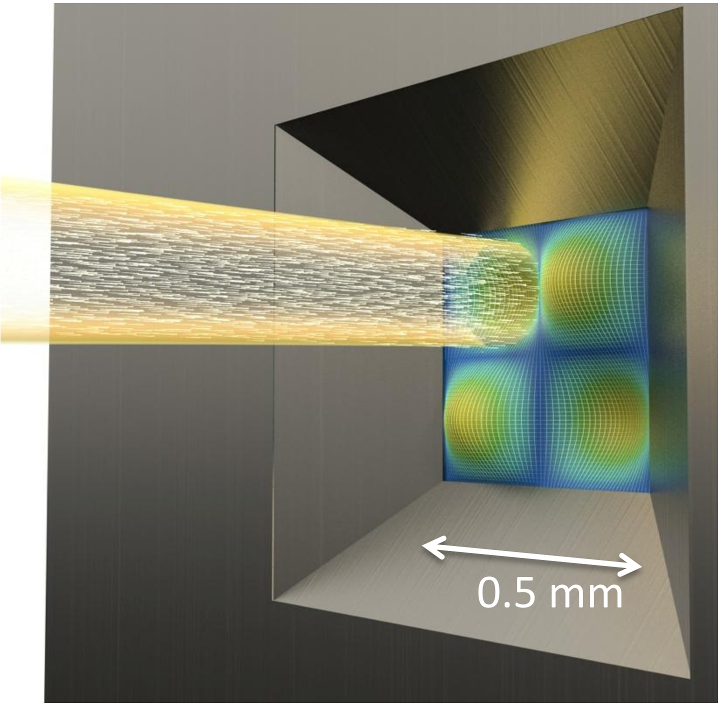
# Observing Radiation Pressure Shot Noise on a Solid Object

Cindy Regal
Tom Purdy
Bob Peterson
Ben Yu



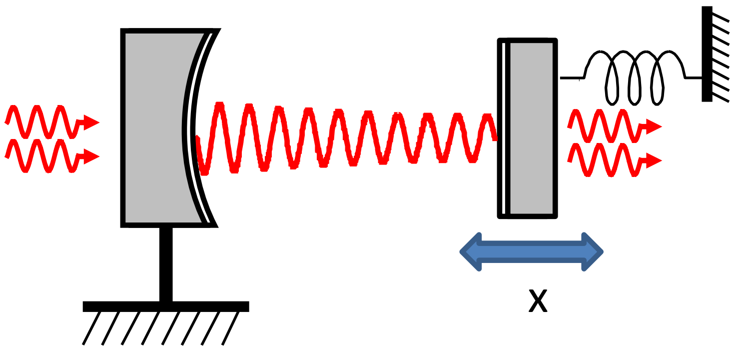

KITP, QuControl, 2013

JILA NIST CU

Boulder, CO, USA

# Orientation and outline

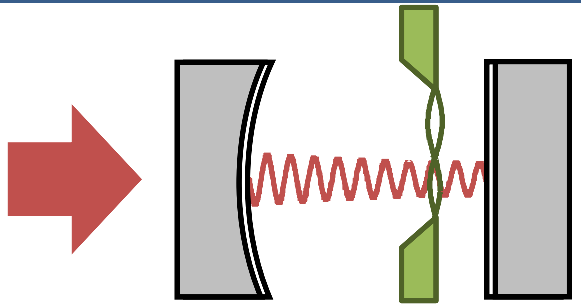
- (Quantum) **Cavity Optomechanics**
  *Measure and control motion of objects in interferometers near quantum limits*
  - One degree of freedom
  - larger – size, mass
  - complex?

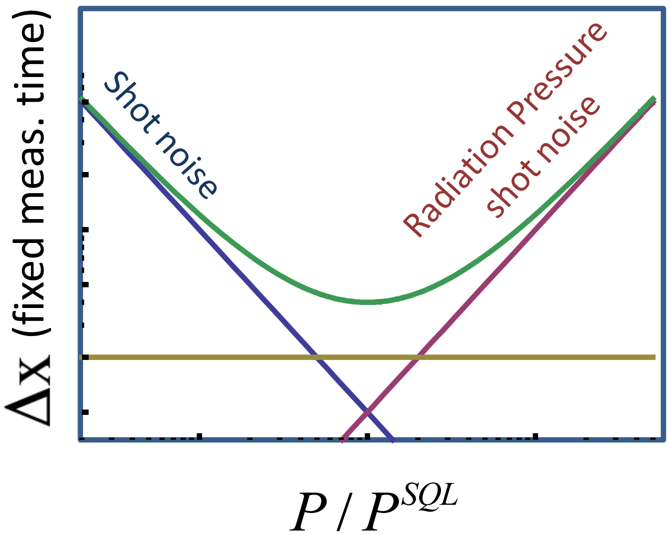


# Outline

- (Quantum) **Cavity Optomechanics**
  *Measure and control motion of objects in interferometers near quantum limits*

- Experiment presented: Observation of radiation pressure shot noise (RPSN)
  - Backaction branch of quantum-limited continuous position measurement





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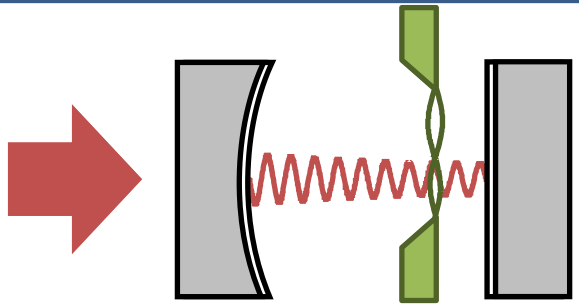

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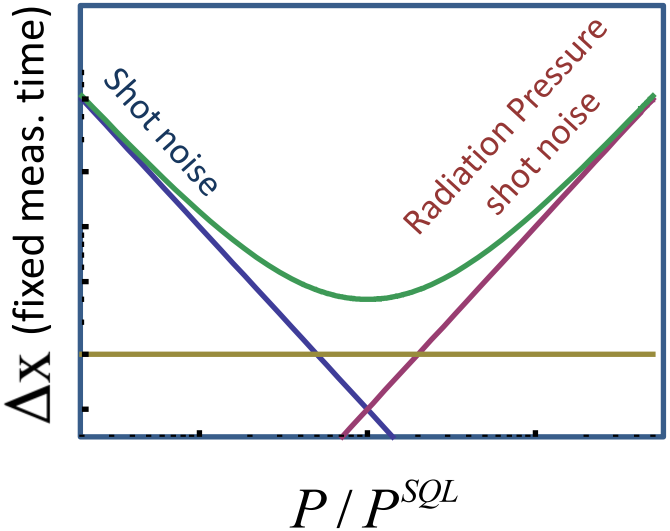
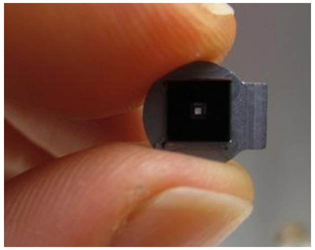
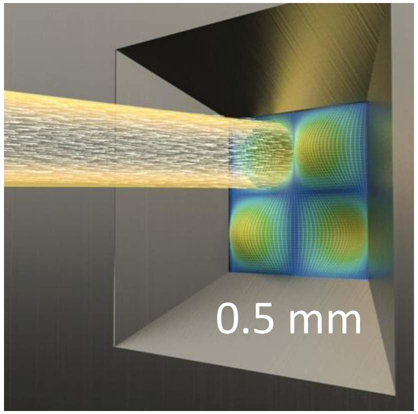



- Physical object: Very thin vibrating membrane
  - $Si_3N_4$ (50 nm by mm-scale)





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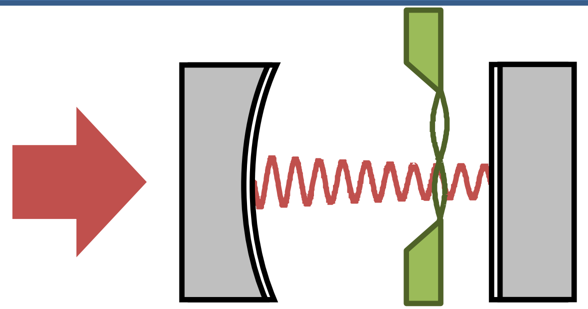
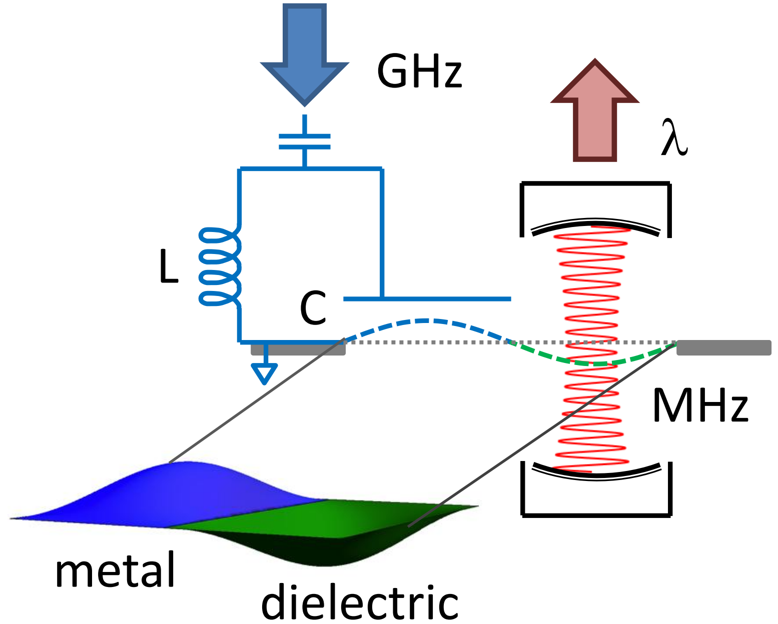
- Quantum information applications
  - Mechanically mediated interactions
  - Microwave - Optical






Electromechanics: Lehnert Group (JILA)

# Introduction

## Heisenberg uncertainty and precision measurement

Free mass limit

Measure to $\Delta x$ at time $t$

Momentum uncertain to

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

At later time…

$$\Delta x(t') = \Delta x(t) + \frac{\hbar(t'-t)}{2m\Delta x(t)}$$

## Heisenberg Microscope: Always some physical origin

Heisenberg's book, 1930…

*a*) *Determination of the position of a free particle.*—As a first example of the destruction of the knowledge of a particle's momentum by an apparatus determining its position, we consider the use of a microscope.[1] Let the particle be moving at such a distance from the microscope that the cone of rays scattered from it through the objective has an angular opening $\epsilon$. If $\lambda$ is the wave-length of the light illuminating it, then the uncertainty in the measurement of the $x$-co-ordinate (see Fig. 5) according to the laws of optics governing the resolving power of any instrument is:

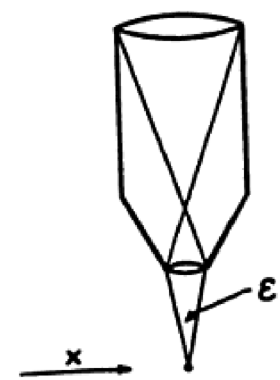
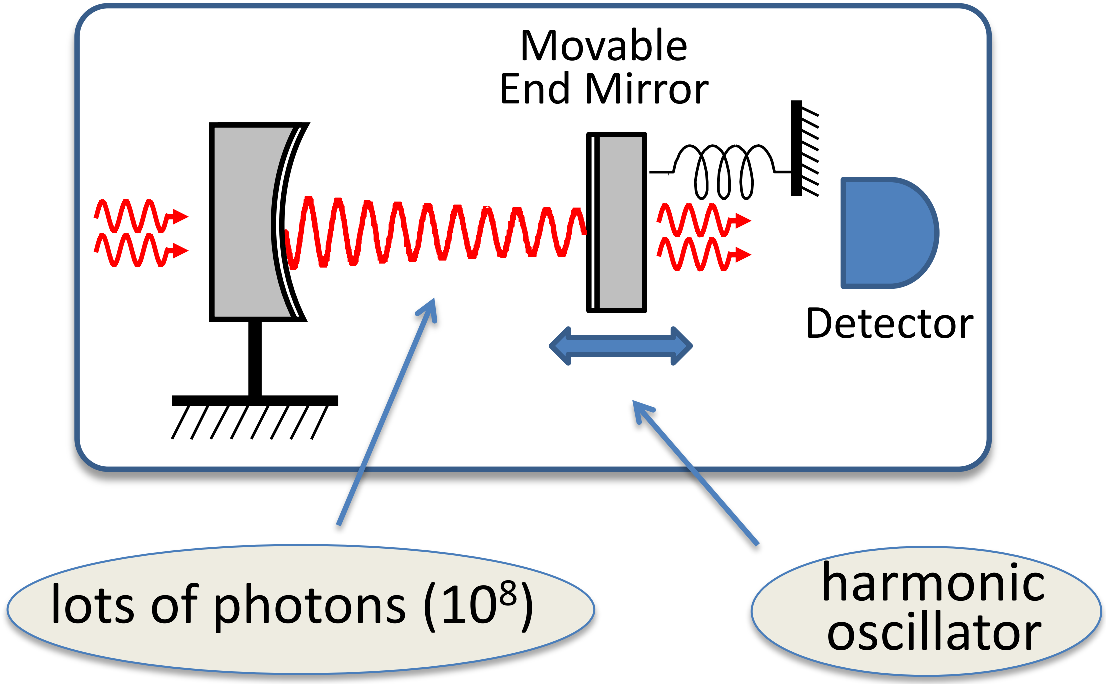



Fig. 5

$$\Delta x = \frac{\lambda}{\sin \epsilon}\,. \qquad (16)$$

See for example: Braginsky and Thorne, Science (1980)
Walls and Milburn, Quantum optics

# Our version




Shot noise $\sqrt{N}$

*Shot noise of radiation pressure* drives up mirror

# Full answer – modern quantum optics

PHYSICAL REVIEW LETTERS

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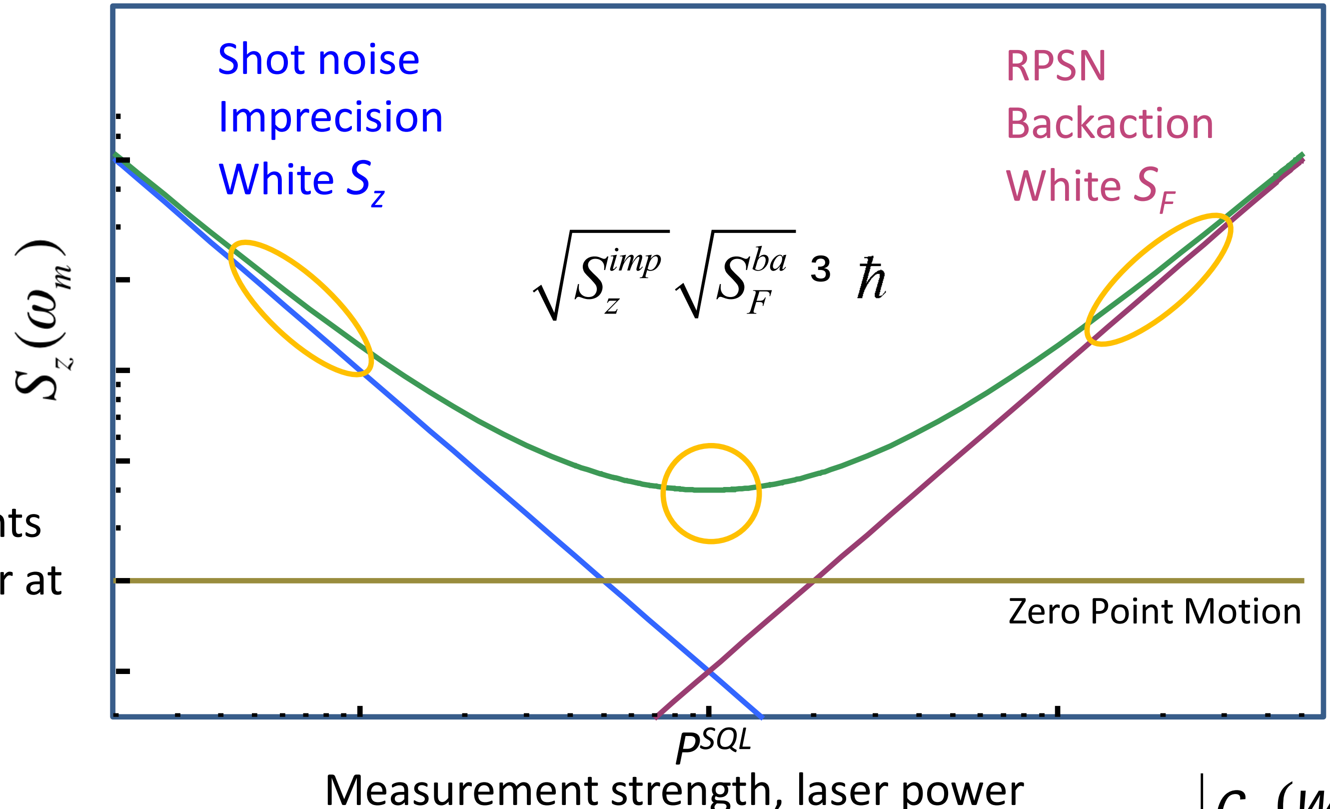
## Quantum-Mechanical Radiation-Pressure Fluctuations in an Interferometer

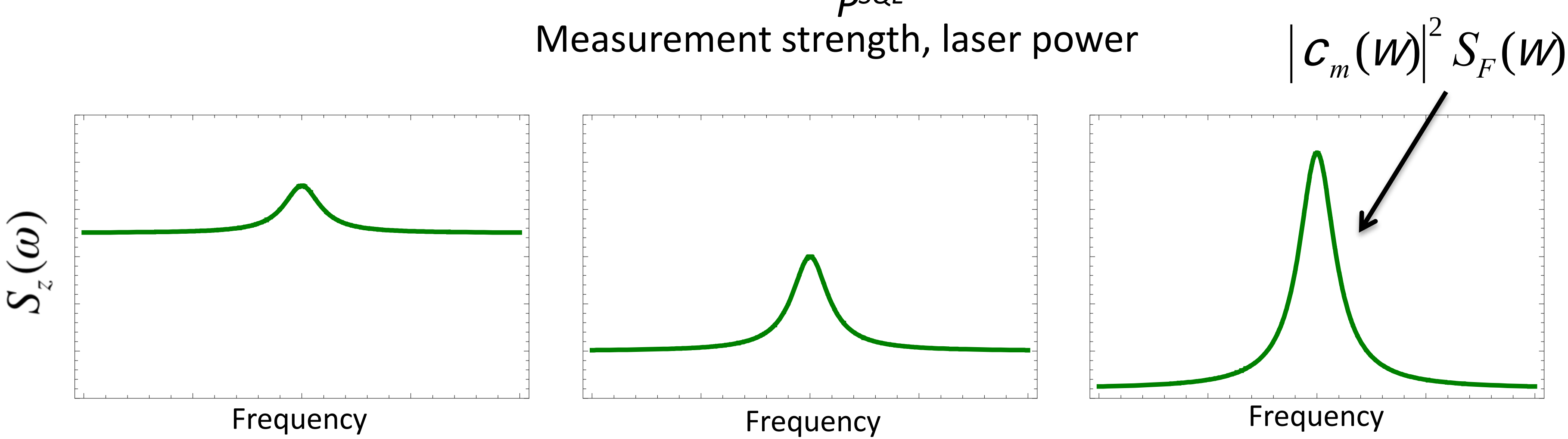
Carlton M. Caves
*W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125*
(Received 29 January 1980)

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.

# Standard Quantum Limit




Our measurements focus on behavior at resonance $\omega_m$



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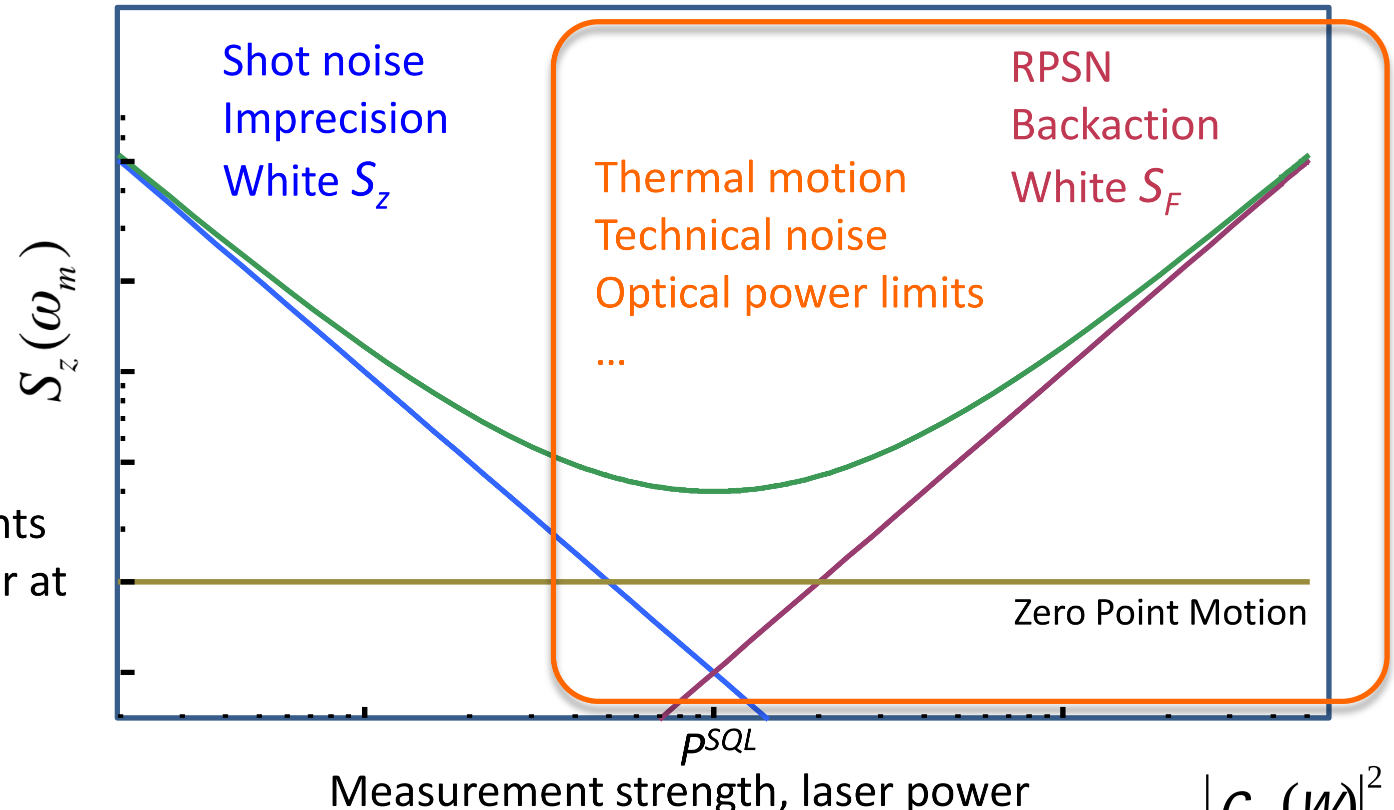
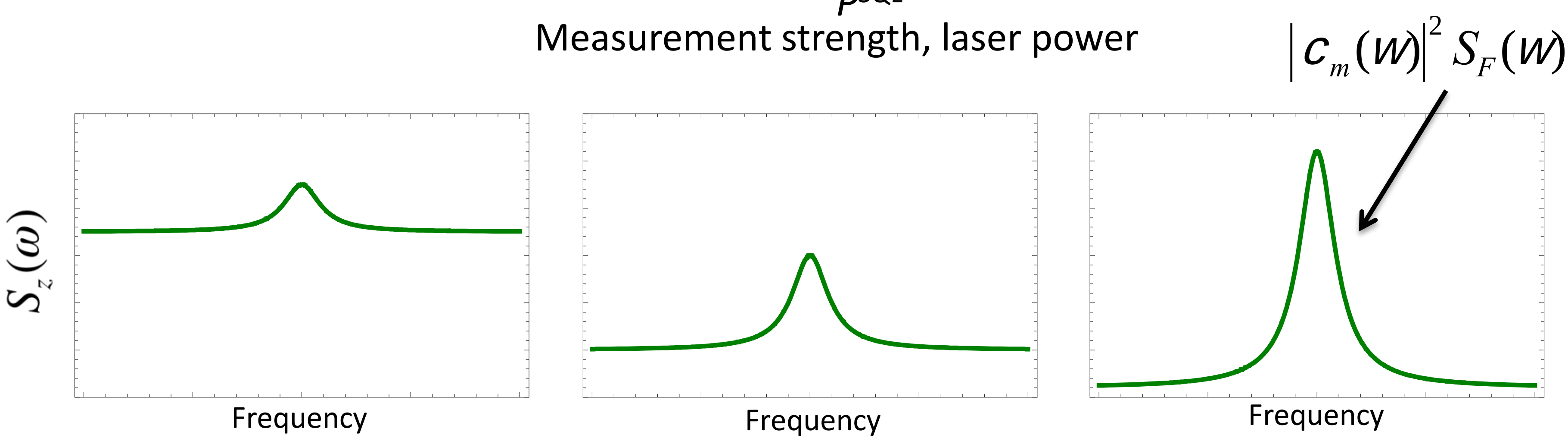


