Cindy Regal

Condensed Matter Summer School, 2018

Day 1: Quantum optomechanics

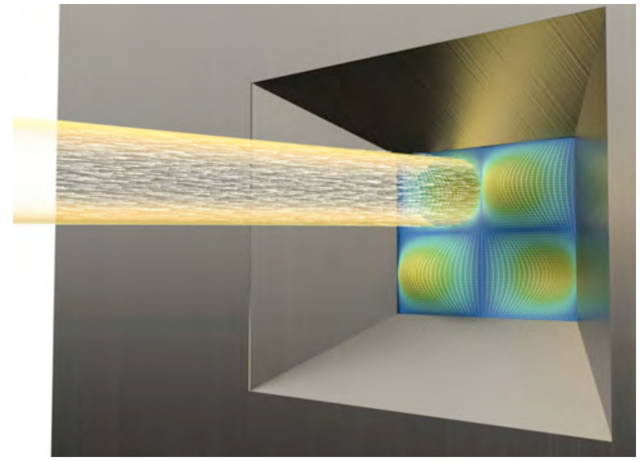
Day 2: Quantum transduction

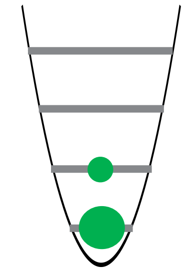
Day 3: Ultracold atoms from a qubit perspective

JILA NIST CU

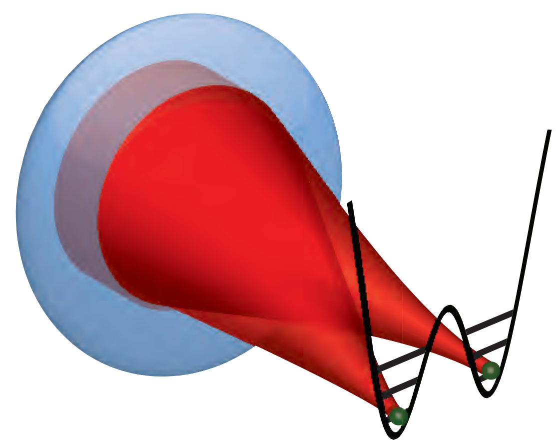
Day 1: Quantum optomechanics

Day 2: Quantum transduction





Day 3: Ultracold atoms from a qubit perspective



Day 1: Quantum optomechanics – quantum limits to continuous displacement detection

Day 2: Quantum transduction – conversion from microwave (superconducting qubits) to optical photons (transmission domain)

Machinery is that of weak nonlineary / gaussian states
Useful to understanding from perspective of quantum metrology, transducers

Day 3: Ultracold atoms from a qubit perspective – interfering and entangling bosonic atoms

Single atom ‘sources’
Overview of field of control of individual neutral atoms
Some examples of how to make a Bell State

From yesterday

Some reading:

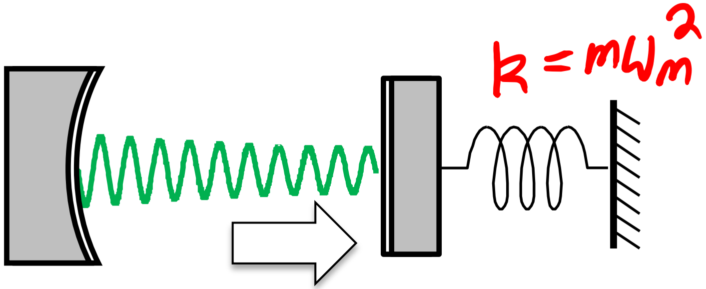
Markus Aspelmeyer, Tobias J. Kippenberg, and Florian Marquardt, Cavity Optomechanics
Rev. Mod. Phys. 86, 1391 (2014)

A. A. Clerk, Introduction to quantum noise, measurement, and amplification, RMP (2010)

C. M. Caves, Quantum Limits on Noise in Linear Amplifiers, Phys. Rev. D 26, 1817 (1982)

N. S. Kampel, R. W. Peterson, R. Fischer, P.-L. Yu, K. Cicak, R. W. Simmonds, K. W. Lehnert, and
C. A. Regal, Improving Broadband Displacement Detection with Quantum Correlations
Phys. Rev. X 7, 021008 (2017)

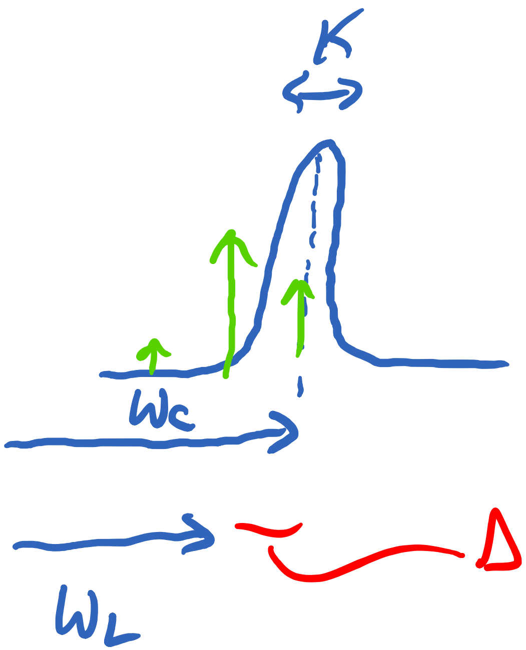
Review of parameters



$$\hat{F} = \hbar G \hat{n} \qquad \hat{n} = \hat{a}^\dagger \hat{a}$$

$$g = G x_{zp} \qquad x_{zp} = \sqrt{\frac{\hbar}{2 m \omega_m}}$$

$$\hat{H}_{int} = \hbar g \hat{a}^\dagger \hat{a} (\hat{b}^\dagger + \hat{b})$$



$$\Delta = \omega_L - \omega_c$$

$$\chi_c = \frac{1}{\kappa/2 - i\Delta}$$

Resolved Sideband

$$\omega_m \gtrsim \kappa$$

Review of parameters

Optomechanical Numbers

$\kappa \simeq 2\pi \times 1\,\text{MHz}$ / $F = 10{,}000$

$\omega_m \simeq 2\pi \times 1.5\,\text{MHz}$

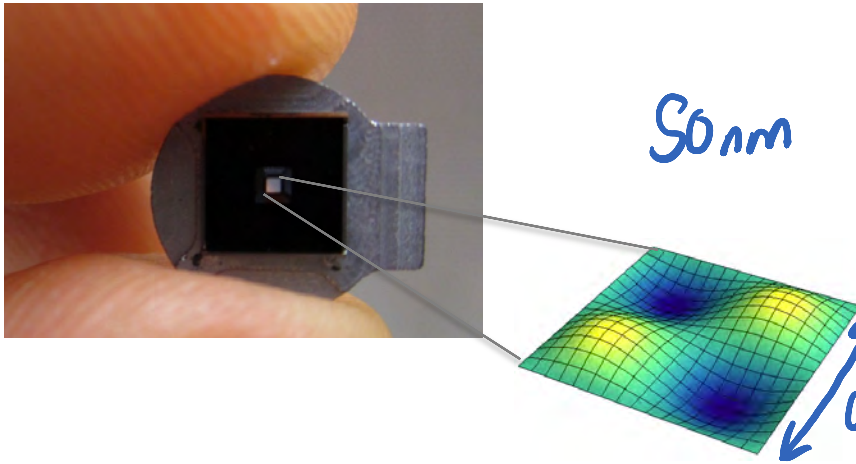
$\Gamma_m \cong 2\pi \times 1\,\text{Hz}$

$x_{zp} \sim \text{fm}$

$\frac{d\omega_c}{dx} \simeq 2\pi \times 20\,\text{MHz/nm}$ / $g = 2\pi \times 10\,\text{Hz}$

$$\Gamma_{opt} = \frac{4Ng^2}{\kappa} \sim 2\pi \times 10\,\text{kHz}$$

More about enabling mechanical motion



50nm

0.5mm = ℓ

$\sigma = 1\,\text{GPa}$

$\rho = 2.7\,\text{g/cm}^3$

$$f_{m,n} = \sqrt{\frac{\sigma(m^2+n^2)}{4\rho\ell^2}}$$

Increase ω_m

Keep dissipation Γ_m ~ constant

Quantum optomechanical transducer outline

Transducer goal

Experimental system we are working on with Konrad Lehnert

Experimental hardware – cryogenic optical system

Input-output theory

Experimental measurements of efficiency and added noise

Another way to remove noise: Measurement and feedfoward

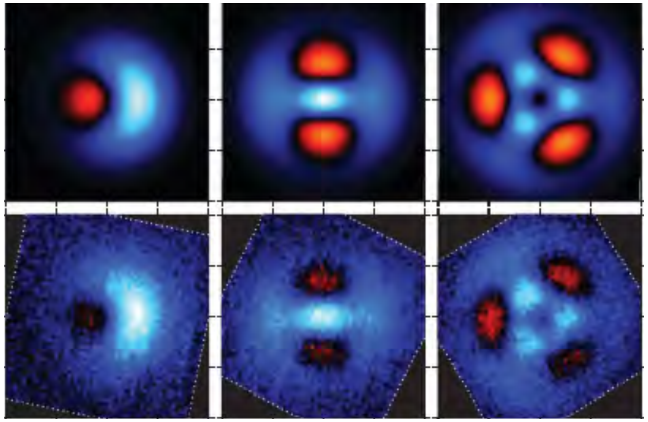
Microwave-optical quantum interface

Microwaves:

- Arbitrary quantum states
- Require ultralow temperatures

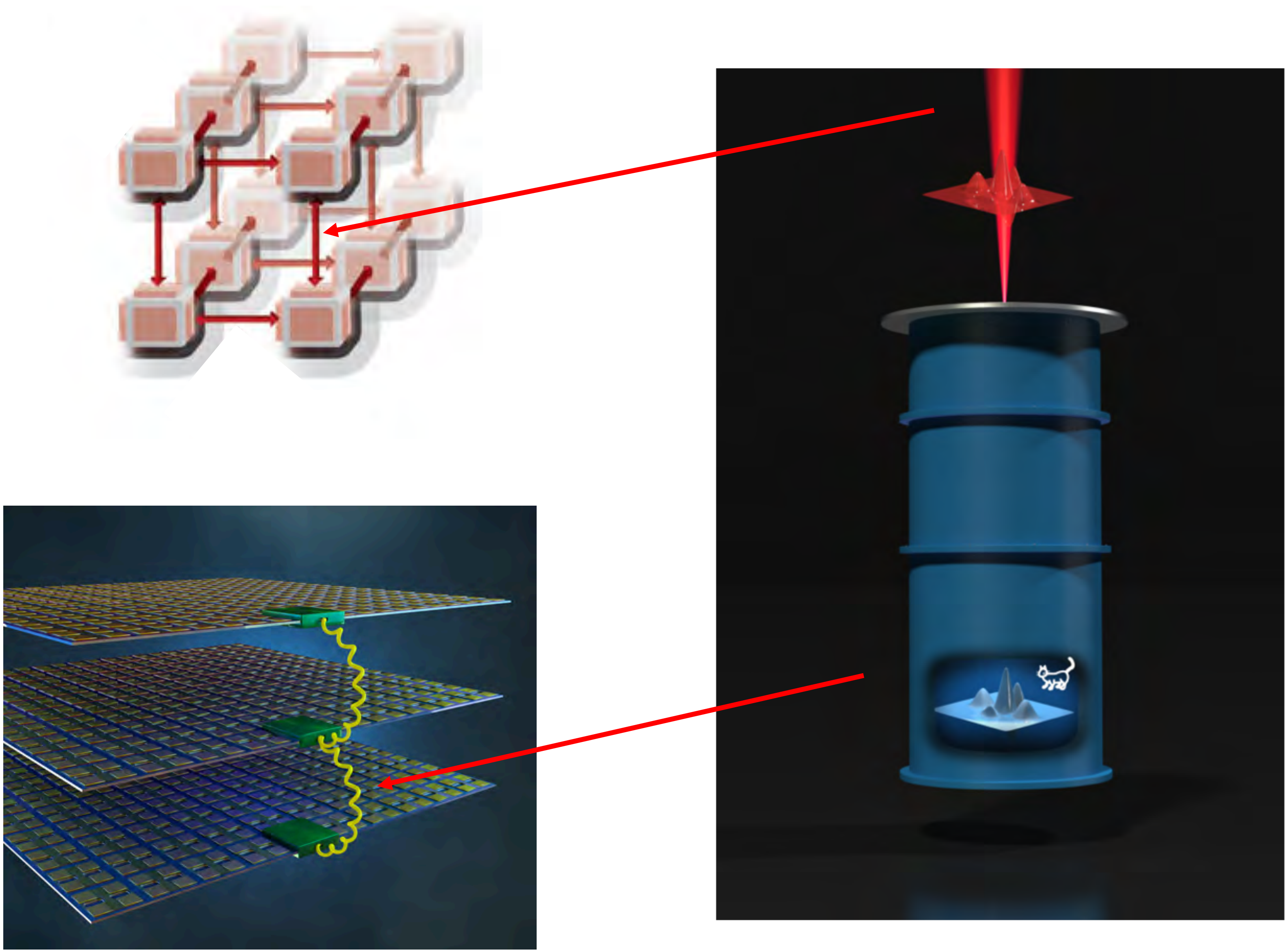
Optics:

- Communication
- Memory (maybe)

