Oscillation Linewidth and Brownian Noise in a Radiation-Pressure-Driven Optomechanical oscillator

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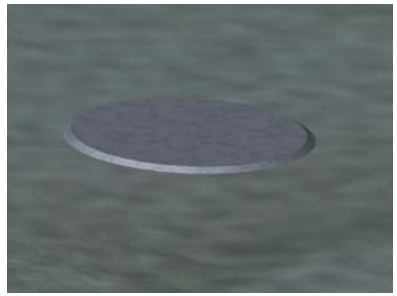
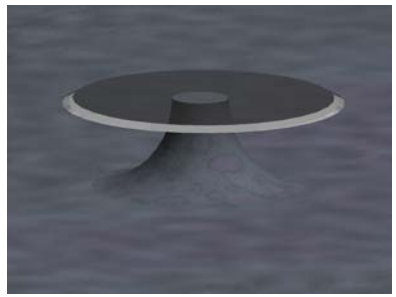
Microtoroid optical resonator

- Microtoroid resonator
  - High *Q*-factor
    - Long photon lifetime (τ_p)
    - Large circulating power (P_{circ})
  - Small mode volume
    - Large intensity
  - Monolithic fabrication

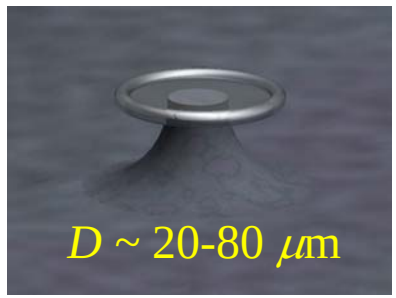
Circular SiO_2 pad (HF wet etching)

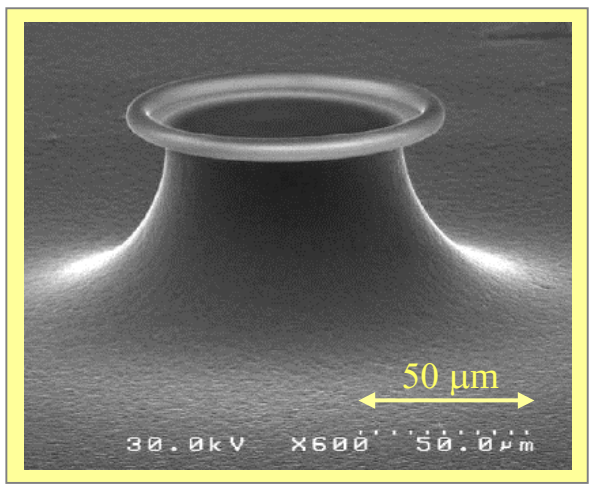


Silicon pillar (XeF_2 dry etching)



Silica microtoroid (CO_2 laser reflow)

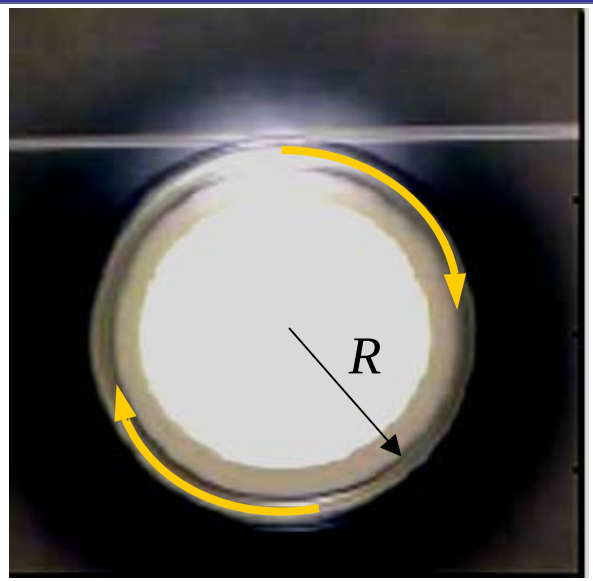


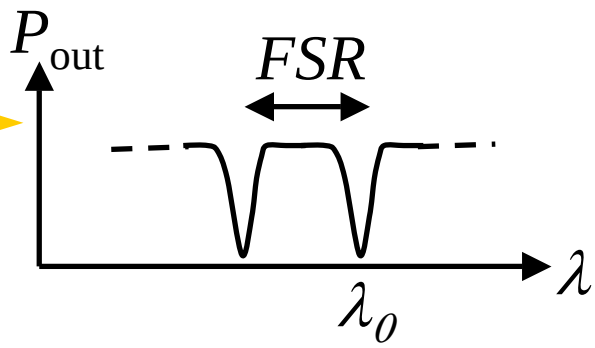


D. K. Armani et al ."Ultra-high-Q toroid microcavity on a chip" Nature, Volume 421,Feb 2003

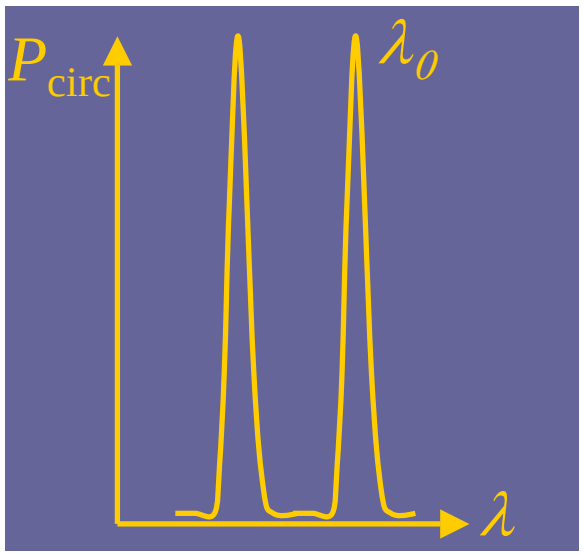
$Q \sim 10^6$-10^8
$\tau_p \sim 0.8$ –80 ns
$\tau_o \sim 0.25$-1 ps

