Quantum limits and benefits to metrology

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Atomic, molecular, and optical physics connecting to quantum challenges

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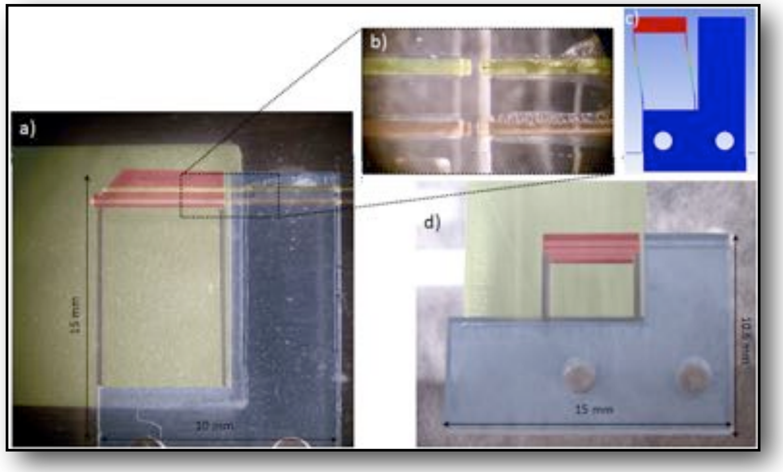
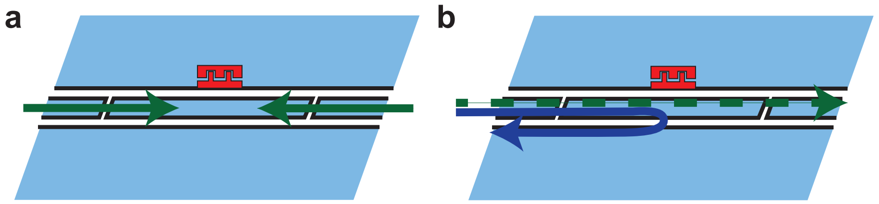
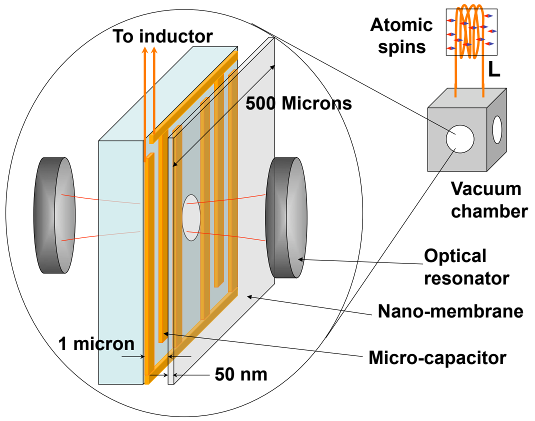
Metrology

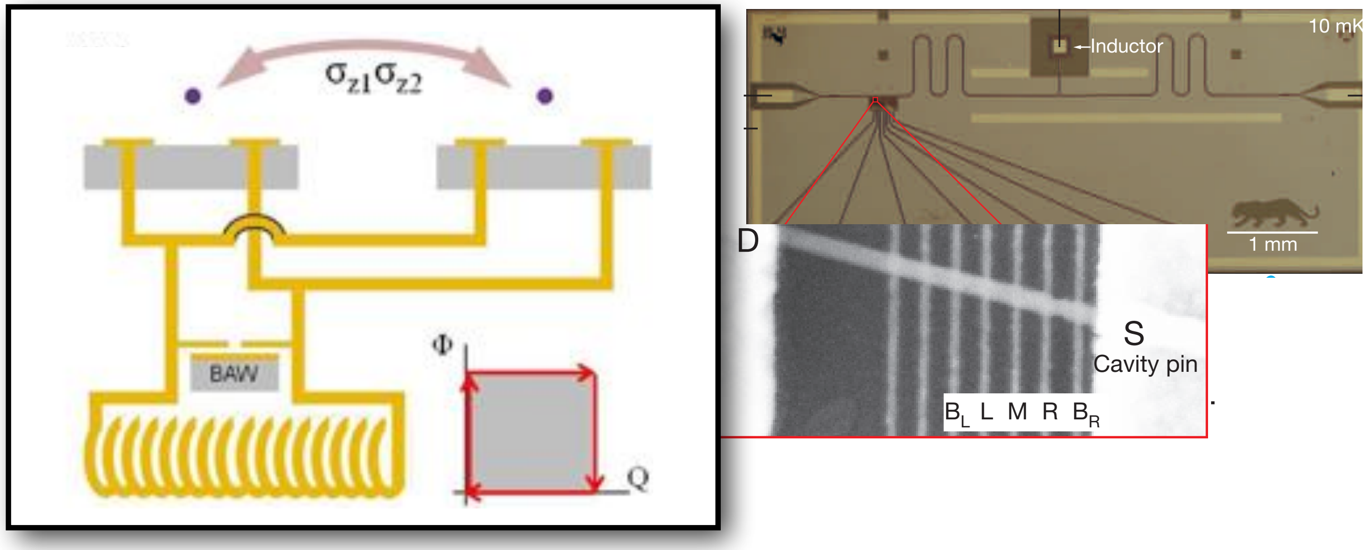


Quantum interfaces and logic

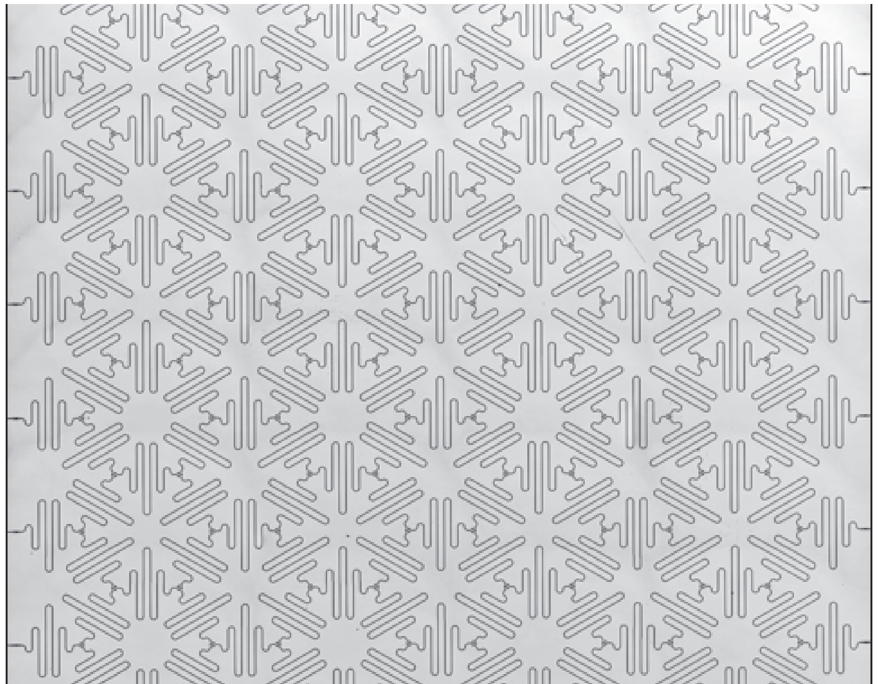




Quantum computation



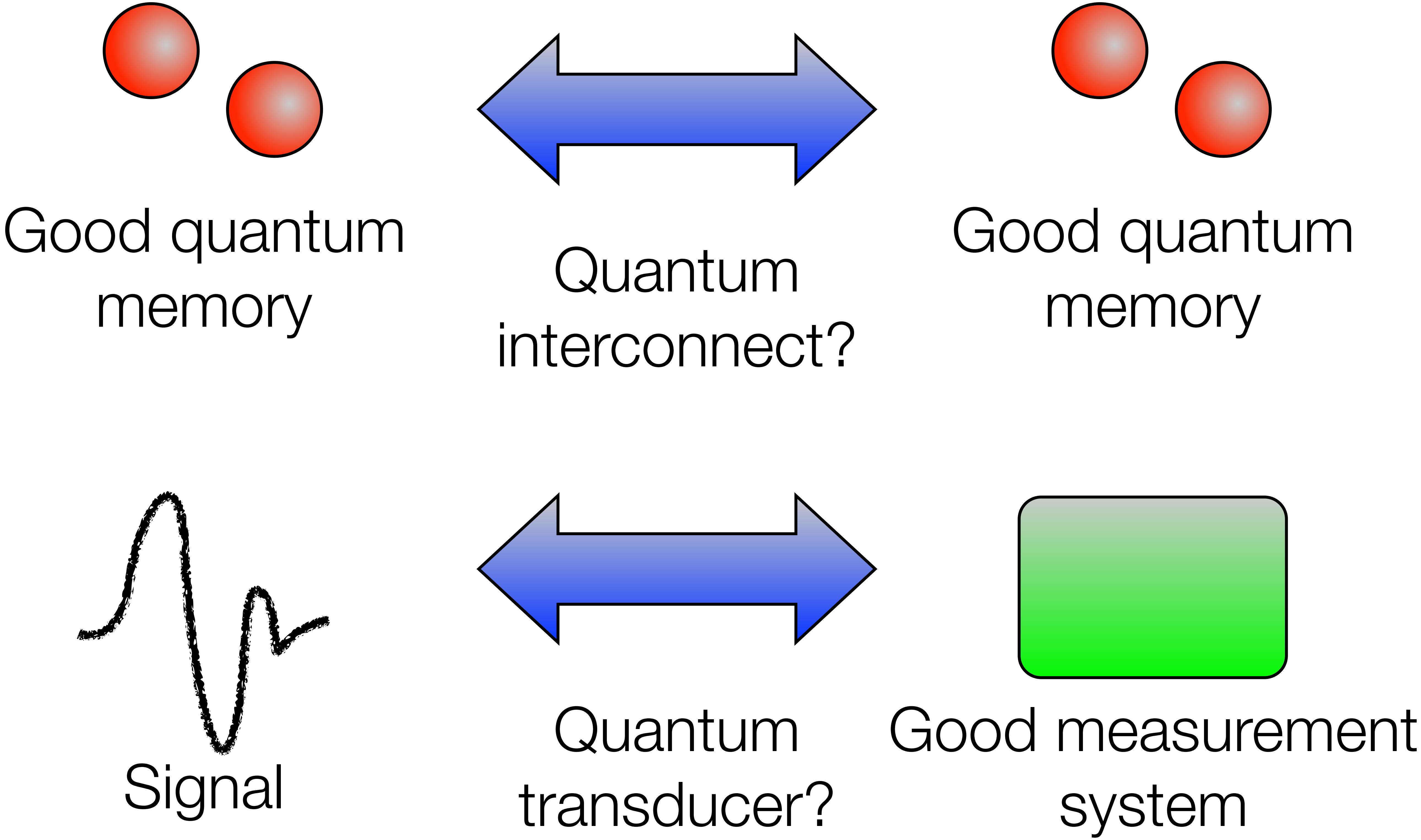
Quantum simulation



The Quantum SI

- Defining quantities based upon fundamental constants and agreed upon physical law, with accepted realizations
- What is quantum about it? Some quantities limited by quantum effects in realization; others determined by single particle quantum physics
- Quantum technology: all of the above… plus using entanglement and multi-body physics to go beyond those limits

Quantum interfaces



Good quantum memory

Quantum interconnect?

Good quantum memory

Signal

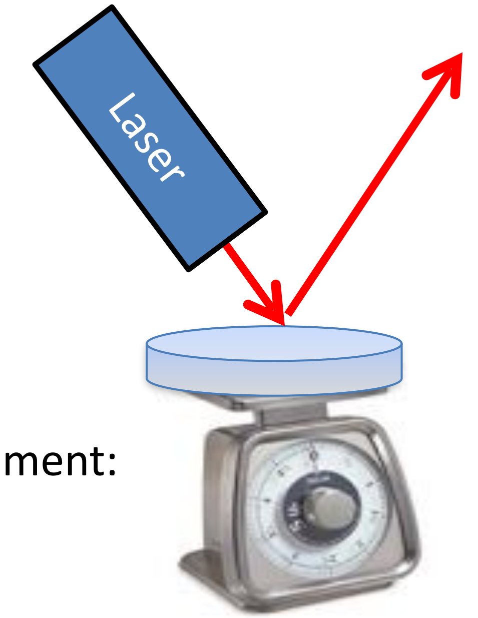
Quantum transducer?

Good measurement system

Optical light as a force

[G. Shaw, J. Lehman, …]

Measurement:



Calibration:

Ways to use optical reference in momentum?

Atom interferometer!

