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Advanced Workshop on Nanomechanics

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Quantum Measurement in an Optomechanical System

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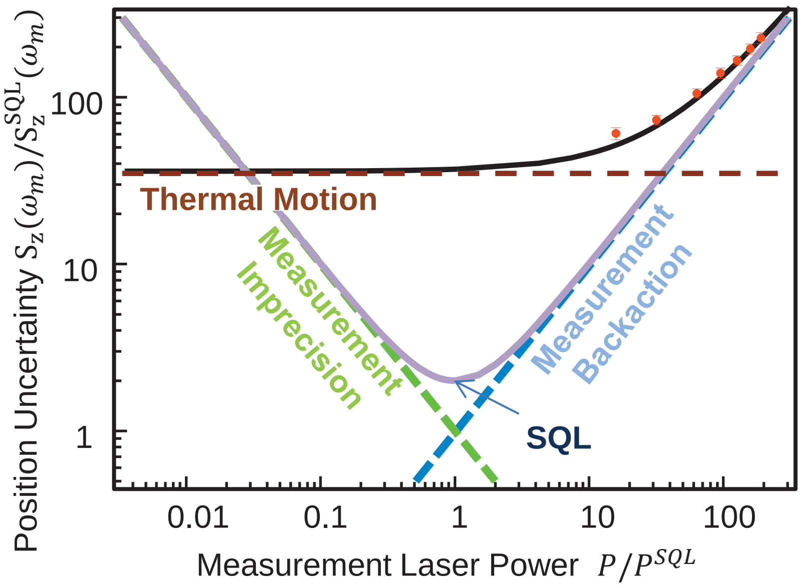
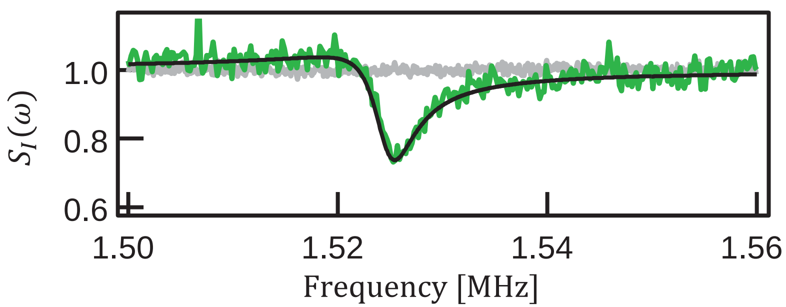
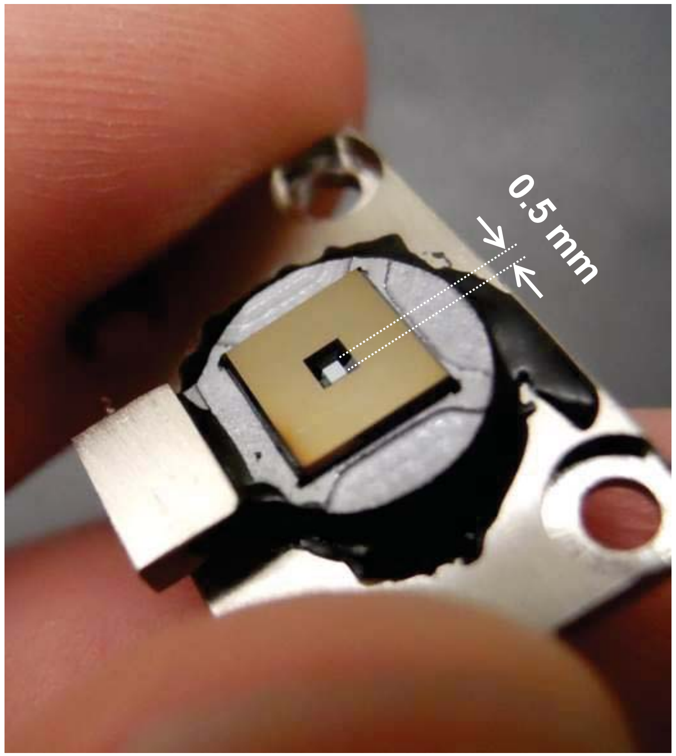
Quantum Measurements in an Optomechanical System

Tom Purdy, JILA – NIST & University of Colorado
with Bob Peterson, Ben Yu, Nir Kampel, Alec Jenkins, Cindy Regal







Range of Optomechanical Systems

Big ⟷ **Small**

LIGO

Macroscopic Systems

Membrane Optomechanics

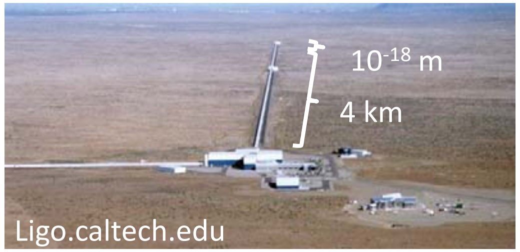
Nanomechanics

Single Atom in Optical Tweezers

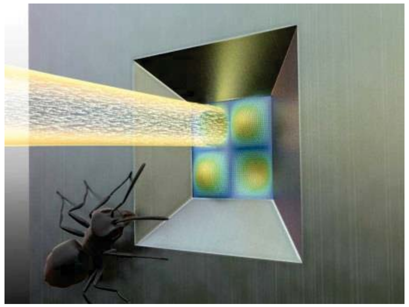
10 kg
10 km

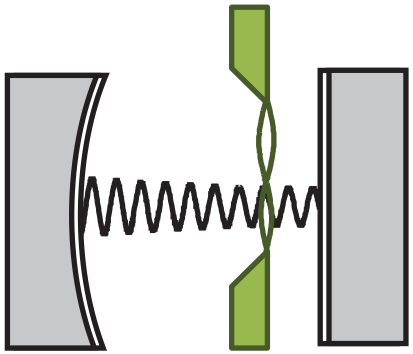
10 ng
1 mm

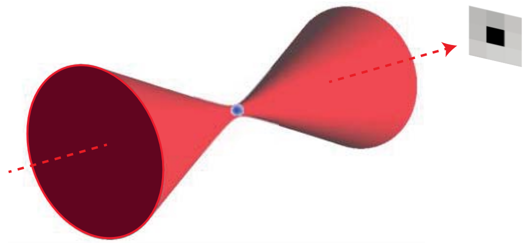
10^{-25} kg
10 nm

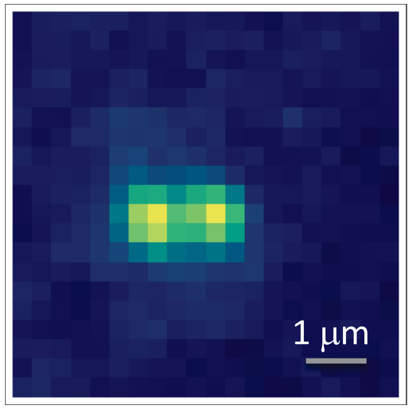


Ligo.caltech.edu







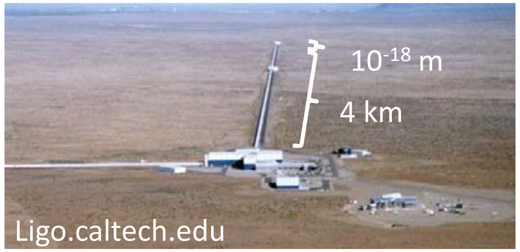


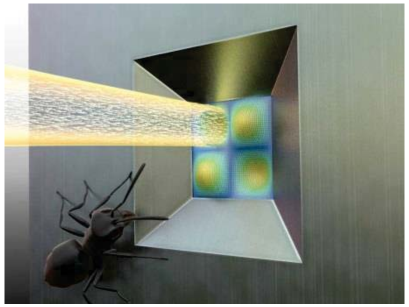
A. Kaufman, et al., *PRX* **2**, 041014 (2012)

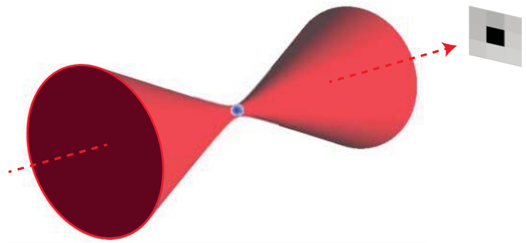
Range of Optomechanical Systems

Big ⟷ **Small**

LIGO	Macroscopic Systems	Membrane Optomechanics	Nanomechanics	Single Atom in Optical Tweezers
10 kg 10 km		10 ng 1 mm		10^{-25} kg 10 nm





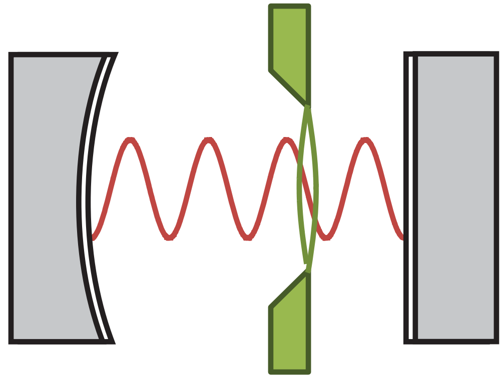


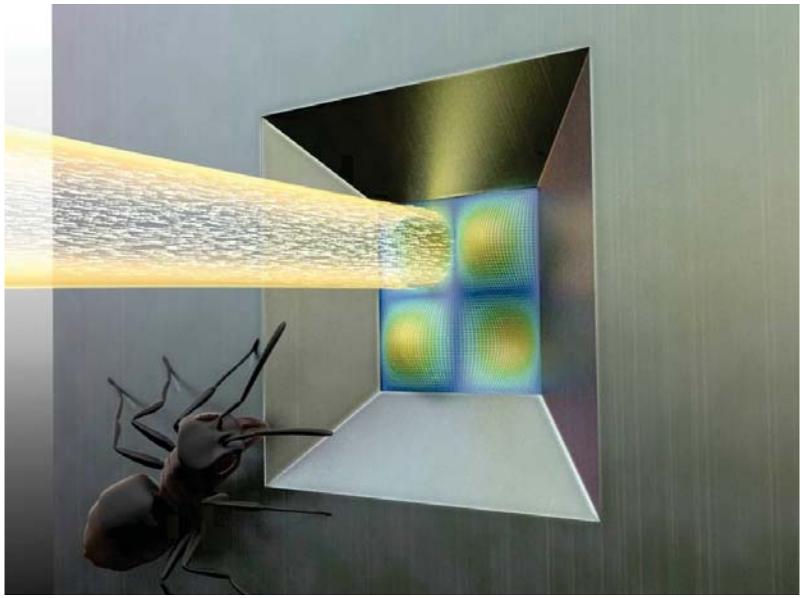
- High precision interferometry
- Squeezed light
- Quantum Nondemolition Measurements

- Raman Sideband Cooling
- Optical Tweezers
- Electromagnetically Induced Transparency

Overview

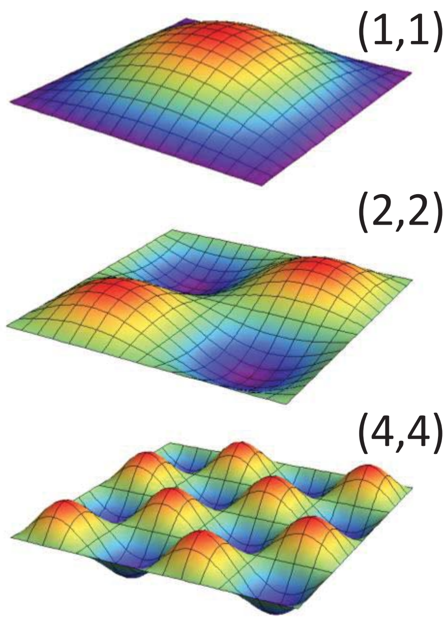
- Membrane Cavity Optomechanical System
- Raman Sideband Cooling
- Introduction to quantum measurement
- Observing quantum measurement backaction
- Using mechanical motion to measure light
- Building better mechanical resonators

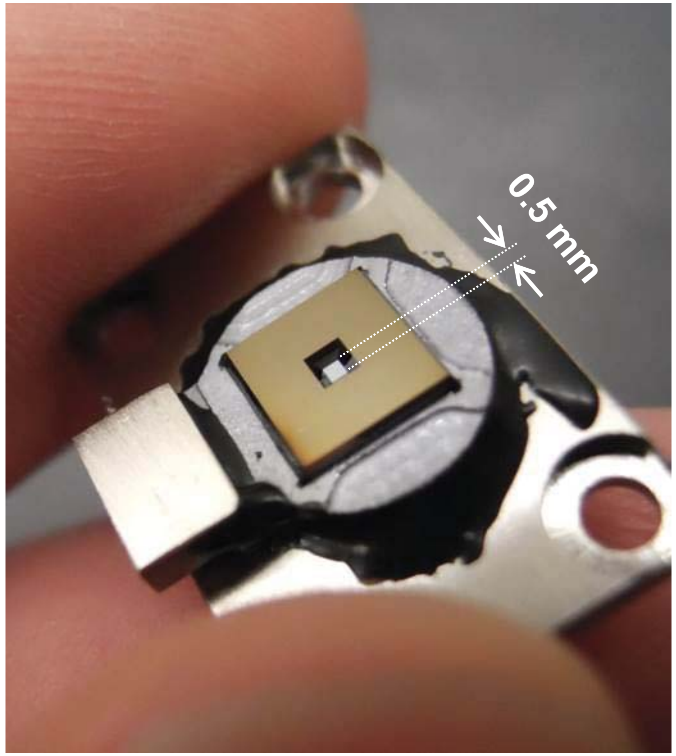


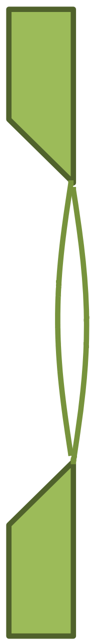


Membrane Optomechanical System

- Si_3N_4 dielectric membrane
- 0.5 mm X 0.5 mm X 50 nm
- High Tension ~ GPa
- High Mechanical Quality Factor $Q\sim10^7$
- MHz mechanical resonance frequencies
- 10% reflectivity, low optical absorption
- Low mass ~10 ng



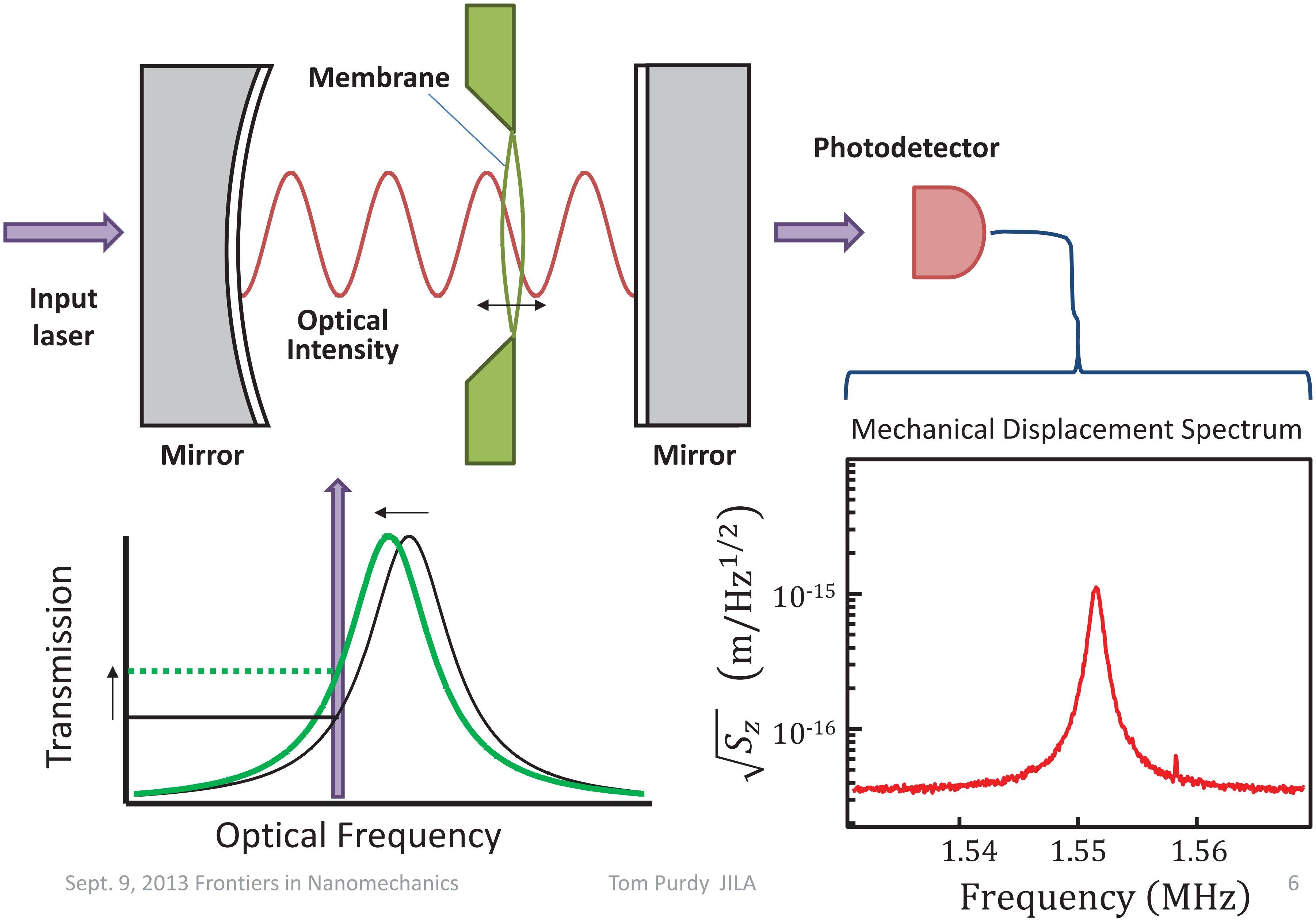




Verbridge, et al., *JAP* **99**, 124304 (2006)
Southworth, et al., *PRL* **102**, 225503 (2009)
Unterreithmeier, et al., *PRL* **105**, 027205 (2010)
Wilson-Rae, et al., *PRL* **106**, 047205 (2011)
Yu et al., *PRL* **108**, 083603 (2012)

