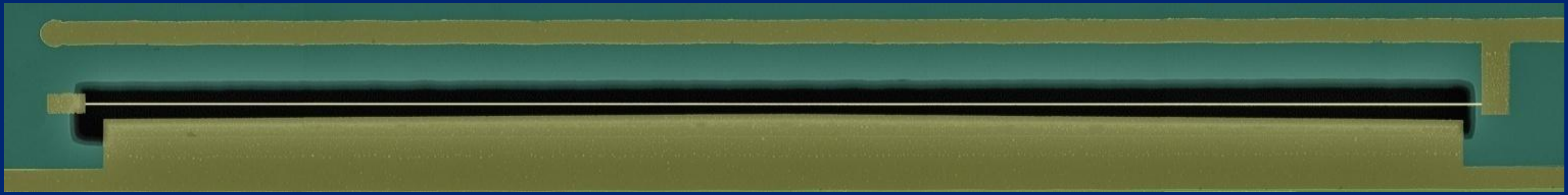
Quantum acoustics

jilawww.colorado.edu/~lehnertk



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Post-docs
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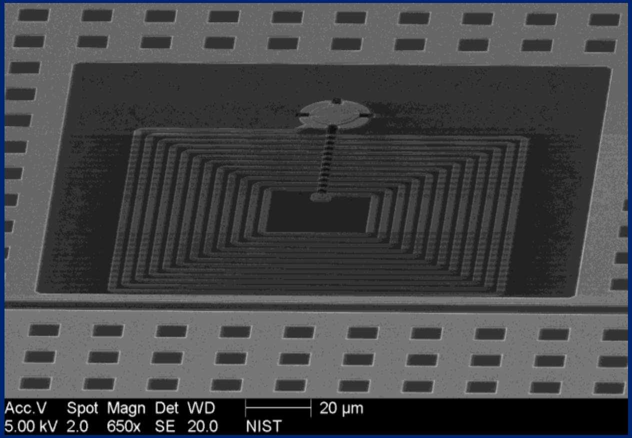
Cindy Regal



Graduate students
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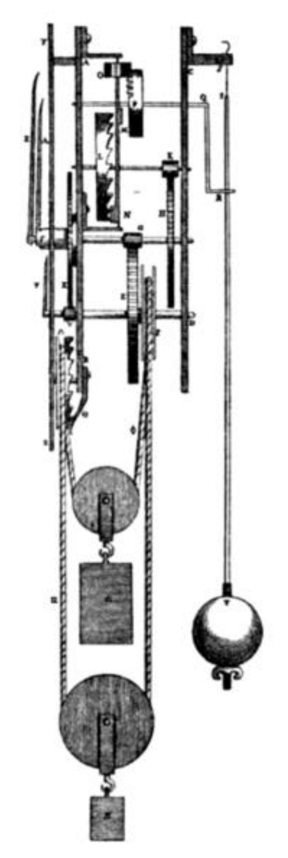
Manuel Castellanos-Beltran
Nathan Flowers-Jacobs

Precision measurement tools were once mechanical oscillators



Huygens pendulum clock

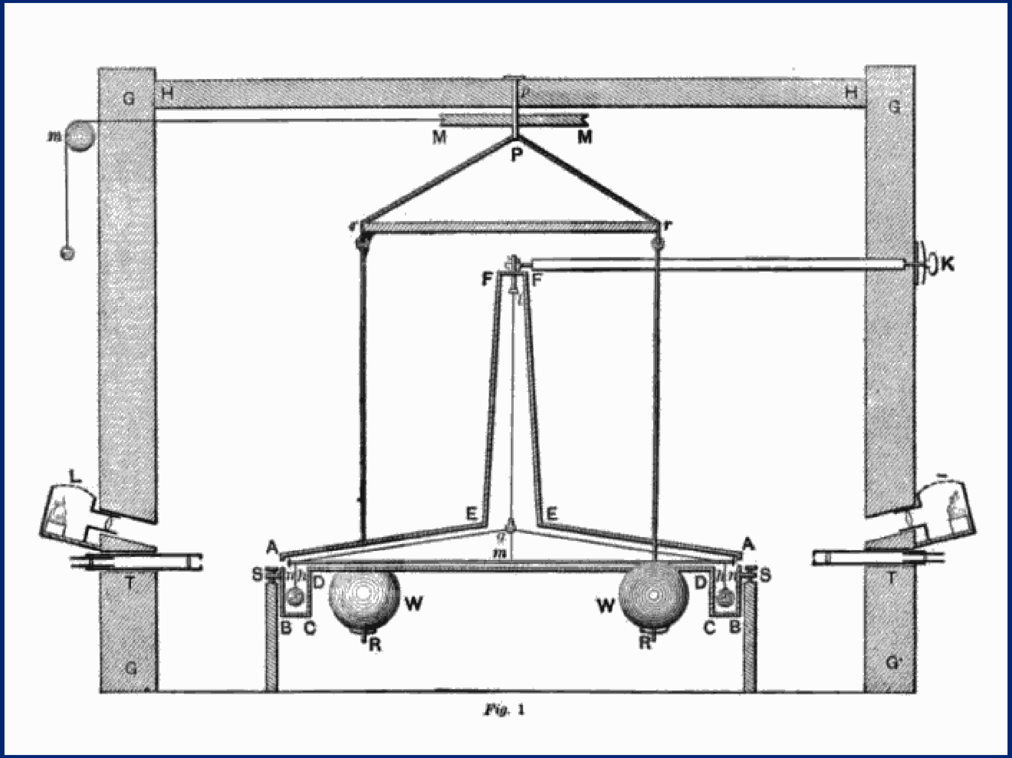


Fig. 1

The Cavendish balance for weighing the earth

Modern measurement tools exploit optics and electronics, not mechanics

Laser light

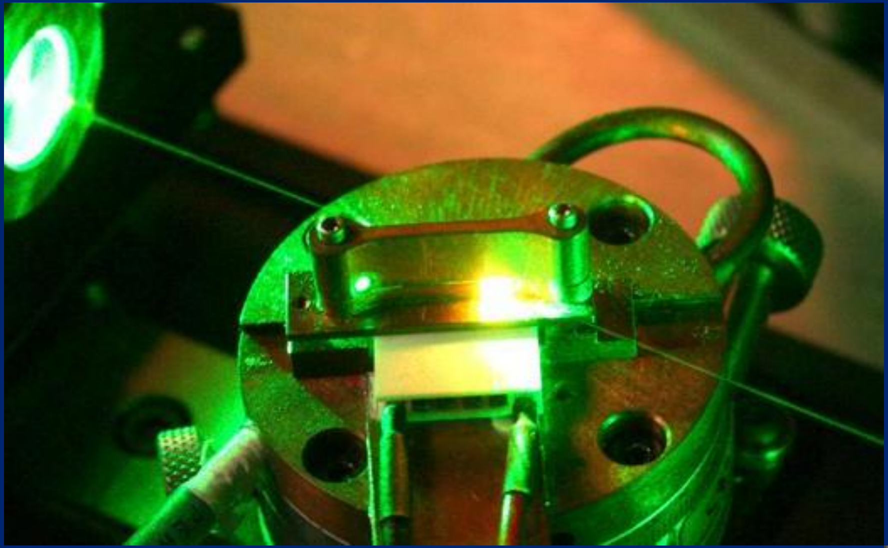
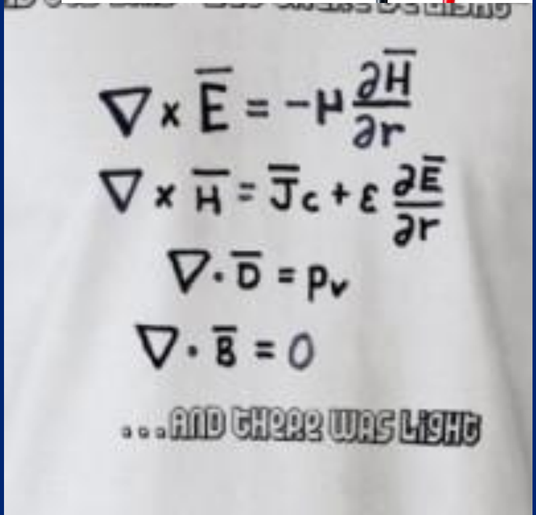


Image: Cundiff lab JILA

electricity

Described by:
Maxwell’s equations



$$\nabla \times \bar{E} = -\mu \frac{\partial \bar{H}}{\partial r}$$

$$\nabla \times \bar{H} = \bar{J}_c + \varepsilon \frac{\partial \bar{E}}{\partial r}$$

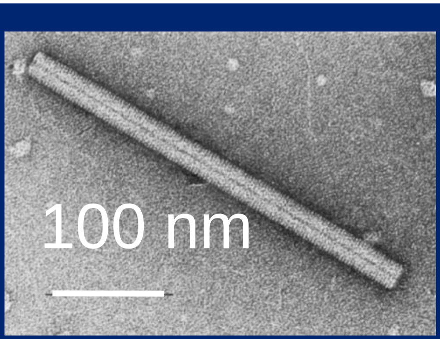
$$\nabla \cdot \bar{D} = \rho_v$$

$$\nabla \cdot \bar{B} = 0$$

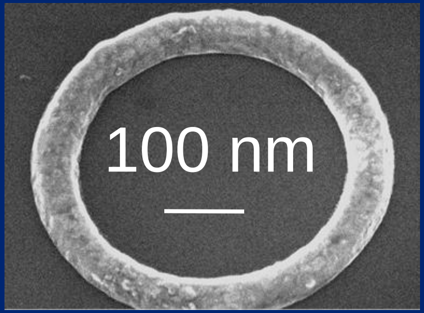
...AND THERE WAS LIGHT

Optical probes are ill-suited to directly measuring many interesting systems

non-atomic system



nuclear spins in a virus



electrons in an aluminum ring
(Harris lab, Yale)

Systems with:

dense low-energy spectra

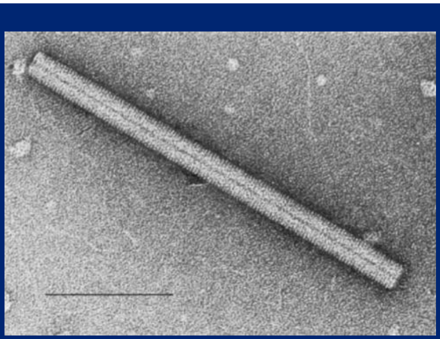
nanometer length scales

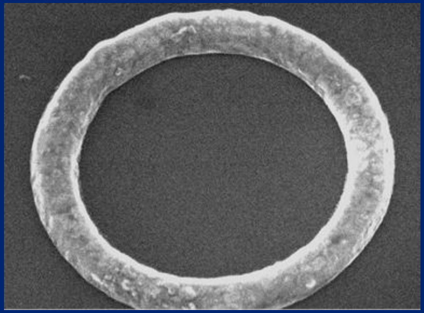
weak coupling to light

quantum probe: light

Mechanical oscillators enable measurements of non-atomic systems

non-atomic system





mechanical intermediary

quantum probe: light

Systems with:

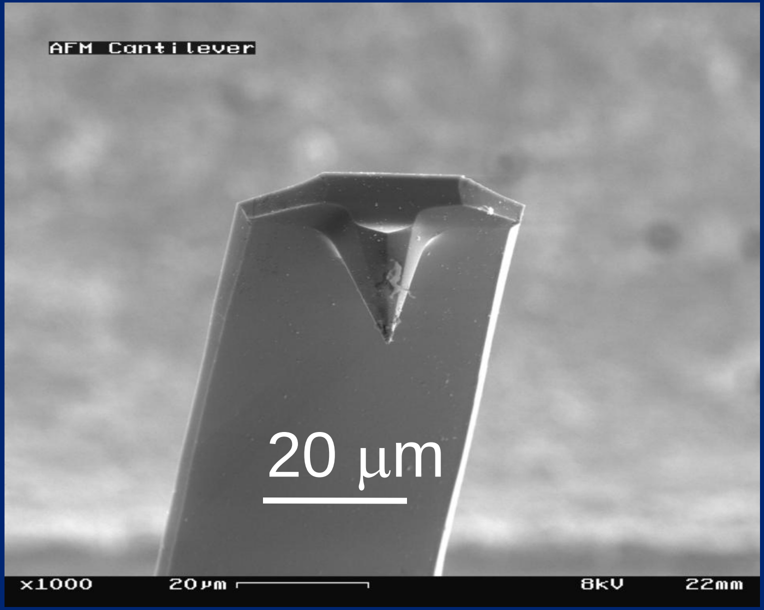
dense low-energy spectra

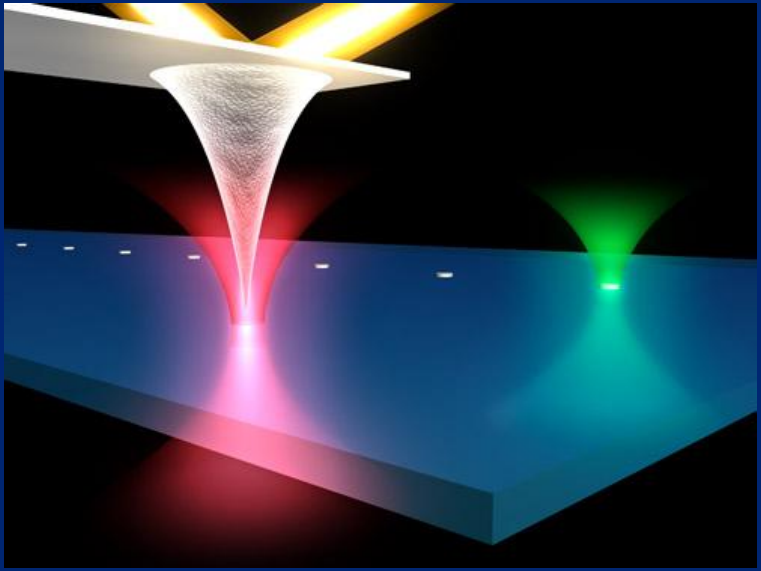
nanometer length scales

weak coupling to light

Mechanical oscillators are tools that access the nano-world

Atomic Force Microscope



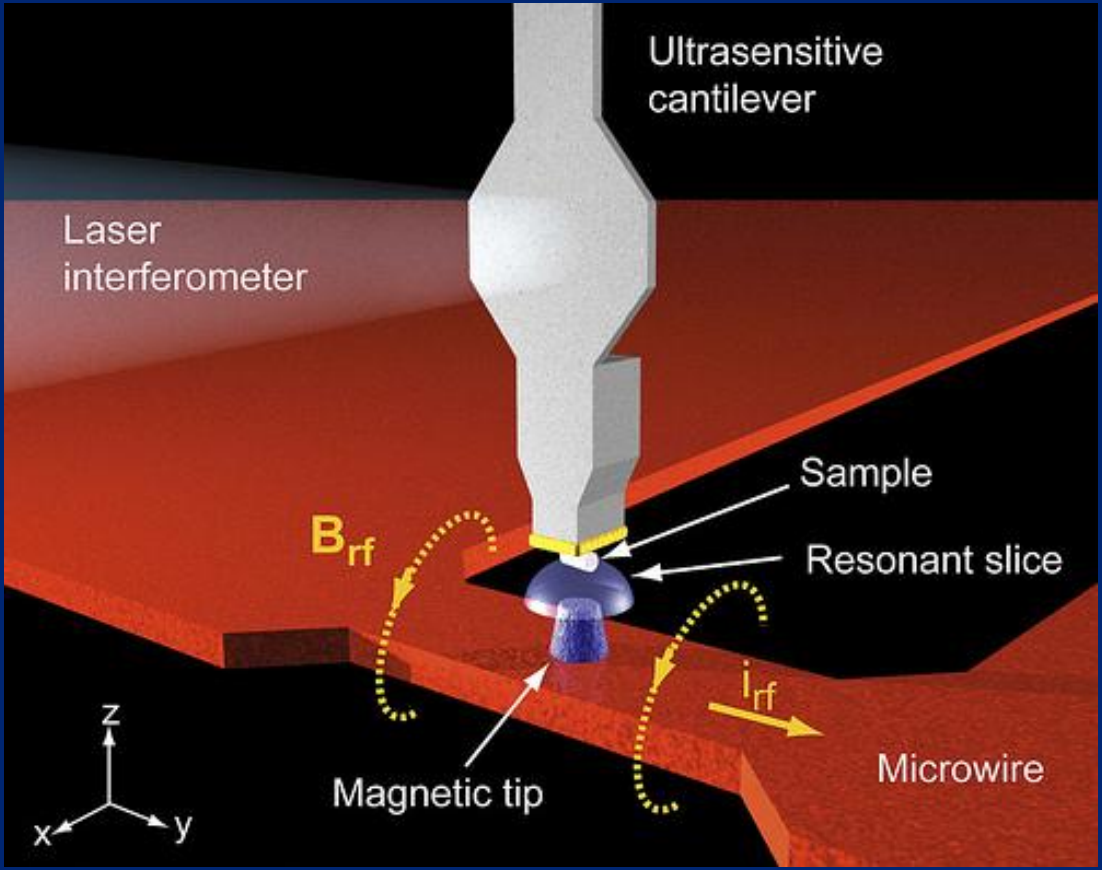


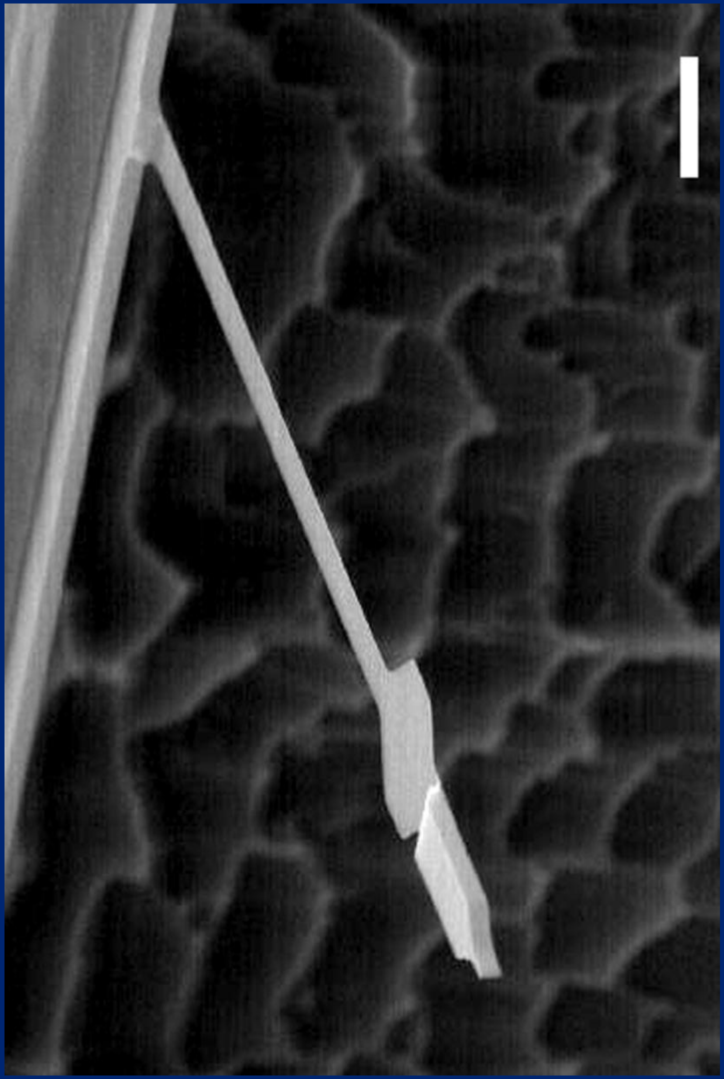
Perkins lab, JILA

Mechanical oscillator
- nanometer probe
- universal coupling (senses any force)

Optical interferometer detects oscillator motion

Mechanical oscillators form ultrasensitive, mesoscopic magnetometers





nanoscale MRI of a single virus

Rugar Lab, IBM

$$\sqrt{S_f^{\mathrm{tot}}} = 0.8\ \mathrm{aN/Hz^{1/2}}$$

Mechanical oscillators as quantum coherent interfaces between incompatible systems