But also…

Each photon bounce induces impulse $\hbar(\vec{k}_{in} - \vec{k}_{out}) \sim \dfrac{2h\nu}{c}$

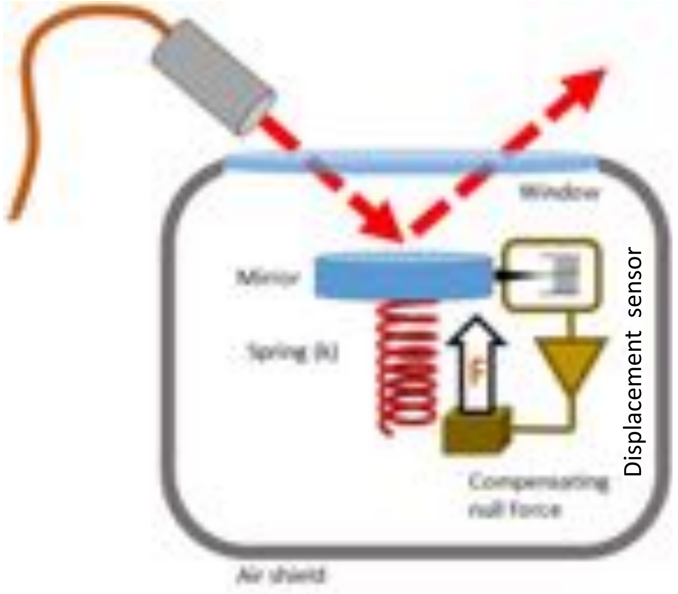
Bounces are (mostly) elastic $E_{\text{recoil}} \sim \dfrac{(\hbar k)^2}{2M} = h\nu \dfrac{2h\nu}{Mc^2}$

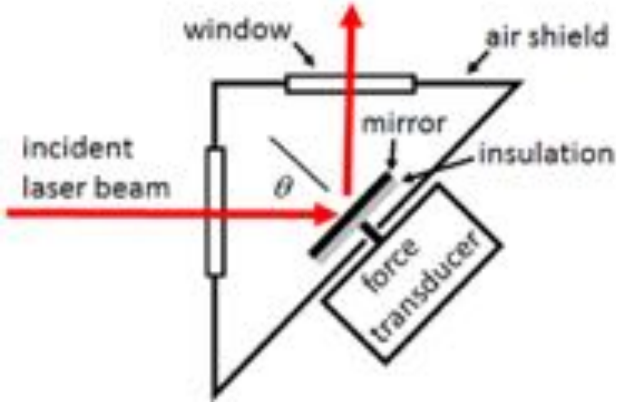
A continuous stream: radiation pressure $F = \dot{N} 2h\nu/c = 2P/c$

Non-demolition measurement of power

“Measure twice, cut once”

John Lehman
Michelle Stephens
Paul Williams
Matt Spidell
Nathan Tomlin
Chris Yung
Brian Simonds
Malcolm White
Thomas Gerrits
Zeus Gutierez (CENAM)
Solomon Woods Ivan Ryger



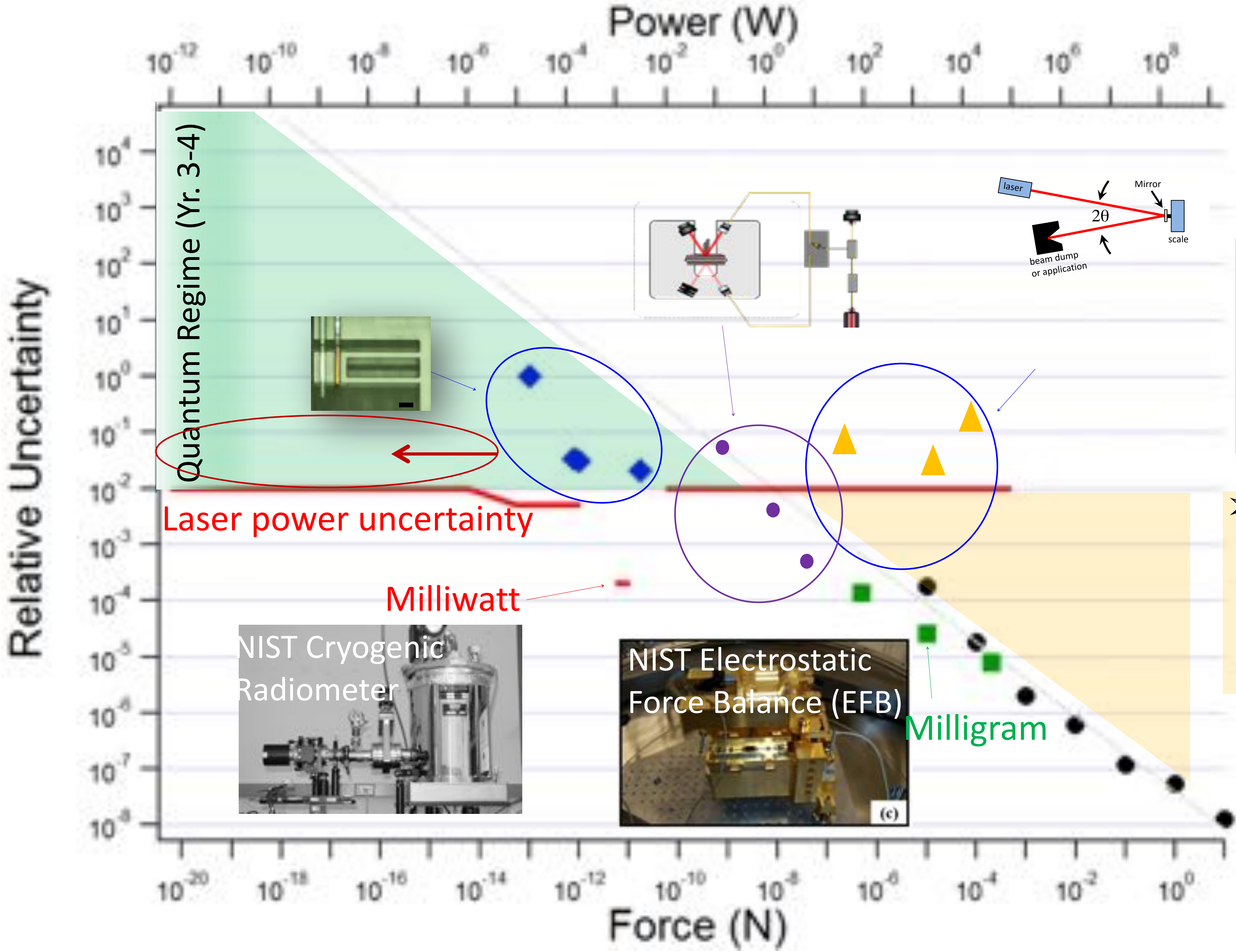


Light bounces off calibrated scale, then can be detected a second time (or used!)

Quantum mechanically:
<> photon number <> force <> displacement <>
measure + feedback

Small Mass and Force: best of both worlds

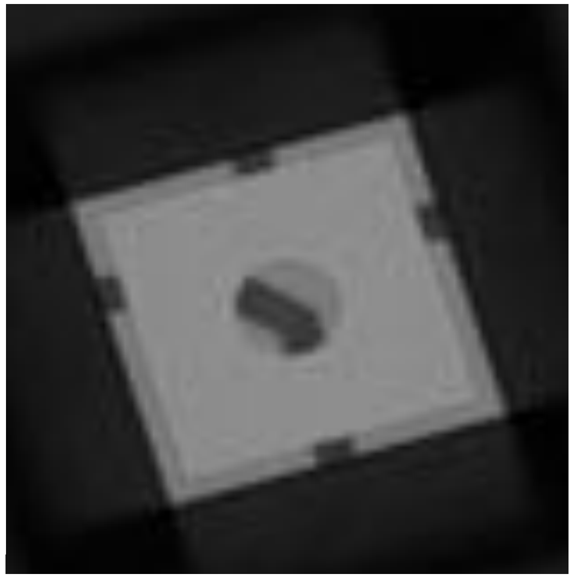
Covered 12 orders of magnitude in force / laser power within the SI



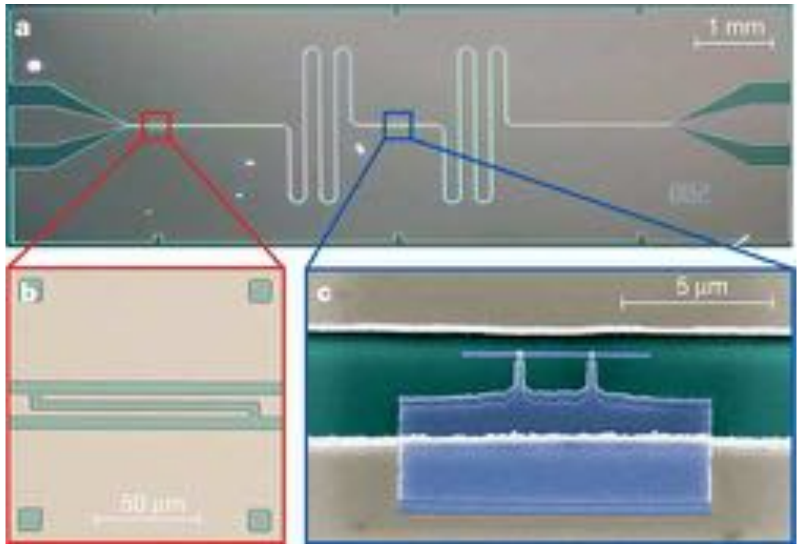
- Laser power calibration improves small force uncertainty
- Mass calibration improves high laser power uncertainty

G. Shaw et al., NIST small force metrology group

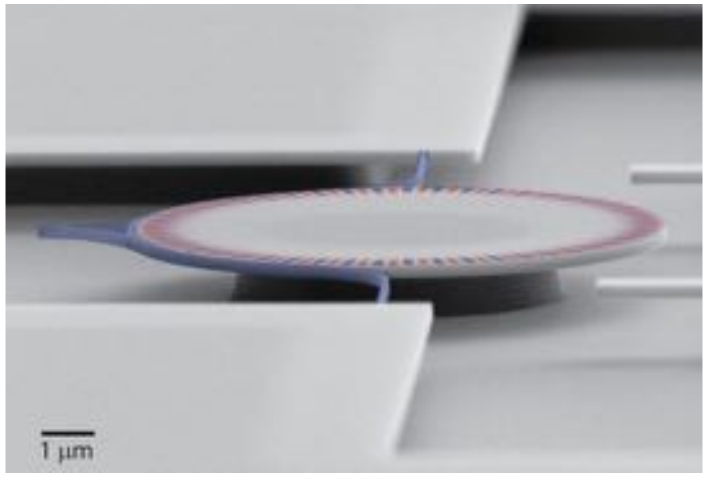
Recent examples of phononic and photonic resonators



