Cindy Regal

Condensed Matter Summer School, 2018

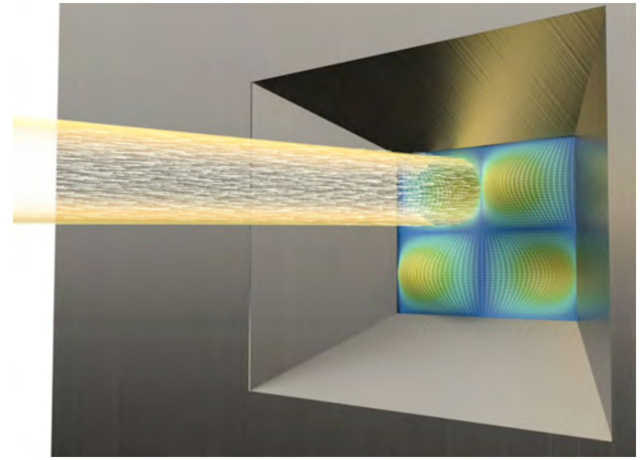
Day 1: Quantum optomechanics

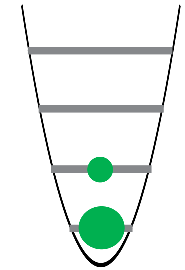
Day 2: Quantum transduction

Day 3: Ultracold atoms from a qubit perspective

JILA NIST CU

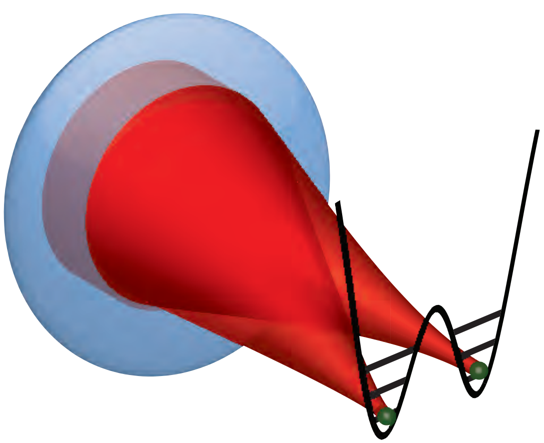
Day 1: Quantum optomechanics





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 nonlinearity / 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 creating Bell states

Quantum optomechanics outline

Basic interaction and cooling of moving mirror in cavity / interferometer – example of more general machinery

Example optomechanics experiments

Continuous displacement detection and squeezing – an old problem

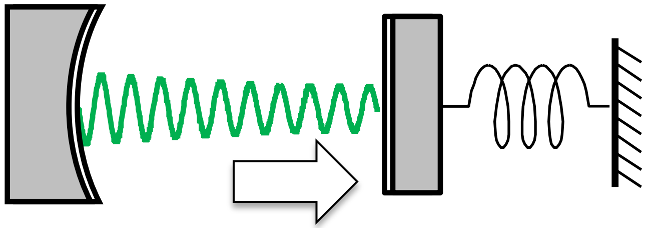
Quantum noise and measurement and amplifiers

Some of our experiments

Will lead into tomorrow – can we optically read out the force of a single microwave photon? – modern problem of quantum transduction from superconducting qubits

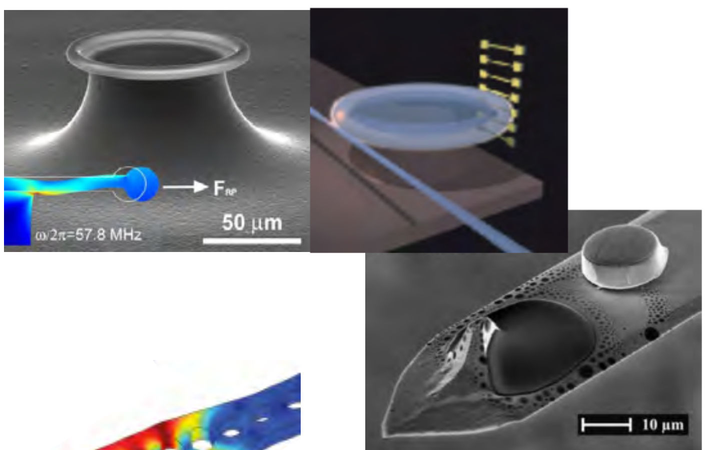
Light controls micromechanical motion

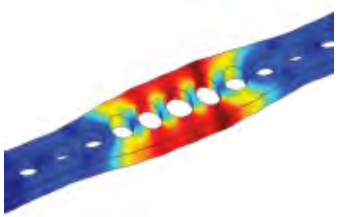
Micromechanical motion controls light

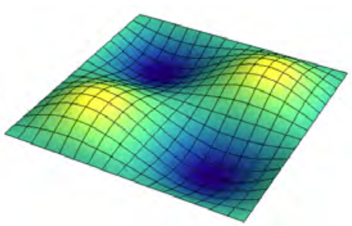


Radiation pressure

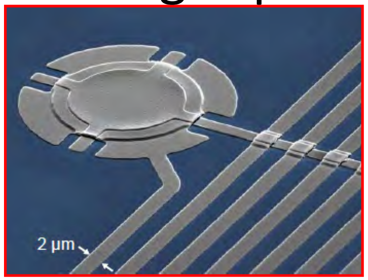
Effectively moving mirrors

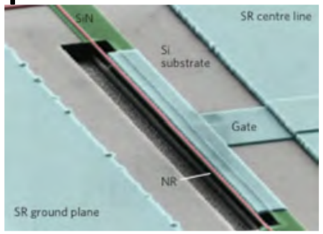




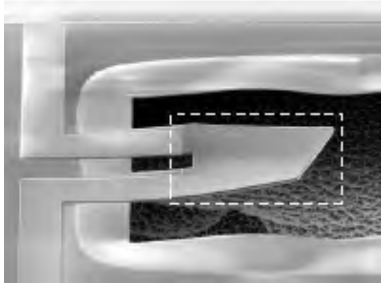


Moving capacitor plate





Piezoelectrics



Optomechanical interaction

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

$$G \rightarrow \frac{d\omega_c}{dx}$$

$\hat{a} \rightarrow$ cavity mode

$$\hat{H}_{int} = \hbar G \hat{a}^\dagger \hat{a} \, x_{zp} \hat{x}$$
$$= \hbar g \hat{a}^\dagger \hat{a} \hat{x}$$

$\hat{b} \rightarrow$ mechanical mode

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

$$g \rightarrow \frac{d\omega_c}{dx} x_{zp}$$

$$\hat{a} \rightarrow \alpha + \delta \hat{a}$$

α stemming from large α_{in}

Optomechanical interaction

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

$$= \cancel{\hbar g |\alpha|^2 (\hat{b} + \hat{b}^\dagger)} + \hbar g (\alpha^* \delta\hat{a} + \alpha \delta\hat{a}^\dagger)(\hat{b} + \hat{b}^\dagger)$$

avg rp

$$+ \hbar g \cancel{\delta\hat{a} \delta\hat{a}^\dagger (\hat{b} + \hat{b}^\dagger)}$$

