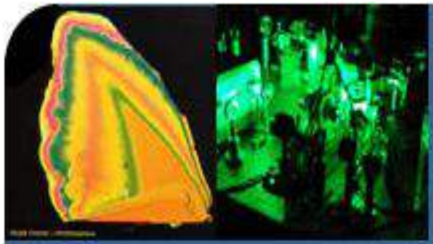


MATÉRIAUX ET
PHÉNOMÈNES
QUANTIQUES

From micro to nano-optomechanical systems:
light interacting with mechanical resonators

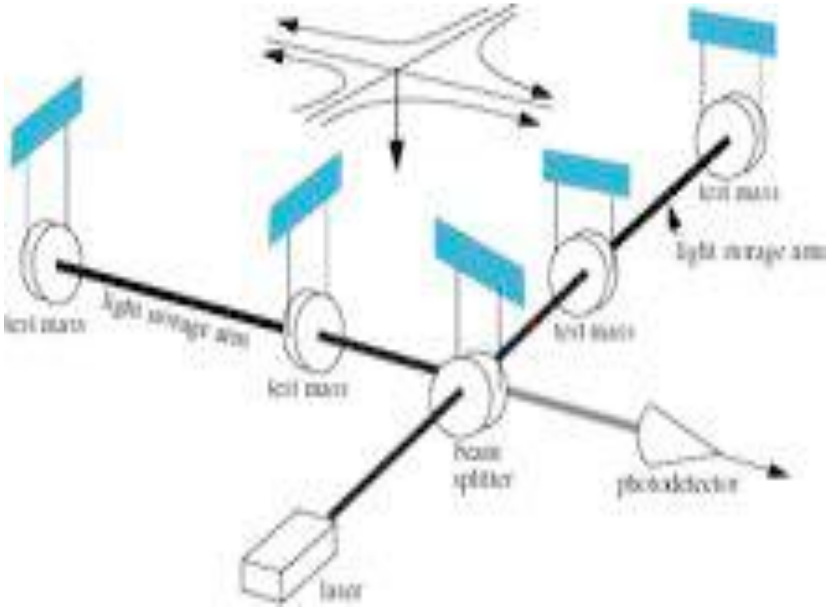
Ivan Favero

MPQ: Christophe Baker, David Parrain, Sara Ducci, Giuseppe Leo, Ivan Favero

LPN: Pascale Senellart, Aristide Lemaitre, Elisabeth Galopin

LMU Munich: Sebastian Stapfner, Khaled Karrai, Eva Weig

Detecting gravitational waves with an optical interferometer



Needs to reach $10^{-20} m/\sqrt{Hz}$

Is it even doable in principle?

Fundamental limits of such measurement

Standard quantum limit in a continuous measurement

$\Delta x \Delta p \geq \hbar/2$ which consequences ?

Carlton M. Caves, Physical Review Letters 45, 14 (1980)
« Quantum-Mechanical Radiation-Pressure Fluctuations in an Interferometer »

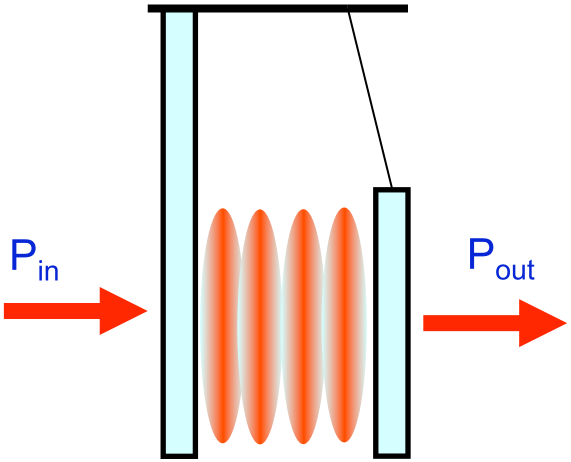
V. B. Braginsky, F. Khalili, « *Quantum measurement* »,Cambridge University Press (1995)

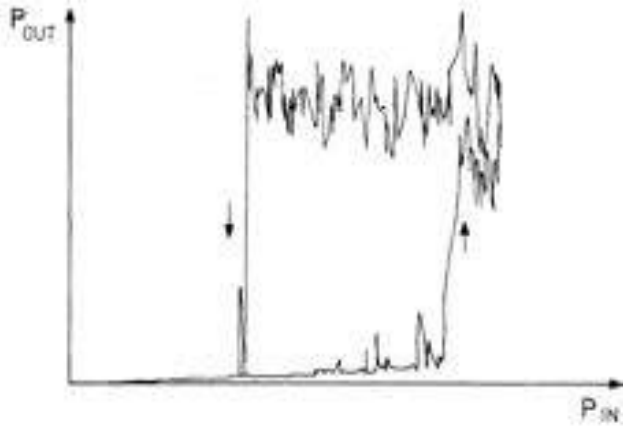
Photons dynamical back-action

V. B. Braginsky, Moscow State University
"Weak forces measurements in physics"
Chicago University Press (1977)

Mechanical action of photons perturbs the system
during the measurement: **Optomechanical coupling**

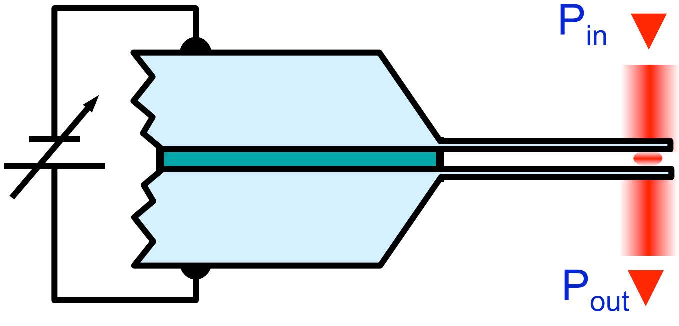
Coupling light to the mechanical motion of a mirror



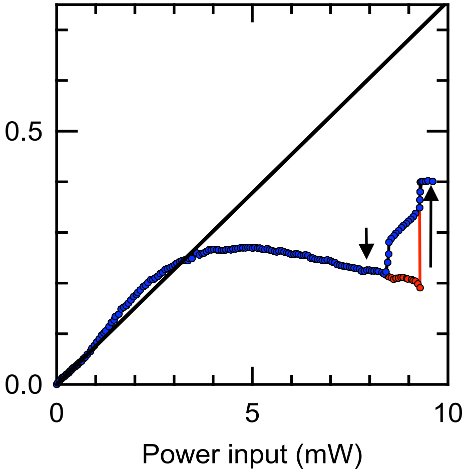


A. Dorsel et al., *PRL 51, 1550 (1983)*

Optical bi-stability and mirror trapping

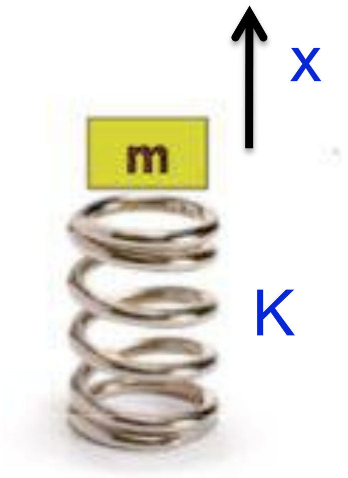


- AFM silicon microlever
  (200 x 20 x 0.5 μm = 5 ng)



Back-action on a micro-mirror (2003)

Quantum regime of a mechanical oscillator



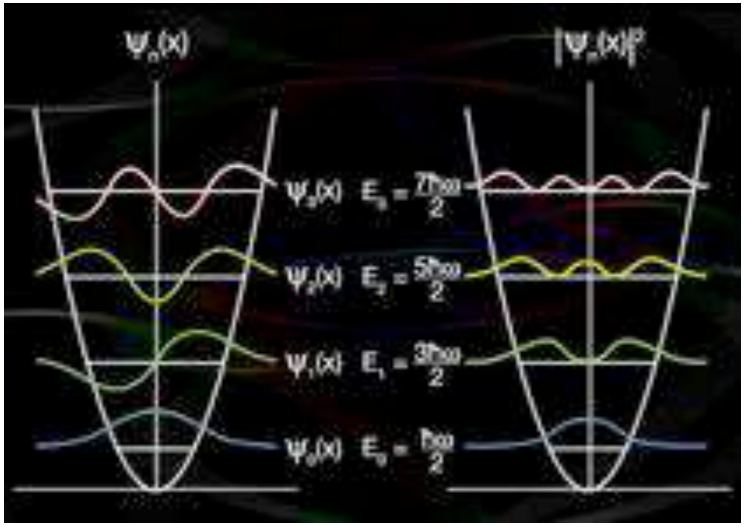
- Classical harmonic oscillator

$md^2x(t)/dt^2+Kx(t)=0$
$x(t)=x_0\cos(\omega_m t+\varphi)$
$\langle E\rangle = ½.m\omega_m^2 x_0^2$

- Quantum harmonic oscillator

$E_n=(n+1/2)\hbar\omega_m$ n phonon number
n=0 is the quantum ground-state

$m\omega_m^2\Delta x_{zpf}^2=\hbar\omega_m$ $\Delta x_{zpf}/\sqrt{Hz} \approx 10^{-16} m/\sqrt{Hz}$

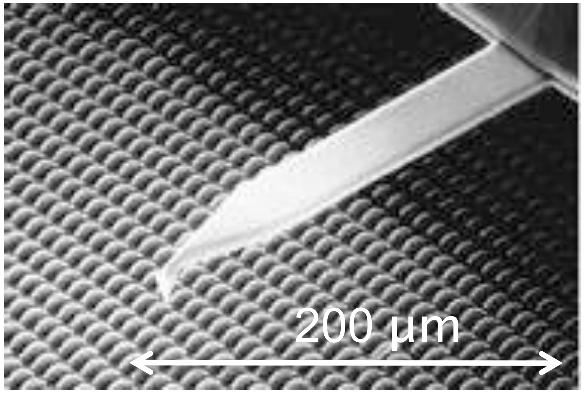


Difficulties

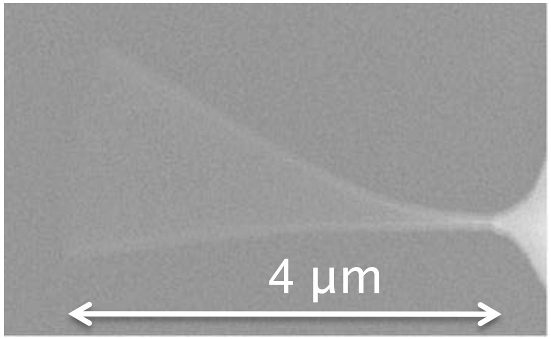
- Detect the « quantum » motion
- Reach the regime $k_BT \leq \hbar\omega_m$

Quantum temperature $k_B T \leq \hbar\omega_m$?

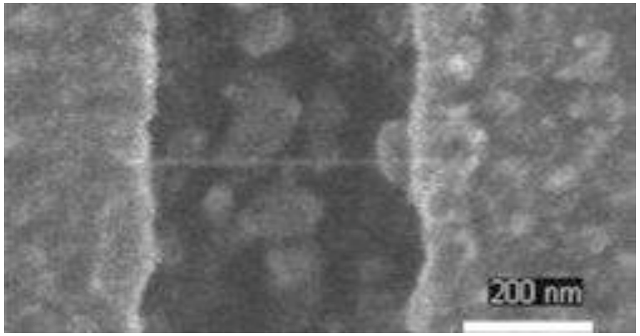
Micro



- **10 KHz corresponds to 500 nK**



- **1MHz corresponsd to 50 µK**

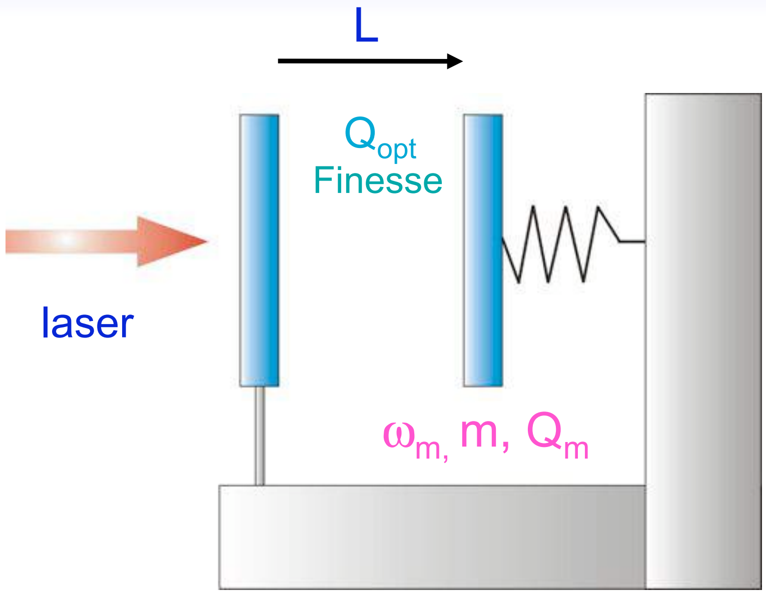


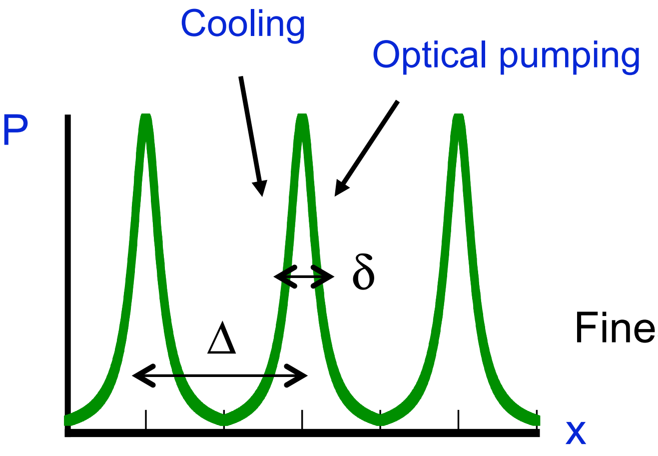
- **1GHz corresponds to 50 mK**

Nano

Principles of optical cooling

Optical cavity cooling of a mirror motion





Finesse=Δ/δ

Cooling efficiency ($\omega_m\tau \approx 1$)

$\alpha P_{opt} .(L/\lambda).\mathrm{Finesse}^3 /(\Gamma_m.m.c^2)$

Figure of merit for quantum cooling ($\omega_m\tau \approx 1$)

$N_{phot} . \alpha . Q_{opt}. (g_{om})^2 .(\Delta x_{zpf})^2. Q_m \quad .(\hbar/k_B T\omega_{opt})$

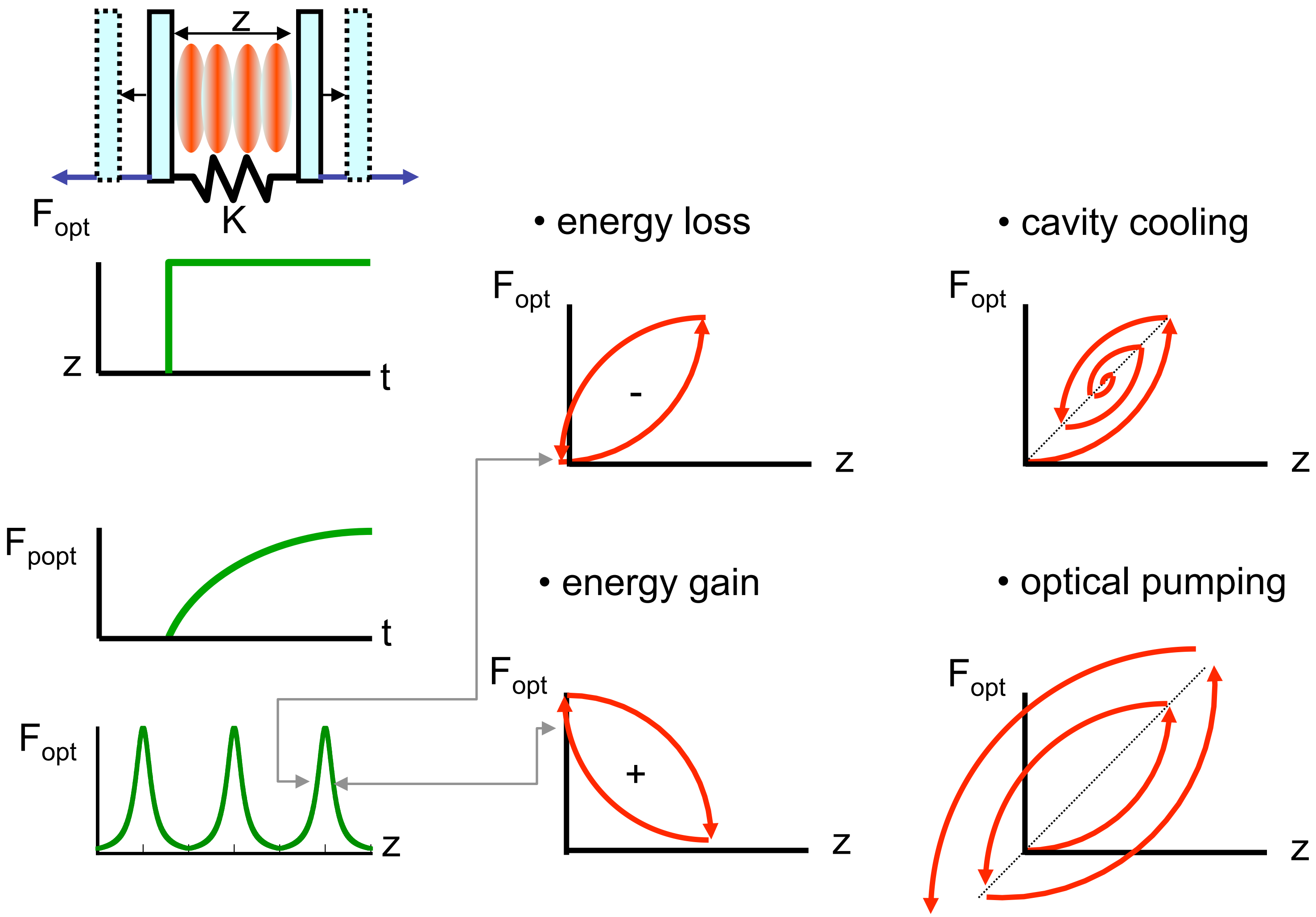
Optical Pressure αP_{opt} /c (delay τ)

