The Sound of Silence:

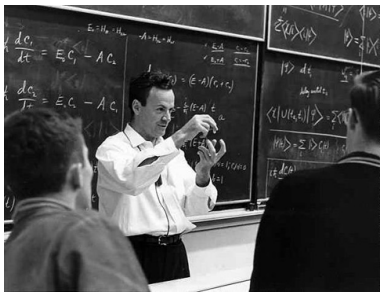
Acoustic Quant

Comet Hale-Bopp; Gerald Rhemann

Oskar Painter
California Institute of Technology
IQIM Quantum Summit, 1.27.2016

Quantum "weirdness"

"… nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy." – Richard Feynman, last line of his lecture, "Simulating Physics with Computers," International Journal of Theoretical Physics, 1982.



- *Entanglement*
- *Superposition*
- **Measurement**

- Classical World
  - Behaviour is independent of measurement.
- Quantum World
  - Behaviour is fundamentally altered by what is measured, and how it is measured.

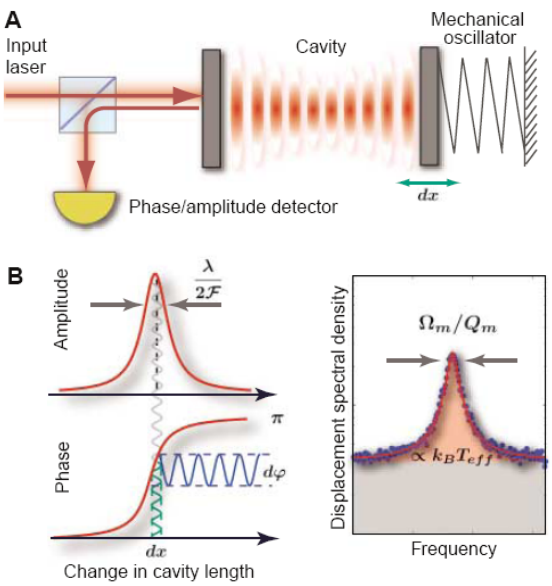
Theory for measurement of a mechanical system: Braginsky, Thorne, Caves, Khalili, …

Cavity-Optomechanics: quantum back-action

Uncertainty Principle

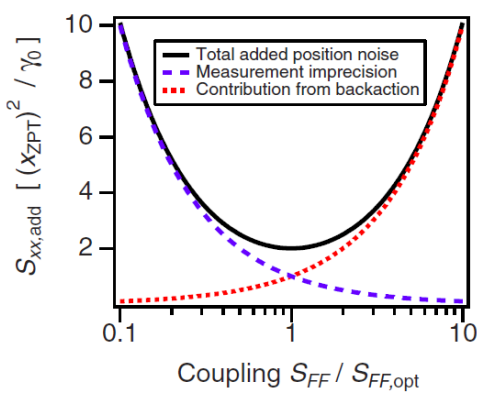
$$\Delta x \Delta p \geq \hbar/2$$

Cavity Optomechanics: Back-Action at the Mesoscale
T. J. Kippenberg, *et al.*
Science **321**, 1172 (2008);
DOI: 10.1126/science.1156032



- ideal detection (no optical loss)
- no correlation between sensing noise and back-action (on-resonance probing)

$$\bar{S}^{\mathrm{I}}_{xx}\bar{S}_{FF} = \frac{\hbar^2}{4}$$



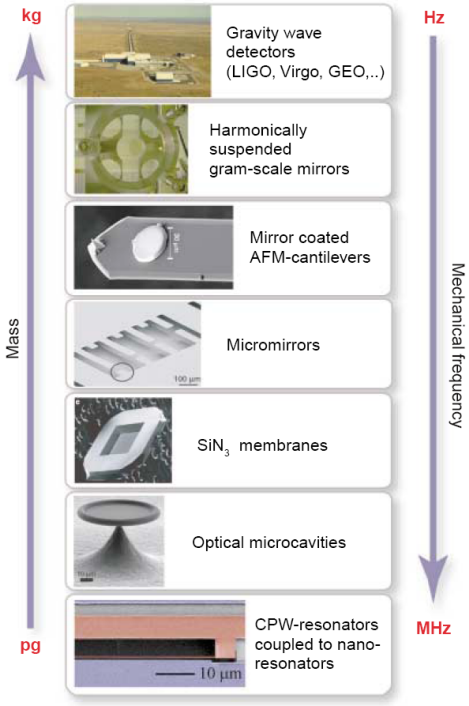
*Brooks, et al., Nature Physics (gas-phase atoms); Purdy, et al., Science 2013 (nanomembrane)

Cavity-Optomechanics: scale and geometry

Rana Adhikari

Yanbei Chen

Kerry Vahala



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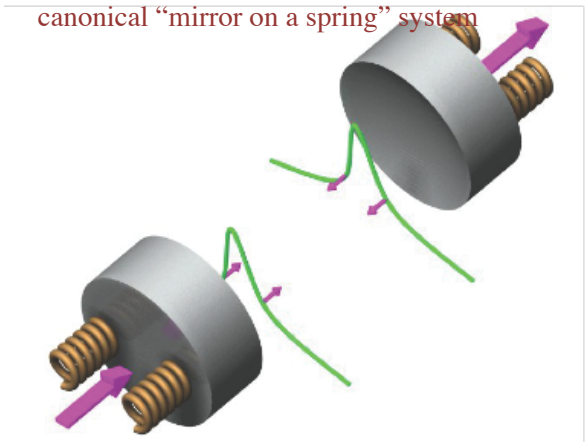
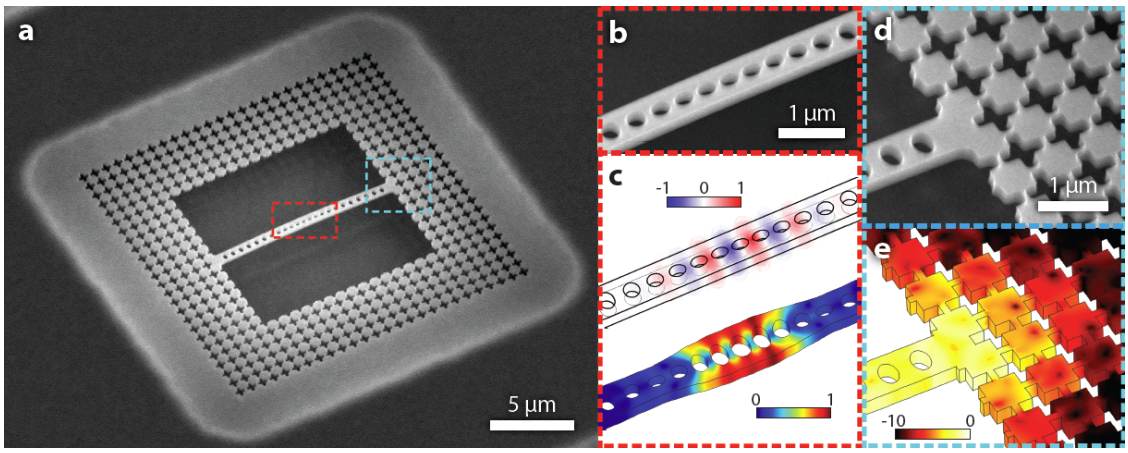
canonical "mirror on a spring" system



Cavity-Optomechanical *Circuits*

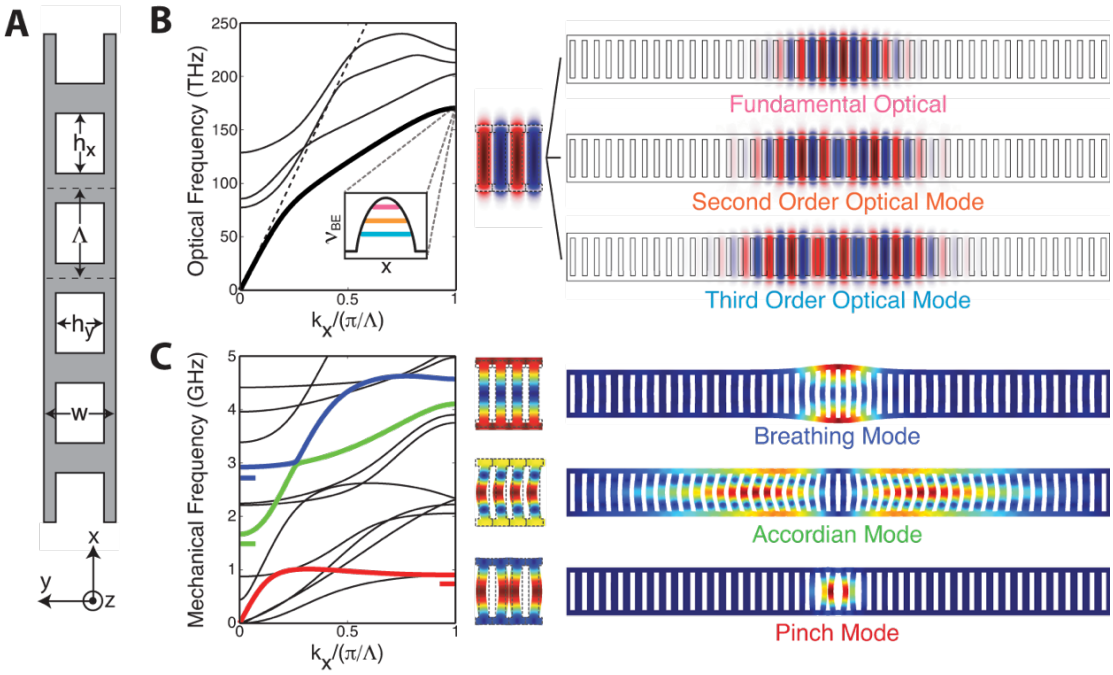


J. Chan, et. al, *Nature*, v478, pg. 89–92 (2011)

- "printable" circuits for photons and phonons formed in the thin-film surface layer of a microchip
- Independent routing of acoustic and optical waves
- Strong localization of acoustic and optical energy leading to large radiation pressure effects

Optomechanical crystal (OMC)

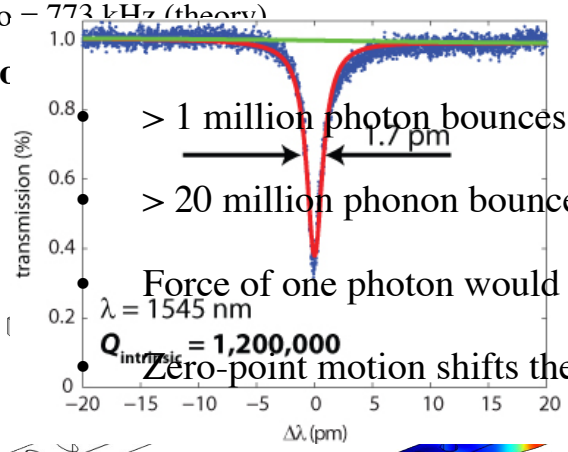
Eichenfield, et al., “Optomechanical Crystals”, Nature (2009)

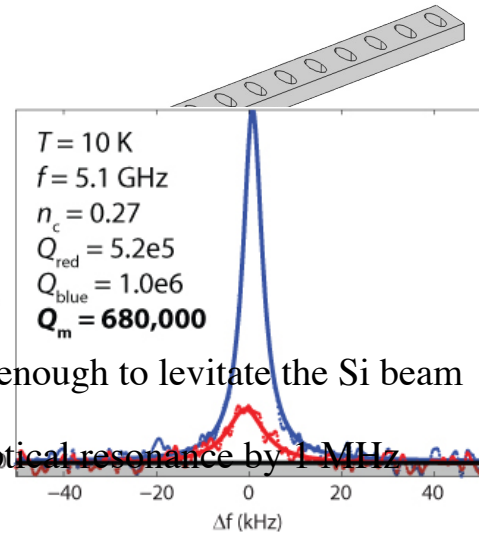


1D nanobeam OMC: state-of-the-art

*g*moving boundary = -96 kHz (theory)
*g*stress optic = 869 kHz (theory)
*g*o = 773 kHz (theory)

g



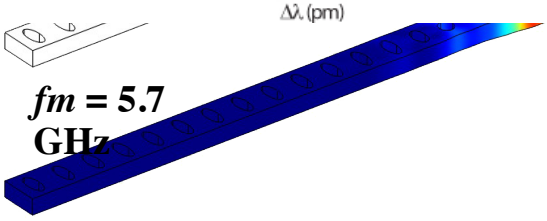


> 1 million photon bounces

> 20 million phonon bounces

Force of one photon would be enough to levitate the Si beam

Zero-point motion shifts the optical resonance by 1 MHz



***fm* = 5.7 GHz**

Ground state … within months!