smaller by α

α real valued $\quad \alpha = \sqrt{N}$

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

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

Red detuned $\Delta = -\omega_m$

$\delta\hat{a}^\dagger \hat{b} + \delta\hat{a} \hat{b}^\dagger$

Beamsplitter

On resonance $\Delta = 0$

$(\delta\hat{a}^\dagger + \delta\hat{a})\hat{x}$

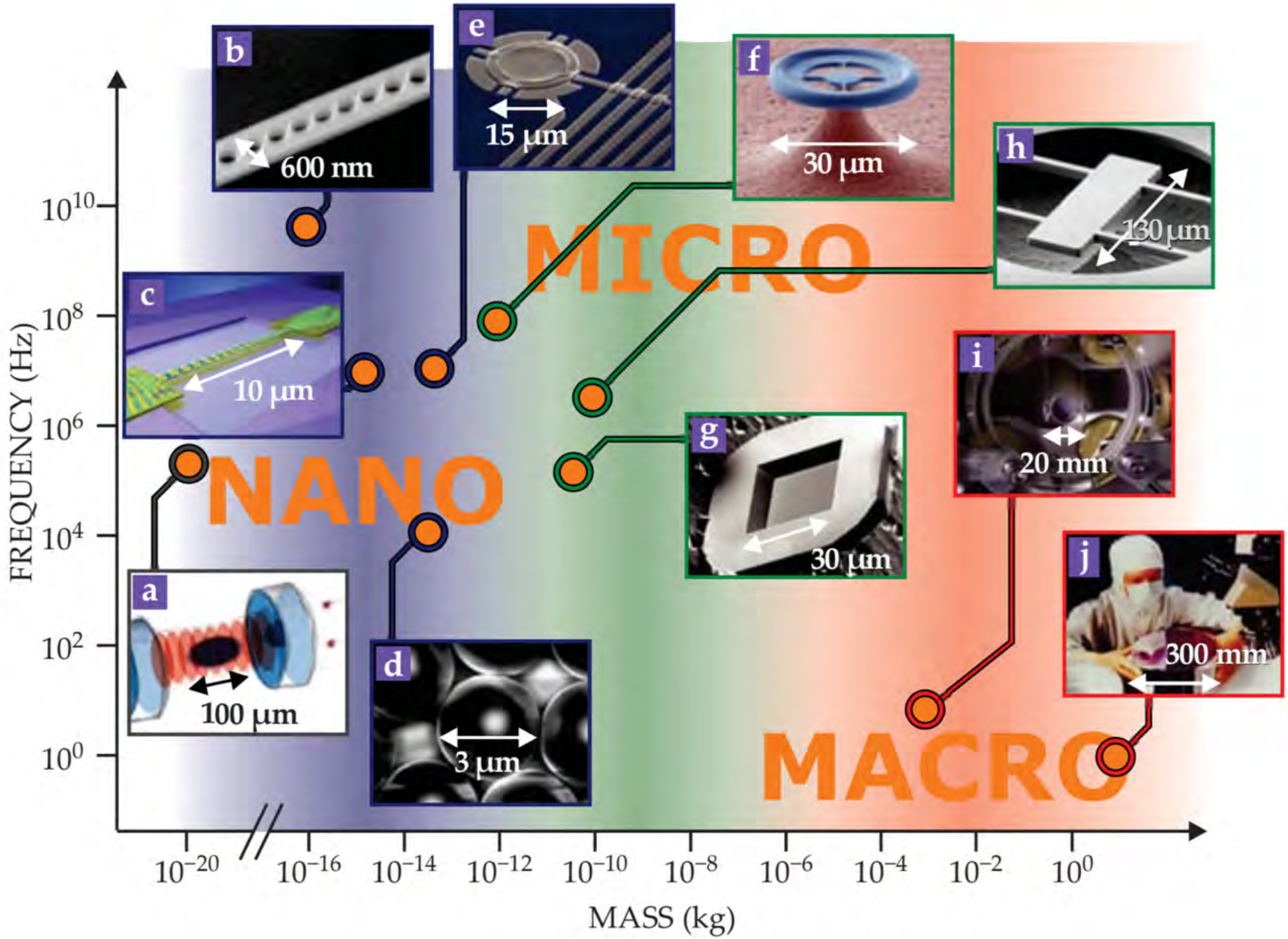
Interferometer

Blue detuned $\Delta = \omega_m$

$\hat{b}\, \delta\hat{a} + \hat{b}^\dagger \delta\hat{a}^\dagger$

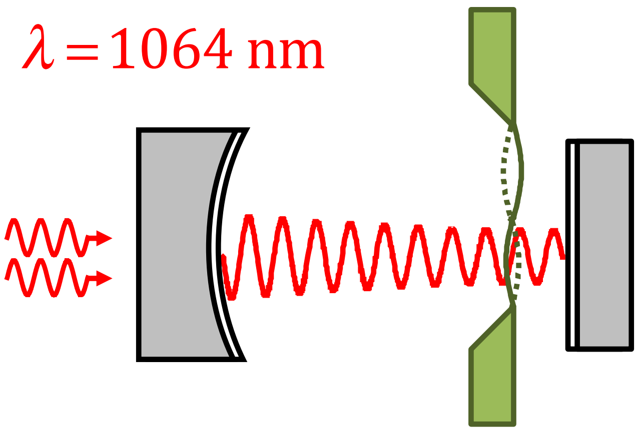
Two-mode squeezing

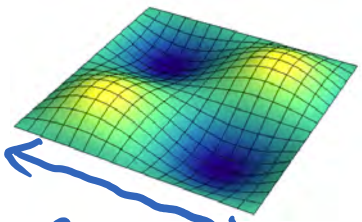
Range of size scales



Our optomechanical device

$\lambda = 1064$ nm



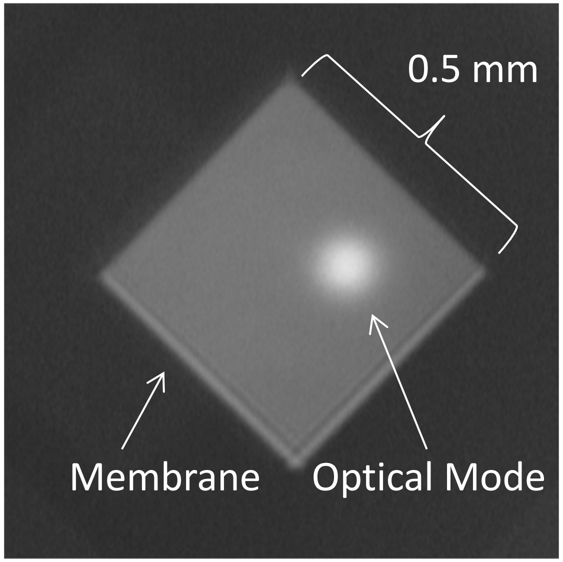


500μm

50nm thick

$m \sim 10$ ng

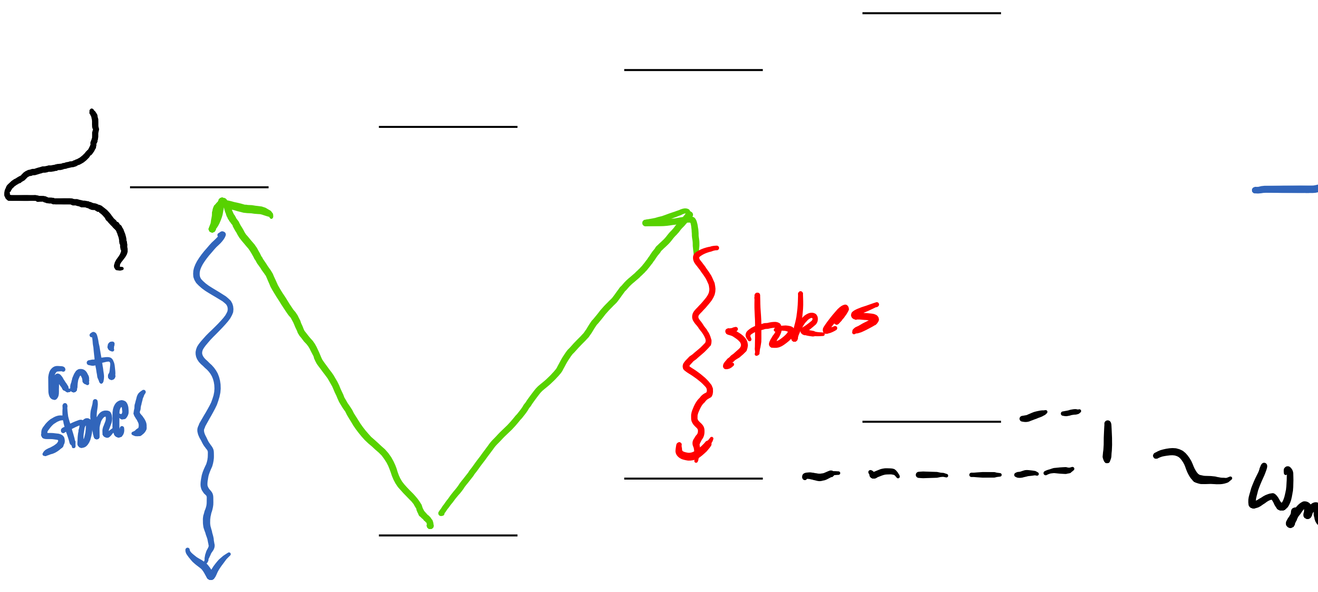
$\nu_m = 1$ MHz

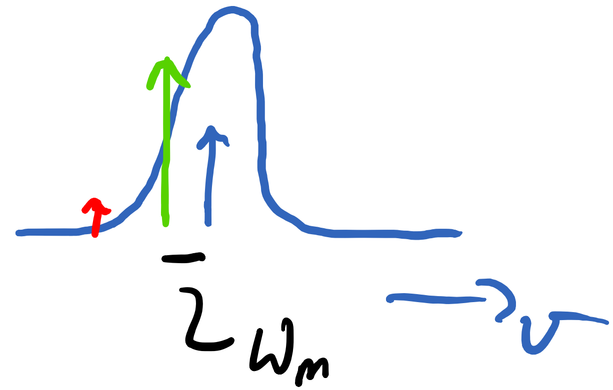


$$x_{zp} = \sqrt{\frac{\hbar}{2m\omega_m}}$$

$$\sim 1\ \text{fm}$$

Resolved sideband cooling





$$\propto \frac{1}{1+(4\omega_m/\kappa)^2} \times (n_m+1)$$

$$\propto n_m$$

$$\frac{S_{FF}(\omega_m)}{S_{FF}(-\omega_m)} = \frac{n_m+1}{n_m} = e^{\hbar\omega/k_BT}$$

Reaching 'quantum' limit

Optical measurement rate / Photon-phonon exchange rate with propagating field

LARGE

$$\Gamma_{opt} = \frac{4\alpha^2 g^2}{\kappa}$$

$$\alpha^2 = N$$

$$\begin{cases} \text{Lots of light} \\ g = x_{zp} \dfrac{d\omega_c}{dx} \end{cases}$$

Thermalization rate with mechanical environment

slow

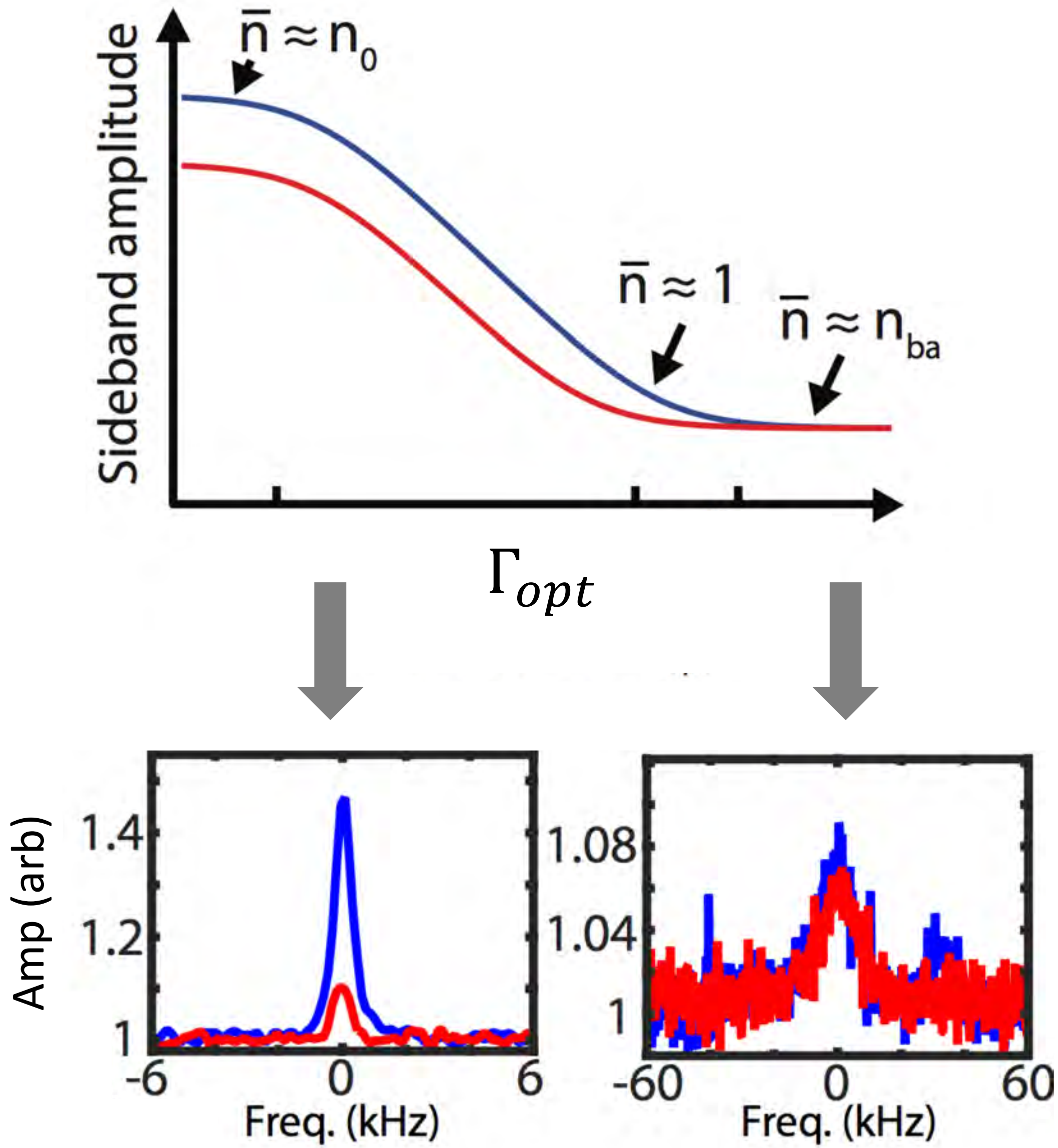
$$\Gamma_{th} = n_{th} \Gamma_m$$

$$\Gamma_m = \frac{\omega_m}{Q_m}$$

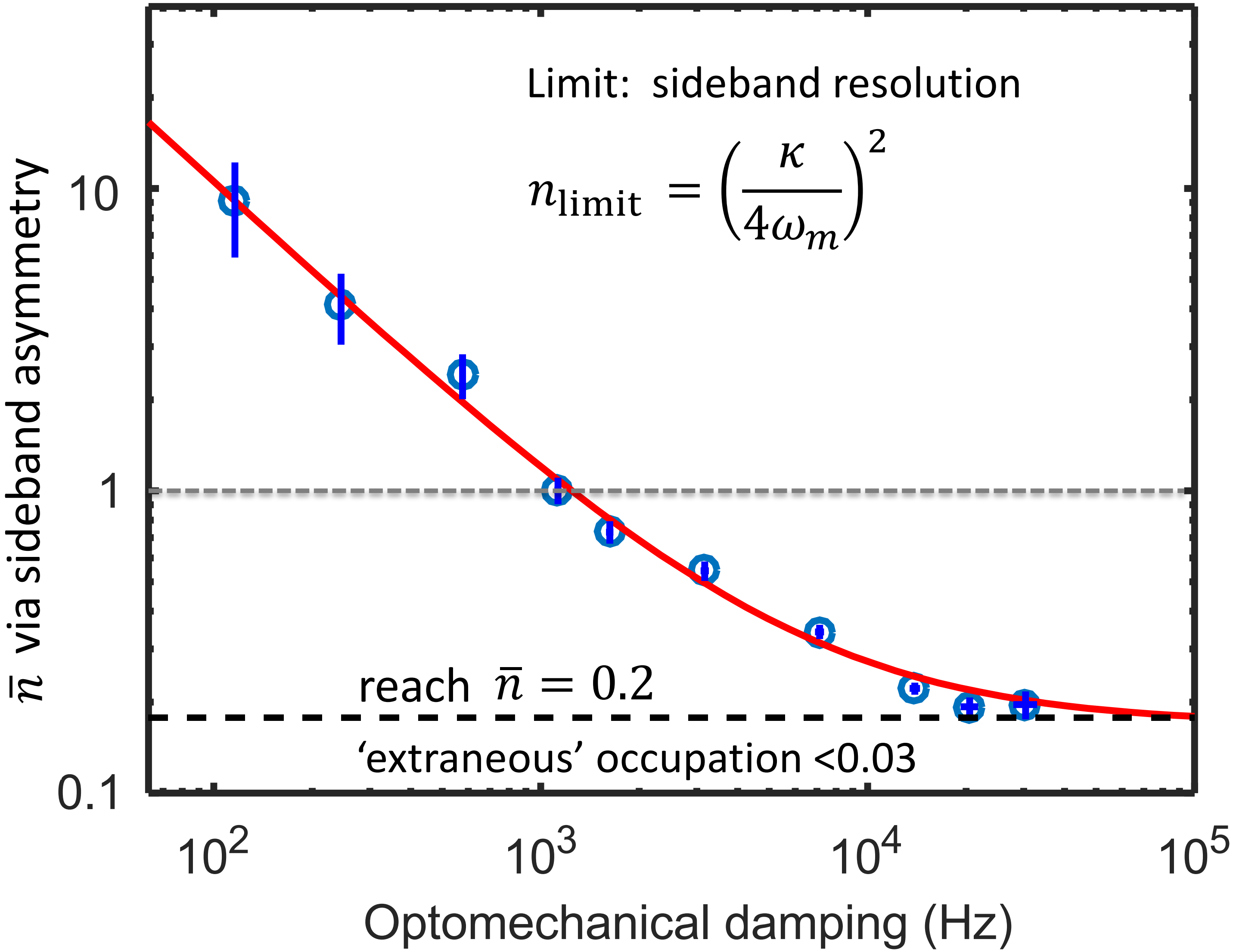
$$n_{th} = \frac{k_b T}{\hbar \omega_m}$$

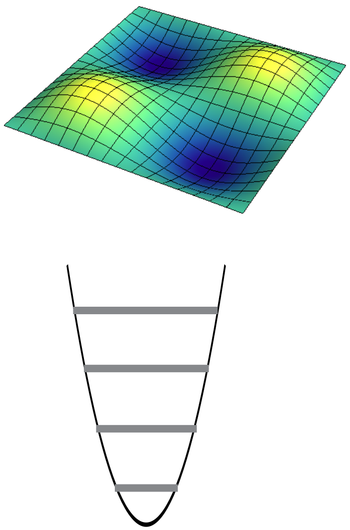
$$\begin{cases} \text{High } Q_m \\ \text{Cold Bath} \end{cases}$$

