# Quantum electro-mechanics: a new quantum technology

Konrad Lehnert

Post-docs

Tauno Palomaki

Tobias Donner

Joseph Kerckhoff

Collaborators

John Teufel

Cindy Regal

Ray Simmonds

Kent Irwin

Graduate students

Jennifer Harlow

Reed Andrews

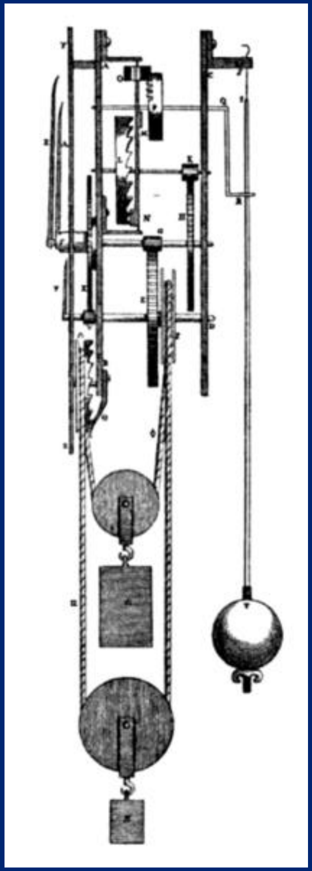
Hsiang-Sheng Ku

William Kindel

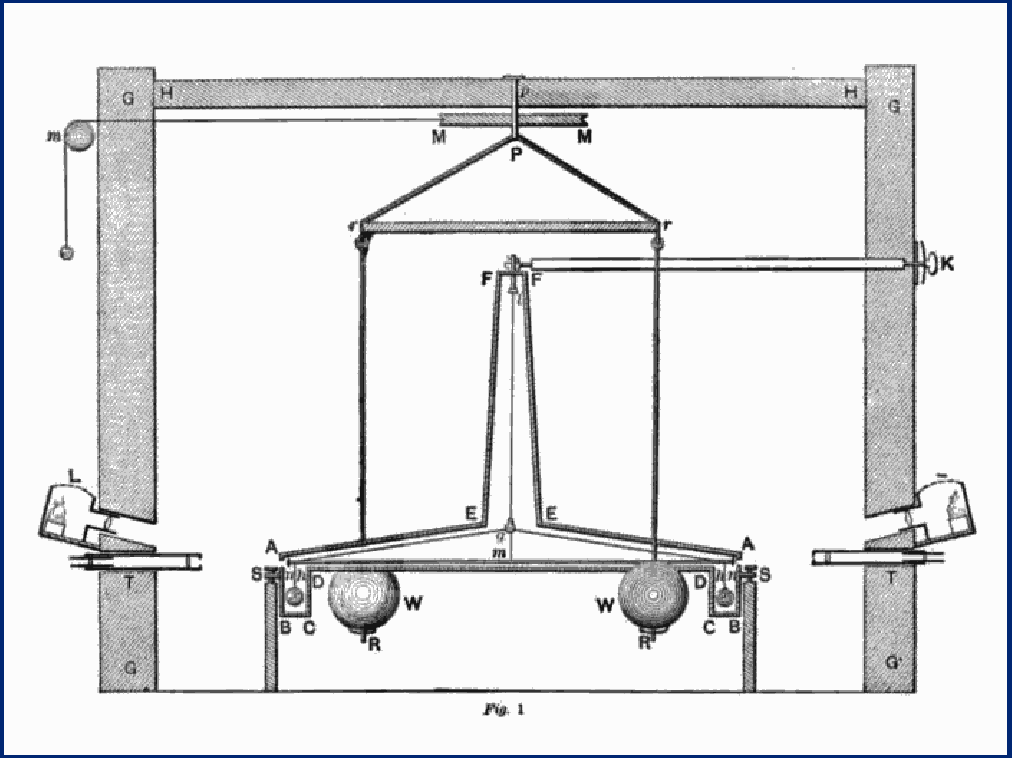
Adam Reed

JILA NIST CU

# Precision measurement tools were once mechanical oscillators



Huygens pendulum clock

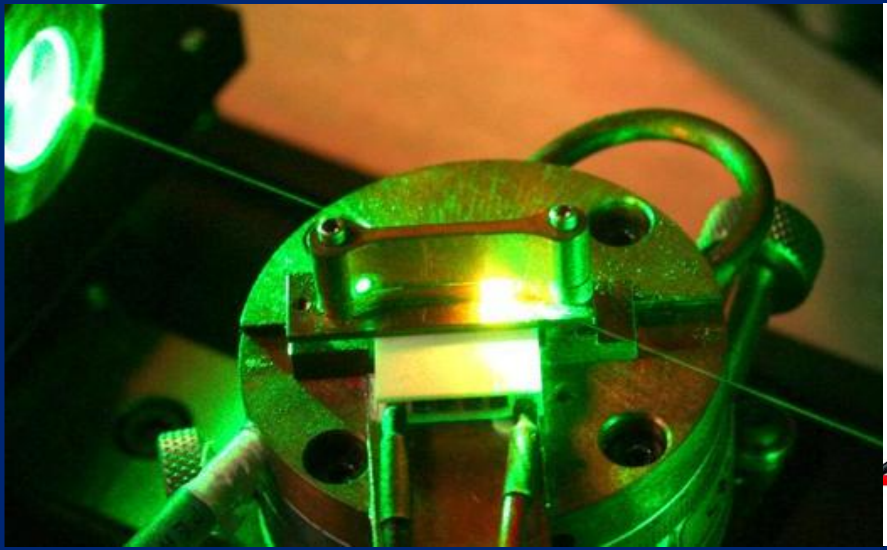



The Cavendish balance for weighing the earth

# Modern measurement tools exploit optics and electronics, not mechanics

Image: Cundiff lab JILA

Laser light

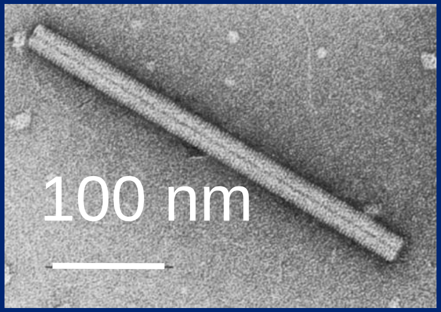


electricity

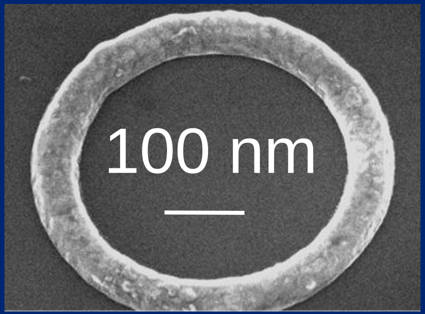

Optical and electrical measurement tools:
Large dynamic range

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

system




nuclear spins in a virus
(Rugar lab, IBM)




electrons in an aluminum ring
(Harris lab, Yale)

Systems with:

dense low-energy spectra

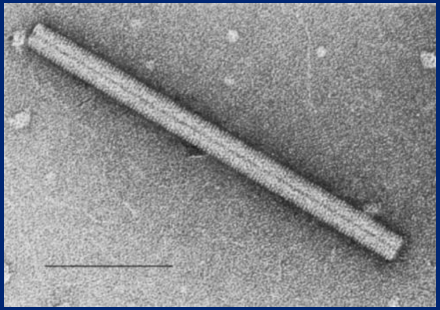
nanometer length scales

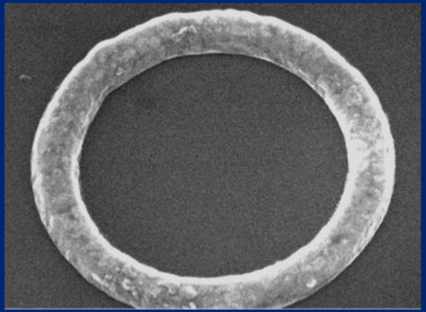
weak coupling to light

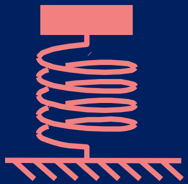
optical or electrical probe

# Mechanics enables measurements of systems that interact weakly with light

system







mechanical intermediary

probe field

Systems with:

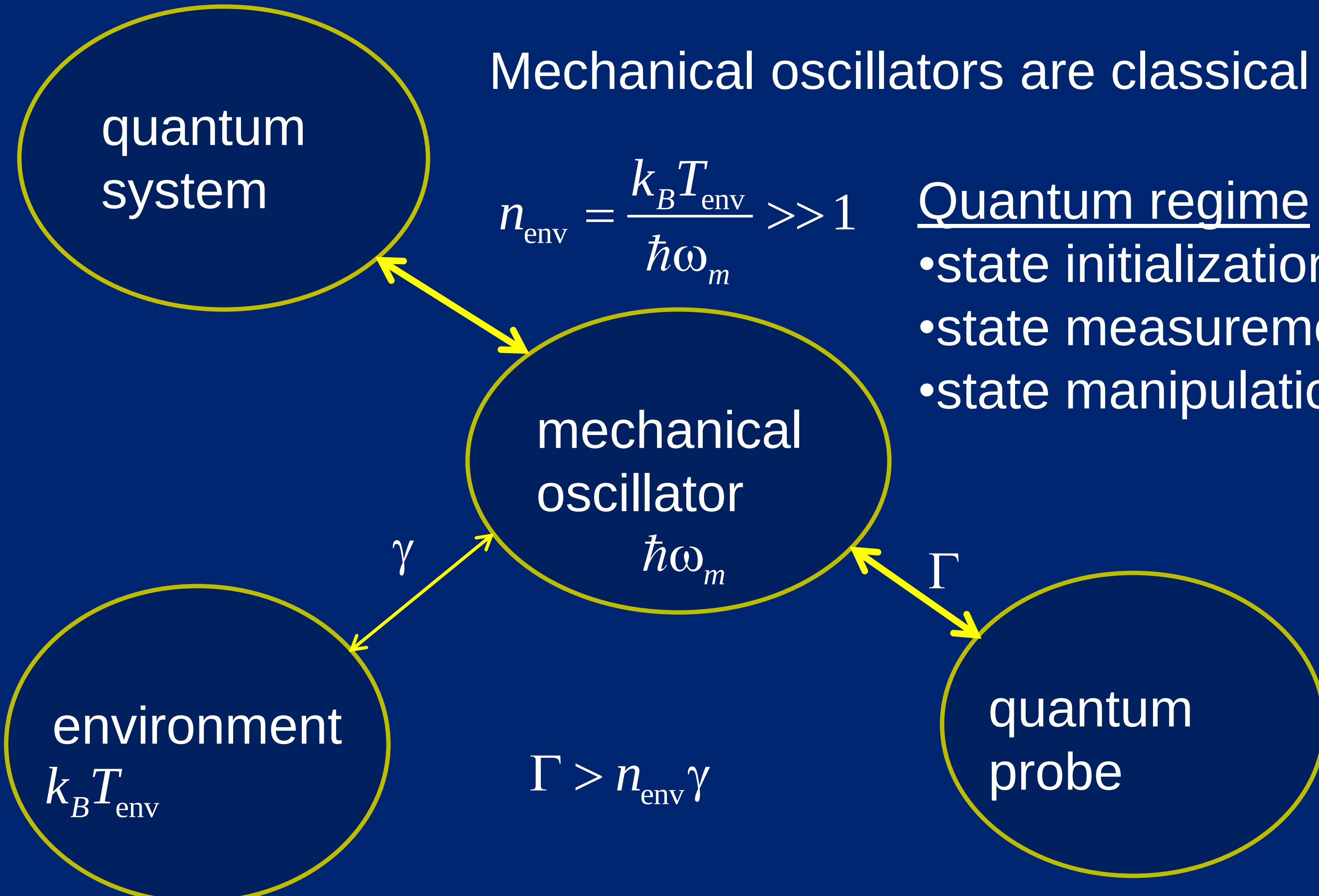
- dense low-energy spectra
- nanometer length scales
- weak coupling to light

# Mechanical oscillators as quantum coherent interfaces between incompatible systems

Mechanical oscillators are classical

$$n_{\mathrm{env}} = \frac{k_B T_{\mathrm{env}}}{\hbar\omega_m} >> 1$$

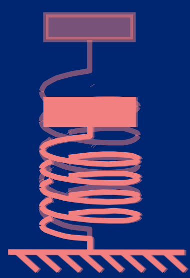
<u>Quantum regime</u>
•state initialization
•state measurement
•state manipulation



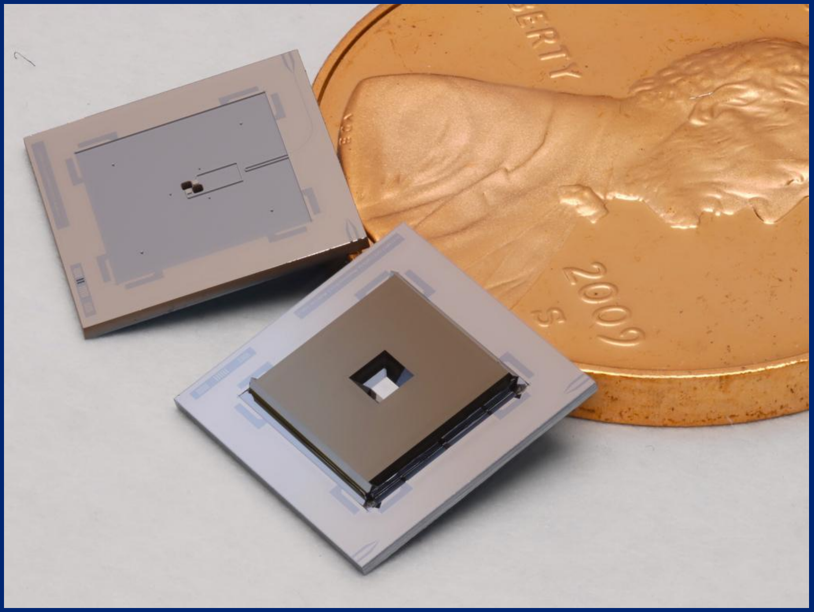

$$\Gamma > n_{\mathrm{env}}\gamma$$

# What is the largest object in which quantum behavior can be observed?

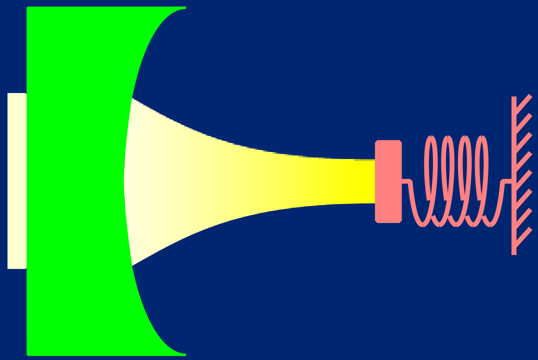
quantum
superposition



Mechanical oscillator
large
tangible



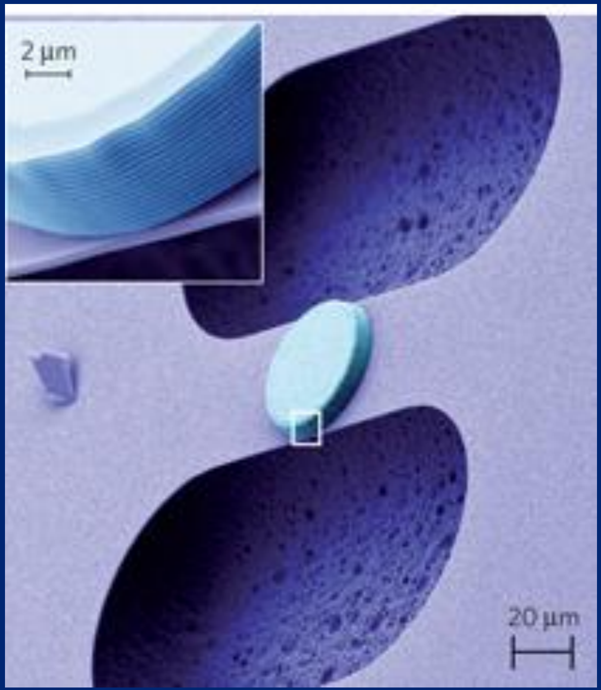
# Cavity optomechanics: Use radiation pressure for state initialization and measurement



Fabry-Perot cavity with oscillating mirror

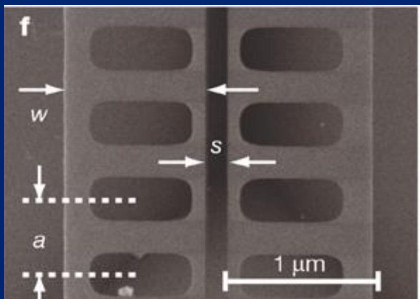
Infer motion through optical phase

Cool with cavity-retarded radiation force

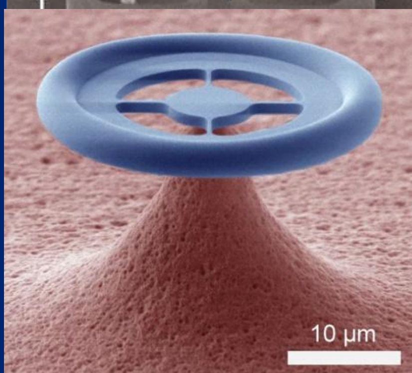



Aspelmeyer lab, IOQOI, Vienna

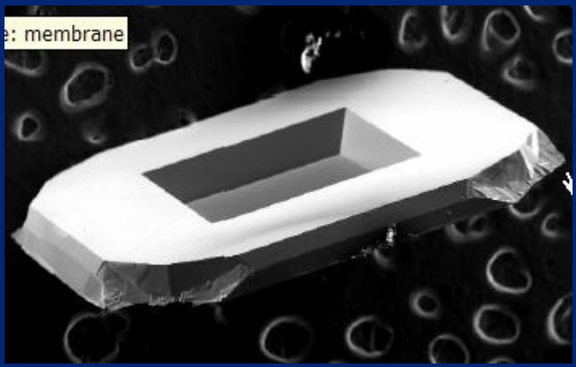
# Images of cavity optomechanical systems