- Photothermal pressure
- Radiation pressure
- Opto-electronic pressure

$g_{om}=d\omega_{opt}/dx$

$(\Delta x_{zpf})^2=\hbar/2m\omega_m$ small mass

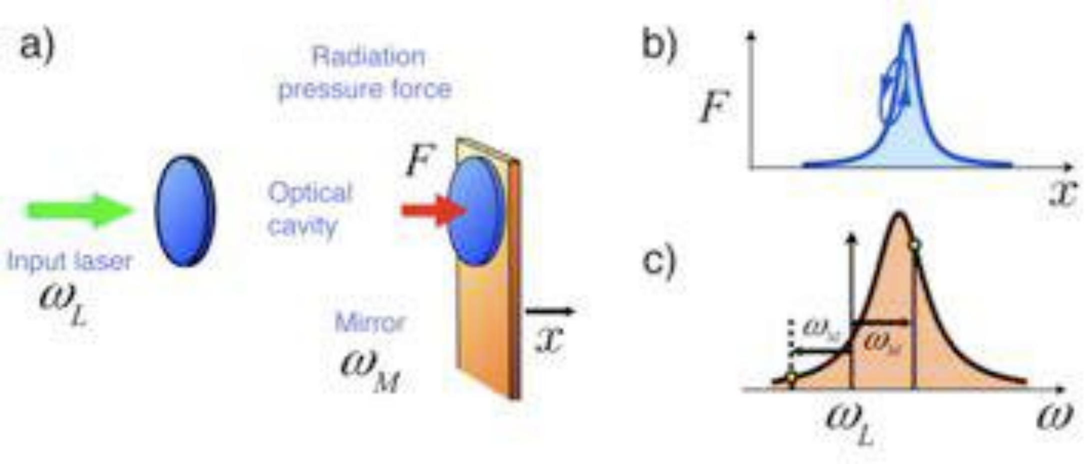
Thermodynamic picture of optomechanical cooling



- energy loss
- cavity cooling
- energy gain
- optical pumping

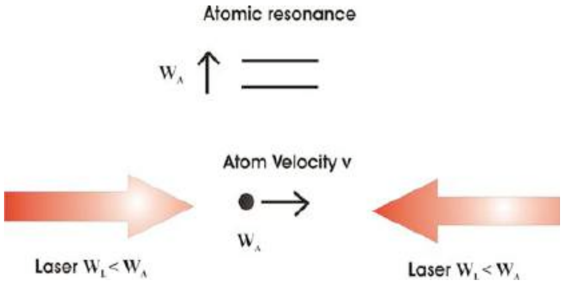
Brownian motion modified by the mechanical action of light

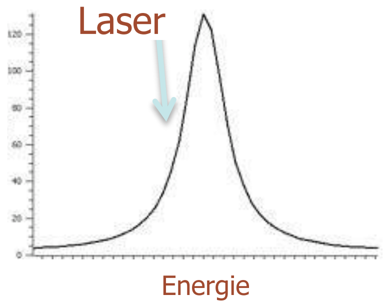
Sideband picture of optomechanical cooling



Kippenberg, Vahala, Science 321, 1172 (2008)
Favero, Karrai, Nature Photonics 3, 201 (2009)
Marquardt, Girvin, Physics 2, 40 (2009)

- Doppler cooling of an atom motion





T. W. Hänsch and A. L. Schawlow, 1975

C.Cohen-Tannoudji, W. Phillips et S. Chu

Karrai, Favero, Metzger PRL 100, 240801 *(2008)*

Optomechanics with an AFM lever mirror

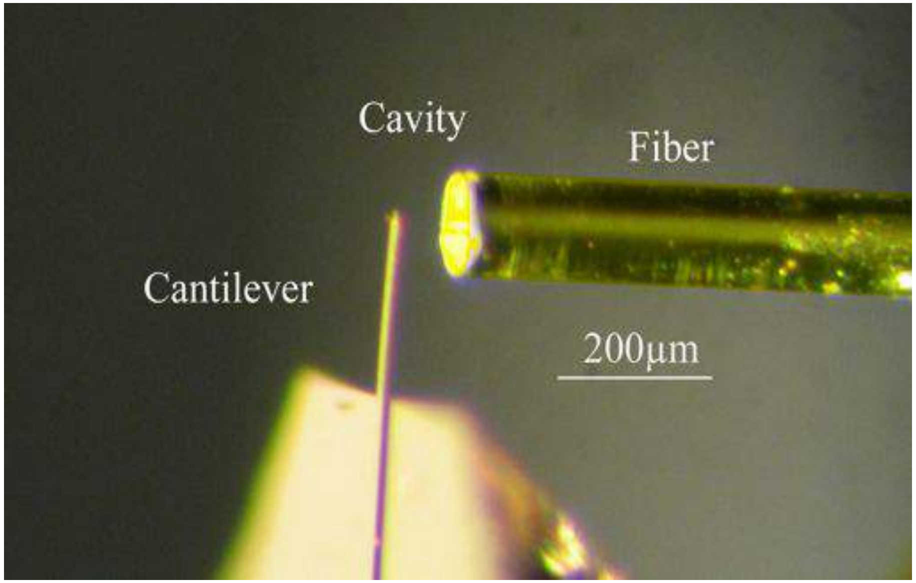
Cavity cooling of a microlever

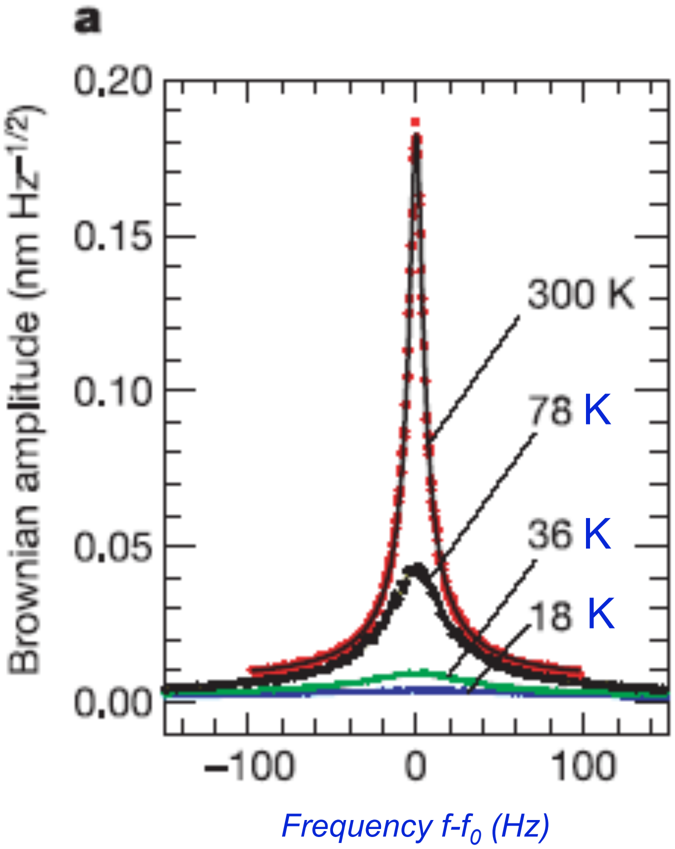
Constanze Höhberger Metzger & Khaled Karrai

Center for NanoScience and Sektion Physik, Ludwig-Maximilians-Universität,
Geschwister-Scholl-Platz 1, 80539 München, Germany

December 2004

18 K !





Frequency =10 KHz

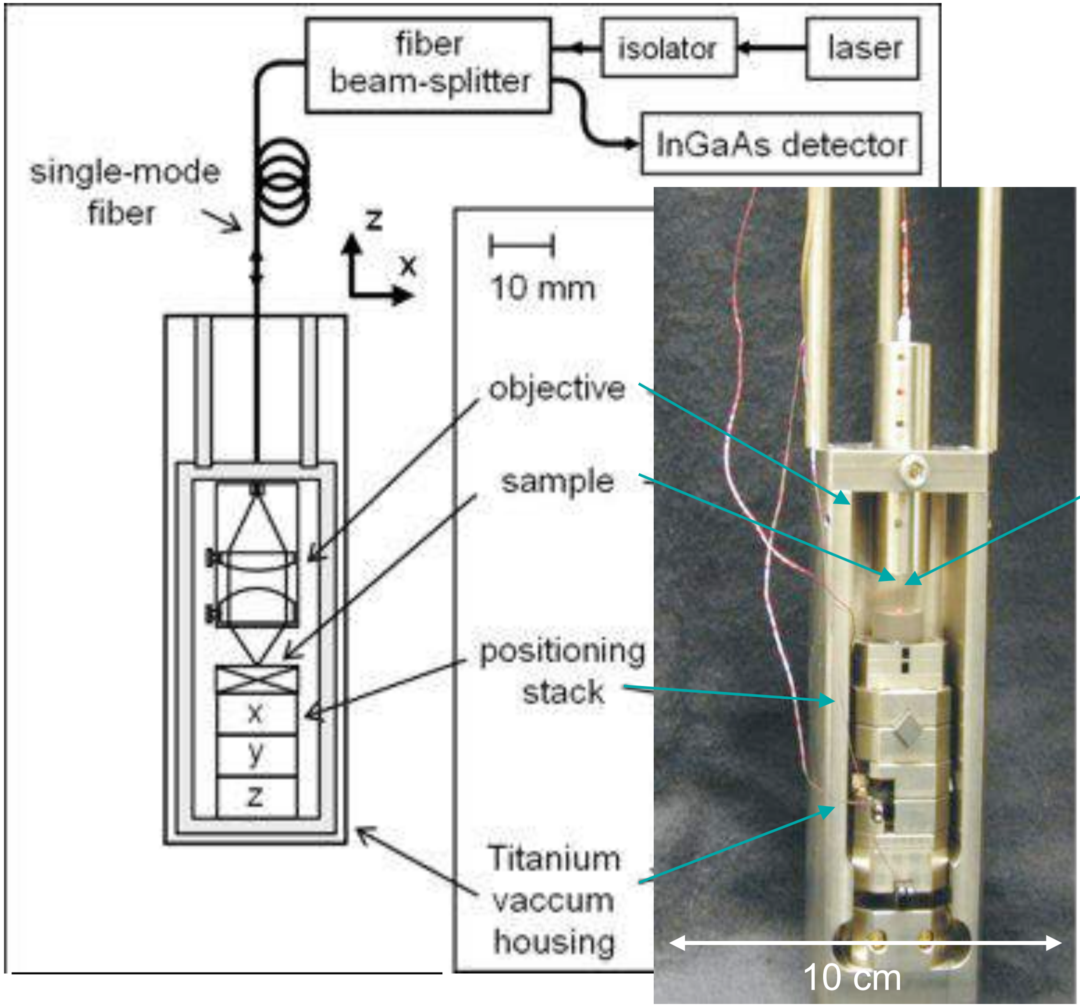
See also external feed-back cooling: PRL 83, 3174 (1999)

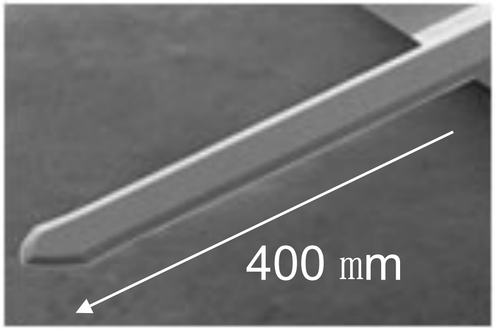
Limits of the system

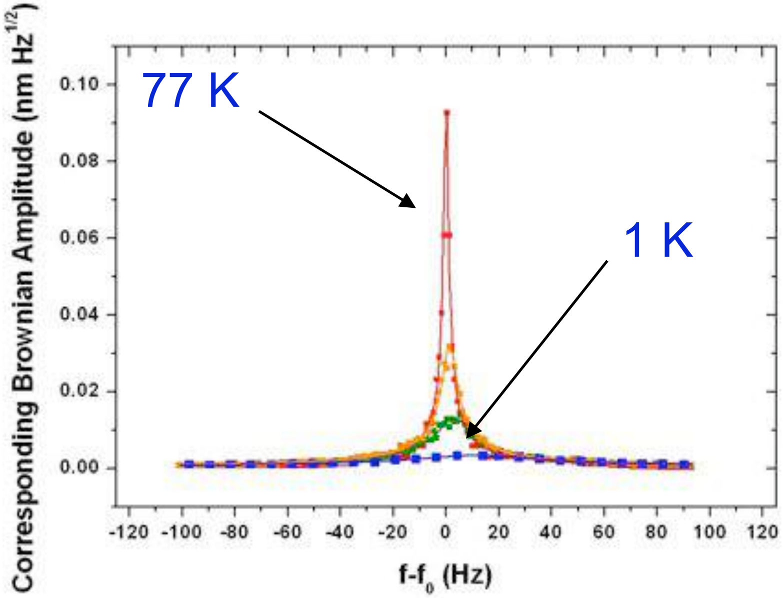
Mass = 10^{-7} g, Finesse = 10

Q_m = 3000,

g_{om}≈100MHz/nm

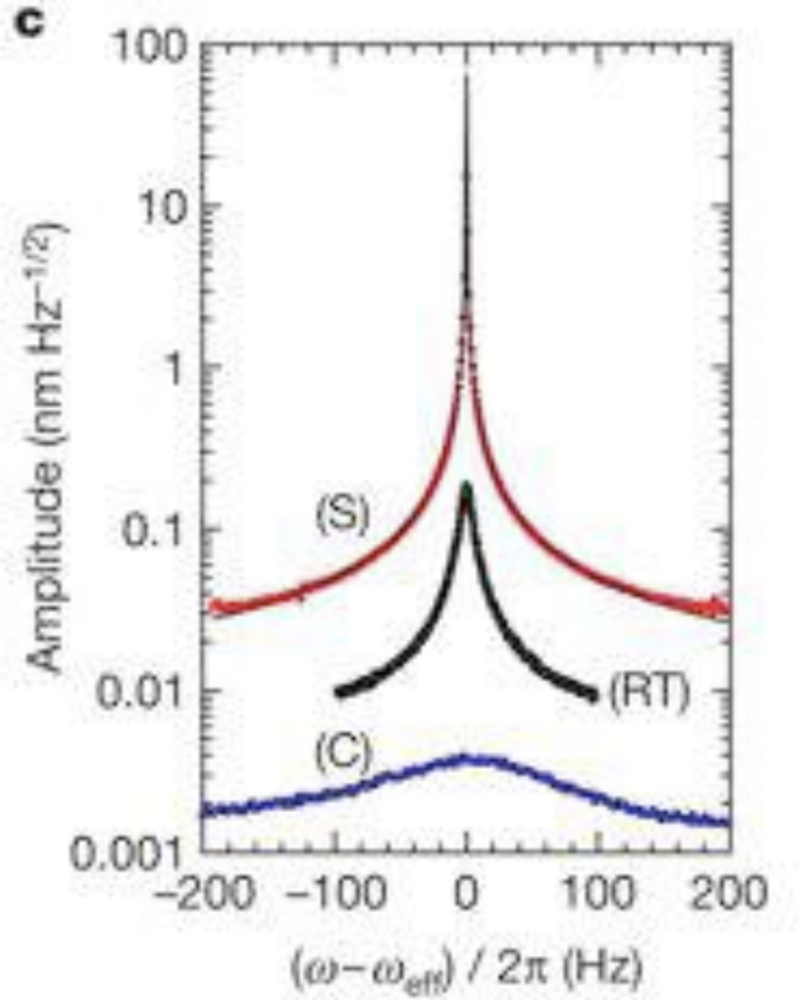


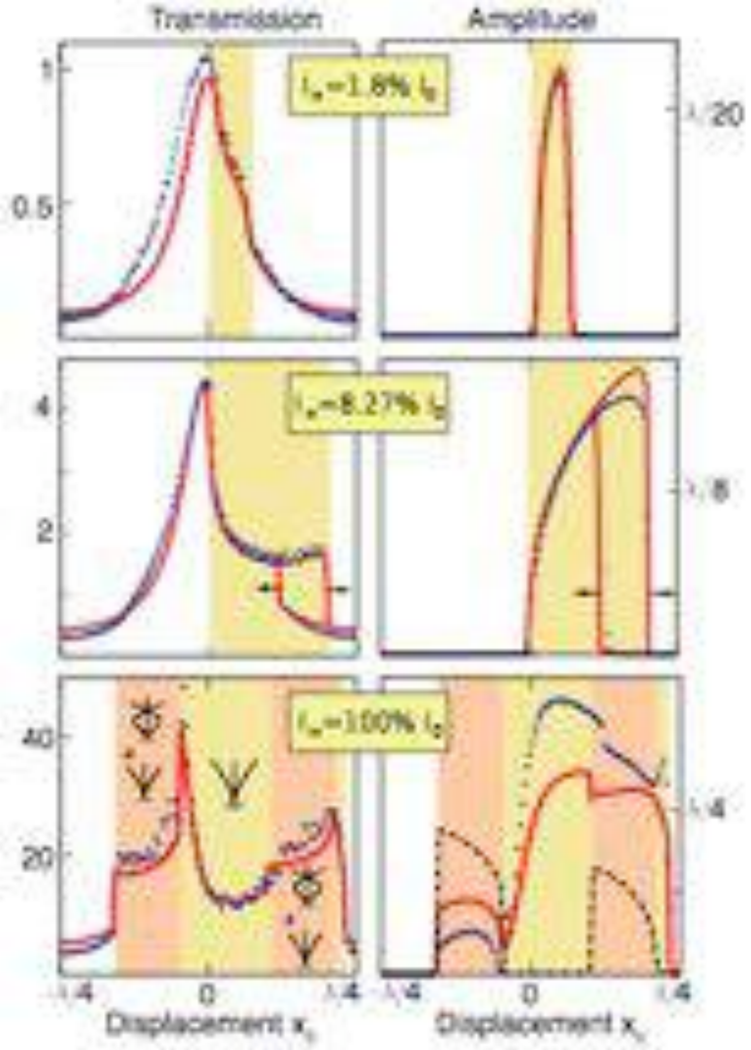




Metzger, Favero, Ortlieb, Karrai Phys. Rev. B 78, 035309 (2008)

