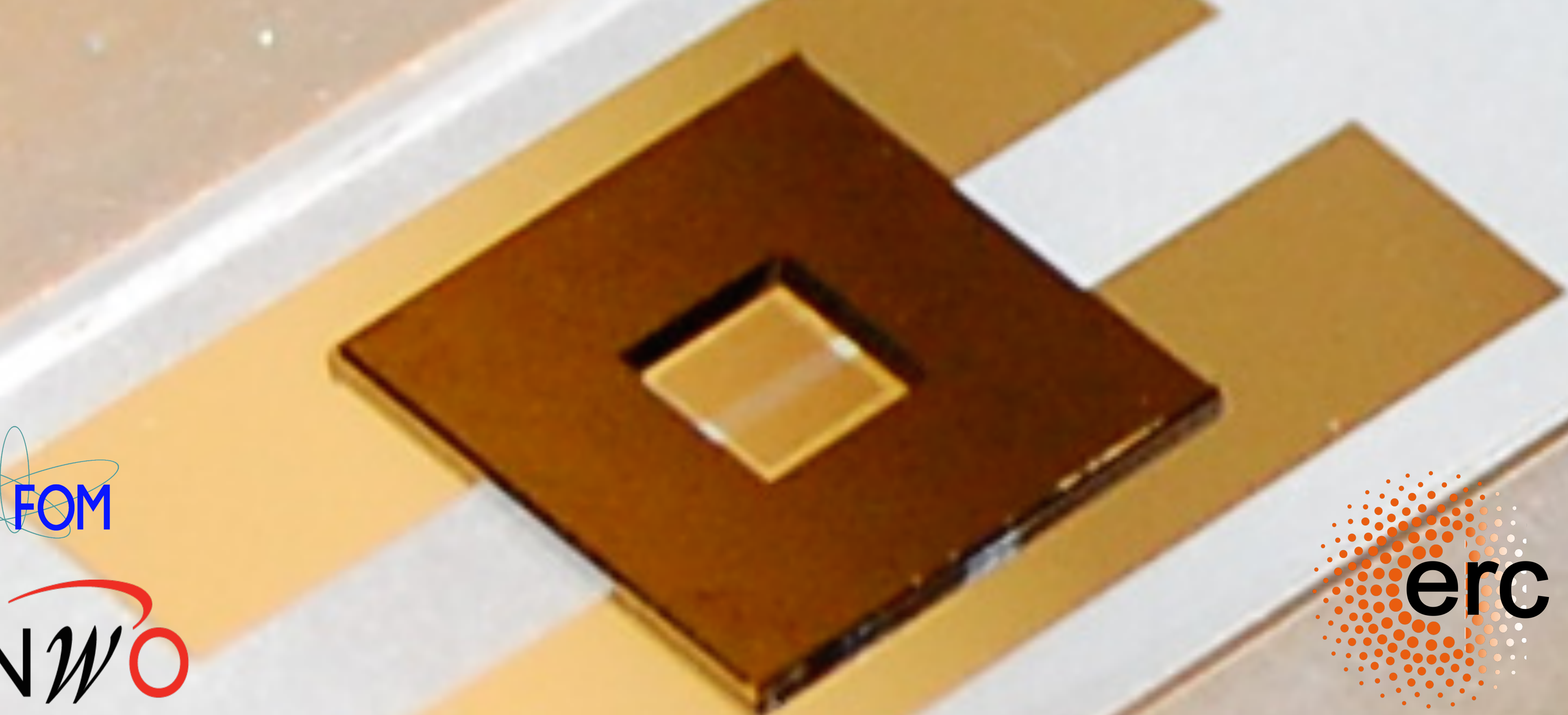
Microwave Optomechanics with 3D Cavities and (Ultra?) High-Q Silicon Nitride Membranes

Gary Steele, Kavli Institute of Nanoscience Delft

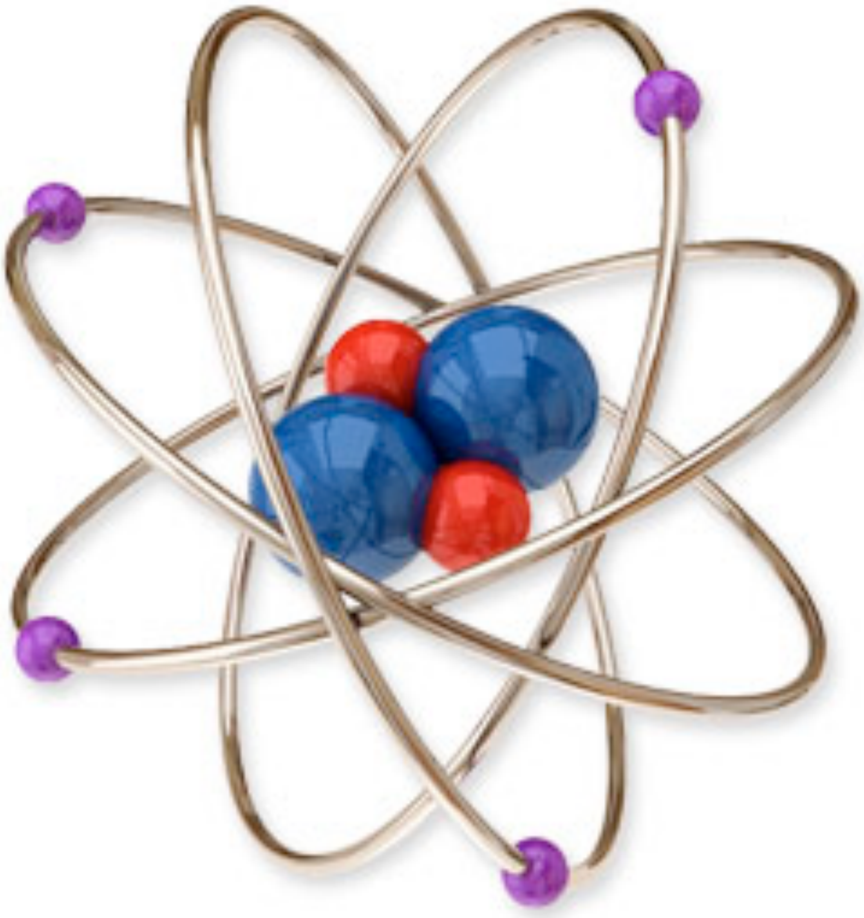


Vibhor Singh *Sal Bosman* *Martijn Cohen* *Mario Gely*
Mingyun Yuan *Shun Yanai* *Yaroslav Blanter* ***Gary Steele***

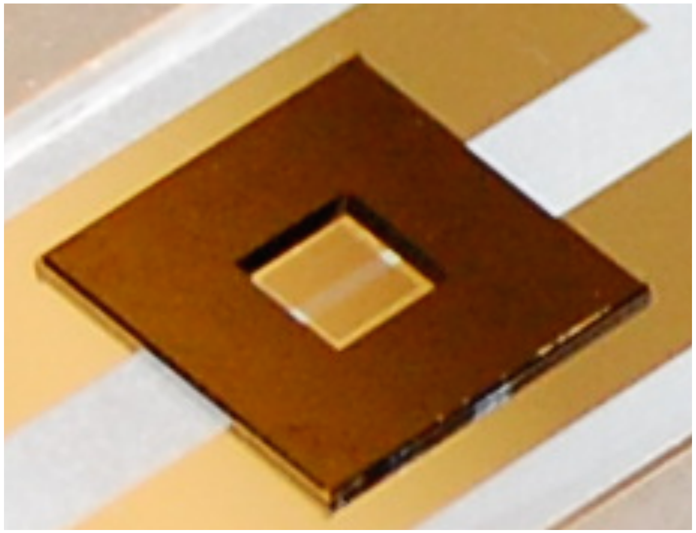
http://steelelab.tudelft.nl

Our motivation

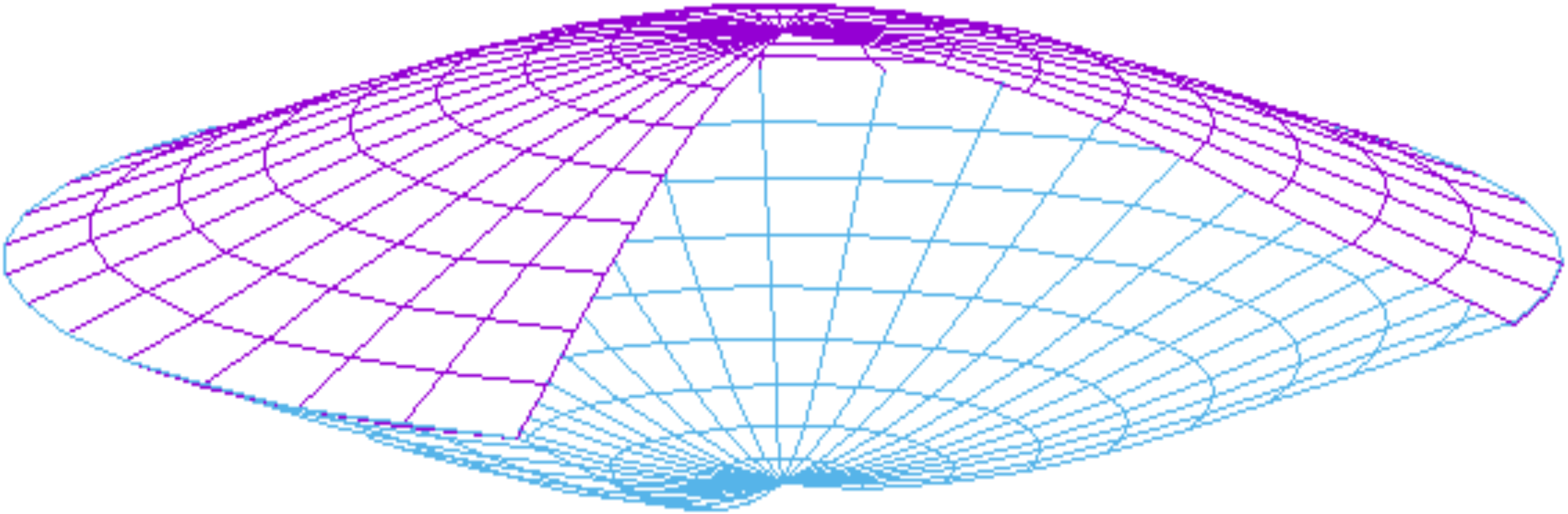
Goal/dream



Bring the quantum control of atomic physics to the vibrations of mechanical objects



Mechanical Cat State



quantum superposition of bouncing “up” and bouncing “down” at the same time

Mechanics as a Quantum Platform

Mechanical resonators:
Very coherent objects

Q-factor:
128 million (20 mK)

Thermal decoherence rate for 20 mK ($n_{th}\,\kappa$):

7 Hz (140 ms)

Motion is also easy to translate into a force:
Useful for quantum transduction?

Can we exploit these in a new quantum platform?

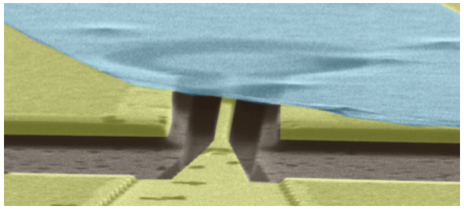
Need to go beyond linear optomechanics

(Mechanics) Projects in the group

Microwave Optomechanics in the SteeleLab

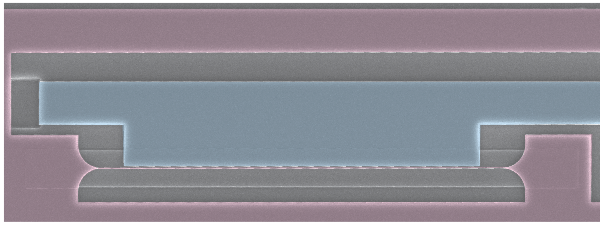
Graphene Microwave Optomechanics

Optomechanics with 2D crystals

Optomechanics with SQUIDS and Nanostrings

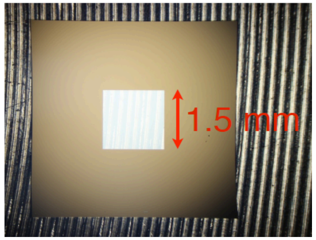
Large single-photon coupling




Mechanics with 3D Cavities

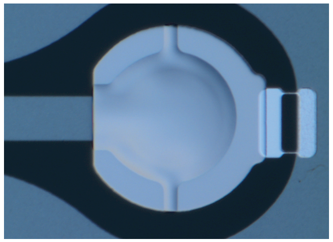
Macroscopic objects in the ground state



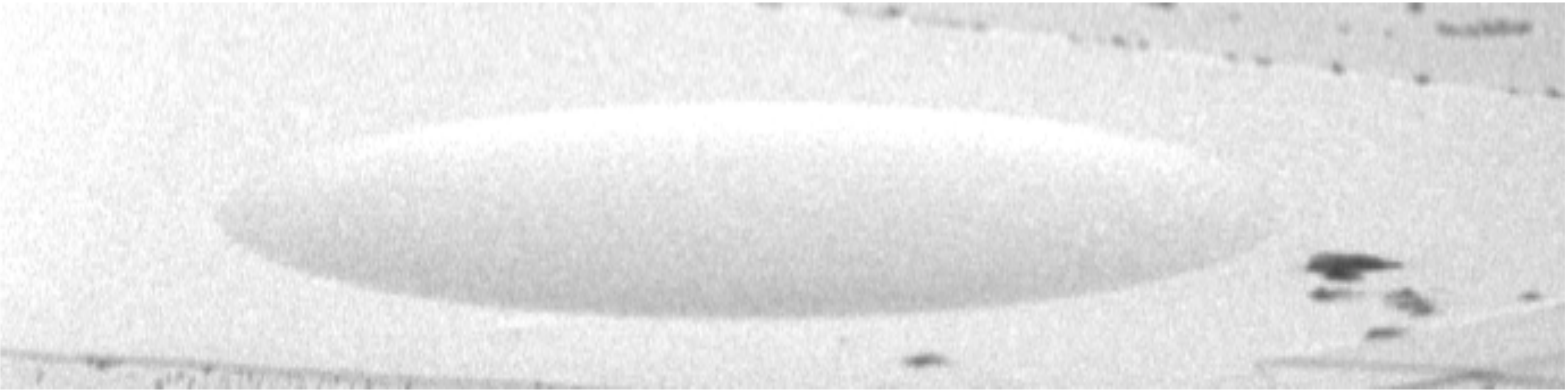


Mechanical Transmons and Metal Drums

Deep / ultra strong coupling regime



Why graphene for optomechanics?



What do we want out of graphene?

Light, Conductive material that shakes with high Q

Multilayer = much higher conductivity
(Graphite: Mobility 10^7)

Light Mass = Stronger Coupling

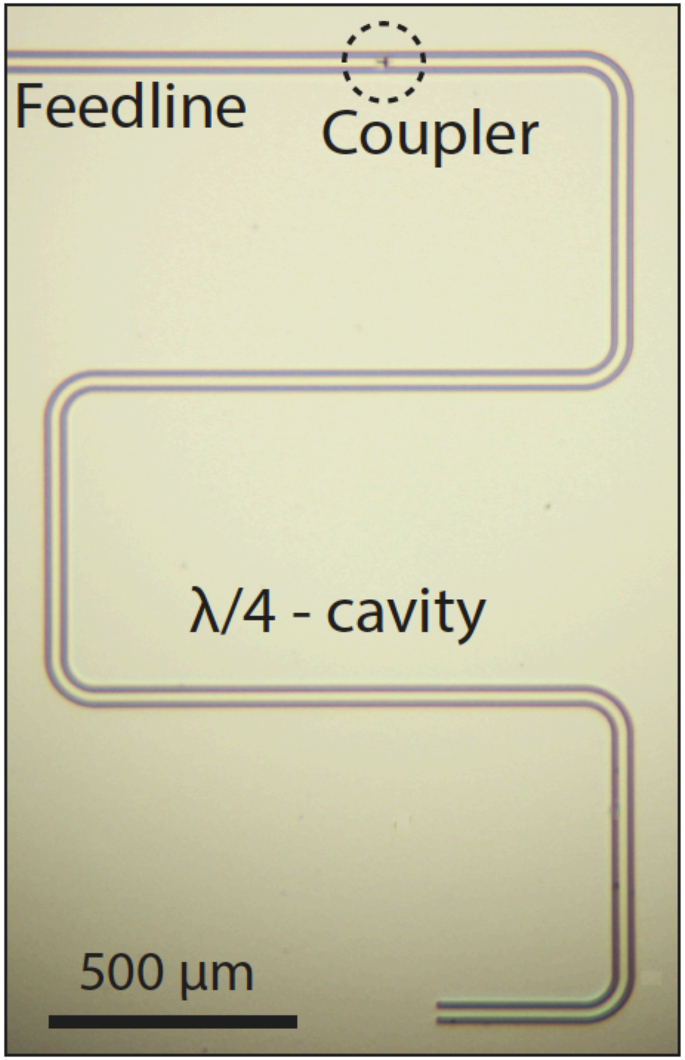
$$g_0 = \frac{d\omega_c}{dx} x_{\text{zpf}}$$

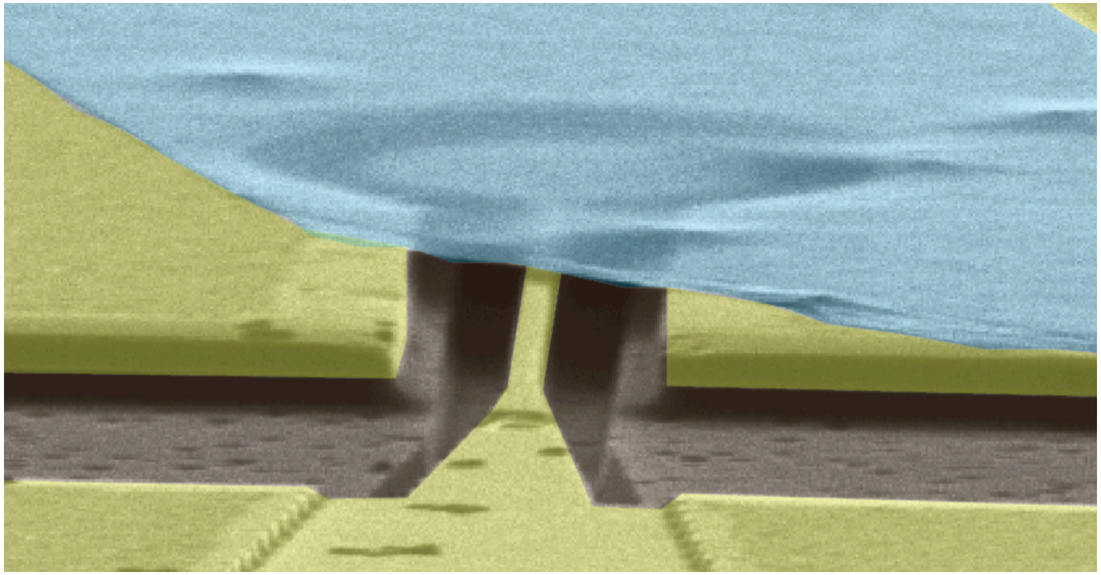
$$x_{\text{zpf}} = \sqrt{\frac{\hbar}{2m\omega}}$$

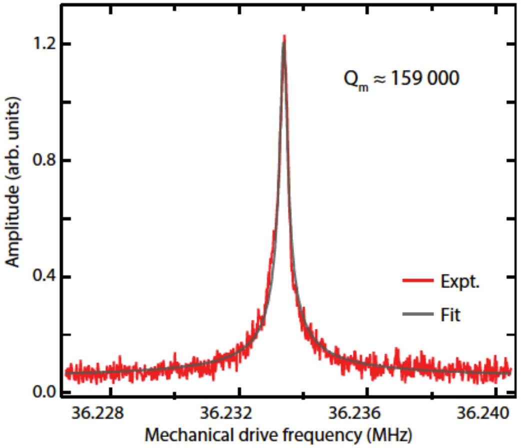
High Q with low stress

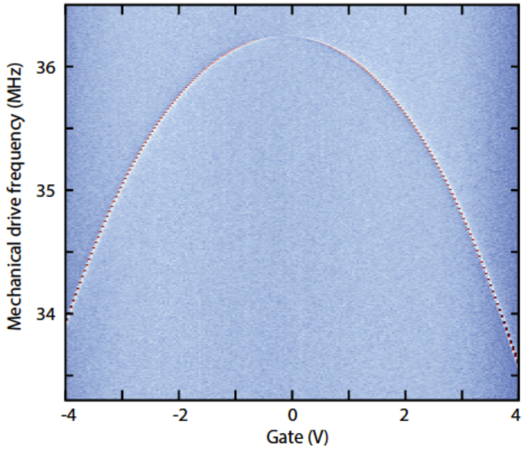
Smaller spring constant
Lower frequency
Larger coupling