Quantum backaction limit of cooling



Ground-state optomechanical cooling

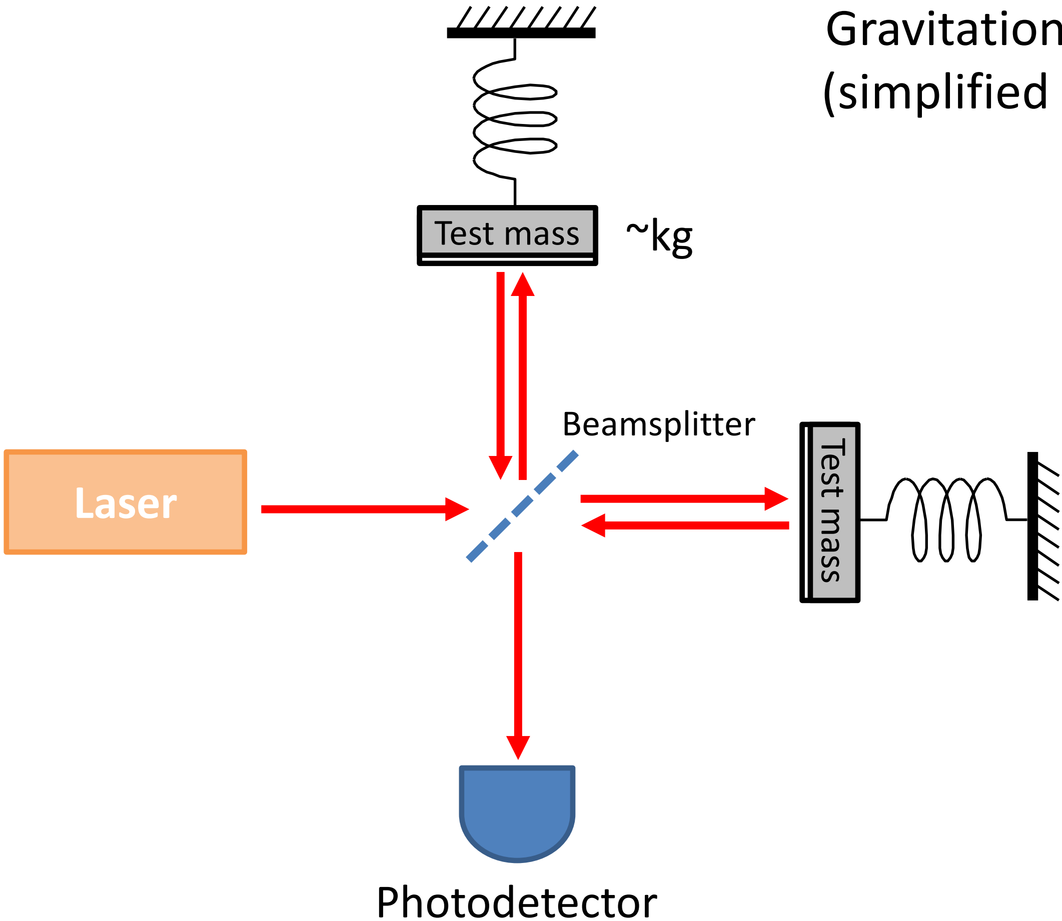




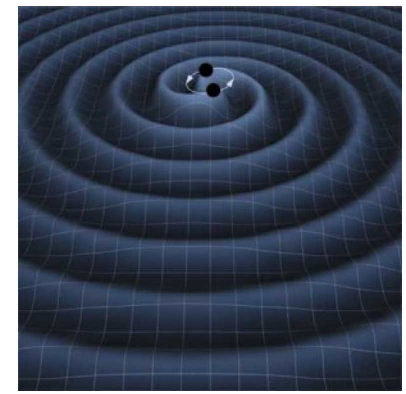
Data here: R. W. Peterson *et al.,* PRL (2016)

Ground state cooling: Teufel *et al.,* Nature (2011), Chan *et al.,* Nature (2012), Khalili *et al.*, PRA (2012)

Gravitational wave detection

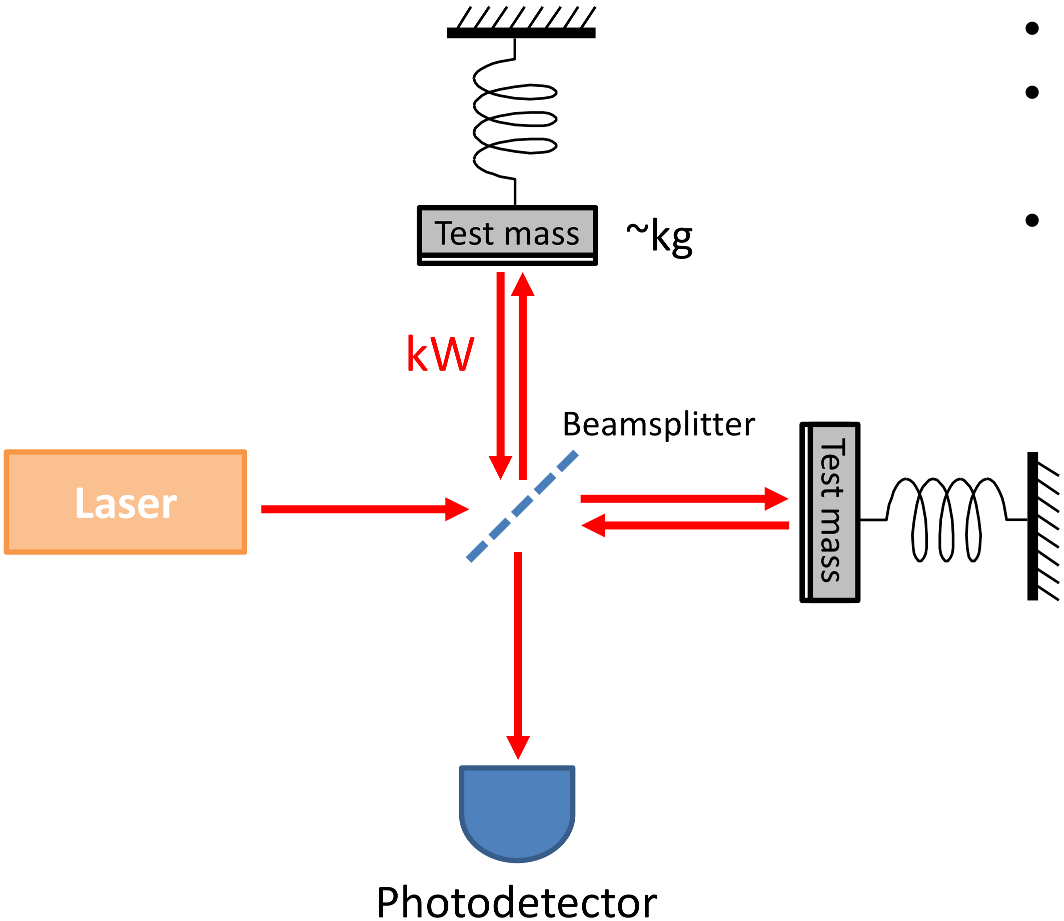


Gravitational wave detector
(simplified version)



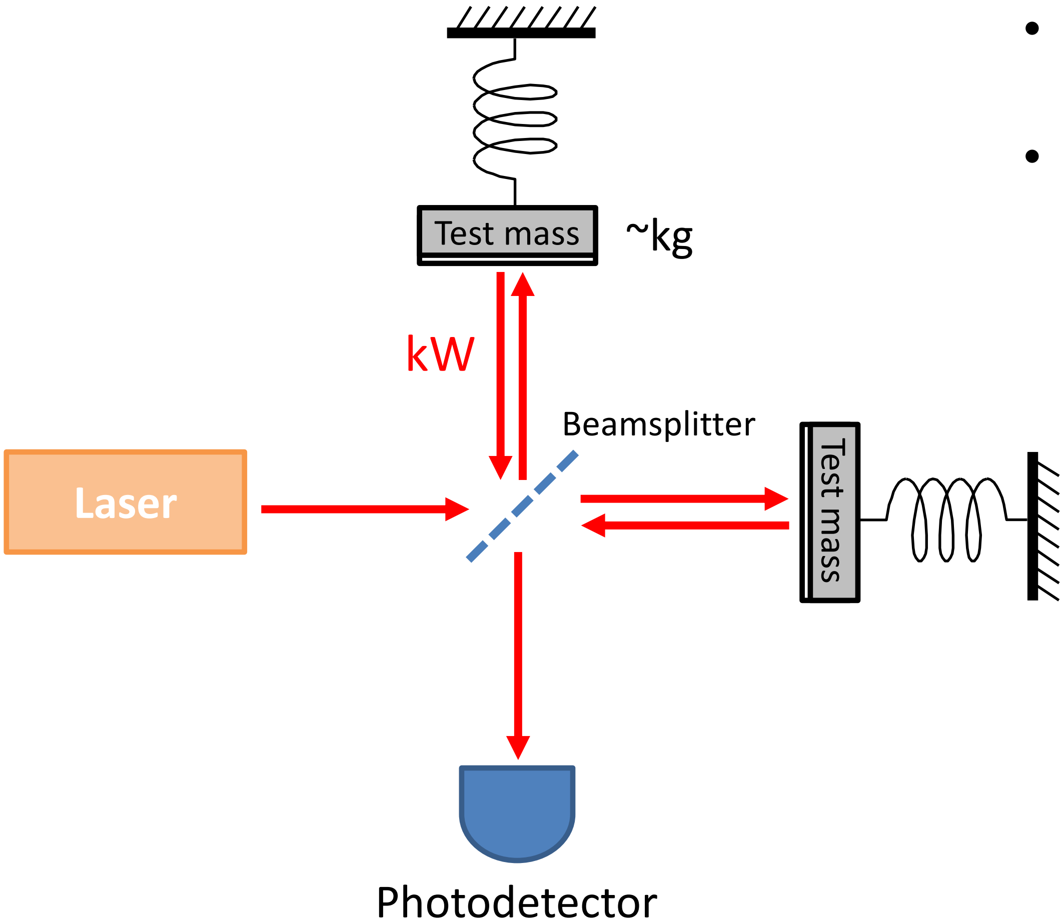
- Sensitive optical interferometer
- Aims to detect $\sim 10^{-18}$ m

In limit of strong probing



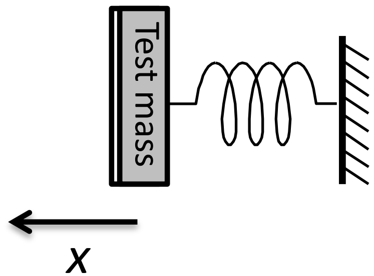
- No longer immutable structure
- Light pressure on mirrors important – radiation pressure
- Vladimir Braginsky, 1970's – instabilities

In limit of strong probing



- Effect on signal to noise?
- Will radiation forces combined with fluctuations of light obscure the motion?

Continuous measurement: Round 1



- *Back of the envelope* calculation (Heisenberg microscope argument)
- Consider free mass limit - time small compared to oscillation period
- To measure passing wave must measure more than once…

Measure to Δx_{meas} @ time t

Momentum uncertain to $\Delta p_{perturb} \geq \frac{\hbar}{2\Delta x_{meas}}$

At a later time….

$$\Delta x(t') = \Delta x(t) + \frac{\hbar(t'-t)}{2m\,\Delta x(t)} \longrightarrow \Delta x_{SQL} = \sqrt{\frac{2\hbar(t'-t)}{m}}$$

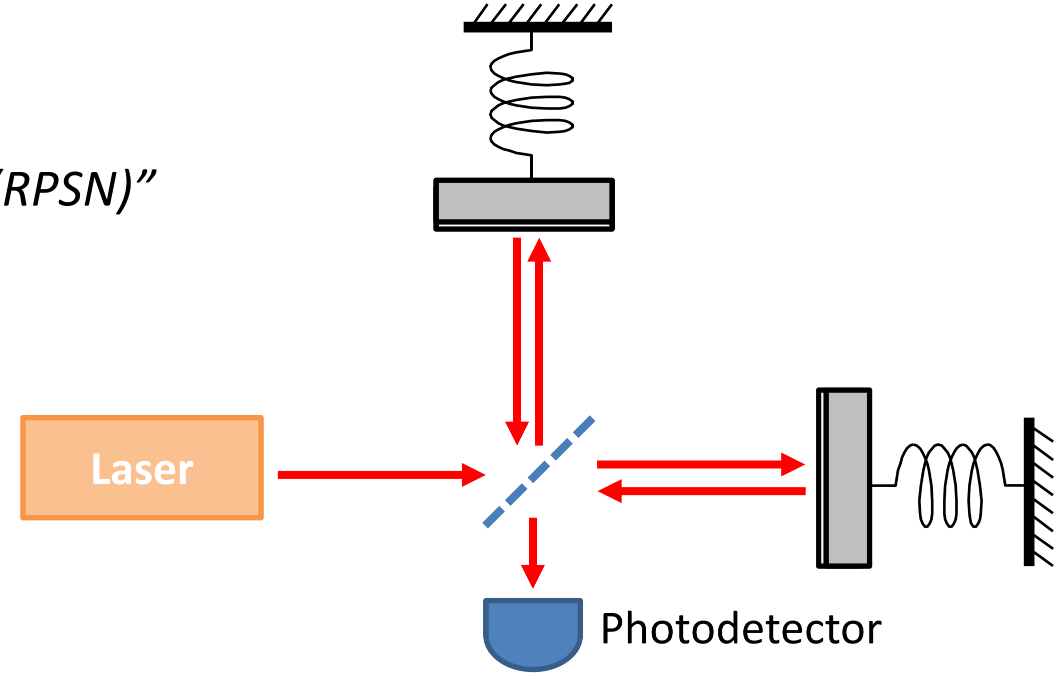
Source of backaction: Radiation pressure SN