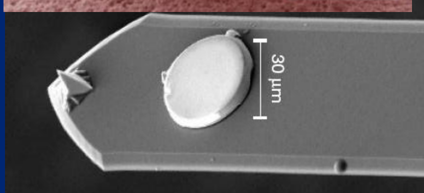

Caltech, Painter




EPFL, Kippenberg

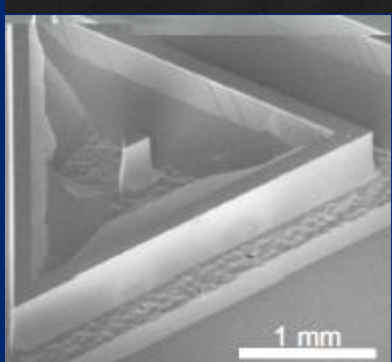



Yale, Harris




UCSB: Bouwmeester

MIT, Mavalvala

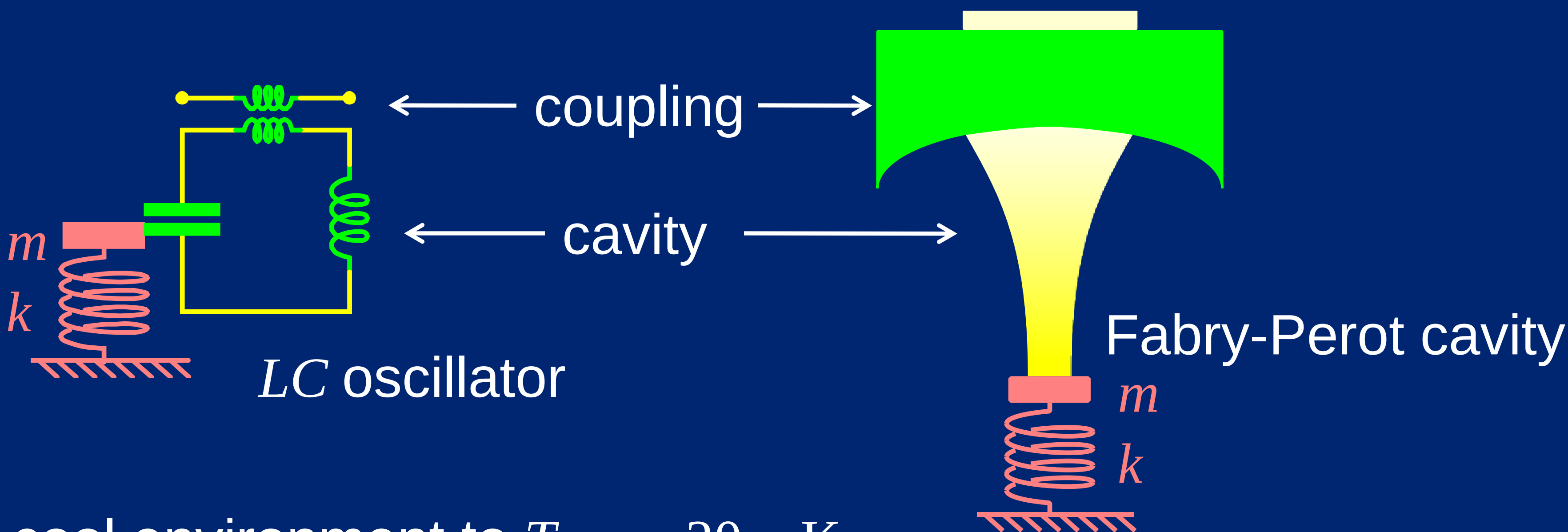



ENS: Cohadon and Heidmann

# Microwave cavity optomechanics

# Reduce coupling to the environment by lowering temperature: microwave optomechanics

Microwave "light" in ultralow temperature cryostat

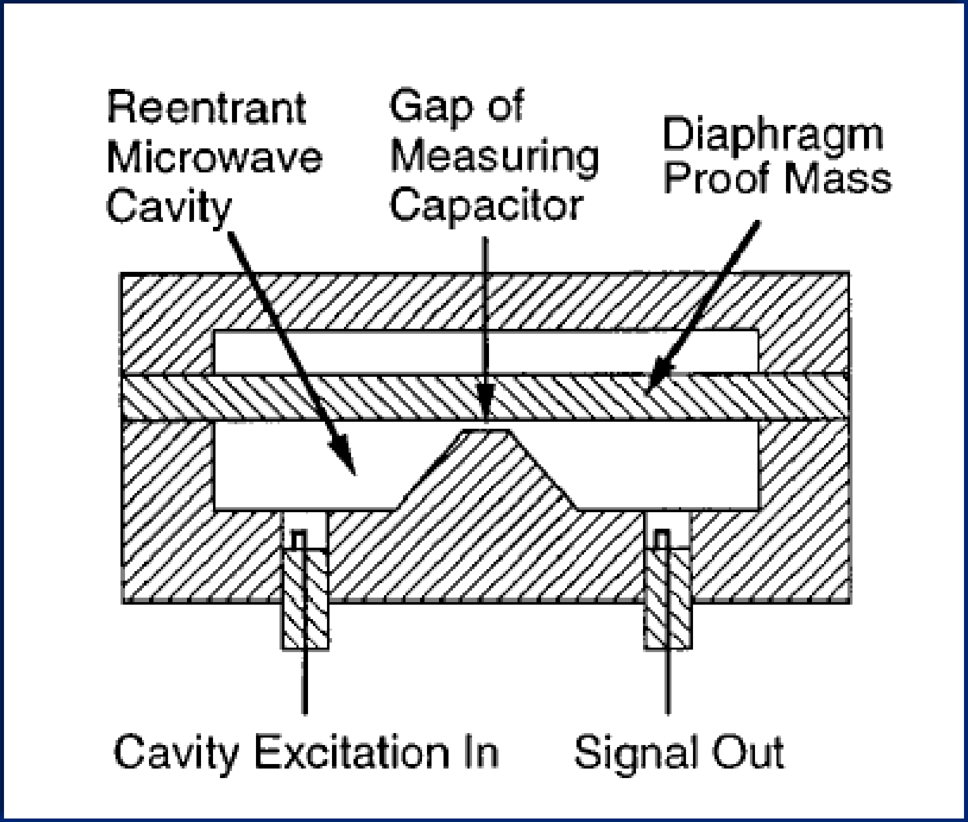



cool environment to $T_{\text{env}} = 20\ \text{mK}$

for 10 MHz oscillator $n_{\text{env}} = 40$

goal: $\Gamma > n_{\text{env}}\gamma$

# Superconducting electromechanics used in resonant mass gravitational wave detectors




centimeter sized superconducting cavity with mechanically compliant element

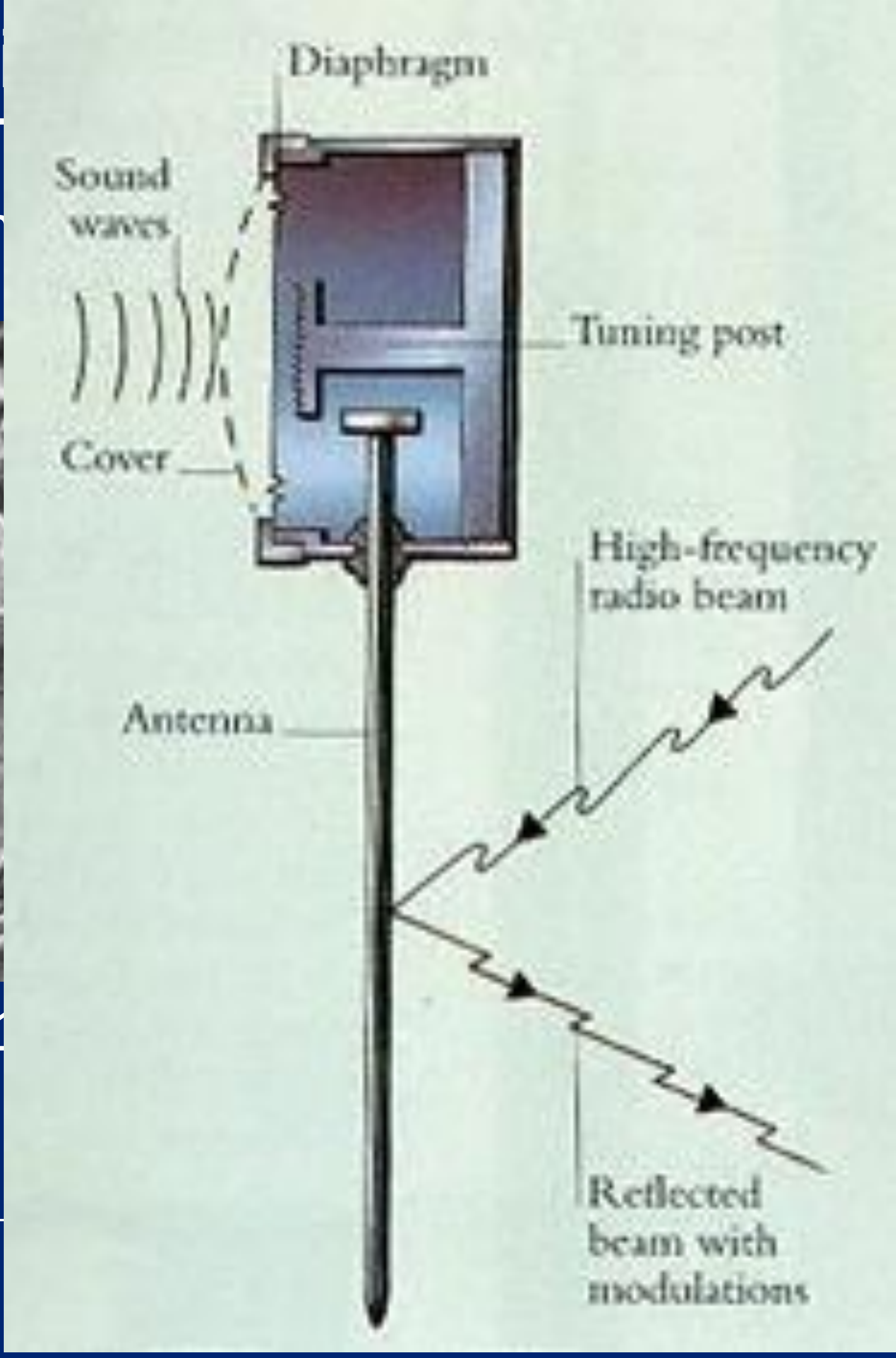
Braginsky, V. B., V. P. Mitrofanov, and V. I. Panov, 1981, *Sistemi s maloi dissipatsei (Nauka, Moscow) [English translation: Systems with Small Dissipation (University of Chicago,* Chicago, 1985)].

# Resonant electromechani

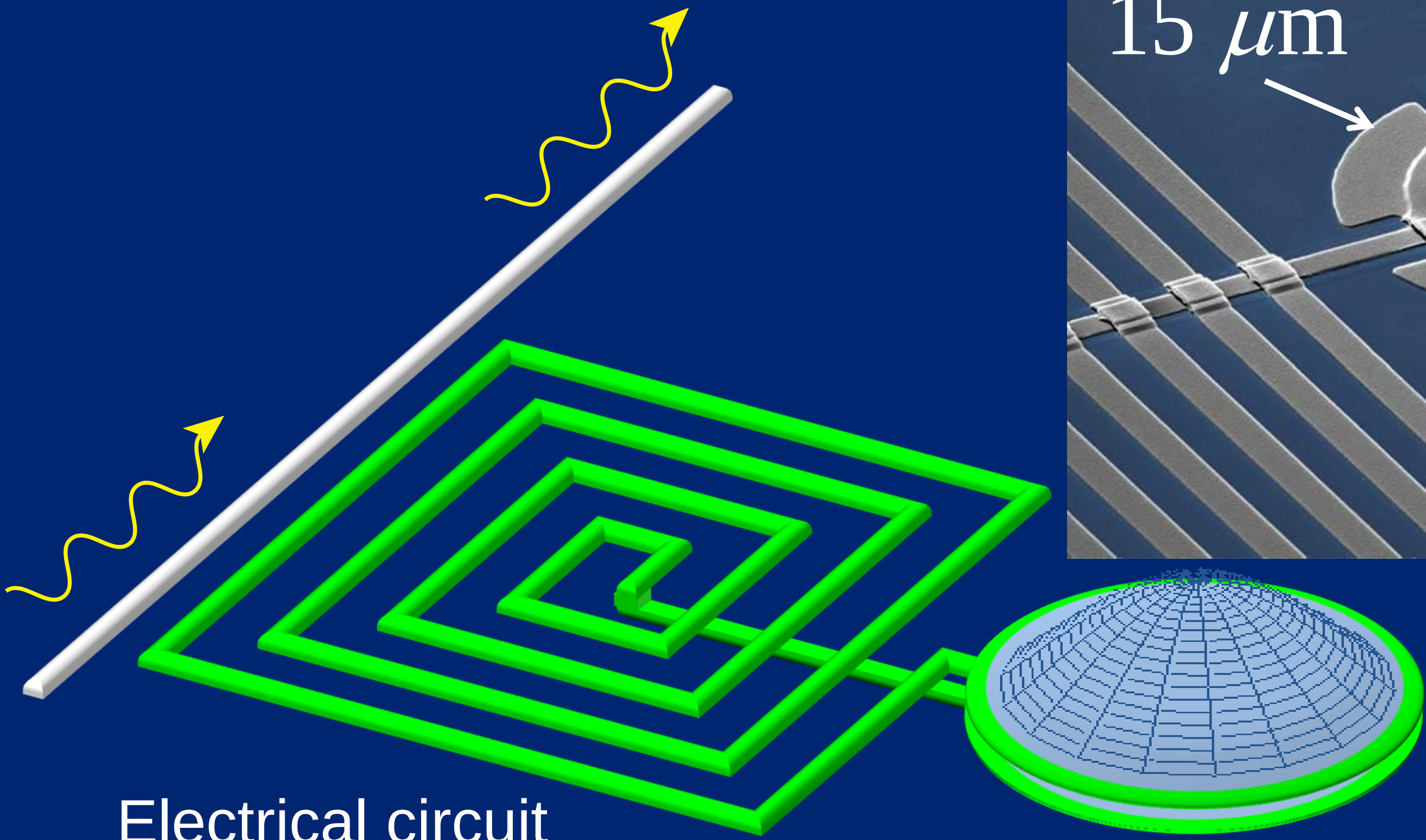
Soviet passive bug hidden in th

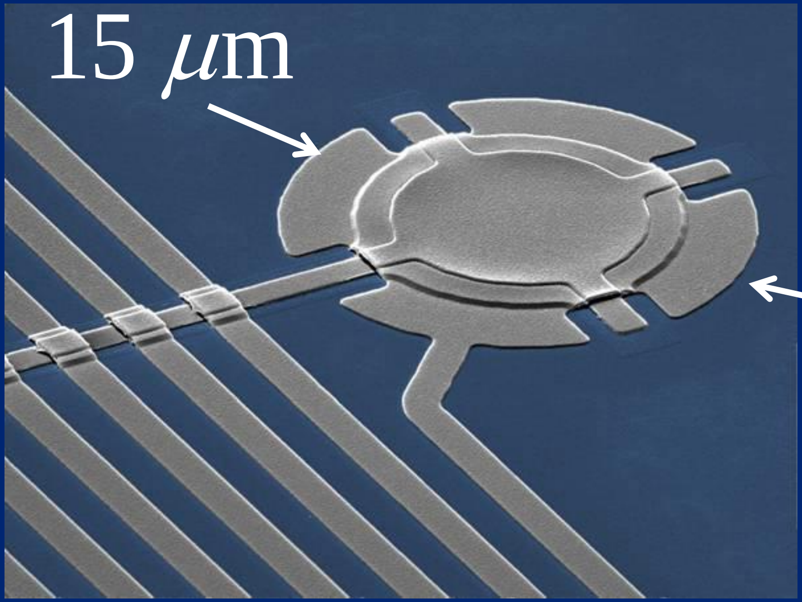
Henry Cabot Lodge, Jr. May 26, 1
in the UN

Images appear in http://www.spybusters.com/Great_Seal_



# Electromechanical system realized from a MEMS capacitor in a resonant circuit





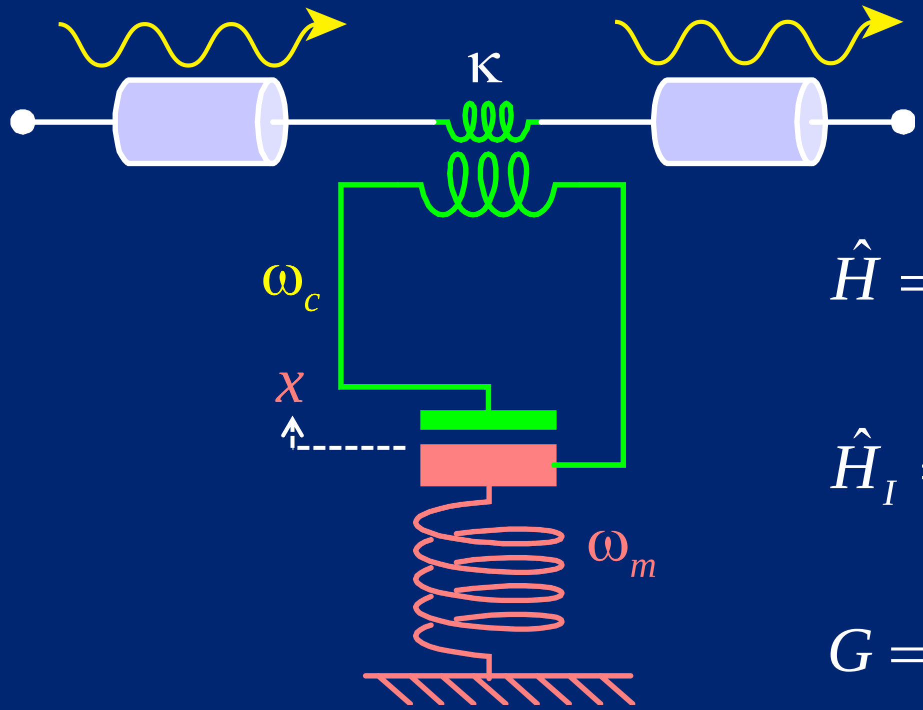

10.5 MHz

Electrical circuit
resonant at 7.5 GHz

capacitor built with suspended
micromechanical drumhead*

*K. Cicak, et al APL **96**, 093502 (2010)
*J. D. Teufel, R. W. Simmonds et al., Nature 471, 204208 (2011).

