# Resolved-sideband cooling of an optomechanical resonator in a cryogenic environment

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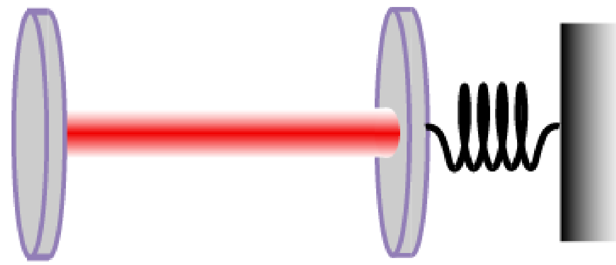
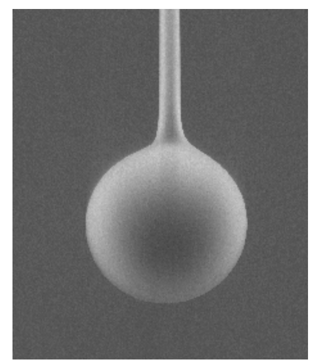
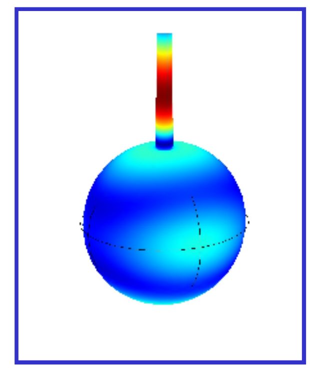
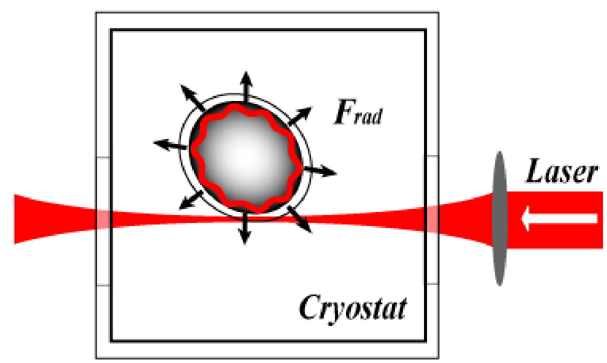
# Outline

- Introduction
- Optomechanical microsphere resonator
  - ✓ Free-space excitation of WGMs
  - ✓ Homodyne detection of mechanical displacement
  - ✓ Mechanical damping
- Resolved sideband cooling at cryogenic temperature
- Summary



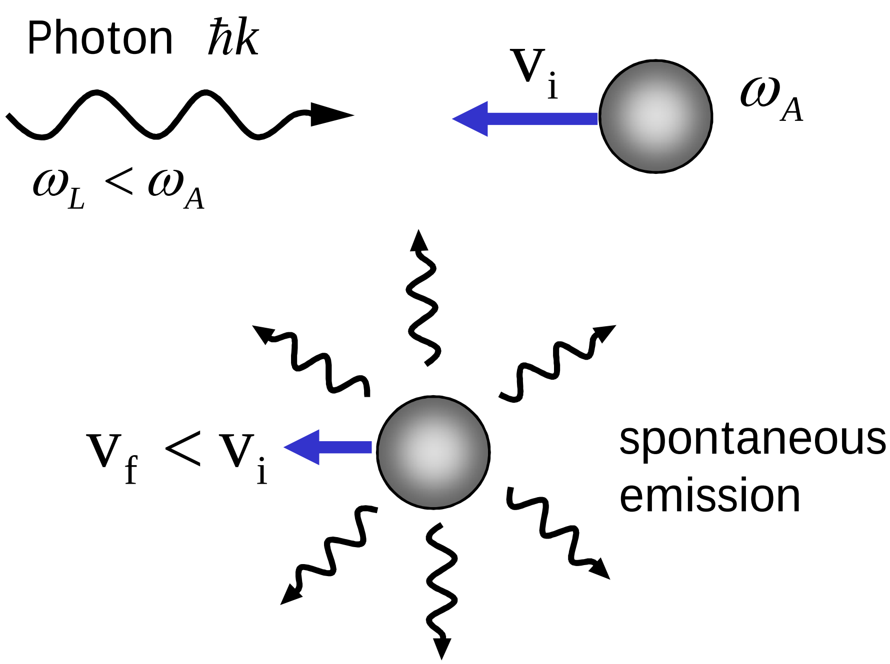






# Laser cooling of atoms

Doppler cooling




Radiation pressure force acts as a velocity dependent viscous force.

$$F = -\alpha \, \mathrm{v}$$

Radiation pressure cooling of Mg ions, Wineland et al., PRL (1978).

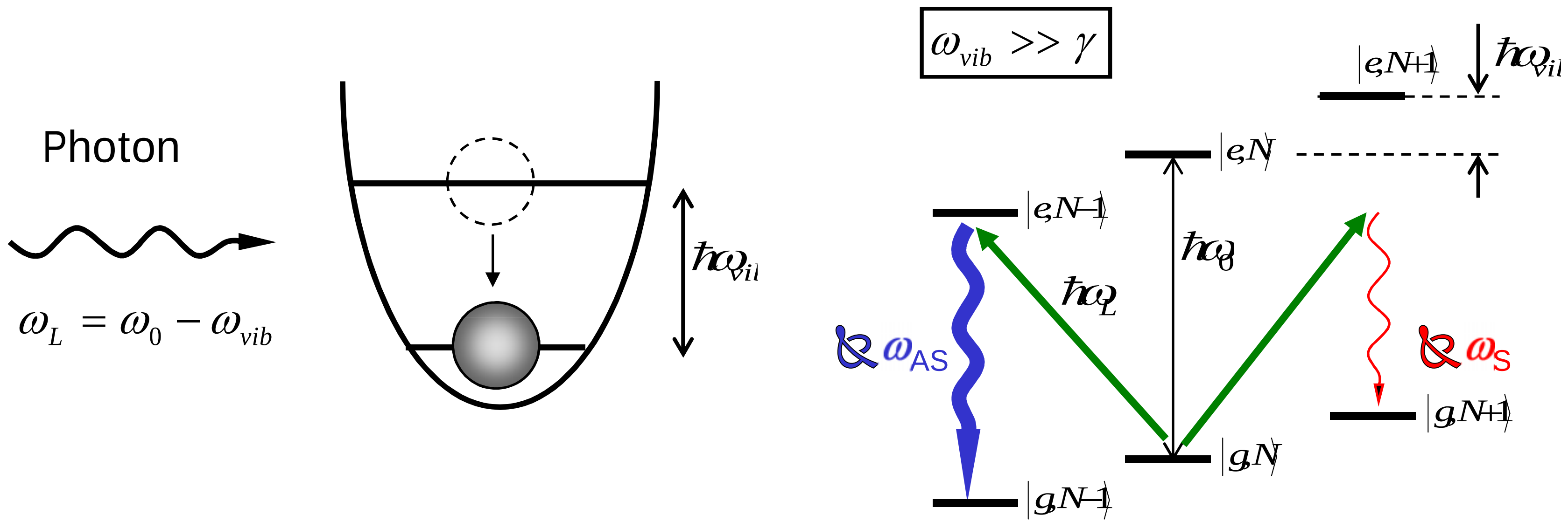
Laser deceleration of Na atoms, Phillips et al., PRL (1982).

Optical molasses, Chu et al., PRL (1982).

Below the Doppler limit (~43μK, Na atoms), Lett et al., PRL (1988).

Below the one photon recoil (~2μK, $^4$He atoms), Aspect et al., PRL (1988).

# Sideband cooling of a trapped ion



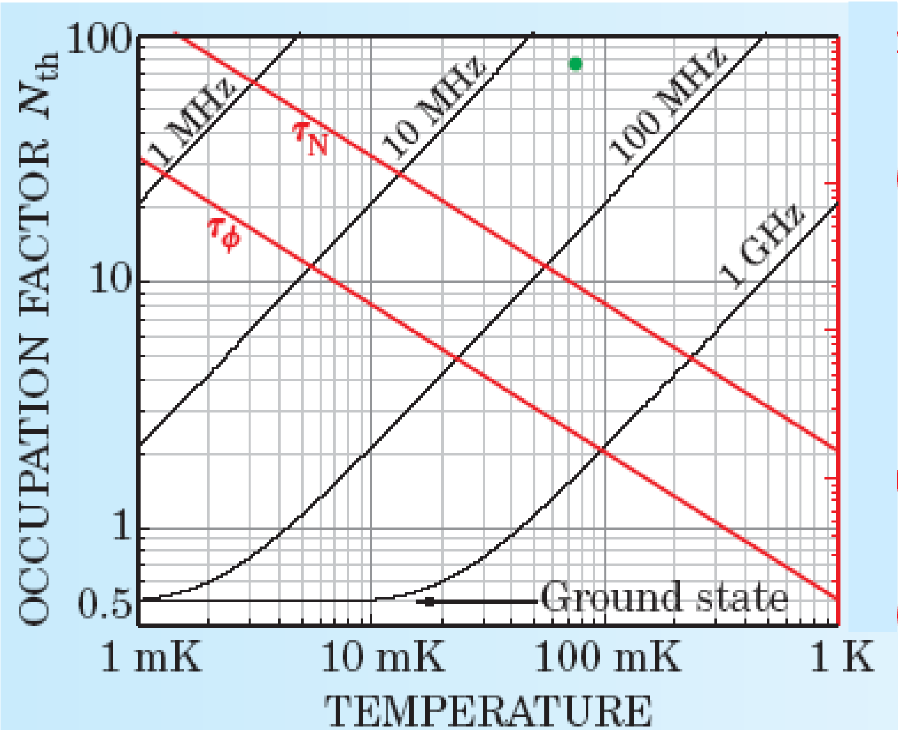

A single Hg ion in the ground state of its confining well, ~95% of the time.

Diedrich et al., Phys. Rev. Lett. 62, 404 (1989).

# "Putting the mechanics back in quantum mechanics"

Cool the macroscopic oscillator to the quantum mechanical ground state:

$$E = N_{th}\hbar\omega_m \qquad N_{th} = \frac{1}{2} + \frac{1}{e^{\hbar\omega_m/k_BT} - 1}$$



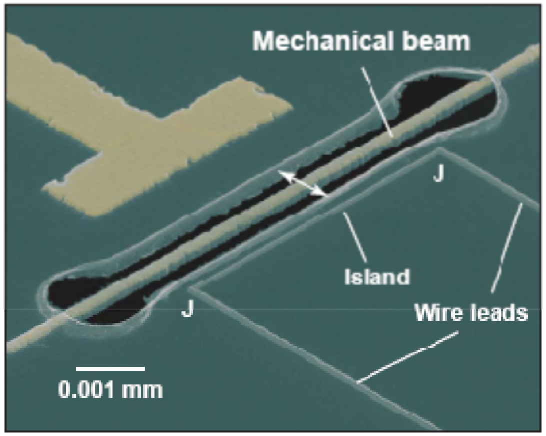

Schwab and Roukes, Physics Today, 58(7), 36 (2005).

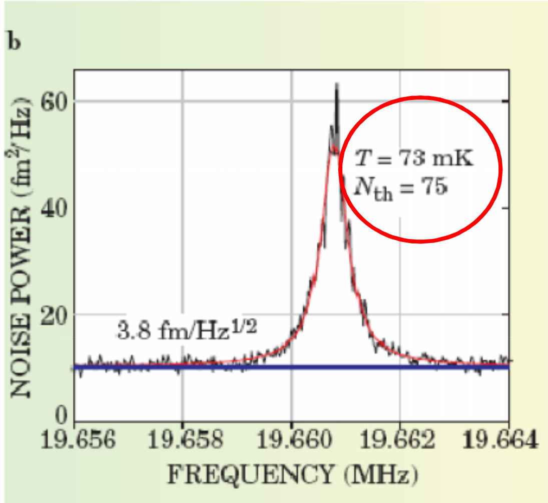
Quantum mechanics in a macroscopic object:

- Quantum state of large ensemble (>$10^{10}$ atoms)
- Macroscopic superposition and entanglement
- Quantum and classical boundary
- Ultrahigh sensitivity measurement in force and displacement


Braginsky, et al., Quantum Measurement (1992).
Marshall, et al., Phys. Rev. Lett. 91, 130401 (2003).
Vitali, et al., Phys. Rev. Lett. 98, 030405 (2007).

# Nanoelectromechanical resonator



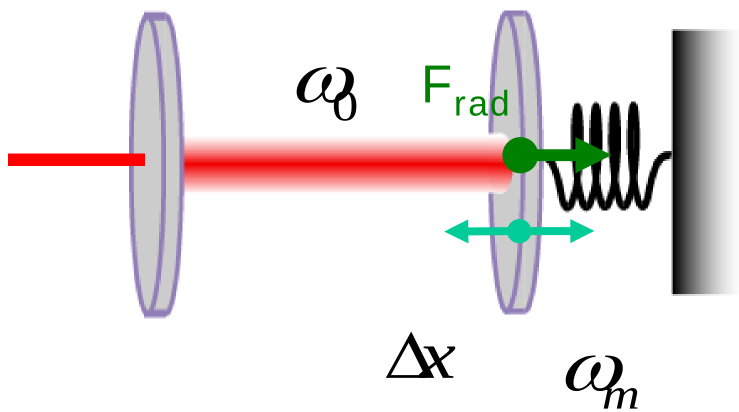




Cryogenically cooled nanoelectromechanical resonator.

LaHaye et al., Science 304, 74 (2004).

# Optomechanical resonator

**Effects of radiation pressure**




Mechanical displacement

Change in optical resonance

Delayed radiation pressure force due to finite cavity lifetime

$$F_{Rad}\left[x(t-\tau)\right] \approx F_{Rad}(x) - \tau \frac{dF_{Rad}}{dx}\dot{x}$$

Optical intracavity power

➔ Dynamical backaction leads to optomechanical cooling or gain

For reviews, see for example


Braginsky et al., Quantum Measurement (1992).

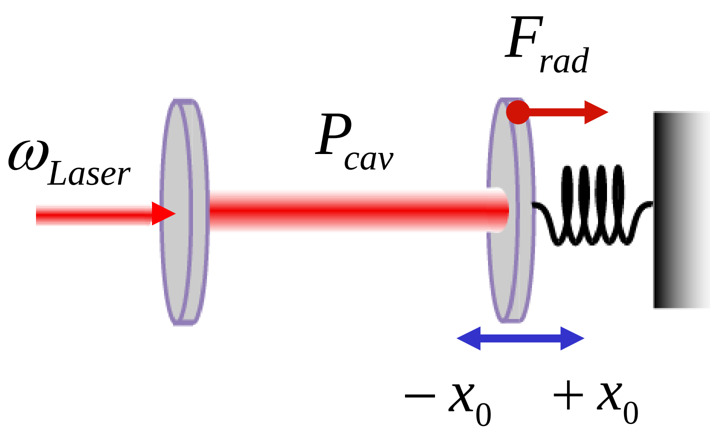
Kippenberg and Vahala, Science 321, 1172 (2008).

Marquardt and Girvin, Physics 2, 40 (2009).

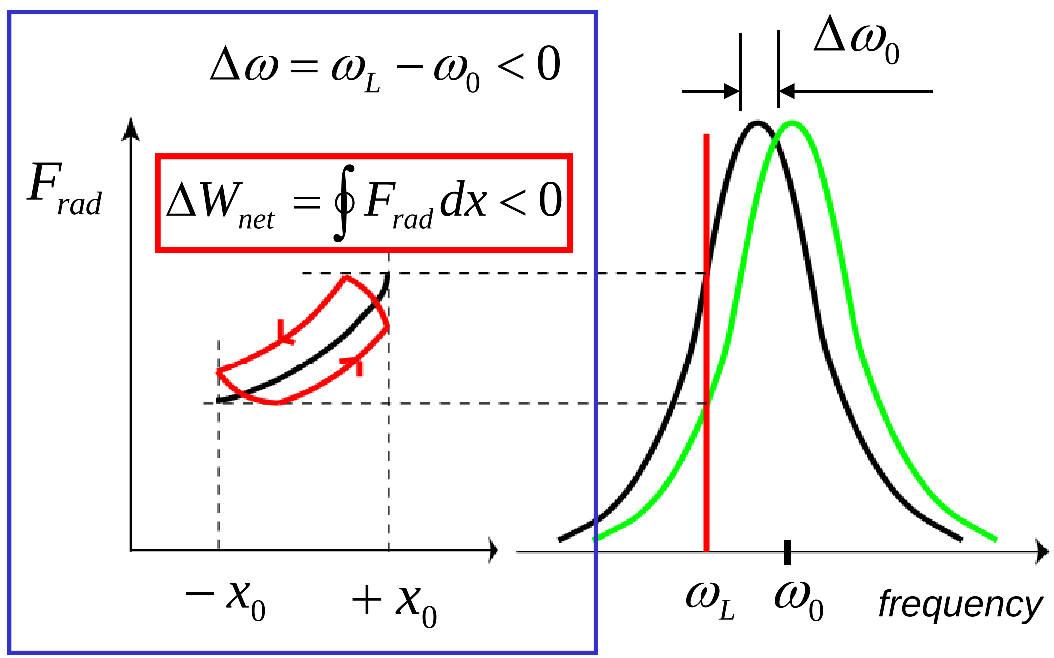
# Dynamical backaction

Finite cavity lifetime

→ Delayed Radiation pressure force



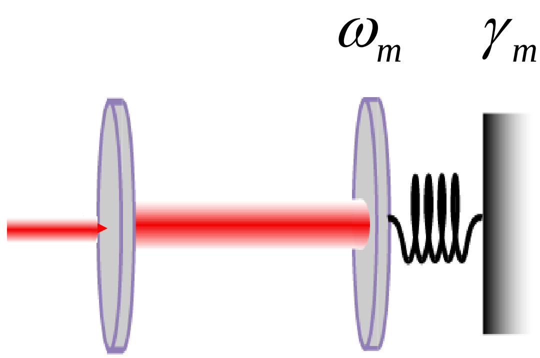

Force – Displacement diagram

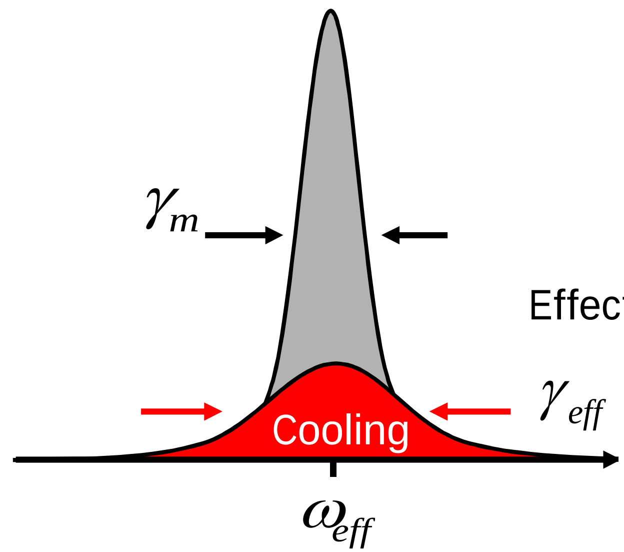



→ <u>mirror's mechanical energy is lowered.</u>

Dynamical backaction leads optomechanical cooling (red-detuning) or heating (blue-detuning).