Graphene Microwave Optomechanics

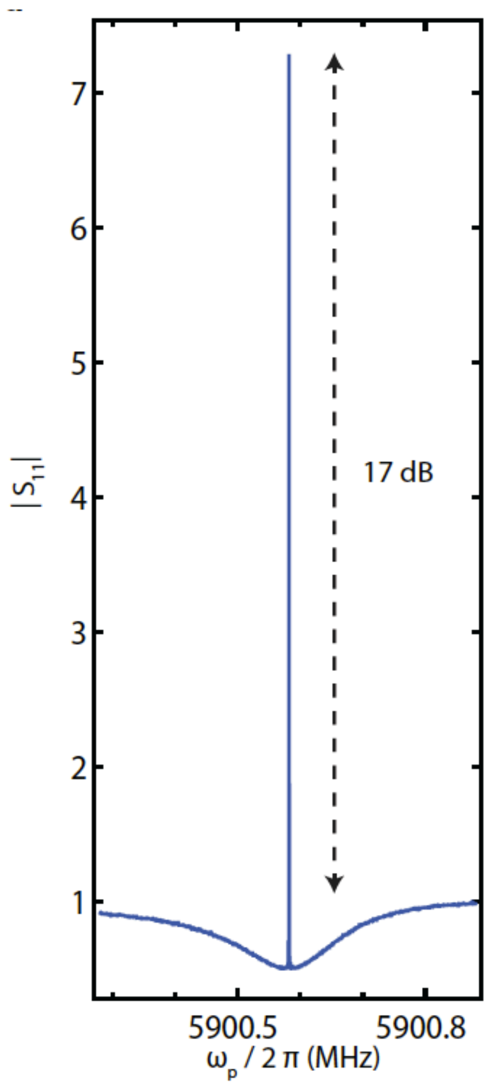


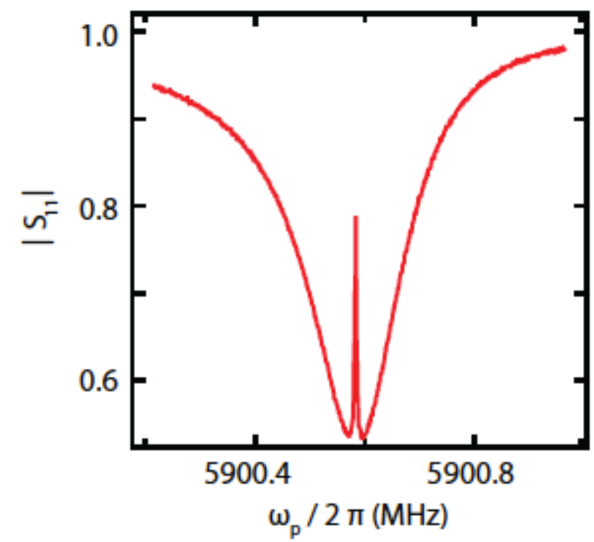


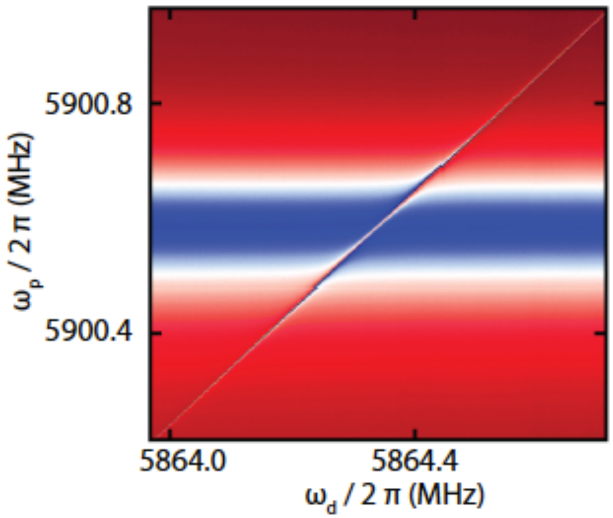


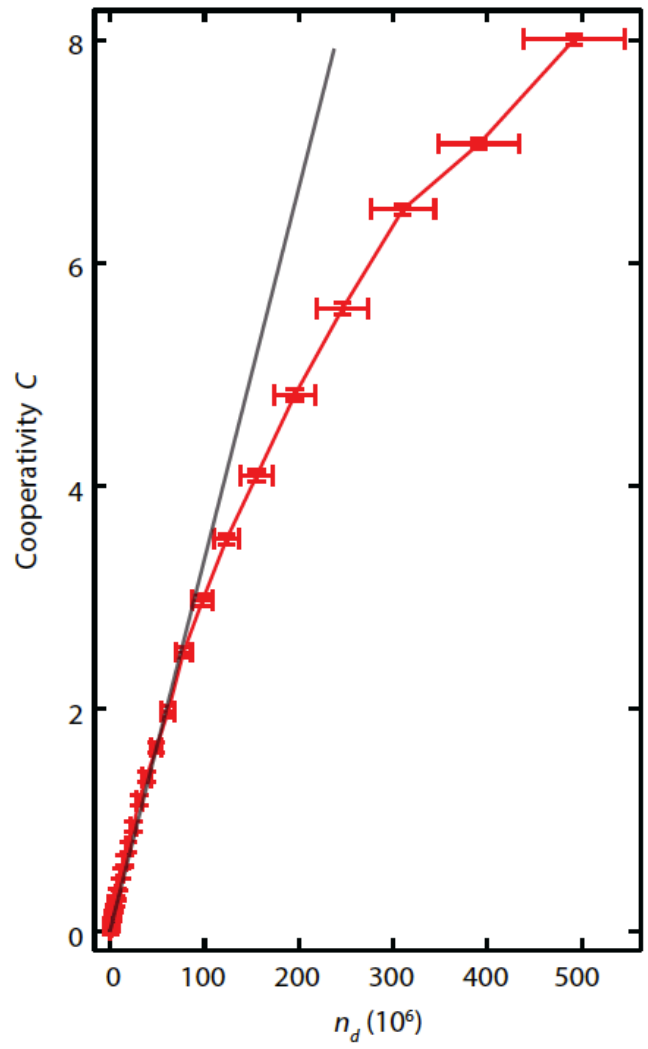


Optomechanics with "decent" C

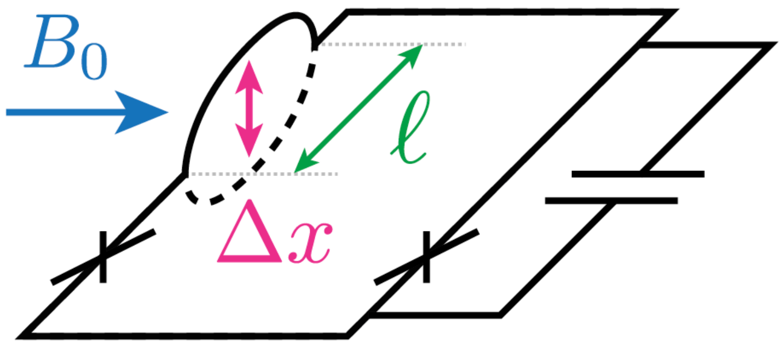


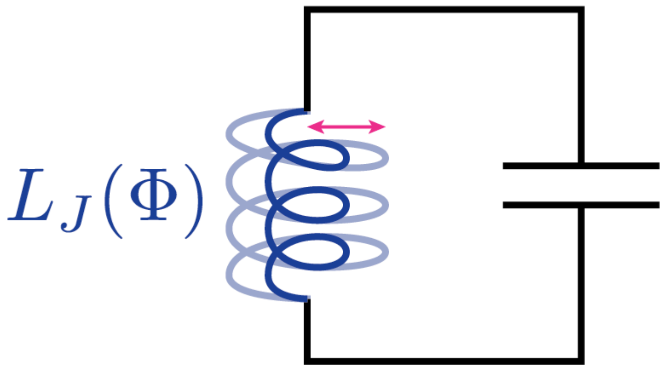


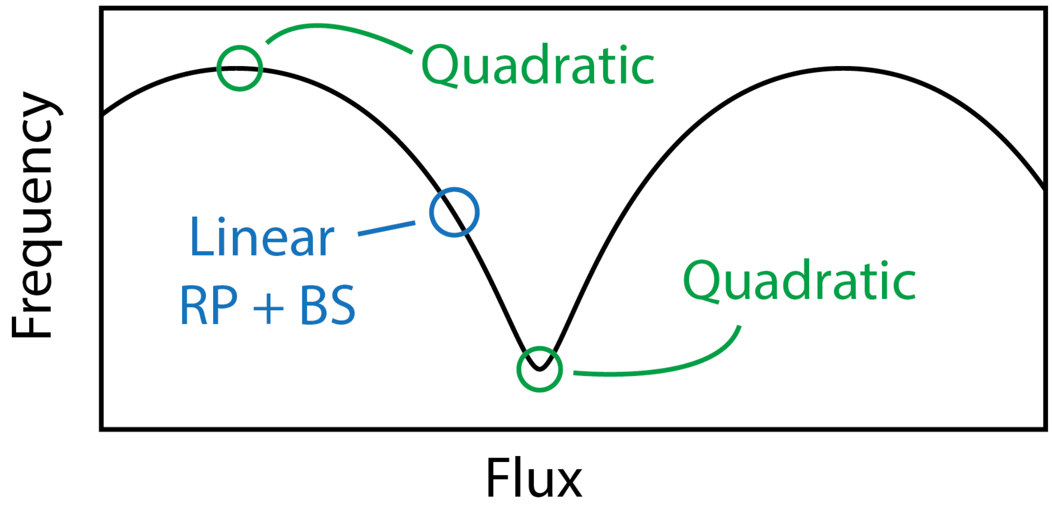




SQUID Optomechanics





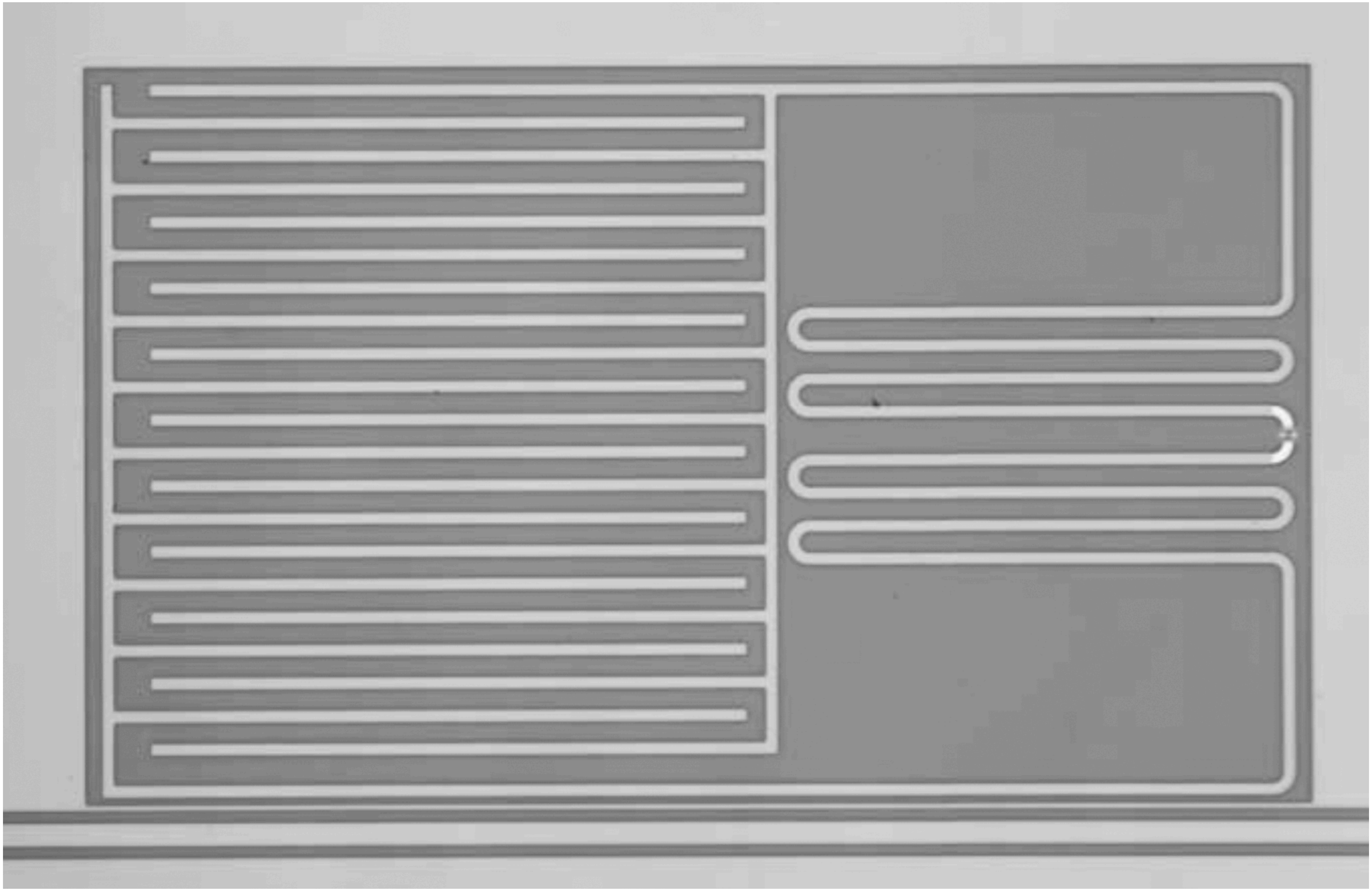


Tunable and strong coupling mediated by flux

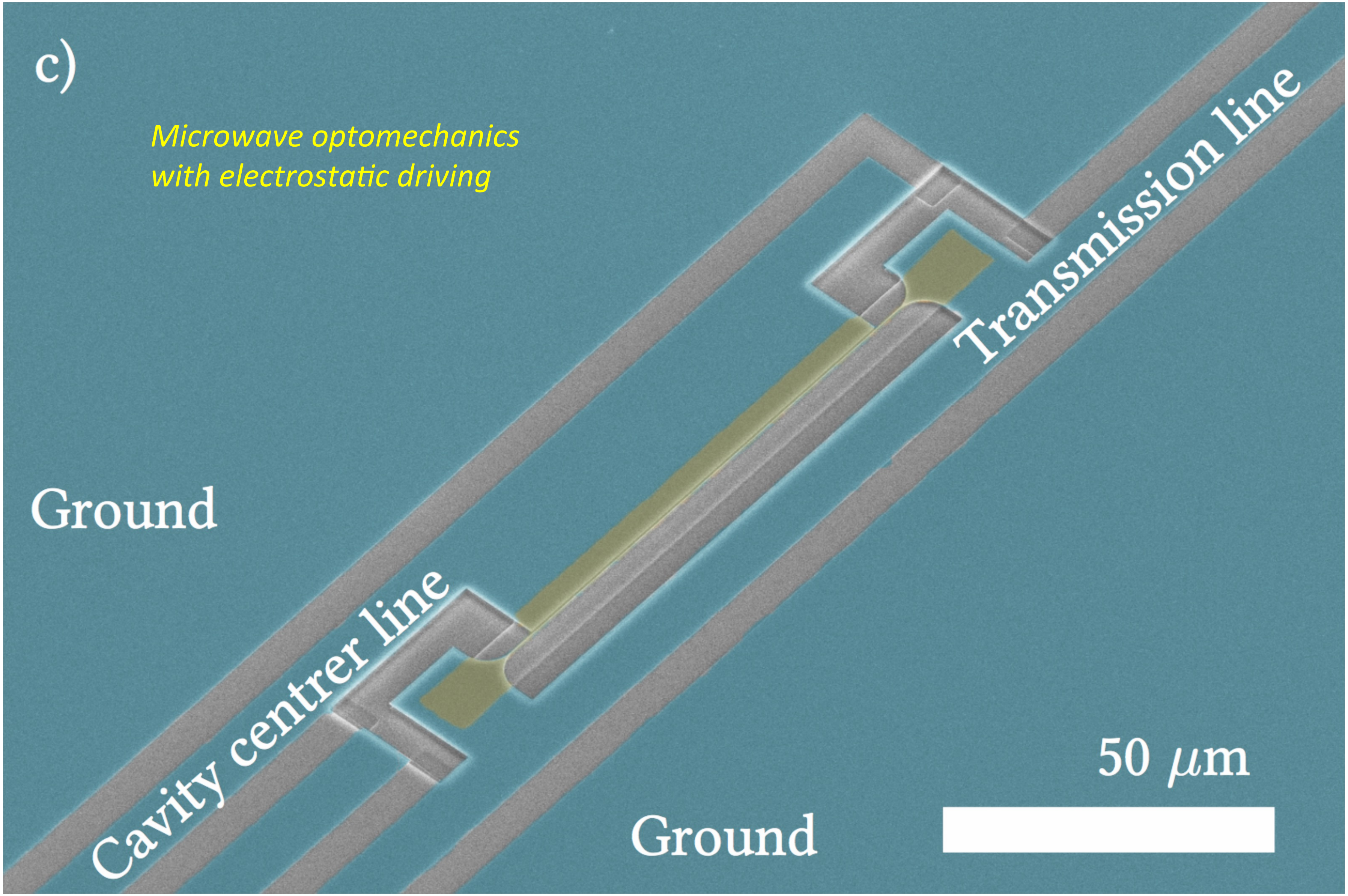
100 micron nanowire + 10 mT:

g_0 = 6 MHz?

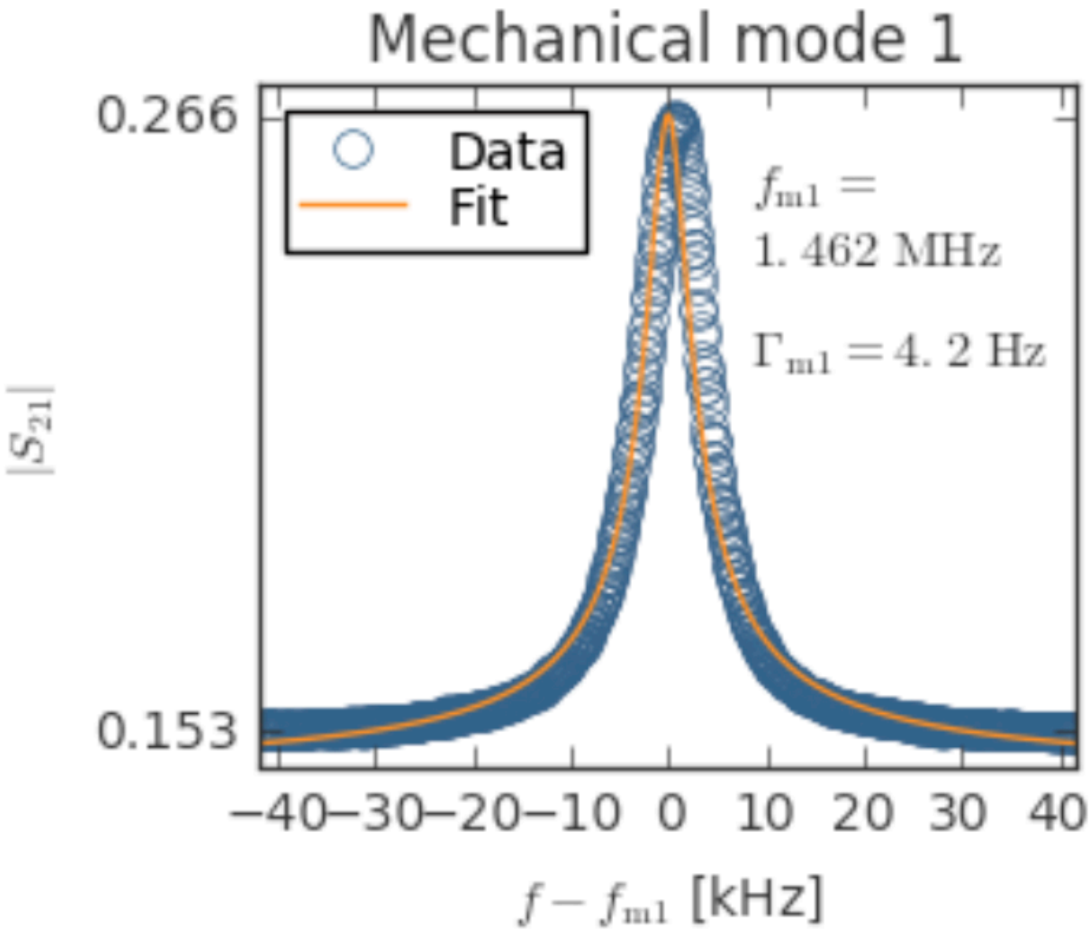
Flux Tunable Cavities

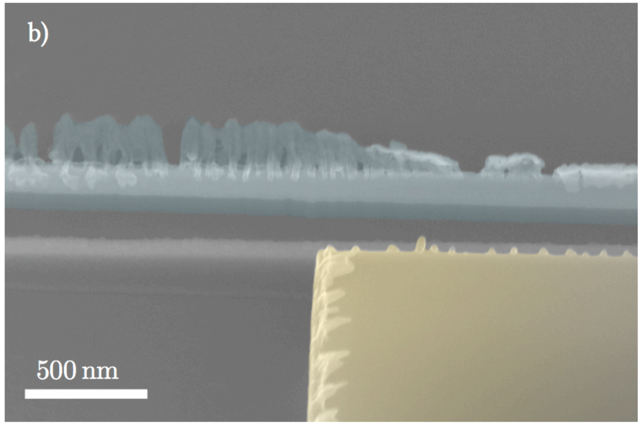


Silicon Nitride Nanowires



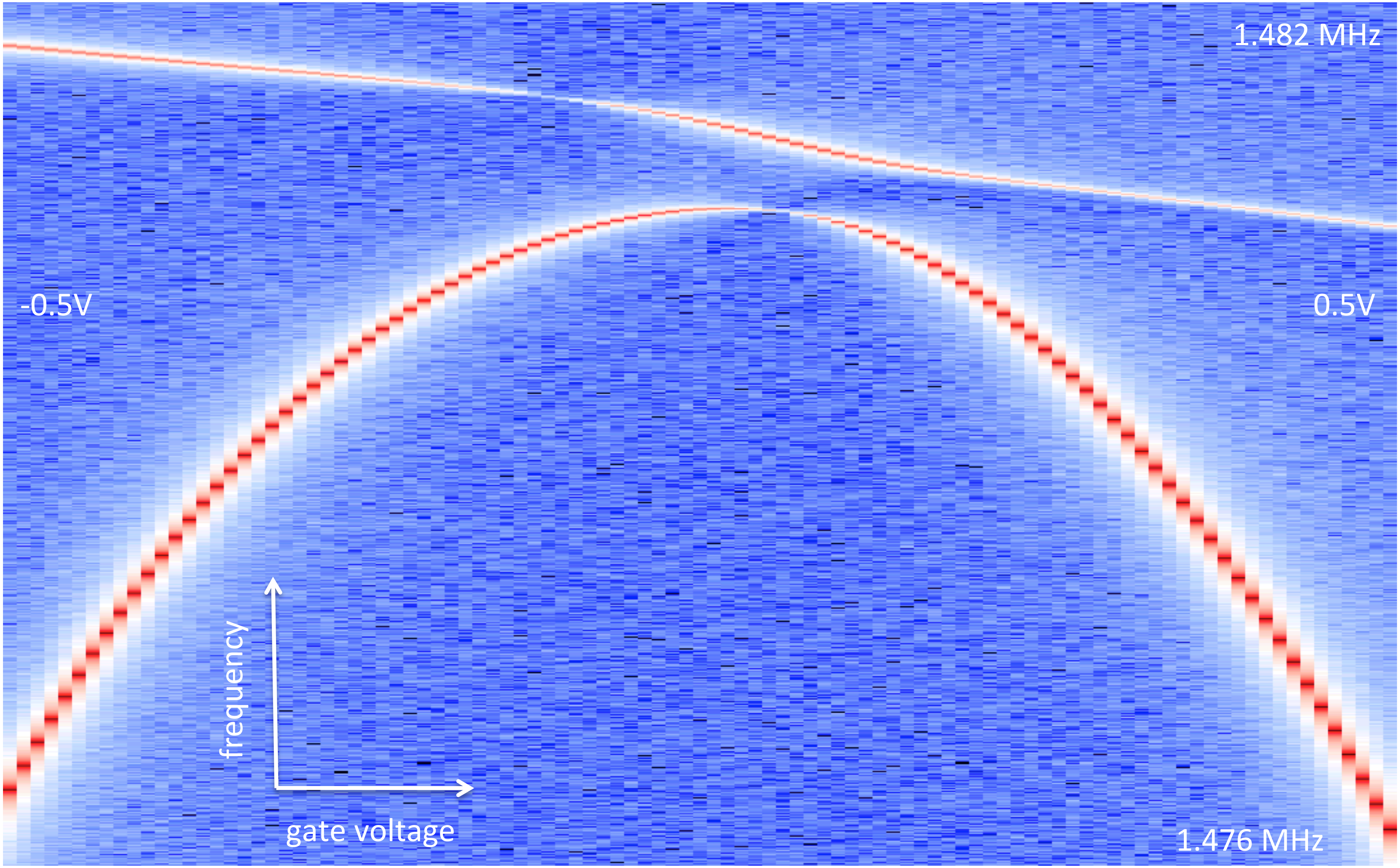
Decent Mechanical Q



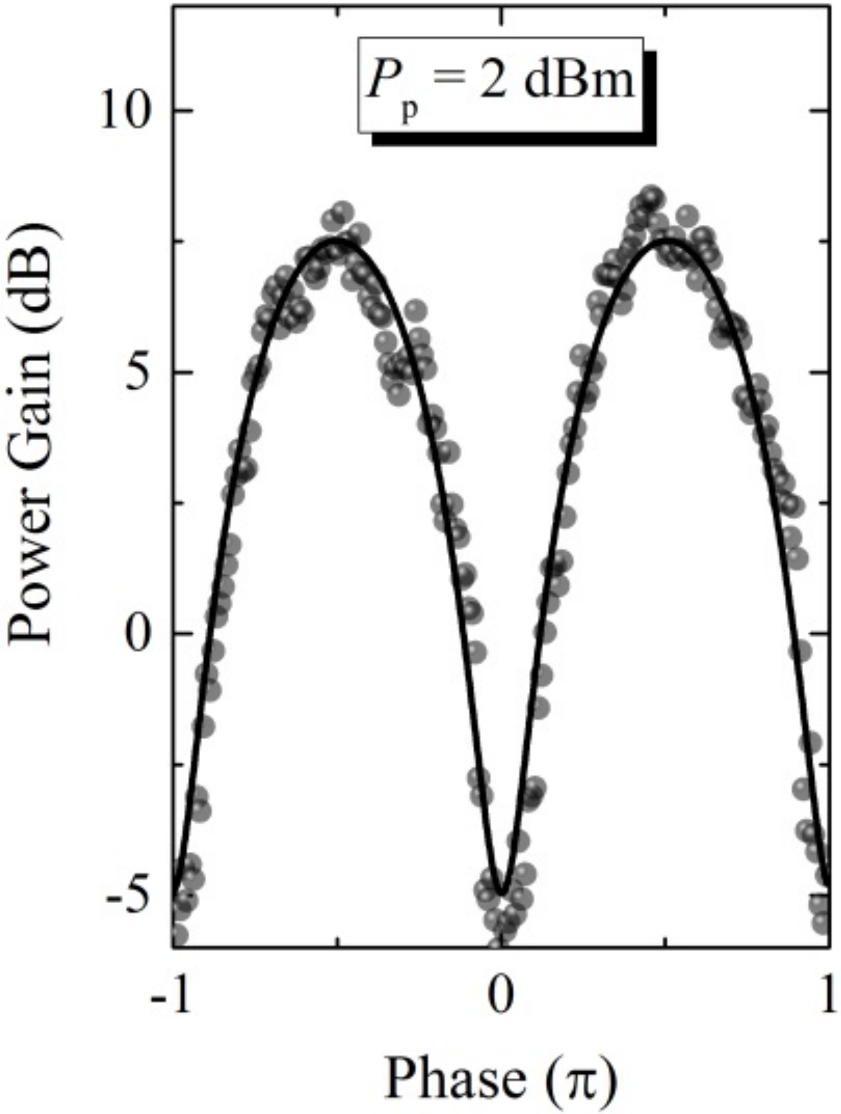


Despite some redeposition problems?