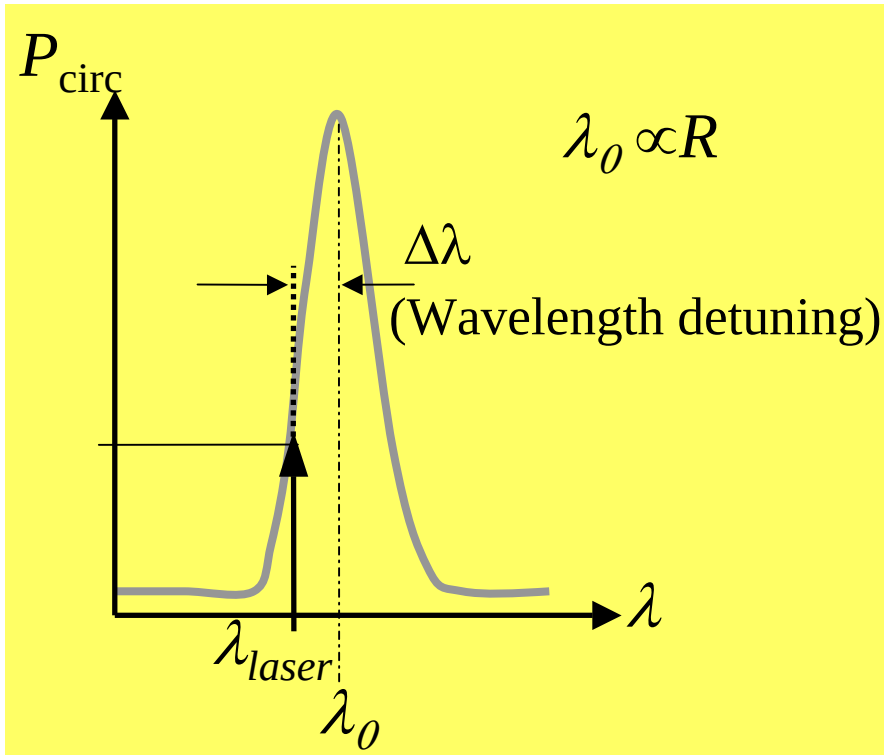
Optical coupling to WG modes





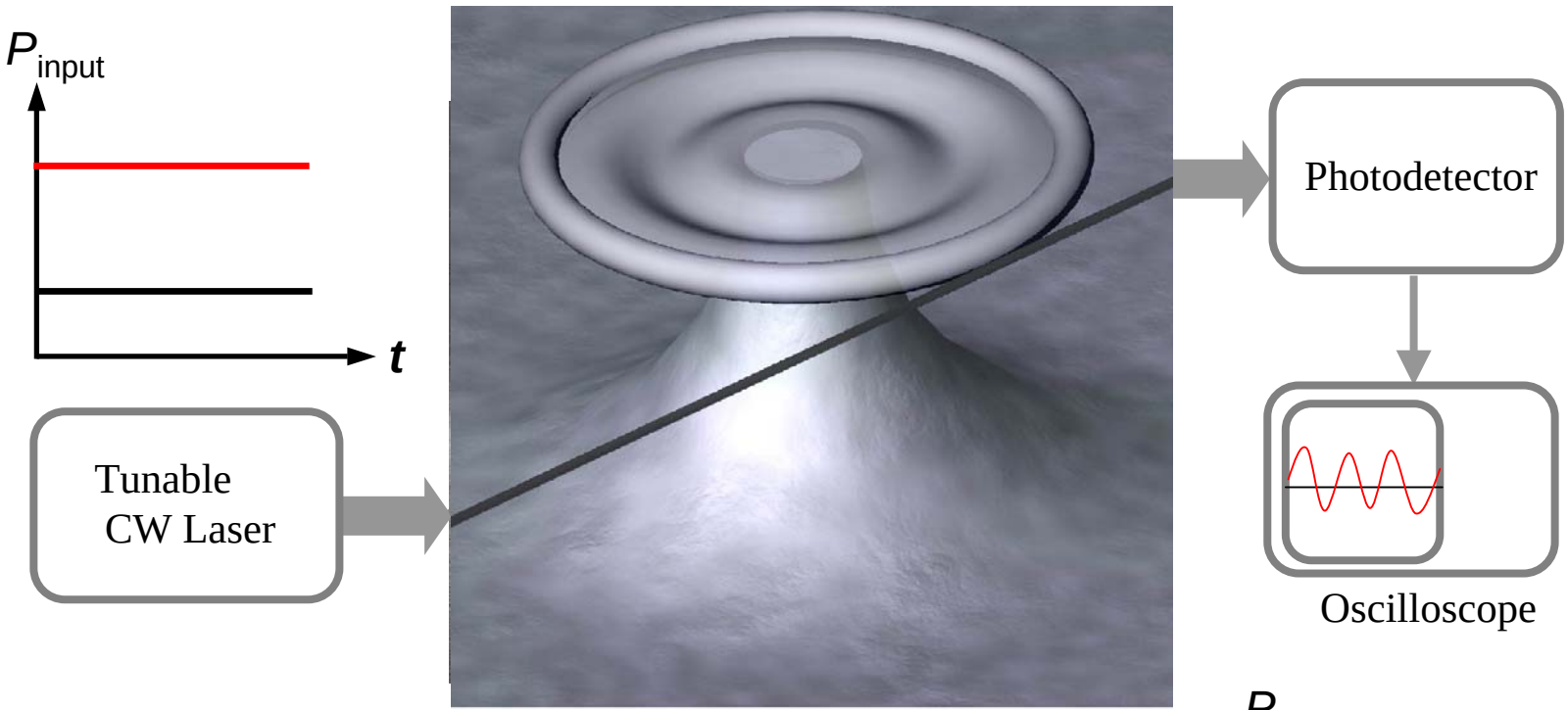
P_{in} ~1 mW,
Q~$10^8 \Rightarrow$
$\boldsymbol{P_{circ}}$~*100* W