# Equipartition theorem




Effective damping rate

$$\gamma_{eff} = \gamma_m + \Gamma_{opto-mech}$$

- The amplitude of thermal mechanical vibration is a measure of the temperature.
- Cooling of mechanical vibration results in the area reduction (or linewidth widening) of displacement spectrum.

$$T_{eff} = \frac{m_{eff}}{k_B}\left\langle x^2 \right\rangle = \frac{m_{eff}}{k_B}\int \omega^2 \left\langle x^2(\omega)\right\rangle \frac{d\omega}{2\pi} = \frac{\gamma_m}{\gamma_{eff}} T_{bath}$$

Displacement spectrum

$$x^2(\omega) = \frac{4k_B T}{m_{eff}} \frac{\gamma}{(\omega^2 - \omega_{eff}^2)^2 + \gamma_{eff}^2 \omega^2}$$

Assuming no other heating.

# Dynamical backaction cooling

## Dynamical backaction cooling

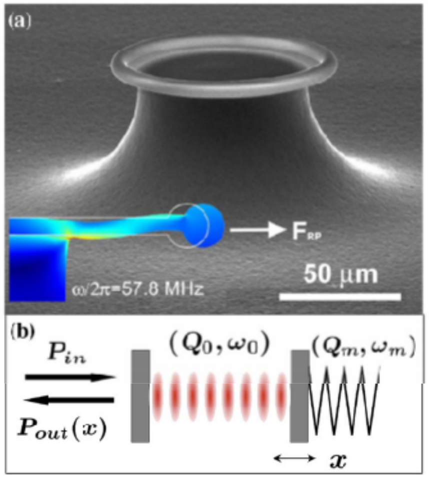
Gigan et al., Nature 444, 67 (2006): ~10K (N~740,000)

Arcizet et al., Nature 444, 71 (2006): ~ 10K (N~260,000)

Schliesser et al., Phys. Rev. Lett. 97, 243905 (2006): ~11K (N~3,900)

Corbitt et al., Phys. Rev. Lett. 98, 150802 (2007): ~ 0.8K (N~$10^8$)

Thompson et al., Nature 452, 72 (2008): ~ 6.82mK (N~1,000)

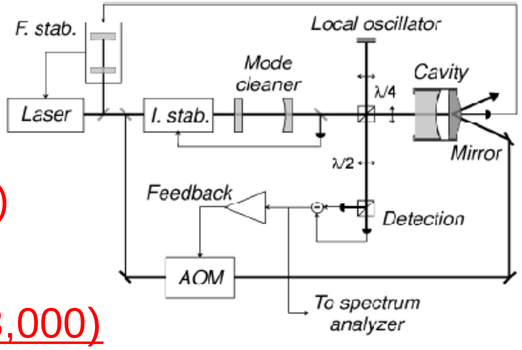



## Active feedback cooling

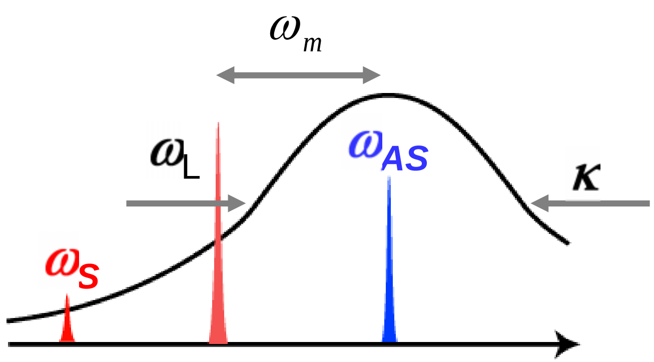
Cohadon et al., Phys. Rev. Lett. 83, 3174 (1999): ~15K (170,000)

Kleckner et al., Nature 444, 71 (2006): ~ 135mK (N~220,000)

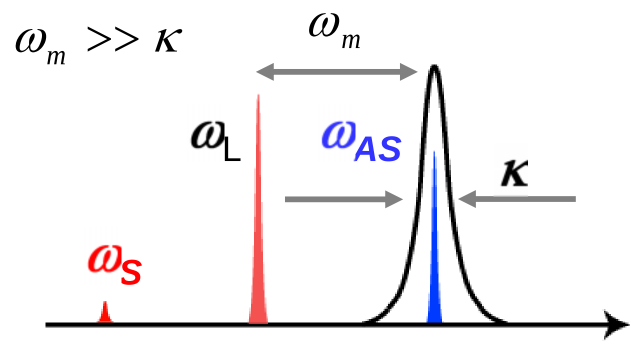
Poggio et al., Phys. Rev. Lett. 99, 017201 (2007): ~2.9mK (N~23,000)



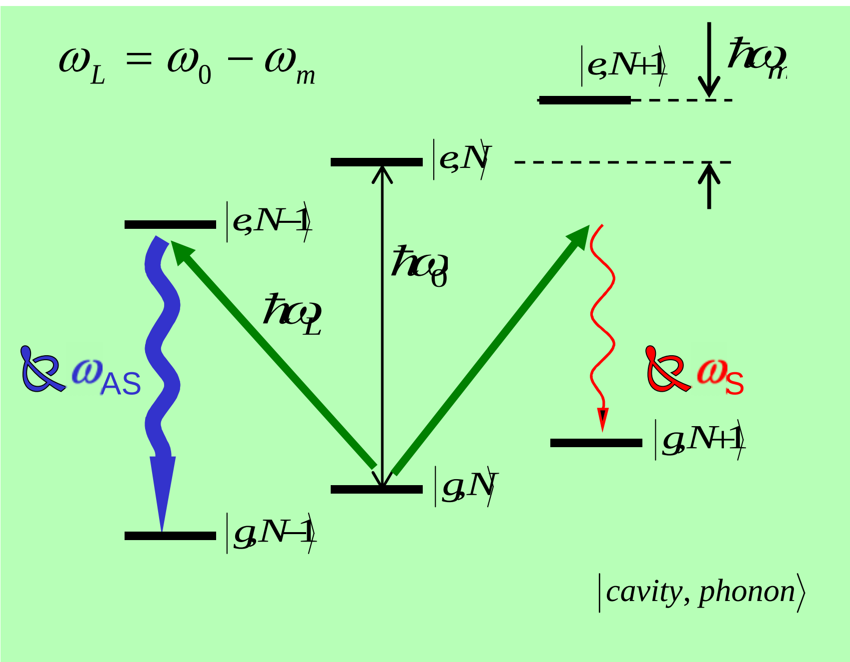
# Resolved-sideband cooling




$$N \approx \frac{4\kappa}{\omega_m} >> 1$$




$$N \approx \frac{\kappa^2}{16\omega_m^2} << 1$$




- Anti-Stokes (Stokes) process decreases (increases) the phonon occupation by one.
- Stokes process is well suppressed in the resolved-sideband limit.


Wilson-Rae *et al.,* Phys. Rev. Lett. **99**, 093901 (2007).
Marquardt *et al.,* Phys. Rev. Lett. **99**, 093902 (2007).

# Why not using a (cryogenic) refrigerator?

- Technically refrigerator operating near quantum

ground state temperature is not available.

- 100 MHz oscillator → T (N=1) ~ 5mK

- **Yes !!** : Bath temperature can be lowered
  with current cryogenic technique.

| |
|---|
| Optomechanical cooling + Cryogenic cooling |

- **Difficulty** : Carrying out the optomechanical cooling
  in a cryogenic environment.

# Experimental challenges

$$N_{final} \approx \frac{\gamma_m}{\gamma_{eff}} N_{initial} + \frac{\kappa^2}{16\omega_m^2} \xrightarrow{\text{Goal}} \ll 1$$

- Mechanical dissipation

→ Cryogenic operation

- Quantum backaction

→ Resolved sideband limit ( $\omega_m \gg \kappa$ )

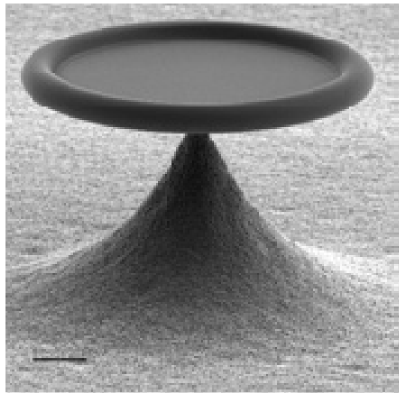
- Experimentally, need to overcome any heating from environment, such as laser noise, laser absorption.

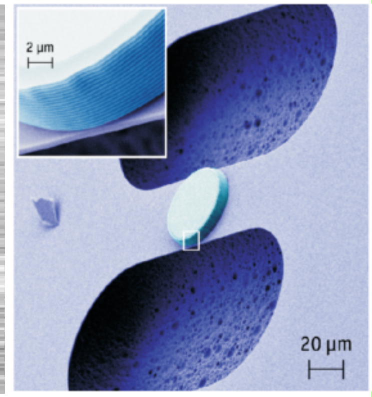
Wilson-Rae *et al.,* Phys. Rev. Lett. **99**, 093901 (2007).

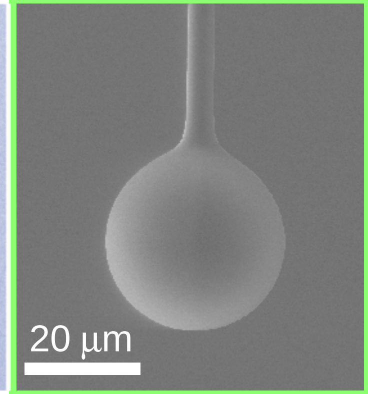
Marquardt *et al.,* Phys. Rev. Lett. **99**, 093902 (2007).

# Route to “the ground”

**Cryogenic cooling**
**+**
**Sideband Cooling**






| | MPQ/EPFL | IQOQI | U. of Oregon |
|---|---|---|---|
| Frequency | 65.2 MHz | 0.95 MHz | 118 MHz |
| Sideband limit | 3.4 | 1.25 | 4.0 |
| Mechanical Q | 2,000 | 30,000 | 3,400 |
| (material) | (silica) | (silicon nitride) | (silica) |
| Bath temperature | 1.65 K | 5.3 K | 1.4 K |
| Final occupation | 63 ± 20 | 32 | 37 |

➔ Approaching the quantum ground state !!

Schliesser et al., Nature Phys. to be published.
Groblacher et al., Nature Phys. to be published.
Park and Wang, Nature Phys. to be published.

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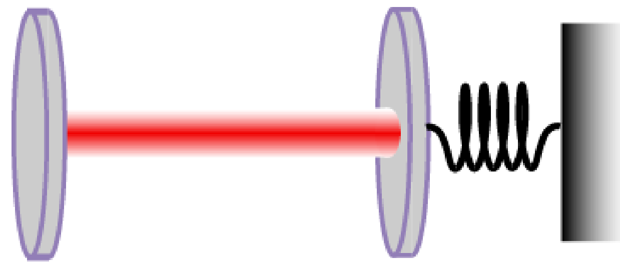
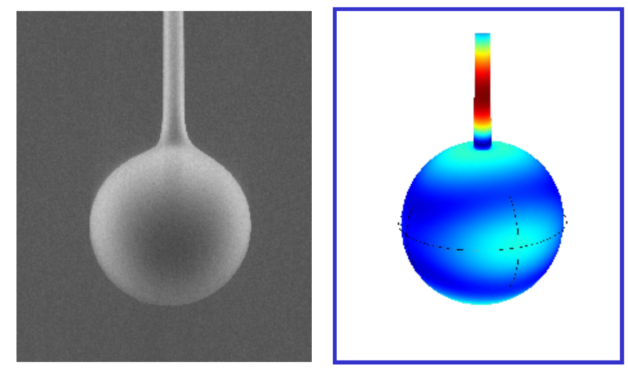
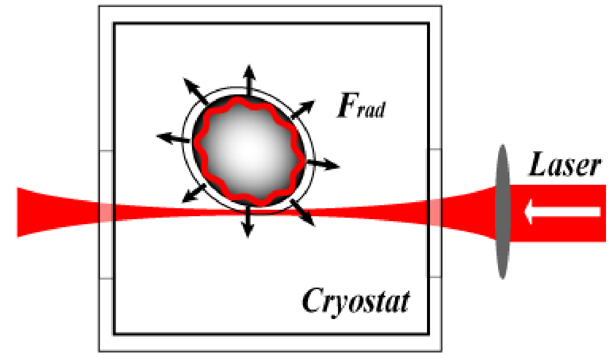
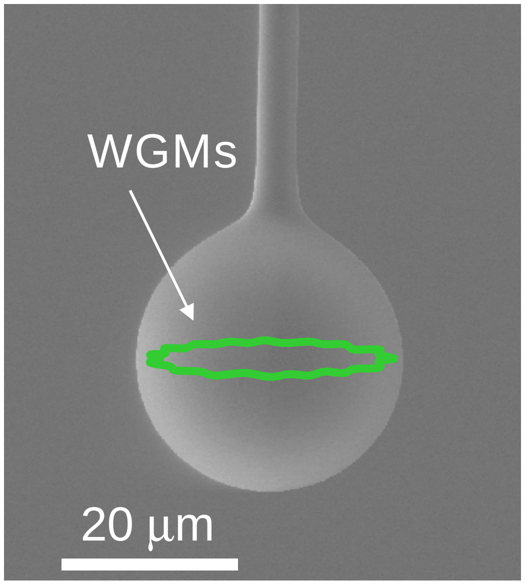
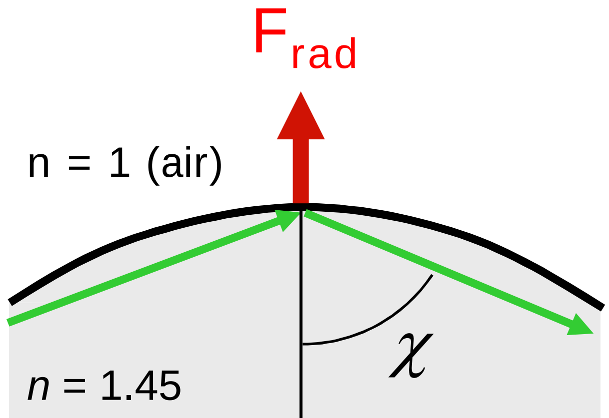




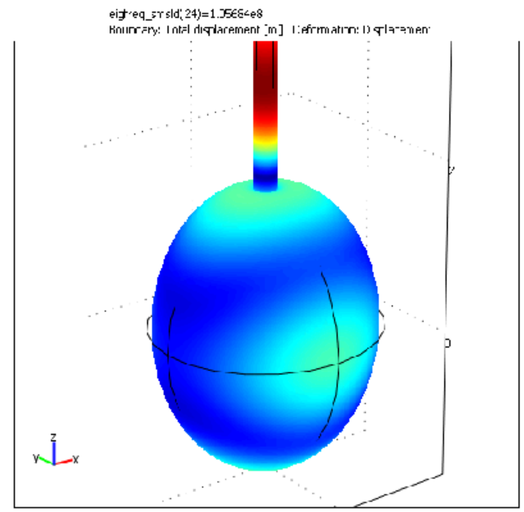


# Optomechanical microsphere resonator




$$\chi \geq \chi_C = \sin^{-1}(1/n)$$



Optical resonator :