Quantum-Mechanical Radiation-Pressure Fluctuations in an Interferometer

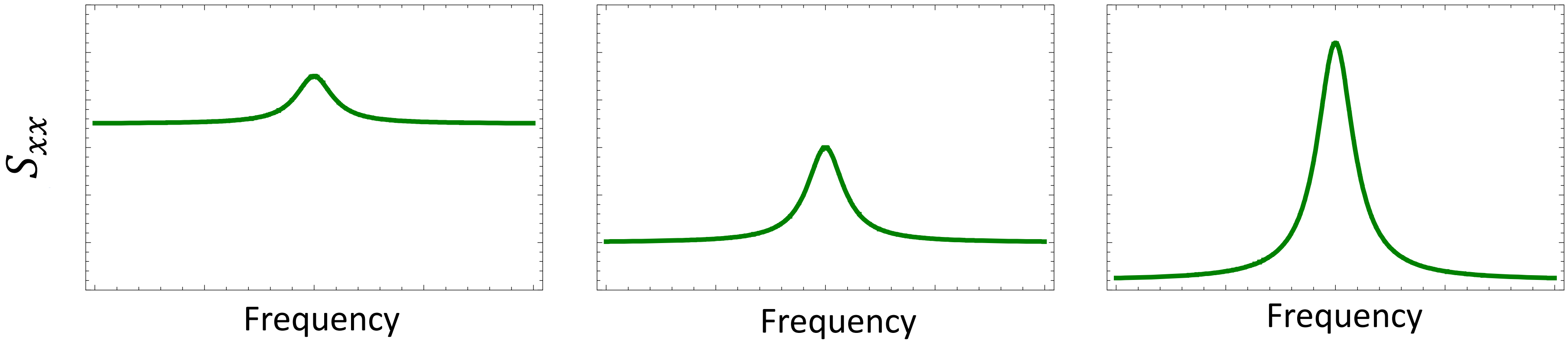
Carlton M. Caves
W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125
(Received 29 January 1980)

The interferometers now being developed to detect gravitational vaves work by measuring small changes in the positions of free masses. There has been a controversy whether quantum-mechanical radiation-pressure fluctuations disturb this measurement. This Letter resolves the controversy: They do.

Our terminology:
"Radiation pressure shot noise (RPSN)"



Standard quantum limit in continuous detection



$\to \omega$

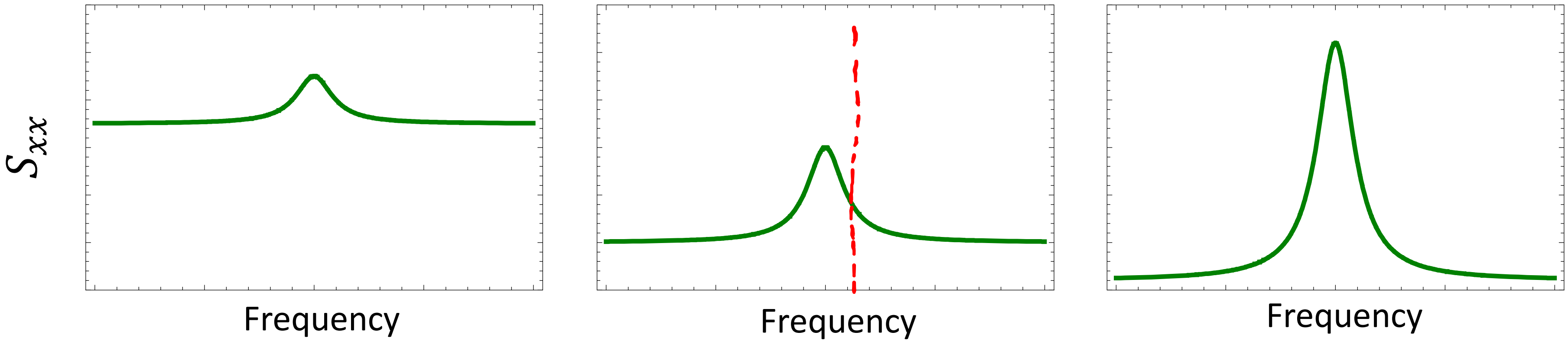
S_{xx} units m^2/Hz $\Rightarrow$ Imprecision S_{II}

Backaction force S_{FF}

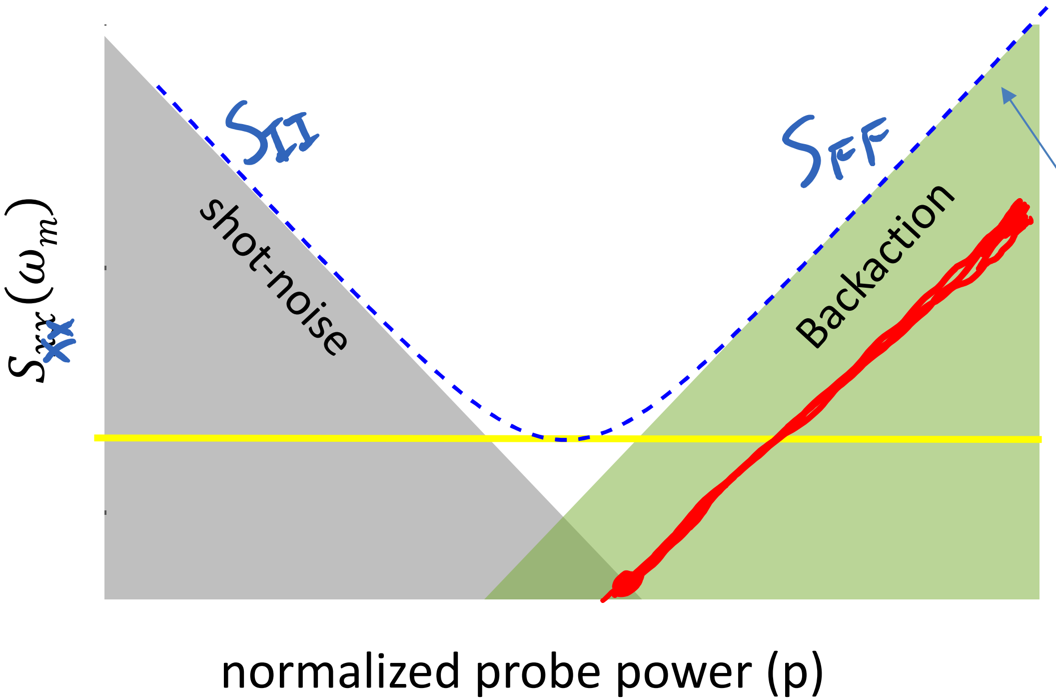
$\to |\chi_m|^2 S_{FF}$

$$\chi_m = \frac{1}{m(\omega^2 - \omega_m^2) + i m \Gamma_m \omega}$$

Standard quantum limit in continuous detection



SQL on mechanical resonance



Measurement added noise
Ideal and 'standard' probe

Mechanical zero-point level

Added noise for two-quadrature measurements

$$X_1 = \frac{1}{2}(a_s + a_s^\dagger)$$

$$X_2 = \frac{1}{2i}(a_s - a_s^\dagger)$$

$$[X_1, X_2] = \frac{i}{2}$$

uncertainty product

$$\langle \Delta X_1^2 \rangle \langle \Delta X_2^2 \rangle \geq \frac{1}{16}$$

amplify

$$Y_1 = \sqrt{G_1} X_1 + F_1$$

$$Y_2 = \sqrt{G_2} X_2 + F_2$$

Also need $[Y_1, Y_2] = \frac{i}{2}$

Ends up implying

$$\frac{\langle \Delta Y_1^2 \rangle}{G_1} \frac{\langle \Delta Y_2^2 \rangle}{G_2} \geq \frac{1}{16}\left(2 - \cancel{\frac{1}{\sqrt{G_1}\sqrt{G_2}}}\right)^2$$

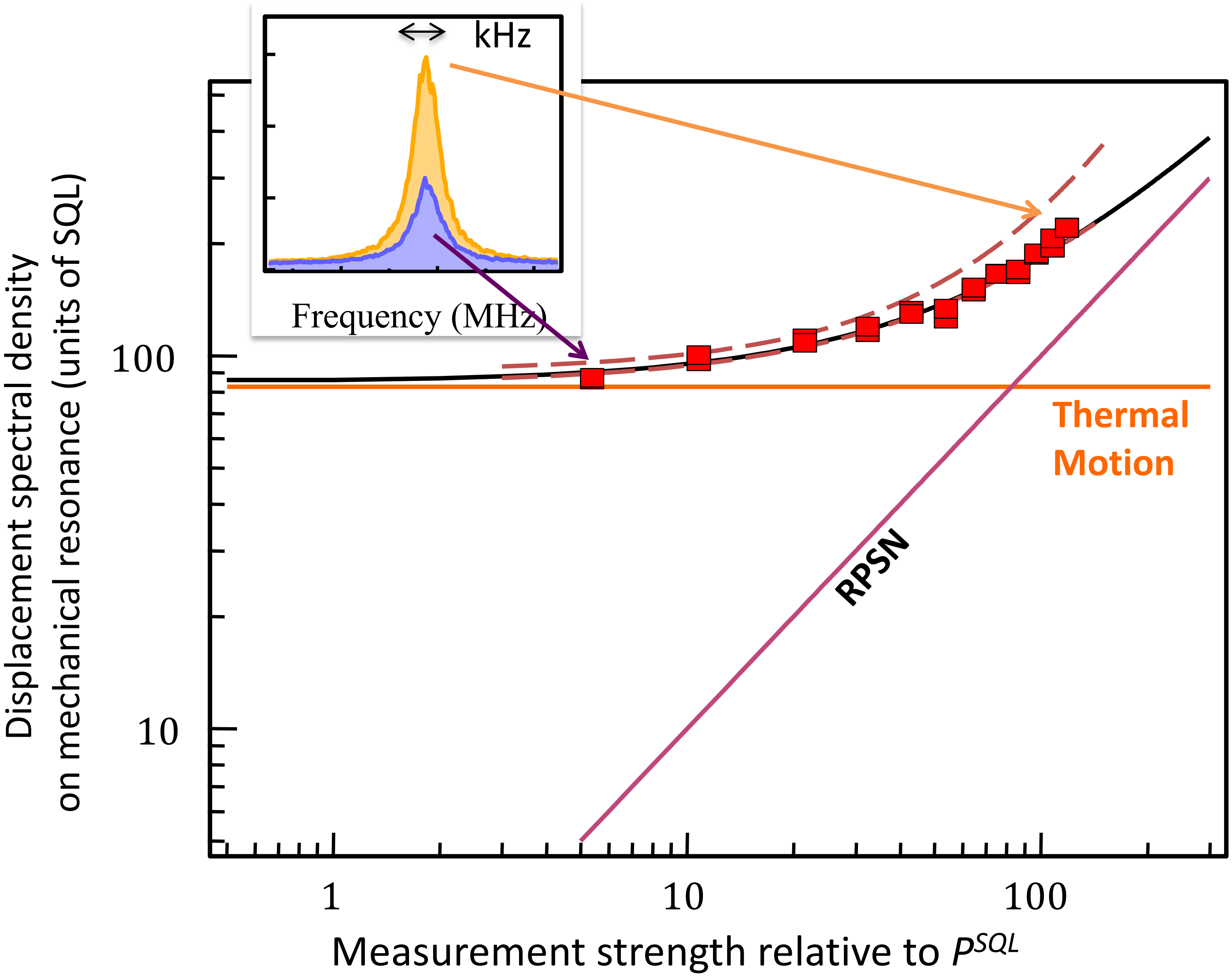
large G

Added noise $A_n = 1/2$

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

Experiment: Observation of RPSN

RPSN: Radiation Pressure Shot Noise

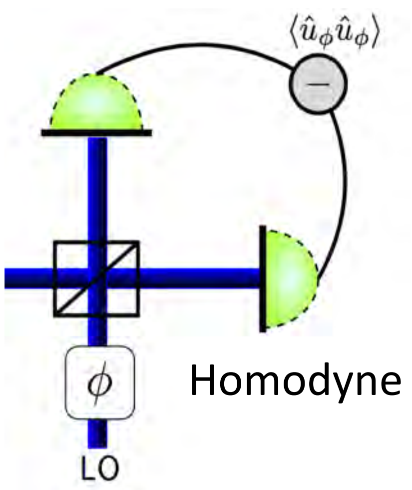


In 4 K cryostat

T. P. Purdy *et al.*, Science (2013)

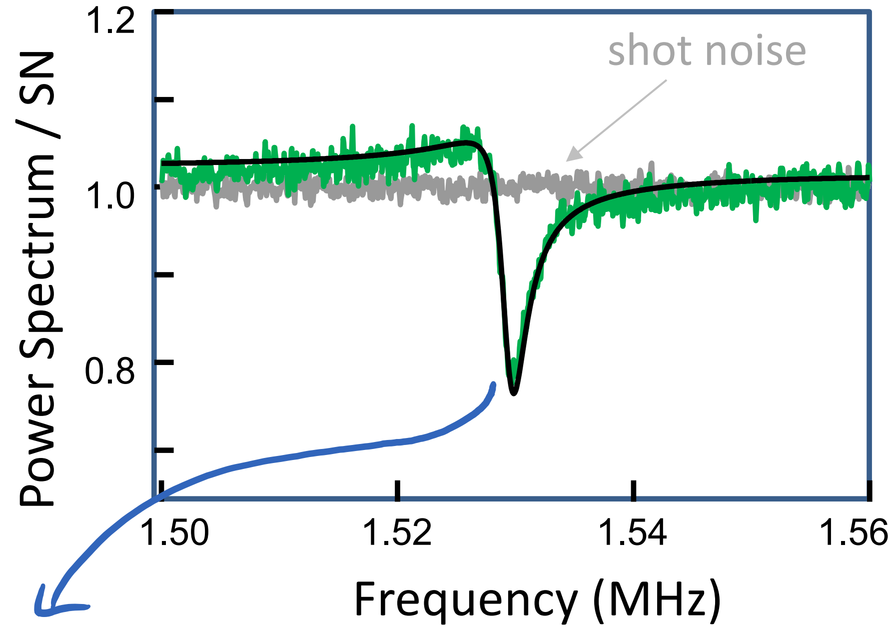
Squeezing of light: Correlations in quantum noise