Gate Tunable Frequency

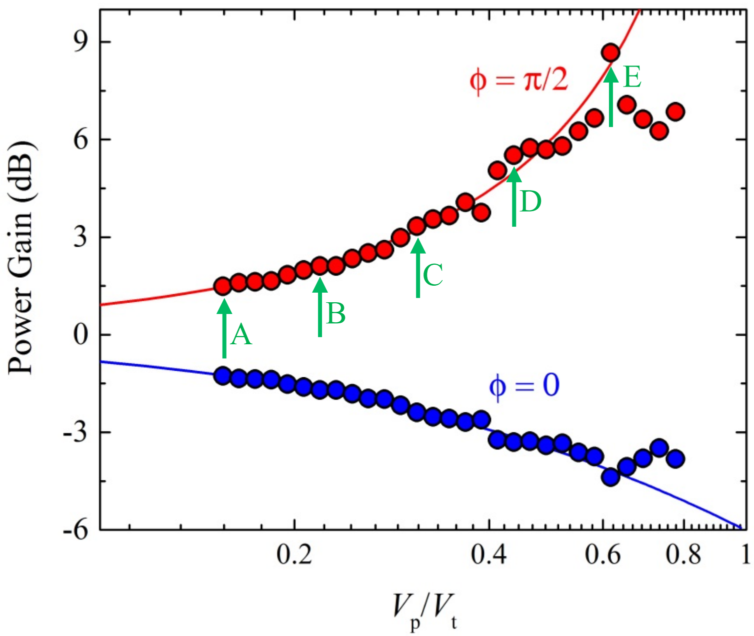


Electrostatic Parametric Driving

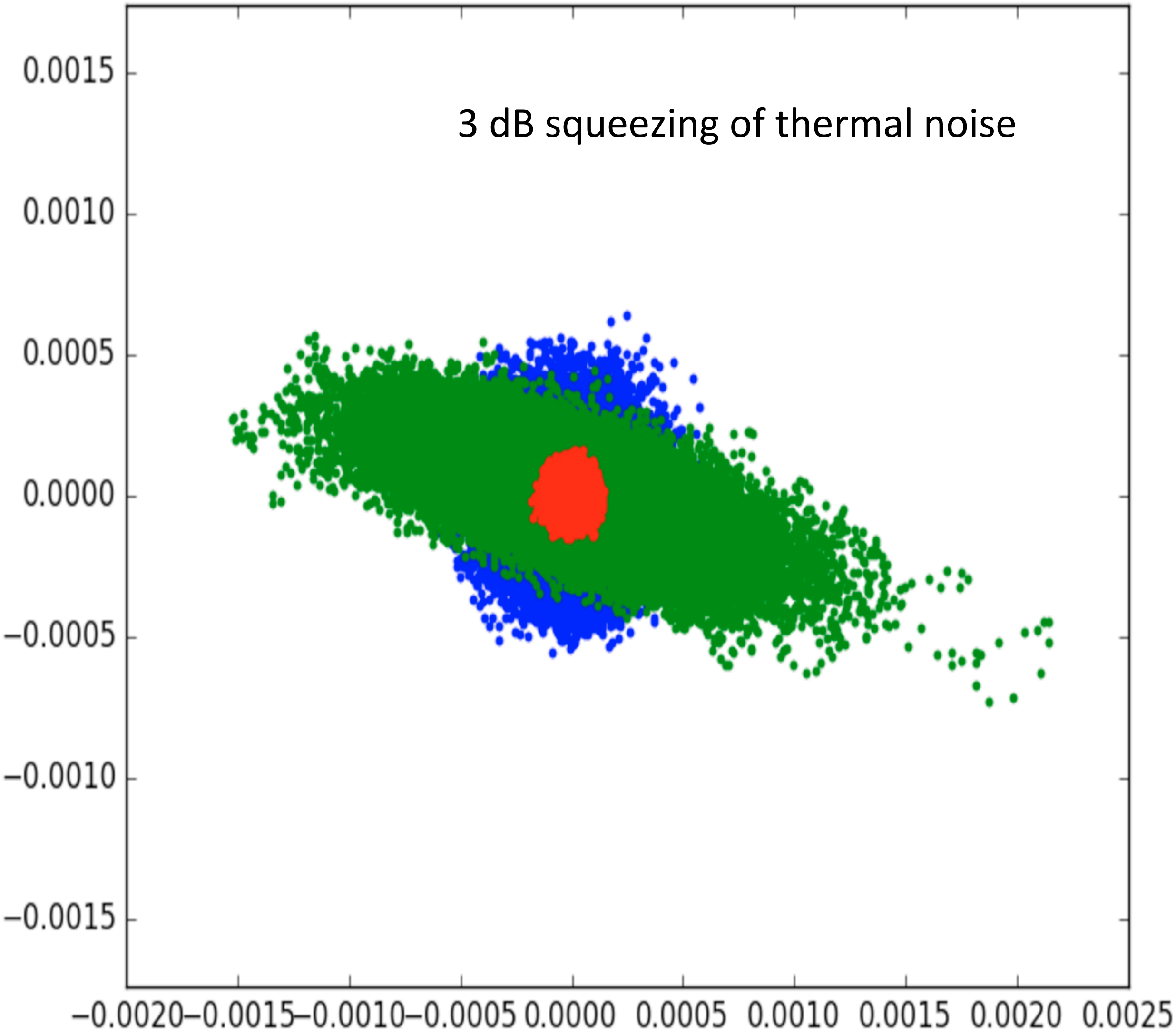


DC Voltage Enhanced Parametric Coupling:

$$F = \frac{dC}{dx} V_{ac} V_{DC} \qquad k = \frac{d^2C}{dx^2} V_{ac} V_{DC}$$



Thermal Noise Squeezing

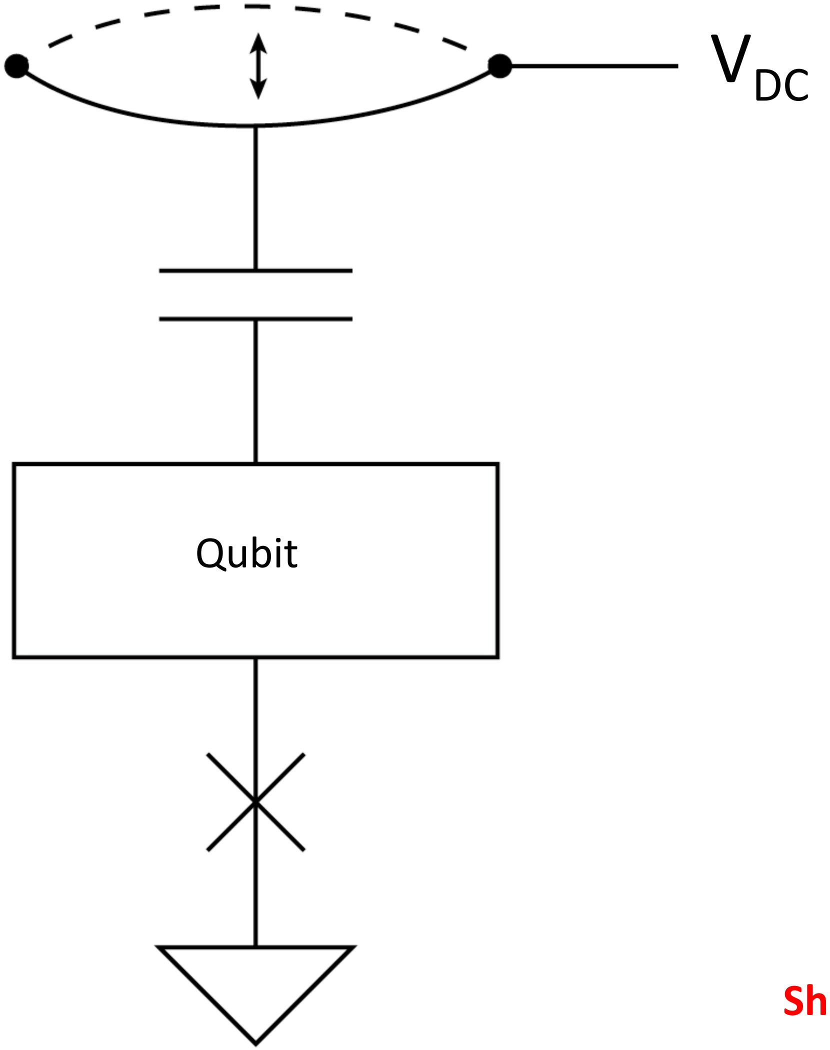


Red:
Amplifier Noise

Blue:
Thermomechanical Noise

Green:
Squeezed Thermal Noise

"Mechanical Transmon"



Qubit is charge sensitive

$$Q = CV$$

$$\delta Q = \delta C \cdot V_{DC}$$

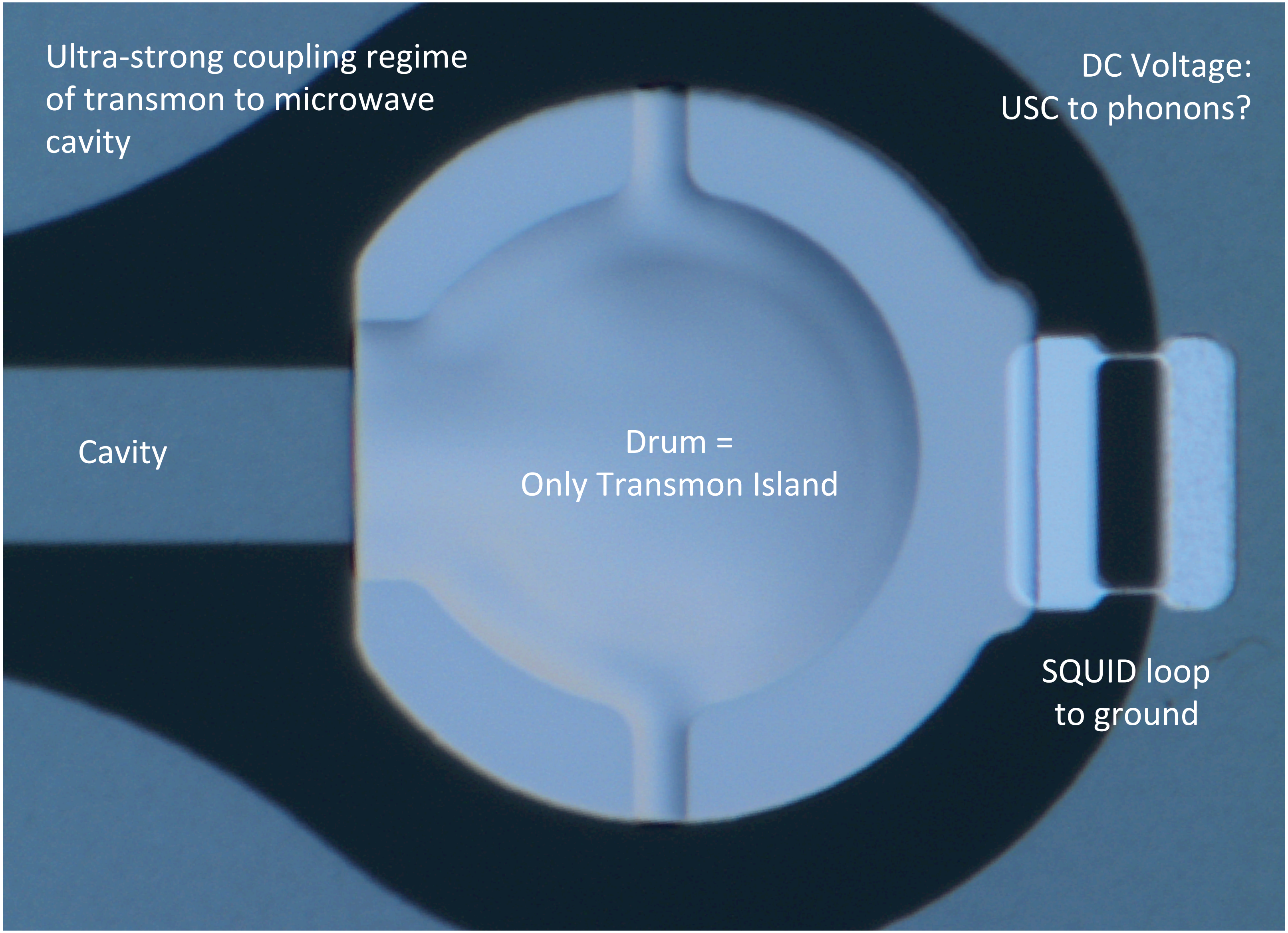
Large and tunable coupling to phonons

$$g_{\varphi} = 2\pi \times 13.5 \text{ MHz/V}$$

$$\chi_{\varphi} \sim 2\pi \times 2\text{MHZ at } 5\text{V}$$

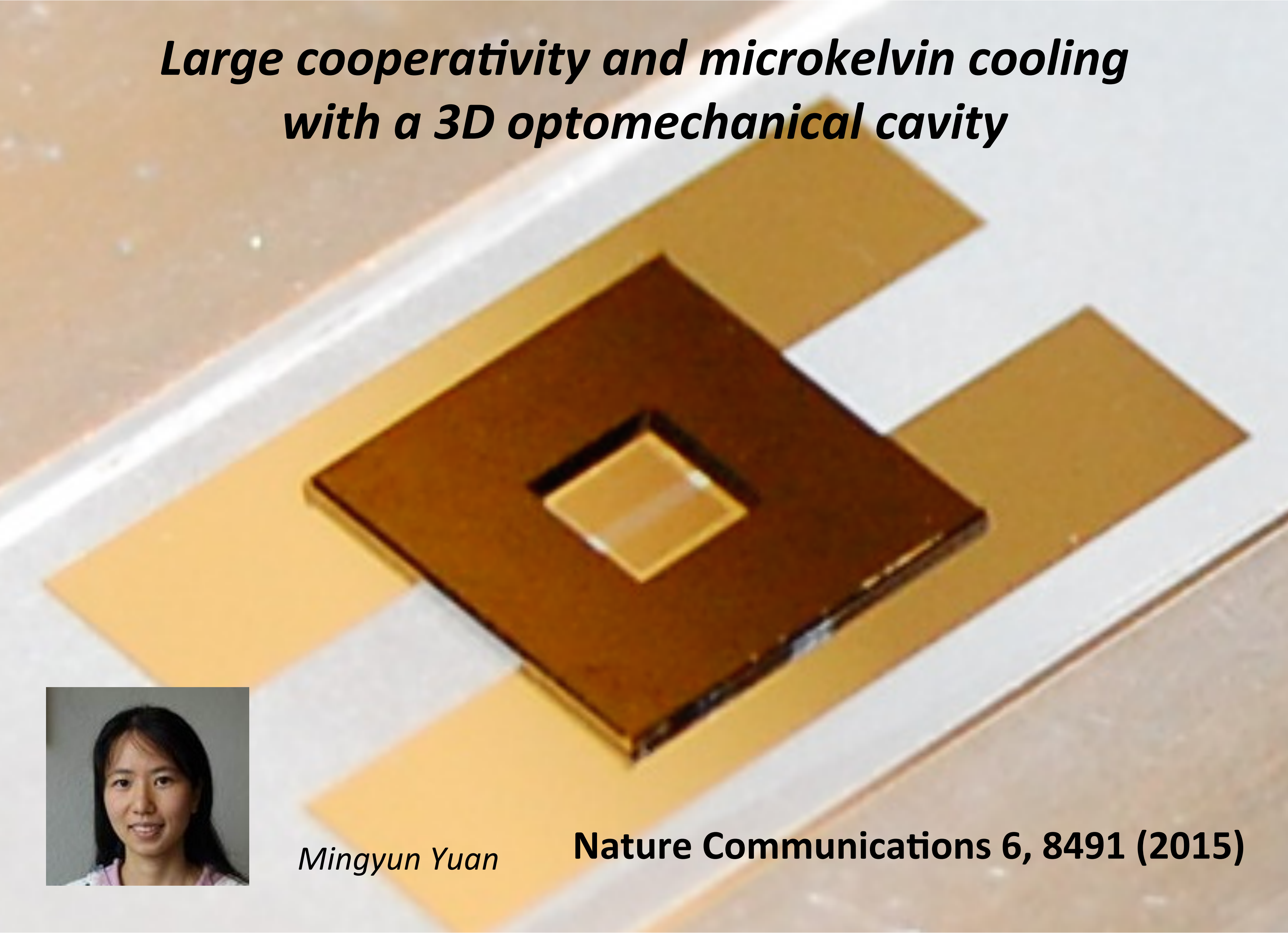
Should reach Phonon Number Resolution Limit!!!

Our Implementation



3D optomechanics

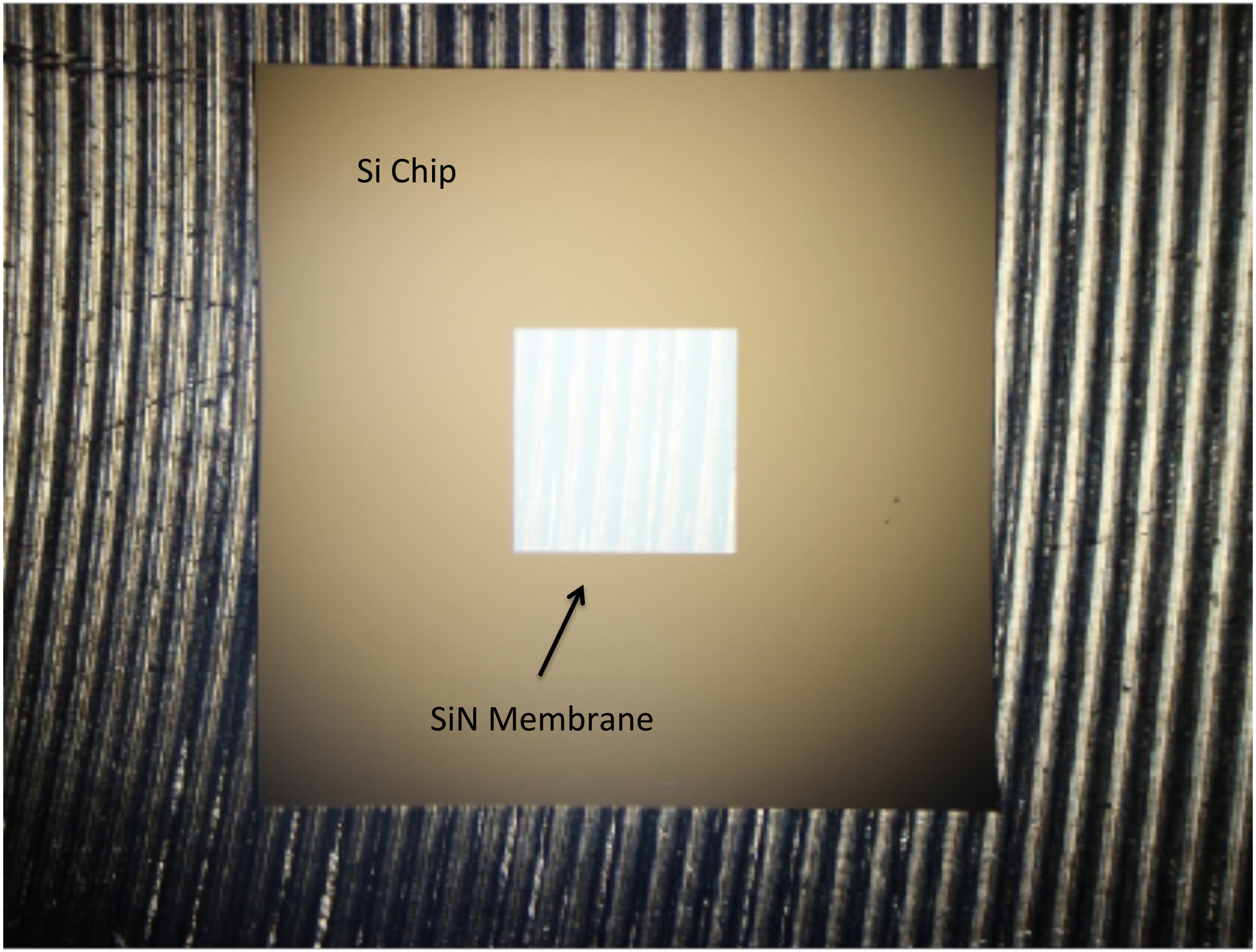
Large cooperativity and microkelvin cooling with a 3D optomechanical cavity



Mingyun Yuan

Nature Communications 6, 8491 (2015)