Whispering gallery modes

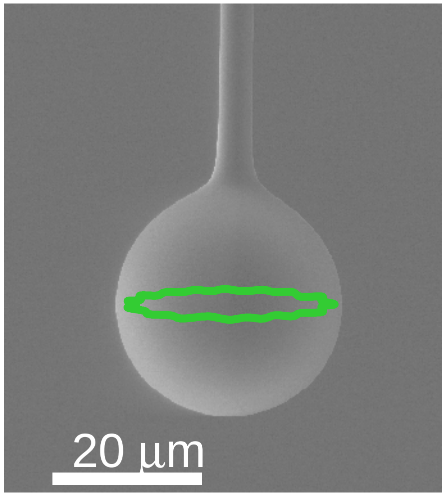
- Frequency ~ $10^{14}$ Hz
- Optical Q-factor ~ $10^9$
- Mode volume ~ 200 $\mu m^3$

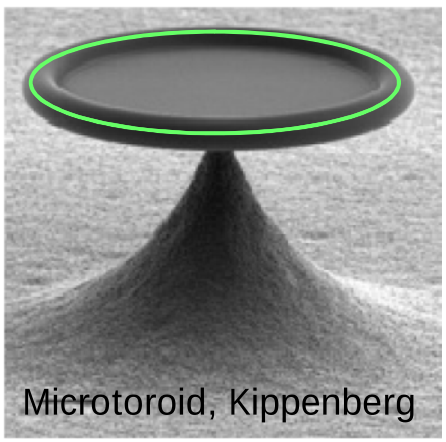
Mechanical resonator (R=15 μm):

Radial breathing modes

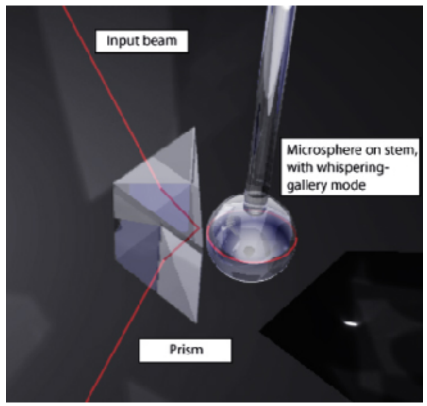
- Frequency > 100 MHz
- Mechanical Q-factor > 10,000
- Effective mass ~ 35 ng

# Excitation of WGMs

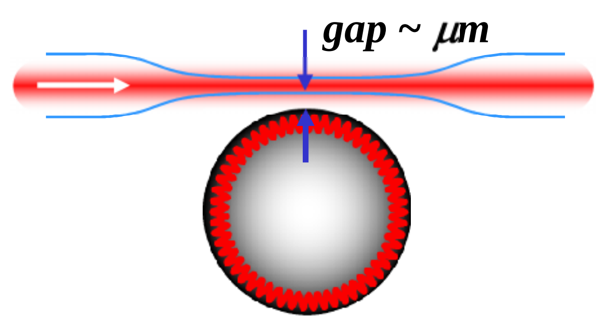



Frustrated total internal reflection



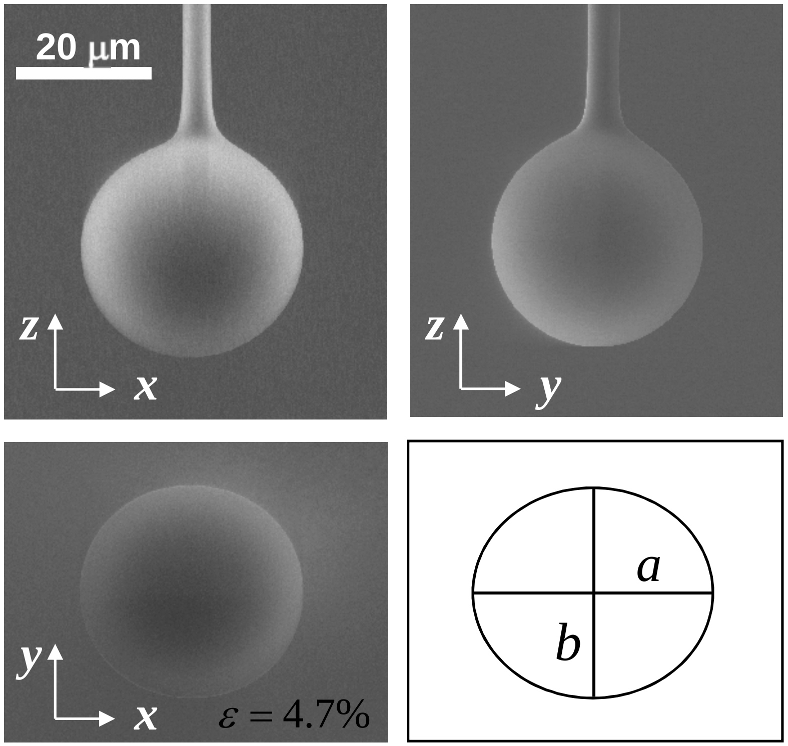

Tapered fiber
( > 99%, critical coupling)



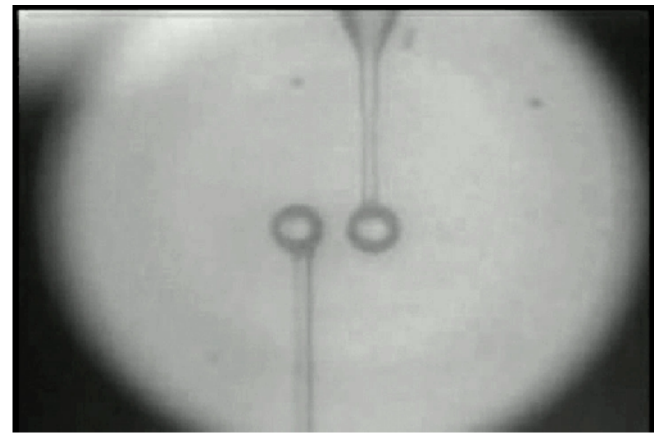

Cai *et al.*, Phys. Rev. Lett. **85**, 74 (2000).

Need to control the gap with nanometer precision.
→ Technically difficult in a cryogenic environment

# Deformed silica microspheres

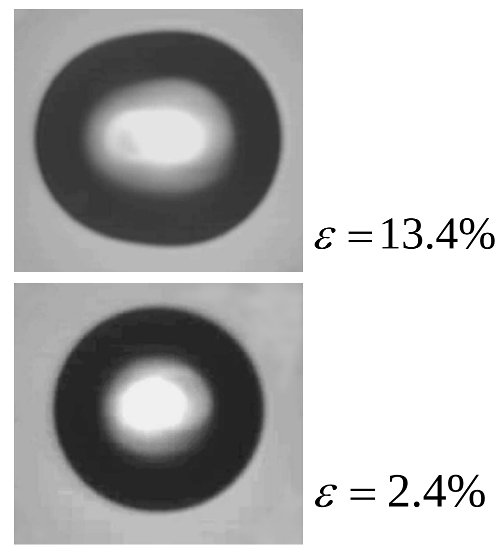



Fabrication



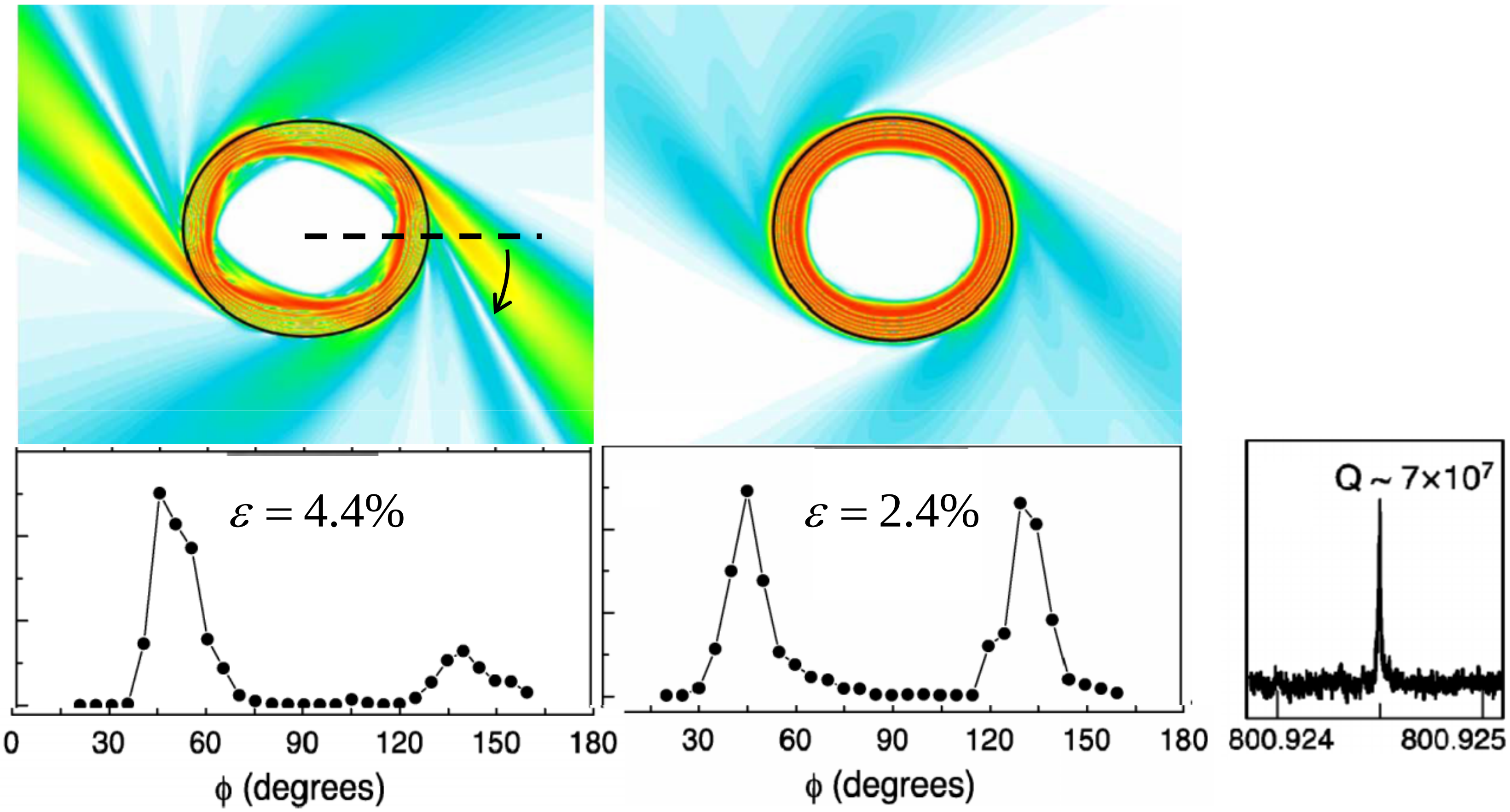
Deformation

$$\varepsilon \equiv \frac{a-b}{b}$$




- Deformed micropheres are formed by fusing two regular microspheres of similar size with a $CO_2$ laser.
- Deformation is controlled by repeated heating.

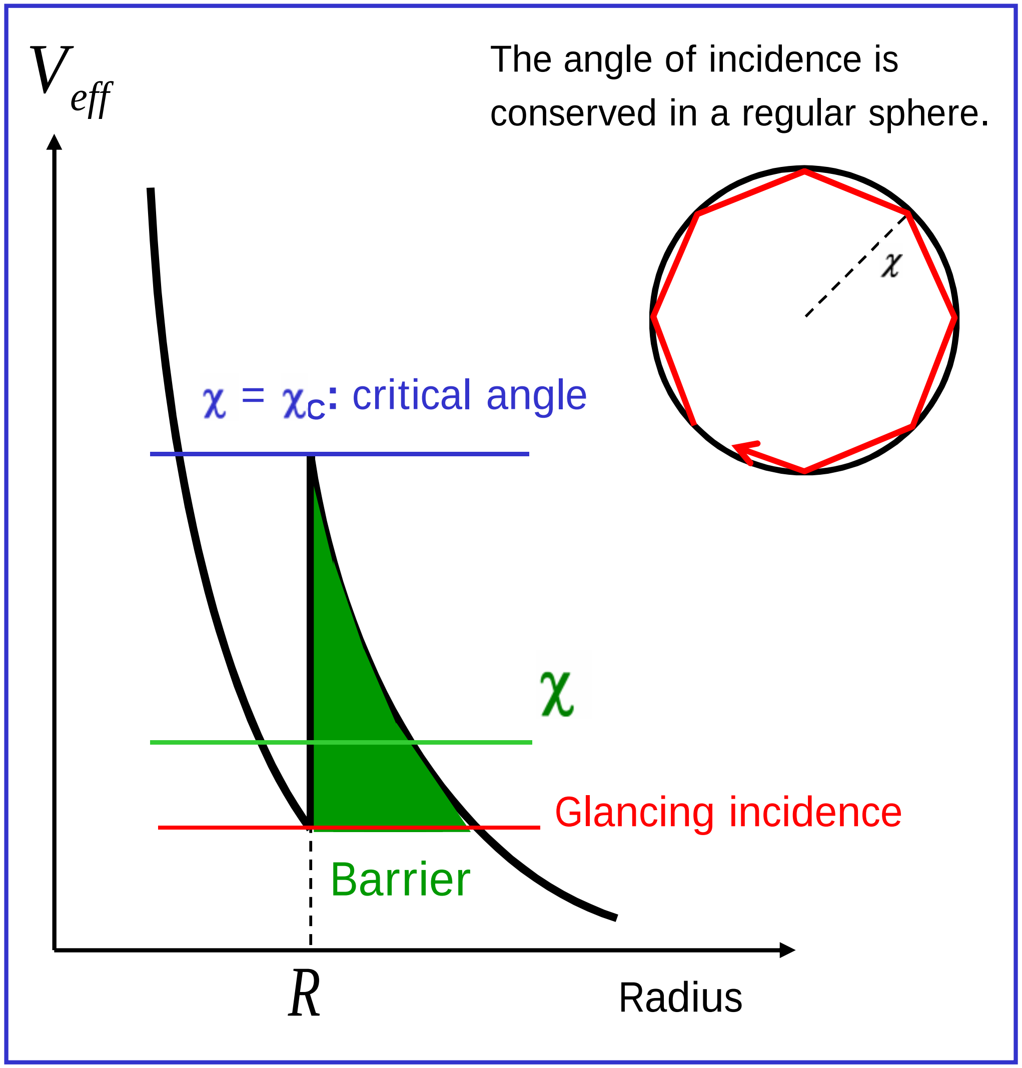
# Directional emission




- Highly directional emission along with high Q-factors.

Lacey *et al.,* Phys. Rev. Lett. **91**, 033902 (2003).

# Evanescent escape




Wave equation of WGMs

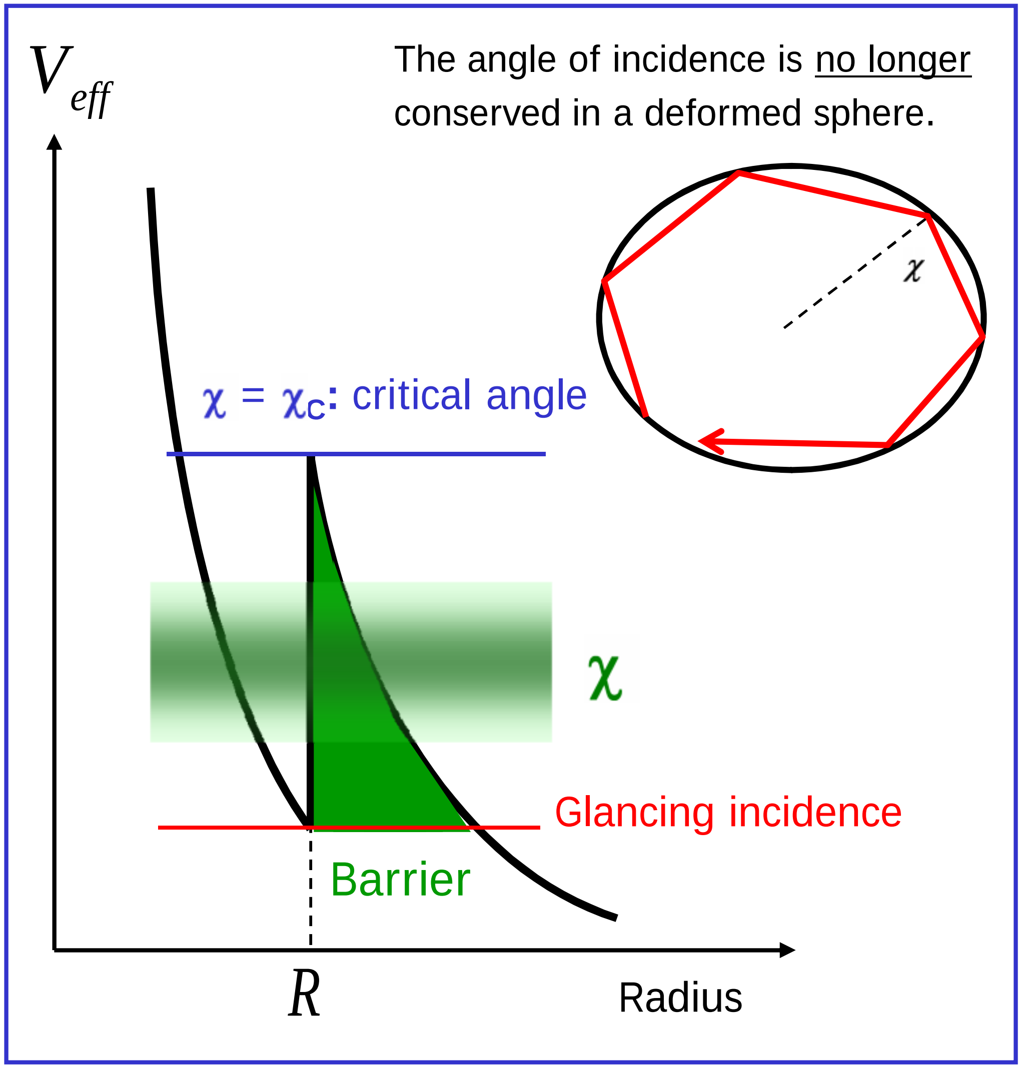
$$\nabla^2 E + n^2 k^2 E = 0$$
$$\rightarrow -\nabla^2 E + k^2(1-n^2)E = k^2 E$$