Silicon nitride membranes
Harris, Regal, Polzik, …

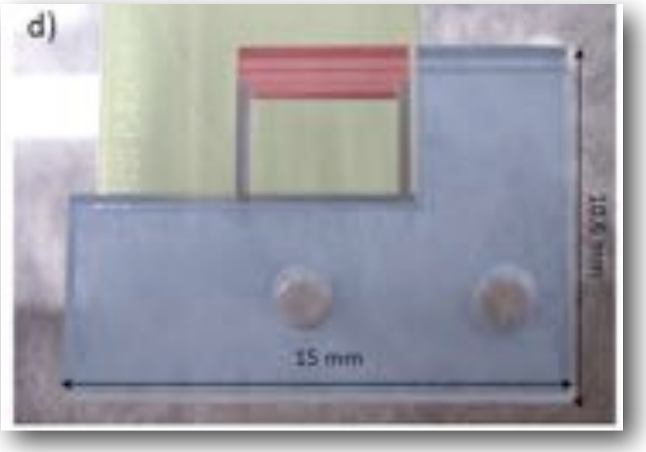


Superconducting strip line resonators
Haroche, Schoelkopf, …

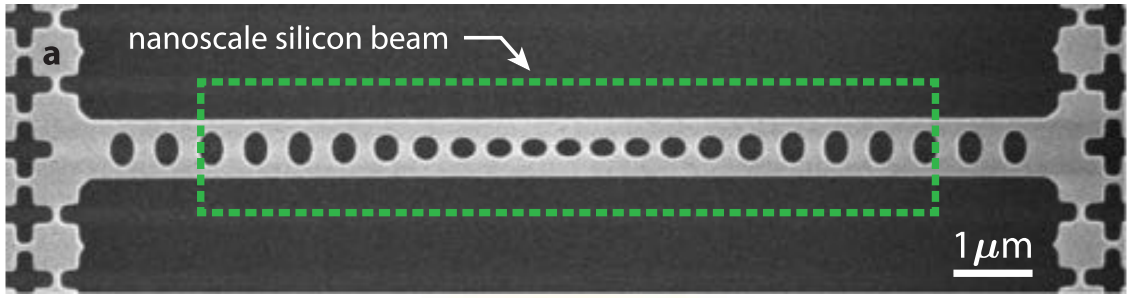


Whispering-galley mode optical resonators
Vahala, Kimble, Srinivasan …

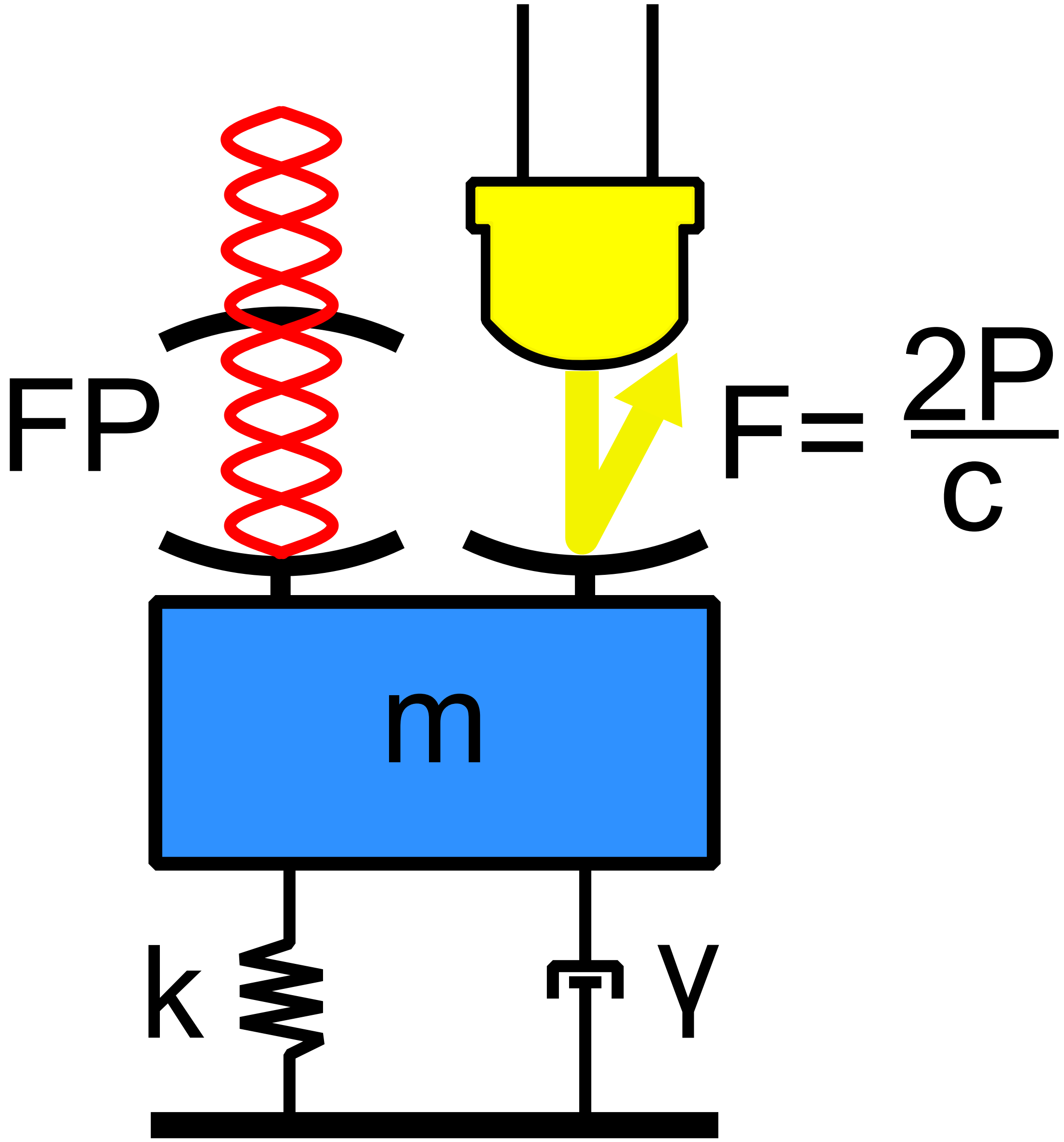
Glass flexures
Pratt, Shaw, JMT…



Photonic-phononic crystals
Painter, Cleland, Tang, …



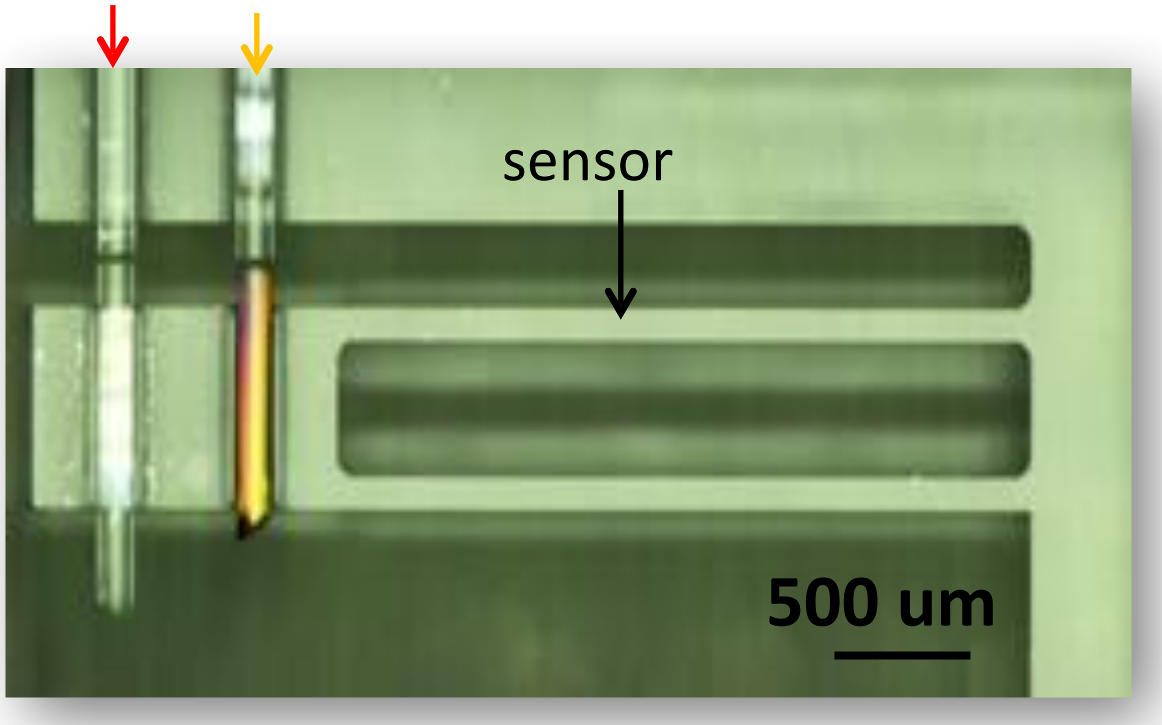
Small force metrology for atomic force microscopy



$$F=\frac{2P}{c}$$

Fabry-Perot Interferometer

Superluminescent diode for photon momentum force



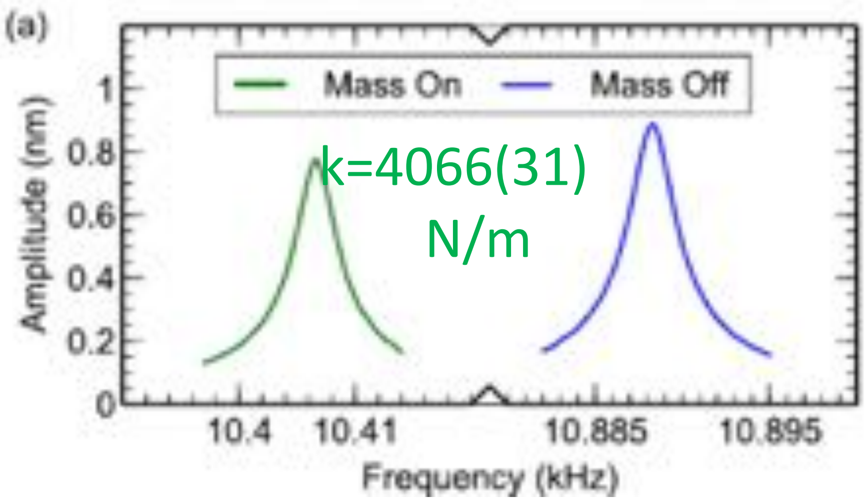
Sensor properties:

- Frequency: ~10.8 kHz
- Stiffness: ~3000 N/m
- Mass: 0.76 mg
- Two v-grooves
  - Fabry-Perot Cavity (displacement)
  - Mirror (photon momentum)

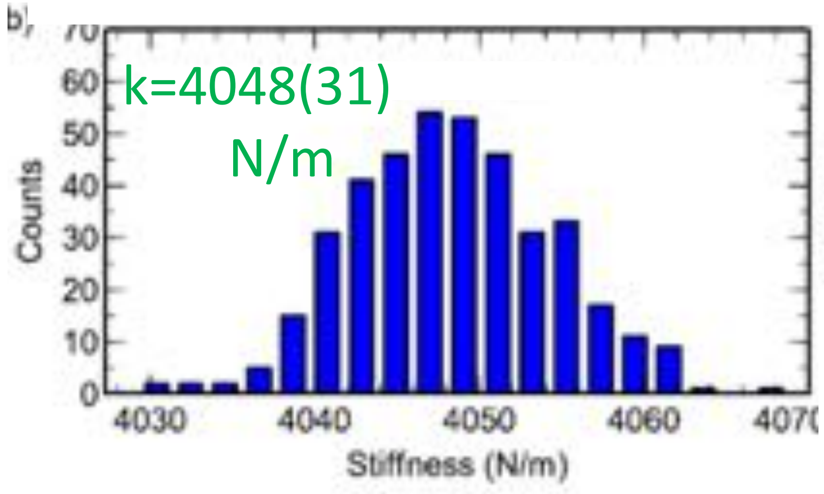
Melcher, et al., *Appl. Phys. Lett.*, 105, 233109 (2014)

Optical measurement of spring constant for calibrated AFM

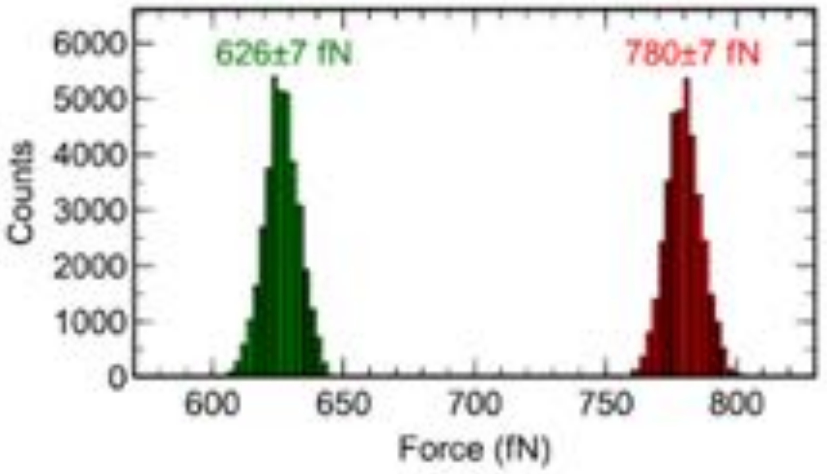
Added mass method



Photon momentum method



Femtonewton Resolution

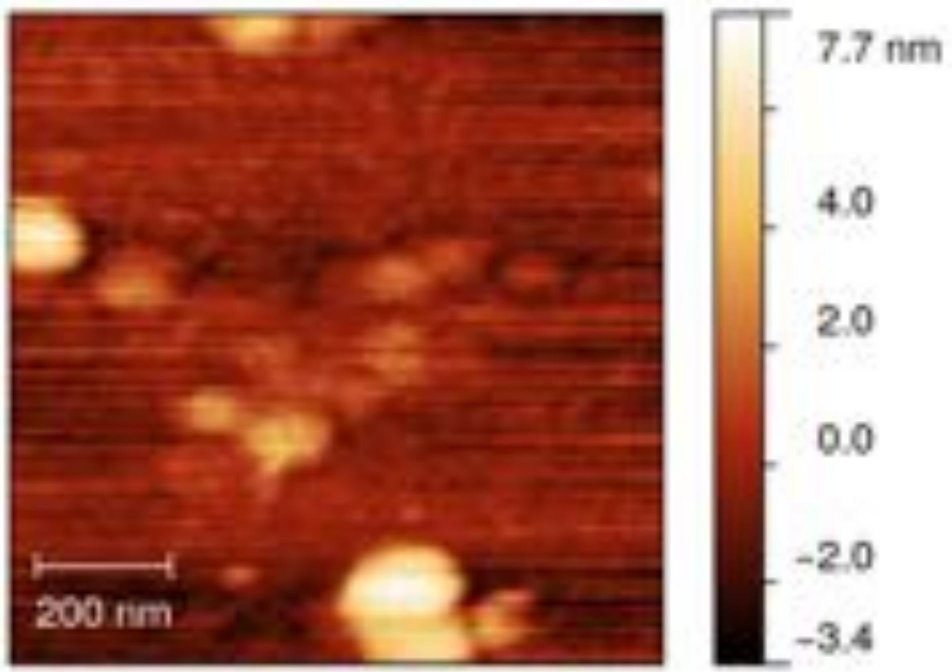


This work links SI mass, force, laser power and frequency in a portable reference device.

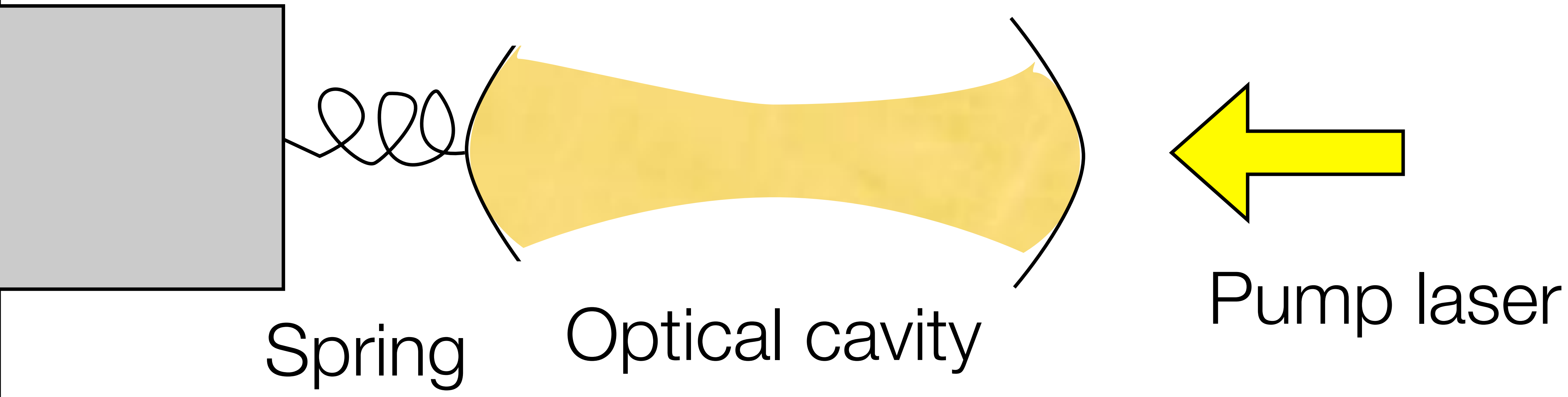
AFM topographical map of an oxidized silicon surface

In Water

In Air



Optomechanics in a cavity: photons coupled to phonons



$$\nu = n\frac{c}{2L}$$

Bounces per second? FSR

Force $\frac{c}{2L}\frac{2h\nu}{c}a^\dagger a = \frac{1}{L}h\nu a^\dagger a$

Adiabatic length change

$$H = h\nu(L)a^\dagger a$$

Frequency shift <> force

$$F = -\partial_L H = h\frac{nc}{2L^2}a^\dagger a = \frac{1}{L}h\nu a^\dagger a$$

From force to position: the harmonic oscillator

Many ways to balance a force… but first,
convert to position

At low frequency, harmonic oscillator displaces adiabatically

$$\Delta x = \frac{F}{M\omega^2} = \frac{a}{\omega^2}$$

For acceleration detection, a frequency-length connection

[F. Guzman-Cervantes et al., Metrologia (2015)]

Estimate position? Interferometry! But it comes with
measurement back action

More generally: transduction, superposition, squeezing…

Measuring at the standard quantum limit

Estimating *x*(*t*) limited by momentum

$$\Delta x(0) =$$

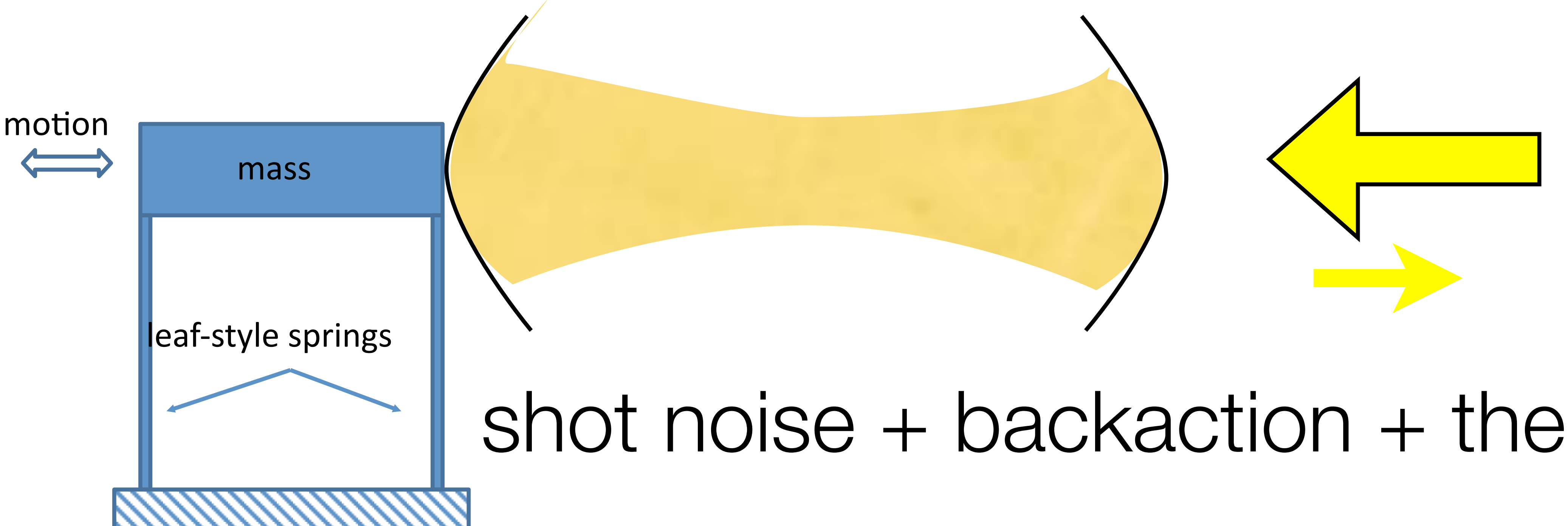
$$) \geq \frac{\hbar t}{2m}$$

↑

shot noise

State-of-the-art:
high enough Q that
backaction matters!