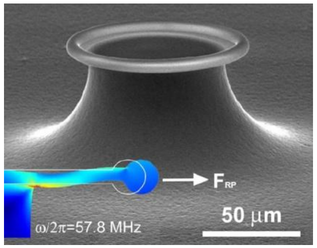

Our measurements focus on behavior at resonance $W_m$



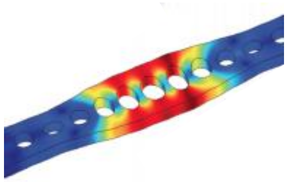
# Subset of spectrum of optomechanics experiments

## Optomechanics

Effectively moving mirrors



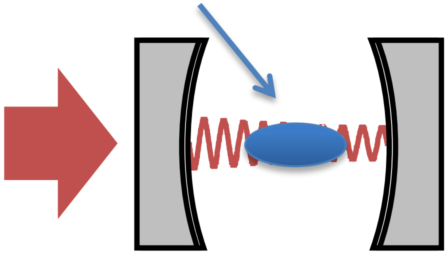

Kippenberg, EPFL



Painter, Caltech

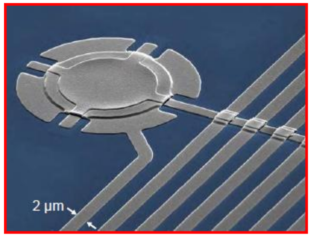
Gravitational wave detectors

trapped atoms



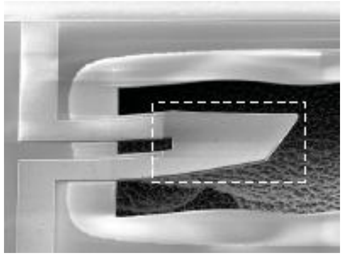
## Electromechanics

Moving capacitor plate




Lehnert/Simmonds, Boulder

Piezoelectrics

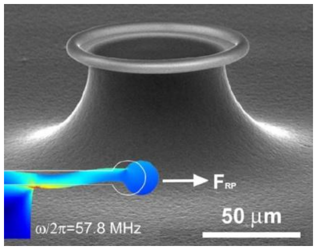


Cleland/Martinis
UCSB

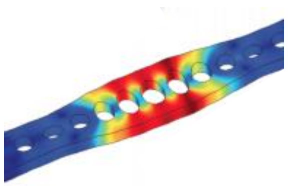
# Closely related optomechanics experiments

## Optomechanics

Effectively moving mirrors




Kippenberg, EPFL



Painter, Caltech

## Electromechanics

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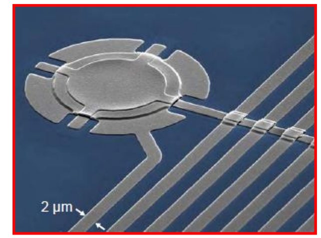
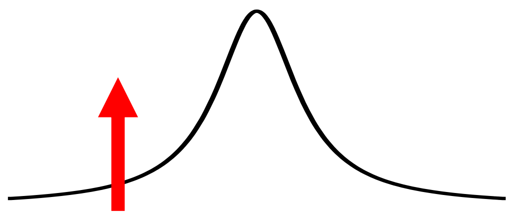
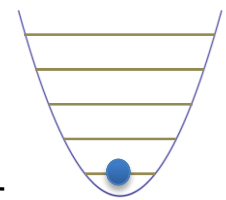
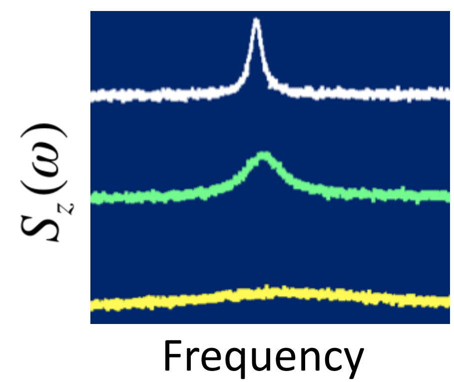



Lehnert/Simmonds, Boulder

"Laser" cooling to near the mechanical ground state
*(combined with cryogenic cooling)*

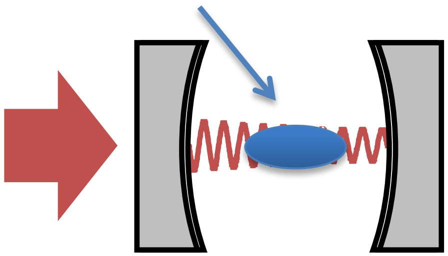






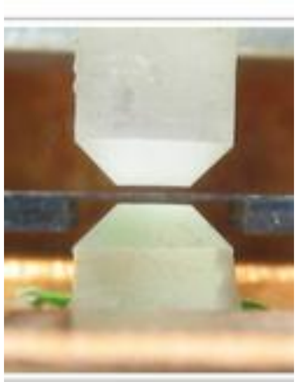

Observation of sideband asymmetry, Painter group

# Closely related optomechanics experiments




Observation of RPSN heating with atom gas
And ponderomotive squeezing

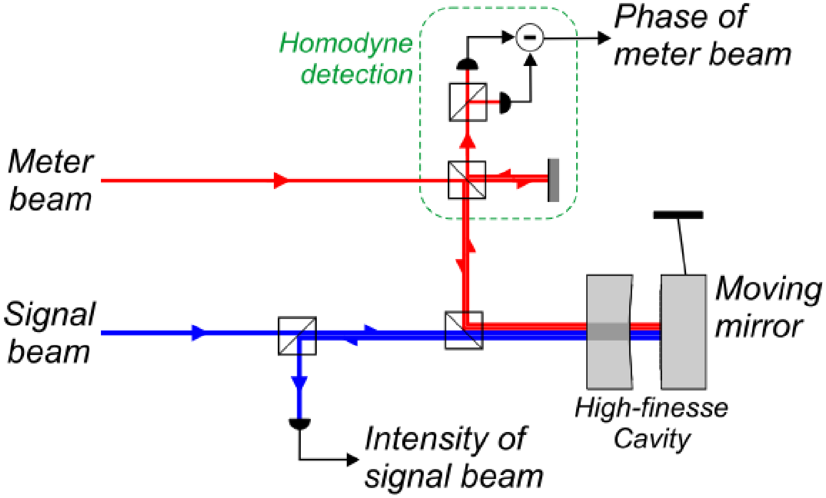
Stamper-Kurn group, Berkeley



# Closely related optomechanics experiments

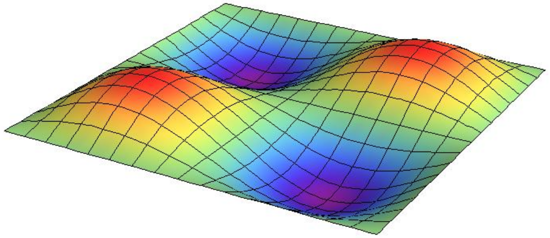
Gravitational wave detectors

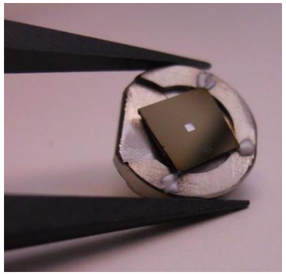
Experimental studies of classical analogs:
Heidmann group, Paris

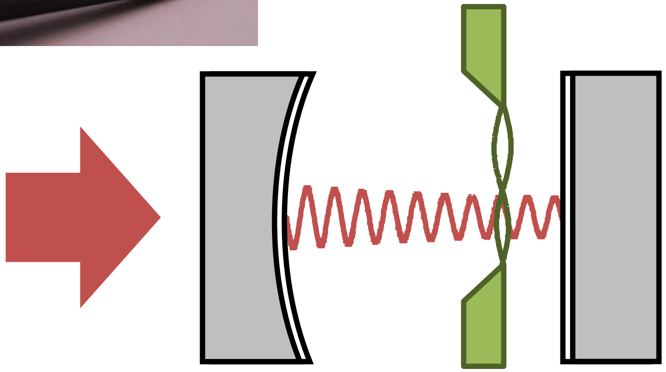


# Our optomechanical device

(2,2) drum mode



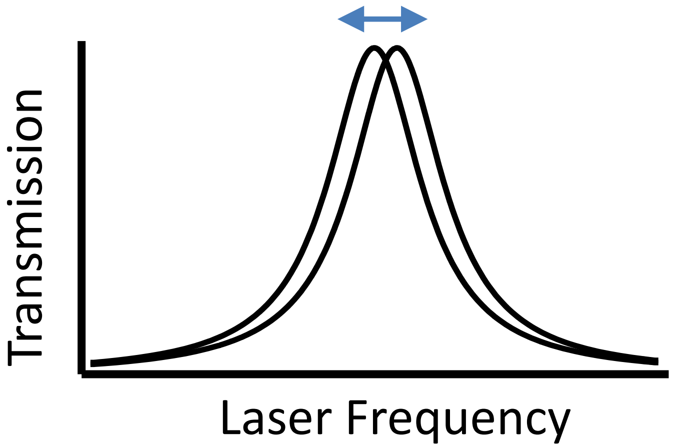




- Stoichiometric silicon nitride* sits in optical standing wave near end of cavity
- 50 nm thick drum - highly stressed, $\nu_m$=1 MHz
- Increases oscillator energy compared to thermal scales while keeping dissipation similar