Quantum mechanical analogy,

$$V_{eff} = \frac{l(l+1)}{r^2} + k^2(1-n^2)$$

$$n = \begin{cases} 1 & \text{for } r < R \\ 0 & \text{for } r > R \end{cases}$$

# Evanescent escape

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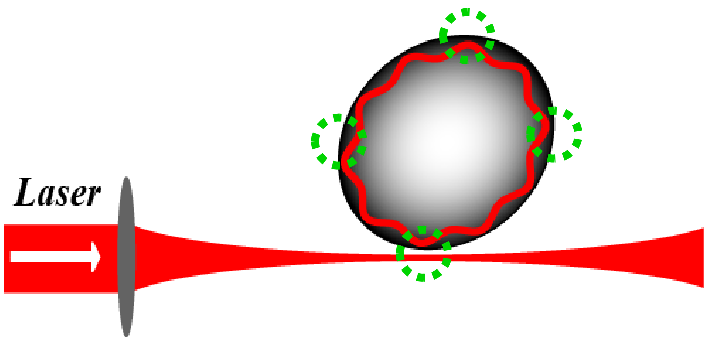
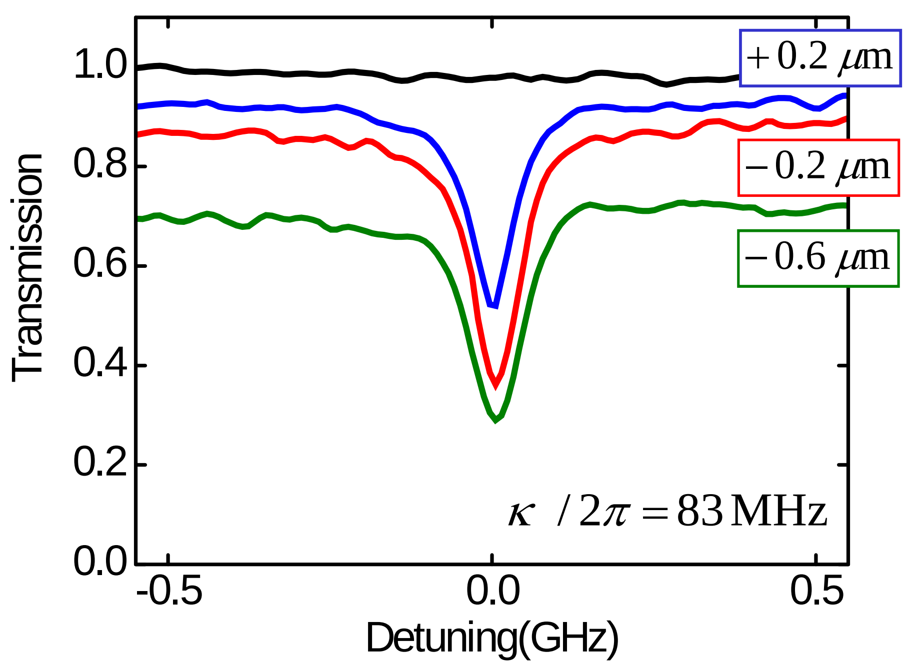
$$n = \begin{cases} 1 & \text{for } r < R \\ 0 & \text{for } r > R \end{cases}$$

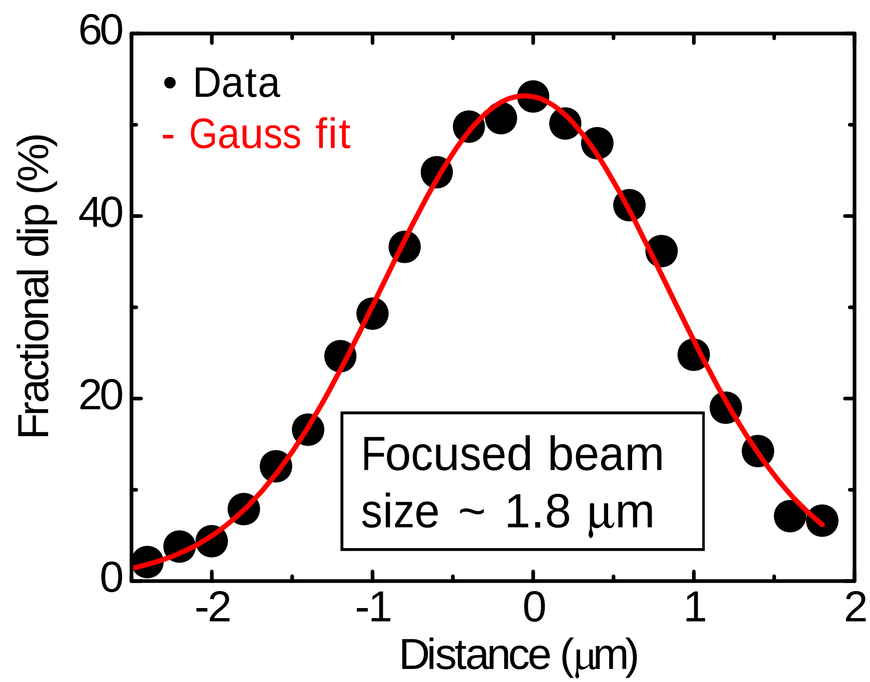
The tunneling escape rate increases exponentially as the incident angle ($\chi$) approaches the critical angle ($\chi_c$).

# Free space evanescent excitation of WGMs




Launching WGMs in free-space by focusing a laser beam in areas 45$^{o}$ from a symmetry axis.



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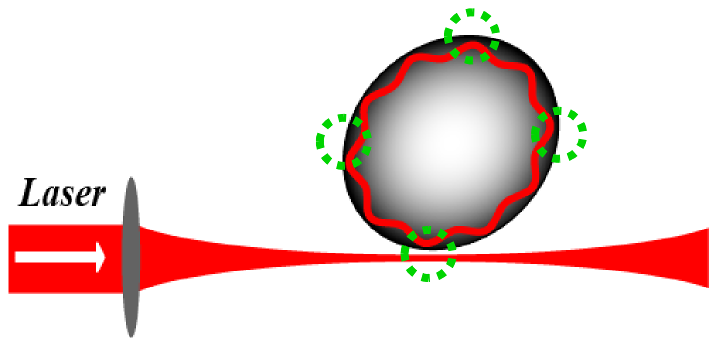
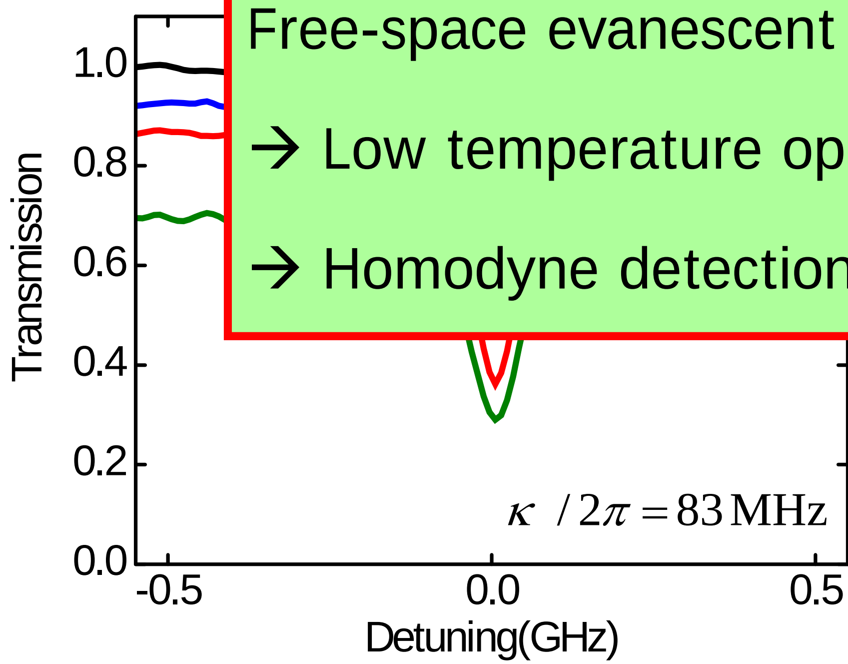


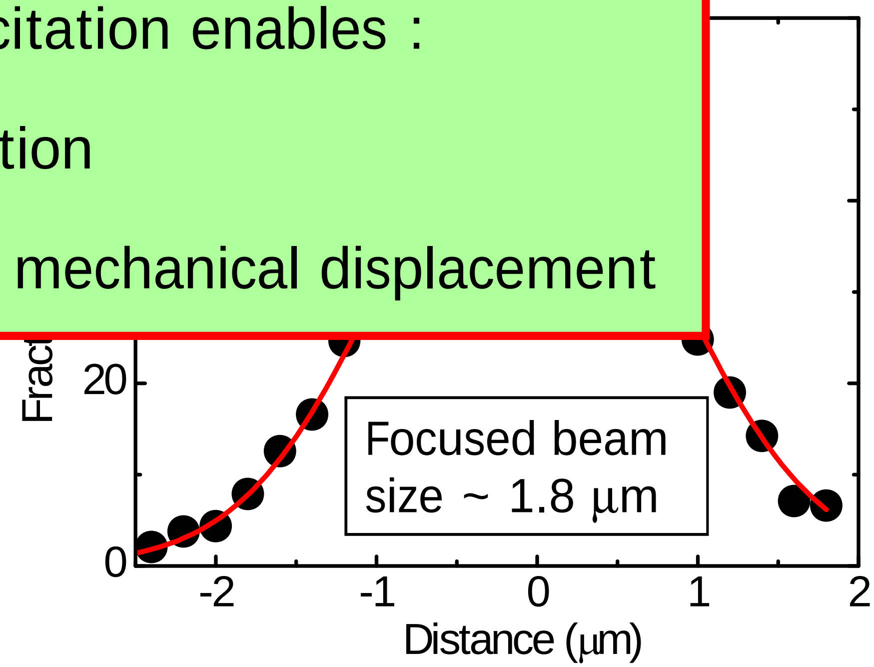

Launching WGMs in free-space by focusing a laser beam in areas 45$^{o}$ from a symmetry axis.




Free-space evanescent excitation enables :

→ Low temperature operation

→ Homodyne detection of mechanical displacement



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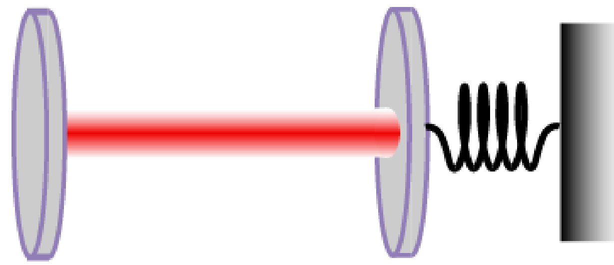
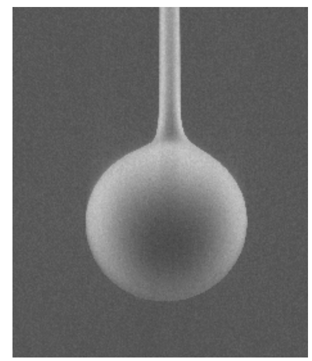
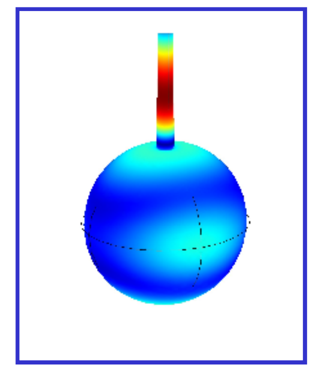
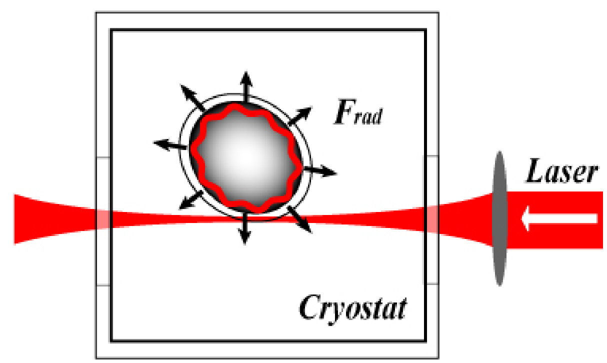
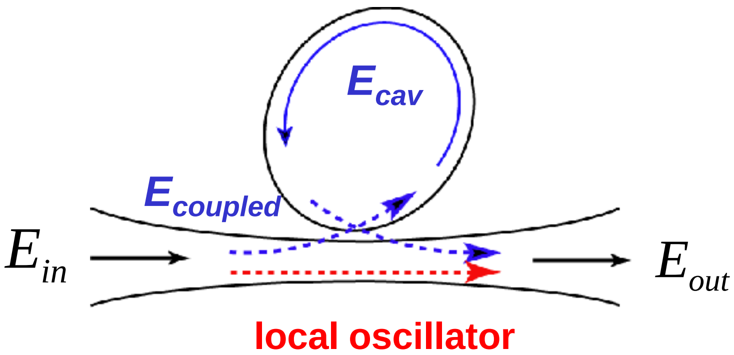








# Direct homodyne detection




$$E_{out} = iTE_{cav} + E_{LO}$$

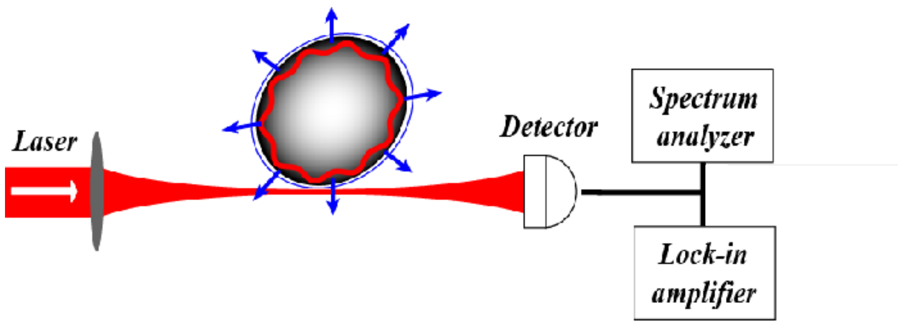
The electric field coupled into the microsphere resonator experiences a phase shift due to the mechanical vibrations ($\omega_m$).

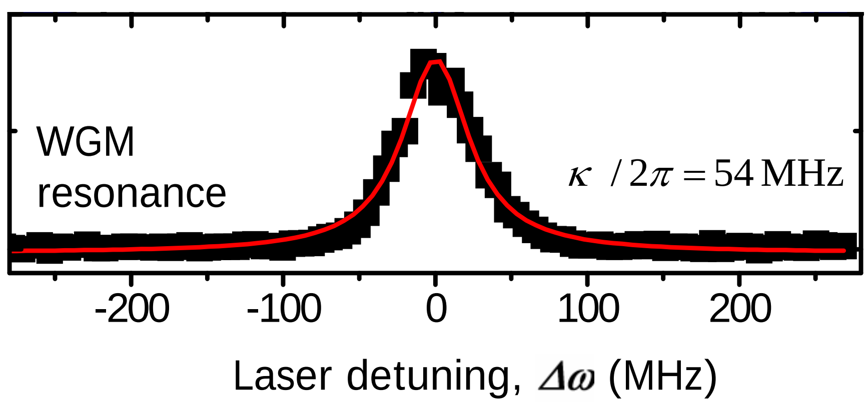
$$\dot{E}_{cav}(t) = \left(-\frac{\kappa}{2} + i(\Delta\omega - \frac{r_0\omega_0}{R}\sin\omega_m t)\right)E_{cav}(t) + \frac{iT\,\Gamma E_{in}}{T_{rt}}$$

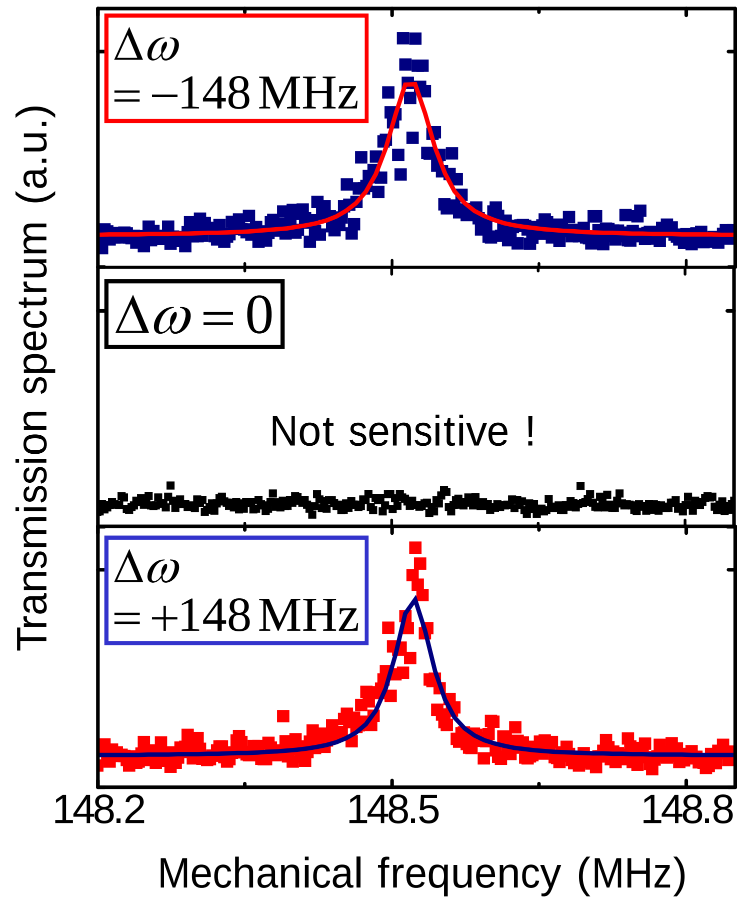
$\Gamma$: mode-matching coefficient  T : transmittance
$\kappa$: cavity decay rate  $r_0$ : radial amplitude  $\eta$ :coupling efficiency

Hadjar *et al.,* Euro. Lett. **47**, 545 (1999).