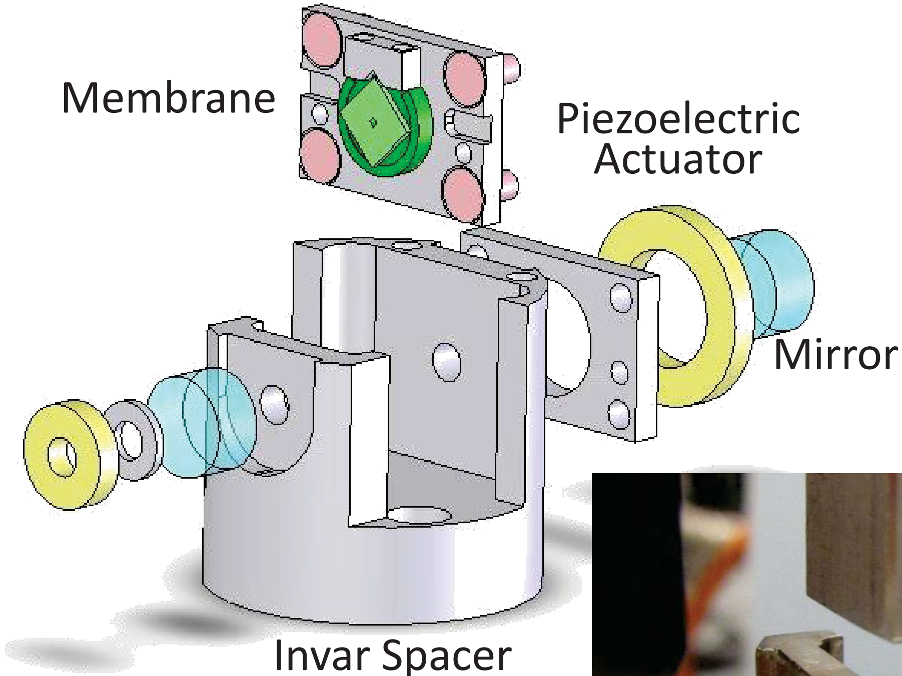
Thompson, et al., *Nature* 452 72 (2008)
Wilson et al., *PRL* 103 207204 (2009)
Karuza, et al., *NJP*, 14, 095015 (2012)
Purdy, et al., *NJP*, 14 115021 (2012)

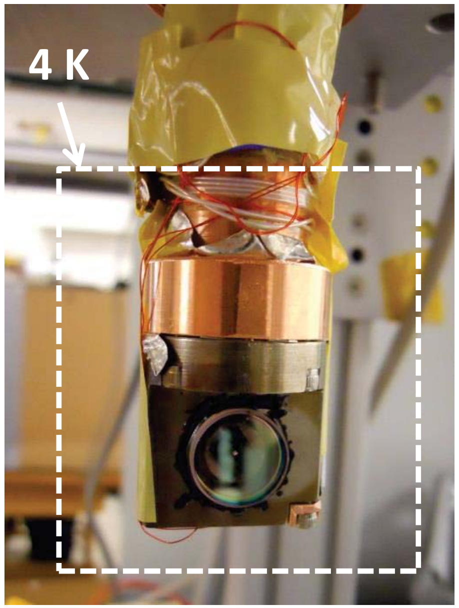
Optomechanical Coupling

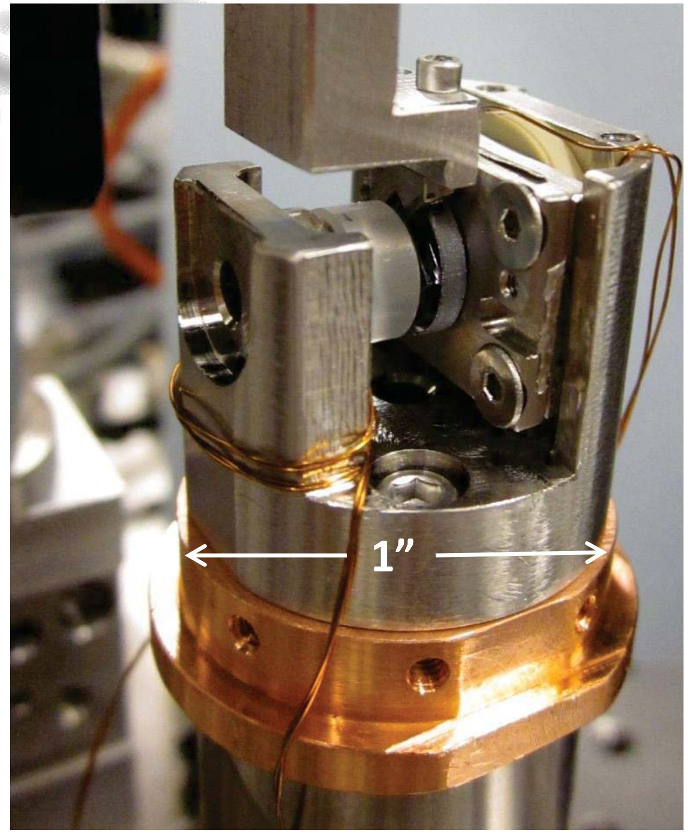


Optomechanical Device

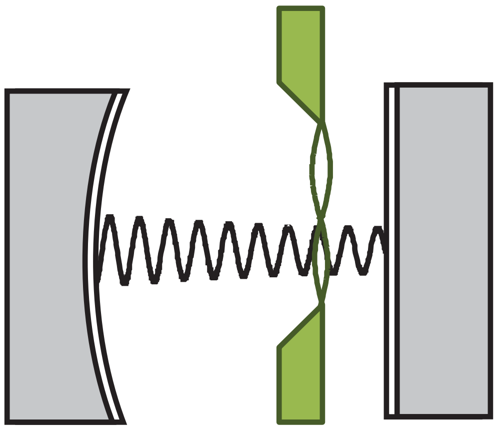
- Compact, low vibration, low drift design
- Cryogenically compatible (4K flow cryostat)
- High optical finesse (<30,000)
- Low mechanical dissipation $Q \sim 10^7$
  $\Gamma_m \, n_{th}$ small



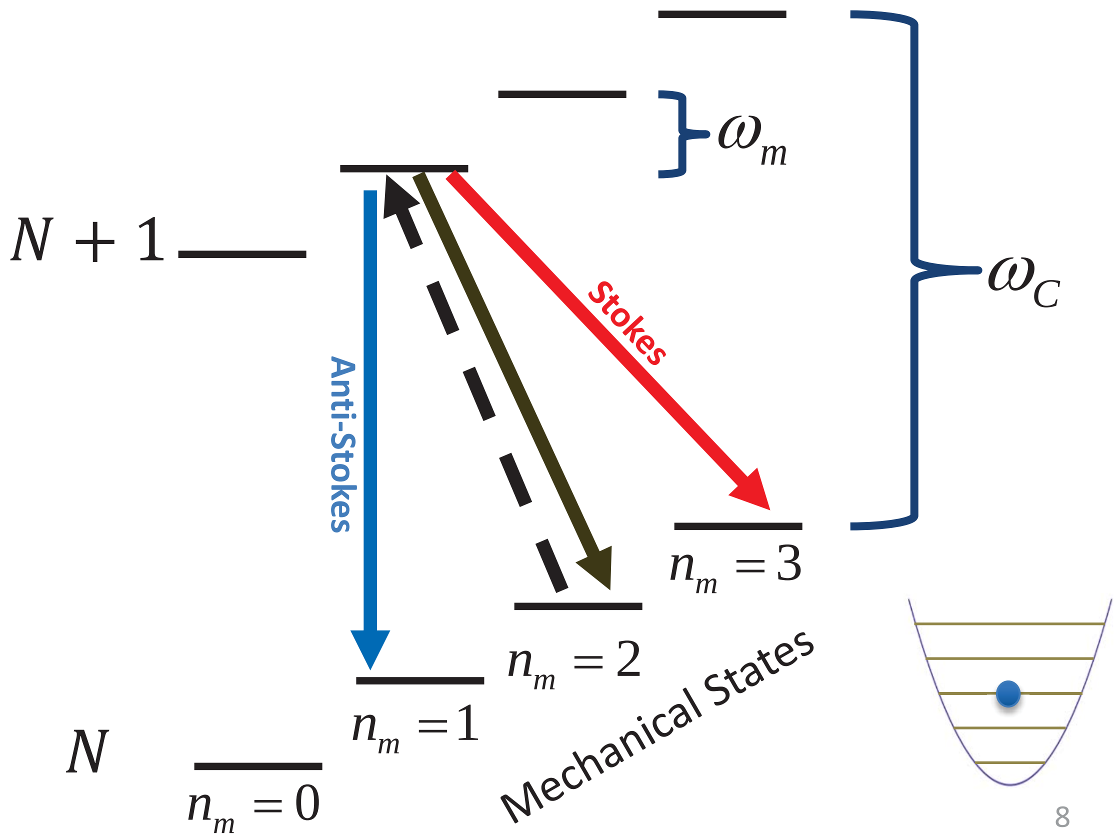




Laser Cooling



Raman Sideband Cooling



ω_m = Mechanical frequency

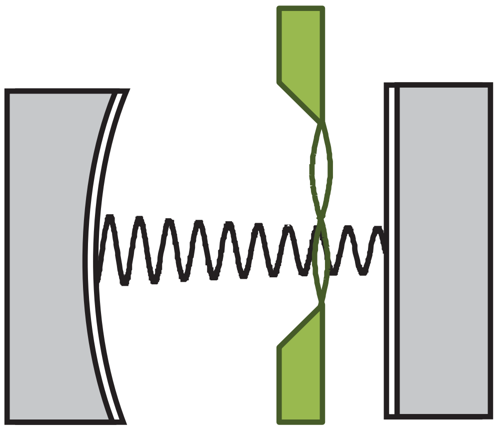
n_m = number of mechanical vibrational quanta

ω_m = Cavity frequency

N = number of photons

Monroe…Wineland, *PRL* **75**, 4011 (1995)
Teufel, et al., *Nature* **475**, 359 (2011)
Chan, et al., *Nature* **478**, 89 (2011)

Laser Cooling



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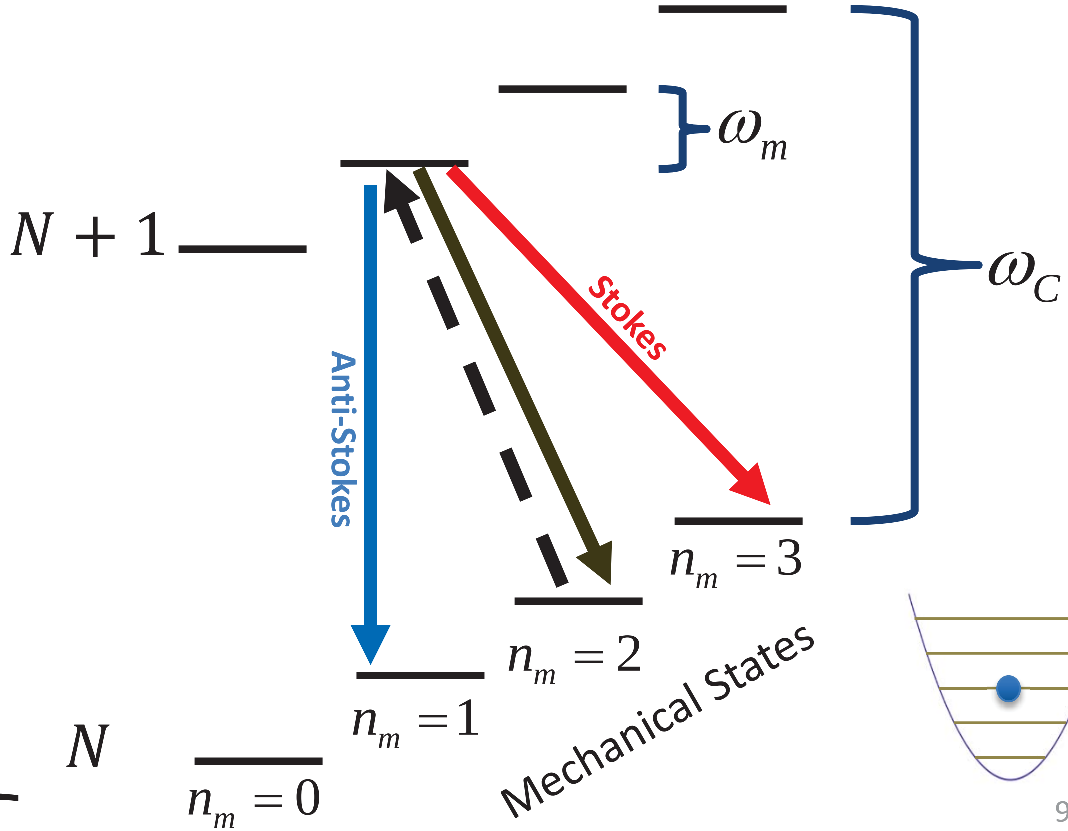