Ingredient #1: mm-sized SiN Membrane



Big

0.1 μg

Low Frequency

100 kHz

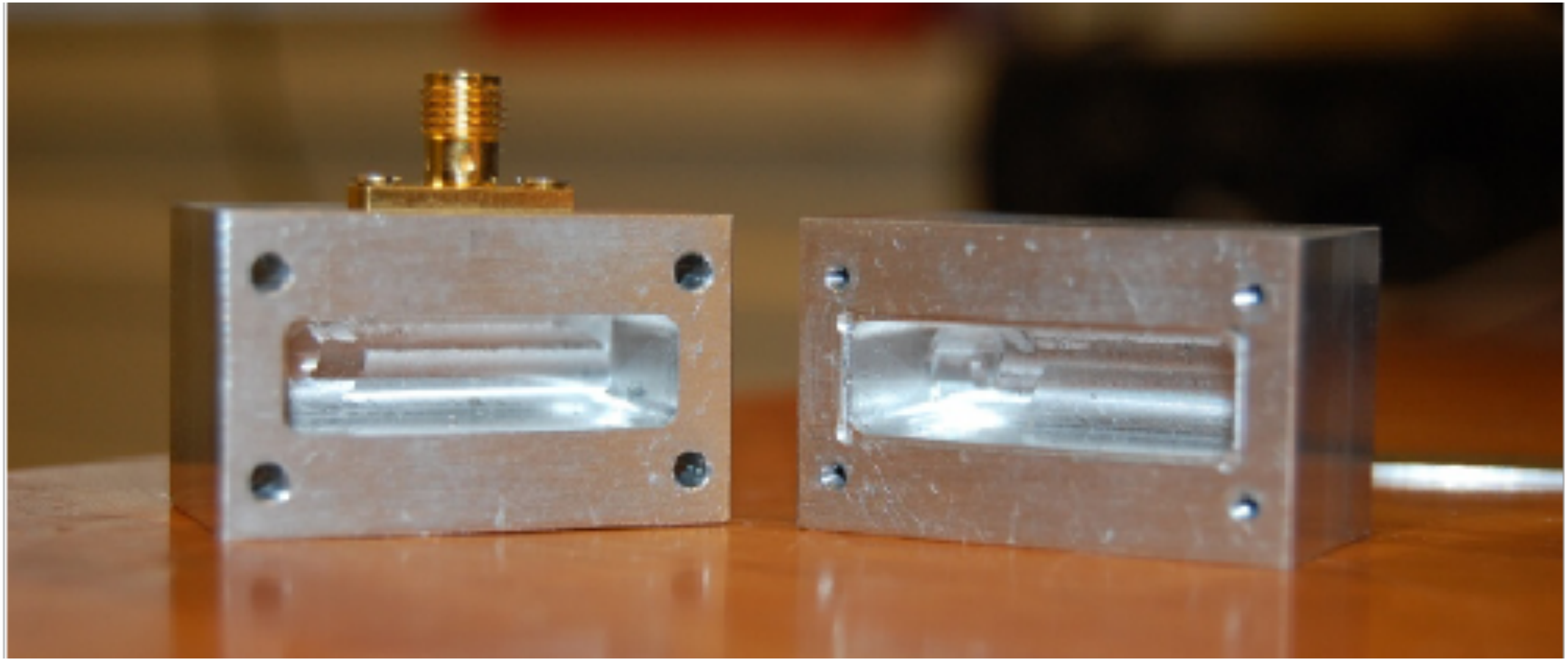
High Q

10^7

High Stress

Easy to handle

Ingredient #2: 3D Microwave cavity

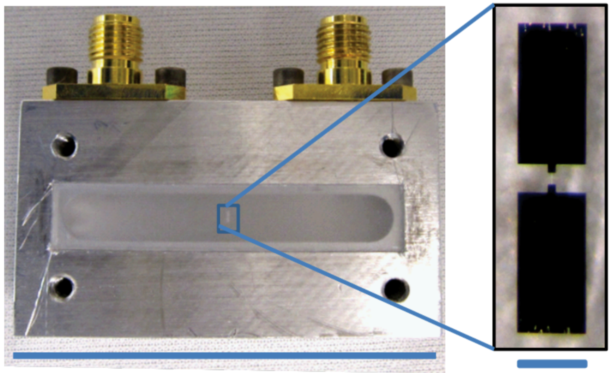


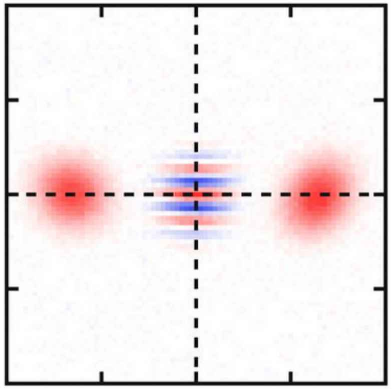
Pioneered by Schoelkopf Lab for cQED

$$Q_c = 500 \times 10^6 \quad (\kappa = 2\pi \times 10\ \text{Hz})$$

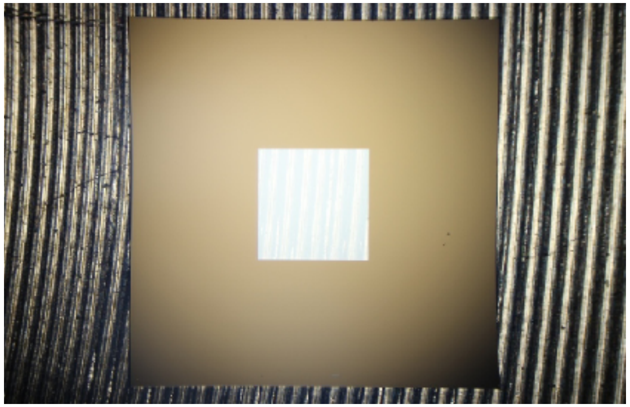
Big impact on the Qubit Community

$$T_2\ (\text{qubit}) = 100\ \mu\text{s}$$

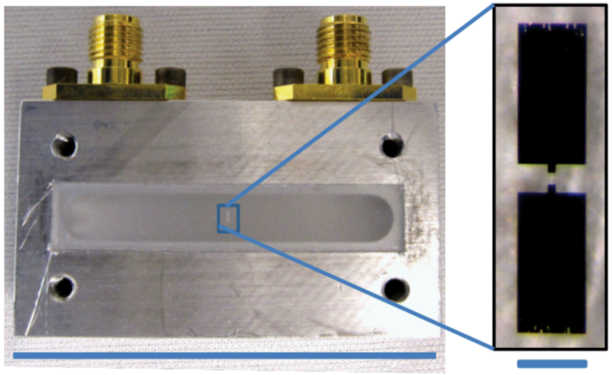




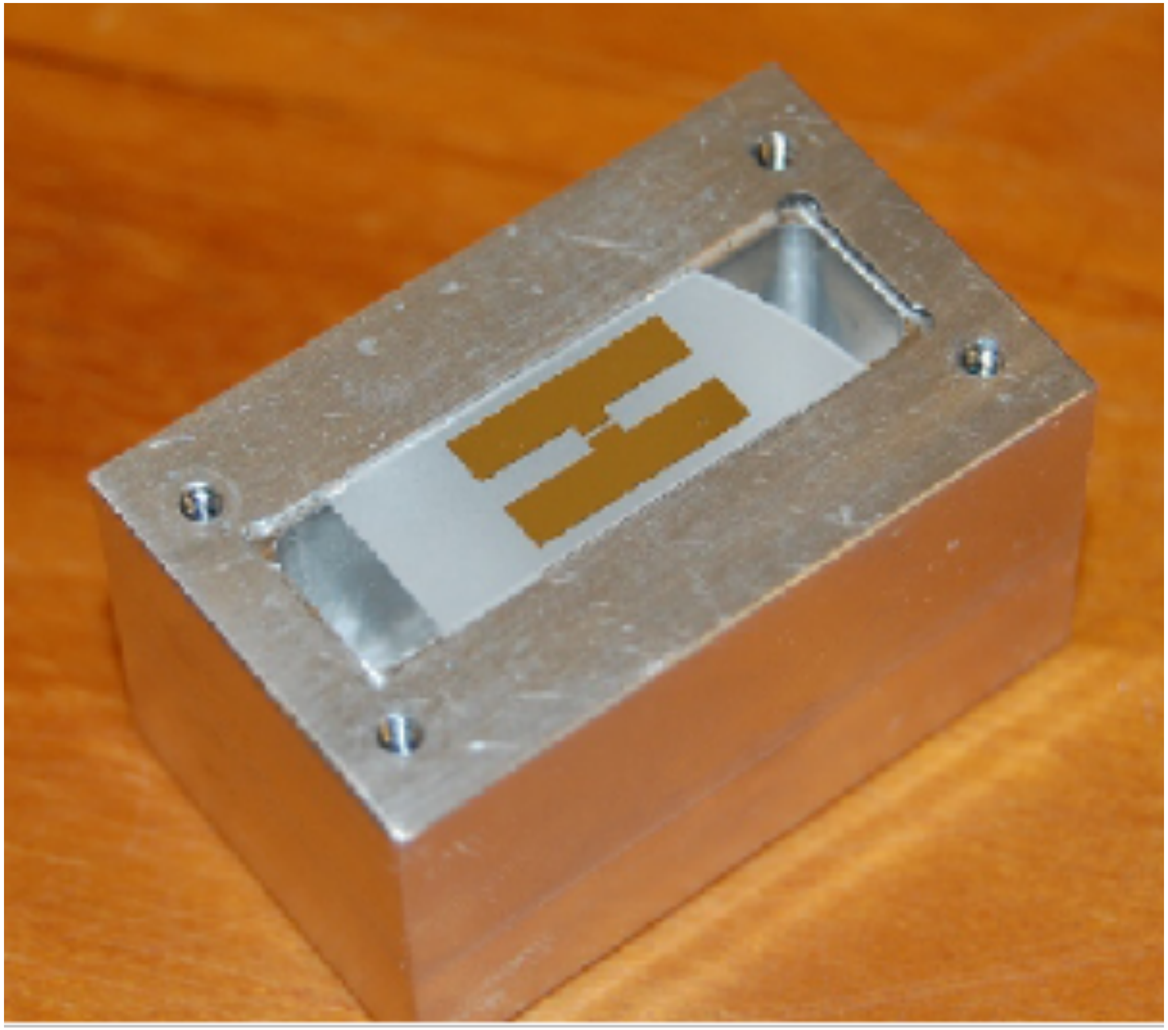
Coupling 3D fields to the membrane motion



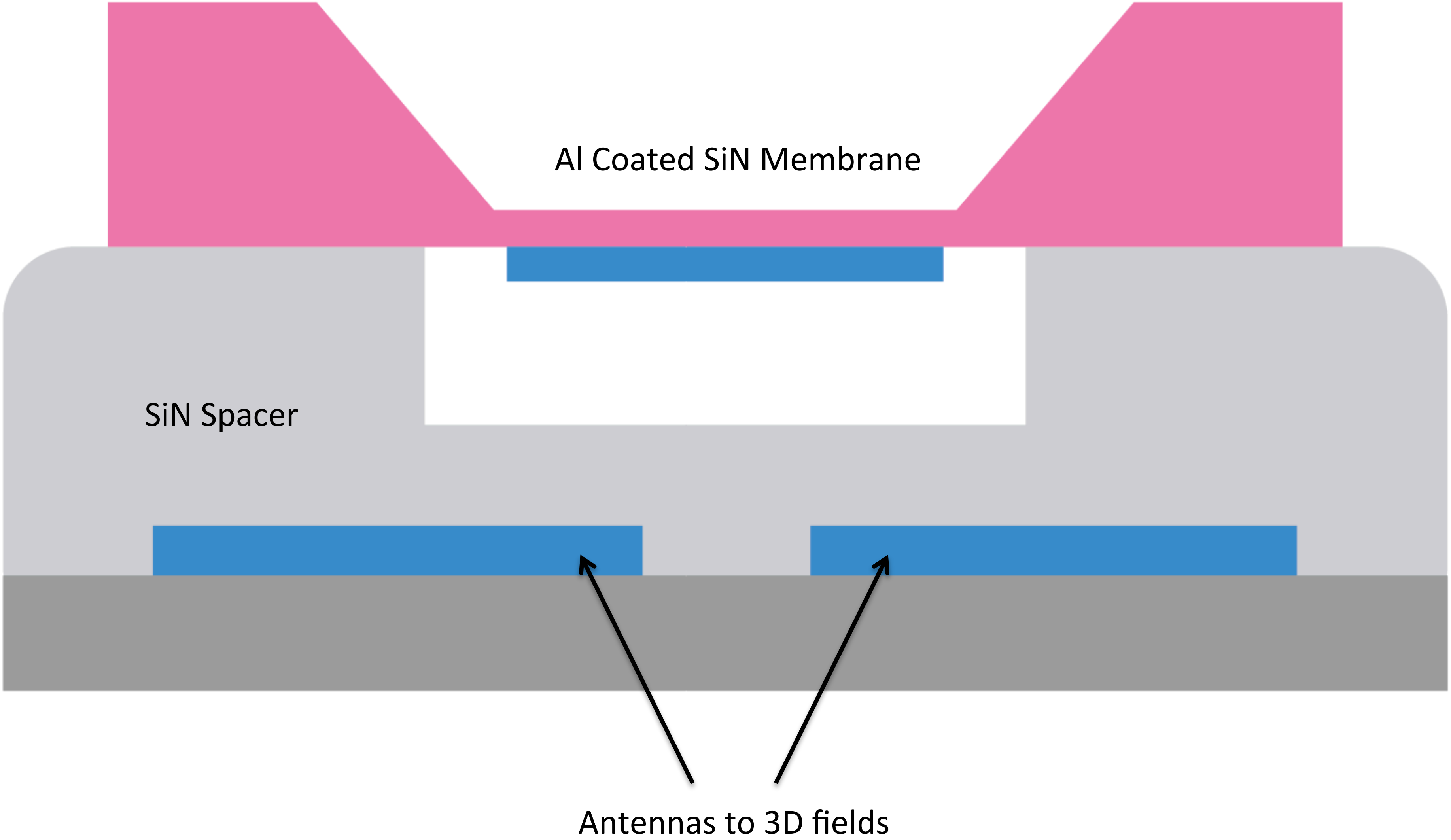
How to couple 1 mm membrane
to 30 mm cavity?



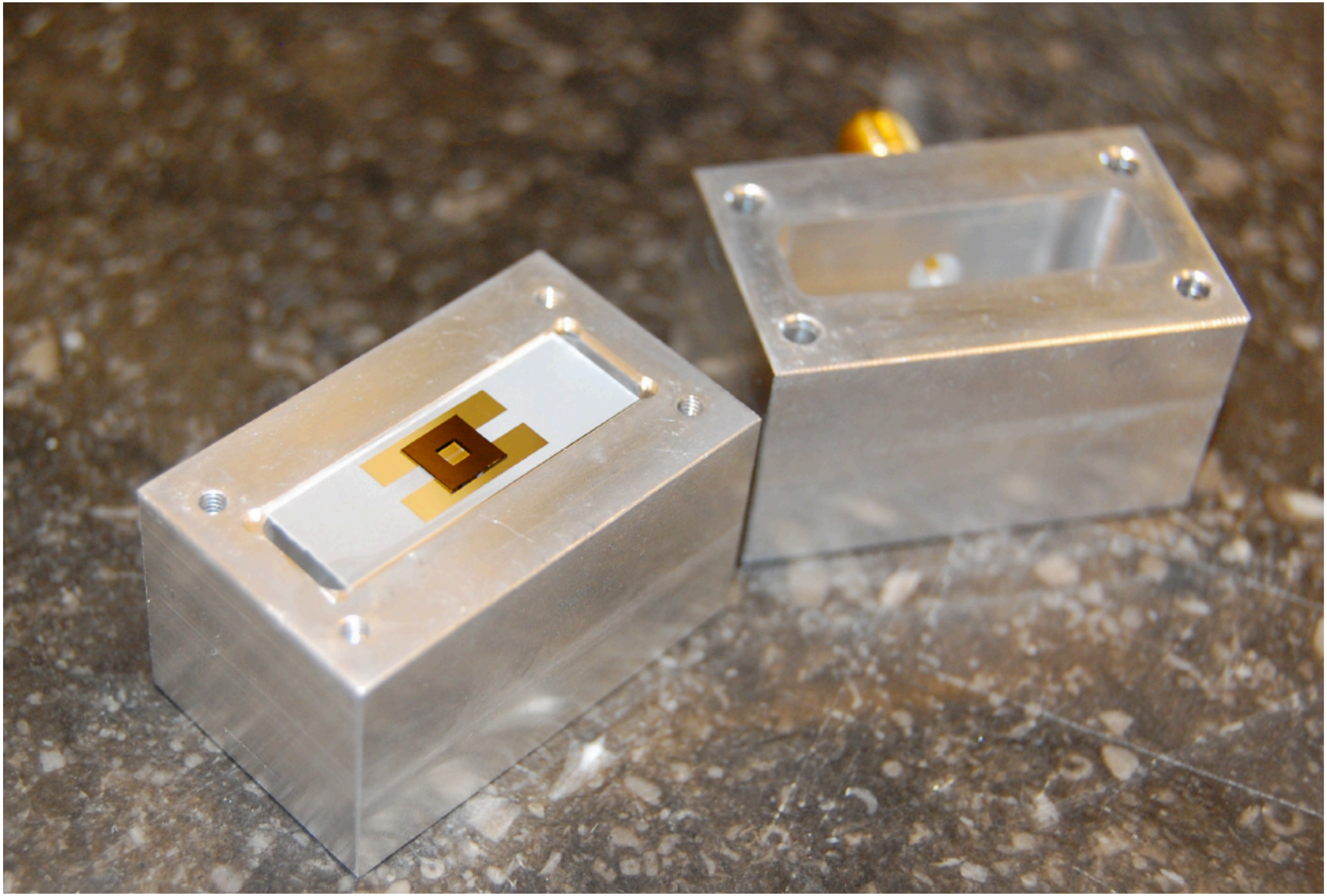
Same trick as with
qubits: antennas!