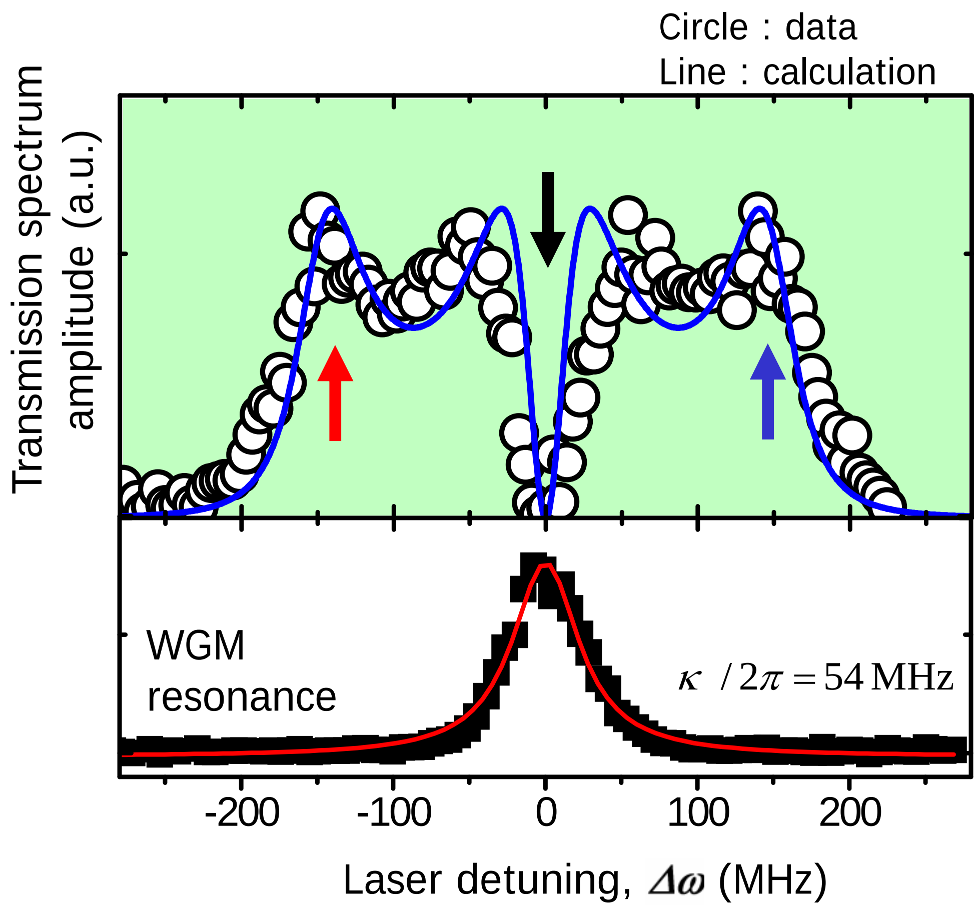
# Detuning dependence

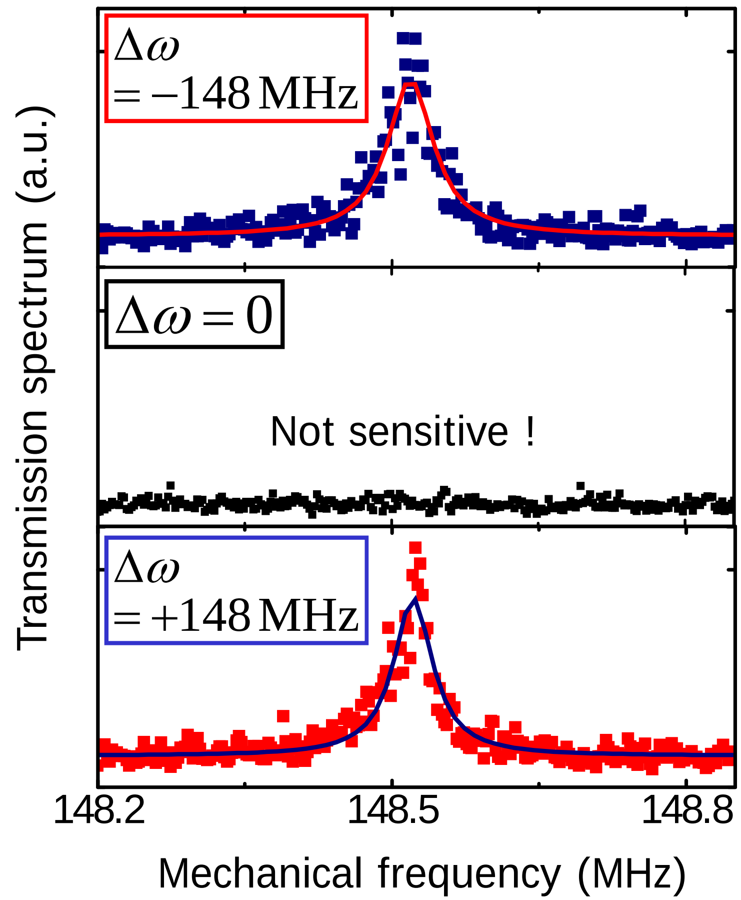


# Detuning dependence




Displacement sensitivity

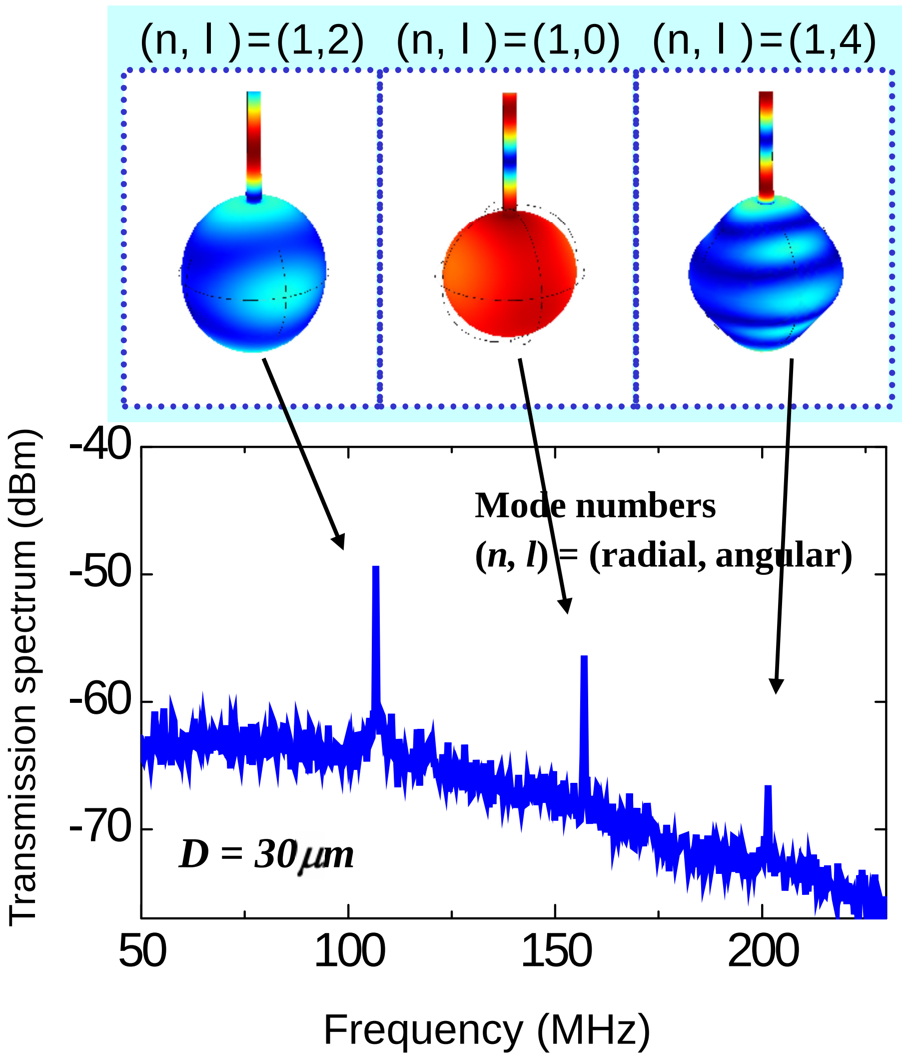
at $\Delta\omega = \pm\,\omega_m$ in the sideband limit,

$$r_{\min} = \frac{R\omega_m}{2\eta\omega_0}\left(\frac{\kappa^2}{4\omega_m^2}+1\right)\sqrt{\frac{2\hbar\omega_0}{P_{in}}} \sim 10^{-18}\, m/\sqrt{Hz}$$

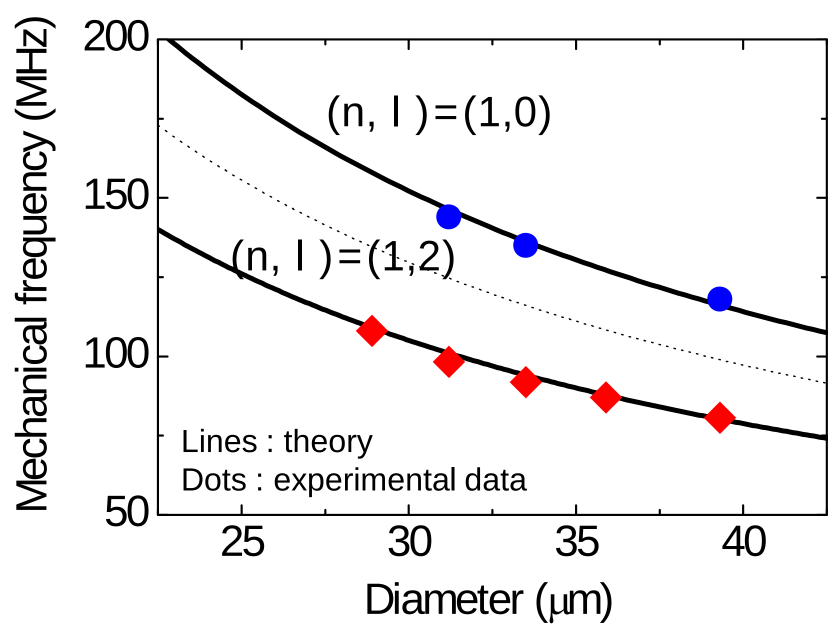
$$\eta = 0.03,\ P_{in} = 1\,\mathrm{mW}$$

# Optically observable mechanical modes

Finite element Analysis




Size dependence of vibration modes




Park and Wang, Opt. Express **15**, 16471 (2007).

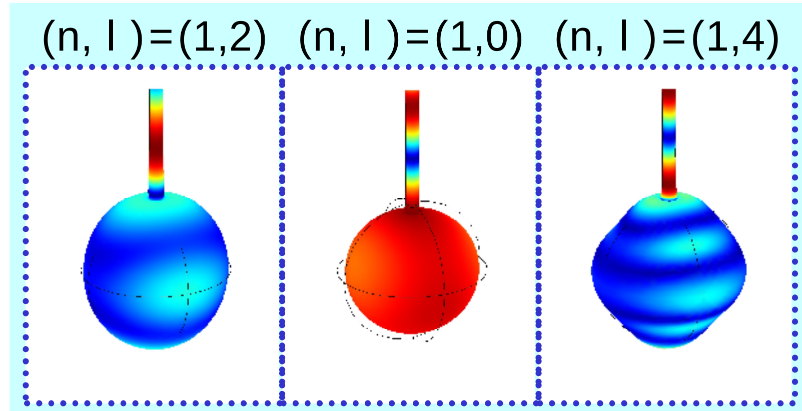
# Effective mass : Calculation

- Effective mass coefficient (α )

$$\alpha \equiv \frac{\text{effective mass } (m_{eff})}{\text{microsphere mass } (m)}$$

$$= \frac{2E_m}{\omega_m^2 A^2} \frac{1}{m}$$

Finite element Analysis




$\alpha = 1.14$ $\alpha \approx 1.0$

- Displacement power spectrum

$$x^2(\omega) = \frac{4k_B T}{m_{eff}} \frac{\gamma_m}{(\omega^2 - \omega_{eff}^2)^2 + \gamma_{eff}^2 \omega^2}$$

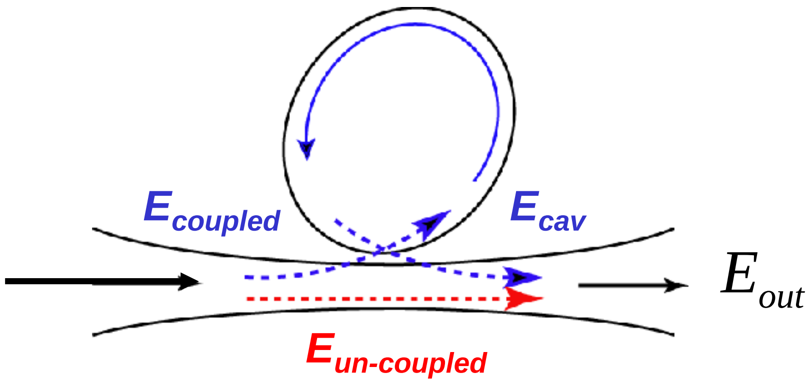
- Equipartition theorem

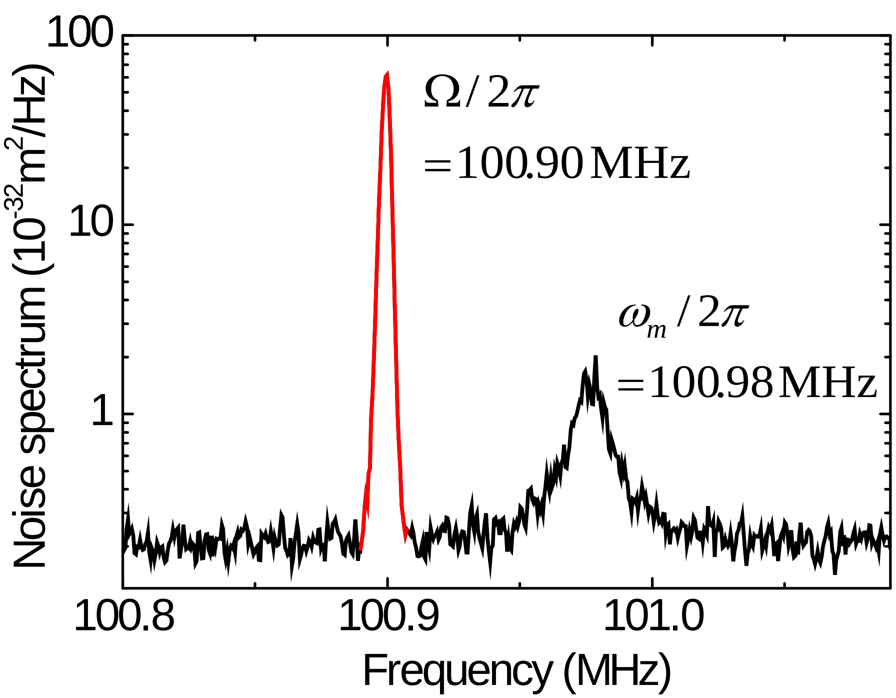
$$\langle x^2 \rangle = \frac{k_B T}{m_{eff} \omega_m^2}$$

# Mechanical Displacement: Calibration

The input field is phase-modulated at frequency $\Omega$ with a depth $\beta$, in order to mimic the phase shift due to mechanical vibration[1].

$$E_{in} \xrightarrow[\text{Modulator}]{\text{Electro-Optic}} E_{in} e^{i\beta \sin \Omega t}$$




Modulation depth for same signal $\beta = \dfrac{\omega_0}{\omega_m R} r_0$

$\alpha_{simulation}$ (= 1.14)

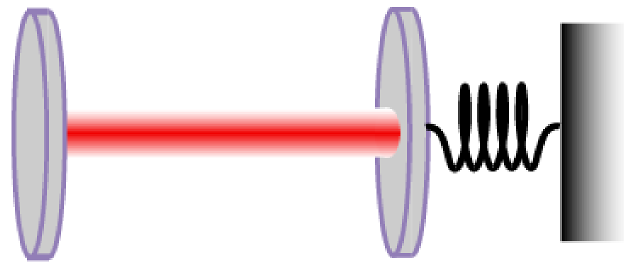
$\approx \alpha_{measured}$ (= 1.16 ± 0.03)

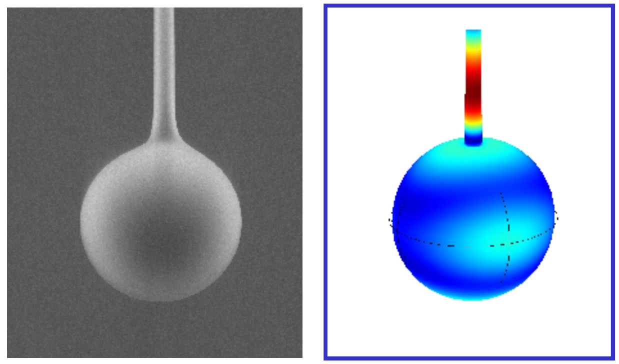
For (n, l ) = (1,2) mode

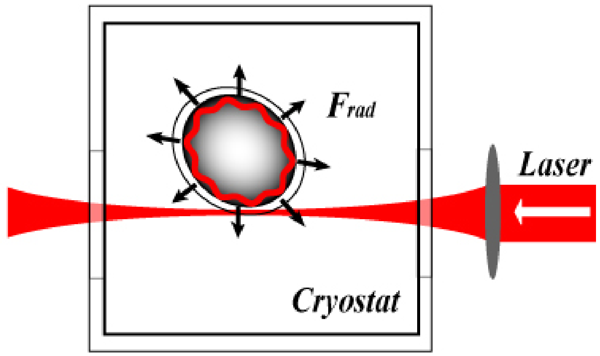
1) Schliesser et al., New J. of Phys. 10, 095015 (2008).