Physics

Researchers Race to Put the Quantum Into Mechanics

Machines that make the slightest possible motion could lead to wild new technologies and help reveal why the weird rules of the microscopic realm don't apply to our everyday world

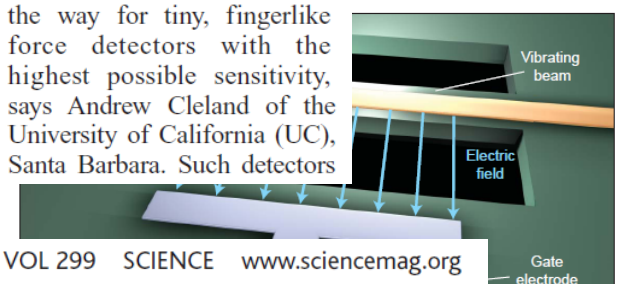
Like fidgety 3-year-olds, tiny objects simply cannot sit still. Atoms, molecules, and other minuscule particles must constantly flit about because of a law of nature that says if you know precisely where so can't know where it's going, The Heisenberg Uncertainty unavoidable nuisance; exper cists have observed countless smallest bits of stuff in natur wriggle whenever they try t pin them down. However, n one has directly observed th ineluctable quantum quiver ing—or zero-point motion— of a larger, humanmade objec

That may soon change Exploiting recent advances in nanotechnology, physicists are racing to fashion vibrating giz-

might enable researchers to quickly decode DNA and other large molecules, and someday they might serve as the guts of superfast quantum computers.

ble motion. At least four groups hope to reach the quantum limit of motion within months. The feat could open the way for tiny, fingerlike force detectors with the highest possible sensitivity, says Andrew Cleland of the University of California (UC), Santa Barbara. Such detectors

ht even help solve antum mechanics ct like an electron it once, whereas a a person cannot?



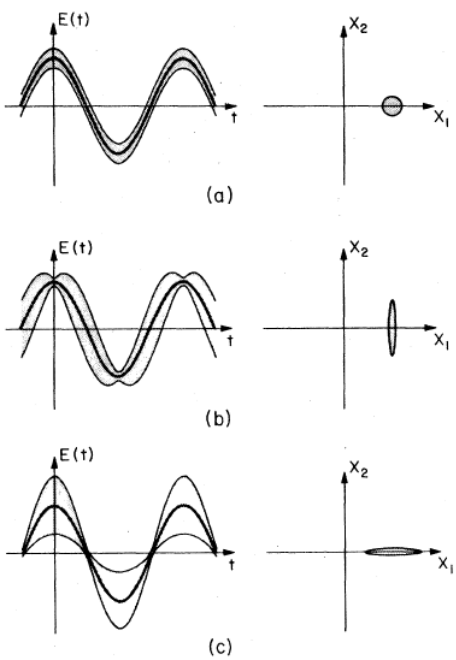
"We don't see quantum behavior in our macroscopic world, so in some sense we're protected from quantum mechanics," says Miles Blencowe, a theoretical physicist at Dartmouth College in Hanover, New Hampshire. "What protects us?" To find out, he says, experimenters might try putting progressively bigger mechanical devices into here-and-there "superpositions" to observe what, if anything, goes wrong.

First, though, physicists must reach the quantum limit of mechanical motion. That will require overcoming serious technical challenges, says Michael Roukes of the California Institute of Technology (Caltech) in Pasadena: "This is just damned hard stuff to do."

A subtle vibe

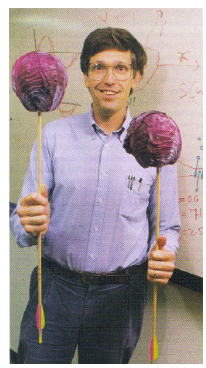
The biggest hurdle is heat. Thermal energy makes large objects wiggle, and at any achievable temperature those vibrations overwhelm the zero-point motion. For example, according to quantum mechanics, a tuning fork can gain or lose energy only in discrete dollops whose size is proportional to the fork's frequency of vibration. Because the frequency is low (440 cycles per sec-

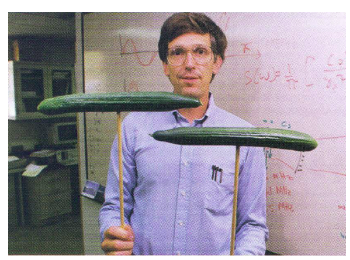
Quantum “fuzz balls”



C. Caves, PRD, v23(8), 1981

H. Jeff Kimble
[from “Light of Darkness”, E&AS, 1993]





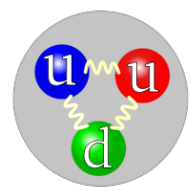
Mechanical Resonator

vibrational frequency

$$x_{\mathrm{ZPF}} = (\hbar/2m_{\mathrm{eff}}\omega_m)^{1/2}$$

motional mass

~ 1 femtometer (10^{-15} meter)



charge radius of a proton = 0.87 fm

Quantum zero-point motion

- Classical

H

- Absorbs energy
- Emits energy

C

- **Doesn't** Absorb energy
- **Doesn't** Emit energy

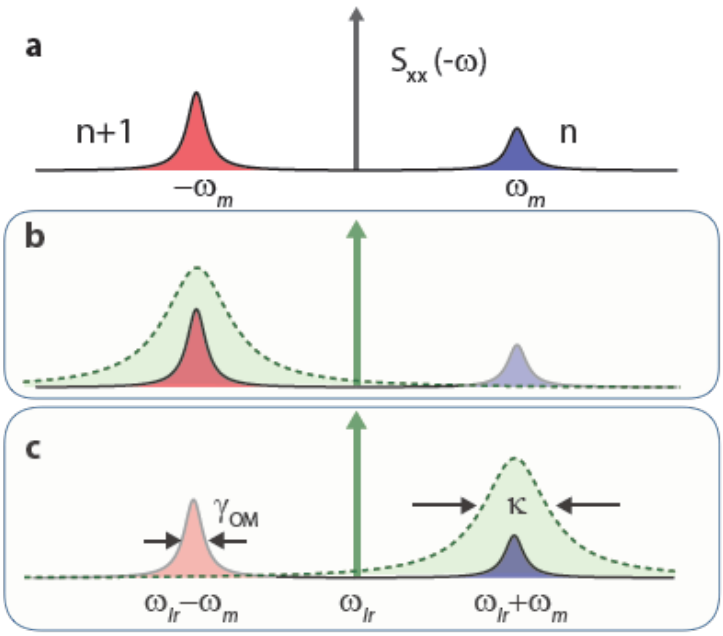
- Quantum

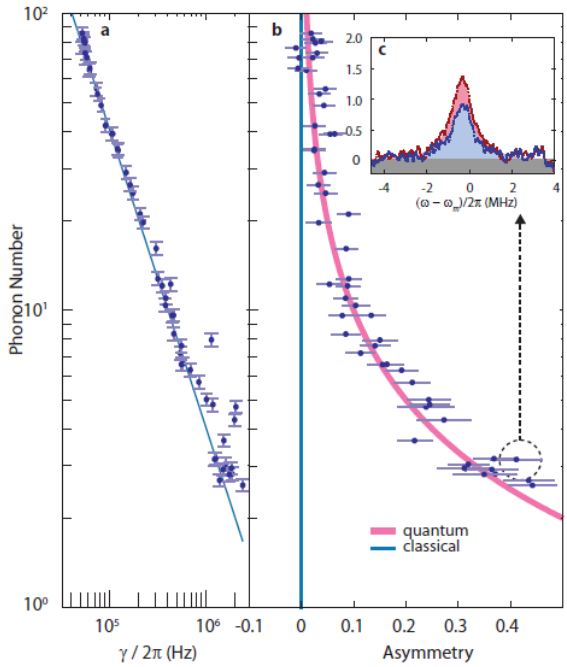
C

- Absorbs energy
- **Doesn't** emit energy

Motional sideband spectroscopy

$$\frac{I_-}{I_+} - 1 \approx \frac{1}{n}$$





Quantum back-action and force measurements

The PHYSICAL REVIEW A **86**, 033840 (2012) nents is

Quantum back-action in measurements of zero-point mechanical oscillations

Vladi Farid Ya. Khalili,[1] Haixing Miao,[2] Huan Yang,[2] Amir H. Safavi-Naeini,[3] Oskar Painter,[3] and Yanbei Chen[2] rne[3], and

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(Received 8 June 2012; published 25 September 2012)
(Received 2 September 2001; Revised 4 July 2002 and 1 December 2002)

Phys. Rev. D 67, 082001 (2003)

$$S_F(\omega) = \frac{S_{zz}(\omega)}{|\chi(\omega)|^2} + 2\mathrm{Re}\left[\frac{S_{zF}(\omega)}{\chi(\omega)}\right] + S^{\mathrm{BA}}_{FF}(\omega) + S^{q}_{FF}(\omega)$$

imp. quant. corr. quant. BA zpf

$$S_{zz}(\omega)S^{\mathrm{BA}}_{FF}(\omega) - S_{zF}(\omega)S_{Fz}(\omega) \geqslant \hbar^2$$

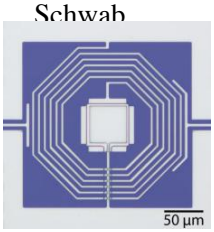
$$S_F(\omega)|_{S_{zF}=0} = \frac{S_{zz}(\omega)}{|\chi(\omega)|^2} + S^{\mathrm{BA}}_{FF}(\omega) + S^{q}_{FF}(\omega)$$

$$\geqslant \frac{2\hbar}{|\chi(\omega)|} + (4\langle n\rangle + 2)\hbar m\kappa_m\omega_m$$

SQL thermal + zpf

Yanbei Chen

Keith Schwab



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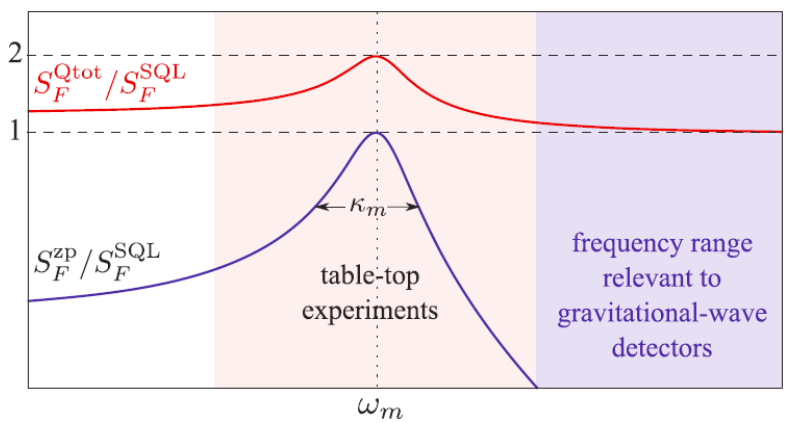


$$S_F^{\mathrm{zp}} \equiv 2\hbar m \kappa_m \omega_m \qquad S_F^{\mathrm{SQL}} \equiv \frac{2\hbar}{|\chi(\omega)|} = 2\hbar m \sqrt{\left(\omega^2 - \omega_m^2\right)^2 + \kappa_m^2 \omega^2}$$

Beyond the quantum ground-state?

