3D microwave optomechanical cavities

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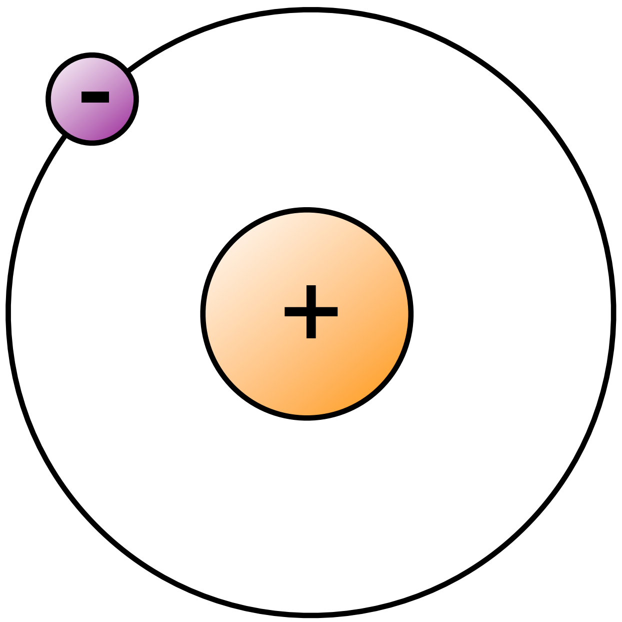
Motivation

- *Quantum* ⟶ - *Classical*



Is quantum mechanics compatible with large, massive structures?

⇩

Nano- or micro-mechanical resonator

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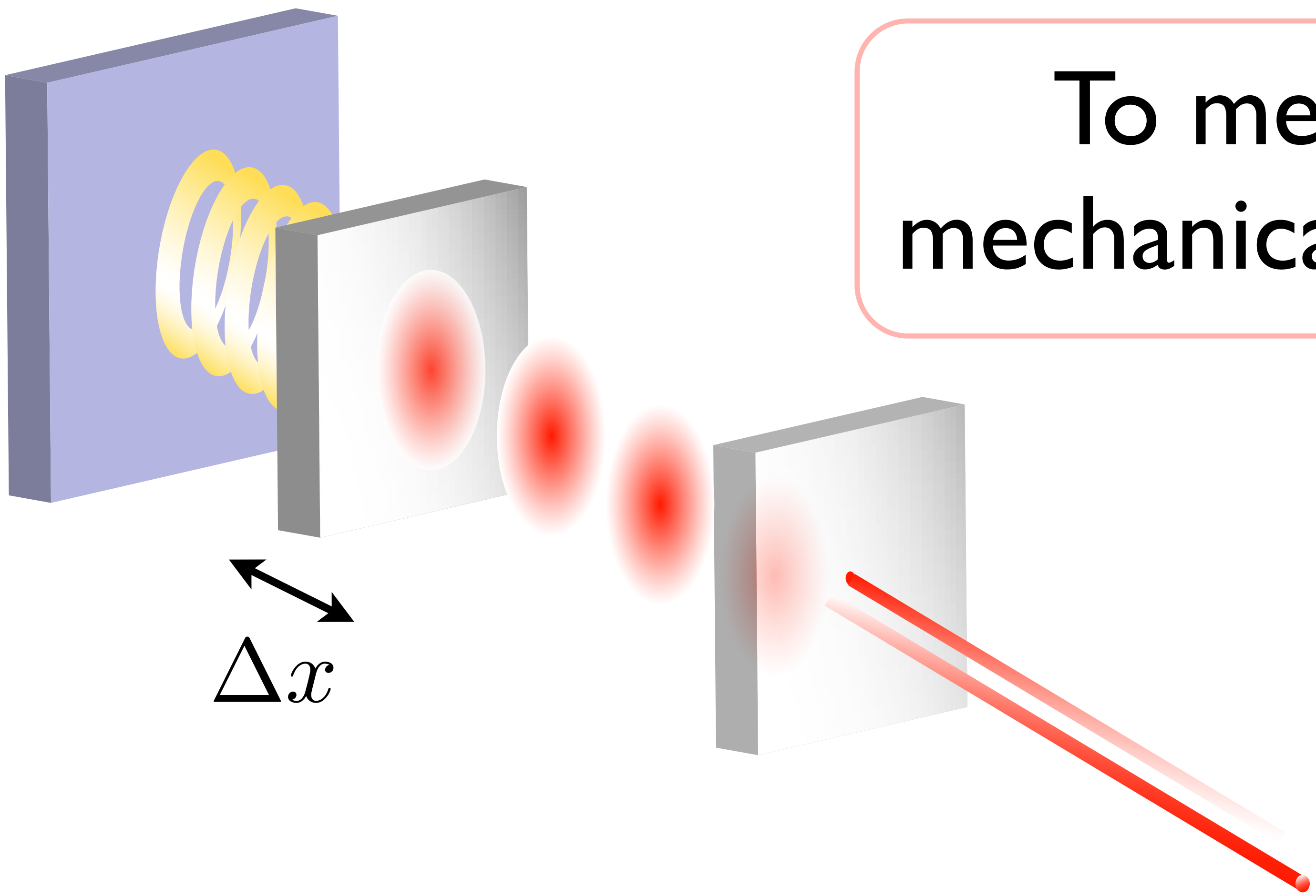
Cavity optomechanics

Interaction between cavity field and a movable mirror



light field

To measure mechanical motion

To create and control mechanical motion

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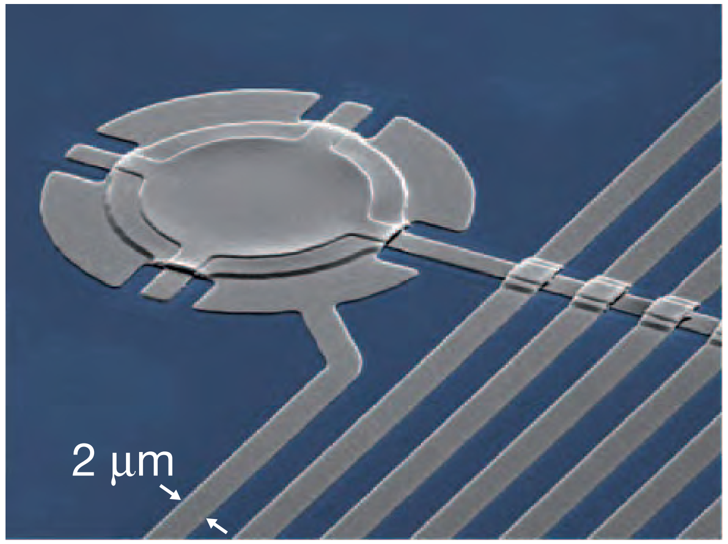
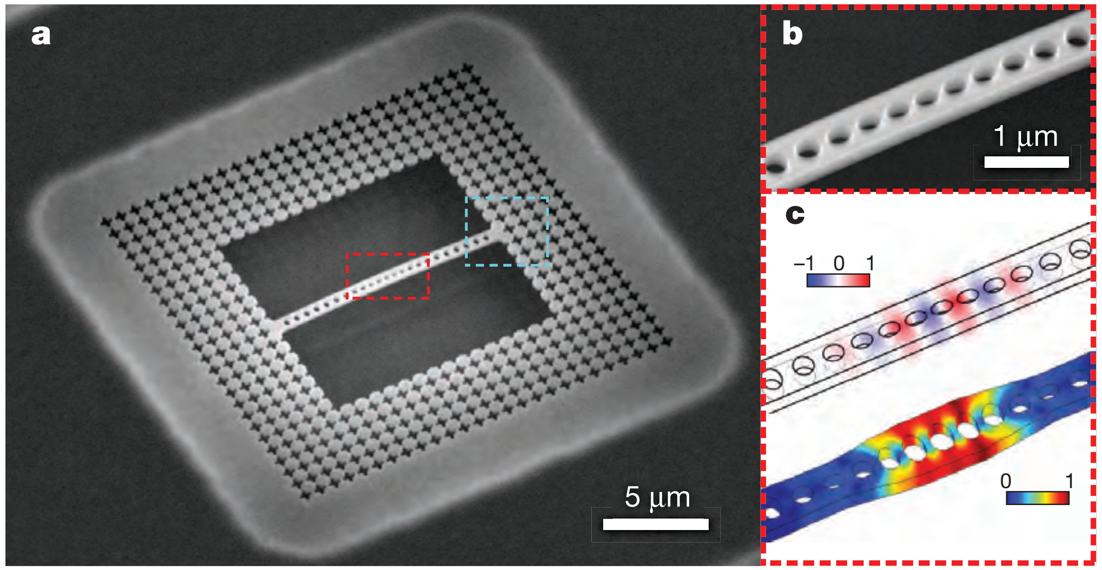
Landmarks