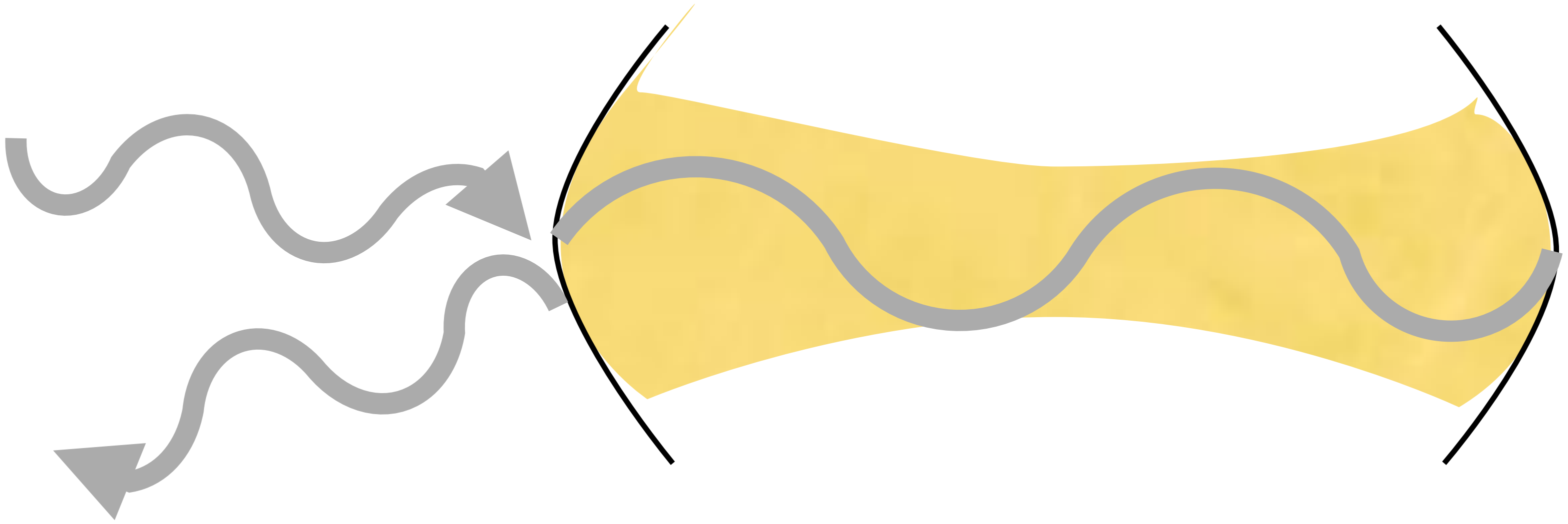
Example: interferometric measurement



shot noise + backaction + thermal noise

More photon force? Bounce more times!

In a cavity, many bounces per photon ('gain')!



Zero bounce p

One bounce $p(1-p)$

M bounces $p(1-p)^M$

Statistics?
Superpoissonian

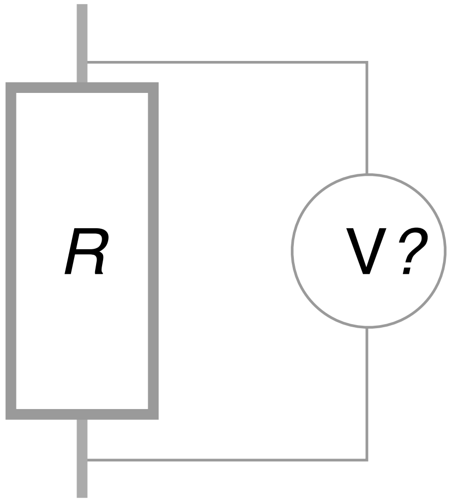
$$\bar{M} = \frac{1-p}{p}$$

$$\mathrm{Var} M = \frac{1-p}{p^2} = \bar{M}\frac{1}{p}$$

Consequence: back action matters! Highly correlated signal!

Brownian motion primary thermometry

[see posters yesterday]



$$\langle V(\omega)V(-\omega')\rangle = 4Rk_bT\delta(\omega-\omega')$$

Classical

Key challenges:

- realization of the Volt (Josephson effect)
- realization of resistance (Quantum Hall)

$$k_bT \rightarrow \frac{\hbar\omega}{2}\left(\boxed{1/2}+\frac{1}{\exp(\beta\hbar\omega)-1}\right)$$

Quantum

Quantum Brownian motion: the mass-temperature connection

Recall...

$$x = \sqrt{\frac{\hbar}{2m\omega}}(a + a^\dagger)$$

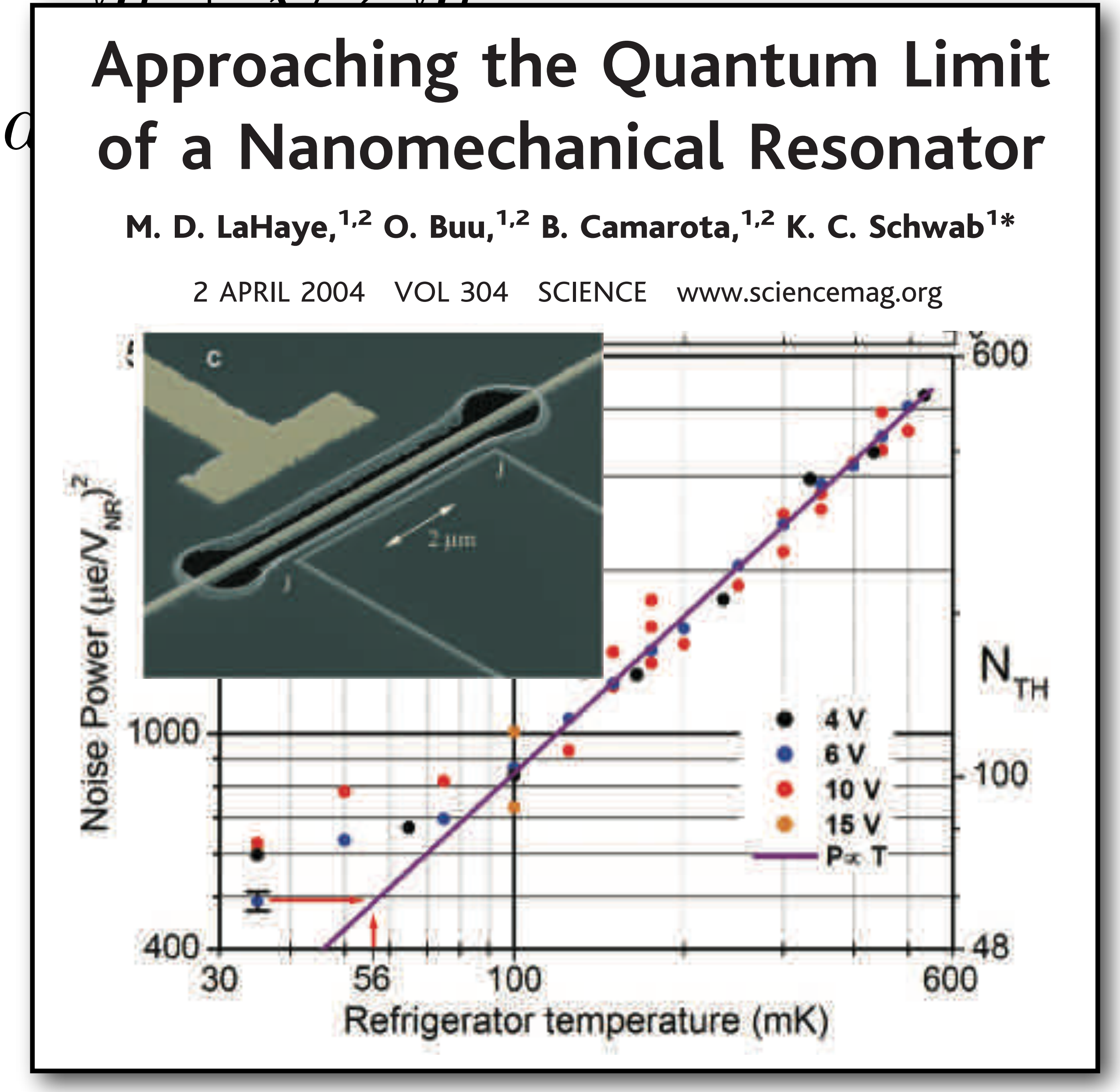
$$\dot{a} = -\omega a - \gamma a + \sqrt{2\gamma a_i}$$

$$\langle a$$

Damping =>
equipartition

$$m\omega^2\langle x^2\rangle = k_b T$$

Measure fluctuations,
connect mass
and temperature



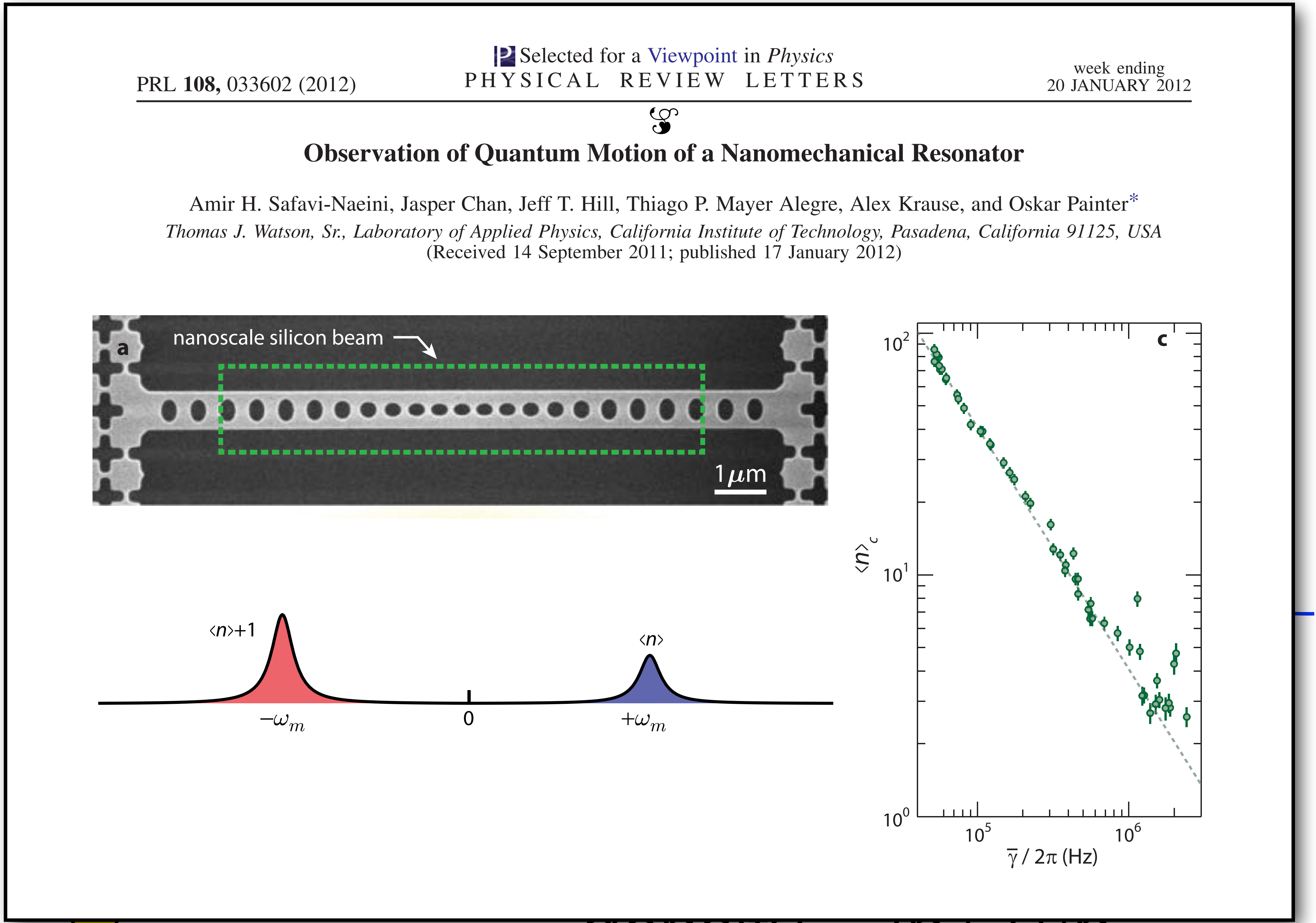
Approaching the Quantum Limit of a Nanomechanical Resonator

M. D. LaHaye,[1,2] O. Buu,[1,2] B. Camarota,[1,2] K. C. Schwab[1]*

2 APRIL 2004 VOL 304 SCIENCE www.sciencemag.org

Temperature / frequency interconnect

Mechanical resonator



PRL **108,** 033602 (2012)

Selected for a Viewpoint in *Physics*

PHYSICAL REVIEW LETTERS

week ending
20 JANUARY 2012

Observation of Quantum Motion of a Nanomechanical Resonator

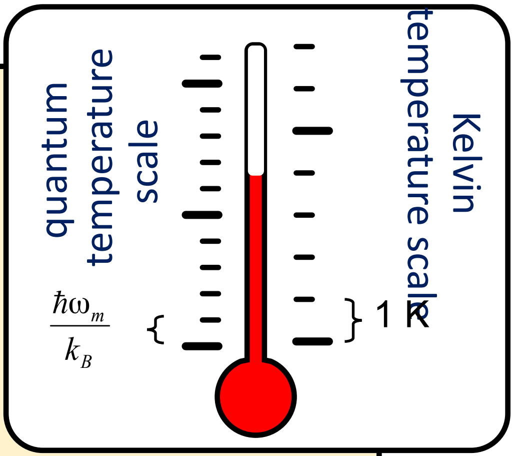
Amir H. Safavi-Naeini, Jasper Chan, Jeff T. Hill, Thiago P. Mayer Alegre, Alex Krause, and Oskar Painter*