Linear and non-linear optomechanical self-oscillation





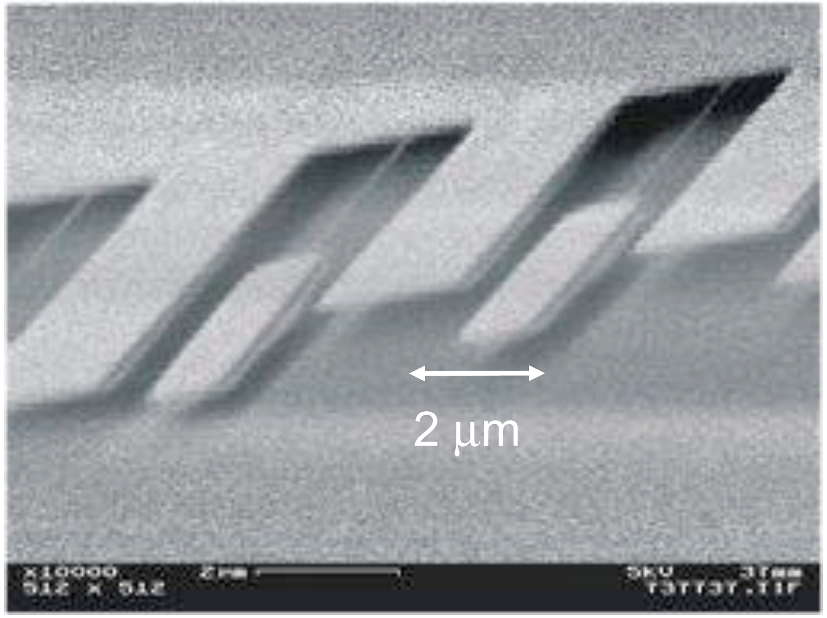
F.Marquardt et al. Phys. Rev. Lett. 96, 103901 (2006)

Ludwig, Neuenhahn, Metzger, Favero, Karrai, Marquardt. PRL 101, 133903 (2008)

Scale down dimensions to boost optomechanical effects

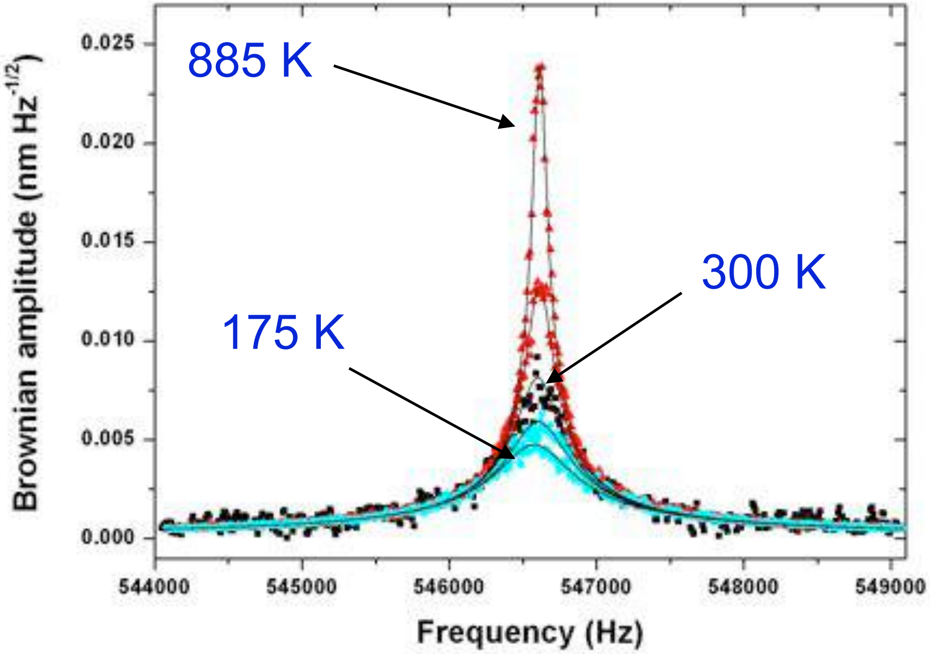
Dwarf micro-mirror at the diffraction limit

$m=10^{-11}$ g !



$Q_m=1000$

g_{om}≈100MHz/nm

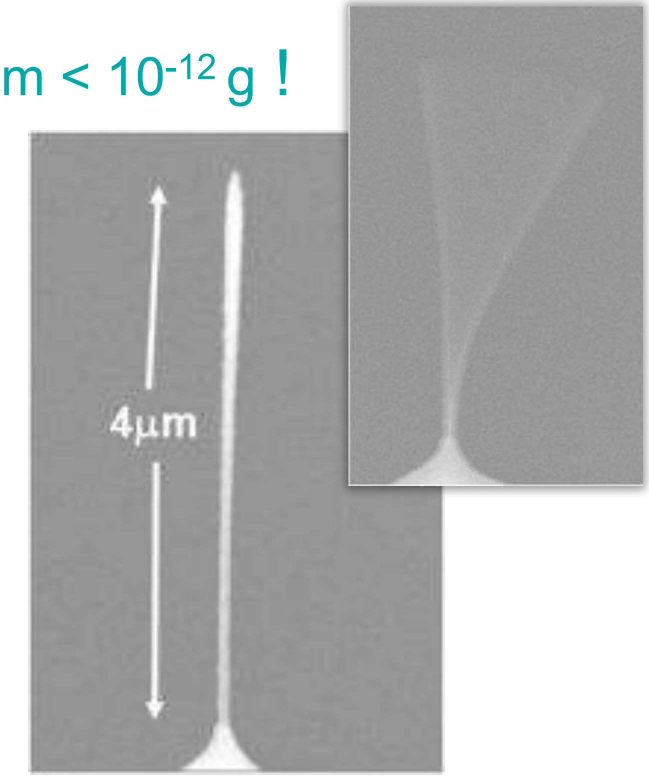


Finesse=10

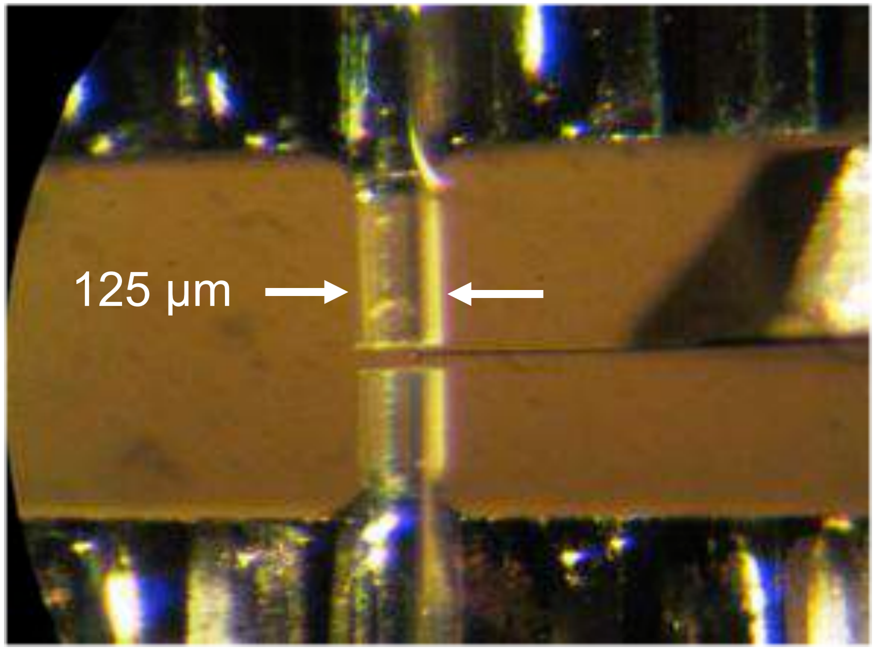
Optical cooling of a micro-mirror with wavelength size
Applied Physics Letters, 90, 104101 (january2007)

Nanomechanical system in a fibered Fabry-Pérot cavity

m < 10^{-12} g !



Finesse=5000



Q_m=1000

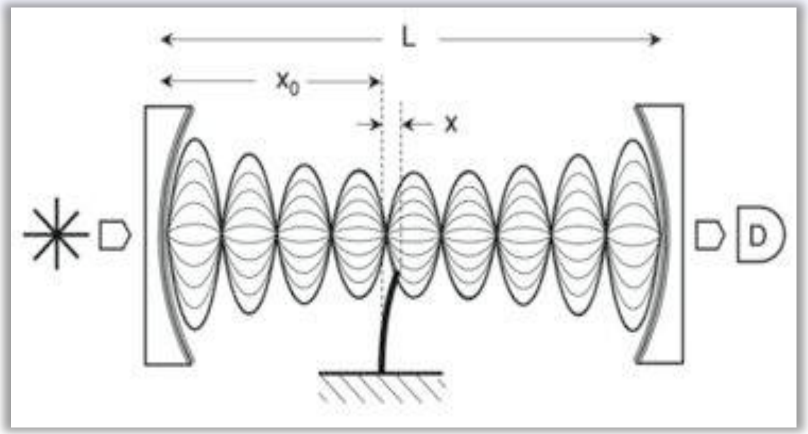
Collaboration: Sebastian Stapfner, Eva Weig group, Jakob Reichel

I. Favero, and K. Karrai. New J. Phys. 10, 095006 (2008)
I. Favero, S. Stapfner et al. Optics Express, Vol. 17, Issue 15, 12813 (2009)

Fluctuating nanomechanical system in an optical cavity

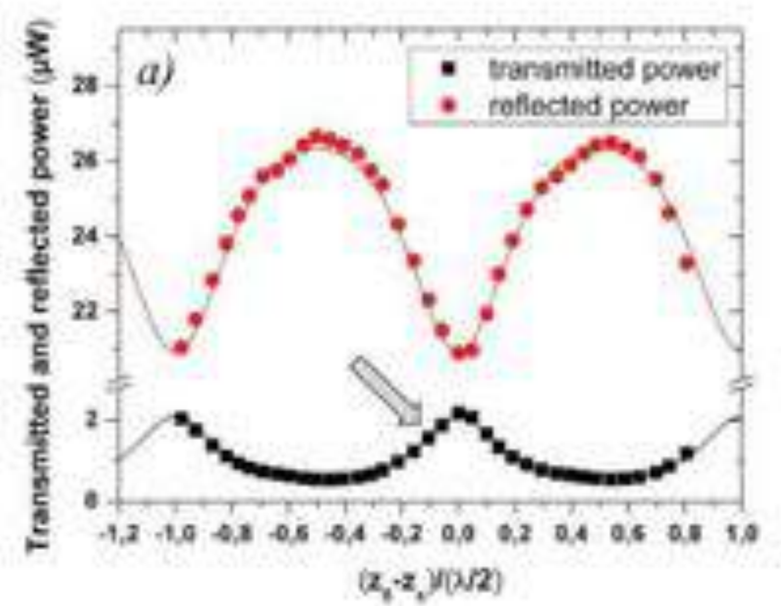
$m < 10^{-12}$ g !

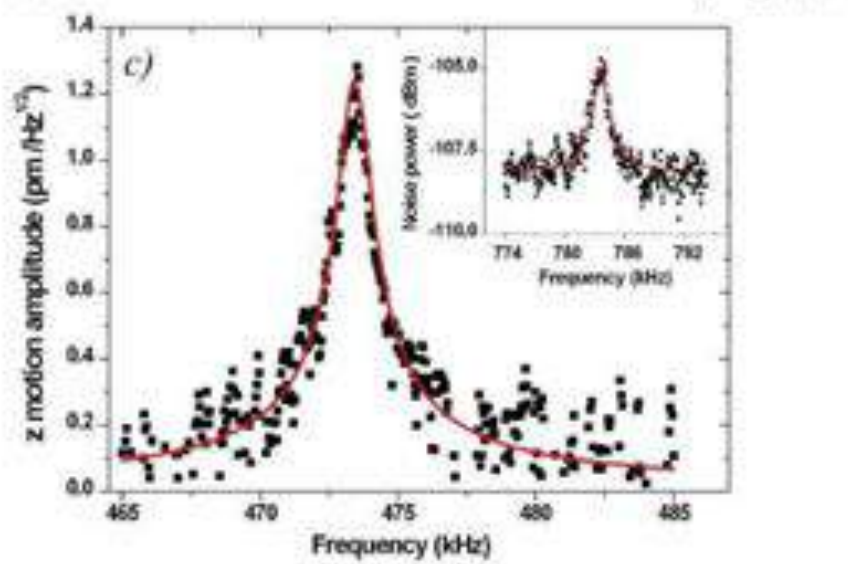
Q_m=1000



Finesse=5000

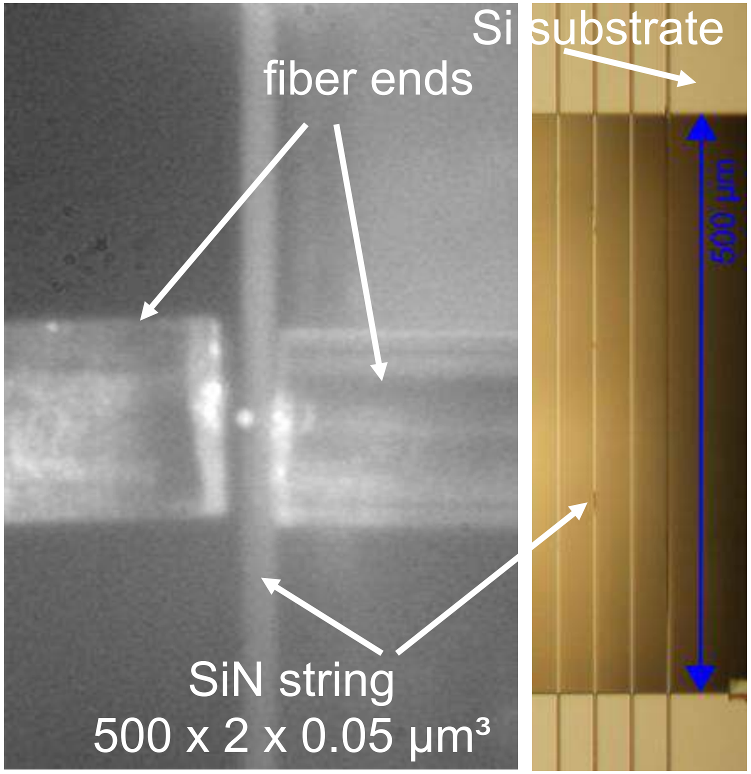
g_{om}≈50MHz/nm



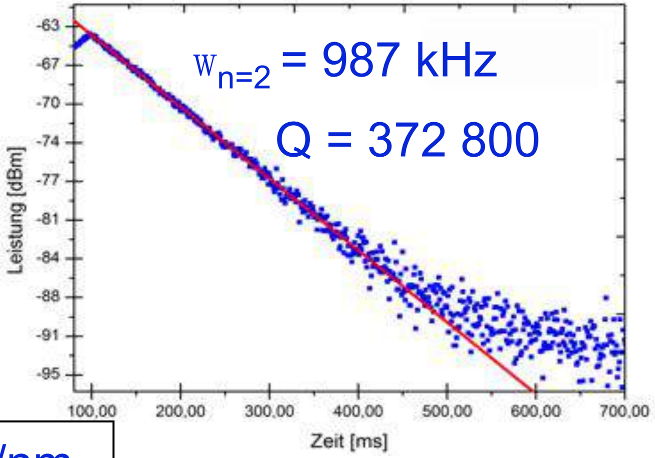


I. Favero, S. Stapfner et al. Fluctuating nanomechanical system in a high finesse optical microcavity.
Optics Express, 17, 12813 (2009)