$$Q \sim 10^6 \text{ - } 10^7$$

Cavity resonance shifts with membrane position

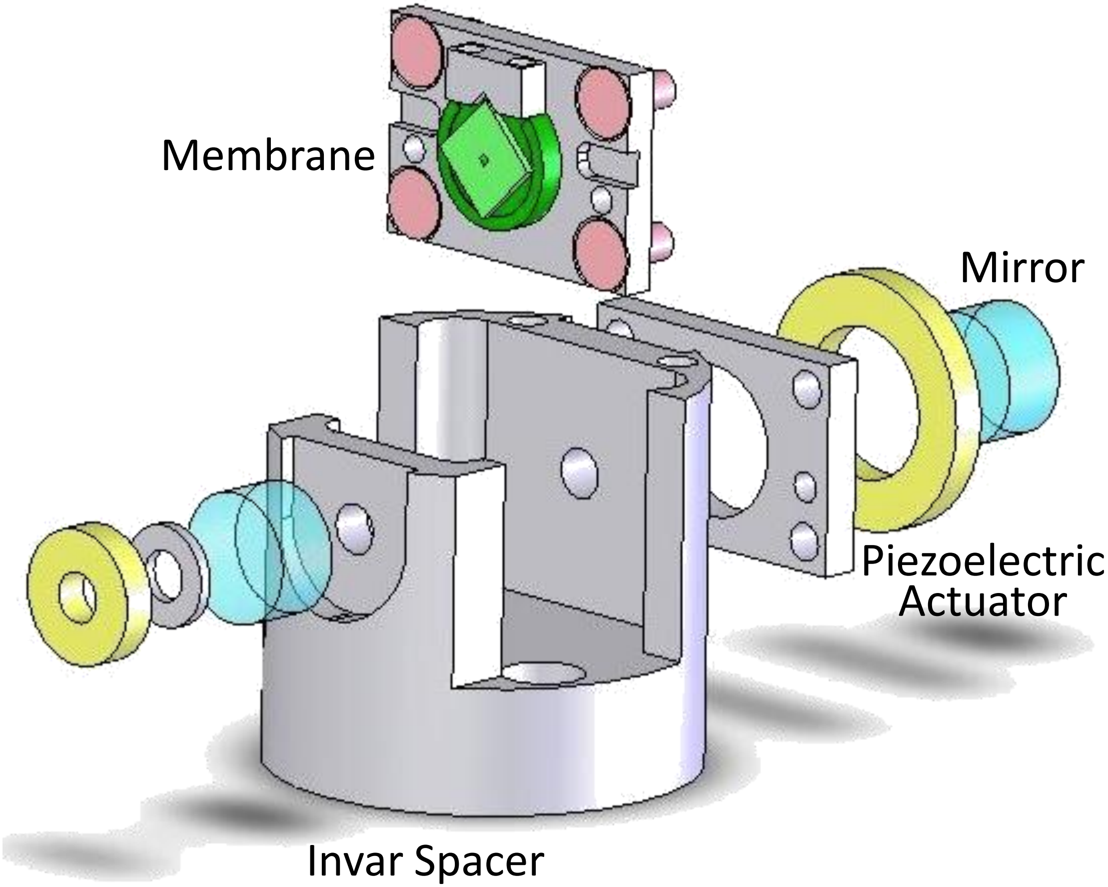


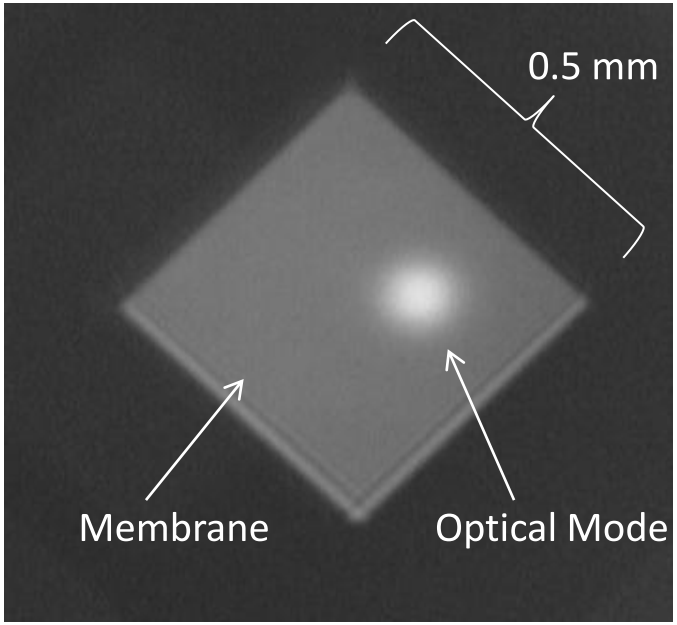

*Introduced to optomechanics: Harris group at Yale, Thompson et al. Nature 2008

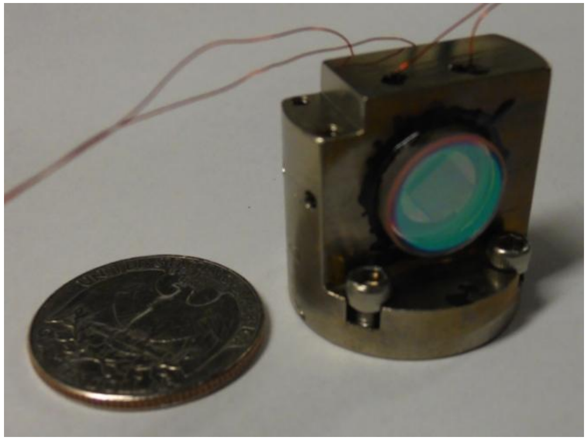
# A cryogenic, three-element Fabry-Perot cavity

Challenge:

- Stability and alignment of cryogenic device

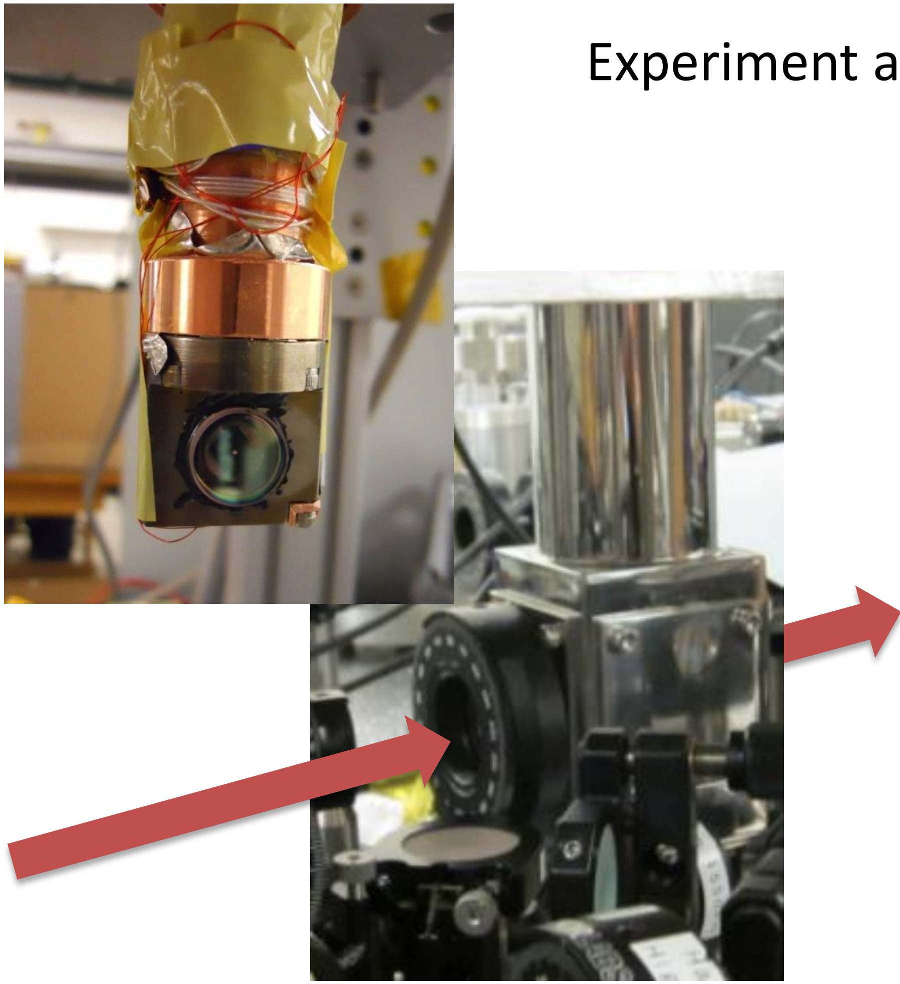


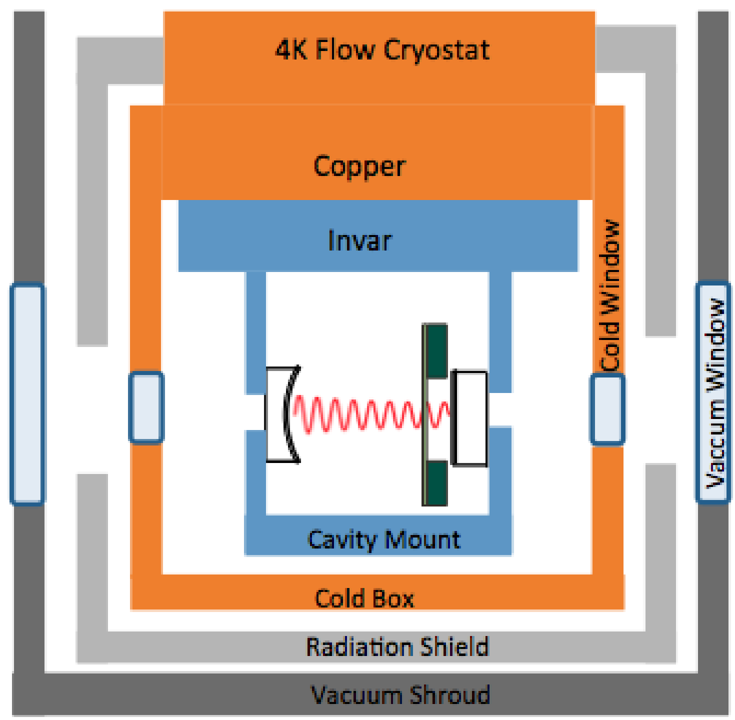



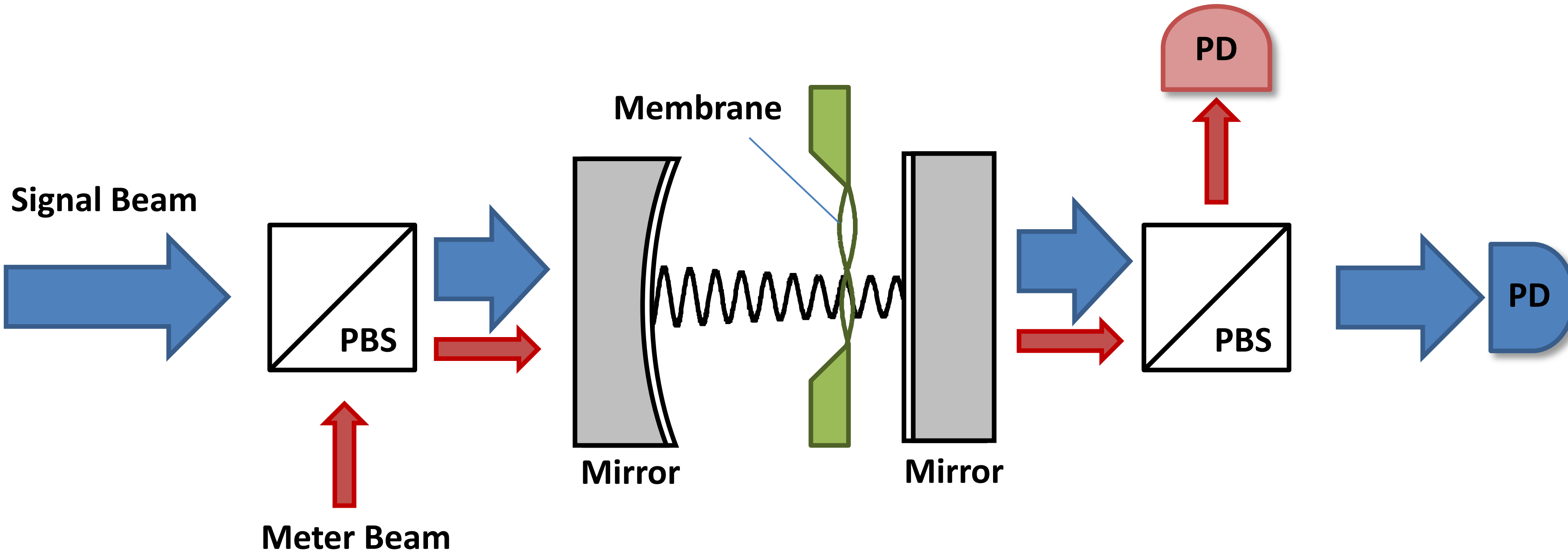
# Cryogenic optomechanical device

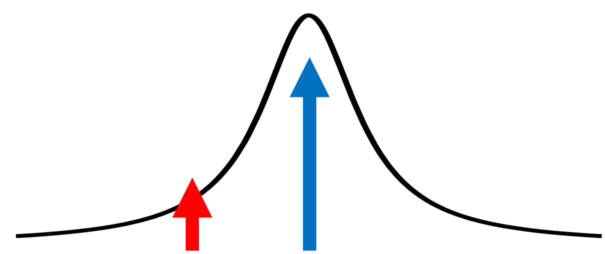
Experiment at 4 kelvin – simple in many ways





# RPSN experiment setup



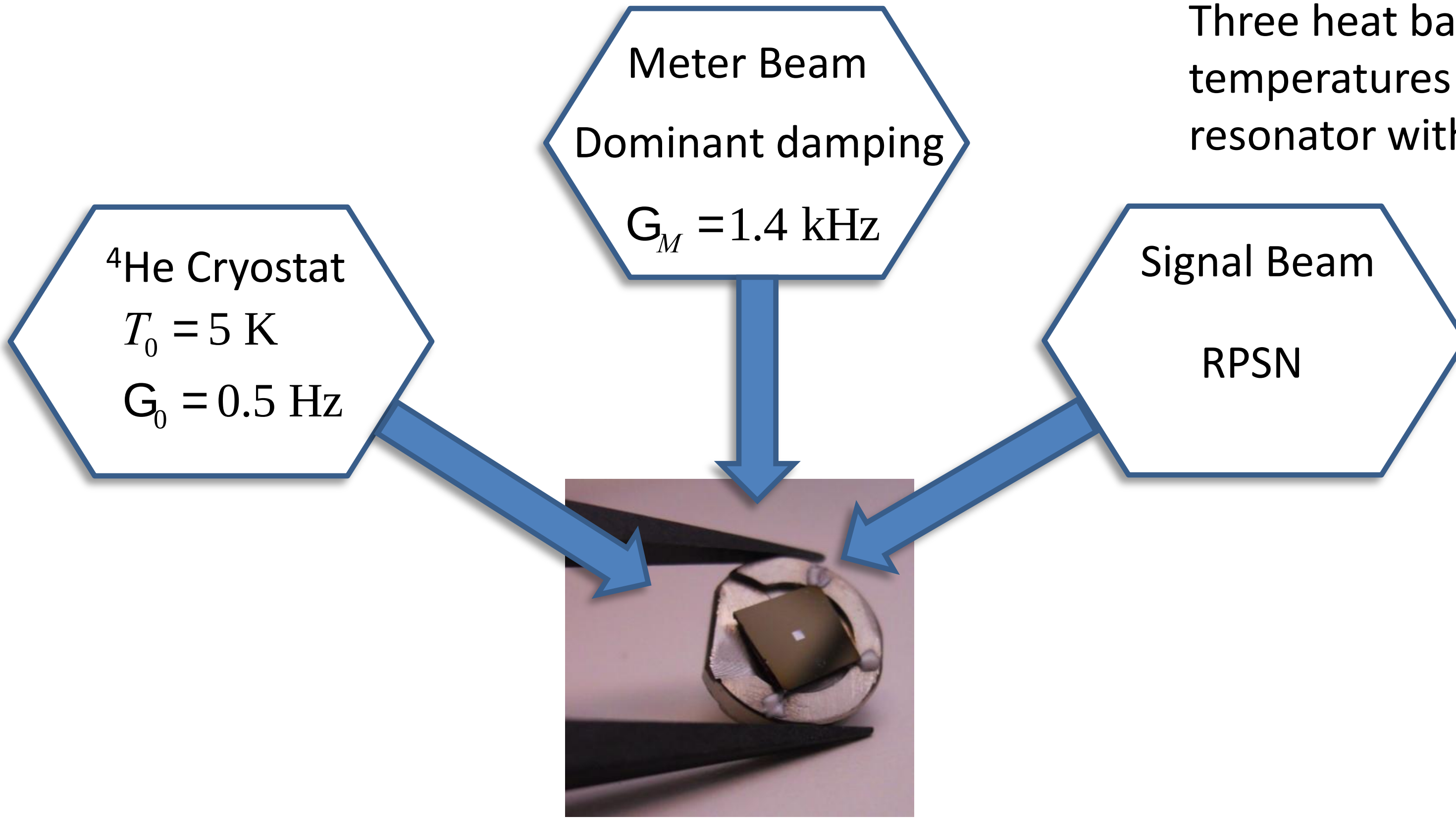
"Signal Beam (S)"
- High Power
- On resonance
- RPSN
- Optical force readout

"Meter Beam (M)"
- Low Power
- Red detuned
- Optical damping/cooling
- Displacement readout

T. P. Purdy, et al., *Science* (2013)
P. Verlot, et al., *PRL* (2009)

# Observing radiation pressure shot noise heating

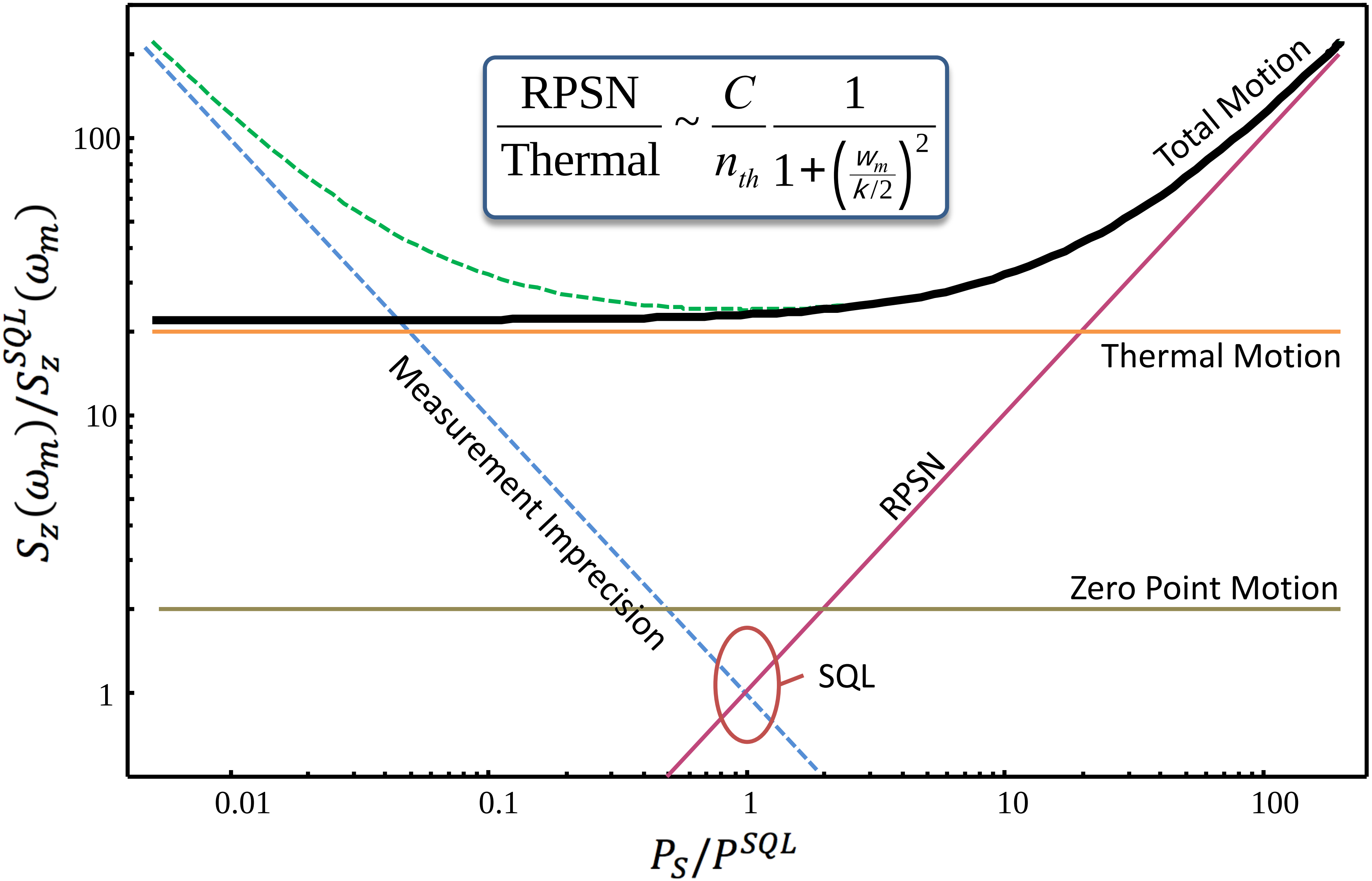
Three heat baths at different temperatures coupled to the resonator with differing strengths




$$T_{eff} = \frac{T_0 G_0 + T_M G_M + T_S G_S}{G_0 + G_M + G_S}$$

Equilibrium Temperature

# Radiation pressure shot noise heating



# Parameters for seeing RPSN heating

$$\frac{\text{RPSN}}{\text{Thermal}} \sim \frac{C}{n_{th}} \frac{1}{1+\left(\frac{w_m}{k/2}\right)^2}$$

