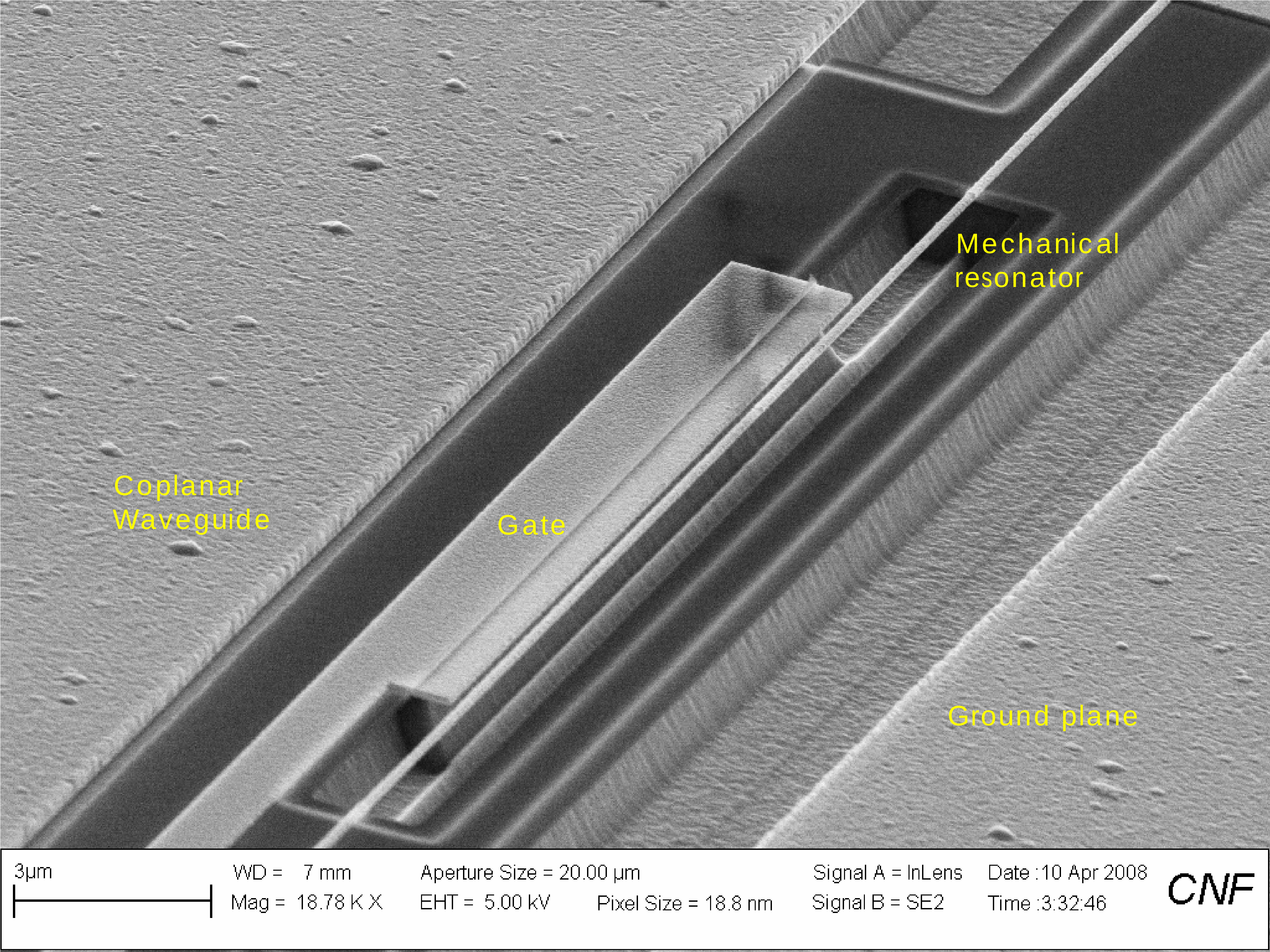


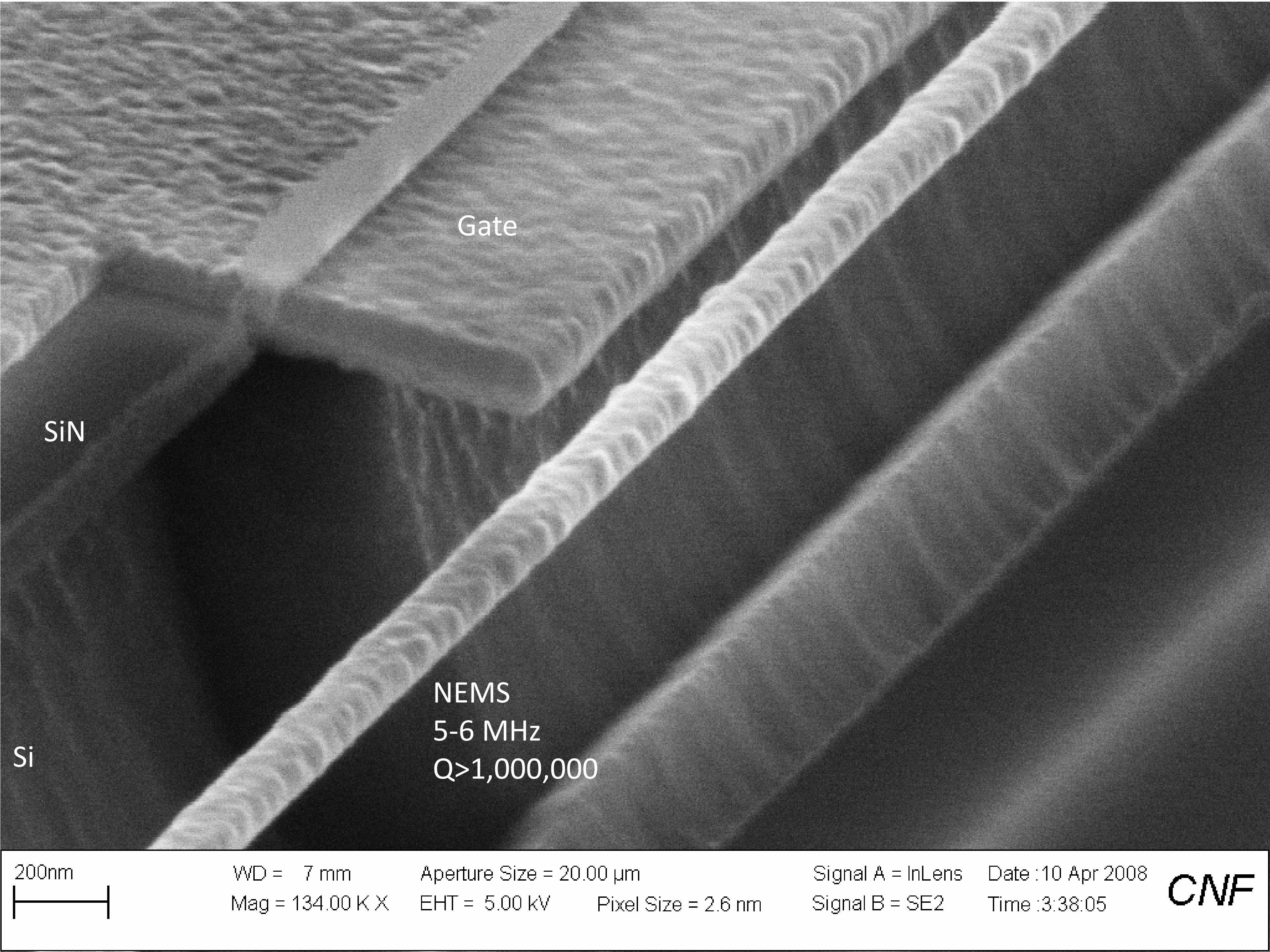


P. Day, R. LeDuc, B. Mazin, A. Vayonakis, J. Zmuidzinas, Nature ***425**, 817 (2003)*.

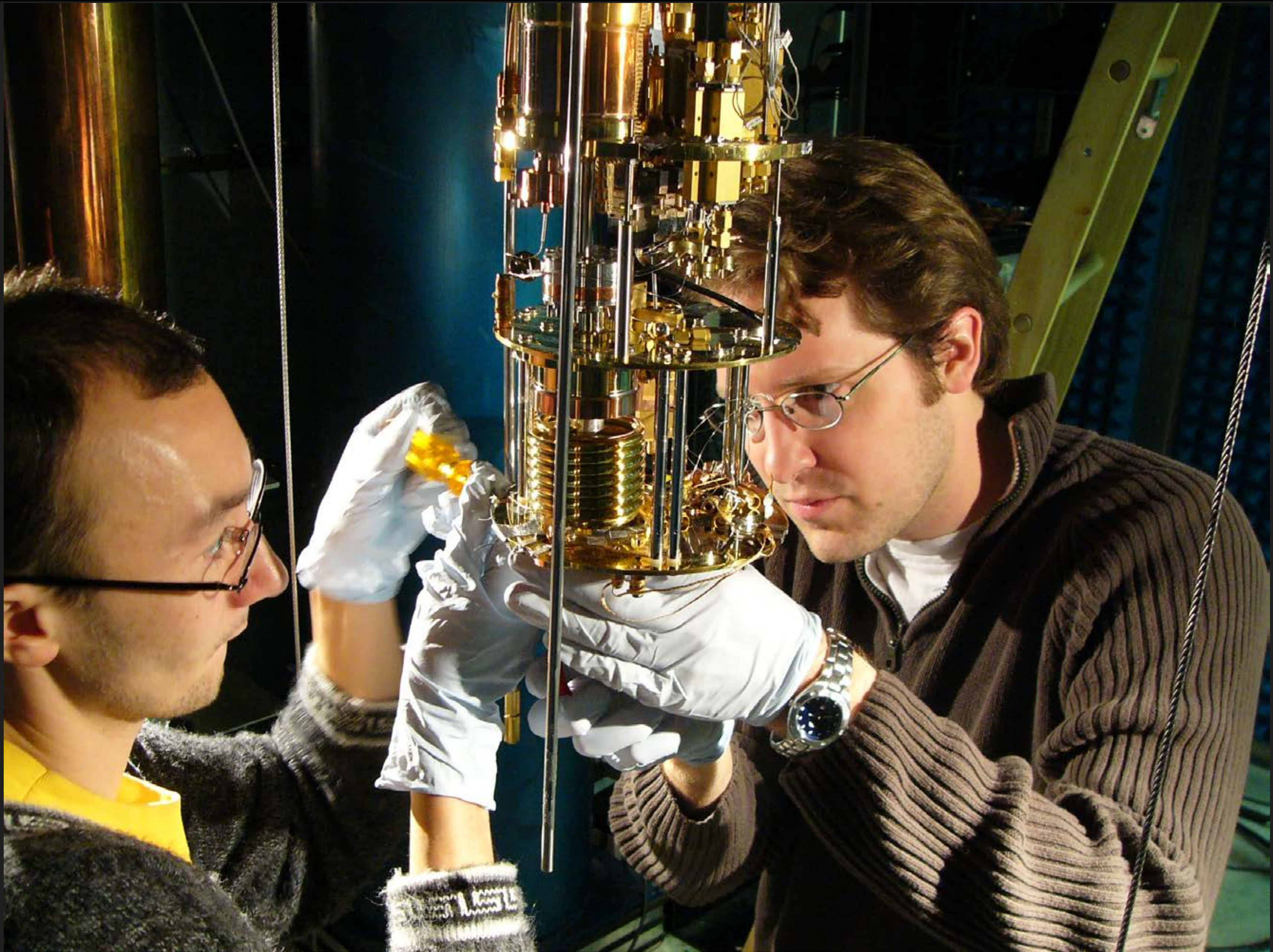


NEMS
Ground plane
CPW
Ground plane
10µm
WD = 7 mm
Mag = 2.30 K X
Aperture Size = 20.00 µm
EHT = 5.00 kV
Pixel Size = 153.8 nm