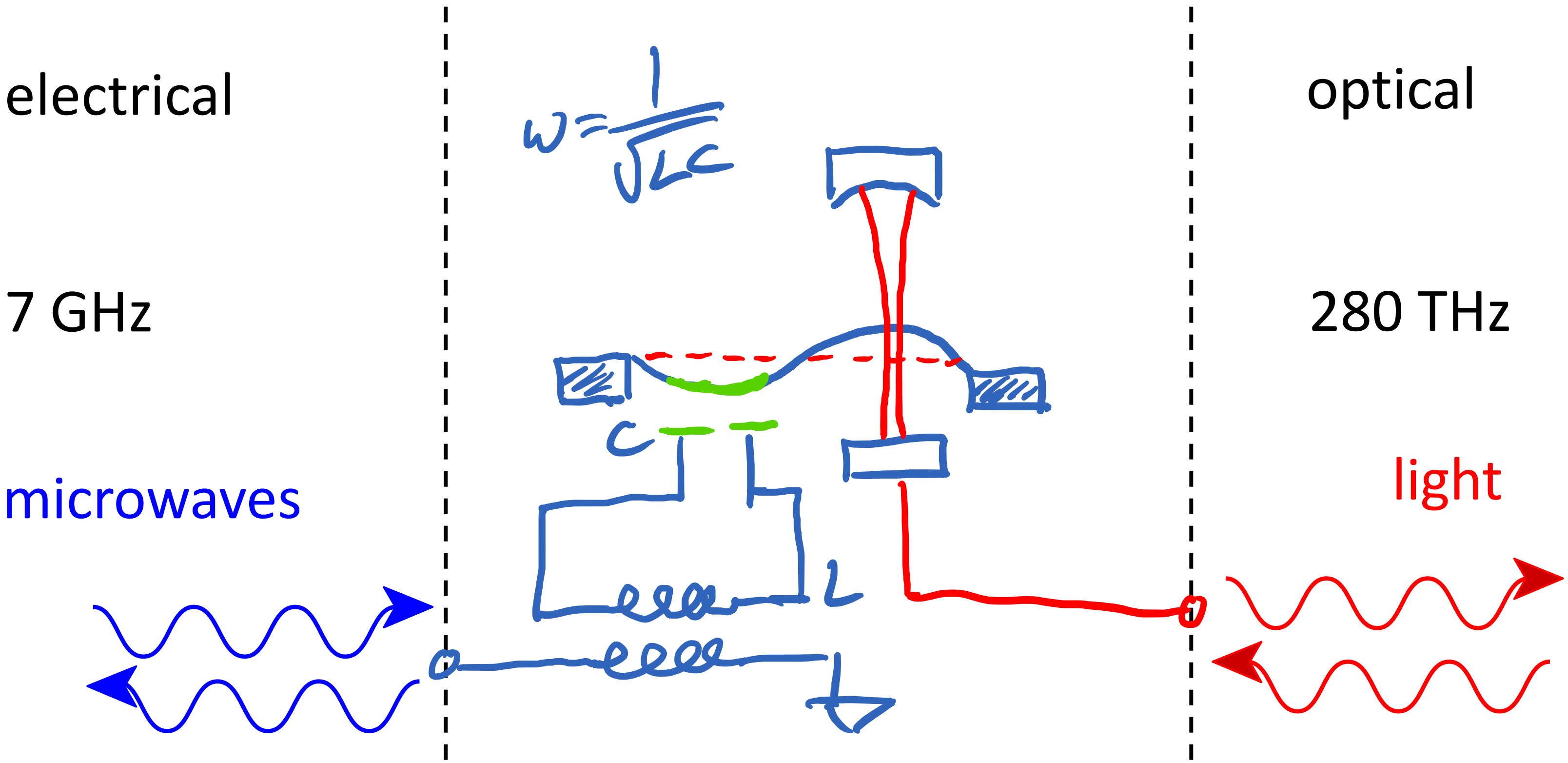


Hofheinz…Martinis, Cleland, Nature (2009)

Microwave-optical quantum interface



Our proposed electro-optic coupling



Requirements:

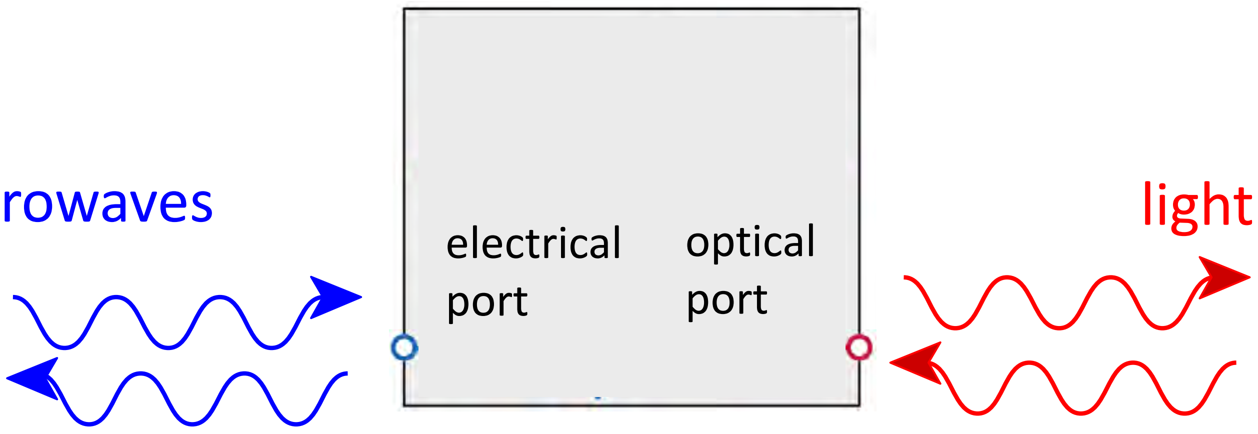
Bidirectional (unitary)

Efficient (photon number preserving)

Low added noise

Bochmann *et al*, Nature Physics (2013)
Andrews *et al*, Nature Physics (2014)
Bagci *et al*, Nature (2013)

Electro-optic devices

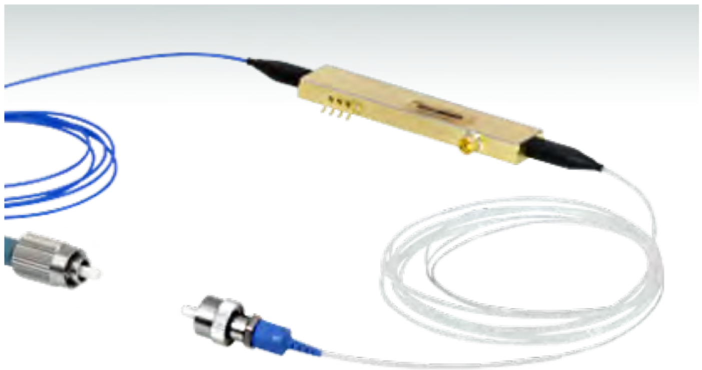


Electro-optic modulator with nonlinear crystal:

- Very common
- Also could achieve these metrics…but also trying to achieve efficiency

Why micromechanical motion?

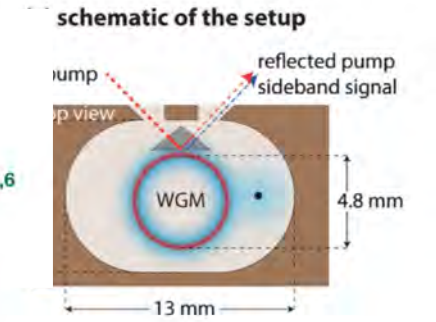
- Engineering nonlinear materials
- Certain amount of flexibility in e.g. materials, geometry



An array of platforms for quantum electro-optics

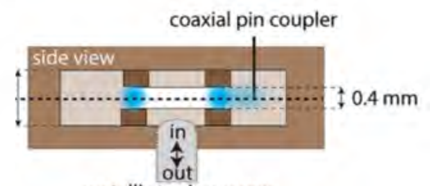
Efficient microwave to optical photon conversion: an electro-optical realization

ALFREDO RUEDA,[1,2,3,†] FLORIAN SEDLMEIR,[1,2,3,9,†] MICHELE C. COLLODO,[1,2,4,5] ULRICH VOGL,[1,2] BIRGIT STILLER,[1,2,6] GERHARD SCHUNK,[1,2,3] DMITRY V. STREKALOV,[1] CHRISTOPH MARQUARDT,[1,2] JOHANNES M. FINK,[4,7] OSKAR PAINTER,[4] GERD LEUCHS,[1,2] AND HARALD G. L. SCHWEFEL[8,*]



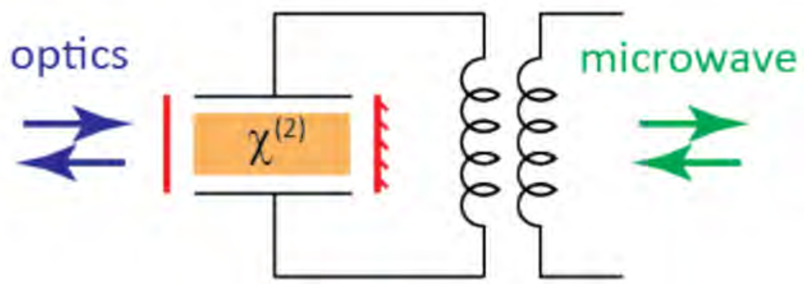
Superconducting cavity electro-optics: a platform for coherent photon conversion between superconducting and photonic circuits

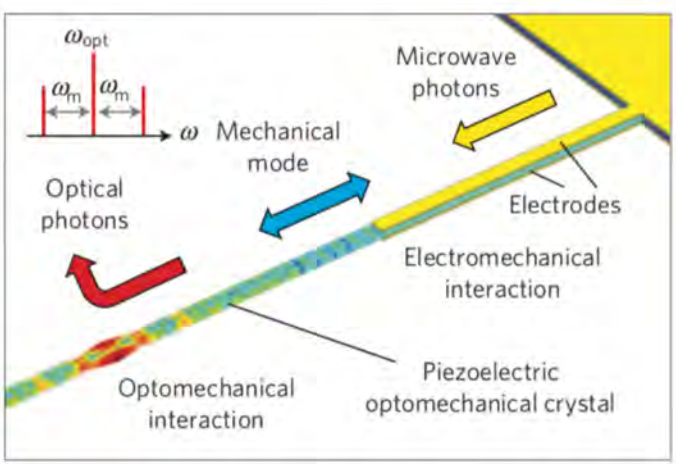
Linran Fan, Chang-Ling Zou, Risheng Cheng, Xiang Guo, Xu Han, Zheng Gong, Sihao Wang, Hong X. Tang



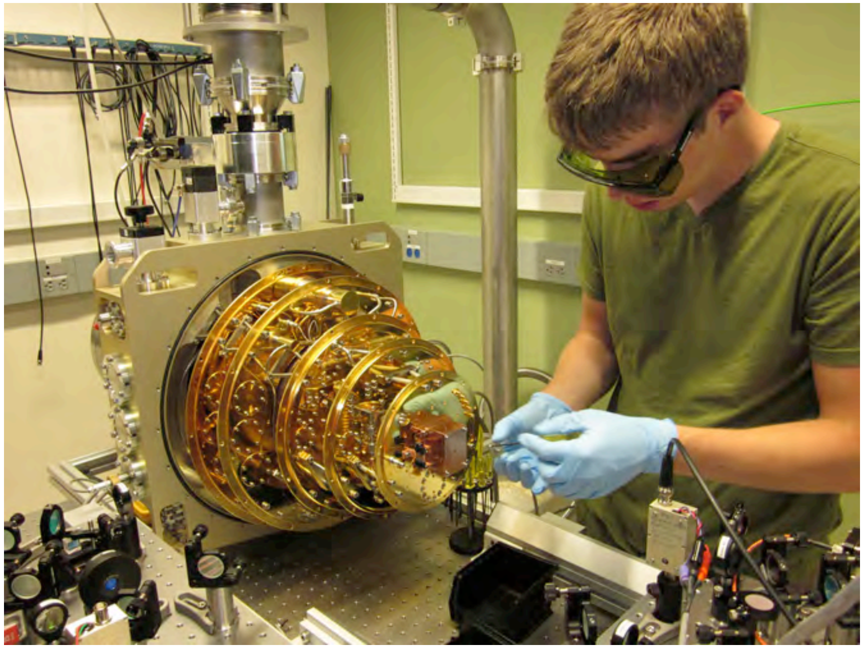
Nanomechanical coupling between microwave and optical photons

Joerg Bochmann[†], Amit Vainsencher[†], David D. Awschalom and Andrew N. Cleland*