Mechanical oscillators are classical

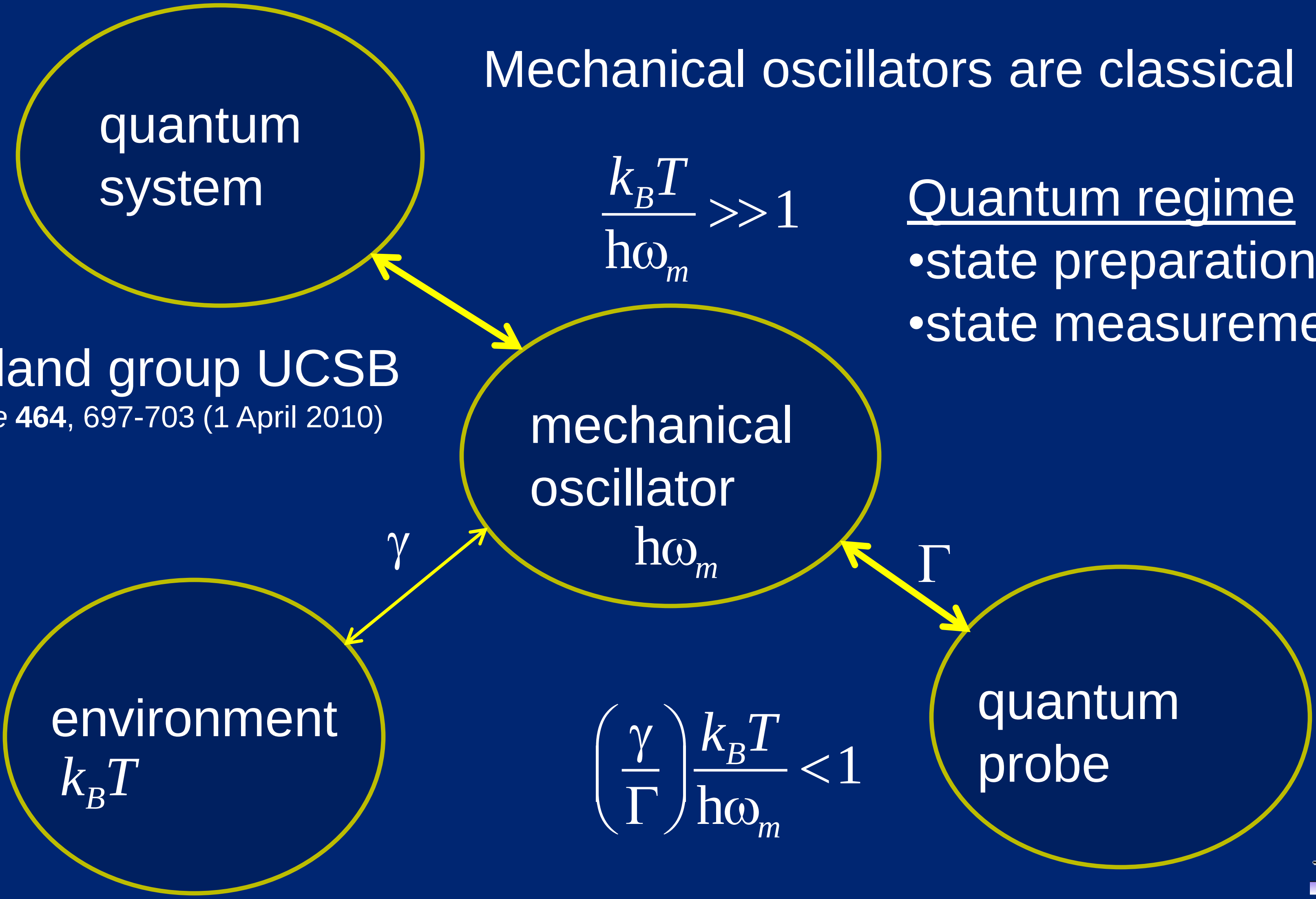
$$\frac{k_B T}{\hbar\omega_m} \gg 1$$

Quantum regime

- state preparation
- state measurement

Cleland group UCSB

Nature **464**, 697-703 (1 April 2010)



quantum system

mechanical oscillator

$\hbar\omega_m$

environment

$k_B T$

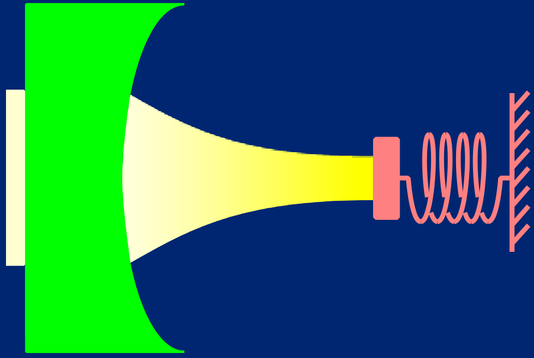
quantum probe

γ

Γ

$$\left(\frac{\gamma}{\Gamma}\right)\frac{k_B T}{\hbar\omega_m} < 1$$

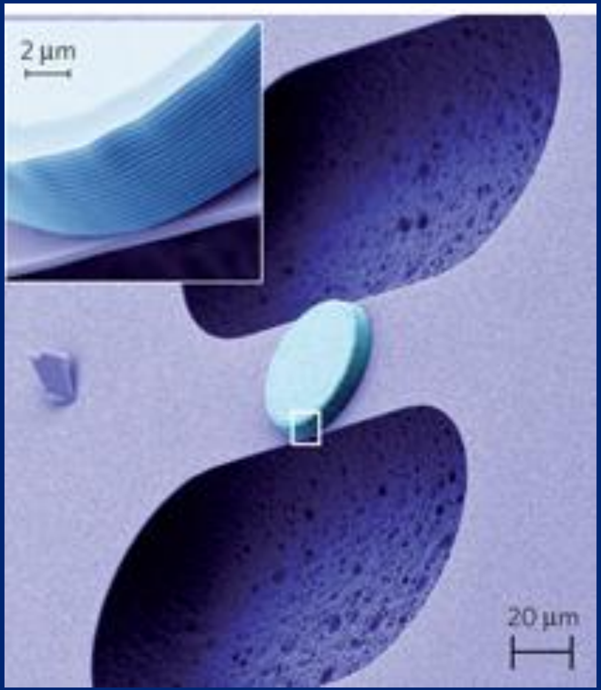
Cavity optomechanics: Use radiation pressure for state preparation and measurement



Fabry-Perot cavity with oscillating mirror

$$\hat{H} = \hbar\omega_c\left(a^\dagger a + \tfrac{1}{2}\right) + \hbar\omega_m\left(b^\dagger b + \tfrac{1}{2}\right) + H_I$$

$$\hat{H}_I = \hat{F}\cdot\hat{x} = \hbar a^\dagger a g x_{zp}(b^\dagger + b)$$



Aspelmeyer lab, IOQOI, Vienna

Infer motion through optical phase

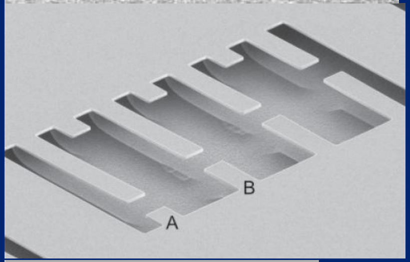
Cool with cavity-retarded radiation force

$$\Gamma \approx \frac{g^2 x_{zp}^2}{4\hbar\omega_c^2\kappa} P_{\mathrm{circ}} \qquad g \sim 100\ \mathrm{MHz/nm}$$

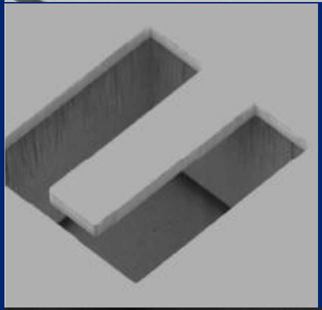
Images of cavity optomechanical systems

Caltech, Vahala
MPQ, Kippenberg

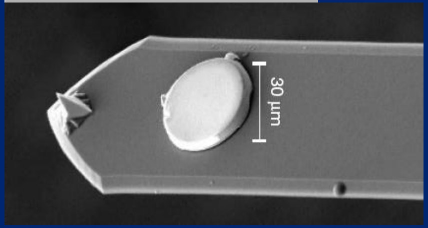
10 ng



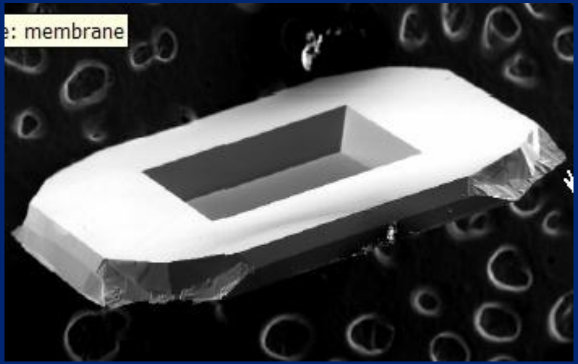
IOQOI: Zeilinger and Aspelmeyer



ENS: Pinard and Heidmann



UCSB: Bouwmeester



Yale, Harris

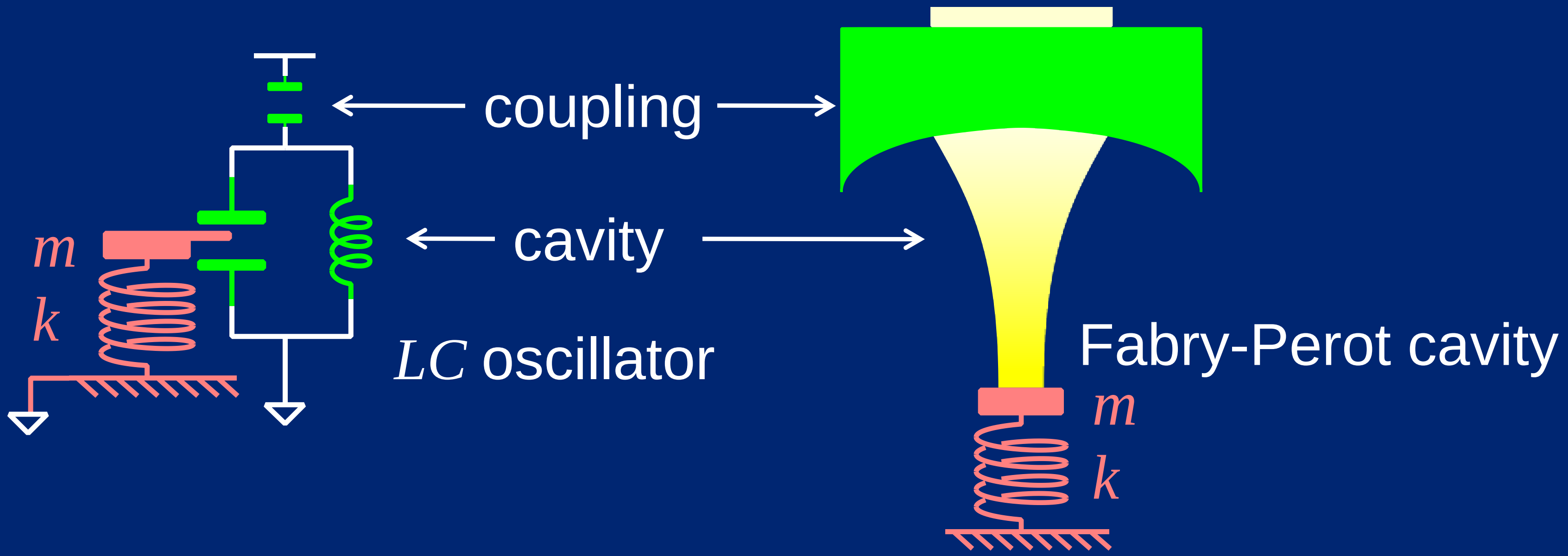
1 g

MIT, Mavalvala

Microwave cavity optomechanics

Reduce coupling to the environment by lowering temperature: microwave optomechanics