# Resonant circuit enhances coupling between microwave fields and mechanical motion




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

$$\hat{H}_I = \hat{F}\cdot\hat{x} = \hbar G a^\dagger a\left(b^\dagger + b\right)$$

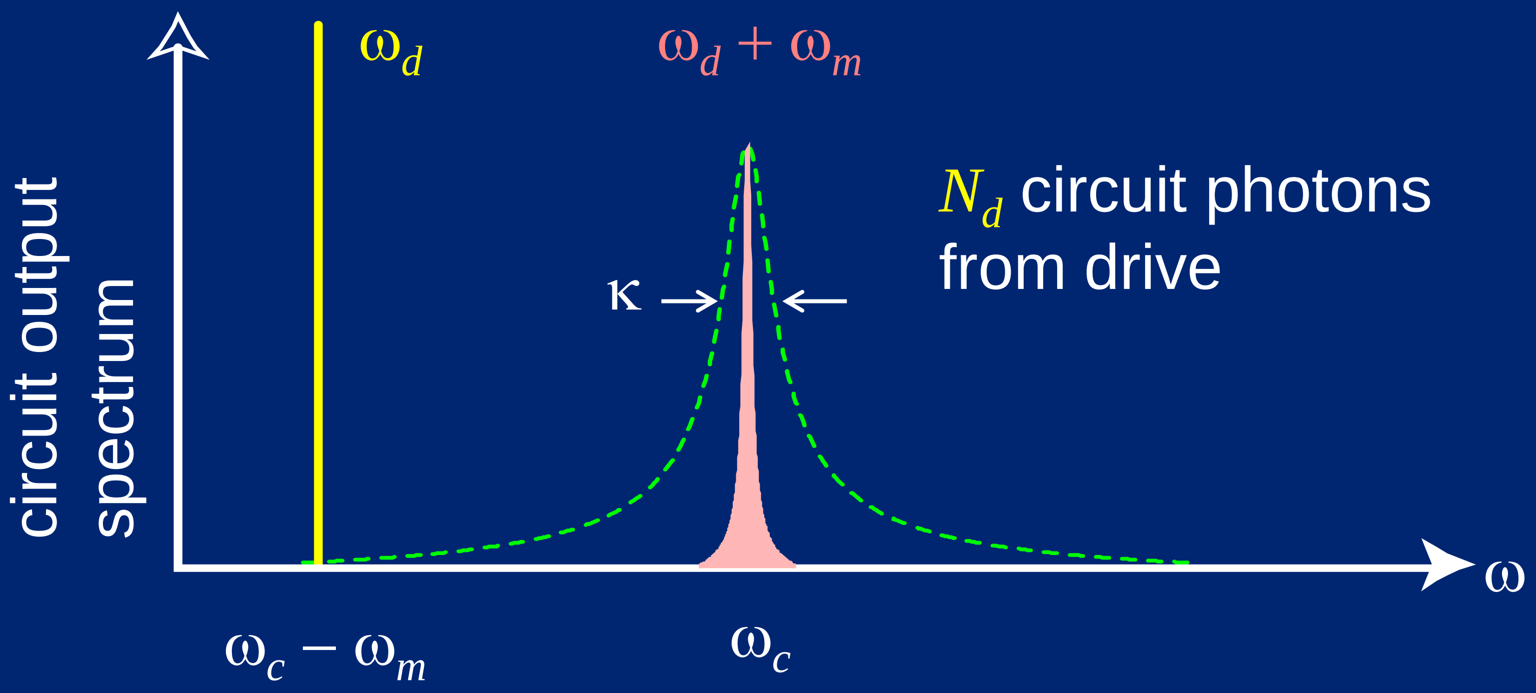
$$G = \frac{\partial\omega_c}{\partial x}x_{\text{zpf}}$$

$\kappa$ decay rate of circuit energy

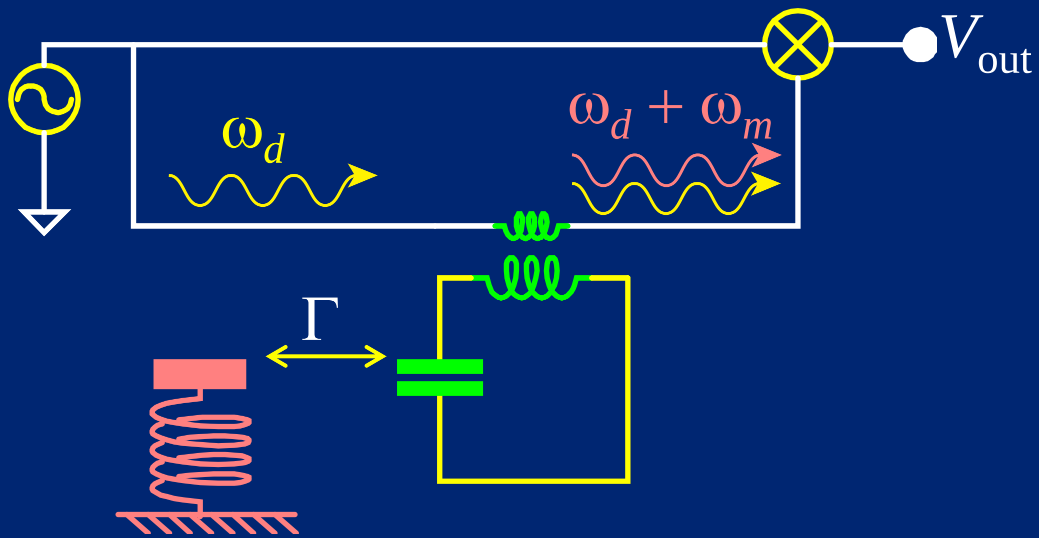
# Detuned microwave drive couples mechanical motion to electrical circuit resonance

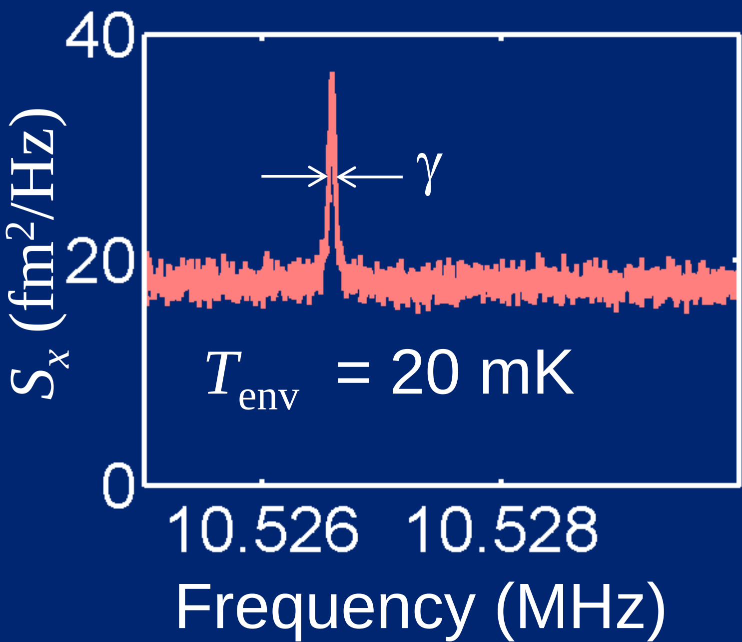
$\hat{H}_I = \hbar G a^\dagger a (b^\dagger + b)$ excite circuit at $\omega_d = \omega_c - \omega_m$

$\hat{H}_I = \hbar G \sqrt{N_d}\left(ab^\dagger + a^\dagger b\right)$ linearized interaction $\Gamma = \frac{4 N_d G^2}{\kappa}$



# Electrically detect thermal motion of drumhead




$$\omega_c = 2\pi \times 7.5 \text{ GHz}$$

$$\kappa = 2\pi \times 200 \text{ kHz}$$

$$\omega_m = 2\pi \times 10.5 \text{ MHz}$$

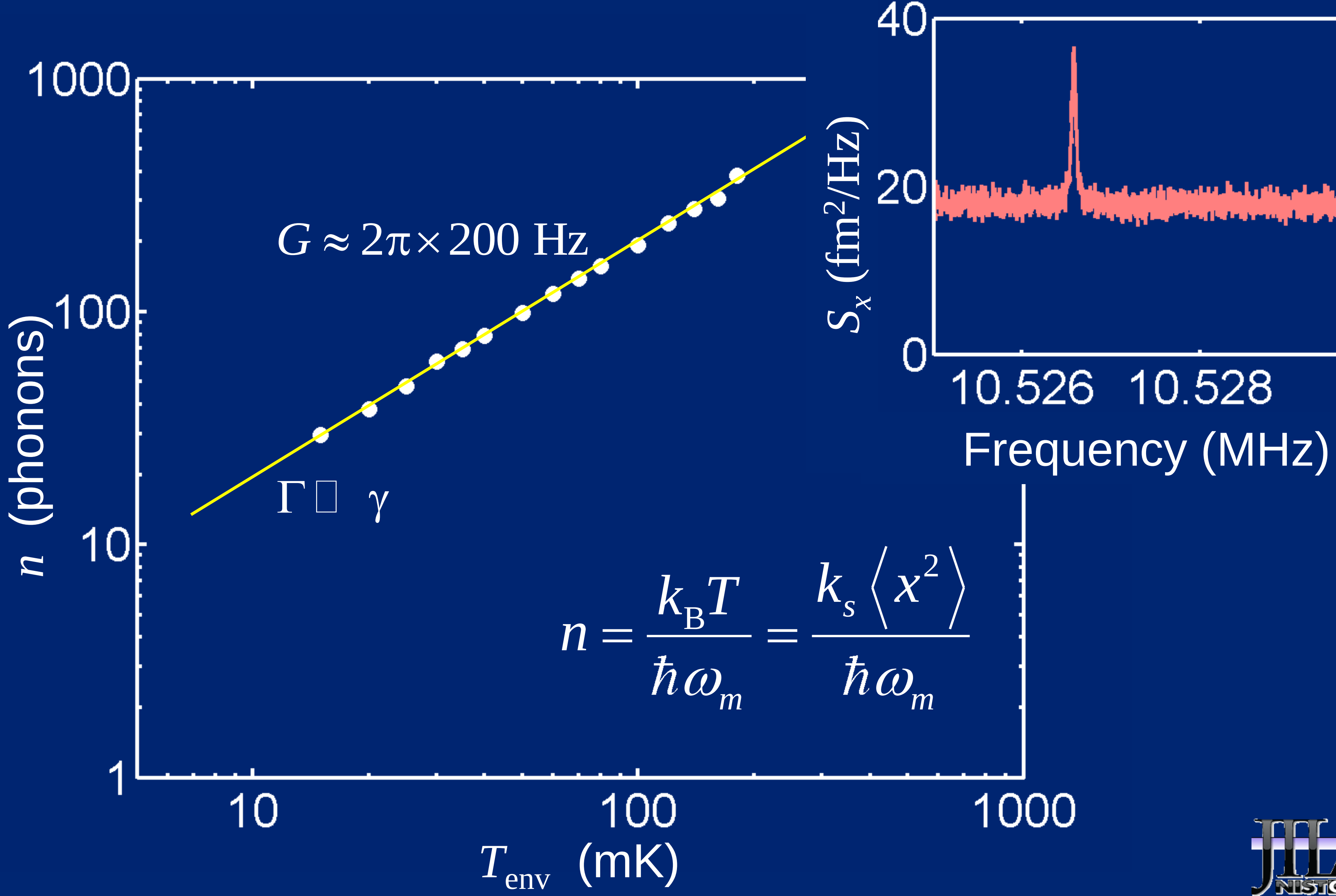
$$\gamma = 2\pi \times 30 \text{ Hz}$$

$$x_{zpf} = 4.1 \text{ fm}$$


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

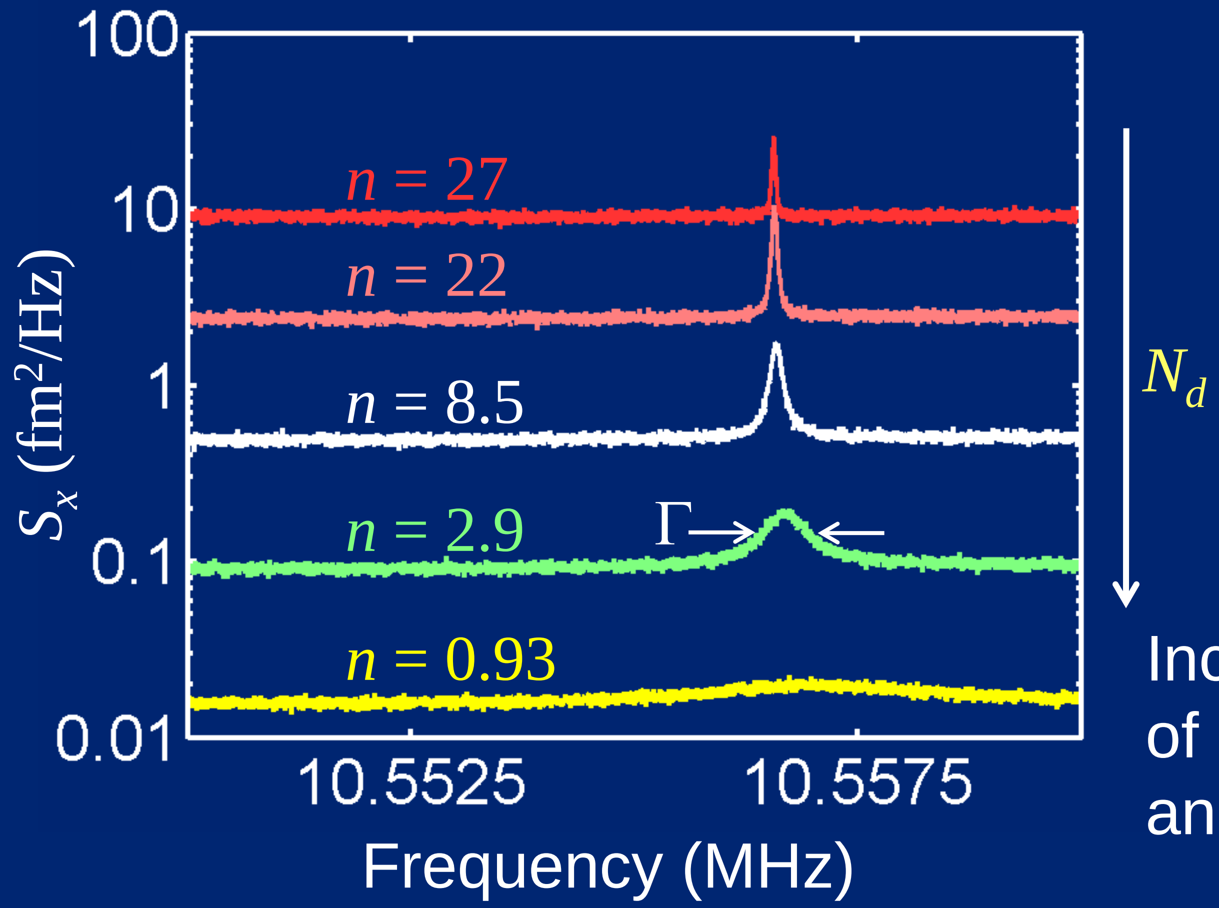
J. D. Teufel, T. Donner, KWL, R. W. Simmonds, *et al* Nature, 475, 359–363 (2011).