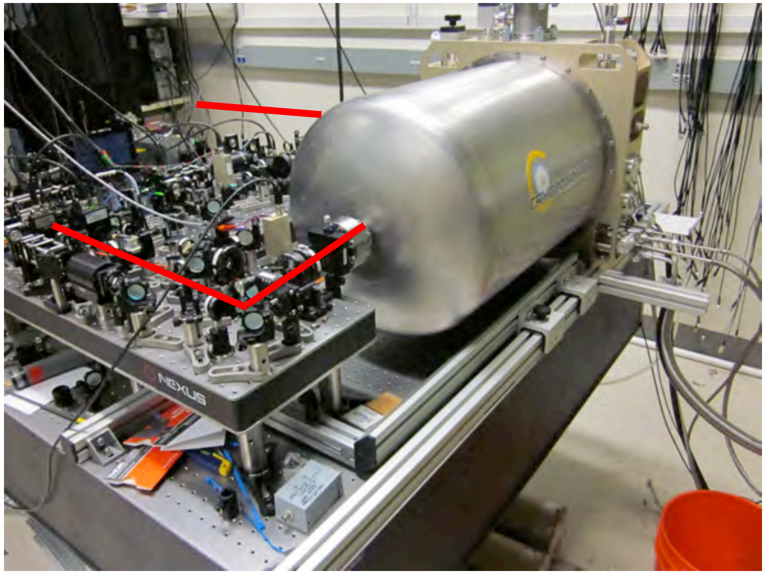


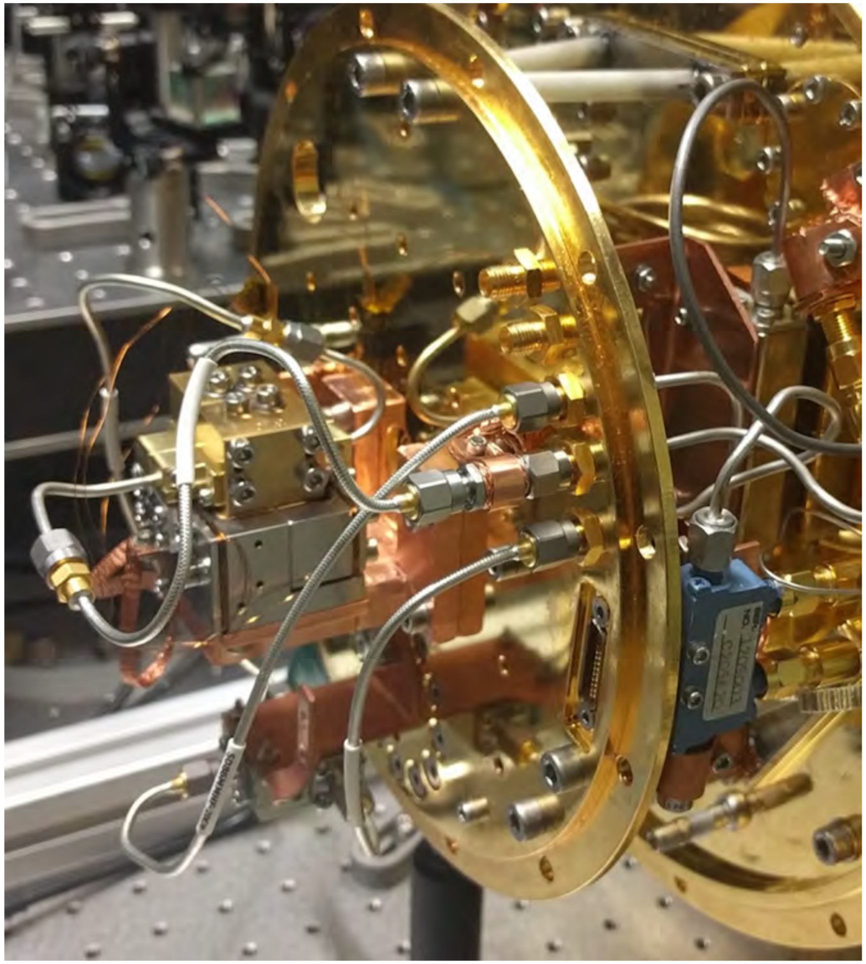


100 mK cryogenic measurements



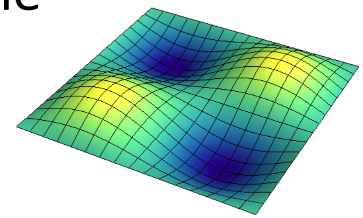
Base = 40 mK
Mechanics thermalizes
to 80 mK with light on





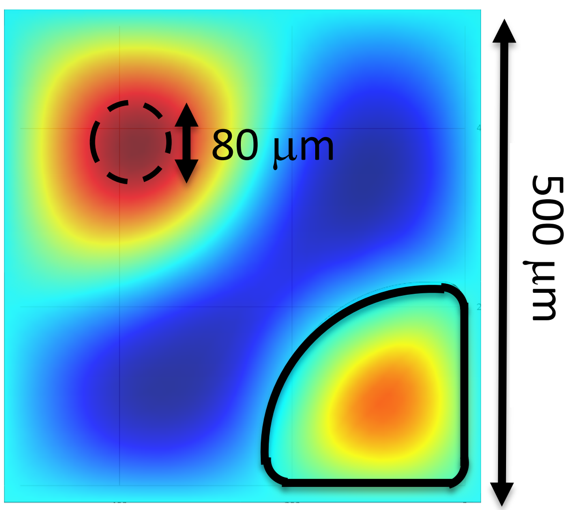
Device hardware: Metallized mechanics

Mechanics: SiN membrane drum with GPa stress



Mechanical Mode 1.47 MHz

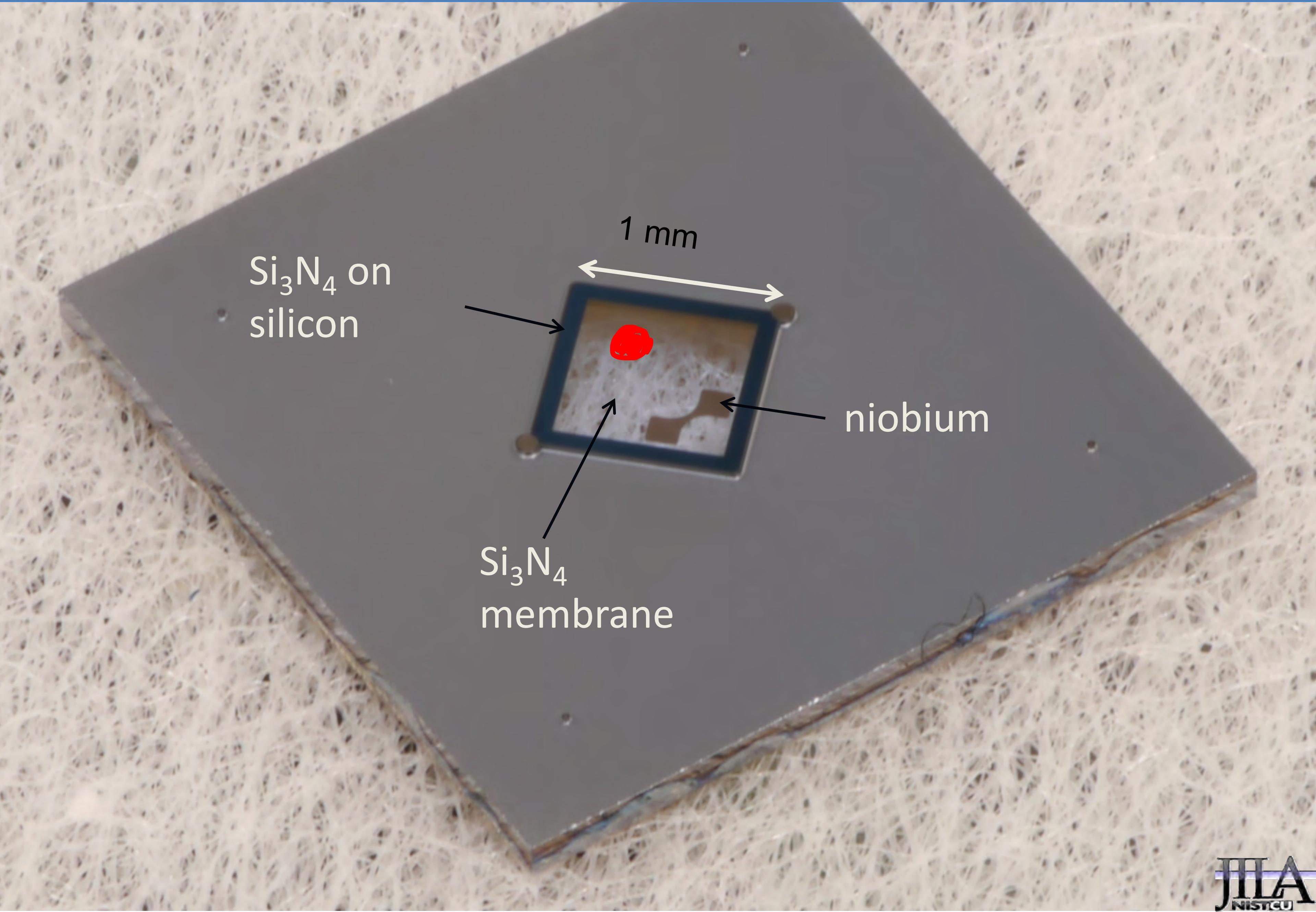
Optical spot



Nb thin film

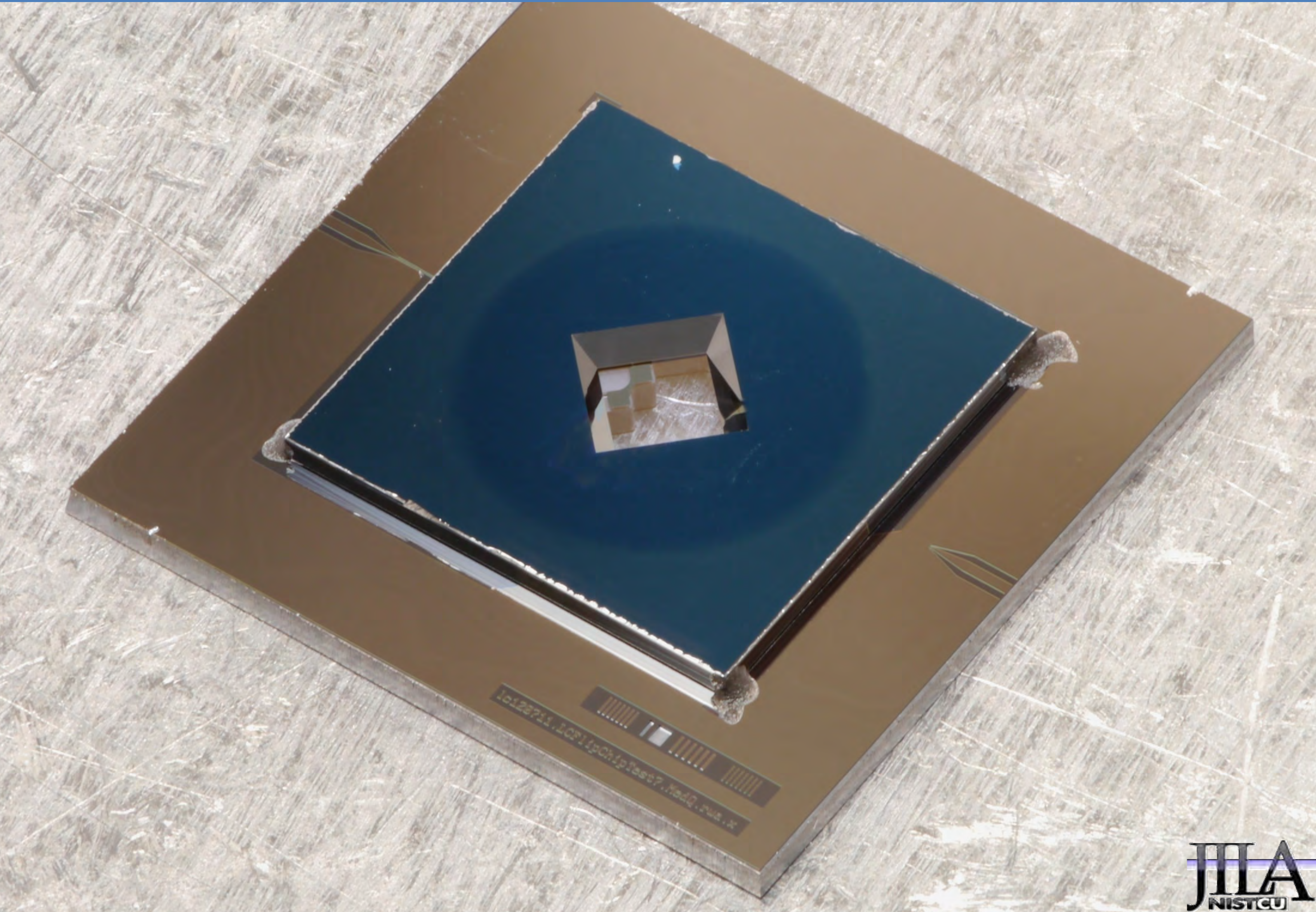
J. D. Thompson…J. E. Harris, Nature (2007)