Signal A = InLens
Signal B = SE2
Date :10 Apr 2008
Time :3:39:34
CNF

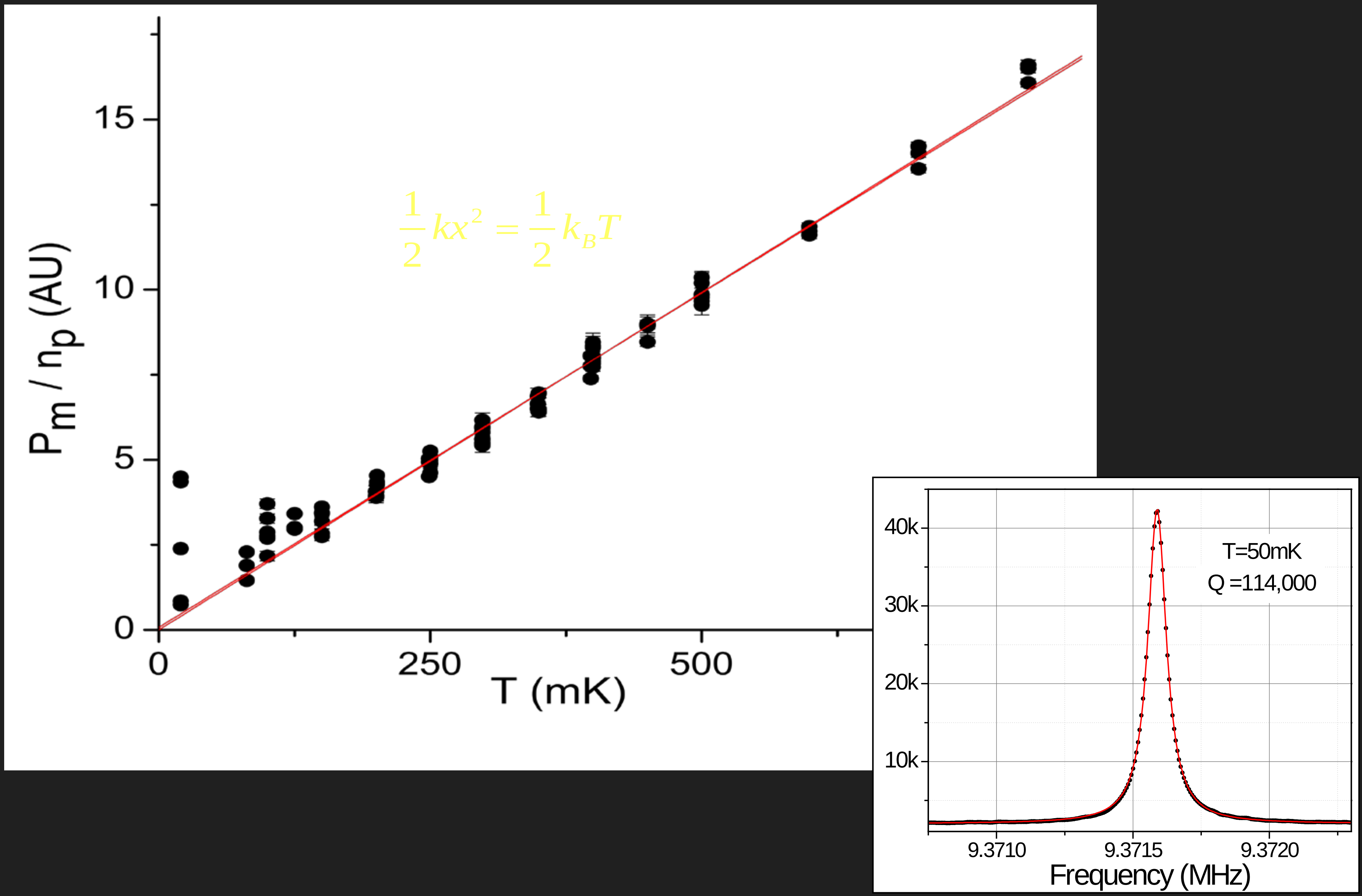

Mechanical
resonator
Coplanar
Waveguide
Gate
Ground plane
3µm
WD = 7 mm
Mag = 18.78 K X
Aperture Size = 20.00 µm
EHT = 5.00 kV
Pixel Size = 18.8 nm
Signal A = InLens
Signal B = SE2
Date :10 Apr 2008
Time :3:32:46
CNF