# Mechanical motion in equilibrium with cryostat



# Measurement cools mechanical motion below single phonon occupancy

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

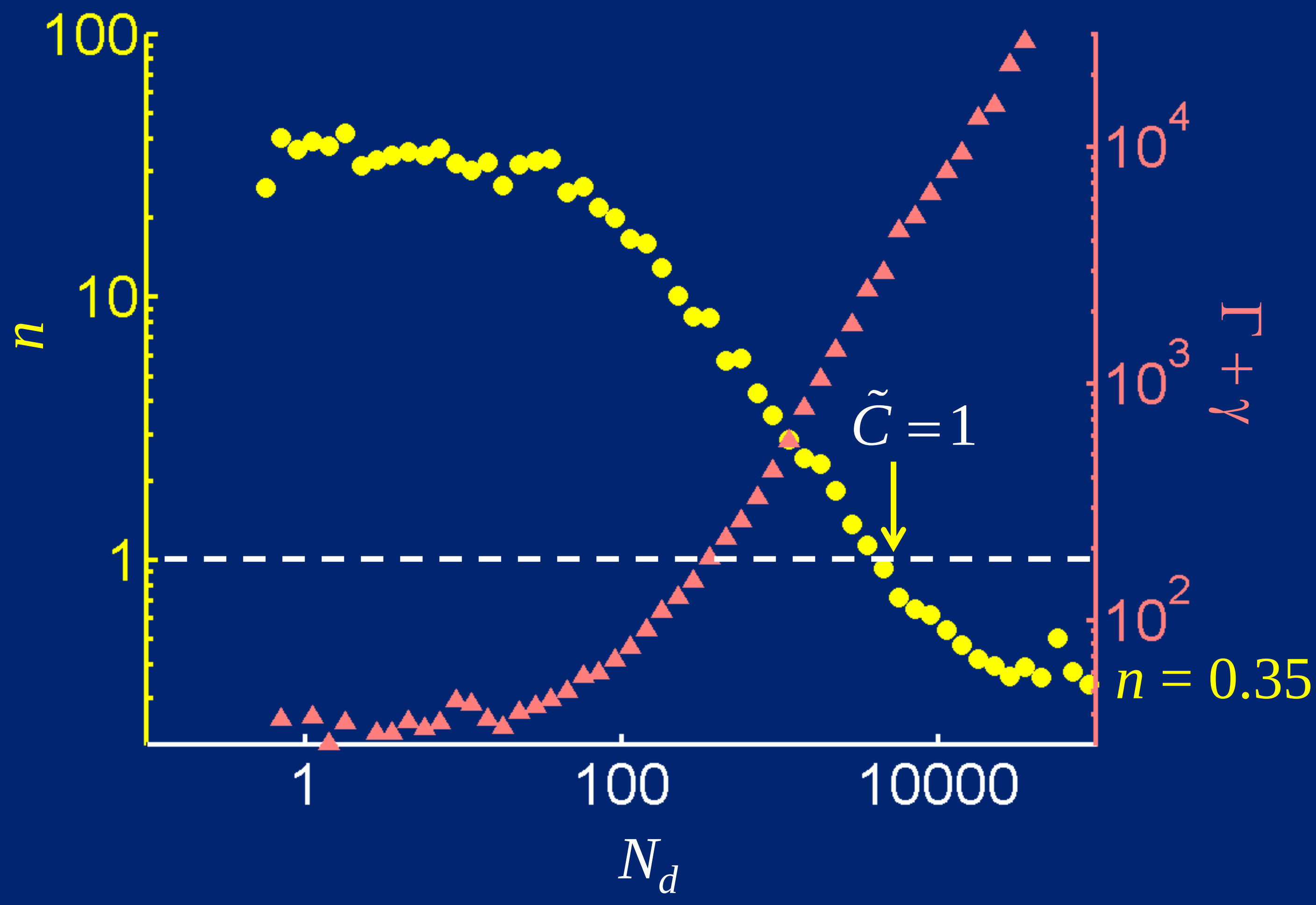



$$\Gamma = \frac{4N_d G^2}{\kappa}$$

Increasing strength of measurement and cooling

JILA NIST CU

# Many-photon cooperativity > 1 accesses the quantum regime

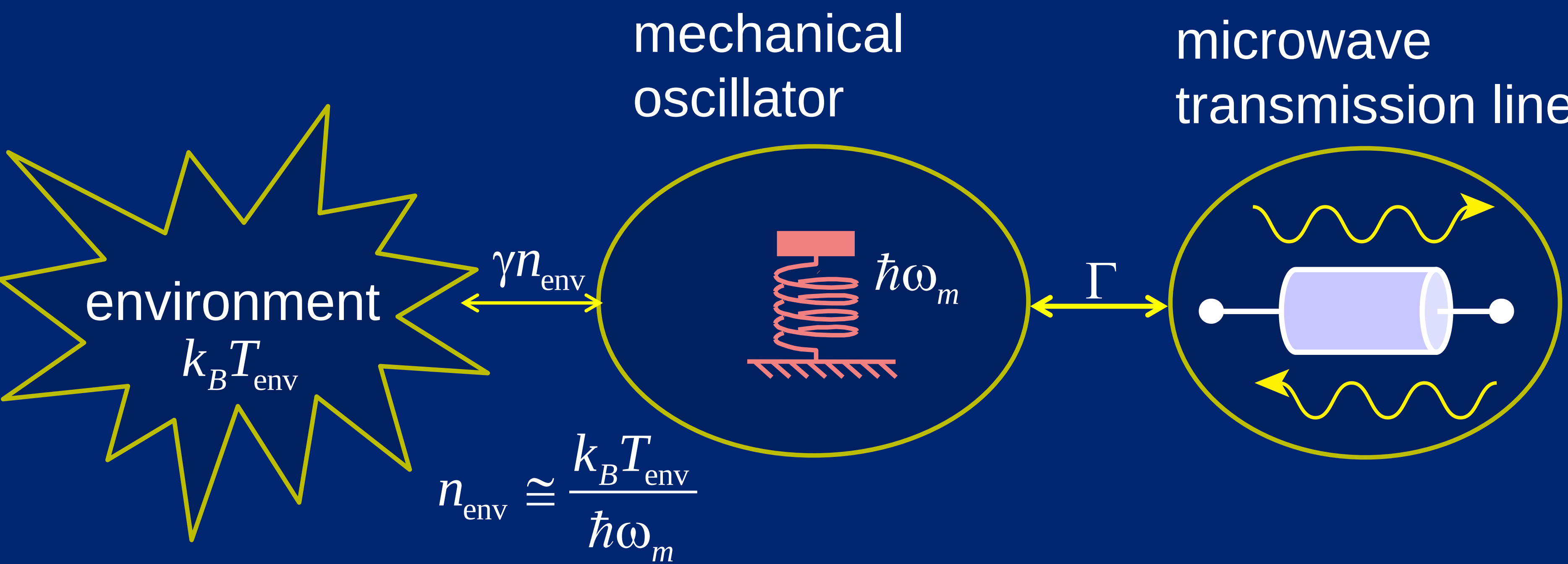



cooperativity

$$\tilde{C} = \frac{4 N_d G^2}{(n_{env}\gamma)\kappa}$$

# State transfer between mechanics and itinerant microwave fields

# Can mechanical oscillators form quantum coherent memories for intinerant microwaves?




catch, store, and release propagating microwaves

mechanical oscillators

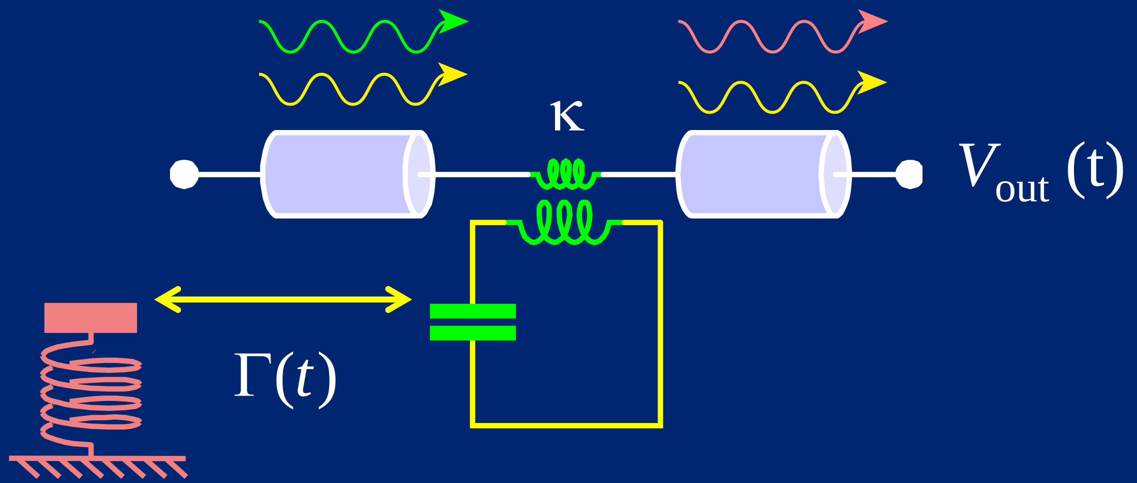
- long-lived coherence $T_2 > 300\ \mu s$
- compact
- integrable with superconducting qubits

# Large cooperativity enables quantum control of mechanics with microwaves

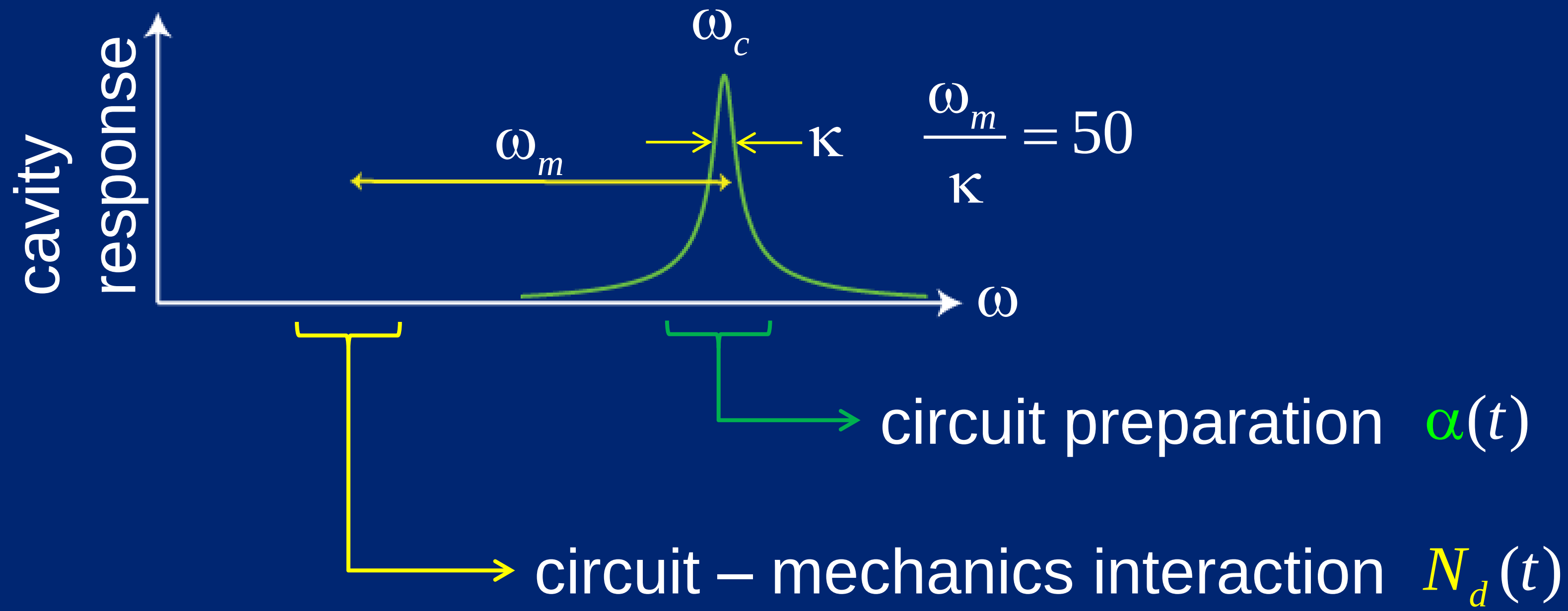
$$\hat{H}_I(t) = \hbar G \sqrt{N_d(t)} \left( a b^\dagger + a^\dagger b \right)$$

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

$n_{\mathrm{env}} \gamma < \Gamma < \kappa$ state transfer between mechanics and itinerant microwave fields

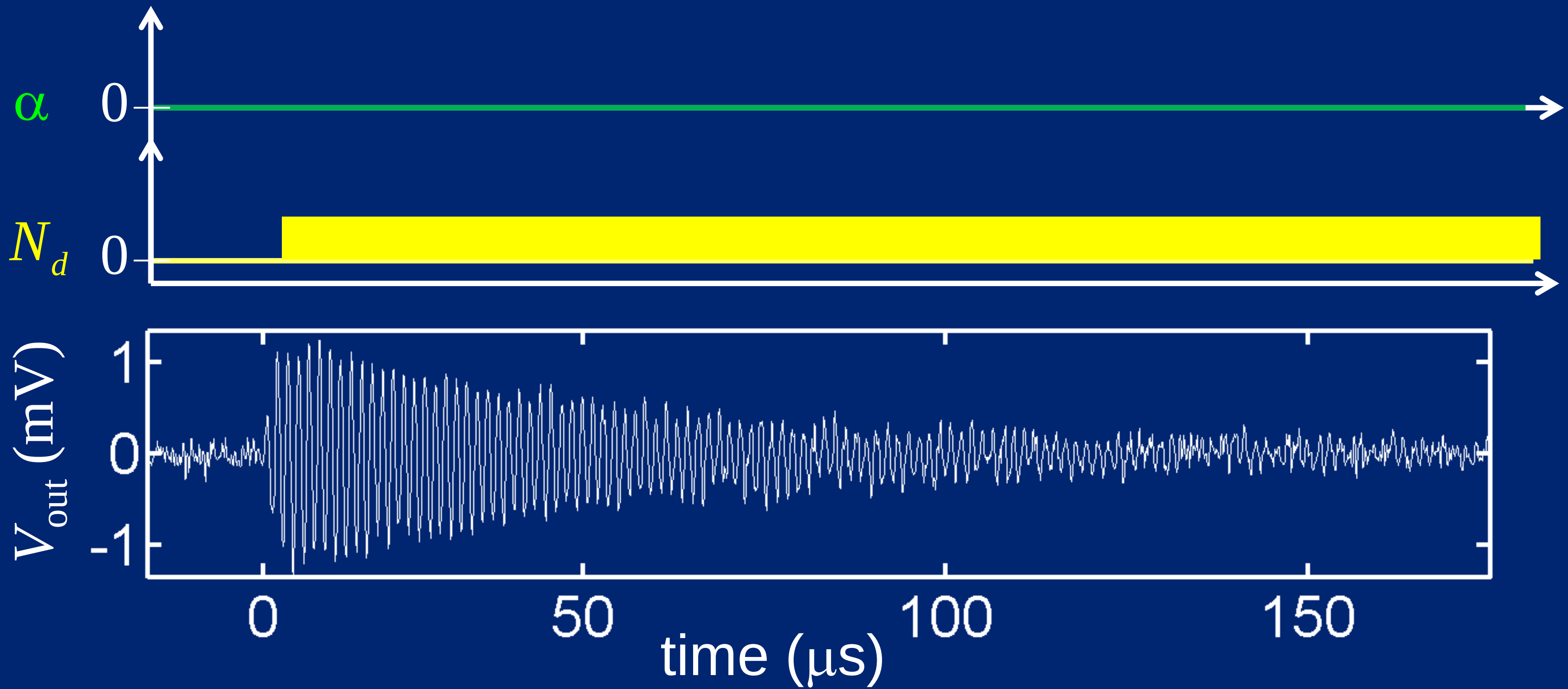


# Extreme resolved sideband limit enables agile state control

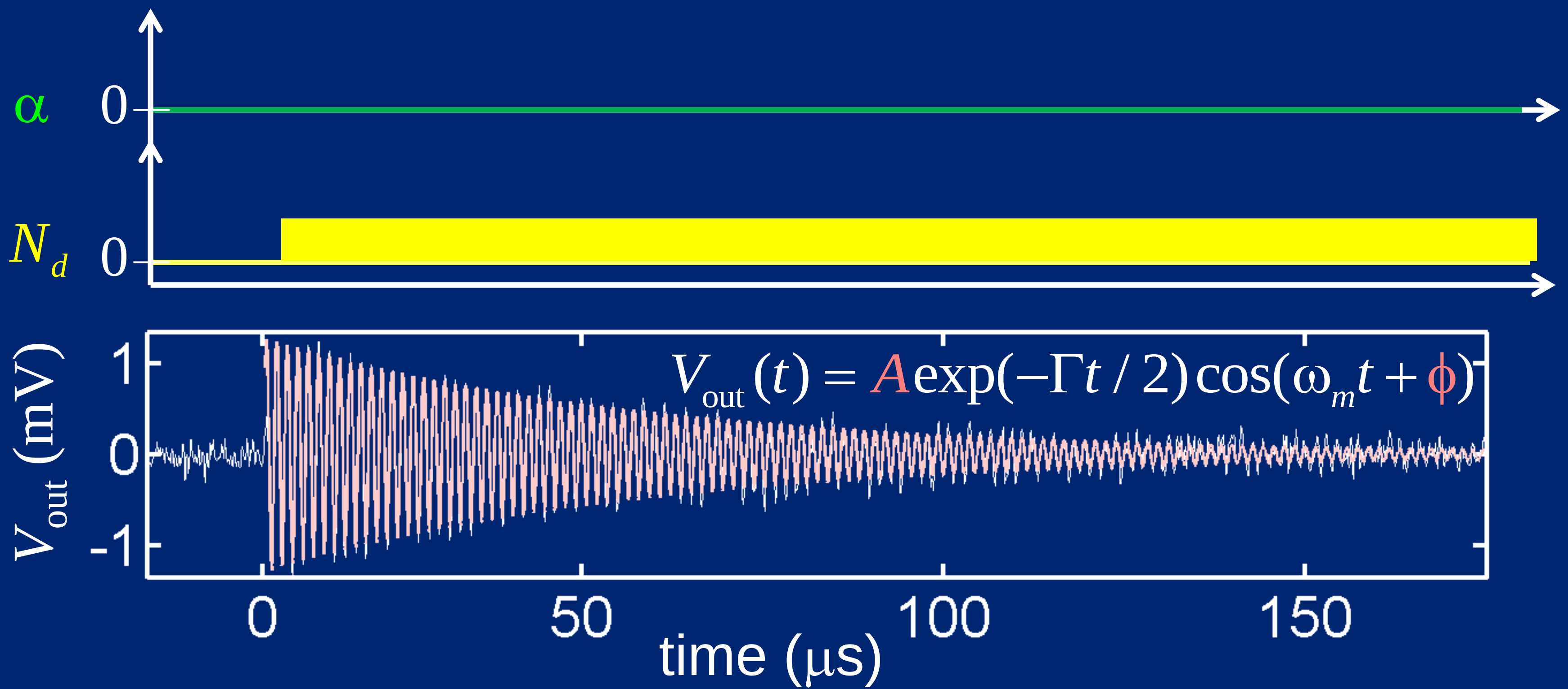



$$\hat{H}_I = \hbar G \sqrt{N_d(t)}\left(ab^{\dagger} + a^{\dagger}b\right)$$

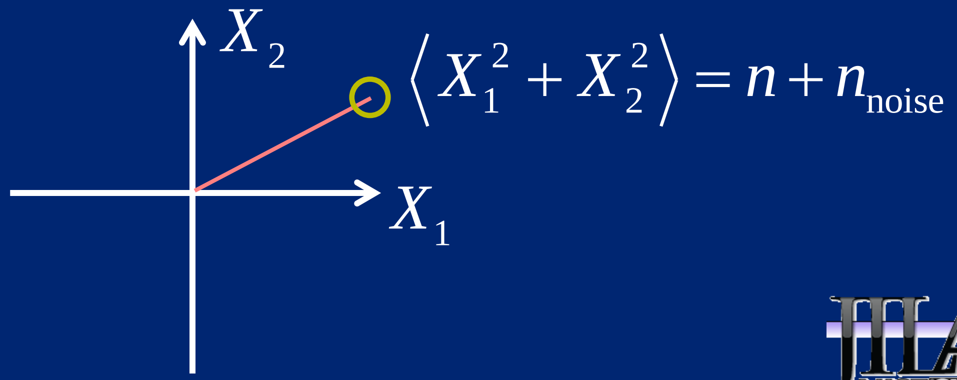
# Measure oscillator via state transfer to itinerant microwave fields