Thomas J. Watson, Sr., Laboratory of Applied Physics, California Institute of Technology, Pasadena, California 91125, USA

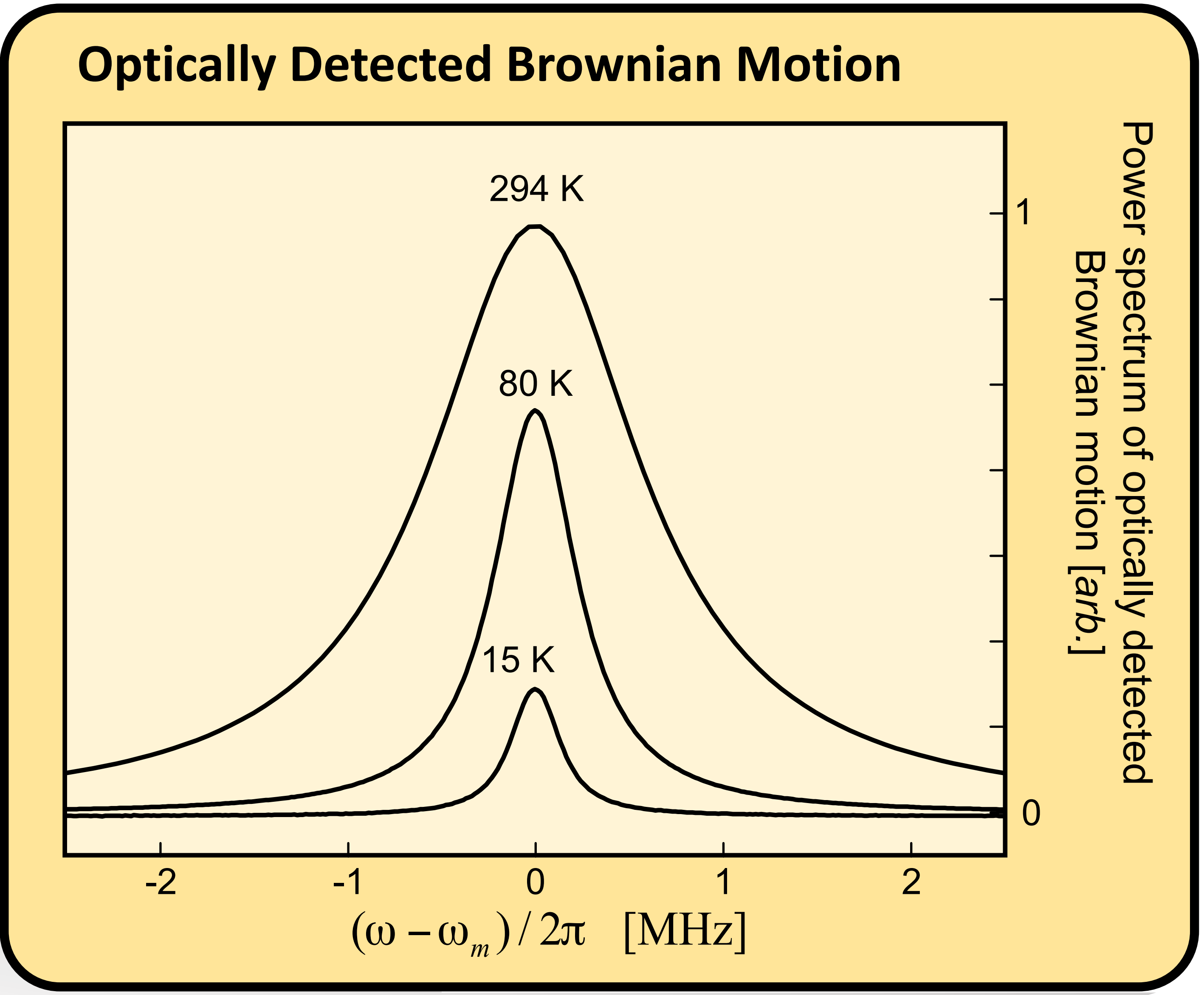
(Received 14 September 2011; published 17 January 2012)

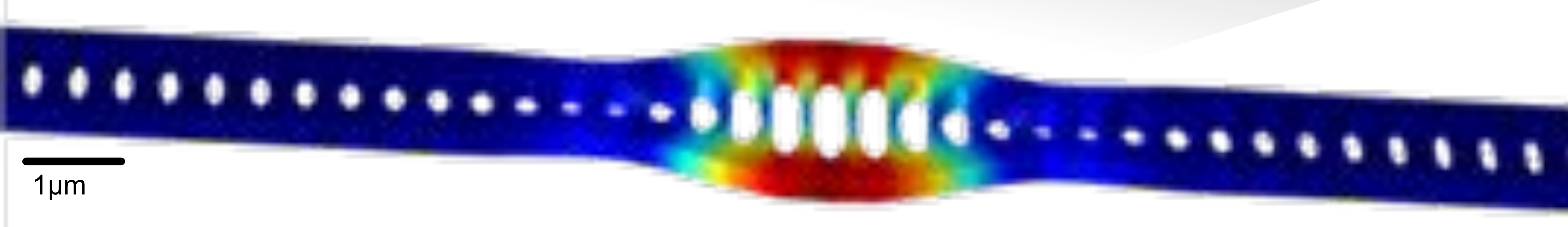
density ~ (n+1)/n

Optomechanical Quantum Correlation Thermometry



- Brownian motion is an absolute noise thermometer (like Johnson noise) but is hard to calibrate
- Use quantum fluctuations as intrinsic force standard
- Look at optical correlations to distinguish thermal from quantum backaction force (similar to Raman sideband asymmetry, but technically easier)
- Goals:
  - Build on-chip, photonic integrated primary thermometer
  - Develop methods to observe quantum measurement backaction at room temperature


Optically Detected Brownian Motion



3.6 GHz vibrational mode of Si_3N_4 nanobeam

Optomechanical Quantum Correlation Thermometry

Quantum Correlations

- Optomechanical interaction creates quantum backaction induced correlations when optically driven motion is written back onto light probing the mechanics

$$\delta X_I \rightarrow \delta X_I \qquad \textit{amplitude fluctuations}$$

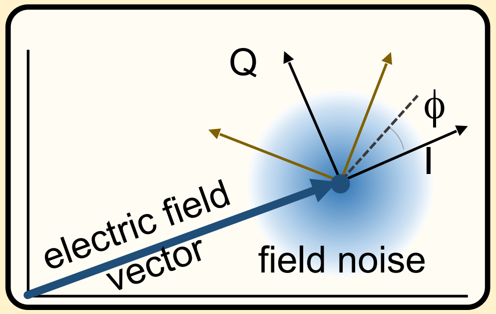
$$\delta X_Q \rightarrow \underbrace{\delta X_Q}_{\textit{shot noise}} + \underbrace{\alpha \delta F_{th}}_{\textit{thermal motion}} + \underbrace{\beta \delta X_I}_{\textit{quantum backaction}} \qquad \textit{phase fluctuations}$$

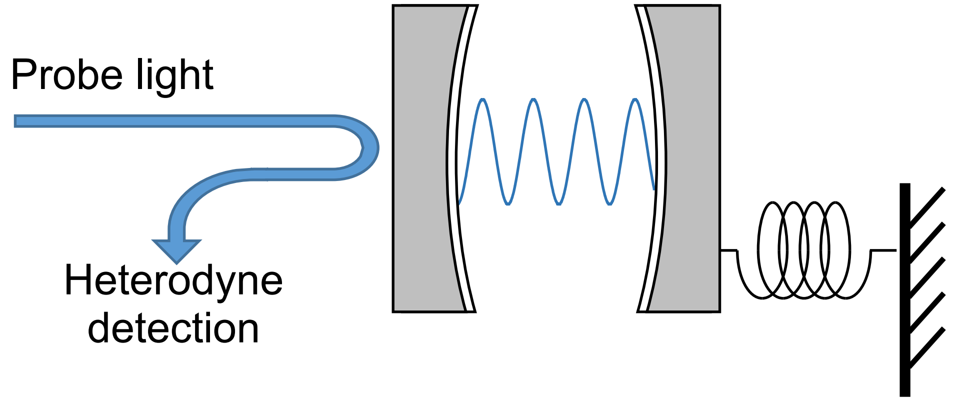
- Correlation spectrum reveals information about quantum and thermal signals

$$S_{\phi_1,\phi_2}(\omega) = \left\langle \delta X^*_{\phi_1}(\omega) \delta X_{\phi_2}(\omega) \right\rangle$$

$$\boxed{\frac{\mathrm{Re}\{S_{\pi/4,3\pi/4}(\omega)\}}{\mathrm{Im}\{S_{\pi/4,3\pi/4}(\omega)\}} = \mathrm{Coth}\left(\frac{\hbar\omega}{2k_B T}\right) \approx \frac{A}{2B}}$$

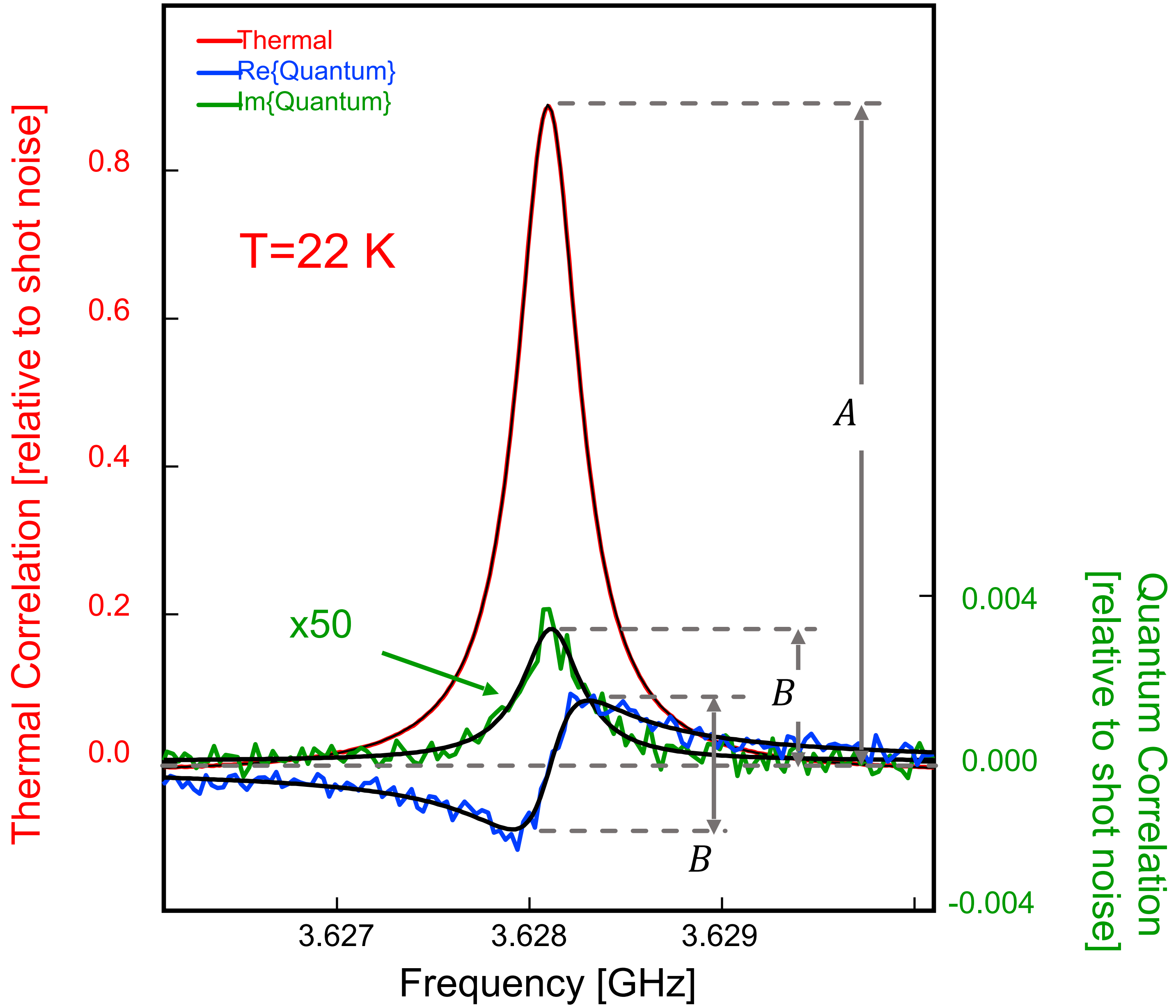
- Ratios of spectral features give temperature directly related to fundamental constants and independent of device parameters





