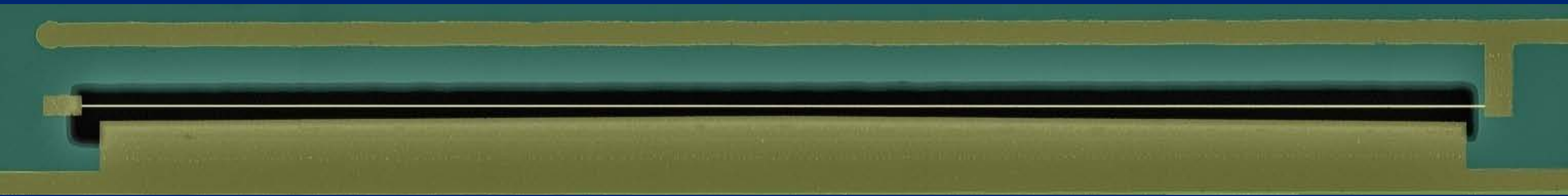
Sensing the quantum motion of nanomechanical oscillators



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Post-docs

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Kent Irwin

Graduate students

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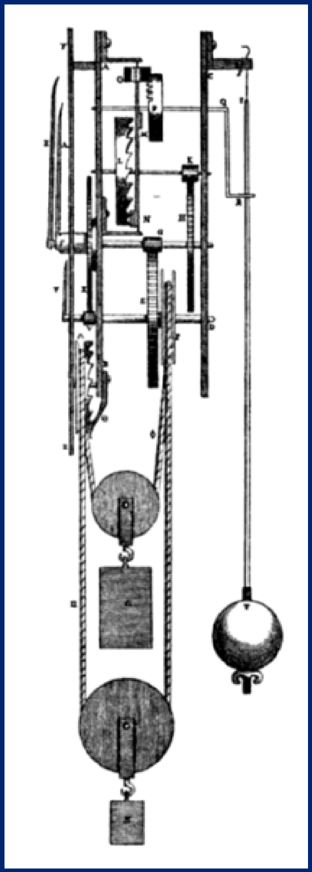
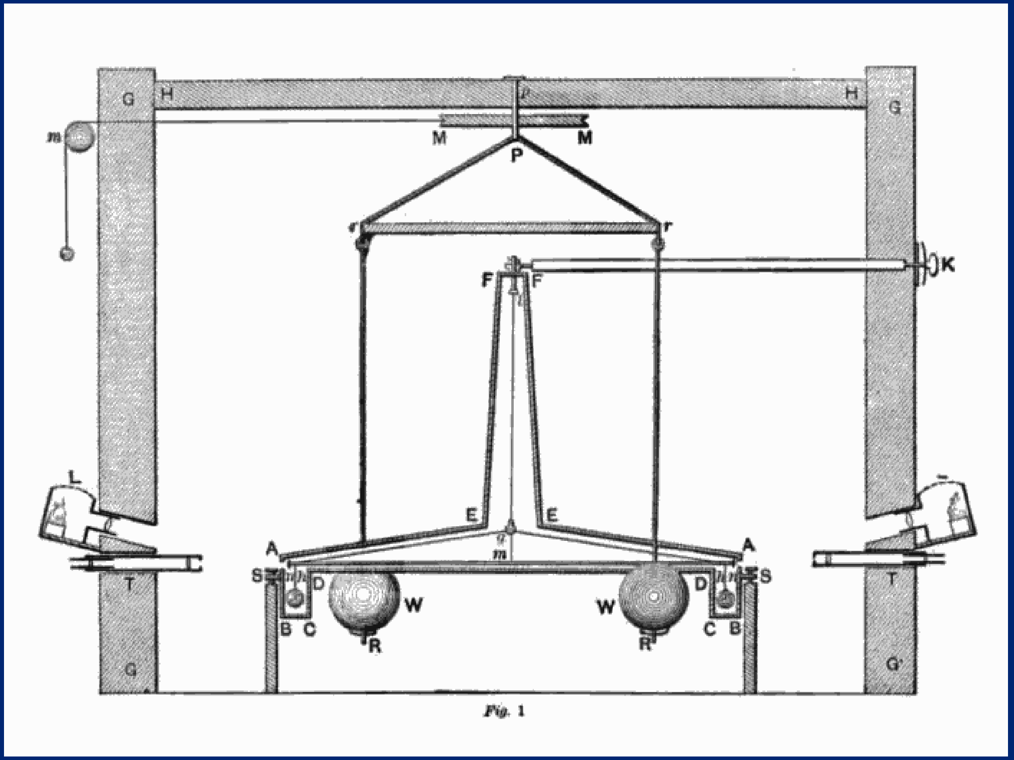
William Kindel

Adam Reed

Precision measurement tools were once mechanical oscillators



Huygens pendulum clock



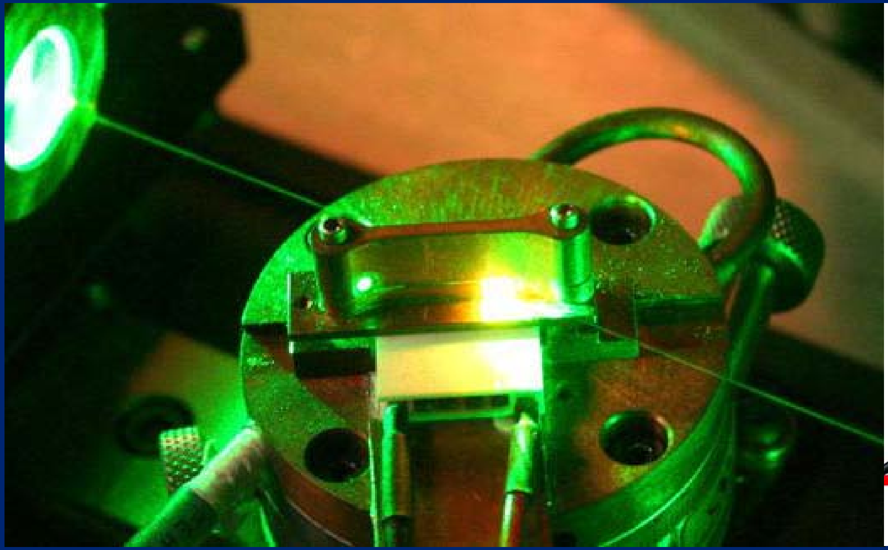
The Cavendish balance for weighing the earth

Modern measurement tools exploit optics and electronics, not mechanics

Laser light

electricity

Image: Cundiff lab JILA



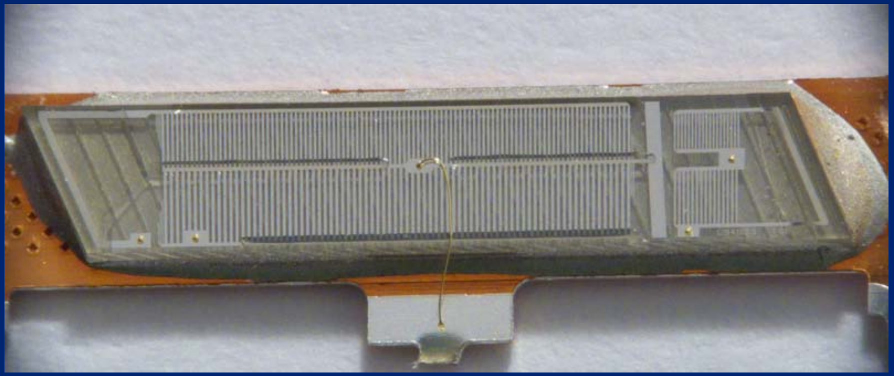
Optical and electrical measurement tools:

Large dynamic range

Compact, high-*Q* mechanical oscillators are ubiquitous in information technology

1 mm

Quartz crystal oscillator:
in everything electronic



Surface acoustic wave filters:
In radios, tuners, mobile phones

Applications:
Timing and filtering

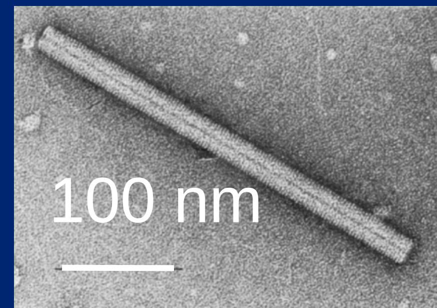
sound speed << light speed
Compact and high-*Q* oscillators

Q ~ 100,000

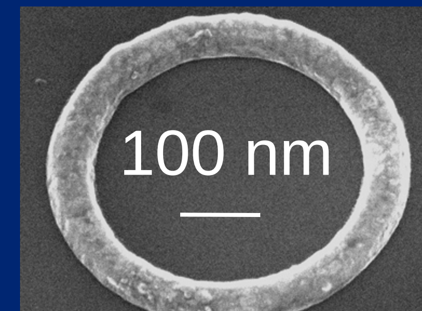
JILA NIST CU

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

system



nuclear spins in a virus



electrons in an aluminum ring
(Harris lab, Yale)

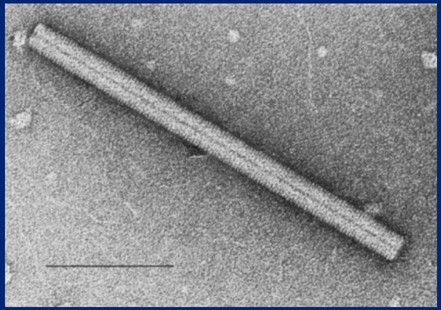
optical or electrical probe

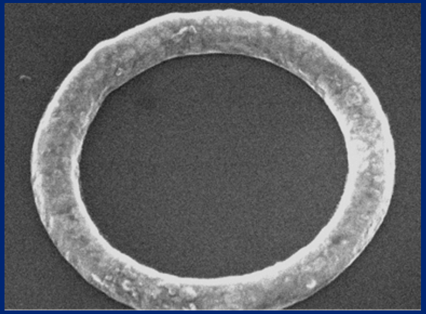
Systems with:

- dense low-energy spectra
- nanometer length scales
- weak coupling to light

Mechanical oscillators enable measurements of non-atomic systems

system





mechanical intermediary

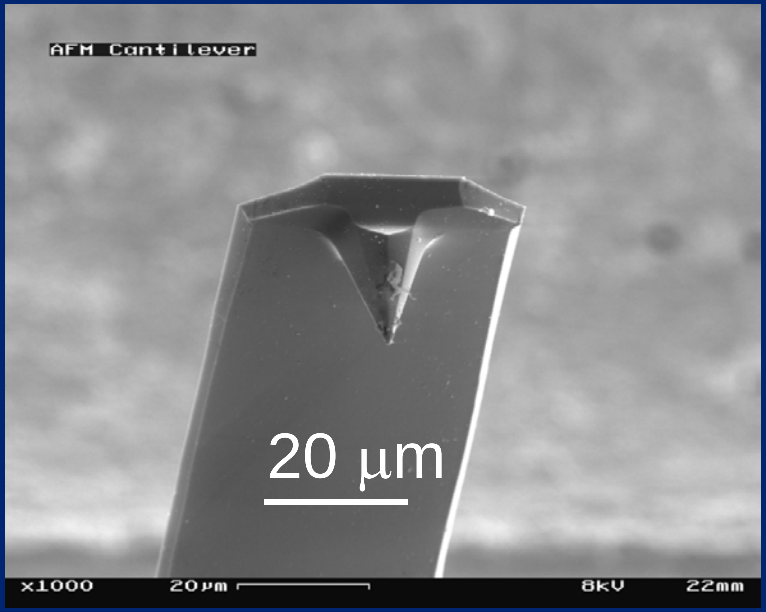
probe field

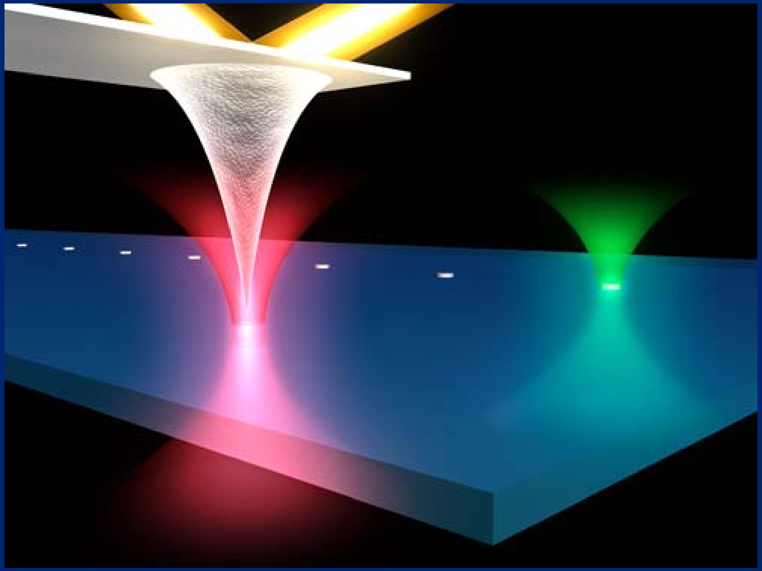
Systems with:

- dense low-energy spectra
- nanometer length scales
- weak coupling to light

Mechanical oscillators are tools that access the nano-world

Atomic Force Microscope





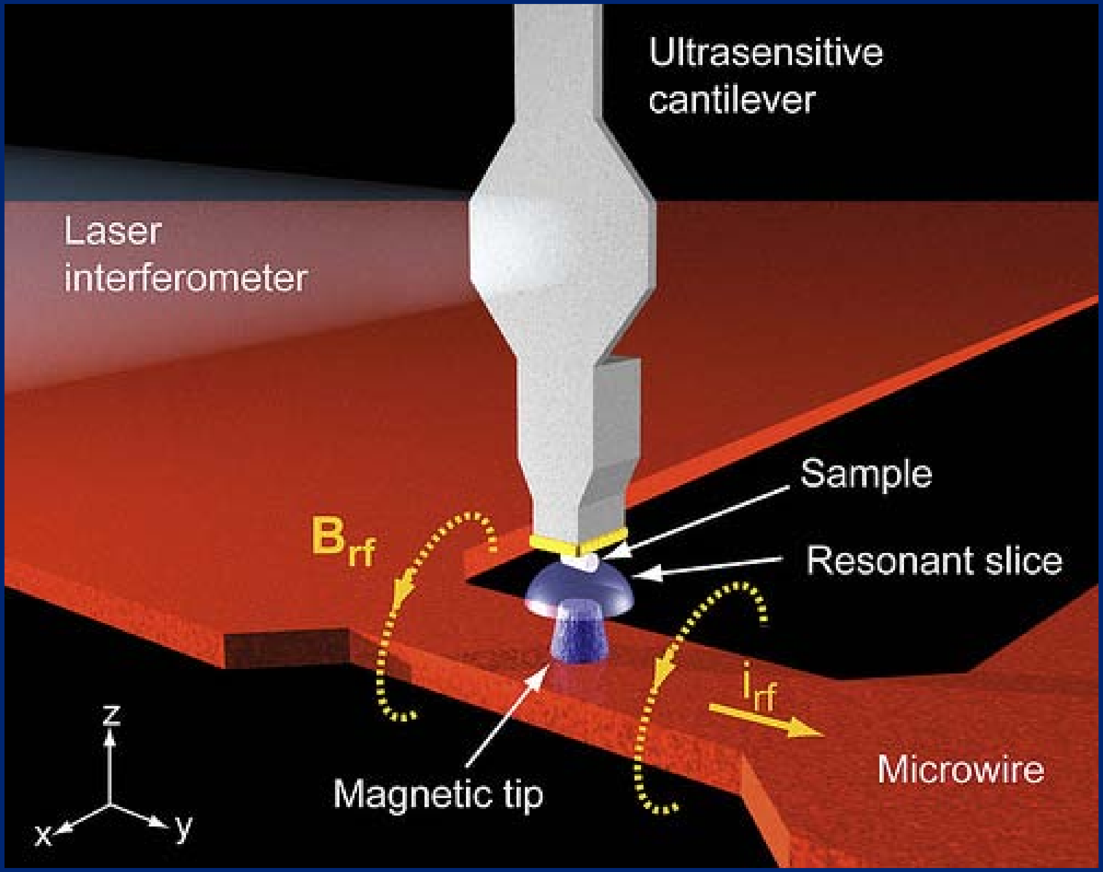
Perkins lab, JILA

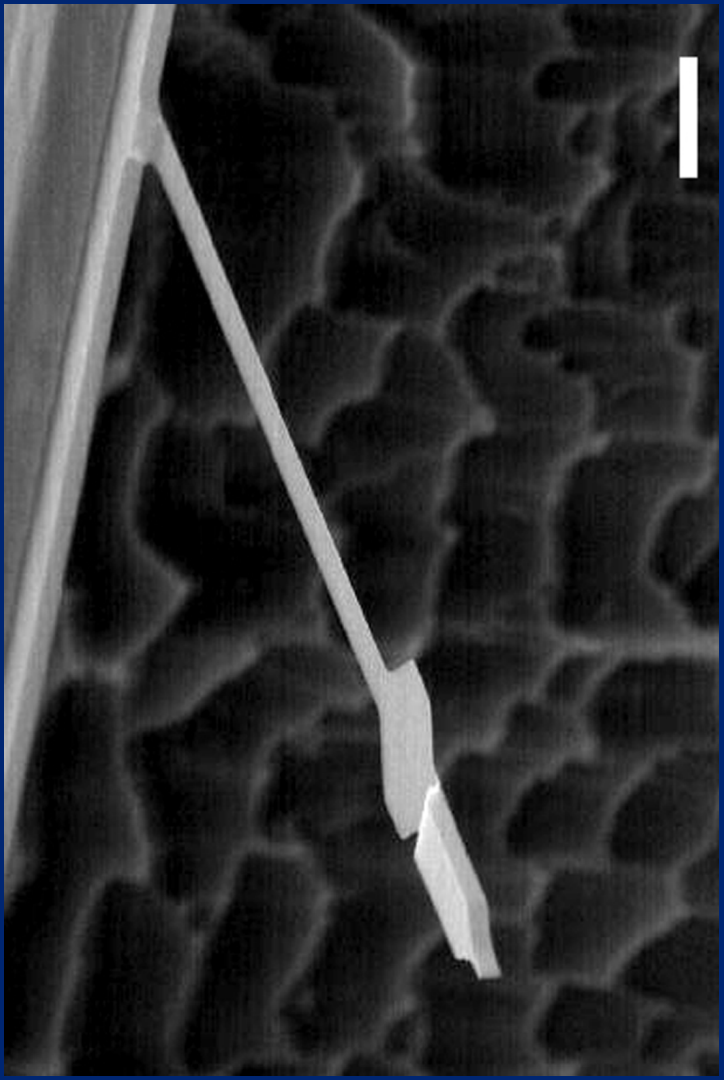
Mechanical oscillator

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

Mechanical oscillators as quantum coherent interfaces between incompatible systems

Mechanical oscillators are classical

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

<u>Quantum regime</u>

- state preparation
- state measurement
- state manipulation

quantum system

mechanical oscillator $\hbar\omega_m$

environment $k_B T_{\text{bath}}$

quantum probe

γ

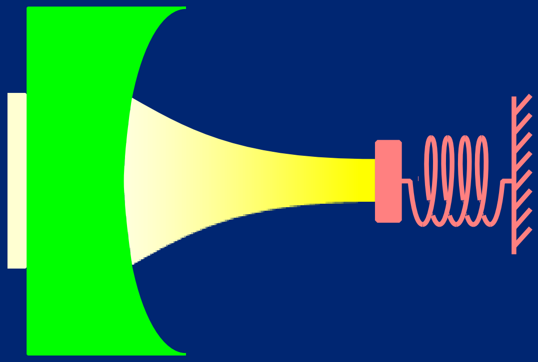
Γ

Cleland group UCSB

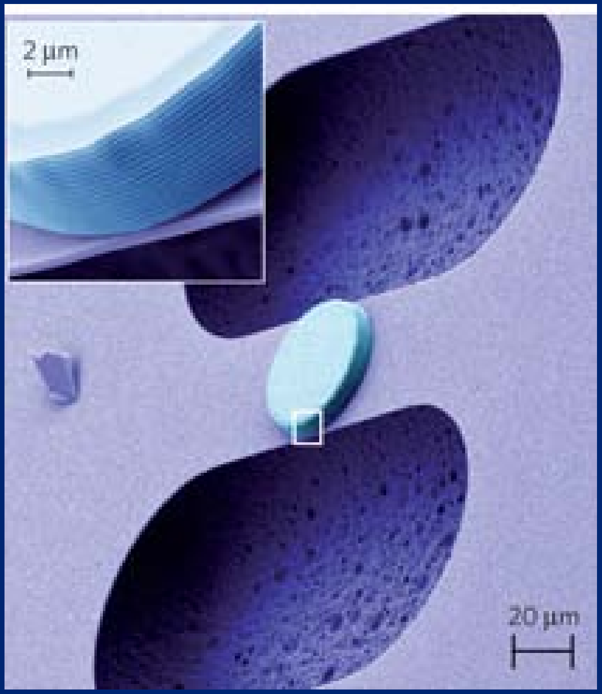
Nature **464**, 697-703 (1 April 2010)

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

Cavity optomechanics: Use radiation pressure for state preparation and measurement



Fabry-Perot cavity with oscillating mirror



Infer motion through optical phase

Cool with cavity-retarded radiation force

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

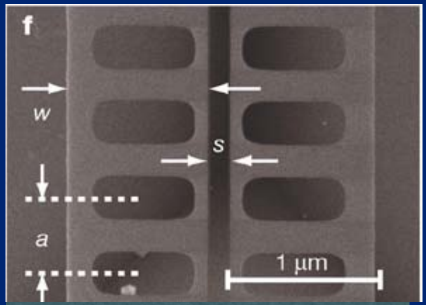
$$\hat{H}_I = \hat{F}\cdot\hat{x} = \hbar a^\dagger a g x_{zp}(b^\dagger + b)$$

$$g x_{zp} \equiv G \sim 2\pi \times 10 \text{ Hz}$$

Aspelmeyer lab, IOQOI, Vienna

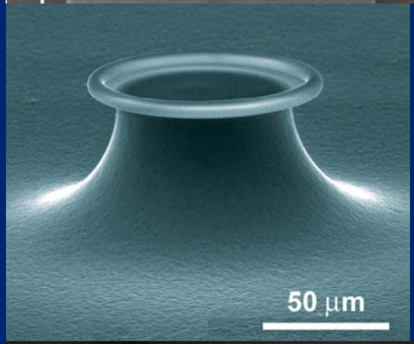
JILA NIST CU

Images of cavity optomechanical systems

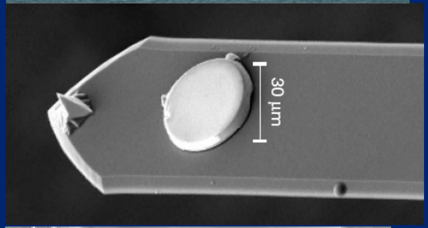


Caltech, Painter

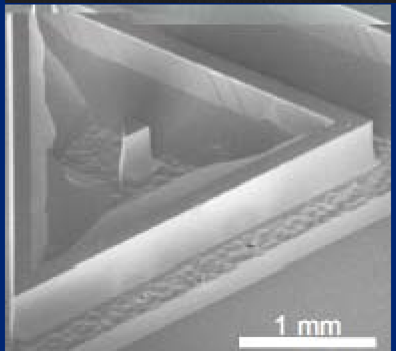
$$G \approx 2\pi \times 1 \text{ MHz}$$



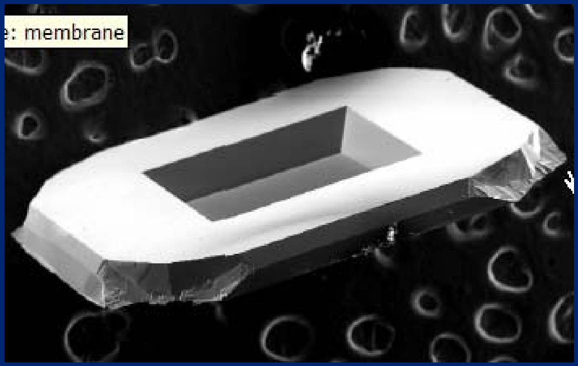
EPFL, Kippenberg



UCSB: Bouwmeester



ENS: Pinard and Heidmann



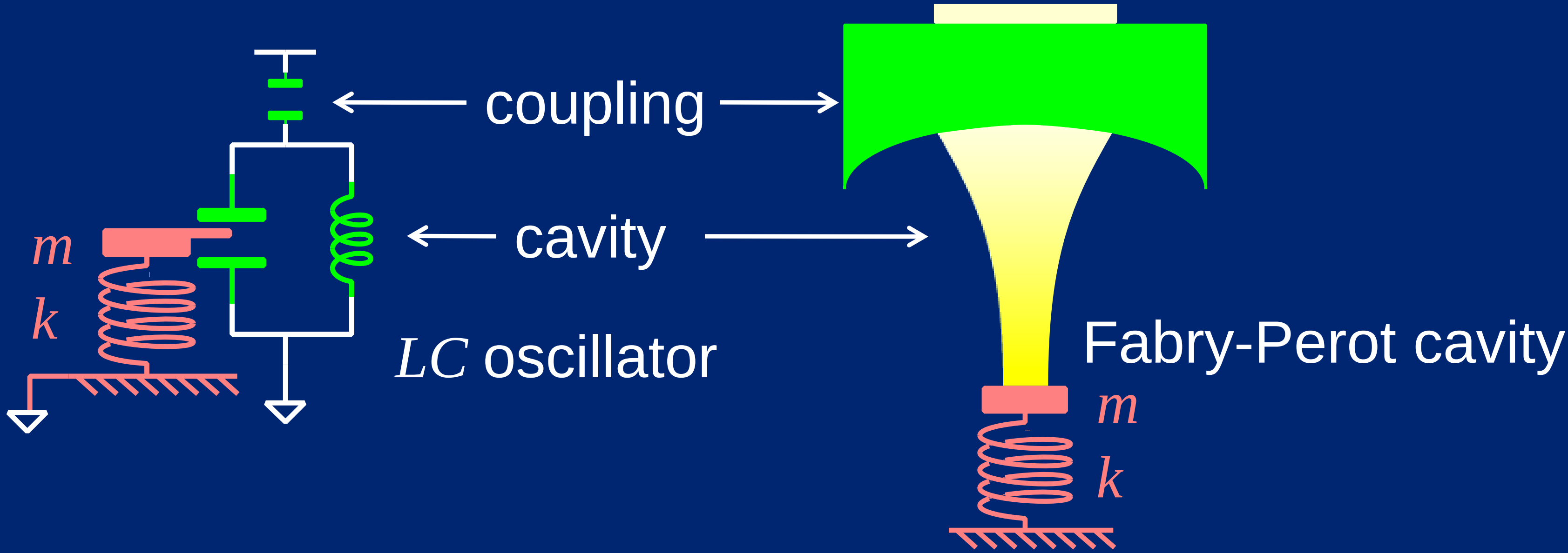
Yale, Harris

MIT, Mavalvala

Microwave cavity optomechanics

Reduce coupling to the environment by lowering temperature: microwave optomechanics

Microwave “light” in ultralow temperature cryostat



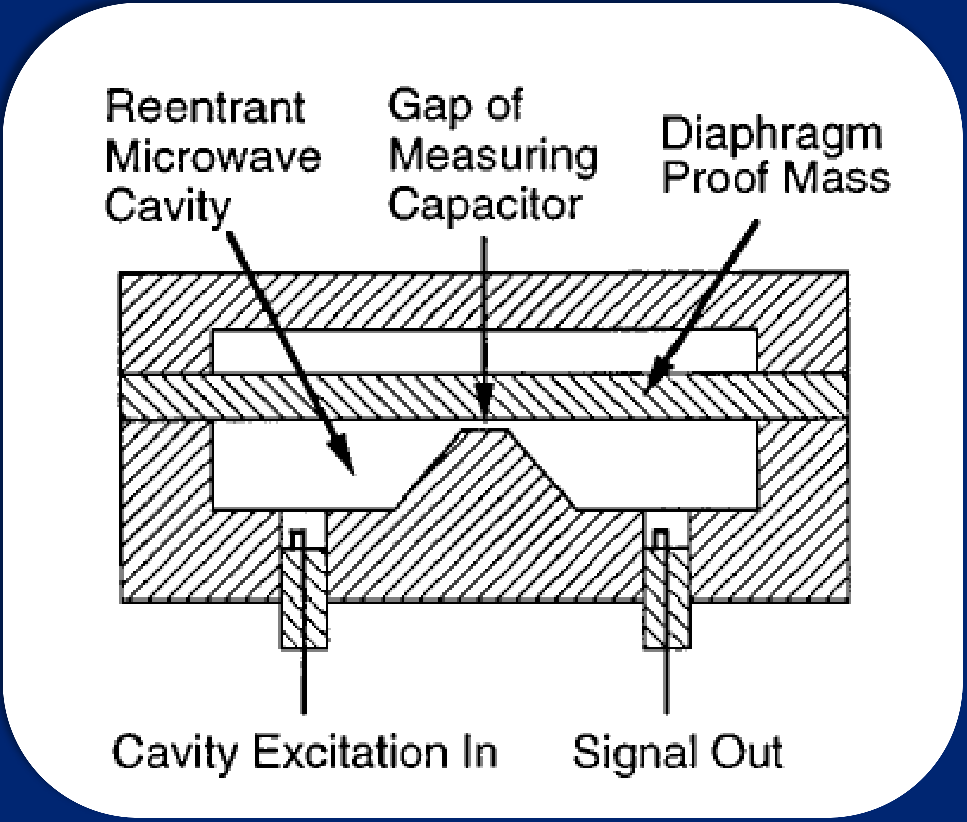
Strategy

Cool environment to $T_{\text{bath}} << 1\text{ K}$ $\quad \left(\frac{\gamma}{\Gamma}\right)\frac{k_B T_{\text{bath}}}{\hbar\omega_m} < 1$

High Q mechanical oscillators

JILA NIST CU

Superconducting electromechanics used in resonant mass gravitational wave detectors



Meter sized superconducting cavity with mechanically compliant element

Braginsky, V. B., V. P. Mitrofanov, and V. I. Panov, 1981, *Sistemi s maloi dissipatsei (Nauka, Moscow) [English translation: Systems with Small Dissipation (University of Chicago,* Chicago, 1985)].