# Measure oscillator via state transfer to itinerant microwave fields




optimally filter to find quadrature amplitudes

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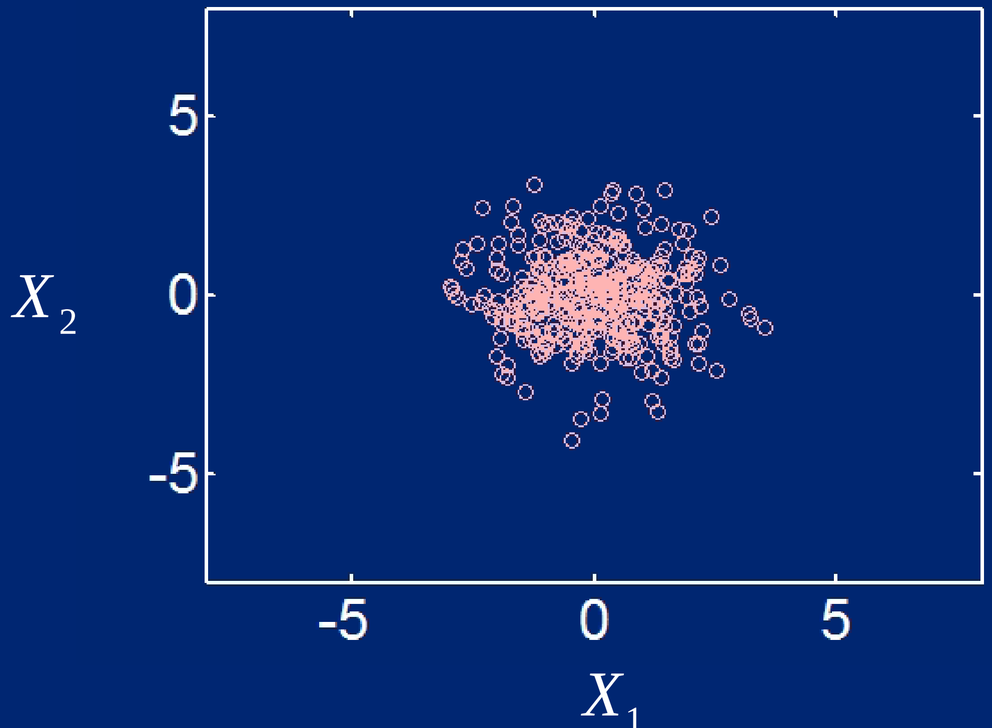
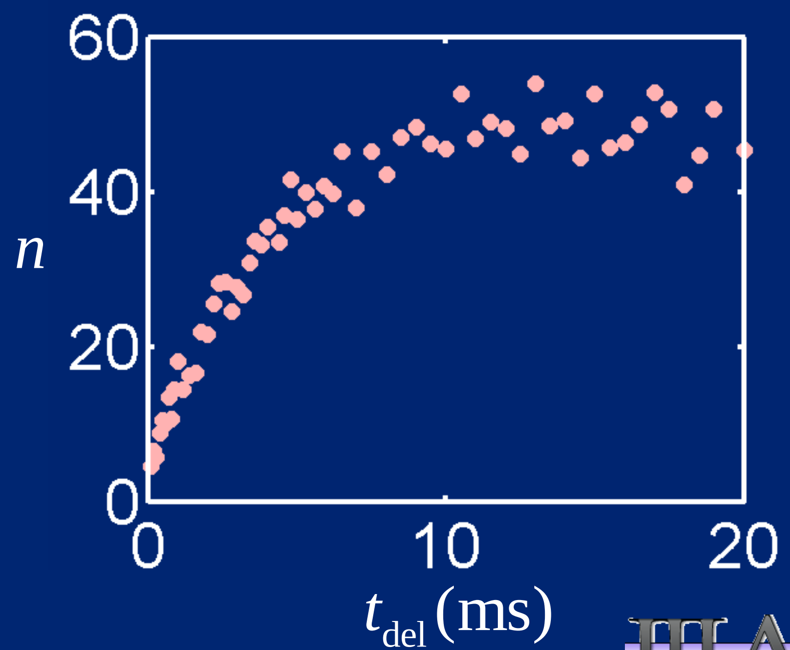
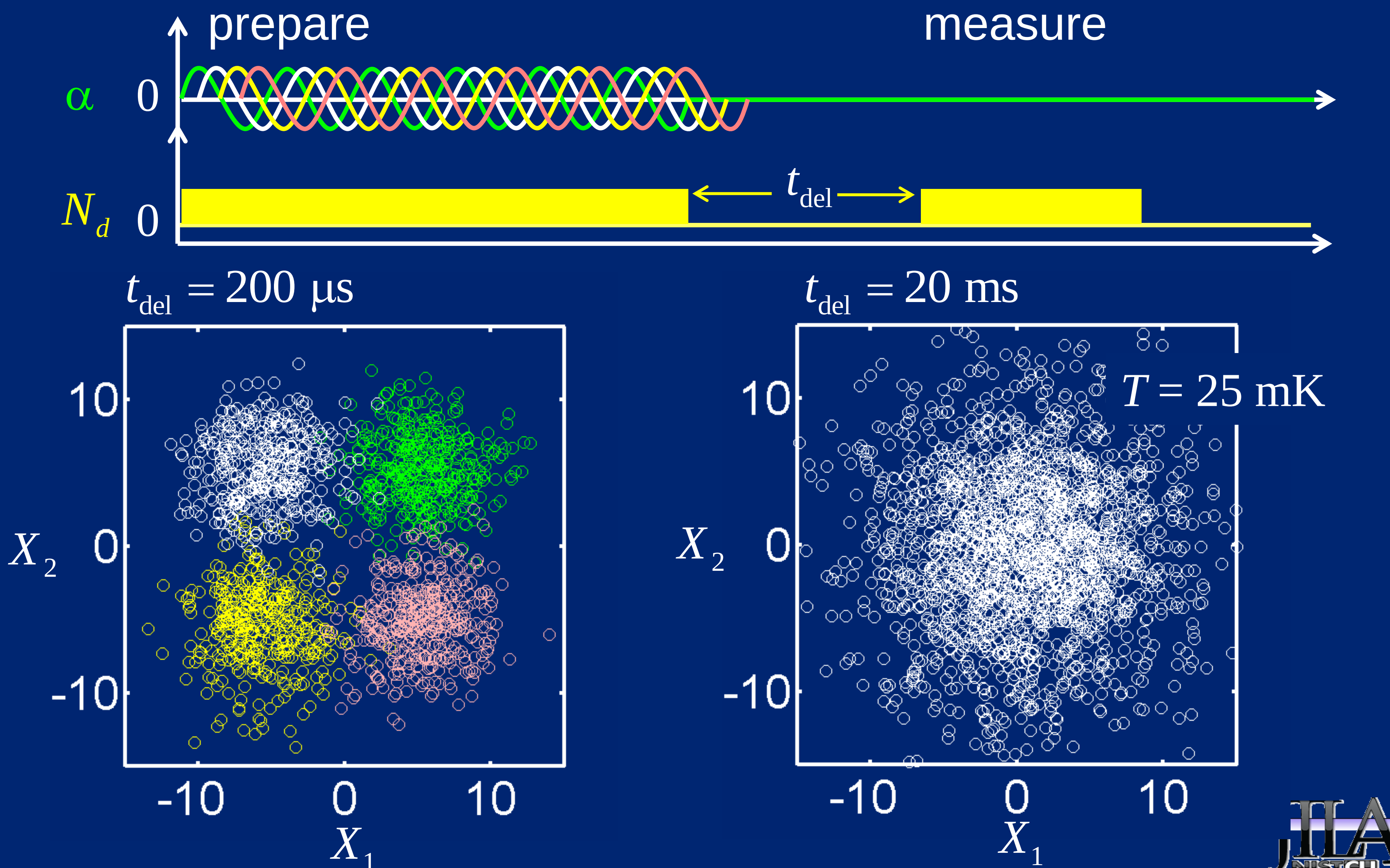
# Thermal state of oscillator reconstructed by repeated measurements


$t_{del} = 0.1$ ms

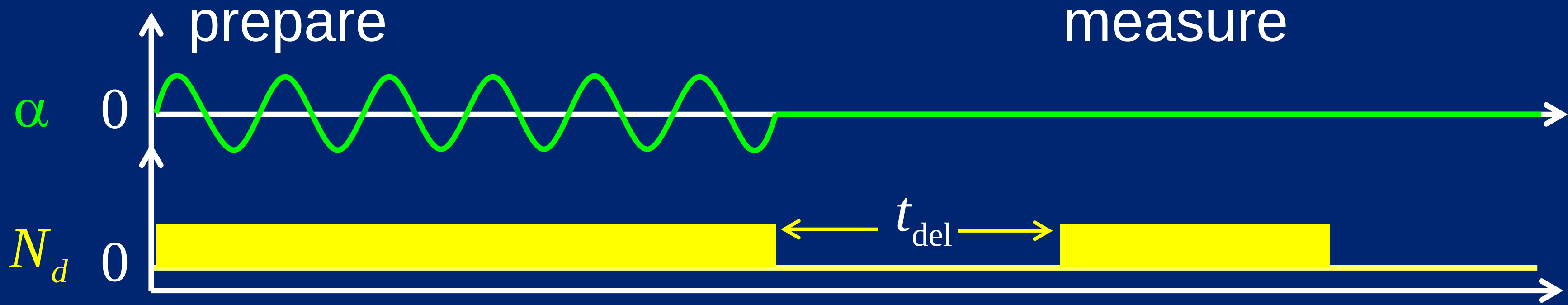


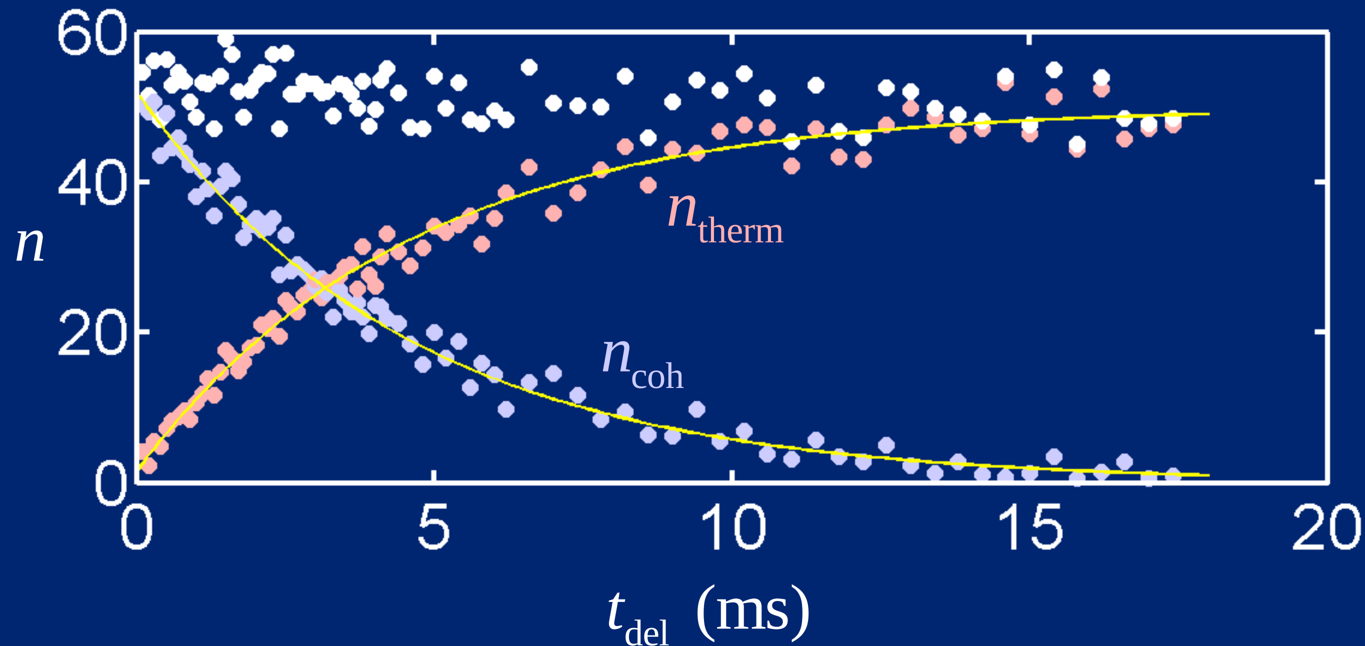
# Mechanical oscillator is a long-lived coherent memory for microwaves



# State transfer prepares mechanical oscillator in a low entropy state

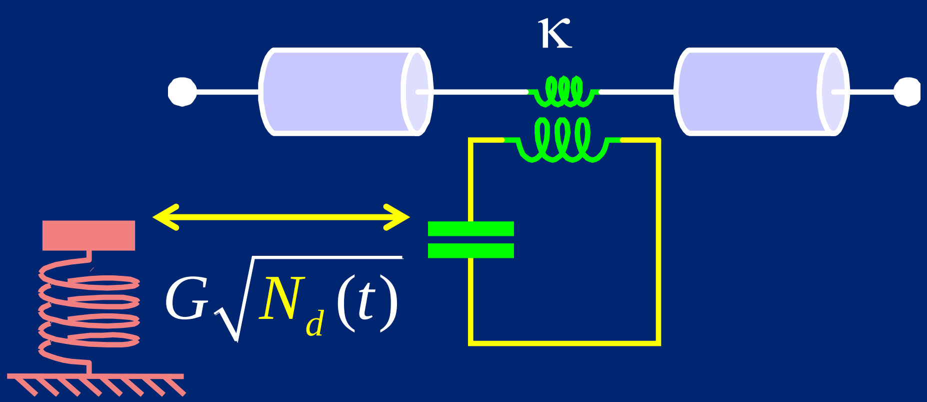



$$n_{coh} = \langle X_1 \rangle^2 + \langle X_2 \rangle^2 - n_{noise} \qquad n_{therm} = \langle \Delta X_1^2 \rangle + \langle \Delta X_2^2 \rangle - n_{noise}$$



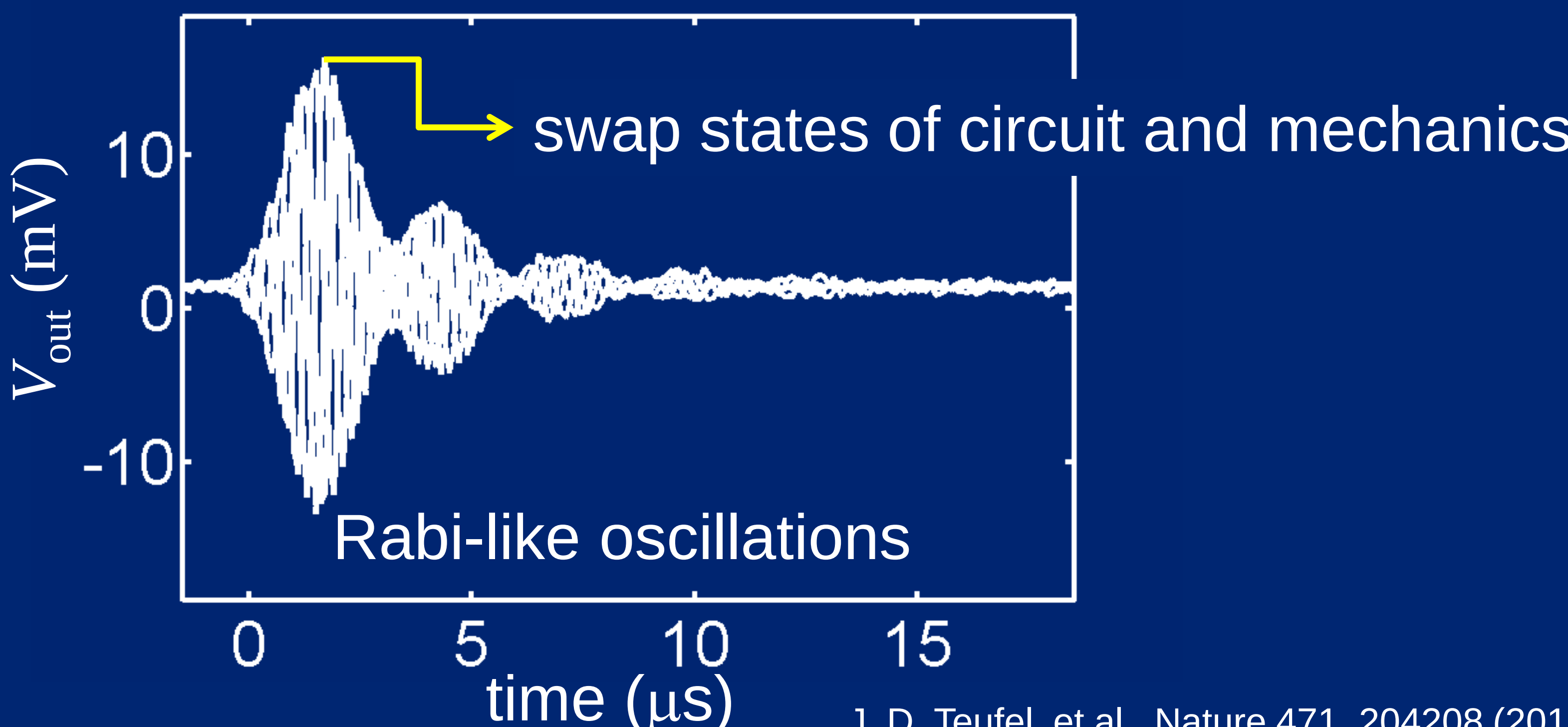
# State transfer between mechanical oscillator and microwave circuit