Top chip



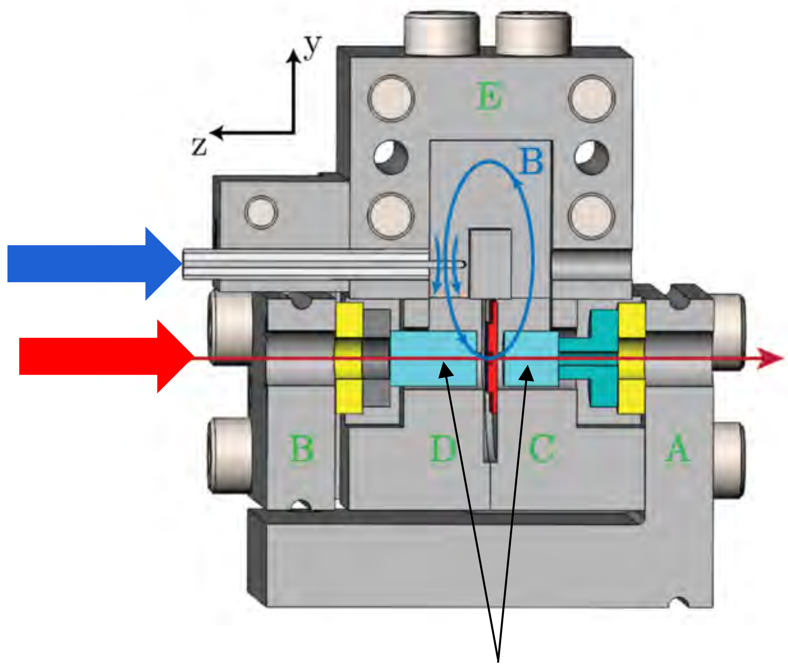
Bottom chip

Assembled chips

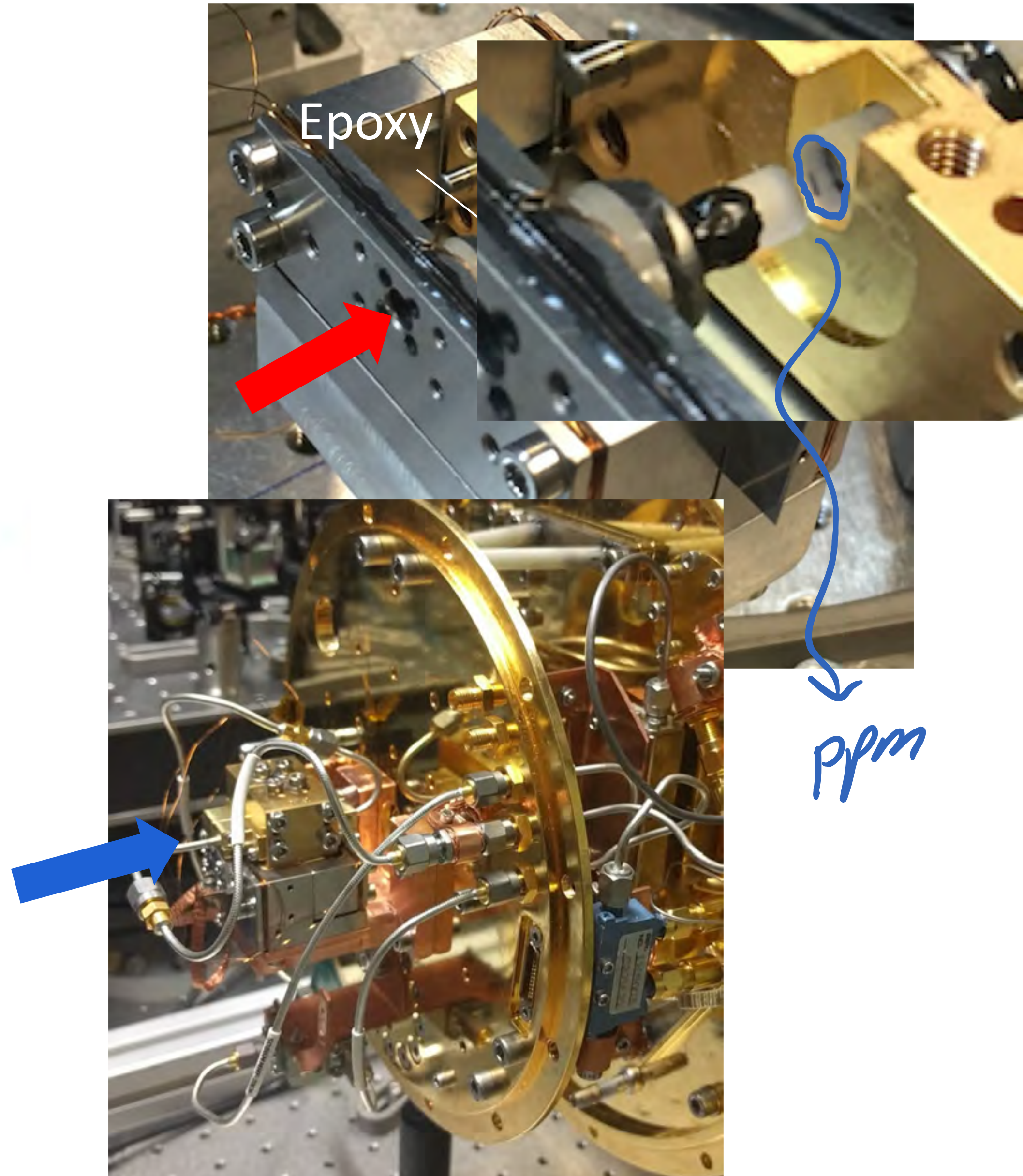


Device hardware: Optical integration

Optical port
Electrical port

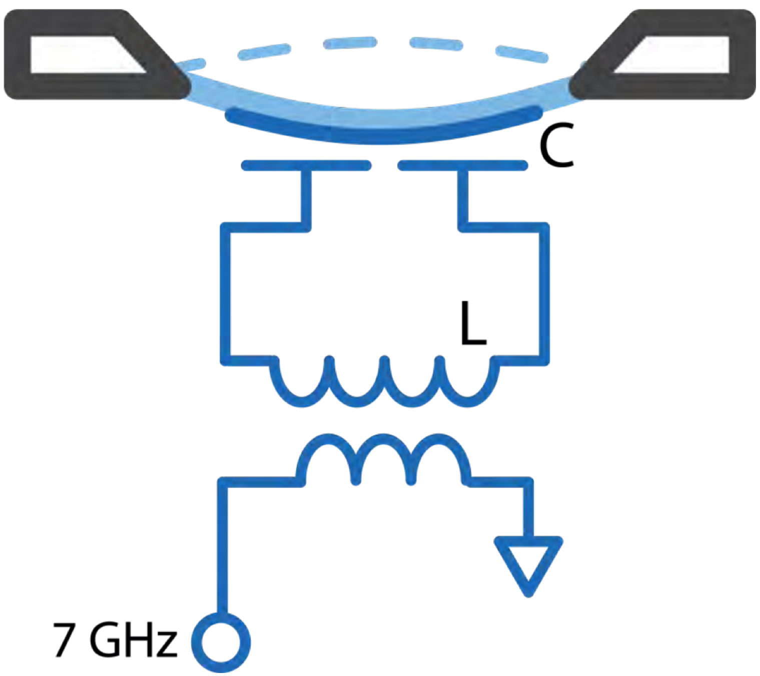


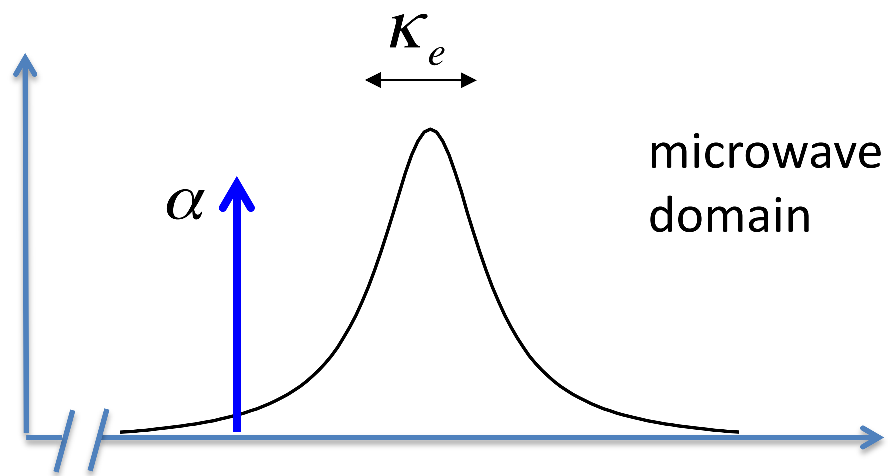
Cavity mirrors



Electrical signal ⟷ Mechanical motion

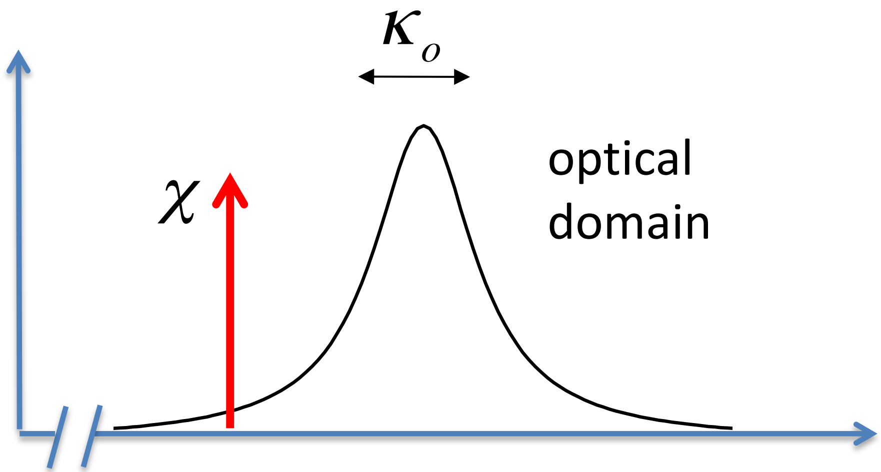
$$G_e \sim 2\pi \times 10\ \mathrm{MHz/nm}$$

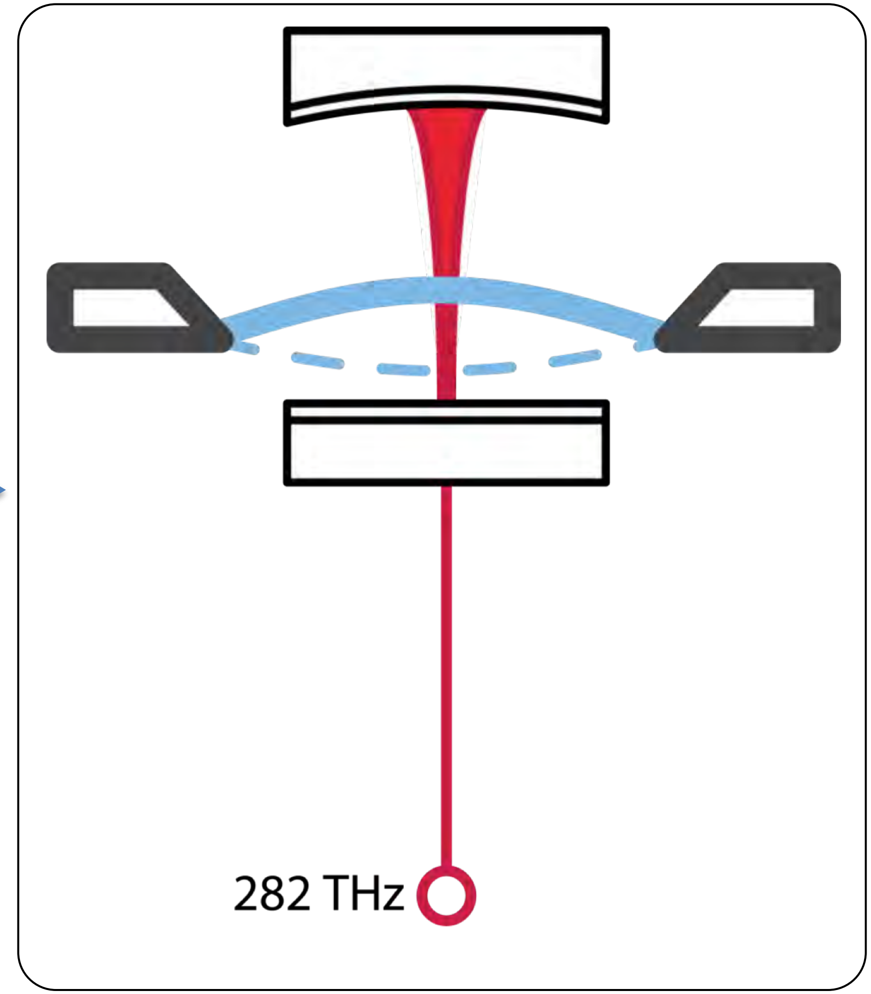




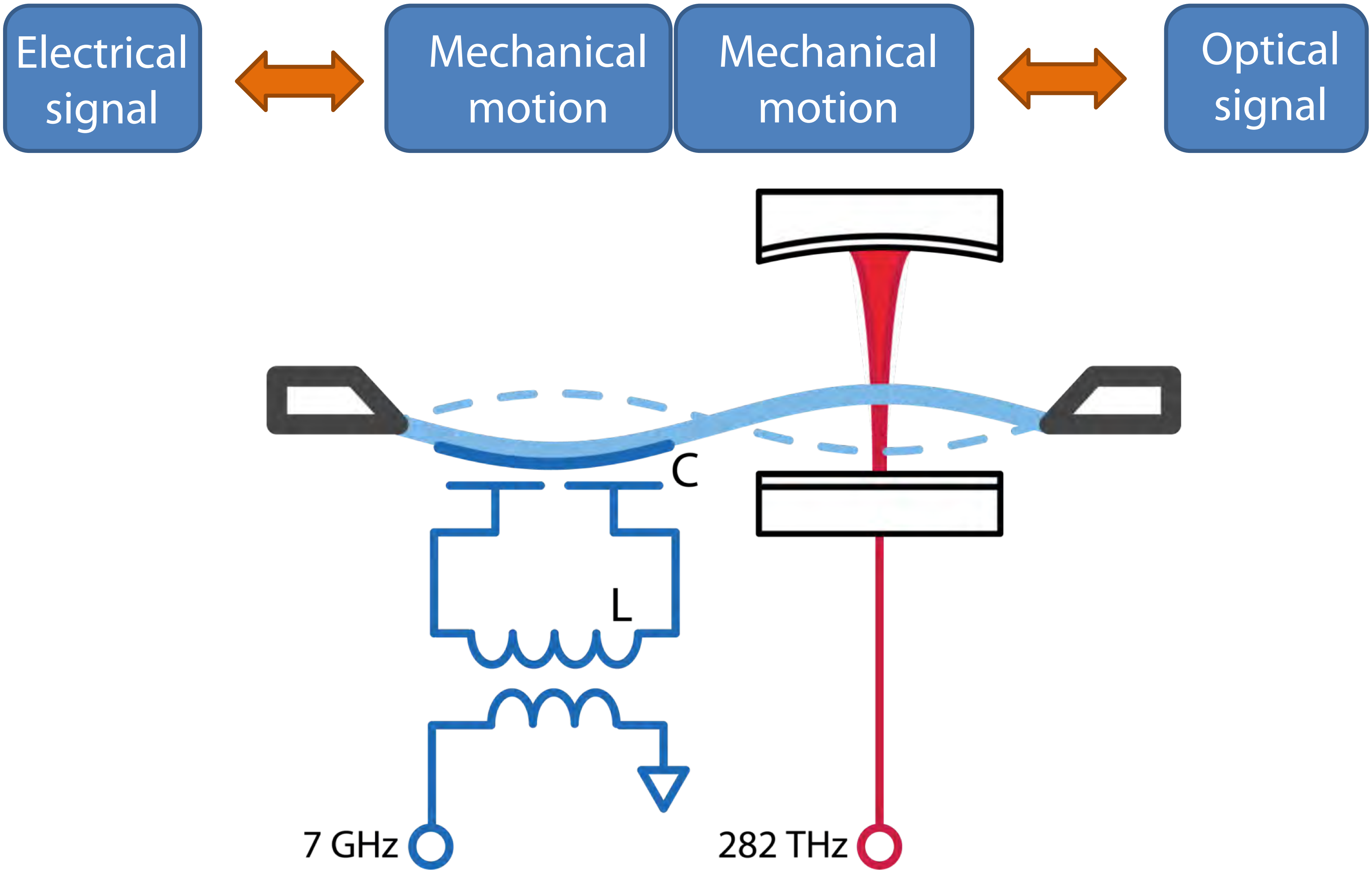
$$H_{int} = \hbar g_e \alpha \left(\hat{a} \hat{b}^{\dagger} + \hat{a}^{\dagger} \hat{b} \right)$$