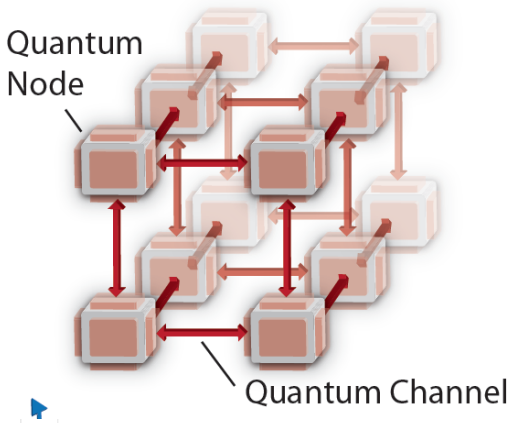
"...I turned my collar to the **cold** and **damp**
When my eyes were stabbed by the flash of a neon **light**
That split the night
And **touched** ***the sound of silence***..."

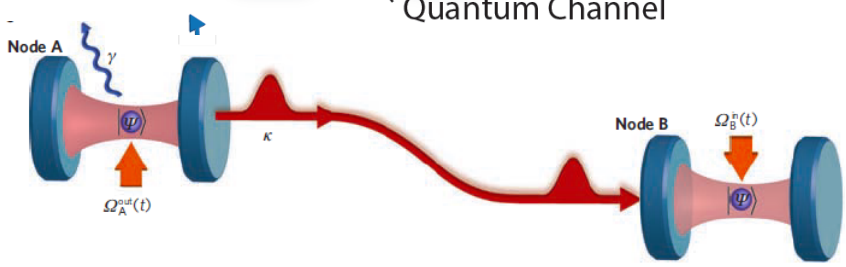
The Sound of
Silence
Simon and
Garfunkel

The Quantum Internet

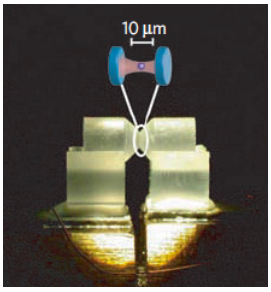
H. Jeff Kimble, “The Quantum Internet,” Nature (2008)

- Distribution of quantum entanglement
- Teleportation of quantum states between quantum nodes
- Relies on an efficient “quantum interconnect”

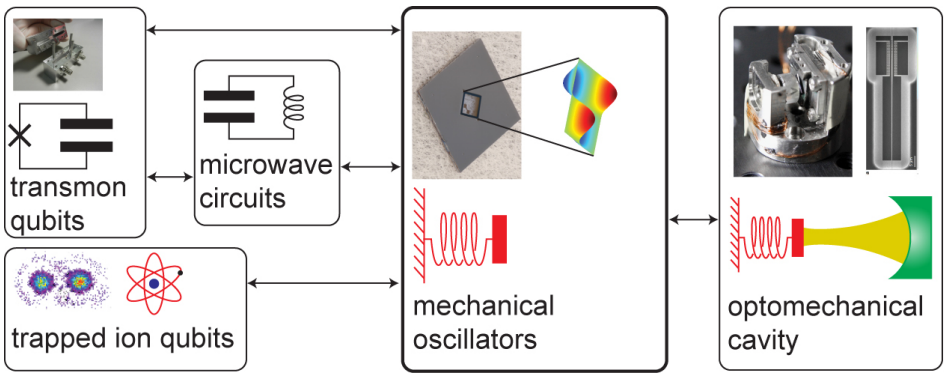




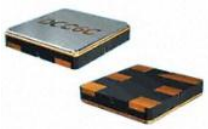
Jeff Kimble

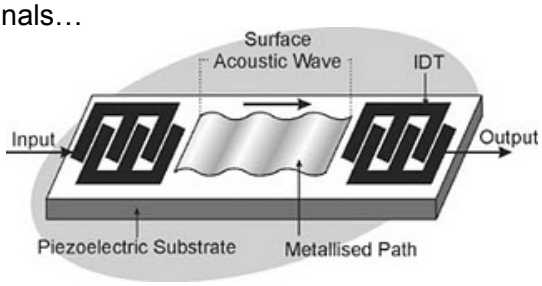


Wiring up quantum systems with mechanics



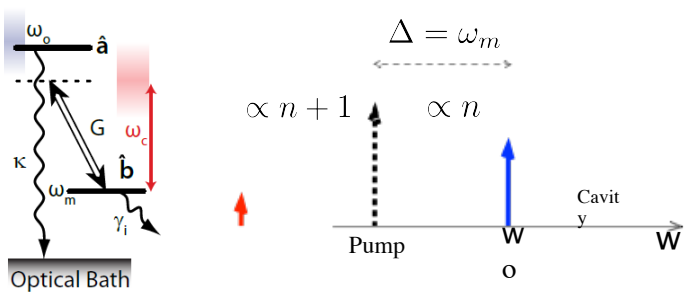
This works very well for classical signals…

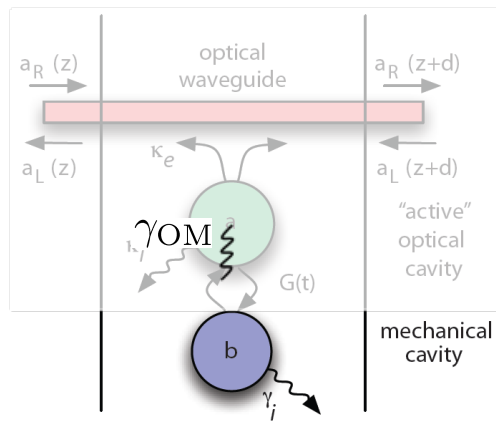




Linearized cavity-OM system…

Can boost interaction by using a strong beam:





$$G = g_o\sqrt{n_c}$$

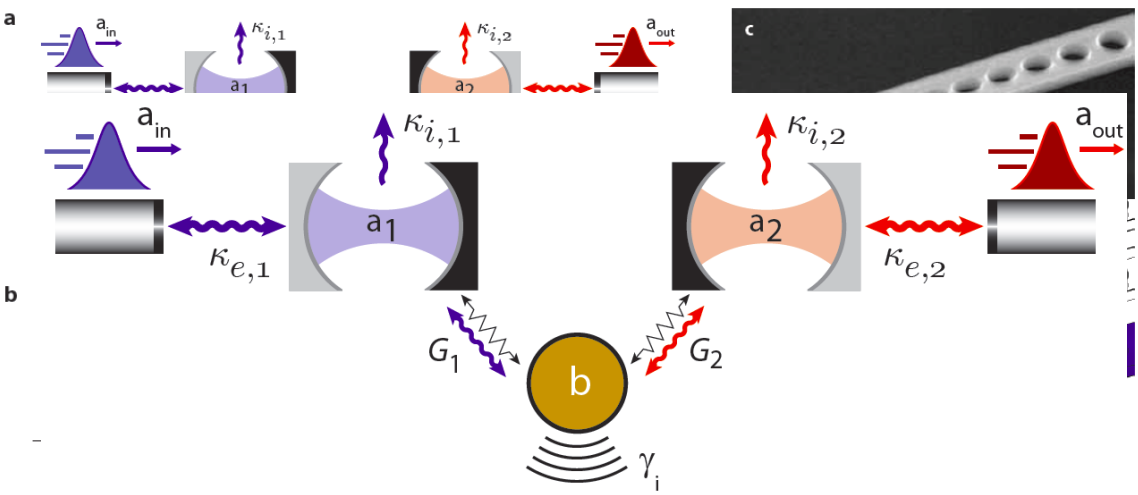
- Interaction becomes *linear*
- Interaction is *tunable* and can be time-dependent.
- System is described by *state-transfer Hamiltonian*:

$$\hat{H}_{\mathrm{RWA}} = \hbar G(t)\left(\hat{a}^\dagger\hat{b} + \hat{a}\hat{b}^\dagger\right)$$

- For $G < \kappa$ the mechanical mode sees a new loss channel with $\gamma_{\mathrm{OM}} \equiv 4G^2/\kappa$
- Cooperativity: $C \equiv \gamma_{\mathrm{OM}}/\gamma_i$

Optical-to-optical □-conversion

Safavi-Naeini, A. H. *et al*., NJP **13**, 013017 (2011); Wang, Y. and Clerk, A., PRL **108**, (2012); Hill, J. T. *et al*., Nat. Commun. **3**, (2012)



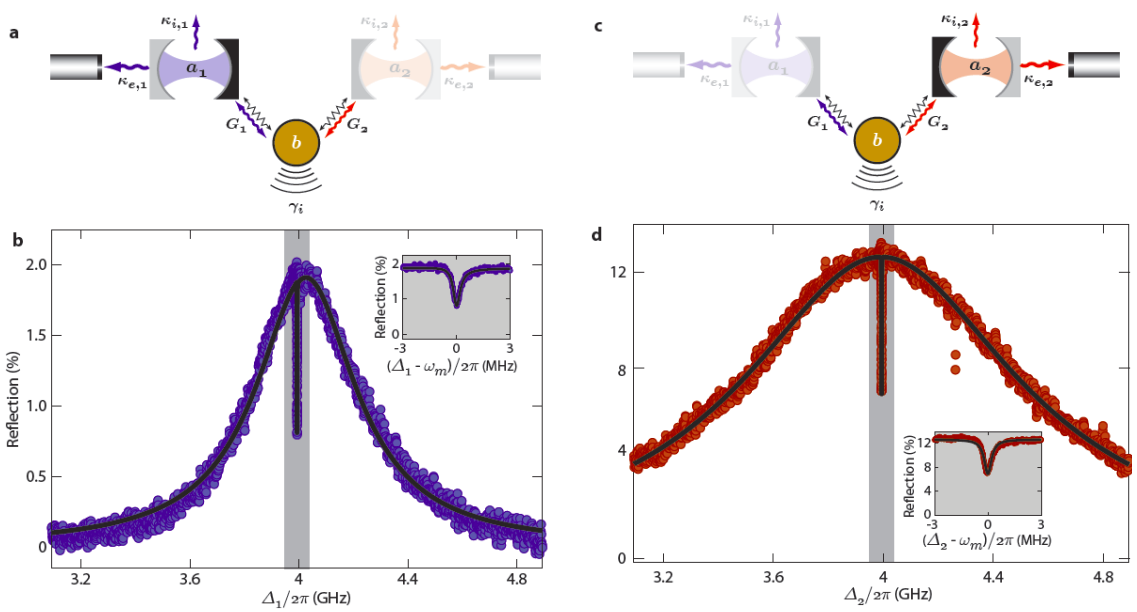
$$S_{\mathrm{out},k}(\omega) = \eta_k \eta_j \frac{\gamma_{\mathrm{OM},k}\gamma_{\mathrm{OM},j}}{(\omega+\omega_m)^2 + (\gamma/2)^2}\left(n_{\mathrm{added}} + S_{\mathrm{in},j}(\omega)\right)$$

$$\eta_{\mathrm{max,int}} = \frac{4C_1C_2}{(1+C_1+C_2)^2} \quad \rightarrow 1 \text{ for } C_1{=}C_2 \gg 1$$

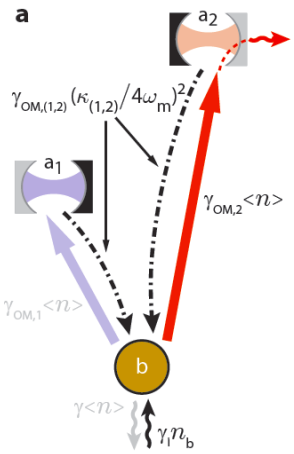
Optomechanically Induced Transparency (OMIT)