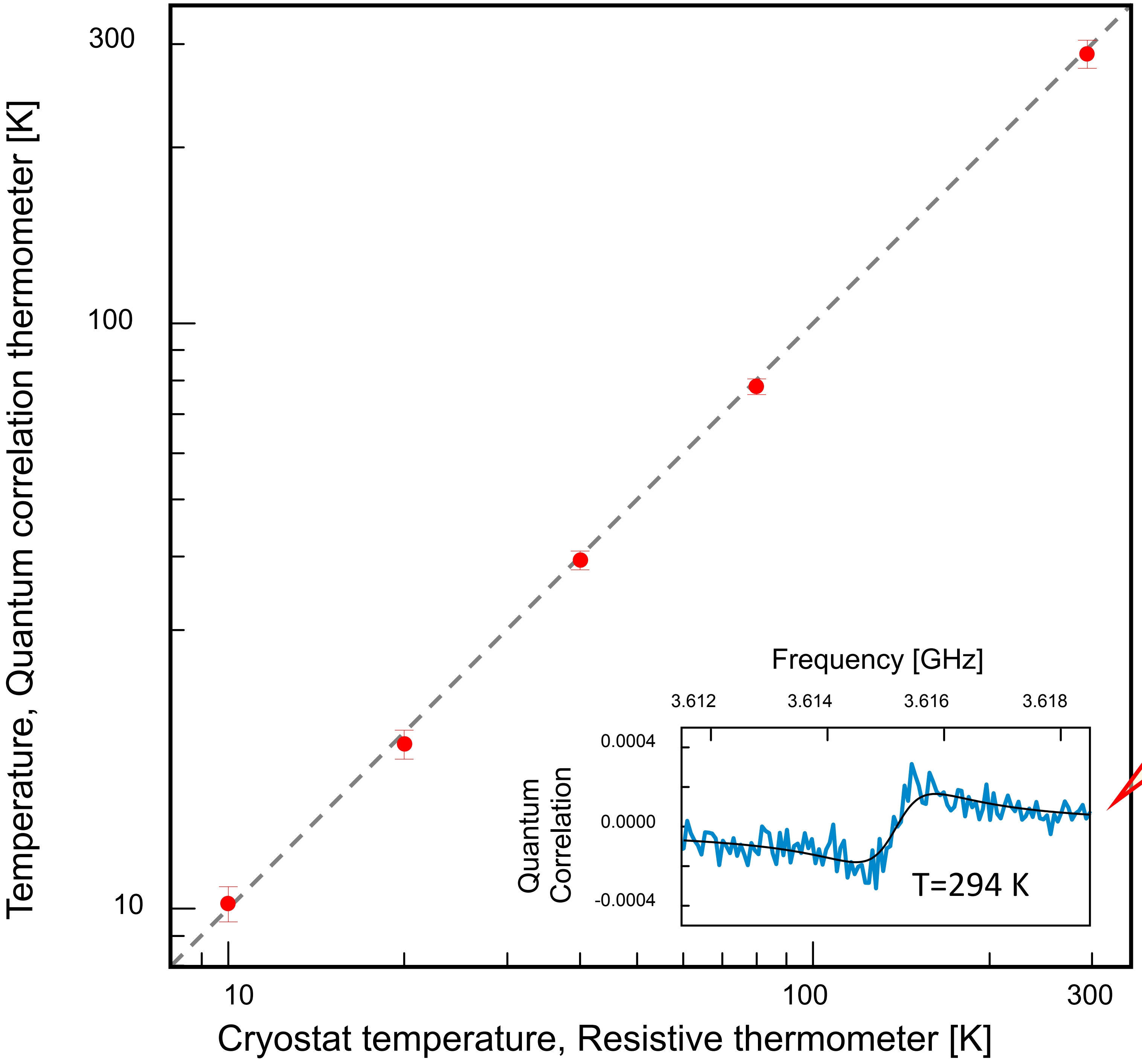
Probe light

Heterodyne detection



Optomechanical Quantum Correlation Thermometry

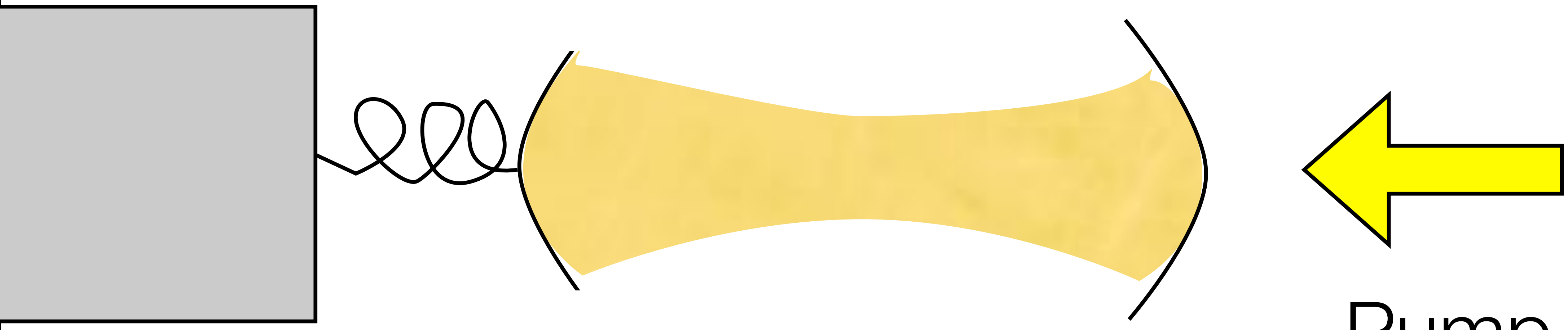
Proof-of-principle demonstration of quantum correlation thermometry



Room temperature signature of quantum measurement backaction

T. P. Purdy, K. E. Grutter, K. Srinivasan, J. M. Taylor, Science (2017)]

Optomechanical transduction: photons coupled to phonons



Spring

Optical cavity

Pump laser

$$2\pi\omega = N\frac{c}{L}\left(1-\frac{x}{L}\right)$$

Radiation pressure force

$$\begin{aligned} V &\sim |E|^2\hat{x} \\ &\sim |E_p e^{i\nu t}+\hat{E}|^2\hat{x} \\ &\to E_p e^{i\nu t}\hat{E}\hat{x} \end{aligned}$$

Opto-mechanics

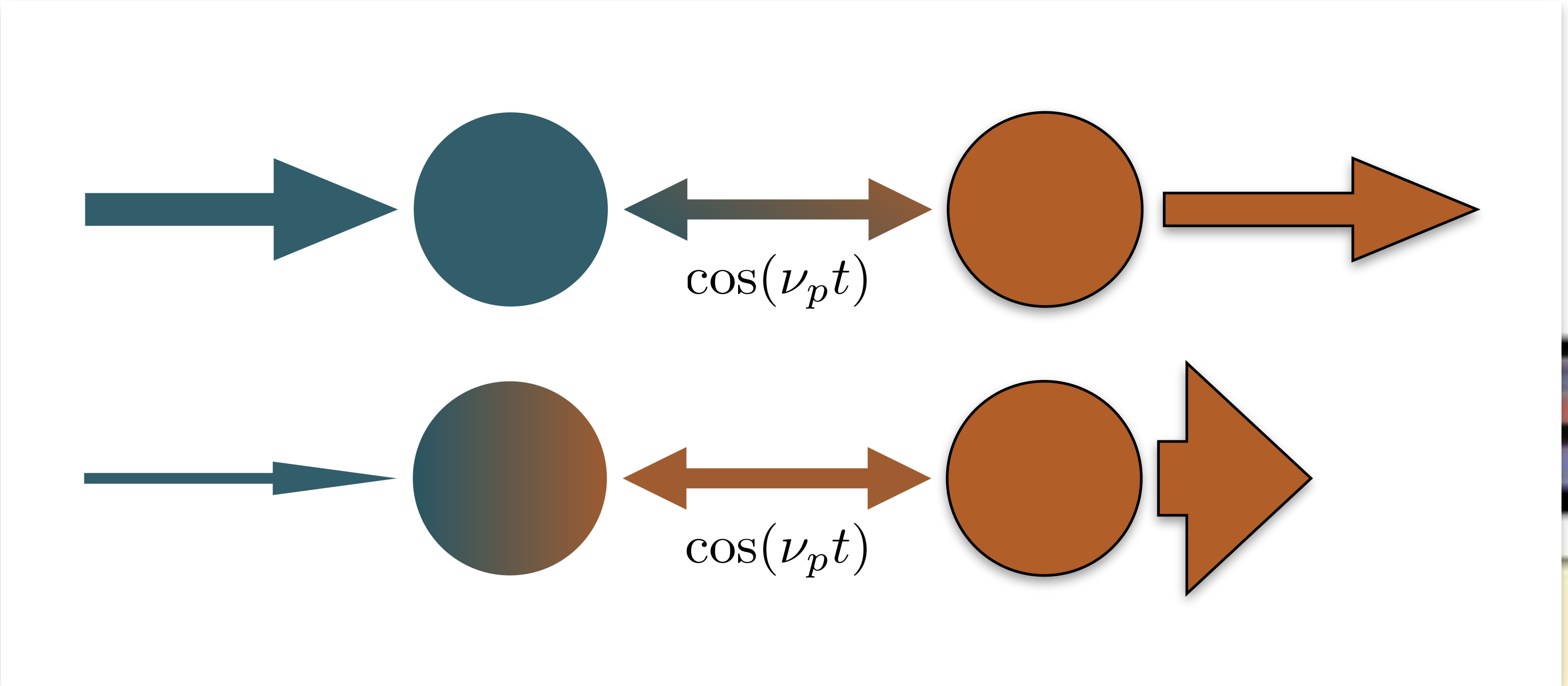
Small non-linear coupling => large linear coupling

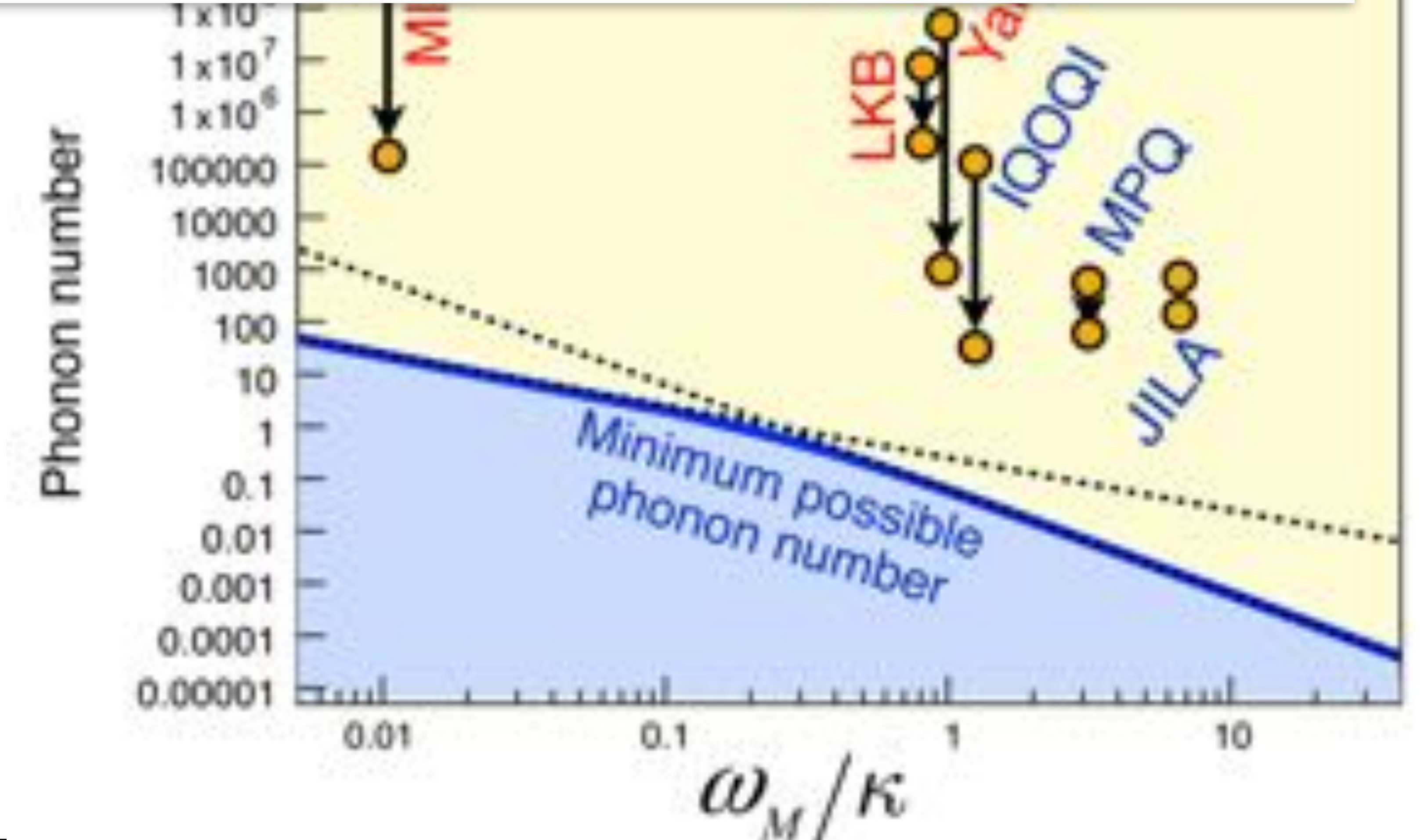
Coupled harmonic oscillators: cooling

Pump laser converted to cavity photons via mechanics

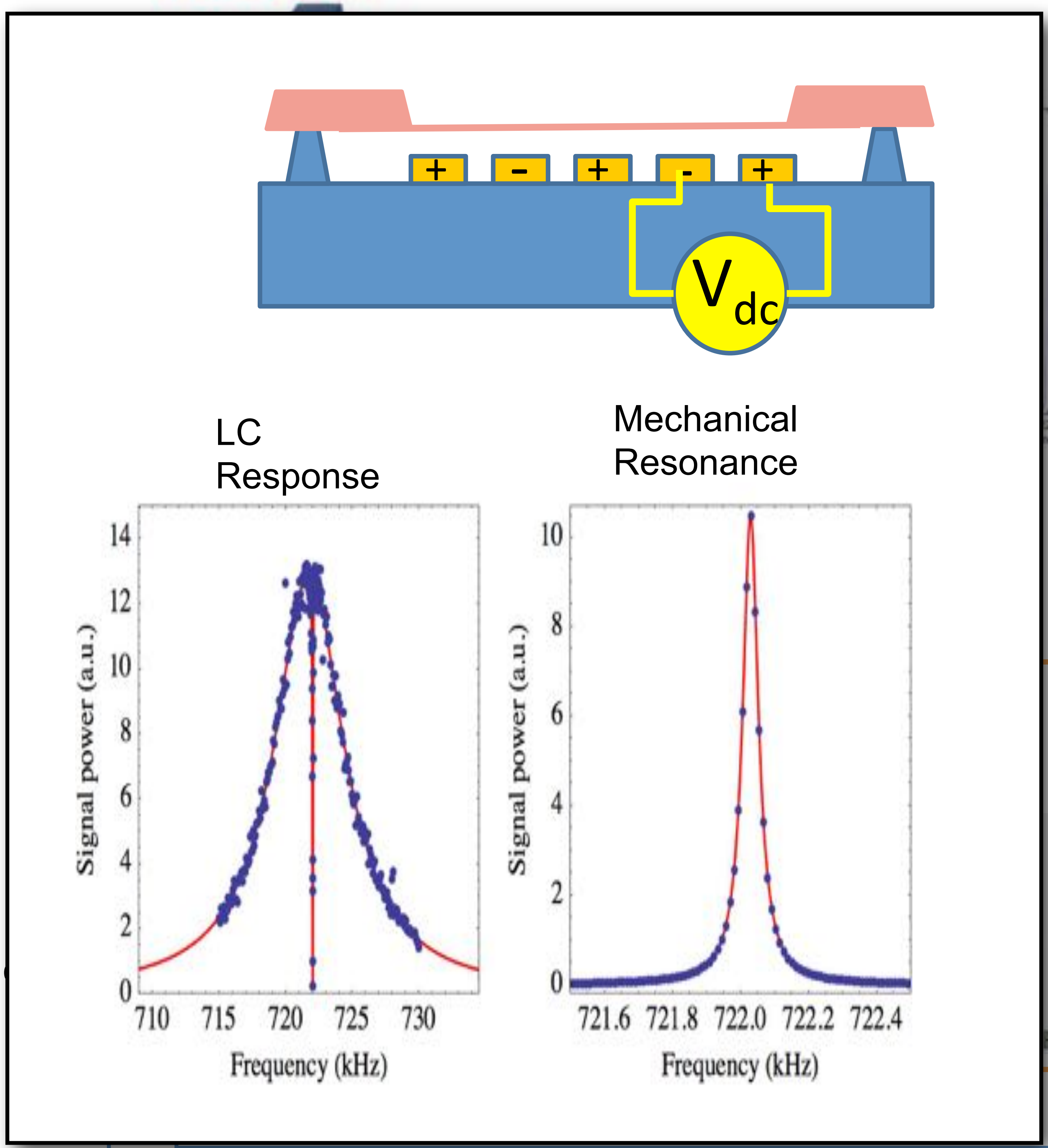
When damping is low enough...
normal mode coupling