<u>Cooperativity</u>

$$C = \frac{4Ng^2}{k\mathrm{G}_0}$$

photon number coupling

cavity damping

mechanical damping

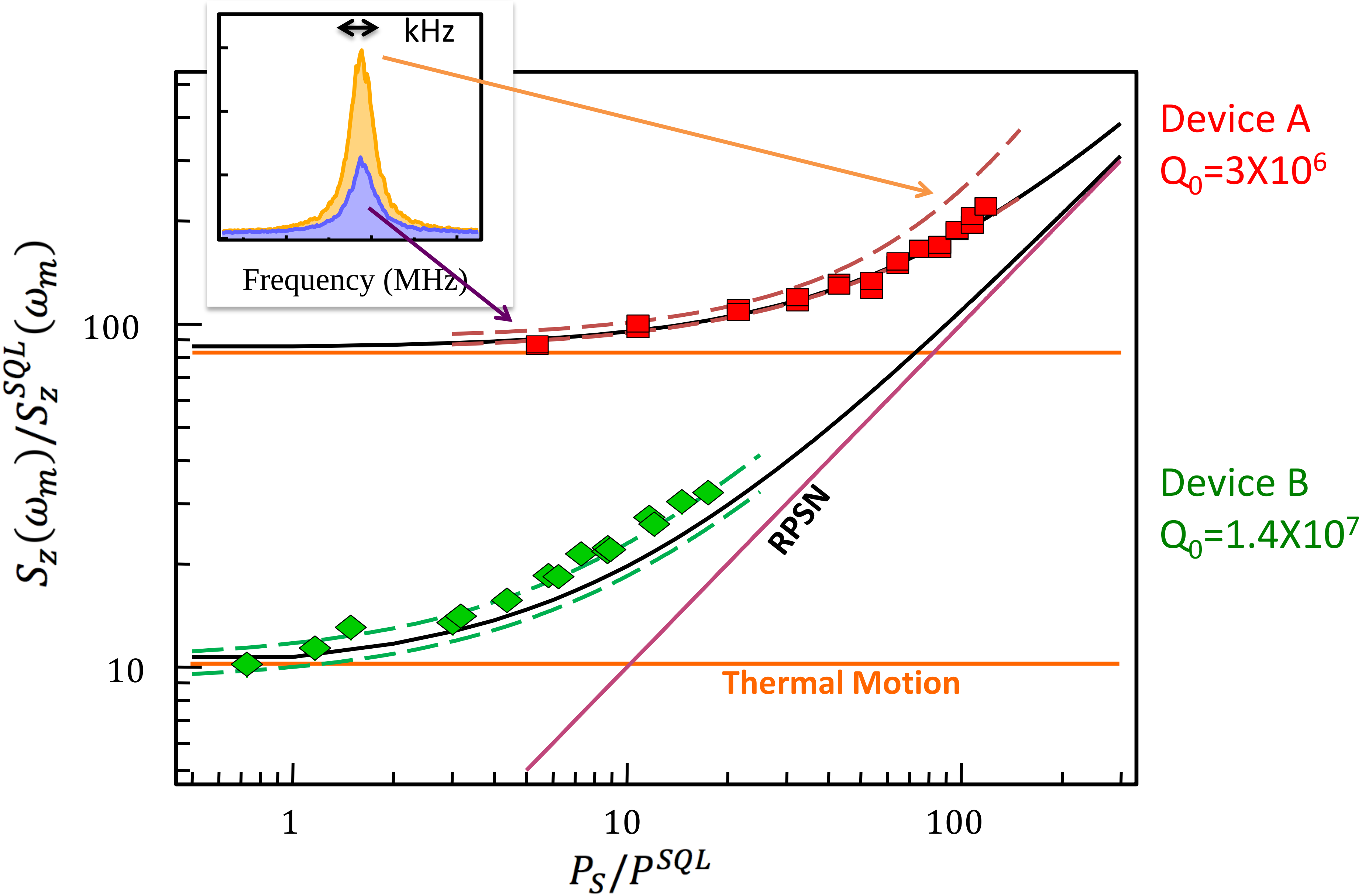
<u>Thermal phonons (4 K bath)</u>

$$n_{th} = \frac{k_b T_0}{\hbar w_m}$$

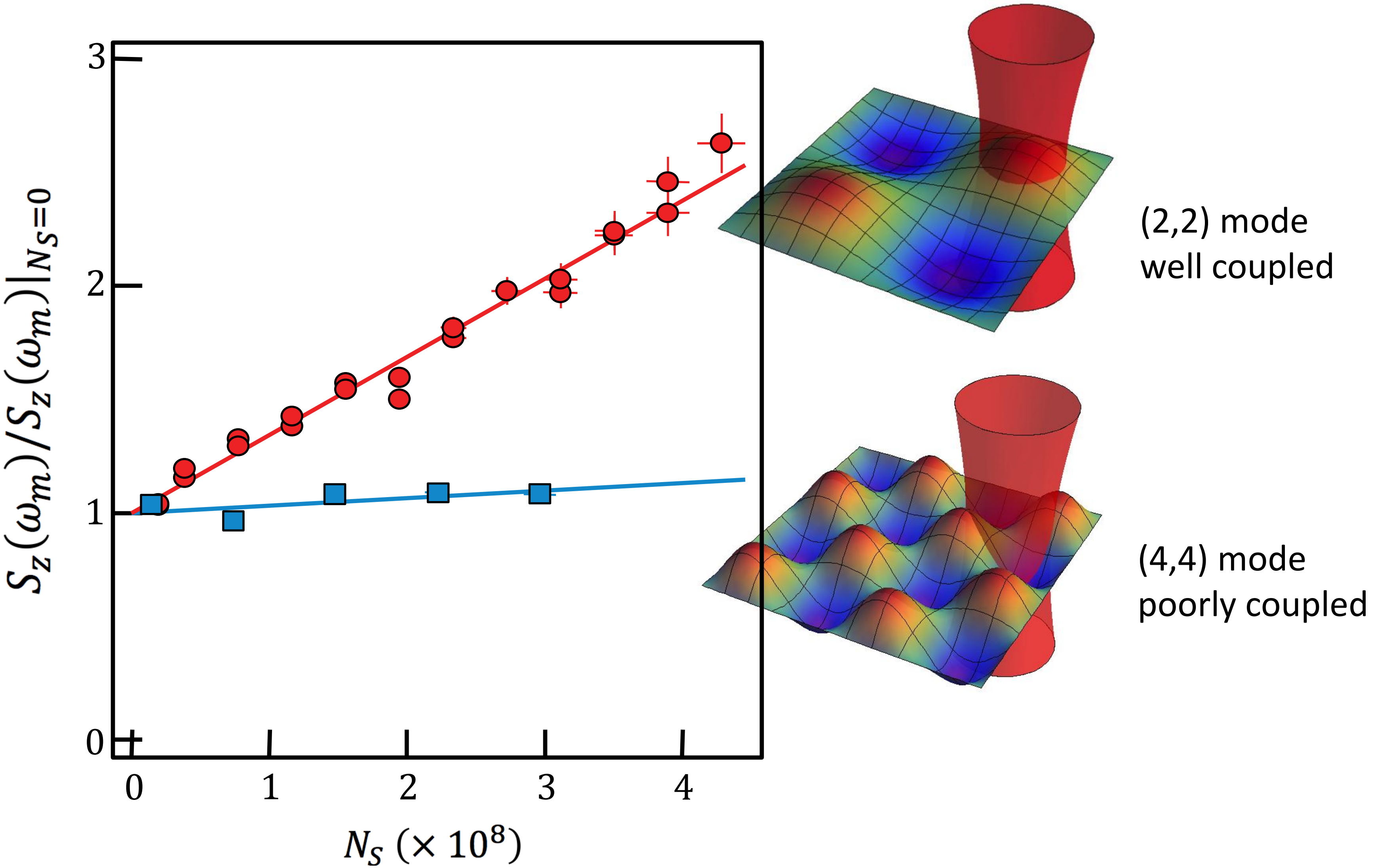
Meter beam damping:

- Plays no role in this ratio
- (Very important) convenience

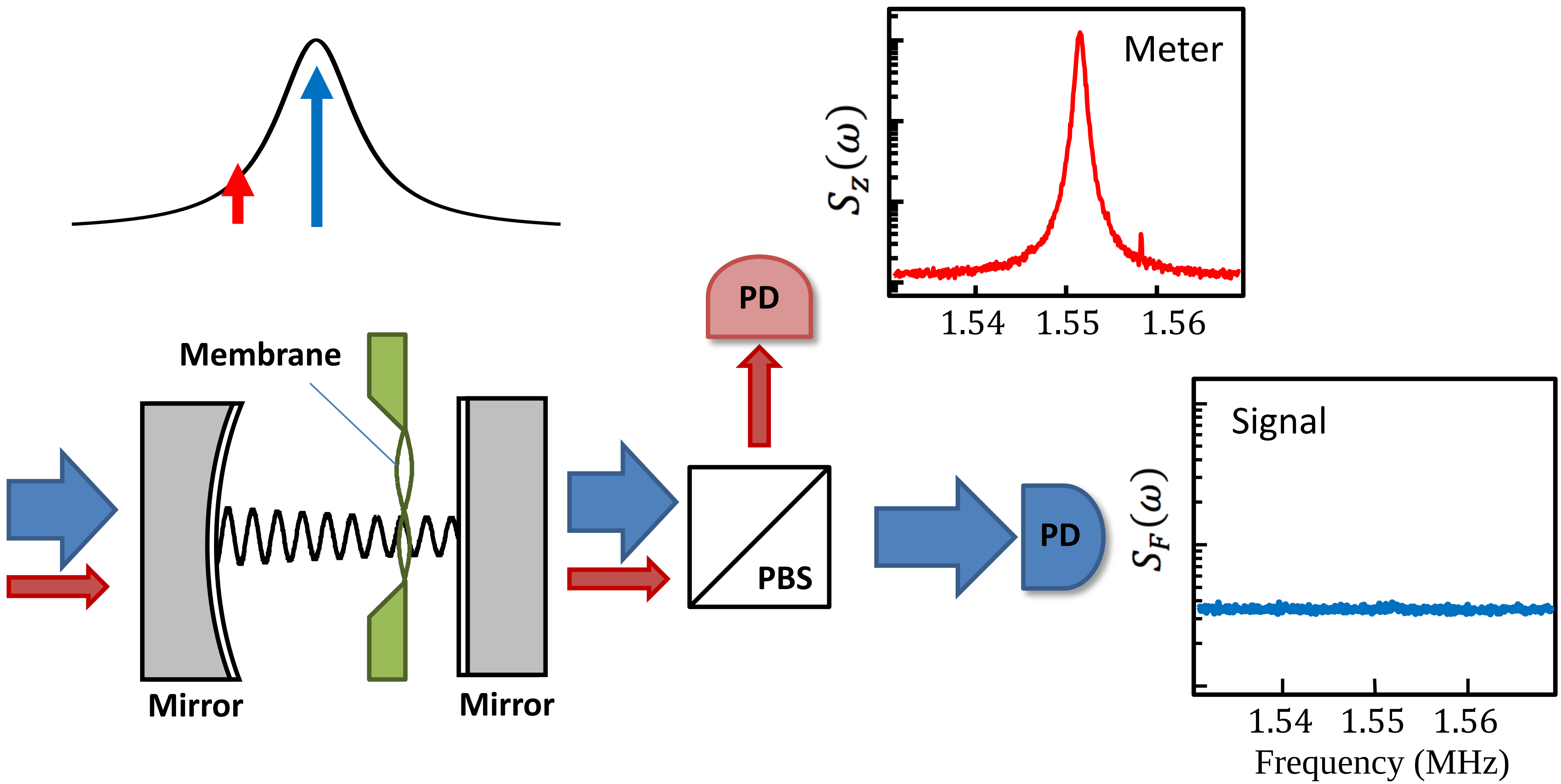
# Radiation pressure shot noise heating



# Check for physical heating



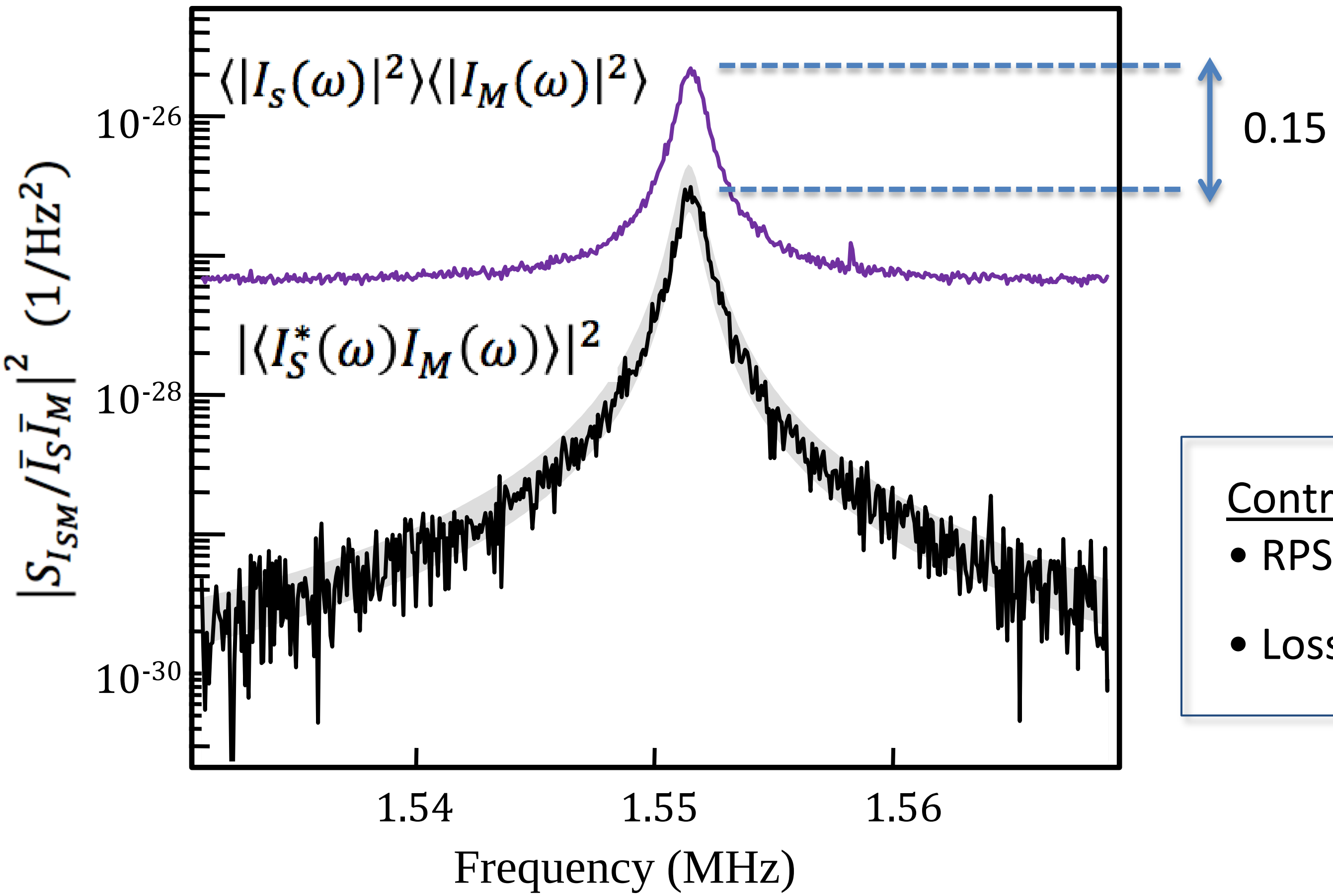
# Signal beam: Record of optical force




- AM quadrature - shot noise intensity fluctuations - record of the optical force on the resonator

# Two beam cross correlation

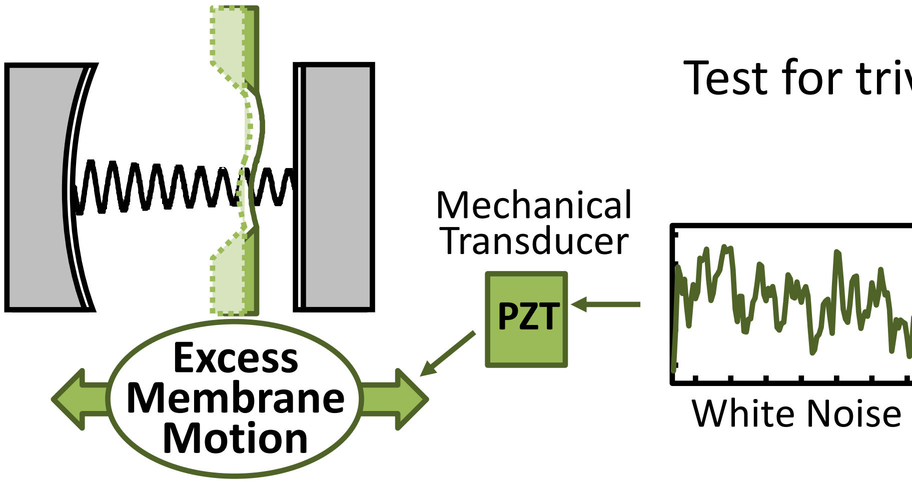
Cross correlation between meter & signal



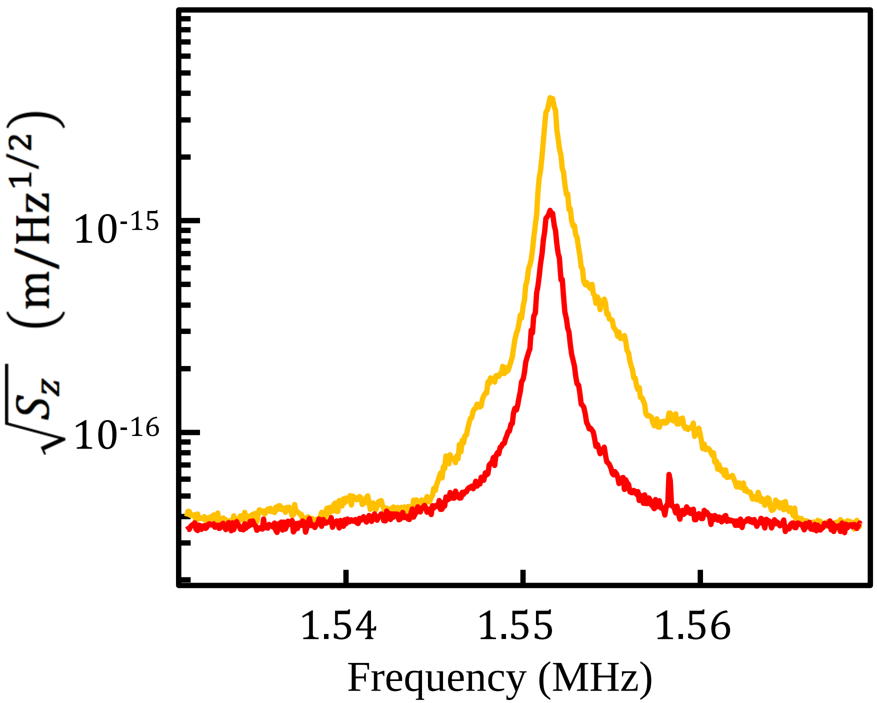

<u>Contributions:</u>

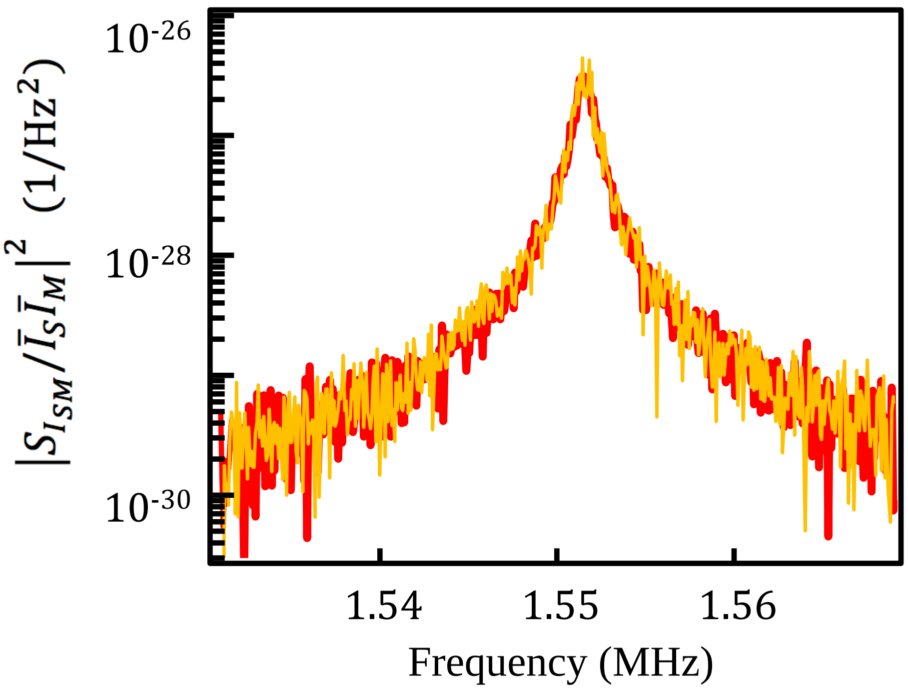
- RPSN to thermal 40%
- Loss (ports, path, QE) 40%