Radiation pressure shot noise (amplitude of light) drives mechanics, writes back onto cavity (phase of light)

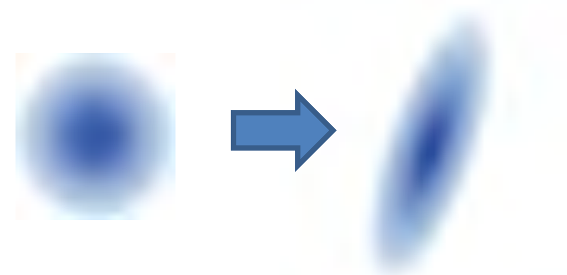


Homodyne detector

Ponderomotive Squeezing



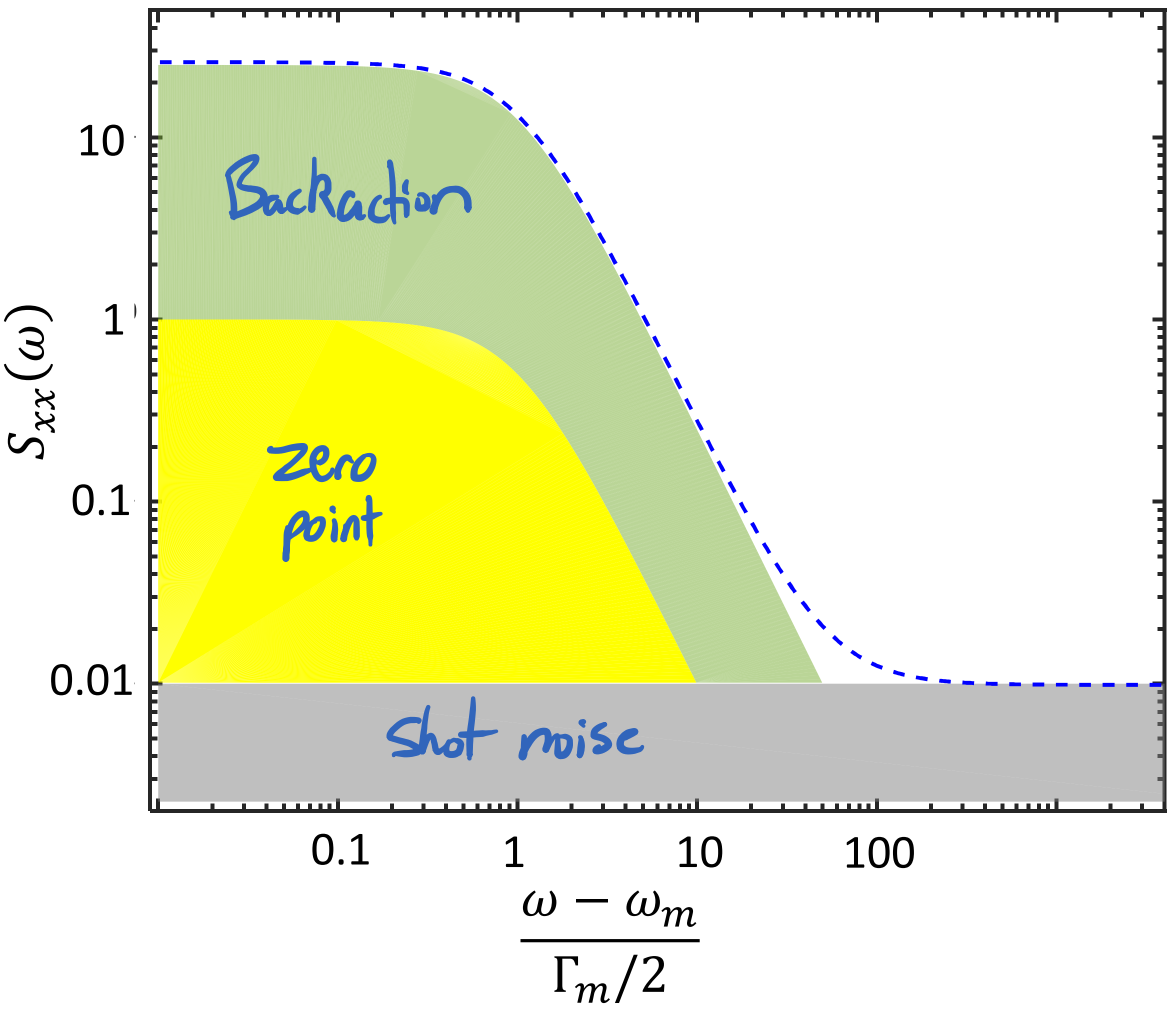
1.7dB



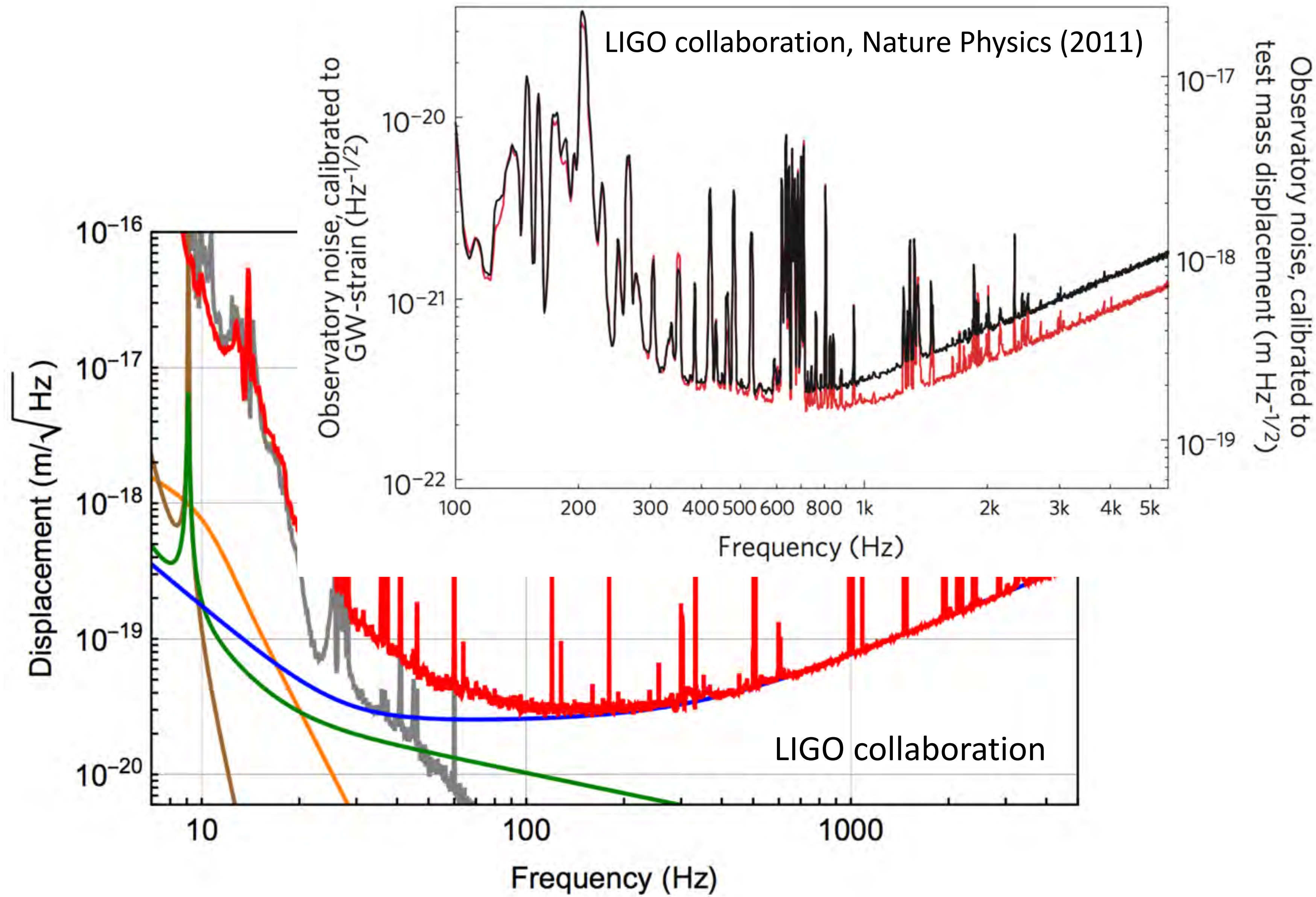
Optomechanical squeezing observed with:
Cold gases: D. W. Brooks…D. M. Stamper-Kurn, Nature (2012)
Nanomechanical devices: A.-H. Safavi-Naeini…O. Painter, Nature (2013); T. P. Purdy *et. al.,* PRX (2013)