Teufel et al., Nature 2011

7.5 GHz; 10.6 MHz





Chan et al., Nature 2011

195 THz; 3.68 GHz

New optomechanical system: SiN membrane in 3d cavity

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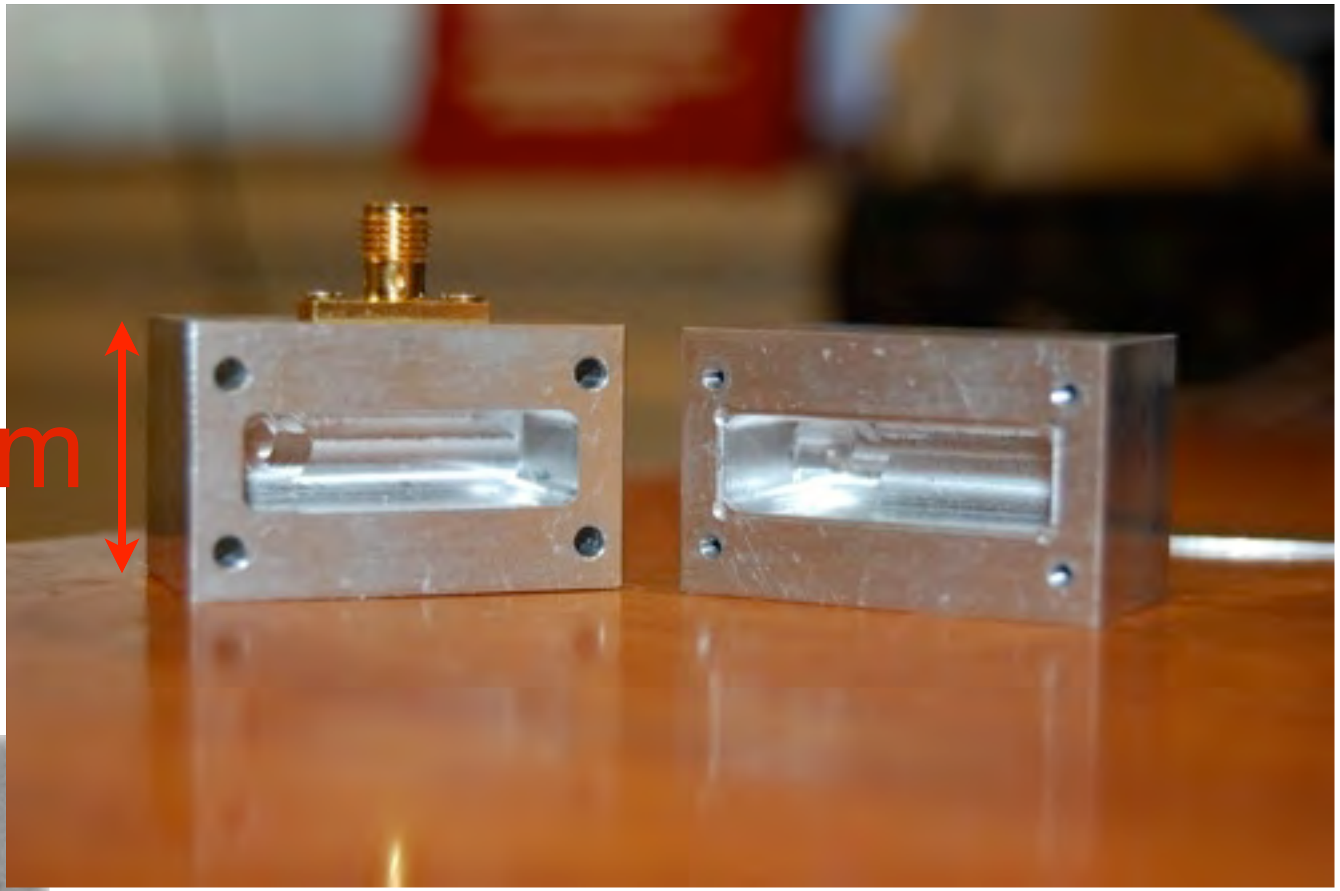
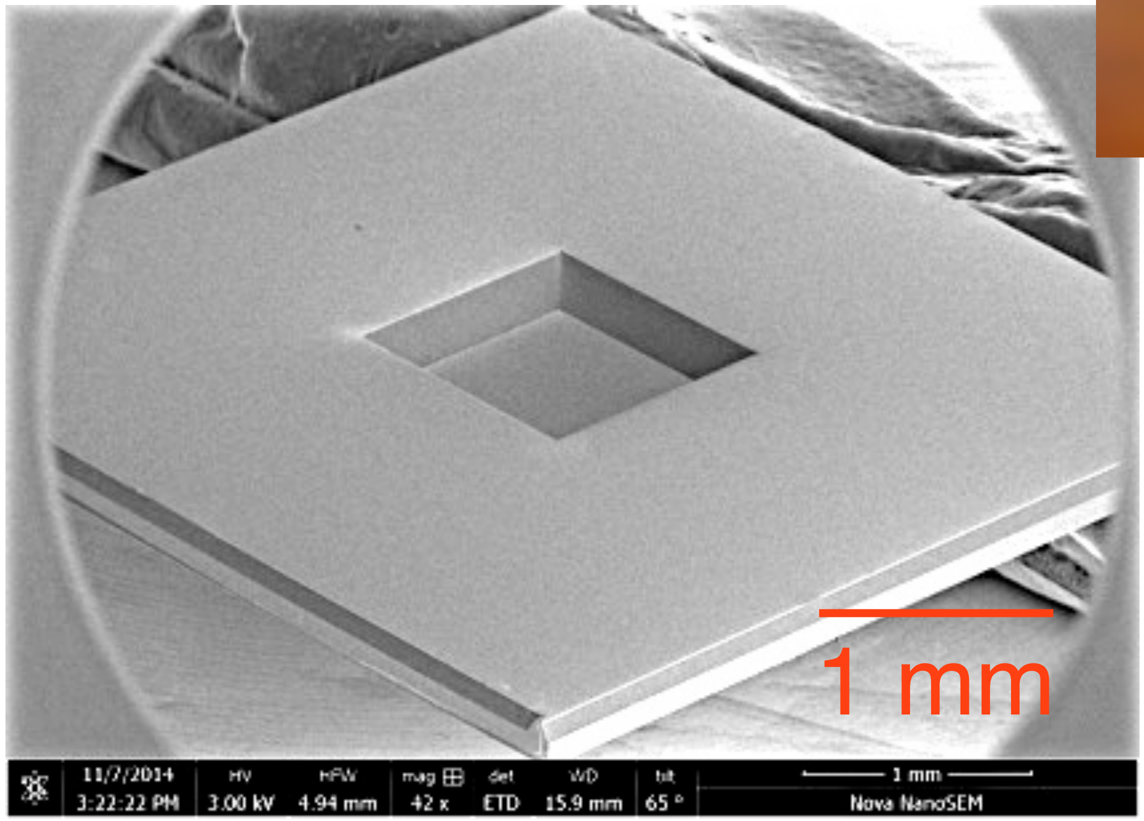
3D cavity and SiN membrane

Al cavity, Q>100,000





SiN membrane, Q>1,000,000

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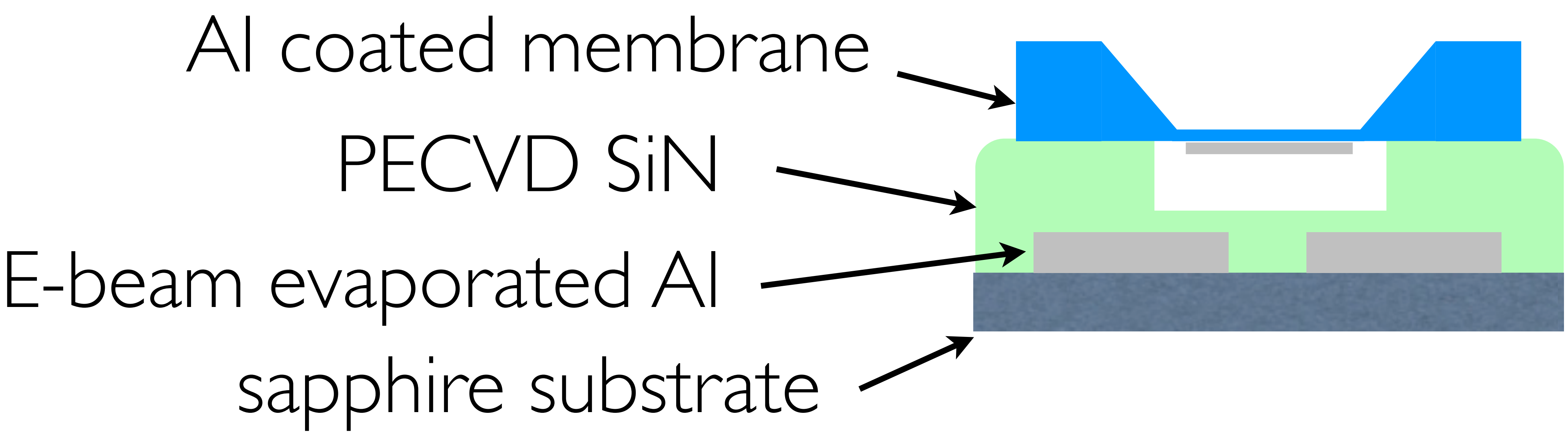
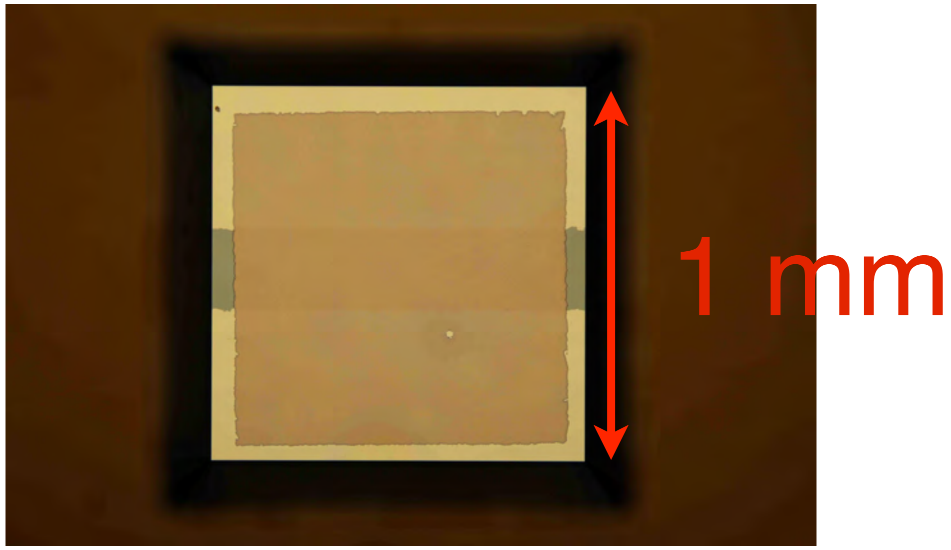
Sample preparation





Membrane window zoom-in

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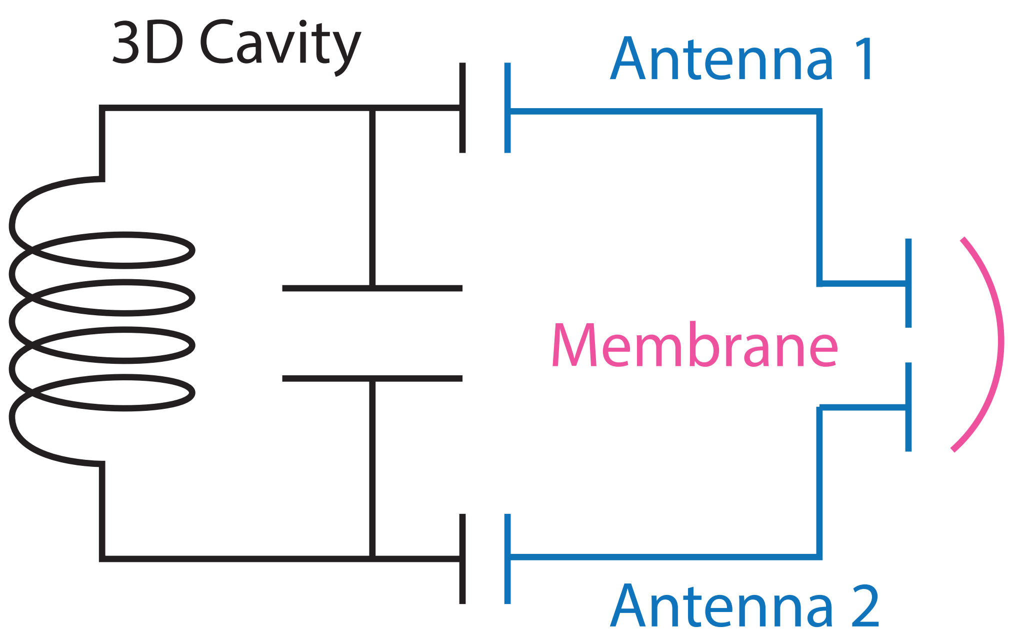
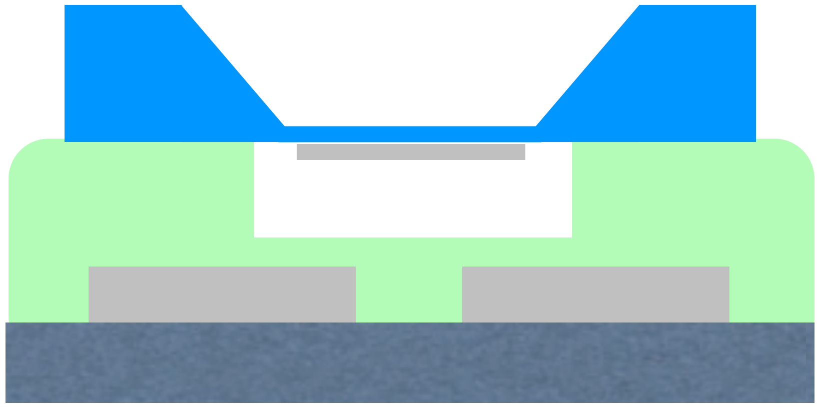
Coupling scheme