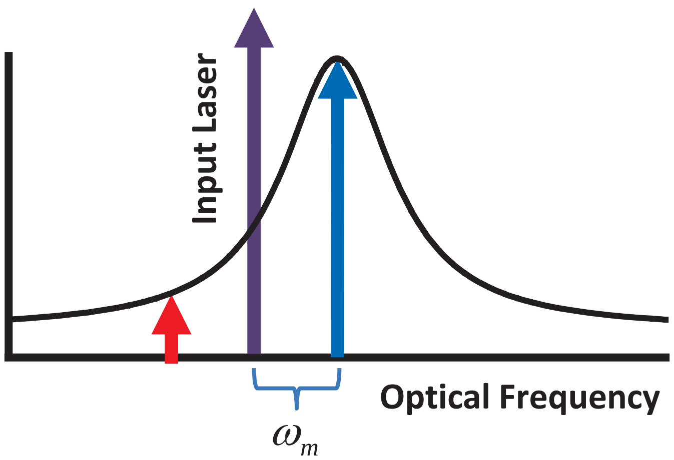

Monroe…Wineland, *PRL* **75**, 4011 (1995)
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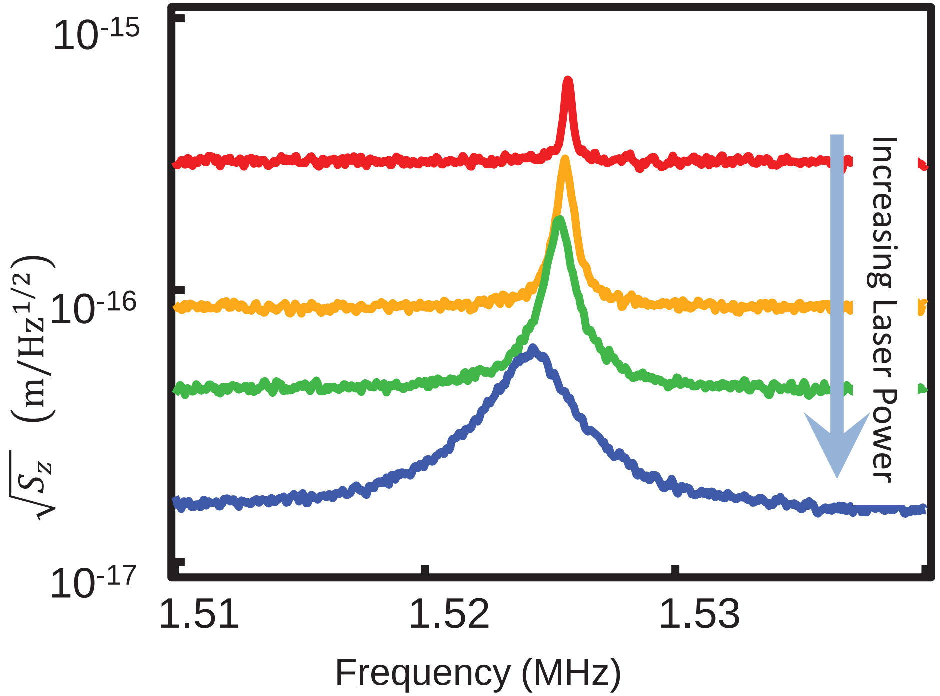
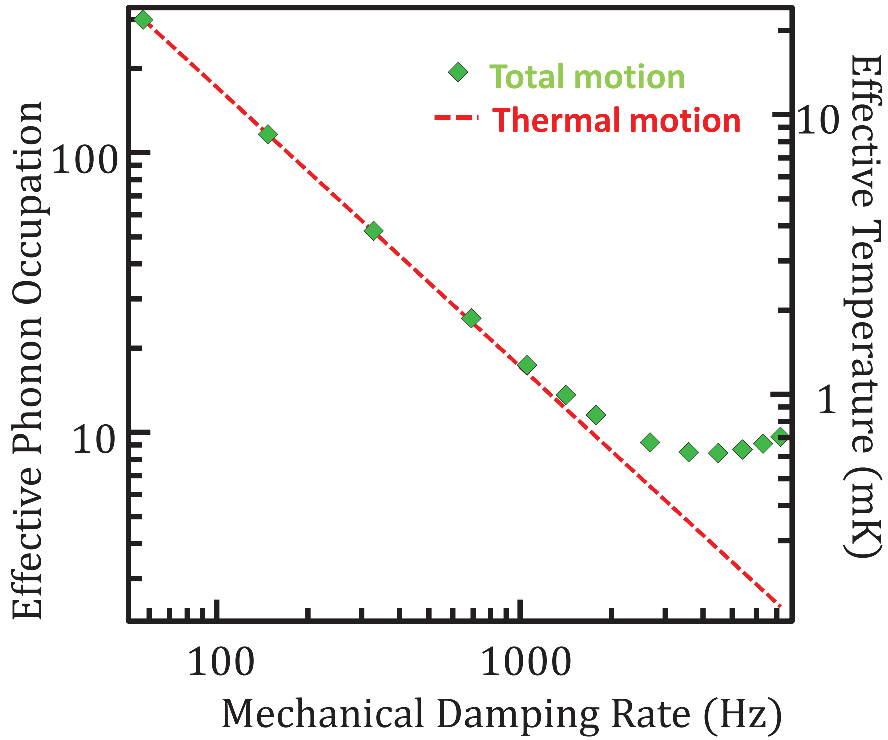
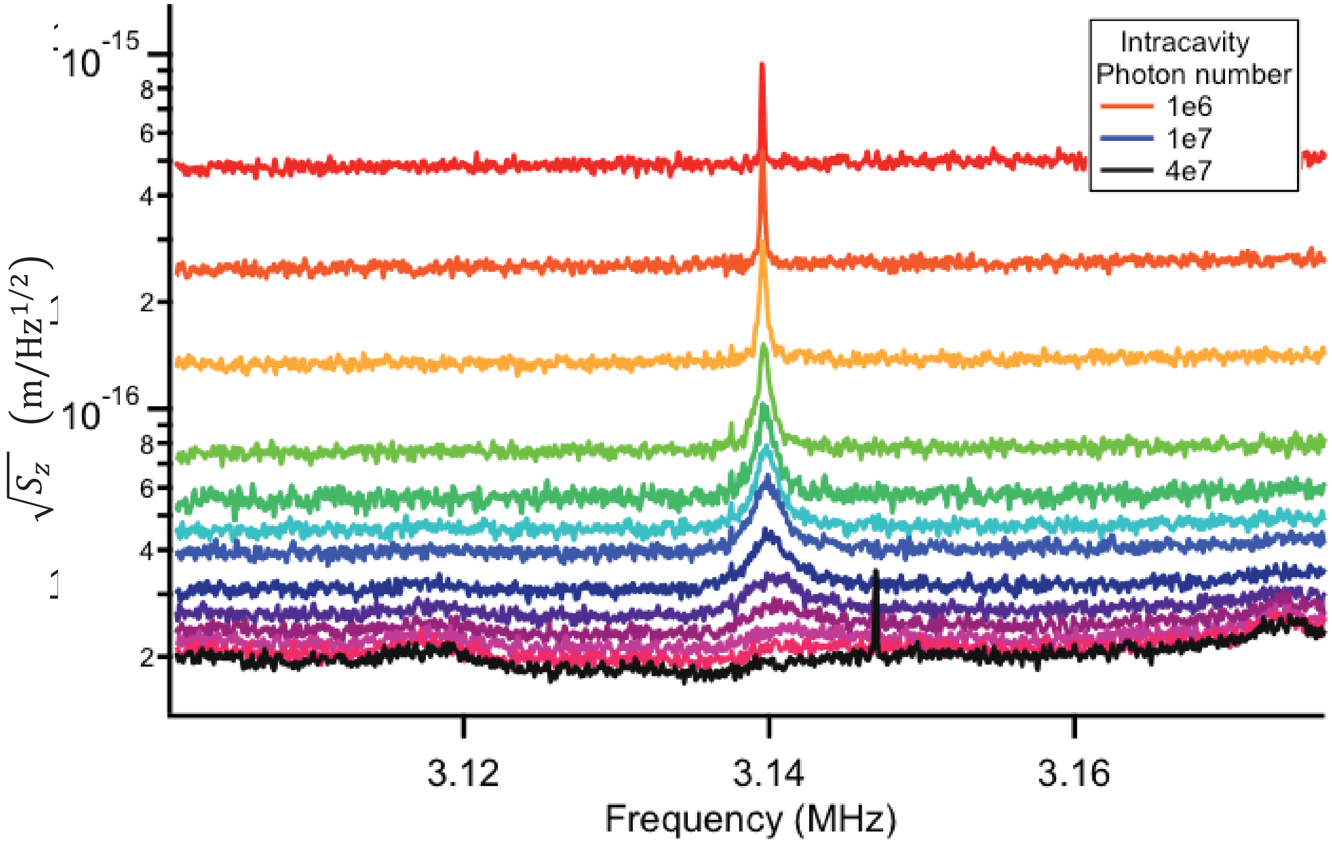
Laser Cooling





Purdy, et al., *NJP*, **14** 115021 (2012)
Jayich, et al., *NJP* **14**, 115018 (2012)

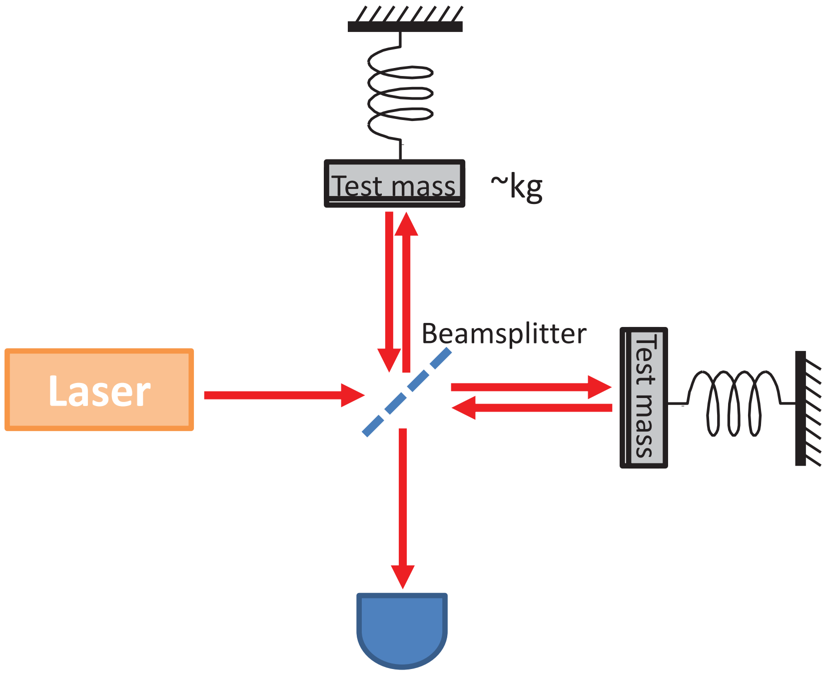
Laser Cooling

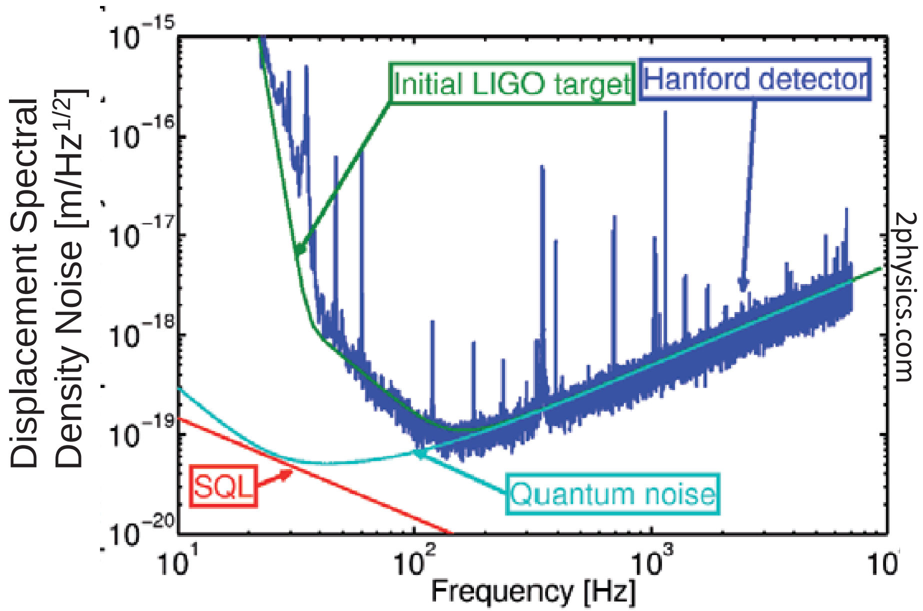


Purdy, et al., *NJP*, **14** 115021 (2012)
Jayich, et al., *NJP* **14**, 115018 (2012)

Quantum Limits of Optical Detection

Interferometric Gravitational Wave Detector: It's like trying to infer the position of the moon by measuring the ocean's tides, but 10^{15} times harder





Limits theoretically identified decades ago,

Caves, *PRL* **45** 75 (1980)

Unruh, *Quant. Opt., Exp. Grav., and Meas. Th.* (1982)

Braginsky, et al., *Science* **209**, 547 (1980)

But little experimental work until recently

LIGO, *Nature Phys*. **7**, 962 (2011)

Purdy, et al., *Science* **339**, 801 (2013)

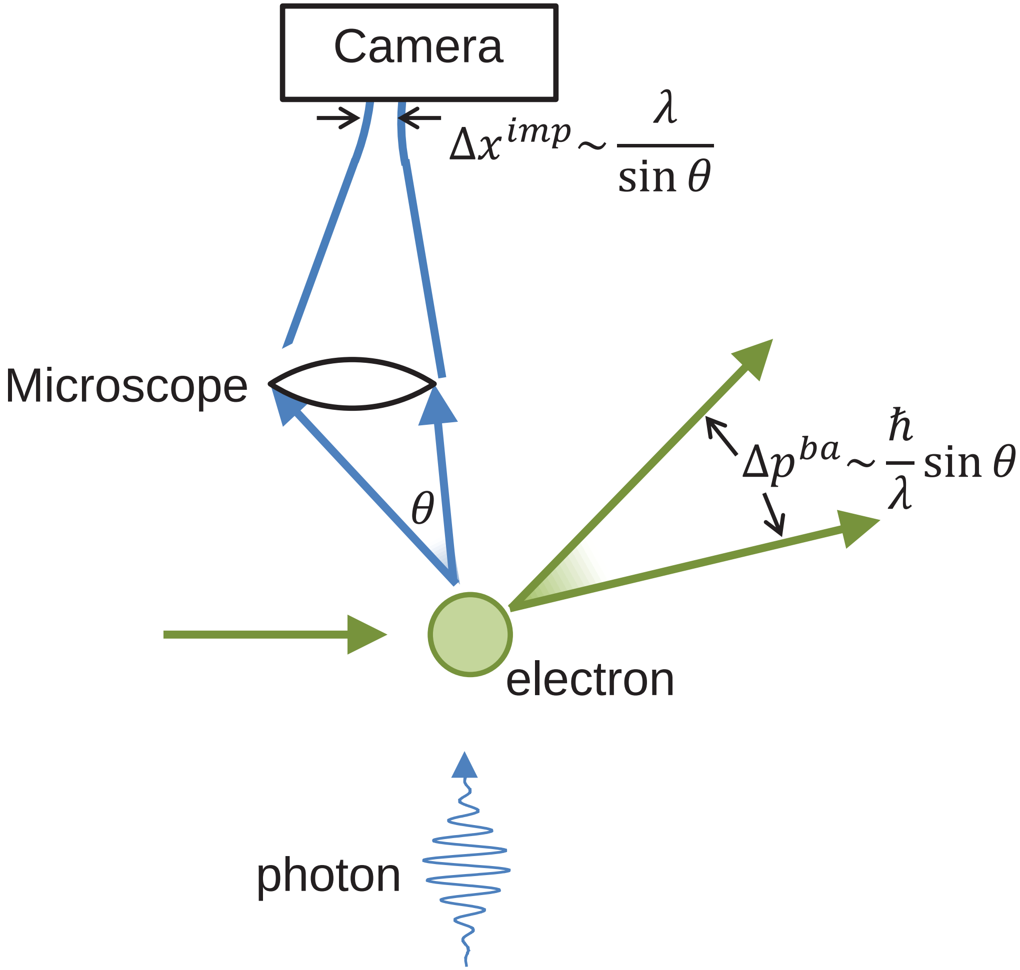
Hertzberg, et al., *Nature Phys*. **6**, 213 - 217 (2010)

Fundamental Sensitivity Limits:

- Optical Shot Noise
- Radiation Pressure Shot Noise

Quantum Limits of Optical Detection

Heisenberg's Microscope Thought Experiment



$$\Delta x^{\text{imp}} \Delta p^{\text{ba}} \geq \hbar / 2$$

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 ϵ. If λ 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:

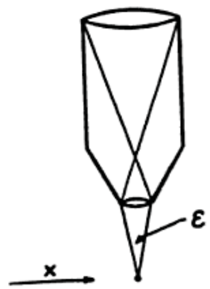


Fig. 5

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

But, for any measurement to be possible at least one photon must be scattered from the electron and pass through the microscope to the eye of the observer. From this photon the electron receives a Compton recoil of order of magnitude h/λ. The recoil cannot be exactly known, since the direction of the scattered photon is undetermined within the bundle of rays entering the microscope. Thus there is an uncertainty of the recoil in the x-direction of amount

$$\Delta p_x \sim \frac{h}{\lambda} \sin \epsilon , \qquad (17)$$

and it follows that for the motion after the experiment

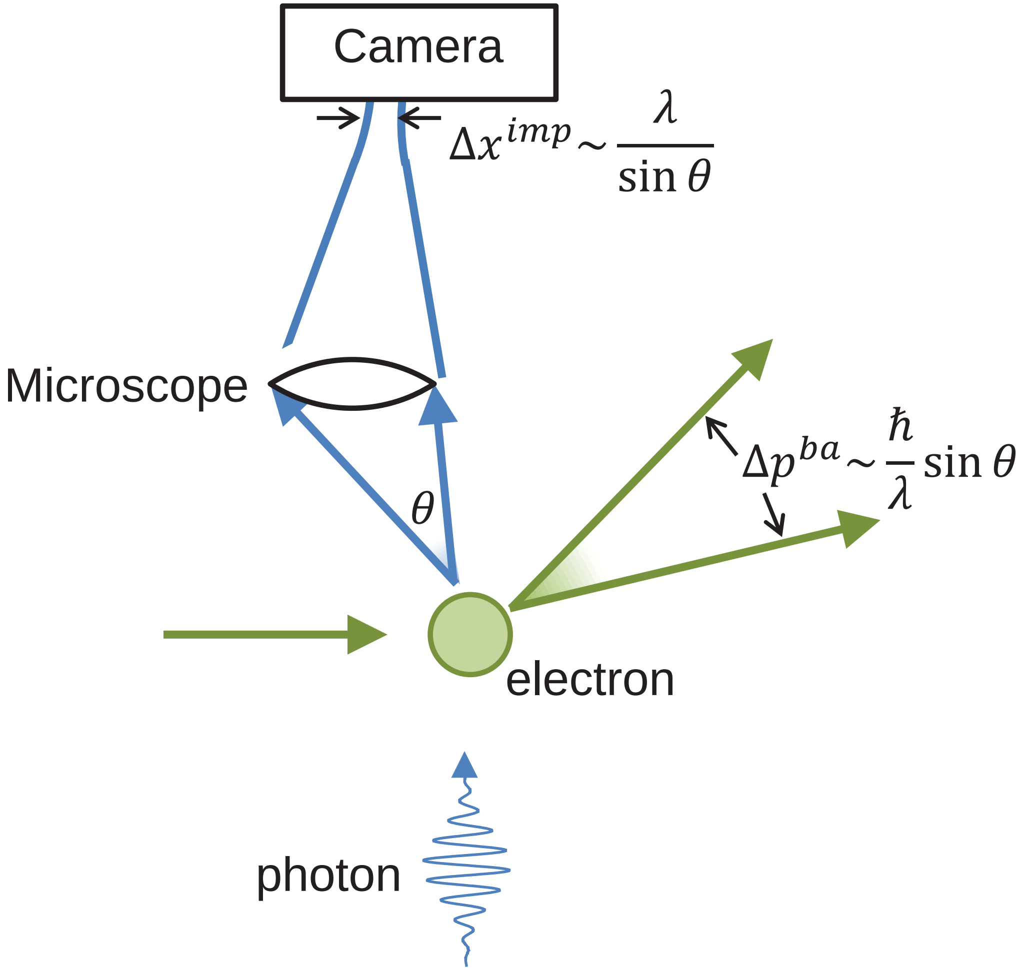
$$\Delta p_x \Delta x \sim h . \qquad (18)$$