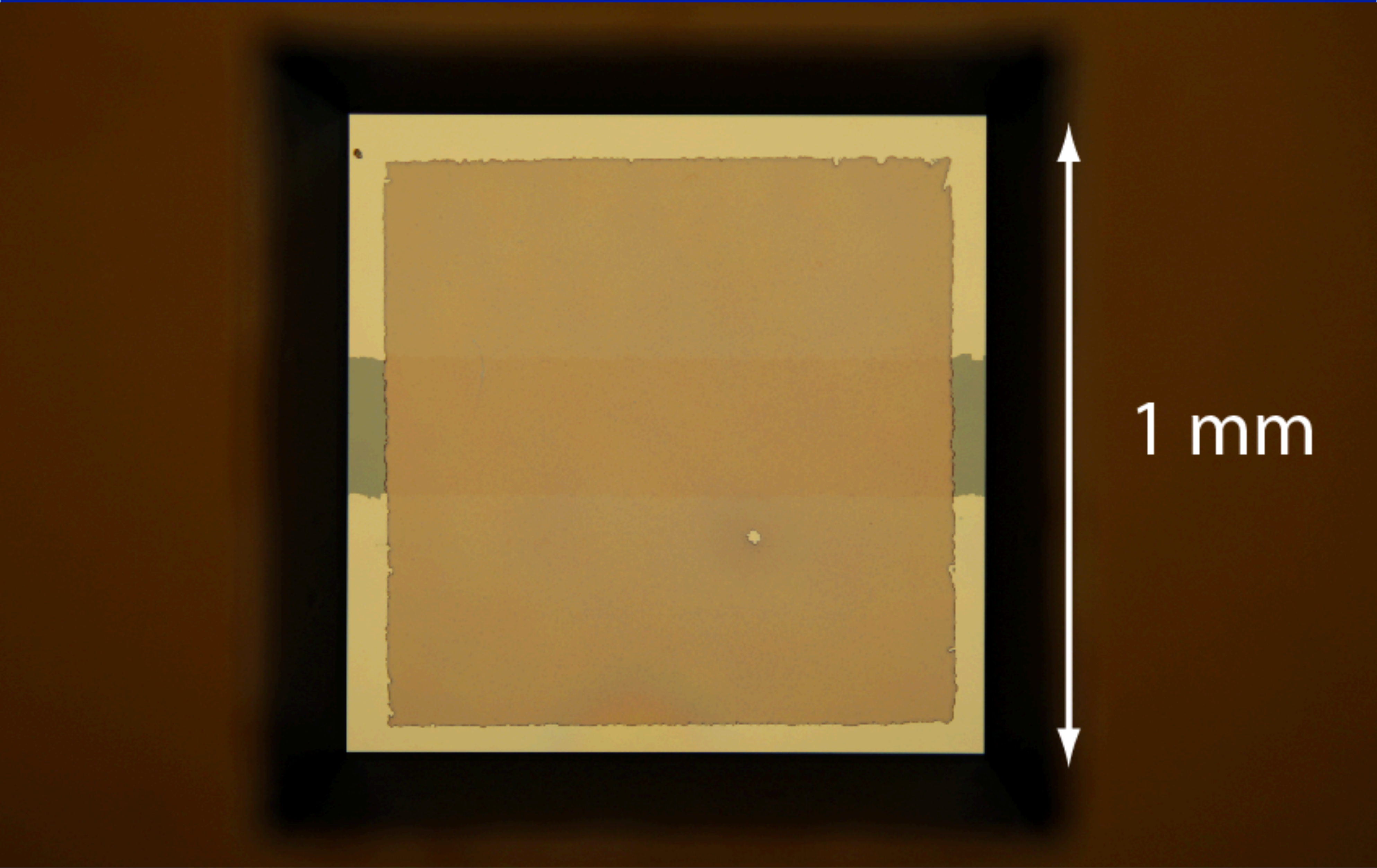
Putting it together



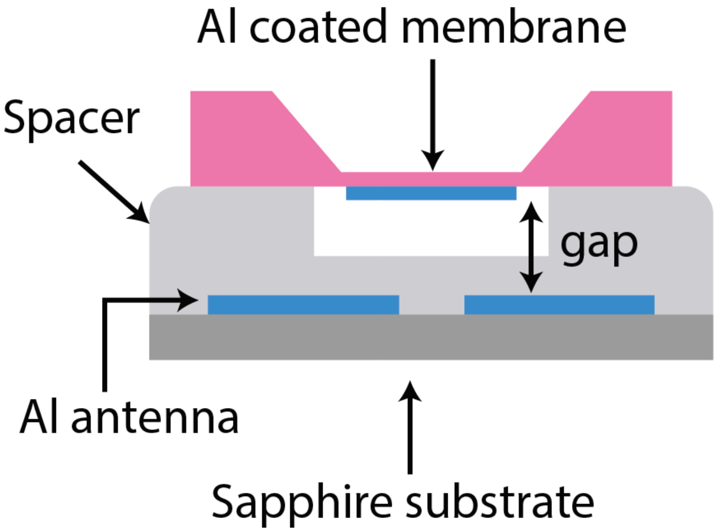
What it looks like

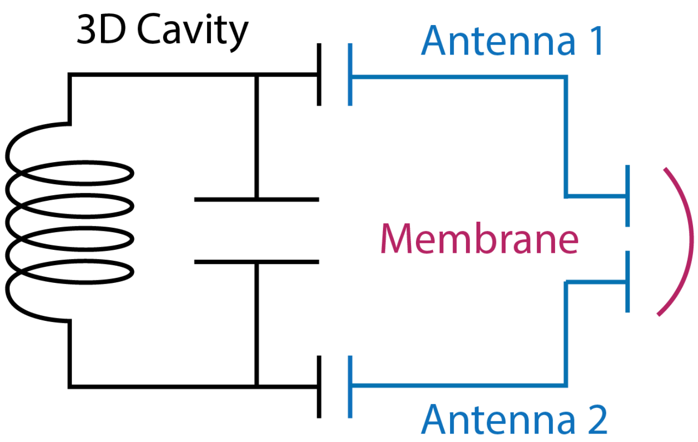


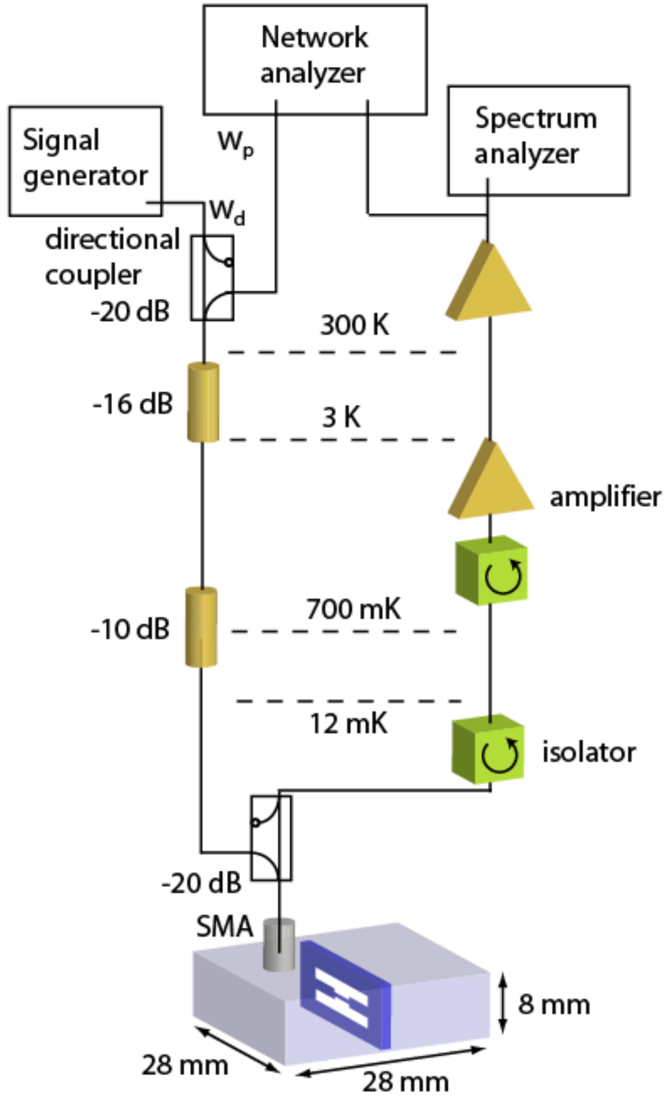
3 micron gap over 1 mm distance



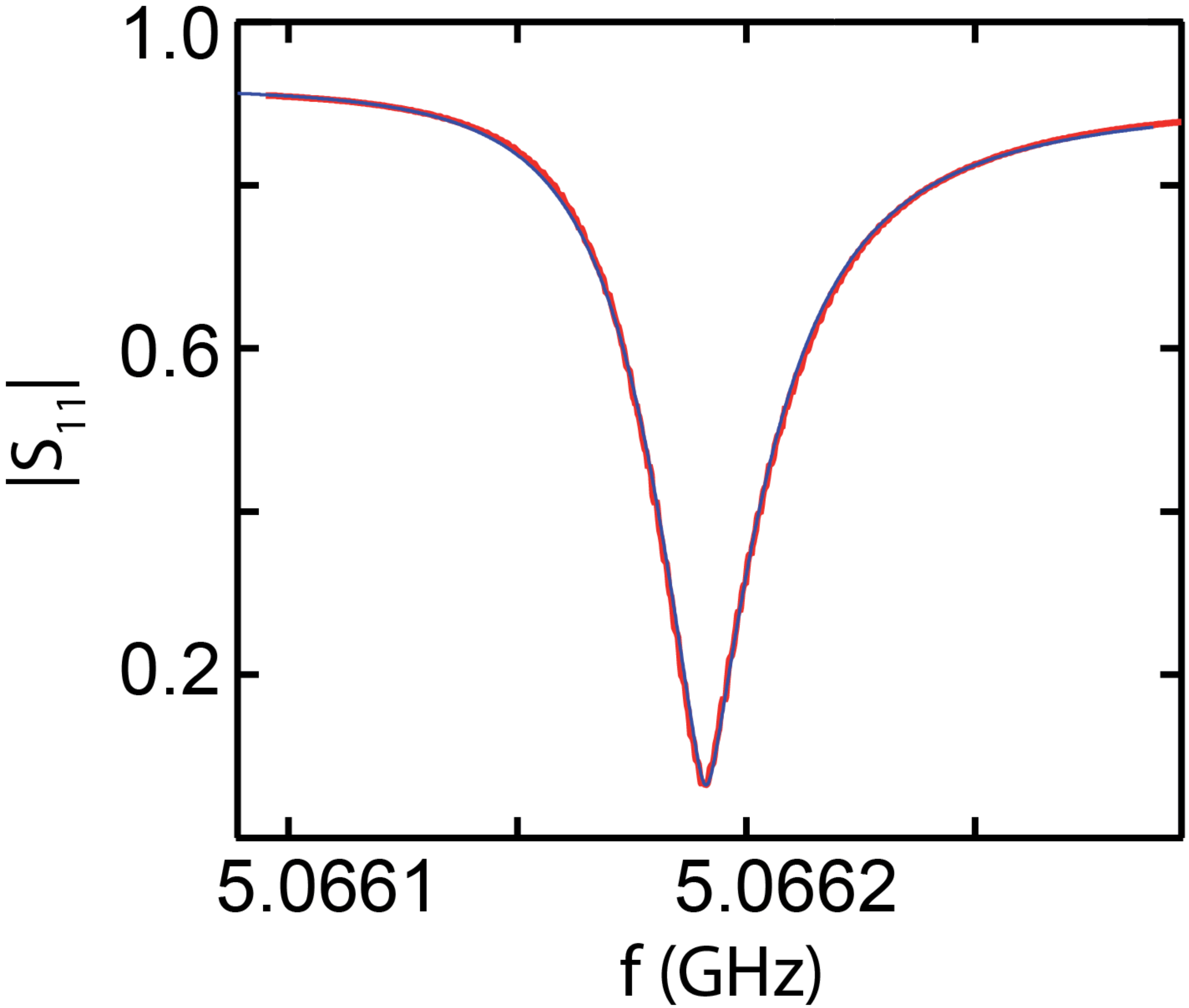
Experimental setup







Cavity Resonance



$$Q_L = 1.1 \times 10^5$$

$$\kappa / 2\pi = 45.5 \text{ kHz}$$

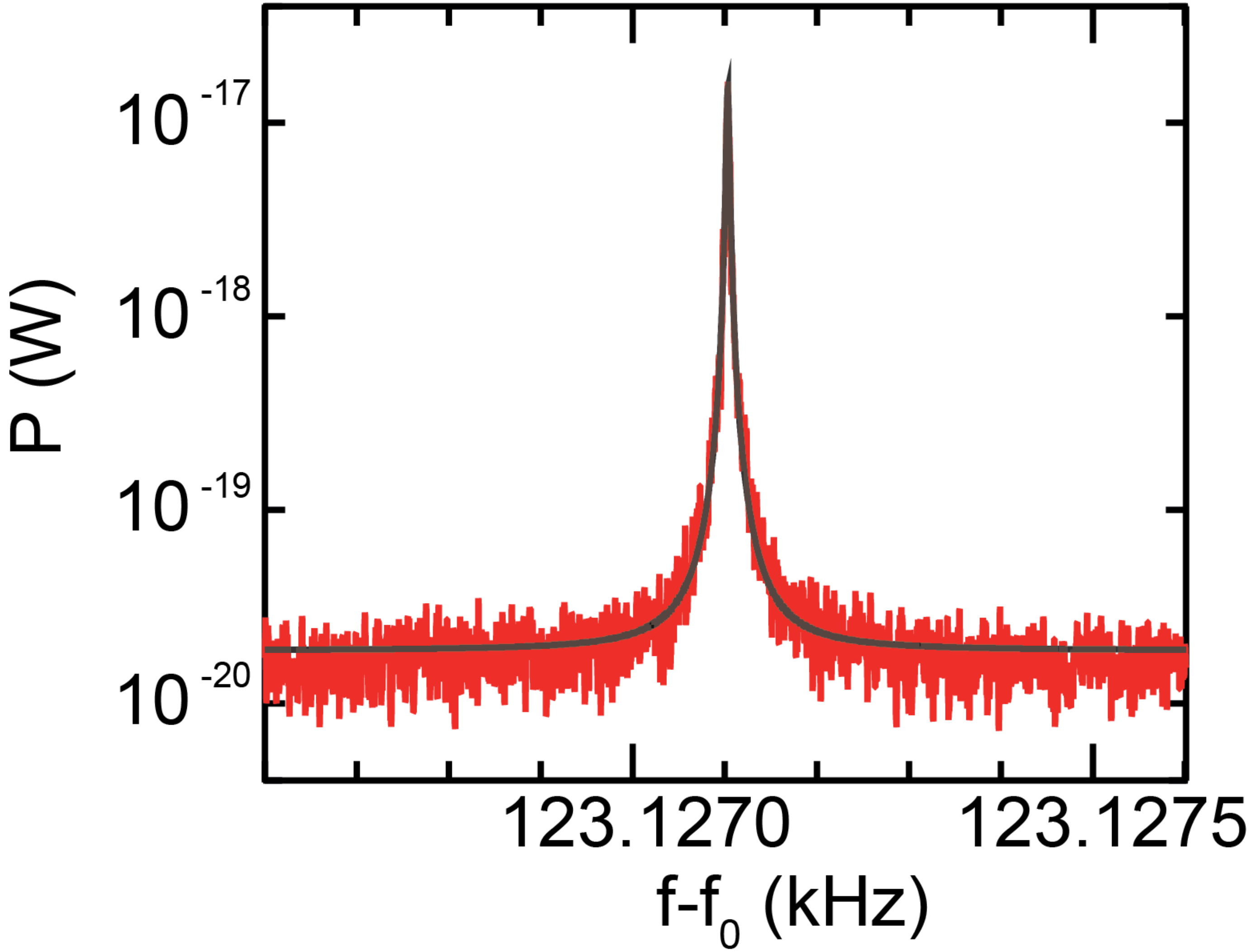
Pretty Good

But can be much better:

Q = 500 x 10^6 (Al)

Q = 10^{11} (Nb)

Mechanical Thermal Noise

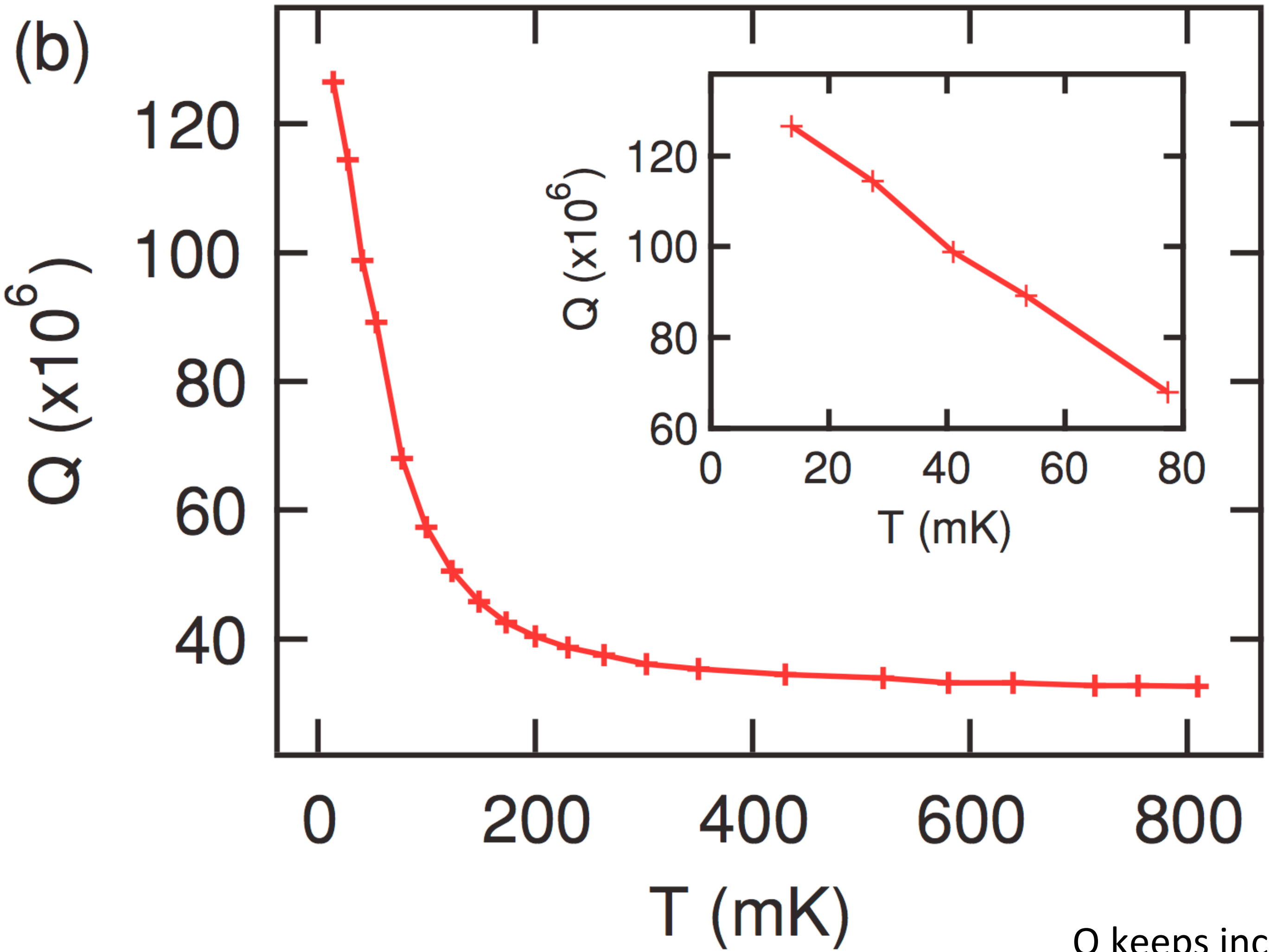


Thermomechanical noise measured with the cavity

$$\gamma_m/2\pi = 3.5 \text{ mHz}$$

$$Q_m = 35 \times 10^6$$

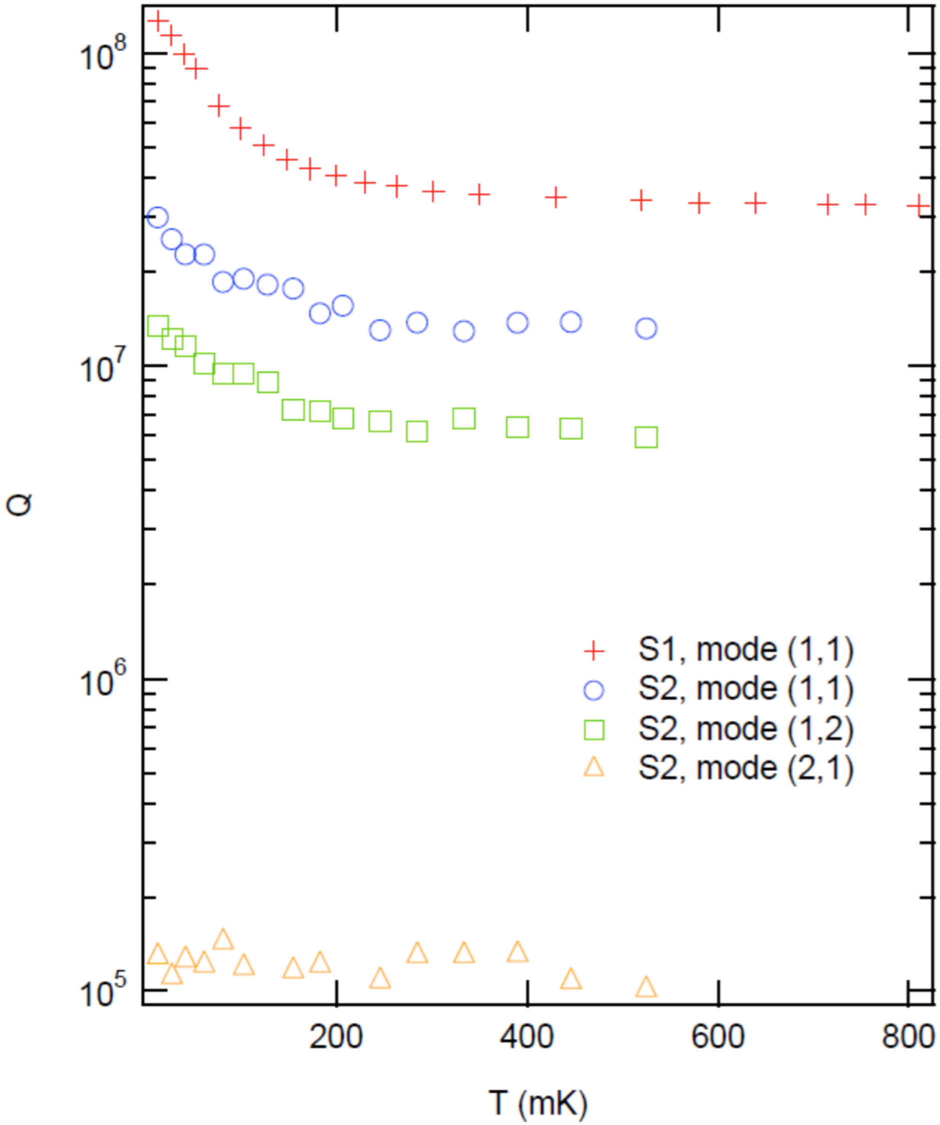
Q up to 128 Million

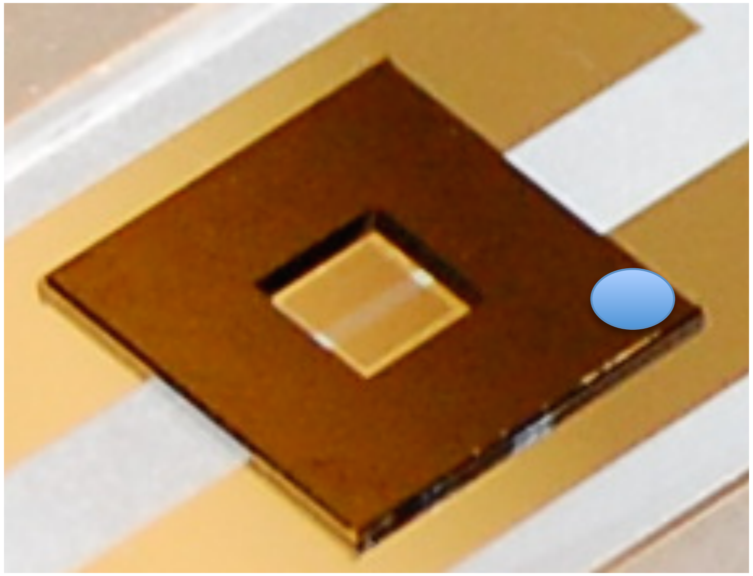


Q keeps increasing far below thermal mode temperature

Yuan, Cohen, Steele, Appl. Phys. Lett. 107, 263501

Clamping losses in the (2,1) mode?





Frequencies (kHz):

S1 (1,1): 241.9

S2 (1,1): 120.9

S2 (1,2): 192.6

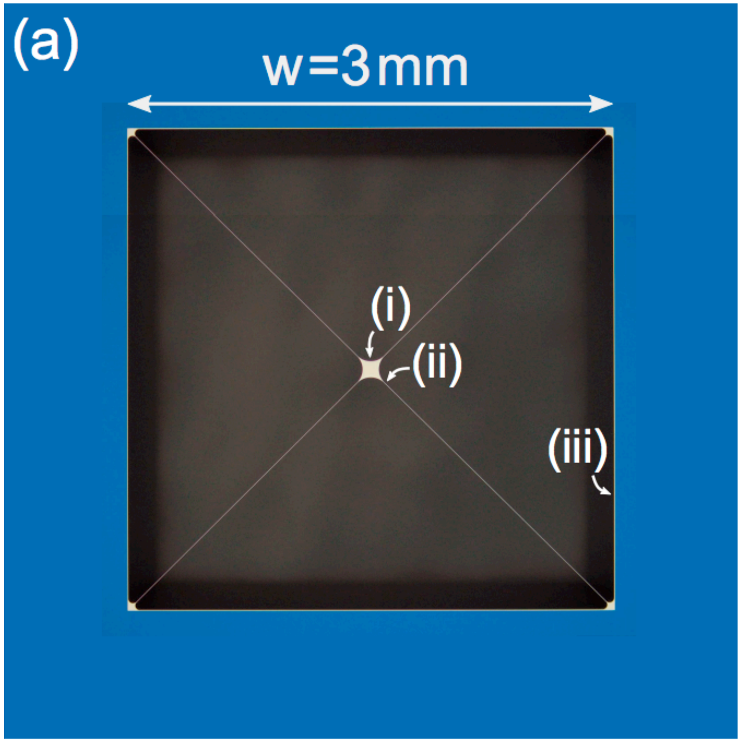
S2 (2,1): 191.7

(1,2) is "dark" to substrate radiation

(tuning fork)

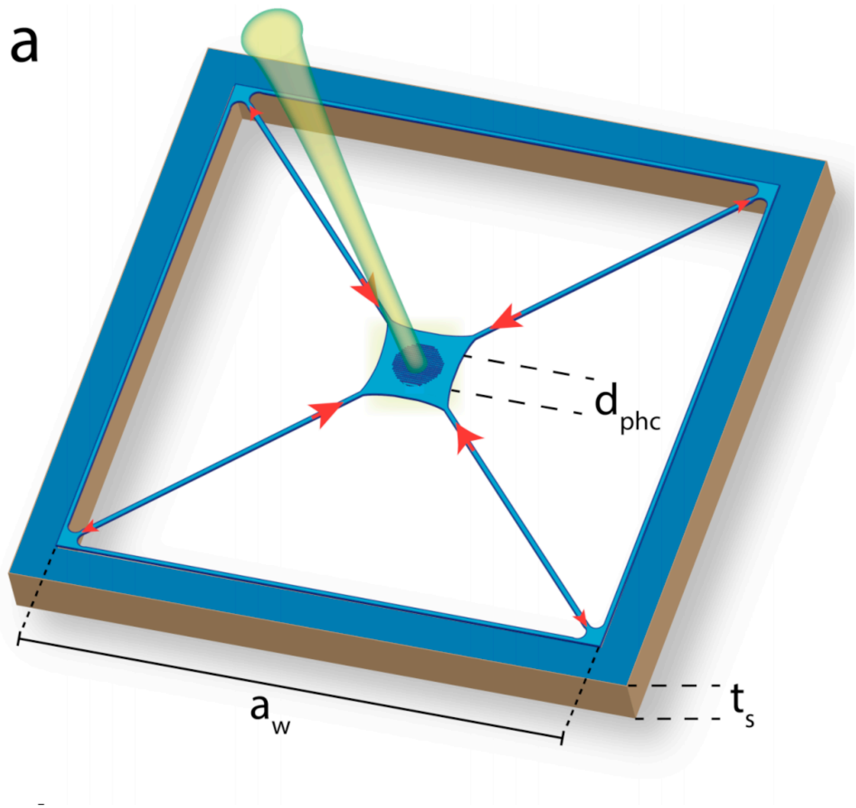
How high can you get at mK? Q = 1 billion?