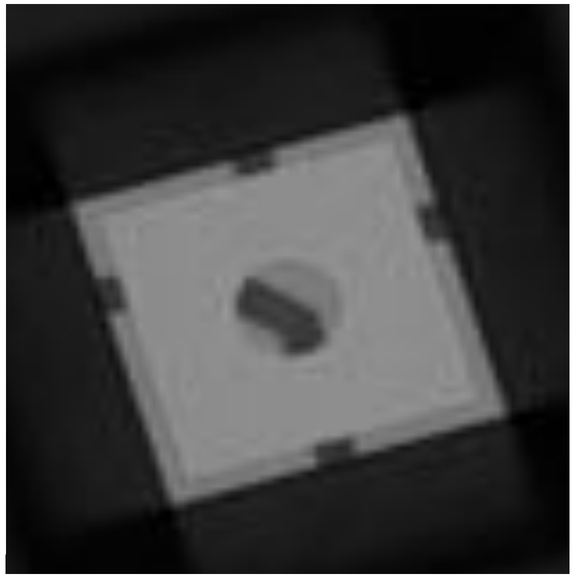
Efficient equalization of disparate temperatures (cooling)





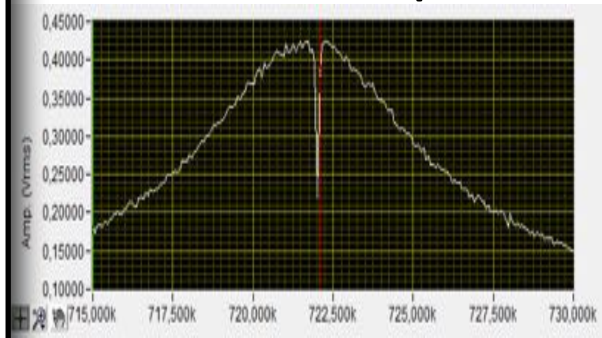
Experimental evidence: mechanically-induced transparency





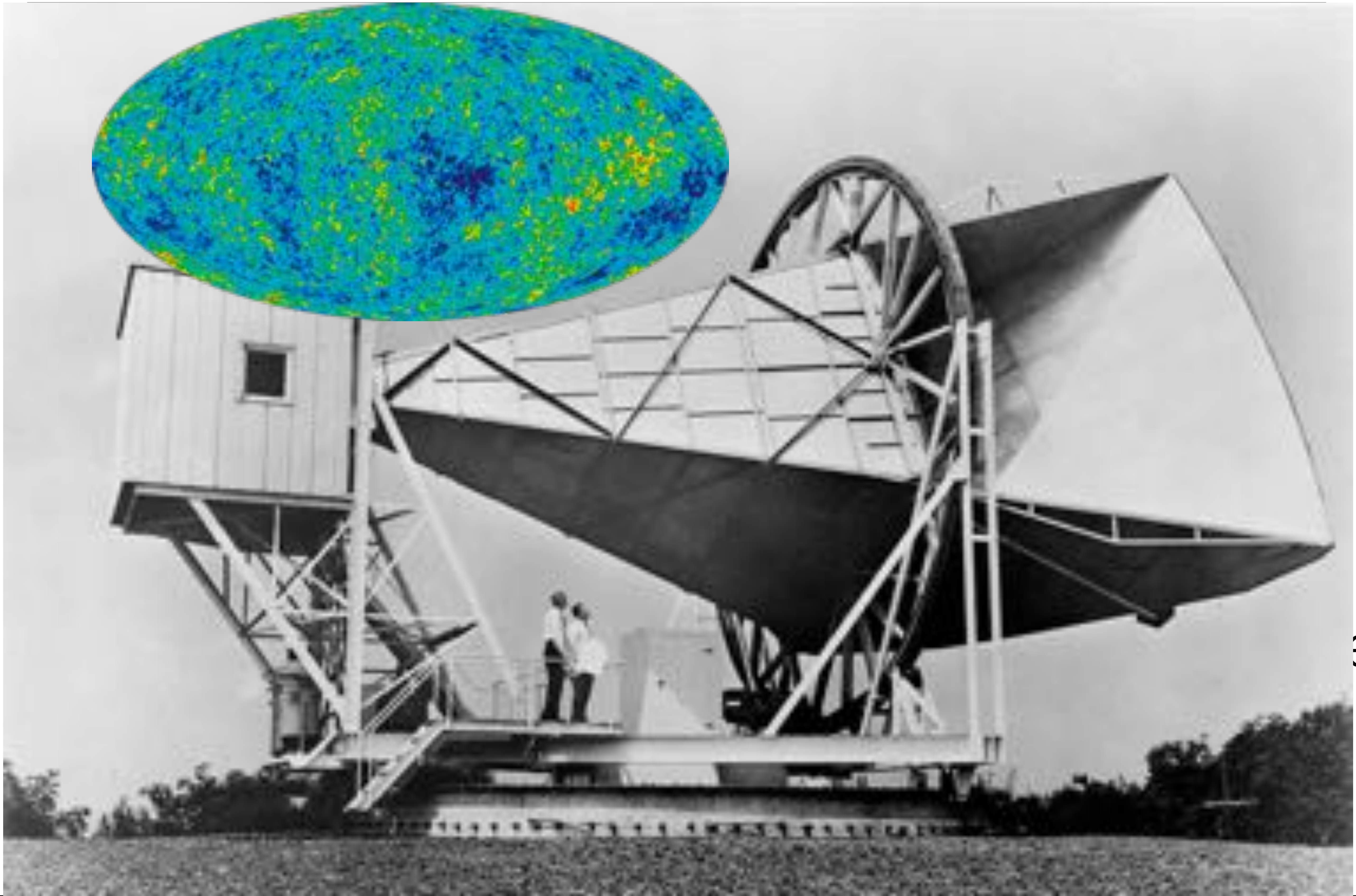
50nm Aluminum Coated SiN Membrane
(at 6 um distance)

Lock-in Amplifier



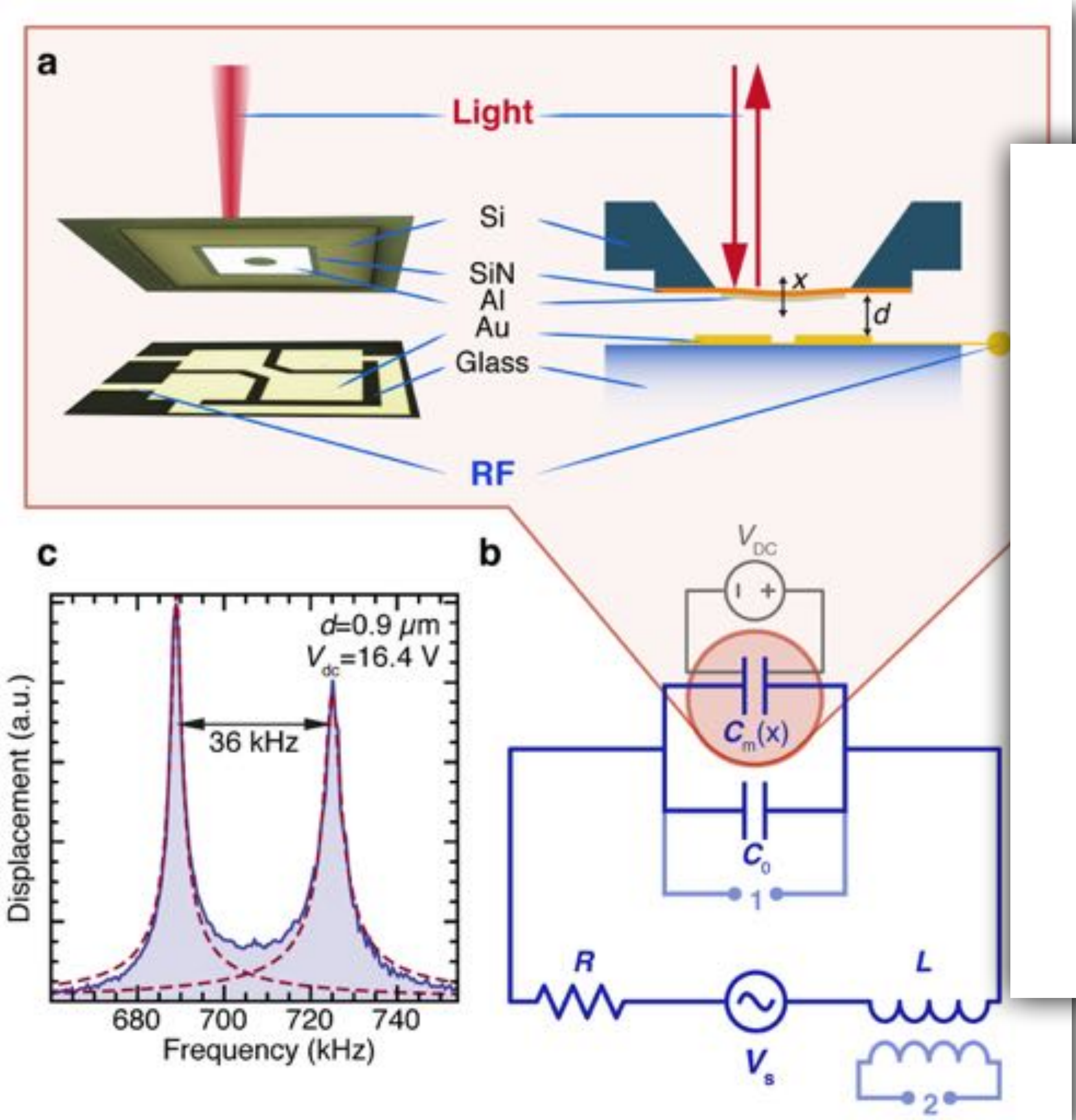
RF drive

Efficient detection of astrophysical rf photons



A universal interface?

[JMT, S rensen, Marcus, Polzik, PRL (2011)]
[Bagci et al., Nature (2014)]



Quantum regime?

Can transduce a cold source when dephasing slow:

$$\omega > \gamma(n_{\mathrm{th}} + 1/2)$$

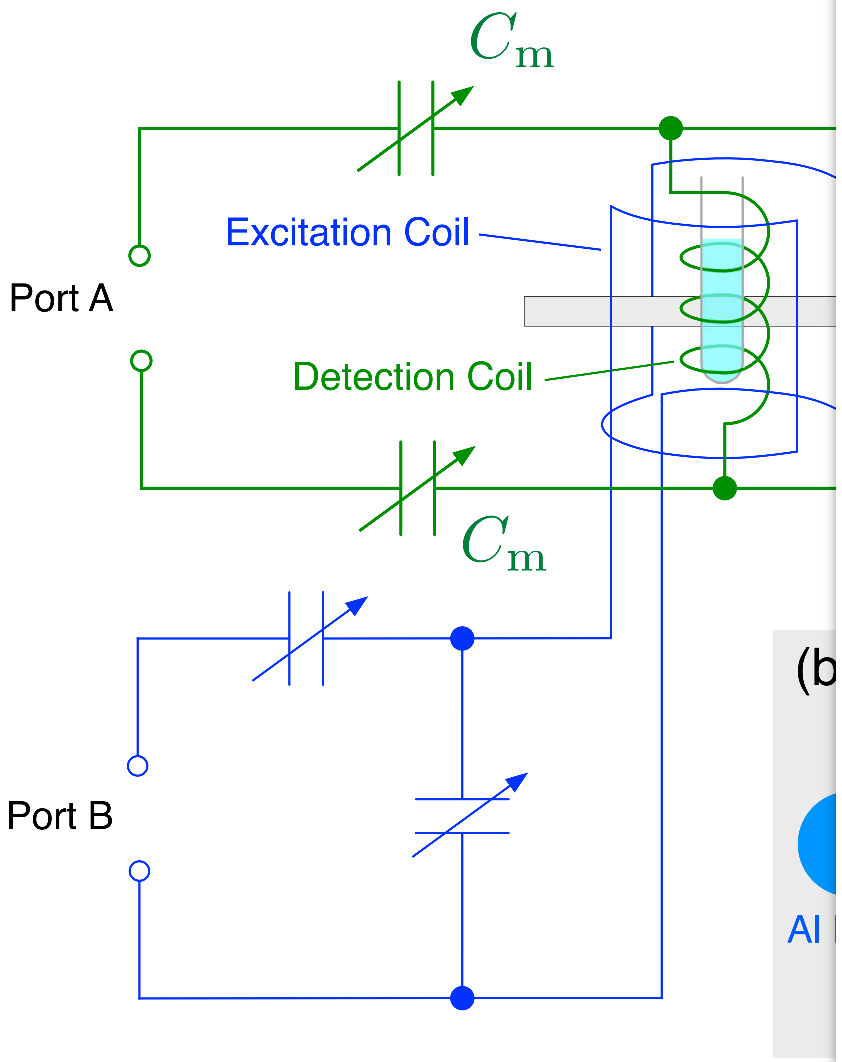
or $$\frac{\omega}{\gamma}\omega \gg \frac{k_b T}{\hbar}$$