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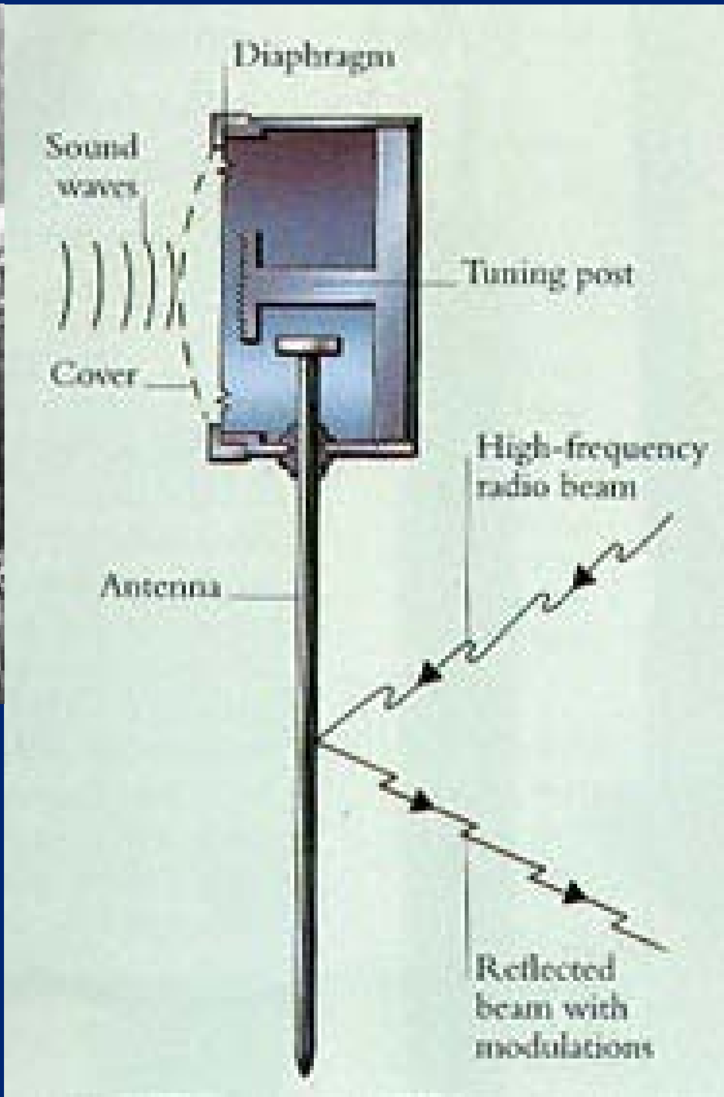
Resonant electromechanics used in surveillance

Soviet passive bug hidden in the United States Seal

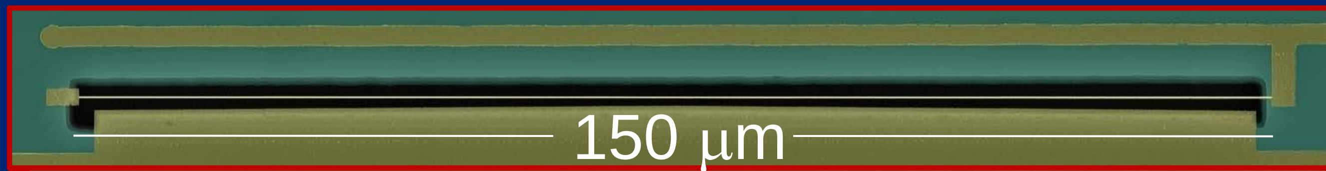
Henry Cabot Lodge, Jr. May 26, 1960 in the UN



Images appear in http://www.spybusters.com/Great_Seal_Bug.html

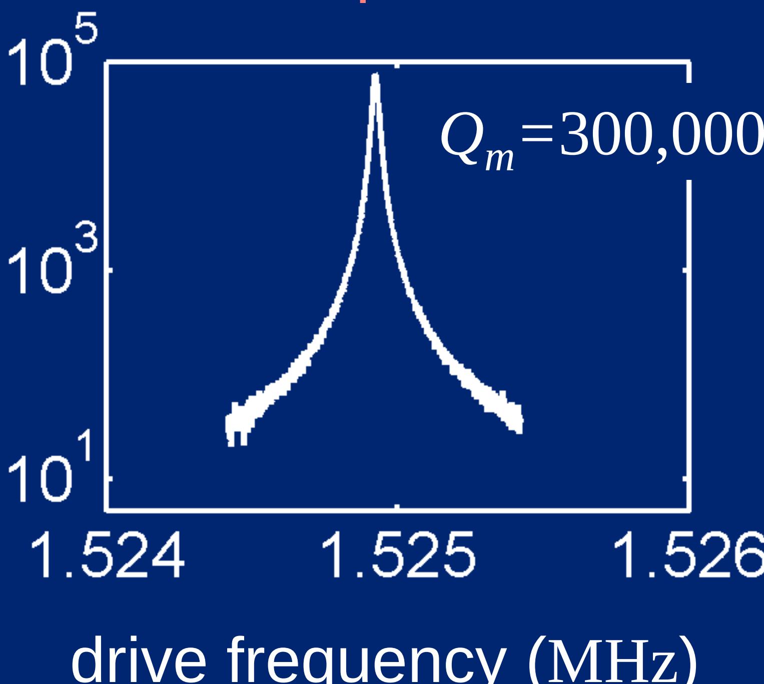
JILA NIST CU

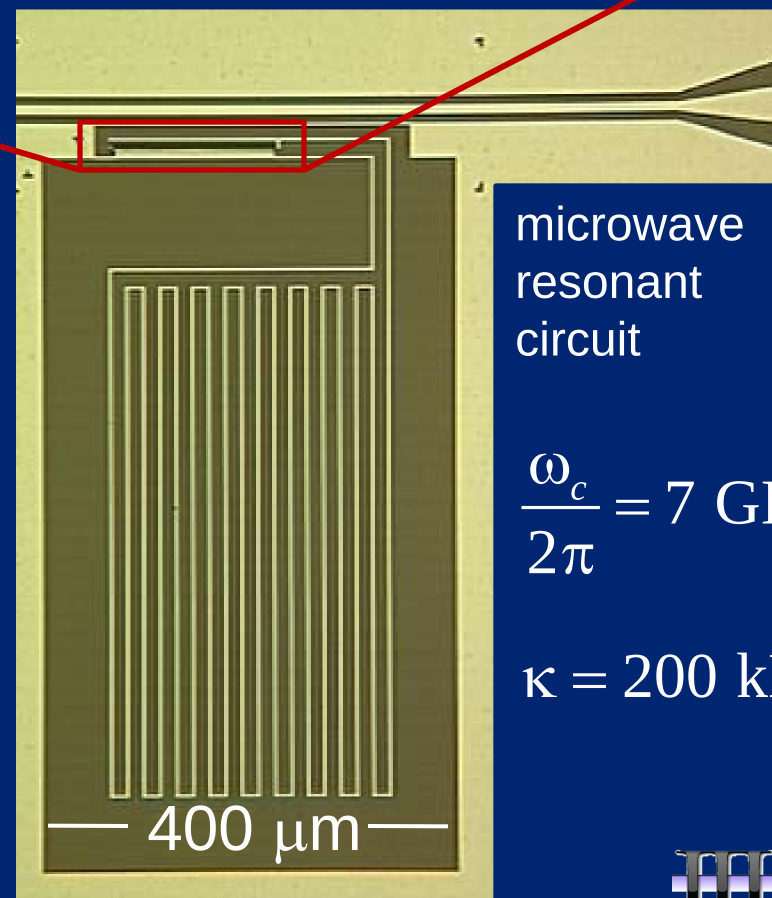
Cavity optomechanical system realized from a nanomechanical wire in a resonant circuit



$$G = 2\pi \times 0.3 \text{ Hz}$$

Wire response





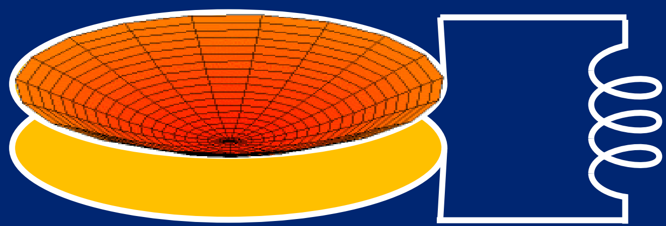
microwave resonant circuit

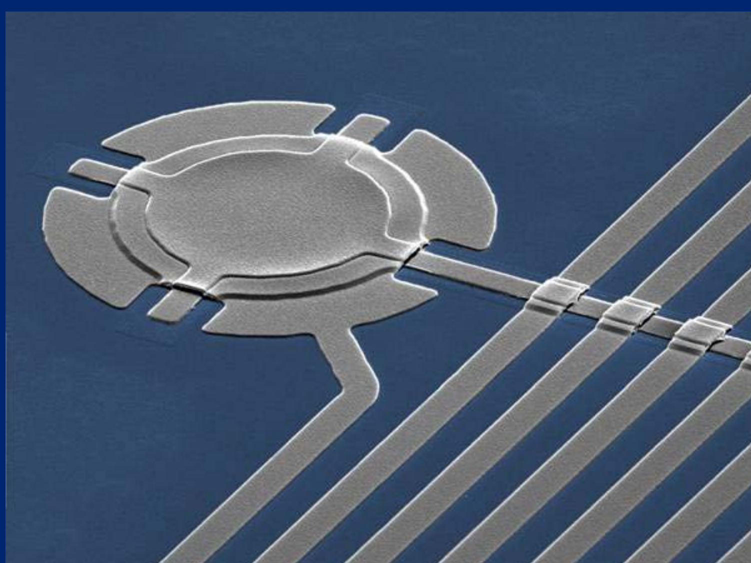
$$\frac{\omega_c}{2\pi} = 7 \text{ GHz}$$

$$\kappa = 200 \text{ kHz}$$

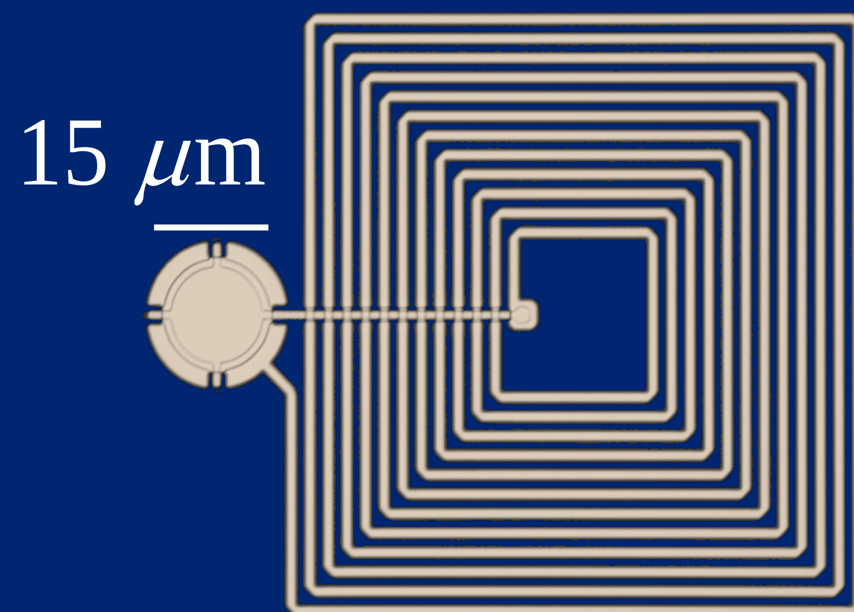
Parallel-plate capacitor geometry enhances microwave—mechanics interaction