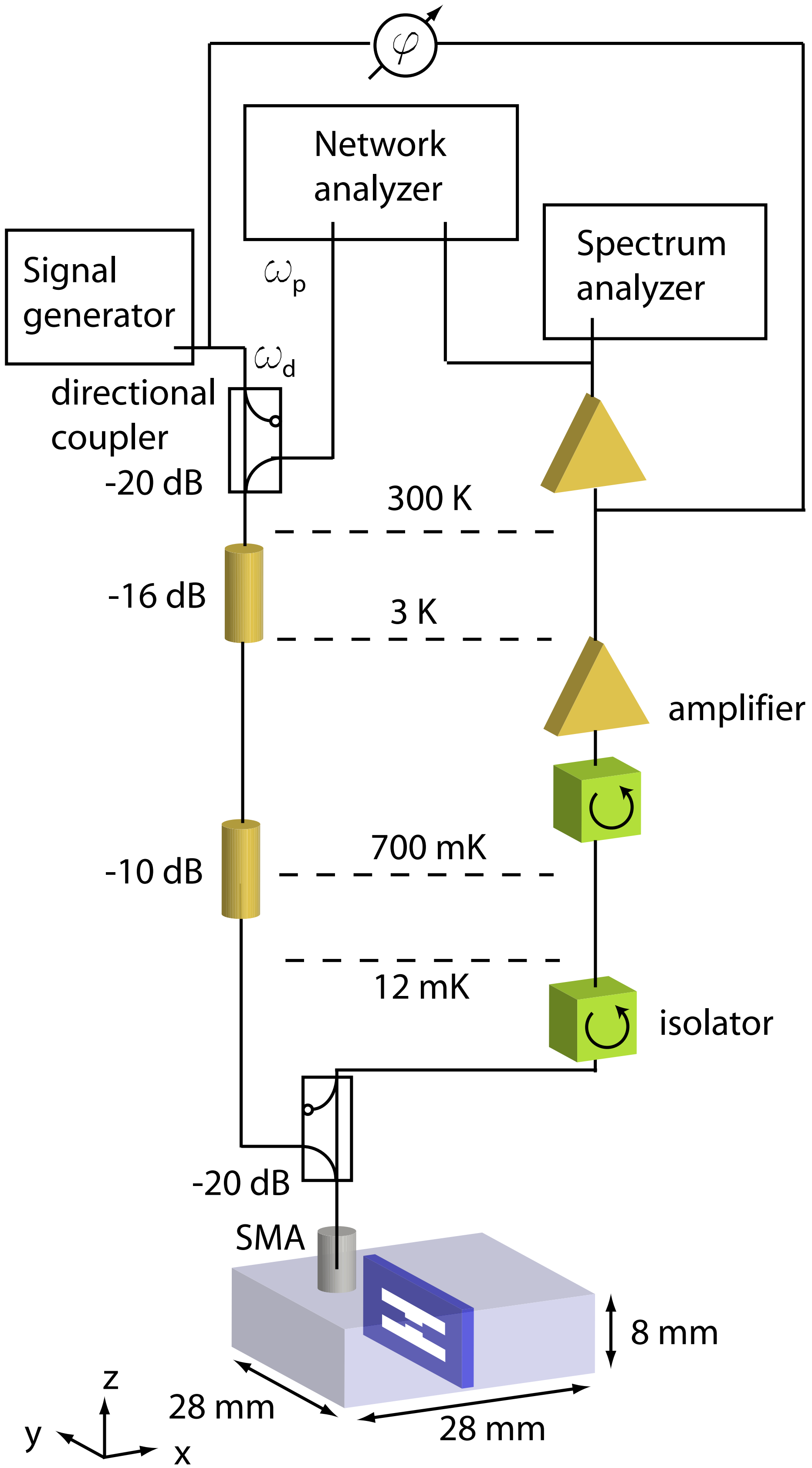


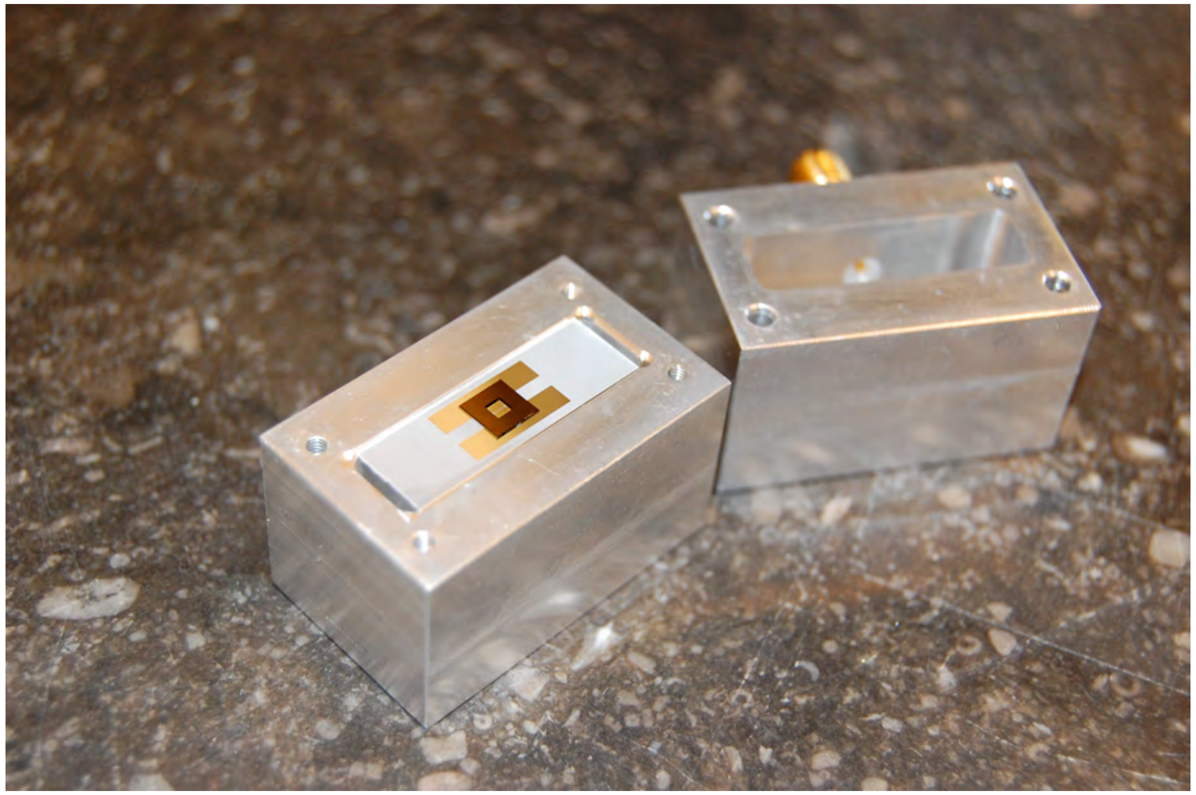


Cavity frequency shift:

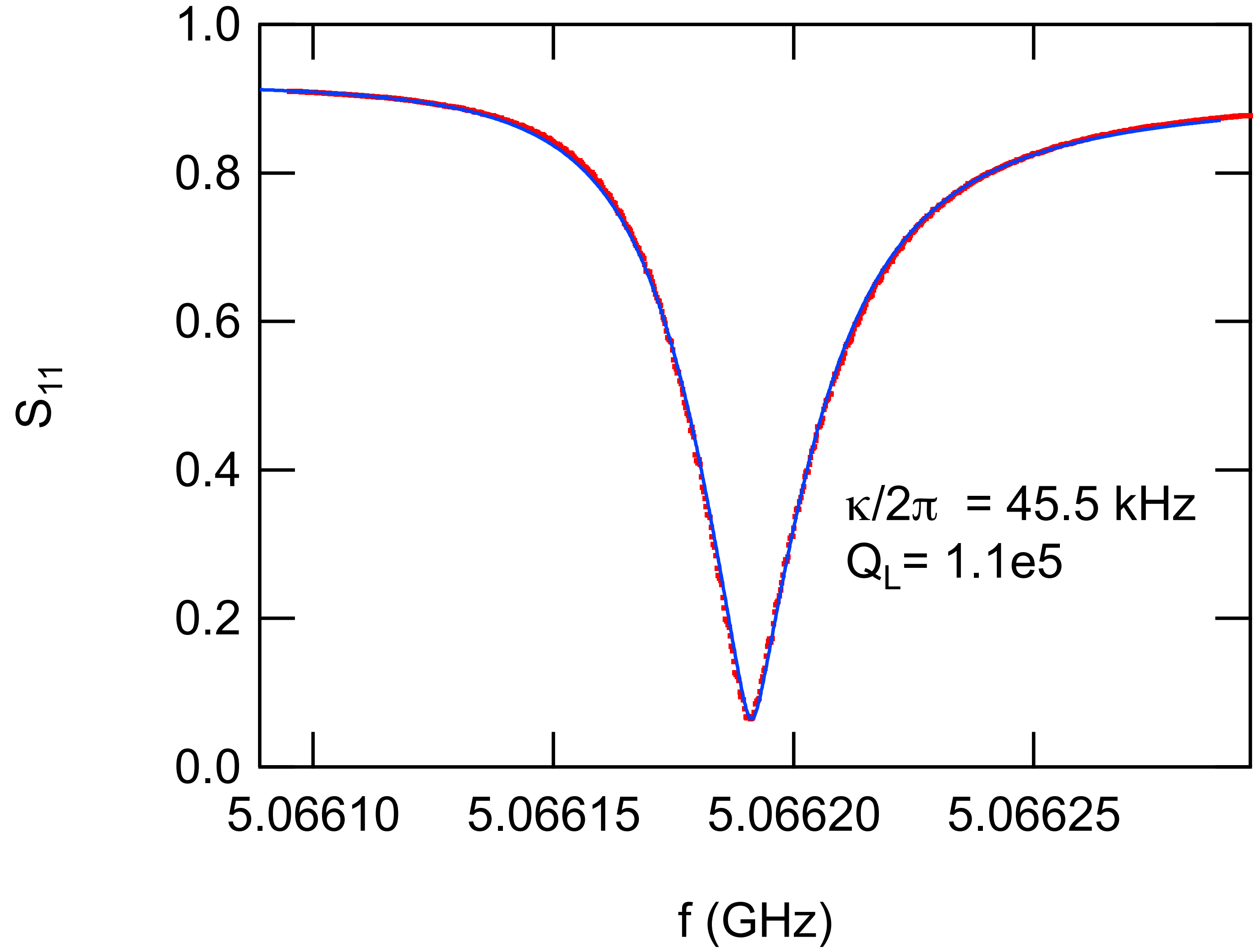
$$G = \frac{\partial \omega_0}{\partial C_m} \frac{\partial C_m}{\partial x}$$