Q = 40 Million at RT



Christoph Reinhardt, Tina Müller, Alexandre Bourassa, Jack C. Sankey, arxiv:1511.01769

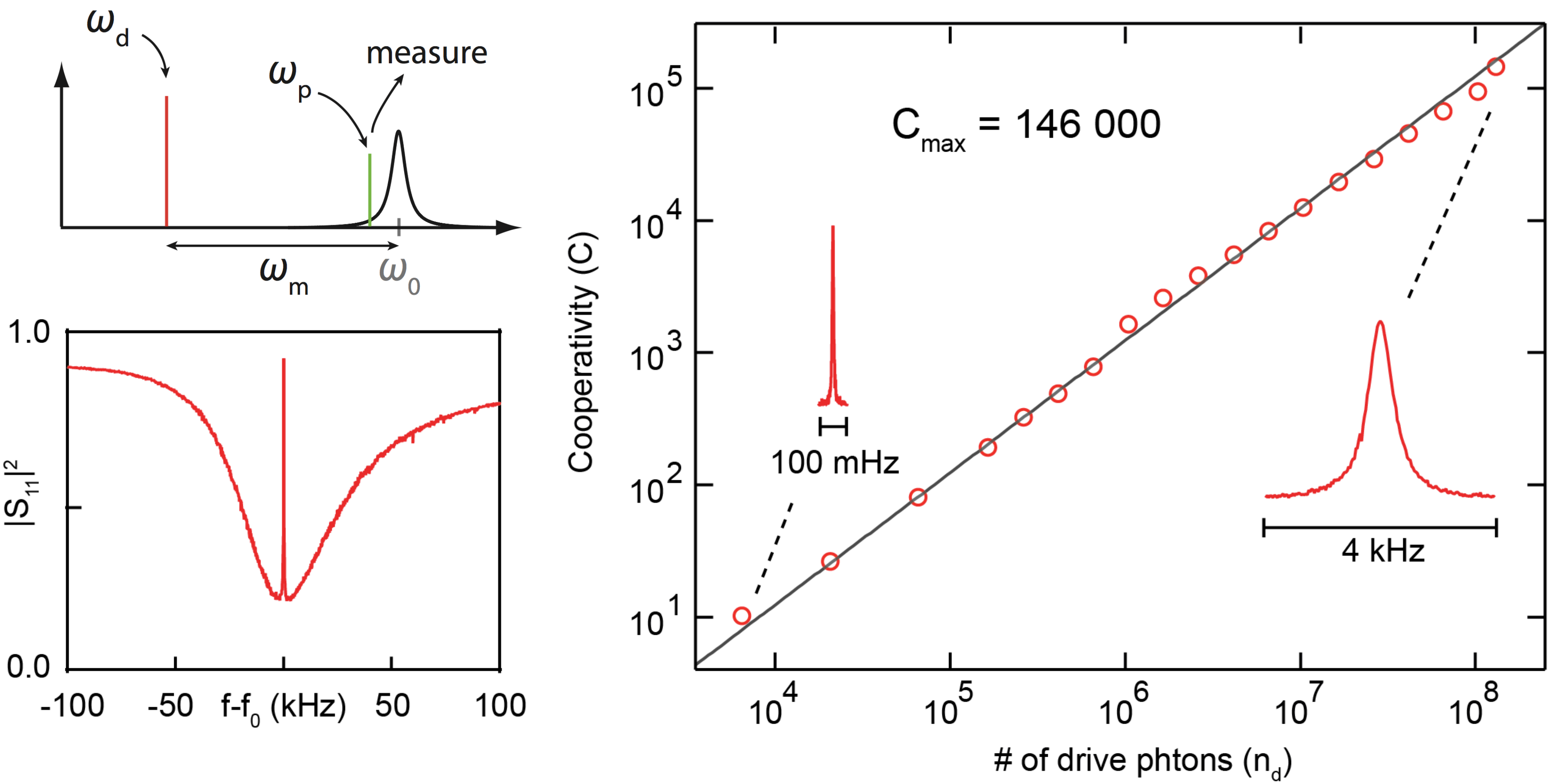
Q = 98 Million at RT



Richard A. Norte, Joao P. Moura, Simon Gröblacher, arxiv:1511.06235

Copenhagen: ***Q = 200 million at RT*** *using phononic sheild for "soft" clamping*

Coupling strength: OMIT



How far can we cool?

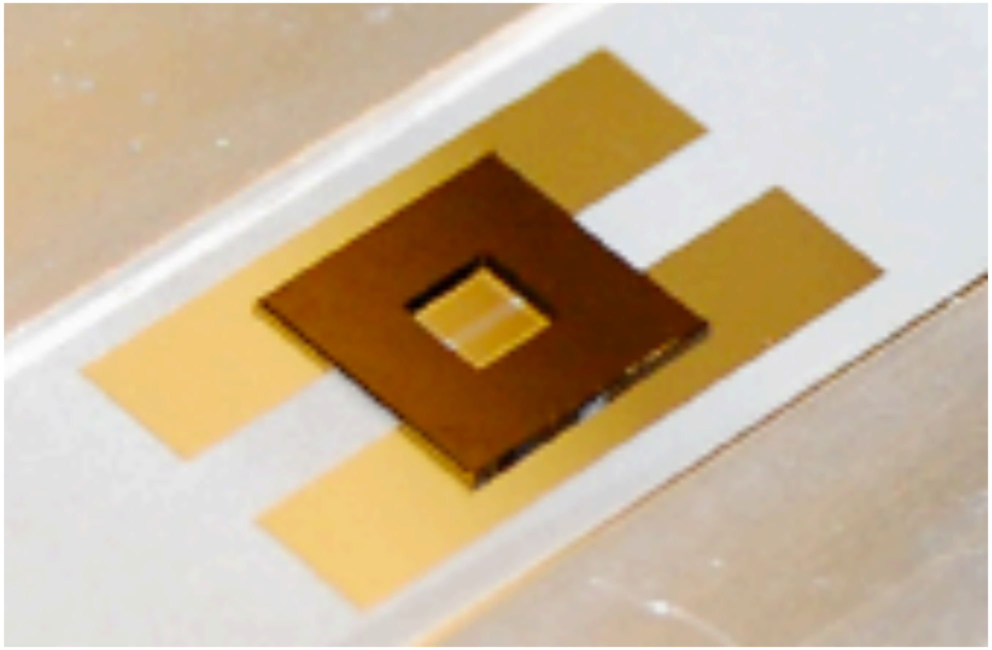
If mode is at 13 mK:

$$n_i = 2000 \ll C_{max}$$

$$C_{max} = 146\ 000$$

$$n_f = 0.013\ ?$$

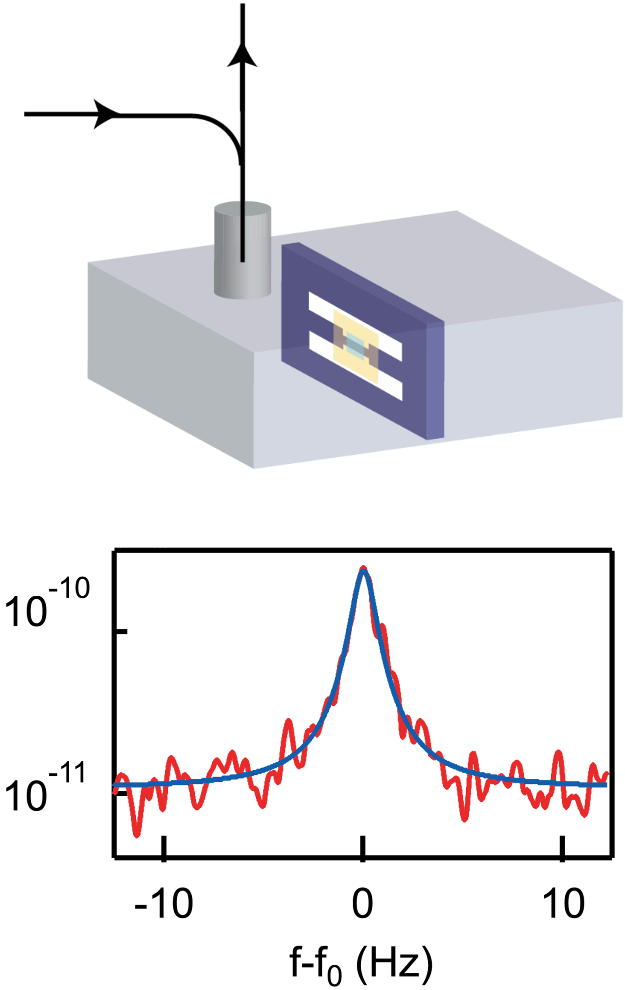
T = 87 nK?

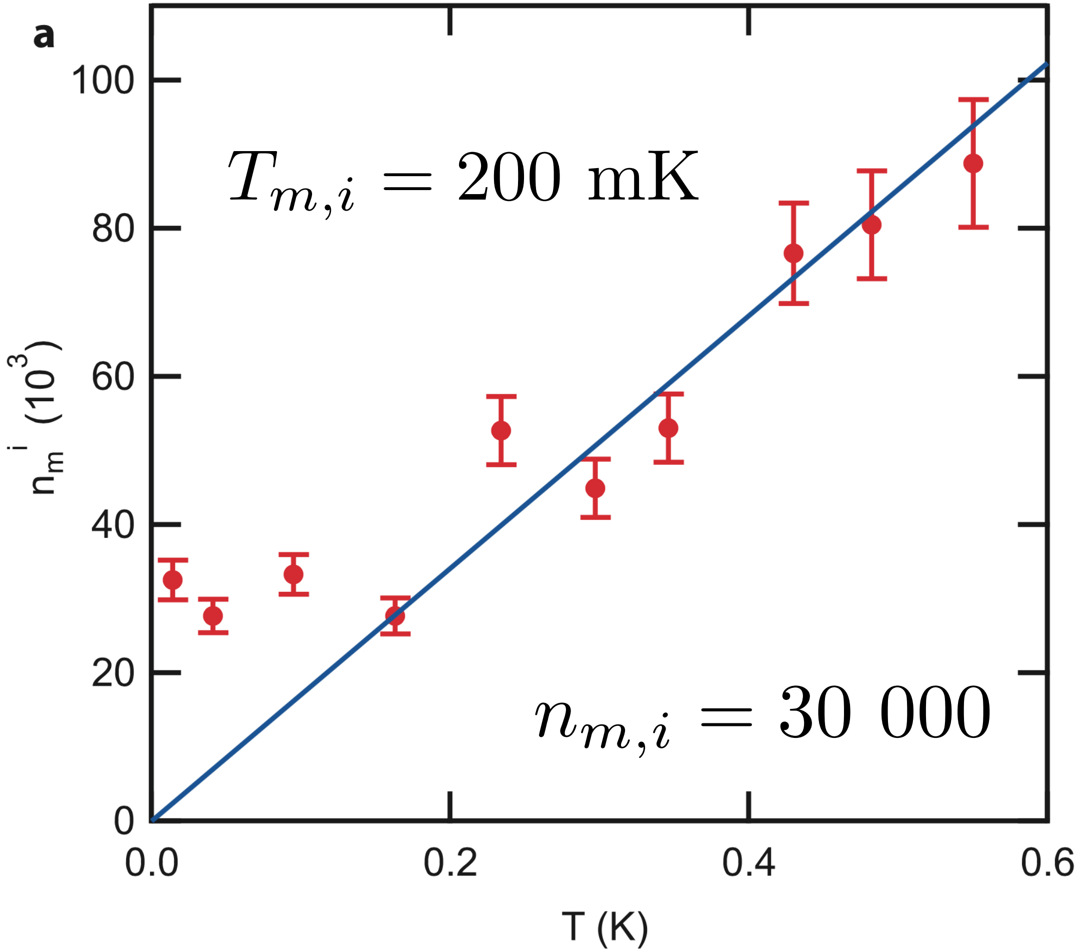


What is starting mode temperature?

What is thermal occupation during cooling?

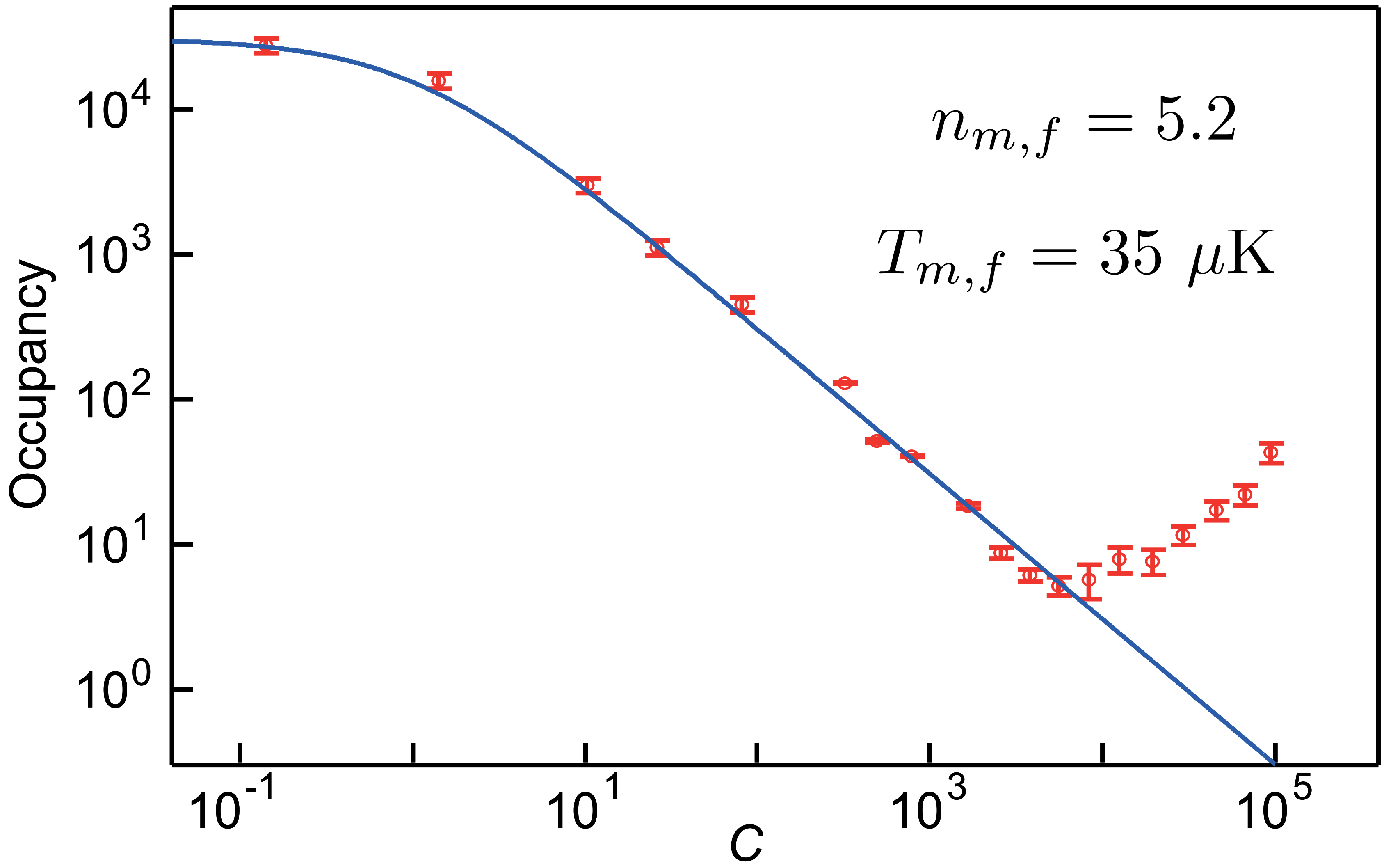
What is our starting mode temperature?



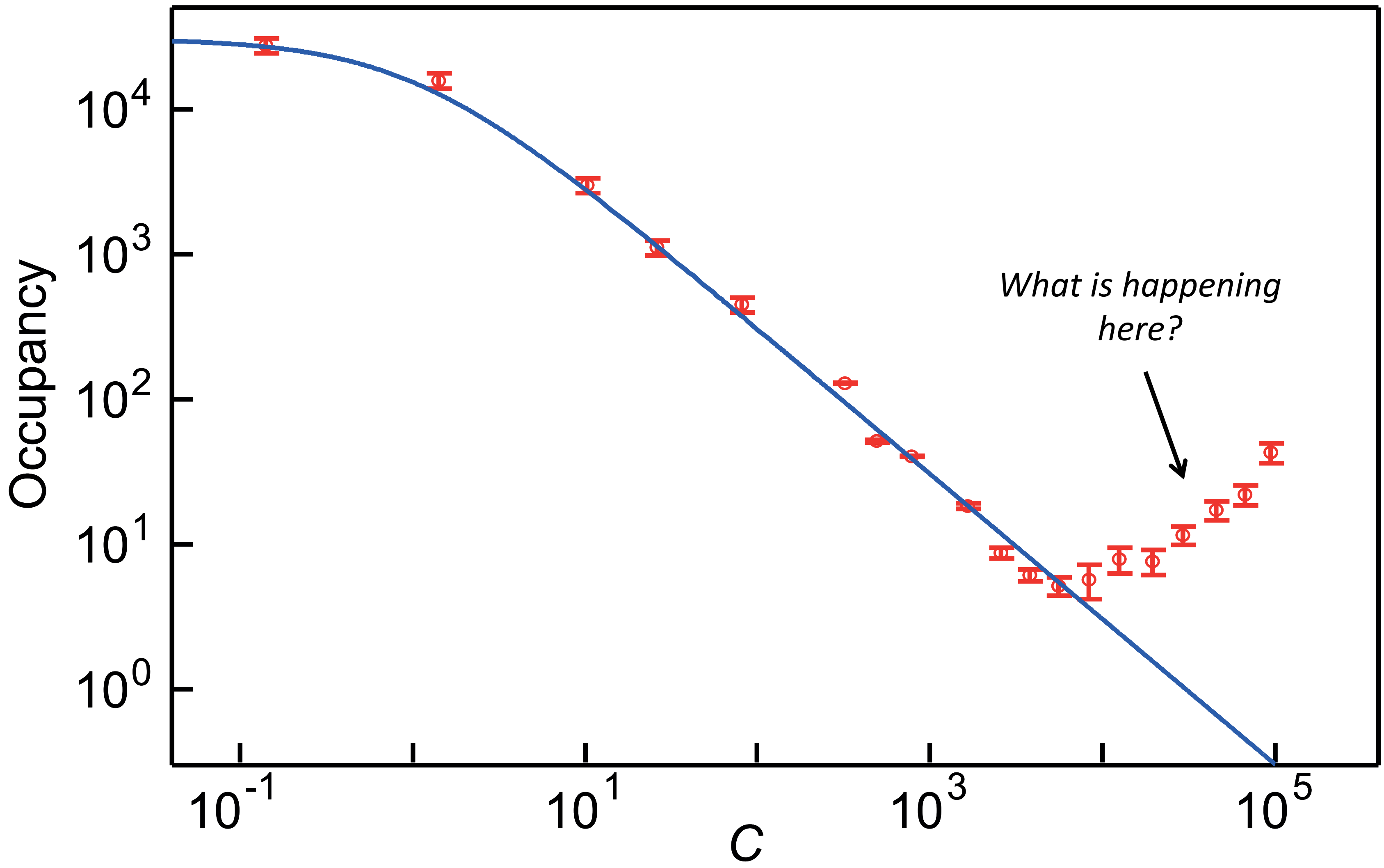


High initial mode temperature: Mechanical vibrations? (Pulse tube is off...)

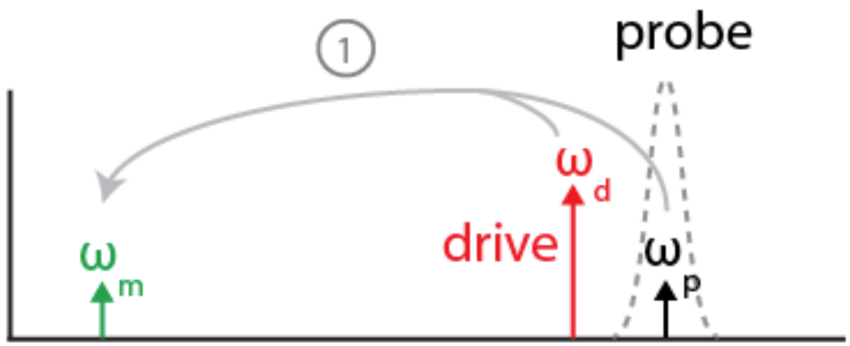
Sideband cooling



Sideband cooling

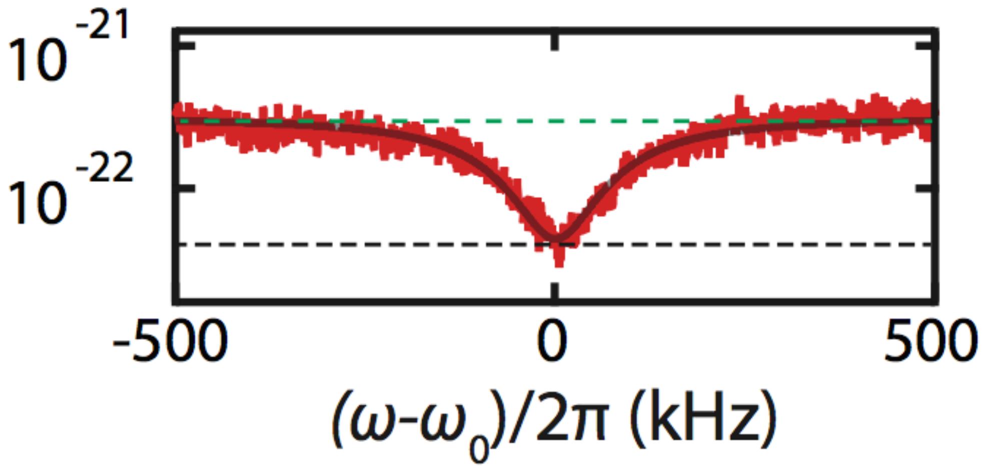


Shaking drum with Cavity Photon Noise



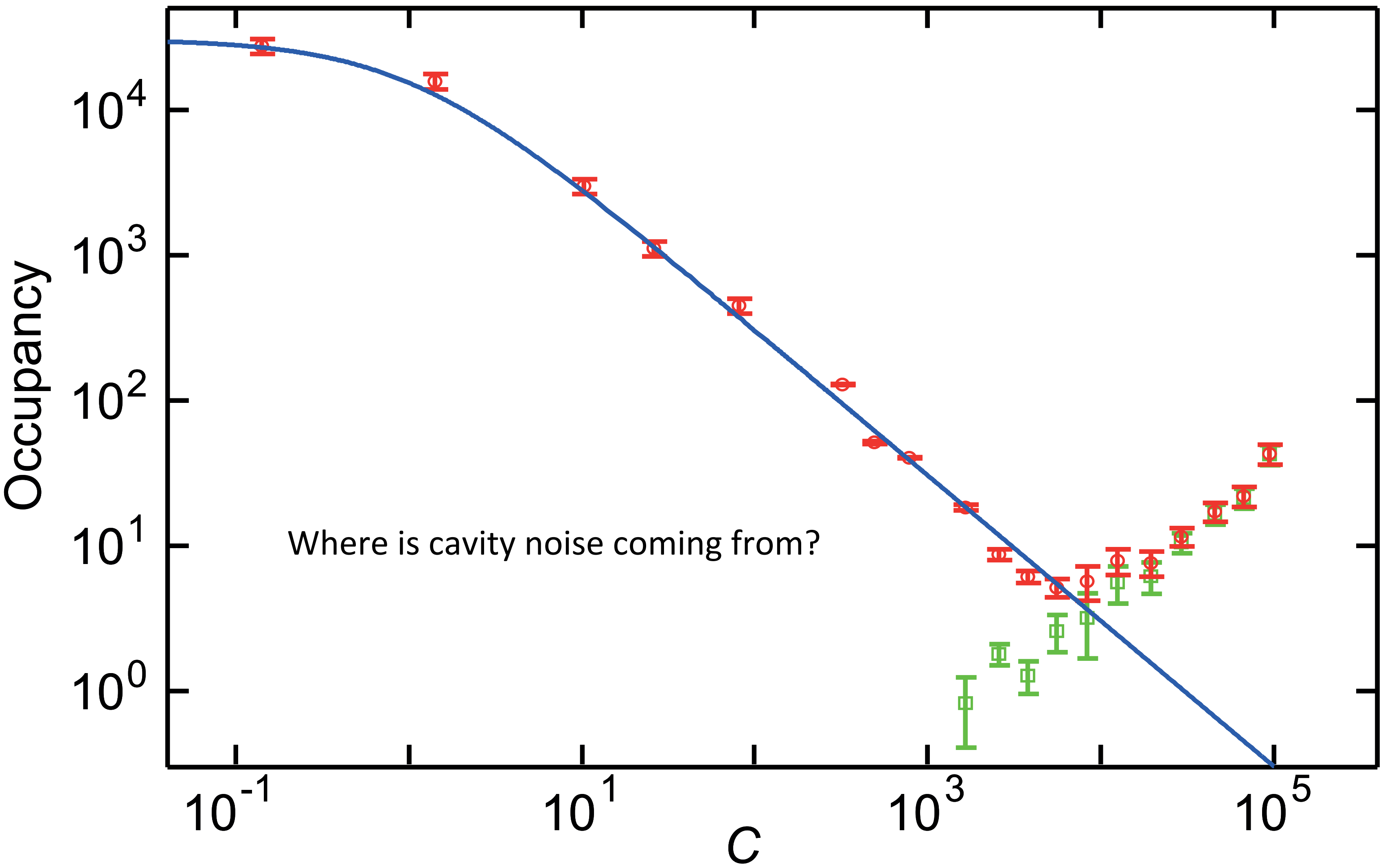
Noise of cooling tone "shaking" the resonator (like OMIT)