capacitor built with suspended micromechanical membrane*





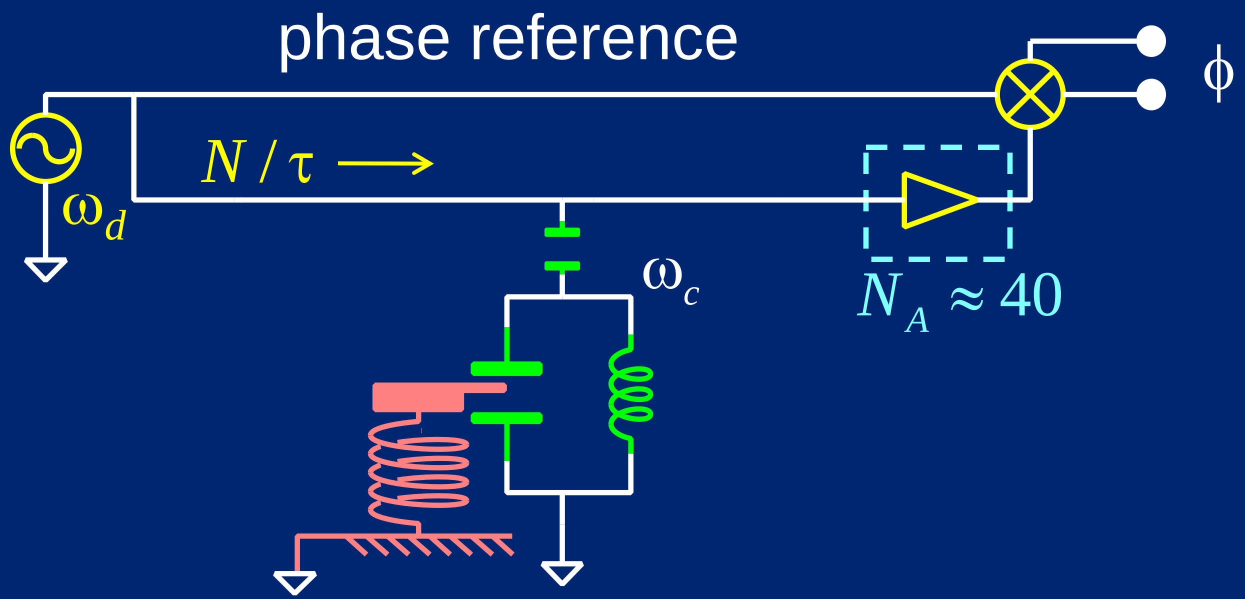
Electrical circuit resonant at 7 GHz

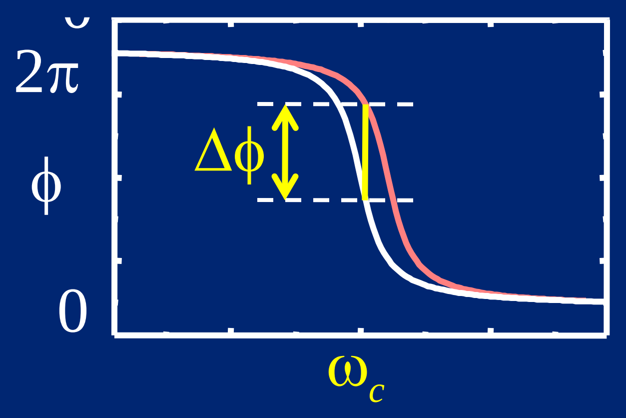


$$G \approx 2\pi \times 50 \text{ Hz}$$

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

Nanomechanical motion monitored with a microwave Mach-Zehnder interferometer





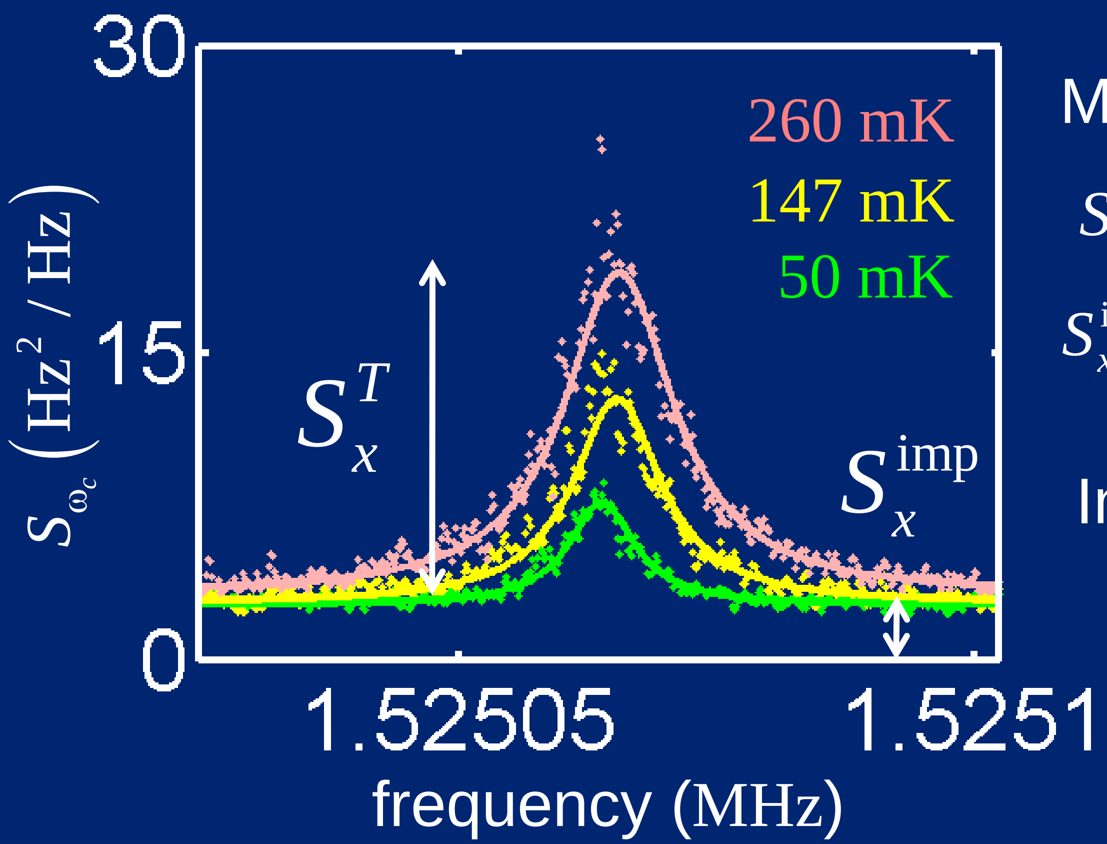
Infer wire motion from phase shift

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

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

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

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

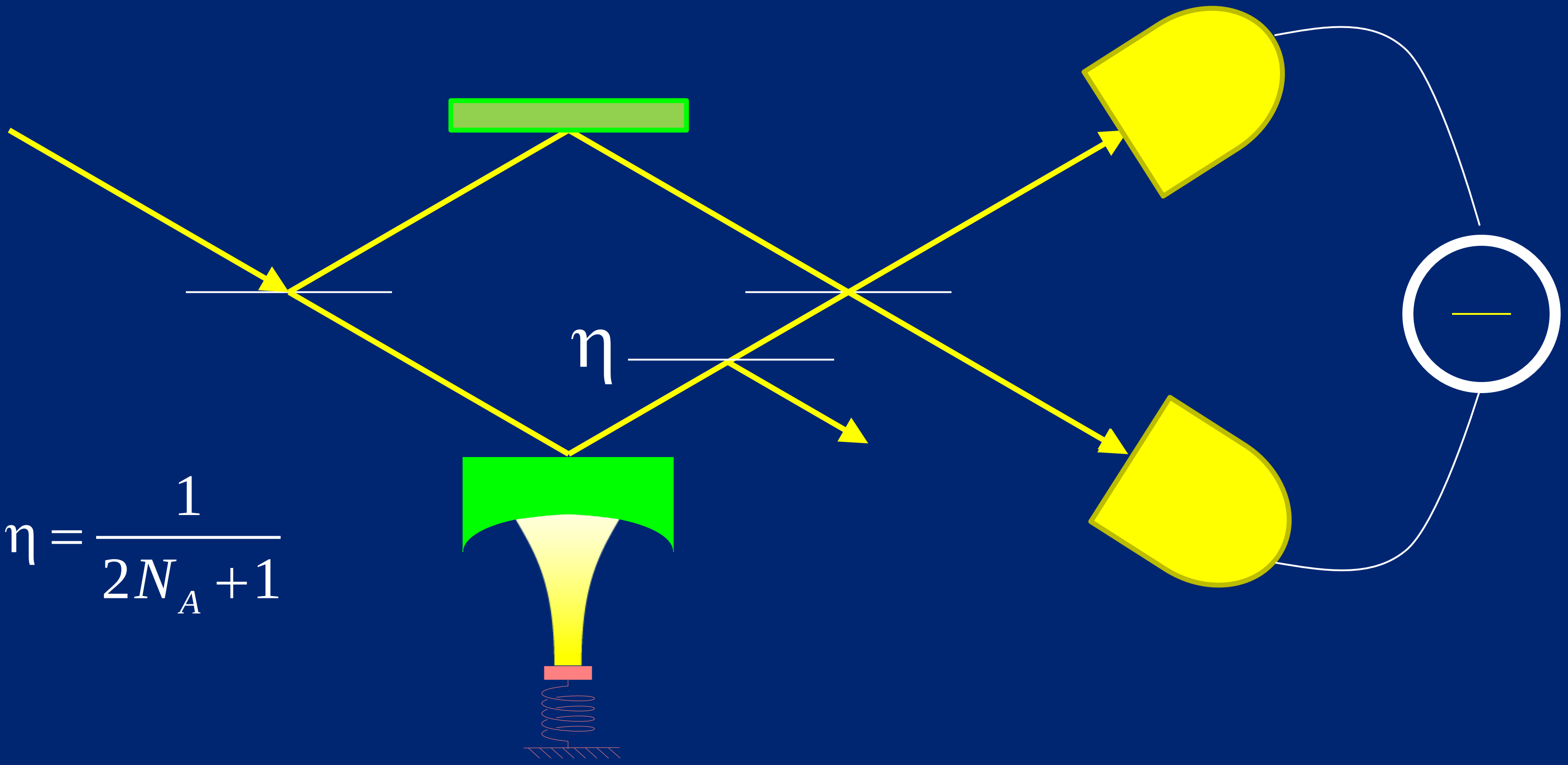
Imprecision at the SQL

$$S_x^{\mathrm{sql}} = \frac{\hbar}{m\omega_m\gamma}$$

Determine measurement imprecision S_x^{imp}

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

Amplifier added noise mimics quantum inefficiency



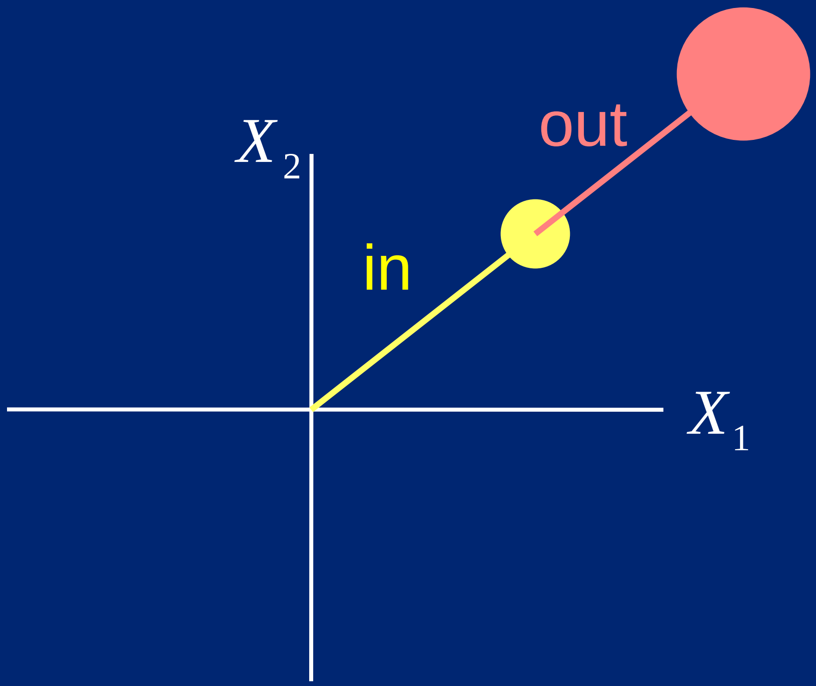
$$\eta = \frac{1}{2N_A + 1}$$

Excellent microwave amplifier:

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

Efficient quantum measurement

Linear amplifiers must add noise



$$V(t) = V_q\left(\hat{X}_1 \cos\omega t + \hat{X}_2 \sin\omega t\right)$$

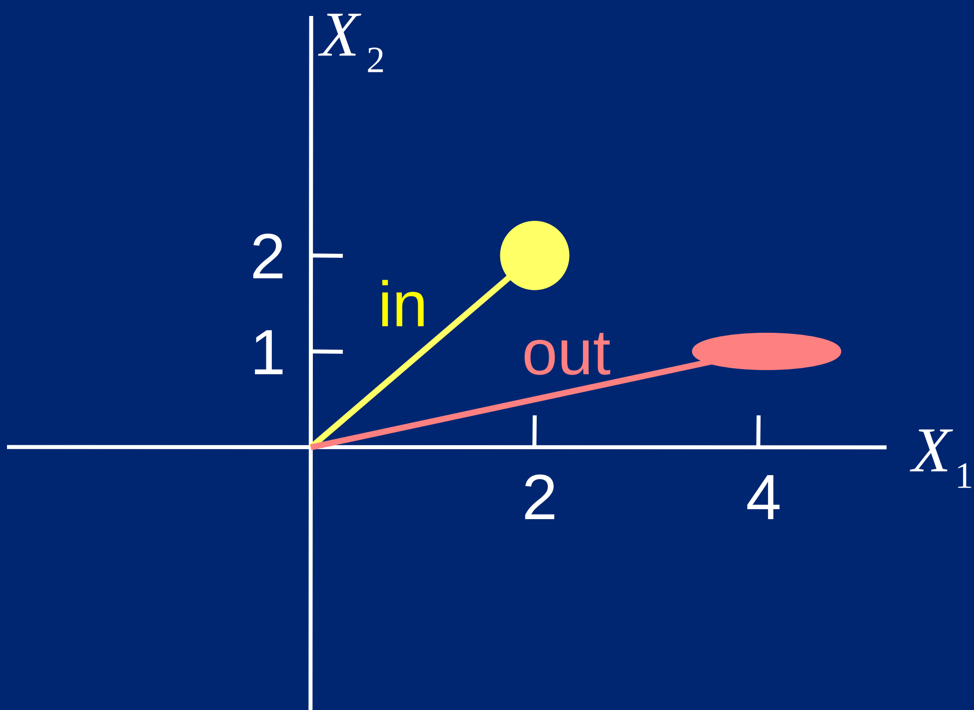
$$V^{out} = G(V^{in} + N_A)$$

Phase-preserving linear amplifiers at least double quantum noise

$$N_A \geq \frac{1}{2}$$

A single quadrature amplifier preserves entropy with photon number gain

$$V(t) = V_q\left(\hat{X}_1 \cos\omega t + \hat{X}_2 \sin\omega t\right)$$



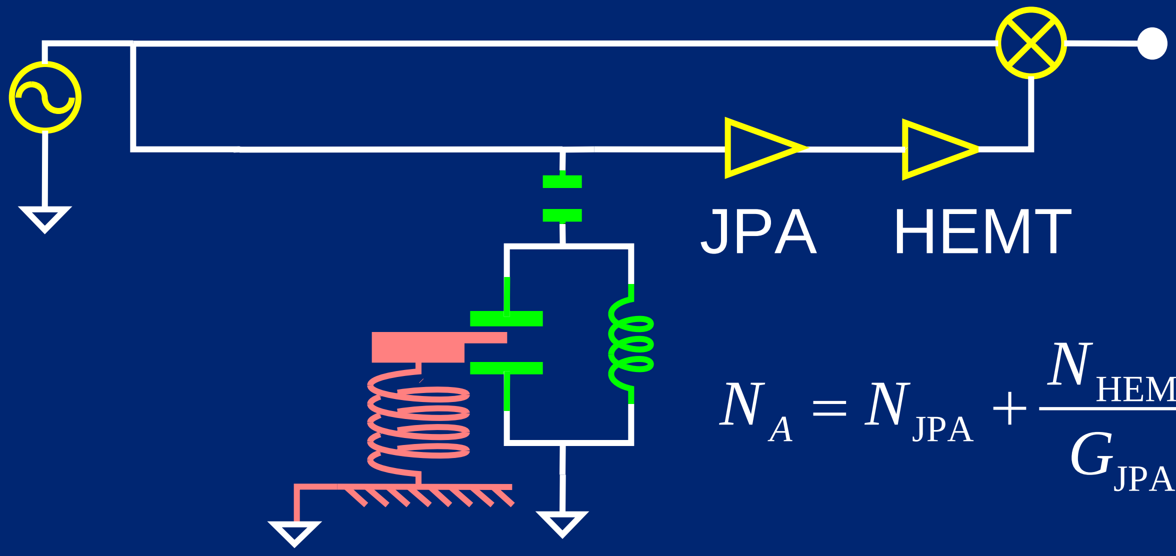
$$\hat{X}_1^{out} = G\hat{X}_1^{in}$$

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

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

$$N_A \geq 0$$

Incorporate quantum pre-amplifier into the Mach-Zehnder interferometer

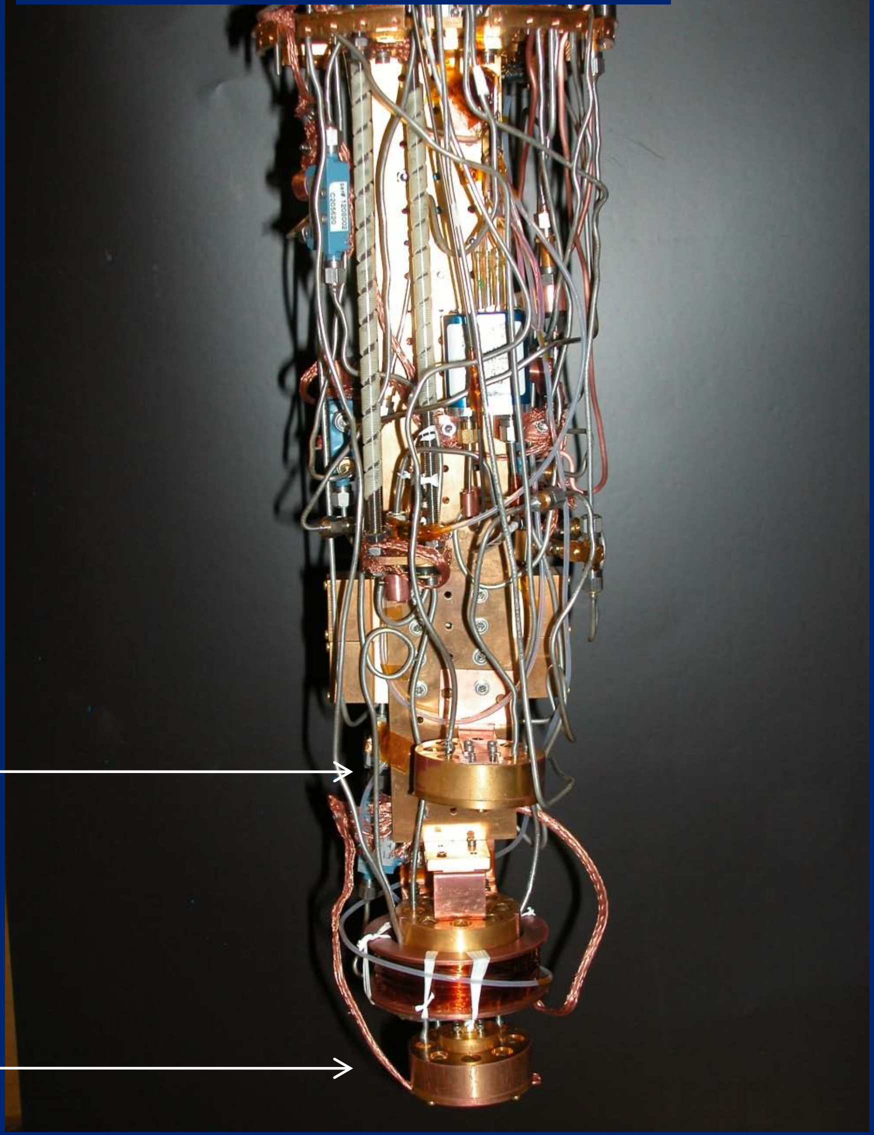


$$N_A = N_{\text{JPA}} + \frac{N_{\text{HEMT}}}{G_{\text{JPA}}}$$

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

Diagram conceals some complexity

Dilution refrigerator

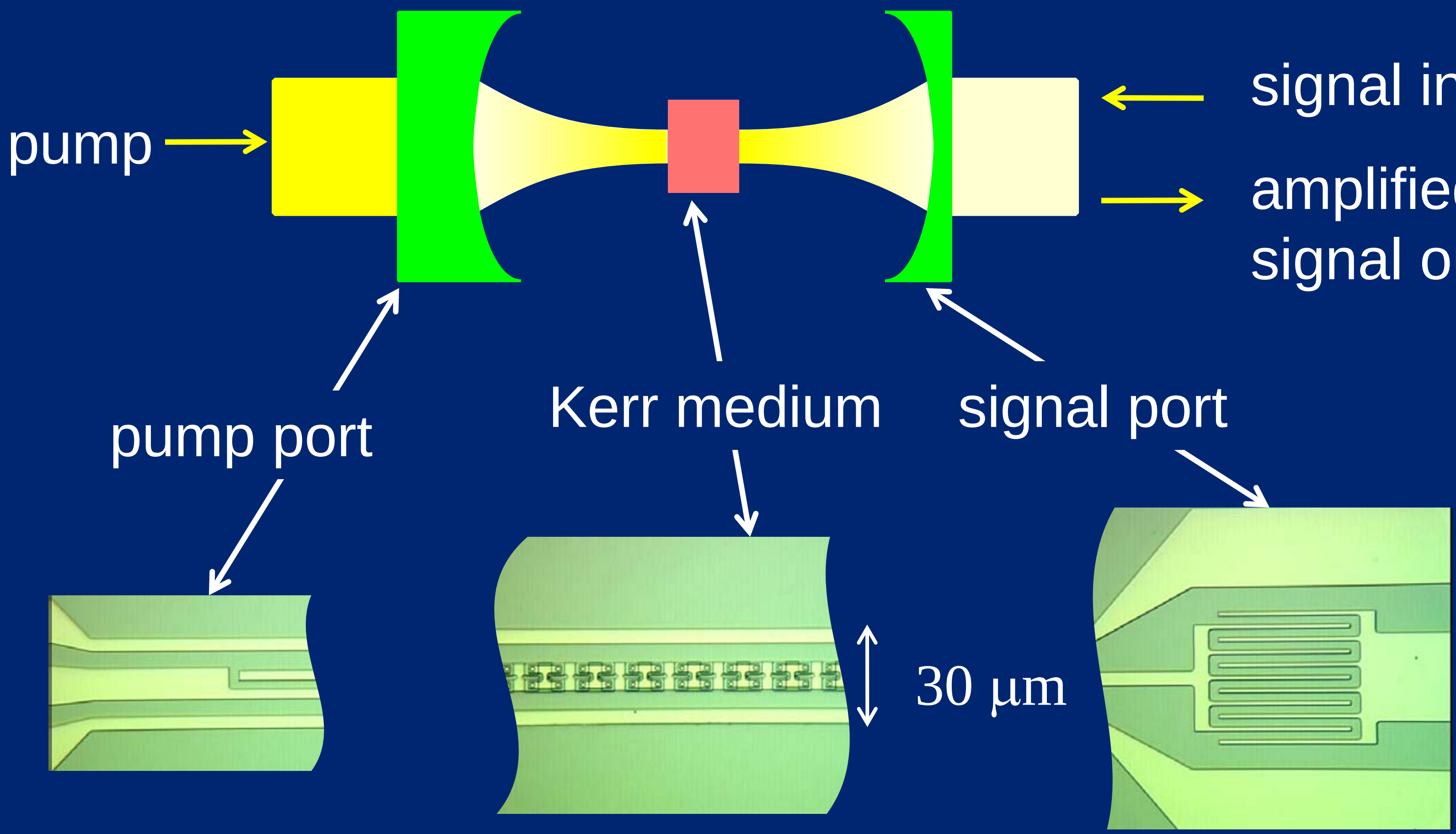


mechanics

JPA

50 cm

Realization of Josephson parametric amplifier

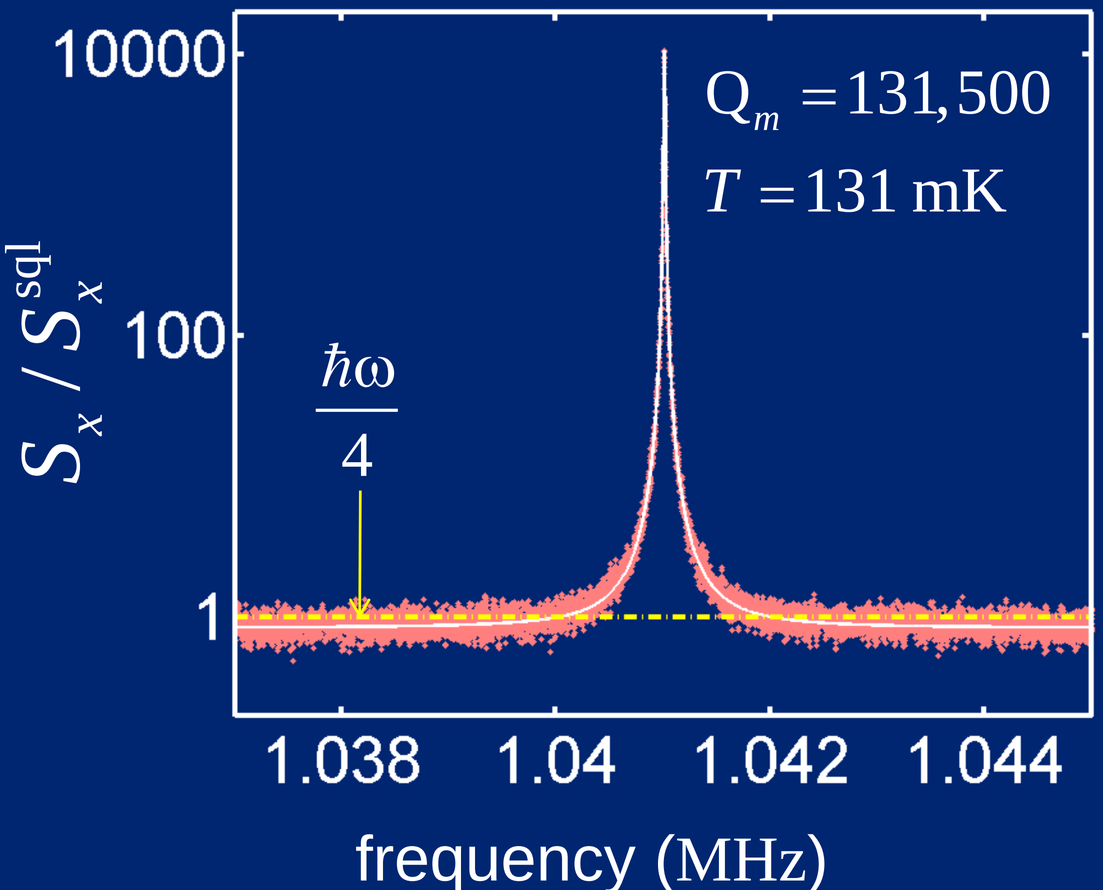


$N_{\mathrm{JPA}} < 0.1$

array of 480 SQUIDs embedded in a CPW resonator

M. A. Castellanos-Beltran, K. D Irwin, KWL, *et al,* Nature Phys. (2008)

Imprecision noise is below the standard quantum limit with the JPA

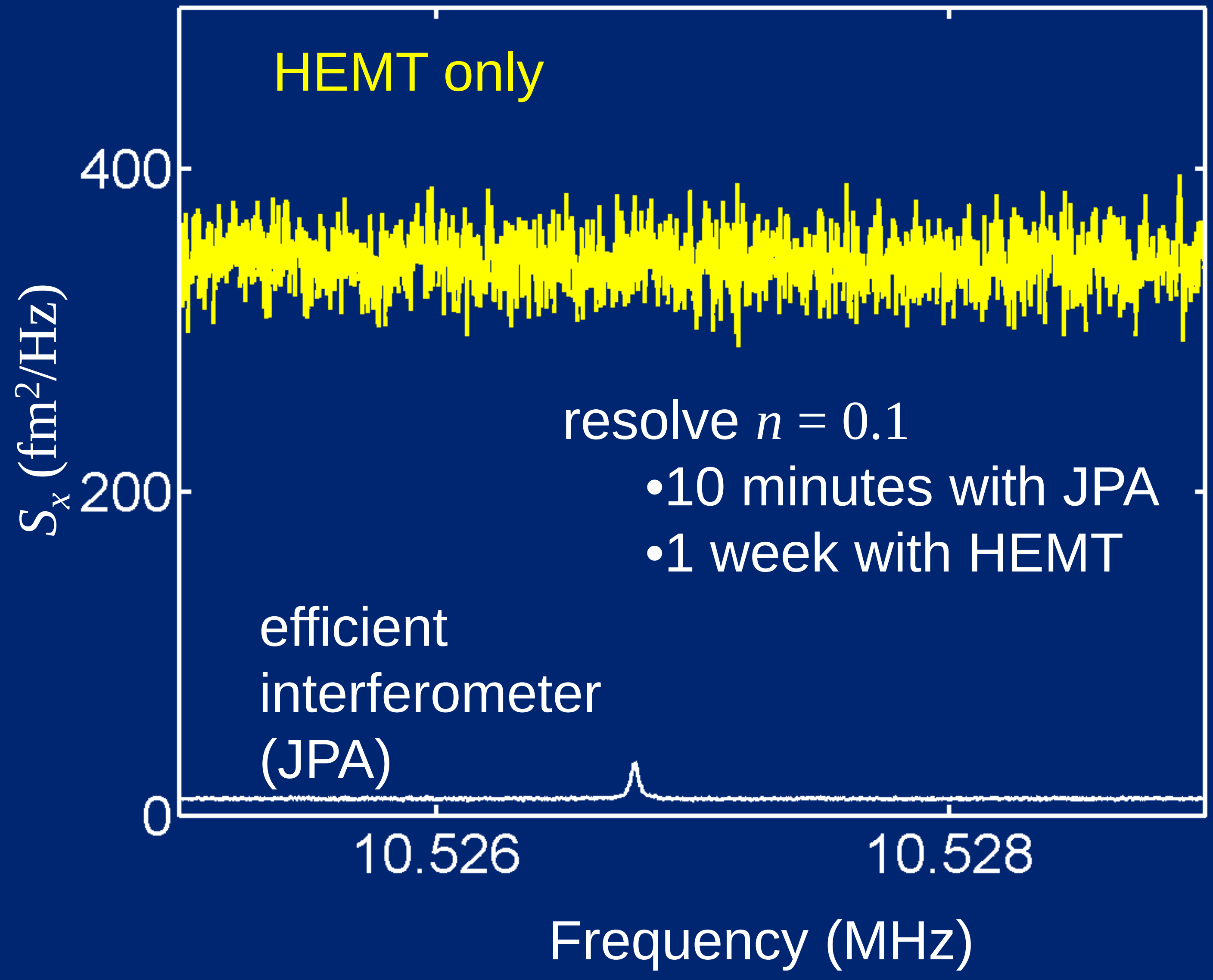


$$S_x / S_x^{sql} = 0.83$$

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

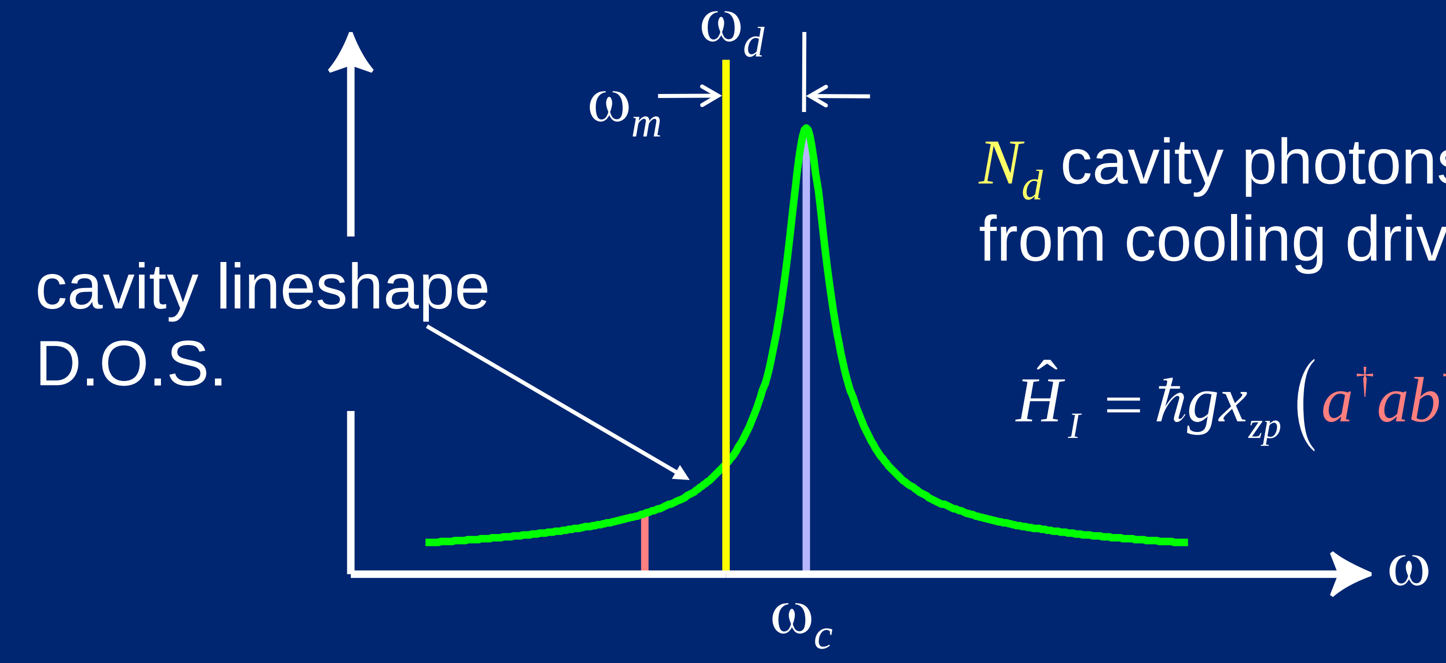
J. D. Teufel, T. Donner, M. A. Castellanos-Beltran,
J. Harlow, KWL, Nature Nanotech., **4**, 820-823 (2009).

Detecting near ground state motion requires a quantum efficient interferometer



Radiation pressure cooling

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



N_d cavity photons from cooling drive

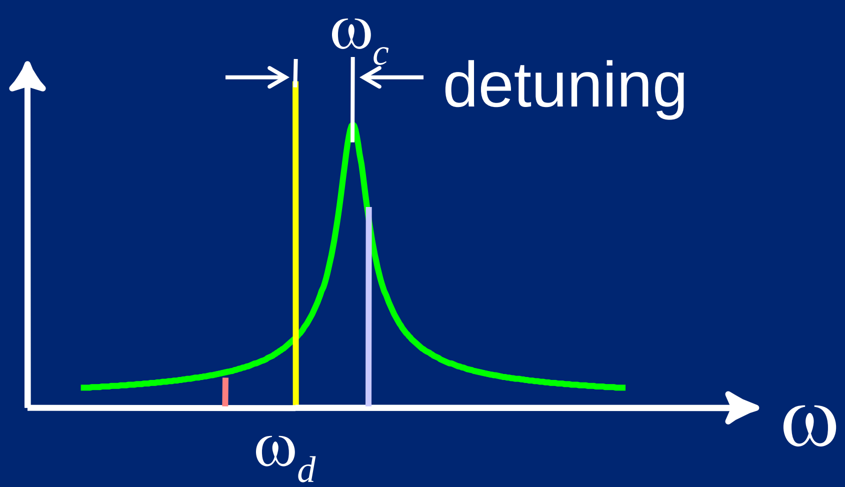
$$\hat{H}_I = \hbar g x_{zp}\left(a^\dagger a b^\dagger + a^\dagger a b\right)$$

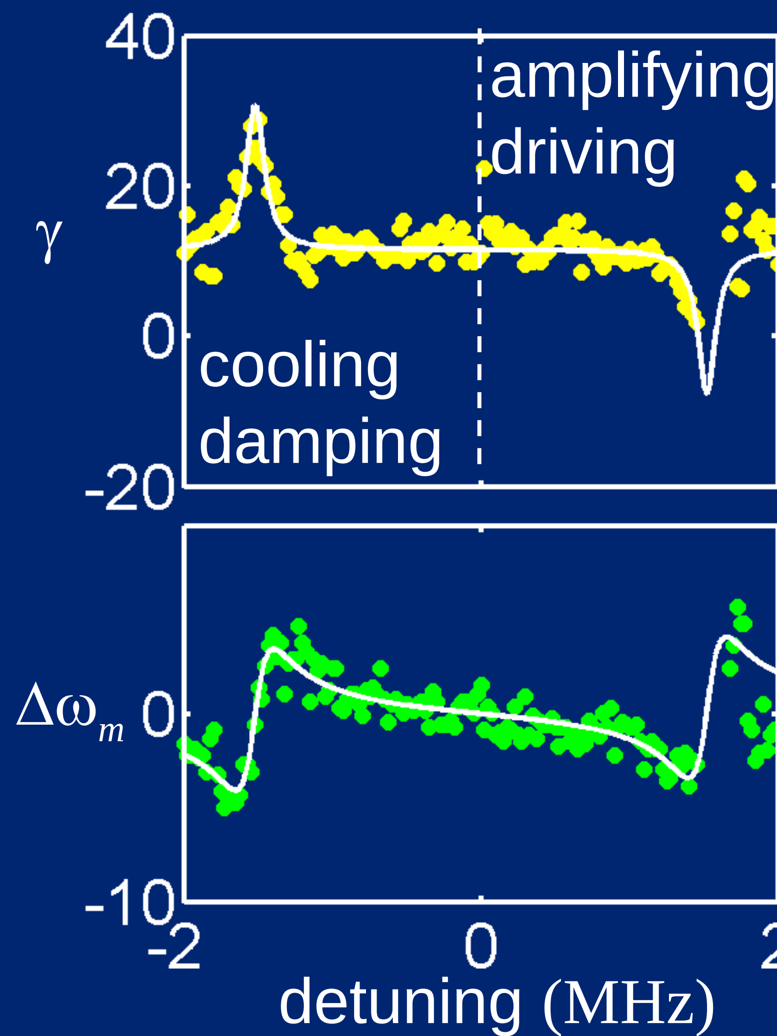
linearized interaction around strong cooling drive