M. Cai et al ."Observation of critical coupling in a fiber taper to a silica microsphere whispering-gallery mode system, " Physical Review letters, Volume 85, pp. 74-77, 2000

Experimental observation of Optomechanical oscillation



H. Rokhsari, T. J. Kippenberg, T. Carmon, and K. J. Vahala
"Radiation-pressure-driven micro-mechanical oscillator"
Optics Express, Volume 13, No. 14, July 2005

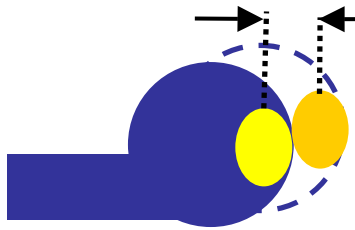
T. Carmon, H. Rokhsari, L. Yang, T. J. Kippenberg, and K. J. Vahala
"Temporal Behavior of Radiation-Pressure-Induced Vibrations of an Optical Microcavity Phonon Mode"
Physical Review Letters, Volume 94, 223902, June 2005

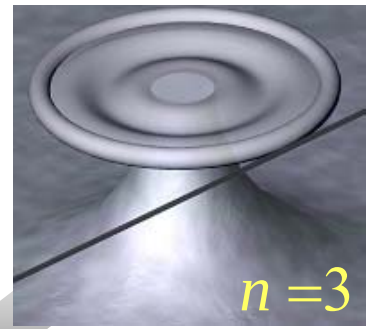
Mechanical modes of a silica microtoroid

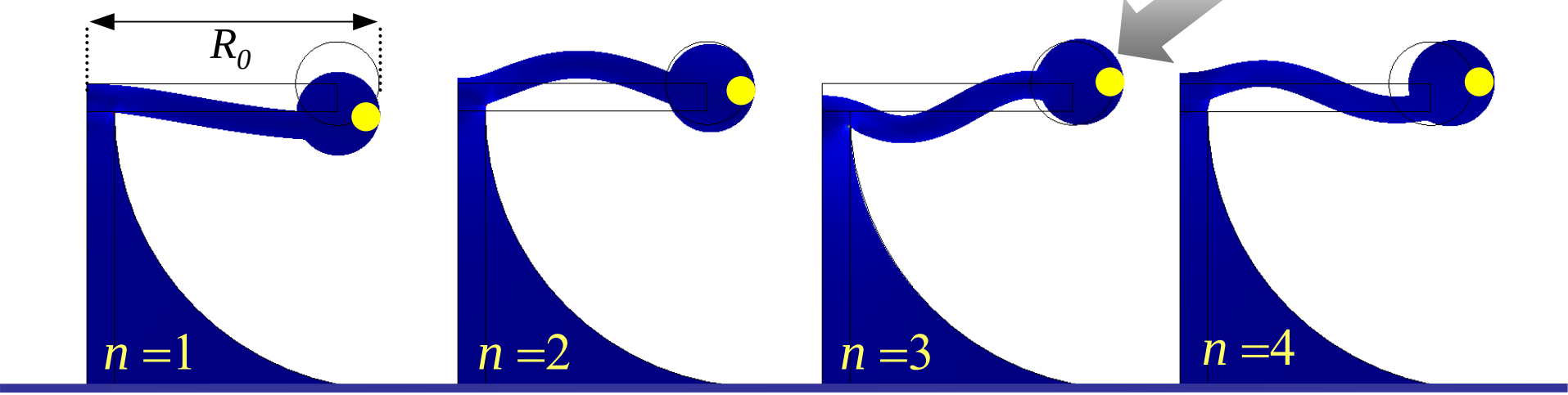
$$\frac{d^2r}{dt^2} + \left(\frac{\Omega_0}{Q_{mech}}\right)\frac{dr}{dt} + \Omega_0{}^2 r = \frac{F_{rad}\left(P_{in}, r\right)}{m_{eff}}$$