Illustrated guide to broadband detection

Frequency dependence for backaction-limited probe

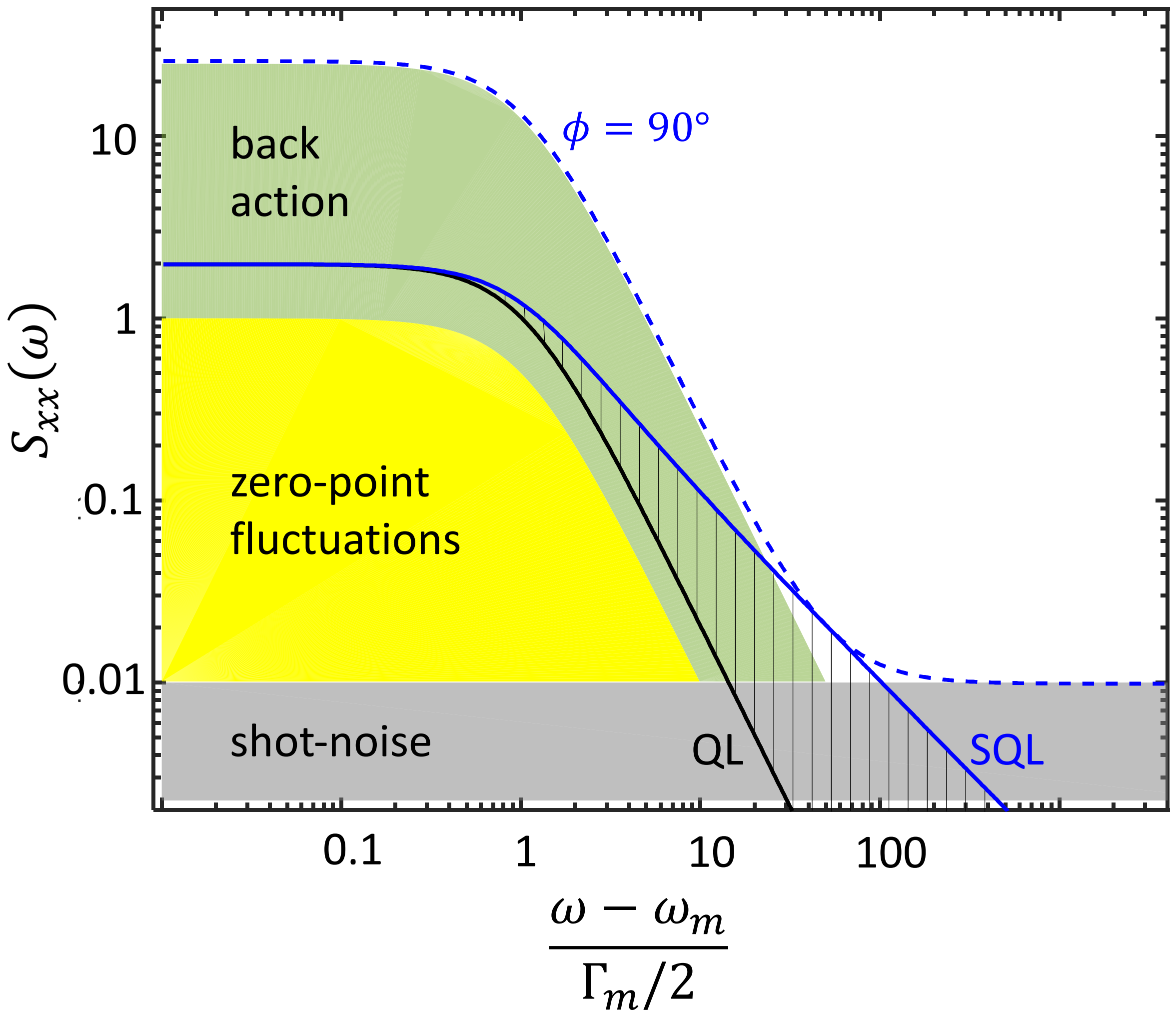


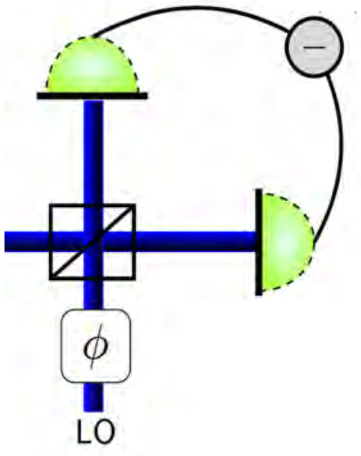
LIGO measurement context



Illustrated guide to broadband detection

$$X_\phi = X_{AM}\cos\phi + X_{PM}\sin\phi$$

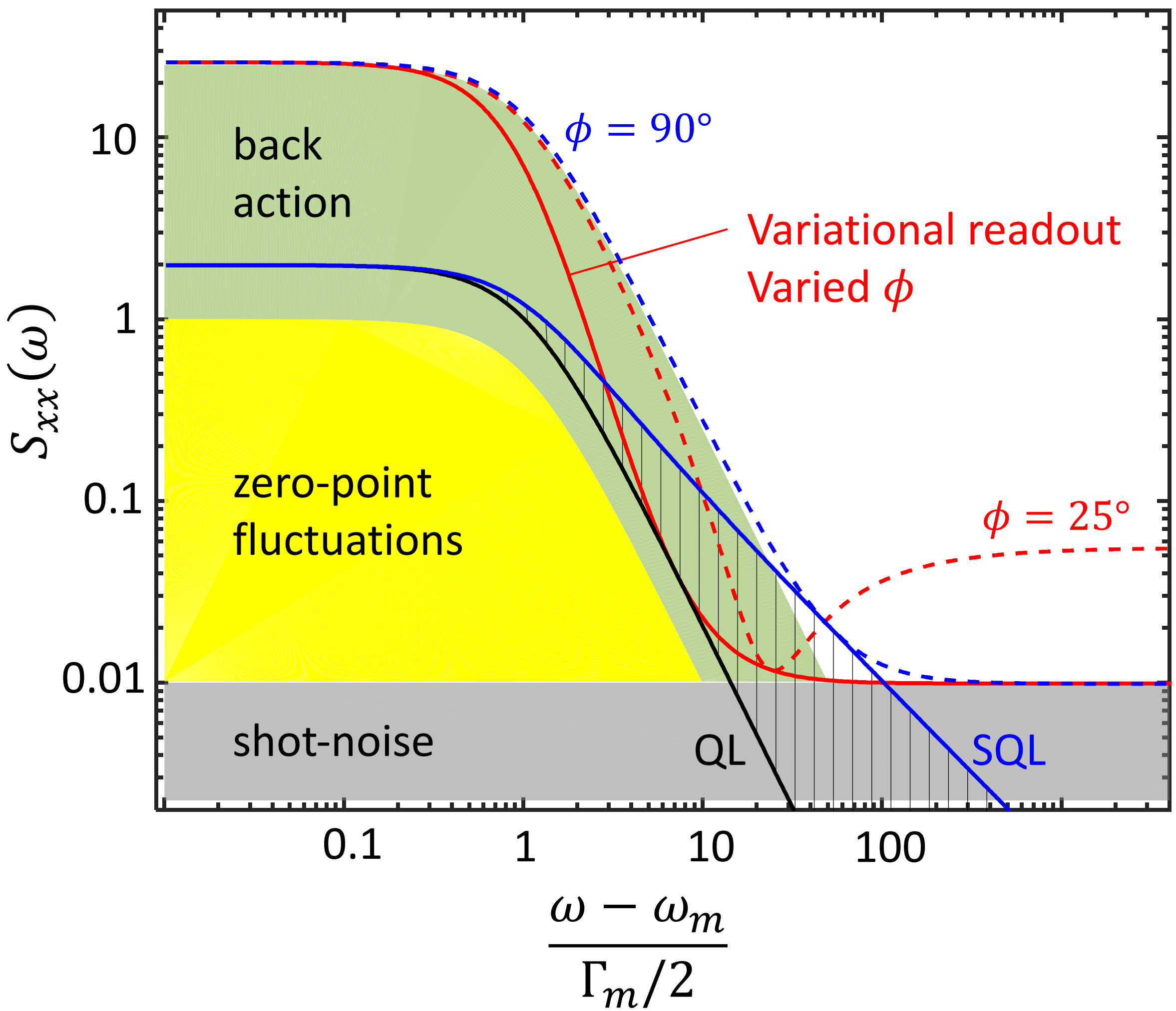


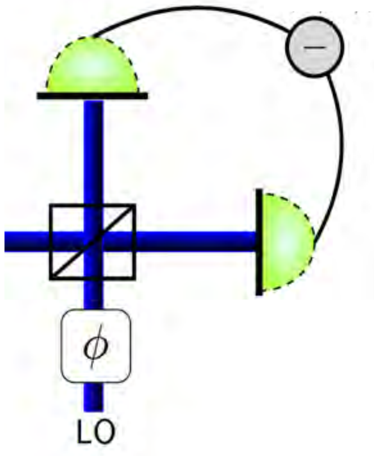


QL – quantum limit for two mechanical quadrature measurement

Using ponderomotive squeezing

$$X_{\phi} = X_{AM} \cos\phi + X_{PM} \sin\phi$$

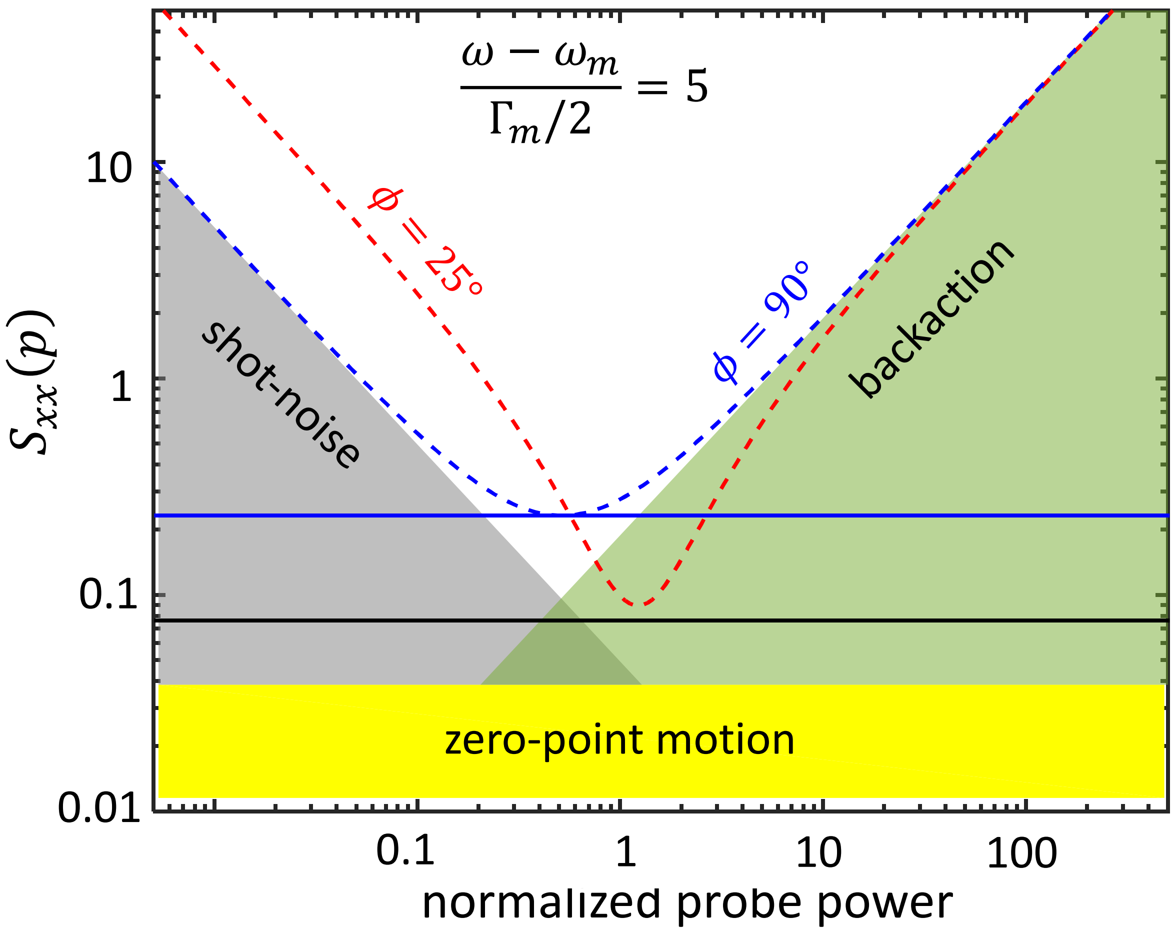




Variational ideas: S. P. Vyatchanin and E. A. Zubova, Phys. Lett. A (1995). H. J. Kimble *et al.* PRD (2001)

As a function of probe power

$$X_\phi = X_{AM}\cos\phi + X_{PM}\sin\phi$$



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

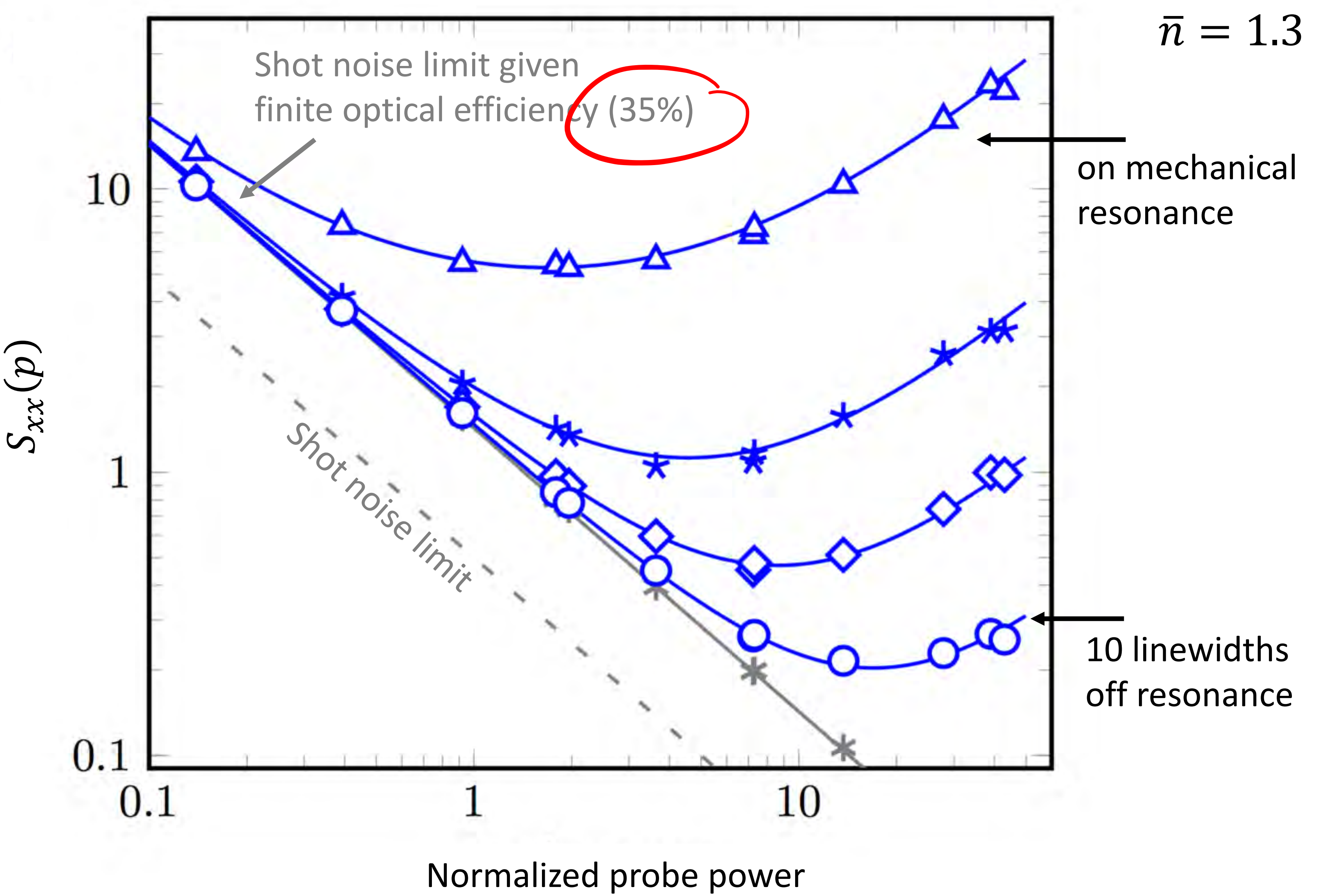
Analysis

$$S_{xx}(\omega) = S_m(\omega) + S_{II} + |\chi_m(\omega)|^2 S_{FF} + 2\,\mathrm{Re}\left[\chi_m(\omega) S_{IF}\right]$$