$$\hat{H}_I = \hbar G\sqrt{N_d}\left(a b^\dagger + a^\dagger b\right)$$

$$\Gamma = \frac{4 N_d G^2}{\kappa}$$

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





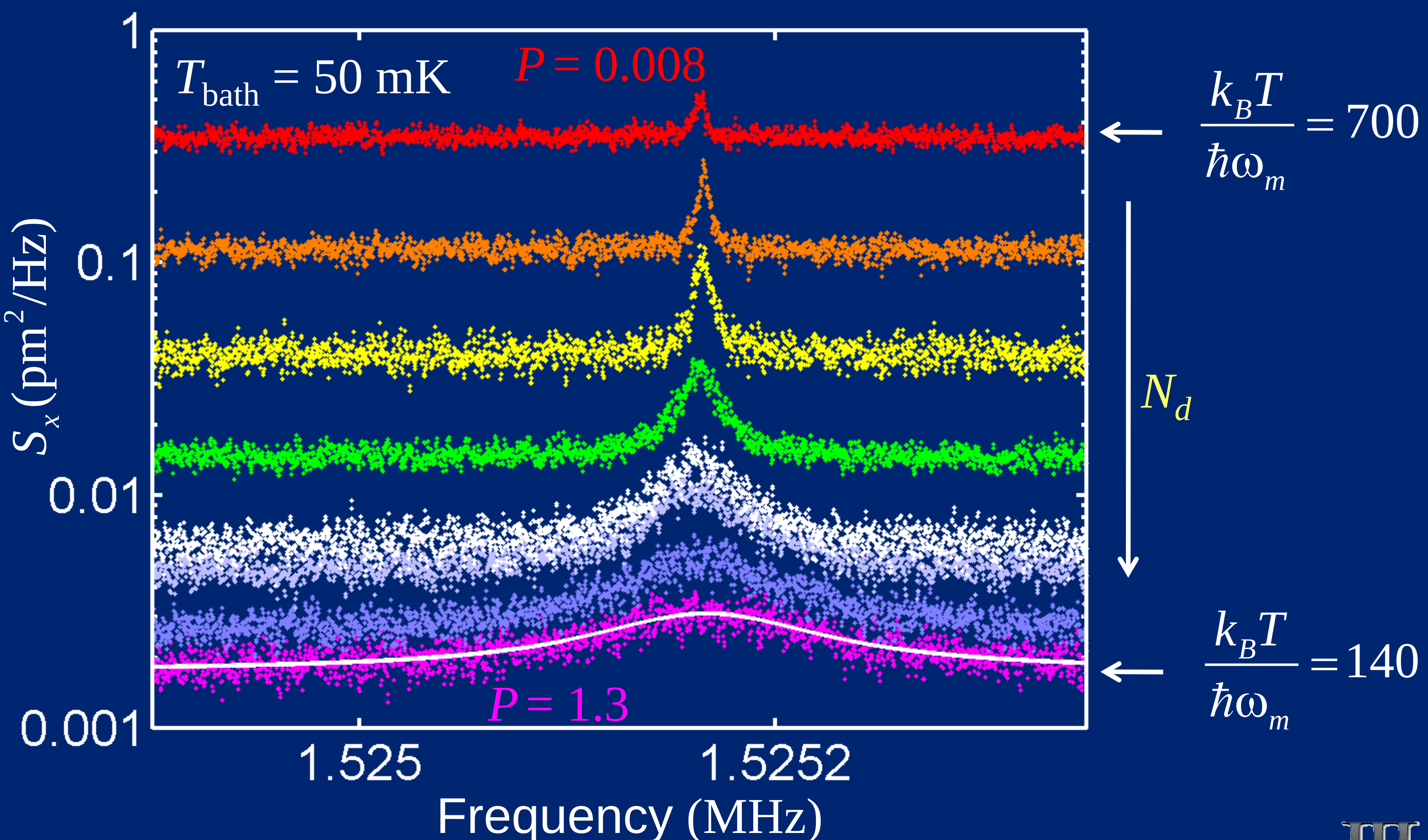
Mechanical response measures antisymmetric force noise

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

$$f = \hbar G a^\dagger a \quad G = 2\pi \times 0.1\ \text{Hz}$$

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

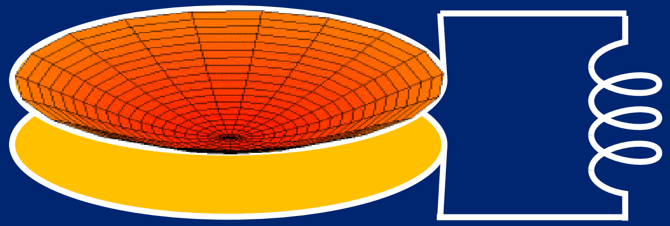
Coupling to radiation is too weak to cool wire to motional ground state



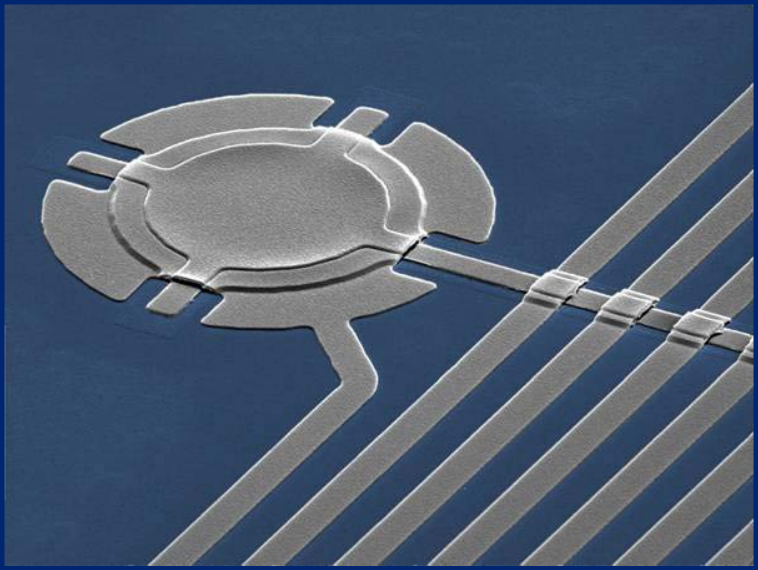
J. D. Teufel, J. W. Harlow, C. A. Regal, KWL *Phys. Rev. Lett*. **101**, 197203 (2008).

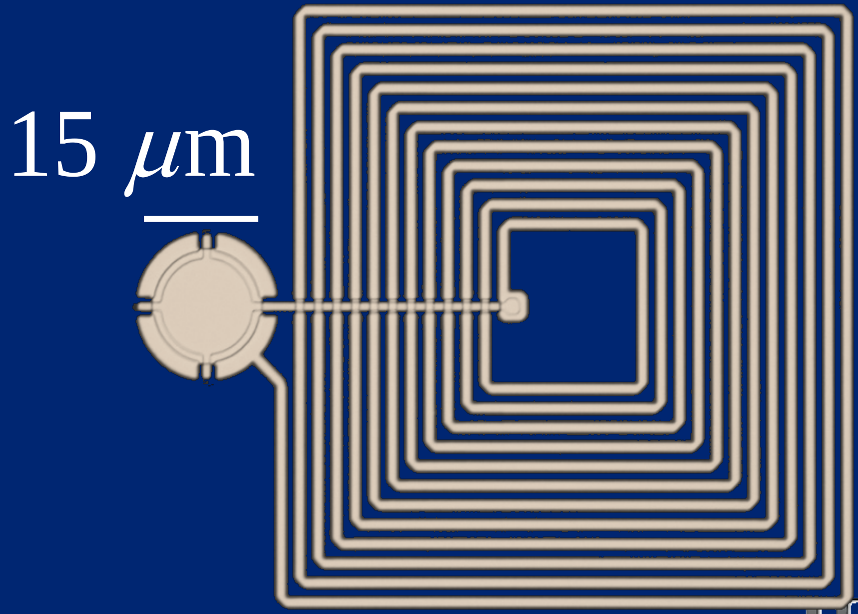
Use parallel-plate capacitor geometry to enhance coupling in microwave optomechanics