$r(t) = r_0 \mathrm{Cos}(\Omega t)$

$R(t) = R_0 + r(t)$

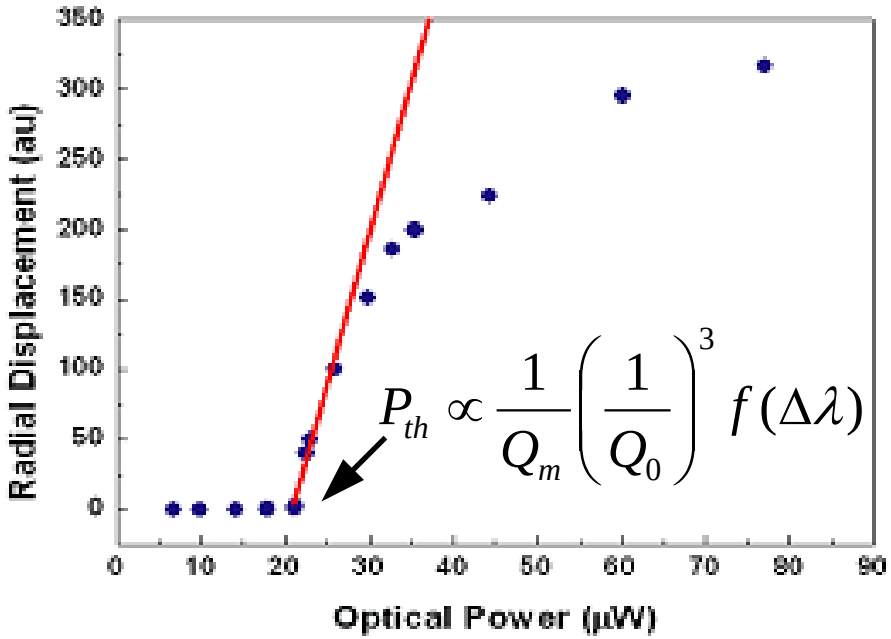


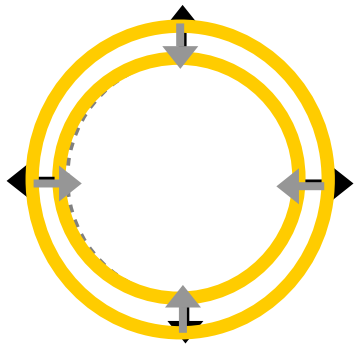


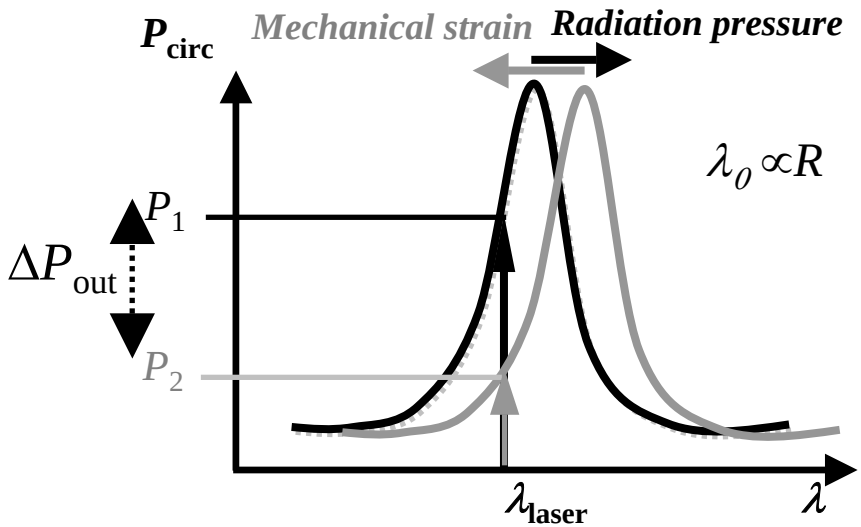


Optomechanical oscillation: mechanism

- Optomechanical coupling between optical and mechanical modes of the microtoroid
  - Inflation : Optical energy → Mechanical energy
  - Deflation : Mechanical energy → Optical energy