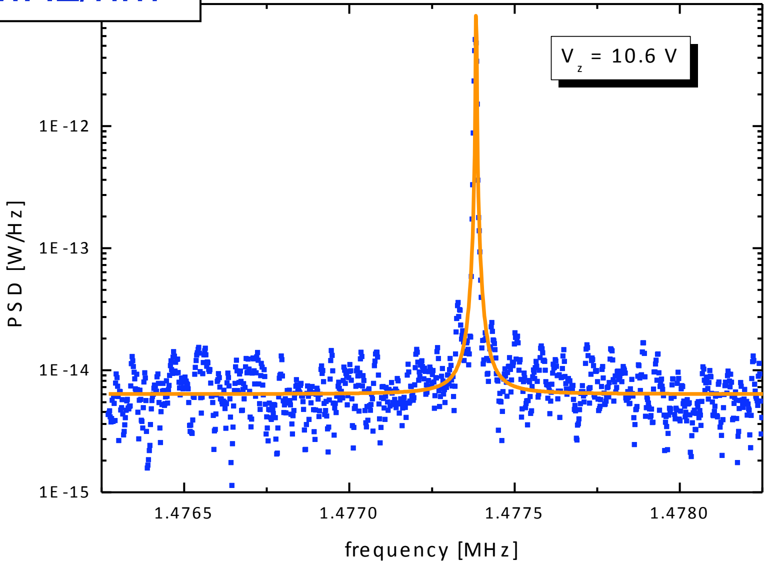
Nanomechanical SiN beam in a Fabry-Pérot cavity



Cavity finesse 40 x 10^3
Mechanical fundamental mode at 500 kHz
Q_m up to 1.2 x 10^6



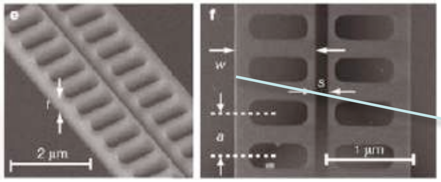
g_{om}≈100MHz/nm



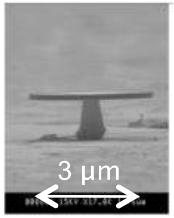
Collaboration: Eva Weig group, Sebastian Stapfner, Jakob Reichel

Optomechanical systems today N=0.5

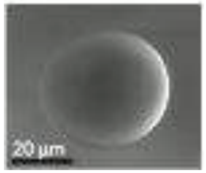
Nature Photonics 3, 201 (2009)



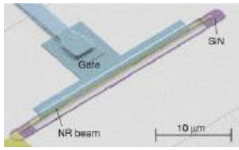
Caltech



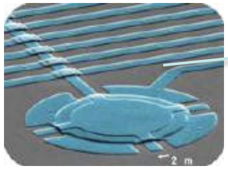
Univ Paris Diderot



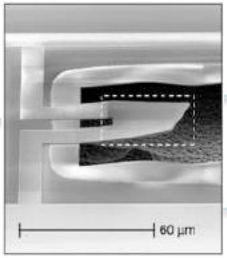
Oregon University



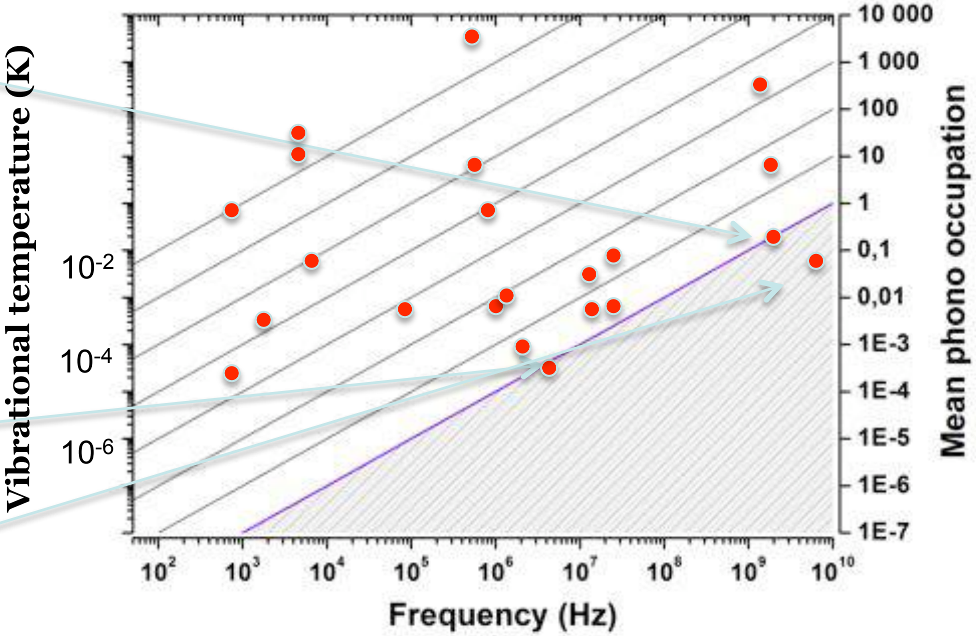
Cornell, Caltech



NIST, Boulder

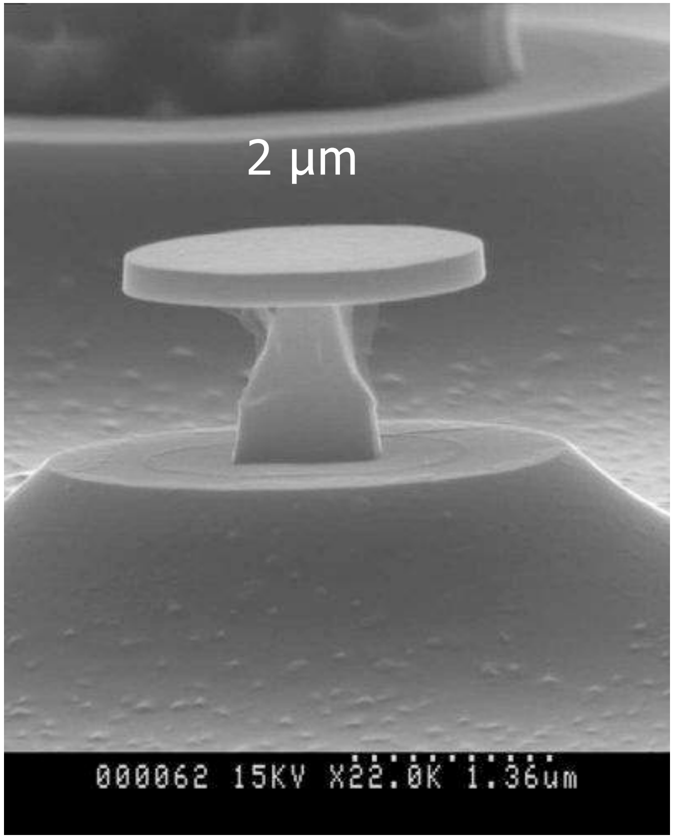


Santa Barbara



Nanoscale GaAs optomechanics

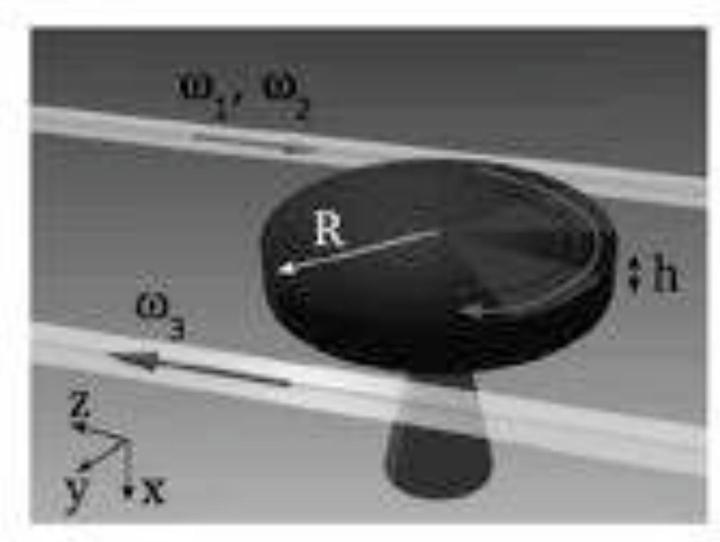
Nano-Optomechanics with GaAs disks



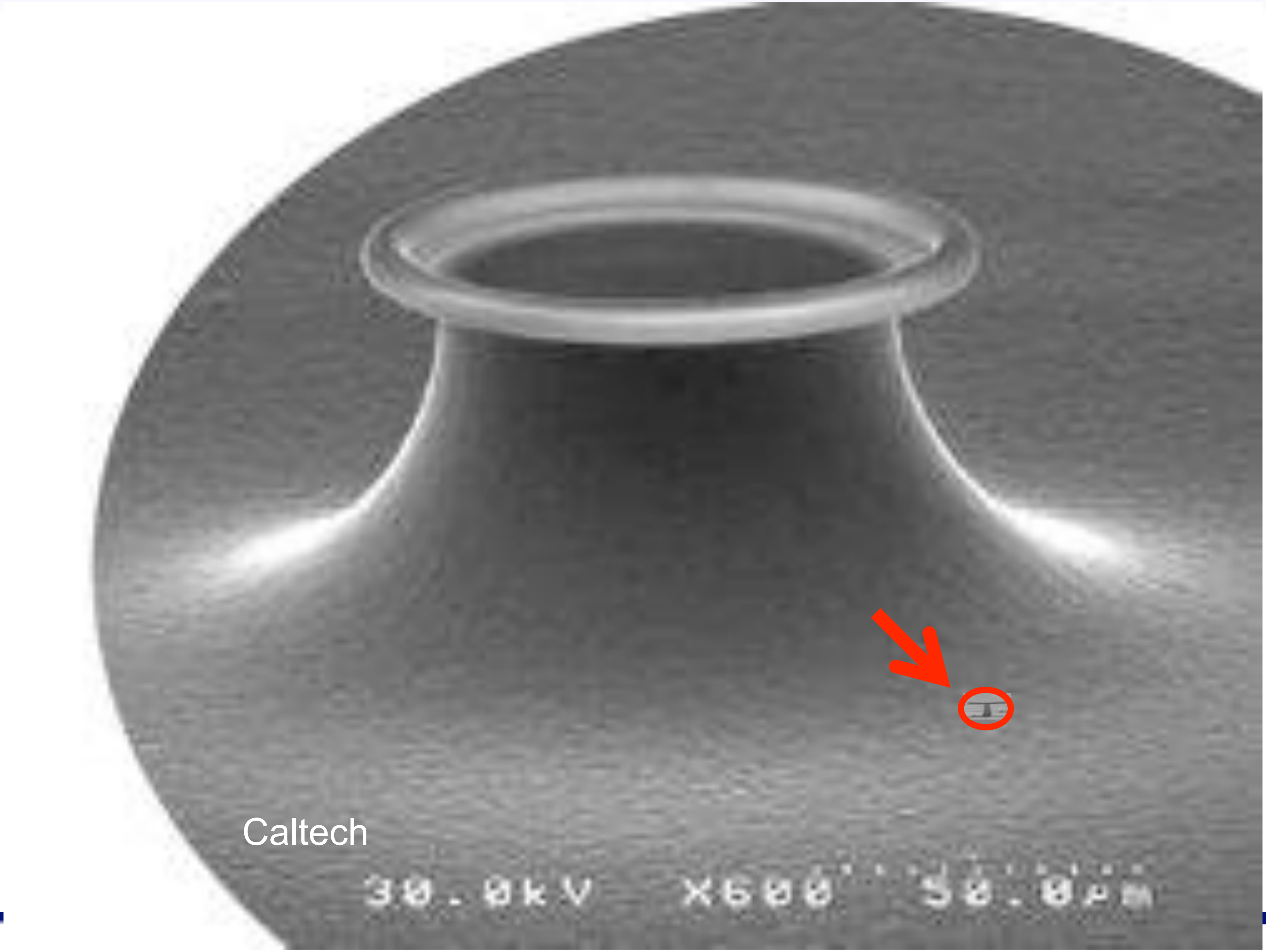
E. Peter et al. Phys. Rev. Lett. 95, 067401 (2005)

- Small mode volume (sub-λ^3)
- High optical Q (high finesse)

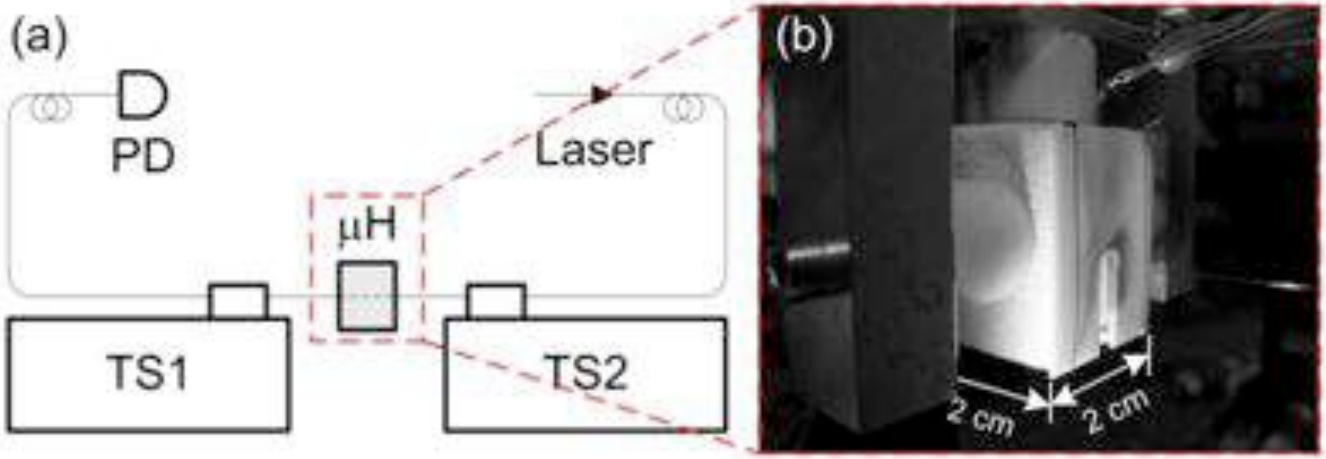
- High frequency
- Small mass (pg)
- Low mechanical dissipation

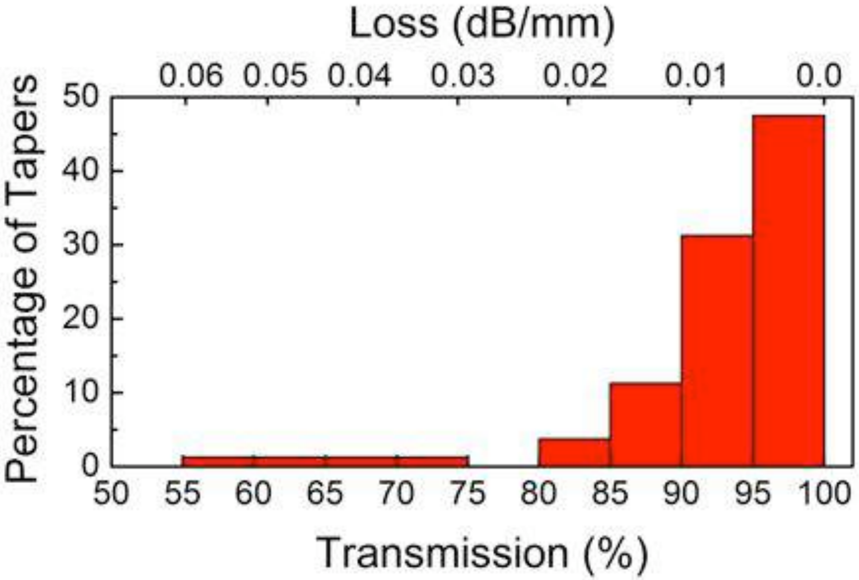


Comparing the scales: size matters !