# Outline

- Introduction
- Optomechanical microsphere resonator
  - ✓ Free-space excitation of WGMs
  - ✓ Homodyne detection of mechanical displacement
  - ✓ Mechanical damping
- Resolved sideband cooling at cryogenic temperature
- Summary







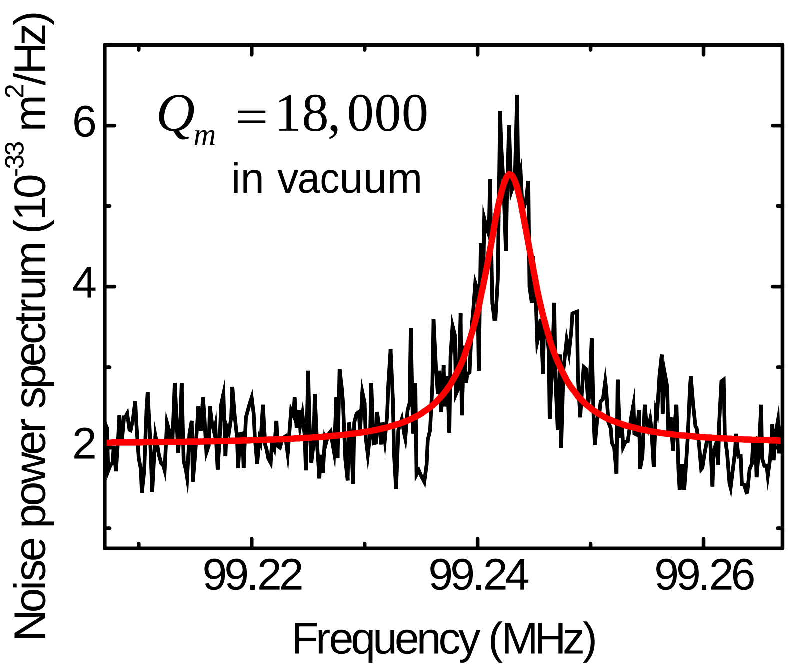
# Mechanical loss

Mechanical quality factor

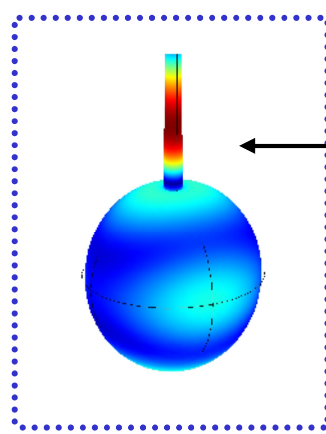
$$Q_m \equiv \frac{\omega_m}{\gamma_m} \qquad \gamma_m = \sum \gamma_i$$

Mechanical loss of a silica micro-resonator

- Acoustic absorption (low temp.)
- Clamping loss (room temp.)
- Loss due to collisions with surrounding gases
- Thermoelastic loss (negligible)




(n, l )=(1,2)

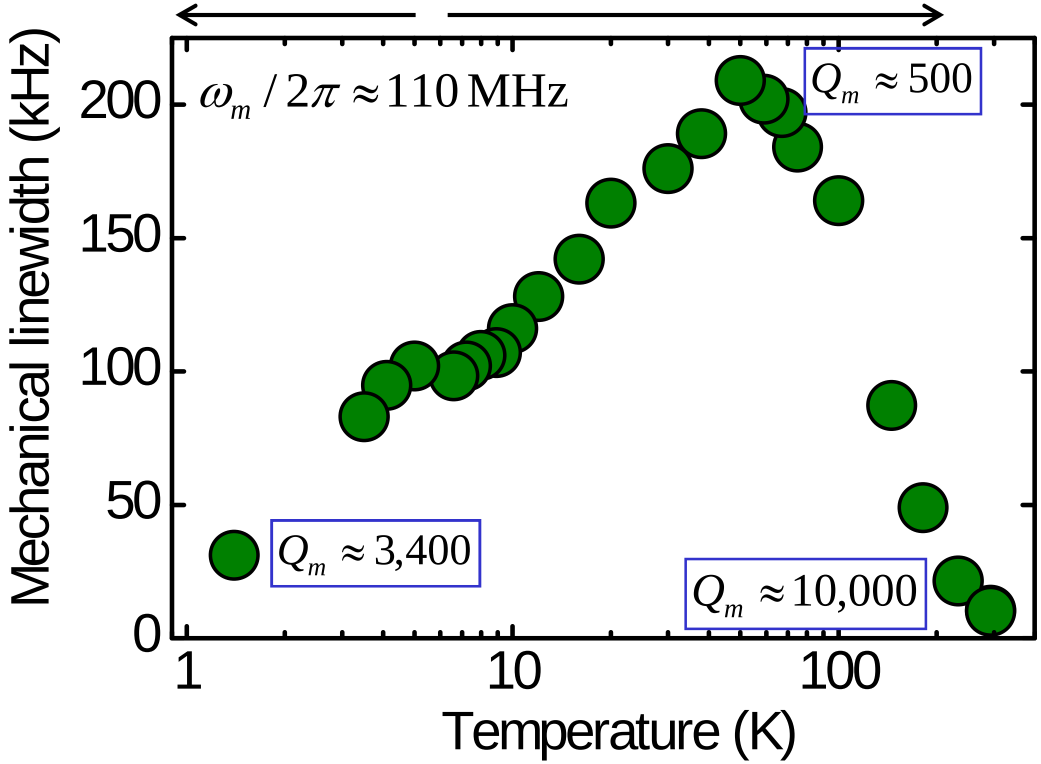


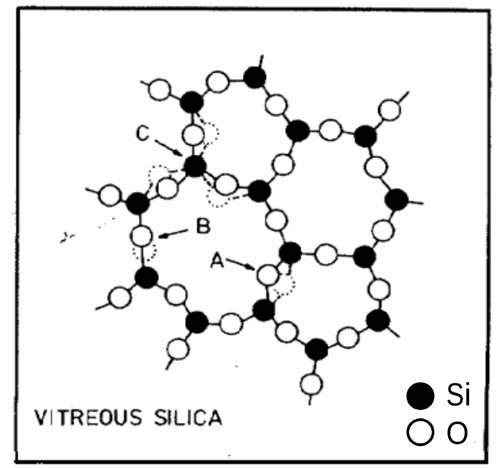
Stem size: ~ 1/10 of microsphere diameter

# Ultrasonic attenuation in silica

Phonon interaction in two-level tunneling defects

Thermally activated relaxation process



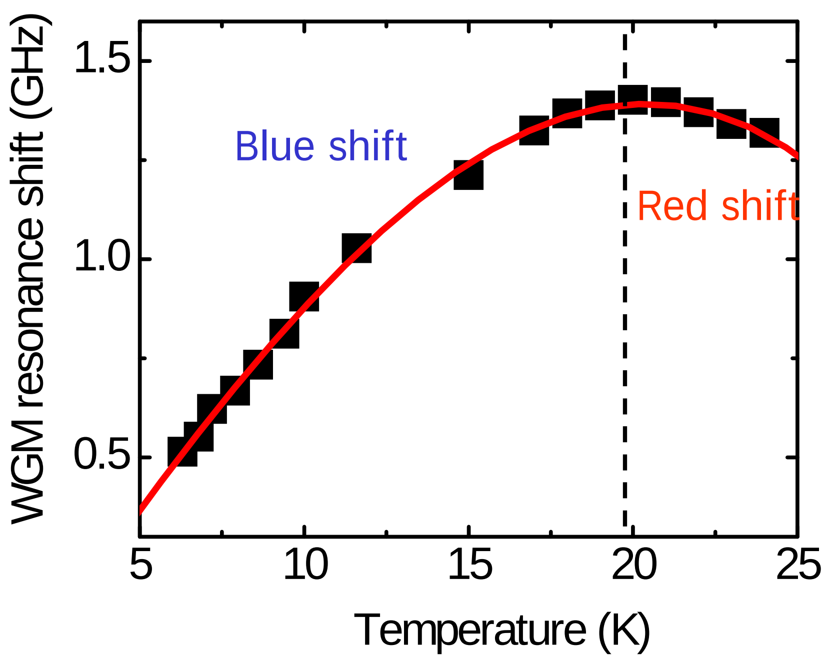




Ultrasonic attenuation in amorphous solids due to redistribution of asymmetric double-well potentials on strained Si-O-Si bonds with changing temperature.

Loss due to ultrasonic attenuation in silica microsphere is important below room temperature.

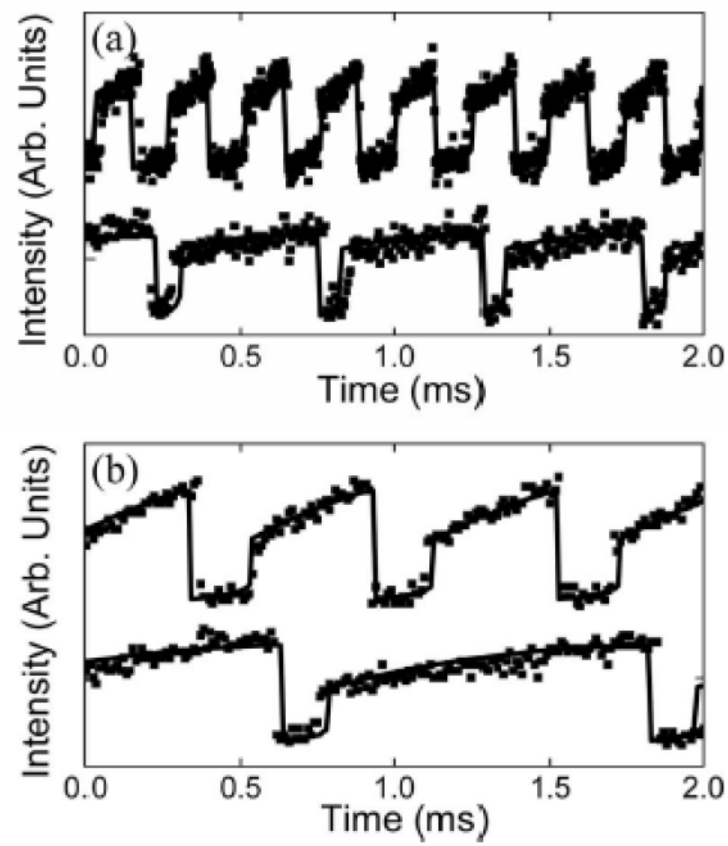

Phillips, Amorphous Solids (1981).
Pohl et al., Rev. Mod. Phys. 74, 991 (2002).
Vacher et al., Phys. Rev. B 72, 214205 (2005).

# Optical properties at low temperature




$$\frac{d\omega}{dT} = -\omega_0\left(\frac{1}{R}\frac{dR}{dT} + \frac{1}{n}\frac{dn}{dT}\right)$$

Thermal effects are reduced at low temperature.




Regenerative pulsation at 18.5 K

Park and Wang, Opt. Lett. 32, 3104 (2007).

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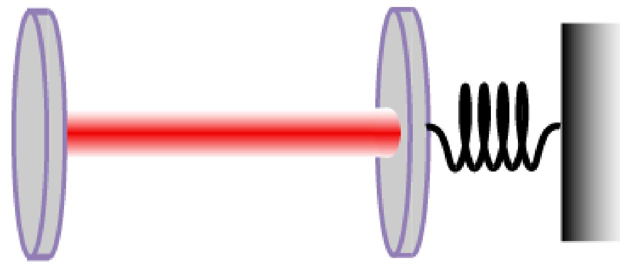
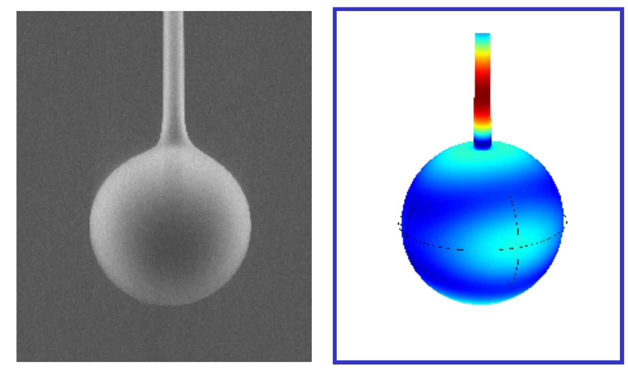
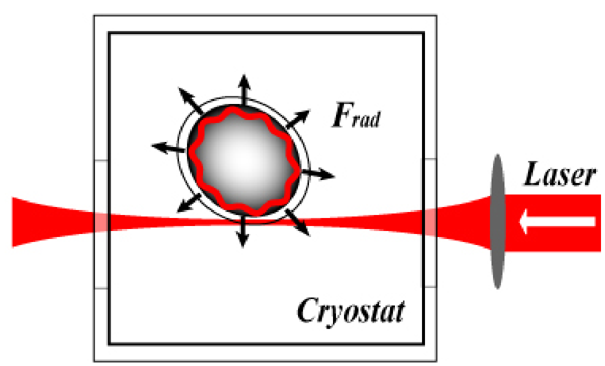
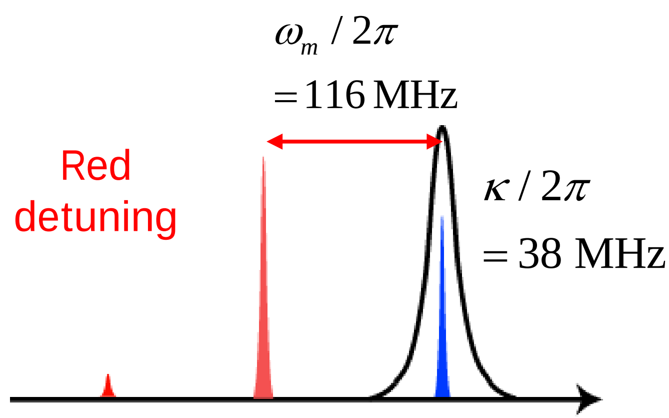
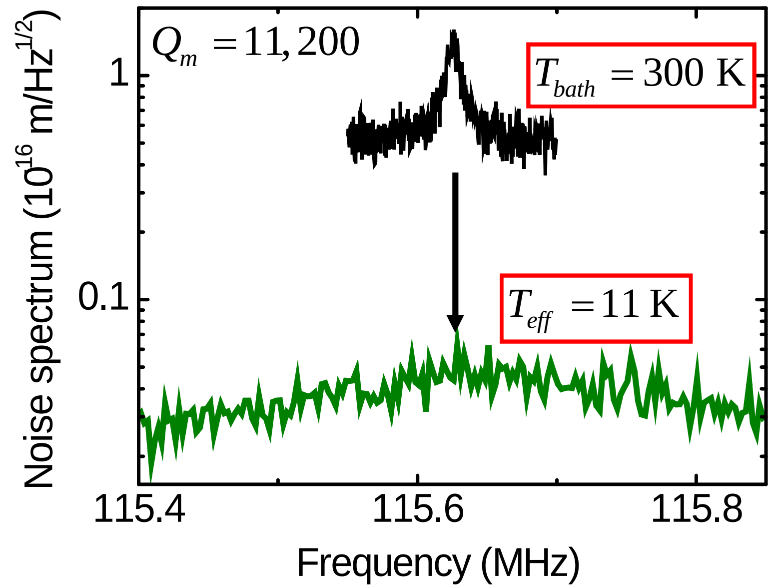






# Resolved-sideband cooling at room temperature



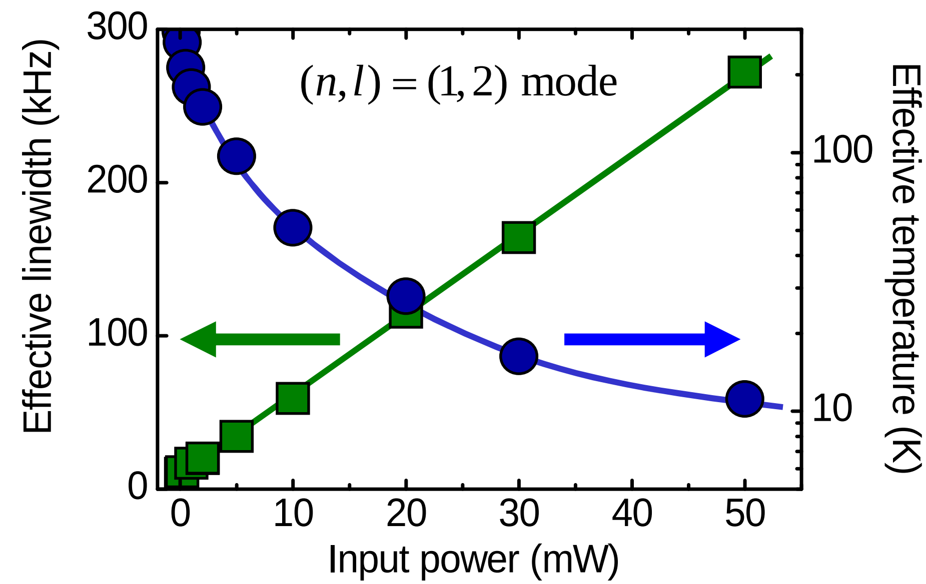




$$\gamma_{eff} = \gamma_m + \Gamma$$
$$= 2\pi \cdot (10 \text{ kHz} + 260 \text{ kHz})$$

- $T_{eff} = (\gamma_{eff} / \gamma_m)\, T_{bath} \sim 11K$

- $< N >_{final} \;\sim\; 2{,}000 \;>>\; 1$

Assuming no other heating.