Gate
SiN
Si
NEMS
5-6 MHz
Q>1,000,000
200nm
WD = 7 mm
Mag = 134.00 K X
Aperture Size = 20.00 µm
EHT = 5.00 kV
Pixel Size = 2.6 nm
Signal A = InLens
Signal B = SE2
Date :10 Apr 2008
Time :3:38:05
CNF

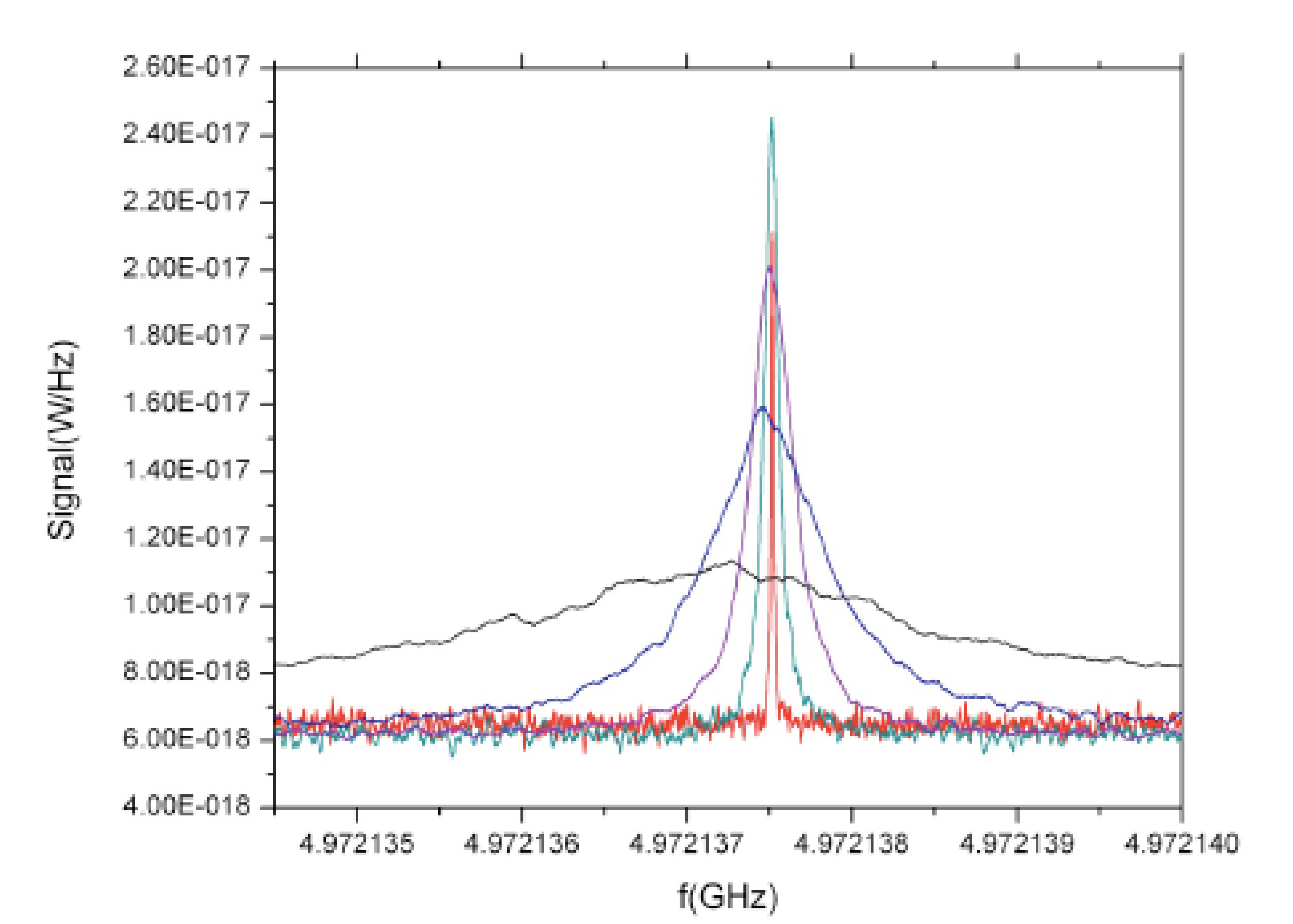
Installing samples onto the fridge



Brownian Motion – Equipartition

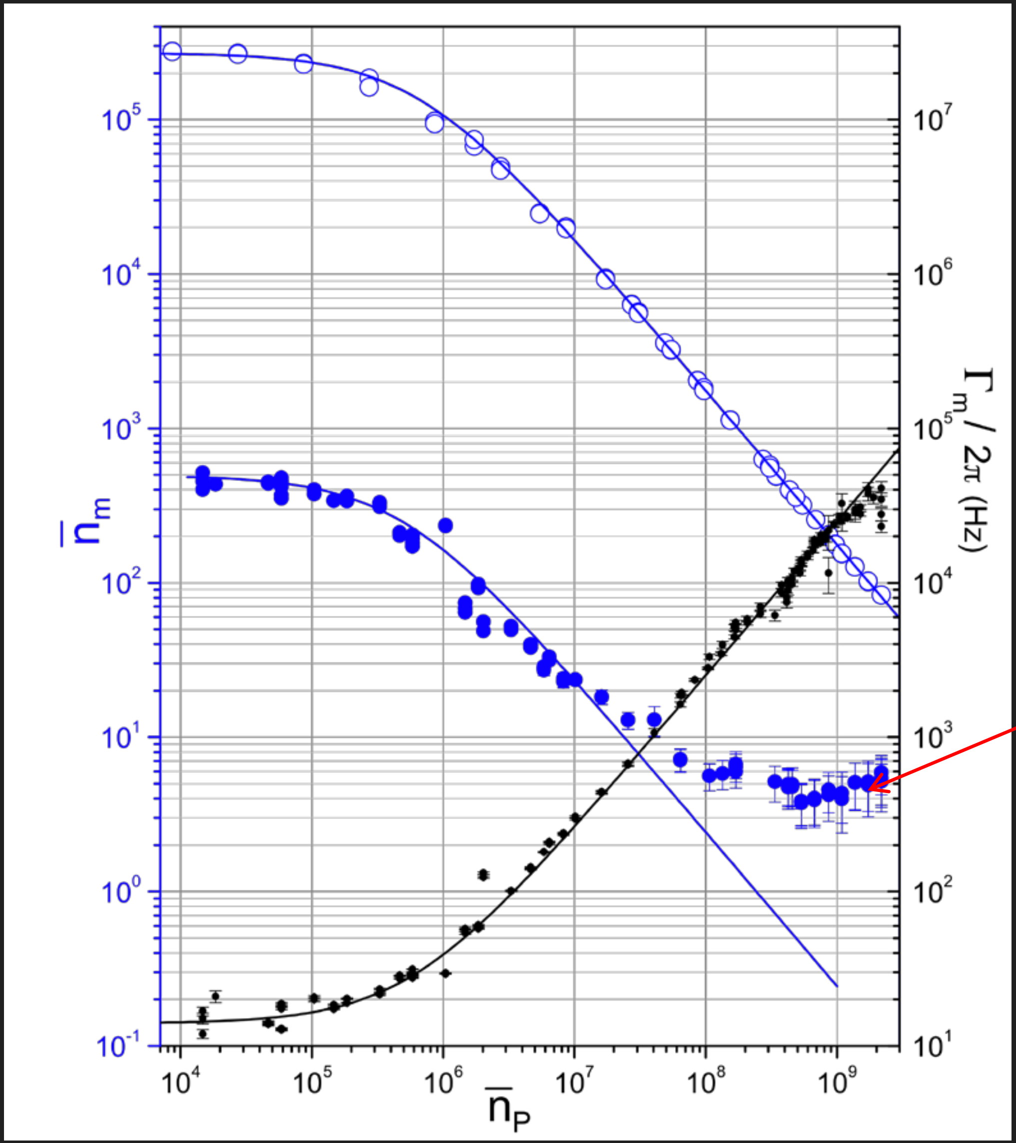


Damping and Cooling



Blair, et al, Phys. Rev. Lett. (1995).