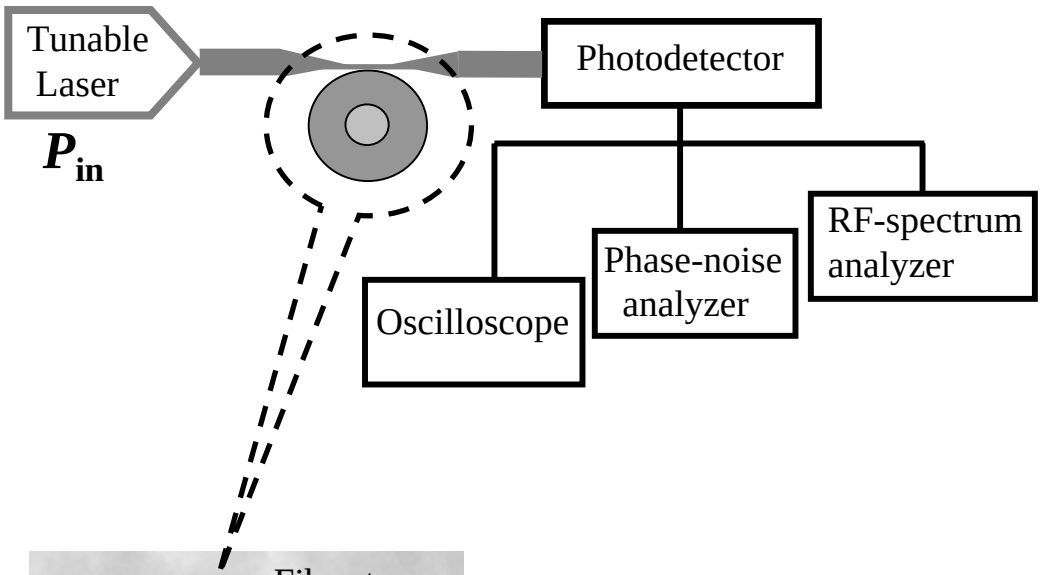


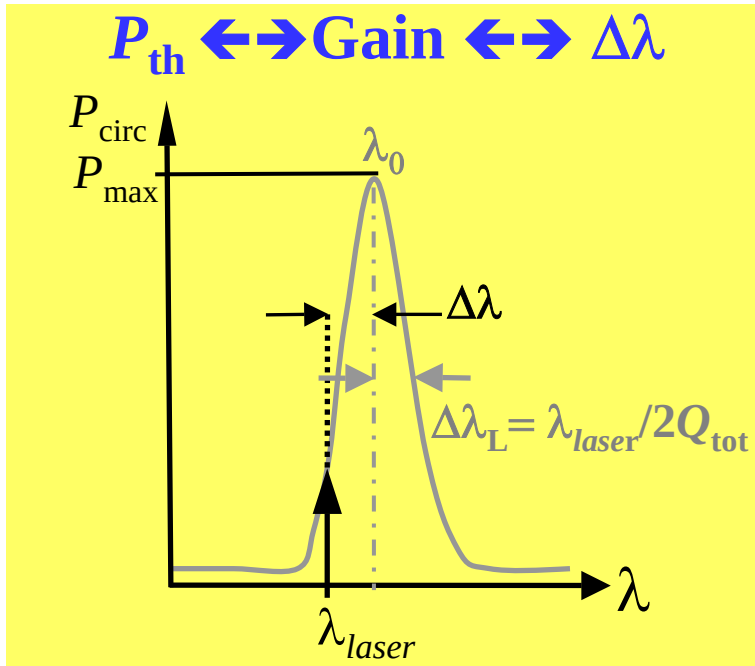


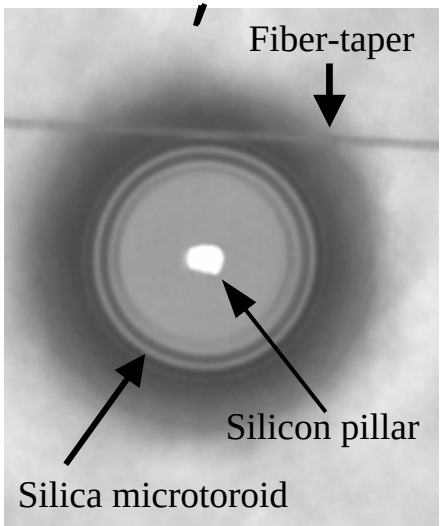


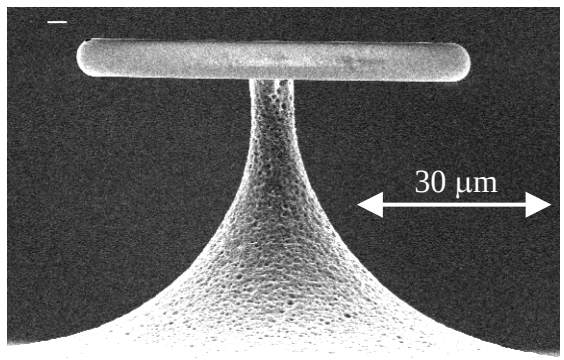
T. J. Kippenberg, H. Rokhsari, T. Carmon, A. Scherer, and K. J. Vahala "Analysis of Radiation-Pressure Induced Mechanical Oscillation of an optical Microcavity" Physical Review Letters, Volume 95, 033901, July 2005

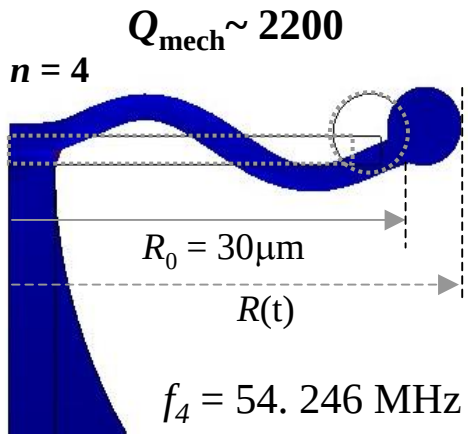
Experiment


Tunable Laser
P_{in}
Photodetector
Oscilloscope
Phase-noise analyzer
RF-spectrum analyzer


P_{th} ↔ Gain ↔ Δλ
P_{circ}
P_{max}
λ_0
Δλ
$\Delta\lambda_L = \lambda_{laser}/2Q_{tot}$
λ
λ_{laser}