Ultra low-loss sub-micron optical fiber taper



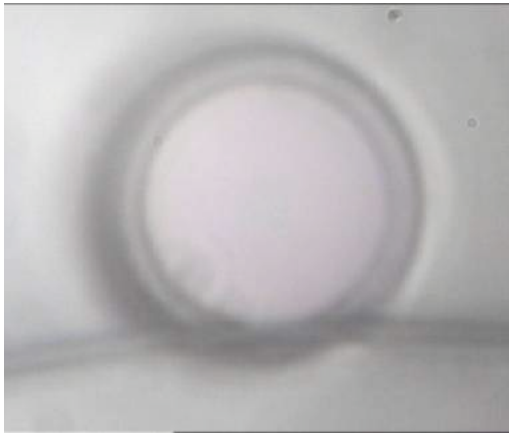


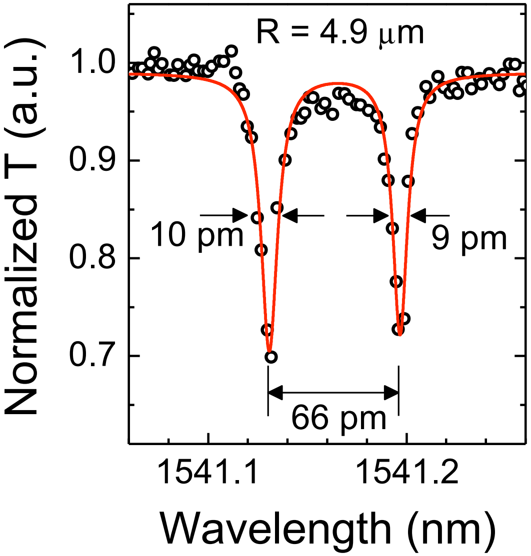
Ave. T = 94 %

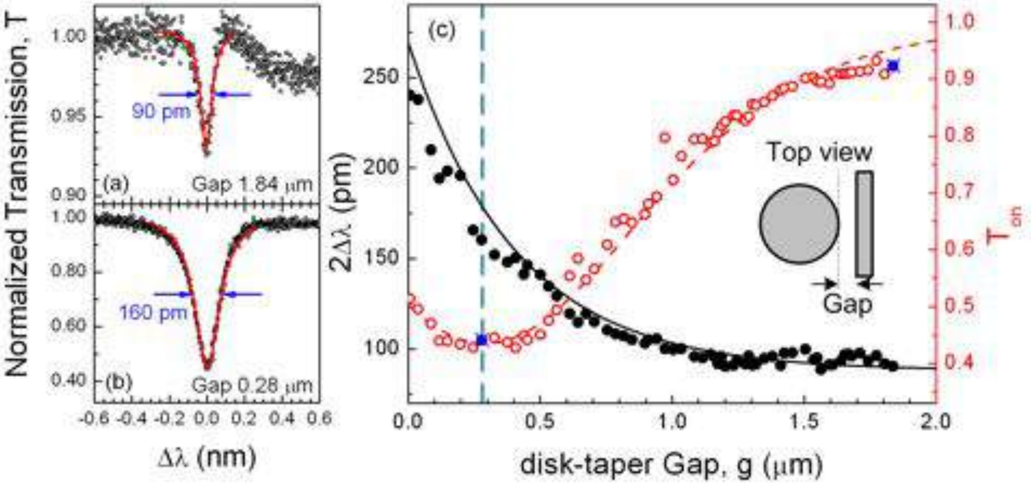
Best T > 99%

L. Ding, C. Belacel, et al.
Applied Optics, 49,
2441-2445 (2010)

Whispering gallery modes with optical Q above 10^5

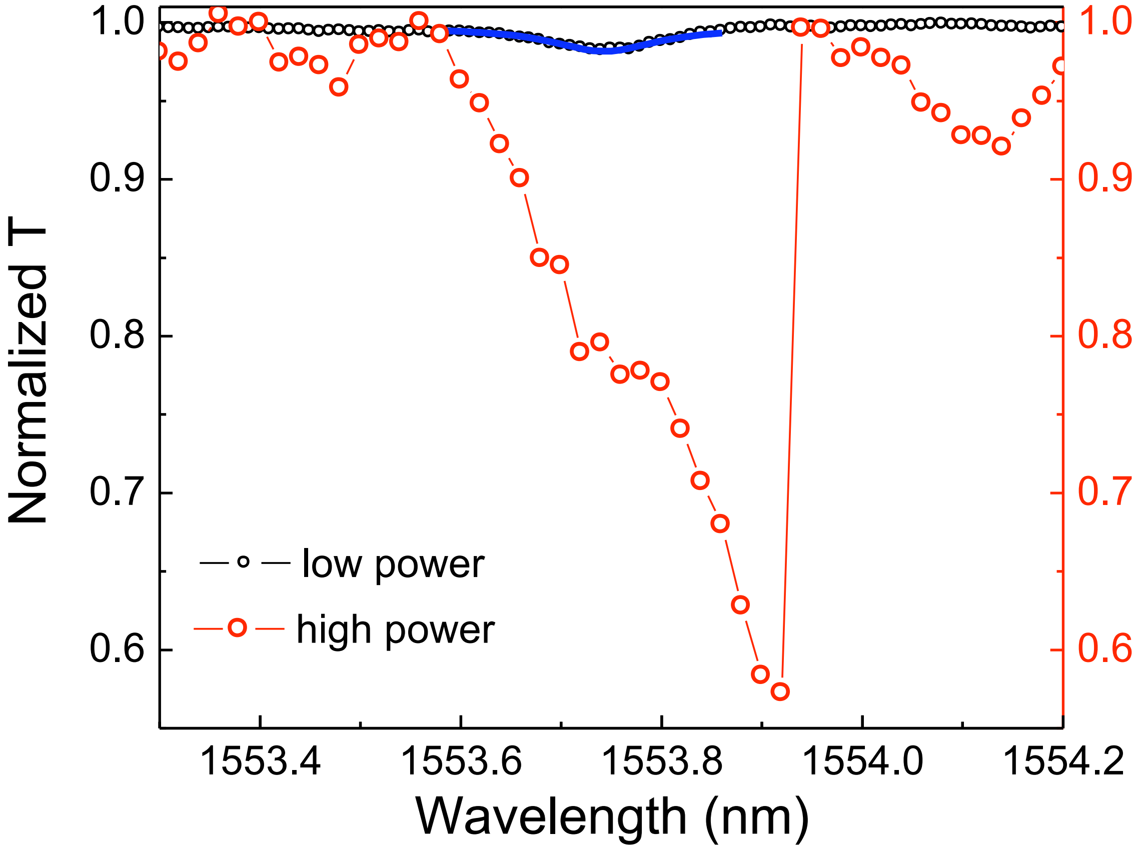






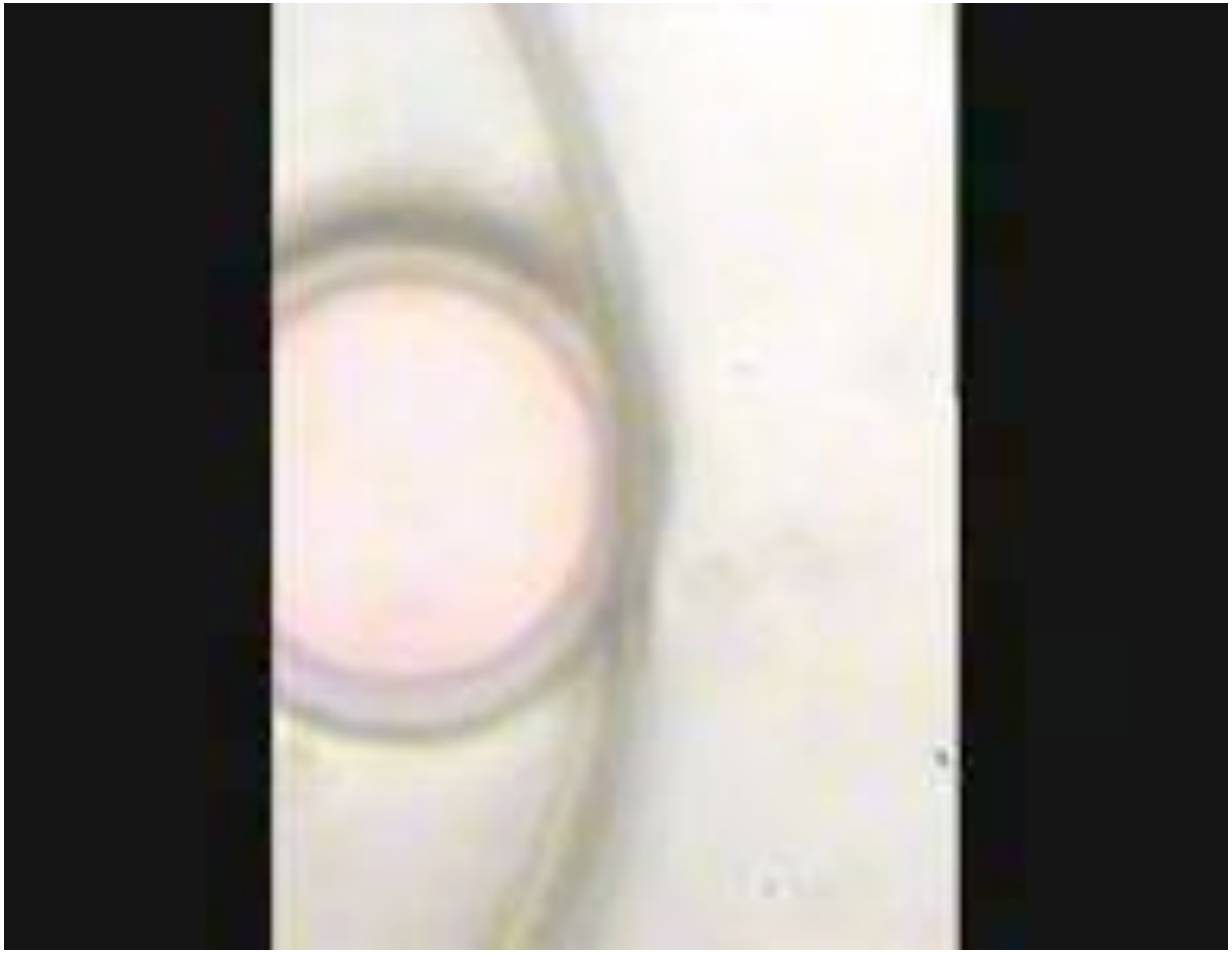
L. Ding et al. Proc. SPIE 7712, 771211 (2010).

Optically actuated micron-scale fiber motion

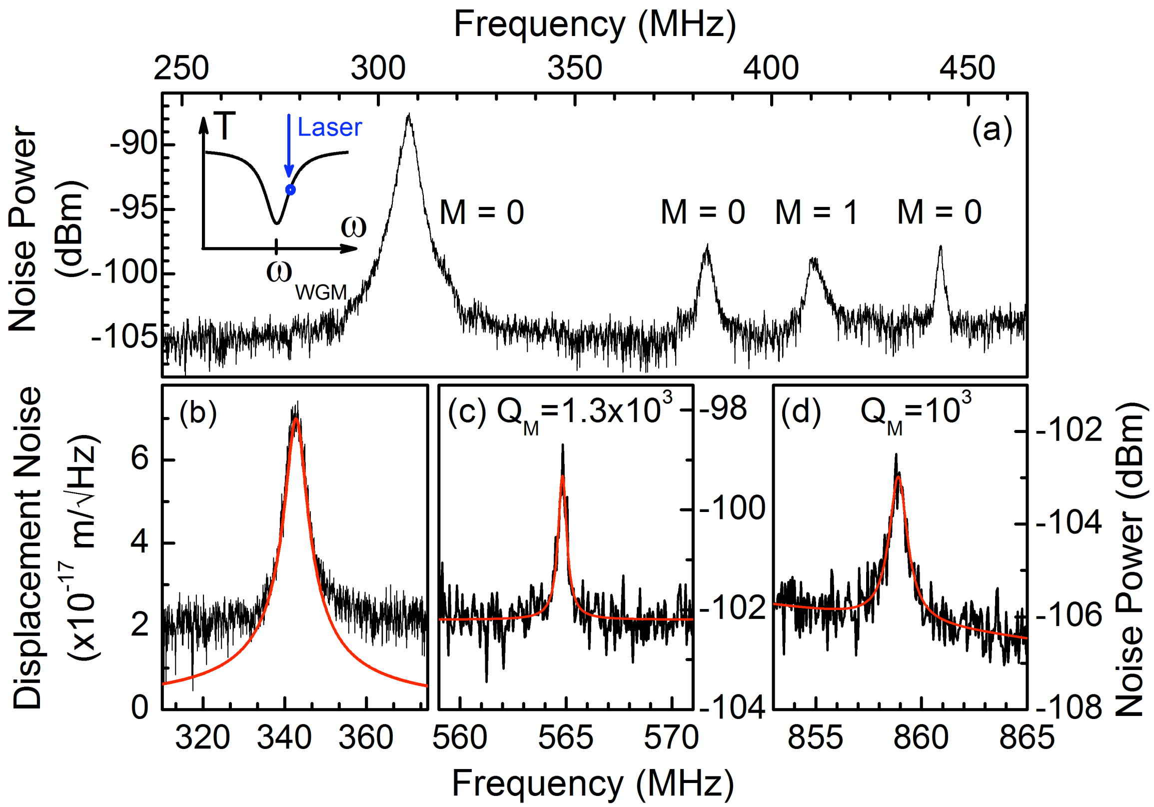


L. Ding et al. Proc. SPIE 7712, 771211 (2010).

Optically actuated micron-scale displacement



Ultra-sensitive optical measurement of disk motion



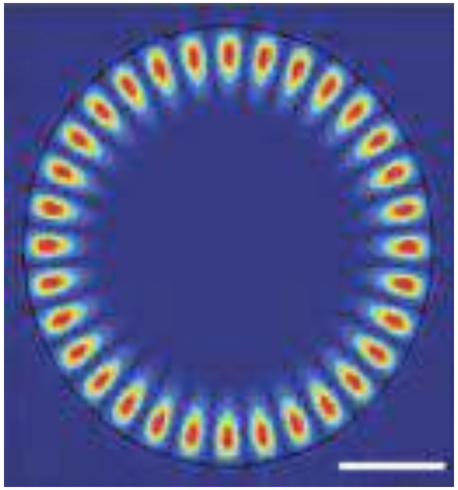
- Frequency of mechanical modes up to GHz
- In air, mechanical Q factor 10^2 to 10^3 with Qf up to 10^{12}
- Sensitivity 10^{-17} m/√Hz (approaching the quantum limit)
- Giant optomechanical coupling 100 - 600 GHz/nm

L. Ding, C. Baker et al. "High frequency GaAs nano-optomechanical disk resonator" Phys Rev Lett 105, 263903 (2010)

Symmetries in whispering gallery optomechanics

Optical modes

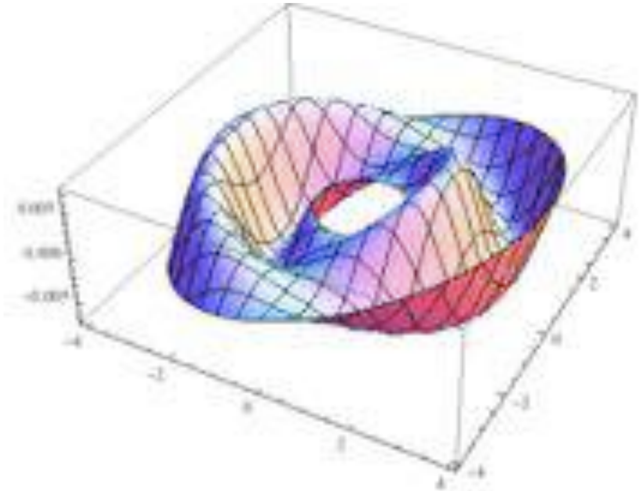
$$F=\Psi(\rho)\Theta(\theta)G(z) \text{ with } \Theta(\theta)=e^{im\theta}$$



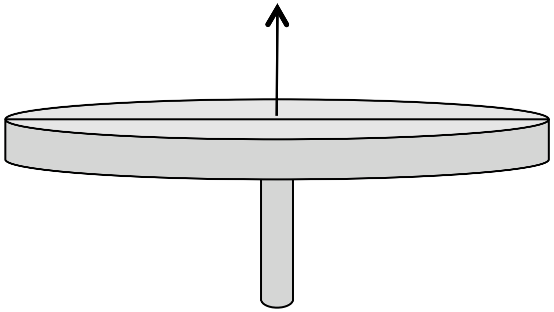
m optical azimuthal number

Mechanical modes

$$q(\rho,\theta,z)=\cos(M\theta)\times f_p(\rho,z)$$



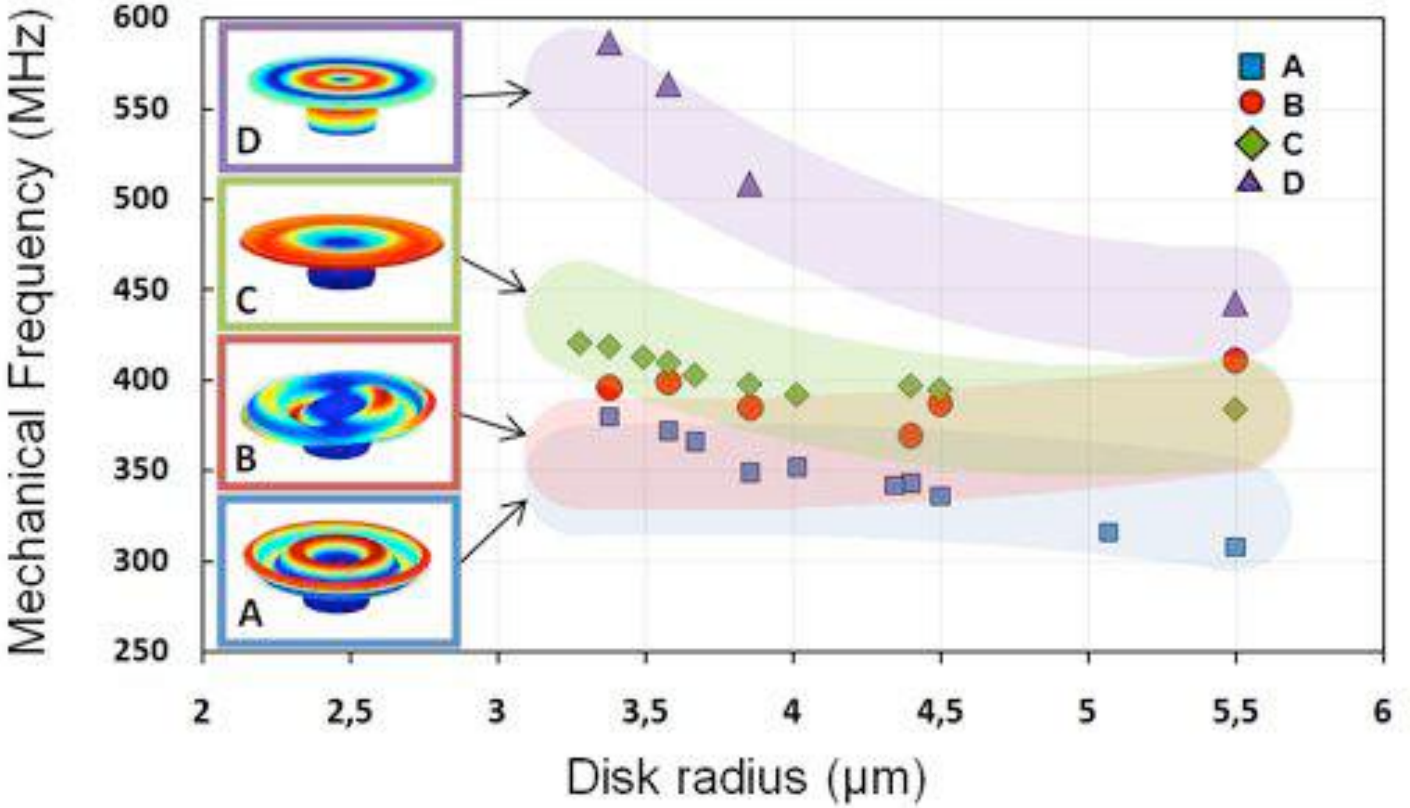
M mechanical azimuthal number



$$g_{om}=\frac{\omega_0}{4}\times\int(\vec{q}.\vec{n})\left[\Delta\varepsilon\left|\vec{e}_{\parallel}\right|^2-\Delta(\varepsilon^{-1})\left|\vec{d}_{\perp}\right|^2\right]dA$$