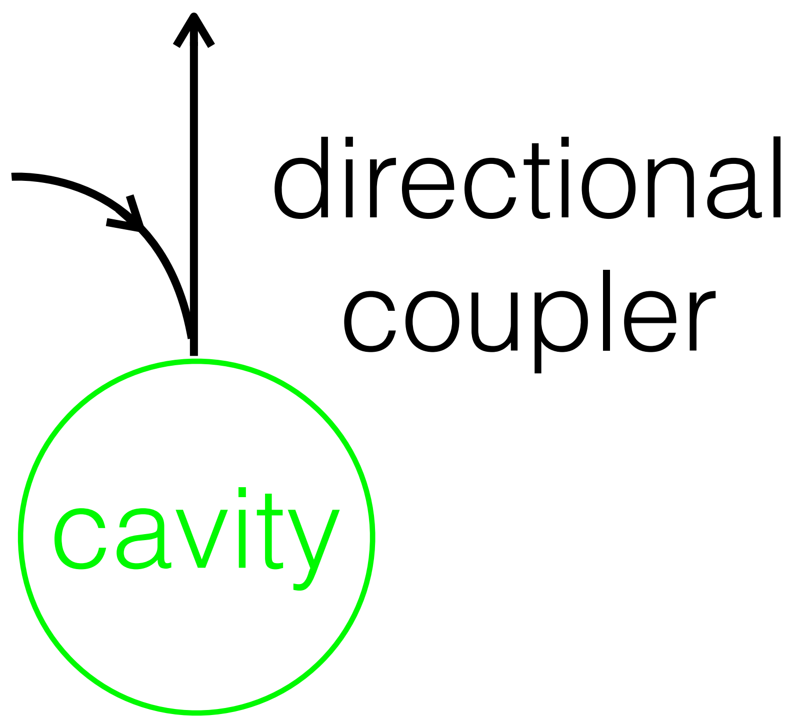
Measurement setup





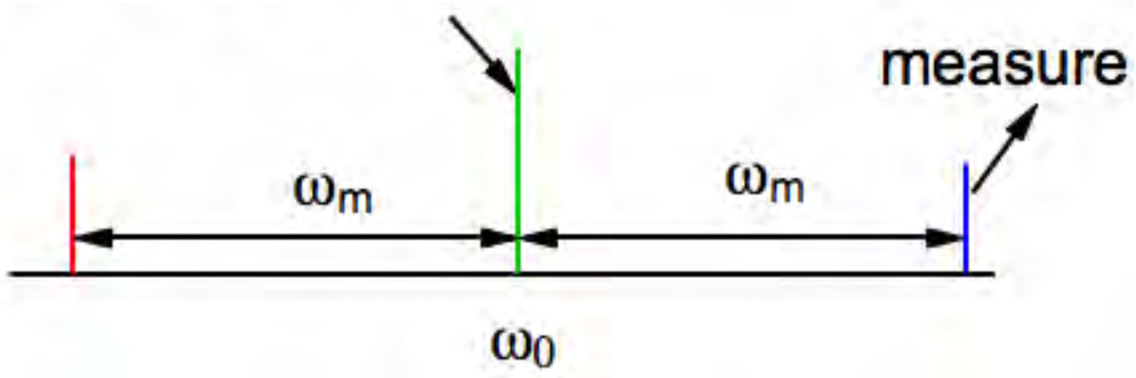
High Q 3d microwave cavity

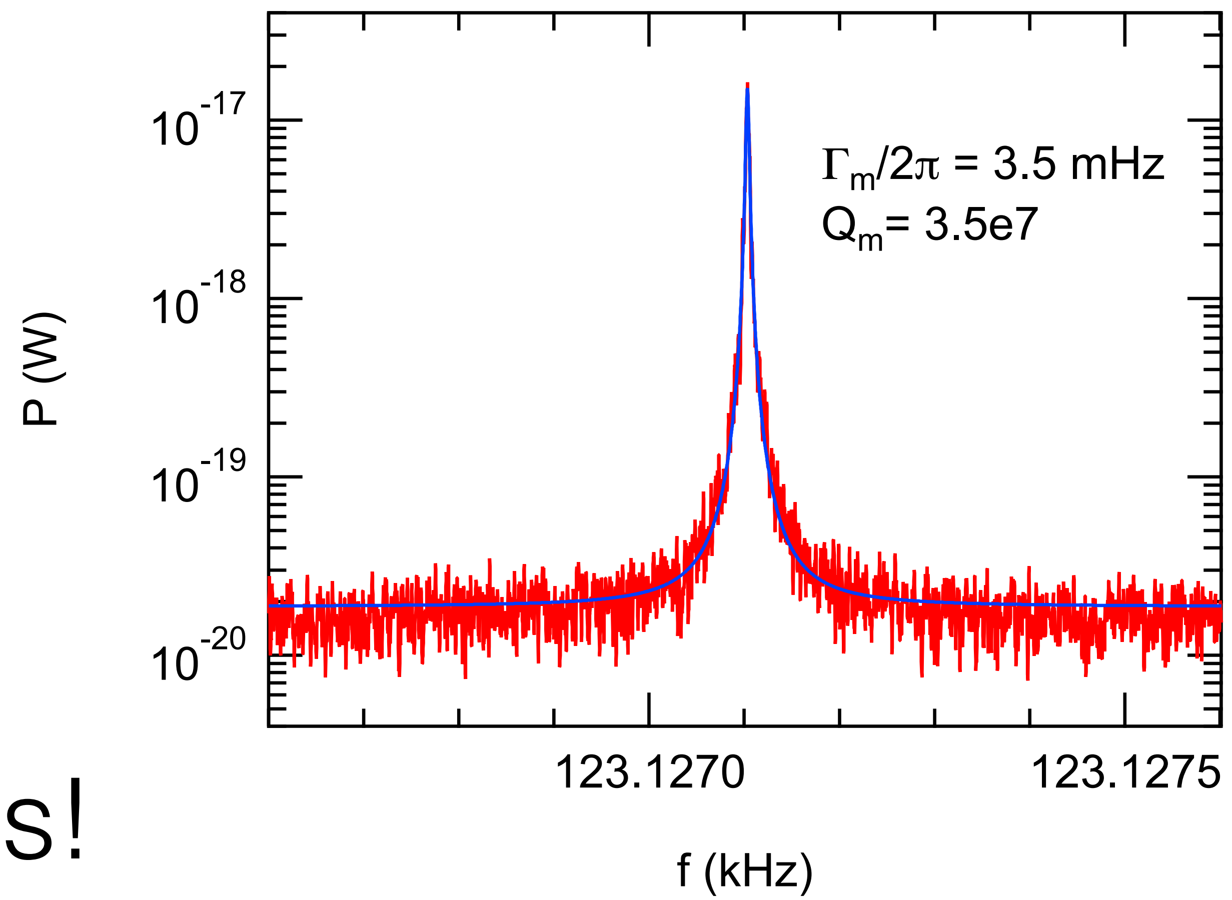




Reflection coefficient of
membrane-embedded cavity

Thermal motion of the membrane





Membrane resonator
time constant: 1.5 minutes!

Al coating: enabling electrical measurement while preserving ultrahigh Q.