Mechanical motion ↔ Optical signal



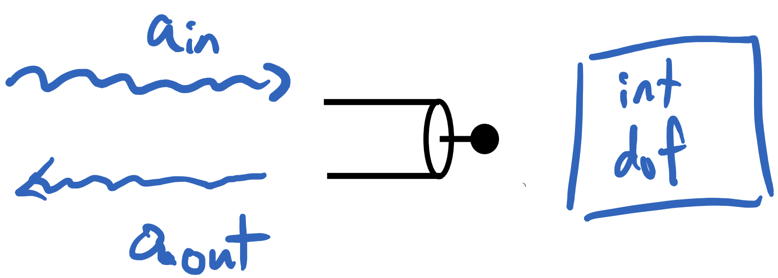


$$\hat{H}_{int} = \hbar g_0 \chi (\hat{c}\hat{b}^\dagger + \hat{c}^\dagger \hat{b})$$



Three linearly coupled resonators

Equations of motion and input-output theory



$$\hat{a}_{out}(t) = \sqrt{\kappa_{ext}}\,\hat{a}(t) - \hat{a}_{in}(t)$$

$$\kappa = \kappa_{ext} + \kappa_{int}$$

Also coupling via κ_{int}

Units $\langle \hat{a}^\dagger \hat{a} \rangle$ number of photons

$\langle a^\dagger_{in} a_{in} \rangle$ number per second

References: Gardiner and Collett, PRA (1984)

Equations of motion and input-output theory

$$\hat{H} = \hbar\omega_c \hat{a}^\dagger \hat{a} + \hbar\omega_m \hat{b}^\dagger \hat{b} + \hbar g \hat{a}^\dagger \hat{a} (\hat{b}^\dagger + \hat{b})$$

$$\dot{a} = \frac{i}{\hbar}[H, a]$$

$$\dot{a} = -i\omega_c a - ig(b^\dagger + b)a$$

$$\dot{b} = -i\omega_m b - ig a^\dagger a$$

Heisenberg Langevin

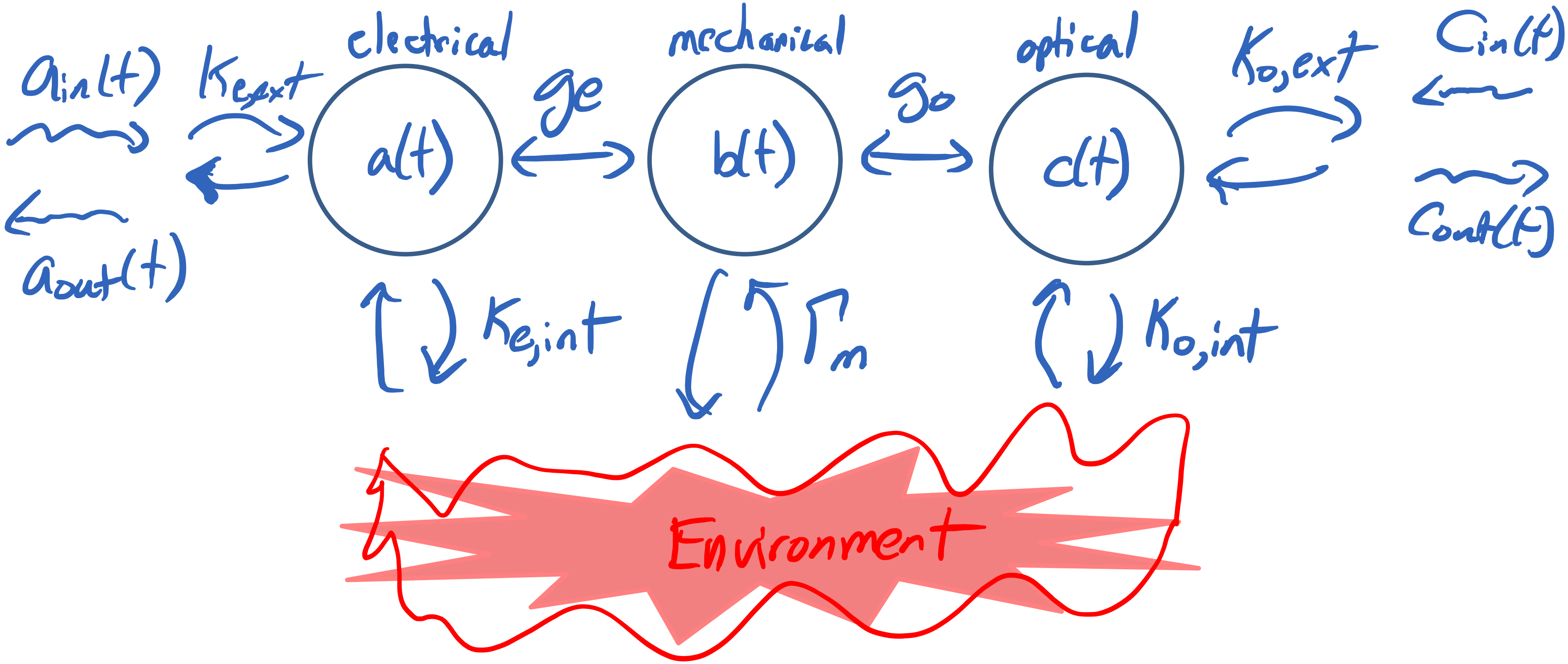
$$\dot{a} = \left(-i\omega_c - \frac{\kappa}{2}\right)a - ig(b^\dagger + b)a + \sqrt{\kappa_{ext}}\, a_{in} + \sqrt{\kappa_{int}}\, a_0$$

$$\dot{b} = \left(-i\omega_m - \frac{\Gamma_m}{2}\right)b - ig a^\dagger a + \sqrt{\Gamma_m}\, b_{in}$$

Linearize in spirit of yesterday, solve system of equations

References: Walls and Milburn Quantum Optics, Clerk, Lehnert Les Houches Lectures

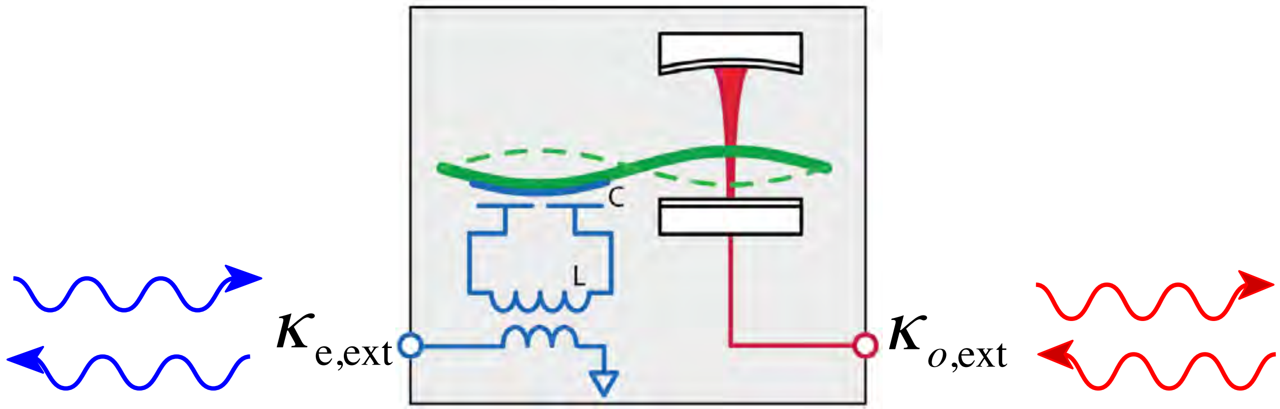
Three oscillators



Want to find "scattering parameters"

$$S_{oe} = \frac{c_{out}(\omega)}{a_{in}(\omega)}$$

Operation of converter

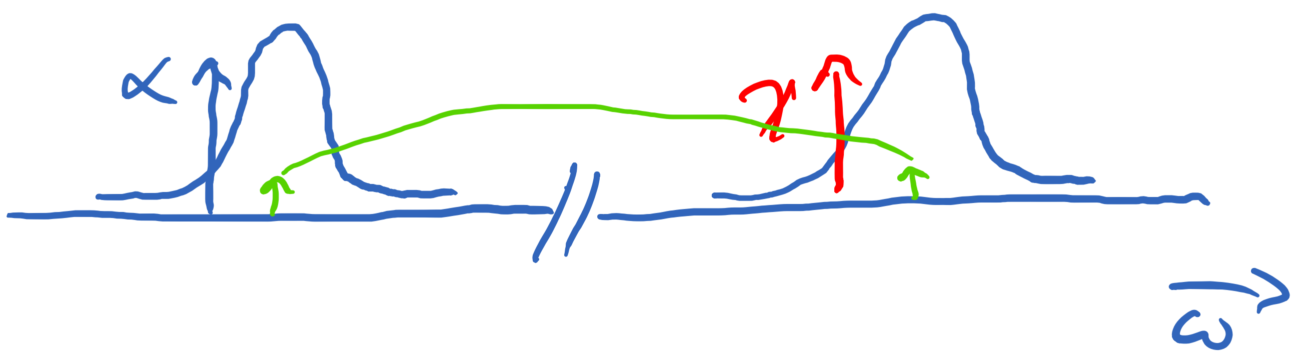


electromechanical photon-phonon exchange rate

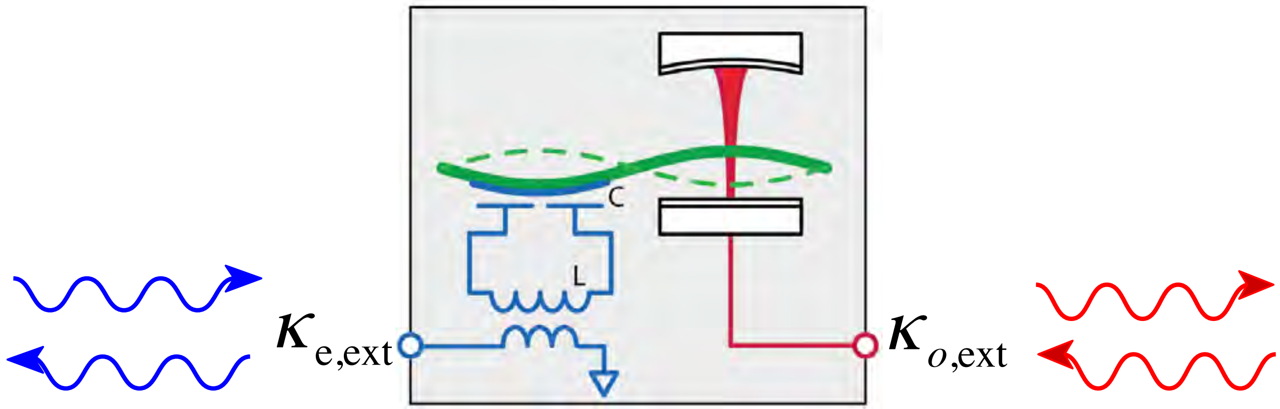
$$\Gamma_e = \frac{4\alpha^2 g_e^2}{\kappa_e}$$

$$\Gamma_o = \frac{4\chi^2 g_o^2}{\kappa_o}$$

optomechanical photon-phonon exchange rate



Operation of converter



$$|S_{eo}|^2 = |S_{oe}|^2 = \frac{4\Gamma_o\Gamma_e}{(\Gamma_o+\Gamma_e+\Gamma_m)^2}\,\eta G$$