Damping and Cooling

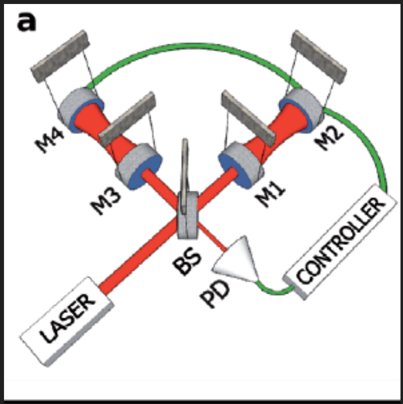


$$n_m = 3.8 \pm 1.3$$

$$P_0 = \frac{1}{1+n_m} = 0.2$$

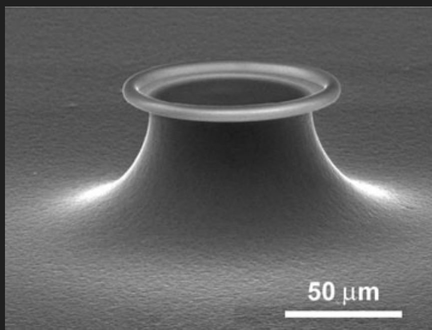
"Preparation and Detection of a Mechanical Resonator Near the Ground State of Motion," T. Rocheleau, T. Ndukum, C. Macklin, J.B. Hertzberg, A.A. Clerk, K.C. Schwab, Nature 463, 72-75 (2009).

Progress in Opto-mechanics



Abbott, et al., *New J. Phys.* **11**, (2009).

N=200
(100Hz)

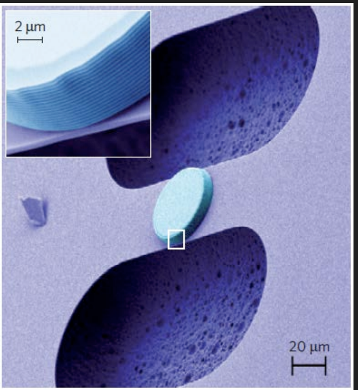


Schliesser, Arcizet, Riviere, Anetsberger, Kippenberg, *Nature Phys.* **5**, (2009).

N~few
(58MHz)

Park and Wang, *Nature Phys.* **5**, (2009).

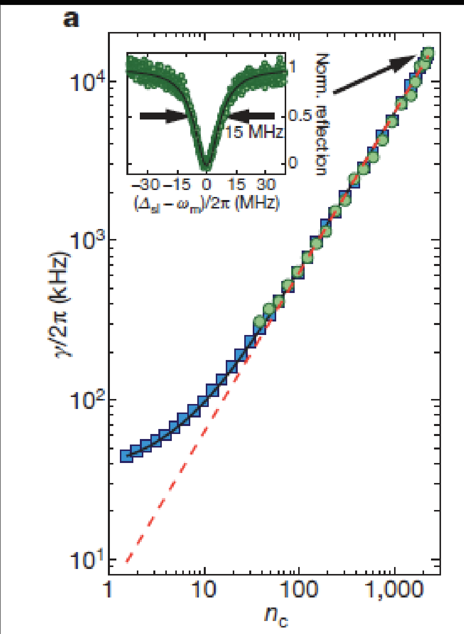
N=37
(100MHz)

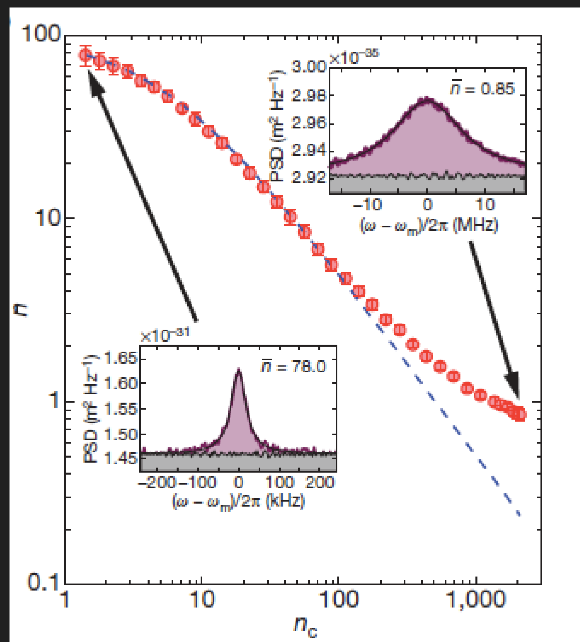


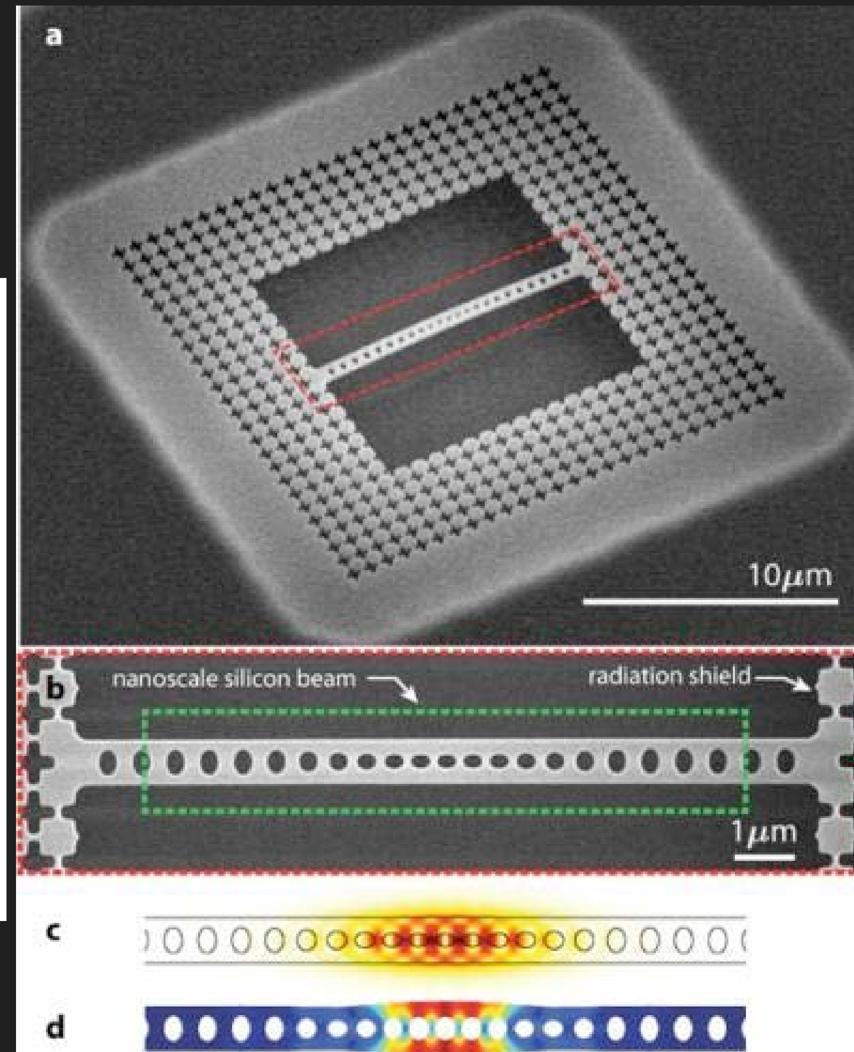
Groblacher, Hertzberg, Vanner, Cole, Gigan, Schwab, Aspelmeyer, *Nature Phys.* **5**, (2009).

N=30
(1MHz)

Progress in Opto-mechanics -- ground state

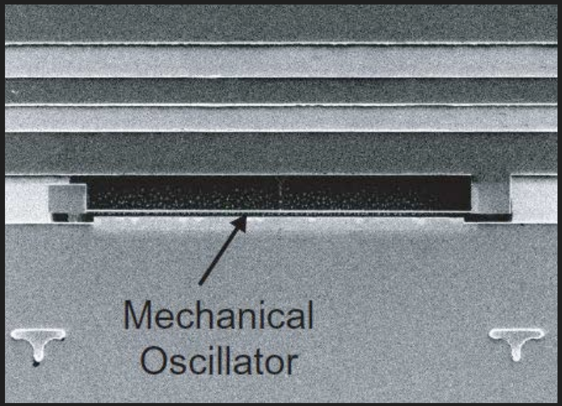






J. Chan, T. Alegre, A. Safavi-Naeini, J. Hill, A. Krause, S. Groblacher, M. Aspelmeyer, O. Painter, *Nature* **478**, 389 (2011).
A. Safavi-Naeini, J. Chan, J. Hill, T. Mayer Alegre, A. Krause, O. Painter, PRL (2012).