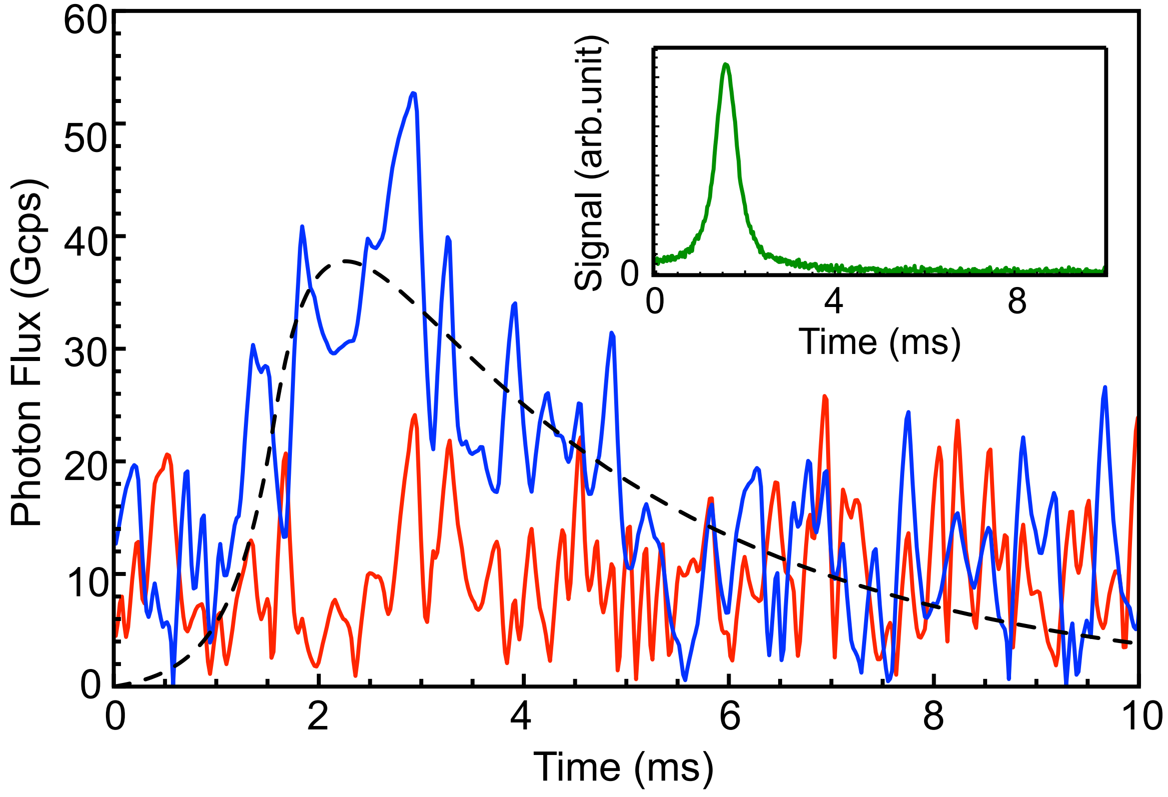
Versatile optical interface

Measuring NMR signals optically

[Takeda et al., 1706.00532]

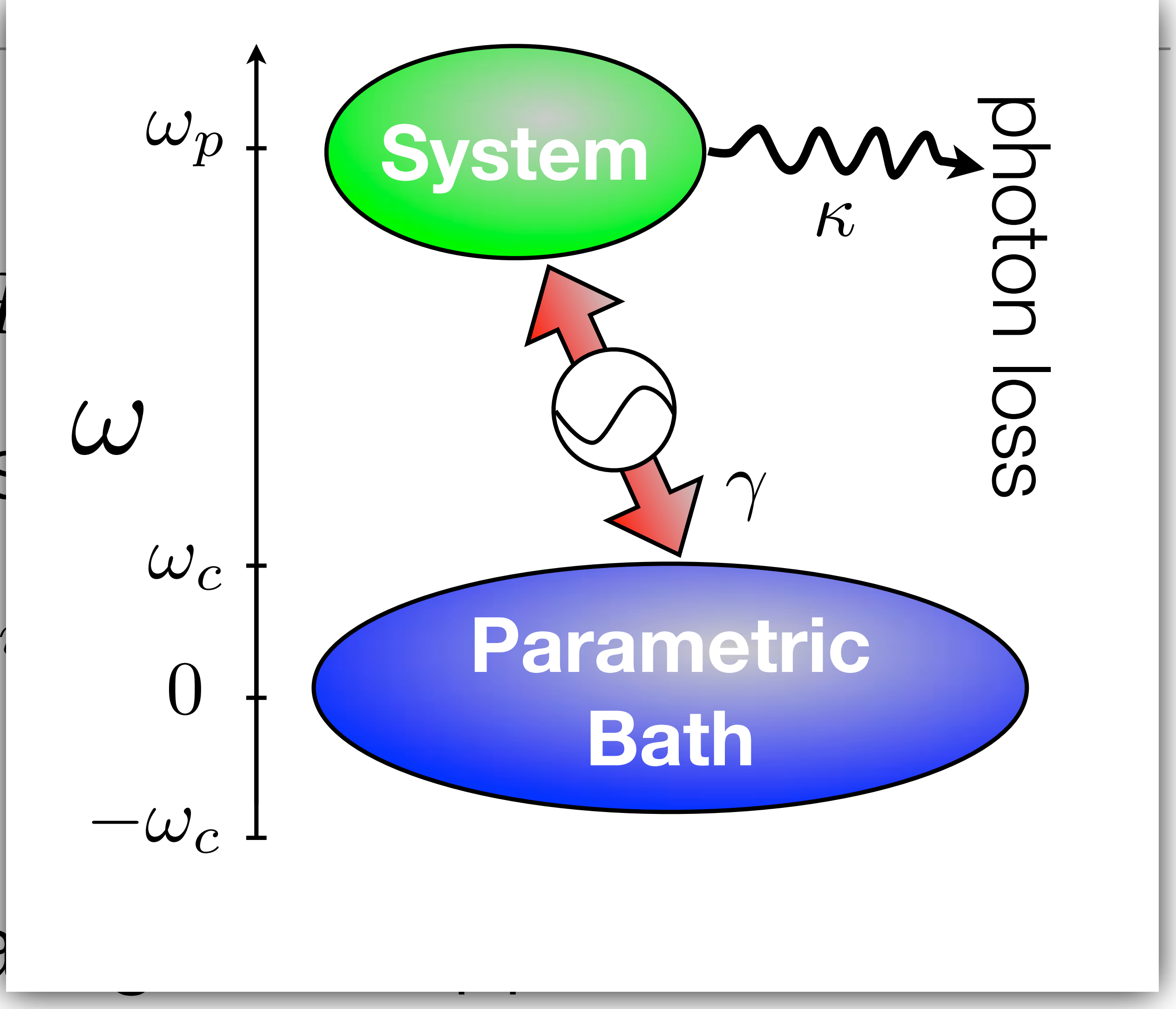
Coil signal to motion to light





Observation of proton spin echo via transduction

Beyond Kelvin: frequency to chemical potential (for light)



The challenge: natural state for

$$H_S + \lambda H_{SB} + H$$

Solution: bring the bath to the s

$$H_S + 2\lambda \sin(\nu t) \sum_i (a$$

Assume bath is low frequency

Rotating frame, rota

$$H_S - \hbar\nu \sum_i a_i^\dagger a_i + \lambda \sum_i (a_i + a_i^\dagger) B_i + H_B$$

$$\to \exp[-\beta(H_s - \hbar\nu N)]$$

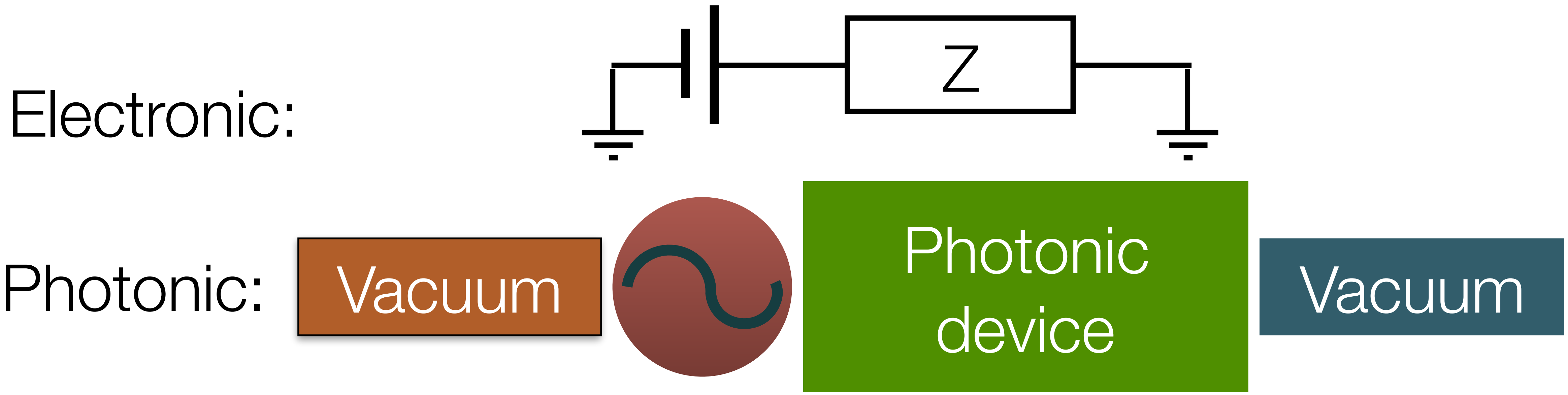
[Y. Subasi, C. H. Fleming, JMT, B. L. Hu, PRE (2012)]

[M. Hafezi, P. Adhikari, JMT, PRB (2015)]

What does it do?

Our results:

Time-dependent coupling between the photonic device and an (low frequency) reservoir leads to a chemical potential



Electronic:

Z

Photonic:

Vacuum

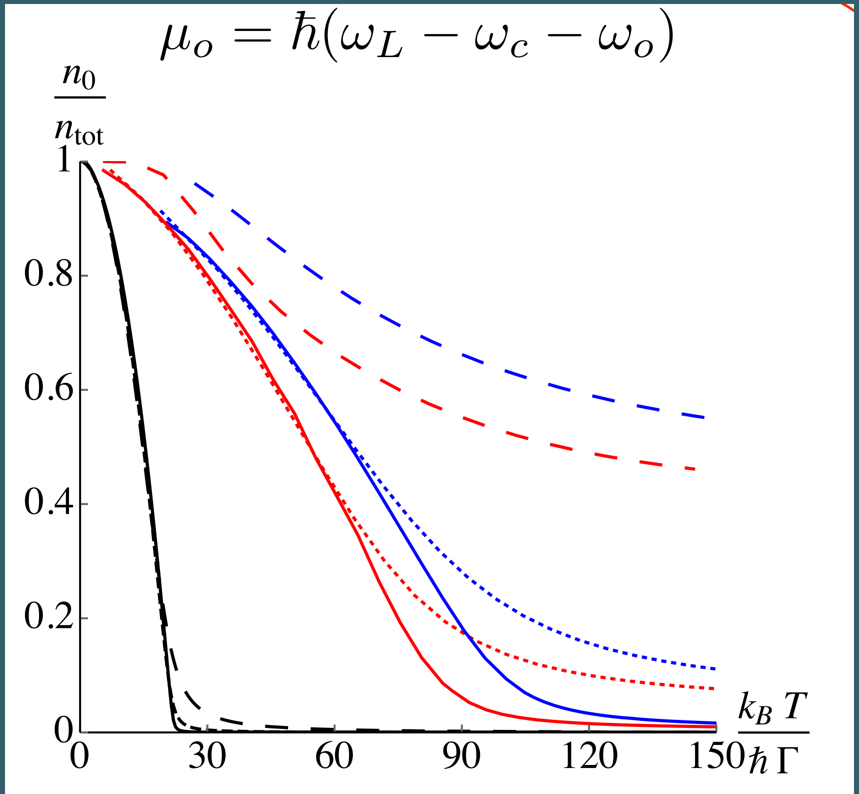
Photonic device

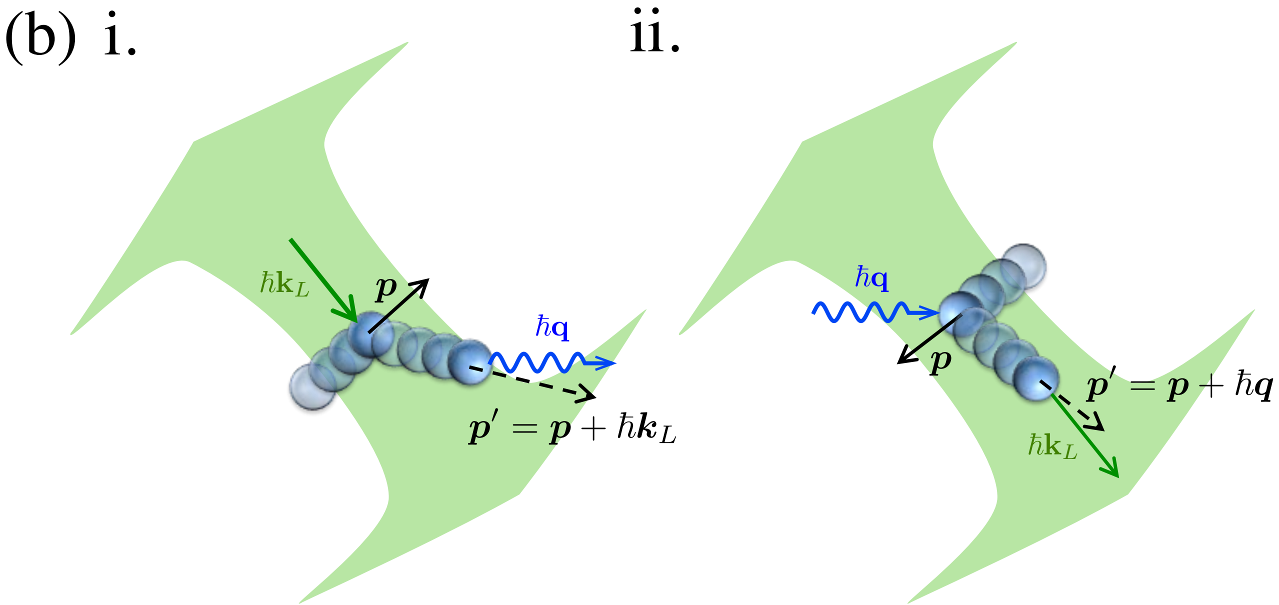
Vacuum

This provides a method for generating the optical or microwave photonic equivalent of a fixed voltage standard, like Josephson-based voltage standards

Laser cooling of atoms implementation

[C.-H. Wang, JMT, arxiv:1706.00789]
[C.-H. Wang, M. J. Gullans, J. V. Porto, W. Phillips, JMT *in prep*]





rs into detailed balance

the high optical depth axis

This detailed balance is in the frame rotating with the cooling lasers

add optical cavity (cf. M. Weitz, Bonn), get photonic BEC

Thanks!

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