capacitor built with suspended micromechanical membrane*

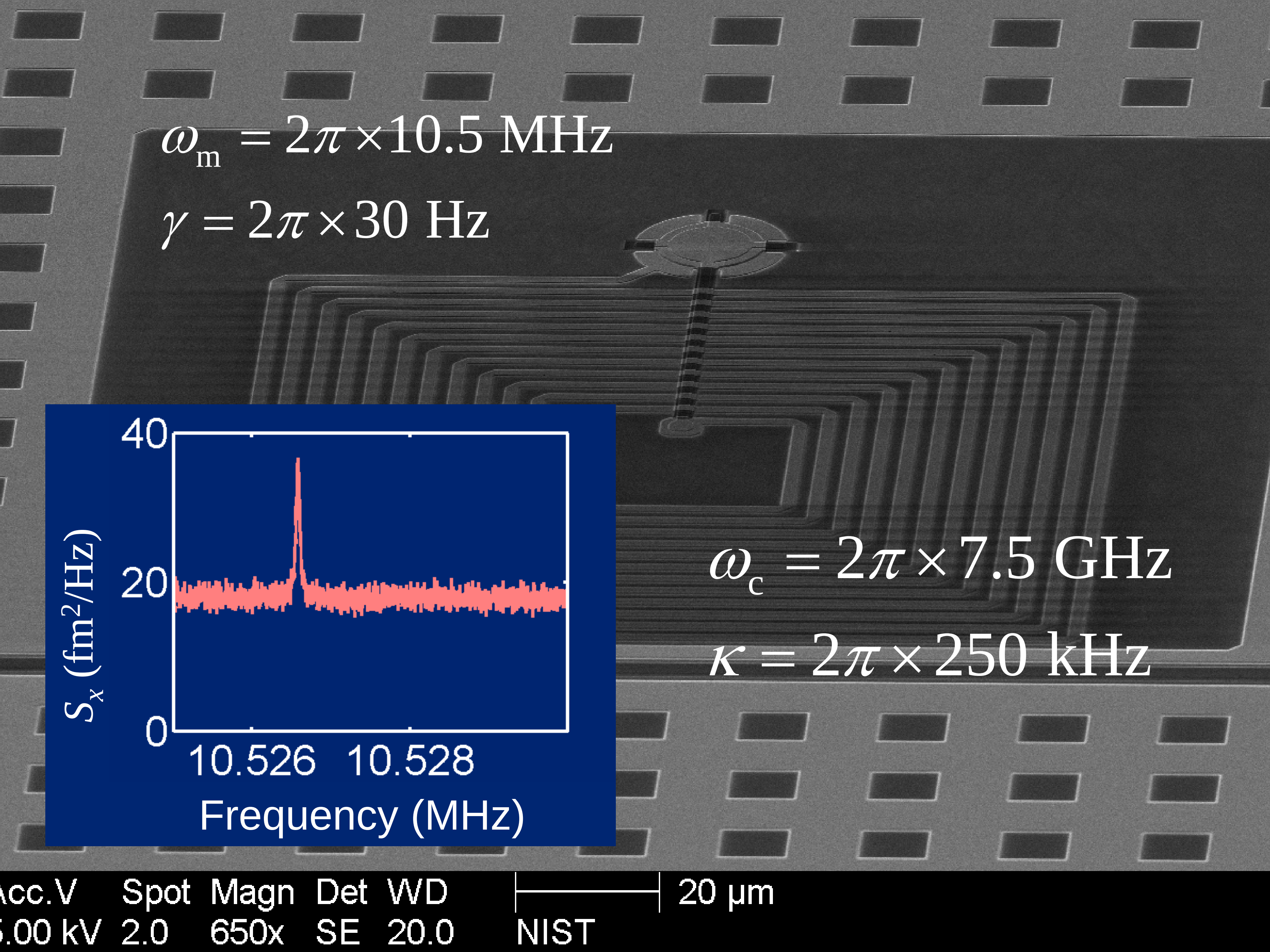


Electrical circuit resonant at 7 GHz



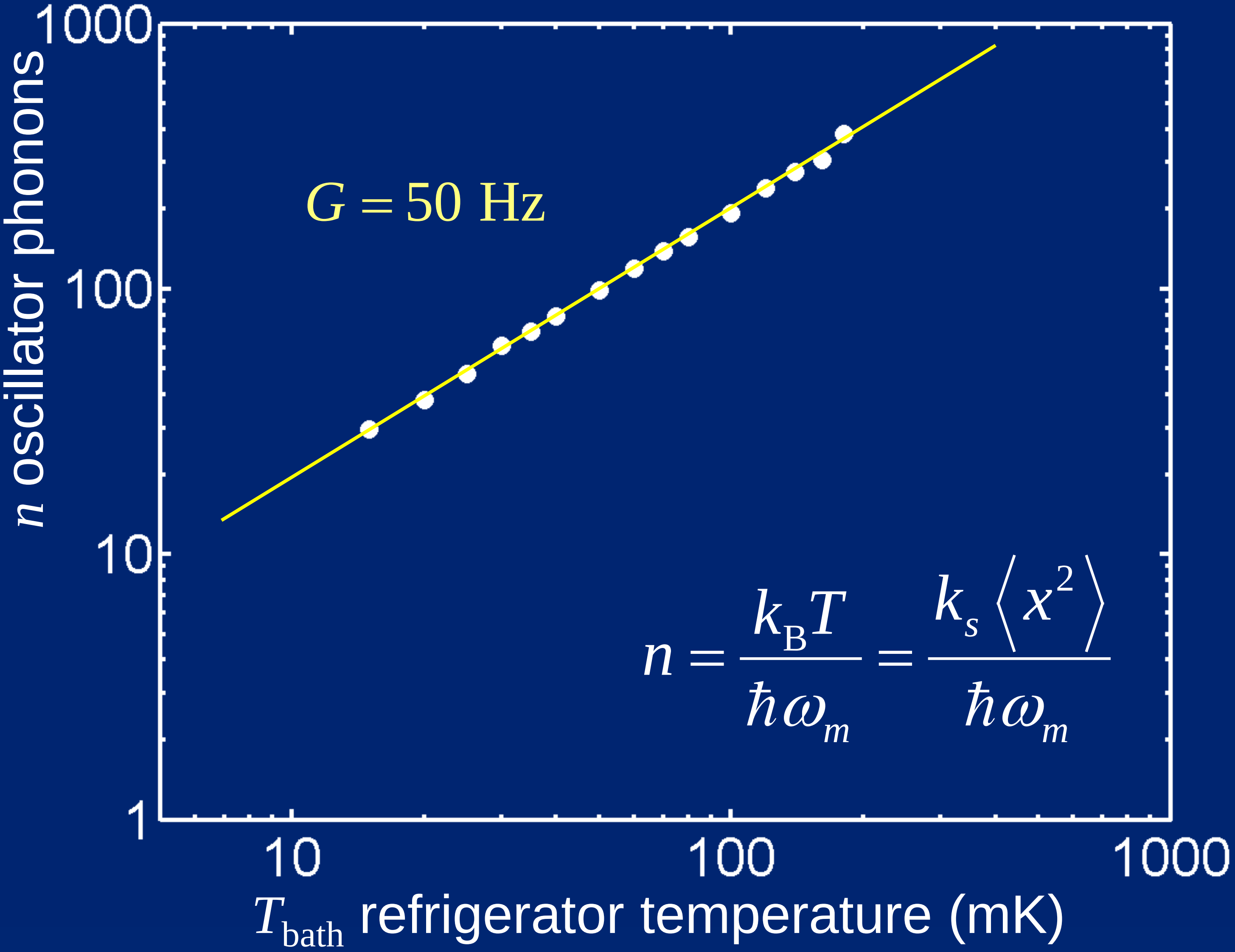


*K. Cicak, et al APL **96**, 093502 (2010)
. J. D. Teufel et al arXiv:1011.3067

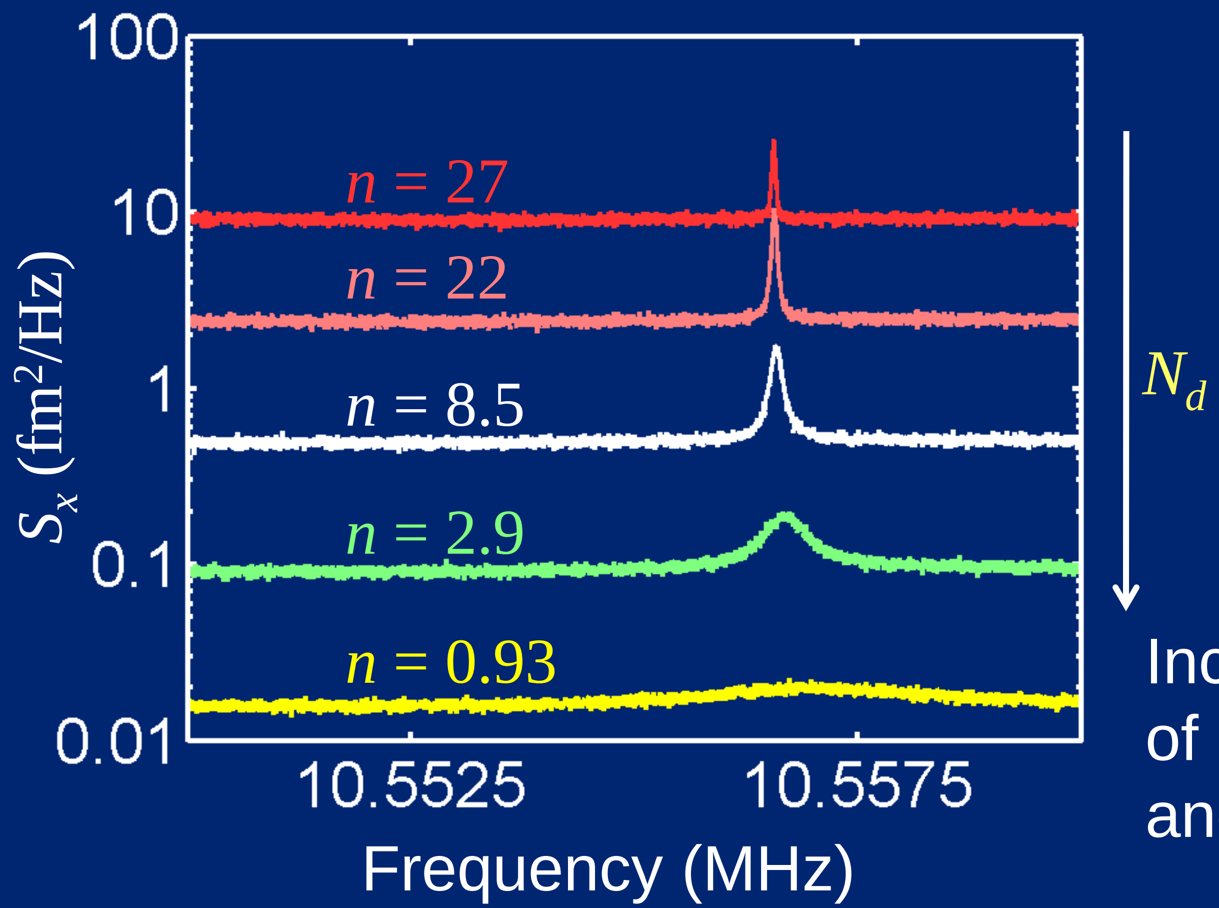


$\omega_m = 2\pi \times 10.5$ MHz
$\gamma = 2\pi \times 30$ Hz
$\omega_c = 2\pi \times 7.5$ GHz
$\kappa = 2\pi \times 250$ kHz
40
20
0
S_x (fm^2/Hz)
10.526
10.528
Frequency (MHz)
Acc.V Spot Magn Det WD
5.00 kV 2.0 650x SE 20.0
20 µm
NIST

Thermal motion reveals large coupling

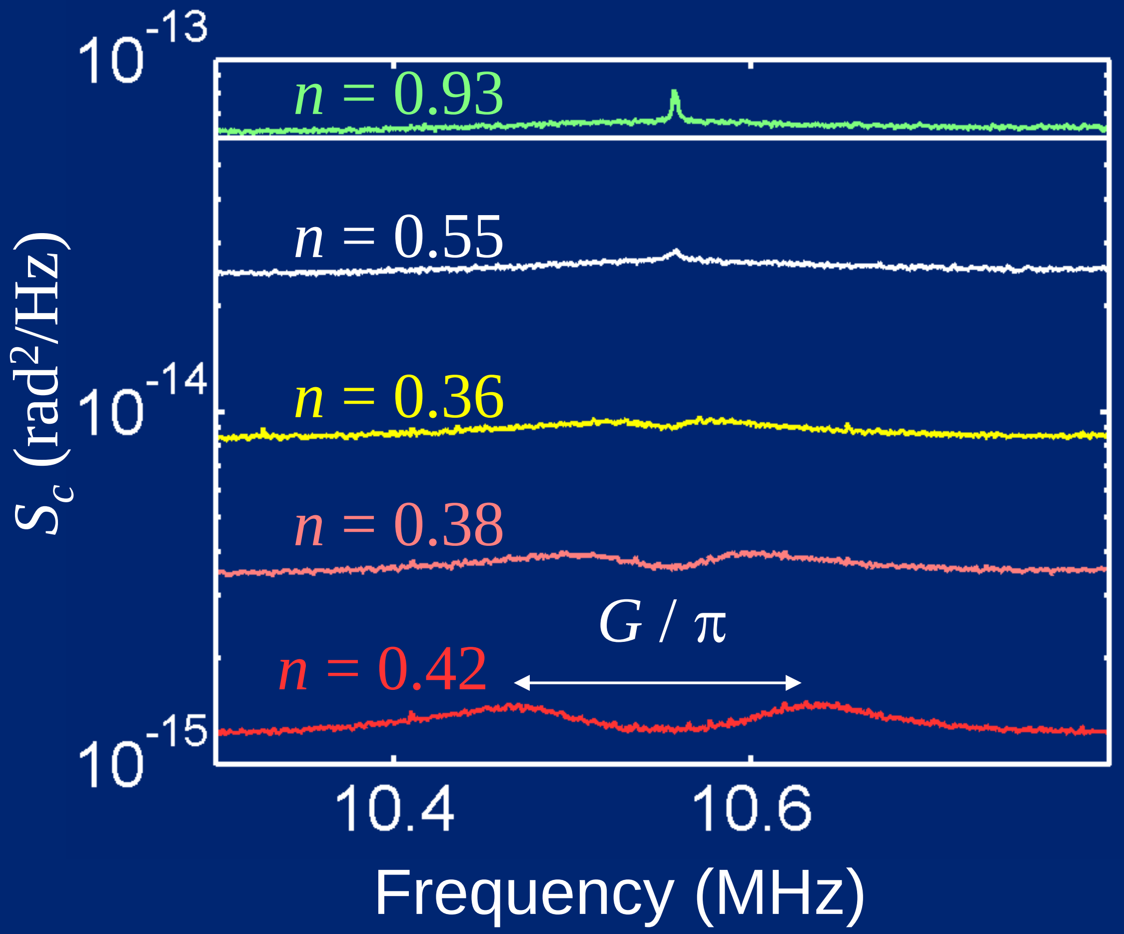


Cooling mechanics to motional ground state



Increasing strength of measurement and cooling

Cooling mechanics to motional ground state

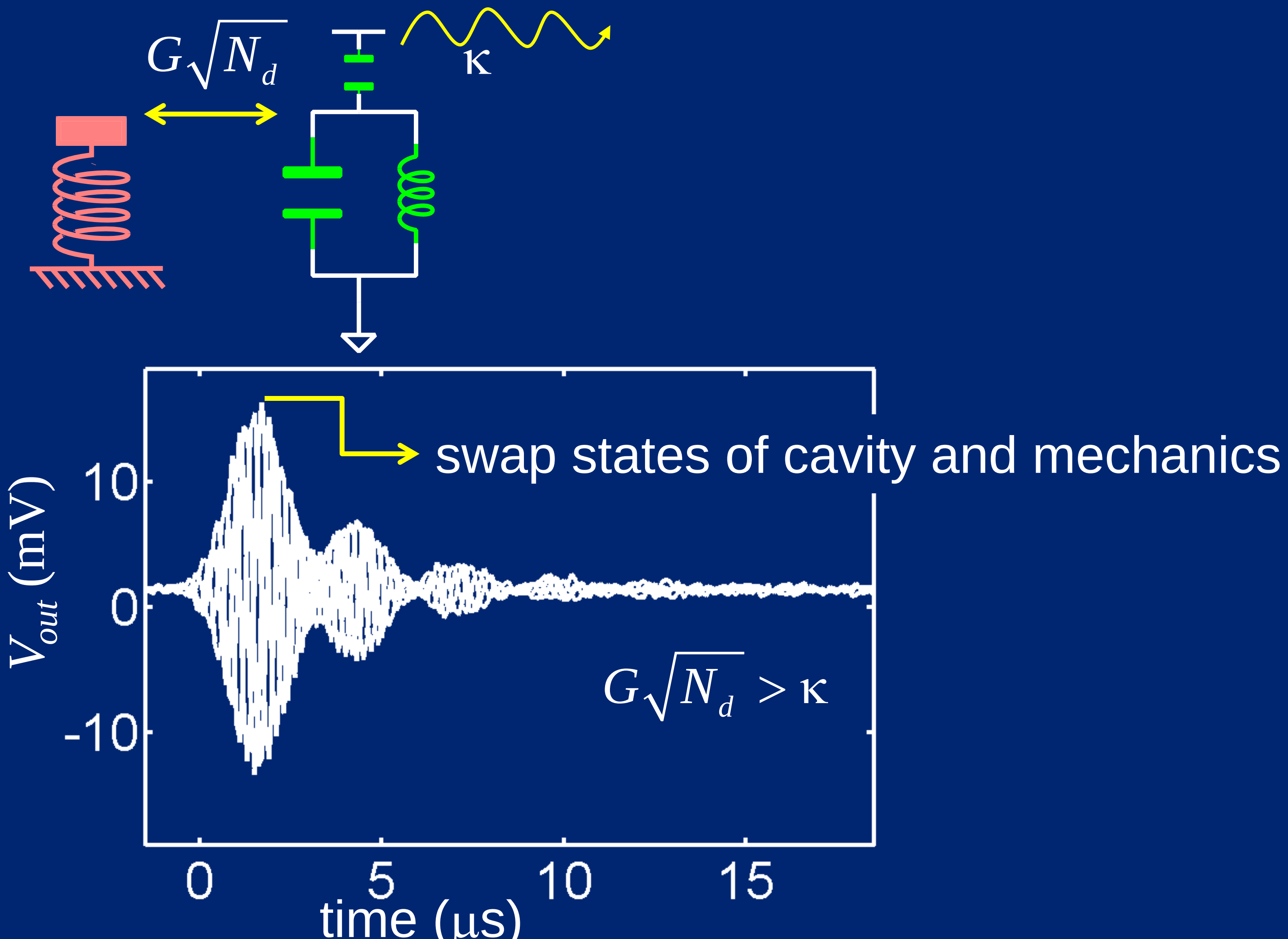


→ ground state and strong coupling

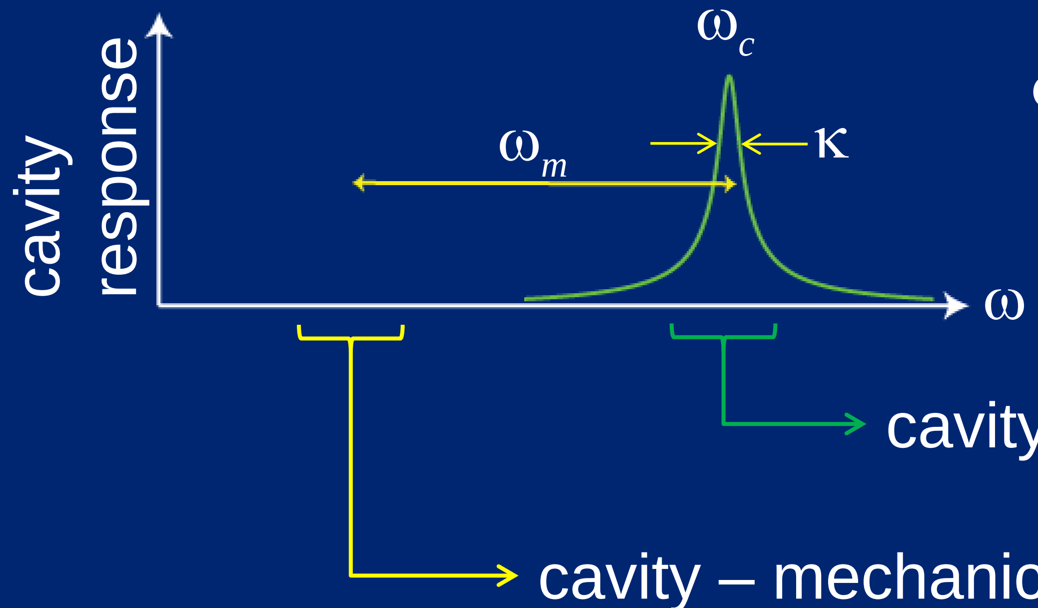
J. D. Teufel, T. Donner, KWL *et al* Nature, 475, 359–363 (2011).