$$\Gamma_o = \Gamma_e$$

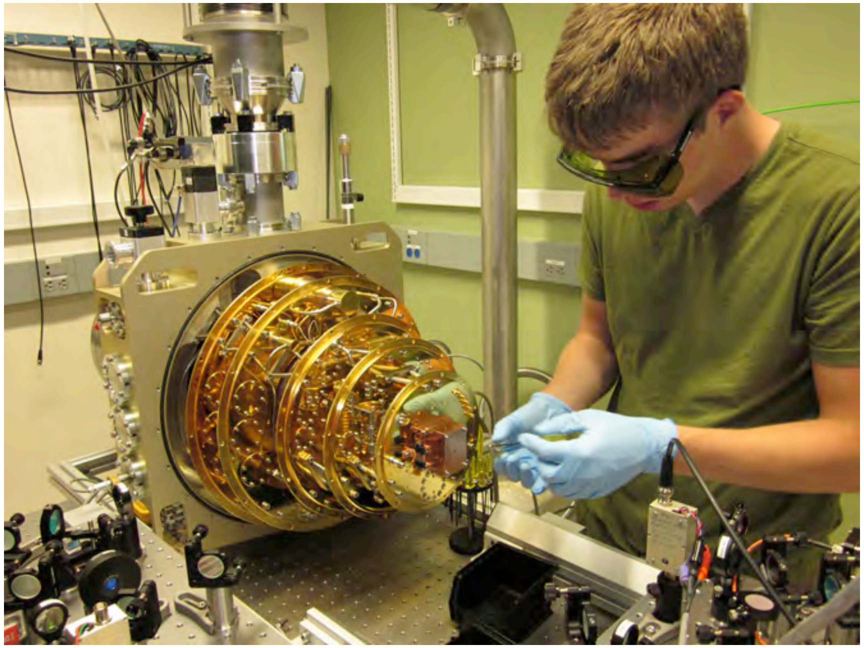
$$= \frac{4\Gamma_o\Gamma_o}{(2\Gamma_o)^2} = 1$$

$$\Gamma_o+\Gamma_e = \Gamma_T \sim 2\pi \times 10\,\text{kHz}$$

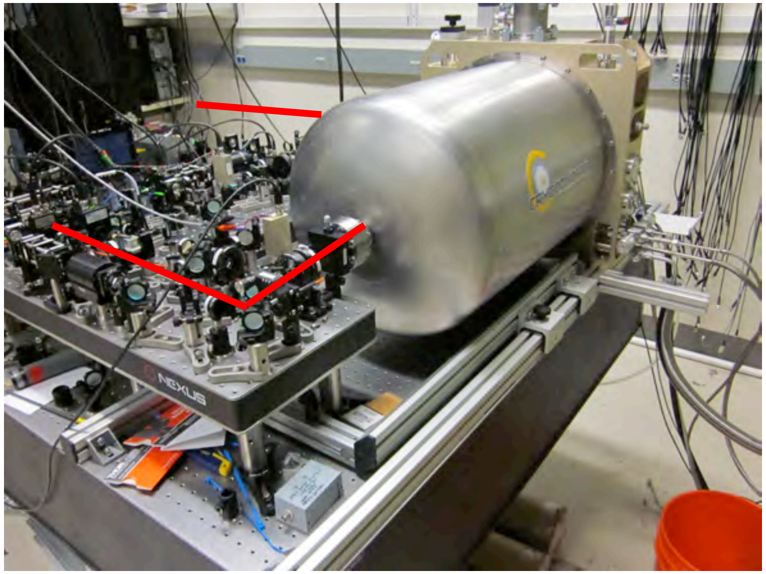
$$< 1\,\text{kHz}$$

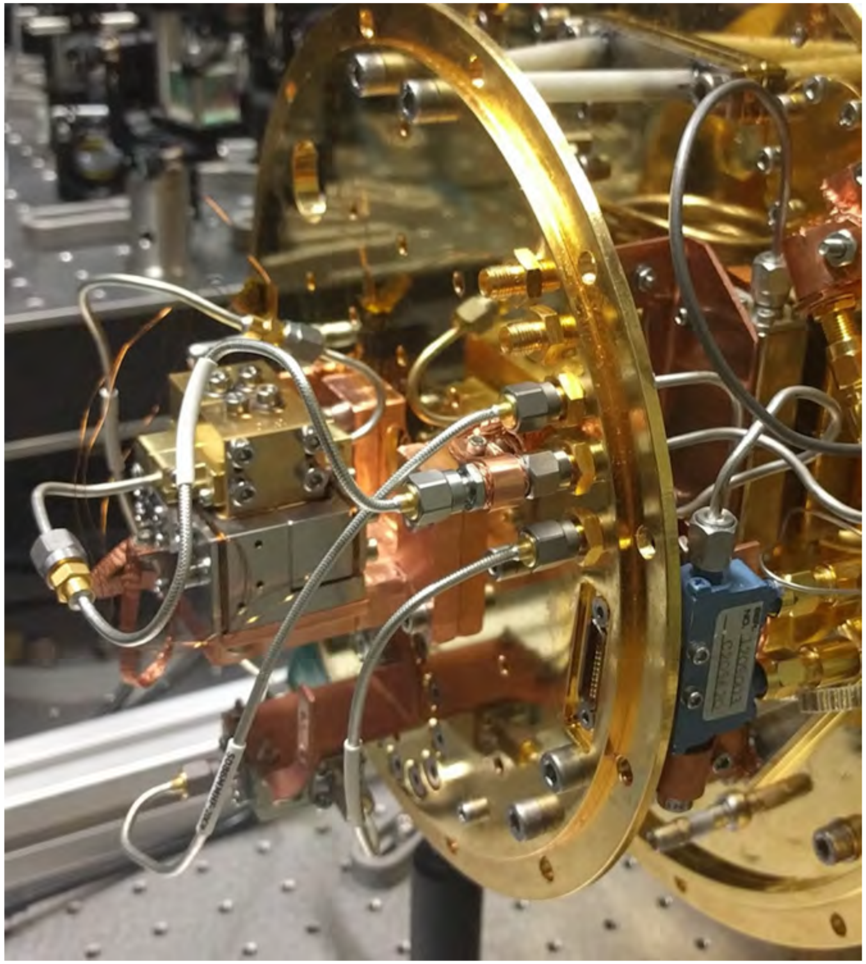
A. Safavi-Naeini…O. Painter, N J Phys (2011)

100 mK cryogenic measurements

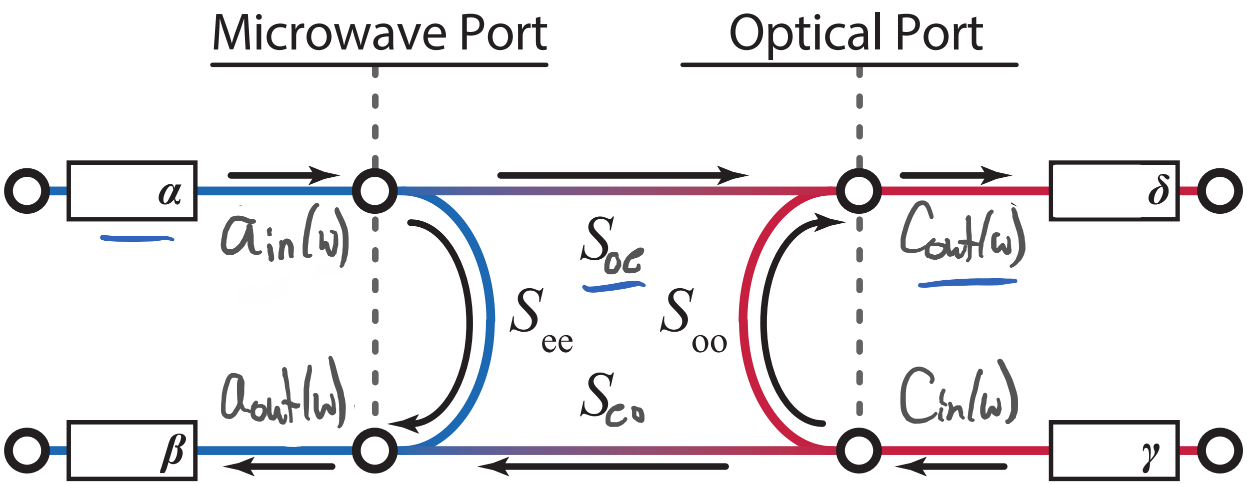


Base = 40 mK
Mechanics thermalizes
to 80 mK with light on





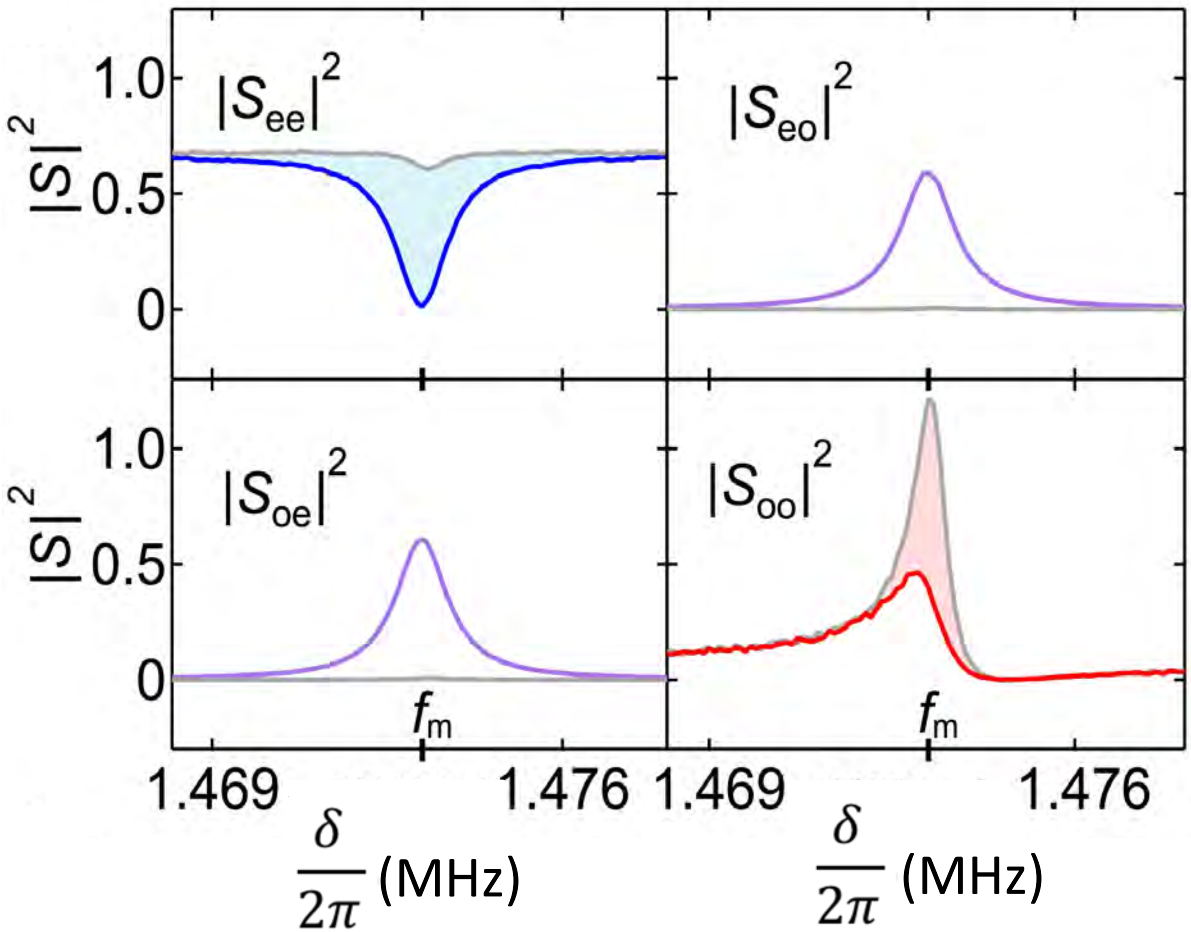
Calibrating efficiencies



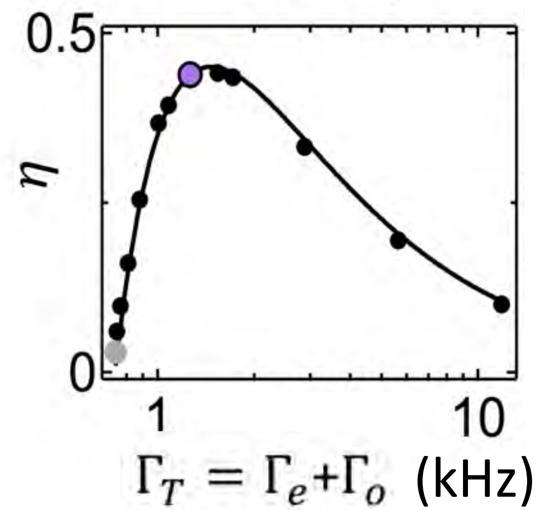
$$\frac{(\alpha S_{oe} \delta)(\gamma S_{eo} \beta)}{(\alpha \beta)(\delta \gamma)} = S_{oe} S_{eo}$$