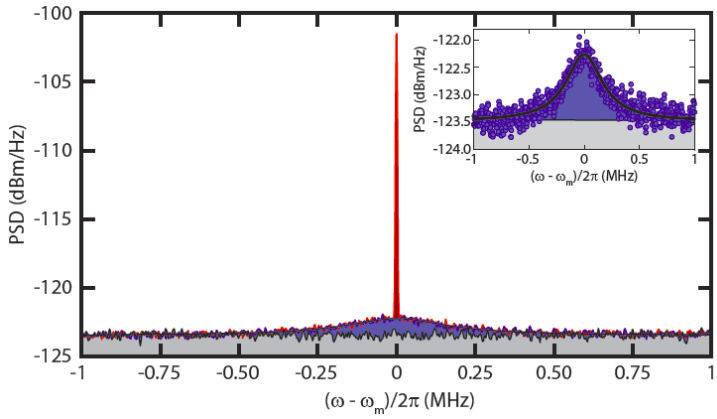
$\lambda_1 \approx 1460$ nm

$\lambda_2 \approx 1545$ nm



Optical-to-optical □-conversion: noise

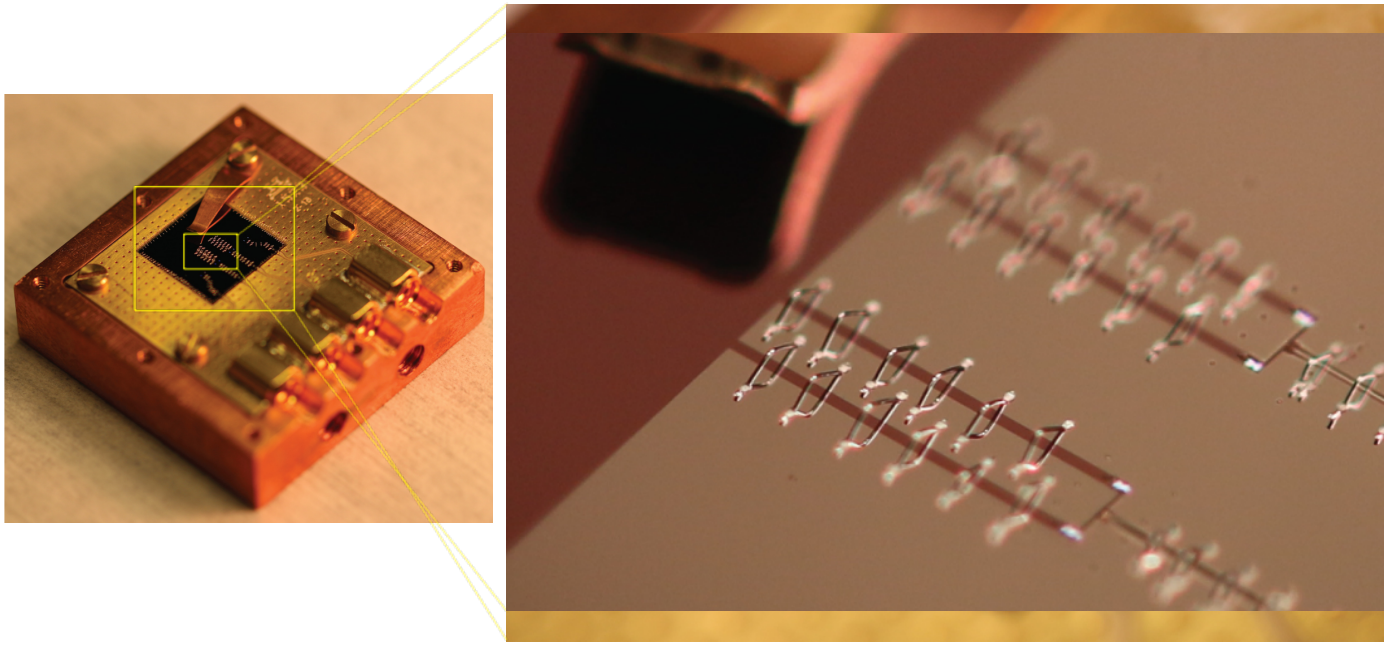




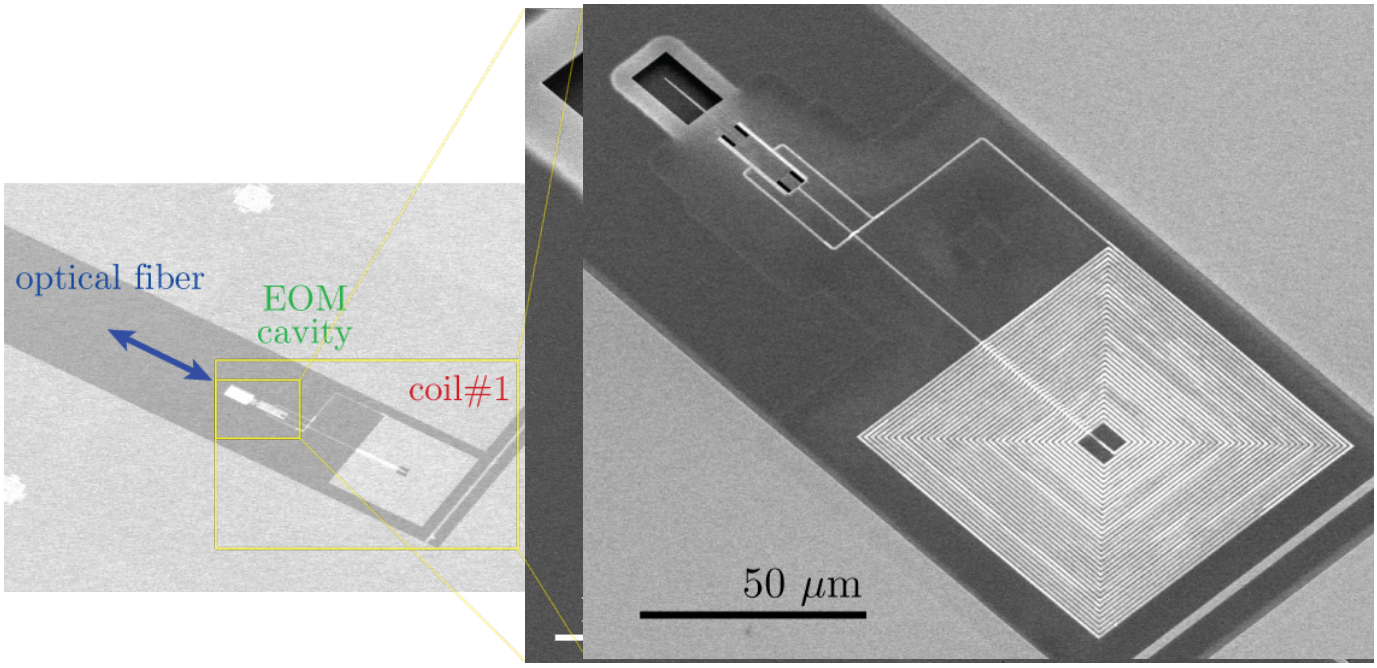
$$n_{\text{added}} = 2\eta_1^{-1}\left(\frac{\gamma_i n_b}{\gamma} + \frac{1}{2}\left(\frac{\kappa_1}{4\omega_m}\right)^2 + \frac{1}{2}\left(\frac{\kappa_2}{4\omega_m}\right)^2\right)$$

3 2x10-3

Si H-bar: microwave package/circuit



Si H-bar: under the microscope



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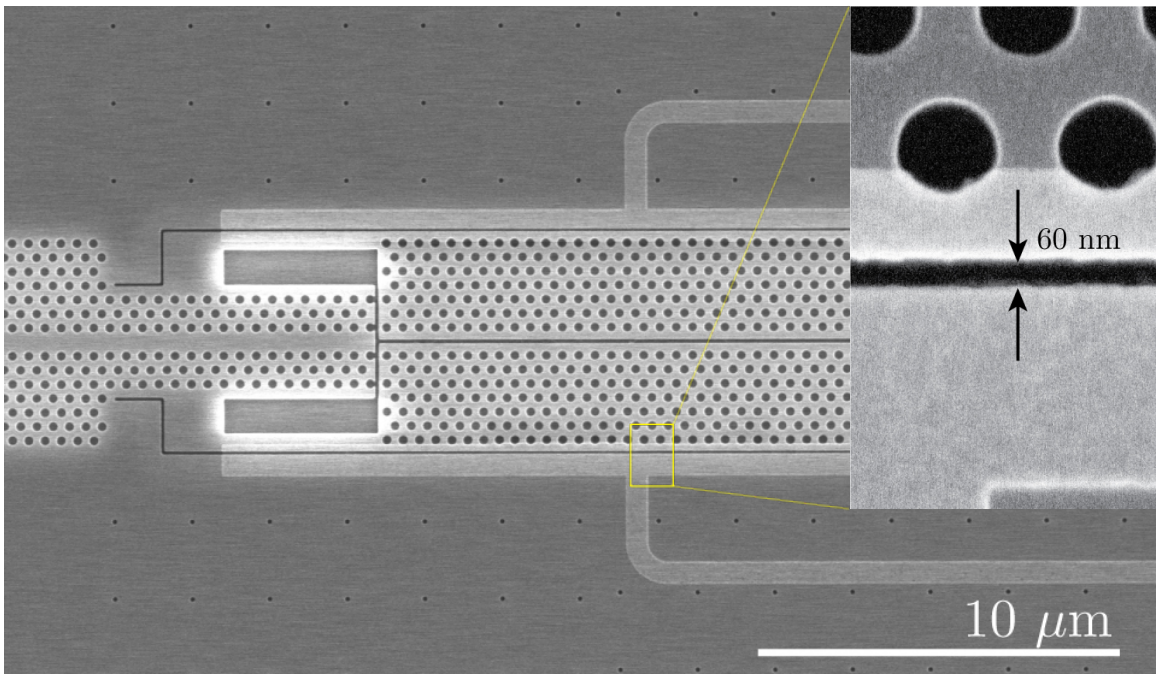
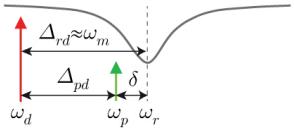
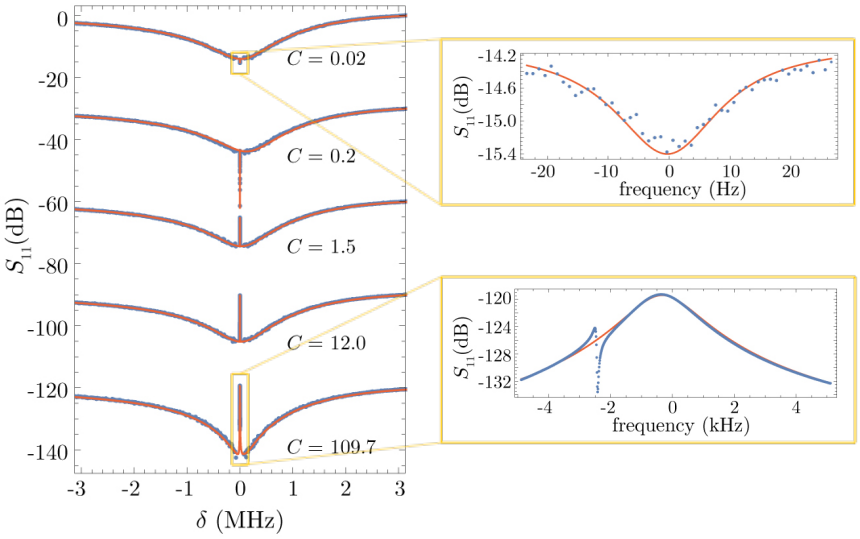
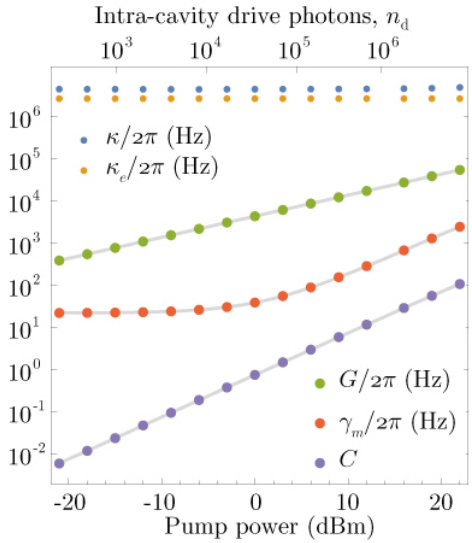