Microwave “light” in ultralow temperature cryostat



Strategy

Cool environment to $T << 1\ \mathrm{K}$

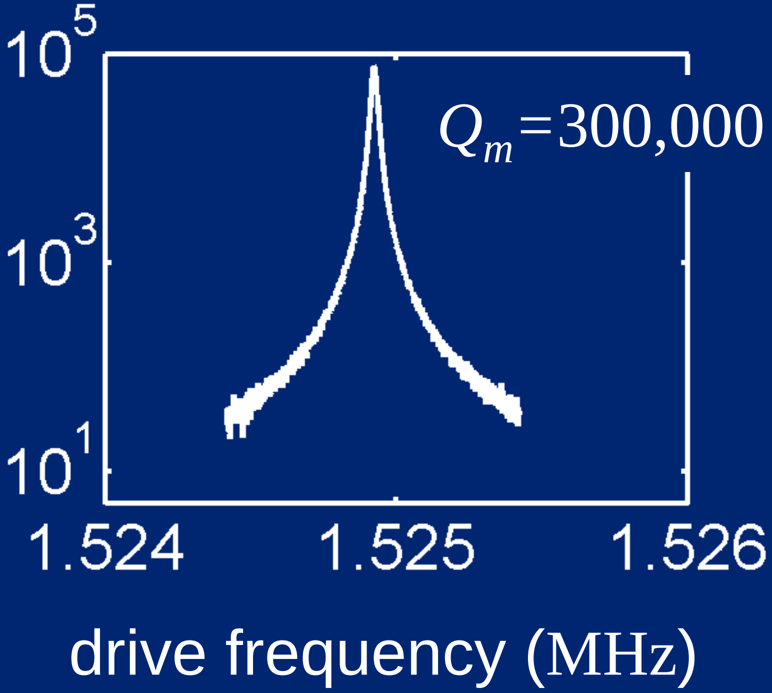
High Q mechanical oscillators

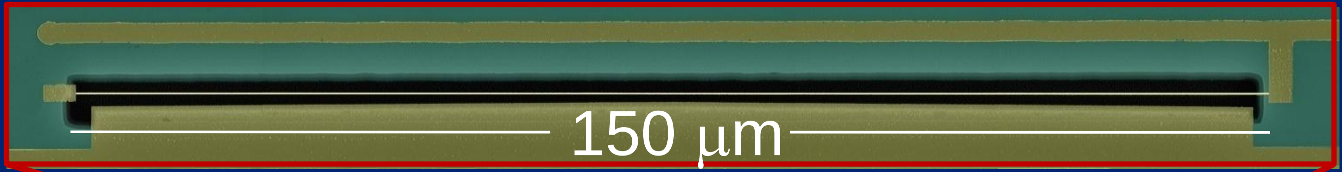
$$\left(\frac{\gamma}{\Gamma}\right)\frac{k_B T}{\hbar\omega_m} < 1$$

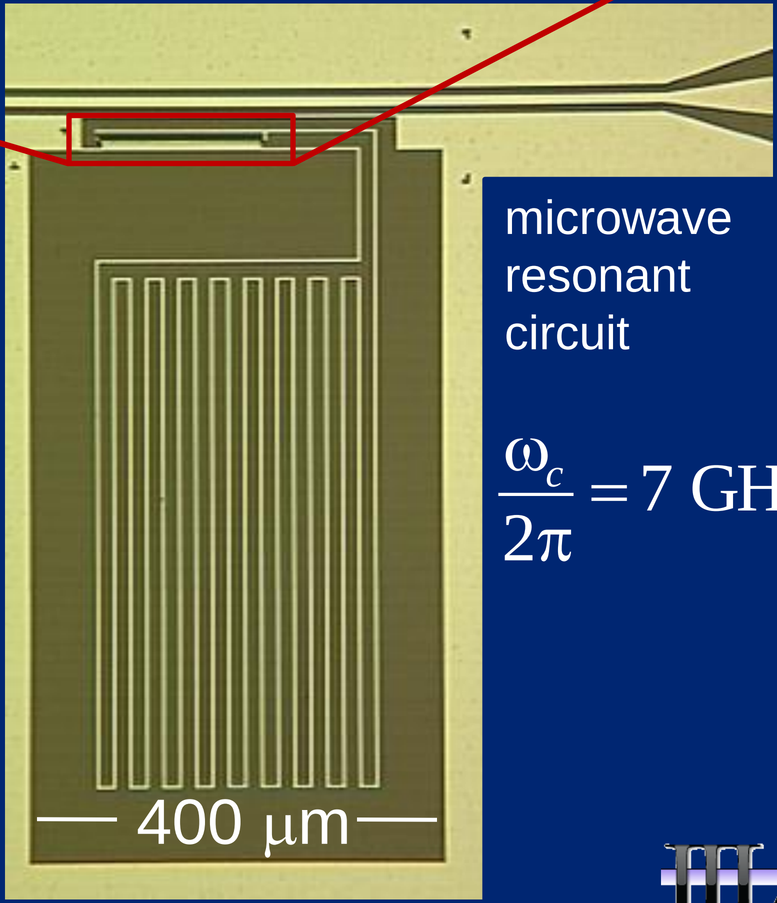
Cavity optomechanical system realized from a nanomechanical wire in a resonant circuit

$g \sim 2\pi \times 30\ \text{kHz/nm}$

Wire response



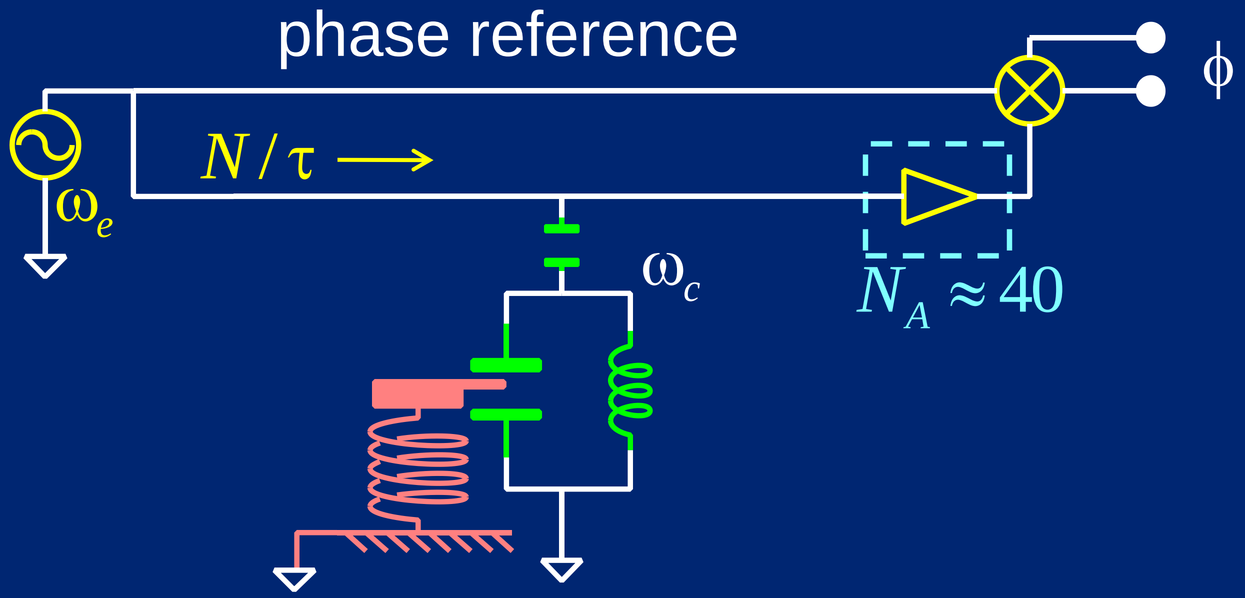


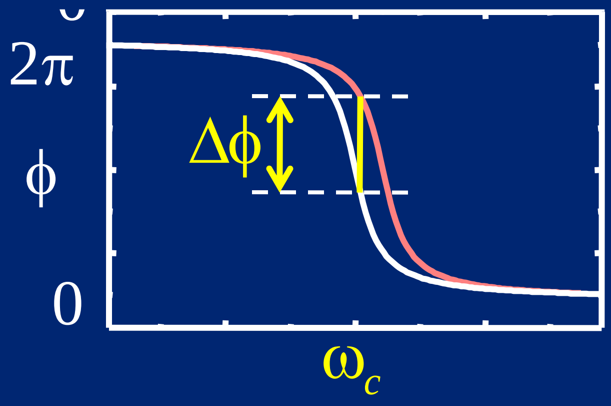


microwave resonant circuit

$$\frac{\omega_c}{2\pi} = 7\ \text{GHz}$$

Nanomechanical motion monitored with a microwave Mach-Zehnder interferometer





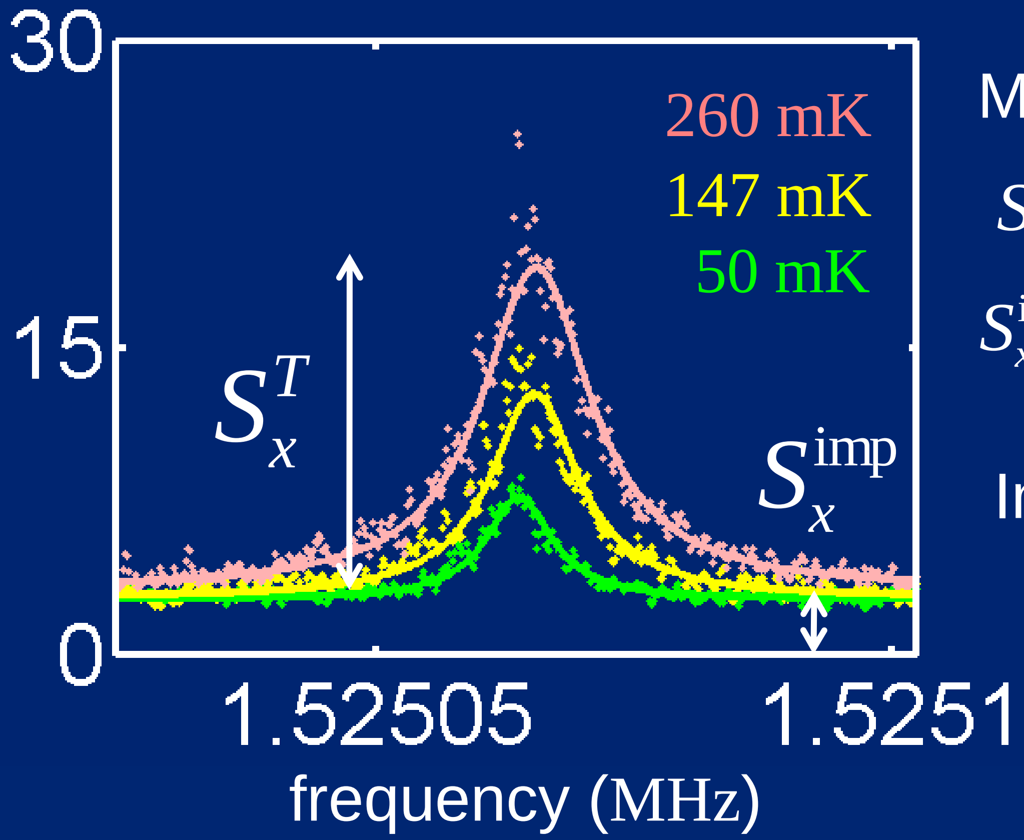
Infer wire motion from phase shift

$$\Delta\phi = \frac{\Delta\omega_c}{\gamma_c} = \frac{gx}{\gamma_c}$$

Phase sensitivity limited by amplifier (HEMT)

$$S_\phi = \frac{N_A + \frac{1}{2}}{N/\tau} = \frac{\text{noise quanta}}{\text{photon flux}}$$

Thermal motion of beam calibrates interferometer noise (imprecision)