R. W. Andrews *et al*, Nature Physics (2014)

Scattering parameters for converter box



$K_{o,int} \sim 1$ MHz
$K_{o,ext} \sim 1$ MHz



i.e. bandwidth

$\eta = 0.43$ here

$\eta = 0.48$ reached

Current added noise

Thermal motion of membrane Γ_m

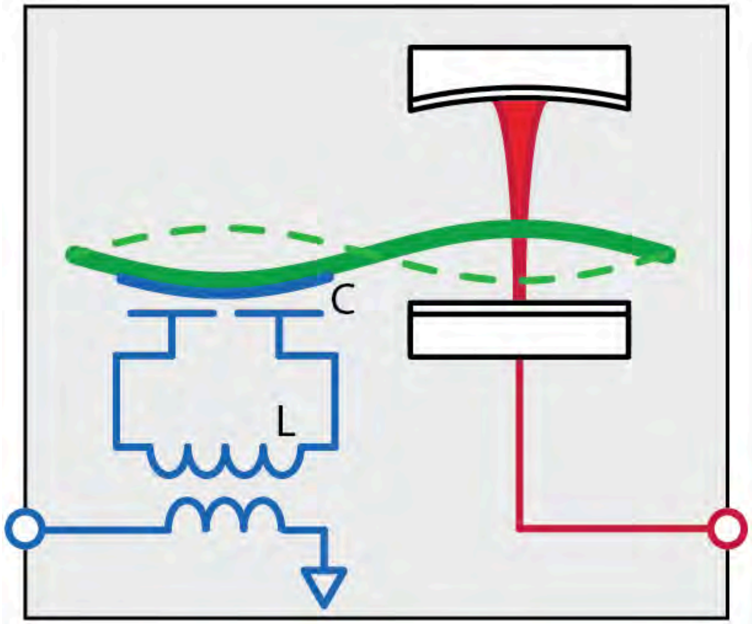
LC circuit noise

Heating of superconductor by optical pump

$\Gamma_0 = \frac{4x^2 g_0^2}{\kappa_0}$ $\Gamma_{th} = n_{th}\Gamma_m$

N_{add} Total of ≈ 10 photons

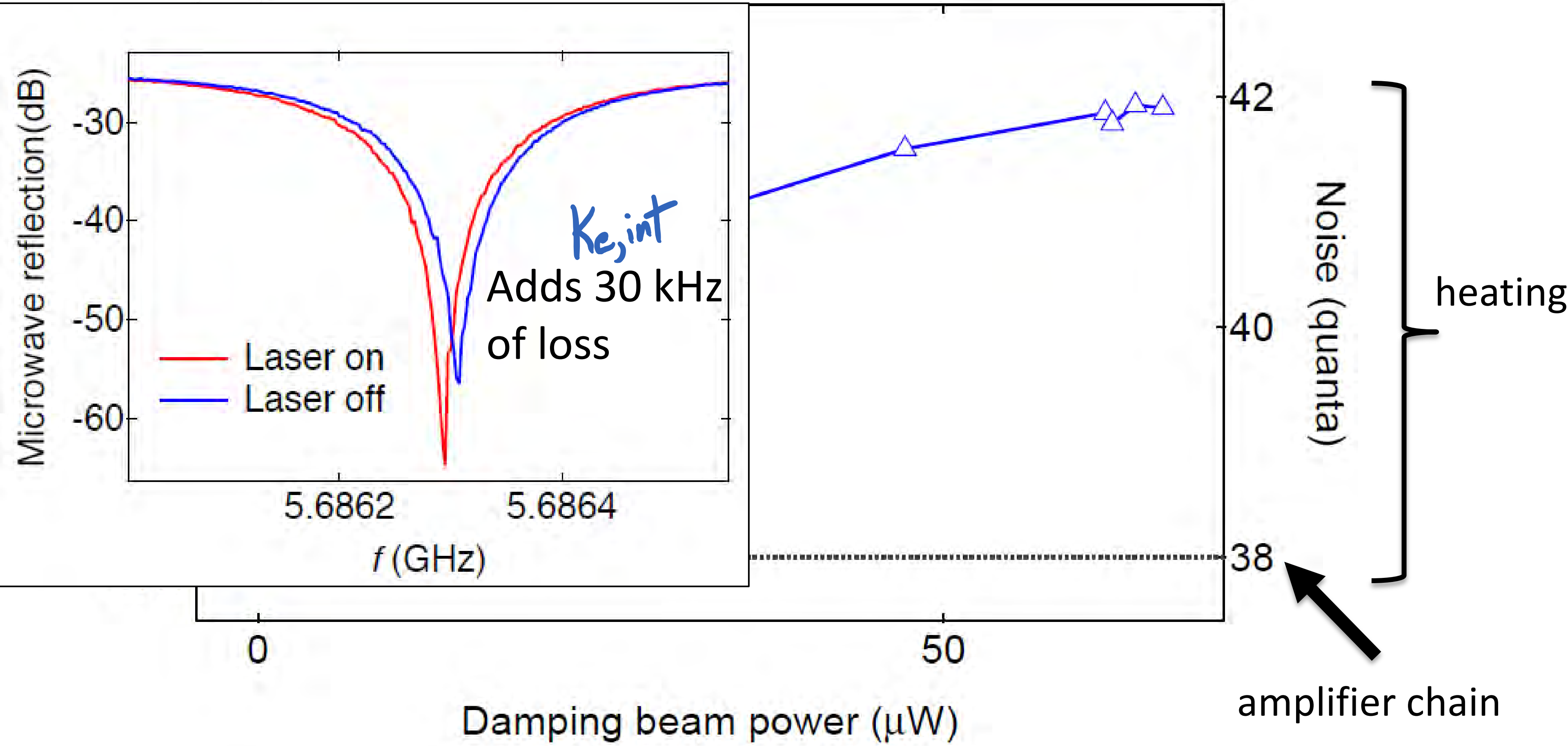
For bandwidth of near 1 kHz



A. P. Higginbotham, *et al.* arxiv (2017)

Quick look at laser effect on superconductor

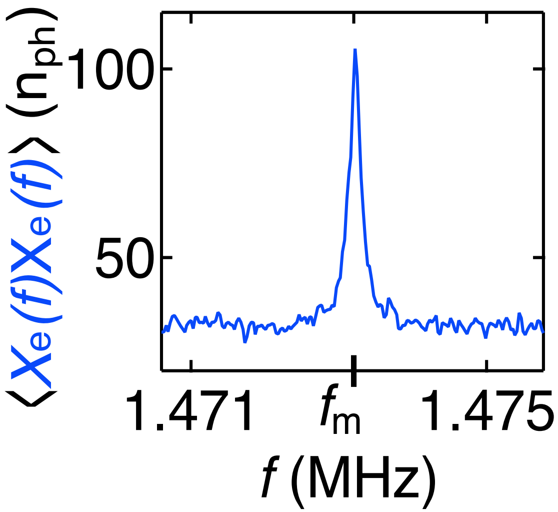
Effect on microwave linewidth

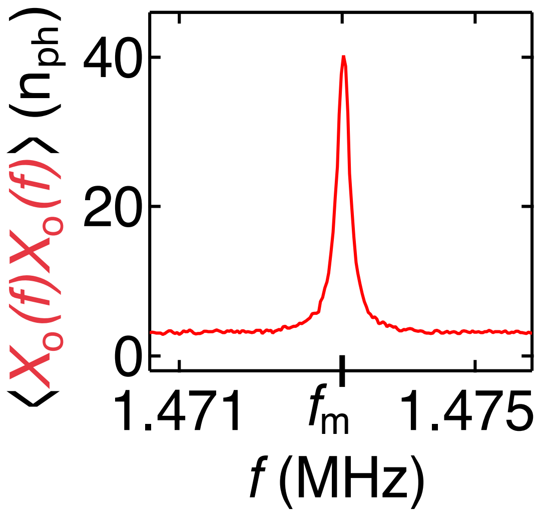


10 μW optical power (input) (1 kHz damping) adds 1.5 quanta of noise

Look closer at the noise

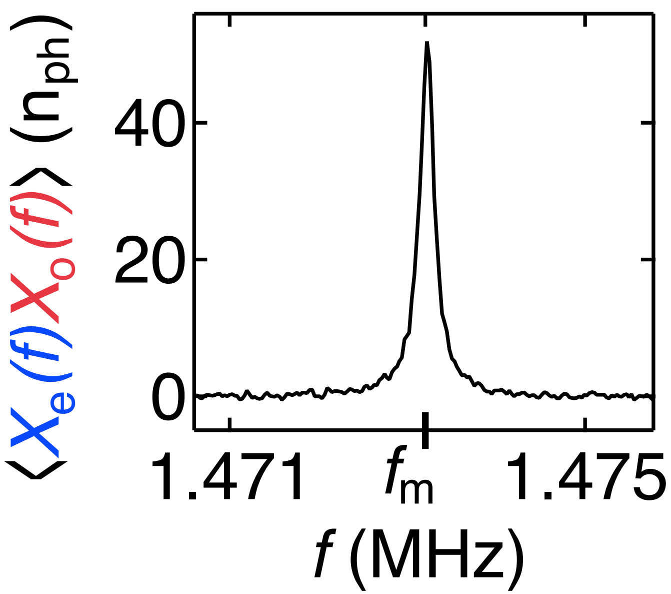
Noise at each port





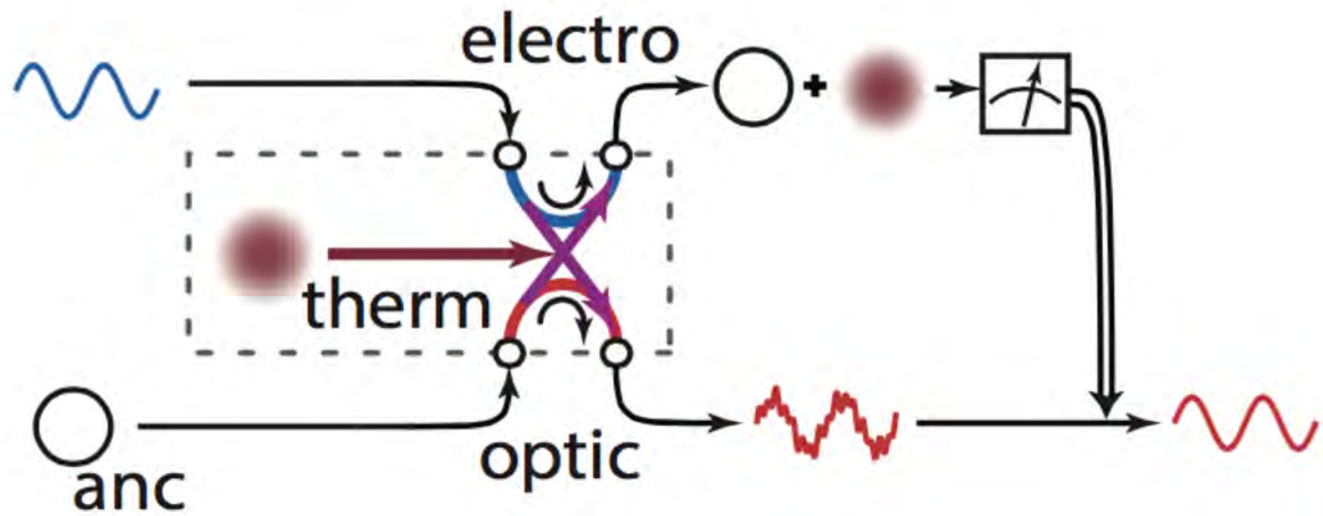
In thermally-dominated noise regime

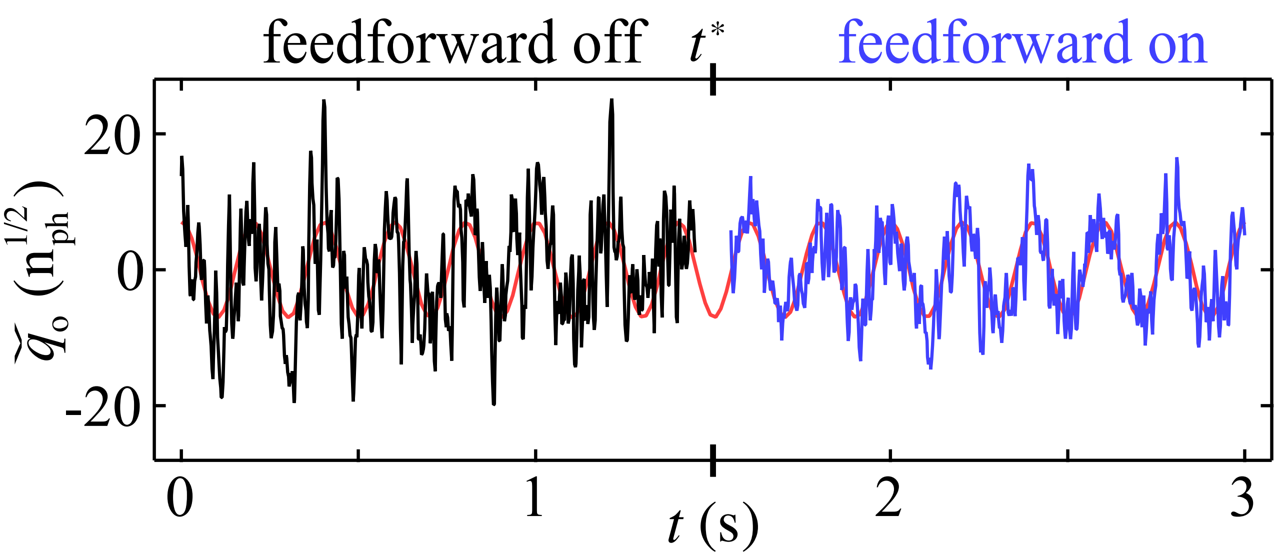
$$\frac{\Gamma_T}{2\pi} = 200 \text{ Hz}$$