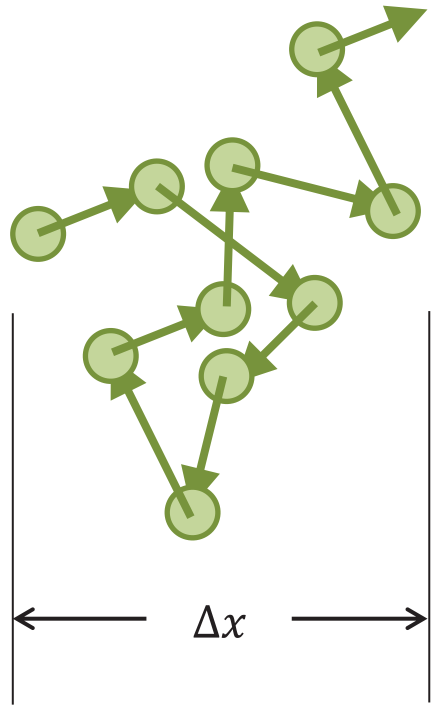
[1] N. Bohr, *loc. cit.*

W. Heisenberg, *Physical Principles of the Quantum Theory* (1930)

Quantum Limits of Optical Detection

Heisenberg's Microscope Thought Experiment

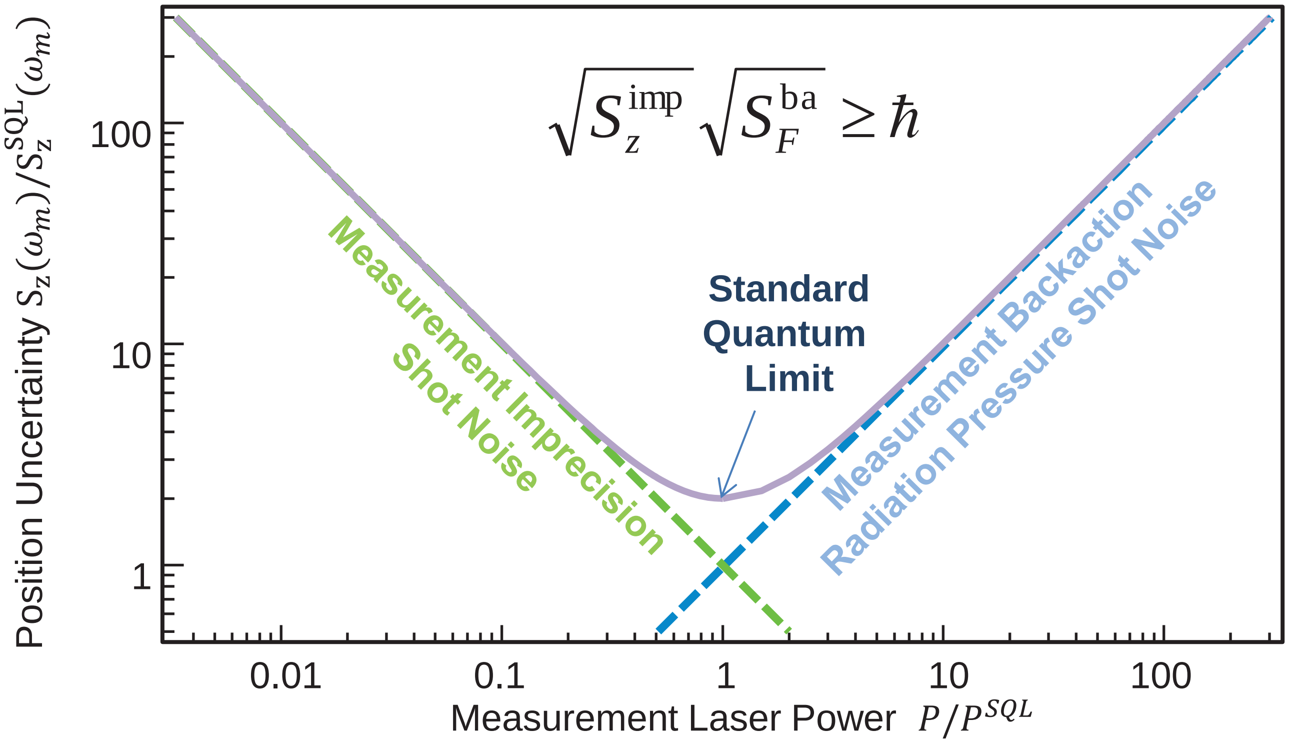




$$\Delta x^{\mathrm{imp}} \Delta p^{\mathrm{ba}} \geq \hbar / 2$$

Quantum Limits of Optical Detection

Standard Quantum Limit



Shot Noise –

$\sqrt{N}$ statistical fluctuations of the number of photons detected in a given time interval

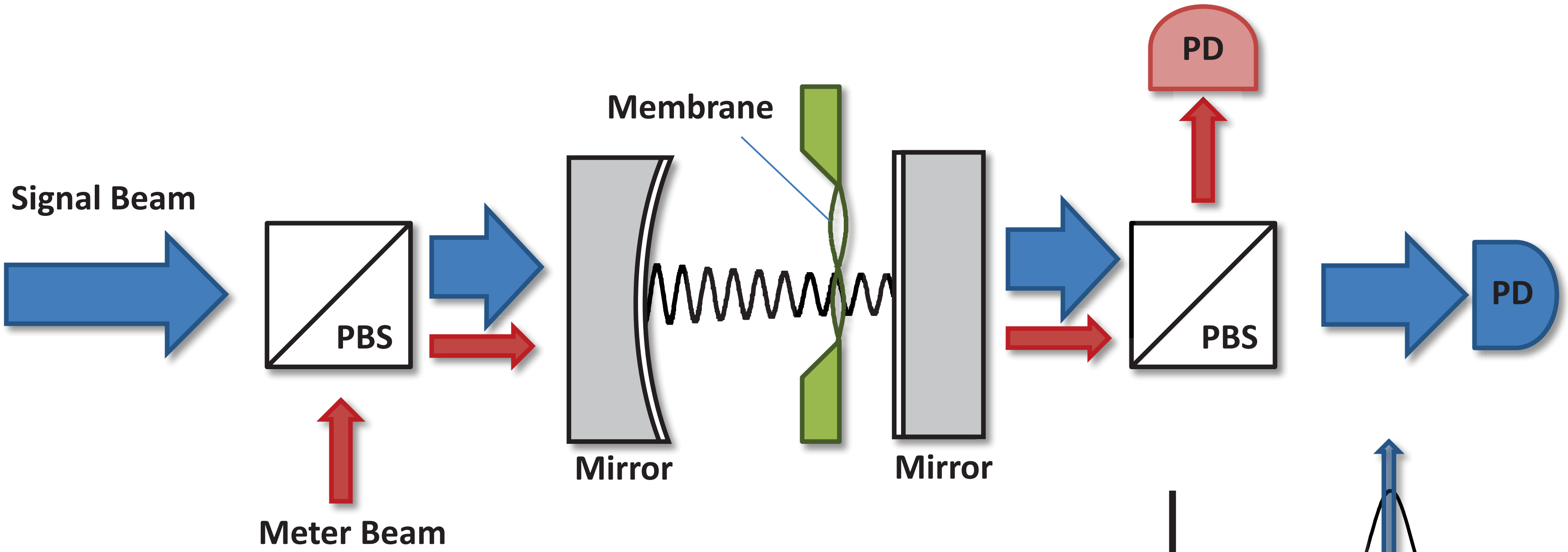
$$S_z^{imp}(\omega) \propto \left(\frac{\sqrt{N}}{N}\right)^2 \propto \frac{1}{P}$$

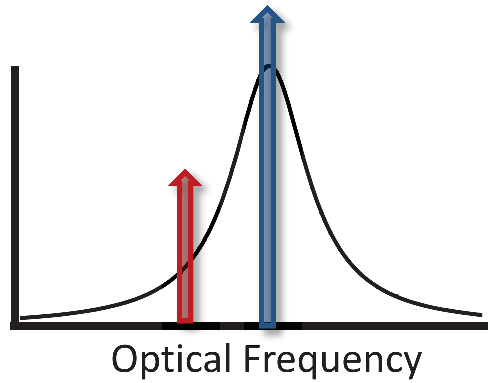
Radiation Pressure Shot Noise –

Randomly varying optical force fluctuations due to shot noise

$$S_F^{ba}(\omega) \propto P$$

Quantum Measurement Experiment Setup

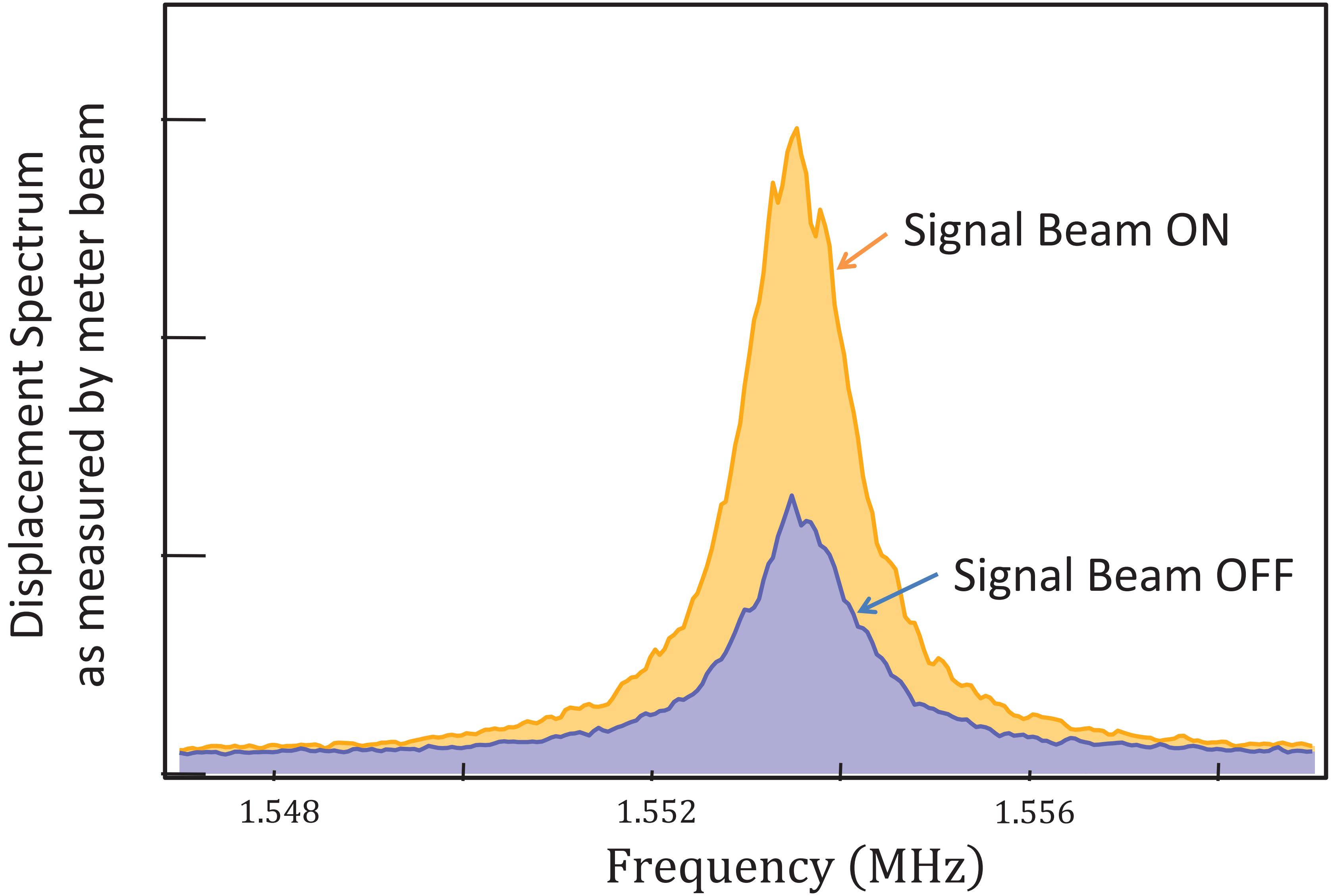




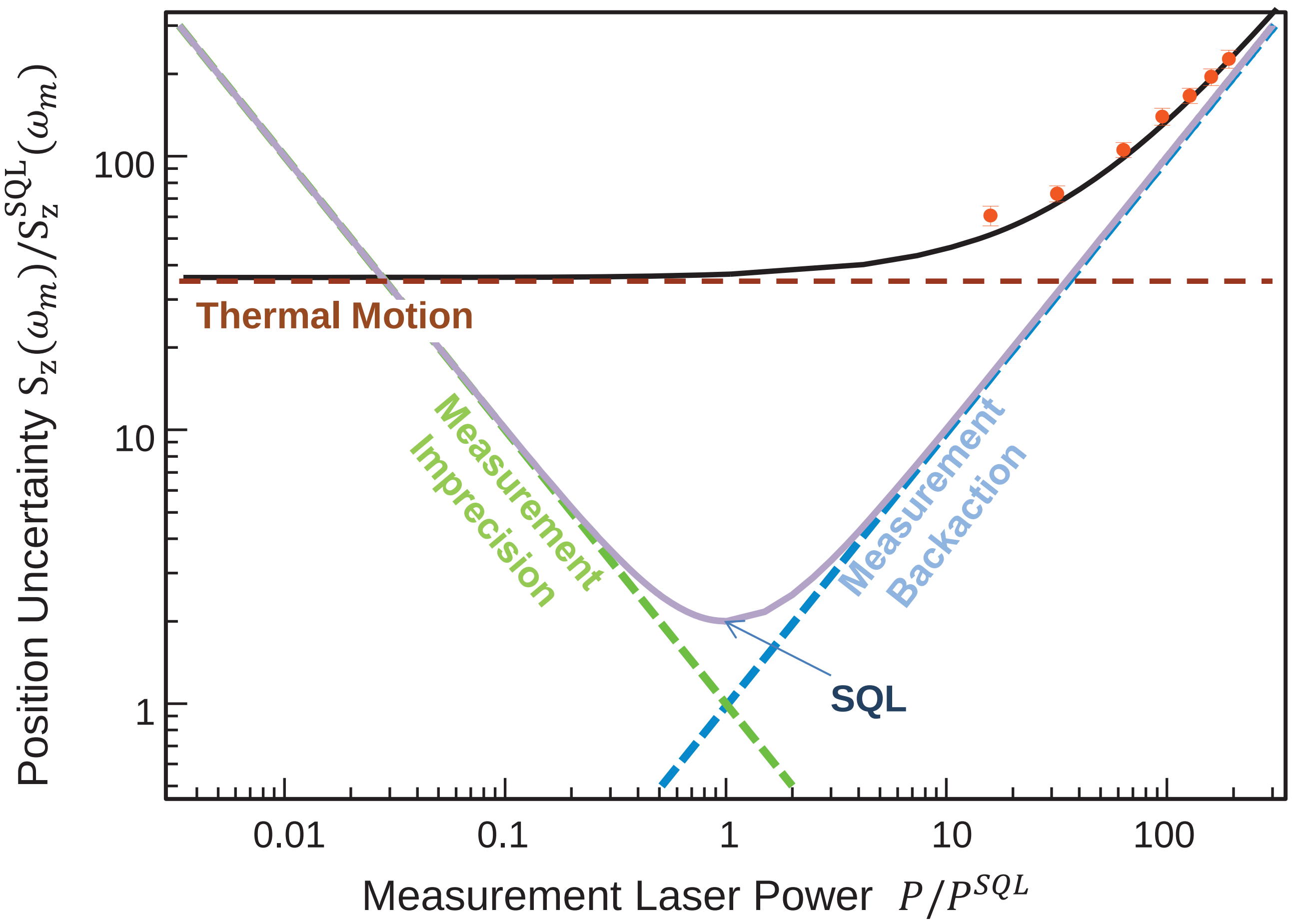
Signal Beam
- High Power (strong measurement)
- On resonance
- RPSN
- Displacement information imprinted in optical phase