Role of probe tone now played by sideband noise

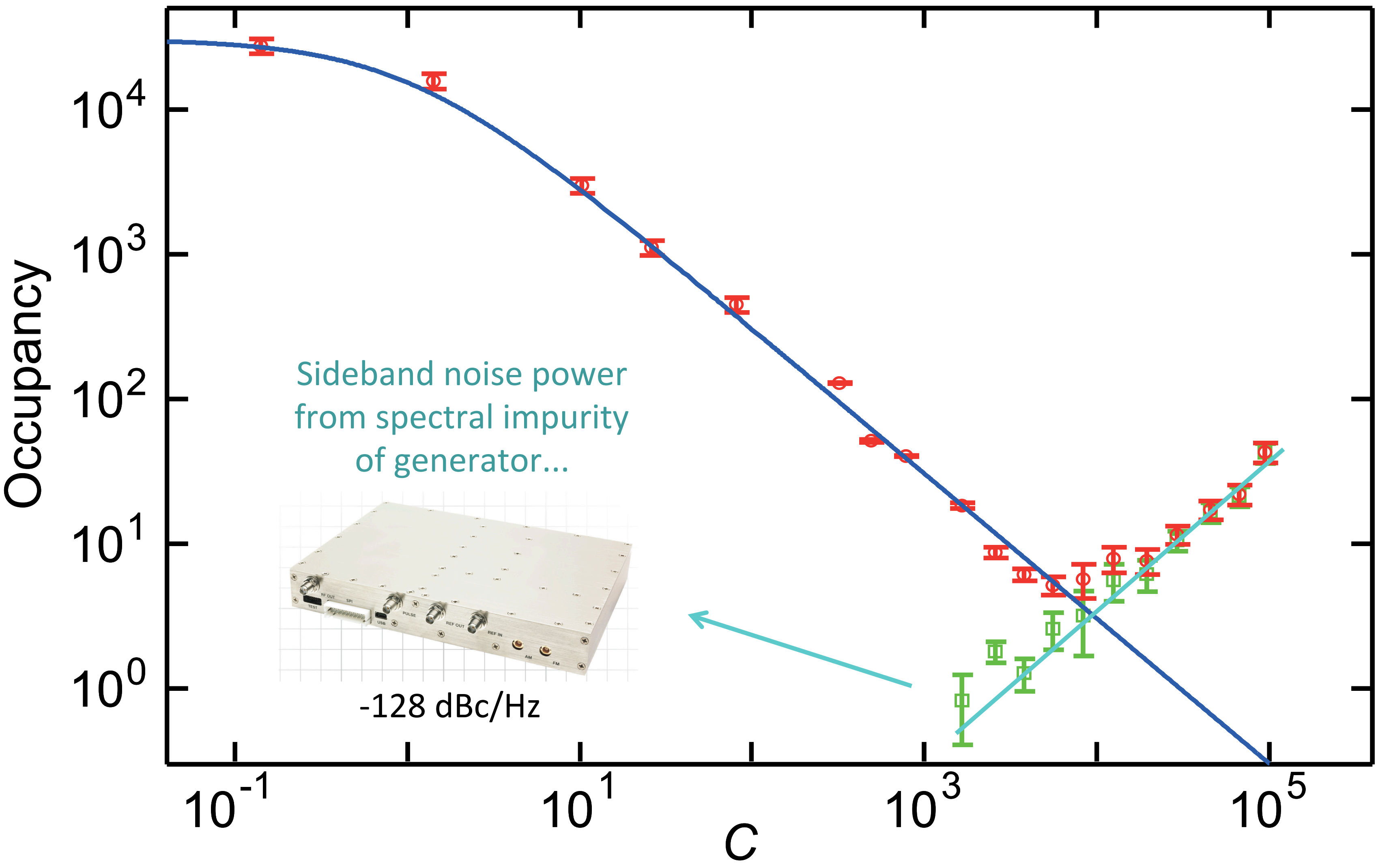


$$\frac{S(\omega_0+\delta\omega)}{\hbar\omega} = 4\eta\left(n_c+\frac{1}{2}\right)+n_{\rm add}$$

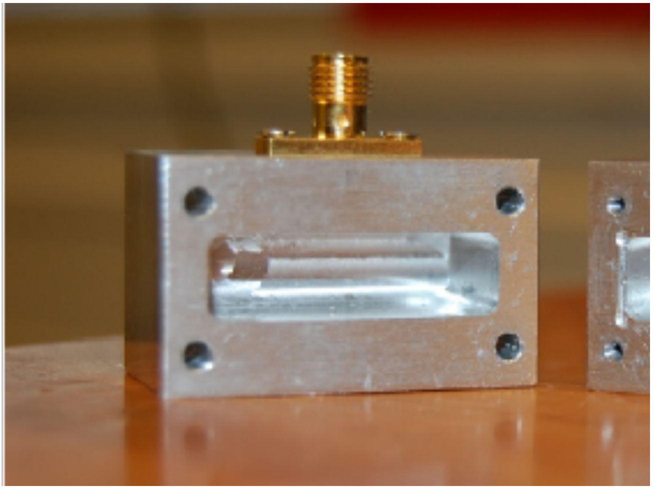
Sideband cooling & cavity noise



Sideband cooling & cavity noise



Exciting future?



Better 3D Cavity:

$$f_c \sim 7\ \mathrm{GHz}$$

$$Q_c \sim 10^5 - 10^{10}$$

$$\kappa \sim 10\ \mathrm{Hz} - 10\ \mathrm{kHz}$$

$$N_{max} \sim 10^7 - 10^{10}$$

Shrink 3 micron gap + trampolines?: g_0 ~ 30 Hz?

Single Photon Cooperativity:

$$C_0 \sim 10^3$$

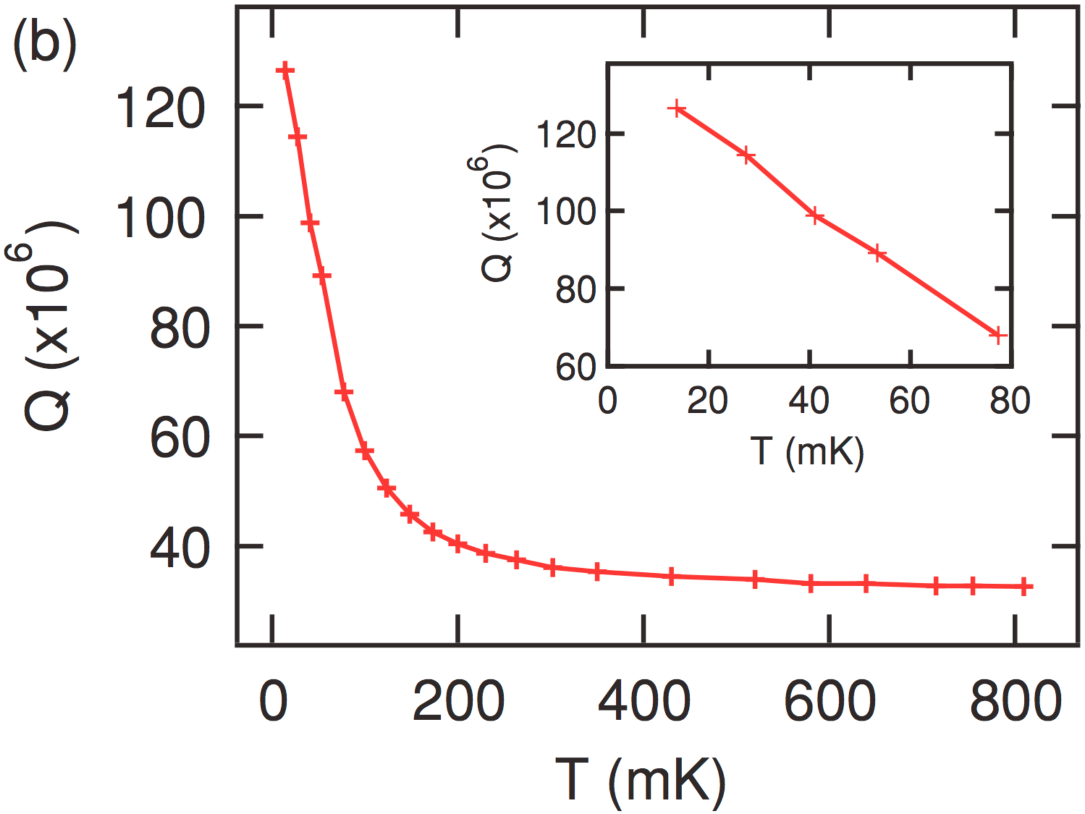
Multi Photon Cooperativity:

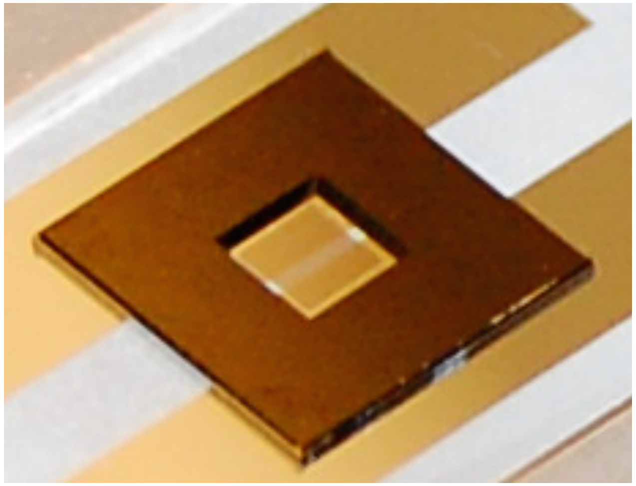
$$C \sim 10^{12}$$

Single photon strong coupling?