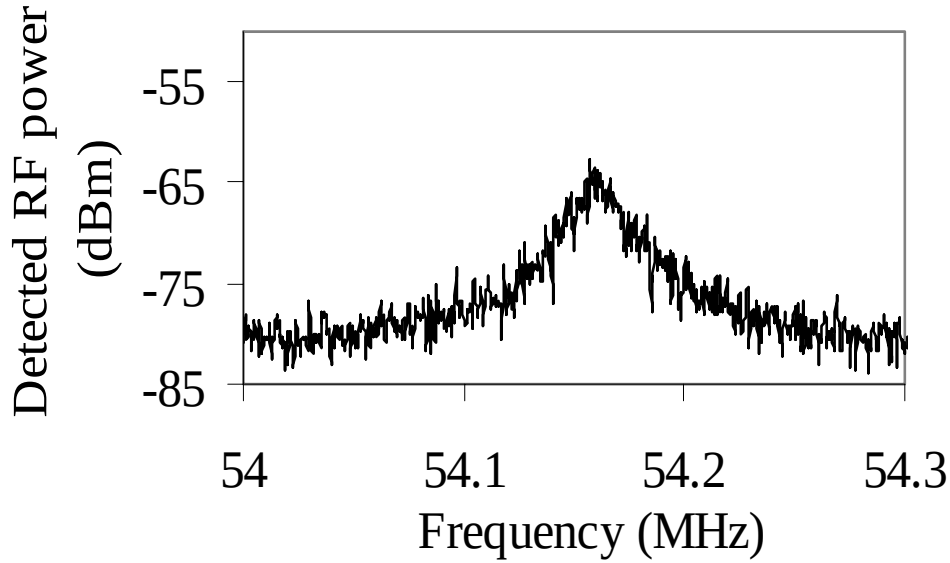

Fiber-taper
Silicon pillar
Silica microtoroid

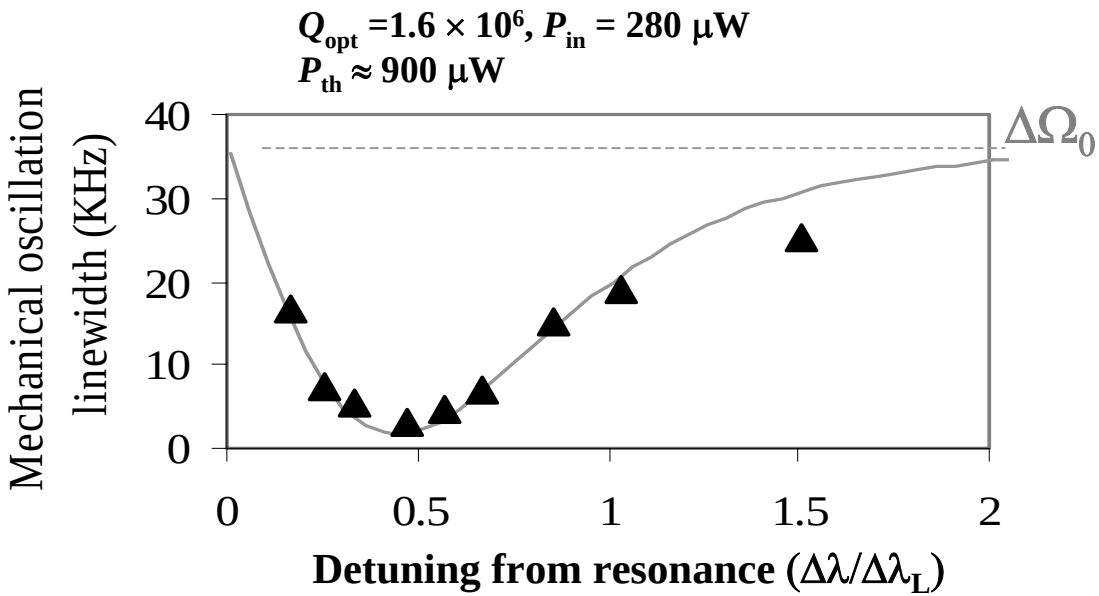

30 μm


Q_{mech}~ 2200
n = 4
R_0 = 30μm
R(t)
f_4 = 54. 246 MHz

Optomechanical oscillation linewidth: Below threshold

- Oscillation linewidth ($\Delta\Omega'_0$)
  - Below threshold ($P_{in} < P_{th}$)
    - Mechanical loss



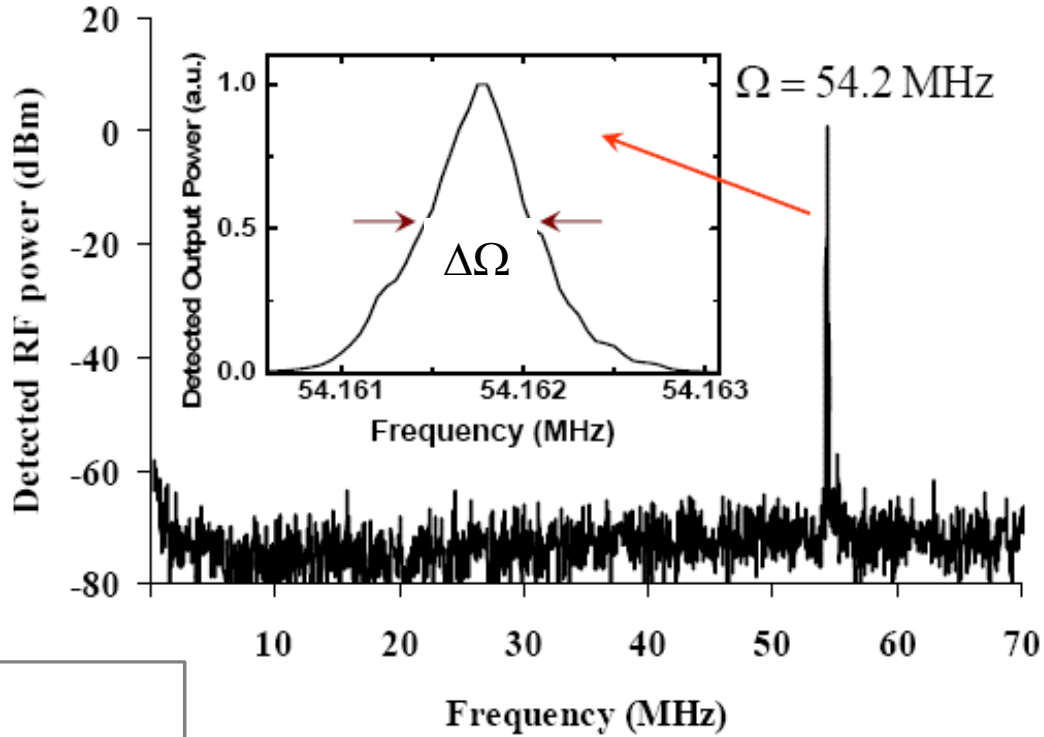


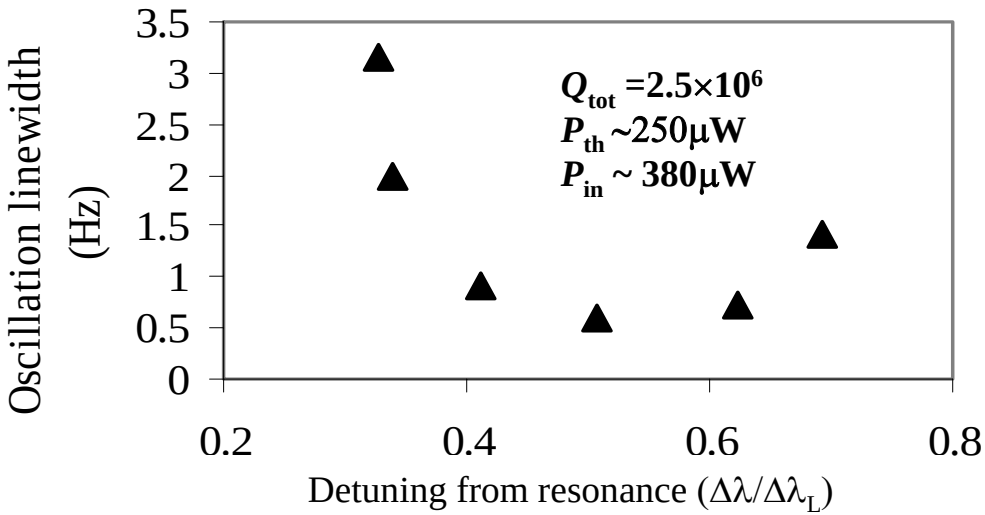
$$\Delta\Omega'_0 = \Delta\Omega_0\left(1 - \frac{P_{in}}{P_{th}(\Delta\lambda)}\right)$$