Si H-bar: OMIT spectroscopy

$T_f = 211$ mK







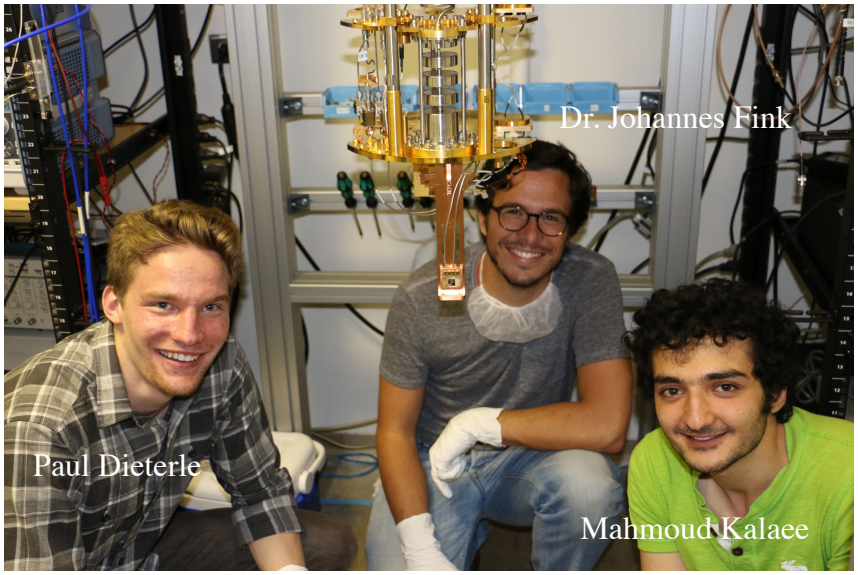
Outlook and Next Steps

1. Efficiency, noise, bandwidth, scalability of quantum optomechanical interface to superconducting circuits

2. SOI looks to be an excellent material for (microwave) electro-opto-mechanical devices
   - mechanical damping in SOI thin-film devices is extremely low @ 10mK ($Qm >$ 107; f-Q product ~ 1017)
   - GHz-frequency mechanical occupancy is ≤ 0.02 @ 10mK (in the dark)
   - microwave resonator Q ~106 on high resistivity Si

3. Monolithic integration of phononic+photonic crystals with transmon-like qubits in SOI (in progress)
   - characterize electro-mechanics
   - redesign of optics to obtain large optomechanical coupling

Acknowledgments



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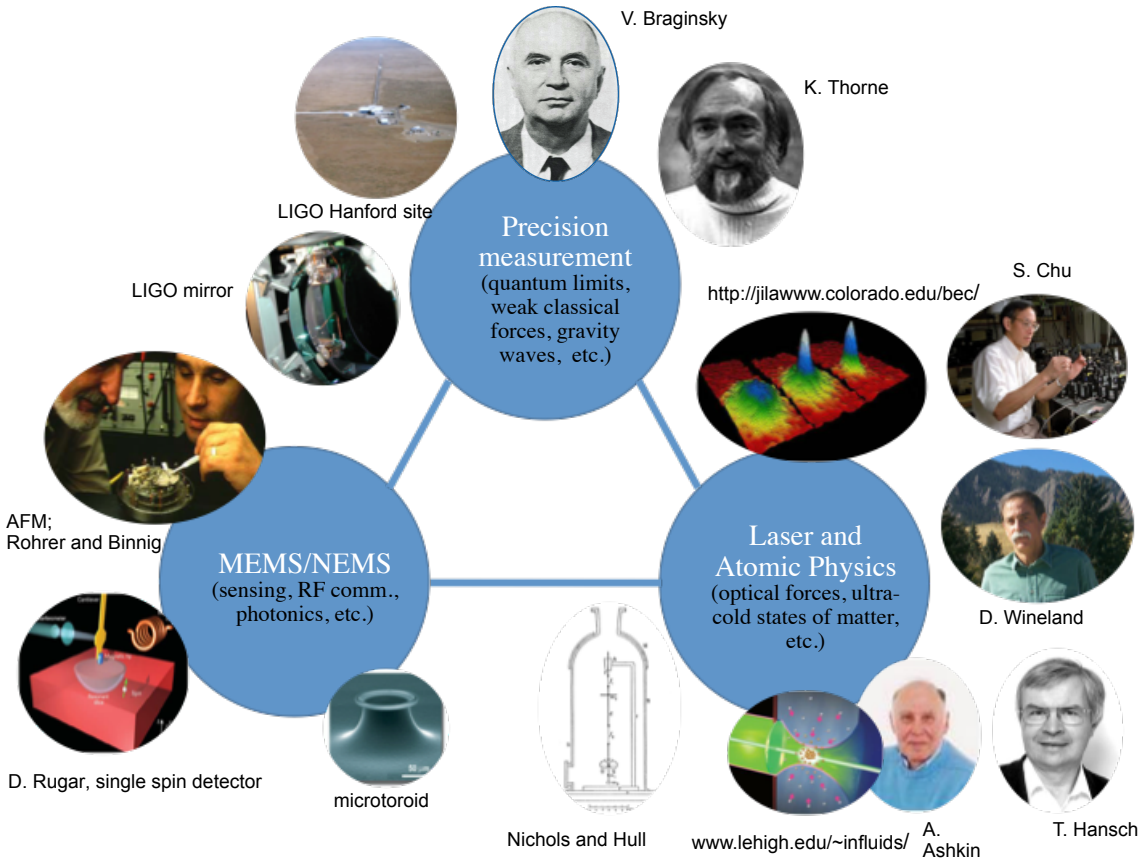
Prof. Darrick Chang (ICFO)
Prof. Amir Safavi-Naeini (Stanford)
Prof. Florian Marqaurdt (Erlangen)
Prof. Marko Loncar (Harvard)
Prof. Misha Lukin (Harvard)

Back-up slides

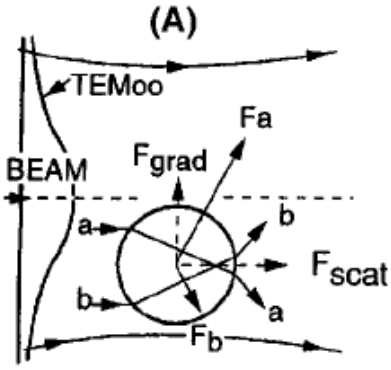

V. Braginsky
K. Thorne
LIGO Hanford site
Precision measurement
(quantum limits, weak classical forces, gravity waves, etc.)
LIGO mirror
S. Chu
http://jilawww.colorado.edu/bec/
AFM;
Rohrer and Binnig
MEMS/NEMS
(sensing, RF comm., photonics, etc.)
Laser and Atomic Physics
(optical forces, ultra-cold states of matter, etc.)
D. Wineland
D. Rugar, single spin detector
microtoroid
Nichols and Hull
www.lehigh.edu/~influids/
A. Ashkin
T. Hansch

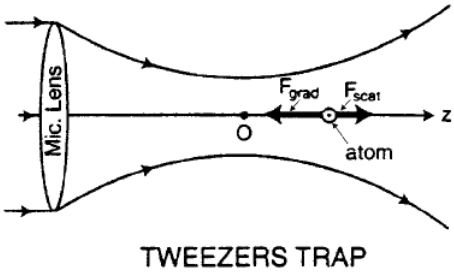
Optical (Laser) Forces

IEEE JOURNAL ON SELECTED TOPICS IN QUANTUM ELECTRONICS, VOL. 6, NO. 6, NOVEMBER/DECEMBER 2000 841

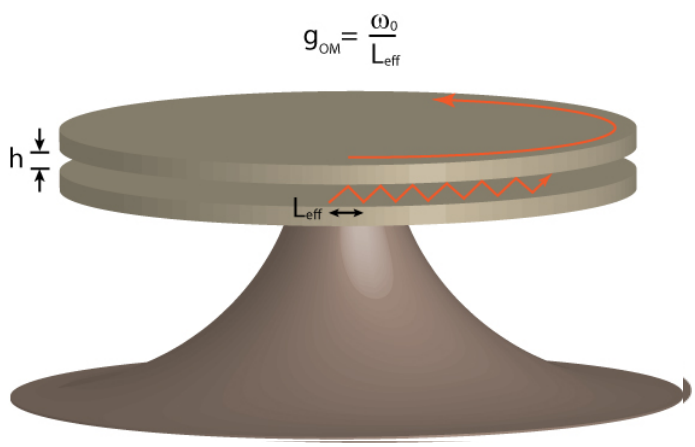
History of Optical Trapping and Manipulation of Small-Neutral Particle, Atoms, and Molecules

A. Ashkin, *Life Fellow, IEEE*





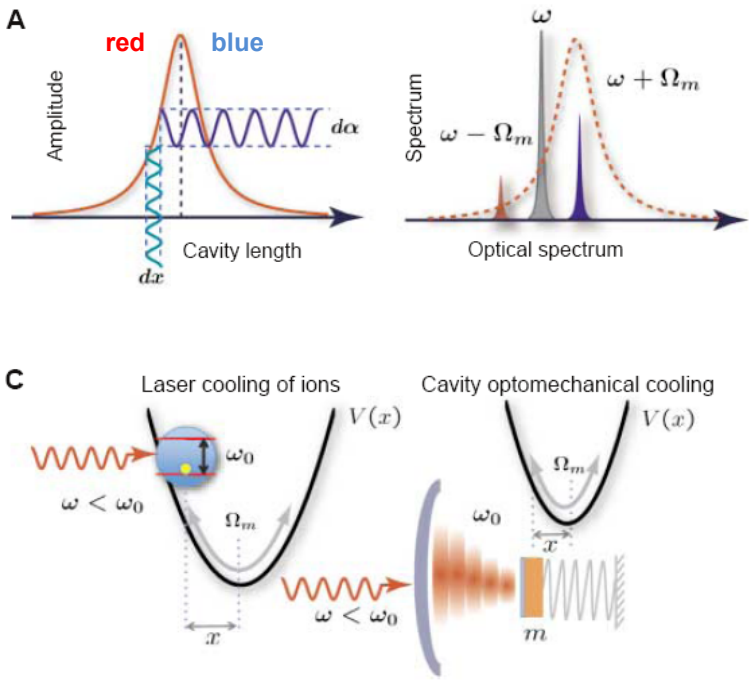
scattering versus gradient forces



cavity length (mechanical mass) and per-photon force are decoupled

Cavity-Optomechanics: dynamical back-action

Cavity Optomechanics: Back-Action at the Mesoscale
T. J. Kippenberg, *et al.*
Science **321**, 1172 (2008);
DOI: 10.1126/science.1156032



Continuous position measurement perspective

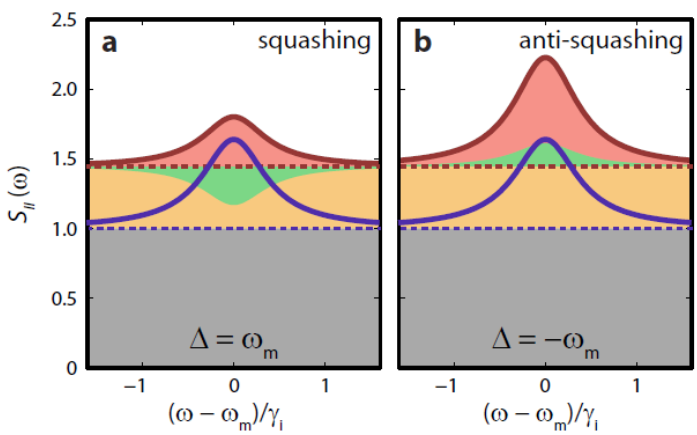
Laser noise in cavity-optomechanical cooling and thermometry