Meter Beam
- Low Power
- Red detuned
- Optical Cooling
- Displacement readout

Radiation Pressure Shot Noise

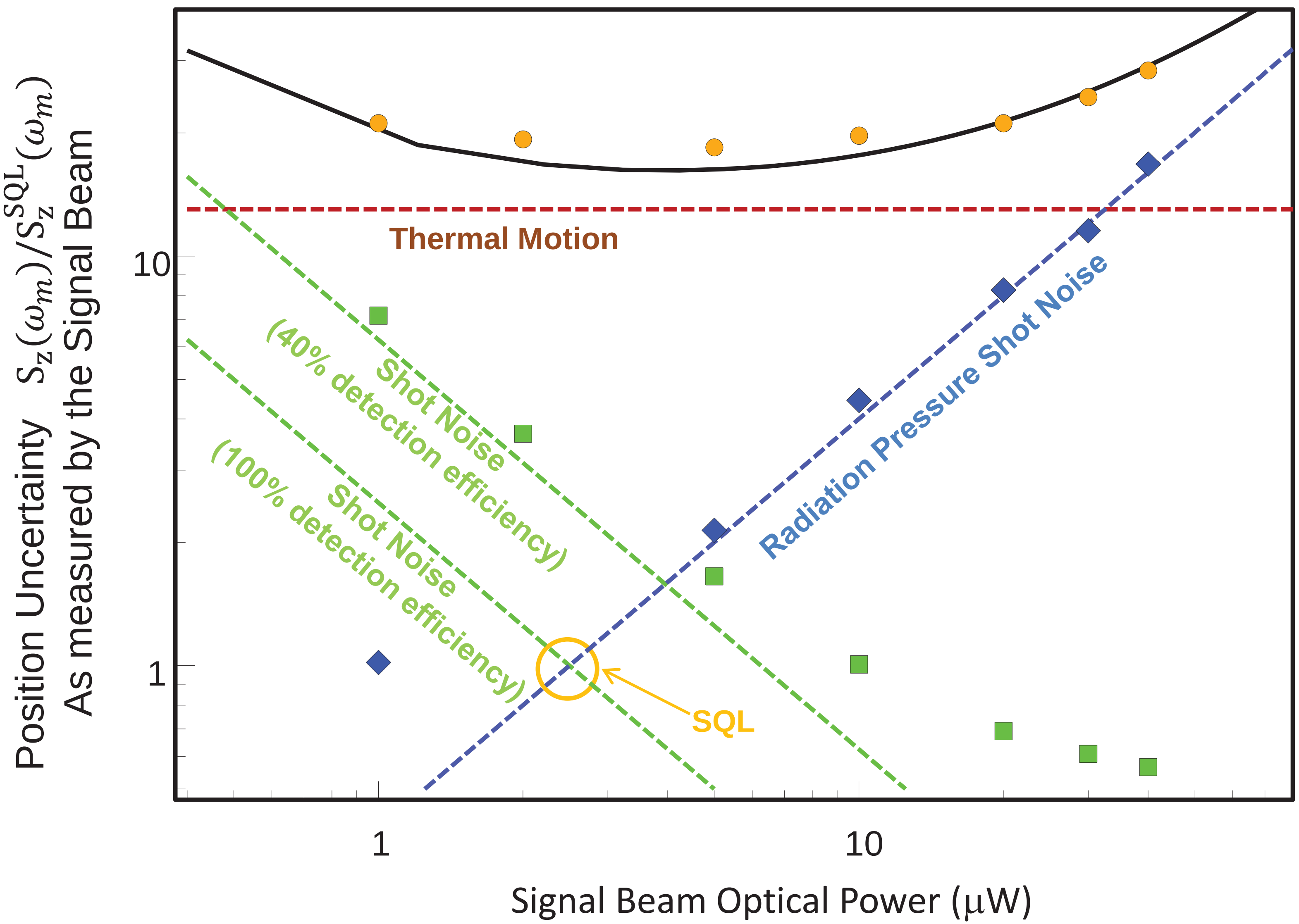


Radiation Pressure Shot Noise

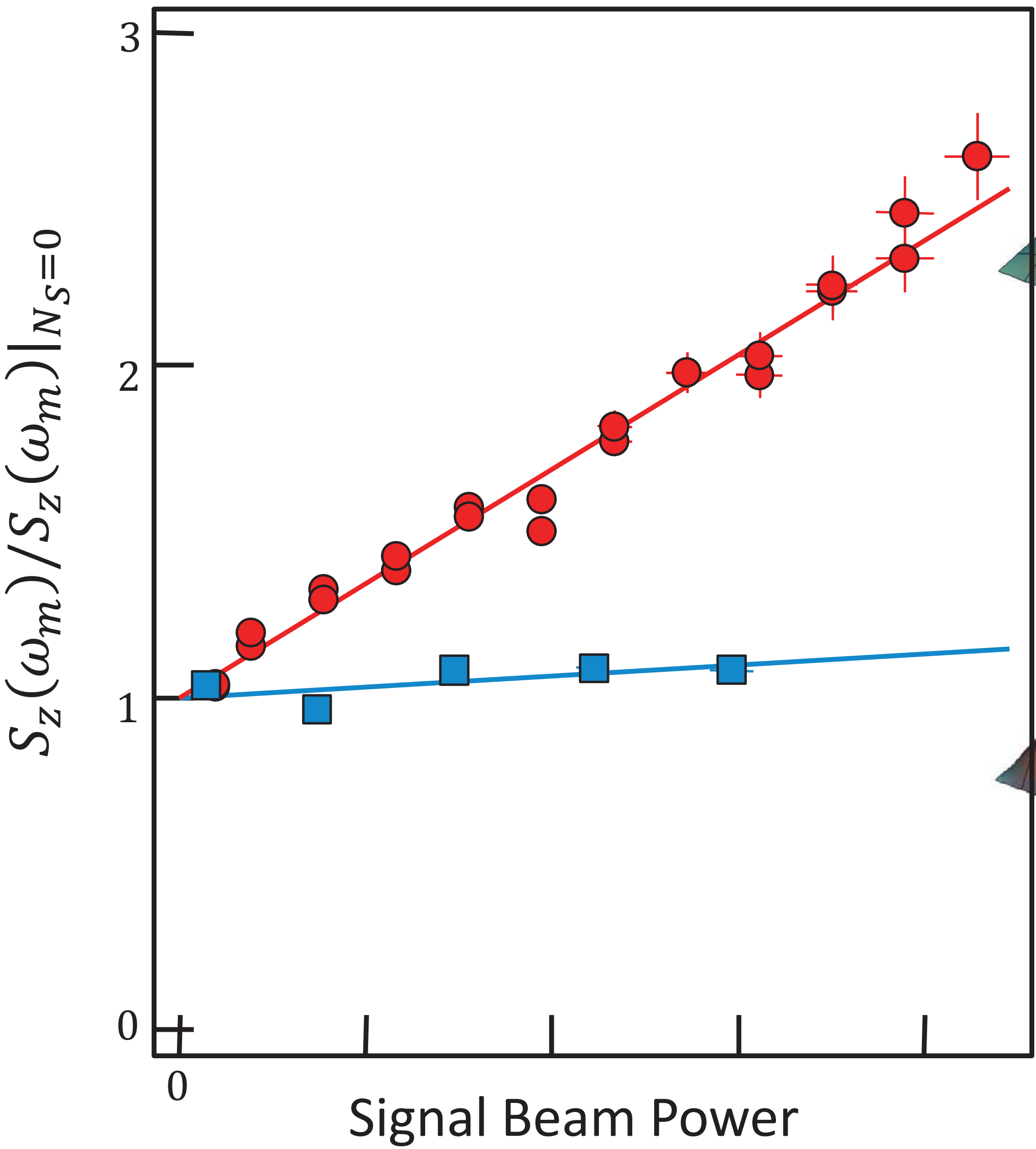


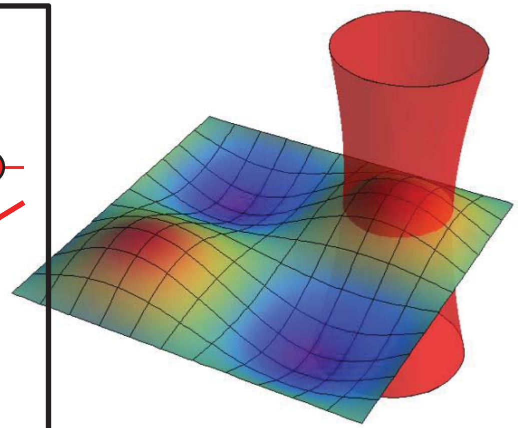
Purdy, et al., *Science* **339**, 801 (2013)
Murch, et al., *Nature Physics* **4,** 561 (2008)
Naik, et al., *Nature* **443**, 193 (2006)
John Teufel, *unpublished*

Approaching the Standard Quantum Limit

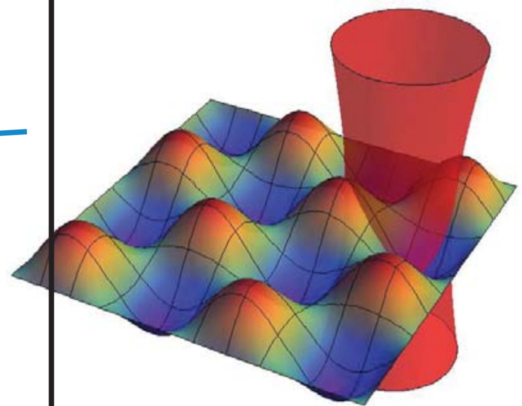


Radiation Pressure Shot Noise



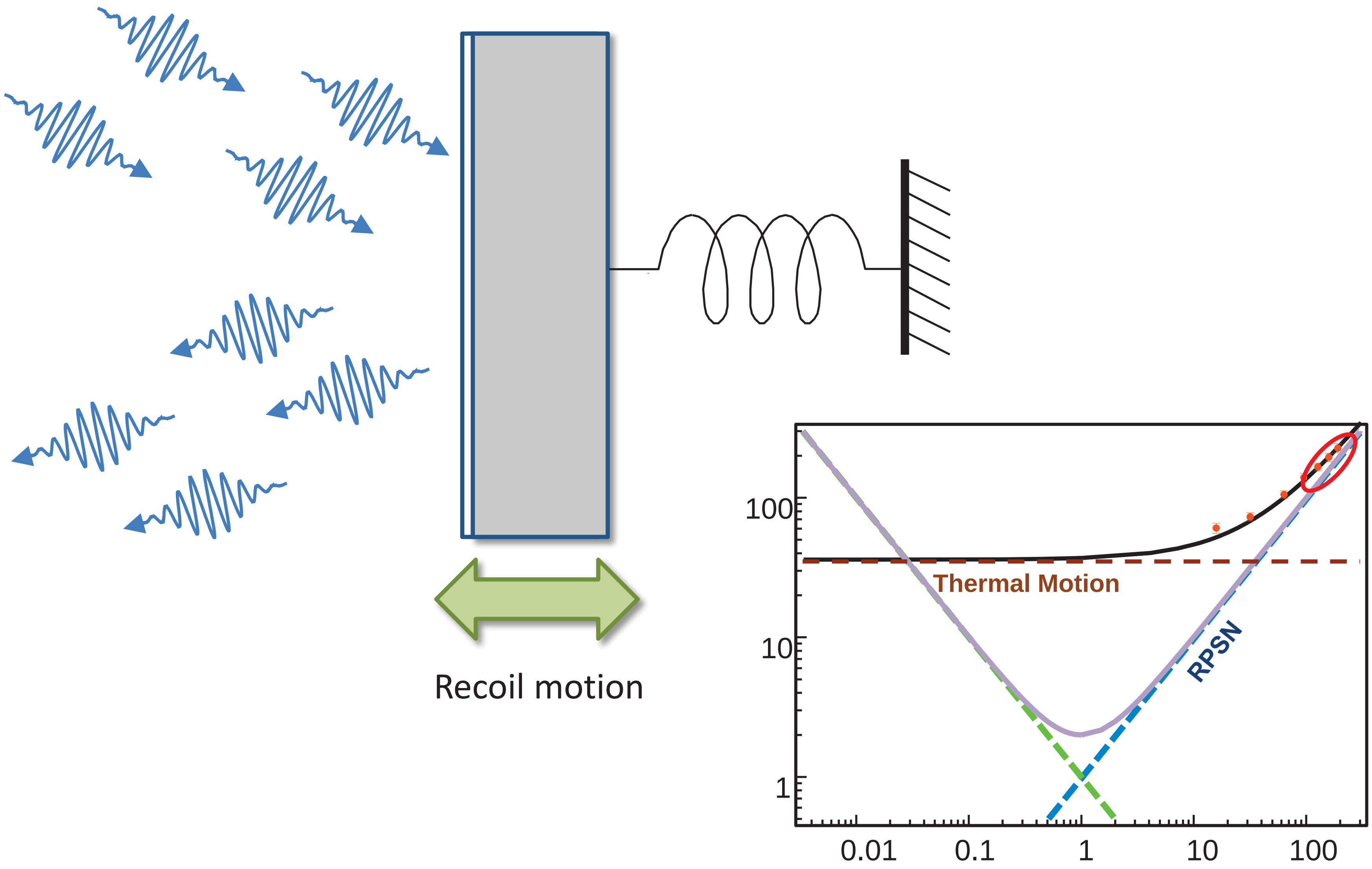


(2,2) mode – well coupled

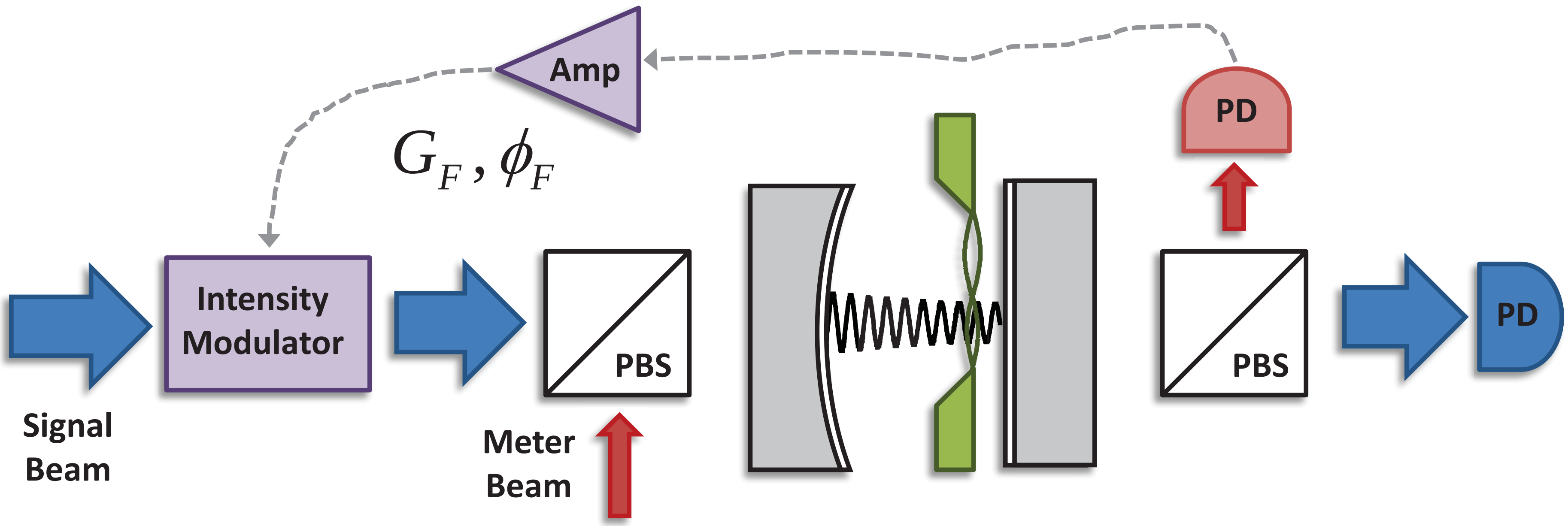


(4,4) mode – poorly coupled

Quantum Measurement of Light



Quantum Noise Cancellation

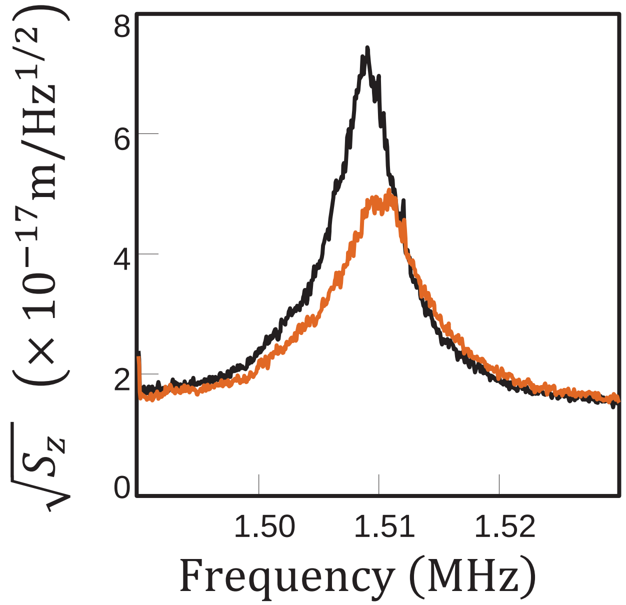


1. Membrane senses signal beam intensity fluctuations
2. Meter beam reads out membrane displacement
3. Active feedback cancels signal beam intensity fluctuations