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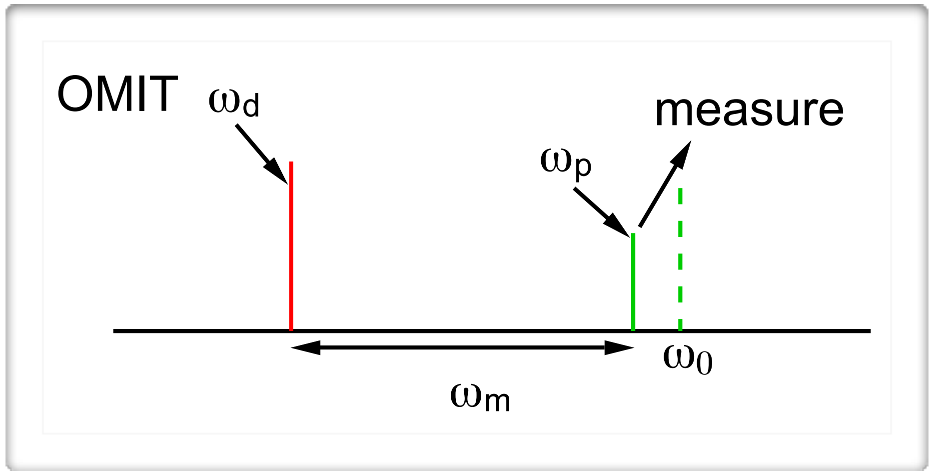
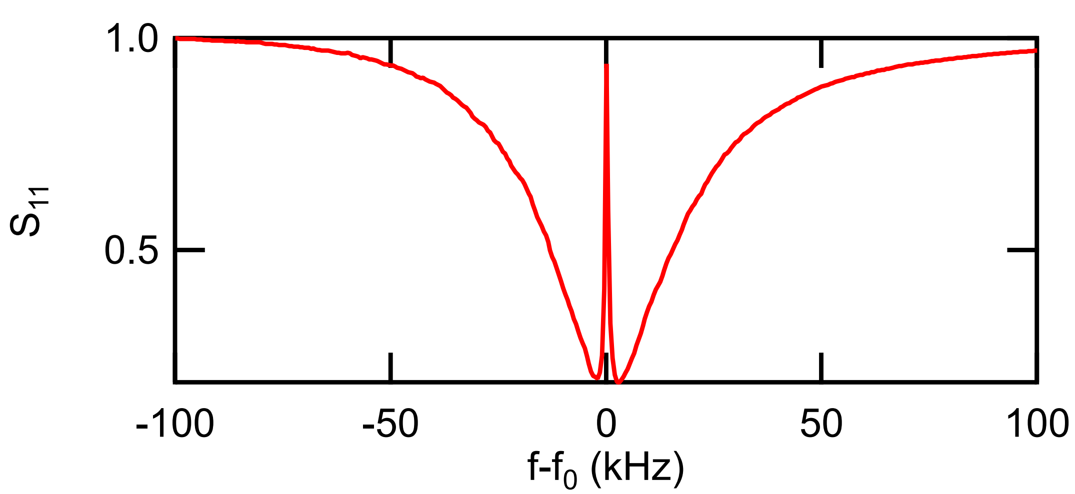
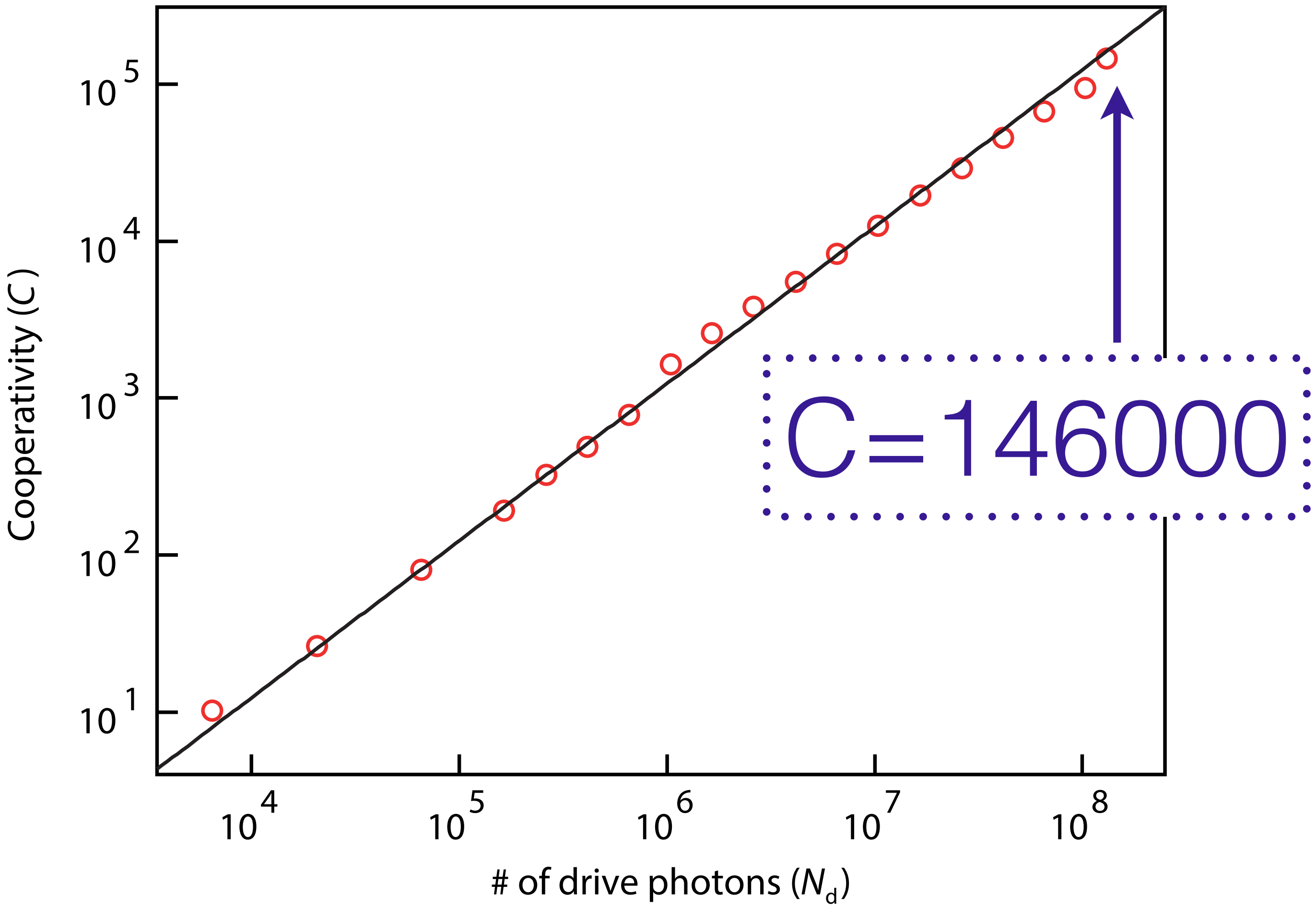
Optomechanical coupling



coupling extracted with OMIT



$$C = \frac{4g_0^2}{\kappa\Gamma_m} n_d$$



Cooperativity vs. driving photon numbers

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Near-ground state cooling of the mm-scale membrane

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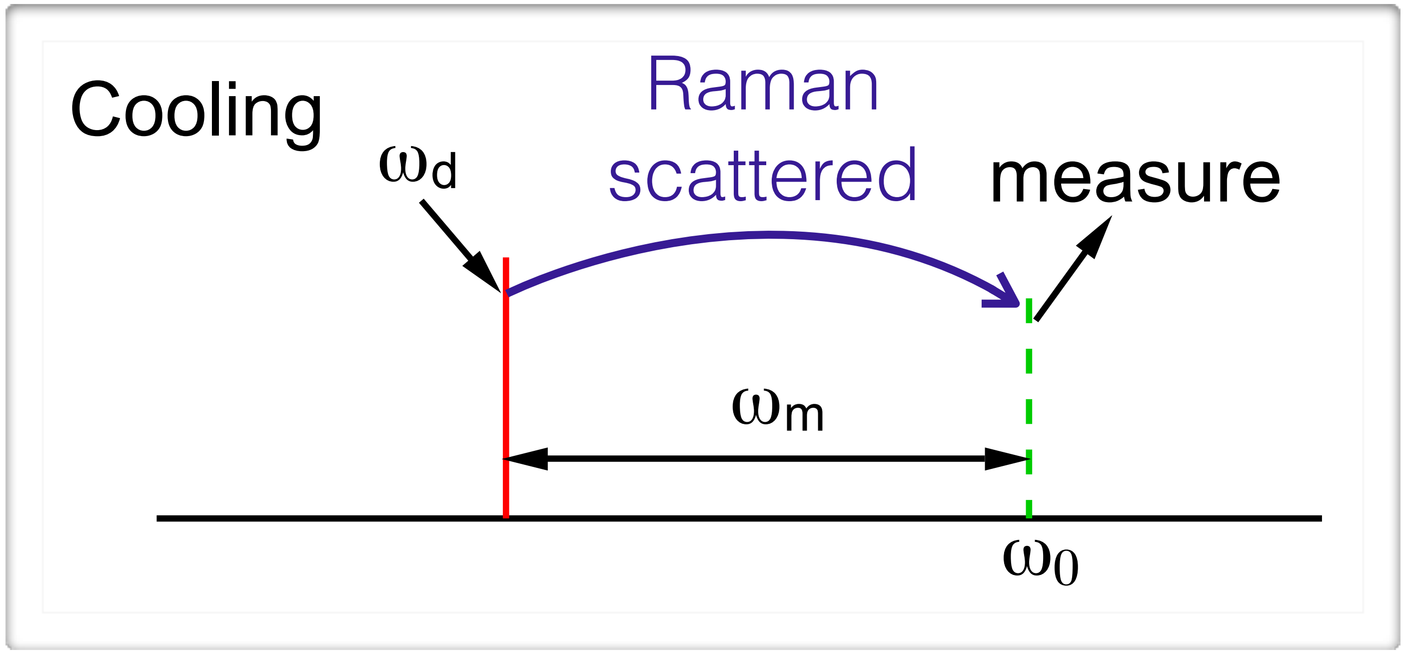
Sideband cooling



Thermal occupancy $$n_m = \frac{1}{e^{\hbar\omega_m/k_B T} - 1}$$

For T=13 mK, initial occupancy $n_0 = 2200$

Occupancy with cooling $$n_m = \frac{n_0}{C+1}$$

$$C_{max} = 10^5 \gg 10^3$$

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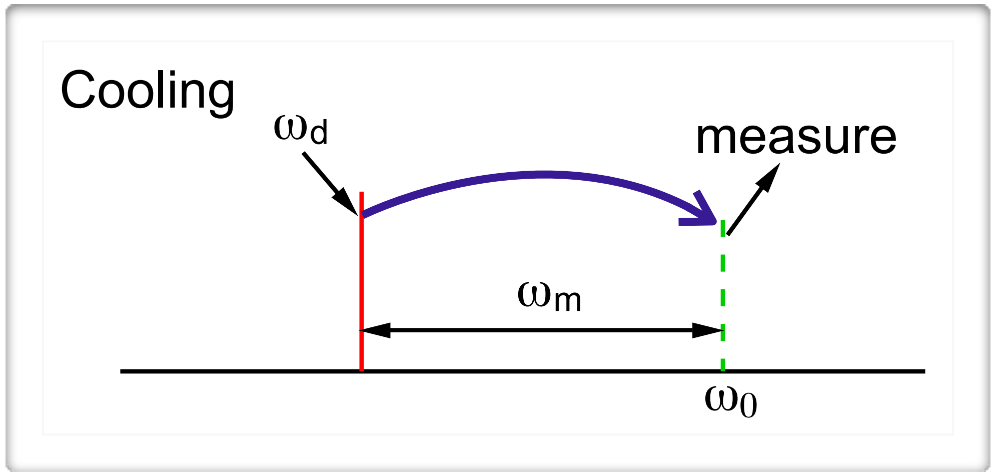
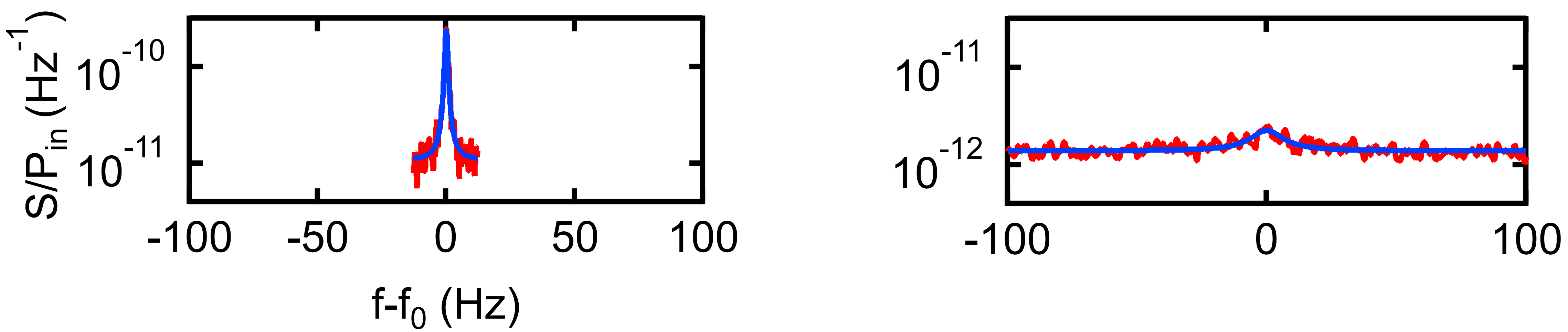
Measurement of cooling