# Strong coupling regime enables state transfer between circuit and mechanical oscillator



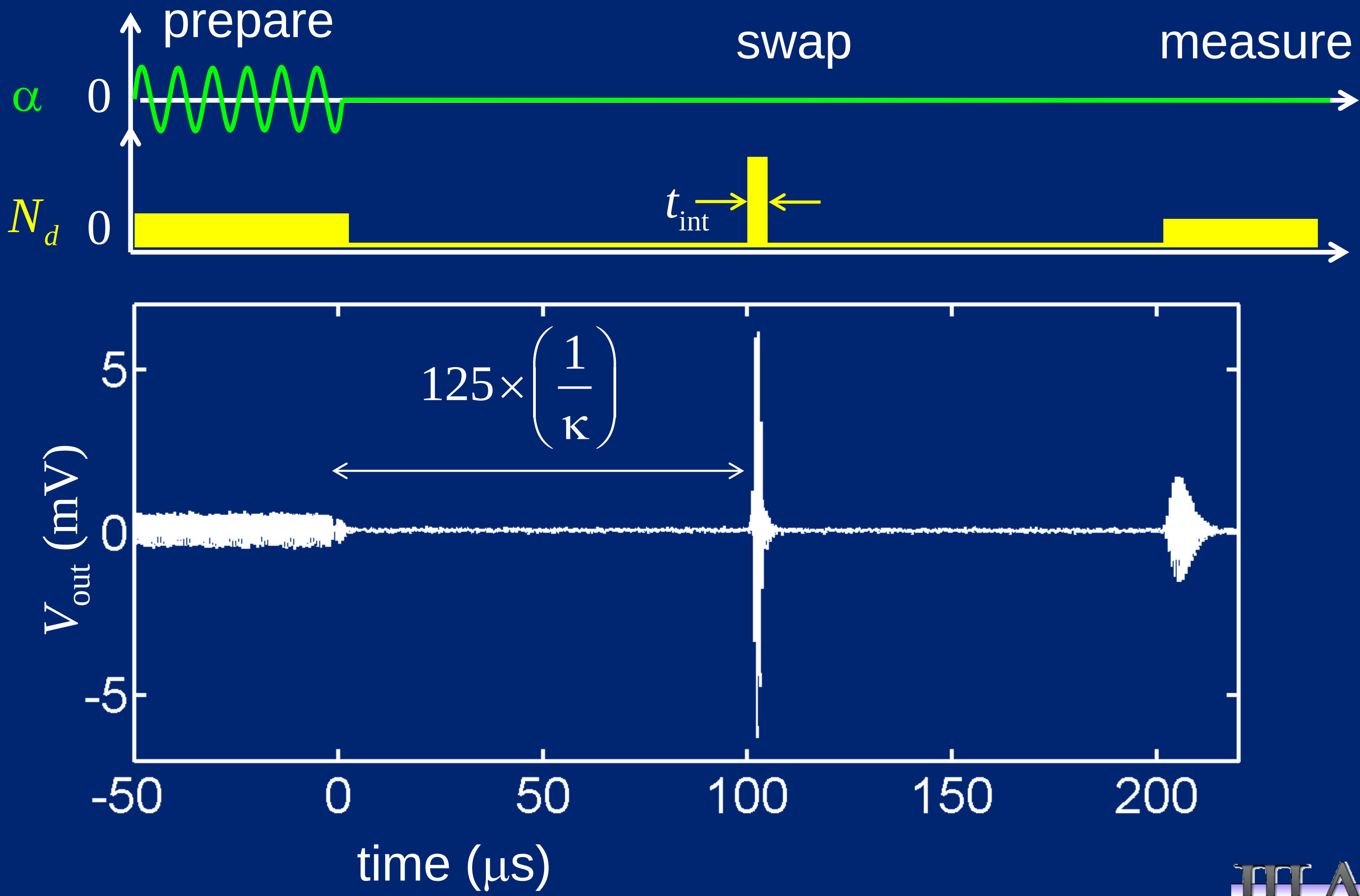

$G\sqrt{N_d} > \kappa, n_{therm}\gamma$

state transfer between mechanics and LC circuit

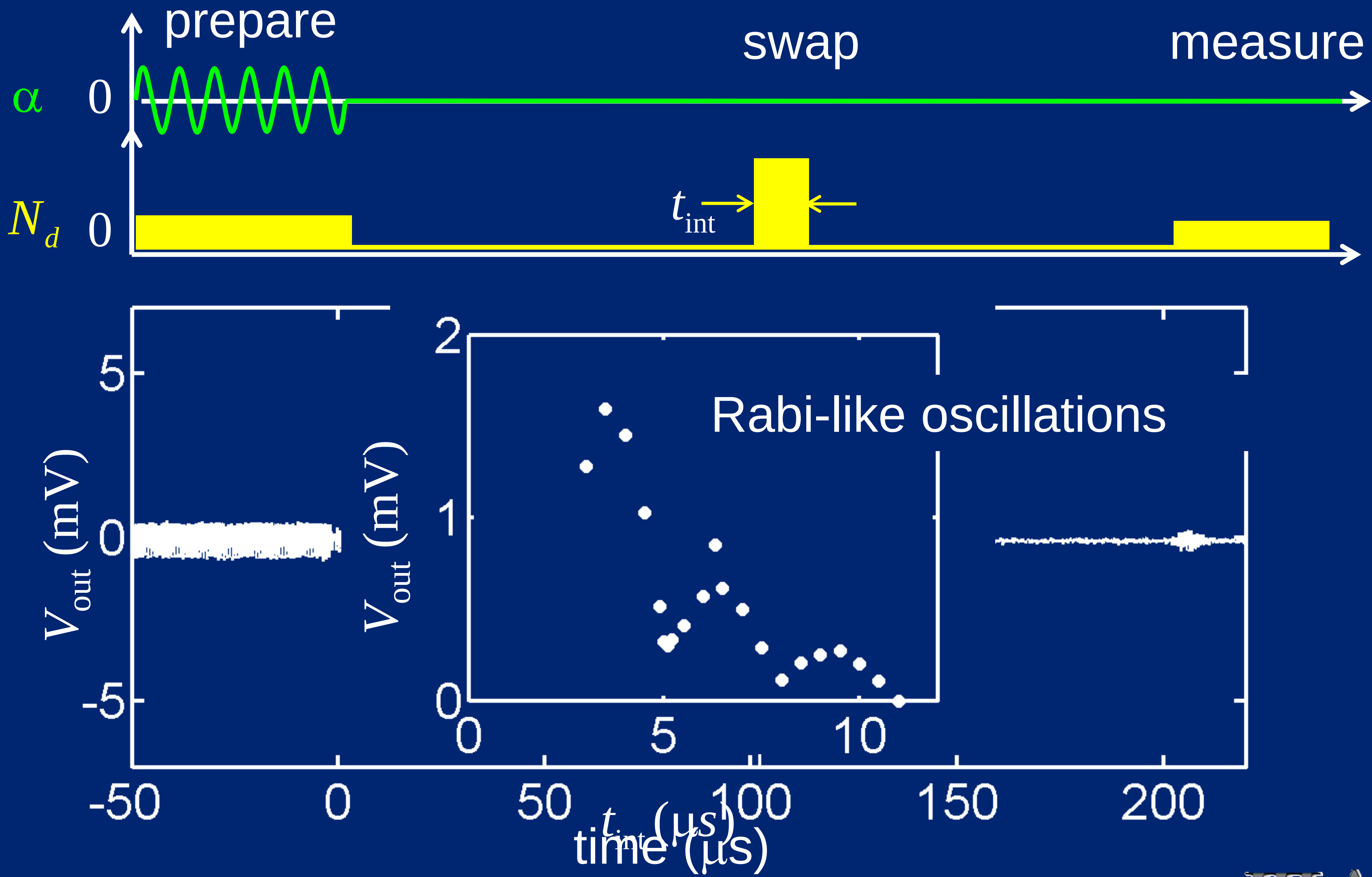



J. D. Teufel, et al., Nature 471, 204208 (2011).

# Mechanical oscillator stores state much longer than resonant circuit



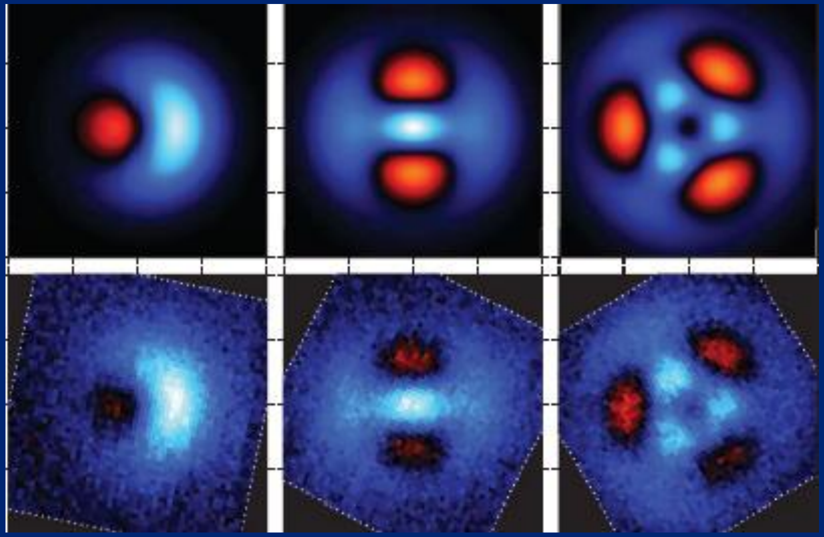
# Mechanical oscillator stores state much longer than resonant circuit



# A quantum interface between electricity and light

with Cindy Regal
and Ray Simmonds

# Microwave to optical quantum state transfer



Hofheinz…Martinis, Cleland, Nature (2009)

Microwaves:

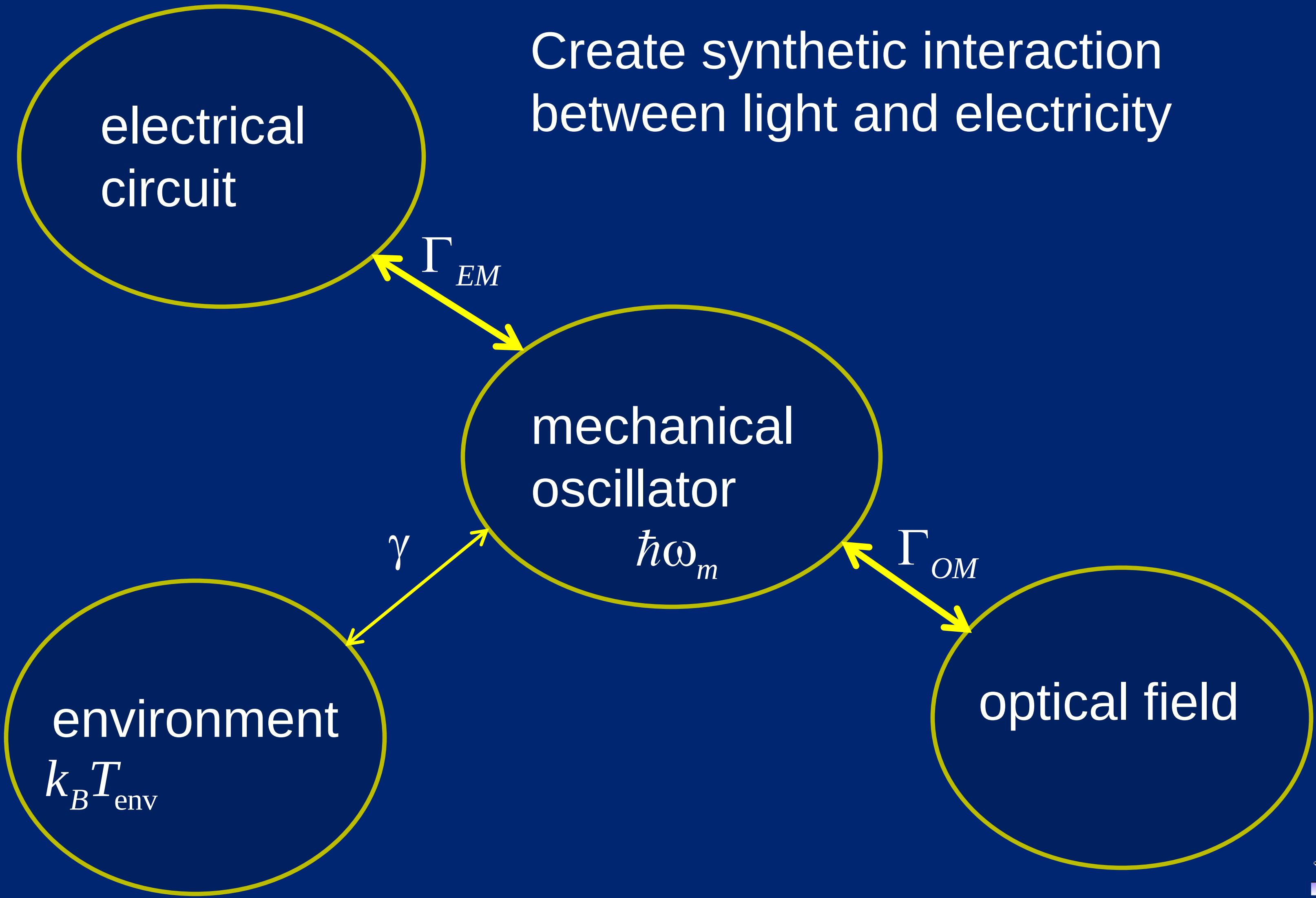
- Arbitrary quantum states
- Require ultralow temperatures

Optics:

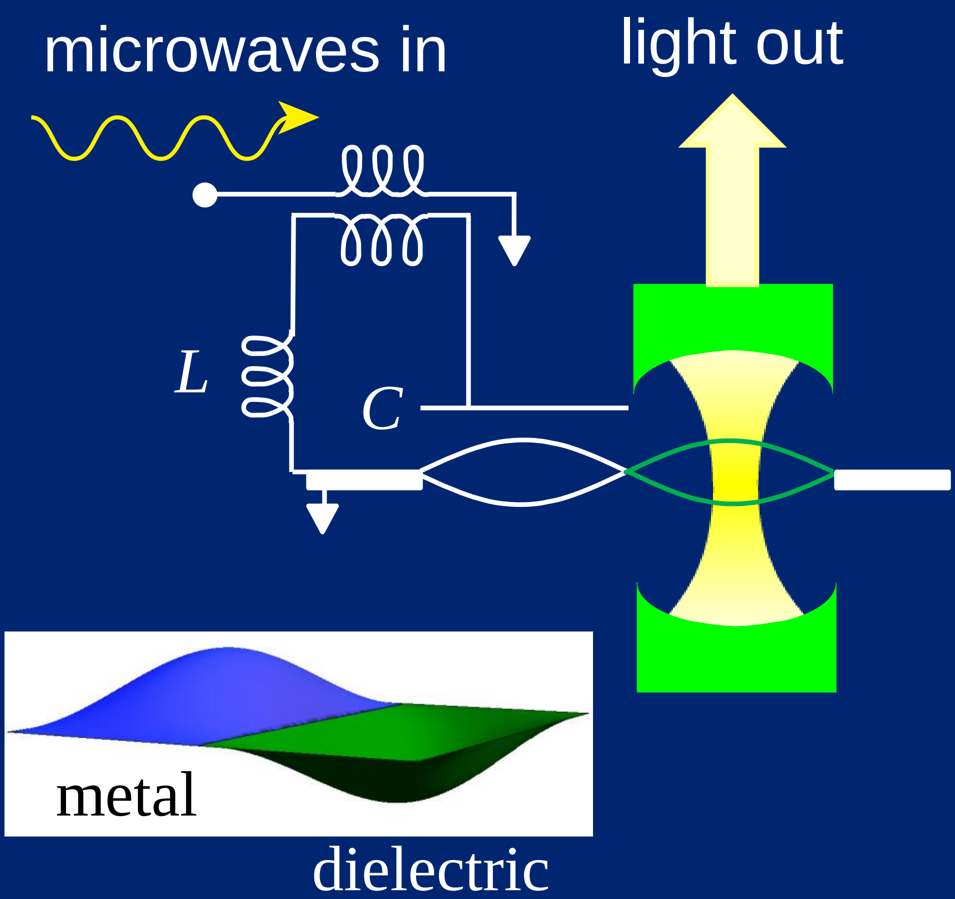
- Communication and storage

# Mechanical oscillators couple to both light and electricity in a quantum regime

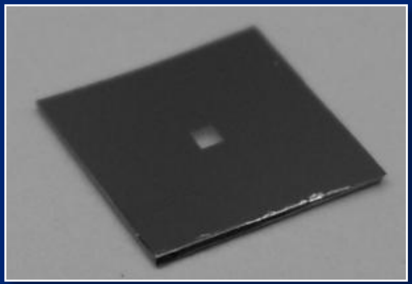
Create synthetic interaction between light and electricity