Minimum imprecision

$$S_x^{\text{imp}} = 145 \text{ ZPE}$$

$$S_x^{\text{imp}} = 290 \times \text{SQL}$$

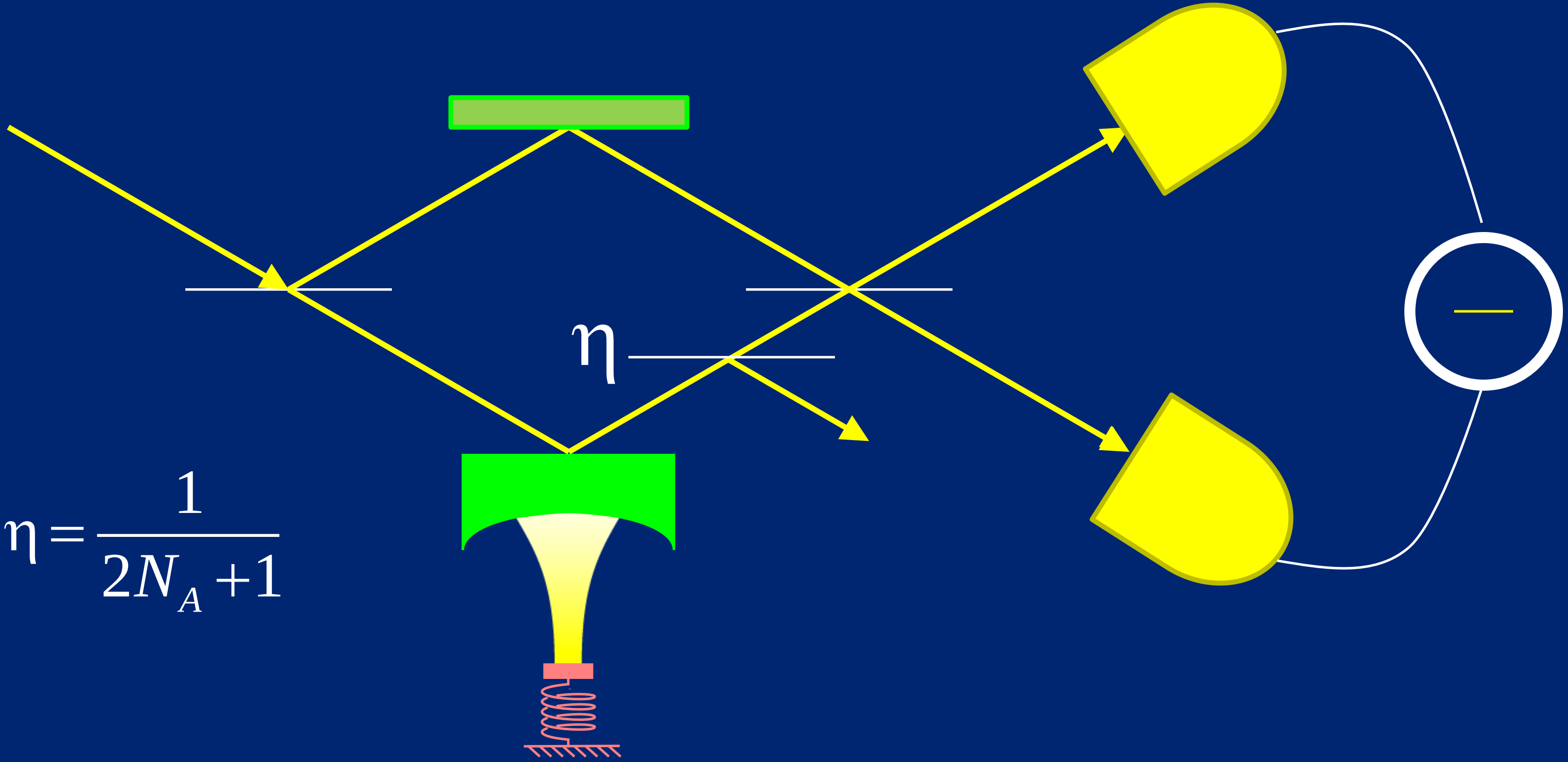
Imprecision at the SQL

$$S_x^{\text{sql}} = \hbar / m\omega_m\gamma_m$$

Determine measurement imprecision S_x^{imp}

C. A. Regal, J. D. Teufel, KWL Nature Phys. (2008)

Amplifier added noise mimics quantum inefficiency



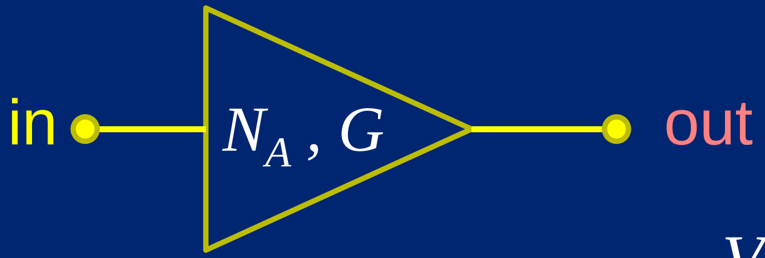
$$\eta = \frac{1}{2N_A + 1}$$

Excellent microwave amplifier:

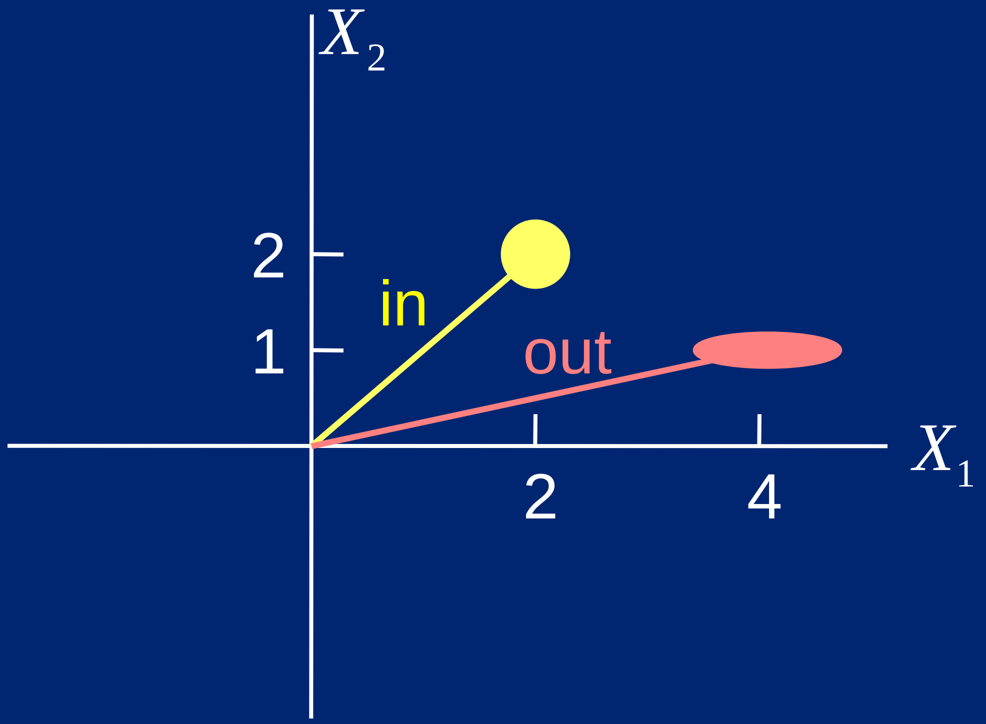
$N_A = 40 \quad \eta = 1.2\%$

Efficient quantum measurement

A single quadrature amplifier preserves entropy with photon number gain



$$V(t) = V_q \left(\hat{X}_1 \cos \omega t + X_2 \sin \omega t \right)$$



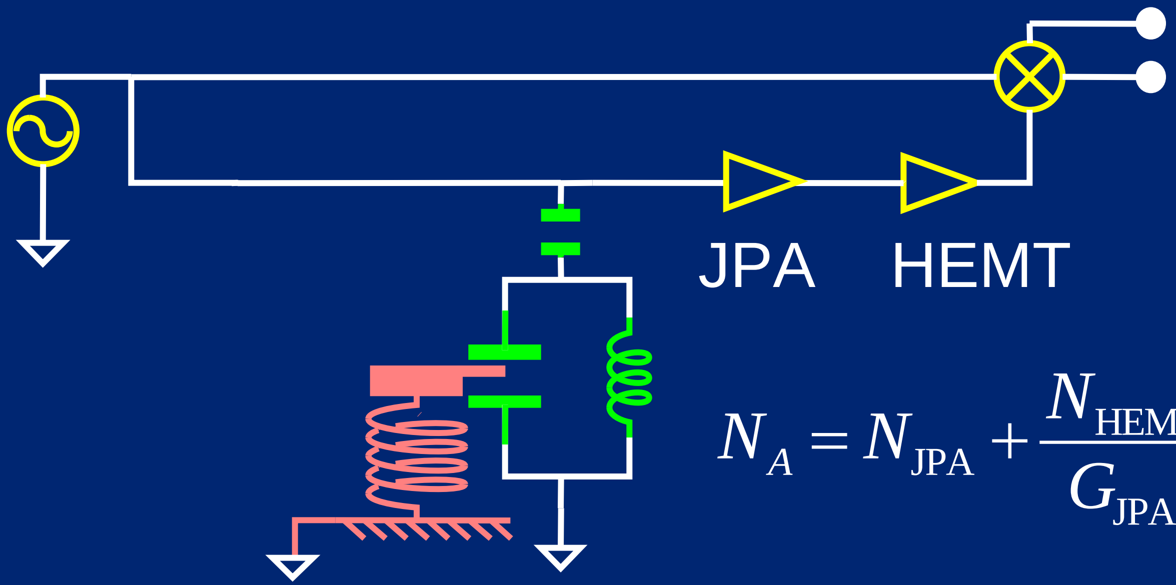
$$\hat{X}_1^{out} = G X_1^{in}$$

$$\hat{X}_2^{out} = \frac{1}{G} X_2^{in}$$

$$\hat{X}_1^{out} X_2^{out} - \hat{X}_2^{out} X_1^{out} = \frac{i}{2}$$

$$N_A \geq 0$$

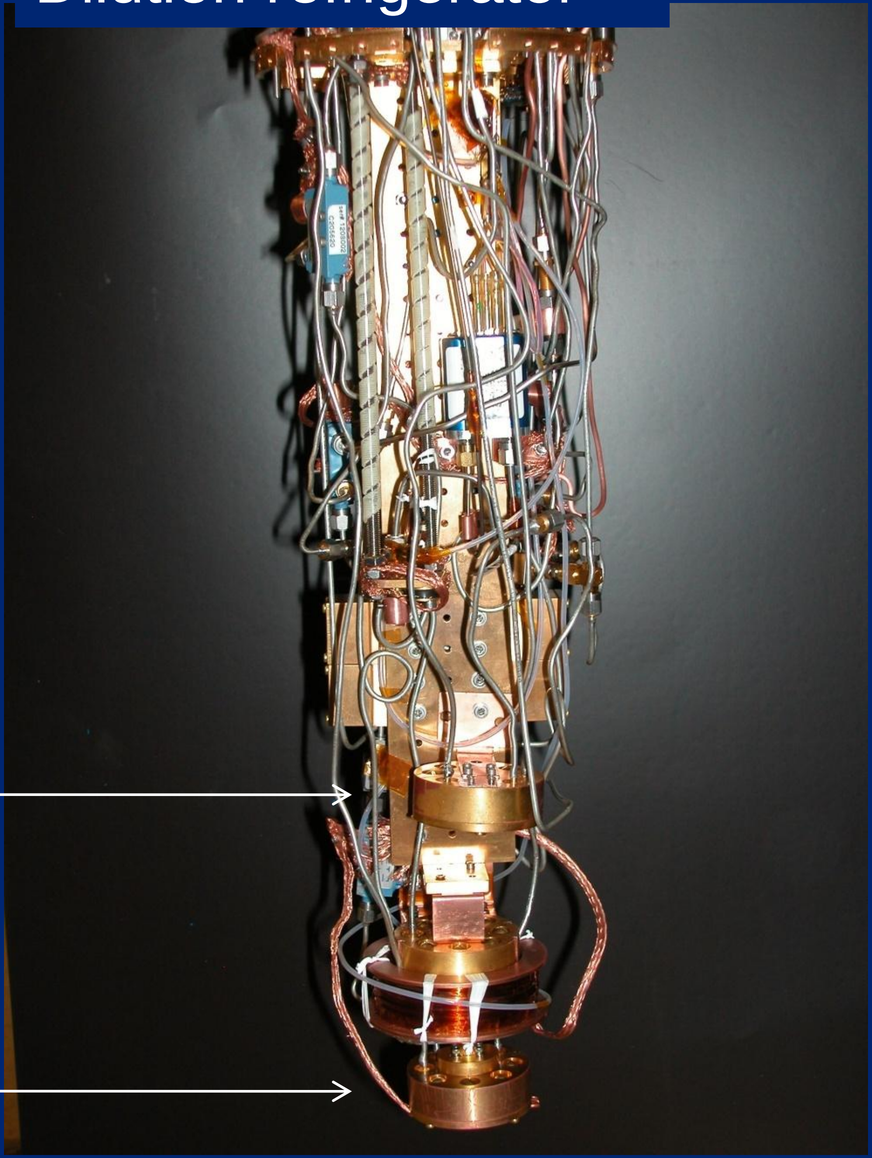
Incorporate quantum pre-amplifier into the Mach-Zehnder interferometer



$$N_A = N_{\text{JPA}} + \frac{N_{\text{HEMT}}}{G_{\text{JPA}}}$$

Josephson parametric amplifier (JPA)
makes more photons without more entropy

Diagram conceals some complexity



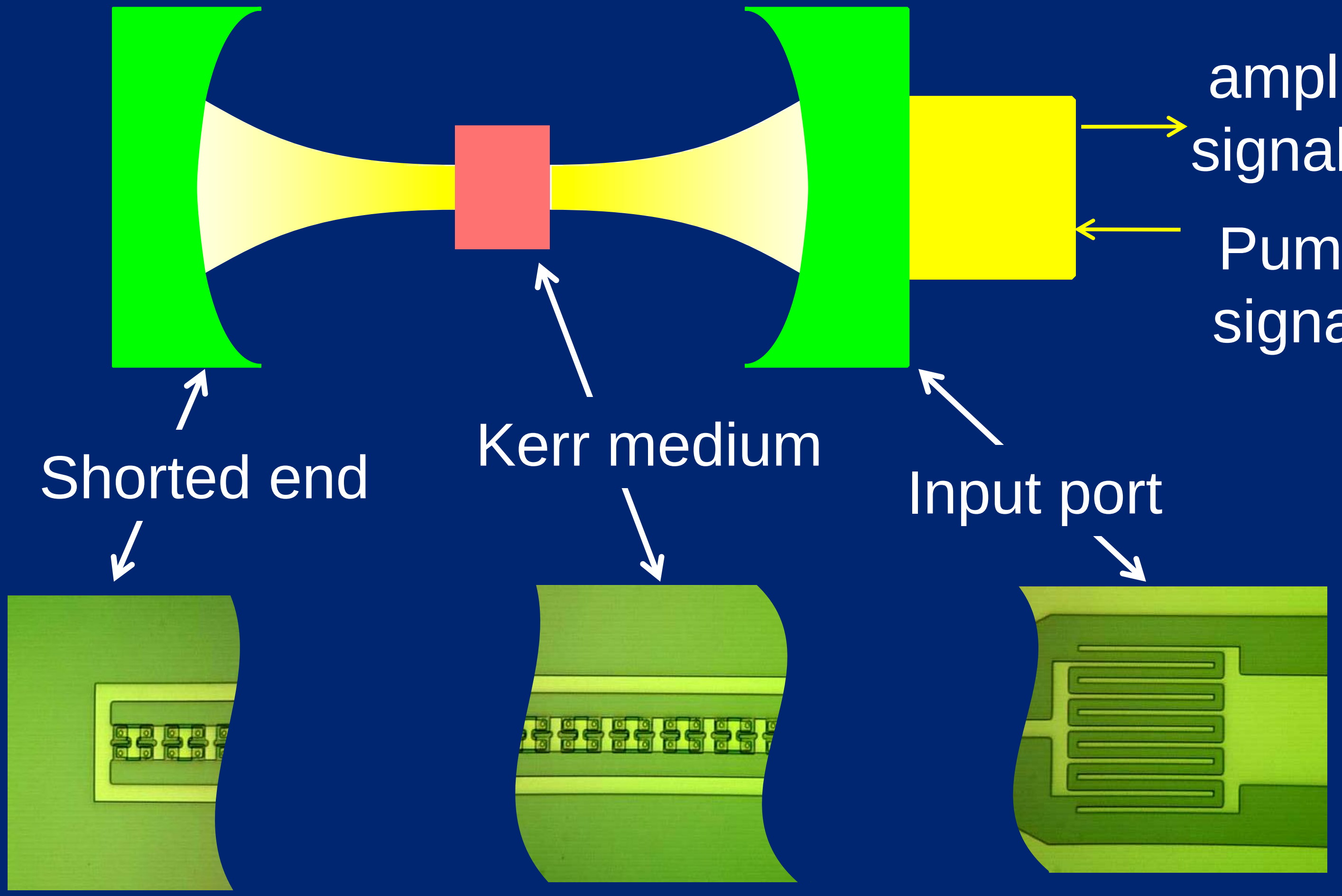
Dilution refrigerator

mechanics

JPA

50 cm

SQUIDs embedded in a cavity form an optical parametric amplifier at microwave frequency



amplified signal out

Pump + signal in

Shorted end

Kerr medium

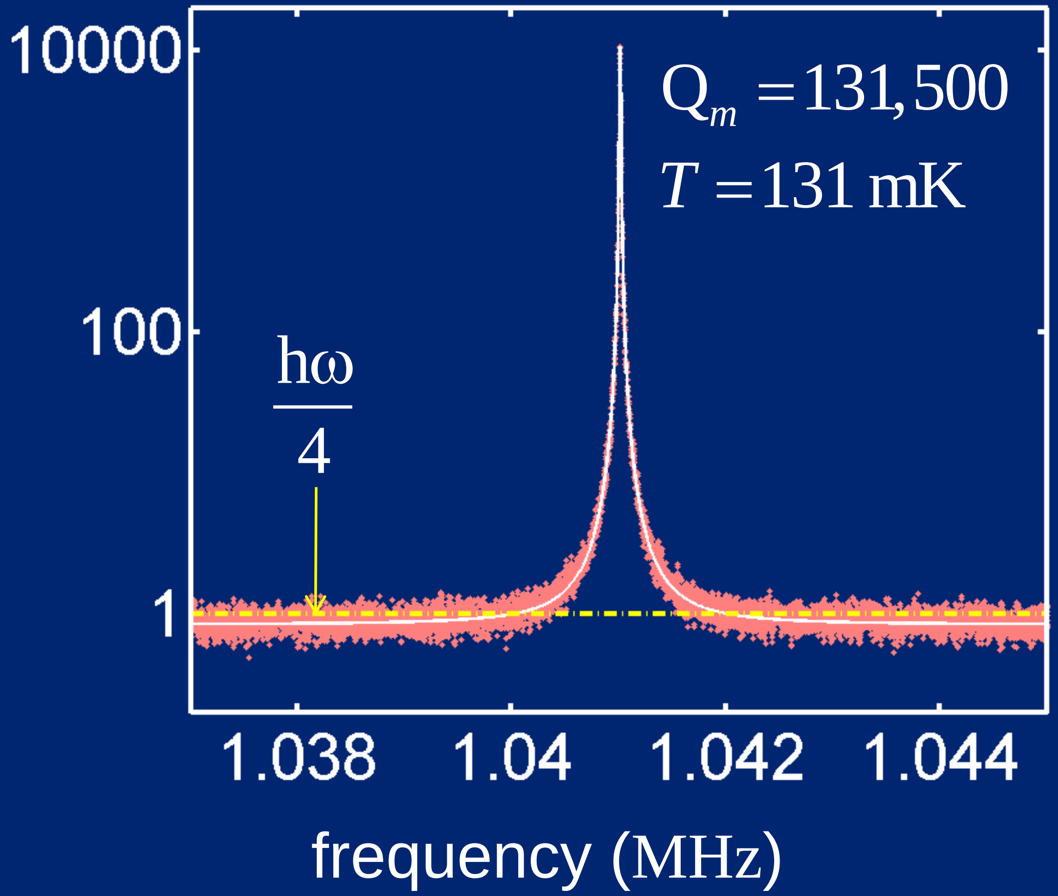
Input port

30 μm

array of 250 SQUIDS
embedded in a CPW resonator

M. A. Castellanos-Beltran, KWL, App. Phys. Lett. (2008)

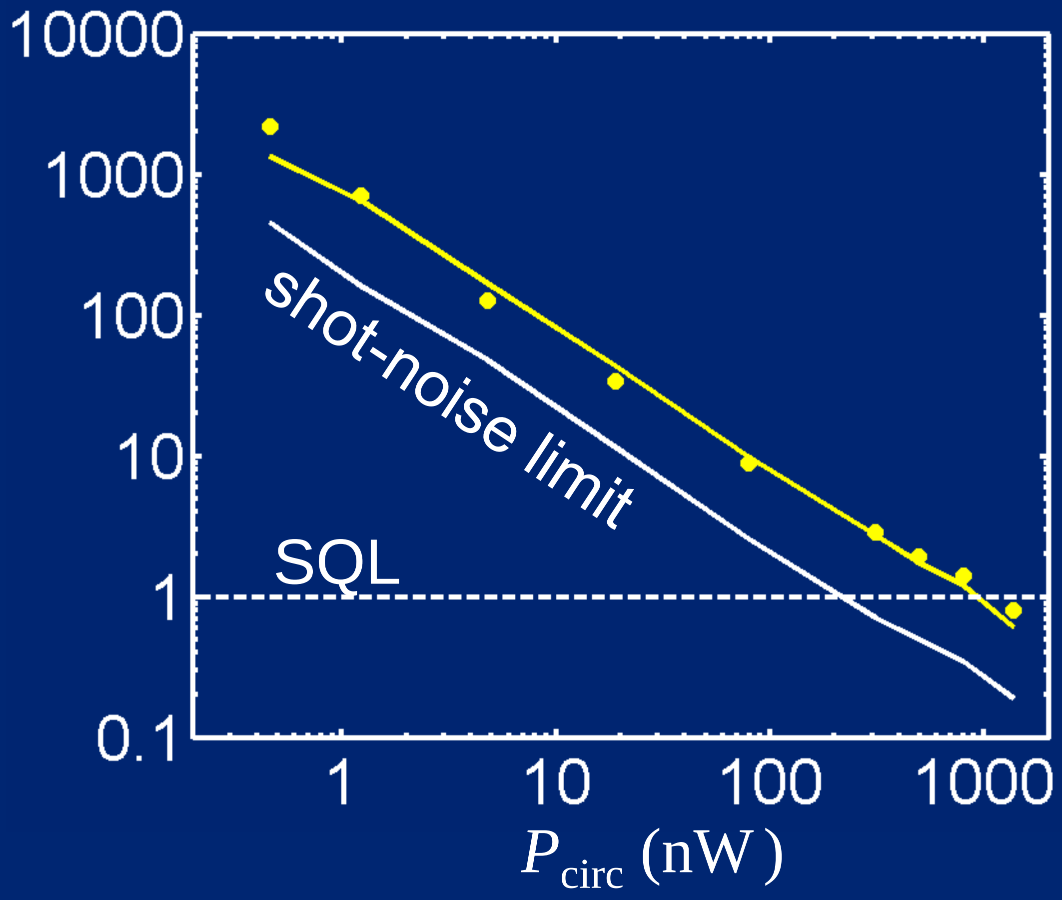
Imprecision noise is below the standard quantum limit with the JPA



$$S_x / S_x^{\mathrm{sql}} = 0.83$$

$$\sqrt{S_x^{\mathrm{sql}}} = 5.7\ \mathrm{fm}/\sqrt{\mathrm{Hz}}$$

All sources of loss and added noise yield an interferometer with 30% quantum efficiency



$$S_x^{\text{imp}} = \gamma_c^2 \frac{(N_A + \frac{1}{2})\hbar\omega_e}{g^2 P_{\text{circ}}}$$