# Two beam cross correlation

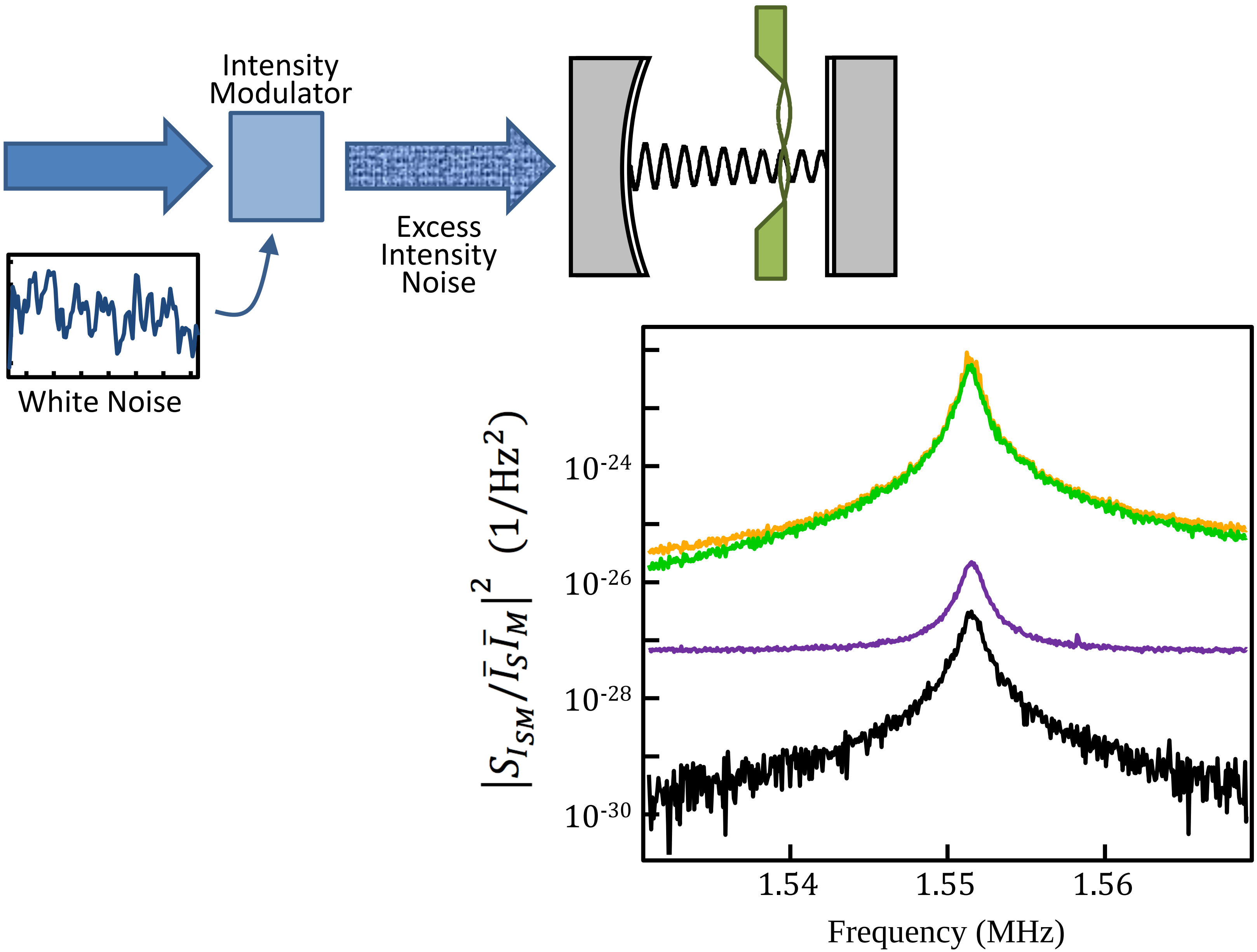



Test for trivial correlations

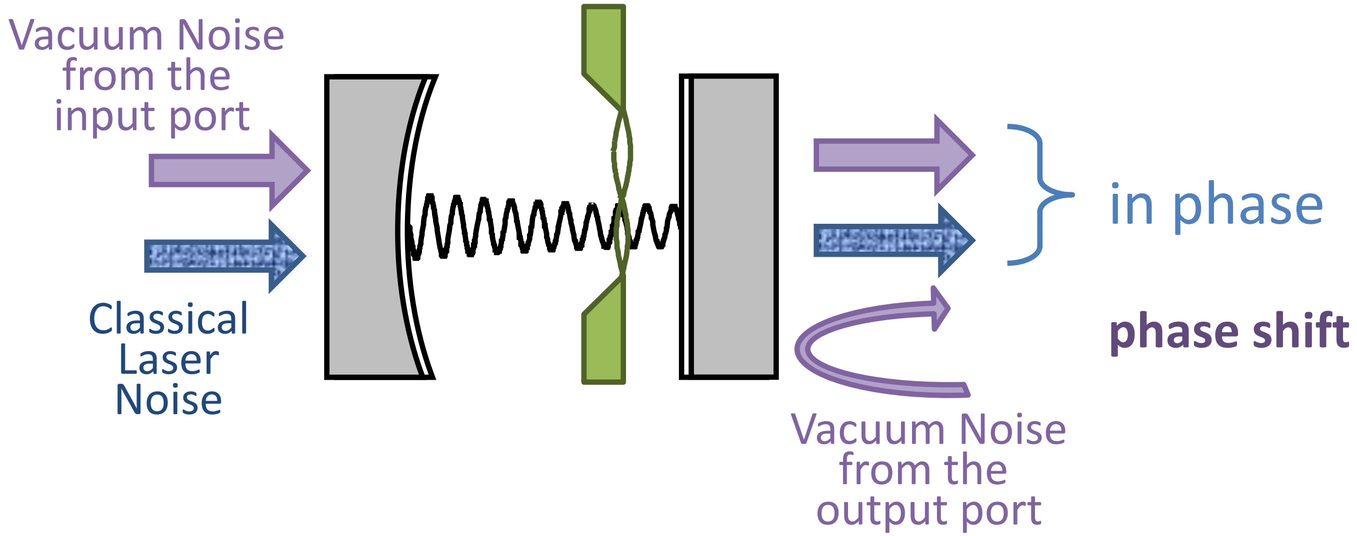


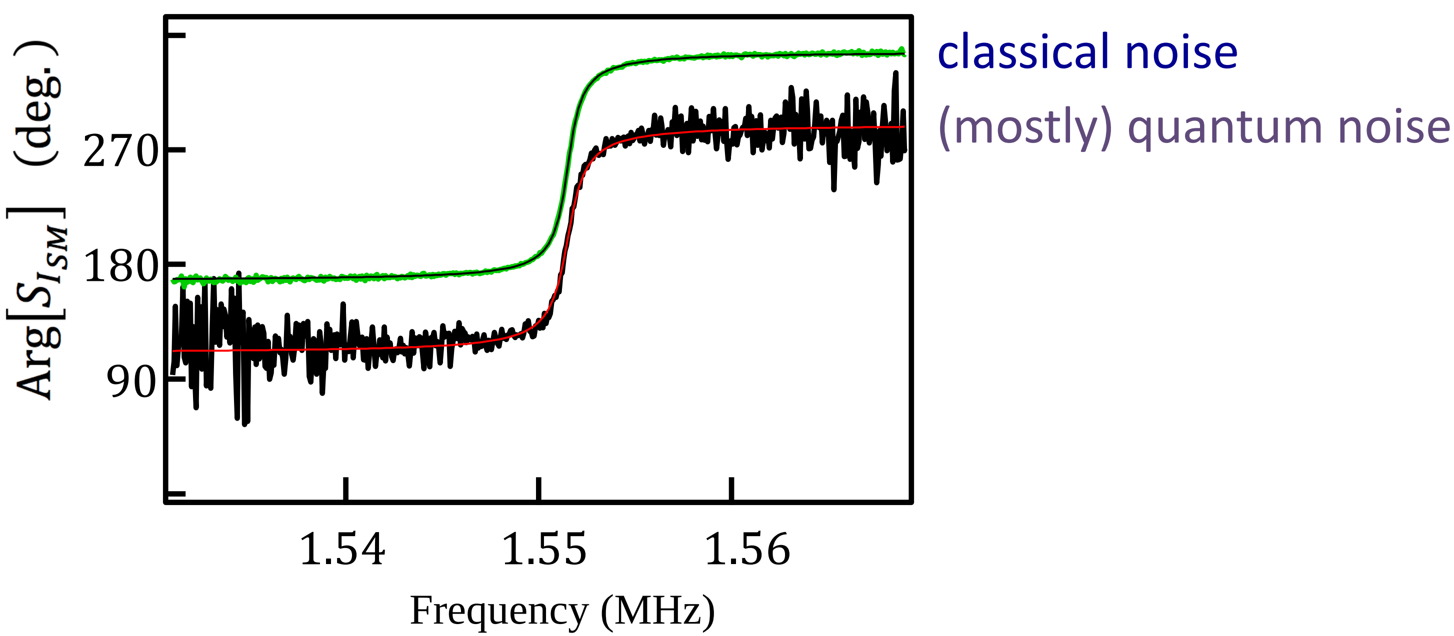



# Classical intensity noise limit

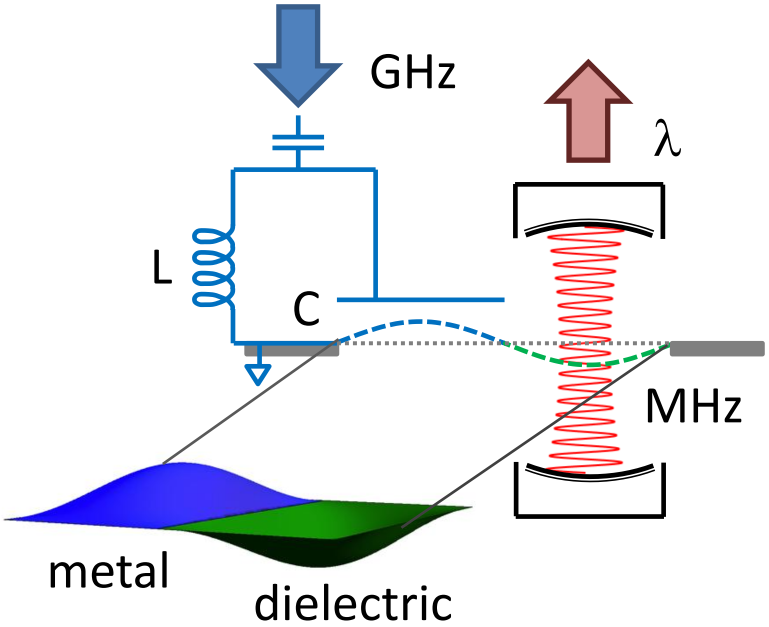


# Consistency with quantum noise

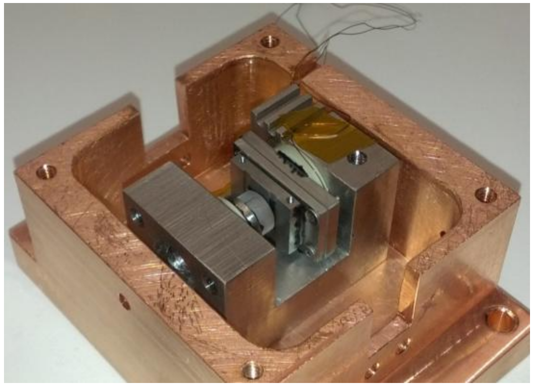


# Microwave to optical quantum link




Electromechanics: Lehnert Group (JILA)



$$C = \frac{4Ng^2}{\kappa\Gamma_0} > n_{th}$$

Transfer rate between phonons and (itinerant) photons exceeds rate at which single phonon leaves to environment

Analogous experiments: UCSB
See for ideas:
J. Zhang…S. L. Braunstein, PRA (2003)
C. A. Regal and K. W. Lehnert, J. Phys. Conf. Series (2011)
A. Safavi-Naeini…O. Painter, New J. Phys. (2011)
J. Taylor et al., PRL (2011)
T. Palomaki…K. W. Lehnert, Nature in press (2013)

# Conclusions and directions

- To do – Standard quantum limit for continuous position measurement

- There is a lot of quantum optics to pursue in these systems, optical squeezing, backaction evasion,…

- Elucidating to study these with physical object in interferometer driven by quantum noise

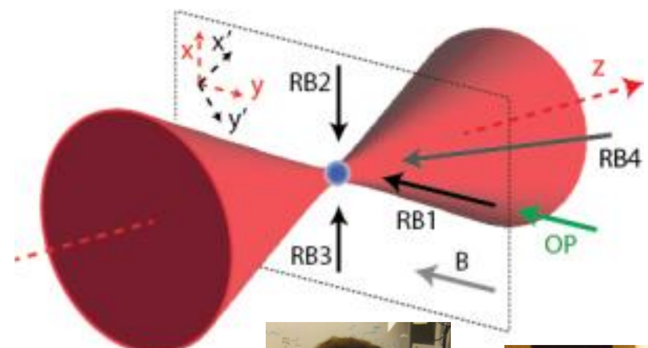
Group members: <u>Optomechanics</u>

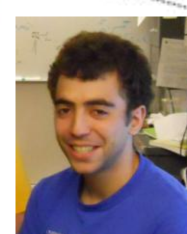
Bob Peterson

Ben Yu

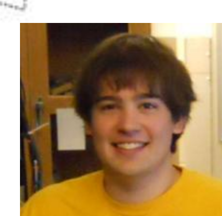
Thomas Purdy

<u>Single neutral atoms</u>



Adam Kaufman



Brian Lester

Collaborators:

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