Amir H. Safavi-Naeini[1], Jasper Chan[1], Jeff T. Hill[1], Simon Gröblacher[1,2], Haixing Miao[3], Yanbei Chen[3], Markus Aspelmeyer[4], Oskar Painter[1]

$$\hat{I}(t)|_{\Delta=\omega_m} = -i\hat{a}_{\rm in}(t) + i\hat{a}^\dagger_{\rm in}(t) + \frac{2G}{\sqrt{\kappa}}(\hat{b}(t) + \hat{b}^\dagger(t))$$

$$S_{II} = 1 + \text{const} \times \langle \hat{x}^2 \rangle$$

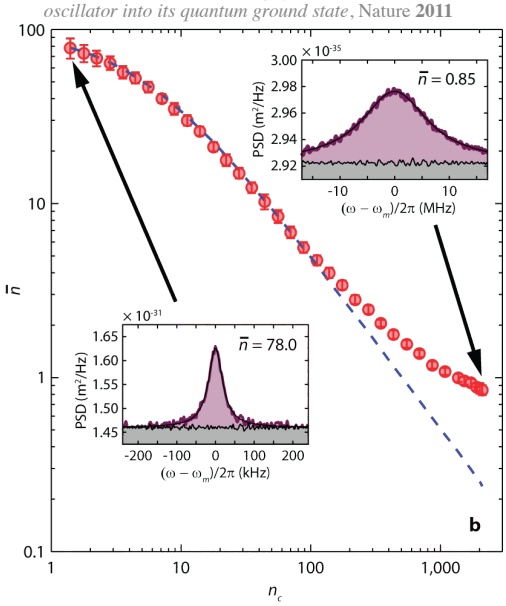
$$S_{zF} \neq 0 \rightarrow \quad S_{II} = 1 + \text{const} \times \langle \hat{n} \rangle$$



1D-OMC experiments…

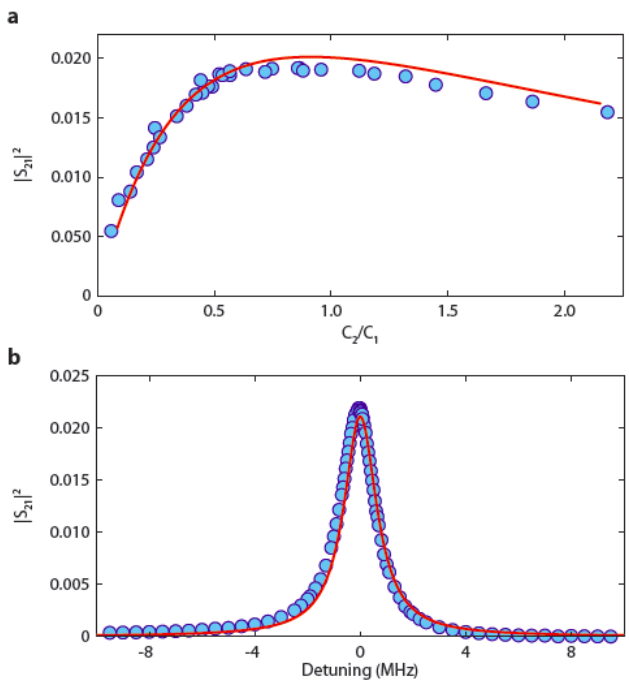
- Electromagnetically induced transparency/amplification ($\langle \bar{n} \rangle_{\min} = 0.85 \pm 0.09$) slow light [1]
  - Optical delay ~50 ns (advance ~1.4 μs)
- Ground-state cooling [2]
  -
- Quantum zero-point motion [3]

[2] Chan *et al.*, *Laser cooling of a nanomechanical oscillator into its quantum ground state*, Nature **2011**



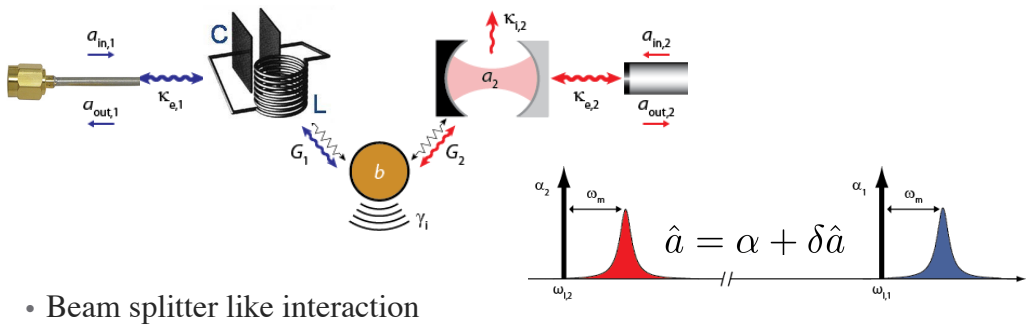
[1] Safavi-Naeini, Alegre *et al.* *Electromagnetically Induced Transparency and Slow Light with Optomechanics*, Nature **2011**
[3] Safavi-Naeini *et al.*, *Observation of quantum motion of a nanomechanical resonator*, Phys. Rev. Lett. **2012**
[4] H[illegible] *coherent wavelength conversion via cavity-optomechanics*, Nature Communications **2012**
[5] [illegible] *ized light from a Silicon micromechanical resonator*, in press **2013**

Optical-to-optical -conversion: conversion efficiency



- Inter-conversion of photons with difference frequency of 11 THz using 4GHz mechanical mode
- Maximum quantum (external) conversion efficiency is 93%

Microwave-to-optical conversion



- Beam splitter like interaction

$$\hat{H}_{\rm int} = \hbar G_1(\hat{a}_1^\dagger \hat{b} + \hat{a}_1 \hat{b}^\dagger) + \hbar G_2(\hat{a}_2^\dagger \hat{b} + \hat{a}_2 \hat{b}^\dagger)$$

$$G_k = g_k \sqrt{n_{c,k}}$$

- Conversion efficiency $\eta_{\rm max,int} = \frac{4C_1C_2}{(1+C_1+C_2)^2}$

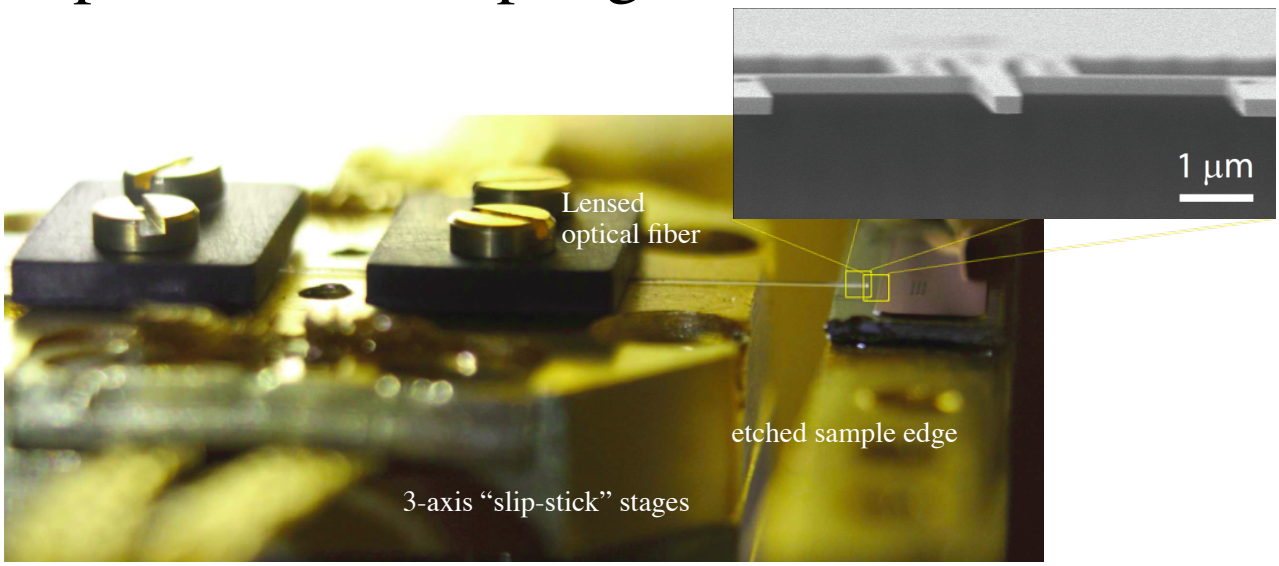
$$C_k = \gamma_{{\rm OM},k}/\gamma_{\rm i} \qquad \gamma_{{\rm OM},k} = 4G_k^2/\kappa_k$$

Beat losses: $C_1 \; C_2 \gg 1$

Impedance match: $C_1 = C_2$

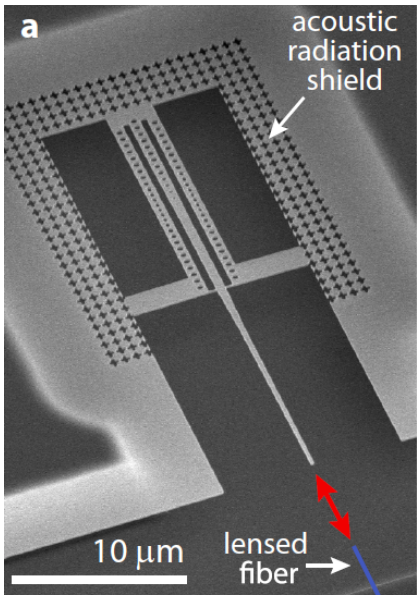
Safavi-Naeini, A. H. *et al*., NJP **13**, 013017 (2011); Wang, Y. and Clerk, A., PRL **108**, (2012); Hill, J. T. *et al*., Nat. Commun. **3**, (2012)

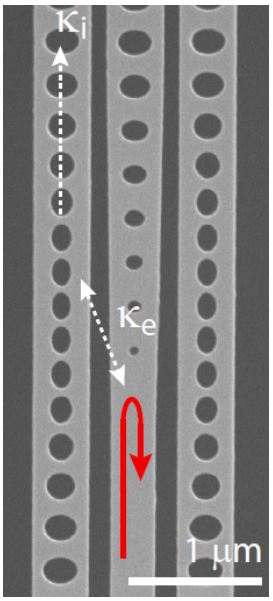
Optical fiber coupling in a DF

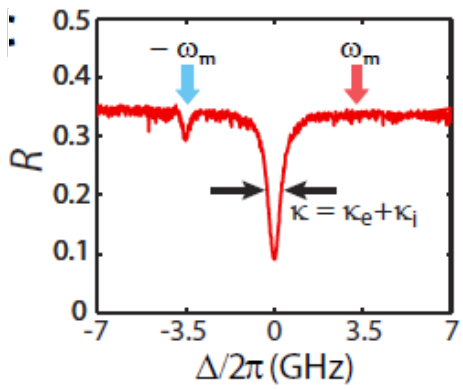


- fiber lens: w.d. = 14 μm, spot size = 2.5 μm
- on-chip tapered waveguide for mode matching