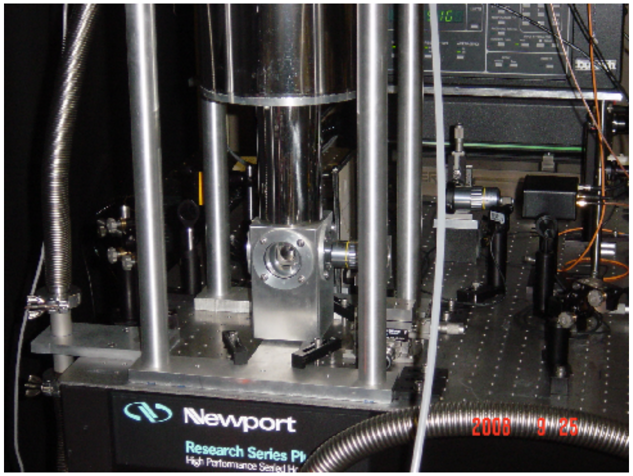
# Experimental setup for cryogenic operation

Via Free space excitation

Cryogenic cooling

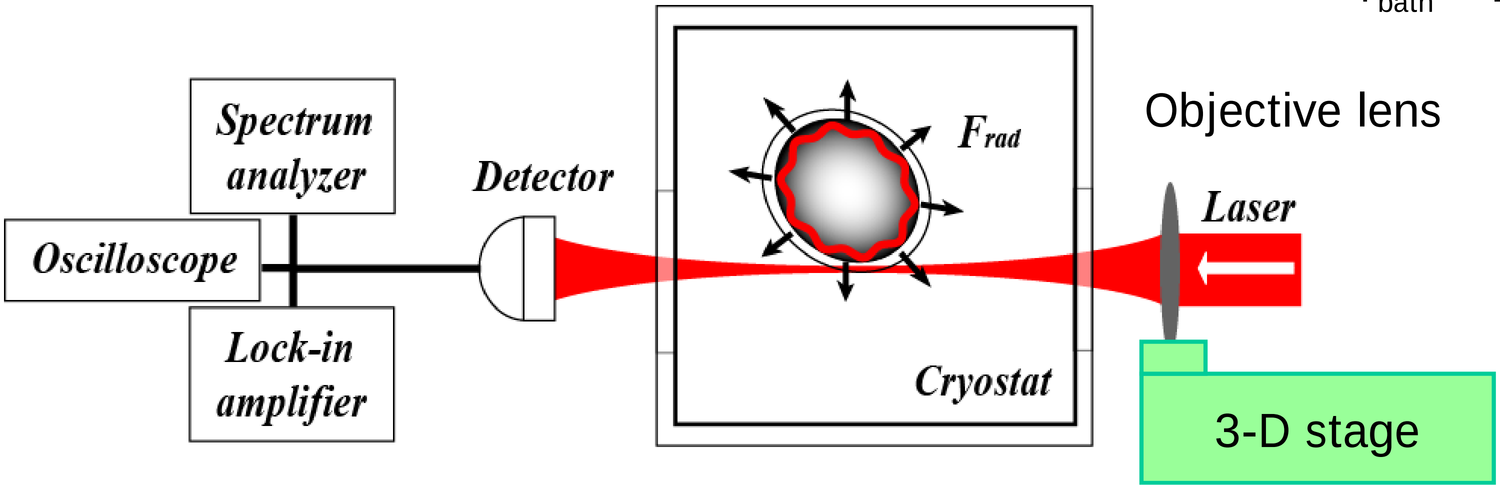
+

Opto-mechanical cooling

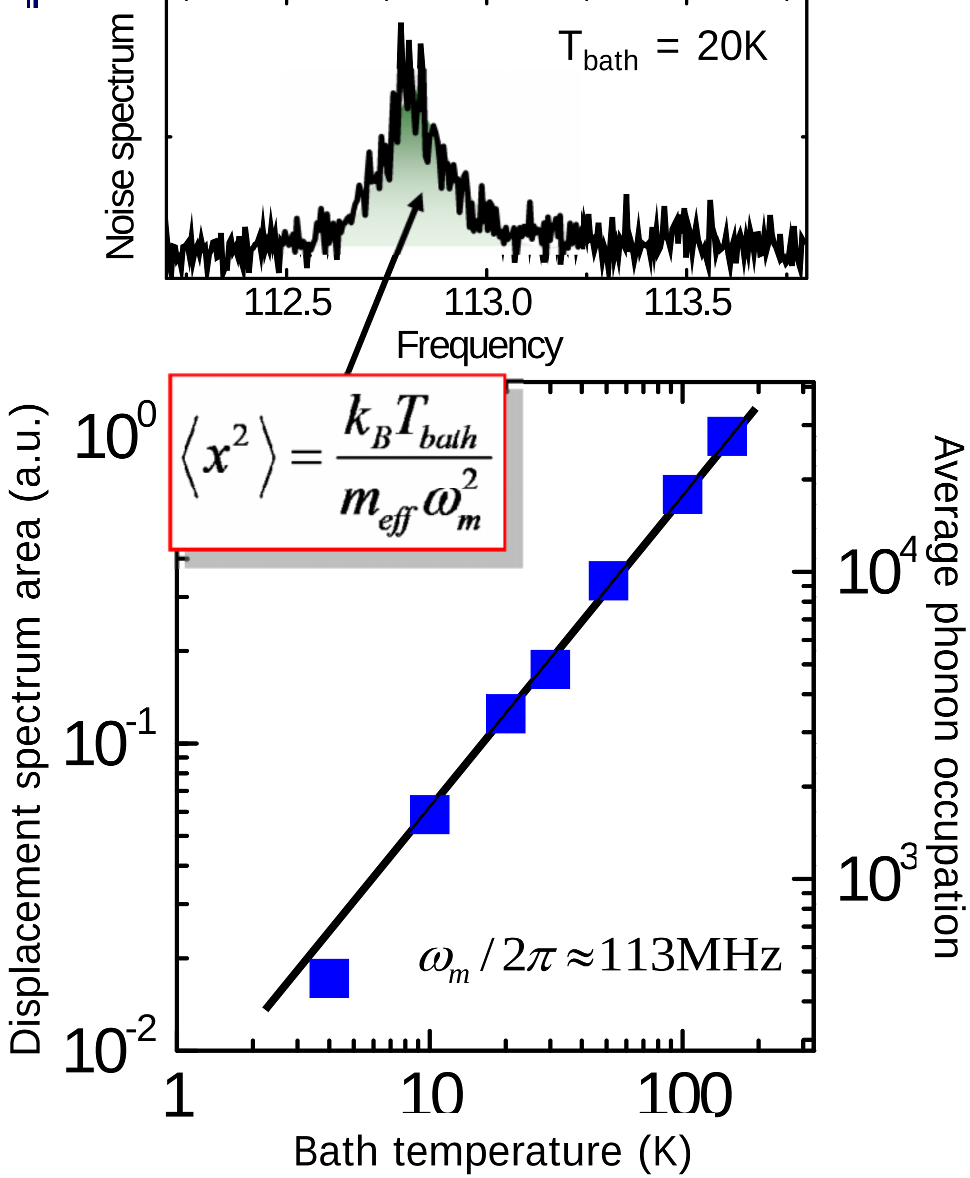


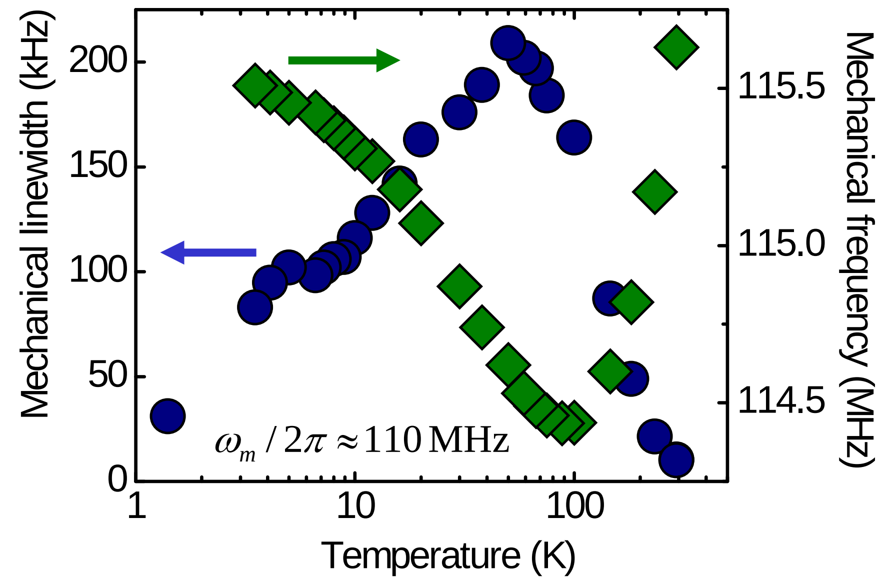

$He^4$ cryostat

$T_{bath}$ ~ 1.4K



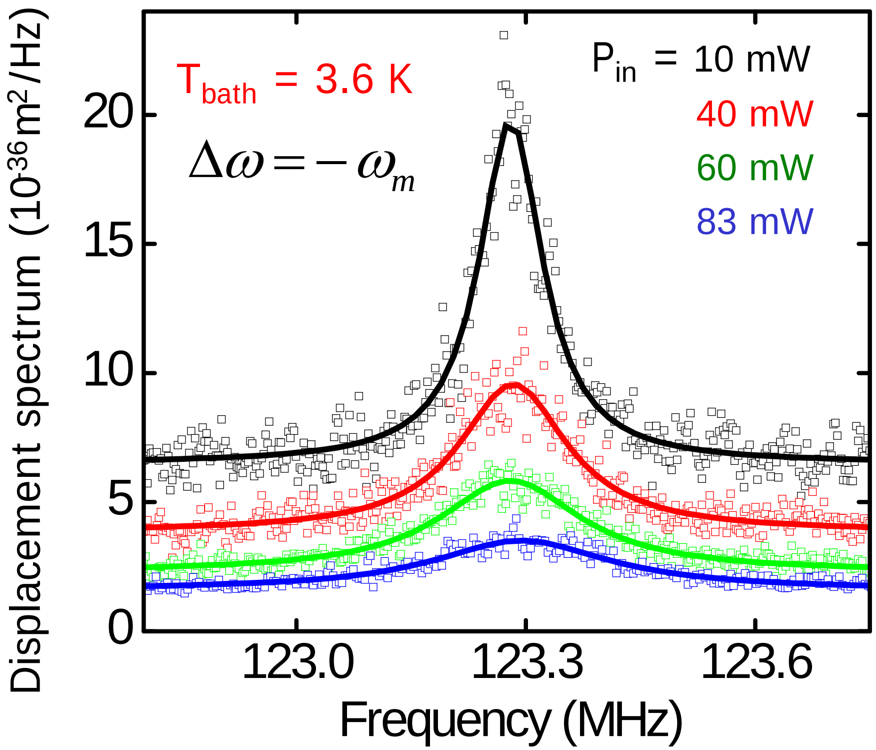
# Cryogenic Cooling

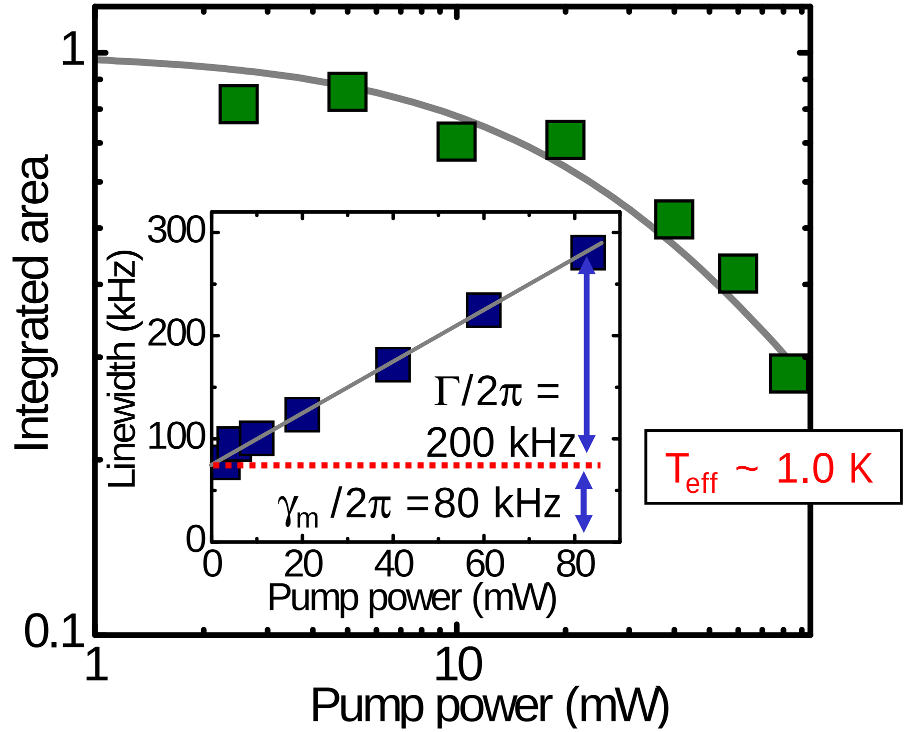


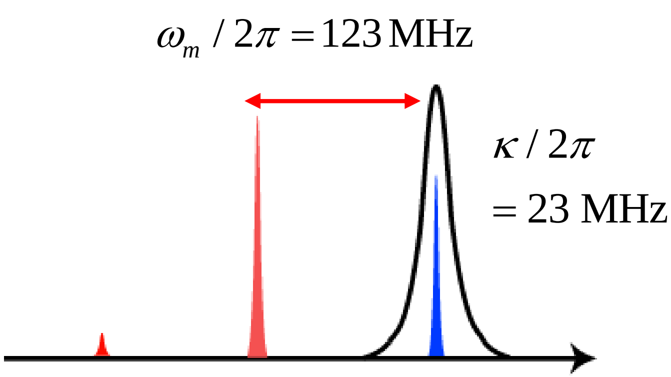




Mechanical mode temperature is in equilibrium with bath temperature.