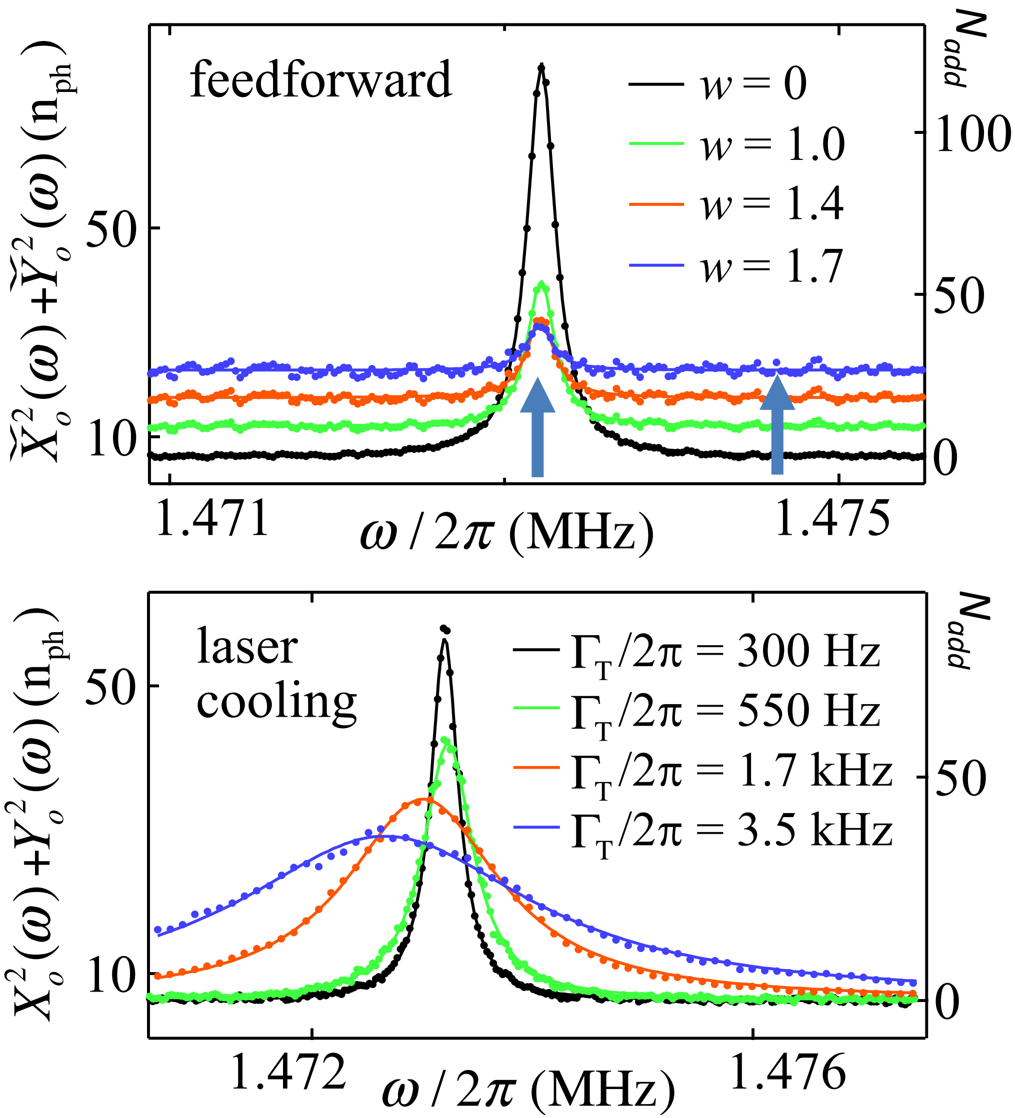
Cross-correlation: Both ports contain redundant record of thermal noise

Feedforward to remove correlated noise





Feedforward to remove correlated noise



Varying feedforward weight

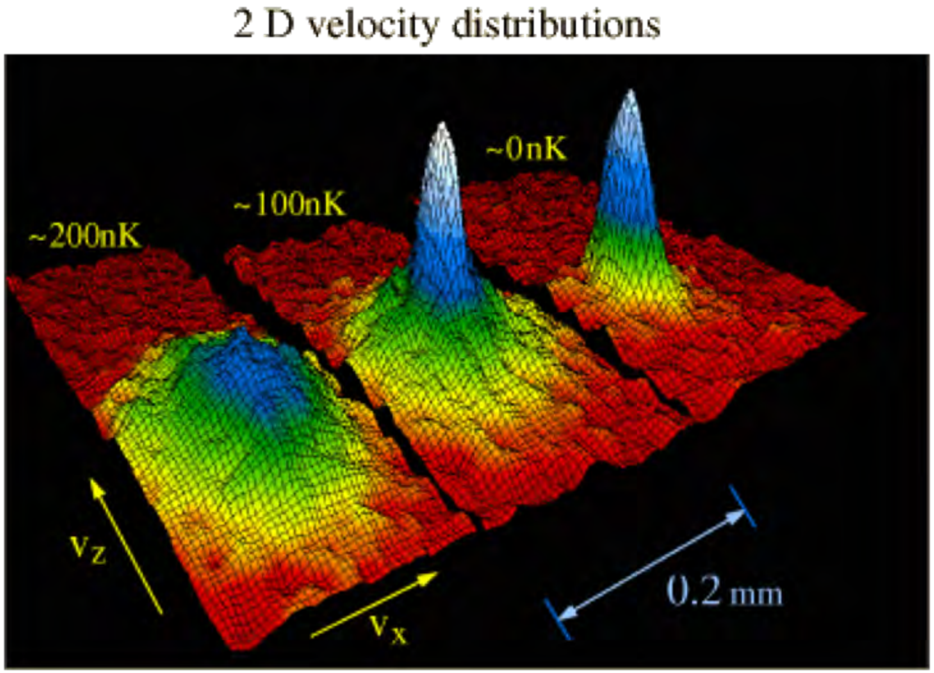
Decrease noise here by 60% while keeping cooperativity the same

$\Gamma_{opt} > \Gamma_{th}$

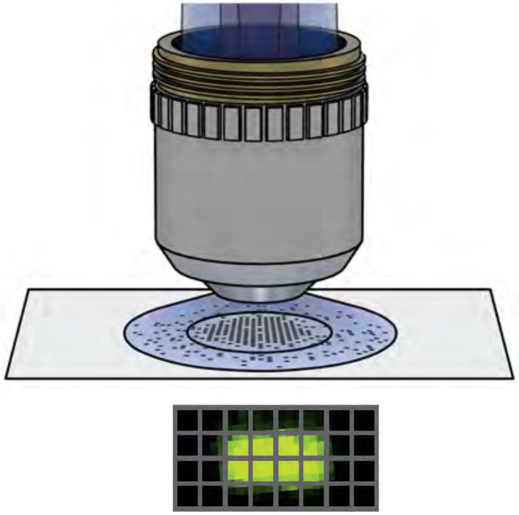
Dominated by microwave measurement chain noise

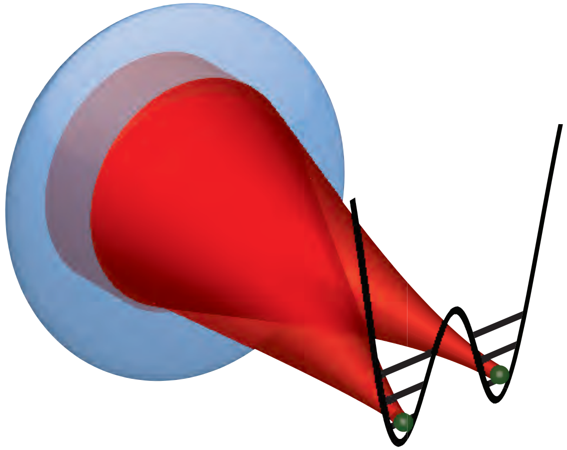
Feedback in optomechanics: M. Rossi…D. Vitali, PRL (2017)

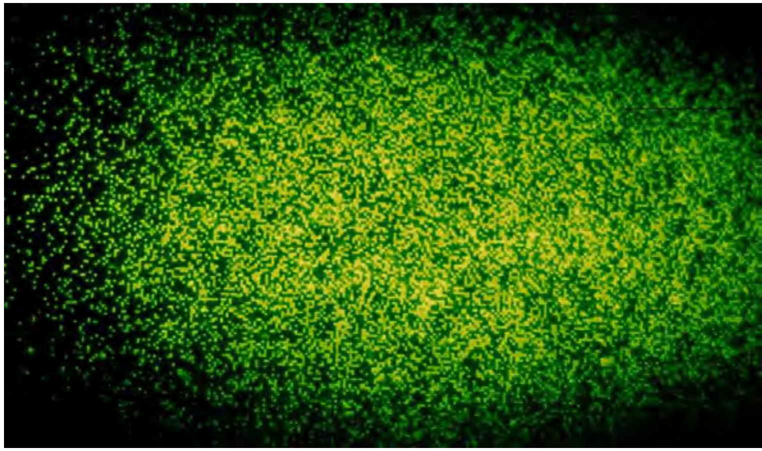
Neutral atoms: Preview



^{87}Rb

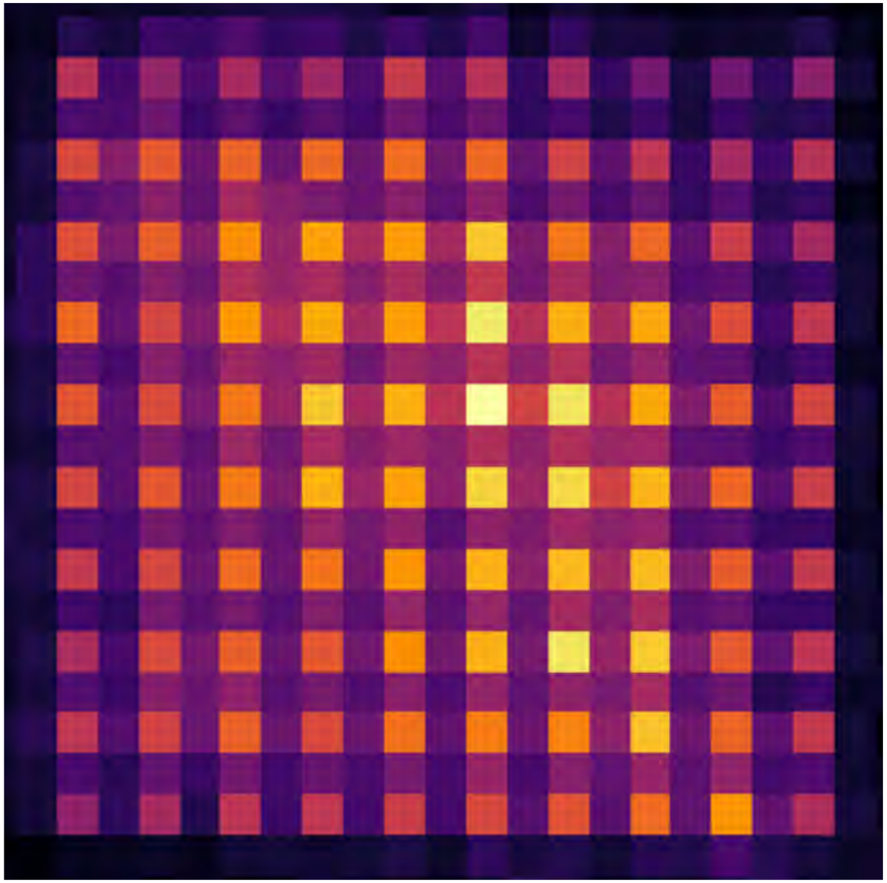


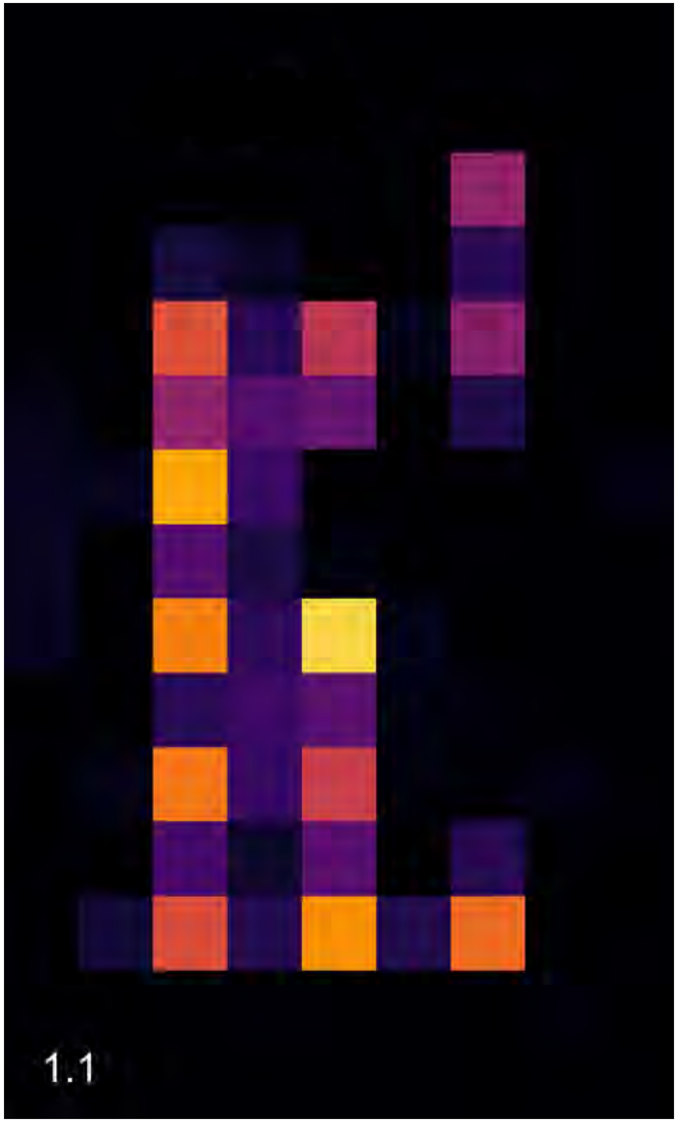




Greiner group, Harvard

Neutral atoms: Preview





The team

<u>Boulder electro-optics:</u>

Konrad Lehnert
Cindy Regal
Graeme Smith
Andrew Higginbotham
Pete Burns
Ben Brubaker
Max Urmey
Reed Andrews
Tom Purdy
Tim Menke
Ray Simmonds
Kat Cicak