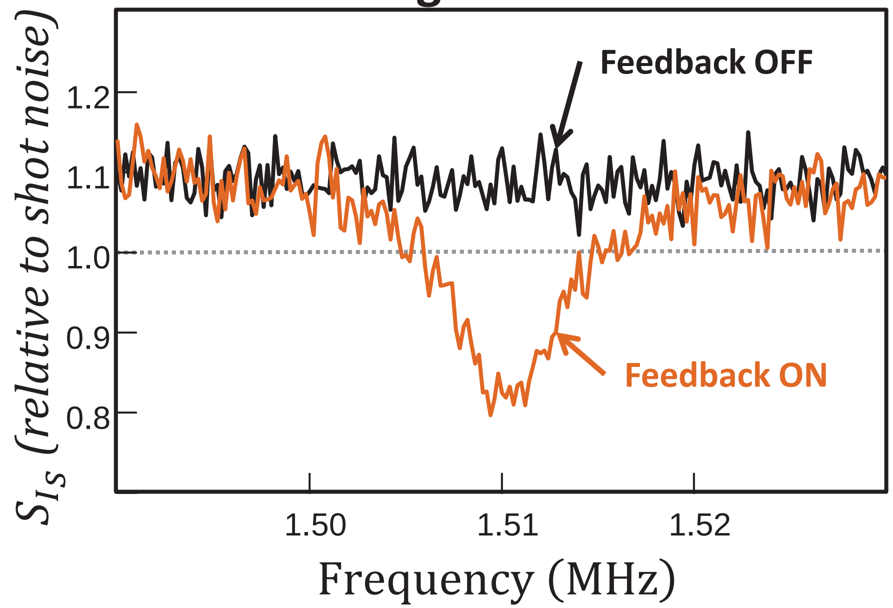
Wiseman and Milburn, *PRA*, **49**:1350 (1994)
Mancini and Wiseman, *J. of Opt. B*, **2**:260 (2000)
See also Haroche group Cavity QED work

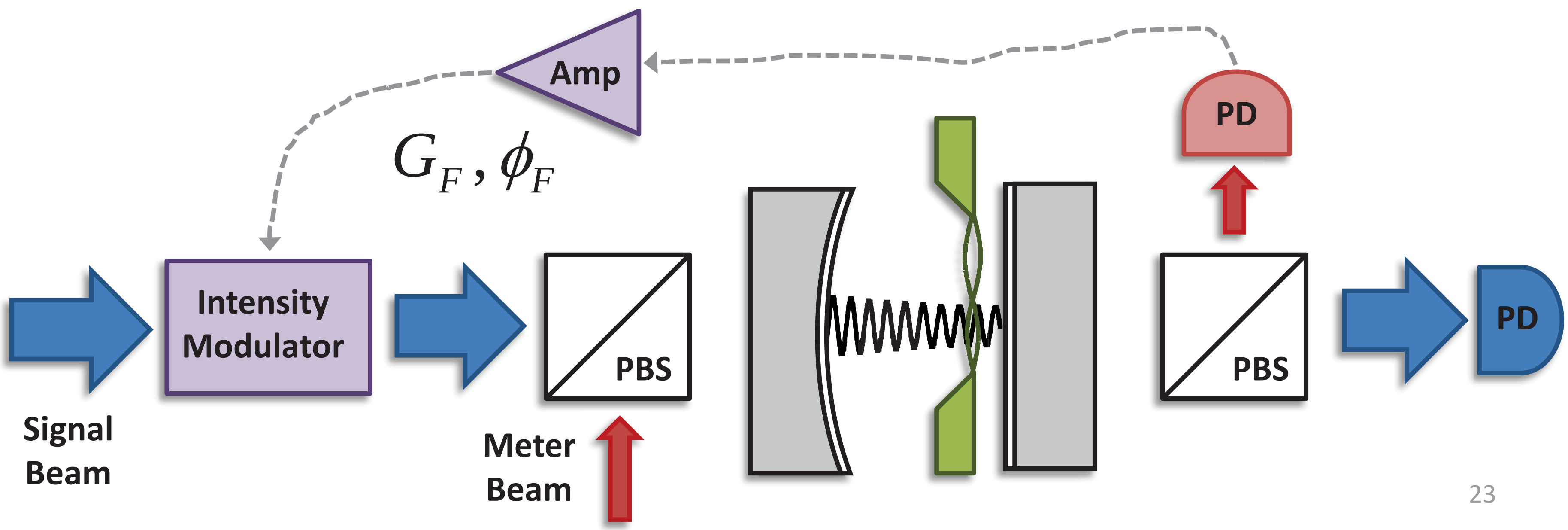
Quantum Noise Cancellation

Meter Beam

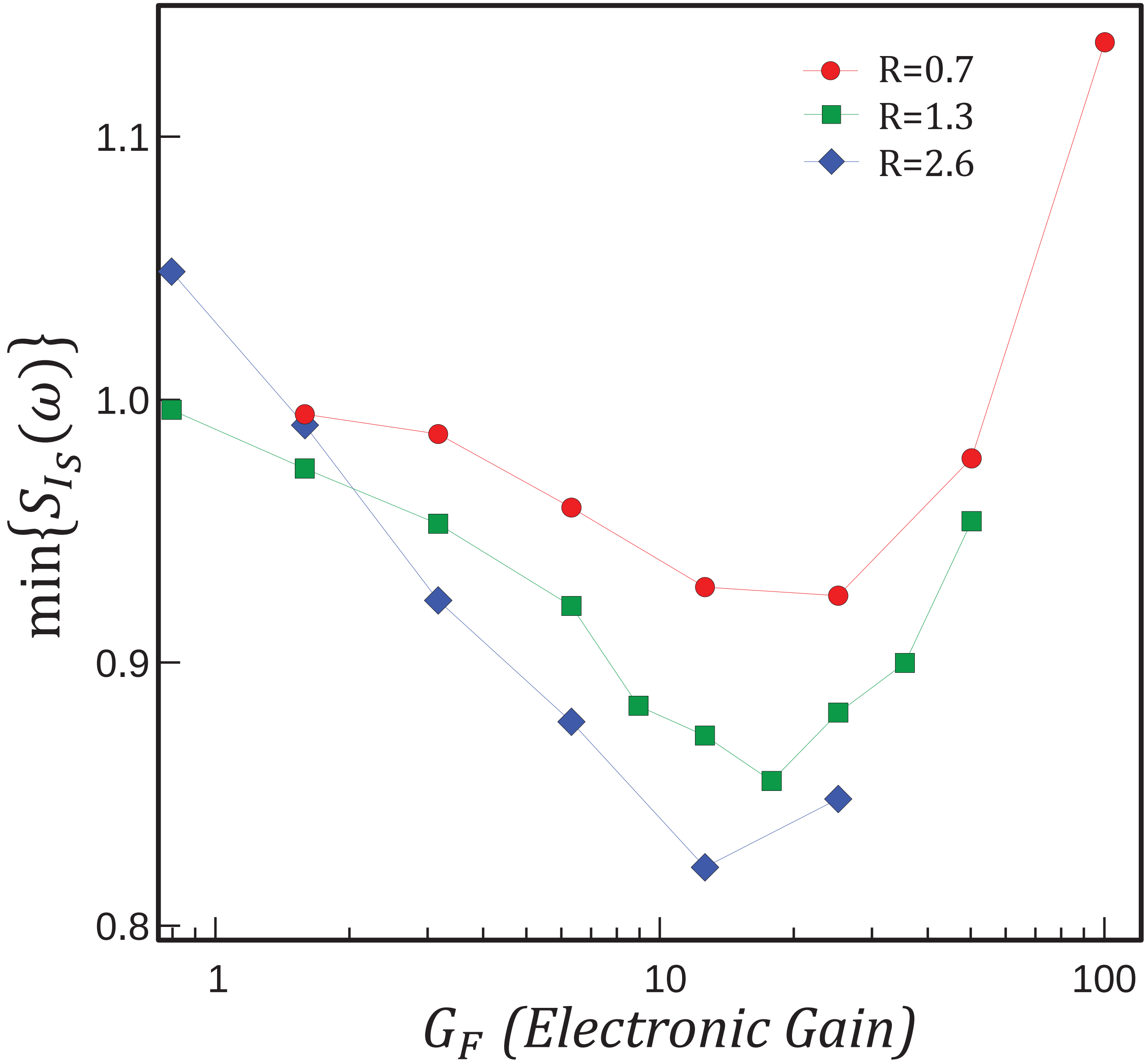


Signal Beam





Quantum Noise Cancellation



RPSN to Thermal Force Ratio

$$R = \frac{4\,\bar{N} g_0^2}{\kappa\,\Gamma_0\, n_{th}} \frac{1}{1+\left(\frac{\omega_m}{\kappa/2}\right)^2}$$