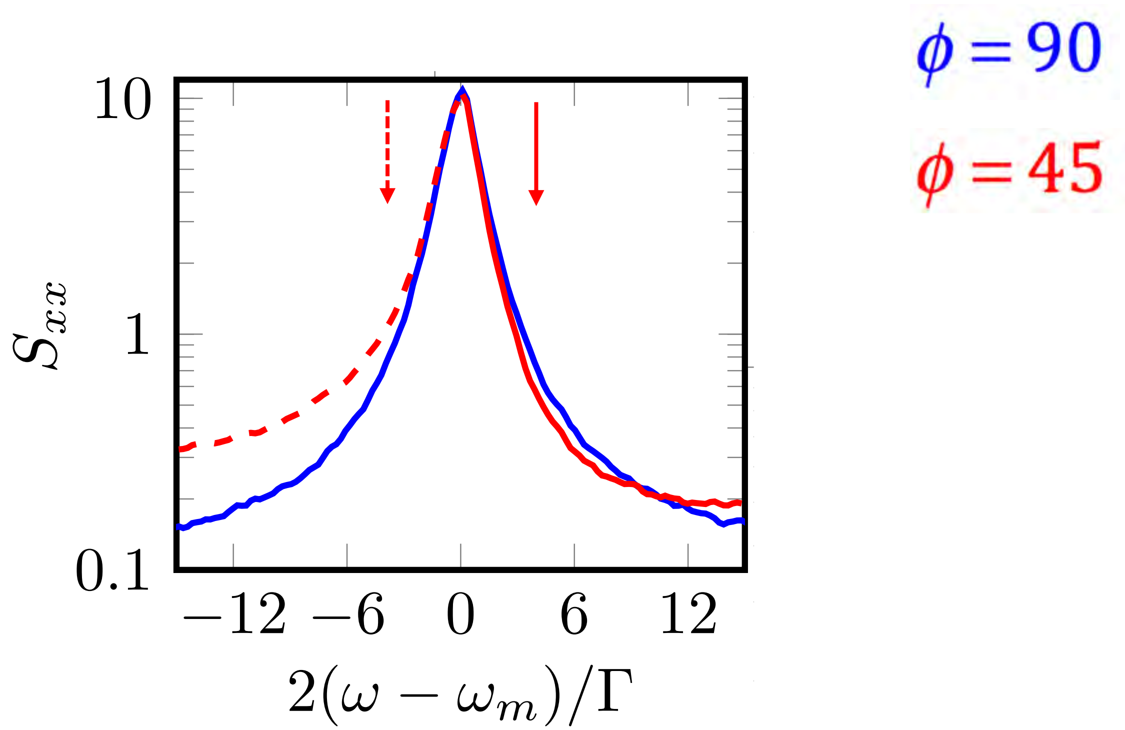
$$\chi_m(\omega) = \frac{1}{m(\omega^2 - \omega_m^2) + i\Gamma_m m\omega}$$

SQL and off-resonant SQL measurements

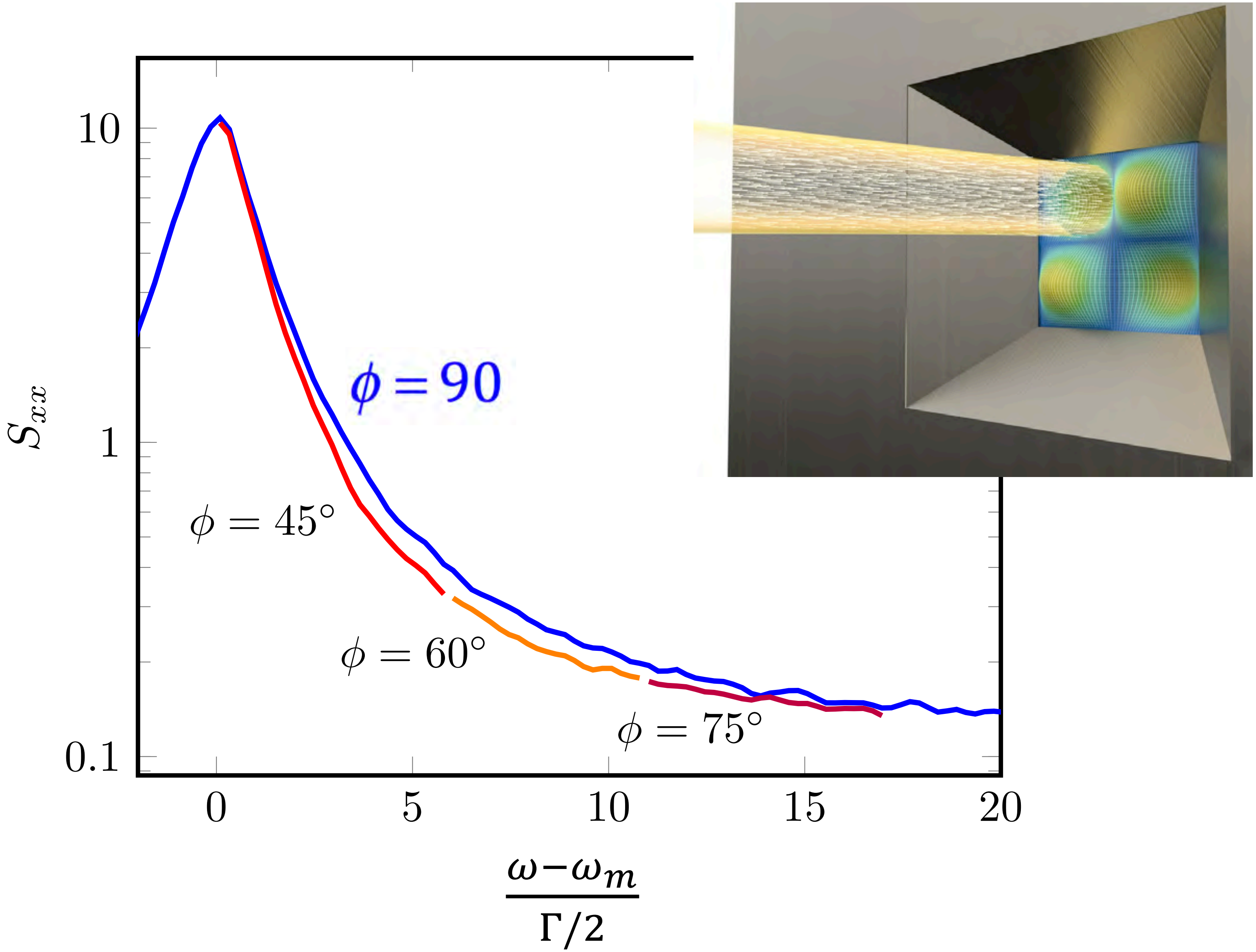
Probe damped mechanics with on-cavity-resonance probe



SQL and off-resonant SQL measurements

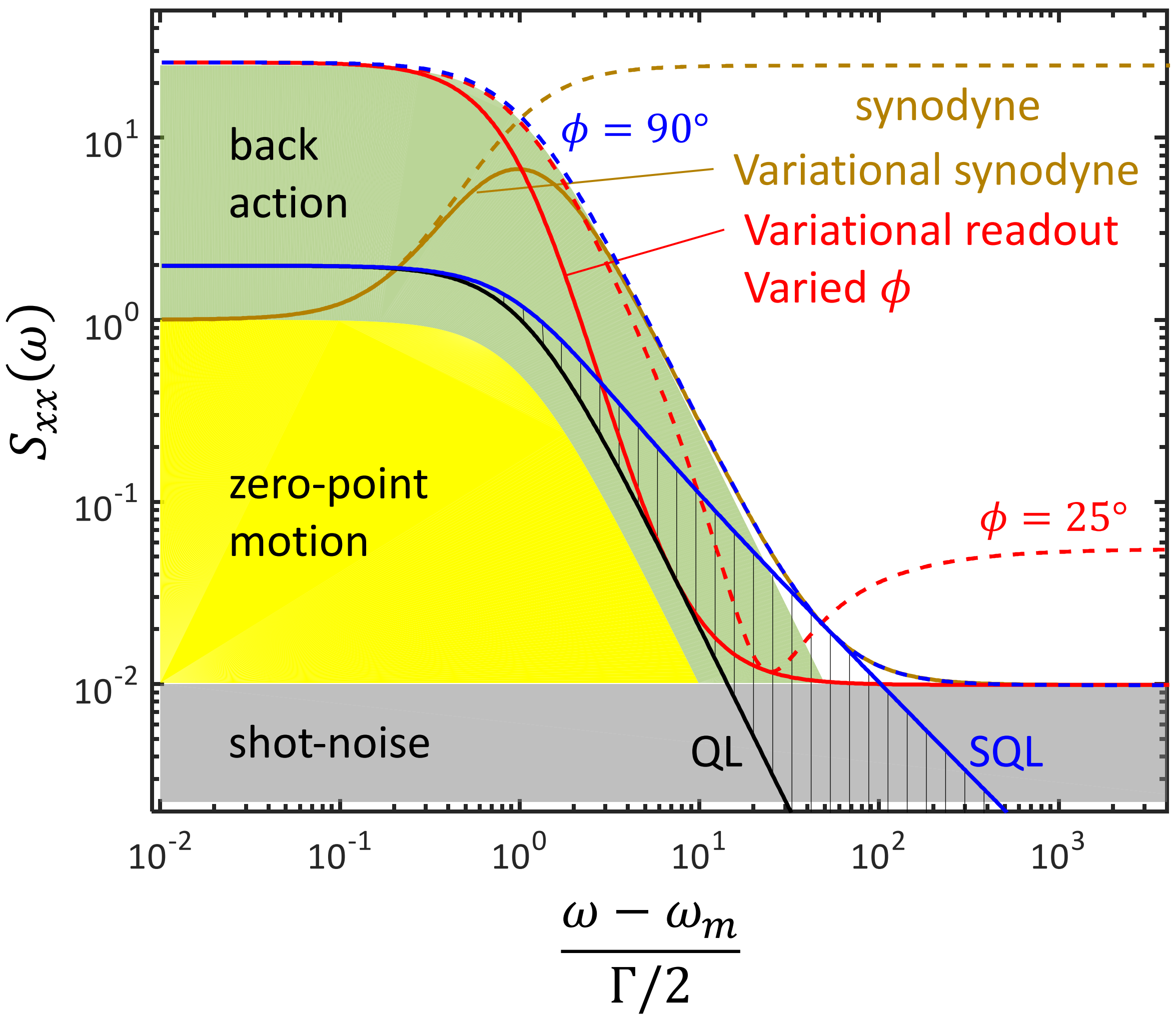


Idea of variational readout



N. S. Kampel…C. A. Regal PRX (2017)

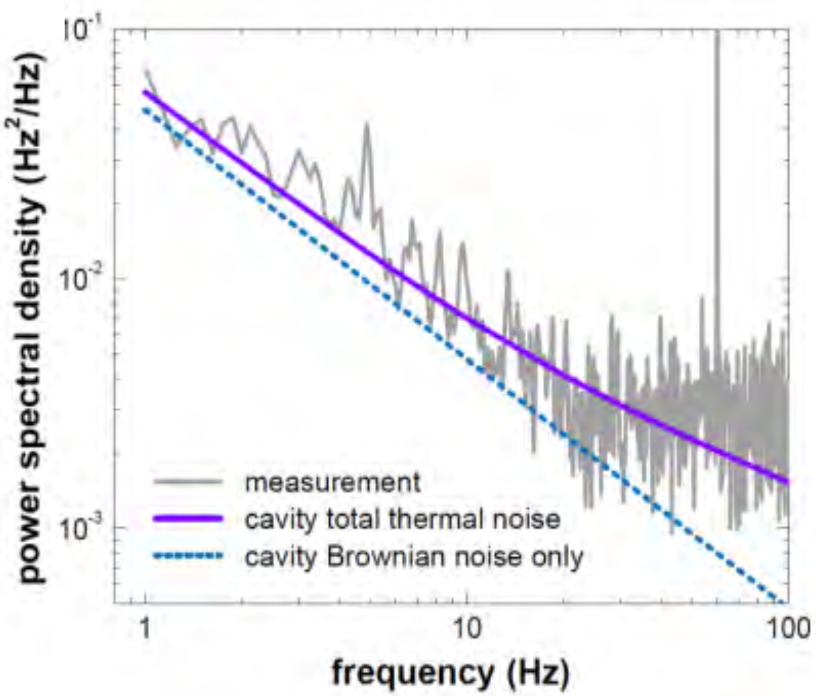
Illustrated guide to broadband detection