Progress in Electro-mechanics -- ground state

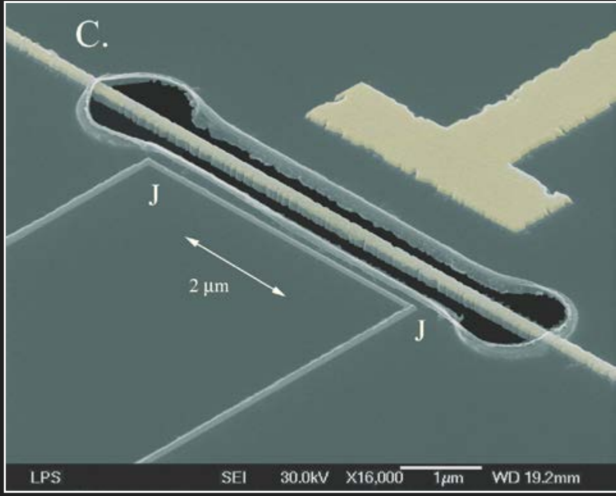


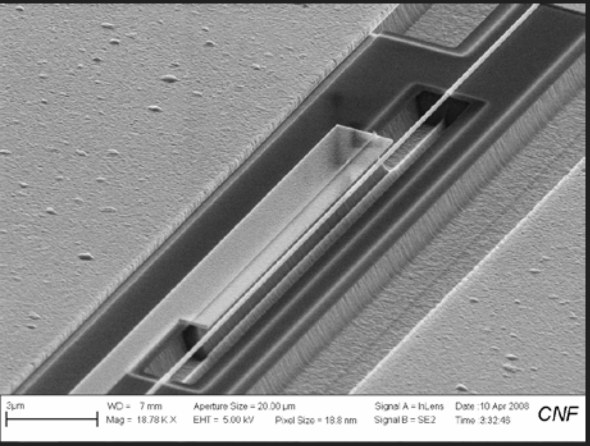
Teufel, Harlow, Regal, Lehnert, *Phys. Rev. Lett.*. **101**, (2008).

N=140
(1MHz)

Naik, LaHaye, Buu, Clerk, Blencowe, Armour, Schwab, *Nature*. **443**, (2006).

N=25
(20MHz)



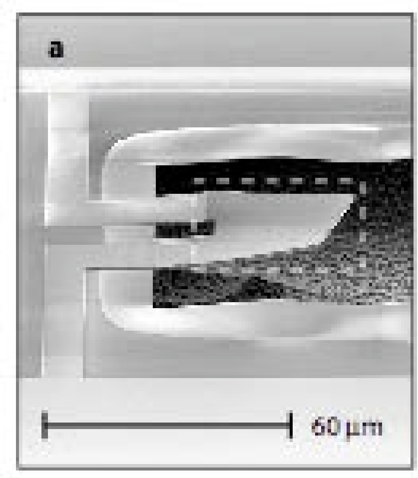


This work….

Rocheleau, Ndukum, Macklin, Hertzberg, Clerk, Schwab, *Nature* (2010)

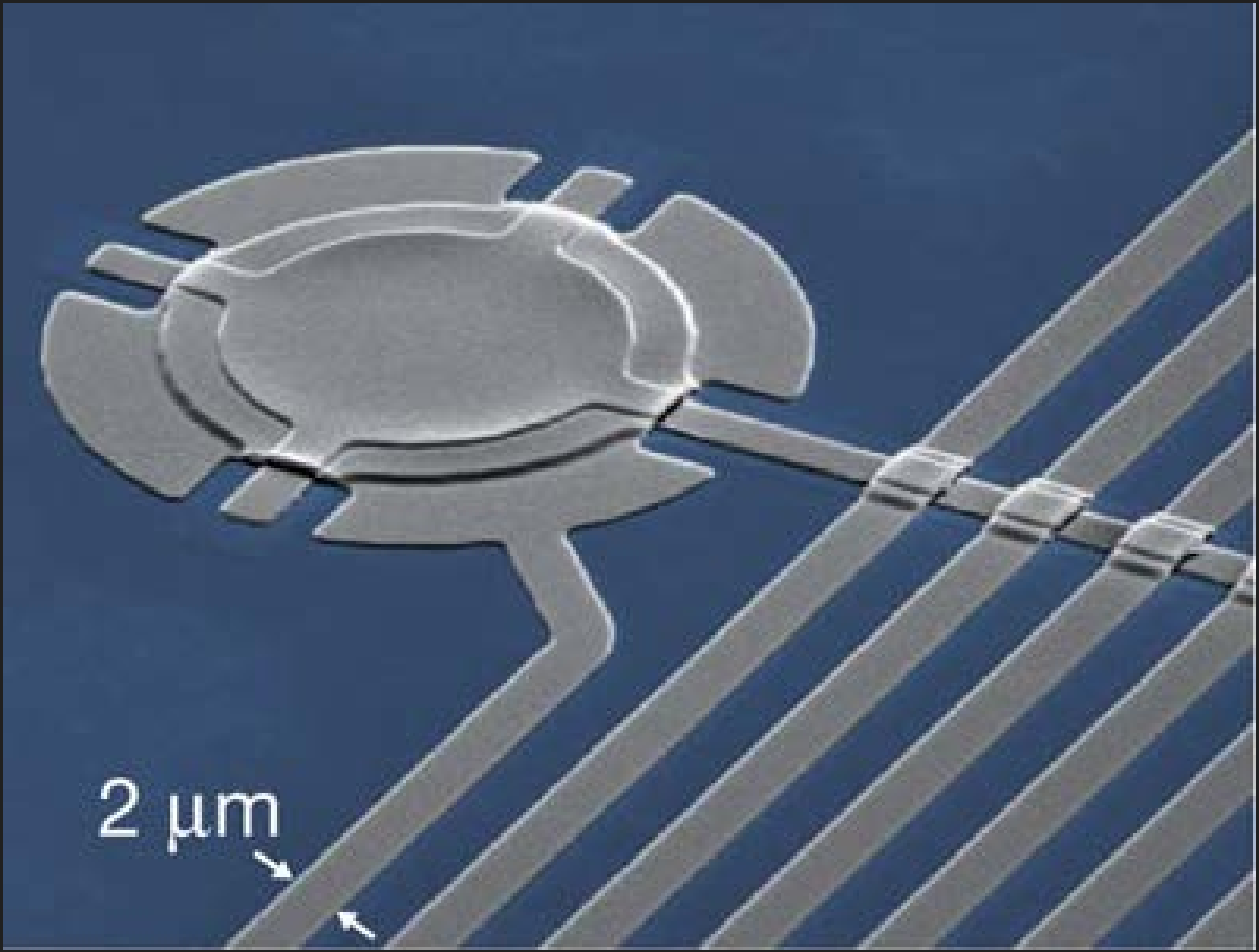
N=3.8 +/- 1
(5MHz)

O'Connel, et al, Nature (2010).
N<0.1
(6GHz)



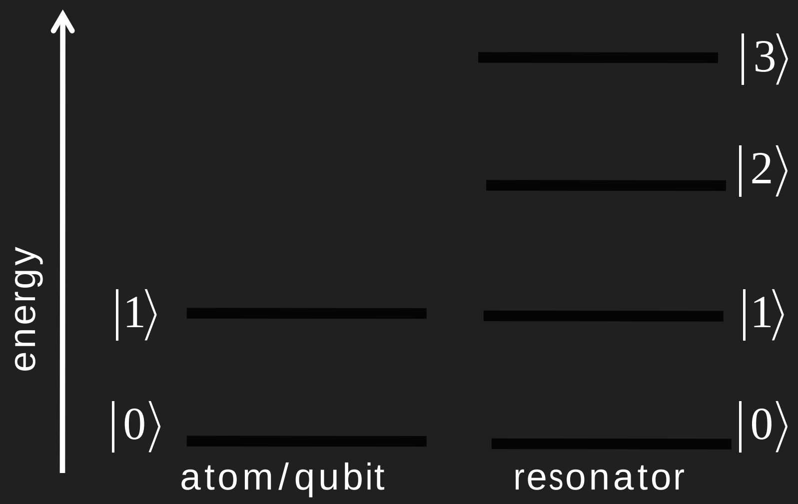
Progress in Electro-mechanics -- ground state