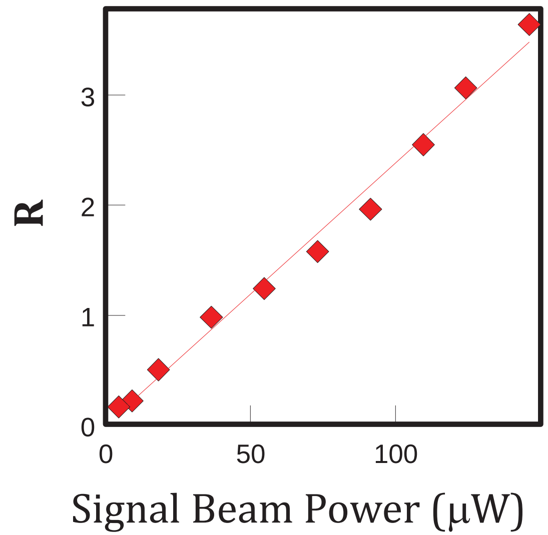
$\bar{N}$ = intracavity photon #

g_0 = optomechanical coupling rate

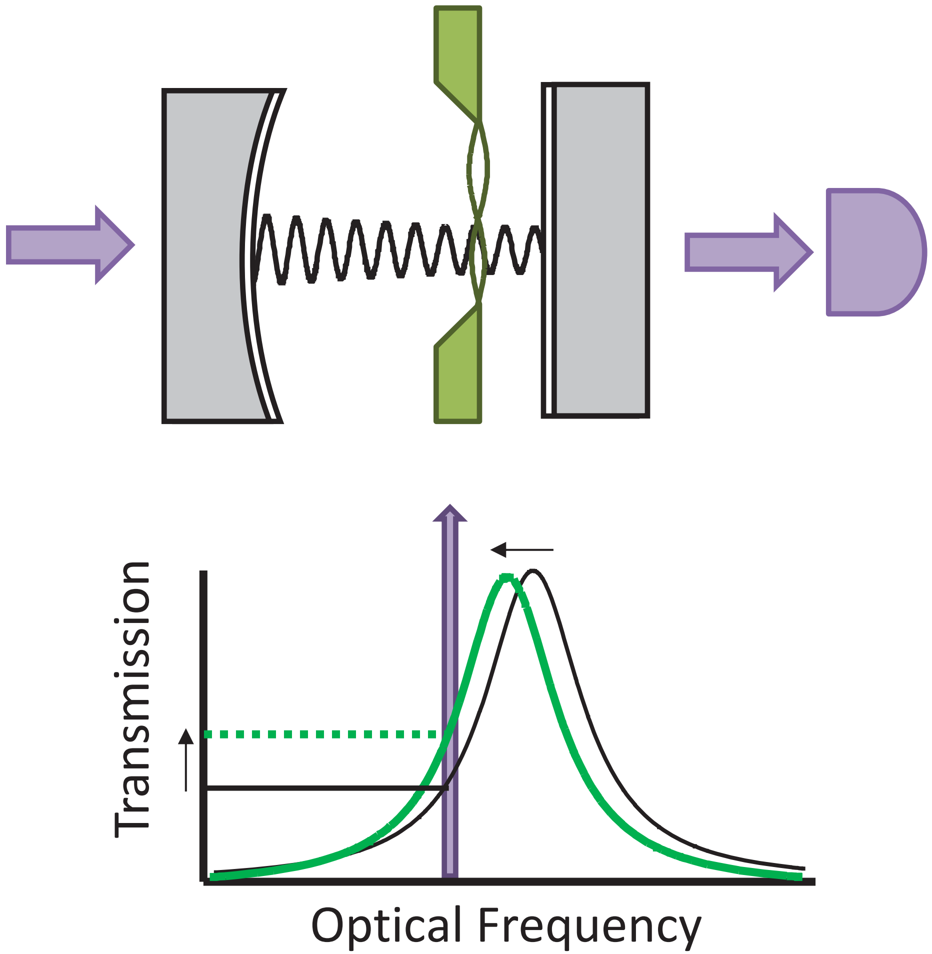
κ = cavity decay rate

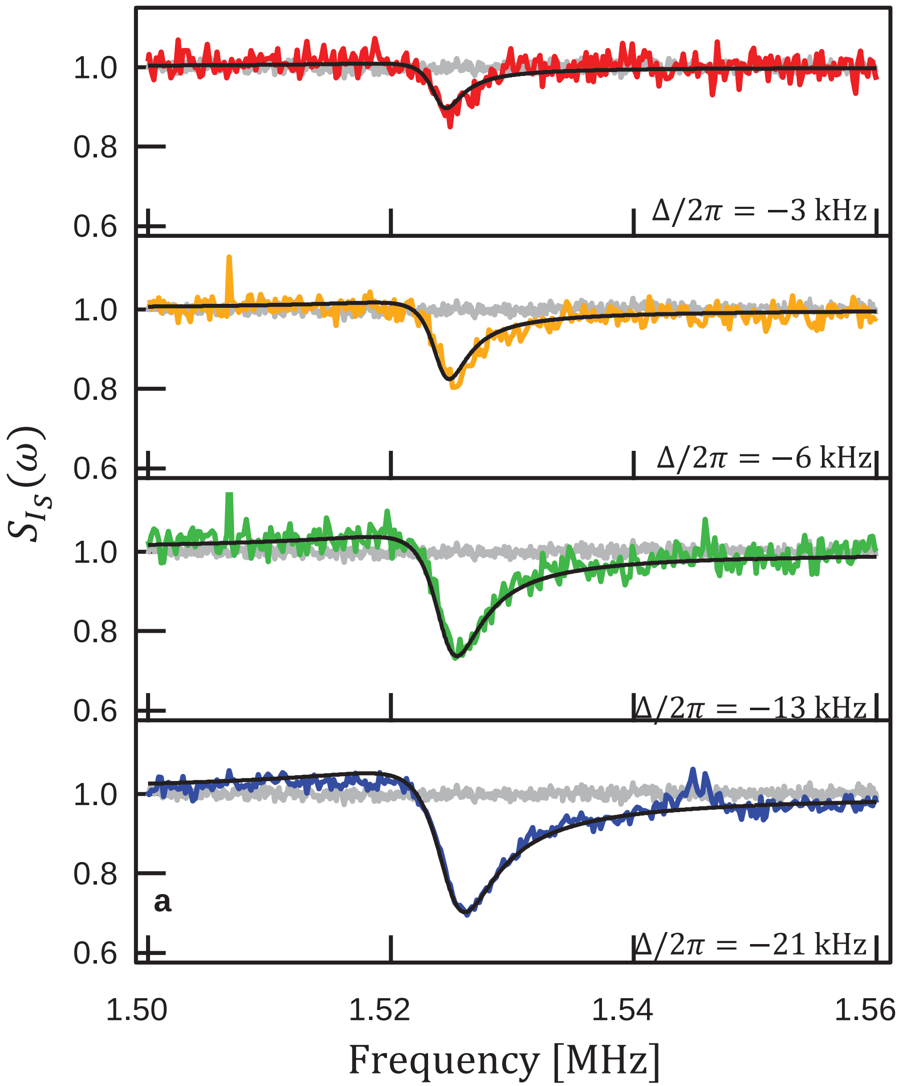
Γ_0 = mechanical decay rate

n_{th} = mechanical occupation #



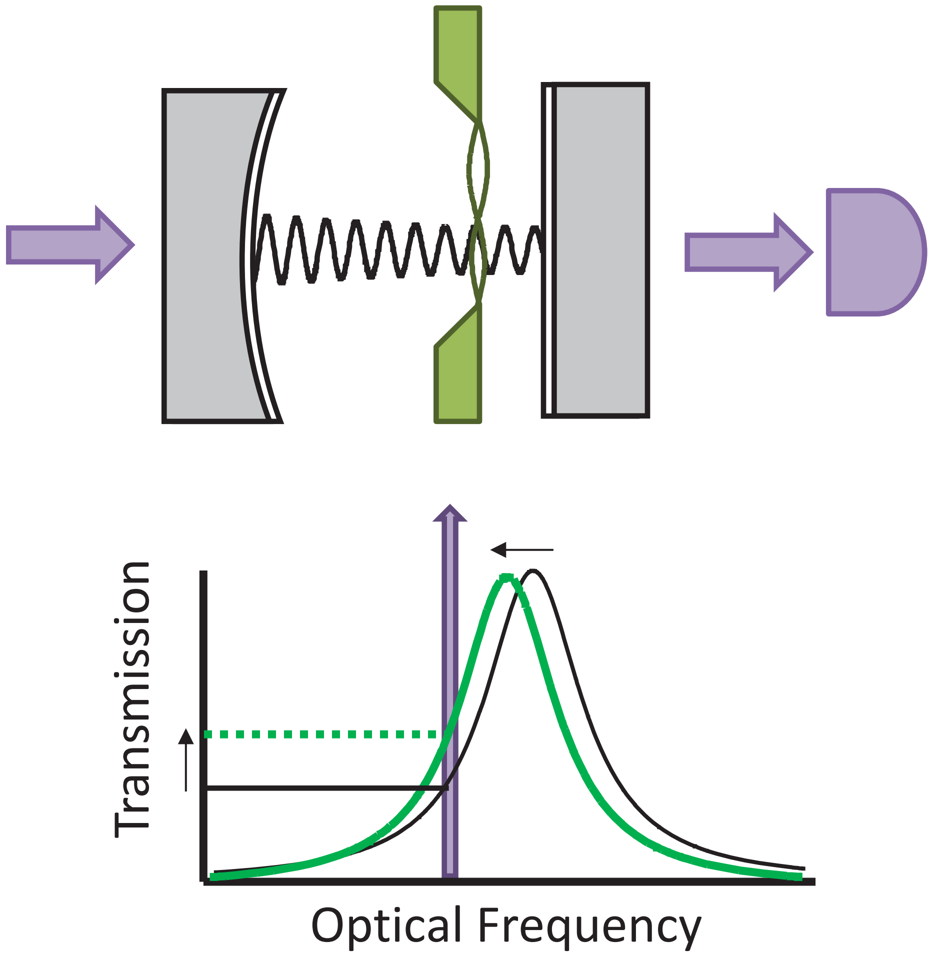
Self-Squeezing of Light

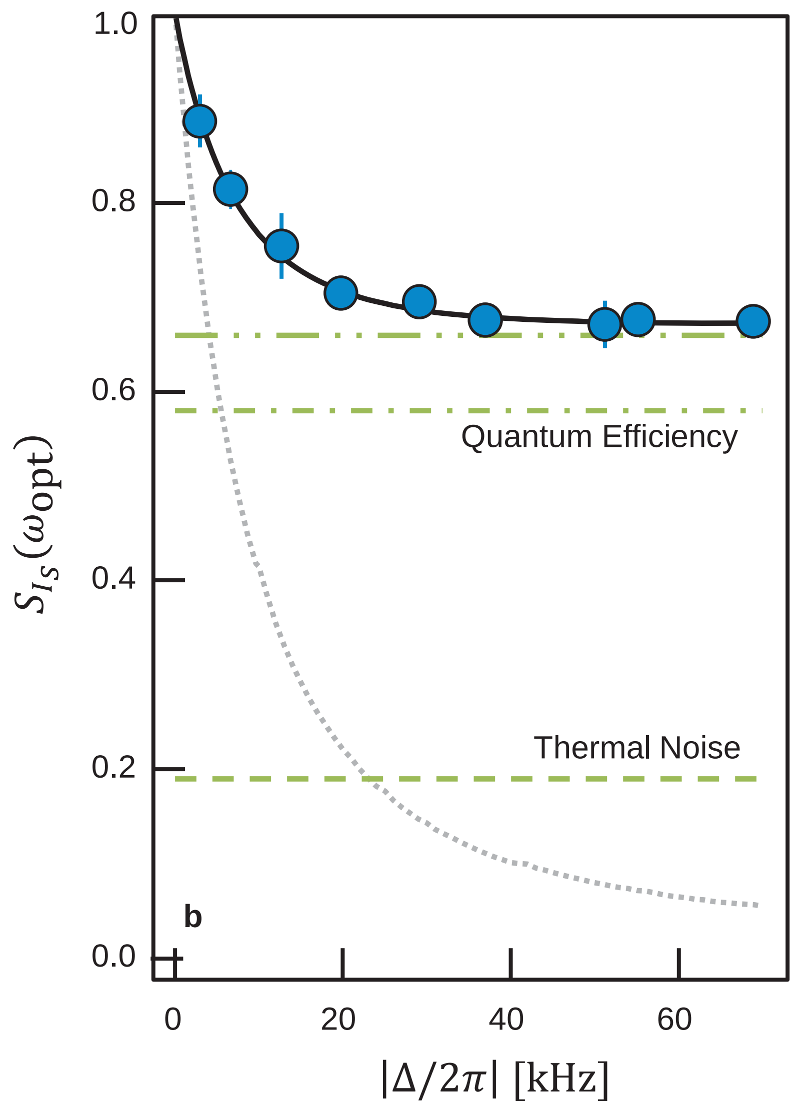




Purdy, et al., *PRX*, *in press* (2013) arXiv:1306.1268
Safavi-Naeini, et al., *Nature* **500**, 185 (2013)
Brooks, et al., *Nature* **488**, 476 (2012)

Self-Squeezing of Light





Purdy, et al., *PRX, in press* (2013) arXiv:1306.1268
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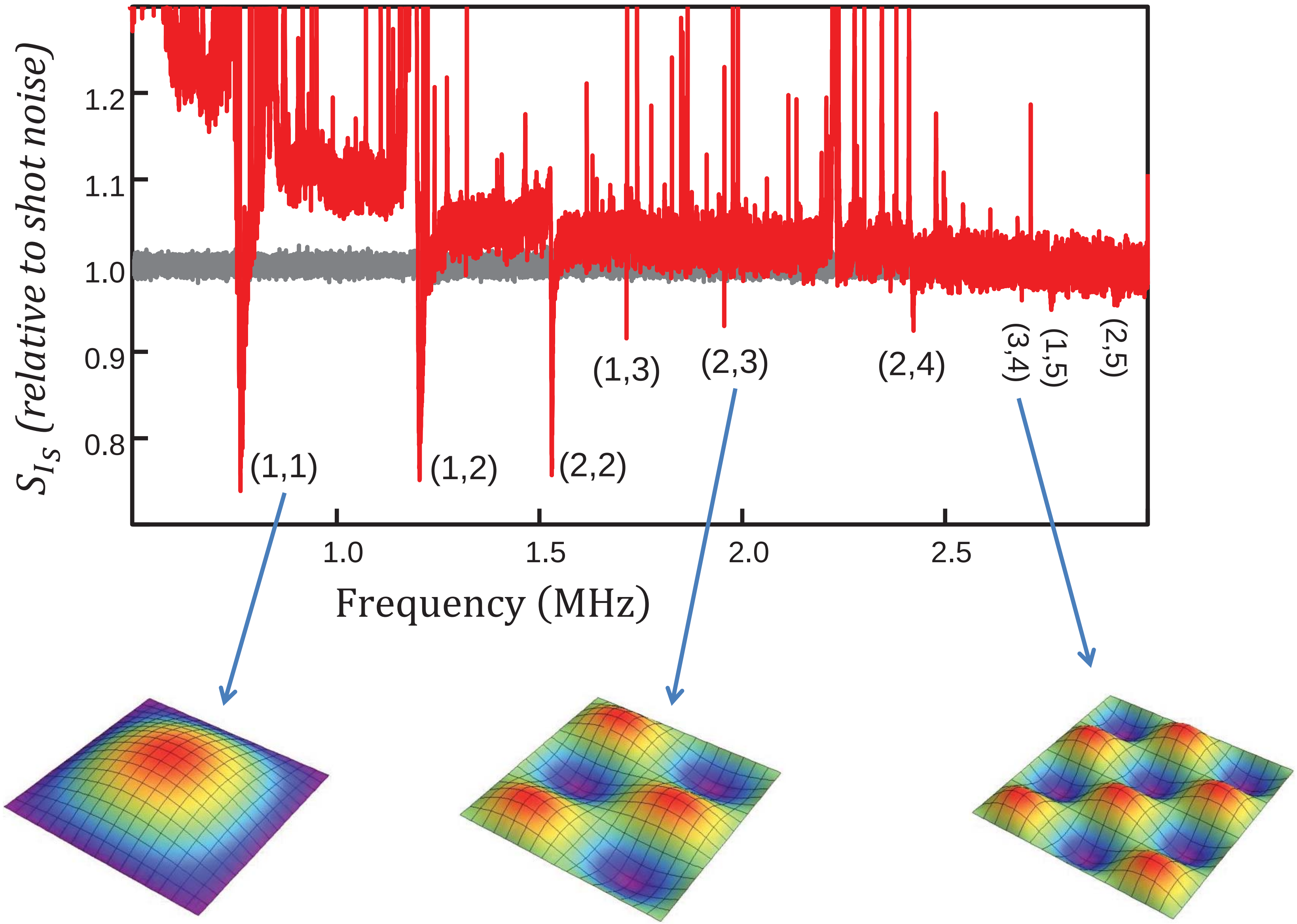


Self-Squeezing of Light

Nonlinear Optics: Complex Kerr Medium

Self Phase Modulation→Squeezed Light

$$X_I^{out} = X_I^{in}$$

$$X_Q^{out} = X_Q^{in} + rX_I^{in}$$

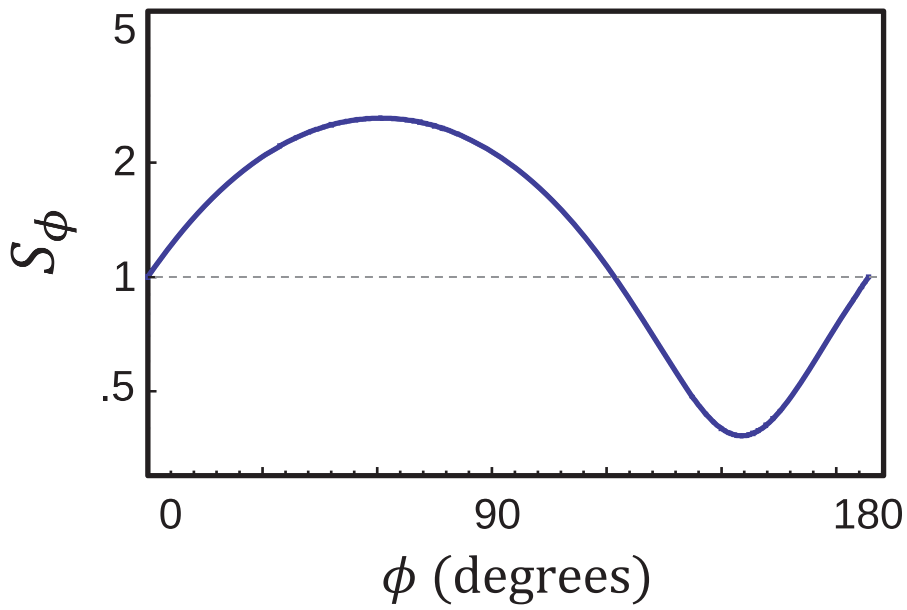
X_I = amplitude quadratue

X_Q = phase quadrature

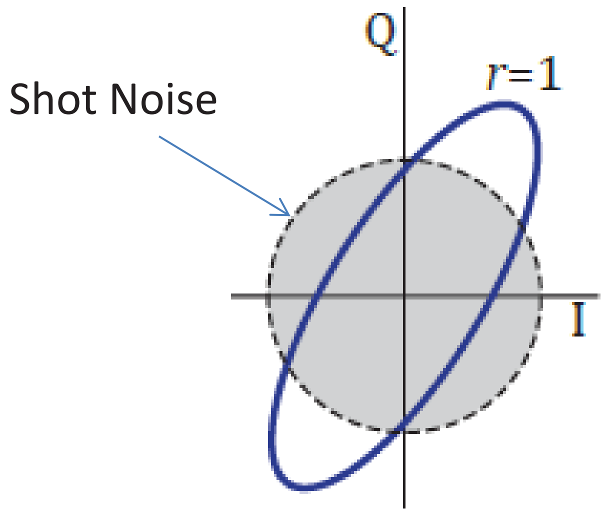
$r \propto$ optomechanical couping, light intensity, mechanical response

$$X_\phi = X_I \cos\phi + X_Q \sin\phi$$

$$S_\phi = \langle \delta X_\phi^*(\omega)\delta X_\phi(\omega)\rangle = 1 + \mathrm{Re}\{r(\omega)\}\sin(2\phi) + \left(|r(\omega)|^2 - 2\,\mathrm{Im}\{r(\omega)\}\right)\sin^2(\phi)$$