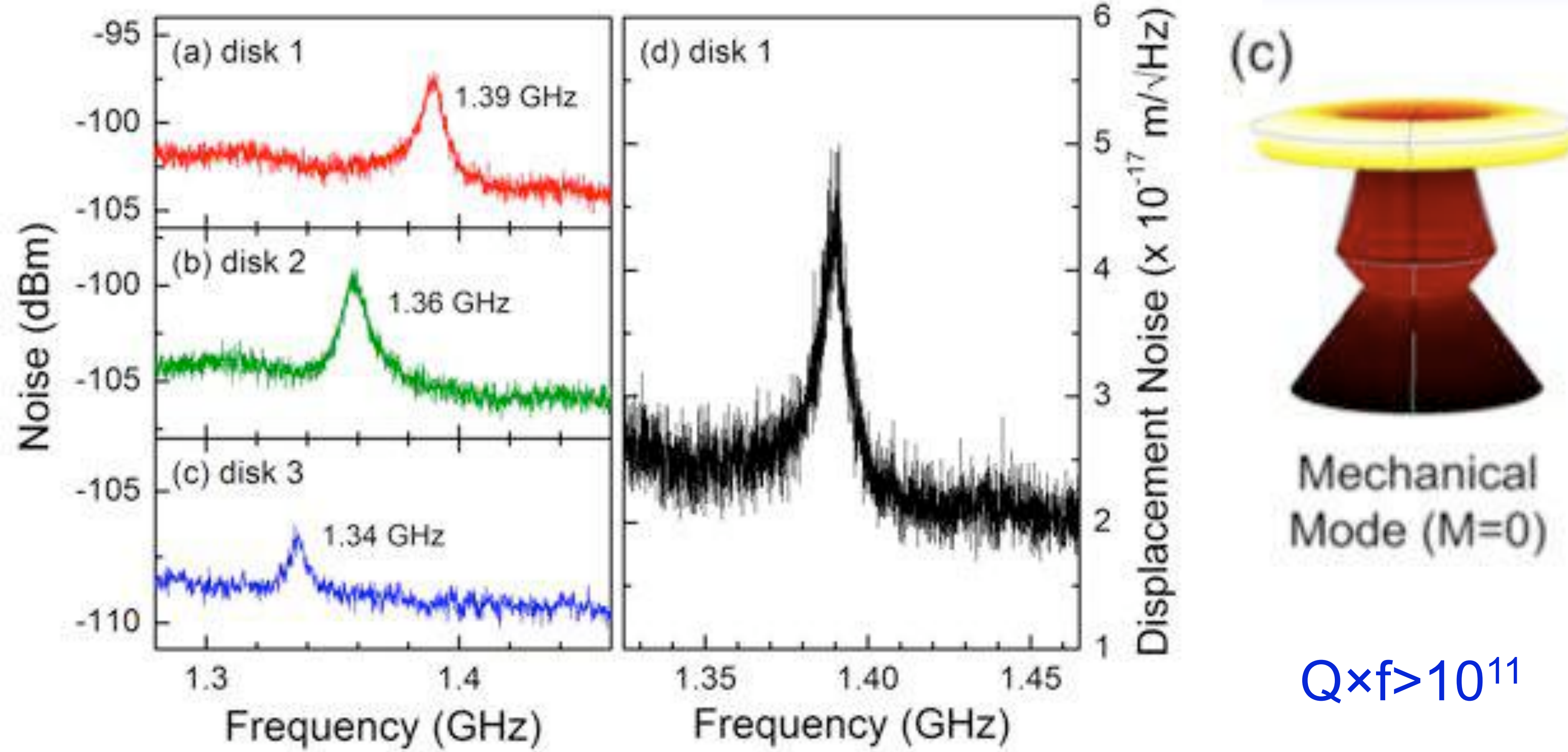
S. G. Johnson et al., Phys. Rev. E 65, 066611 (2002)

Dispersion of disk mechanical modes



L. Ding, C. Baker et al. "High frequency GaAs nano-optomechanical disk resonator"
Phys Rev Lett 105, 263903 (2010)

Disk Mechanical modes above the GHz !



$Q \times f > 10^{11}$

Radius= 1 μ m, Thickness=200nm, $g_{om} \approx$ 600GHz/nm, $g_o \approx$ 1 MHz

$g_o = g_{om} \Delta x_{zpf}$ vacuum coupling

L. Ding, C. Baker, et al.
« Wavelength-sized GaAs optomechanical resonators with GHz frequency »
Applied Physics Letters 98, 113108 (2011).

M. Eichenfield et al. Nature 462, 78 (2009).
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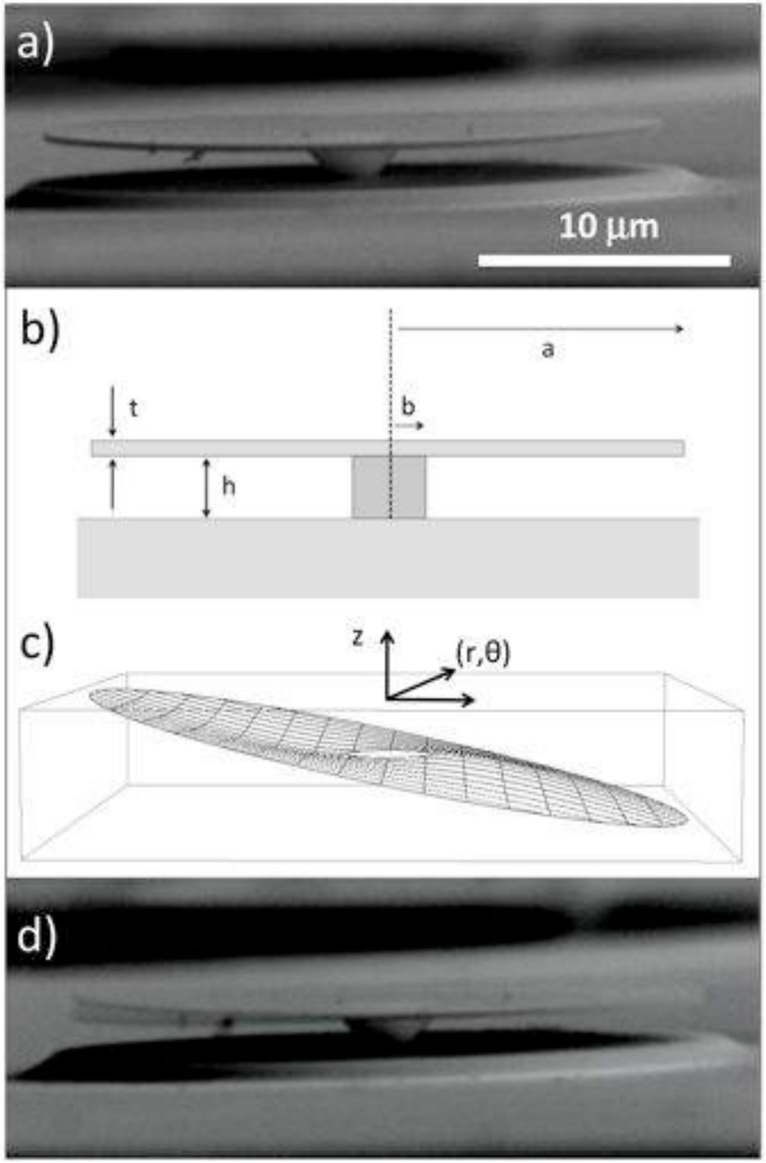
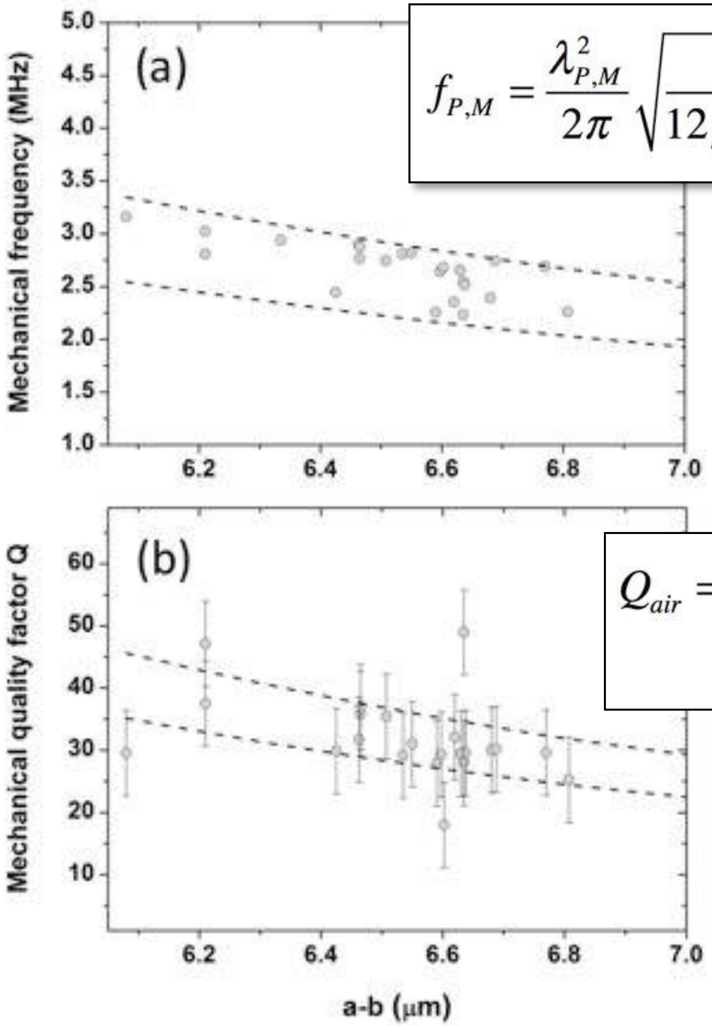
Mechanical dissipation in GaAs disk resonators

Mechanical dissipation of GaAs disk resonators in air



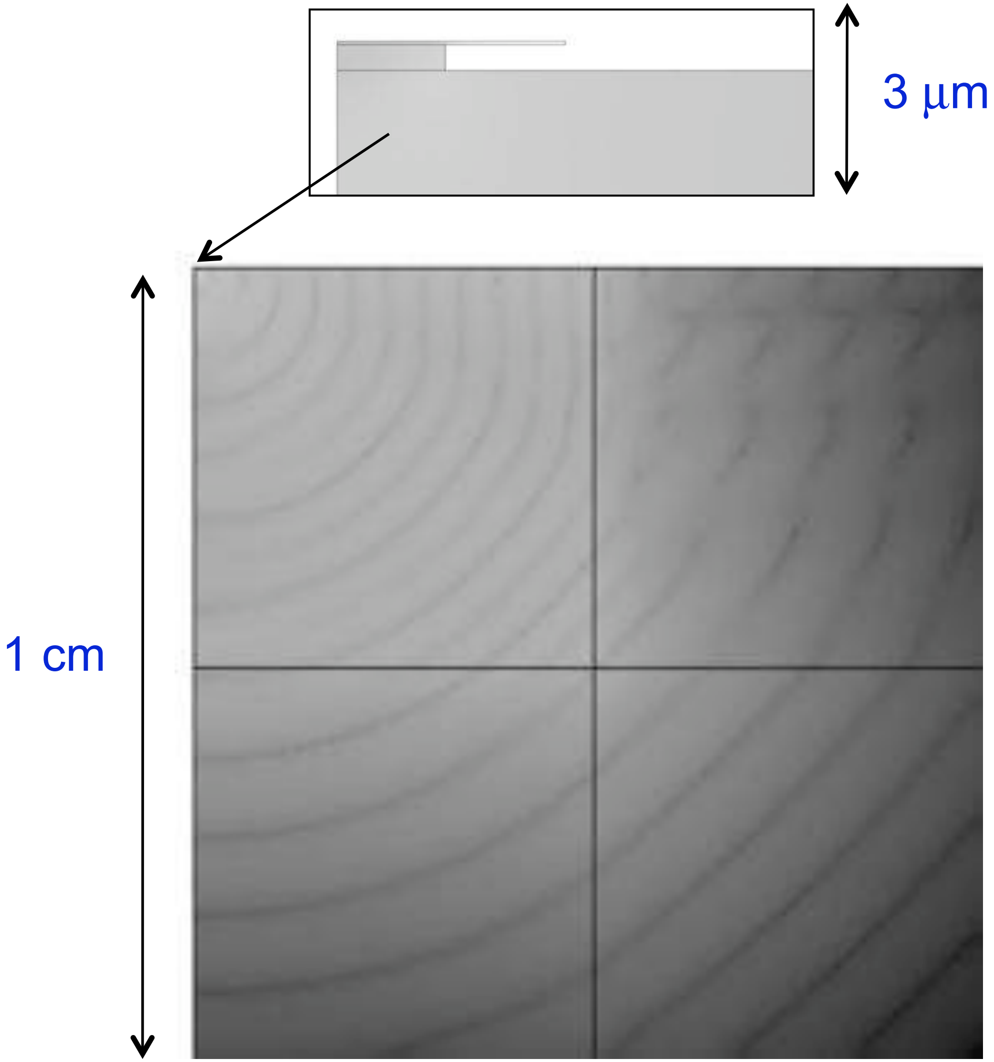


$$f_{P,M} = \frac{\lambda_{P,M}^2}{2\pi}\sqrt{\frac{E}{12\rho(1-\nu^2)}}\,\frac{t}{a^2}$$

$$Q_{air} = \frac{\rho t \omega_m}{6\eta}\,\frac{1}{\frac{1}{R}+\frac{1}{\delta}}$$

D. Parrain, C. Baker, T. Verdier et al. To appear in APL (2012)

Clamping losses of GaAs disk resonators



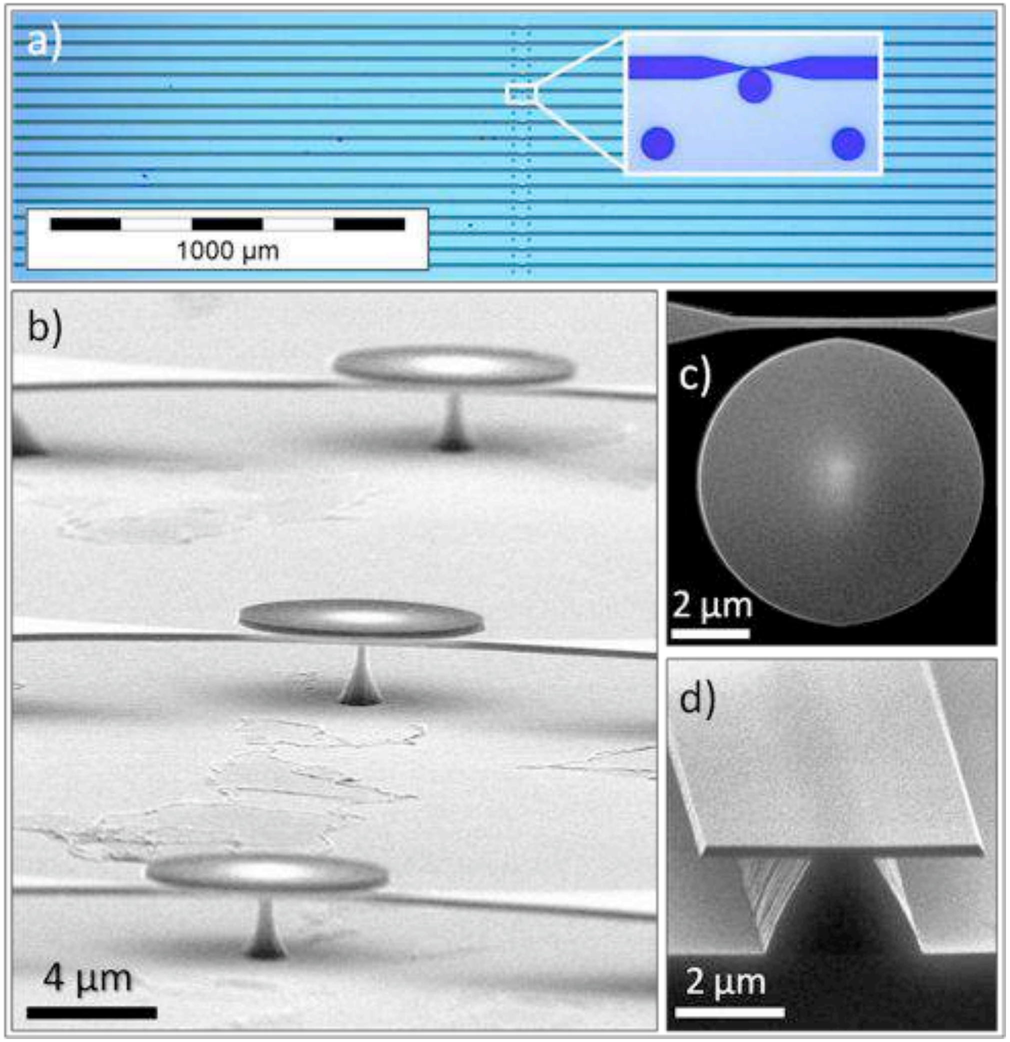
For a GHz disk mode,
Q clamping of the order 10^4 to 10^5