Optical fiber coupling in a DF

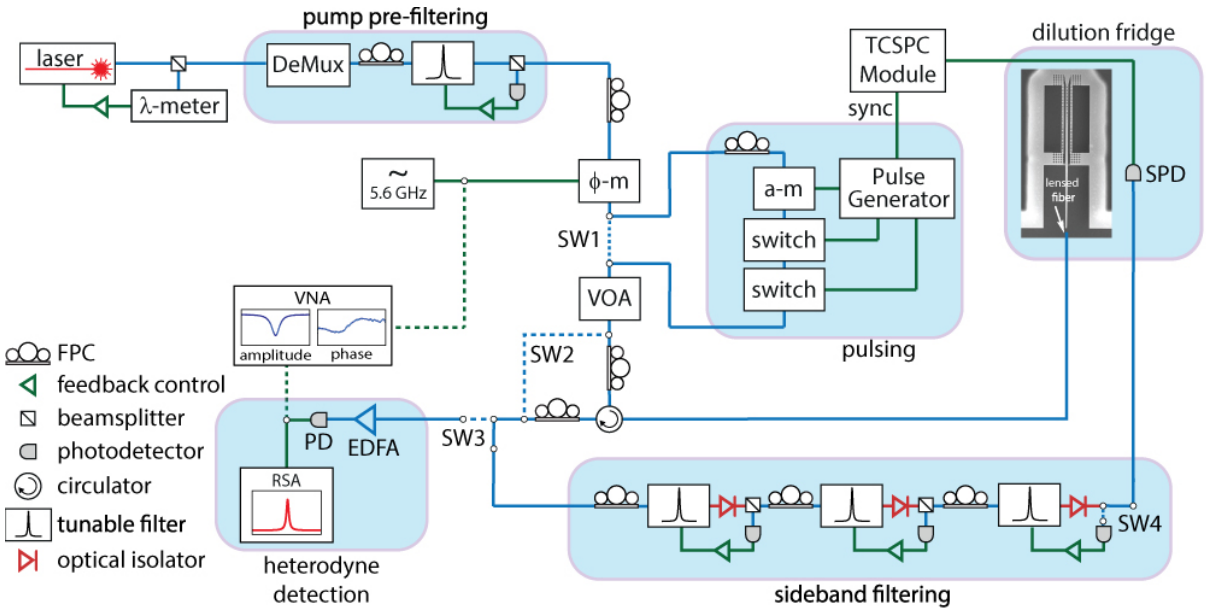






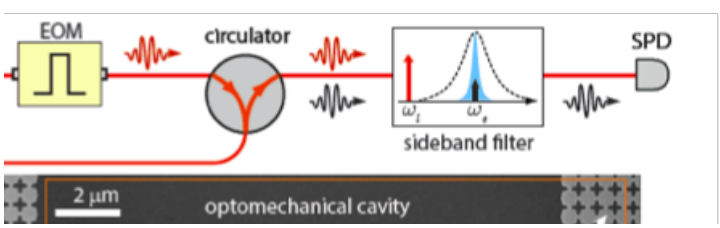
- η cpl, th. = 0.6-0.7
- η cpl, th., opt. = 0.95
- η cpl, meas. = 0.55-0.6

Pulsing and phonon counting set-up



Pulsed measurements

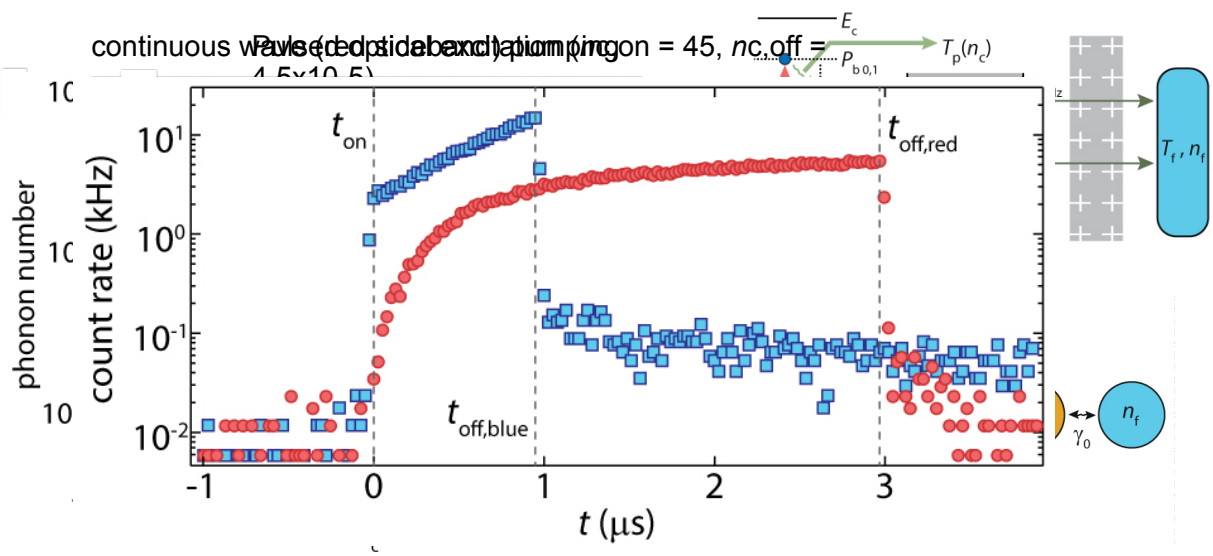
- pump pulses, Δt = 0.1-3 μs; pulse period, Tper = 5ms
- time bin (resolution) ~25 ns, much shorter than both thermal and back-action time constants



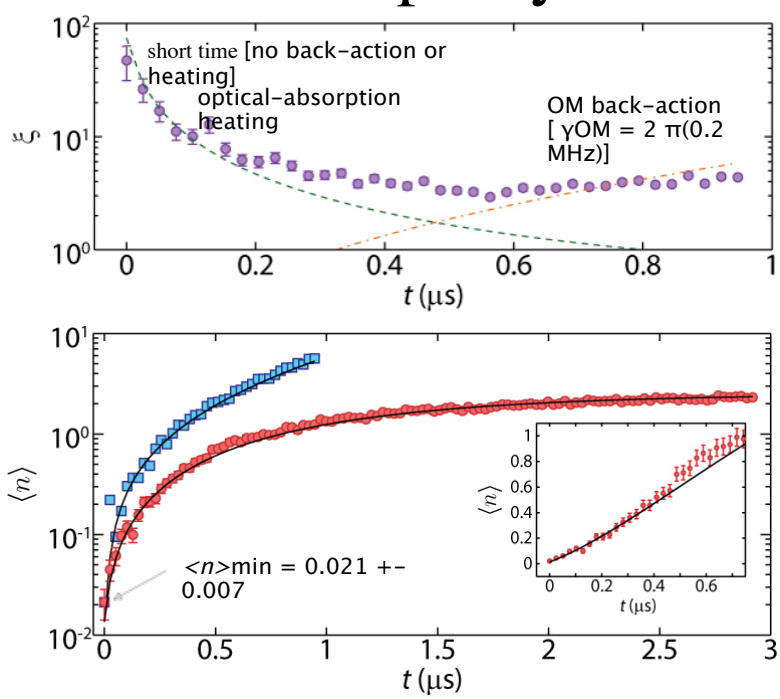
- $\kappa/2\pi = 443$ MHz
- $\kappa_e/2\pi = 221$ MHz
- $g_0/2\pi = 0.71$ MHz
- $\omega_m/2\pi = 5.6$ GHz
- $n_{c,\mathrm{on}} = 45$
- $\gamma_{\mathrm{OM,on}}/2\pi = 205$ kHz
- $n_{c,\mathrm{off}} \approx 4.5 \times 10^{-5}$

Pulsed measurements

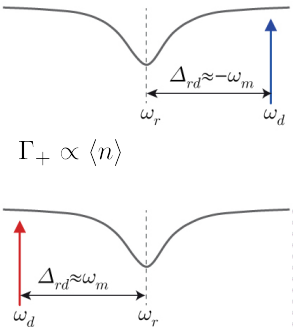
- pump pulses, Δt = 0.1-3 μs; pulse period, Tper = 5ms
- time bin (resolution) ~25 ns, much shorter than both thermal and back-action time constants



Phonon occupancy calibration

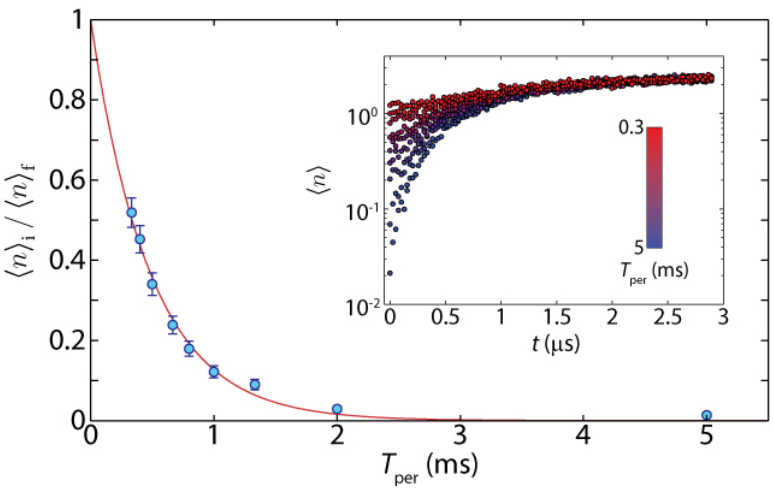


$\Gamma_- \propto \langle n \rangle + 1$



- $\Gamma_\pm \equiv$ sideband photon scattering rate for $\Delta = \pm\omega_m$
- $\Gamma_+ \propto \langle n \rangle$
- $\Gamma_- \propto \langle n \rangle + 1$
- $\xi \equiv \Gamma_-/\Gamma_+ - 1$
- heating, no back-action: $\xi(t) = \langle n \rangle^{-1}(t)$
- back-action, $n_\mathrm{b} \gg 1$: $\xi(0) = n_\mathrm{b}^{-1} \approx 0$

Mechanical damping (in the dark)



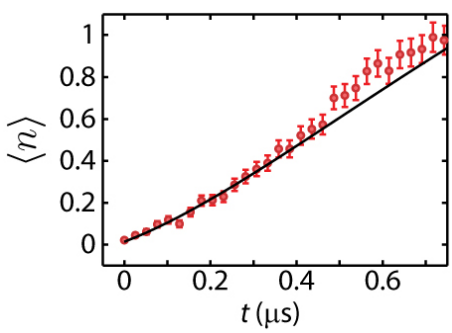
- $\gamma_0/2\pi = 328 \pm 14$ Hz ($Q_m = 1.7 \times 10^7$, f-$Q \approx 10^{17}$)
- $\tau_{\rm th} = (\gamma_0(1 + \langle n \rangle_{\rm min}))^{-1} = 475 \pm 21\ \mu$s

- Frequency jitter of the mechanical mode makes spectral measurement of the energy damping rate difficult
- Optical absorption heating also adds an additional damping bath (γp)
- Pulsed ring down measurements solve both problems as:

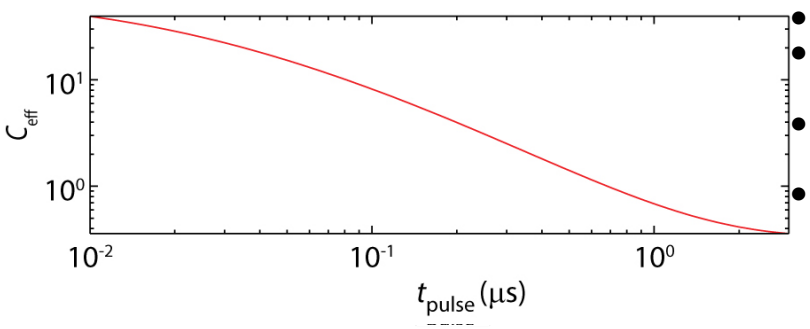
$$\langle n \rangle_{\rm i} = e^{-\gamma_0 T_{\rm per}} \langle n \rangle_{\rm f}$$

with mechanical damping occurring during pulse-off period

Optical-absorption-induced bath

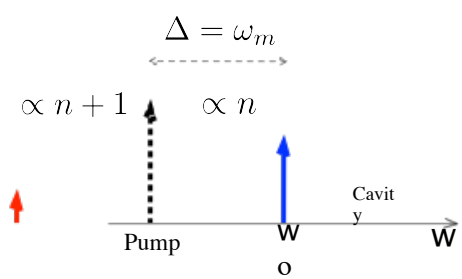


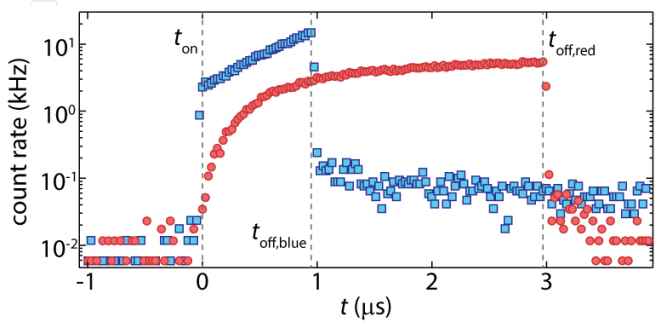
- $\langle \dot{n} \rangle = -\gamma \langle n \rangle + \gamma_{\mathrm{p}} n_{\mathrm{p}} (1 - \delta_{\mathrm{b}} e^{-\gamma_{\mathrm{s}} t})$
- $\gamma = \gamma_{\mathrm{OM}} + \gamma_{\mathrm{p}} + \gamma_0$
- $\delta_{\mathrm{b}} = 0.79 \pm 0.08$
- $\gamma_{\mathrm{s}}/2\pi = 215 \pm 29$ kHz