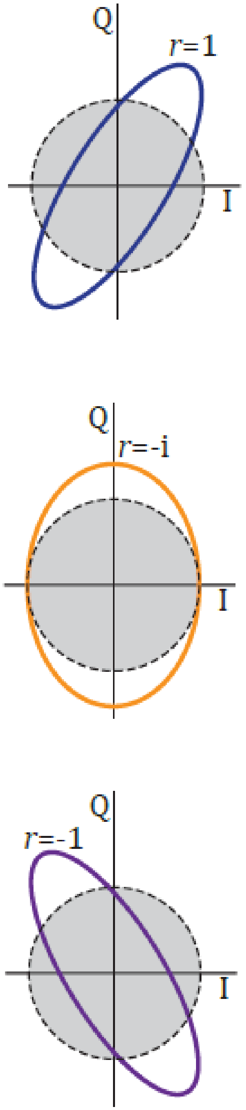


Phase Space Distribution

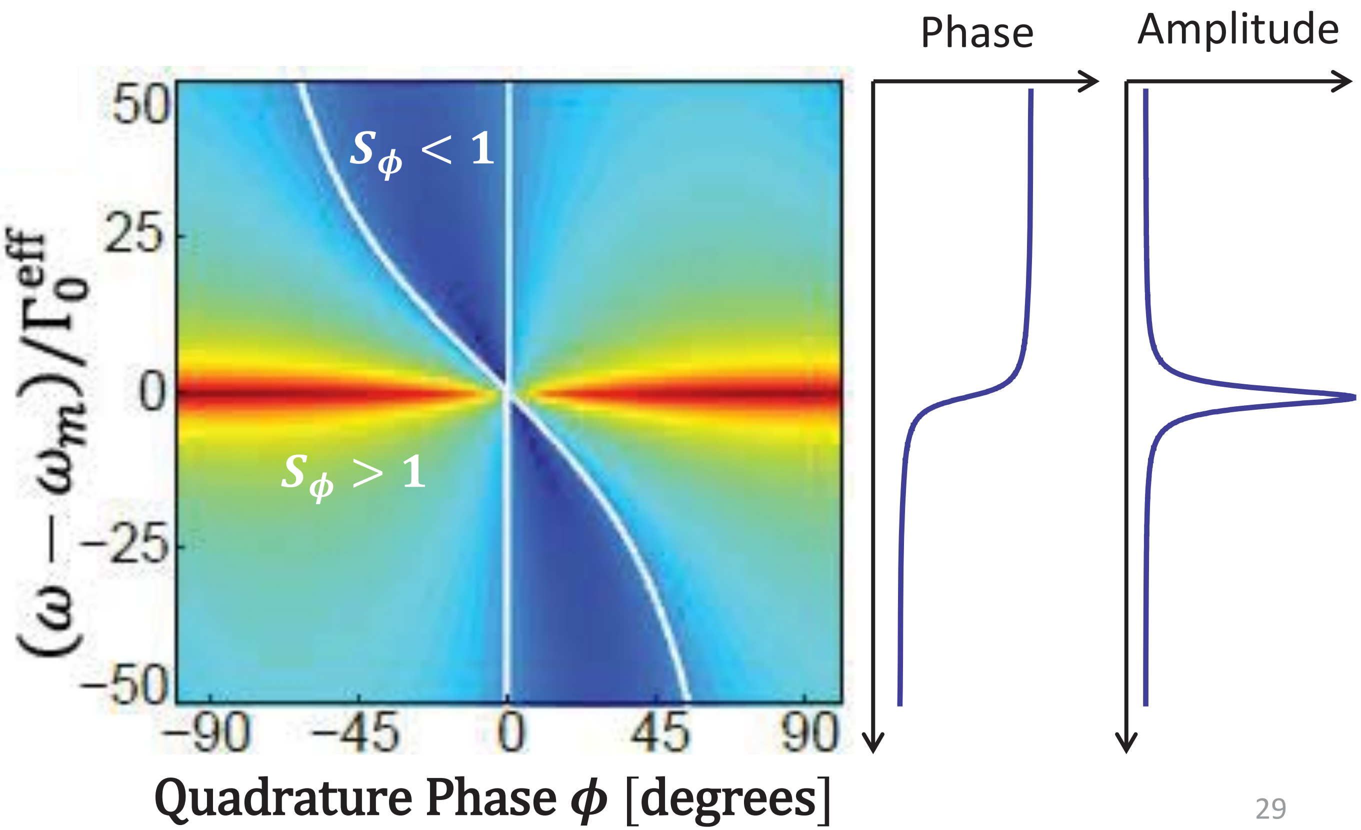


Self-Squeezing of Light

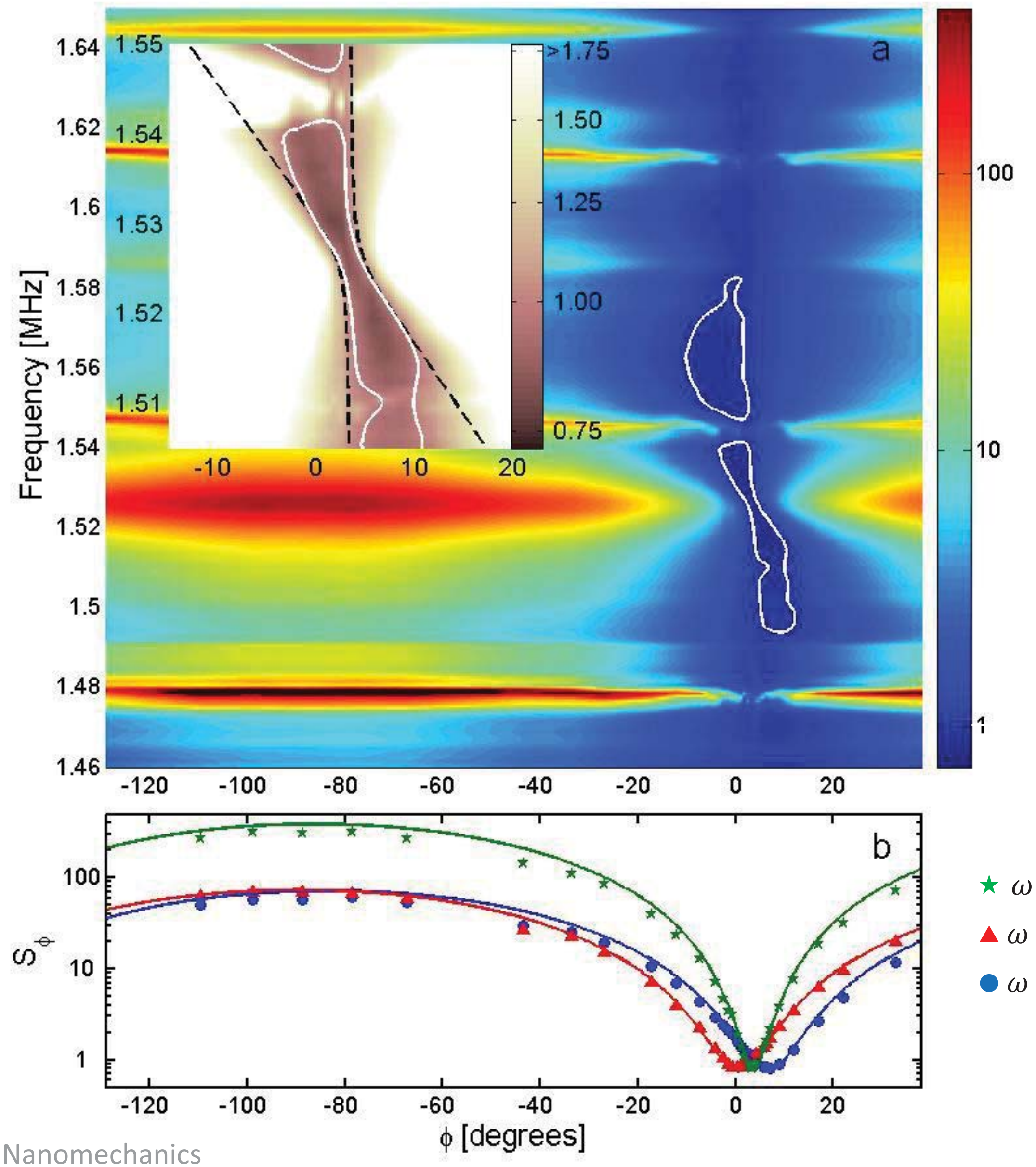
Nonlinear Optics: Complex Kerr Medium



$r \propto$ optomechanical couping,
light intensity,
mechanical response



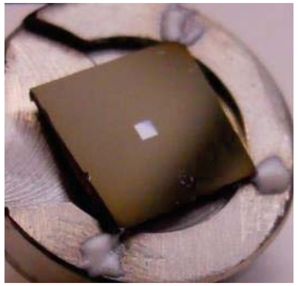
Self-Squeezing of Light



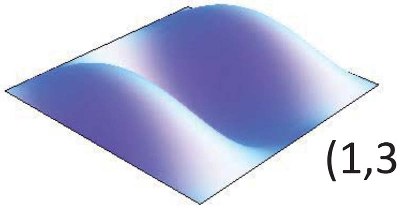
★ $\omega = \omega_m$
▲ $\omega - \omega_m = 2\pi \times 9$ kHz
● $\omega - \omega_m = -2\pi \times 9$ kHz

Building Better Mechanical Resonators

The membrane acts as an acoustic radiatior.
Energy is dissipated when the radiated waves encounter lossy boundary.

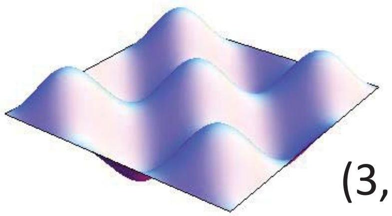


asymmetric modes
are dipole-like.
Radiate more, lower *Q*

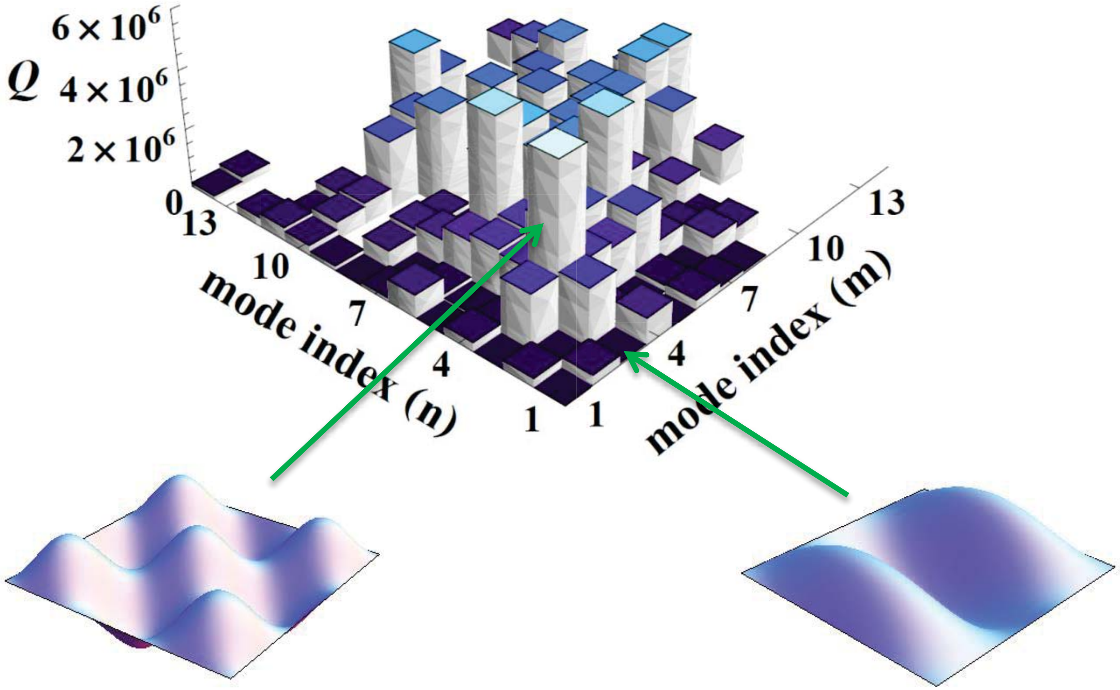


(1,3)

symmetric modes
are quadrupole-like (or higher order).
Radiate less, higher *Q*

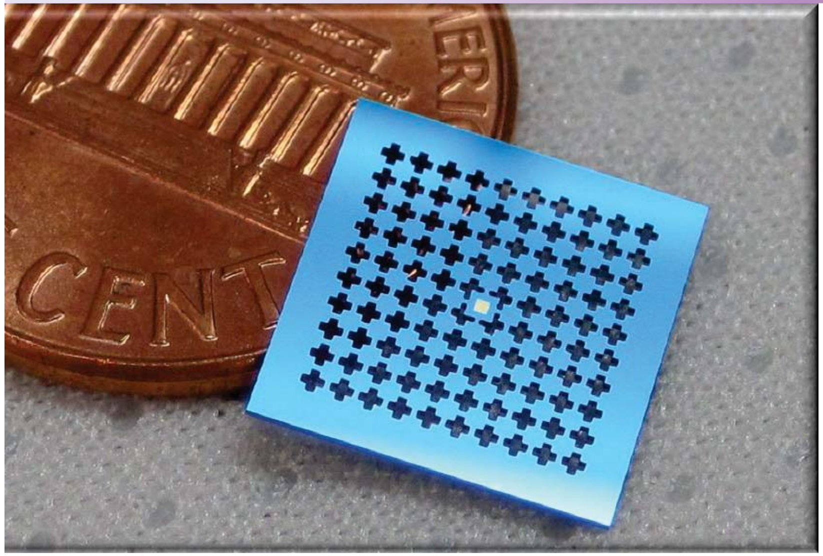


(3,3)



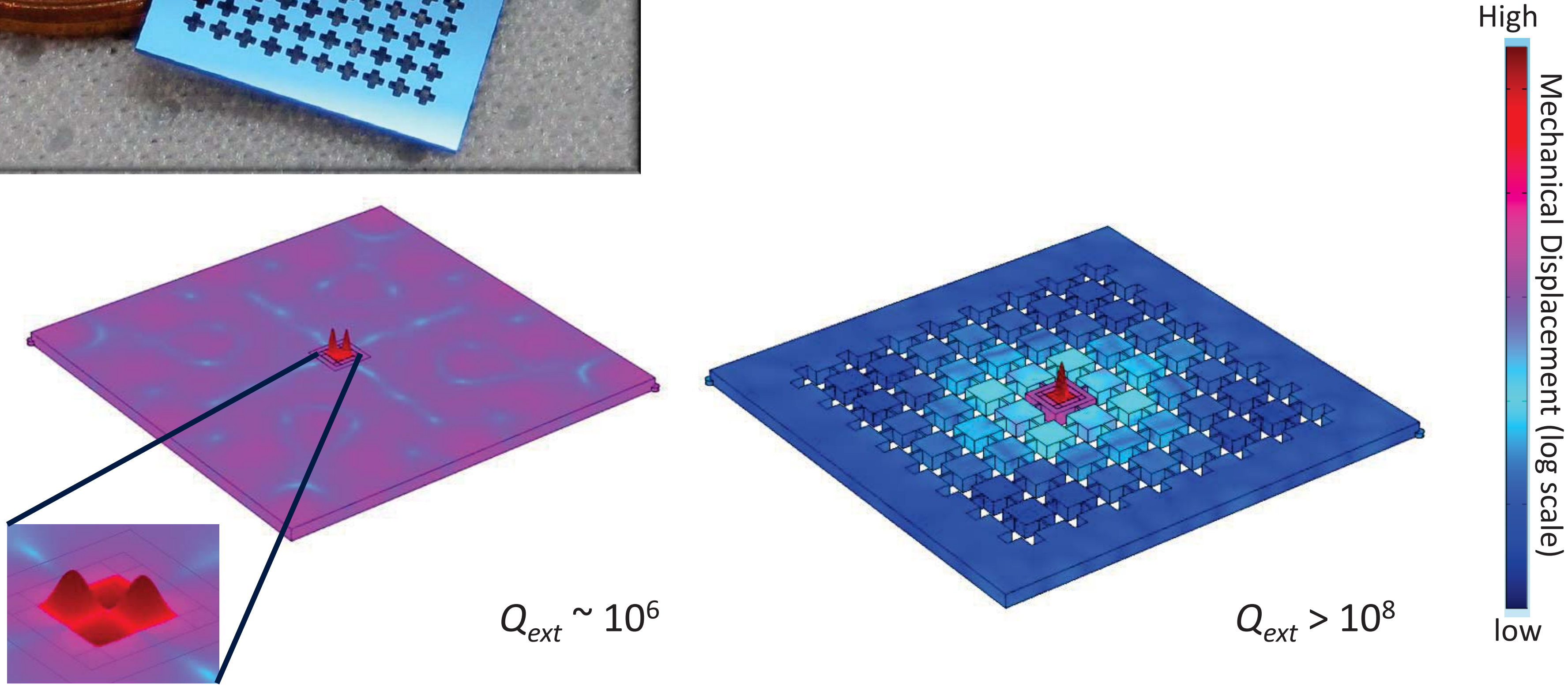
I. Wilson-Rae, et al., PRL (2011)
P.-L. Yu, T. P. Purdy, and C. A. Regal, PRL (2012)

Building Better Mechanical Resonators



Eliminate acoustic radiation

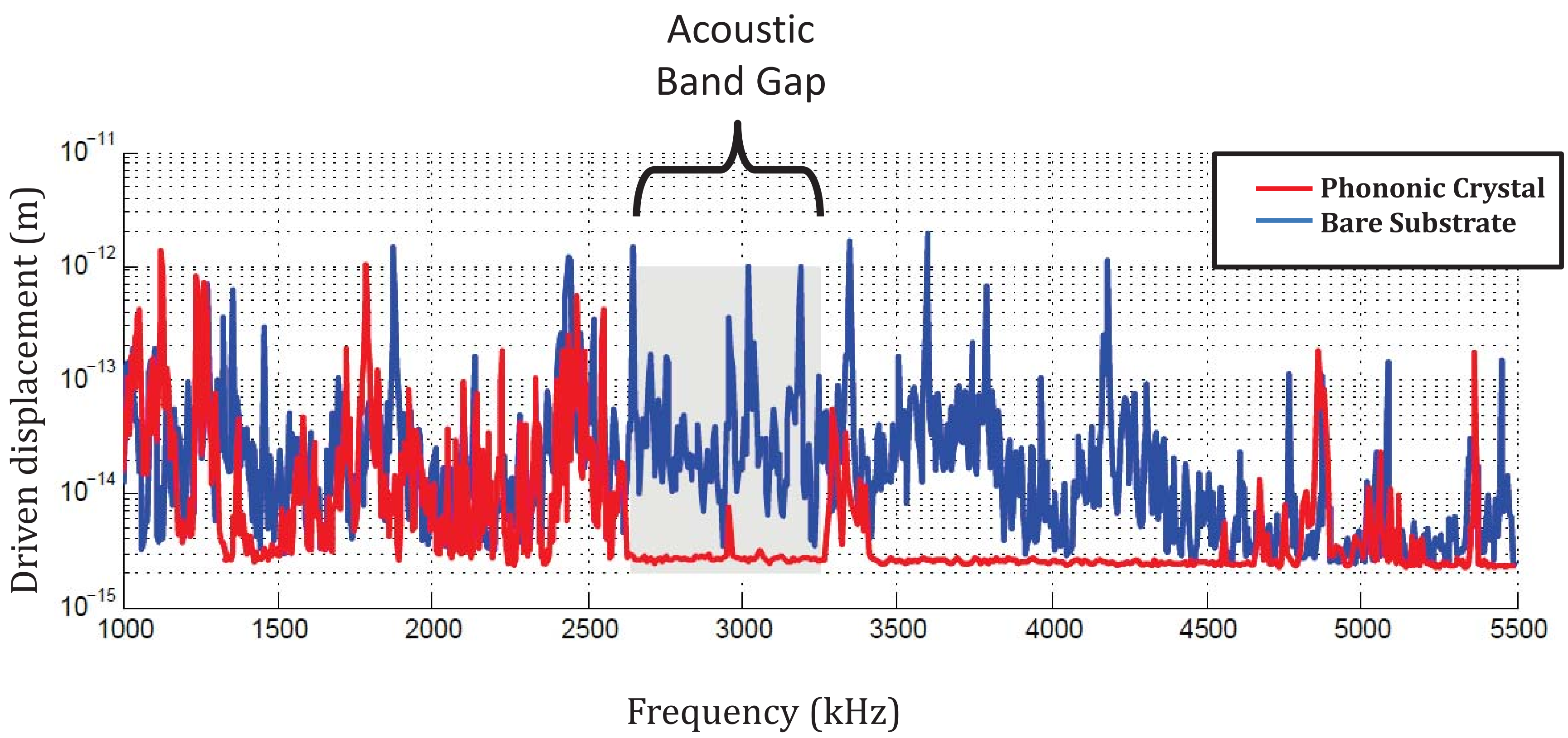
Wilson-Rae, et al., *PRL* **106**, 047205 (2011)
Yu et al., *PRL* **108**, 083603 (2012)



Acoustic radiation shield at GHz: J. Chan et al., APL (2012) Painter Group

Building Better Mechanical Resonators

Work in progress: Measuring band gaps



Conclusions

- Optomechanics experiments in a strong measurement regime
  1. Observe radiation pressure shot noise
  2. Create squeezed light

- This resource is useful to:
  1. Avoid measurement backaction using squeezed light
  2. Perform microwave ↔ optical state transfer at the single quanta level

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