Manipulating mechanics with microwave

Strong coupling enables coherent control of mechanics



Agile state control provided by extreme resolved sideband limit



$\omega_m / \kappa = 50$

cavity preparation

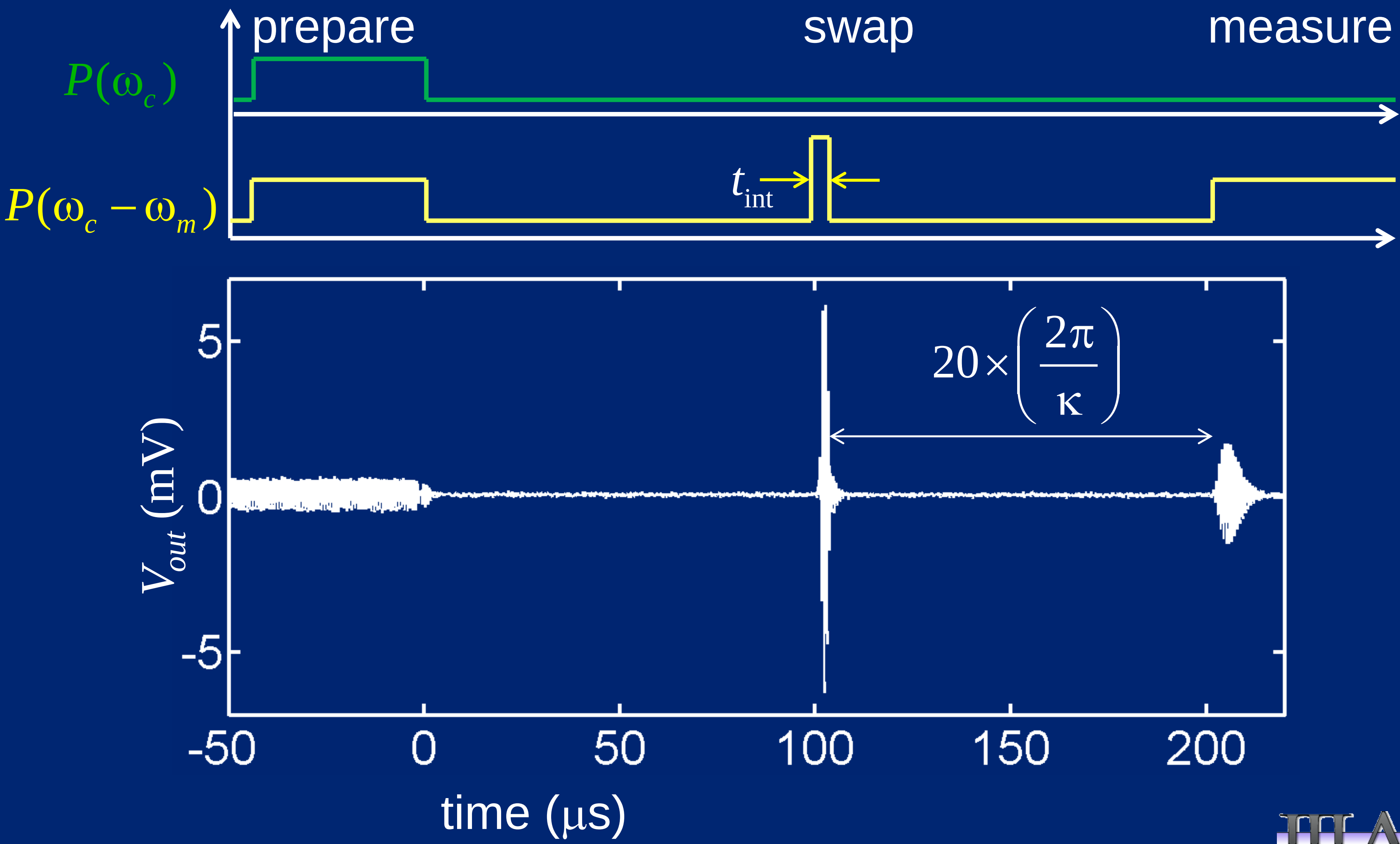
cavity – mechanics interaction $N_d(t)$

$$\hat{H}_I = \hbar G \sqrt{N_d(t)} \left(a b^\dagger + a^\dagger b \right)$$

linearized phonon – photon interaction

- beam splitter
- time dependent

Mechanical oscillators are long-lived coherent memories



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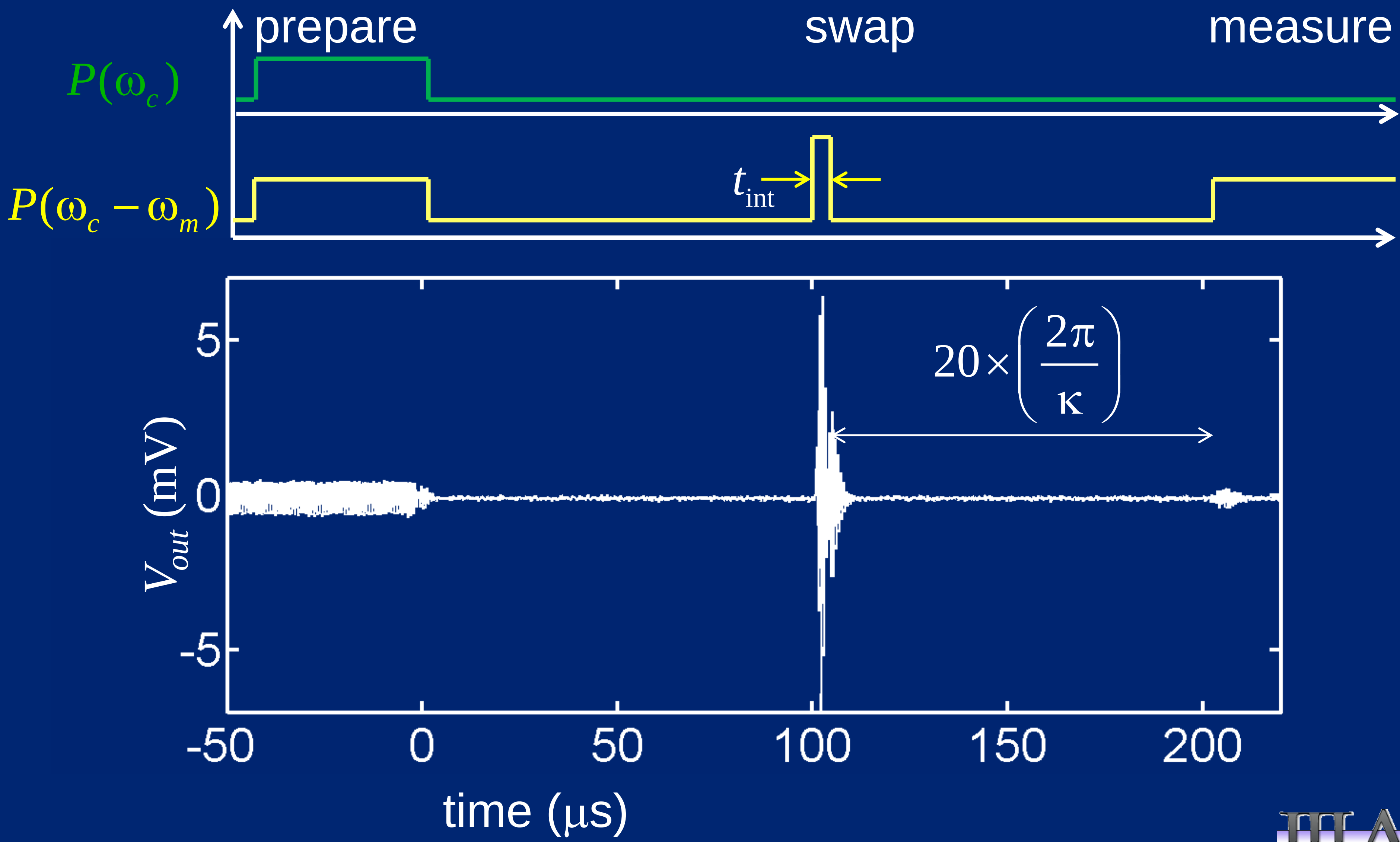

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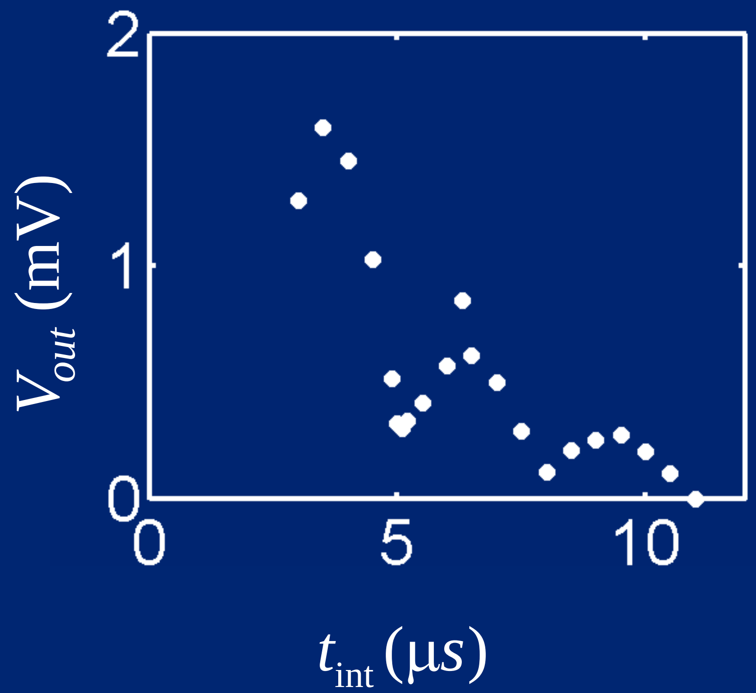
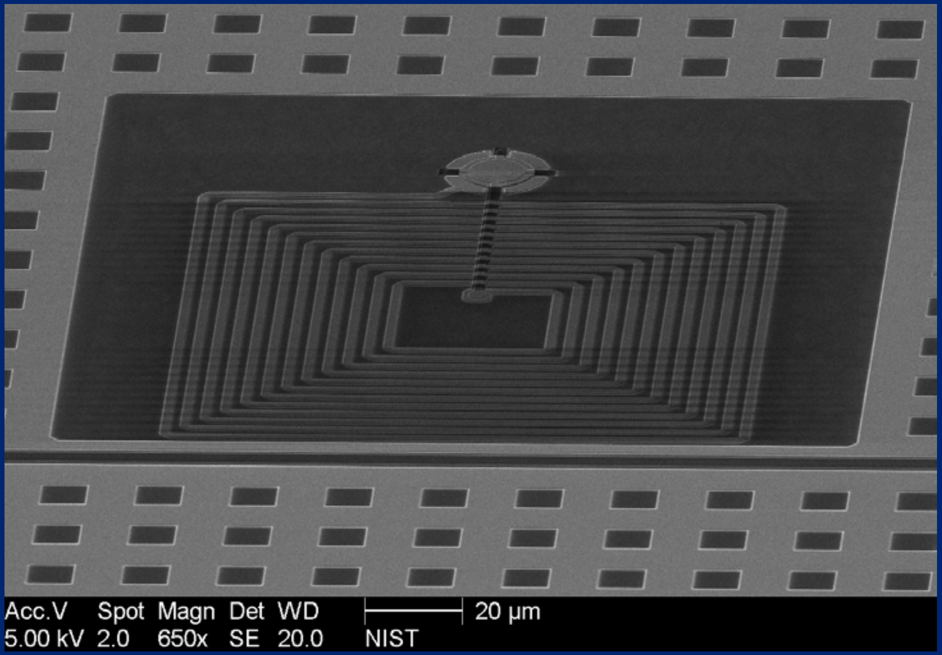


Ramsey like oscillation in coupled microwave-mechanical system

Quantum states of the micro-drum harmonic oscillator are long-lived

$T_1 = 6.1\ \text{ns}$



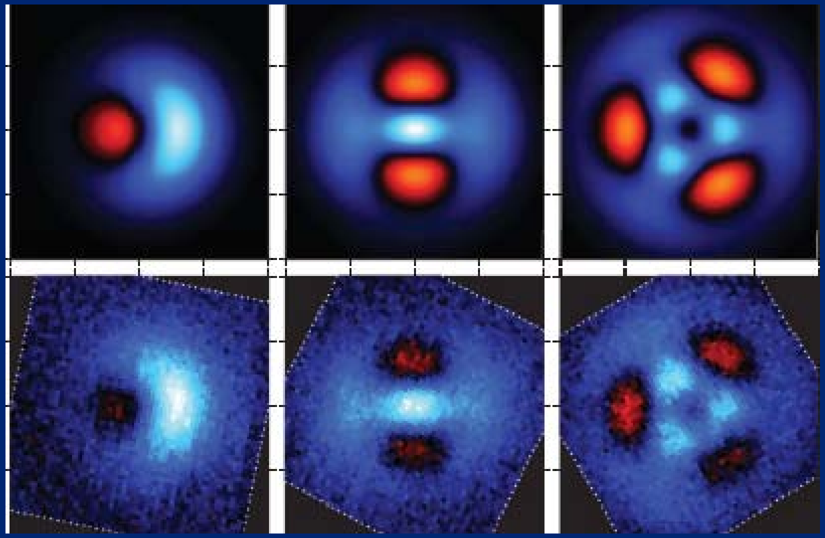
$T_1 \approx 100\ \mu\text{s}$

$1/T_1 = n_{\text{bath}}\gamma$

Cleland group UCSB

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

Microwave to optical quantum state transfer



Hofheinz…Martinis, Cleland, Nature (2009)

Microwaves:

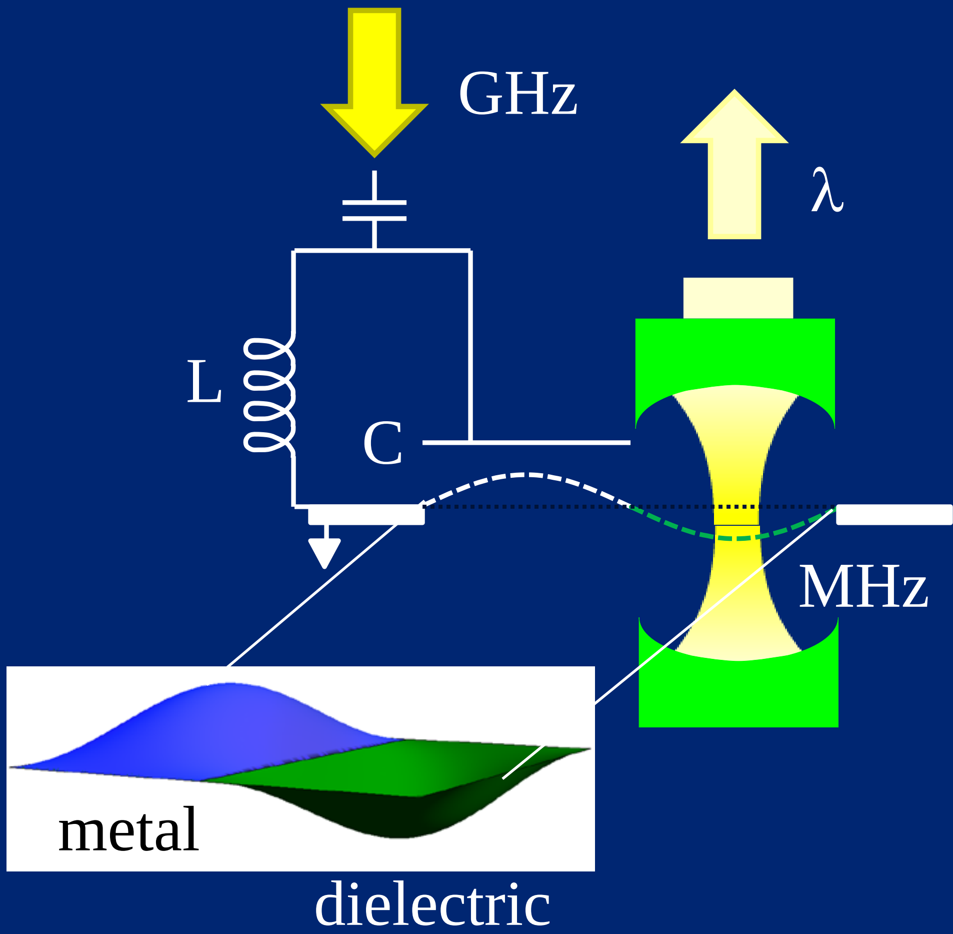
Arbitrary quantum states

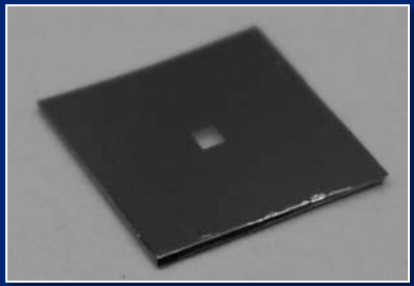
Require ultralow temperatures

Optics:

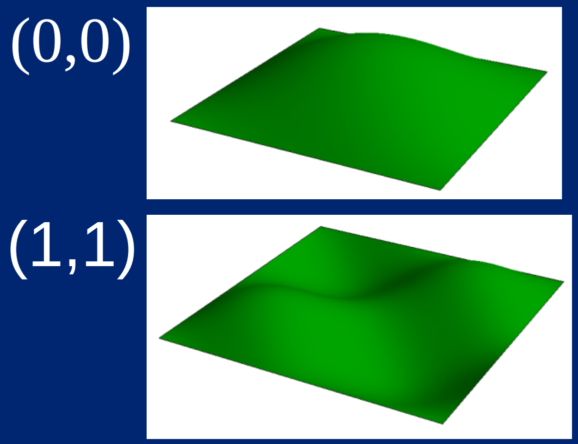
Communication and storage

Ingredients for two cavities coupled to one oscillator





Si_3N_4 membrane



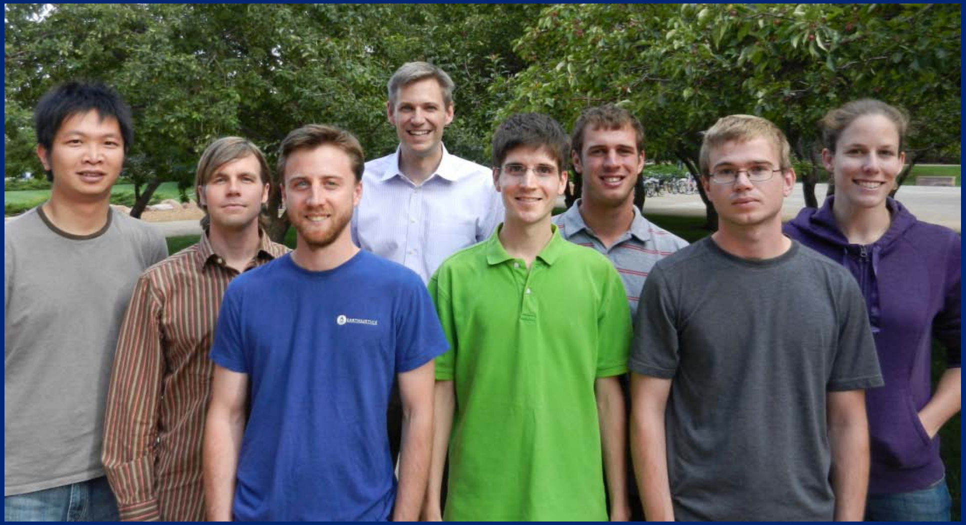
Membrane in free-space cavity
Superconducting LC circuit

Mechanics and optics
couple to different antinodes

Conclusions

- Measure, cool, and manipulate nanomechanical elements with microwaves

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



- Microwave Mach-Zehnder interferometer
  quantum efficiency 30%

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JILA NIST CU