Optomechanical oscillation linewidth: Above threshold

- Oscillation linewidth ($\Delta\Omega$)
  - Above threshold ($P_{in} > P_{th}$)
    - Optomechanical gain

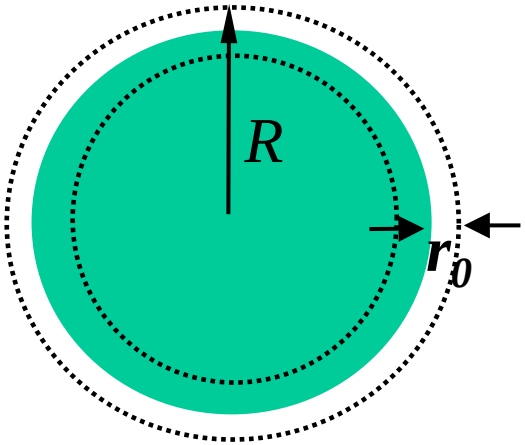
Noise mechanism ?





Optomechanical oscillation linewidth: Above threshold

Thermally limited oscillation linewidth in a mechanical oscillator



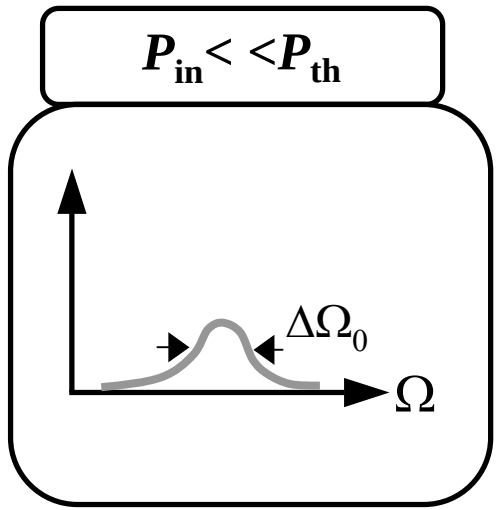
$$\Delta\Omega = \frac{k_B T}{2P}\left(\Delta\Omega_0\right)^2$$

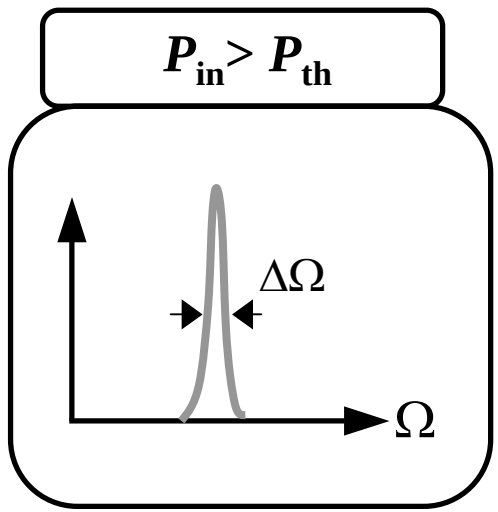
$$P = P_{diss} = \frac{E_{stored}\Omega_0}{Q_{mech}}$$