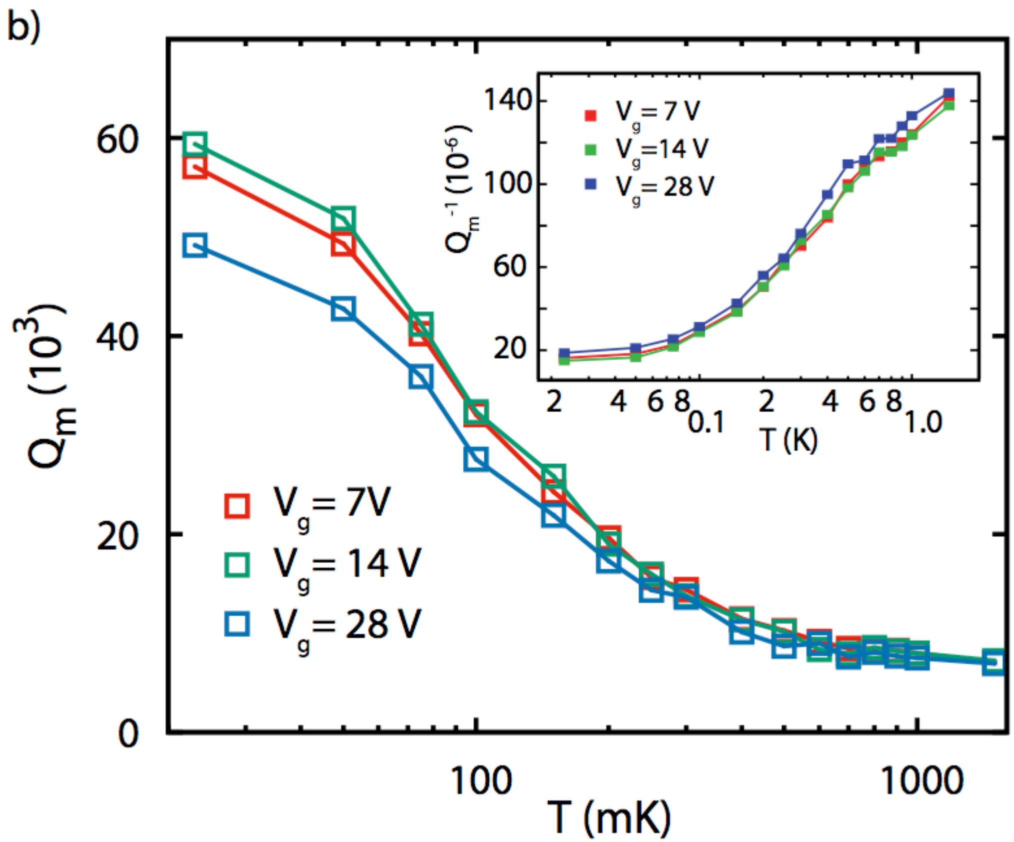
Mechanical Dissipation: Phenomenology

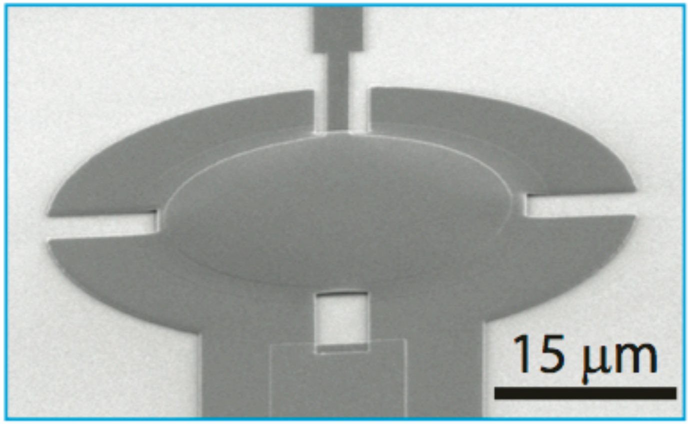
Temperature Dependent Q: SiN

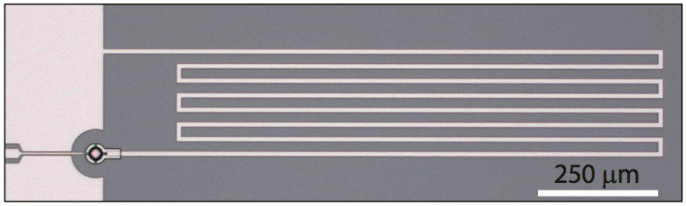




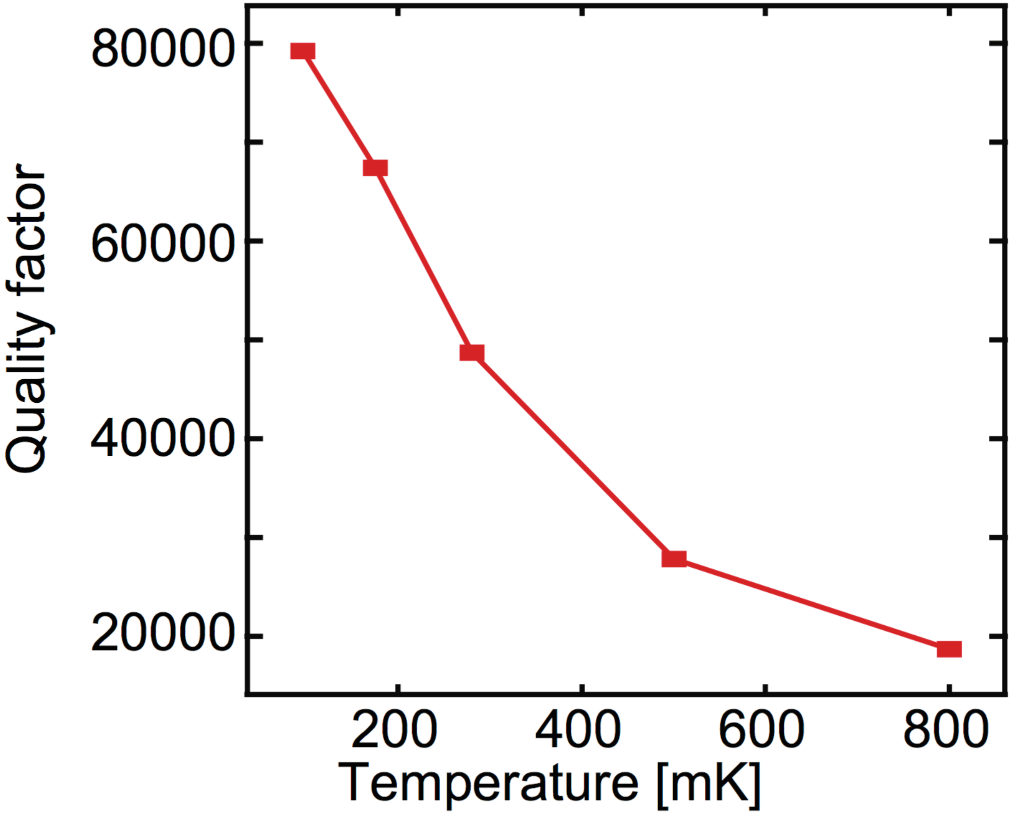
Temperature Dependent Q: Metal

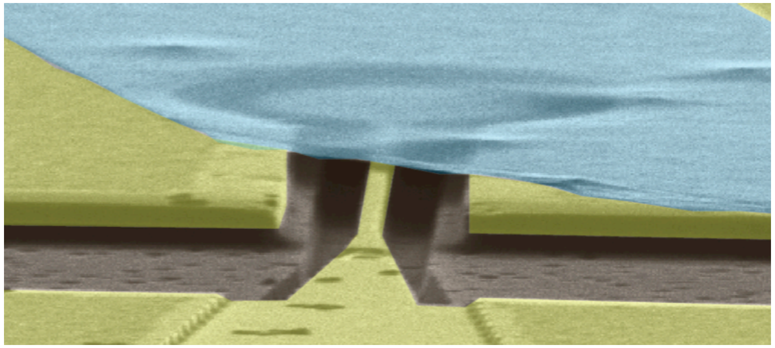






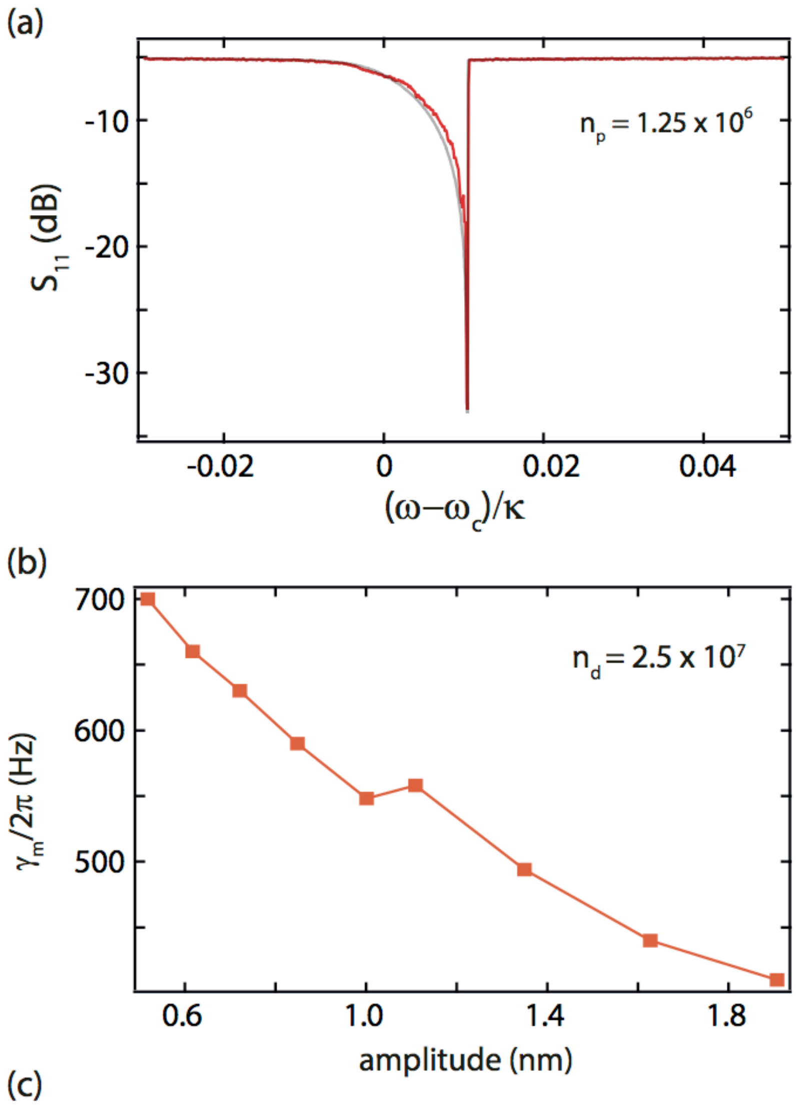
Temperature Dependent Q: Graphene

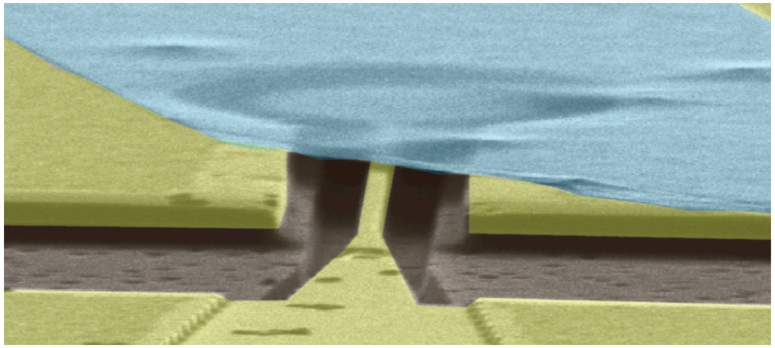




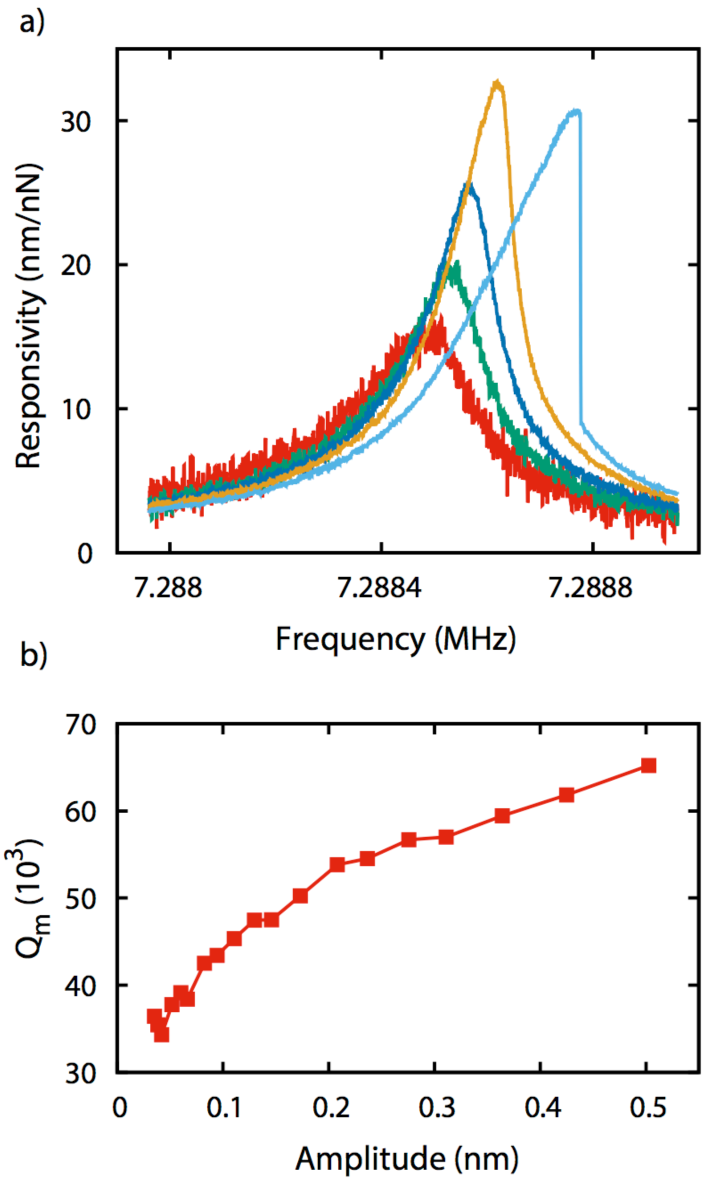
Room temperature: Q = 50

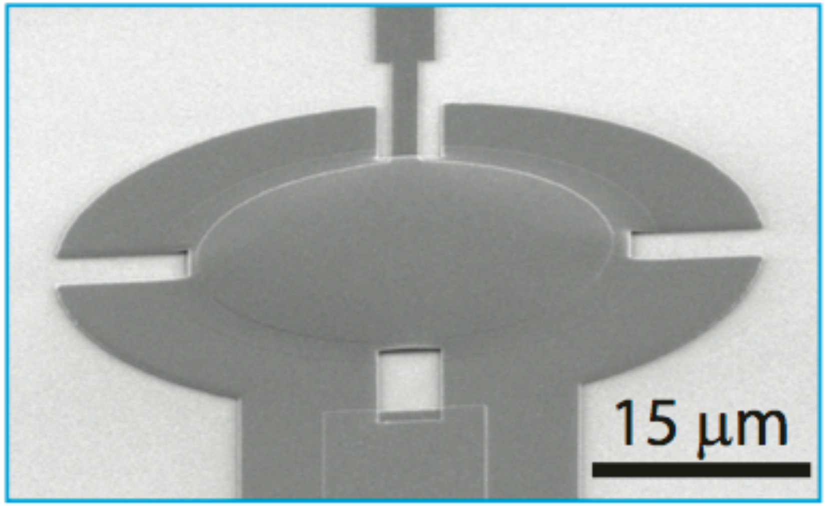
“Negative” nonlinear damping: Graphene

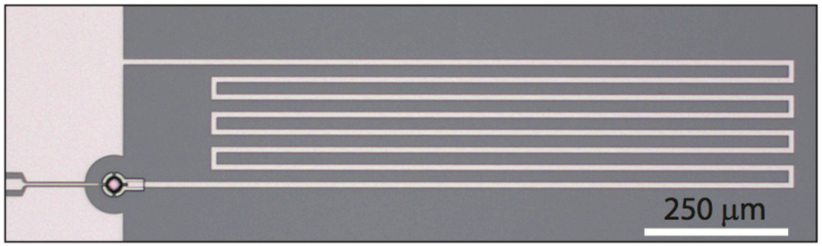




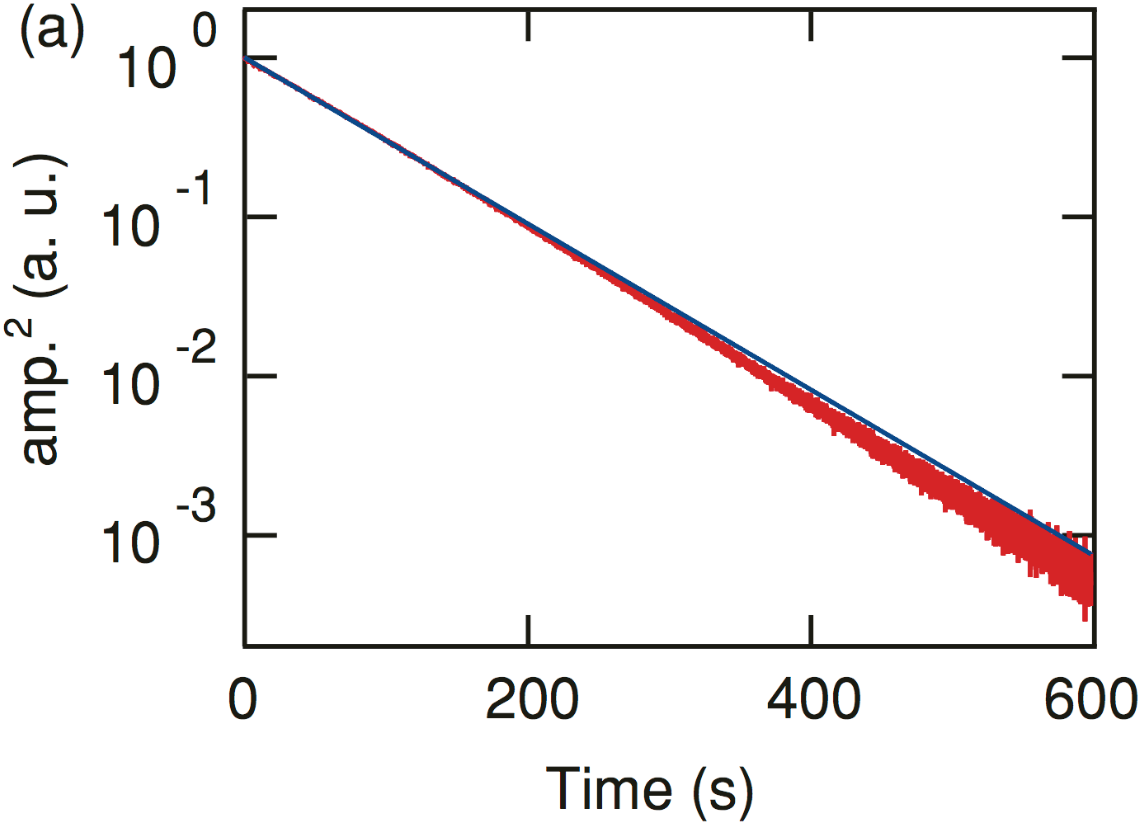
“Negative” nonlinear damping: Metal

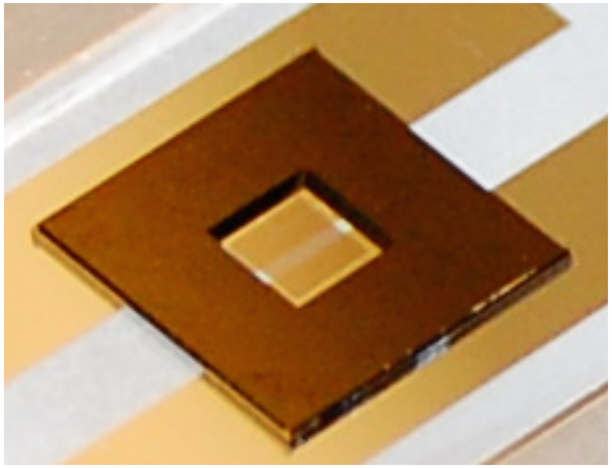






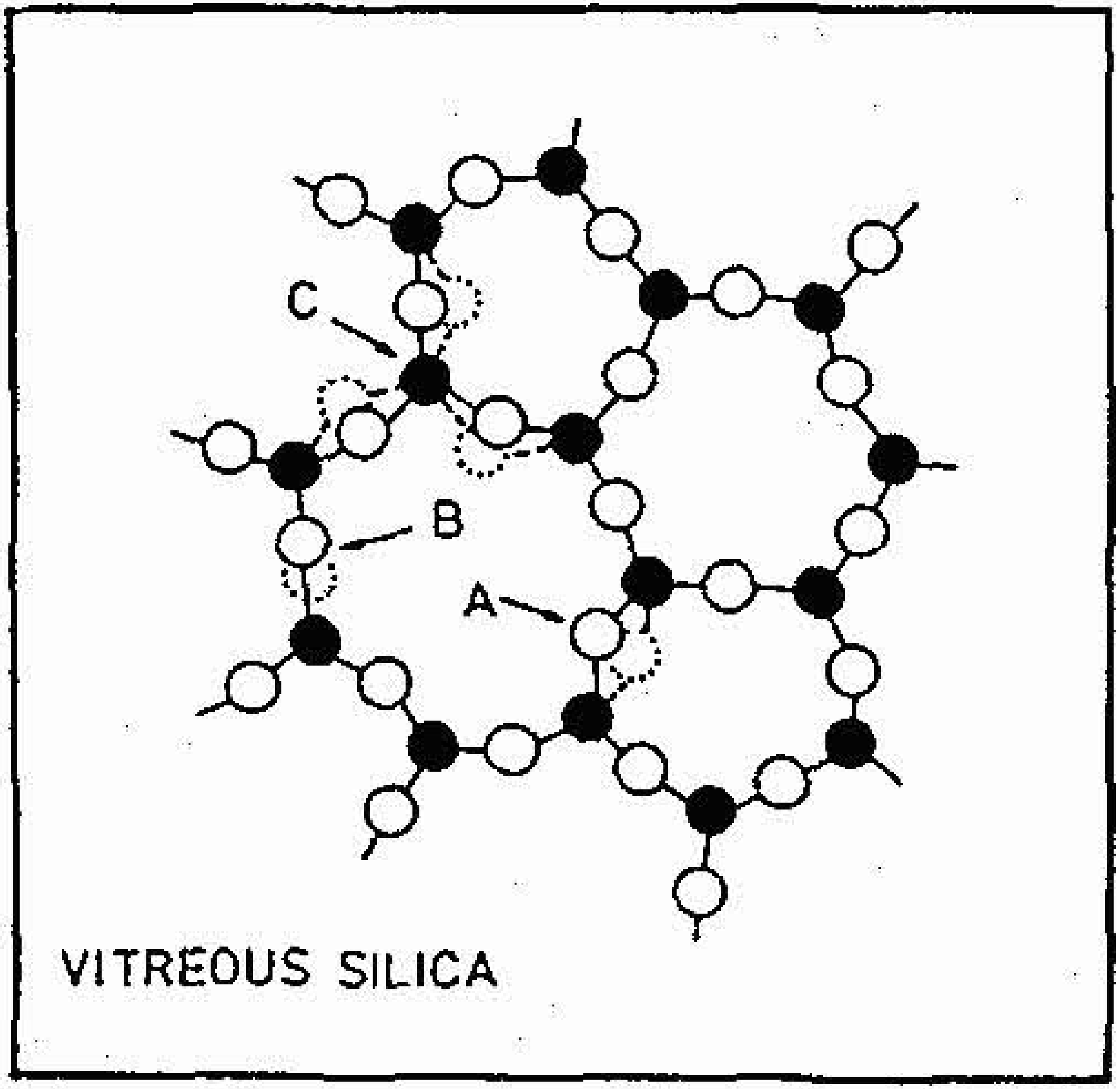
"Negative" nonlinear damping: SiN



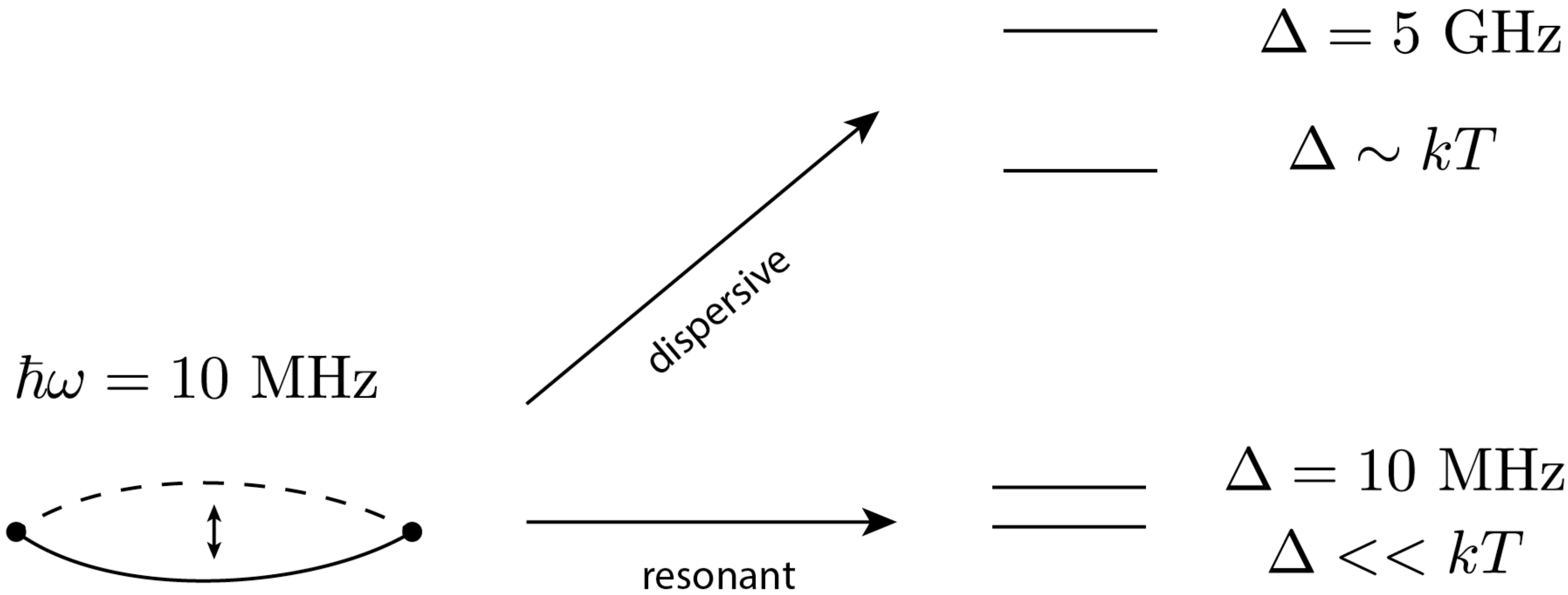


Mechanical Dissipation:
TLS physics?

Mechanical (strain coupled) TLSs



Types of coupling to TLS

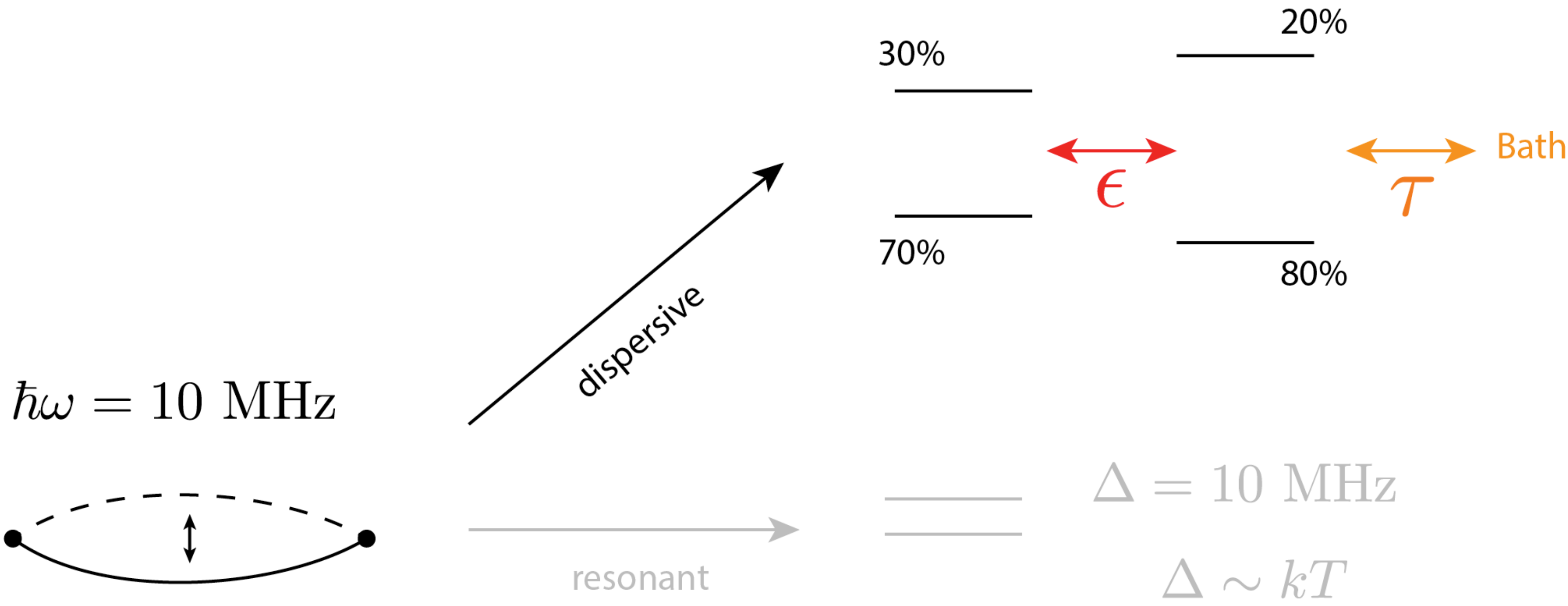


Mechanics:

Resonant Coupling is irrelevant

(Superconducting Cavities: dominated by resonant coupling. Q goes up with increasing T...)

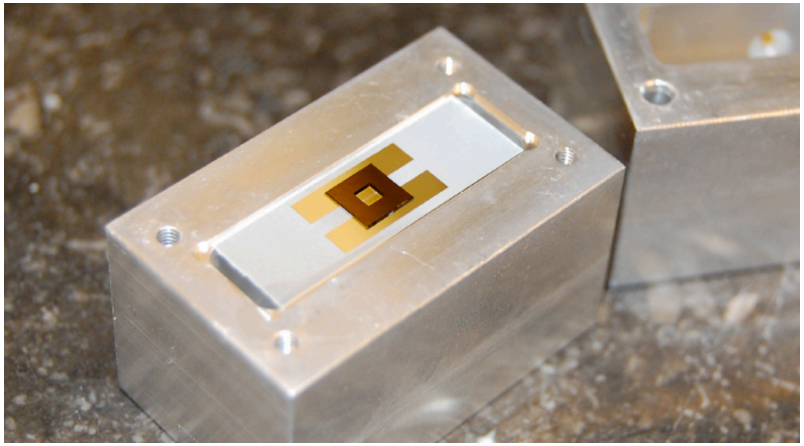
How does dispersive coupling dissipate energy?



- Mechanical Displacements dispersively shift energy splitting.
- If mechanical displacements are slow, the TLS ensemble re-equilibrates with bath
- Lag between displacement and re-equilibration gives dissipation
- Lowering T: TLS population shifts to ground state and decouples
- Open question: saturation effects are not expected for non-resonant coupling?

Summary

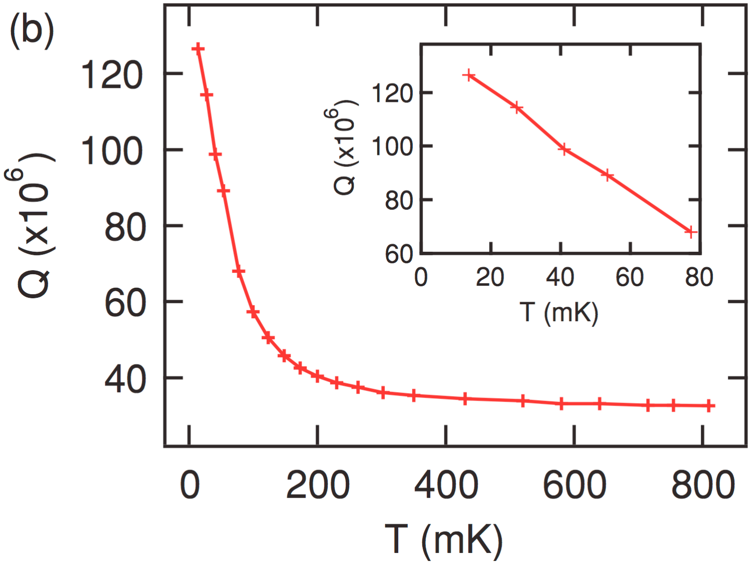
Microwave optomechanics with a mm-sized membrane and a 3D superconducting cavity



Cooling close to the quantum ground state
(limited by generator noise...)

Scaling to Single-Photon Coupling and C = 10^{12}?

Trends in mechanical dissipation?



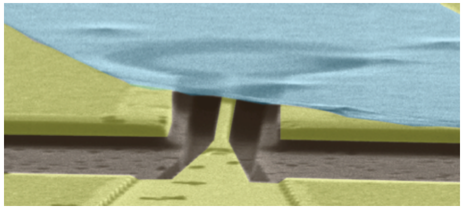
Trends in mechanical dissipation:

Temperature Dependence
Saturation?
TLS?

Microwave Optomechanics in the SteeleLab

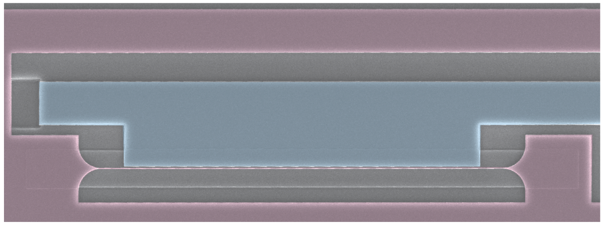
Graphene Microwave Optomechanics

Optomechanics with 2D crystals

Optomechanics with SQUIDS and Nanostrings

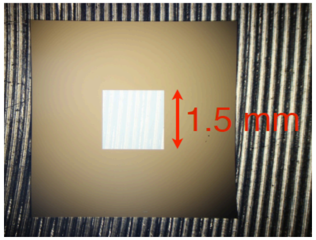
Large single-photon coupling




Mechanics with 3D Cavities

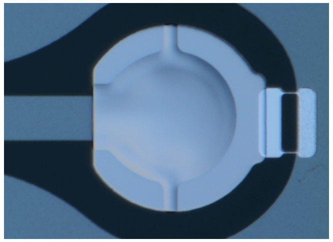
Macroscopic objects in the ground state





Mechanical Transmons and Metal Drums

Deep / ultra strong coupling regime

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