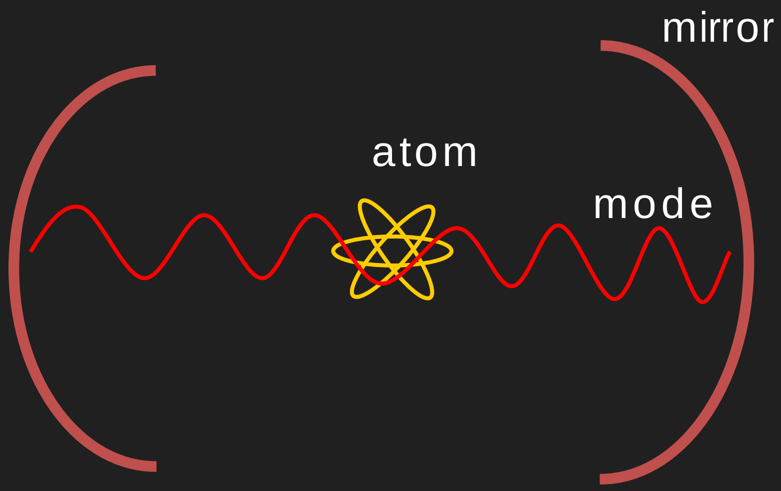
N=0.4 !



Teufel, Dale, Harlow, Allman, Cicak, Sirois, Whittaker, Lehnert, Simmonds, *Nature* **475**, 359 (2011).

Control at the single quanta level





resonator

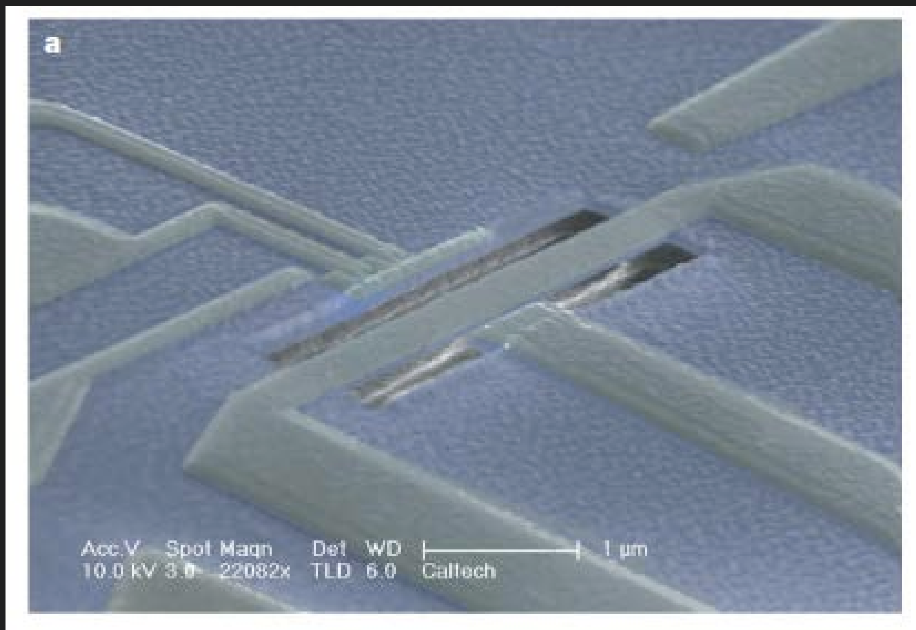
Interaction with exchange of quanta

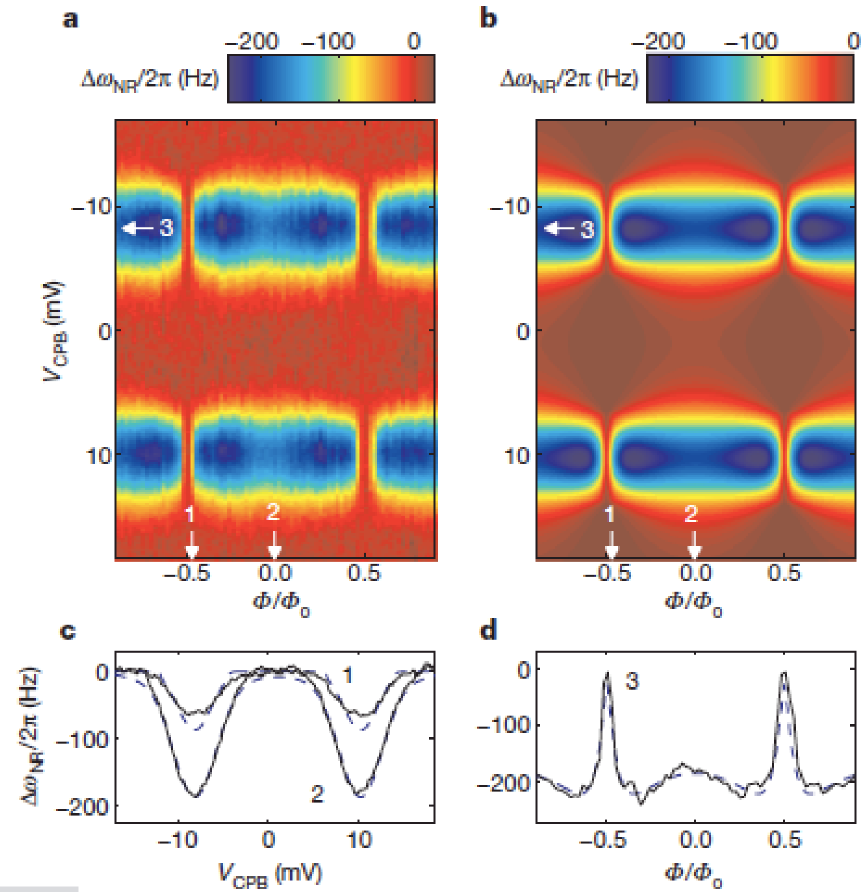
$$H_{total} = \hbar\omega_r a^+ a + \frac{1}{2}\hbar\omega_q \sigma_z + \hbar g(\sigma_+ + \sigma_-)(a + a^+)$$

Two state system

E. Irish, K.C. Schwab, *PRB* **68**, 155311 (2003).

NEMS coupled to superconducting qubit





$$H = \hbar\omega_{NR}\hat{a}^{+}\hat{a} + \frac{\Delta E}{2}\hat{\sigma}_z + \hbar\lambda\left(\hat{a}+\hat{a}^{+}\right)\left(\frac{E_{el}}{\Delta E}\hat{\sigma}_z - \frac{E_j}{\Delta E}\hat{\sigma}_x\right)$$