- *C*eff ≡ *C*/*n*b
- γb*n*b ≡ γ0*n*f + γp*n*p ; γb ≡ γ0 + γp
- *C*eff > 1 for *t*pulse < 300ns
- Pulsed phonon-to-photon conversion and high fidelity mechanical state preparation possible

Sideband photon counting



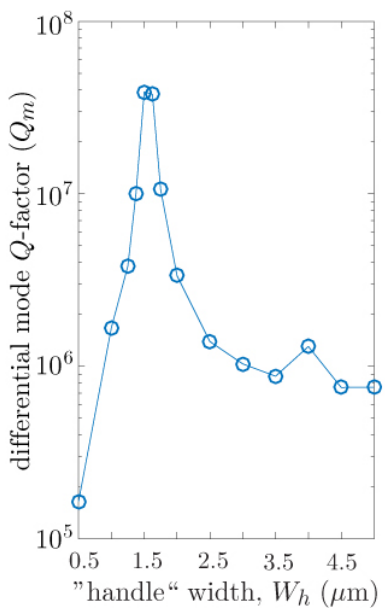


- Optical filtering and photon counting of motionally generated sidebands can be used to measure either phonon emission or absorption process
- Vacuum noise not detected
- Absolute thermometry can be performed by measuring sideband asymmetry
- **Creation and heralding of non-Gaussian mechanical states (one-phonon state), entanglement of mechanical systems, etc.**

Challenges:

- Requires extra filtering of pump beam (cavity not enough)
- Still susceptible to technical laser noise (excess sideband photons)

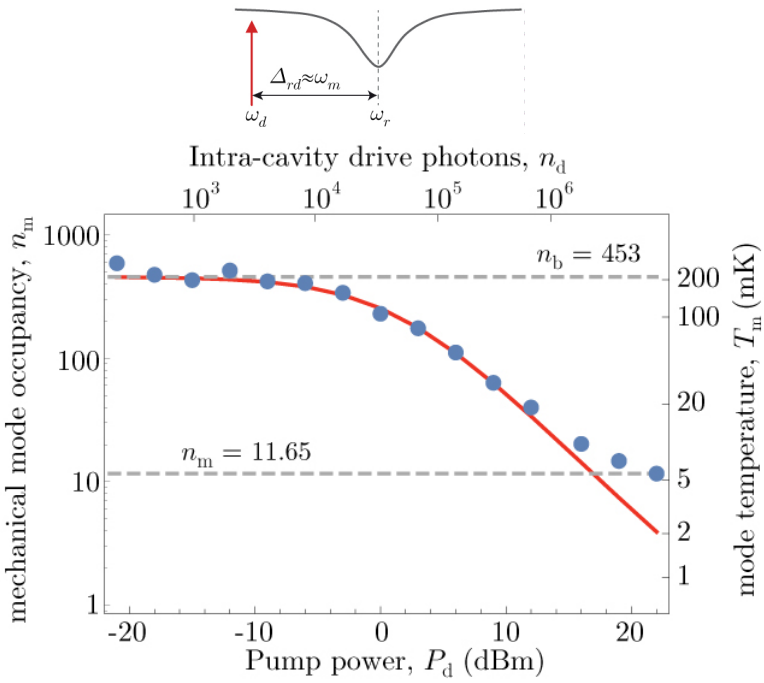
Si H-bar: mechanical design



- $m_{\text{eff}} \equiv$ motional mass $= 39.5$ pg
- $\omega_m/2\pi = 10$ MHz
- $x_{\text{ZPF}} = 4.4$ fm
- $Q_{m,\text{max}} = 3.7 \times 10^7$

Si H-bar: back-action cooling

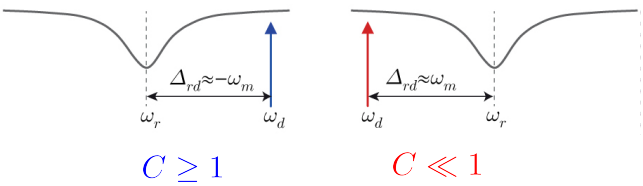
$T_f = 211$ mK



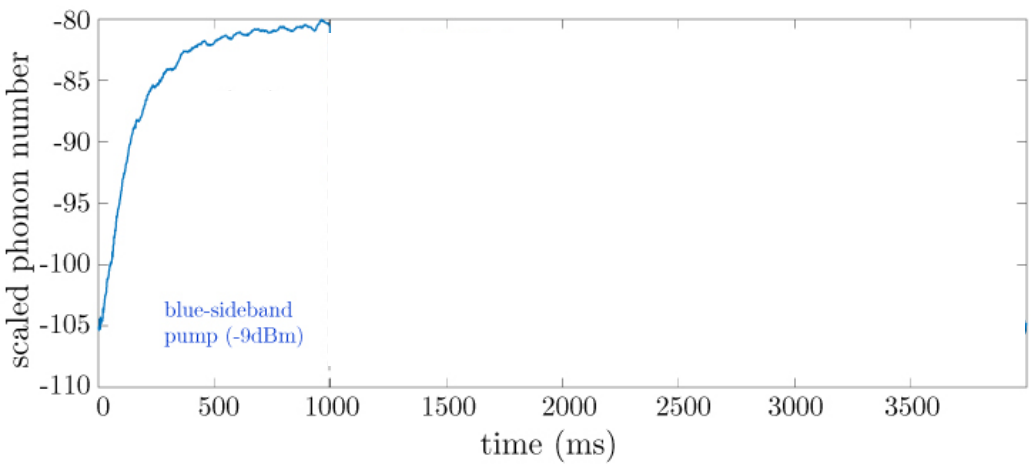
- At *Tf* = 211mK behavior of back-action cooling is well behaved.
- *Q* = 5x105 at *Tf* = 211mK.
- At *nd* > 106 we see heating of the resonator, and for *nd* > 107 the *LC* resonator goes normal.
- There is a saturation in the back-action cooling at high power that we don't understand yet.
- For *Tf* = 11mK we see anomalous "heating" even at *nd* ~ 10 photons.

Si H-bar: mechanical ring down

$T_f = 11$ mK

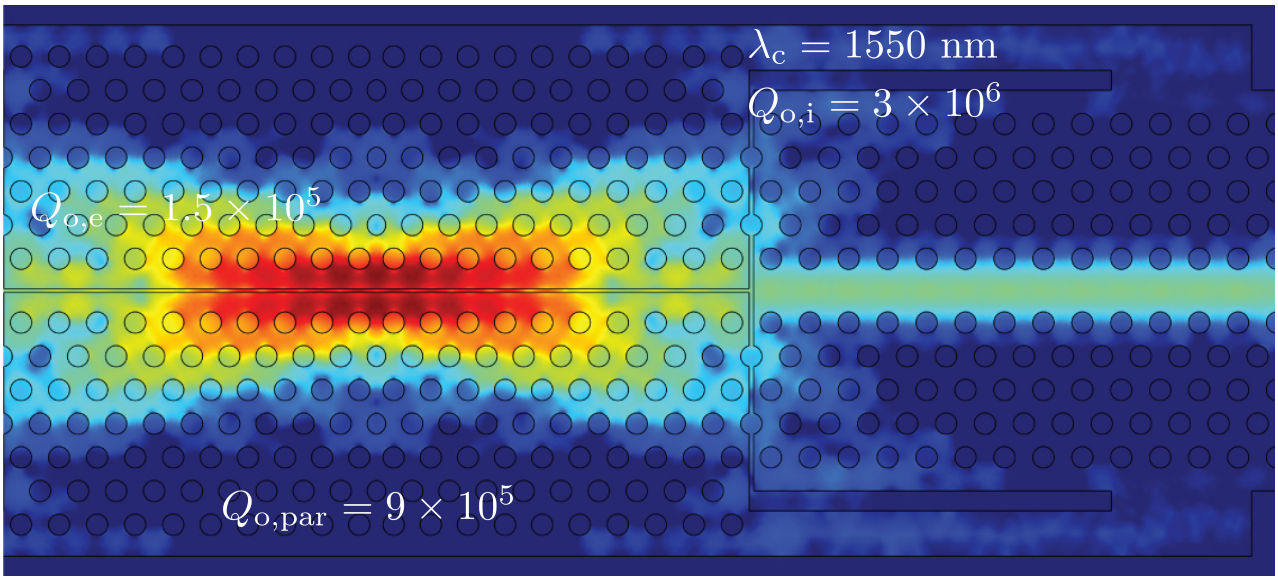


- $Q_m = 1.38 \times 10^7$ @ $T_\mathrm{f} = 11$ mK
- $g_{0,\mathrm{cm}}/2\pi = 25.5$ HZ [theory $\rightarrow$ 80 Hz]

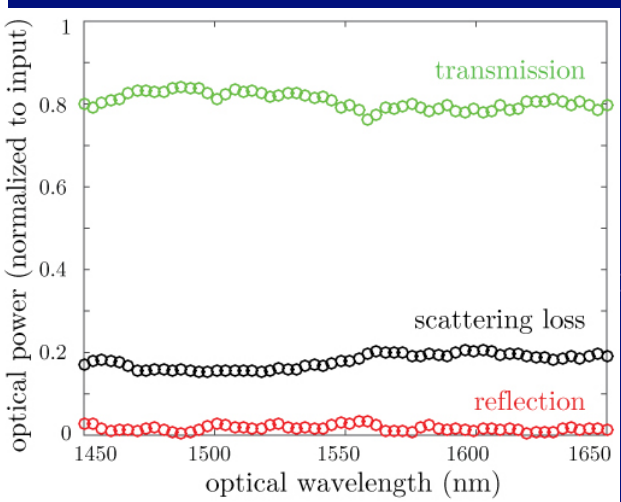


Si H-bar: cavity-to-WG coupling

log10 scale of radiated cavity field



Si H-bar: fiber-to-WG coupling



- $Q_{o,i,\mathrm{th}} \geq 3 \times 10^7$

  $\rightarrow \kappa_{o,i,\mathrm{th}}/2\pi \approx 60$ MHz.
- $\kappa_{o,i,meas.}/2\pi \approx 200$ MHz @ $\lambda_{o,0} = 1550$ nm.
- $Q_{o,e} = 1.5 \times 10^6$ ($Q_p = 9 \times 10^6$)

  $\rightarrow \kappa_{o,e}/2\pi \approx 1.3$ GHz.
- $\eta_{o,\mathrm{coup.}} \equiv$ fiber-to-chip effic. $= 0.8$.
- $\eta_{o,\mathrm{cav}} \equiv$ WG-to-cav effic. $= \kappa_{o,e}/\kappa_{o,i} = 0.85$.