$$E_{stored} = \frac{1}{2} m_{eff}\Omega_0^2 r_0^2$$

r_0 :Oscillation amplitude

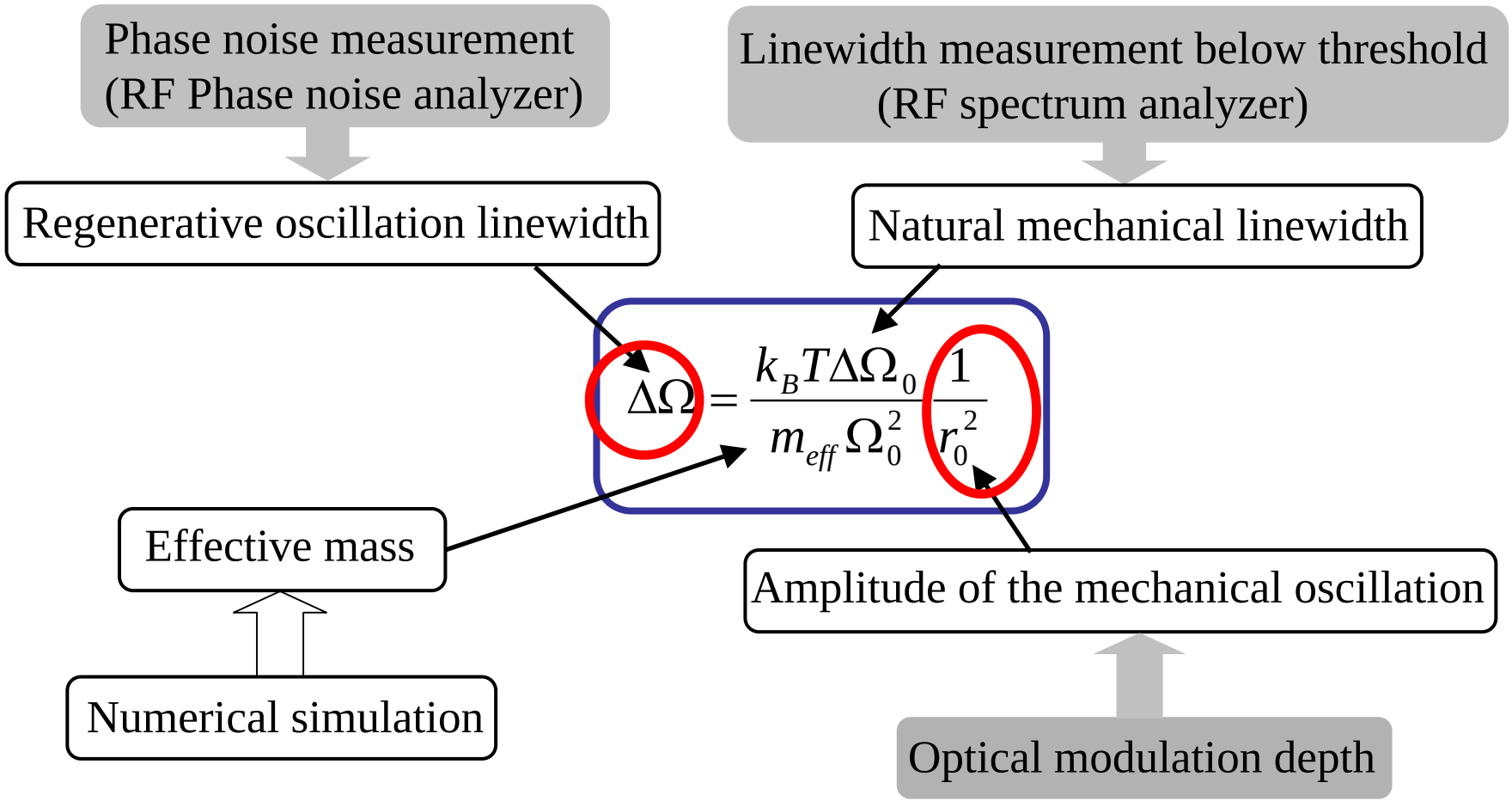
$$\Delta\Omega = \frac{k_B T}{m_{eff}\Omega_0^2}\frac{\Delta\Omega_0}{r_0^2}$$





W. A. Edson, "Noise in oscillators"
Proceedings of the Radio Engineers, Volume 48, pp. 1454-1466, 1960

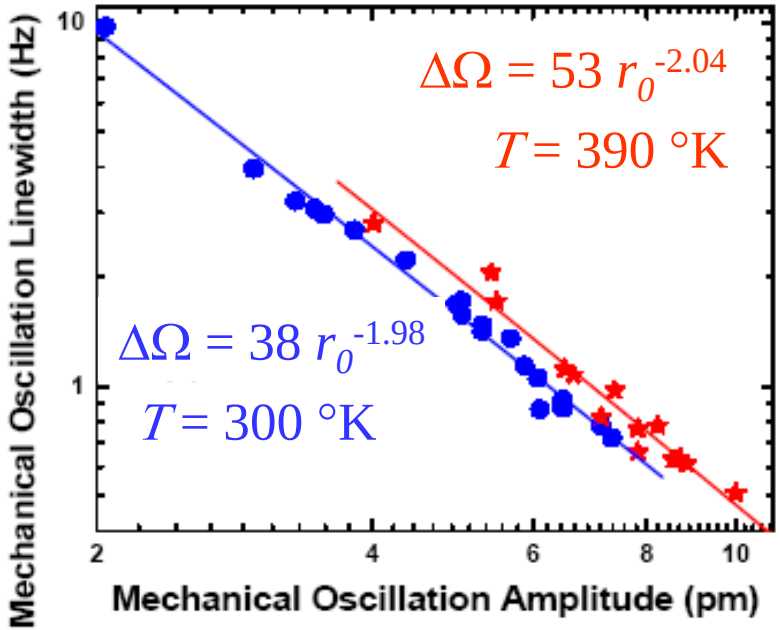
Experimental verification of linewidth narrowing

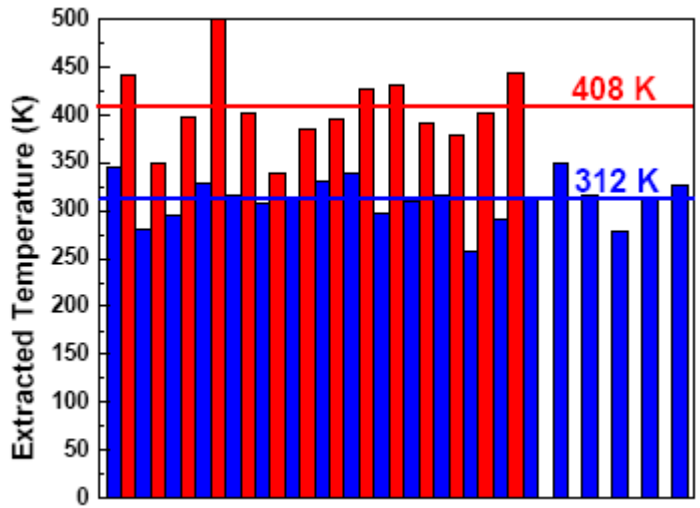


Experimental results

$$\Delta\Omega \propto \frac{1}{r_0^2}$$

$$T = \frac{\Delta\Omega}{\Delta\Omega_0}\frac{m_{eff} r_0^2 \Omega_0^2}{k_B}$$





- The fundamental linewidth is limited by Brownian noise
  - Inverse relation with mechanical energy ✓
  - Temperature dependency ✓

Summary and outlook

- Optomechanical oscillator
  - Oscillation linewidth
    - Sub-Hertz oscillation linewidth
    - Linewidth is limited by Brownian noise in the structure.
- Applications
  - All-optical oscillator
  - New platform for exploring quantum-optical phenomena