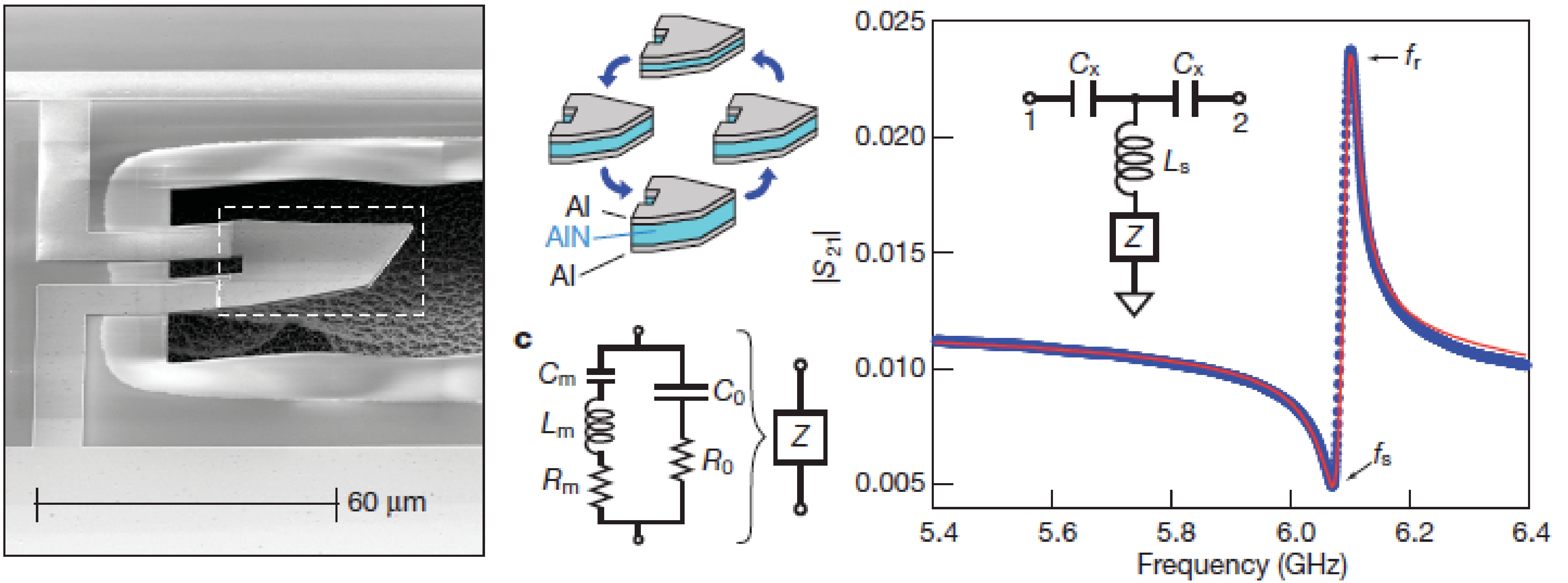
nature Vol 459|18 June 2009|doi:10.1038/nature08093

LETTERS

Nanomechanical measurements of a superconducting qubit

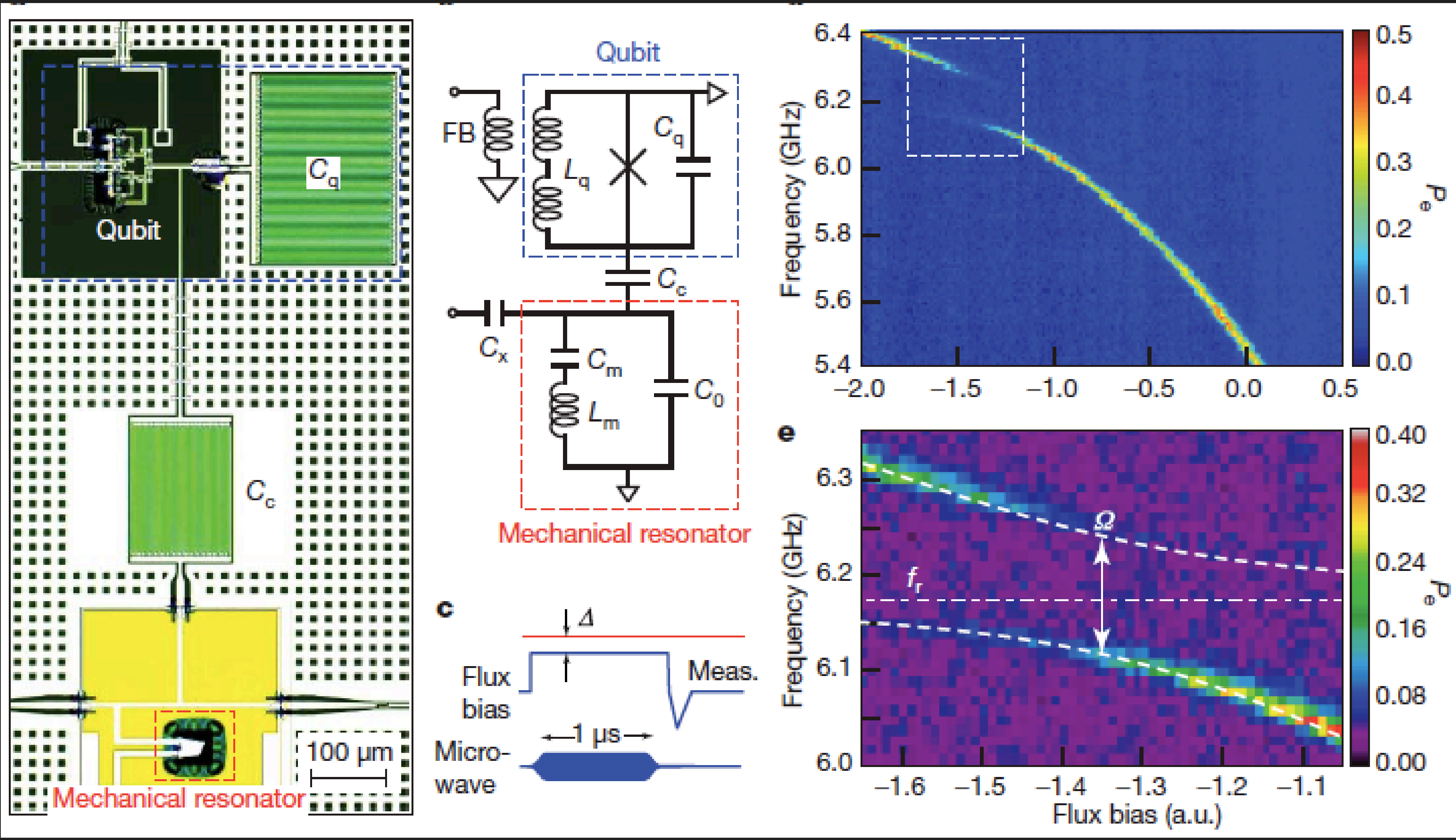
M. D. LaHaye[1], J. Suh[1], P. M. Echternach[3], K. C. Schwab[2] & M. L. Roukes[1]

Control at the single quanta level



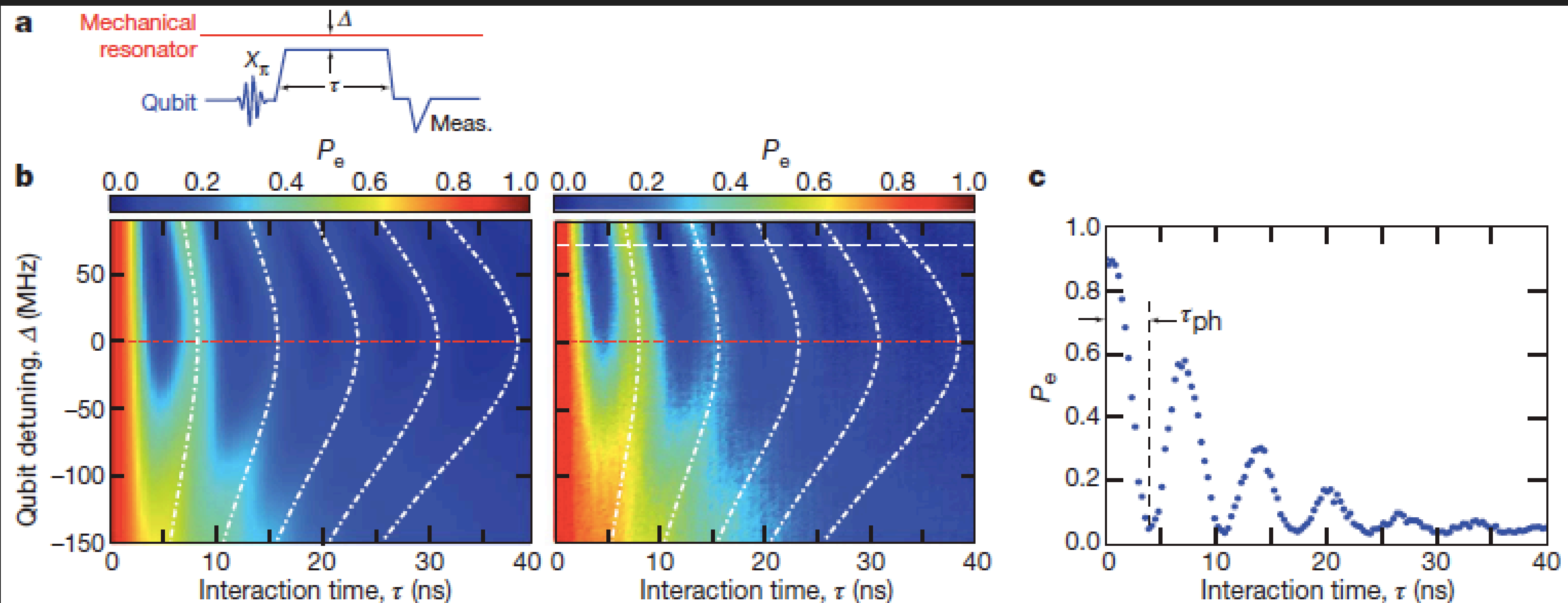
O'Connell, et al, *Nature* **464**, 697 (2010).