# Couple microwave to optics through one mechanical oscillator

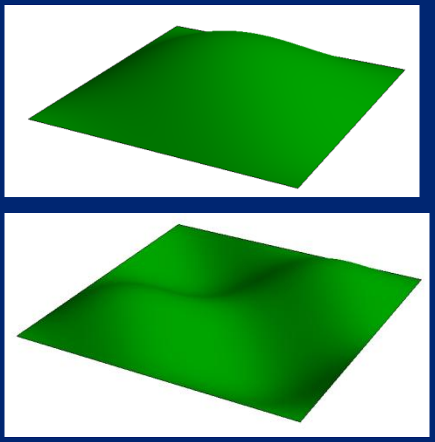



Membrane in free-space cavity
Superconducting LC circuit



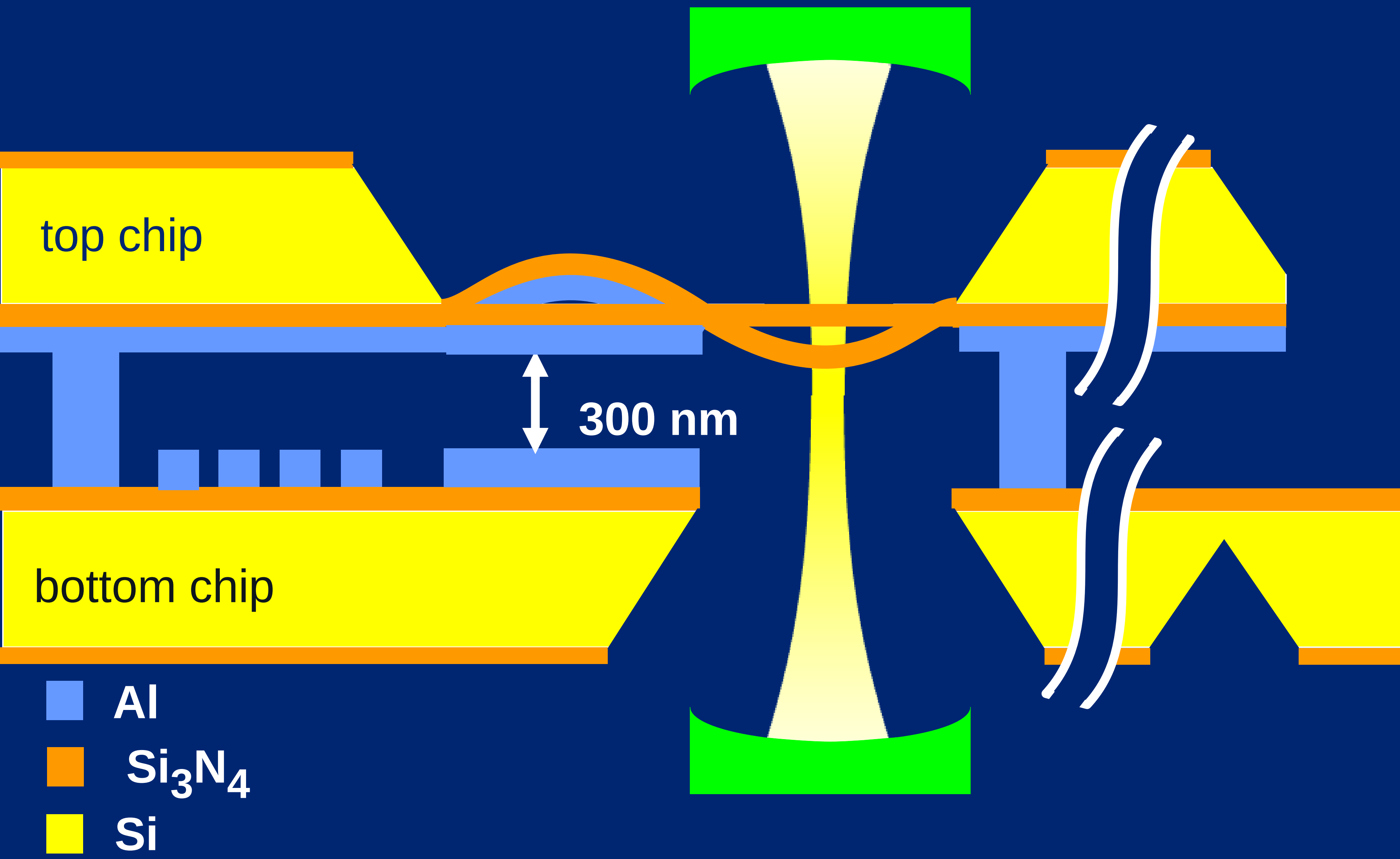
$Si_3N_4$ membrane

(1,1)
(2,2)

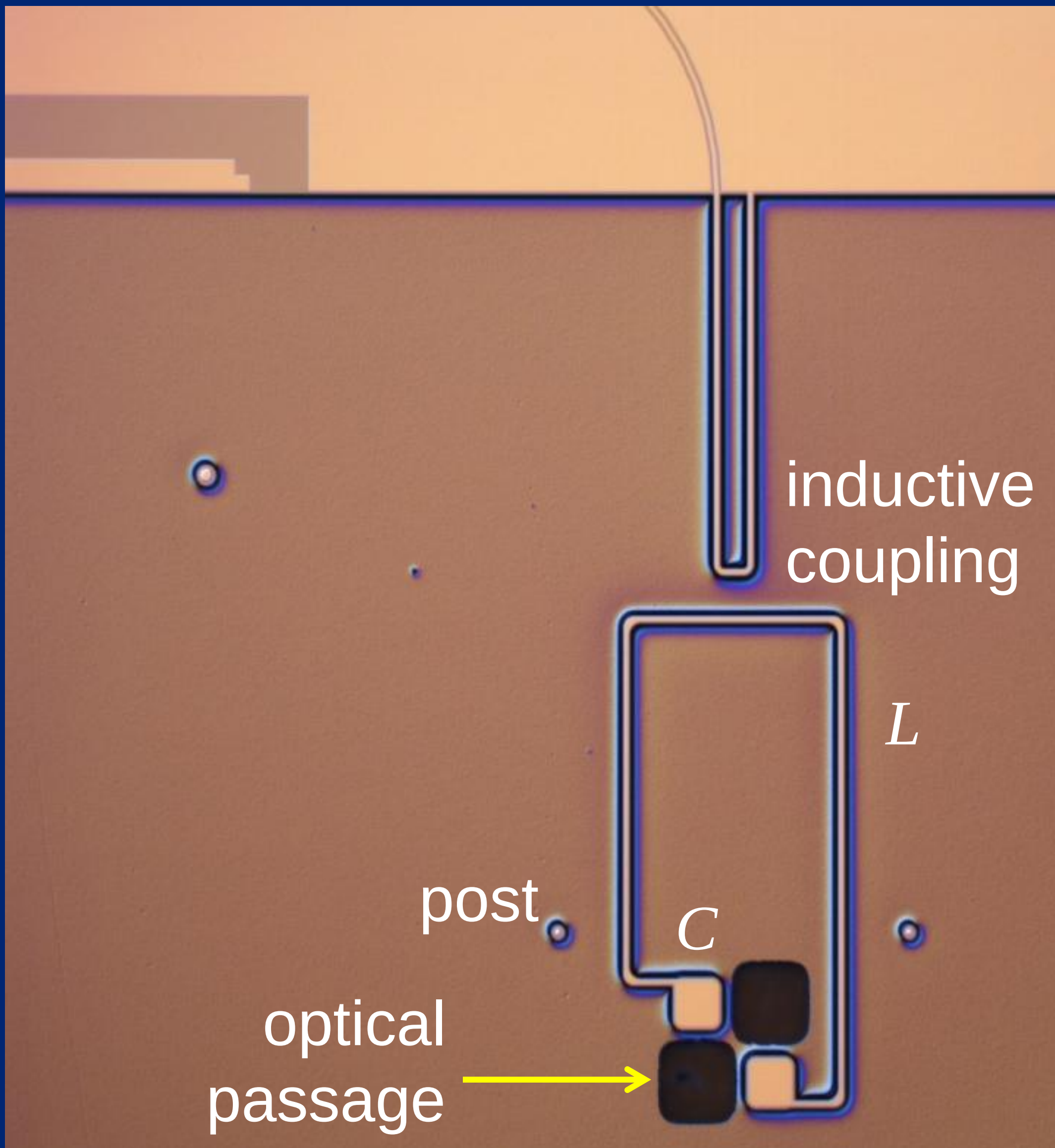


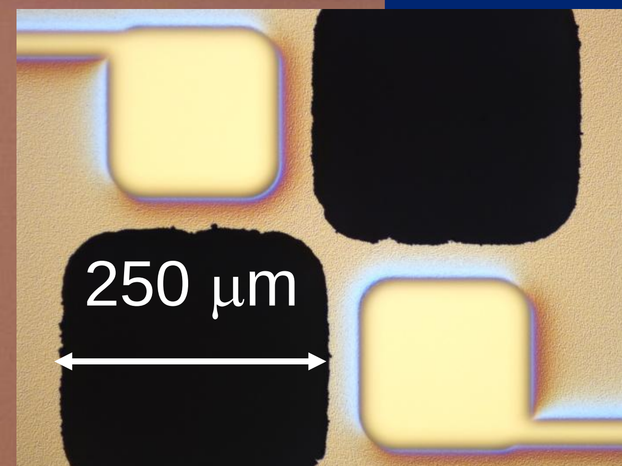
Mechanics and optics couple to different antinodes

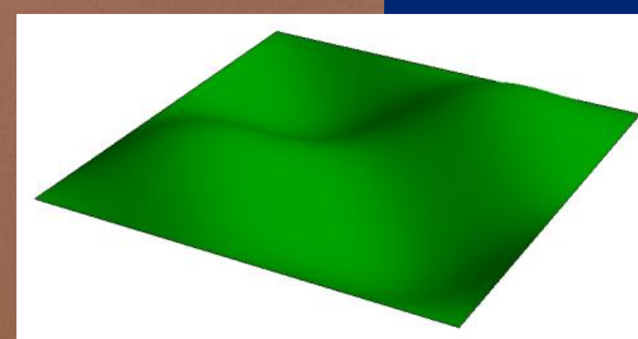
# Assemble optical-electrical-mechanical device by joining two chips



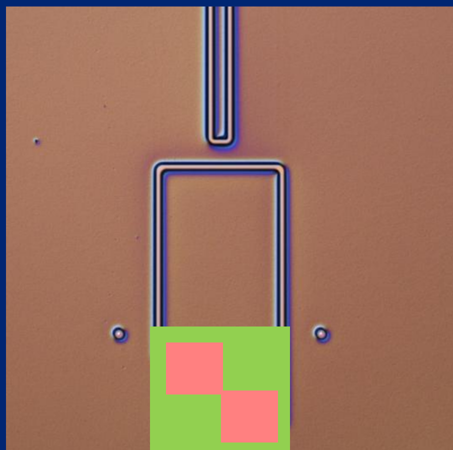
# Bottom chip: part of a microwave resonant circuit