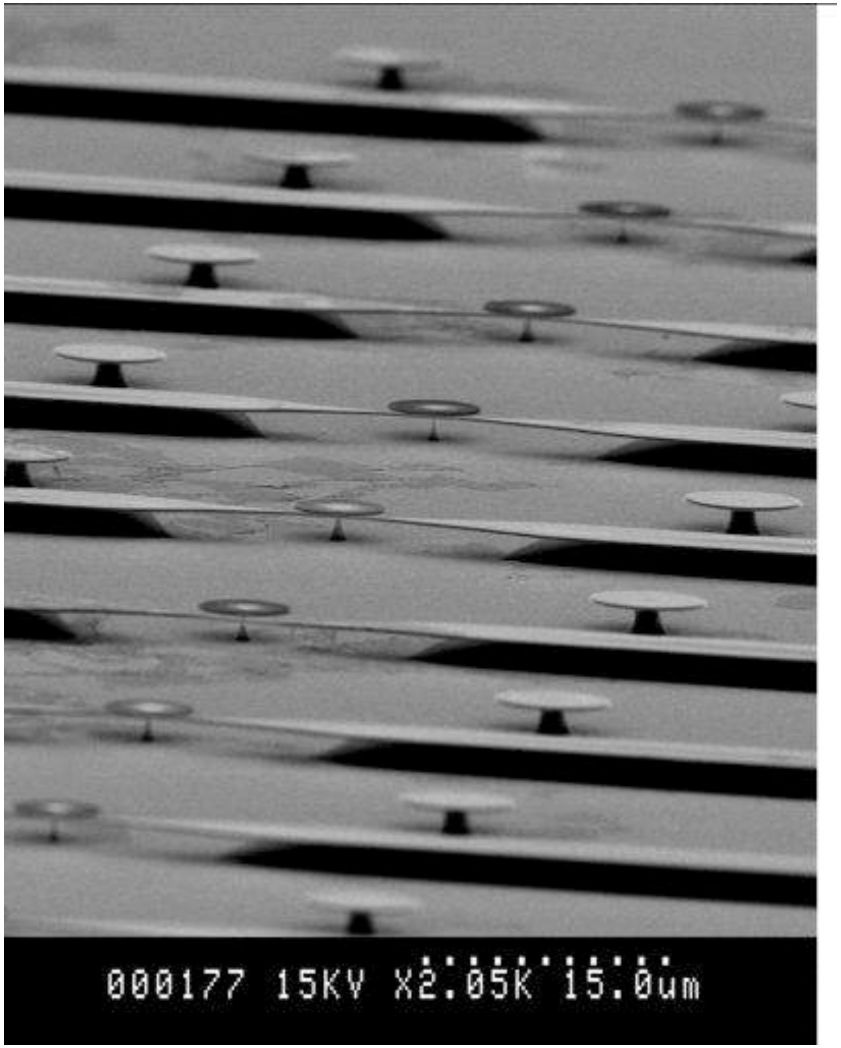
Q×f between 10^{13} and 10^{14}

Best Q×f in the litterature:
a few 10^{15} at 2 K, Smagin, A.G. (1974)

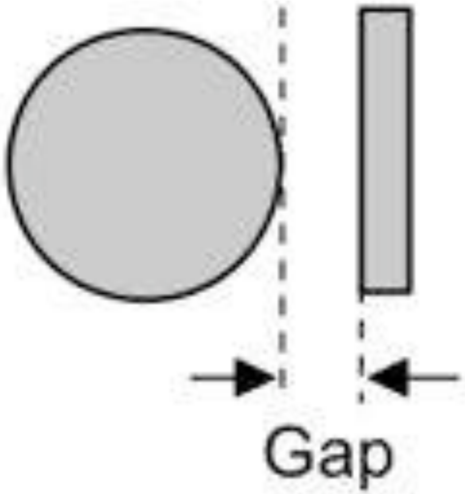
Integrated GaAs nano-optomechanics

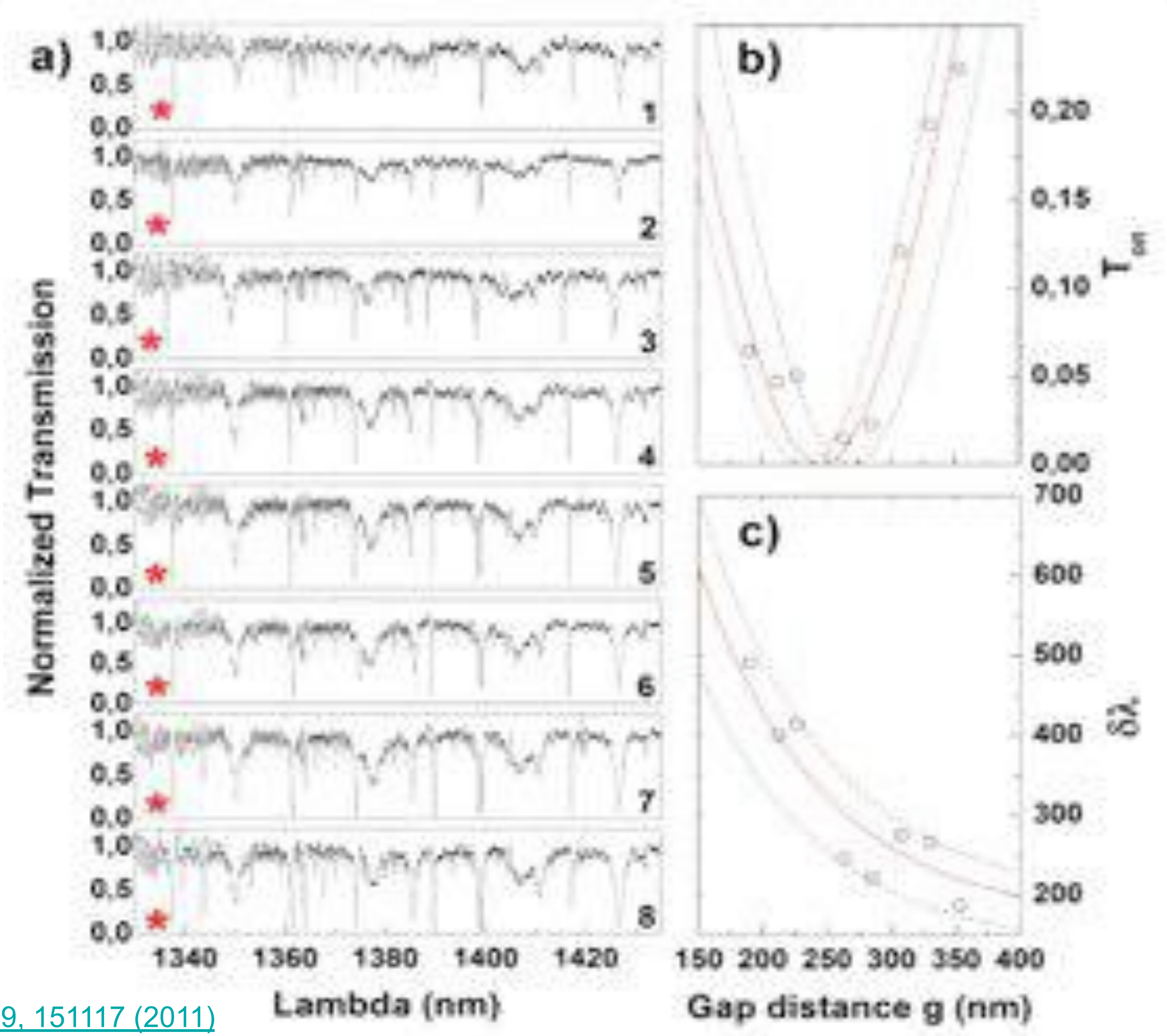
Integrated GaAs optomechanical resonators





On-chip critical evanescent coupling

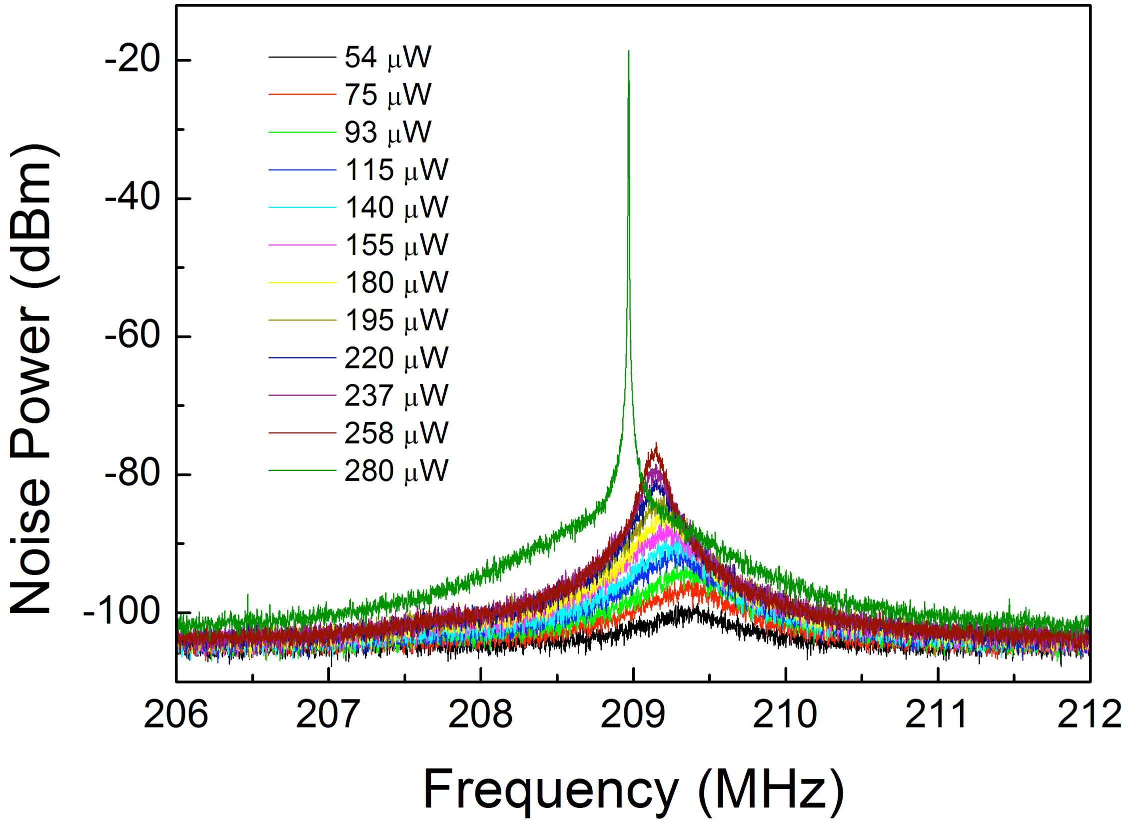




C. Baker et al. Applied Physics Letters 99, 151117 (2011)

Dynamical back-action in GaAs disk resonators

Optomechanical self-oscillation of a GaAs disk



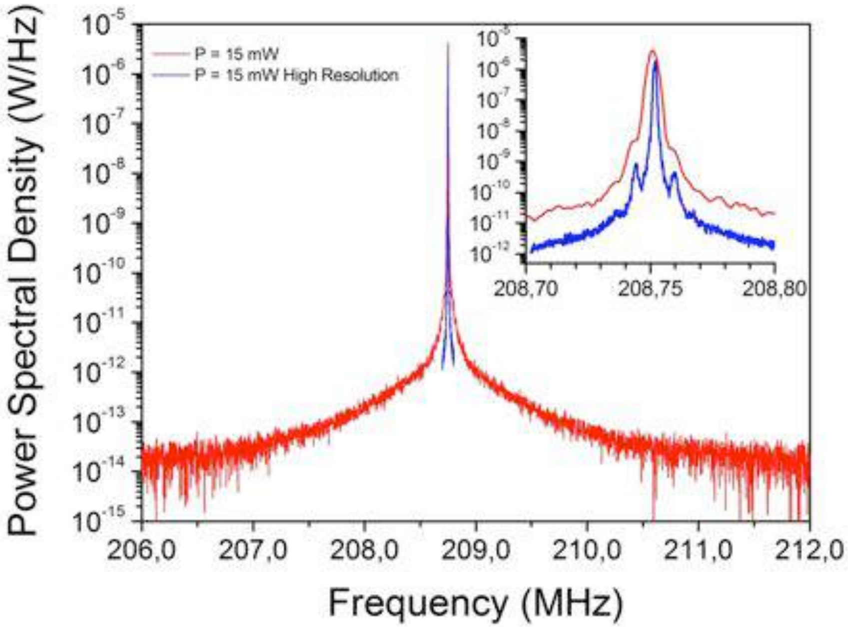
C. Metzger and K. Karrai, *Cavity cooling of a microlever,* Nature 432, 1002 (2004).

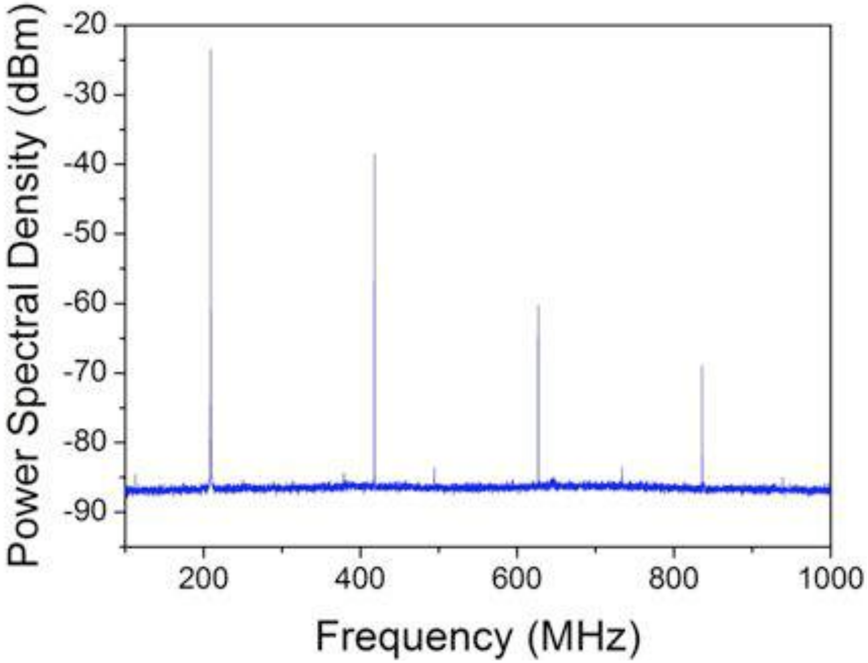
C. Höhberger Metzger and K. *Karrai* 2004 4th *IEEE* Conf. on *Nanotechnology,* pp 419–21 (2004).

Carmon, T., Rokhsari, H., Yang, L., Kippenberg, T.J. and Vahala, K.J. Physical Review Letters 94, 223902 (2005).