Coupling to a superconducting qubit



O'Connell, et al, *Nature* **464**, 697 (2010).

Exchanging a single quanta



O'Connell, et al, *Nature* **464**, 697 (2010).

The Standard Quantum Limit

$$[\hat{x}, \hat{p}] = i\hbar$$

$$\Delta x \cdot \Delta p \geq \frac{\hbar}{2}$$

$$\hat{x} \qquad\qquad \hat{p}$$

$$\hat{H} = \frac{1}{2} m\omega^2 \hat{x}^2 + \frac{1}{2m} \hat{p}^2$$

$$\frac{d\hat{x}}{dt} = -\frac{i}{\hbar}\left[\hat{x}, \hat{H}\right]$$

QND Measurement of Quadratures

$$\hat{x} + i\frac{\hat{p}}{m\omega} = \left(\hat{X}_1 + i\hat{X}_2\right)e^{-i\omega t}$$

$$\hat{x}(t) = \hat{X}_1 \cos(\omega t) + \hat{X}_2 \sin(\omega t)$$

$$\left[\hat{X}_1, \hat{X}_2\right] = i\frac{\hbar}{m\omega}$$

$$\Delta X_1 \cdot \Delta X_2 \geq \frac{\hbar}{2m\omega}$$

$$\hat{X}_1 \qquad \hat{X}_2$$

$$\frac{d\hat{X}_{1,2}}{dt} = \frac{\partial X_{1,2}}{\partial t} - \frac{i}{\hbar}\left[\hat{X}_{1,2}, \hat{H}\right] = 0$$

Braginskii, V.B., Vorontsov, Yu.I., Quantum-mechanical limitations in macroscopic experiments and modern experimental design. *Sov. Phys.Usp.* **17**, 644 (1975).

Thorne, Kip S., Drever, Ronald W.P., Caves, Carlton M., Zimmerman, Mark, Sandberg, Vernon D., Quantum Nondemolition measurements of Harmonic Oscillators. *Phys. Rev. Lett.* **40**, 667-671 (1978).

Summary, take home messages, and good things to know

•Small particles (photons, electrons, ect) don't behave in a way consistent with our classical/ancient notions of reality.

•Large molecules (Buckyballs and now larger) can act like waves, going both ways around an obstacle and interfering with itself.

•There is probably no limit to the size where quantum behavior stops; we are building small mechanical devices to see the wave behavior or larger objects.

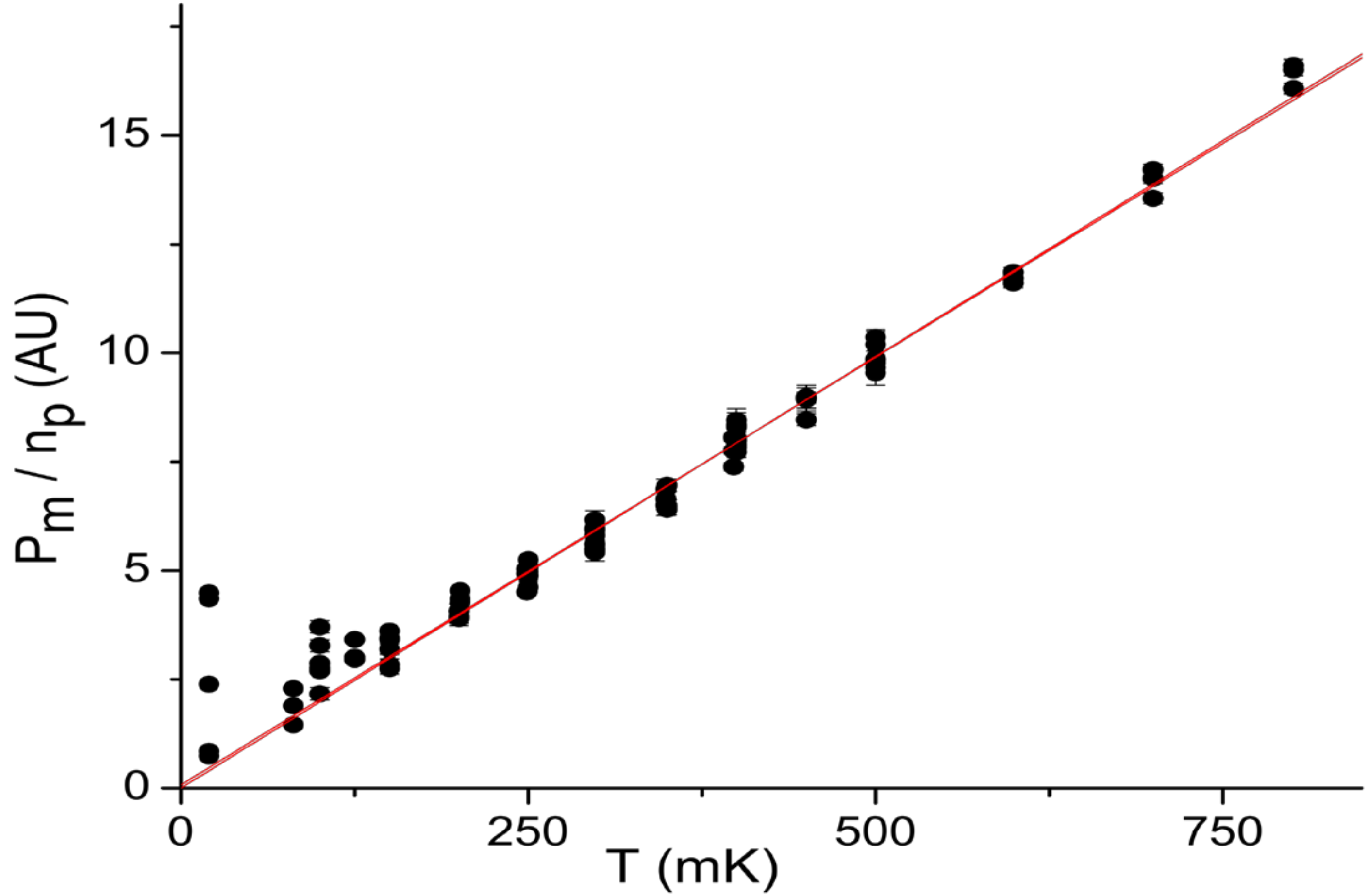
•Our community has recent produced the quantum ground state of mechanical structures in both electro-mechanical and opto-mechanical devices.

•The Uncertainty Principle fluctuations of a mechanical mode have been recently measured.

•Manipulation of a single phonon, using a qubit, has recently been demonstrated.

www.kschwabresearch.com

Mechanical Brownian Motion – Signal



Schrödinger's cat

- Wave function for a single atom: $|\Psi\rangle = |0\rangle_{atom}$ $|\Psi\rangle = |1\rangle_{atom}$

$$|\Psi\rangle = |1\rangle_{atom} + |0\rangle_{atom}$$

- After measurement:

$$|\Psi\rangle \rightarrow |1\rangle_{atom} \, or \, |0\rangle_{atom}$$

- What if a microscopic degree of freedom is coupled to a macroscopic state?

$$|\Psi\rangle = |1\rangle_{atom} \otimes |alive\rangle_{cat} + |0\rangle_{atom} \otimes |dead\rangle_{cat}$$

- Can something as complex as a cat become entangled with microscopic entity?

- Before you look, is the cat in a superposition of alive and dead?

Schrodinger, ***Naturwissenschaften*** (1935).