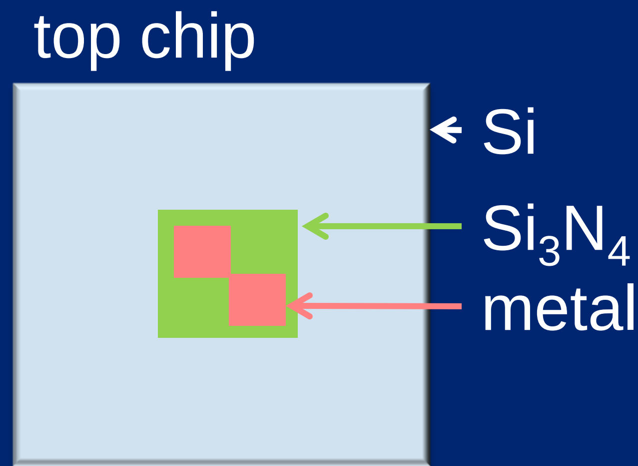


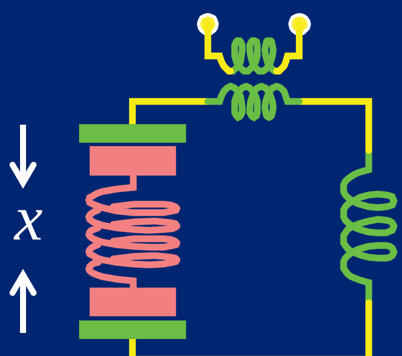



# Opto-electromechanical exploits symmetry of 2,2 membrane mode

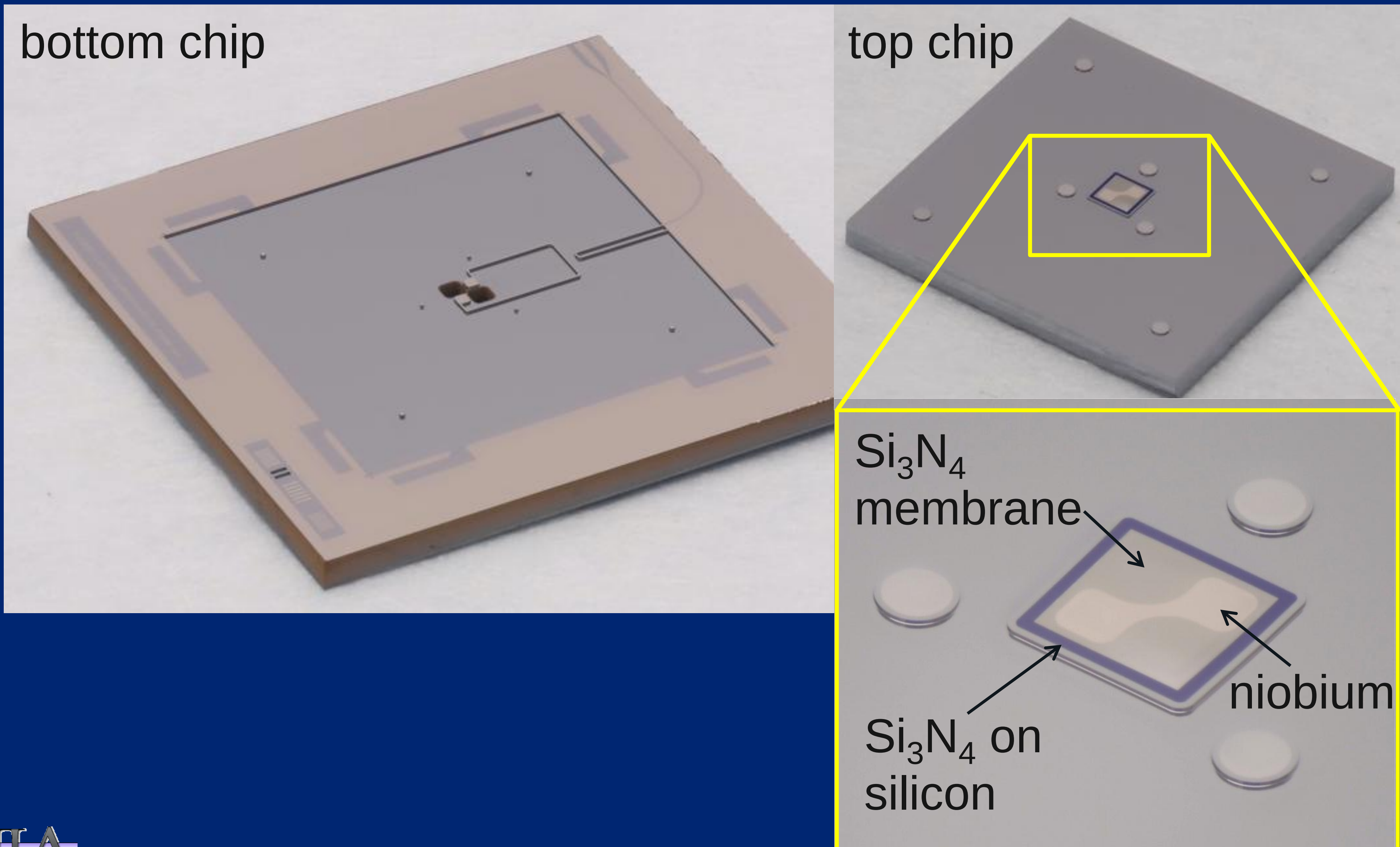




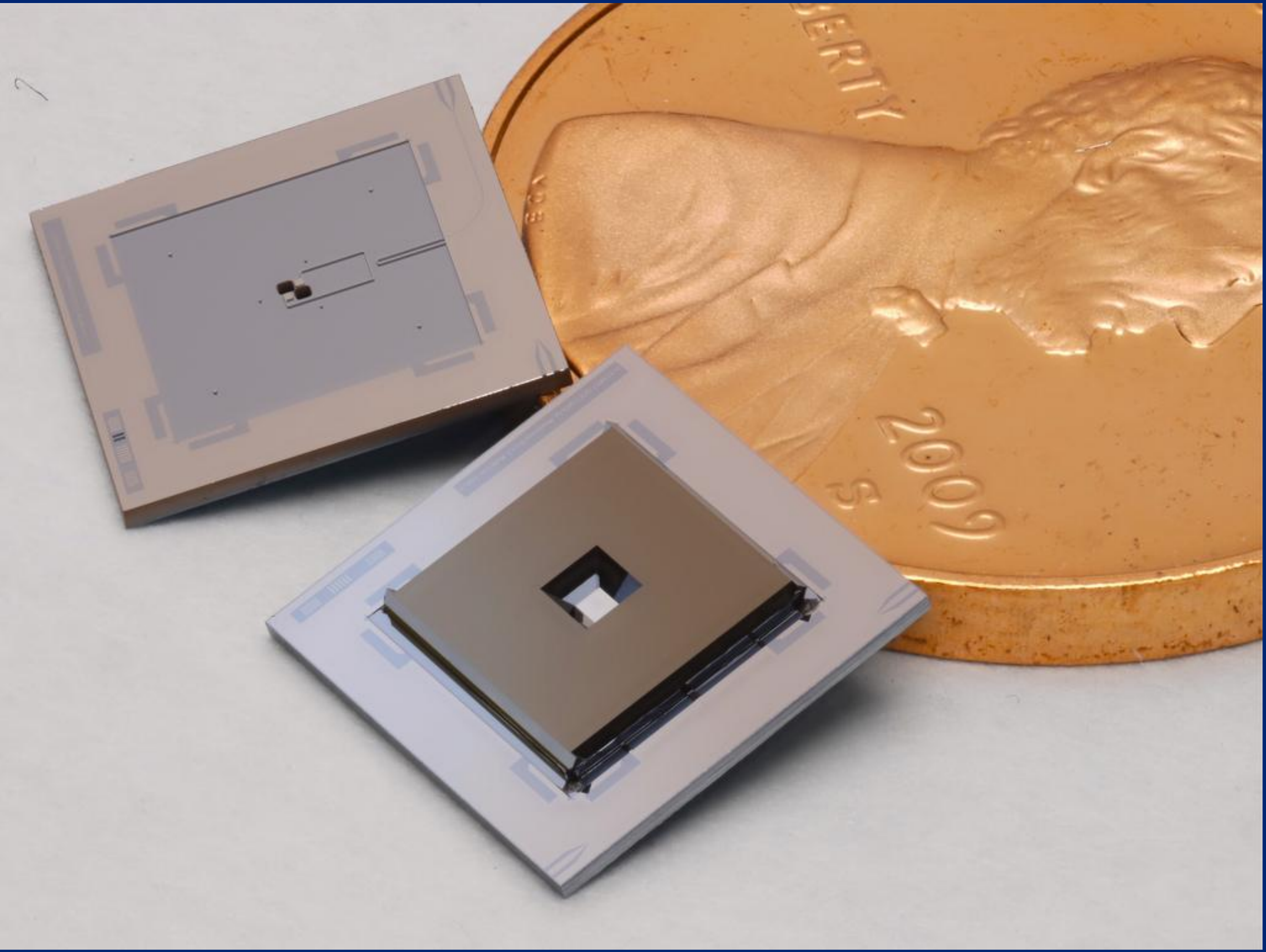




no galvanic connection
between top and bottom chip

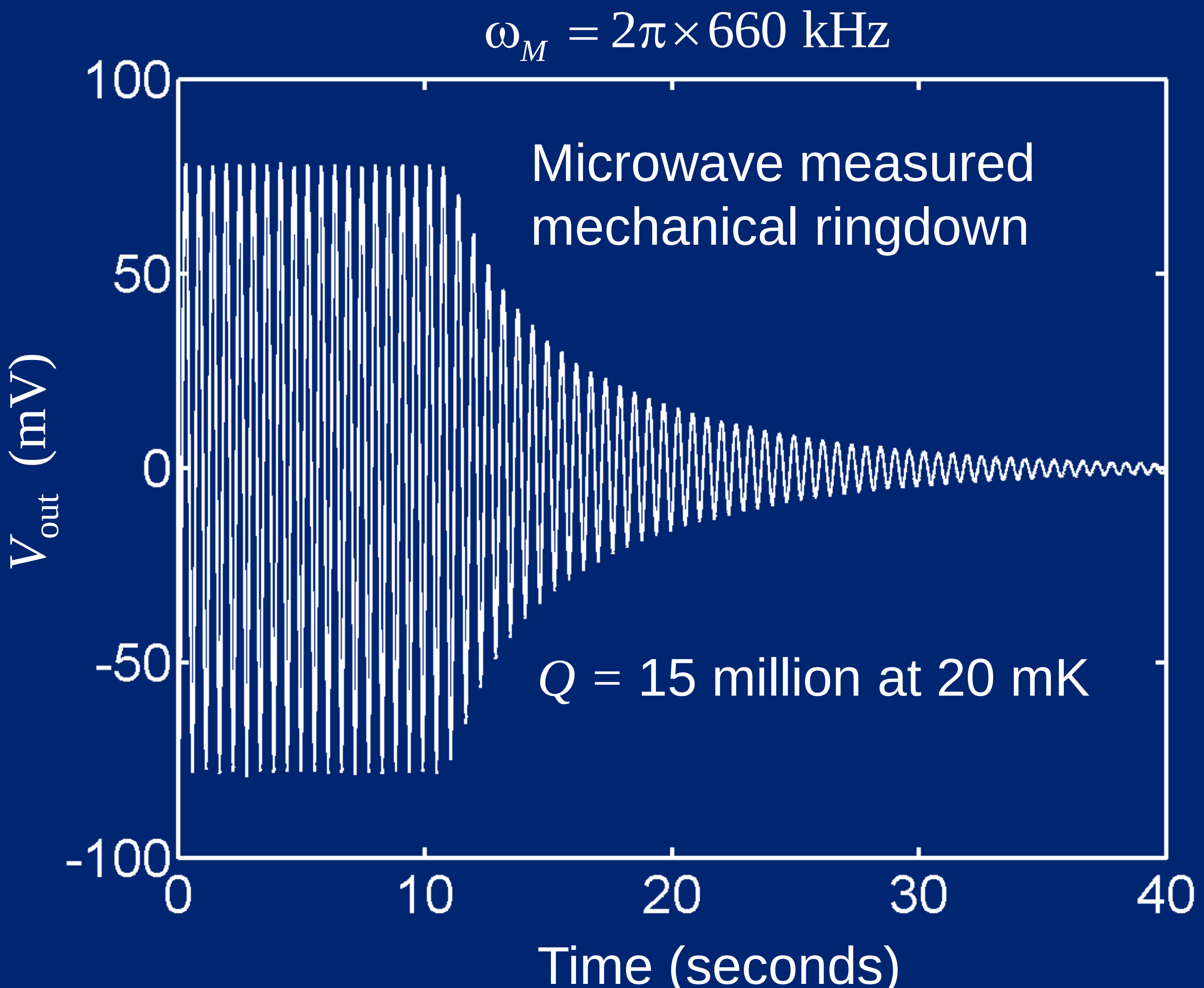
# Images of bottom and top chips



# Assembled flip-chip structure



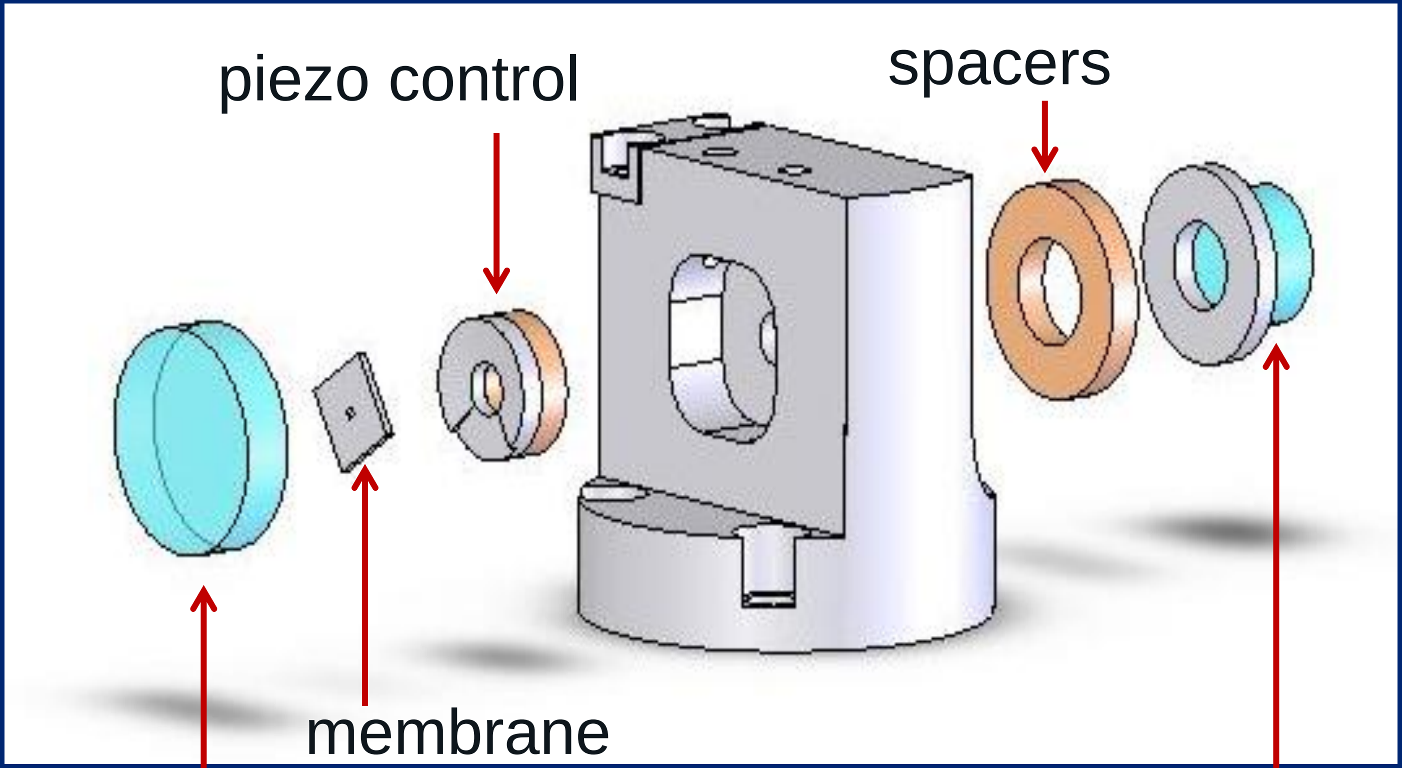
# Electromechanics with a $Si_3N_4$ membrane



# Dielectric membrane in optical cavity*

Regal group

design of optical cavity coupled to membrane motion




high finesses end mirror

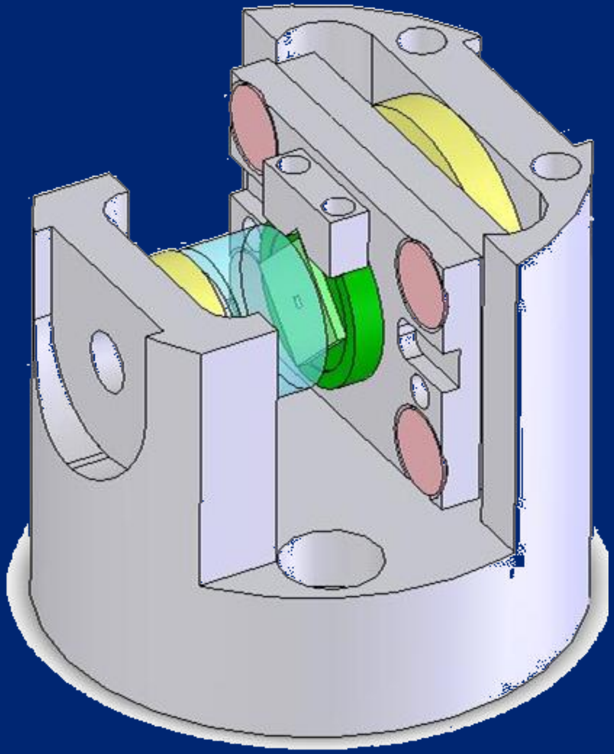
high finesses end mirror

"*Membrane in the middle"

J. D. Thompson, J. G. E. Harris, et al Nature 452 72–75 (2008)

# Compact, cryogenic optical cavity designed to incorporate opto-electromechanical structures

Regal group



design diagram

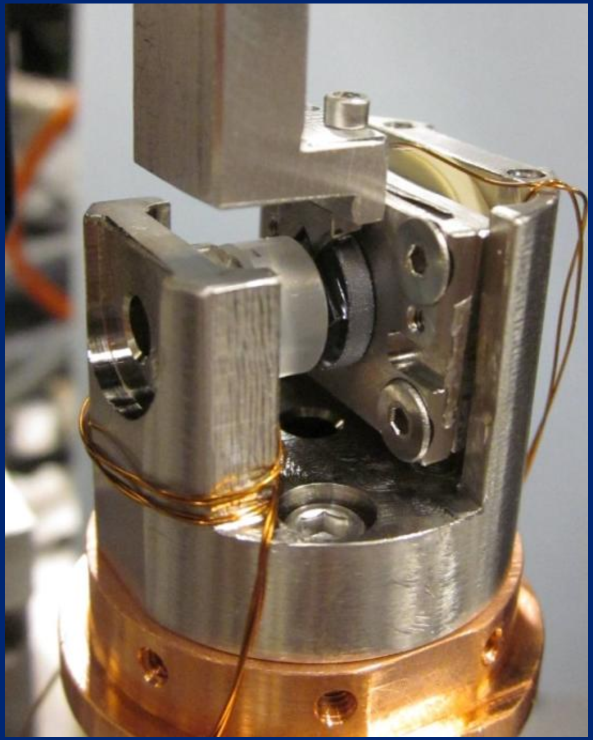
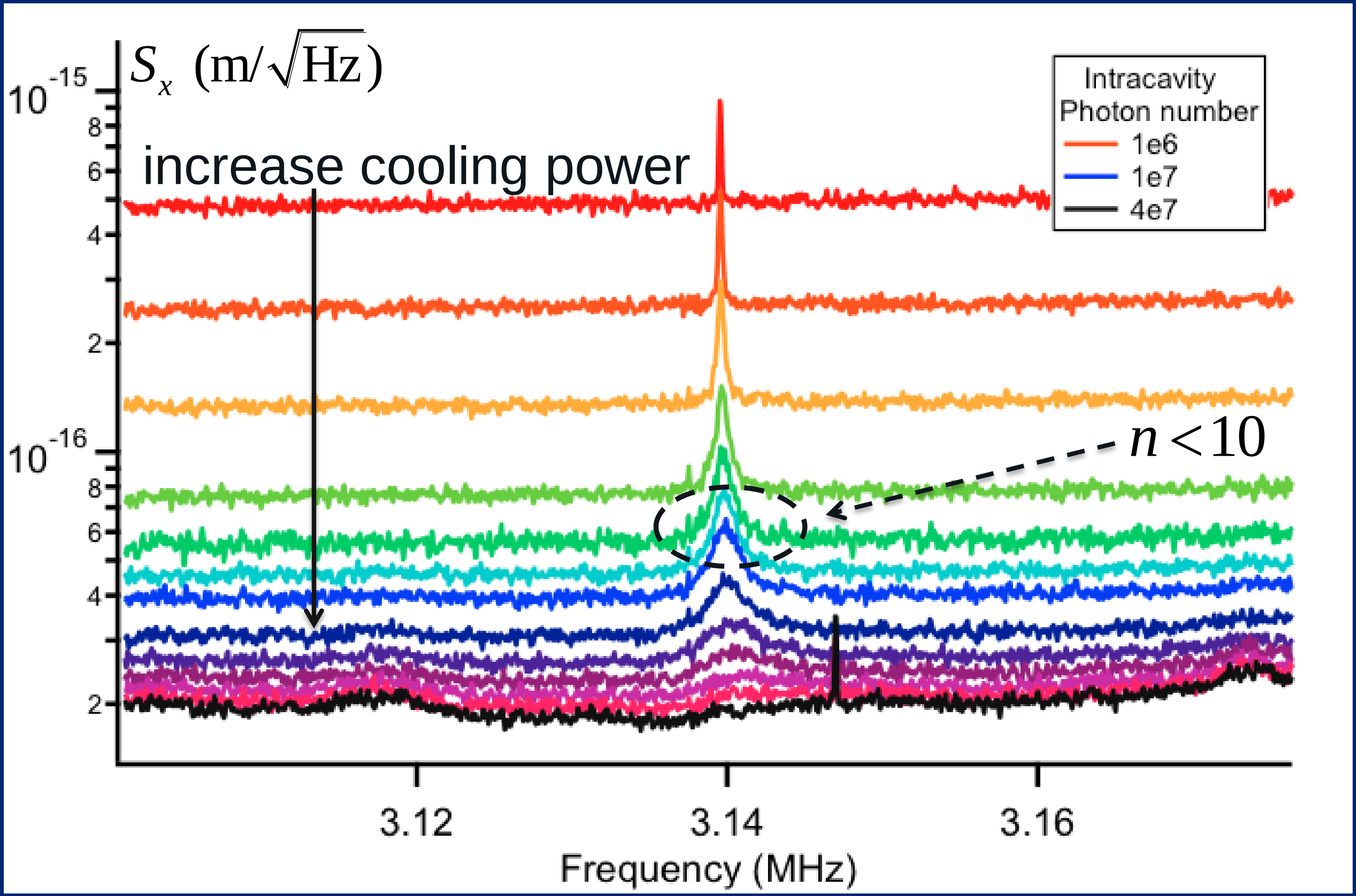


image in cryostat

# Membrane motion cooled to near ground state with optical light




# Conclusions

- Ground state cooling of a low-frequency mechanical oscillator

- Mechanics: long-lived  coherent memory
    classical: 10 ms
    quantum: 300 μs (estimate)

- Ultrahigh Q electromechanics
with $Si_3N_4$ membranes

- Opto-electromechanics

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