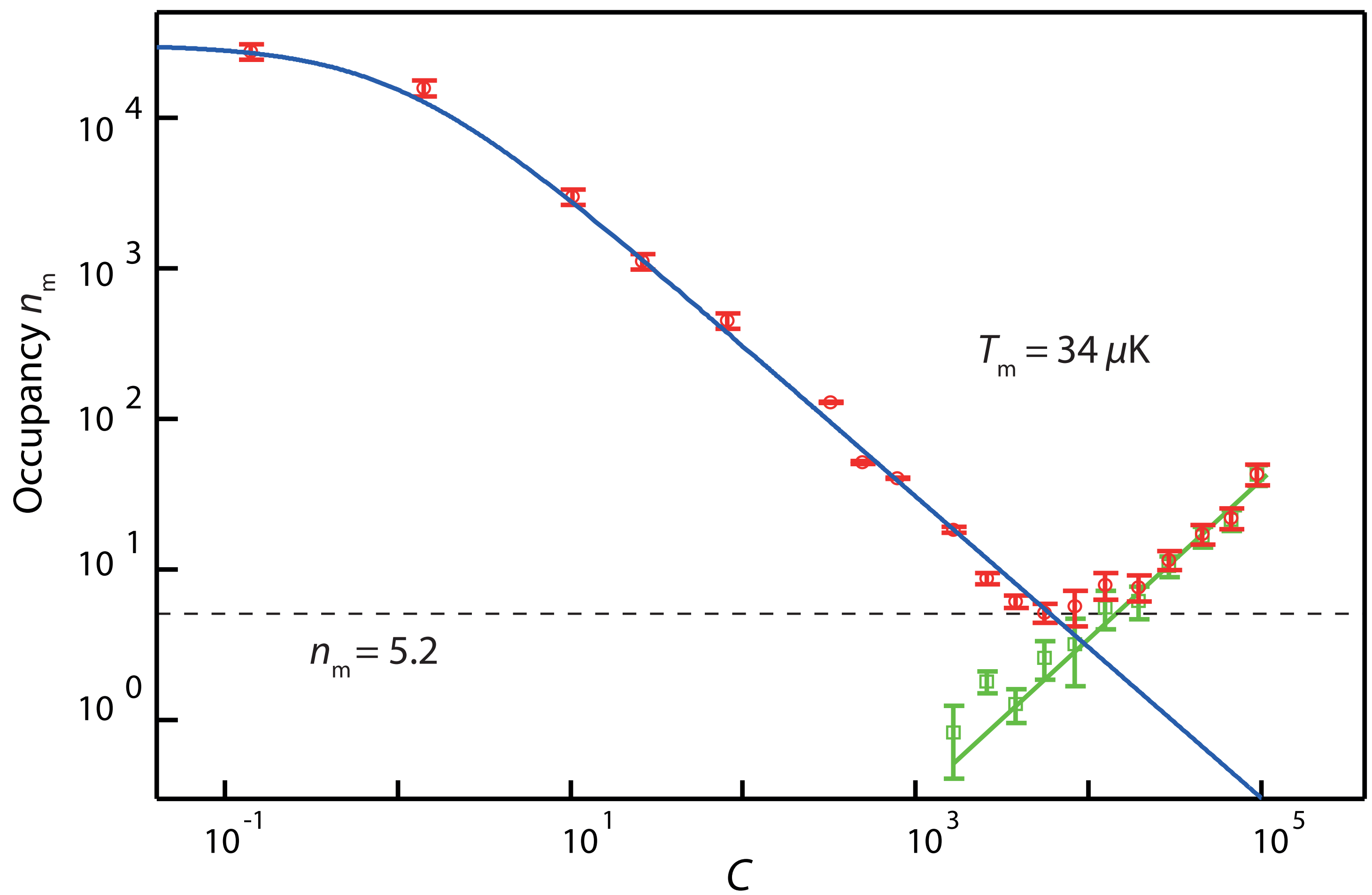
weak cooling

strong cooling



Area under the curve is reduced.

Occupancy of the membrane



Minimum occupancy: $n_m = 5$

$$T_m = 34\mu K$$

Yuan et al., Nat. Commun. 2015

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High mechanical Q
of SiN membranes at mK

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Q factor and mechanical quantum state

higher Q ⟺ less energy loss

- Preparation and measurement of mechanical quantum superposition state:

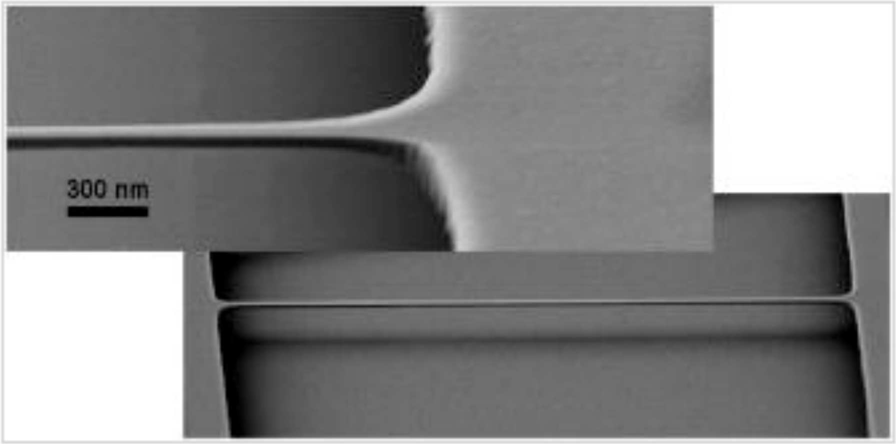
  — Prerequisite: deep ground state cooling

  Cooling ability $\propto Q$

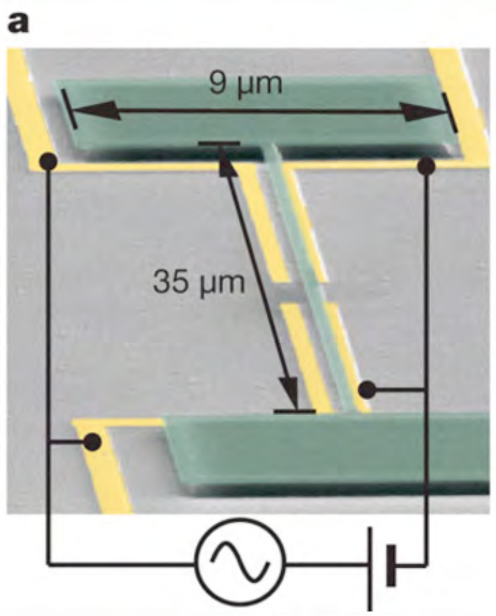
  — Longer state lifetime

Overview: silicon nitride resonators

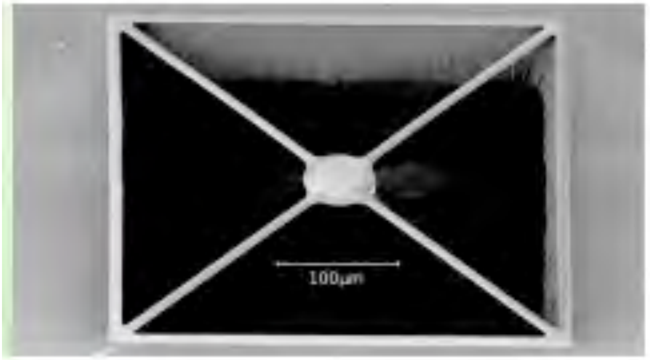
Nanostrings: 10^6
Cornell, JAP 2006



Beams: 10^5
Munich, Nature
2009

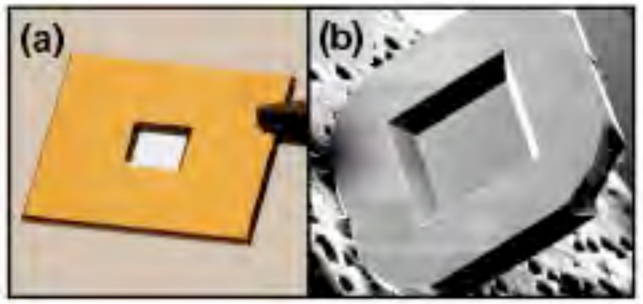


Trampolines: 10^5
UCSB/Leiden, OE 2011
Sankey group, McGill;
Groeblacher group, Delft: 10^7



Lower temperature?