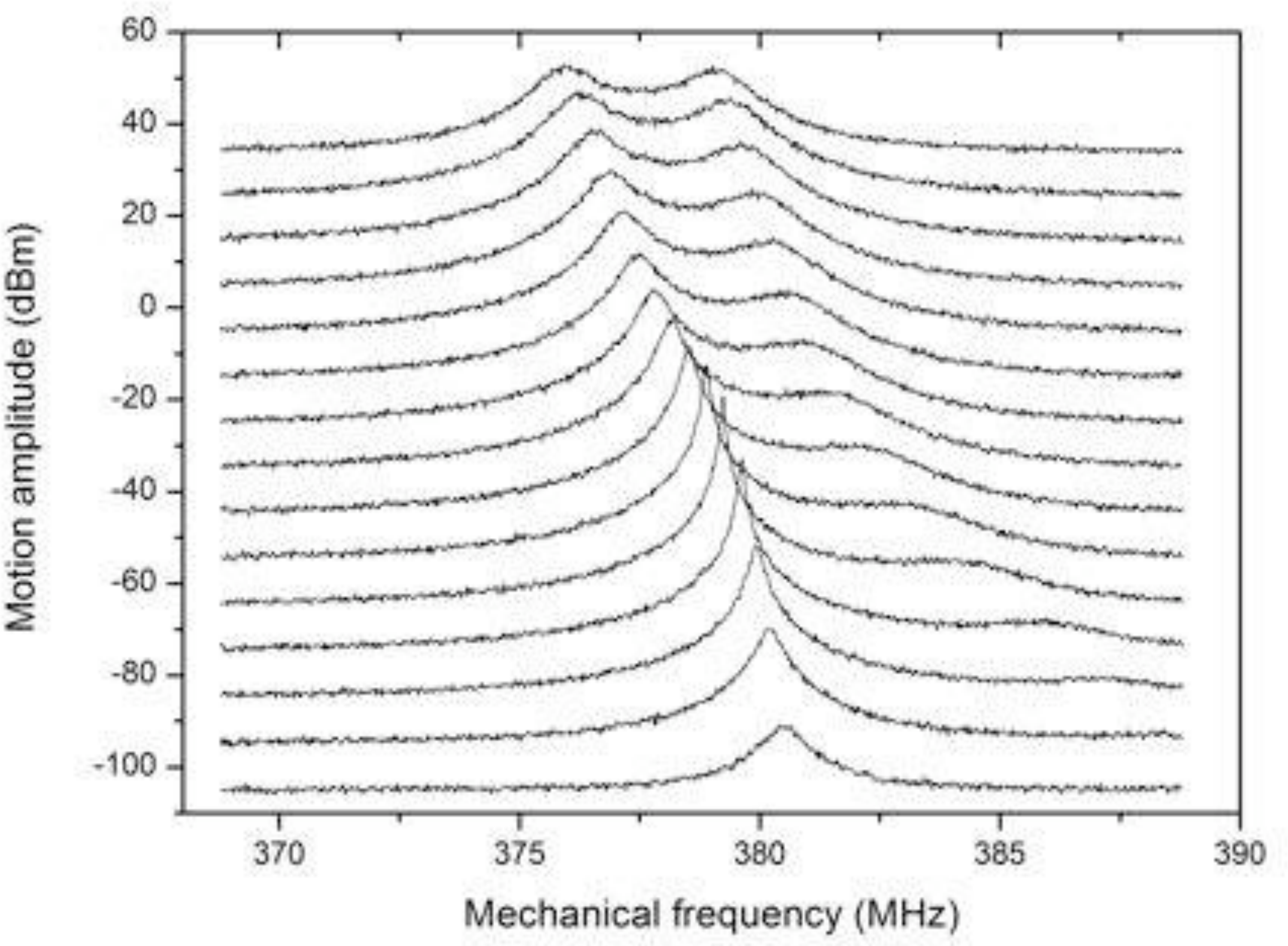
Rokhsari, H., Kippenberg, T.J., Carmon, T. and Vahala, K.J. Optics Express 13, 5293 (2005).

Optomechanical self-oscillation of a GaAs disk





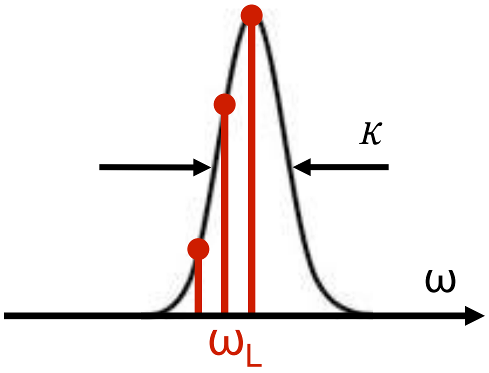
Strong coupling versus self-oscillation in a GaAs disk



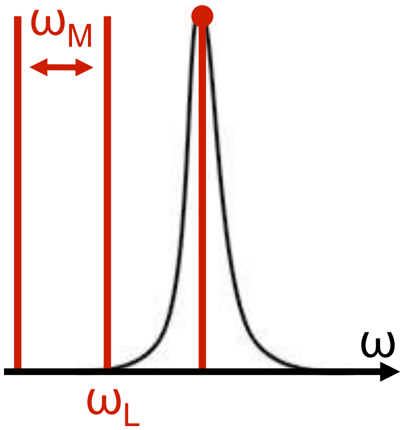
Gröblacher et al. Nature 460, 724–727 (2009). Teufel, J. D. et al. Nature 475, 359–363 (2011). E. Verhagen et al, Nature 482, 63 (2012).

Perspectives for ground state cooling ?

Radiation pressure



Bad cavity limit $\omega_M < \kappa$



Good cavity limit $\omega_M > \kappa$

Optical Q ~$5*10^5$
f_M~2 Ghz
λ~1 to 1.5 µm

Mechanical Q ~10^4 ?

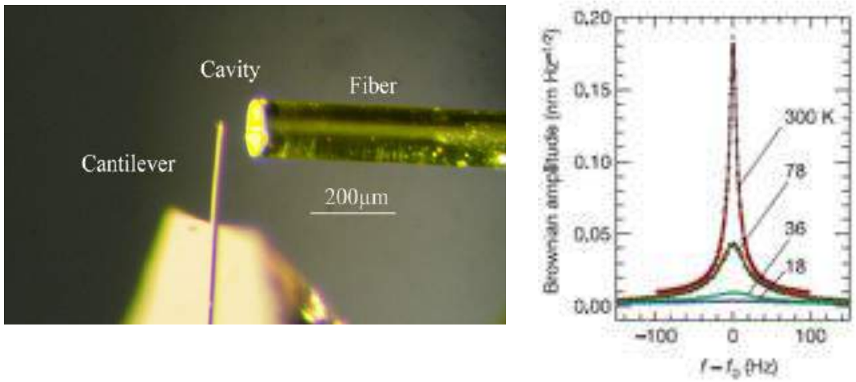
→

$\omega_M > 5* \kappa$
N=40 @ 4Kelvin
$N_{min} \leq 1/100$

F. Marquardt, J. P. Chen, A. A. Clerk, and S. M. Girvin, Phys. Rev. Lett. 99, 093902 (2007).
I. Wilson-Rae et al. Phys. Rev. Lett. 99, 093901 (2007).
C. Genes et al. Phys. Rev. A 77, 033804 (2008). A. Dantan et al. Phys. Rev. A 77, 011804 (2008).

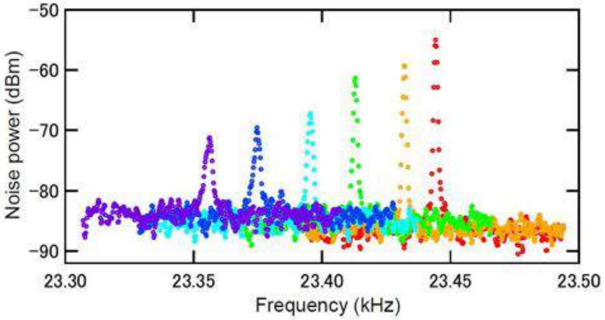
Cooling by other « dissipative » forces in GaAs ?

Photothermal forces

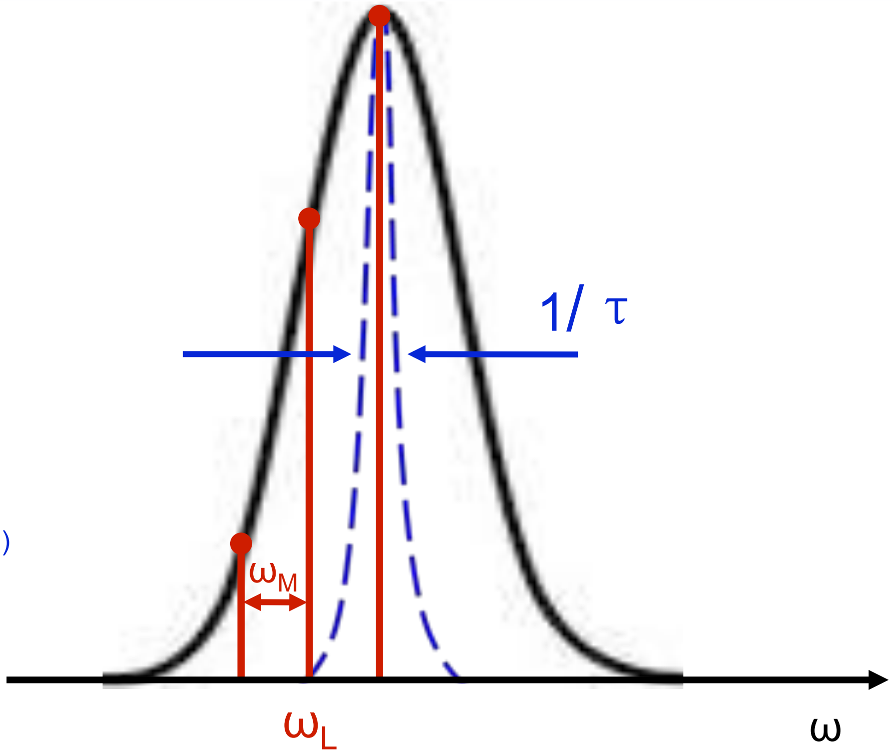


C. Metzger and K. Karrai, *Cavity cooling of a microlever,* Nature **432,** 1002 (2004)

Opto-electronic forces



K. Usami et al. Nature Physics 10, 2196 (2012).
H. Okamoto et al. Phys. Rev. Lett. 106, 036801 (2011).



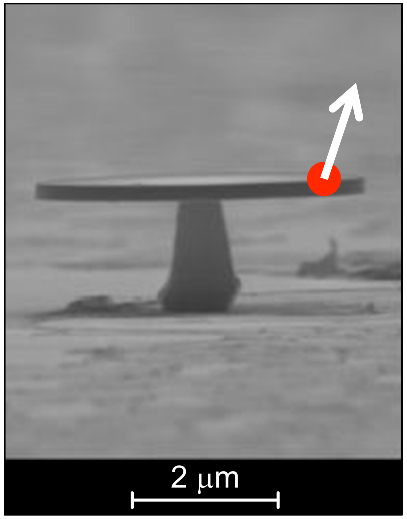
J. Restrepo, J. Gabelli, C. Ciuti and I. Favero.
Comptes Rendus Physique 12, 860 (2011).

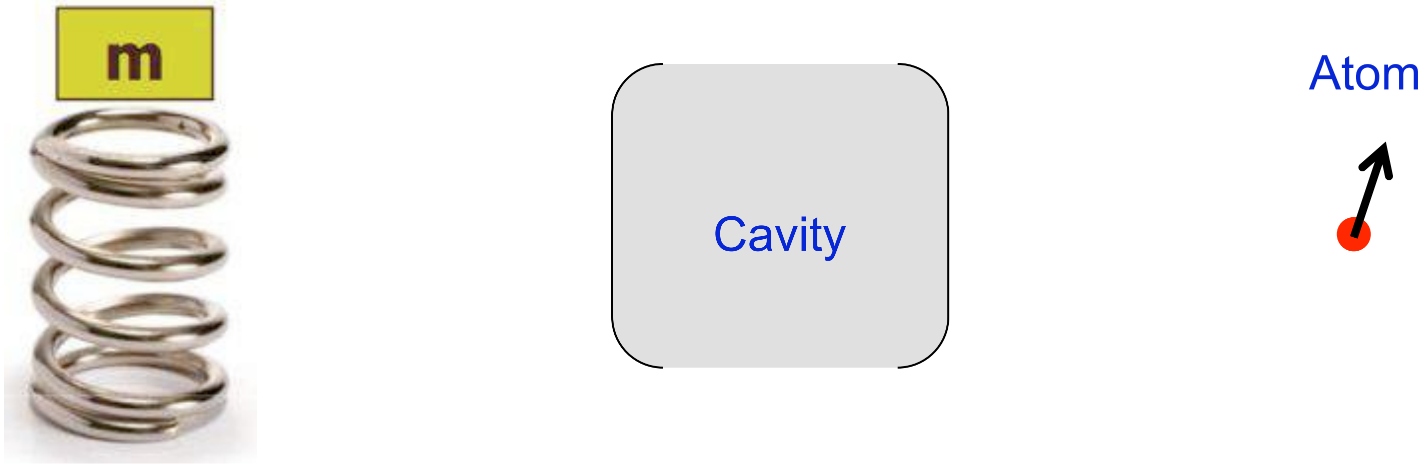
S. DeLiberato, et al. Phys Rev A 83, 033809 (2011).

C. Genes, H. Ritsch, and D. Vitali, Phys. Rev. A 80, 061803 (2009)
F. Elste, S. M. Girvin and A. A. Clerk, Phys. Rev. Lett. 102, 207209 (2009)
A. Xuereb, R. Schnabel, K.Hammerer, Phys. Rev. Lett. 107, 213604 (2011)

Conclusions/Perspectives

- GaAs optomechanical resonators
  - Motional Sensitivity of 10^{-17} m/√Hz
  - Mechanical modes in the GHz range
  - Strong coupling of optics and mechanics
  - Optomechanical resonator with a single quantum dot





Optical dissipation: TEM analysis

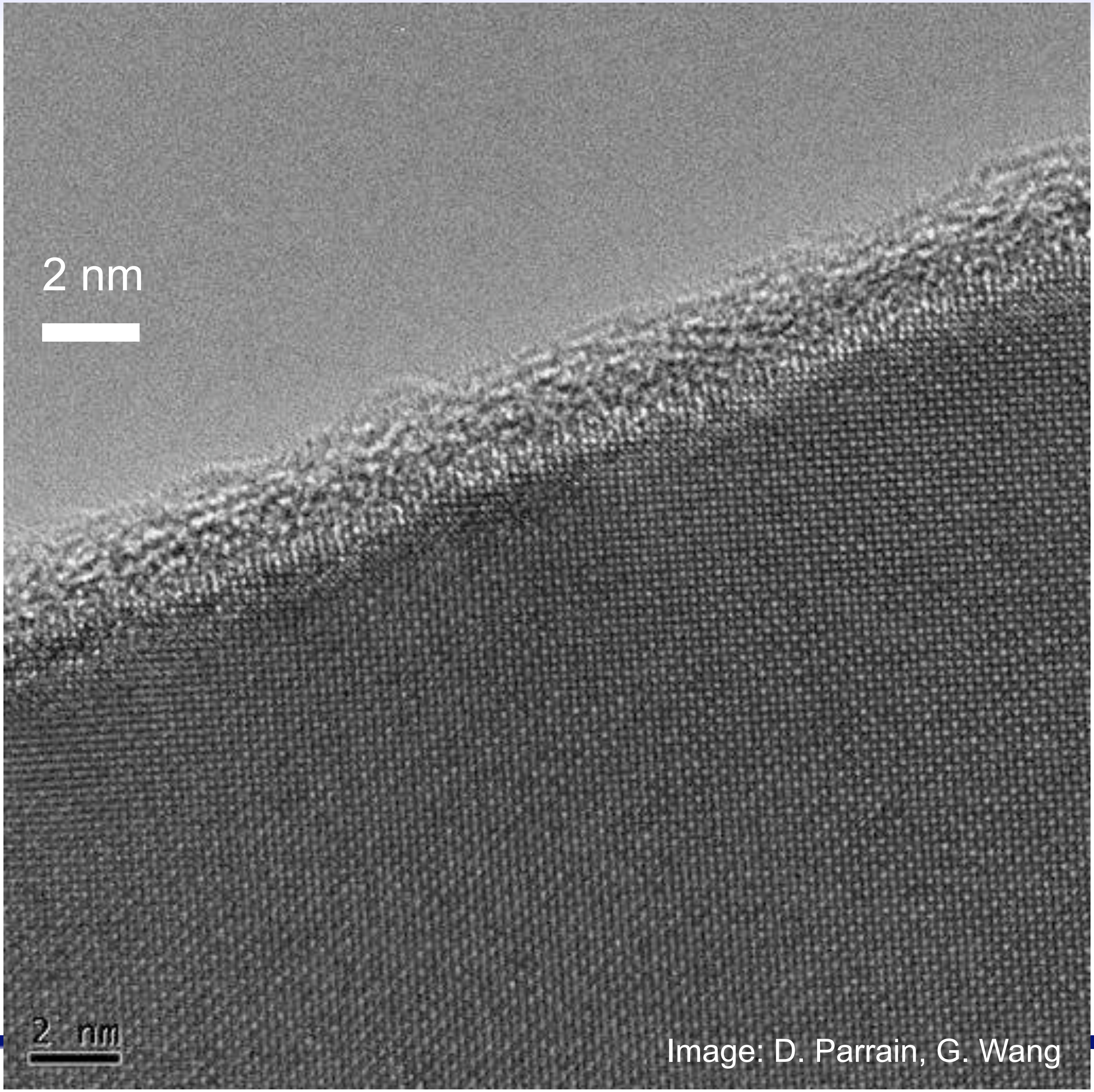


Image: D. Parrain, G. Wang

σ=0.15 nm (RMS)
L_c= 0.91 nm

Optical Q of 10^7-10^9

↓

Surface Absorption

↓

Surface Passivation

Thank you