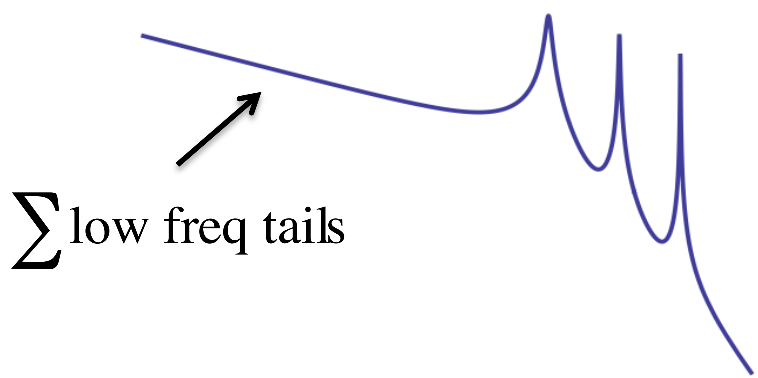


L. Buchmann *et al.*, PRL (2016)

Thermal noise – ubiquitous problem in metrology

State of the art reference cavities





- Tail grows with material loss (smaller Q)
- Crystalline materials are desired

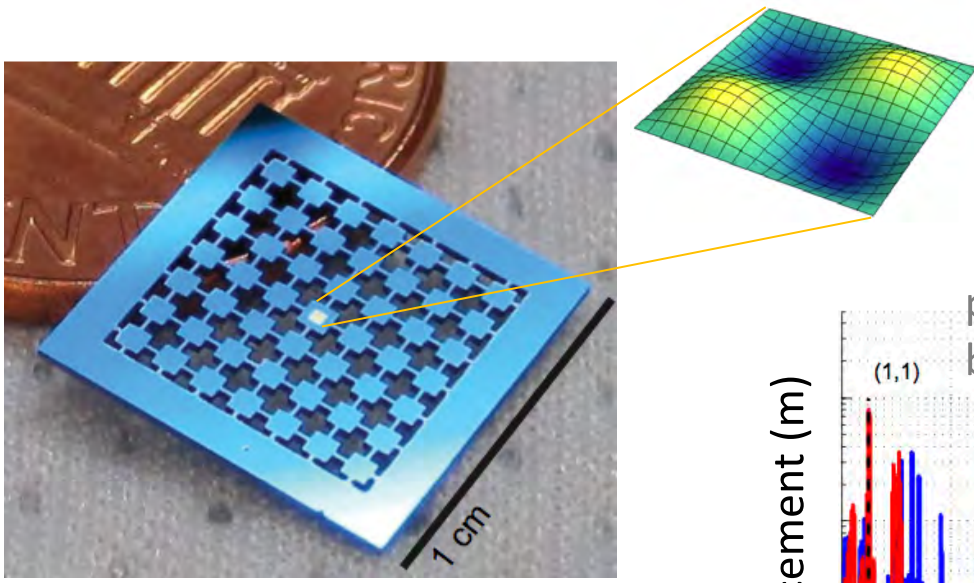
- We live in a forest of modes at higher frequency

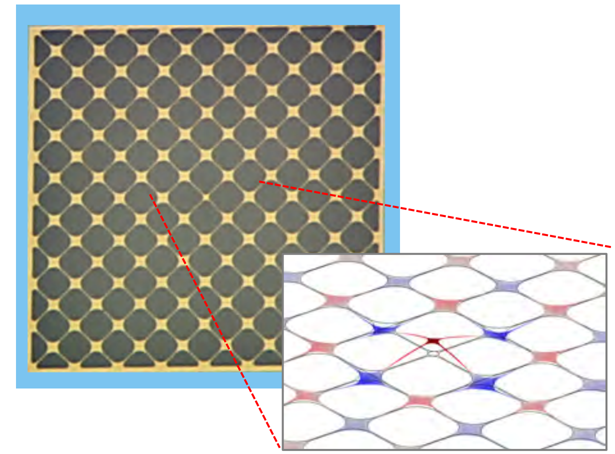
G. D. Cole *et al.* Nature Photonics (2013)

Phononic crystals

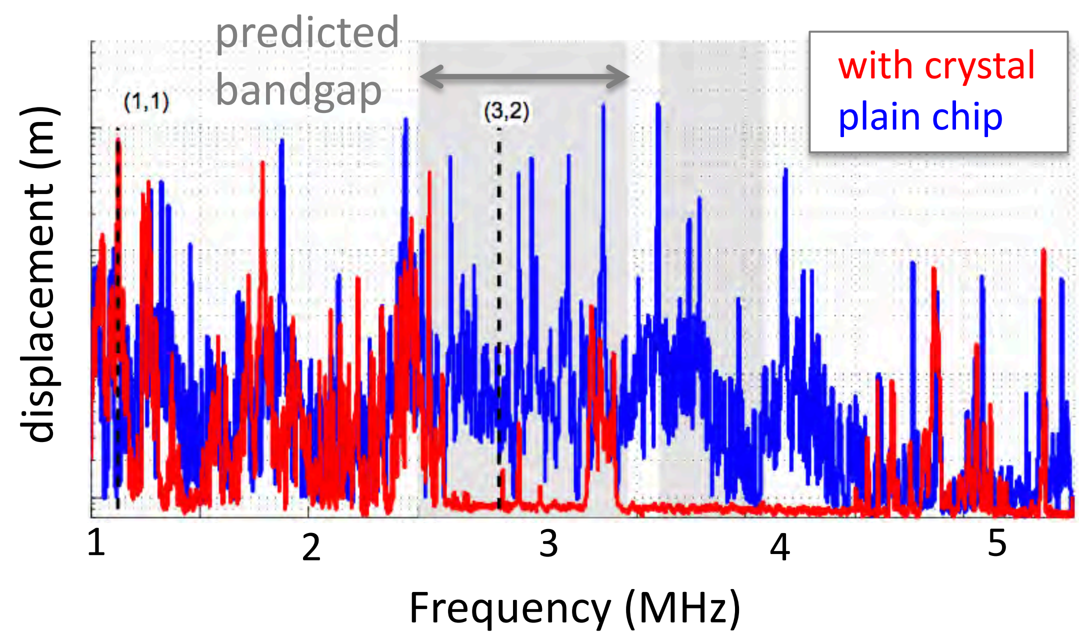
Period structures: Phononic crystal

- Control mode structure
- Reduce acoustic energy at lossy boundary





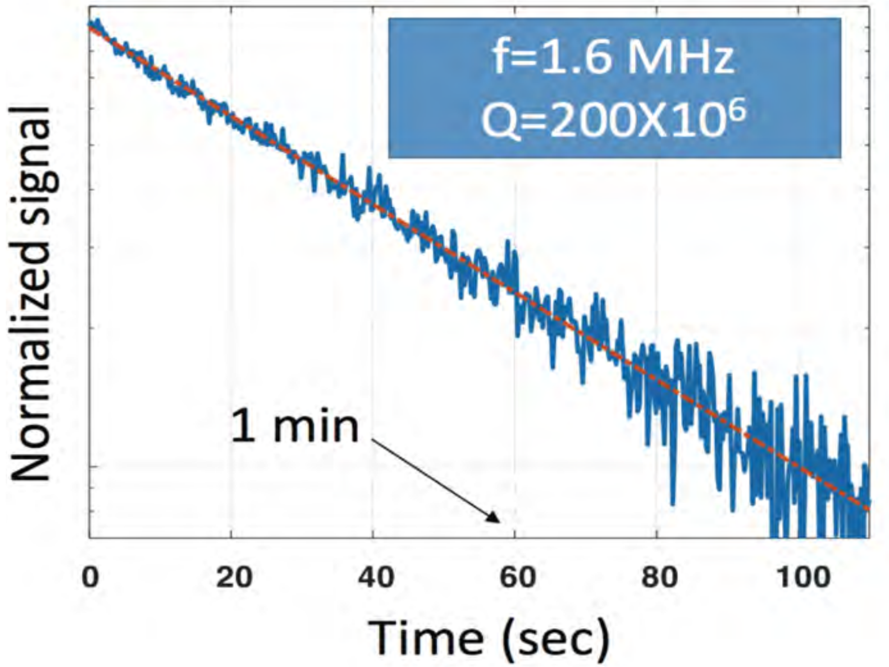
Displacement on membrane

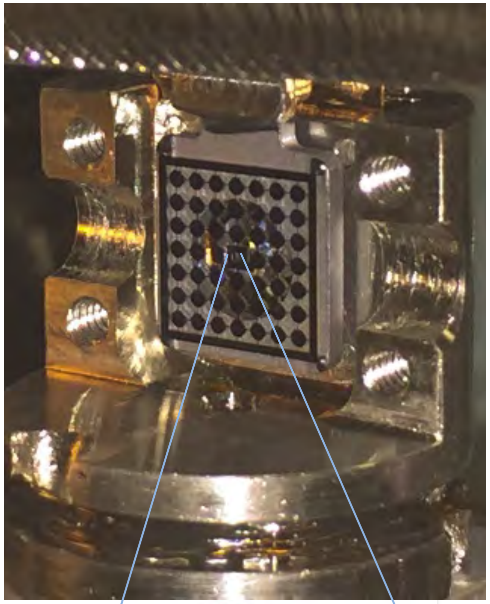


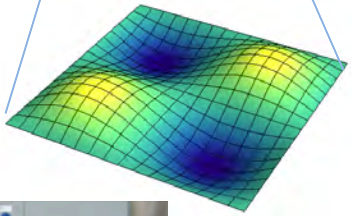
Mayer Alegre *et al.,* Optics Express (2011); Yu *et al.,* APL (2014)
Y. Tsaturyan *et al.,* Nature Nanotech (2016); M. Yuan…Steele, APL (2015)

Extreme mechanical properties

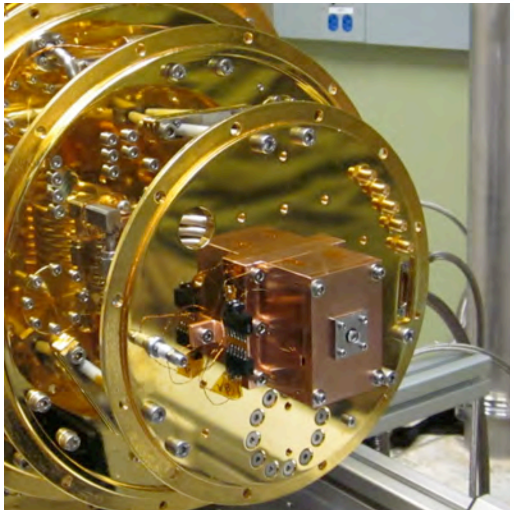
Drive membrane and watch energy decay







Corresponding heating rate = 10 quanta/ms

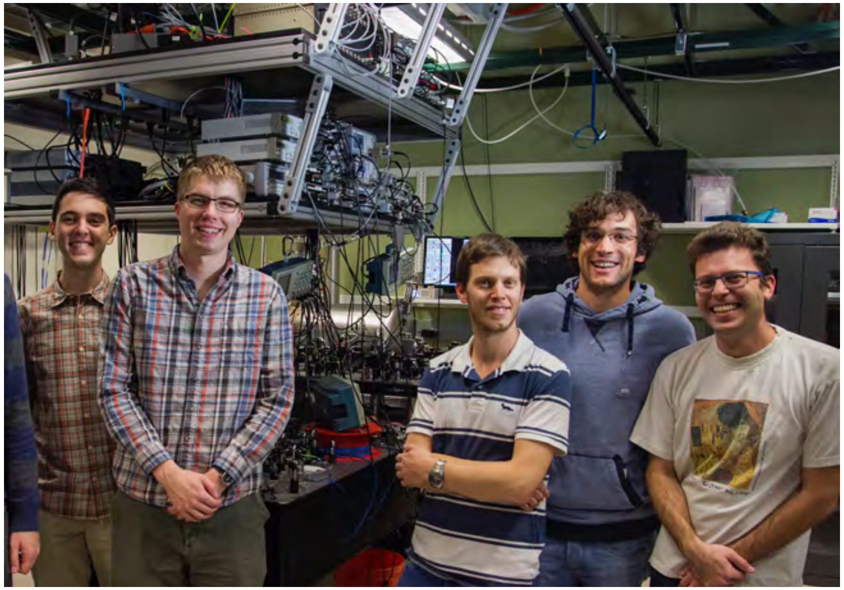


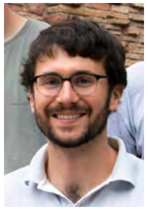
T=40 mK

M. Yuan…Steele, APL (2015)
R. Fischer *et al.,* in preparation

The team

Regal group optomechanics team





Max Urmey

Bob Peterson Ran Fischer Nir Kampel

Gabriel Assumpcao (undergrad) Oliver Wipfli

DURIP