Membranes: 10^7, 0.3 K
Yale, APL 2007



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Measurement of mechanical Q

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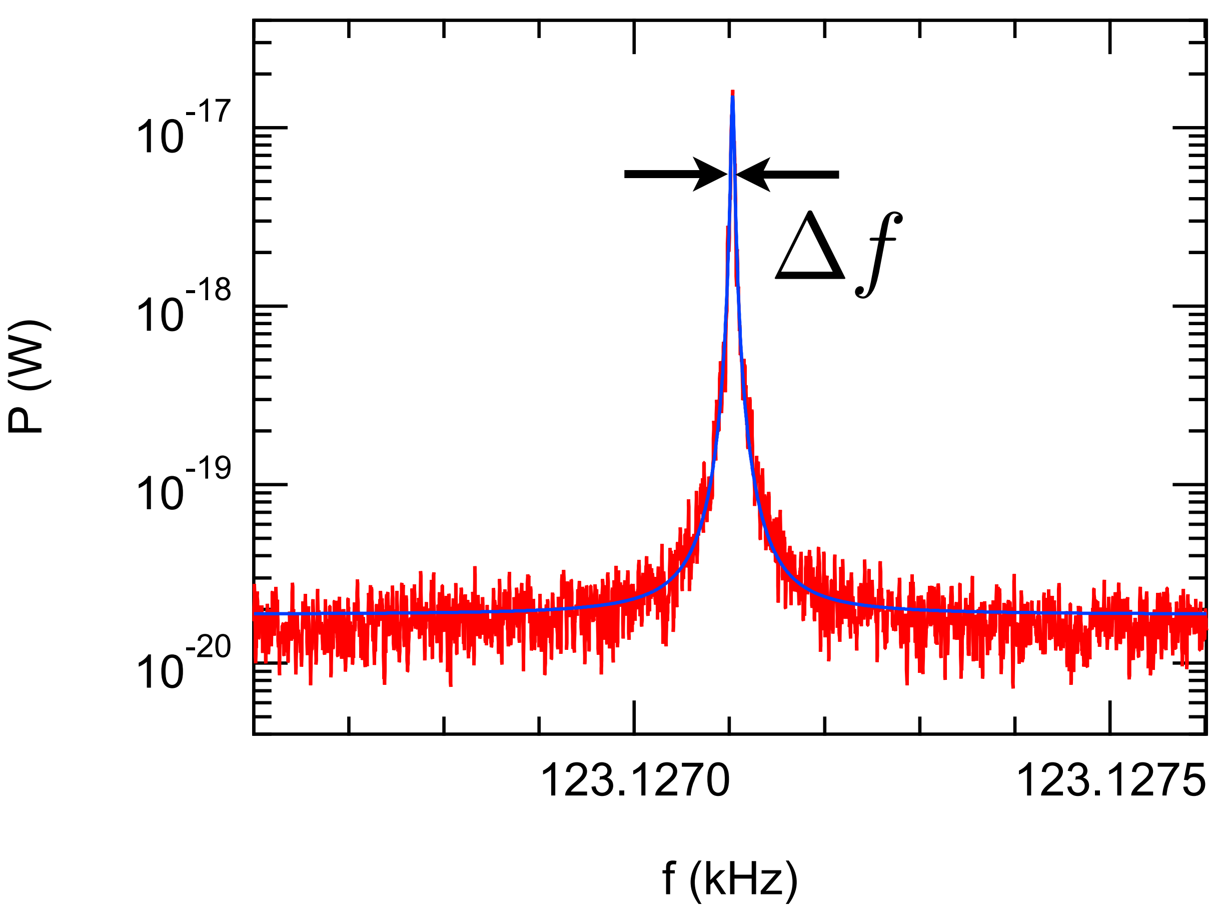
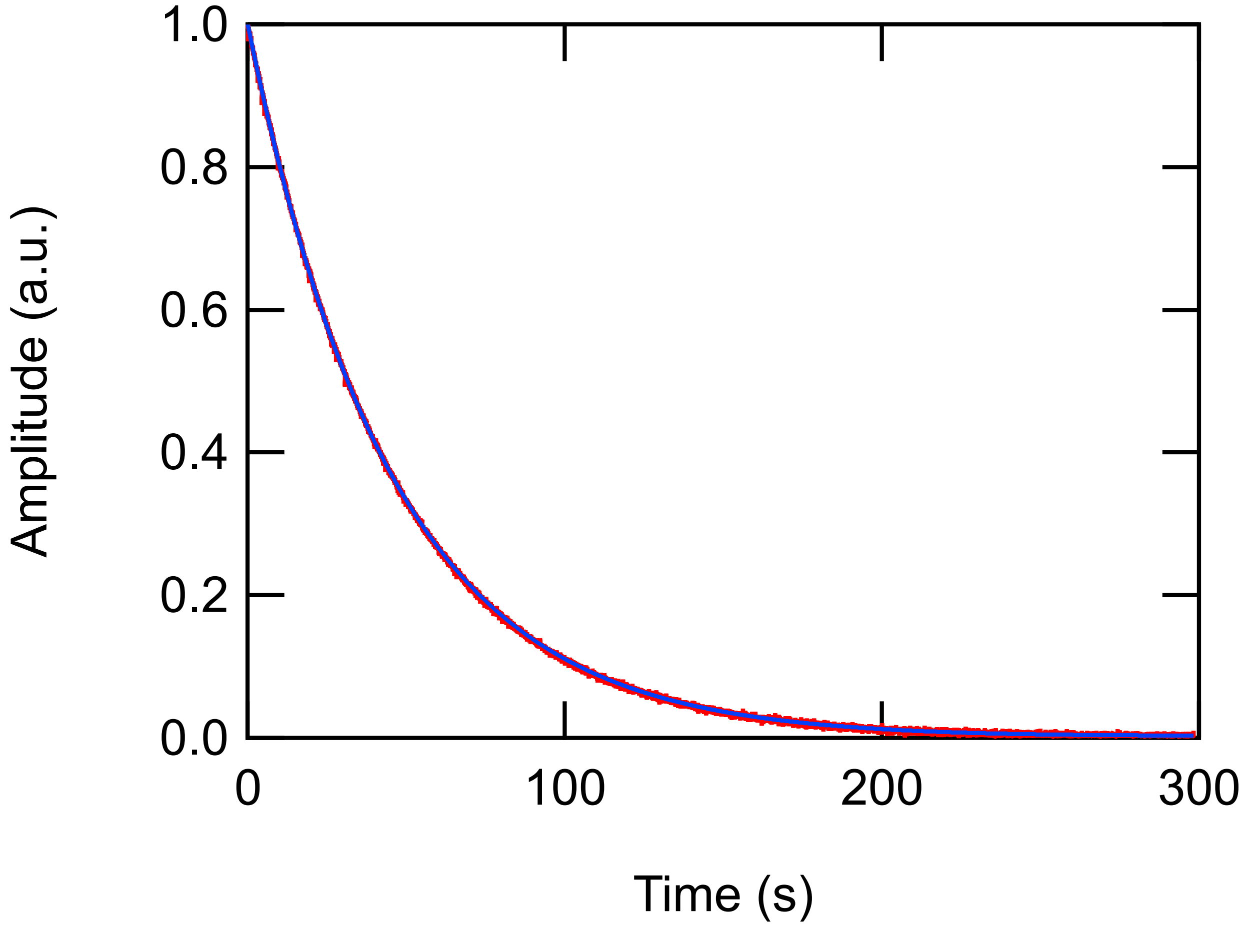
Methods: spectral & ringdown





$$amp. \propto e^{-\frac{\gamma_m}{2}t}$$

$$Q_{spec} = \frac{f_m}{\Delta f}$$

$$Q_{ring} = \frac{\omega_m}{\gamma_m}$$

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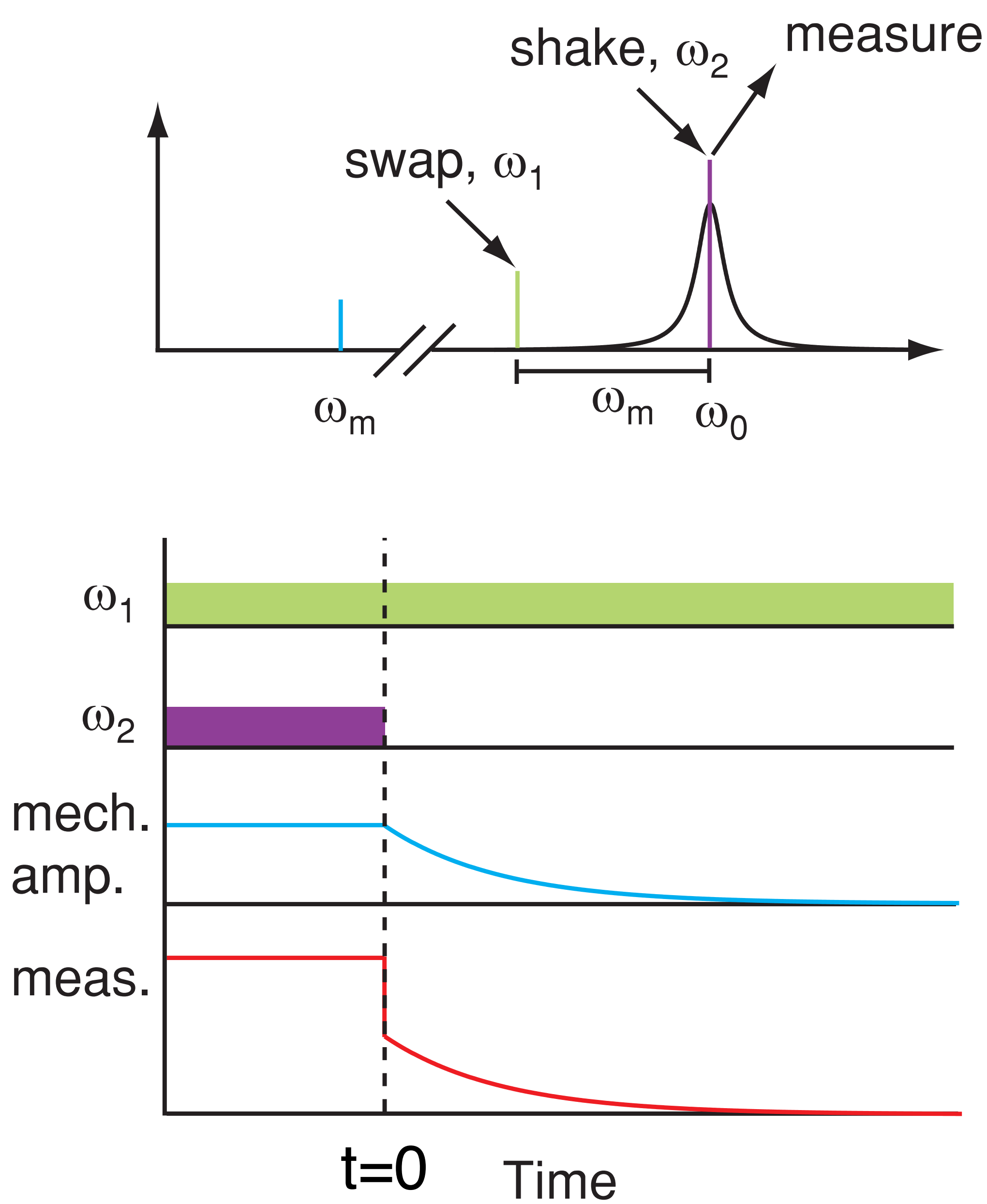
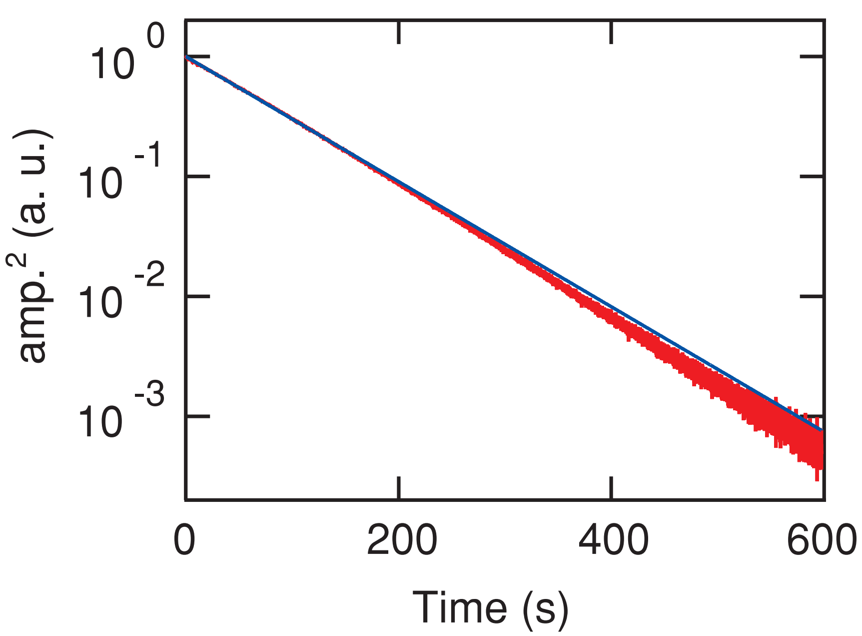
Optomechanical ringdown