# Resolved-sideband cooling at $T_{bath}$=3.6 K



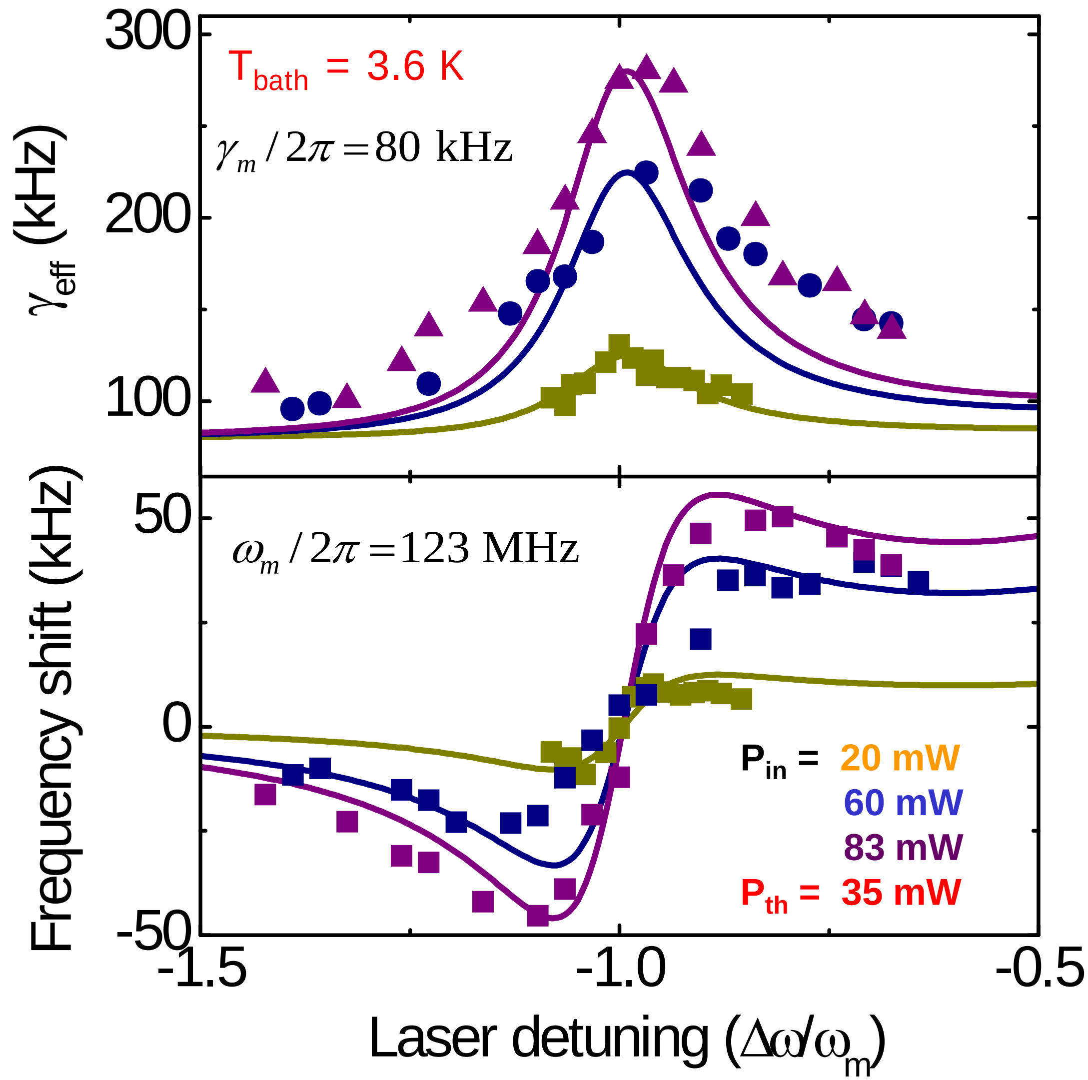

Area reduction
Linewidth widening } Cooling ratio ~ 3.5

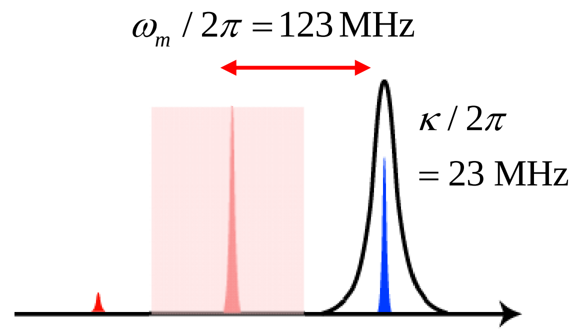
- Incident laser induces negligible heating.
- Limited by ultrasonic attenuation

  Qm = 1,600 ← 10,000 (room T)

# Resolved-sideband cooling at $T_{bath}$=3.6 K

Lines : theory, Dots : data




Radiation pressure cooling is dominant.

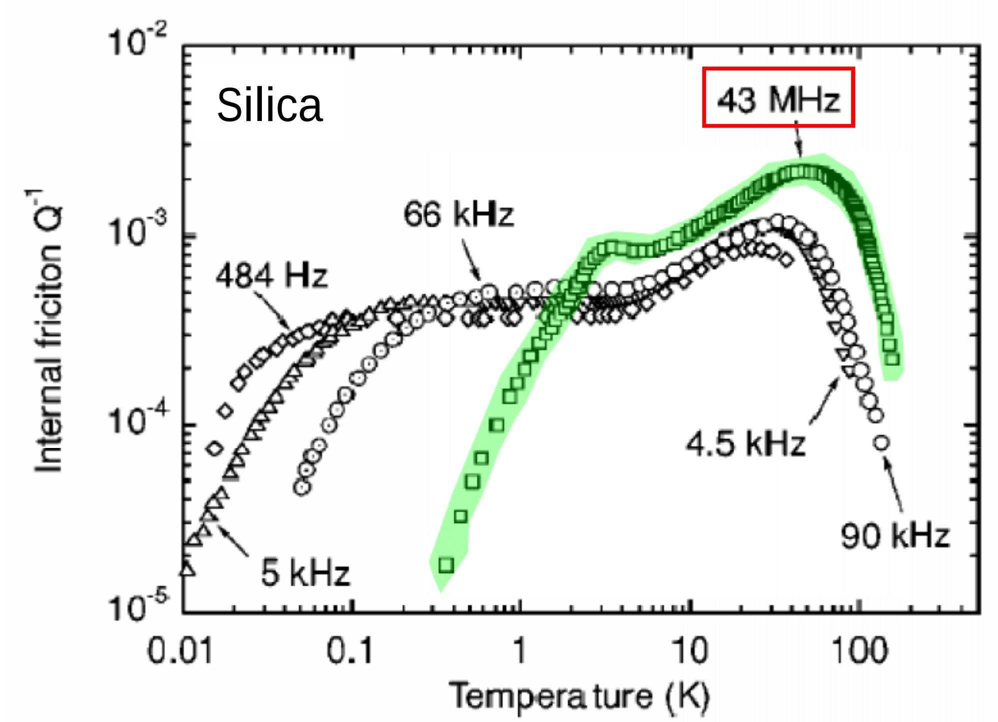
(No other free parameters)

$$\Gamma = \gamma_m \frac{P}{P_{th}} \frac{4\omega_m^2 \kappa}{4(\Delta\omega)^2 + \kappa^2} \times \left[\frac{\kappa}{4(\Delta\omega + \omega_m)^2 + \kappa^2} - \frac{\kappa}{4(\Delta\omega - \omega_m)^2 + \kappa^2}\right]$$

$$\Omega = \gamma_m \frac{P}{P_{th}} \frac{4\omega_m^2 \kappa}{4(\Delta\omega)^2 + \kappa^2} \times \left[\frac{\Delta\omega + \omega_m}{4(\Delta\omega + \omega_m)^2 + \kappa^2} + \frac{\Delta\omega - \omega_m}{4(\Delta\omega - \omega_m)^2 + \kappa^2}\right]$$

$P_{th}$ : parametric oscillation threshold power.

# Ultrasonic attenuation at lower temperature

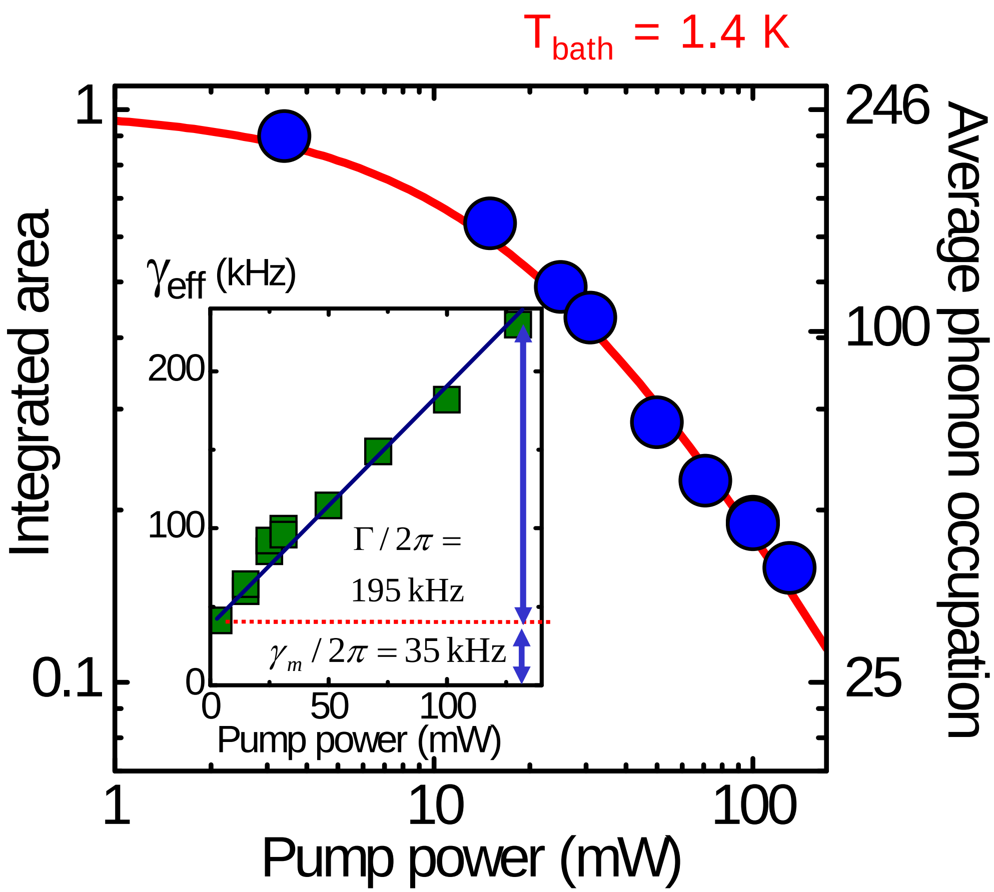


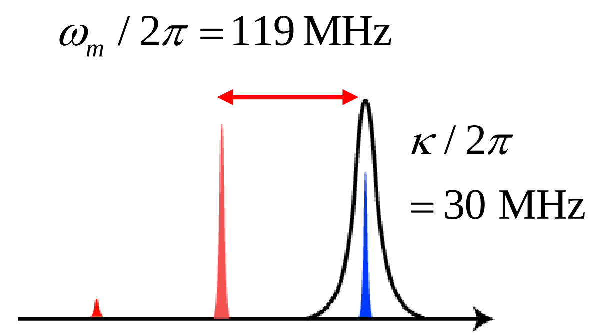

Ultrasonic attenuation decreases rapidly below ~ 5K

for ultrasonic frequencies.

Pohl *et al.,* Rev. Mod. Phys. **74**, 991 (2002).

# Resolved-sideband cooling at $T_{bath}$=1.4 K




Area reduction
Linewidth widening

$T_{eff}$ ~ 210mK.
$<N>_{final}$ ~ 37.

- Incident laser induces negligible heating.
- Limited by ultrasonic attenuation

  Qm = 3,400 ← 10,300 (room T)

# Cooling of nanomechanical resonator

For comparison :

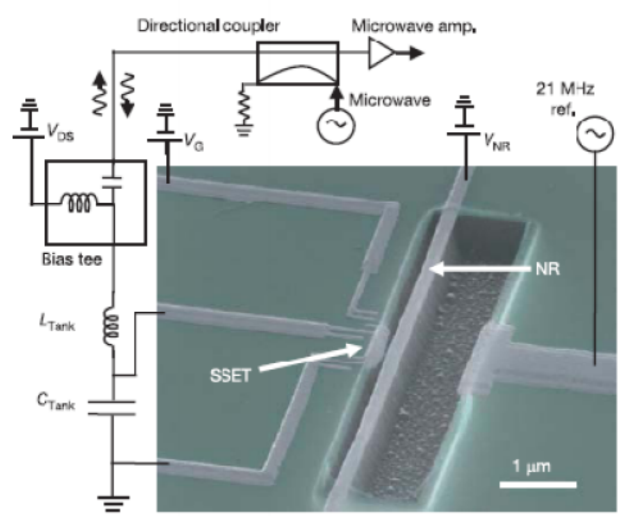
Nanomechanical resonators in a sub-Kelvin cryogenic temperature.

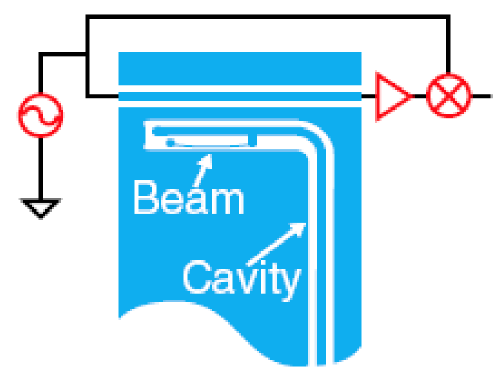
$<N>_{final}$ ~ 25 : cryogenically cooled nanomechanical resonator.

Naik et al., Nature, 443, 193 (2006).

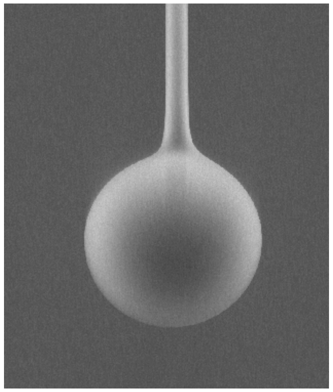
$<N>_{final}$ ~ 140 : Dynamical backaction cooling is limited by radiation heating.

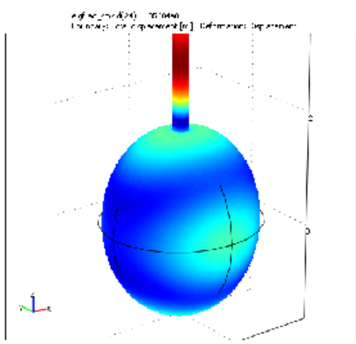
Teufel et al., Phys. Rev. Lett. 101, 197203 (2008).

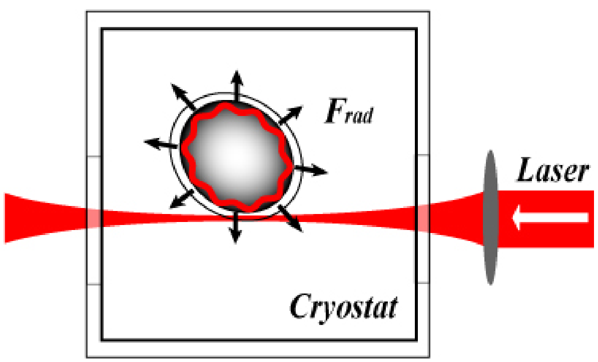


# Summary and Future work








## Summary

- ✓ Demonstrated the resolved sideband cooling of a silica microsphere resonator in a cryogenic environment by utilizing free space excitation of WGMs.
- ✓ Achieved average phonon occupation, <N> ~ 37, for a 110MHz mechanical oscillator, limited by acoustic absorption.

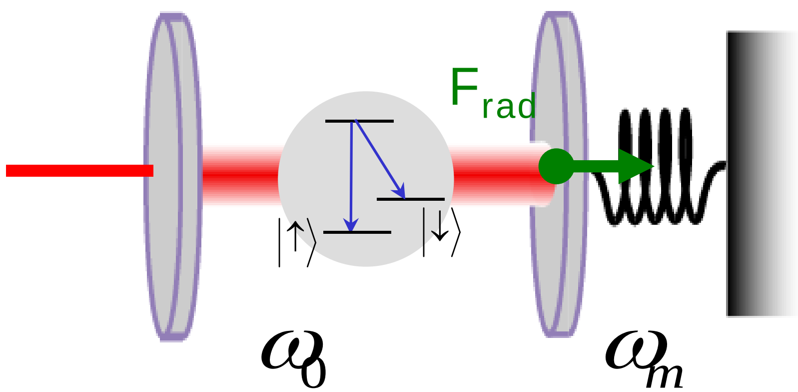
## Future work

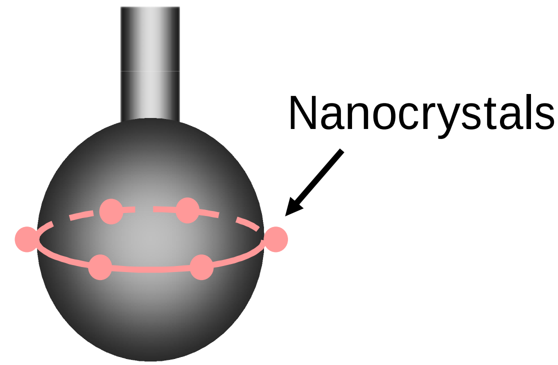
- ✓ Carry out experimental studies in a $He^3$ cryostat in order to lower both bath temperature and acoustic absorption.

# Future work

Combining cavity-QED with cavity optomechanics:

e.g. Coupling a mechanical oscillation to a spin excitation.




Park *et al.*, Nano Lett. **6**, 2075 (2006).

Thank you for your attention !