Shot-noise limit

$N_A = 0$

This interferometer

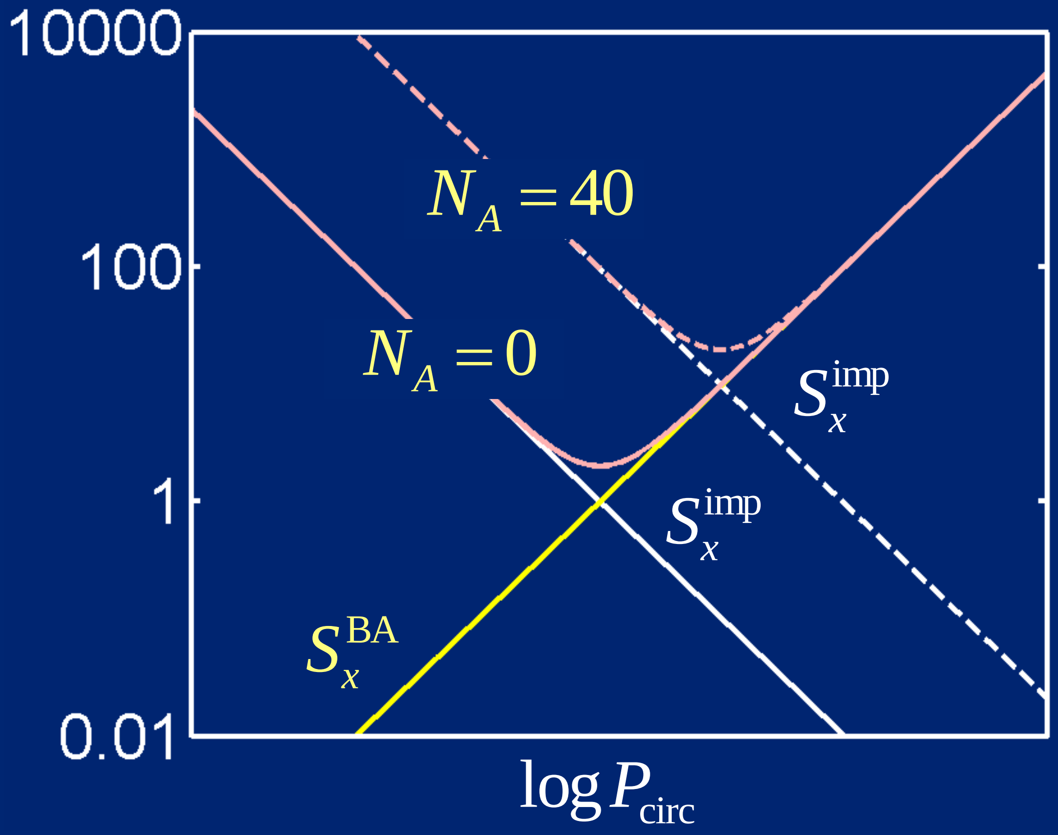
$N_A = 1.3 \quad \eta = 0.3$

Can we measure zero-point motion?

YES!

J. D. Teufel, T. Donner, M. A. Castellanos-Beltran,
J. Harlow, KWL, Nature Nanotech., **4**, 820-823 (2009).

The SQL is a compromise between imprecision and backaction



$$S_x^{\mathrm{imp}} = \gamma_c^2 \frac{(N_A + \frac{1}{2})\hbar\omega_e}{g^2 P_{\mathrm{circ}}}$$

$$P_{\mathrm{circ}}^{\mathrm{sql}} = \gamma_c^2 \frac{(N_A + \frac{1}{2})\hbar\omega_e}{g^2 S_x^{\mathrm{sql}}}$$

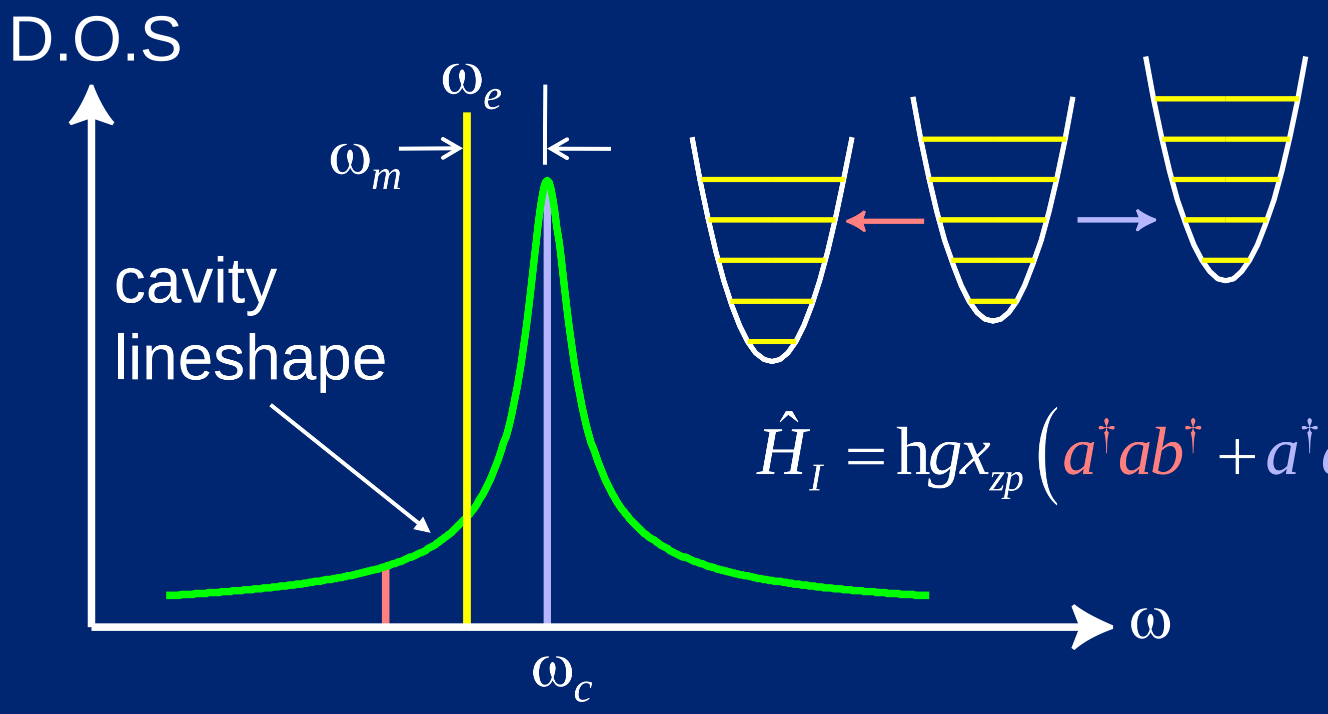
P_{circ} is constrained

- -dumb heating
- -superconductivity

Imprecision at the SQL $S_x^{\mathrm{sql}} = \dfrac{\hbar}{m\omega_m\gamma_m}$

Radiation pressure cooling

Radiation pressure can cool the beam to ground state in the resolved sideband limit



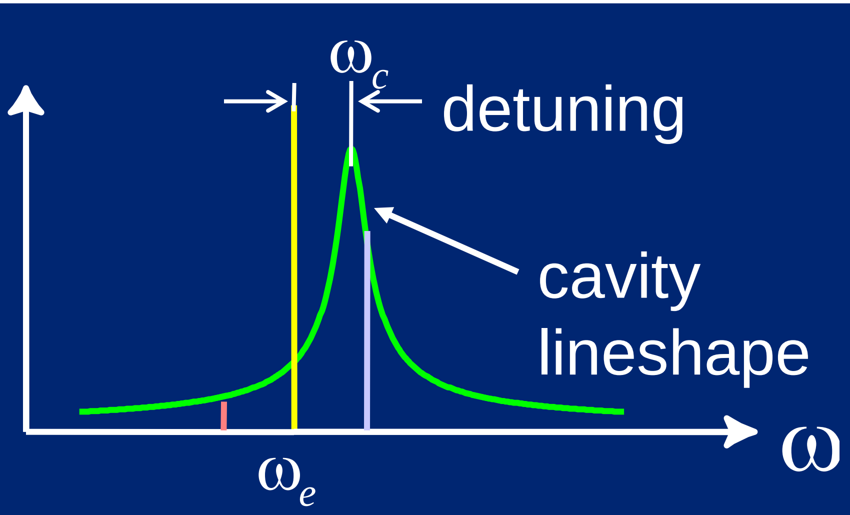
$$\hat{H}_I = \hbar g x_{zp}\left(a^\dagger a b^\dagger + a^\dagger a b\right)$$