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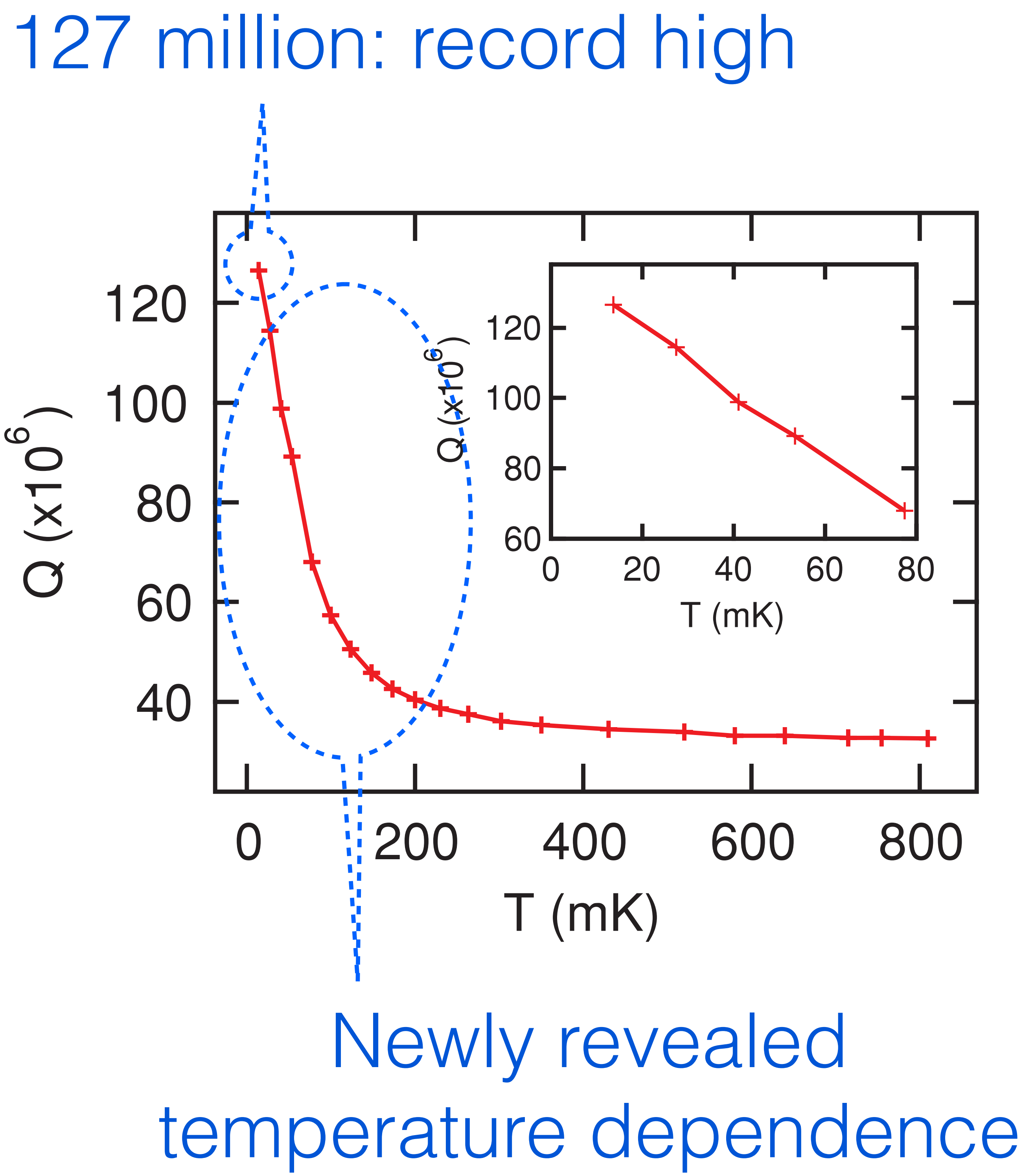
Results

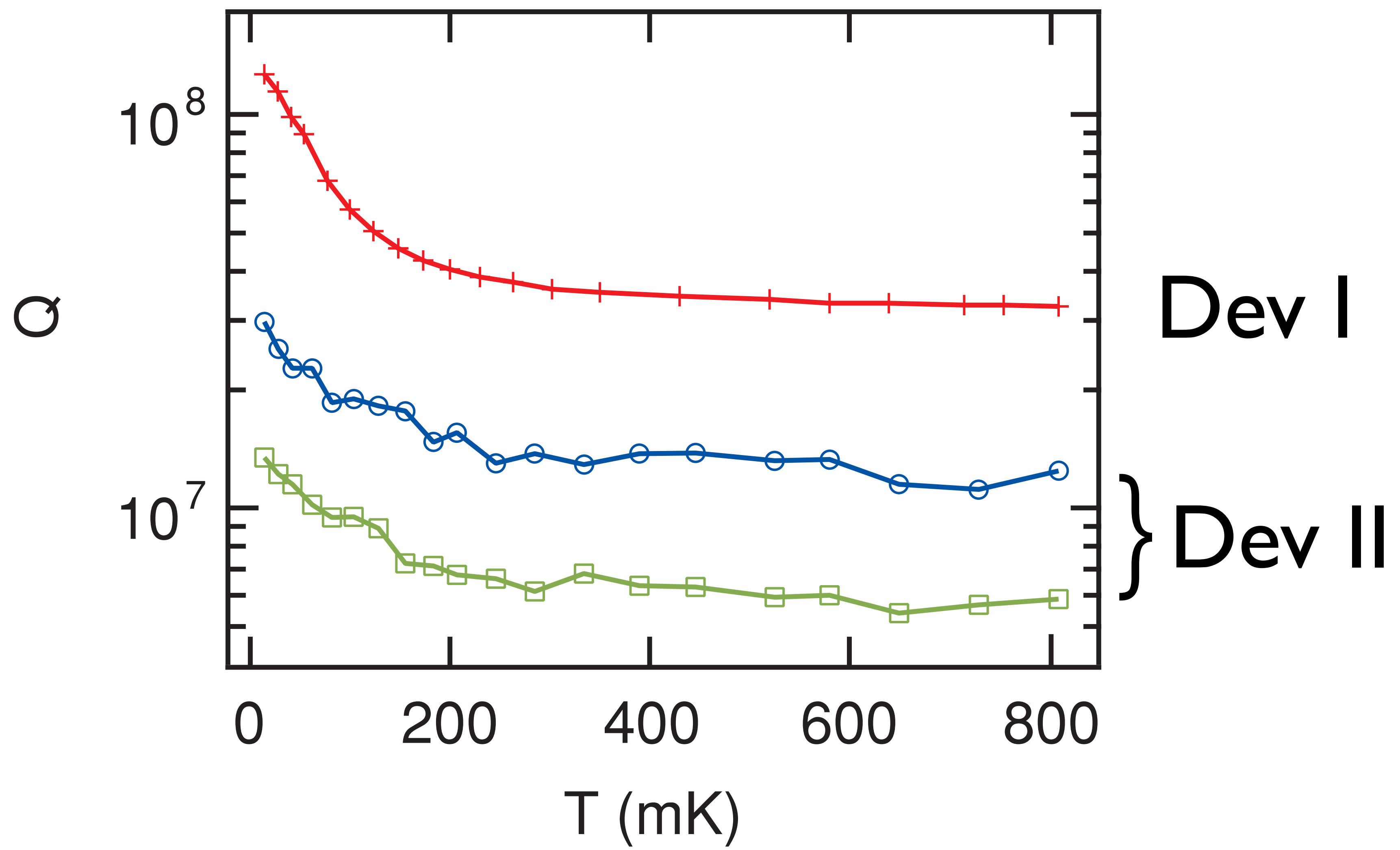
Temperature dependence



242 kHz

Yuan et al., APL 2015

More modes



	Dev I	Dev II
size	1.5mm x 1.5mm x 50 nm	1mm x 1mm x 50nm
tensile stress	0.8 GPa	0.09 GPa

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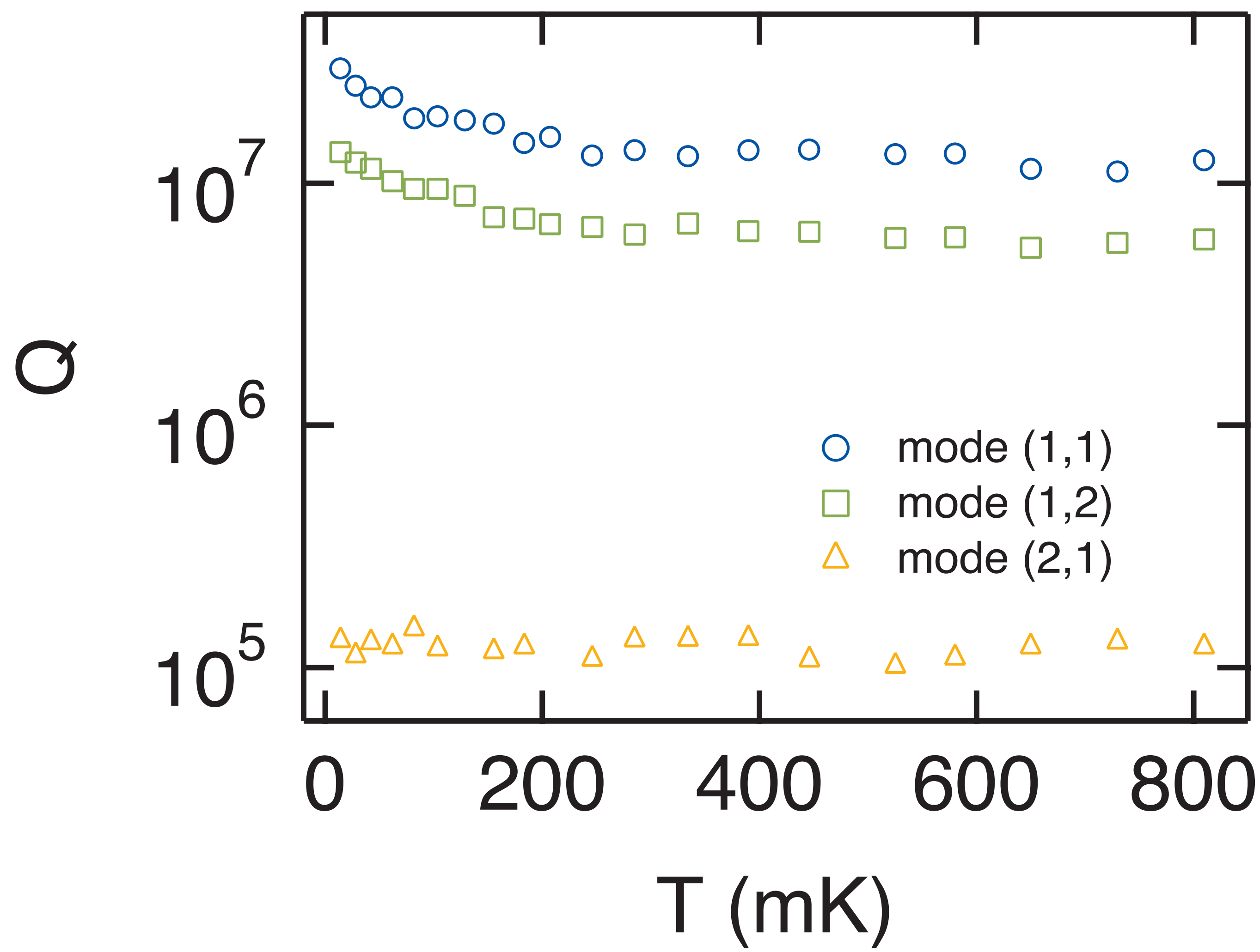
High Q vs. low Q modes



Dev II

Conclusion

- Optomechanical system with 3d cavity and SiN membrane
- Large cooperativity that enables cooling close to ground state
- Temperature dependence of Q below 200 mK; Q exceeding 10^8 at 14 mK
- Potentials for hybrid devices

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Members

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Gary Steele

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