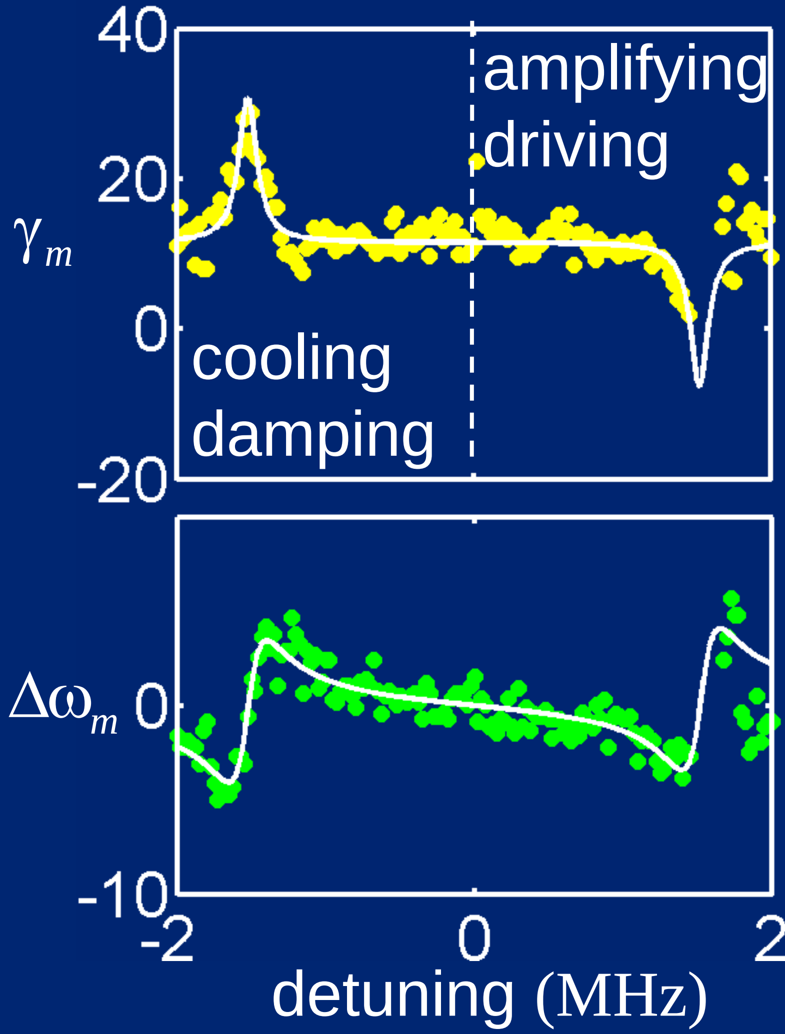
$$\Gamma \approx \frac{g^2 x_{zp}^2}{4\hbar\omega_c^2\gamma_c} P_{\mathrm{circ}}$$

Requirements for sideband cooling to the ground state

- ✓ resolved sideband limit $\omega_m > \gamma_e$
- ✓ high frequency, high quality beams $Q_m > \frac{k_B T_{\mathrm{bath}}}{\hbar\omega_m} = \langle n_{\mathrm{bath}} \rangle$
- ✓ strong coupling $\Gamma > \langle n_{\mathrm{bath}} \rangle \gamma_m^0$

Radiation pressure changes the wire's damping rate and resonance frequency





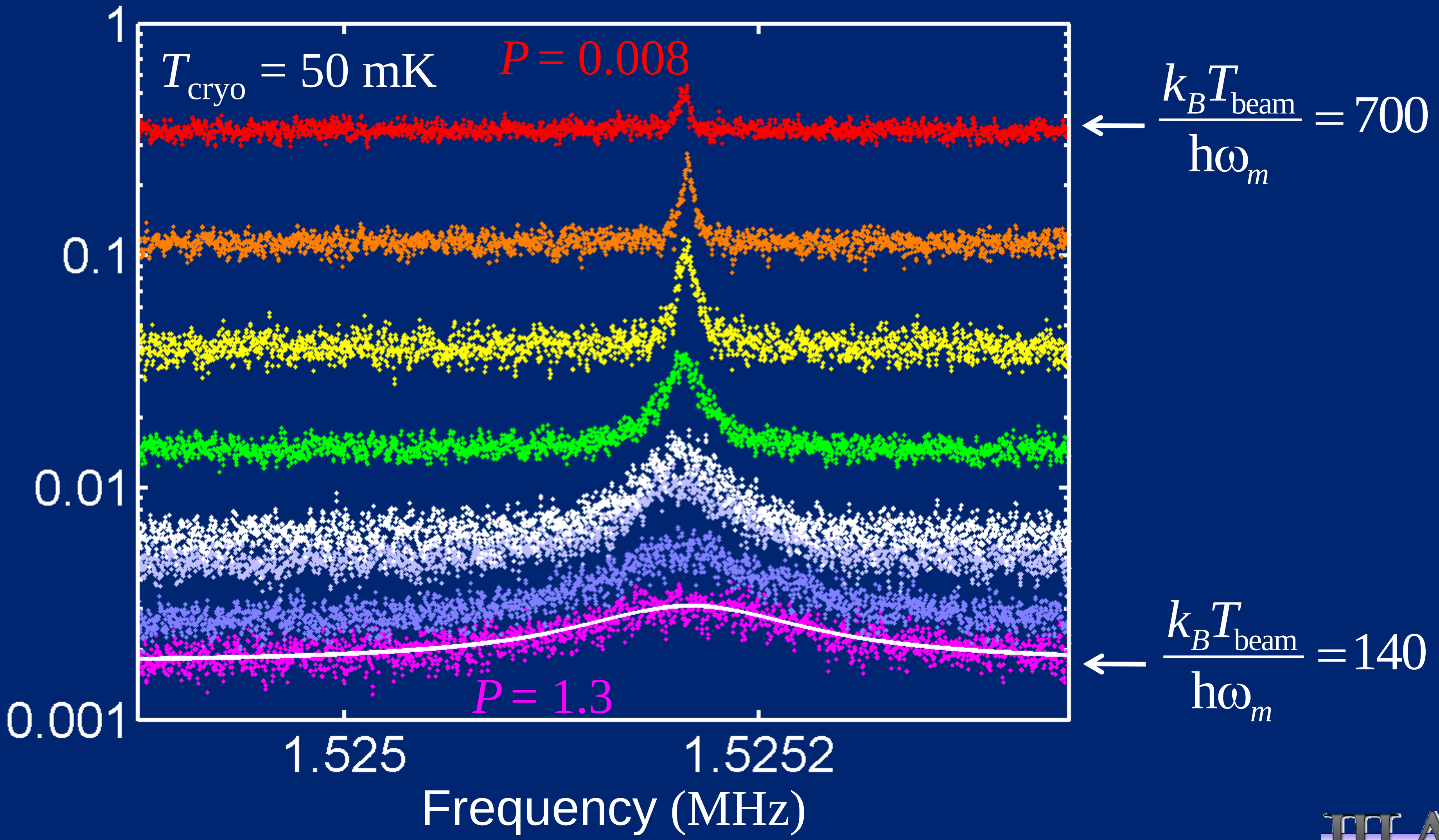
Mechanical response measures antisymmetric force noise

$$\Gamma = \frac{x_{zp}^2}{\hbar^2}[S_f(\omega_m) - S_f(-\omega_m)]$$

$$f = \hbar g a^\dagger a \qquad g = 6.4\ \frac{\text{kHz}}{\text{nm}}$$

F. Marquardt *et al*., PRL **99** 093902 (2007)

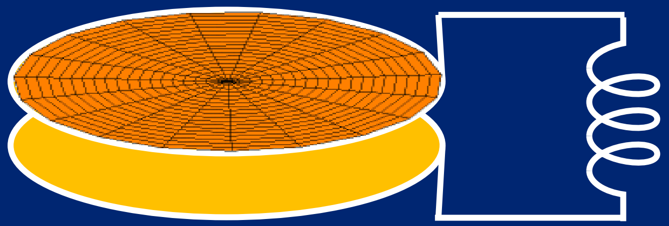
Coupling to radiation is too weak to cool wire to motional ground state

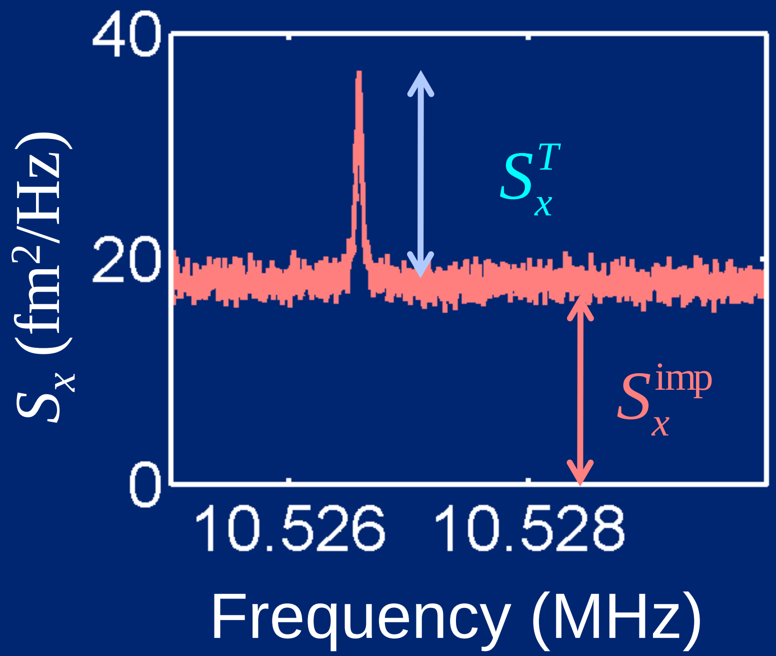


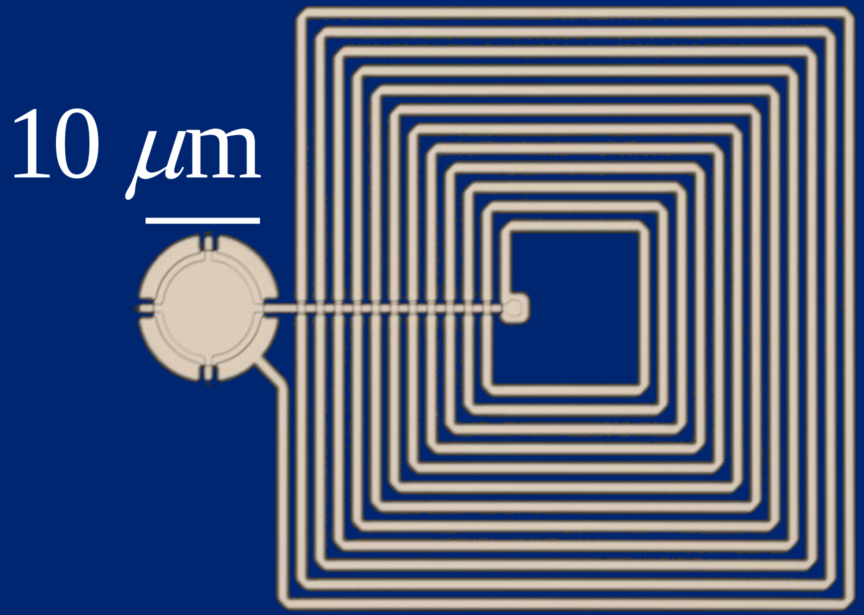
J. D. Teufel, J. W. Harlow, C. A. Regal, KWL *Phys. Rev. Lett*. **101**, 197203 (2008).

Cooling and measuring mechanical motion

capacitor built with suspended micromechanical membrane*







Electrical circuit resonant at 7 GHz

John Teufel and Ray Simmonds

K. Cicak, et al APL **96**, 093502 (2010)
J. D. Teufel et al arXiv:1011.3067

Conclusions

- Measure and manipulate nanomechanical elements with microwaves

- Optomechanical performance: in quantum regime!
  - cooling: 0.35 phonons
  - imprecision: 0.83 X SQL
  - force: $0.5\ \mathrm{aN/Hz}^{1/2}$

- Microwave Mach-Zehnder interferometer
  - quantum efficiency 30%

Graduate and post-doc positions available

Funding: NSF, NIST, DARPA, NASA

JILA NIST CU